

# Байкальский глубоководный нейтринный эксперимент Baikal-GVD: на пути к нейтринной астрофизике высоких энергий



Баир Шайбонов, 22.04.2020, ЛЯП ОИЯИ



# Содержание

- Введение: принцип регистрации нейтрино высоких энергий
- Состояние нейтринной астрофизики высоких энергий в мире
  - Астрофизический поток нейтрино
  - Поиск локальных источников
  - Многочастичная астрономия. Кампания по исследованию AGN блазара TXS 0506+056.
- Строительство нейтринного телескопа на Байкале
- Обработка данных и восстановление событий в Байкальском эксперименте.  
Моделирование событий в телескопе
- Первые результаты





M.Markov, **1960**: 4 years after  $\nu$  discovery

„We propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation“ Proc. 1960 ICHEP, Rochester, p. 578.



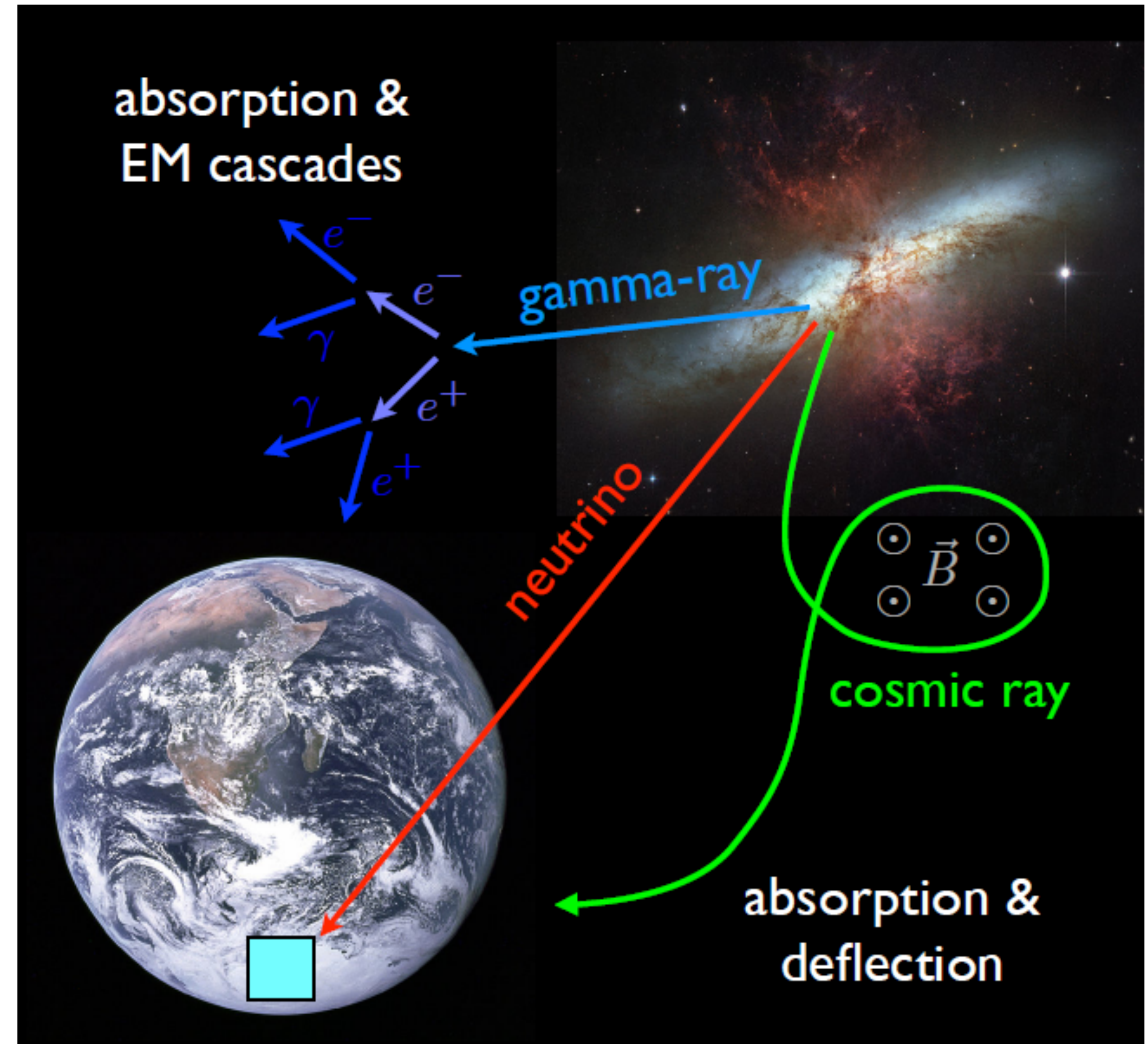
# High-energy Neutrino astrophysics

$$p + p, \quad p + \gamma \rightarrow \pi^\pm + \dots$$

$$\pi^\mp \rightarrow \mu^\mp + \nu_\mu (\bar{\nu}_\mu)$$

$$\mu \rightarrow e + \nu_\mu + \nu_e$$

- Easily born:
  - in space accelerators
  - in cosmic rays interactions with interstellar media
- Unlike high-energy photons:
  - freely fly out of the area of birth
  - the Universe is transparent to neutrinos
- Unlike cosmic rays:
  - not deflected by magnetic fields
  - we can measure the direction of arrival → cosmic neutrino sources
- Disadvantage:
  - hard to detect → we have to build a huge detector

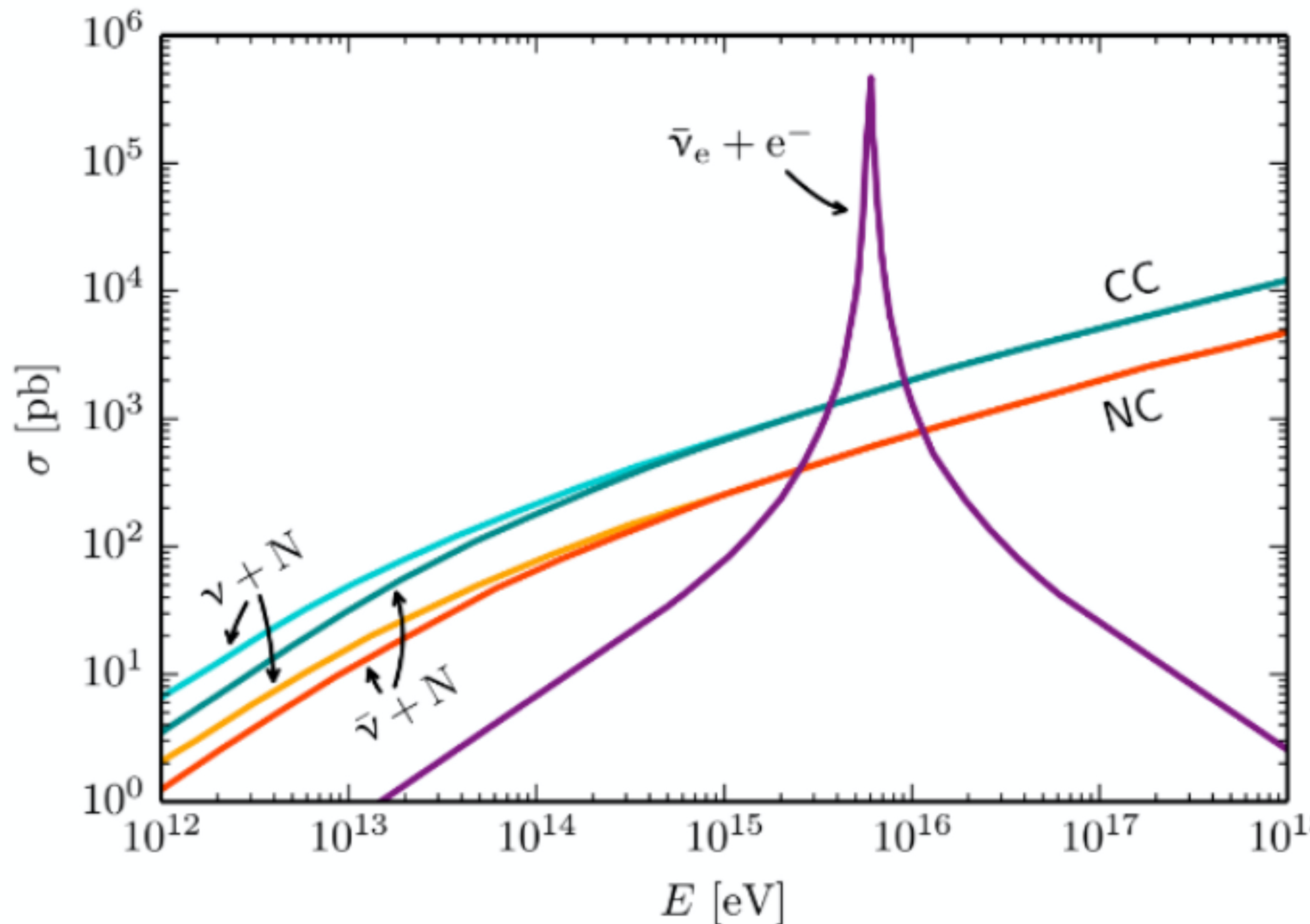




# Нейтрино высоких энергий

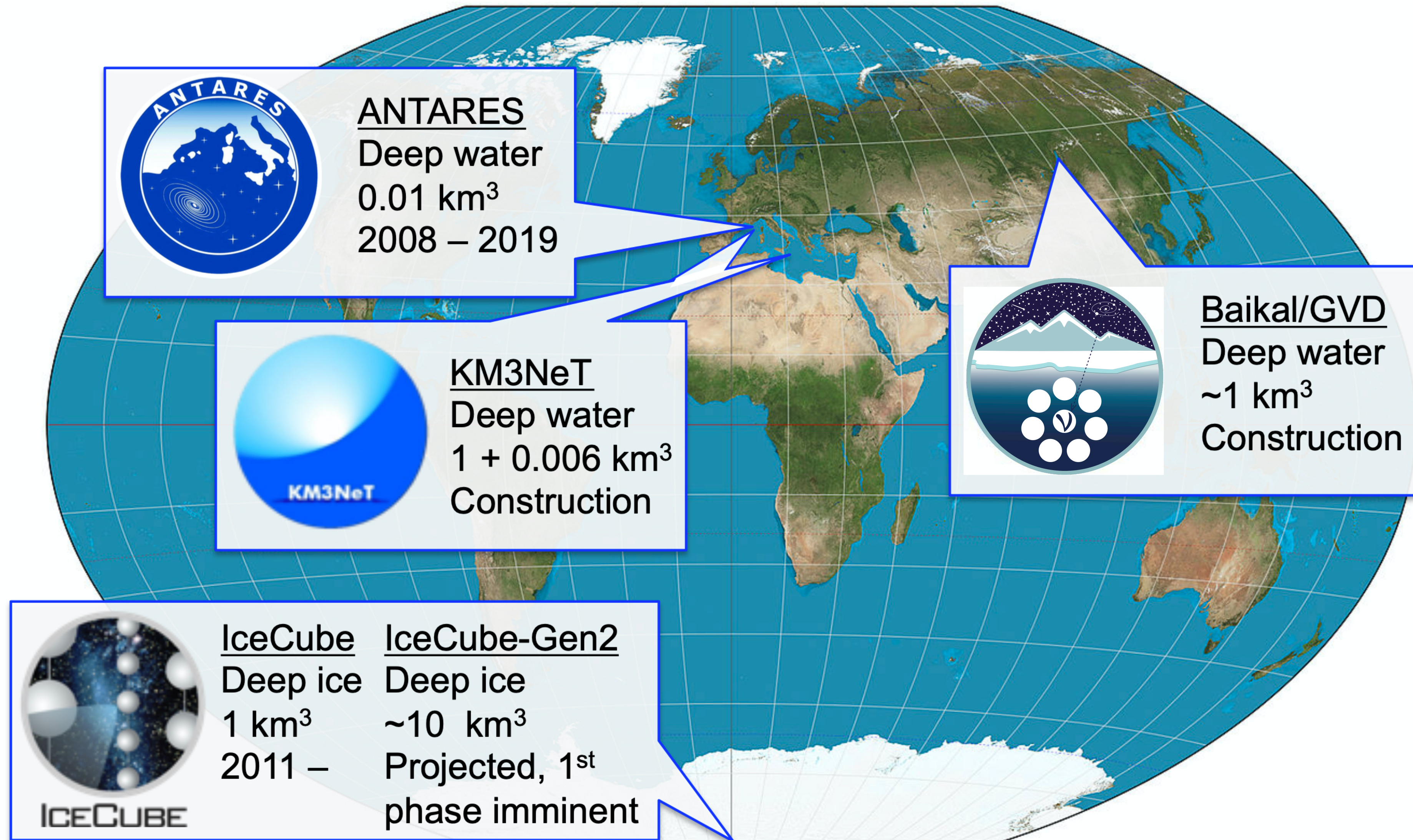
Благоприятные особенности:

- Сечение взаимодействия нейтрино с веществом растет с ростом энергии ( $\sim 10^{-33}$  см<sup>2</sup> при  $10^{15}$  эВ)
- Высокоэнергичные события гораздо проще регистрировать - больше энерговыделение в установке. Требуется меньше регистрирующих элементов детектора. Возможность использовать большие объемы естественных прозрачных сред



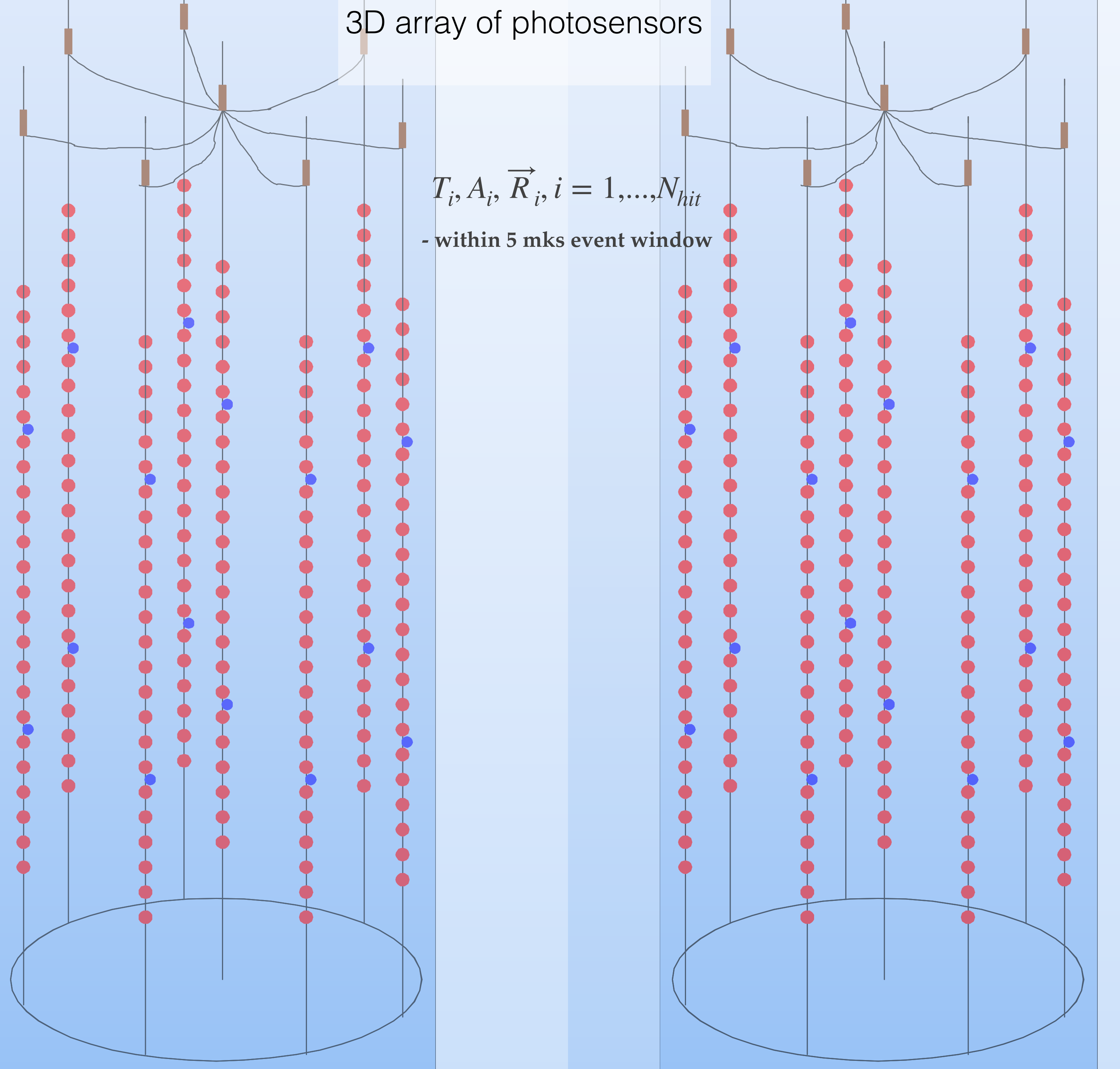


# Ice/water Cherenkov neutrino telescopes - global view





# Detection principle

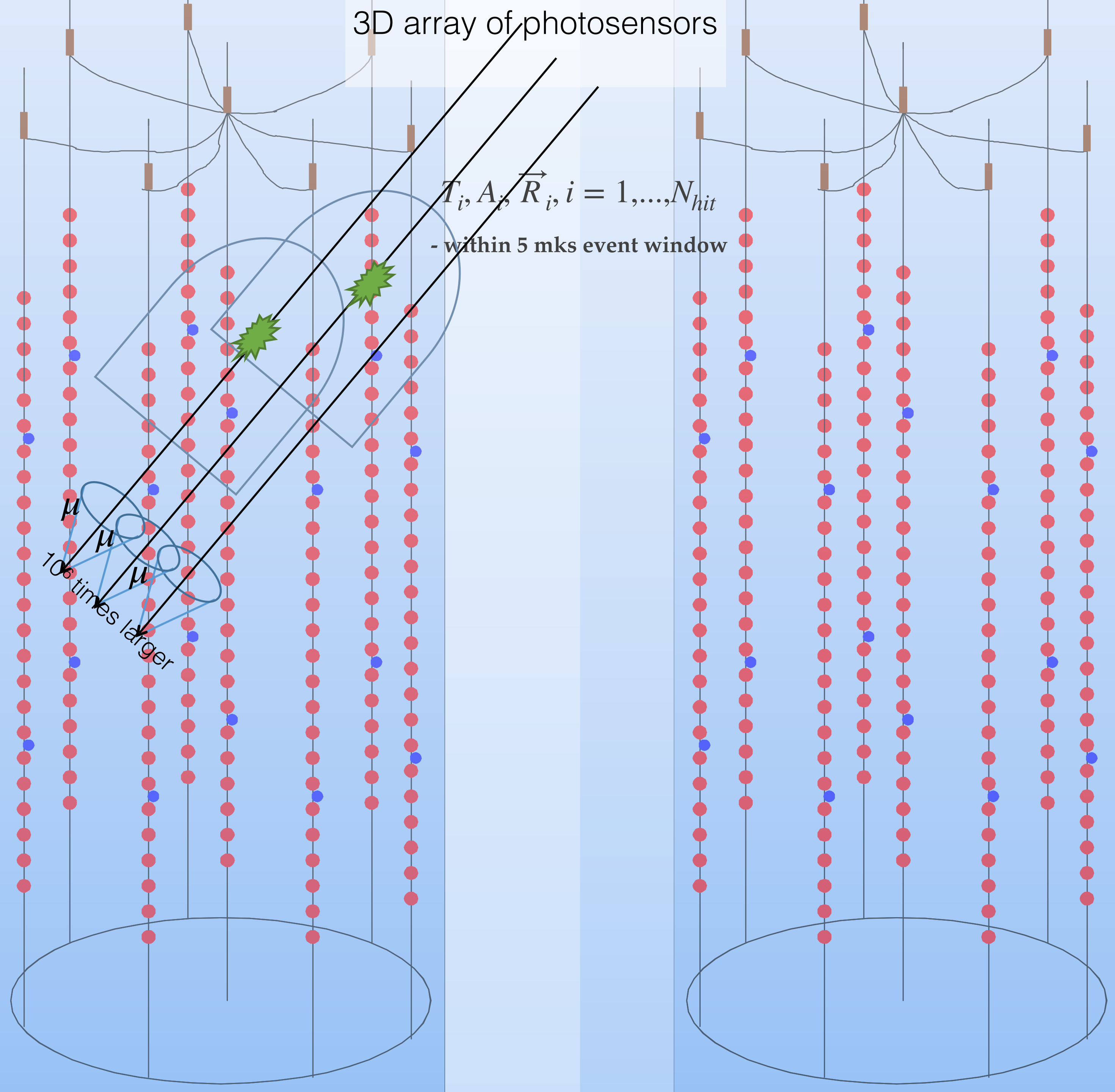




# Detection principle

## Atmospheric muons

- Factor of  $10^6$  more abundant than atm. neutrino
- Very complex signature -> mimic neutrino events





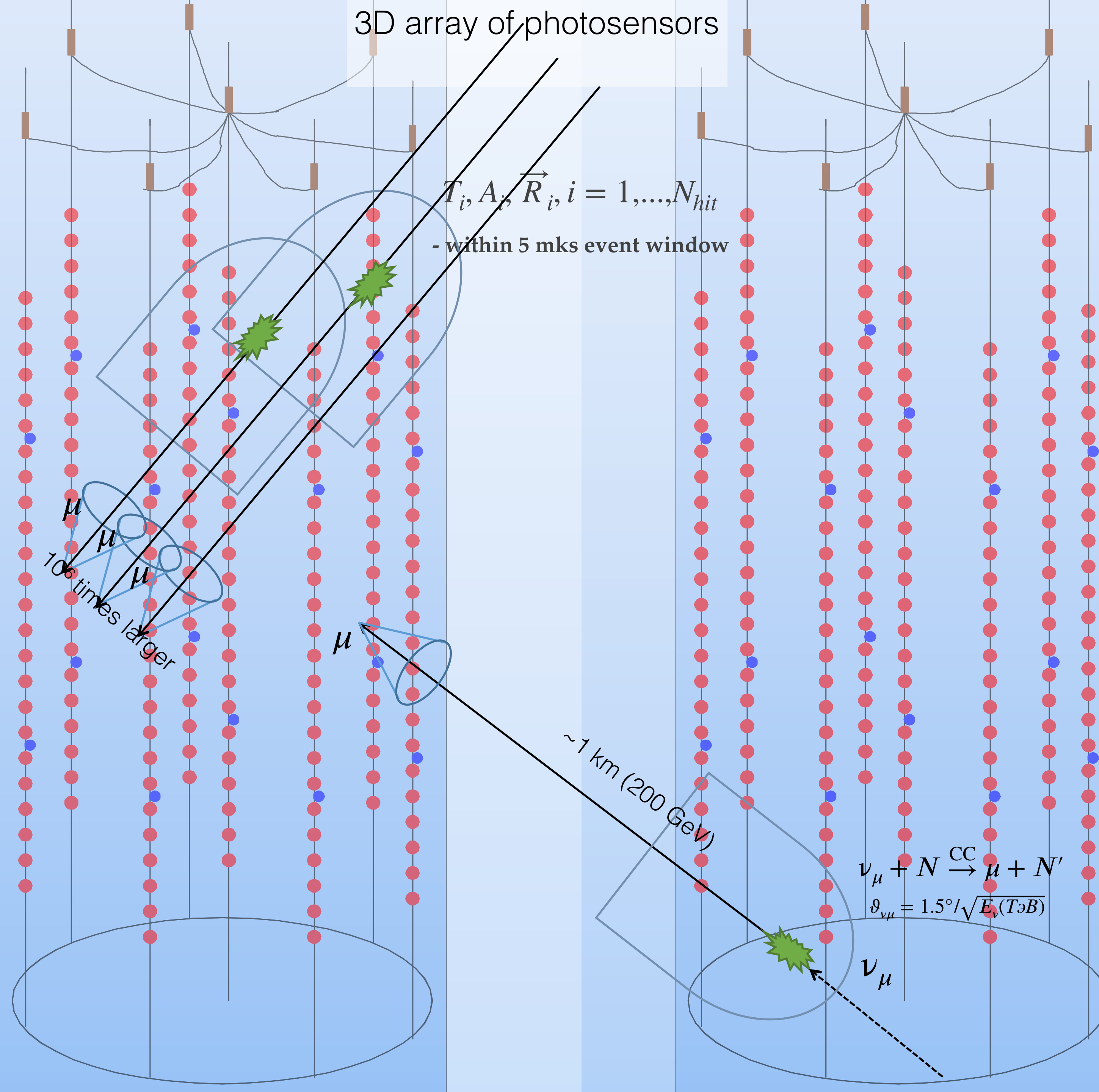
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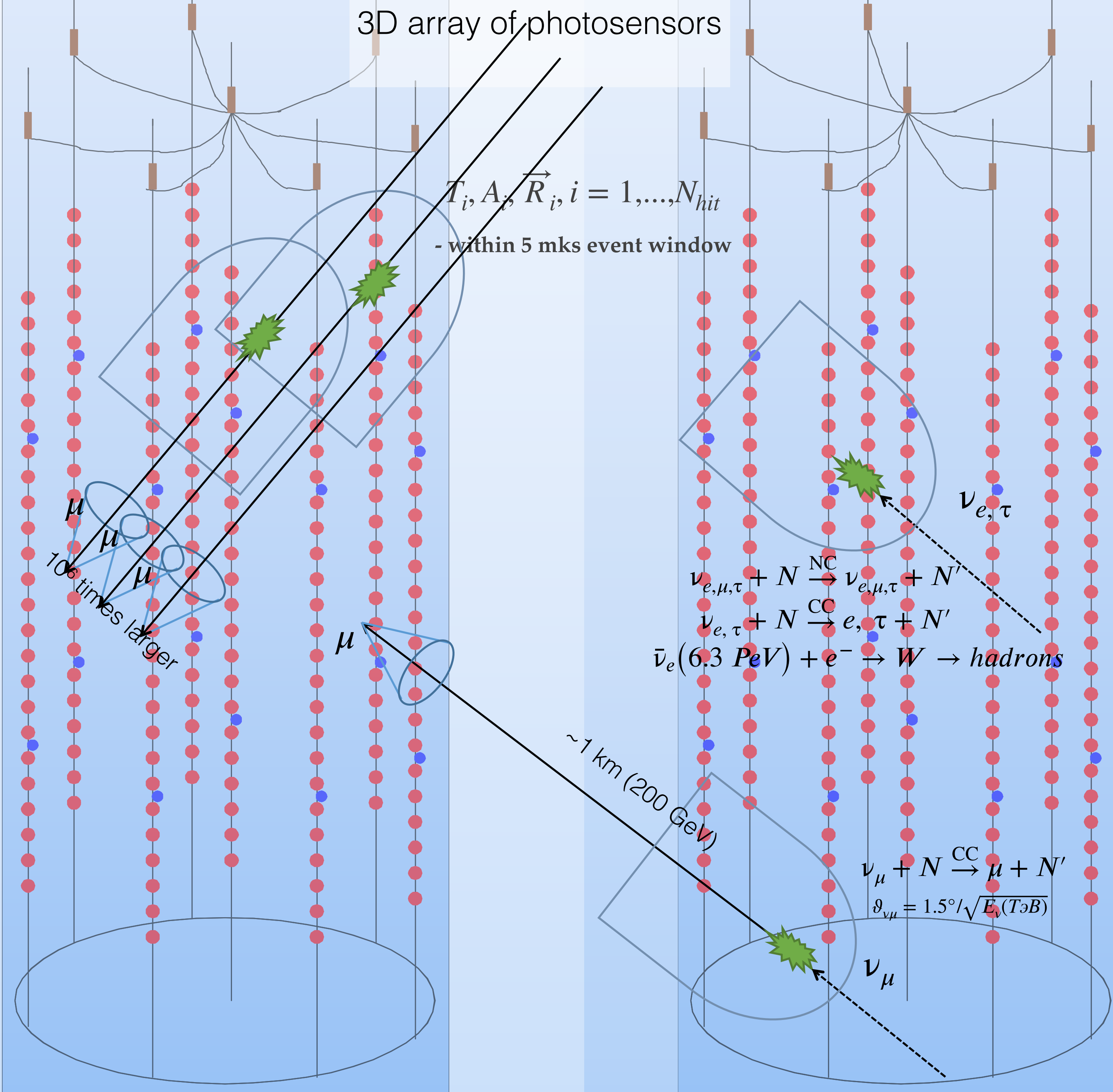
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## Neutrino induced muons

- Long track in the detector
- Good angular resolution  $< 1^\circ$
- Neutrino interaction vertex can be located at several km from the detector  $\rightarrow$  large detection volume







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## Neutrino induced showers

- Showers are produced in all neutrino interaction channels and by all neutrino flavors
- Bright anisotropic point-like source of Cherenkov light
- Moderate angular resolution
- Good energy resolution

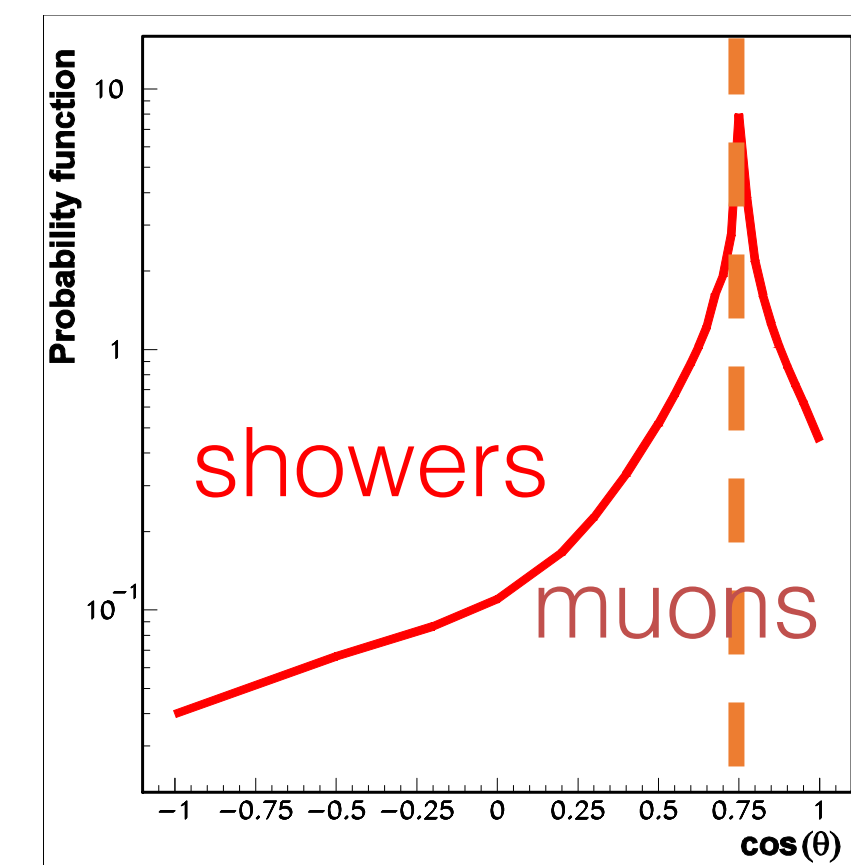
relative cross sections

|    | $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ |
|----|---------|-----------|------------|
| NC | 1       | 1         | 1          |
| CC | 2       | 2         | 2          |

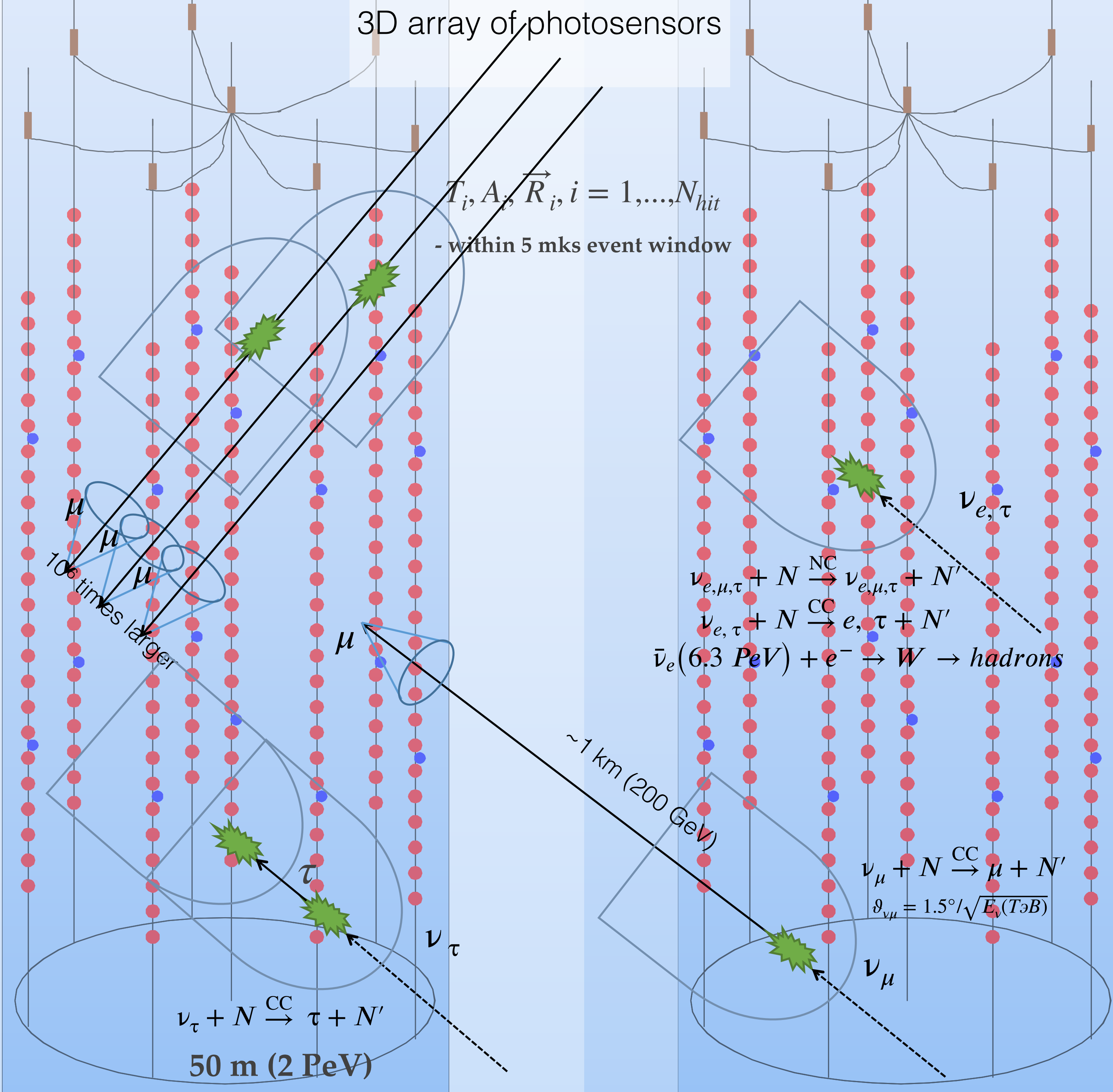
cascades

tracks

3.5:1







# Detection principle

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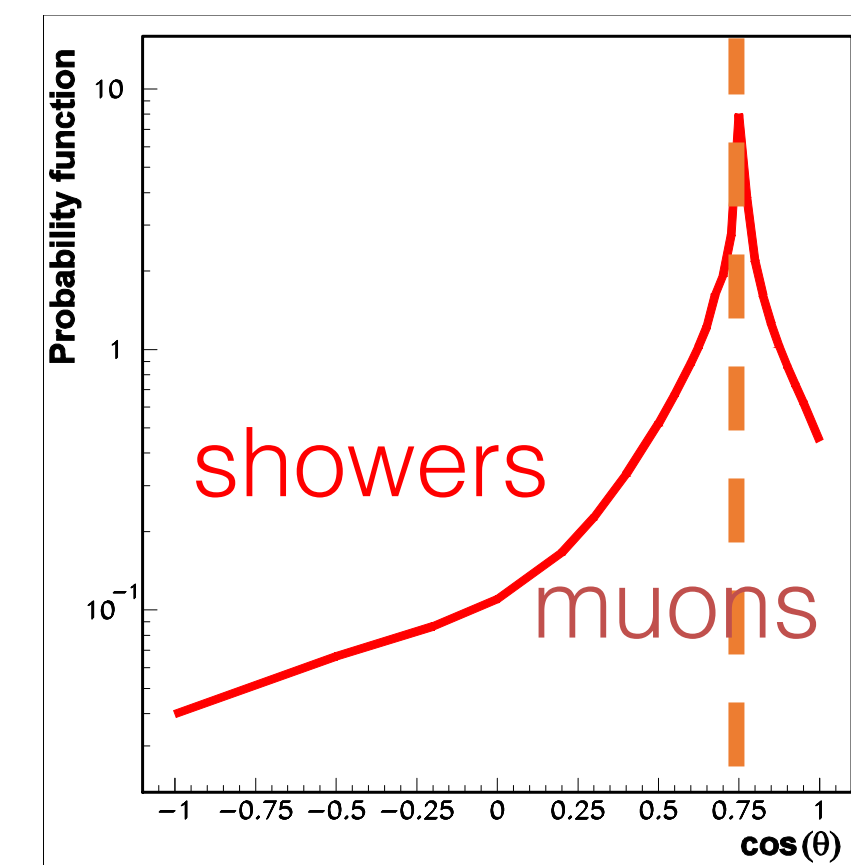
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| CC | 2       | 2         | 2          |

cascades

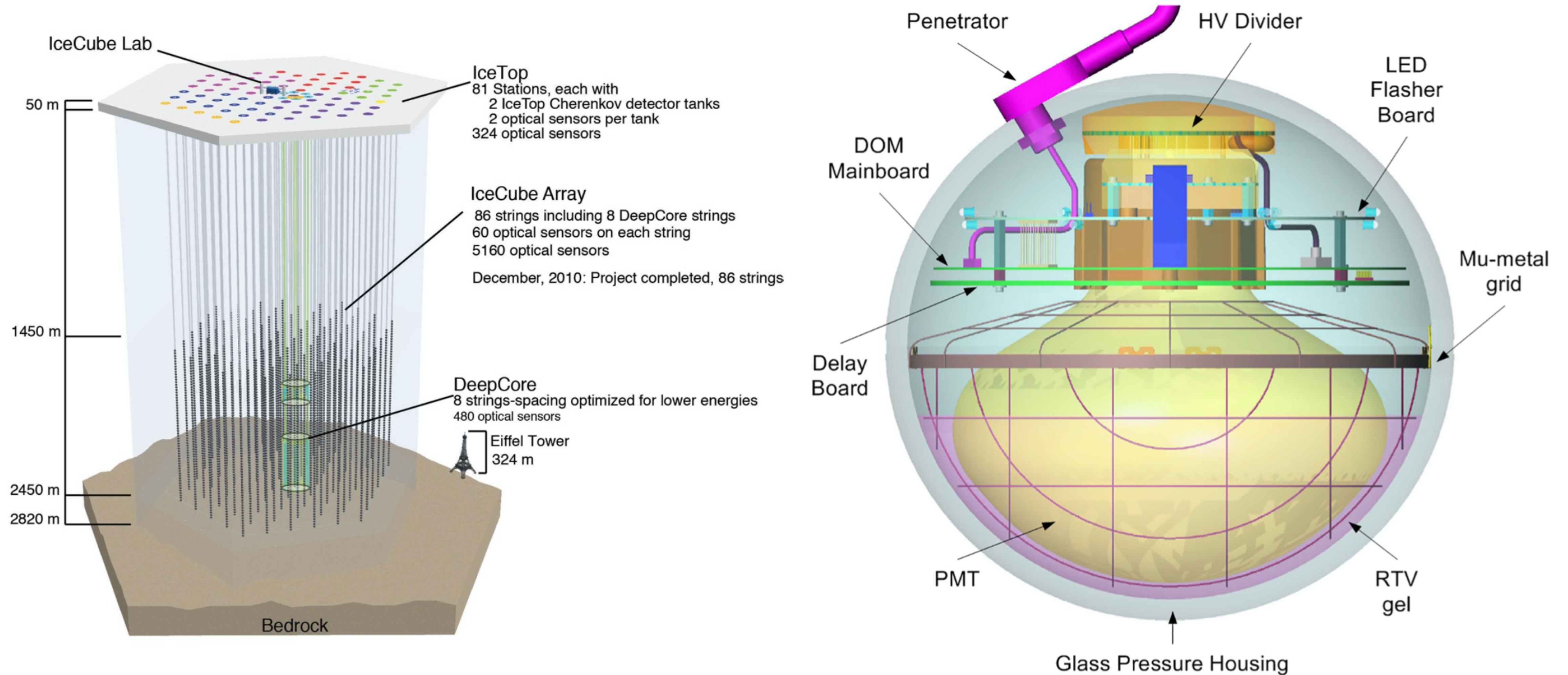
tracks

3.5:1

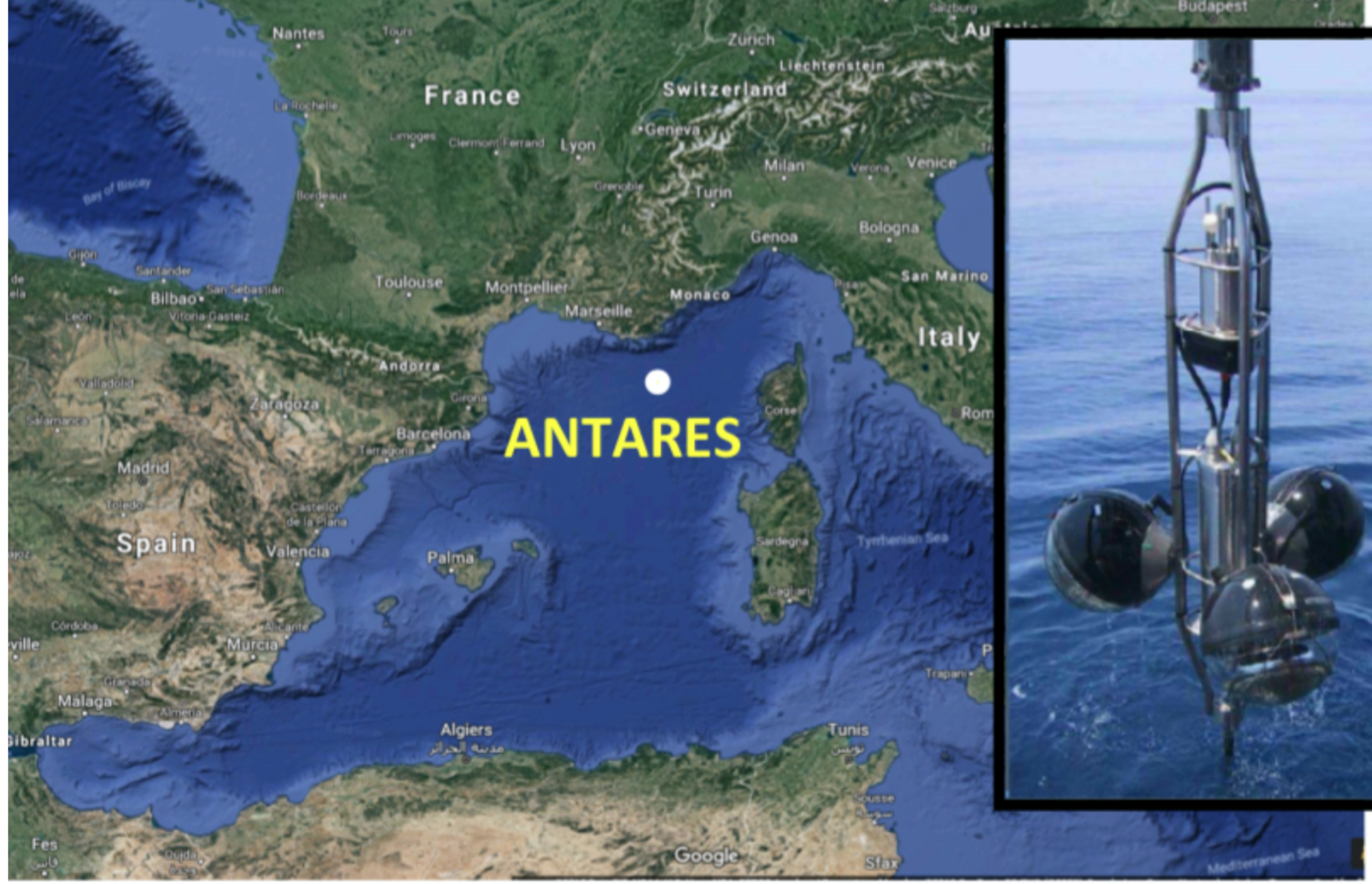




# The IceCube Neutrino Observatory







# ANTARES

Running since 2007

885 10" PMTs

12 lines

25 storeys/line

3 PMTs / storey

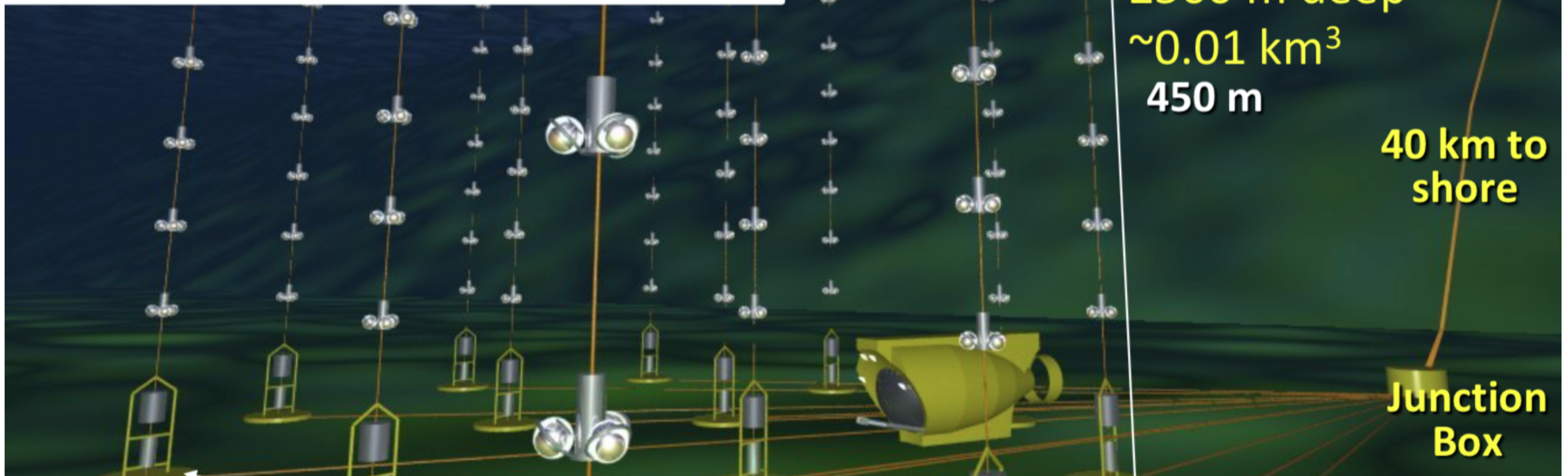
2500 m deep

$\sim 0.01 \text{ km}^3$

450 m

40 km to  
shore

Junction  
Box





# Neutrino Signatures in IceCube

## Cascade

10° angular resolution (> 100 TeV)  
15% deposited energy resolution

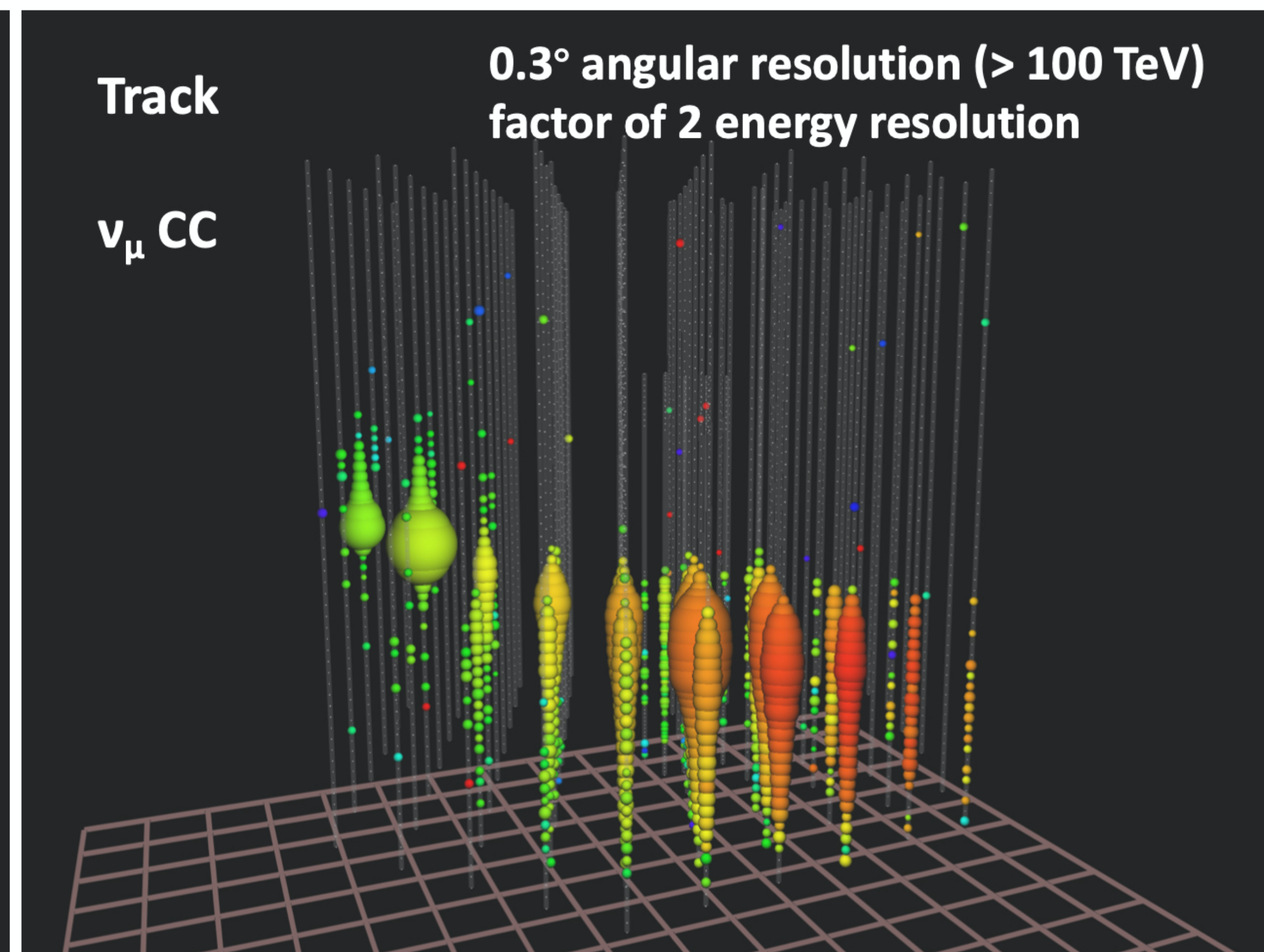
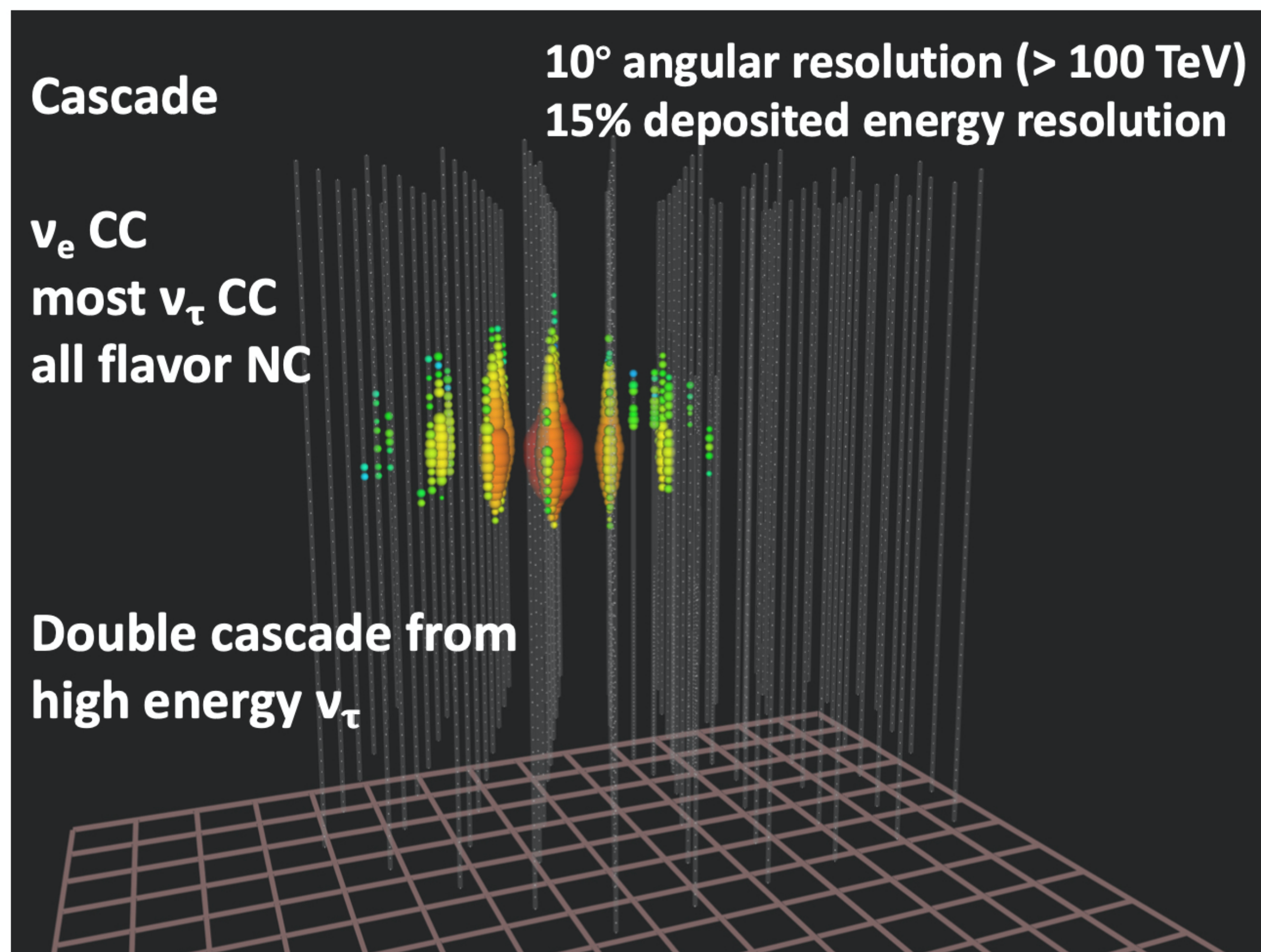
$\nu_e$  CC  
most  $\nu_\tau$  CC  
all flavor NC

Double cascade from  
high energy  $\nu_\tau$

## Track

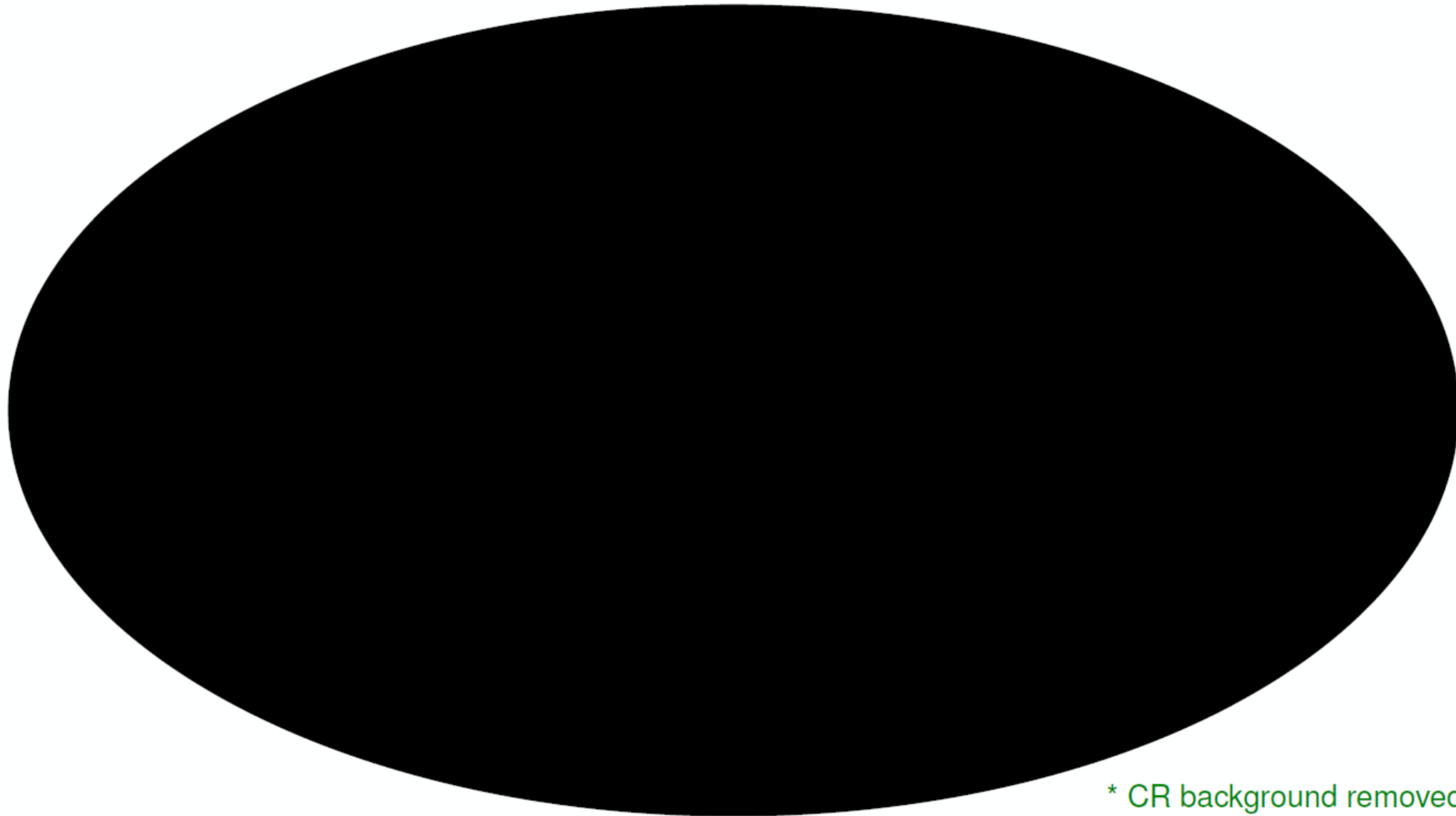
0.3° angular resolution (> 100 TeV)  
factor of 2 energy resolution

$\nu_\mu$  CC





# Neutrino sky map\* at very high energies **2012**



\* CR background removed



# Two events passed the selection criteria

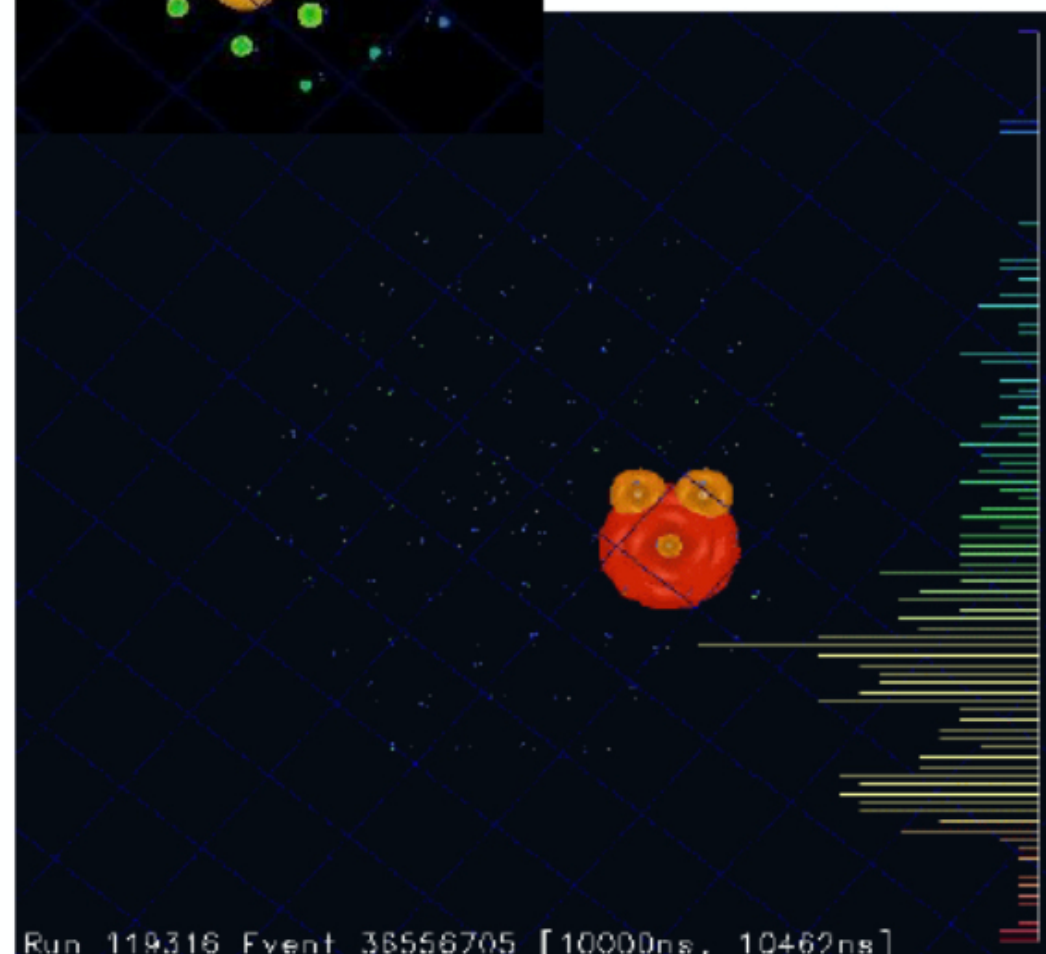
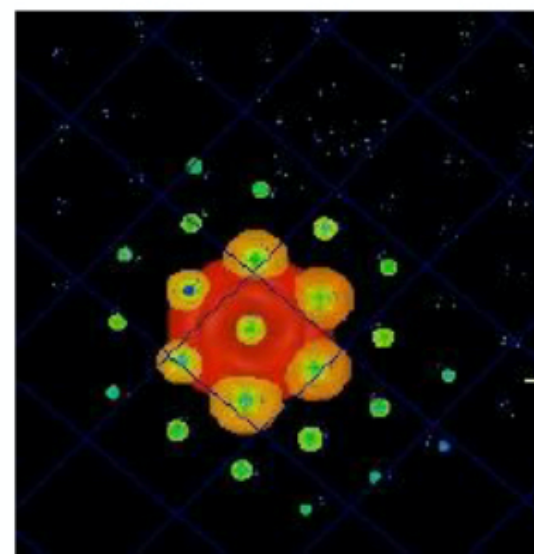
2 events / 672.7 days - background (atm.  $\mu$  + conventional atm.  $\nu$ ) expectation 0.14 events  
preliminary p-value: 0.0094 ( $2.36\sigma$ )

Run119316-Event36556705

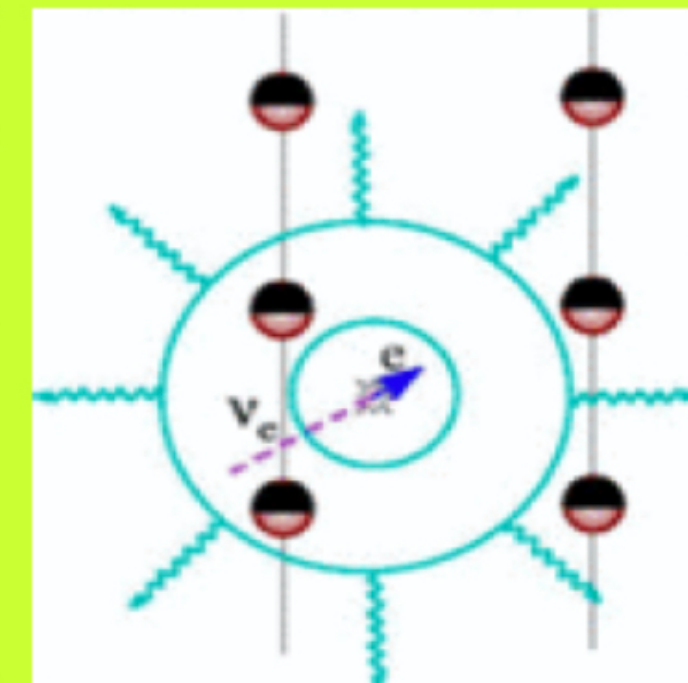
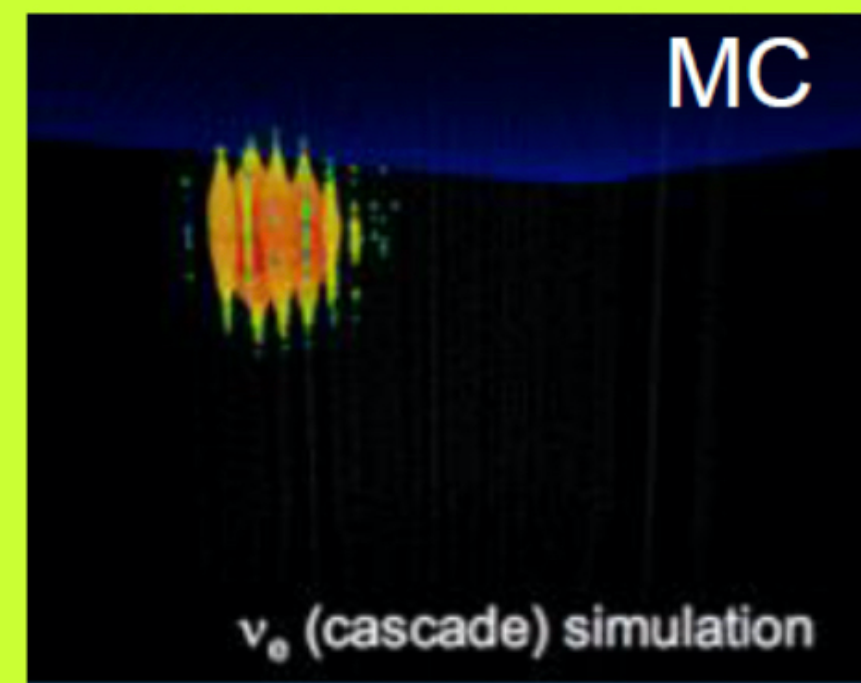
Jan 3<sup>rd</sup> 2012

