The TAIGA Observatory -

a hybrid approach Gamma Astronomy at >10TeV

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for the TAIGA-Collaboration

LHAASO Inauguration
Workshop, 25.-27.4.2019

HELMHOLTZ
ASSOCIATION

DESY

The TAIGA Observatory

***T**unka **A**dvanced **I**nstrument for CR and **G**amma **A**stronomy*

A multi-component detector for Gamma astronomy and CR physics 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

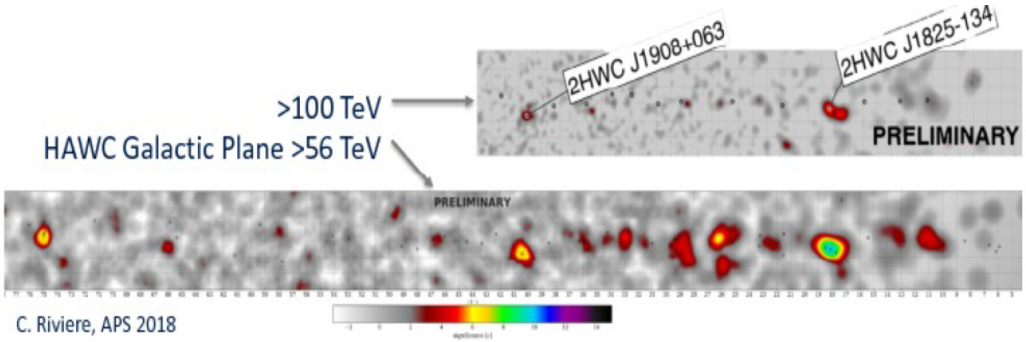
ISS, Bucharest

Gamma Astronomy above 10 TeV

- **Where are the Galactic Pevatrons? Source-cutoffs? Extended sources, AGN monitoring, MM-observations, surveys, LIV, …**

- **HAWC opened the 100TeV sky in 2018:**

  2 sources + Crab

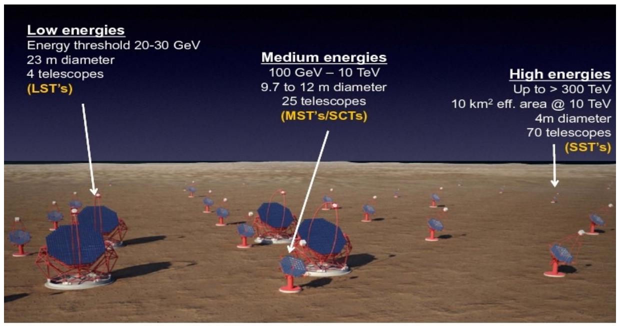


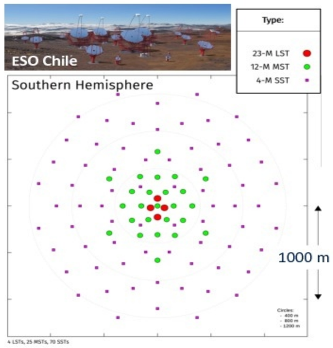
- **The CTA detector concept: rely on established IACT technology.**

  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 lower costs significantly ?

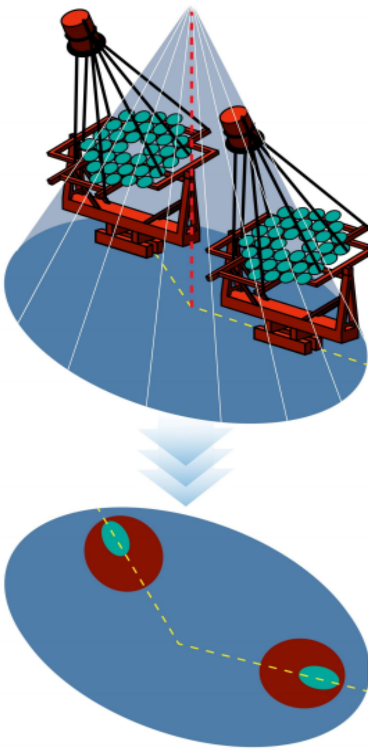
TAIGA: a new, hybrid Cherenkov detection concept

IACTs in Stereo Mode

(standard approach)

Inter-IACT distance

~100-300 m



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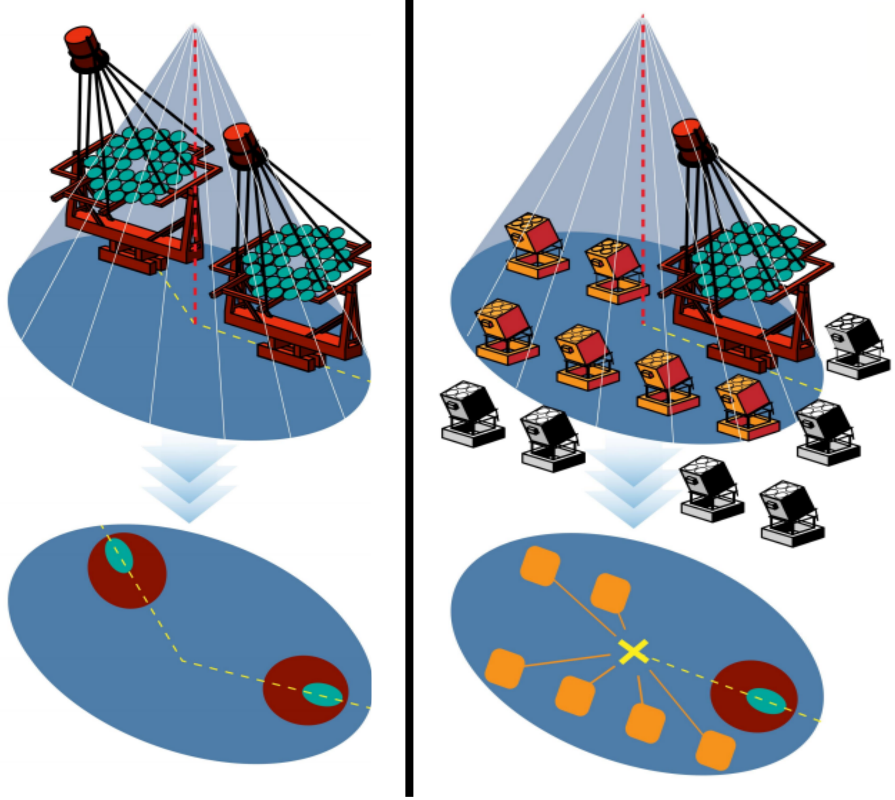


Single IACT and Timing Array (TAIGA approach)

1. Timing array for
   shower core / direction / energy

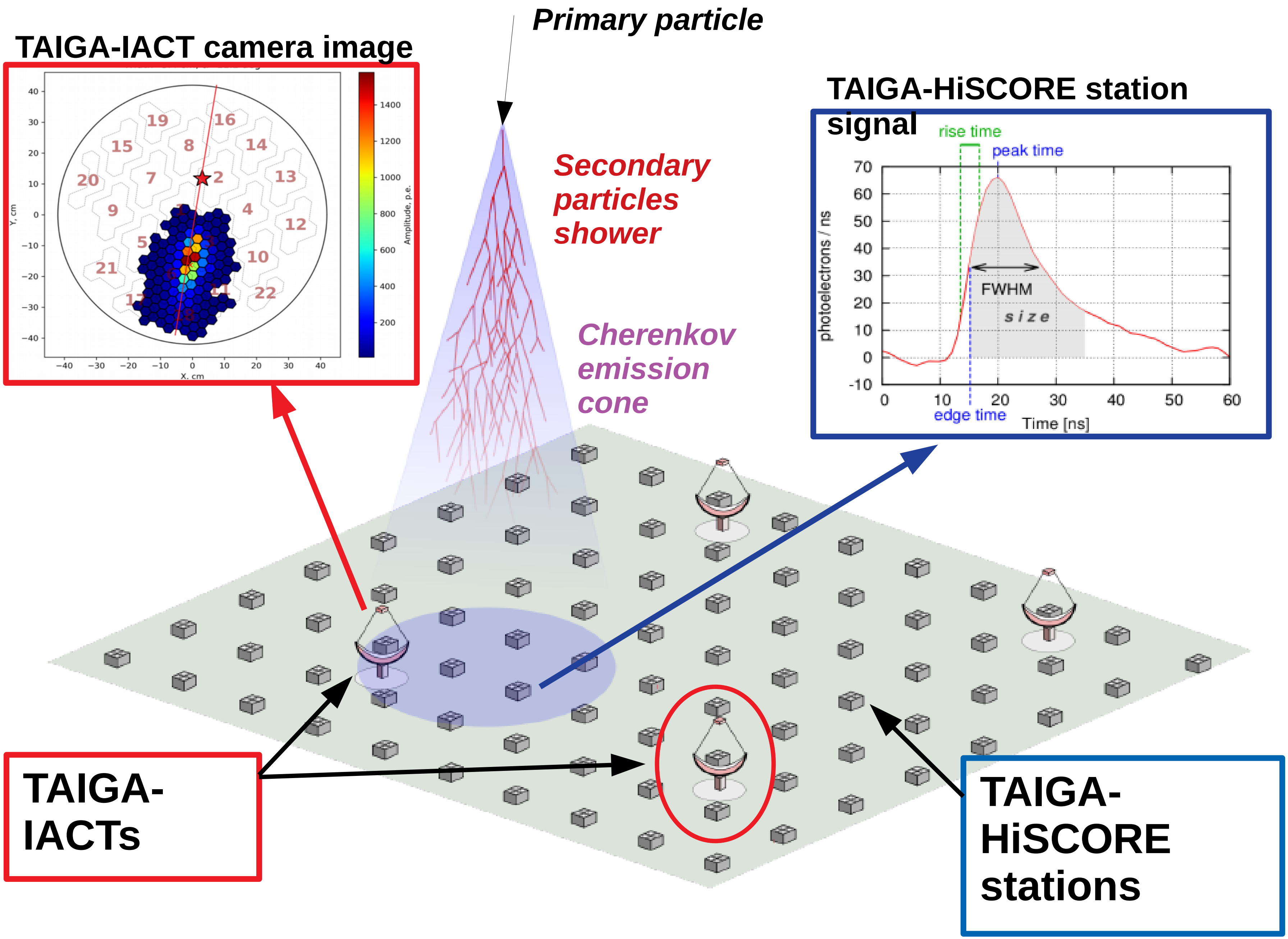
2. IACT in mono mode:
   - g/h separation

600 - 900 m between IACTs
→ sparse, low-cost IACT array

> Rely on IACTs in mono-mode operation, and supply missing information by wide-aperture timing array

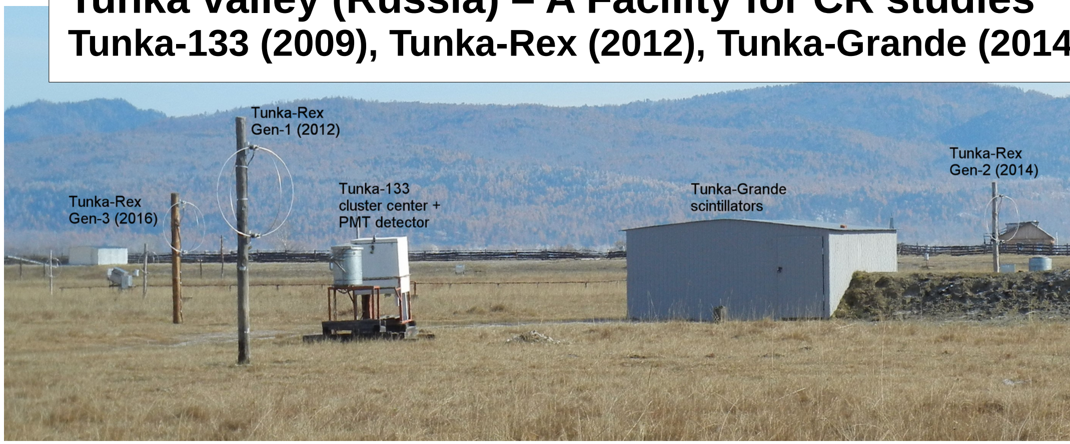
> Key feature: Large detector area (>10 km^2) at minimal cost with a Cherenkov hybrid system

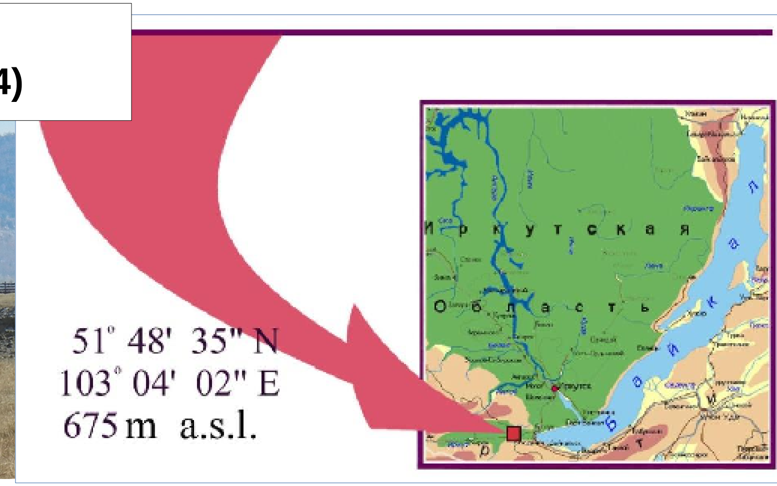
TAIGA Hybrid EAS Cherenkov Detection Concept



