Technological Advances in Ground-Based Gamma-Ray

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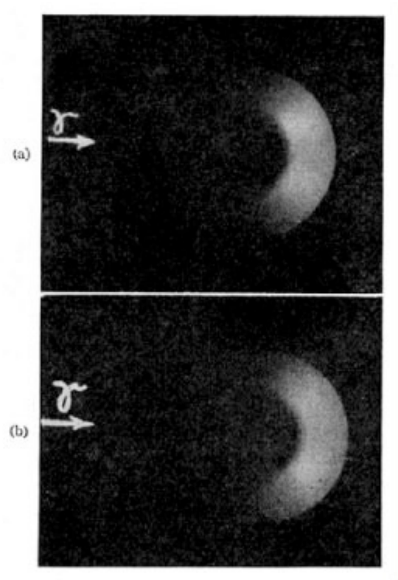
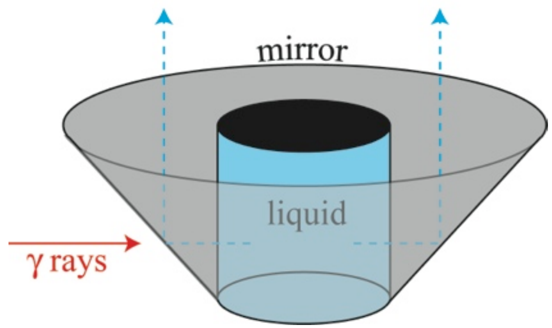
From human eyes to huge size telescopes

- Long time before and during the discovery the Cherenkov emission light has been observed by the readily available light sensors – human eyes. The story tells that initially Pavel Cherenkov did not like the topic of his PhD thesis; he had to spend many hours in a cold and dark cellar for accomodating his eves to darkness
- Then he has used a

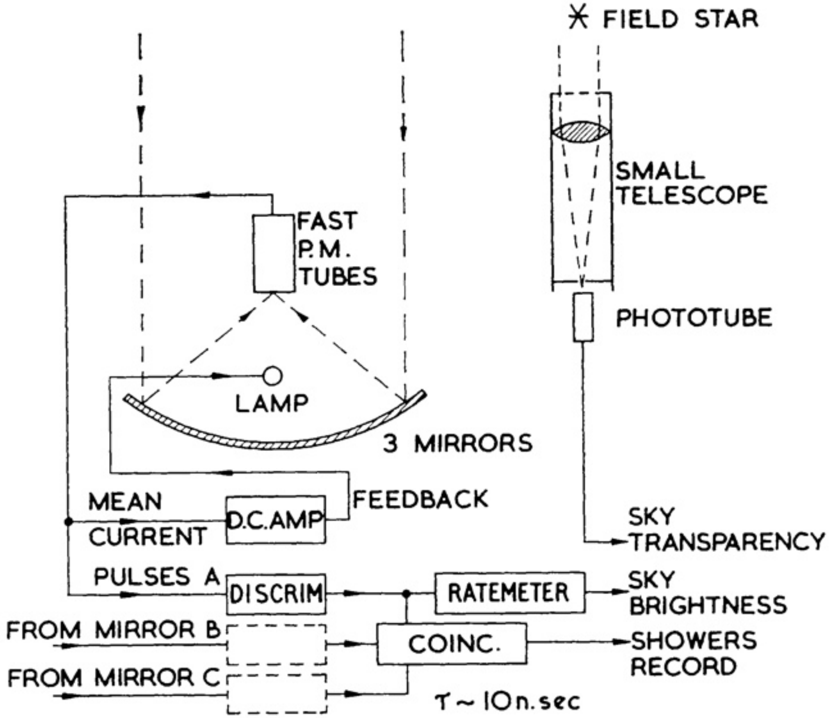


(camera above)

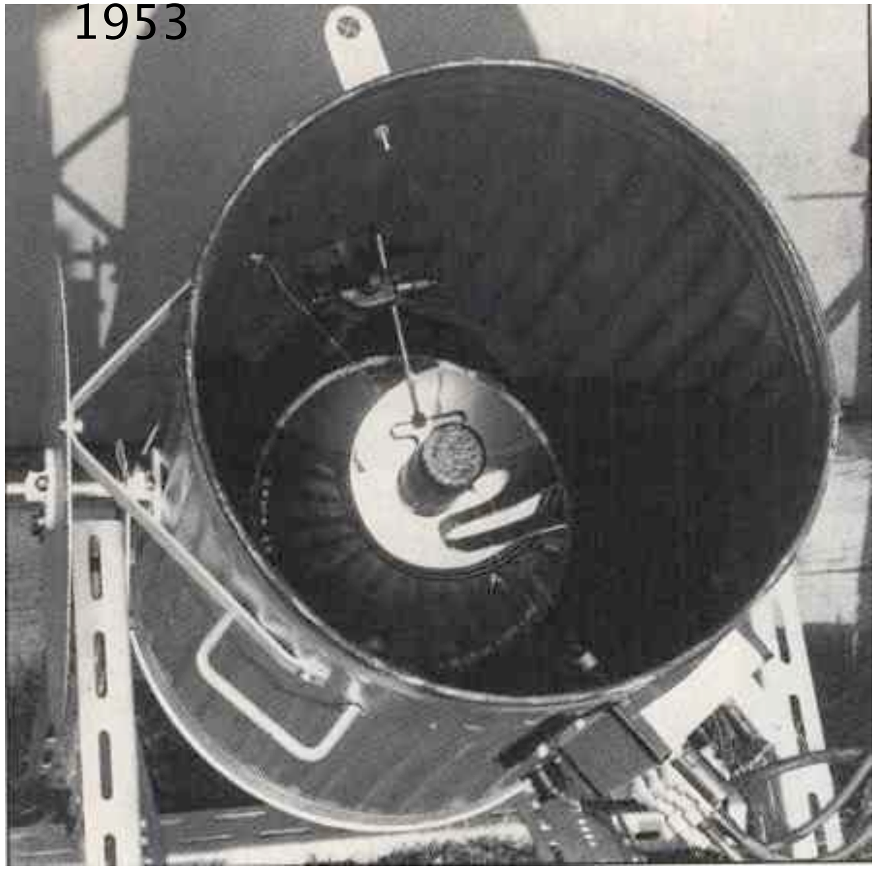


1st Cherenkov pulses from the sky

- The classical PMTs have radically improved the situation



Galbraith & Jelley, 1st telescope, 1953



Gamma-ray Astronomy,

Interesting paper by Phillip Morrison, 1958; suggesting to measure γ's from radioactive debris from SNR explosion @ 0.2-400 MeV γ's

IL NUOVO CIMENTO VOL. VII, N. 6 16 Marzo 1958

On Gamma-Ray Astronomy.

P. MORRISON

Department of Physics, Cornell University - Ithaca, N. Y.

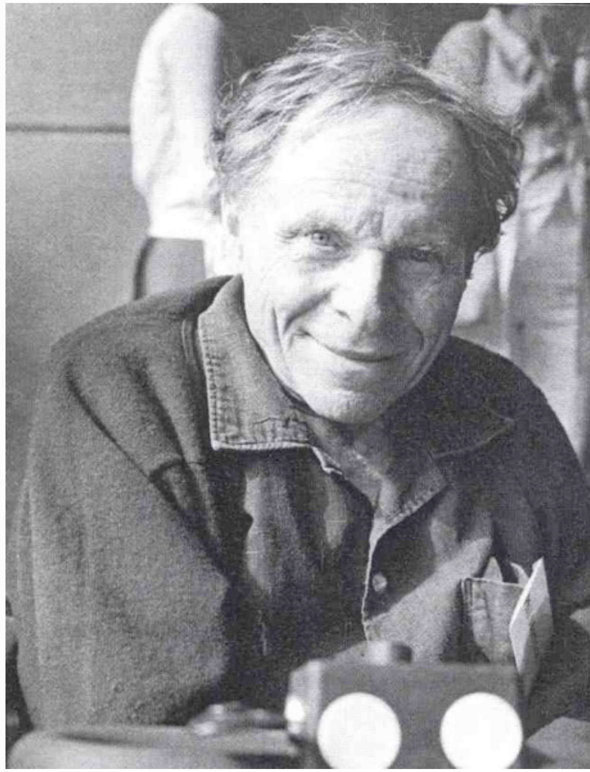
(ricevuto il 22 Dicembre 1957)

Summary. — Photons in the visible range form the basis of astronomy. They move in straight lines, which preserves source information, but they arise only very indirectly from nuclear or high-energy processes. Cosmic-ray particles, on the other hand, arise directly from high-energy processes in astronomical objects of various classes, but carry no information about source direction. Radio emissions are still more complex in origin. But γ-rays arise rather directly in nuclear or high-energy processes, and yet travel in straight lines. Processes which might give rise to continuous and discrete γ-ray spectra in astronomical objects are described, and possible source directions and intensities are estimated. Present limits were set by observations with little energy or angular discrimination; γ-ray studies made at balloon altitudes, with feasible discrimination, promise valuable information not otherwise attainable.

1. – The nature of the problem.

Astronomy is based on information carried by incoming radiation of optical frequencies. The photons in this channel retain the momentum with which they were originally emitted: with precision in direction, subject only to a rather easily interpreted Doppler shift in magnitude. On the other hand, such photons are very indirectly related indeed to the processes, generally nuclear in nature, which form the ultimate source of the radiated energy.

Insofar as energy-releasing processes are thermonuclear in nature, they proceed deep in stellar interiors, screened by dense layers of matter. We cannot hope to obtain direct signals from such regions (except by way of the still unexploited neutrino channel). But it is increasingly clear that energy-releasing processes of quite different type are also of importance for the evolution of



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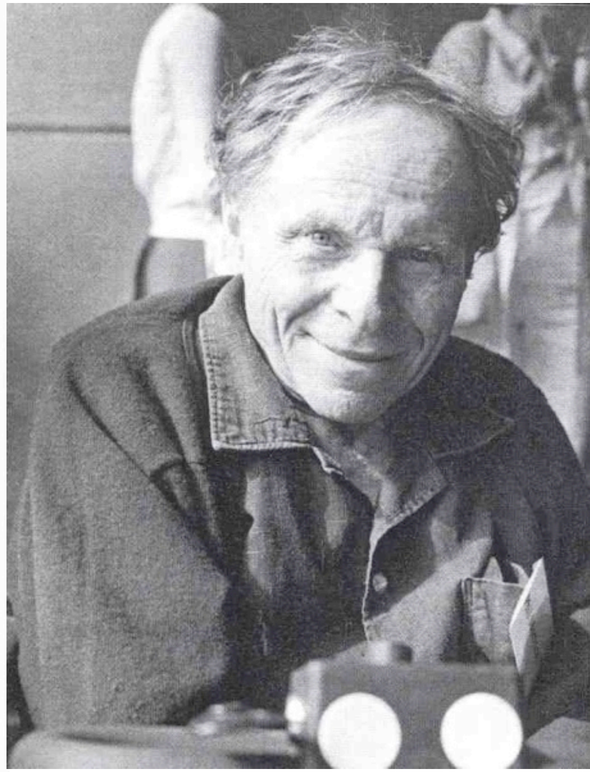

Gamma-ray Astronomy,

AN AIR SHOWER TELESCOPE
AND THE DETECTION OF 10^{12} eV PHOTON SOURCES
Giuseppe Cocconi *
CERN - Geneva.

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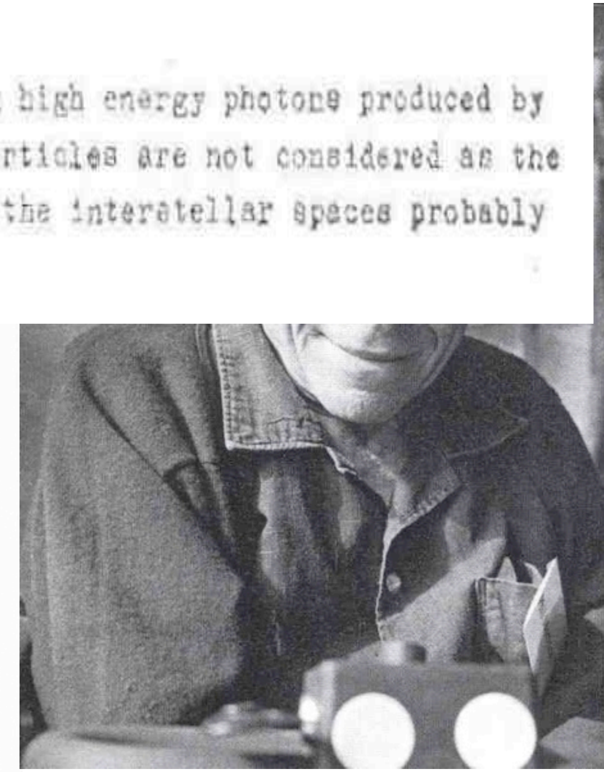

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3). Here are some numerical estimates.

The Crab Nebula: Visual magnitude of polarized light m = 9.
Magnetic field in the gas shell $H \simeq 10^{-4}$ gauss.
Therefore: $U_\gamma = 10^{12}$ eV and $R(10^{12} eV) \approx 10^{-3.2}\ m^{-2} s^{-1}$.

The signal is thus about 10^3 times larger than the background (2). Probably in the Crab Nebula the electrons are not in equilibrium with the trapped cosmic rays, and our estimate is over-optimistic. However, this source can probably be detected even if its efficiency in producing high energy photons is substantially smaller than postulated above.

487, the Jet Nebula: m = 13.5 $H \simeq 10^{-4}$ gauss.
$R(10^{12} eV) \simeq 10^{-5} m^{-2} s^{-1}$, still well above the background (2). For this object our evaluation is probably not fundamentally wrong.

The 1st large-scale instrument for γ astronomy

A serious experimental work has been performed by this team. The technique and the instrument were well-understood, below some excerpts from a paper from 1964

АКАДЕМИЯ НАУК СССР

1964 ТРУДЫ ФИЗИЧЕСКОГО ИНСТИТУТА им. П. Н. ЛЕБЕДЕВА Том XXVI

А. Е. ЧУДАКОВ, В. Л. ДАДЫКИН, В. И. ЗАЦЕПИН, Н. М. НЕСТЕРОВА

ПОИСКИ ФОТОНОВ С ЭНЕРГИЕЙ ~10^{13} *эв* ОТ ЛОКАЛЬНЫХ ИСТОЧНИКОВ КОСМИЧЕСКОГО РАДИОИЗЛУЧЕНИЯ

В данной статье описываются методика и результаты эксперимента, в котором сделана попытка обнаружения потока фотонов высокой энергии от некоторых космических объектов (и в первую очередь от объектов Лебедь А и Телец А). Эти наблюдения велись в течение четырех летних сезонов 1960, 1961, 1962 и 1963 гг. Предварительные результаты работы были доложены на международных конференциях по космическим лучам в Японии [1] и Боливии [2] и на Всесоюзной конференции по космическим лучам в Якутске.

Методика эксперимента была основана на регистрации широких атмосферных ливней в небольшом телесном угле (порядка нескольких тысячных стерадиан) по создаваемому ими в атмосфере Земли черенковскому излучению и сравнении интенсивности частиц высокой энергии, идущих от различных точек небесной сферы. Для этой цели была разработана телескопическая аппаратура большой светосилы, способная регистрировать вспышки черенковского света от ливней относительно небольшой начальной энергии (~ $2 \cdot 10^{12}$ *эв* при наблюдении на уровне моря). Благодаря большой эффективной площади регистрации ливней таким методом темп счета ливней (по направлениям, близким к вертикали) мог быть доведен до 200—250 в минуту и соответственно получена хорошая статистическая точность в сравнении интенсивностей от различных участков неба.

