Астрофизические исследования в эксперименте TAIGA (продление проекта)

Ткачев Л.Г.

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14. Altai State University, Barnaul, Russia

ГАММА-ЛУЧИ ВЫСОКИХ ЭНЕРГИЙ

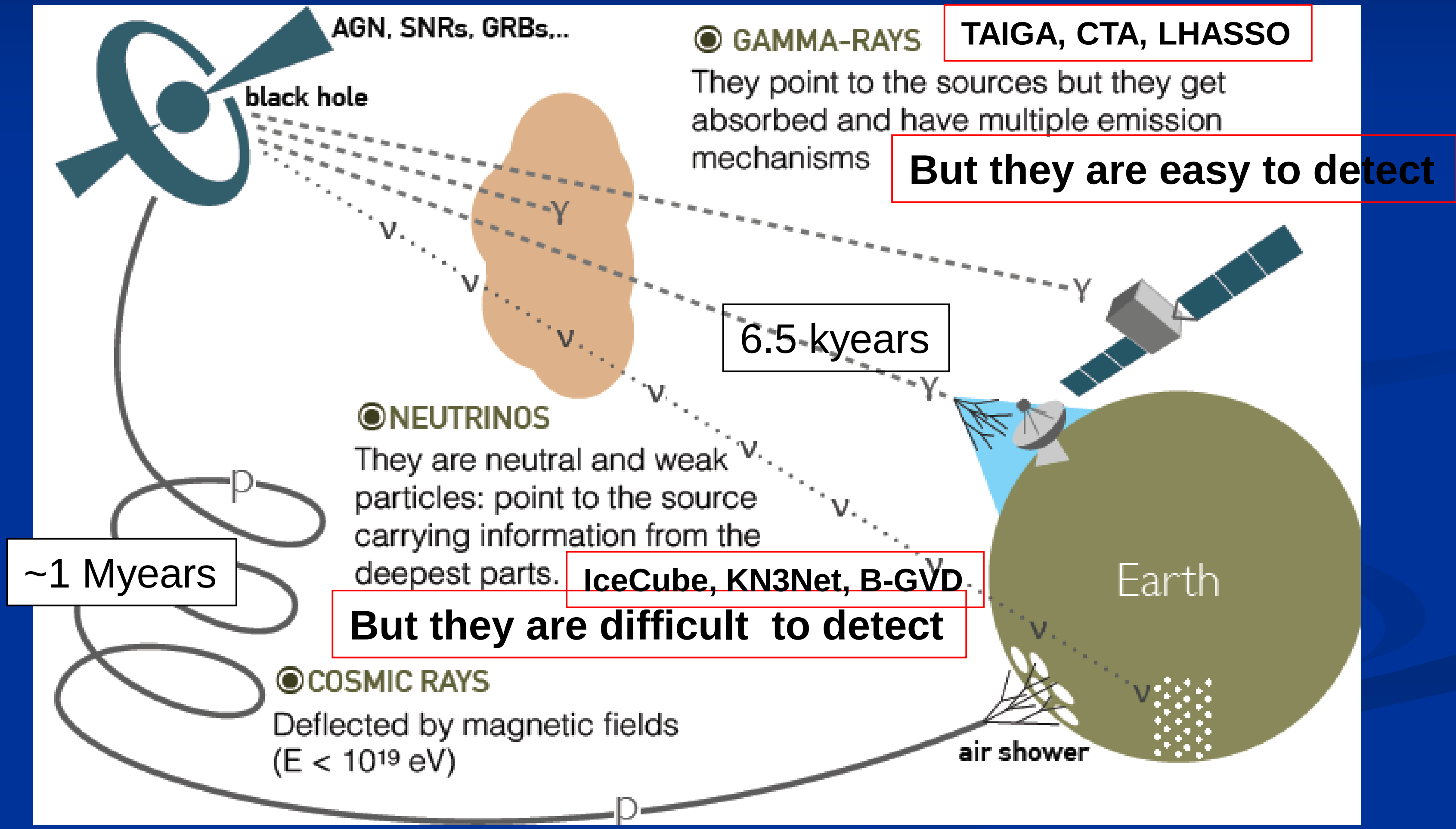
- Источники
- Методы исследования
- Существующие детекторы
- Результаты исследования
- Проектируемые детекторы
- Multimessenger astronomy

ПРОДЛЕНИЕ ПРОЕКТА TAIGA

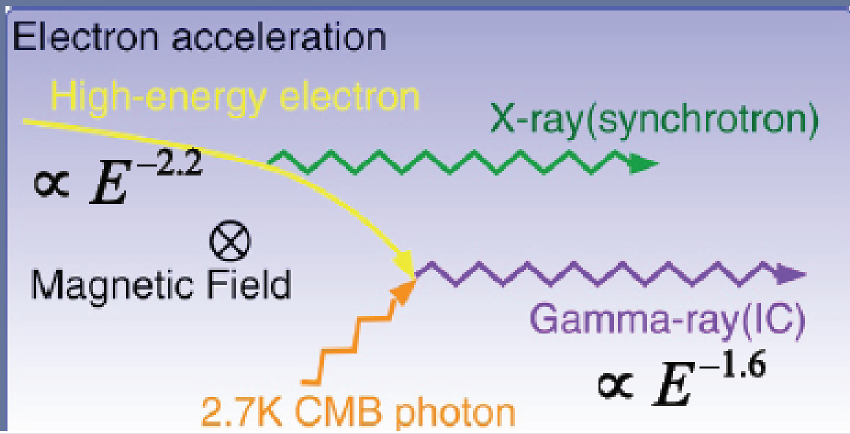
- Детектор TAIGA
- Исследования КЛ и гамма-лучей на детекторе TAIGA
- Продление проекта TAIGA в ОИЯИ

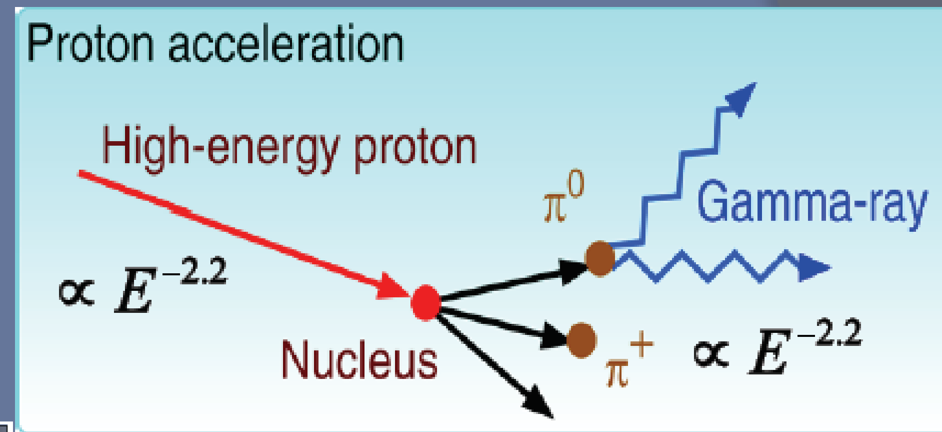
Why gamma-ray astronomy?

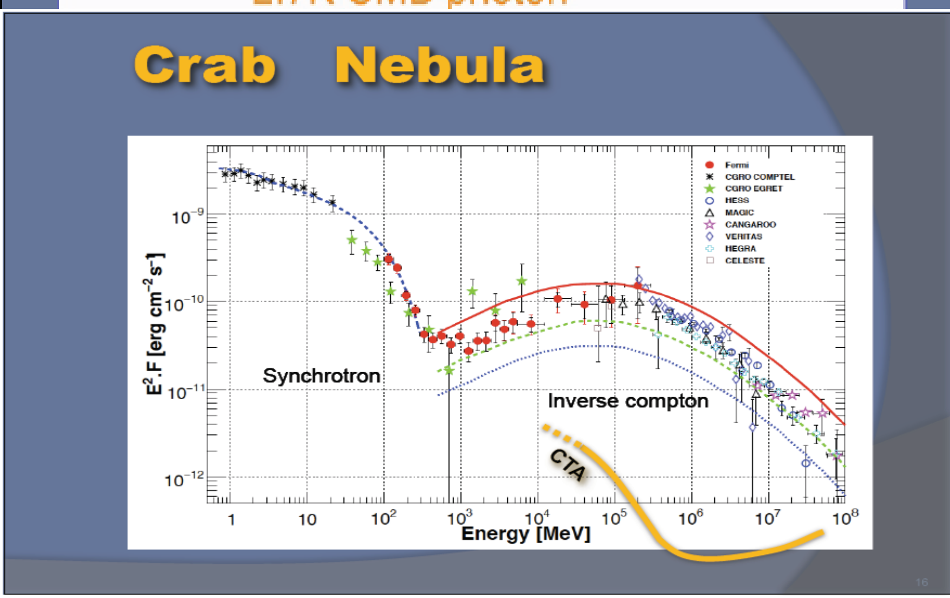
To understand how **Cosmic Accelerators work** we need to detect cosmic rays, gamma – rays and neutrinos

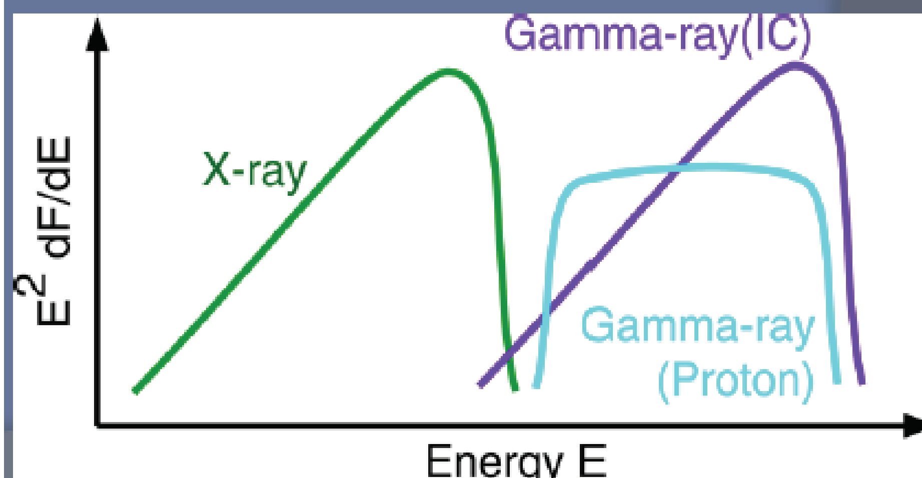


ИСТОЧНИКИ ГАММА-ЛУЧЕЙ ВЫСОКИХ ЭНЕРГИЙ

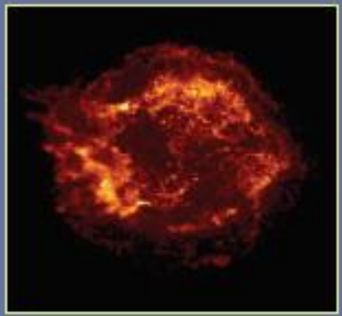




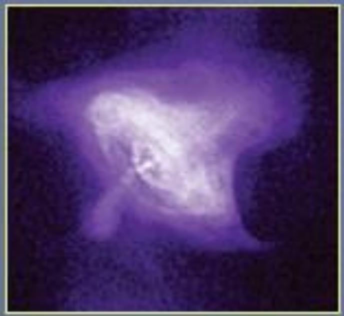




Physics objectives

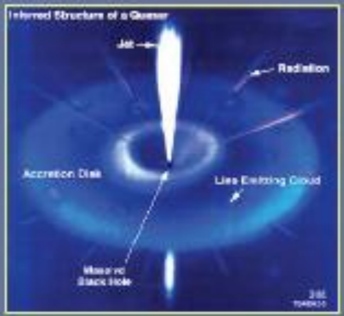


SNRs



Pulsars and PWNe

Micro quasars X-ray binaries

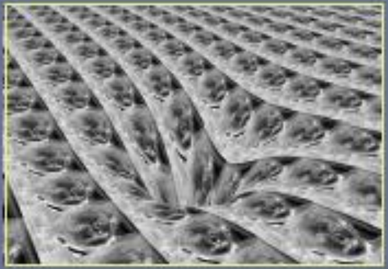


AGNs

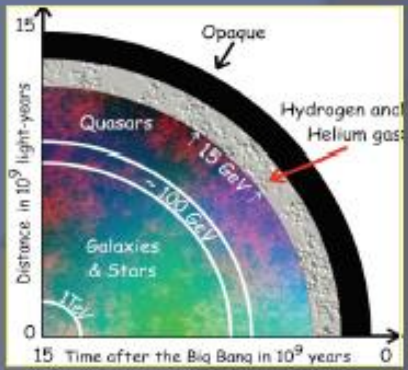
GRBs

Origin of cosmic rays

Dark matter



Space-time & relativity



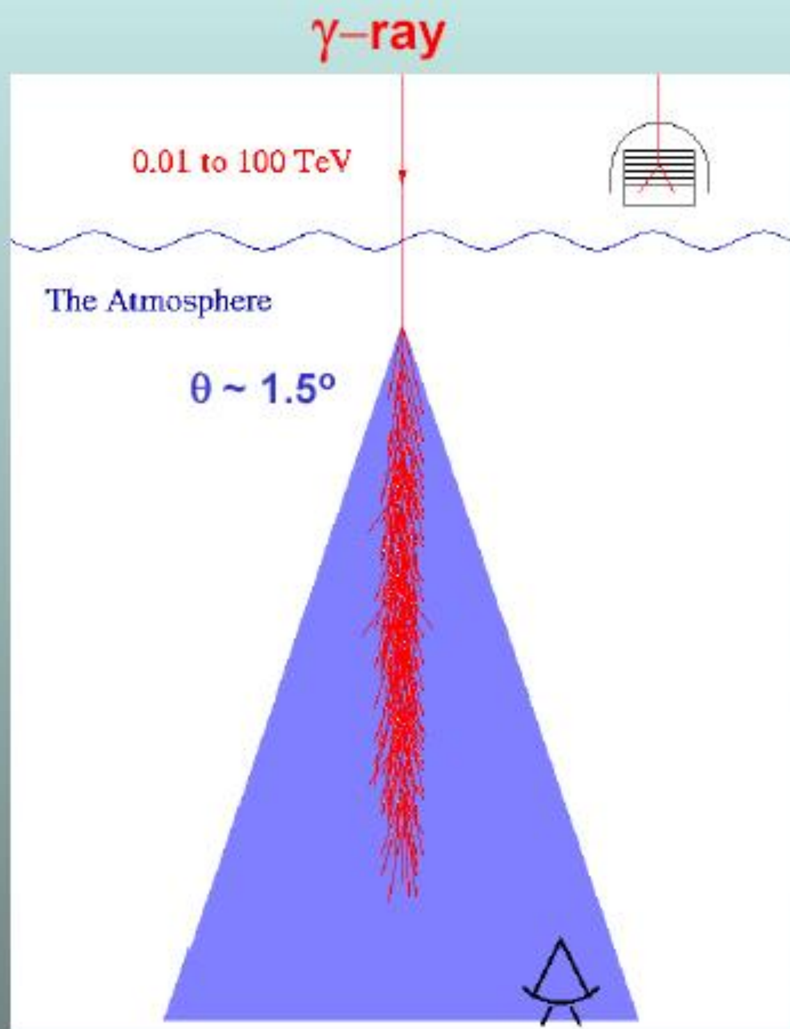
Cosmology

МЕТОДЫ ИССЛЕДОВАНИЯ ГАММА-ЛУЧЕЙ ВЫСОКИХ ЭНЕРГИЙ

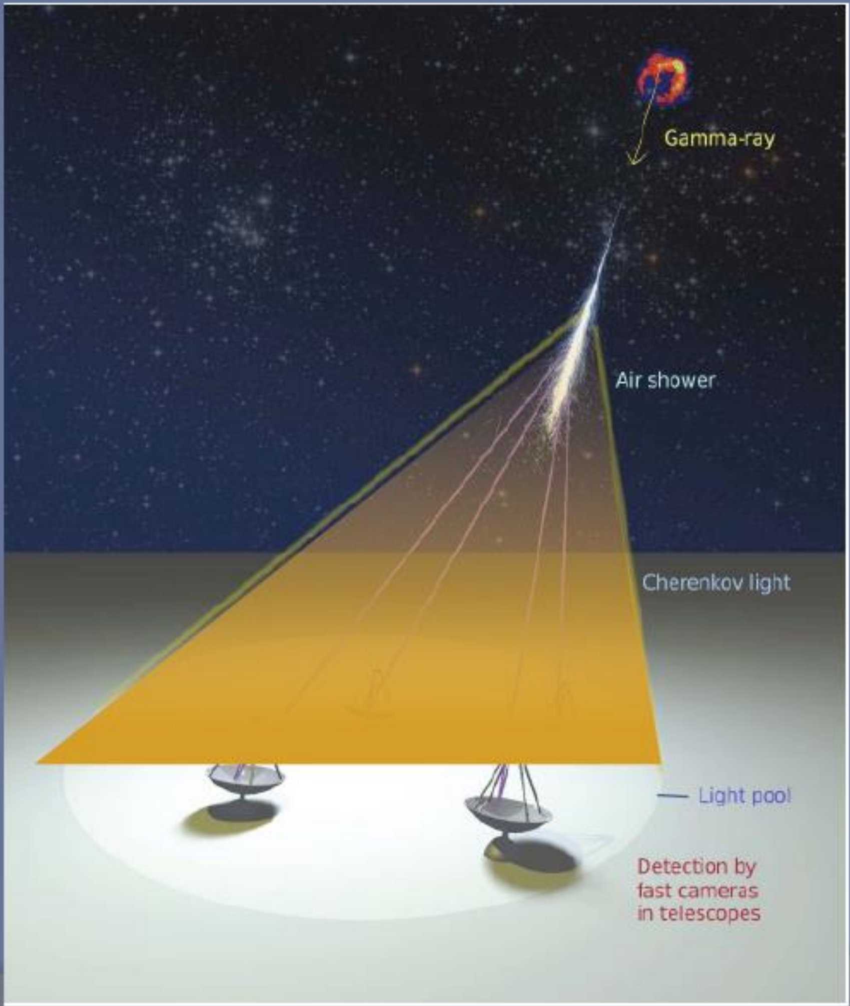
ENERGY SPECTRUM OF GAMMA: ~ E^{-2}

FOR MULTI-TEV GAMMA – RAY ASTRONOMY WE NEED ARRAY WITH AREA MORE THAN 1 KM^2

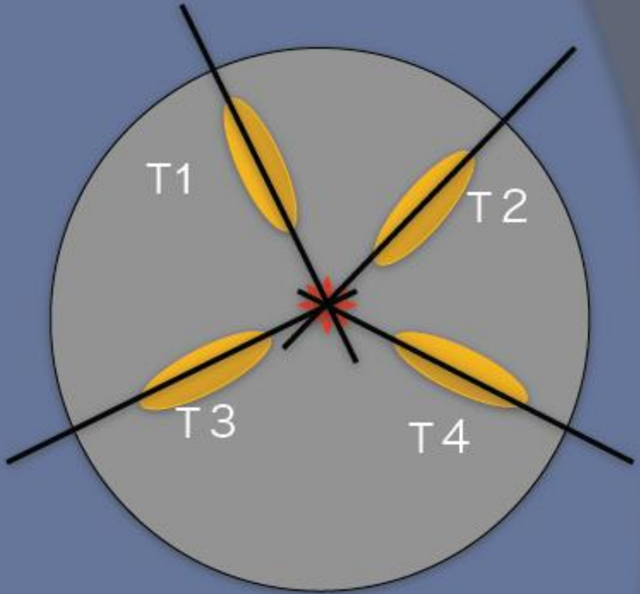
Cherenkov Telescopes



Imaging Air Cherenkov



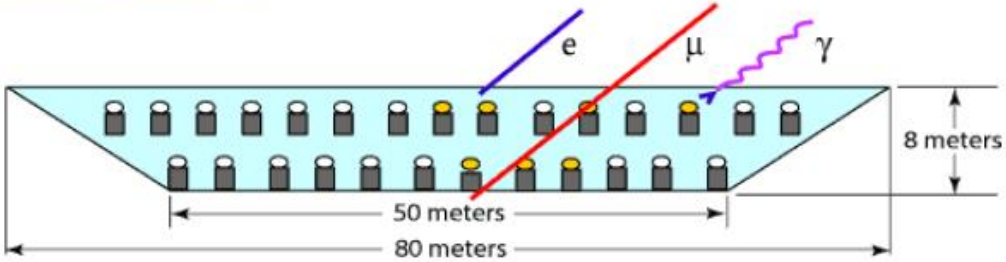
Cherenkov Light
50photons/m^2 (5 pe/m^2) at 1TeV
➔ MAGIC 2 x240 m^2, HESS 4 x106 m^2

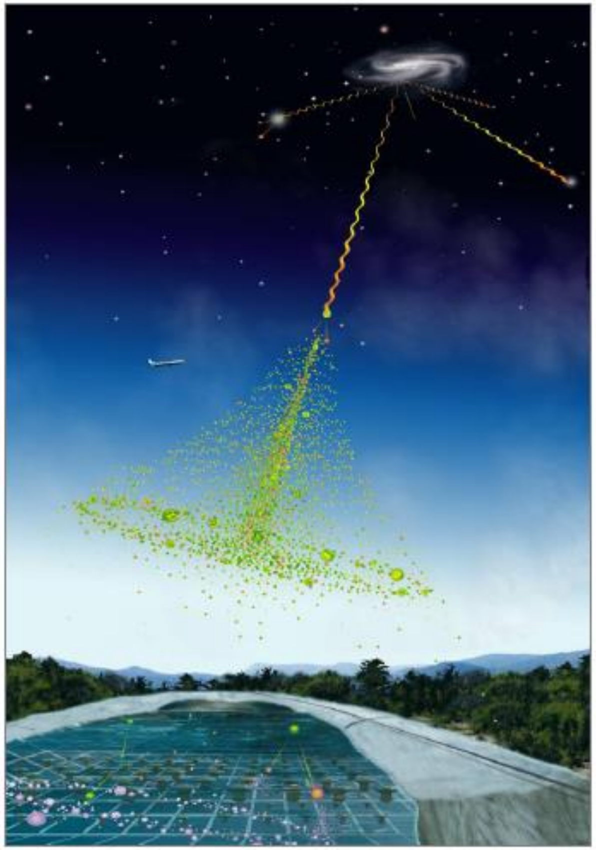


Typical parameters

Energy range 50GeV ~ 10TeV
CR rejection power >99%
Angular resolution ~0.1 degrees
Energy resolution ~20%
Detection area ~10^{5}m^2
Sensitivity ~1% Crab Flux (10^{-13} erg/cm^{2}s)

Detection Principle

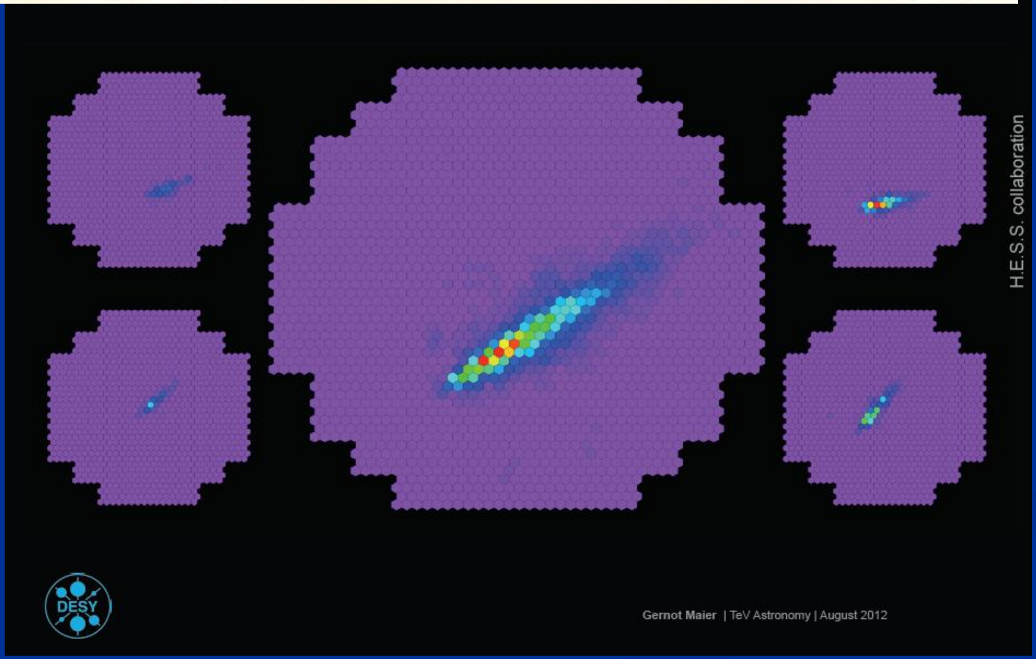




- Pond is instrumented with two layers of photomultipliers (PMTs):
  - Air shower layer: 450 PMTs at 1.4m depth
    ⇒ accurate measurements of air shower particle arrival times, used for arrival direction reconstruction and triggering.
  - Muon layer: 273 PMTs at 6m depth
    ⇒ detection of penetrating muons and hadrons, used for rejection of cosmic ray background.

