Search for nanosecond-fast optical transients with TAIGA-HiSCORE array

Alexander Panov for the TAIGA collaboration

TAIGA - collaboration

Germany

Hamburg University(Hamburg)

DESY (Zeuthen)

MPI (Munich)

Italy

Torino University (Torino)

Romania

ISS (Bucharest)

Russia

MSU (SINP) (Moscow)

ISU (API) (Irkutsk)

INR RAS (Moscow)

JINR (Dubna)

MEPhI (Moscow)

IZMIRAN (Moscow)

BINR SB RAS (Novosibirsk)

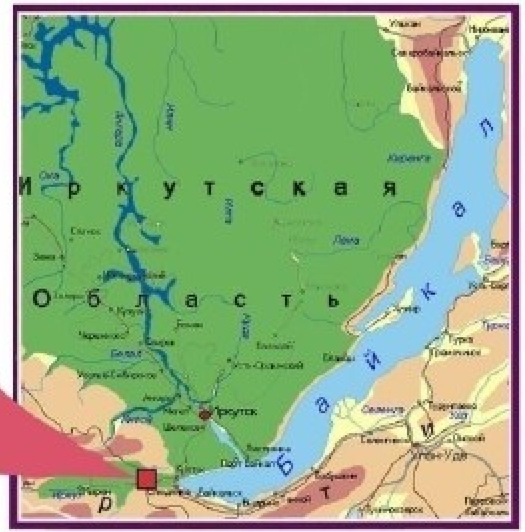
NSU (Novosibirsk)

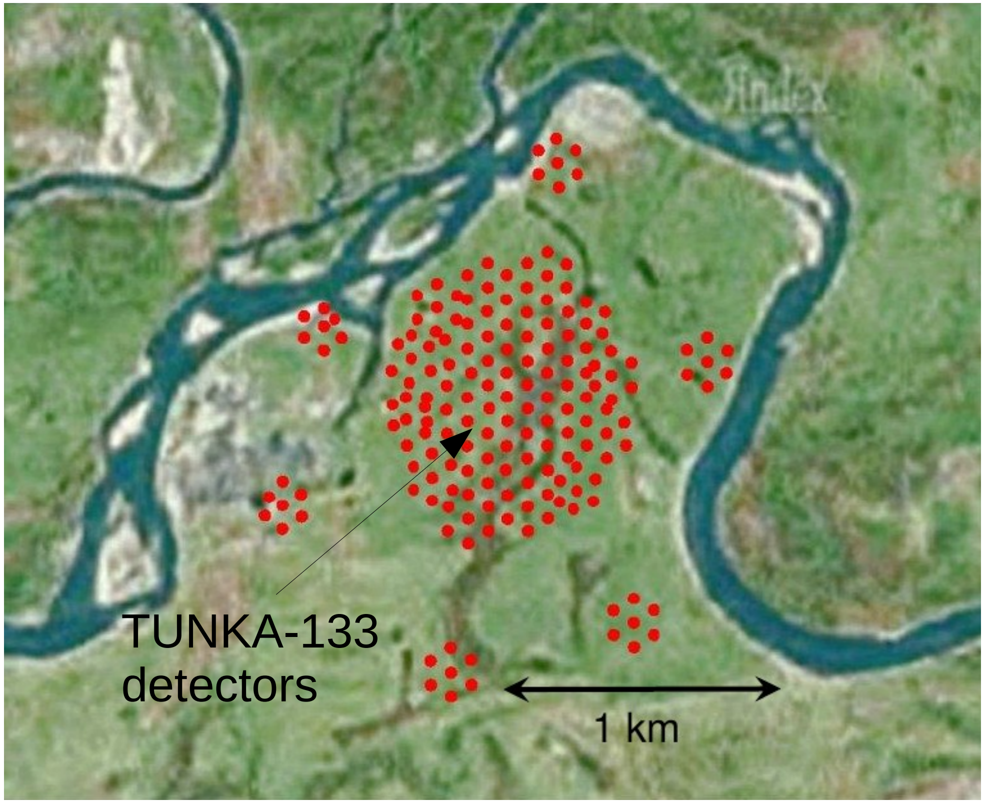
ASU (Barnaul)

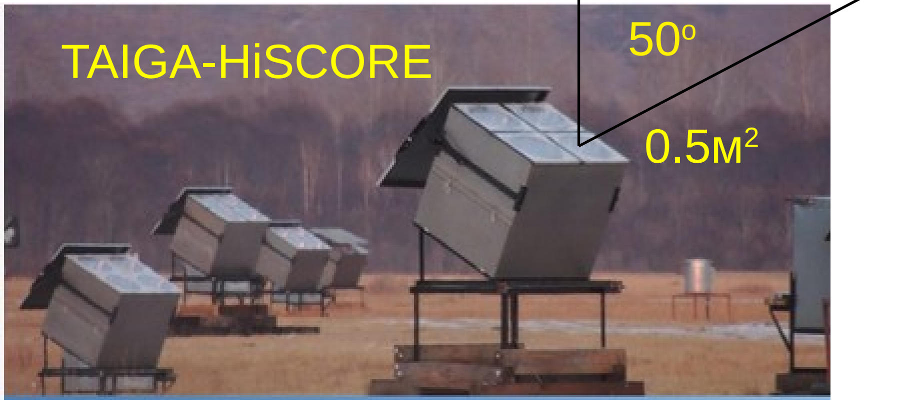
SAO RAS (Nizhnij Arkhyz,
Karachai-Cherkessian Republic

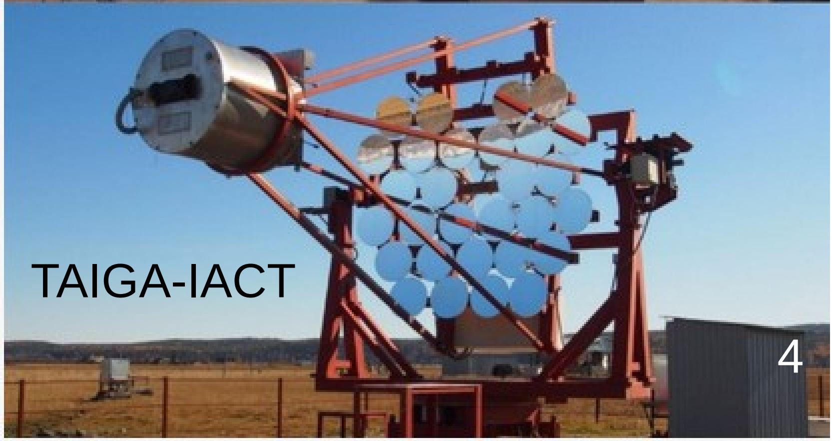
Astrophysical complex TAIGA, 50 km from the lake Baikal, Tunka Valley