Окончательный результат всех четырех серий наблюдений оказался отрицательным. Во всех случаях с точностью около 1% не обнаружено возрастания интенсивности вблизи обследованных объектов. Придавать реальное значение эффектам порядка 1%, наблюдавшимся для объекта Лебедь А, оказалось невозможным. Таким образом, получен верхний предел возможной интенсивности фотонов. Для энергий фотонов $E \geqslant 5 \cdot 10^{12}$ *эв*, этот предел составляет $5 \cdot 10^{-11} см^{-2} \cdot сек^{-1}$.

Введение

В последнее время все большее внимание исследователей уделяется задаче экспериментального обнаружения фотонов высокой энергии в составе первичных космических лучей. При этом предполагается, что фотоны с энергией от 10^8 *эв* и сколь угодно выше должны возникать при столкновениях частиц космических лучей с ядрами атомов разреженной среды (благодаря генерации π^0-мезонов и последующему их распаду). Поэтому

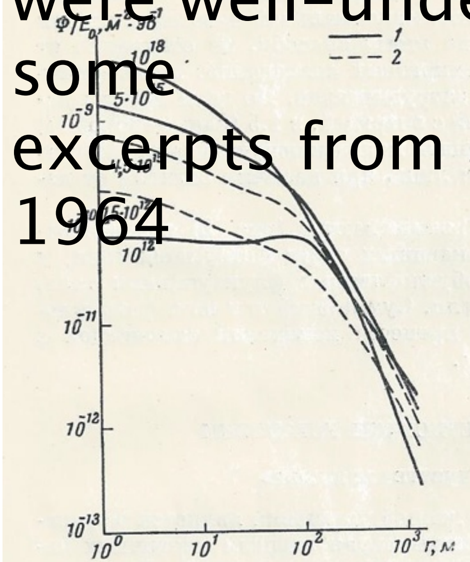


Рис. 3. Пространственное распределение интенсивности черенковского света в широких атмосферных ливнях на уровне моря

1 — первичные фотоны; *2* — первичные протоны; цифры у кривых показывают энергию первичных частиц в *эв*

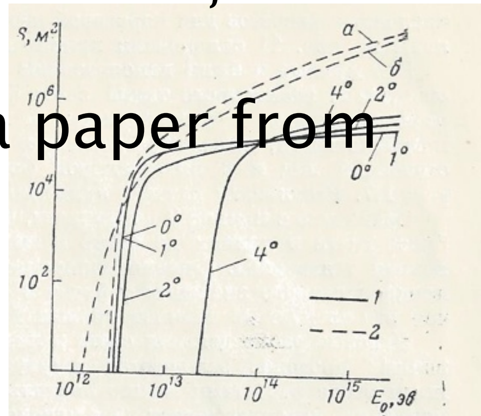


Рис. 11. Зависимость эффективной площади регистрации ливней от энергии

1 — для телескопов с углом зрения 1,75° для случая ливней от локального источника фотонов (цифры у кривых — угол между оптической осью телескопов и направлением на источник); *2* — для светоприемников с неограниченным углом зрения: *а* — для случая ливней от фотонов, *б* — для случая ливней от протонов

По оси ординат отложены значения площади S, *м²*, по оси абсцисс — энергия первичных частиц в *эв*; масштаб по осям логарифмический

Таблица 1

Астрономический объект и период наблюдений	Часовой угол	Склонение	Число сеансов	$\delta \pm \sigma$, % $\vartheta_{эф} \approx \pm 1°$	$\vartheta_{эф} \approx \pm 3°$
Дискретные радиоисточники					
Телец А (Крабовидная туманность) — Crab					
1960	5^h32^m	+22°00′	15	−0,15±1,32	+1,30±0,95
1961			13	−0,70±1,20	−0,60±0,84
1962 *			19	−1,40±0,82	−0,45±0,54
Кассиопея А — Cas A					
1962	$23^h21^m,6$	+58°35′	8	+0,60±0,93	−0,47±0,56
1962 *			12	−0,36±1,10	−0,77±0,66
Лебедь А — Cyg A					
1960	$19^h58^m,4$	+40°32′	19	+1,60±0,92	+1,60±0,80
1961			70	+0,22±0,35	+0,67±0,28
1962			62	+0,15±0,63	−0,65±0,52
1962 *			20	+0,50±0,76	+0,60±0,54
1963 *			20	+1,16±0,77	+0,97±0,53
Дева А					
1961	$12^h28^m,9$	+12°38′	10	−0,23±3,0	−0,14±2,10
1962			10	+0,37±1,0	+0,54±0,70
Персей А — Perseues A					
1962	3^h14^m	+42°24′	4	−1,80±2,30	−2,00±1,24
Стрелец А — Center of galaxy					
1963	$17^h43^m,3$	−28°58′	7	—	+10,5±20
Скопления галактик — Galaxy clusters					
Большая Медведица II 1962	10^h54^m	+56°30′	1	−5,0±2,9	−3,0±1,24
Северная корона 1962	15^h22^m	+27°24′	2	+3,3±2,1	+1,9±1,4
Волосы Вероники 1962	12^h55^m	+28°41′	1	+1,5±3,4	+1,7±2,4
Волопас 1962	14^h33^m	+31°16′	1	+2,4±6,9	+6,6±4,7

* Звездочкой отмечены измерения с компенсацией тока от неба.

- A multitude of sources have been observed and serious statistical treatment of data has followed
- Except for some small fluctuations no significant flux has been observed ≥ 3.5-5 TeV, Flux upper limit: 5×10^{-11} ph/cm^{2}s
- Turned down the too optimistic prediction of Cocconi about 1000:1 S/N from Crab

Cherenkov Technique used for Gamma Ray Astronomy

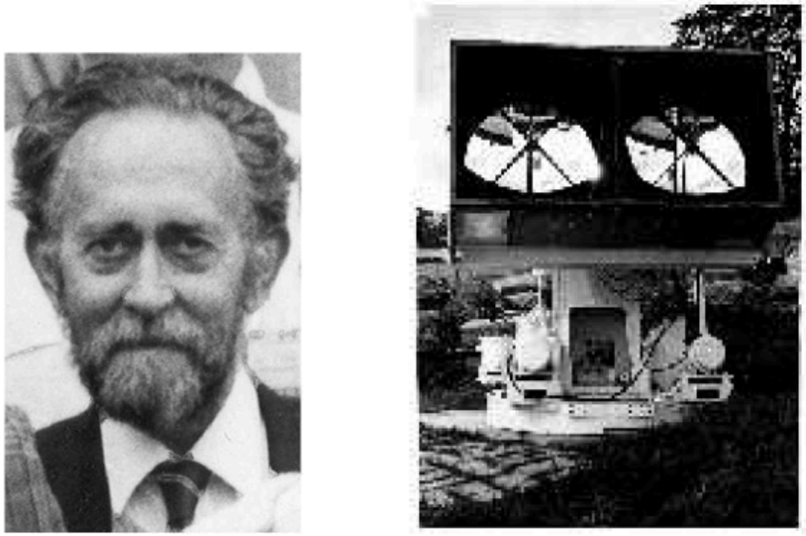


Figure 3. **Left:** Neil A. Porter (1930-2006) (Photo: D.J.Fegan) **Right:** The second ground-based gamma-ray telescope; the British-Irish experiment at Glencullen, Ireland c. 1964; the telescope consisted of two 90 cm searchlight mirrors on a Bofors gun mounting. The experiment was led by Jelley and Porter.

1st Gen. Atmospheric Cherenkov Telescope

Glencullen, Ireland ~1962-66

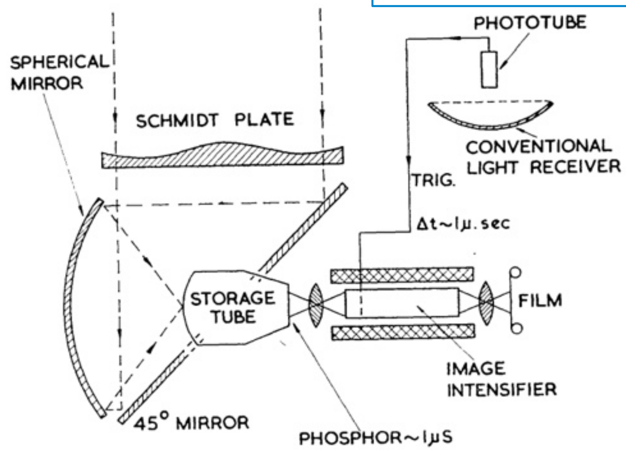
Univ. College, Dublin group led by Neil Porter (in collaboration with J.V. Jelley)

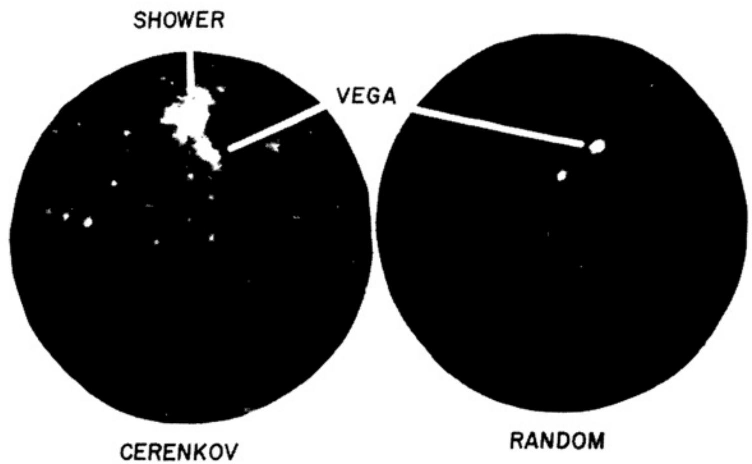
(quasars (AGN), variable stars)

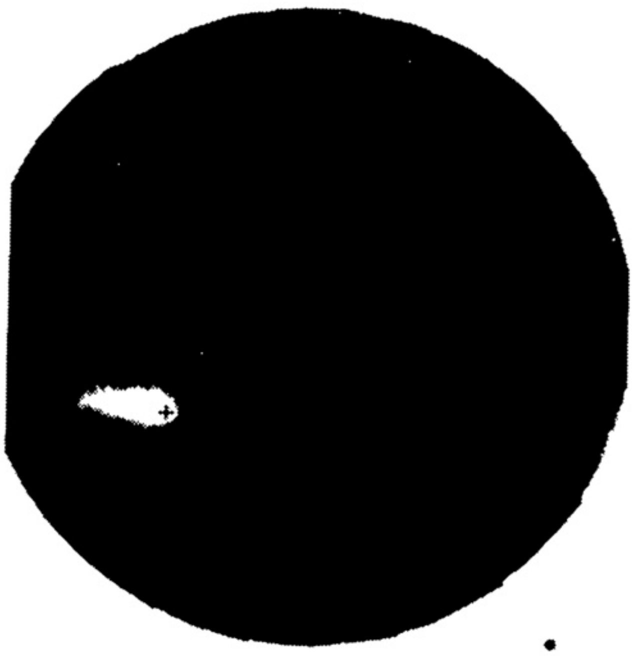
Imaging: 1st snapshots of air showers

- Image Intensifier with phosphor memory
- realizing the power of

Hill & Porter, 1960







FIELD OF VIEW ± 12°

moon Ø

1st Monte Carlo simulted air shower images

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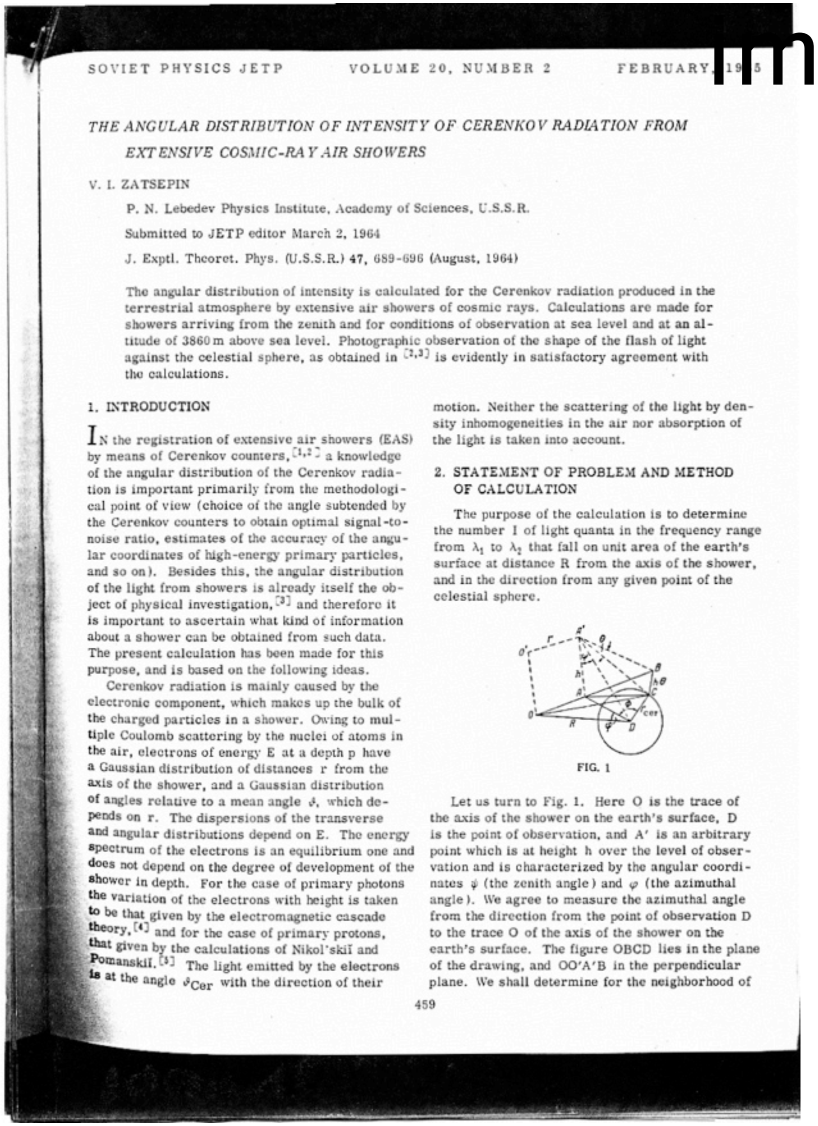

SOVIET PHYSICS JETP VOLUME 20, NUMBER 2 FEBRUARY, 1965

THE ANGULAR DISTRIBUTION OF INTENSITY OF CERENKOV RADIATION FROM EXTENSIVE COSMIC-RAY AIR SHOWERS

V. I. ZATSEPIN

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor March 2, 1964

J. Exptl. Theoret. Phys. (U.S.S.R.) **47**, 689-696 (August, 1964)

The angular distribution of intensity is calculated for the Cerenkov radiation produced in the terrestrial atmosphere by extensive air showers of cosmic rays. Calculations are made for showers arriving from the zenith and for conditions of observation at sea level and at an altitude of 3860 m above sea level. Photographic observation of the shape of the flash of light against the celestial sphere, as obtained in [2,3] is evidently in satisfactory agreement with the calculations.