- Outrigger array (added in 2003) ⇒ improvement of angular resolution, providing longer lever arm for event reconstruction.

СУЩЕСТВУЮЩИЕ ДЕТЕКТОРЫ



Four telescopes,
107 m^2 mirror area each

960 PMT cameras, field of view 5^o

Observation in moonless nights, ~1000 h / year

Each night several objects are tracked and ~300 images recorded per second

Energy threshold:
~ 100 GeV

Sensitivity:
1% Crab in 25 h

HAWC - 2016

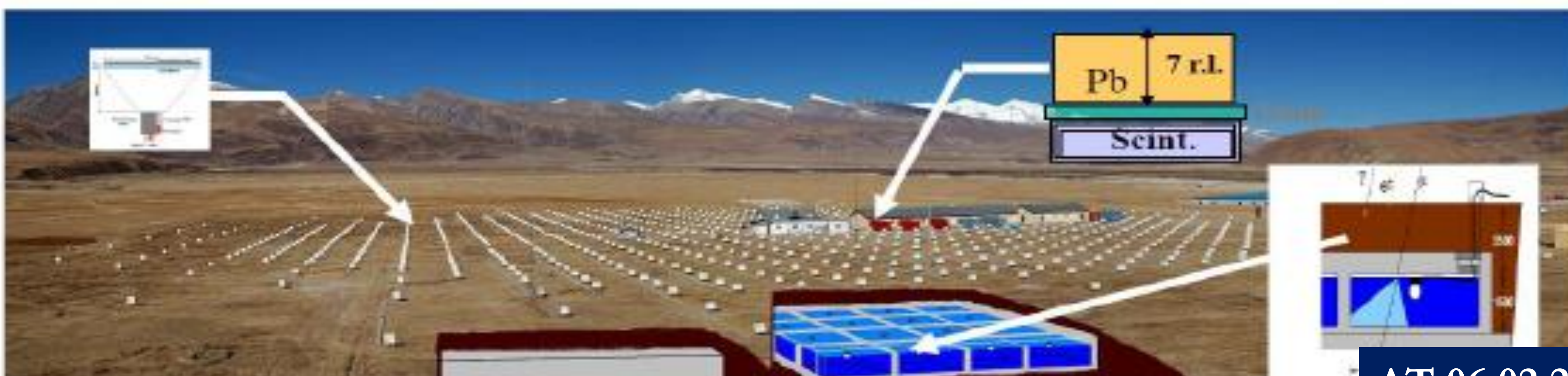
Гамма+CR-телескоп HAWC в Мексике, 160x160 м^2, 4100m a.s.l.

MAGIC – Канарские острова

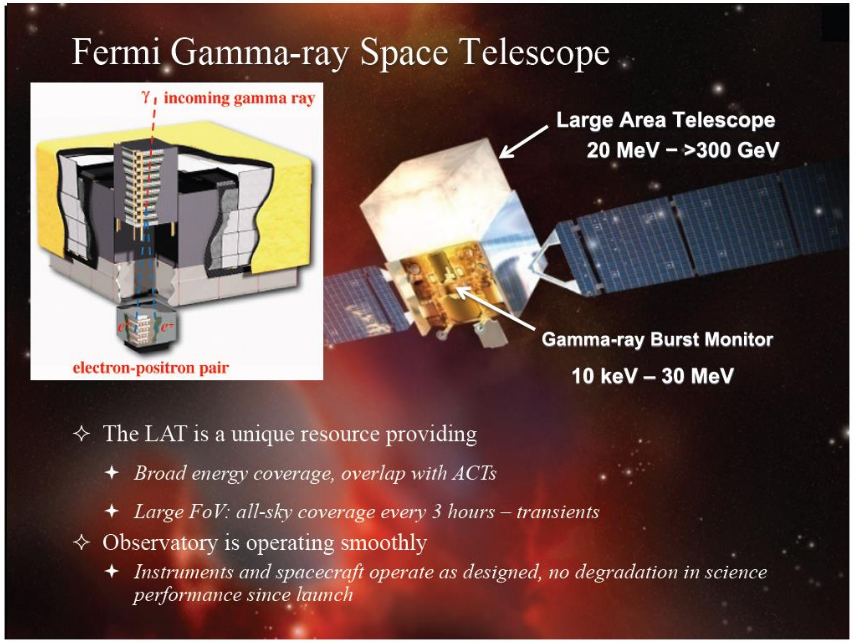
La Palma ~28° N, ~18° W, 2200 m a.s.l.

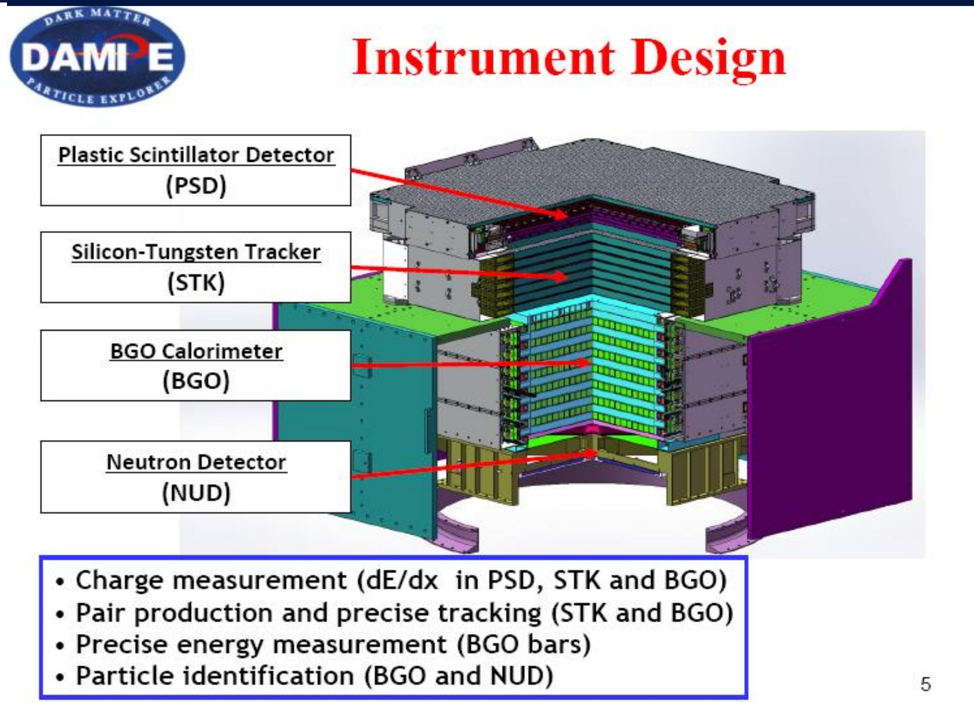
Tibet hybrid experiment (YAC+Tibet-III+MD)

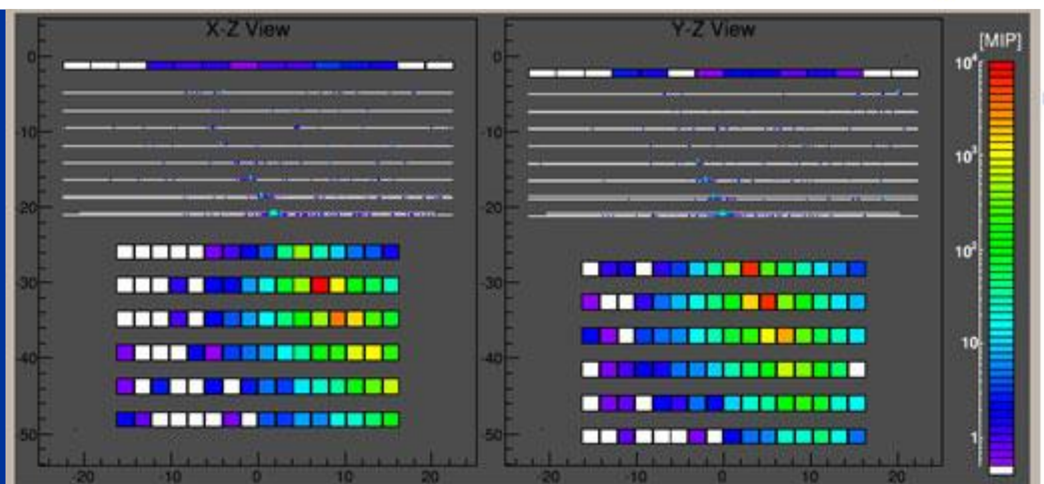
This hybrid experiment consists of low threshold Air shower core array (YAC) and Air Shower (AS) array and Muon Detector (MD) .

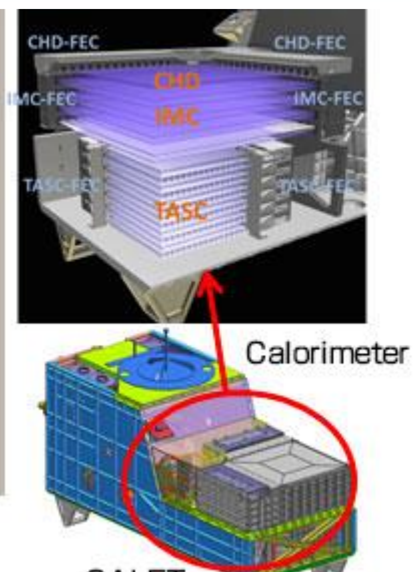


КОСМИЧЕСКИЕ ДЕТЕКТОРЫ ГАММА-ЛУЧЕЙ ВЫСОКИХ ЭНЕРГИЙ



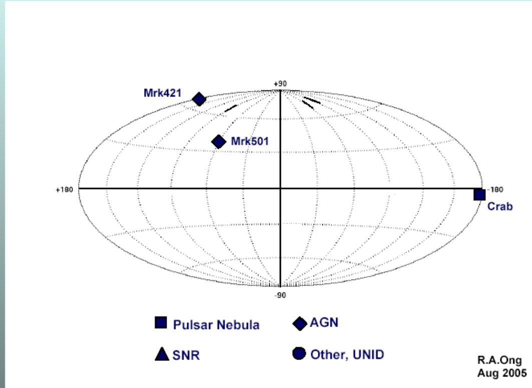




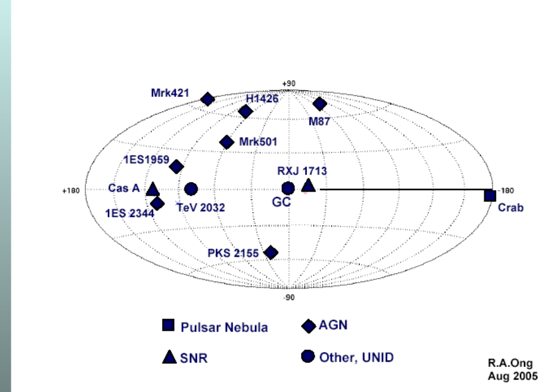


РЕЗУЛЬТАТЫ ИССЛЕДОВАНИЯ ГАММА-ЛУЧЕЙ ВЫСОКИХ ЭНЕРГИЙ

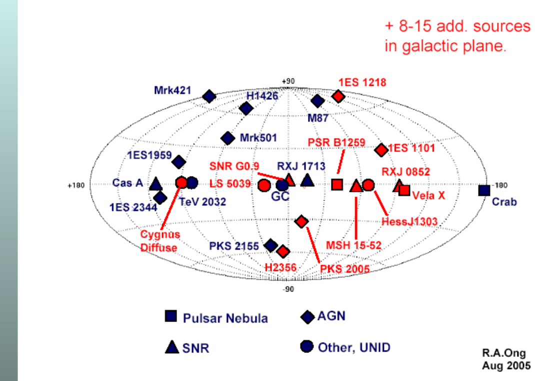
The VHE Sky - 1995



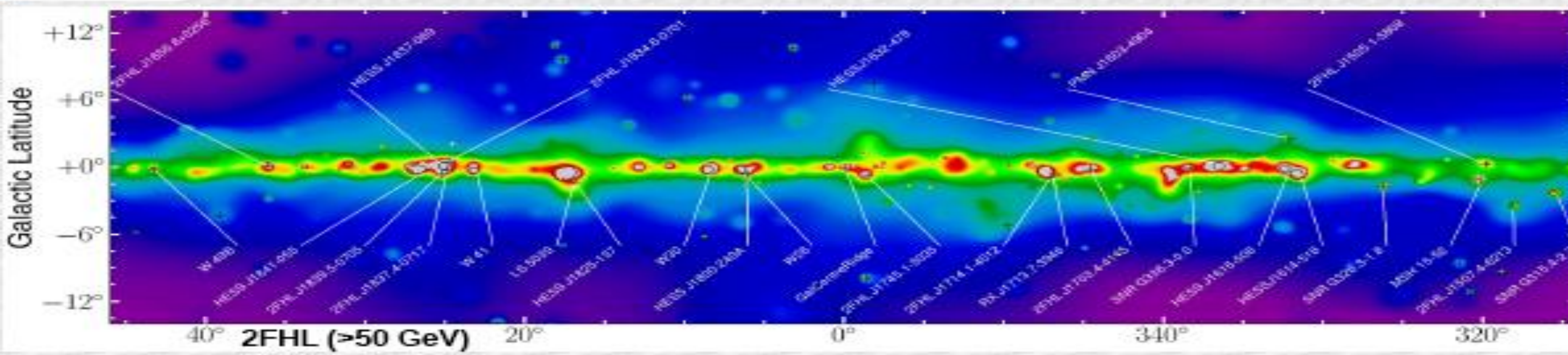
The VHE Sky - 2003

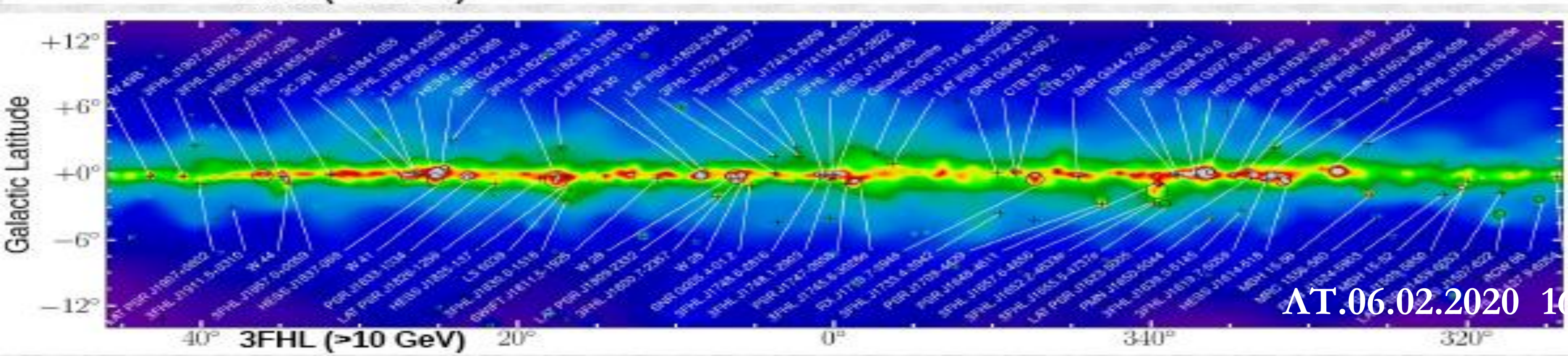


The VHE Sky - 2005

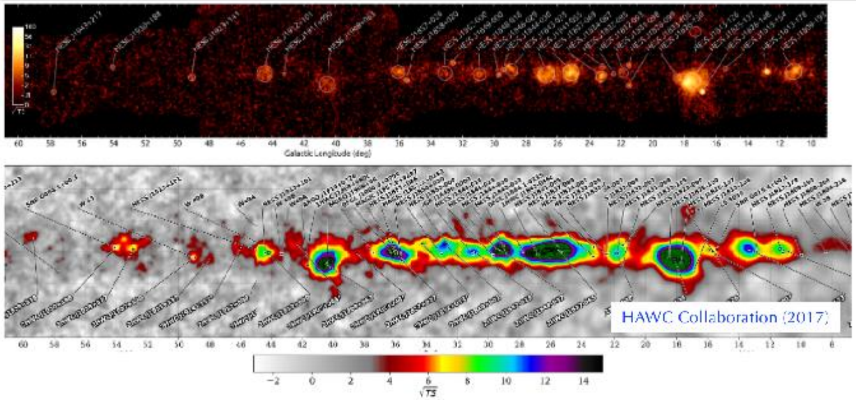


Galactic Plane Maps





HAWC Galactic Plane Survey Follow-ups

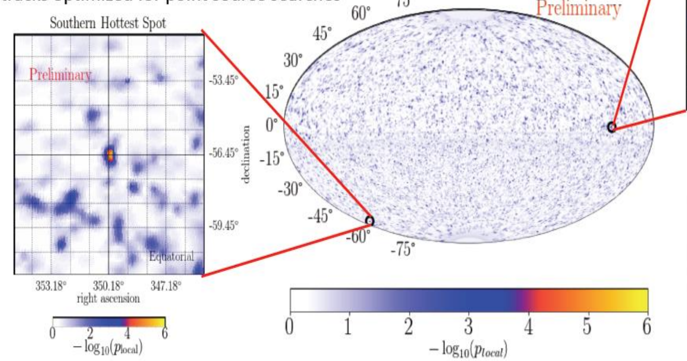


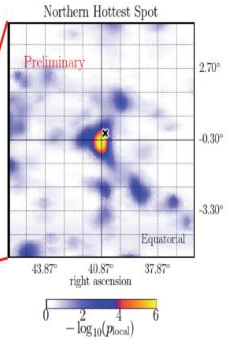
- HAWC: 507 days of observation, found 39 γ-ray sources
- HAWC detected 24 sources and only 15 have a counterpart in the H.E.S.S. catalogue
- 9 HAWC sources undetected by IACTs
  - lack of sensitivity to very extended sources?
  - energy-threshold effects?
  - different background estimation methods?

H.E.S.S. Collaboration, A&A, Special Issue (2018)
+ Jardin-Blicq et al. ICRC2019

All sky combined 10 year search

Using high energy through-going tracks and tracks optimized for point source searches





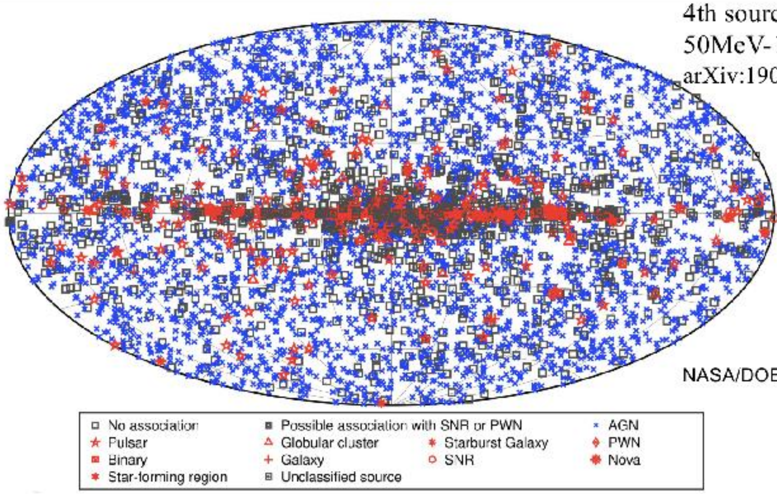
NASA, ESA & A. van der Hoeven

T. Carver NU5c

New source list of 110 Galactic and Extragalactic objects
Hottest spot in Northern Hemisphere coincides with 2.9σ excess at the position of NGC 1068

Fermi-LAT γ-ray sky

4th source catalog
50MeV-1TeV (8 yrs)
arXiv:1902.10045_v3

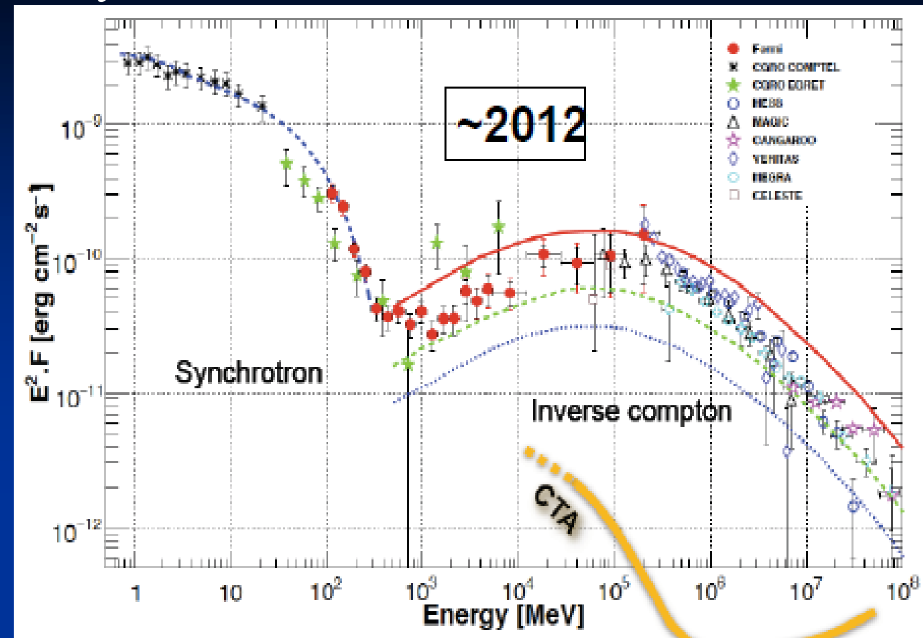


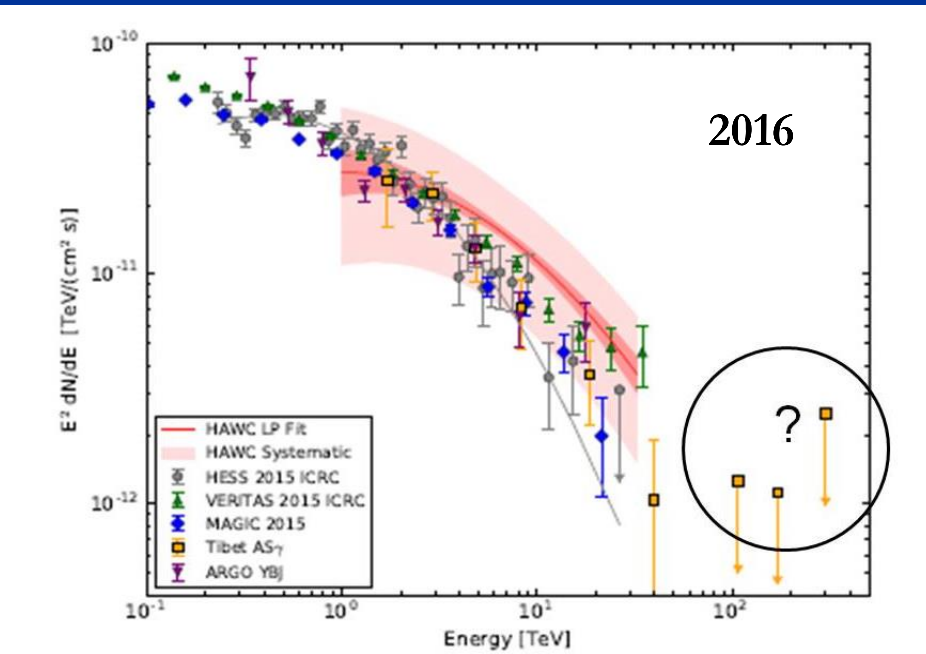
NASA/DOE/Fermi-LAT

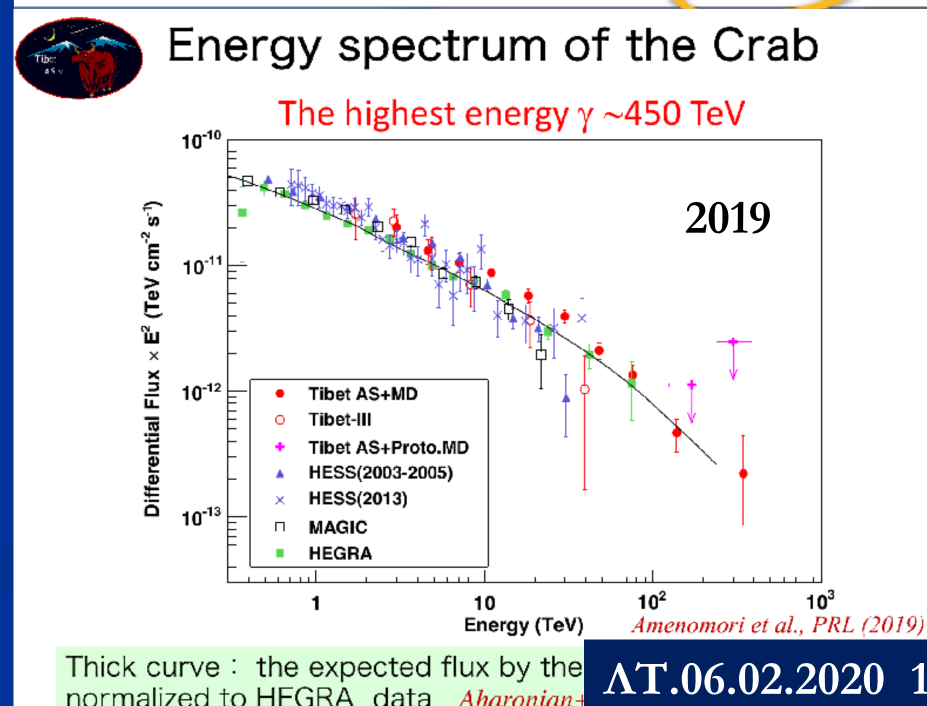
- > 5000 sources > 100 MeV
- > 1550 sources above 10 GeV (3FHL) Fermi-LAT Collab., ApJS, 232 (2017)

