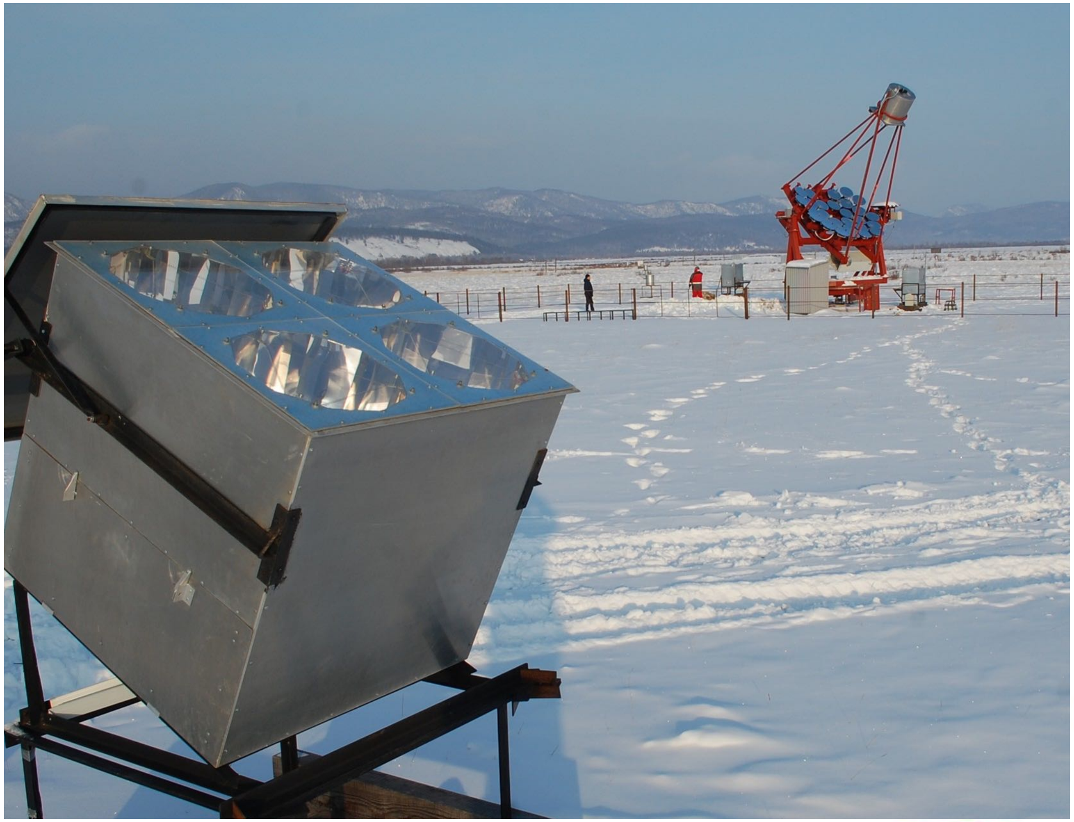
The TAIGA Experiment

Prototyping a new technology for gamma-ray astronomy >10TeV

Ralf Wischnewski (DESY)

for the TAIGA-Collaboration

Ricap2018, Rome, 7.9.2018



TAIGA :

Tunka Advanced Instrument for CR and Gamma Astronomy

A multi-component Gamma-Ray and CR-Detector In the Tunka-Valley/Siberia

The collaboration

Russia

ISU, Irkutsk
MSU, Moscow
MEPhI, Moscow
INR, Moscow
JINR, Dubna
IZMIRAN, Troitsk/Moscow
Budker INP, Novosibirsk
NSUniv, Novosibirsk
IPSM, Ulan Ude

Germany

Hamburg Univ.
DESY, Zeuthen
MPI, Munich

Italy

Torino, INFN

Romania

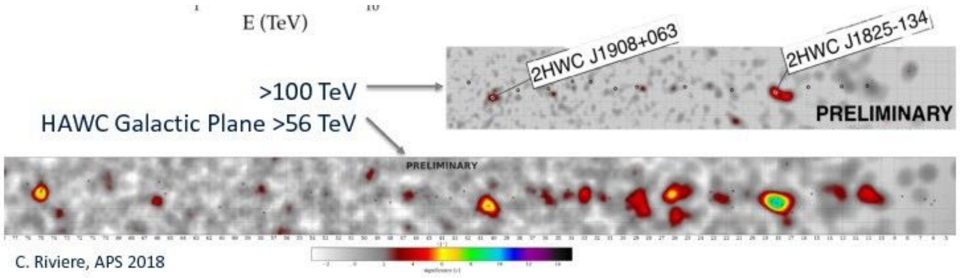
ISS, Bucharest

Gamma Astronomy beyond 10 TeV

> Where are the Galactic Pevatrons? Source-cutoffs? extended sources, AGN monitoring, MM-obs., surveys, LIV, …

> HAWC opened the 100TeV sky in 2018:

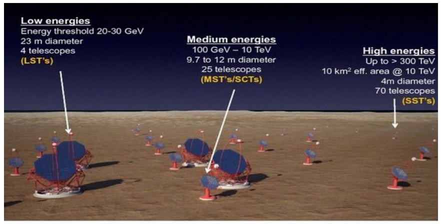
2 sources + Crab

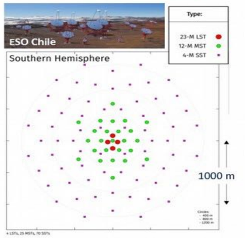


> The CTA detector concept: rely on established IACT technology.

Distribute 70 Imaging SST Telescopes (Small Size Telescopes) over 10 km2 .

==> SSTs are at ~270 m distance (stereo-mode)





> To reach instrumented areas beyond 10 km2 :

Is there an alternative detector concept, to keep costs significantly lower ?

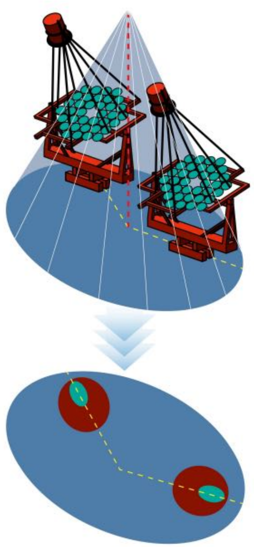
TAIGA approach

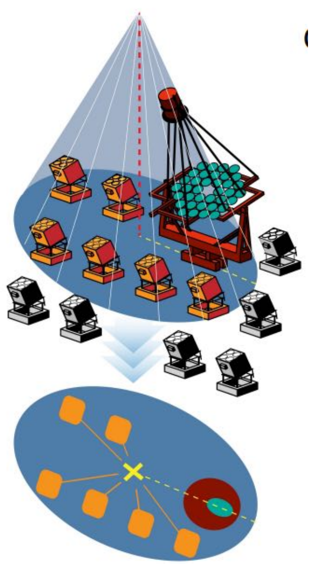
- Rely on IACT mono-mode operation, supply missing information by wide-angle timing array
- Key feature: Large detector area (>10 km²) at minimal cost with a hybrid system

IACTs in Stereo Mode

(standard approach)

Inter-IACT distance
~100-300 m





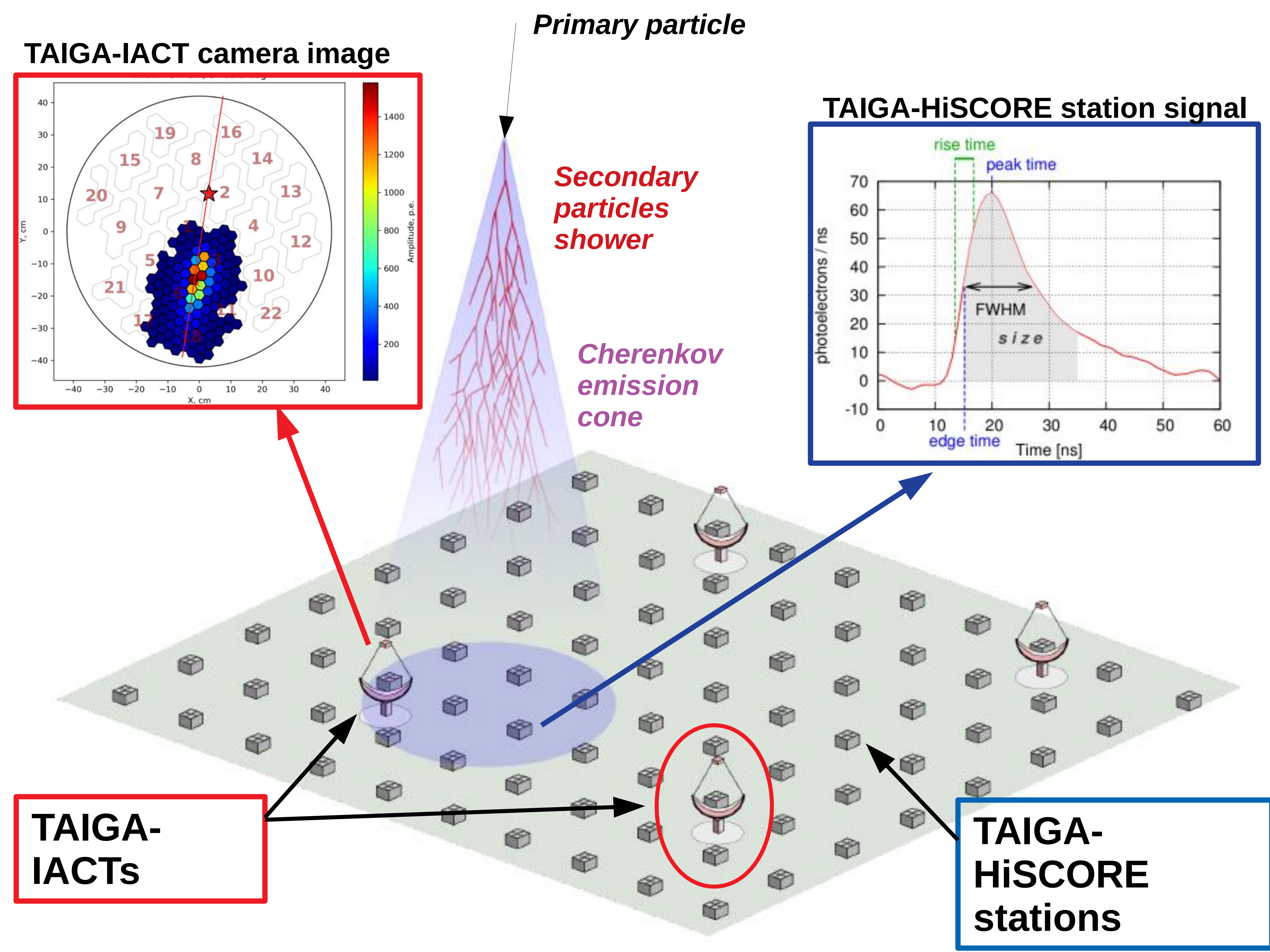
IACTs and Timing Array

(TAIGA approach)

1. IACT in mono mode:
   g/h separation

2. Timing array:
   shower core/direction/energy

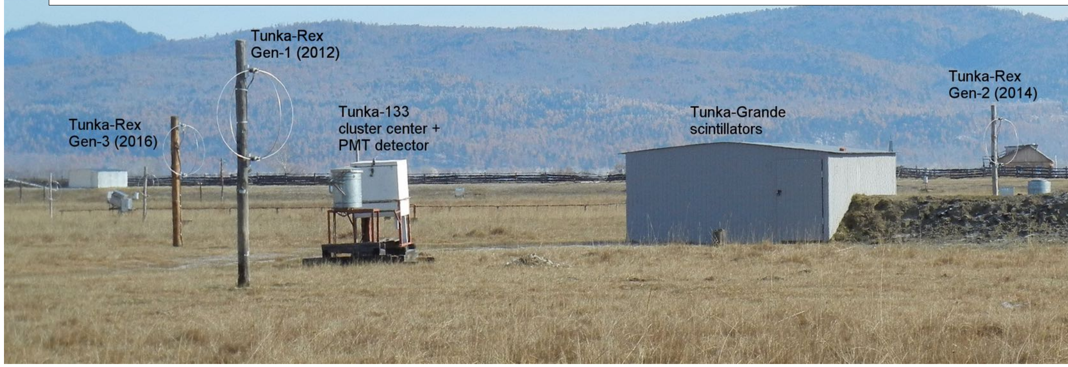
Inter-IACT distance 600-900 m
→ sparse, low-cost IACT array



Primary particle
TAIGA-IACT camera image
Secondary particles shower
Cherenkov emission cone
TAIGA-HiSCORE station signal
rise time
peak time
FWHM
size
edge time
photoelectrons / ns
Time [ns]
X, cm
Y, cm
Amplitude, p.e.
TAIGA-IACTs
TAIGA-HiSCORE stations

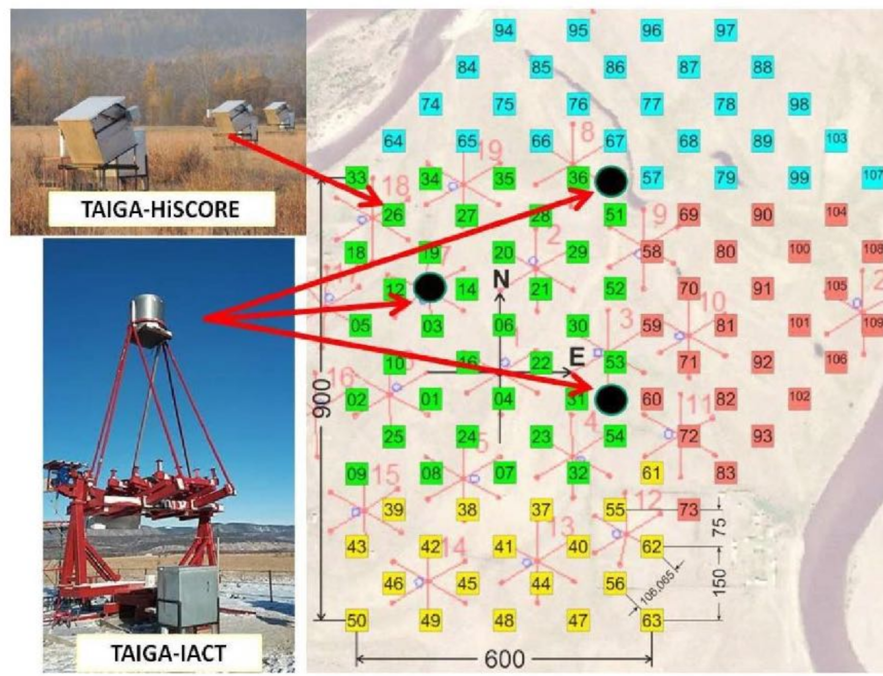
TAIGA: Gamma Astronomy in the Tunka valley

Tunka valley (Russia) – A Facility for CR studies
Tunka-133 (2009), Tunka-Rex (2012), Tunka-Grande (2014)



> **TAIGA collaboration started in 2012**

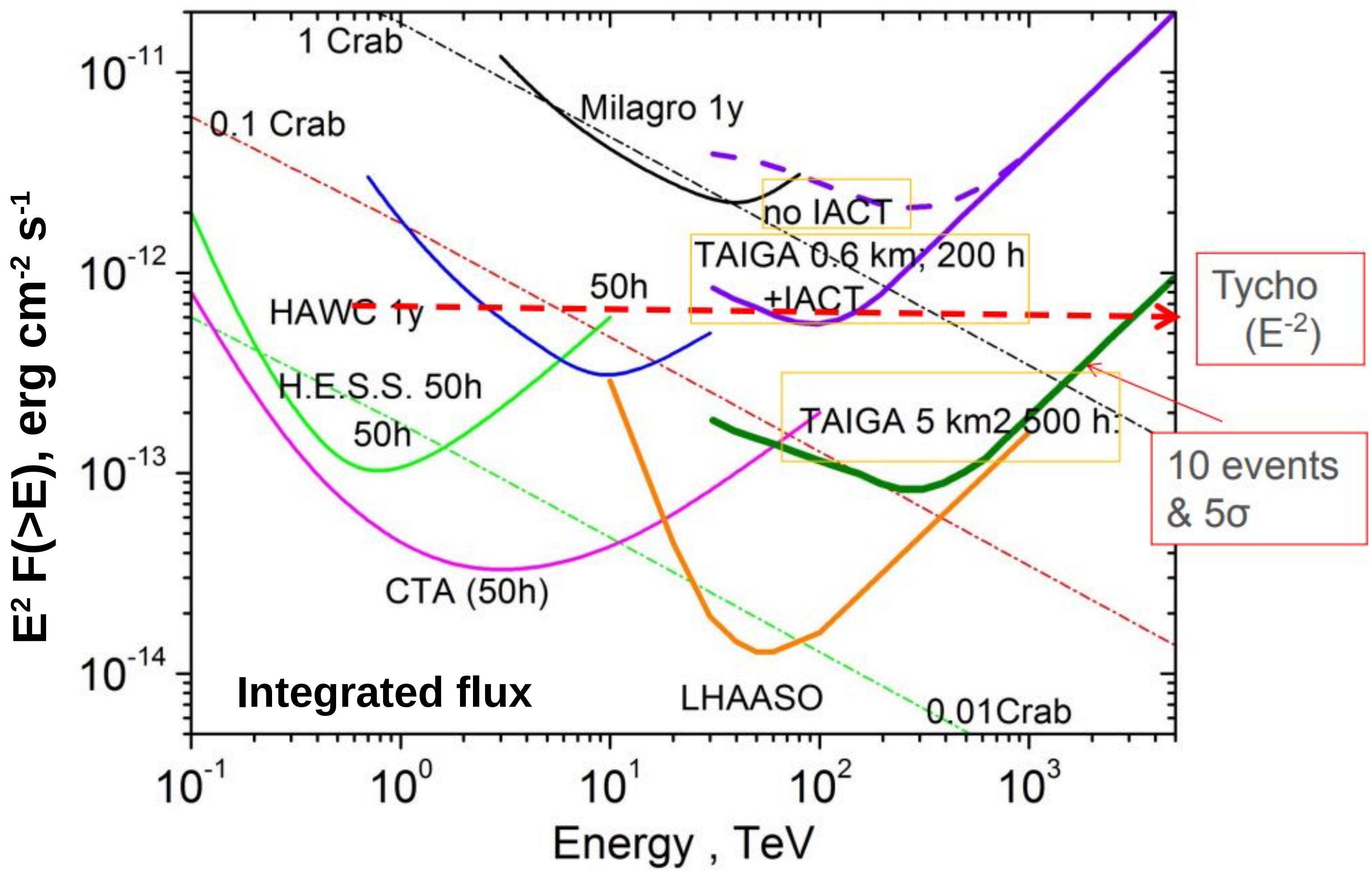
- **2013 9 HiSCORE stations array (first prototype)**
- **2014 28 HiSCORE station array A=0.25 km2**
- **2017 IACT commissioning started**
- **2017/18 IACT-HiSCORE joint operations**



