Baikal-GVD: Deep-Underwater Neutrino Telescope

The XXVII International Scientific Conference of Young Scientists and Specialists (AYSS-2023)

Bair Shaybonov on behalf of the Baikal-GVD collaboration, JINR, 01.11.2023

Baikal-GVD Collaboration

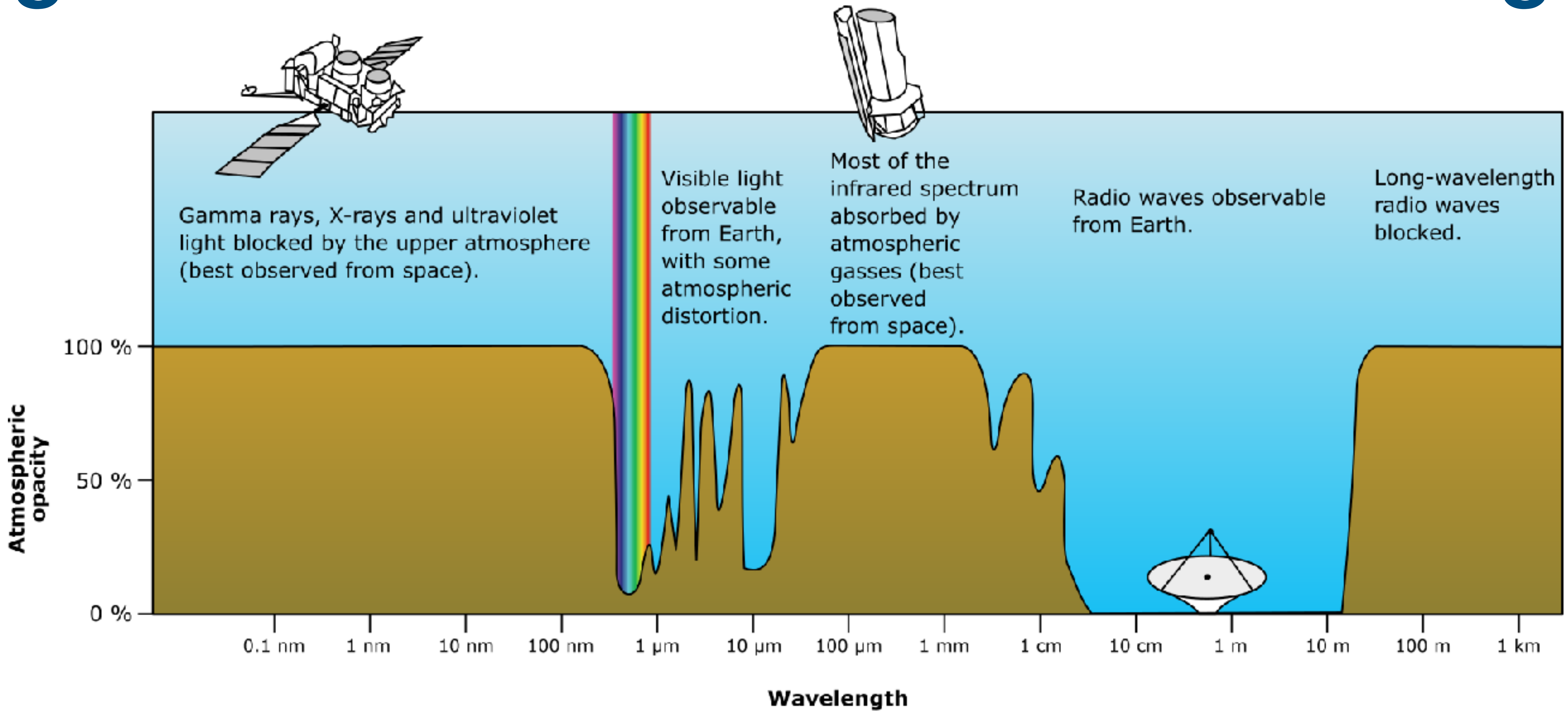
- Joint Institute for Nuclear Research, Russia
- Institute for Nuclear Research of the Russian Academy of Sciences, Russia
- Comenius University, Slovakia
- Czech Technical University in Prague, Czech Republic
- Irkutsk State University, Russia
- Skobeltsyn Research Institute of Nuclear Physics, Russia
- Institute of Nuclear Physics ME RK, Kazakhstan
- AO ‘LATENA’ (Joint Stock Company), Russia
- St. Petersburg State Marine Technical University, Russia

