




# Multi-messenger and real-time astrophysics with the Baikal-GVD telescope






*Olga Suvorova*

INR RAS, Moscow,

for the Baikal-GVD collaboration

 **Baikal-GVD collaboration**

10 organizations from 5 countries, ~70 collaboration members

- Institute for Nuclear Research RAS (Moscow)
- Joint Institute for Nuclear Research (Dubna)
- Irkutsk State University (Irkutsk)
- Skobeltsyn Institute for Nuclear Physics MSU (Moscow)
- Nizhny Novgorod State Technical University (Nizhny Novgorod)
- Saint-Petersburg State Marine Technical University (Saint-Petersburg)
- Institute of Experimental and Applied Physics, Czech Technical University (Prague, Czech Republic)
- EvoLogics (Berlin, Germany)
- Comenius University (Bratislava, Slovakia)
- Krakow Institute for Nuclear Research (Krakow, Poland)

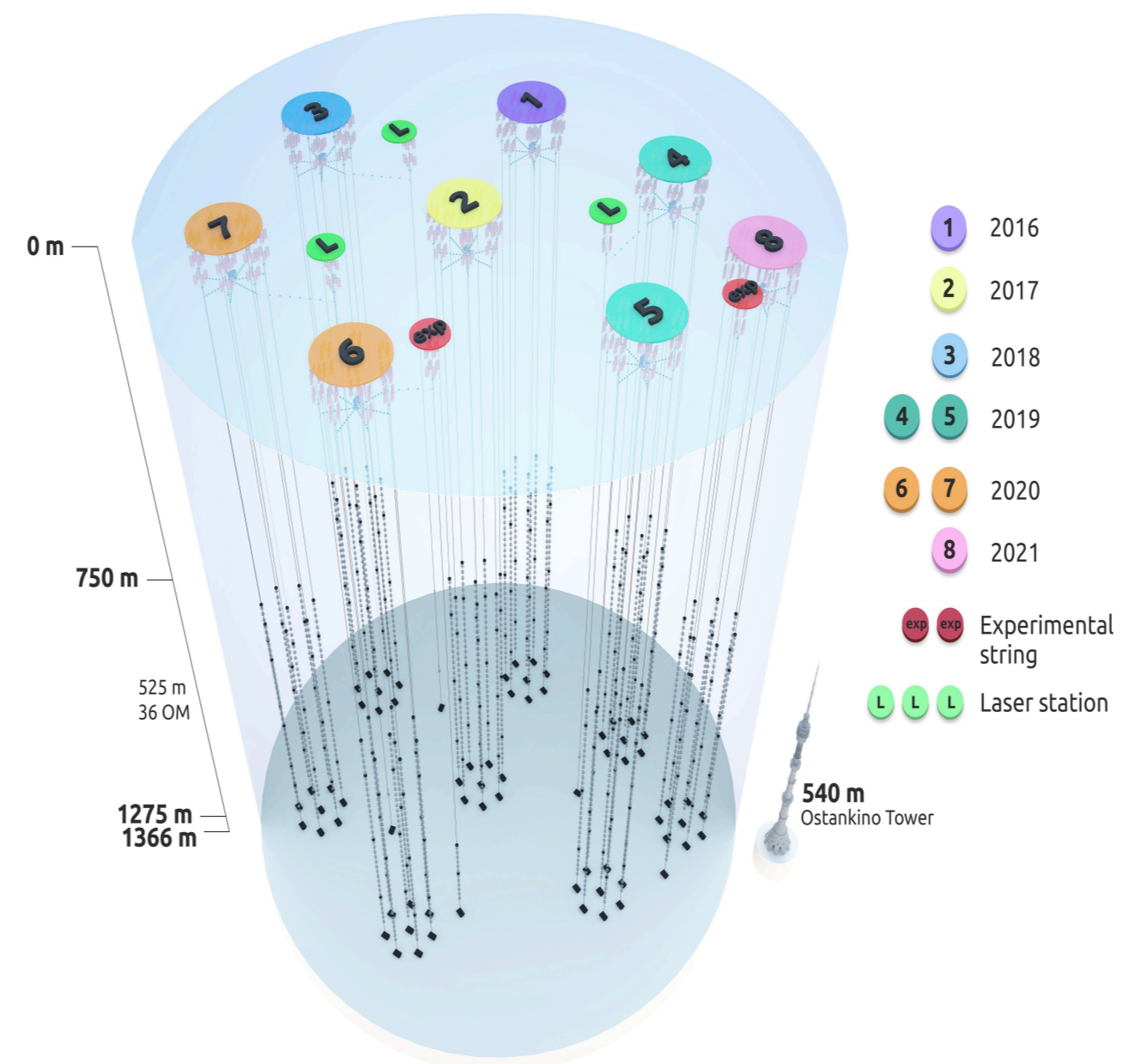
ICRC2021, Berlin, 16 July 2021

# Current MM studies at the Baikal-GVD telescope

- Progress in online stream analysis
- Follow up of ANTARES/TAToO alerts
- Results on GCN IceCube-alerts of 2020
- Off line analysis of ZTF TDE source ATdsg2019
- Follow up of multi signals of magnetar SGR1935+2154 (2020)



# Baikal-GVD horizons



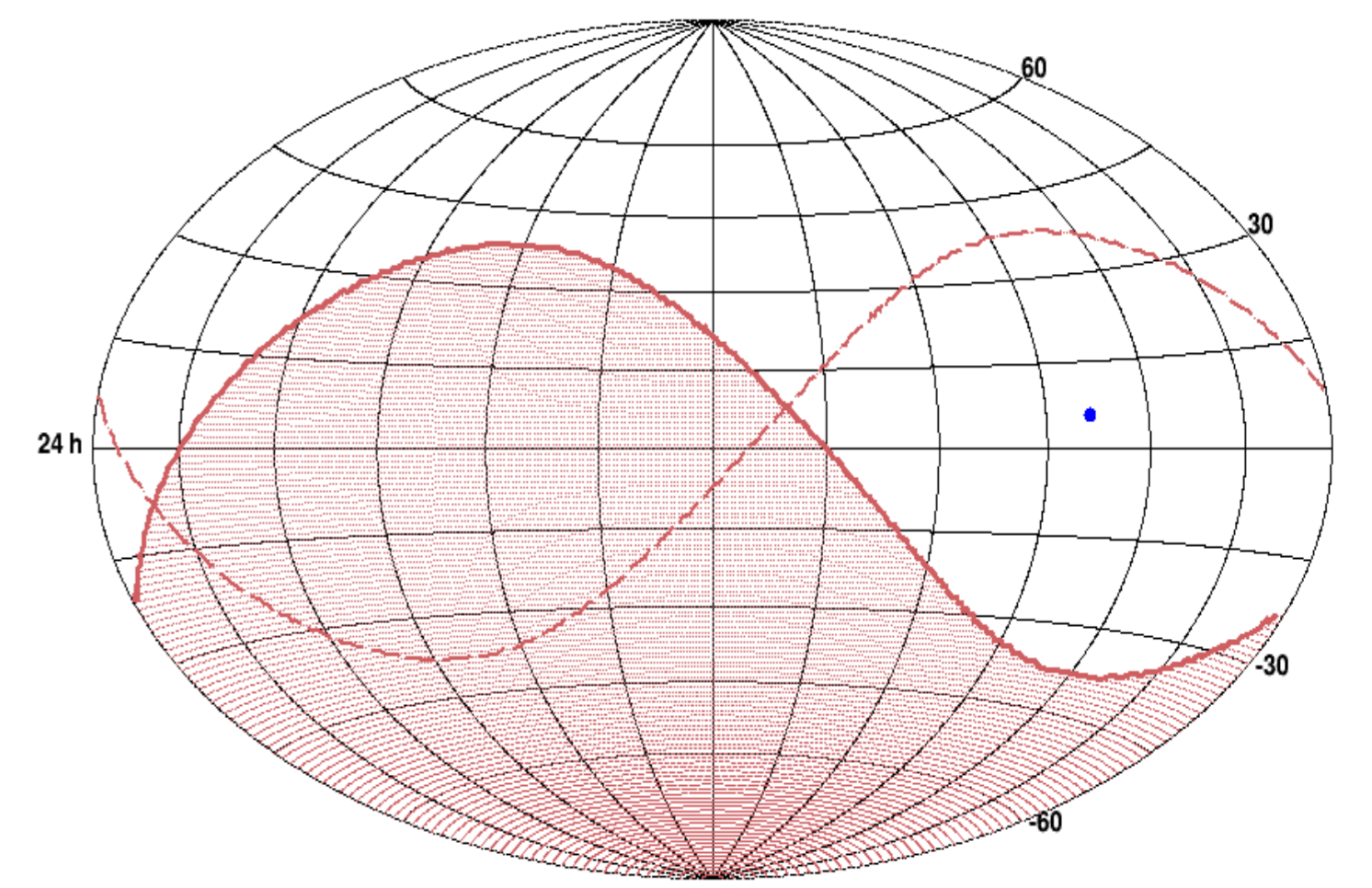
Deployment schedule

Year	Number of clusters	Number of OMs
2016	1	288
2017	2	576
2018	3	864
2019	5	1440
2020	7	2016
2021	8	2304
2022	10	2880
2023	12	3456
2024	14	4032

~0.4km<sup>3</sup>

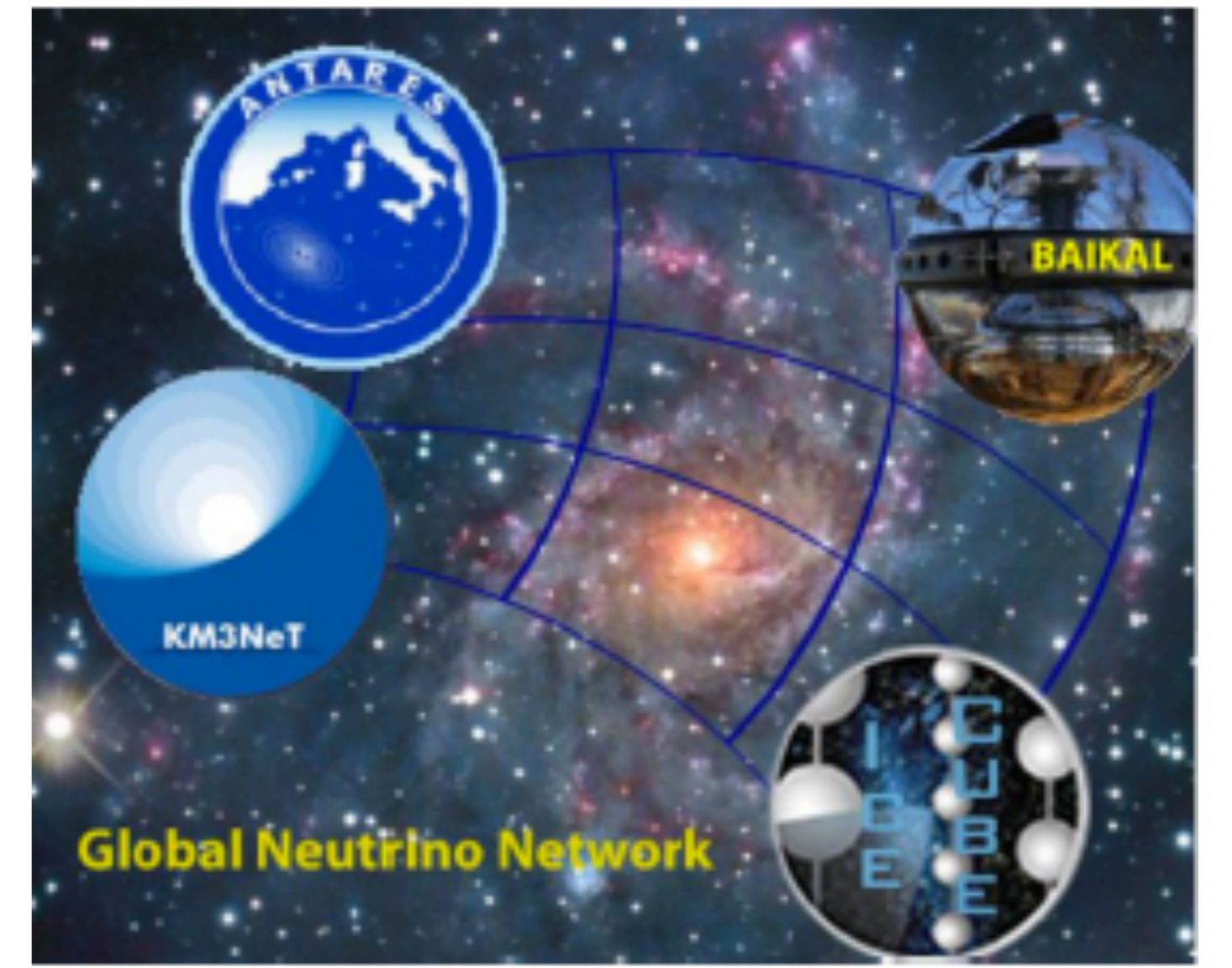
See talk by *Zh.Dzhilkibaev*

IC170922A: TXS0506+056



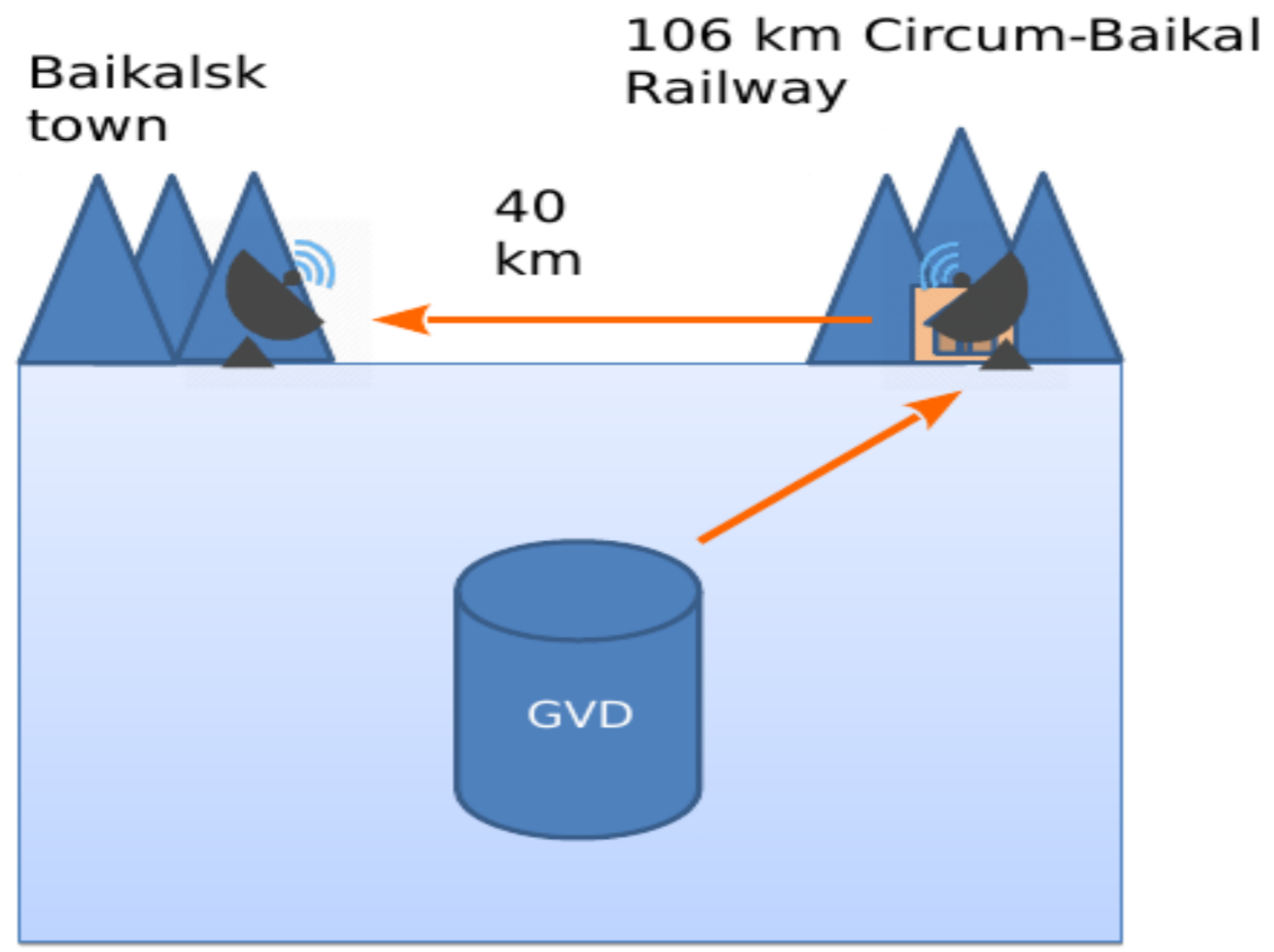
GVD / ANTARES horizon (eq.c.)