> **Near future:**

- **complete the 1 km2 array + 3 IACTs by fall 2019**

TAIGA expected sensitivity



Outline

- HiSCORE-9 (HiS9): first array prototype
  - Detection concept verification
  - tested hardware / timing / EAS reconstruction

Milestone-1

- HiSCORE-28 (HiS28)
  - Event reconstruction and MC verification
    - Array time calibration
    - Pointing resolution
  - ISS/CATS-LIDAR
  - Crab search with 3 years HiSCORE-28 data

Milestone-2

- First IACT: commissioning standalone & HiSCORE joint operation
  - coincidence analysis

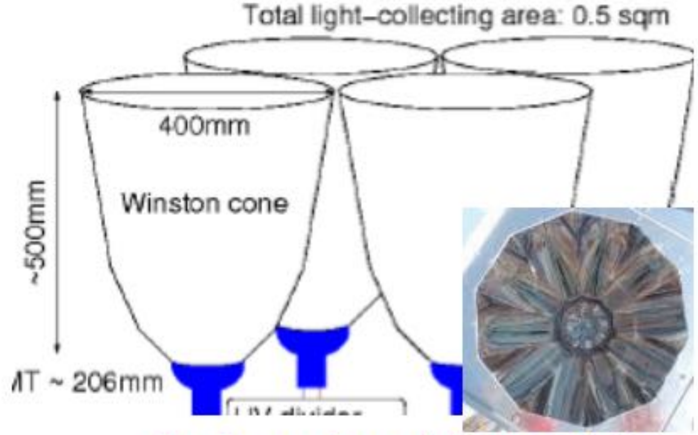
Milestone-3

HiSCORE – The TAIGA Timing Array

HiSCORE: the TAIGA timing array

High Sensitivity Cosmic Origin Explorer

Non-imaging Air Cherenkov Array
Angular resolution : ~ 0.1 deg
Large Field of view (FOV): ~ 0.6 sr
Area: 0.25 km² ⟹ 5 km²
Station spacing: 100-200m

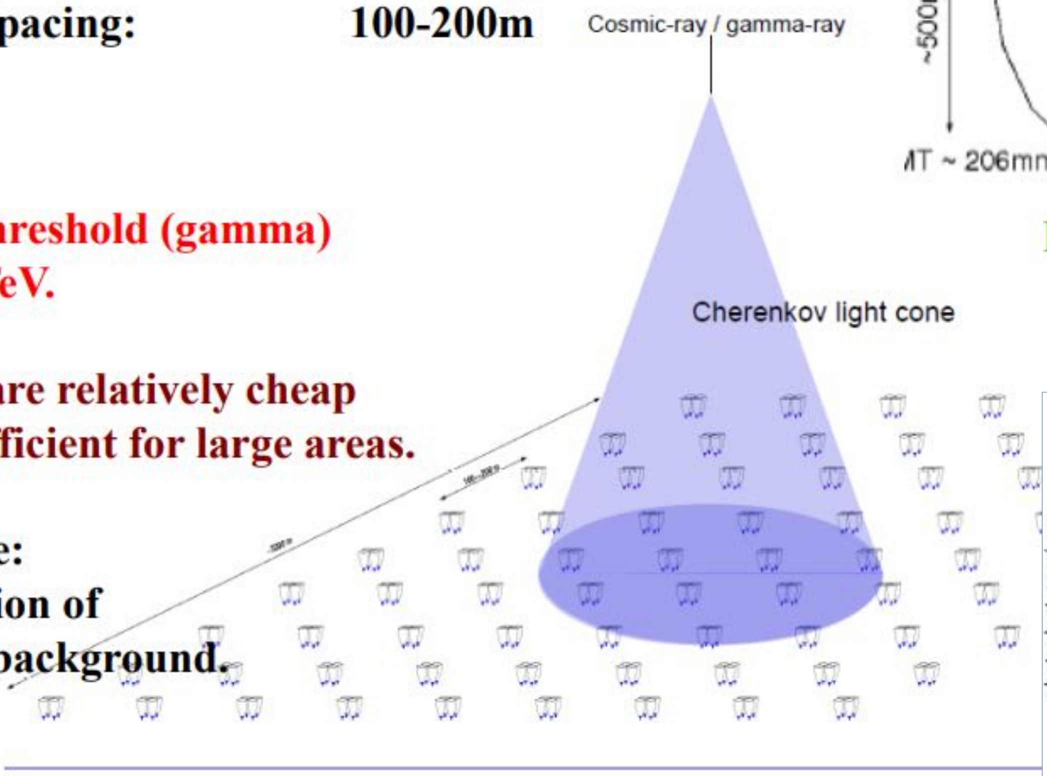


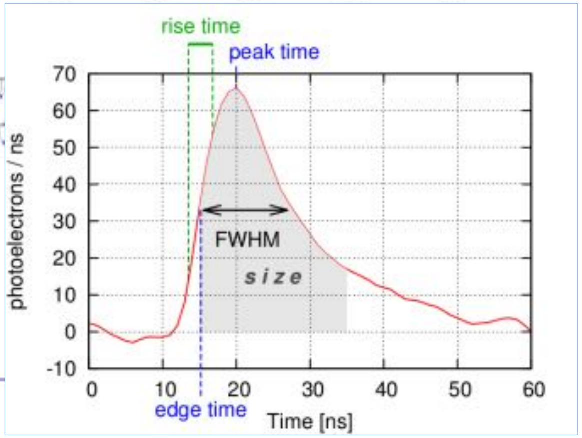
Each station: 4 large PMTs

Energy threshold (gamma)
Eγ > 30 TeV.

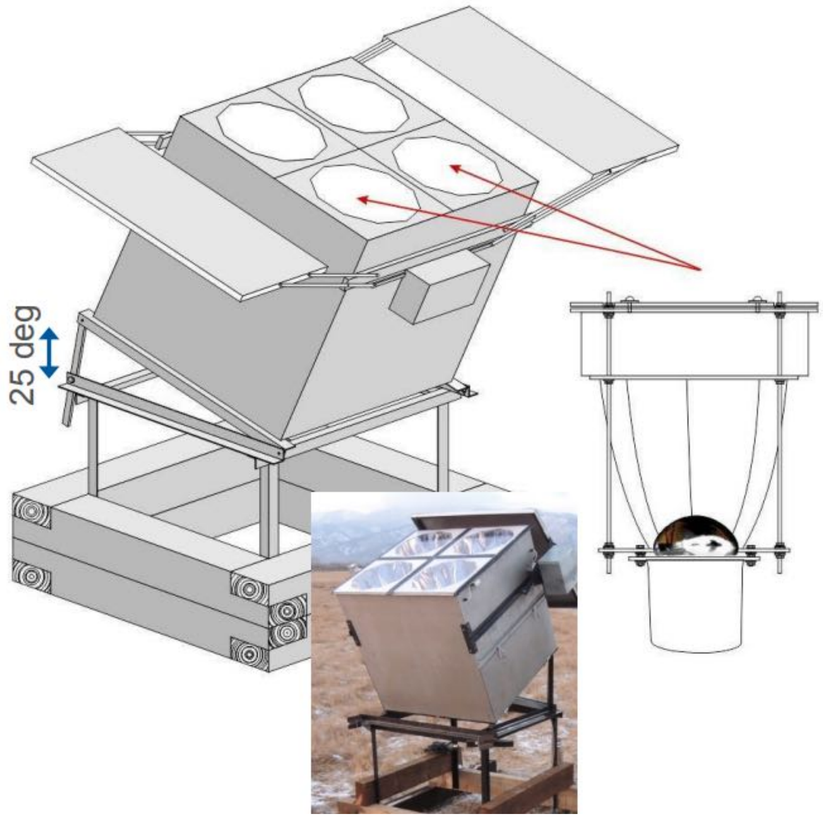
Stations are relatively cheap
→ cost-efficient for large areas.

Challenge:
Suppression of
of CRay background.





HiSCORE detector station

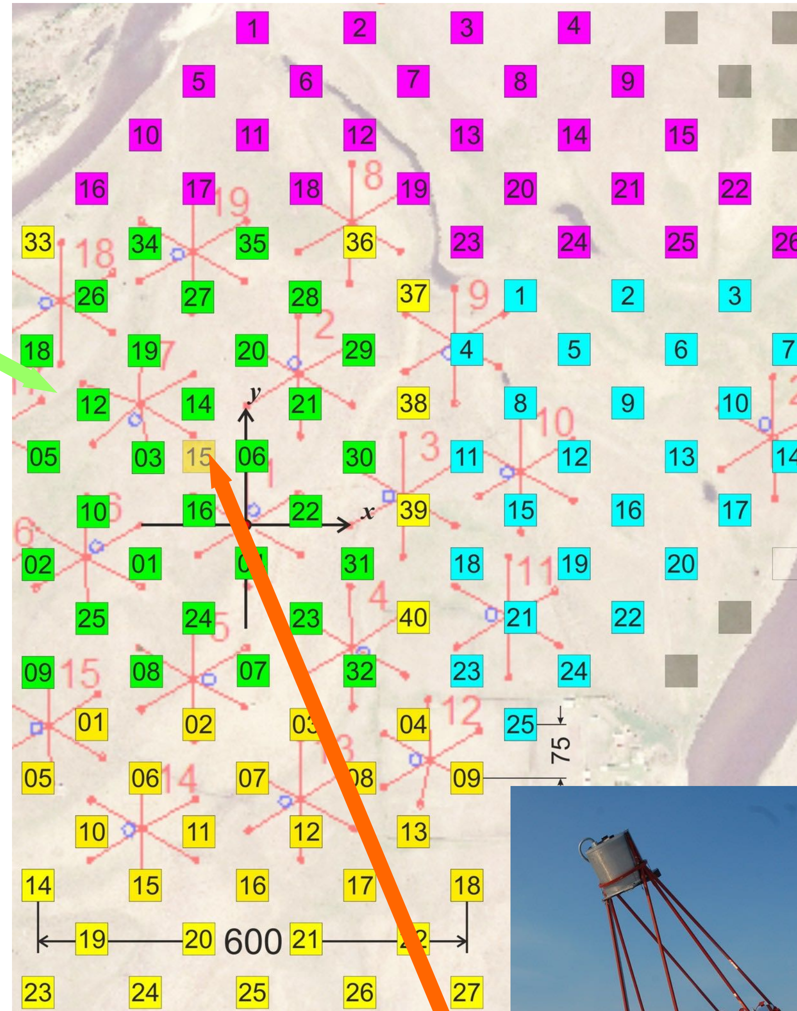


> **Optical station**
- **Four 8” / 10” PMT per station**
- **Winston Cone, sensitive area ~0.5m2**
- **FOV ~0.6 sr**
- **Sky coverage: vertical / tilted mode**

> **DAQ**
- **DRS4-based GHz readout**
- **Sub-ns array wide time synchronization (hybrid)**
  - **Custom 100 MHz fiber (MSU)**
  - **WhiteRabbit (DESY)**

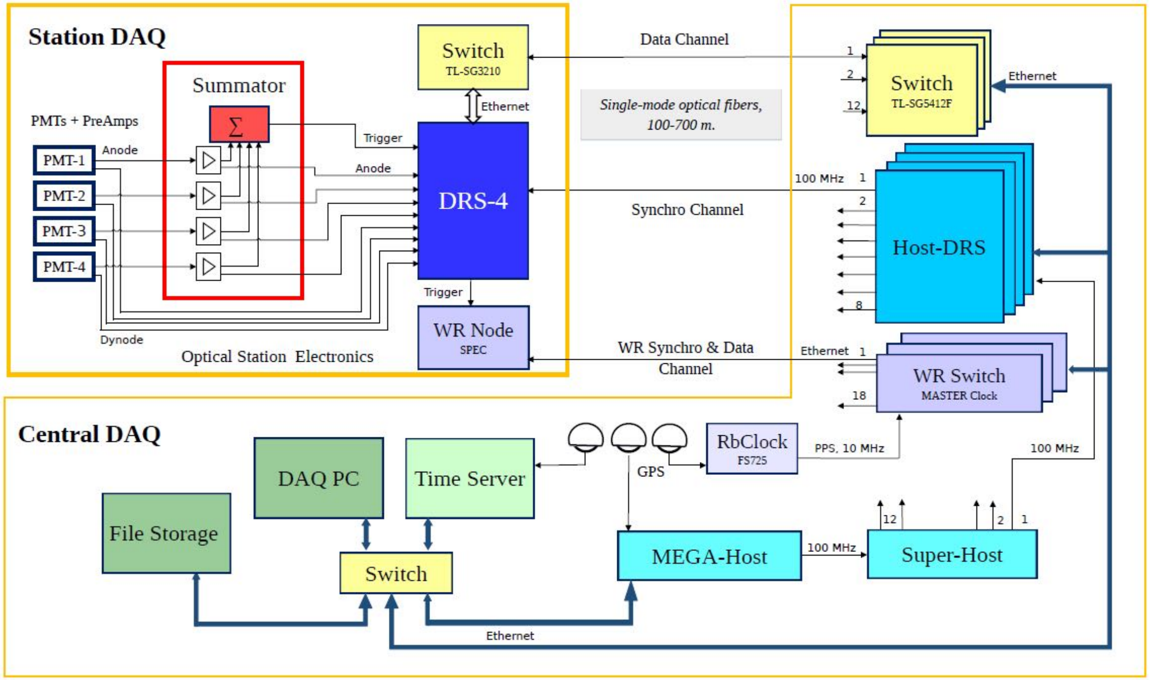
HiSCORE Array

- HiS28: 28 stations w/ 0.25km2 instrumented area
- 0.5 km2 by fall 2018
- Station spacing 106m



IACT #1

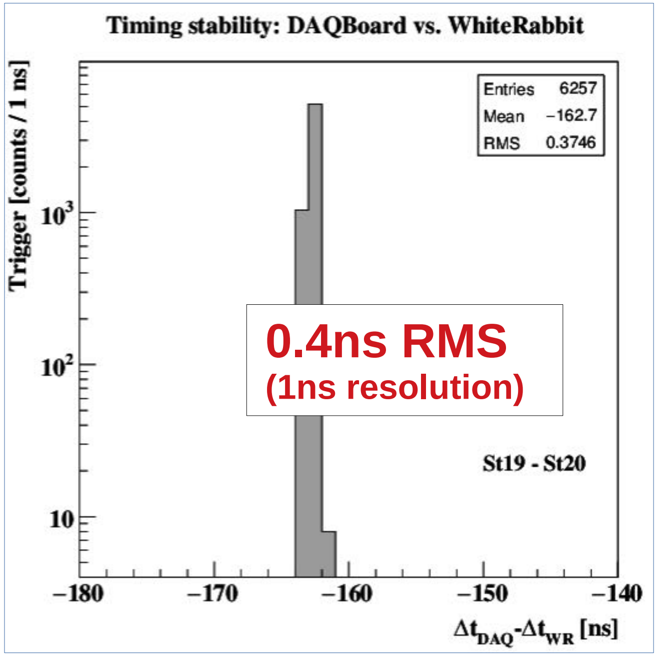
HiSCORE: Hybrid DAQ system



> **HiSCORE - DAQ system**
- **1 DRS4 for pulse sampling (2GHz)**
  - **8 PMT channels (4 anode + 4 dynode)**
- **2 timing systems (custom fiber MSU + WhiteRabbit)**