NPE  $9.628 \times 10^4$

Number of Optical Sensors 312



CC/NC interactions in the detector

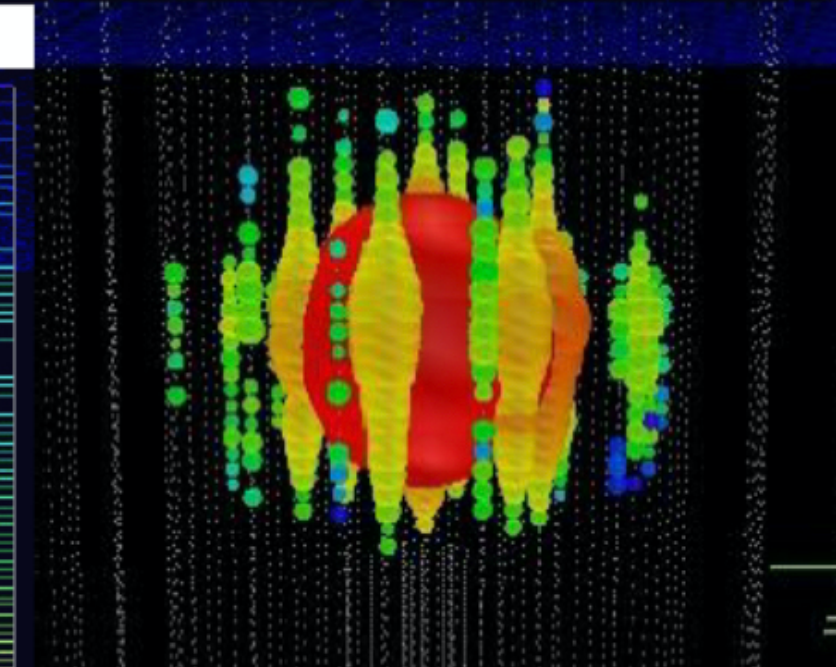
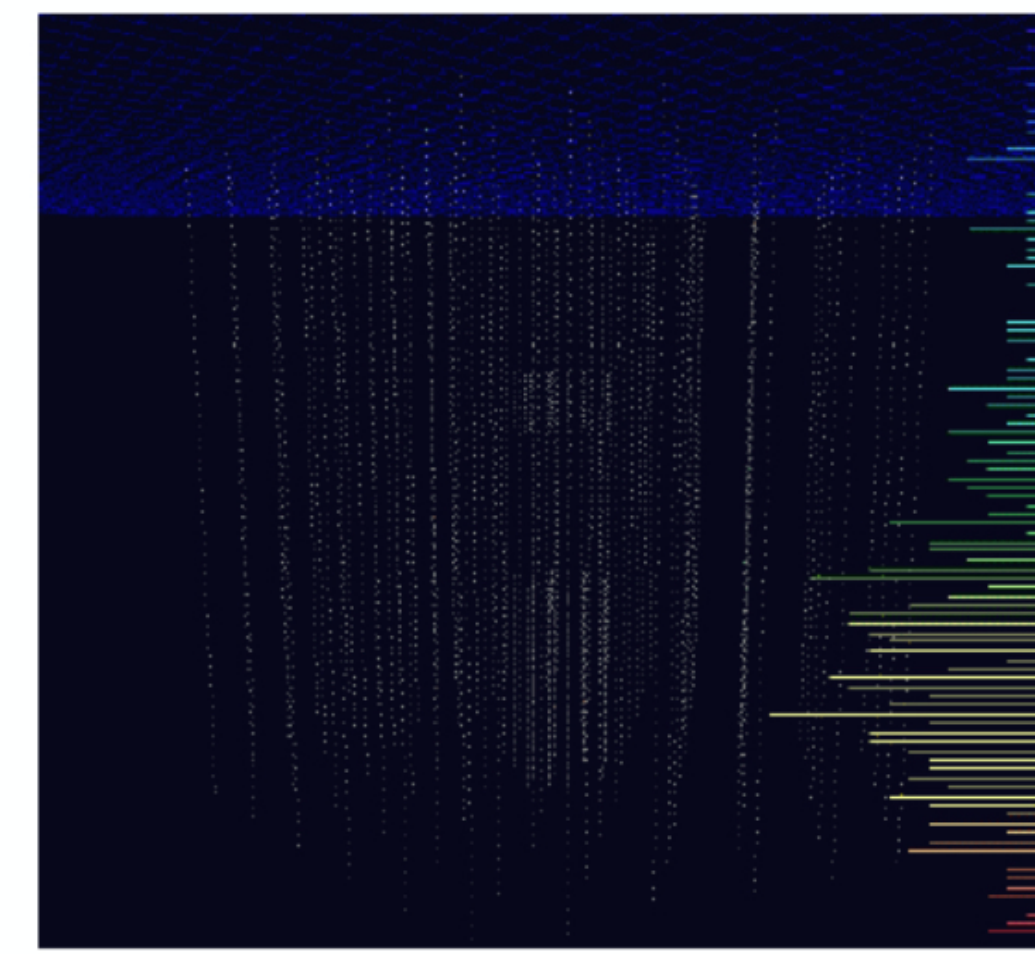
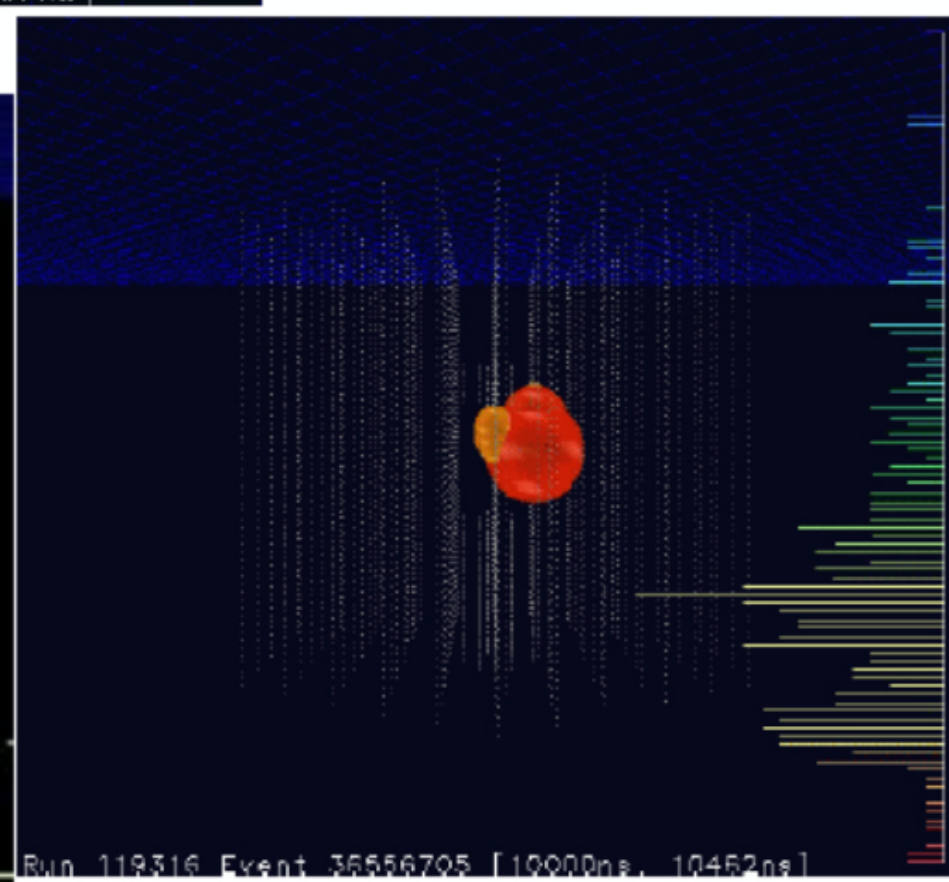
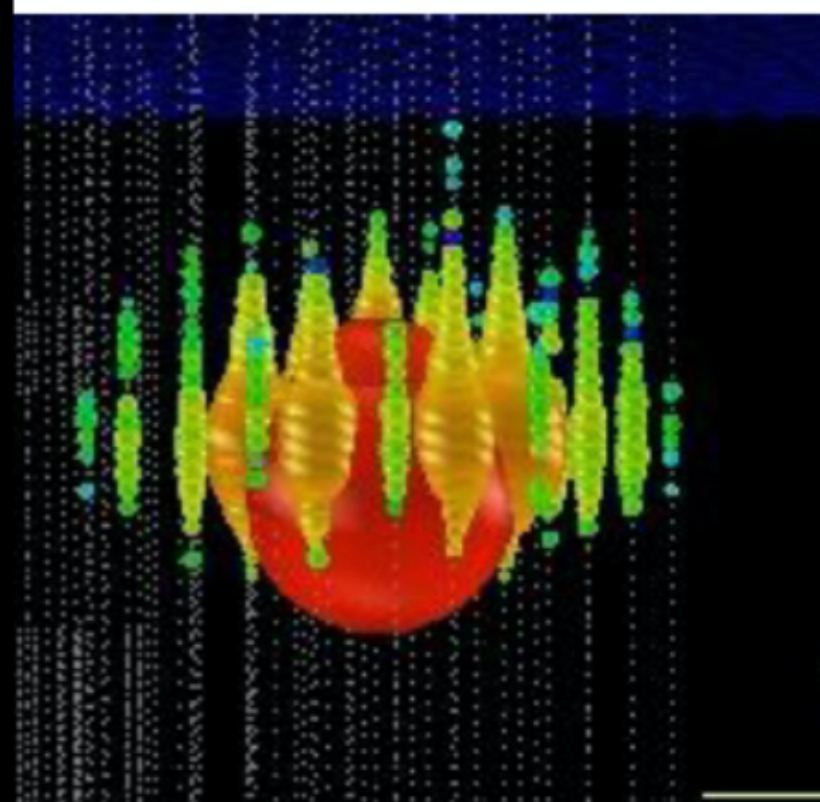
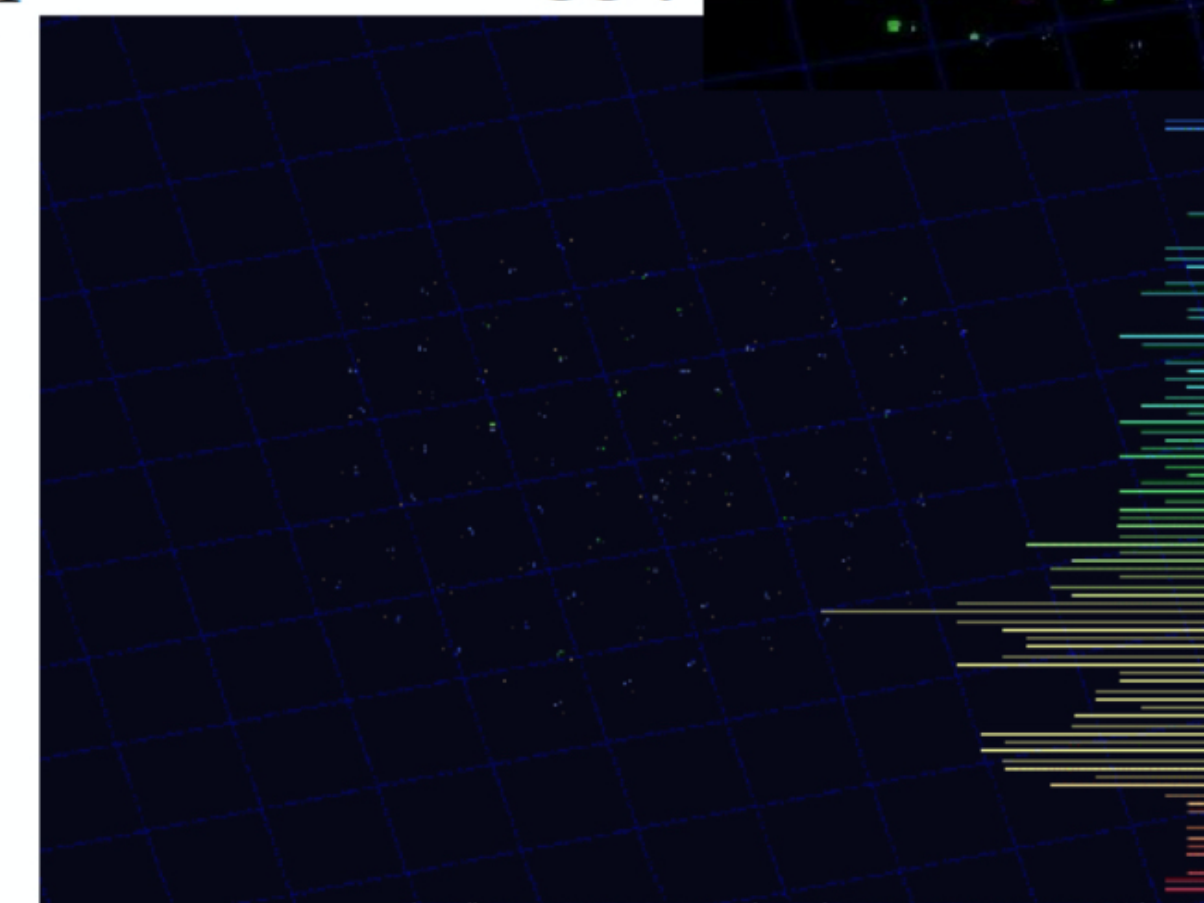
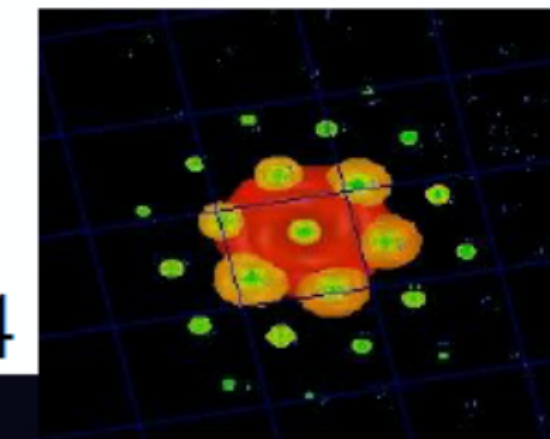


Run118545-Event63733662

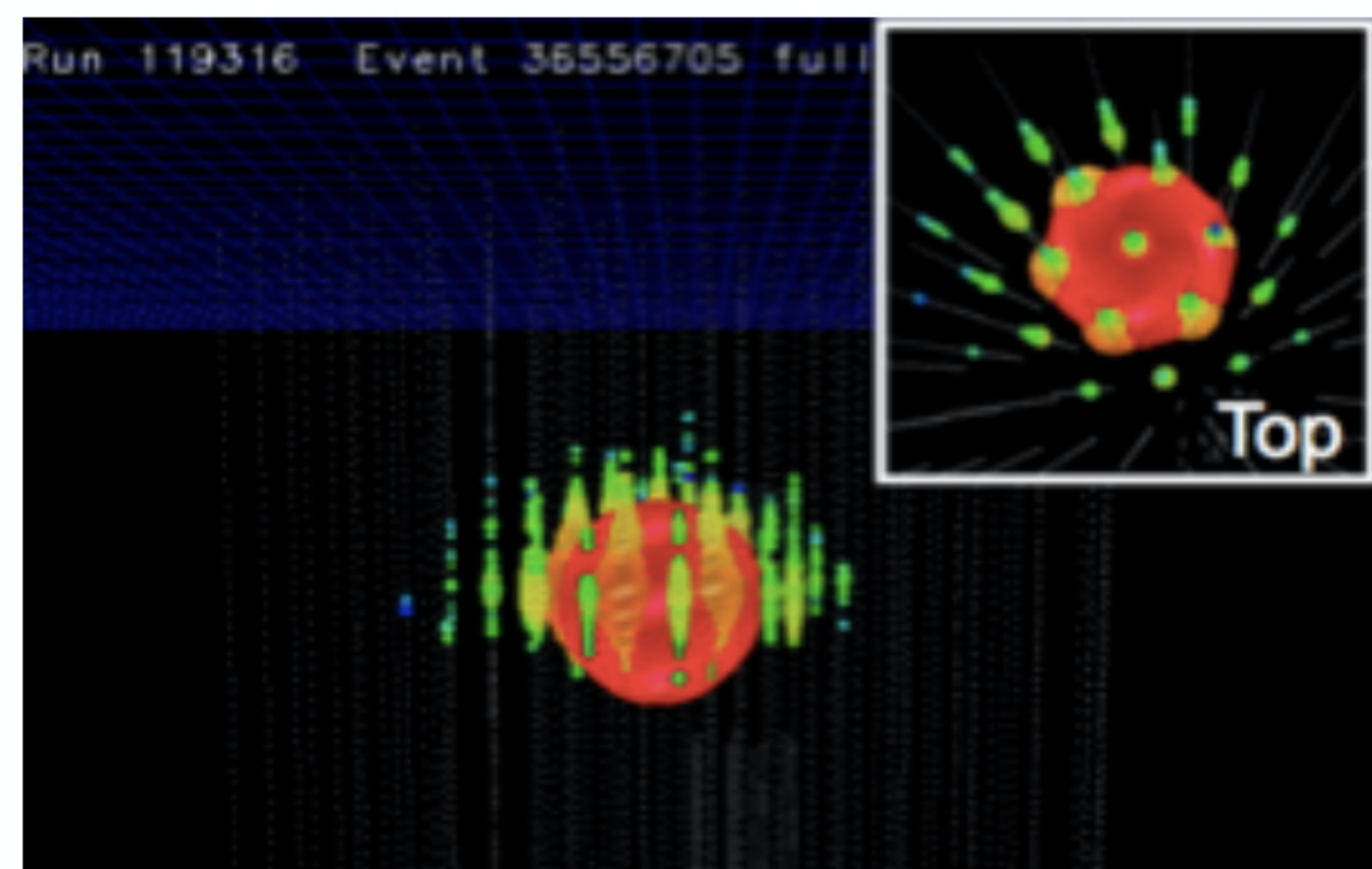
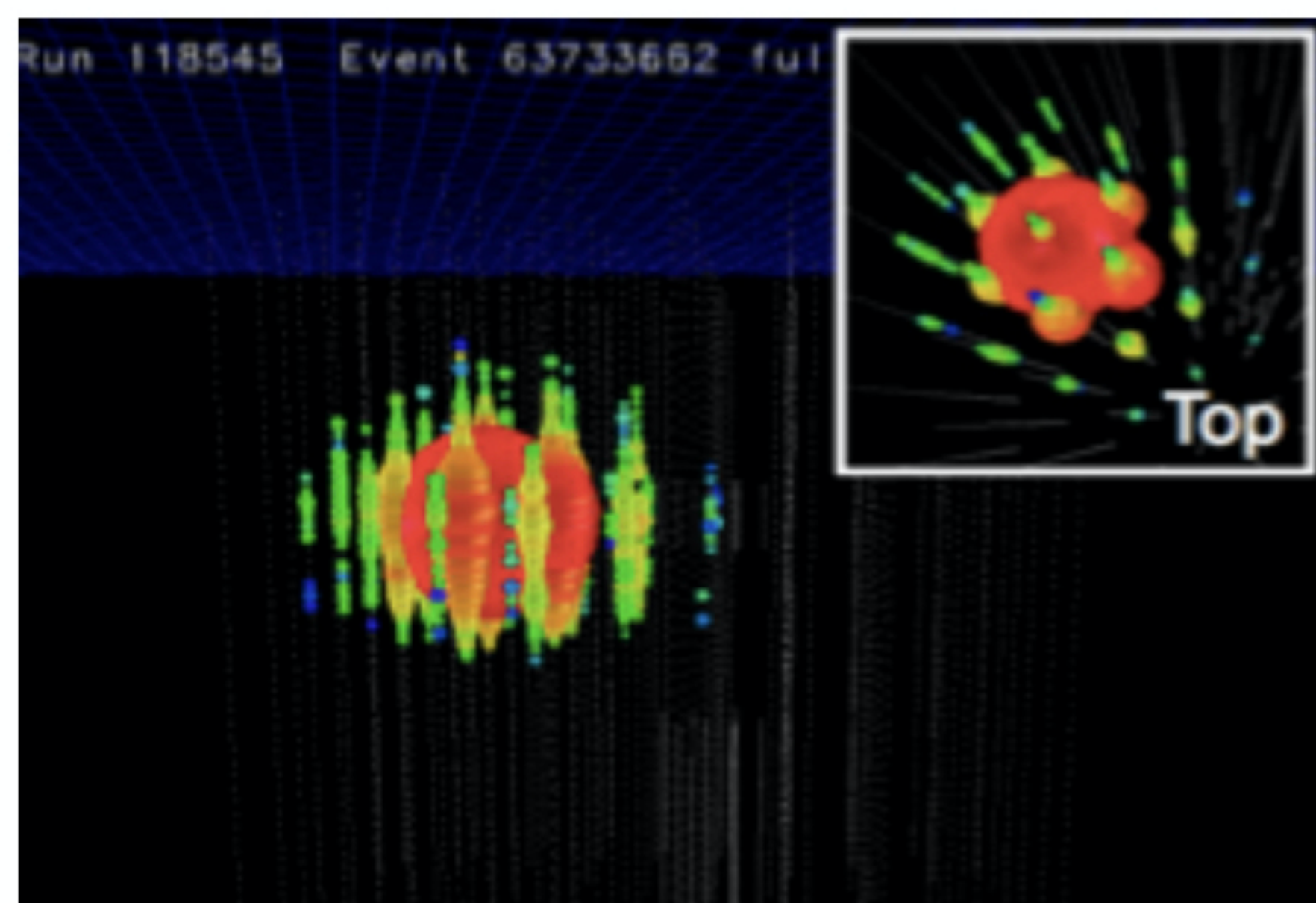
August 9<sup>th</sup> 2011

NPE  $6.9928 \times 10^4$

Number of Optical Sensors 354







| date (GMT)                              | Aug. 8, 2011      | Jan. 3, 2012      |
|-----------------------------------------|-------------------|-------------------|
| NPE                                     | $7.0 \times 10^4$ | $9.6 \times 10^4$ |
| number of recorded DOMs                 | 354               | 312               |
| reconstructed deposited<br>energy (PeV) | $1.04 \pm 0.16$   | $1.14 \pm 0.17$   |
| reconstructed $z$ vertex (m)            | $122 \pm 5$       | $25 \pm 5$        |



# ANTARES – Diffuse flux

## Sample:

- 2007 – 2015, 2450 days of livetime (**9 years**)
- All-flavour analysis (track+showers)

Event selection chain + energy-related cut applied to

- obtain a high-purity neutrino sample
- maximize sensitivity

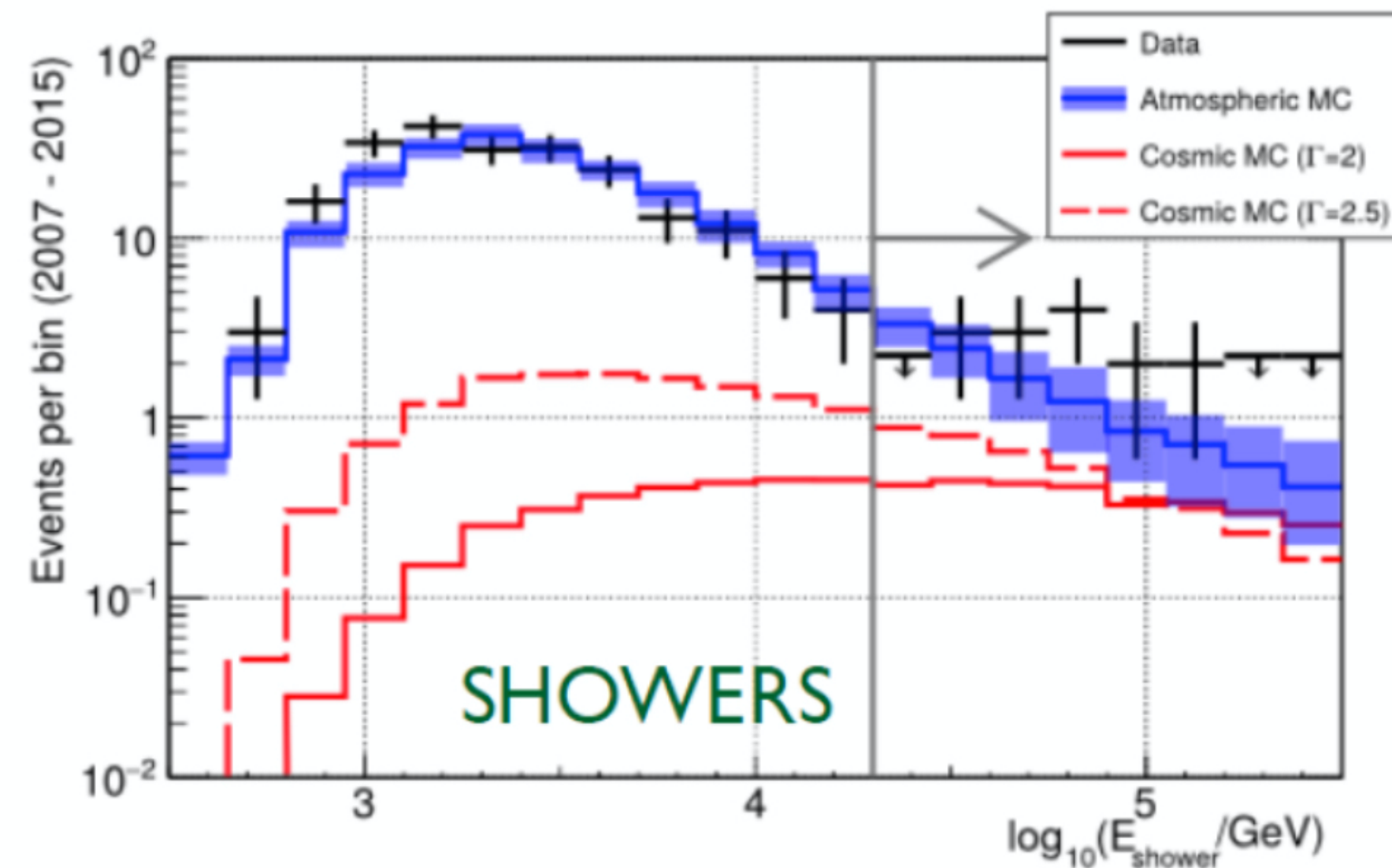
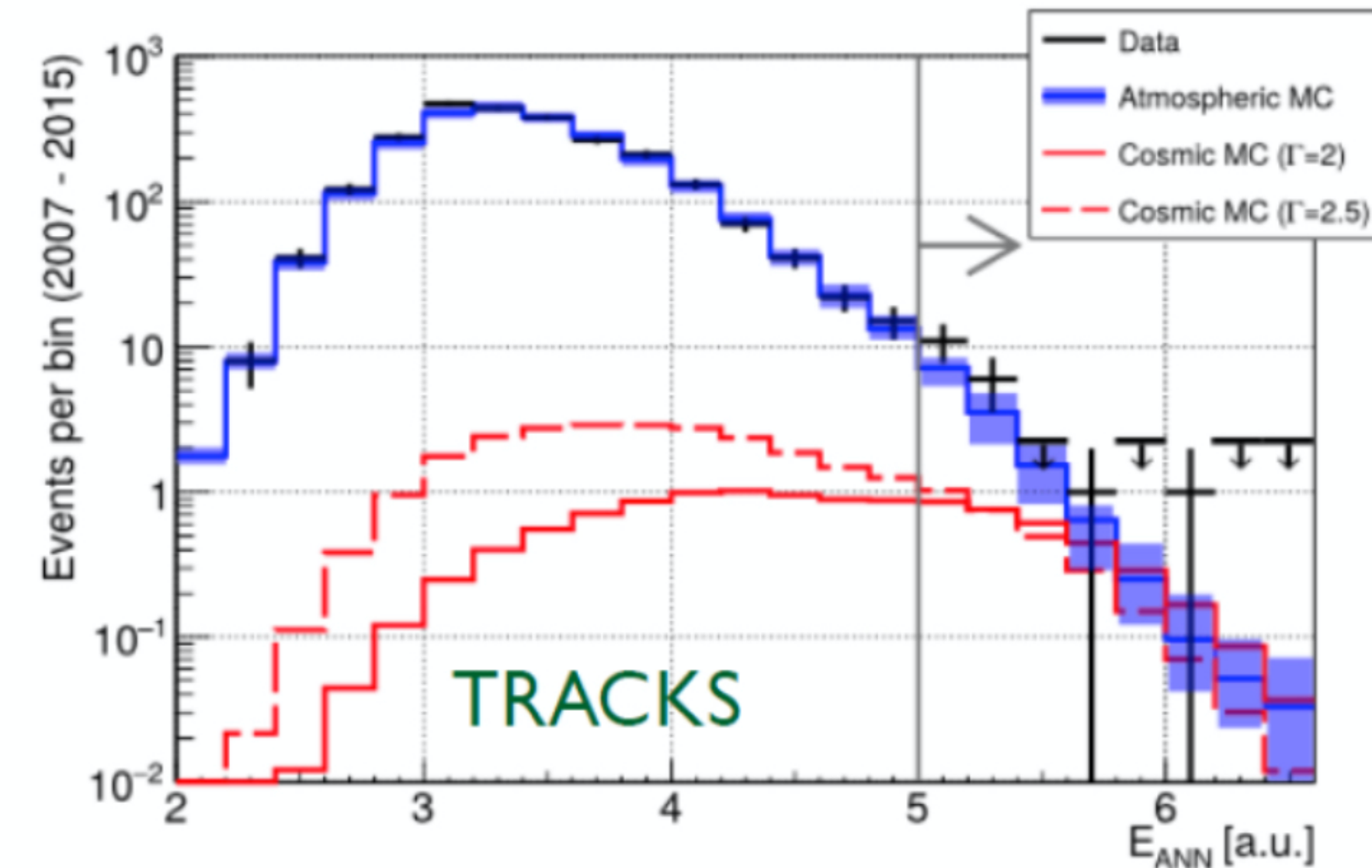
Signal modeled according to the IceCube flux

## Result:

**33 events** (19 tracks + 14 showers) in data  
 **$24 \pm 7$  (stat.+syst.) events** background in MC

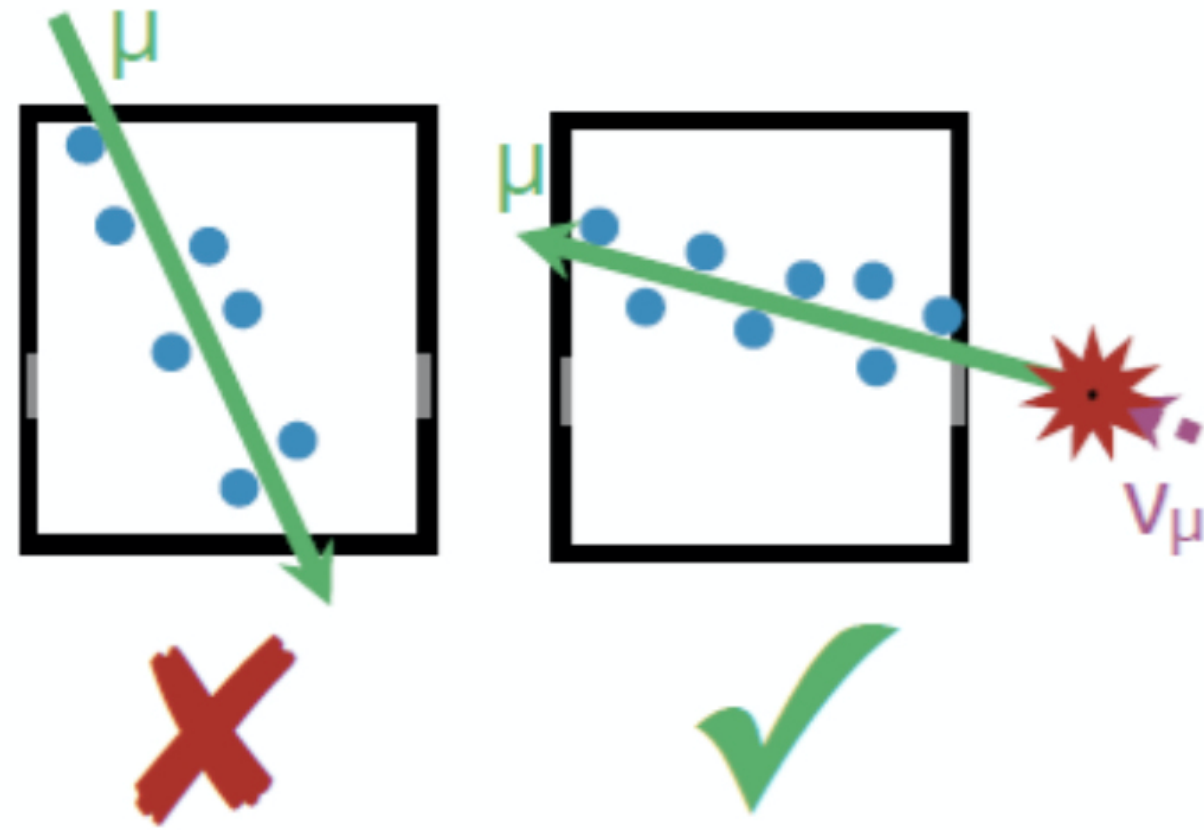
$1.6\sigma$  excess, null cosmic rejected at 85% CL

ApJ 853, (2018) L7  
arXiv:1711.07212v1



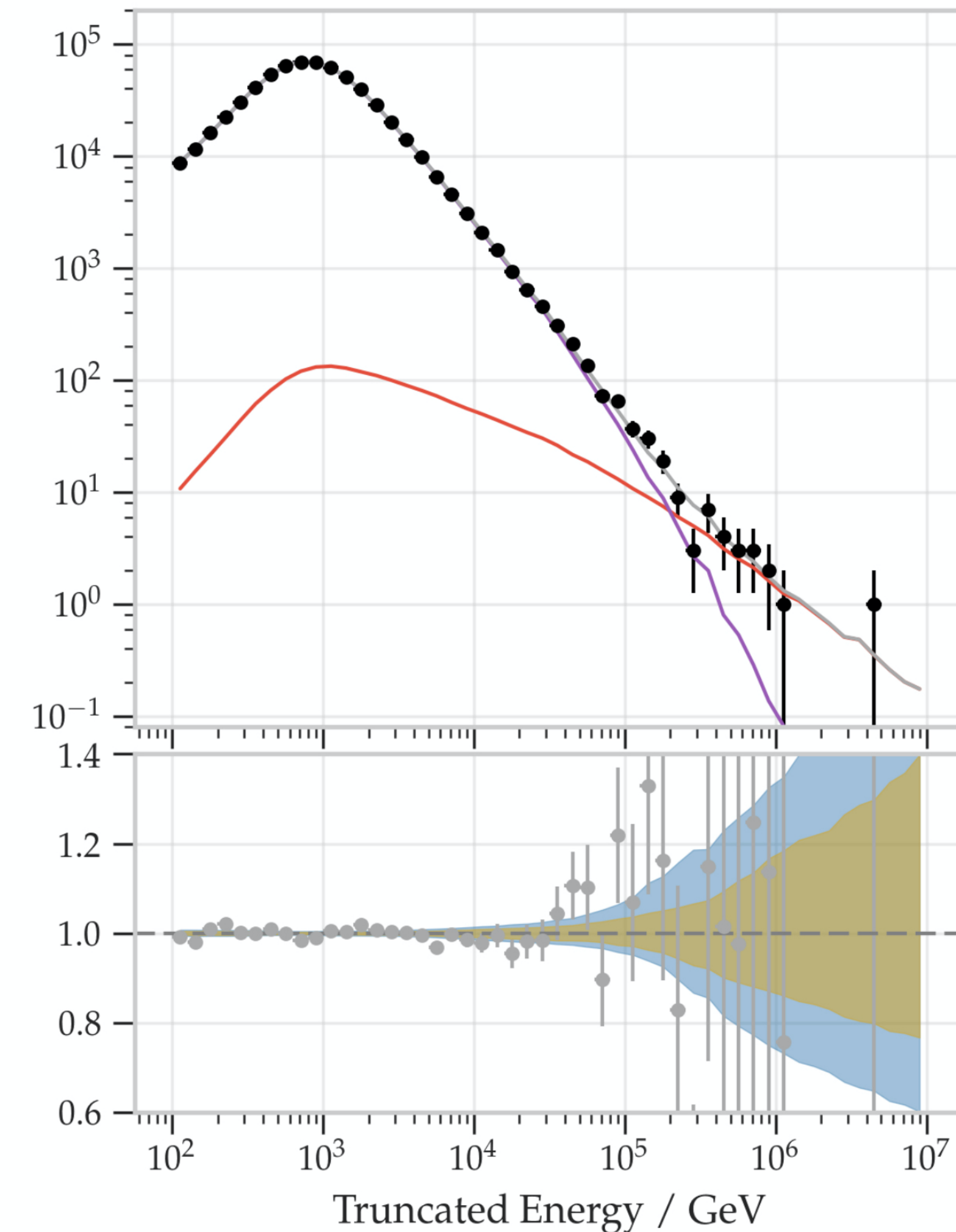
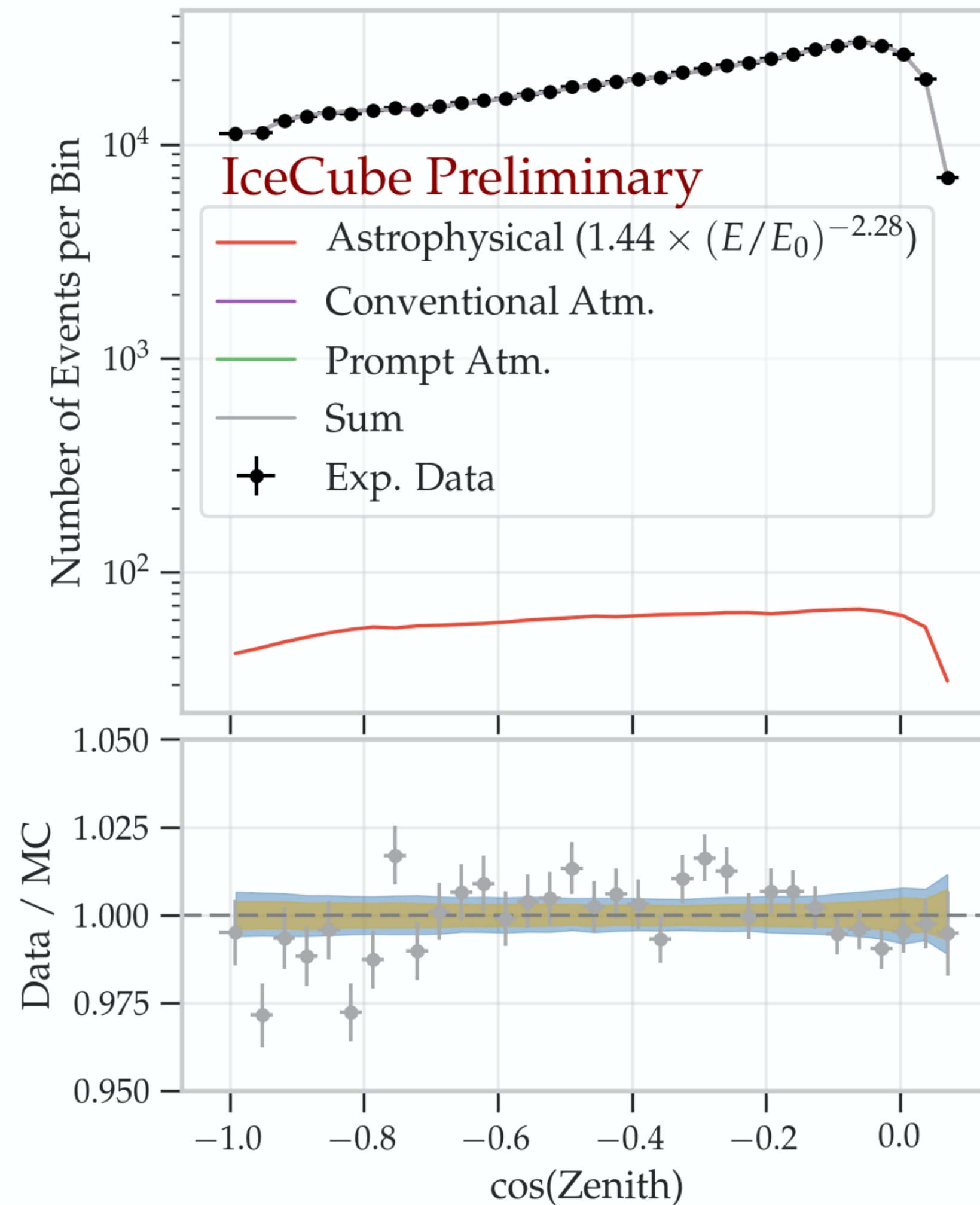


# $\nu_\mu$ from the Northern sky 10 years (2010 - 2018), $> 650000$ atm. neutrinos



- Selected horizontal and up-going muon tracks
- Sensitive to astrophysical neutrinos above  $\sim 120$  TeV
- Power law index:  

$$\gamma_{astro} = 2.28 \pm_{0.09}^{0.08}$$
 arXiv:1908.09551v1

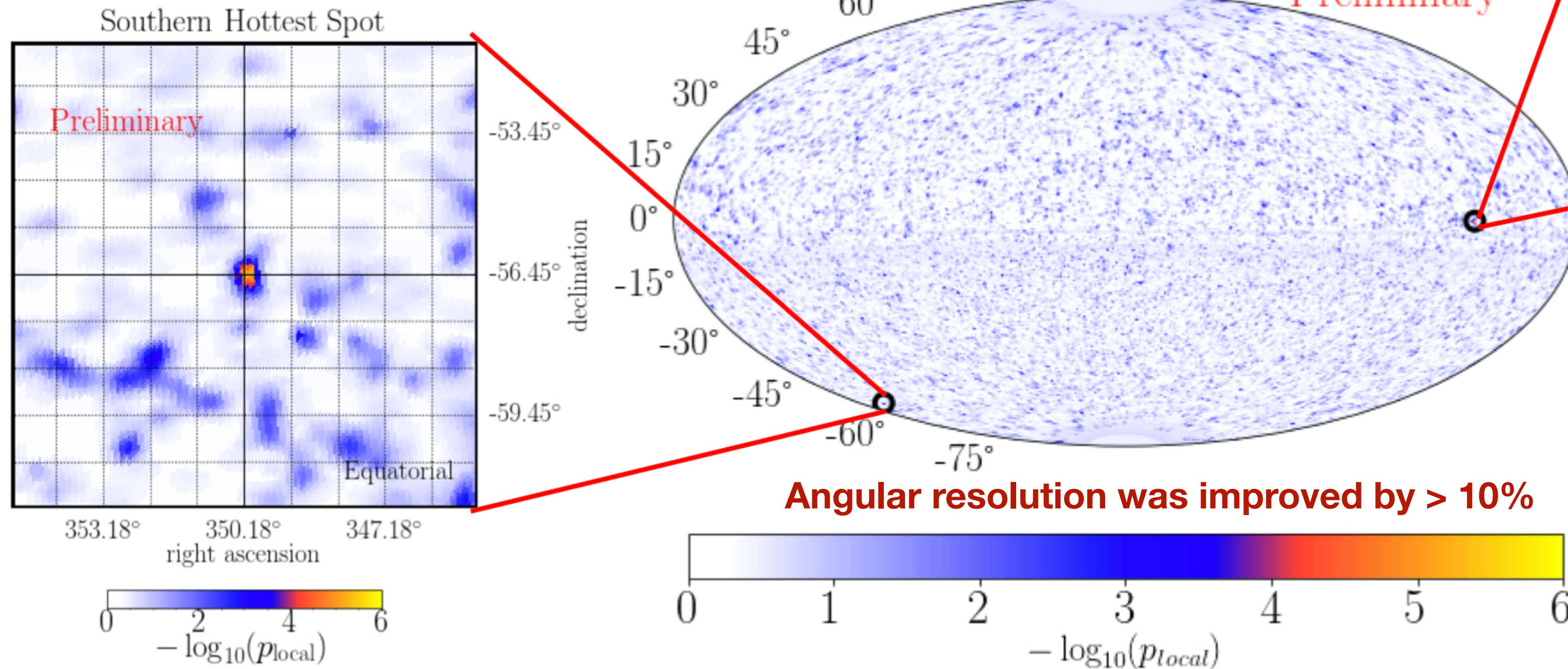


Astrophysical contribution is observed at  $5.6 \sigma$  significance arXiv:1607.08006v1



# All sky combined 10 year search

Using high energy through-going tracks and tracks optimized for point source searches



T. Carver NU5c

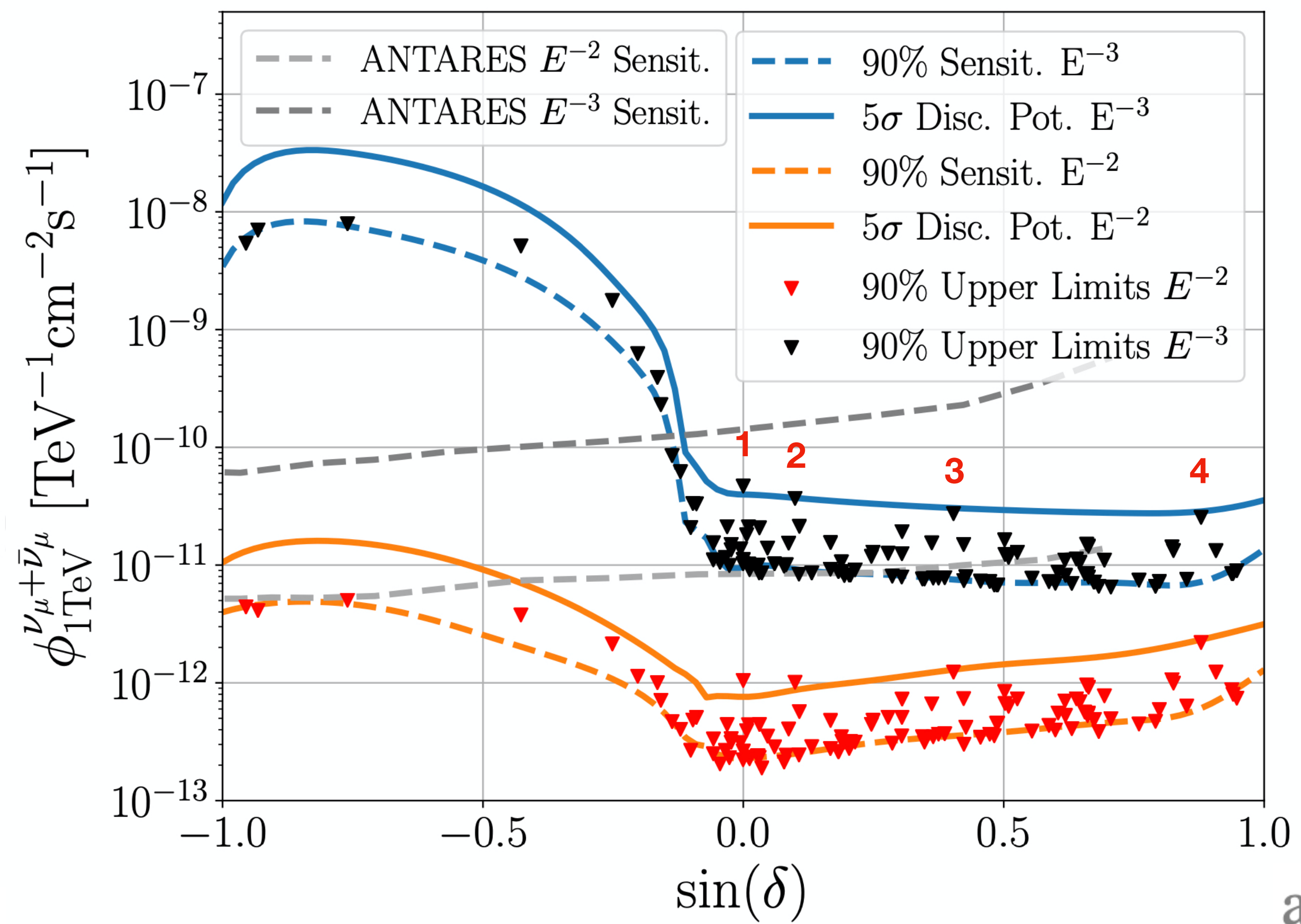
New source list of 110 Galactic and Extragalactic objects  
Hottest spot in Northern Hemisphere coincides with  
2.9 $\sigma$  excess at the position of NGC 1068



arXiv:1910.08488v1



# All sky combined 10 year search



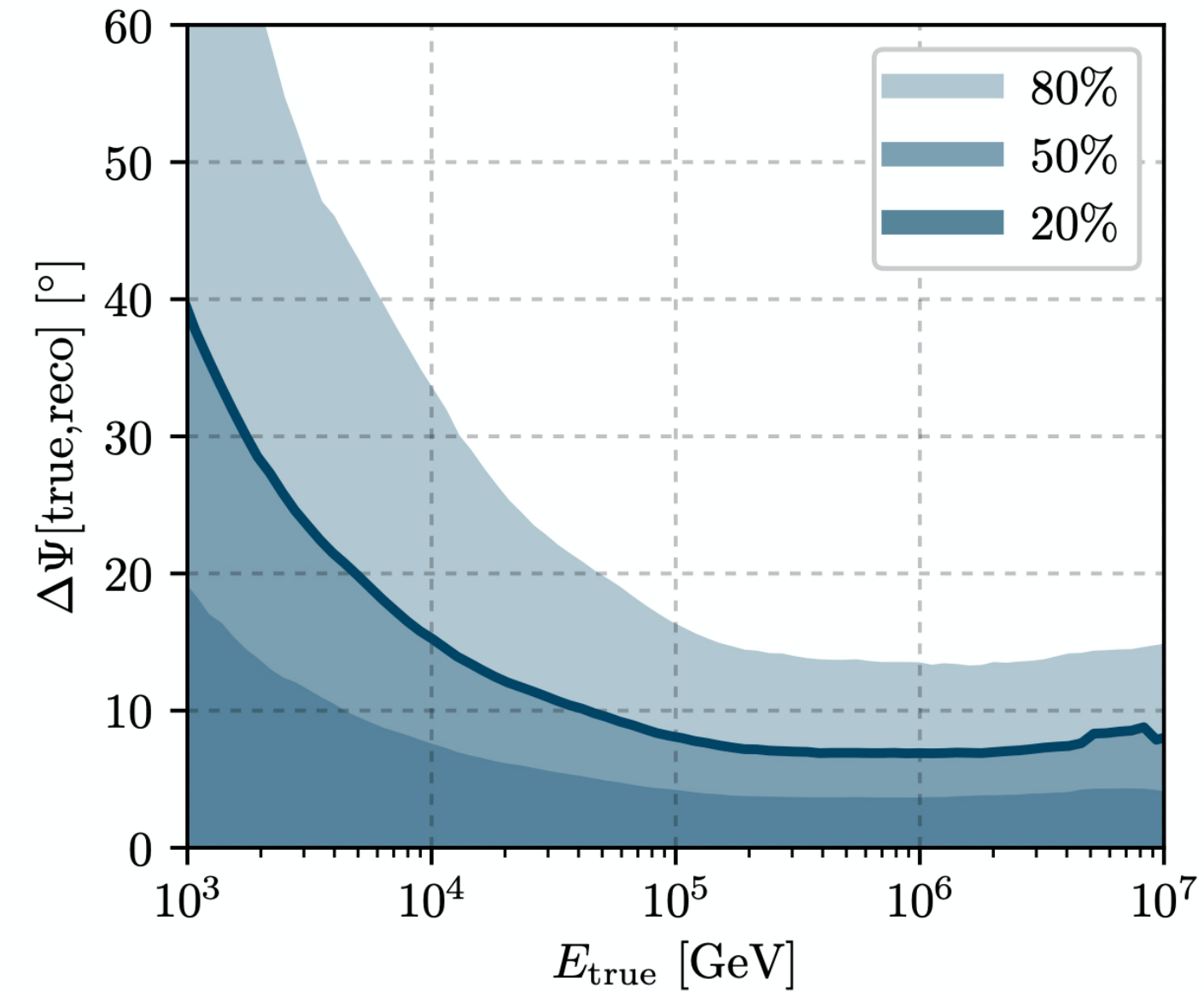
1. **NGC 1068**
2. **TXS 0506 + 056**
3. **PKS 1424 + 240**
4. **GB6 J1542+6129**

Source list search is incompatible with background at  $3.3\sigma$  ( $2.25\sigma$  without TXS 0506)

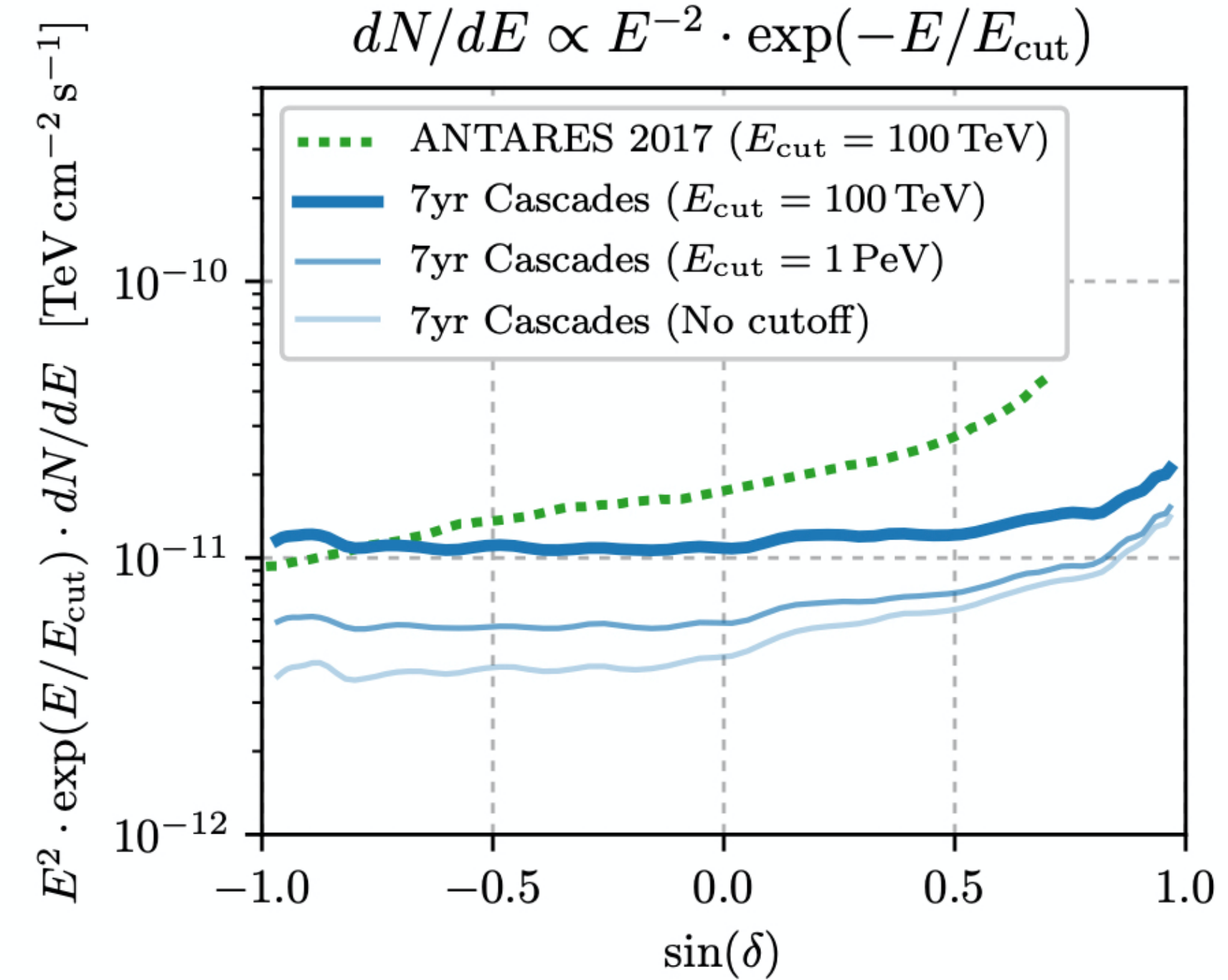
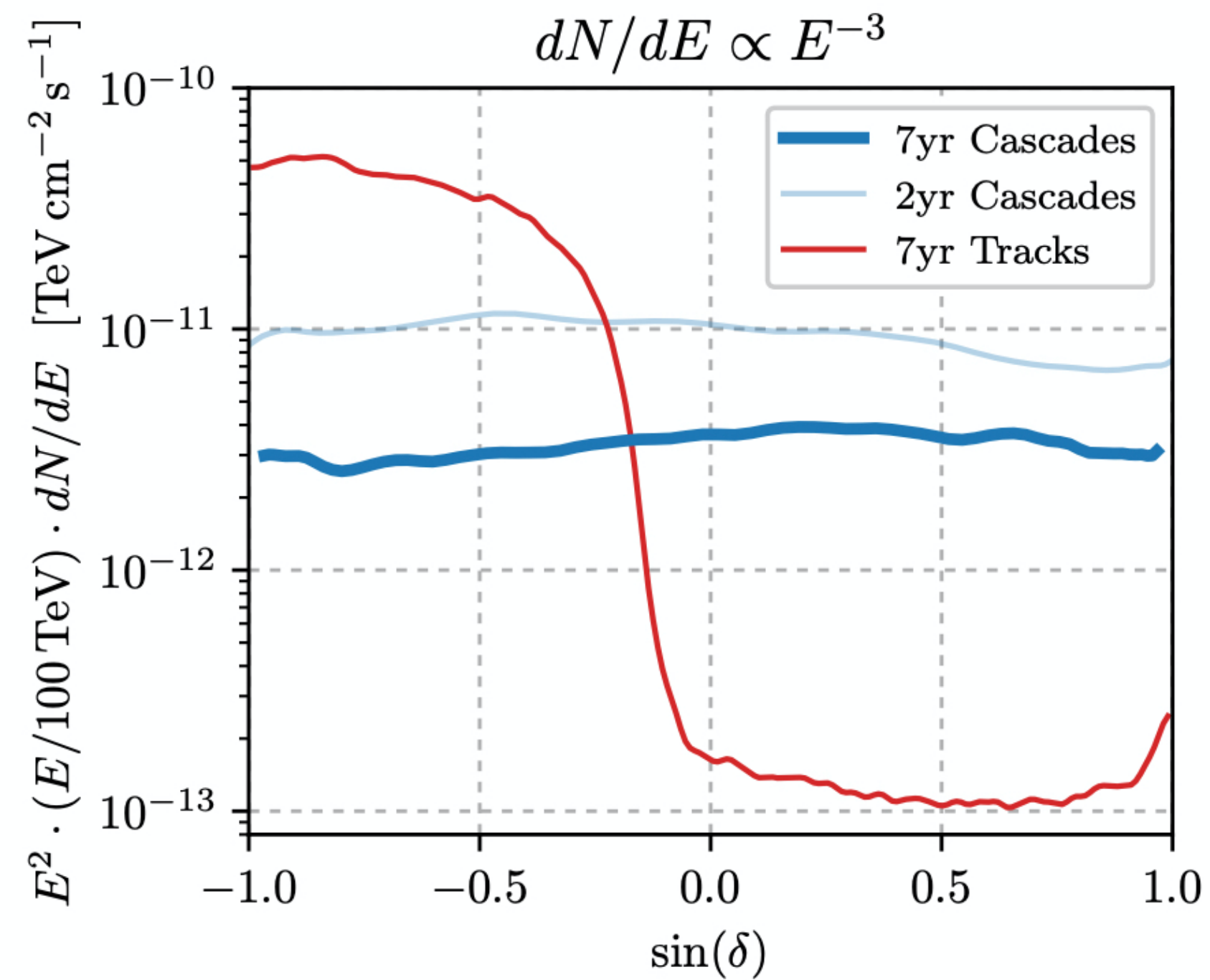
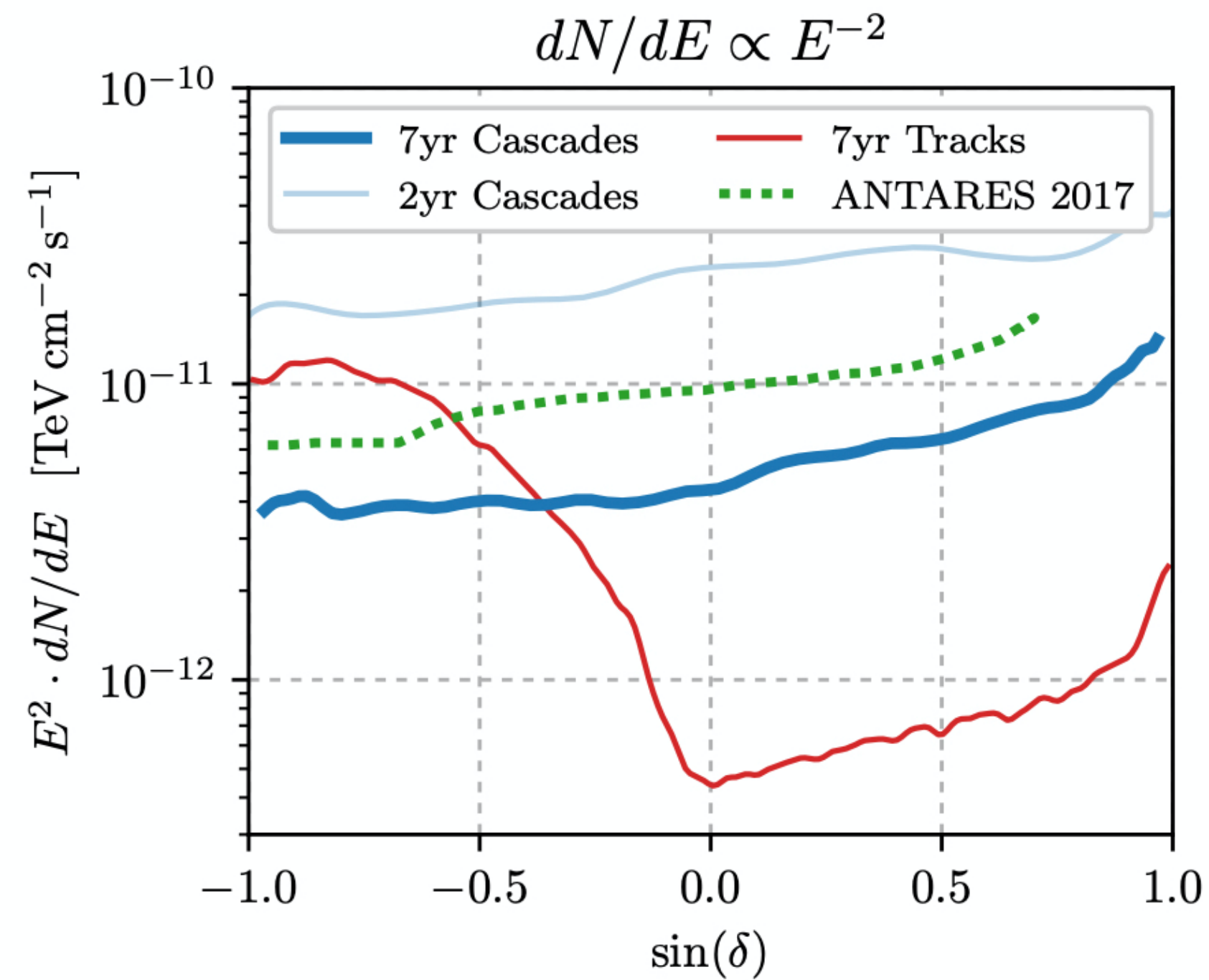
T. Carver NU5c



