

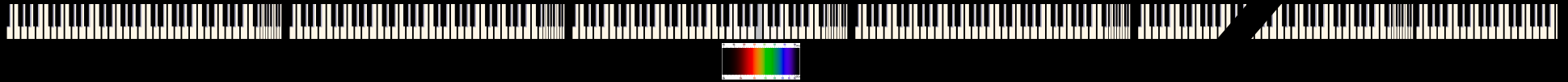


L'Astronomie gamma: Une nouvelle fenêtre sur l'Univers des phénomènes violents

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CNRS, Université P7, Observatoire de Paris, CEA**

Thanks to many: W.Hofmann, M. Punch,....

Les gammes de lumière



Radio

IR

Visible/UV

Rayons-X

Rayons- γ

| Chaque longueur d'onde | \Leftrightarrow fréquence | \Leftrightarrow énergie |
|--|--|---|
| Lumière Jaune : $\sim 5.80 \cdot 10^{-7} \text{m}$ | $\Leftrightarrow 5 \times 10^{14} \text{Hz}$ | $\Leftrightarrow 2.2 \text{ eV}$ |
| Radio (FM) : $\sim 3 \text{ m}$ | $\Leftrightarrow 10^8 \text{Hz}$ | $\Leftrightarrow 4 \times 10^{-7} \text{ eV}$ |
| Rayon γ : $\sim 1.2 \times 10^{-17} \text{m}$ | $\Leftrightarrow 2.5 \times 10^{25} \text{Hz}$ | $\Leftrightarrow 100 \cdot 10^9 \text{ eV}$ |

Un piano de concert (>1845) : 7 octaves
Visible: 1 Octave

Hautes énergies

Rayons X: 10 eV- $\sim 1 \text{ MeV}$ ~ 2 Octaves

Rayons γ : 1 MeV - $> 100 \text{ TeV}$ 27 Octaves!



Roentgen
1895

100 GeV-100 TeV

Notre vision avant la 2ème guerre: univers thermique

étoiles

gaz

poussières

3000-

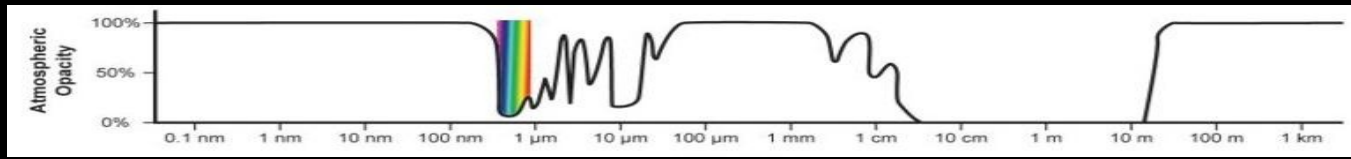
10000 K



Comment cette “vision” a-t-elle changé?

Un peu d'histoire

Naissance de la radioastronomie



1933-37: Karl Jansky (USA) :
découverte ondes radio extraterrestres
1943-46: Grote Reber (USA) :
Cartes à 160 et 480 MHz

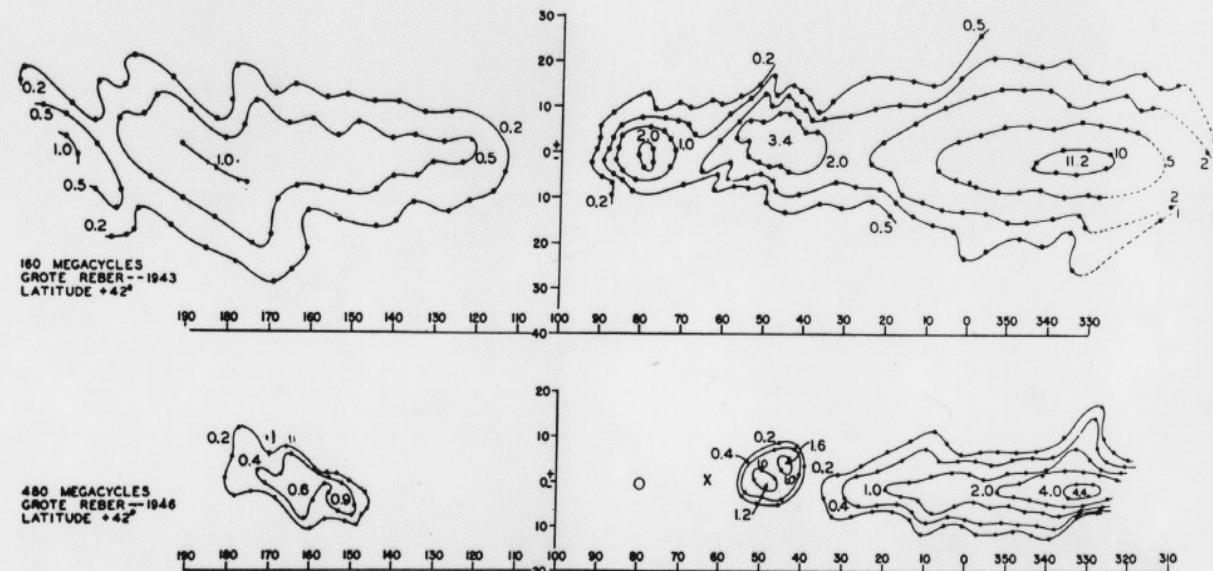
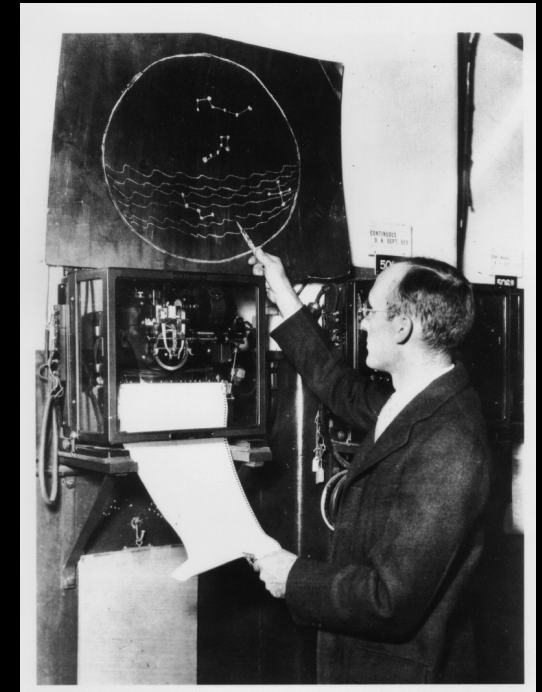
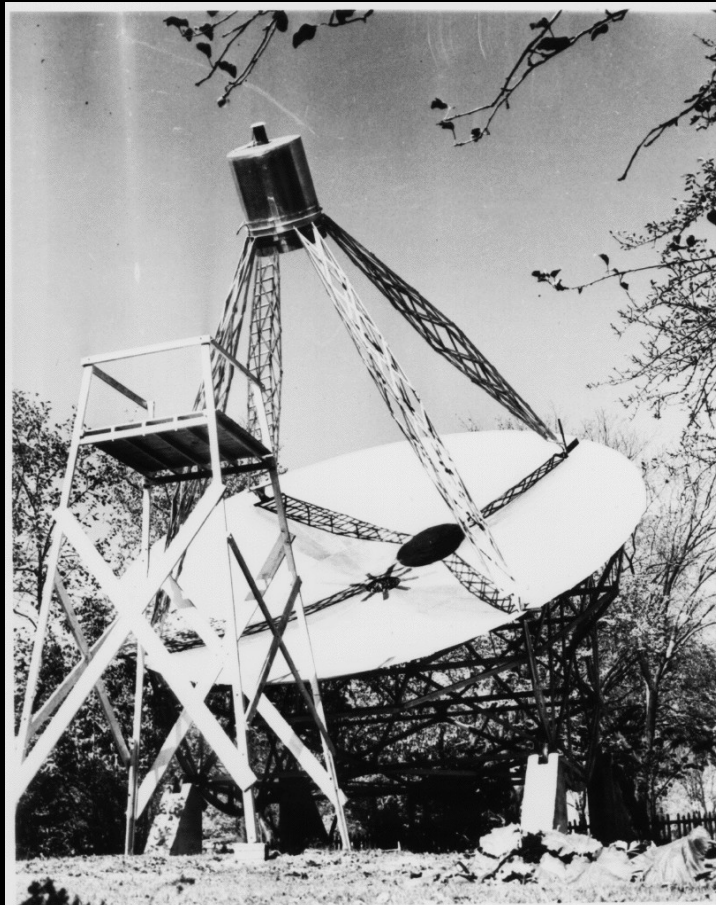
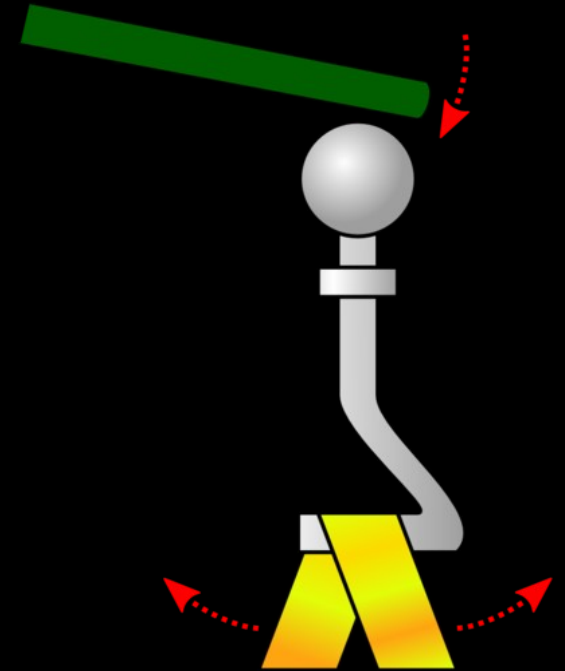
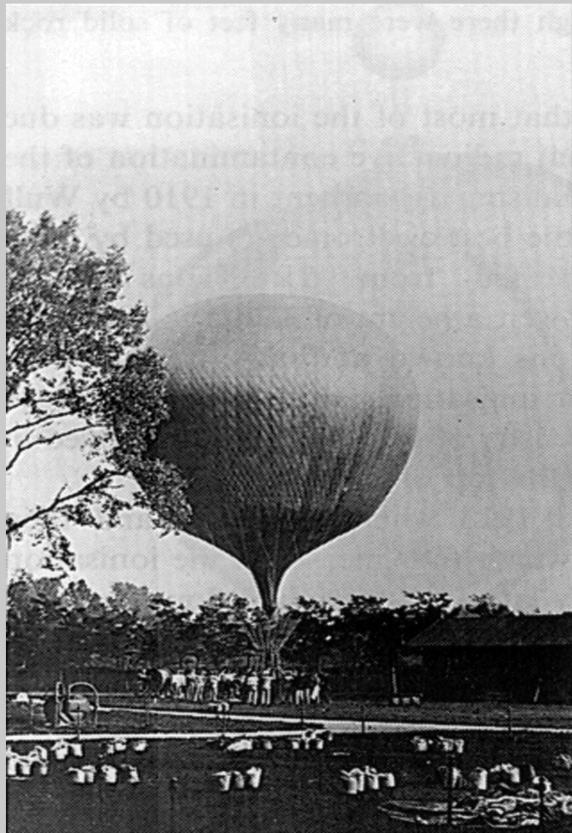


FIG. 7—Contours of constant intensity at 160 MHz and 480 MHz, taken at Wheaton, Illinois.

Rayons cosmiques : découverte

1896: Découverte de la radioactivité Henri Bequerel

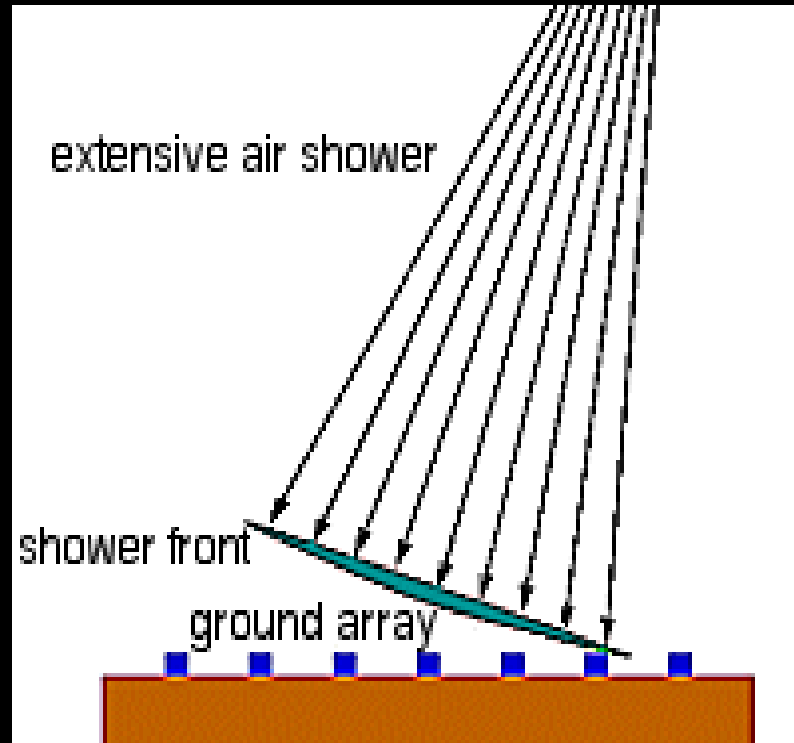
1912-13: Vols héroïques de Victor HESS et Werner Kolholster :
découverte origine extraterrestre des rayonnements ionisants
L'hypothèse admise seulement en 1927



Rayons cosmiques : apogée

1934 Bruno Rossi : Compteurs Geiger

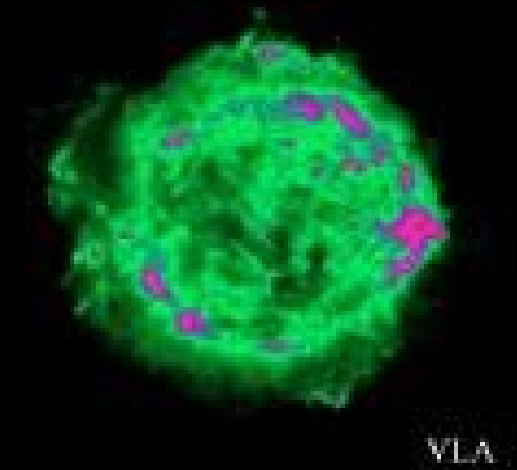
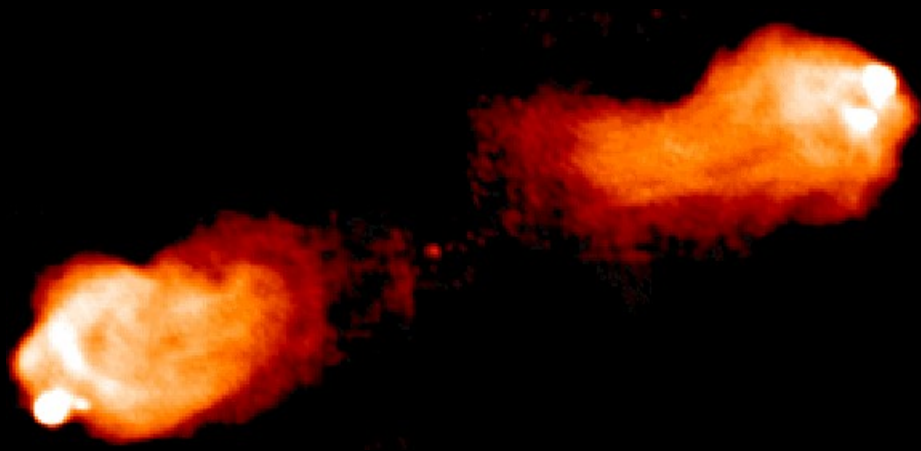
1937-38: Expériences de Pierre Auger : Particules d'énergies 10^{15} eV



Années 1950-54
Pont entre la radioastronomie
et
les rayons cosmiques

La radioastronomie

1946-50: Premières sources discrètes : Cyg A, Cas A, Crabe ...



Rayonnement synchrotron et polarisation

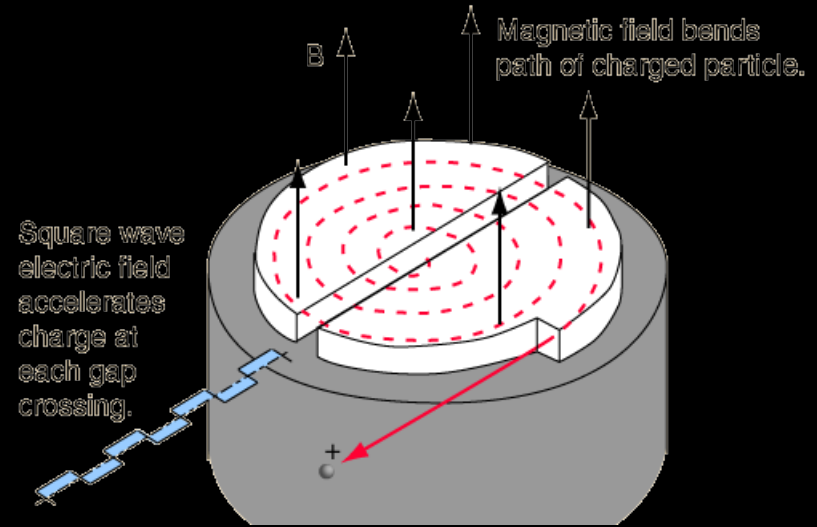
1946: John Blewett: Première observation du rayonnement synchrotron

1946-49: Julia Schwinger : calculs théoriques

1950 Karl-Otto Kiepenheuer, puis Guinzburg 1951:
émission diffuse : rayonnement synchrotron

1952: Iosif Shklovskii :
émission optique du Crabe : synchrotron

1954: Victor Dombrovski et Mikhail Vashakidze:
mesure en optique





VLA: 6 cm

Radio lobe size ~ 200 kpc!

The radio lobes are fed by relativistic jets; we see only one sided jet due to relativistic beaming.

Cen A

(distance ~ 2.5 Mpc)

HST & 6 cm VLA



Crab nebula (Plerion)

Blue: x-ray

Red: optical

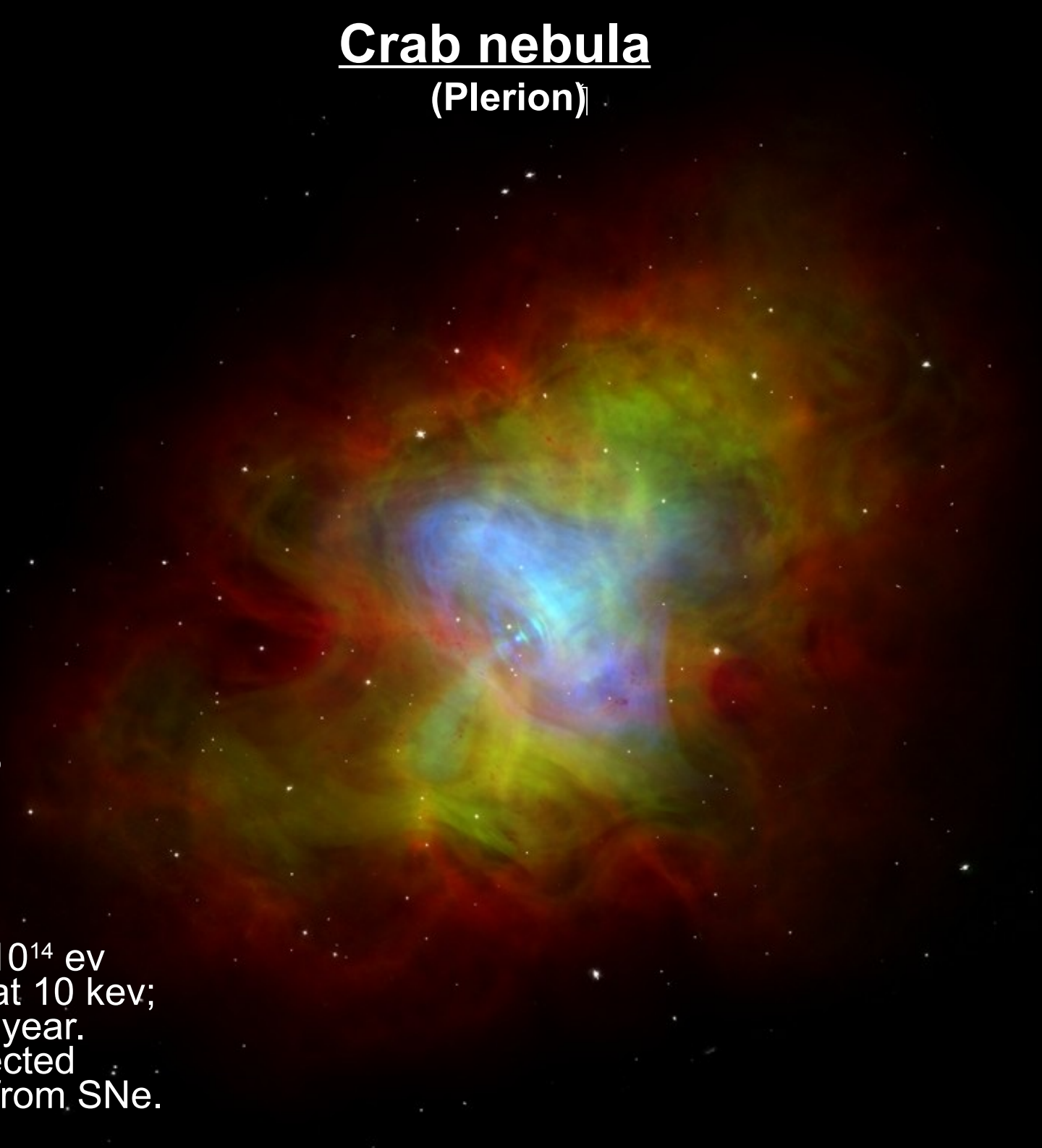
Green: radio

Luminosity $\sim 10^{38}$ erg/s
(mostly x-ray & gamma)

Synchrotron radiation:

(linear polarization of 9%
averaged over nebula).