1. INTRODUCTION

In the registration of extensive air showers (EAS) by means of Cerenkov counters, [1,2] a knowledge of the angular distribution of the Cerenkov radiation is important primarily from the methodological point of view (choice of the angle subtended by the Cerenkov counters to obtain optimal signal-to-noise ratio, estimates of the accuracy of the angular coordinates of high-energy primary particles, and so on). Besides this, the angular distribution of the light from showers is already itself the object of physical investigation, [3] and therefore it is important to ascertain what kind of information about a shower can be obtained from such data. The present calculation has been made for this purpose, and is based on the following ideas.

Cerenkov radiation is mainly caused by the electronic component, which makes up the bulk of the charged particles in a shower. Owing to multiple Coulomb scattering by the nuclei of atoms in the air, electrons of energy E at a depth p have a Gaussian distribution of distances r from the axis of the shower, and a Gaussian distribution of angles relative to a mean angle ϑ, which depends on r. The dispersions of the transverse and angular distributions depend on E. The energy spectrum of the electrons is an equilibrium one and does not depend on the degree of development of the shower in depth. For the case of primary photons the variation of the electrons with height is taken to be that given by the electromagnetic cascade theory, [4] and for the case of primary protons, that given by the calculations of Nikol'skiĭ and Pomanskiĭ. [5] The light emitted by the electrons is at the angle ϑ_{Cer} with the direction of their motion. Neither the scattering of the light by density inhomogeneities in the air nor absorption of the light is taken into account.

2. STATEMENT OF PROBLEM AND METHOD OF CALCULATION

The purpose of the calculation is to determine the number I of light quanta in the frequency range from λ_1 to λ_2 that fall on unit area of the earth's surface at distance R from the axis of the shower, and in the direction from any given point of the celestial sphere.

FIG. 1

Let us turn to Fig. 1. Here O is the trace of the axis of the shower on the earth's surface, D is the point of observation, and A' is an arbitrary point which is at height h over the level of observation and is characterized by the angular coordinates ψ (the zenith angle) and φ (the azimuthal angle). We agree to measure the azimuthal angle from the direction from the point of observation D to the trace O of the axis of the shower on the earth's surface. The figure OBCD lies in the plane of the drawing, and OO'A'B in the perpendicular plane. We shall determine for the neighborhood of

459

1st Monte Carlo simulted air shower images

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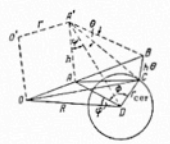

FIG. 1

Let us turn to Fig. 1. Here O is the trace of the axis of the shower on the earth's surface, D is the point of observation, and A′ is an arbitrary point which is at height h over the level of observation and is characterized by the angular coordinates ψ (the zenith angle) and φ (the azimuthal angle). We agree to measure the azimuthal angle from the direction from the point of observation D to the trace O of the axis of the shower on the earth's surface. The figure OBCD lies in the plane of the drawing, and OO′A′B in the perpendicular plane. We shall determine for the neighborhood of

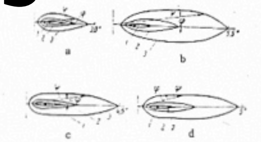

FIG. 6. Contours of equal intensity in light flashes from showers from primary protons and primary photons of various energies, for sea level and R = 100 m from the axis. The curves 1, 2, 3 correspond to intensity values $10^{-1} I_{max}(100)$, $10^{-2} I_{max}(100)$, and $10^{-3} I_{max}(100)$. Diagrams a and b correspond to primary photons of energies 10^3 and 5×10^4 BeV, and diagrams c and d to primary protons of energies 1.5×10^3 and 4.5×10^4 BeV.

primary photons. For lower energies of the primary particles ($E_0 \approx 10^{12}$ eV) the situation is somewhat better (Fig. 6). Here the shape of the line $I = 10^{-3} I_{max}$ in showers from photons differs appreciably from that of the corresponding line in showers from protons. This difference, however, is entirely due to the difference in the shapes of the cascade curves. If we allow for the fact that owing to fluctuations the cascade curves for proton showers can differ decidedly from the average curve, the difference in the shape of the light spots which we have mentioned can also be insufficient for a reliable distinction between showers produced by photons and those produced by protons. Figures 7 and 8, which are analogous to Figs. 2 and 3, give an idea of the angular distribution of the light in showers from primary protons when the observation is at altitude 3860 meters above sea level. A comparison of Figs. 3 and 8 shows that on mountains the spot of light from a shower from a proton

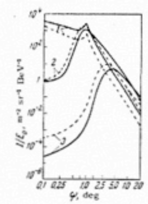

FIG. 7. Section of angular distribution of the intensity of Cerenkov light against zenith angle for azimuthal angle $\varphi = 0$, for altitude 3860 m above sea level. Curves 1, 2, and 3 are for the respective distances 0, 100, and 400 m from the axis of the shower. The solid curves correspond to a primary proton with energy 4.5×10^4 BeV, and the dashed curves to one with energy 1.5×10^3 BeV.

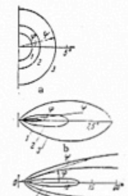

FIG. 8. Contours of equal intensity in the light flash at various distances from the axis of a shower arising from a primary proton with $E_{ep} = 4.5 \times 10^4$ BeV (3860 m above sea level). Curves 1, 2, and 3 correspond to the intensities $10^{-4} I_{max}(R)$, $10^{-2} I_{max}(R)$, and $10^{-3} I_{max}(R)$, and diagrams a, b, and c are for distances 0, 100, and 400 m from the axis of the shower.

with $E = 4.5 \times 10^{15}$ eV is considerably larger than that from such a shower at sea level. This difference is mainly due to the different distance of the registering device from the maximum of the shower. Thus the shape of the spot of light is sensitive to the height of the maximum of the shower, and at least in principle an analysis of the shape can be used also to determine the position of the maximum of a shower.

The present calculations have been made on the same assumptions as the calculations of the spatial distribution of the light made in [6], and therefore they can be checked directly by calculating the total luminous flux density

$$Q(R, E_0) = \int_0^{2\pi}\int_0^{10^\circ} I(E_0, R, \psi, \varphi)\sin\psi\, d\psi\, d\varphi \qquad (11)$$

at a given distance from the axis of the shower and comparing it with the results obtained in [6]. Calculations by Eq. (11) have been made for seal level for R = 100 m and R = 400 m. The results agreed with the results of [6] to an accuracy of several percent.

CONCLUSION

The calculations that have been made enable us to draw the following conclusions:

1. Since the maximum intensity of the light from a shower does not coincide with the direction of arrival of the primary particle, in researches in which the determination of the angular coordinates of the primary particle is made by photographing the light flash from the shower one should seek improved accuracy in this determination by photo-

Potential of the Stereo Imaging Detector is Recognised

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1. Since the maximum intensity of the light from a shower does not coincide with the direction of arrival of the primary particle, in researches in which the determination of the angular coordinates of the primary particle is made by photographing the light flash from the shower one should seek improved accuracy in this determination by photographing the shower simultaneously from several positions.

1st Smithsonian venture into VHE gamma-ray used Solar Furnace at Natick, MA ~ 1965-6.

Davis-Cotton design

First Gamma-ray Experiment at Whipple Observatory, 1967-68

Work on the Mt. Hopkins Observatory proceeds at an astonishing pace. The laser and Baker-Nunn systems are now installed and operating and the large optical reflector is scheduled to arrive by the end of next month. In preparation for the LOR installation, Trevor Weekes (above, left) and George Rieke have conducted seeing tests with two movable searchlight reflectors. Look carefully – some outcroppings at the base of Mt. Hopkins are visible upside-down in the reflector.

The Pioneer: all life-long trying really hard,
until succeeding in 1988

THE ASTROPHYSICAL JOURNAL, Vol. 154, November 1968

A SEARCH FOR DISCRETE SOURCES OF COSMIC GAMMA RAYS OF ENERGIES NEAR 2×10^{12} eV

G. G. FAZIO AND H. F. HELMKEN
Smithsonian Astrophysical Observatory and Harvard College Observatory, Cambridge, Massachusetts

G. H. RIEKE
Mount Hopkins Observatory, Smithsonian Astrophysical Observatory, Tubac, Arizona, and Harvard University, Cambridge, Massachusetts

AND

T. C. WEEKES*
Mount Hopkins Observatory, Smithsonian Astrophysical Observatory, Tubac, Arizona
Received September 3, 1968

ABSTRACT

By use of the atmospheric Čerenkov nightsky technique, a study has been made of the cosmic-ray air-shower distribution from the direction of thirteen astronomical objects. These include the Crab Nebula, M87, M82, quasi-stellar objects, X-ray sources, and recently exploded supernovae. An anisotropy in the direction of a source would indicate the emission of gamma rays of energy 2×10^{12} eV. No statistically significant effects were recorded. Upper limits of $3\text{–}30 \times 10^{-11}$ gamma ray cm^{-2} sec^{-1} were deduced for the individual sources.

Cherenkov Shower Stereo Detectors (1972-76)

- Josh Grindlay demonstrates value of stereo imaging with two-pixel system (Double Beam Technique) at Mt. Hopkins and Narrabri (1972-76)
- 2 PMT per „camera“: one watching the shower max and the other one the „μ-core“; ~ 2-times suppressing the hadrons

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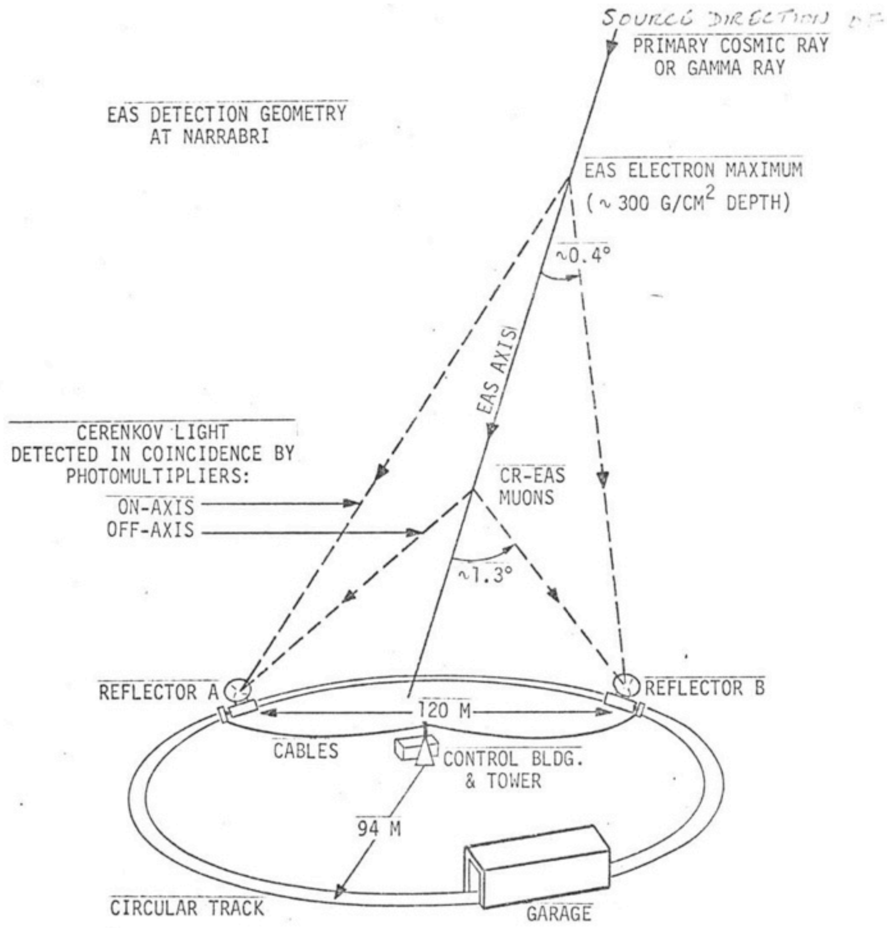


One of numerous mysteries in old days

THE ASTROPHYSICAL JOURNAL, 174:L9–L17, 1972 May 15

DETECTION OF PULSED GAMMA RAYS OF $\sim 10^{12}$ eV FROM THE PULSAR IN THE CRAB NEBULA

J. E. GRINDLAY
Smithsonian Astrophysical Observatory and Harvard College Observatory, Cambridge, Massachusetts
Received 1972 March 10

ABSTRACT

The previous evidence we have given for the detection of pulsed γ-rays of $\sim 10^{12}$ eV from NP 0532 has been confirmed by an additional 99 drift scans on the Crab in 1971 November and December. Again, only those extensive air showers detected to be possibly initiated by γ-rays showed a 4.5 σ excess at the phase of the optical interpulse. The sum of these data and those reported previously yielded a 5.5 σ peak at the interpulse and a 3.5 σ peak at the main pulse, consistent with a pulsed flux $F(E_\gamma \geq 6.8 \times 10^{11}\ \text{eV}) \simeq 1.25 \times 10^{-11}$ photons cm^{-2} s^{-1}. The ratio of interpulse to primary pulse is $\sim$3.5:1, and the spectrum appears consistent with an extrapolation from the X-ray data. Some implications of these results are discussed.

~ 5σ pulsating signal is reported from the Crab pulsar at ~ 1 TeV
at the absense of any steady emission from the Crab Nebula

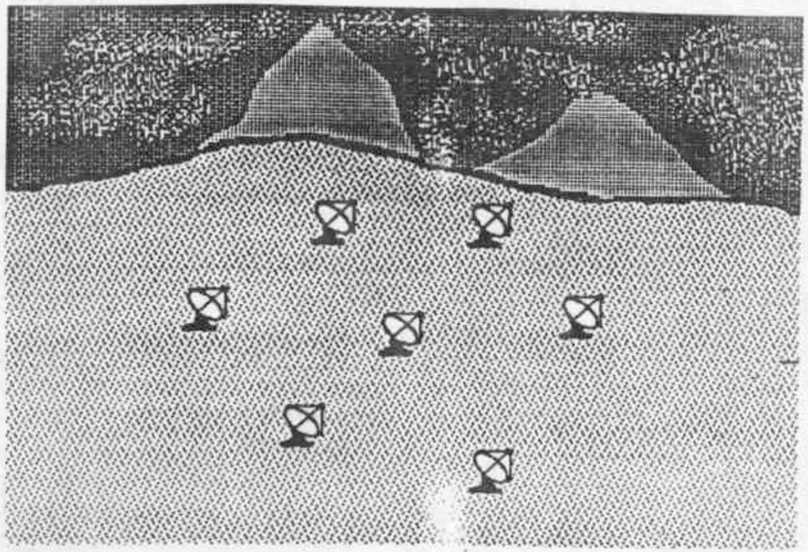


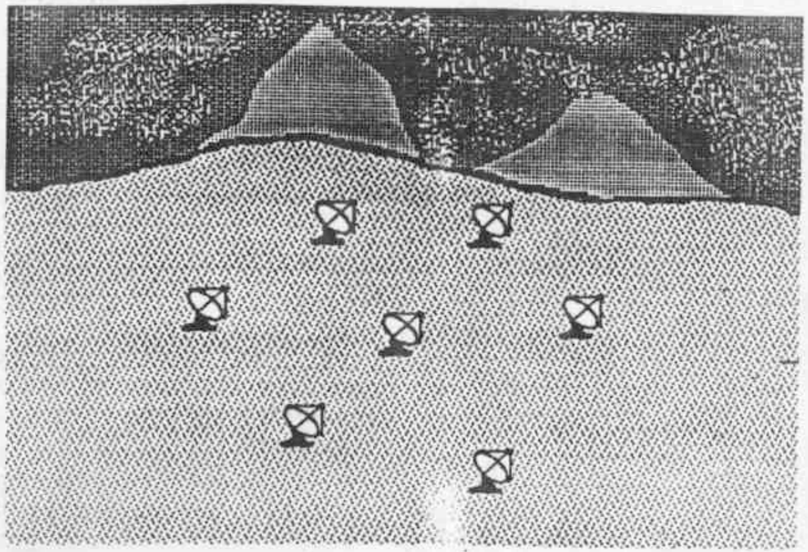
Figure 1a. Artist's concept of VHE Gamma Ray Observatory showing seven 15 m aperture atmospheric Cherenkov cameras with spacing of 75 m.