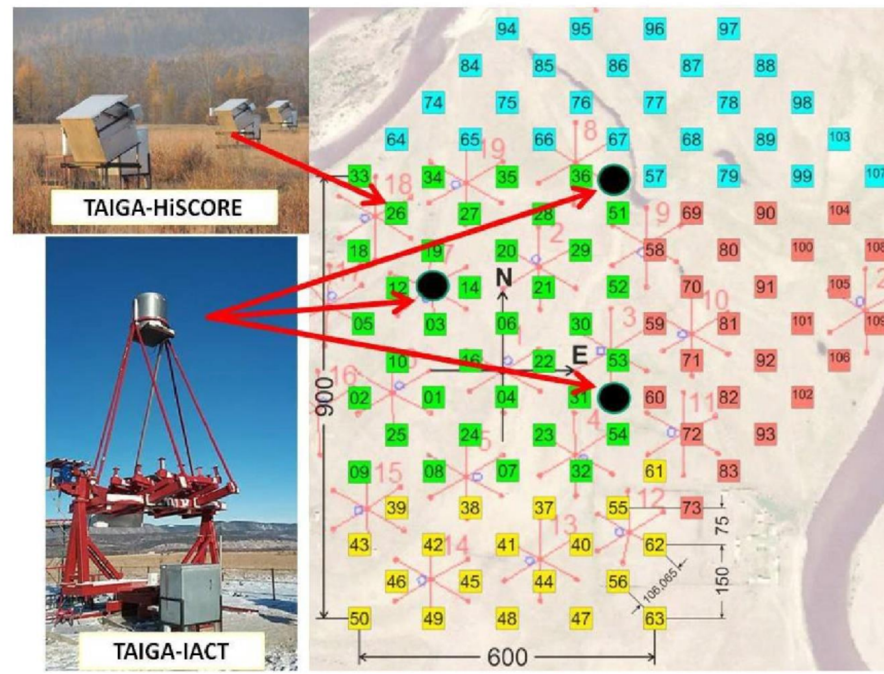
TAIGA at the Astrophysical Facility in the Tunka Valley

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



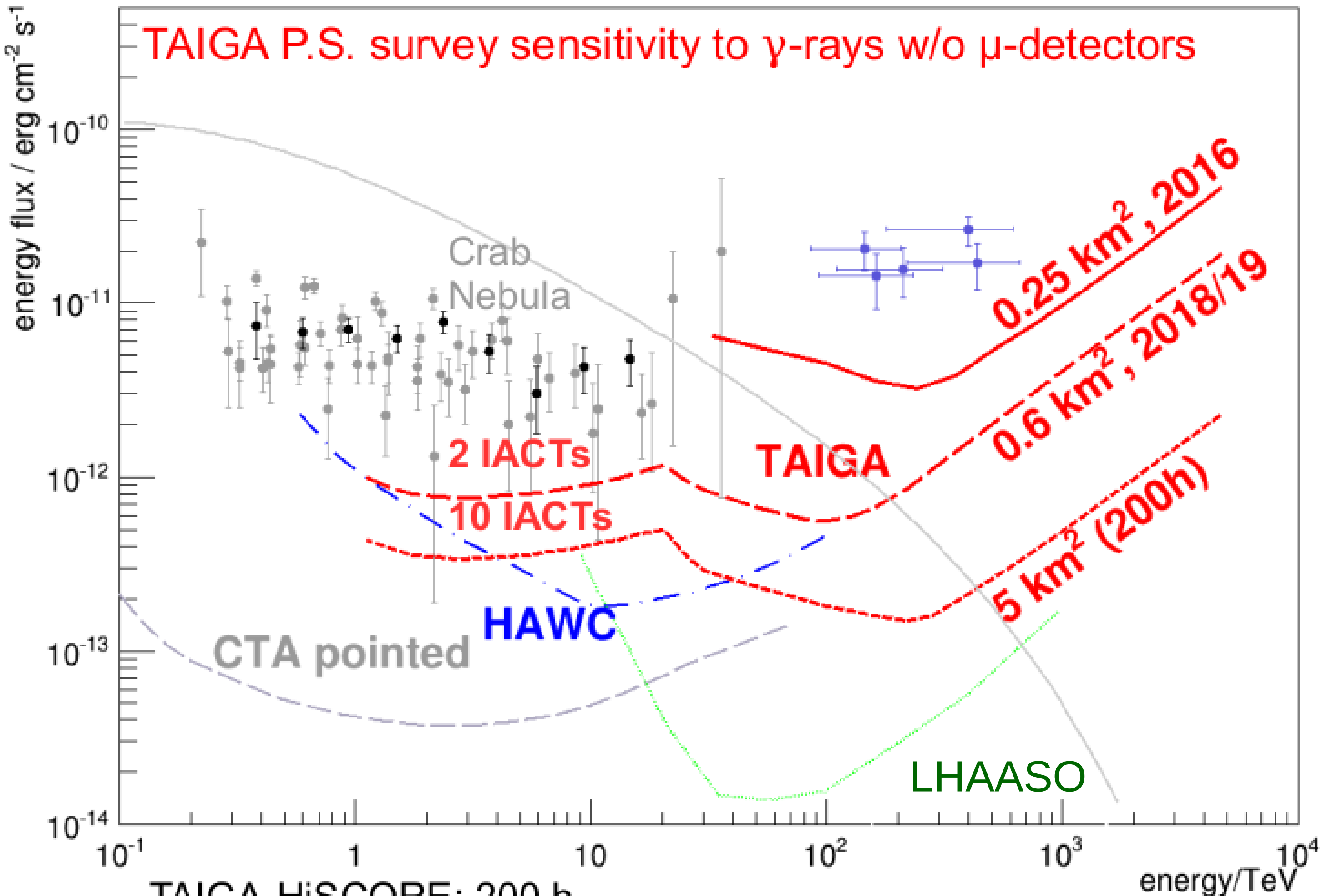


- **TAIGA collaboration started in 2012**
  - **2013: 9 HiSCORE stations array (first prototype)**
  - **2014: 28 HiSCORE station array A=0.25 km2**
  - **2017: IACT commissioning started**
  - **2017/18: IACT-HiSCORE joint operations**



- **Next: complete the 1 km2 array by fall 2019**
  - **120 HiSCORE stations**
  - **3 IACTs**

TAIGA expected sensitivity



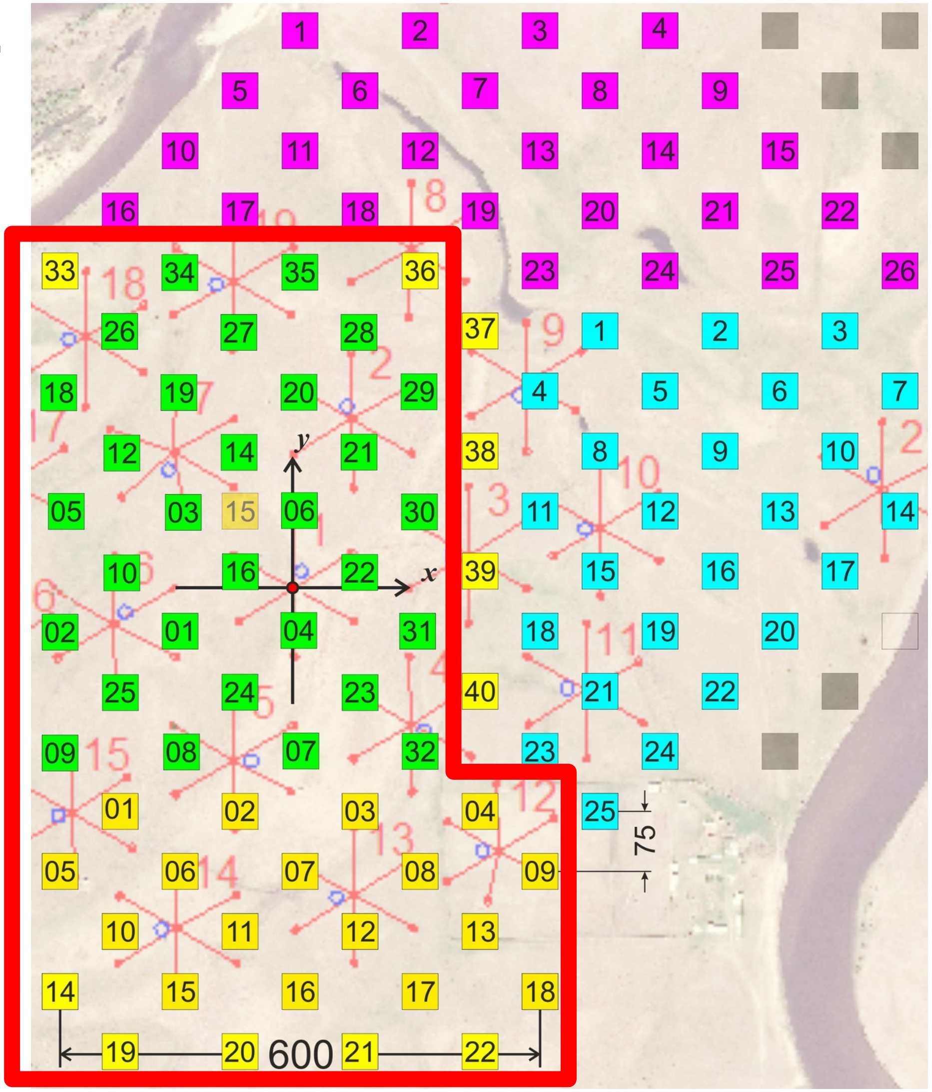
TAIGA-HiSCORE: 200 h
TAIGA-IACT: 50 h

energy resolution: 10-20%

TAIGA-HiSCORE: the timing array

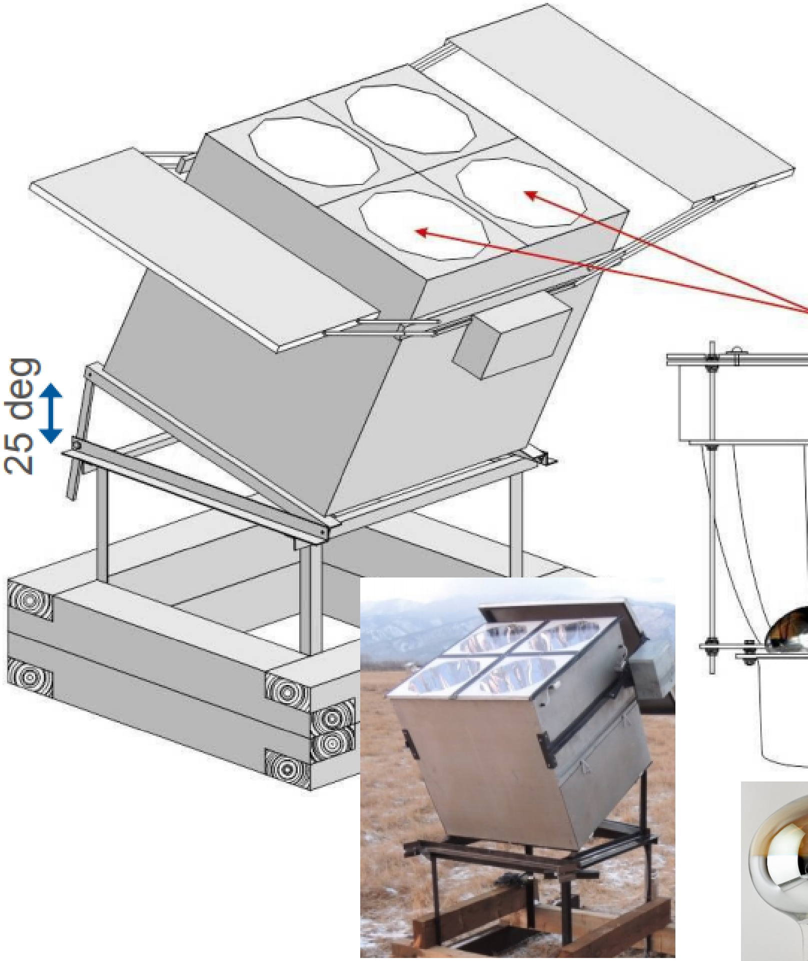
High Sensitivity Cosmic Origin Explorer

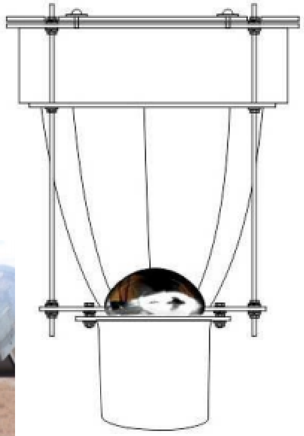
- 54 optical stations (fall 2018)
- 0.5km2 instrumented area
- Station spacing 106m



