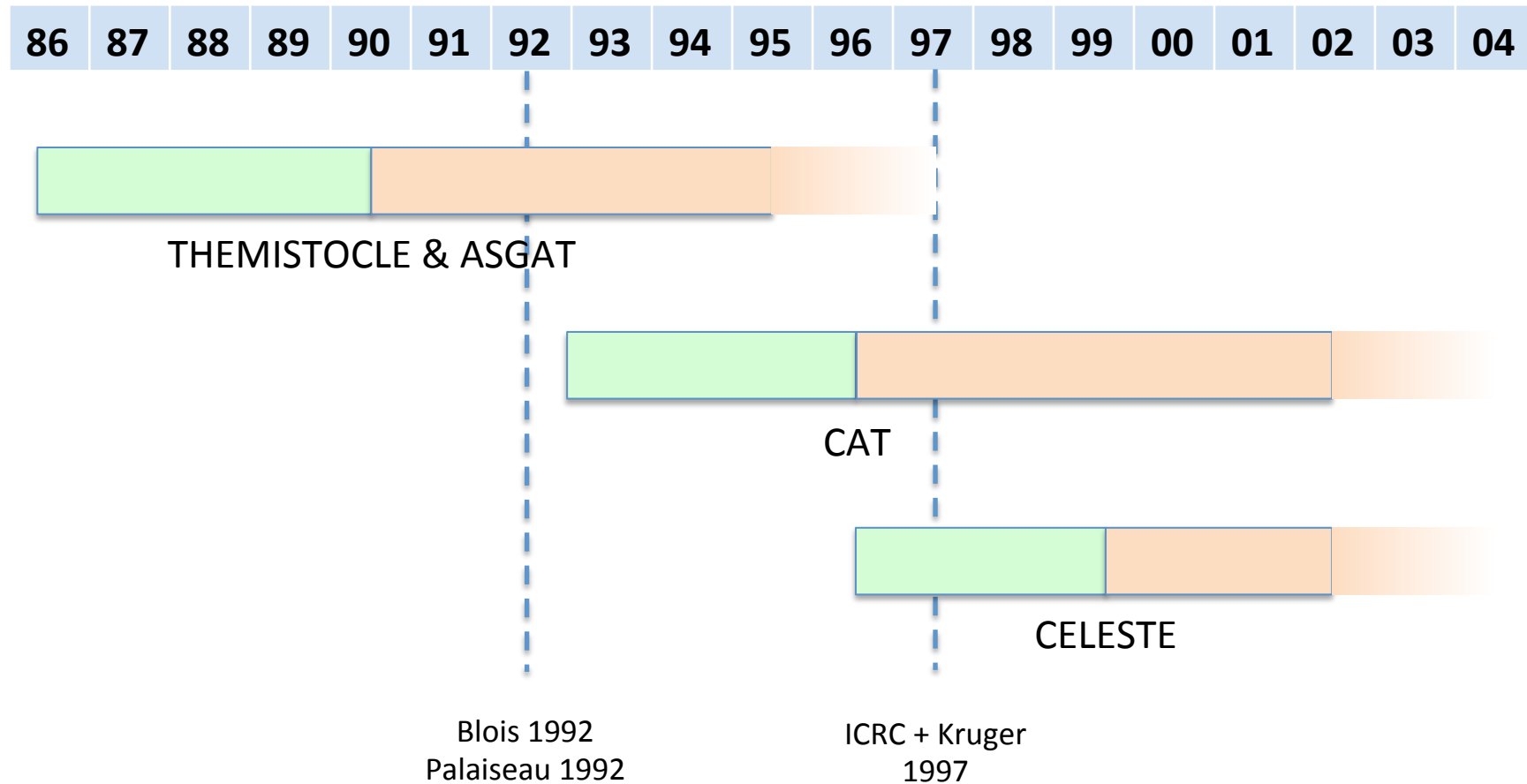


# The early days of ground-based gamma-ray astronomy in France



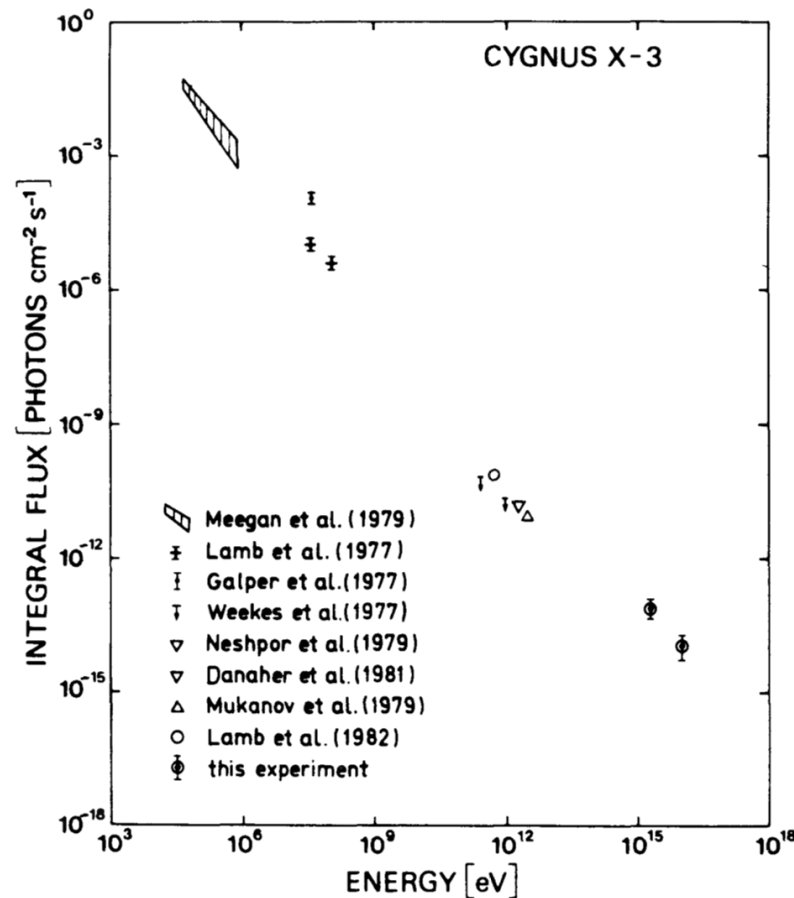
Gerard Fontaine - Hillas symposium – Heidelberg – December 10-12 2018

# Timeline from 1986 to 2004



# It all started from controversial observations !

- Claim from EAS experiments (Kiel & Haverah Park) of PeV photons with anomalous muon production



THE ASTROPHYSICAL JOURNAL, **268**:L17–21, 1983 May 1  
 © 1983. The American Astronomical Society. All rights reserved. Printed in U.S.A.