Stereo Imaging suggested by
Weekes and Turver, 1977

An array of ACIT's was first proposed in 1984 (prior to the detection of the Crab Nebula).

(NASA Workshop, Space Lab. Science, Baton Rouge, 1984)

This is the configuration that was later adopted for



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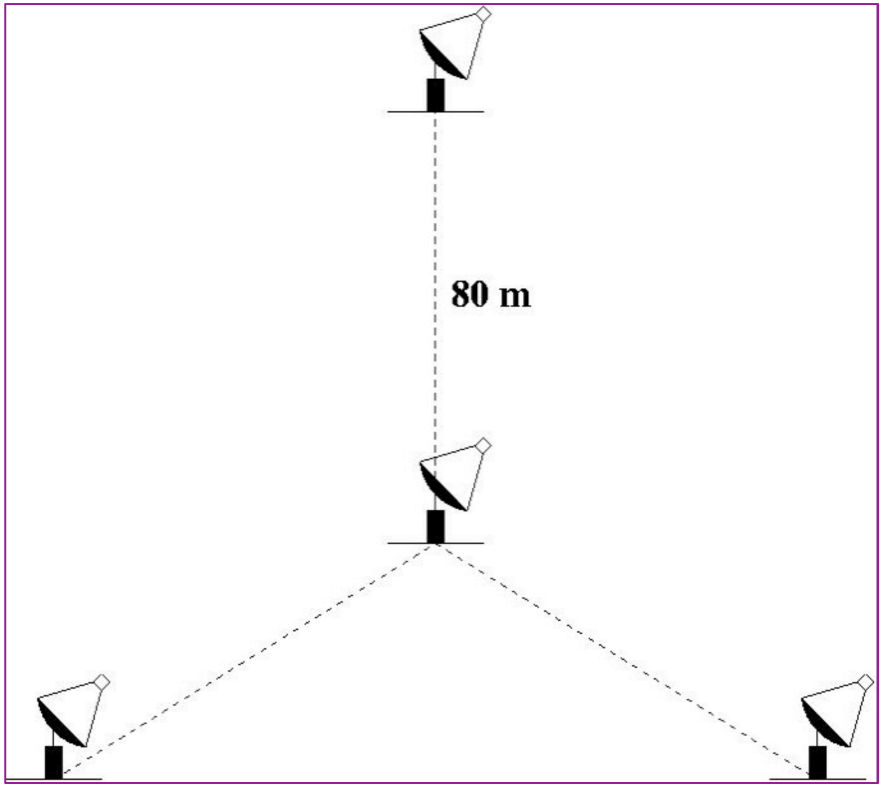

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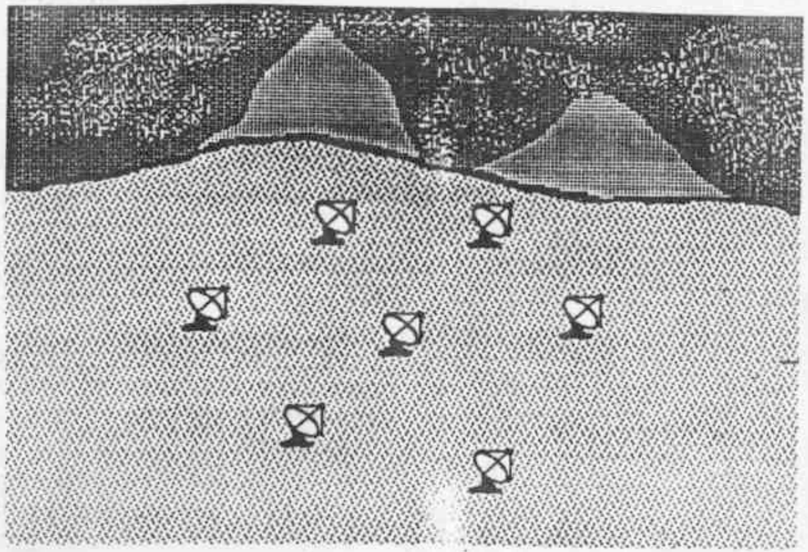

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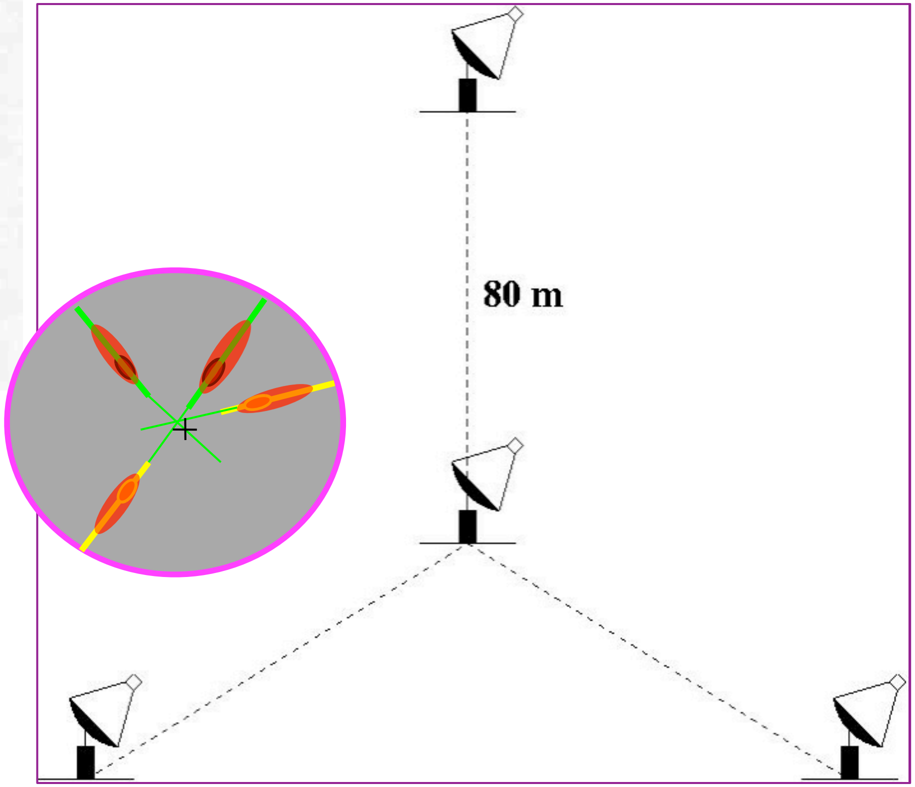

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Arnold Stepanian and his 1st imaging “stereo ”telescopes: GT-48 in Crimea

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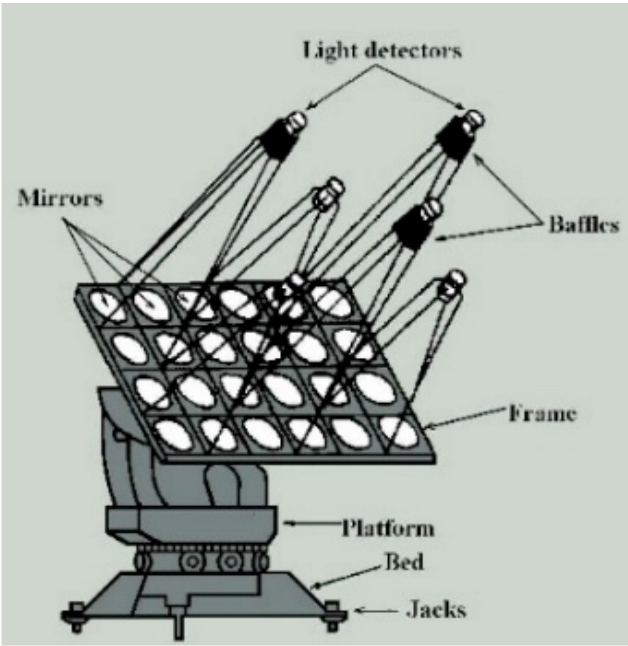
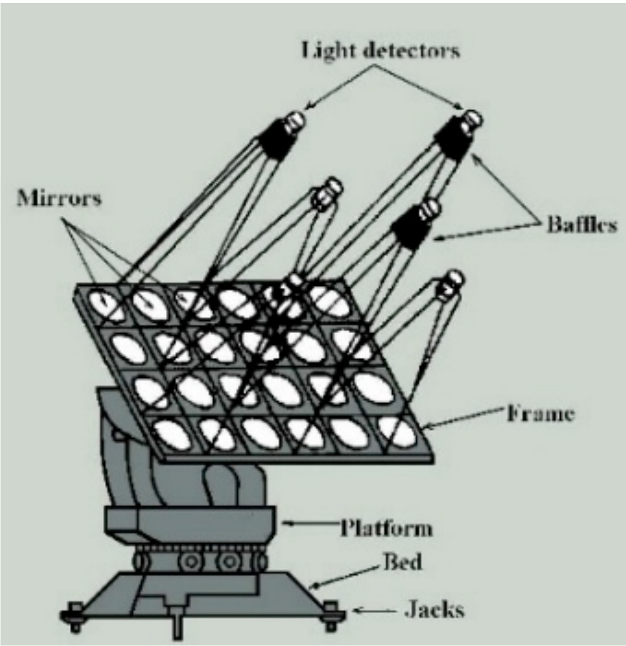
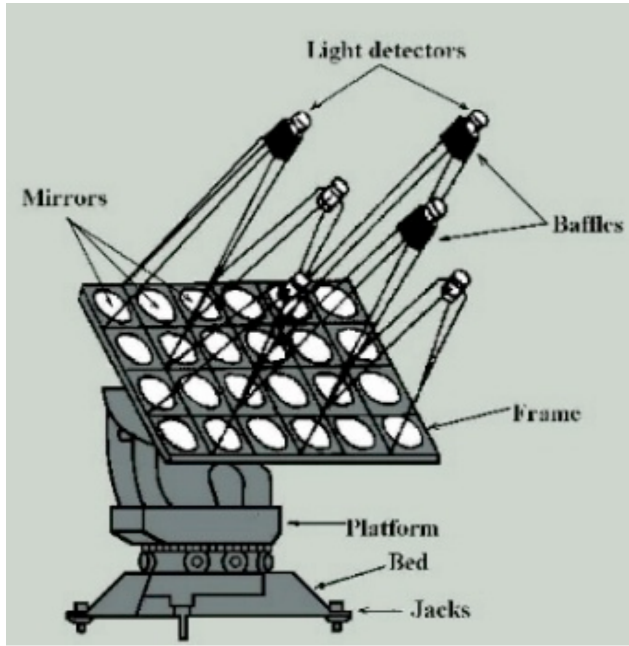


Arnold Stepanian and his 1st imaging "stereo "telescopes: GT-48 in Crimea





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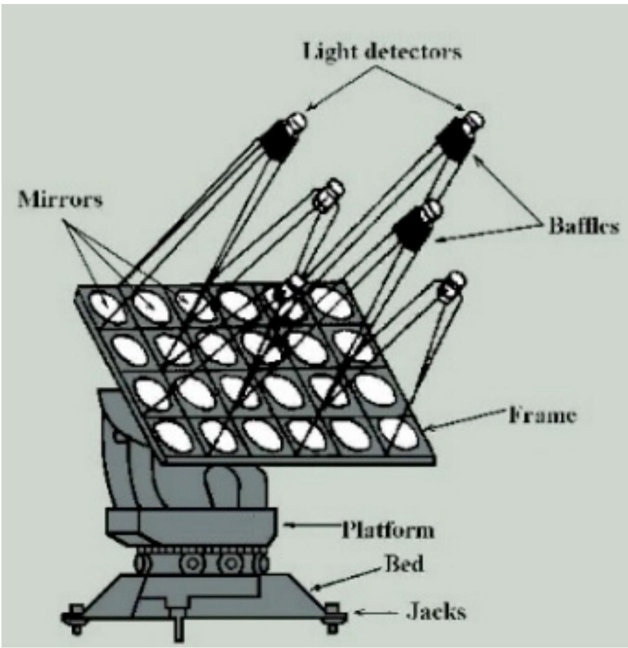

