JINR participation in the TAIGA project

L.Tkachev

Tunka Advanced Instrument for cosmic rays and Gamma Astronomy - TAIGA

TAIGA Collaboration

Germany
Hamburg University(Hamburg)
DESY (Zeuthen)
MPI (Munich)

Italy
Torino University

Romania
Institute of Space Science

Poland
Warsaw University

Russia
MSU(SINP)(Moscow)
ISU (API) (Irkutsk)
INR RAS(Moscow)
MEPHI(Moscow)
IZMIRAN(Moscow)
NSU+BINP Novosibirsk
+
JINR (Dubna)

TAIGA is one of the rare case where Western scientists join a Russia-based experiment ~ 70 authors in total

JINR authors:
V. Boreyko, A.Gorbunov, A.Demenko, N. Gorbunov, V. Grebenyuk, A. Grinyuk, A. Kalinin, M.Lavrova, S. Porokhovoy, V.Romanov, Ya.Sagan, B. Sabirov, S. Slepnyov, M. Slunecka, V.Temirbulatov, A. Tkachenko, L. Tkachev

The main topics of the TAIGA array

Multi –TeV gamma-ray astronomy

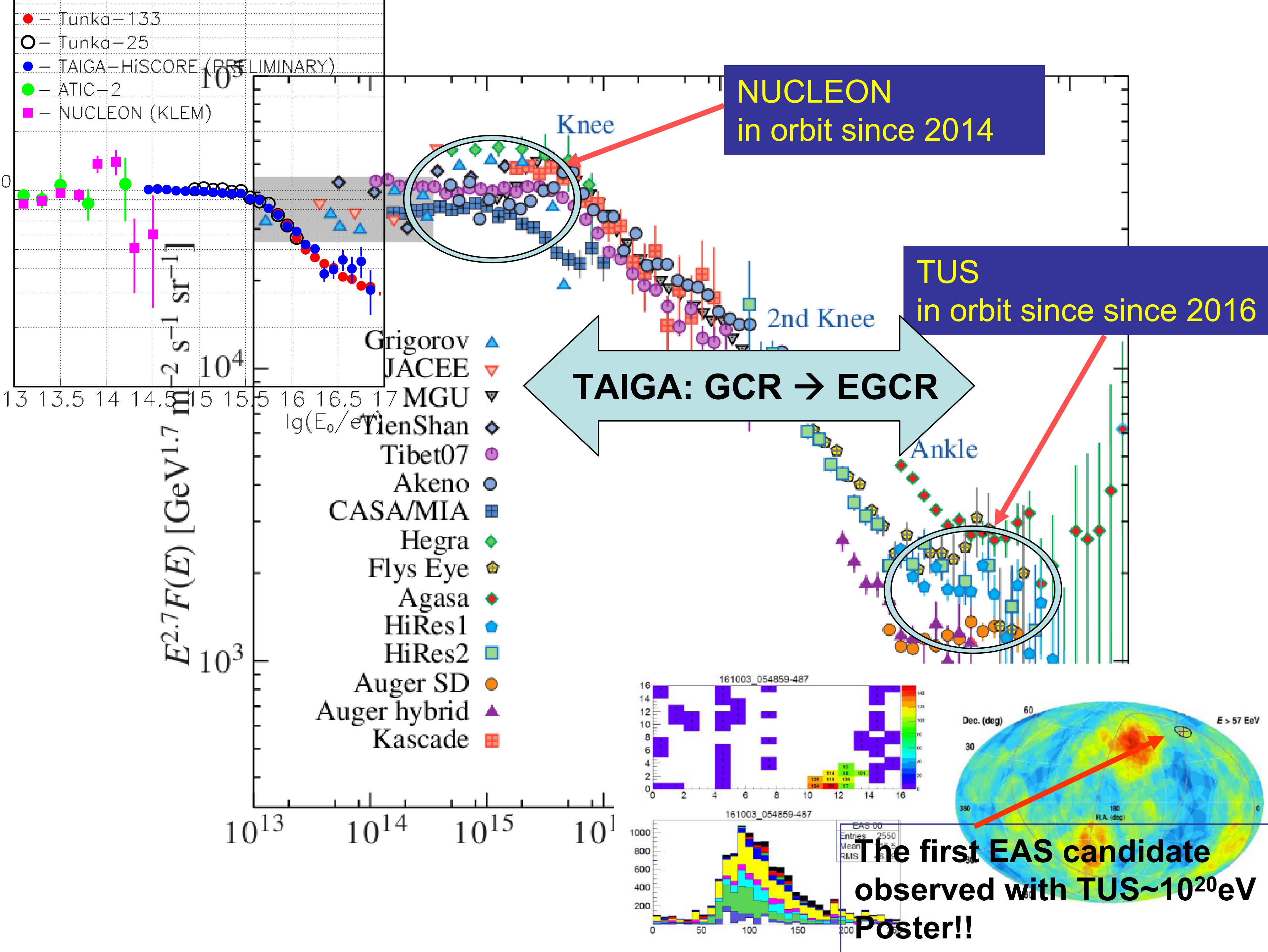
- a search for galactic objects for accelerating of particles up to PeV-energies (the so-called Pevatrons);
- a measurement VHE spectra of known sources: where do they stop;
- a measurement diffuse emission from galactic plane and local supercluster.

Charged cosmic ray physics

- Study of the energy spectrum and mass composition measurements from 10^{14} to 10^{18} eV at very high statistical level

Particle physics

-
- axion/photon conversion;
- Lorentz invariance violation;
- pp and pA cross-section measurement;
- search for quark-gluon plasma phenomena;
- indirect search of dark matter particles



NUCLEON
in orbit since 2014

TUS
in orbit since since 2016

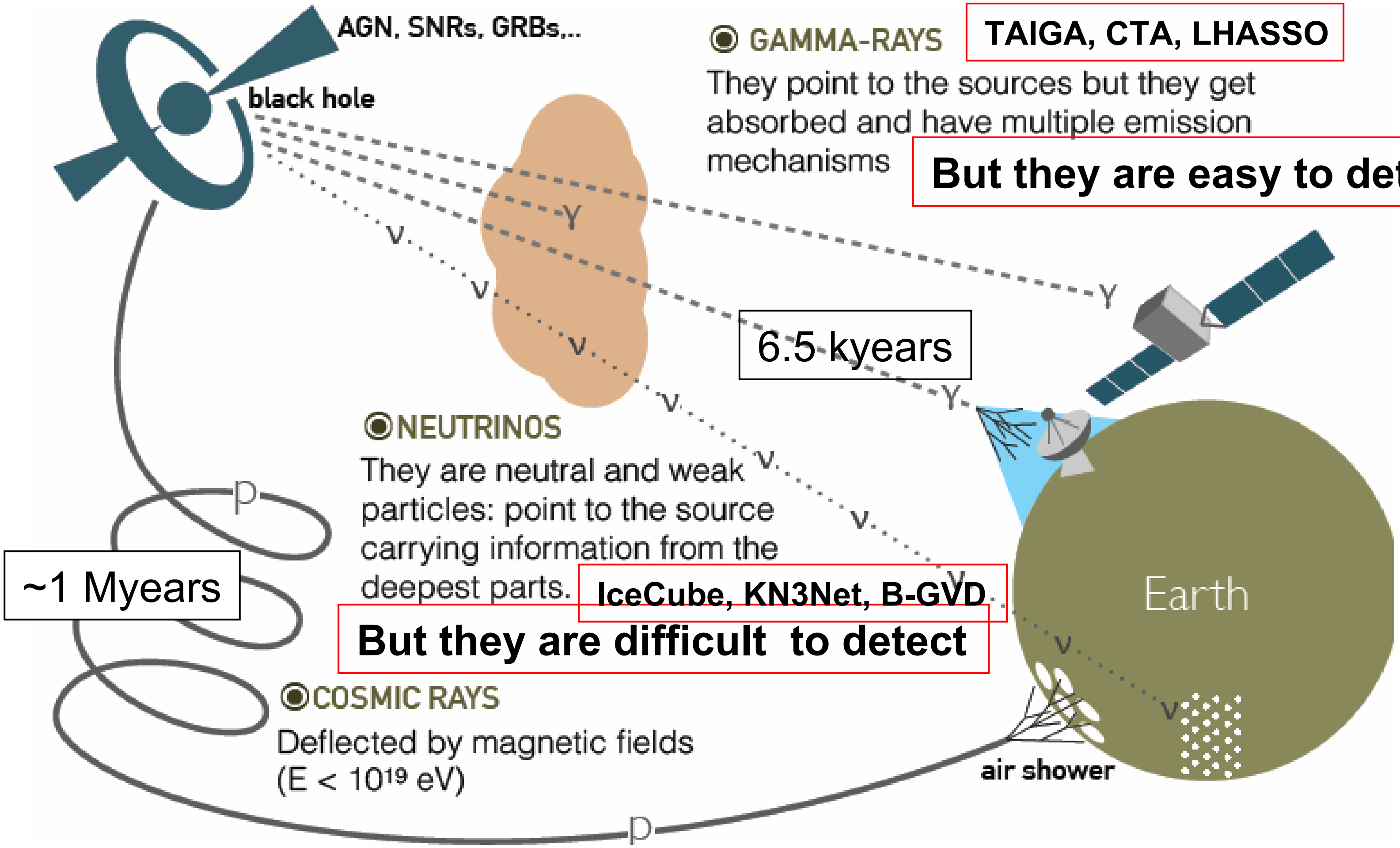
TAIGA: GCR → EGCR

The first EAS candidate observed with TUS~10^{20}eV

Poster!!

Why gamma-ray astronomy?

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



◉ GAMMA-RAYS **TAIGA, CTA, LHASSO**

They point to the sources but they get absorbed and have multiple emission mechanisms

But they are easy to detect

6.5 kyears

◉ NEUTRINOS

They are neutral and weak particles: point to the source carrying information from the deepest parts.

IceCube, KN3Net, B-GVD

But they are difficult to detect

~1 Myears

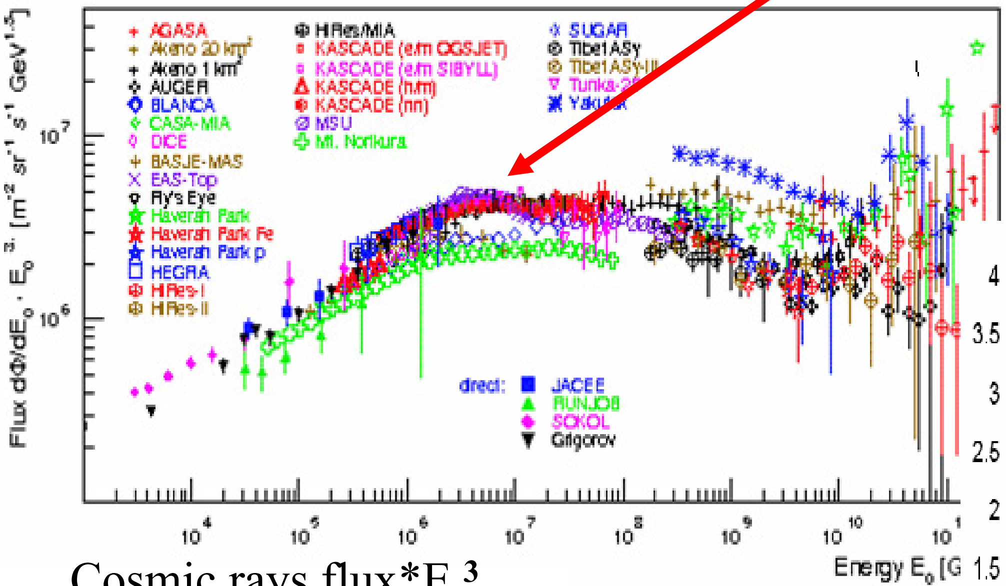
◉ COSMIC RAYS

Deflected by magnetic fields ($E < 10^{19}$ eV)

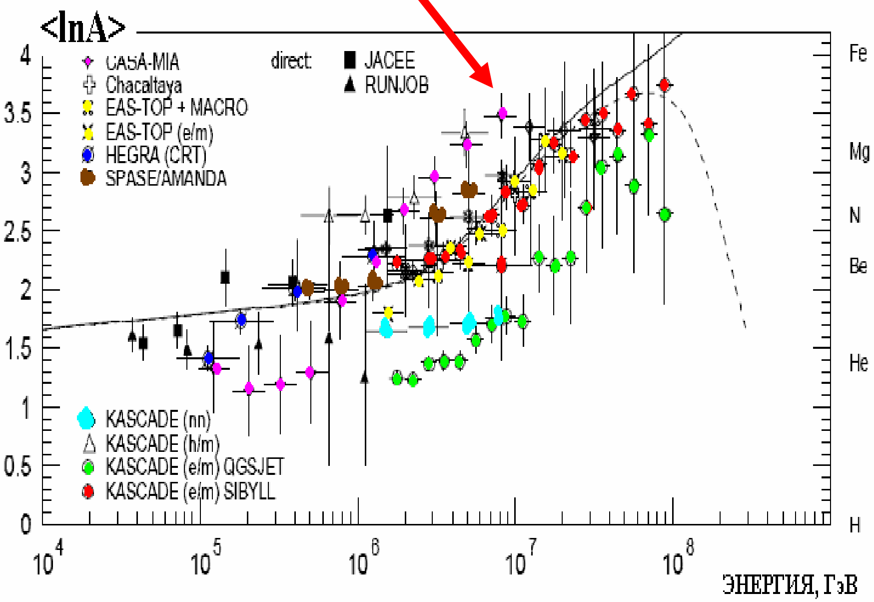
Motivation:

1. There is a large difference in data for the CR nuclear component flux and composition around of the knee region
2. No direct measurement data around knee

Knee

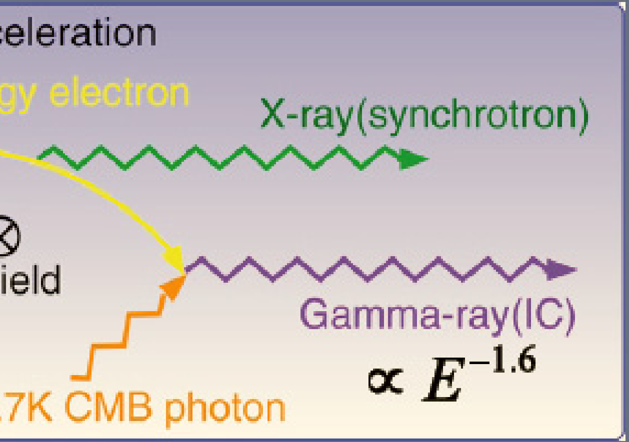


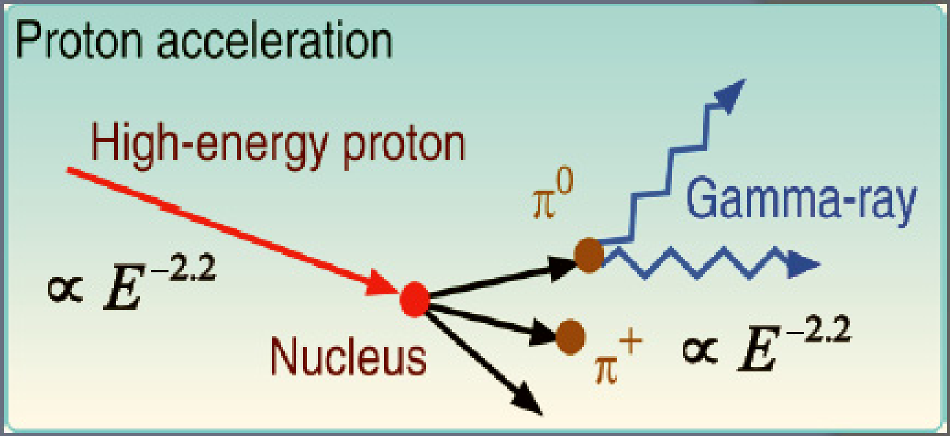
Cosmic rays flux*E ^{3}

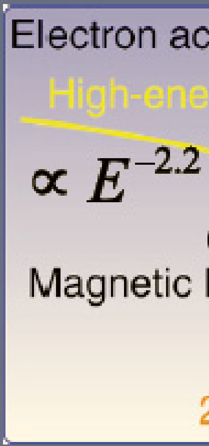


Change of the CR composition at the knee region

Gamma-Ray Emission Processes(1)
Astrophysical process

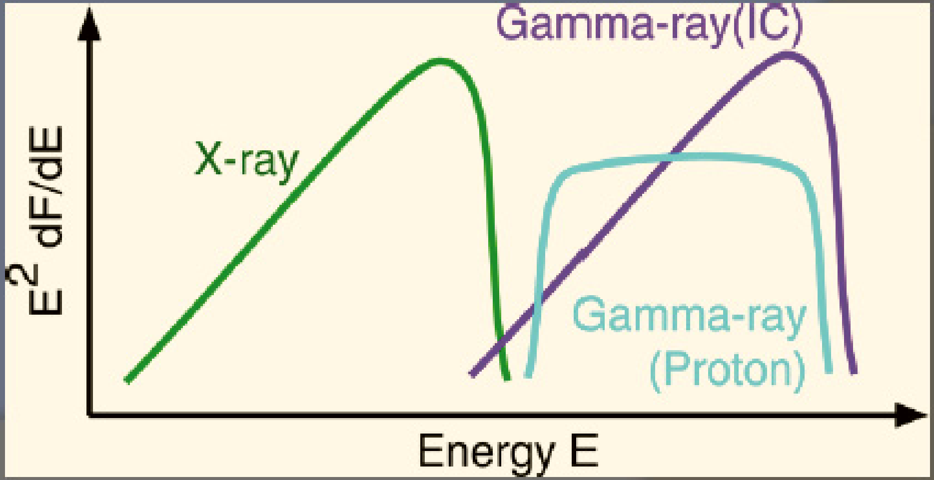






$$= \frac{4}{3}\sigma_T c\tilde{a}^2_{\max} U_{\text{photon}}$$

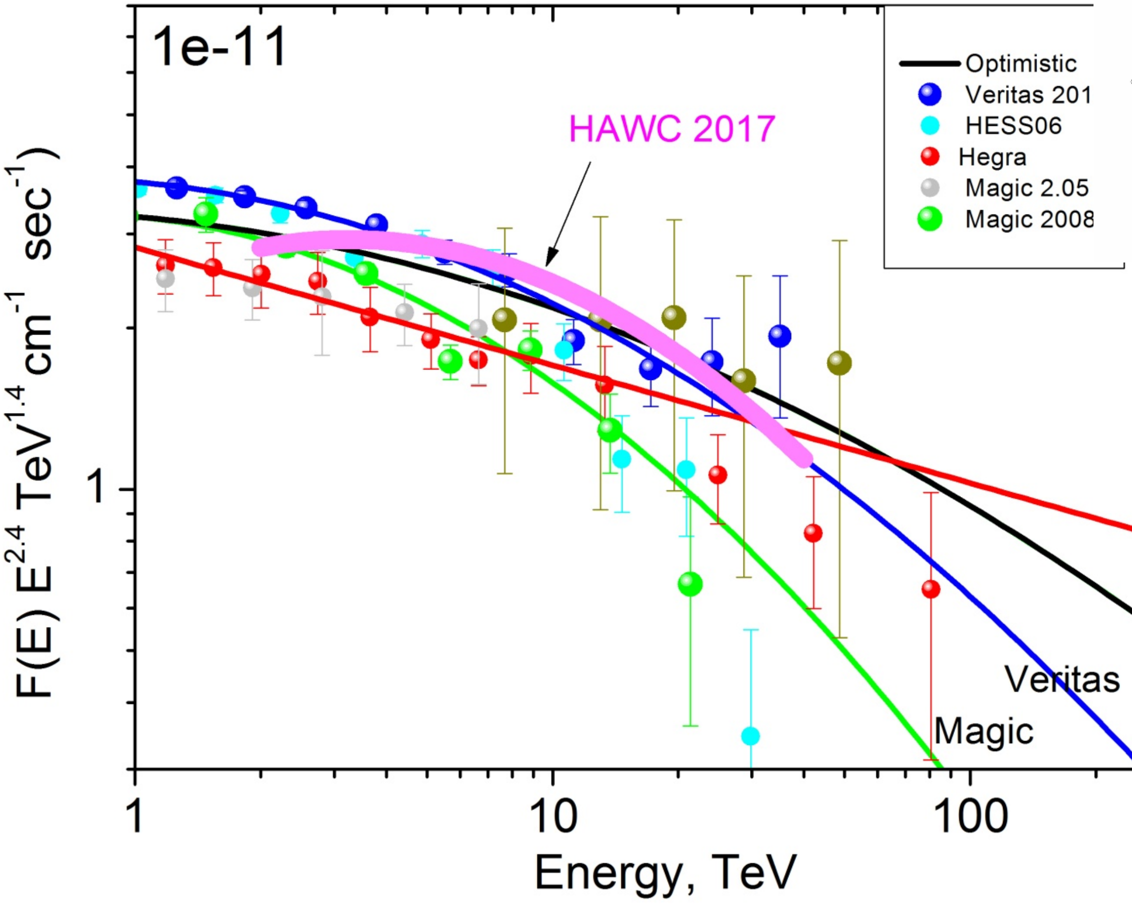
$$= \frac{4}{3}\sigma_T c\tilde{a}^2_{\max}\frac{B^2}{2}$$