## HE neutrino alerts



## Data transmission:

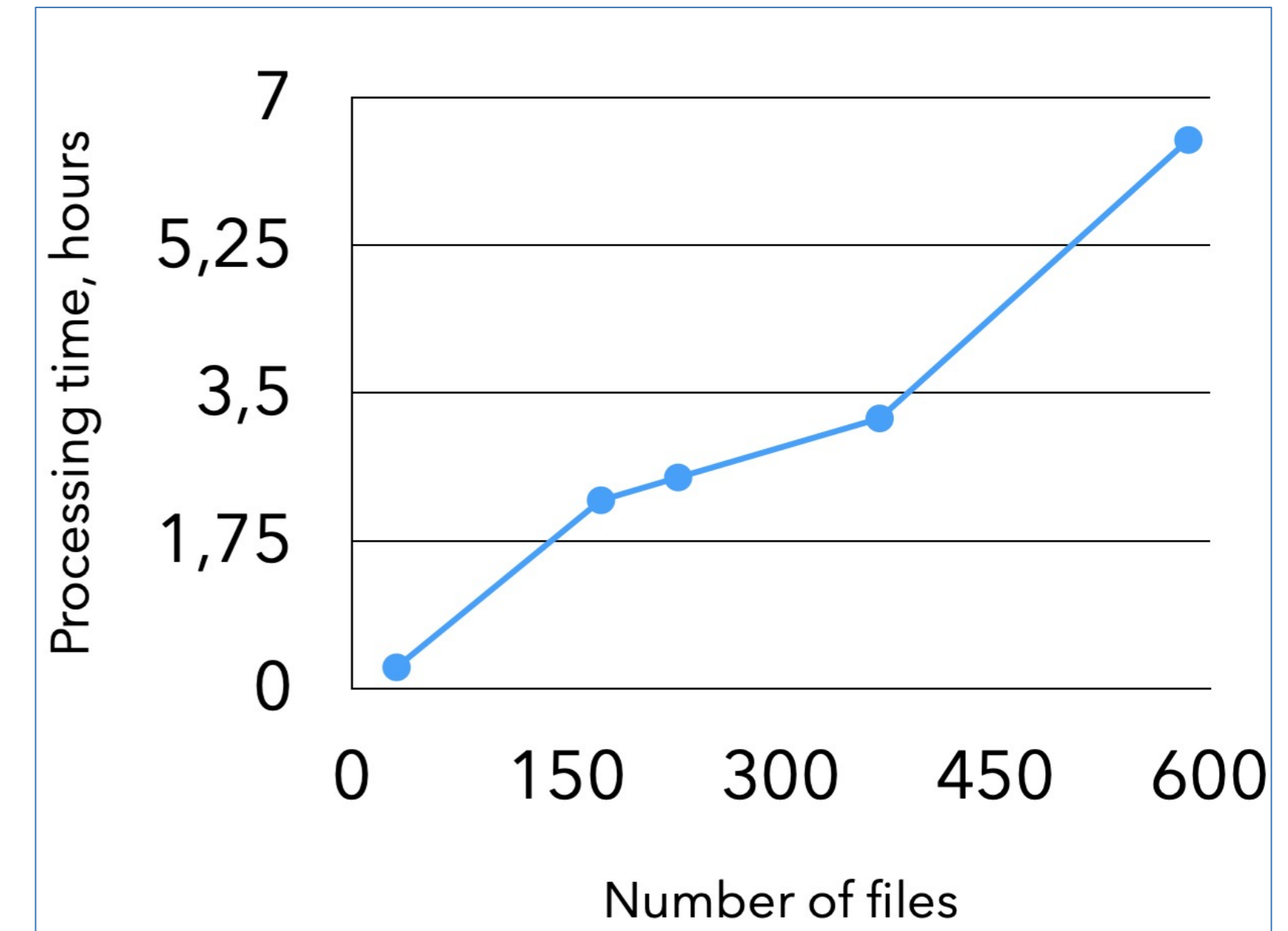
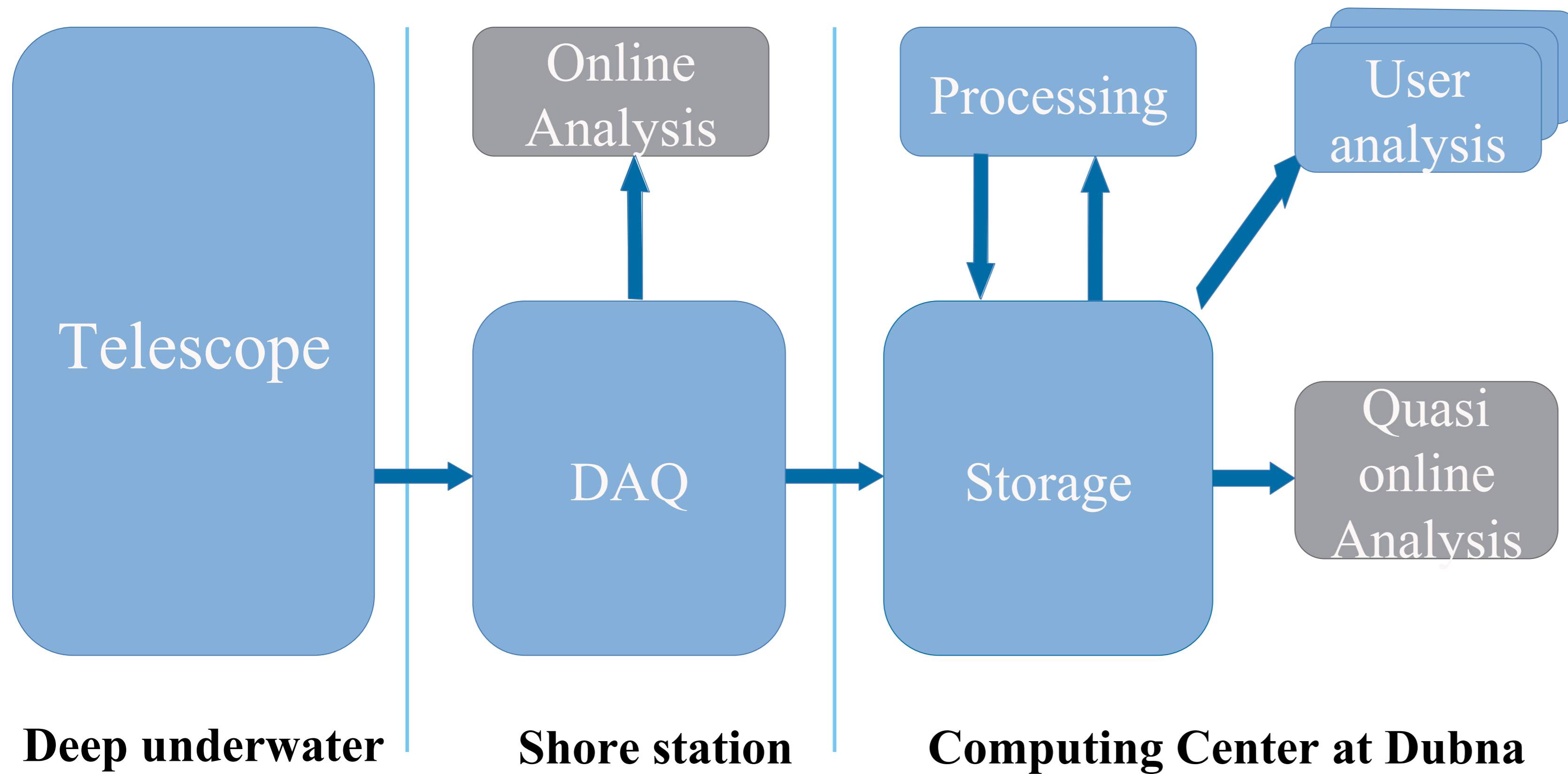
- 40 Gb per cluster per day to shore
- 250 Mb/s 40 km radio channel to Baikalsk
- Raw data transferred to storage Dubna facility through Internet





# Data transfer and processing scheme

Data performance  
delay of 3-5 hours



## Time delays:

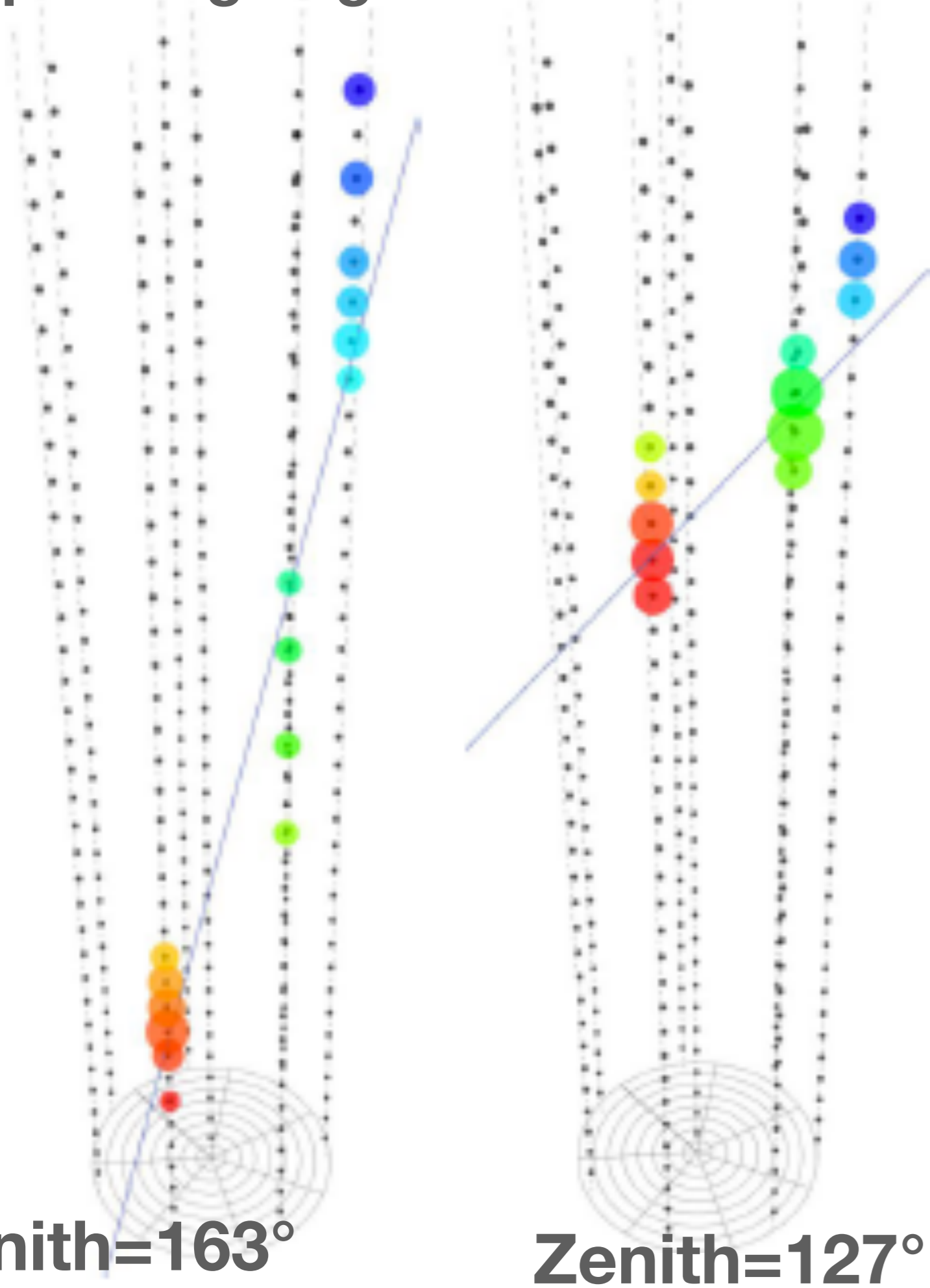
1. Few minutes from shore
2. Few hours in data processing ~ lake noises



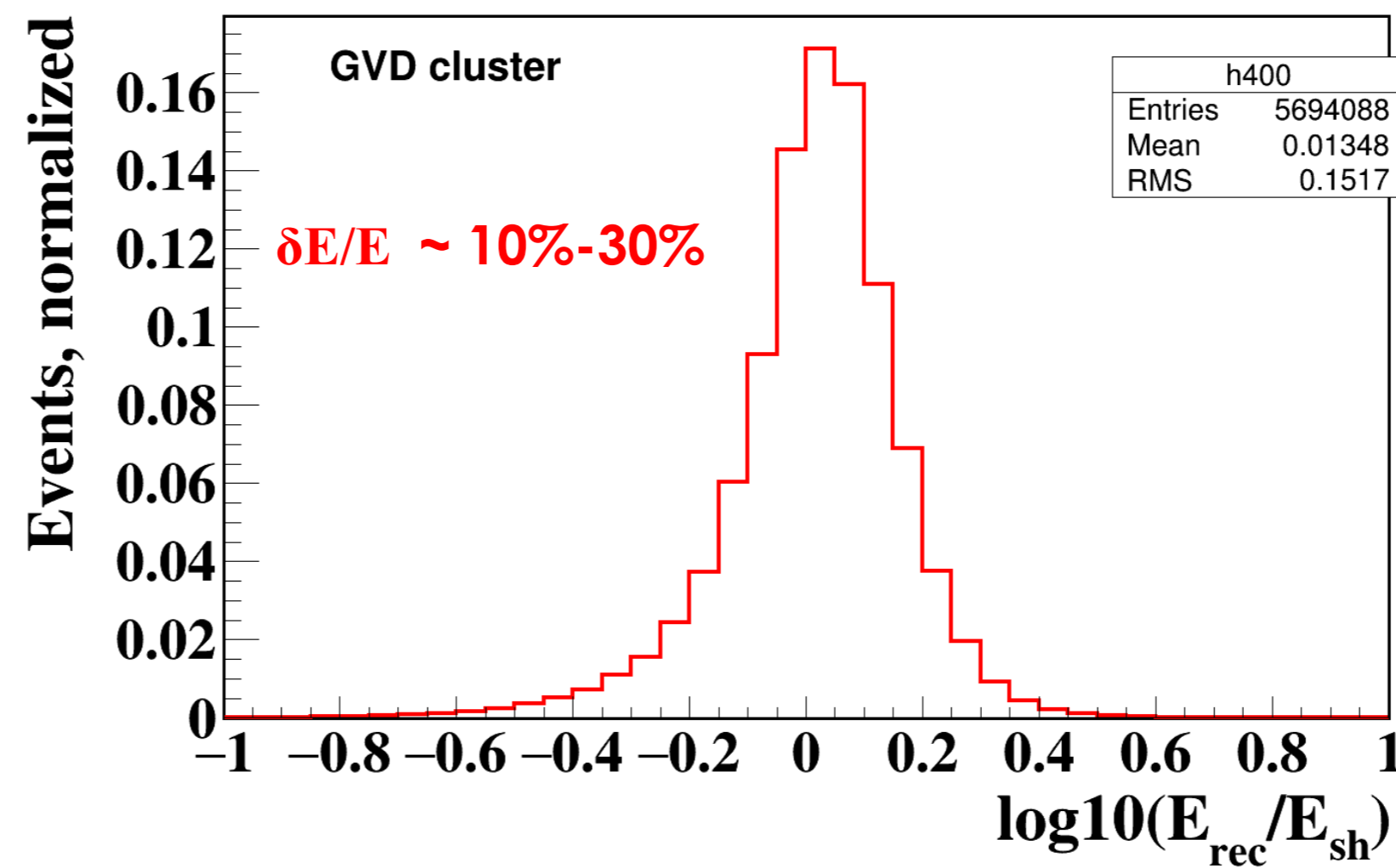
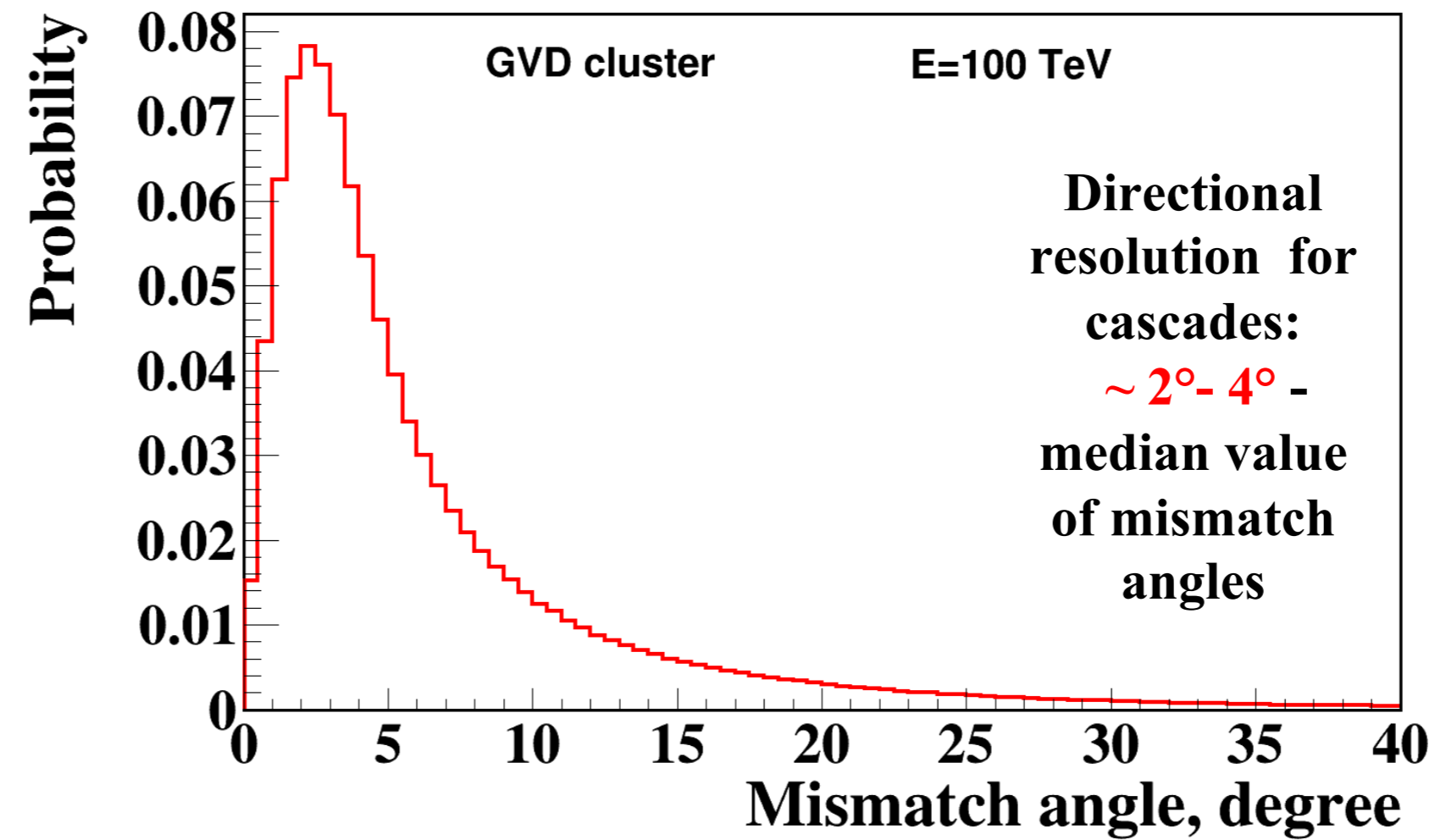
# Quasi-online regime in alert performance

Publ.: Avrorin A.D. et al., *Astronomy Letter*, Vol.47, N 2, 114 (2021)