## DETECTION OF $2 \times 10^{15}$ TO $2 \times 10^{16}$ eV GAMMA-RAYS FROM CYGNUS X-3

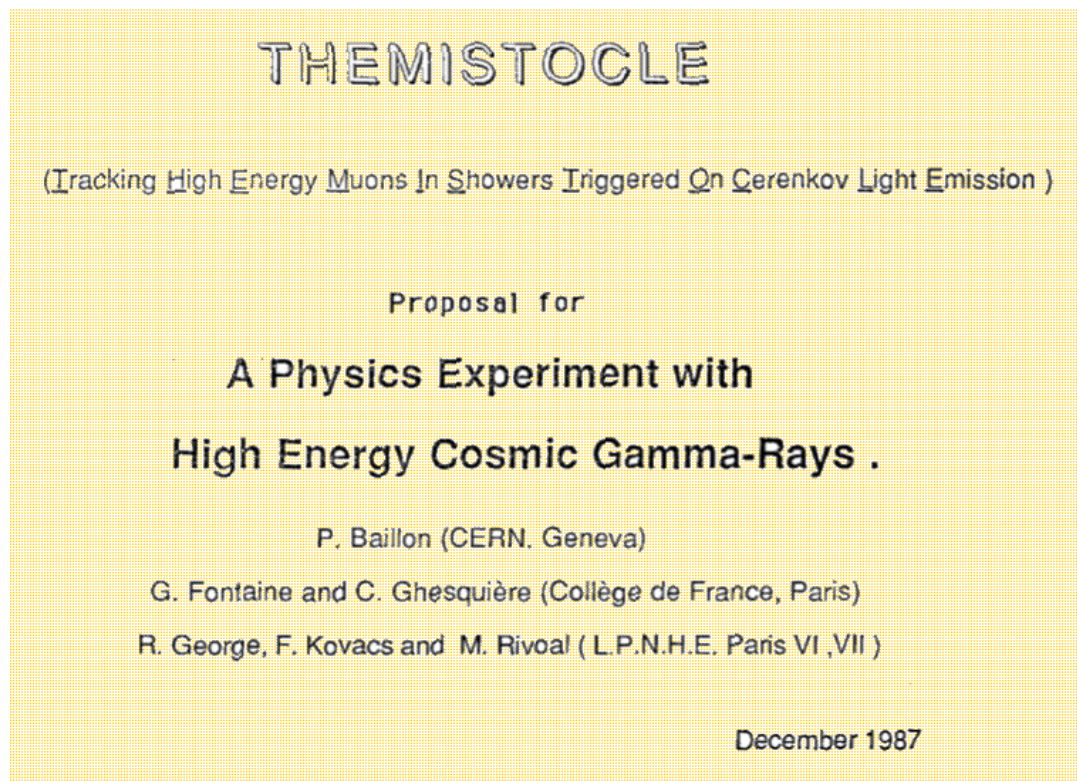
M. SAMORSKI AND W. STAMM  
 Institut für Reine und Angewandte Kernphysik, University of Kiel  
 Received 1982 November 22; accepted 1983 January 5

- 28 scintillation counters,  $1\text{m}^2$  each
- 60,000 showers over 16,775 hours
- In the direction of Cygnus X-3 (3,838 hours):  
 excess of 16.6 showers ( $4.4 \sigma$ )  
 with an angular resolution of  $1^\circ$   
 + characteristic 4.8 h signal modulation
- Very high flux:  
 $\Phi_{> 2 \text{ PeV}} = (7.4 \pm 3.2) \times 10^{-14} \text{ photons cm}^{-2} \text{ s}^{-1}$
- Muon content similar to hadronic showers...



# THEMISTOCLE Concept

- Tracking High Energy Muons In Showers Triggered On Cherenkov Light Emission

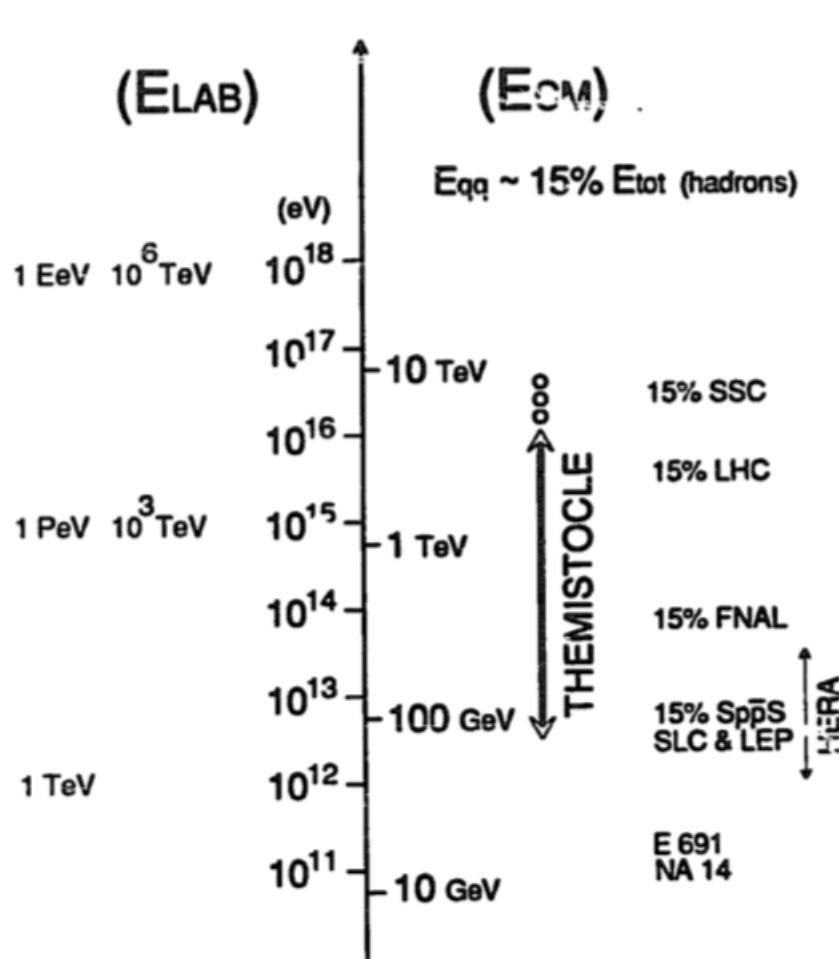


- Use gamma beams from cosmic sources to reveal possible new mechanism of photo production at high energies (*Cl. Ghesquière*).
- Cherenkov detection allows a much better **angular resolution**;
- Use the atmosphere as a GigaTon calorimeter => better energy measurement;
- Themis site available with 200 heliostats (*Ph. Goret – ASGAT expt*).

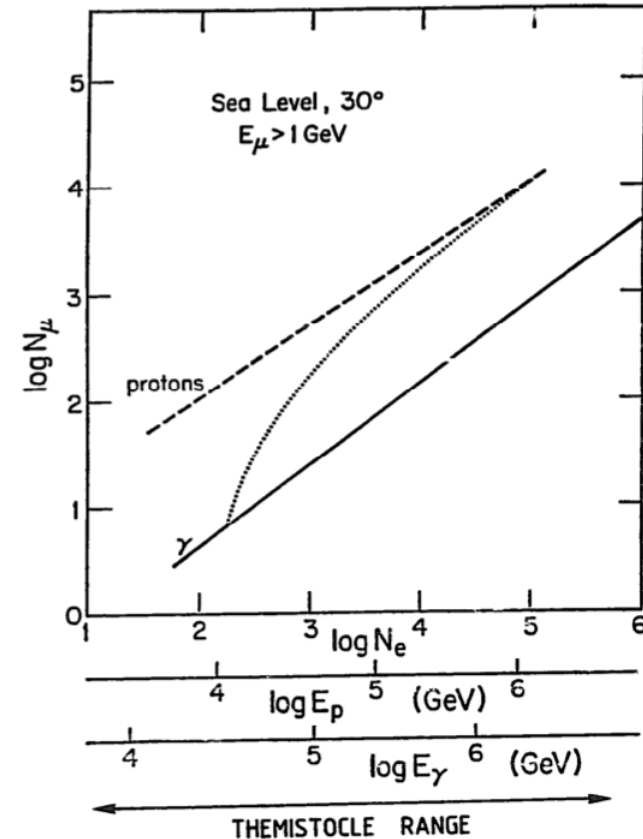
April 1986: Letter of intent;  
Dec. 1986: Proposal



# Energy Scale aimed at by THEMISTOCLE



**FIGURE 1**  
Energy scale in the Lab. and in the constituent Center of Mass system for Cosmic Ray and Accelerator experiments.