~ 65 physicists and engineers

Outline

- Physics motivation
- Principle of neutrino telescope operation
- History and status
- Detector and selected results
- Prospects

Traditional Astronomy is Based on the Registration of Photons of Various Energies



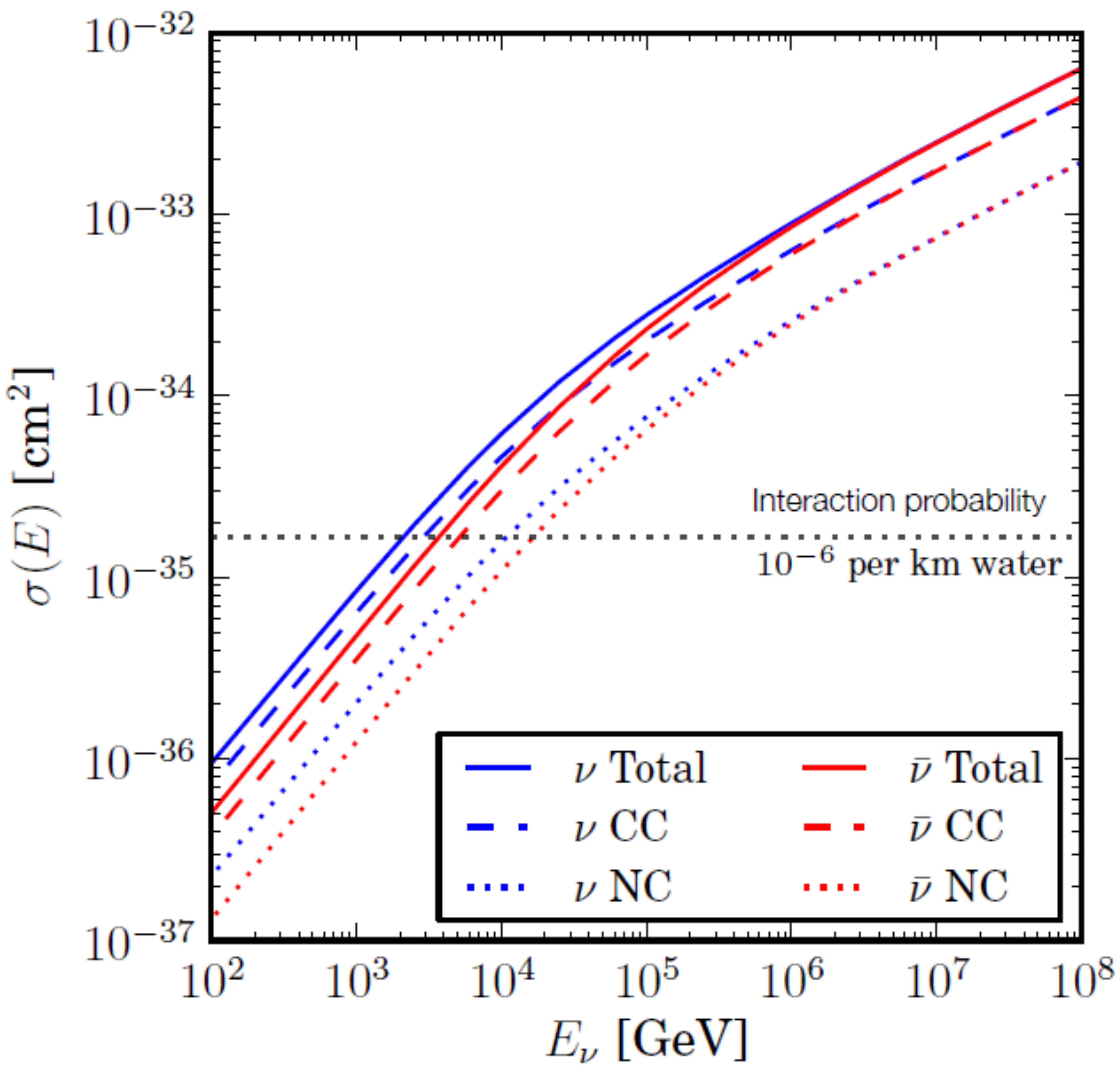
Visible range - stars, galaxies, expansion of the universe, etc.
Radio Astronomy – pulsars, quasars, radio galaxies, relic radiation etc.
X-rays - diffuse flux, X-rays sources etc.
Gamma astronomy – gamma-ray bursts etc.