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



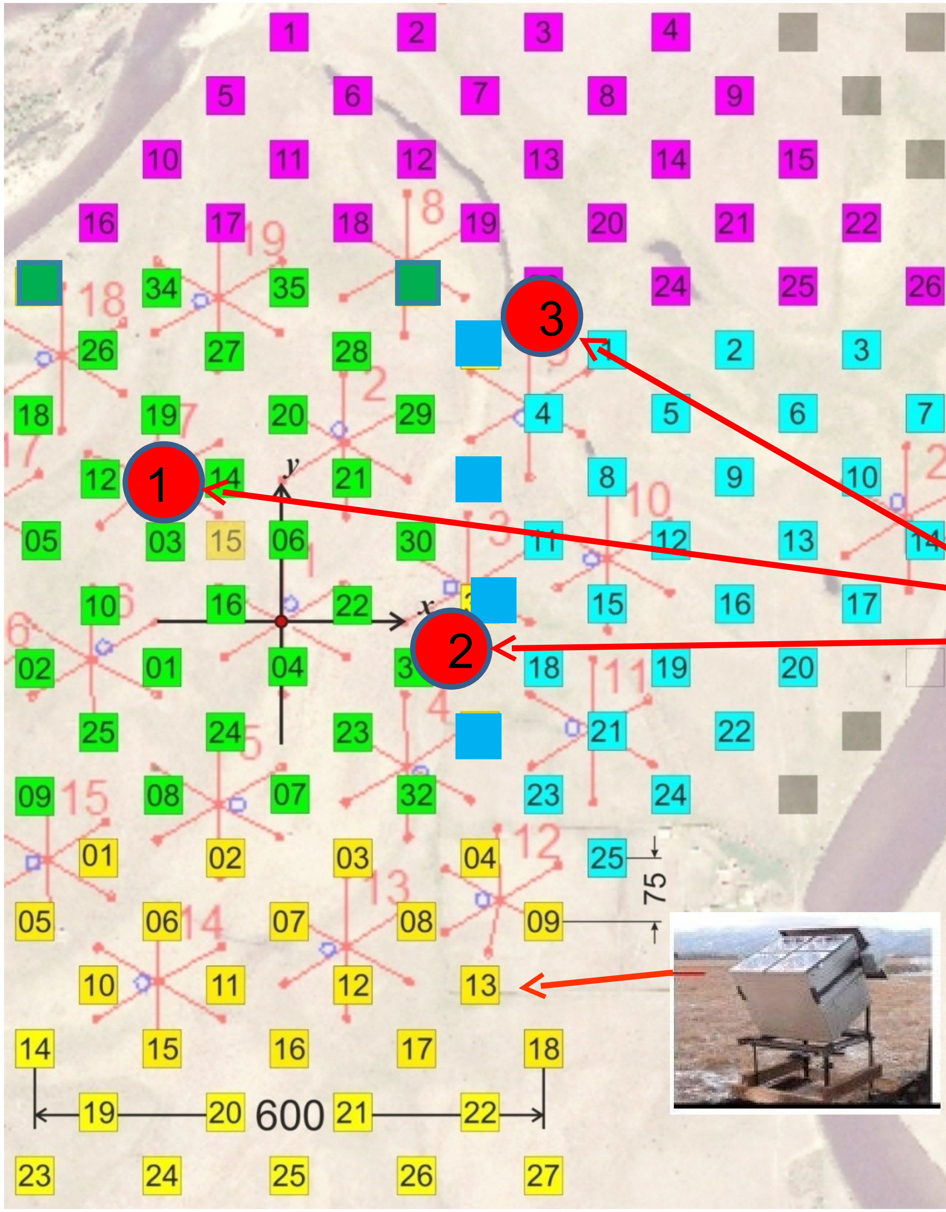






120 HiSCORE station and 3 IACTs, plan for addition 2 IACTs

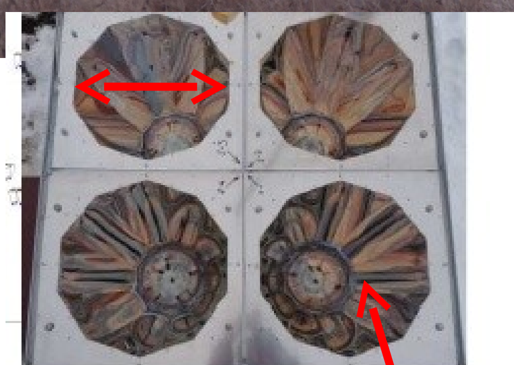
Current (2021) configuration



IACT
Two in operation
One is almost ready

HiSCORE station

Wide angle HiSCORE station



Spacing between stations 100 m

FOV: 0.6 ster (2000 deg^2)

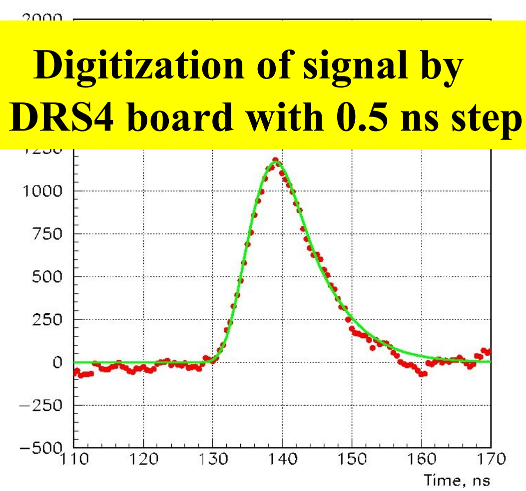
Threshold flux: 3000 photons/m^2 per 10 ns

Signal duration: 5 ns – 100 ns

Accuracy of time synchronization – 1 ns

S tot = 0.5 m^2

Winston cone and PMT with 20-photocathode diameter



Digitization of signal by DRS4 board with 0.5 ns step

Main idea of the work:

The HiSCORE array can register not only EAS events, but also any optical flashes above the threshold, that could be caused particularly by distant optical nanosecond transients of astrophysical nature.