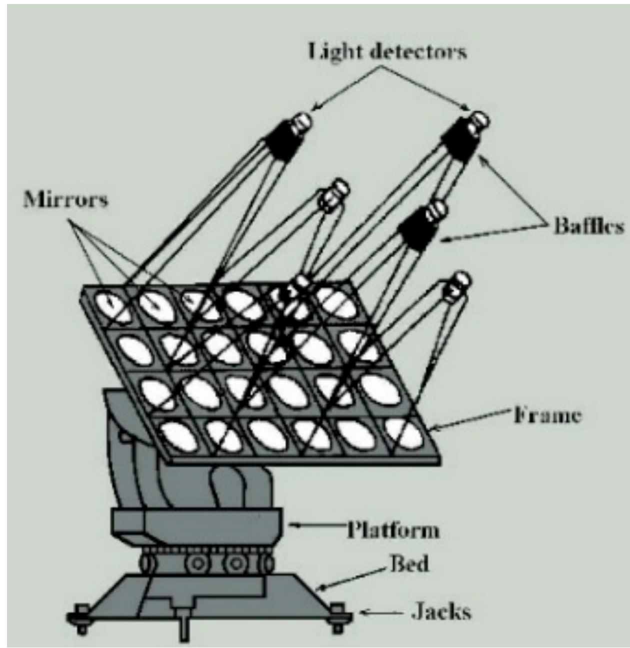

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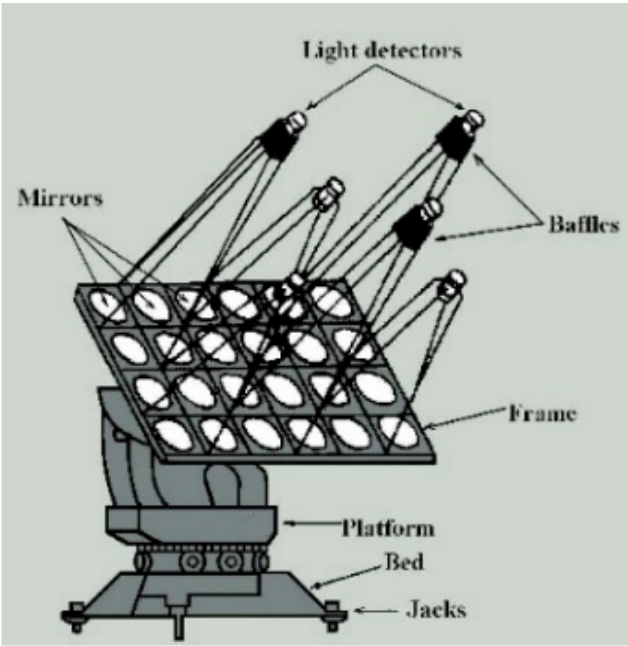
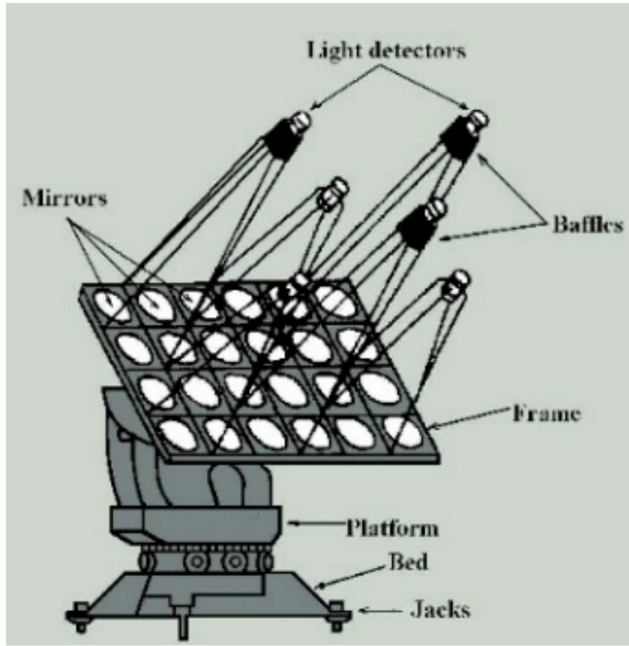
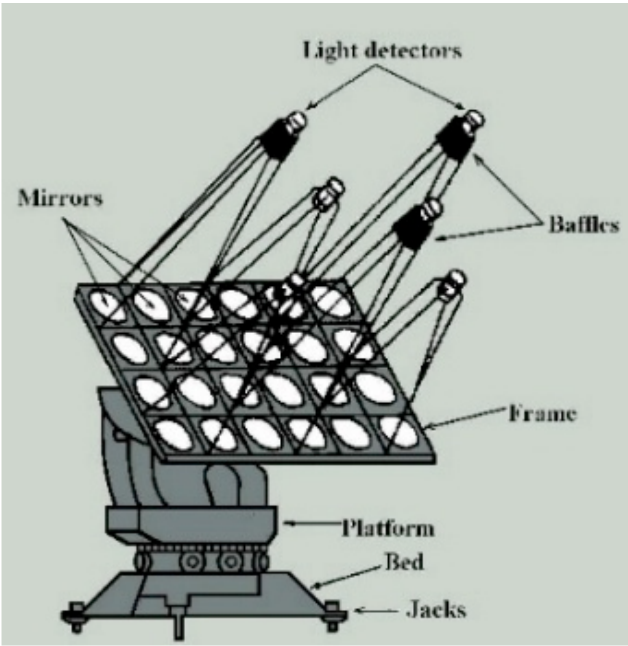


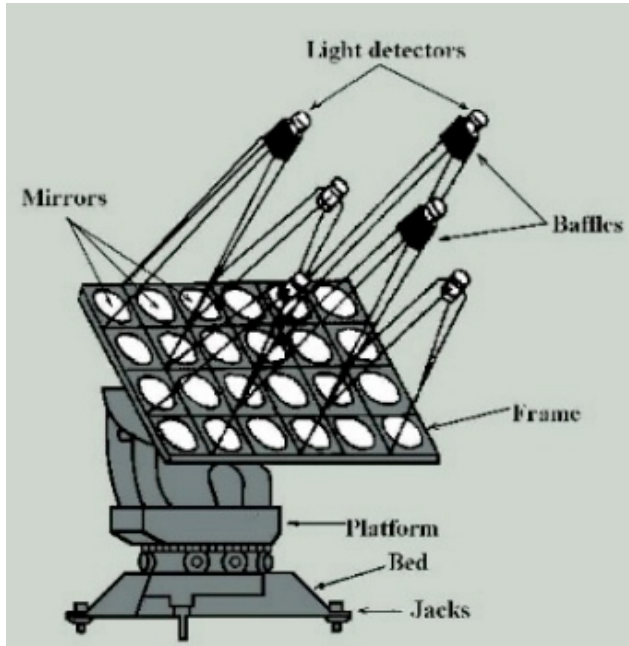


20 m distance between the telescopes

Arnold Stepanian and his 1st imaging “stereo ”telescopes: GT-48 in Crimea

Construction and start of operation 1985 – 1989





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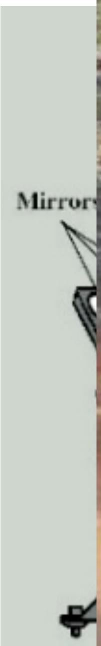

VERITAS INAUGURATION, Arizona, April 28th 2007

The 10m Ø Whipple telescope of Trevor gave birth to γ-ray astrophysics: 9σ from Crab Nebula in 1988 !

„not only my telescope c
measure gamma rays, bu
it can in a few s evapora
solid piece of steel“
;-)

The 1st telescope (of 5 planned) we´ve built: 1989

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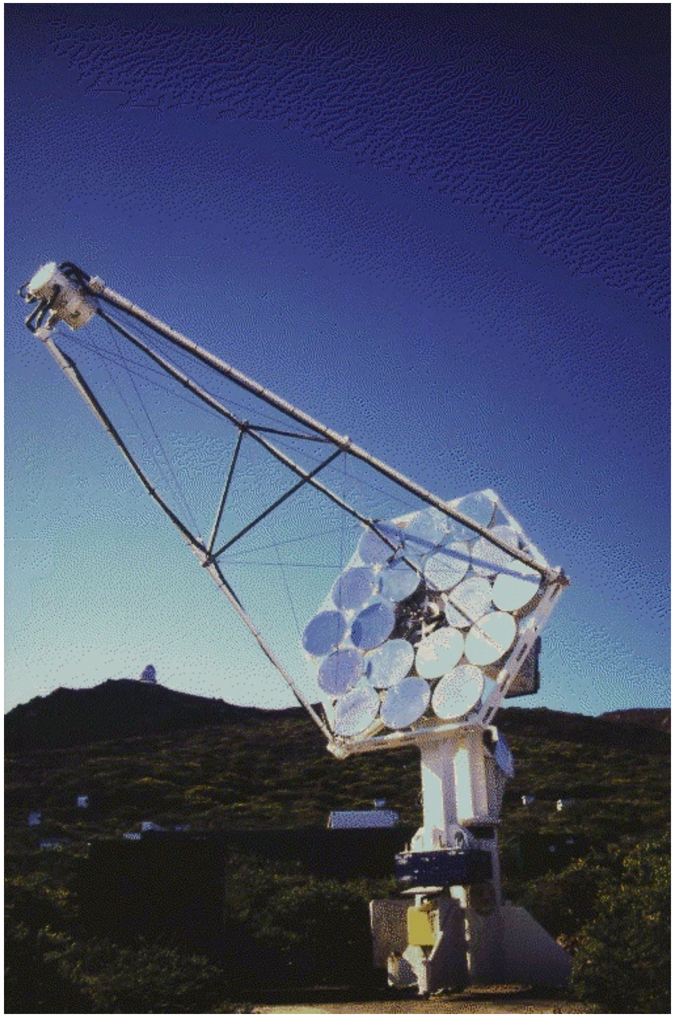
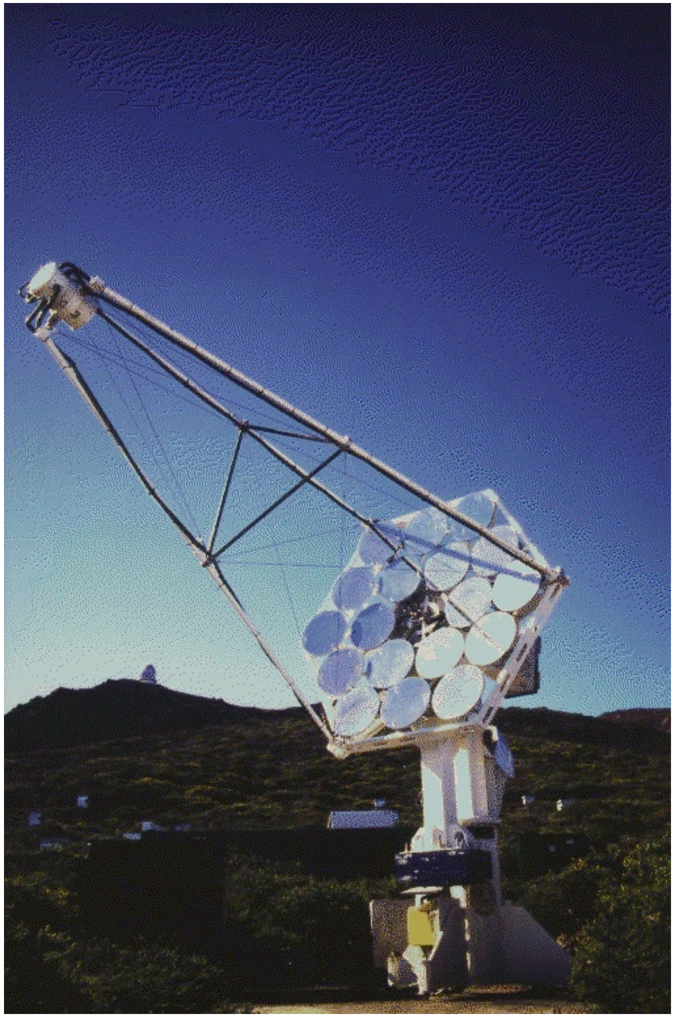
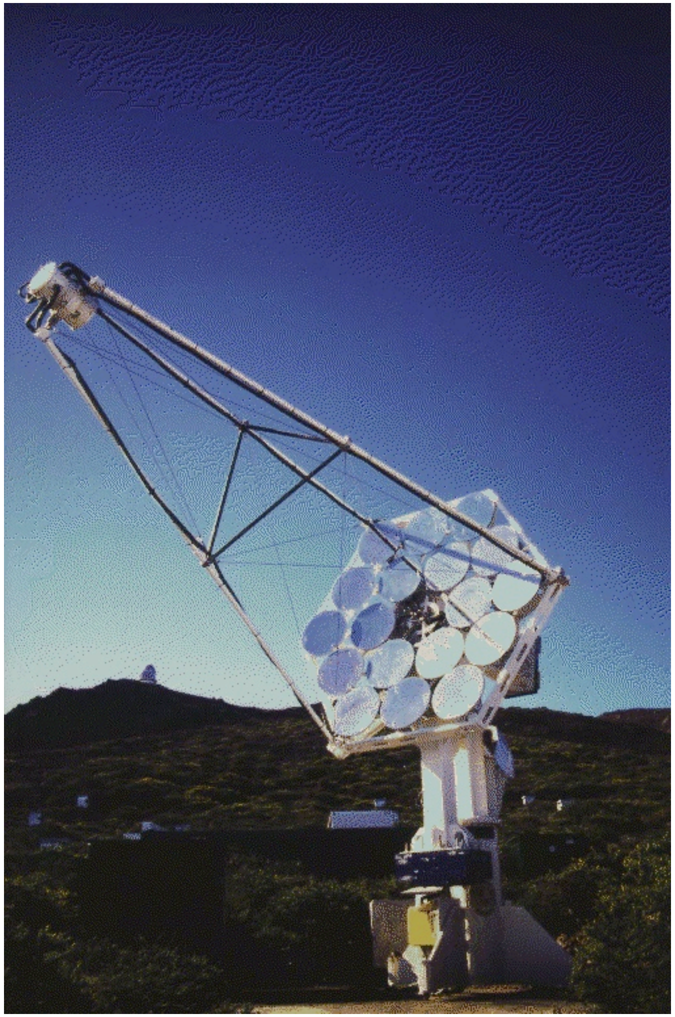




The 1st telescope of HEGRA, the CT1 (installed spring 1992)



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CT1 started to collect data in summer 1992
The 1st signal from Crab Nebula fall 1992

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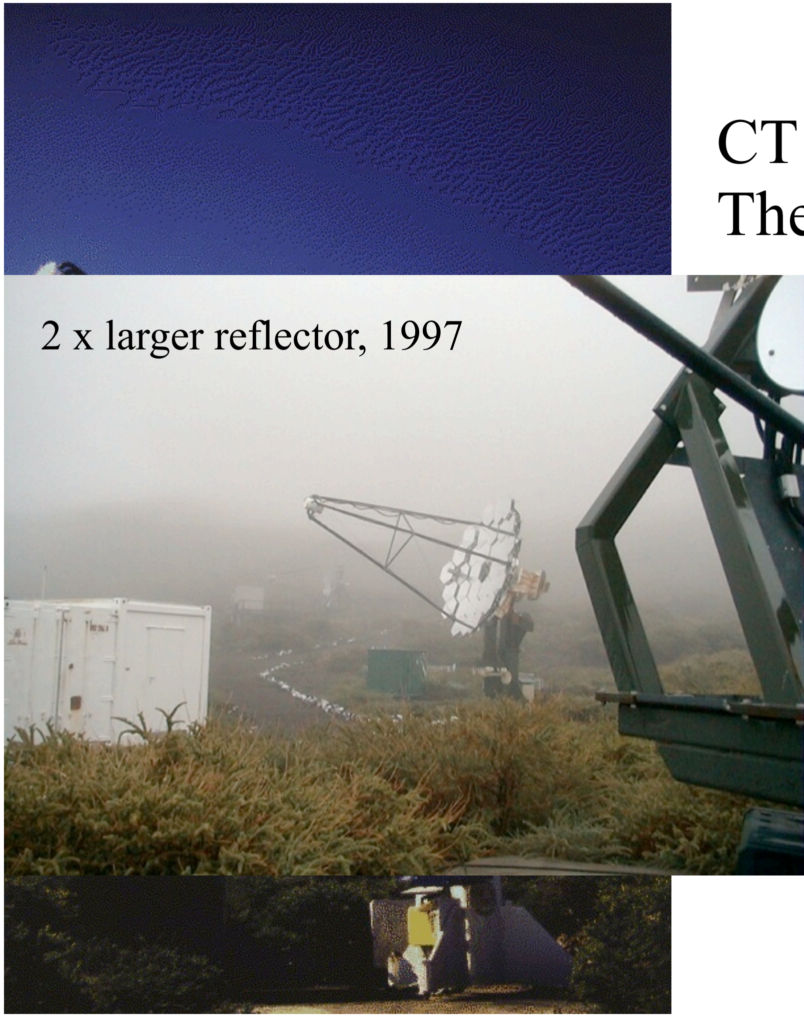