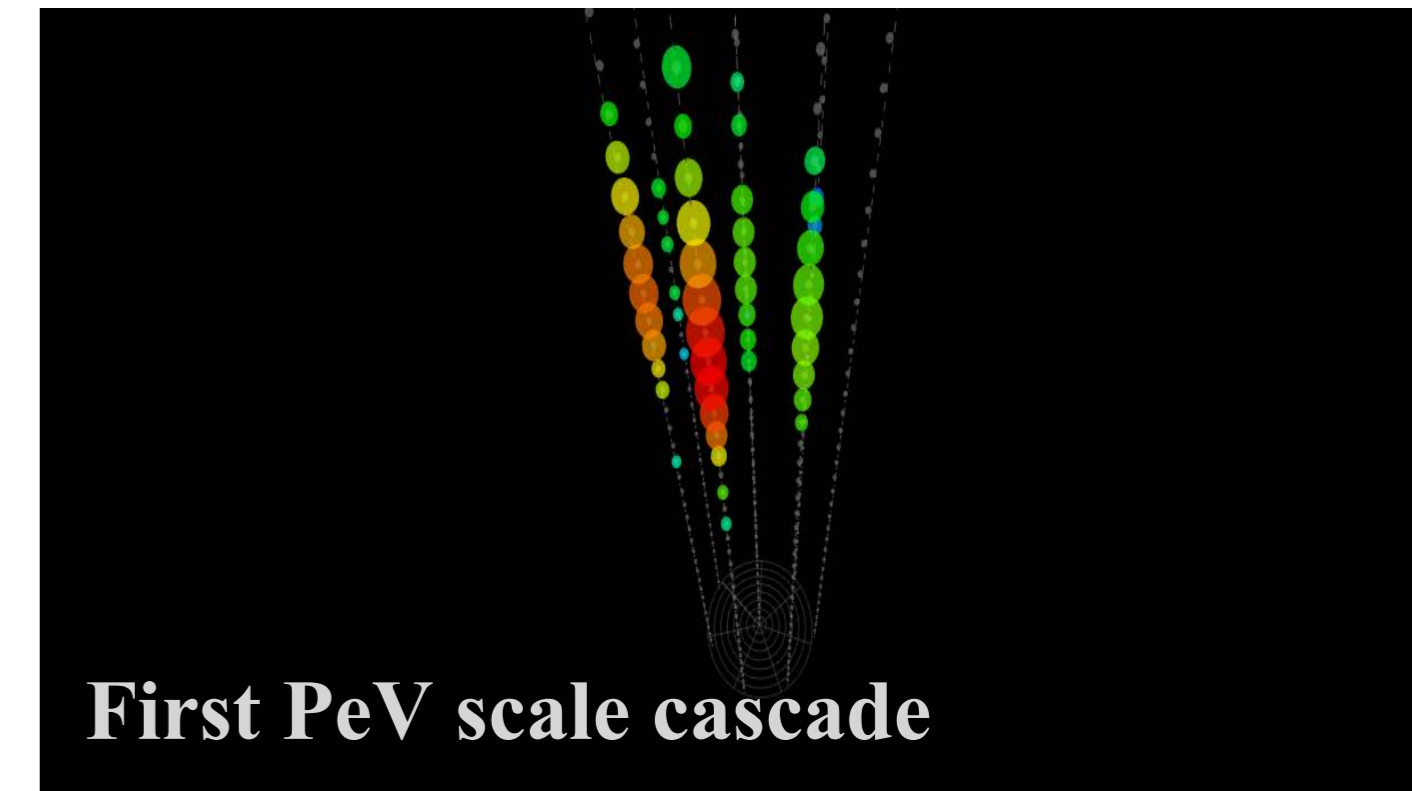
Upward going muon-like alert



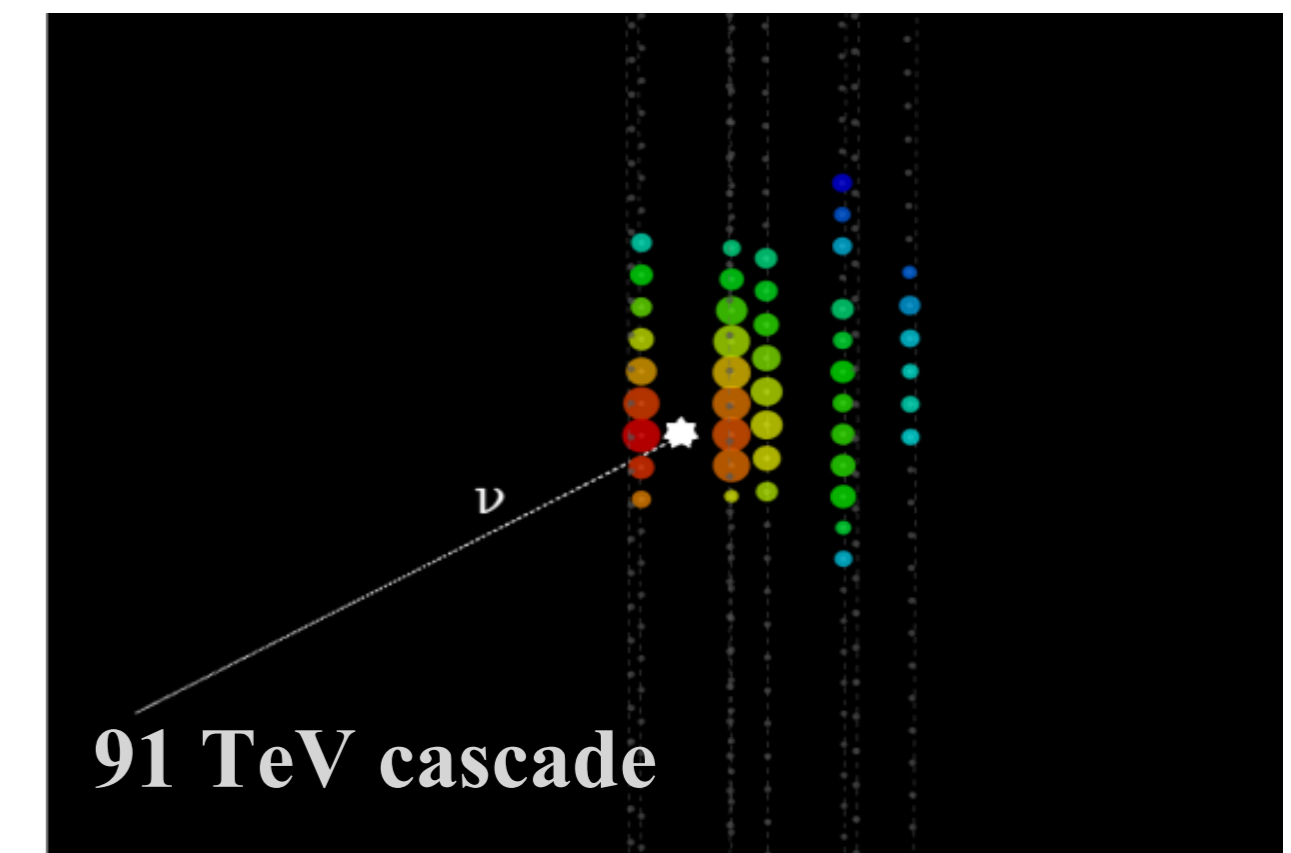
Fast algorithm of track reco in a single cluster events rejects a near horizon directions (<120°)  
(see talks by G.Safronov, D.Zaborov)



Downward going HE cascade-like alert



Upward going HE cascade-like alert



Cascades reco algorithm, selections and HE alerts - see talk by Zh.Dzhilkibaev



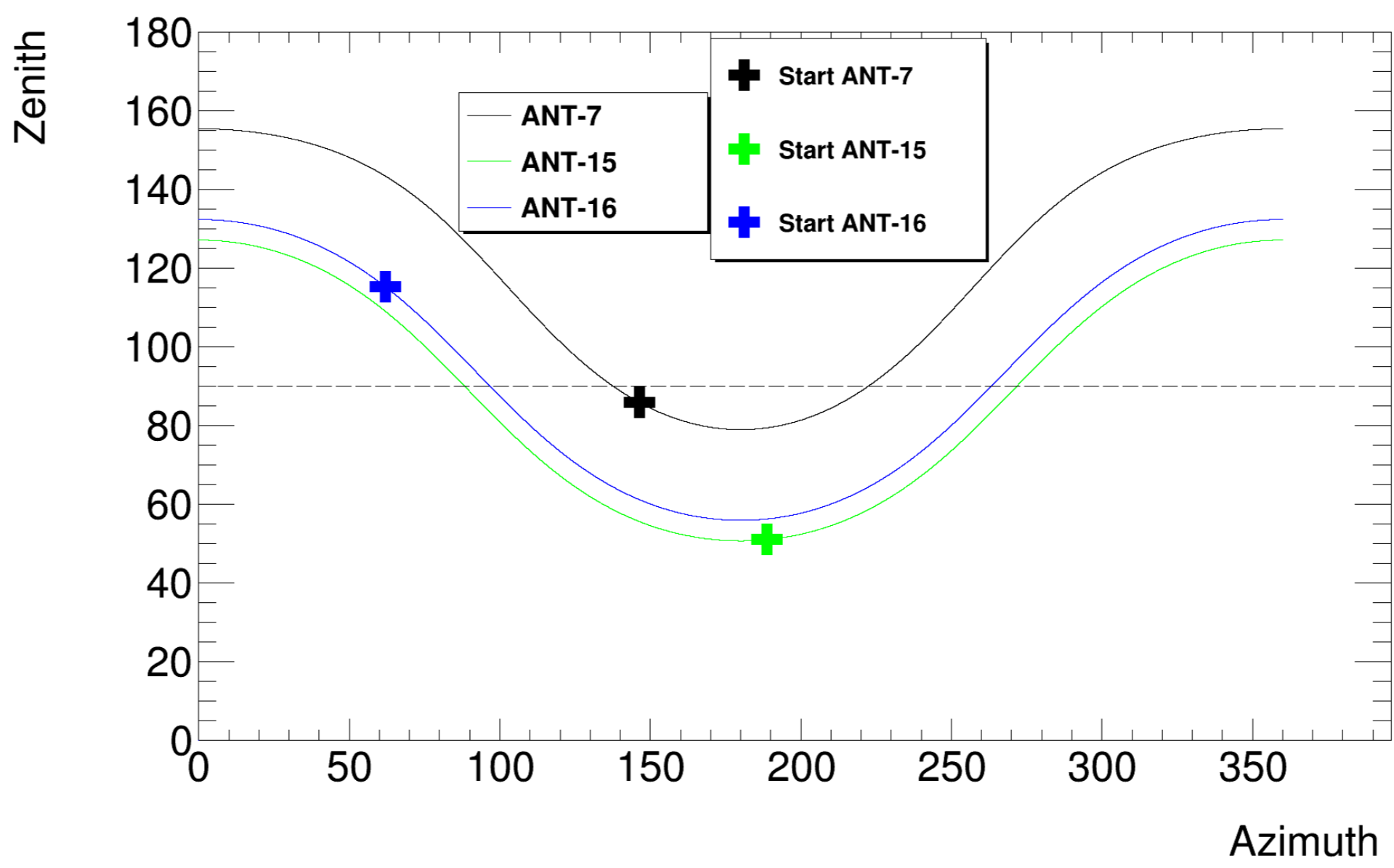
# ANTARES (TAToO) alerts

Since Dec 2018 in total of 48(-6) alerts have been analysed;  
 15 alerts in 2020 and 6 alerts in 2021

Following up alarm of  $\mu_{\uparrow}$  trigger ( $\langle E \rangle \sim 7$  TeV), we look for events on each cluster in time windows  $\pm 500$  sec,  $\pm 1$  hour and  $\pm 1$  day around alerts inside  $\frac{1}{2}$  cones  $\sim \Psi_{\text{median}}$ ;

Mn	2018	2019	2020	2021
Jan		3	2	2
Feb		3 ★	-	2
Mar		2	1	-
Apr		3	1	2
May		-	1	
June		3 ★★	-	
July		4	2	
Aug		1	2	
Sept		-	2	
Oct		3	-	
Nov		1	1	
Dec	3	1	3	
<n>	-	2	1.2	1.5

3 candidates in GVD-ANTARES analysis

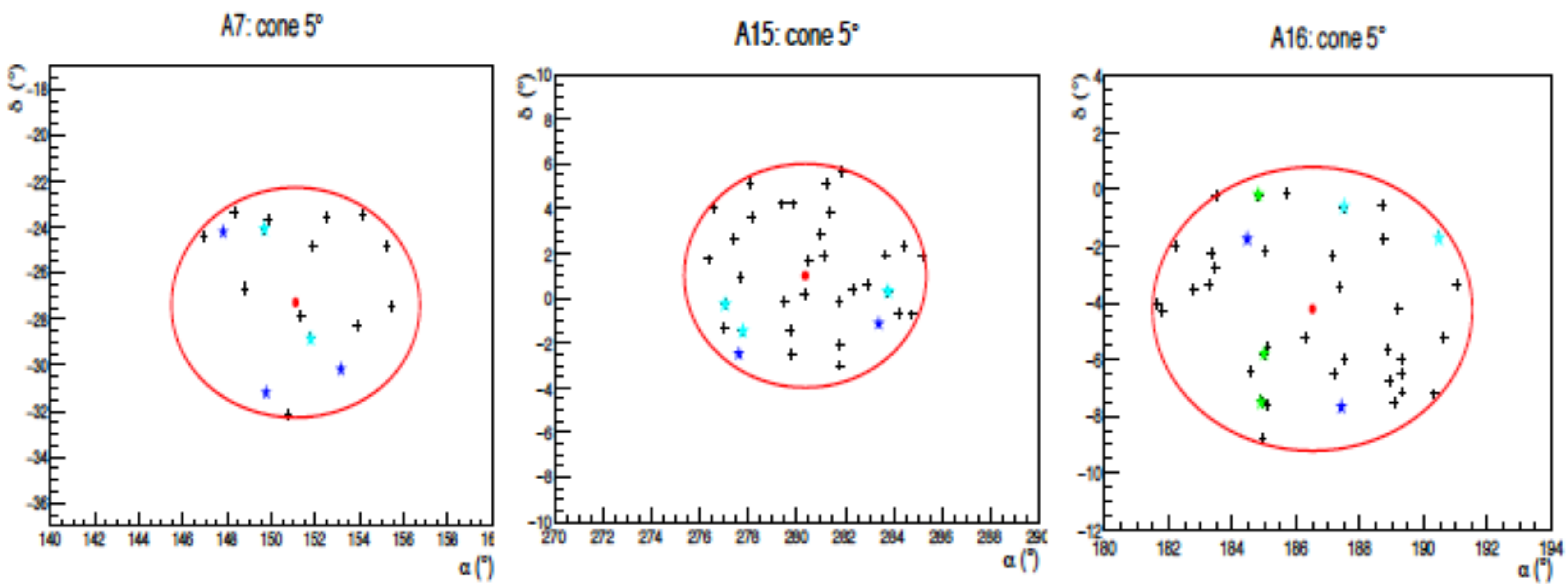


ANT alert	GVD cluster	T-T <sub>alert</sub> hours	Energy, TeV
A7	3	+20.8	13.5
A7	3	-23.2	<b>158</b>
A7	2	-3.2	2.9
A15	2	+20.4	3.0
A15	3	-0.64	3.98
A16	2	-18.7	3.99
A16	4	-14.35	3.89

*No prompt coincidence in time and direction was found with ANTARES trigger, while details are in conversation with ANTARES group.*

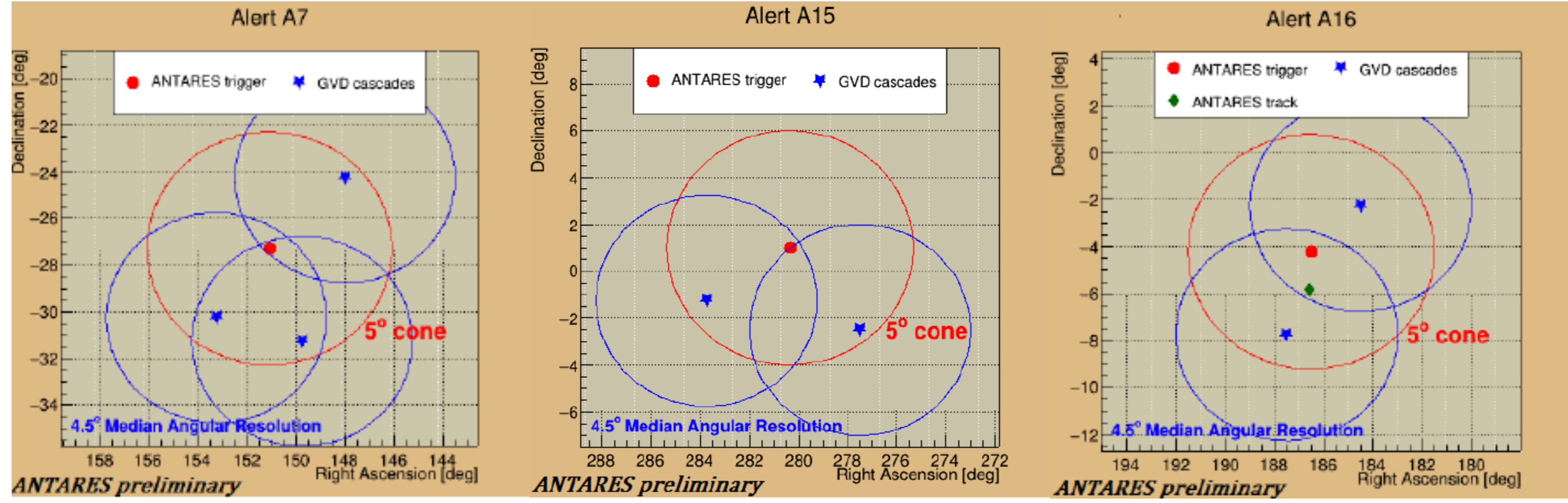
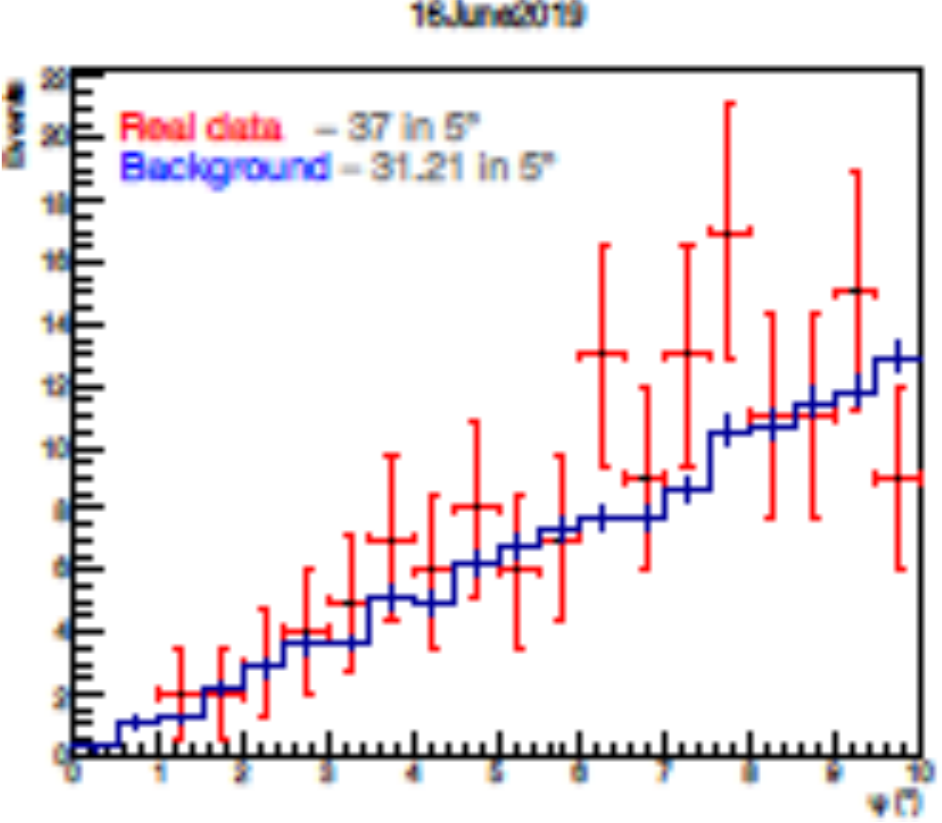
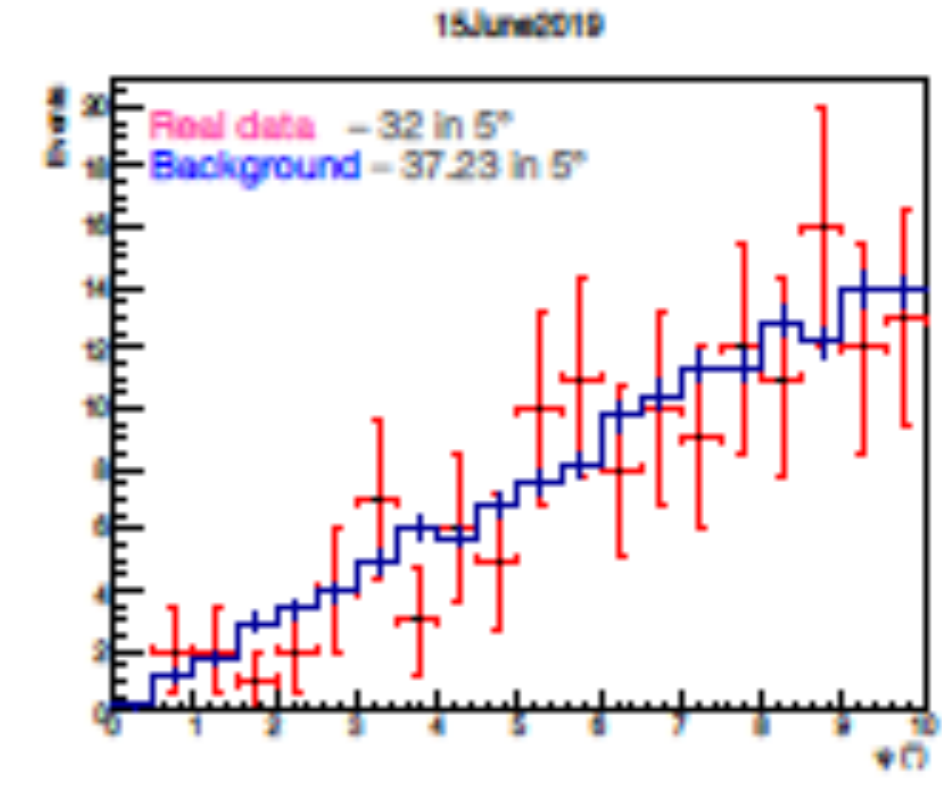
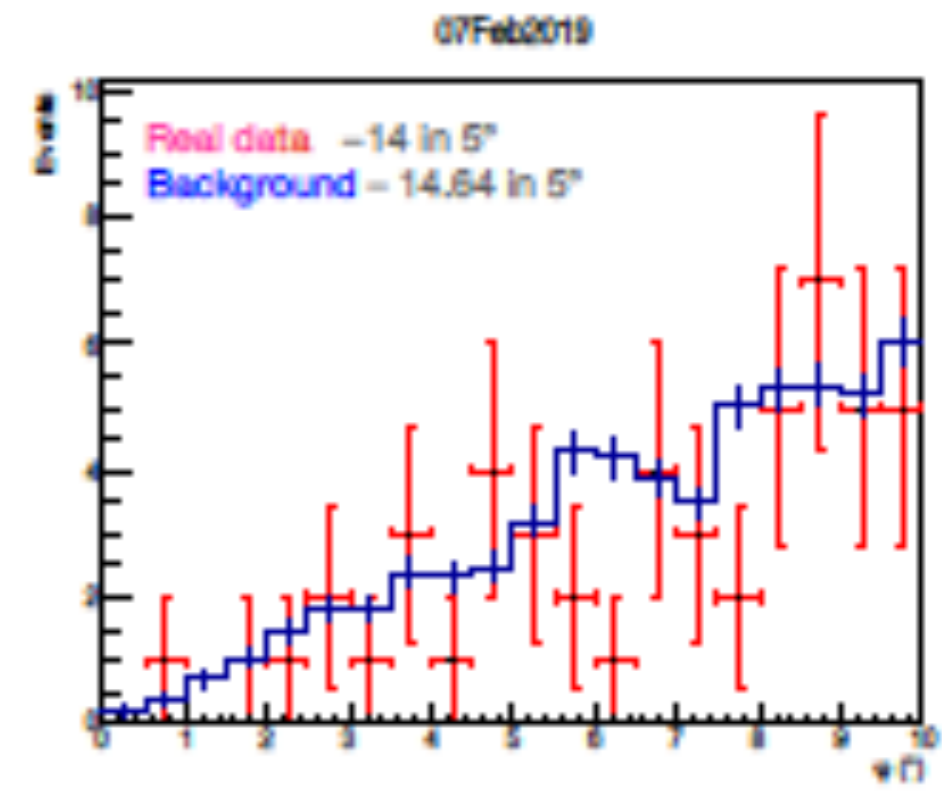