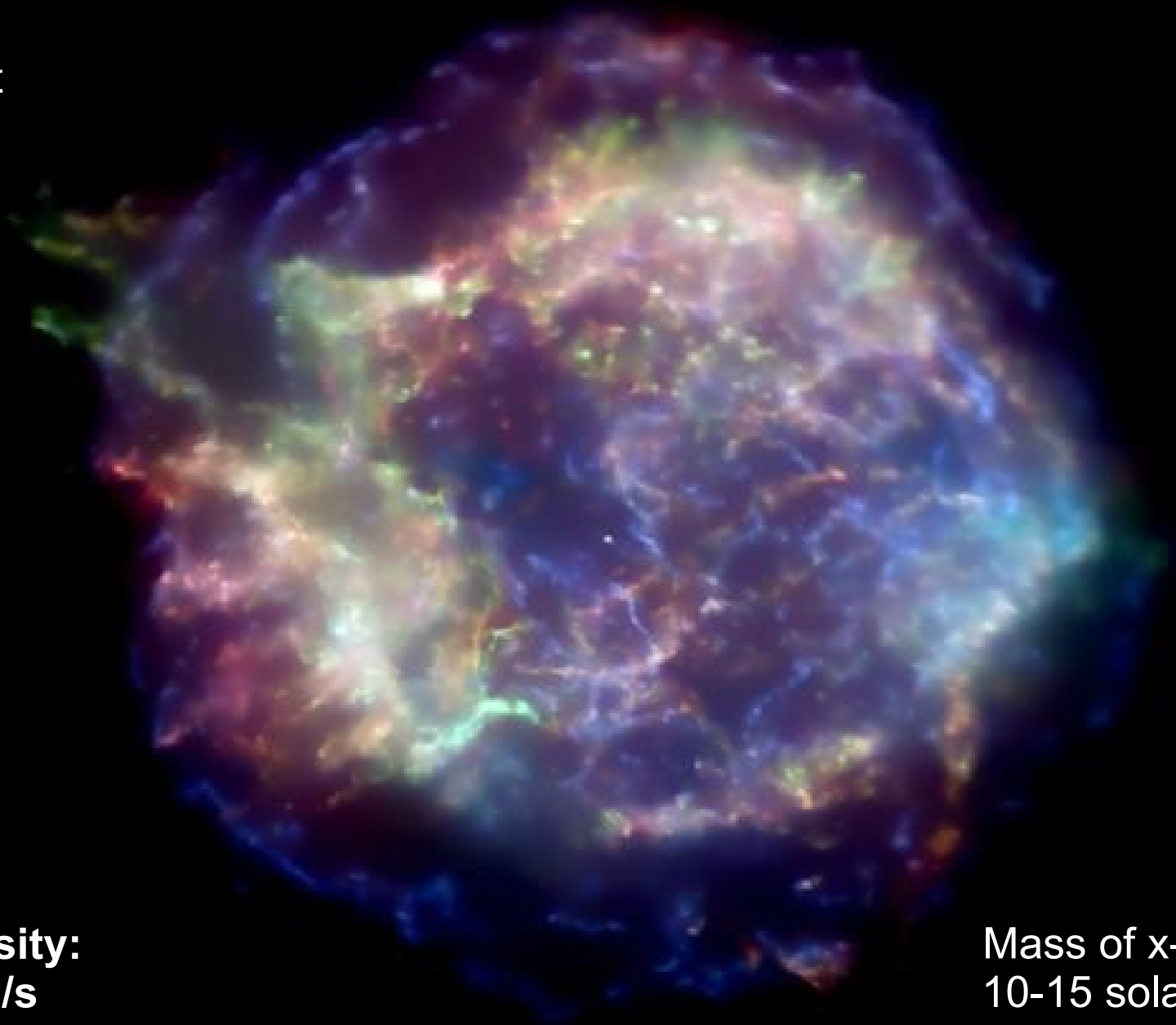
Electrons with energy $> 10^{14}$ eV
are needed for emission at 10 keV;
lifetime for these e's < 1 year.
So electrons must be injected
continuously & not come from SNe.



SN remnant: Cas A (3-70 keV; Chandra) (Plerion)

SNe II remnant

Age 300 yr
(1670 AD)



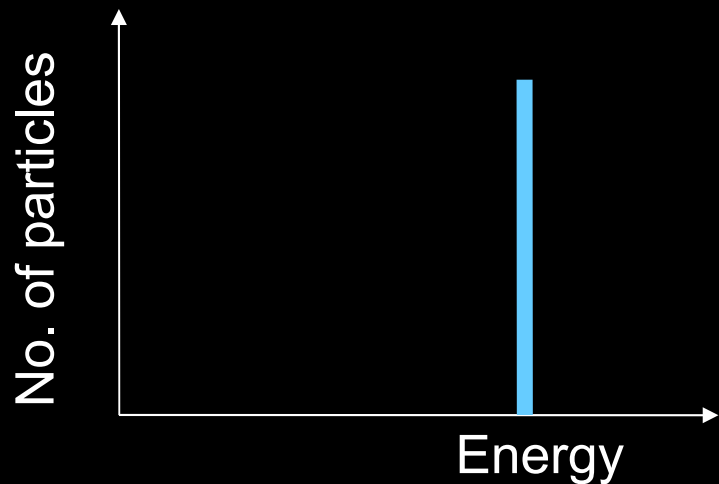
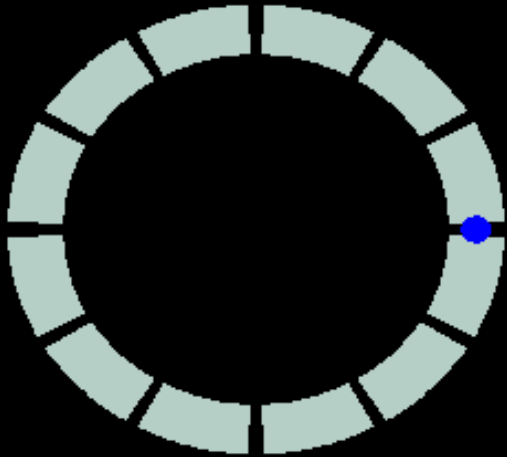
X-ray luminosity:
 3.8×10^{36} erg/s

Mass of x-ray gas
10-15 solar mass.

Une nouvelle fenêtre sur l'Univers non-thermique:
Les rayons gamma de très haute énergie

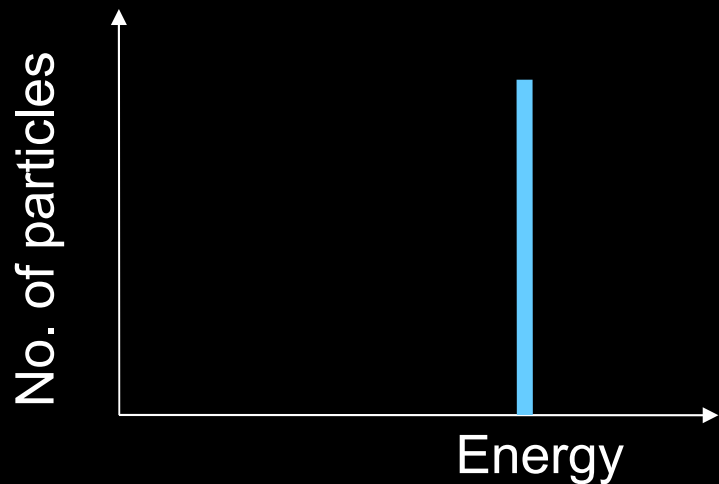
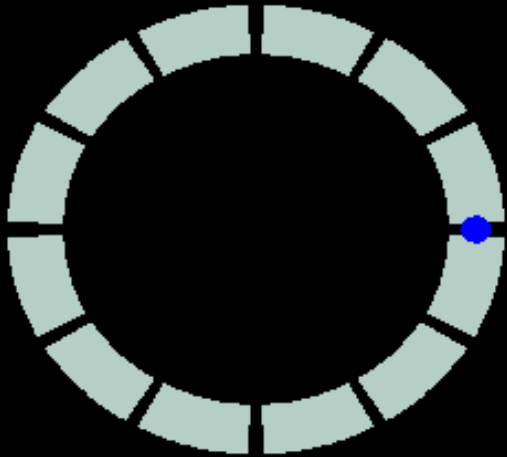
How could cosmic accelerators work?

Man-made accelerators

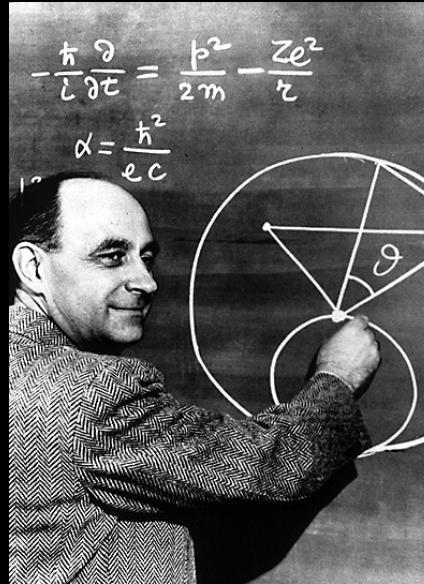


How could cosmic accelerators work?

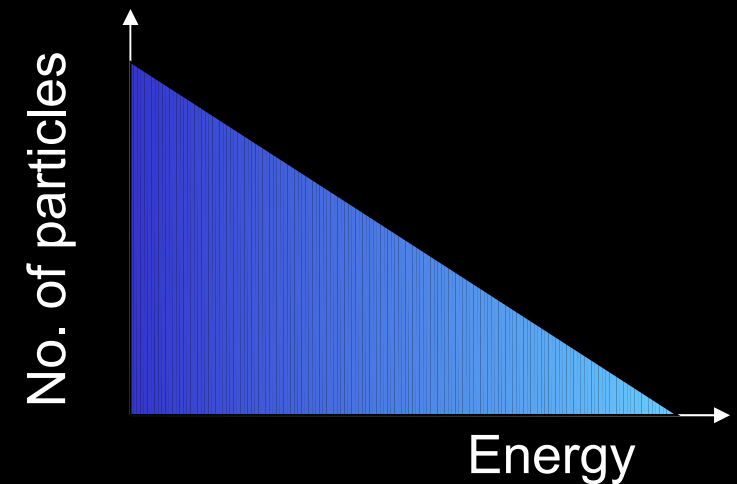
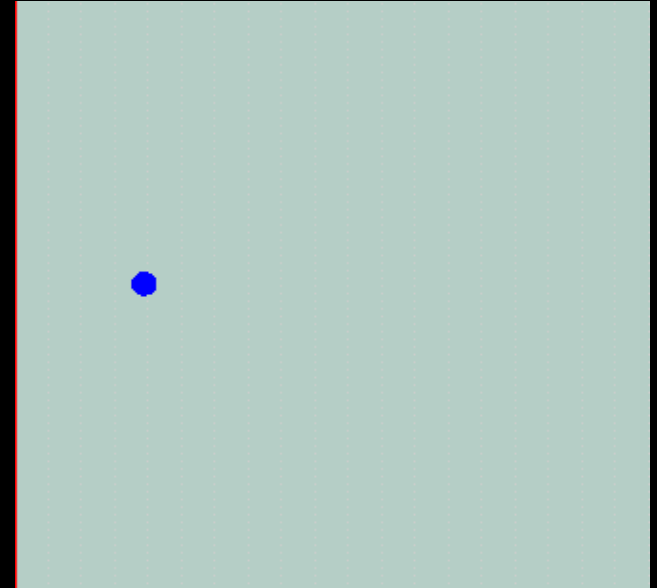
Man-made accelerators



Nature's accelerators



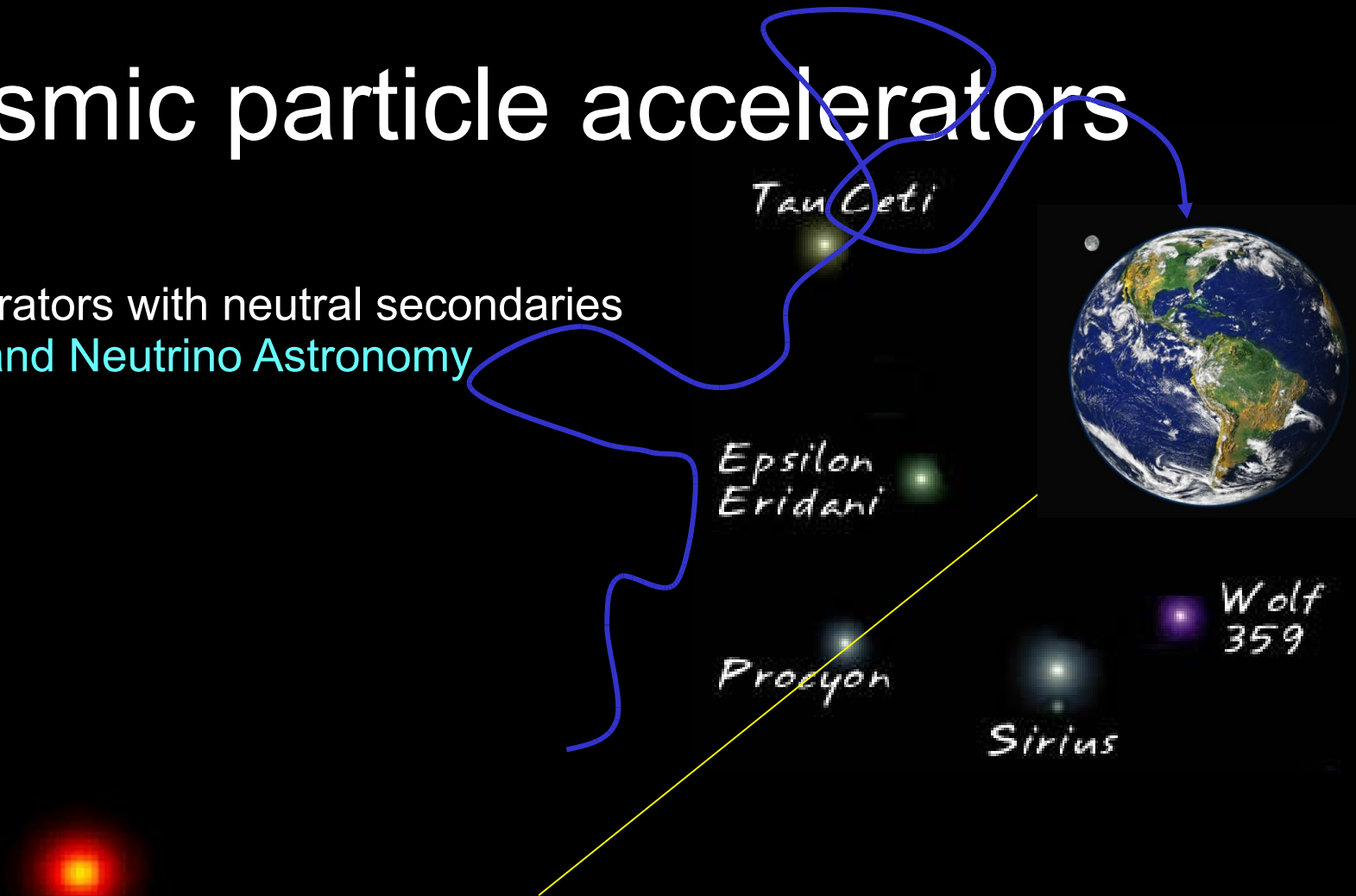
Enrico
Fermi



Cosmic particle accelerators

→ Image accelerators with neutral secondaries

→ Gamma-ray and Neutrino Astronomy

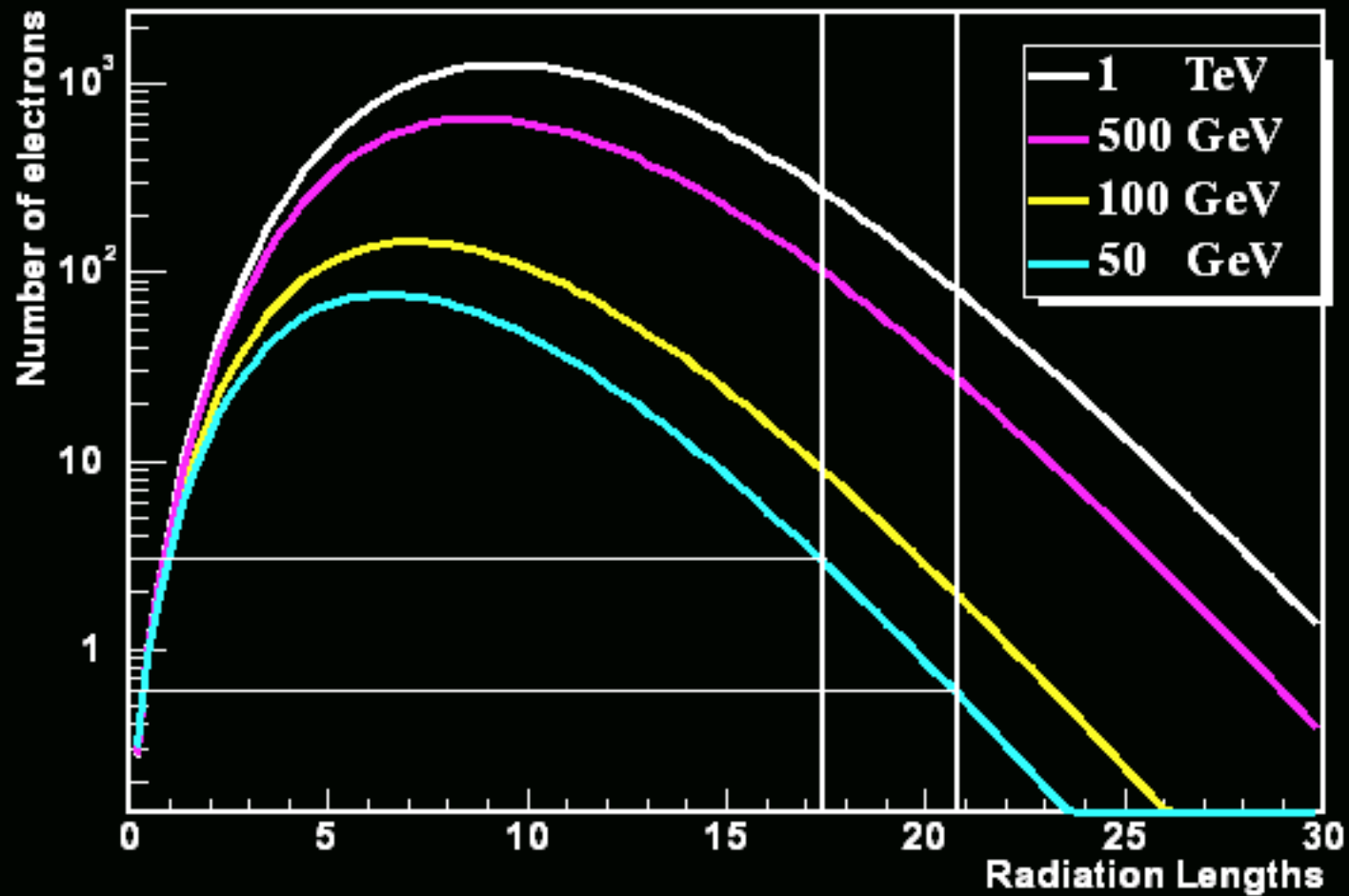


$$p + \text{nucleus} \rightarrow \pi + X$$

$$\pi^0 \rightarrow \gamma\gamma$$

$$\pi^\pm \rightarrow \mu^\pm \nu$$

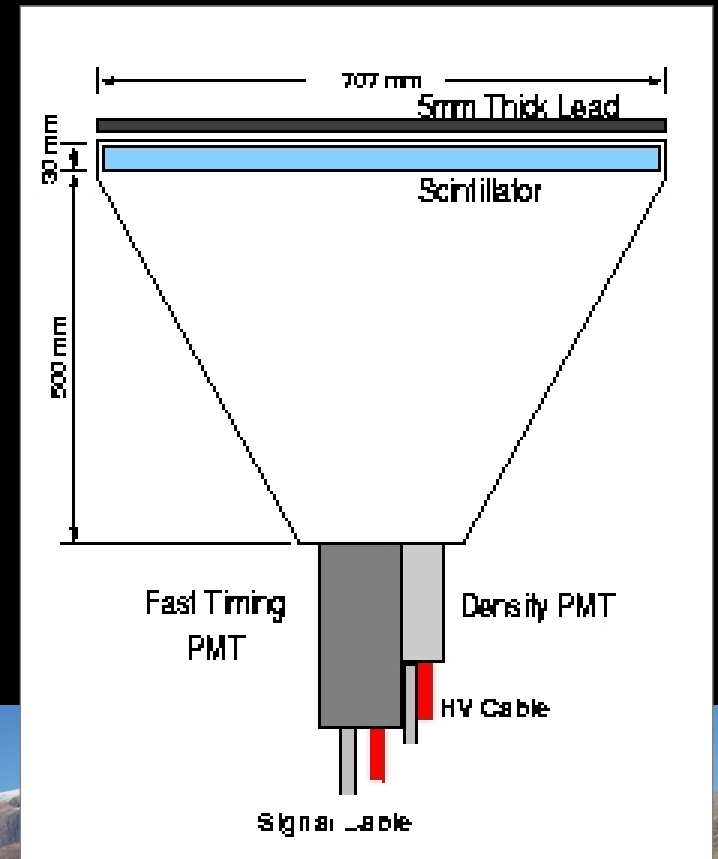
Ground-level detection of shower particles