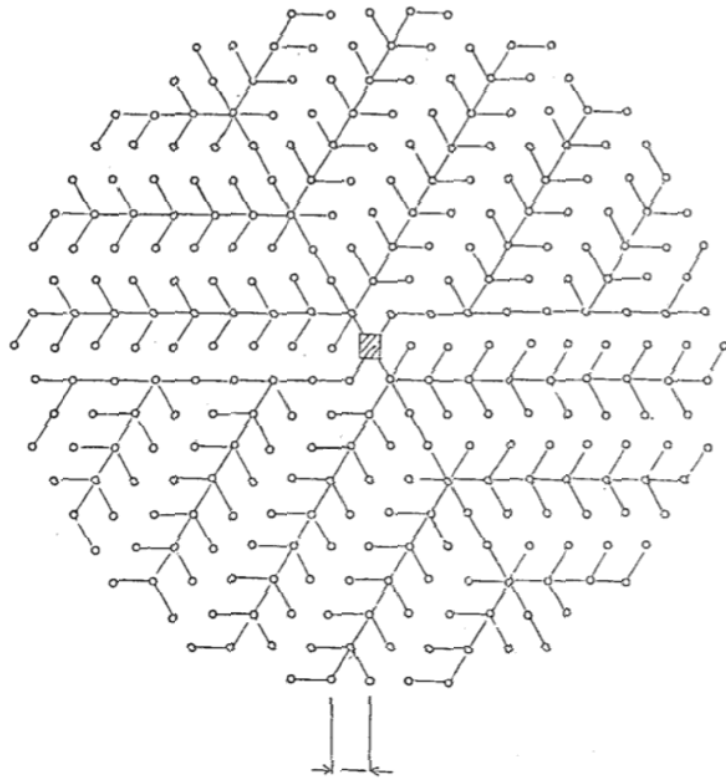


**FIGURE 4**  
Number of muons above 1 GeV ( $N_\mu$ ) versus Shower size (Number of electrons  $N_e$ ) for :  
- standard proton showers (dashed line)  
- standard gamma showers (solid line)  
- a model of strong coupling for photons above 0.25 TeV (dotted line)  
 $N_e$  is connected to the primary particle energy as shown by the bottom scales; (from ref 5).

# Descoping from THEMISTOCLE-300 to THEMISTOCLE-18

## Proposal (300 telescopes)

Telescope array 300 mirrors

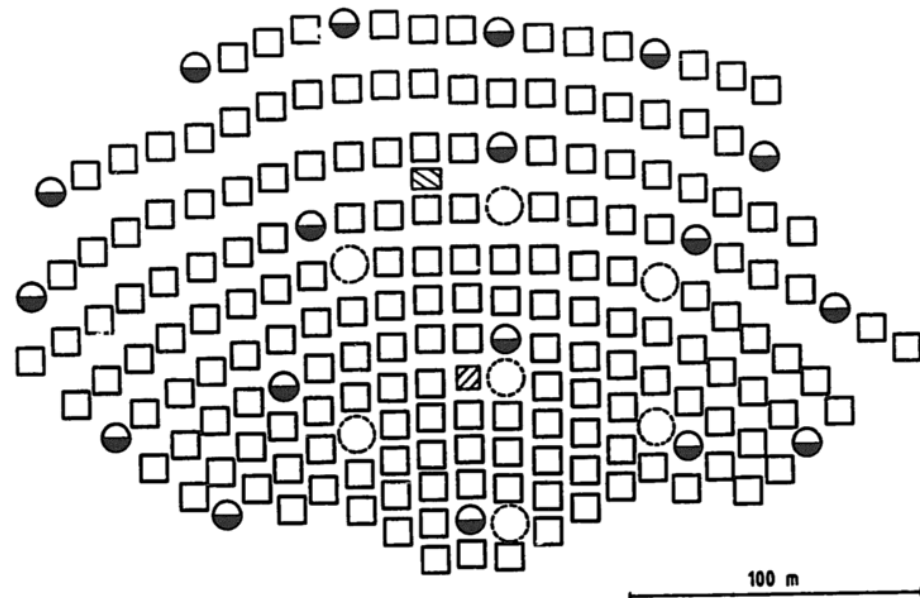


16m tight geometry

80m loose //

Schematic view of a possible lay-out of mirrors .

## Pilot Cherenkov experiment with 18 telescopes approved by IN2P3 in March 1988



THEMIS SITE  
mirror layout

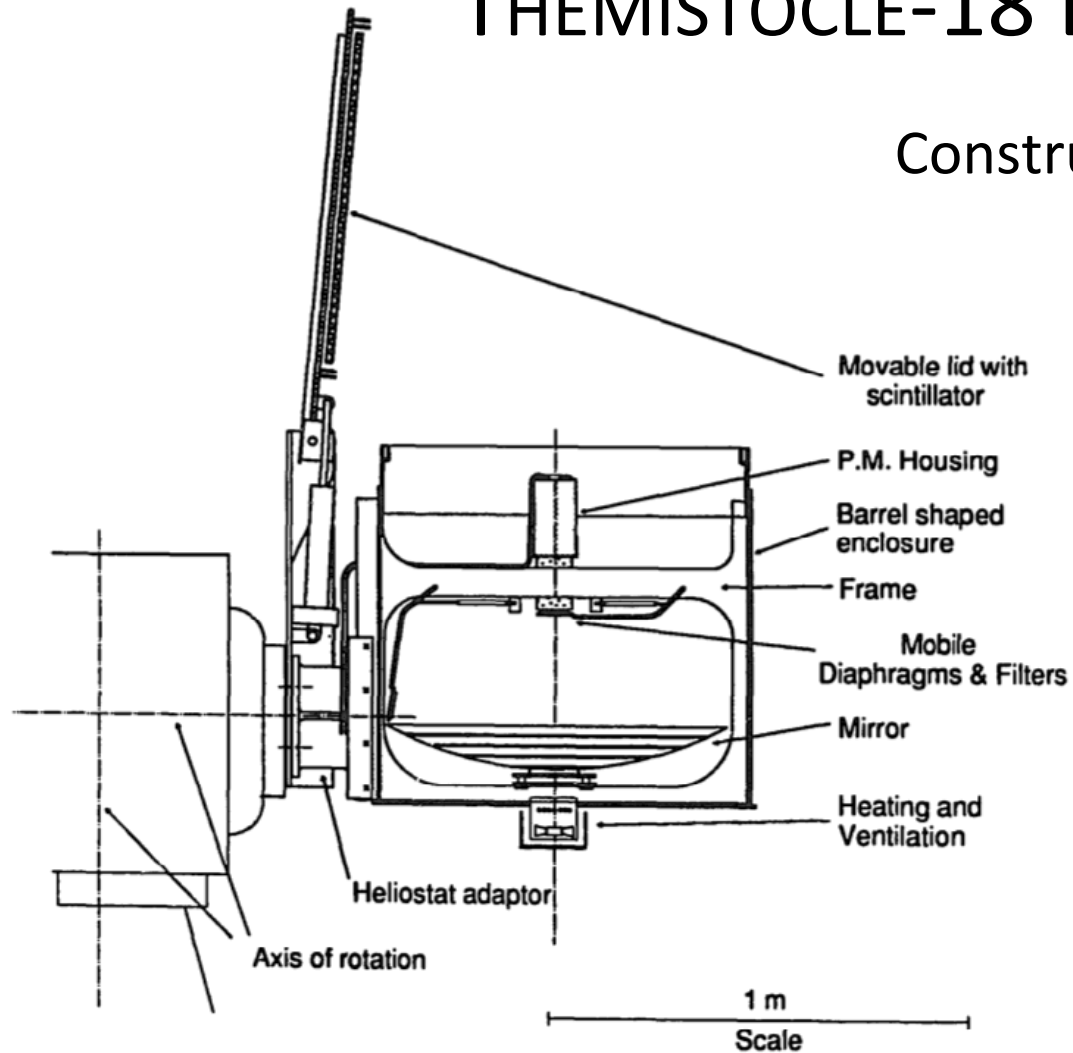


≈ Elliptical field  
280 x 190 m

	mirrors	Electronic huts
THEMISTOCLE 18		
ASGAT		
SOLAR MIRRORS (unused)		