New Astronomies:

- gravitational-wave
- neutrino

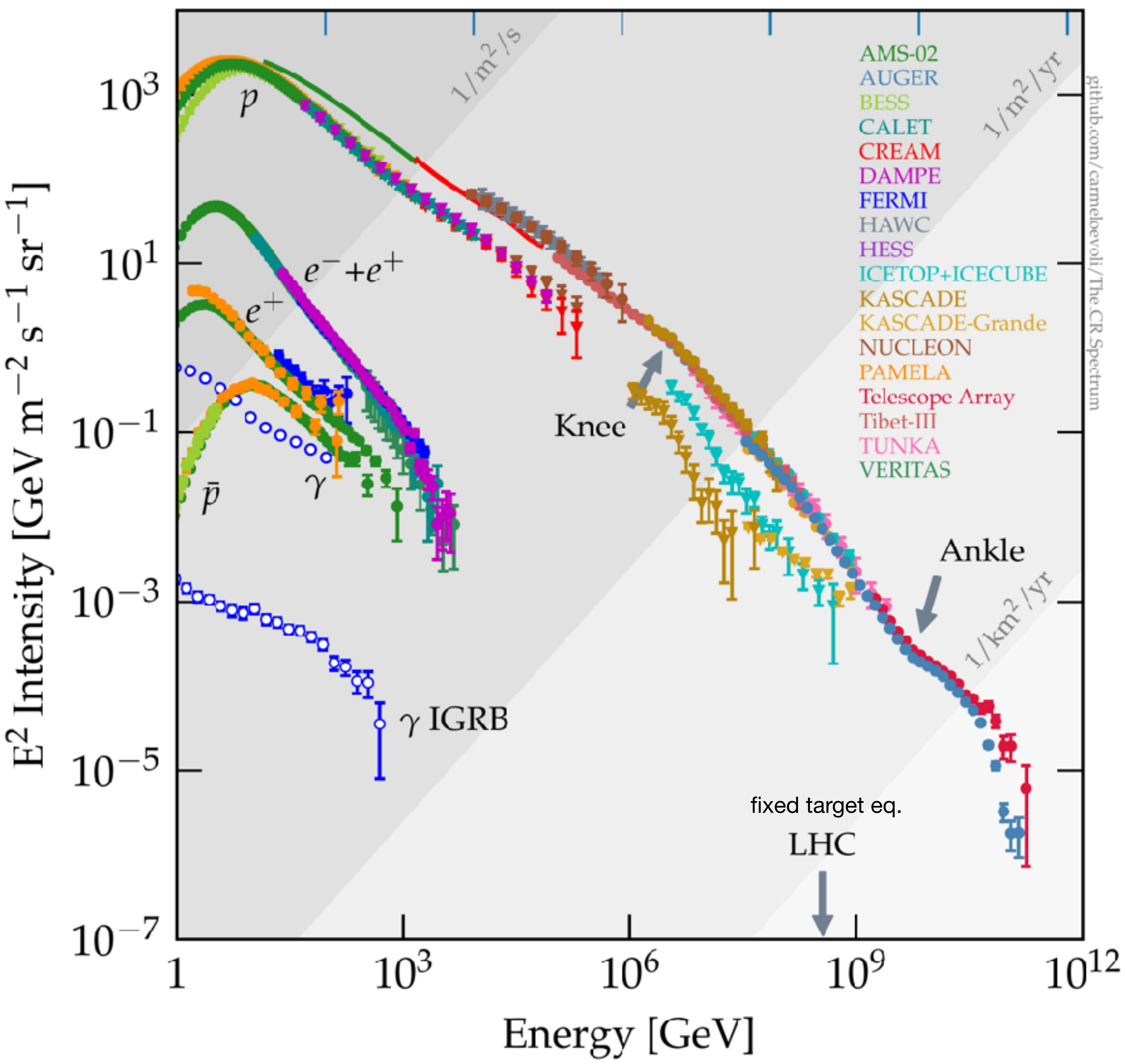
Favourable Features of High-Energy Neutrino

