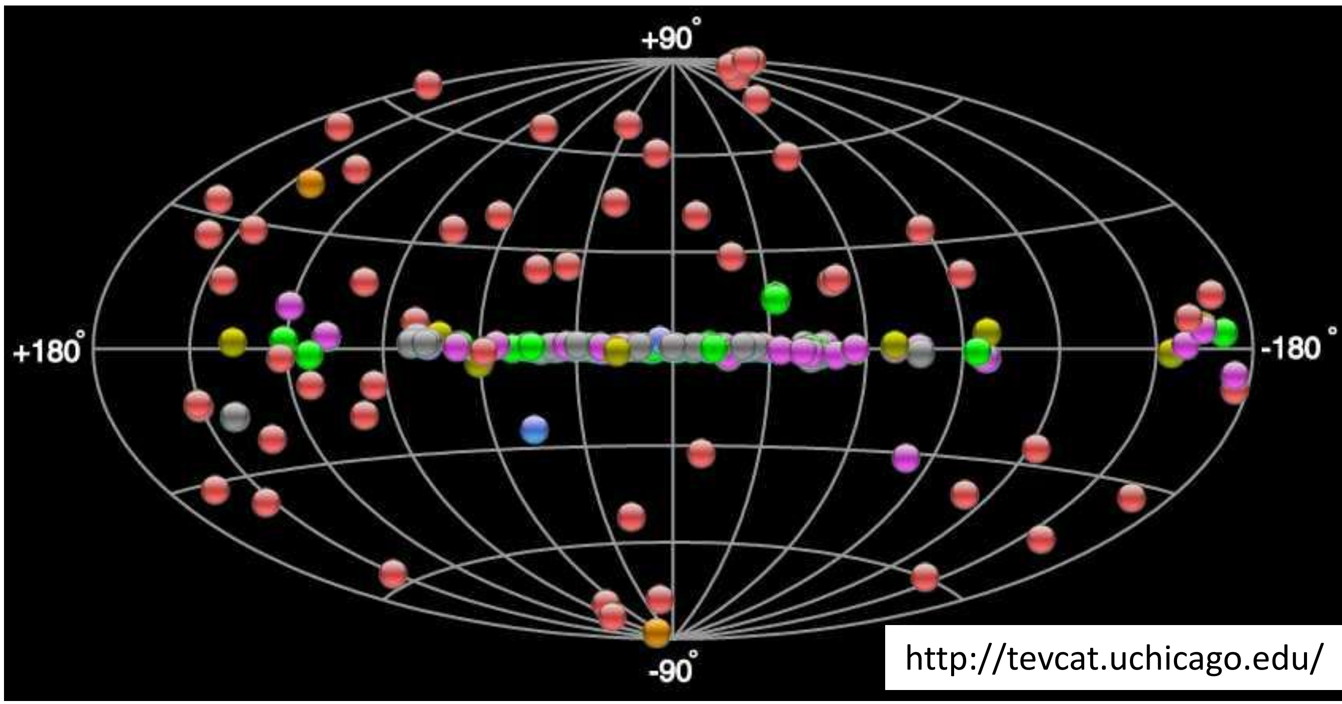
Ground-Based VHE γ-Astrophysics by Means of Imaging Air Cherenkov Telescopes: 1989 - 2014

Razmik Mirzoyan

Max-Planck-Institute for Physics, Munich, Germany

Irkutsk State University, Irkutsk, Russia

Today's VHE γ–ray Sources in the Sky



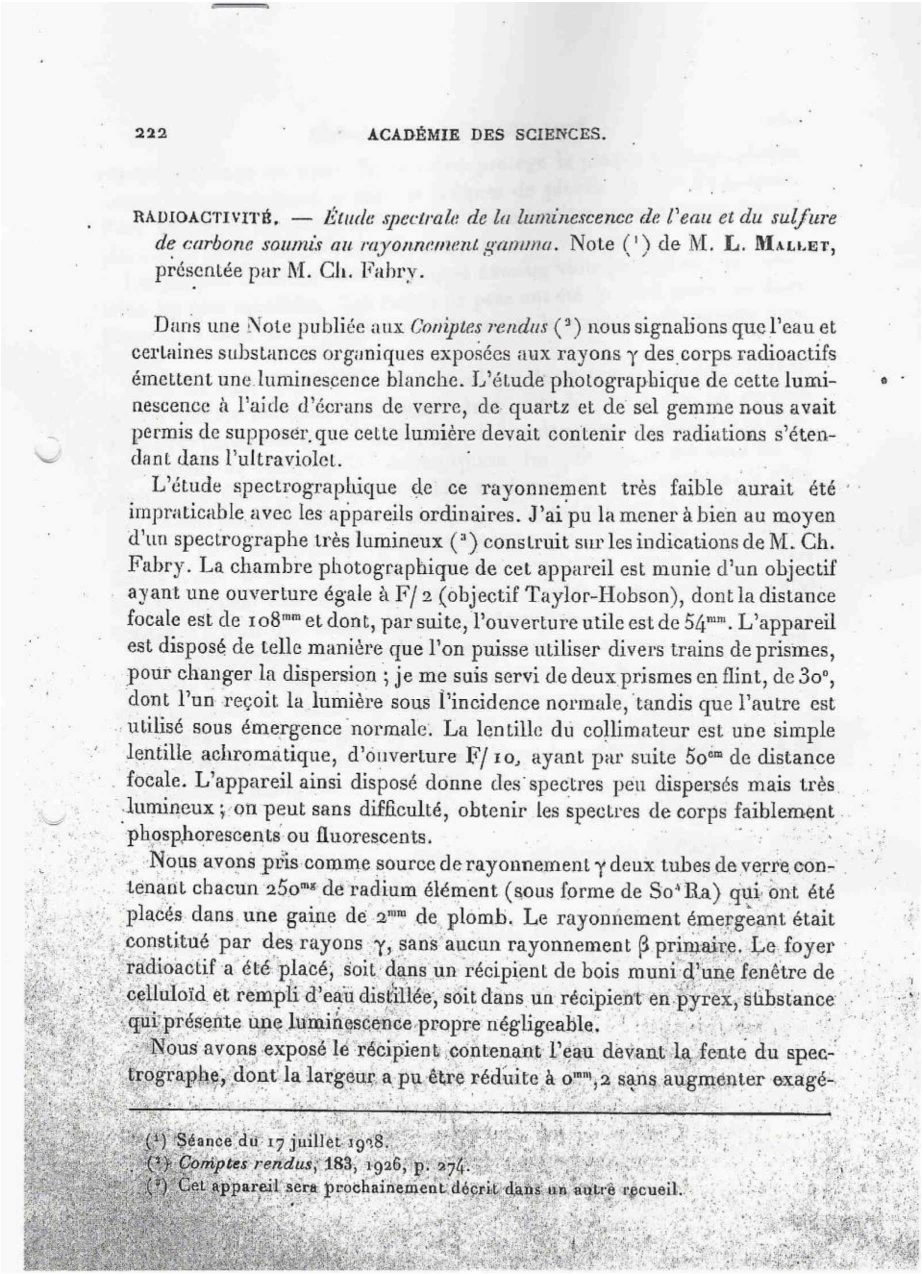
≥ 160 Established Sources

Cherenkov light: the beginnings

- In a series of publications Oliver Heaviside has calculated and predicted the main features of a special emission when an e- movs in a transparent medium with a speed higher than that of light.
- The work of the genius, who advanced his time by half a century, was not appreciated by contemporary scientists and was forgotten. In 1912 he calculated the geometry and the angle of emission relative to the axis of movement of the charge (1888, 1889, 1892, 1899, 1912a,b)
- Please note that during the end of 19th century scientists believed the space was feeled-in with Ether.

Cherenkov light: the beginnings

- It took almost 50 years until the effect was experimentally discovered and later on got the name Cherenkov
- Also Sommerfeld studied the problem of a charge moving in vacuum with a speed $v > c$ (1904). The relativistic principles prohibit such a motion in vacuum but in a medium with given *n* then his equations give valid solution („sonic boom").
- First observation of ghostly bluish glow of bottles in the dark cellar, containing radium salts dissolved in distilled water, by Marie Curie in 1910 (E. Curie, 1937). It was thought to be a type of fluorescence.



222 ACADÉMIE DES SCIENCES.

RADIOACTIVITÉ. — *Étude spectrale de la luminescence de l'eau et du sulfure de carbone soumis au rayonnement gamma.* Note (1) de M. L. Mallet, présentée par M. Ch. Fabry.

Dans une Note publiée aux *Comptes rendus* (2) nous signalions que l'eau et certaines substances organiques exposées aux rayons γ des corps radioactifs émettent une luminescence blanche. L'étude photographique de cette luminescence à l'aide d'écrans de verre, de quartz et de sel gemme nous avait permis de supposer que cette lumière devait contenir des radiations s'étendant dans l'ultraviolet.

L'étude spectrographique de ce rayonnement très faible aurait été impraticable avec les appareils ordinaires. J'ai pu la mener à bien au moyen d'un spectrographe très lumineux (3) construit sur les indications de M. Ch. Fabry. La chambre photographique de cet appareil est munie d'un objectif ayant une ouverture égale à F/2 (objectif Taylor-Hobson), dont la distance focale est de 108mm et dont, par suite, l'ouverture utile est de 54mm. L'appareil est disposé de telle manière que l'on puisse utiliser divers trains de prismes, pour changer la dispersion ; je me suis servi de deux prismes en flint, de 30°, dont l'un reçoit la lumière sous l'incidence normale, tandis que l'autre est utilisé sous émergence normale. La lentille du collimateur est une simple lentille achromatique, d'ouverture F/10, ayant par suite 50cm de distance focale. L'appareil ainsi disposé donne des spectres peu dispersés mais très lumineux ; on peut sans difficulté, obtenir les spectres de corps faiblement phosphorescents ou fluorescents.

Nous avons pris comme source de rayonnement γ deux tubes de verre contenant chacun 250mg de radium élément (sous forme de SO^4Ra) qui ont été placés dans une gaine de 2mm de plomb. Le rayonnement émergeant était constitué par des rayons γ, sans aucun rayonnement β primaire. Le foyer radioactif a été placé, soit dans un récipient de bois muni d'une fenêtre de celluloïd et rempli d'eau distillée, soit dans un récipient en pyrex, substance qui présente une luminescence propre négligeable.

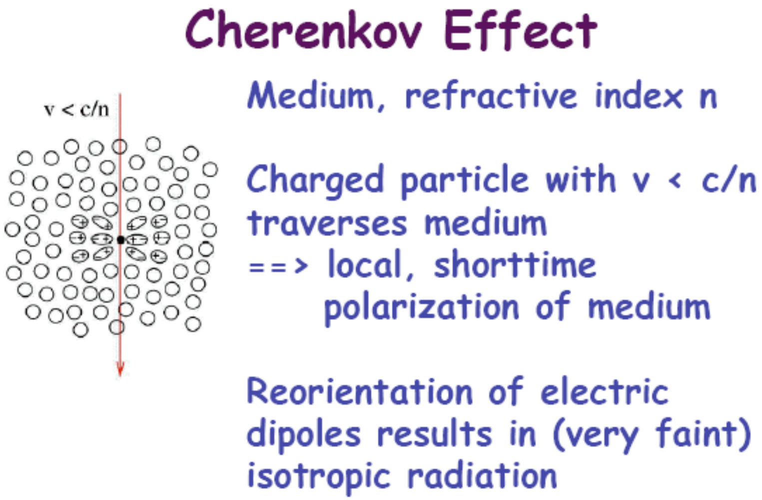
Nous avons exposé le récipient contenant l'eau devant la fente du spectrographe, dont la largeur a pu être réduite à 0mm,2 sans augmenter exagé-

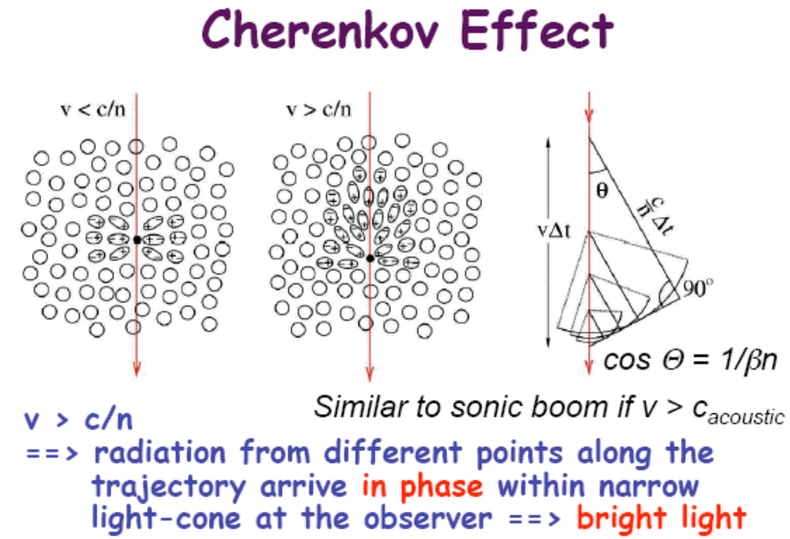
(1) Séance du 17 juillet 1928.
(2) *Comptes rendus*, 183, 1926, p. 274.
(3) Cet appareil sera prochainement décrit dans un autre recueil.

- French scientists M.L. Mallet published 3 articles on the bluish glow in transparent liquids (1926-1929).
- On the left one can see a scan of one of those papers (1926)
- Mallet recongnised the continuous spectrum of emission that was contradicting the fluorescence theory, but failed to offer any deep explanation

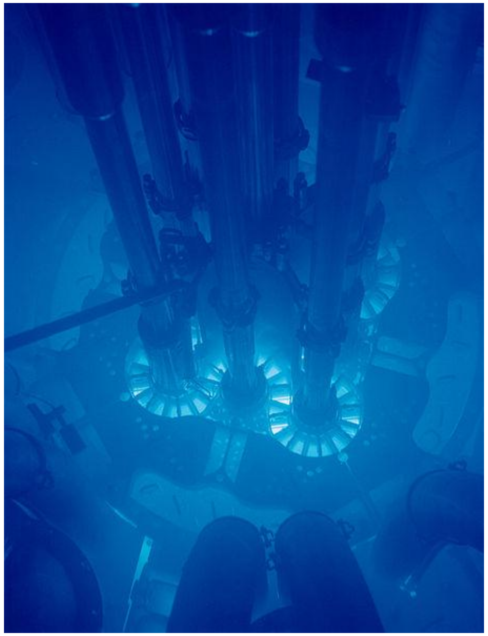
Cherenkov light: the beginnings

- Pavel Cherenkov: born July 28th 1904 in a poor peasant family in village Novaya Chigla, Voronezh province.
- 1924-1928 studying in Voronezh sate university.
- 1930: postgraduate student of Sergej Vavilov at the Institute of Physics of Soviet Academy of Sciences in Sankt-Petersburg (later on FIAN).
- Had to find the fluorescence nature of solvents of uranium salts, emitting bluish light
- Big was his surprise that also pure solvents and even water were emitting the annoying background light





- Initially complaning about his boss: he had to spend >1-1,5 hours in a dark, cold cellar, for accomodating his eyes
- He noticed that the emission is not chaotic, but is related to the track of moving particle.
- 1934-1938 conducting a series of brilliant expeirments.
- Obtained doctorate in 1940



тации опыта Боте-Гейгера), следовательно длительность возбуждения должна быть исчезающе малой, как это и имеет место в опытах Черенкова. Можно сказать даже, что неспособность γ-свечения к тушению является новым и более тонким экспериментальным доказательством справедливости утверждения об одновременности рассеяния фотона и электрона.

По теории Клейна и Нишина ([4]) рассеянные электроны в случае жестких γ-лучей пространственно направлены по преимуществу вдоль первичных γ-лучей. Отсюда непосредственно следует, что электрический вектор излучения при торможении комптоновских электронов будет расположен главным образом вдоль γ-лучей в согласии с опытами Черенкова. Факт независимости измеренной степени поляризации от вязкости среды, т. е. от броуновского вращения молекул, дает еще новое доказательство одновременности актов рассеяния фотона и электрона в эффекте Комптона.

Гипотеза торможения делает наконец понятным, что интенсивность синего свечения при возбуждении лучами Рентгена значительно меньше. В этом случае процессы комптоновского рассеяния происходят значительно реже, и только самые внешние, весьма слабо связанные электроны могут обусловливать свечение. Следует заметить также, что в случае мягких лучей Рентгена значительная энергия лучей поглощается в жидкости, и в ней могут иметь место совершенно иные процессы свечения, например люминесценция.

Таким образом, все свойства нового эффекта качественно свободно объясняются с точки зрения гипотезы торможения. Дальнейшей проверкой предложенного объяснения может служить зависимость степени поляризации свечения от жесткости возбуждающих лучей, требуемая теорией. Для лучей Рентгена поляризация должна быть меньше.

В заключение отметим, что γ-свечение может наблюдаться вероятно только в прозрачных жидкостях. В газах, по причине малой плотности, оно должно быть исчезающе слабым (напомним, что эффект заметен только для вполне адаптированного глаза и при большой интенсивности γ-лучей). В твердых прозрачных телах неизбежно имеются люминесцирующие центры и свет люминесценции несомненно будет значительно сильнее γ-свечения.

Физико-математический институт
Академии Наук им. В. А. Стеклова.
Ленинград.

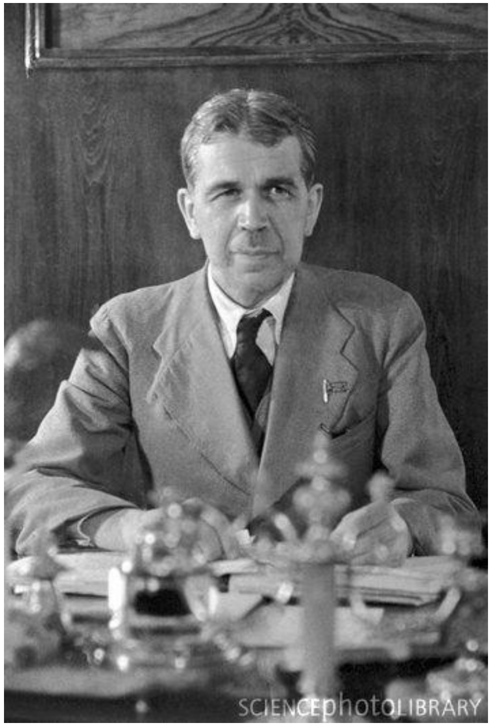
Поступило
27 V 1934.