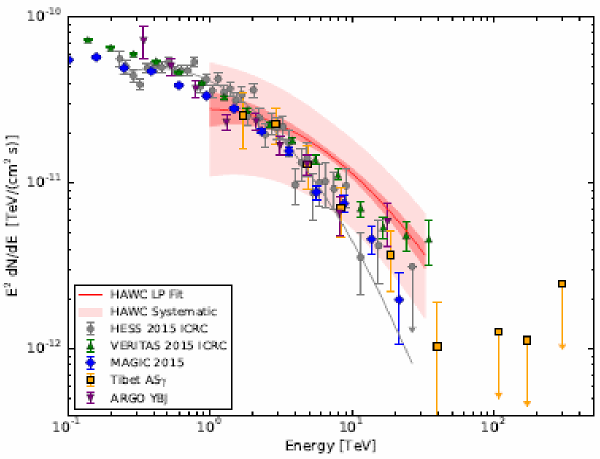


$$\left(\frac{dE}{dt}\right)_{\text{I.C}}$$

$$\left(\frac{dE}{dt}\right)_{\text{Sy}}$$

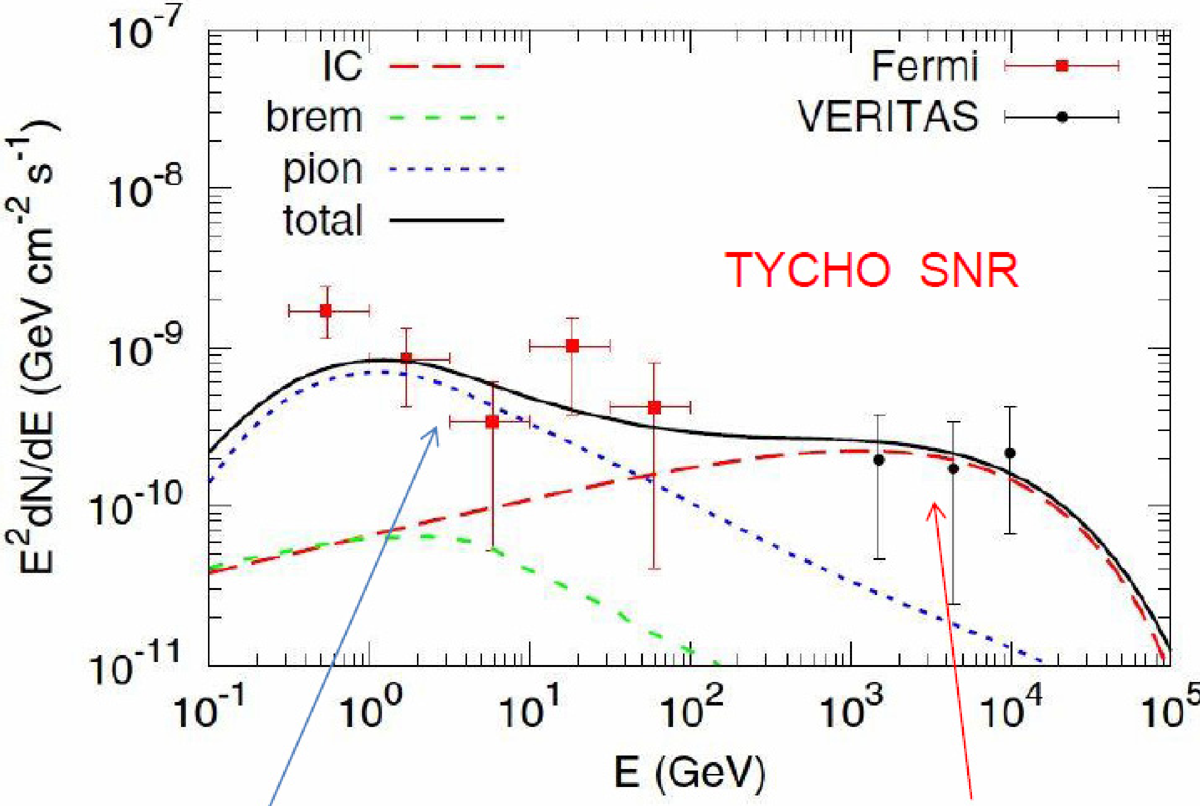
VHE Crab spectrum obtained up to now:





The Crab Nebula is the brightest TeV gamma-ray source in the sky and has been used for the past 25 years as a a reference source in TeV astronomy, for calibration and verification of new TeV instruments.

Hadronic + leptonic



Yuan et al., 2013

Hadronic emission
π^0 decay

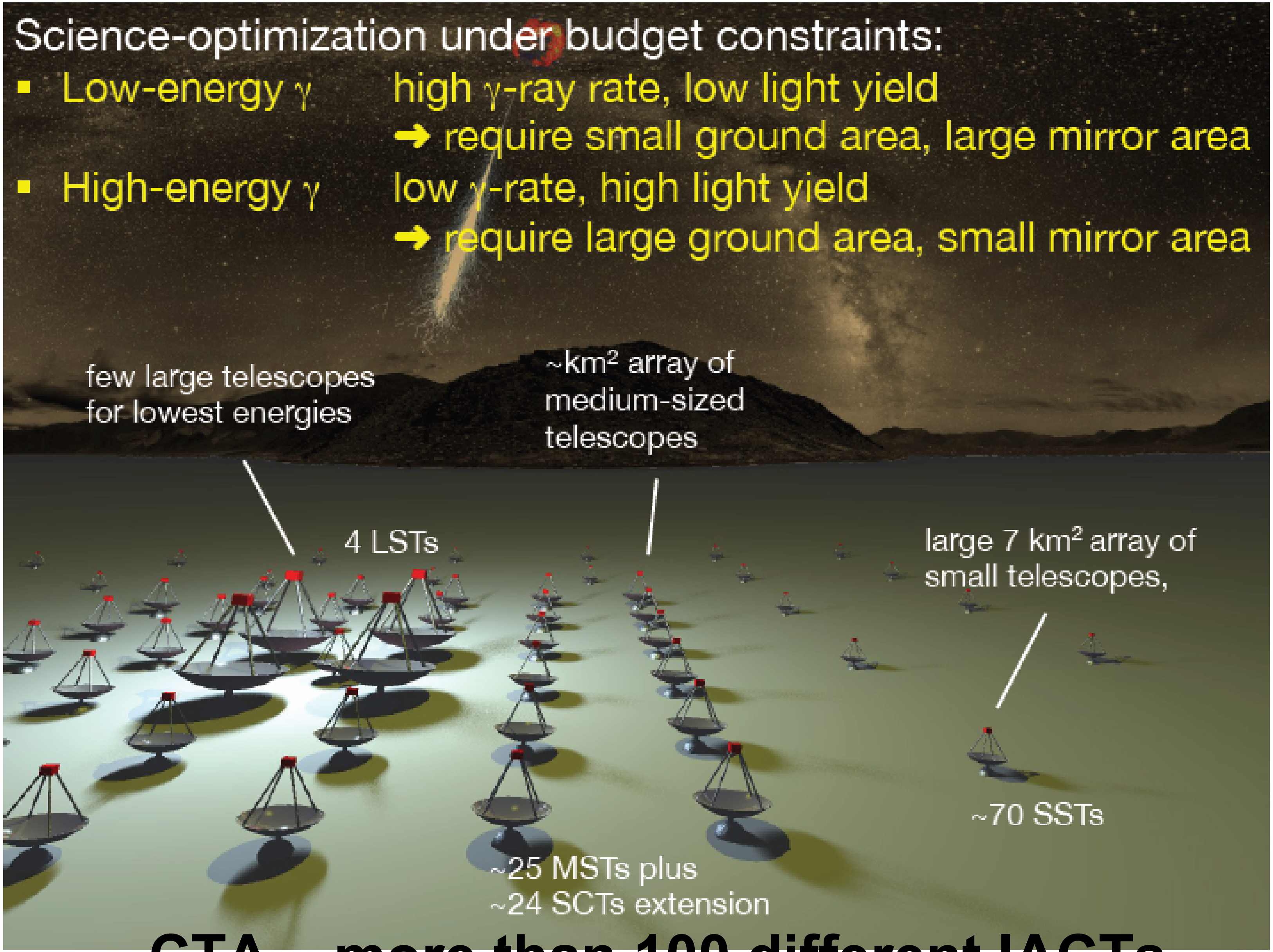
Leptonic emission
Electron Inverse Co
cutoff in the electron

mpton with a
n spectrum

Energy spectrum of gamma:
$\sim E^{-2}$

For Multi-Tev Gamma – ray astronomy we need array with **area more than 1 km²**

CTA (Cherenkov Telescope Array) approach



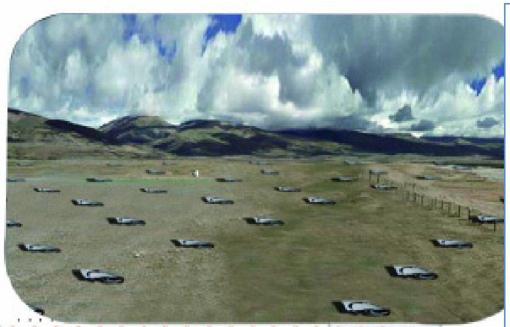
Science-optimization under budget constraints:

- Low-energy γ high γ-ray rate, low light yield
  ➜ require small ground area, large mirror area
- High-energy γ low γ-rate, high light yield
  ➜ require large ground area, small mirror area

CTA – more than 100 different IACTs

LHAASO – A multi component experiment

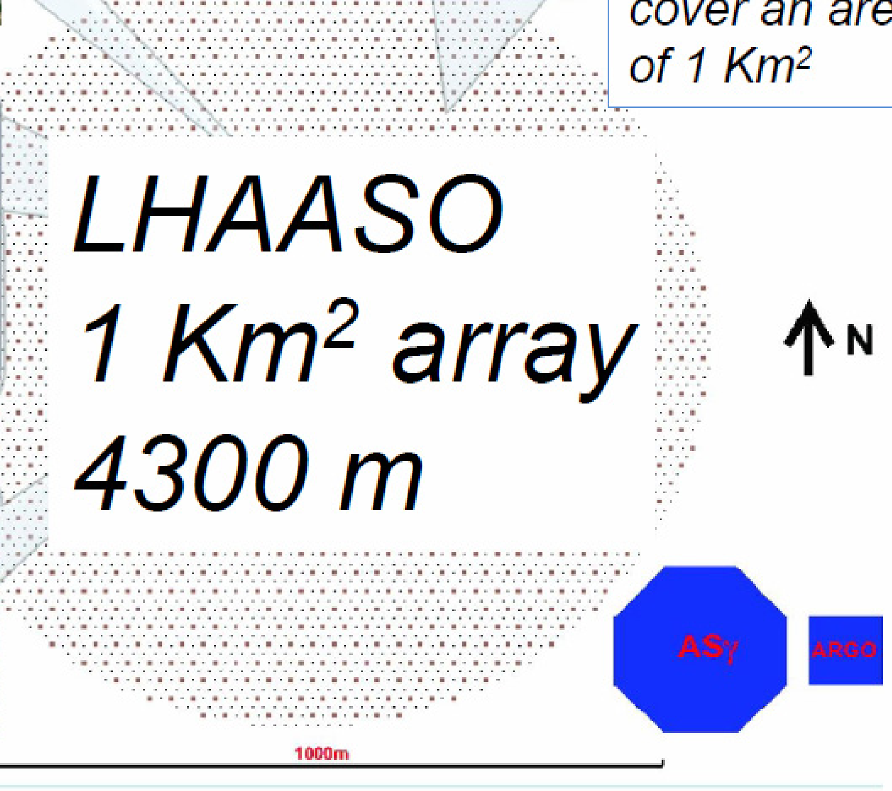
Four 90000 m^2 Water Cherenkov detectors. Each one has the size of HAWC



6100 scintillator detectors and 1200 μ detectors cover an area of 1 Km^2

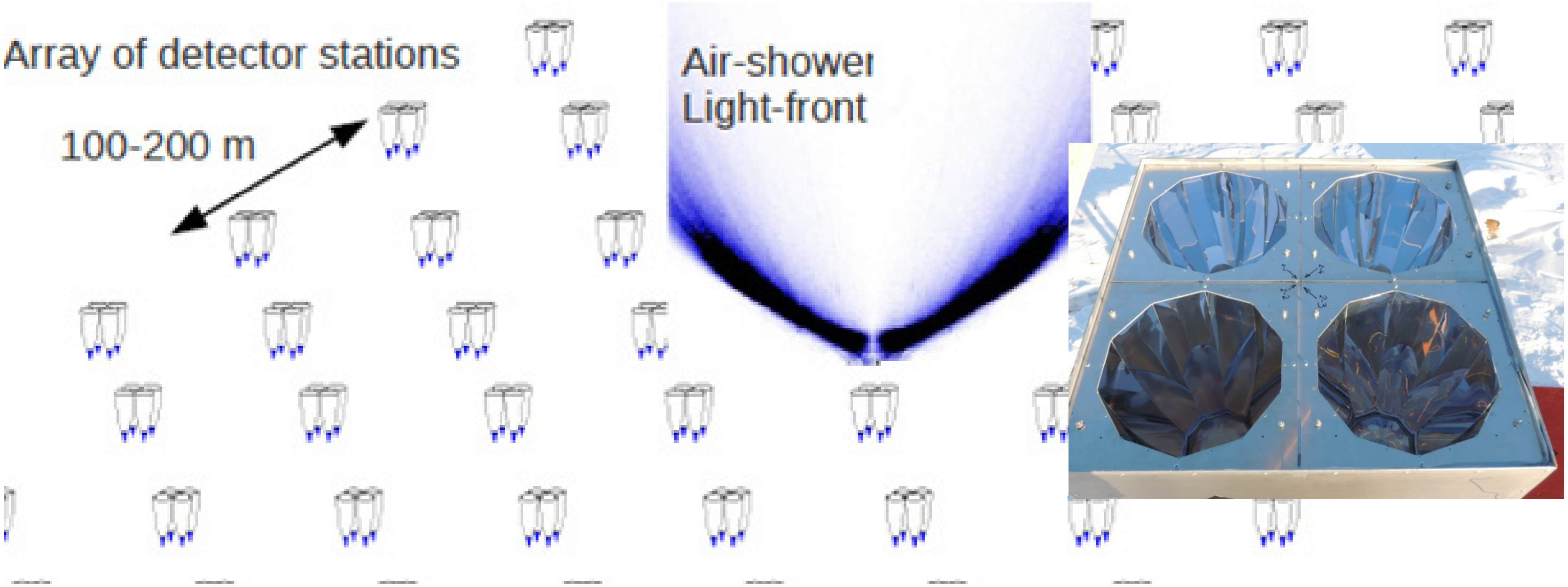
24 Wide FOV air Cherenkov image Telescopes

400 burst detectors for high energy secondary particles near the core of showers



LHAASO
1 Km^2 array
4300 m

Concept of HiSCORE approach

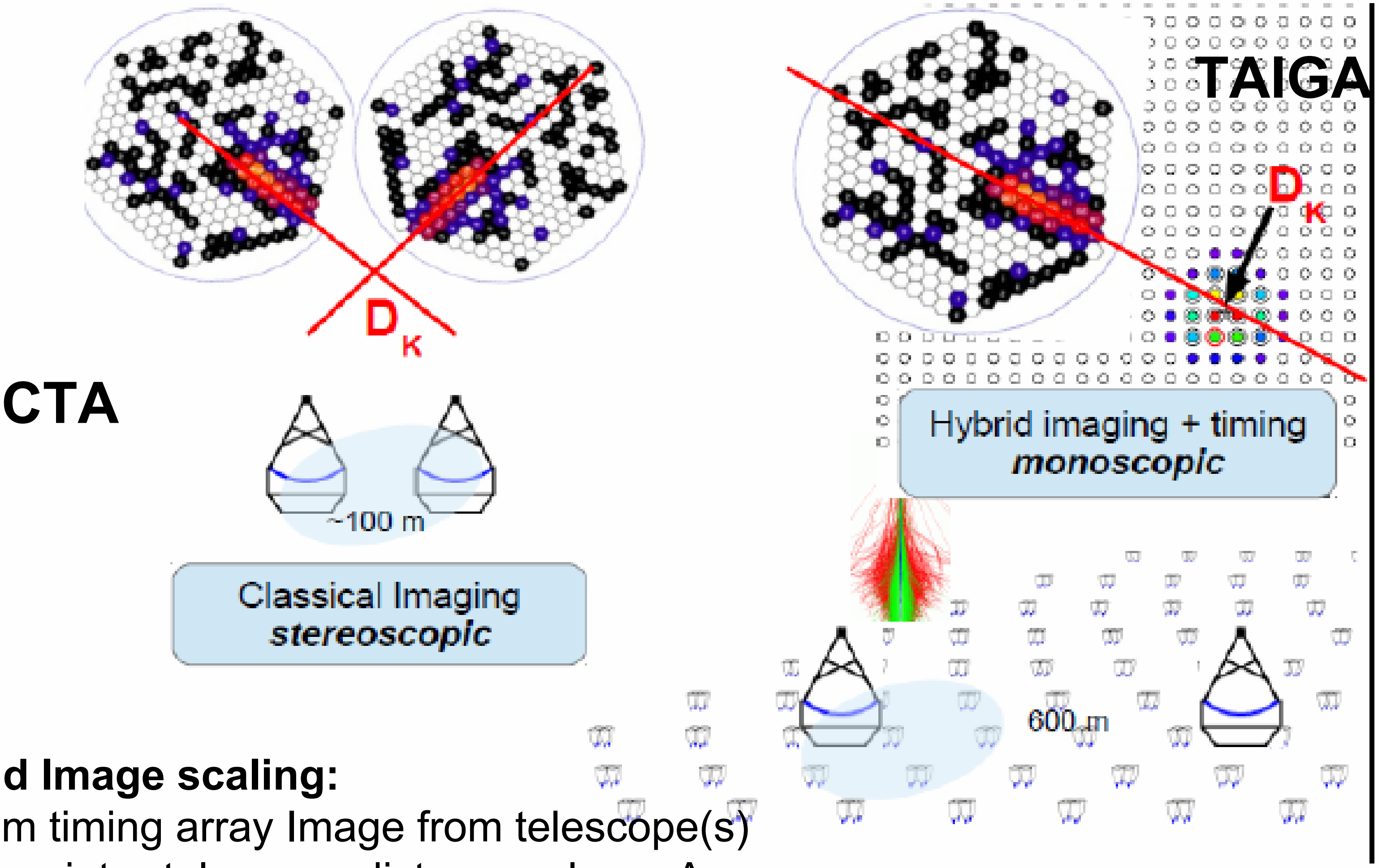


-Excellent angular resolution,- up to 0.1 degree
 - energy threshold – down to 30 TeV .
 -Field of View (FOV) – 0.6 sr (±30 deq)
- Low cost of each station – possibility to cover large area

HiSCORE – Hundred* i Square-km
Cosmic Origin Explorer

But: some problems with background suppression at low energies !

Hybrid approach to hadron rejection



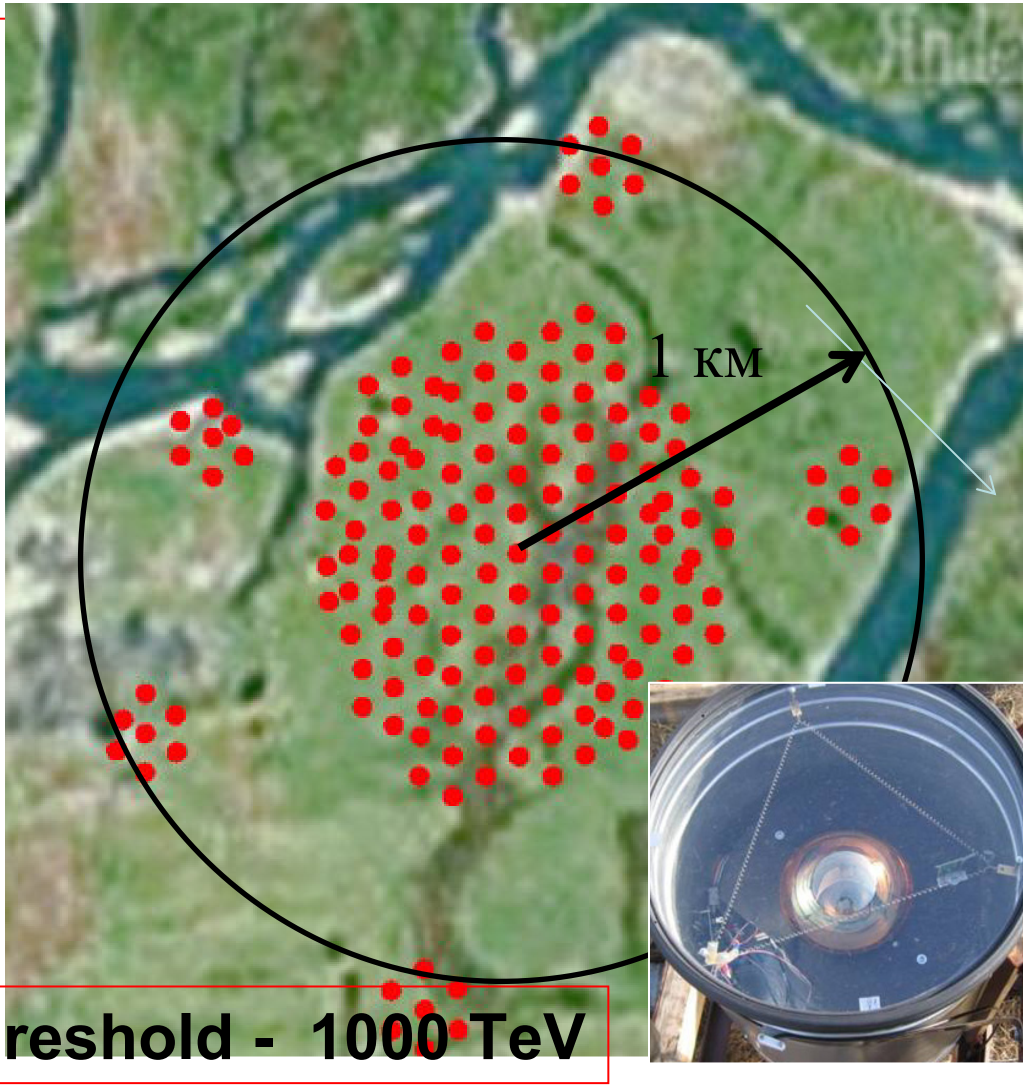
Hybrid Image scaling:

D_K from timing array Image from telescope(s)

1) large inter-telescope distance = large A_{eff},
2) scaled width separation parameter

Tunka-133 array:
175 optical detectors on 3 km^2 area

51° 48' 35" N
103° 04' 02" E
675 m a.s.l.