- The cross-section of the interaction of neutrinos with matter increases with increasing energy (~1 nb at 10^{15} eV)
- High–energy events are much easier to register - there is more energy release in the installation. Fewer detector recording elements are required. The ability to use large volumes of natural transparent media



Cosmic Rays

Diffuse cosmic ray flux



The range of measured charged cosmic ray (CR) particle energies extends up to 10^{11} GeV [10^{20} eV]

That's an evidence for the existence of cosmic systems accelerating particles far beyond the LHC energy

Cosmic rays origin is still unknown

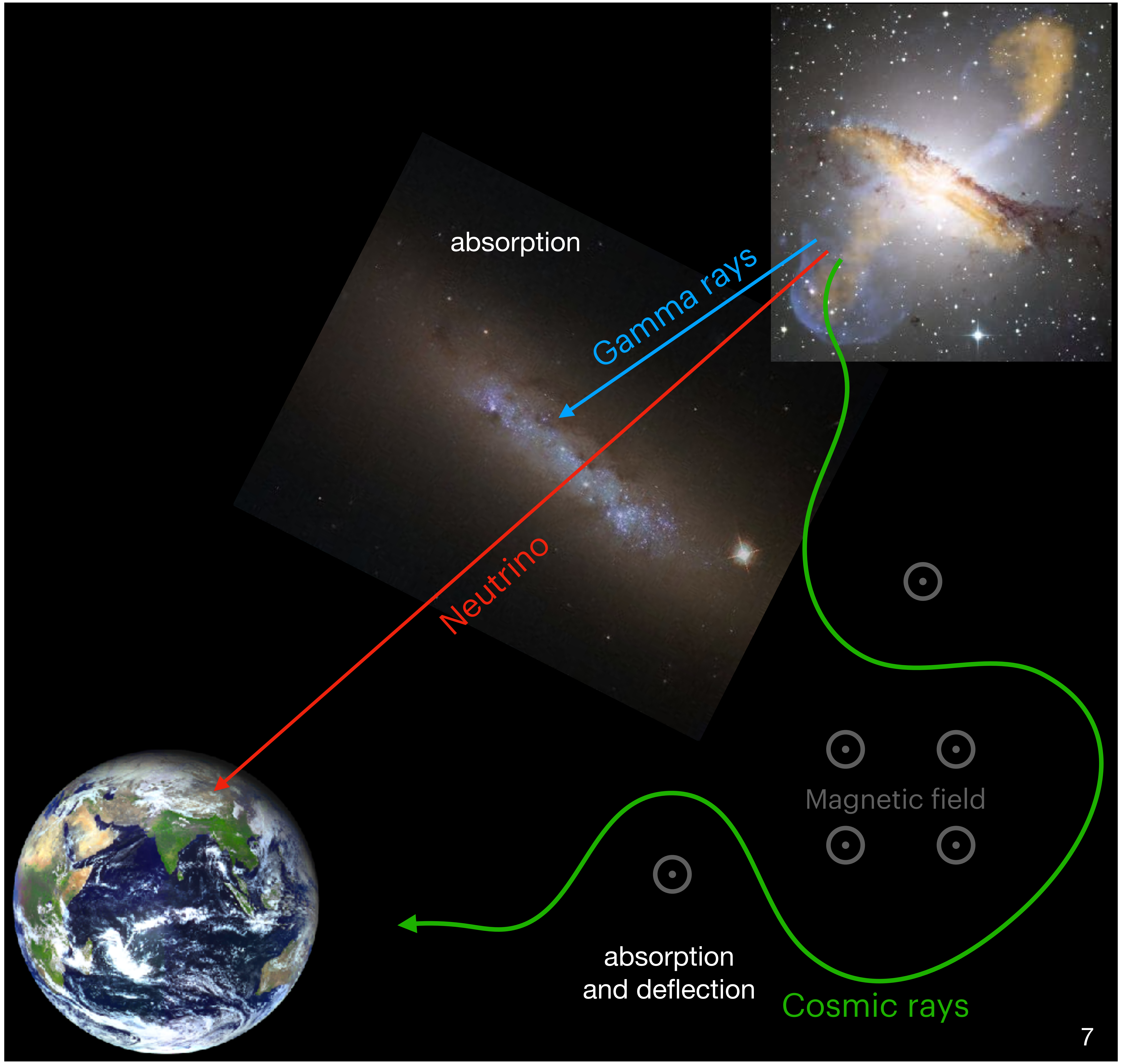
High-Energy Neutrino (>10 GeV) as an Astrophysical Messenger