Tibet AS – γ air shower array

Yangbajing, 90° E, 30° N, 4300 m asl

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

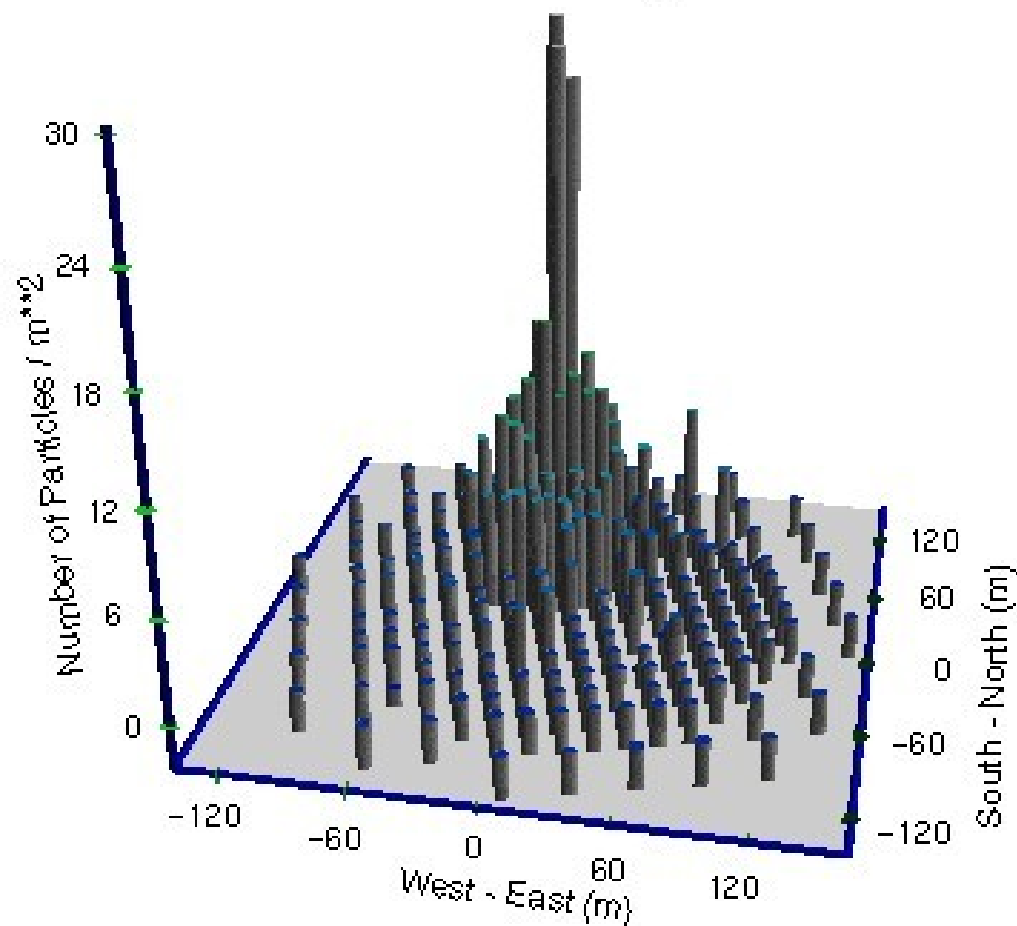


Shower reconstruction

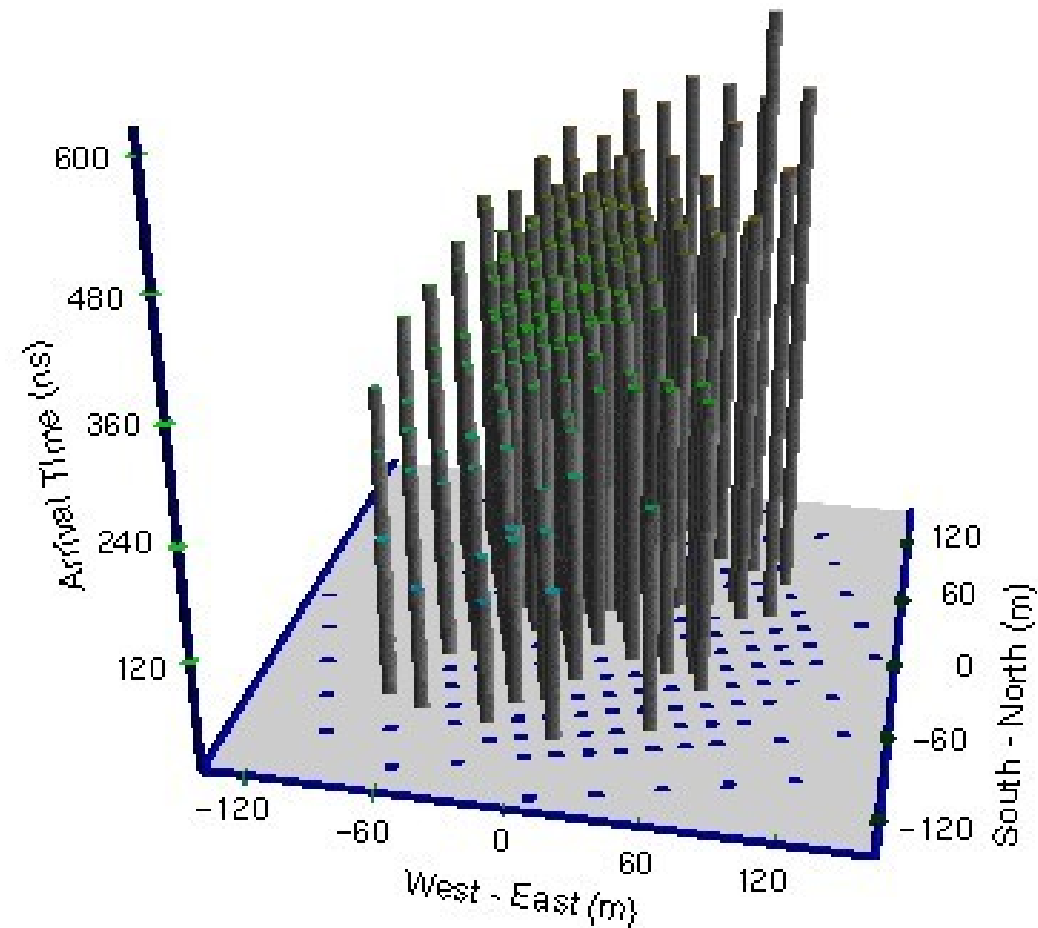
Tibet
AS-gamma

Density Map

$$\Sigma \rho_{fi} \sim 660$$

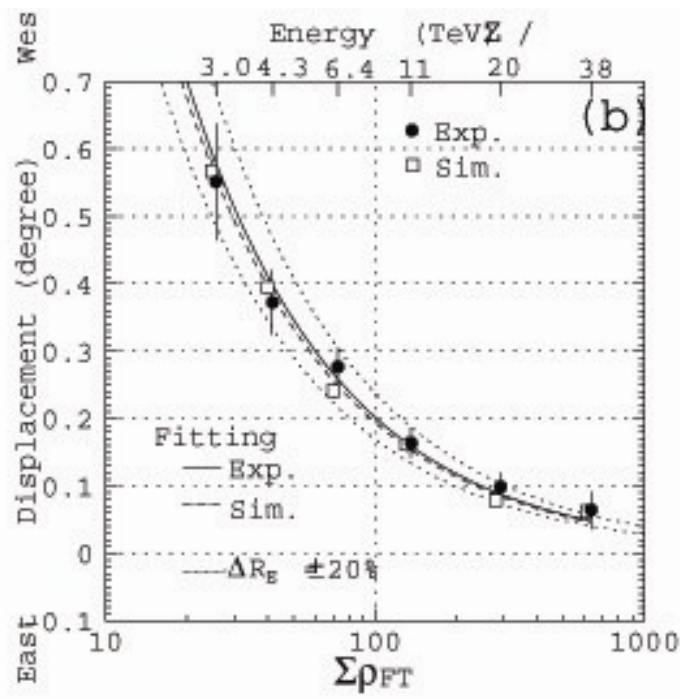
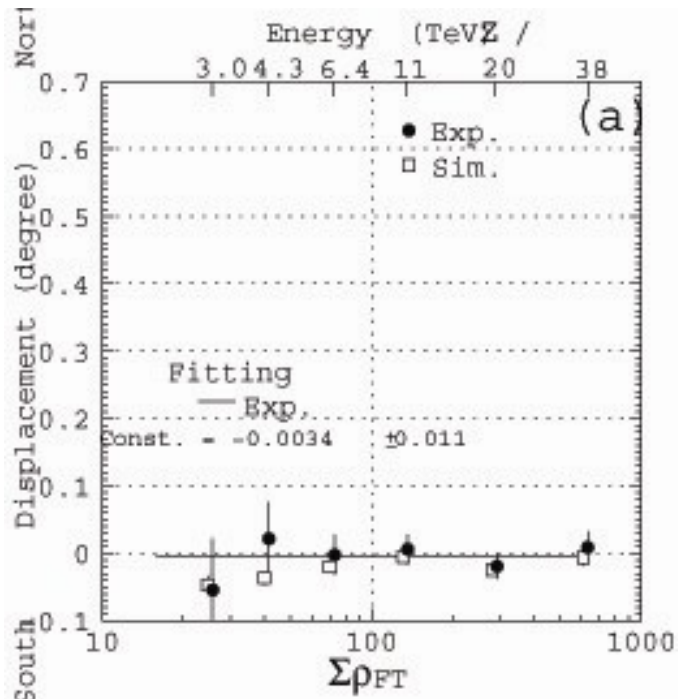
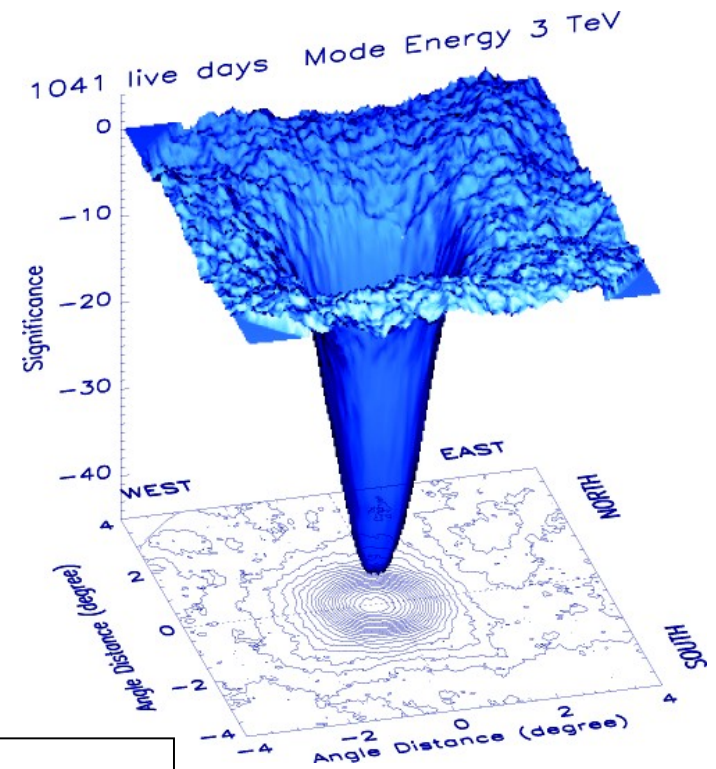


Timing Map



Moon shadow

Deflection of CR protons
in geomagnetic field



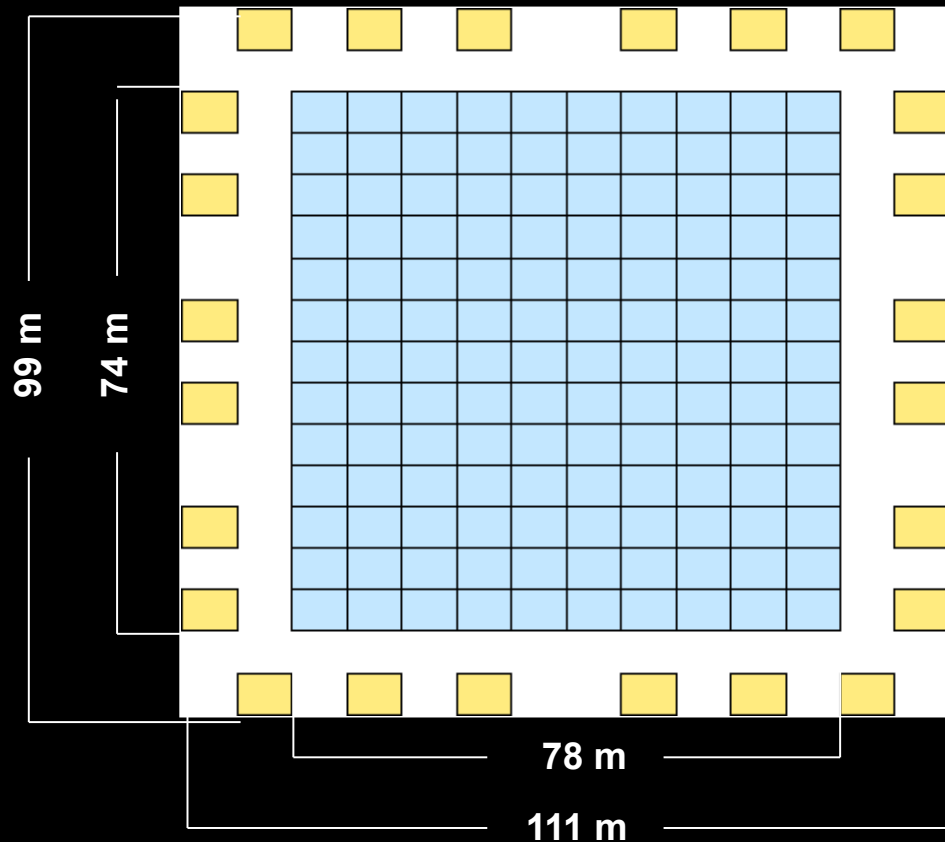
→ Energy

ARGO - YBJ



ARGO - YBJ

Detector layout



7000 m² active area
Resistive plate chambers
(RPC)



$E_{\text{thr}} \sim 0.5 \dots 1 \text{ TeV}$

Angular resolution: $0.5^\circ \dots 1^\circ$

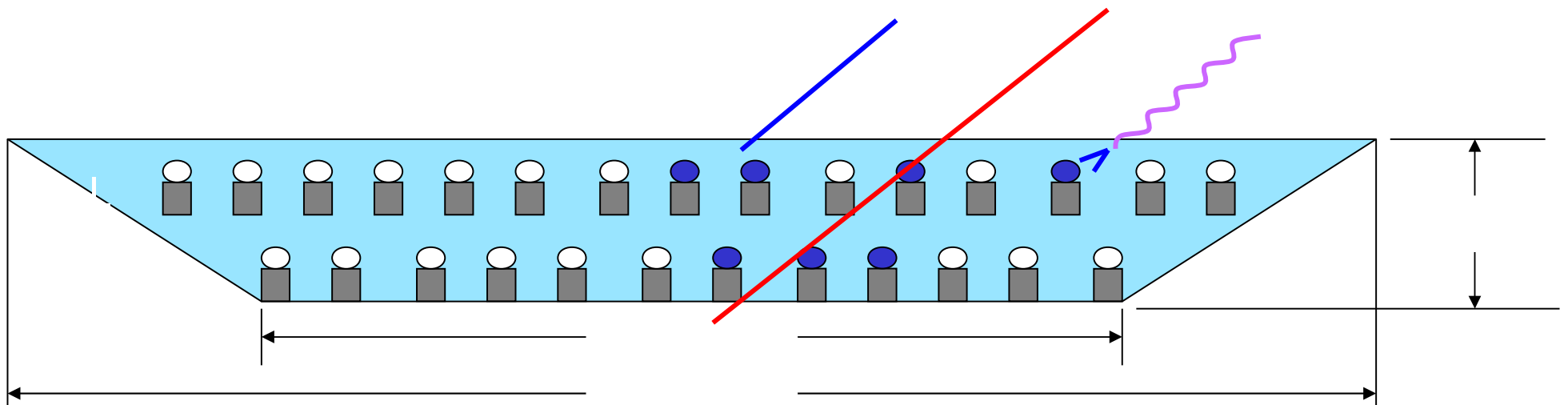
Sensitivity: 0.5 Crab in 1 year

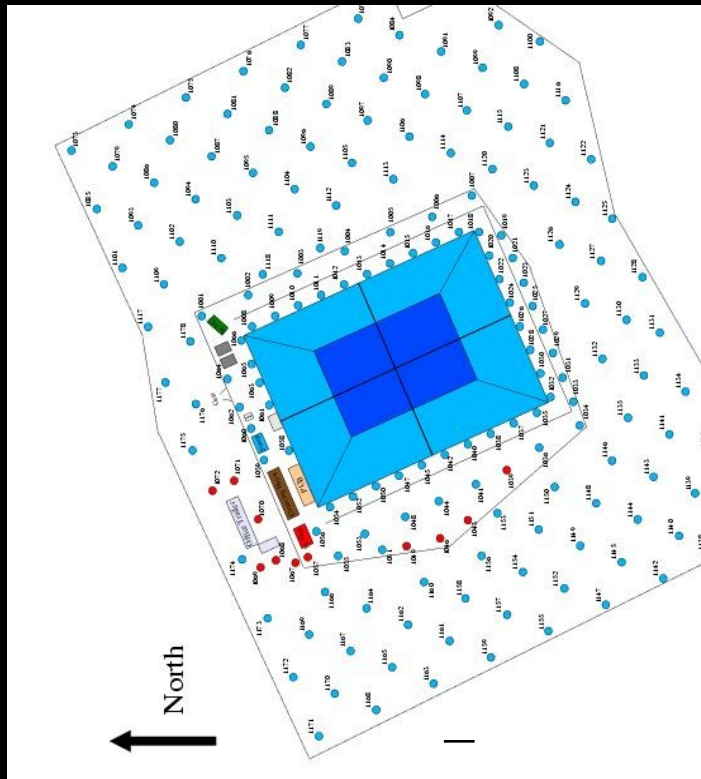
Water Cherenkov: Milagro

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

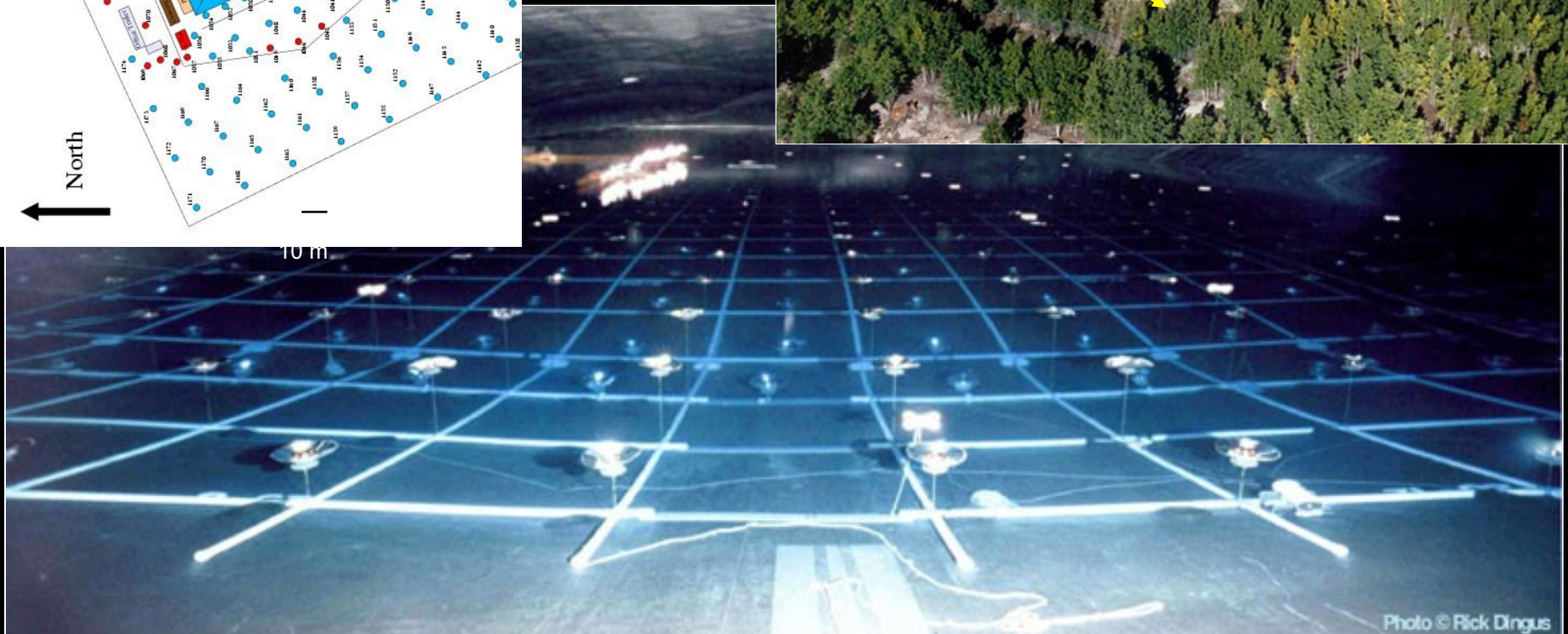
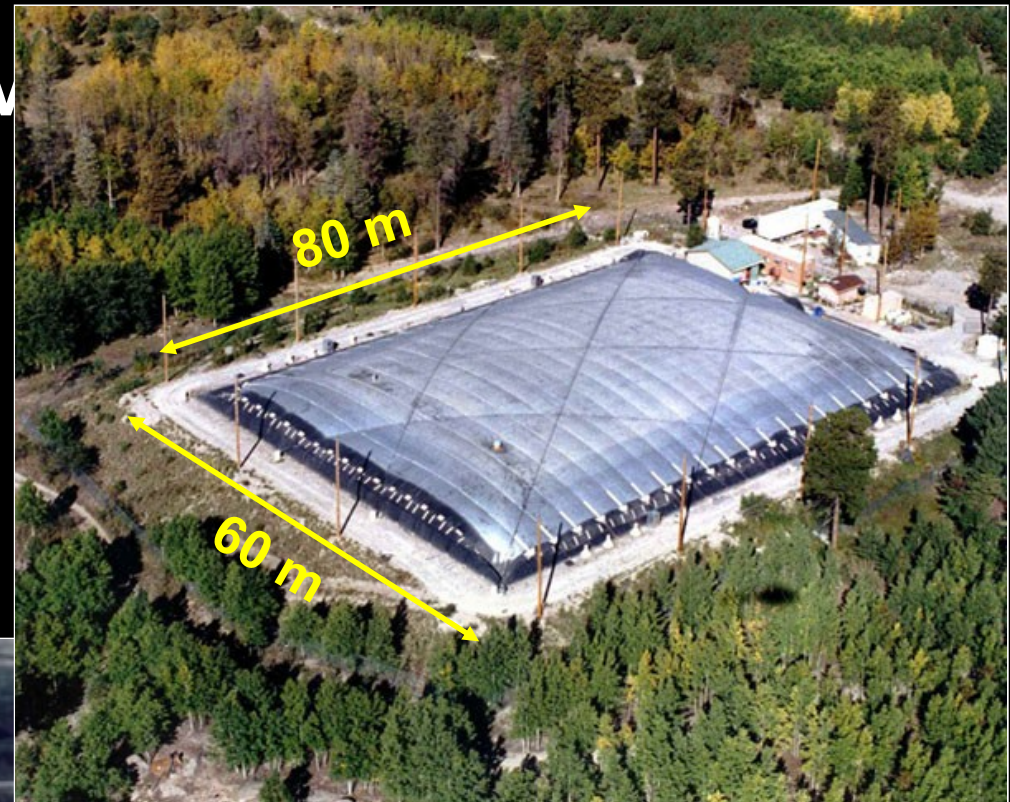
Observables:

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

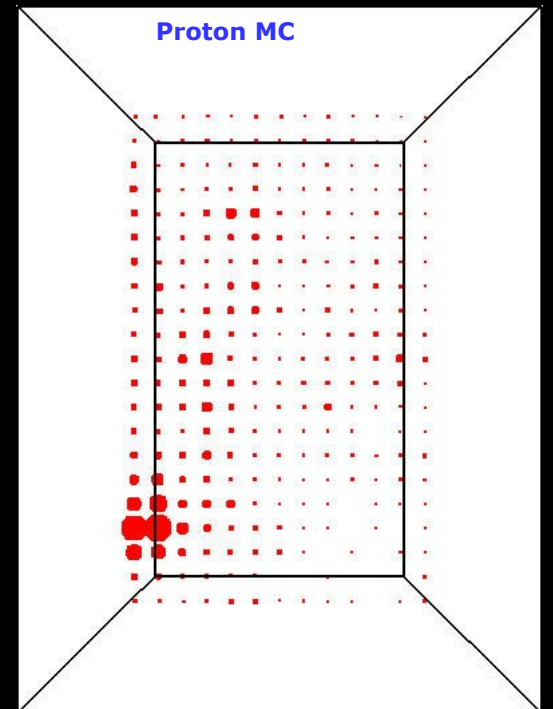
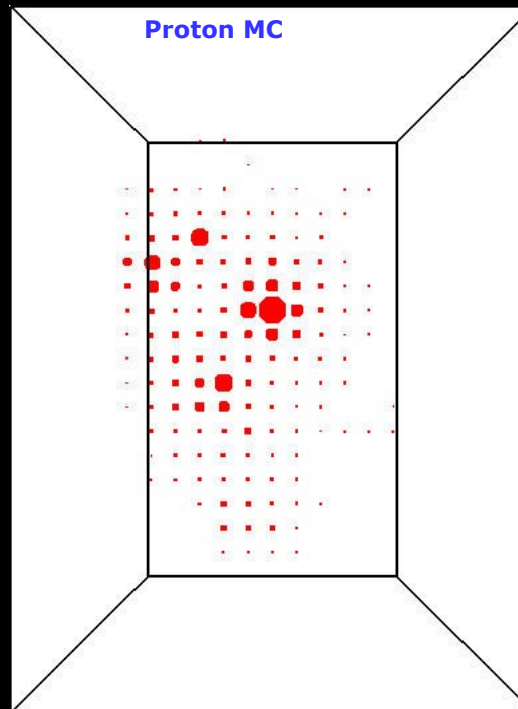
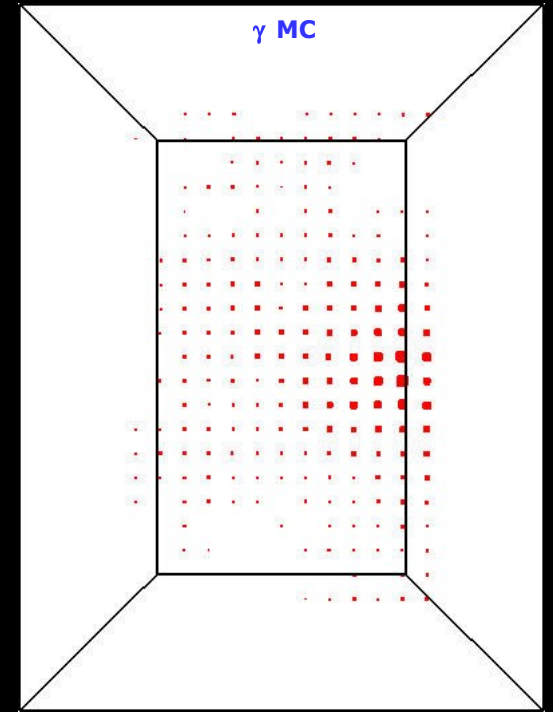
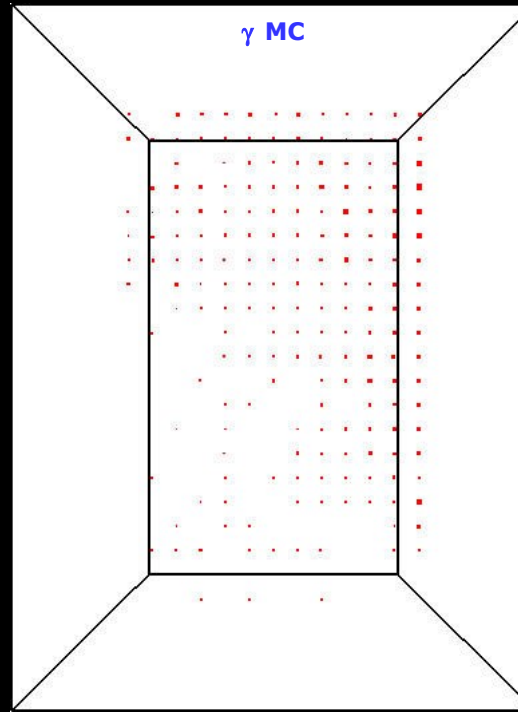




N



Background rejection



Gamma-ray

Particle shower

~ 10 km

Detection of
TeV gamma
rays

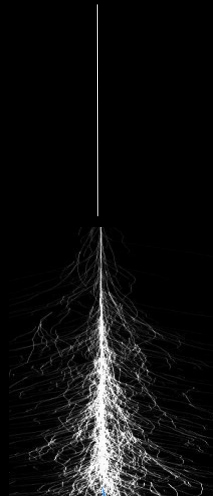
using Cherenkov
telescopes

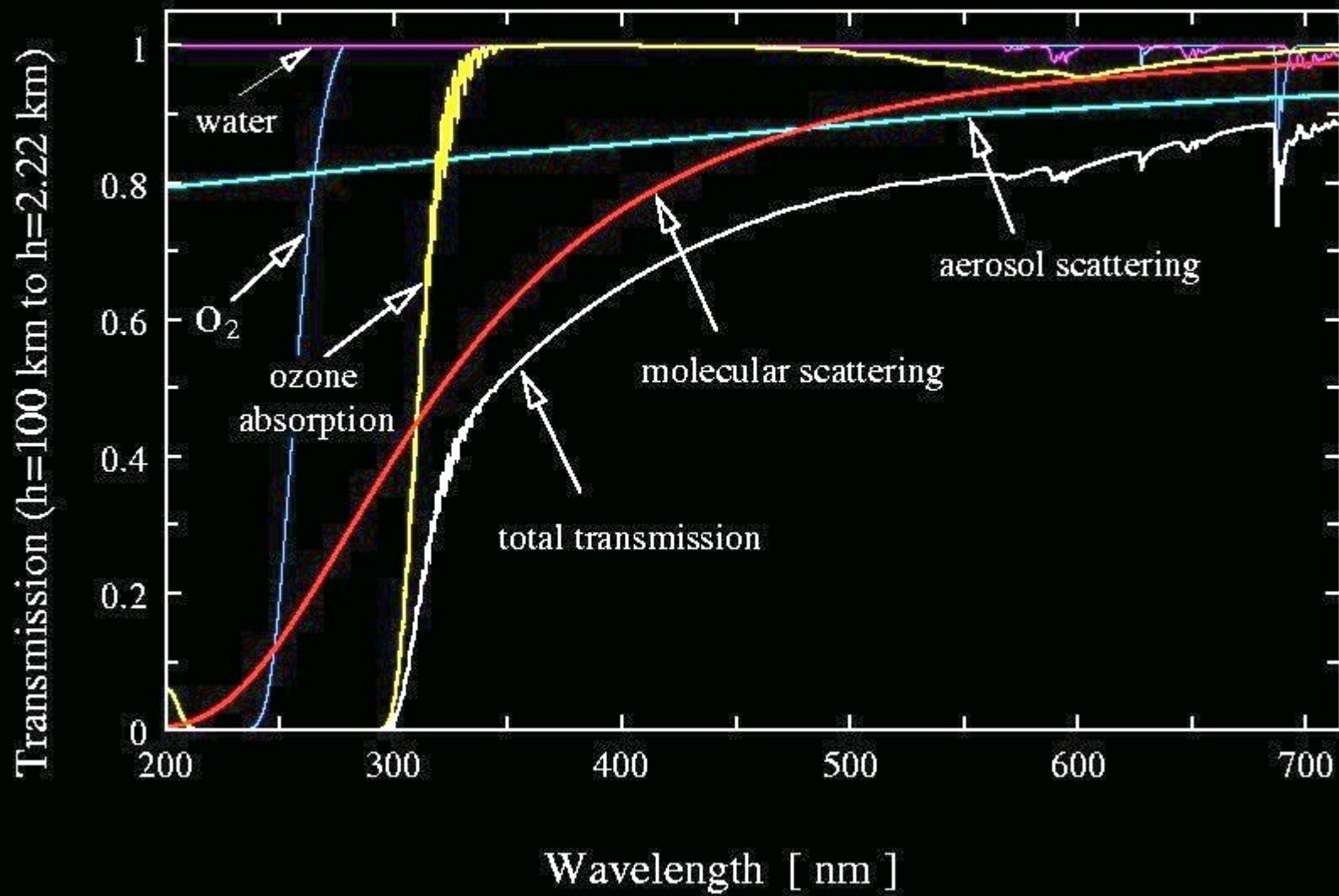
Cherenkov light

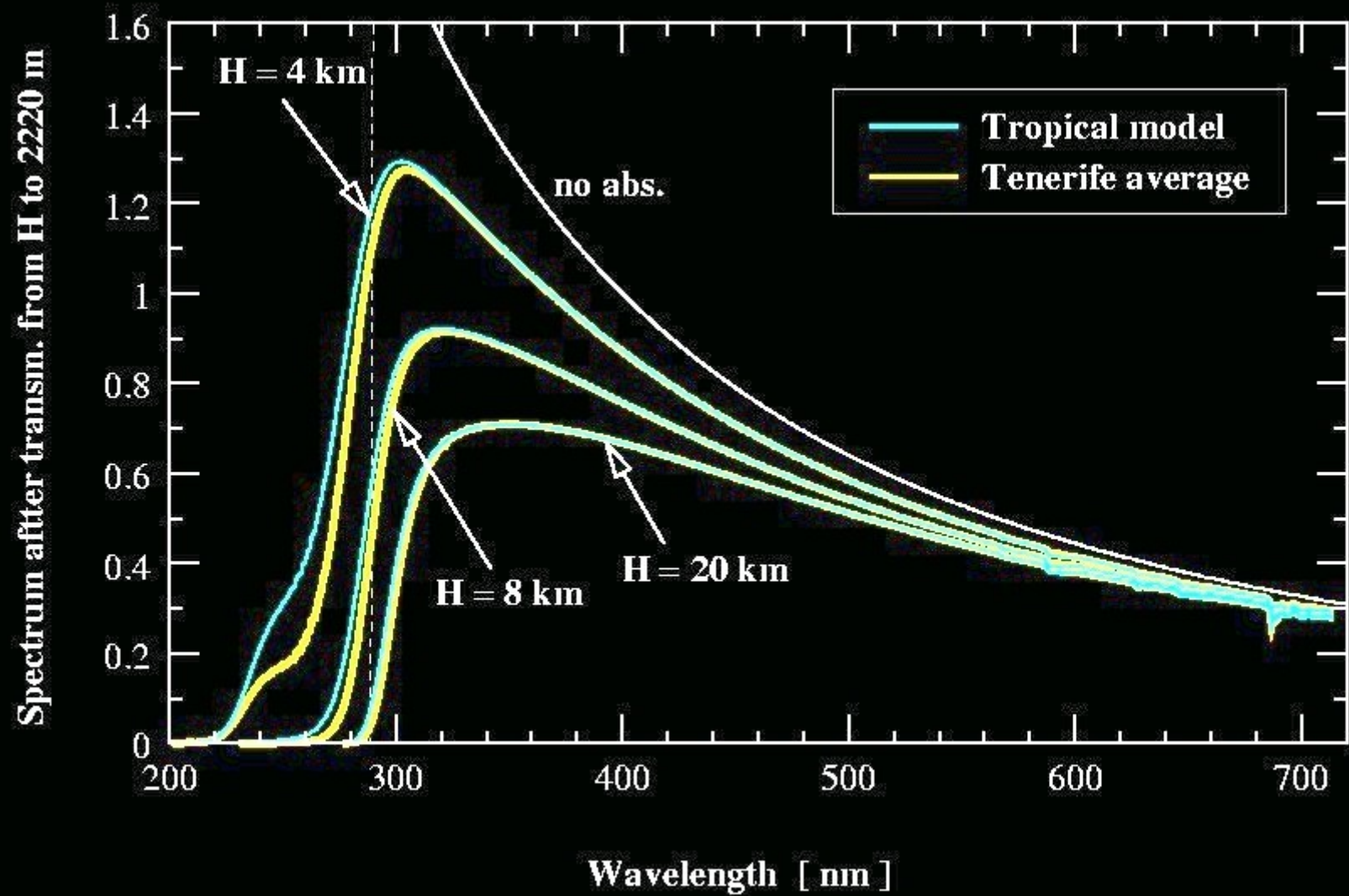
1°

~ 120 m

Key issue:
huge detection area
 $\sim 10^5 \text{ m}^2$

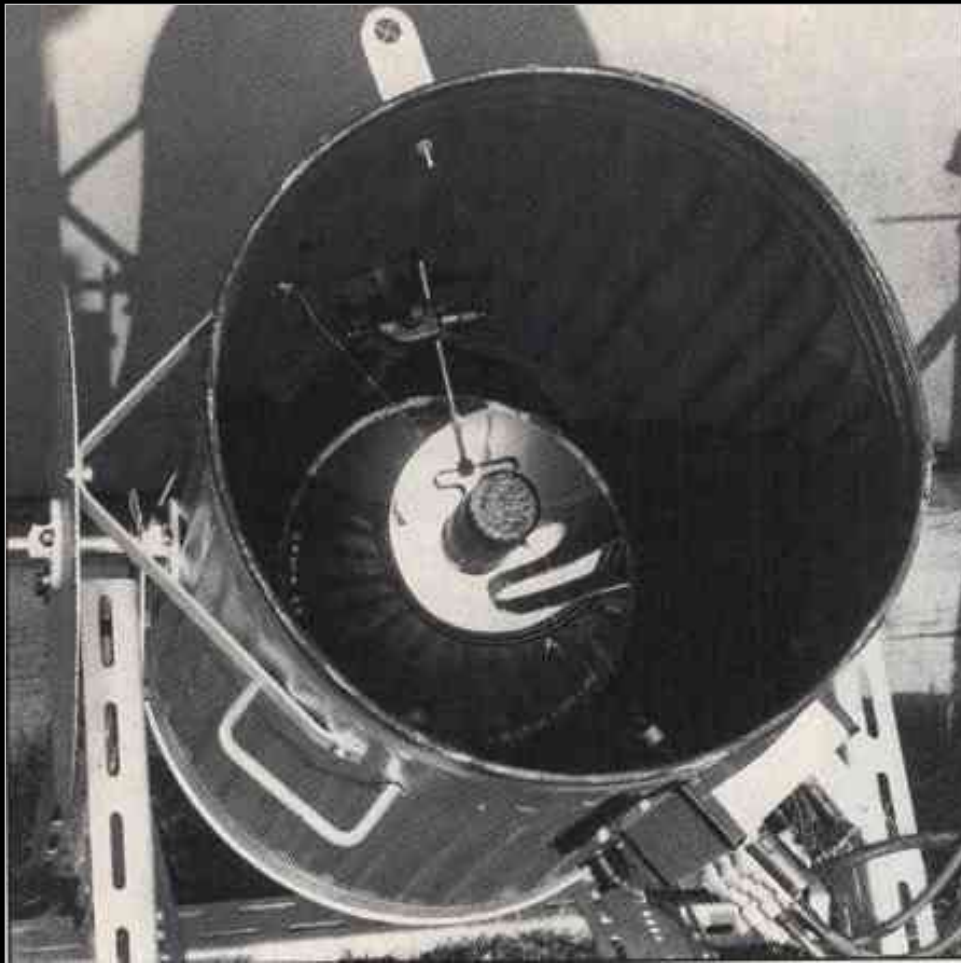






The early days

Source:
T. Weekes



Galbraith and Jelley, 1953

February 21, 1953

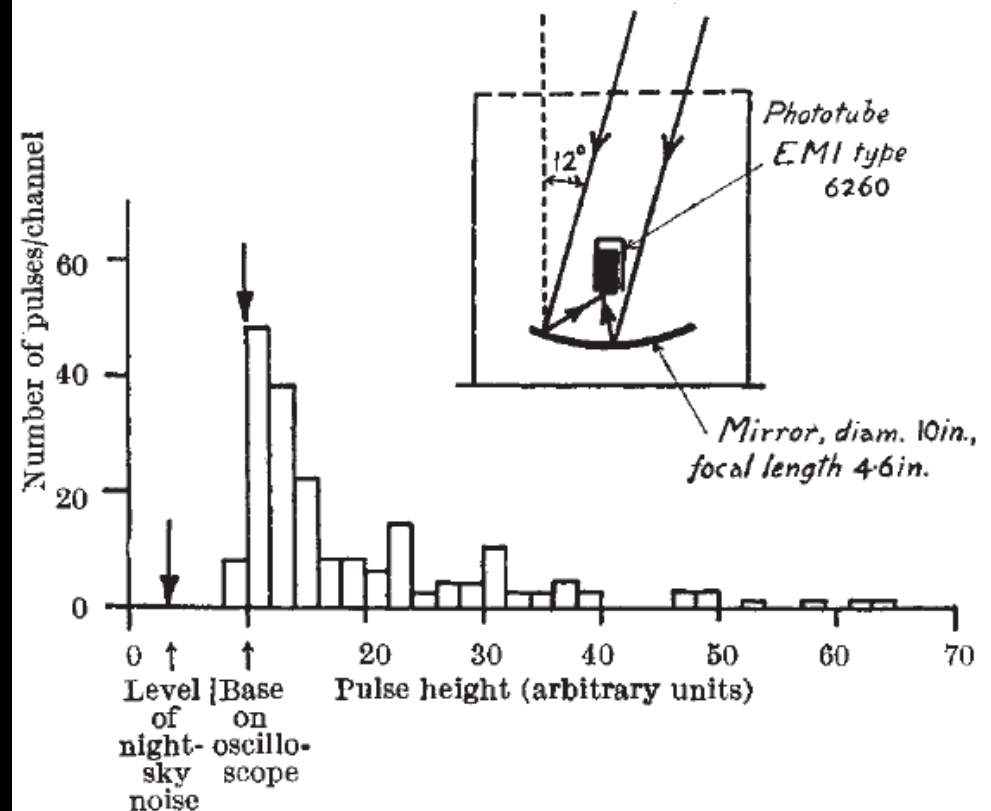
NATURE

Light Pulses from the Night Sky associated with Cosmic Rays

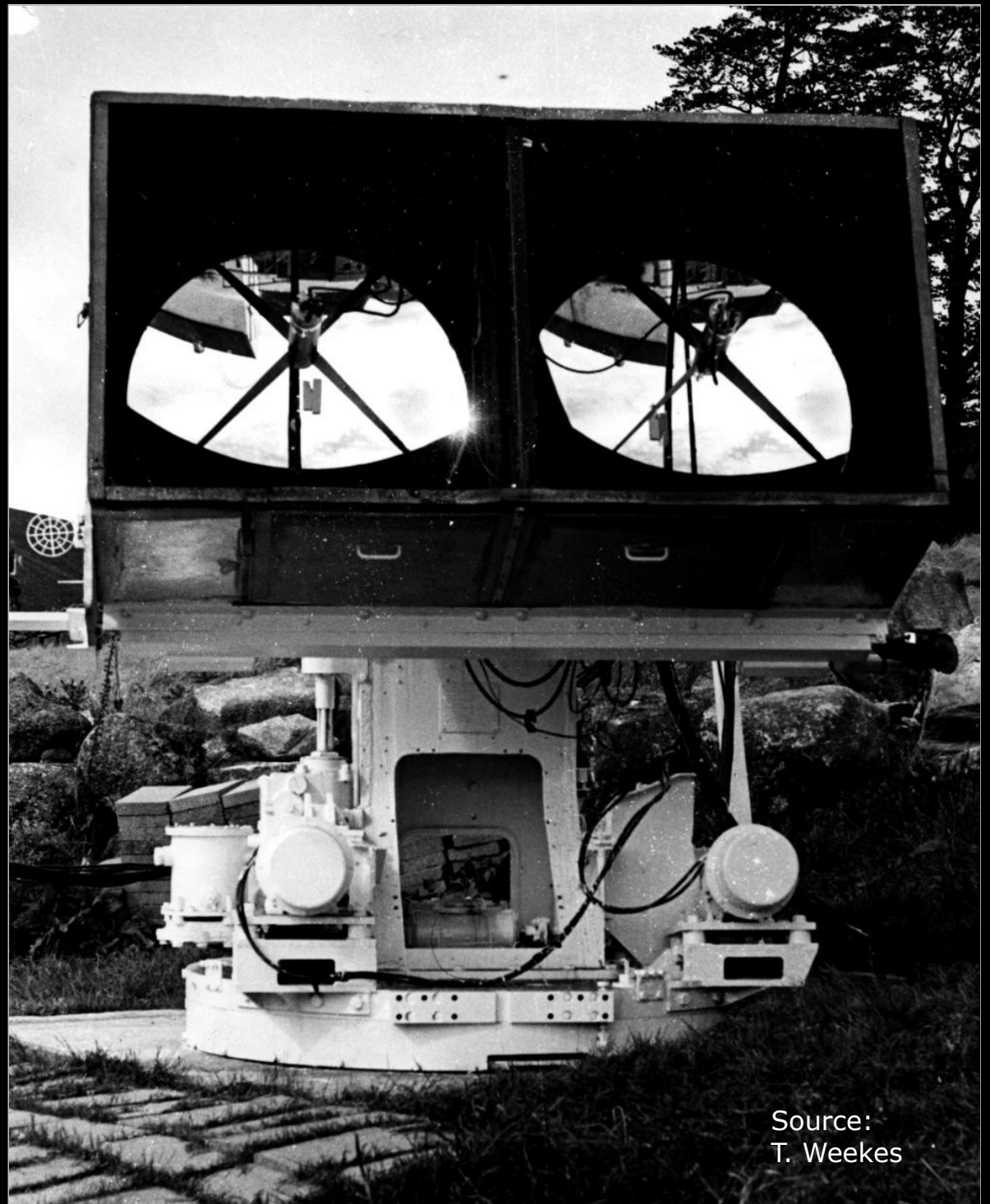
IN 1948, Blackett¹ suggested that a contribution approximately 10^{-4} of the mean light of the night-sky might be expected from Čerenkov radiation² produced in the atmosphere by the cosmic radiation. The purpose of this communication is to report the results of some preliminary experiments we have made 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