Energy threshold - 1000 TeV

Array of **63 antennas**

TAIGA gamma-observatory

+

+

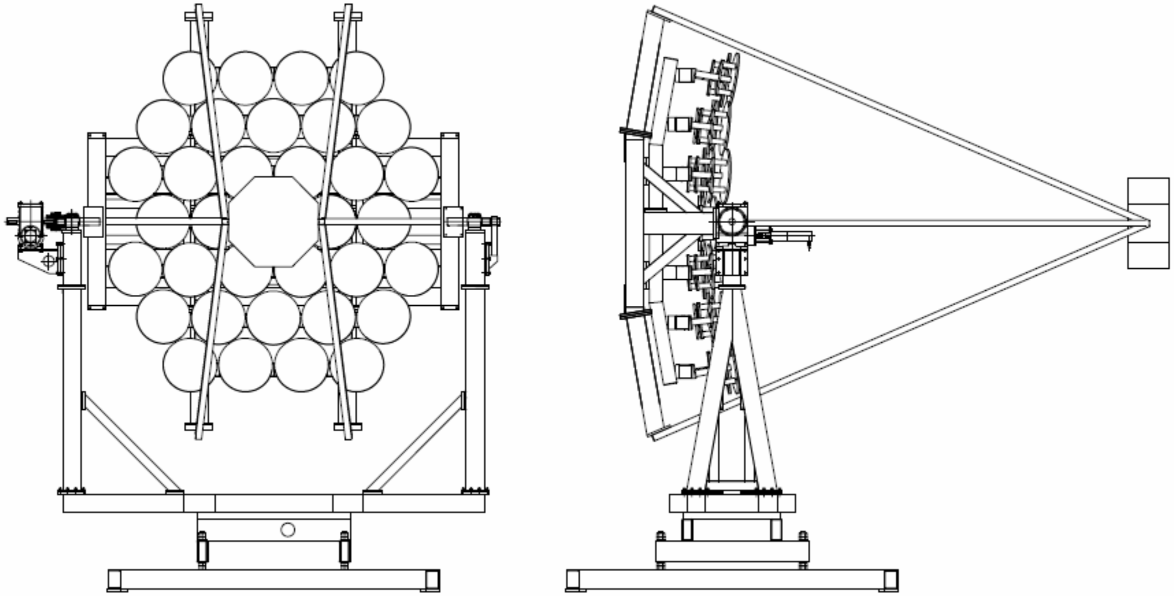
500 wide angle optical stations n the 5 km^2 area, energy hreshold 30 TeV

- **up to 16 IACT (10 m^2 mirrors).**

- **Muon detectors with total area 2.0 10^3 m^2.**

Tunka-REX: TUNKA Radio EXtension
Cosmic and g-rays for E ≥ 10^{15} eV
Array of 63 antennas

IACT fabrication in JINR, Dubna



The mechanical structure of the TAIGA-1 IACT in a workshop hall of the JINR in Dubna in June 2016

IACT insallation in Tunka

26.08.2016

TAIGA-IACT

D = 4.32m F = 4.75m

34 mirrors of 60 cm diameters (now only 6)

Camera : 547 PMTs (XP 1911) with 15 mm useful diameter of photocathode
Winston cone: 30 mm input size, 15 output size
1 single pixel = 0.36 deg
full angular size 9.6x9.6 deg

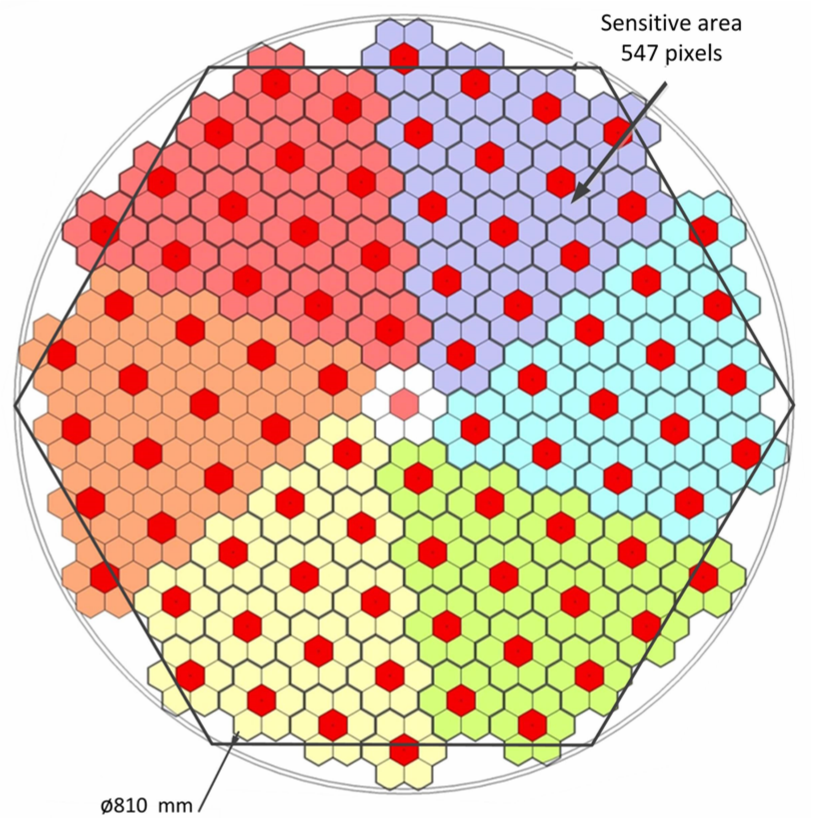
Energy threshold ~1.5 TeV

Tunka-IACT setup

Mirror:
- Davies-Cotton optic type
- Focal length: 4750 mm
- 34 spherical mirror segments
- Diameter of each segment: 60 cm
- Diameter of the mirror: 4.3 m

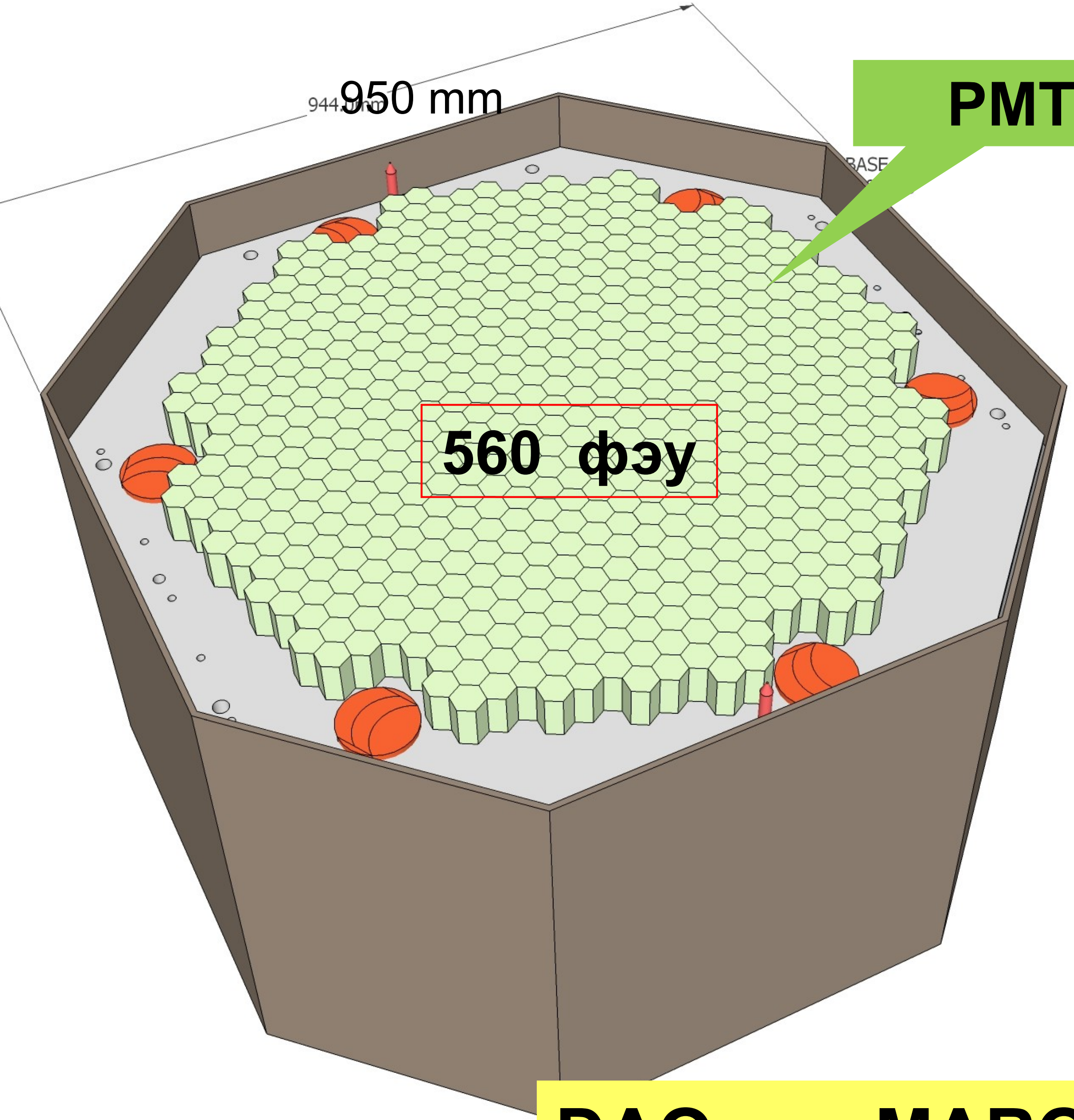
Camera:
- 547 hexagonal-shaped pixels
- PMT XP1911: window of DIA 15 mm
- Winston cone: 30 mm input size, 15 mm output
- FOV of single pixel: 0.36°
- Full FOV: 9.72°

Camera



Operation at the conditions of hard Siberian winter!!!

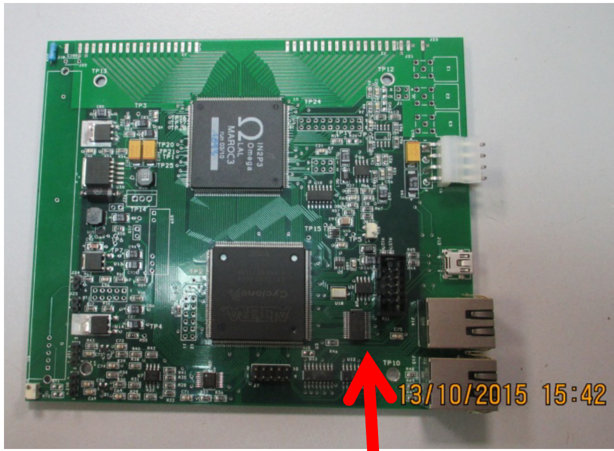
Camera of the TAIGA-IACT

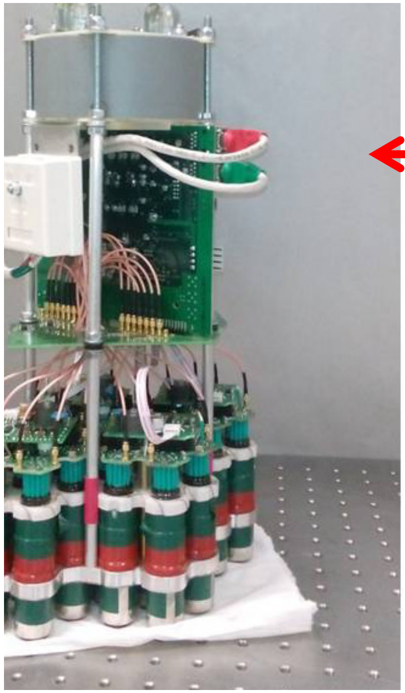


950 mm

PMT

560 фэу





**Maroc-3
64 channel
board**

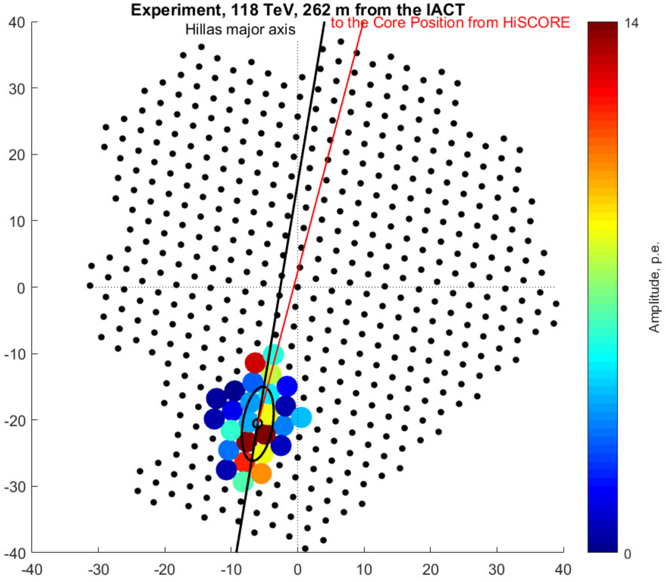
DAQ - MAROC3

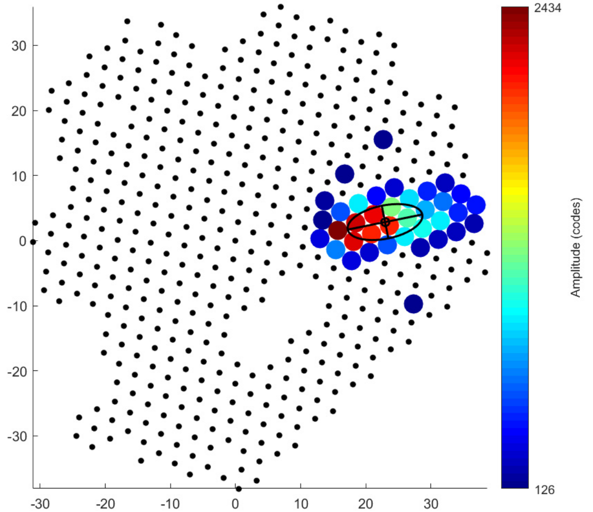
Cluster – 28 PMTs

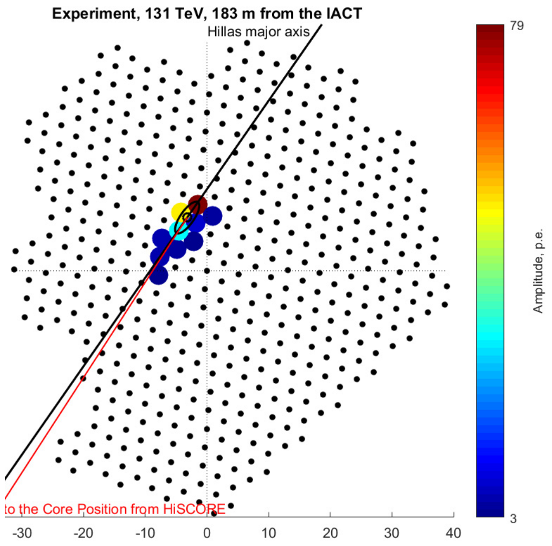
Left : Cluster of 28 PMTs.

Right: The first TAIGA-IACT

IACT + HiSCORE results of 2016

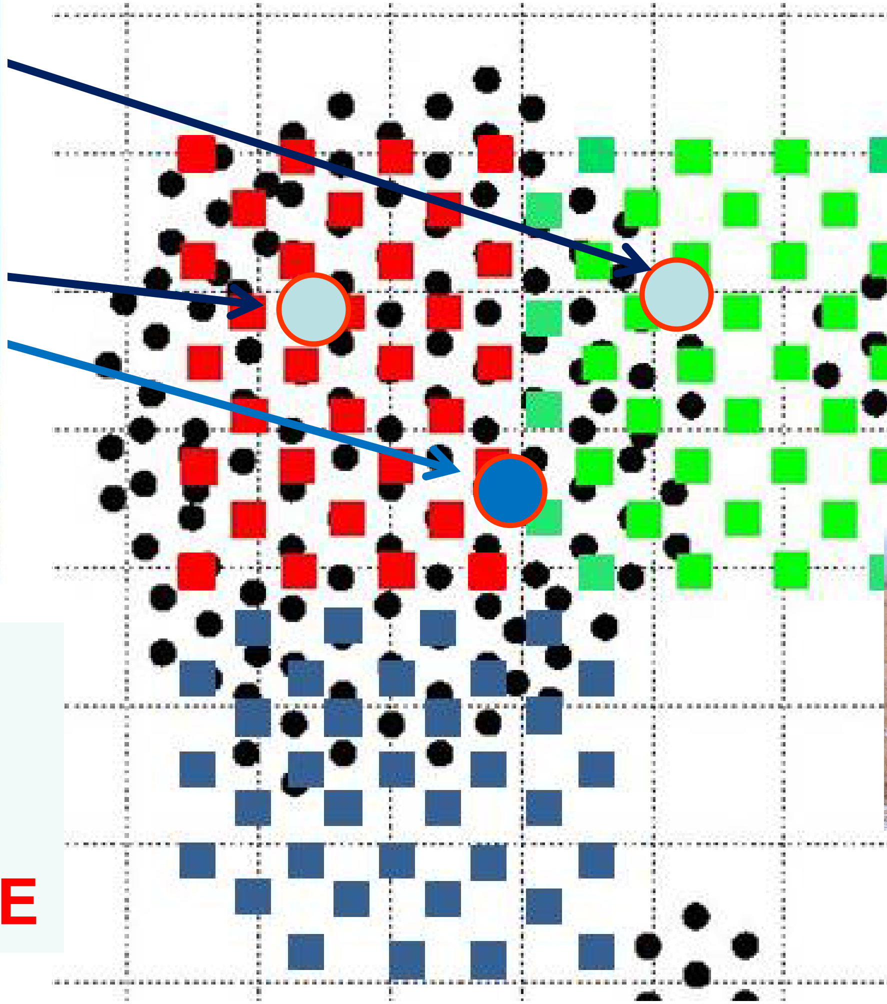






A few showers registered both by IACT and by TAIGA-HiSCORE. One of the I mages of showers. The energy of these shower is 700 TeV.

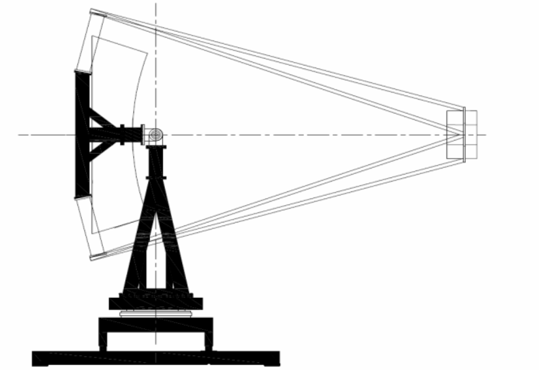
Plan for TAIGA on 2018-2019

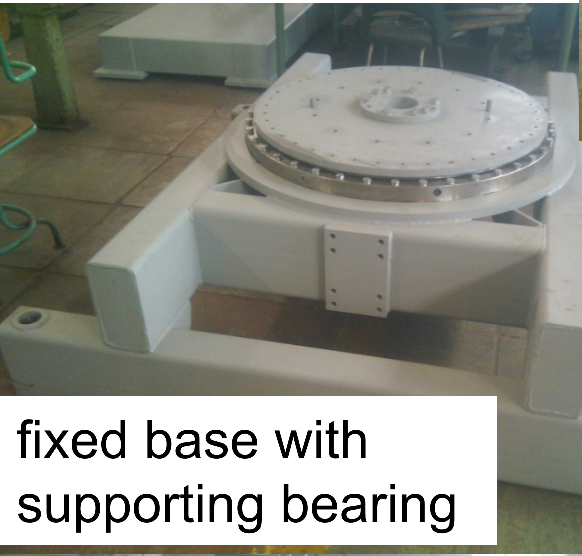


3 telescopes TAIGA-IACT

100 station TAIGA-HiSCORE

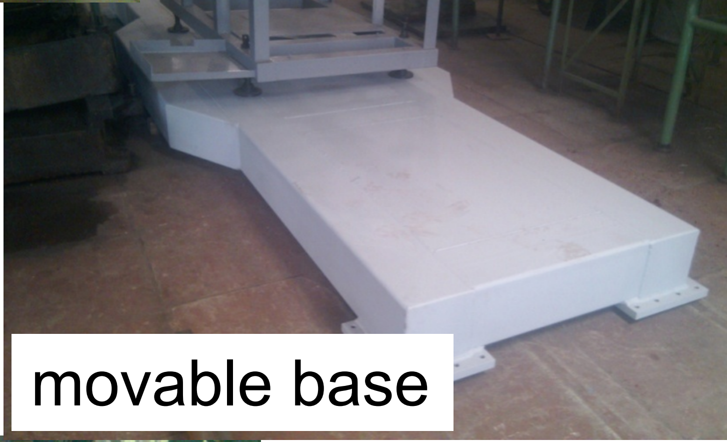
IACT2. Movable base fabrication. New paint.