PHYSIK

ÜBER DIE MÖGLICHEN URSACHEN DES BLAUEN γ-LEUCHTENS VON FLÜSSIGKEITEN

Von S. WAWILOW, Mitglied der Akademie

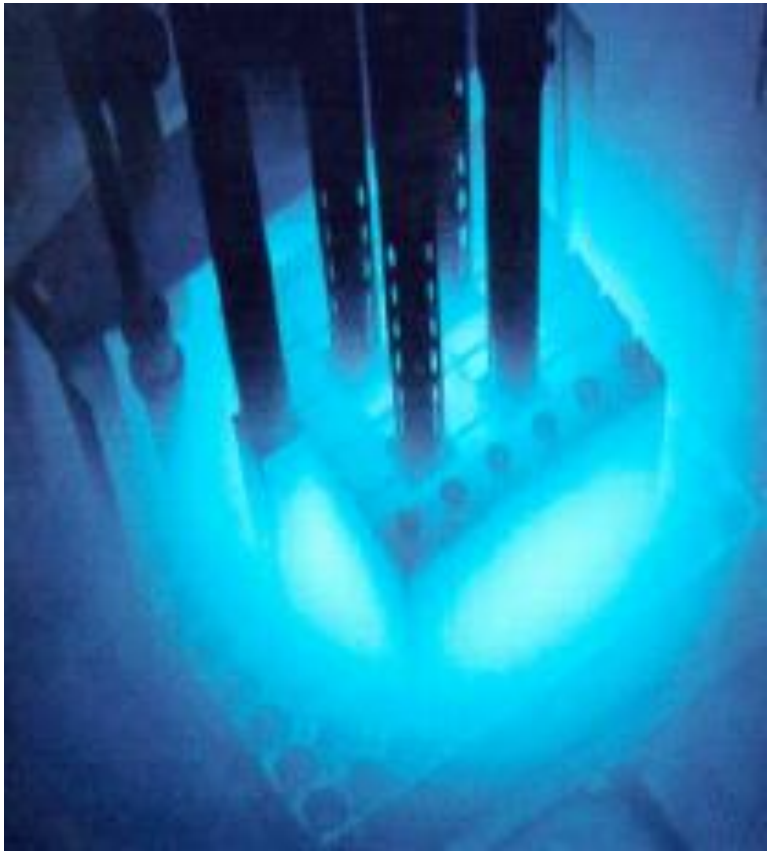
Die allgemeine Erscheinung von Leuchten reiner Flüssigkeiten bei Anregung durch γ-Strahlen, weiterhin kurz als γ-Leuchten bezeichnet, die in der vorangehenden Mitteilung von P. Čerenkov beschrieben ist, lässt sich nicht mit der blauen Fluoreszenz identifizieren, die bei Bestrahlung „reiner" Flüssigkeiten mit ultravioletten Licht fast immer zum Vorschein kommt([1]). Hier wird das Leuchten zweifellos durch Verunreinigungen verursacht, die sich bisweilen durch mehrfache Destillation entfernen las-



- Theory paper by Sergej Vavilov about the possible bremsstrahlung nature of the bluish emission (1934).
- In the same issue a paper by P. Cherenkov about the experiment, that Vavilov refused to co-author.

The Suspicious Emission

- In 1937 Cherenkov succeeded to measure the anisotropy of the emission and submitted it to the journal „Nature“
- „Nature“ declined his paper
- Fortunately „The Physical Review“ accepted it
- In that paper he has mentioned the possibility to measure fast e-



P.A. Cerenkov Phys. Rev. **52**, 378 **1937**

LETTERS TO THE EDITOR

Prompt publication of brief reports of important discoveries in physics may be secured by addressing them to this department. Closing dates for this department are, for the first issue of the month, the eighteenth of the preceding month, for the second issue, the third of the month. Because of the late closing dates for the section no proof can be shown to authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents.

Communications should not in general exceed 600 words in length.

P.A. Cerenkov
The Physical Institute of the Academy of Sciences U.S.S.R., Moscow
Received June 15, 1937

Visible Radiation Produced by Electrons Moving in a Medium with Velocities Exceeding that of Light

In a note published in 1934 [1] as well as in the subsequent publications [2] [3] [4] the present author reported his discovery of feeble visible radiation emitted by pure liquids under the action of fast electrons (β-particles of radioactive elements or Compton electrons liberated in liquids in the process of scattering of γ-rays). This radiation was a novel phenomenon, which could not be identified with any of the kinds of luminescence then known as the theory of luminescence failed to account for a number of unusual properties (insensitiveness to the action of quenching agents, anomalous polarization, marked spacial asymmetry, etc.) exhibited by the radiation in question. In 1934 the earliest results obtained in the experiments with γ-rays led S.I. Wawilow [5] to interpret the radiation observed as a result of the retardation of the Compton electrons liberated in liquids by γ-rays. A comprehensive quantitative theory subsequently advanced by I.M. Frank and I.E. Tamm

1

[6] afforded an exhaustive interpretation of all the peculiarities of the new phenomenon, including its most remarkable characteristic – the asymmetry.

According to their theory, an electron moving in a medium of refractive index n with a velocity exceeding that of light in the same medium ($\beta > 1/n$) is liable to emit light which must be propagated in a direction forming an angle θ with the path of the electron, this angle being determined by the equation:

$$\cos\theta = 1/\beta n, \qquad (1)$$

where β is the ratio of the electron velocity to that of light in vacuum.

A successful experimental verification of formula (1) was only performed with water [4] for which, at the moment

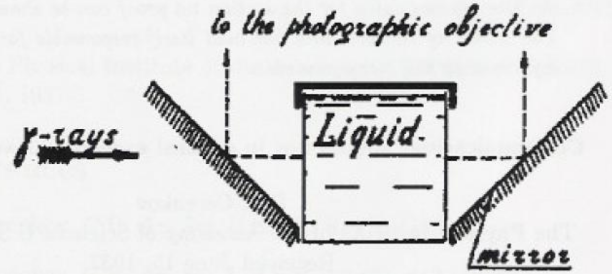


Figure 1: Arrangement of apparatus.

of publication of the above theory, data were already available which had been obtained by visual observations by the method of quenching [7] [8].

We recently performed additional experiments in which the intensity of radiation was recorded photographically, the records being taken simultaneously for all the angles θ lying in a plane passing through the primary electron beam. The liquid was placed in a cylindrical glass vessel with very thin walls, and the light emitted by the liquid was reflected by a conical mirror in an upward direction to the object glass of a photographic camera as indicated in Fig. 1. An approximately parallel beam of γ-rays, filtered through a 3-mm lead plate, fell on the liquid horizontally. The γ-radiation used was equivalent to that of 794 mg of radium. The considerable thickness of the lead screen, the large aperture of the object glass (f : 1.4) and the long exposure (72 hours) ensured sufficient distinctness of the photographs.

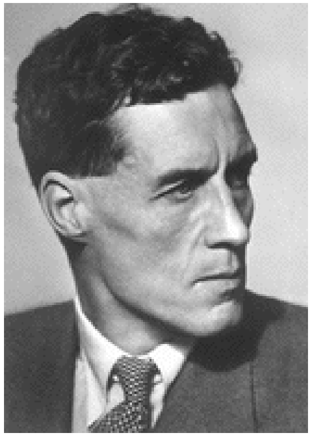
2

Cherenkov light: the beginnings

- 1946: Vavilov (who just became the president of the Academy of Sciences of USSR), Cherenkov, Tamm (head of theory division in FIAN) and Frank obtained Stalin's prize for their work
- Vavilov in former USSR was/is usually given higher credit for the effect (which is not clearly justified)
- 1958: Cherenkov, Tamm and Frank were awarded Nobel prize
- 1964: (rather late) Cherenkov became corresponding member of Soviet Academy of Sciences

Cherenkov, Tamm and Frank awarded Nobel Prize in 1958

- S. I. Vavilov has passed away in 1951 (after ~10 heart attackes).
- Nobel prize is awarded only to scientists who are alive



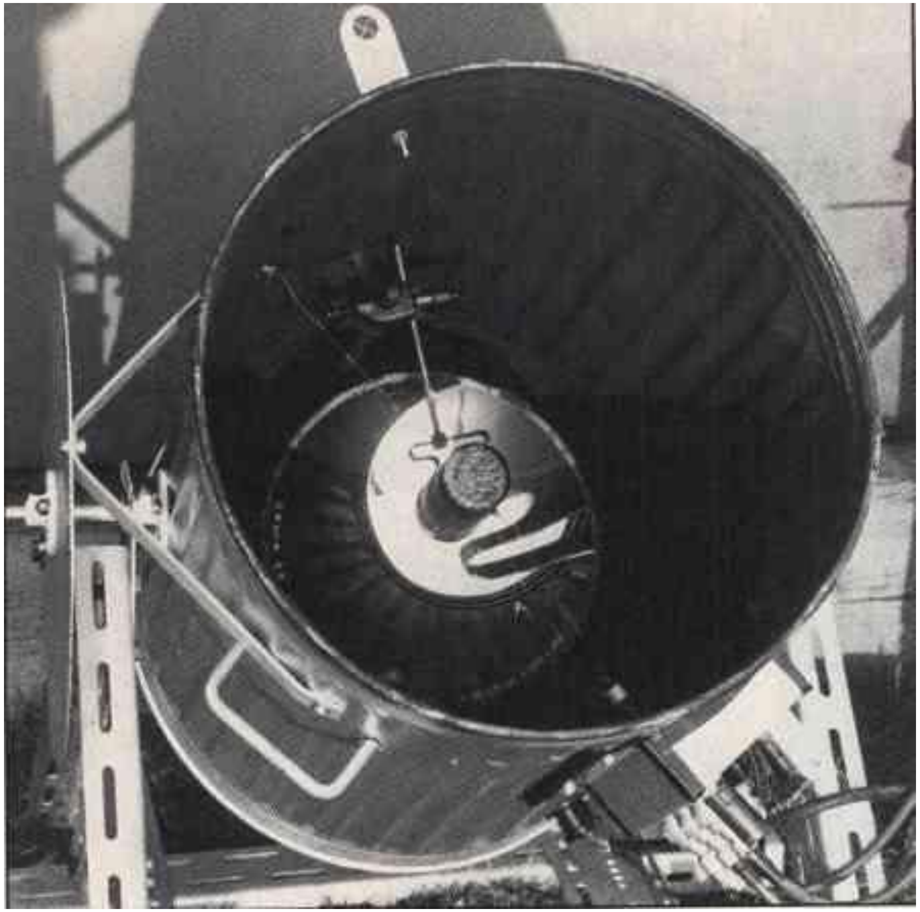
The Very Beginning of Atmospheric Air Cherenkov Telescope Technique

1948

- Patrick Blackett (Nobel prize laureate of 1948: study of cosmic rays using counter-controlled cloud chamber) was the first to mention that there shall be Cherenkov light component from relativistic particles in air showers (mostly e-, e+, μ-, μ+) marginally contributing (~ 10^{-4}) to the intensity of the light of night sky (LoNS)

- Until that the Cherenkov light has been detected only in solids and liquids

The Experimental Beginning



1953
By using a garbage can,
a 60 cm diameter mirror
in it and a PMT in its focus
Galbraith and Jelly had
discovered the
Cherenkov light pulses
from the extensive air
showers.

Gamma-ray Astronomy, the beginning

Seminal paper by Phillip Morrison, 1958

AN AIR SHOWER TELESCOPE

AND THE DETECTION OF 10^{12} eV PHOTON SOURCES

Giuseppe Cocconi *

CERN - Geneva.

1) This paper discusses the possibility of detecting high energy photons produced by discrete astronomical objects. Sources of charged particles are not considered as the smearing produced by the magnetized plasmas filling the interstellar spaces probably obliterates the original directions of movement.

5). 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.

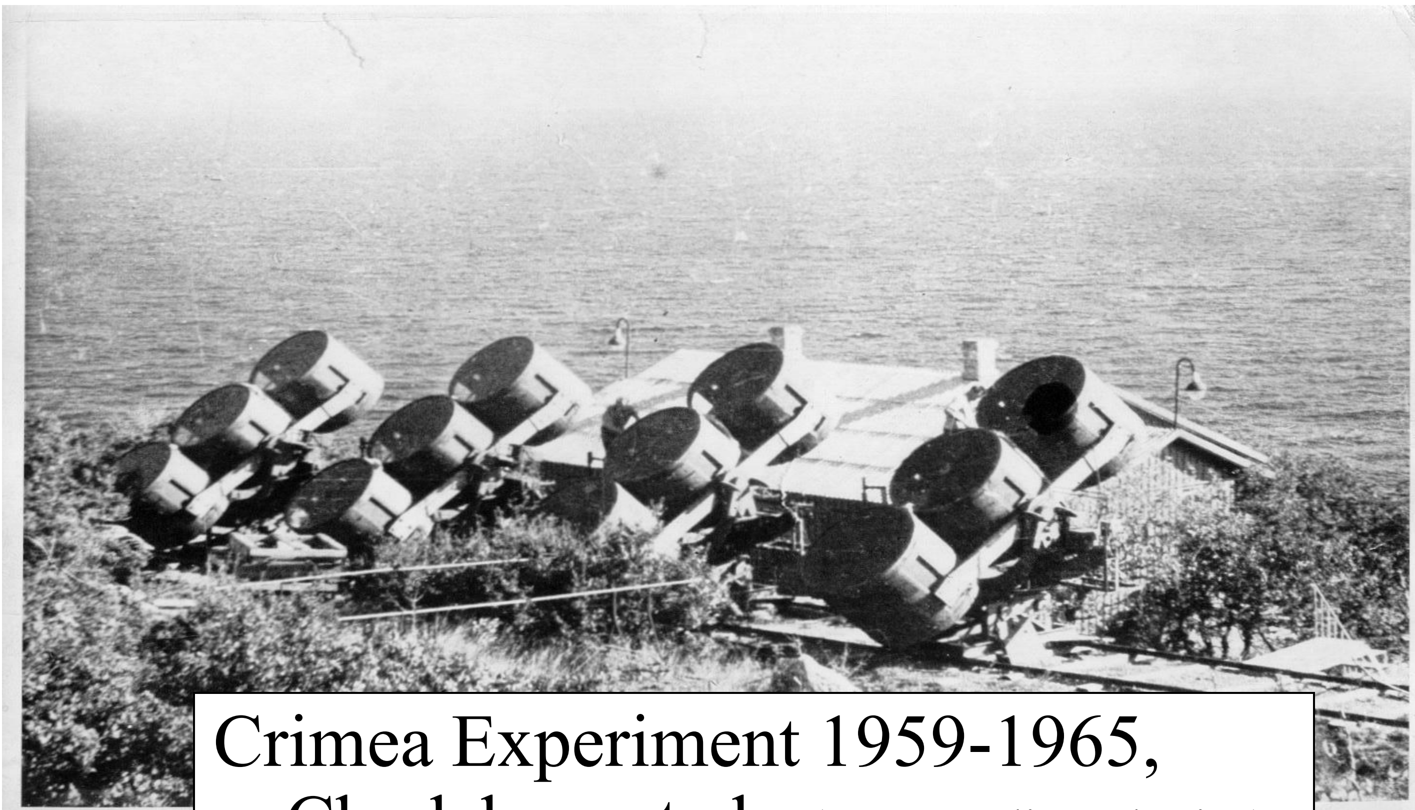
M87, the Jet Nebula: m = 13.5 $H \simeq 10^{-4}$ gauss.

$R(10^{12} eV) \simeq 10^{-5} m^{-2} s^{-1}$, still well above the background (2). For this object our evaluation is probably not fundamentally wrong.

Also proposed at higher energies independently by Giuseppe Cocconi, 1959

1921-2001

Alexander Chudakov and the Cherenkov Technique for Gamma Ray Astronomy



Crimea Experiment 1959-1965,
Chudakov, et al., (SNR, radio galaxies)

Таблица 1

Астрономический объект и период наблюдений	Часовой угол	Склонение	Число сеансов	$\delta \pm \sigma$, % $\vartheta_{эф} \approx \pm 1°$	$\delta \pm \sigma$, % $\vartheta_{эф} \approx \pm 3°$
Дискретные радиоисточники					
Телец А (Крабовидная туманность)					
1960			15	−0,15±1,32	+1,30±0,95
1961	5^h32^m	+22°00′	13	−0,70±1,20	−0,60±0,84
1962 *			19	−1,40±0,82	−0,45±0,54
Кассиопея А					
1962			8	+0,60±0,93	−0,47±0,56
1962 *	$23^h21^m,6$	+58°35′	12	−0,36±1,10	−0,77±0,66
Лебедь А					
1960			19	+1,60±0,92	+1,60±0,80
1961	$19^h58^m,4$	+40°32′	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			10	−0,23±3,0	−0,14±2,10
1962	$12^h28^m,9$	+12°38′	10	+0,37±1,0	+0,54±0,70
Персей А					
1962	3^h14^m	+42°24′	4	−1,80±2,30	−2,00±1,24
Стрелец А					
1963	$17^h43^m,3$	−28°58′	7	—	+10,5±20
Скопления галактик					
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

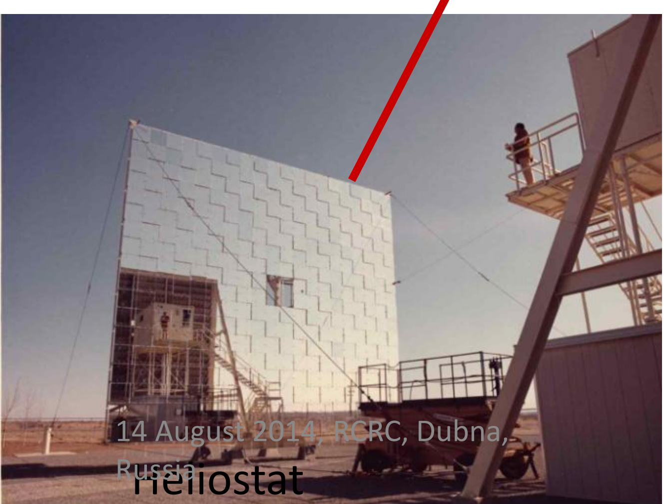
* Звездочкой отмечены измерения с компенсацией тока от неба.

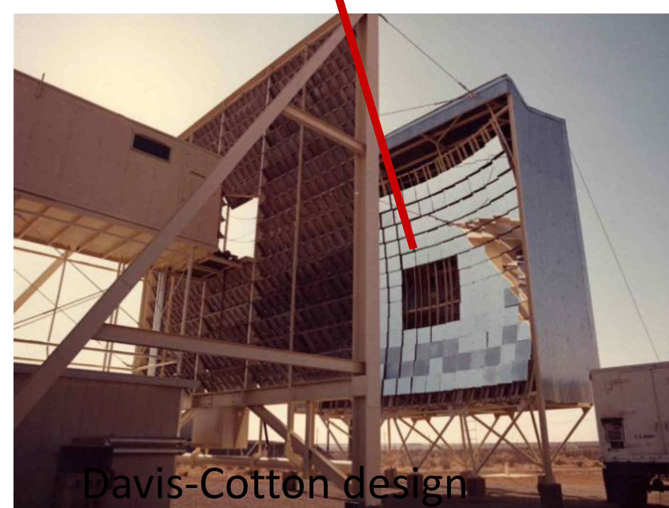
- A multitude of sources have been observed and serious statistical treatment of data has followed

- Except for some small fluctuations no significant flux has been observed
$\geq$ 3.5-5 TeV,
Flux upper limit:
5 x 10-11 ph/cm²s

- They turned down the too optimistic prediction of Cocconi about 1000:1 S/N

1st Smithsonian venture into VHE gamma-ray used Solar Furnace at Natick, MA ~ 1965-6.
Gamma-ray Astronomy Group led by Giovanni Fazio





The Pioneer Trevor Weekes; life-long trying hard, until succeeding with Crab Nebula 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 Imaging using Image Intensifiers (1960-65) and Stereo Detectors (1972-76)

Image Intensifier Pictures of Cherenkov light Image from Cosmic Ray Air Shower.
On short time-scale images are brighter than bright star (Vega).
Work by David Hill (M.I.T.) and Neil Porter (U.C.D.) in 1960

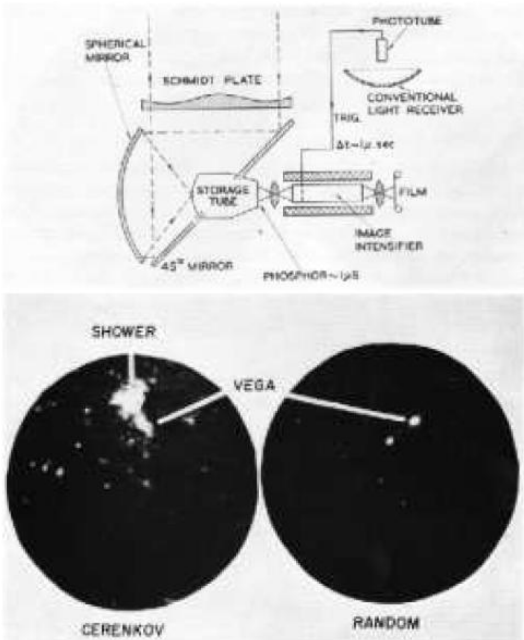
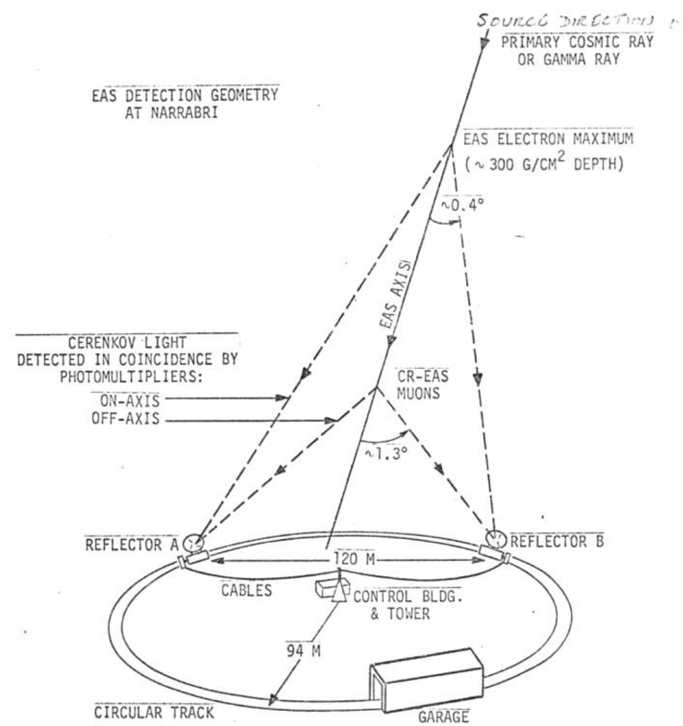


Figure 5. **Top:** Image Intensifier used by Hill and Porter to record the images of cosmic ray air showers [24]. **Bottom** Images of the night-sky triggered by an ACT (left) and triggered randomly (right). The field of view was ±12.5°.