Source:
T. Weekes

The early days



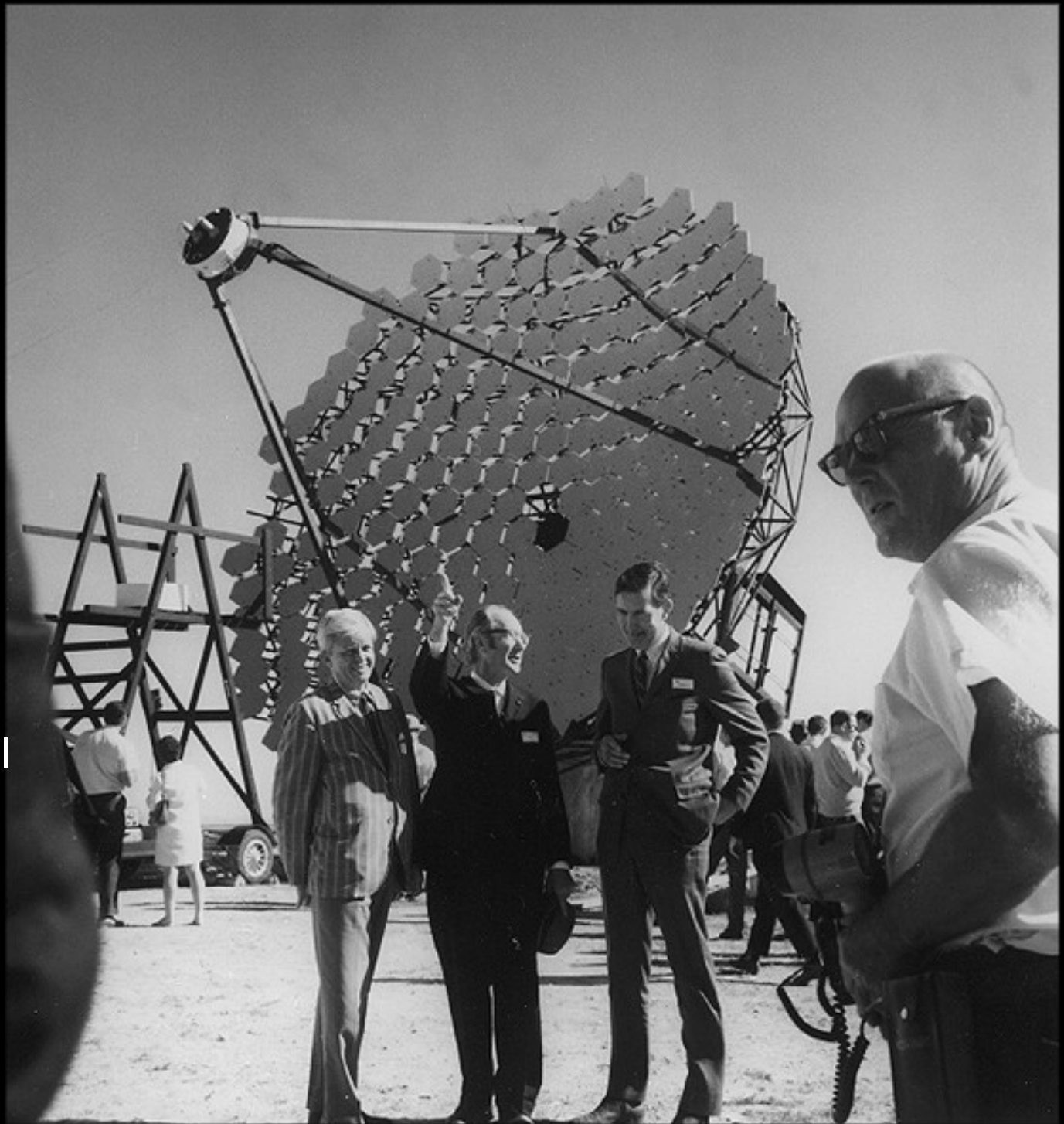
Weekes,
1967

Source:
T. Weekes

Whipple 1968

Detection of
the Crab Nebula
1968:

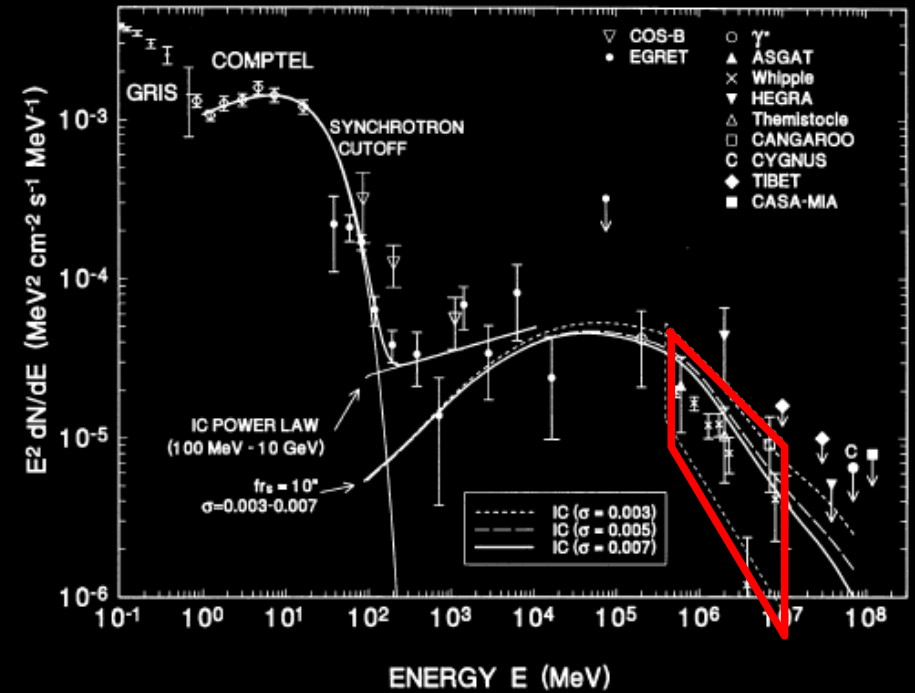
50 h observation
time for 5 sigma signal



Copyright Digital Image Smithsonian Institution, 1998

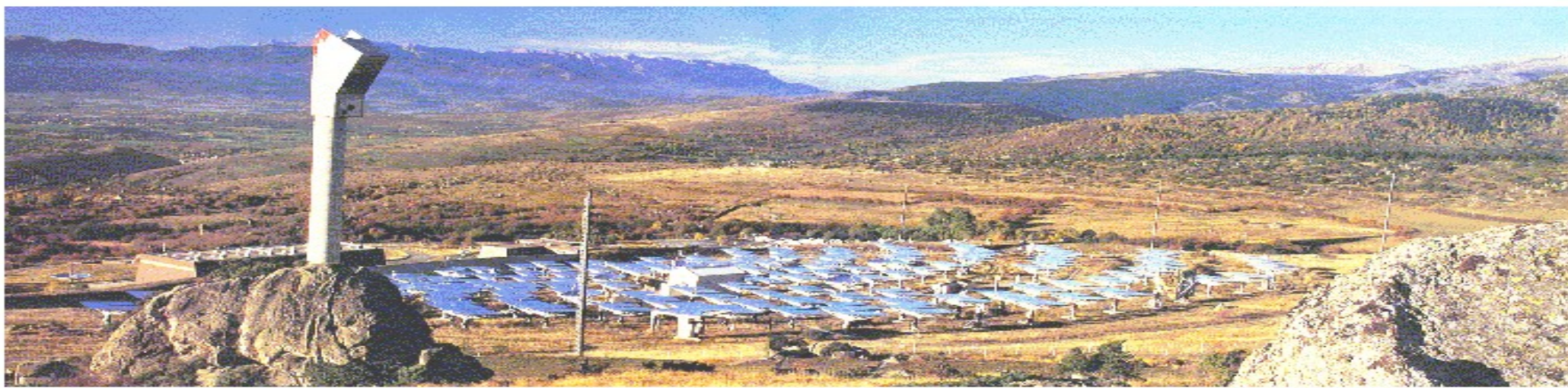
Astronomie gamma depuis le sol en France

Une longue histoire qui a commencé
sur le site de la centrale
solaire Thémis, Pyrénées Orientales
LPC Collège de France, CNRS
CEA-SAp



Spectre du Crabe

Themistocle: pionnier 1989-1996



Imaging single dish pioneering telescopes



The Pioneers:

WHIPPLE

10 m dish, 60s
Arizona, USA



CAT

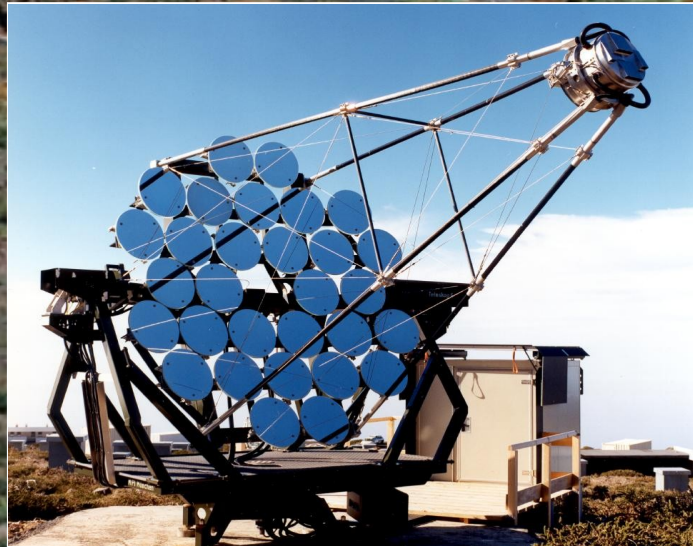
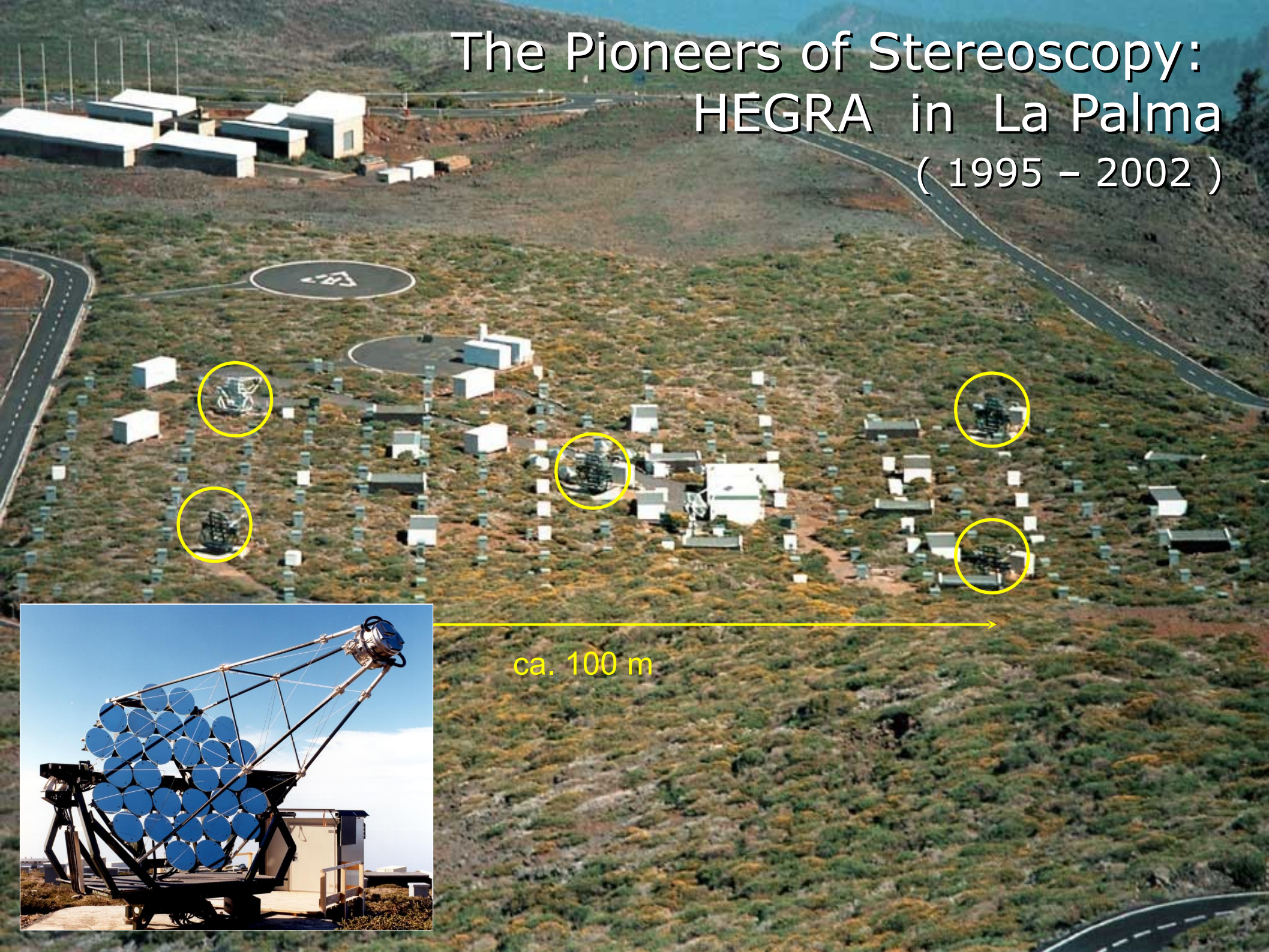
5 m dish
Themis, France
1996-2002



CANGAROO

3.8, 7, 10 m dish
Australia
1992 - ...

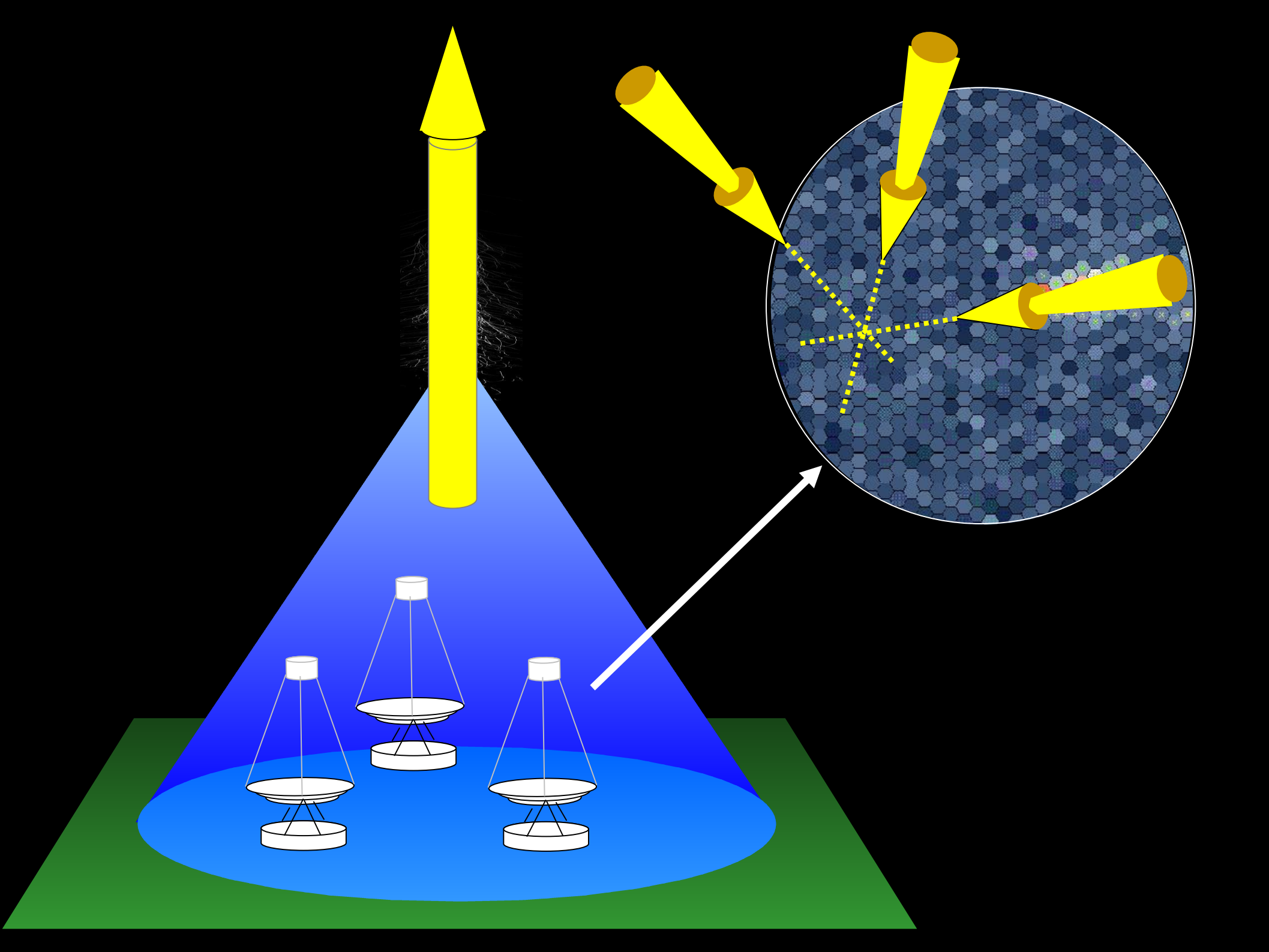
The Pioneers of Stereoscopy: HEGRA in La Palma (1995 – 2002)



Air showers look a bit like meteors

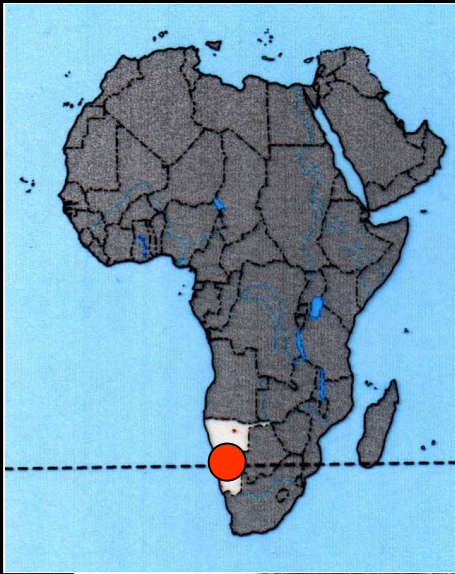


(from Sky & Telescope)