> **Station readout/trigger independently. Array trigger: offline.**

> **E_thr(gam) ~30-50TeV**



Longterm timing study (ICRC2017)

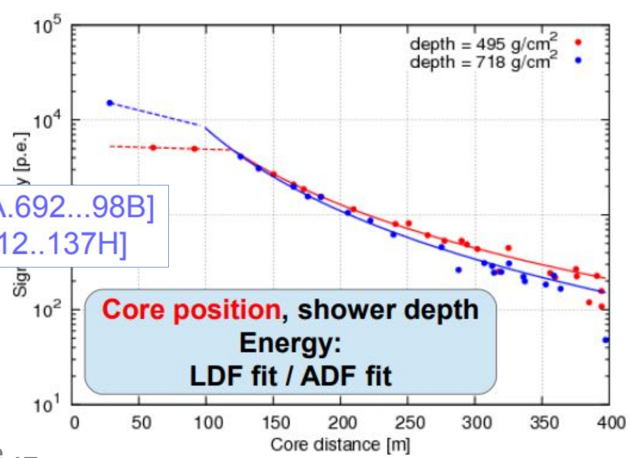
HiSCORE: MC simulation and reconstruction

> **EAS: CORSIKA**
- **IACT package for Cherenkov photon propagation**

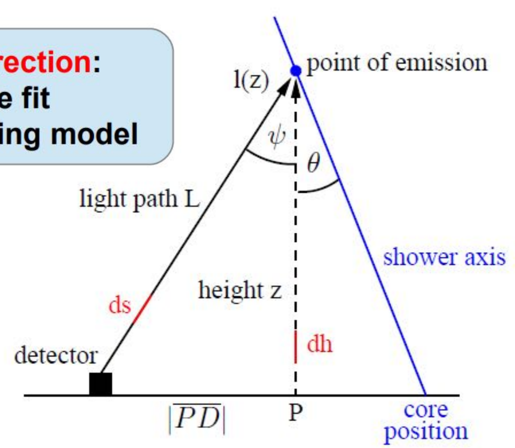
> **sim_score: detector response**
- **Based on sim_telarray (reads CORSIKA-IACT output)**
- **Full detector simulation**
  - **WCone acceptance, PMTs (QE, pulse shape, afterpulses,…)**
  - **NSB simulation**
  - **Pulse triggering, read-out**

> **Event reconstruction**
- **shore core, direction**
- **energy, Xmax**

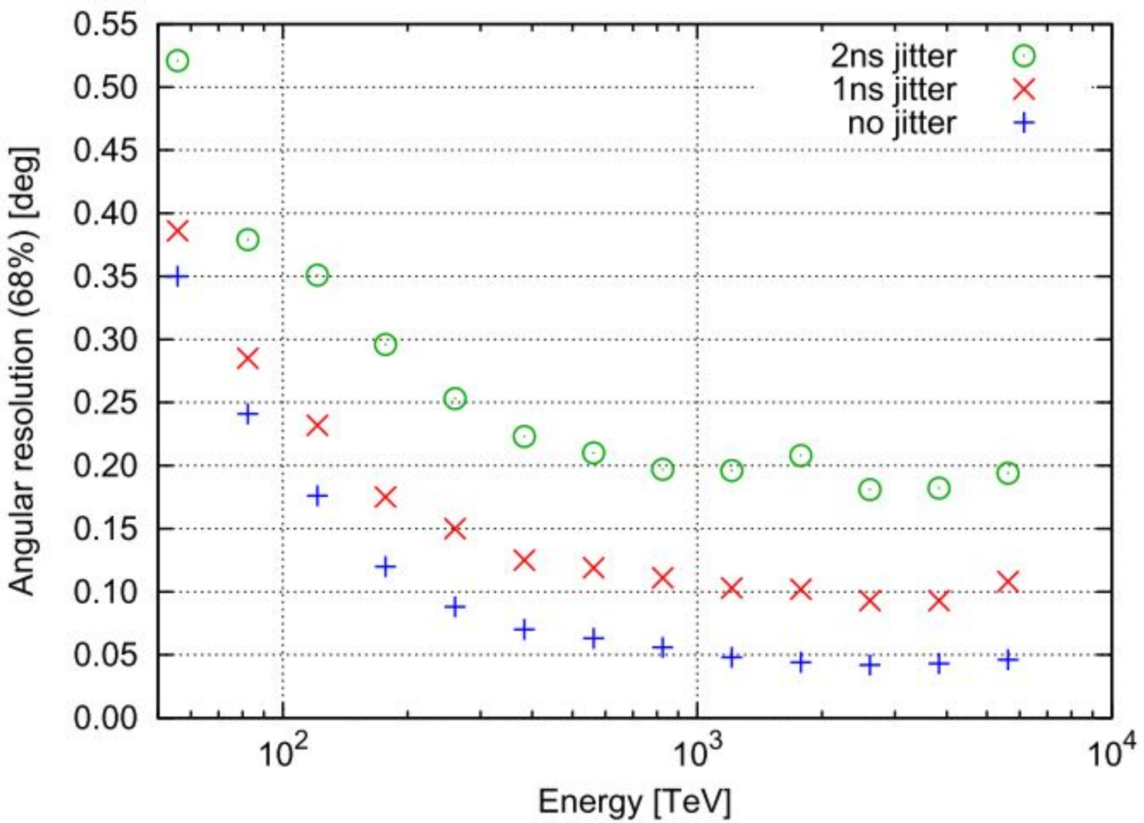
Tunka-133 [Berezhnev et al. 2012NIMPA.692...98B]
HiSCORE [Hampf et al. 2013NIMPA.712..137H]



Direction:
- Cone fit
- Timing model



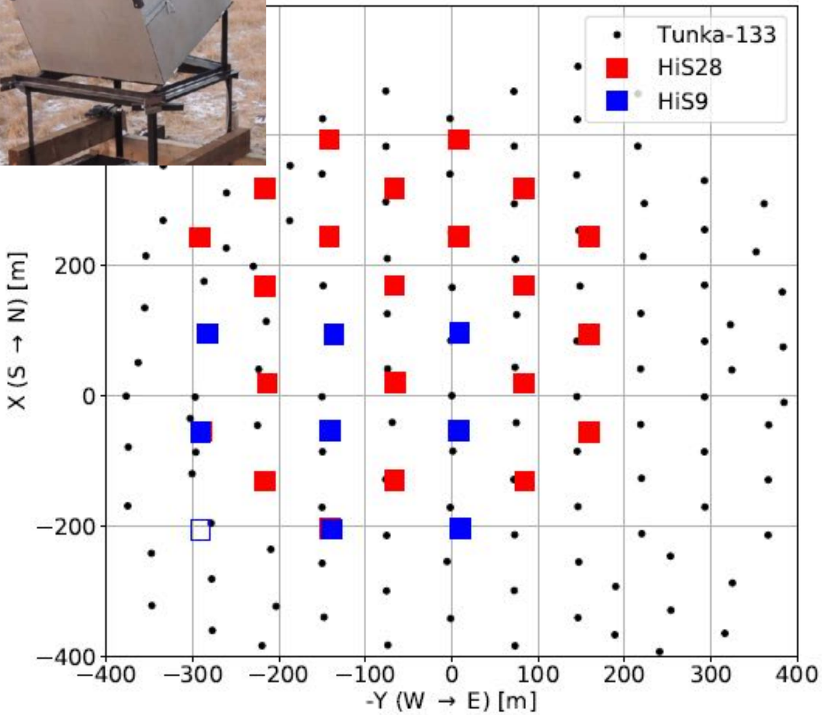
Angular resolution: Importance of timing



- MC study, variiying the time precsion
- Crucial for pointing:
  - Time synchronization < 1ns: low time jitter [Hampf, 2014]
  - Precise array time calibration (systematic mispointing induced by static station time offsets) [see ICRC2017]

TAIGA-HiSCORE (HiS28)

- **HiSCORE-9 early prototype (2013)**
- **Fall 2014 – upgrade to**
  - **28 stations, 106m spacing**
  - **25° tilting southward (Crab exposure)**



- **Goals / results:**
  - **Verify final detector design**
  - **Event reconstruction – array time calibration, angular resolution estimation**

    Verify/Tune MC
  - **Detection of standard candle: Crab**

    - Crab search with 3 years data (very prelim.)
  - **Unexpected: ISS CATS-LIDAR detection and analysis**
    - **Absoulte array pointing obtained !**

EAS reconstruction

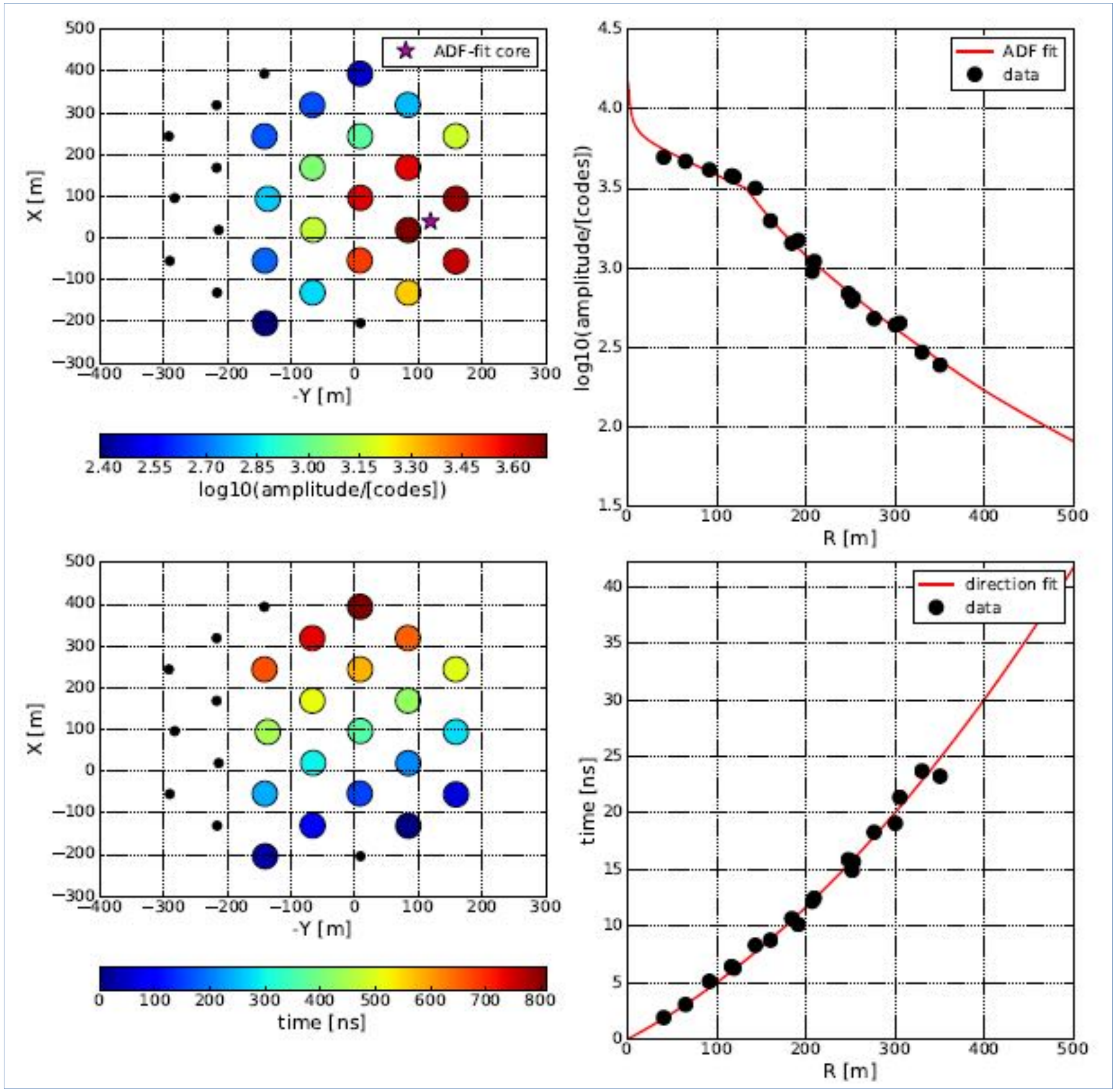
- **Shower core reconstruction:**
  - **First guess: COG Amplitude**
  - **ADF/LDF fit (N_{TRG} >= 5)**

- **Shower arrival direction fit**

$$ti = t_i^{PW}(\theta, \phi, t_0) + Dt(R_i)$$

$$Dt(R_i) = \frac{(R_i + R_c)^2}{cR_s^2}$$

- **Problem: bad reconstruction for "out-trigger EAS"**
  - **main source of error for precise direction reconstruction**
  - **special cuts: see Crab analysis**

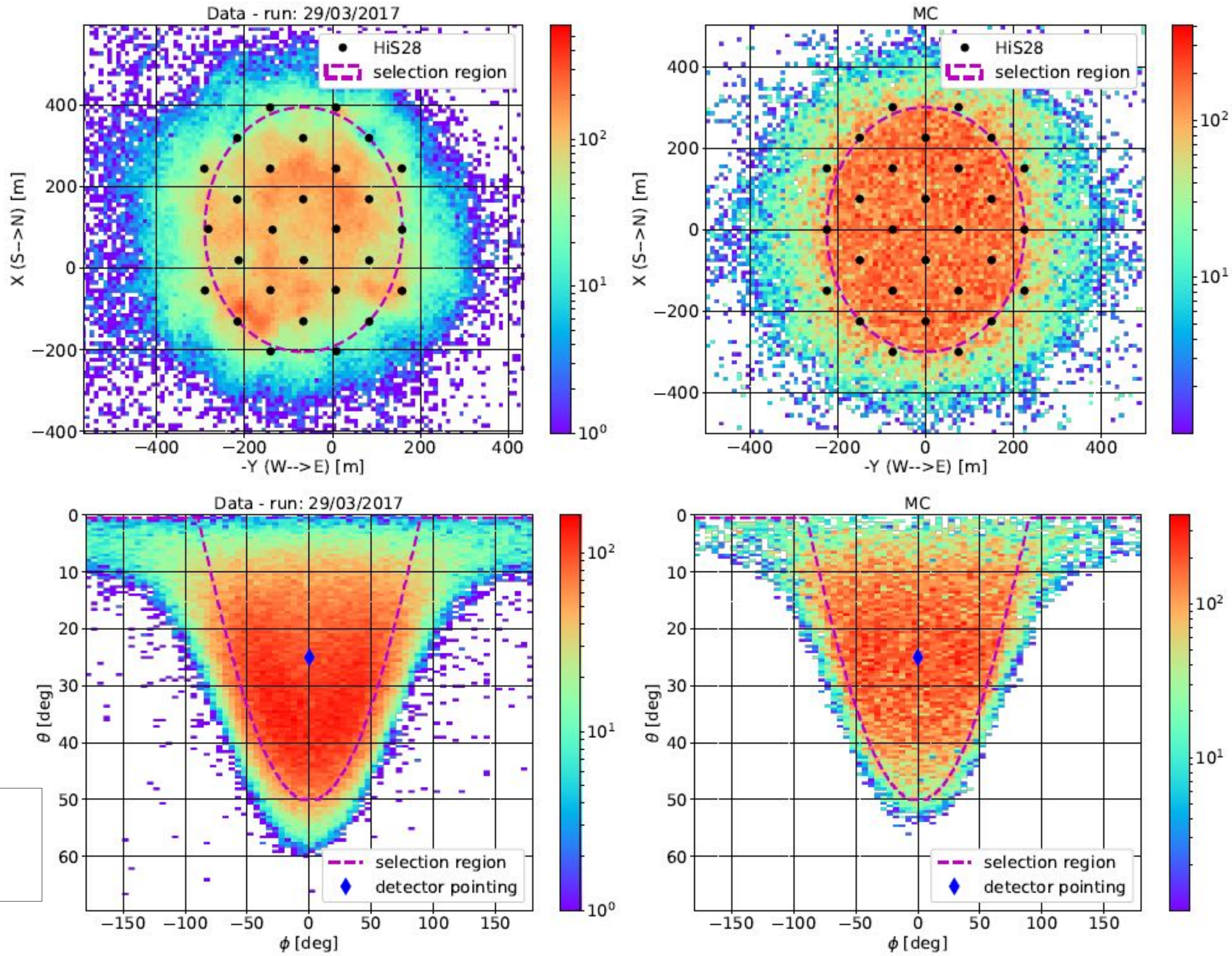


Detector acceptance: Data/MC comparison

> **Reconstructed core and arrival direction distributions: Detector acceptance, Data/MC comparison**