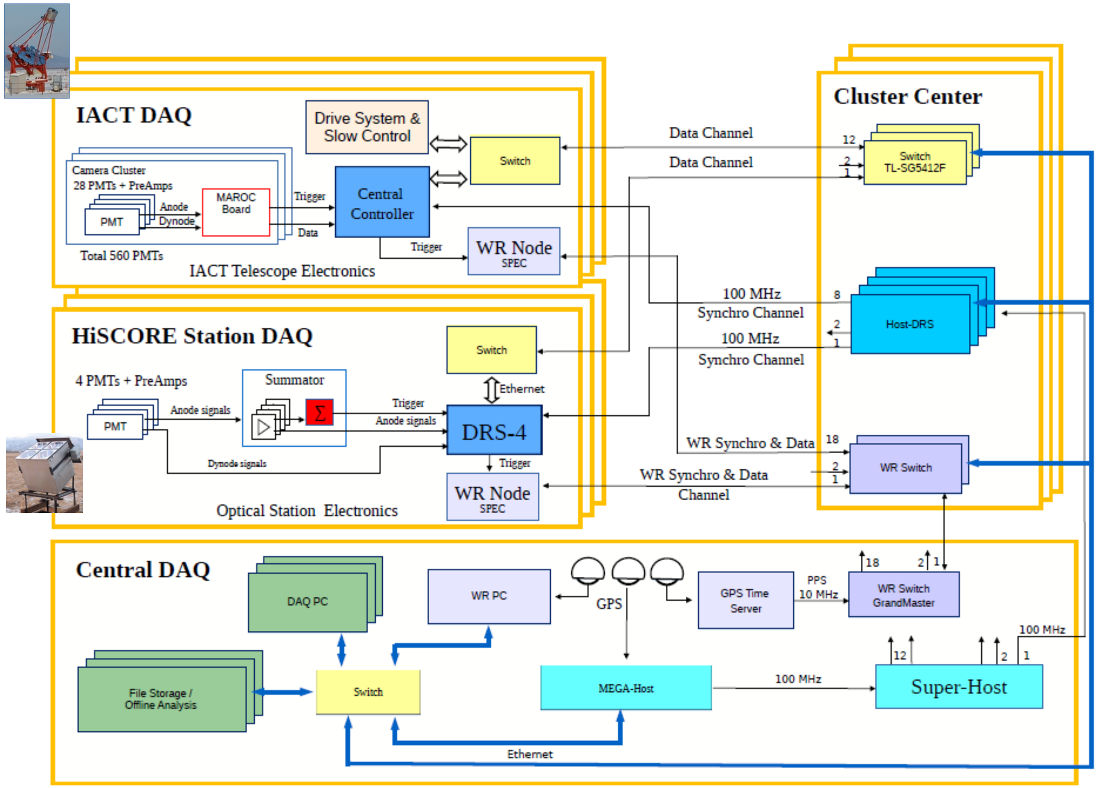
TAIGA-HiSCORE: detector station

- Four 8” / 10” PMT per station
- Winston Cone light collector sensitive area ~0.5m2
- FOV ~ 0.6sr
- Sky coverage: vertical / tilted mode
- DAQ system:
  - DRS4-based GHz readout (2GHz sampling)
  - Sub-ns array wide time synchronization
    - Custom 100 MHz fiber (MSU)
    - WhiteRabbit (DESY)





TAIGA-HiSCORE: Hybrid DAQ system

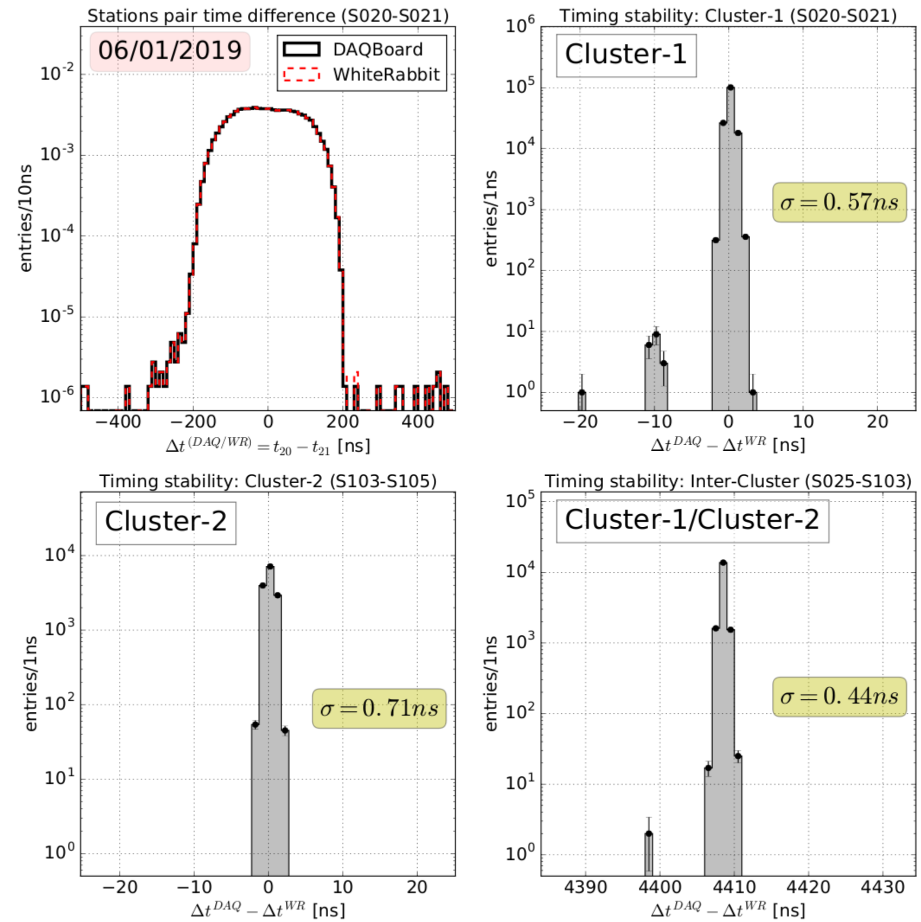


> HiSCORE DAQ system

- DRS4 for pulse sampling (2GHz)
    - 8 PMT channels (4 anode + 4 dynode)
- Timing systems (custom fiber MSU + WhiteRabbit)

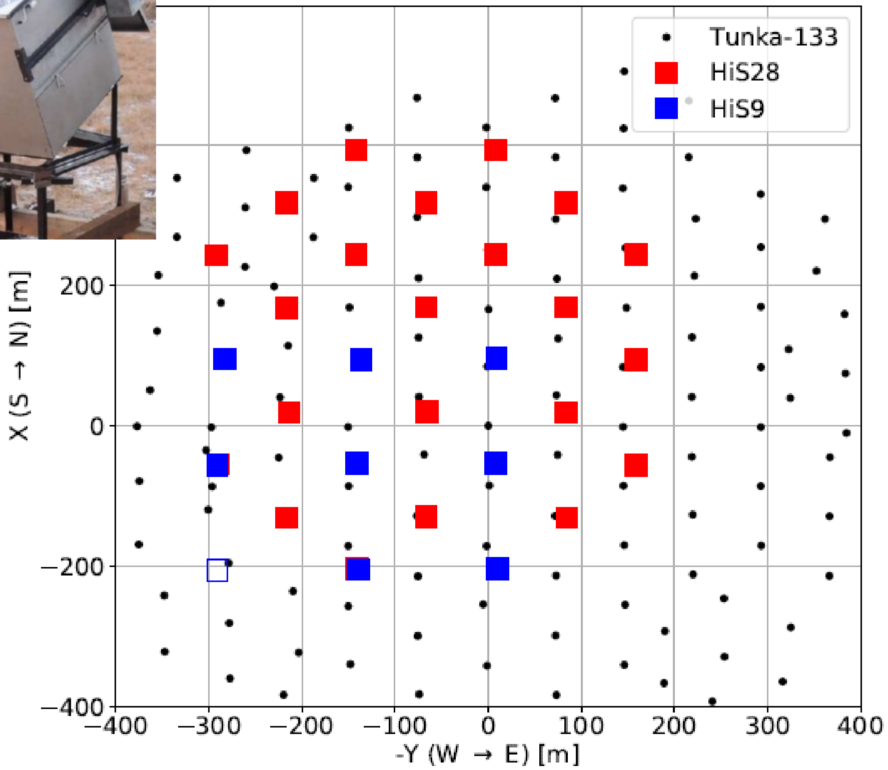
> Station readout/trigger independently. Array trigger: offline.

> E_thr(gam) ~30-50TeV



Intra- and inter-clusters sub-nsec time syncronization between stations is verified by comparing the trigger timestamps from two systems on an event-by-event basis

TAIGA-HiSCORE (HiS28)



> **HiSCORE-9 early prototype (2013)**

> **HiSCORE-28 (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 a standard candle: Crab**
  - **Crab search with 3 years data (very prelim.)**
- **Unexpected: ISS CATS-LIDAR detection and analysis**
  - **Absoulte array pointing obtained without a detected PSoure !**

EAS reconstruction

> **<u>Shower core</u> reconstruction:**

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

> **<u>Shower arrival direction</u> fit**

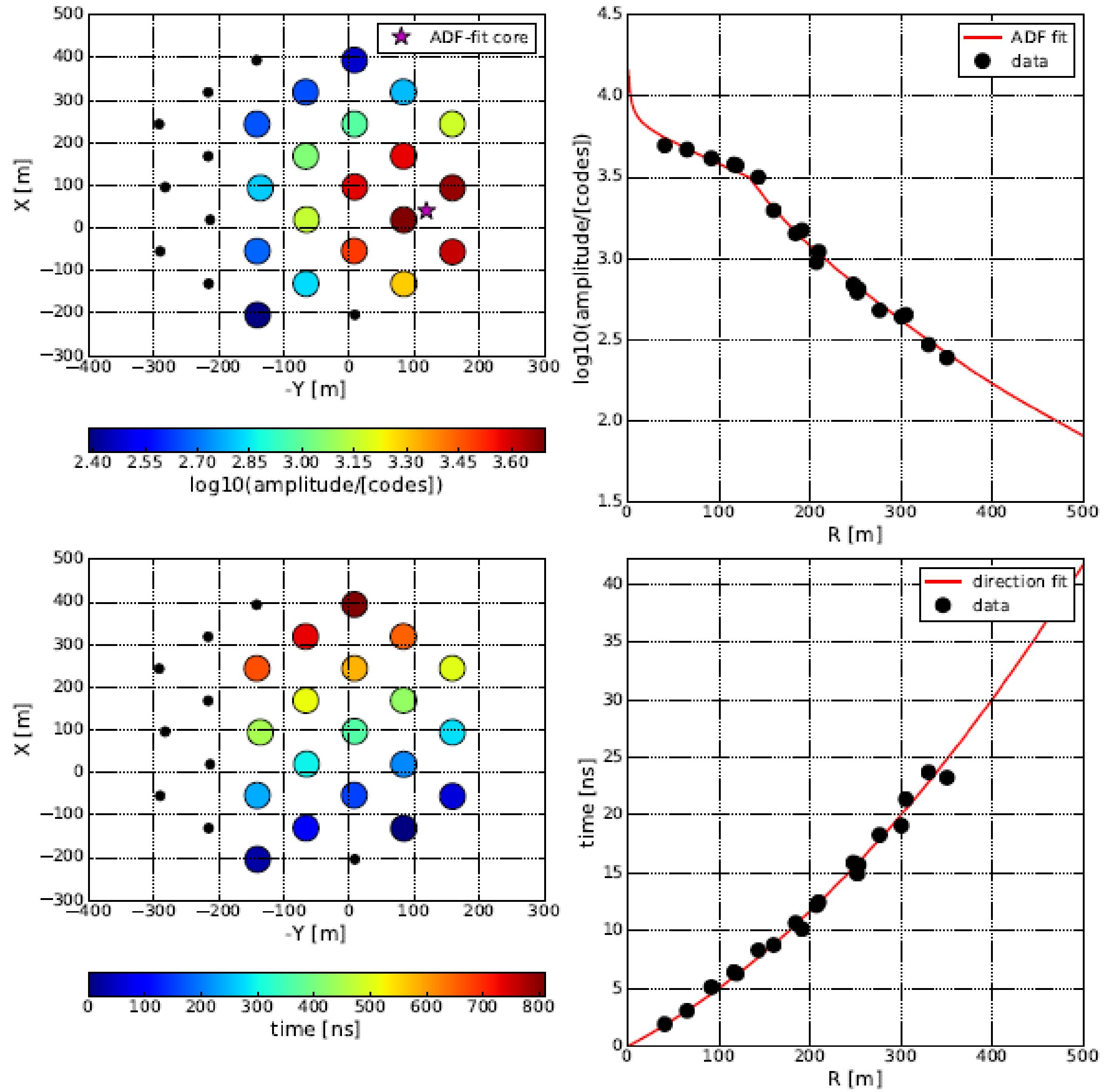
$$ti = t_i^{PW}(\theta, \phi, t_0) + Dt(R_i)$$

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

- **Station time offsets corrected by combining EAS data and external precise calibration**

> **Problem: bad reconstruction for "out-trigger EAS"**

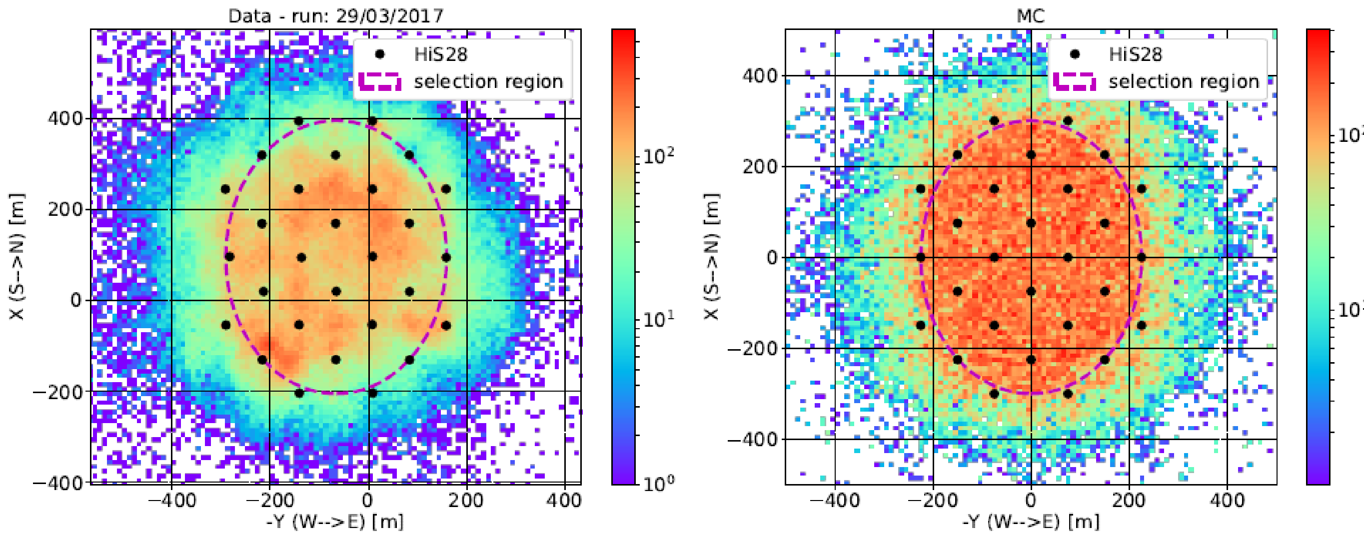
- **main source of error for precise direction reconstruction**
- **special treatment under investigation**