Крабовидная туманность

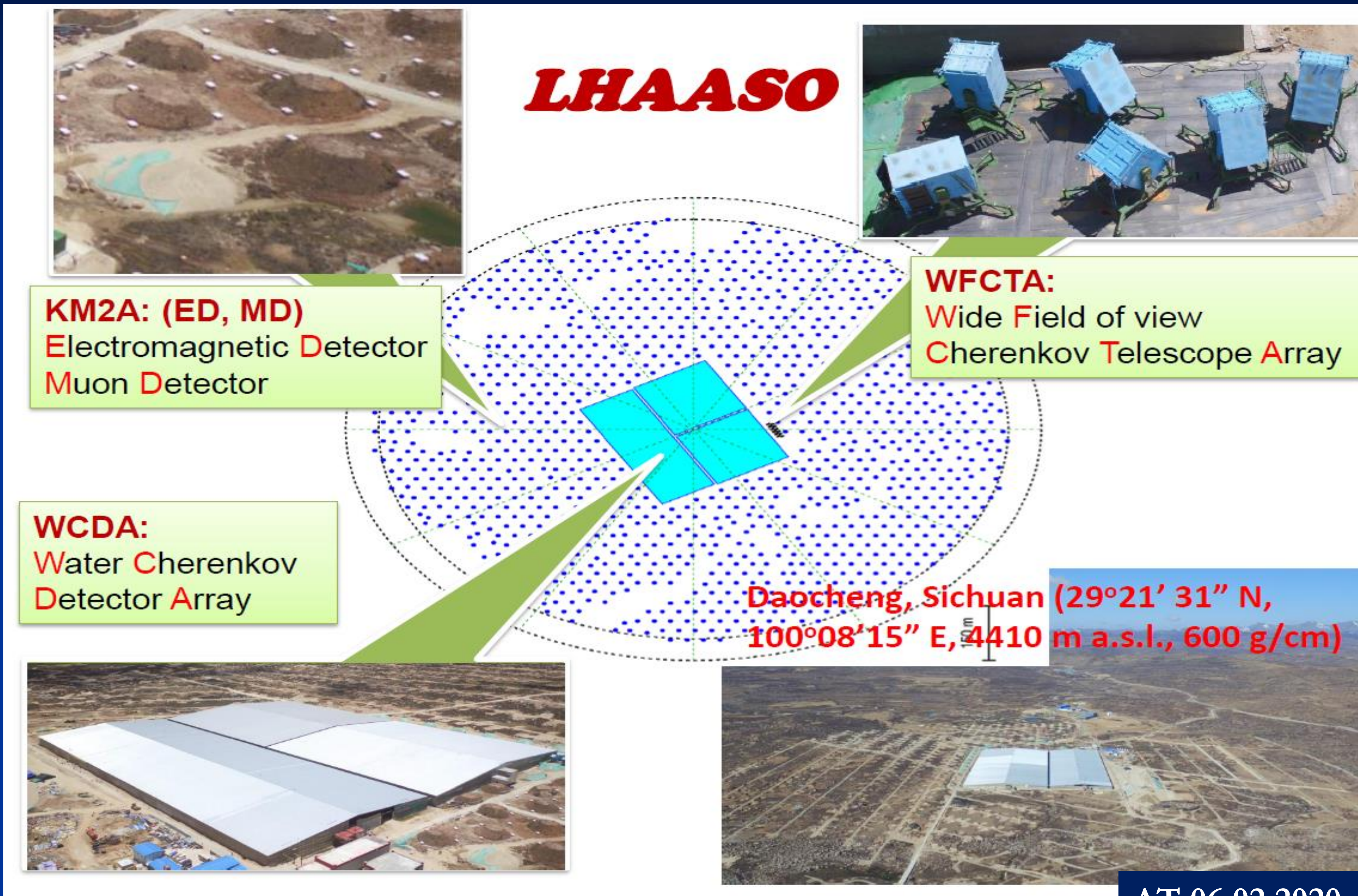
- В центре туманности находится пульсар PSR B0531+21, являющийся нейтронной звездой, оставшейся после взрыва сверхновой,
- его диаметр около 10 км. Пульсар был открыт в 1968 году; это было первое наблюдение, связывающее остатки сверхновой и пульсары
- Пульсар Краба вращается вокруг своей оси, совершая 30 оборотов в секунду.
- Излучение пульсара регистрируется начиная от радиодиапазона и заканчивая γ-излучением.
- **В гамма GeV-PeV диапазоне Краб считается стандартной свечей для калибровки всех гамма-детекторов**





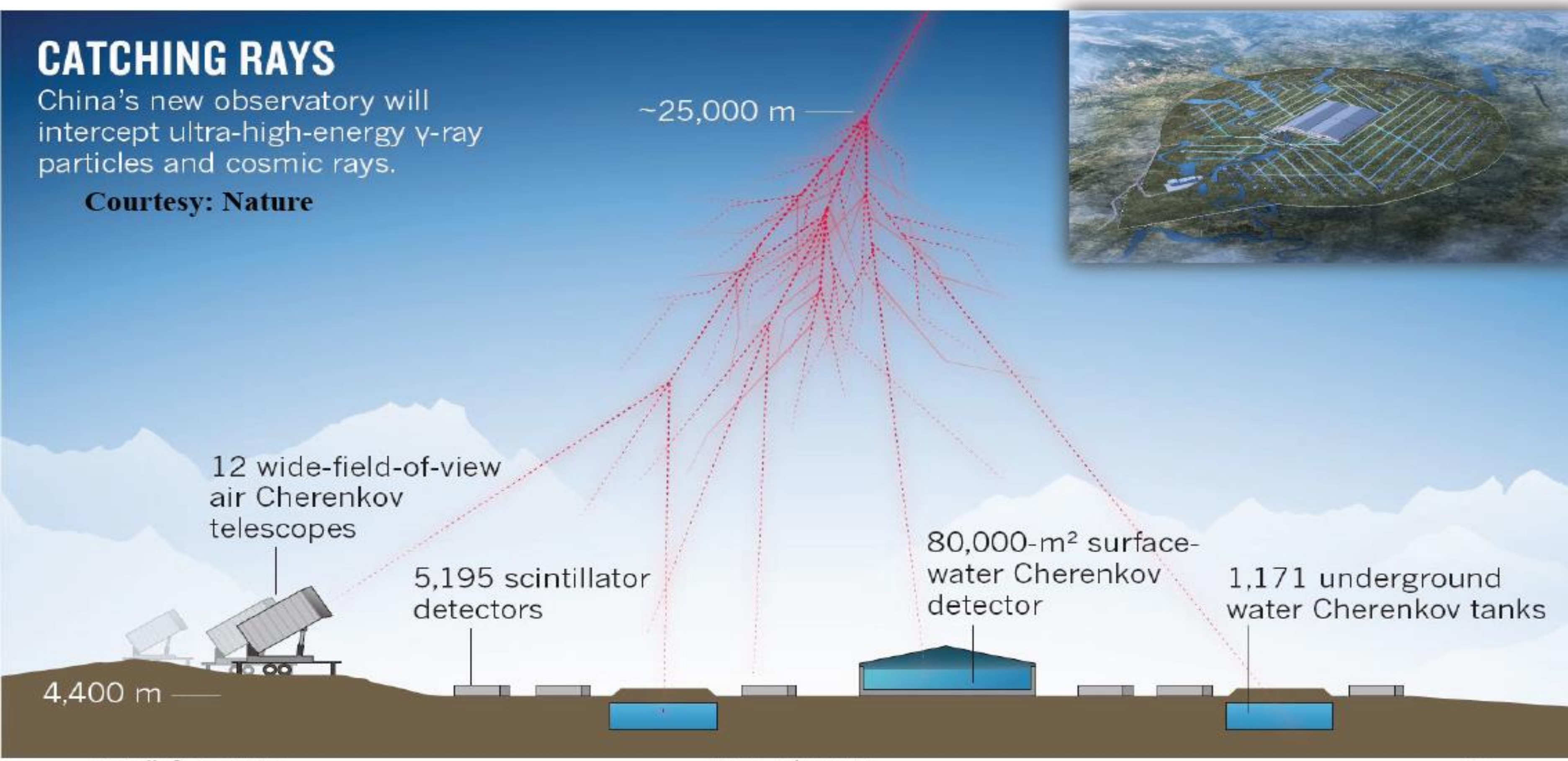


ПРОЕКТИРУЕМЫЕ ДЕТЕКТОРЫ

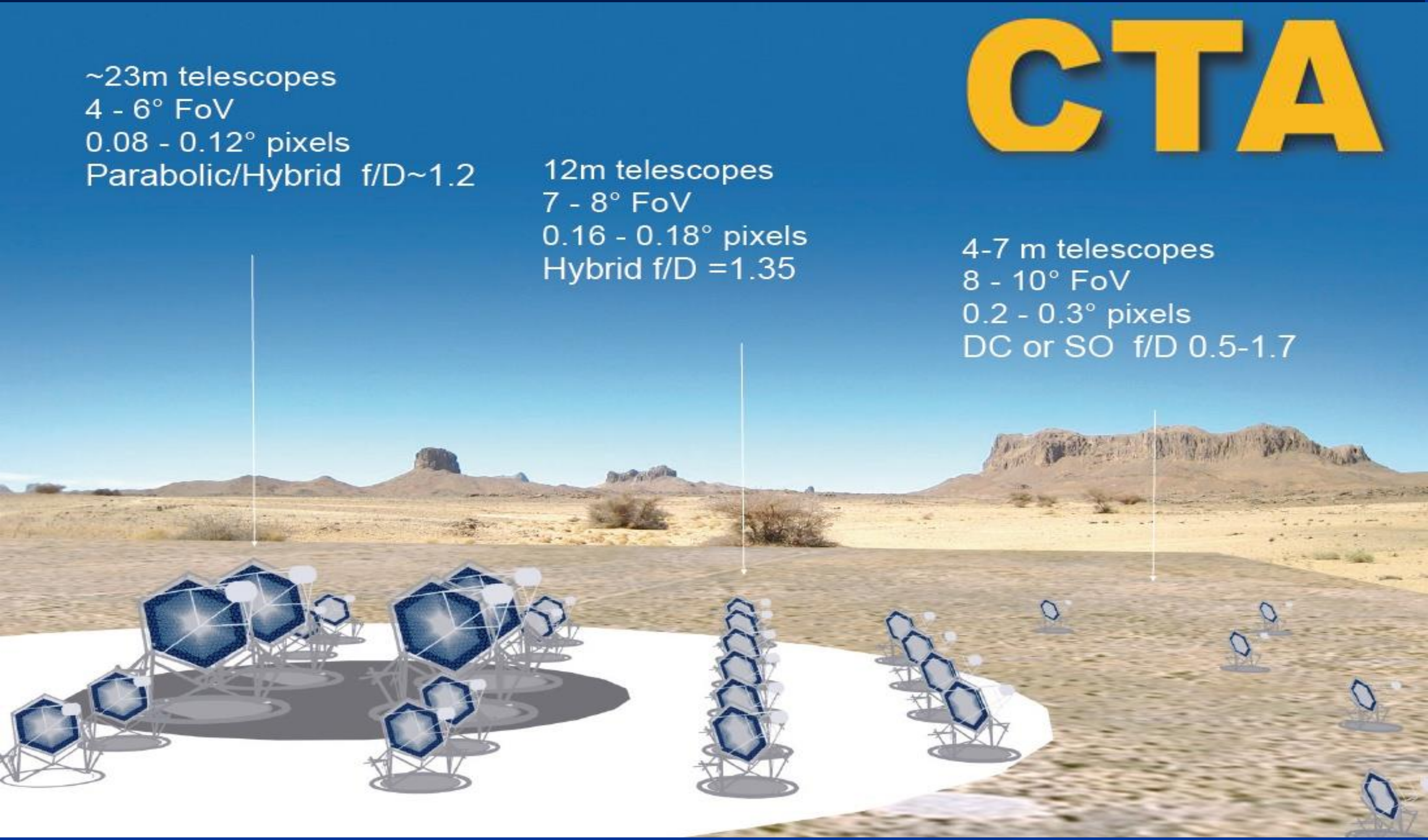


ПРОЕКТИРУЕМЫЕ ДЕТЕКТОРЫ

Hybrid Detection of EASs by LHAASO

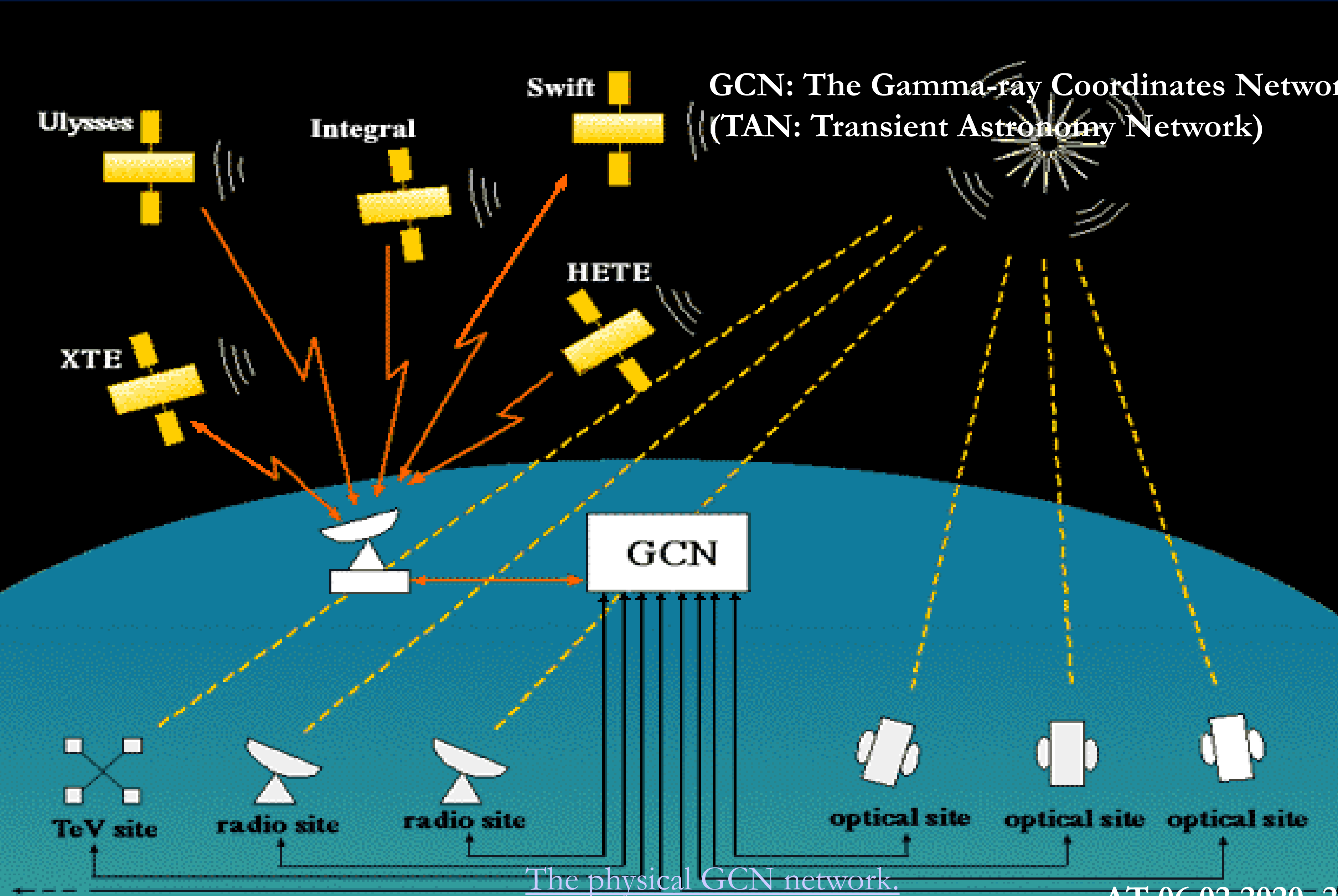


ПРОЕКТИРУЕМЫЕ ДЕТЕКТОРЫ



Multimessenger astronomy

GCN: The Gamma-ray Coordinates Network
(TAN: Transient Astronomy Network)



The physical GCN network.

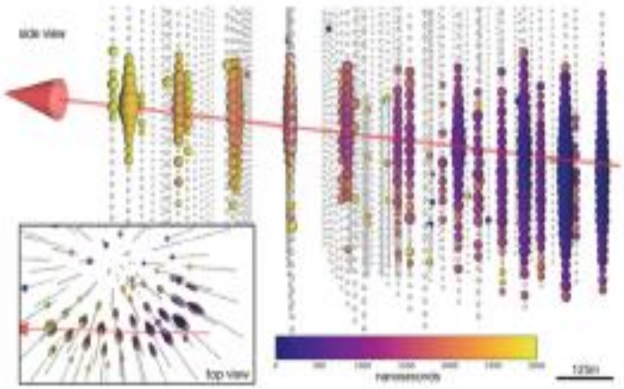
Understanding neutrinos from TXS 0506+056

PoS(ICRC2019)1032

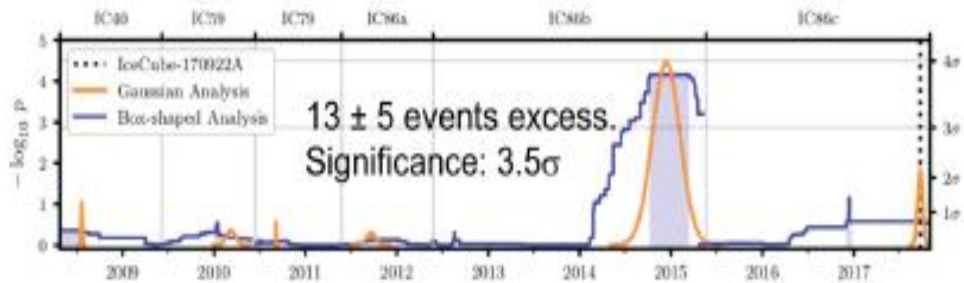
Neutrinos from the AGN blazar TXS 0506+056

E_ν ~ 290 TeV

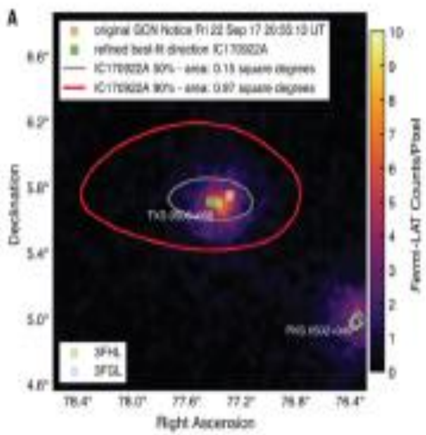
Sept. 22, 2017: Z=0.34 distance ~1.7 Gpc
A neutrino in coincidence with a blazar flare



2014-2015: A (orphan) neutrino flare found from the same object in historical data