Shower core

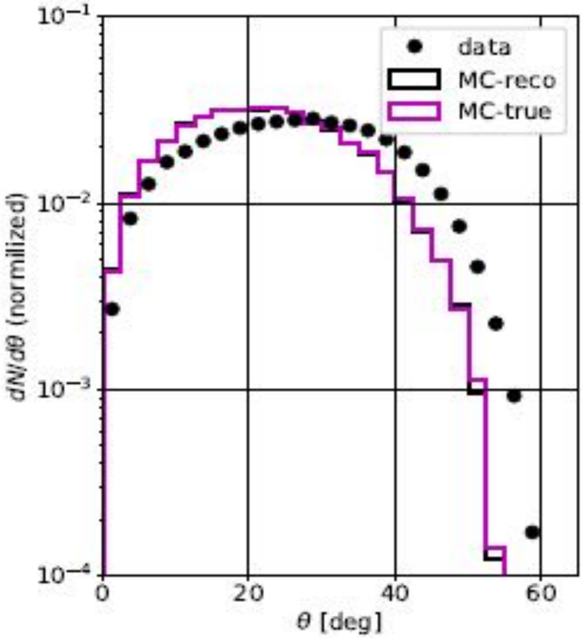
Shower arrival direction



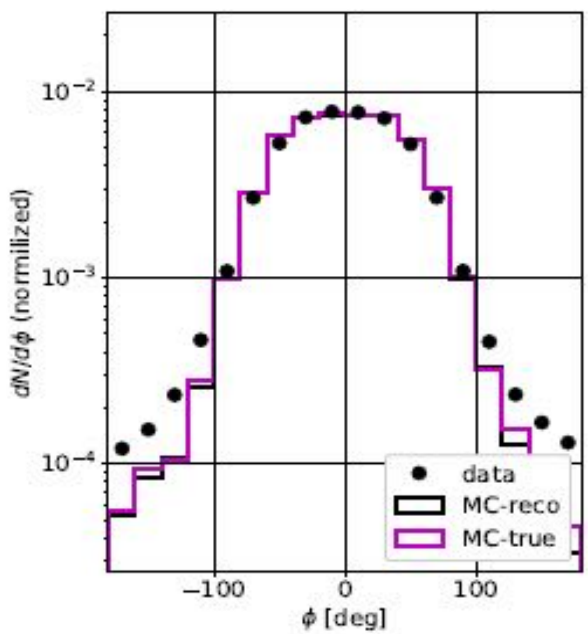
Detector acceptance: Data/MC comparison

> **Reconstructed arrival direction distributions: Detector acceptance, Data/MC comparison**

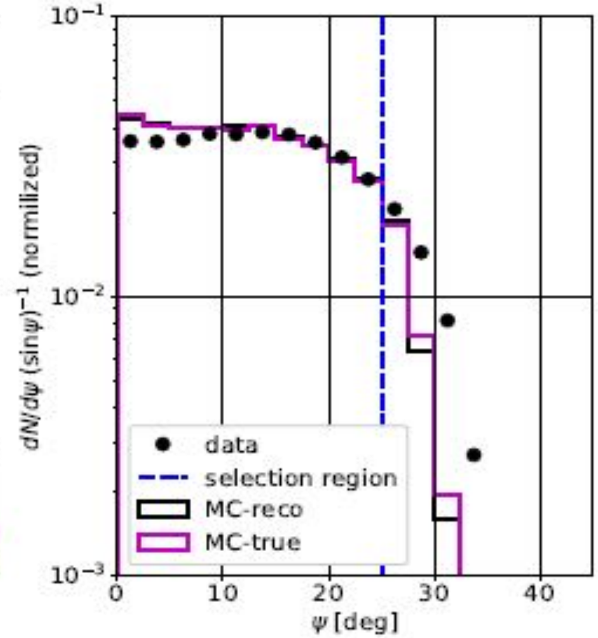
ZENITH



AZIMUT



PSI



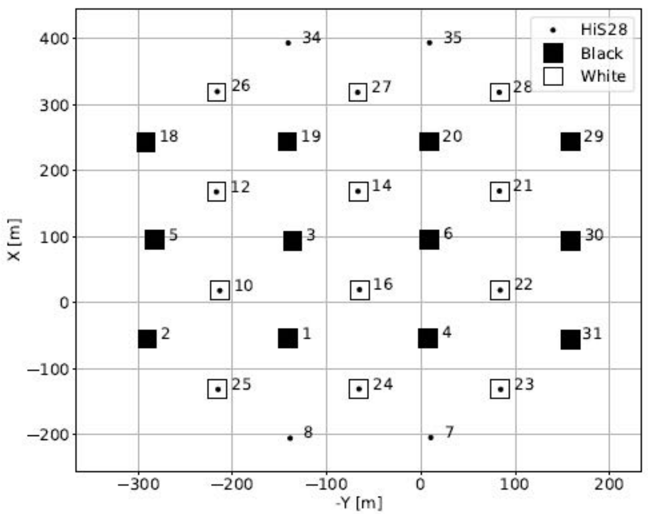
> **Good Data/MC agrrement for detector acceptance**

> **Small mismatch for zenith: tune energy threshold (station trigger threshold)**

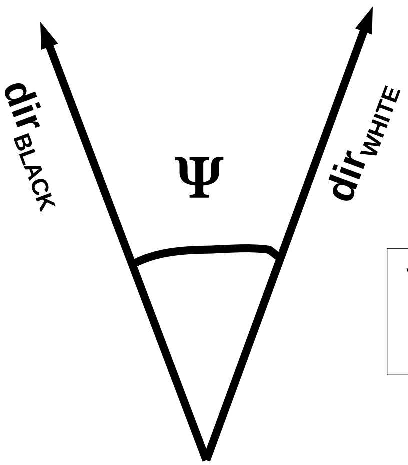
- **Experimental station trigger threshold likely 200-250ph.e.**
- **MC station trigger threshold: 180ph.e. (work in progress)**

Angular resolution check with data: chessboard method

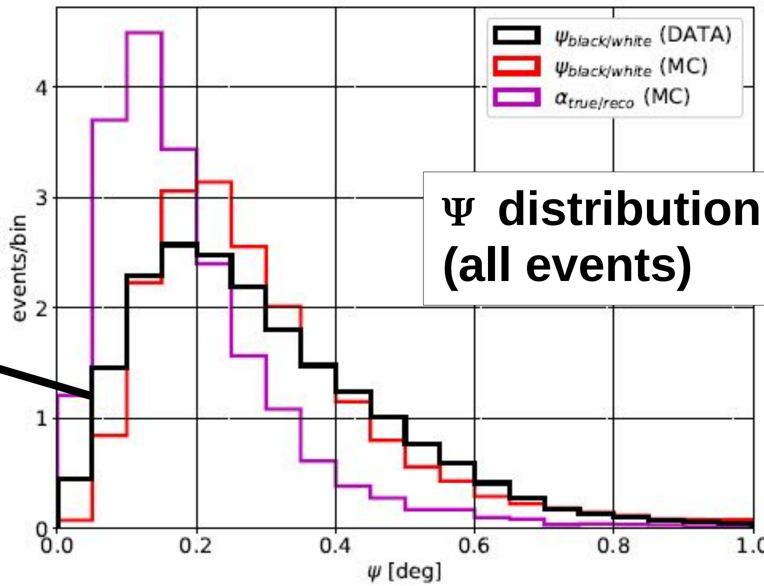
- **Chessboard method: determine detector angular resolution from the data (see AIROBICC, ARGO-YBJ)**
  - **split array in two sub-arrays: two event reconstructions**
  - **use space angle between the two reconstructed directions (Ψ) to estimate the full-array error, α**
  - **Method checked using MC simulation**



$$\Psi_{\text{BLACK/WHITE}} = (\text{dir}_{\text{BLACK}} \cdot \text{dir}_{\text{WHITE}})$$



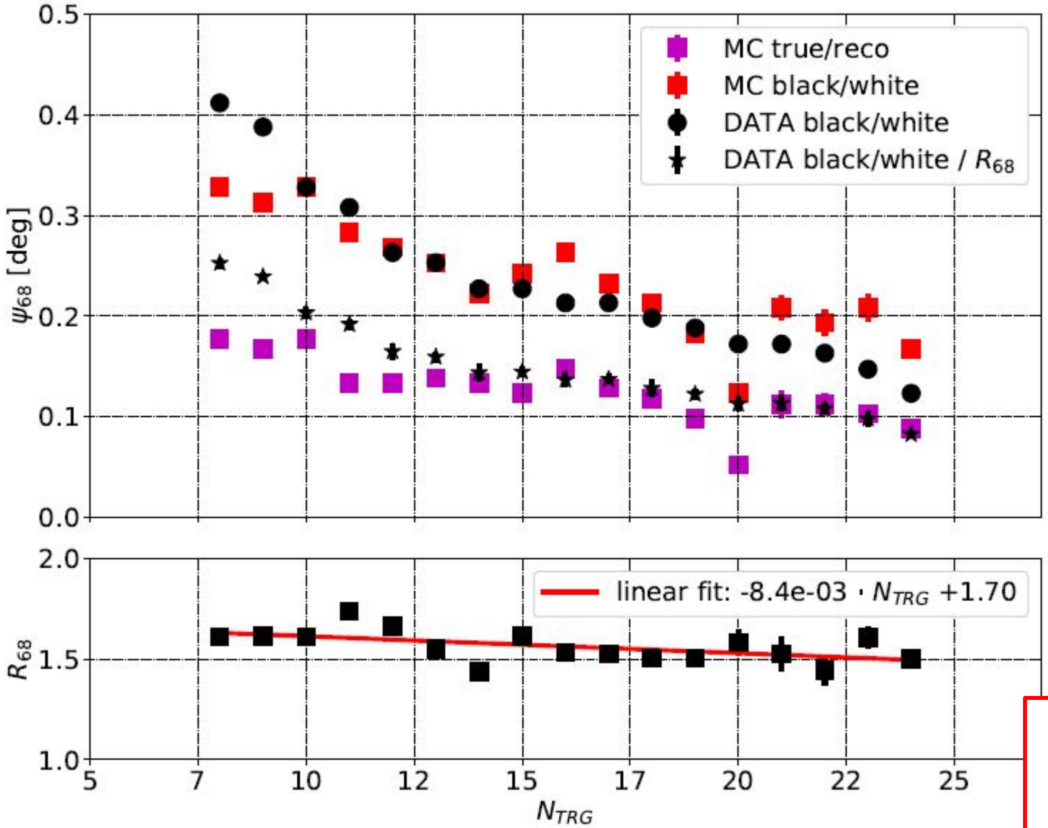
Very good agreement between Data/MC



Ψ distribution (all events)

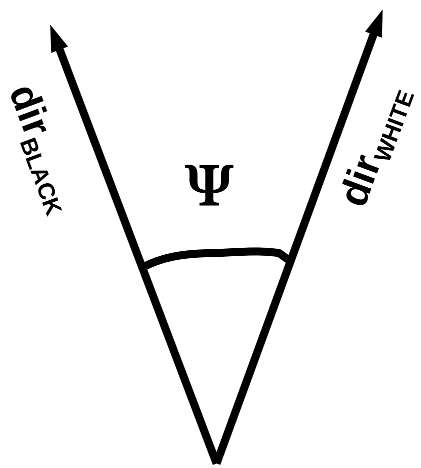
Angular resolution check with data: chessboard method

> **Angular resolution VS triggered stations**



$R^{68} = \Psi^{68}_{BLACK/WHITE} / \alpha^{68}_{TRUE/RECO}$

$\Psi_{BLACK/WHITE} = (dir_{BLACK} \cdot dir_{WHITE})$
$\alpha_{TRUE/RECO} = \Psi_{BLACK/WHITE} / R$

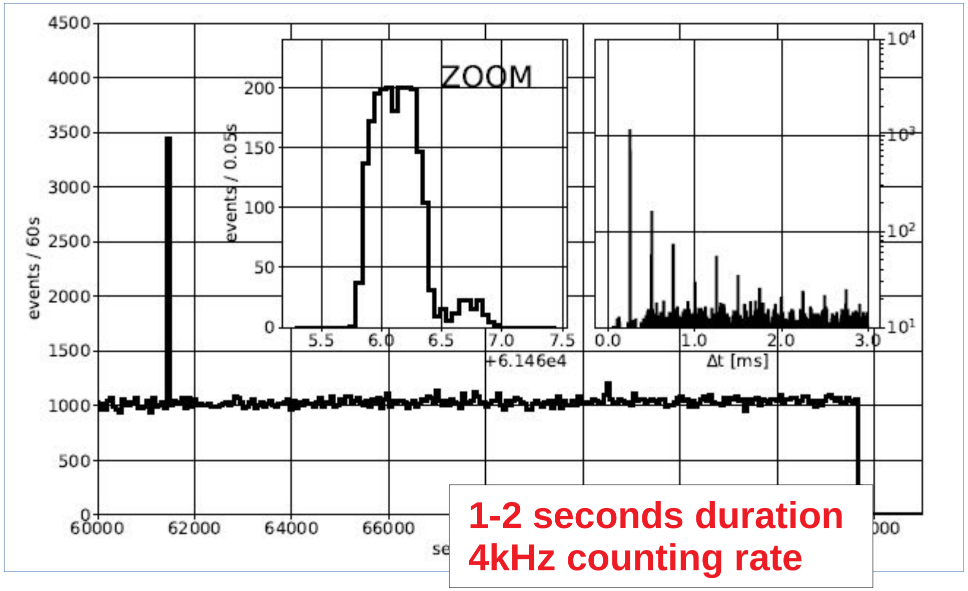


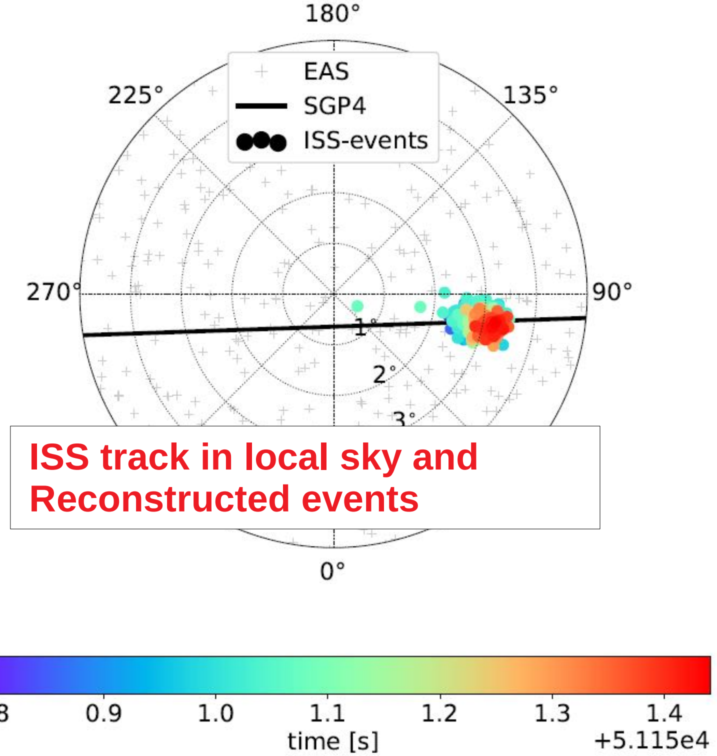
Conclusion: Full array angular resolution (68% containment)