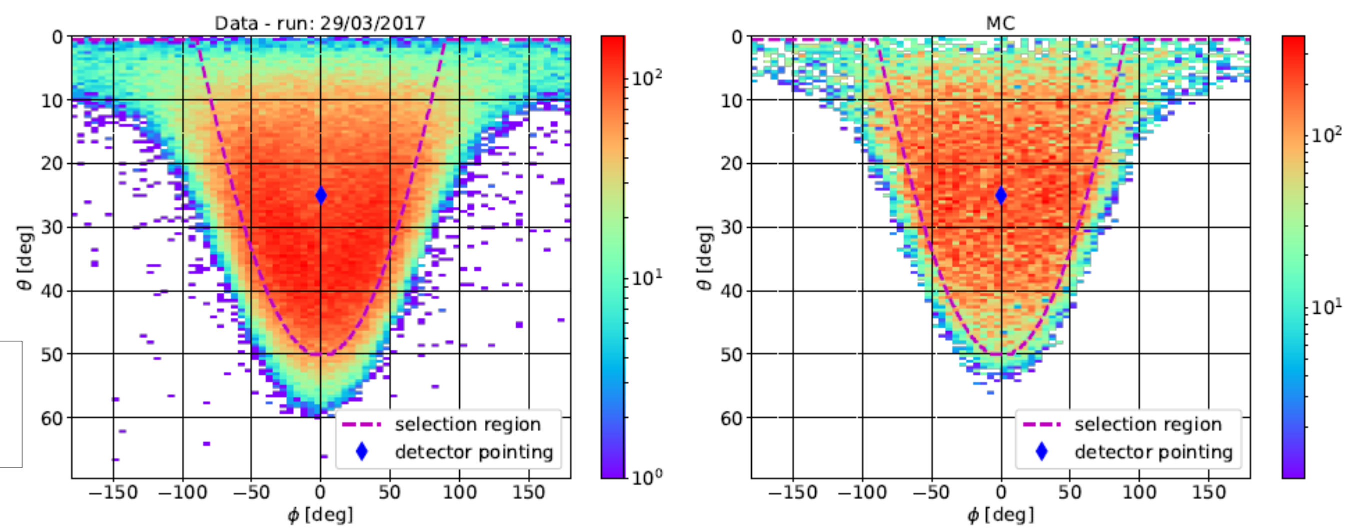
Detector acceptance: Data / MC comparison

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

Shower core



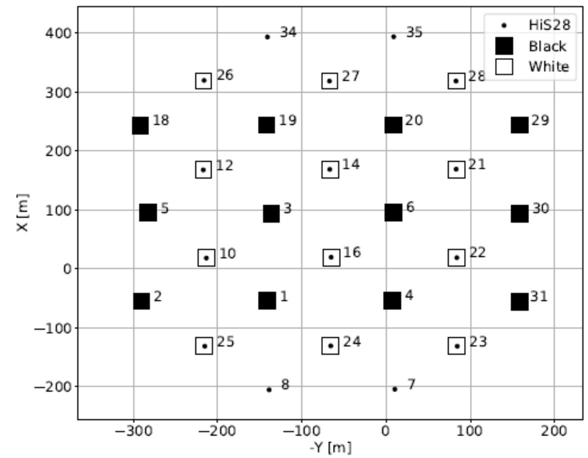
Shower arrival direction

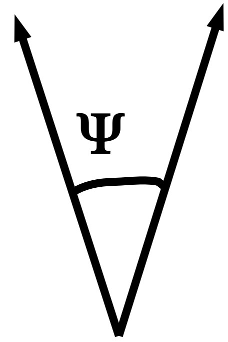


Angular resolution: chessboard method

> **Chessboard method: determine detector angular resolution from data (see AIROBICC, ARGO-YBJ)**

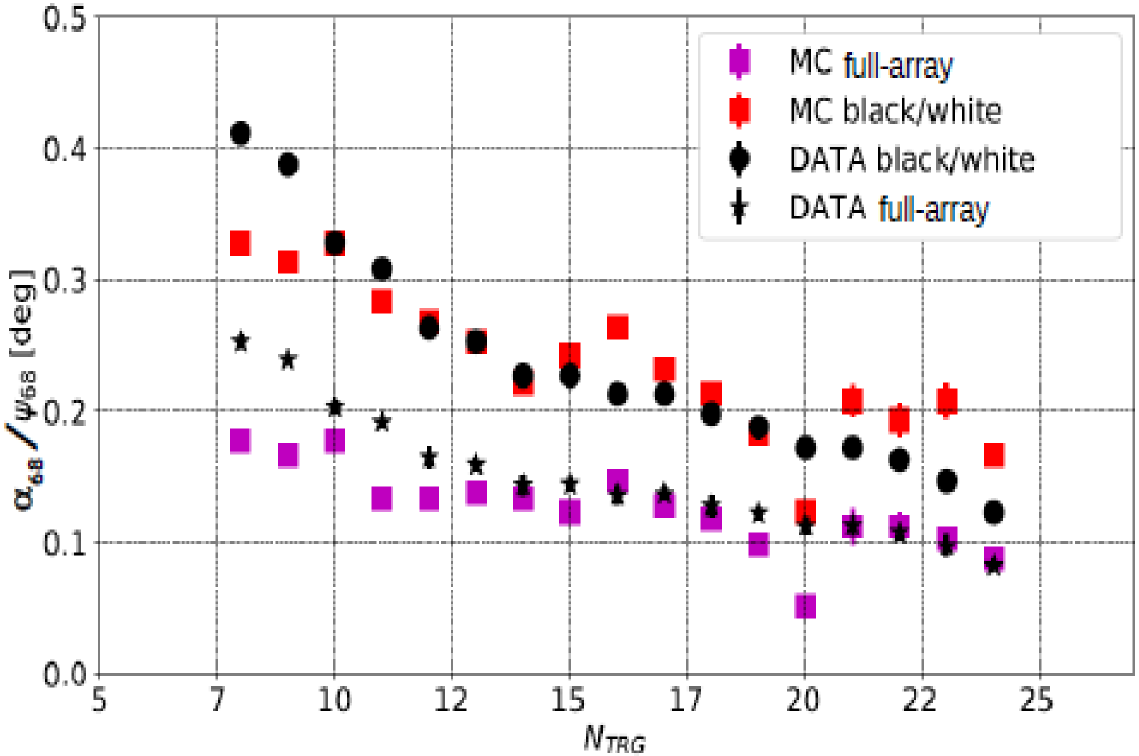
- **split array in two sub-arrays: two event reconstructions**
- **use space angle between the two reconstructed directions (Ψ) to estimate the full-array error, α**
- **Method checked using MC simulation**





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

$\alpha_{\text{TRUE/RECO}} = \Psi_{\text{BLACK/WHITE}} / R$



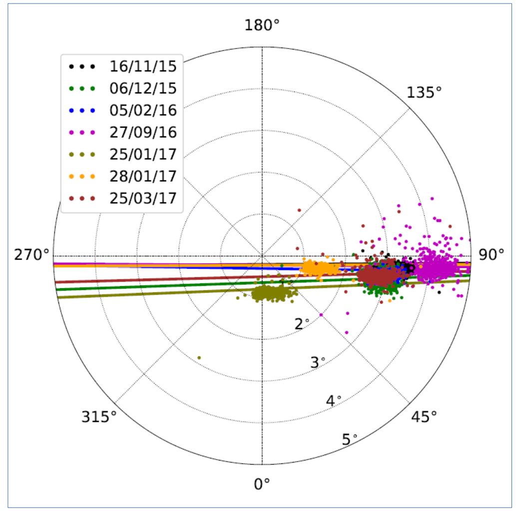
Conclusion: Full array angular resolution (68% containment)

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

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

First HiSCORE source: the ISS

For details,
see NASA website
https://cats.gsfc.nasa.gov

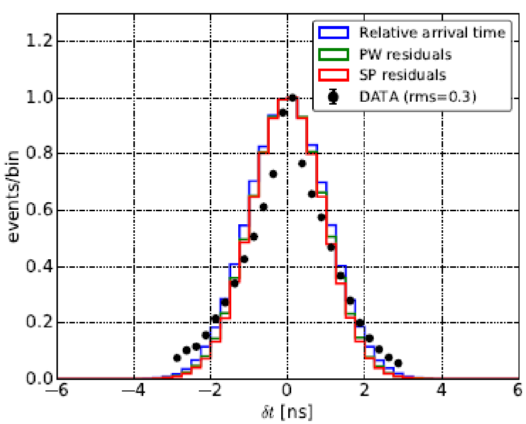


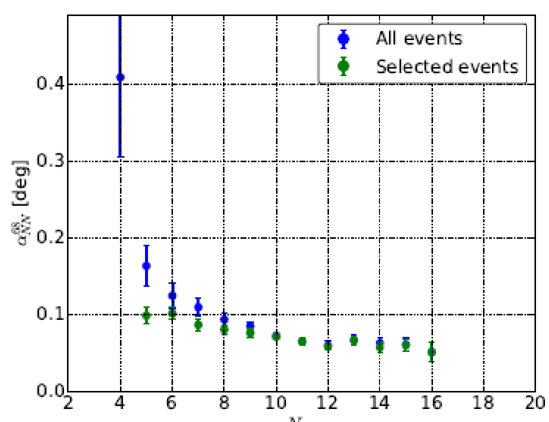
> The **CATS-LIDAR** on the ISS at 415 km a.s.l
- 4 kHz Laser repetition rate
- 11 passages detected
- observed at large distance o(km)

> "ISS-events" reconstructed direction
- Plane wave fit of light front

Reconstructed "ISS-events" proved to be a unique tool for checking the detector performance:

1) Time resolution between stations

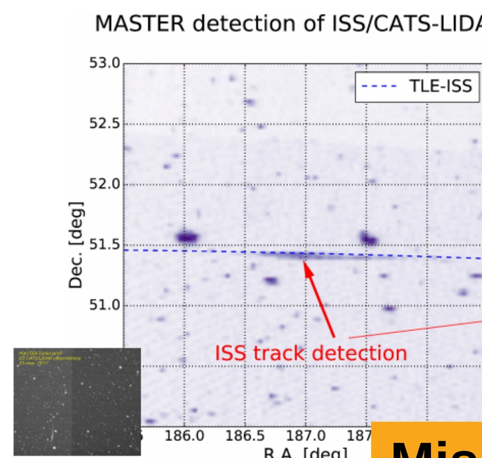


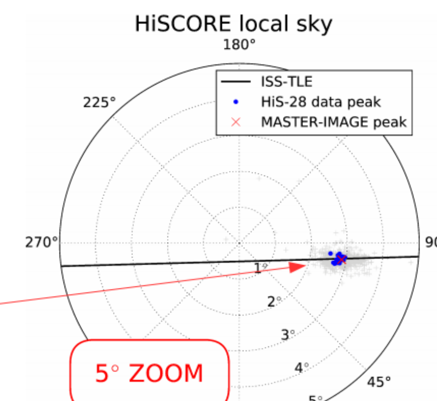


0.3ns time resolution

Angular resolution: < 0.1°

2) Prove correct array time calibration



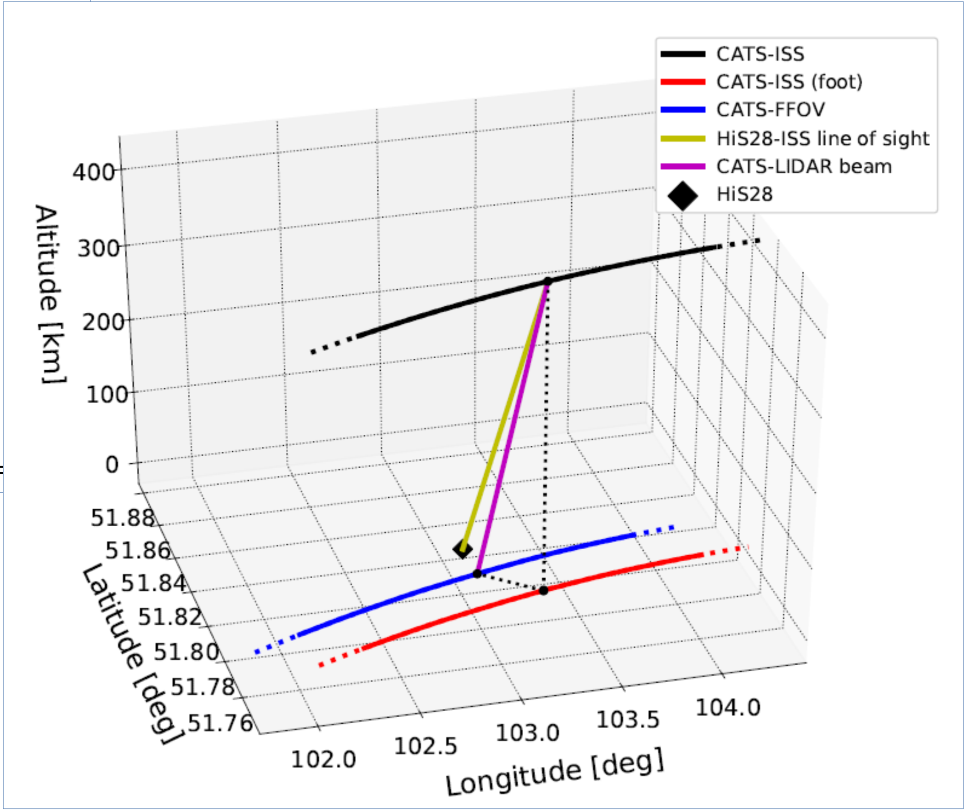


Mispointing <=0.1°

ISS/CATS-LIDAR: First TAIGA-HiSCORE point source

11 passages detected during 2015-2017 observations

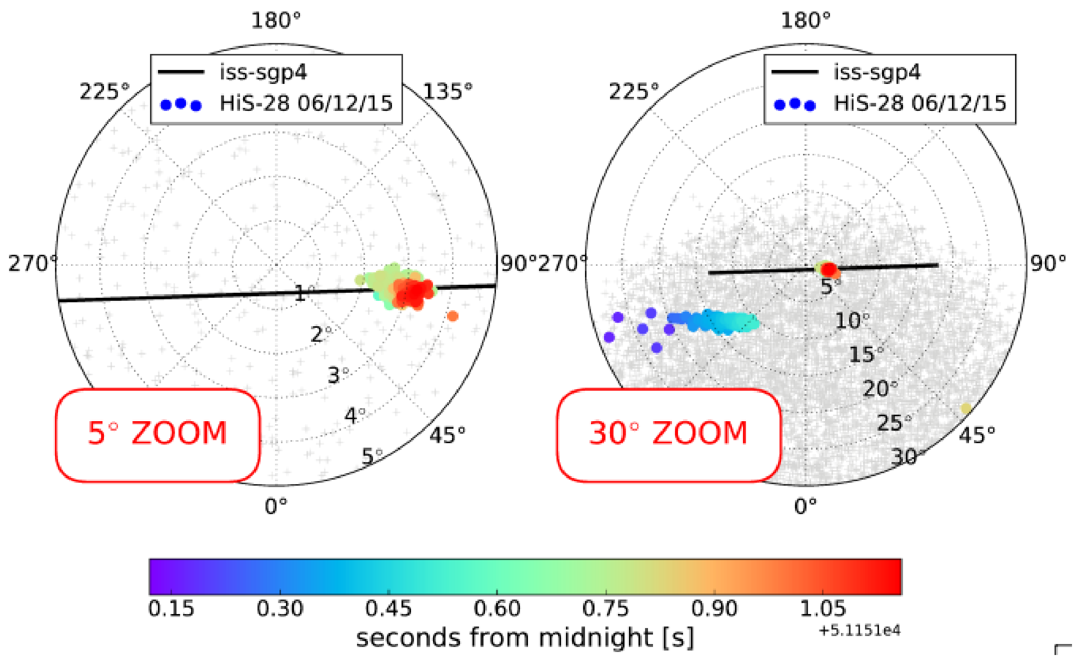
Date	ISS-events (Selected)	CATS data	MASTER Image
16/11/15	2780 (1760)	YES	NO
19/11/15	50 (7)	YES	NO
06/12/15	3830 (1850)	YES	NO
05/02/16	1990 (1320)	YES	NO
08/02/16	3421 (1056)	NO	NO
27/09/16	2040 (1590)	YES	NO
26/11/16	1821 (0)	YES	NO
25/01/17	2300 (1730)	YES	NO
28/01/17	2140 (1300)	YES	NO
25/03/17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

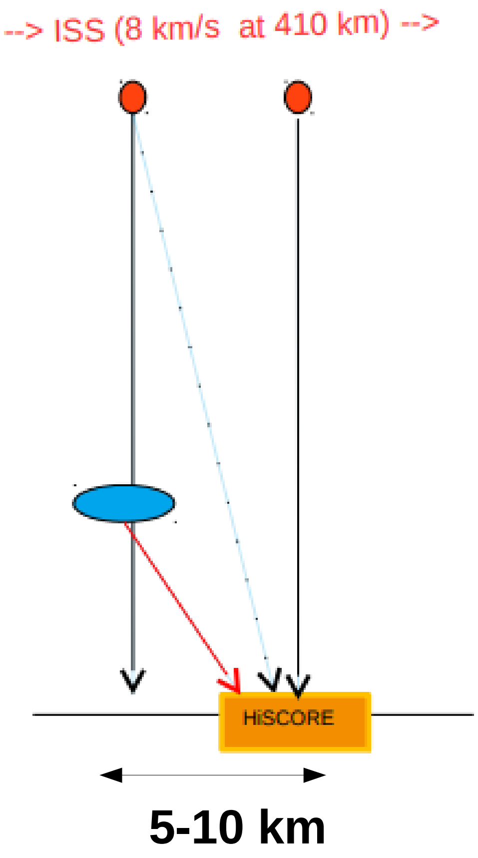


3D passage reconstruction using CATS data
“DIRECT LIGHT” SIGNAL DETECTION

„ISS Cloud Events“ : Forward scattered LIDAR light by clouds

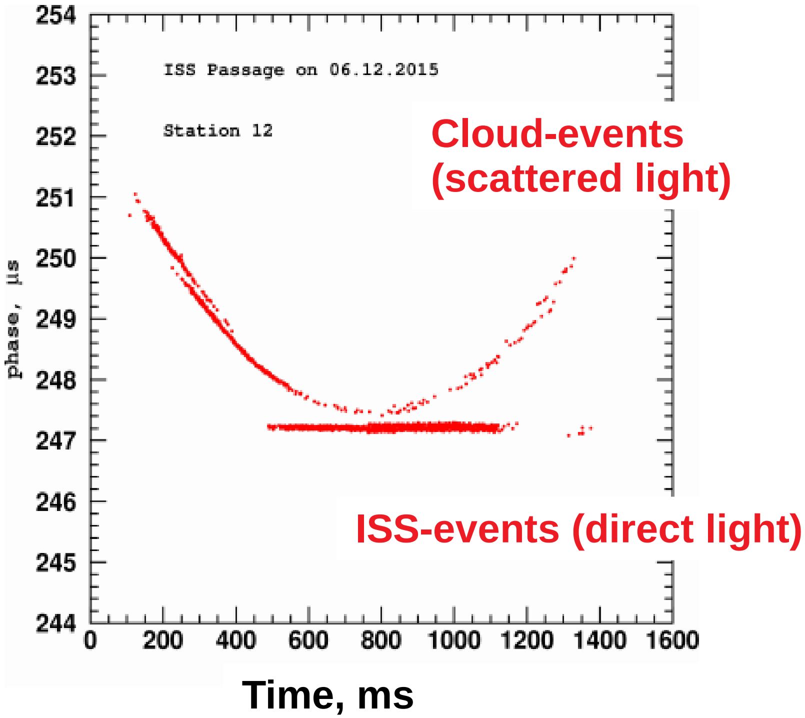
> **Detection of LIDAR photons scattered by clouds**



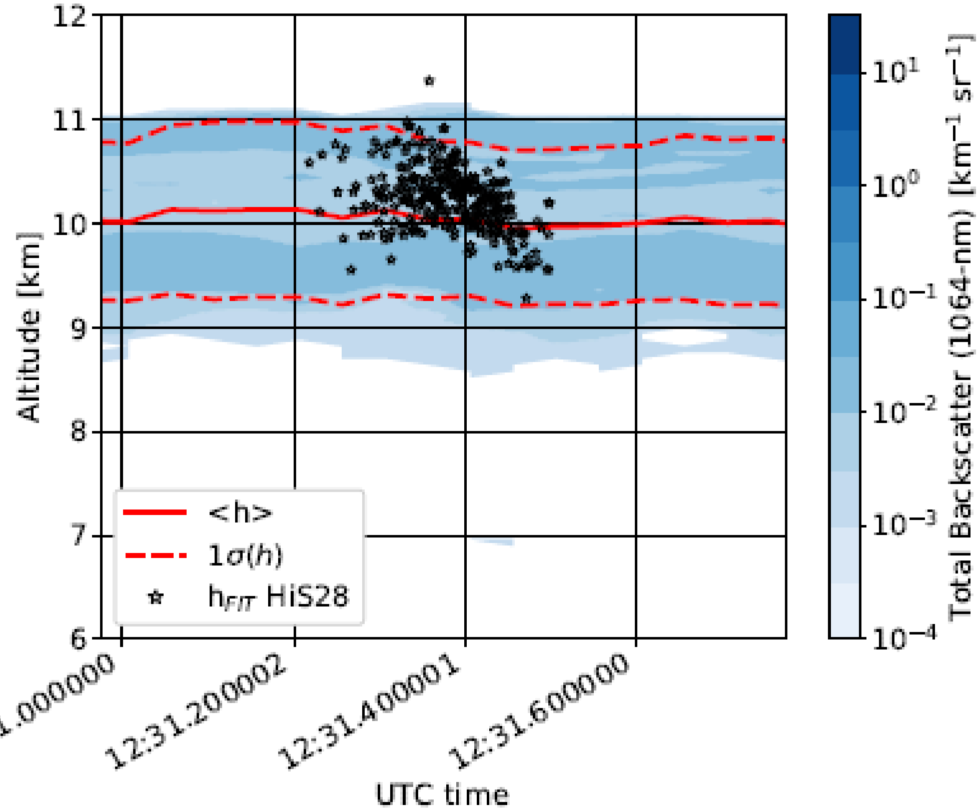


„ISS Cloud Events" : Measured Cloud location

- 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



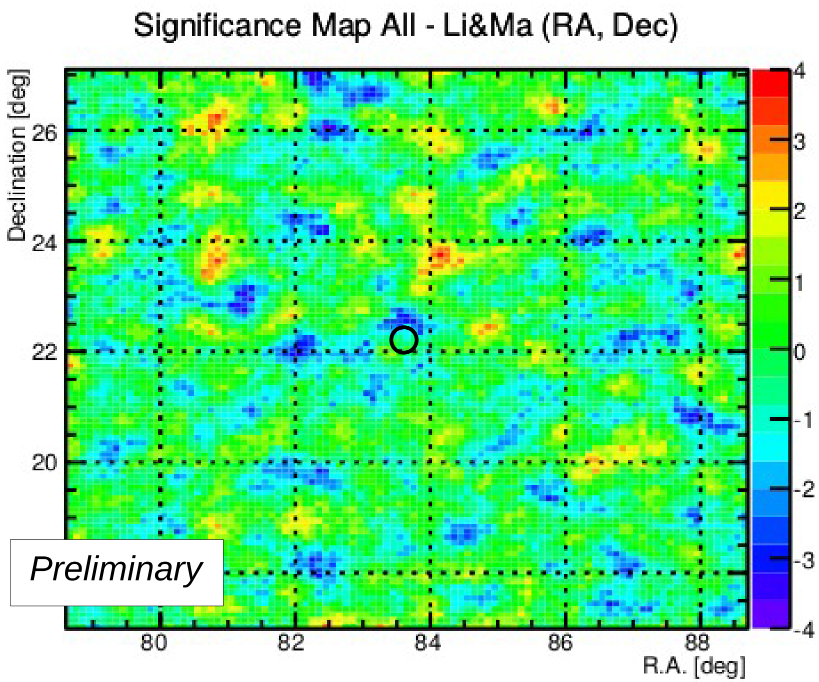
LIDAR-phase analysis

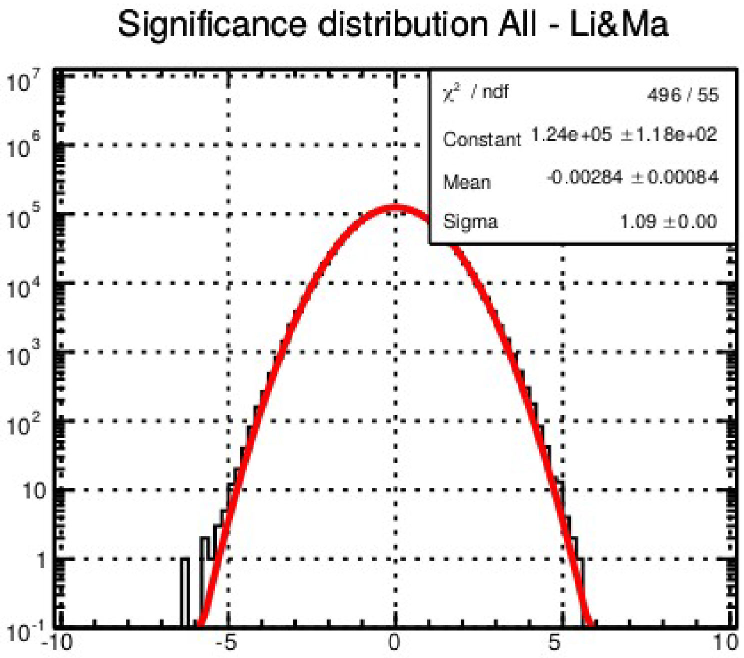


Reconstructed cloud height

HiS28: Point source analysis

- > Full sky point source analysis developed TAIGA-HiSCORE in stand-alone mode
- > Background estimation and Significance calculation:
  - Direct Integration (Milagro, HAWC) + Rings (used in IACT analysis
  - Significance: Li&Ma
- > Analysis:
  - Use only events reconstructed direction (no energy, no g/h separation)
- > No significant signal observed from Crab direction (prelim.)