Josh Grindlay demonstrates value of stereo imaging with two-pixel system (Double Beam Technique) at Mt. Hopkins and Narrabri (1972-76)



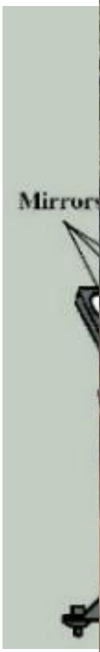
Victor Zatsepin

In 1960's he well-understood the main features of air Cherenkov technique.

In his 1964 paper he performed detailed Monte Carlo simulations and *concluded that stereo observations can strongly reduce the background*

„URAL" was the name of the russian computer that was operated by a specially trained staff.

Arnold Stepanian’s pioneering imaging “stereo ”telescopes: GT-48 in Crimea



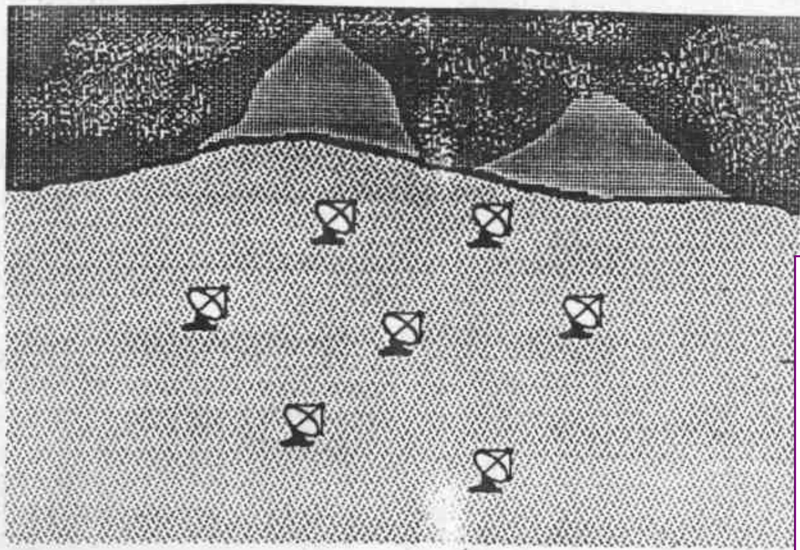
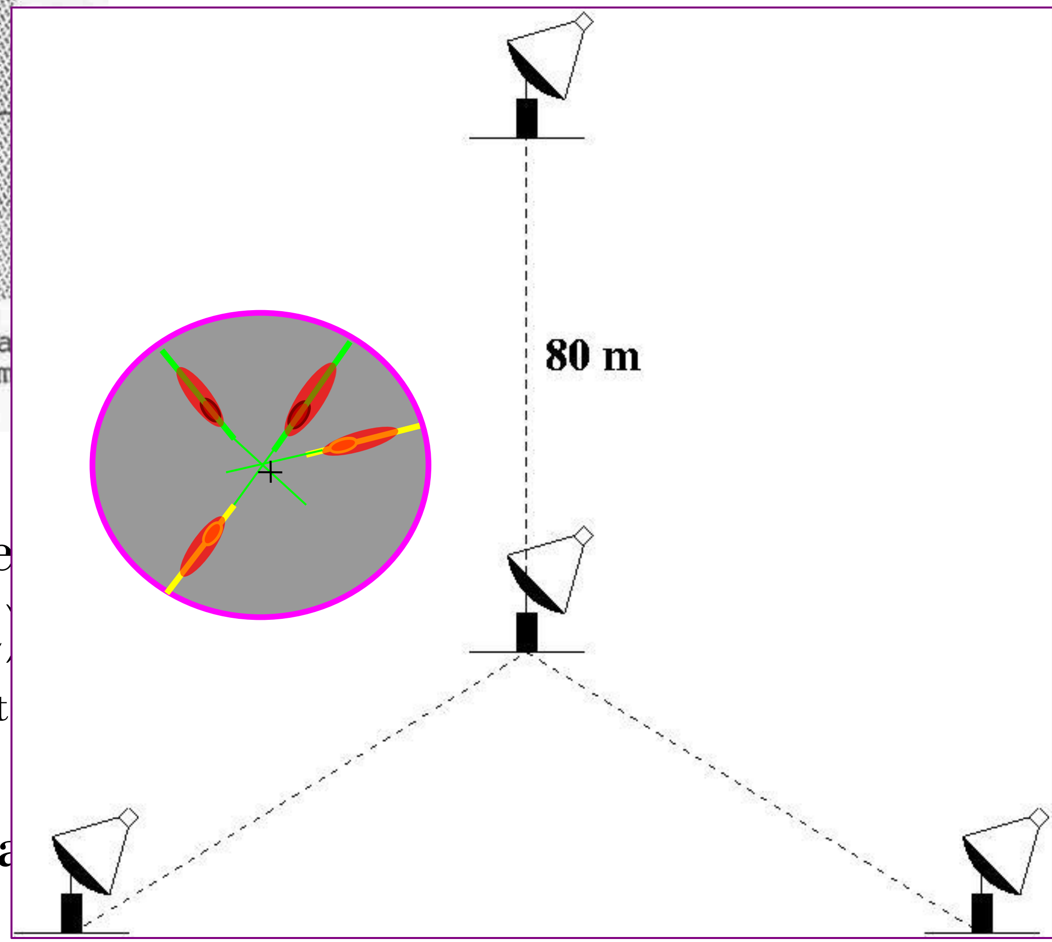


Figure 1a. Artist's concept of VHE Gamma Ray Observa
showing seven 15 m aperture atmospheric Cherenkov cam
with spacing of 75 m.



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

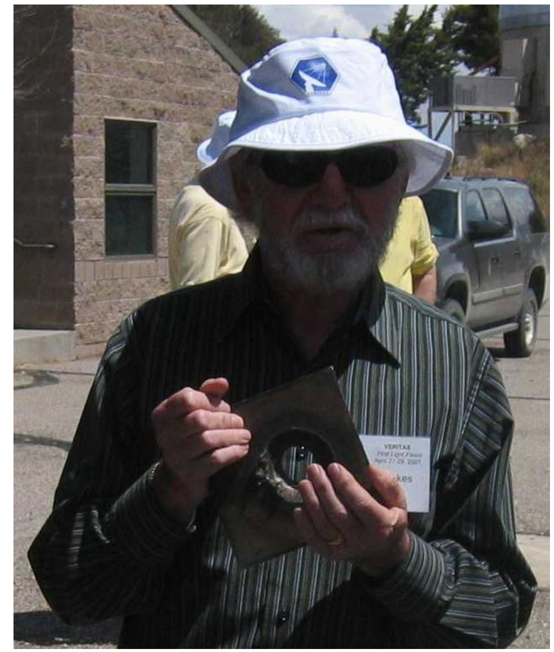
(NASA Workshop, Space Lab. Science, Bat Rouge, 1984)

This is the configuration that wa later adopted for VERITAS.

Some key developments

- 70-80‘s: plenty of „discoveries“ on 3-4 σ level
- M. Hillas: „A physicist‘s aparatus gradually learns what is expected of it (blame the apparatus for a dog-like desire to please)“
- La Jolla, 1985: Michel Hillas suggested to use the „Hillas“ parameters
- 1989: Whipple discovers 9σ signal from Crab

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



„If a telescope can within a few s evaporate a solid piece of steel, it can also measure gamma rays“
;-)

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

31. 5. 91

Proposal for Imaging Air Cherenkov Telescopes in the HEGRA Particle Array

F.A. Aharonian, A.G.Akhperjanian, A.S. Kankanian, R.G. Mirzoyan, A.A. Stepanian*

Yerevan Physics Institute

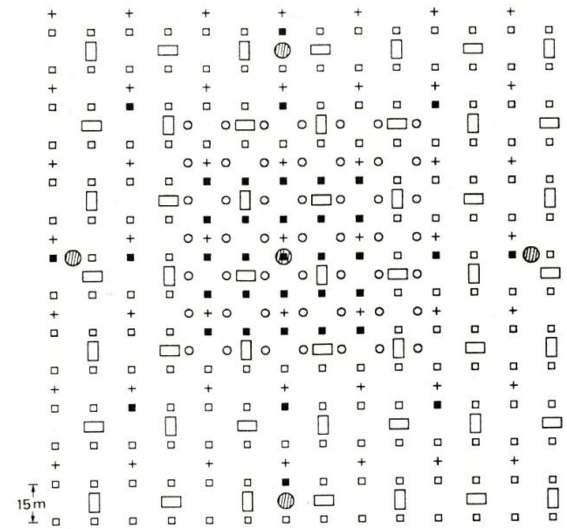
* Crimean Astrophysical Observatory

M. Samorski, W. Stamm

Institut für Kernphysik, University of Kiel

M. Bott-Bodenhausen, E. Lorenz, P. Sawallisch

Max-Planck-Institute for Physics and Astrophysics
Munich



ELECTRON DETECTORS: 1 m^2 scintillation counters for particle density and fast-timing measurements (2 PM's each), with 5 mm of lead for photon conversion.

- ■ 37 detectors in operation since July 1988 (University of Kiel)
- □ 159 additional detectors, 90 of them in operation since July 1989, the rest since December 1990 (MPI Munich together with University of Madrid)
- ○ 49 further detectors to increase the detector density in the centre of the array, planned for 1991 (University of Hamburg)

▭ 49 MUON DETECTORS: 15 m^2 each, consisting of sandwiches of Geiger tube and absorber layers, planned for 1991/92 (University of Wuppertal together with University of Kiel)

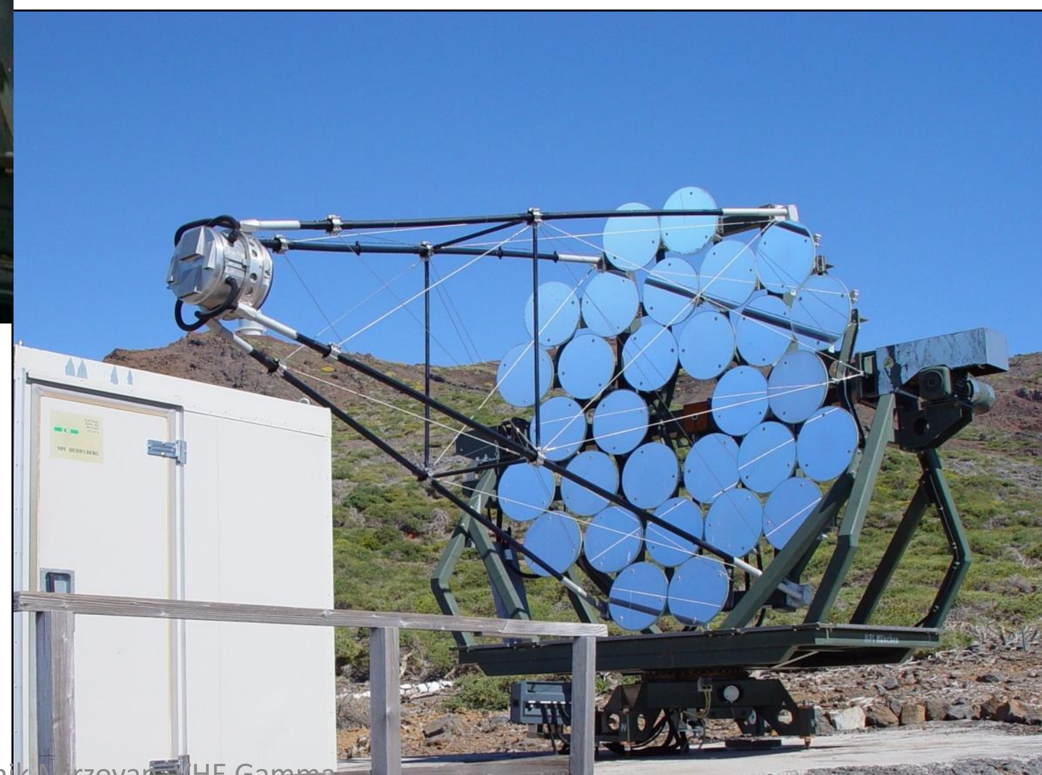
\+ 49 CHERENKOV-LIGHT DETECTORS: each consisting of a 20 cm diameter PM and a light-collecting cone, planned for 1991 (MPI Munich together wit h University of Madrid)

⊘ 5 CHERENKOV TELESCOPES: 3 m in diameter with 19 mirrors and 37 PM's each, imaging technique, planned for 1991/92 (Yerevan Institute of Physics together with MPI Munich and University of Kiel)

Fig. 1: Status and planned extensions of the HEGRA detector array.

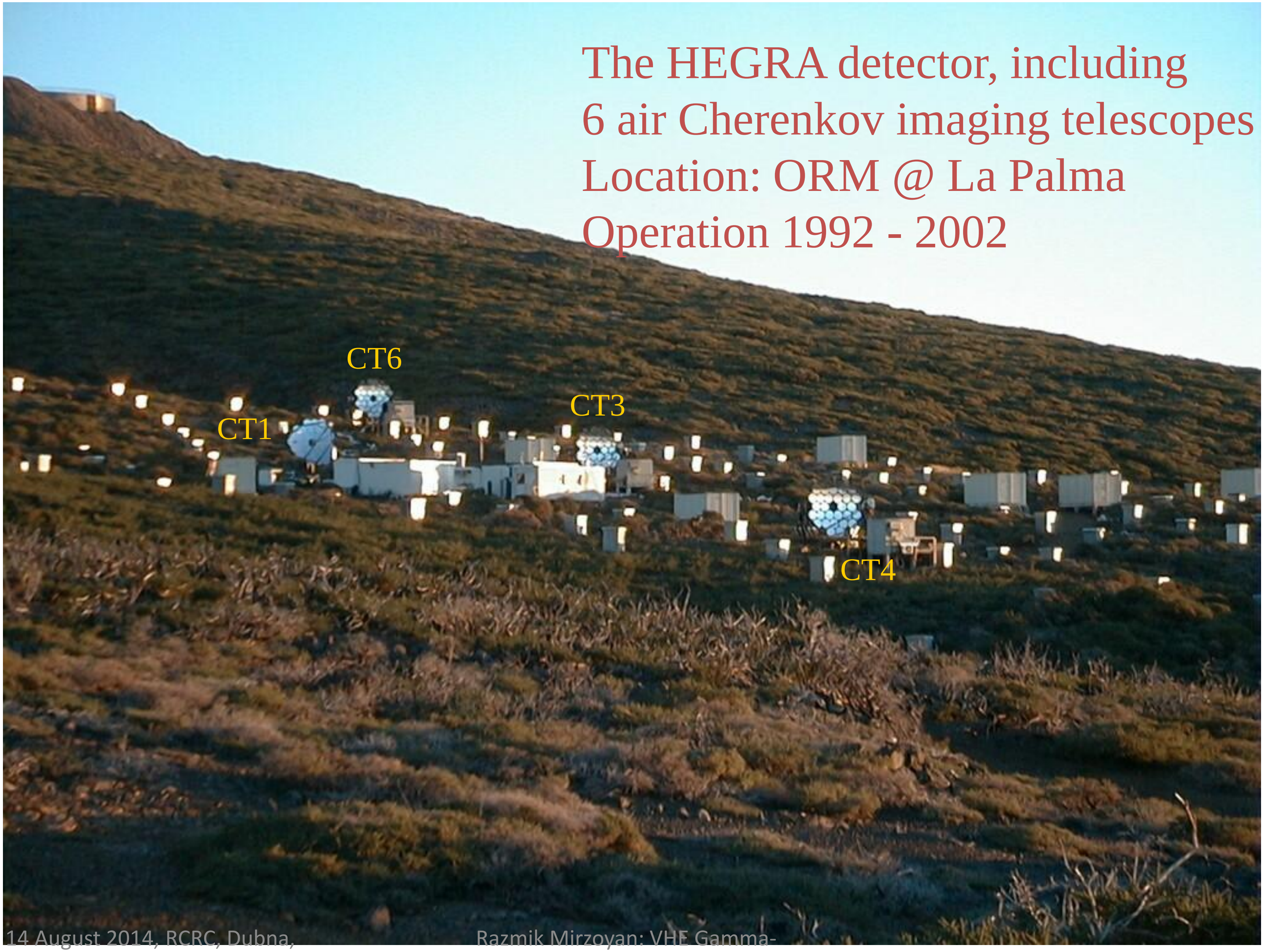
CT1 started to collect data in summer 1992
The 1st signal from Crab Nebula fall 1992