Space-time structure of EAS HiSCORE events expected to differ significantly from space-time structure of distant point-like optical events.

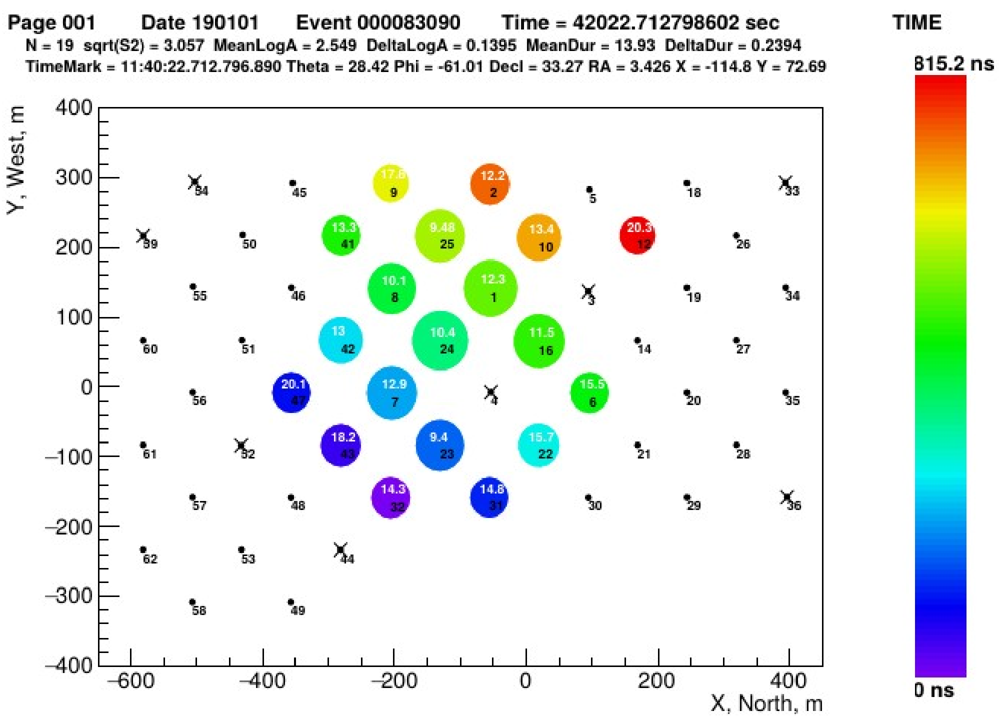
Therefore, we can use the HiSCORE data not only for cosmic-ray physics and gamma-ray astronomy, but for usual optical astronomy.

Important: no special triggers are required to search for optical transients; all work is performed in a pure accompanying mode, without interfering with the main task of the instrument.

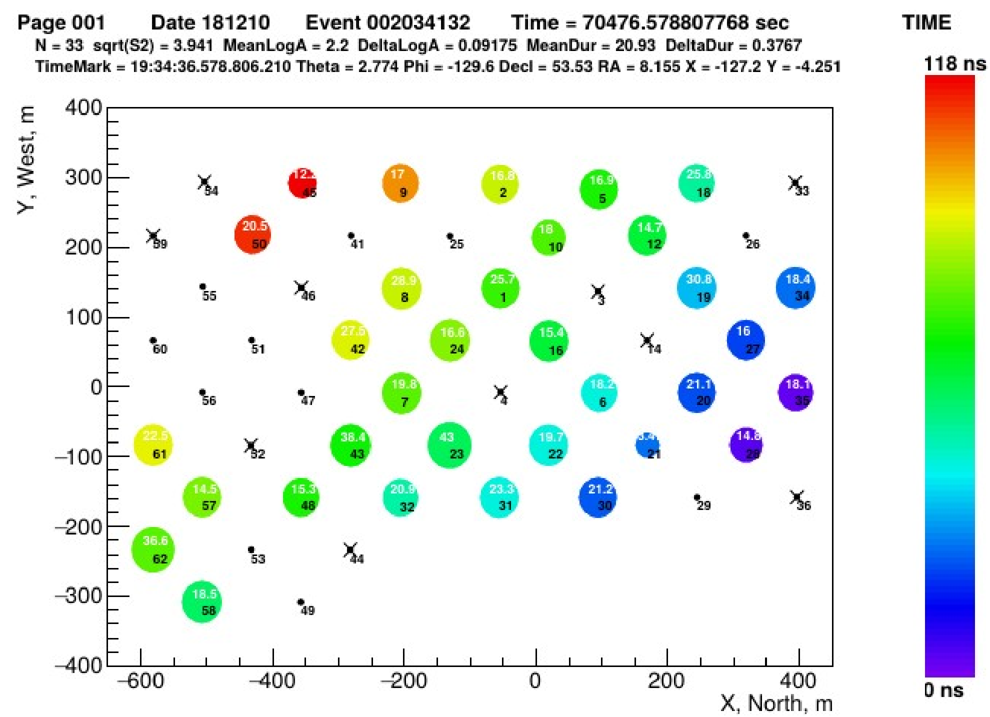
EAS event and distant point optical event

2018-2019 HiSCORE configuration (this work)

EAS



Distant point source (SATELLITE)



Thresholds and cosmic nanosecond lasers
SETI (Search for Extra Terrestrial Intelligence)

Energy of laser pulse (MJ)/10 ns depending on
L (light years) - distance to the laser
D (meters) - size of aperture

L, l. years \ D, m	1	10	100	1000
10	10	10^{-1}	10^{-3}	10^{-5}
100	-	10	10^{-1}	10^{-3}
1000	-	-	10	10^{-1}
10000	-	-	-	10

- Large aperture lasers (like 1000 m) are not single lasers, they are phasing laser arrays (already exist)

- Energetic of existing systems (thermonuclear synthesis):
  4 MJ (2 ns); 1.5 MJ (4 ns)

Methods

All present work is based on the HiSCORE data of 2018-2019 winter.
80 clear nights of observations, 475 hours, exposition 288 ster·hour