# GVD cascades repeated around 3 ANTARES alerts $\pm 1$ day



sample 2018-2019,  
690 days livetime

A7 3.1 $\sigma$   
A15 2.6 $\sigma$   
A16 2.7 $\sigma$



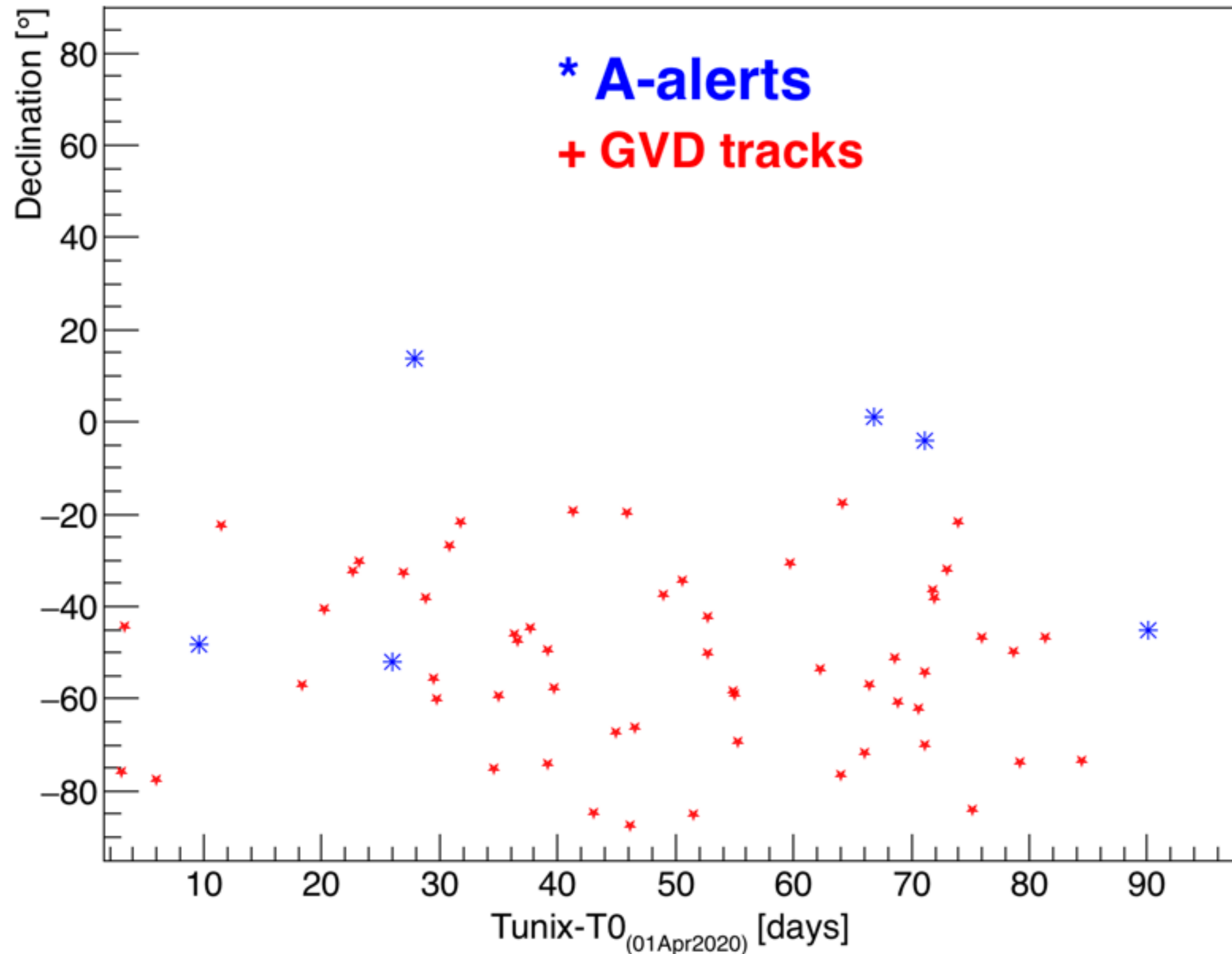
See also talk by Sergio A.Garre (results with the UpL on fluences)

Preliminary results



# Follow-up in upward going muons

2019: ANTARES/Baikal-GVD upgoing muons



sample 2019 (5 clusters),  
323 days single cluster livetime

No correlation was found  
between events in the GVD  
sample of muon neutrinos  
and the ANTARES alerts

In tracks the first neutrino sample (see talks  
by [G.Safronov](#), [D.Zaborov](#)) with about 50  
events in 2019 has been tested for alerts.



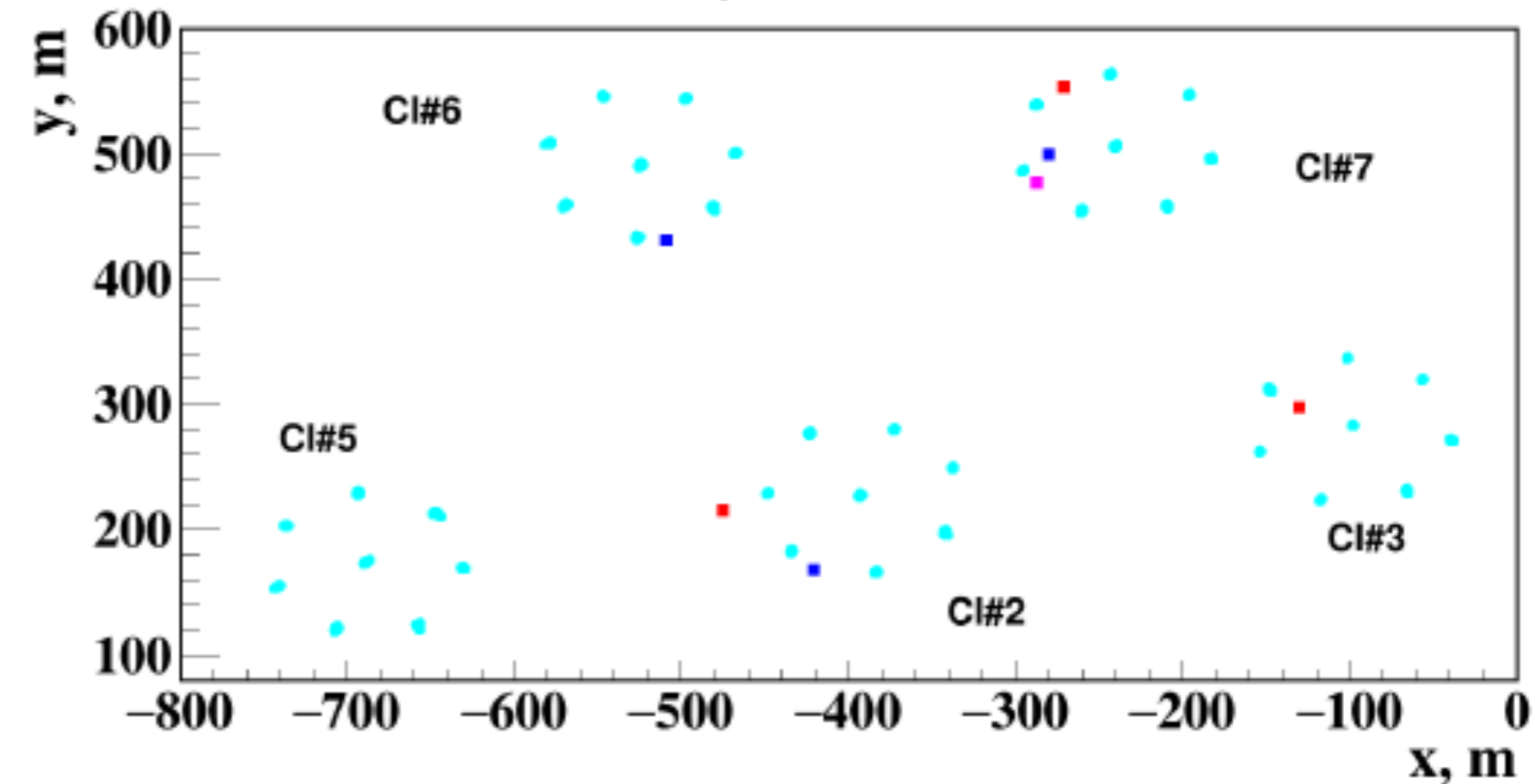
# GVD follow up of GCN IC-alerts: $\mu_{\uparrow}$ , $E > 100\text{TeV}$ , $\pm 12$ hours

Starting from Sept 2020 Baikal-GVD follow IC alerts (GCN) in fast regime. Assuming  $E^{-2}$  spectral behavior and equal fluence in all flavors, upper limits at 90% c.l. have been derived on the neutrino fluence from IC alerts in Fall 2020:  $\sim 1 \div 2 \text{ GeV cm}^{-2}$  for energy range  $1\text{TeV} - 10\text{PeV}$  for  $\pm 12\text{h}$  interval.

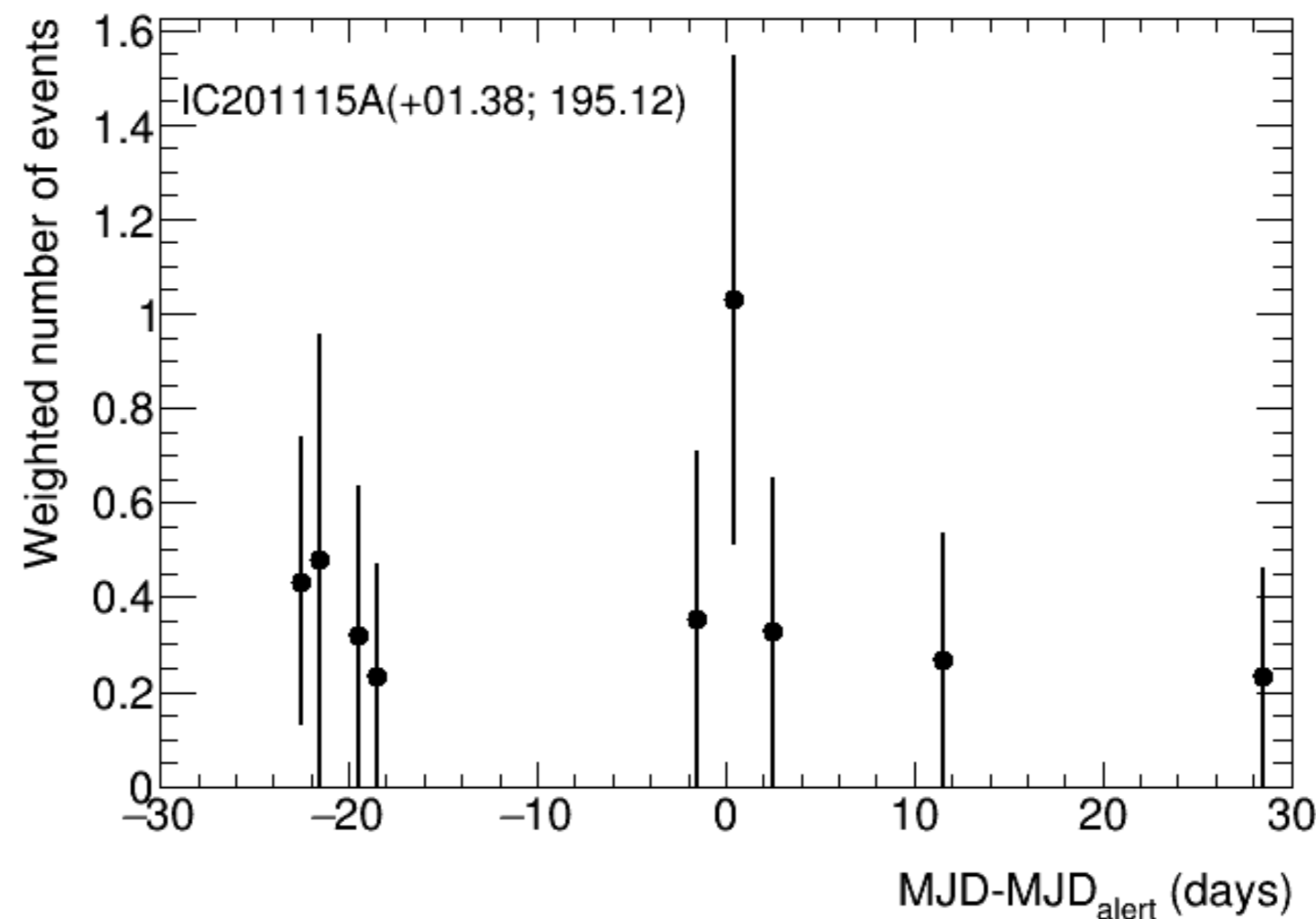
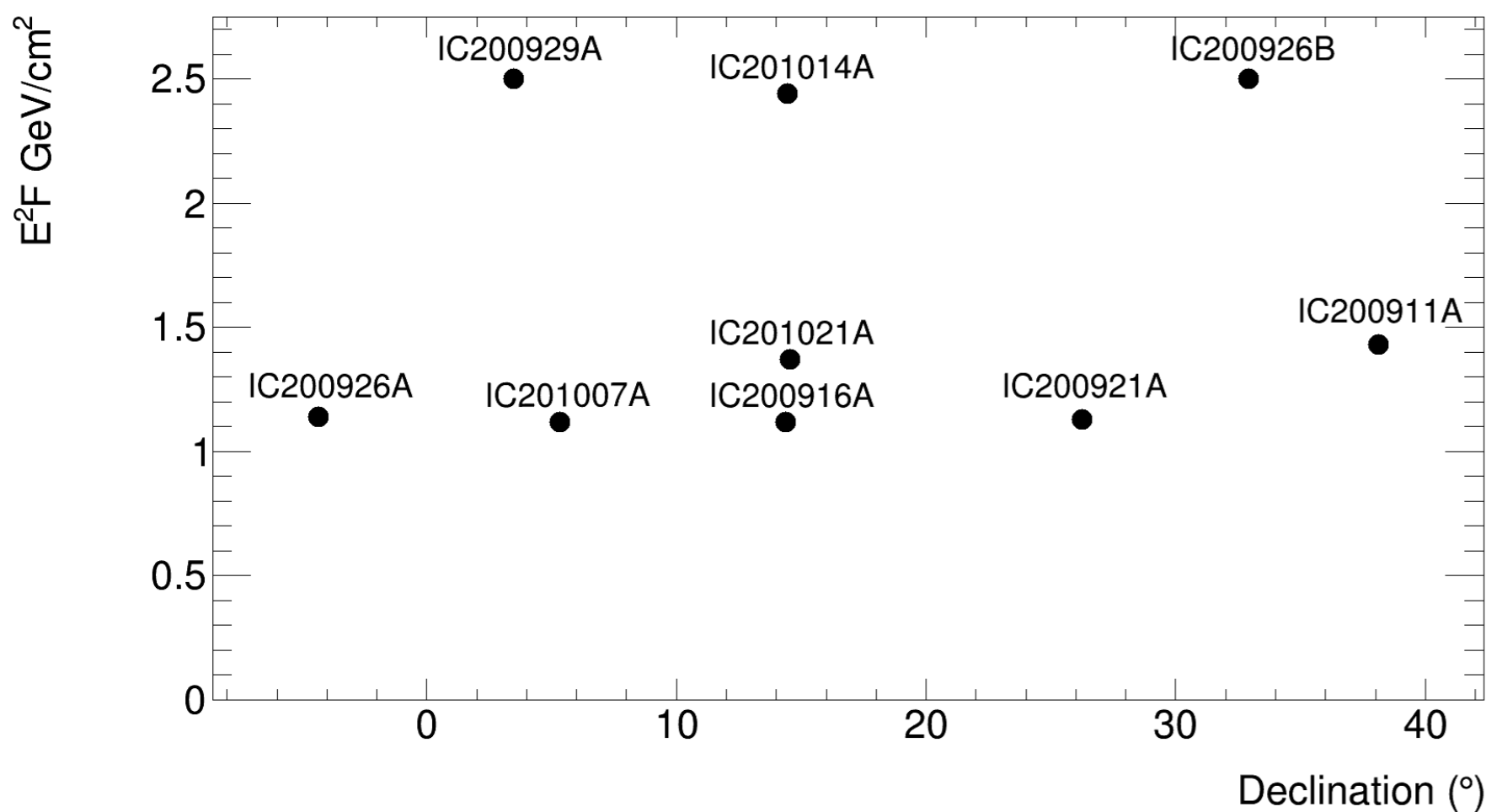
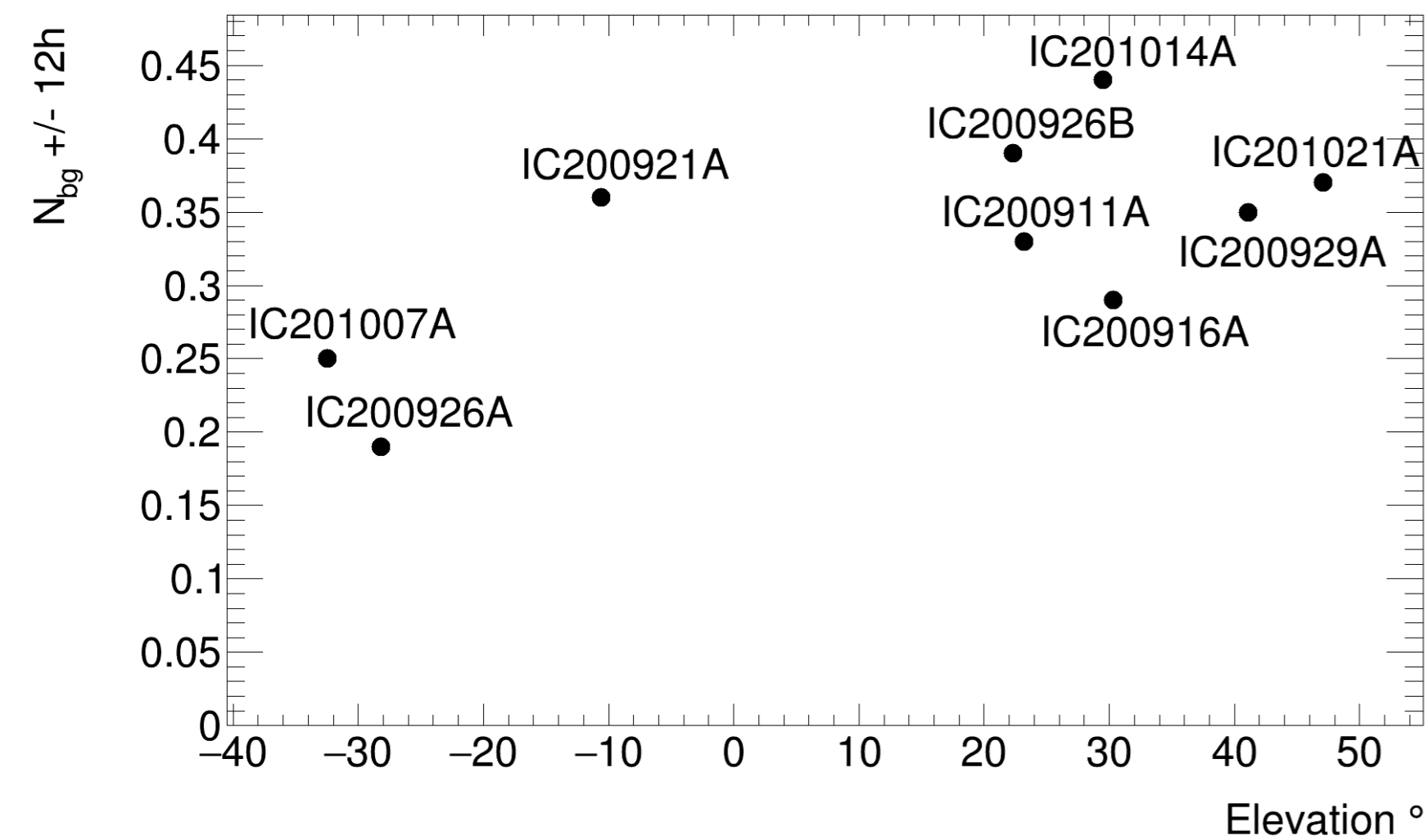
*Publ., Avrorin A.D. et al., Astronomy Letter, Vol.47, N 2, 114 (2021)*