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



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

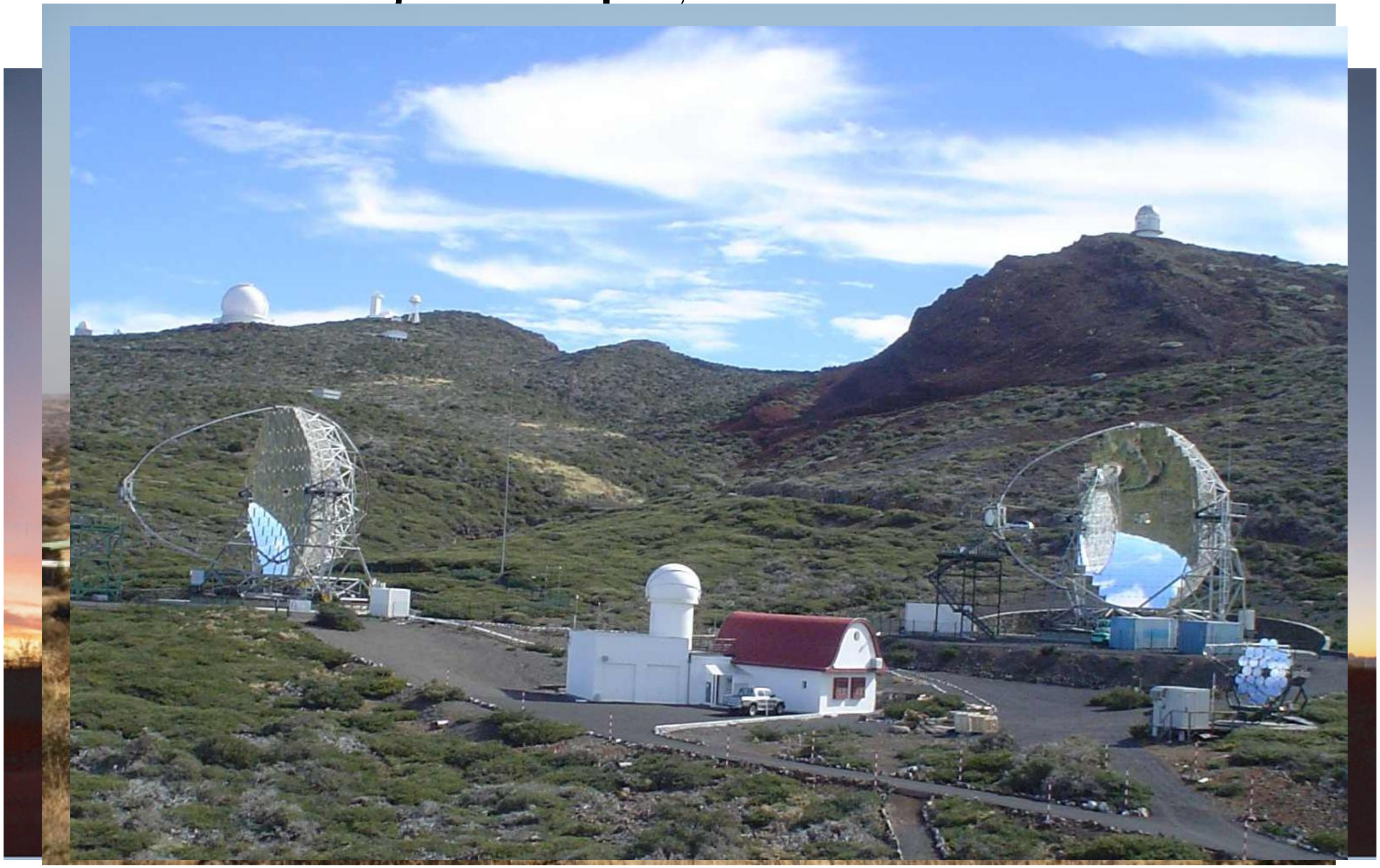
The HEGRA detector, including
6 air Cherenkov imaging telescopes
Location: ORM @ La Palma
Operation 1992 - 2002



Milestones in VHE γ astro-physics

- 2nd generation imaging telescopes, lead by the pioneering 10m Ø Whipple telescope, made the breakthrough, in the first time allowing to measure reliably γ sources at E ≥ 300 GeV
- 2nd generation telescope arrays, put in proximity and set into coincidence (later on dubbed as „Stereo“), led by HEGRA, allowed increasing the sensitivity and precision of measurements
- 3rd generation telescope MAGIC was 1st to lower the operational energy range of an IACT by one order of magnitude, down to 25 GeV (discovery of γ pulses from Crab pulsar at E ≥ 25 GeV, SCIENCE,2008)

VERITAS, H.E.S.S. & MAGIC: pushing the VHE γ-astro-physics to its limits



System of 2 MAGICs: the main parameters

- Energy threshold (trigger): ~ 50 GeV
- Energy threshold in *"Sum-Trigger"* modus: 30 - 35 GeV
- Energy resolution: 15 % - 23 % for E ≤ 10 TeV
- Angular resolution: 0.07° for E ≥ 300 GeV;   0.05° @ 1 TeV
- Sensitivity: source with 6/1000 of Crab Nebula 5σ in 50h
- Light-weight construction, only ~ 70 T
- Fast re-positioning to any coordinates in the sky: 20s/180°
- Opto-electric design optimized to provide ~ 2.5ns FWHM pulses
- Data digitized by using DRS4 chips operated at 2 GigaSample/s
- Producing ~ 1 TB data per observation night

Fast Rotation of MAGIC to„catch“ GRB

Outlook : the next 5-7 years

Next generation VHE γ ray Observatory: CTA

MAGIC Phase II (MAGIC-I + MAGIC-II Upgrade Sept. 2012)

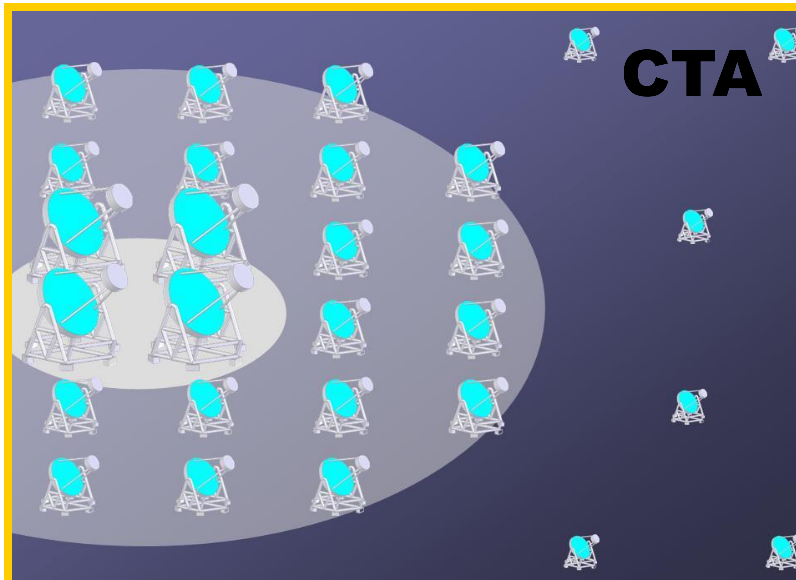
~1000 scientists
~120 institutions

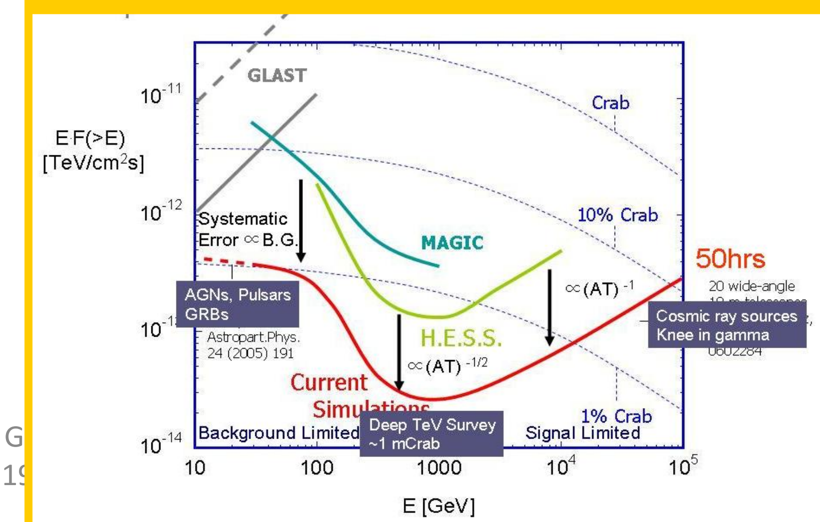
HESS Phase II (HESS + 28m Telescope) in July 2012

Astronomers in EU

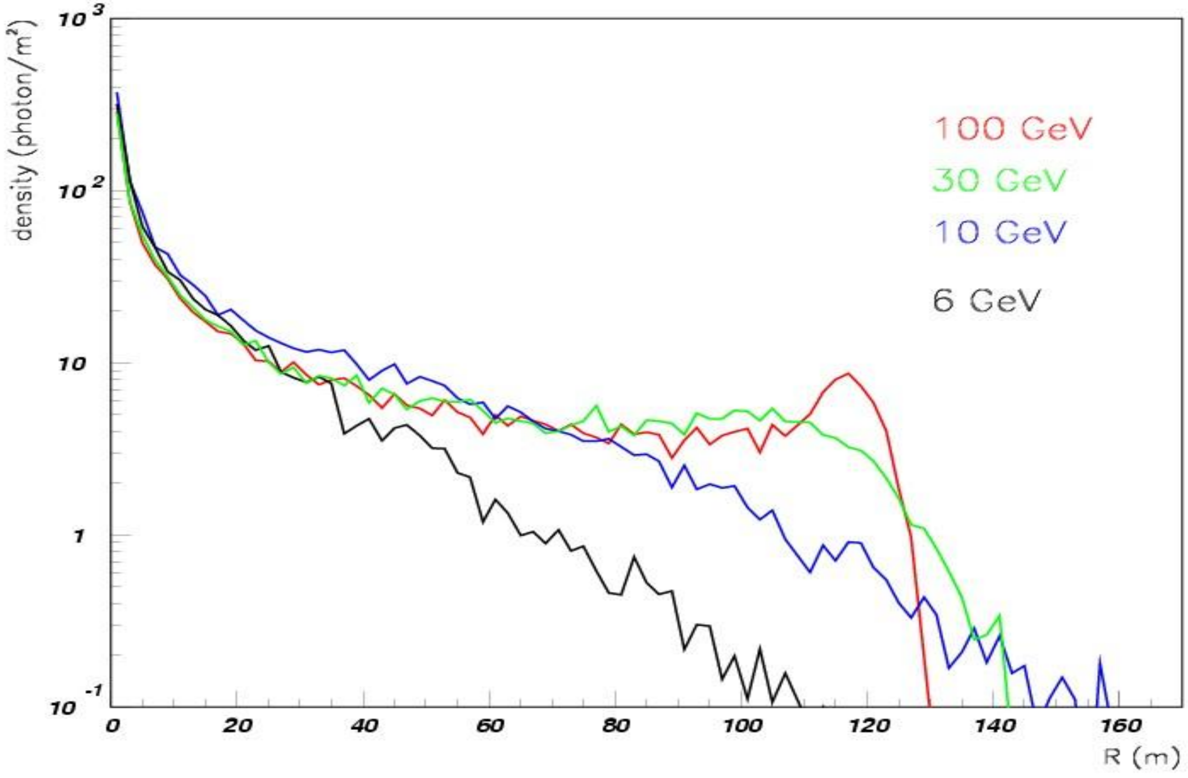
JAPAN, US

Cherenkov Telescope Array
1000's of sources will be discovered

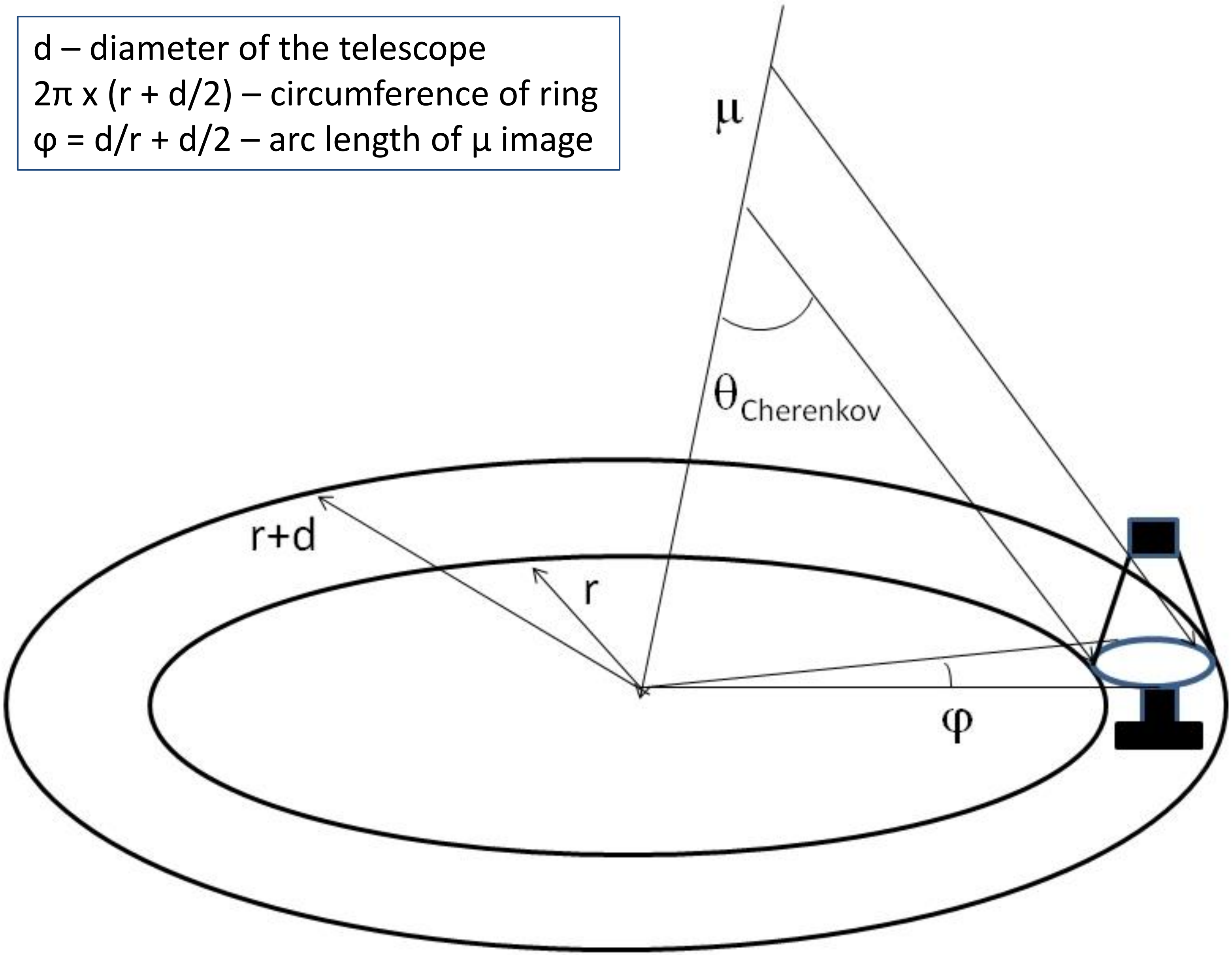




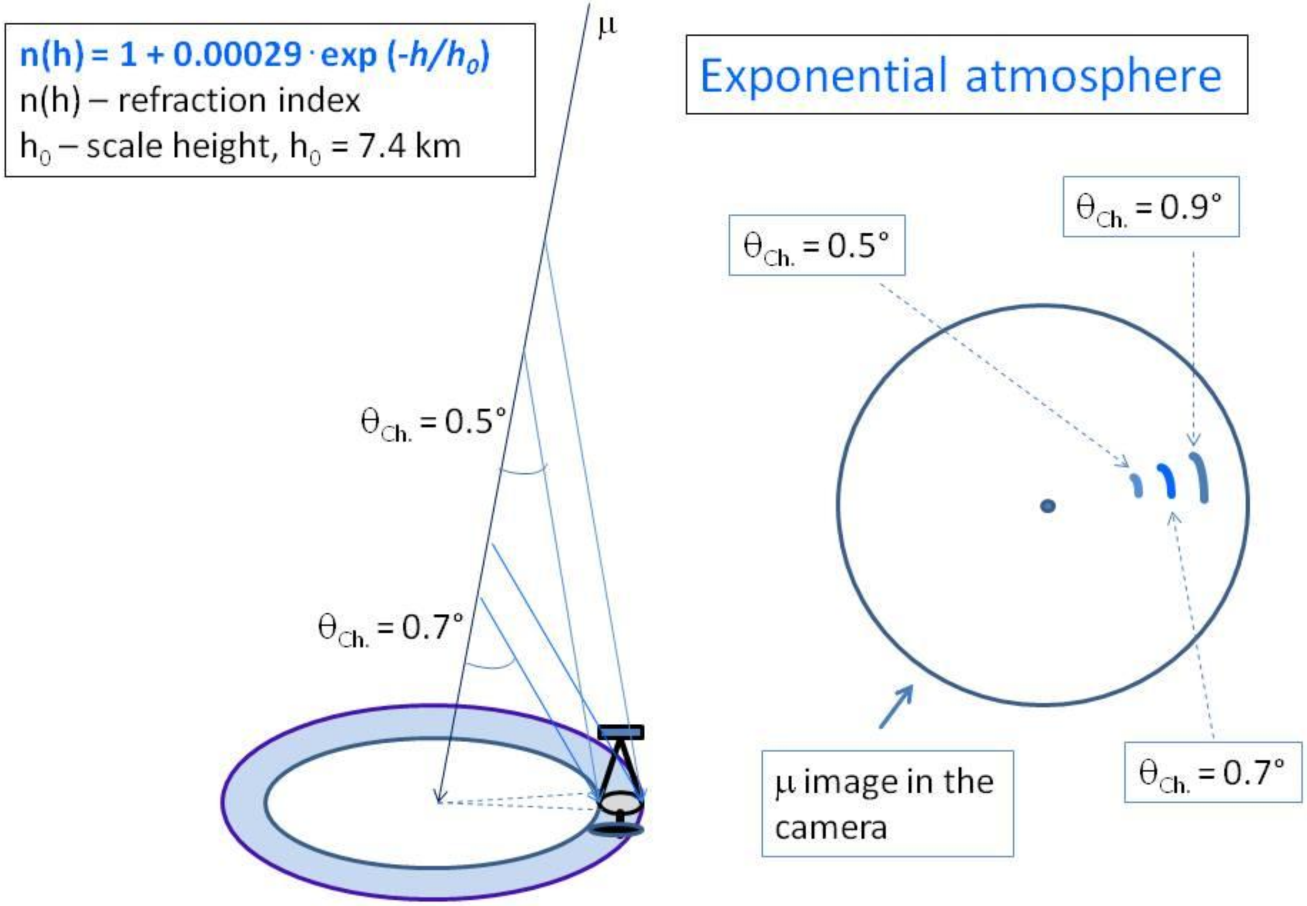
Lateral distribution of light from a single μ



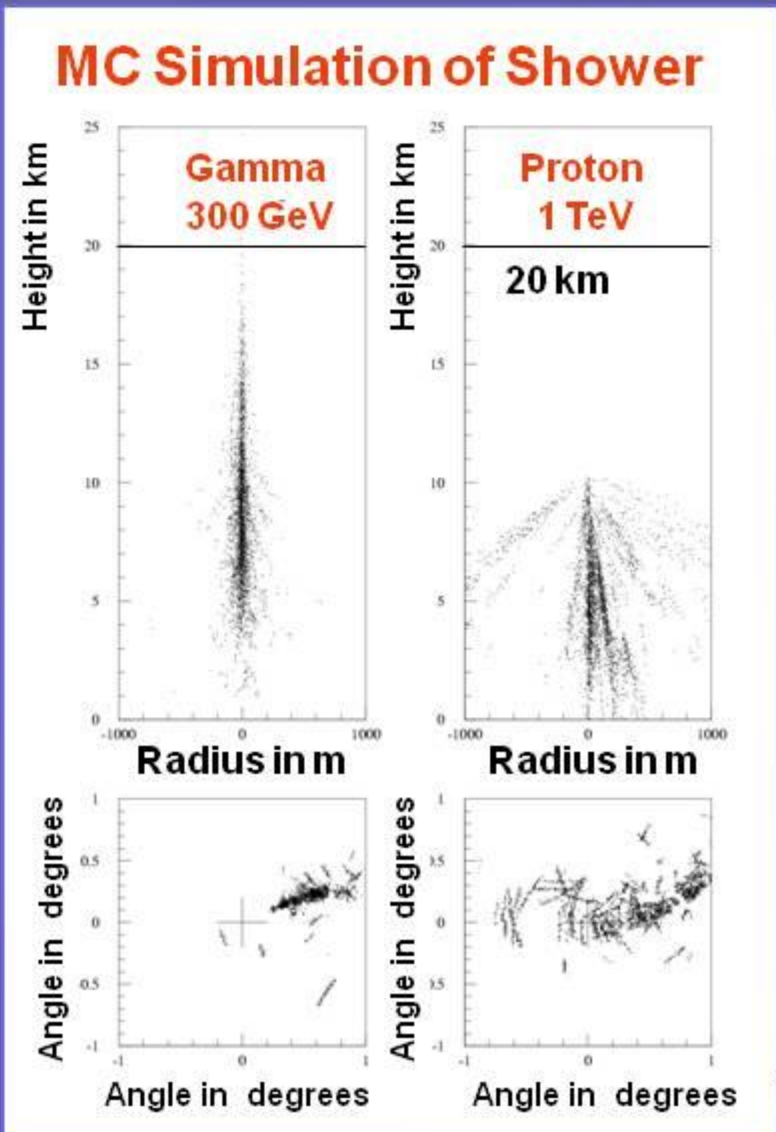
d – diameter of the telescope
2π x (r + d/2) – circumference of ring
φ = d/r + d/2 – arc length of μ image