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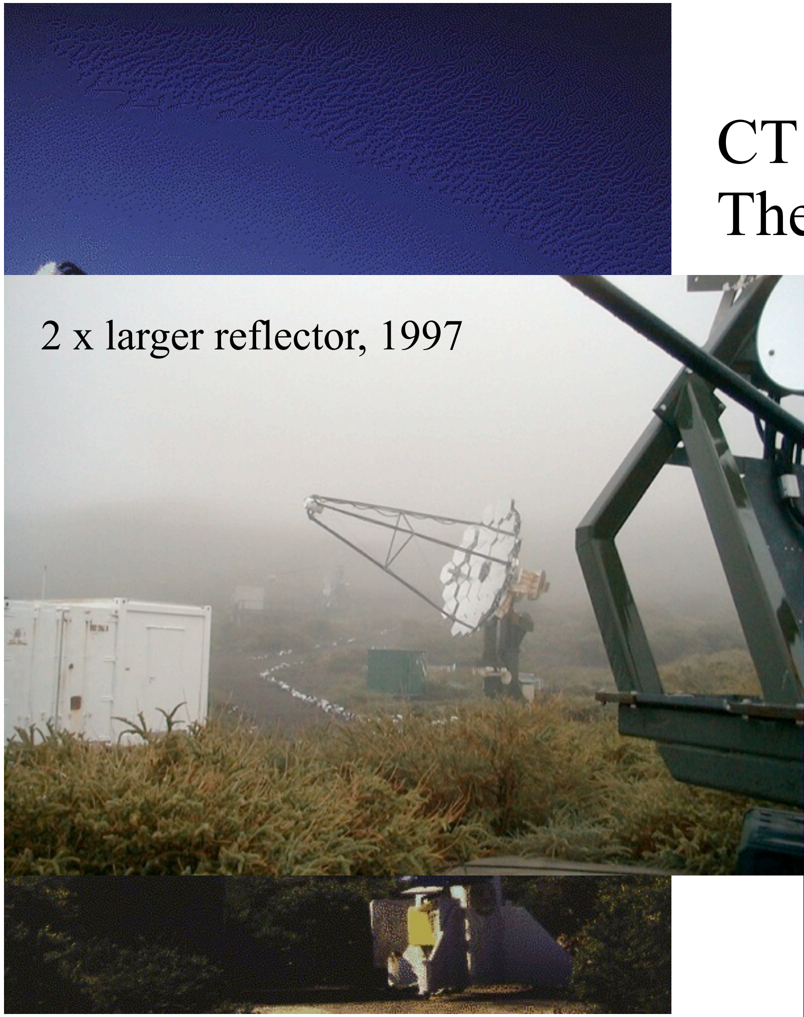

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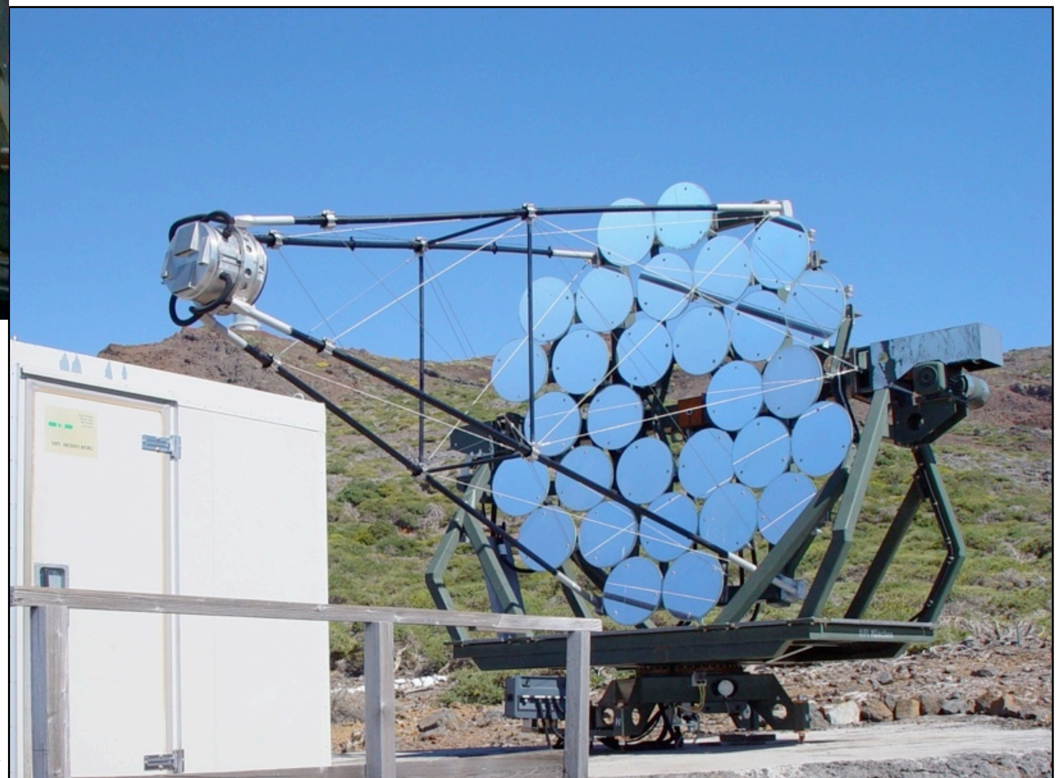

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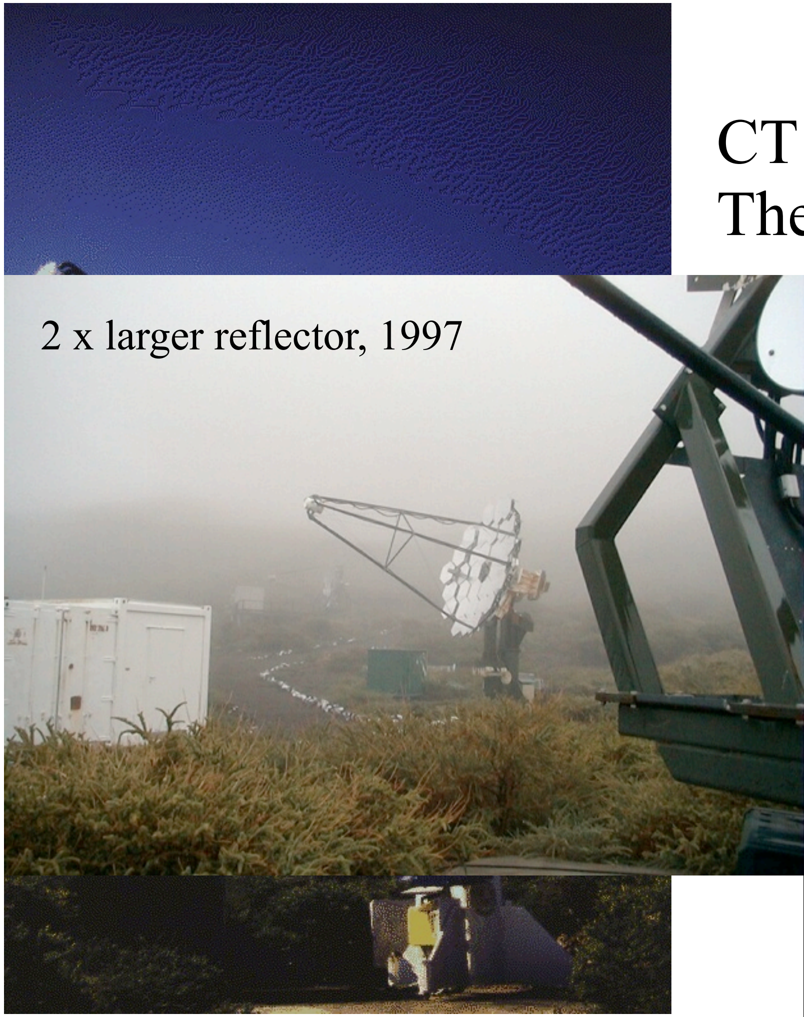
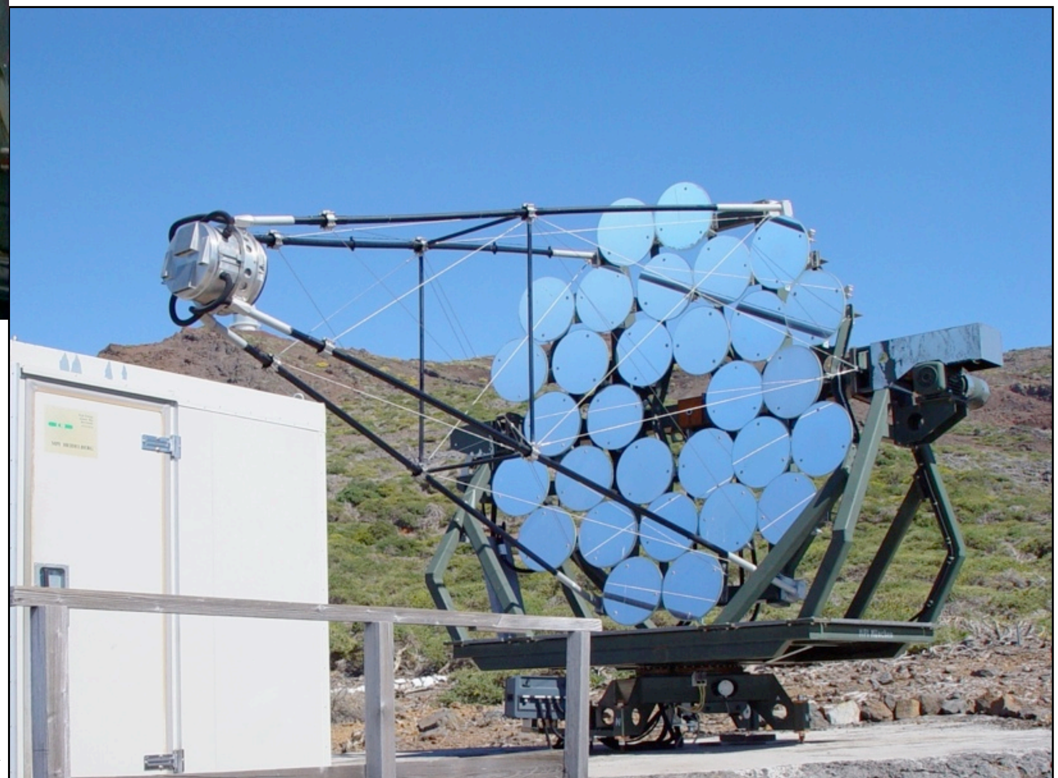


CT2 – CT6: 5 more telescopes were built until 1997.



The 1st telescope of HEGRA, the CT1 (installed spring 1992)

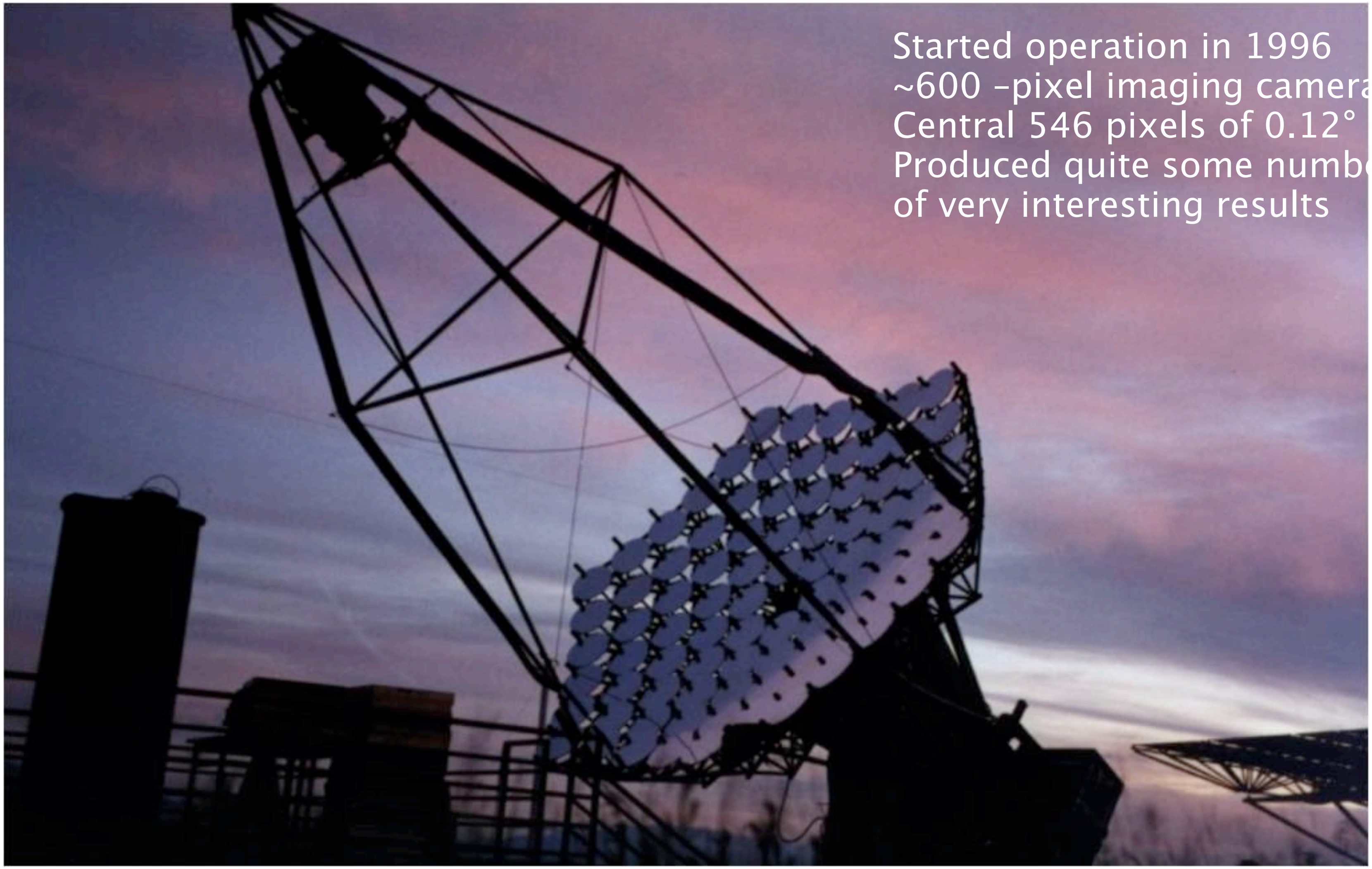

The HEGRA detector, including
6 air Cherenkov imaging telescopes
Location: ORM @ La Palma
Operation 1992 - 2002
CT6
CT1
CT3
CT4

The Japanese 1st Cangaroo telescope in Australia

Kifune, et al.,

The 3.8m telescope on a alt-azimuth mount was an ex-lunar-ranging telescope used in Dodaira observatory of the National Astronomical Observatory of Japan