The IC20115A (Dec= $+1.38^\circ$ ) altitude= $+39.5^\circ$

Cascade vertex positions



First level of selection:  
 $N_{\text{hit}} > 7$ , cone ( $5^\circ$  or  $10^\circ$ ) &  $\pm 12\text{h}$ .  
 $4 \div 7$  cascades at 4 clusters !!



Last level of selection (chi2, hit/nhit, bkg\_muons):

## preliminary results

Cone	$\psi = 5^\circ$	$\psi = 10^\circ$
$N_{\text{obs}}/N_{\text{bg}}$	1/0.3	4/1.19
p-val	0.26	0.033



# Transients (ZTF) family and dedicated follow-ups

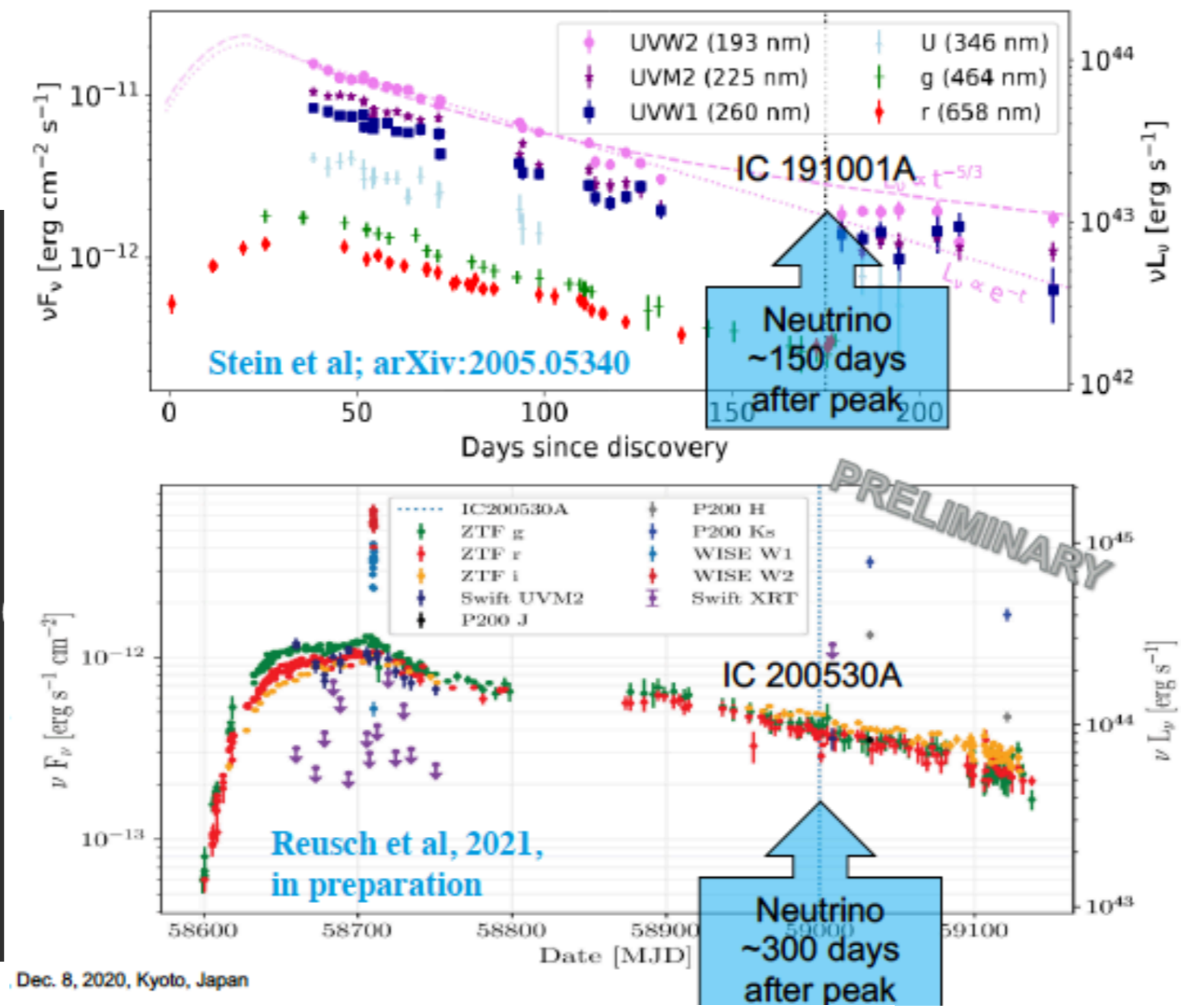
<https://www.wis-tns.org/object/2019>

RA/DEC (2000)	Type	Redshift
<b>20:57:02.974 +14:12:15.86</b>	<b>TDE</b>	<b>0.0512</b>
314.2623926 +14.2044063		

RA/DEC (2000)	Type	Redshift
<b>17:09:06.859 +26:51:20.50</b>	<b>SLSN-II</b>	<b>0.2666</b>
257.278578935 +26.8556946632		

**AT2019dsg: 2019-Apr-09**

TNS Astronomical Transient Report No. 33340 [ [2019TNSTR.615....1N](#) ]  
 Date Received (UTC): 2019-04-22 08:02:56  
 Sender: ZTF (ZTF\_AMPEL\_COMPLETE)  
 Reporting Group: ZTF Discovery Data Source: ZTF  
 J. Nordin, V. Brinnel, M. Giomi, J. van Santen (HU Berlin), A. Gal-Yam, O. Yaron, S. Schulze  
 IAU Designation: **AT 2019dsg**  
 Discoverer internal name: ZTF19aapreis  
 Coordinates (J2000): RA = 20:57:02.974 (314.2623926) DEC = +14:12:15.86 (14.2044063)  
 Discovery date: 2019-04-09 11:09:28.000 (JD=2458582.9649074)

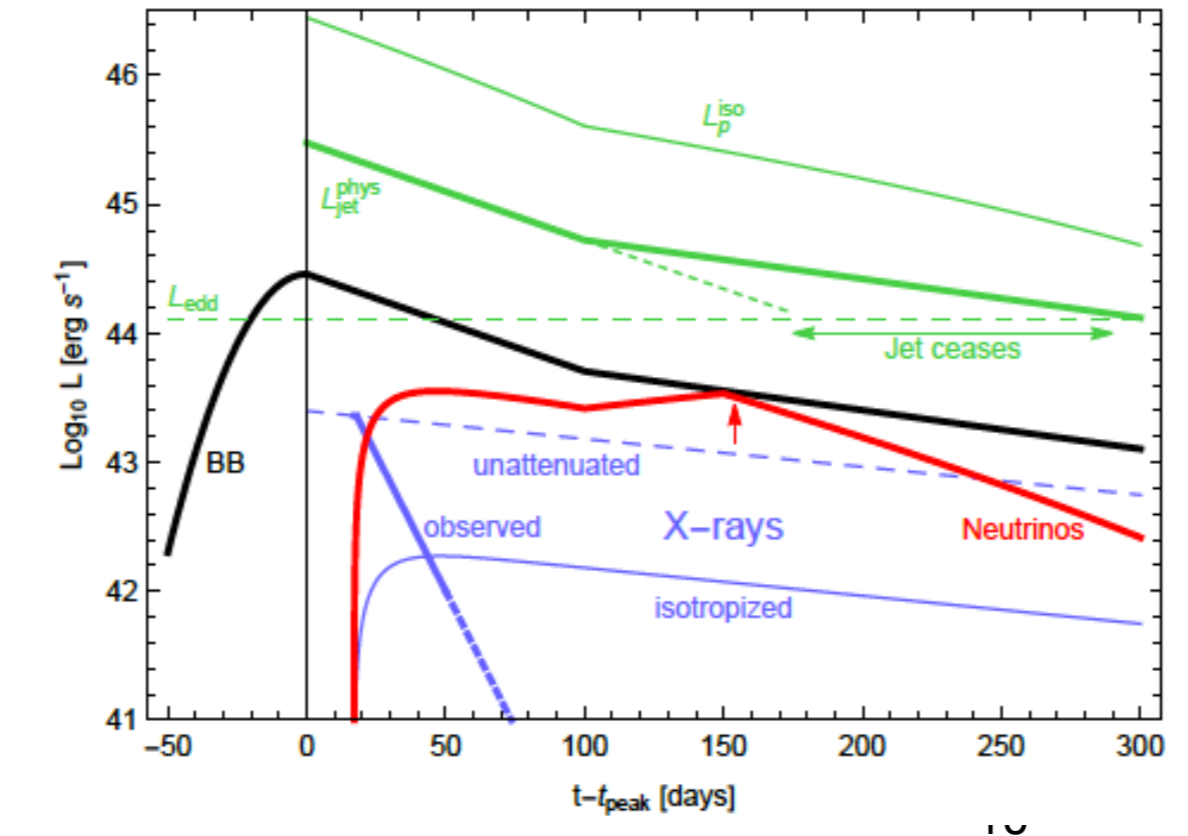


TNS Astronomical Transient Report No. 34906 [ [2019TNSTR.771....1N](#) ]  
 Date Received (UTC): 2019-05-13 19:44:54  
 Sender: ZTF (ZTF\_AMPEL\_COMPLETE)  
 Reporting Group: ZTF Discovery Data Source: ZTF  
 J. Nordin, V. Brinnel, M. Giomi, J. van Santen (HU Berlin), A. Gal-Yam, O. Yaron, S. Schulze  
 IAU Designation: **SN 2019fdr**  
 Discoverer internal name: ZTF19aatubsj  
 Coordinates (J2000): RA = 17:09:06.848 (257.278534) DEC = +26:51:20.11 (26.8555874)  
 Discovery date: 2019-05-03 07:25:43.000 (JD=2458606.8095255)

**AT2019fdr: 2019-May-03** Gaia; ATLAS

**IC191001A: 2019-Oct-01**  
**ANT200211: 2020-Feb-11**

**IC200530A: 2020-May-30-2020**  
**ANT190925: 2019-Sept-25**



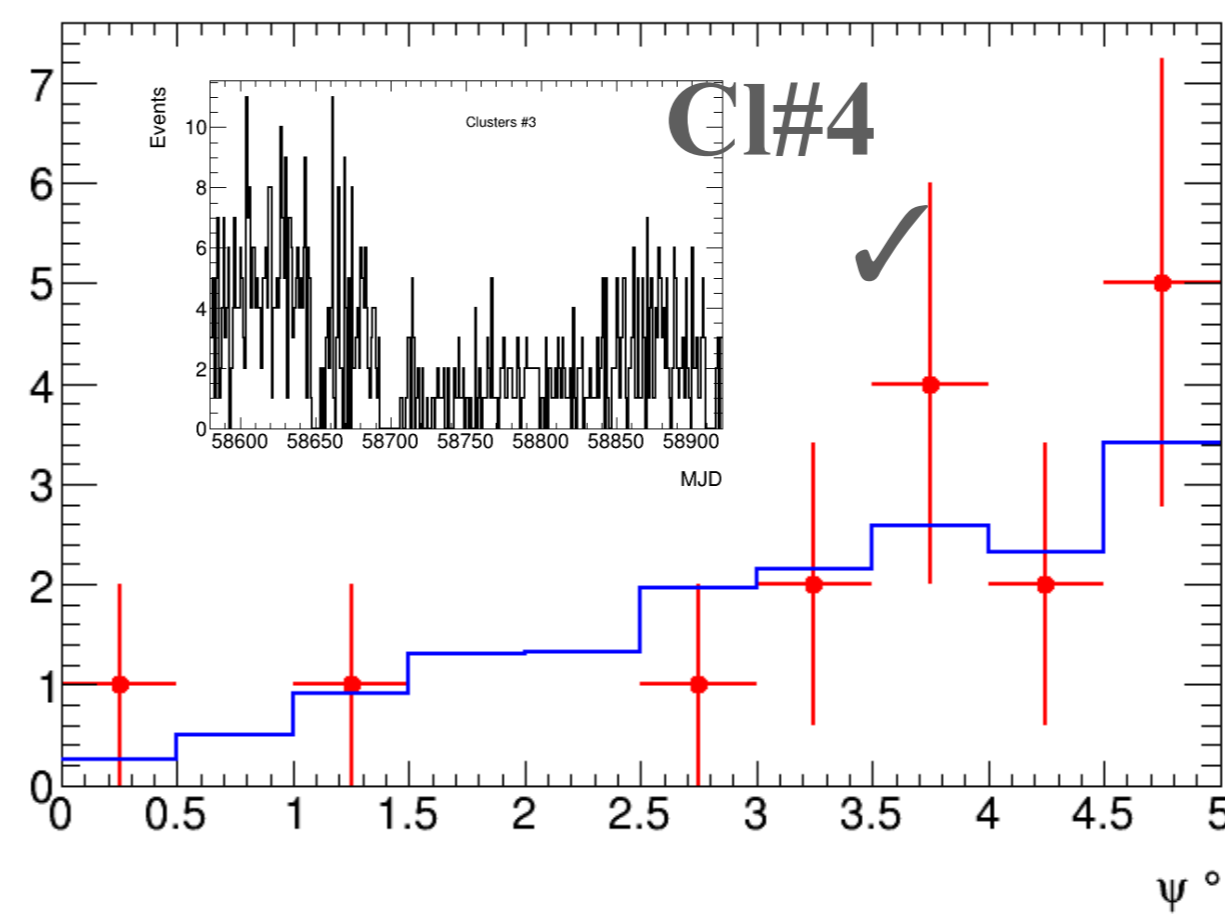
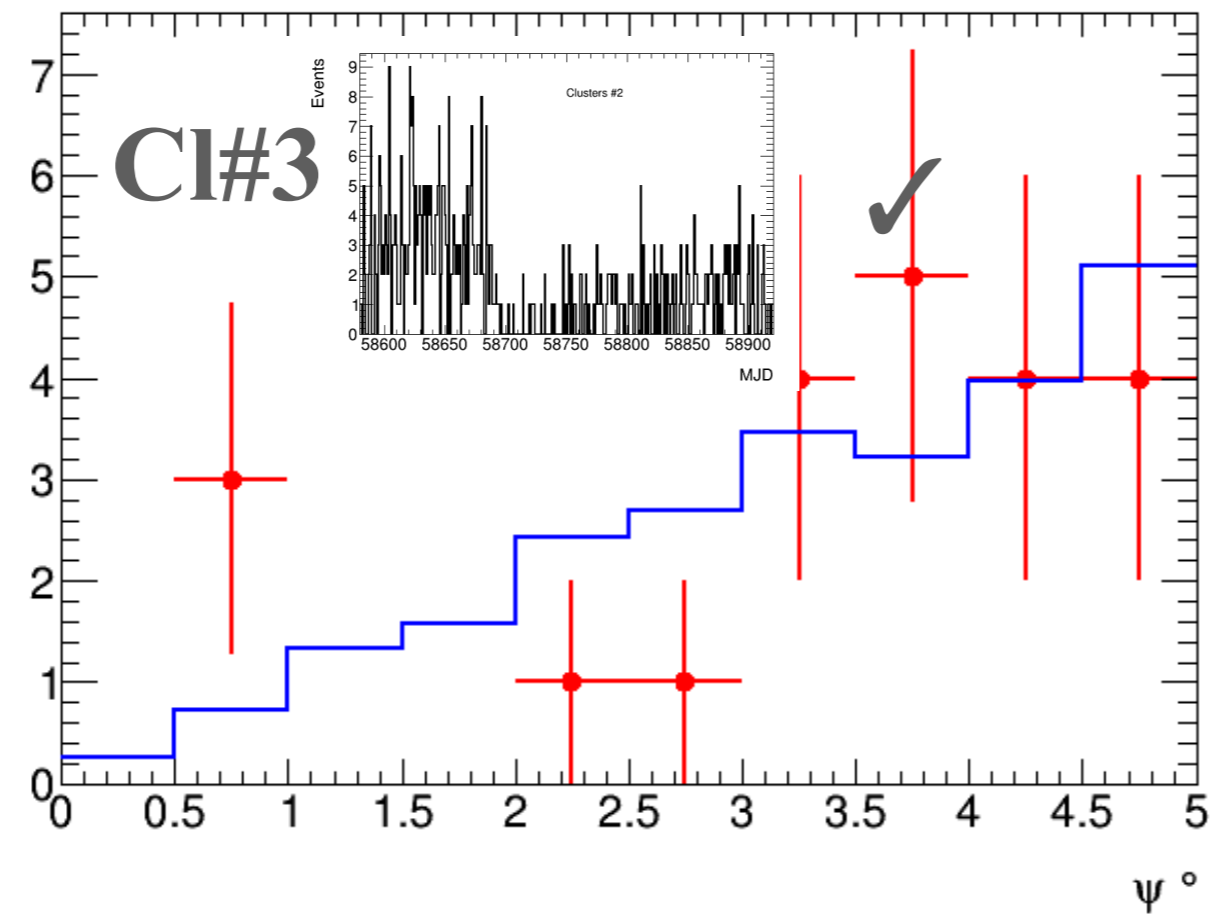
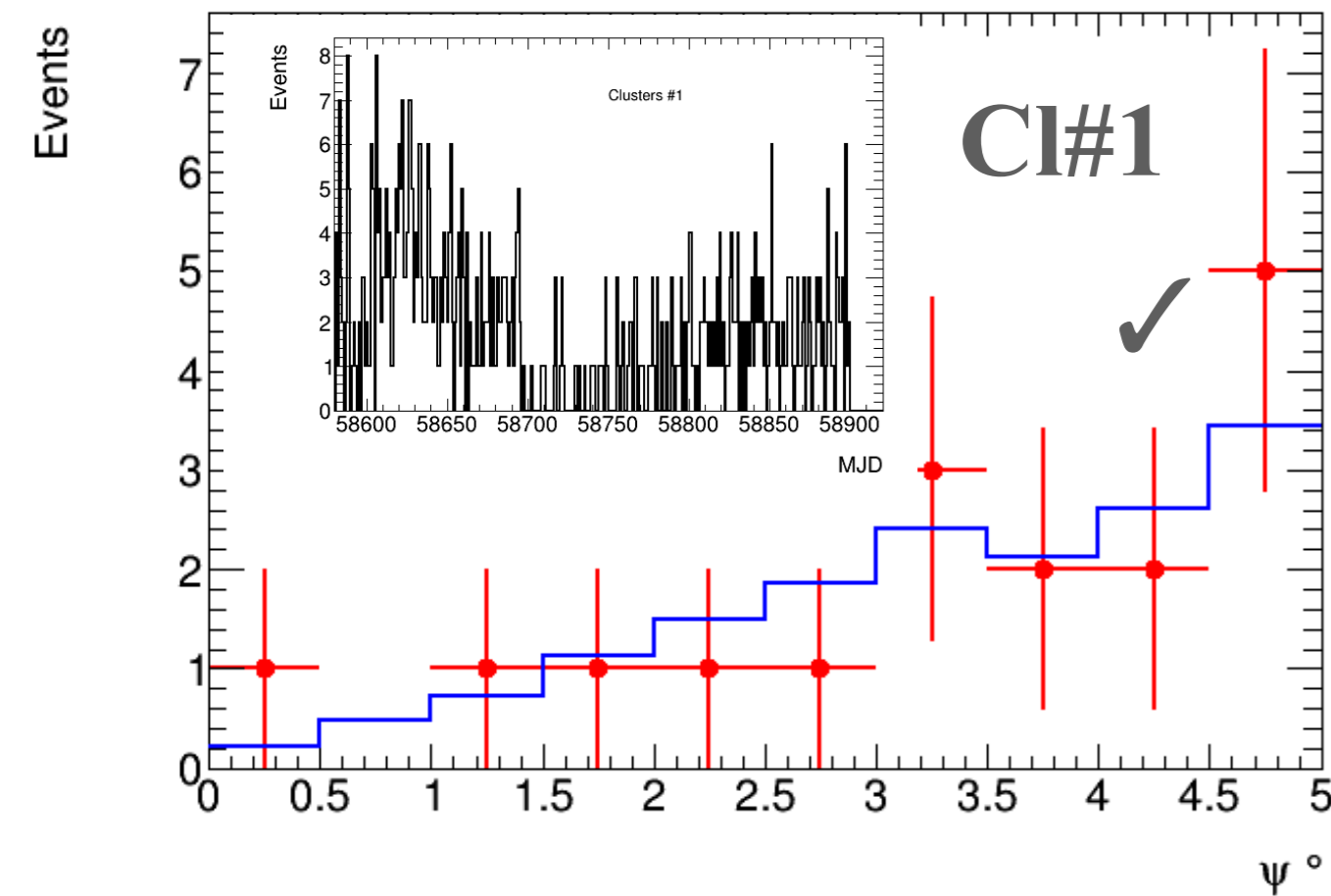
Winter&Lunardini, 2020