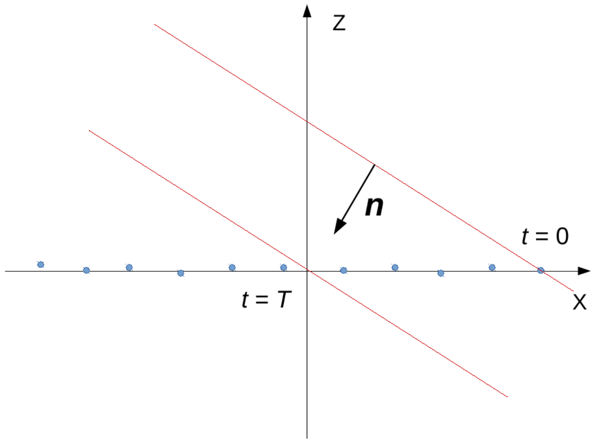
Expected signatures of optical transients:

1. Small amplitude spreading among the triggered optical stations in one event

2. Good fit of optical stations response times by an exactly plane optical front

3. Uniform distribution of positions of triggered optical stations upon the surface of the HiSCORE array
(no spot-like distribution like in EAS)

Reconstruction of direcion of the axis (azimuth φ, zenith angle θ) - fitting of plane optical front to splash times of stations



$$t_i = T + \frac{\mathbf{r}_i \cdot \mathbf{n}}{c}$$

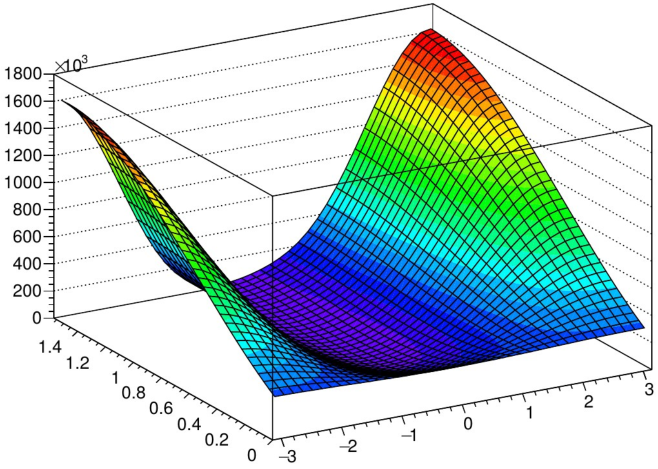
$$t_i(\theta, \phi, T) = T + \frac{1}{c}(x_i \sin\theta\cos\varphi + y_i \sin\theta\sin\varphi + z_i\cos\theta)$$

$$W(\theta, \varphi, T) = \sum_{i=1}^{N}\left[T + \frac{1}{c}(x_i \sin\theta\cos\varphi + y_i \sin\theta\sin\varphi + z_i\cos\theta) - t_i^*\right]^2 \to \min$$

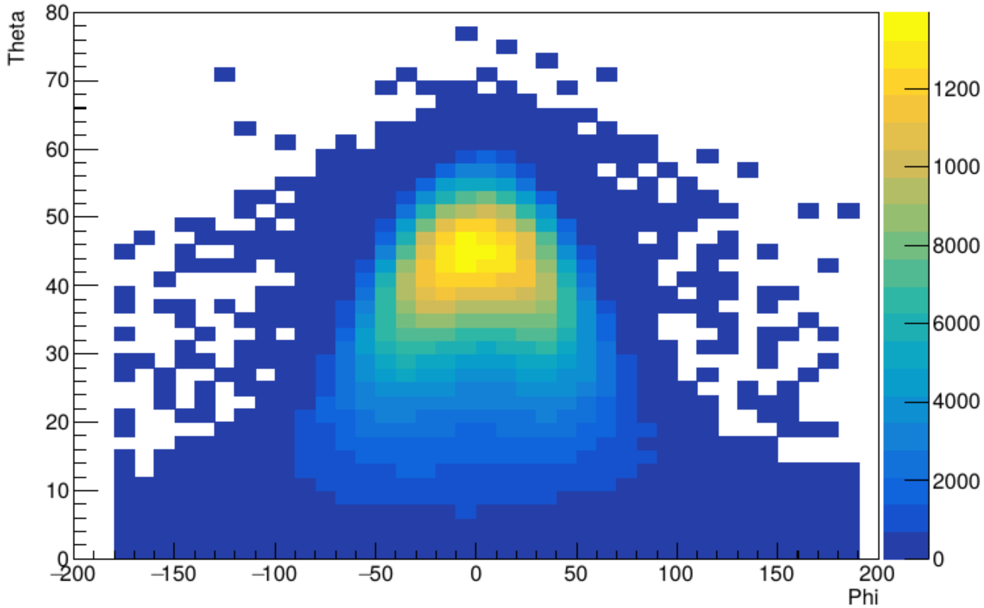
Reduction of dimension 3 => 2:

$$T(\theta, \varphi) = \frac{1}{N}\sum_{i=1}^{N}\left[t_i^* - \frac{1}{c}(x_i \sin\theta\cos\varphi + y_i \sin\theta\sin\varphi + z_i\cos\theta)\right]$$

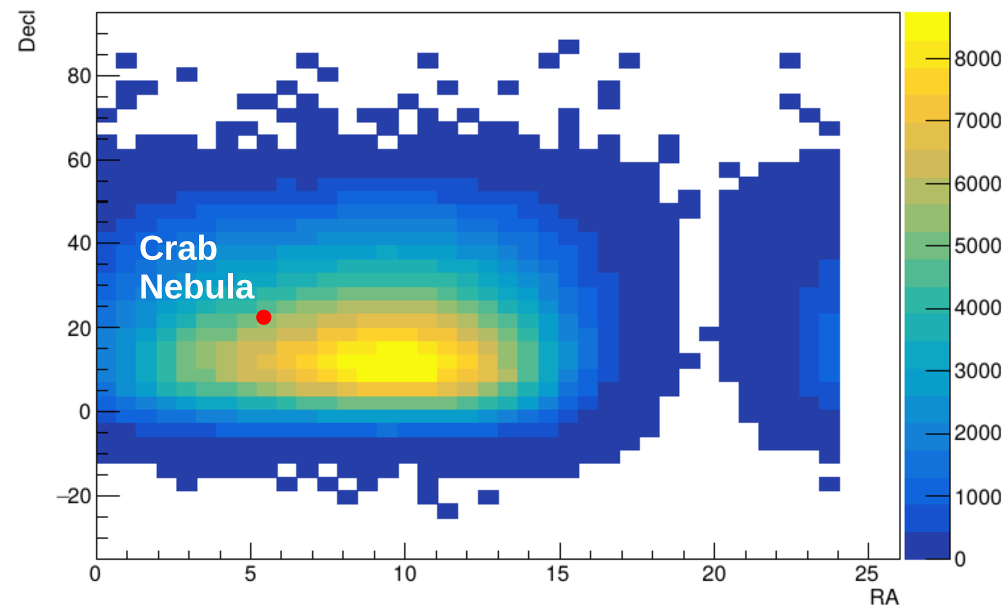
$$\widetilde{W}(\theta, \varphi) = W[\theta, \varphi, T(\theta, \varphi)]$$