Key Feature: Location in Namibia

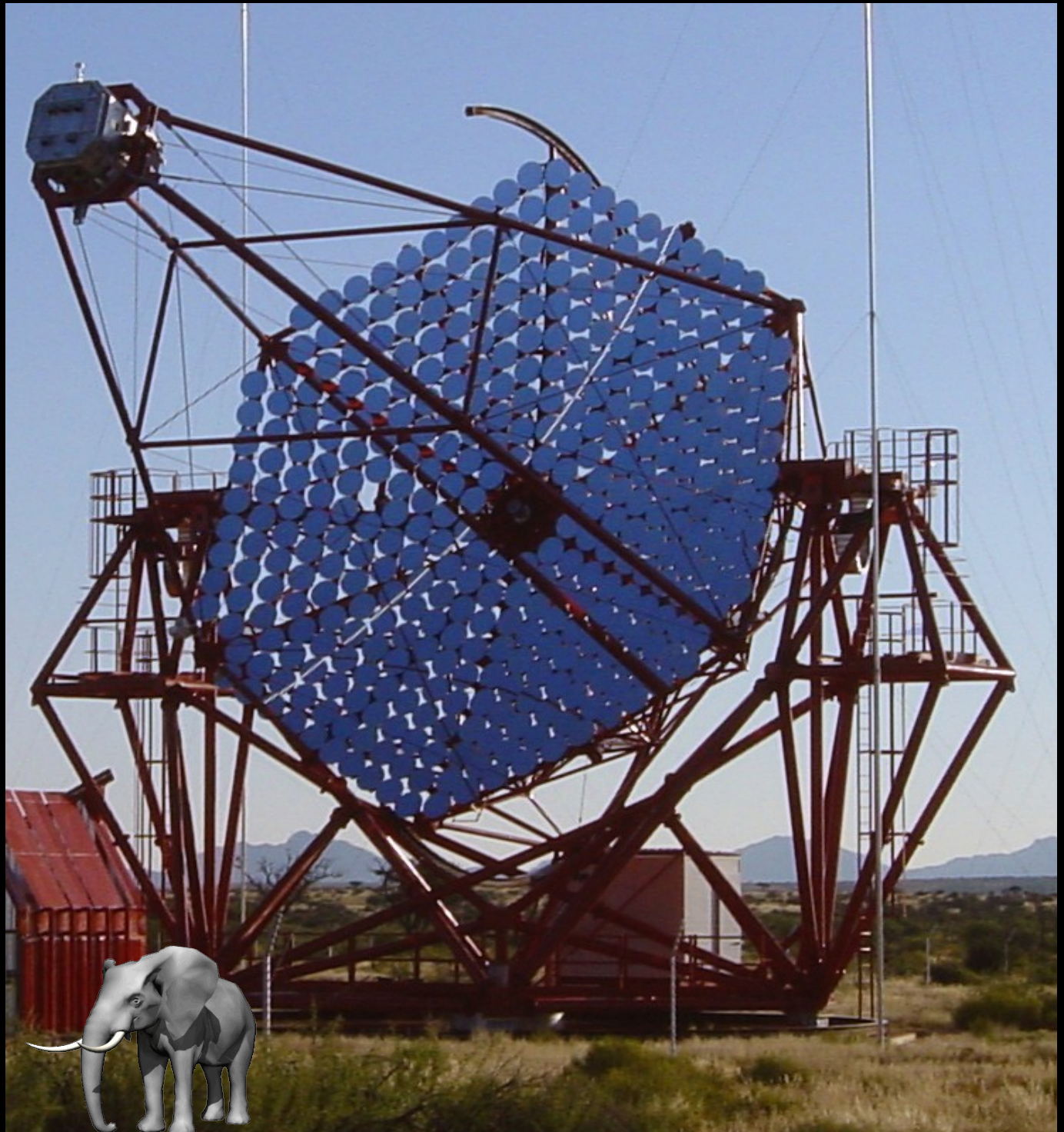


H.E.S.S.
2003

Detects Crab-like
source in

30 seconds

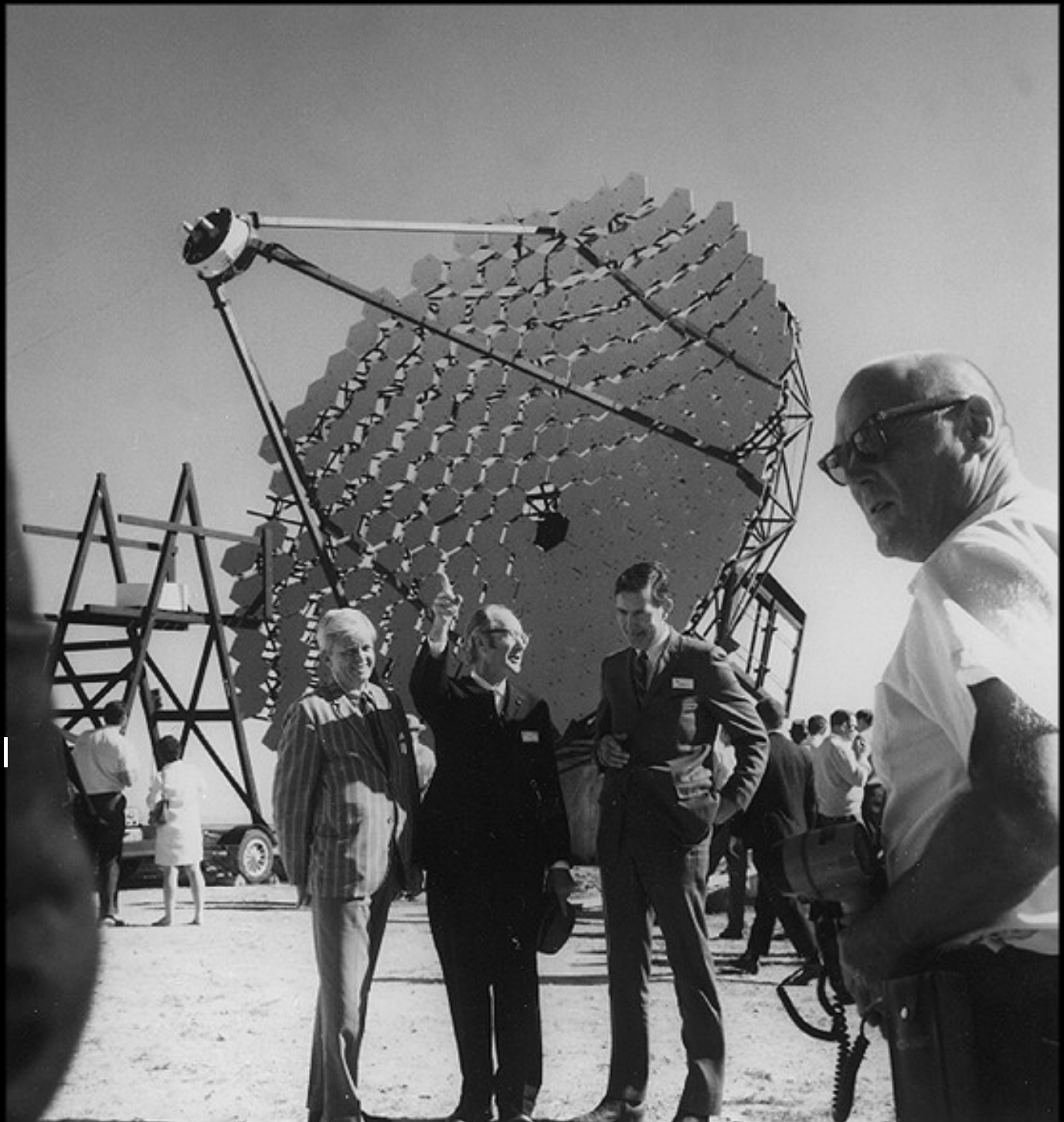
1% Crab in 25 h



Whipple 1968

Detection of
the Crab Nebula
1968:

50 h observation
time for 5 sigma signal



Copyright Digital Image Smithsonian Institution, 1998

Key feature: Wide field of view of 5°



Camera:
960 pixels, 0.16°
5° field of view
Readout electronics in
camera body
1 GHz analog memory
for signal recording



VERITAS

4 x $\sim 100 \text{ m}^2$ dish

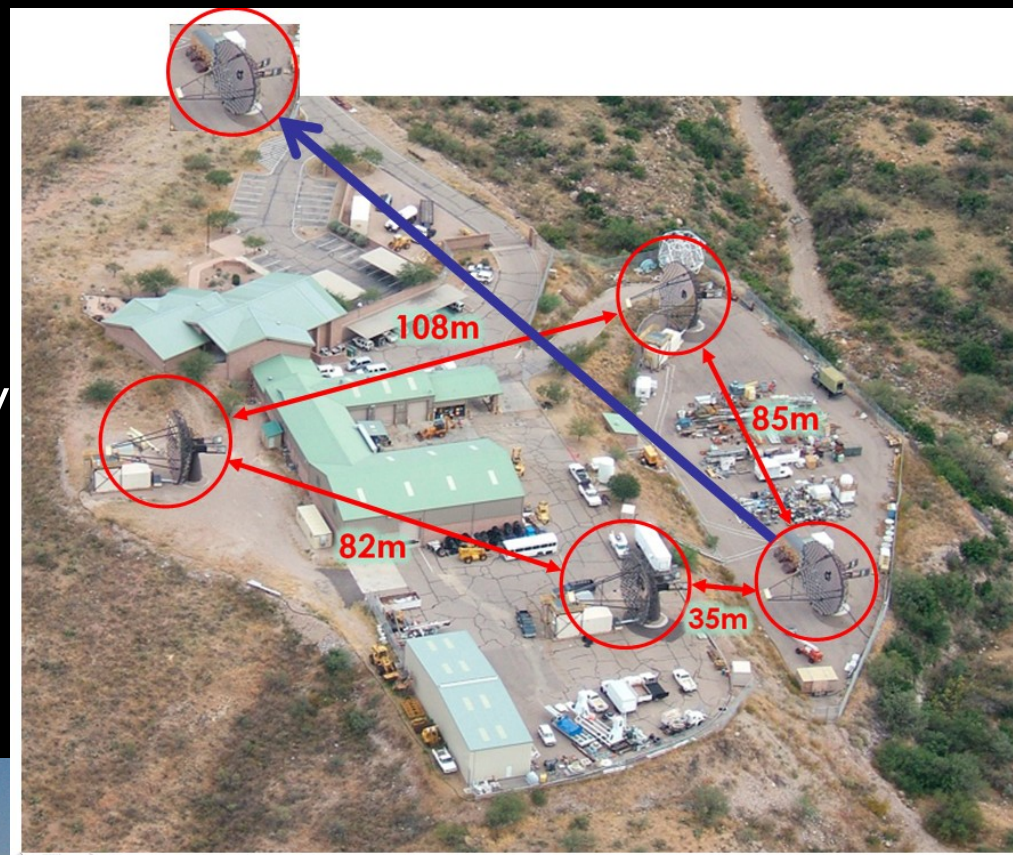


VERITAS

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

Proposed upgrades:

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



MAGIC on La Palma

240 m² dish



MAGIC II: Stereo, 2 x 236 m²



TeV astronomy in India

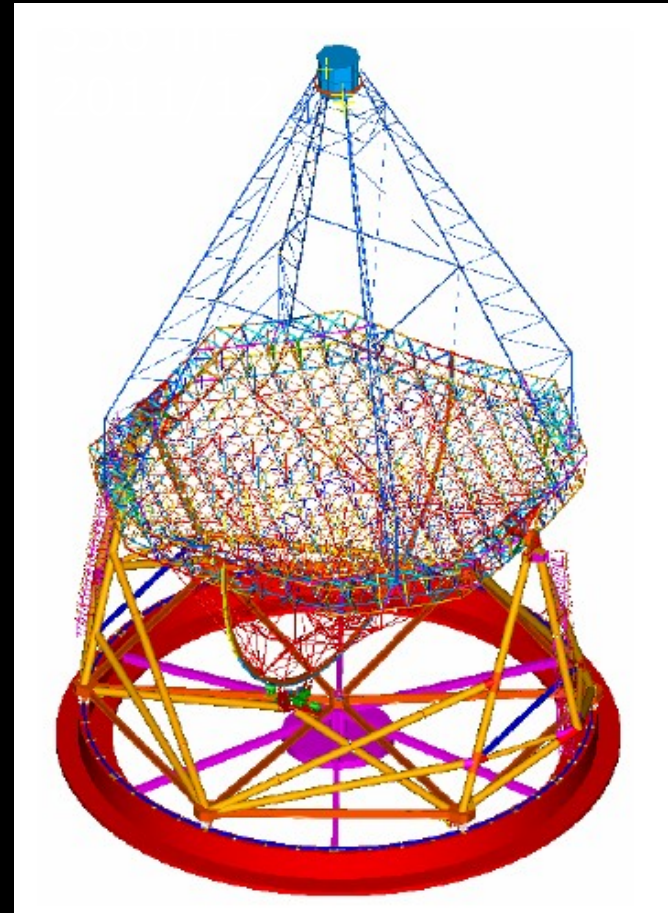
TACTIC, Mt. Abu



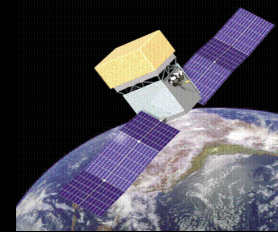
PACT Array, Pachmari



MACE



Current VHE γ -ray Instruments

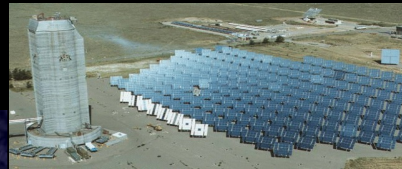


GLAST

MILAGRO



STACEE



MAGIC



TIBET

TIBET
ARGO-YBJ

MILAGRO

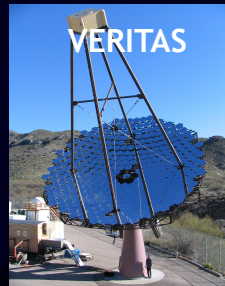
STACEE

MAGIC

TACTIC

PACT

VERITAS



VERITAS



TACTIC

HESS

CANGAROO III



HESS

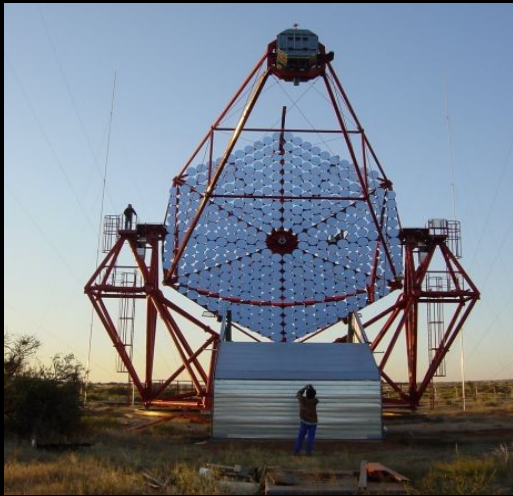


CANGAROO

Current VHE γ -ray Instruments

High Sensitivity

HESS, MAGIC, CANGAROO, VERITAS



Energy Range .05-50 TeV
Area $> 10^4 \text{ m}^2$
Background Rejection $> 99\%$
Angular Resolution 0.05°
Aperture 0.003 sr
Duty Cycle 10%

High Resolution Energy Spectra
Studies of known sources
Surveys of limited regions of sky

Low Energy/Large Aperture

EGRET/GLAST



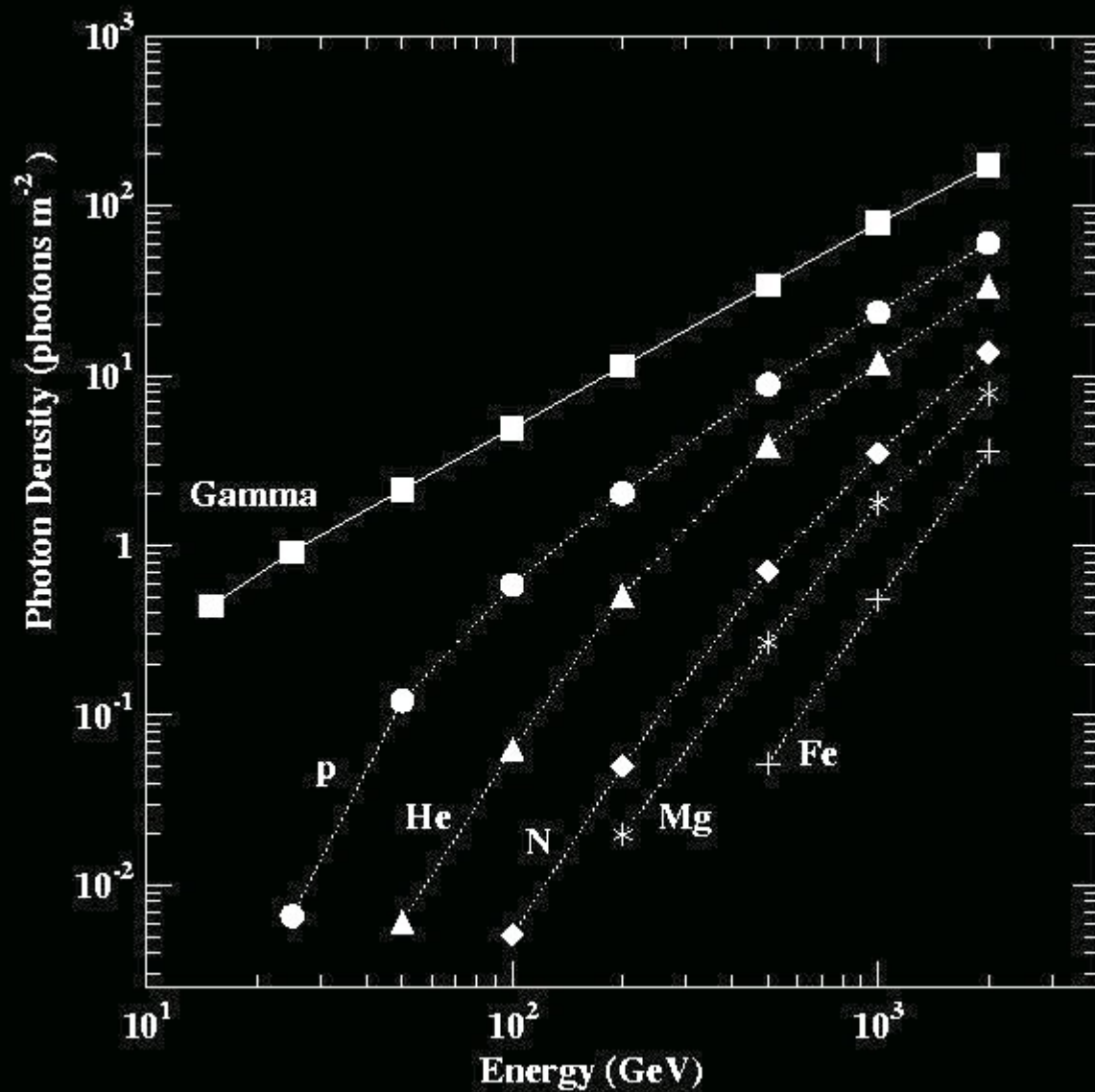
Energy Range 0.1-100 GeV
Area: 1 m^2
Background Free BUT diffuse γ
Angular Resolution $0.1^\circ - 0.3^\circ$
Aperture 2.4 sr
Duty Cycle $> 90\%$

Unbiased Sky Survey ($< 100 \text{ GeV}$)
Extended Sources
Transients (AGN, GRBs) $< 100 \text{ GeV}$
Simultaneous ν Observations

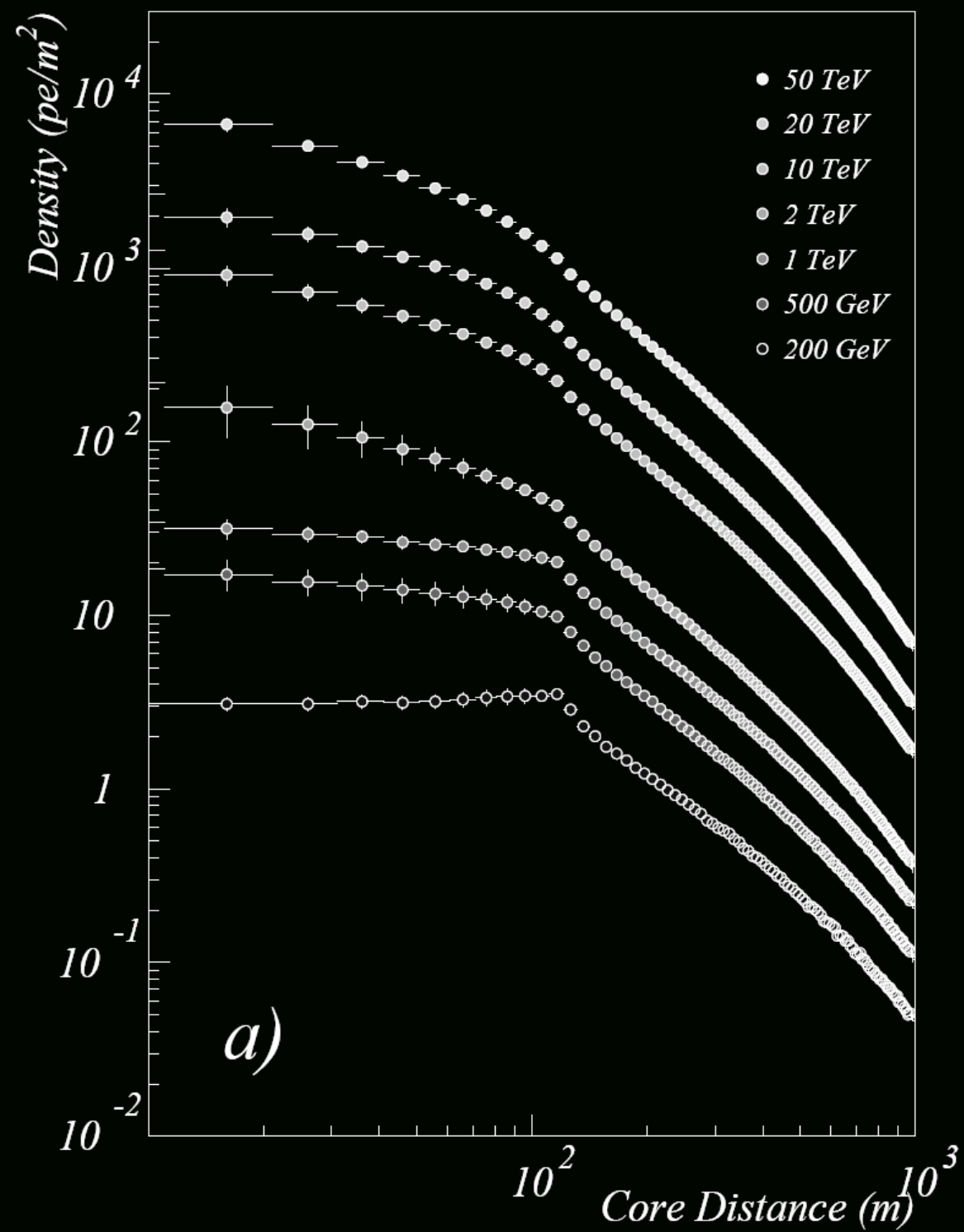


Energy Range 1-100 TeV
Area $> 10^4 \text{ m}^2$
Background Rejection $> 95\%$
Angular Resolution $0.3^\circ - 0.7^\circ$
Aperture $> 2 \text{ sr}$
Duty Cycle $> 90\%$

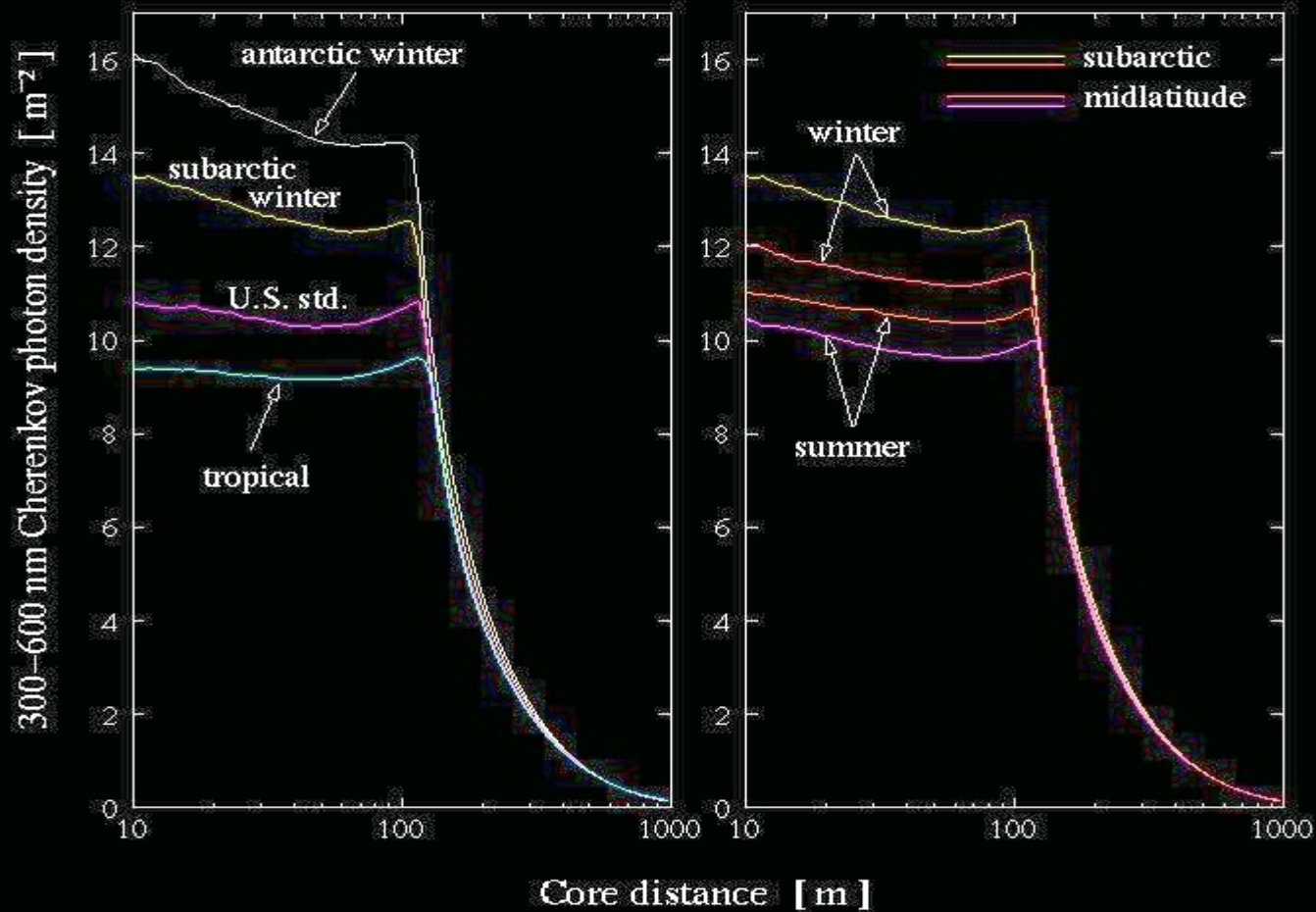
Unbiased Sky Survey
Extended Sources
Transients (GRB's)
Simultaneous ν Observations