- Neutrino is a neutral stable light elementary particle weakly interacting with matter
- Abundantly born in hadronic processes in space accelerators (active galactic nuclei, supernova remnants, microquasars, gamma-ray bursts, tidal disruption events etc.)
- Unlike high-energy gamma rays:
  - freely escape from the source
  - freely distributed in the Universe
- Unlike cosmic rays (high-energy p, He, etc.):
  - not deflected by magnetic fields
  - trace production and acceleration sites of neutrino and thus cosmic rays

$$p + p, \quad p + \gamma \rightarrow \pi^{\pm} + \ldots$$

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

$$\mu \rightarrow e + \nu_{\mu} + \nu_{e}$$

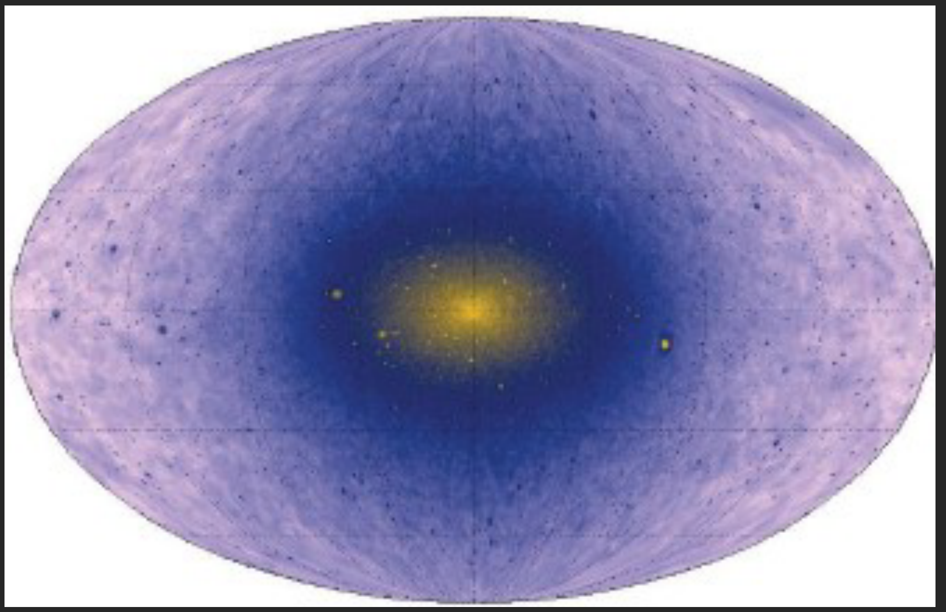


Prominent Source Candidates

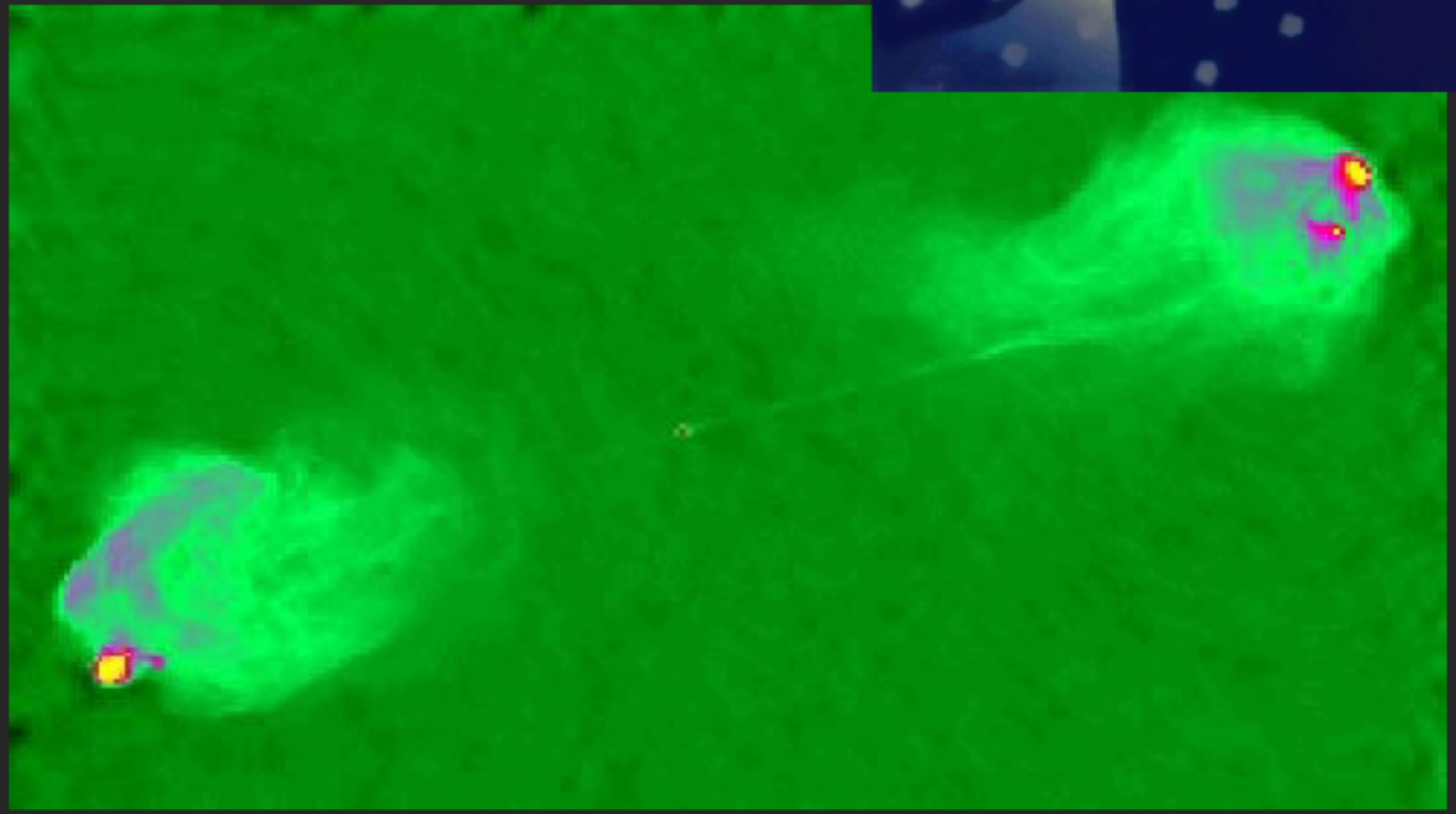
Galactic

SNR
Microquasars
Young SN shells
Pulsars

Extra-Galactic



Dark Matter

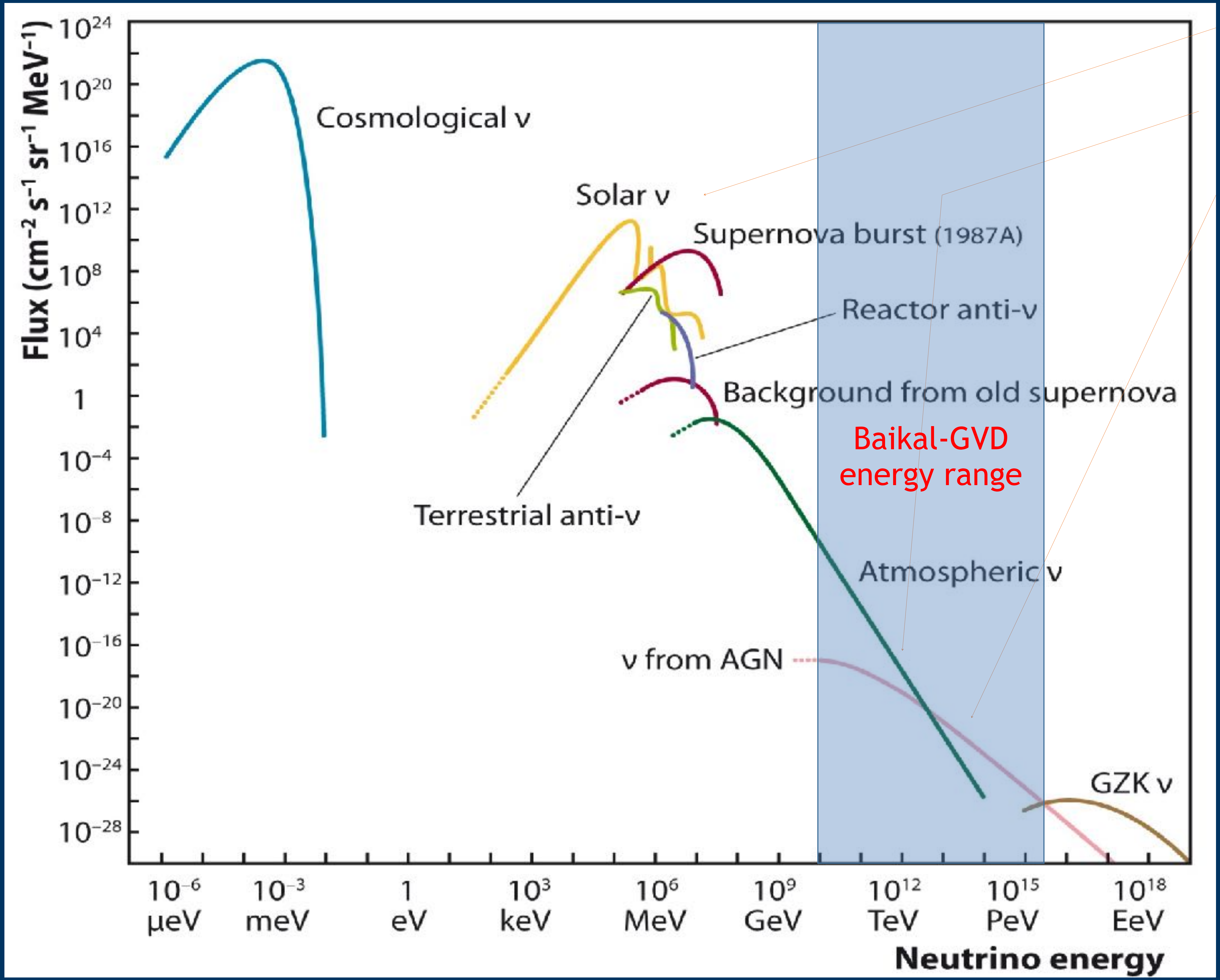


AGN
Starburst Galaxies
Galaxy Clusters
GRB

M.Markov, **1960**: (JINR)