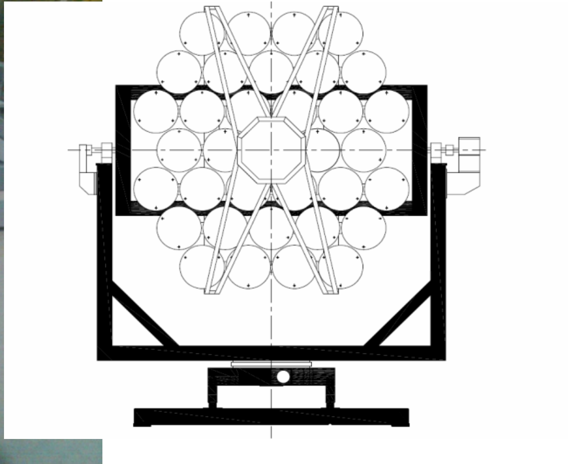
fixed base with supporting bearing

Second IACT production at JINR

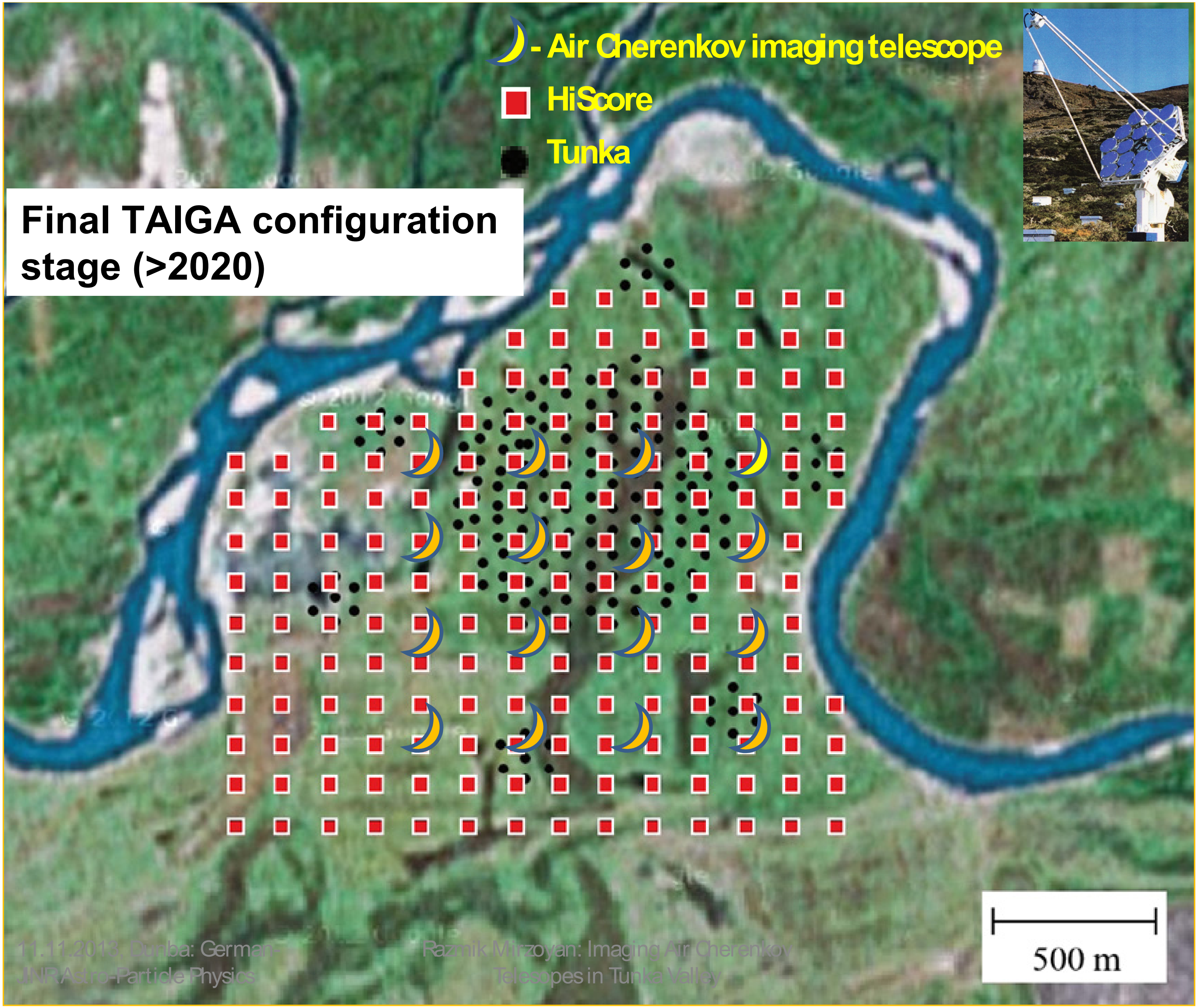


movable base

The different parts of movable base and cradle

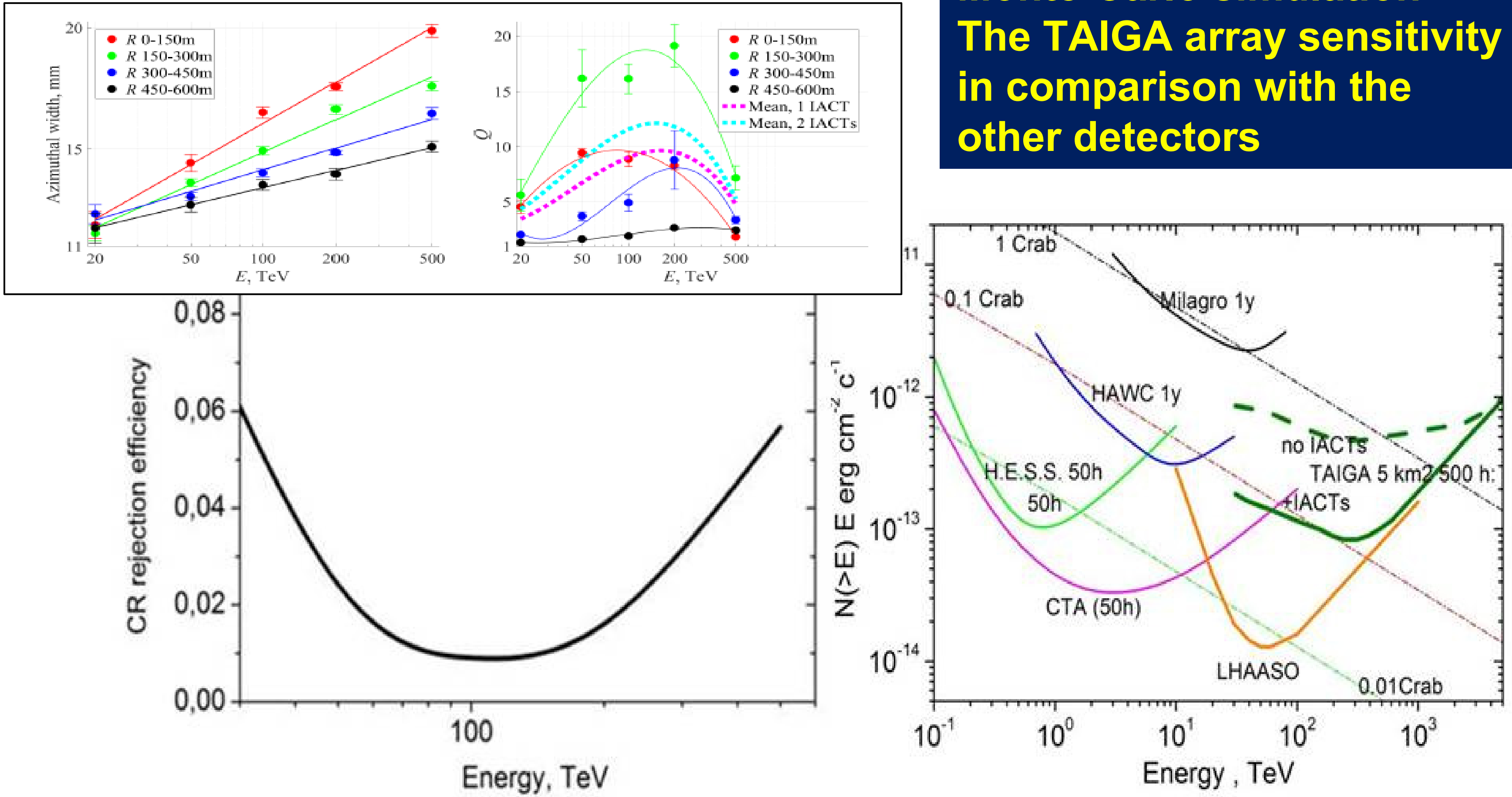


Final TAIGA configuration stage (>2020)



JINR activity

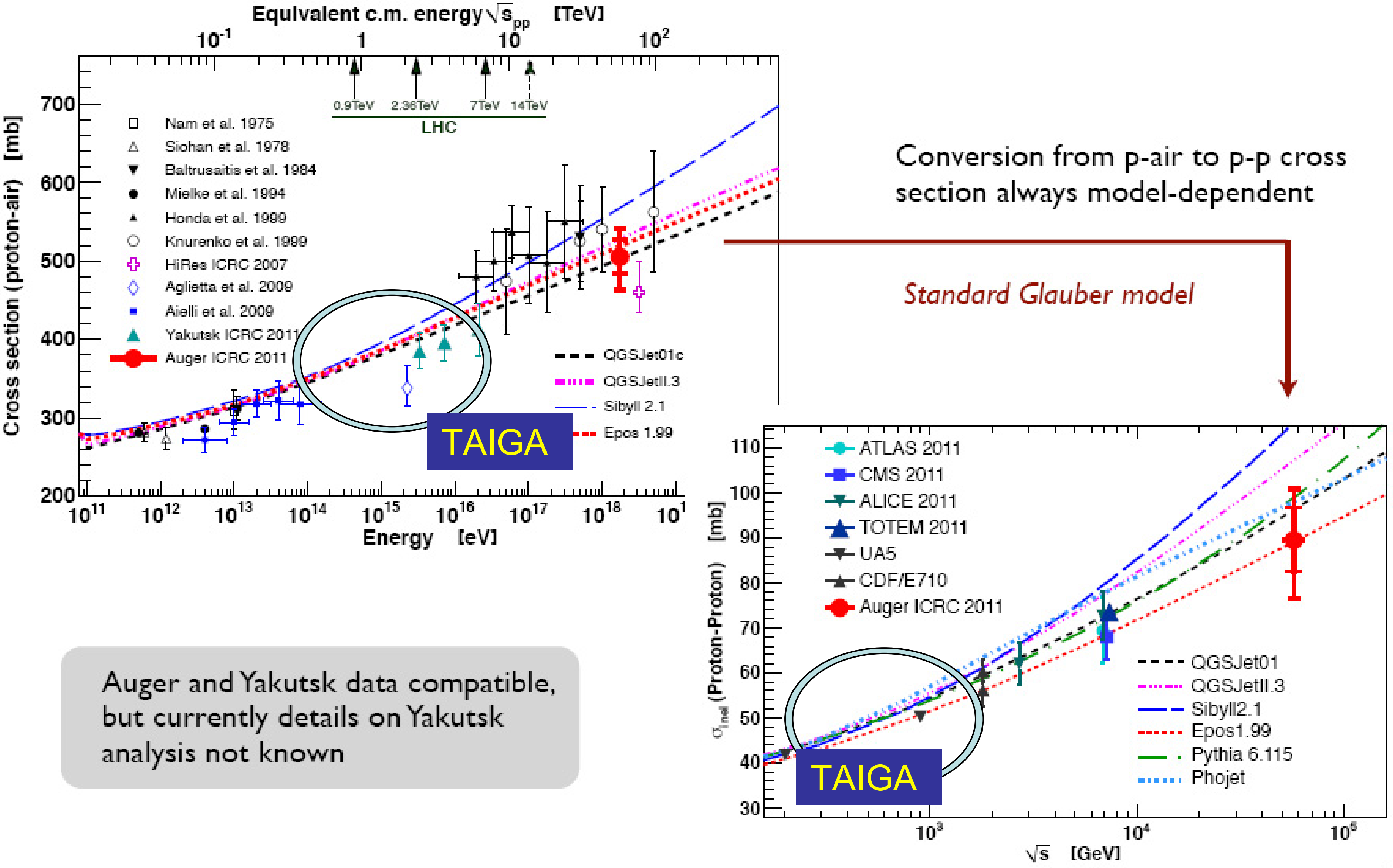
Monte-Carlo simulation
The TAIGA array sensitivity in comparison with the other detectors



Left: Cosmic rays rejection efficiency from IACT+HiCSORE Monte-Carlo study.
Right: Integral sensitivity for point-like sources for a 5 km^2 observatory in the energy range of 30 – 200 TeV is expected to be 10^{-13} erg cm^{-2} sec−1 for 500 h of observation. The dashed line marks the sensitivity without IACTs

High-energy frontier: proton-air cross section

JINR activity



Conversion from p-air to p-p cross section always model-dependent

Standard Glauber model

Auger and Yakutsk data compatible, but currently details on Yakutsk analysis not known

JINR activity

2016
IceCube data
CR anisotropy

COSMIC-RAY ANISOTROPY IN ICECUBE 11

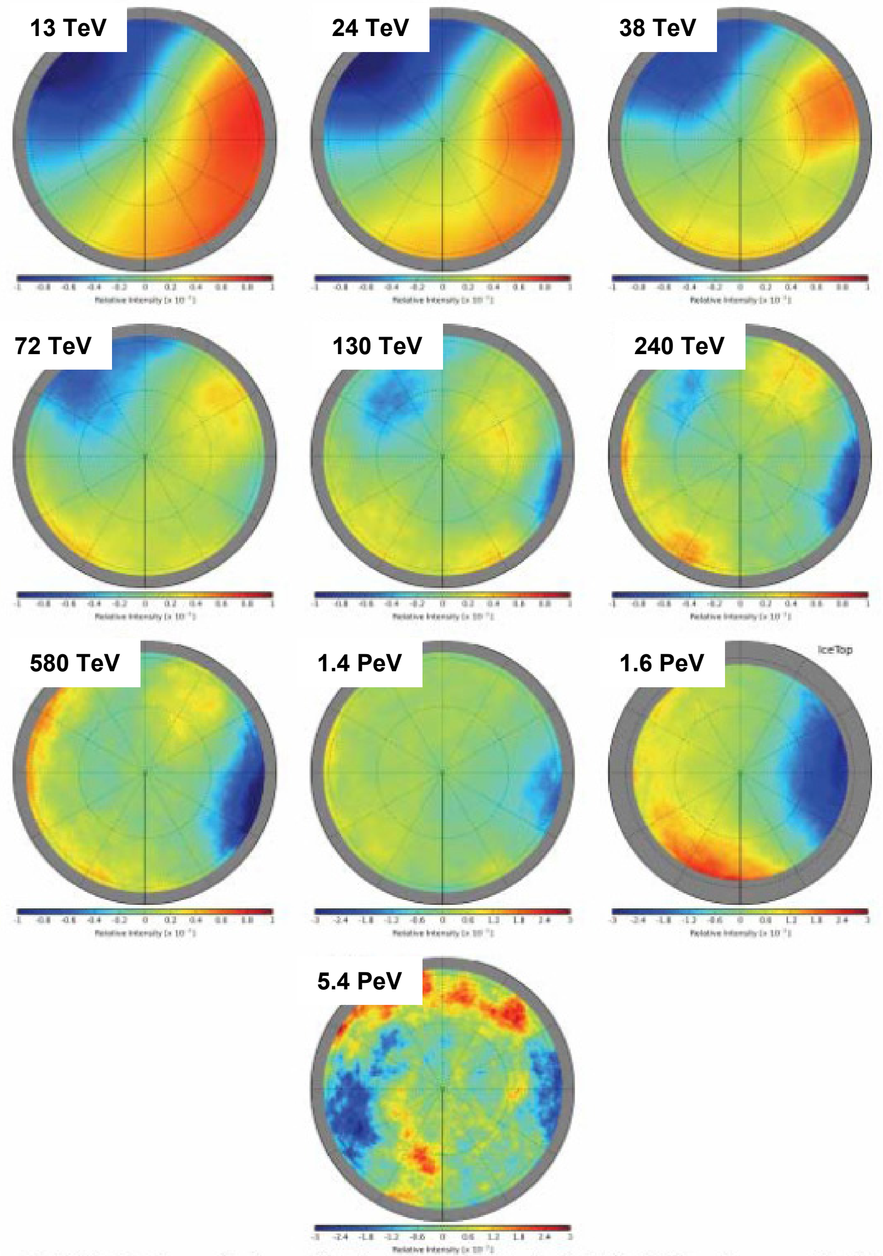


Figure 8. Relative intensity maps in polar coordinates for the energy bins described in Section 3.2. The median energy of the data shown in each map is indicated in the upper left. Maps have been smoothed with a 20° smoothing radius. The final three maps are shown on a different relative intensity scale. The 1.6 PeV map is based on IceTop data. All other maps show IceCube data.

Conclusion

1. Participations in **TAIGA** experiment preparation
    - design, construction mechanics and tests for (IACT) at JINR
    - IACTs commission and tests in Tunka
    - tests of IACT PMTs at JINR
    - IACT mirror production
2. Participations in **TAIGA** experiment physical program
    - Monte-Carlo simulation,
    - data taking
    - data analysis

Backup slides

Proposed time-schedule and necessary resources for implementation of project (k$)

Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy (TAIGA)

Parts and systems of set-up resources and sources of financial support	Costs of parts of set-up. Required financial support			
		2018	2019	2020
LNP Design. Bureau, hours LNP Workshop, hours NPO “Atom”, hours	1000 2400 60	800 800 20	100 800 20	100 800 20
Project total	150.0	50	50	50
JINR budget	150.0	50.0	50.0	50.0
Extra-budgetary: from grants, agreements (Russia, Romania, Poland, Germany grant BMBF)	90.0	30.0	30.0	30.0

Things are not simple...

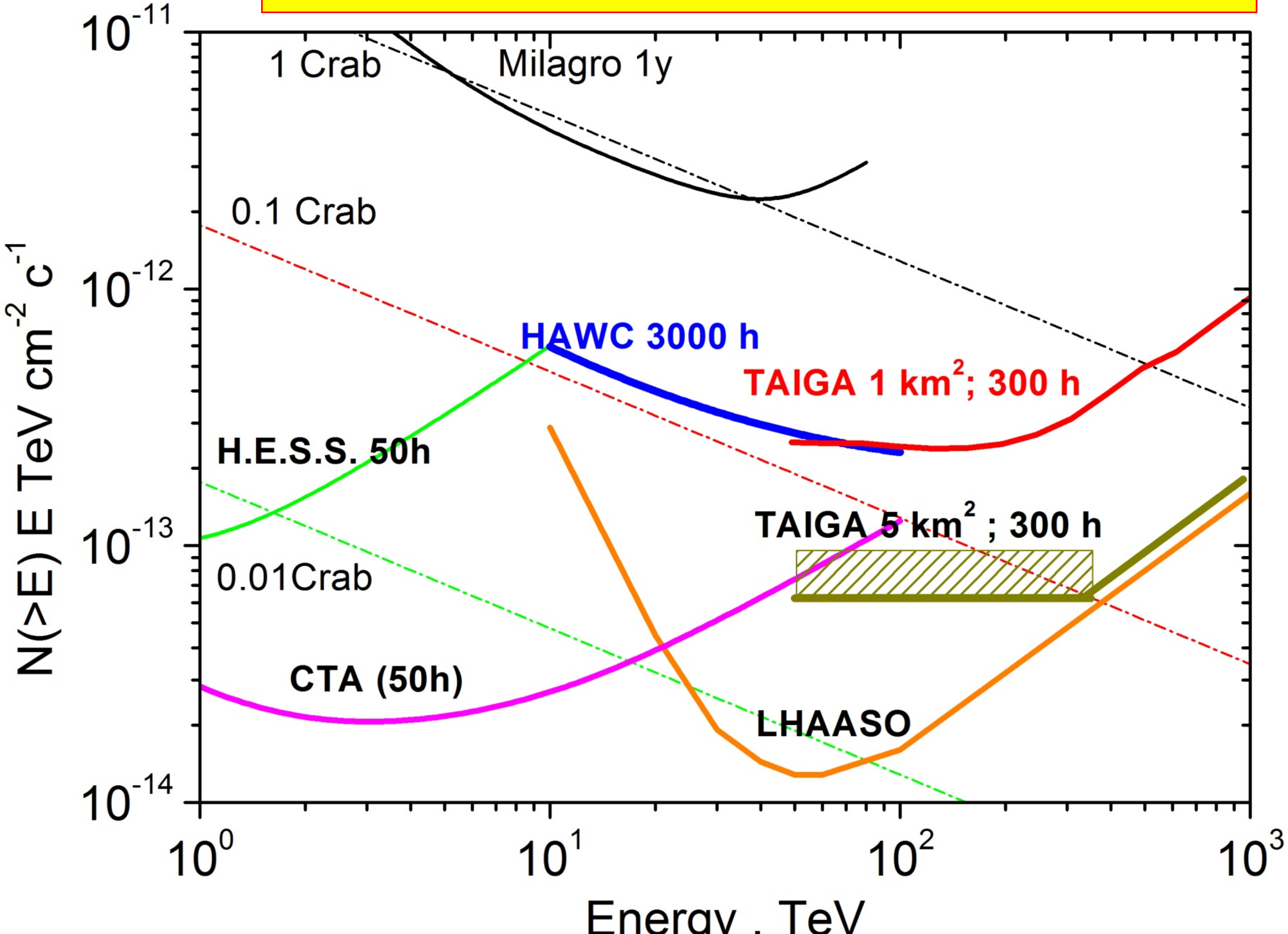
Each SNR is individual and has a unique behaviour
In general one expects a combination of leptonic and hadronic emission

The relative contributions depend on:

- Ratio of the injected electrons and protons
- Electrons and protons spectra (Power law? Breaks ? Cutoff ?)
- Particle confinement, escape time
- Density of target material for proton interactions
- Density of low energy seed photons for electron IC
- Magnetic field strength (synchrotron emission)
- SN type
- SNR age and morphology
- Presence of Molecular Clouds
- Absorption of gamma rays
- *......*

Multi-wavelength studies can help

Integral sensitivity to local sources



Schedule of TAIGA deployment

2017:
32 additional HiSCORE stations.
Demonstration of scientific potential of IACT+HiSCORE operation.