# ZTF AT2019dsg / Baikal-GVD 2019 data of 5 clusters

cone\_5° around point “Decl=14.2°” and for bckg “RA=0°÷360°” step=10° ; Apr-2019-Feb2020

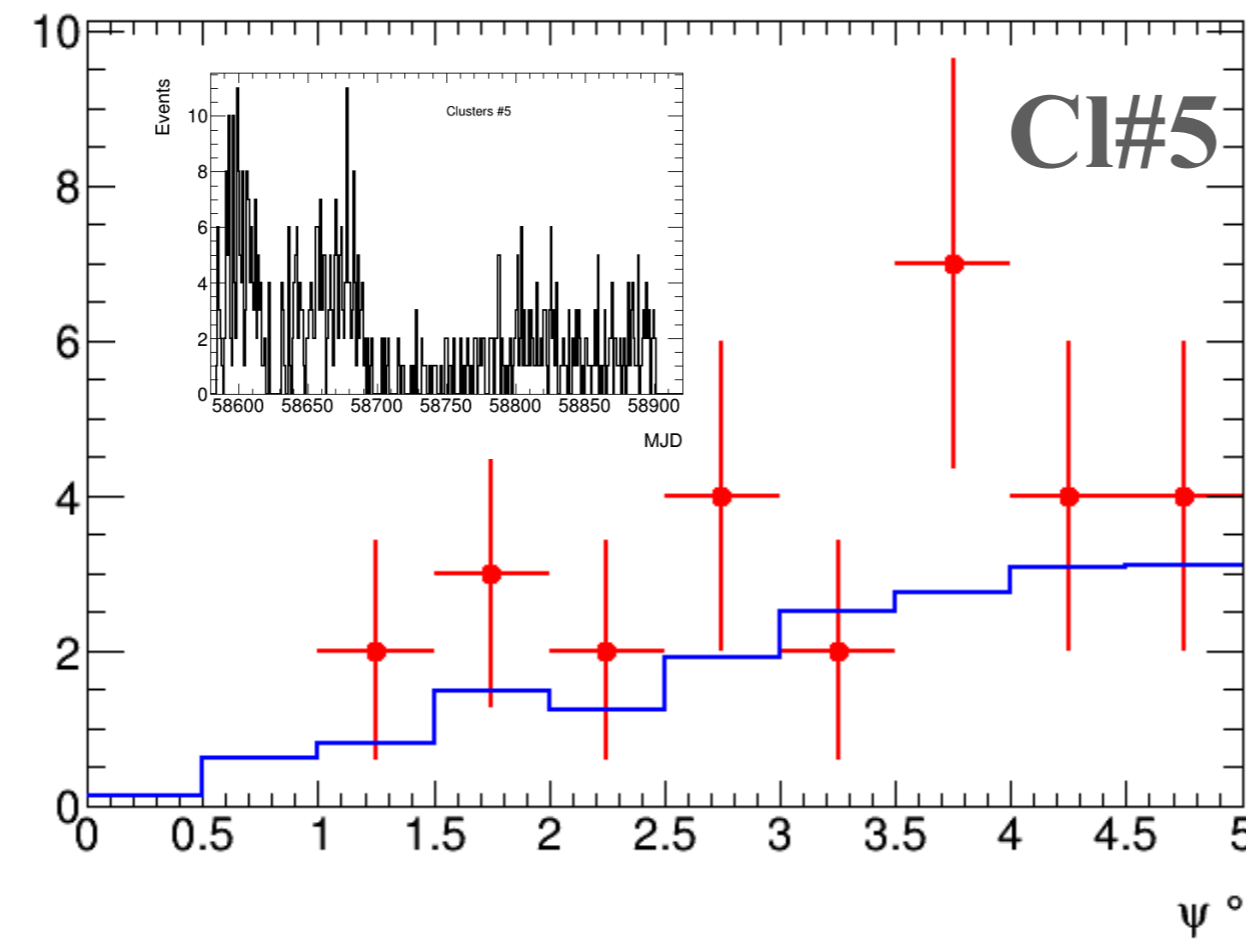
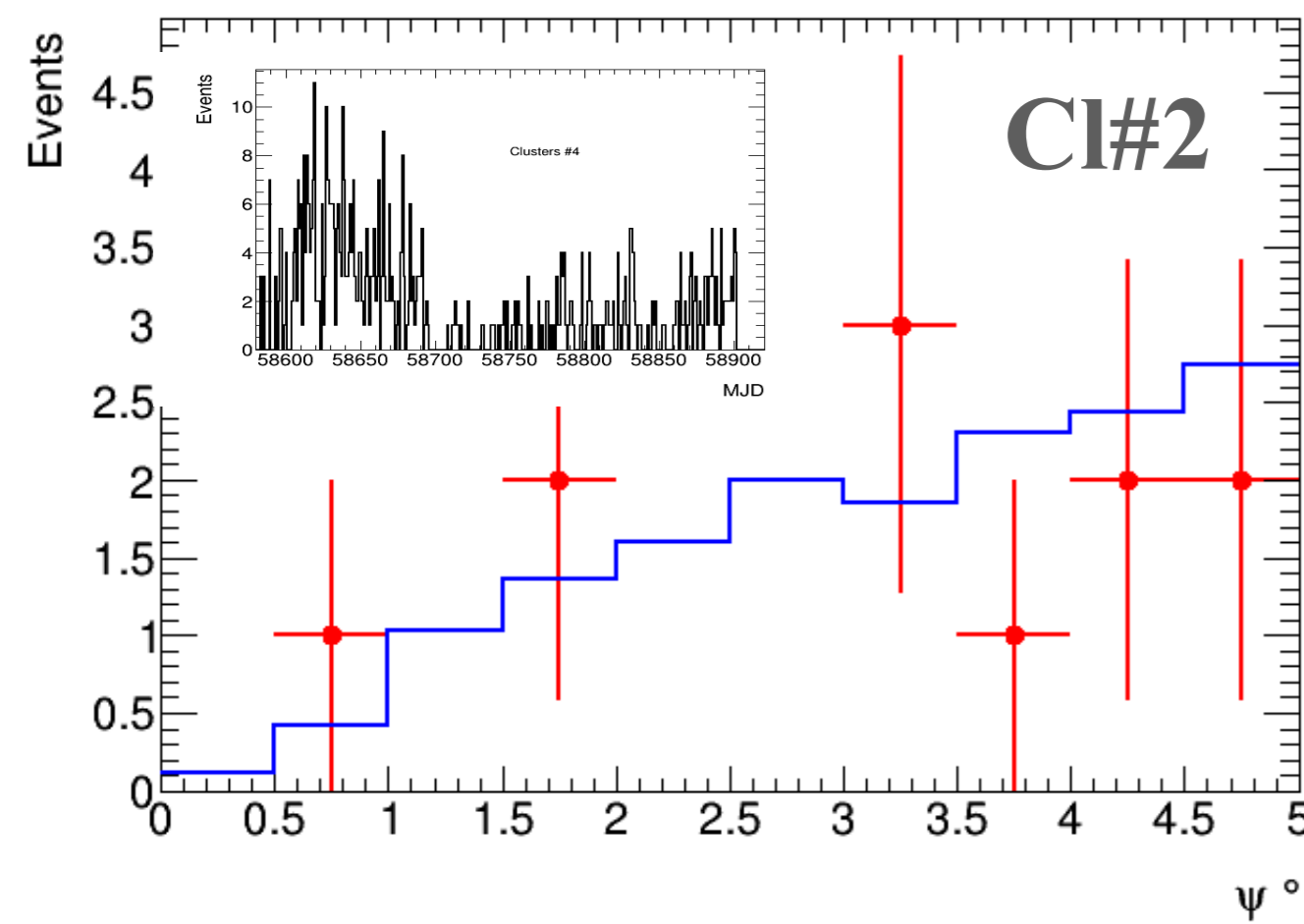
Mismatch angles: **obs**/**bkg**