# THEMISTOCLE-18 Detector

Construction from 1988 to 1990



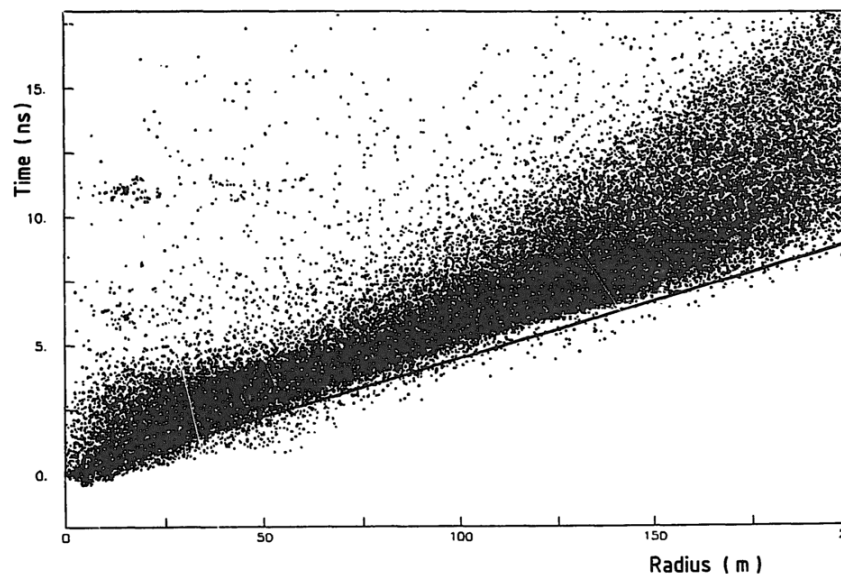
=> 80 cm  $\varnothing$  mirror + fast XP2020 PMT + preamp  
+ constant fraction discriminator + 0.1 ns TDC +  
ADC for each channel





# THEMISTOCLE-18 first results (½)

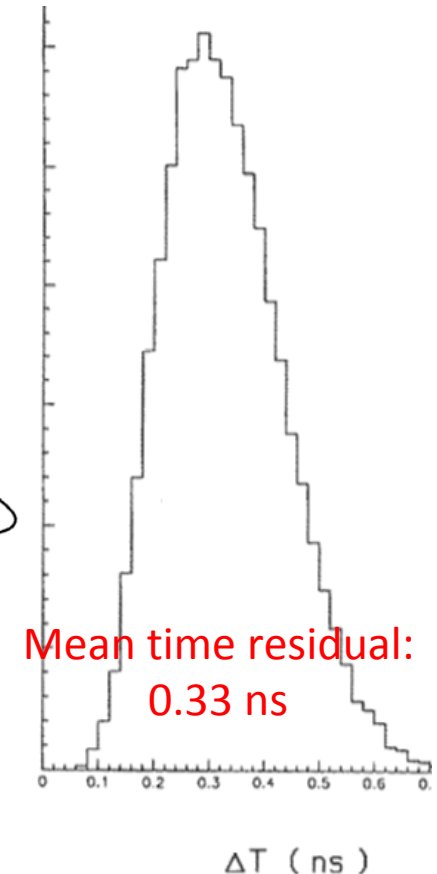
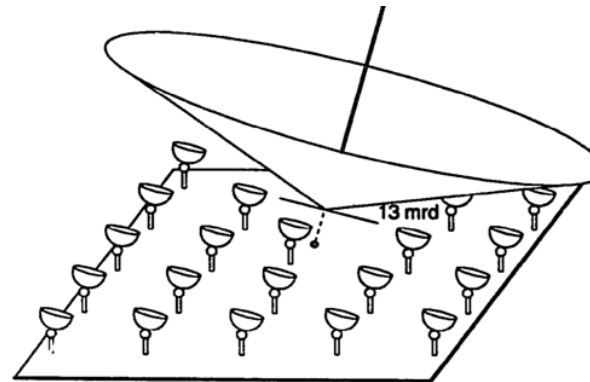
- Event reconstruction: in the TeV energy range, the light wave front is well described by a cone



Laser calibrated timing:

$$\sigma_t = \left( a^2 + \frac{b^2}{N_{\text{Phe}}} \right)^{1/2}$$

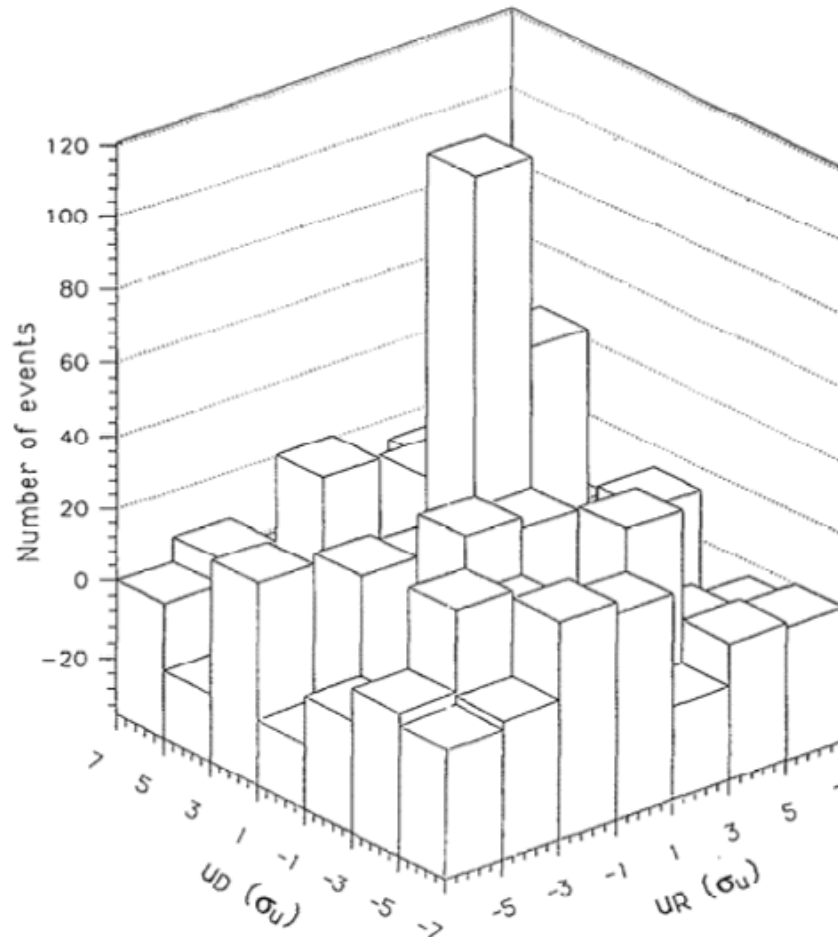
$a \approx 0.17 \text{ ns}$   $b \approx 2.7 \text{ ns}$



*Fitting a 6 parameter cone is highly non-linear. Convergence is slow due to the singularity at the apex and many ridges in the parameter space!*

- Ready for science observations in Summer 1990

# THEMISTOCLE-18 first results ( $^2/2$ )



Crab Nebula signal

## Signal extraction (based on Timing):

Distribution of reconstructed directions,  
 $u_D, u_R$  : Euler angles, local orthonormal  
coordinate system in mrd.

Maximum likelihood method to test the existence  
of a source signal against the hypothesis of pure  
background (OFF data).

First season on **Crab** (67 h / winter 1990-91):  
95 gamma detected at  $3.5 \sigma$ .

1991 data on **Her X-1** and **Cyg X-3**: NO signal

With additional 95 h (1991-92) on **Crab**:  
 $282 \pm 54$  gamma at  $\approx 6 \sigma$ , with an angular  
resolution of 2.2 mrad ( $0.13^\circ$ ).