$\alpha^{68}_{TRUE/RECO} <= 0.15° @ N_{TRG} > 10$

$\alpha^{68}_{TRUE/RECO} <= 0.1° @ N_{TRG} >= 20$

HiSCORE observation of the ISS/CATS-LIDAR





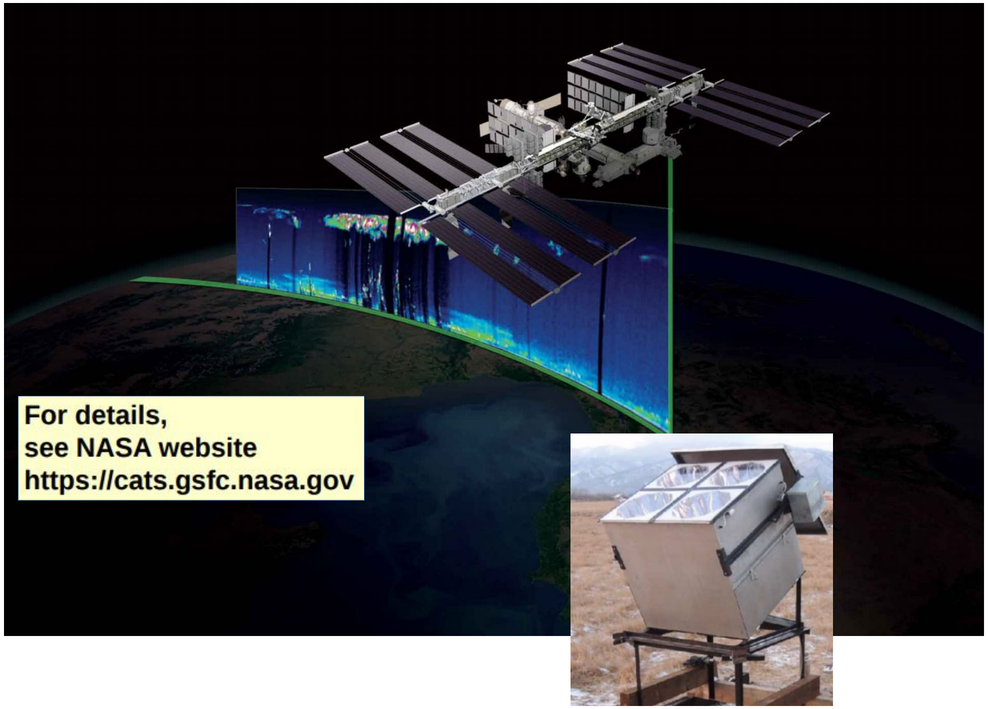
> **Serendipitous discovery – 2015/16**

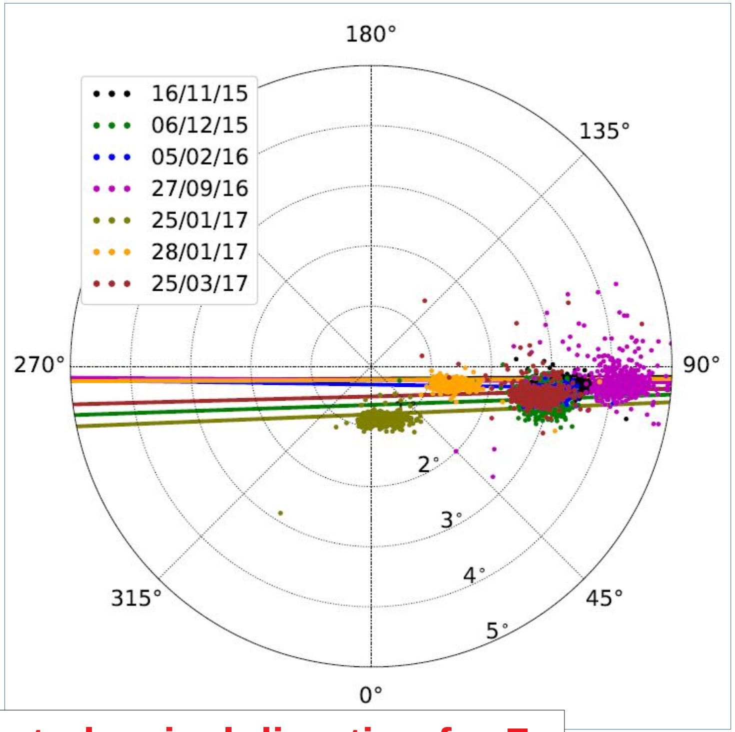
- **Several passages observed (and predicted) partially 3/4 days period; also during 2016/17**
- **Passages must be close to zenith**
- **Perfect plane wave reconstruction instead of curved EAS profile**

Unique tool for HiSCORE calibration / verification

- **absolute (astronomical) pointing**
- **angular resolution (PSF)**
- **hardware performance, ...**

ISS/CATS-LIDAR: first TAIGA-HiSCORE source





> **The CATS-LIDAR on ISS at 415 km a.s.l**
- **4 kHz repetition rate**
- **11 passages observed**
- **observed at large distance o(km)**

Reconstructed arrival direction for 7 of the 11 detected passages
(see next slide summary table)

ISS/CATS-LIDAR: a first TAIGA-HiSCORE point source

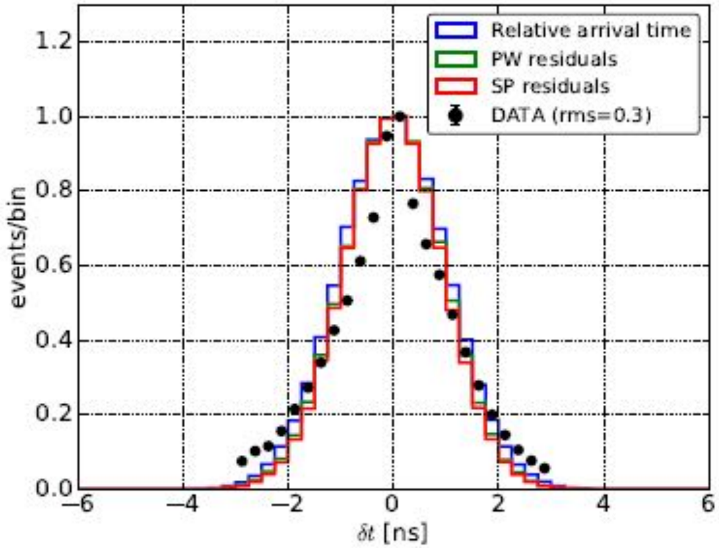
11 passages detected during 2015-2017 observations

Date	ISS-events (Selected)	CATS data	MASTER Image
16/11/15	2780 (1760)	YES	NO
19/11/15	50 (7)	YES	NO
06/12/15	3830 (1850)	YES	NO
05/02/16	1990 (1320)	YES	NO
08/02/16	3421 (1056)	NO	NO
27/09/16	2040 (1590)	YES	NO
26/11/16	1821 (0)	YES	NO
25/01/17	2300 (1730)	YES	NO
28/01/17	2140 (1300)	YES	NO
25/03/17	2140 (1710)	YES	YES
31/03/17	1780 (13)	YES	NO

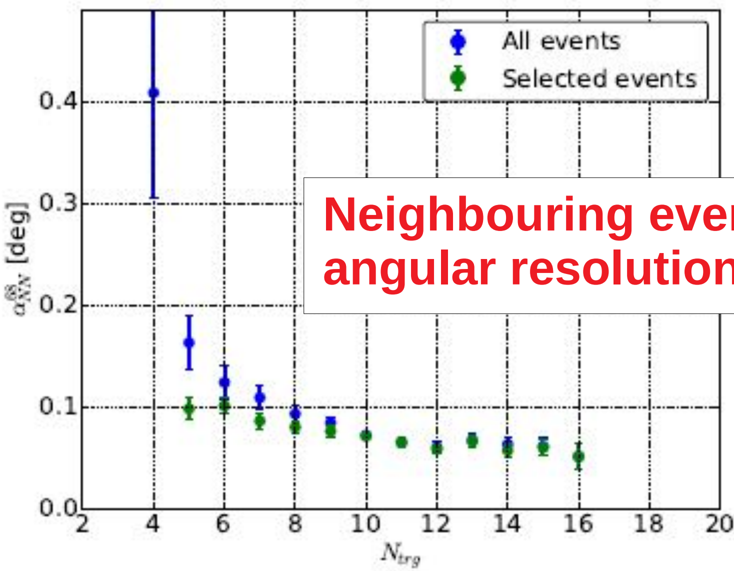
ISS-event analysis

- **Arrival direction reconstruction: plane wave fit**
  - **Station time resolution: residual distribution width= 0.3ns**
- **Angular resolution: compare reconstructed directions from neighboured events**
  - **Angular resolution (68% containment) <= 0.1 @ very low multiplicity**
  - **→ Main source of error in EAS direction reconstruction: shower core misreconstruction**

0.3ns time resolution (pulls)



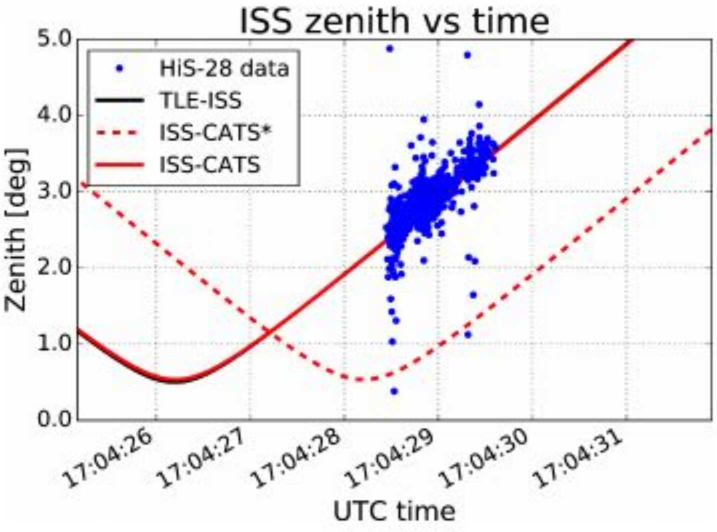
$$\alpha_i^{NN} = \arccos(\overrightarrow{dir}_i \cdot \overrightarrow{dir}_{i-1})/\sqrt{2}$$

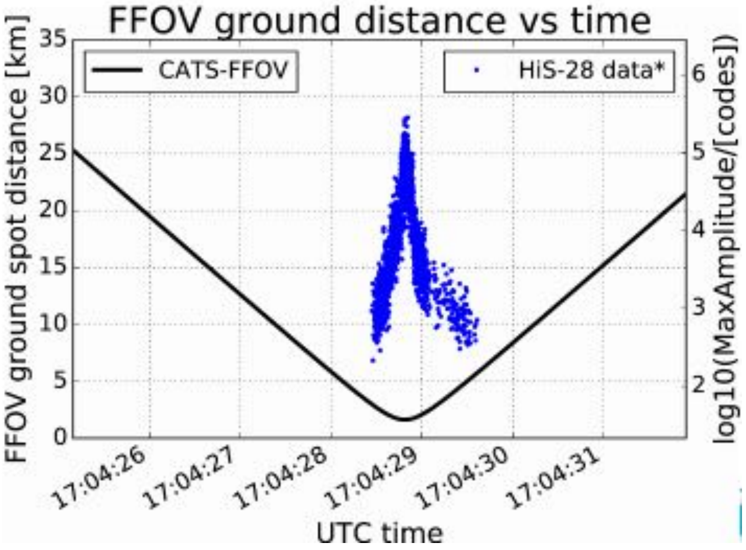


Neighbouring event angular resolution: < 0.1°

HiSCORE-CATS combined analysis

- GOAL: obtain complete description of the detection process
- For each detected passage (10):
  - HiSCORE data (ISS-events)
  - CATS data: ISS (position, attitude, time,...) & LIDAR (pointing, repetition,..)
  - ISS TLE (NASA) + SGP4 propagator (refernce for ISS position/time)
- Main problems: systematic errors in the public CATS data
  - Finally settled (e.g. time shift) after discussions with CATS scientists (see DESY internal note 10/05/17 to NASA/CATS)
  - Uncertainty on precise ISS position: no simple precision pointing verification





HiSCORE-CATS combined analysis

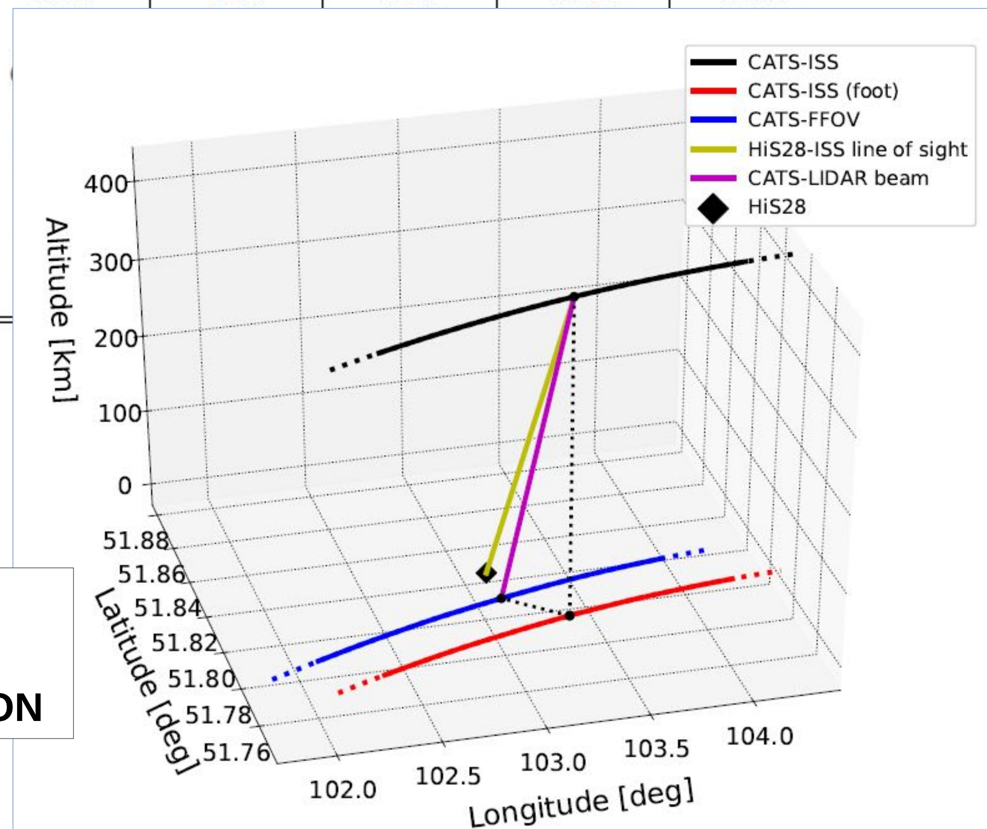
> **Summary table for passage characterization**

Var name	16/11/15	06/12/15	05/02/16	27/09/16	25/01/17	28/01/17	25/03/17
Time (θ_{ISS}^{min})	22:10:34	14:12:29	14:08:26	16:29:05	16:30:22	15:30:02	17:04:26
θ_{ISS}^{min} [deg]	0.21	0.64	0.3	0.23	0.8	0.23	0.5
t_{rise} [s]	0.35	0.29	0.42	0.3	0.32	0.31	0.36
t_{fall} [s]	0.55	0.38	0.33	0.39	0.5	0.54	0.63
t_{tot} [s]	0.90	0.67	0.75	0.69	0.82	0.85	0.99
$Max(Amp_{max})$ [codes]	3.8e+04	1.1e+05	6.6e+04	1.7e+06	5.8e+04	1.6e+04	2.8e+05
R_{FFOV}^{mim} [km]	3.8	2.98	3.03	1.15	4.43	4.9	2.1
α_{FFOV}^{mim} [deg]	0.82	0.68	0.79	0.33	0.89	0.93	0.58
δt_{CATS} [s]	-2.1	-1.7	-0.8	-0.45	-3.15	-2.0	-2.0
δt_{TLE} [s]	0.75	0.71	0.75	0.55	0.8	0.78	0.55
passage type	SSS	SSN	SNN	SNN	SSN	SSS	SSN

HiSCORE-CATS combined analysis

> Summary table for passage characterization

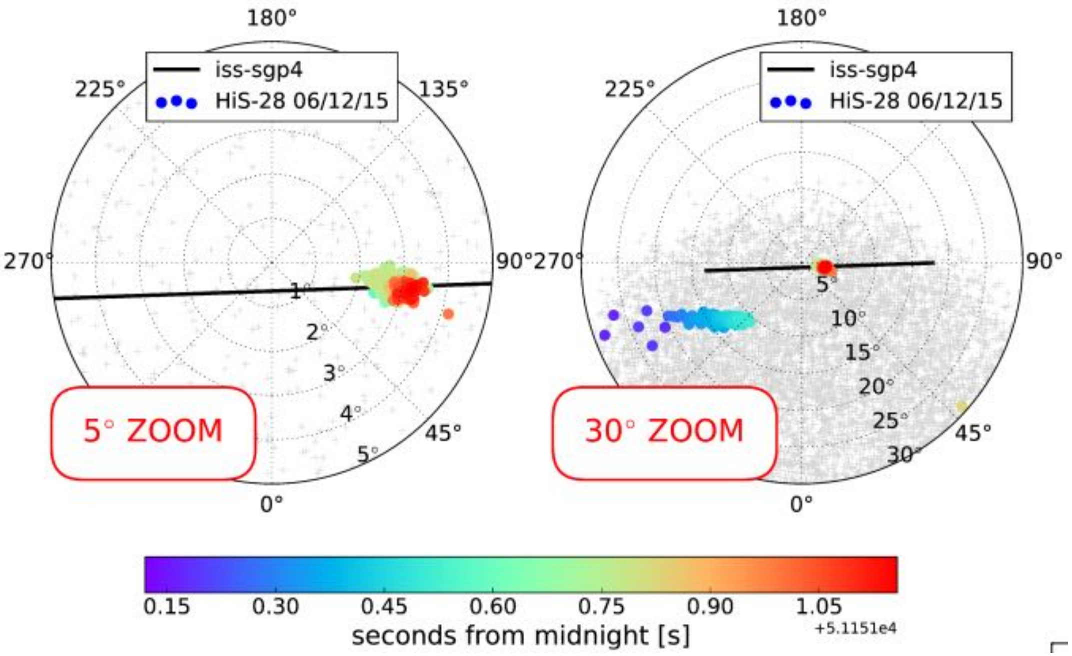
Var name	16/11/15	06/12/15	05/02/16	27/09/16	25/01/17	28/01/17	25/03/17
Time (θ_{ISS}^{min})	22:10:34	14:12:29	14:08:26	16:29:05	16:30:22	15:30:02	17:04:26
θ_{ISS}^{min} [deg]	0.21	0.64	0.3	0.23	0.8	0.23	0.5
t_{rise} [s]	0.35	0.29	0.42	0.3	0.32	0.31	0.36
t_{fall} [s]	0.55	0.38	0.33	0.39	0.5	0.54	0.63
t_{tot} [s]	0.90	0.67					
$Max(Amp_{max})$ [codes]	3.8e+04	1.1e+05					
R_{FFOV}^{mim} [km]	3.8	2.98					
α_{FFOV}^{mim} [deg]	0.82	0.68					
δt_{CATS} [s]	-2.1	-1.7					
δt_{TLE} [s]	0.75	0.71					
passage type	SSS	SSN					