Science 361 (2018) no. 6398, eaat2890

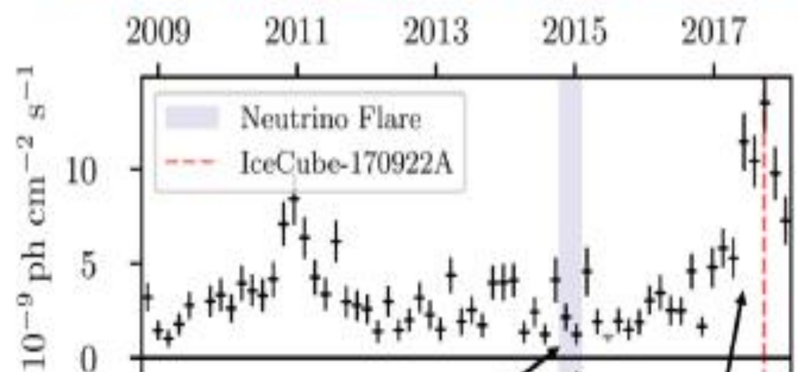


Observed by Fermi-*LAT* and MAGIC

Significance for correlation: 3σ

Science 361 (2018) no. 6398, eaat1378

Fermi-*LAT* data; Padovani et al, MNRAS 480 (2018) 192

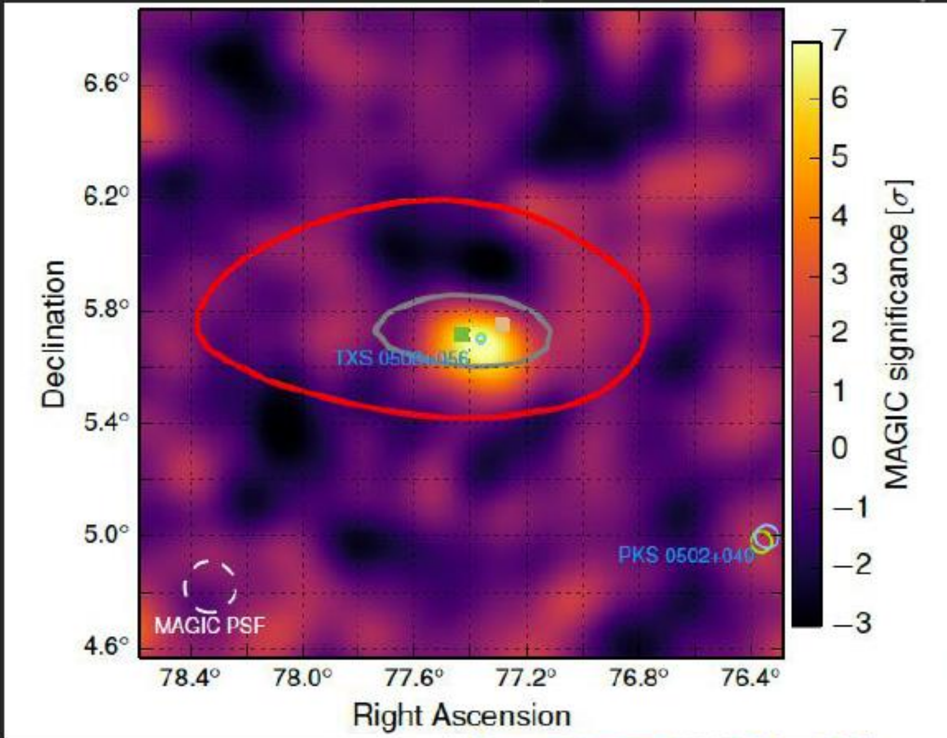


At 2014-15 neutrino flare

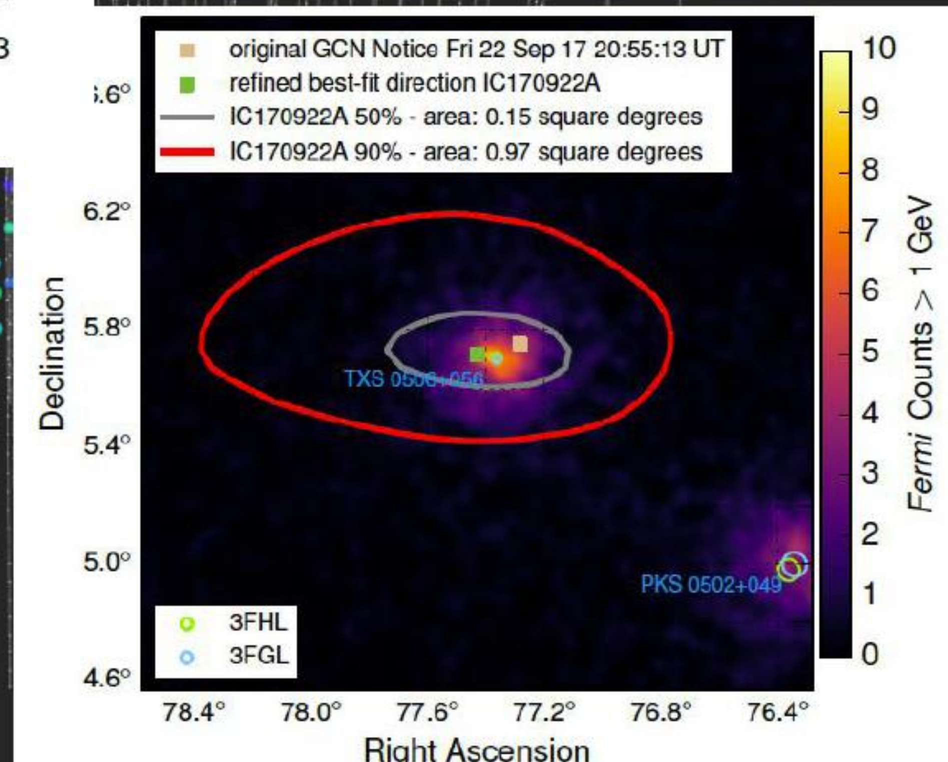
The 2017 flare

IceCube 170922

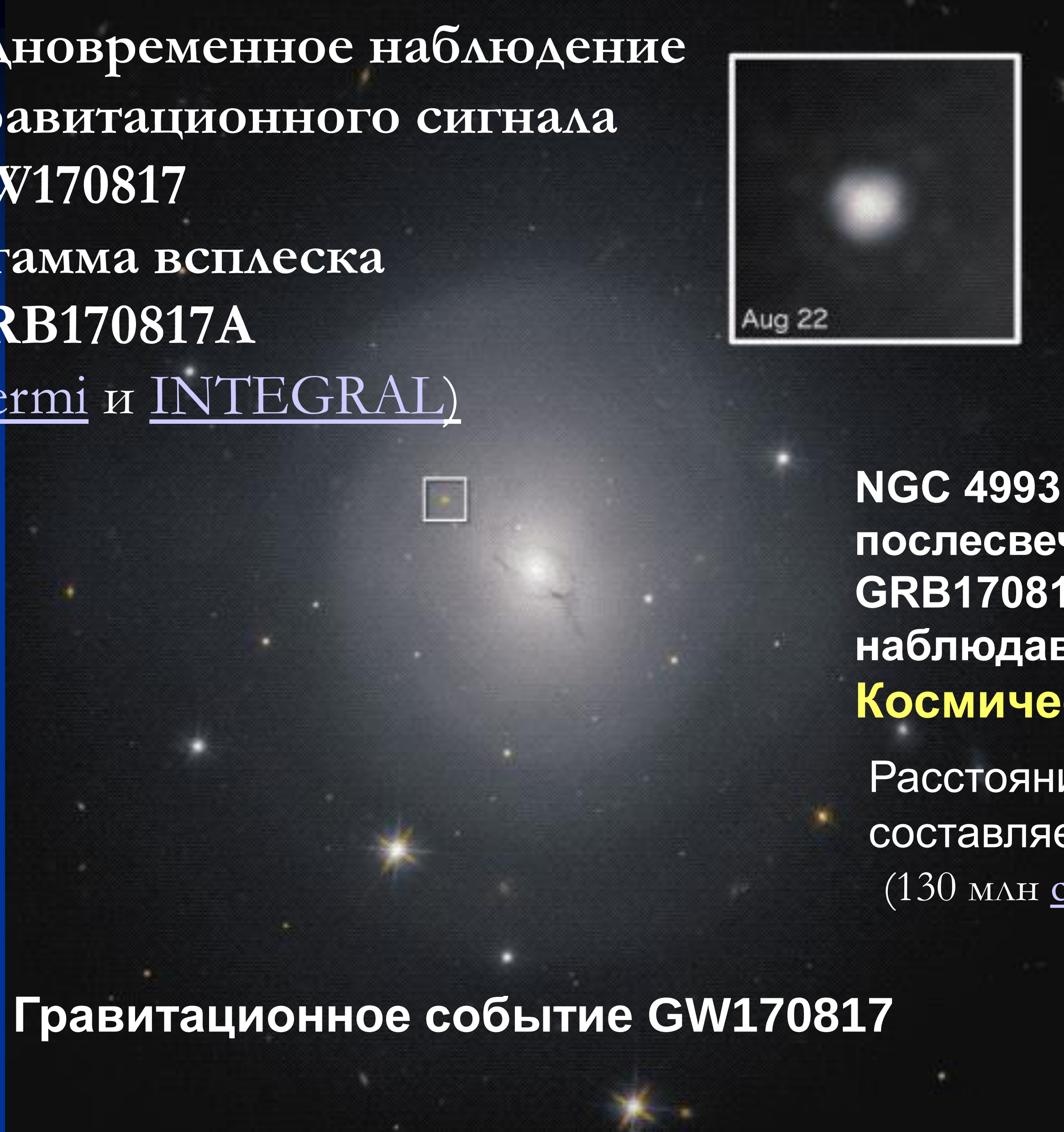
Fermi
detects a flaring
blazar within 0.06°



MAGIC
detects emission of
> 100 GeV gammas



Одновременное наблюдение Гравитационного сигнала GW170817 и гамма всплеска GRB170817A
(Fermi и INTEGRAL)



NGC 4993 и оптическое послесвечение гамма-всплеска GRB170817A (врезка), наблюдавшееся на Космическом телескопе Хаббл

Расстояние до источника составляет 40+8 −14 Мрс
(130 млн световых лет).

Гравитационное событие GW170817

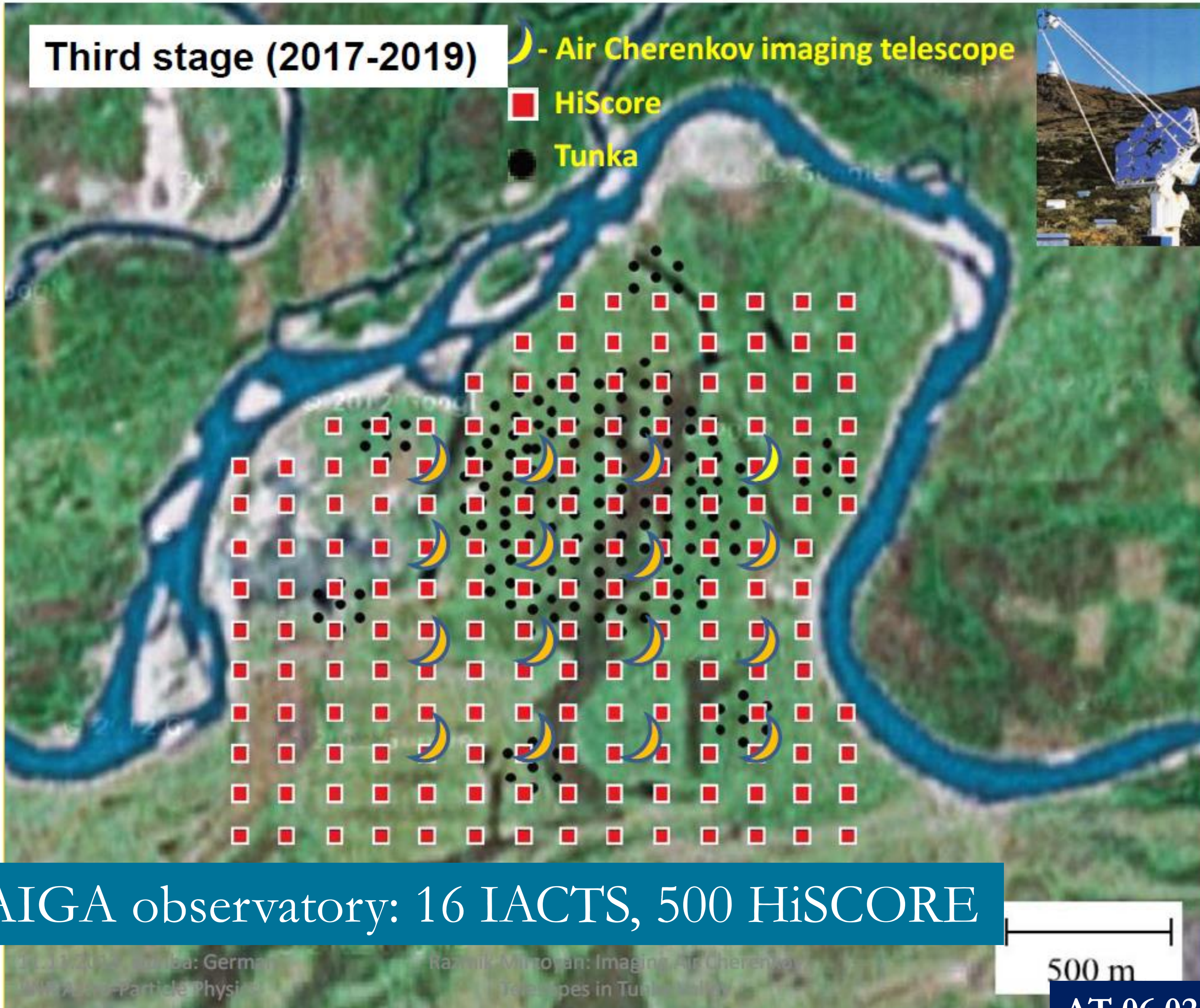
ДЕТЕКТОР TAIGA

The full scale TAIGA observatory will include 16 TAIGA- IACTs distributed with 600 – 800 m spacing over an area of 5 km^2.
The 34-segment reflector in Davis-Cotton design, with a diameter of individual mirrors 60 cm. The full diameter of the reflector is 4.3 m, the area ~10 m^2, the focal length 4.75 m.

The TAIGA- IACT operate together with Tunka-133, Tunka-Rex,
TAIGA-HiSCORE – 500 detectors
and TAIGA-Muon - 2000 sq, m/

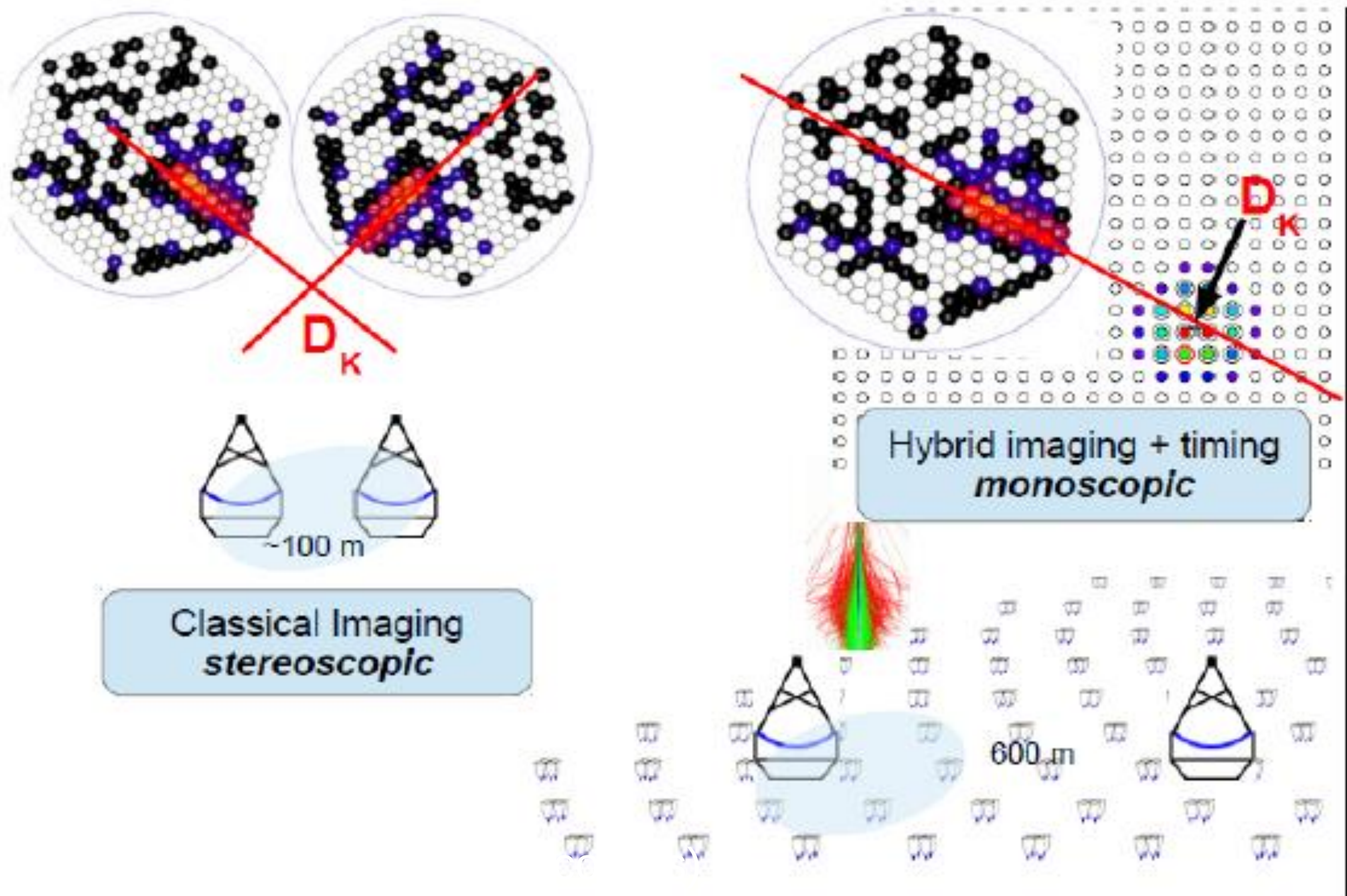
Threshold energy ~ 1.5 TeV
The sensitivity in the energy range 1-20 TeV is 10^{-12} erg cm^{-2} s^{-1} (for 50 hours of observation)
The sensitivity in the energy range 30-200 TeV is 10^{-13} erg cm^{-2} s^{-1} (for 500 hours of observation)

Camera : 560 PMTs (XP 1911) with 15 mm useful diameter of photocathode
Winston cone: 30 mm input size, 15 mm exit window 1 single pixel = 0.36 deg.
Camera FOV 10x10 deg



TAIGA observatory: 16 IACTS, 500 HiSCORE

Hybrid approach to hadron rejection



TAIGA-IACT

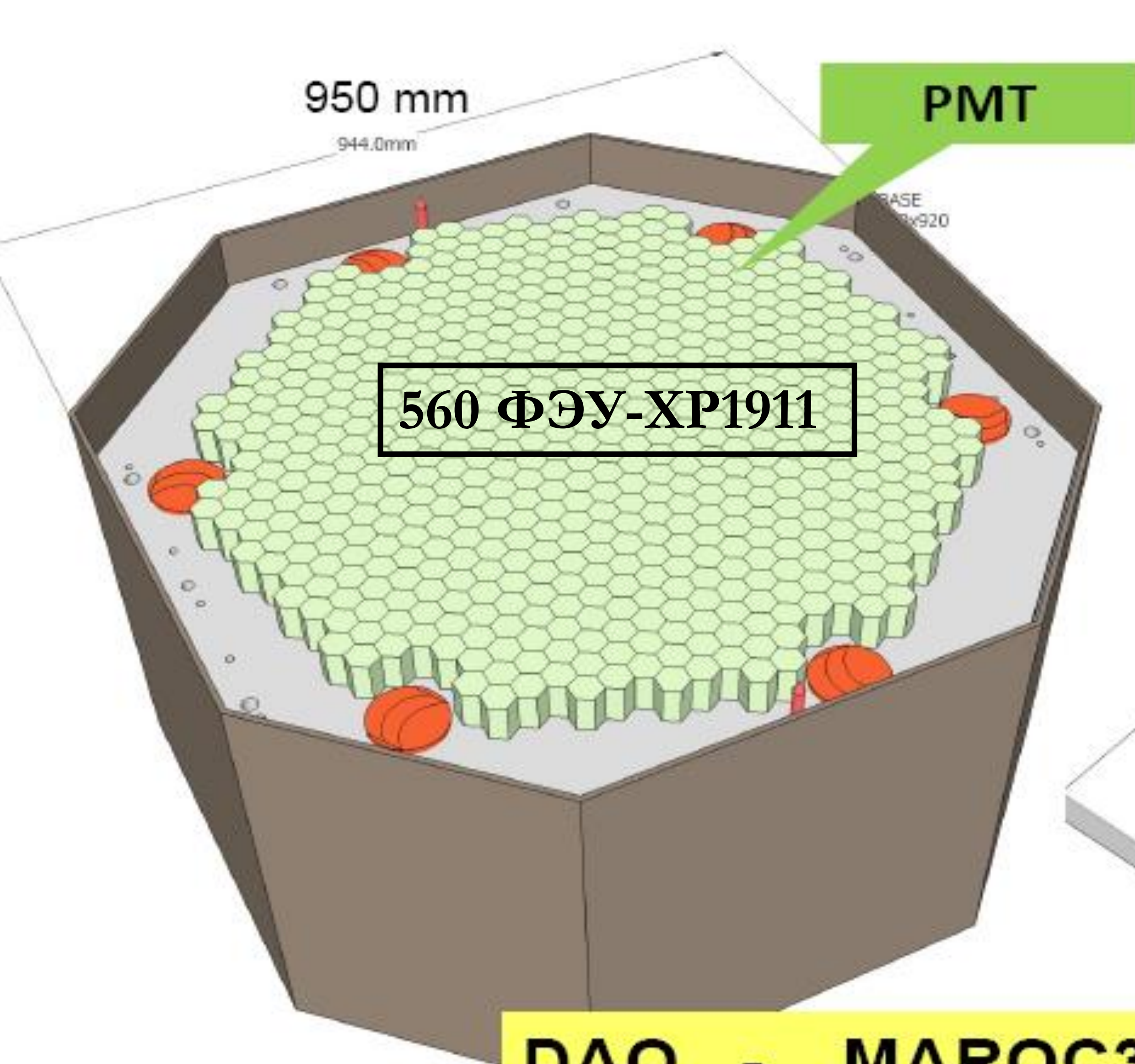
D = 4.32m F = 4.75m

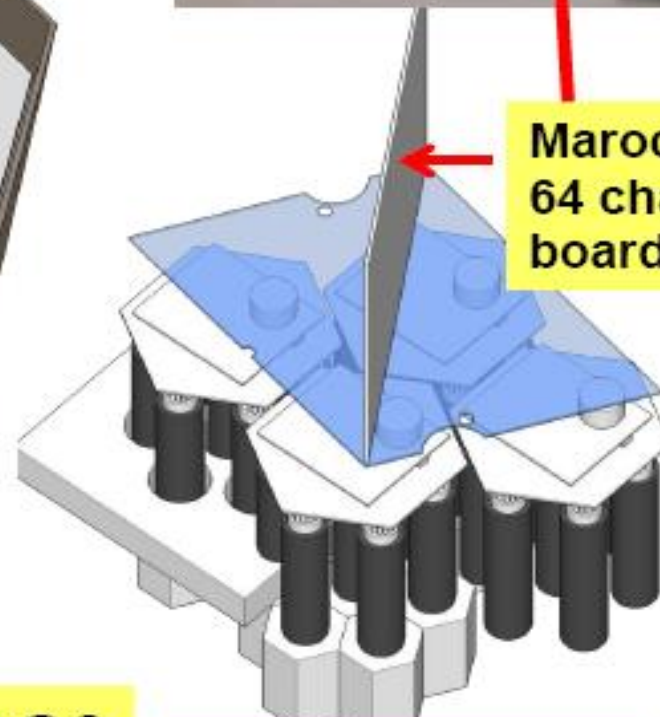
34 mirrors of 60 cm diameters

Camera : 560 PMTs (XP 1911)
Winston cone: 30 mm input size, 15 output size
1 single pixel = 0.36 deg
full angular size 9.6x9.6 deg

Energy threshold ~1.5 TeV

Camera of the TAIGA-IACT





Maroc-3
64 channe
board

DAQ - MAROC3

Cluster – 28 PMTs

Alt-azimuth mount;

Spherical shape of 34 mirror modules with a diameter 60 cm and with a total mirror area of 9.6 m^2;

Viewing angle ± 4.86°;

Turn around the horizontal axis (zenith angle) -10 + 95°;

Turn around the vertical axis (azimuthal angle) 0-410°;

The angular accuracy is 0.01°;

Driving and positioning system – manual and remote – with the possibility of computer control;

The rotation speed is ~ 2 deg/sec;

The camera with diameter of ~ 95 represents the matrix of PMTs with FE and DAQ electronics. The weight of the camera is ~ 200 kg and it is fixed at a focal length of 475±1 cm from the dish. Operating conditions – temperature: минус 40 to plus 30°C and high humidity

HiSCORE & IACT REPORTs
2020-02-25

Ya.Sagan logbook report of data taking at 25.02.2020 from Tunka area

Weather:

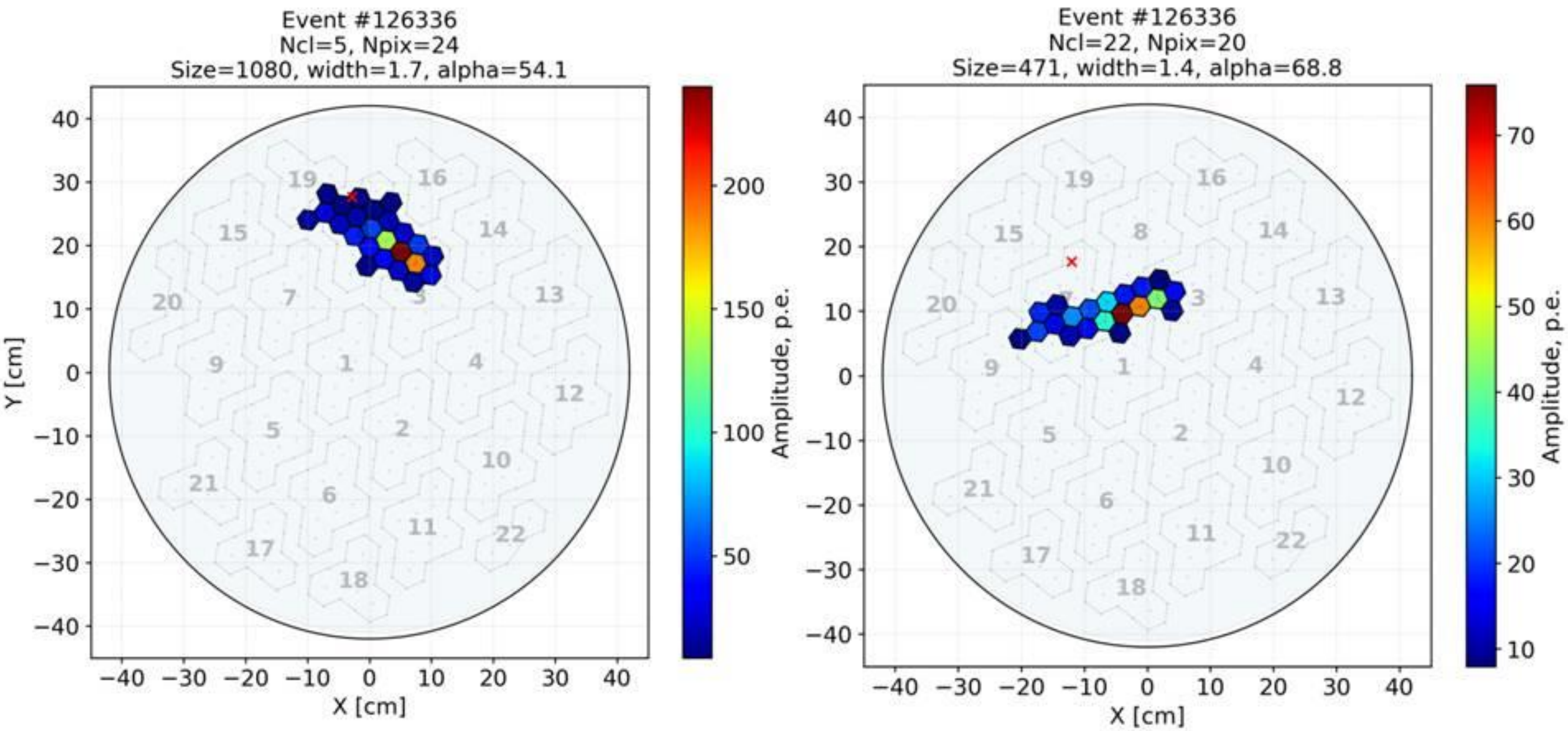
Night Sky: 5 → 4(-) (very good, good enough)
Outside Temperature : -15,4/-23,1 °C
Atmospheric Pressure : 710 mmHg
Relative Humidity : 78 %
Comments:

HiSCORE:

Status: On operation → Run: 250220
Cluster 1 data dir: .115/~/krs/NEW_PROGRAMMS/hiscore_2018/250220,
Stations in operation: 32 stations
Cluster 2 data dir: .116/~/krs/NEW_PROGRAMMS/hiscore_2018/250220,
Stations in operation: 26 stations
Cluster 3 data dir: .116/~/krs/NEW_PROGRAMMS/hiscore_2018/250220, 250220.1
Stations in operation: 19 stations
Data Taking time: 12:40 – 22:03 UT, Coin4(HiS-01) - 16-5 Hz, Coin4(HiS-02) – 11-8 Hz, Coin4(HiS-03) – 12-3 Hz
Problems:
Comments:

IACT:

IACT01:
Status: On operation → Run: 250220, .01, .02.
Mode: 00 - Tracking Crab wobble mode (1.2 deg shift, 20 min period), 7-10 Hz, start: 12:43 stop: 14:56.
01 - Tracking Mrk421 wobble mode (1.2 deg shift, 20 min period), 5-8 Hz, start: 15:10 stop: 20:44.
02 - Tracking Mrk501 wobble mode (1.2 deg shift, 20 min period), 4-8 Hz, start: 20:57 stop: 22:03.
IACT02:
Status: On operation → Run: 250220, .01, .02.
Mode: 00 - Tracking Crab wobble mode (1.2 deg shift, 20 min period), 20-30 Hz, start: 12:44 stop: 14:56.
01 - Tracking Mrk421 wobble mode (1.2 deg shift, 20 min period), 16-20 Hz, start: 15:11 stop: 20:44.
02 - Tracking Mrk501 wobble mode (1.2 deg shift, 20 min period), 8-14 Hz, start: 20:58 stop: 20:03.
Problems: --
Comments: --



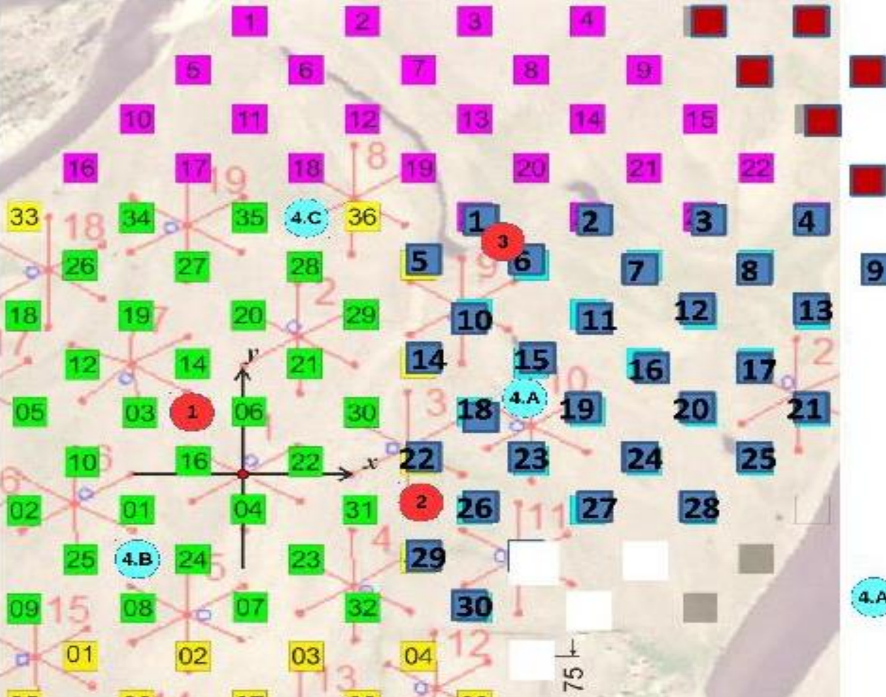
Size = 1080 pe, Width = 0.20 °

Size = 471 pe, Width = 0.17°

Пример события, измеренного одновременно двумя TAIGA-IACTs

Работы в ОИЯИ. Изготовление и тесты 3 телескопа. Разработка технологии и производство фокусирующих зеркал

Монтировка 3-го телескопа
в 5 корпусе ЛЯП



Конфигурация детекторов TAIGA-HiSCORE - 79 работают

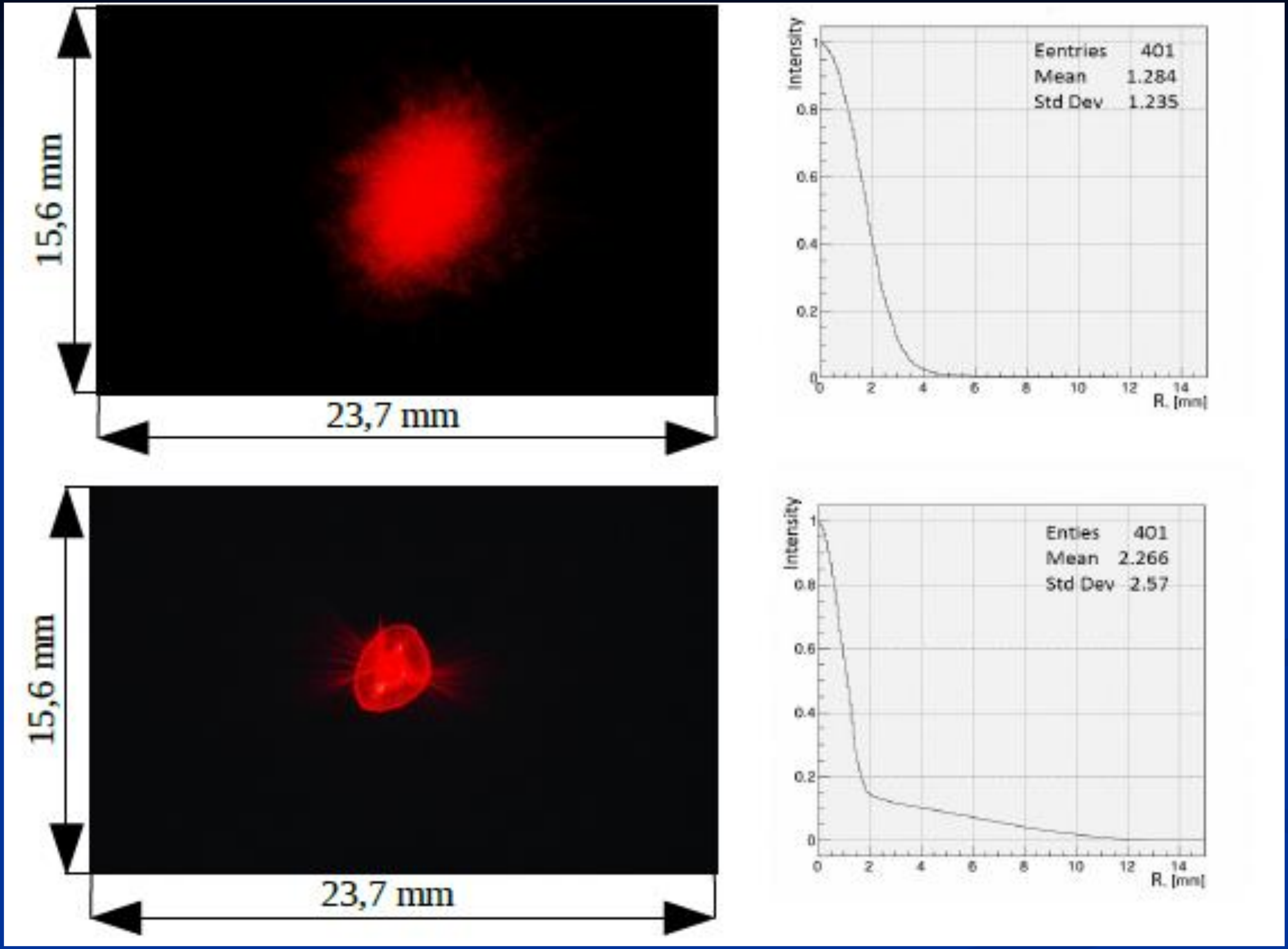
Изготовленный по заказу ОИЯИ
Фундамент под 3-Й телескоп
в Тунке

Glass-bending oven and the polishing machine

Large vacuum chamber
for reflective and protective layers
evaporation of mirror facets

Powerful spiral vacuum pump Triscroll 600
Inverter for vacuum chamber operation

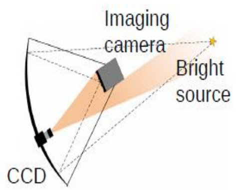
Шлифовально-полировальный станок для изготовления фокусирующих зеркал. Первые образцы зеркал

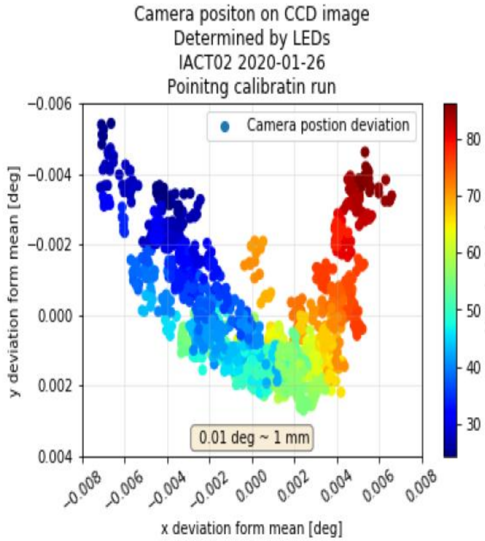


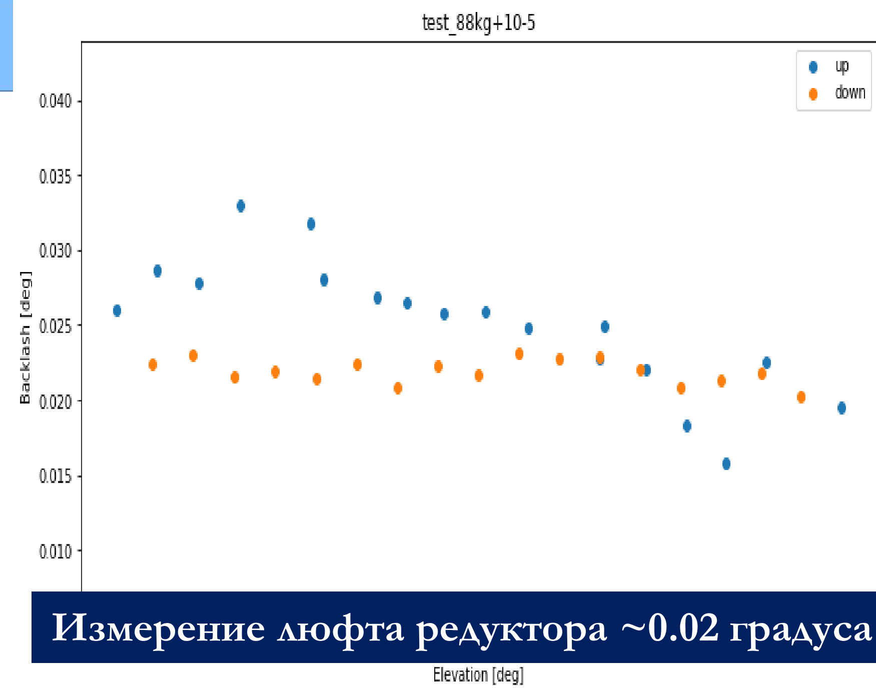
The spot shape and the relative intensity distribution measurements for the composite mirror of the Media Lario company (top) and the prototype mirror fabricated at JINR (bottom).)

Position of IACT02 camera on the CCD image

- On the image position of the camera is stable
- Max deviation < 0.015 deg (~ 1.2 mm)
- Altitudes form 25 to 85



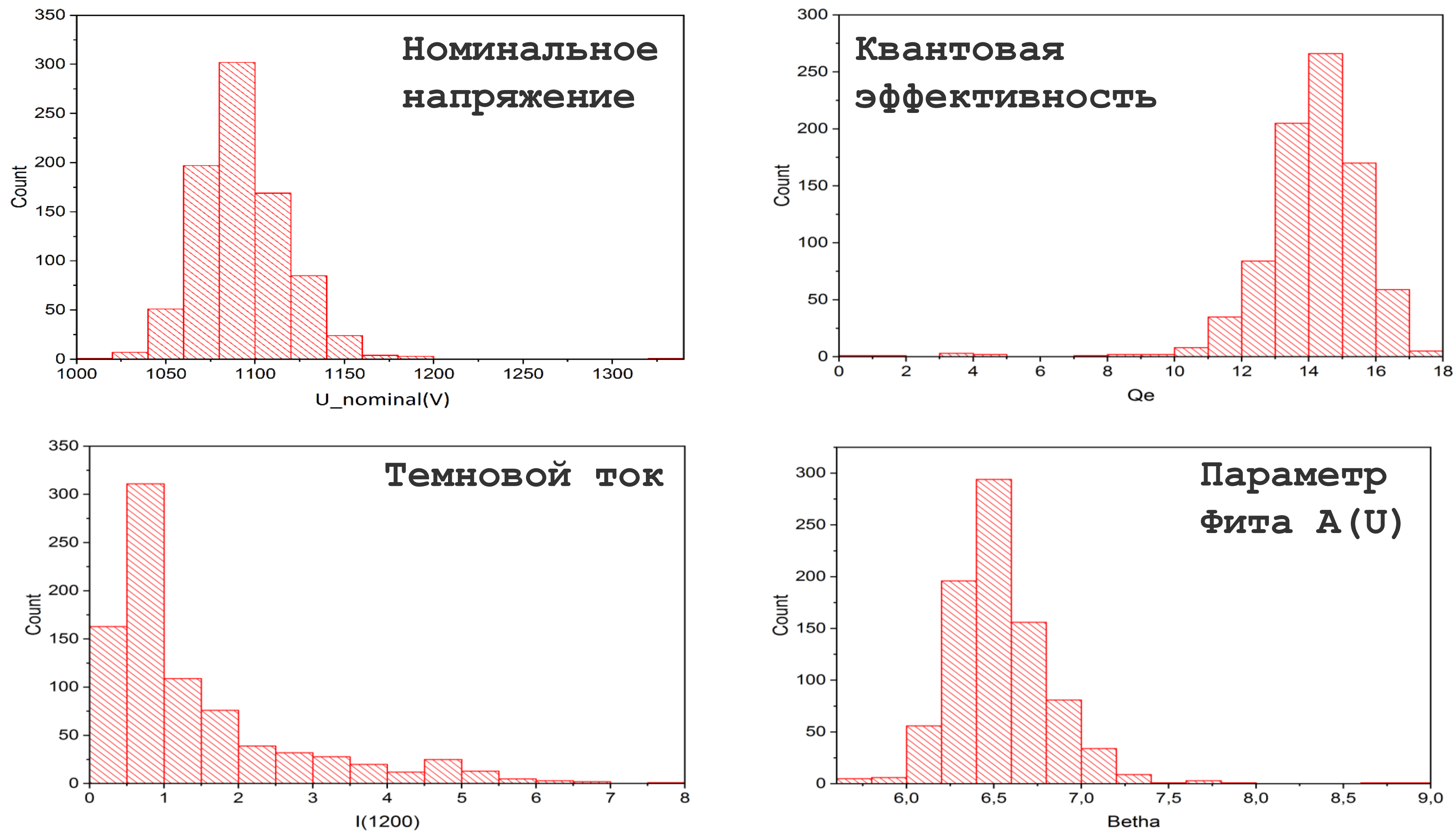




Измерение люфта редуктора ~0.02 градуса

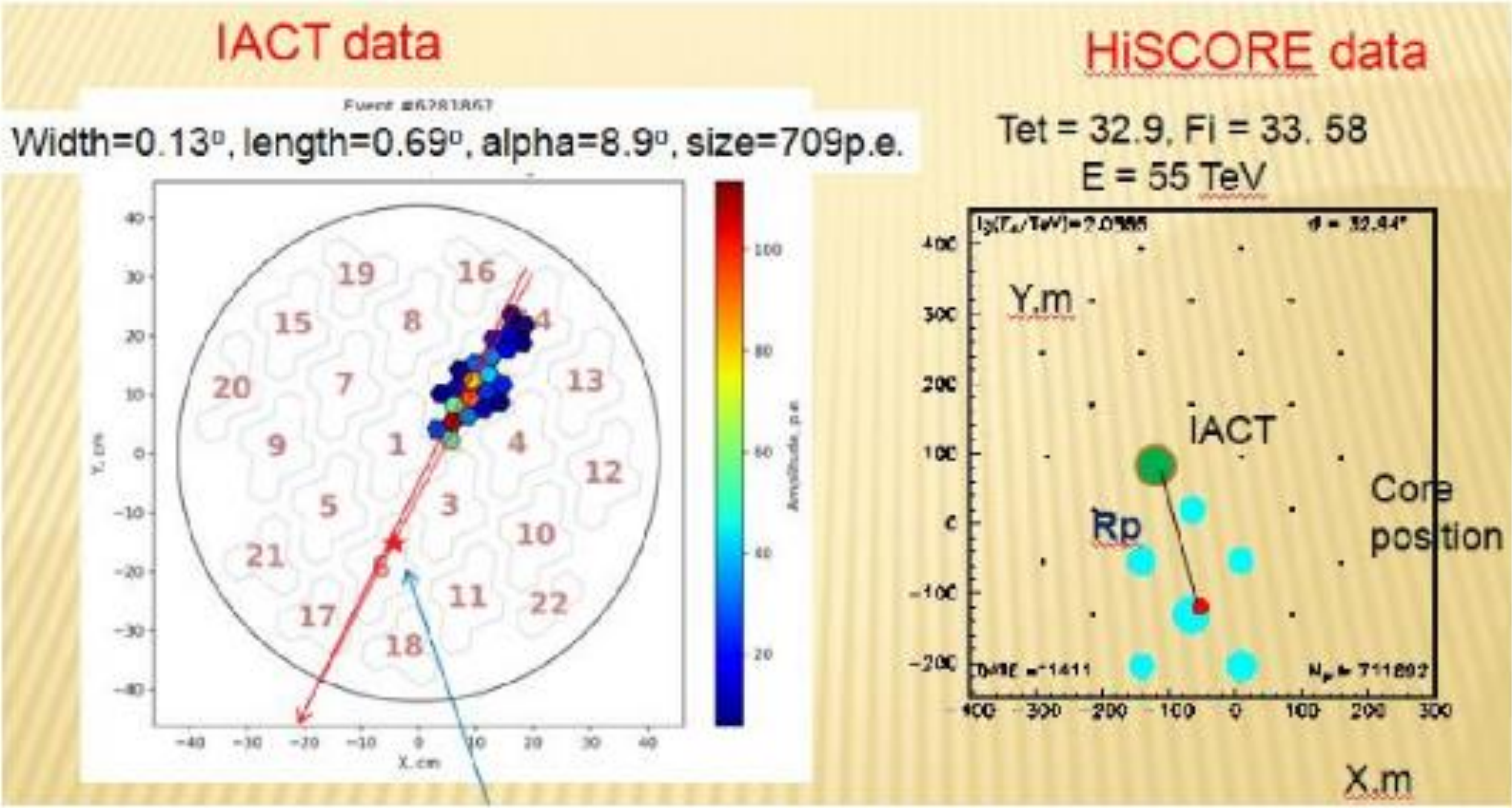
Измерение относительной деформации зеркала и положения камеры ~3 мм в интервале 0-90 градусов

Используются старые ФЭУ с установок H1 и ZEUS из DESY



Калибровка ФЭУ по отношению к сигналу от калибровочного фотодиода, у которого QE=66% при длине волны 450нм.