2017-18:
Second IACT.
~40 additional HiSCORE stations.
Measurement of energy spectrum of gammas from Crab Nebula

2018-19 :
Third IACT.
Starting deployment of muon detectors.
Beginning of the physical program

2019-2020.
Forth IACT.
Deployment of muon detectors.
Full-scale physical program realiztion.

TAIGA publication

1. N. Budnev et al. (TAIGA Collaboration), Jour.Phys: Conf. Series **718** 052006 (2016)
2. Budnev N. et al., (TAIGA Collaboration), NIMA **845**, 384 (2017)
3. M. Tluczykont, D. Hampf, D. Horns, L.Kuzmichev et al. Astropart. Phys., 56:42, 2014.
4. M. Tluczykont, M. Br ¨uckner, N. Budnev, et al.Jour Phys: Conf Ser, 632:012042, 2015.
5. Budnev N. et al.// Tunka-25 Air Shower Cherenkov array v.50, с. 18-25 (2013)
6. V.Prosin et al. (Tunka Collaboration) NIMA 756, 94 (2014)
7. I.Yashin et al (TAIGA Collaboration), ICPPA-2015, J. of Physics: Conference Series **675**, 032037 (2015)
8. E.B. Postnikov, A.A,Grinyuk et al. Bull.Rus.Acad.Scie. Phys 2017, V. 81, No. 4, pp. 428-430
9. E.B. Postnikov, A.A,Grinyuk et al. to published in proc. of ISVHECRI-2016
10. L.Kuzmichev et al.(TAIGA Collaboration) to published in proc. of ISVHECRI-2016
11. L.Tkachev et al., The Proceedings of UHECR2016, T03002-001
12. M.Tluczykont et al, Proceedings of RICAP16, Web of Conferences. 136, 03008
13. 3-4 papers to ICRC2017 at 10-20 July

List of the TAIGA project participants

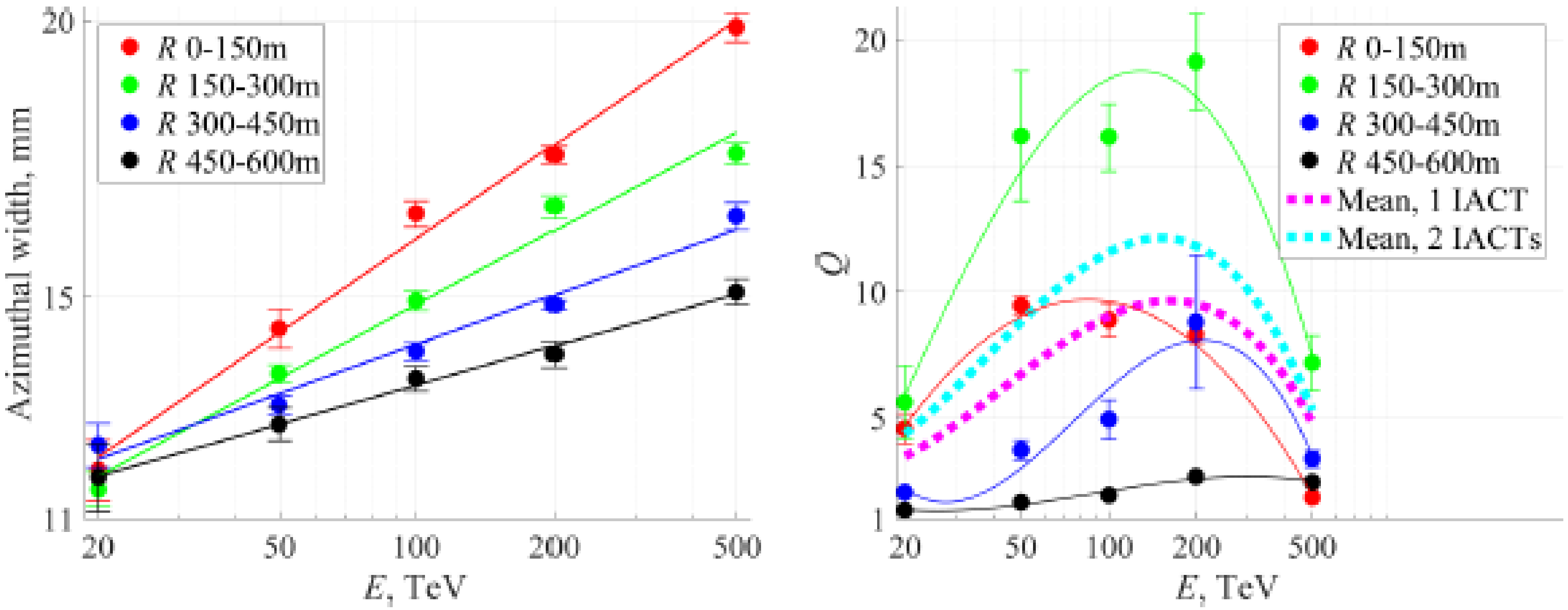
Name	employment	involvment	PhD	Age
1. V. Boreyko	engineer	100%	no	>40
2. A.Borodin	senior scientist	100%	yes	>40
3. A.Demenko	designer	100%	no	>40
4. N.Gorbunov	head of sector	10%	yes	>40
5. V. Grebenyuk	senior scientist	70%	yes	>40
6. A. Grinyuk	programmist	50%	in preparation	<40
7. A. Kalinin	engineer	50%	yes	>40
8. M. Lavrova	programmist	30%	no	<40
9. S. Porokhovoy	engineer	20%	no	>40
10. V.Romanov	designer	10%	no	>40
11. Ya.Sagan	graduated student	100%	no	<40
12. B. Sabirov	scientist	20%	no	>40
13. S. Slepnyov	senior scientist	20%	yes	>40
14. M. Slunecka	senior scientist	10%	yes	>40
15. V.Temirbulatov	engineer	50%	no	<40
16. A. Tkachenko	programmist	20%	in preparation	<40
17. L. Tkachev	head of sector	80%	yes	>40

Presentations at TAIGA collaboration meetings : A.Borodin, A.Grinyuk, L.Tkachev
Presentations of TAIGA at conferences : A.Grinyuk, Ya.Sagan, L.Tkachev

What we can see with 1 km^2 array (short list)

Source Names	RA degrees	Decl	Flux at 1 TeV, 10^{-12}cm^{-2} s^{-1}TeV^{-1} slope Γ	Flux at 35 TeV, 10^{-17}cm^{-2}s^{-1}TeV^{-1} (from Milagro)	Time of observation per one year (x 0.5- weater factor)	Number of events per one season E> 20 TeV
Tycho SNR (J0025+641)	6.359	64.13	0.17 ±0.05 Γ=1.95 ±0.5		**236h**	**88**
Crab	83.6329	22.0145	32.6 ±.9.0 Γ=2.6 ±0.3	162.6 ±9.4	**110h**	**680**
SNR IC443 (**MAGIC J0616+225**)	94.1792	22.5300	0.58 ±0.12 Γ=3.1 ±0.30	28.8 ±9.5	**112h**	**2** –(from MAGIC) **50** (from Milagro)
Geminga MGRO C3 PSR	98.50	17.76		37.7 ±10.7	**102h**	**80**
M82 (Starburst Galaxy)	148.7	69.7	0.25 ±0.12 Γ=2.5 ±0.6±0.2		**325h**	**22**
Mkn 421 (BL, z=0.031 Variable)	166.114	38.2088	50-200 Γ=2.0-2.6		**140h**	**20 - 1000**
SNR 106.6+2.7 (J2229.0+6114)	337.26	61.34	1.42 ±0.33 ±0.41 Γ=2.29 ±0.33 ±0.30	70.9 ±10.8	**167h**	**140** (from VERITAS **235** (from Milagro)
Cas A (SNR)	350.853	58.8154	1.26 ±0.18 Γ=2.61 ±0.24±0.2		**177h**	**40**
CTA_1(SNR,PWN)	1.5	72.8	1.3 Γ=2.3		**266 h**	**200**

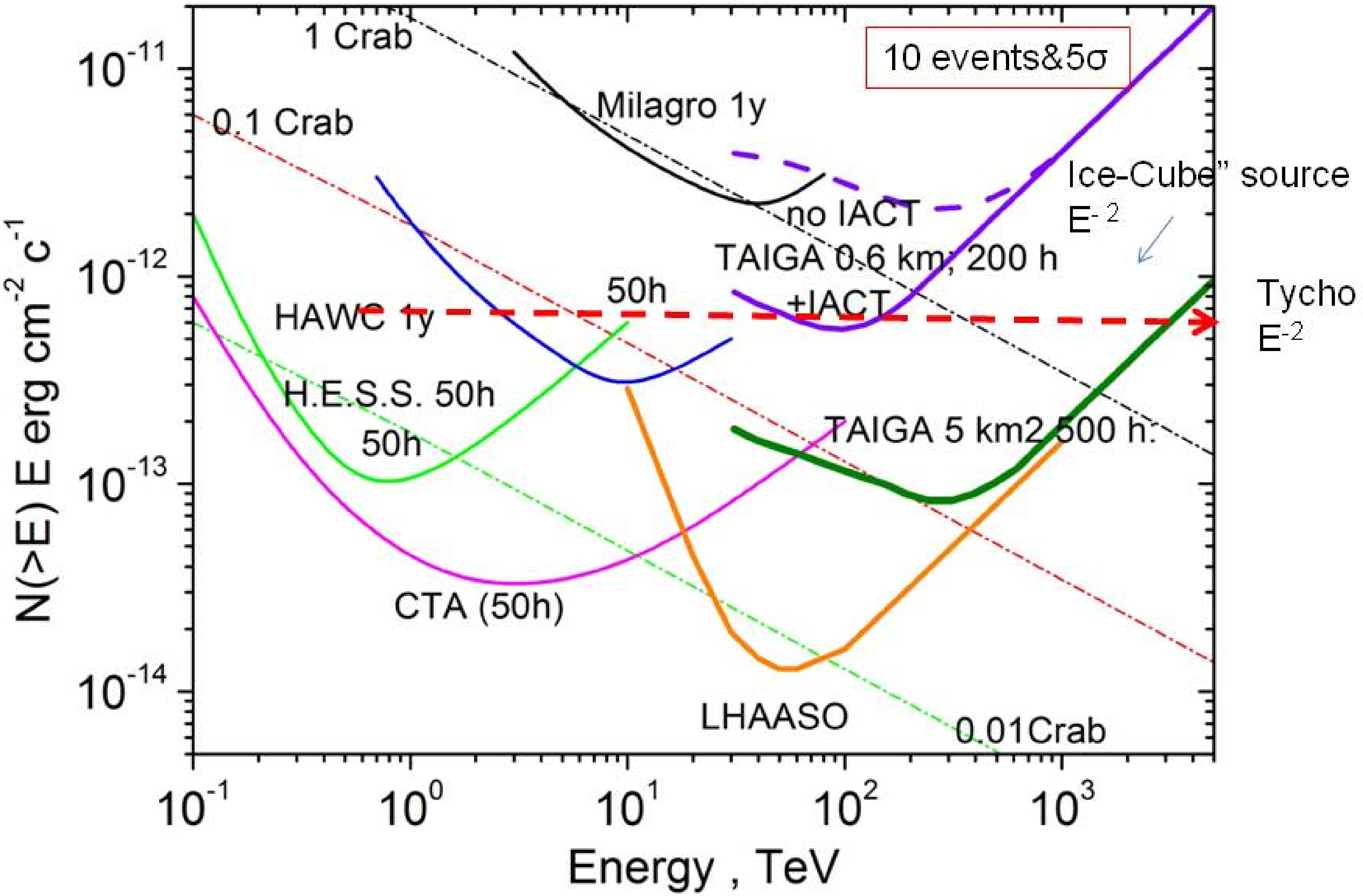
$$Q = \varepsilon_{\gamma} \ / \ \sqrt{\varepsilon_{proton}}$$



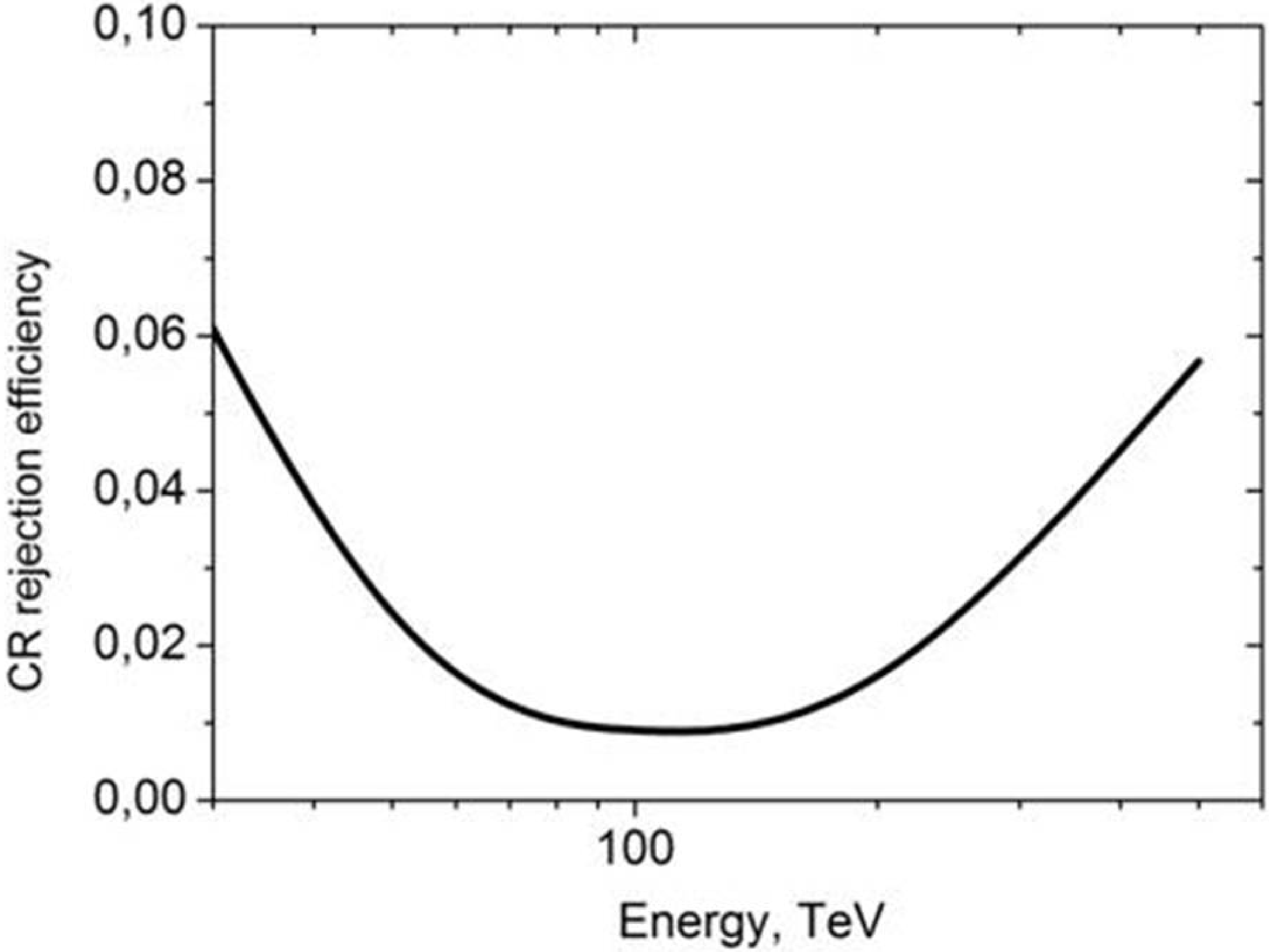
Left: Selection cut depending on energy for different distances
Right: Q factor depending on energy and distance. The dashed lines are averaged over the whole installation area with one or two IACTs.

ε_g and ε_{proton} are the fraction of events, classified as gamma-ray events from samples of true gamma-ray events and of proton-induced air showers.

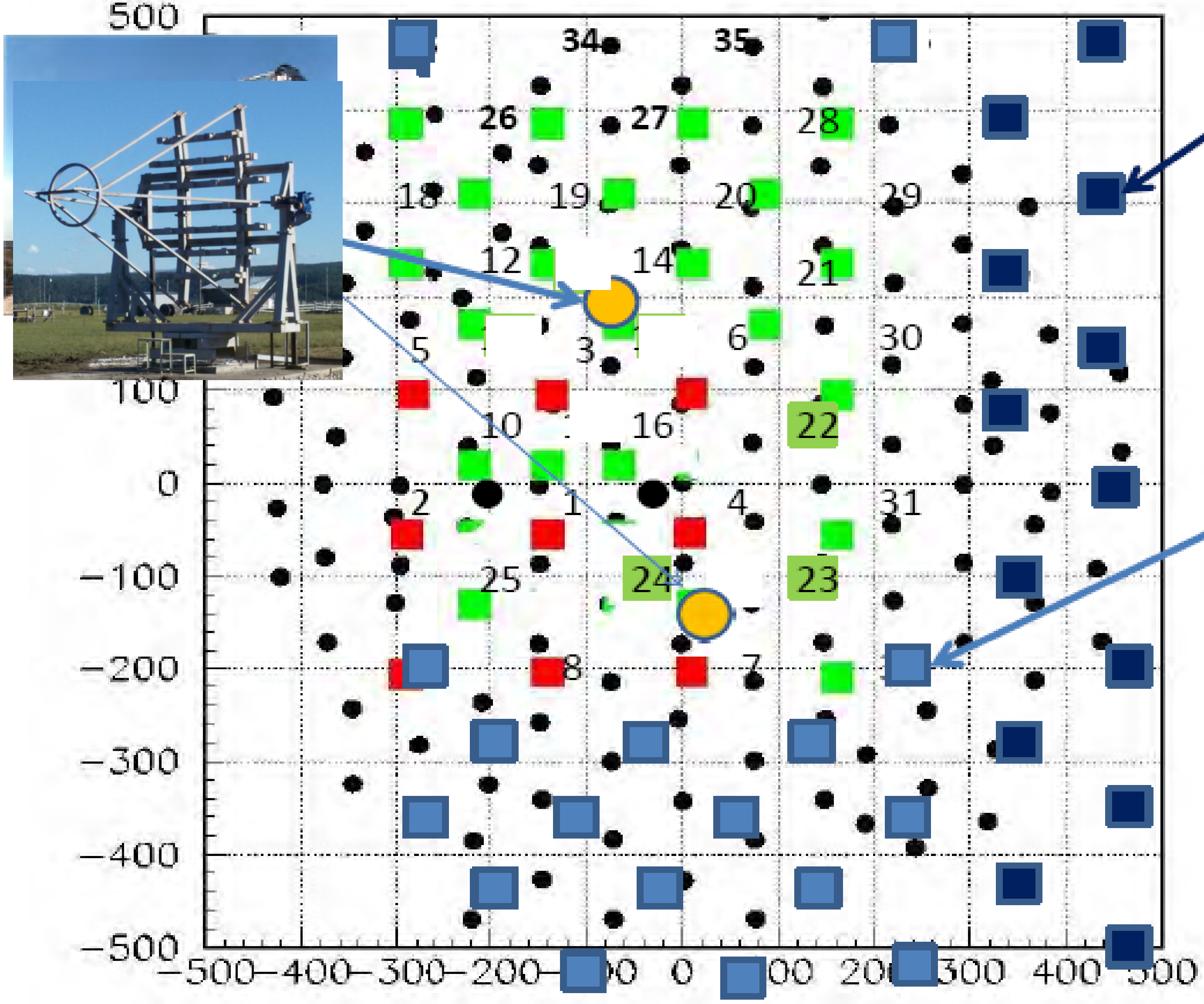
Integral sensitivity to local sources



Rejection of CR



One of TAIGA high-priority goals: operate 58 HiSCORE stations with the 1st IACT



Plan of TAIGA configuration at the end of 2017

13 new stations (2017)

N

17 new stations (2016)

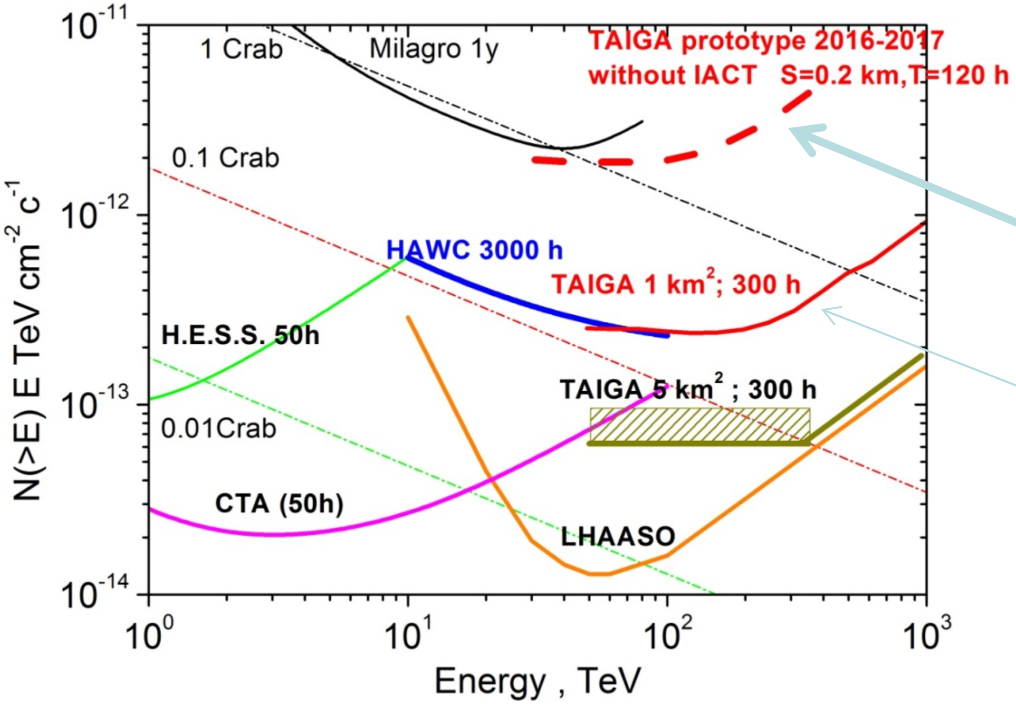
A = 0.6 km²

58 stations

● IACTs

What we can expect with current Prototype ?