Local coordinates



Absolute coordinates



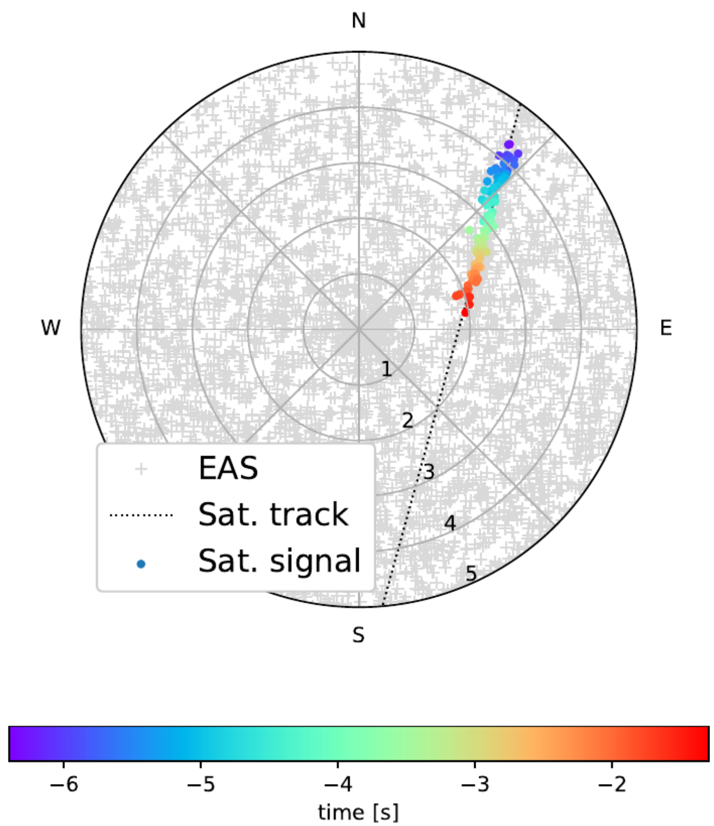
All reconstructed direction in local coordinate system (Phi, Theta) and absolute equatorial coordinate system (Right Accession, Declination)

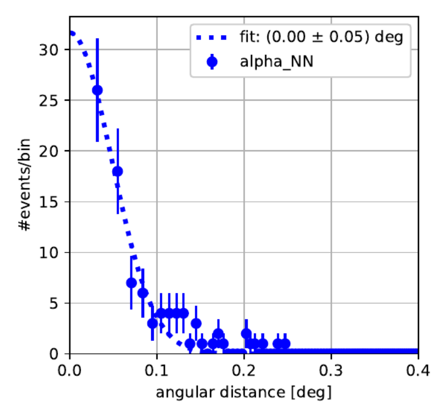
N_{trig} >= 15

TAIGA: HiSCORE + IACT observes LIDAR onbard **CALIPSO** Satellite

- Space based LIDARs are ideal to imitate OSETI point source + study instrument response, background...
- Satellites seen by HiSCORE : ISS, Calipso
  - 2015-2021: 10 Calipso observations
  - 2016-2017: 12 observations of Int.SpaceStation Laser [see PoS(ICRC2017)754]
- Calipso: started targeted IACT observation in April, 2021 (stereo mode)

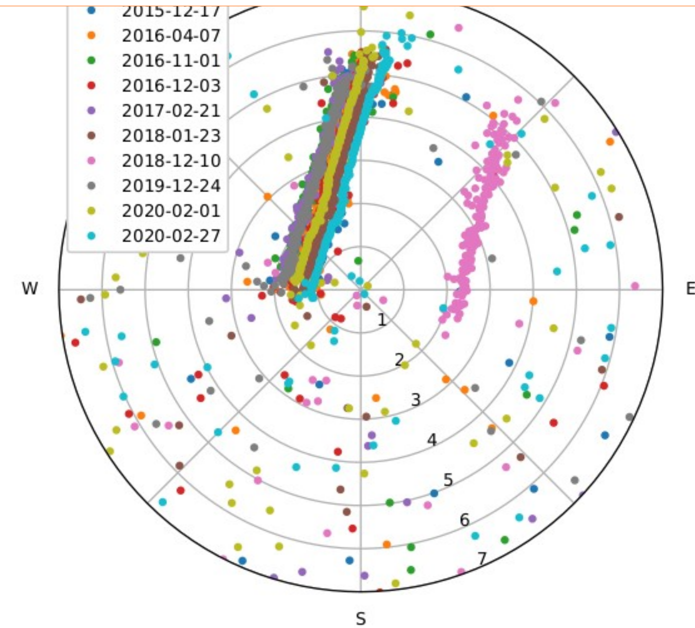
Example: Calipso Satellite passage over TAIGA-IACT on 18.12.2018