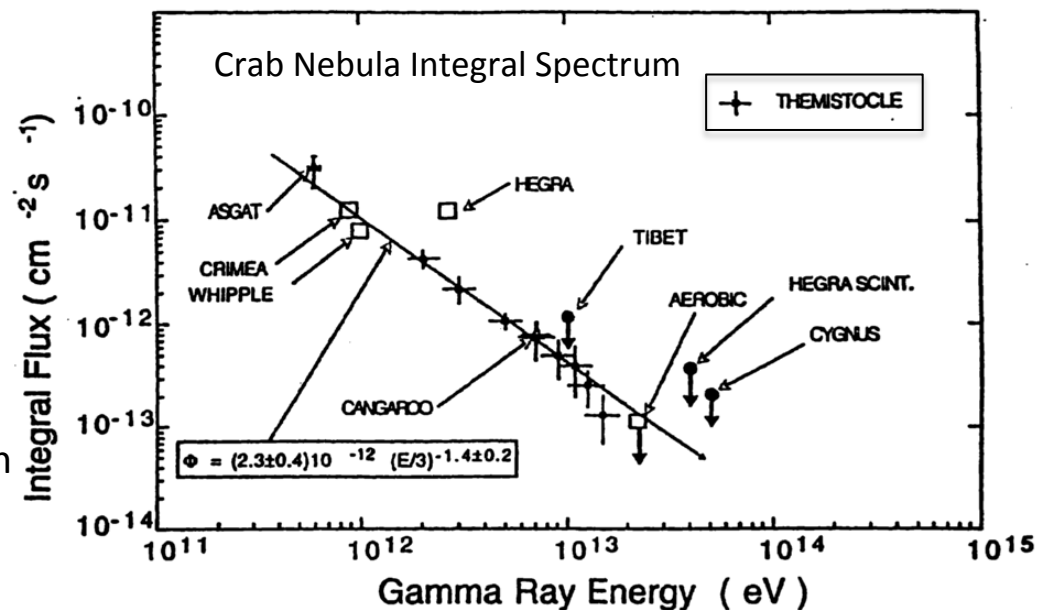
( ICHEP Dallas Feb 1992,  
XIII "Physics in Collision" Heidelberg 1993 )

# THEMISTOCLE energy measurement & hadron rejection

- Energy estimation and spectrum:

- The amplitudes of the signals from a shower are used in a global fit of the radial density distributions predicted by MC generation of gamma showers at different energies.
- In addition to the energy estimate, the quality of this fit provides a discrimination between gamma rays (good fit) and hadrons (bad fit).
- The **energy scale is set by fitting the trigger rate** (dominated by hadronic showers).

- Publication in Astropart. Phys (1993) done with pure proton background has a biased energy scale !  
The threshold is NOT 3 TeV as stated...
- Roma ICRC paper (1995), with a more realistic background taking into account He and heavier ions.  
A total of 388 h of Crab data =>  $407 \pm 68$  gamma  $E > 2$  TeV detected at  $6.6 \sigma$ , with spectrum extending **from 2 to 13 TeV**.



22 publications in conference proceedings over 8 years, but only one in a referred journal!

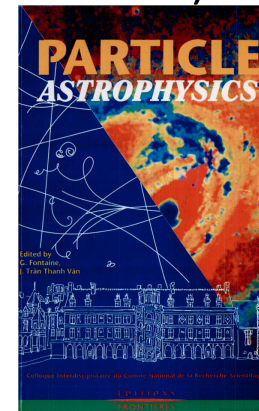


# THEMISTOCLE lessons learned

- On the technical side
  - Wavefront sampling can be used for gamma-ray astronomy;
  - Good reconstruction (direction and energy) requires a minimum of 12 samples for each shower;
  - 18 telescopes was a bit too low in this respect and an array of 40 would have been much more efficient.
- On the scientific side
  - Confirmation that TeV gamma rays are emitted in the Universe;
  - But their fluxes are much lower than anticipated and no emission is seen from Her X-1 and Cyg X-3;
  - No hope for a discovery of a new mechanism of photo production at high energies, while at the same time the first results of the HERA collider were showing a conventional  $\gamma$ -p interaction up to 200 GeV CM energy.
- Observations (almost) stopped in 1995  
But a strong interest in gamma-ray sources had been triggered, and was going to continue...

# Gamma-ray astronomy status in 1992

- **Gamma-ray emission of the Crab Nebula**  
had already been discovered by the Whipple Obs. group (Ap J 1989)  
(Thanks to T. Weekes' tenacity and to A.M. Hillas' analysis method)



- **A.E Chudakov's worries and satisfaction**  
at the Blois conference on "*Particle Astrophysics*" (1992):

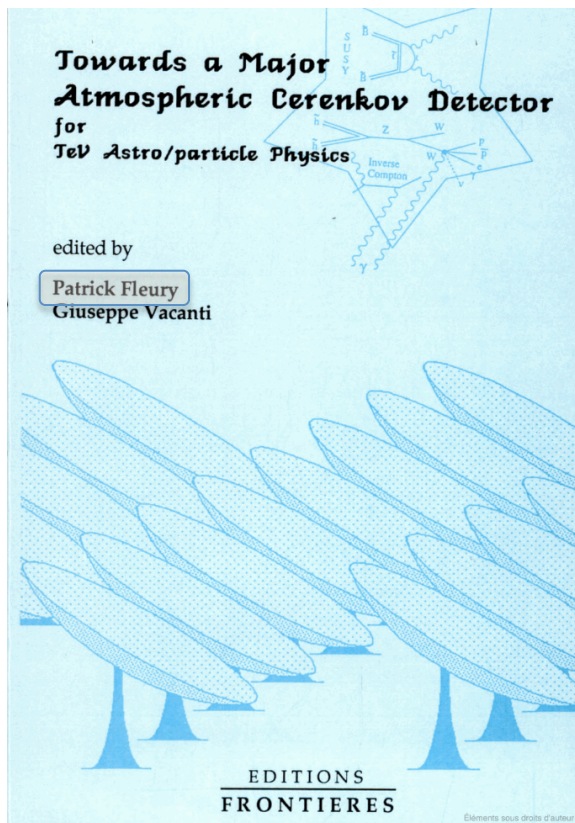
One should have in mind that, though already 4 years passed after the announcement of the first significant Whipple result, their data on Crab remains unique, still not repeated and confirmed by another group. <sup>1</sup> . . .

---

<sup>1</sup>At this Conference two important developments arrived: 1) the confirmation of the Whipple result on Crab using a different air Cerenkov technique (fast timing long base multimirror systems Asgat and Themistocle), and 2) observation of Mrk 421 by Whipple telescope itself. The last one is the most exciting expanding the area of research to distant extragalactic object . . .

# Towards a Major Atmospheric Cherenkov Detector

A Dream not yet true in 1992!



And a wink to a [concept of hybrid array](#) with  
54 Small sized,  
16-30 Medium sized and  
3-7 Large sized telescopes...