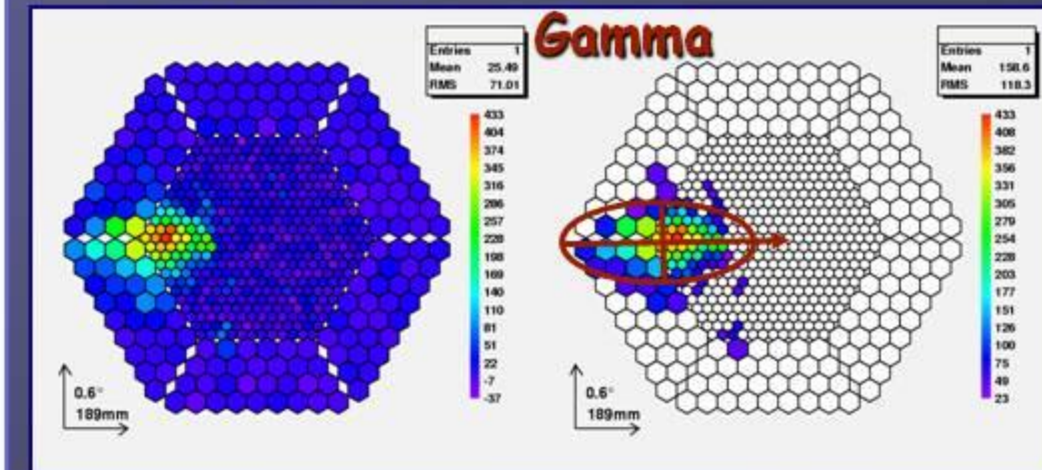
VHE γ-astrophysics with IACTs is possible thanks to exponential atmosphere

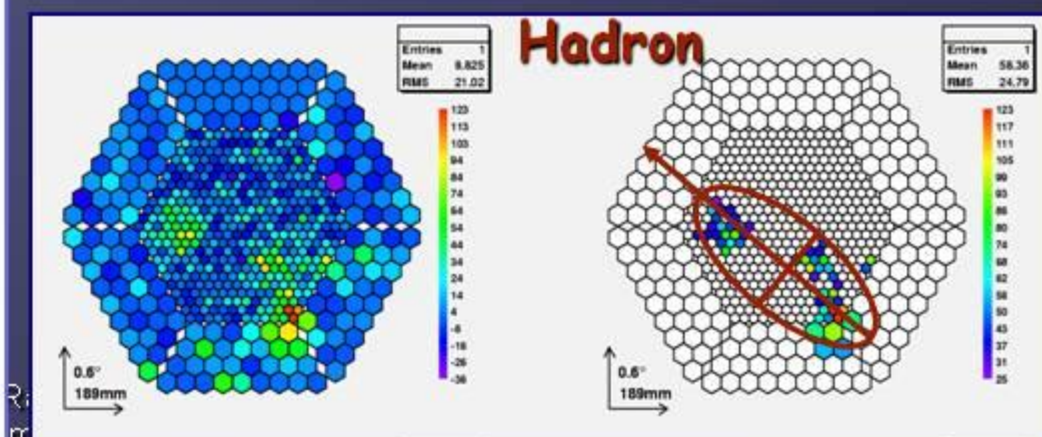


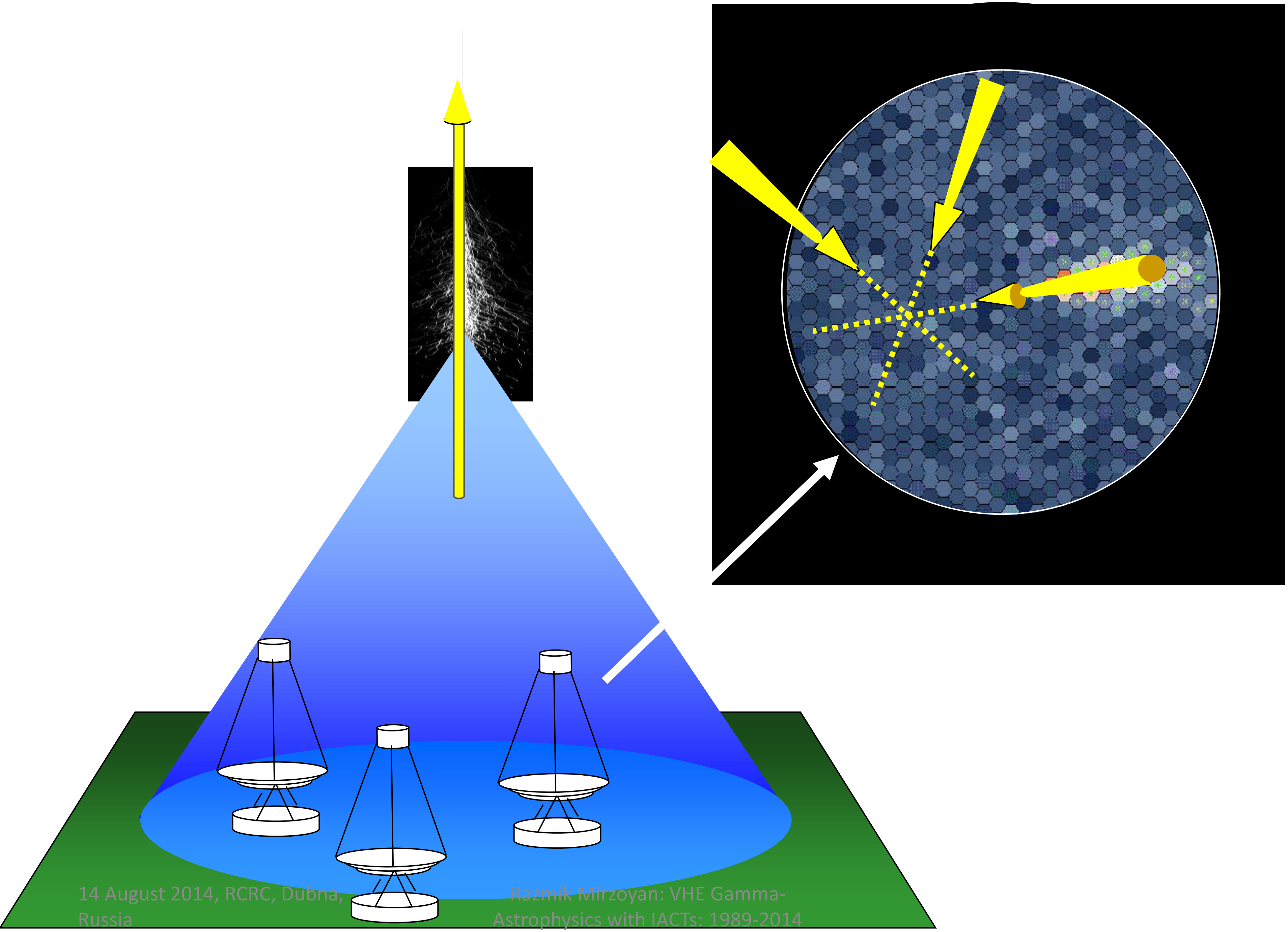
Gamma/Hadron separation



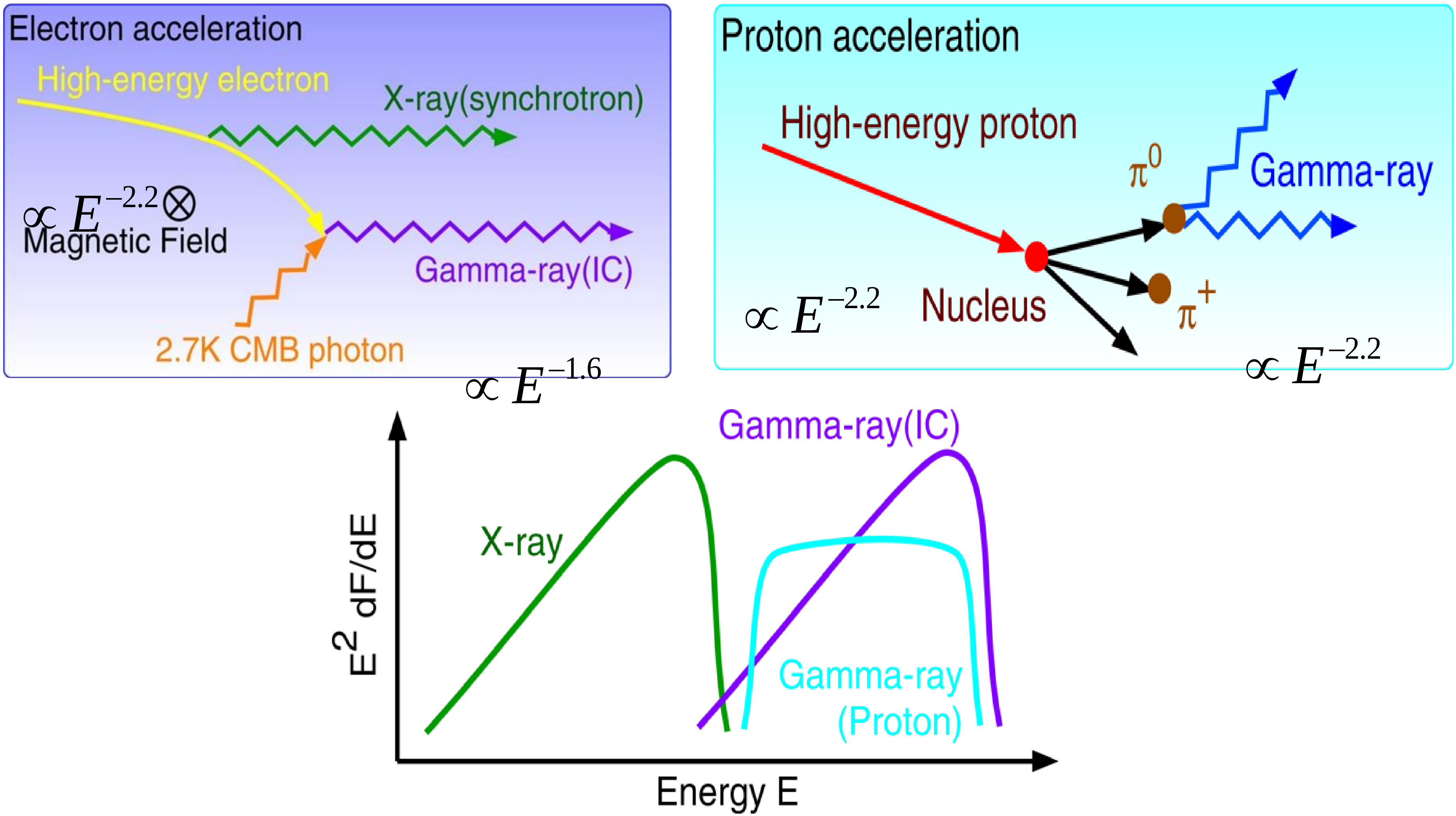
Hadron Rejection by Image Shape
+ Orientation ~ 99.9 %





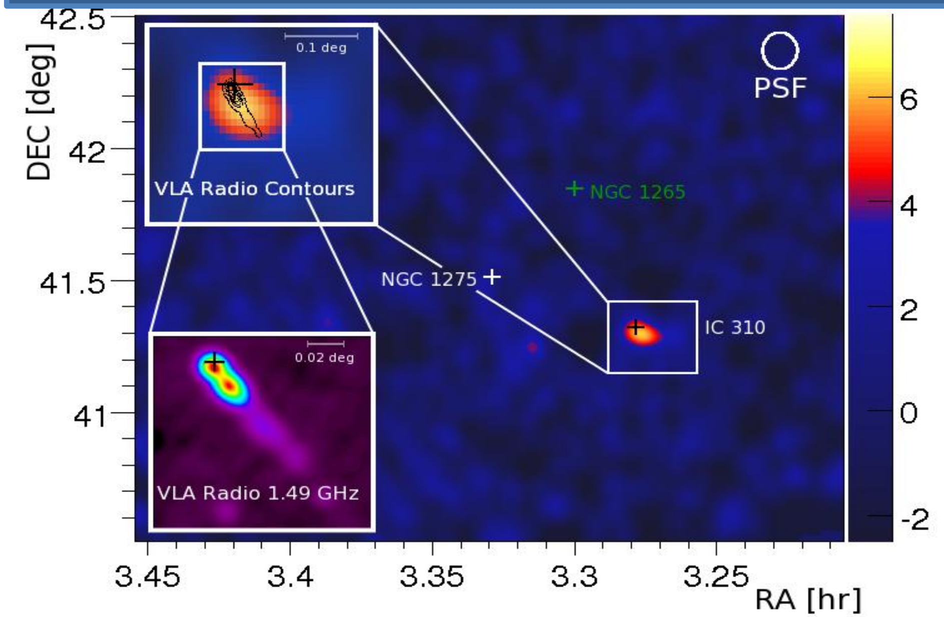


Gamma-Ray Emission Processes
Astrophysical process



IC 310: Unexpected Discovery in the Perseus Cluster of Galaxies

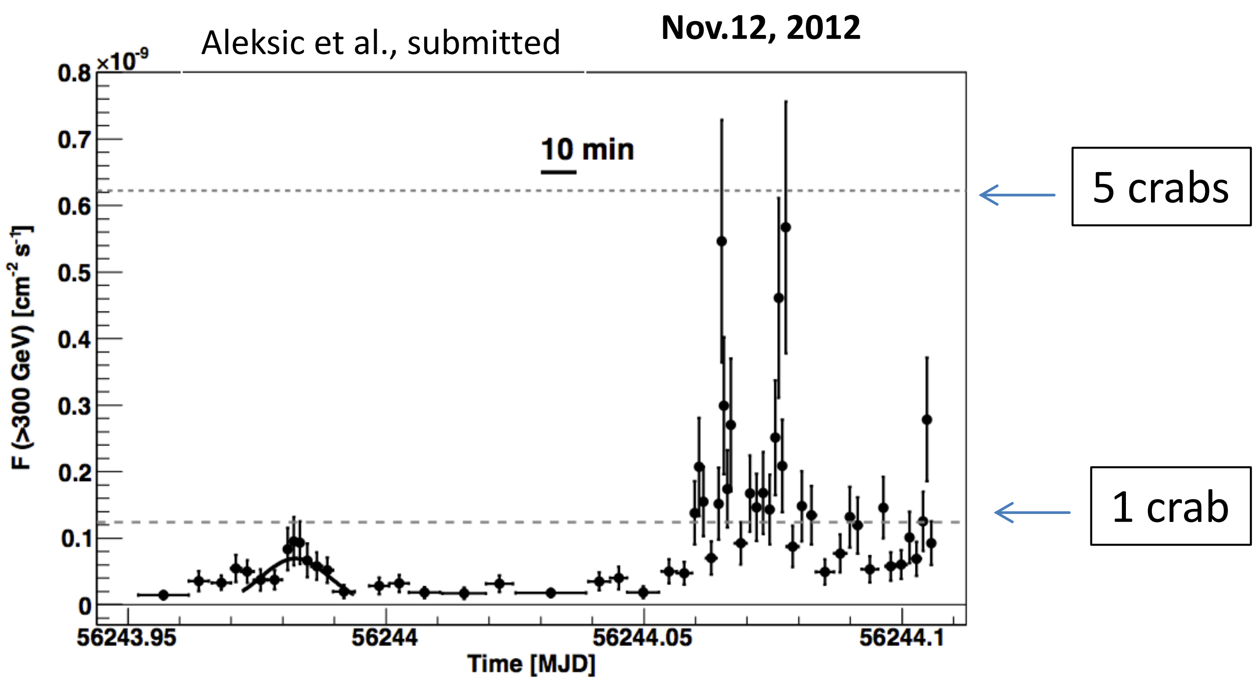
IC 310: detected ≥ 30GeV by *Fermi*/LAT (Neronov et al. 2010) & ≥ 260GeV by MAGIC (Aleksic et al. 2010)



- Flux and spectral variability in X-ray
- Day-scale variability in VHE, no spectral variability
- Hard spectrum in HE and VHE → 2nd hump ≥ 1TeV
- Original head-tail classification not supported
- VLBI reports parsec-scale blazar-like structures; $\theta \leq 38°$

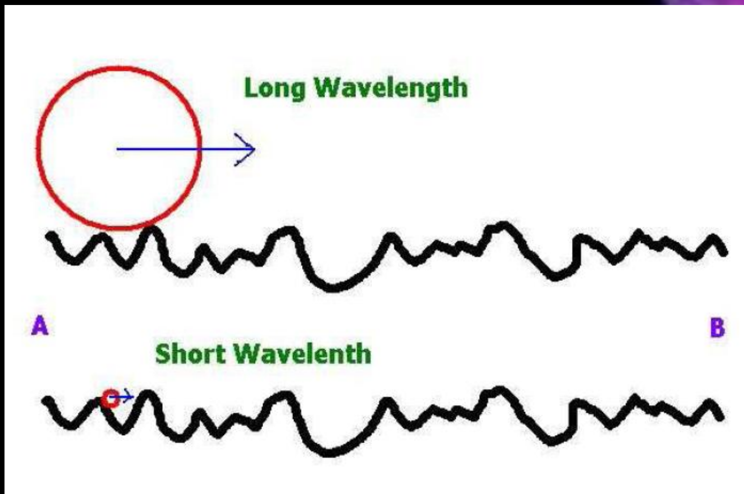
➢ MWL campaign in Nov. 2012 to Feb 2013

Radiogalaxy IC 310



- Light curve with 1-minute bins shows extreme variability; unusual for a radio galaxy
- Still, spectral shape in the VHE remains constant
- No curvature in spectrum from 60 GeV – 10 TeV
- Difficult to explain with current (standard) theoretical scenarios !

Exotic Physics: Test of Lorentz Invariance Violation with VHE γ



$$E_{Pl} = \sqrt{\frac{\hbar c^5}{G}} \approx 1.22 \times 10^{19}\, GeV$$

If Gravity is a Quantum theory,
at a very short distance it may show a very complex "foamy" structure due to quantum fluctuation.