Angular pointing resolution for satellite tracks: 0.05º

Analysis of 2015-2020 data archive: 10 precision-reconstructed passages

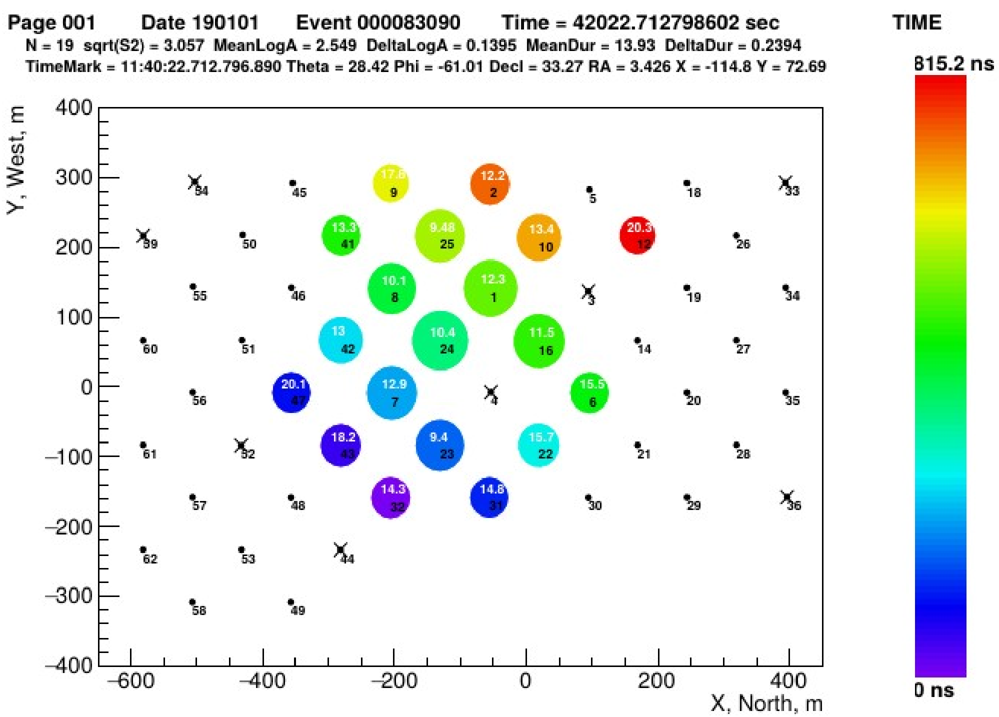


CALIPSO lidar pulse duration is ~20 ns
Altitude 700 km

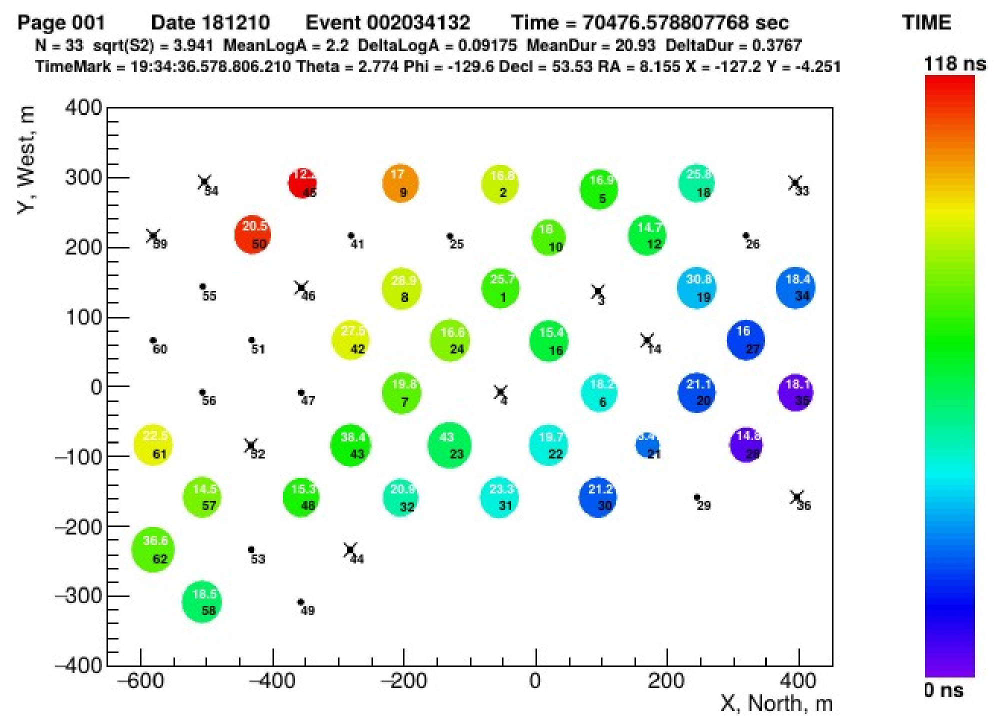
EAS event and distant point optical event

2018-2019 HiSCORE configuration

EAS



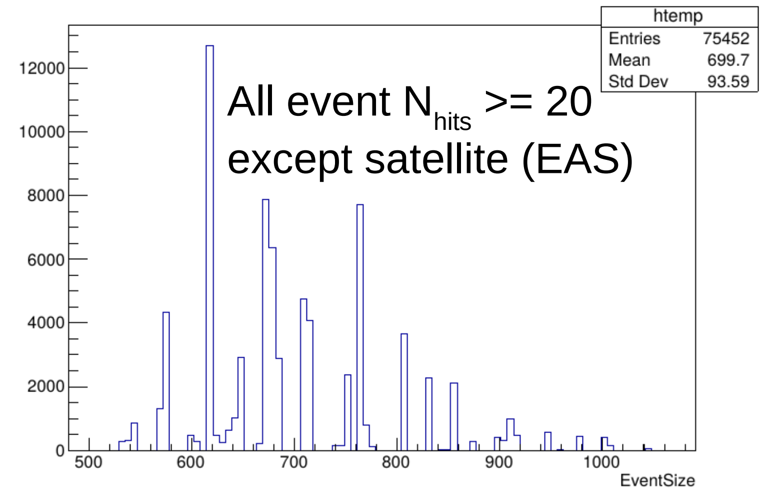
Distant point source (CALIPSO event)