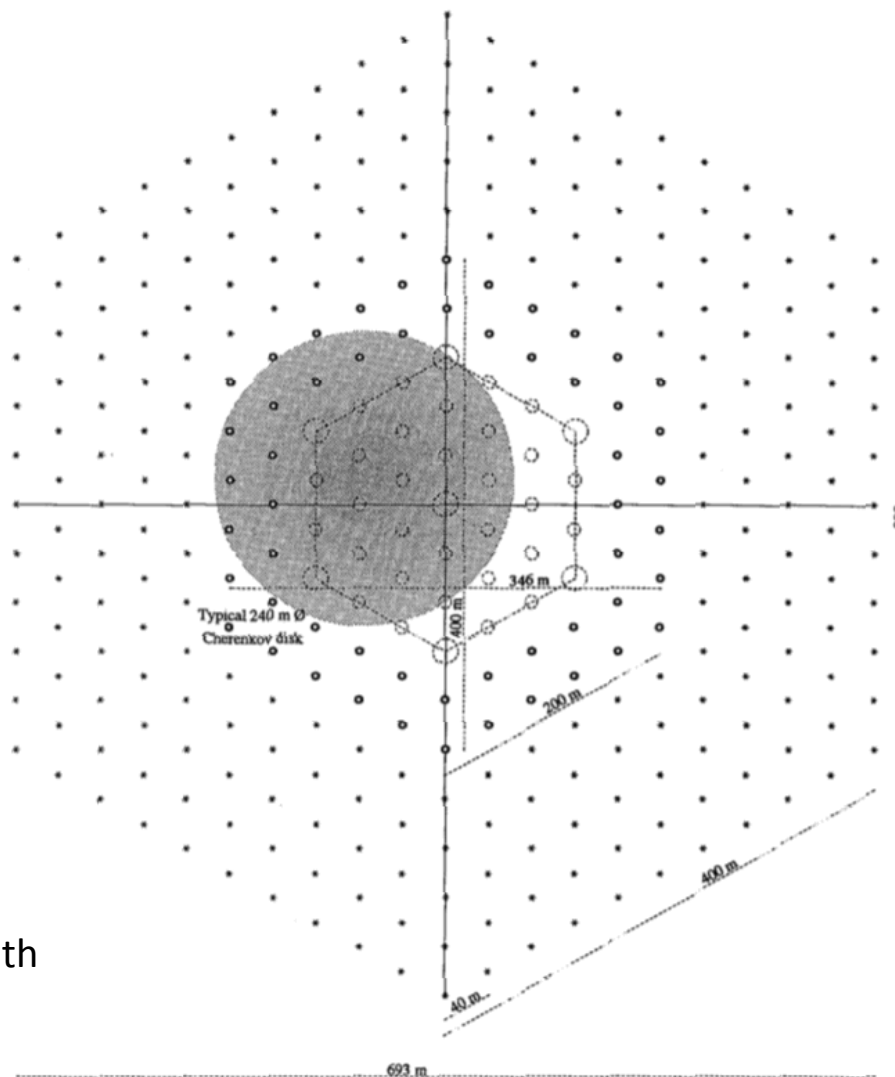


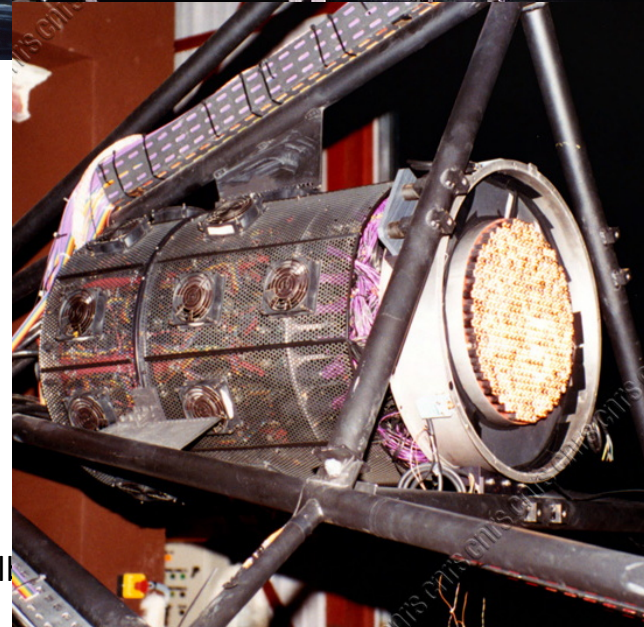
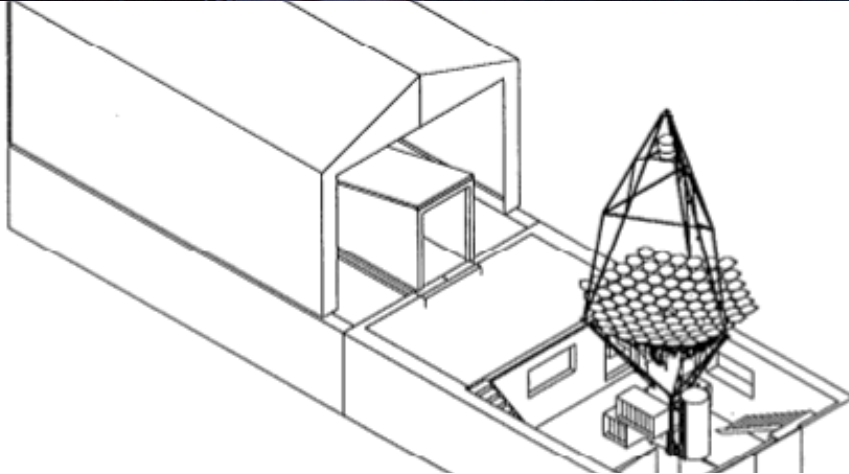
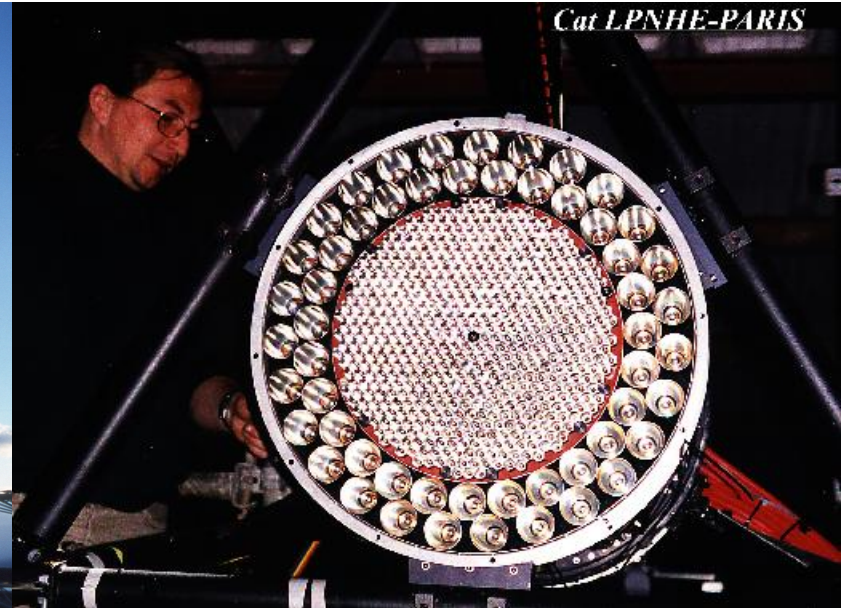
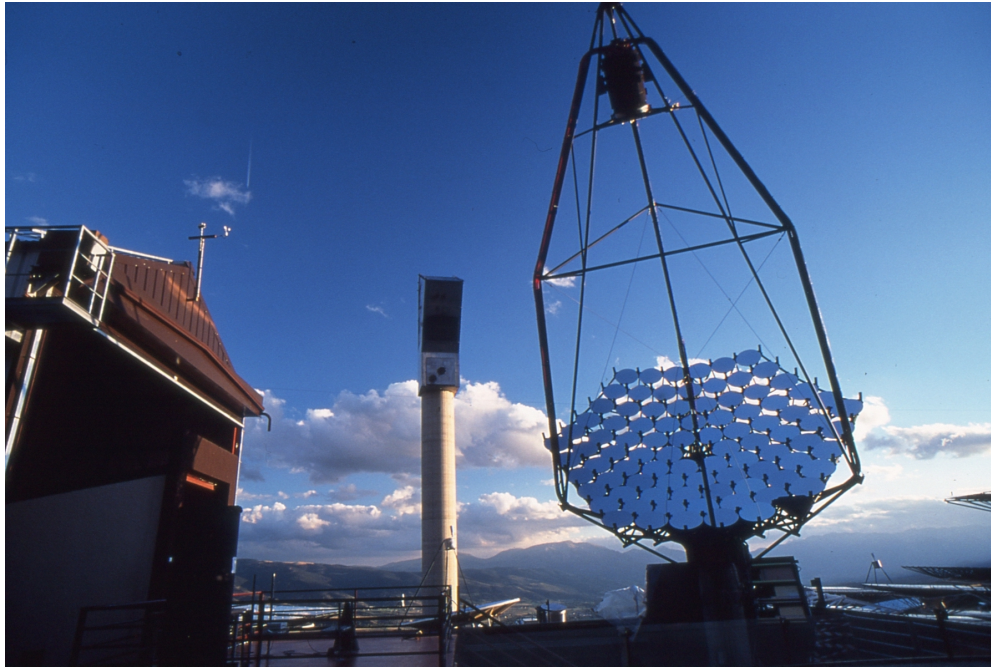
Fig 5 : Large Atmospheric Cherenkov Detector (G.F.)