# Search for Sources of Astrophysical Neutrinos Using Seven Years of IceCube Cascade Events

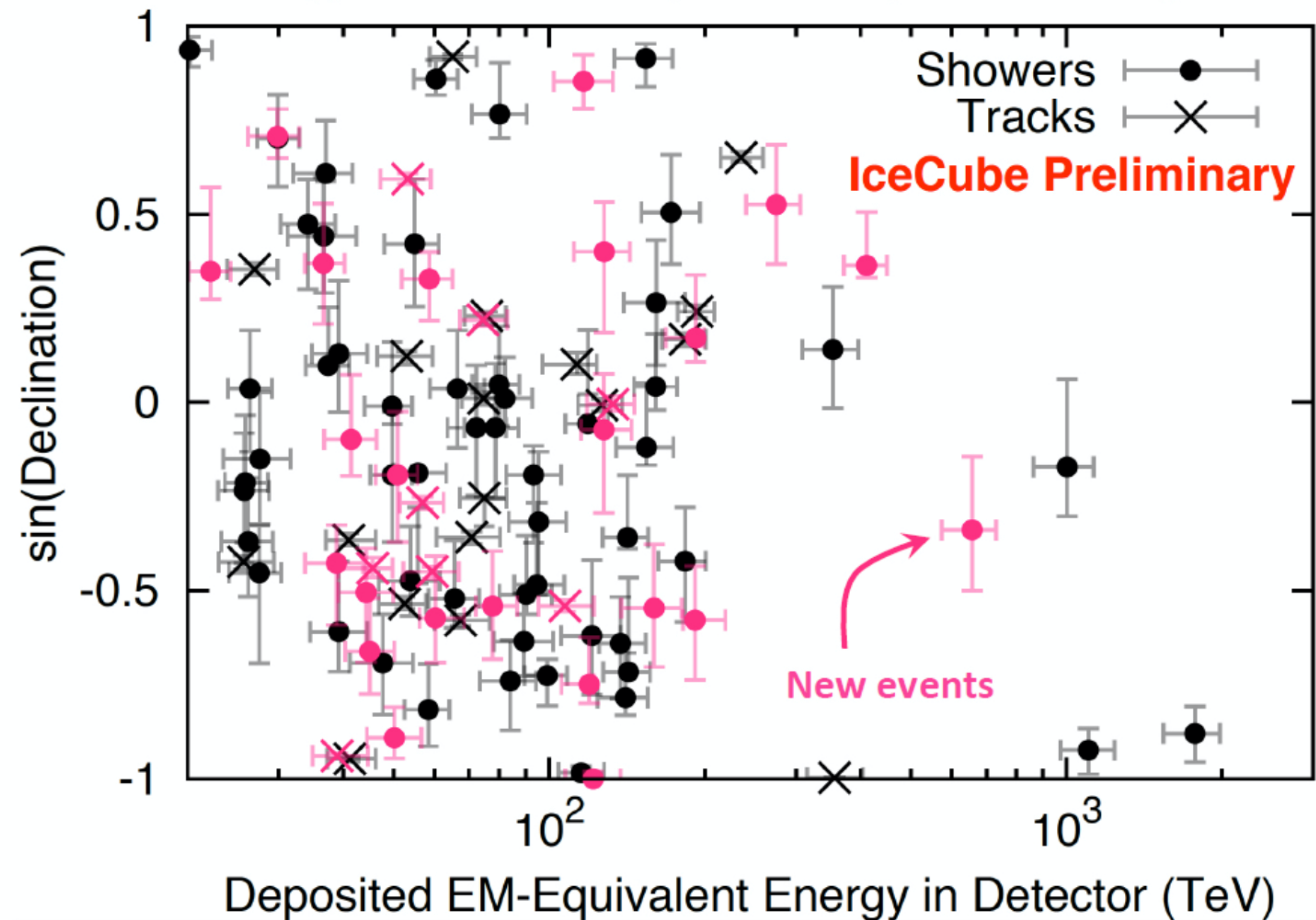
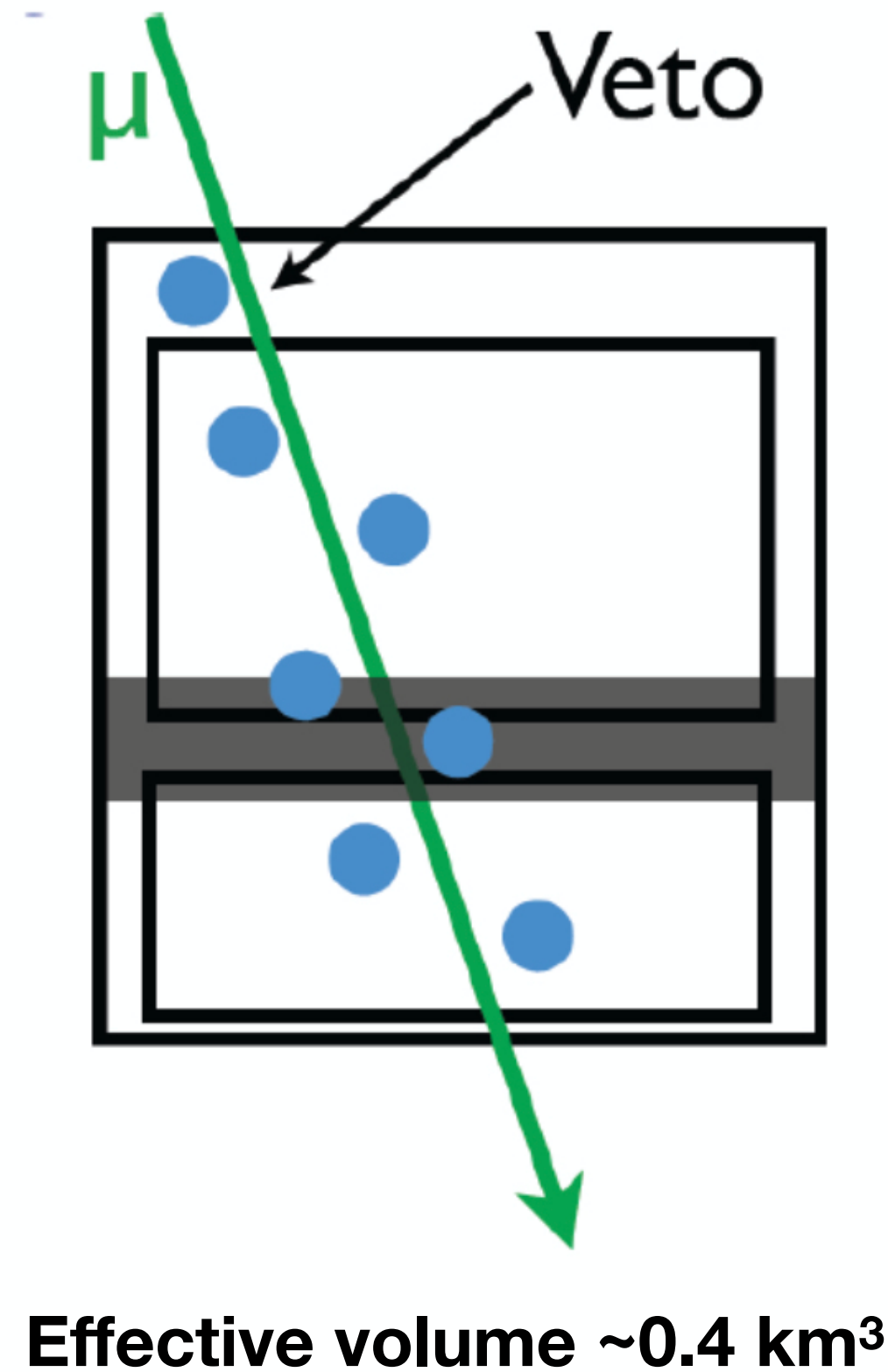


arXiv:1907.06714v1





# High-Energy Starting Events (HESE) – 7.5 yr



Prior result 6 years [ICRC 2017 arXiv:1710.01191](#)

[arXiv:1907.11266v2](#)

Updates to calibration and ice optical properties

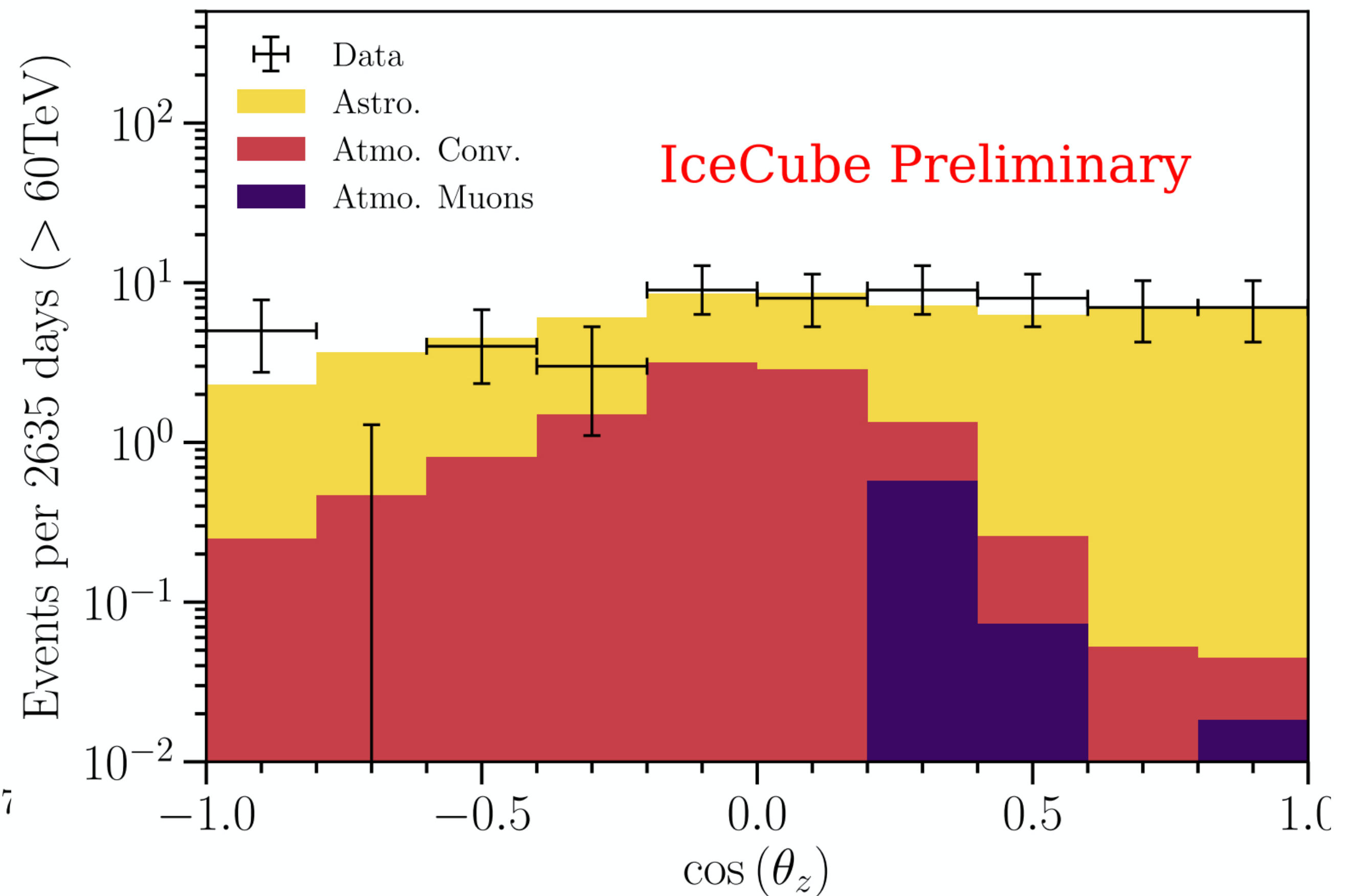
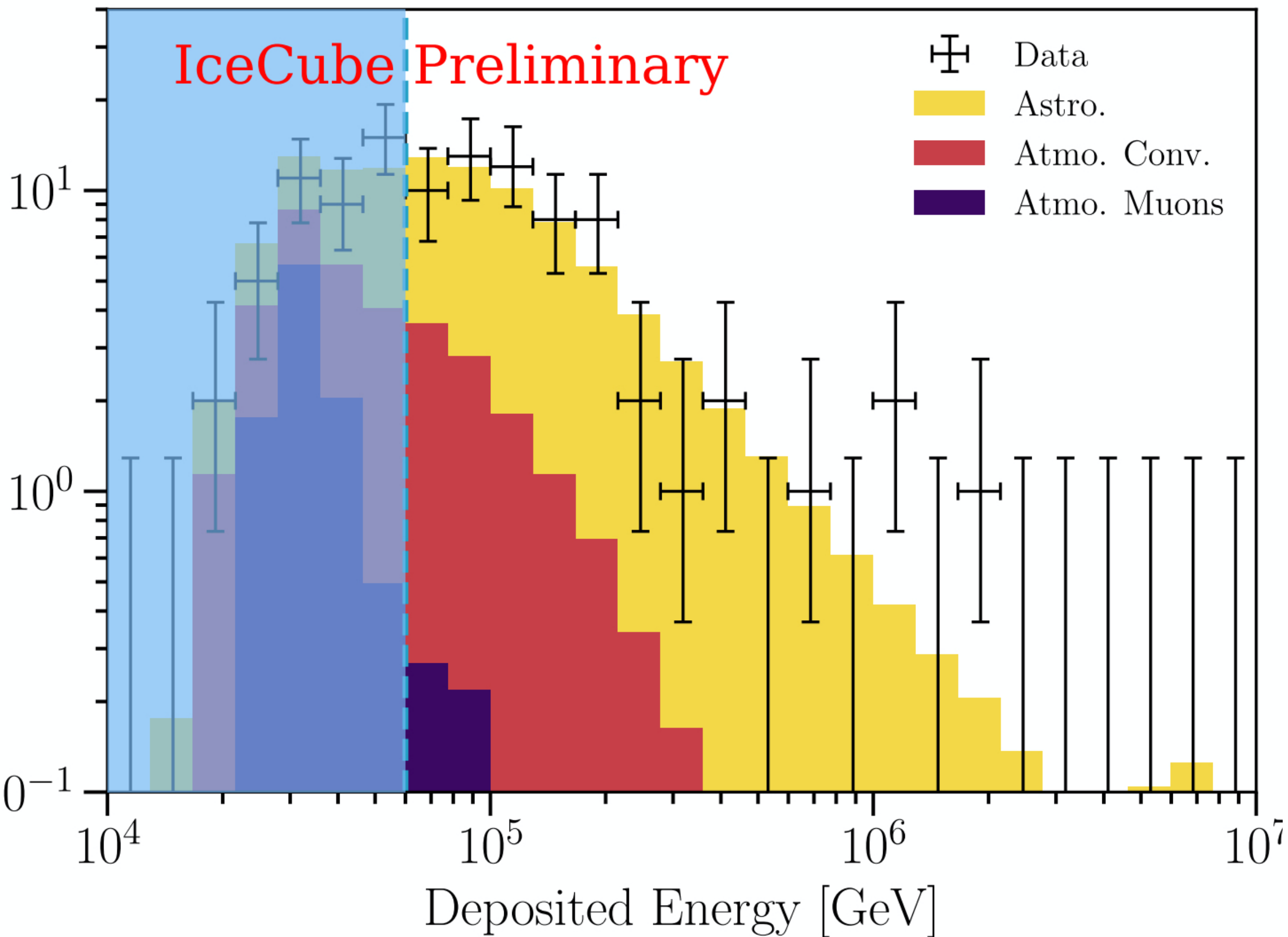
103 events, with 60 events  $> 60 \text{ TeV}$

→ Changes to RA, Dec, energy

[IceCube. Nature volume 551 \(2017\) 596](#)  
[Poster #175. Wandkowsky et al. \(IceCube\)](#)



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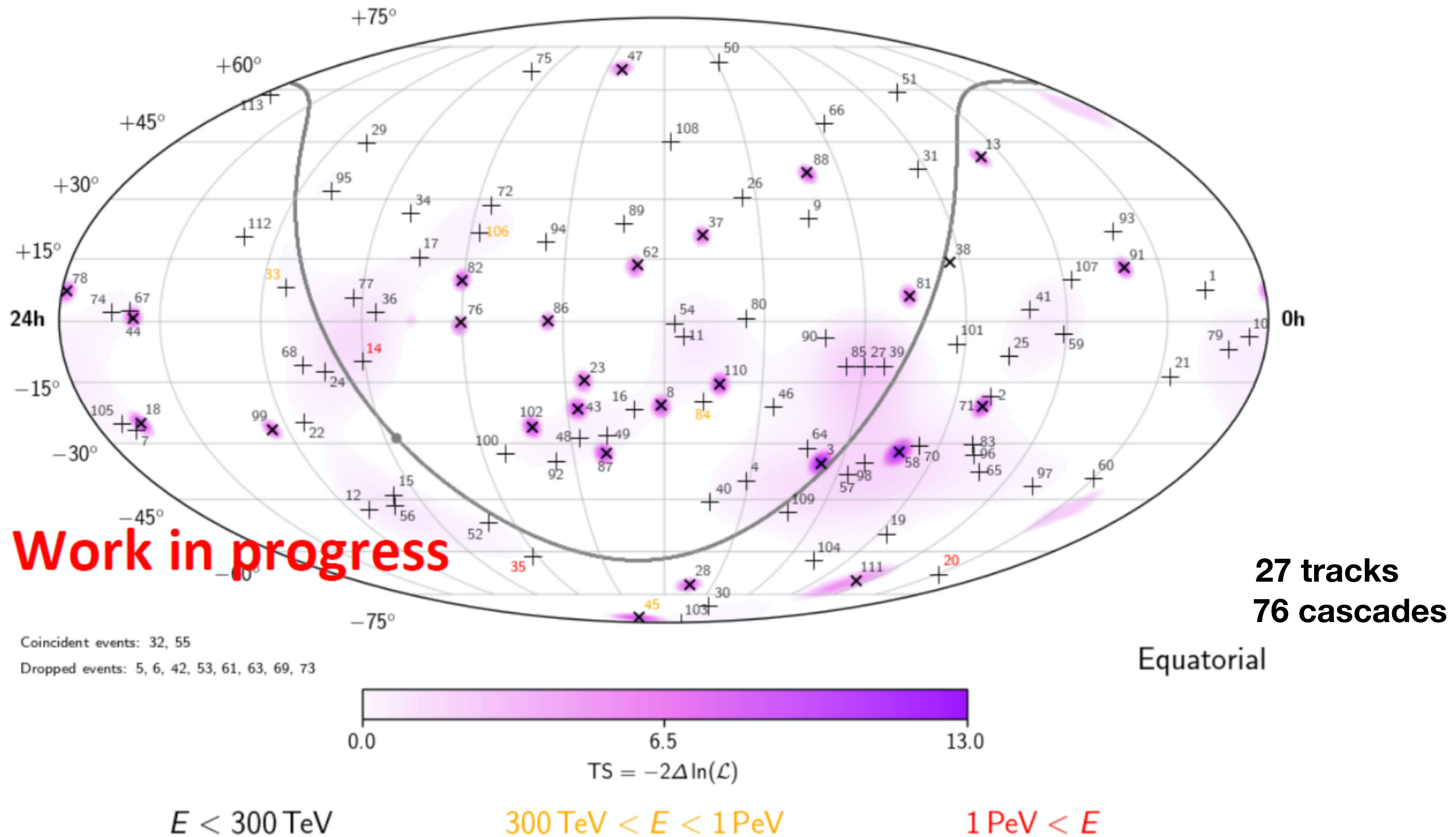
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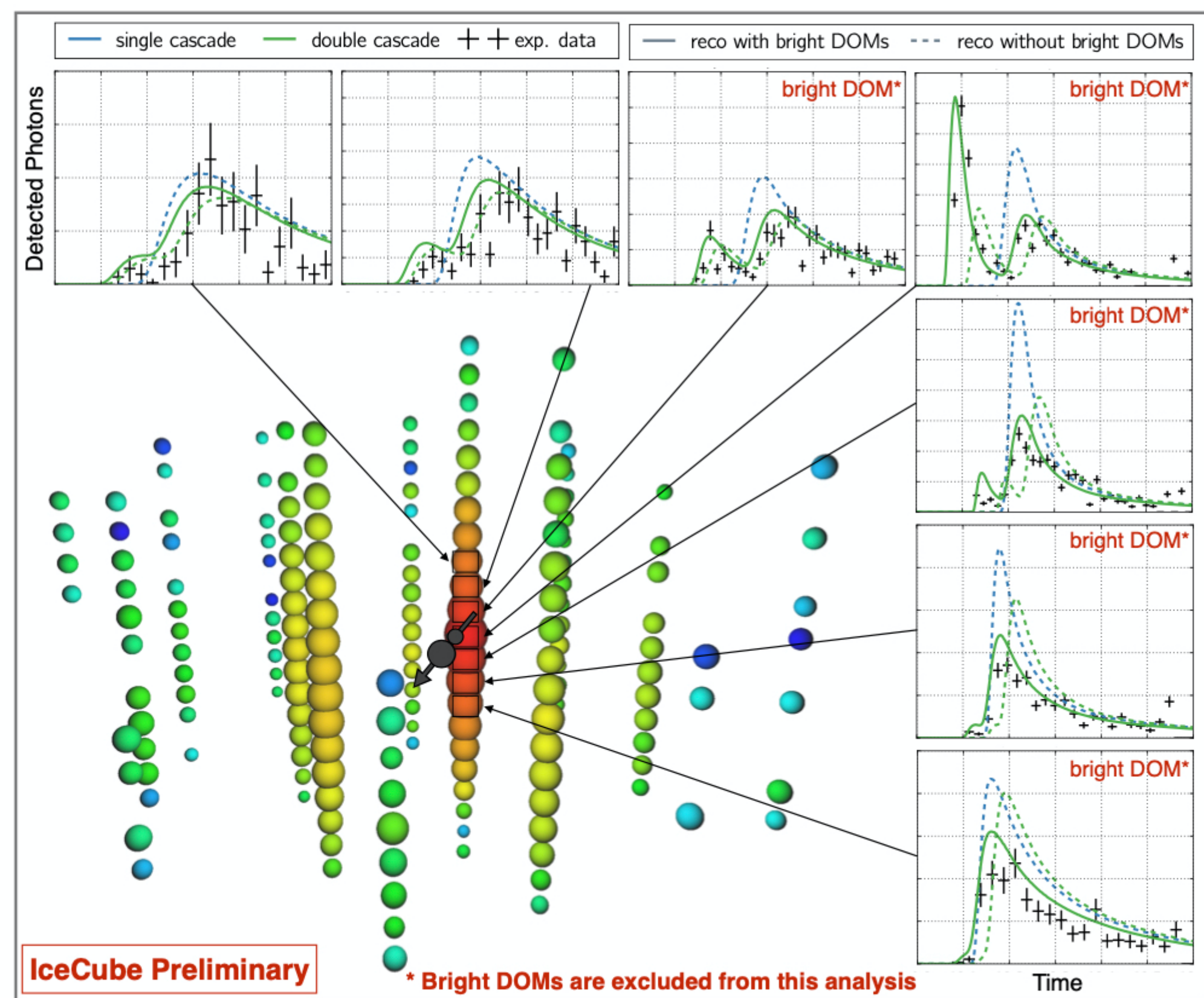


No evidence for point sources, nor a correlation with the galactic plane

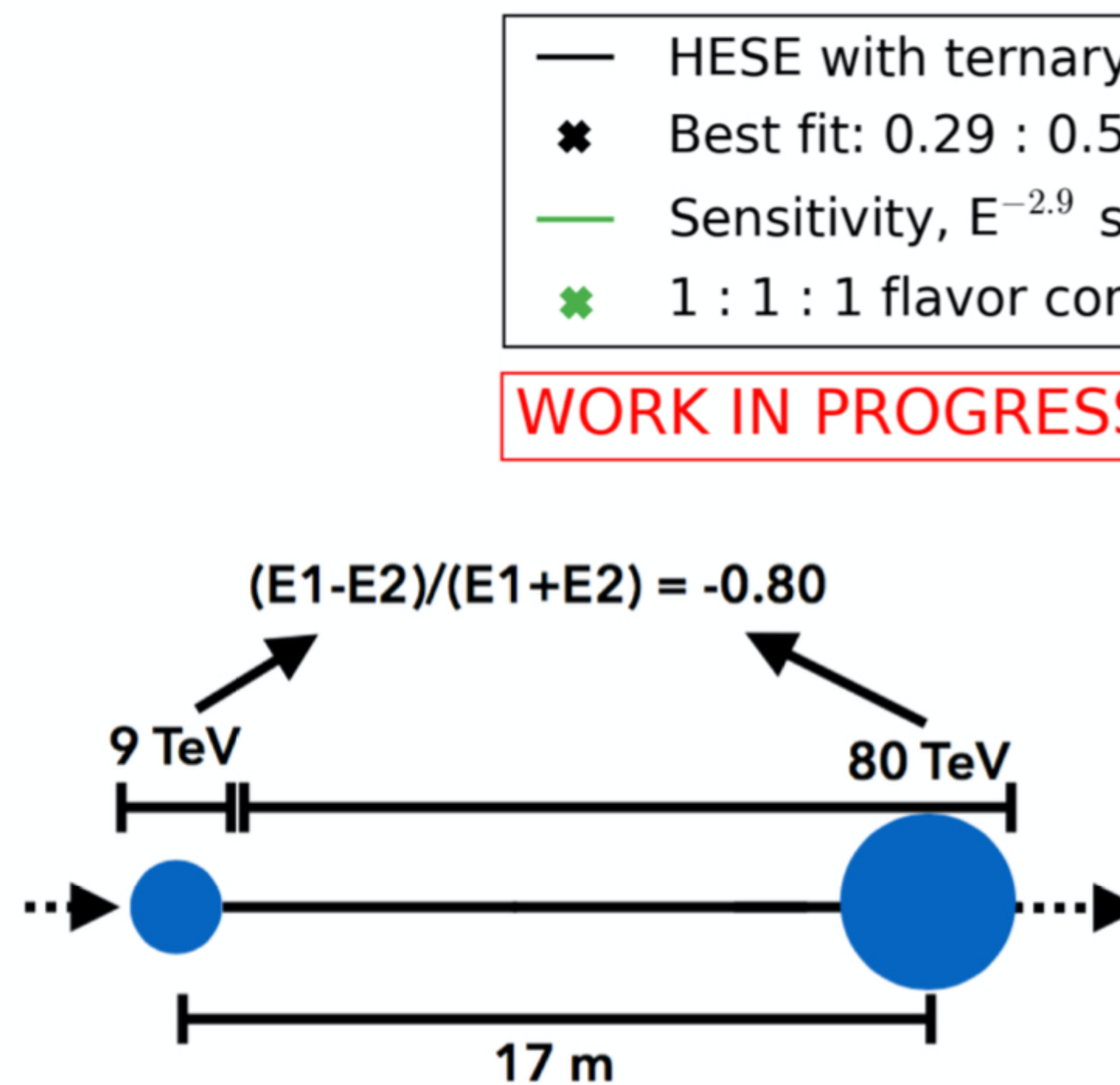
Poster #175. Wandkowsky et al. (IceCube)



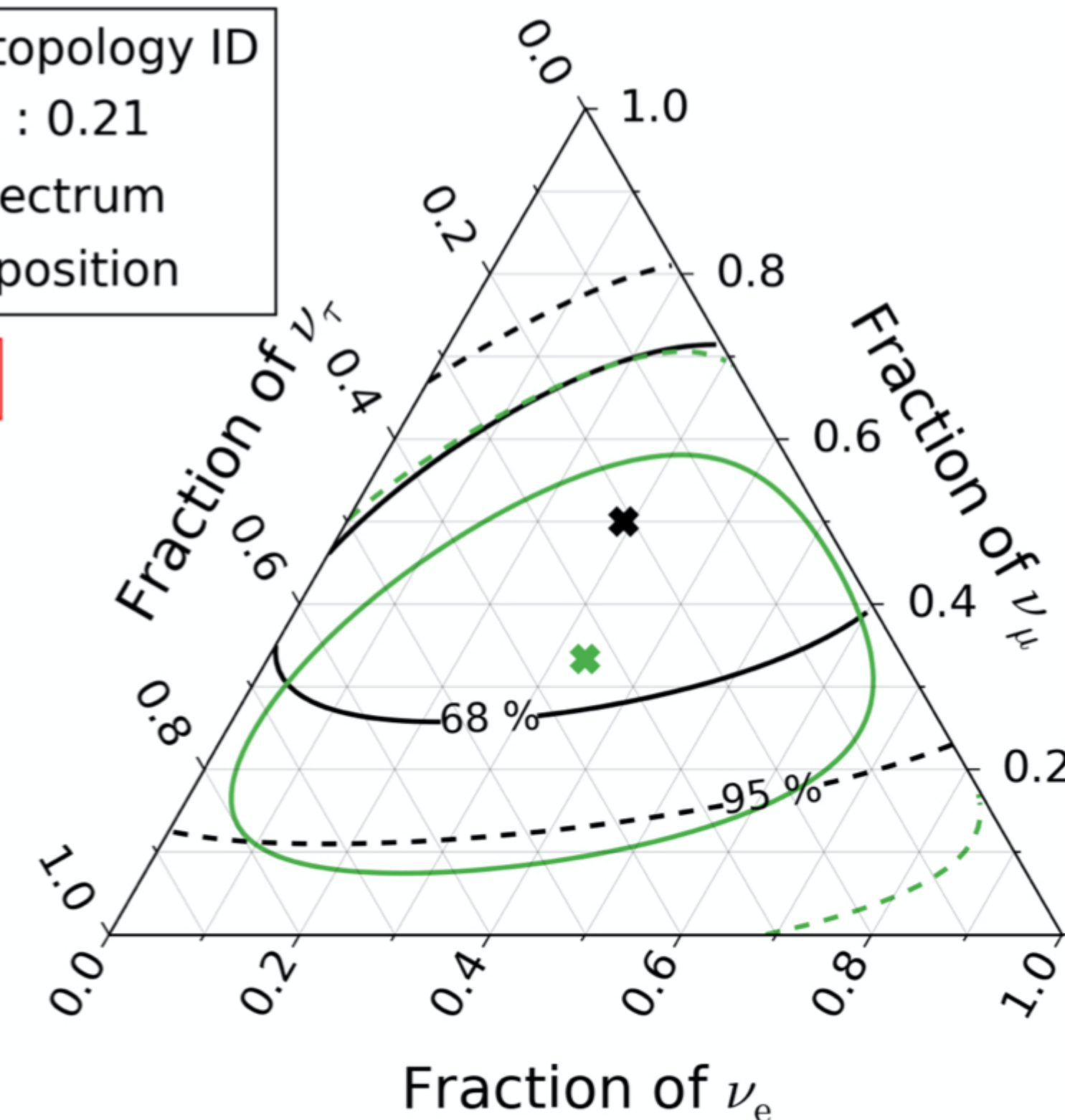
# A tau neutrino candidate in the 7.5 year HESE sample: “Double Double”



J. Stachurska NU8f

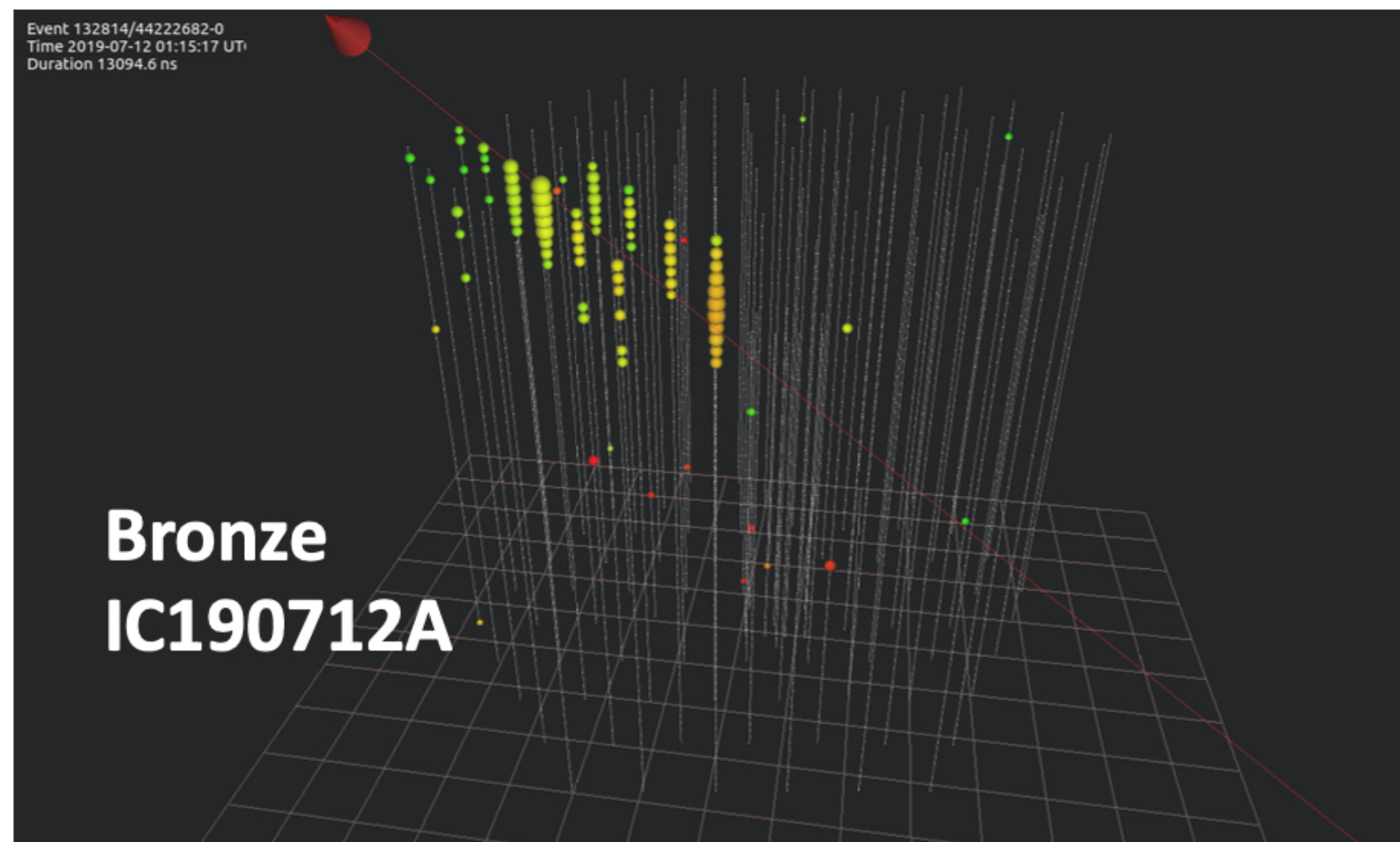
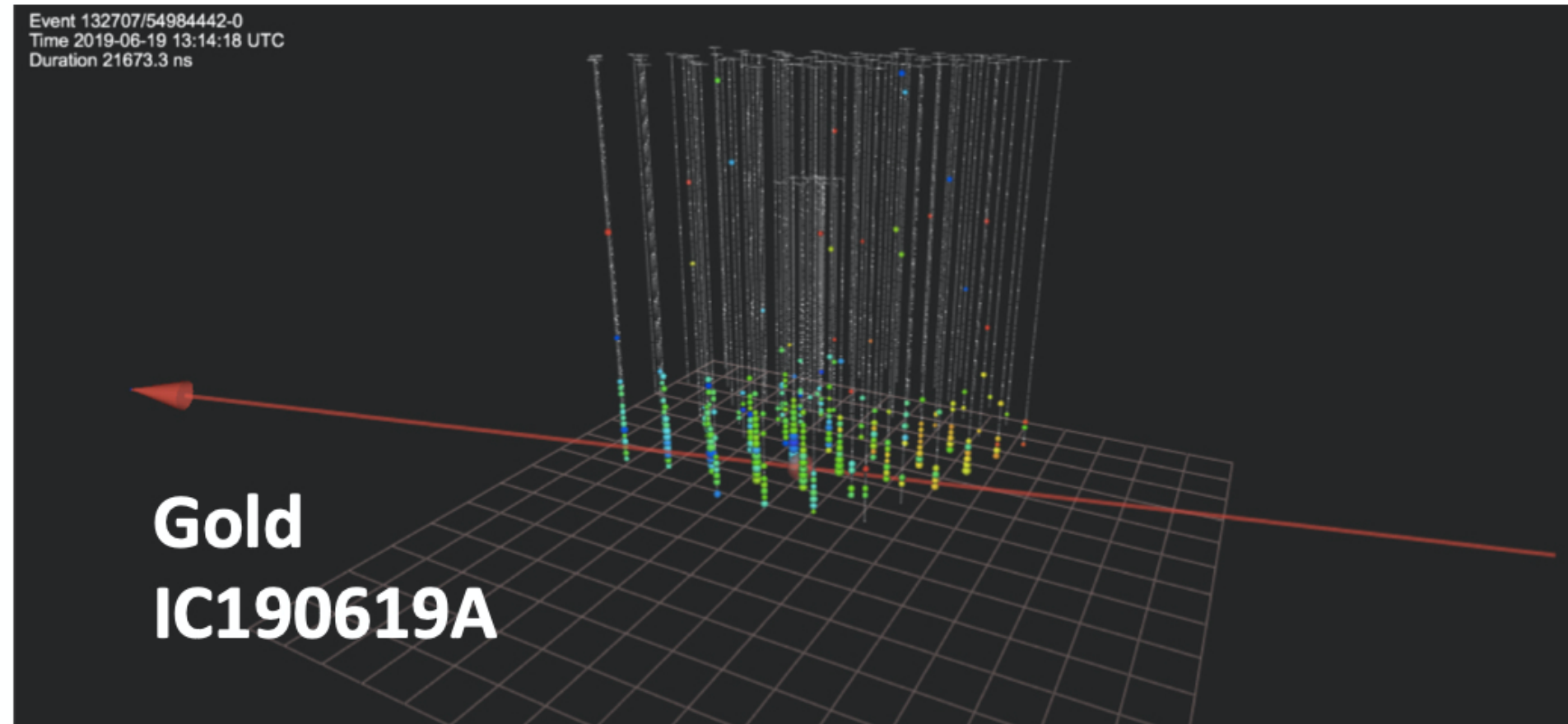


Negative energy asymmetry





# IceCube Realtime Alerts

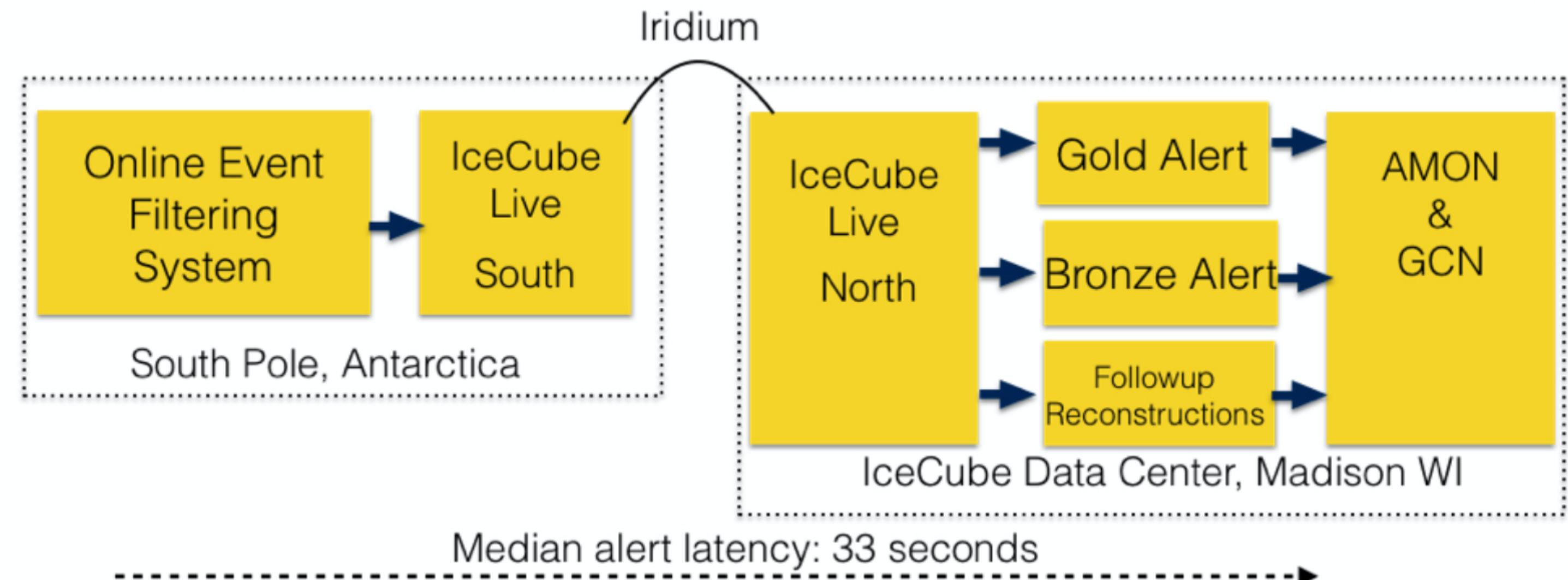


IceCube sending alerts since  
April 2016  
Updated alerts as of June 2019

Initial GCN Notice followed by  
GCN Circular with updated  
reconstruction

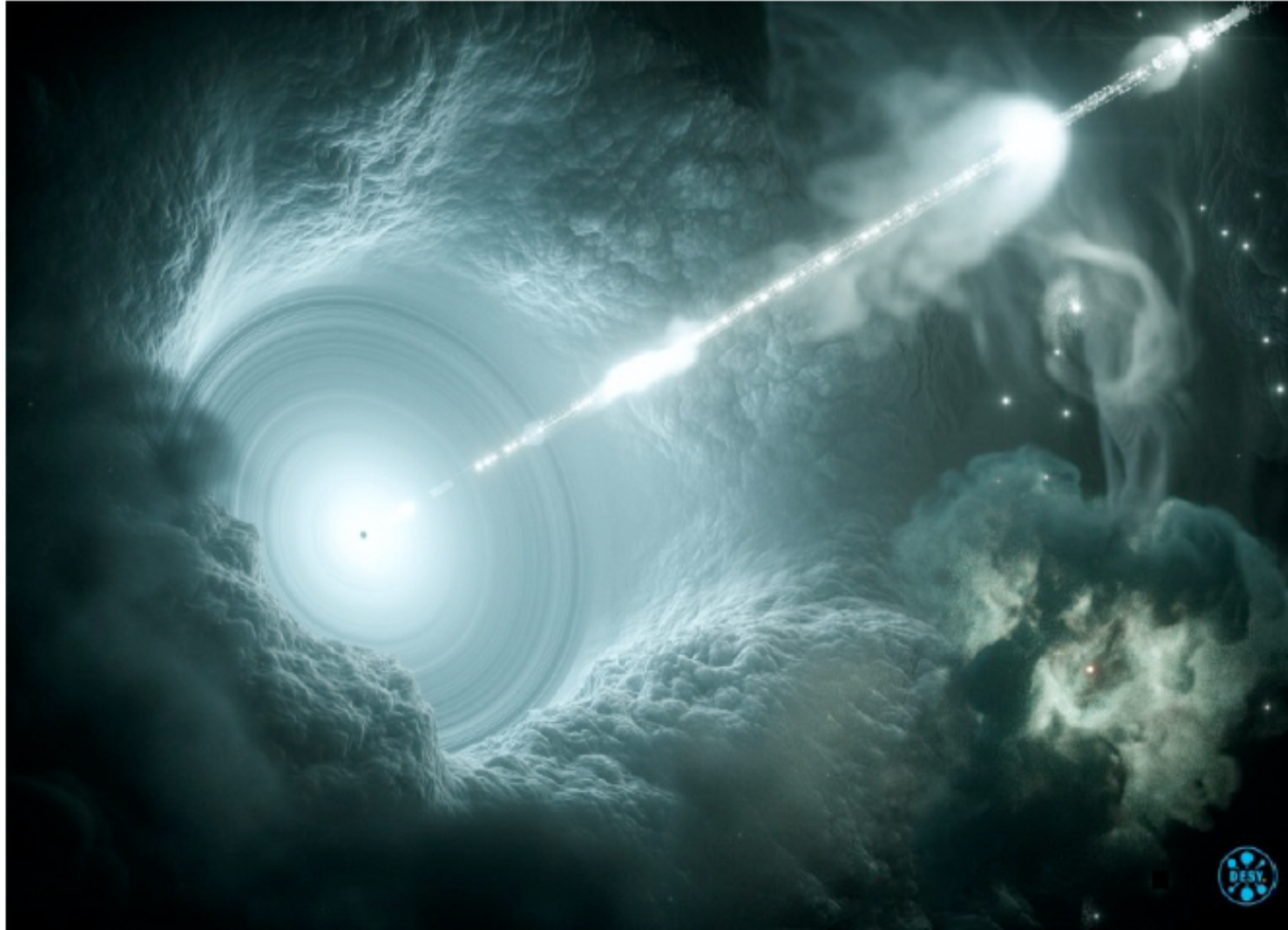
C. Tung NU9b

| Updated alerts     | Gold  | Bronze |
|--------------------|-------|--------|
| Signalness         | > 50% | >30%   |
| Expected signal/yr | 6.6   | 2.8    |
| Expected bkgd/yr   | 6.1   | 14.7   |





# Breaking News (July 12, 2018)



## Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift*/*NuSTAR*, VERITAS, and VLA/17B-403 teams\*†

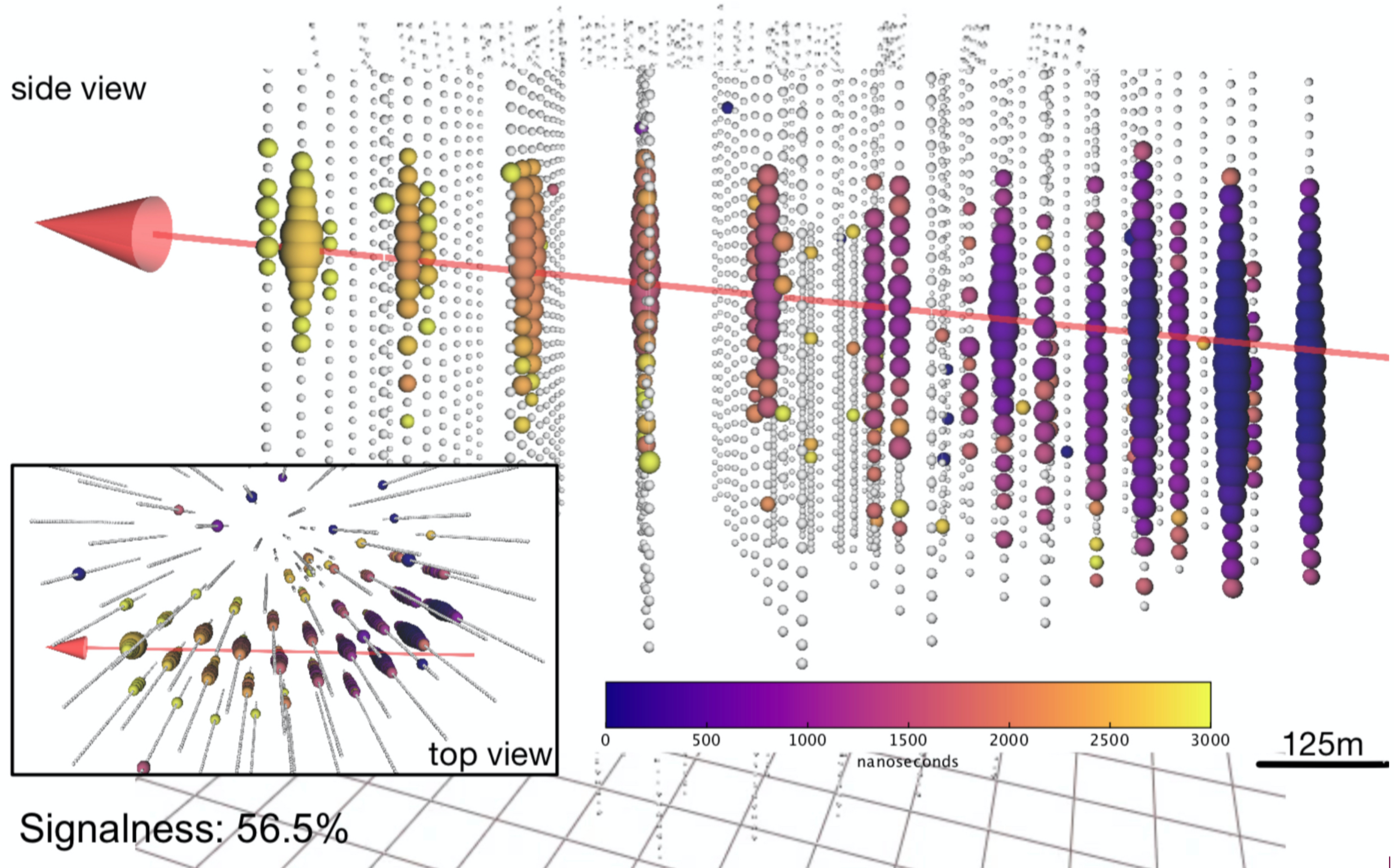
## Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

IceCube Collaboration\*†

+ 16 observatories!

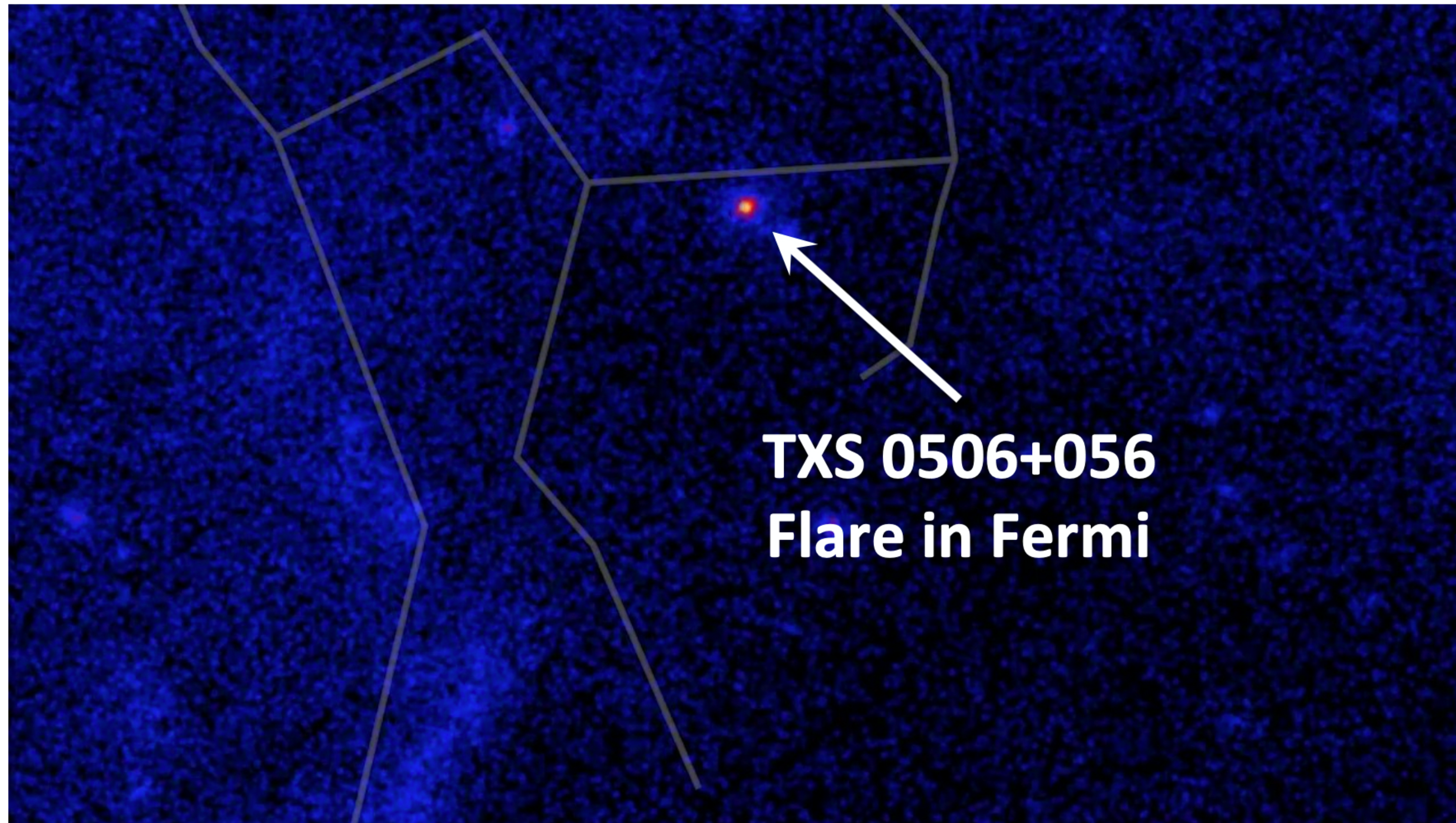


# IC-170922A – a 290 TeV Neutrino





# TXS 0506+056: First evidence of a $\nu$ source



Science 361 (2018) eaat1378

Science 361 (2018) 147-151

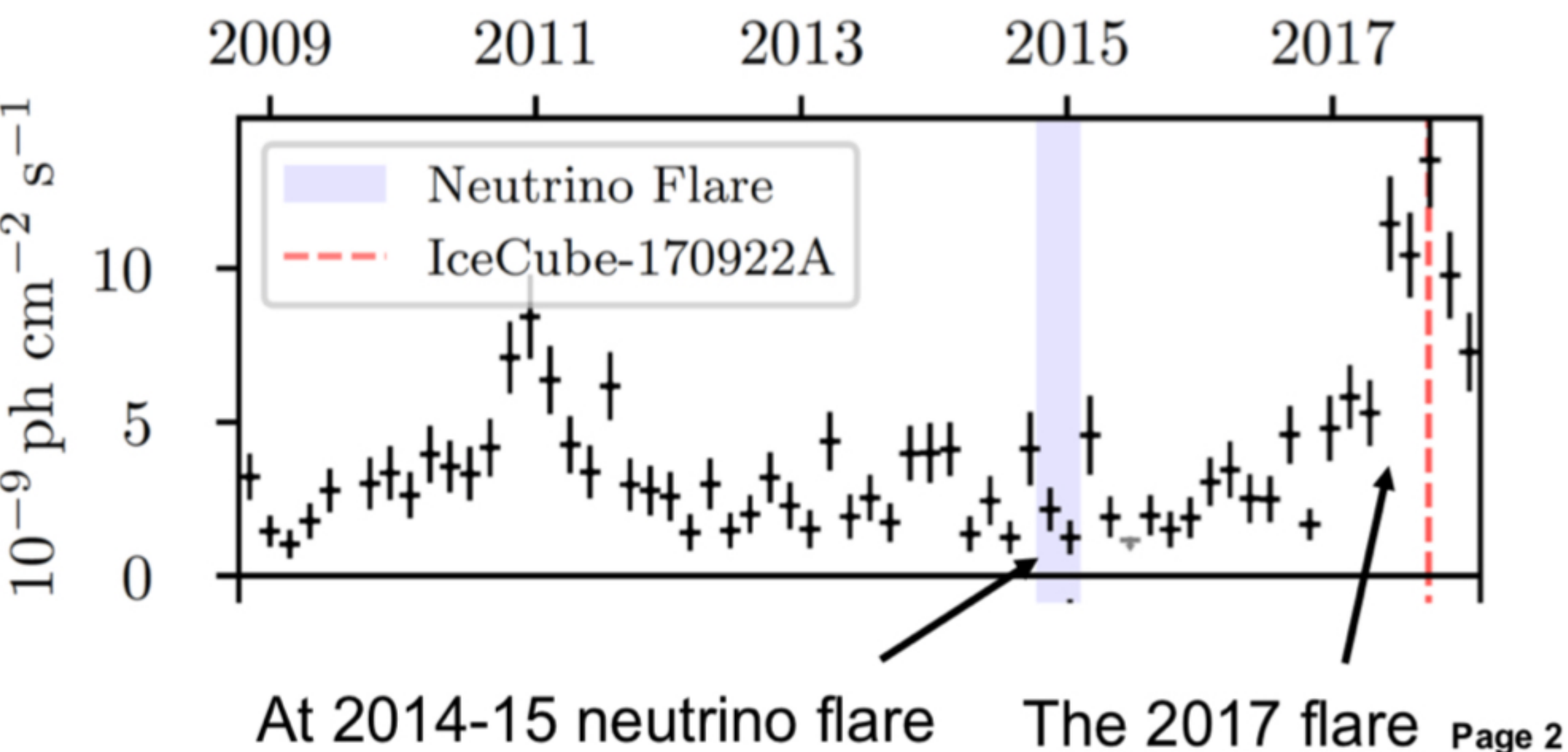
IceCube-170922: a neutrino alert issued by IceCube

Fermi and MAGIC identify a spatially coincident flaring blazar (TXS 0506+056)

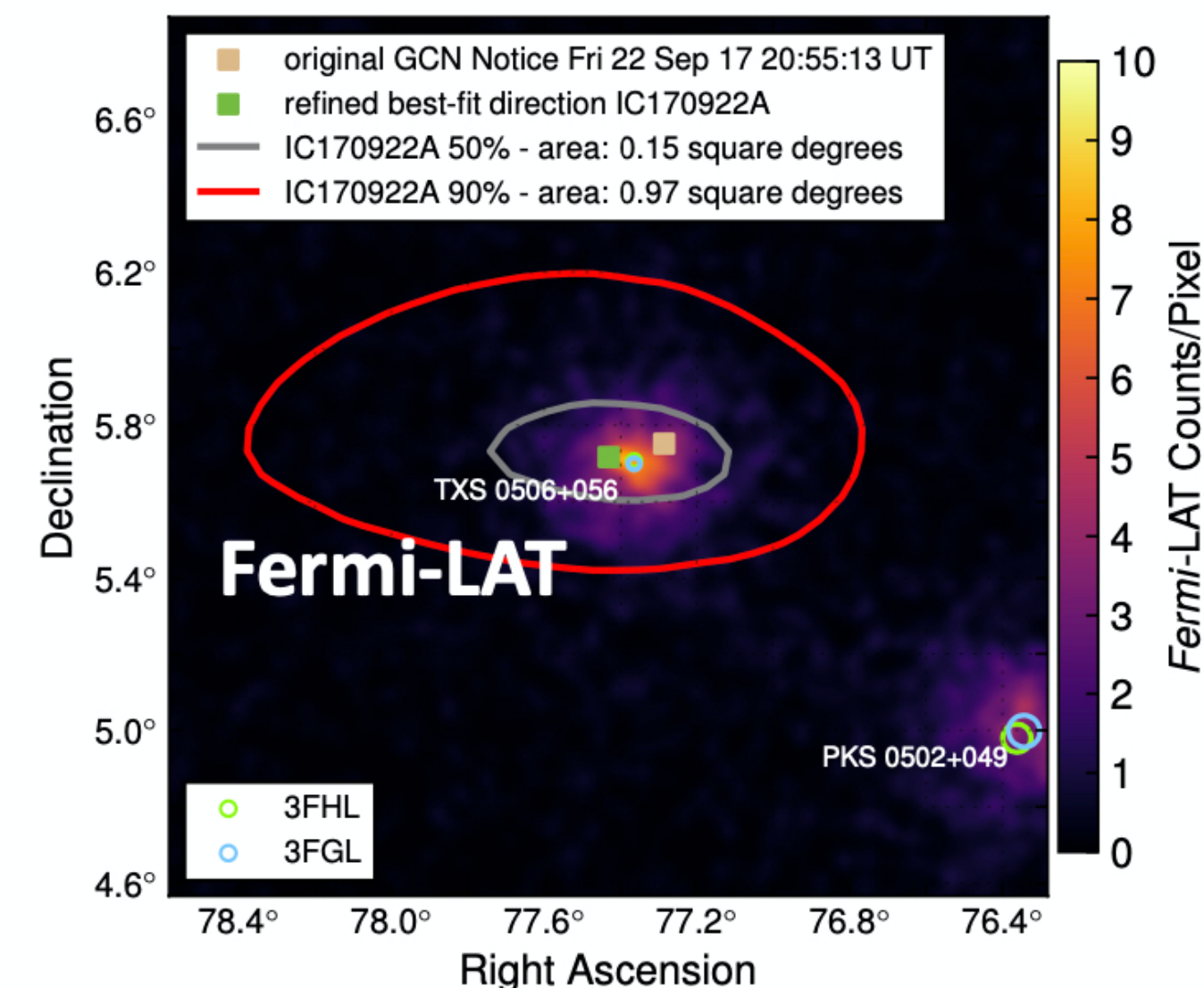
A  $\nu$ -flare was found in archival IceCube data (10/2014 – 03/2015)



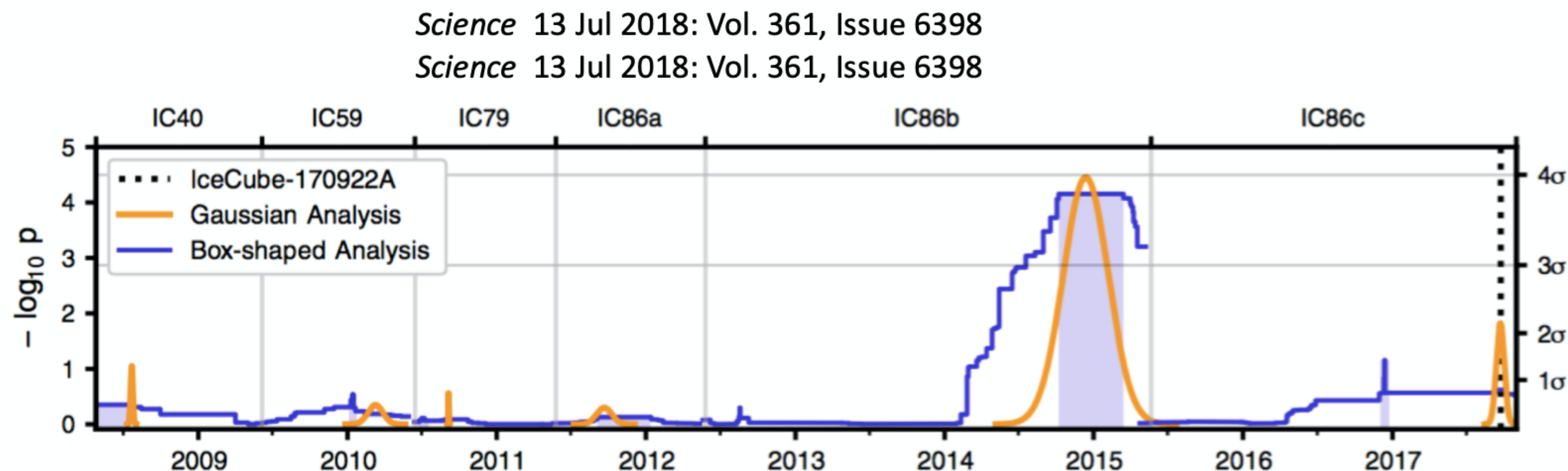
## Fermi-LAT data; Padovani et al, MNRAS 480 (2018) 192



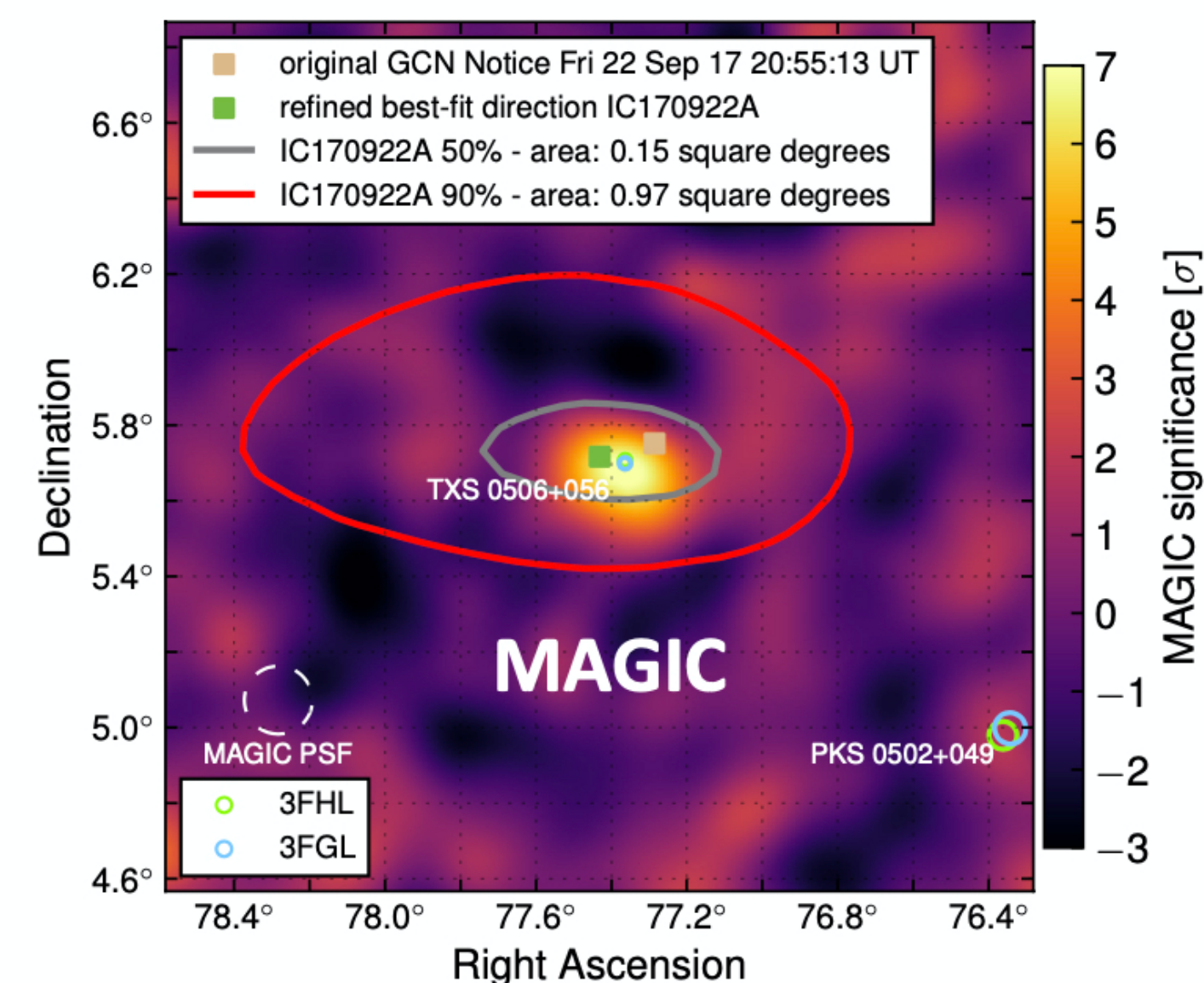
**Correlation of  
IC170922A with TXS  
0506+056 preferred  
to chance at  $3\sigma$  level**