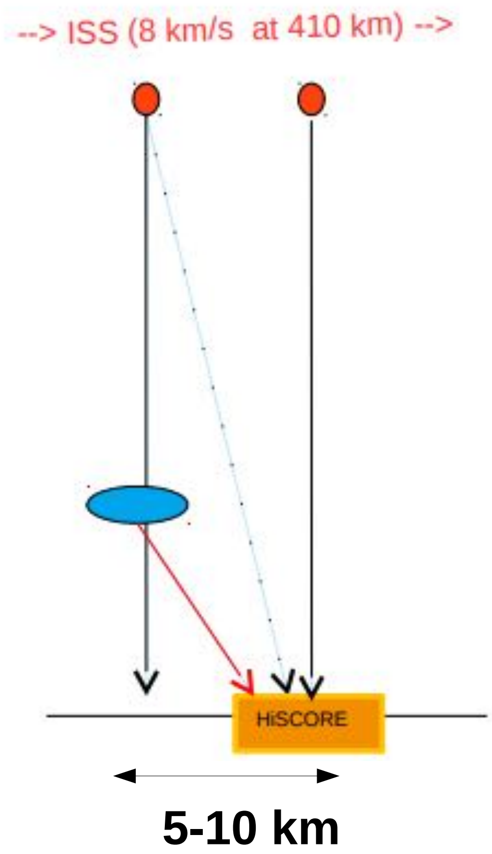


3D passage reconstruction using CATS data
“DIRECT LIGHT” SIGNAL DETECTION

CATS Cloud-events

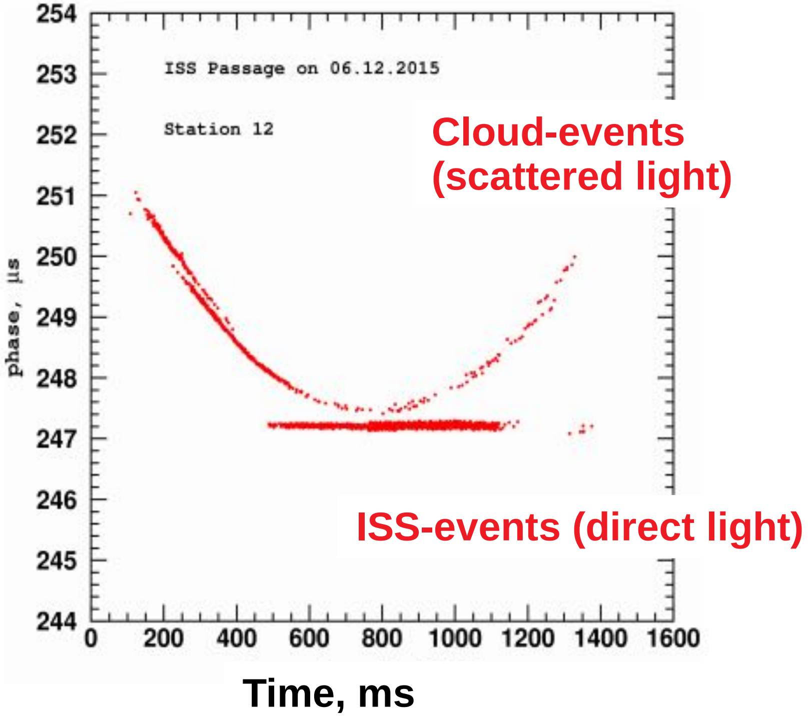
> **Detection of LIDAR photons scattered by clouds**



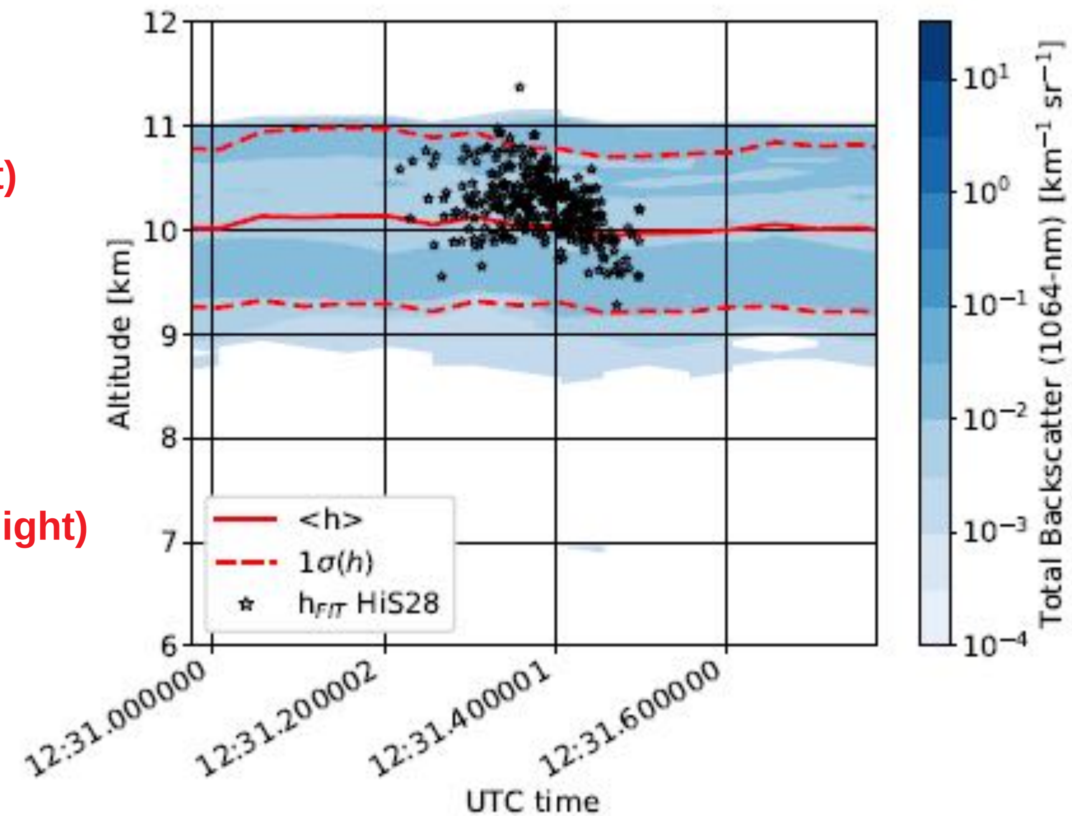


CATS Cloud-events

- Left: phase analysis w.r.t. 4 kHz : bunch delay by the additional path length from forward scattering
- Right: inferred cloud height using reconstructed Cloud-events



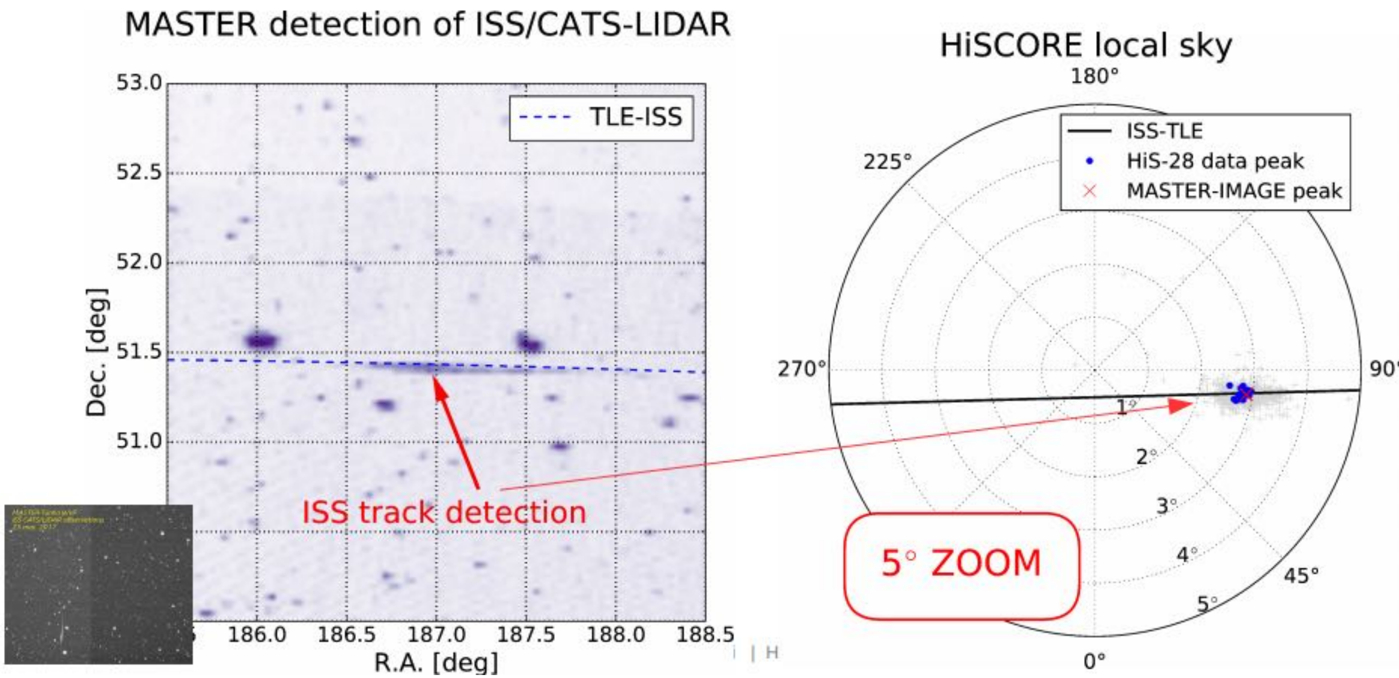
LIDAR-phase analysis



Reconstructed cloud height

Absoulte pointing: HiSCORE-MASTER combined

- March 2017: campaign to detect “ISS passage” with the closeby (500m) ‘Tunka-MASTER’ optical telescope. Direct communication with both Tunka-MASTER and CATS/NASA operators
- 25.03.2017 the ‘Golden event’: we obtained synchronous and independent detection by Tunka-MASTER VWF camera
  - Image analysis: brightest point gives precise position of ISS
  - Compared with brightest ISS-events (largest amplitude) for HiS28 mispointing verification



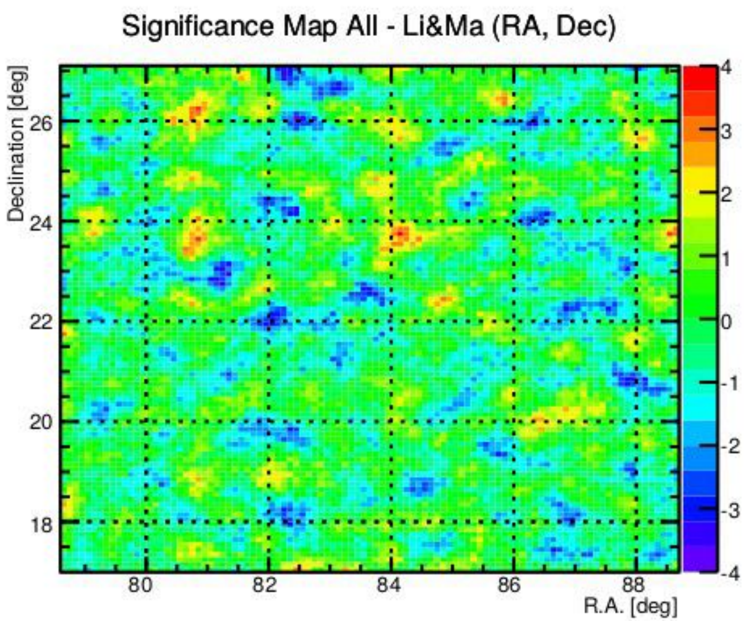
Mispointing <=0.1°

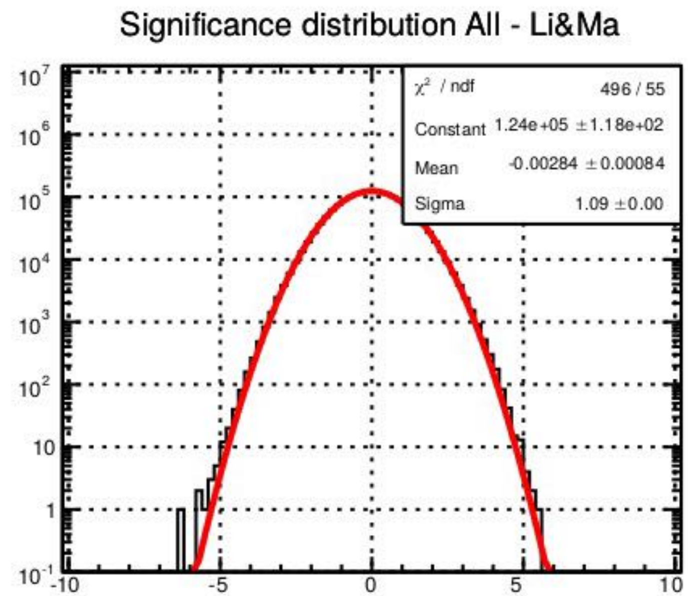
Crab-Search with HiS28, BG estimation, ...

> **Signal and Background maps smoothing: integrate events inside search radius**

Vary: smoothing radius (0.2°, 0.3°, 0.4°, 0.5°), nb.of stations (E-proxy), energy cuts. Also: calibration schemes. Tbd: work on g/h cuts.

> **Significance calculation (following Li&Ma)**





Blinded data. Verifying the BG estimation method, smoothing, significance calculation.