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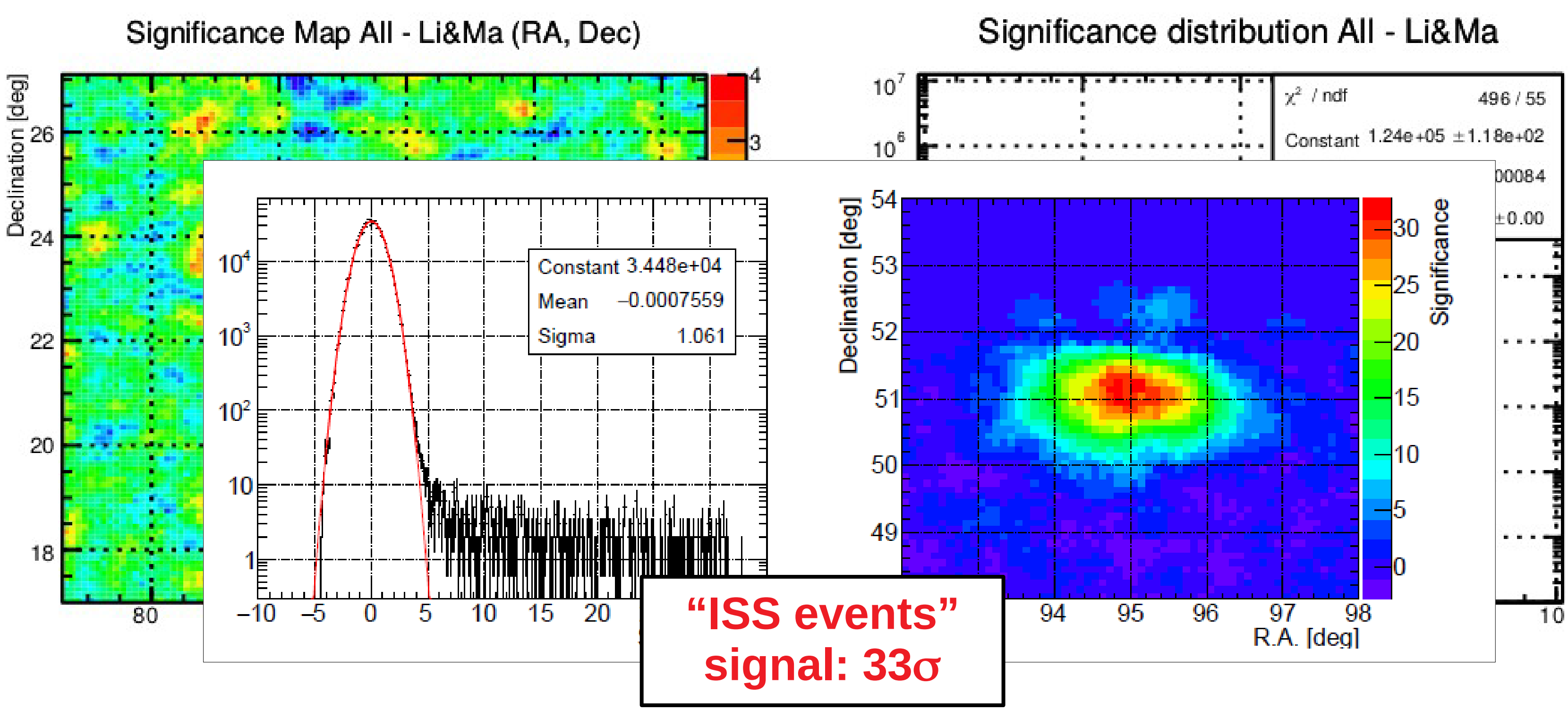
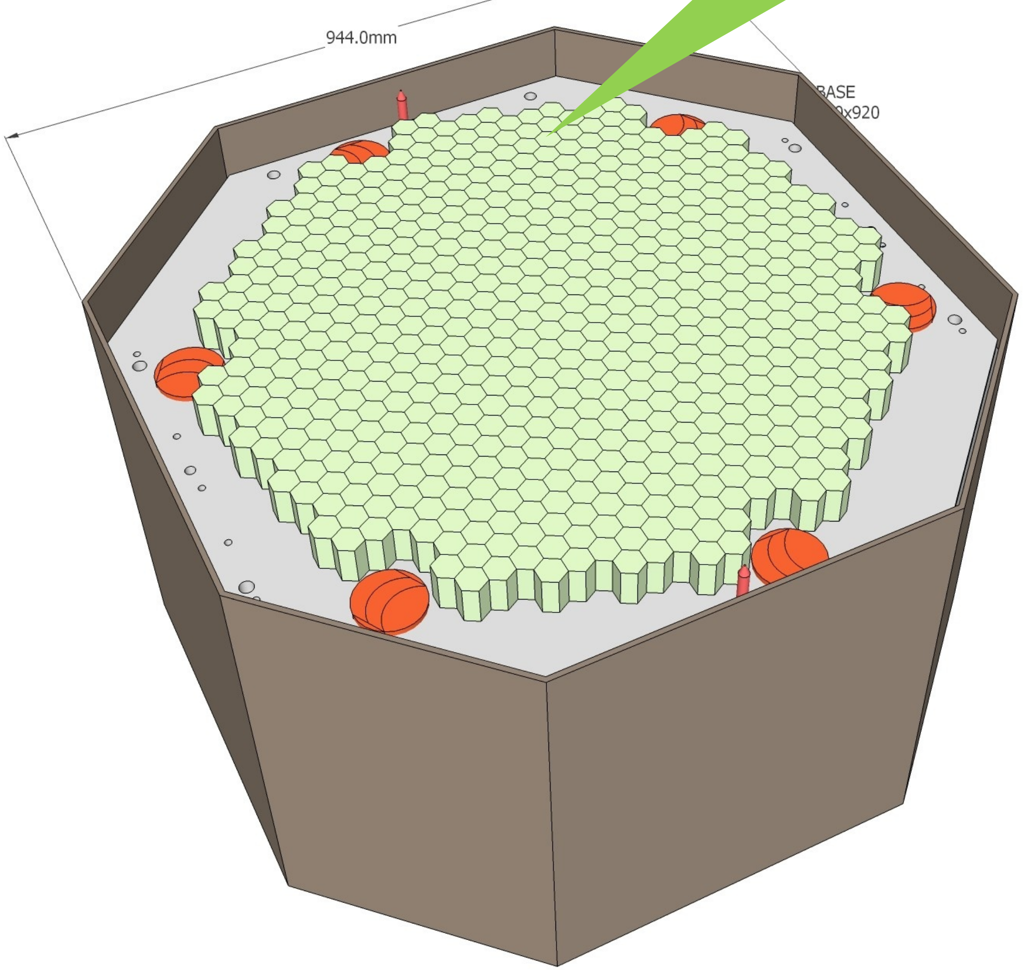


The first TAIGA-IACT

- Davies-Cotton Reflector Ø: 4.32m
- f = 4.75m
- FOV ~ 9.6 deg
- 30 Glass mirrors of Ø = 60cm
- Camera:
  - 560 PMT XP1911 (15mm photocathode)
  - Winston Cone: 30mm input / 15mm output
  - Pixel-aperture: 0.36 deg
- Energy threshold ~ 1.5 TeV
- Pointing accuracy up to ~0.02°
- IACT-Image analysis and IACT-HiSCORE Hybrid analysis are in progress.

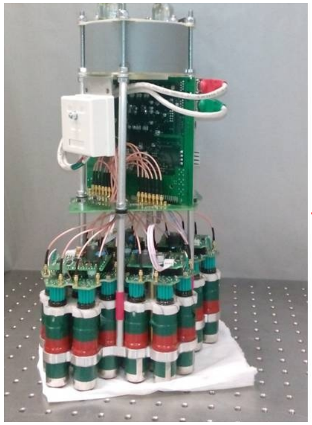
The TAIGA-IACT camera

560 PMT



Camera DAQ is based on MAROC3 ASIC

MAROC3 64 channel F/E board



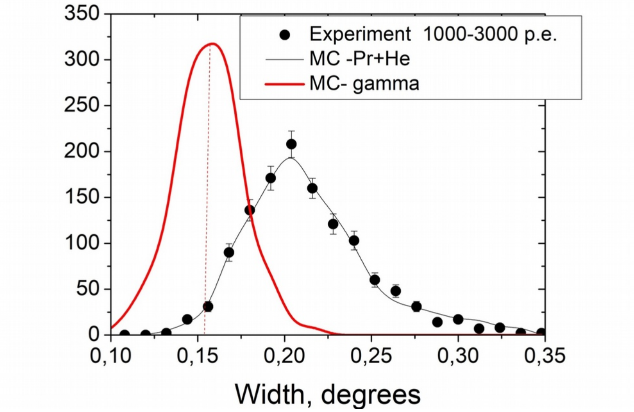
22 Cluster w/ 28 PMTs

IACT and HiSCORE: mono and hybrid events

First full TAIGA-IACT operations started in fall 2017

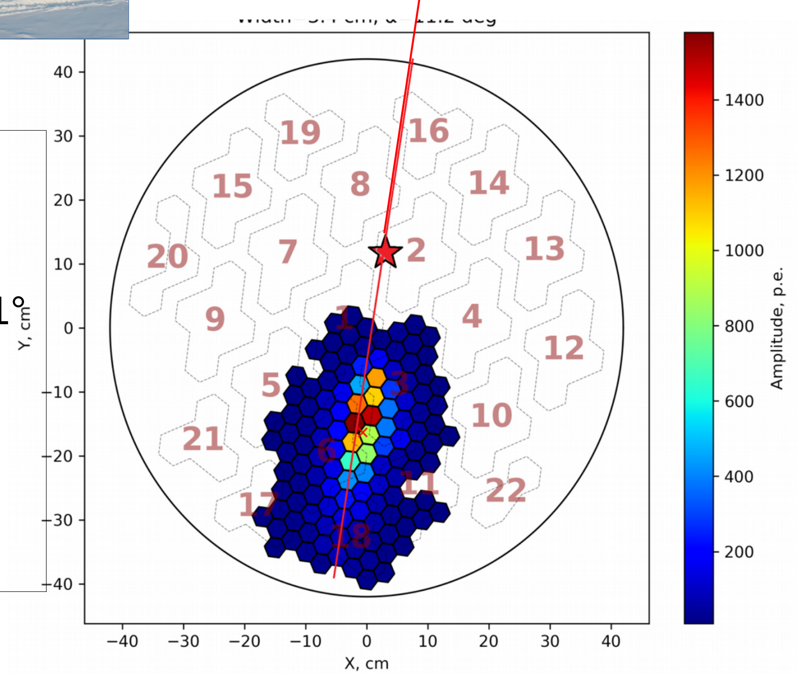
- **<u>IACT mono data</u>: good agreement between reconstructed IACT images and MC prediction**
- **Analysis of mono IACT data is in progress**

Width distribution: MC/data (mono)



- **<u>An example of a TAIGA Hybrid event</u> :**
  - **Image from IACT**
  - **Core, direction, energy by HiSCORE**

EAS core position
(by 15 HiS stations)



<u>A “hadron-like” event</u>

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

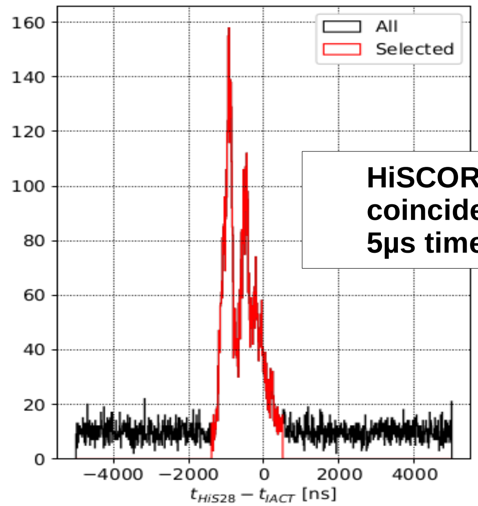
HiSCORE: full EAS-reco.
Energy: 840 TeV
Core: 134m,
Zen/Az= 30.1 / 33.6 deg

Crab observation (2017/18):
- 17000 hybrid events in 50 hours
  (~300 evt in 0.7° around Crab direction)