**Blazar redshift  $0.3365 \pm 0.0010$  (Paiano *et al.*)**



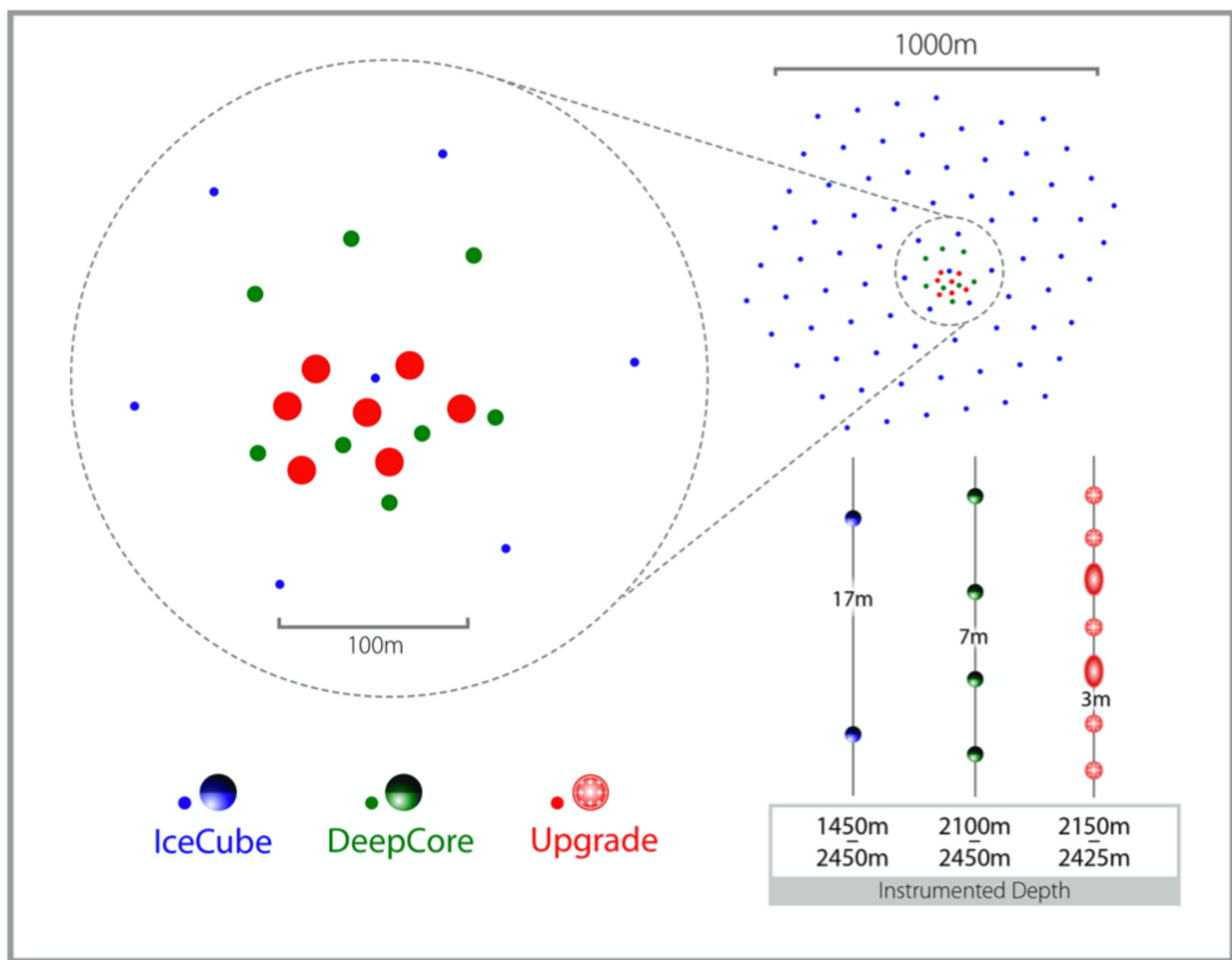
**Excess of neutrinos observed between September 2014 and March 2015  
Background only hypothesis rejected at  $3.5\sigma$**



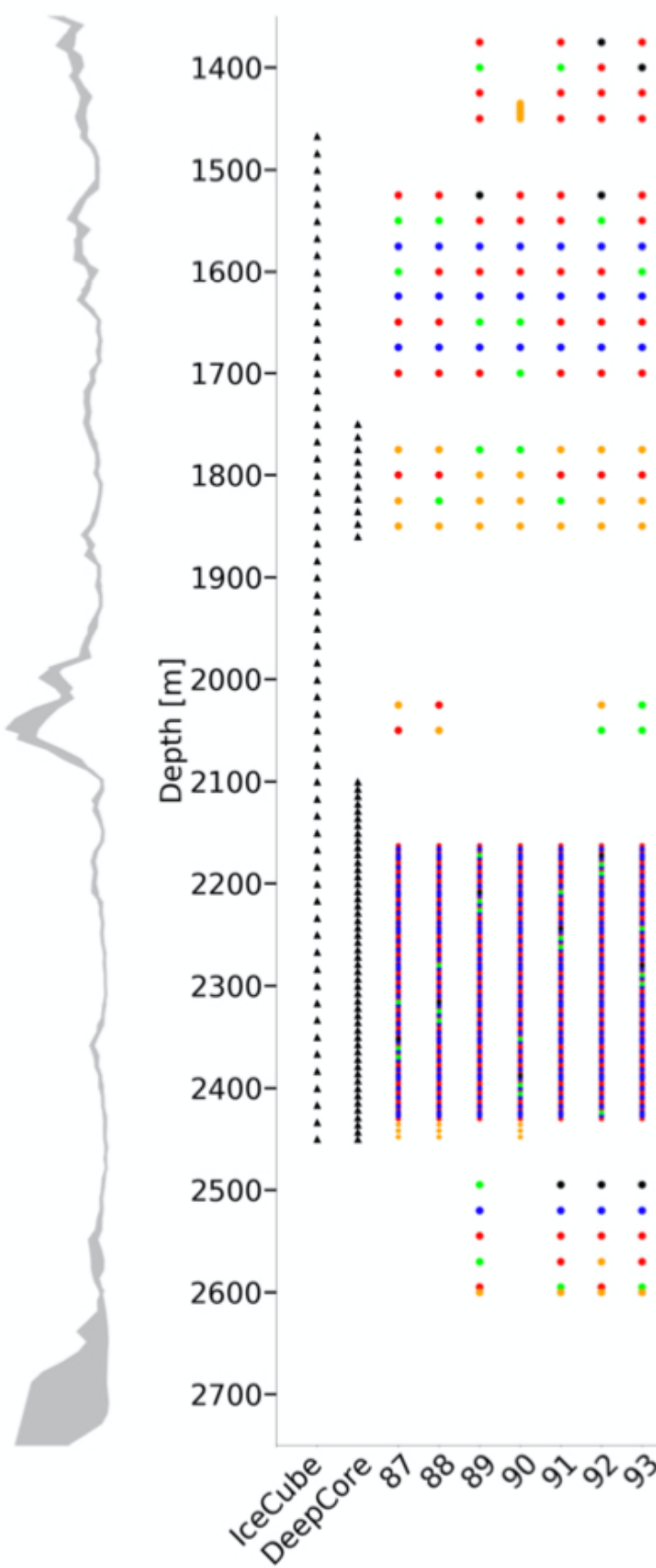
$374 \pm 62$  excess photons with observed energies up to about 400 GeV



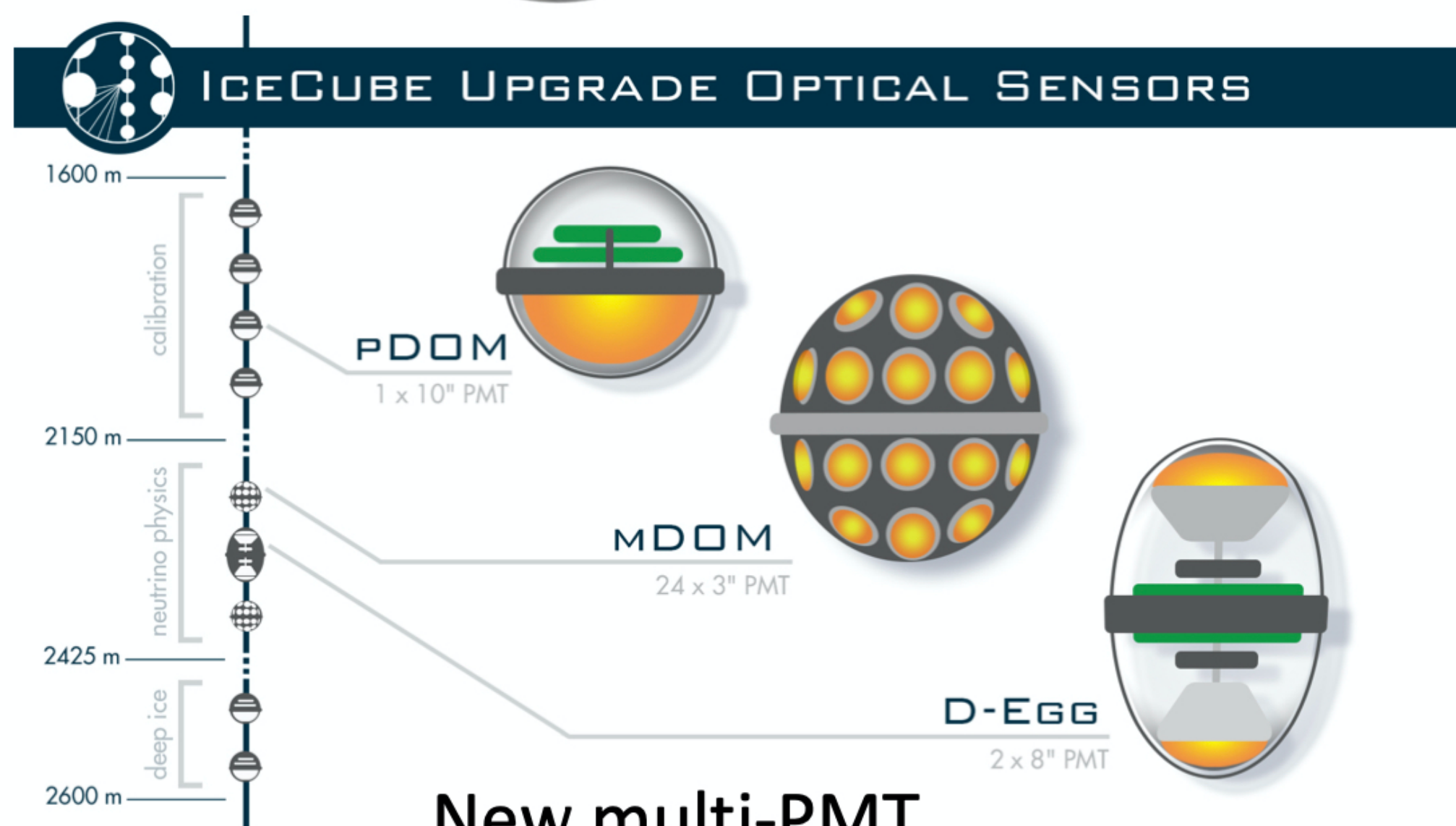
# The IceCube Upgrade



Approved by NSF, planned to deploy in 2022-23  
7 new strings near the center of IceCube



A. Ishihara NU7a



New multi-PMT  
sensors

New calibration  
devices

L. Classen PS3-98

A. Ishihara PS3-123



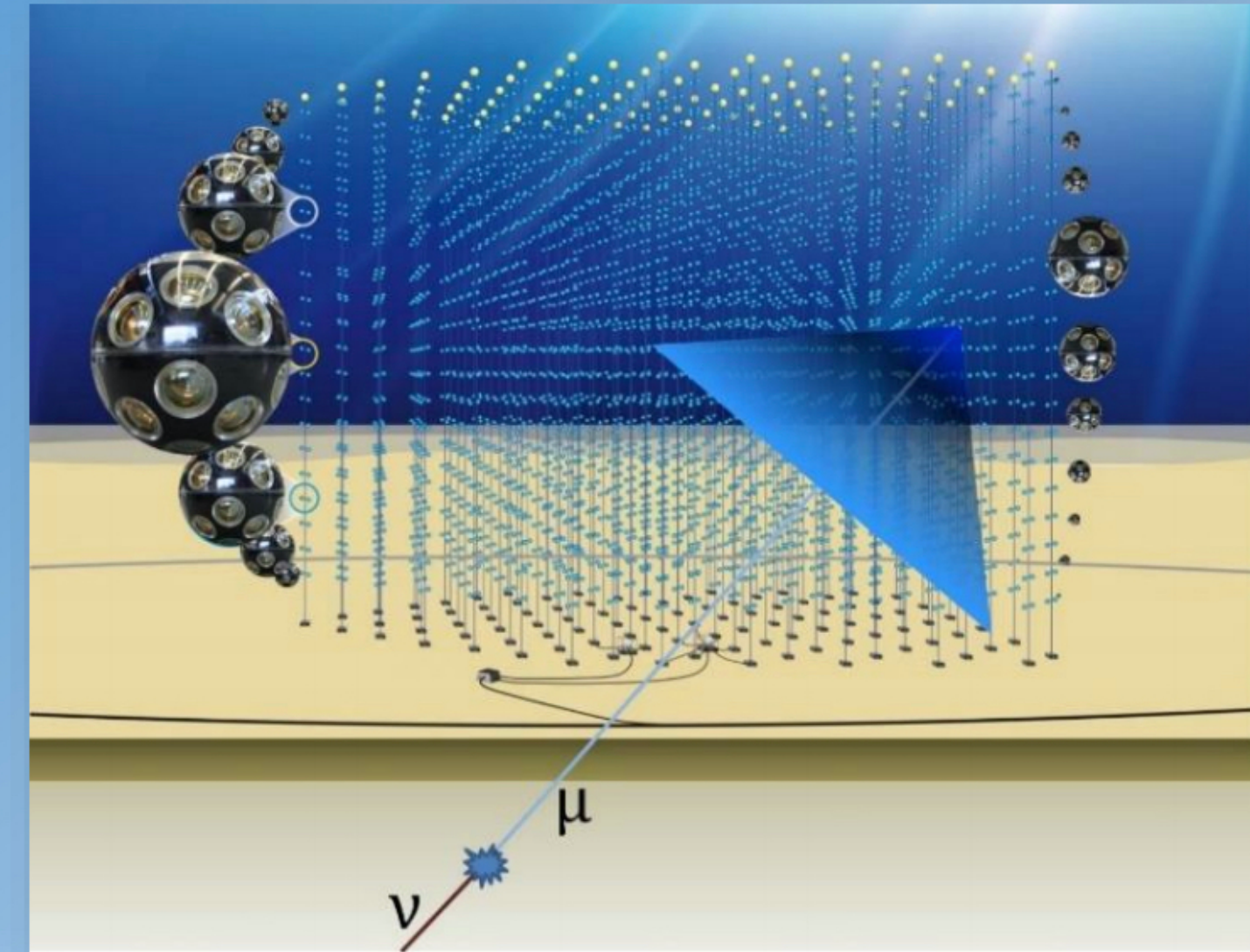




# The KM3NeT Telescope Design



- Detection principle Optical Cherenkov radiation
  - 6 order of magnitude in energy (GeV-PeV)
  - All flavour detection
- A 3D array built with a modular design
- Optical sensor: multi-PMT (DOM)
- Detection units (DU)
  - vertical slender strings host 18 DOMs
- Building blocks of 115 DUs each
- Power and data distributed by a single backbone cable with breakouts at DOMs
- Sea network of submarine cables and Junction Boxes connected to shore via a main e/o cable
- All data to shore



|                   | ARCA       | ORCA   |
|-------------------|------------|--------|
| Location          | Italy      | France |
| DU distance       | 90 m       | 23 m   |
| DOM spacing       | 36 m       | 9 m    |
| Instrumented mass | 2*500 Mton | 8 Mton |

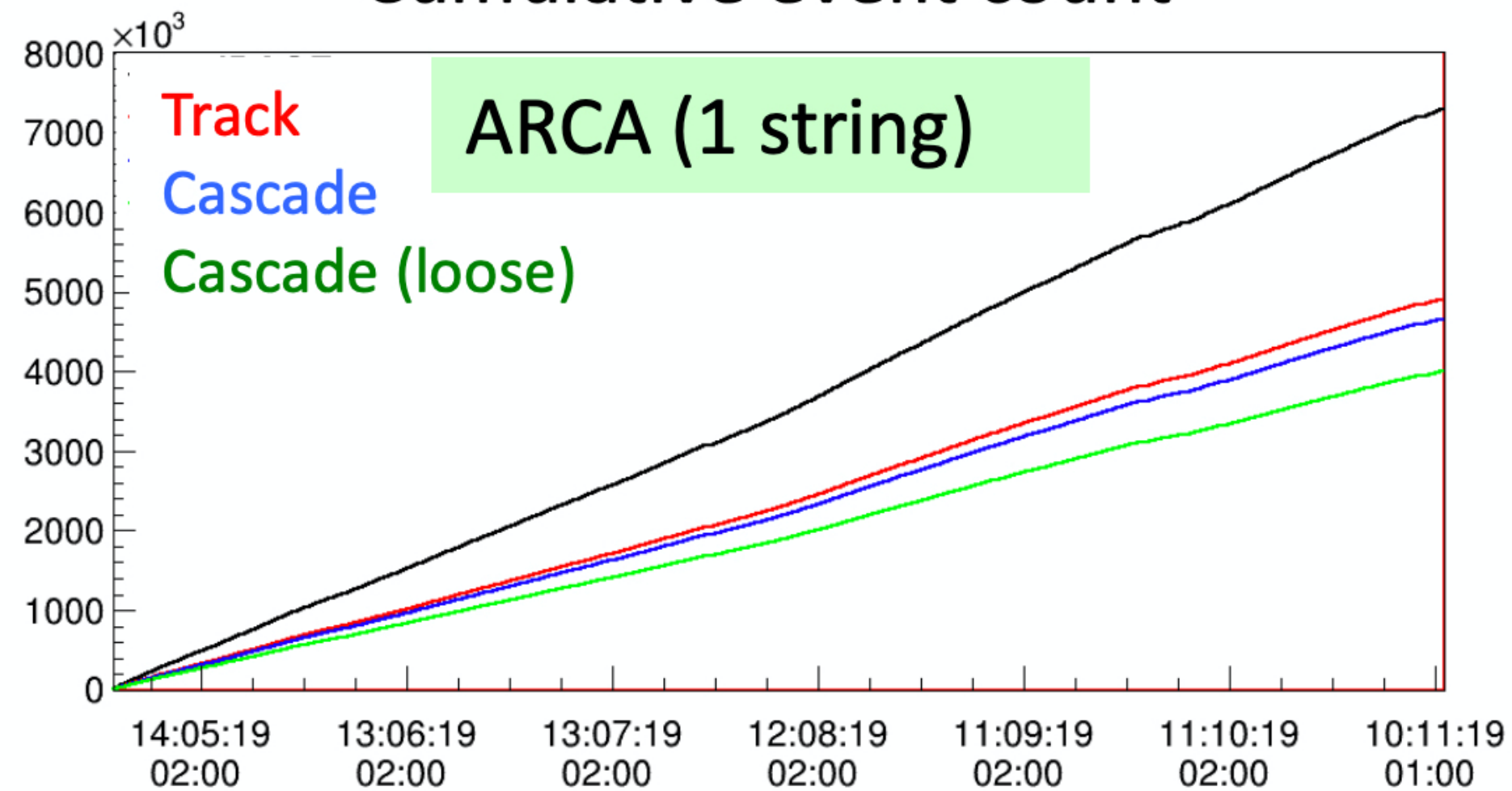


# Current KM3NeT Data

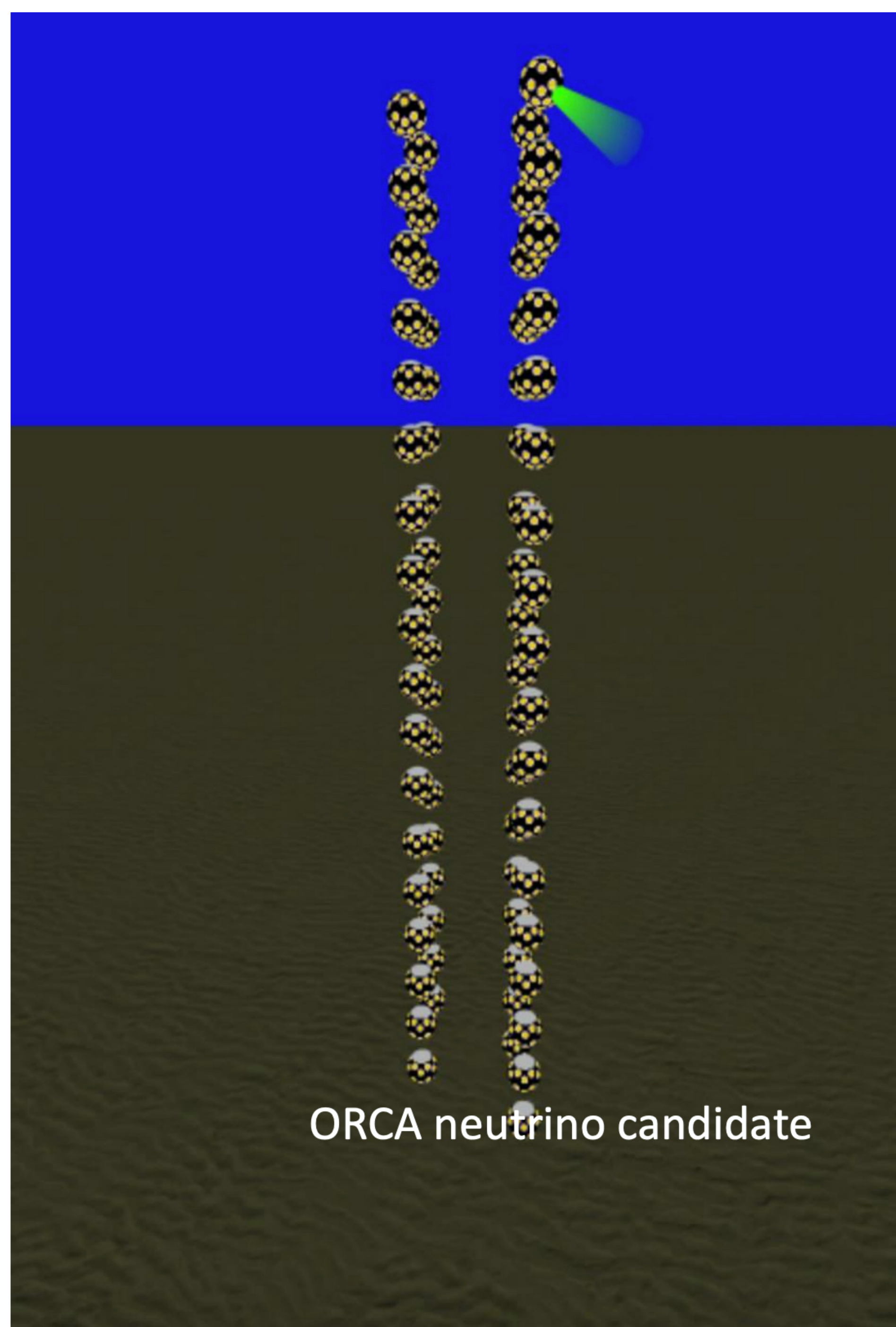
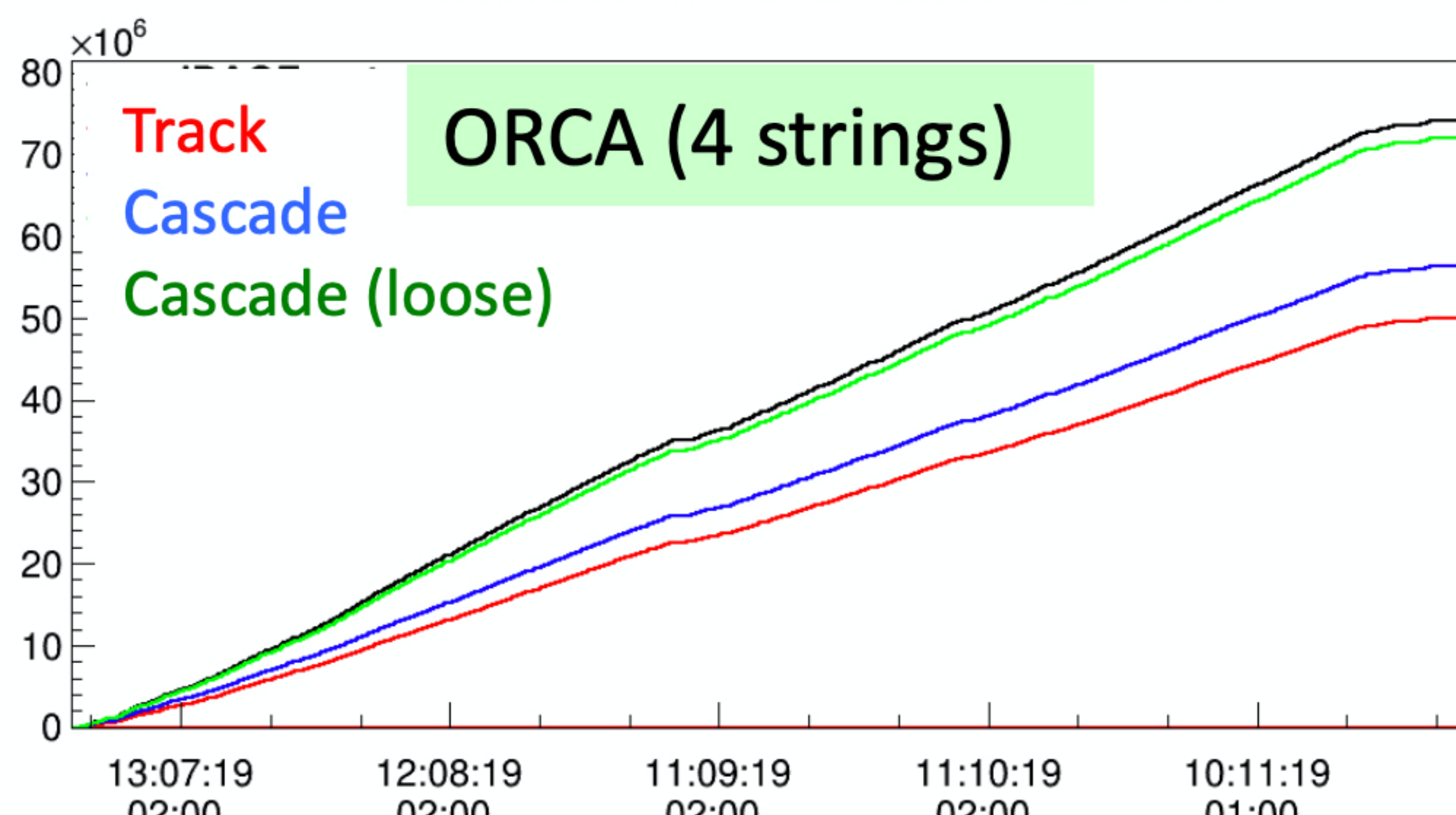
Triggering on **track** and **cascade** signatures

Trigger rates  $\sim 0.5(7)$  Hz for ARCA (ORCA)

Cumulative event count



Cumulative event count







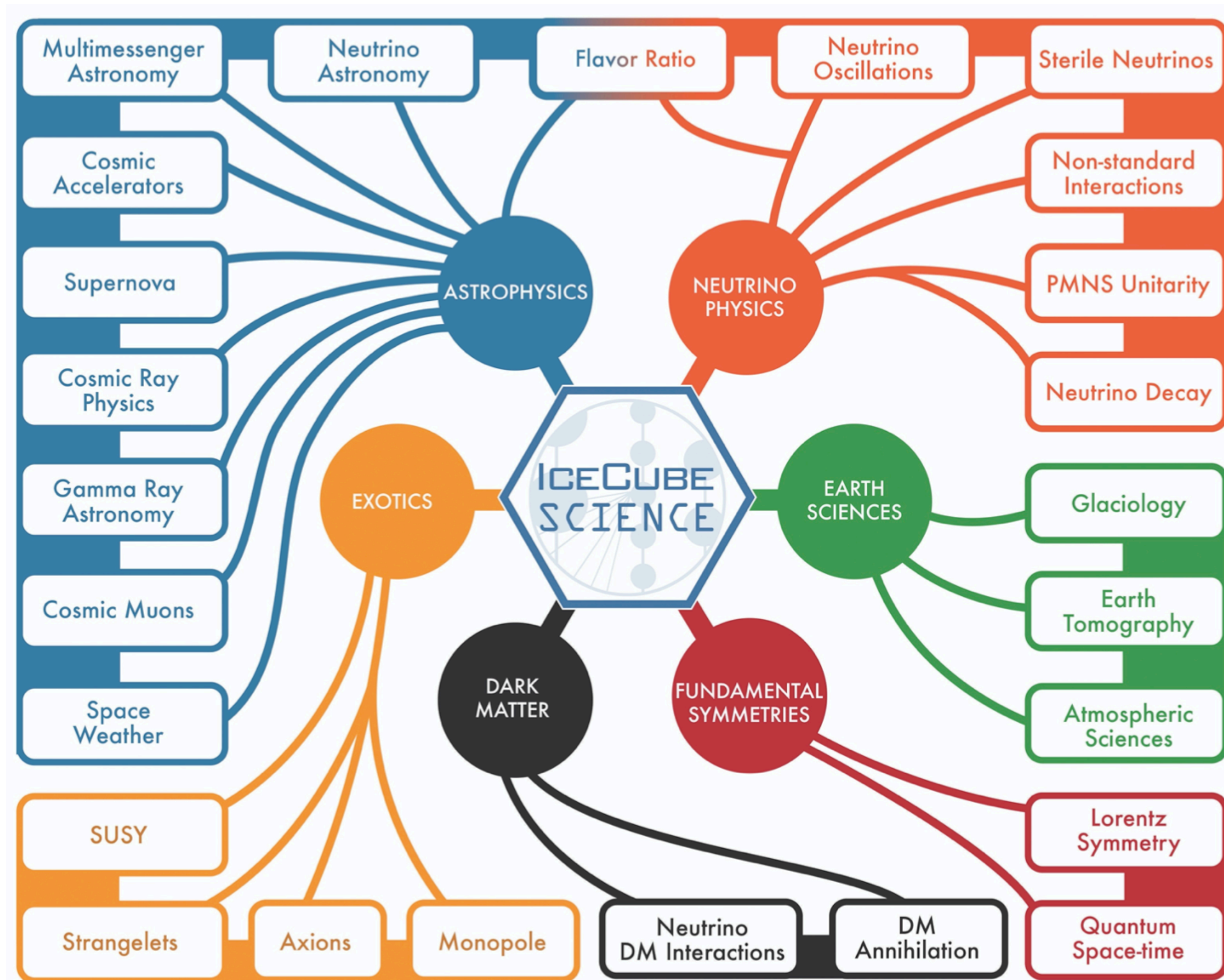
# Phase 1 - ARCA

- ARCA-DU1 and ARCA-DU2 deployed December 2015 and May 2016 at Capo Passero, Sicily and worked till April 2017
- ARCA-DU1 operativity resumed in January 2019
- plenty of statistics
- presently the on-shore station is under renovation to host the second cable power supply
- the seafloor network is scheduled to return operative before summer 2020 with 6 DUs connected

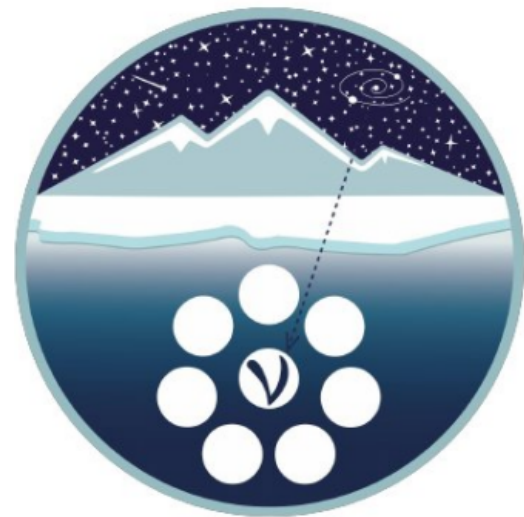




# Neutrino telescope is a multi-purpose detector

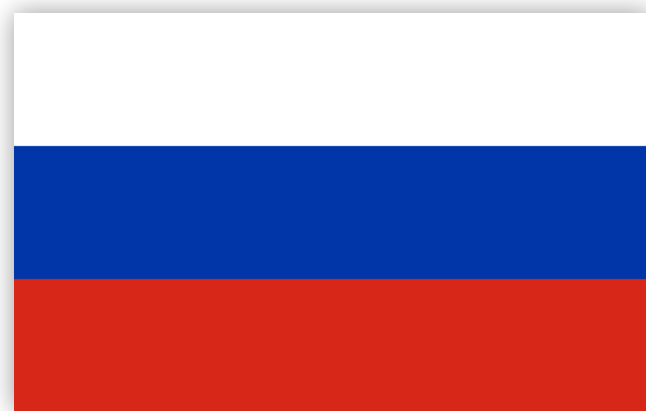






# Эксперимент Baikal-GVD

10 институтов, ~70 участников



- Институт Ядерных Исследований (Москва)
- [Объединенный Институт Ядерных Исследований \(Дубна\)](#)
- Иркутский Государственный Университет (Иркутск)
- [НИИ Ядерной Физики им. Д.В. Скобельцина МГУ \(Москва\)](#)
- Нижегородский Государственный Технический Университет (Нижний Новгород)
- [Санкт-Петербургский Государственный Морской Технический Университет \(Санкт-Петербург\)](#)
- Institute of Experimental and Applied Physics, Czech Technical University (Prague, Czech Republic)
- [EvoLogics \(Berlin, Germany\)](#)
- Comenius University (Bratislava, Slovakia)
- [Krakow Institute for Nuclear Research \(Krakow, Poland\)](#)





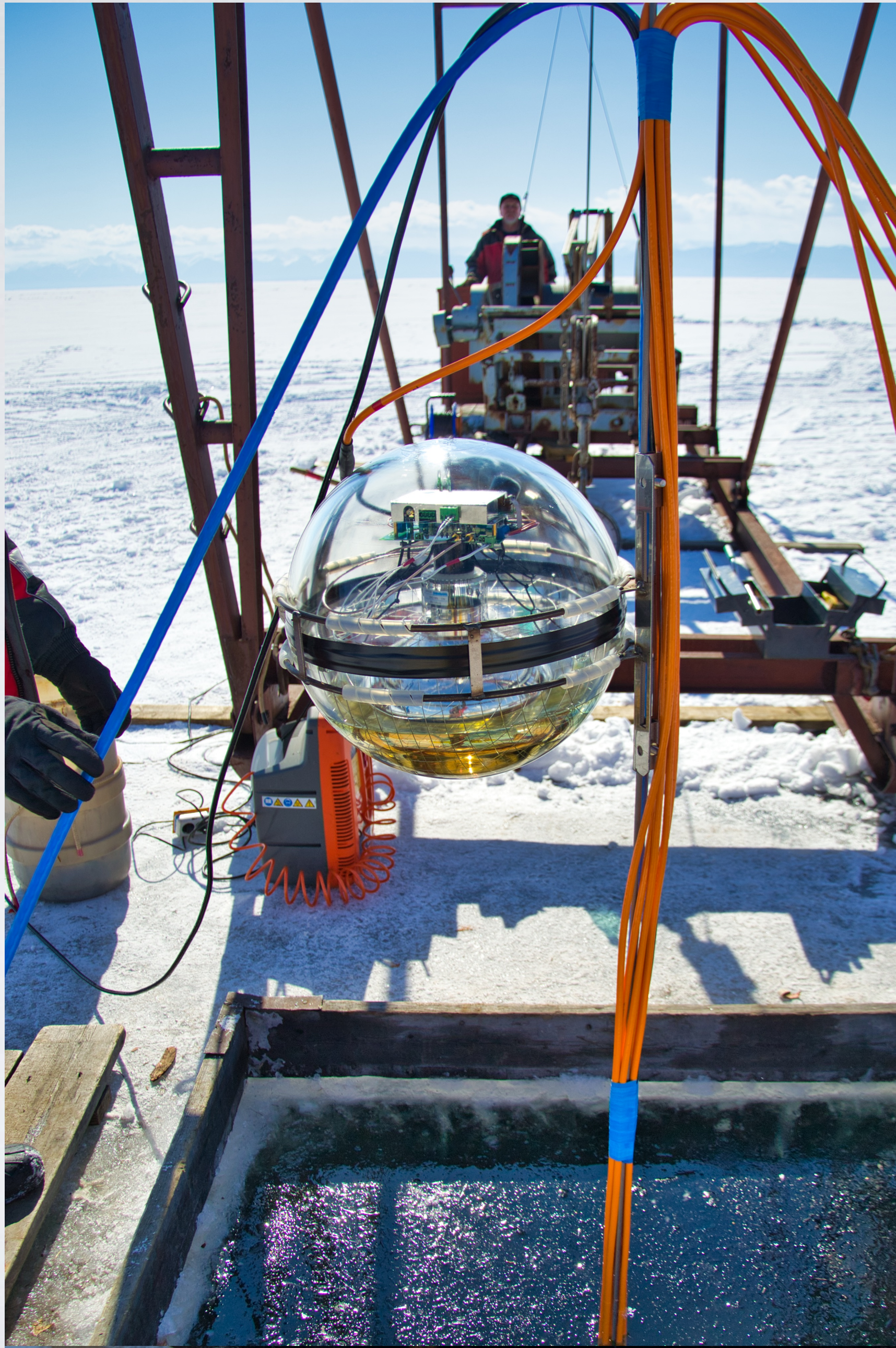
# BAIKAL SITE





















# INFRASTRUCTURE



OM production line in JINR (Dubna) (12 OM/day)



The control center at the Baikal shore



The local lab and OM storage in Baikalsk



# Детектор Baikal-GVD I

Чувствительный элемент телескопа: оптический модуль (ОМ),





гирлянда:  
3 секции

# Детектор Baikal-GVD II

Кластер - независимая структурная единица телескопа

Кластер включает 288 ОМ распределенных по 8-ми гирляндам на глубинах от 750 до 1275 м

ОМ ориентированы ко дну озера

Каждая гирлянда закреплена якорем на дне озера

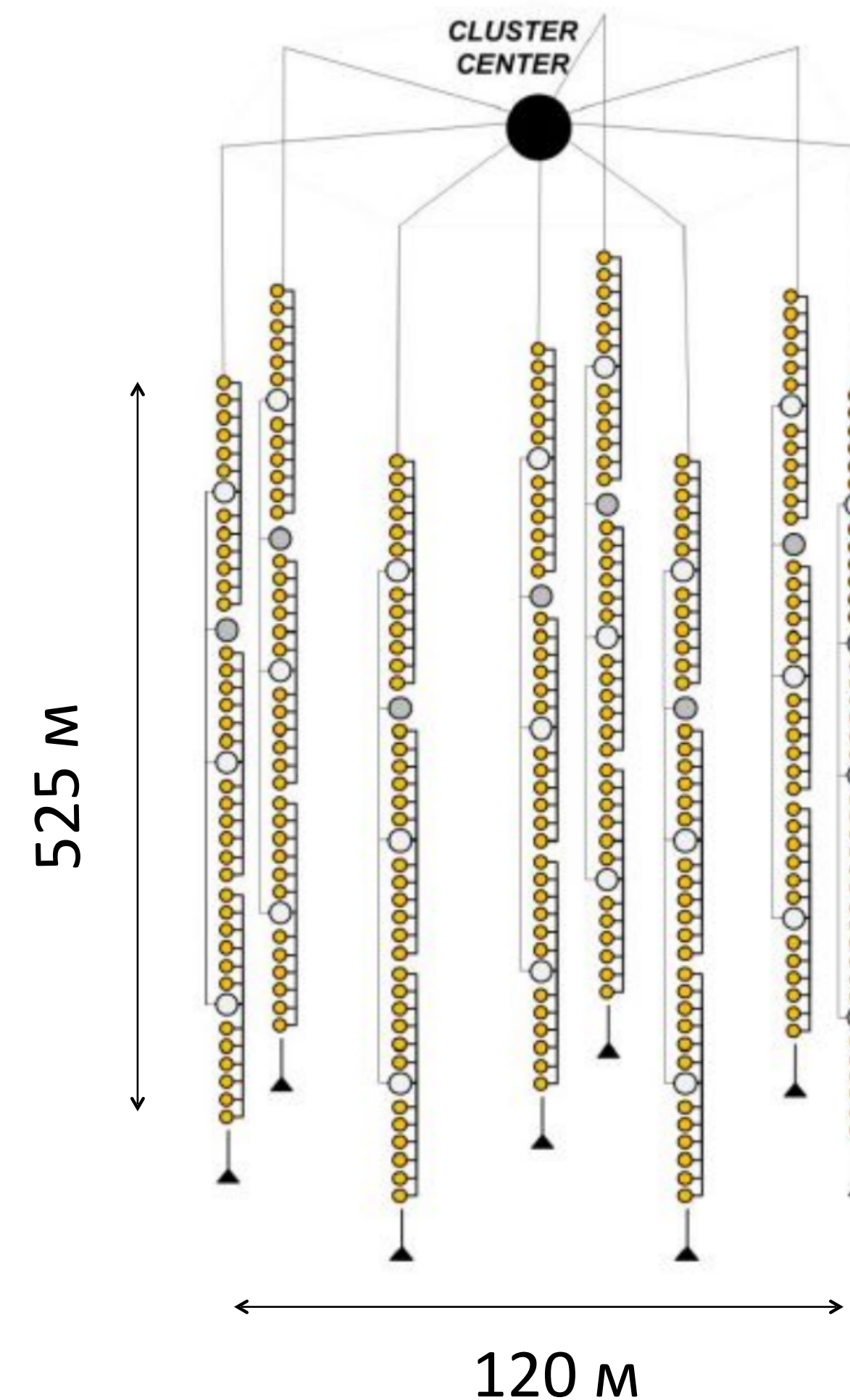
Расстояние между ОМ по вертикали 15 м

Расстояние между гирляндами 60м

На глубине 30м расположен центр кластера

- Триггерная электроника
- Питание
- Оборудование для передачи данных

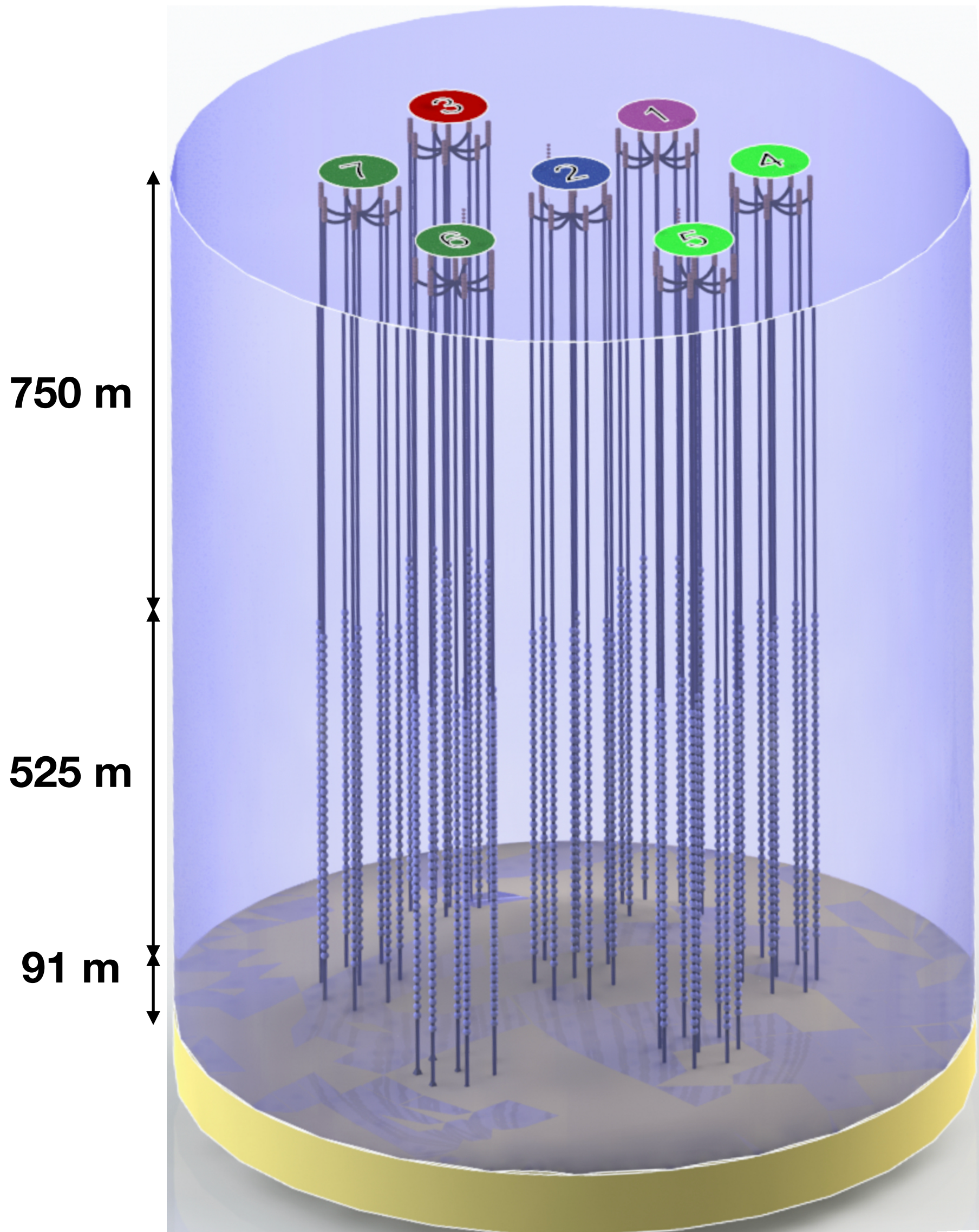
Кластер: 8 гирлянд





# Детектор Baikal-GVD III

Baikal-GVD 2020: 7 кластеров, 56 гирлянд



расстояние  
между  
кластерами  
~300 м

План развертывания телескопа

| Год  | Суммарное<br>число<br>кластеров | Число<br>ОМ |
|------|---------------------------------|-------------|
| 2016 | 1                               | 288         |
| 2017 | 2                               | 576         |
| 2018 | 3                               | 864         |
| 2019 | 5                               | 1440        |
| 2020 | 7                               | 2016        |
| 2021 | 9                               | 2592        |

- + Экспериментальная гирлянда:
- оптическая линия до Центра секции
    - 1 Гбит/с
    - пониженные триггерные пороги
    - синхронизированные часы
  - новая FPGA Zynq
    - множественный триггер
    - монопольная DAQ

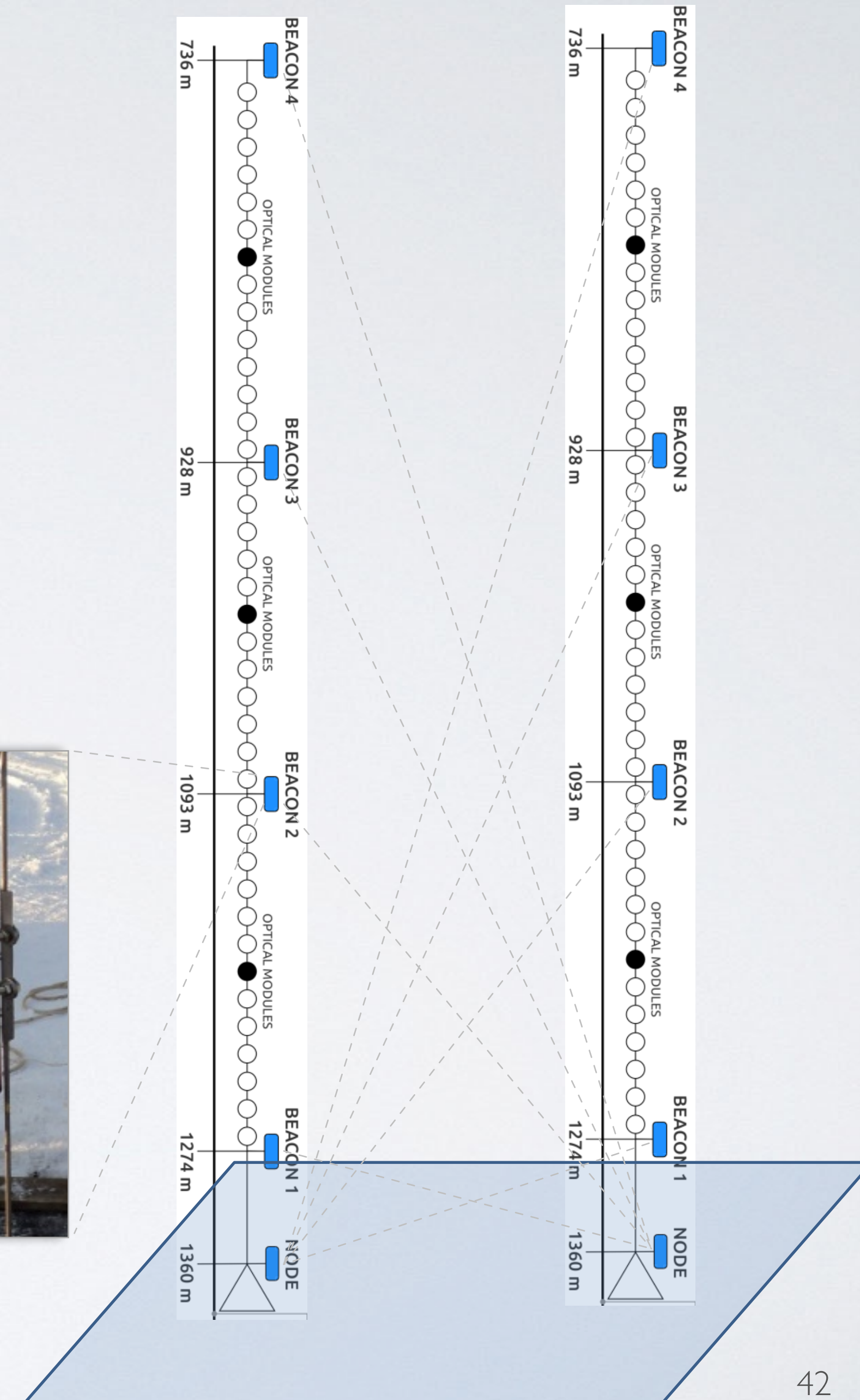
Донная оптоэлектрическая кабельная линия до каждого кластера



# GEOMETRY CALIBRATION

Acoustic positioning system:

- 5 acoustic modules (AMs) on each string (4 AMs in 2016)
- One module is fixed to anchor (node), the rest are along the string (beacons)
- Acoustic signal delays between node and beacons are measured every 5 min
- Relative positions of the AMs are obtained by triangulation
- Monitor pictures are obtained automatically with a delay about 7 minutes





# Калибровка времени отклика

Время импульса ФЭУ - важнейшая характеристика сигнала, используемая в реконструкции

Межканальная внутрисекционная калибровка:

Калибровочные светодиоды

Межсекционная калибровка:

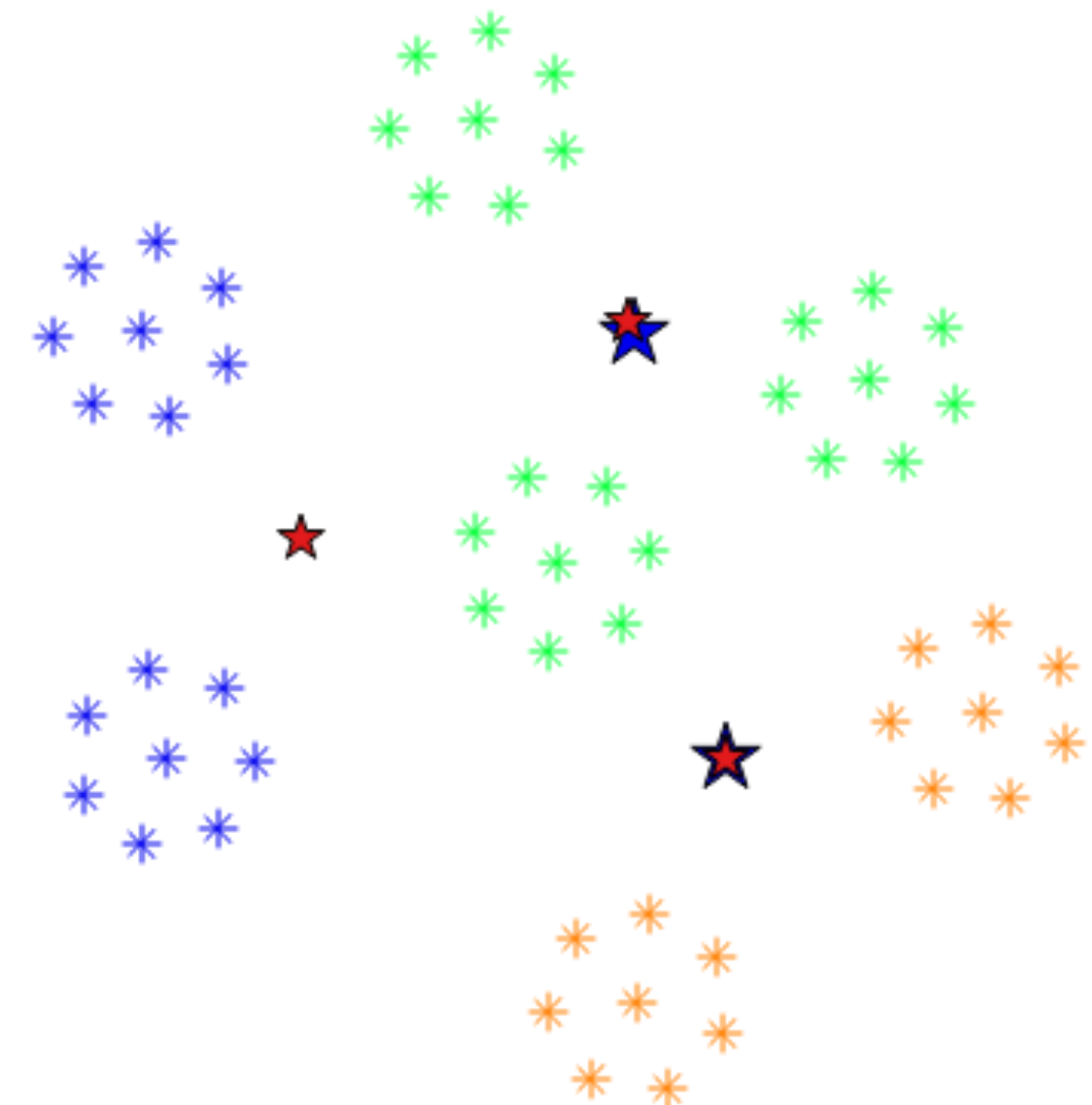
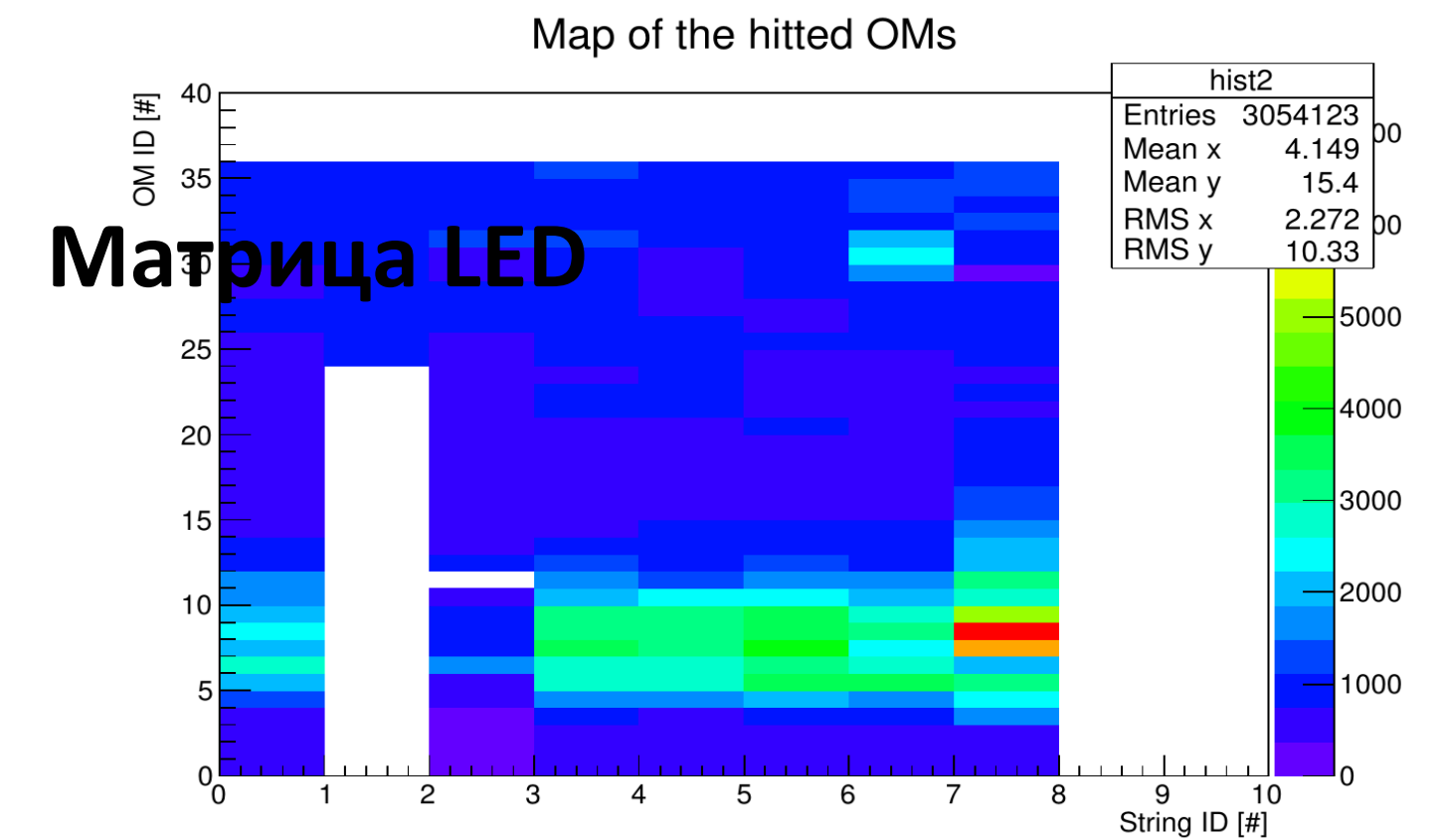
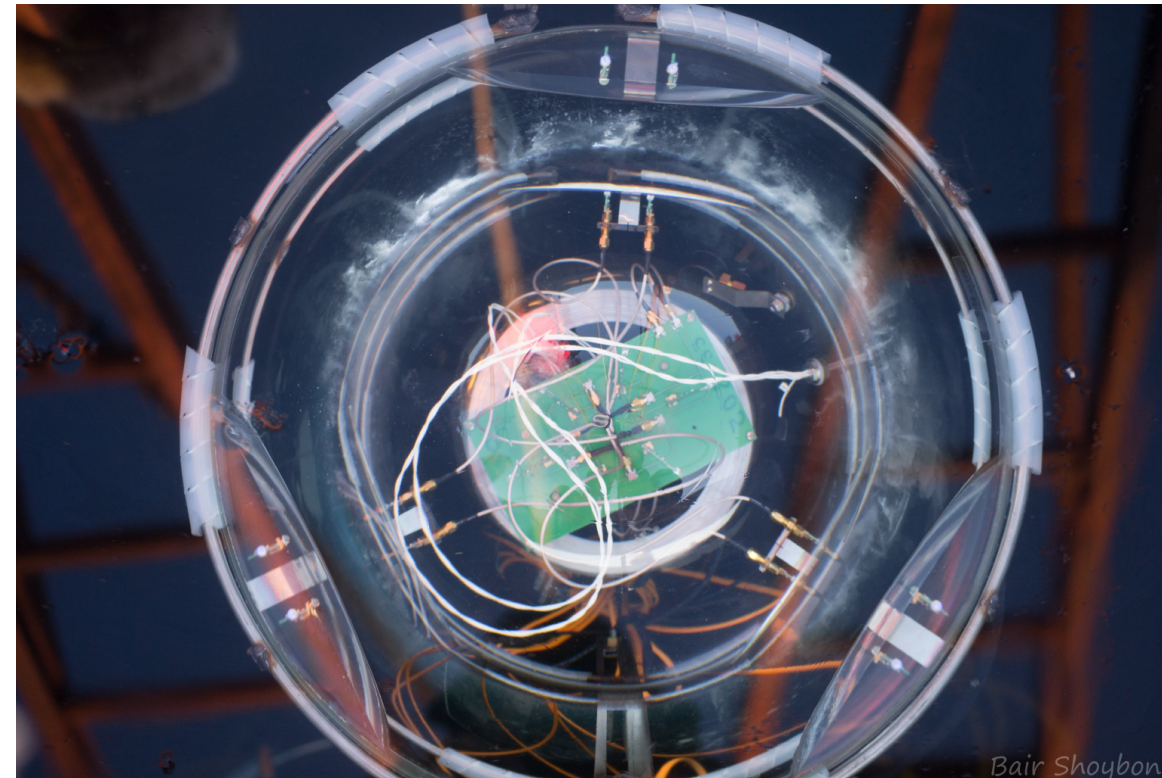
Матрица светодиодов

Межкластерная калибровка:

Два специально разработанных изотропных лазера

- Вспышки 532нм, 0.37 мДж ( $10^{15}$  фотонов) , длительность 1 нс
- В 2020 будет установлено еще 4 лазера

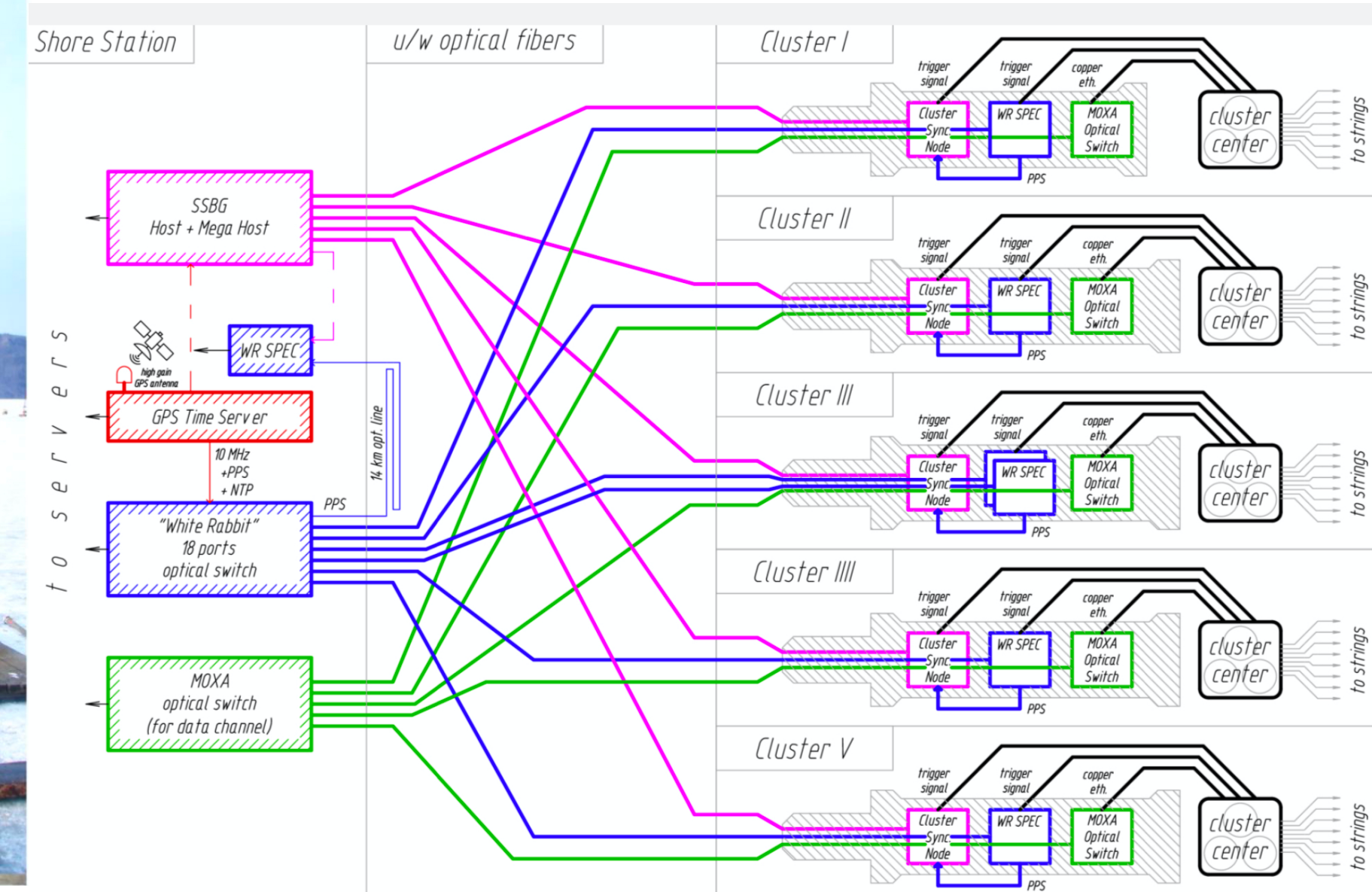
**Точность внутрисекционной и межсекционной калибровки  $\sim 2.5$  нс**