Between 300-550 nm
0.033 ph/m²/GeV @ 25 GeV
0.065 ph/m²/GeV @ 1 TeV



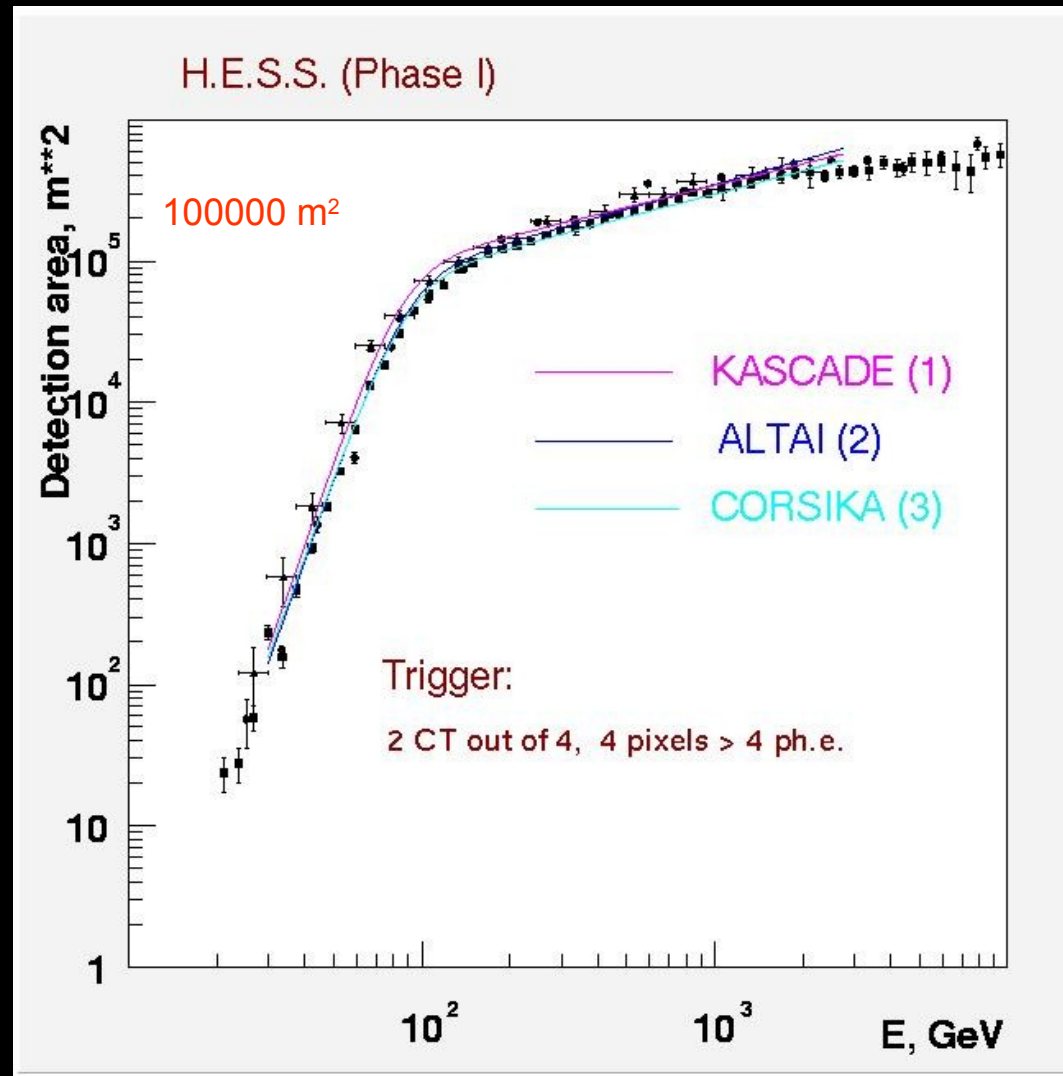
Atmospheric profile, Cherenkov Intensity



Atmospheric density profile influences both shower development and Cherenkov emission

Potentially large (> 10%) effects on energy calibration

Effective Area, Energy threshold

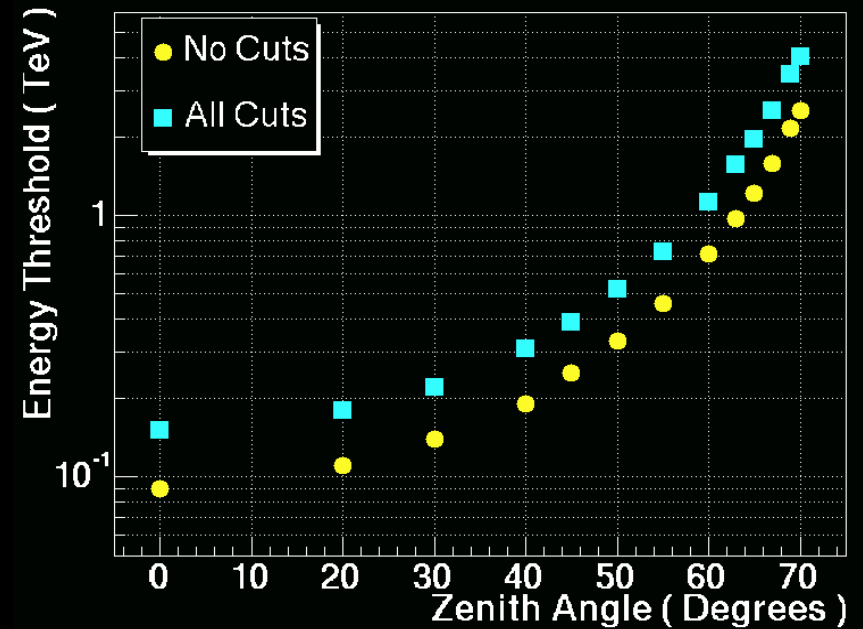


Energy threshold vs zenith

Small zenith angle:

■ low threshold

■ $\sim 10^5 \text{ m}^2$ area



large zenith angle:

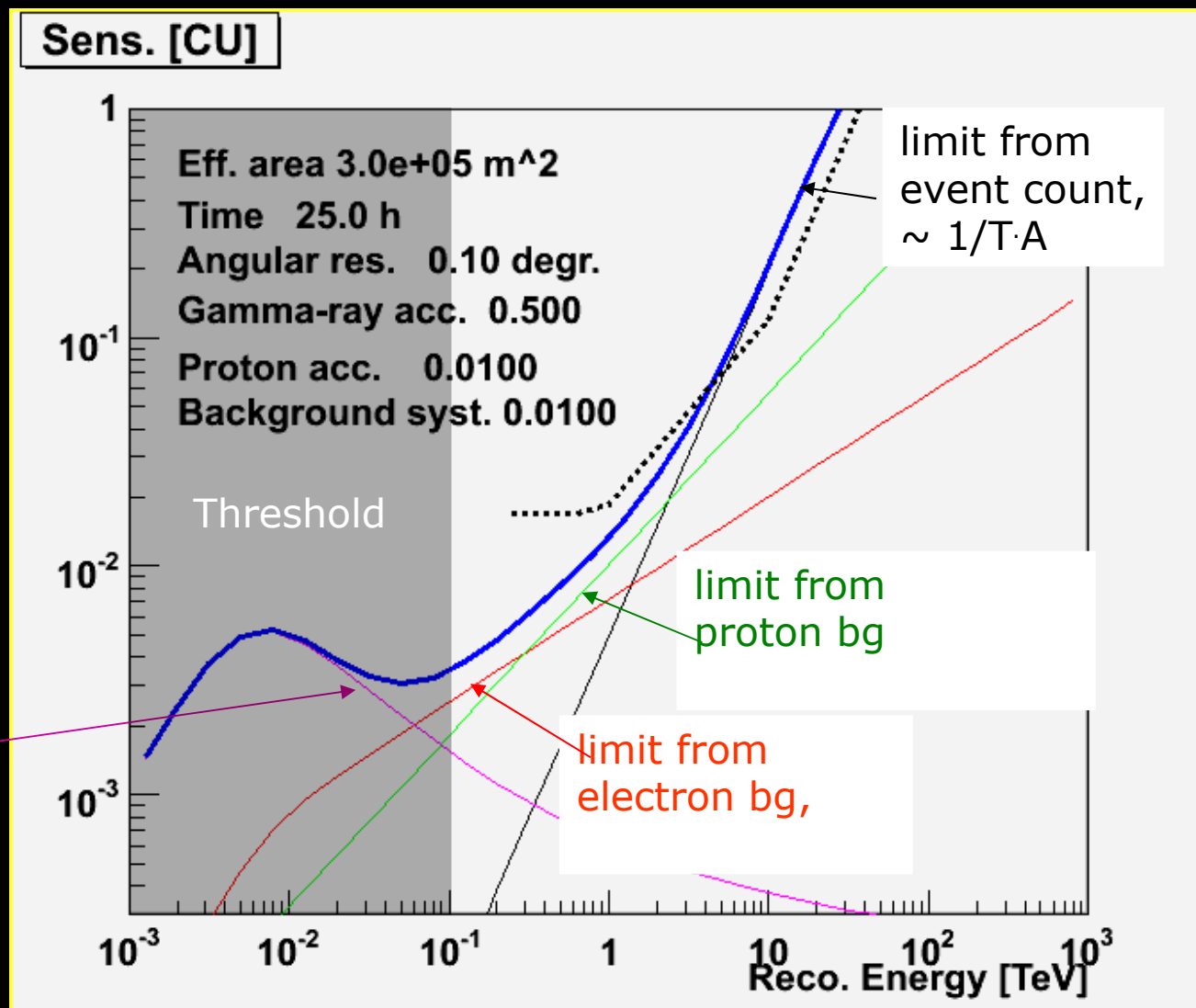
■ high threshold

■ $> 10^6 \text{ m}^2$ area

Sensitivity

Minimal detectable
flux per band
 $\delta \log_{10} E = 0.2$, relative
to a
power-law
Crab spectrum

limit from
syst. error
on background



Background modeling techniques

Prior:

Key point: Whatever the power of a given analysis technique

There is an irreducible Background due to CR's
as opposed to e.g. Space-based γ -ray astronomy

Only a statistical determination of a signal $N_{\text{exc}} = N_{\text{On}} - \alpha * N_{\text{Off}}$

The sensitivity of a Cherenkov telescope system depends on our ability to:

- A- reject the background: typically shape-cuts yield $\sim 10^2$ rejection
- B- understand and minimize the systematics

Some historical “background”

Single telescopes such as Whipple or CAT:

- had a small field of view ($\sim 2.5^\circ$ - 3°)
- were sensitive only to point-like sources : Crab, Mkn421, Mkn 50, ...

The Background determination was originally made in the so-called On/Off mode:

- On : source centred in the field of view (fov)
- Off: data taken on an “empty” field observed typically with $RA_{\text{Off}} = RA_{\text{On}} \pm 30'$

Motivations:

- The threshold of a Cherenkov telescope is a function of zenith angle
the altitude of the shower maximum rises as a f (zenith)
- The atmosphere is part of the detection instrument, the calorimeter
variations of the atmospheric conditions (transparency, haze, pressure, ...)
imply variations of the “detector” characteristics:
threshold, effective area, rejection factor, ...

Drawback:

- One loses half of the dark period time to do Off observations

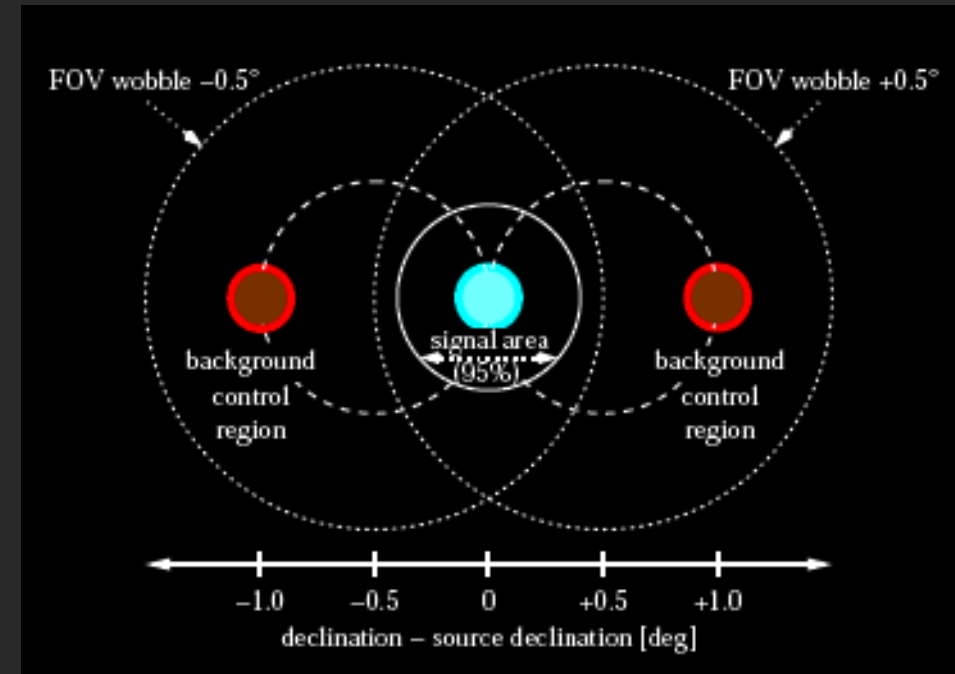
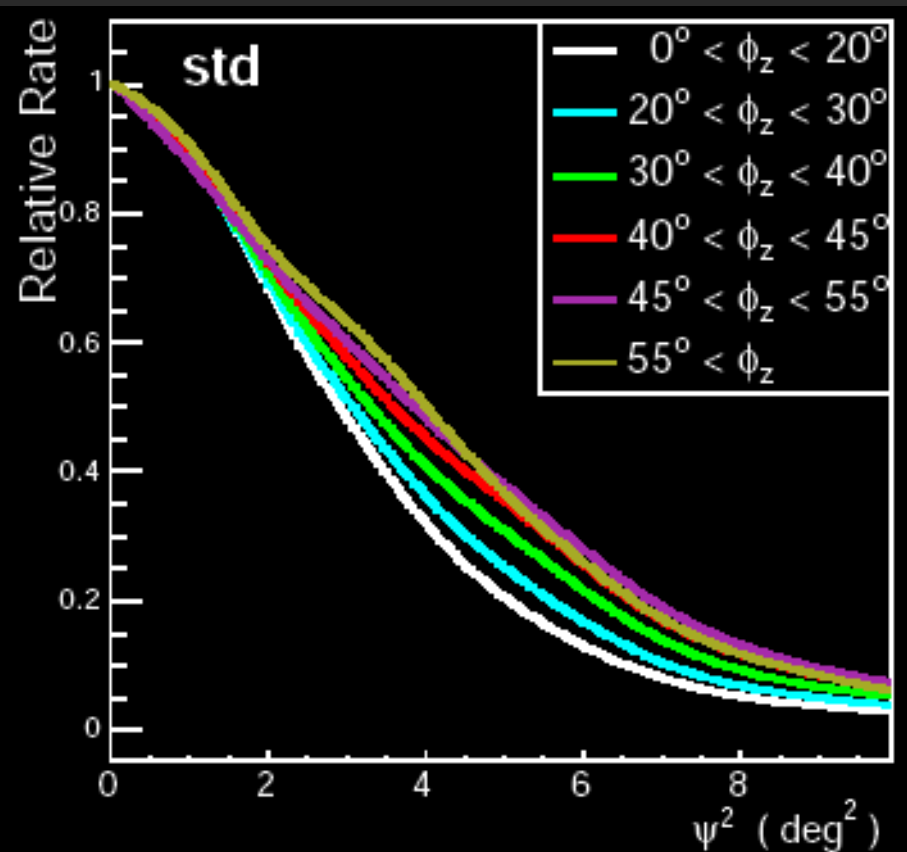
The ping-pong/tracking or wobble mode or how to save time

Pioneered by the Whipple collaboration (tracking) and subsequently developed by HEGRA

- Offset the source in the fov by $\pm 0.5^\circ$ alternatively
- Estimate the background from the opposite side of the fov: Mirrored Bg, Reflected

Why the opposite side/ fov ?

The acceptance (detection efficiency) is not uniform but is radially decreasing :



The position and extension of the candidate source should be known

Assumes : azimuthal symmetry

The Reflected/multiple background model

Can be extended to get higher statistics on Off:

Average over the fov at same radial distance

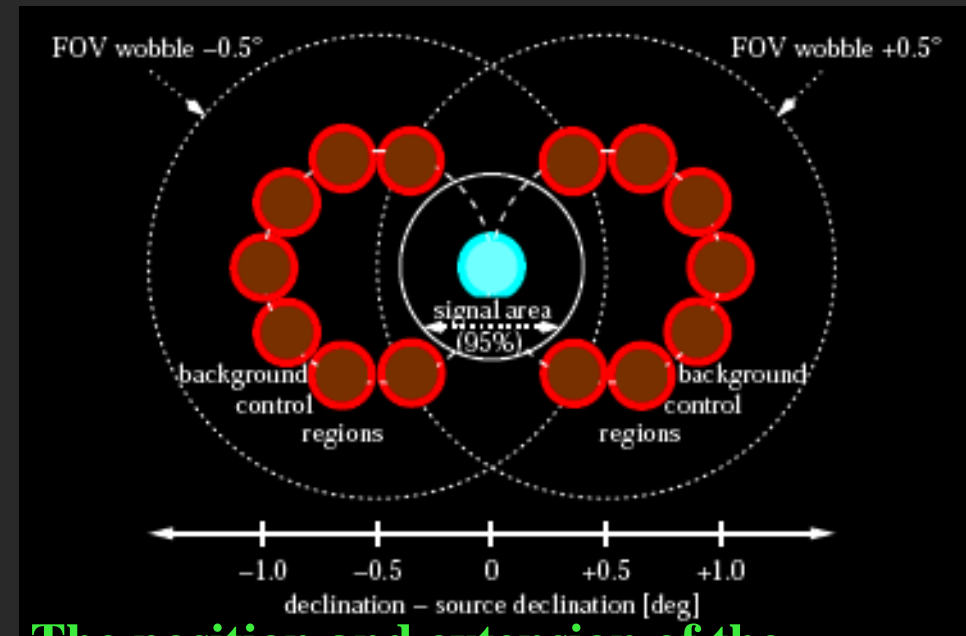
Typically the source is offset by 0.5° to 0.7° (point-like sources)

⇒ a factor 7 to 10 more Off statistics

For an extended source offset is increased
But for very large sources On/Off method becomes mandatory

Again assumes : azimuthal symmetry but less subject to systematics due to averaging

One should avoid contamination of the background estimate by γ -rays from a neighbouring source ⇒ forbid known sources' positions for being used as background

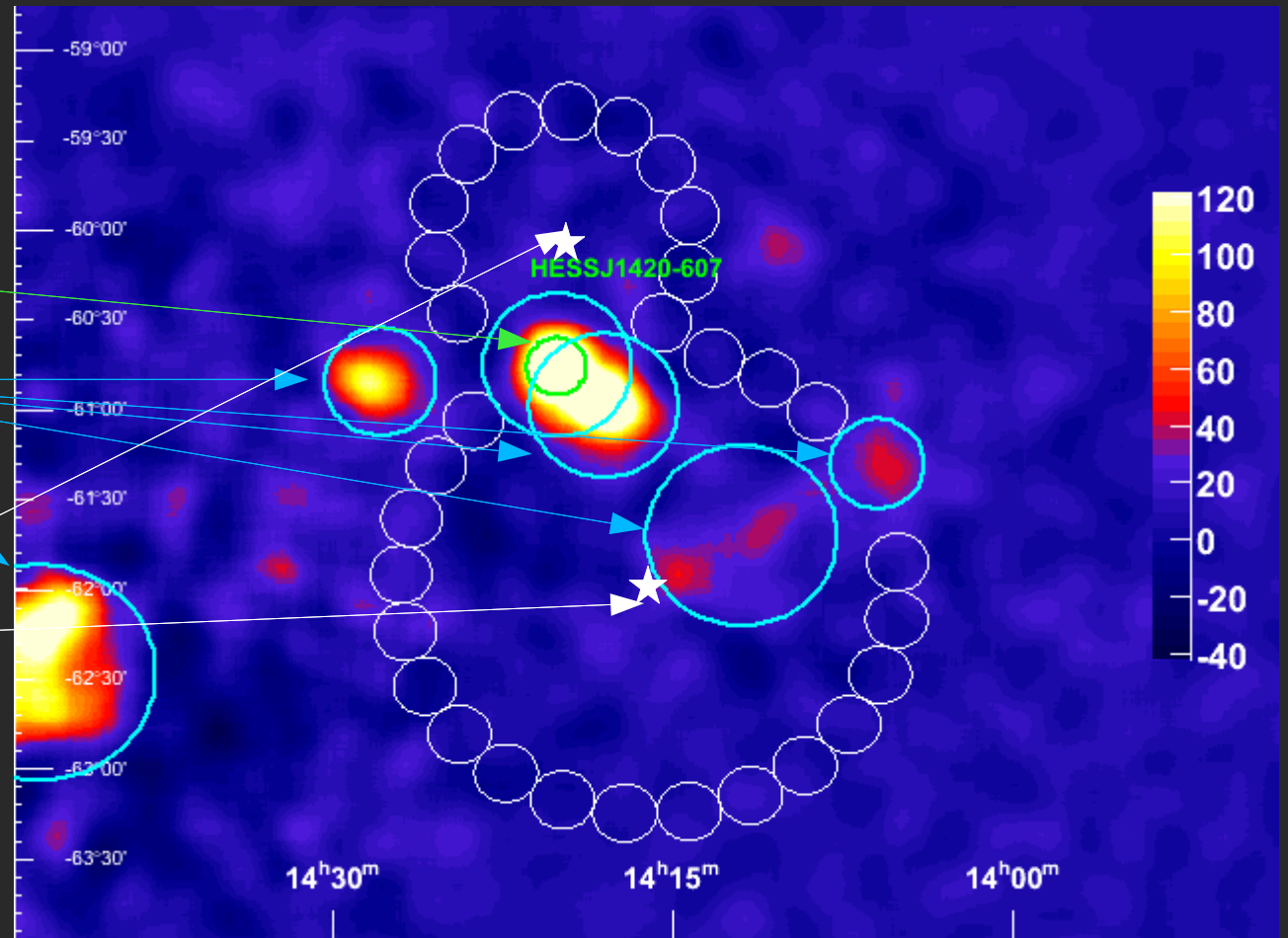


**The position and extension of the candidate source should be known:
AGN's : point-like, known
Galactic sources: need to measure those properties before...**

A concrete example: the Kookaburra ($l \sim 313.4^\circ$)

The region of
interest:
HESS J1420-607
Exclusion regions
For Bg estimation

Center of fov
for
2 runs



For large data-sets, various offsets \Rightarrow Different α : need for a proper averaging procedure to weight runs: use radial acceptance

To avoid contamination by γ -rays from a neighbouring source one needs to know their positions and extensions : need for 2D maps of Bg

Background models : some general points

$$N_{\text{exc}} = N_{\text{On}} - \alpha * N_{\text{off}}$$

A Background model has to provide N_{off} and α

The significance is larger for smaller α

But the systematics may be larger for $\alpha \ll 1$

Different goals \Rightarrow different methods

Detection of a source: N_{off} , α global

Spectrum : $N_{\text{off}}(E)$, $\alpha(E)$

Morphology, Sky maps : $N_{\text{off}}(x,y)$, $\alpha(x,y)$

Morphology, Sky maps=f(E) : $N_{\text{off}}(x,y,E)$, $\alpha(x,y,E)$

Note : in general α should not depend on E to minimize systematics

The Ring background model : 2D maps

A ring can be defined around each trial position in the fov (celestial coordinates)

α is the ratio of the ring solid angle (radius 0.5° - 0.8° typically)
to the trial source region

α is typically $\sim 1/7$.