The French CAT telescope in Pirenees



Japanese 7-telescope Array in Utah, USA

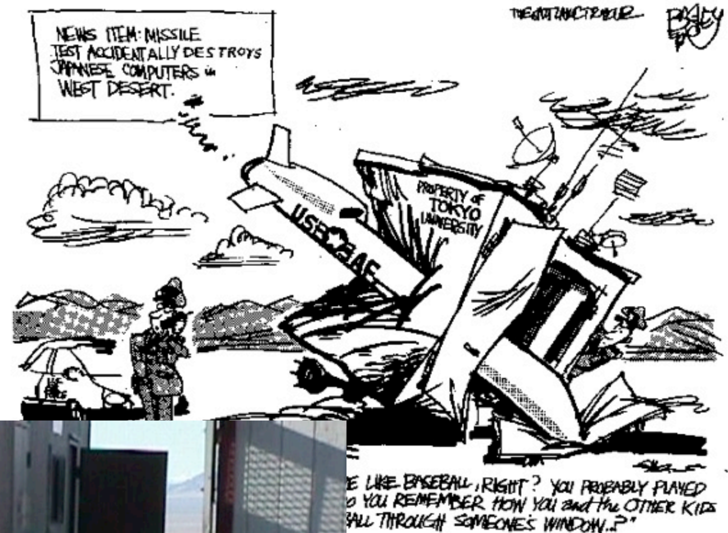
Teshima, et al.,

Japanese 7-telescope Array in Utah, USA

Teshima, et al.,

But …
gamma-ray
astronomy is a
risky business…

Cruise Missile Mishap
10. Dec.'97



Beginning of sub-100 GeV telescopes

- A $10m^2$ telescope has a threshold of ~1TeV

- Long time it was a common belief that the threshold of a Cherenkov telescope

$$E_{thr} \sim \sqrt{(1/A_{mirror})}$$

- That was suggesting that one needs a $A_{mirror} \sim 10^4$ m^2 for measuring few 10's of GeV; → the only seeming solution: use huge solar power plants for air Cherenkov

- In 1994 understood that the above relation is wrong for an imaging telescope. It scales simply as

Sub-100 GeV telescopes

- Started looking for a telescope with $A_{mirror} \geq 200$ m^2.
- Found the 17m solar telescope near Stuttgart, served as prototype of MAGIC
- A feasibility study for the 17m telescope showed a threshold of

$$E_{thr} \sim 40 \text{ GeV}$$

- MAGIC was born, threshold ~50 GeV
- Strong background at several tens of GeV
→ multiple telescopes were needed; build at least two

and today…

VERITAS, H.E.S.S. & MAGIC: the triumphal procession of VHE γ-astro-physics is continueing

and today…

VERITAS, H.E.S.S. & MAGIC: the triumphal procession of VHE γ-astro-physics is continueing

VERITAS, H.E.S.S. & MAGIC: the triumphal procession of VHE γ-astro-physics is

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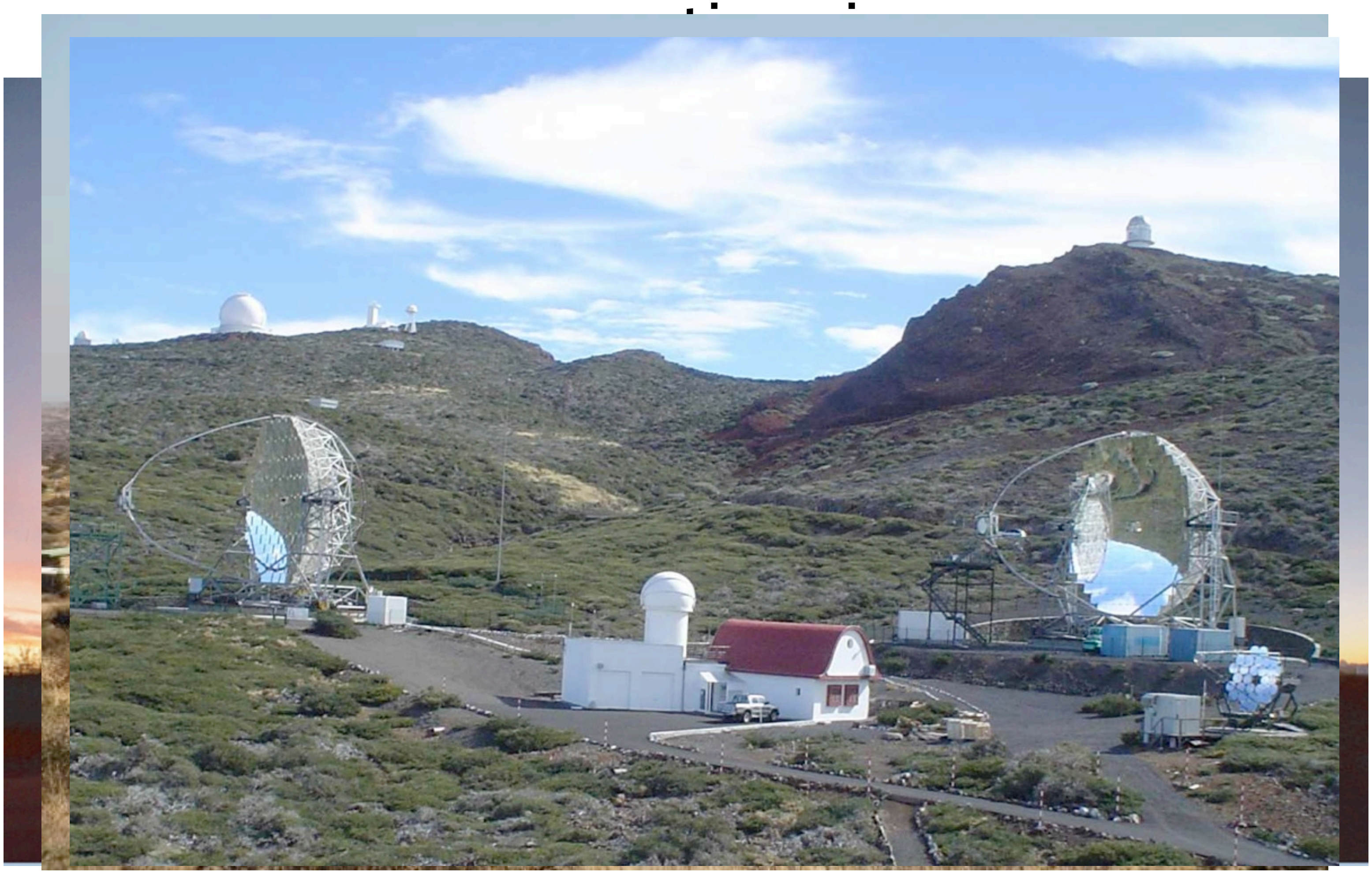


Outlook : the next 5-7 years

Next generation VHE γ ray Observatory: CTA

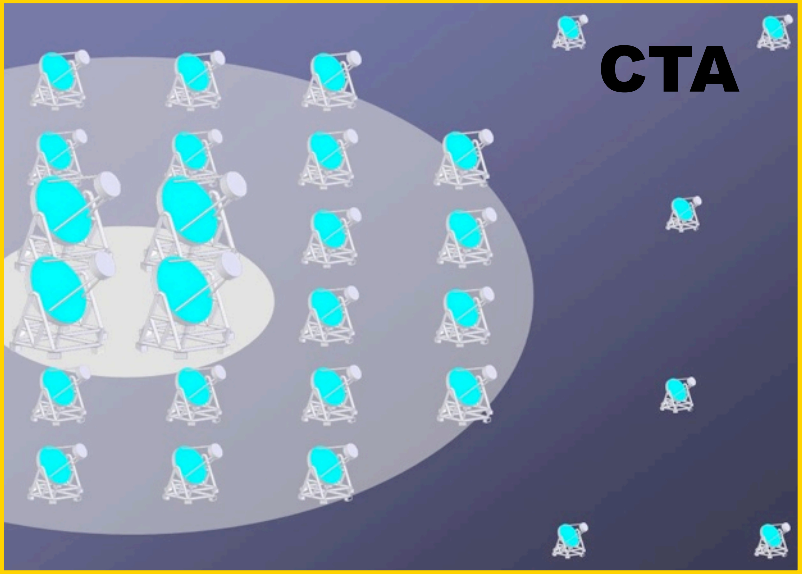
MAGIC Phase II (MAGIC-I + MAGIC-II) since 2009
~160 sources are already discovered

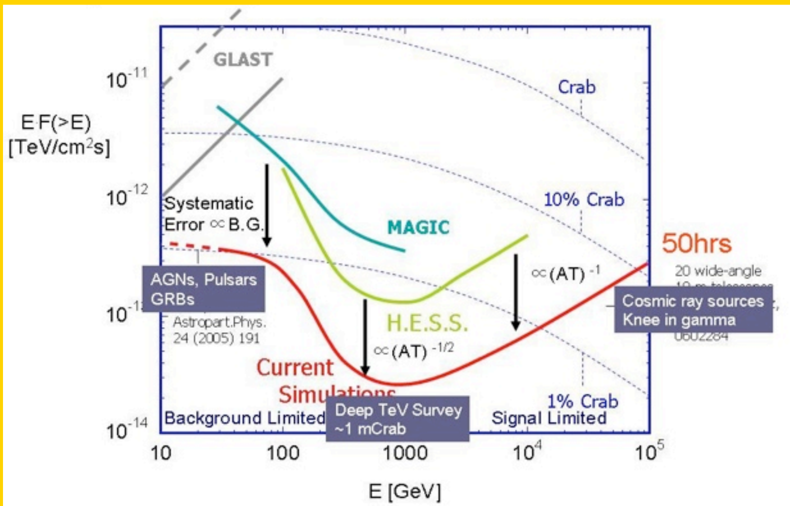
HESS Phase II (HESS + 28m Telescope) in 2012