Use gamma ray beam from AGNs/GRBs
to study the space-time structure

Energy 1000GeV ~ $10^{-16} E_{Pl}$
Distance 100~1000Mpc ($10^{16\text{-}17}$sec)

Visible time delay ~ 1 - 10 sec

Linear deviation:

$$\xi_1 < 0; \quad v = c\left(1 - \frac{E}{M_{QG1}}\right); \quad n(E) = 1 + \frac{E}{M_{QG1}}$$

Quadratic deviation:

$$\xi_1 = 0; \quad \xi_2 < 0; \quad v = c\left(1 - \frac{E^2}{M_{QG2}^2}\right); \quad n(E) = 1 + \frac{E^2}{M_{QG2}^2}$$

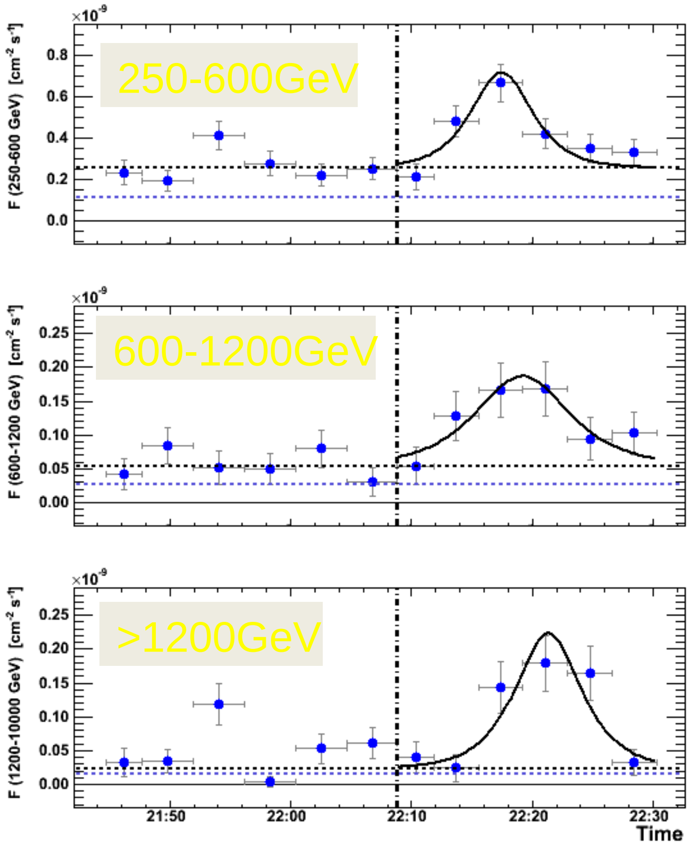
Fast time variation of VHE γ from AGN Mrk-501 by MAGIC, PKS 2155 by HESS

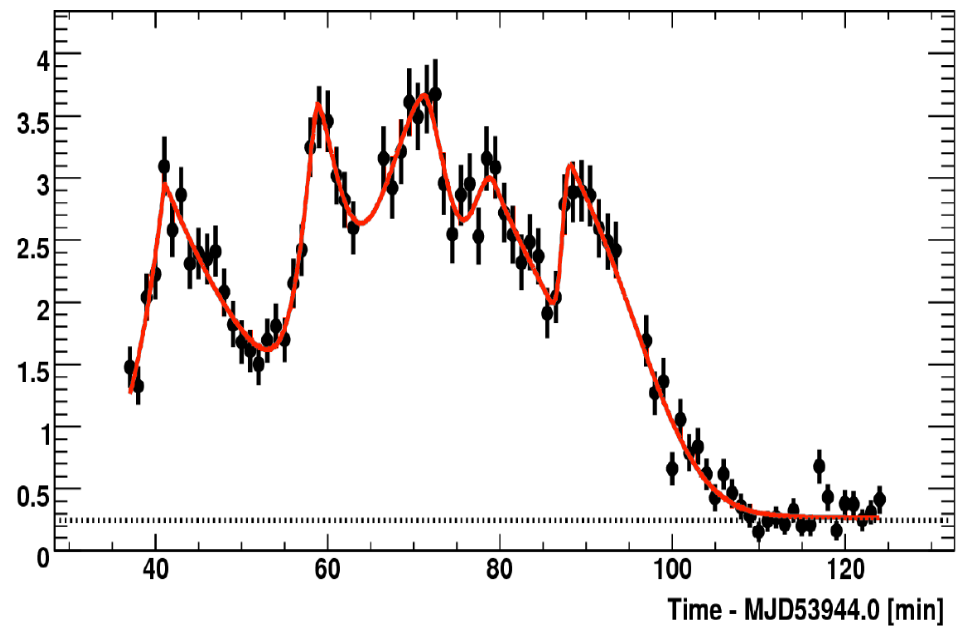
Mrk501(z=0.03) MAGIC observation

$M_{QG1} > 0.26 \times 10^{18}$GeV

PKS2155(z=0.116) HESS observation

$M_{QG1} > 0.72 \times 10^{18}$GeV

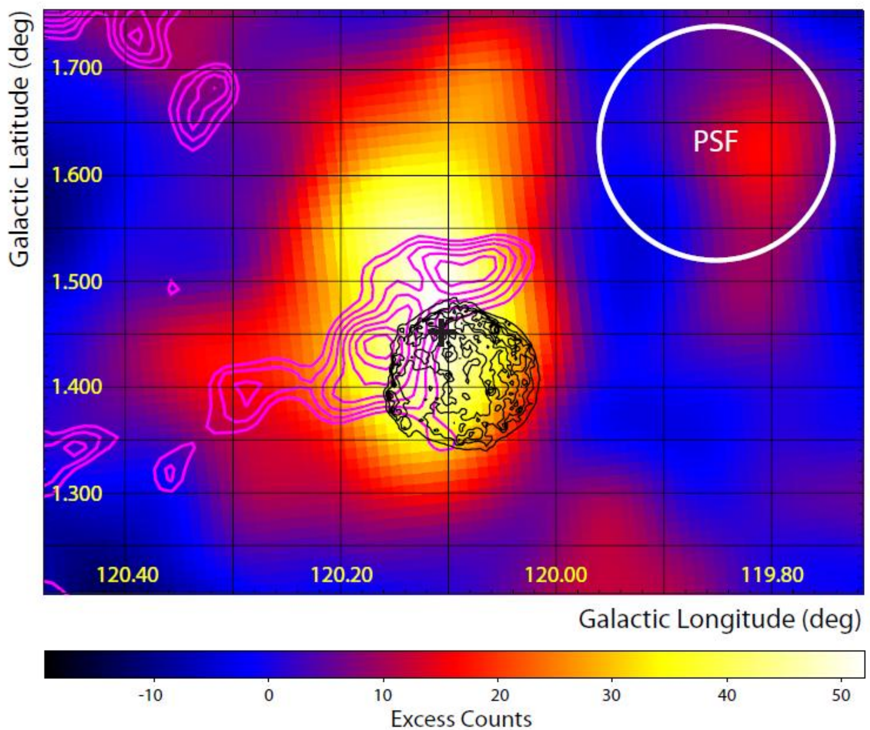




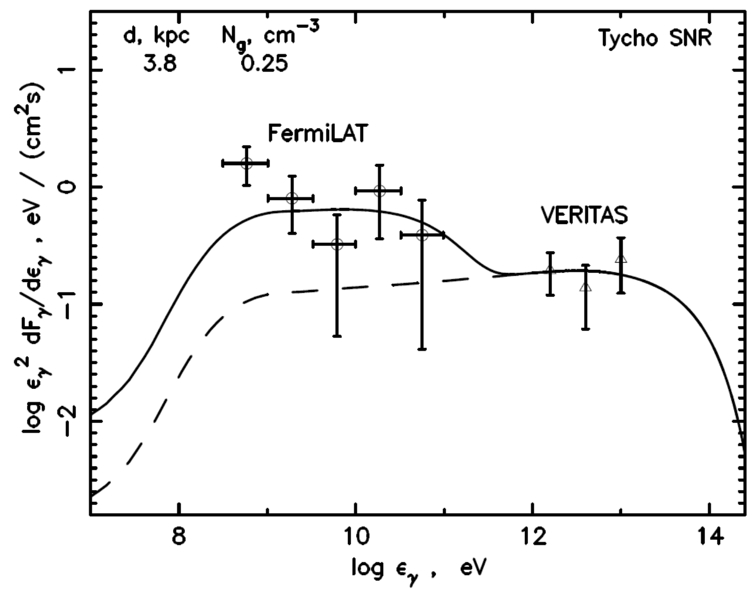
CTA can provide ~10sec time resolution for the fast variation

VERITAS discovery of Tycho SNR

Historical SNR first observed in 1572
Type Ia; estimated distance: 3.8 kpc
0.9 % crab units



Berezhko, et al., 2012

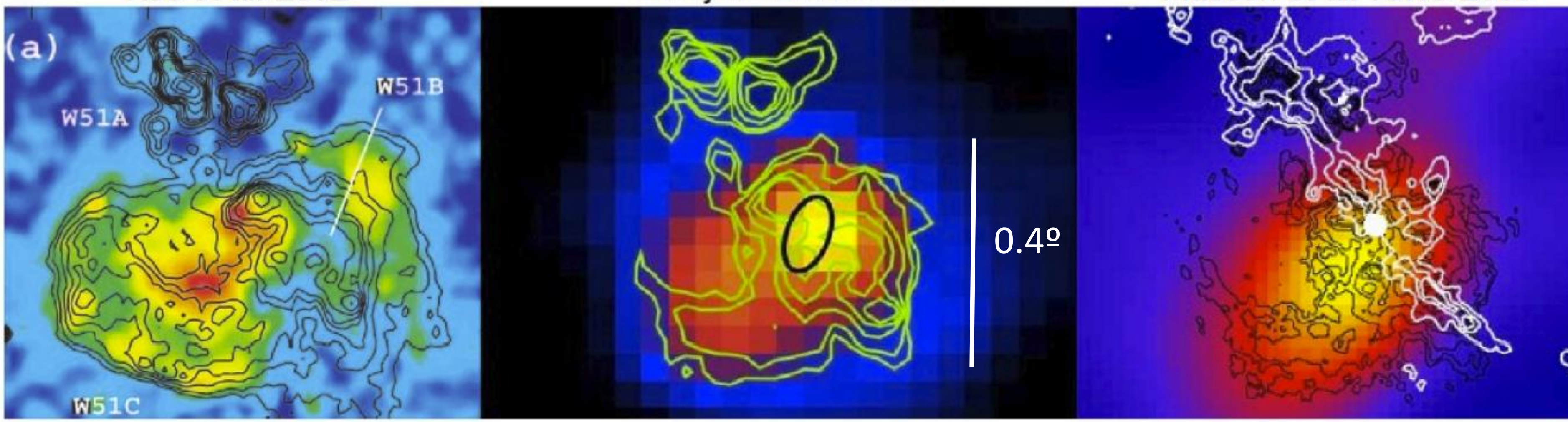


W51

ROSAT 0.7-2.5 keV
Koo et al. 2002

Fermi / LAT 2-10 GeV
Uchiyama et al. 2011

H.E.S.S. >1 TeV
Fiasson et al. ICRC 2009

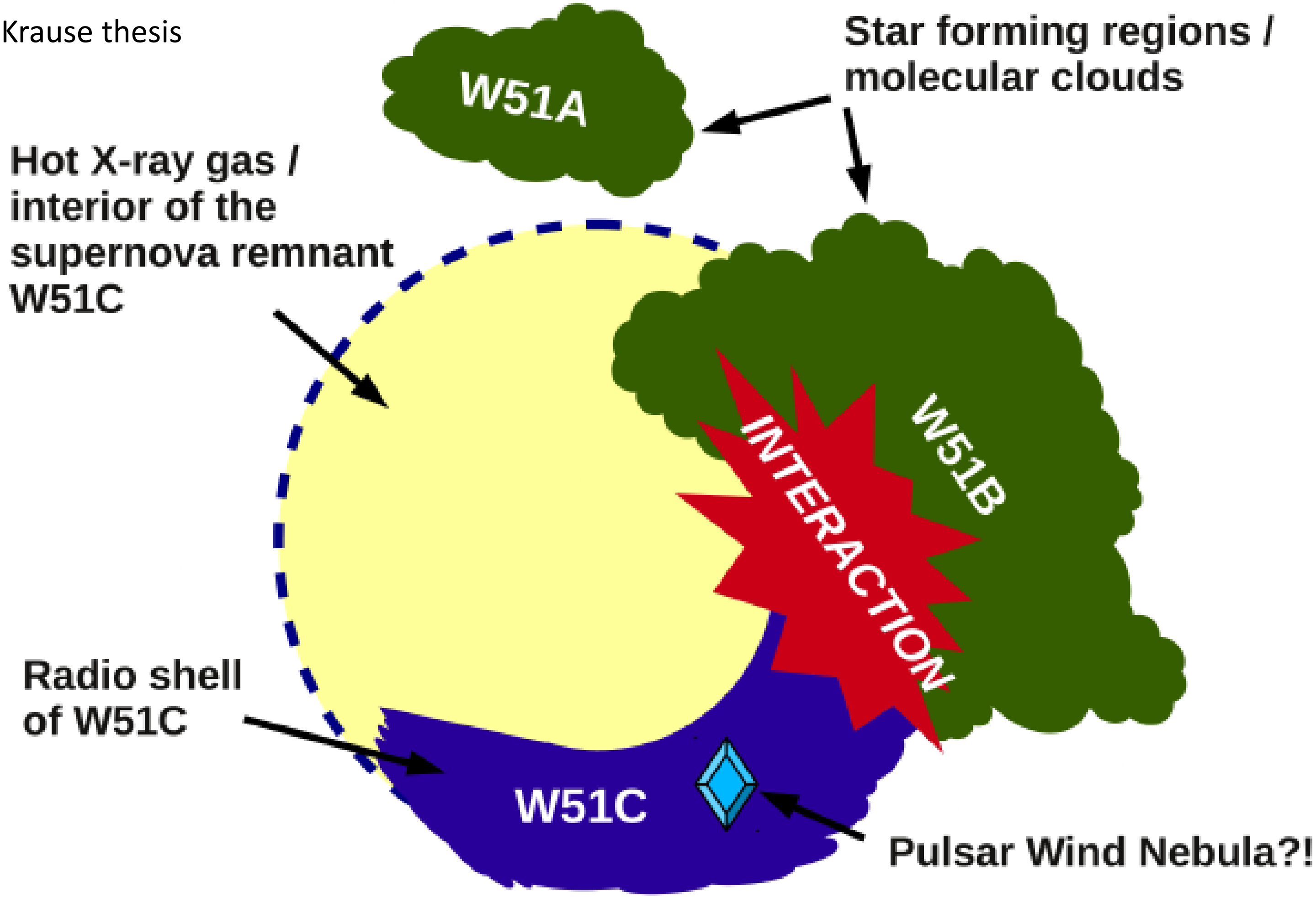


- W51A & W51B: star forming regions, W51C medium-age (~30kyr) SNR @ ~5.5 Kpc.
- Possible PWN CXO J192318.5+1403035 maybe associated with W51C (*Koo et al 2005*)
- The SNR appears to be interacting with W51B (*Koo et al. 1997, Green et al. 1997*)
- High Cosmic Ray ionization, ~100xISM value (*Ceccarelli et al. 2011*)

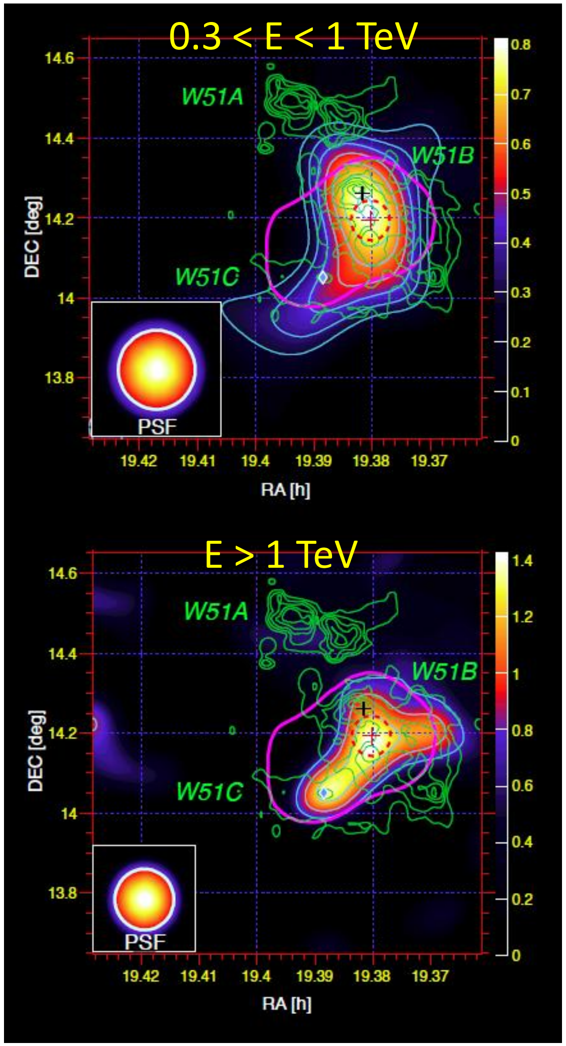
MAGIC stereo data taken in 2010 and 2011 (53h), 11 σ signal

The morphology cartoon of W51

J.Krause thesis

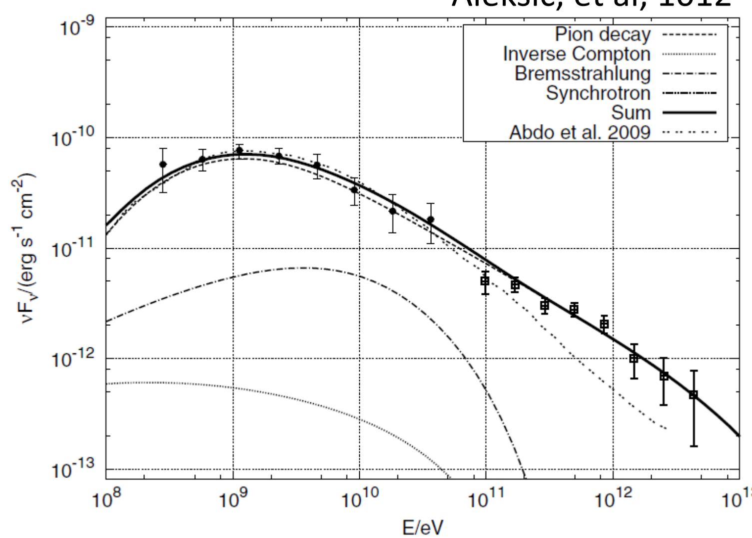


W51 as seen by MAGIC

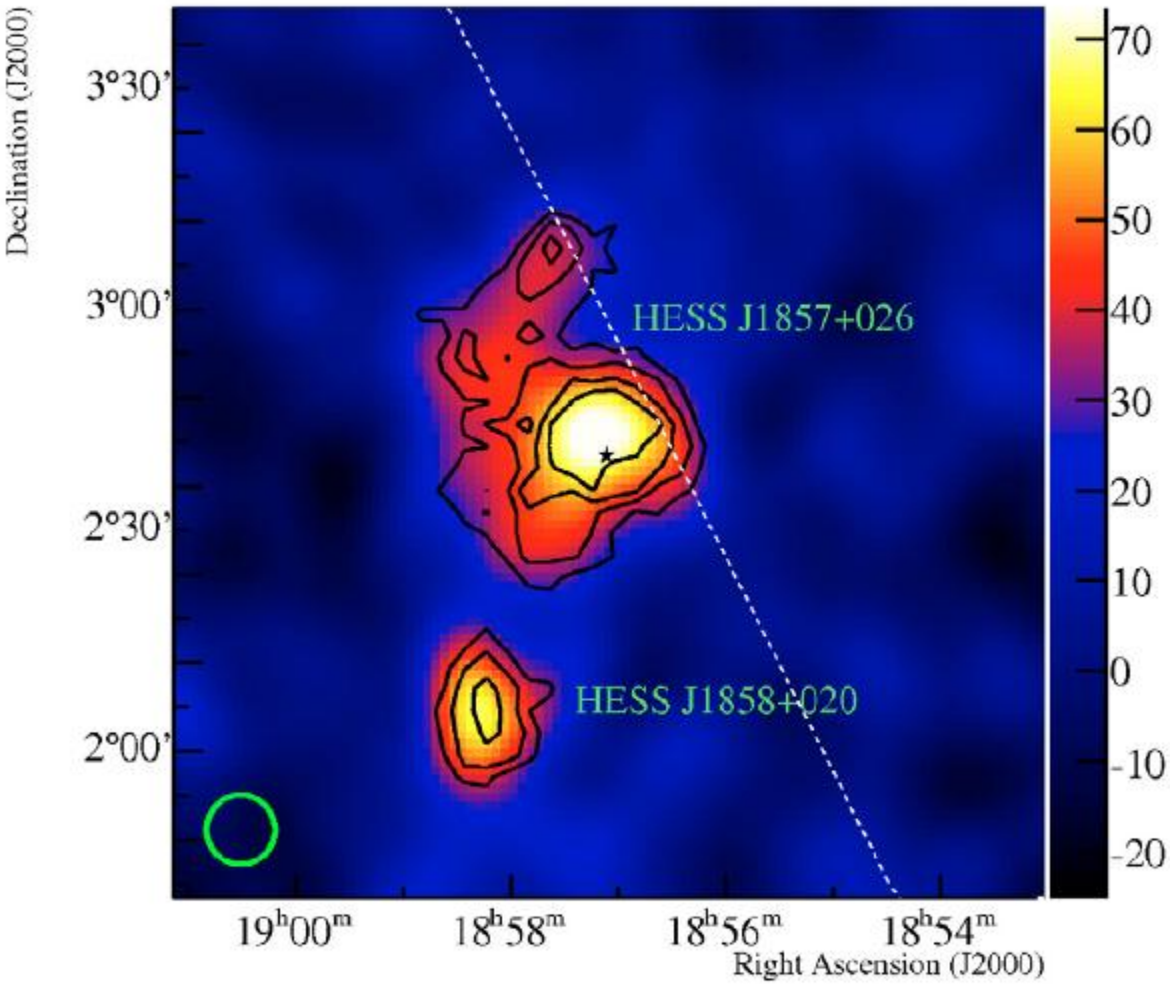


W51: SNR W51C interacts with molecular clouds in W51B The broad-band spectral energy distribution can be explained *only* (1-zone) with a hadronic model. This implies proton acceleration ≥ 50 TeV. This result, together with the morphology of the source, tentatively suggests that we are observing ongoing acceleration of ions in the interaction zone between the supernova remnant and the cloud.