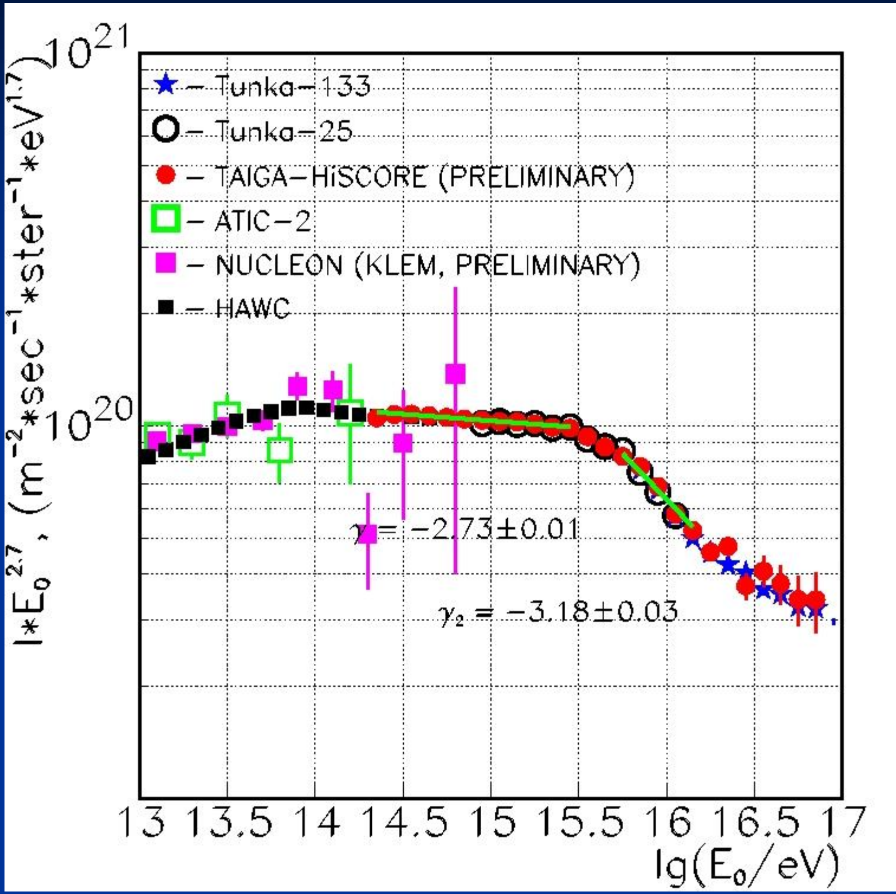
Анализ данных

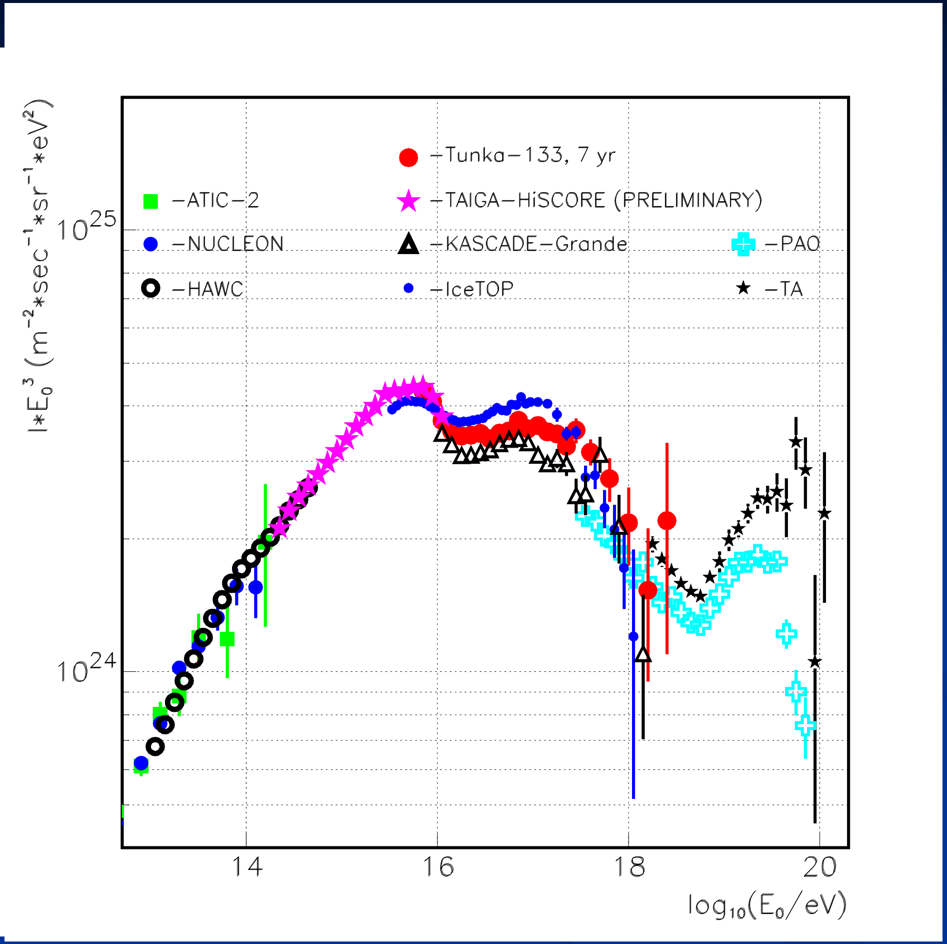


Пример события, зарегистрированного телескопом TAIGA-IACT и станциями TAIGA-HiSCORE.

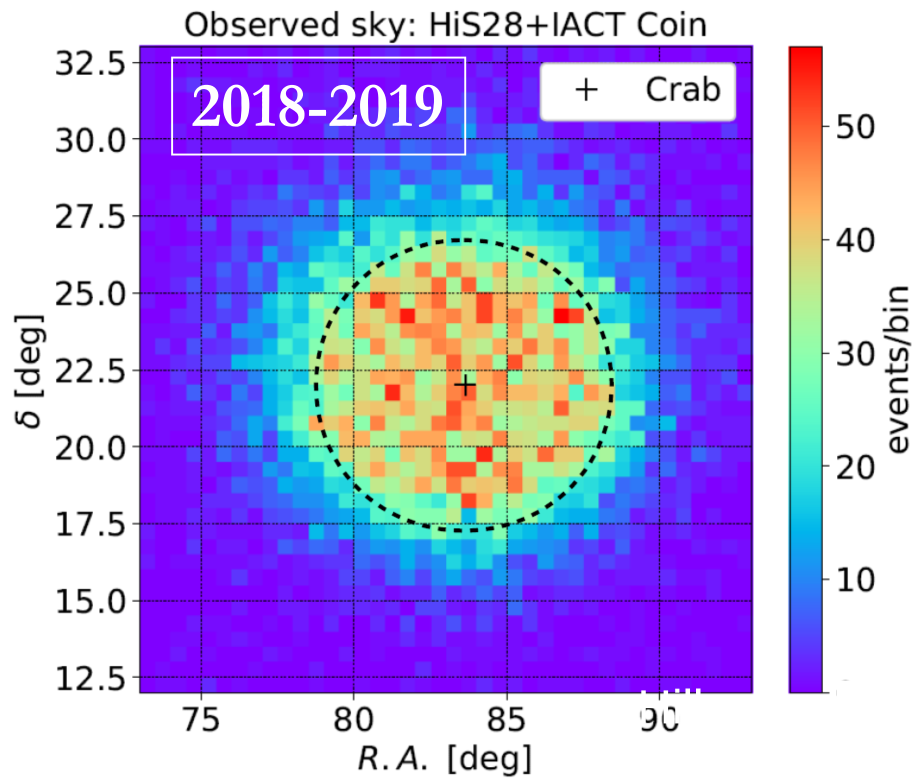
TAIGA-HiSCORE обеспечивают хорошую локализацию ШАЛ – положение оси и углы прихода, а также энергию.

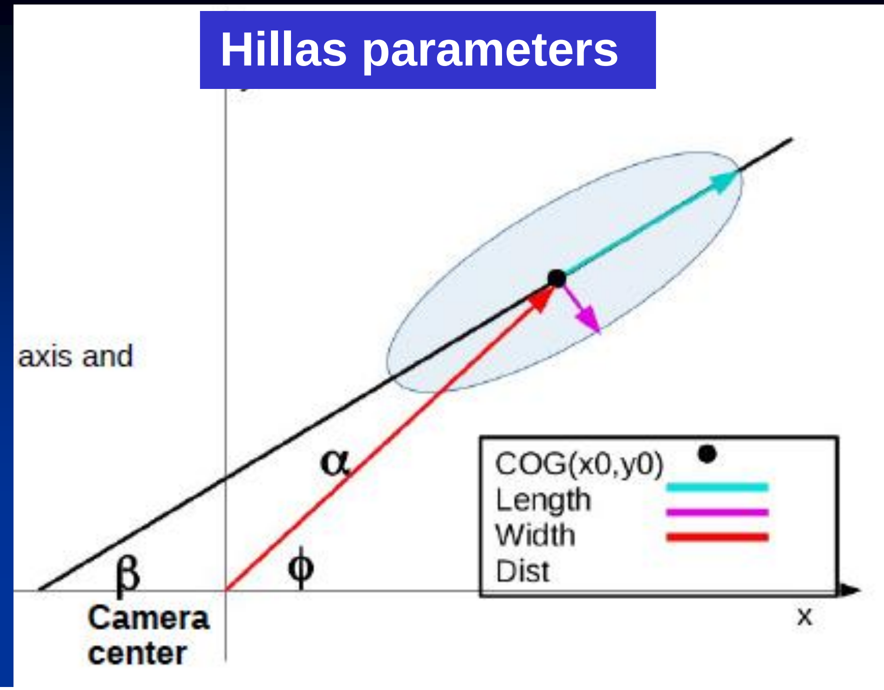
Основная роль TAIGA-IACT – дискриминация адрон-ядерных ШАЛ от фотонных ШАЛ.





Energy spectrum of primary cosmic rays measured by the TAIGA-HiSCORE array in comparison with other experiments


Observed sky: HiS28+IACT Coin
2018-2019
+ Crab
δ [deg]
R.A. [deg]
events/bin


Hillas parameters
axis and
α
β
ϕ
Camera center
x
COG(x0,y0)
Length
Width
Dist

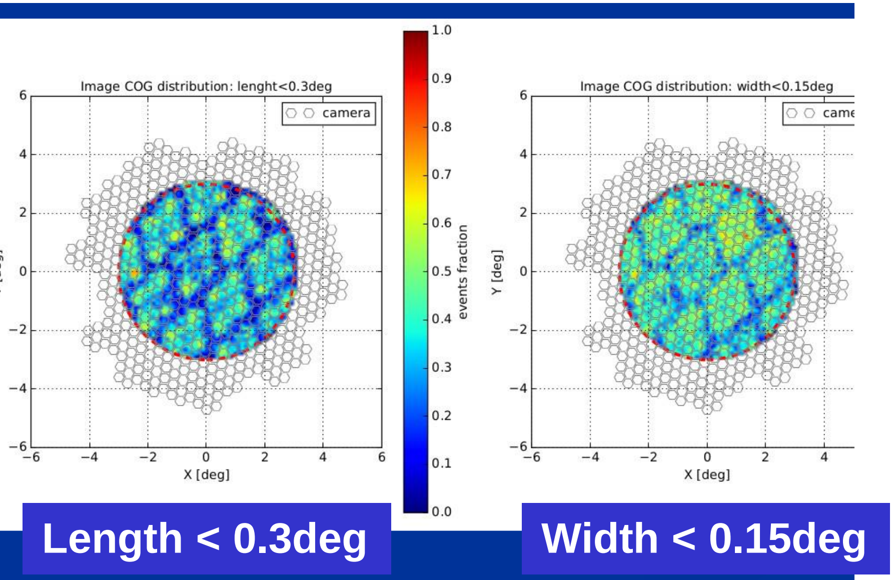
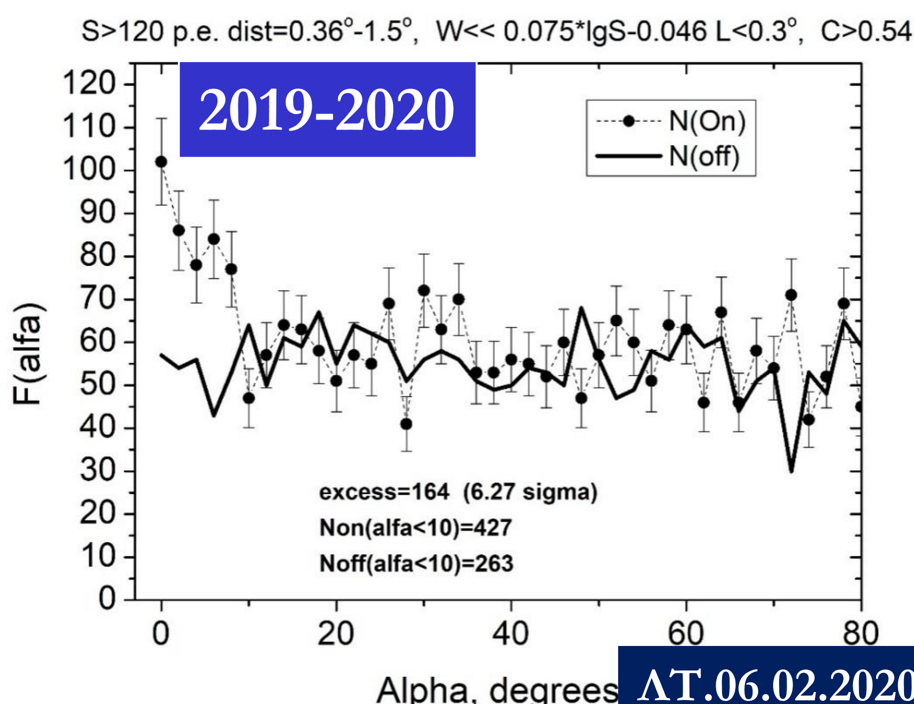
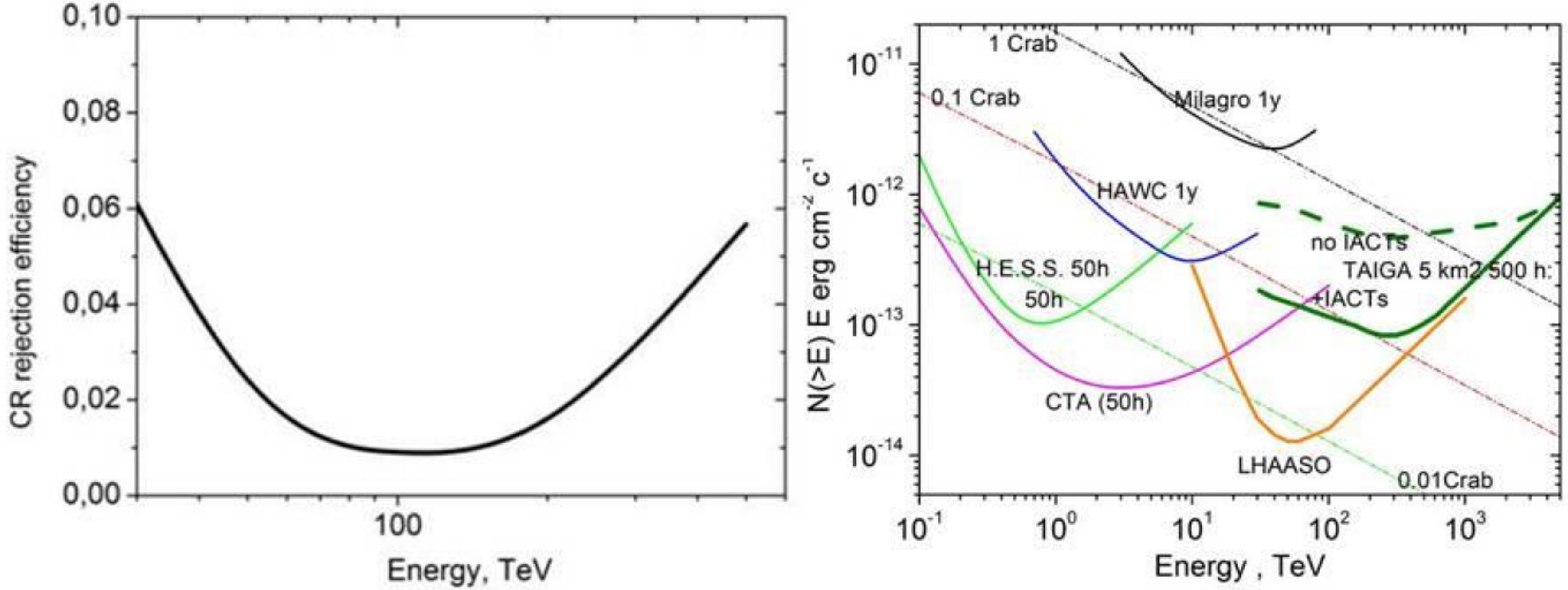


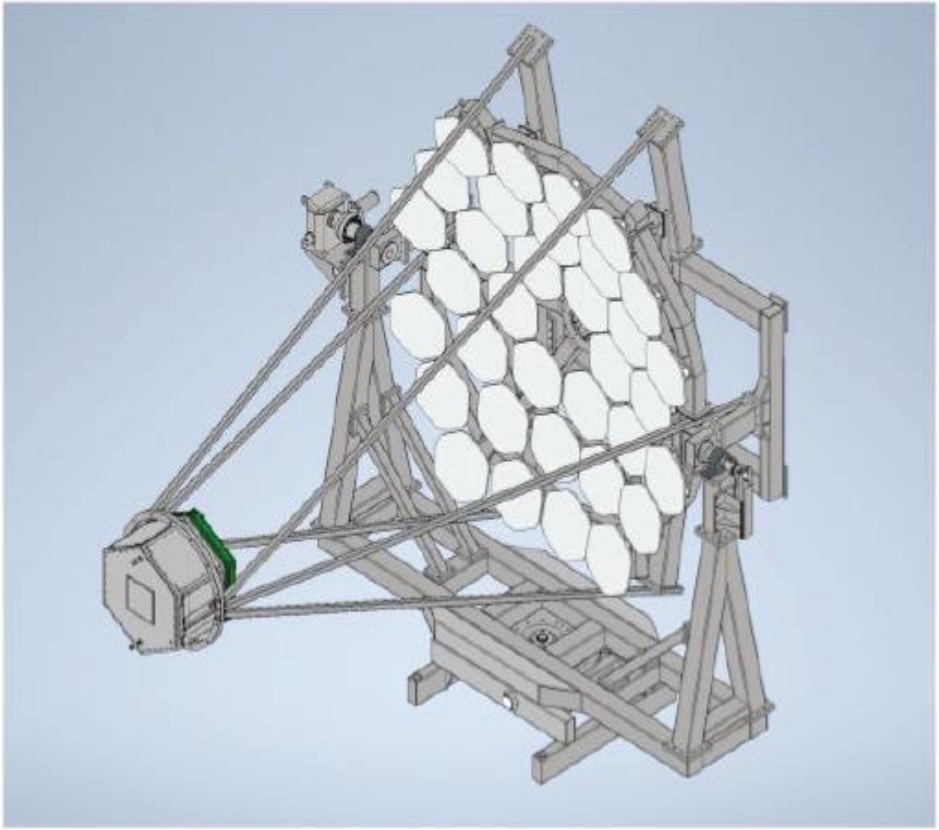
Image COG distribution: lenght<0.3deg
Image COG distribution: width<0.15deg
camera
X [deg]
Y [deg]
events fraction
Length < 0.3deg
Width < 0.15deg

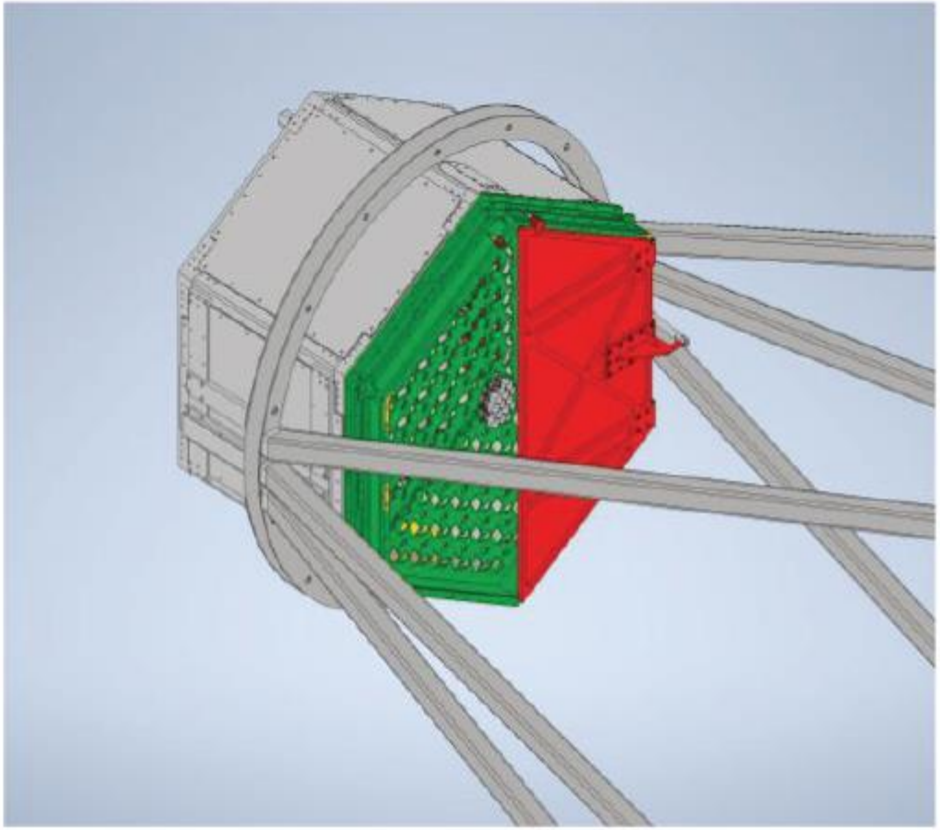

S>120 p.e. dist=0.36°-1.5°, W<< 0.075*lgS-0.046 L<0.3°, C>0.54
2019-2020
N(On)
N(off)
F(alfa)
excess=164 (6.27 sigma)
Non(alfa<10)=427
Noff(alfa<10)=263
Alpha, degrees



Left: Cosmic rays rejection efficiency. Right: Integral sensitivity for point sources for a 5 km^2 observatory. The dashed line marks the sensitivity without IACTs.