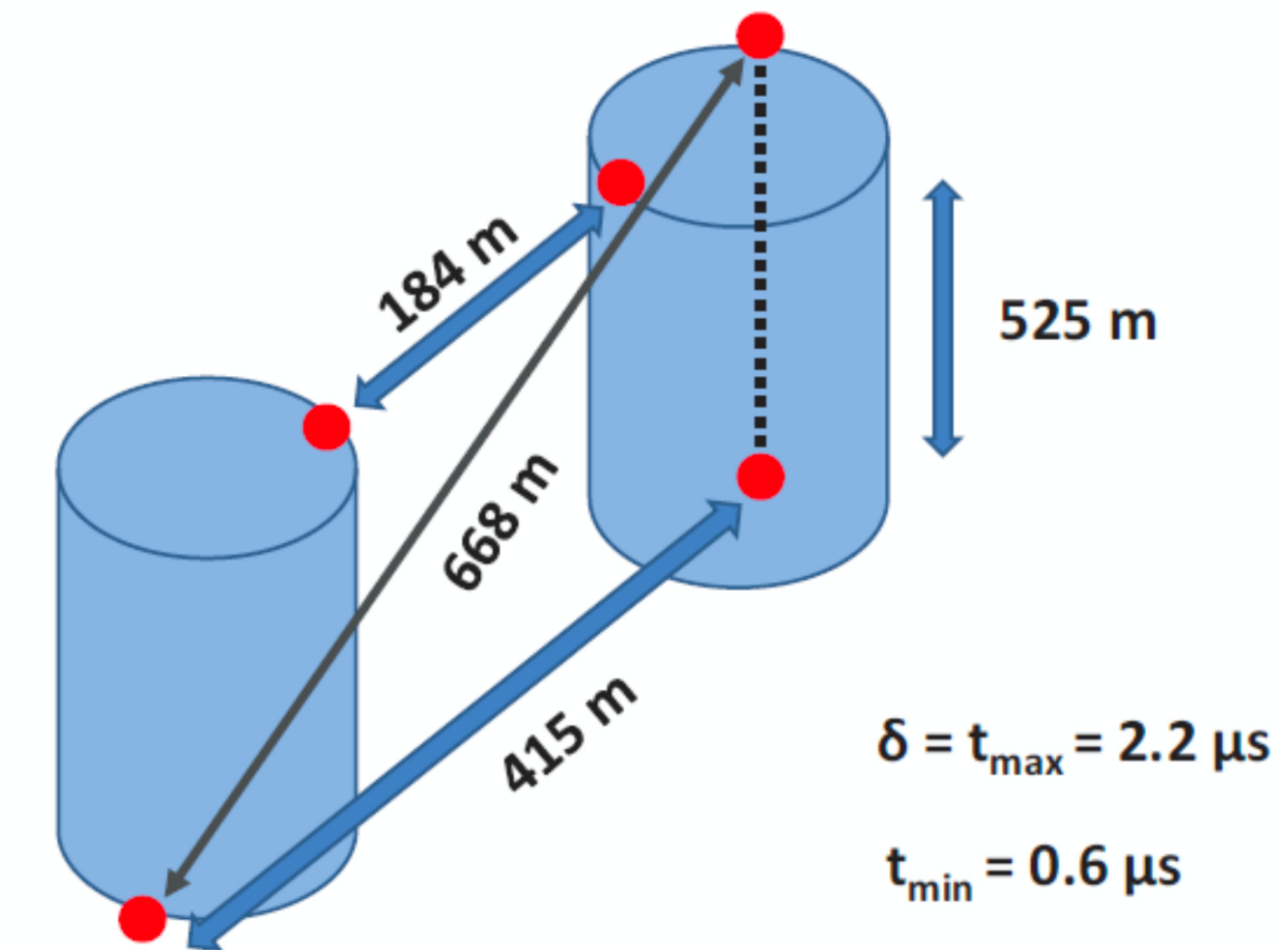
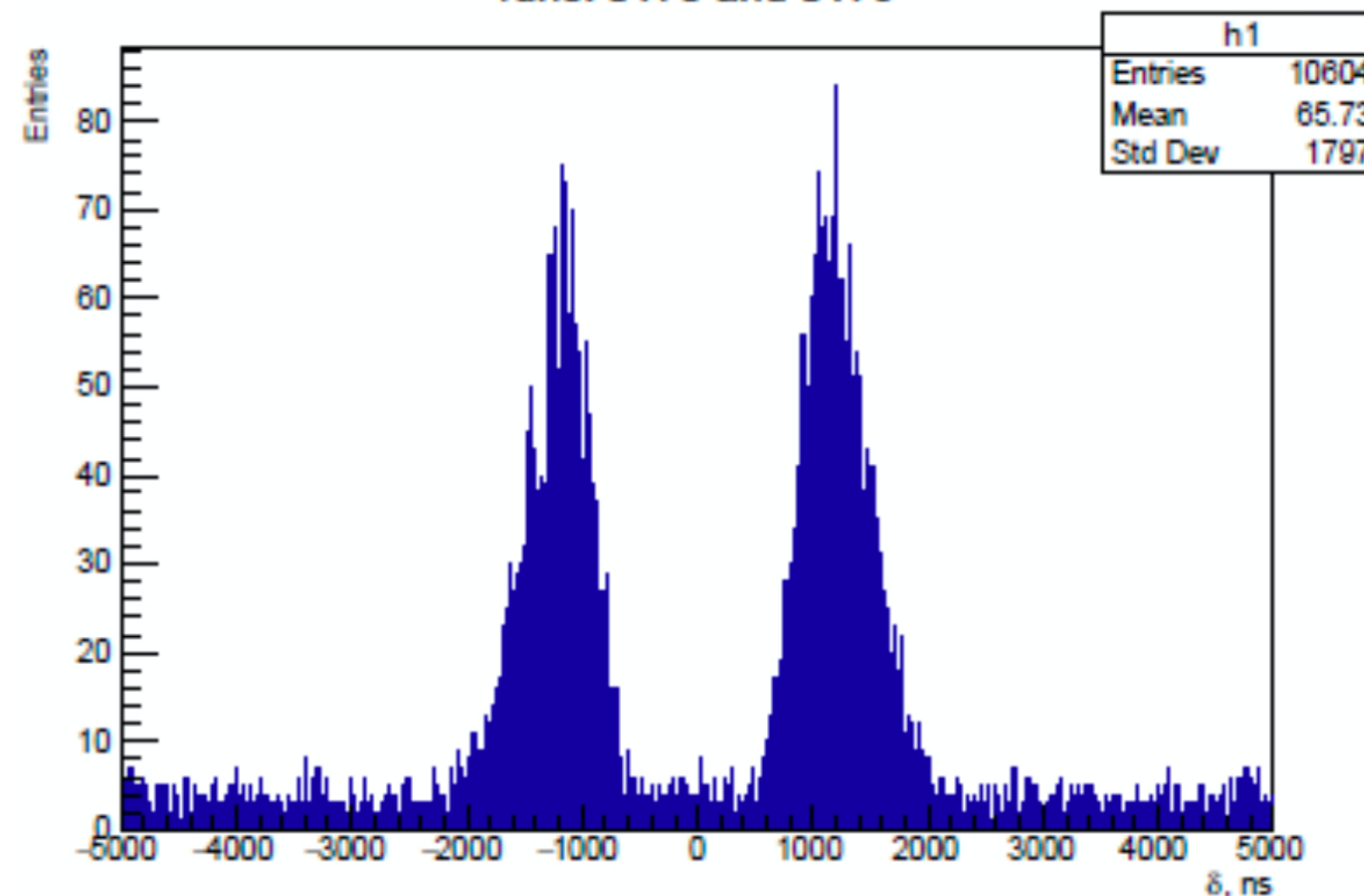


# Система синхронизации кластеров

- Однокластерное событие приобретает временную метку, синхронизированную с мировым временем, благодаря
  - оптической линии связи берег - ЦК
  - оборудованию систем синхронизации WhiteRabbit (CERN) и SSBG (МГУ), установленных на берегу и в ЦК
- Мультикластерные события создаются путем нахождения однокластерных событий с близкими значениями временных меток

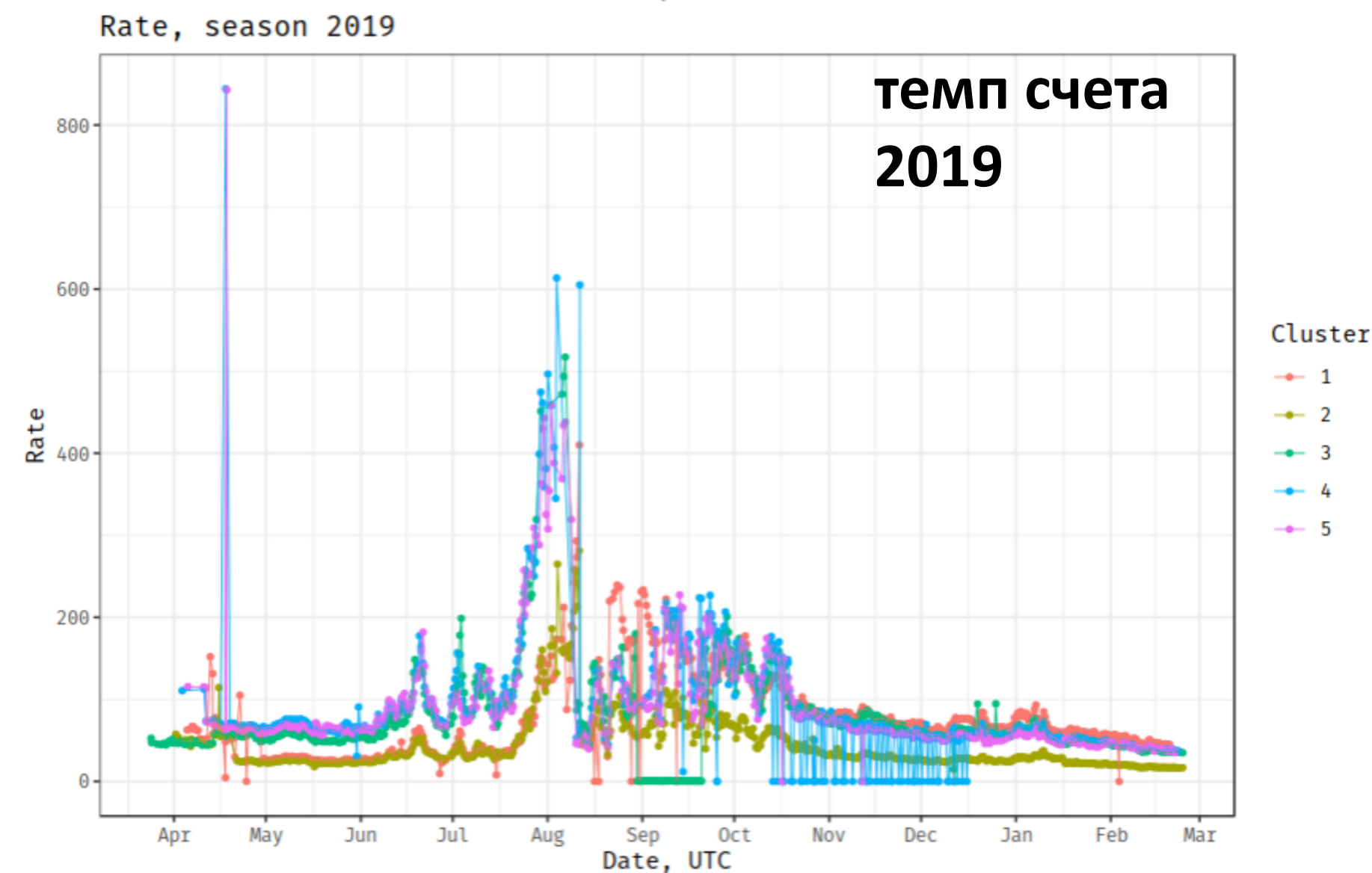
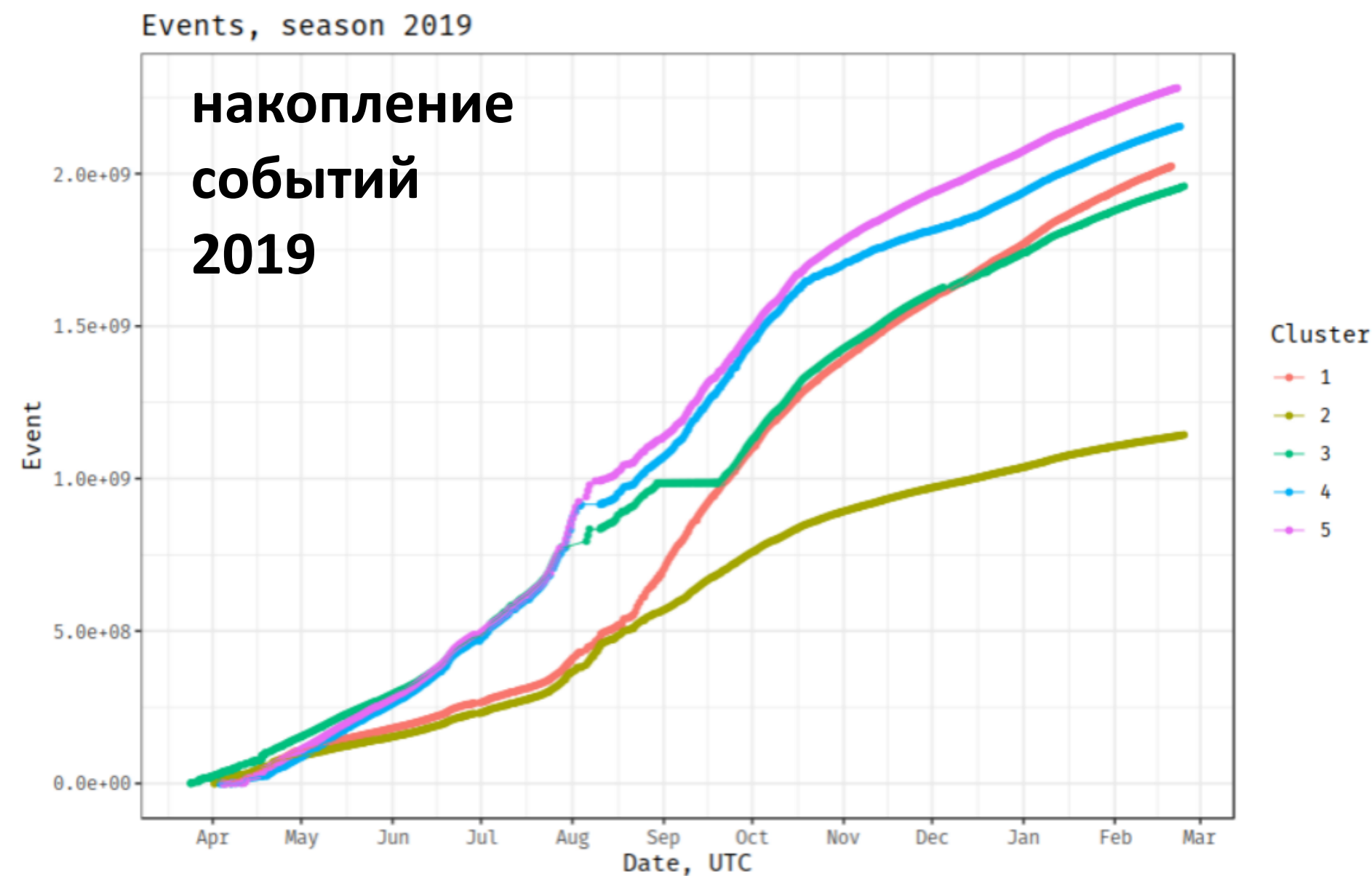


runs: 0175 and 0176

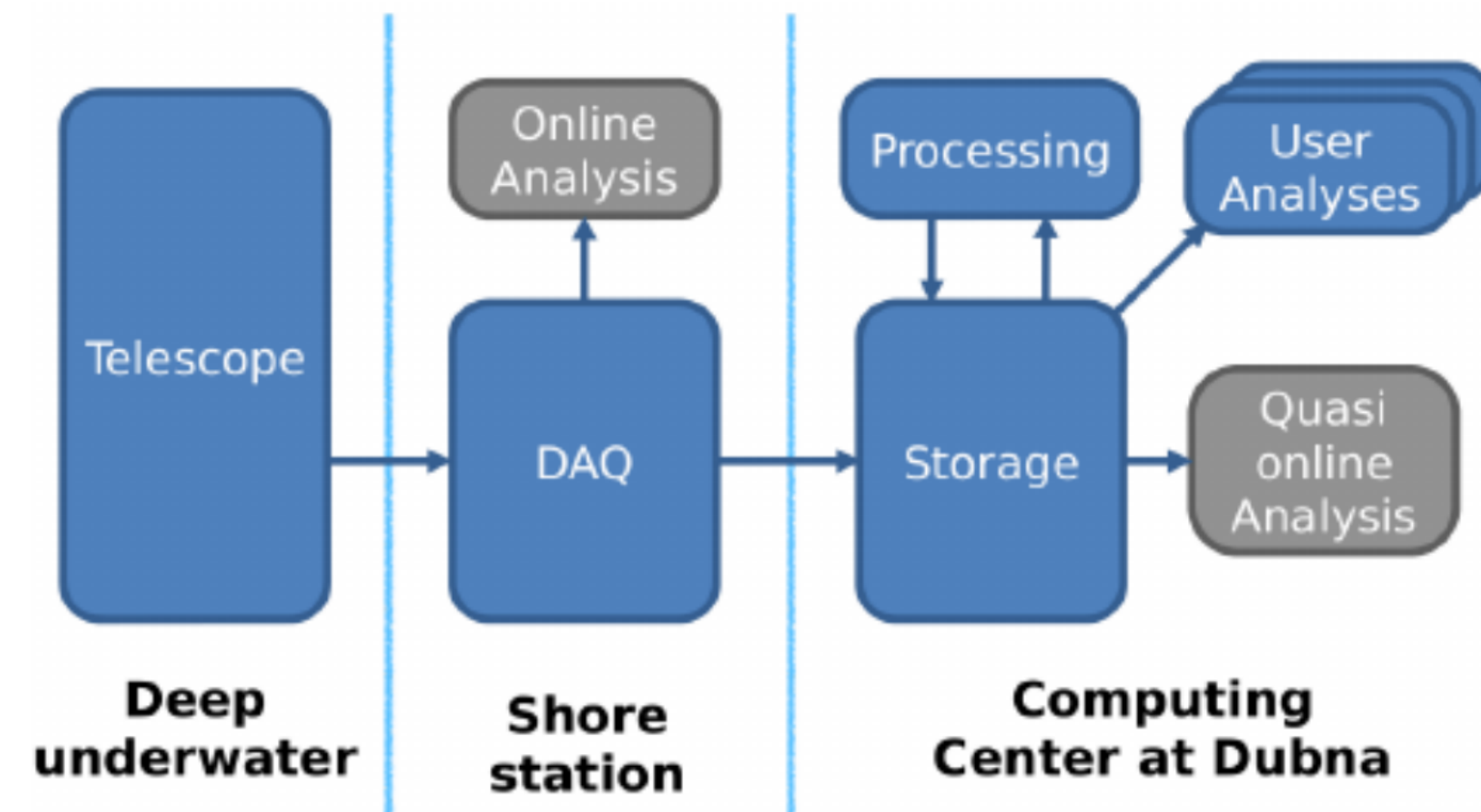
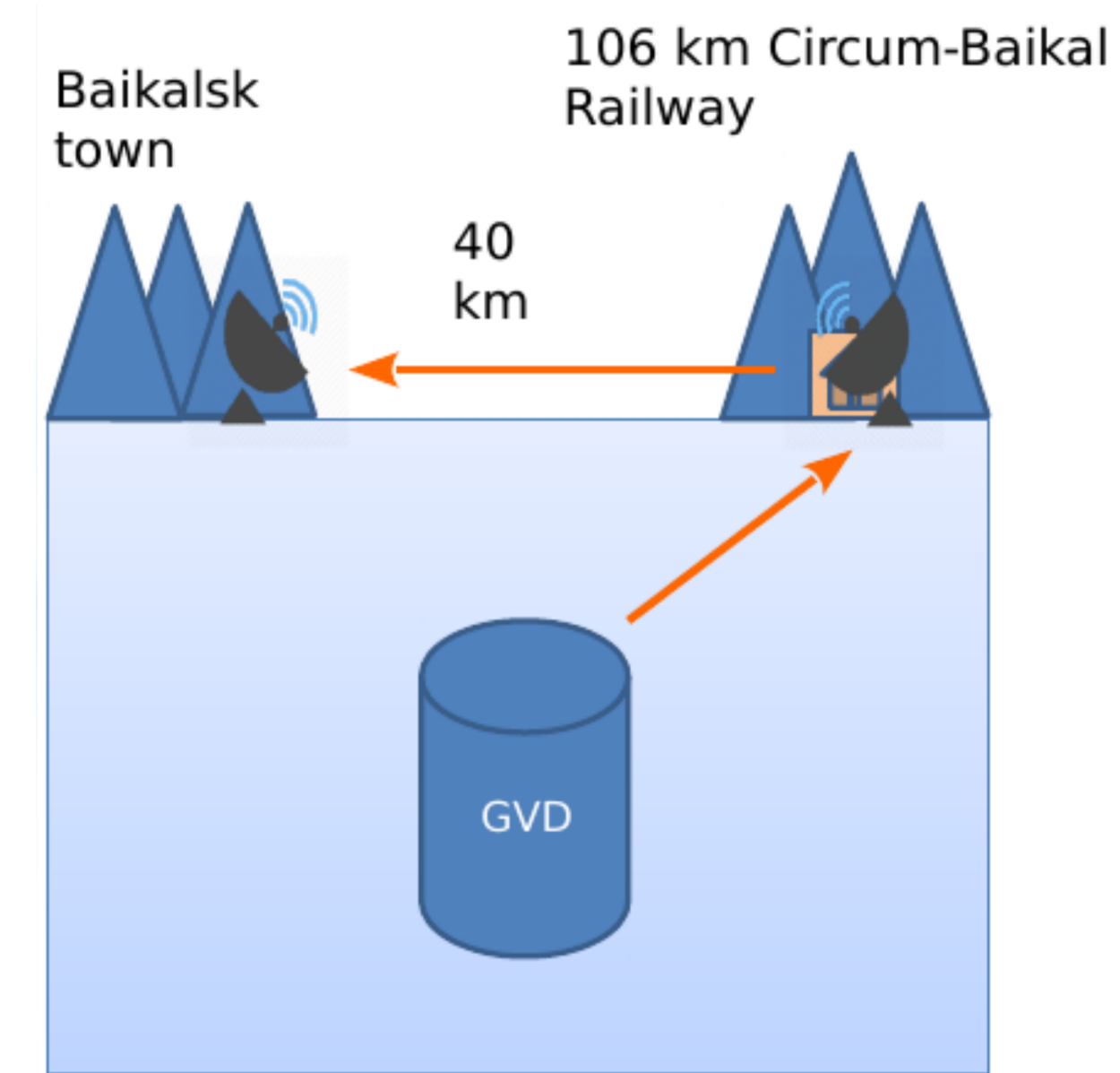




# Поток данных с телескопа

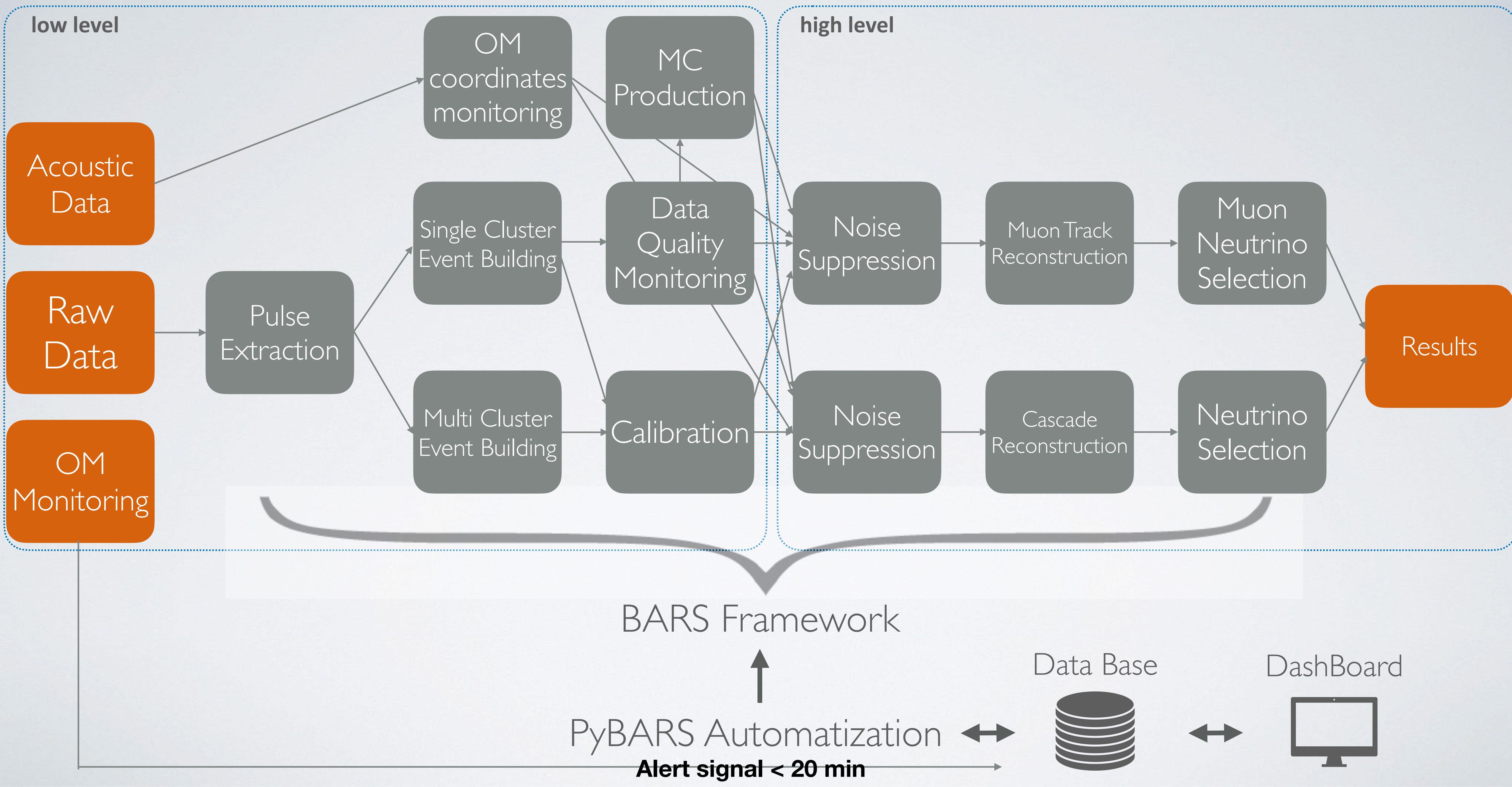


- 40 Гб с кластера в день в береговой центр
- Радиоканал 250 Мб/с (БЦ - г. Байкальск)
- Данные передаются в ОИЯИ по интернету файлами с экспозицией 6 мин
- Автоматическая обработка первичных данных в ОИЯИ
- Пользовательский анализ на вычислительной ферме в ОИЯИ





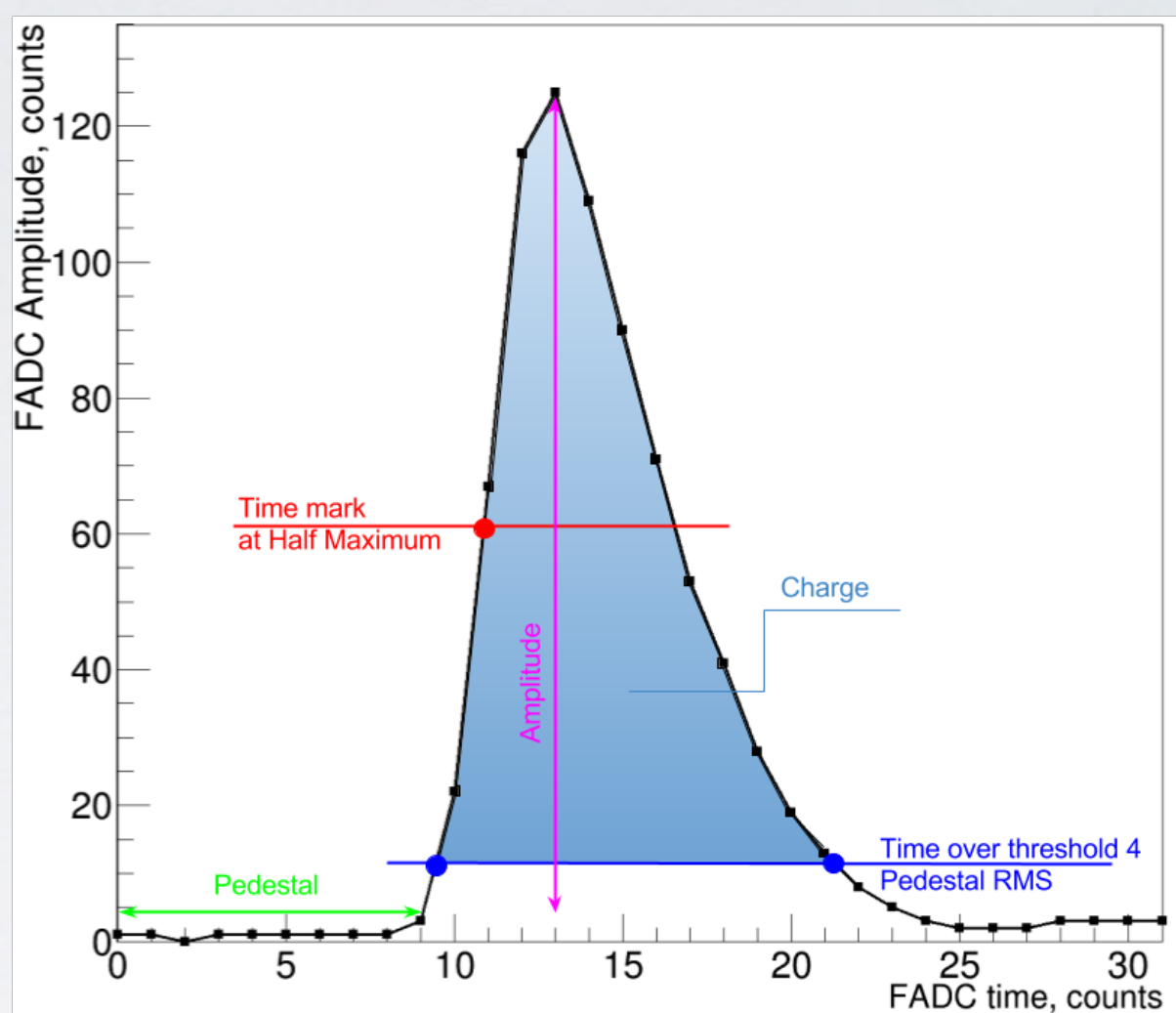
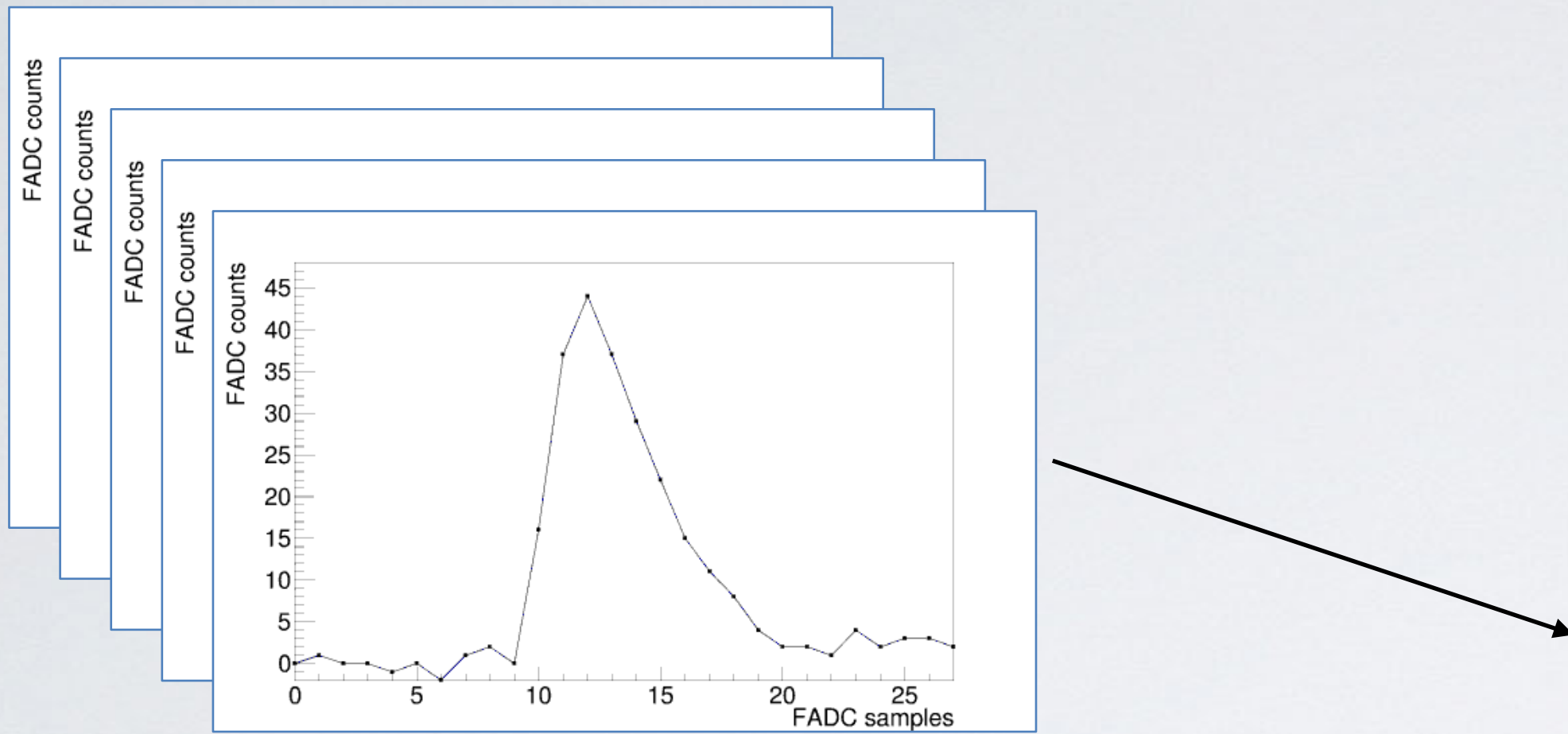
# DATA PROCESSING AND ANALYSIS SCHEME





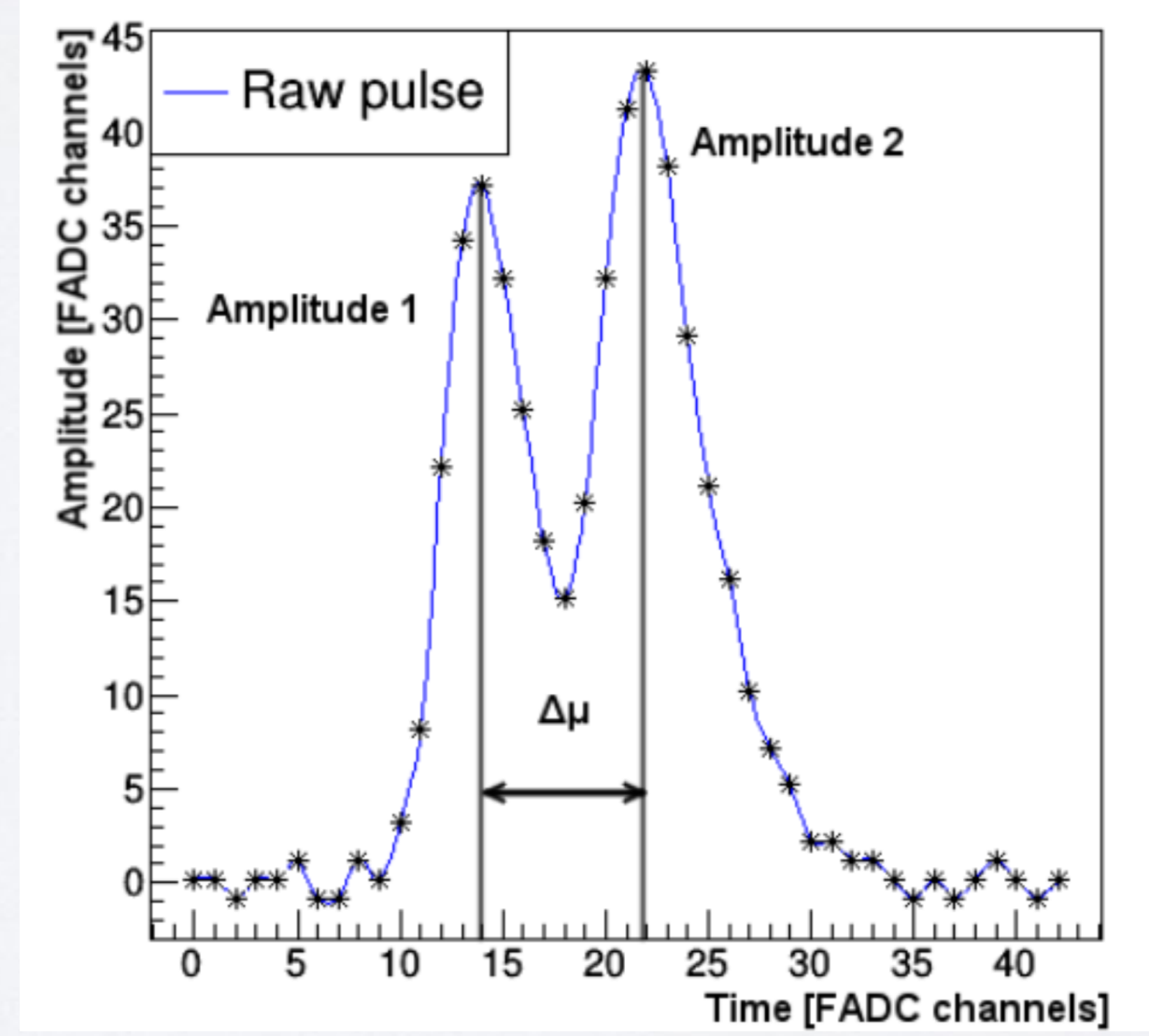
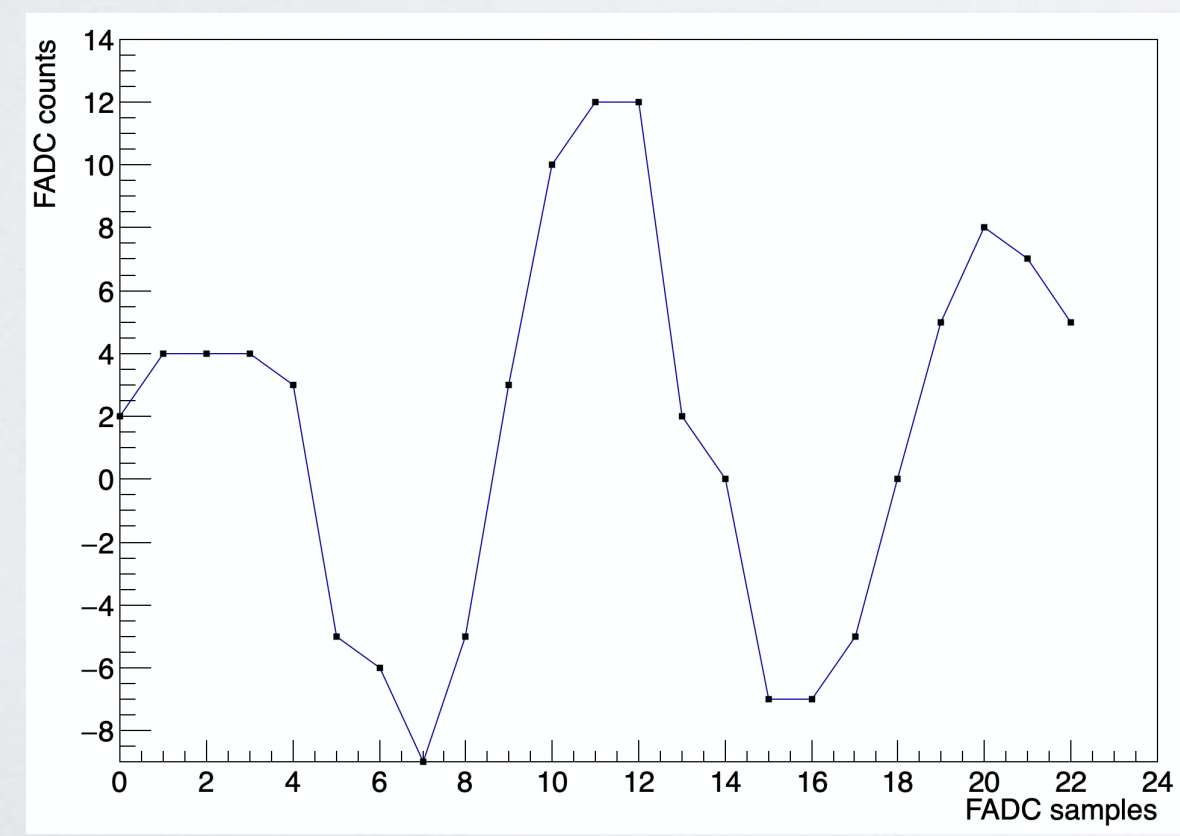
# PULSE EXTRACTION AND FILTRATION

Full FADC waveform data (12 bit, 5 ns)



Extracted data

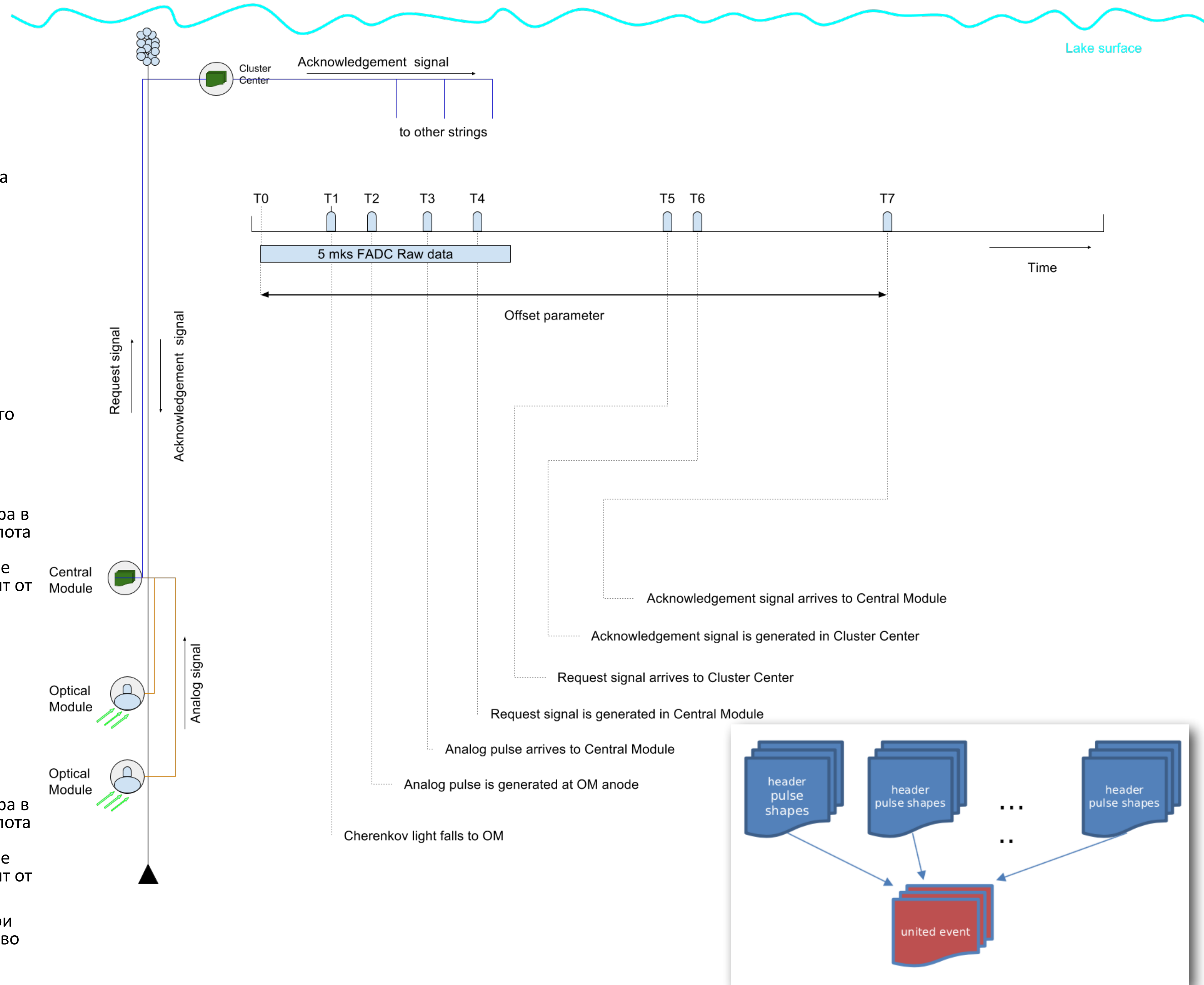
$Q_i, A_i, T_i, N_{chi}, i = 1..N_{ch}$





# Trigger system

- Два соседних ОМ передают импульсы на ЦМ, которые
  - Превышают низкий и высокий пороги в 4 соседних отсчетах
  - Разность времен между превышениями меньше заданного окна 100 нс
- ЦМ генерирует локальный запрос, при этом:
  - Отправляется сигнал запроса в ЦК с задержкой в соответствии с выставленным параметром задержки
  - Инкрементируется счетчик запросов ЦМ
  - Вход запирается на 30 мкс (мертвое время)
- На ЦК на соответствующем этой секции FADC канале появляется импульс, который превышает низкий порог
  - ЦК генерирует сигнал подтверждения в разветвитель и на самого себя
  - Инкрементируются счетчики запросов и подтверждений
  - Считывается показание таймера
  - Считывается кусок 5мкс данных со всех каналов из 30 мкс буфера в соответствии с параметром оффсет в двойной буфер. Если оба слота пустые, то событие записывается в 1-ую позицию. Если первая позиция занята, то пишется во 2-ую. Если обе заняты, то событие теряется. Время освобождения позиции около 600 мкс и зависит от версии мастера
  - Вход запирается на 30 мкс
- Разветвитель распределяет сигнал подтверждения на все секции и запирается на 100 мкс.
- ЦМ-ы принимают сигналы подтверждений:
  - Инкрементируется счетчик подтверждений
  - Считывается показание таймера
  - Считывается кусок 5мкс данных со всех каналов из 30 мкс буфера в соответствии с параметром оффсет в двойной буфер. Если оба слота пустые, то событие записывается в 1-ую позицию. Если первая позиция занята, то пишется во 2-ую. Если обе заняты, то событие теряется. Время освобождения позиции около 600 мкс и зависит от версии мастера
  - В ЦМ-е есть буфер на 1000 событий, который освобождается при периодическом считывании программой Е. Плисковского. Если во время не освободить буфер, то данные могут теряться

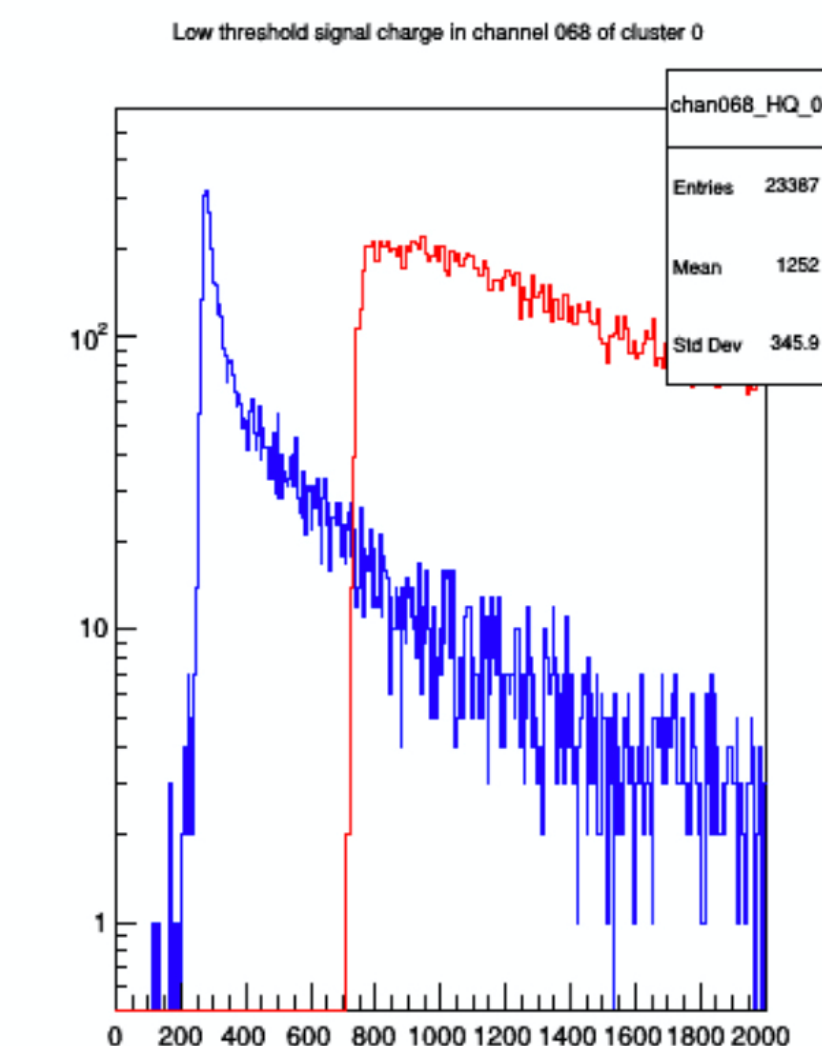
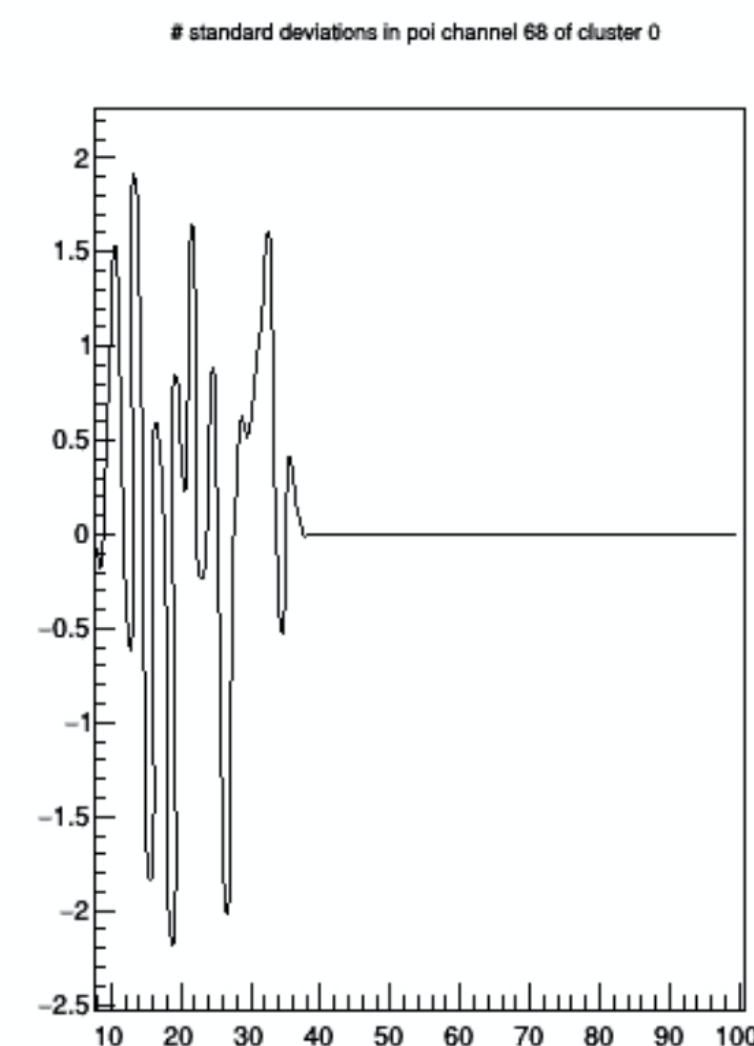
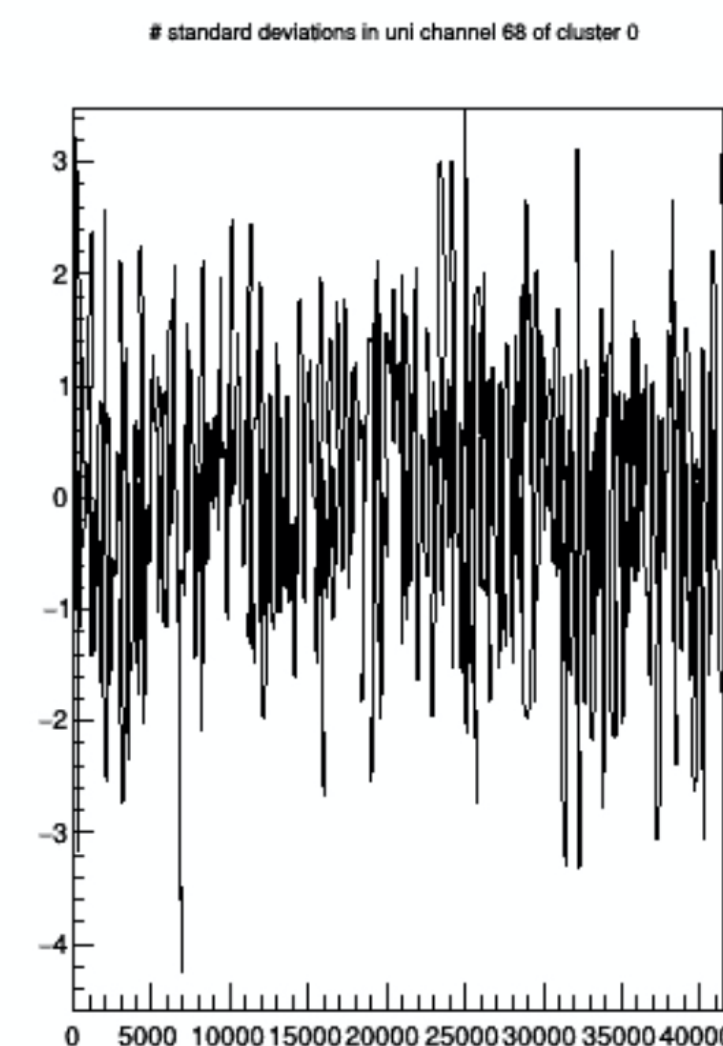
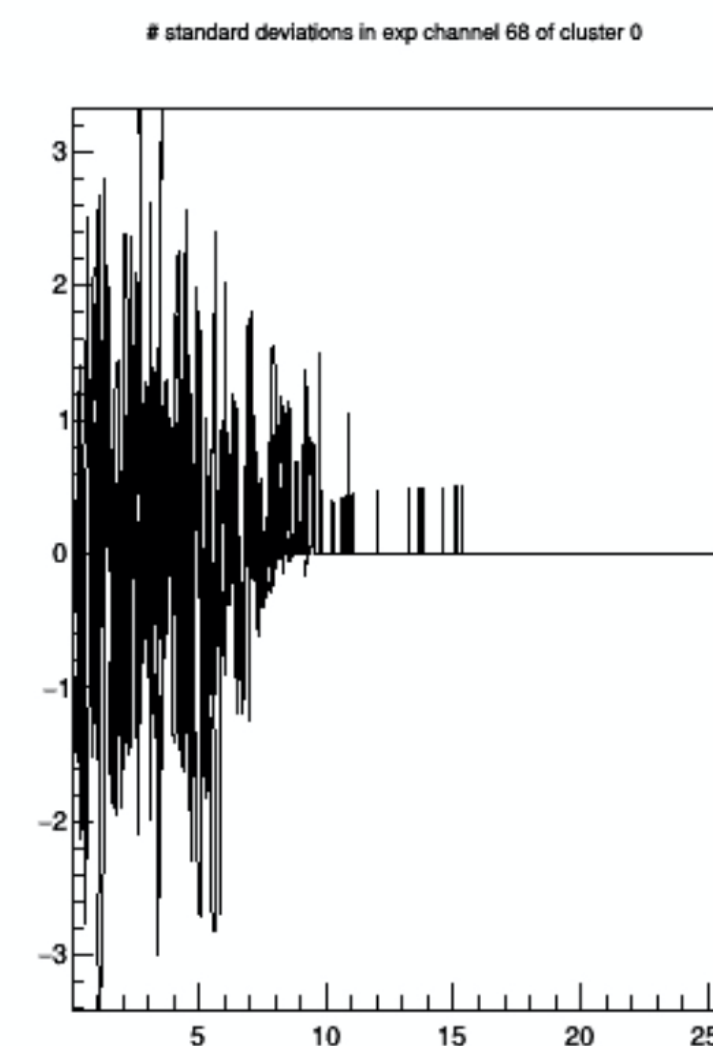
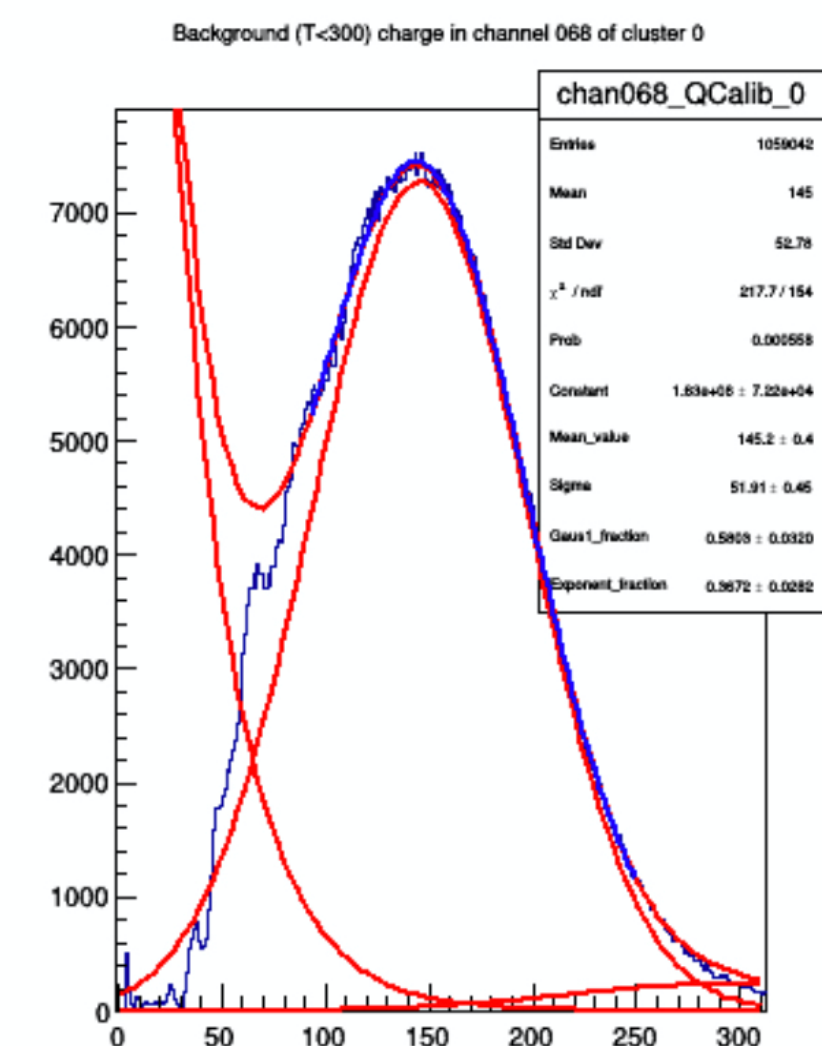
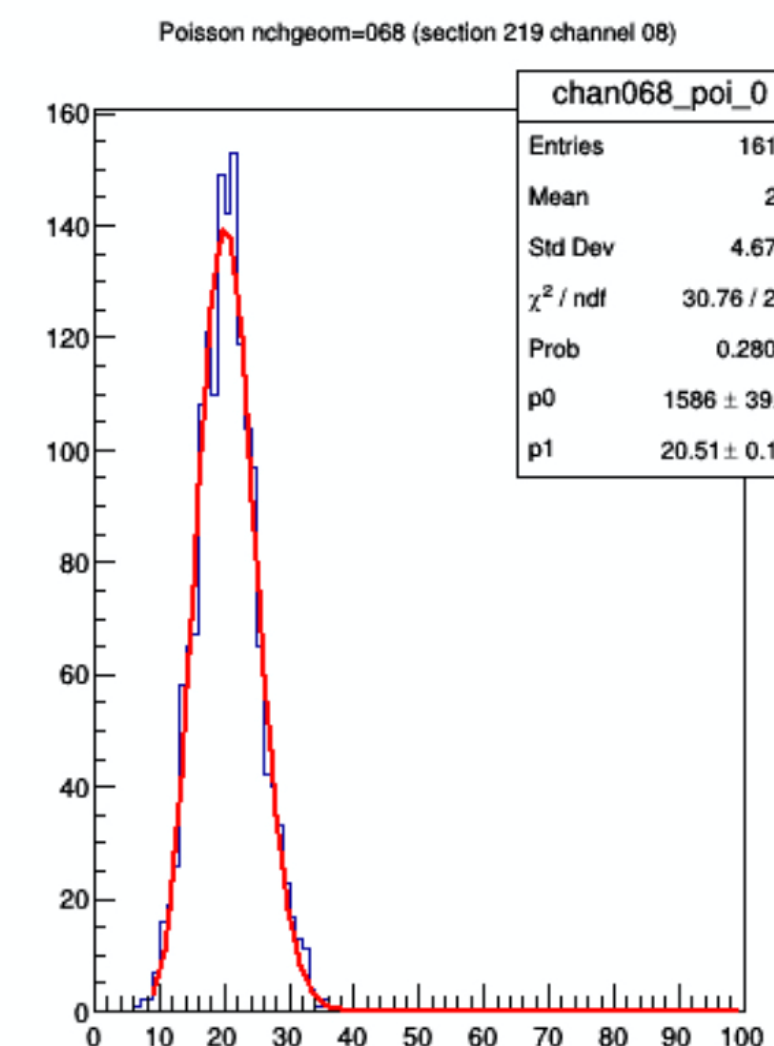
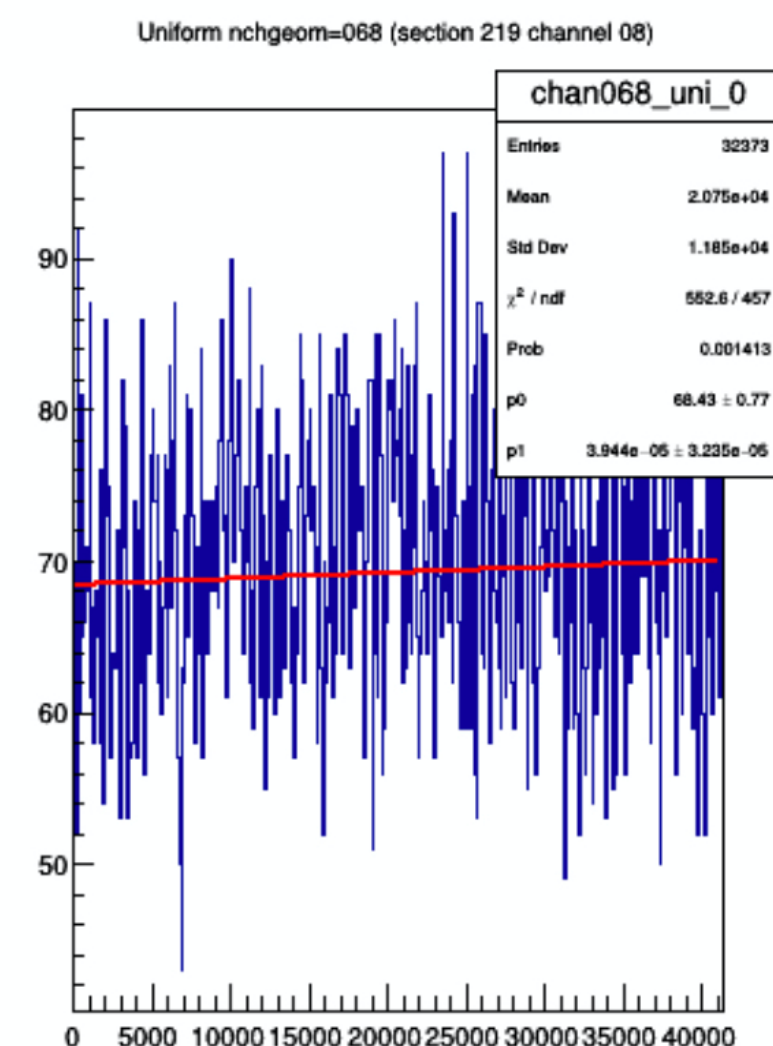
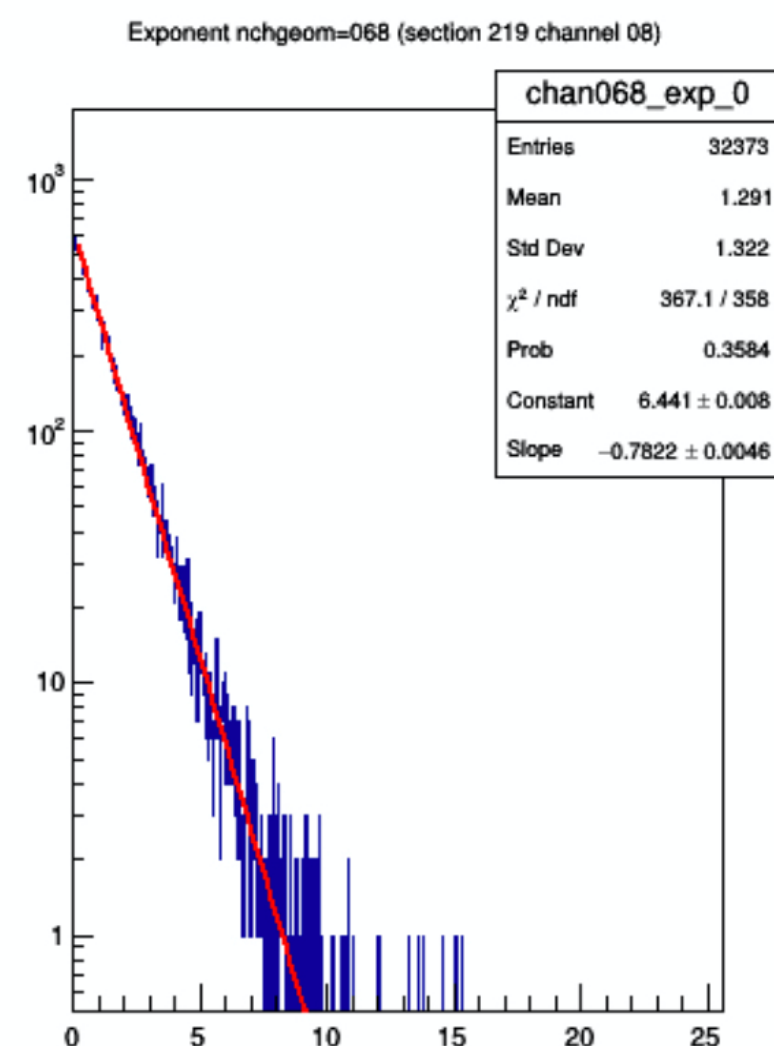




# Data quality monitoring

Quality from fit of distributions:

- time difference between events (exponent)
  - check of artificial light
- rate during run (uniform)
  - check stability of channel
- number of events per equal intervals (Poisson)
  - check stability of channel
- 1 p.e. charge distribution
  - check of cross talks
- etc.