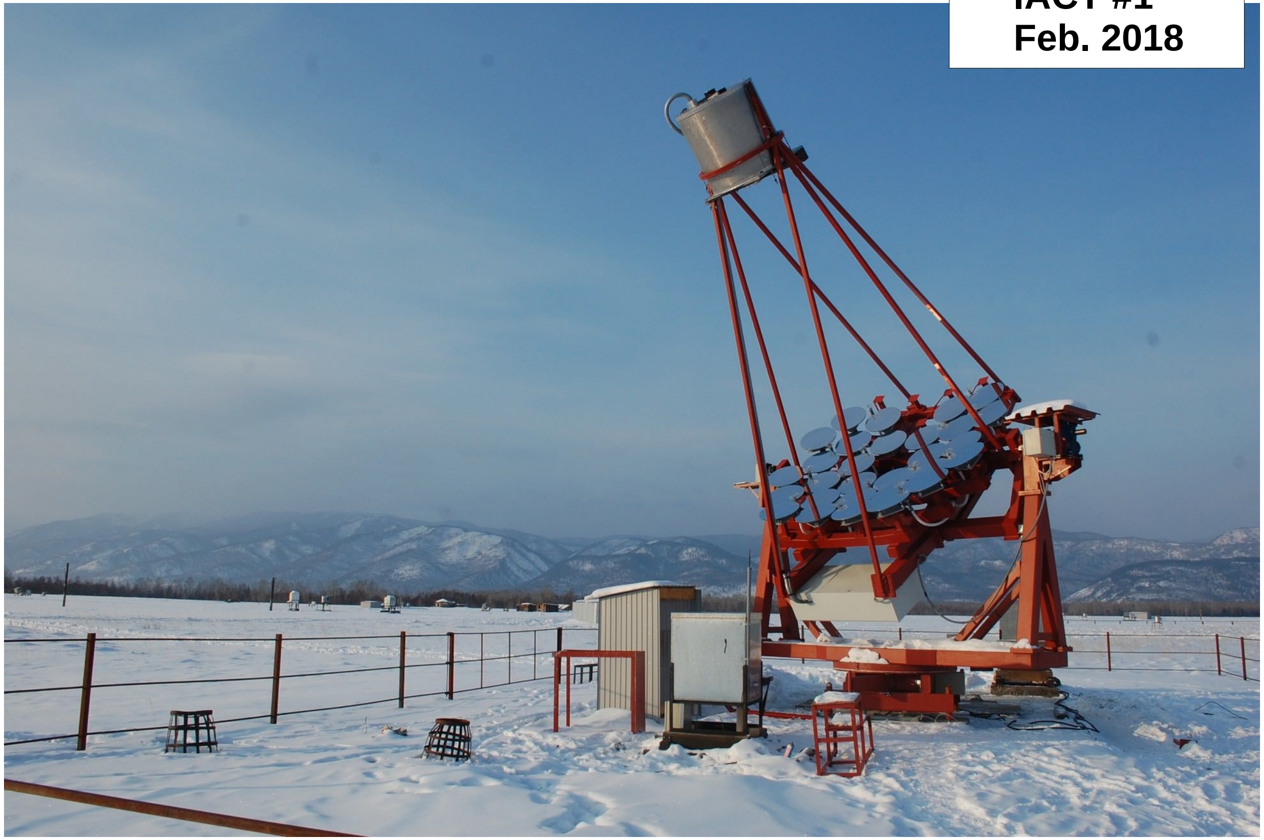
Analysis in progress, not yet released

The TAIGA-IACTs

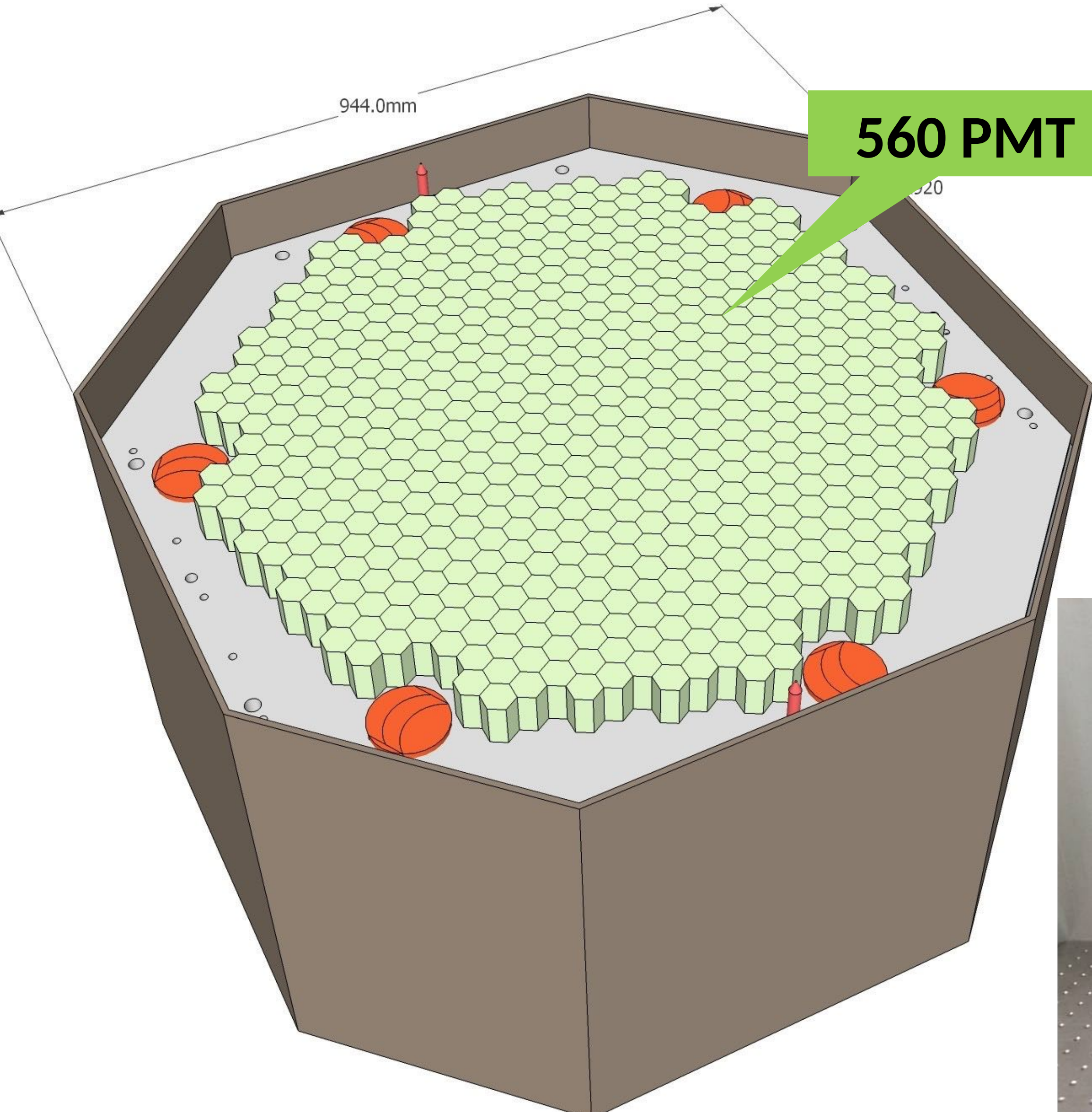
The TAIGA-IACT

- D = 4.32m   f = 4.75m
- FOV ~ 9.6 deg
- 30 Glass mirrors of 60cm diameter
- Camera:
  - 560 PMT XP1911 (15mm photocathode)
  - Winston Cone: 30mm input / 15mm output
  - pixel-aperture 0.36 deg
- E_th ~1.5 TeV
- IACT-Image analysis and
  IACT-HiSCORE Hybrid analysis
  are in progress.

IACT #1
Feb. 2018

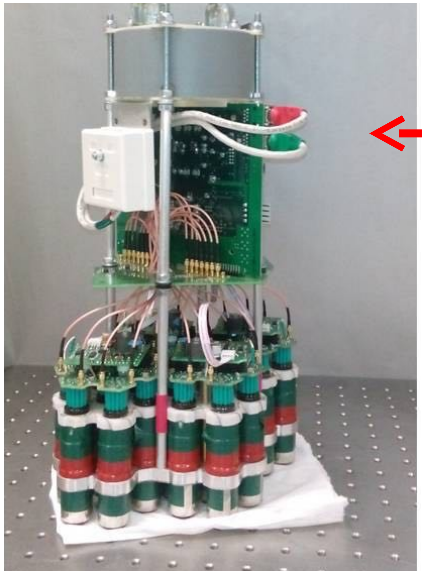


The TAIGA-IACT Camera



560 PMT

Camera DAQ is based on MAROC3 ASIC



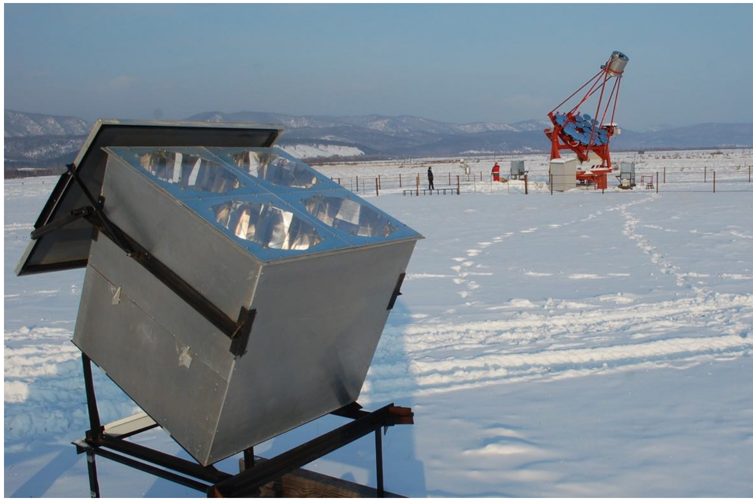
MAROC3 64 channel F/E board

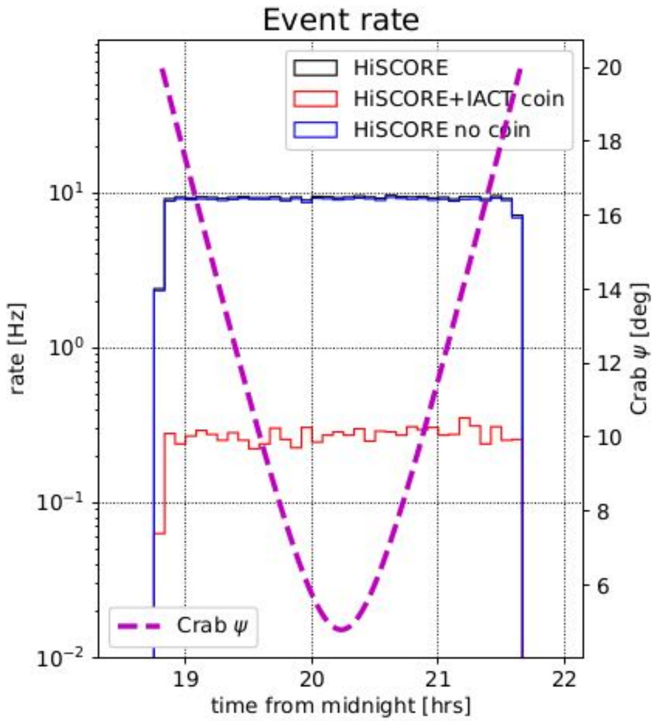
22 Cluster w/ 28 PMTs

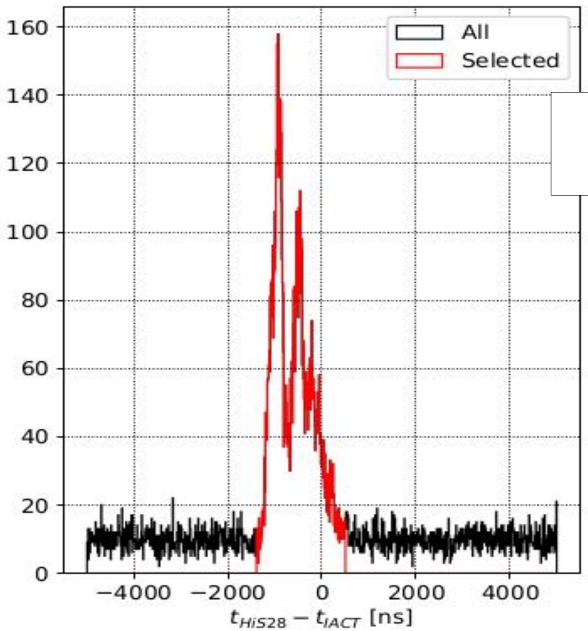
HiSCORE + IACT : Hybrid events

- Cross-verification of both instruments
- Analyze subset of EAS seen by both HiSCORE (reconstructed) and by IACT (triggered or reconstructed)
- Example: a 3hr run, for acceptance and efficiency check
- IACT follows the Crab, HiS is pointing south (fixed)

Cut for full acceptance overlap: IACT-FOV and HiS-FOV <20deg







HiSCORE-IACT coincidence events: 5μs time window

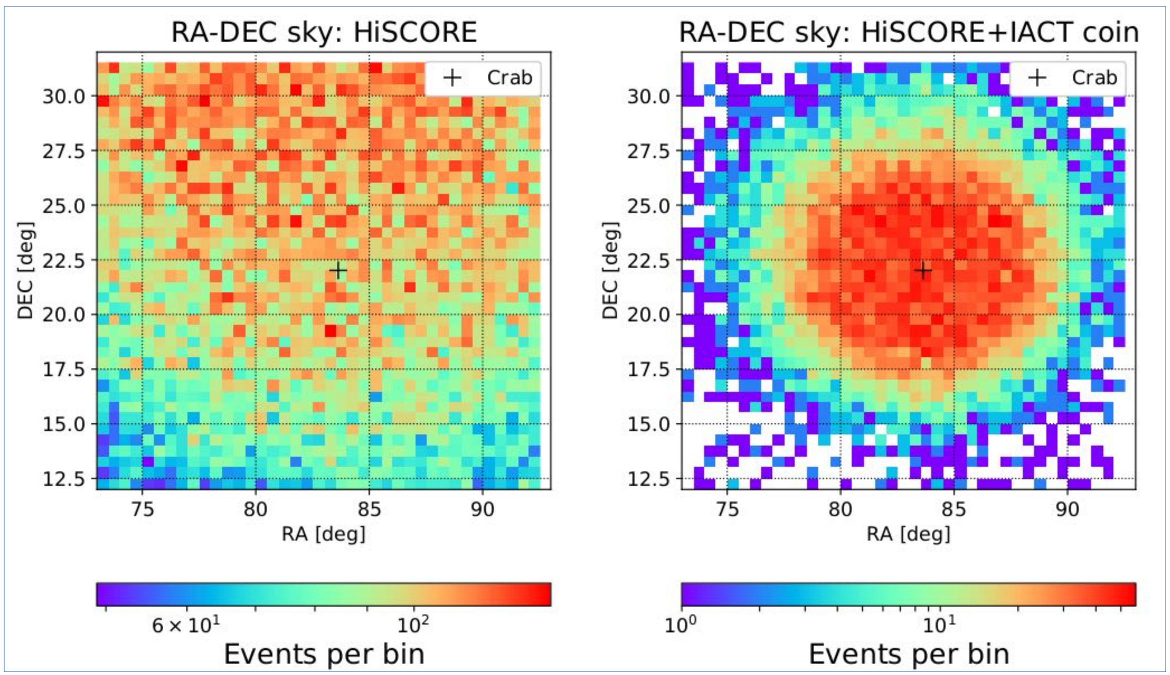
Timedifference: first HiS station and IACT, given driven by HiS station tolpology

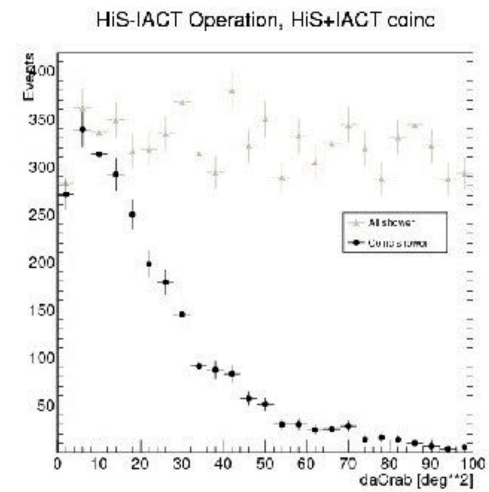
HiSCORE + IACT : Hybrid events

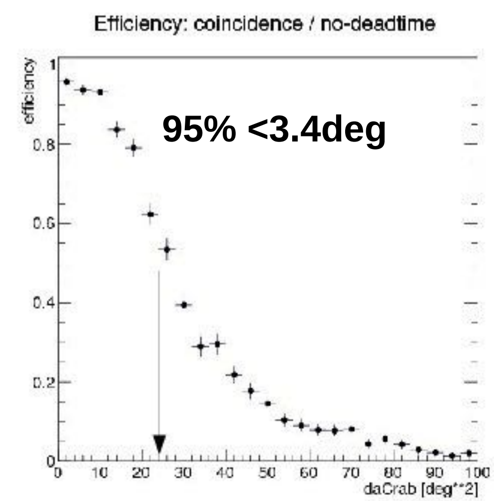
> **First full TAIGA-IACT operations started in fall 2017**

> **IACT-HiSCORE combined analysis – very preliminary**

require only >=2 pix in IACT (account for livetime-effects)







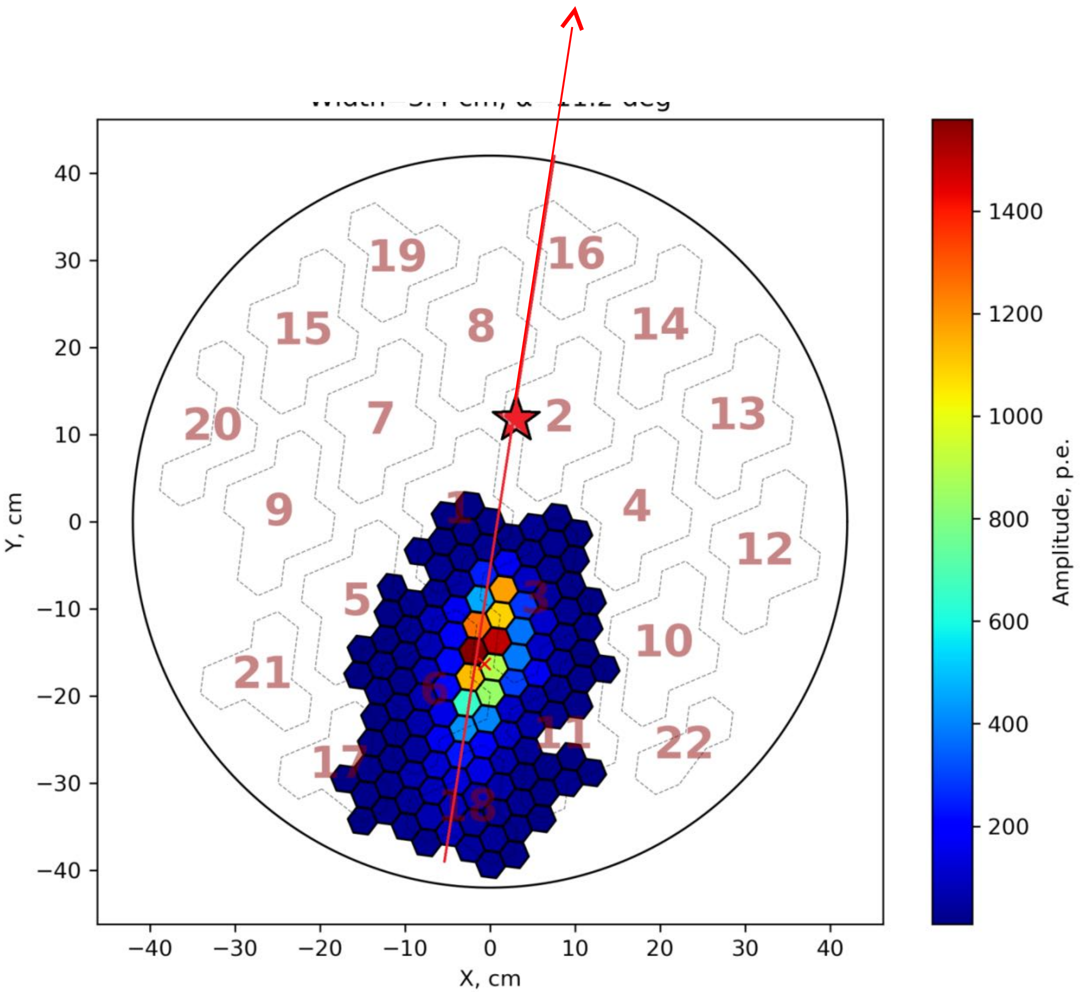
4.8 deg Dish size

IACT and HiSCORE: Hybrid events - an example

17000 Hybrid events in 25 hours

(~300 in 0.7° around Crab direction)