✓ Cl-1 mjd 58603.92444  
22:11:11.616 UTC

✓ Cl-3 mjd 58603.82667  
19:50:24.288 UTC

✓ Cl-4 mjd 58603.95556  
22:56:00.384 UTC



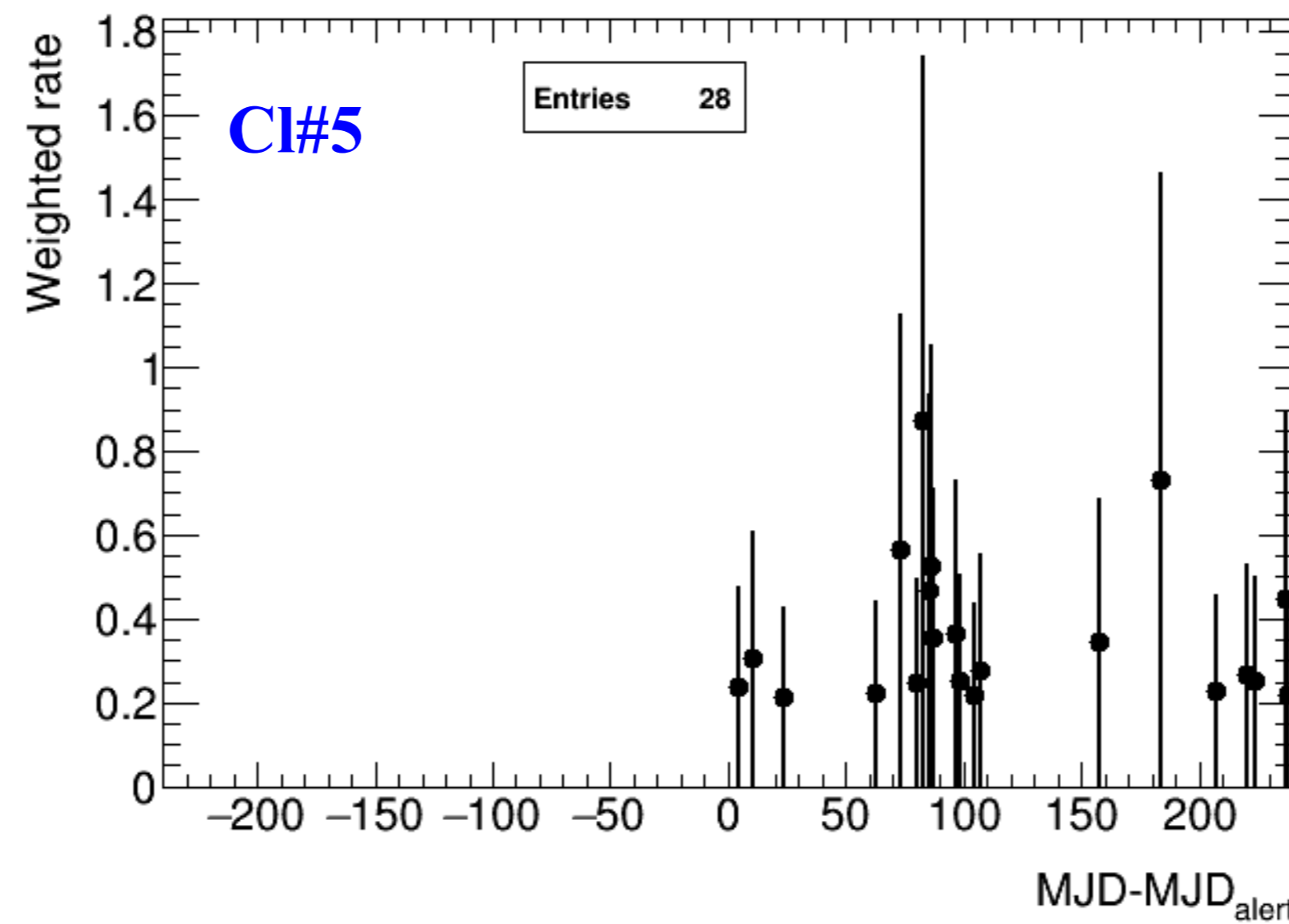
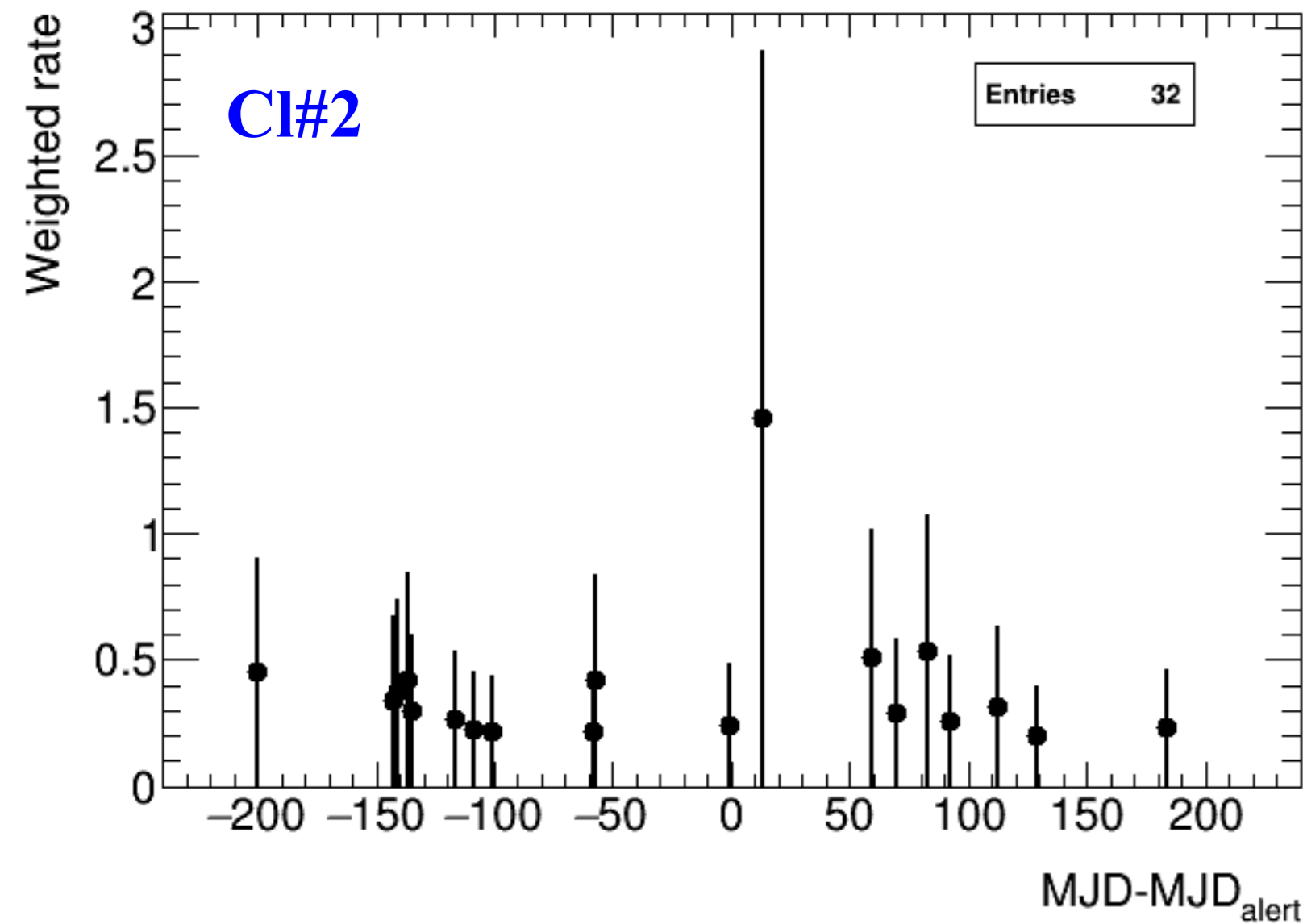
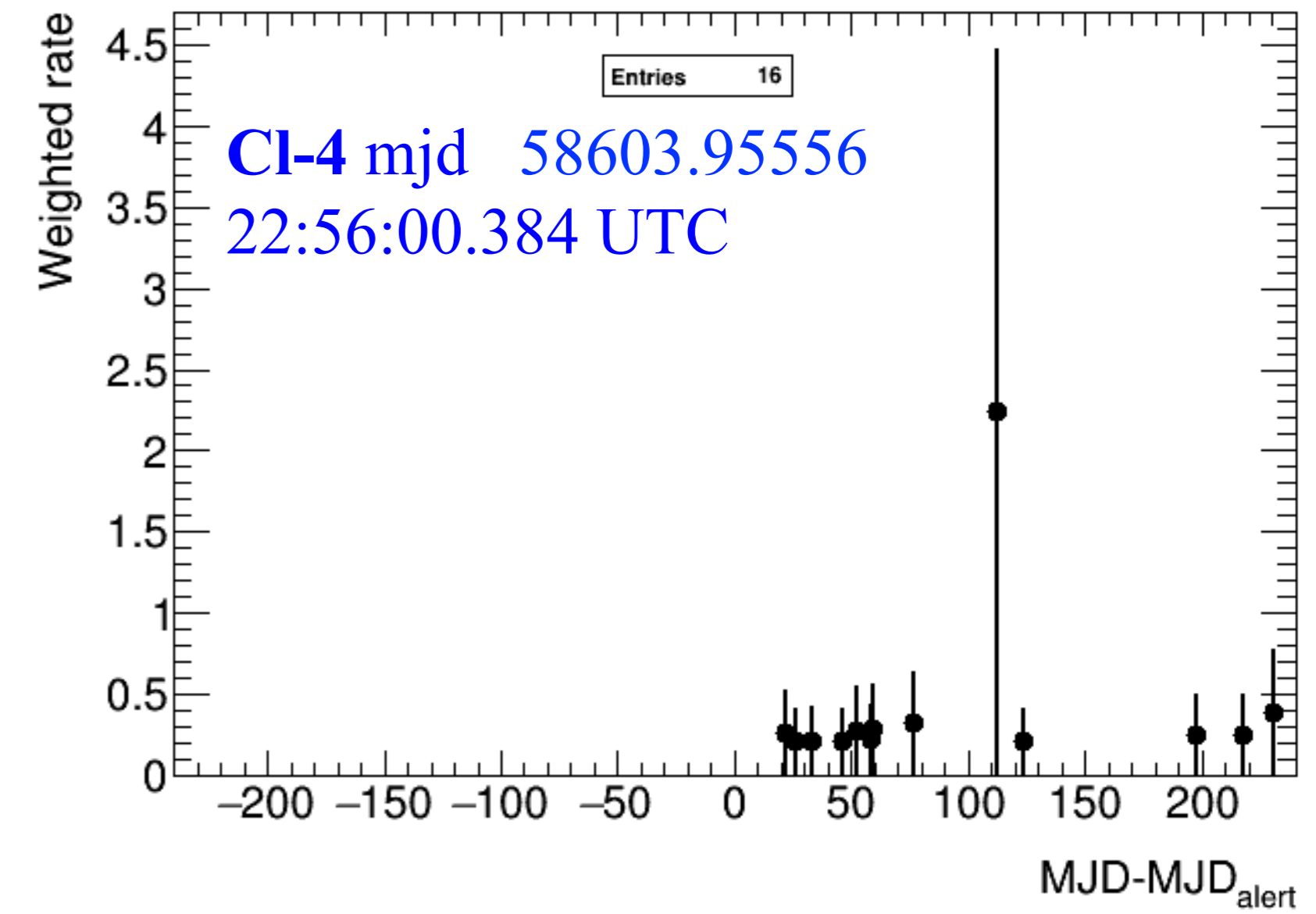
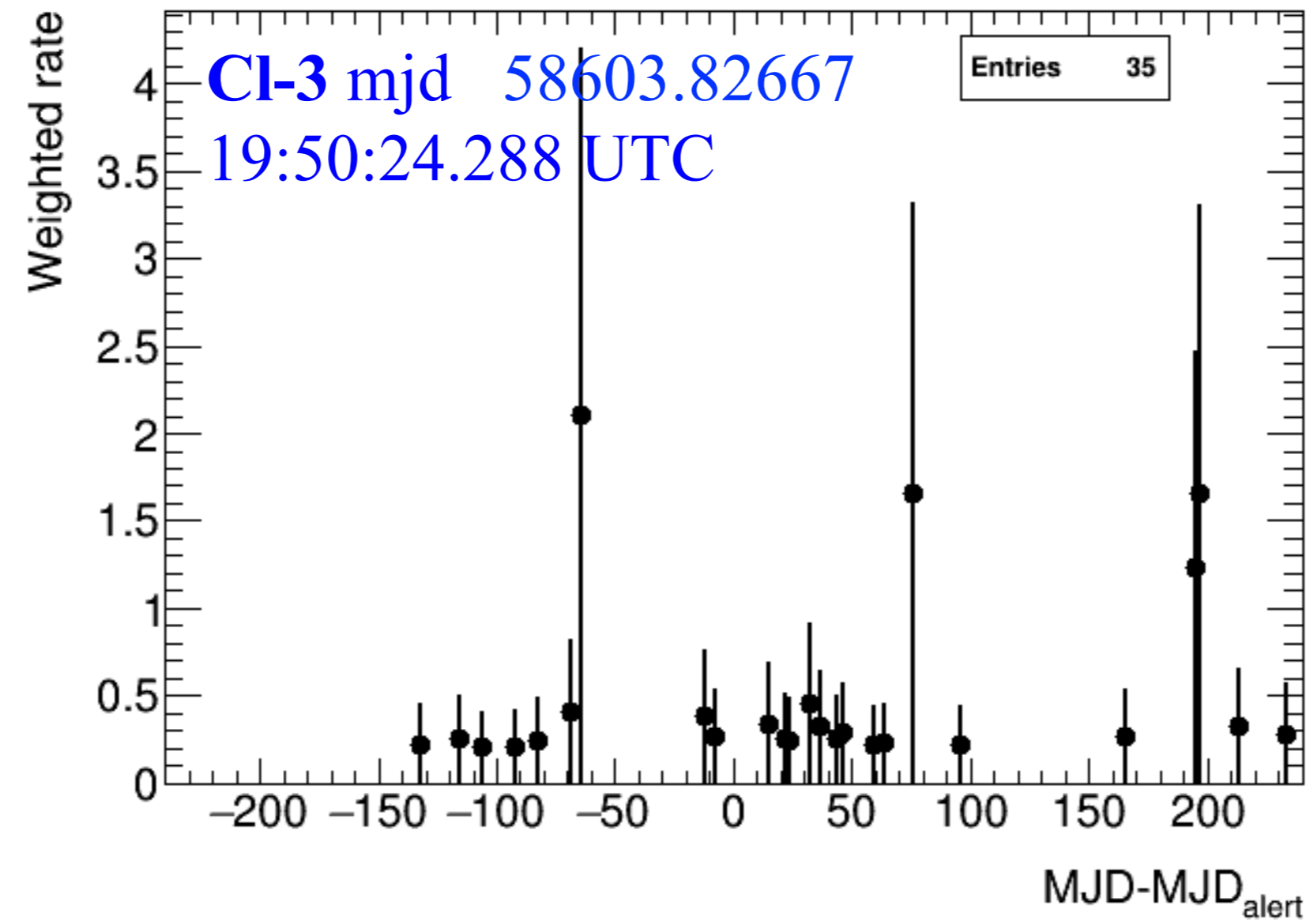
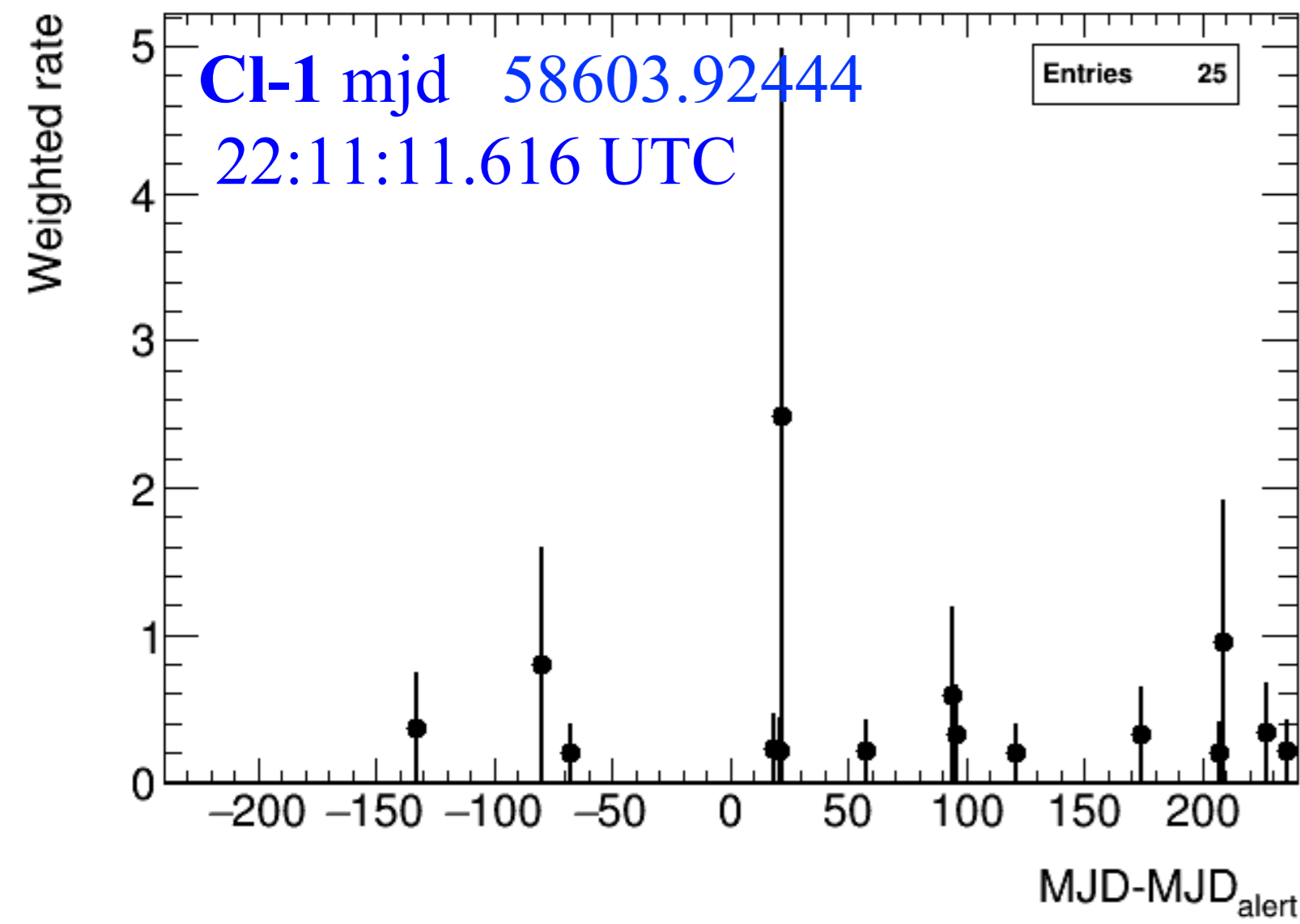
Selection:  $N_{hit} > 7$  &  $l_{lh}$  &  $phit \& n_{hit}$  & cone(5°):  
3 cascades at 3/5 clusters in the same day:  $MJD_{TDE} + 21d$

Level	5cls(<ra>)/+-12h	.../+-1h
Nobs/Nbkg	3/ 0.485	2/ 0.0286
p-val	0.0117	0.000397
sigma	2.26σ	3.35 σ

**Very preliminary results**



# ZTF AT2019dsg : GVD cascades around $\text{MJD}_{\text{TDE}} \pm 200$ days



$\text{MJD}_{\text{TDE}}$  58582.9649074  
11:09:28.000 UTC

$\text{MJD}_{\text{triplet}}$  58603.(826/924/955)  
 $\text{MJD}_{\text{TDE}} + 21\text{day}$

Very preliminary results



# Magnetar SGR1935+2154: 28 Apr 2020

SGR 1935+2154: Ra = 293.75°; Dec = 21.54°

CHIME/FRB observed radio burst: **28.04.2020 14:34:33 GMT**; INTEGRAL discovery of FRB;  
**associated with SNR G57.2+0.8**

**IceCube:** one track-like event consistent with atm. background with a p-value of 0.033.  
Upper limit for this source of  $E^2 dN/dE = 5.2 \times 10^{-5} \text{ TeV cm}^{-2}$  at 90% CL, for  $E^{-2}$  spectrum.

**ANTARES:** No up-going muon neutrino candidate events were recorded at the location of the source during  $\pm 1$  hour time window. Upper limit of  $14 \text{ GeV cm}^{-2}$  for  $E^{-2}$  spectrum.

**Baikal-GVD:** At burst time, the source was located 0 degrees below the horizon for GVD. Data of first 5 GVD clusters recorded in time window of  $\pm 24$  hours around the burst time have been analyzed to search for neutrino events associated with burst.

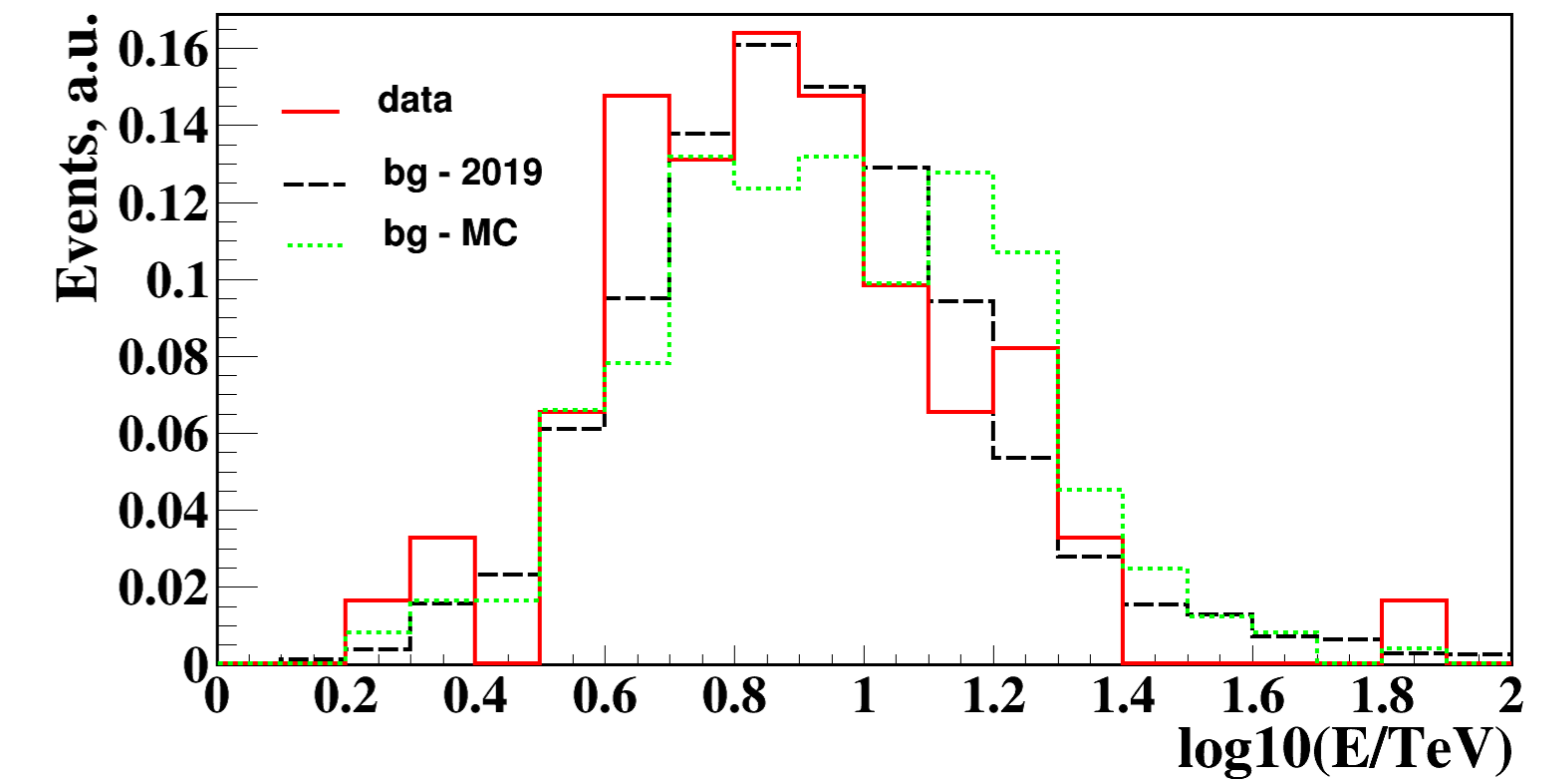
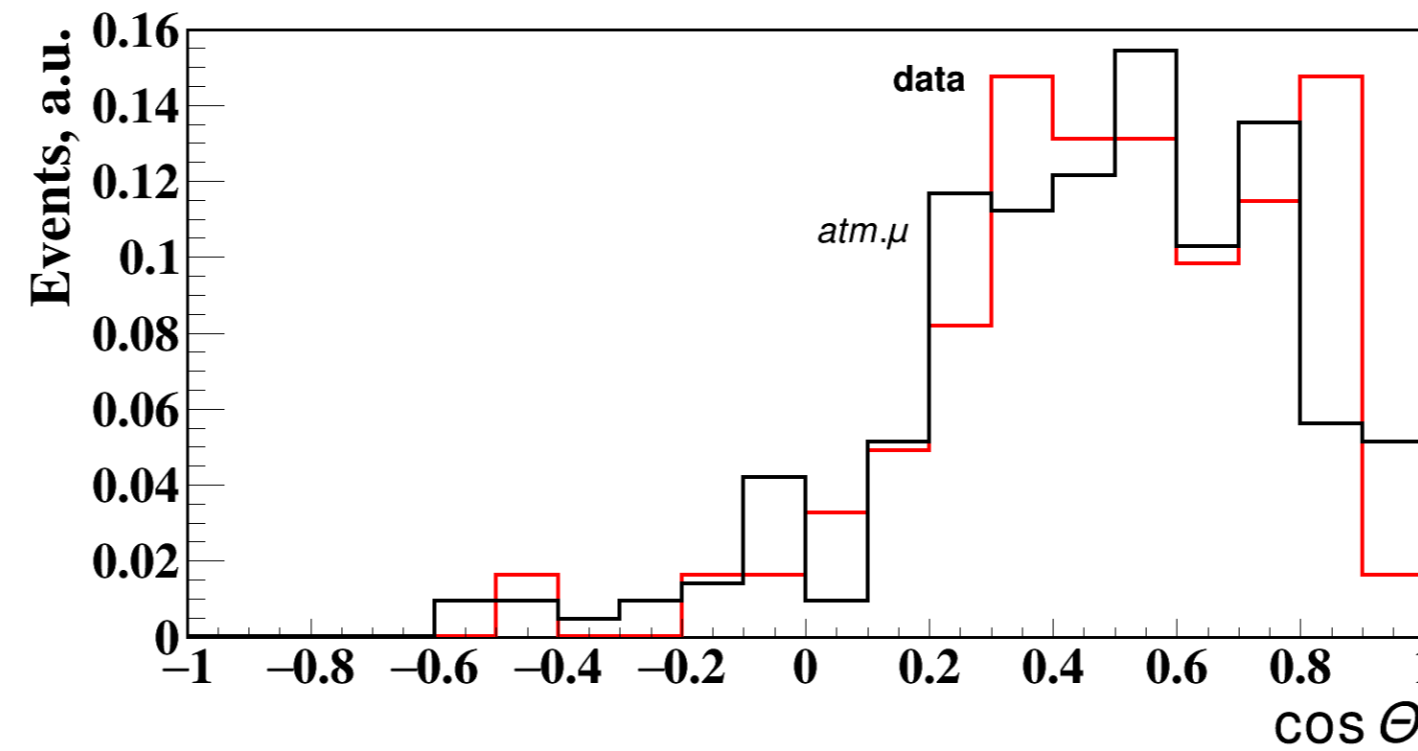