# Data quality monitoring

| Cluster 2, Run 436, T <sub>start</sub> = 2019-10-01 13:59:51, T <sub>stop</sub> = 2019-10-02 02:30:57 |    |           |     |           |     |            |     |            |     |            |     |            |     |            |     |
|-------------------------------------------------------------------------------------------------------|----|-----------|-----|-----------|-----|------------|-----|------------|-----|------------|-----|------------|-----|------------|-----|
| String 0                                                                                              |    | String 1  |     | String 2  |     | String 3   |     | String 4   |     | String 5   |     | String 6   |     | String 7   |     |
| Section 2                                                                                             | 35 | Section 5 | 71  | Section 8 | 107 | Section 11 | 143 | Section 14 | 179 | Section 17 | 215 | Section 20 | 251 | Section 23 | 287 |
|                                                                                                       | 34 |           | 70  |           | 106 |            | 142 |            | 178 |            | 214 |            | 250 |            | 286 |
|                                                                                                       | 33 |           | 69  |           | 105 |            | 141 |            | 177 |            | 213 |            | 249 |            | 285 |
|                                                                                                       | 32 |           | 68  |           | 104 |            | 140 |            | 176 |            | 212 |            | 248 |            | 284 |
|                                                                                                       | 31 |           | 67  |           | 103 |            | 139 |            | 175 |            | 211 |            | 247 |            | 283 |
|                                                                                                       | 30 |           | 66  |           | 102 |            | 138 |            | 174 |            | 210 |            | 246 |            | 282 |
|                                                                                                       | 29 |           | 65  |           | 101 |            | 137 |            | 173 |            | 209 |            | 245 |            | 281 |
|                                                                                                       | 28 |           | 64  |           | 100 |            | 136 |            | 172 |            | 208 |            | 244 |            | 280 |
|                                                                                                       | 27 |           | 63  |           | 99  |            | 135 |            | 171 |            | 207 |            | 243 |            | 279 |
|                                                                                                       | 26 |           | 62  |           | 98  |            | 134 |            | 170 |            | 206 |            | 242 |            | 278 |
| 25                                                                                                    | 61 | 97        | 133 | 169       | 205 | 241        | 277 |            |     |            |     |            |     |            |     |
| 24                                                                                                    | 60 | 96        | 132 | 168       | 204 | 240        | 276 |            |     |            |     |            |     |            |     |
| Section 1                                                                                             | 23 | Section 4 | 59  | Section 7 | 95  | Section 10 | 131 | Section 13 | 167 | Section 16 | 203 | Section 19 | 239 | Section 22 | 275 |
|                                                                                                       | 22 |           | 58  |           | 94  |            | 130 |            | 166 |            | 202 |            | 238 |            | 274 |
|                                                                                                       | 21 |           | 57  |           | 93  |            | 129 |            | 165 |            | 201 |            | 237 |            | 273 |
|                                                                                                       | 20 |           | 56  |           | 92  |            | 128 |            | 164 |            | 200 |            | 236 |            | 272 |
|                                                                                                       | 19 |           | 55  |           | 91  |            | 127 |            | 163 |            | 199 |            | 235 |            | 271 |
|                                                                                                       | 18 |           | 54  |           | 90  |            | 126 |            | 162 |            | 198 |            | 234 |            | 270 |
|                                                                                                       | 17 |           | 53  |           | 89  |            | 125 |            | 161 |            | 197 |            | 233 |            | 269 |
|                                                                                                       | 16 |           | 52  |           | 88  |            | 124 |            | 160 |            | 196 |            | 232 |            | 268 |
|                                                                                                       | 15 |           | 51  |           | 87  |            | 123 |            | 159 |            | 195 |            | 231 |            | 267 |
|                                                                                                       | 14 |           | 50  |           | 86  |            | 122 |            | 158 |            | 194 |            | 230 |            | 266 |
| 13                                                                                                    | 49 | 85        | 121 | 157       | 193 | 229        | 265 |            |     |            |     |            |     |            |     |
| 12                                                                                                    | 48 | 84        | 120 | 156       | 192 | 228        | 264 |            |     |            |     |            |     |            |     |
| Section 0                                                                                             | 11 | Section 3 | 47  | Section 6 | 83  | Section 9  | 119 | Section 12 | 155 | Section 15 | 191 | Section 18 | 227 | Section 21 | 263 |
|                                                                                                       | 10 |           | 46  |           | 82  |            | 118 |            | 154 |            | 190 |            | 226 |            | 262 |
|                                                                                                       | 9  |           | 45  |           | 81  |            | 117 |            | 153 |            | 189 |            | 225 |            | 261 |
|                                                                                                       | 8  |           | 44  |           | 80  |            | 116 |            | 152 |            | 188 |            | 224 |            | 260 |
|                                                                                                       | 7  |           | 43  |           | 79  |            | 115 |            | 151 |            | 187 |            | 223 |            | 259 |
|                                                                                                       | 6  |           | 42  |           | 78  |            | 114 |            | 150 |            | 186 |            | 222 |            | 258 |
|                                                                                                       | 5  |           | 41  |           | 77  |            | 113 |            | 149 |            | 185 |            | 221 |            | 257 |
|                                                                                                       | 4  |           | 40  |           | 76  |            | 112 |            | 148 |            | 184 |            | 220 |            | 256 |
|                                                                                                       | 3  |           | 39  |           | 75  |            | 111 |            | 147 |            | 183 |            | 219 |            | 255 |
|                                                                                                       | 2  |           | 38  |           | 74  |            | 110 |            | 146 |            | 182 |            | 218 |            | 254 |
| 1                                                                                                     | 37 | 73        | 109 | 145       | 181 | 217        | 253 |            |     |            |     |            |     |            |     |
| 0                                                                                                     | 36 | 72        | 108 | 144       | 180 | 216        | 252 |            |     |            |     |            |     |            |     |

green - excellent fits

yellow - normal fits

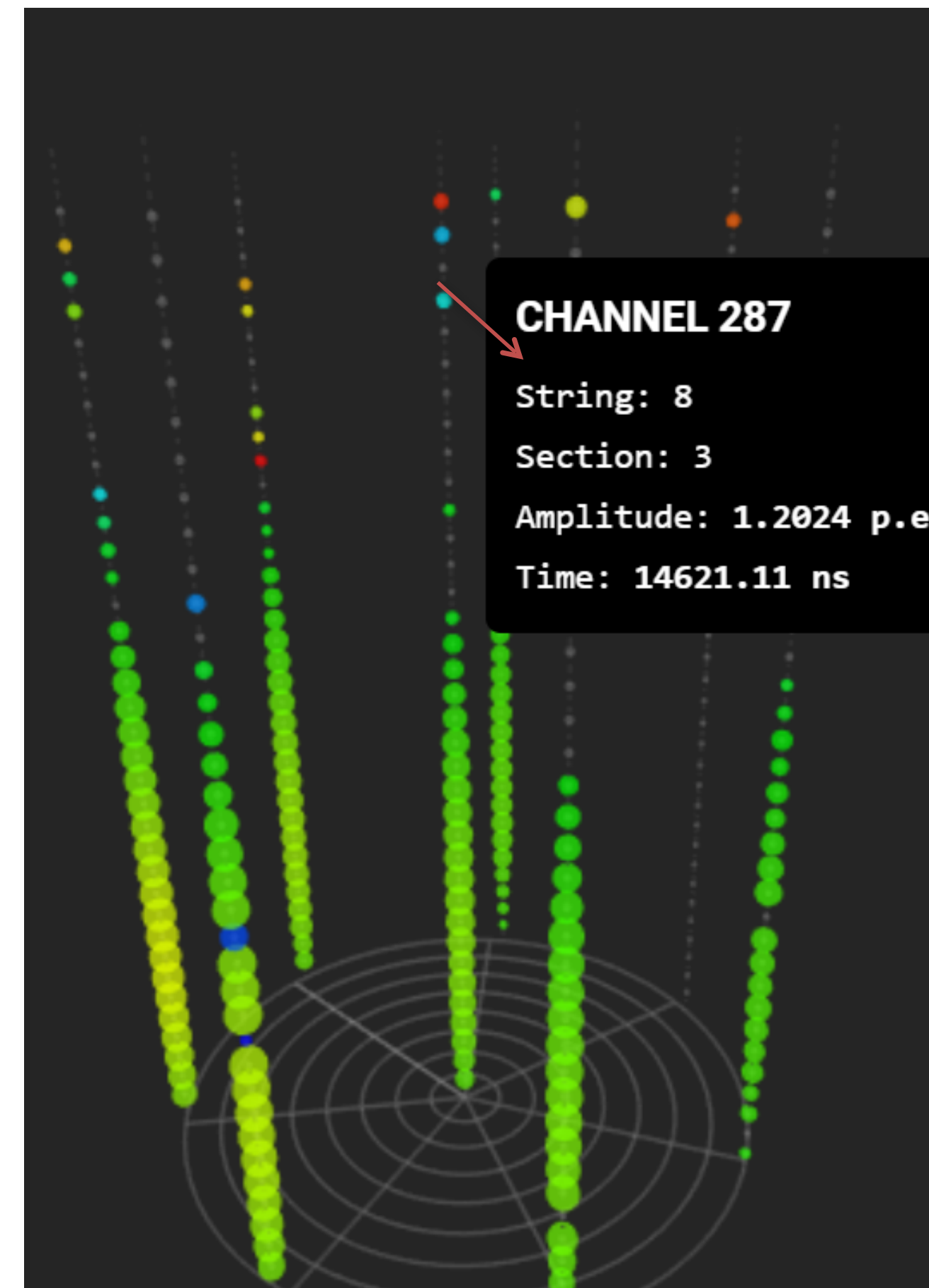
red - bad fits



# Подготовка событий для анализа

- Сырые данные -> События кластера  
-> Мультикластерные события
- Калибровка:
  - Отсчеты FADC -> ф.э.
  - Отсчеты FADC -> нс
  - Акустические данные -> положение ОМ, м vs время
- Выделение срабатываний ОМ, вызванных прохождением частиц, от срабатываний ОМ, вызванных свечением озера
- Восстановление трековых событий
- Восстановление ливневых событий
- Онлайн обработка данных -> Alert система

Подготовленные данные в виде откалиброванных откликов детектора

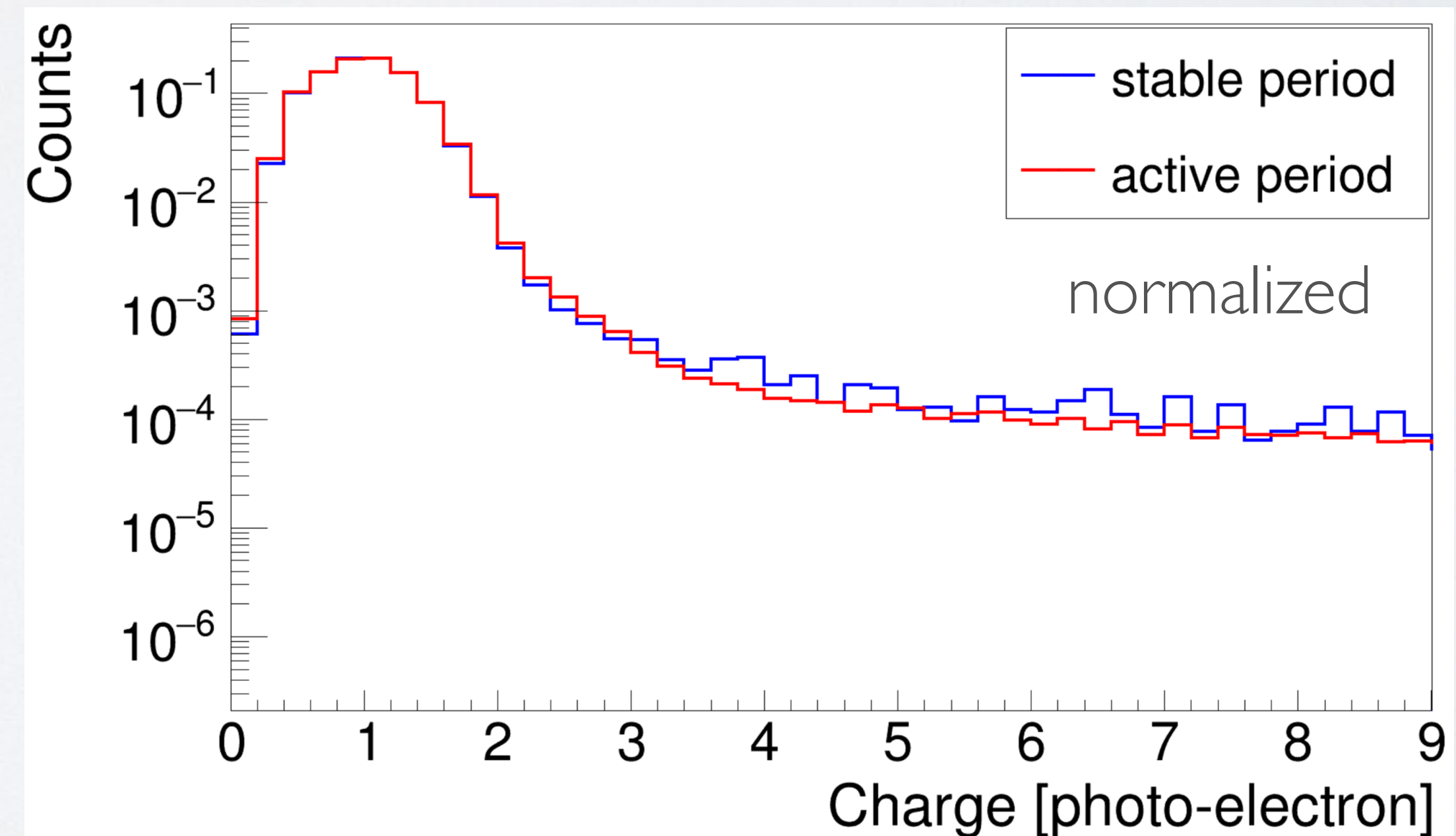
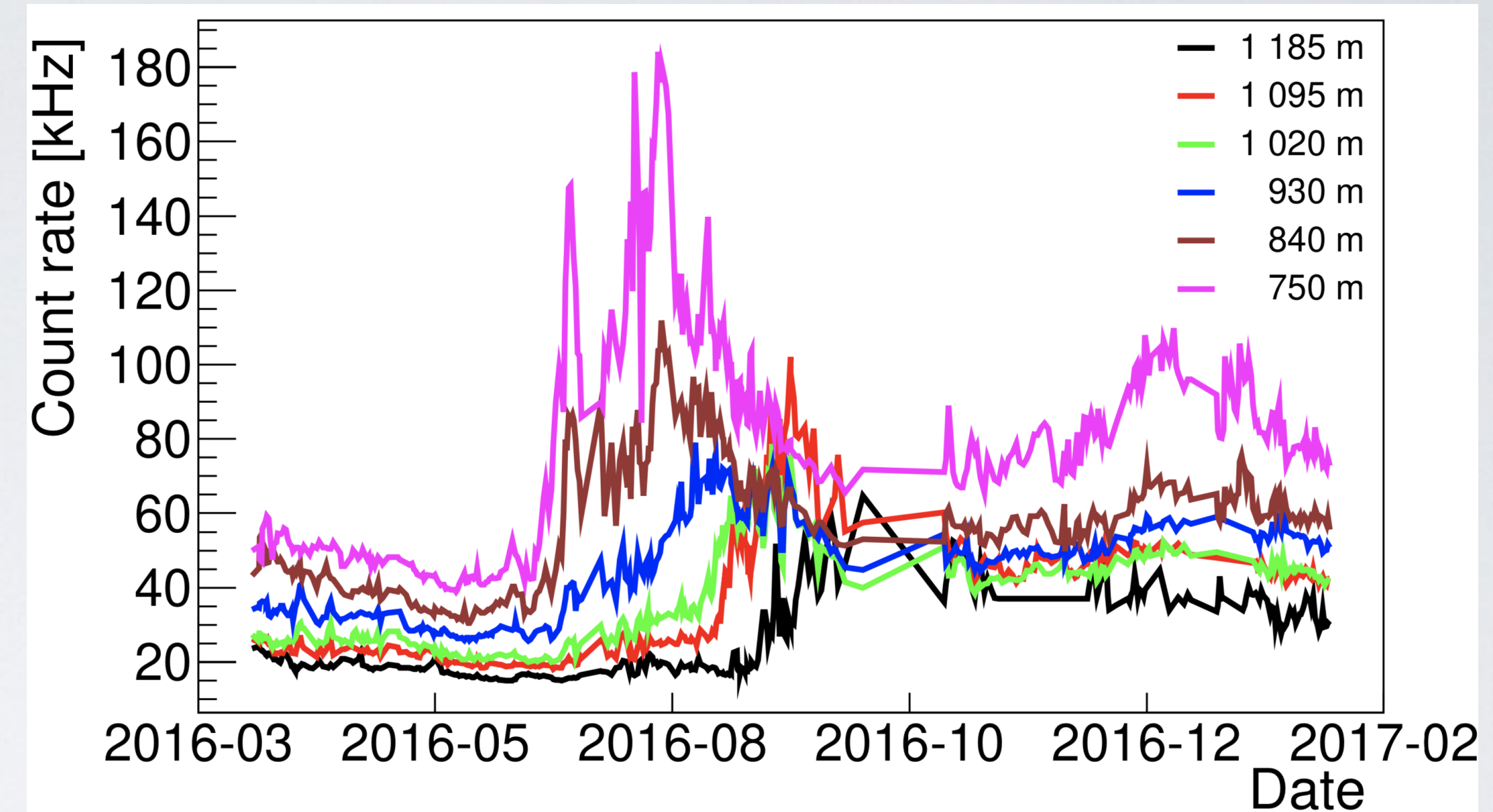


$$Q_i, T_i, \vec{R}_i, Nch_i, i = 1..Nhit$$



# LAKE BACKGROUND NOISE

- Lake chemiluminescence level varies during a year
- It has one-p.e. nature
- 20-40 kHz for "low noise" period
- The shallower the OM the higher the noise level
- The same charge distributions for low noise and active periods



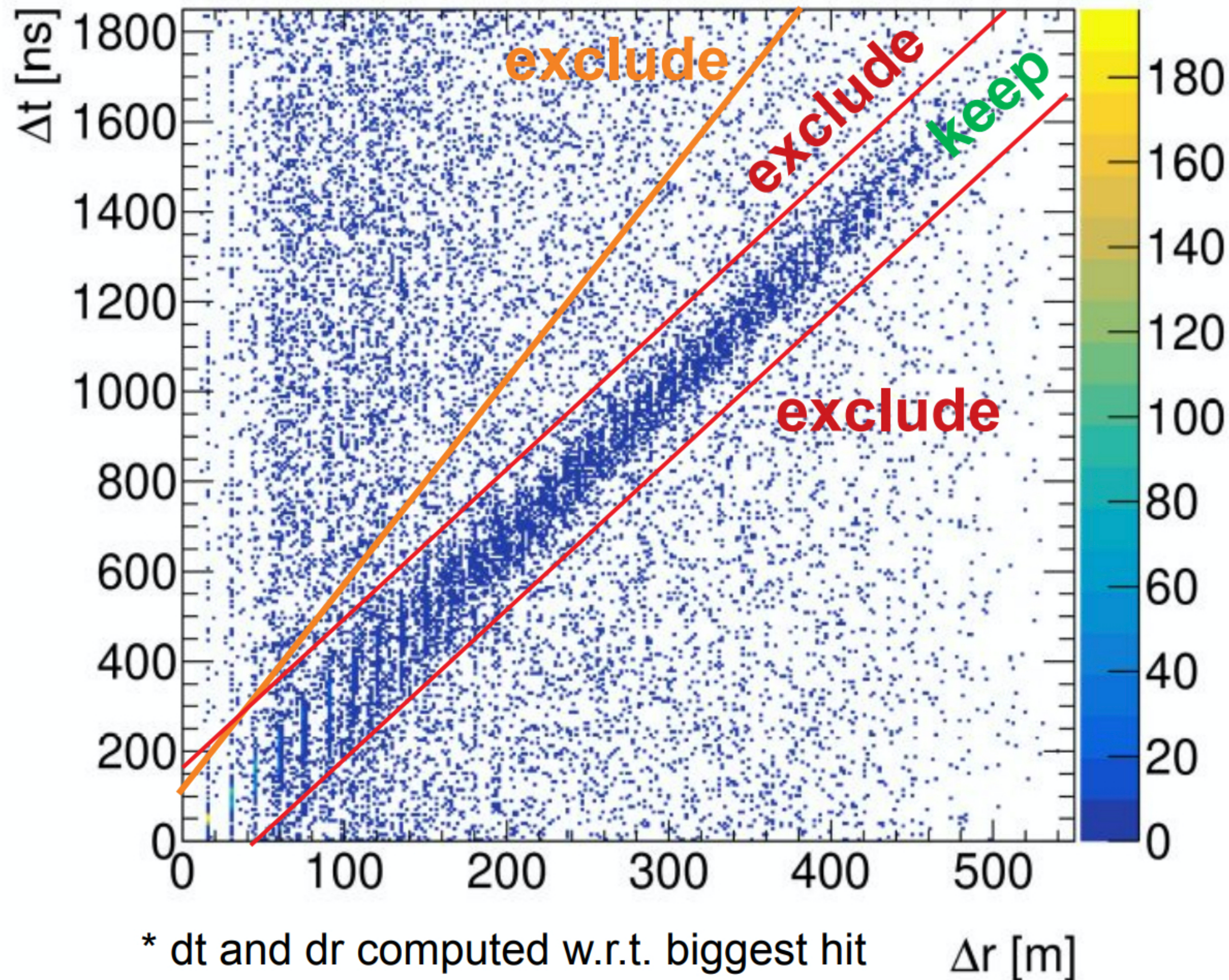


# Improved two-hit causality condition

Recently we have extended our causality condition with "long distance causality"

Monte Carlo high-energy nu\_mu\_CC with realistic noise

D. Zaborov



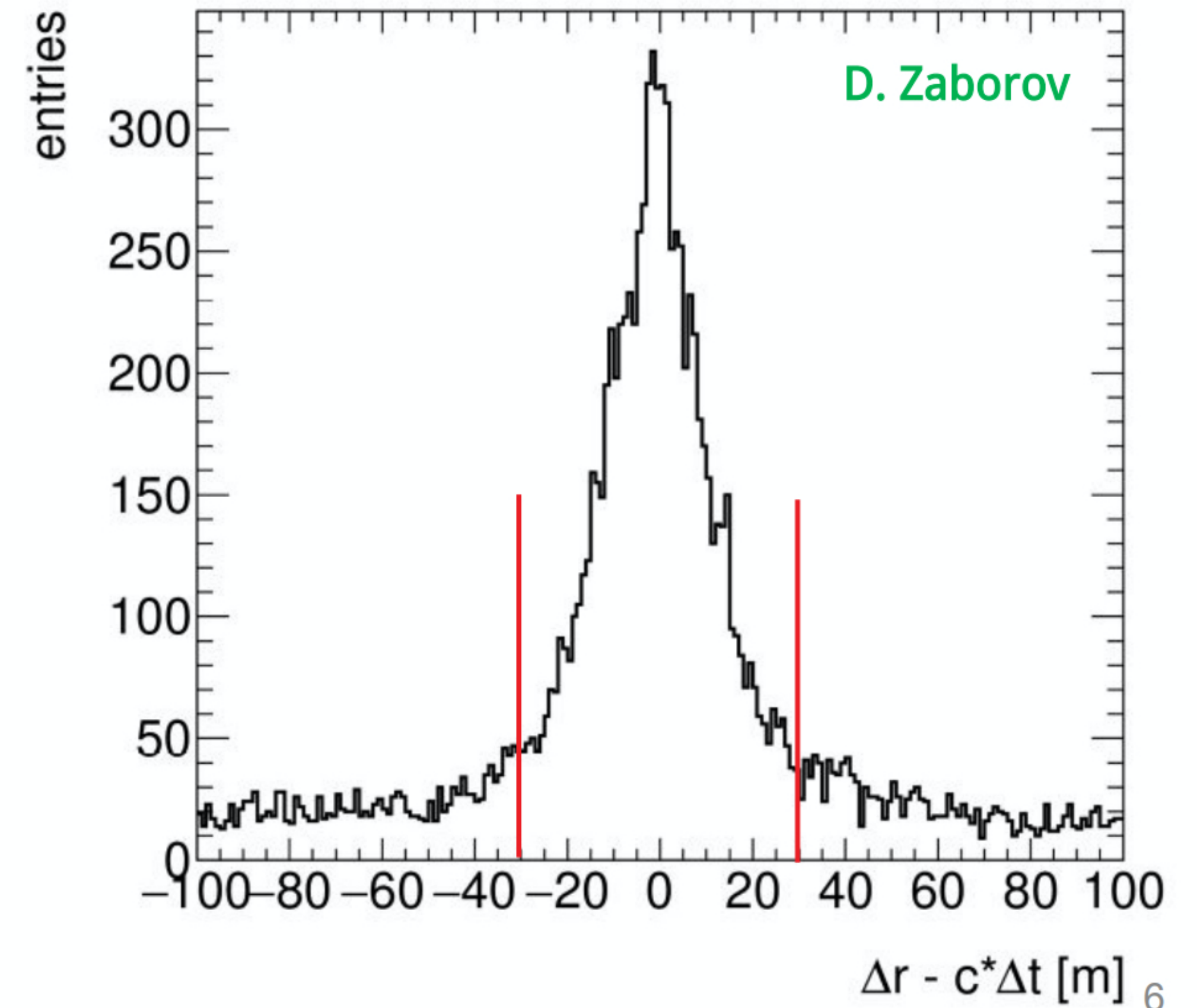
Grigory Safronov

Classic causality condition:

$$dt < dr / v + a$$

Long-distance causality condition:

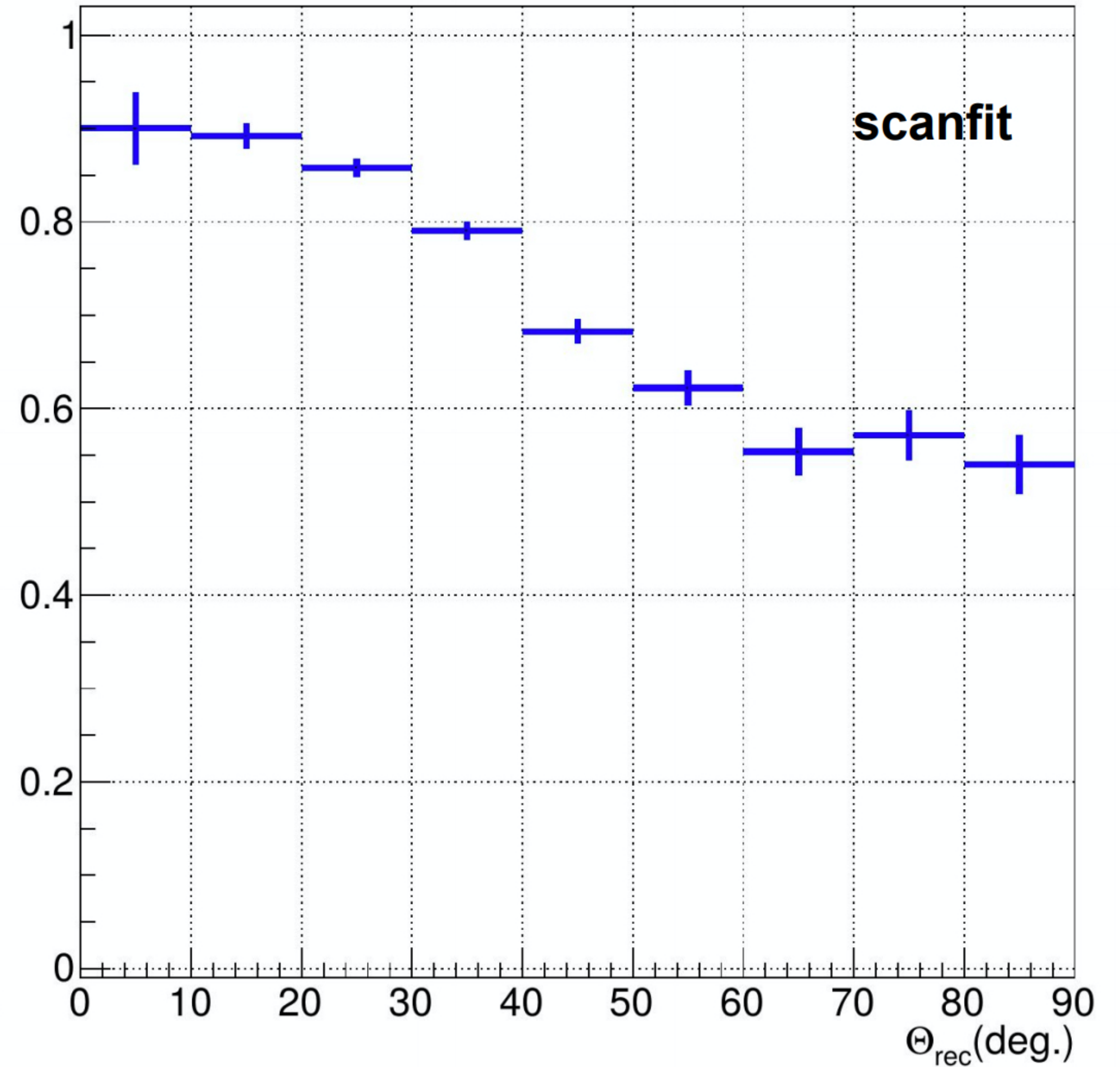
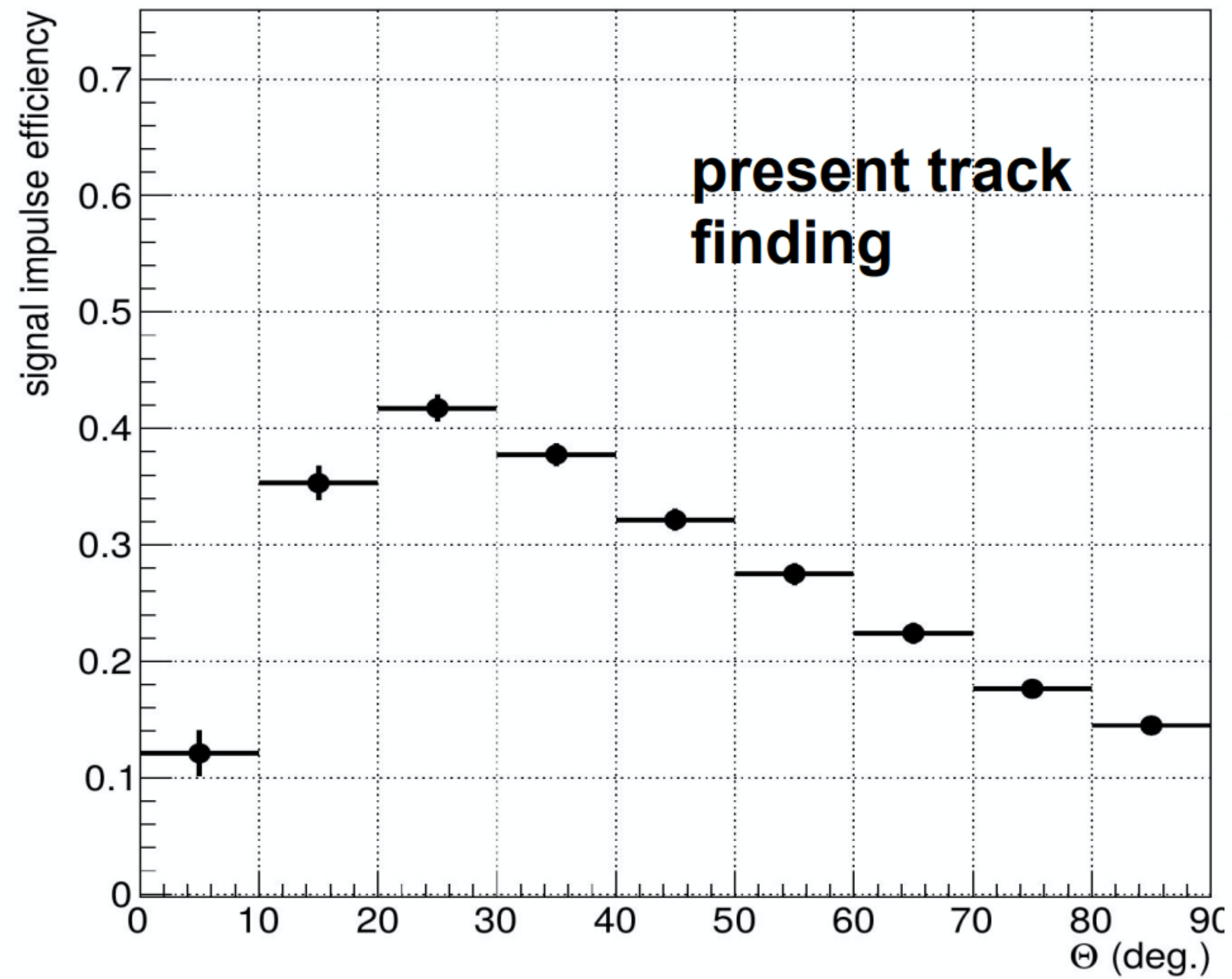
$$|dt - dr / c| < b$$





# Scanfit I

**Drastic improvement of the  
impulse selection  
efficiency with scanfit**

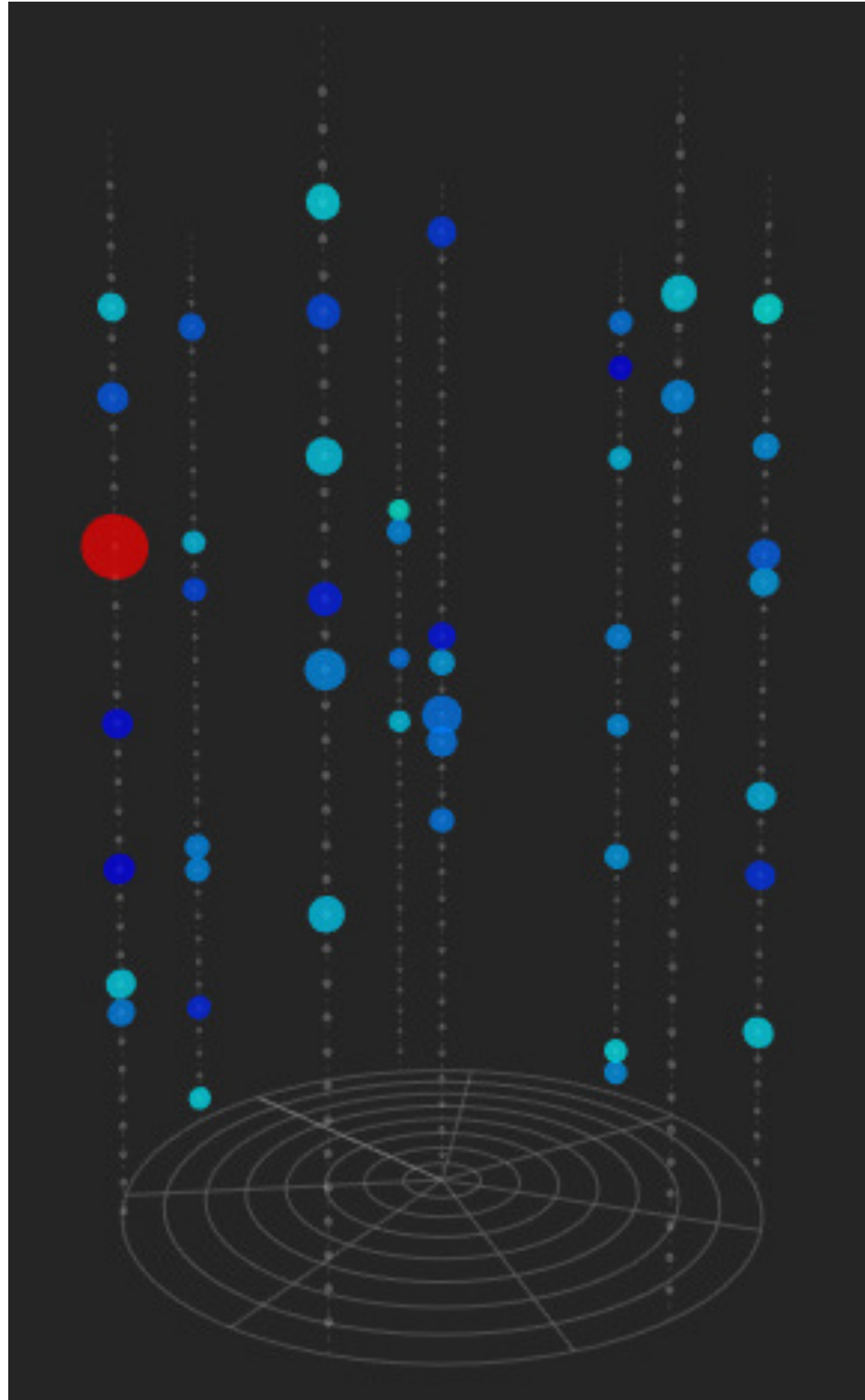


atmospheric neutrino  $E > 100$  GeV

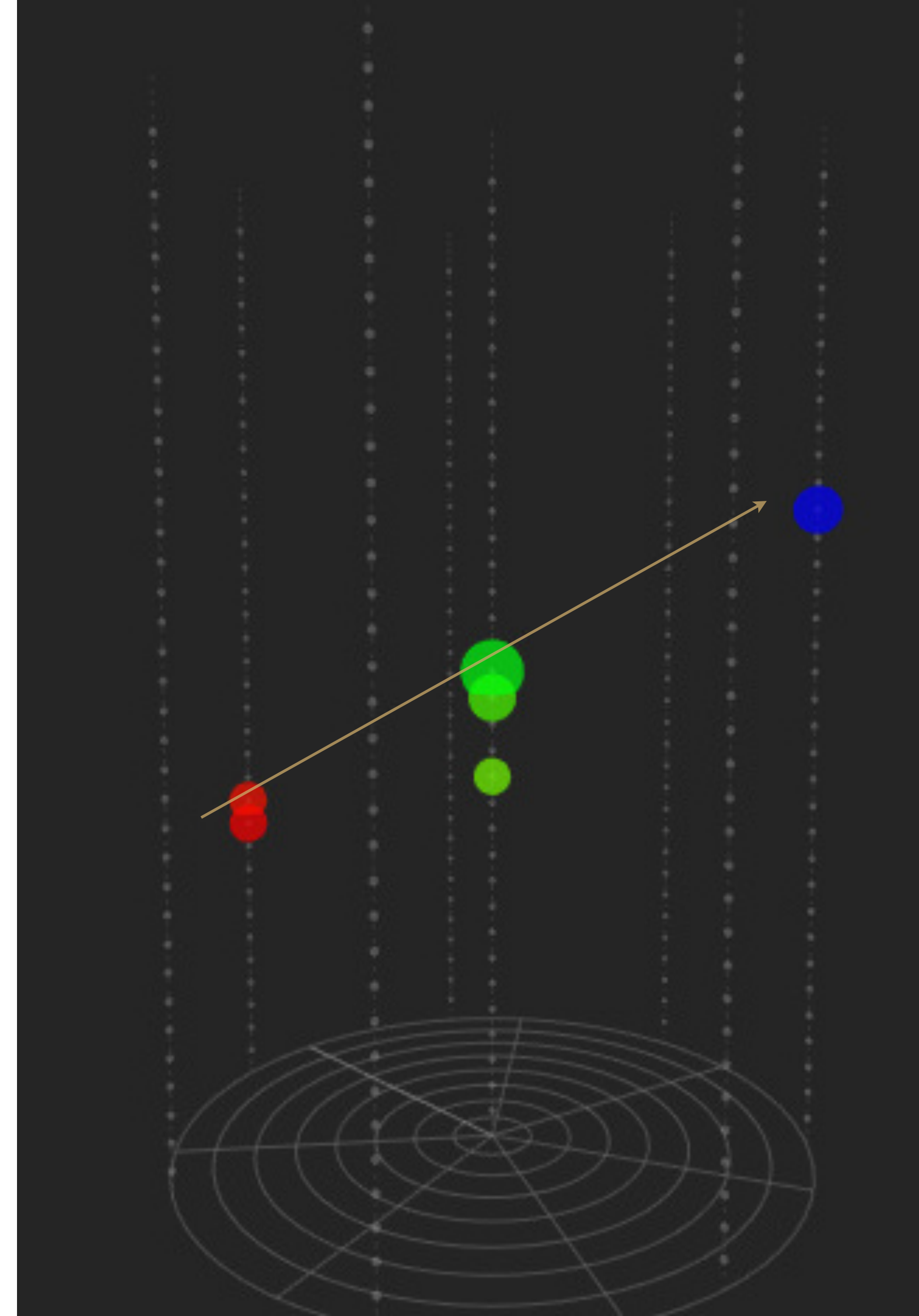


## Faint event

Neutrino induced muon before noise rejection

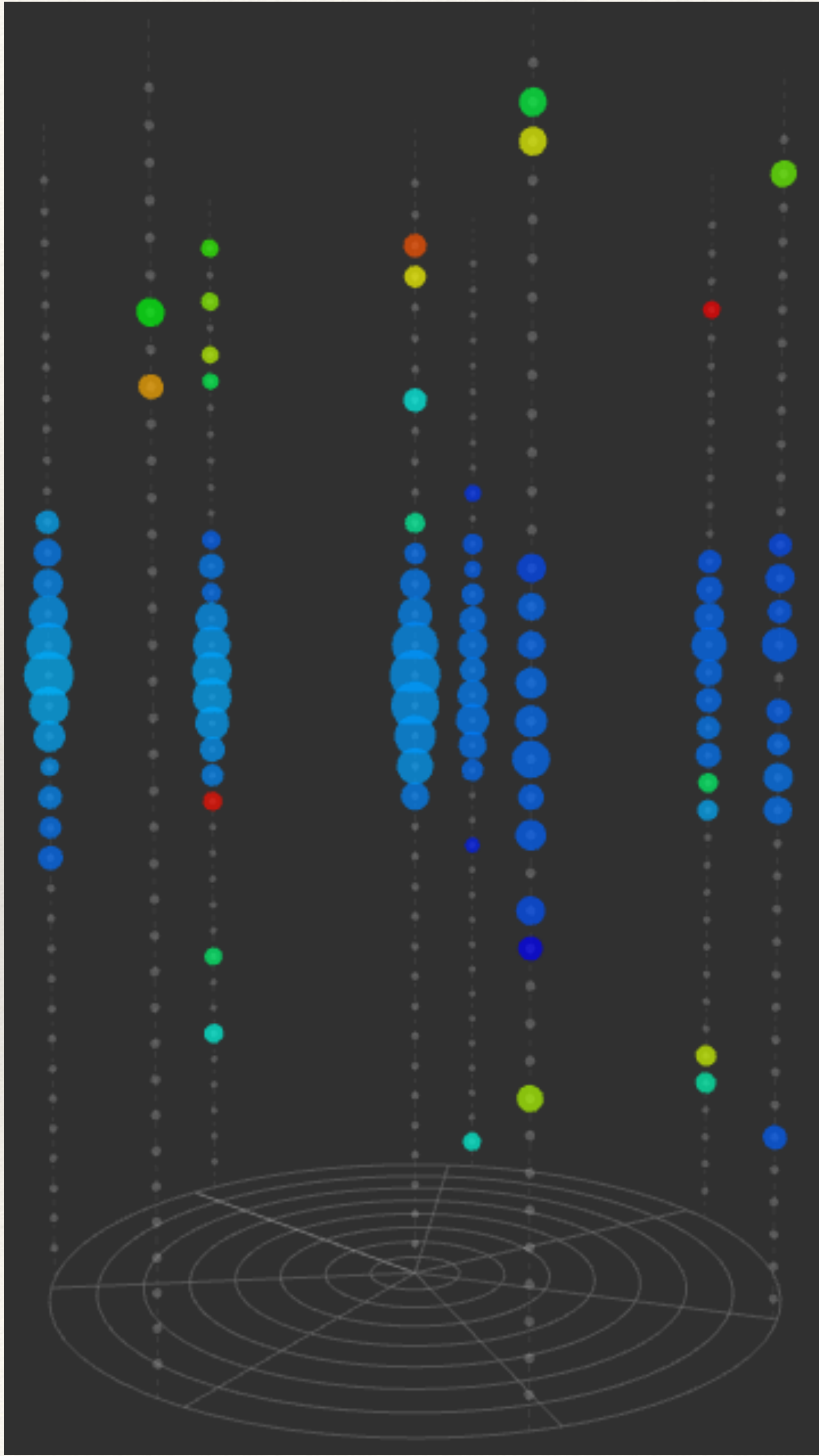


Neutrino induced muon after noise rejection



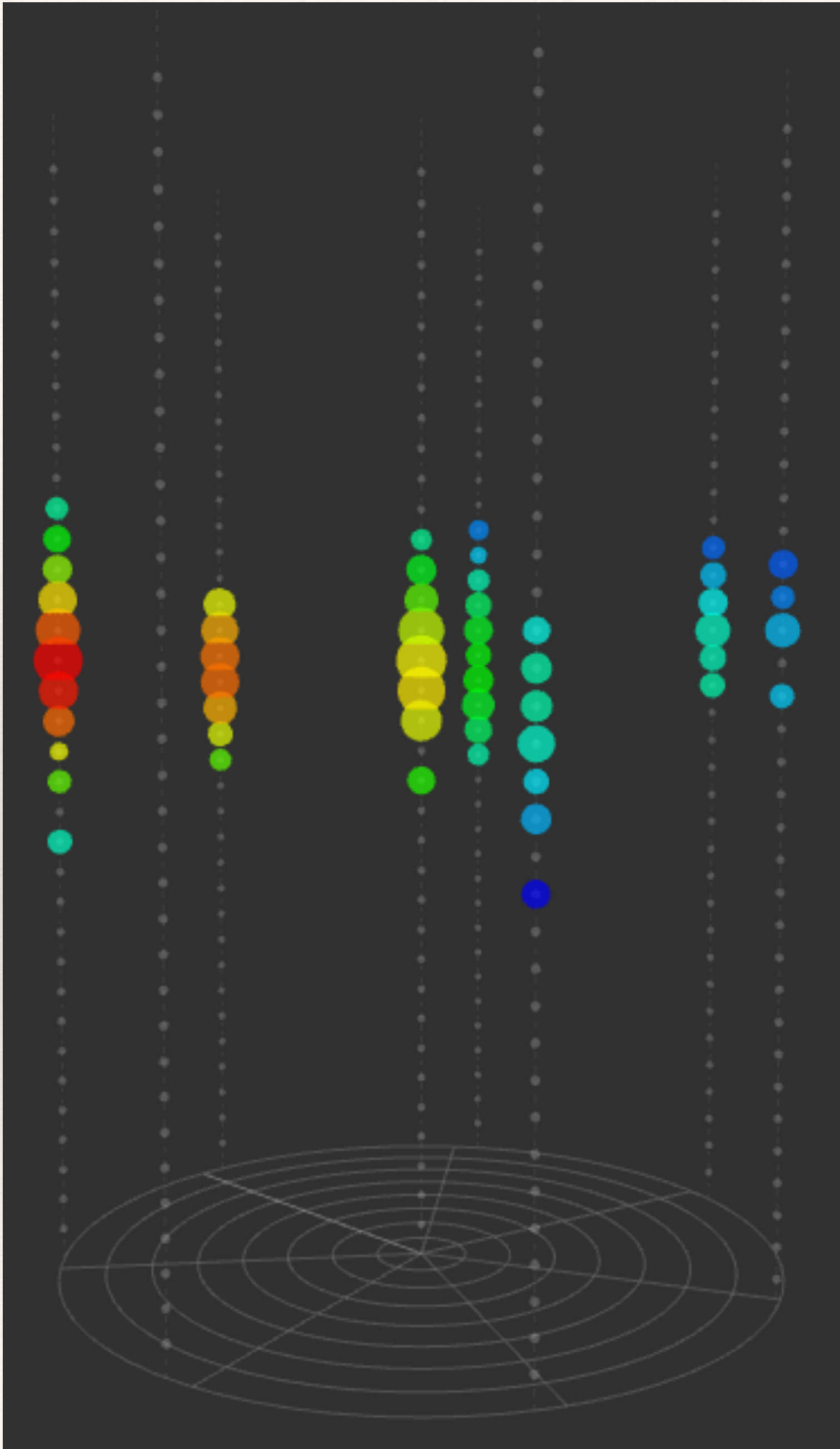


Cascade event before noise rejection



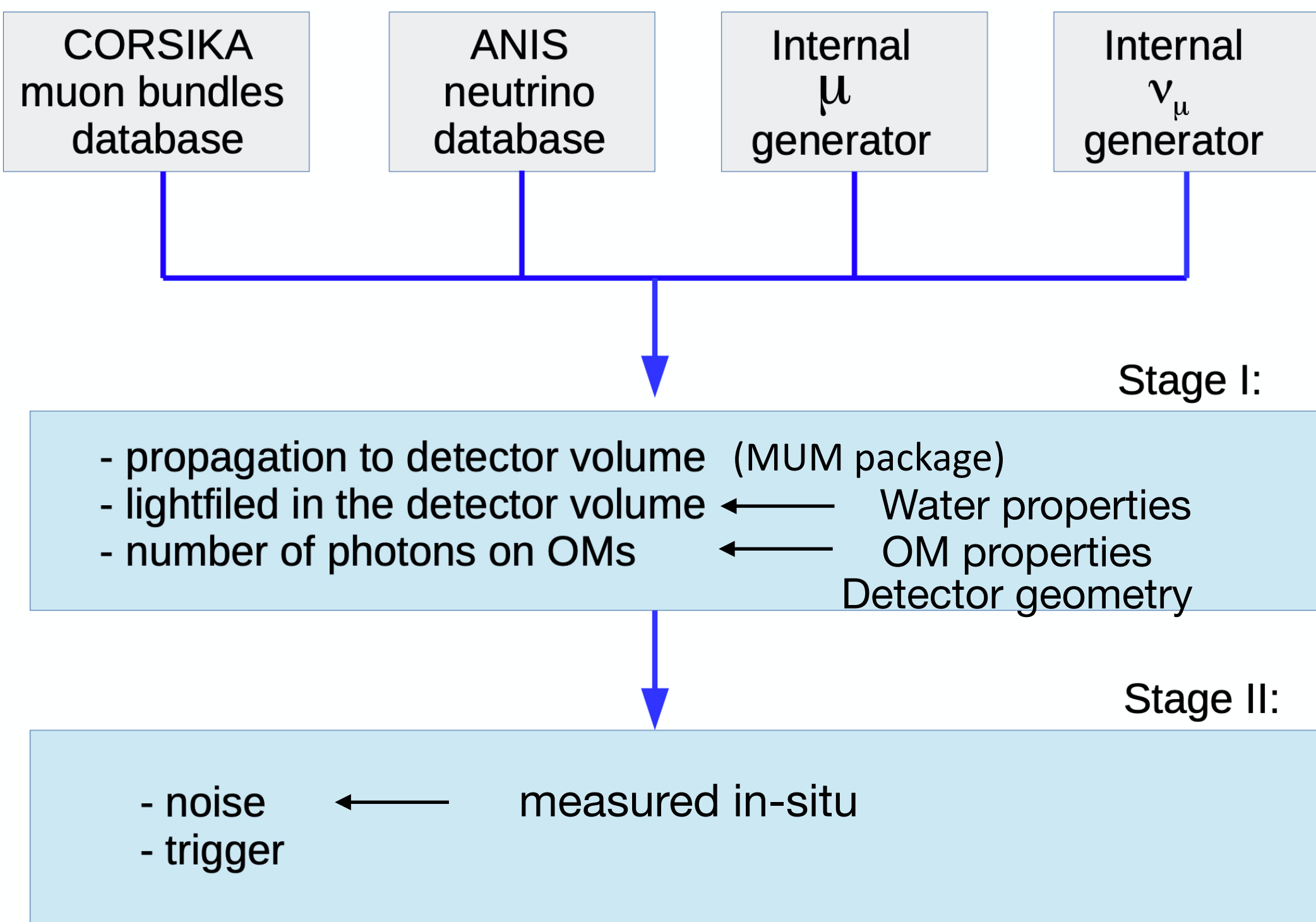
**Bright event**

Cascade event after noise rejection





# MC simulation package



- Custom fortran codes (legacy from NT-200)
- Transition from Corsika 5 to Corsika 7 (post LHC) package
- Lack of high-energy events
- Not flexible enough, hard to modify

Transition to the new C++/Python package

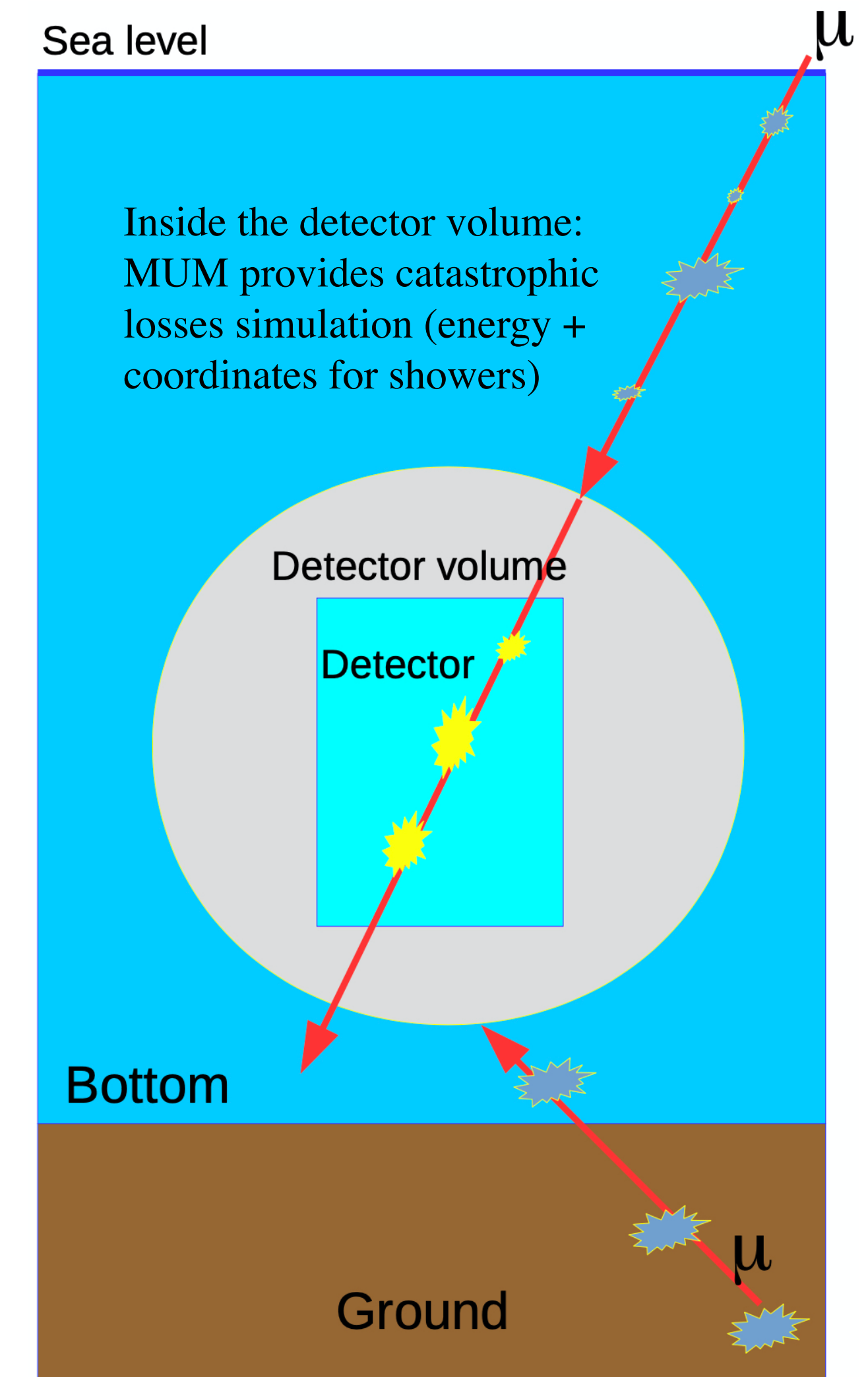
Chemical composition:

CORSIKA 5 - old KASCADE chemical composition (B.Wiebel-Sooth, P.Biermann 1999)

CORSIKA 7 - Thomas K. Gaisser, Ralph Engel, Elisa Resconi -

Cosmic Rays and Particle Physics (2016, Cambridge University Press)

Bartol flux for atmospheric neutrino simulation Phys.Rev D53(1996) 1314-1423, hep-ph/9509423



MUM package

PHYSICAL REVIEW D, VOLUME 64, 074015



# **Байкальский эксперимент**

## **Анализ данных. Первые результаты**



# Track reconstruction basics

Simple  $\chi^2$  - like fit is used so far

**Track parametrisation:**  $\vec{R}(t) = \vec{R}_0 + c(t - t_0)\vec{V}$   
 $\vec{V}$  is unit vector in polar coordinates,  $\vec{R}_0$  and  $t_0$  are taken in plane  $Z=0$

---

**Initial track approximation:**  $\vec{V}_{init} = (1/|\sum_{t_i < t_j} \vec{R}_{ij}|) \sum_{t_i < t_j} \vec{R}_{ij}$  where  $i$  and  $j$  are ordered in time and belong to different strings  
Initial values for  $\vec{R}_0$  and  $t_0$  are obtained using hit with largest amplitude

---

**Minimisation function (quality):**  $Q = \sum_{i=1}^{N_{hit}} \left[ \frac{(t_i^{est} - t_i)^2}{\sigma_t^2} + \frac{A(a_i)D(d_i)}{d_0} \right]$  inspired by ANTARES paper: <https://arxiv.org/abs/1105.4116>

**Muon prompt Cerenkov radiation approximation is used for the time estimation**

$A$  and  $D$  are amplitude and distance functions

+ Likelihood approach has been developed

OM signal jitter:  $\sigma_t = 3$  ns

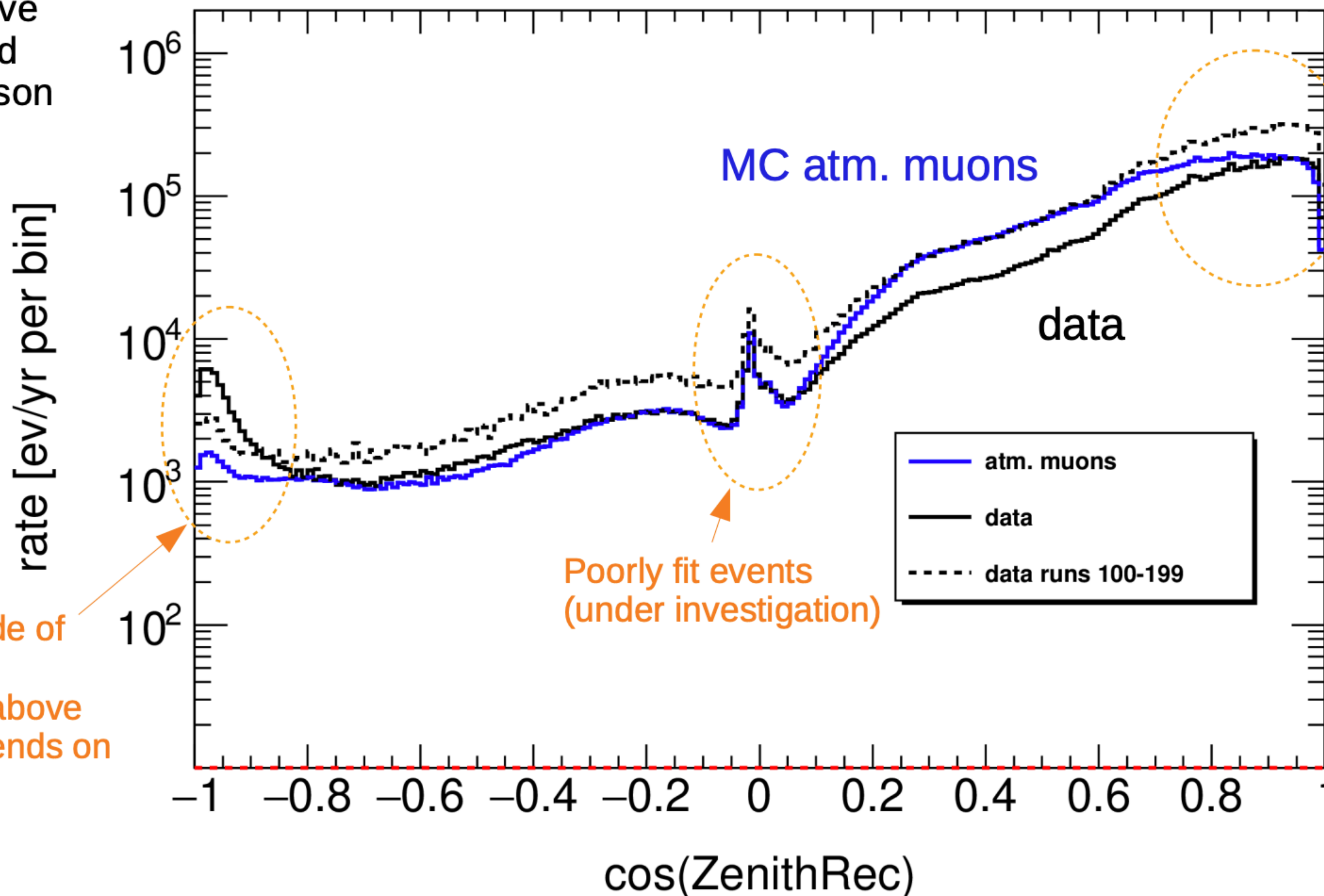


# Data-MC comparison : zenith angle

cuts: `CovMatrixStatus==3 && NStrings>1 && Nhit>=6`

Number of active channels varied during the season

MC mimics conditions of run 102



event migration between single-string & multi-string categories could affect this region