Sensitivity - the minimal gamma ray flux possible for observation with given array with 5 sigma above background



Current array S=0.2 km2, T~120 hr with 2.5 sigma

Main Array – 3 km2 + IACT in our array That allows to improve Sensitivity by 3-5 times.

Expected number of excess events for different peak energy

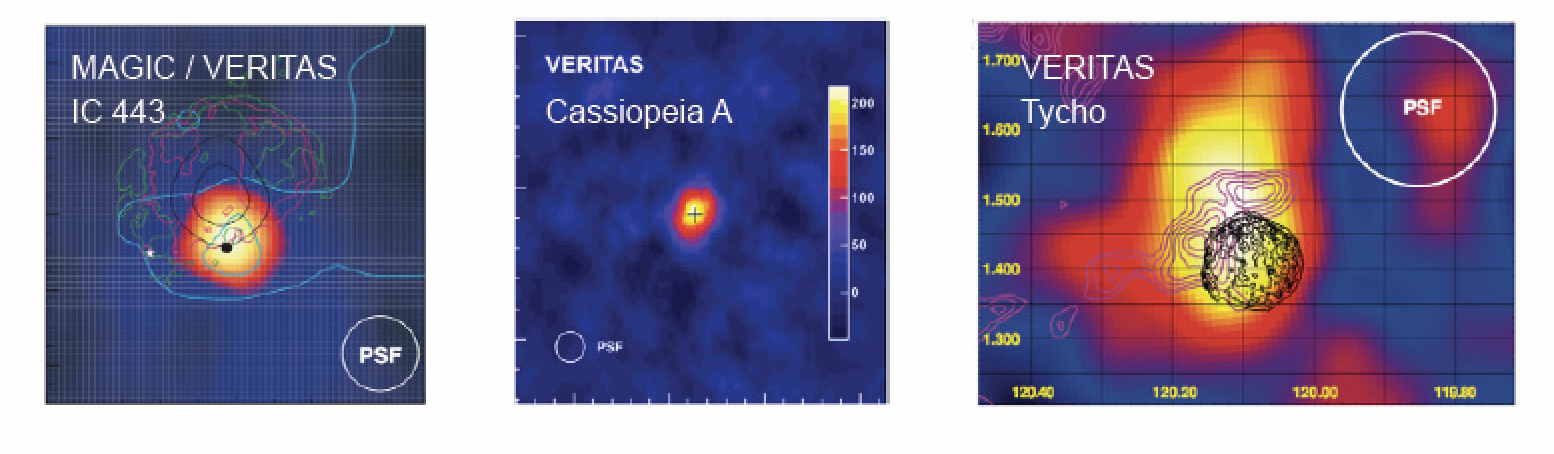
Ethr (TeV)	40	50.	63.	80	100.0
Hegra	27.0	18.5	13.4	10.1	7.9
Magic	11.7	7.1	4.6	3.2	2.3

Why data above 30 TeV are important

It is generally believed that cosmic rays of energy at least to the knee ($3 \cdot 10^{15}$) are accelerated in our Galaxy

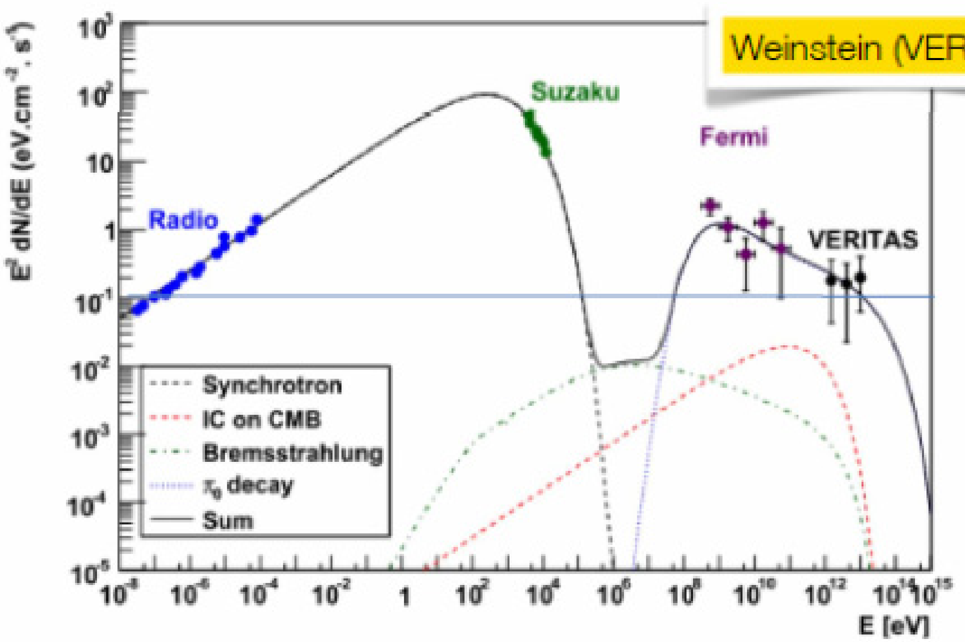
SNRs (Super Nova Remnants) are the favorite sites for the acceleration of of Galactic cosmic rays

Gamma rays up to a few TeV have been observed from 7 SNRs

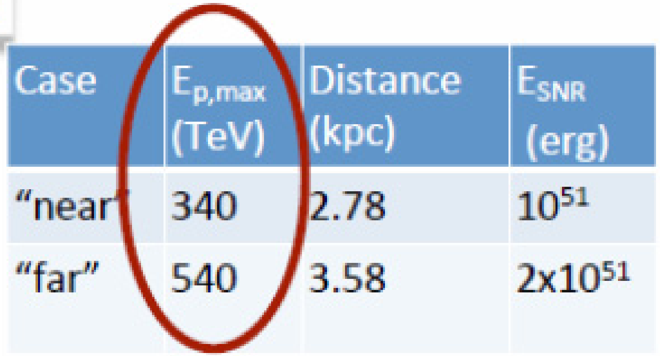


Tycho SNR might now be the best case

- Tycho detected with both Fermi-LAT and VERITAS
- Leptonic model strongly disfavored
- No cutoff in VERITAS →acc time = SNR age → max proton energy > 300 TeV
- But beware drawing strong conclusion from spectral modeling. Also very weak source, both in Fermi-LAT and in VERITAS

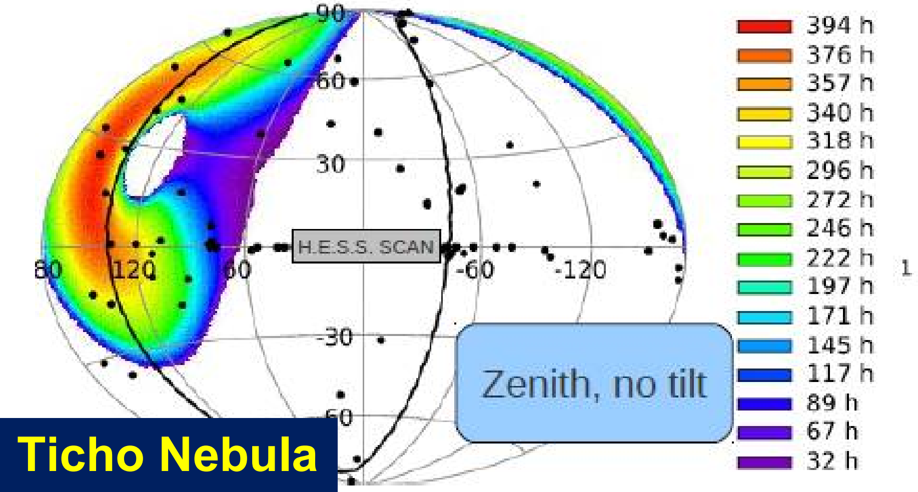


Weinstein (VERITAS)



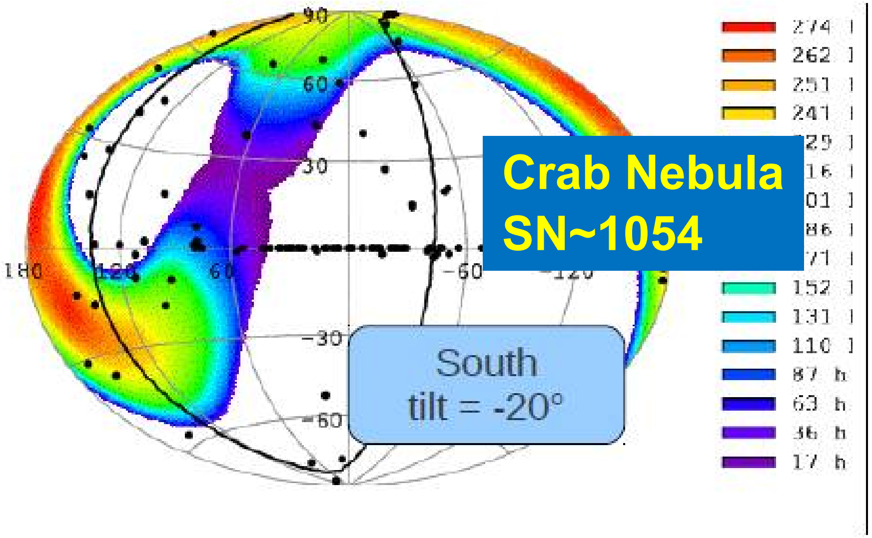
Case	$E_{p,max}$ (TeV)	Distance (kpc)	E_{SNR} (erg)
"near"	340	2.78	10^{51}
"far"	540	3.58	$2x10^{51}$

Half a pevatron?



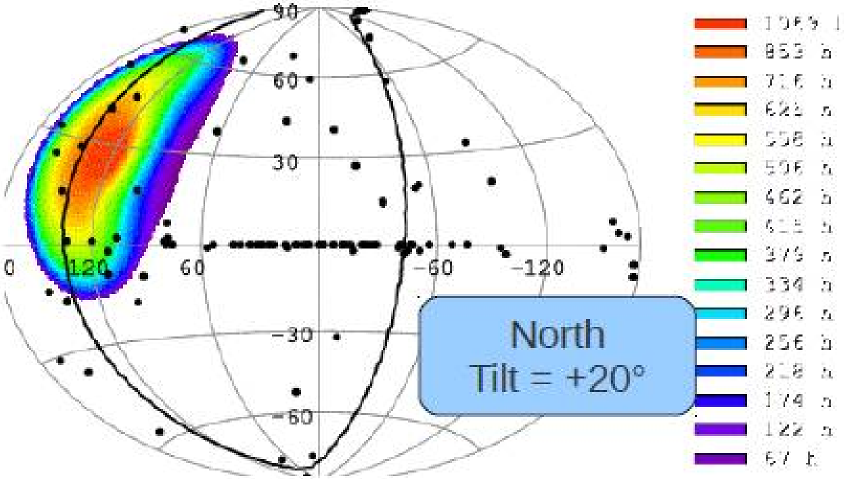
Zenith, no tilt

Ticho Nebula
SN ~1500 y



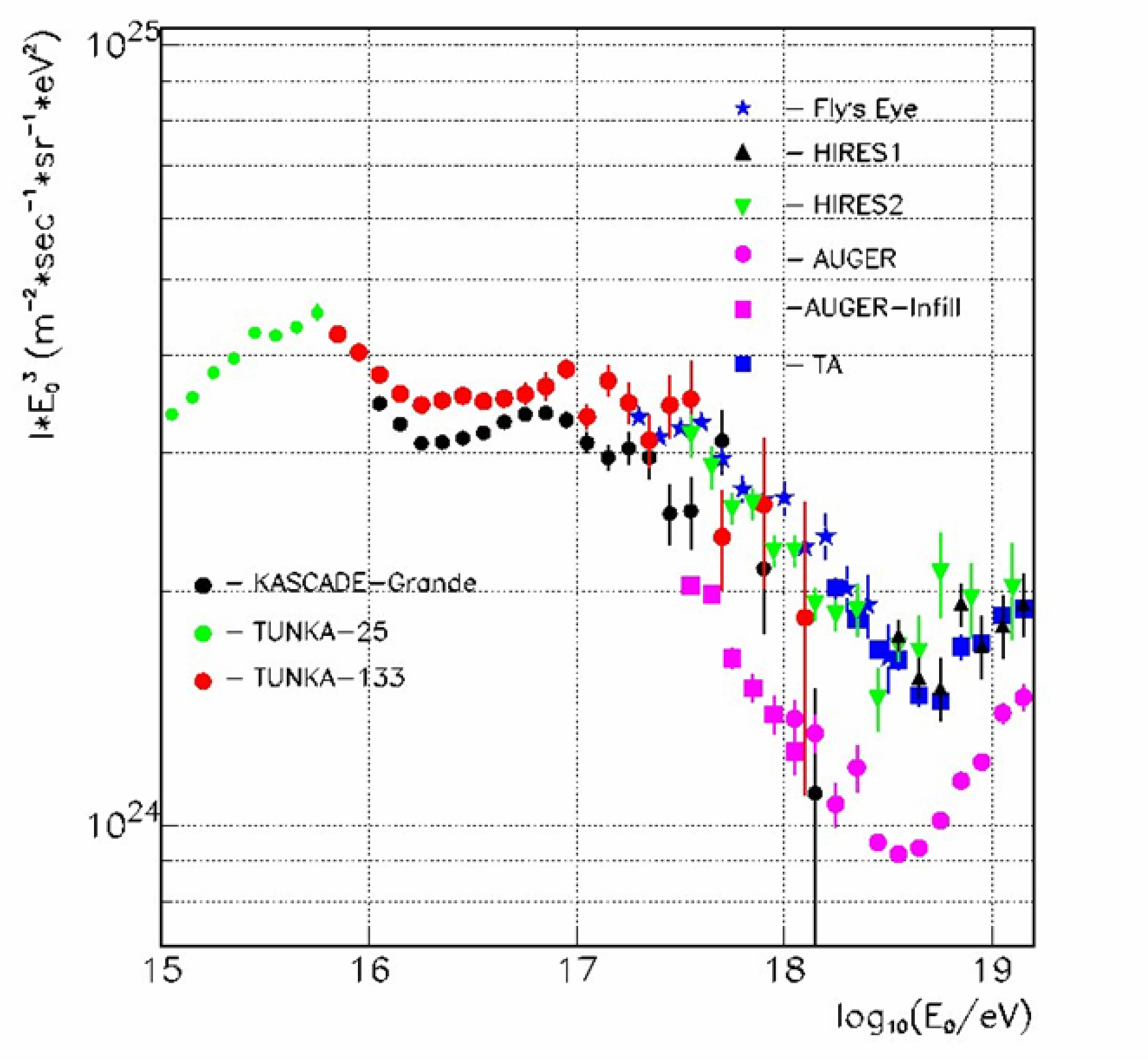
Crab Nebula
SN~1054

South
tilt = -20°

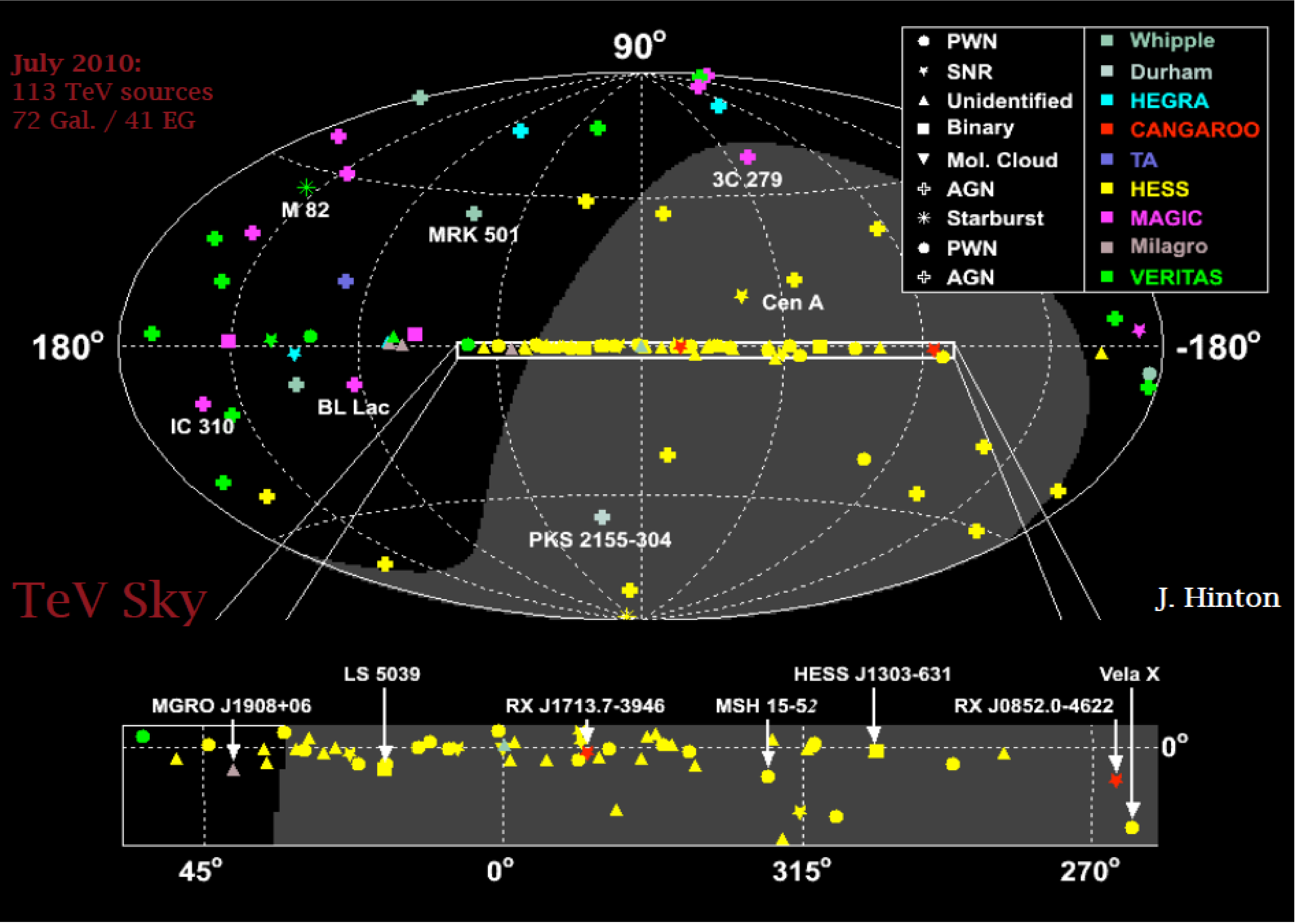


North
Tilt = +20°

New TAIGA detectors at E > 100 TeV will be able to discriminate lepton / hadron accelerator models of CR acceleration mechanisms at SN explosion