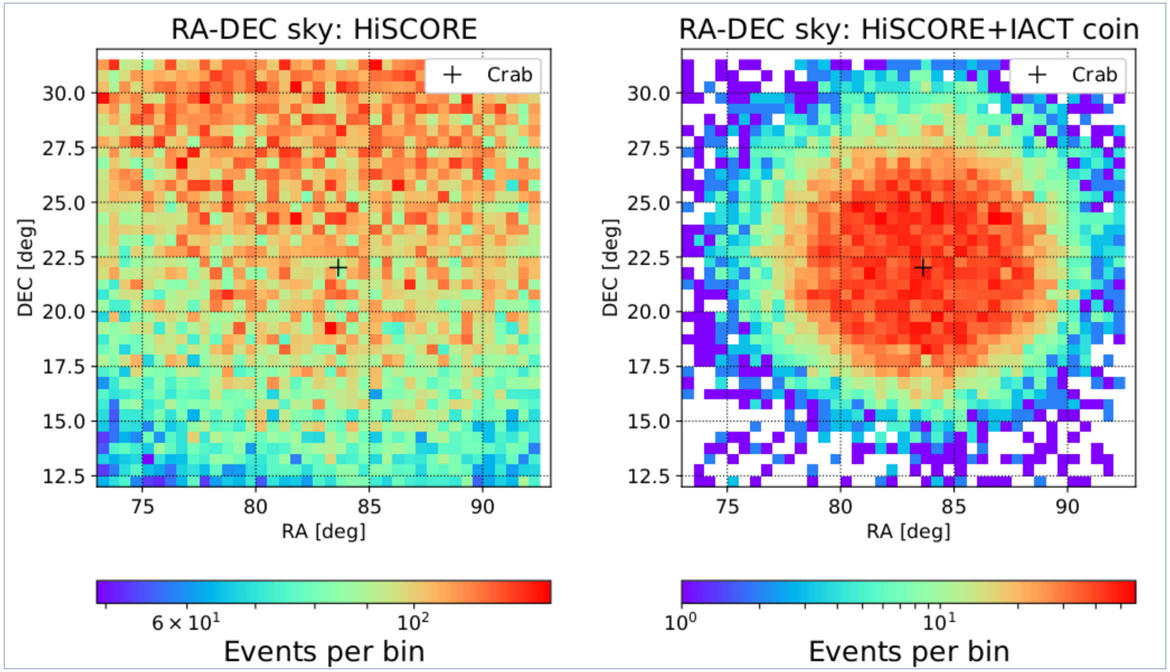
- **Focus now: detect Crab in mono & hybrid mode.**

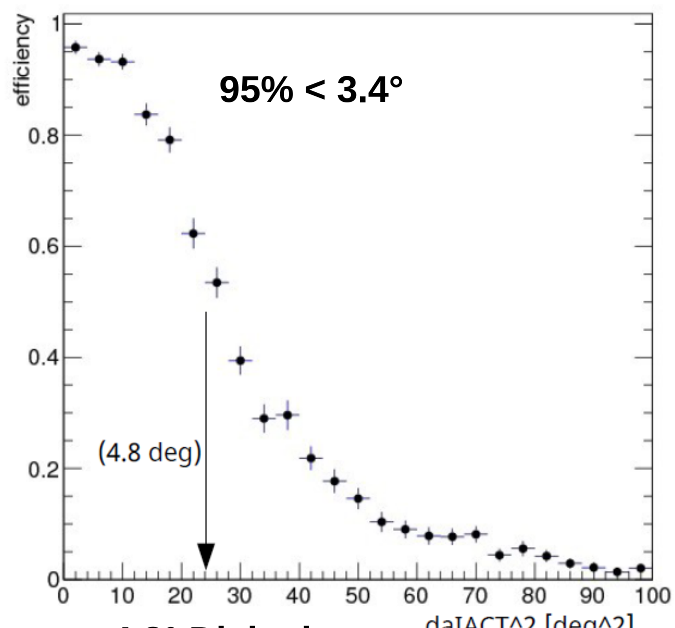
IACT and HiSCORE: hybrid events

- Cross-verification of both instruments
- Analyze the subset of EAS seen by both HiSCORE (complete spatial reconstruction & EAS energy), and by IACT (triggered or reconstructed)
- 95% efficiency to trigger IACT up to 3.4° from the IACT pointing direction



HiSCORE-IACT coincidence events: 5μs time window





4.8° Dish size

Hybrid events detected during long Crab-IACT tracking runs
Left: all, Right: coincident evts

Summary

> **TAIGA is a prototype installation to test a a new technology for gamma astronomy above 10 TeV and CR physics (>100TeV)**

- **Large area detector, composed of (sparse) IACT + HiSCORE timing 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° at E>100 TeV; absolute pointing verified to ~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; after hybrid gamma detection: reconsider g/h in standalone mode.**

> **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 confirm HiS-operation**

Summary (2)

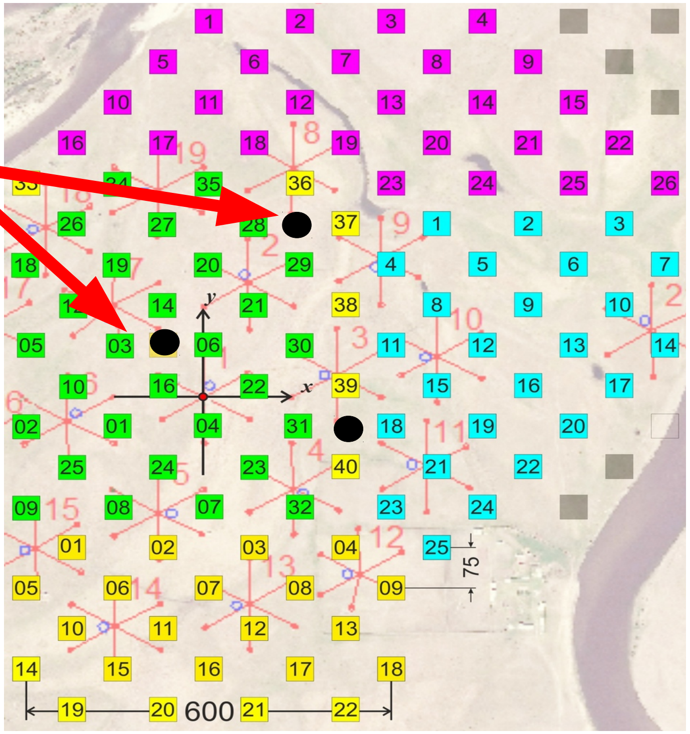
> **By fall 2019:**

A 1 km2 HiSCORE array + 3 IACT will be installed by fall 2019

- **Point source sensitivity: 300 hr 5 10-3 TeV cm^{-2} s**
- **50-100 hybrid Crab events >40 TeV / 100 hr (1 season)**

120 TAIGA-HiSCORE stations

3 TAIGA-IACT

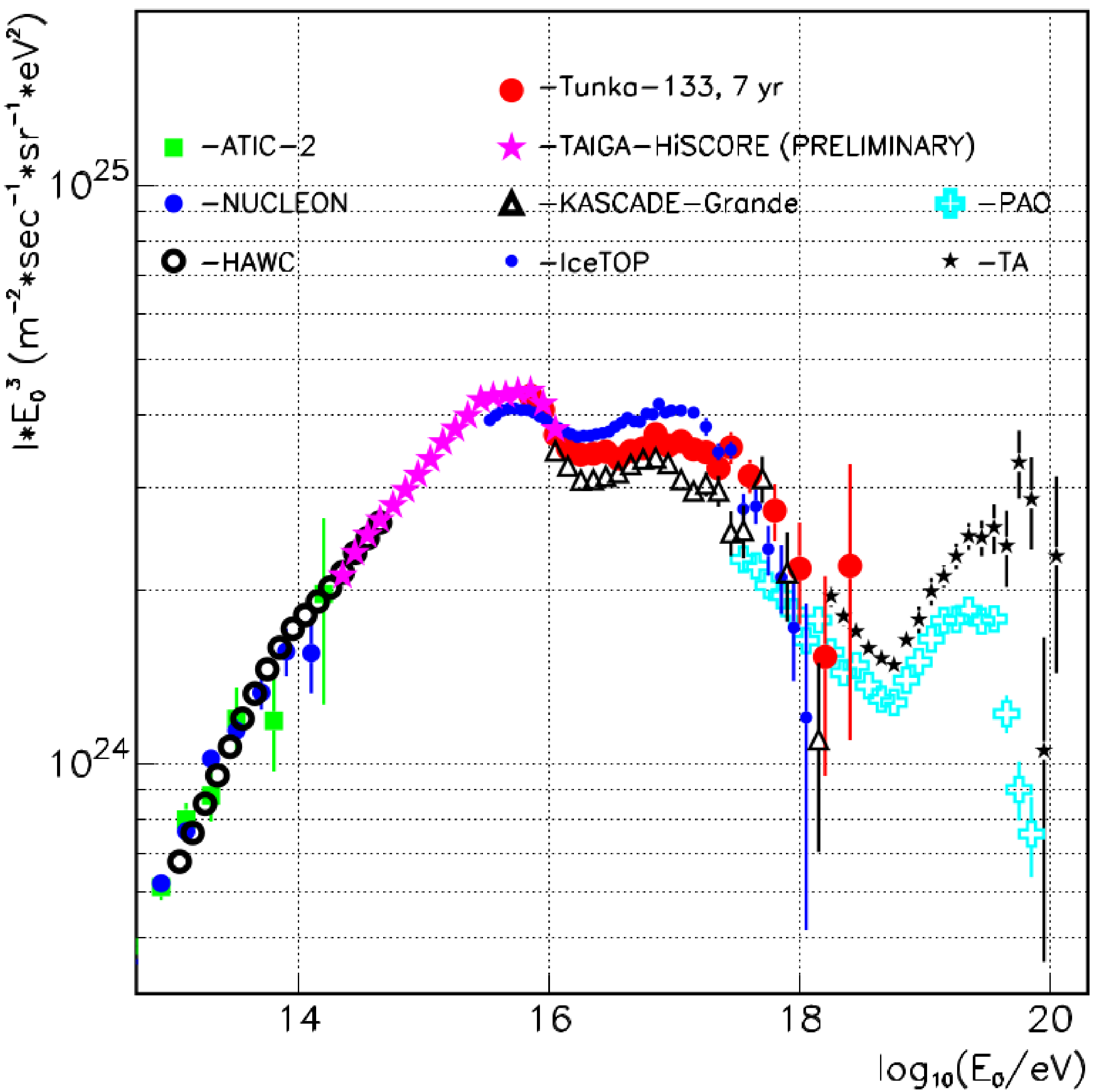


> **Future:**
Considering a 10km2 Gamma detector with 16 IACTs and 1000 stations @2000m a.s.l

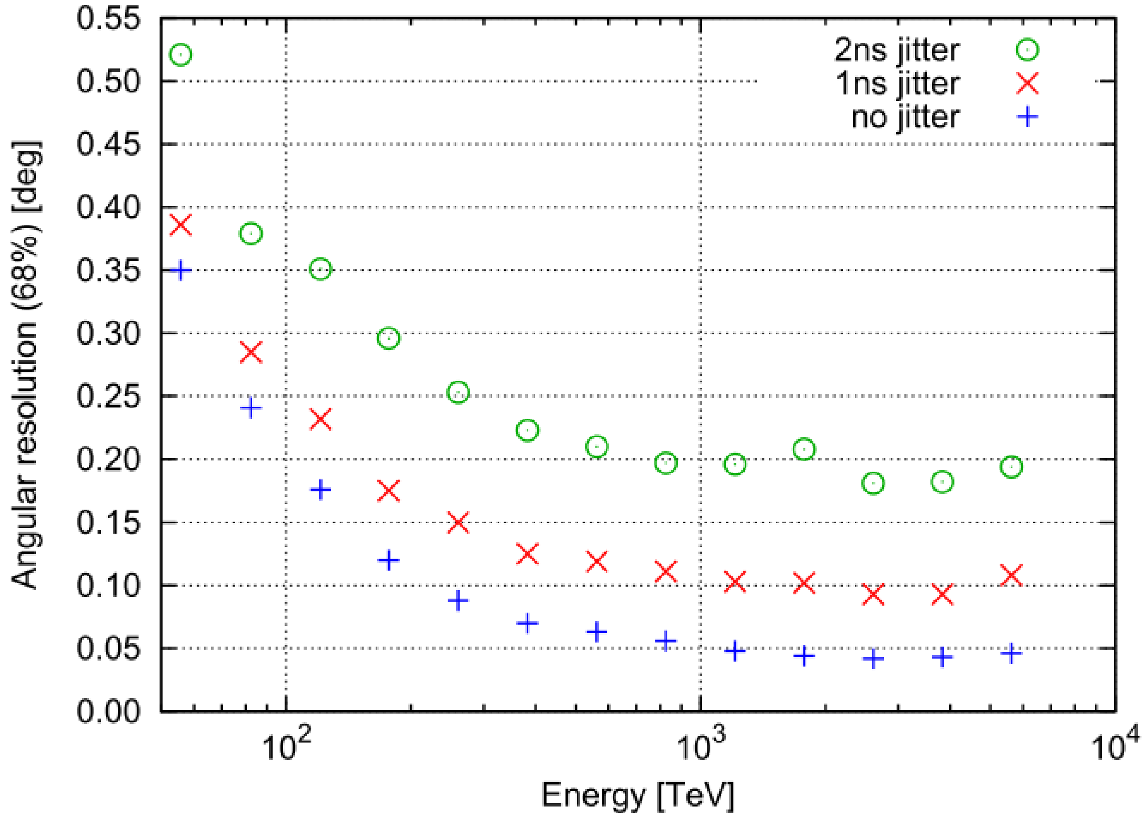
Thank you

Backup slides

Energy spectrum by HiSCORE (2018)