Runs 100-199 is a low noise period

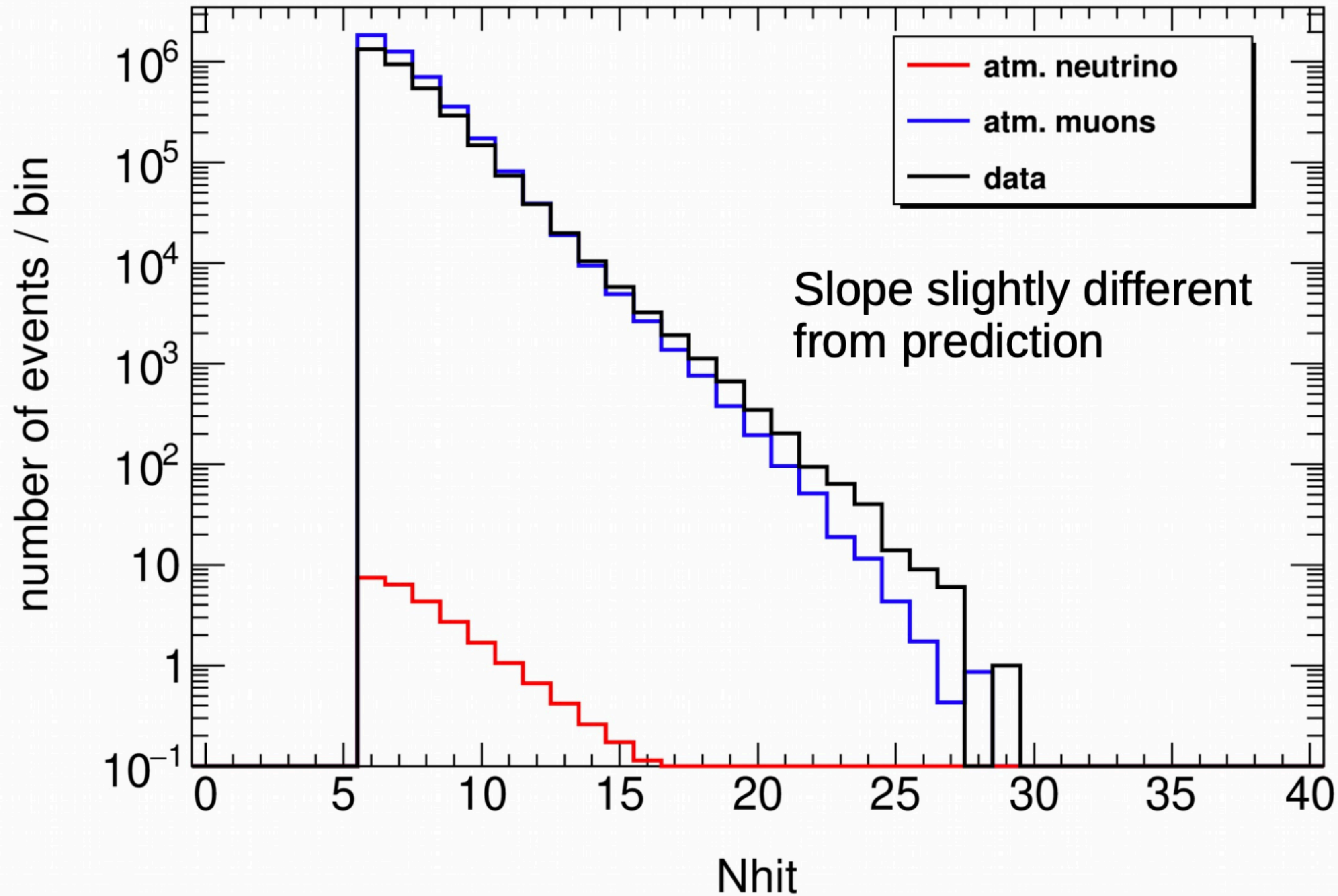
Background made of real muon hits + a noise hit high above (so the rate depends on the noise level)

Poorly fit events (under investigation)

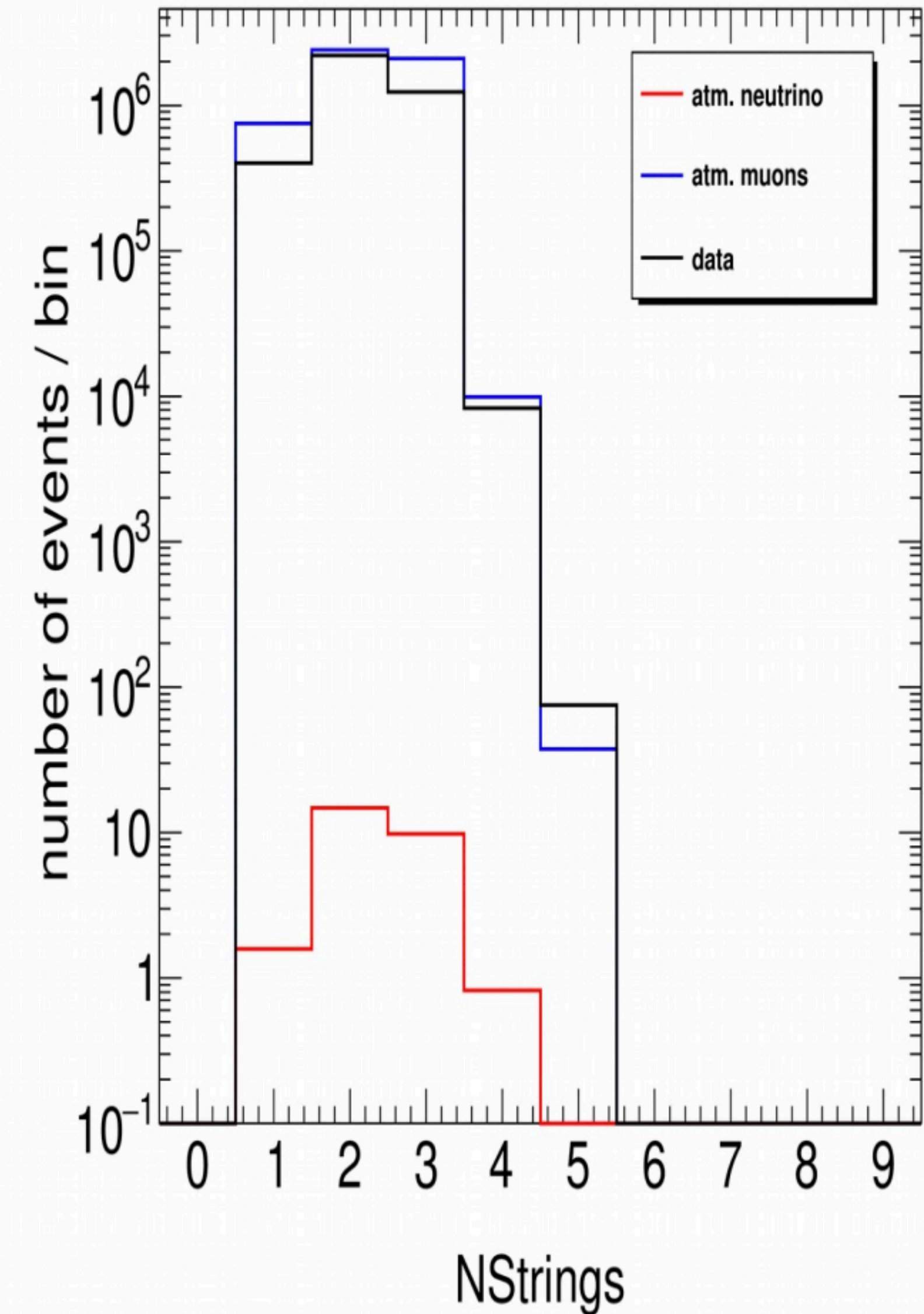


# Data-MC comparison: Nhit & NStrings

cuts: CovMatrixStatus==3 && NStrings>1 && Nhit>=6



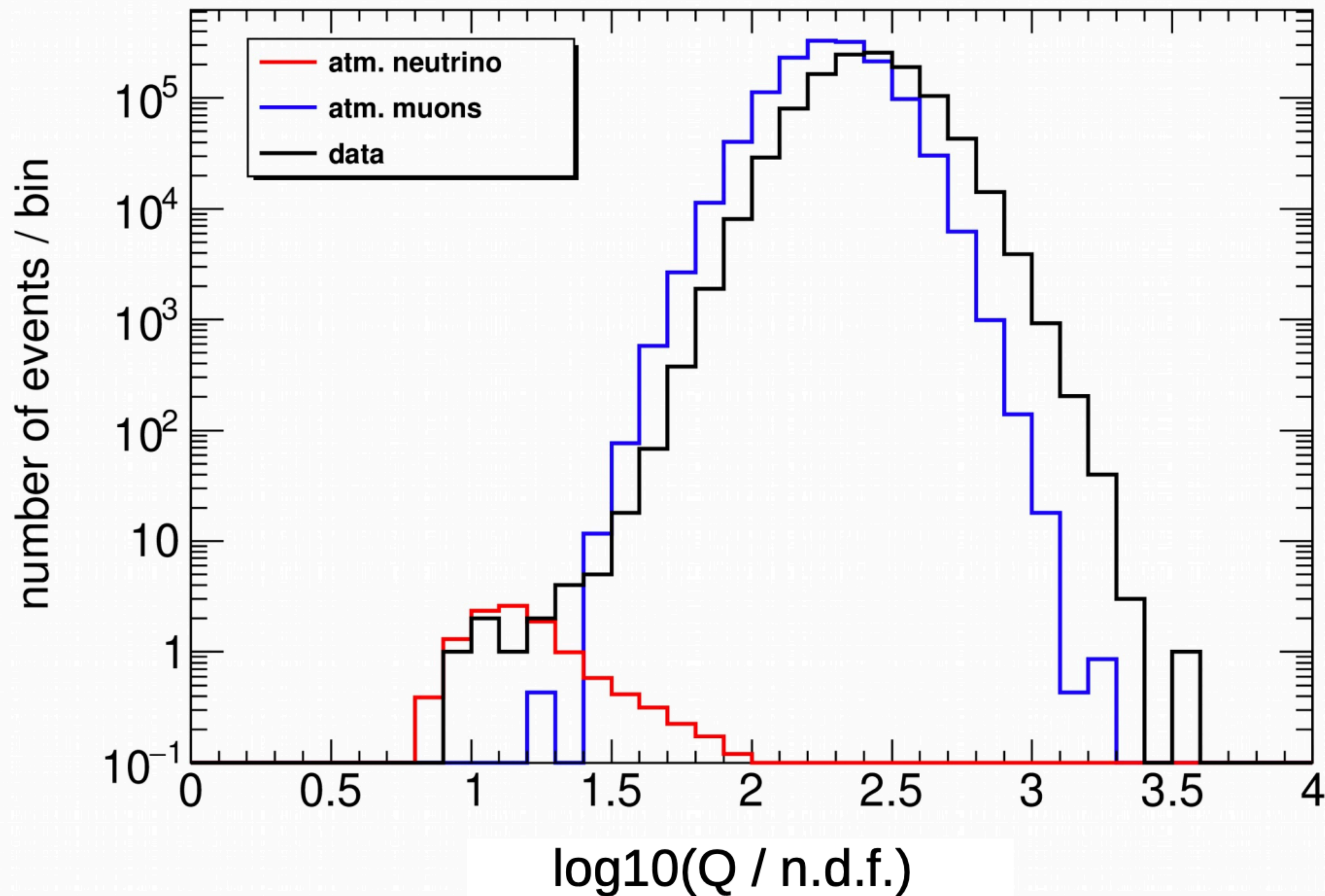
cuts: CovMatrixStatus==3 && Nhit>=6





# Data MC comparison: fit quality

cuts: `CovMatrixStatus==3 && NStrings>1 && Nhit>=8`

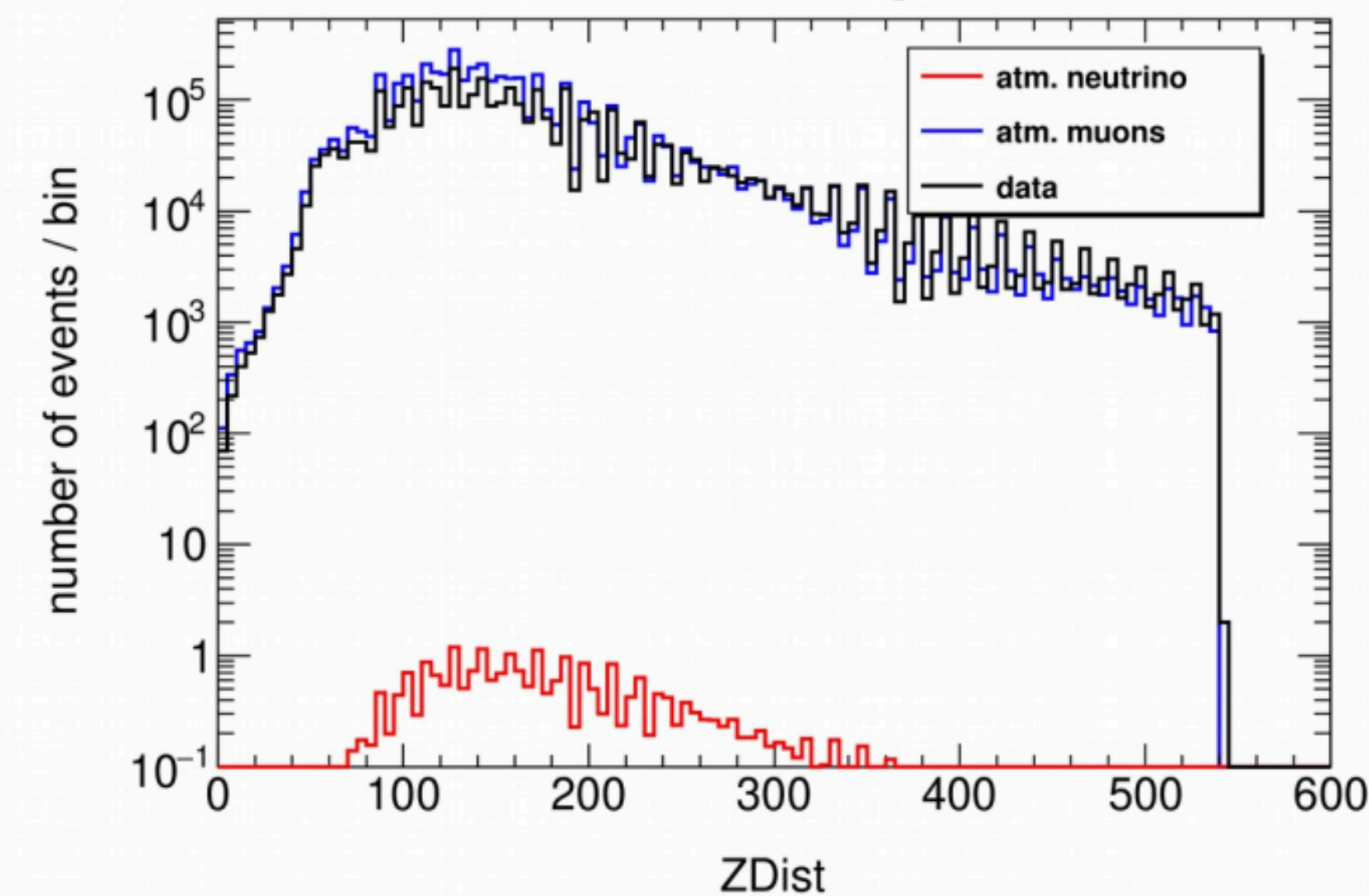


Distribution for atm. muons appear shifted: for downgoing events a positive shift is observed

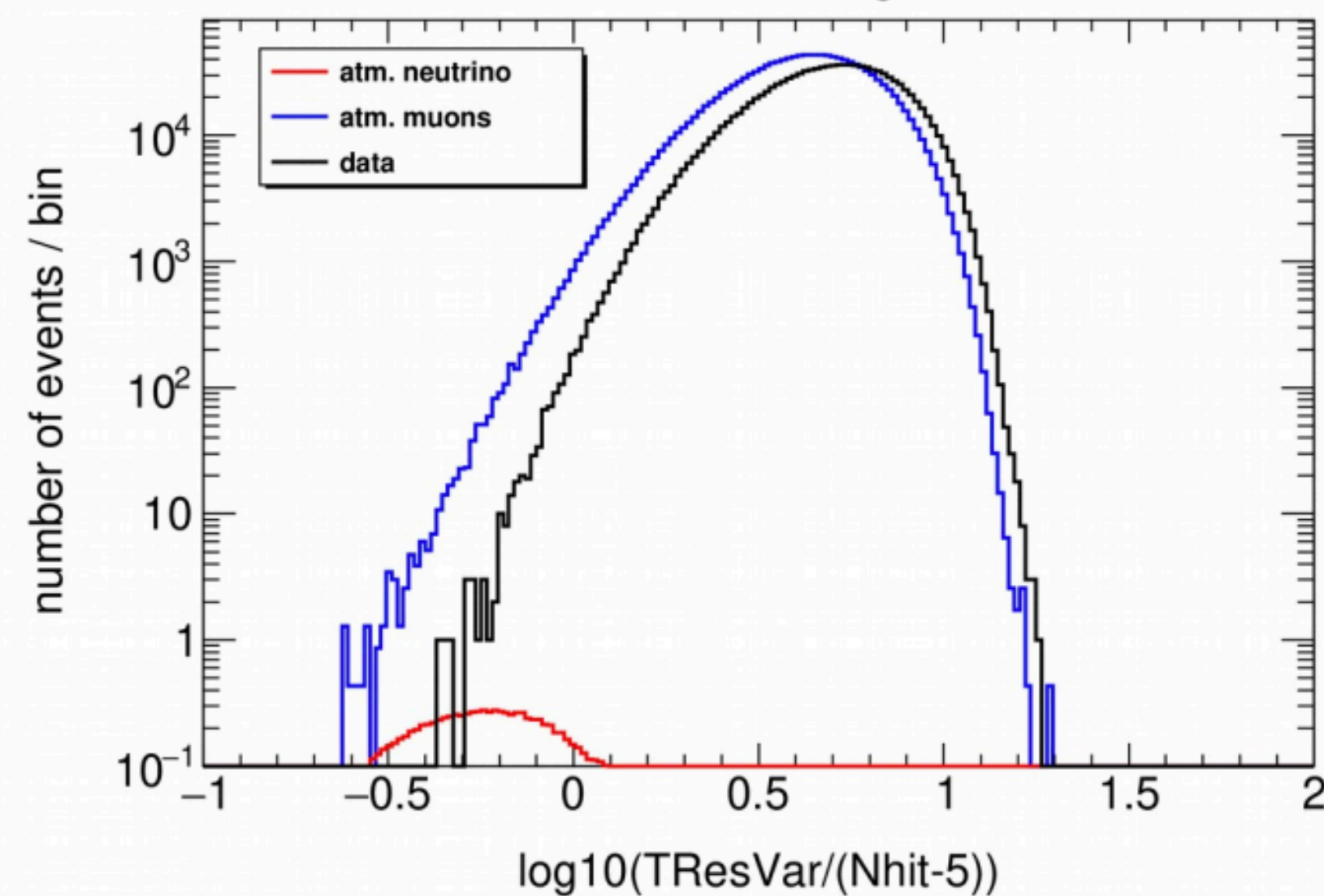


# Data-MC comparison: auxiliary variables

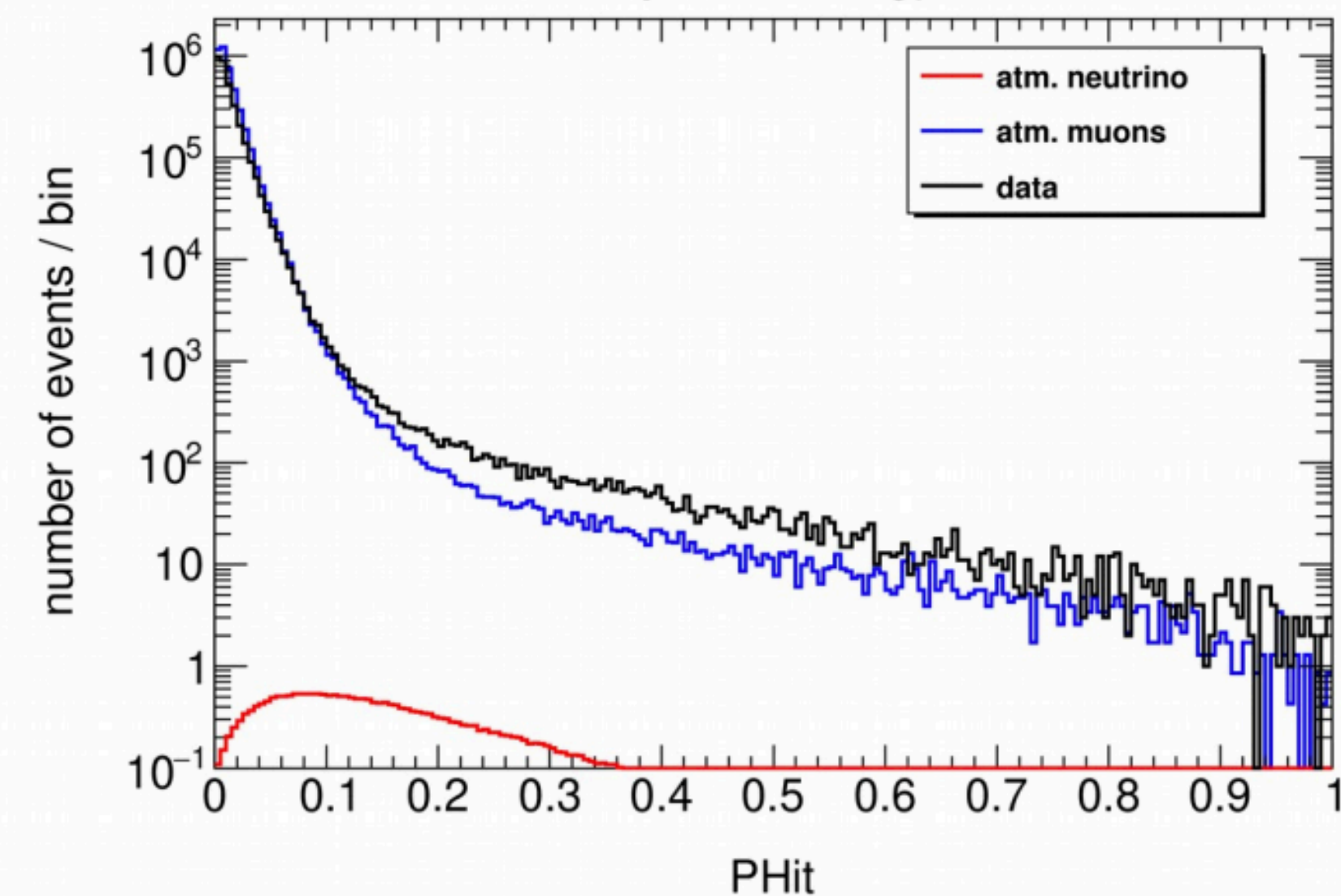
## Track length



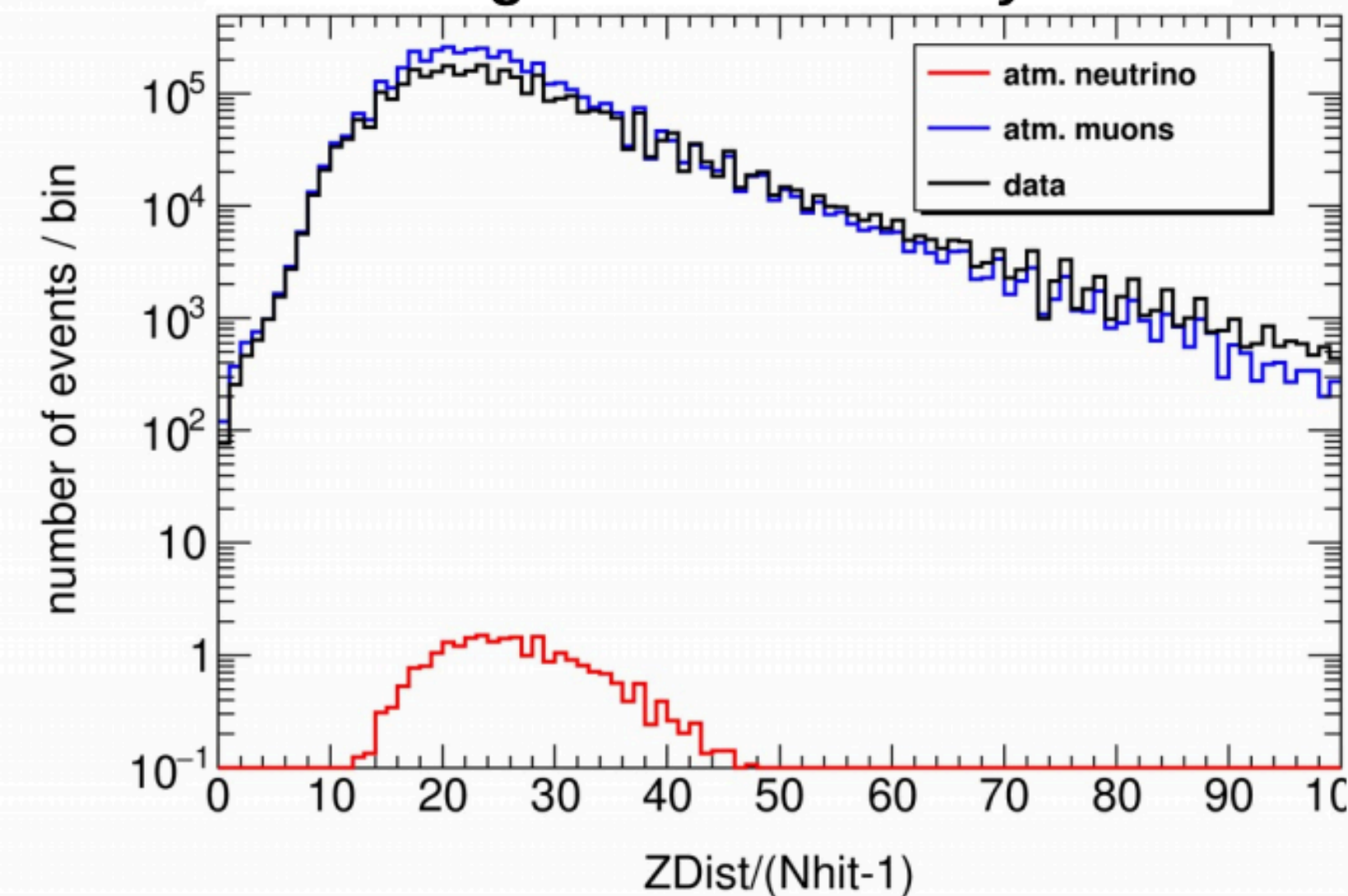
## Time residual variance



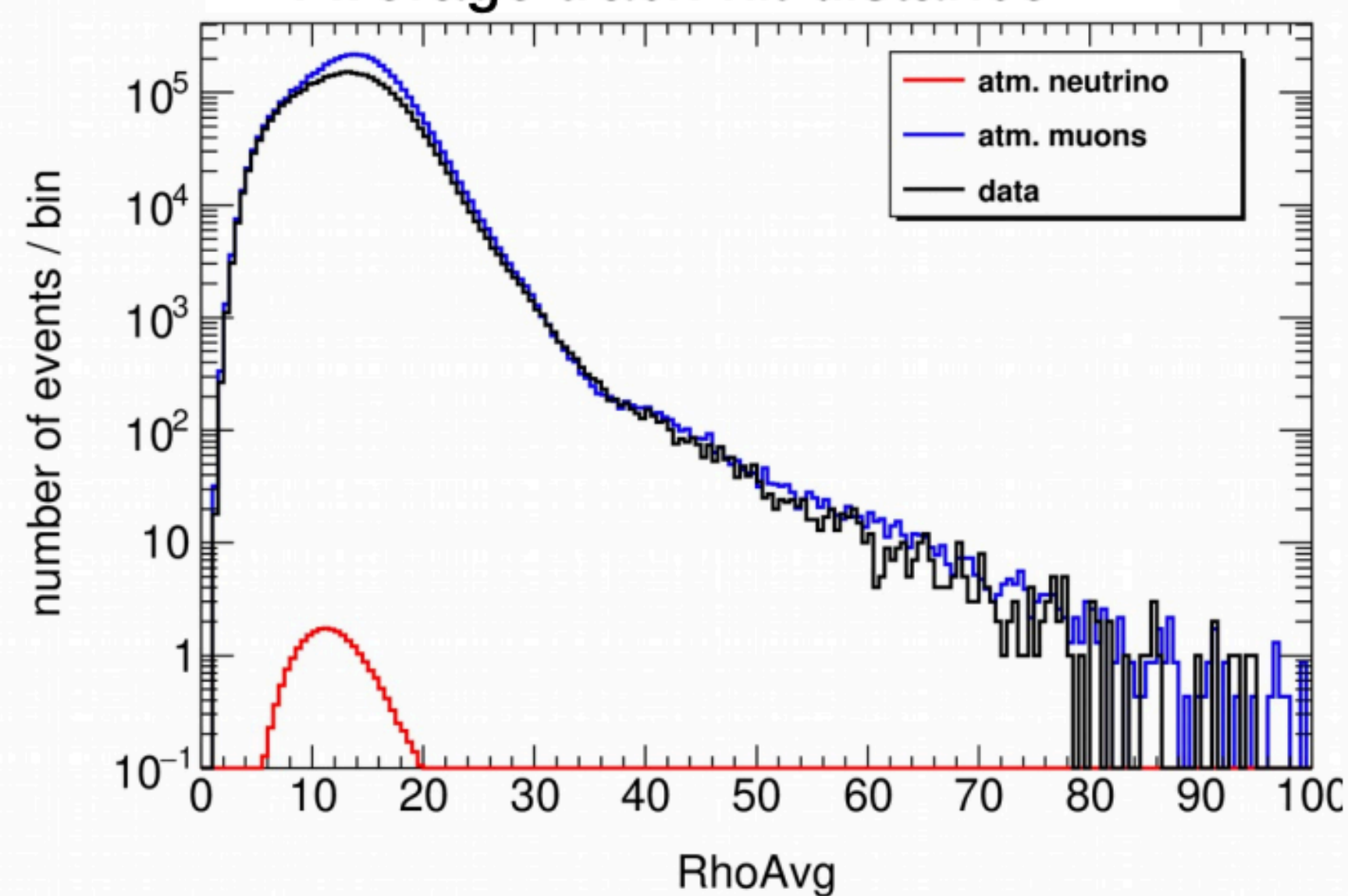
## Combined probability of hits



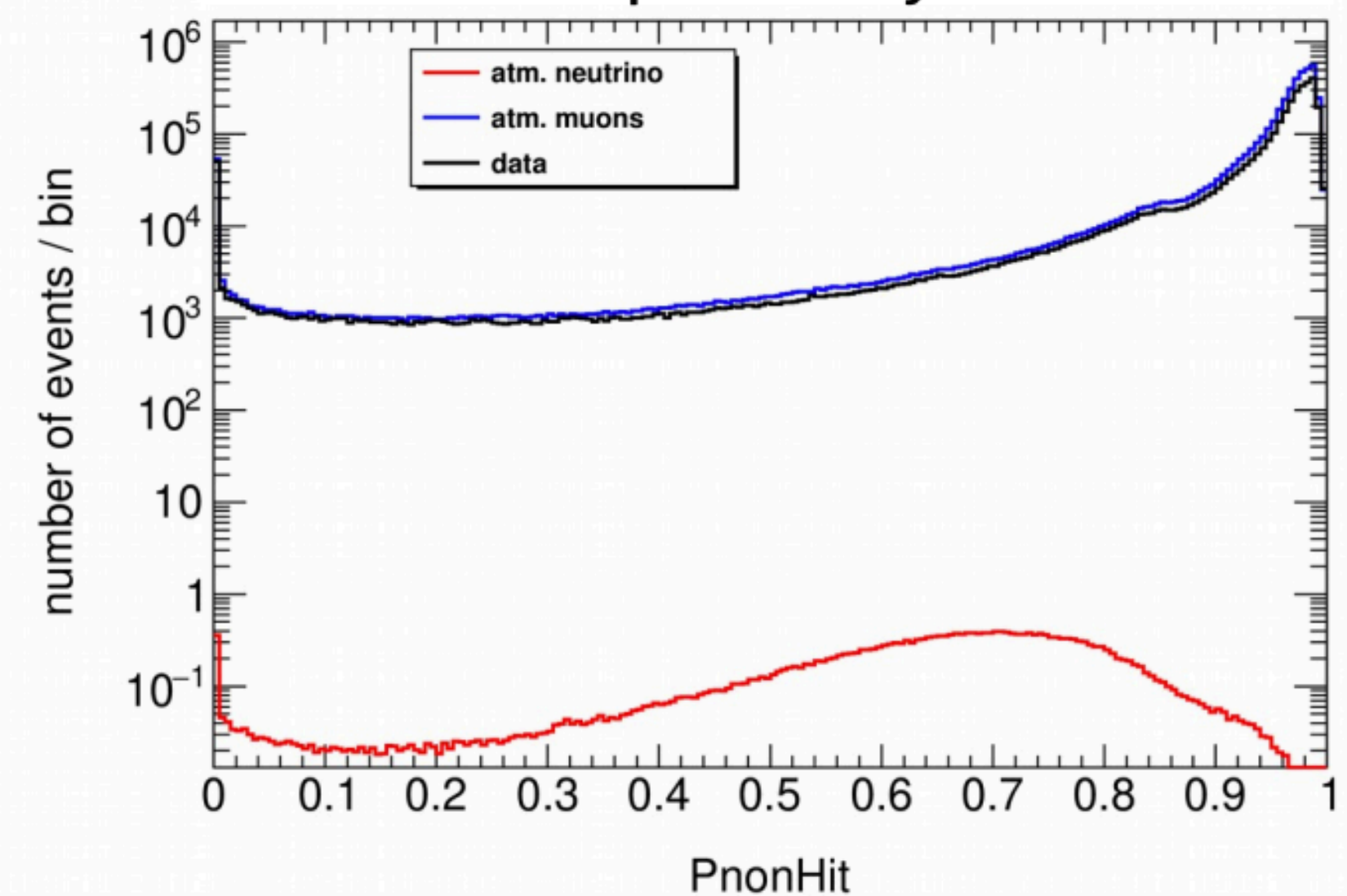
## Track length normalized by Nhit



## Average track-hit distance



## Combined probability of non-hits





# Summary of analysis cuts for neutrino selection 2016

low energy neutrino selection

ZenithRec > 120 deg

Q / ndf < 25

TResVar / ndf < 3.0

ZDist > 67 m

ZDist / (Nhit-1) < 40 m

PHit > 0.025

PnonHit > 0.1

RhoAvg < 18

CovMatrixStatus == 3

Nhit >= 6

NStrings > 1

Obtained from an iterative  
procedure optimizing

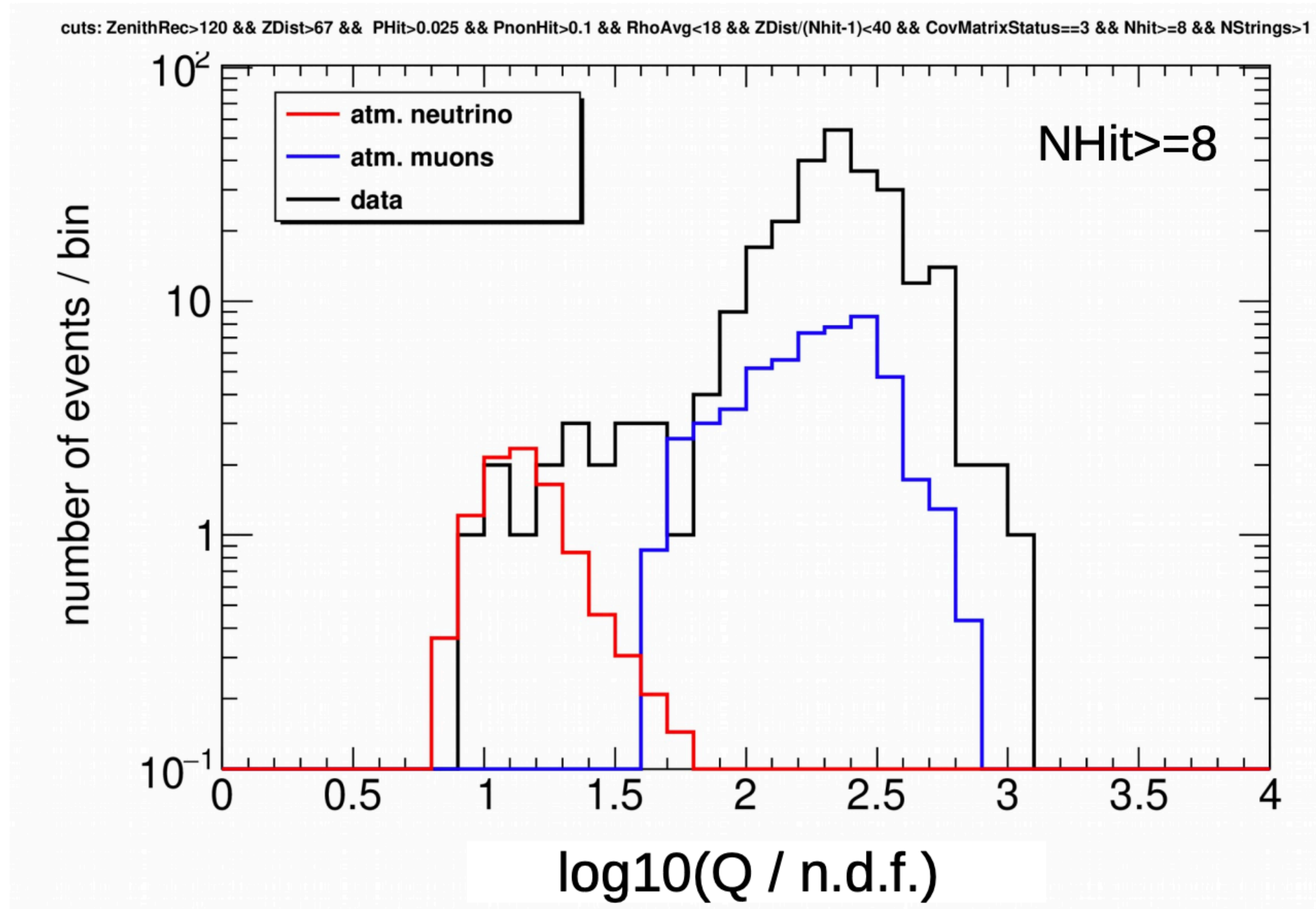
$$S/B^a$$

where S is signal,  
B is background, and  
 $a = 1/7$

The choice of  $a$  is motivated  
by balance between  
high purity and high rate



# Q/ndf distribution (golden event sample)

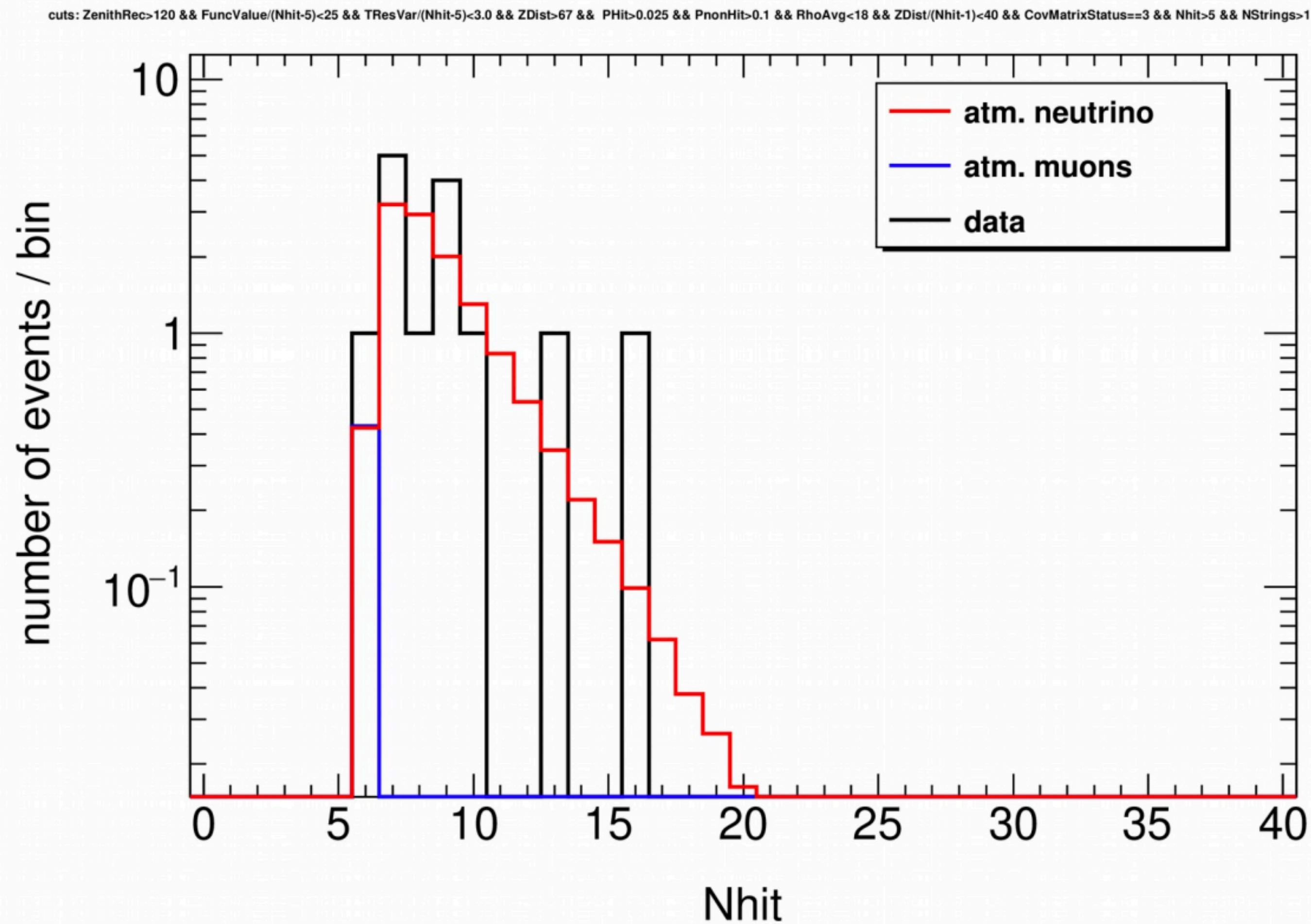


Discrepancy for atmospheric muons under investigation (can be partly due to noise level)

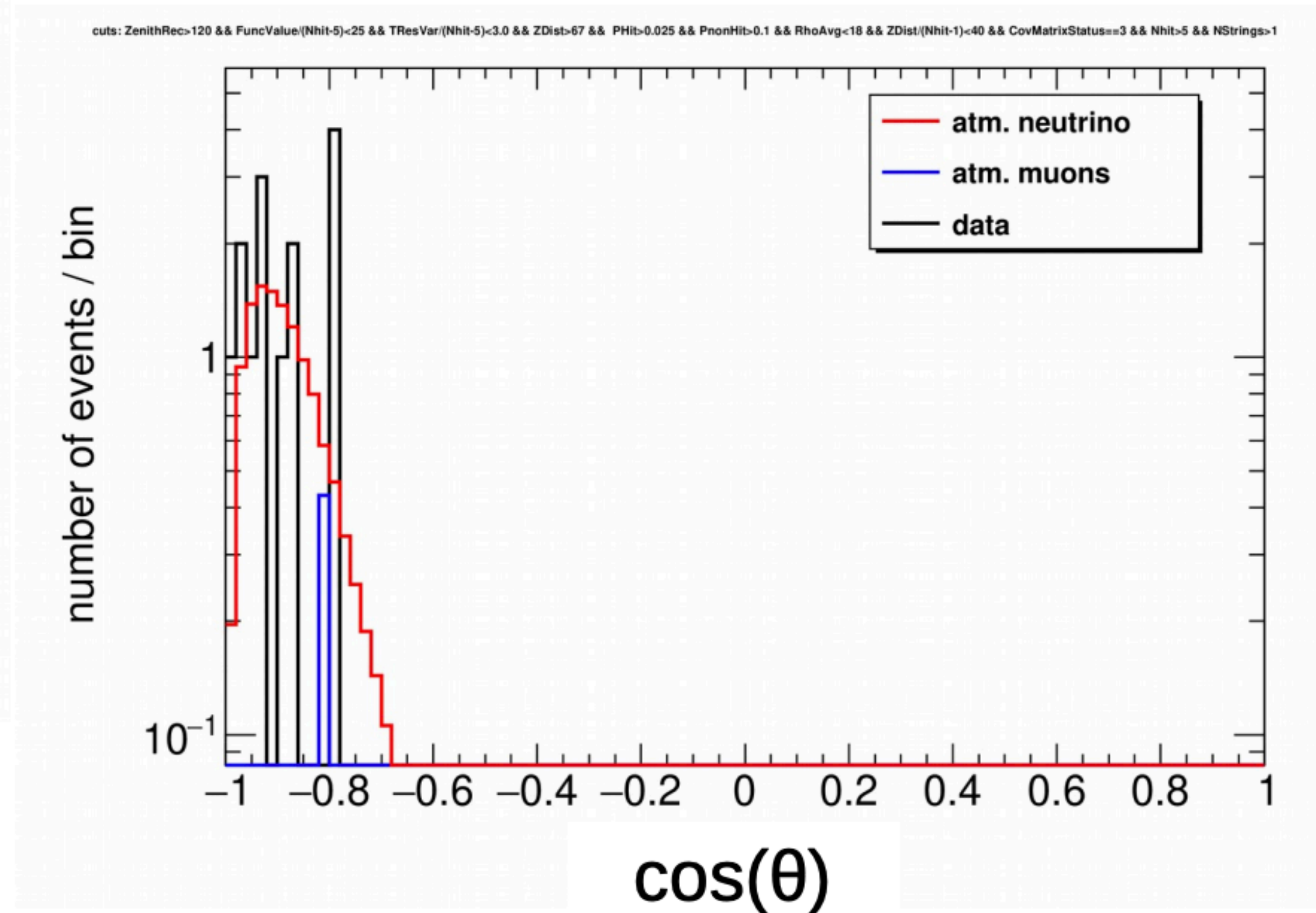


# Results after cuts

185 days livetime, 2016, single cluster

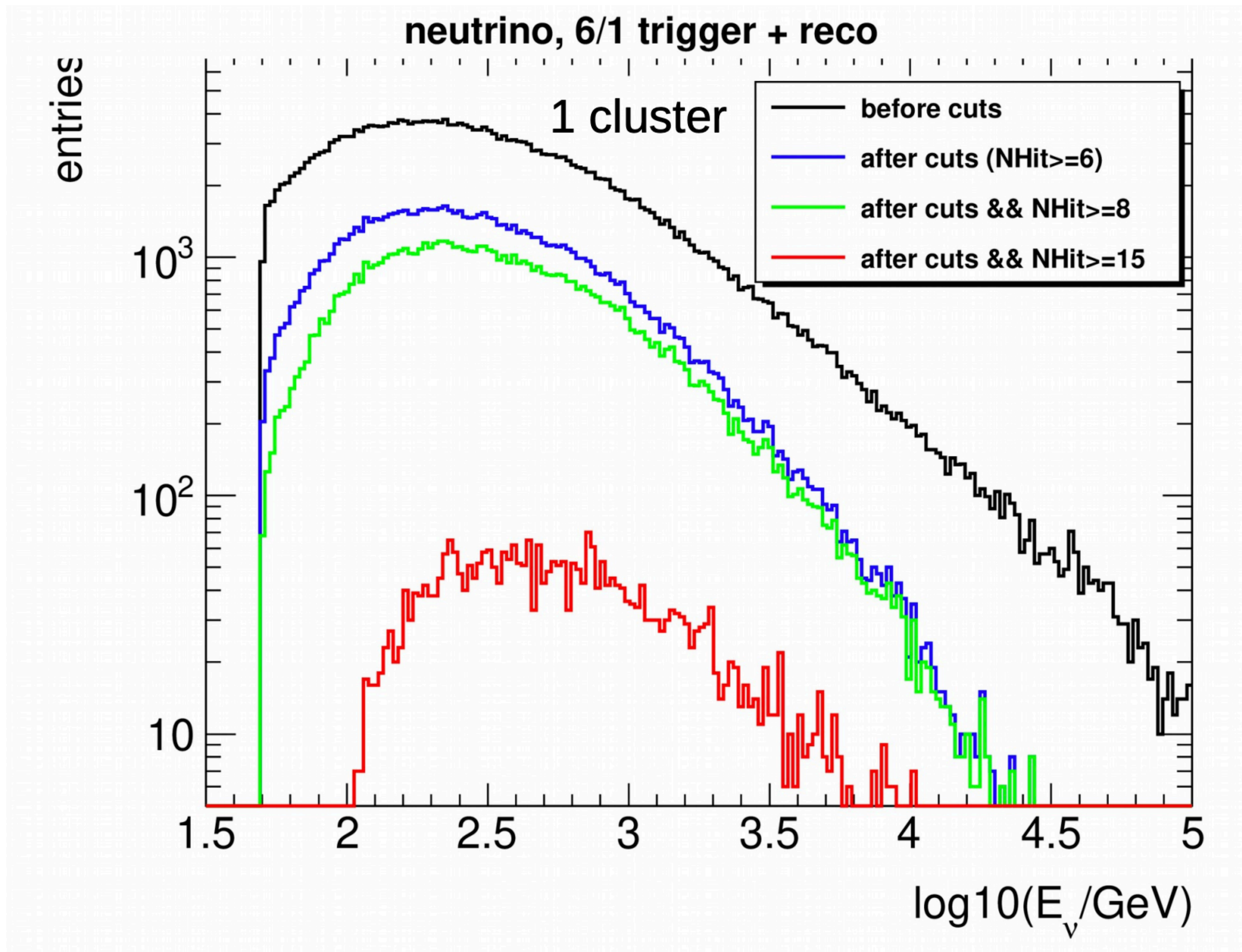


**Expected : 12.6 events**  
atm. neutrino: 12.2 ev  
atm. muon : 0.4 ev  
**Observed : 14 events**  
**True 5/2 Expected: 118 events/cluster in 0.5 year**





# Neutrino energy (MC truth)



## Median energy

Before cuts:  $\sim 270$  GeV

After cuts :  $\sim 270$  GeV

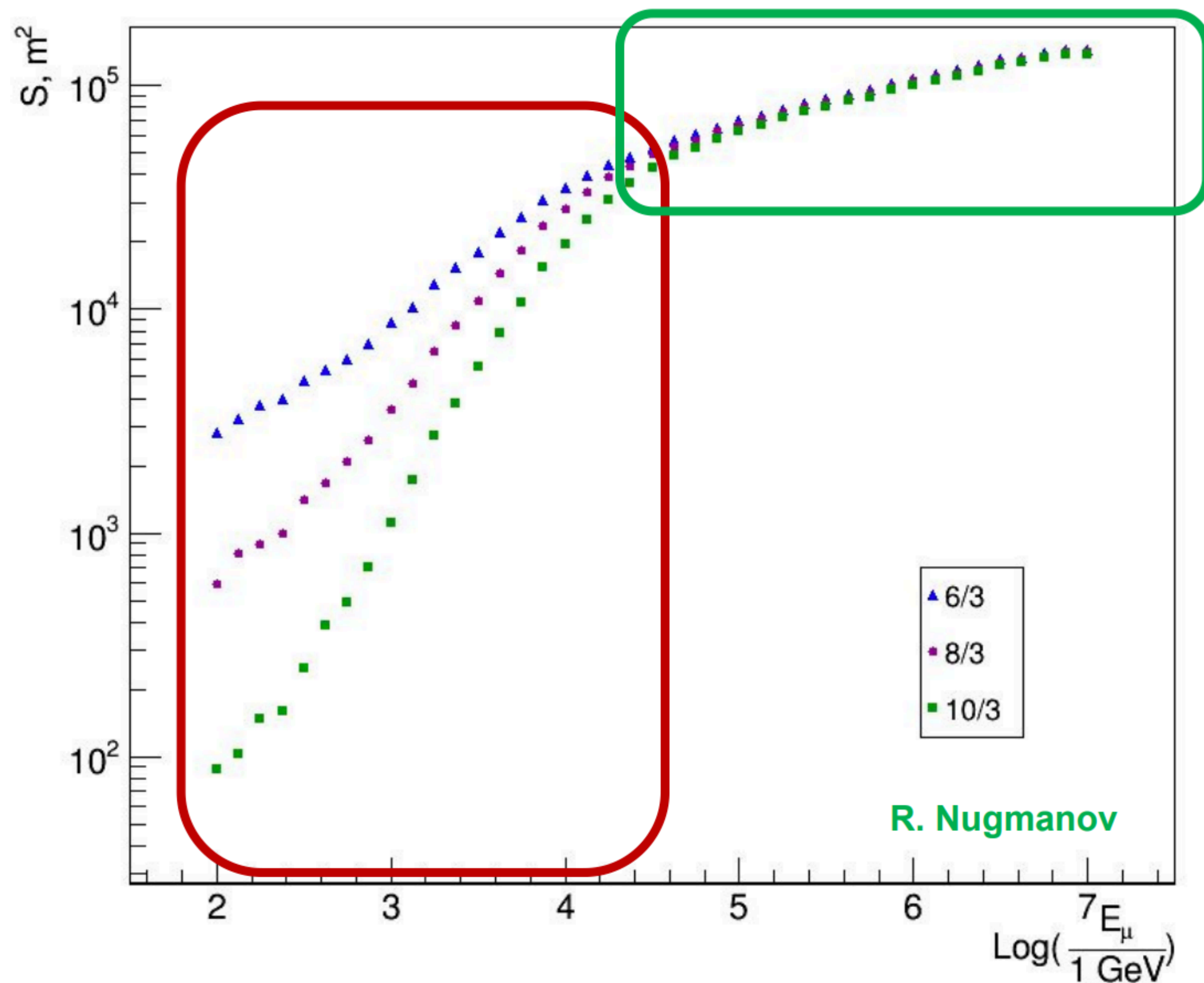
Nhit  $\geq 8$  :  $\sim 300$  GeV

Nhit  $\geq 15$  :  $\sim 550$  GeV



# Cluster sensitivity to muons

Muon effective area energy dependence



## Astrophysical muon neutrino flux

- Primary purpose of the experiment

## Low-energy muon neutrino flux

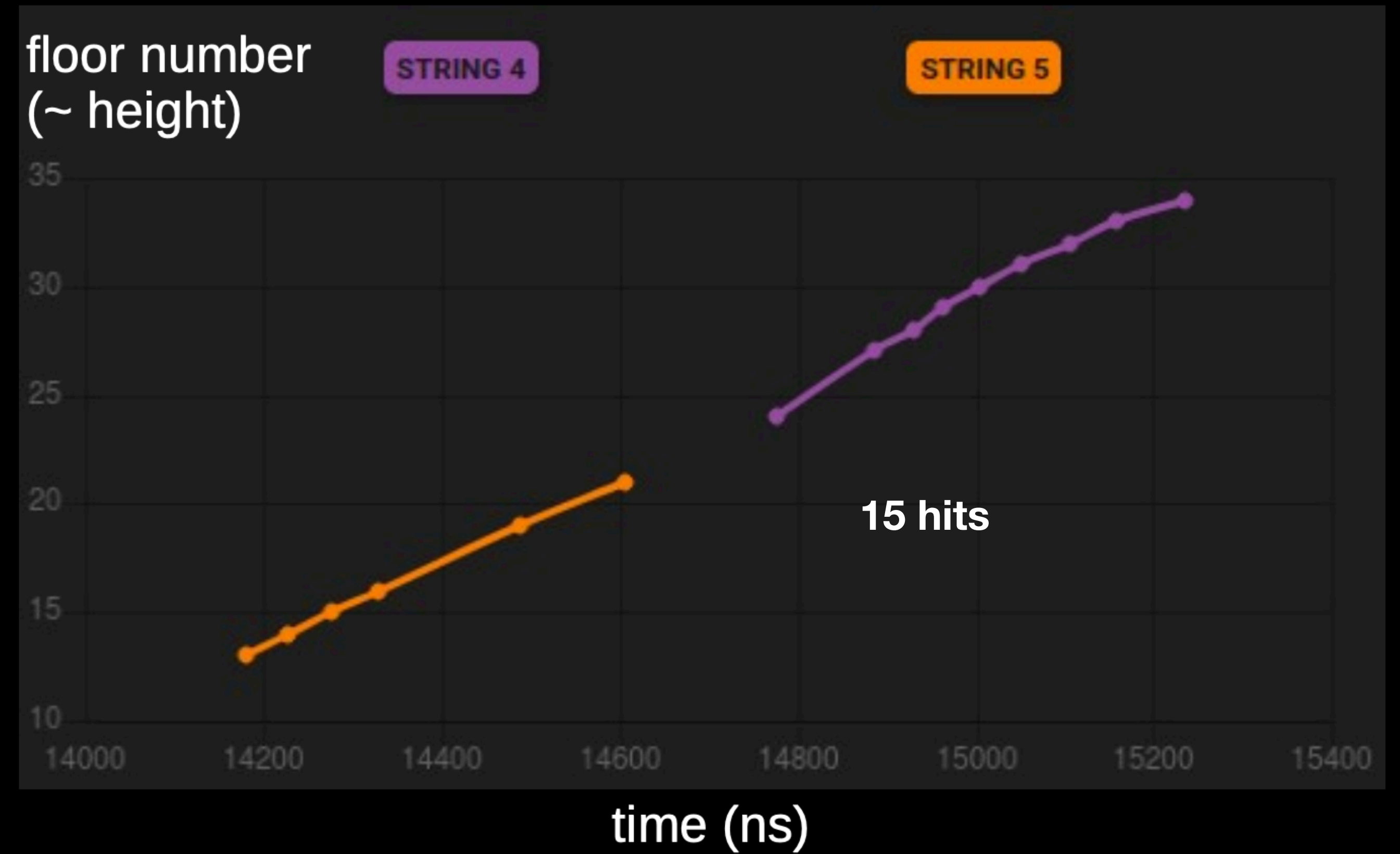
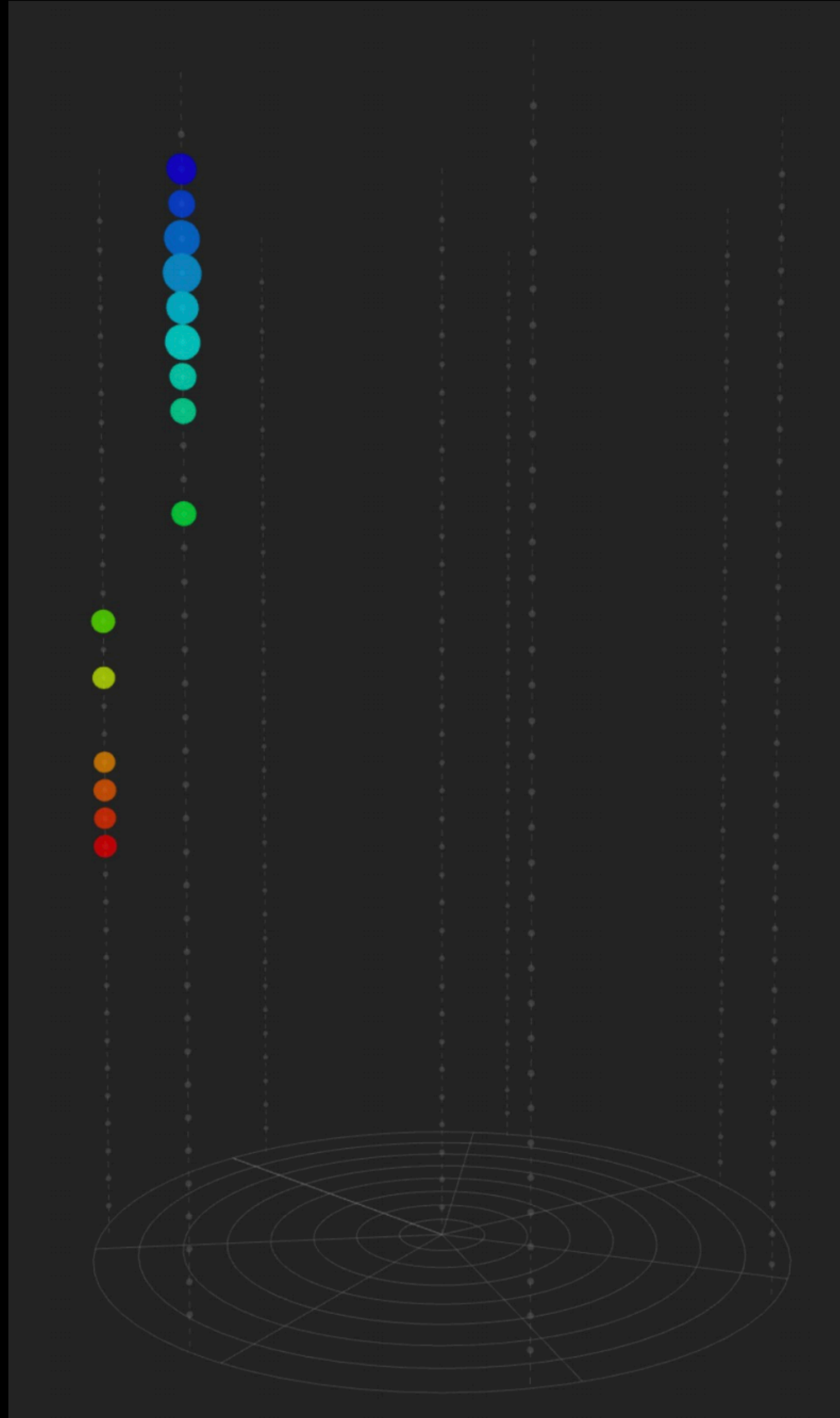
- Atmospheric neutrino:
  - background to astrophysical flux
  - understanding of the detector and MC
- Dark matter search

Our main focus at the moment is to establish reliable reconstruction for low-energy muon neutrino

**Small effective area for low energy muons**  
**Strong dependence on number of selected hits**



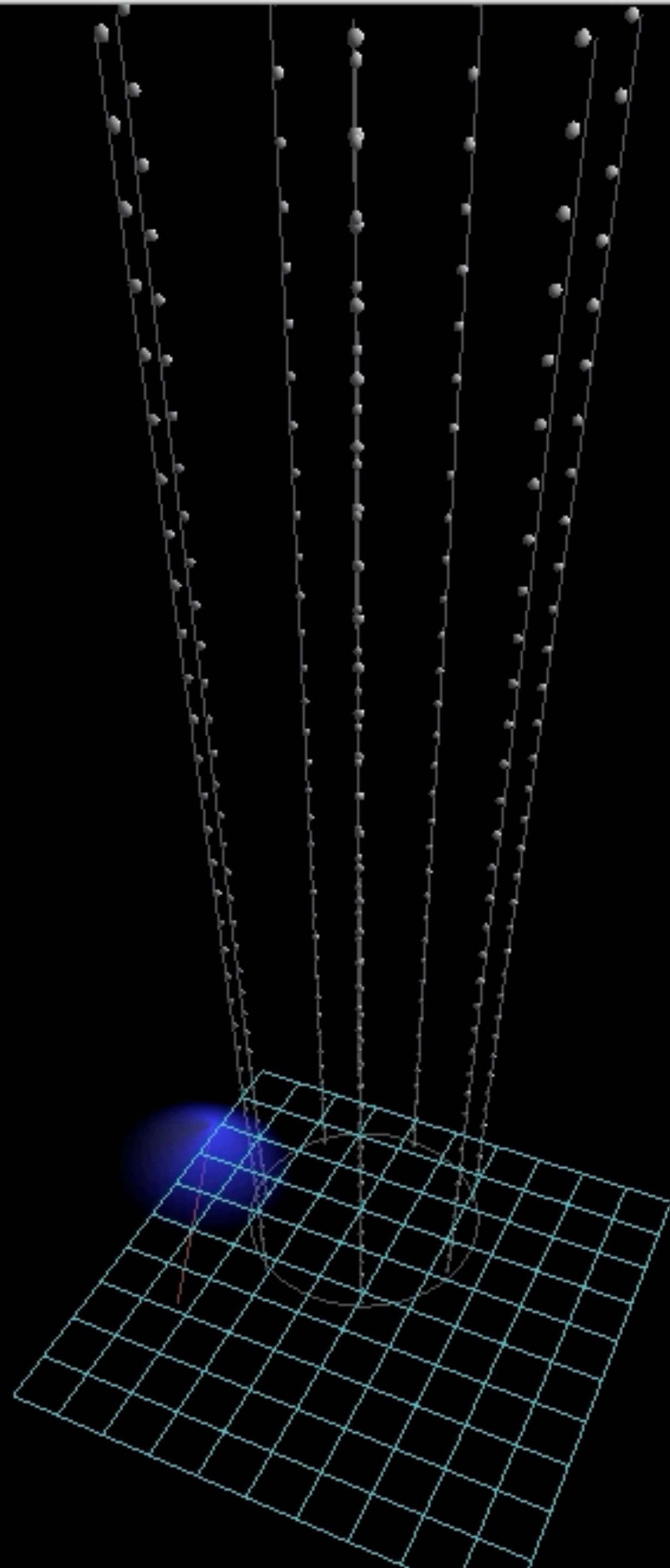
# The largest event in 2016



reconstructed zenith = 169 deg (11 deg from vertical)  
reconstructed track length = 400 m