Astronomers in EU

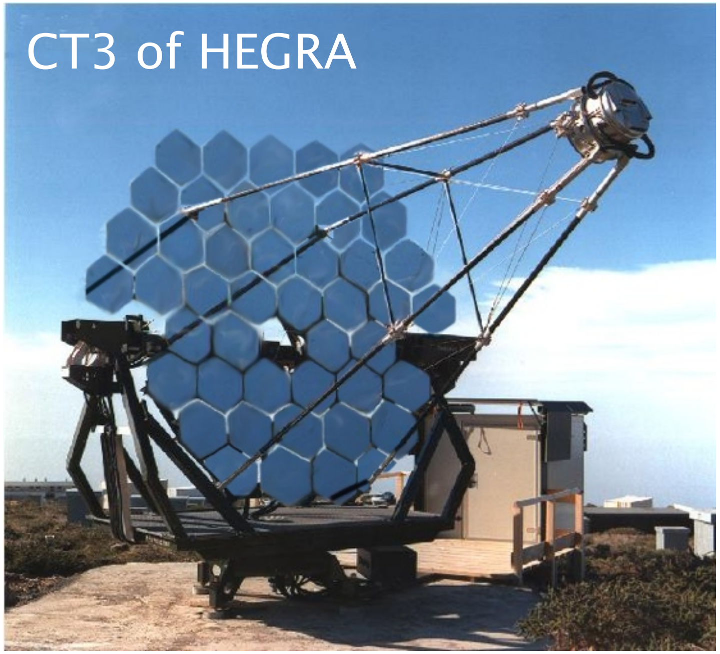
~1200 scientists
~130 institutions

Cherenkov Telescope Array
1000's of sources will be discovered

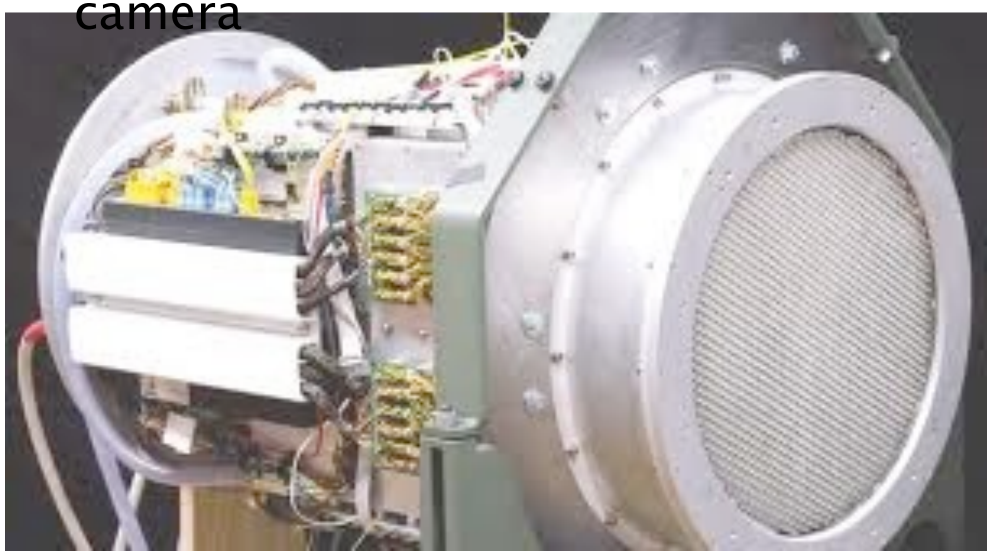


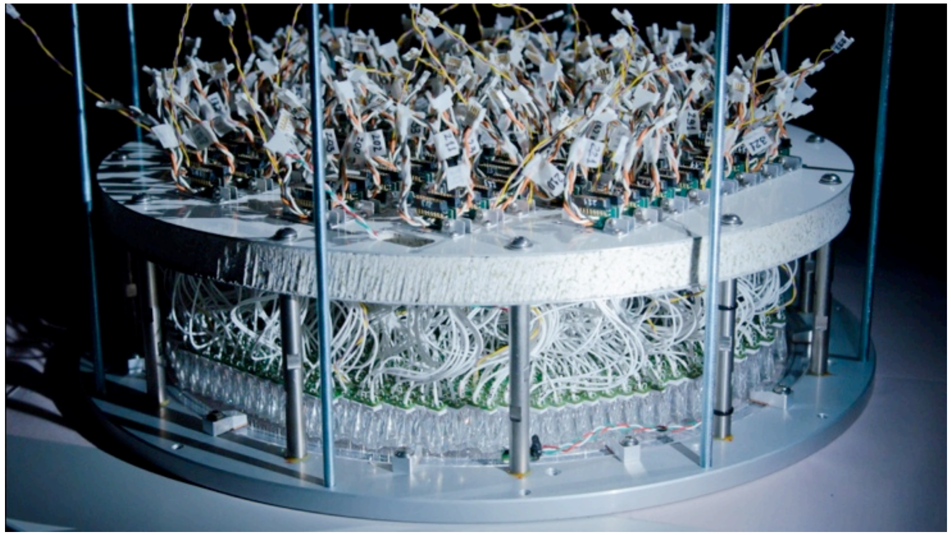


JAPAN, US

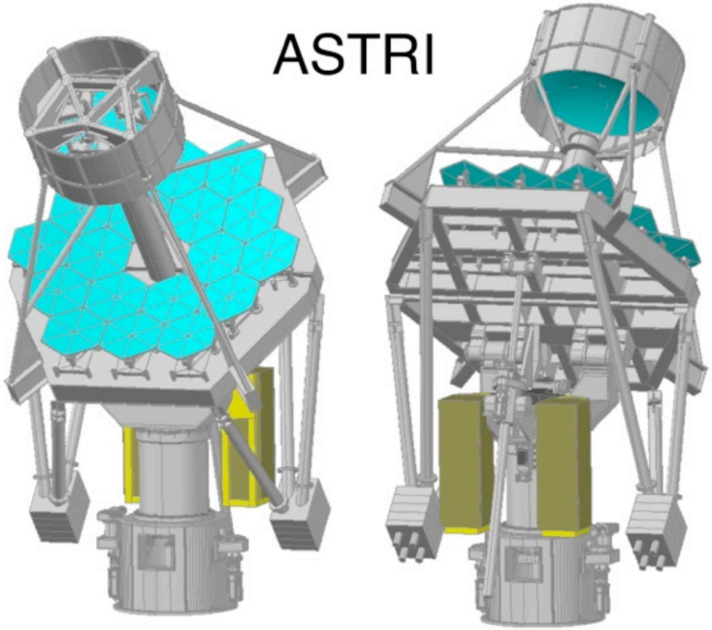


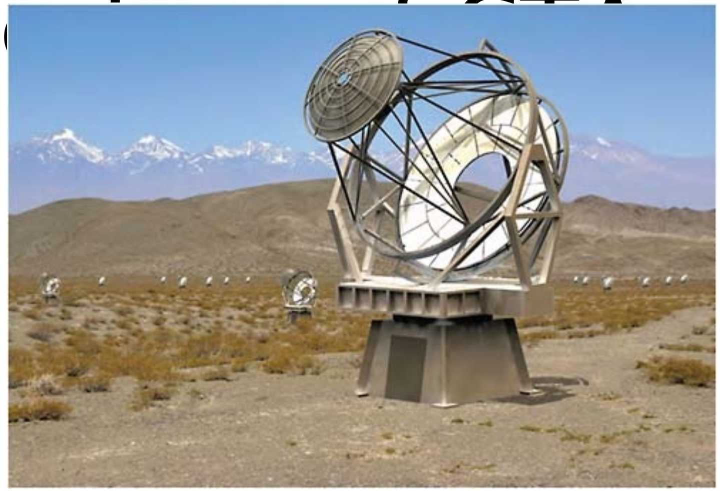
The 1st MPPC- (SiPM) based FACT camera

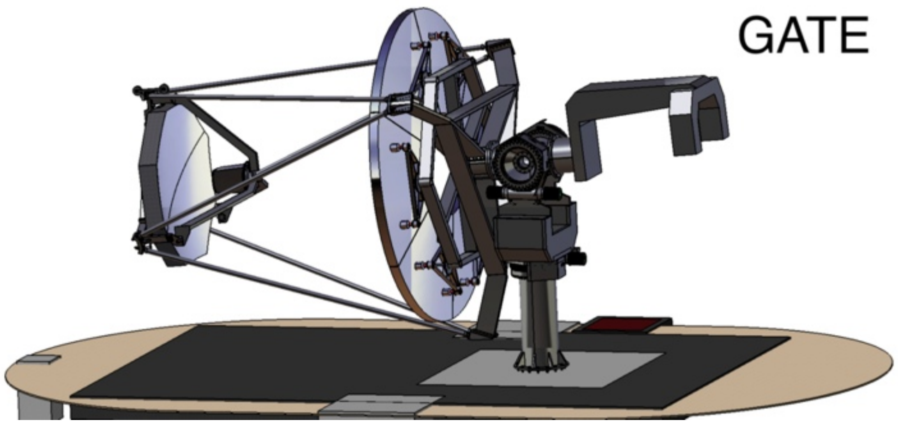




Dual mirror telescope d







QE of “old” and new PMTs

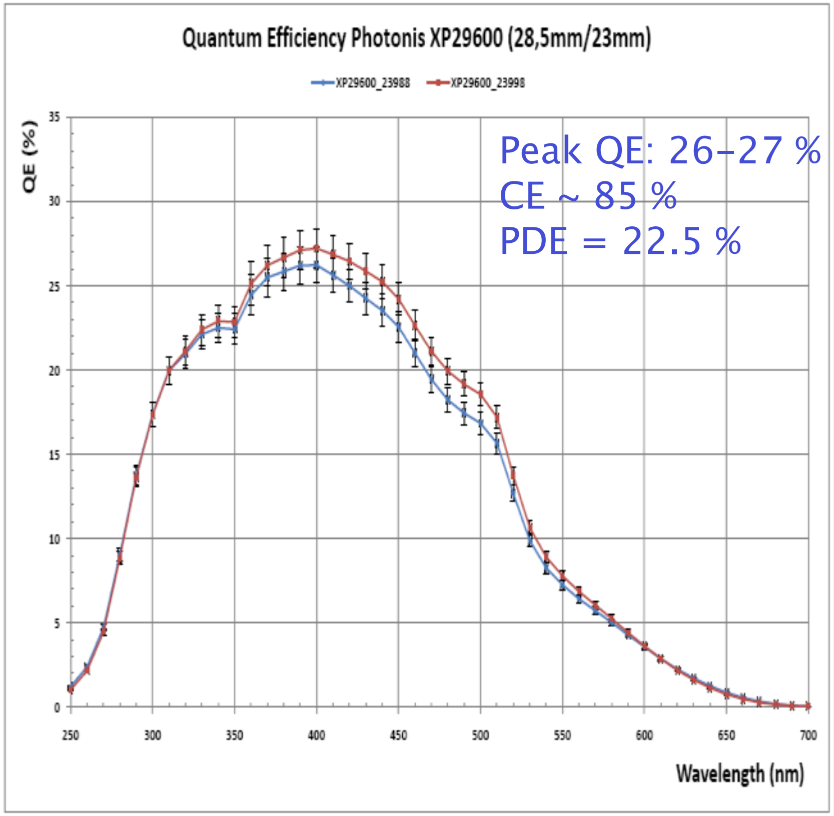
PMTs used by H.E.S.S.

Peak QE: 26-27 %
CE ~ 85 %
PDE = 22.5 %

Hamamastu PMT(2013) VS Electron Tube PMT(2012)

QE of “old” and new PMTs

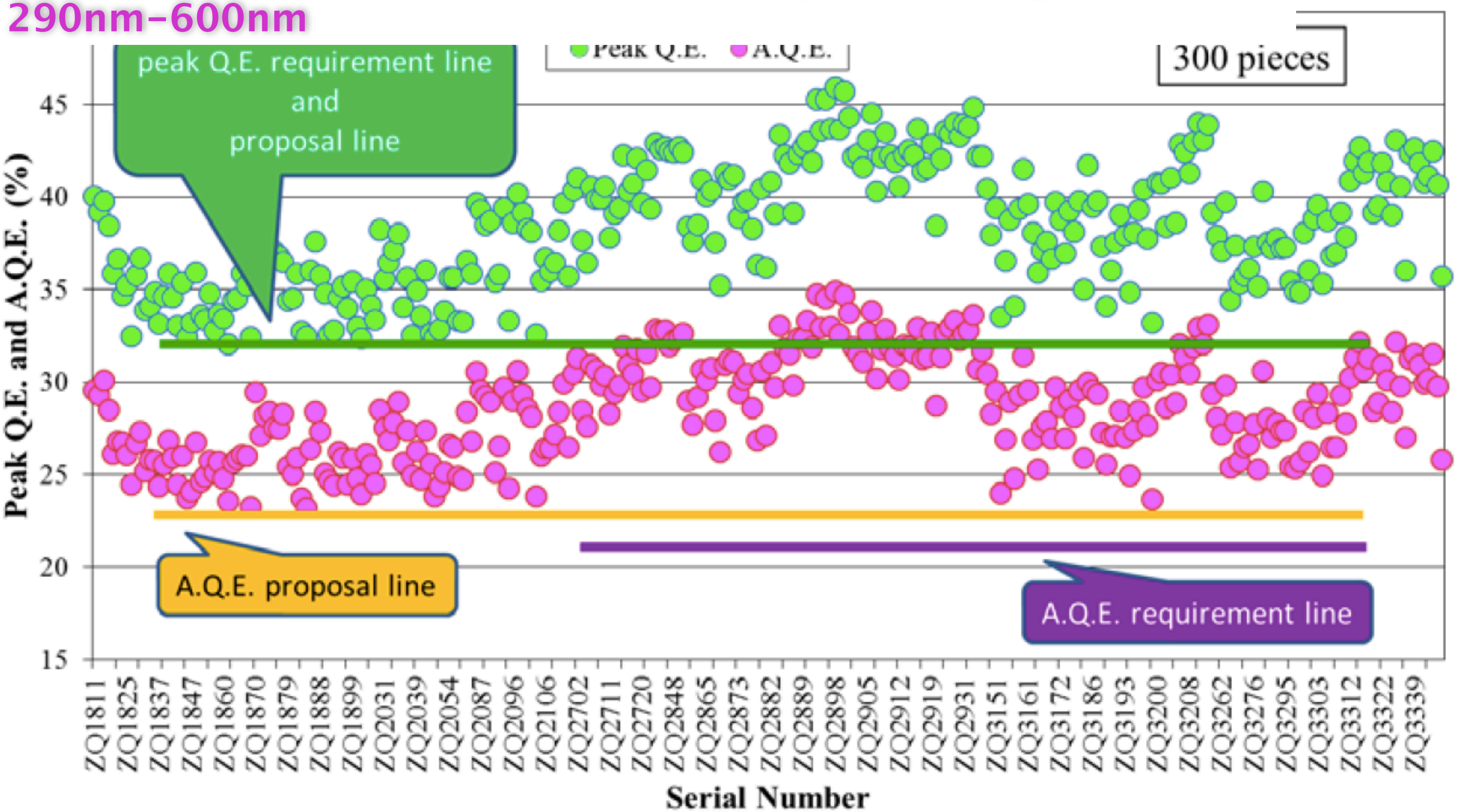
PMTs used by H.E.S.S.



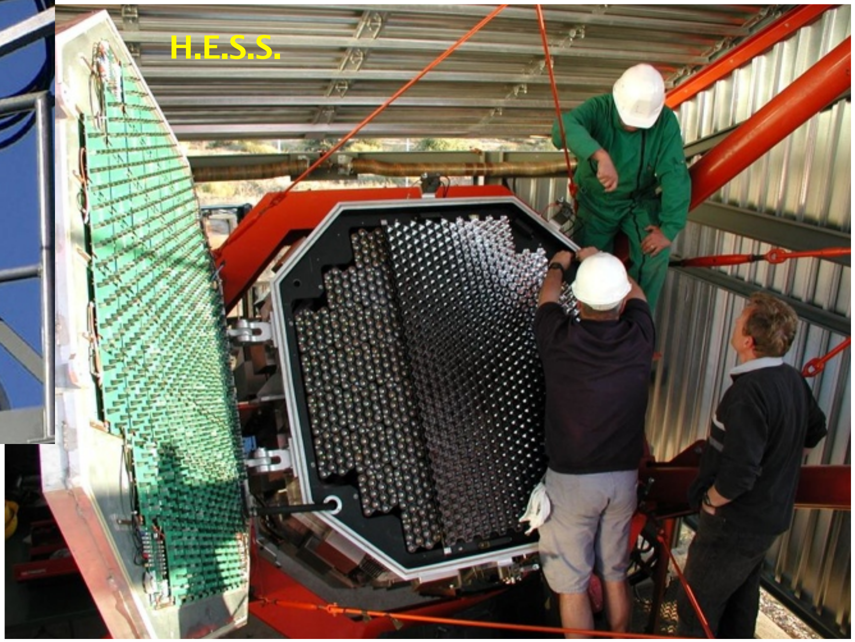
Hamamastu PMT(2013) VS Electron Tube PMT(2012)

Peak and average QE of recently produced Hamamatsu PMTs for CTA

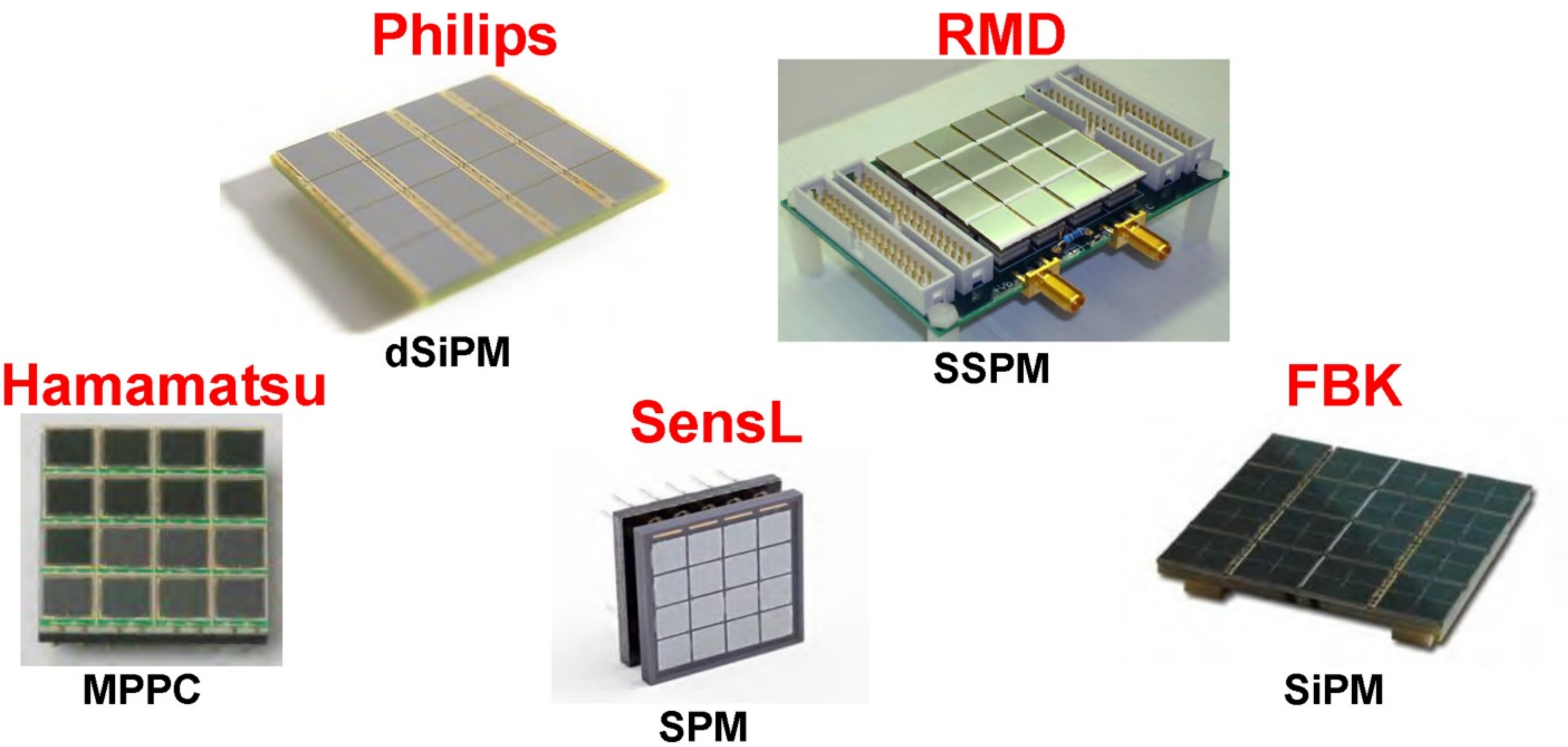
R11920-100-05 **Peak Quantum Efficiency** and **Average QE over 290nm-600nm**



1039-pixel camera of MAGIC-I.
Pixels of 0.10° Ø are based on 1‘ superbialkali PMTs



Near future: assmeble imaging cameras from matrixes of SiPMs with readout, as



Technological improvements

- Compared to 1st detection of Crab in 1988, sensitivity is increased by a huge factor.
- Today we can detect Crab with 5σ in 1-minute!
- Operating in sub-100 GeV range, down to 50 (30) GeV
- Improving mirror parameters, telescope structures, materials
- Moving towards more complex designs, robotic operation
- Towards sealed, T° controlled and robust cameras
- Towards strongly reducing the remaining γ-mimicking background