# Data performance towards the magnetar

Selected cascade events for  $N_{hit} > 7$  and  $N_{hit} > 9$  (red)

Data/bg-MC/bg-data2019

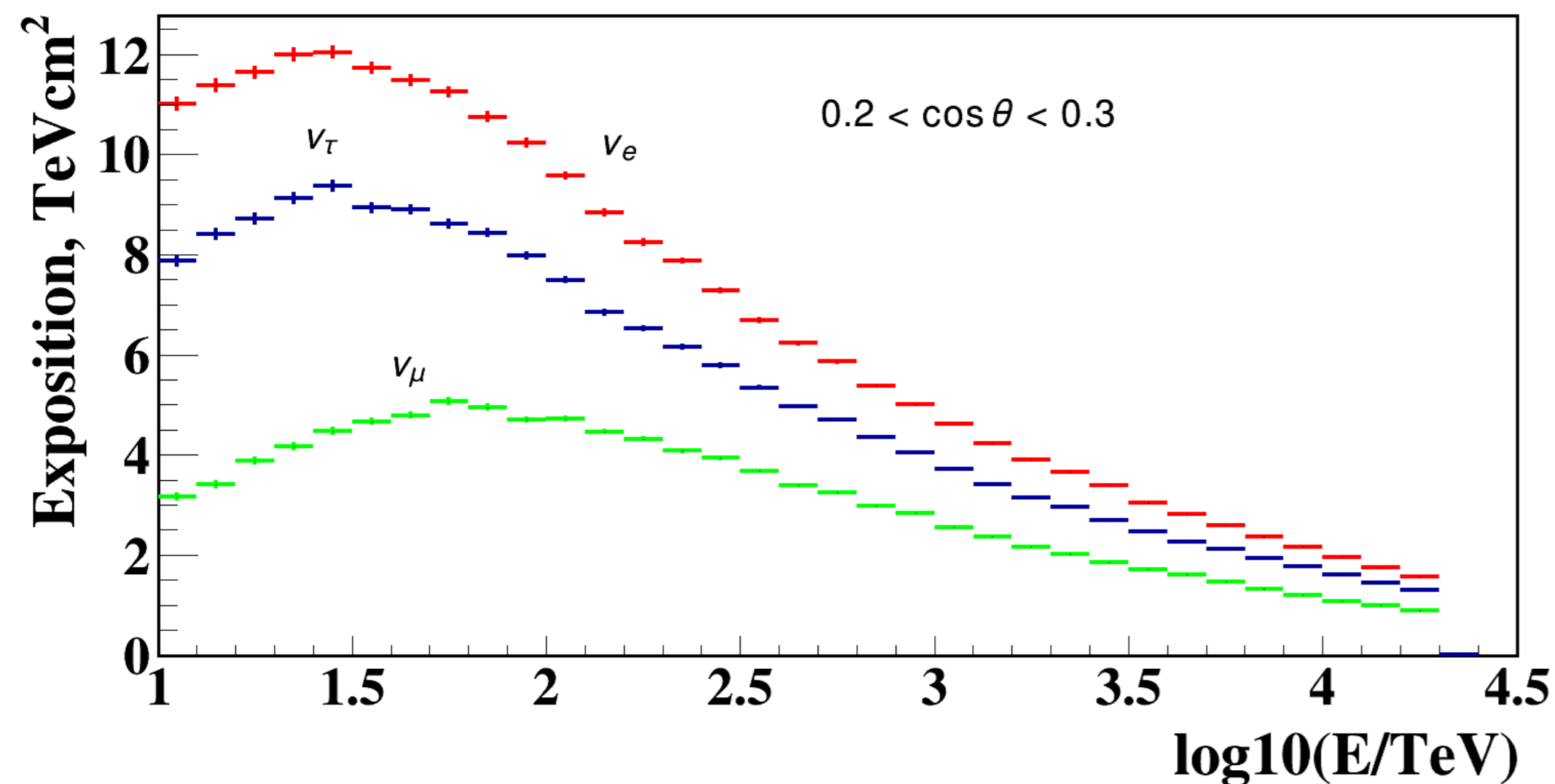
Cl#	Operation efficiency	Selected events	$\psi < 20^\circ$	$\psi < 15^\circ$	$\psi < 10^\circ$	$\psi < 5^\circ$
1	0.91	33 6	2 1	0 0	0 0	0 0
2	0.94	46 11	5 1	3 1	2 1	0 0
3	0,89	59 18	4 3	2 2	2 2	2 2
4	0.94	51 12	2 0	0 0	0 0	0 0
5	0,94	44 14	1 1	1 1	0 0	0 0
Total		233 61	14 6	6 4	4 3	2 2



For trigger  $N_{hit} > 9$  &  $\psi < 5^\circ$

$$P(n \geq 2, \mu = 0.35) = 0.0487 \rightarrow 1.97 \sigma$$

$$E^2 F = n_{90\%} / \text{Expos} = 2.0 \cdot 10^{-3} \text{ TeV/cm}^2$$





- ◆ **Baikal-GVD** collaboration started a follow-up of HE neutrino alerts in fast regime since Sept 2020. Further steps are towards interval of minutes in data transmission for online stream analysis and **trigger HE alerts**.
- ◆ No prompt coincidences were **found in time and direction with ANTARES triggers**. Plans are to continue fruitful conversation between us and WG of ANTARES and update analysis in muon-track search.
- ◆ Obtained **UpL on neutrino fluence towards IC-alerts** are our first estimates of the GVD sensitivity to Northern sky astroph sources. We plan to follow other GCN alerts of HE/VHE experiments and **alarms on transients**;
- ◆ **First estimates on ZTF TDE of 2019 are presented. Our further analysis is developing.**
- ◆ ***The UpL on neutrino fluence towards SGR1935+2154 was obtained at 90% c.l. as  $2 \text{ GeV} \cdot \text{cm}^{-2}$ .***
- ◆ ***GVD cooperation in MM investigations with groups of radio observatories RATAN, OVRO***  
(see talk by Zh.Dzhilkibaev).

# BACK UP SLIDES

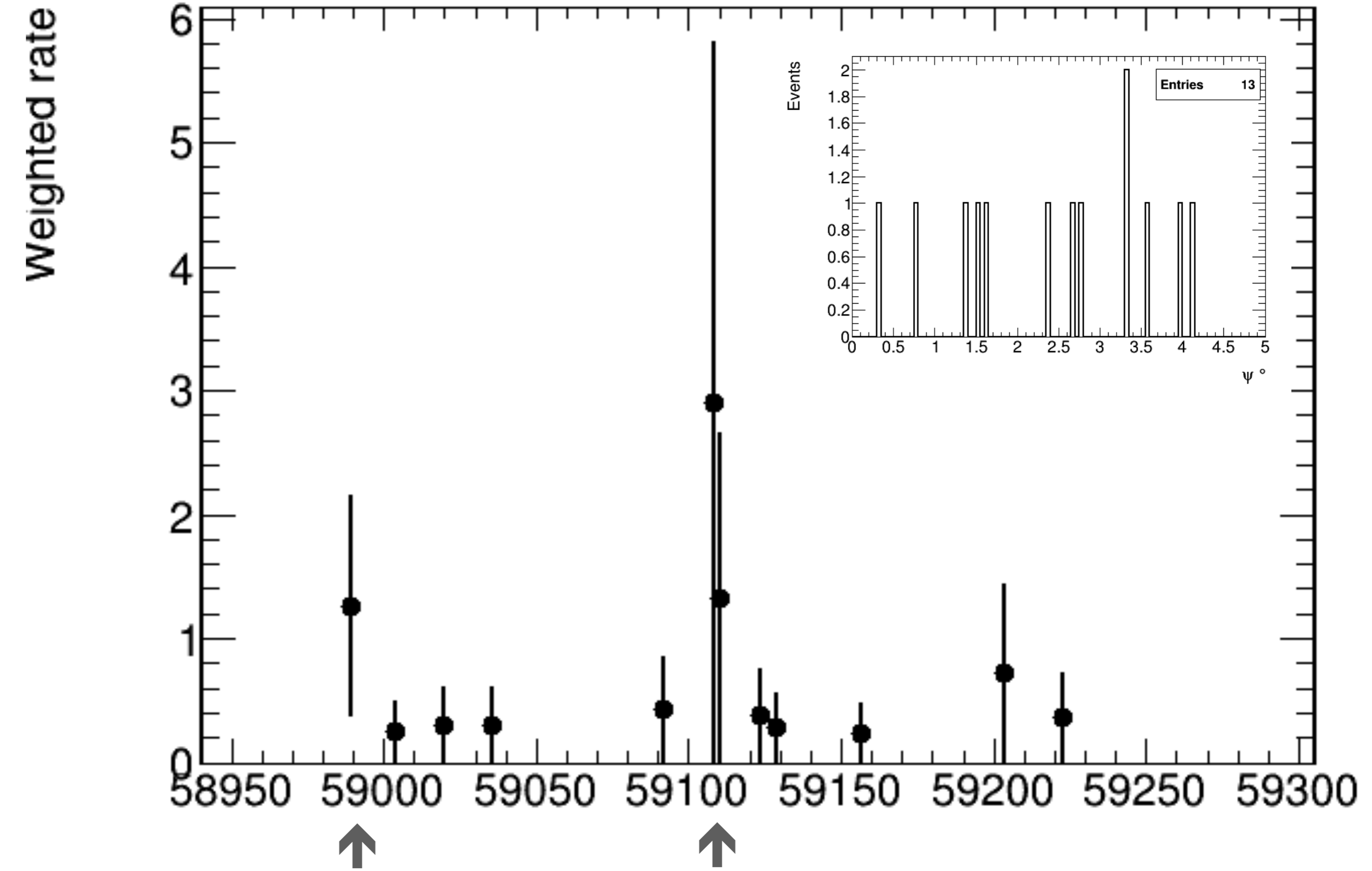
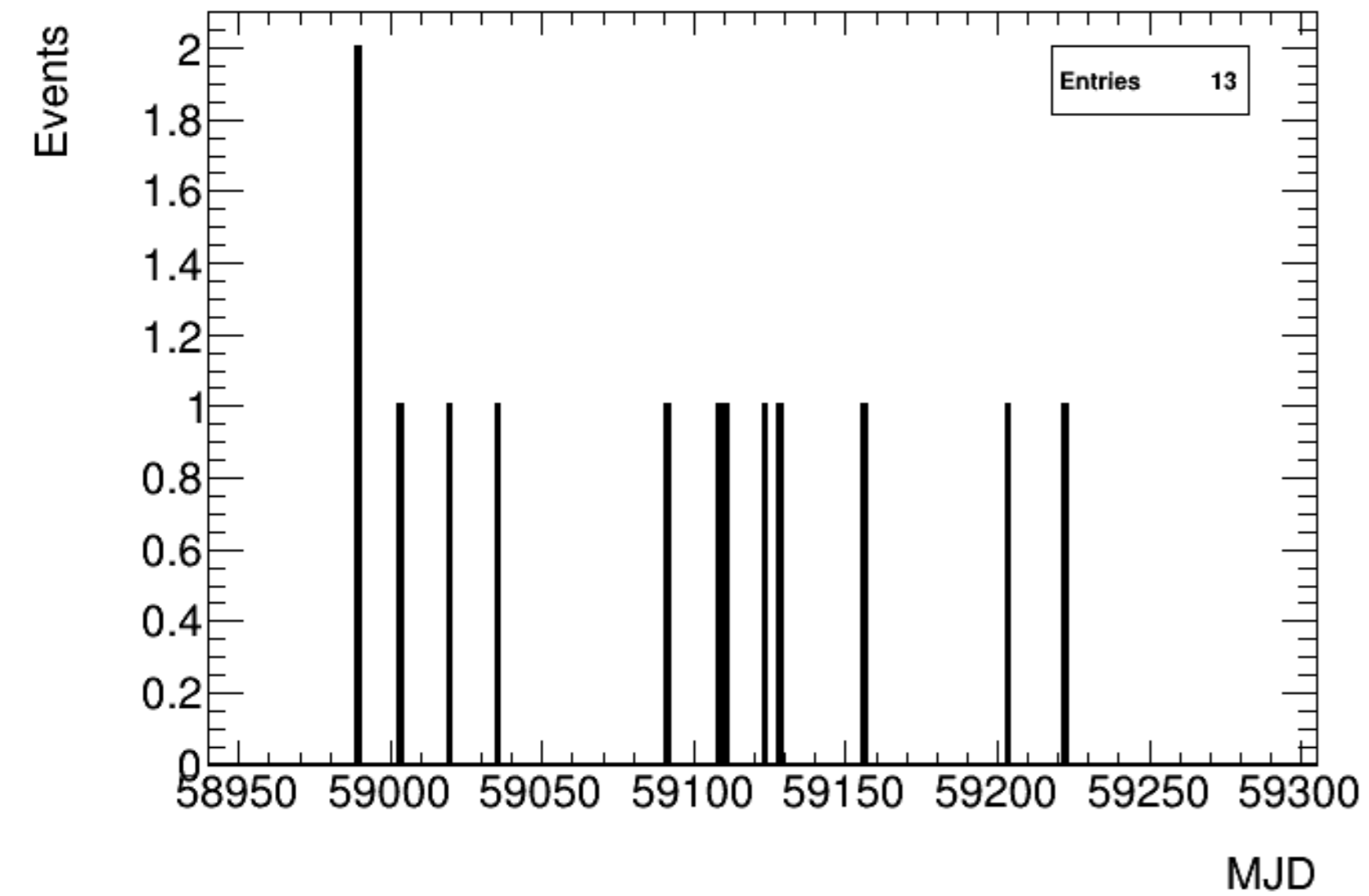
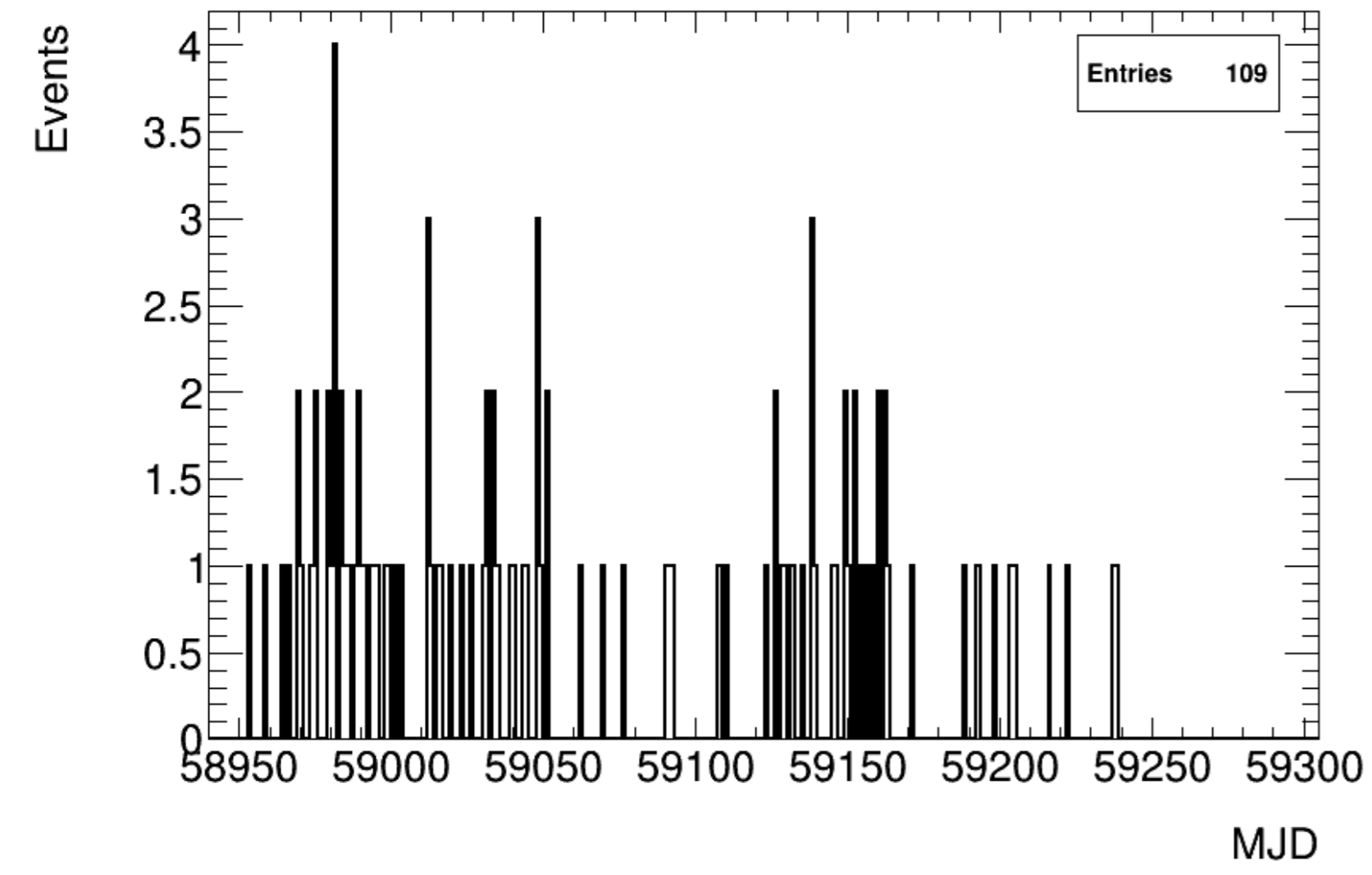




# ZTF AT2019fdr :

# GVD-2020 Apr--Feb

Rate of events vs MJD within cone\_5° & Decl==+26.5°±0.5°



2020-05-20 12:35:11.616 UTC  
2020-05-20 17:18:55.872 UTC

2020-09-16 04:24:31.680 UTC  
2020-09-18 13:17:51.648 UTC

**Further analysis is developed**