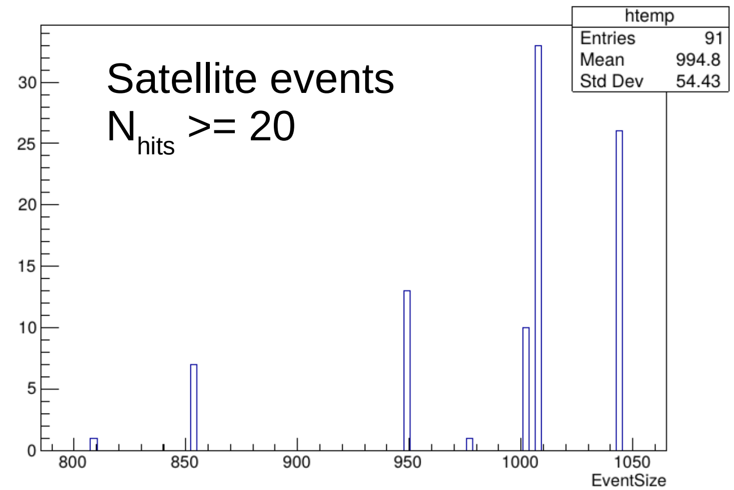


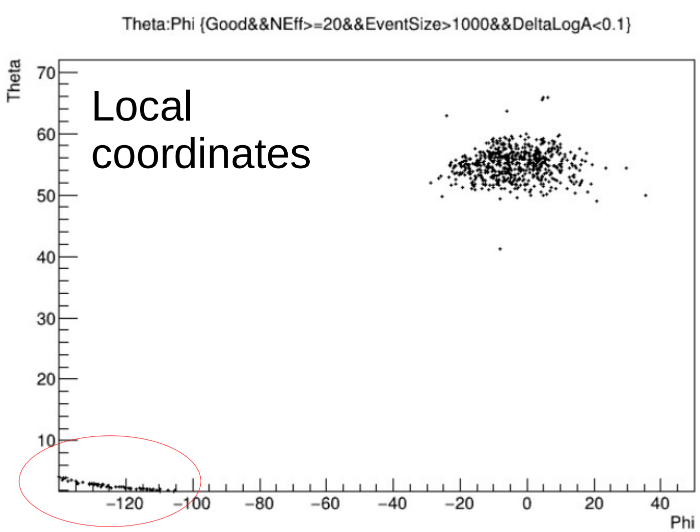
The structure of satellite events compared to EAS events confirms the method to select events from distant optical point-like sources

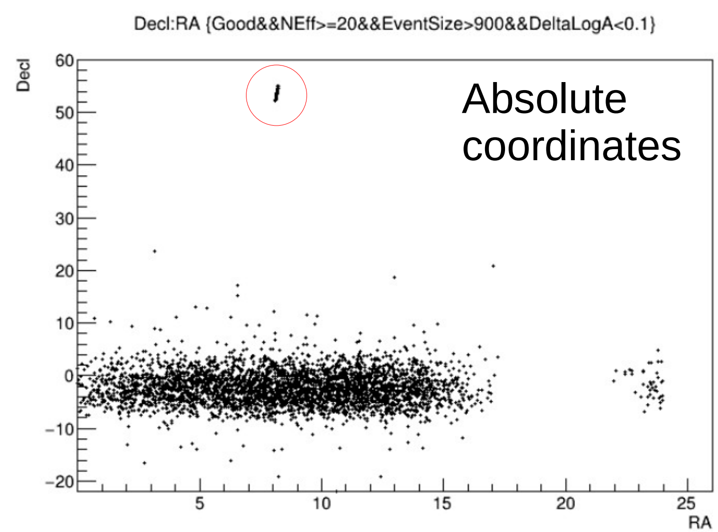
Search for candidates to astrophysical optical transients

“Size of event” - important criterion of selection







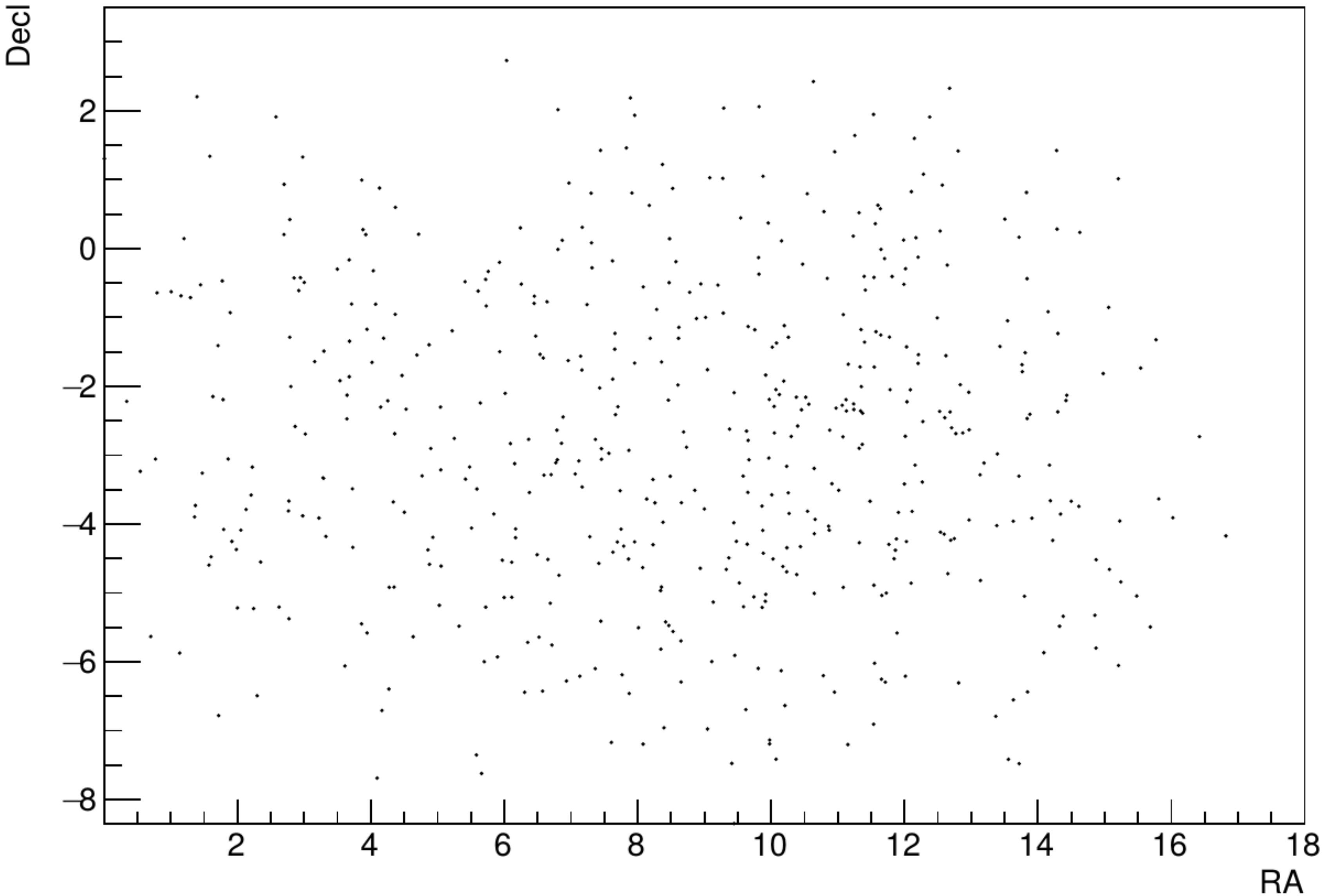


Apart from satellite events, there are ***no single candidates*** for optical transients in the region of small zenith angles.