Aleksic, et al, 1012



Unidentified source HESS J1857+026

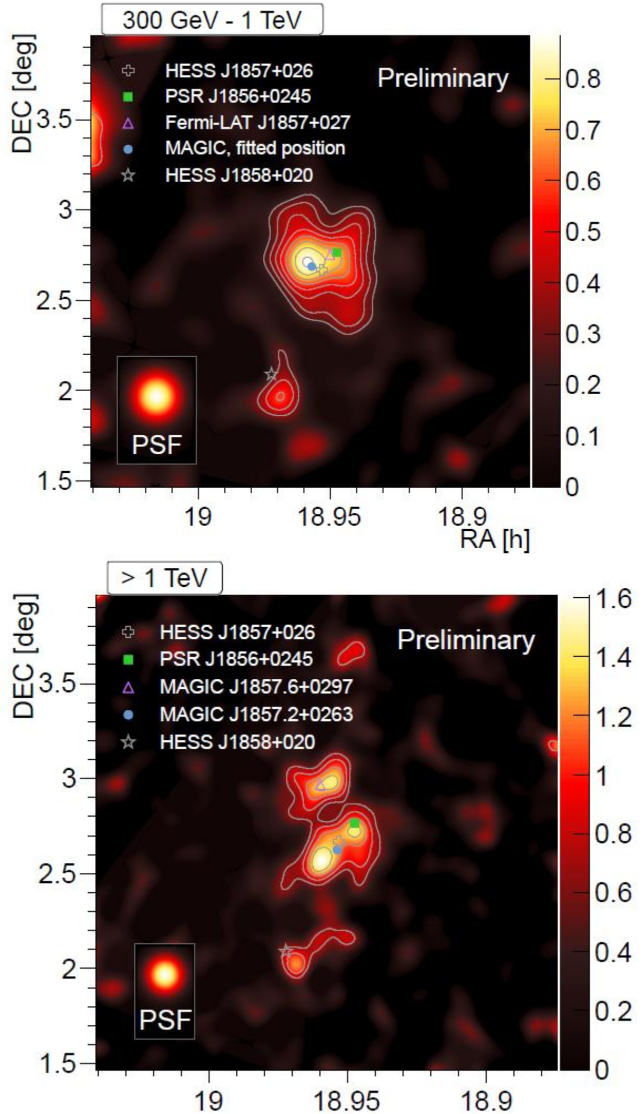


- HESS discovery 2008
- Crab-like spectrum, ~0.15 C.U.
- Extention: 0.11°x0.08°
- Distance: 9 kpc (factor 2-3 uncertain)
- Age: 21 kyr
- PWN candidate: PSR J1856+0245 detected
- Vela-like pulsar nearby
- Spin-down luminosity 4.6 x 10^{36} erg/s

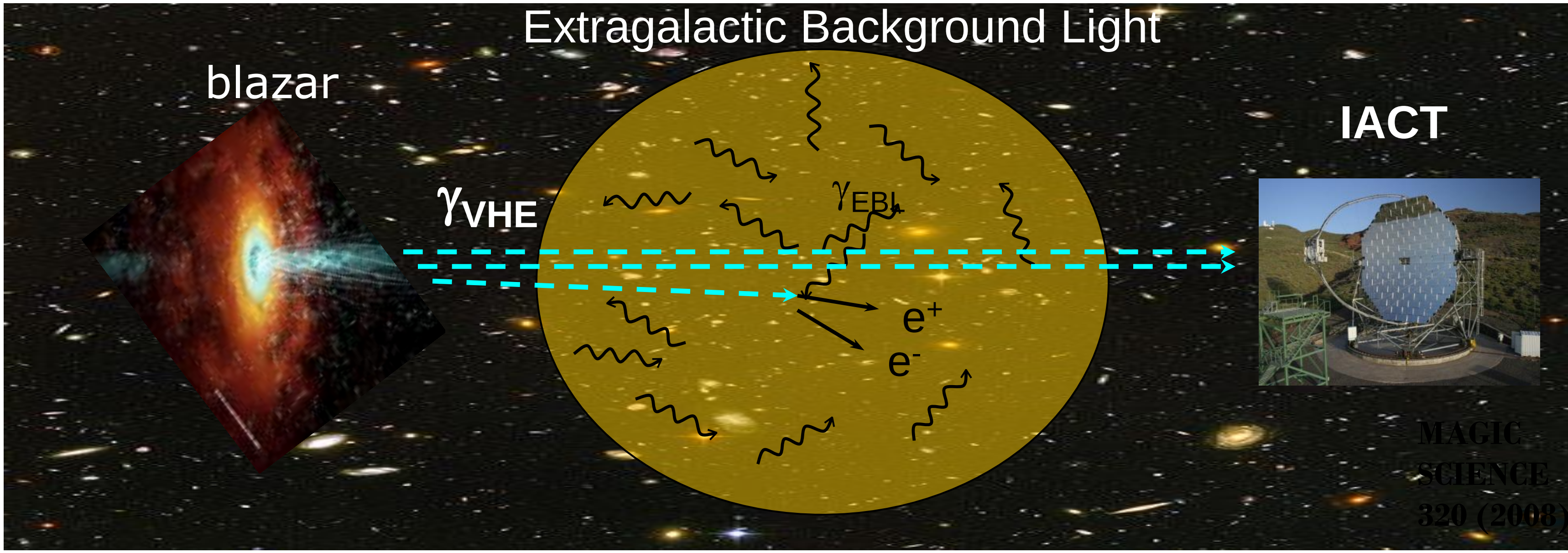
New source: MAGIC J1857.6+0297

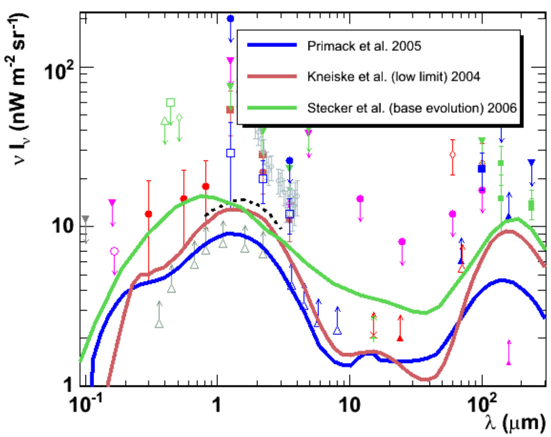
For E ≥ 1TeV

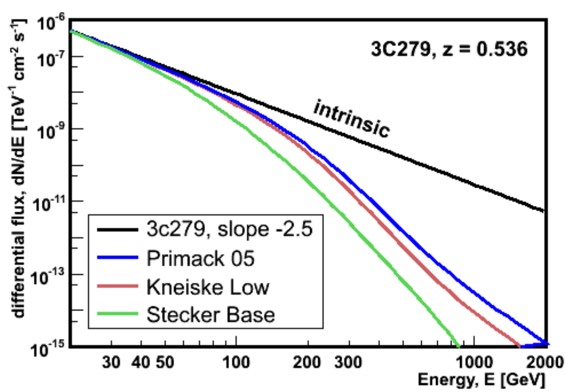
- 2 spatially separated emission regions, strong signal from each
- MAGIC J1857.2+0263 likely the PWN of the pulsar J1856+02245
- MAGIC J1857.6+0297 lies in the vicinity of an HII region, the position of the TeV emission coincides with the possible gas cavity

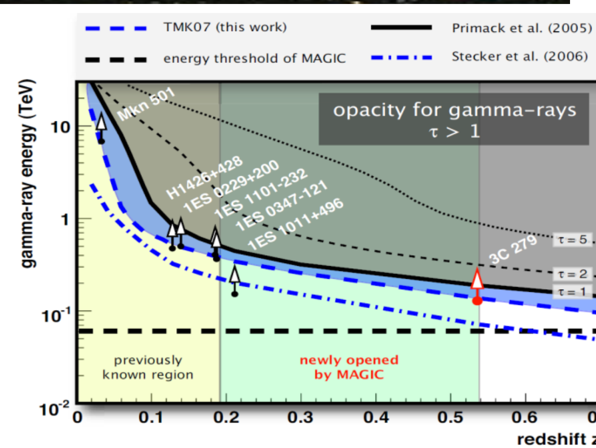


Gamma Ray Absorption by EBL









Oldest VHE γ-rays in Universe from a source at red shift of z = 0.944 detected

Discovery of Very High Energy Gamma-Ray Emission From Gravitationally Lensed Blazar S3 0218+357 With the MAGIC Telescopes

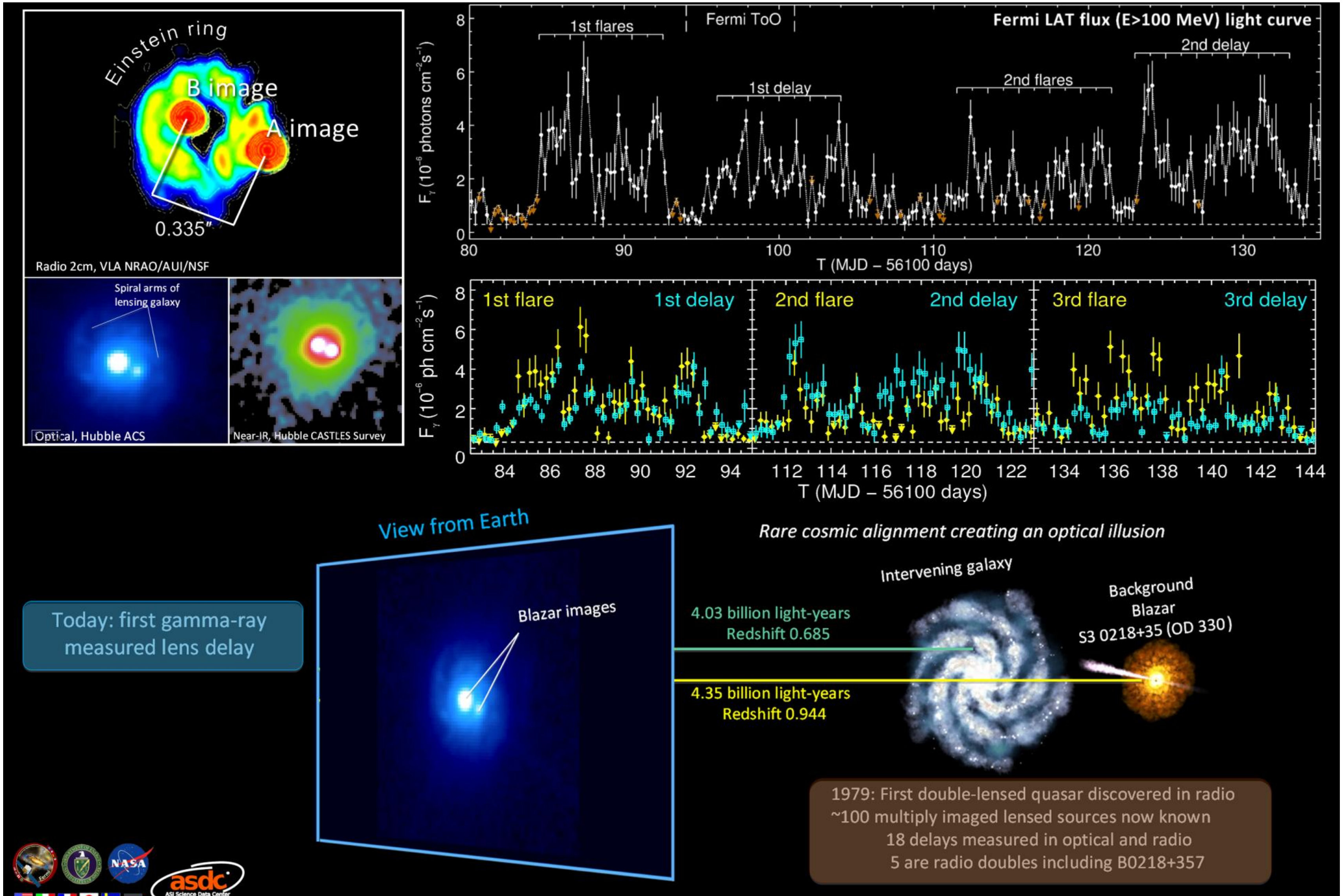
ATel #6349; ***Razmik Mirzoyan (Max-Planck-Institute for Physics) On Behalf of the MAGIC Collaboration***

on ***28 Jul 2014; 14:20 UT***

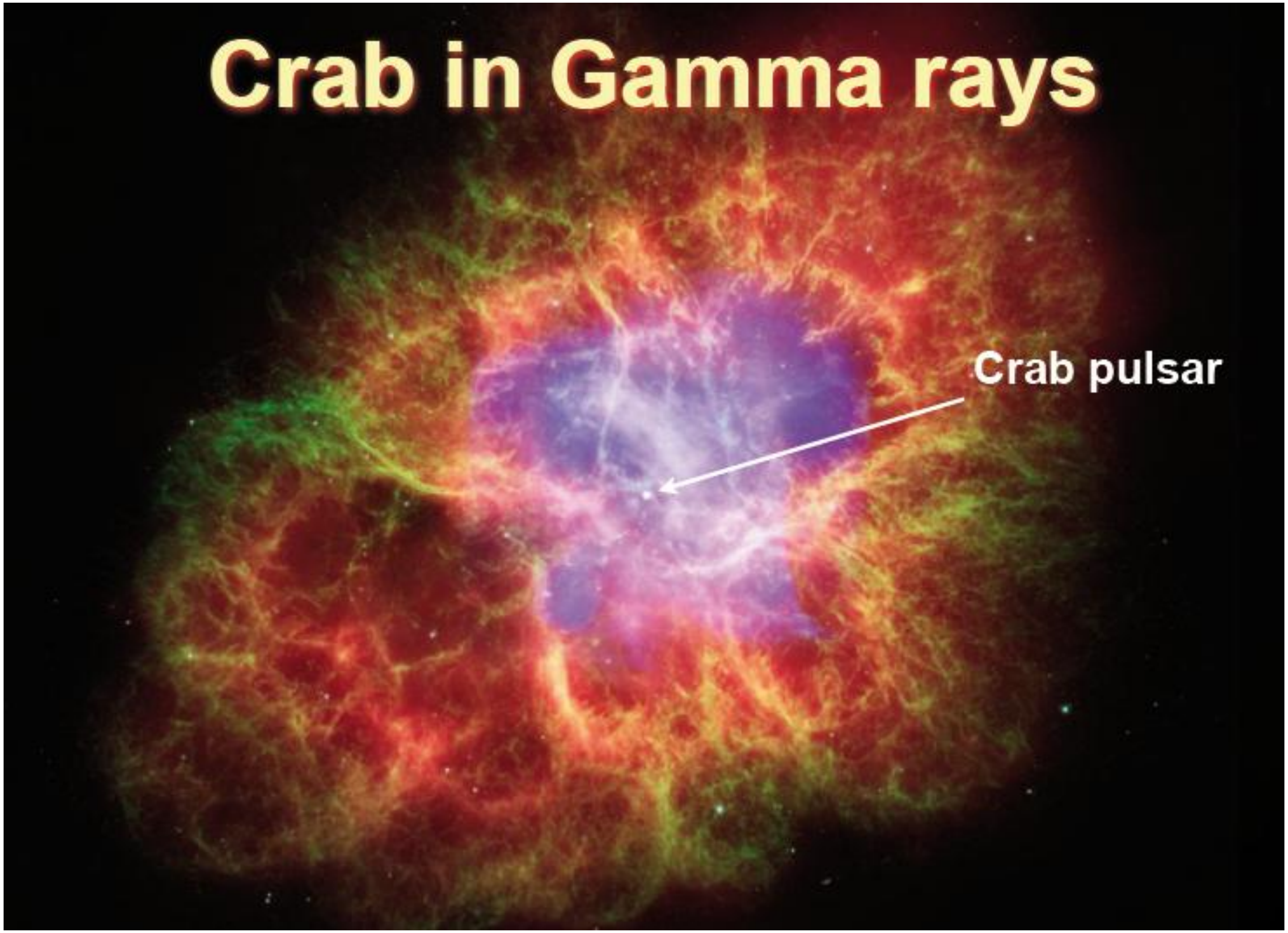
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

- On a few occasions Fermi mission measured flares of the blazar S3 0218+357 *with a time lag of 11.5 days*.
- This was interpreted as due to the gravitational lensing effect
- 2 weeks ago MAGIC detected a flare with > 5 σ at the anticipated time of the arrival of Fermi gravitational lense echo
- The most distant source discovered @ VHE !