# The CAT Project

- After the 13<sup>th</sup> ECRS conference in Geneva (1992) and the announcement of the HEGRA Cherenkov project : the **CAT imaging telescope** was proposed in 1993 by *B. Degrange* et al for the Themis site:
  - Imaging technique (following *A.M. Hillas*' pioneering work)
  - Modest mirror size (16 m<sup>2</sup>)
  - Very fast and fine grained camera (546 pixels 0.12° in Ø)
  - Advanced analysis techniques based on image matching with a library of precomputed shapes.
- First light in 1996: Despite a much smaller mirror size (16 m<sup>2</sup>) than that of Whipple (75 m<sup>2</sup>), **fine grained imaging** made it possible for CAT to reach a similar sensitivity and energy threshold (250 GeV)!

# CAT Telescope and Camera



Gerard Fontaine - Hillas Symposium – Heidelberg

# CAT Results and Timeline

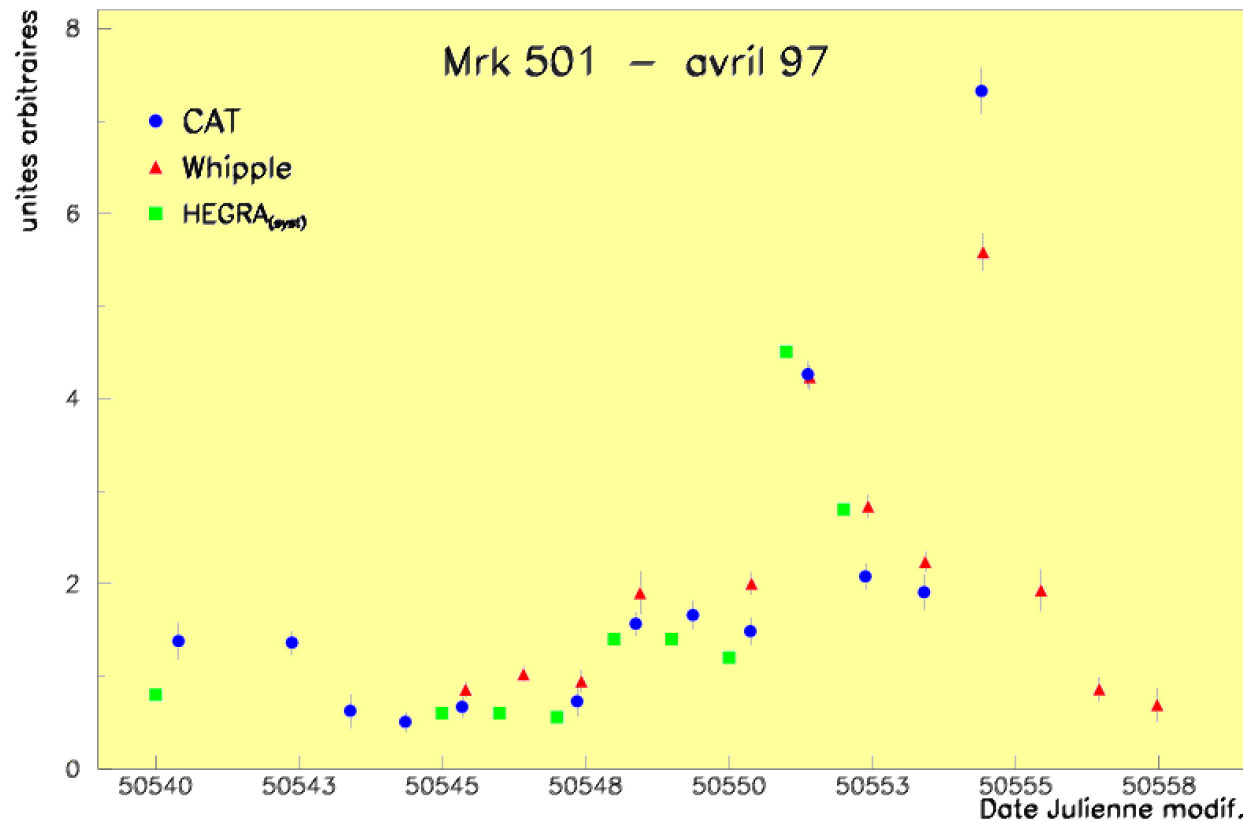
- Dec. 1992: Letter of Intent
  - July 1993: Proposal
  - 1994: Approved by IN2P3
  - 1996: First light
  - Nov. 1998: « *The CAT imaging telescope...* » NIM, vol. A 416, pp 278-292
  - Nov. 1998: « *A new analysis method ...* » NIM, vol. A 416, pp 425-437
  - Oct. 1999: « *VHE ... Mkn 501 ... in 1997* » A&A, vol. 350, pp 17-24
  - Aug. 2001: « *Temporal ... Mkn 421 ...* » A&A, vol. 374, pp 895-906
  - Aug. 2002: « *Detect. ... 1ES1426+428 ...* » A&A, vol. 391 (2002), pp L25-L28
  - 2002: End of observations
  - 2004: End of the experiment
- + 31 publications in conference proceedings over 9 years  
*incl. 1ES1959+650 (& 1ES1426+428) at Meudon 2003*



# April 1997: An important Milestone

- Simultaneous observation of the Mrk 501 flare by Whipple, HEGRA and CAT

*Reported at the 25th ICRC in Durban and the Kruger Workshop (1997)*



# Revisiting wave-front sampling

- Scientific need to bridge the energy gap [10 GeV – 250 GeV] between space-borne and ground-based observations
- Cherenkov technique below 100 GeV requires very large mirrors
- Opportunity to use again the Themis solar plant array!



200 heliostats  
(54 m<sup>2</sup> each)  
concentrating the sun's  
power at the top of a  
100 m height tower.

# The CELESTE project

- Wave-front sampling detector approved in 1996 as a multi-step project (6 -> 18 -> 40 mirrors  $\approx 2000 \text{ m}^2$ ) led by *E. Paré*
- Required secondary optics on top of the tower
- 1 GHz FADCs
- First light in 1998