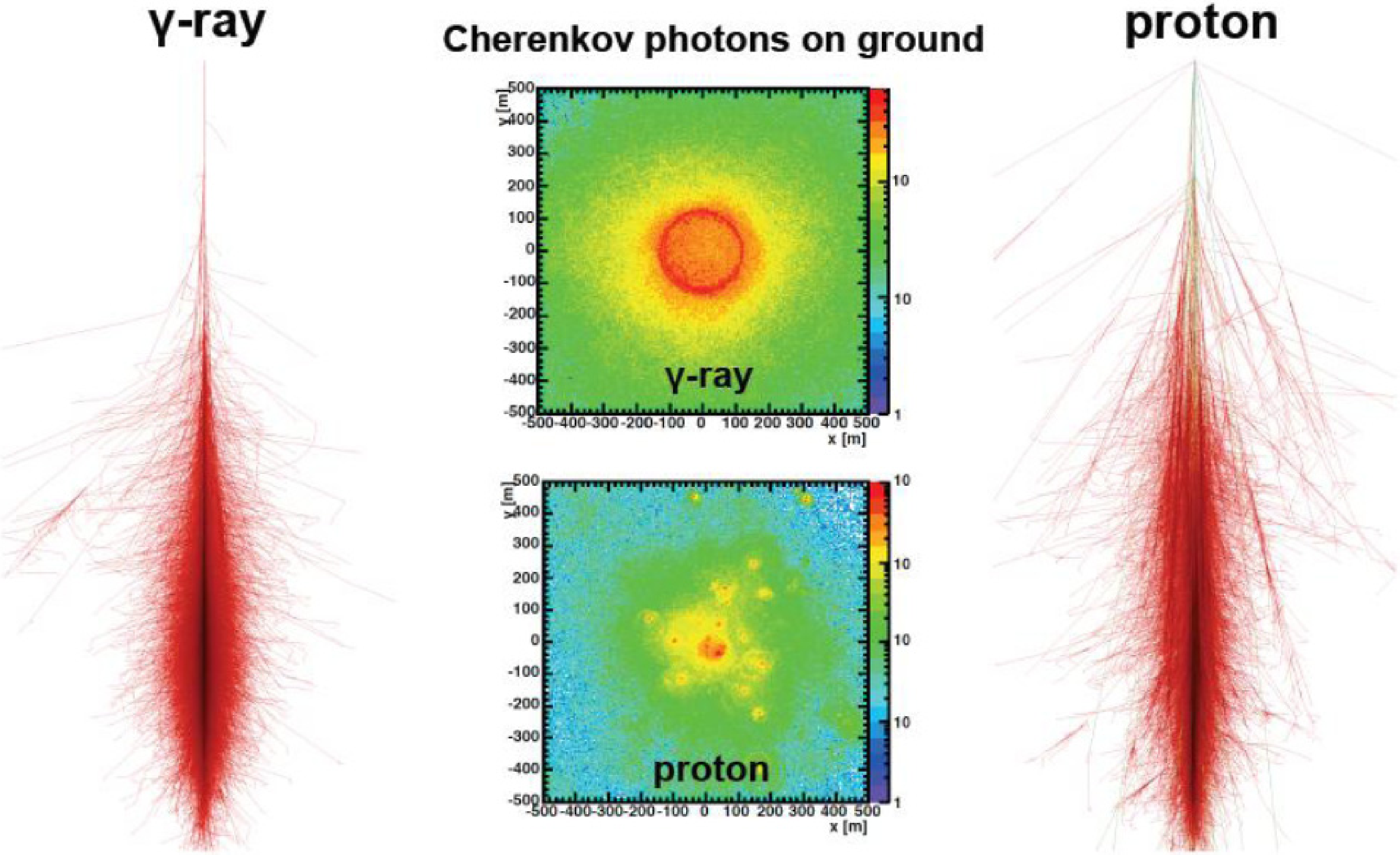


CR energy spectrum measurement at the TUNKA detector



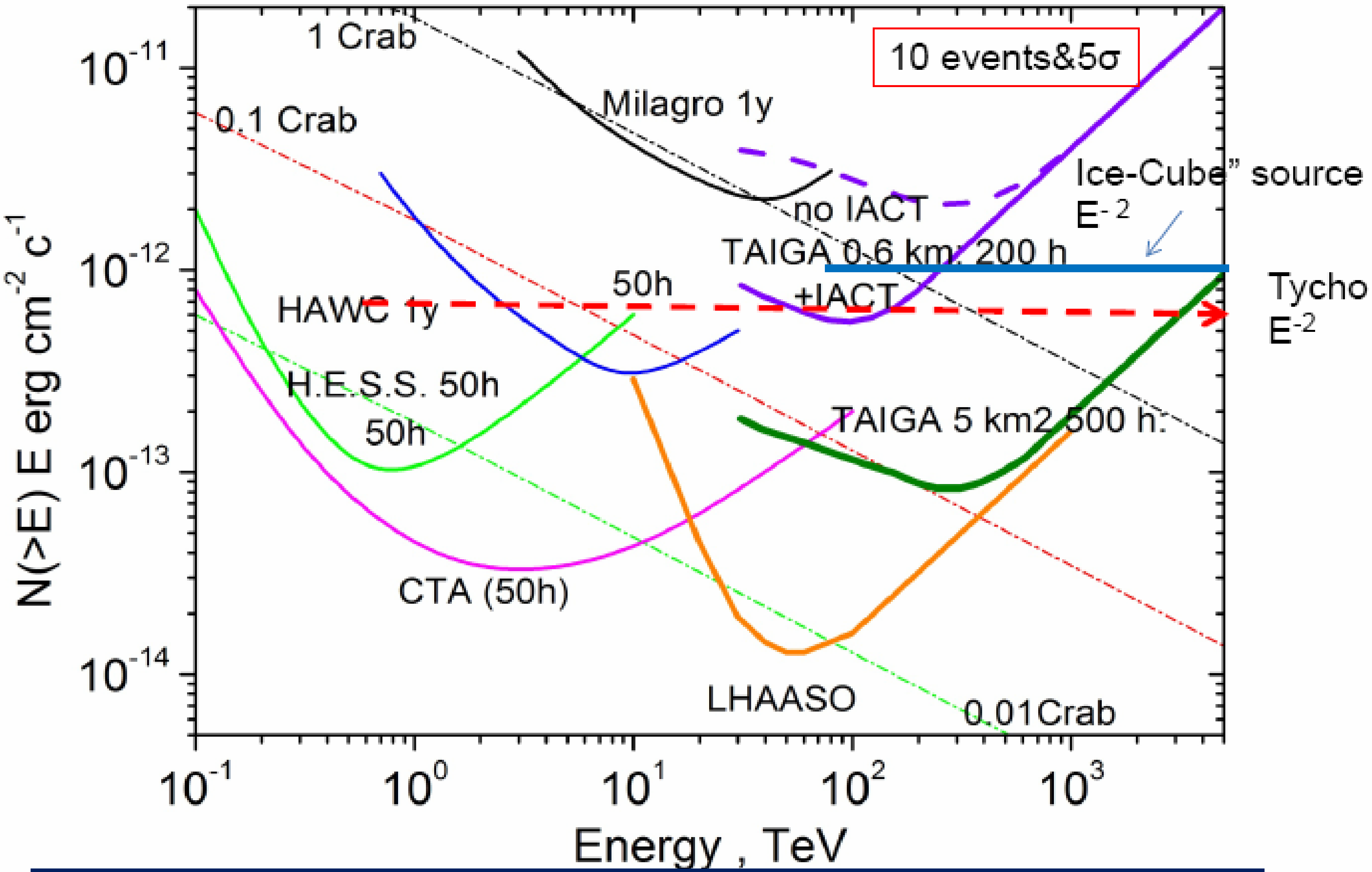
Galactic and extragalactic gamma-ray TeV-sources

Proton vs Gamma-ray showers



Gamma-ray and proton EAS development

Integral sensitivity to local sources



The TAIGA array sensitivity in comparison with the other detectors

CR acceleration mechanisms

It is a complicated problem of
Particle-, plasma- and astro-physics.

Basic Hillas formula:

$$E_{max} \sim Ze \cdot B \cdot V \cdot T \sim Z \cdot 10^{14}\ \mathrm{eV}$$

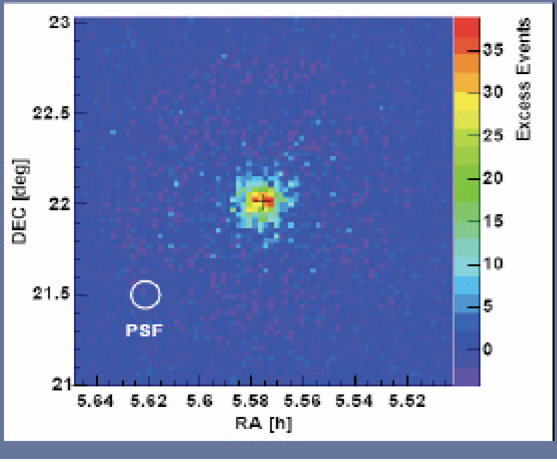
Z-charge,

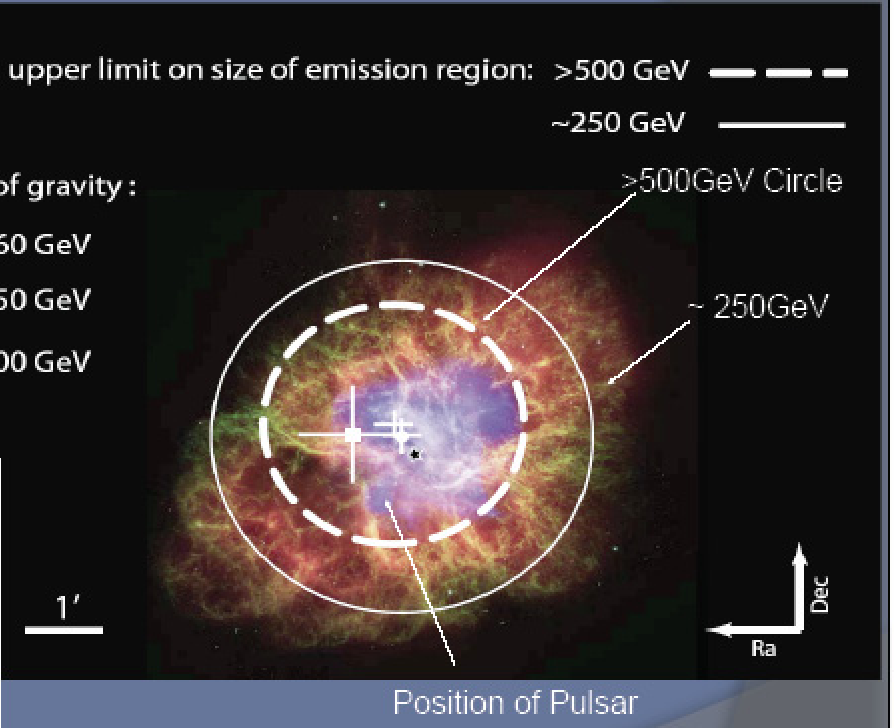
V ~ 5000 km/s - shock expansion speed,

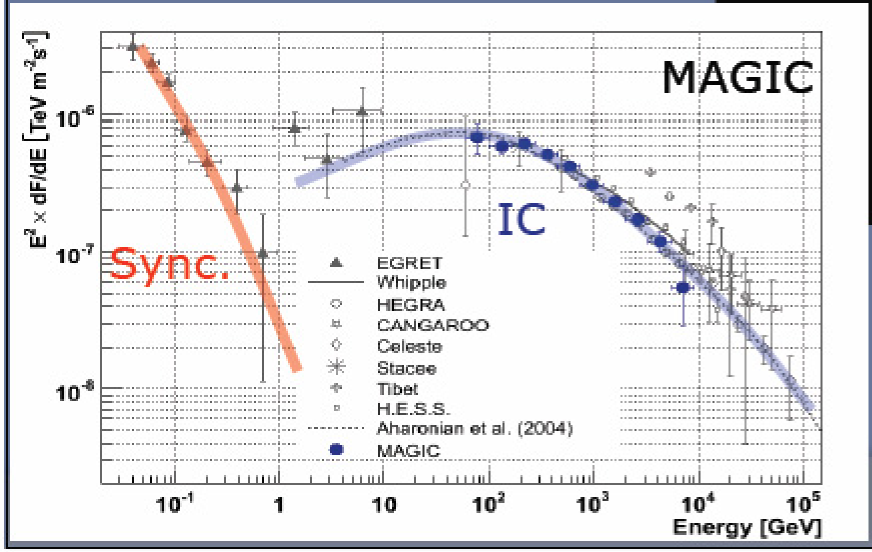
B ~ 3 μG - magnetic field,

T ~ 1000 years – the shock propagation time

MAGIC Crab Nebula (PWN)





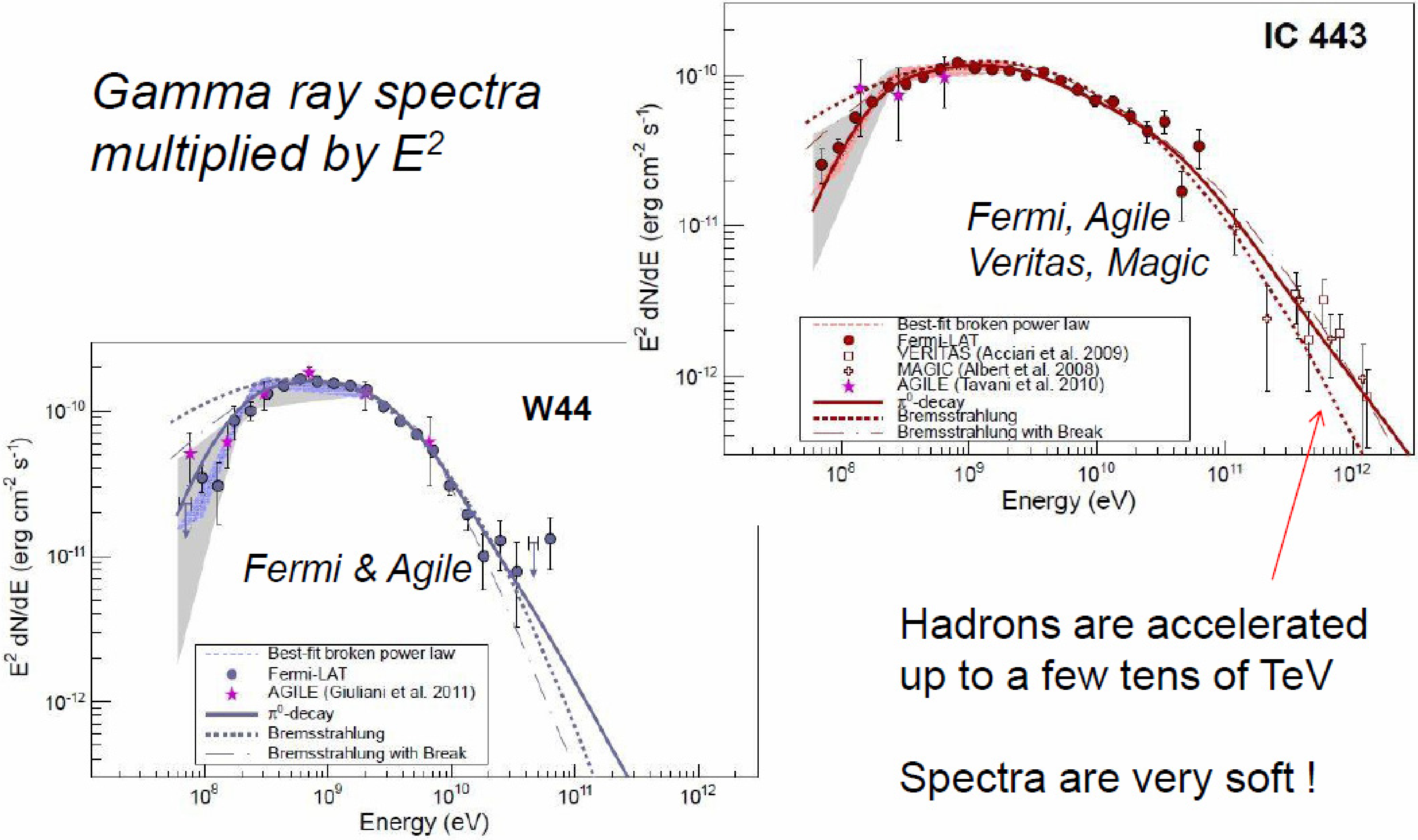


IC peak is estimated to be

IC_peak = 77 ± 35 GeV

Two observations of π^0 bumps

Gamma ray spectra multiplied by E^2



Hadrons are accelerated up to a few tens of TeV

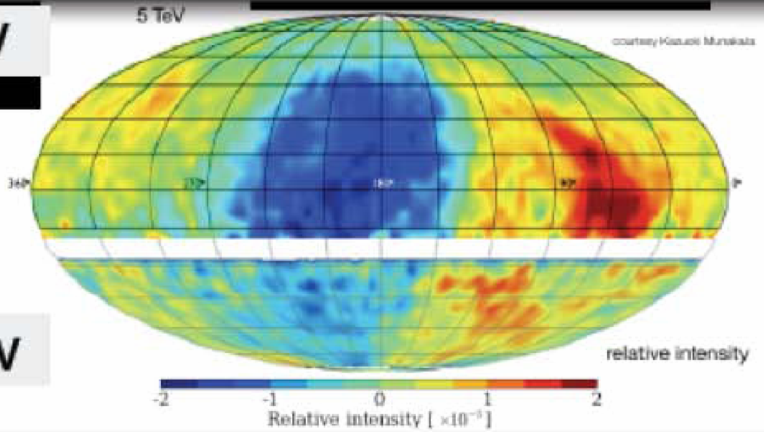
Spectra are very soft !

Comparison between different energies

5 TeV

[redacted]

20 TeV



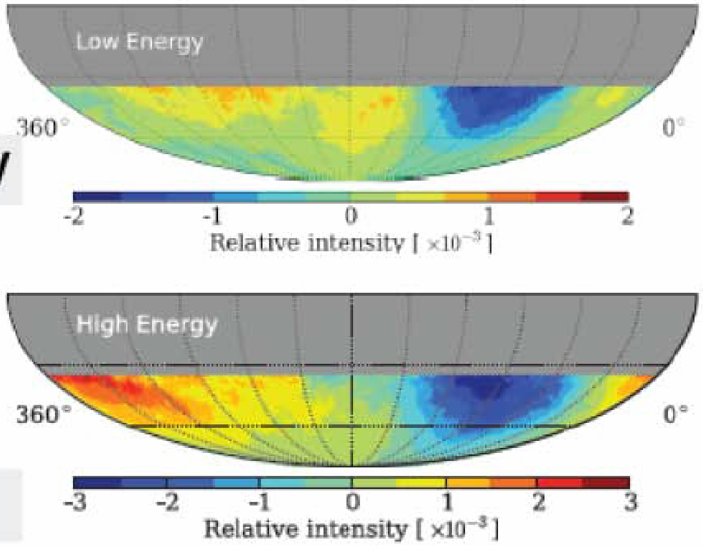
- The anisotropy changes position
- Similar peak-to-peak strength
- Smaller characteristic size at high energies