But a given ring covers areas with different offsets wrt the fov centre

\Rightarrow need for an acceptance correction function

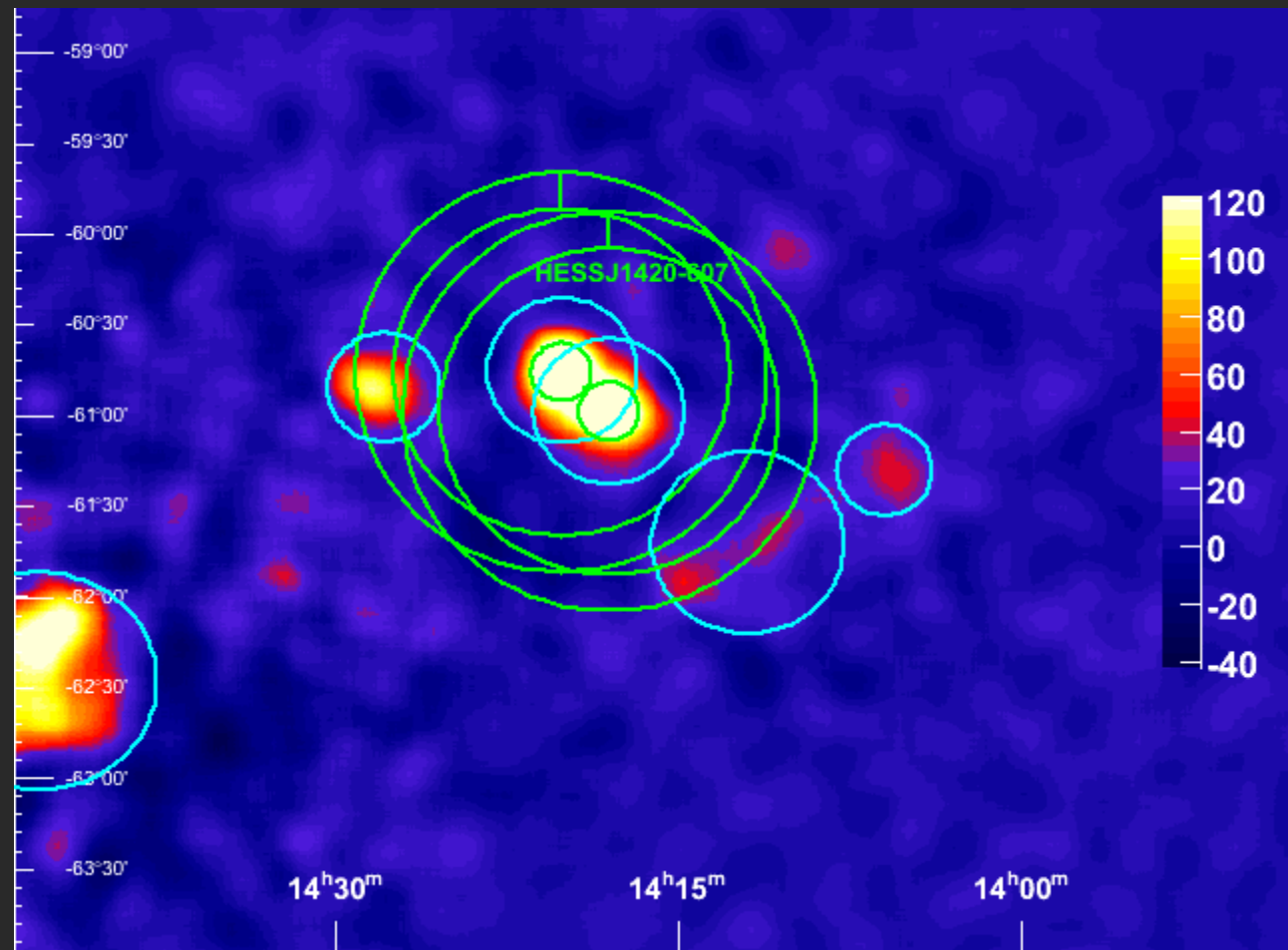
Also avoid the known sources
to prevent γ -ray containment

\Rightarrow further correction of α

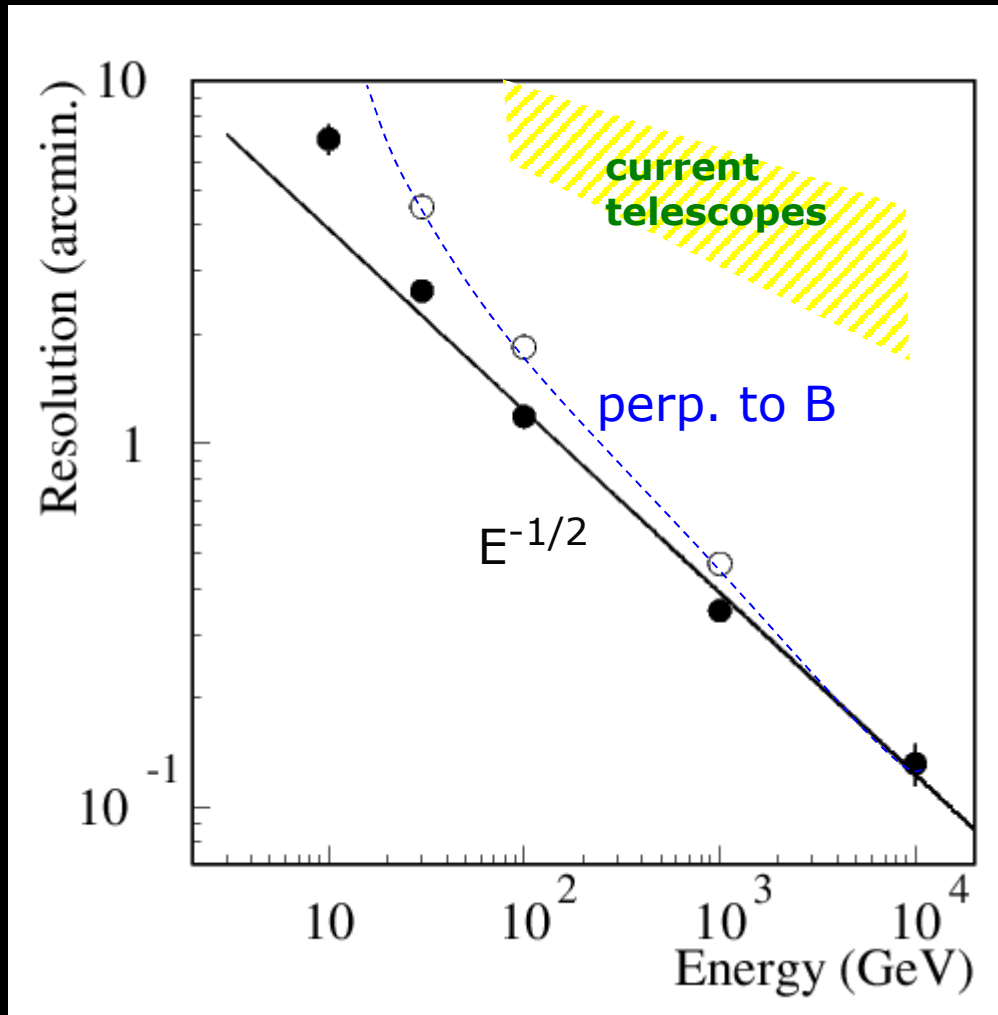
Due to overlap of rings
neighbouring pixels are
correlated

NOT suitable for crowded fov

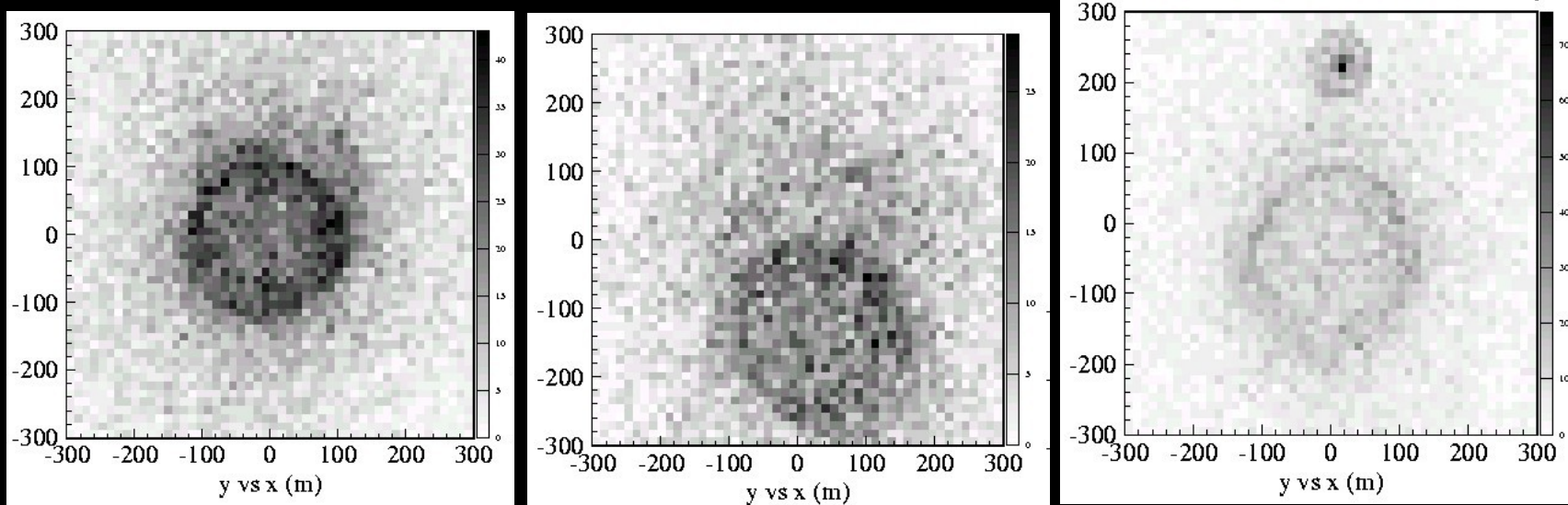
NOT suitable for Spectra :
Radial acceptance= $f(E)$ strongly



Angular resolution limit



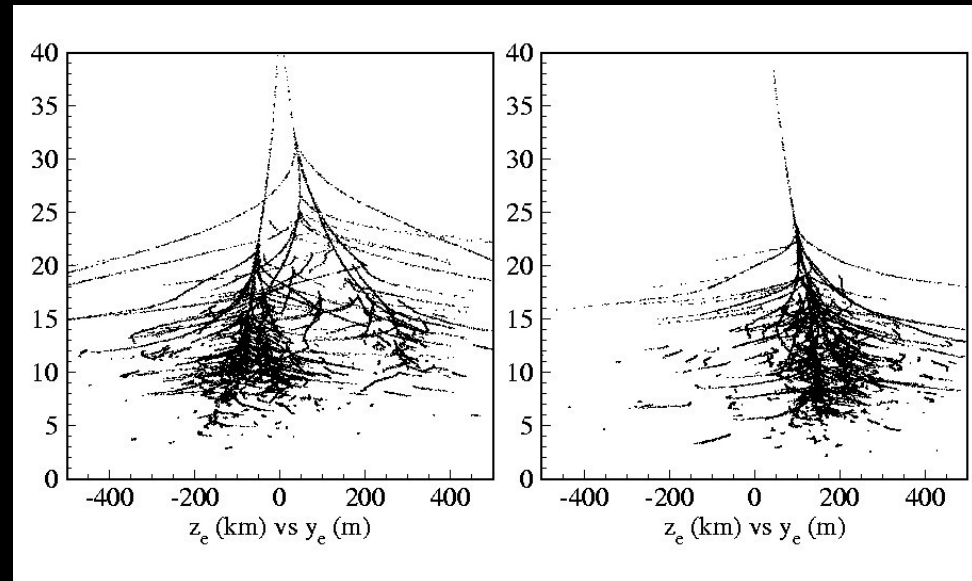
.... assuming that
impact point and
direction of ALL
Cherenkov photons are
measured perfectly



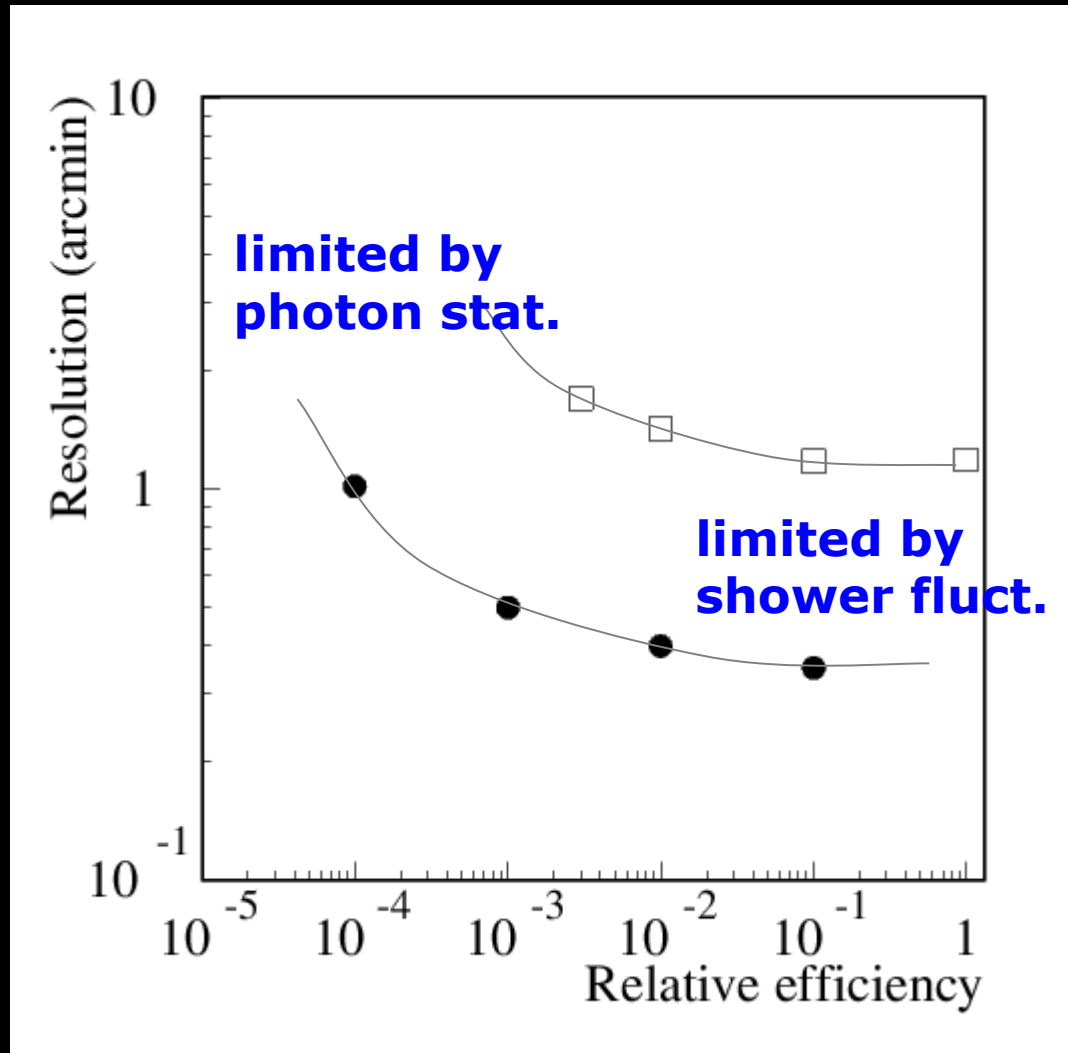
Geomagnetic deflection of primary pair limits angular resolution at low energies (starts to become relevant at a few 100 GeV)

Effect:

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



Angular resolution limit

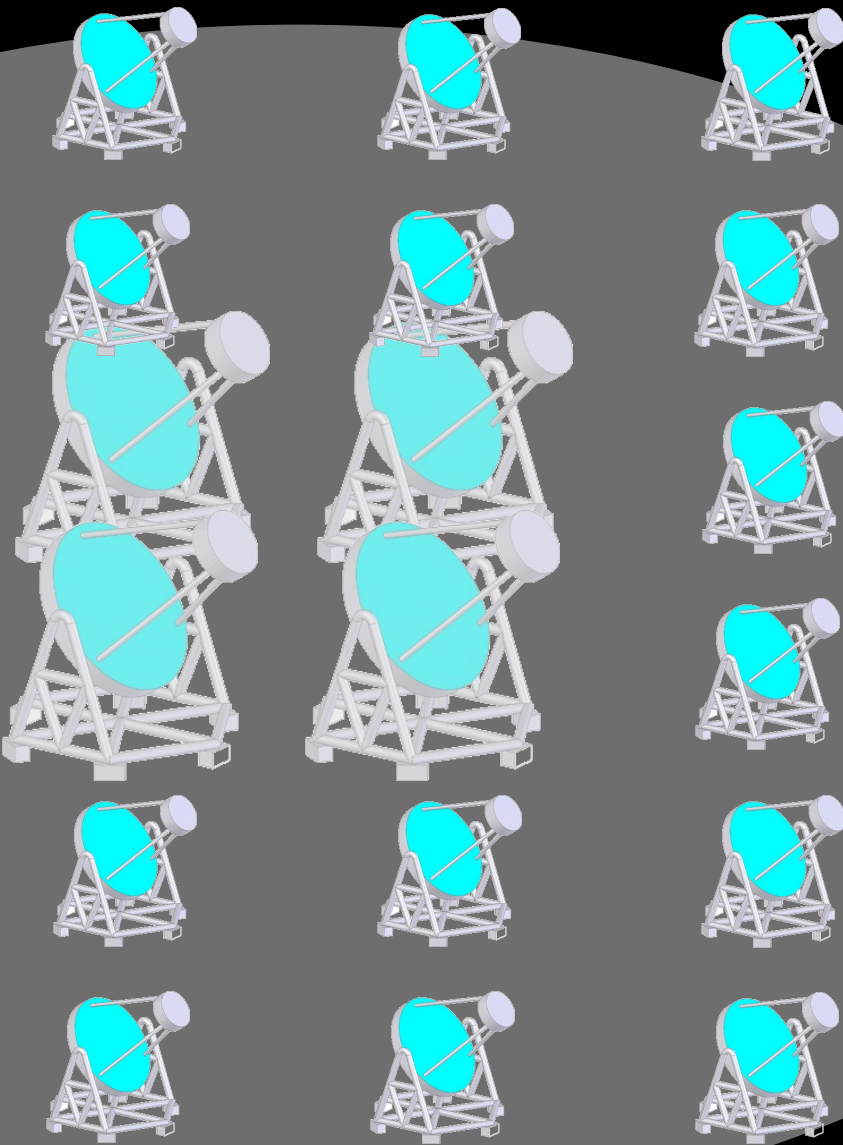


► Need to cover 0.1% or better 1% of area (assuming PMTs as detectors)

H.E.S.S.: 0.7%
but only over 240 m x 240 m

Relative to
PMT efficiency

The future



- Large telescope arrays
- Dense telescope arrays
- Large mirror area
- Large field of view
- Advanced photon detectors
- Advance signal & trigger processing

Not to scale !