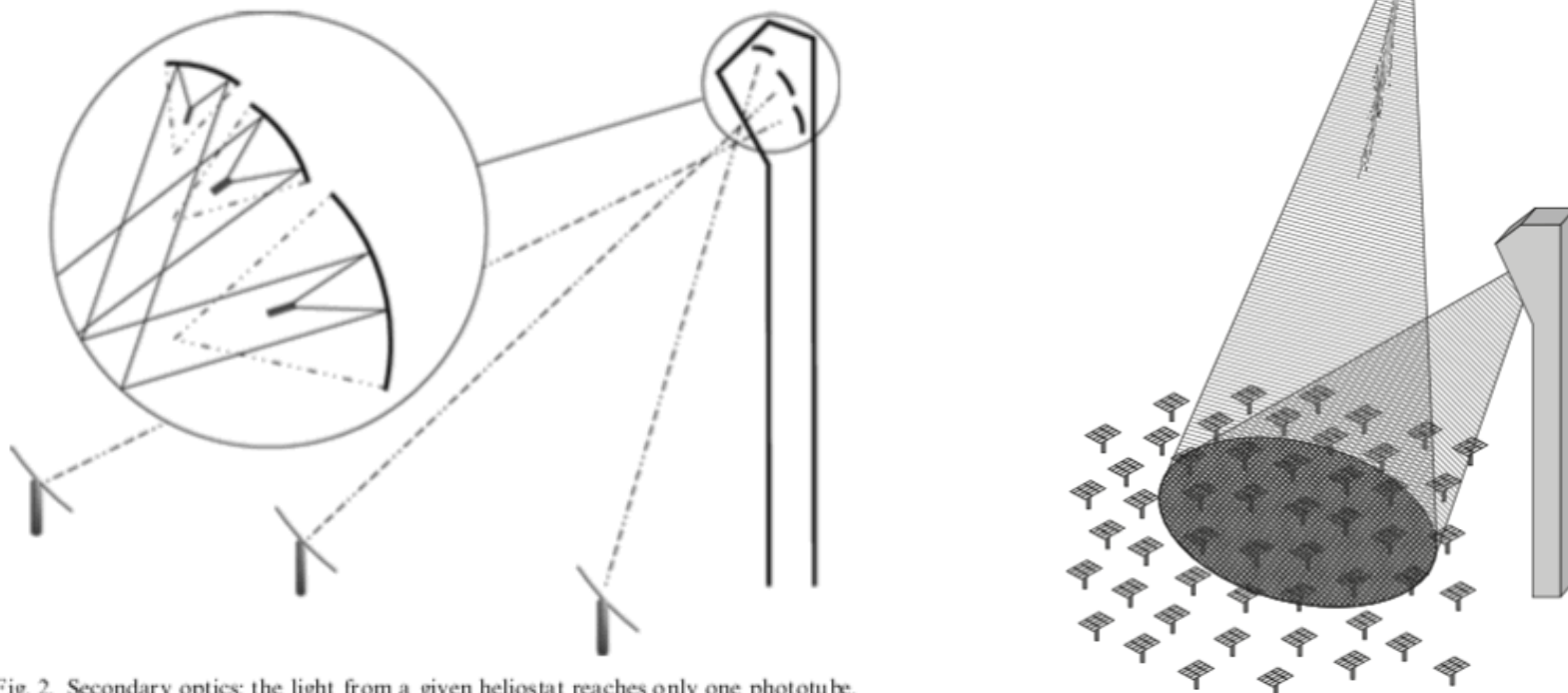
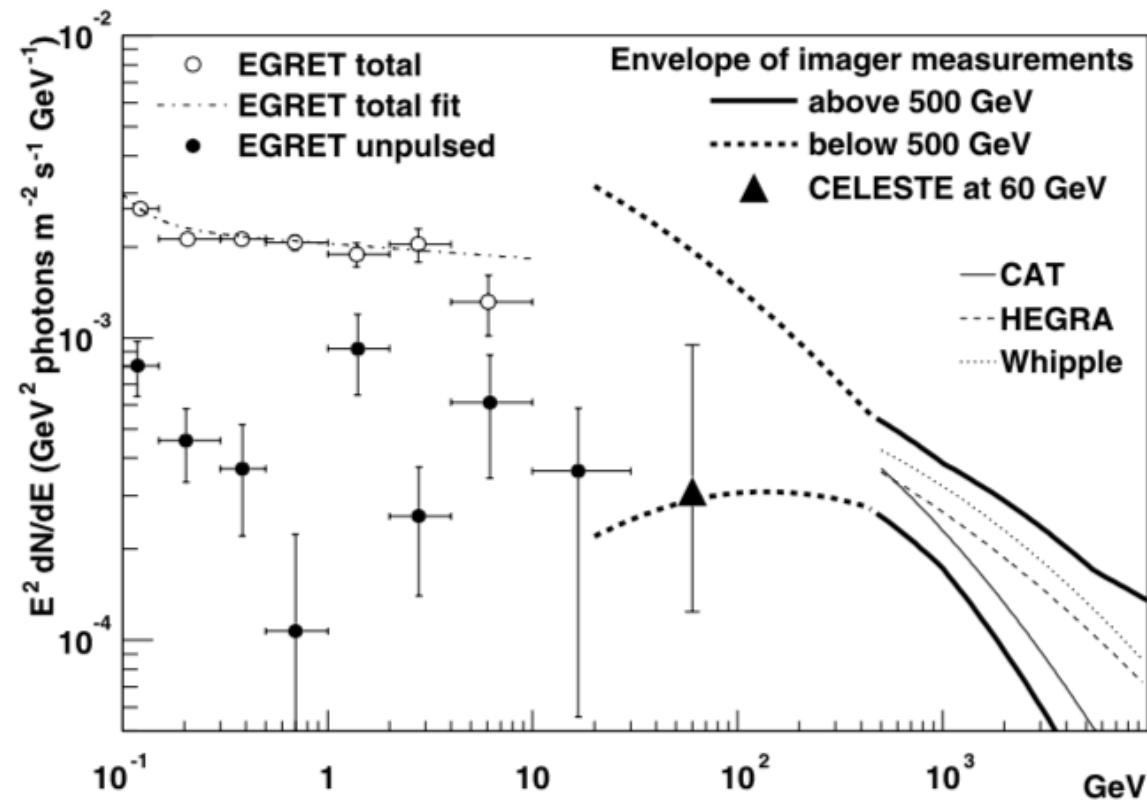


Fig. 2. Secondary optics: the light from a given heliostat reaches only one phototube.

# CELESTE results

Sensitivity down to 30 GeV

- 1998: « *Prototype tests ...* » NIM, vol. A 412, pp 329-341
- 2002: « *CELESTE: an atmospheric ...* » NIM, vol. A 490, pp 71-89
- Feb. 2002: « *Measurement ... Crab ... 60 GeV ...* » ApJ 566, pp 343-357
- 2006: « *Mrk 421, Mrk 501 and 1ES 1426 ... 100 GeV ...* » A&A 459, 453-464



Crab nebula  
gamma-ray  
spectrum



# Moral of the story

- **Difficulties with the CELESTE solar farm approach:**

Shape of the wave-front (conical above 1 TeV, but spherical around 100 GeV)

Limited field of view ( $\approx 1^\circ$  defined by the size of the secondary optics)

Albedo and weather issues ...

Better move to another site and ...

- **Go for imaging!** 😊

Thanks again to **A.M. Hillas** ❤️

**Combining :**

- Large dish as in Whipple,
- Stereoscopy as in HEGRA
- Fast and fine grained camera(s) + advanced analysis techniques as in CAT
- With a field of view as large as possible.





And then came the H.E.S.S. era ...

Thank you

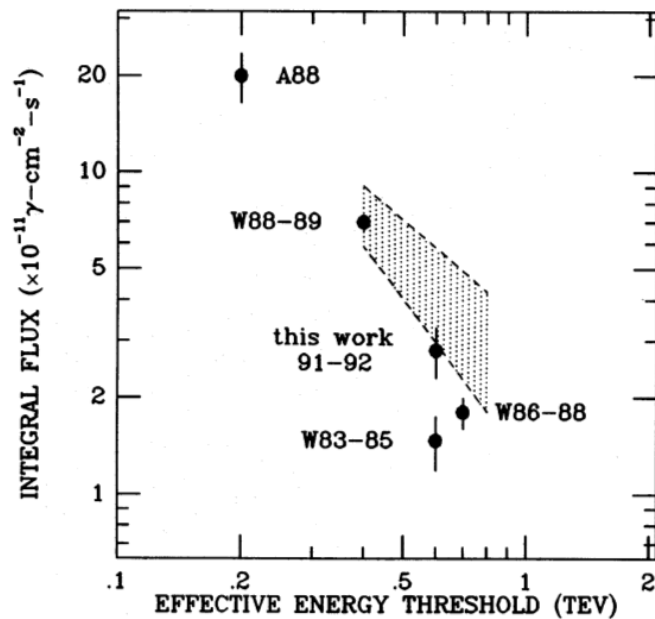
Any questions?



# Backup slides

# Measurement of the Crab Nebula Spectrum

ASGAT 0.6 TeV



THEMISTOCLE [2 – 13 TeV]