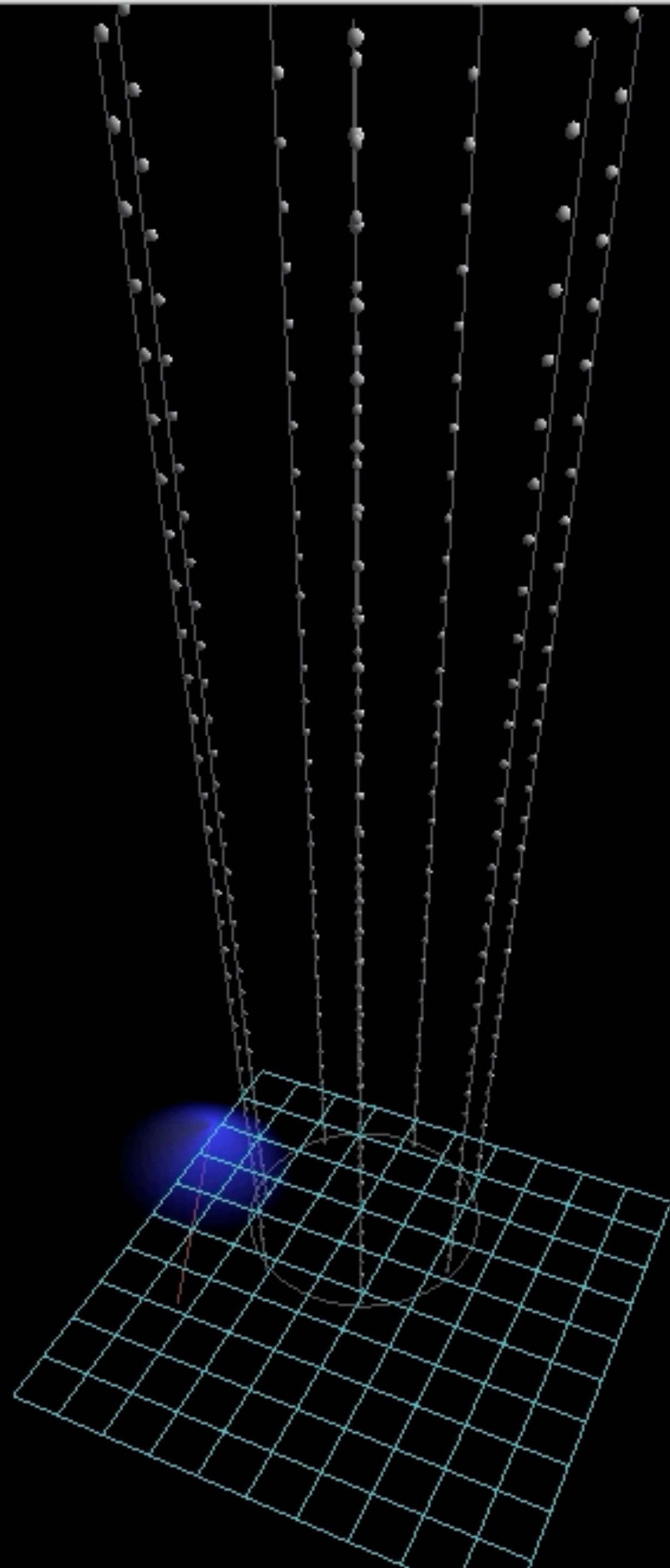


Time: 13951.0 ns





Time: 13951.0 ns





# Preliminary analysis of 2019

Analysis by G. Safronov

Preliminary conservative analysis of 2019 data: quiet period, date < 01/07/2019

**number of hits  $\geq 8$**

| cluster | exposition<br>(days) | N events<br>after cuts | per week |
|---------|----------------------|------------------------|----------|
| 1       | 63.5                 | 6                      | 0.7      |
| 2       | 14.5                 | 0                      | 0        |
| 3       | 53.5                 | 10                     | 1.3      |
| 4       | 35.0                 | 6                      | 1.2      |
| 5       | 52.3                 | 7                      | 0.9      |
| sum     | 219                  | 29                     | 0.9      |

← Cluster 2 analysis  
affected by a noisy  
channel (to be re-done)

Averaged over all clusters: 1 candidate per ~7.5 days

No MC comparison so far, work is in progress for MC for 2019



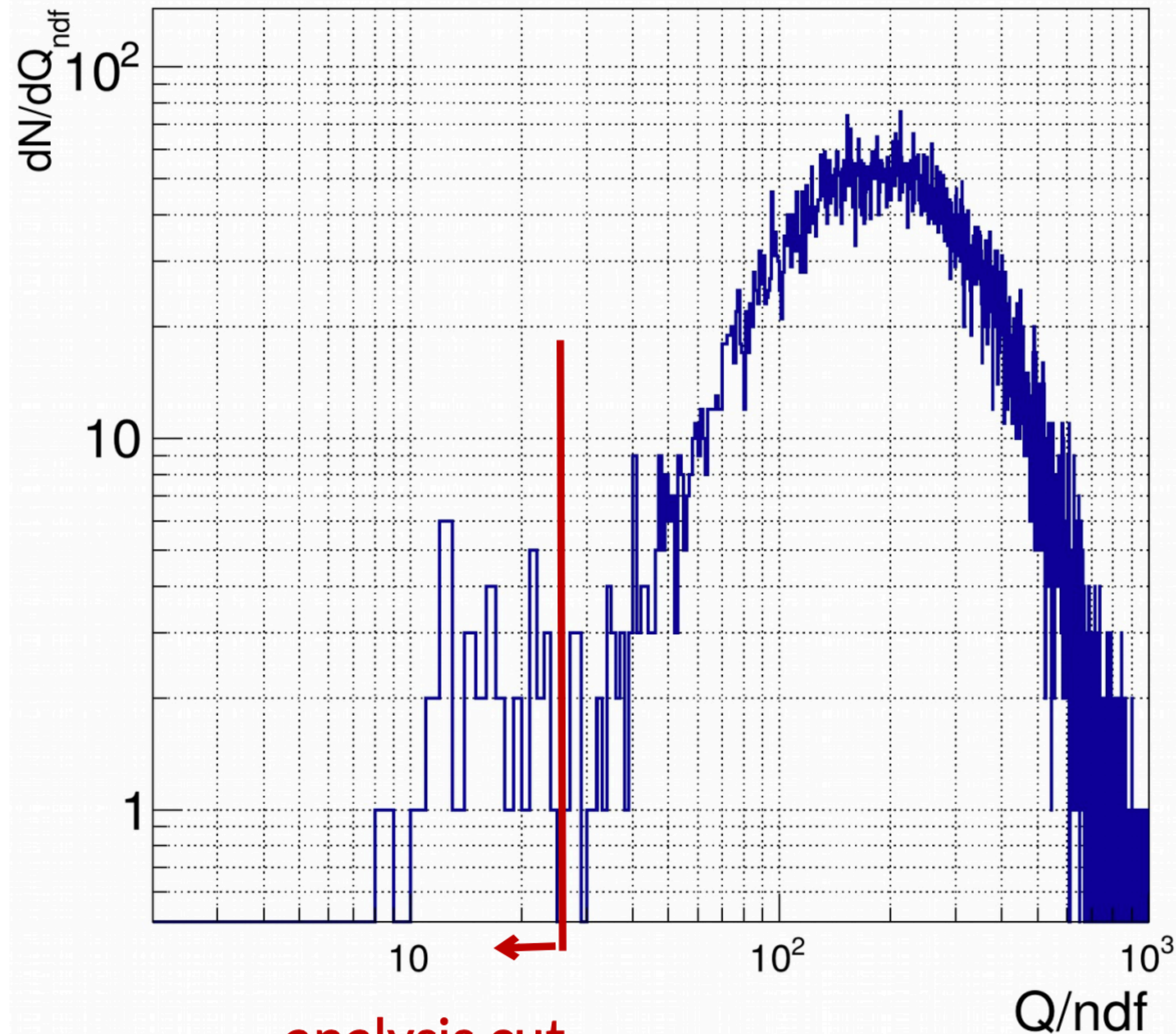
# Preliminary analysis of 2019

Analysis by G. Safronov

Q/ndf after simple quality cuts

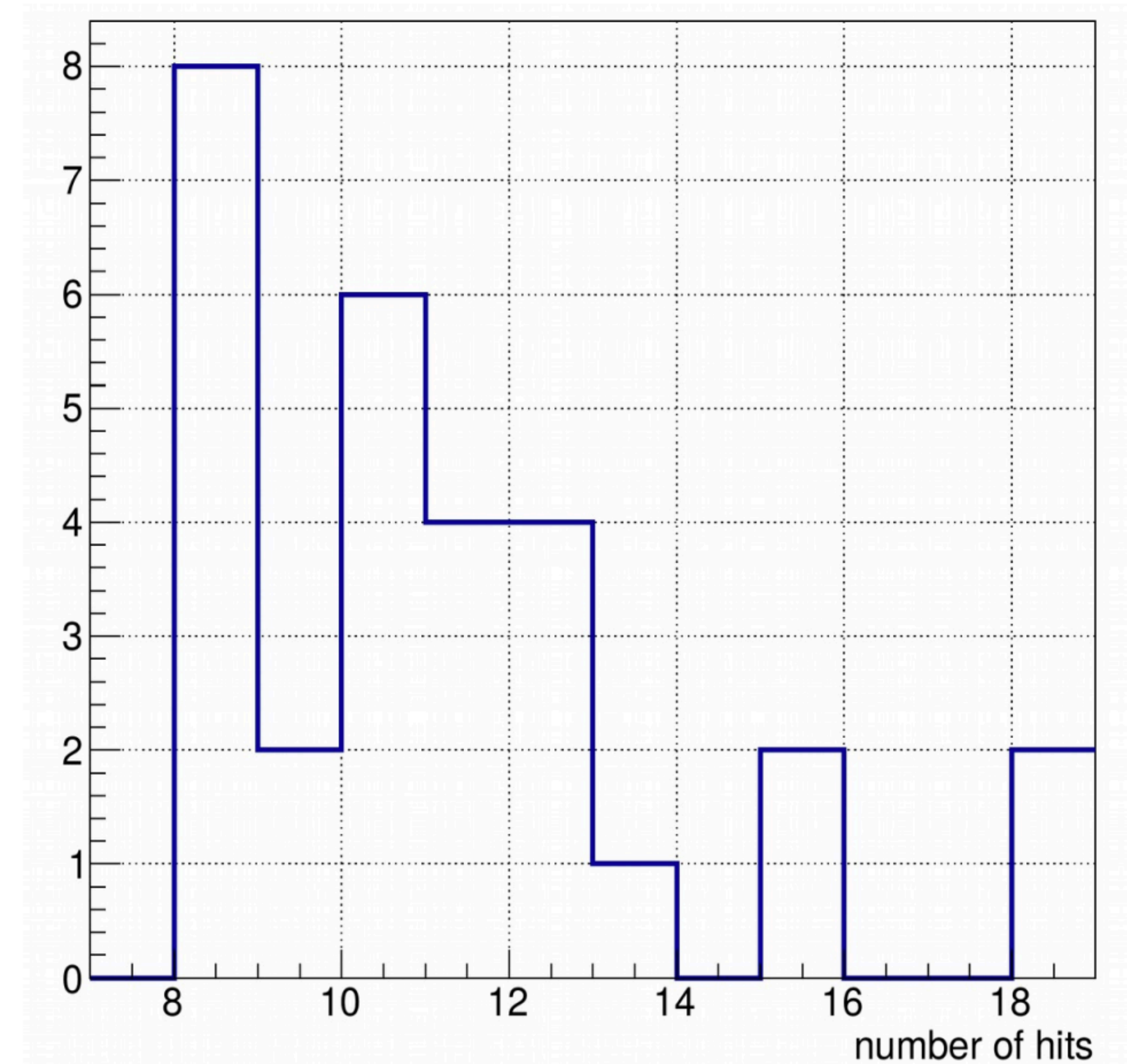
good data (no LEDs, or noisy channels)

cov. matrix status=3,  $N_{\text{hits}} \geq 8$ ,  $N_{\text{strings}} \geq 2$ ,  $\theta > 110^\circ$



analysis cut

number of hits distribution for  
neutrino candidates



29 events



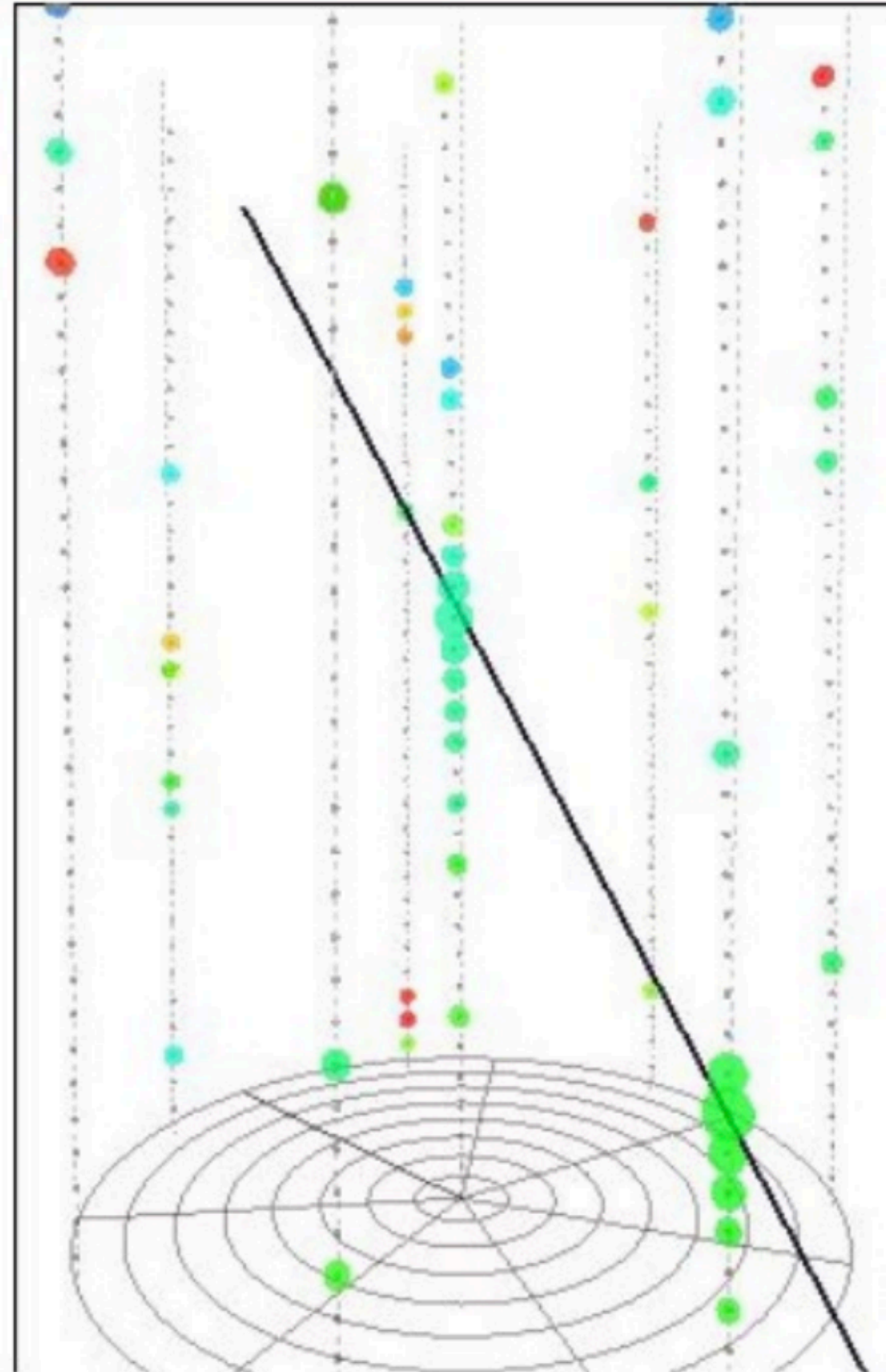
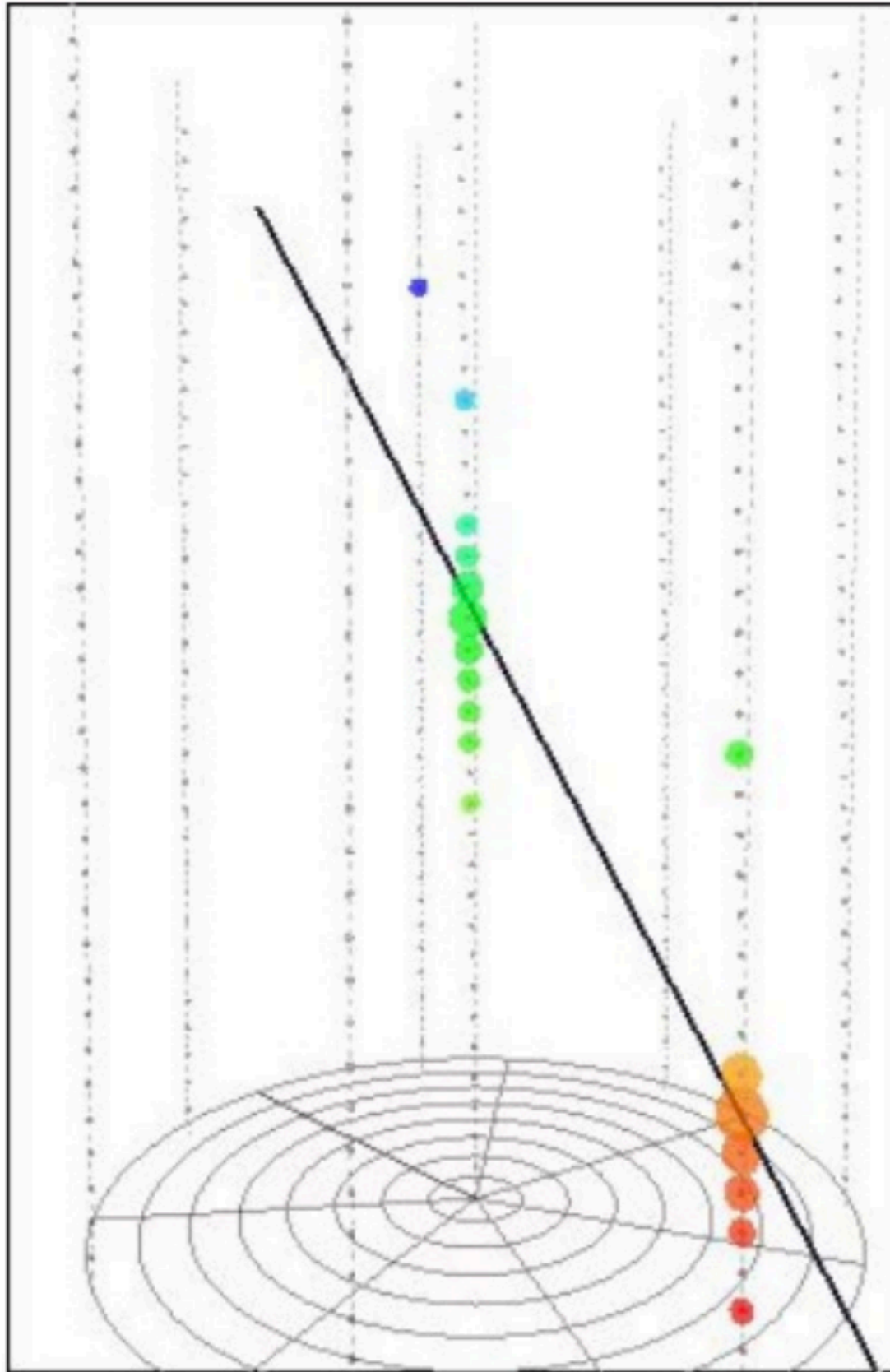
# Neutrino candidate events 2019 (two examples)

after noise filter

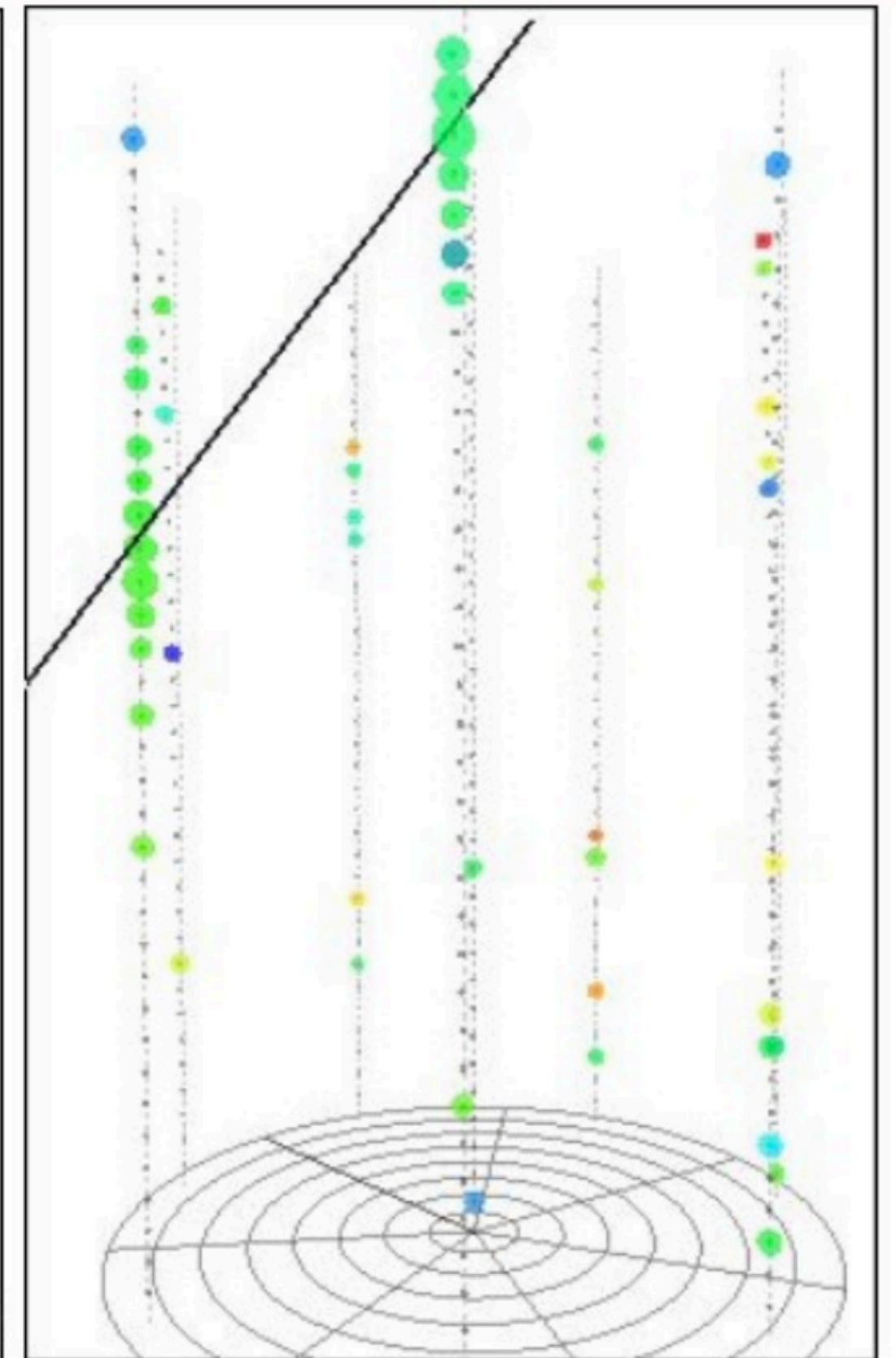
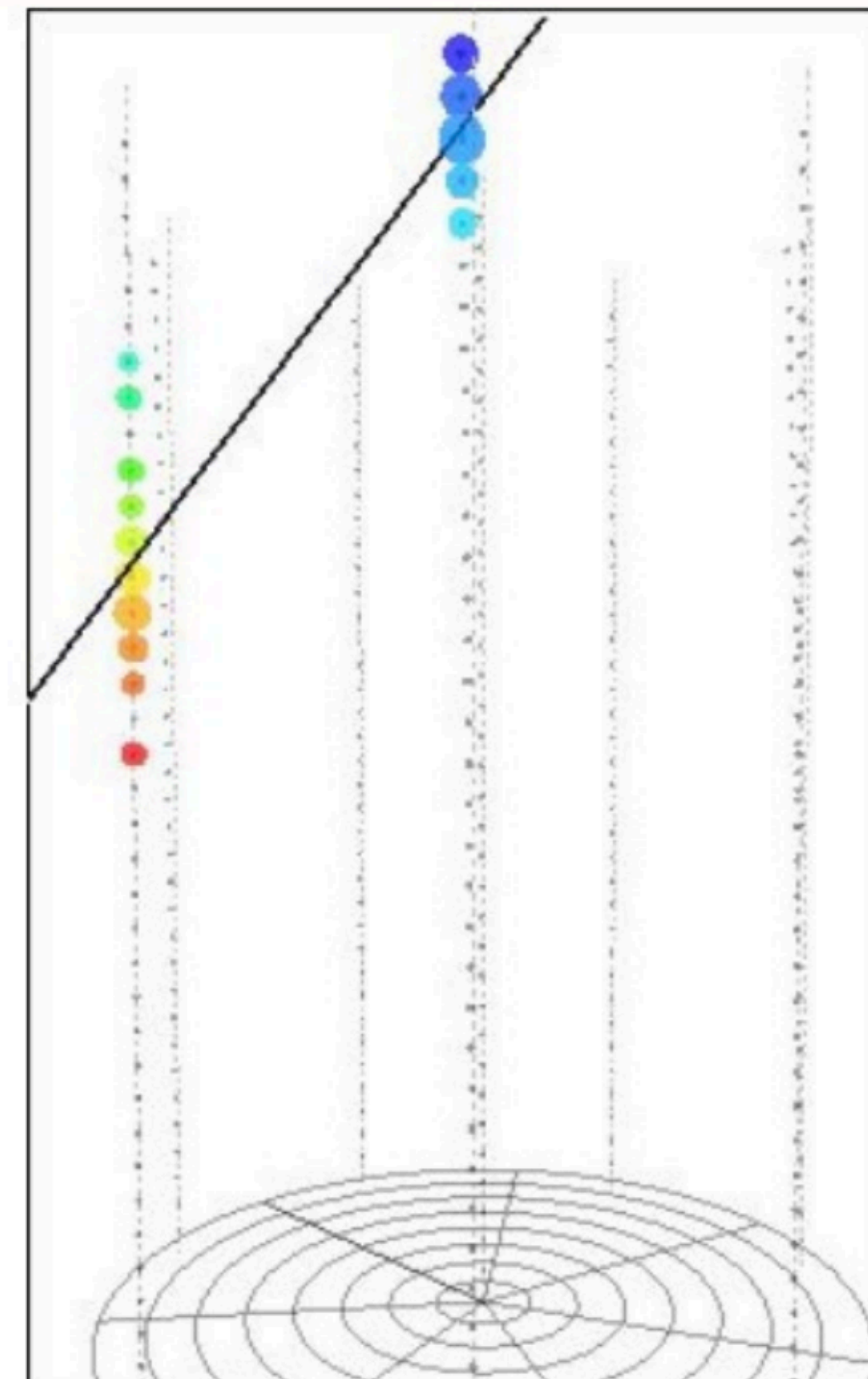
w/o noise filter

after noise filter

w/o noise filter



cluster 4, run 99, event 438088  
21/05/2019, time: 16:43:34 (+202180160 ns)  
**nHits = 18, nStrings = 3**  
theta = 17.99 deg.



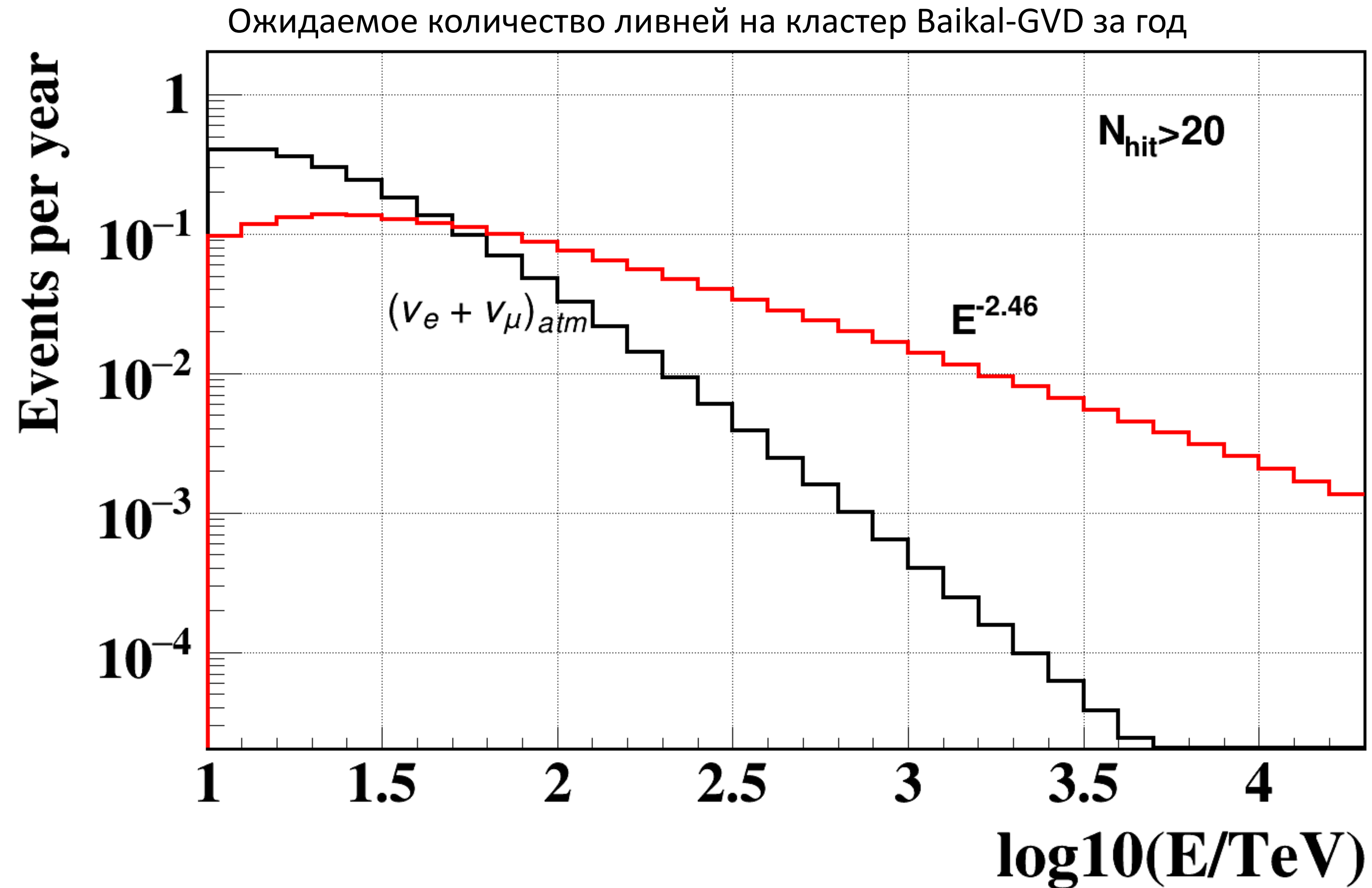
cluster 1, run 157, event 1414737  
12/06/2019 time: 1:12:12 (+463421230 ns)  
**nHits=15, nStrings = 2**  
theta=18.29



# Ливни высоких энергий I

Спектр энергий астрофизических нейтрино, измеренный IceCube:

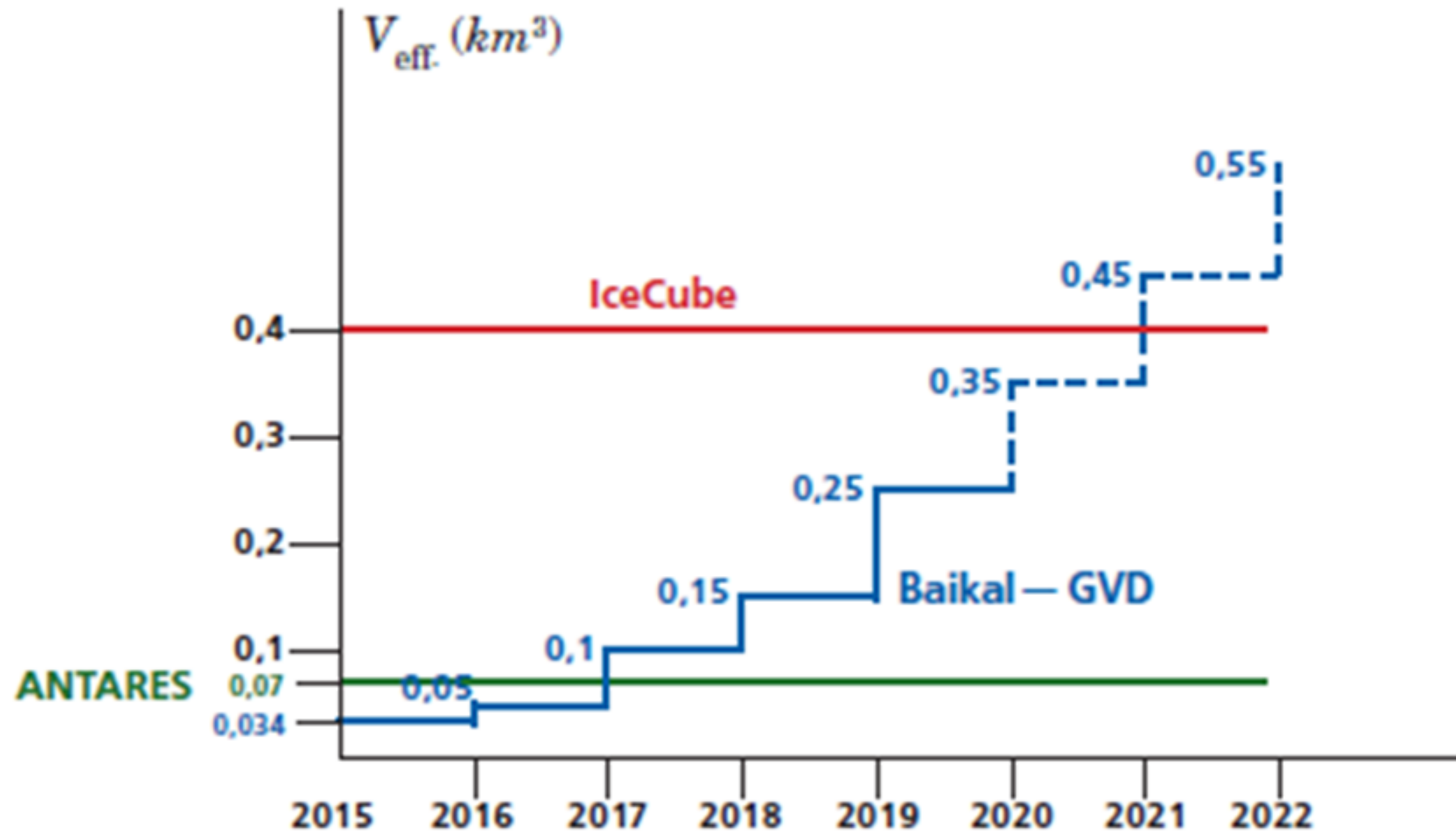
$$4.1 \cdot 10^{-6} E^{-2.46} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$



Ожидается 0.6 ливневых событий с  
 $E > 100 \text{ ТэВ}$  и  $N_{hit} > 20$   
на кластер за год

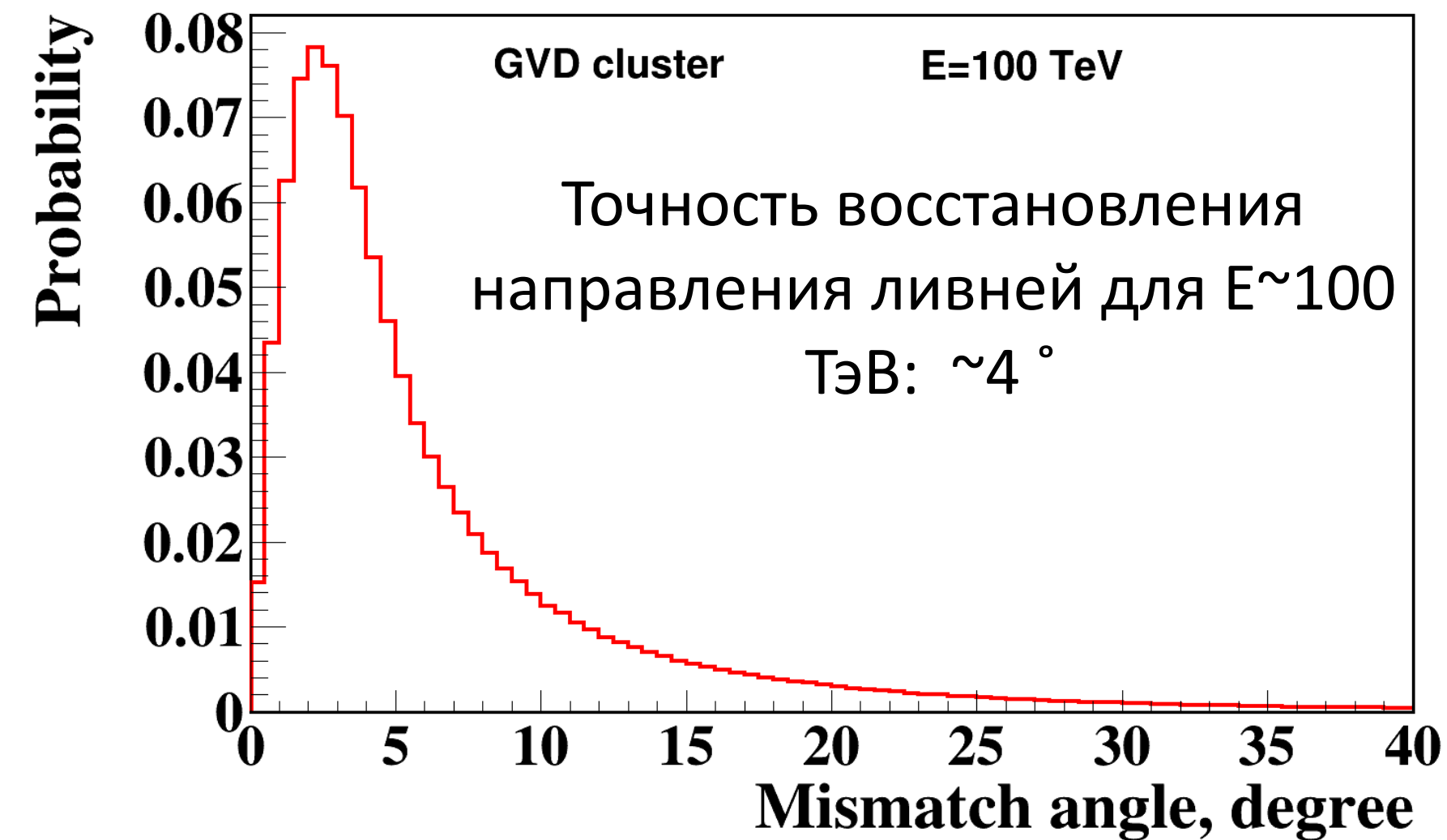


# Эффективный объем детекторов для регистрации ливневых событий от нейтрино в области энергий 100 TeV — 10 PeV





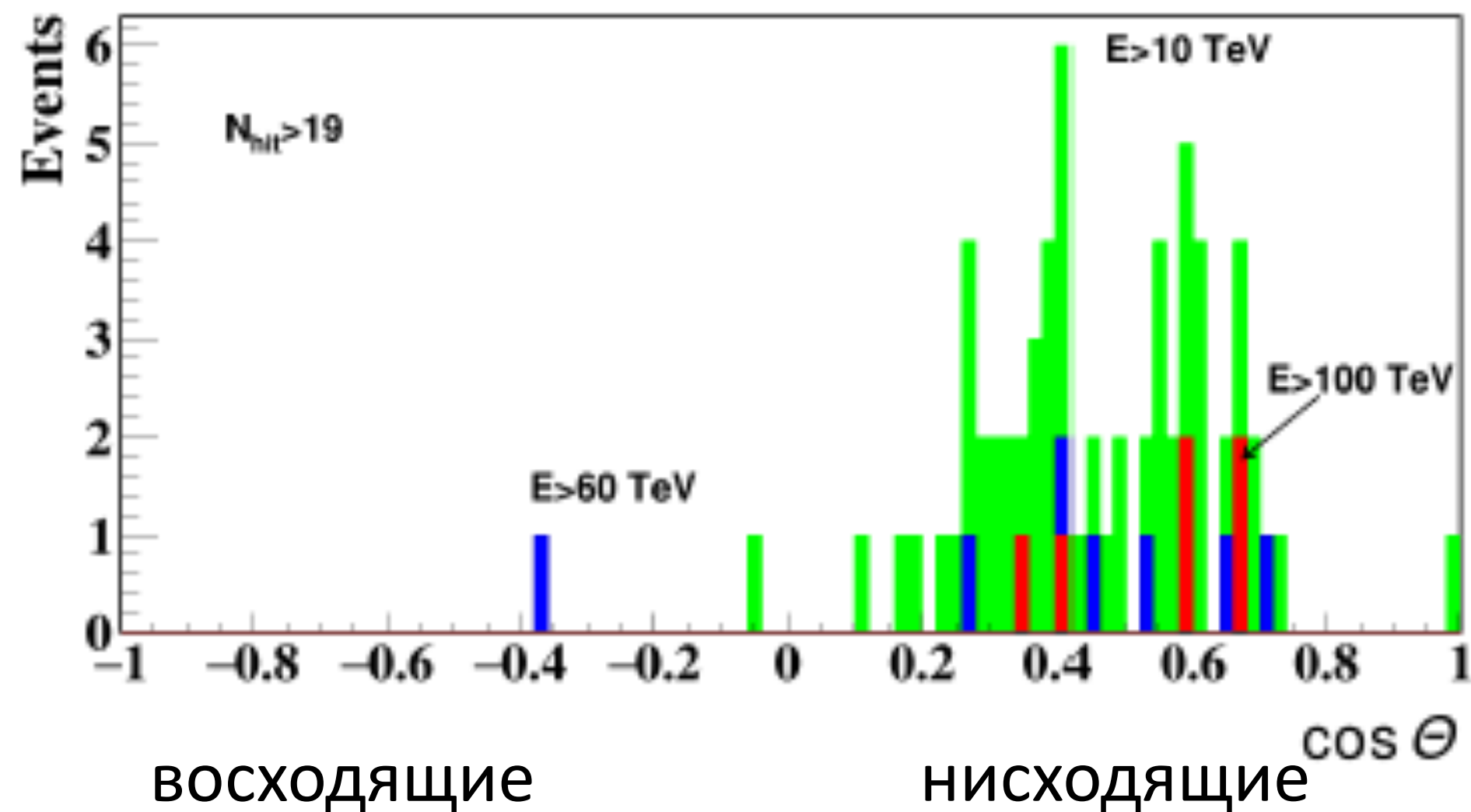
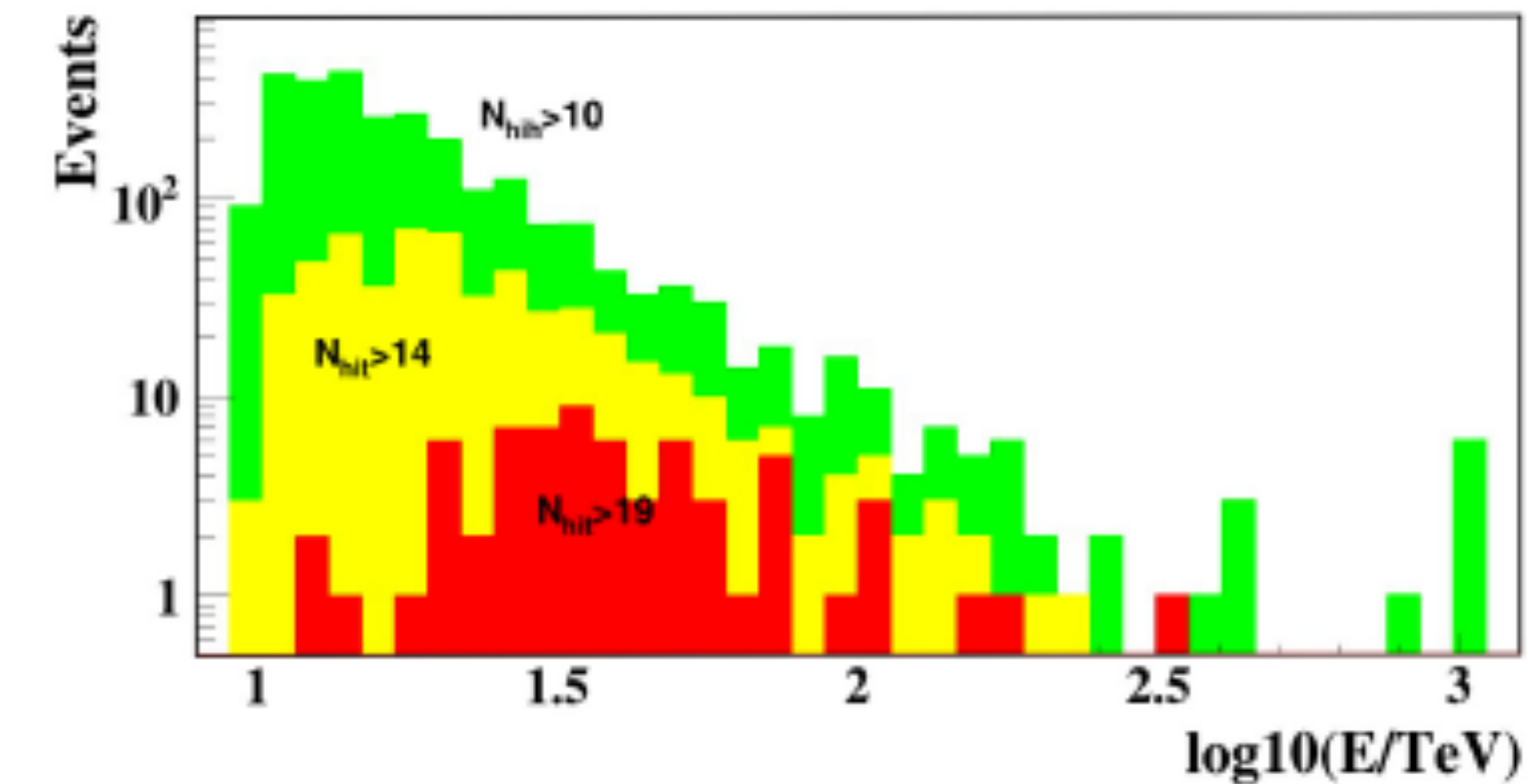
# Ливни высоких энергий II



Обработаны данные  
2016, 2018 и 2019 (4 месяца) годов,  
полная экспозиция: 1364 дня

Найдено 7 кандидатов с энергией  $E > 100$  ТэВ и числом хитов  $> 19$

Найден восходящий ливень  
с  $E = 71$  ТэВ

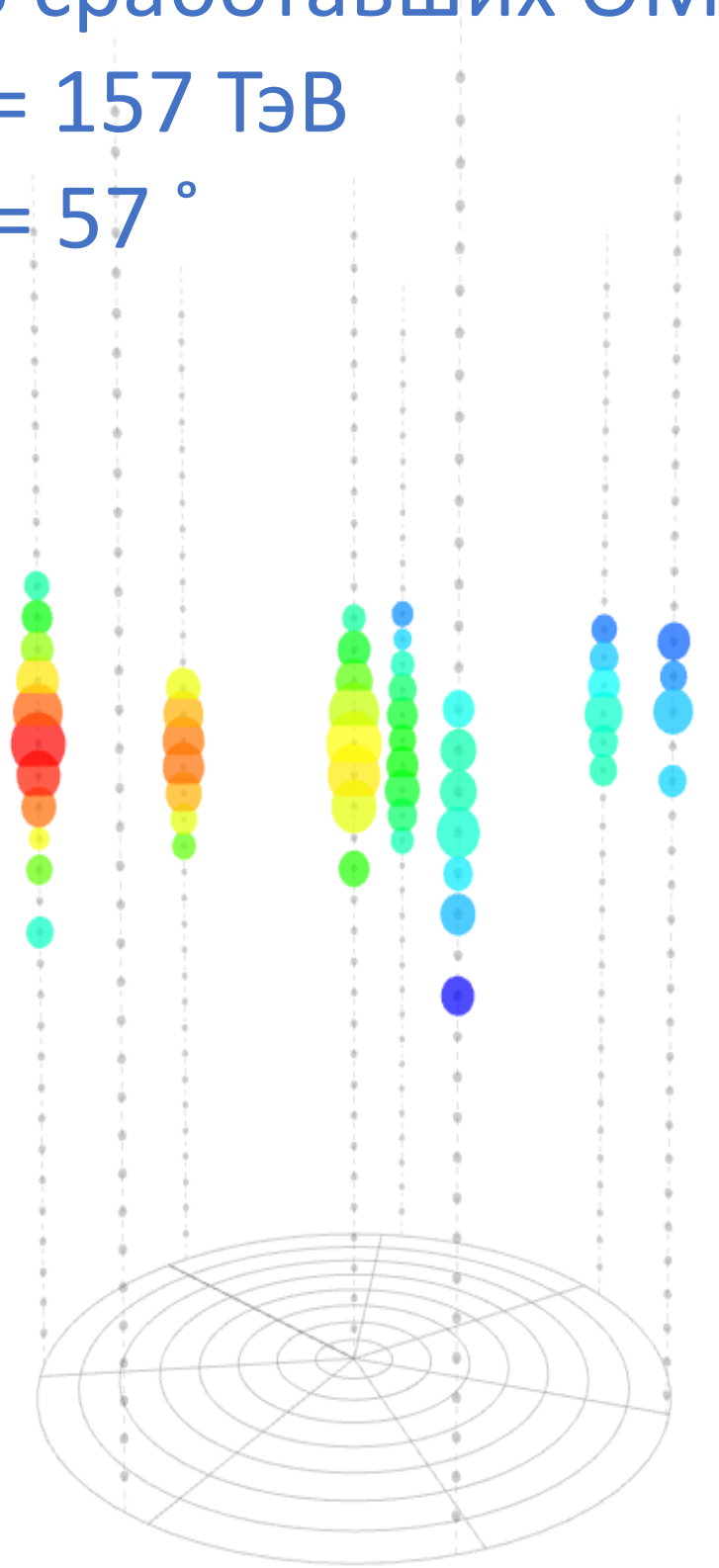


Ливневое событие

53 сработавших ОМ

$E = 157$  ТэВ

$\theta = 57^\circ$





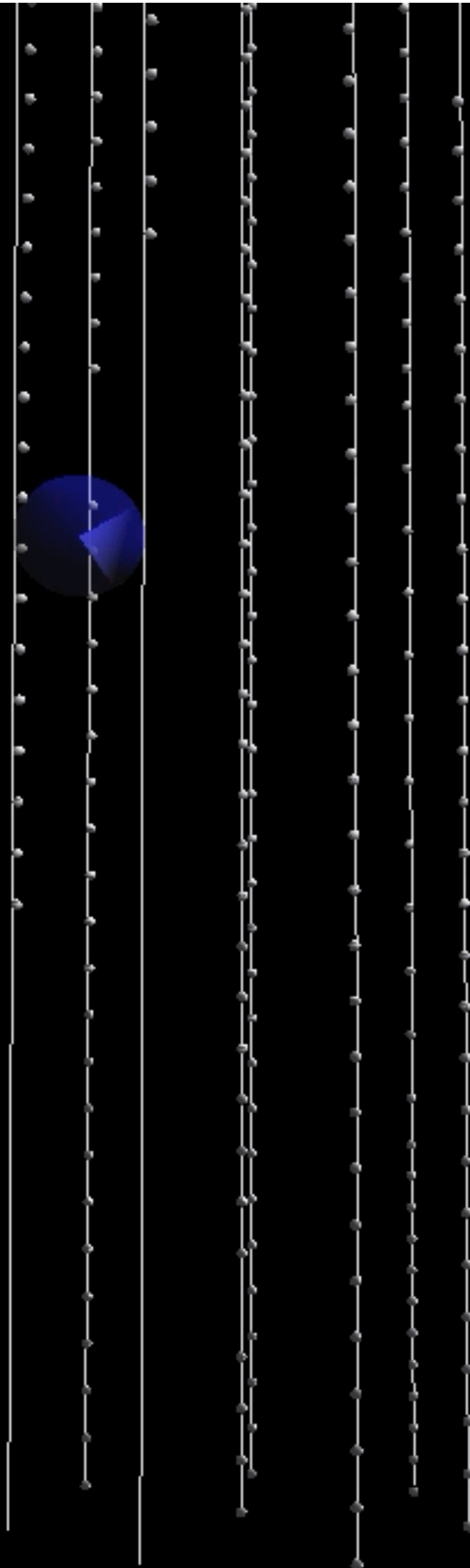
Alert events *Preliminary!*

Selection: N<sub>hit</sub> >=20 and E > 100 TeV

| Year   | Energy<br>(TeV) | MJD      | Decl.<br>(deg) | R.A.<br>(deg) | Zenith<br>(deg) | Azm_loc<br>(deg) | ρ-dist<br>(m) | Depth<br>(m) |
|--------|-----------------|----------|----------------|---------------|-----------------|------------------|---------------|--------------|
| 2015   | 107             | 57342.06 | 5.56           | 139.3         | 56.6            | 130.5            | 70.6          | 1073.2       |
| 2016   | 157             | 57507.44 | 14.0           | 173.4         | 57.3            | 249.4            | 44.7          | 1001.1       |
| 2018   | 153             | 58351.68 | 50.7           | 238.5         | 48.7            | 56.7             | 76.5          | 1106.3       |
| 2018   | 107             | 58415.89 | 3.7            | 37.7          | 69.0            | 112.0            | 100.8         | 861.5        |
| 2019   | 339             | 58530.03 | 60.2           | 63.7          | 67.0            | 350.0            | 89.6          | 1008.2       |
| 2019   | 107             | 58612    | 70.9           | 247.7         | 47.2            | 334.8            | 68.2          | 807          |
| 2019   | 110             | 58638    | 62.3           | 33.2          | 48.7            | 322.2            | 52.1          | 775          |
| 2019up | 71              |          | -22.9          | 48.8          | 111.7           | 99.9             | 48.9          | 991          |

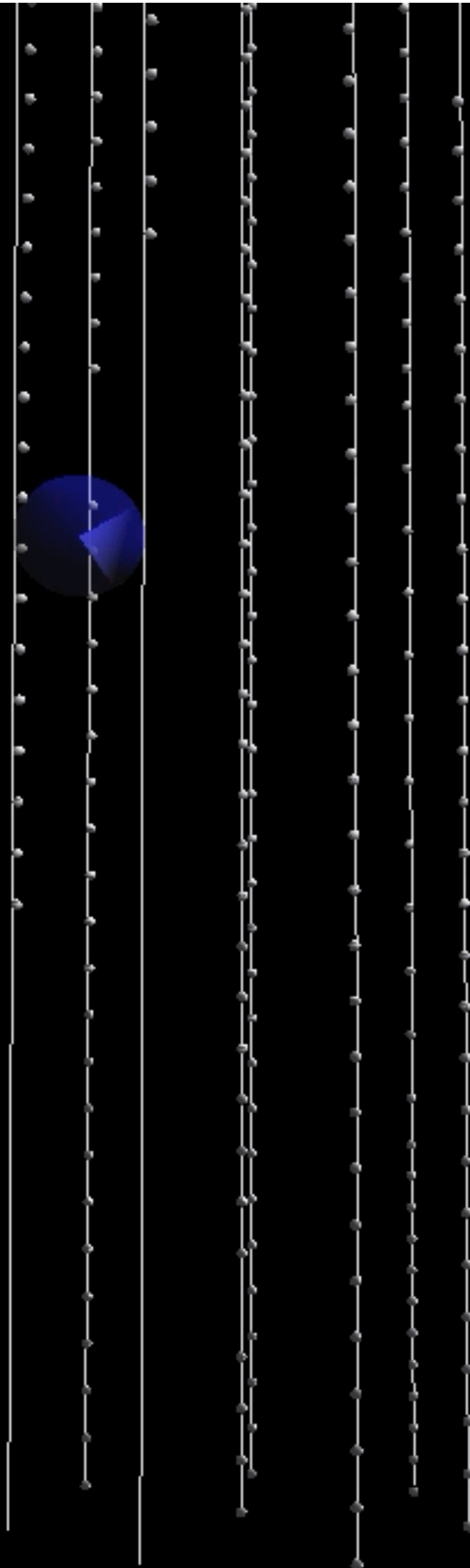


eventID: 297850 season: 2016 cluster: 1  
Time: 16591.0 ns





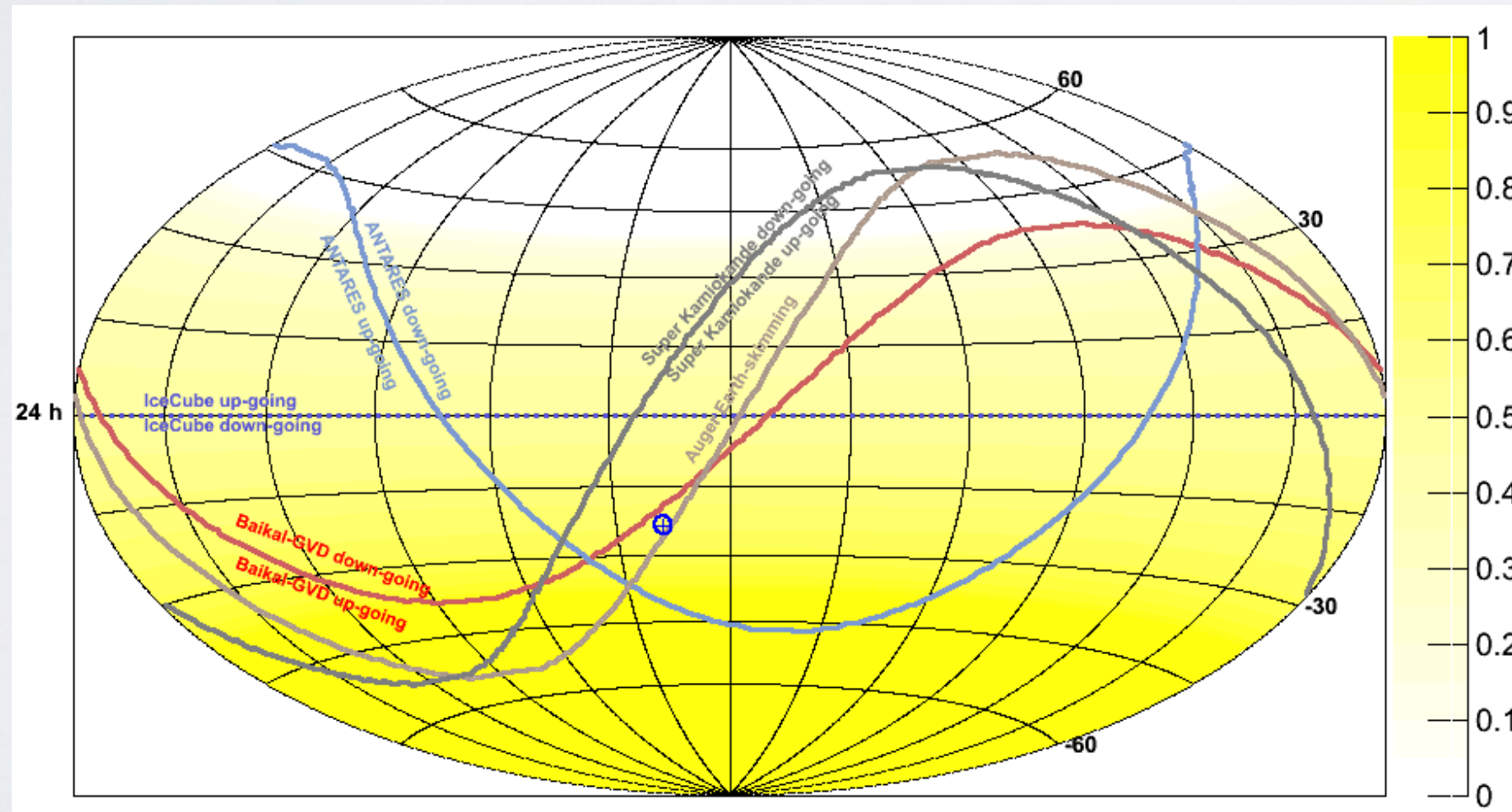
eventID: 297850 season: 2016 cluster: 1  
Time: 16591.0 ns



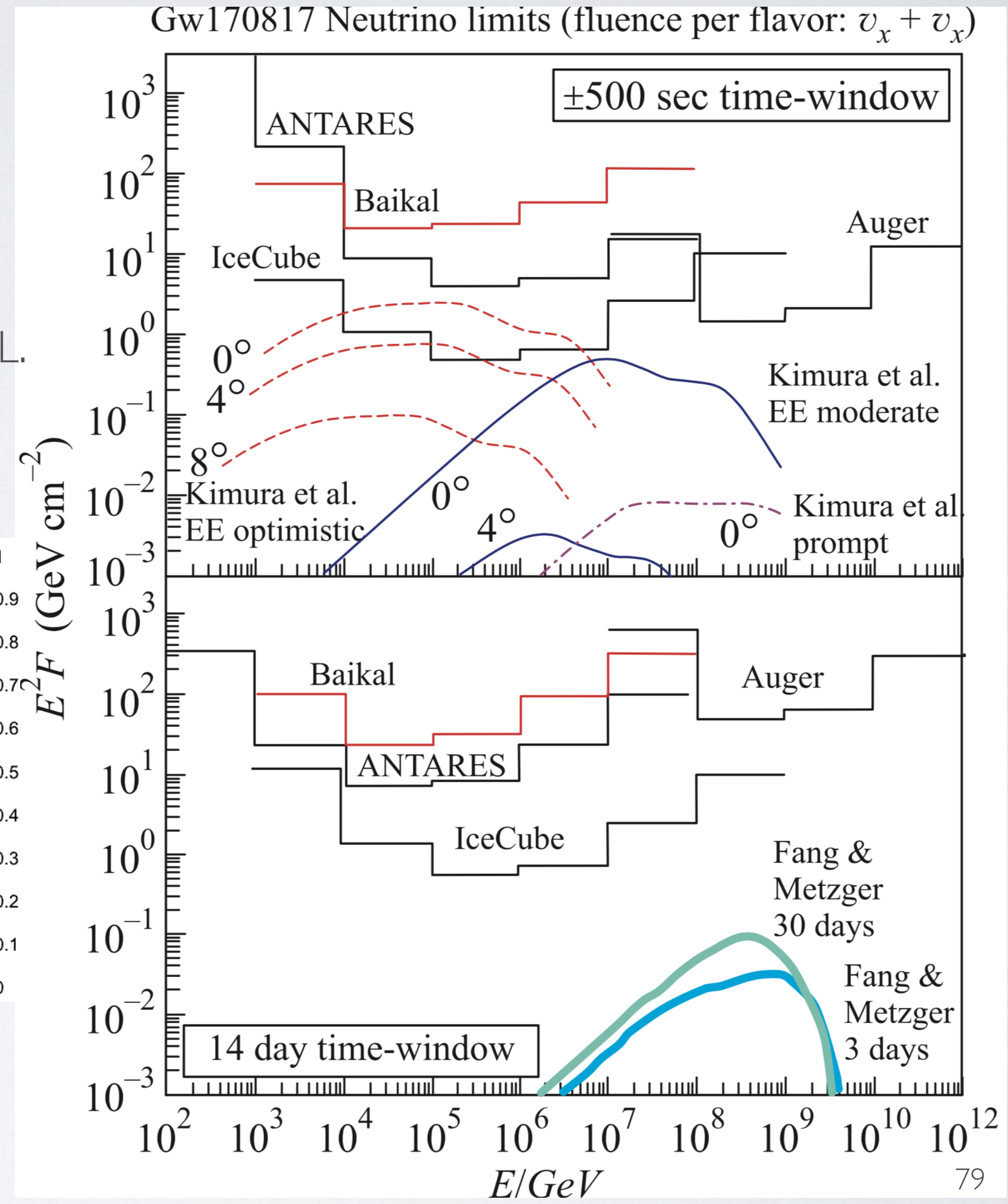


# SEARCH FOR HIGH-ENERGY NEUTRINO INDUCED CASCADES ASSOCIATED WITH GW170817

- The source was under horizon at registration time:  $93.3^\circ$
- No neutrino events associated with GW170817 using cascade mode within both  $\pm 500$  sec and 14 days
- Assuming  $E^{-2}$  spectral behavior and equal fluence in all flavors upper limits at 90% C.L. are obtained on the neutrino fluence from GW170817 for each energy decade



ISSN 0021-3640, JETP Letters, 2018,  
Vol. 108, No. 12, pp. 787–790.





# Заключение

- Нейтринная астрофизика высоких энергий:
  - наблюдается значимое превышение над фоном потоков астрофизических нейтрино в мюонном и каскадном каналах регистрации
  - зарегистрированы нейтрино от источников NGC 1068 / M77 с достоверностью  $2.9\sigma$  (47 млн. св. лет) и TXS 0506+056 с достоверностью  $3.5\sigma$  (4 млрд. св. лет)
- В апреле 2020 года введены в эксплуатацию еще 2 кластера гирлянд Байкальского телескопа (+16 гирлянд, +576 ОМ)
- Байкальский телескоп является самым крупным нейтринным детектором в Северном полушарии с 2016 ОМ и с эффективным объемом порядка  $0.35 \text{ км}^3$  в задаче регистрации ливневых событий с энергией более 100 ТэВ
- Проведен первичный анализ данных и получен первый банк атмосферных мюонных нейтрино.
- Выделено 8 каскадных событий с  $E > 100 \text{ ТэВ}$
- Идет интенсивная работа по всем аспектам обработки и анализа данных.
- Проект значительно пополнился новыми участниками
- Яркие результаты впереди!





106 км КБЖД

*Спасибо за внимание!*