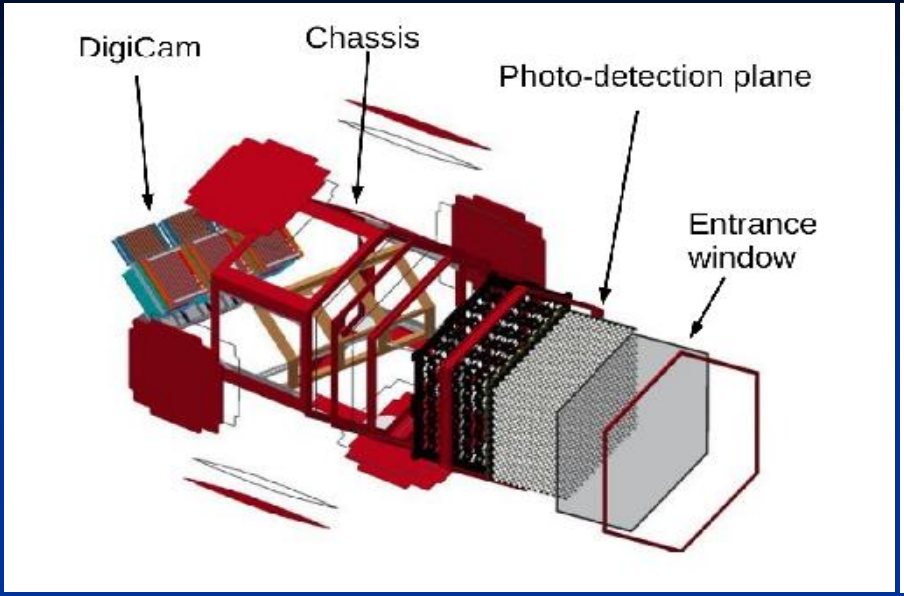
New SiPM digitizing camera for TAIGA IACT-3

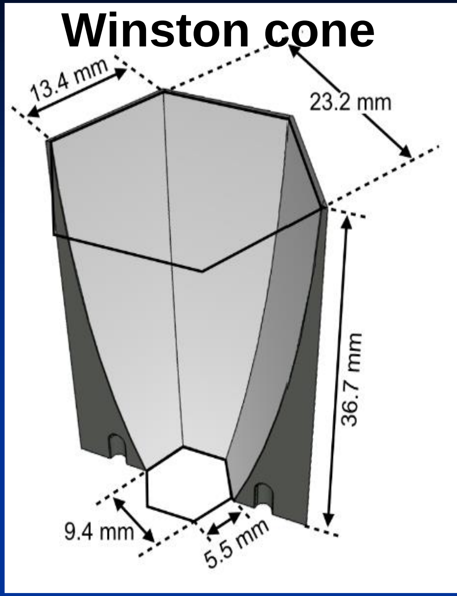




Technical drawings for production of SST-1M camera support system is in progress

New SiPM digitizing camera for gamma-ray astronomy

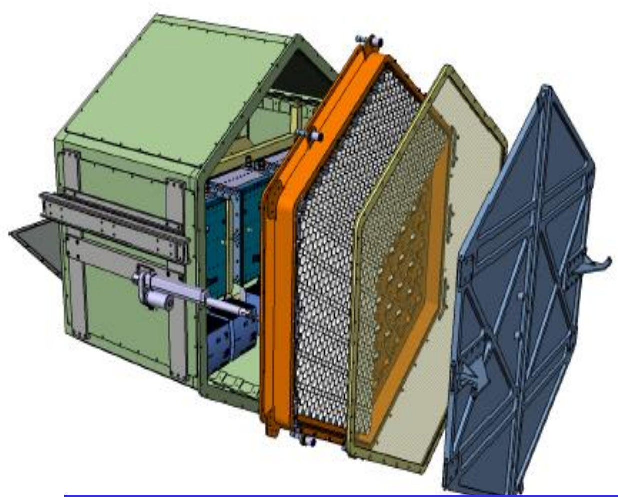


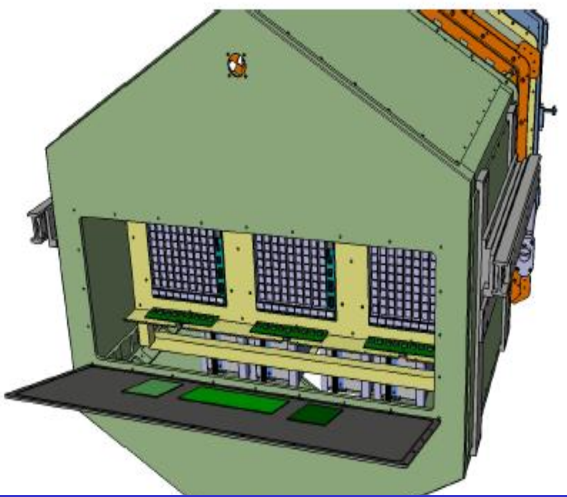


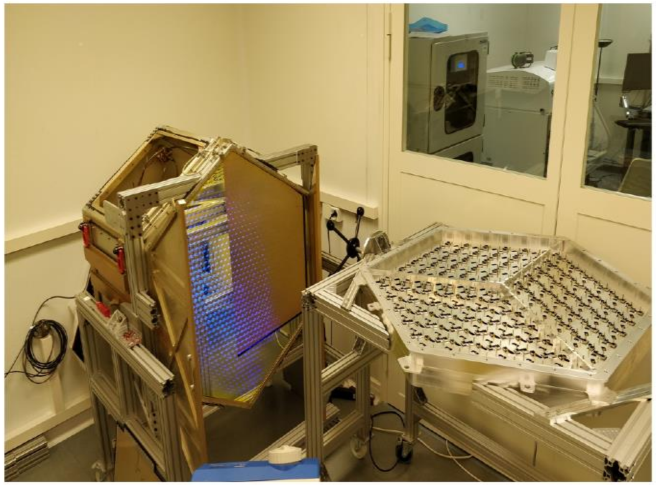
The SiPM pixel of 36’840 cells are grouped into four channels

SiPM камера из Женевы позволит работать при полной Луне

It consists of 1296 hexagonal Hammamatsu (S10943-3739(X)) SiPM pixels

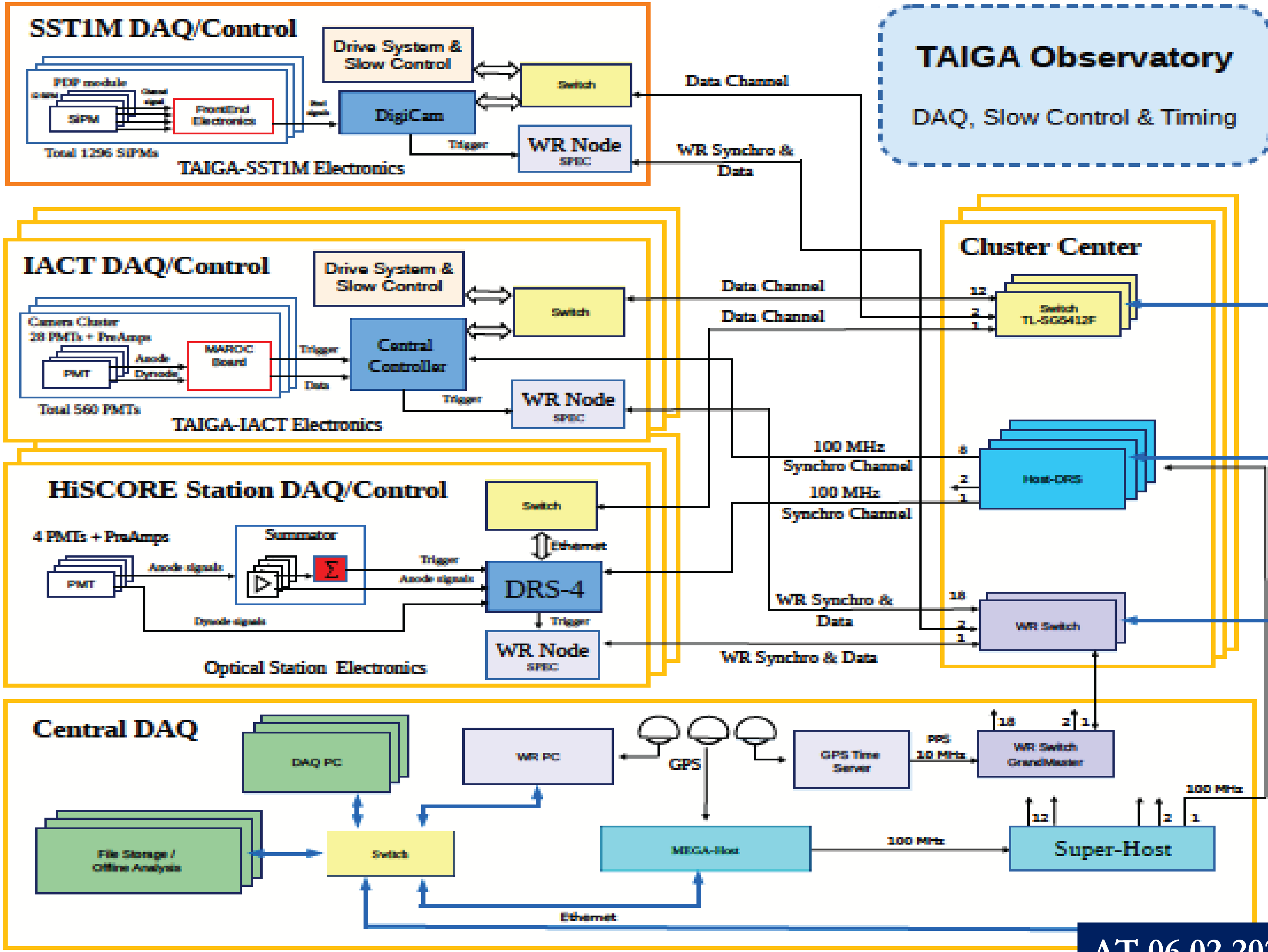


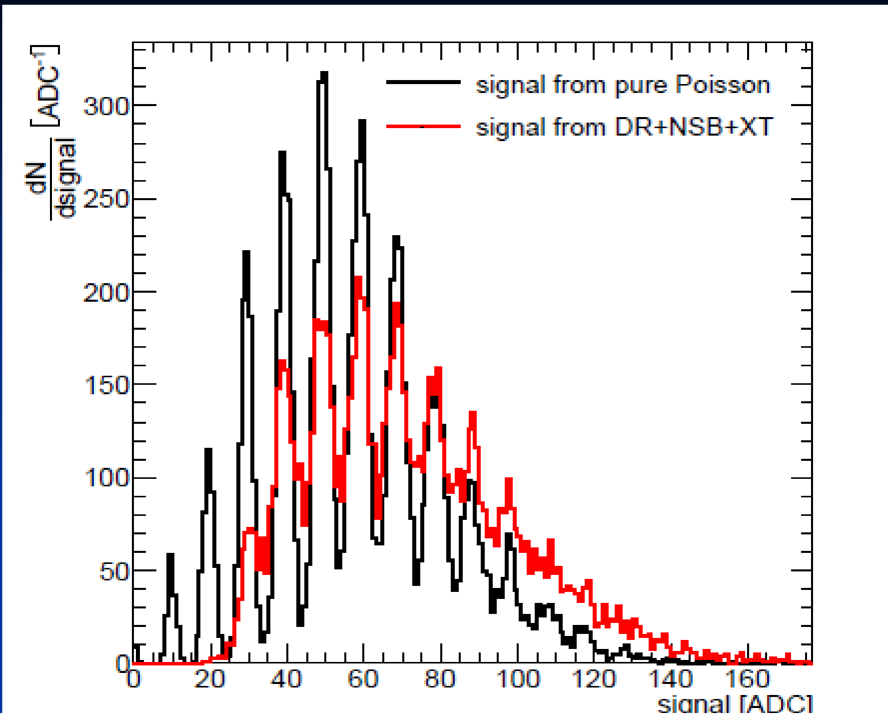


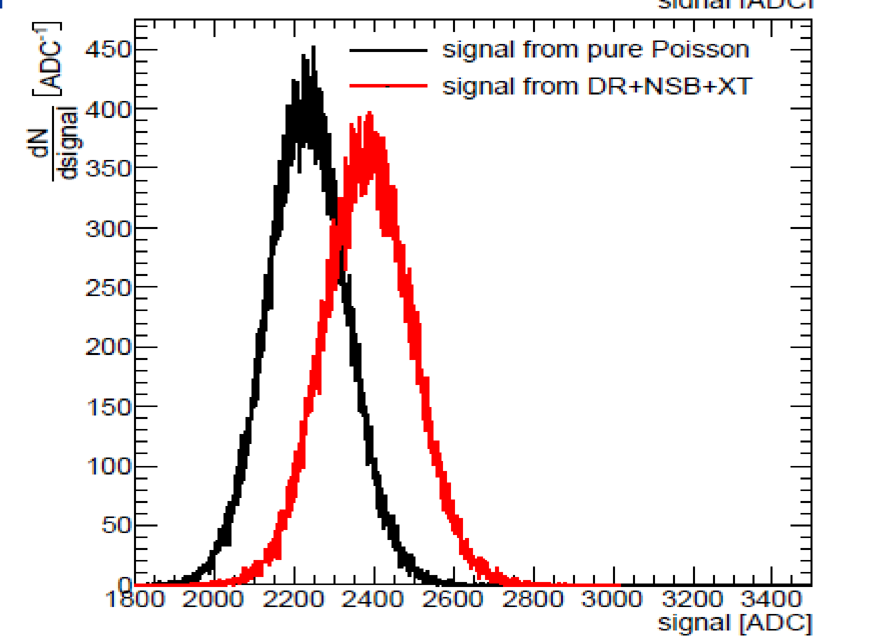


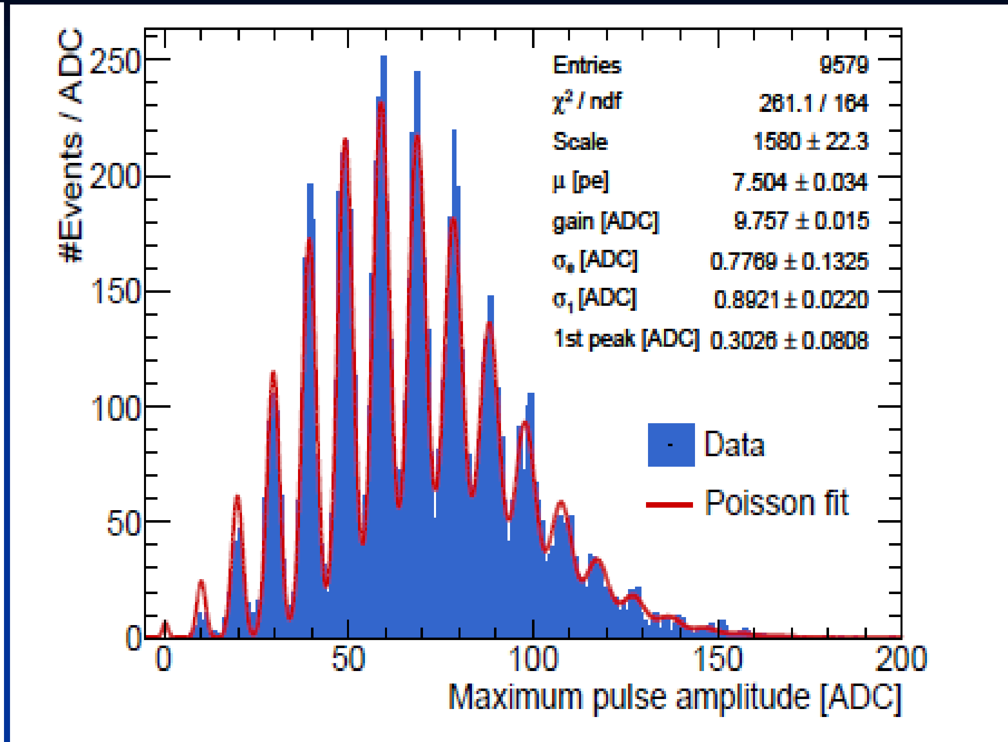
SiPM photo-detection efficiency ~0.4 at λ = 400 nm

New SiPM camera in TAIGA DAQ





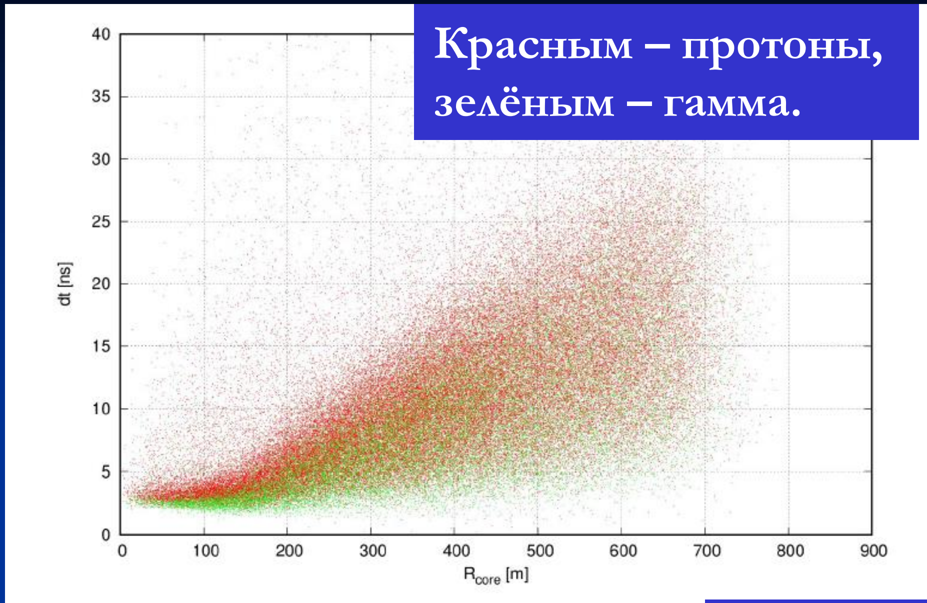




Left: toy MC simulation of low BG-light levels (top 6 p.e.) and high BG-light levels (bottom 519 p.e.) with and without dark count rate DR, NSB and cross talk XT

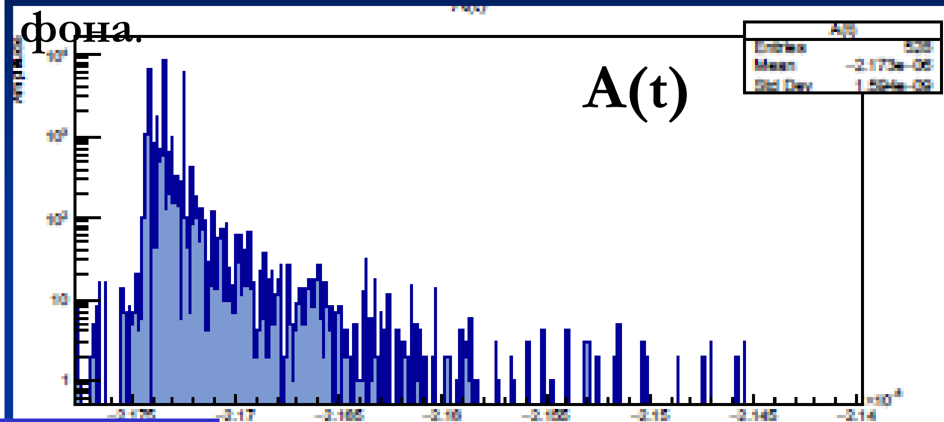
Right: the multiple photoelectron spectrum of a SiPM obtained pulsing at 1 kHz a 400 nm LED with readout window of 80 ns.

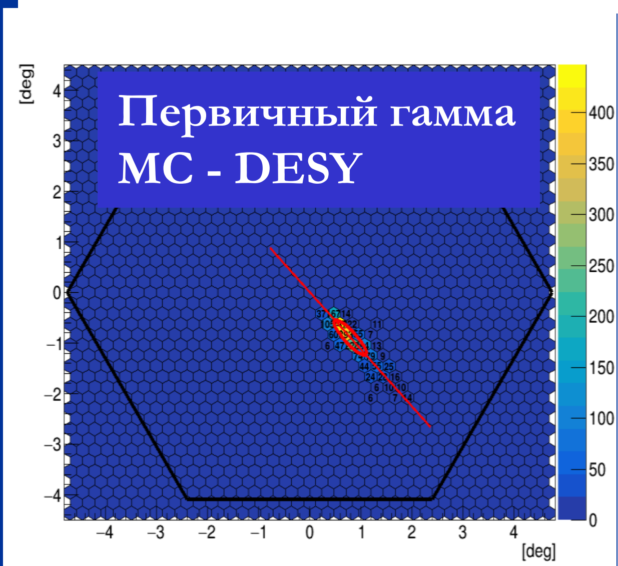
MC simulation of the new SiPM camera in JINR



Красным – протоны, зелёным – гамма.

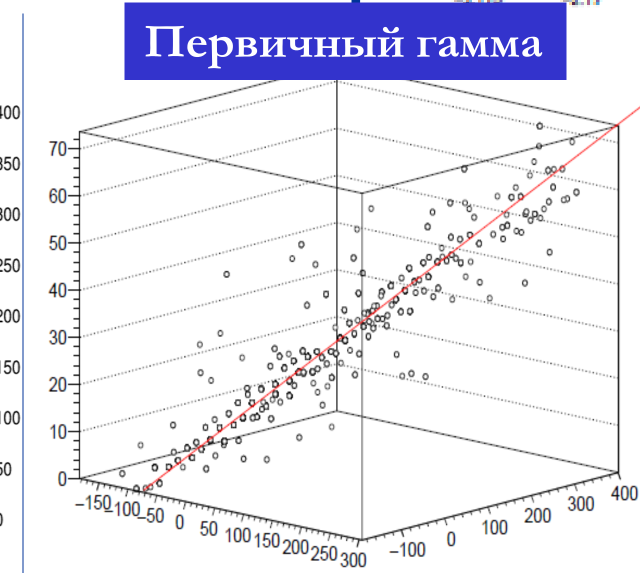
RMS(R_EAS). При врем. разрешении ~1 нс продолжительность сигнала из критериев выделения первичных гамма из адронного фона.



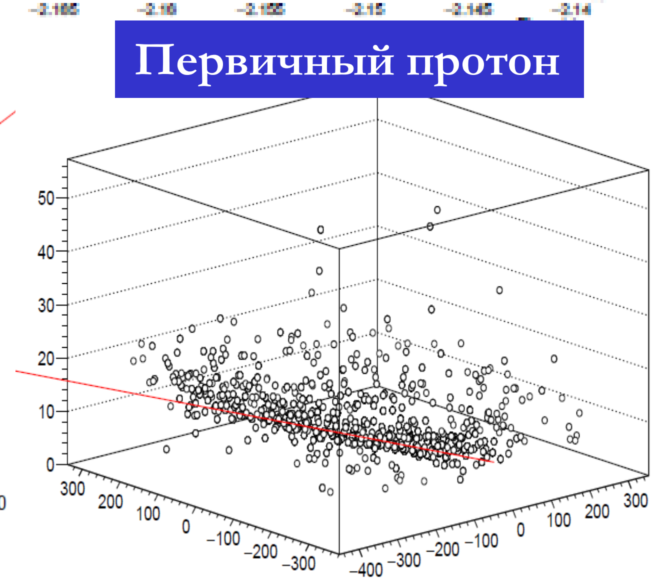


Первичный гамма MC - DESY

Первичный гамма



Первичный протон



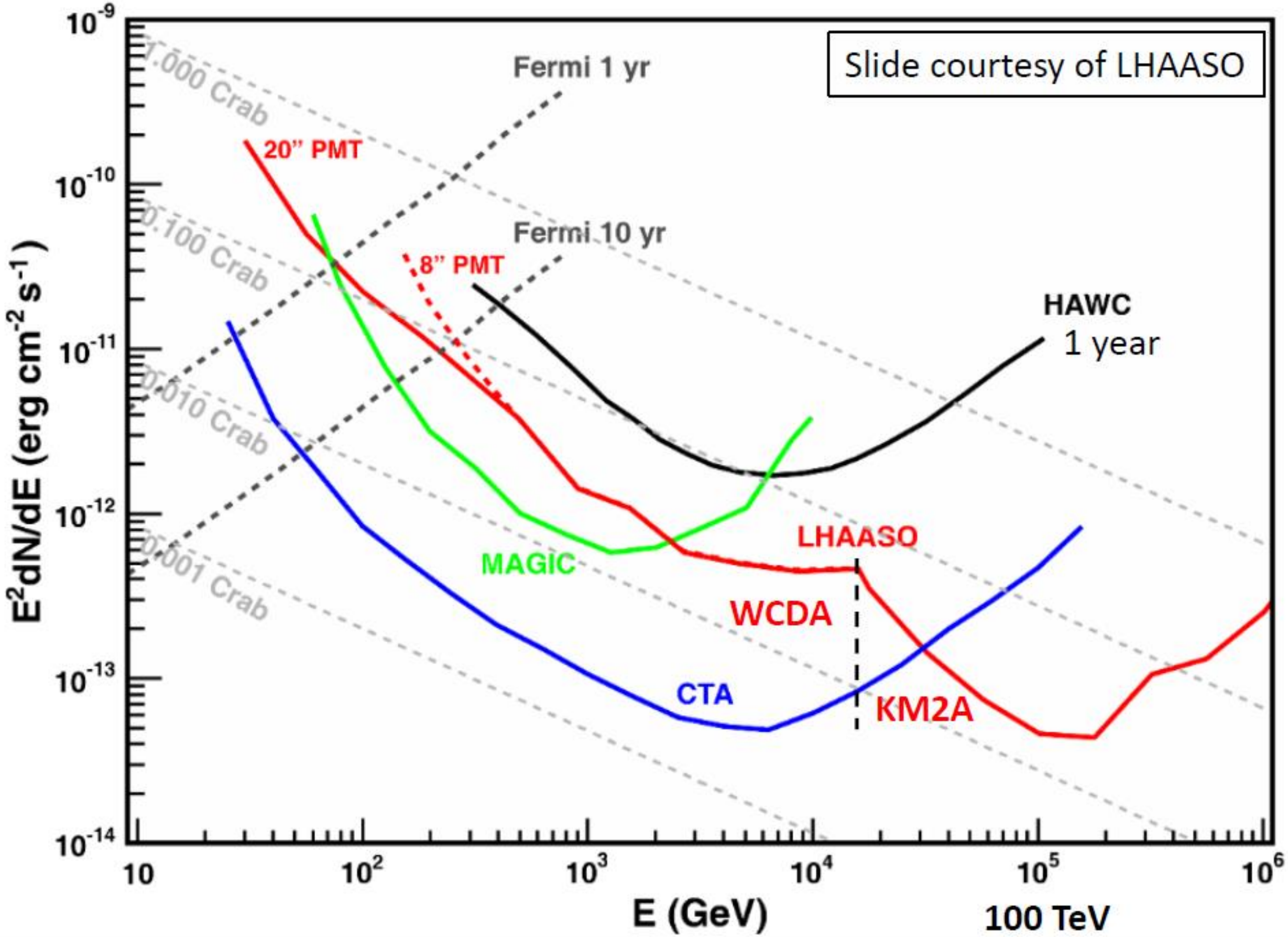
Временная зависимость амплитуды сигнала в каждом пикселе позволяет 3D-фит ливней вместо стандартного 2D-анализа параметров Хилласа