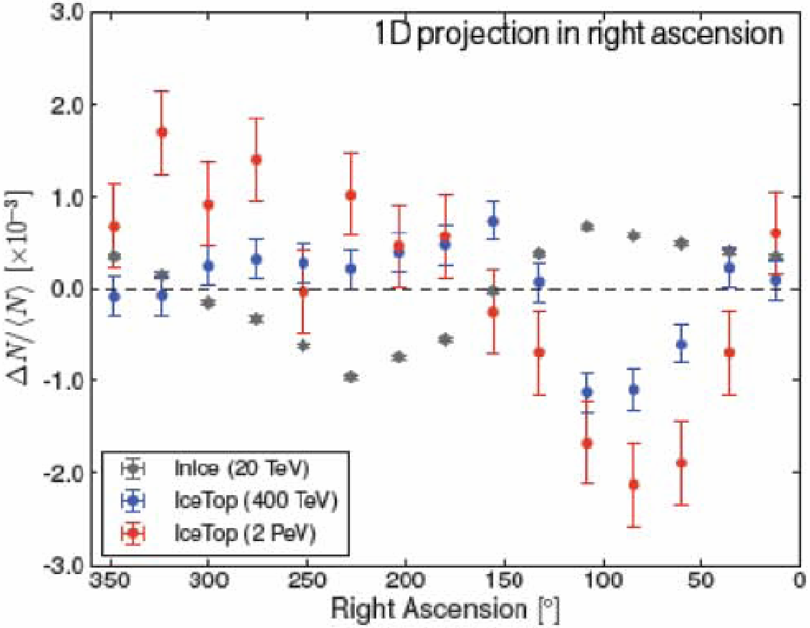
IceTop

Aarsten et al., 2013 ApJ 765 55
arxiv/1210.5278

400 TeV

2 PeV

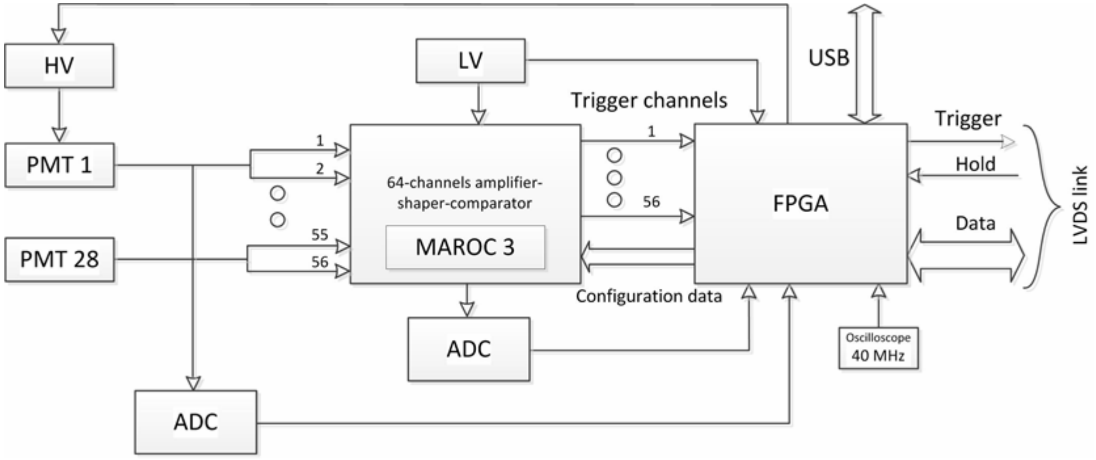


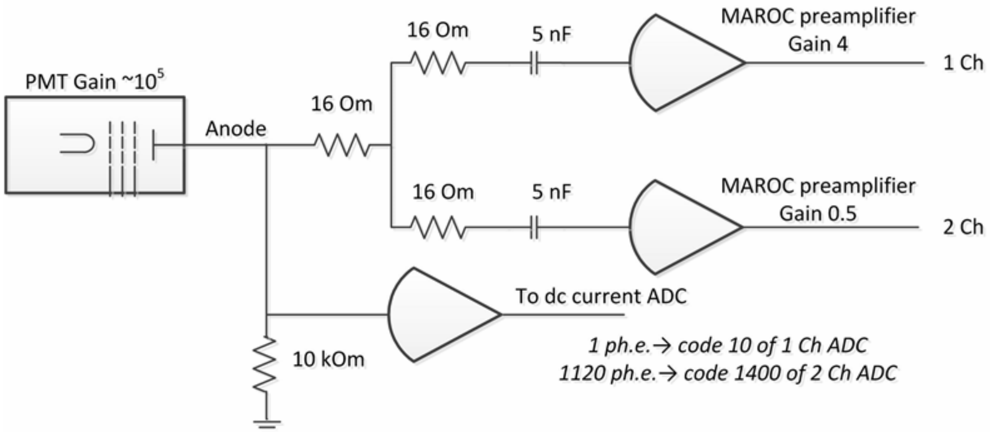


IceTop @ 400 TeV agrees with IceCube @ 400 TeV

Abbasi et al., 2012 ApJ 746 33 arxiv/1109.1017

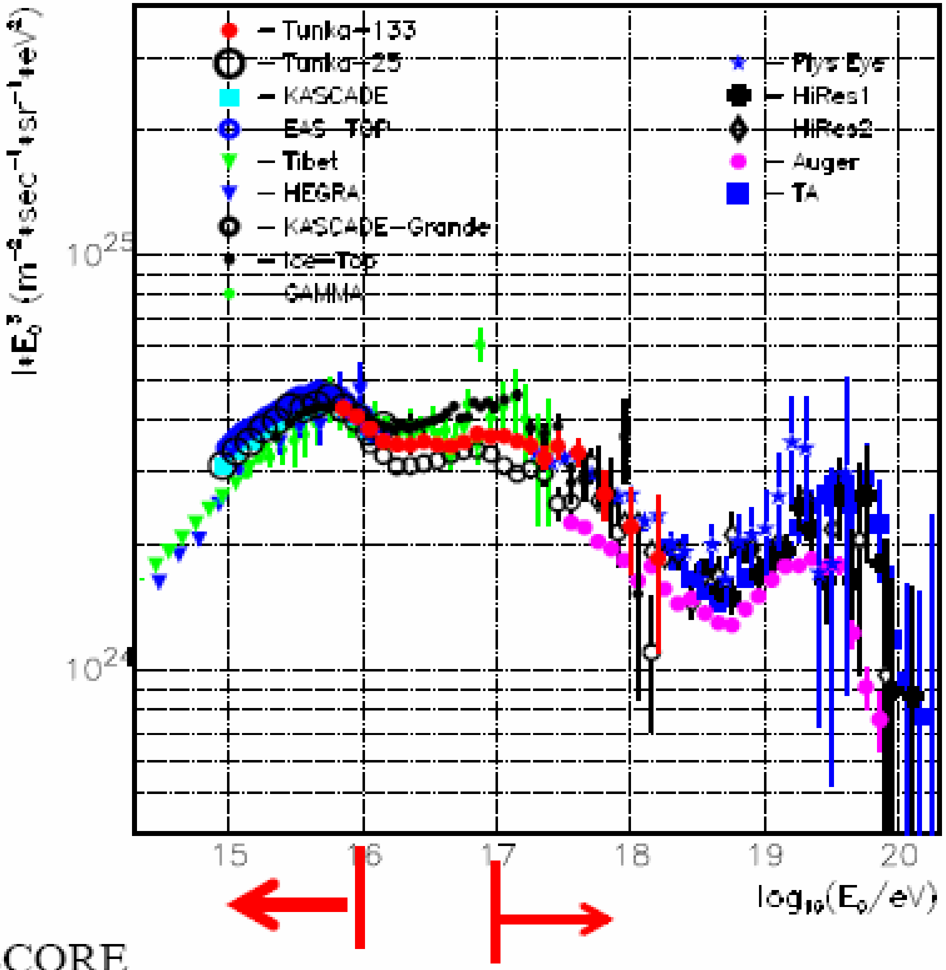
Two channels of MAROC3 process the signals from one PM splitted to provide the necessary dynamic range.





The "Dead" time is not more than 200 μs which is about 1% of full-time detection at the expected rate of ~ 50 s^{-1}

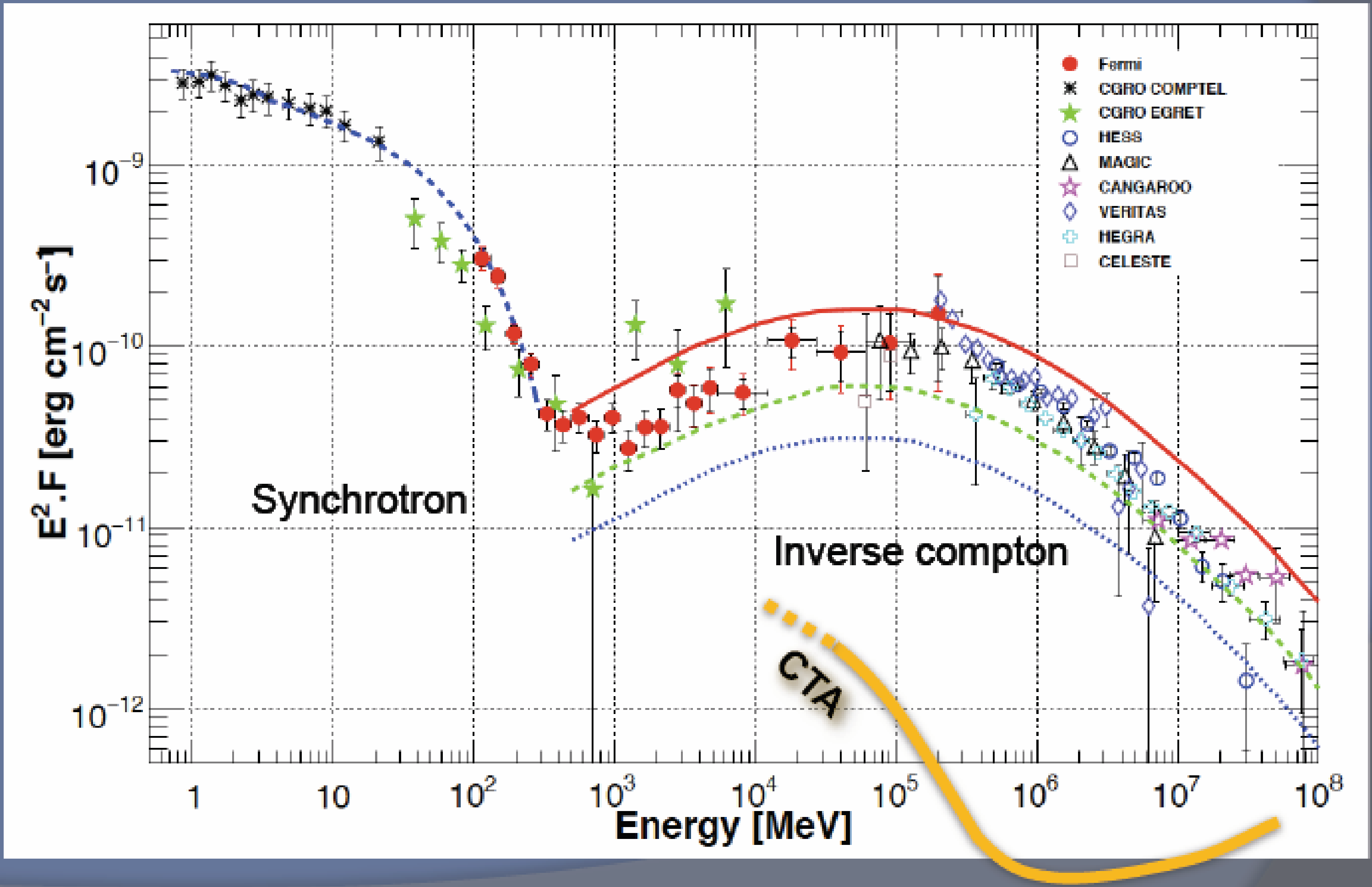
All particle energy spectrum



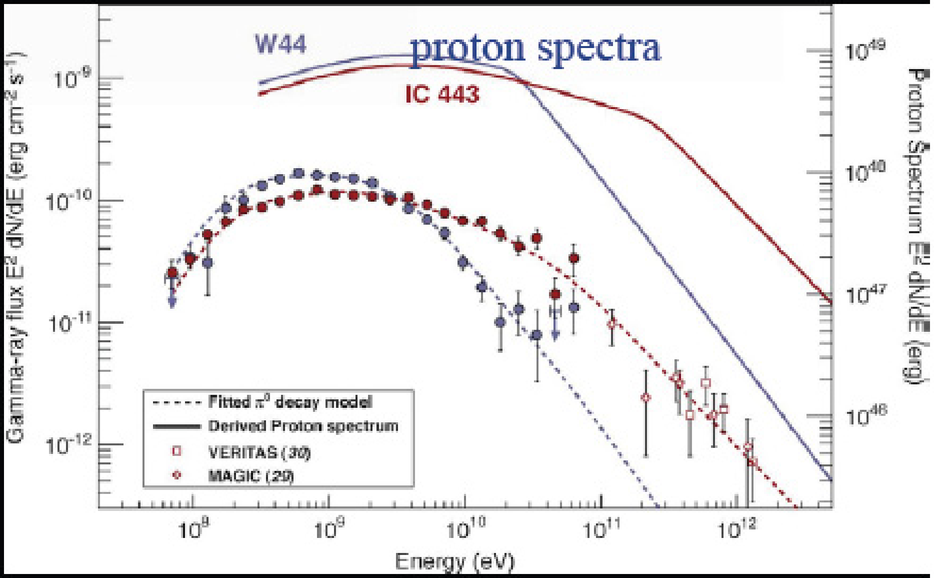
TAIGA -HiSCORE

Tunka –Grande + Tunka-REX

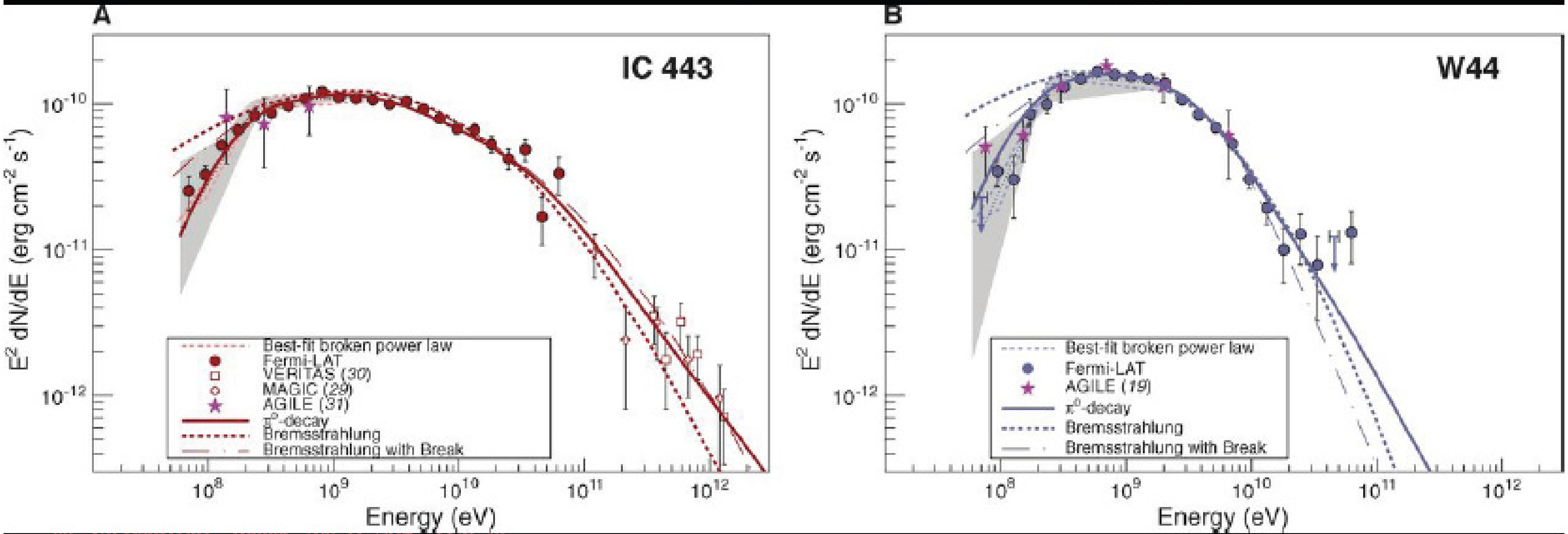
Crab Nebula


● Fermi
✱ CGRO COMPTEL
★ CGRO EGRET
○ HESS
△ MAGIC
☆ CANGAROO
◇ VERITAS
✚ HEGRA
☐ CELESTE
Synchrotron
Inverse compton
CTA
$E^2.F$ [erg cm^{-2} s^{-1}]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
Energy [MeV]
1
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8

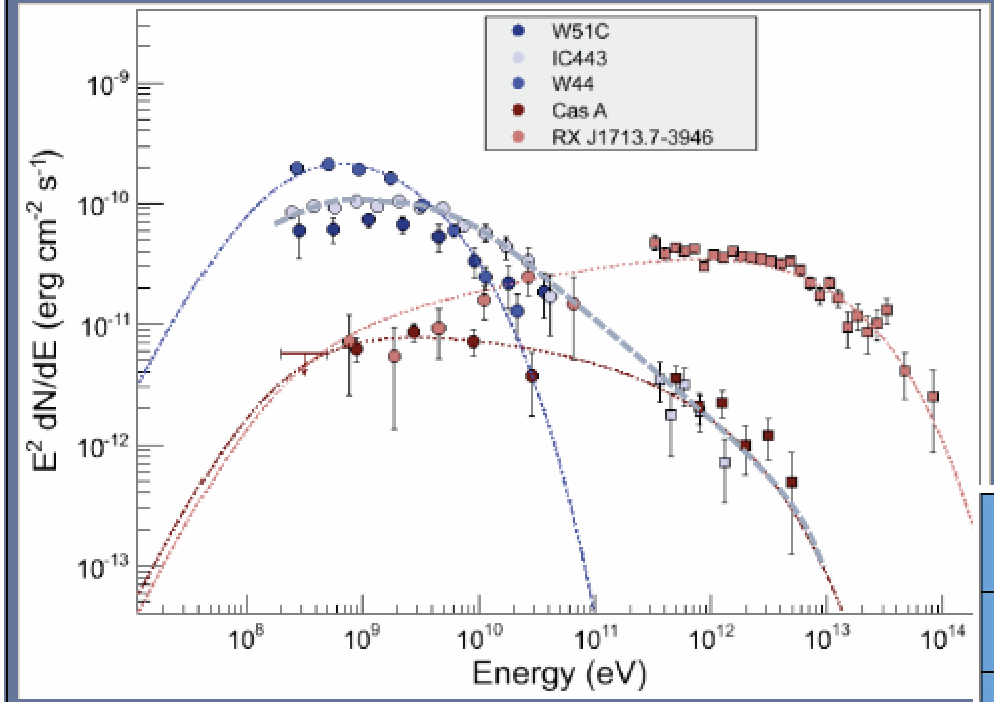
Fermi-LAT spectra of IC443 & W44: π^0 decay γ-rays



- Low-energy cut off at half the π^0 mass
- Clear evidence for SNR as hadronic acceleration sites



SNRs in different



We can study SNRs in different evolutionary stages

	Cas A	RX J1713.7 -3946	IC443	W44	W51C
Age (kyears)	0.3	2	10	20	30
$n_{average}$ (cm-3)	10	0.1	10	100	10
$CR_{fraction}$	2%	50%	25%	5%	10%

Courtesy of S.Funk

Hadronic interactions

eV in a

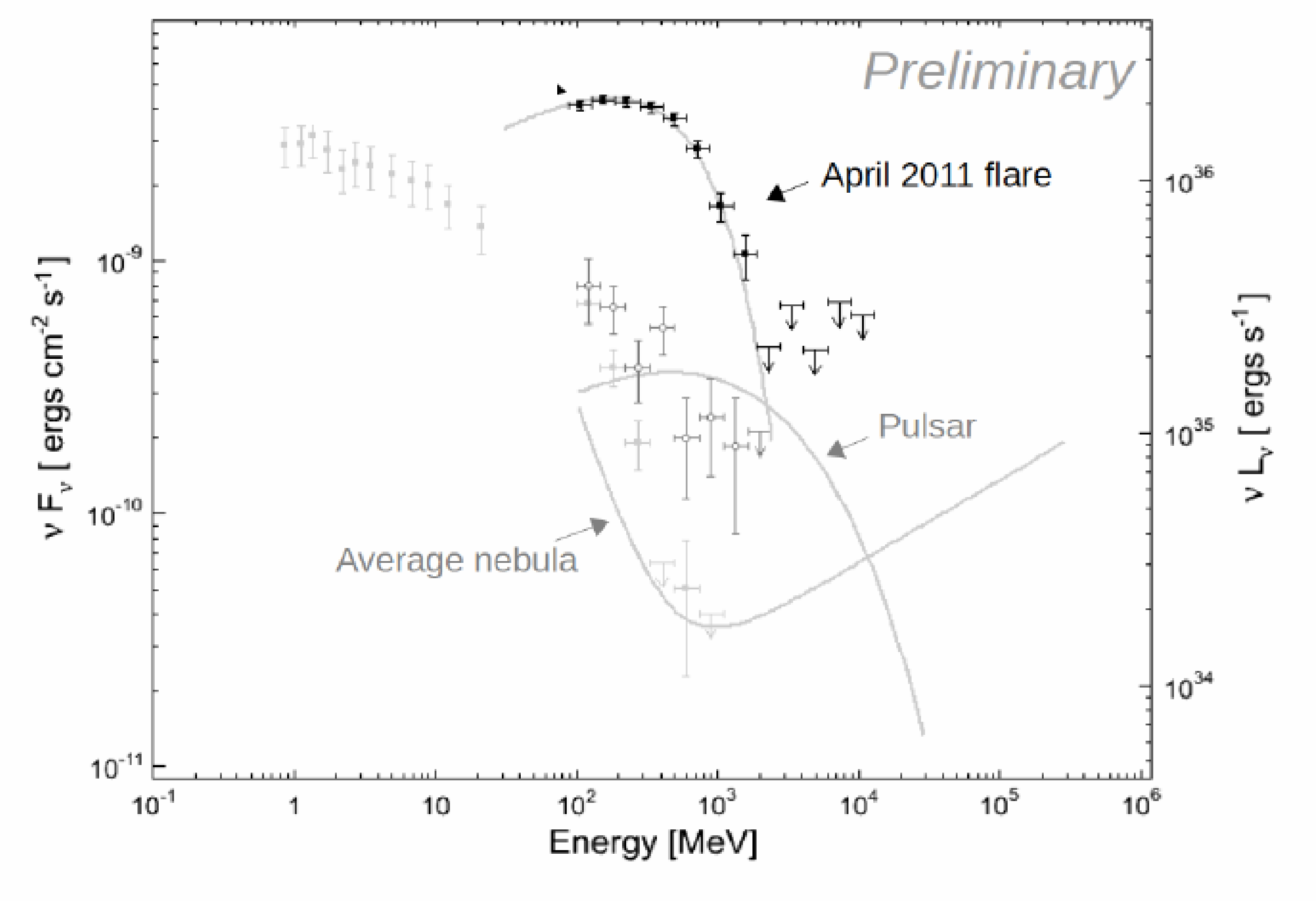
nt

00 cm^{-3}

$$p\,p \longrightarrow \pi^0 + \text{other particles} \qquad \pi^0 \longrightarrow 2\,\gamma$$

- The gamma ray spectrum is simmetric around $m_\pi/2 = 67.5$ Me log-log scale (π^0 bump)
- Above a few GeV has the same slope of the parents protons
- There is no suppression at high energy as IC, unless the pare proton spectrum has a cutoff
- The emission depends on the environment *gas density*
  In SNR the gas density can range from ~ 0.01 cm^{-3} up to ~10
  in case of *Molecular Clouds*

Crab flare spectrum



New spectral component of power law of index 1.6 and exponential cutoff at 580 MeV (Pulsar like, but no sign of pulsation in flare photons)

R. Buehler, Fermi Symposium 2011