Gravitational lense system S3 0218 (also known as B0218+357)

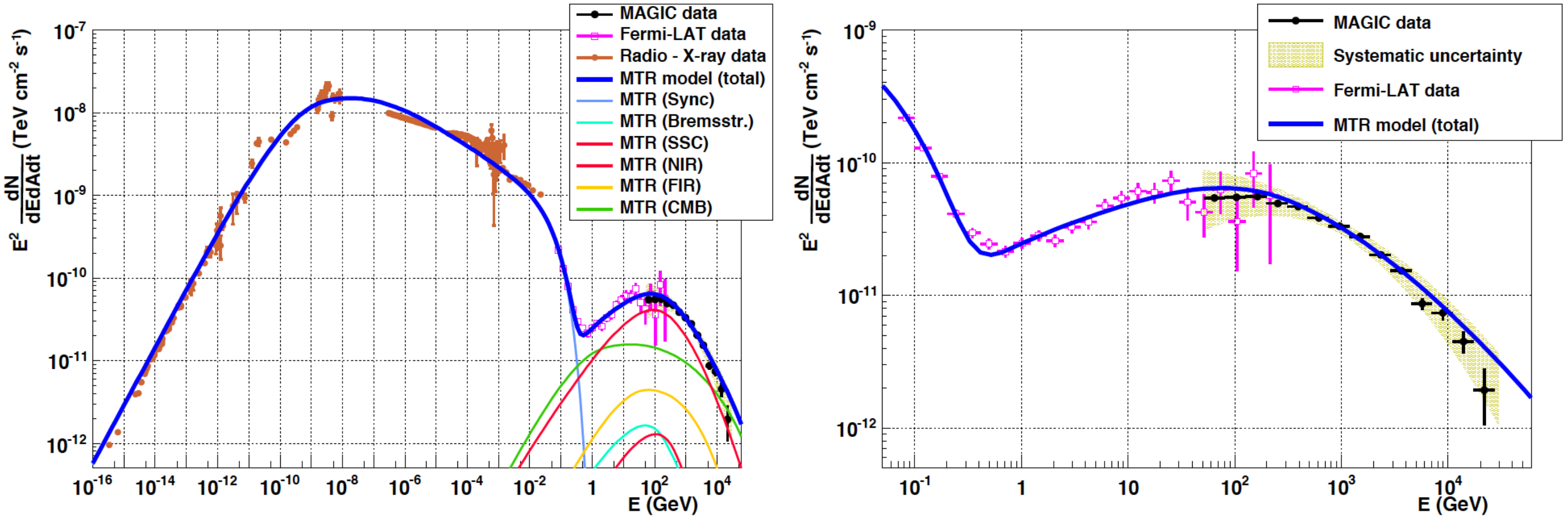


Composite figure of Crab Nebula



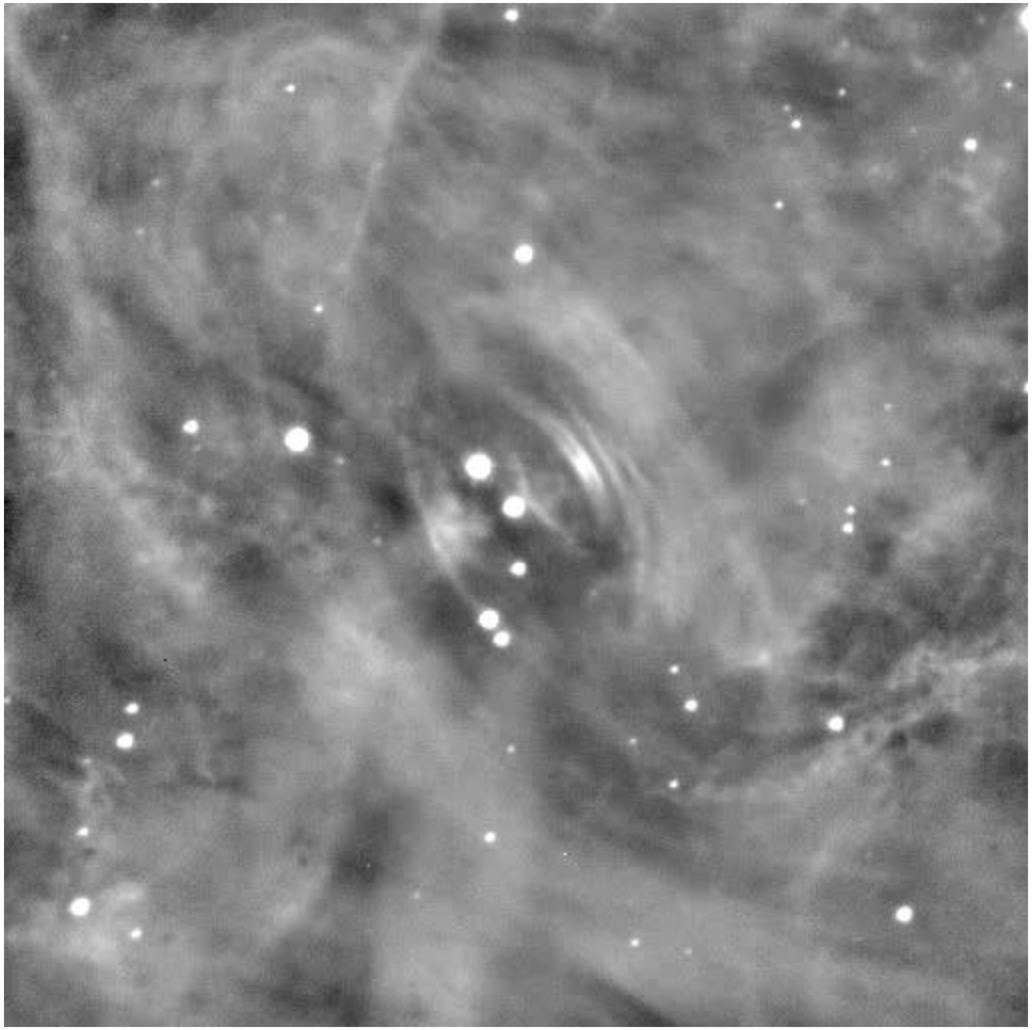
Crab Nebula

Aleksić et al. JHEAP submitted (arXiv:1406.6892)



- 70h MAGIC data 2009-2011: spectrum 50 GeV - 30 TeV
- IC peak position: 52.5±2.6 GeV (Fermi LAT & MAGIC data)
- Precision measurement became available: model predictions can be tuned and tested with this data

Crab pulsar



Aliu et al. (MAGIC collab.)
Science 322 (2008) 1221
First detection of emission above 25GeV for a pulsar

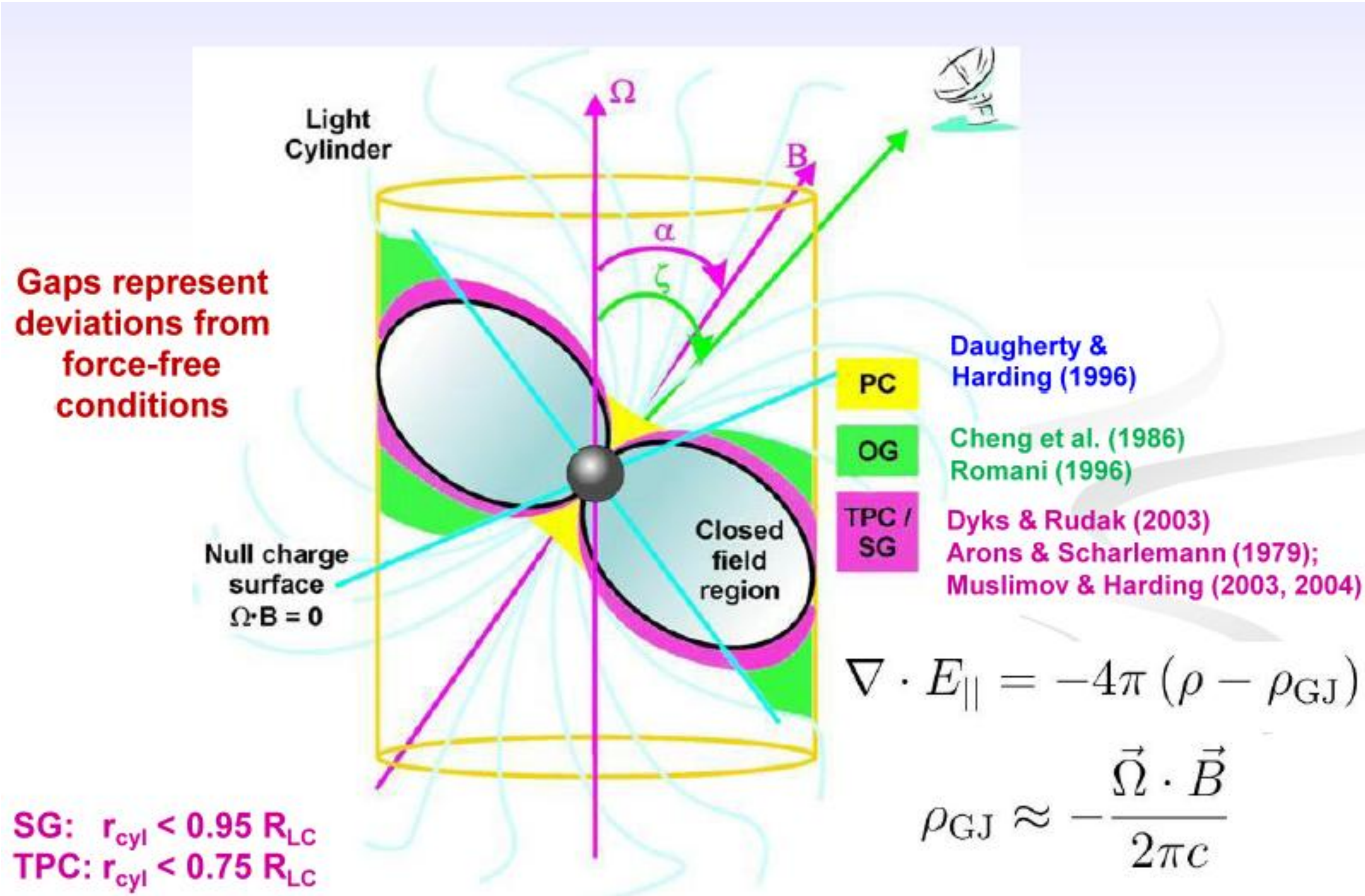
Aliu et al. (VERITAS collab.)
Science 334 (2011) 69-72
First detection of emission above 100GeV

Aleksic et al (MAGIC collab.), ApJ, 742 (2011) 43,
First spectrum 25-100GeV

Aleksic et al (MAGIC collab.), A&A, 540 (2012) A69
First spectrum 50-400GeV

Aleksic et al (MAGIC collab.), A&A, accepted for publication
Discovery of Bridge Emission

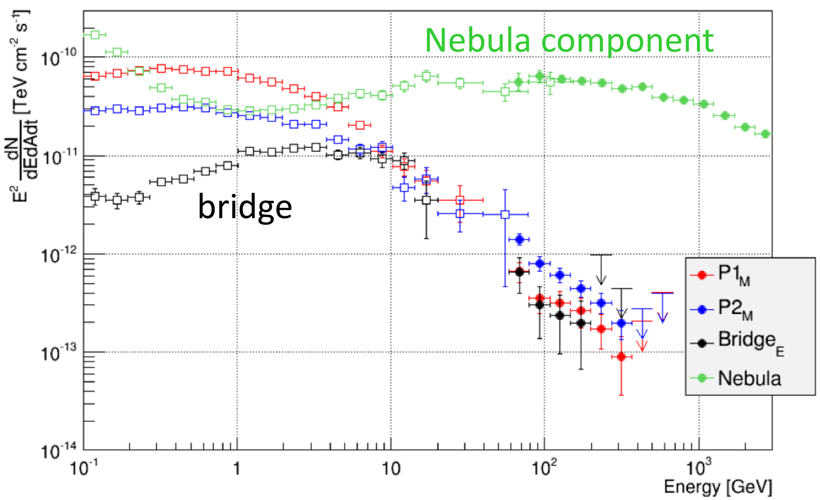
Cartoon of a pulsar

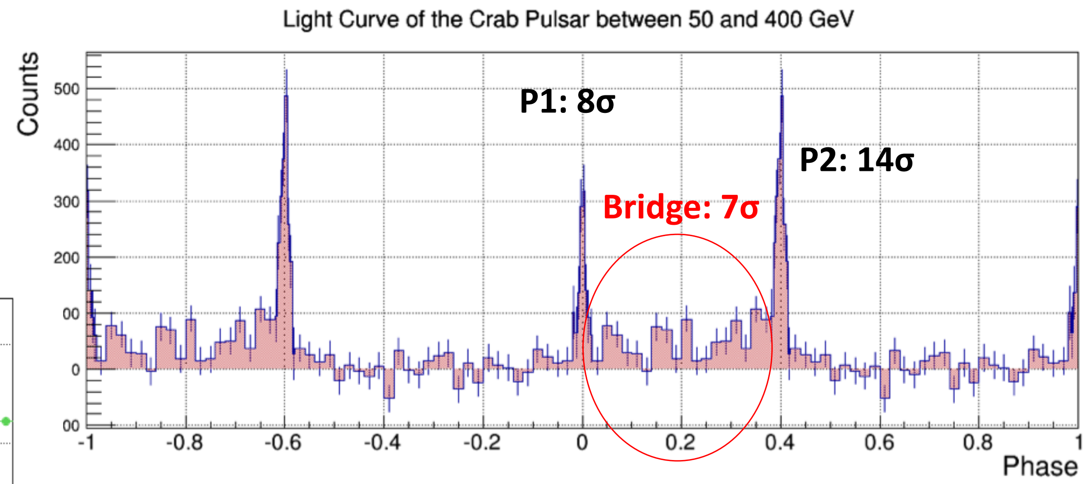


MAGIC bridge emission & very narrow pulses

J. Aleksic, et al., arXiv:1402.4219

Fermi bridge emission becomes strong above few GeV

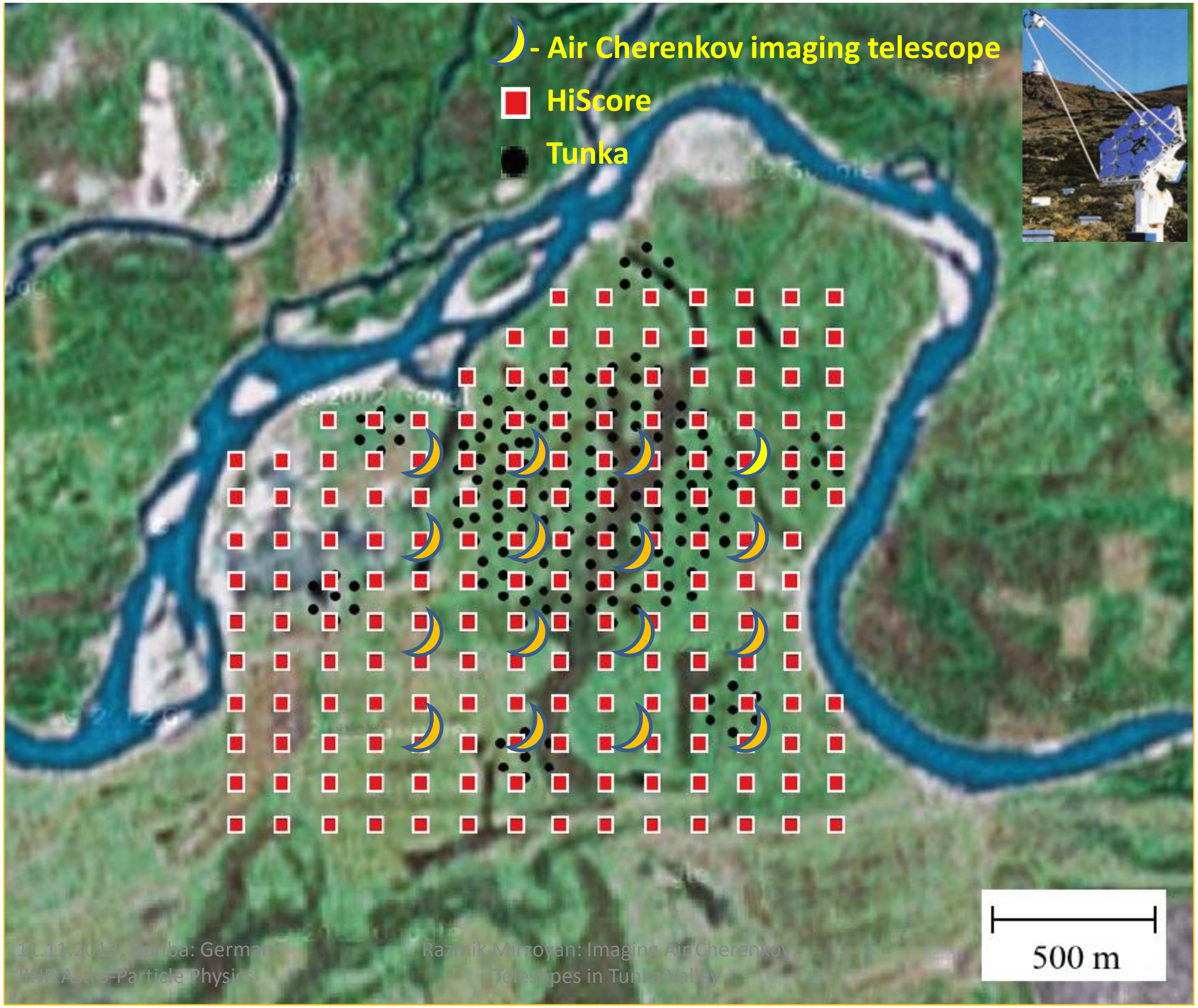




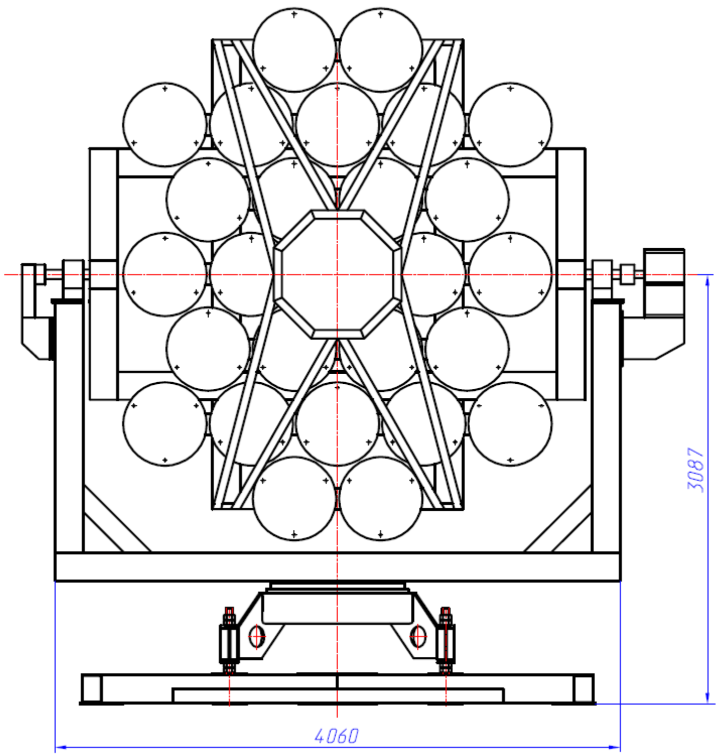
- bridge hints on toroidal bending of magnetic lines near LC
- This result set a quest for precision Crab pulsar theories

The last word is not yet said: soon new results, new insights…

TAIGA: hunting for Pevatrons and Cosmic Rays



TAIGA IACTs



- Mechanical outline of the 1st TAIGA IACT
- **Currently under construction in Dubna**

Parameters of the imaging telescope:

Optical system
- Davies-Cotton design
- 34 mirror segments
- segment Ø 600 mm, of round shape
- distance between centers of mirror 620 mm
- focal length of 4752 mm

Imaging camera:
- Winston cone on each PMT-based pixel
- hexagonal input window for pixel
- center-to-center pixel size ~ 30 mm
- 397 pixels (11 hexagonal “rings” around the central pixel)
- 8.3° full field of view
- Threshold of single telescope: ~ 2 TeV

Next ~ 3 - 5 years

- Planning smooth operation for at least next ~ 3 - 5 years
- Successful source hunting and deep observation of diverse source types entered in its best phase with current telescopes
- It will take a few more years until CTA telescopes will be built and start producing scientific data
- TAIGA is a novel hybrid detector concept for operating HiSCORE together with IACTs. We can start proving this novel concept in one year from now
- TAIGA has a promise of becoming the most cost-efficient and powerful detector for exploring the multi-TeV sky in γ and cosmic rays