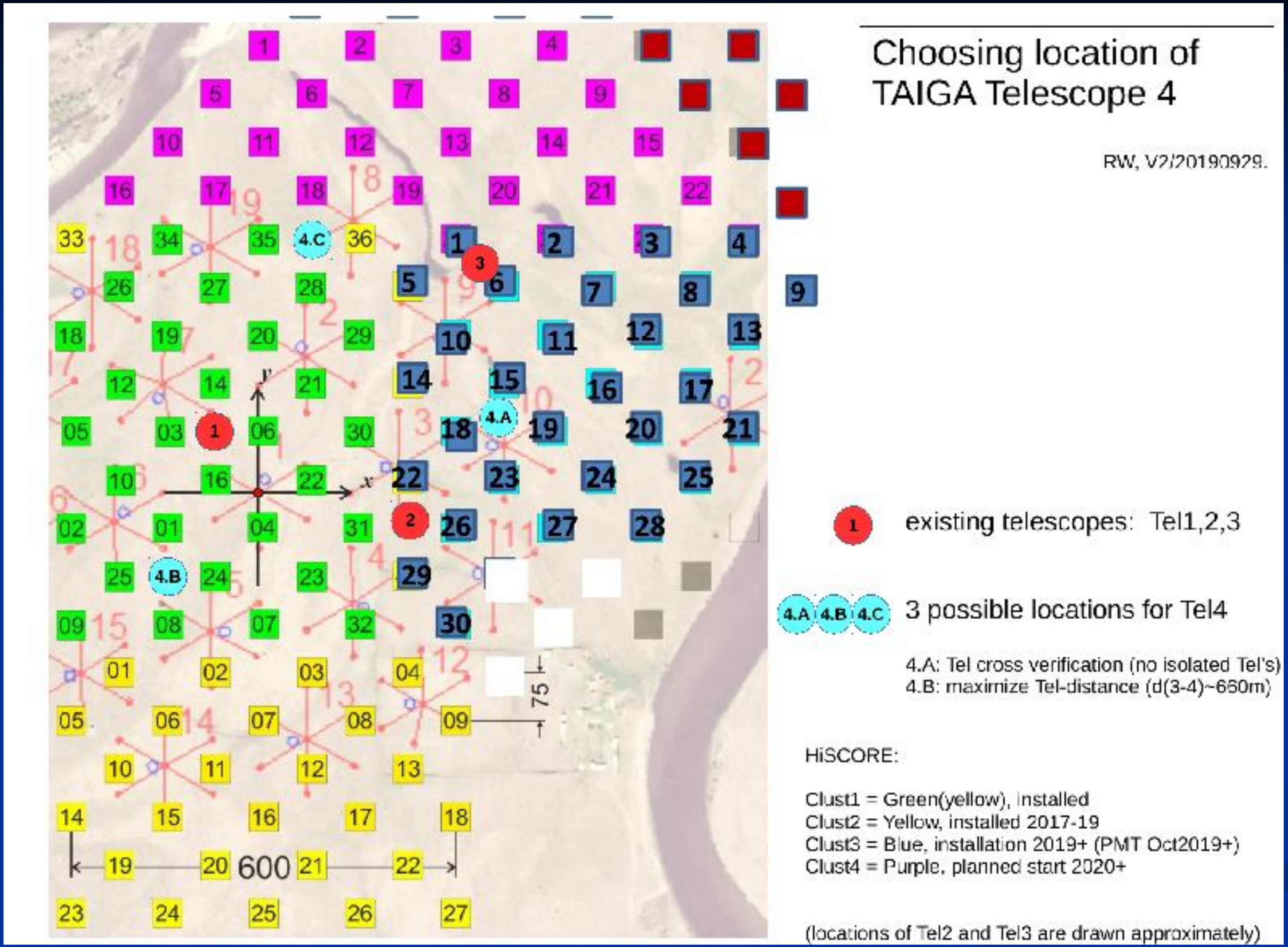
Conclusion

- - Mechanics of 3 IACTs have been designed, produced in JINR and delivered to Tunka astrophysical center at 2016-2020
- Plans for 2021-2023:
- - University of Geneva SiPM camera installation on the 3rd IACT for data taken at Tunka - 2020-2021(КО ЛЯП, Бородин, Сагань, Пан, Гринюк , Журов, Вишневский)
- - 4th IACT fabrication and tests with Dubna's focusing mirror facets -2020-2021 (КО ЛЯП, ЛТ, Бородин, Скрыпник, Пан, Гринюк , Журов, Сагань)
- - 4th IACT delivery and commission at Tunka (ЛТ, Бородин, Пан , Журов)
- - Dubna's group activity - 2020-2023
- in MC simulation (Гринюк, Сатышев, Лаврова, Пан, Порелли)
- in data taken at Tunka area (Сагань, Пан, Журов)
- in physical analysis (ЛТ, Гринюк, Сатышев, Лаврова, Пан, Порелли, Журов, Вишневский, Гребенюк)
- - full TAIGA project observatory preparation (ЛТ, Бородин, Гринюк , Журов, Вишневский)

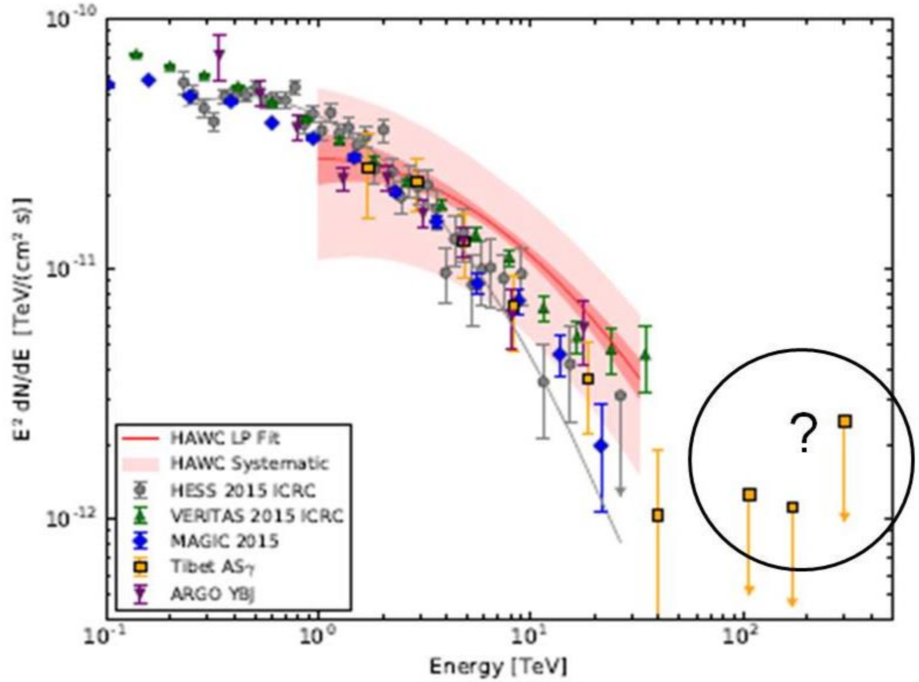
Спасибо за внимание

LHAASO 1 Year sensitivity



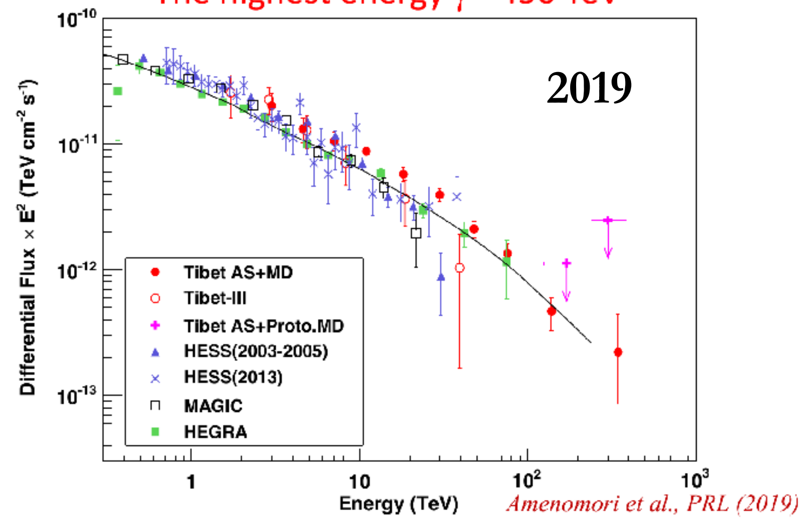


Конфигурация детекторов TAIGA-HiSCORE на конец 2020
4С – место закладки фундамента для 4-го телескопа



Energy spectrum of the Crab

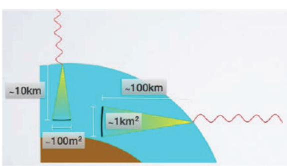
The highest energy γ ~450 TeV



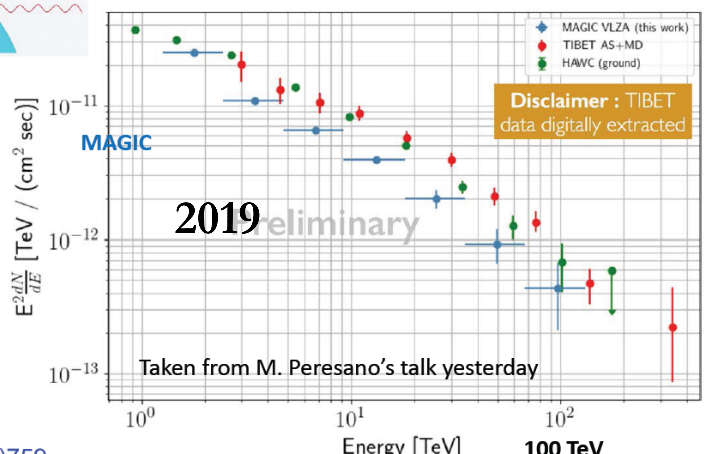
Amenomori et al., PRL (2019)

Thick curve : the expected flux by the inverse Compton model normalized to HEGRA data *Aharonian+, ApJ, 614, 897 (2004)*

IACTs Getting to Higher Energies

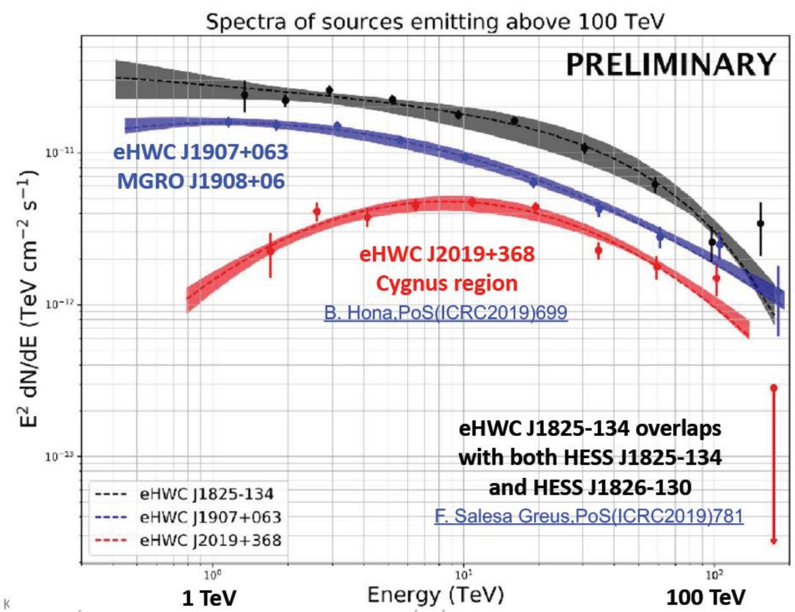


IACTs can observe at very high zenith angles to get to higher energies

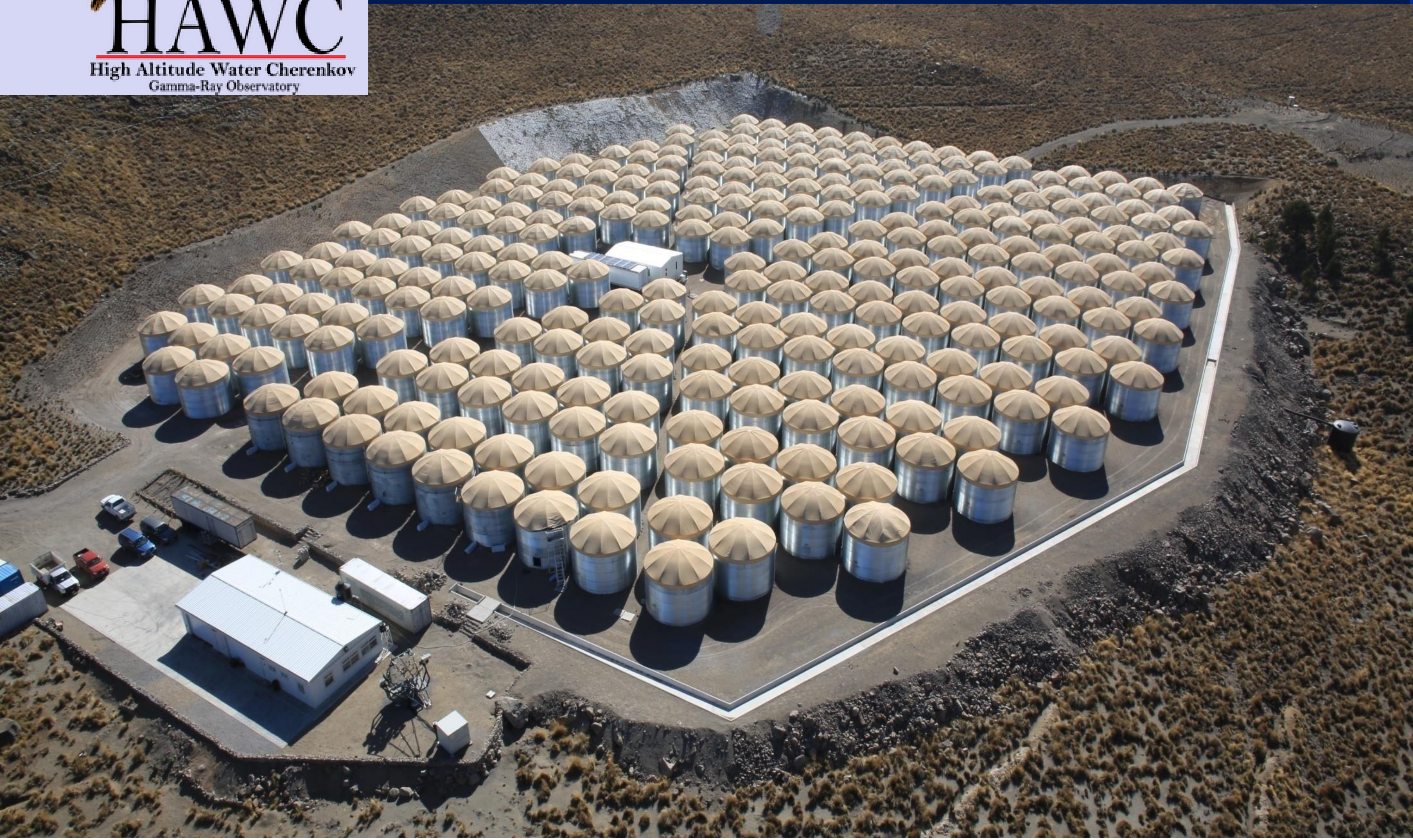


PoS(ICRC2019)759

Spectra of 100 TeV Sources



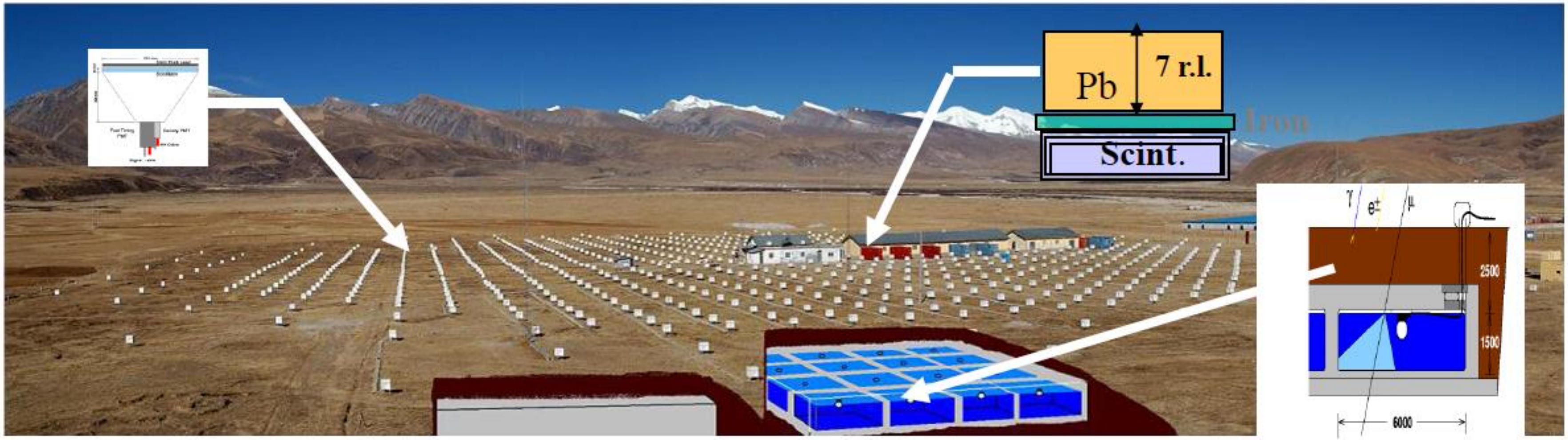
HAWC - 2016

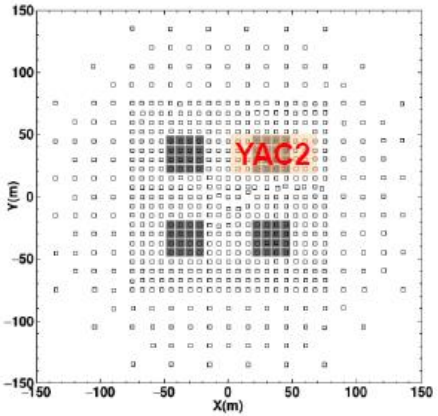


Гамма+CR-телескоп HAWC в Мексике, 160x160 м^2, 4100m a.s.l.

Tibet hybrid experiment (YAC+Tibet-III+MD)

This hybrid experiment consists of low threshold Air shower core array (YAC) and Air Shower (AS) array and Muon Detector (MD) .





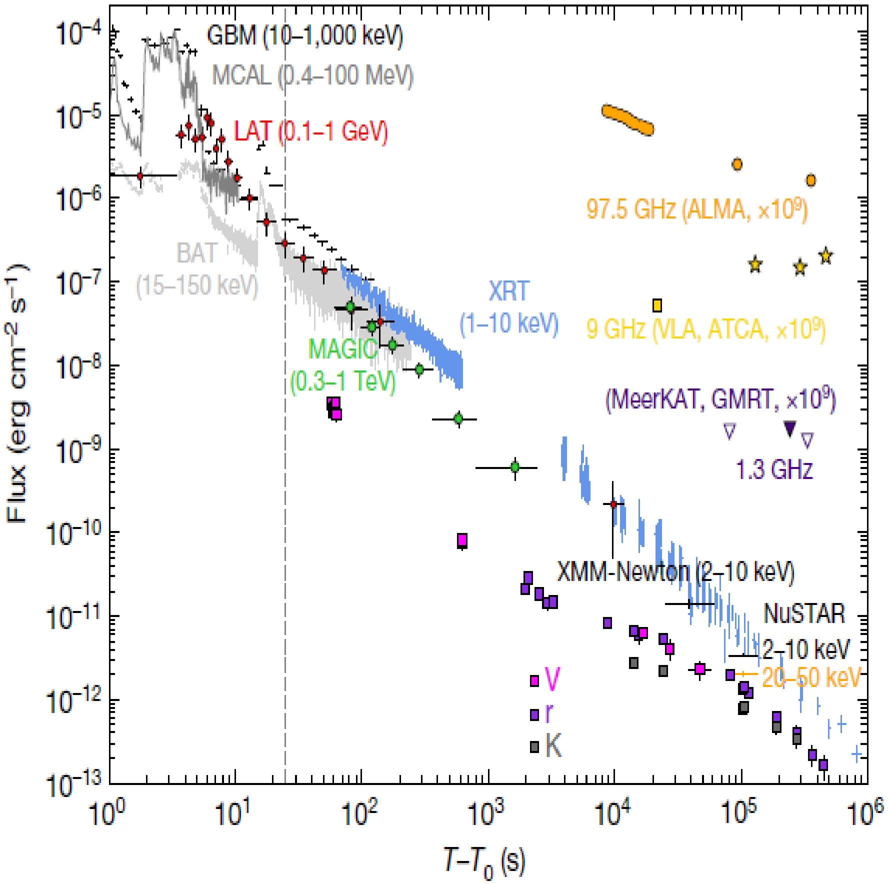
Tibet-III (65700 m^2) : Primary energy and incident direction.

YAC2 (500 m^2): High energy AS core within several x 10m from the axis.

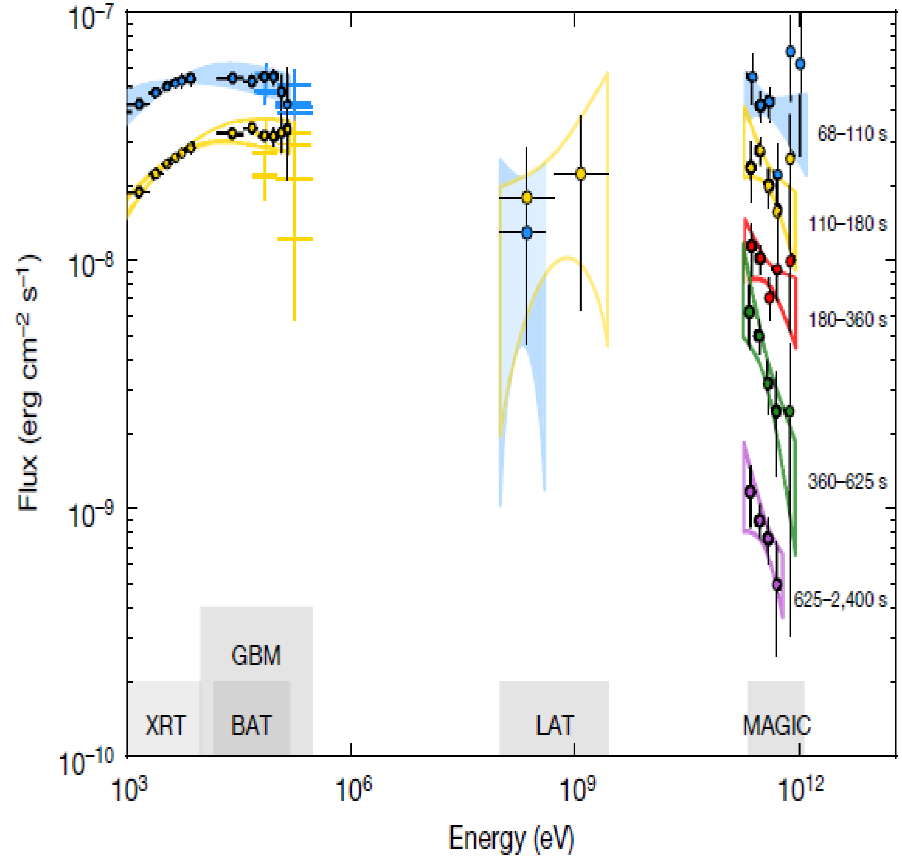
Tibet-MD (3400 m^2) : Number of muon.

Гамма+CR-телескоп Timet-SA-MD 300x300 $м^2$, 4300m a.s.l.

MAGIC Gamma Ray Bursts on 14 January 2019



Multi-wavelength light curves of GRB 190114C



Multi-band spectra in the time interval 68–2,400 s

z = 0.4245 ± 0.0005 (Methods) of the GRB (corresponding to a luminosity distance of about 2.3 Gpc), the γ-ray burst GRB 190114C. γ-rays were observed in the energy range **0.2–1 TeV** from about one minute after the burst (at more than 50 standard deviations in the frst 20 minutes)