Angular resolution: Importance of timing



> **MC study, variying the time precsion**

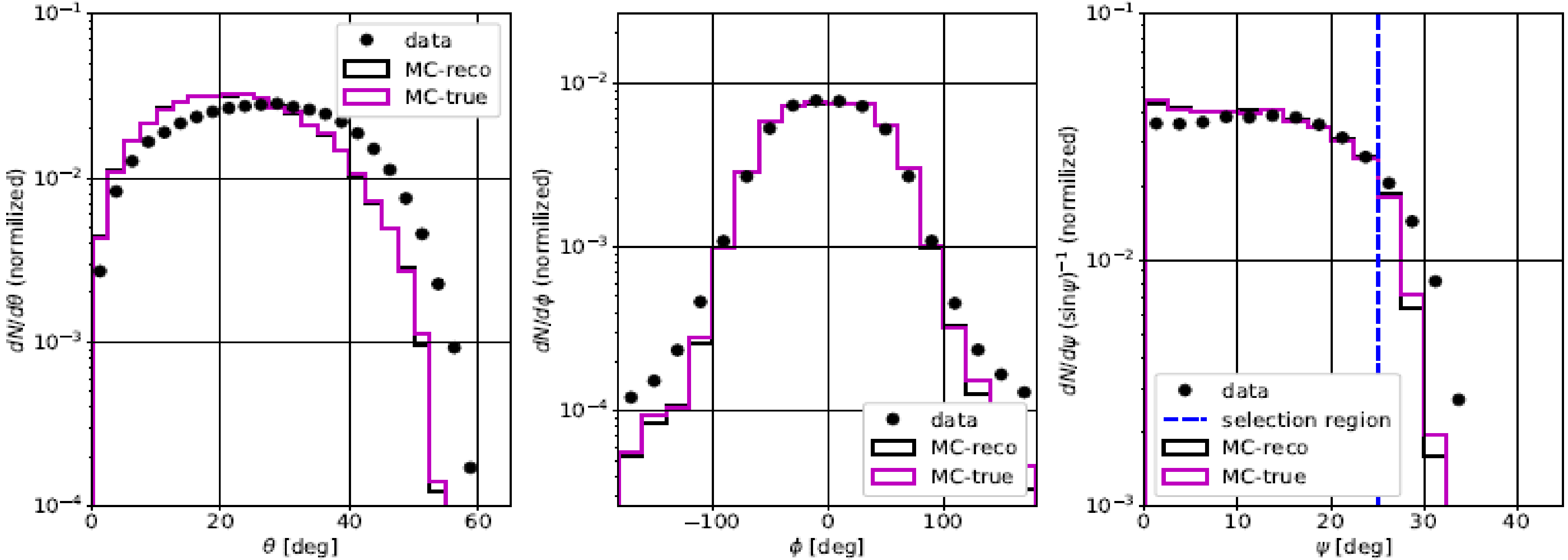
> **Crucial for pointing:**

- **Time synchronization < 1ns: low time jitter [Hampf, 2014]**
- **Precise array time calibration (systematic mispointing induced by static station time offsets) [see ICRC2017]**

Detector acceptance: Data/MC comparison

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

ZENITH **AZIMUT** **PSI**

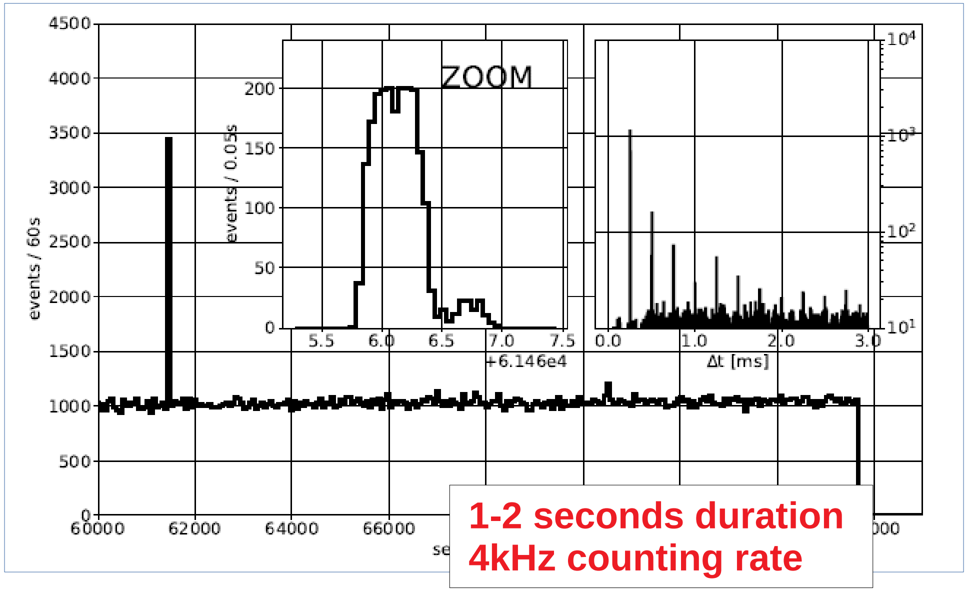


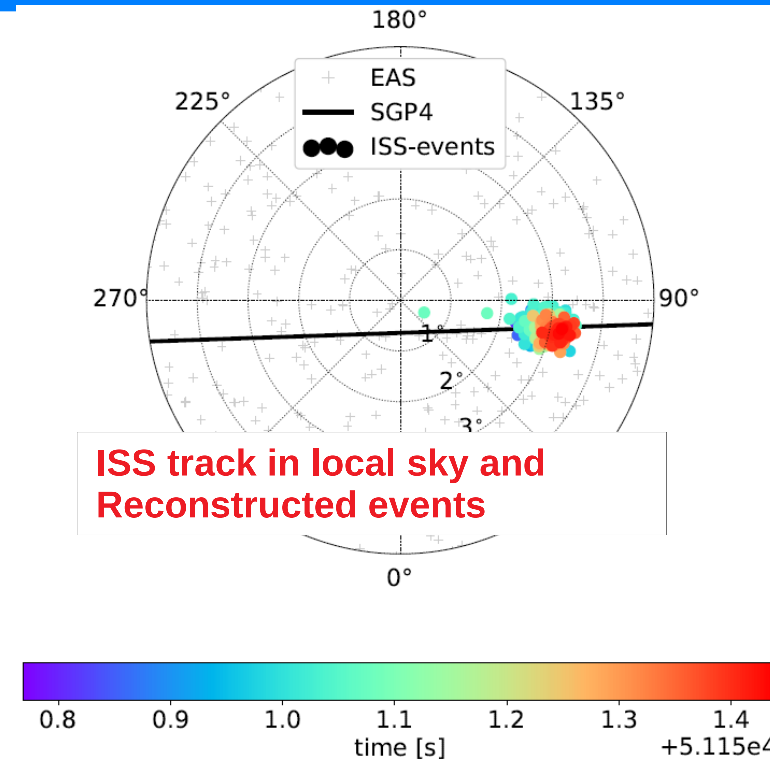
> Good Data/MC agrement for detector acceptance

> 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)

HiSCORE observation of the ISS/CATS-LIDAR





> **Serendipitous discovery – 2015/16**

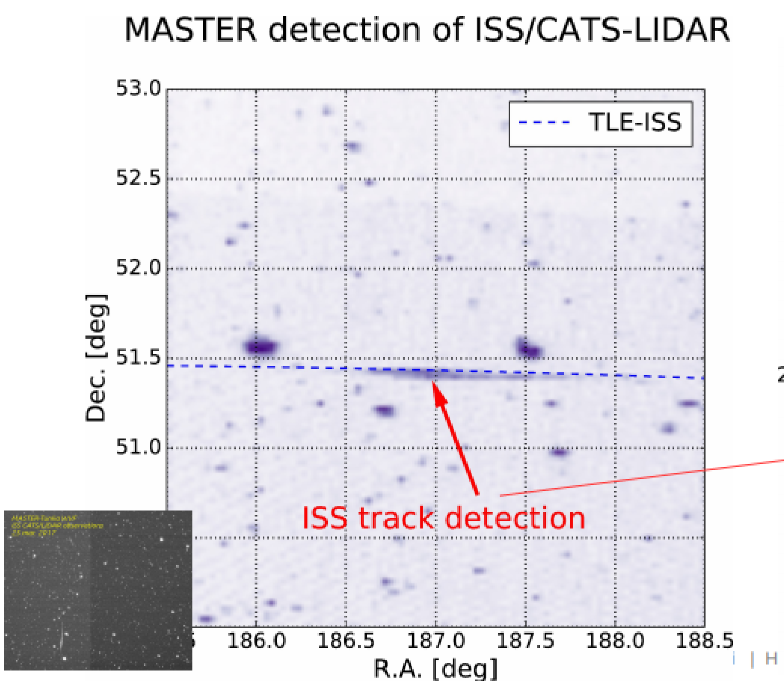
- **Several passages observed (and predicted) partially 3/4 days period; also during 2016/17**
- **Passages must be close to zenith**
- **Perfect plane wave reconstruction instead of curved EAS profile**

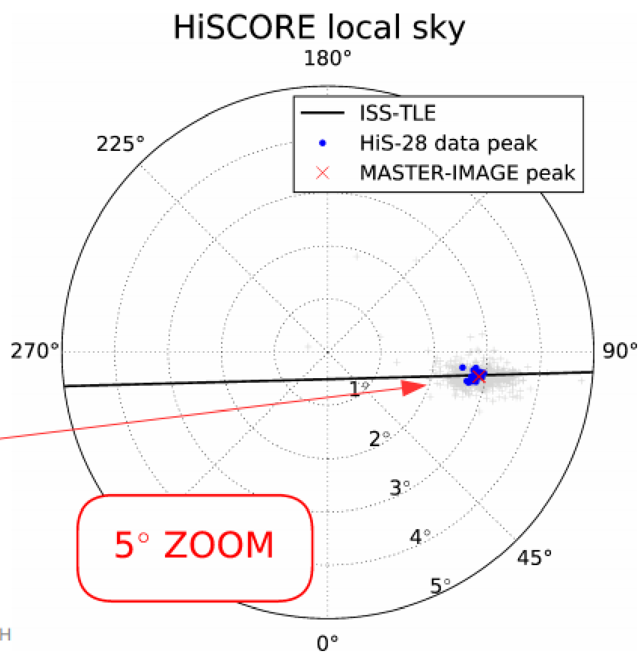
Unique tool for HiSCORE calibration / verification

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

Absoulte pointing: HiSCORE-MASTER combined

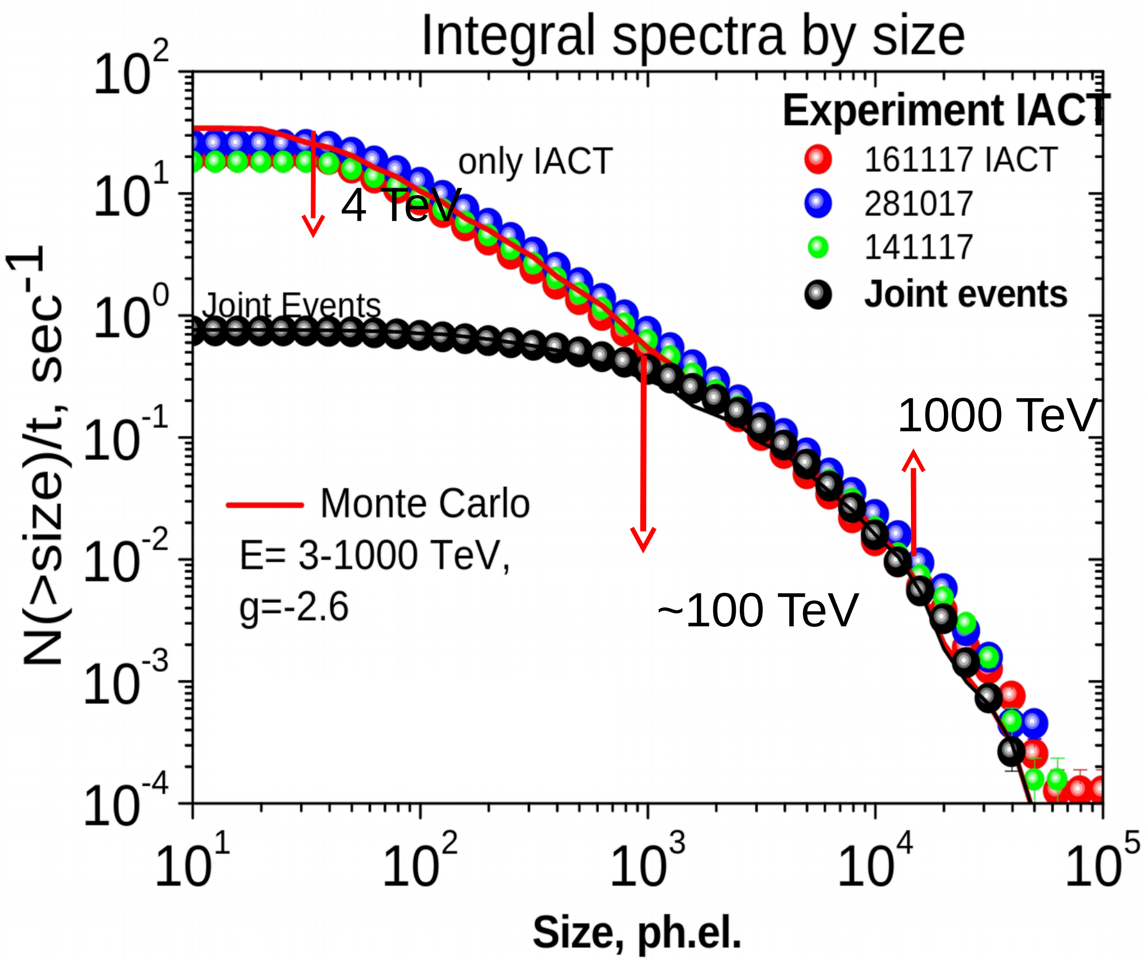
- March 2017: campaign to detect "ISS passage" with the closeby (500m) 'Tunka-MASTER' optical telescope. Direct communication with both Tunka-MASTER and CATS/NASA operators
- 25.03.2017 the 'Golden event': we obtained synchronous and independent detection by Tunka-MASTER VWF camera
  - Image analysis: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





Mispointing <=0.1°

IIntegral Size spectra: IACT and Hybrid events



HiSCORE energy spectra In linear scale

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