Angle distribution for events with size > 900 m

Search for multiple (repeated) transients in the region of large zenith angles in the background of flat EAS events

511 candidates after selection



What does it mean for two different events "to come from one point of the sky?"

- "Coming from one point in the sky" means actually having the same angular coordinates within the error bars.
- It is necessary to know the errors in determination of the angular coordinates for events - primary candidates for transients
- The errors were calculated by Monte Carlo method (large zenith angle!)

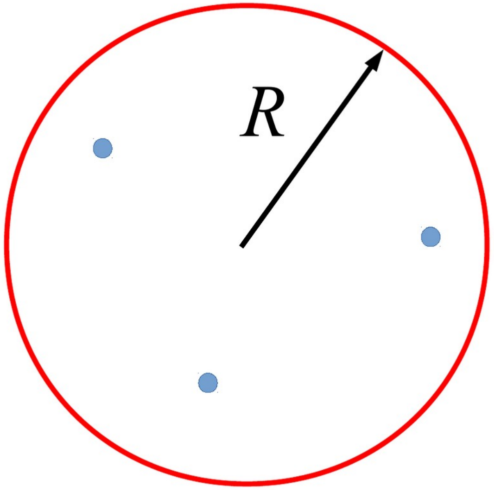
$\Delta\varphi = 0.03^{o}$

(From CALIPSO data, zenith region: 0.05^{o})

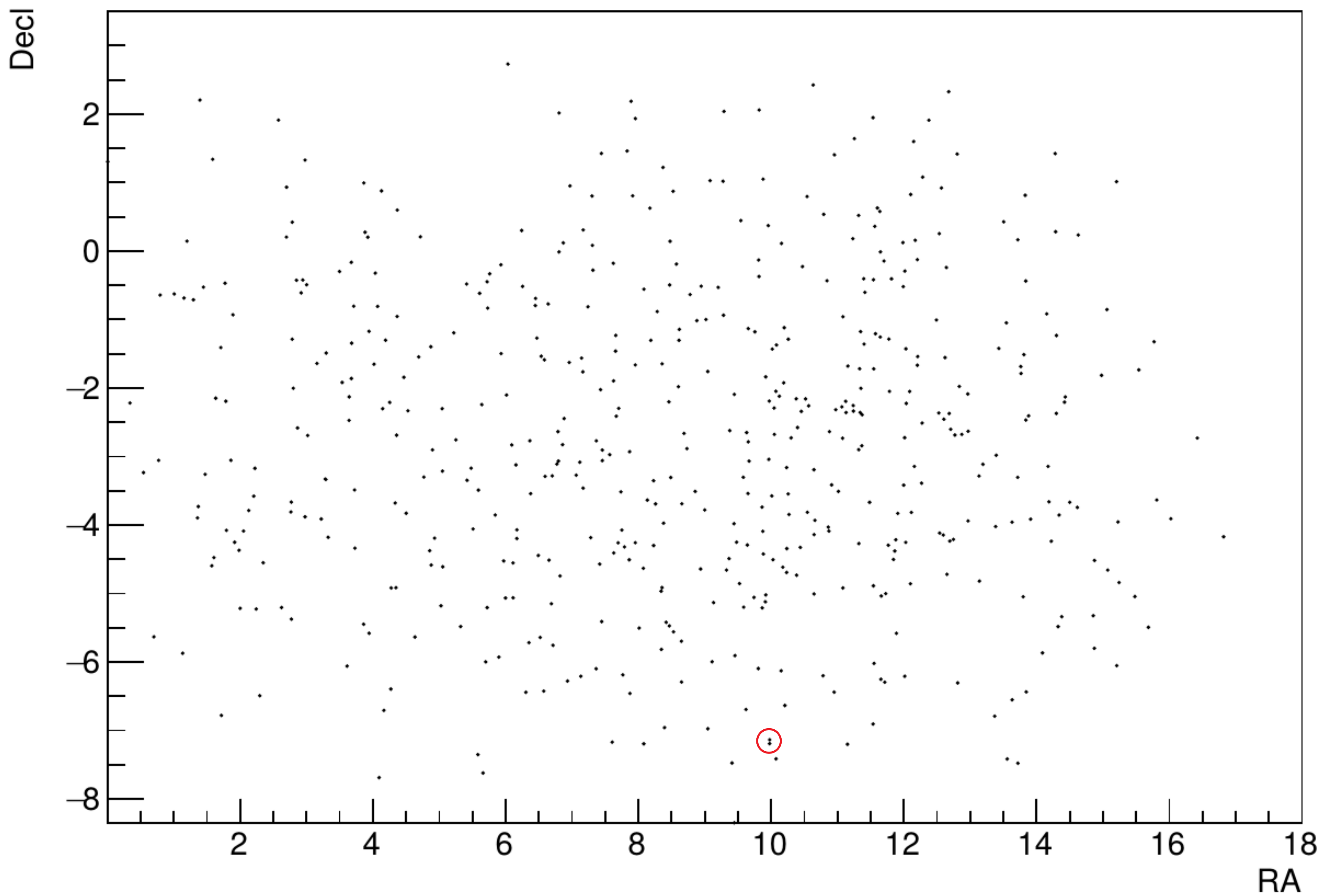
Some problems: non gaussian distribution...

Final decision: the events considered to be
In "one point in the sky" if they are in the circle
around the center of mass of events with radius

$$R = \Delta\varphi\sqrt{2} = 0.041^{o}$$



511 events – one candidate to double event



Probability of random simulation
by background EAS events
of one double event,
calculated by MC simulation,
is 78%

Therefore we can’t comclude that
the found repeater is a real candidate
to distant optical transients

In what case could we say that a real candidate for transients has been found?

1. Any single or, moreover, multiple event in the region of small zenith angles, which satisfies the used criteria for selecting transients (in the region of absence of the EAS background)

2. At least one triple event: the probability of a random realization of one triple event for is 0.002 (about 3σ).

4. Events of multiplicity greater than three should be considered as real candidate to optical repeater.

Limits for the optical transient probability

For the observation time in the winter season 2018-2019
the exposure of HiSCORE array was 288 sr·hour.

No optical transients were found =>

An approximate upper limit on the rate of events is:
for events with a flux density of photons greater than 10^{-4} erg/s/cm^2
and with a duration of pulse greater than ~5 ns,
the flux is less than ~2×10^{-3} events/sr/hour

Will be processed soon:

2019-2020 winter season – larger array, lower background

2020-2021 winter season – even larger array, even lower background

Thank you!