EAS core position

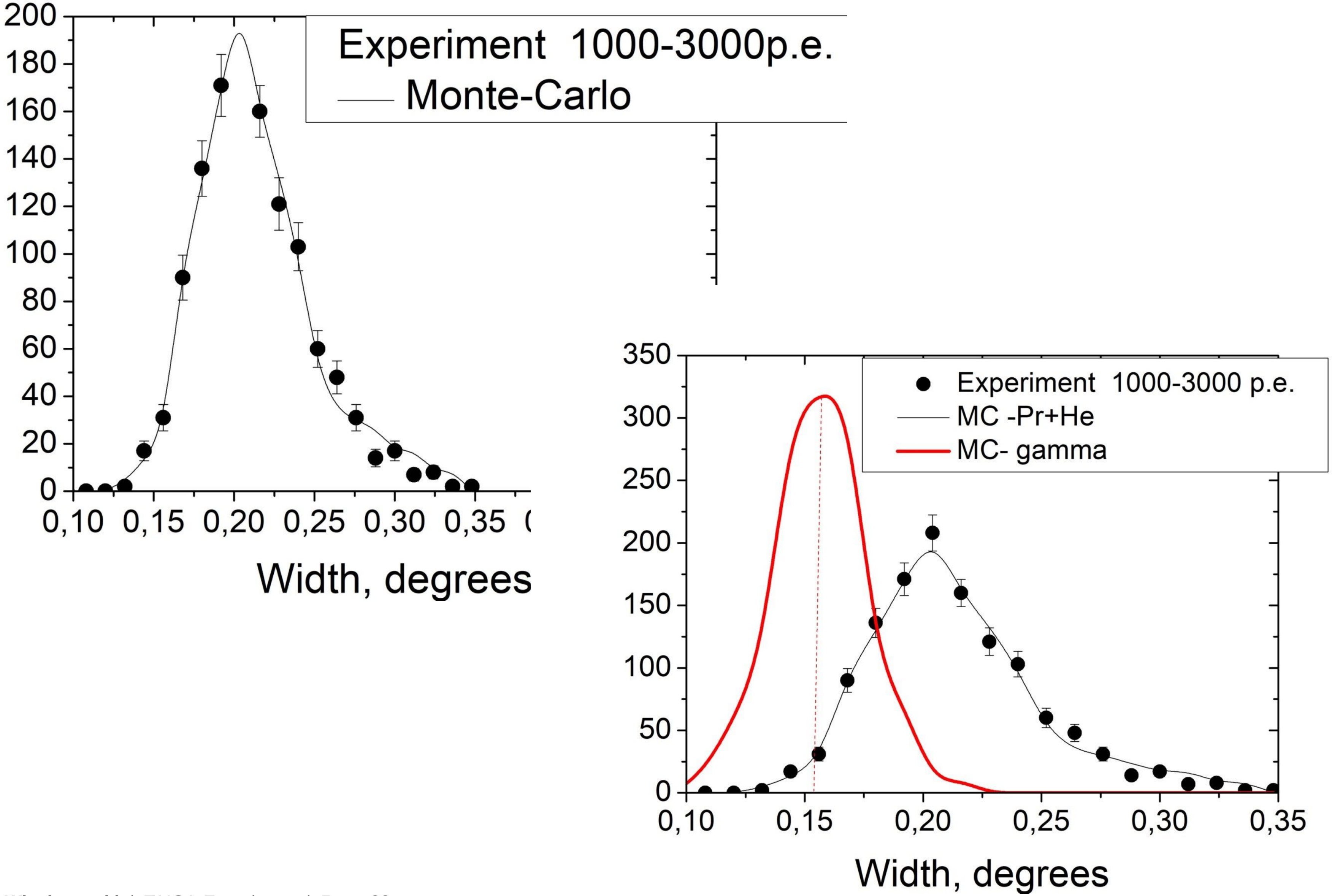


“Hadron –like” event

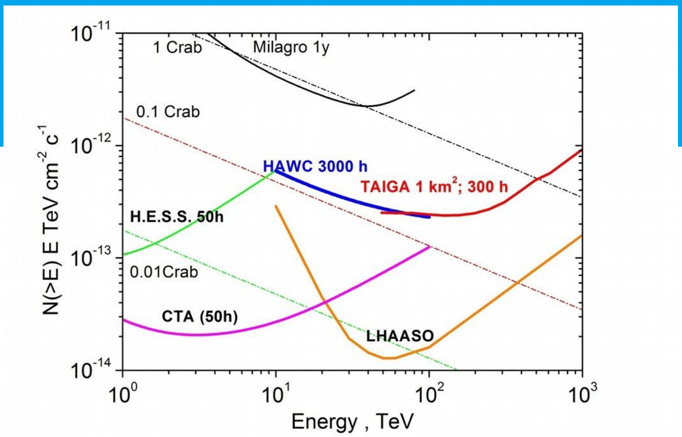
Size = 18500 pe.
Width = 0.4° alpha = 11°

Energy determined from HiSCORE: 840 TeV

IACT and HiSCORE: Hybrid events MC comparison



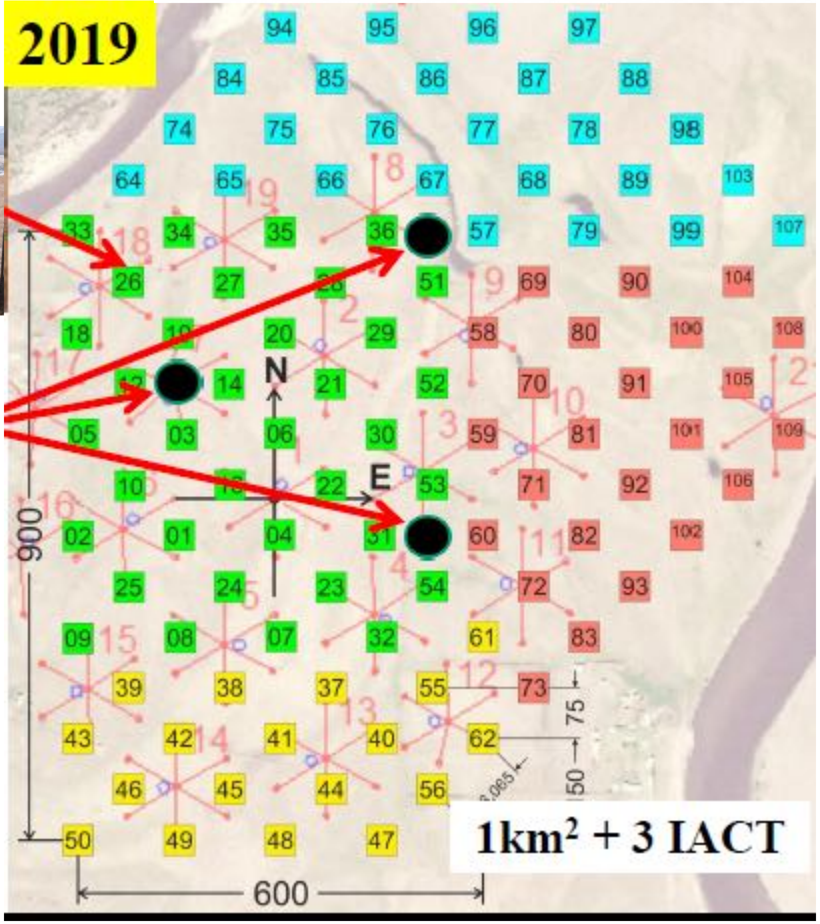
TAIGA in 2019



> **The full TAIGA Prototype will be commissioned by fall 2019:**

1 km2 HiSCORE array + 3 IACT

120 stations



> **expected**

> **For 100 hours :**

- **50-100 hybrid Crab events >40 TeV**
- **3 10^15 hybrid CR events (→ composition)**

Summary

- TAIGA: Implementing a new technology for gamma astronomy above 10 TeV and CR physics (>100TeV)
  - Large area detector, composed of IACT (sparse) + HiSCORE stations array
  - Field operations in Tunka valley started in 2013

- HiSCORE-28 array (0.25 km^2) with 3 years of data
  - well understood, stable oparation
  - PSF: 0.1-0.2 deg at E>100 TeV; asbolute pointing verified as ~0.1 deg
  - ISS CATS/LIDAR detected as point source (unique tool for calibration / verification)
- Crab signal search with HiS28 standalone 3 years data
  - Analysis in progress (w/o g/h separation): no signal seen – compatible with MC

- First TAIGA-IACT: commissioning in progress
- 2017/18 - Hybrid operation HiSCORE-28 + IACT#1
  - Exploit gamma/hadron separation from mono-mode IACT
  - coincidence events analysis confirms excellent HiS-operation

Summary (2)

- Plans
- Fall 2018: HiSCORE array extension up to 60+ stations (0.6 km2)
- The 1 km2 HiSCORE array + 3 IACT will be installed by fall 2019

- Future 10km2 array:

  A “Large Research Infrastructure Proposal” for 40 MEuro was submitted to russian government in 4/2018 (‘MEGAScience facility’) :

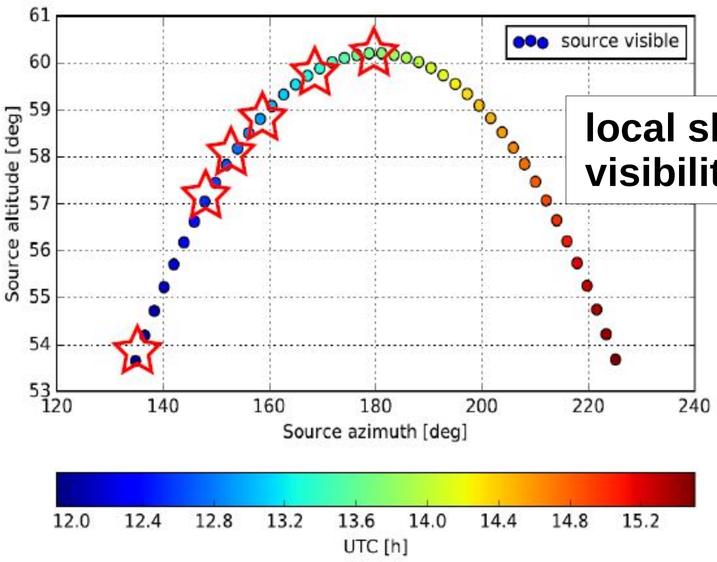
  10 km2 Gamma Telescope with 16 IACTs and 1000 HiSCORE stations @2000m a.s.l.

Thank you

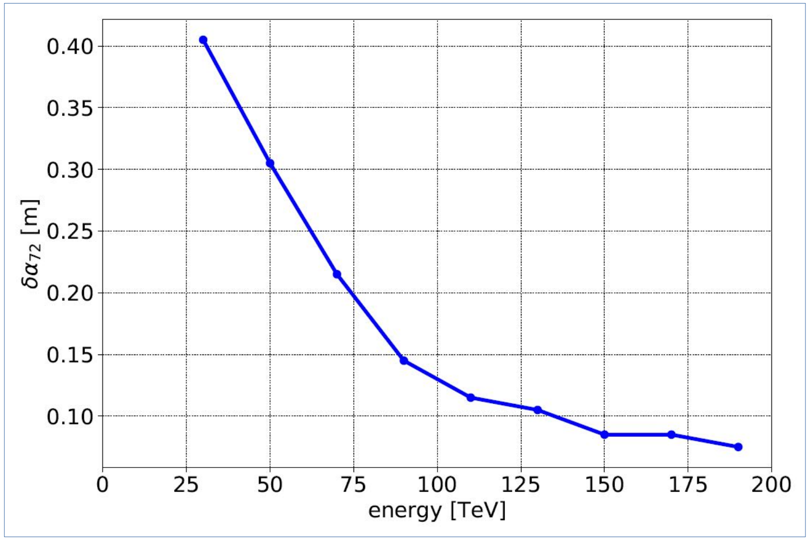
BACKUP SLIDES

Crab search with HiS28: MC study

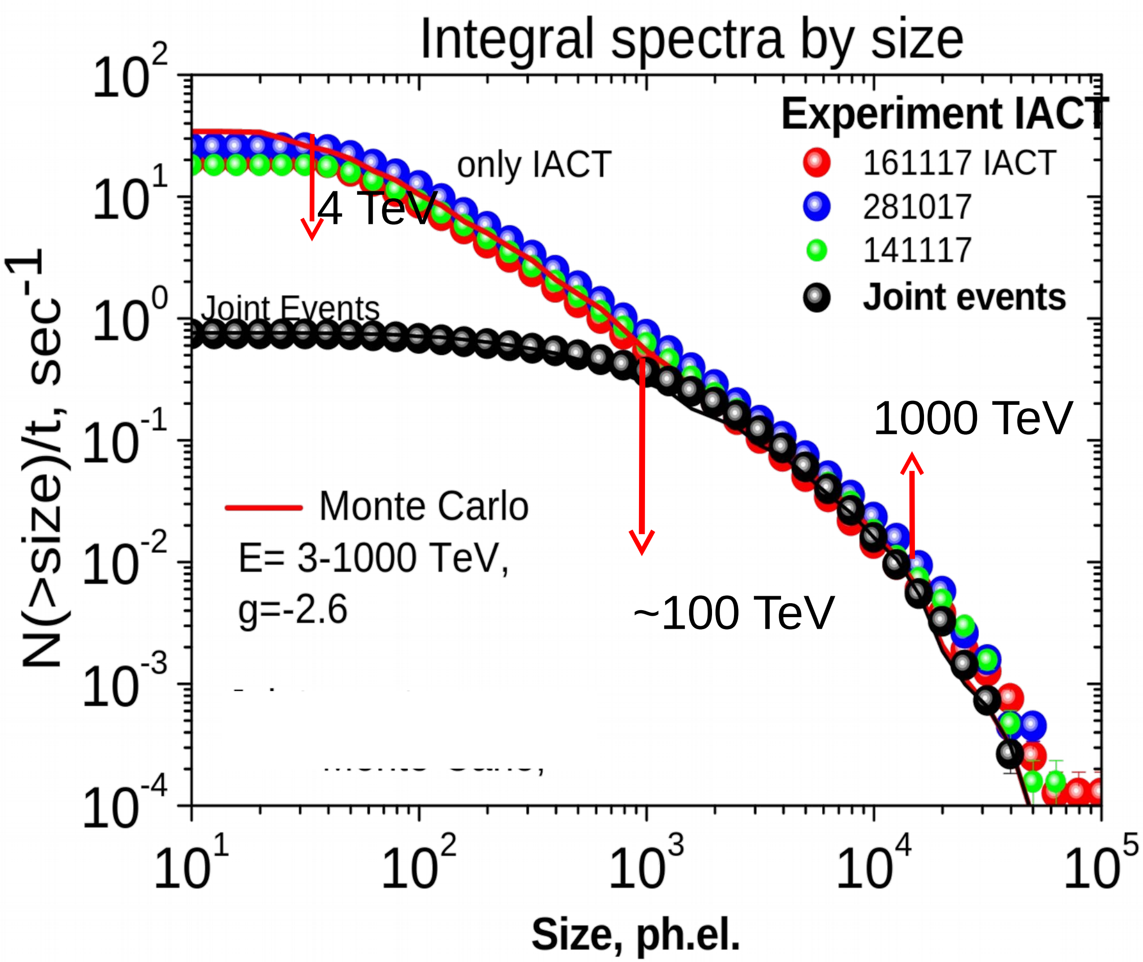
- **Dedicated MC simulation for Crab signal detection with HiS28 array**
  - **EAS: γ/p – 20TeV<E<200TeV – on track**
  - **Standard HiS28 detetector response and reconstruction**
  - **Event selection: acceptance cuts + low multiplicity veto**



local sky Crab visibility



Integral Size spectra: IACT and Hybrid events



HiSCORE energy spectra In linear scale

Peak energy
~100 TeV – CR
~ 50 TeV – gamma