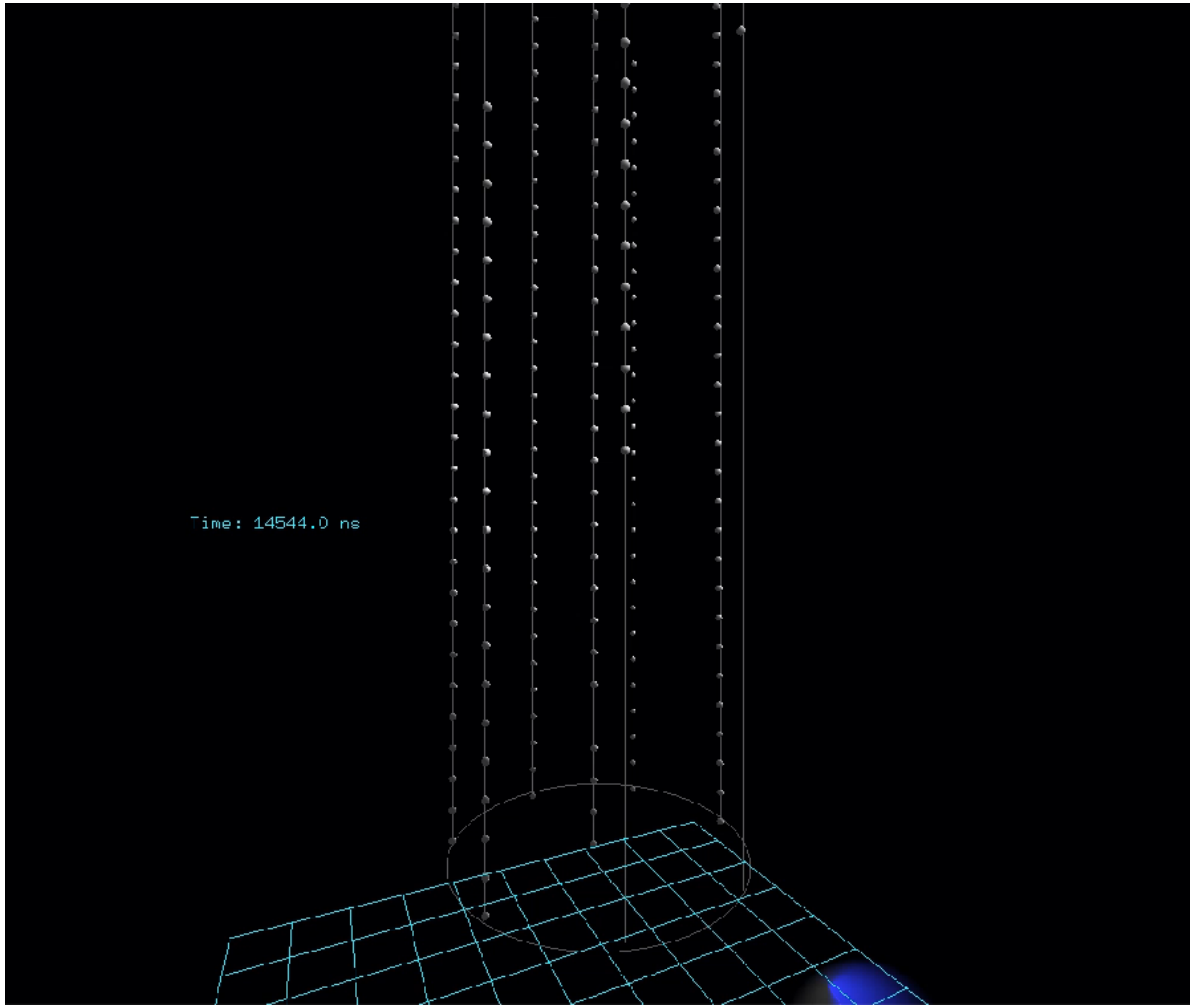
„We propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation“ Proc. 1960 ICHEP, Rochester, p. 578.

Neutrino Sources and Energy Scale



Neutrino Telescope: Operation Principle

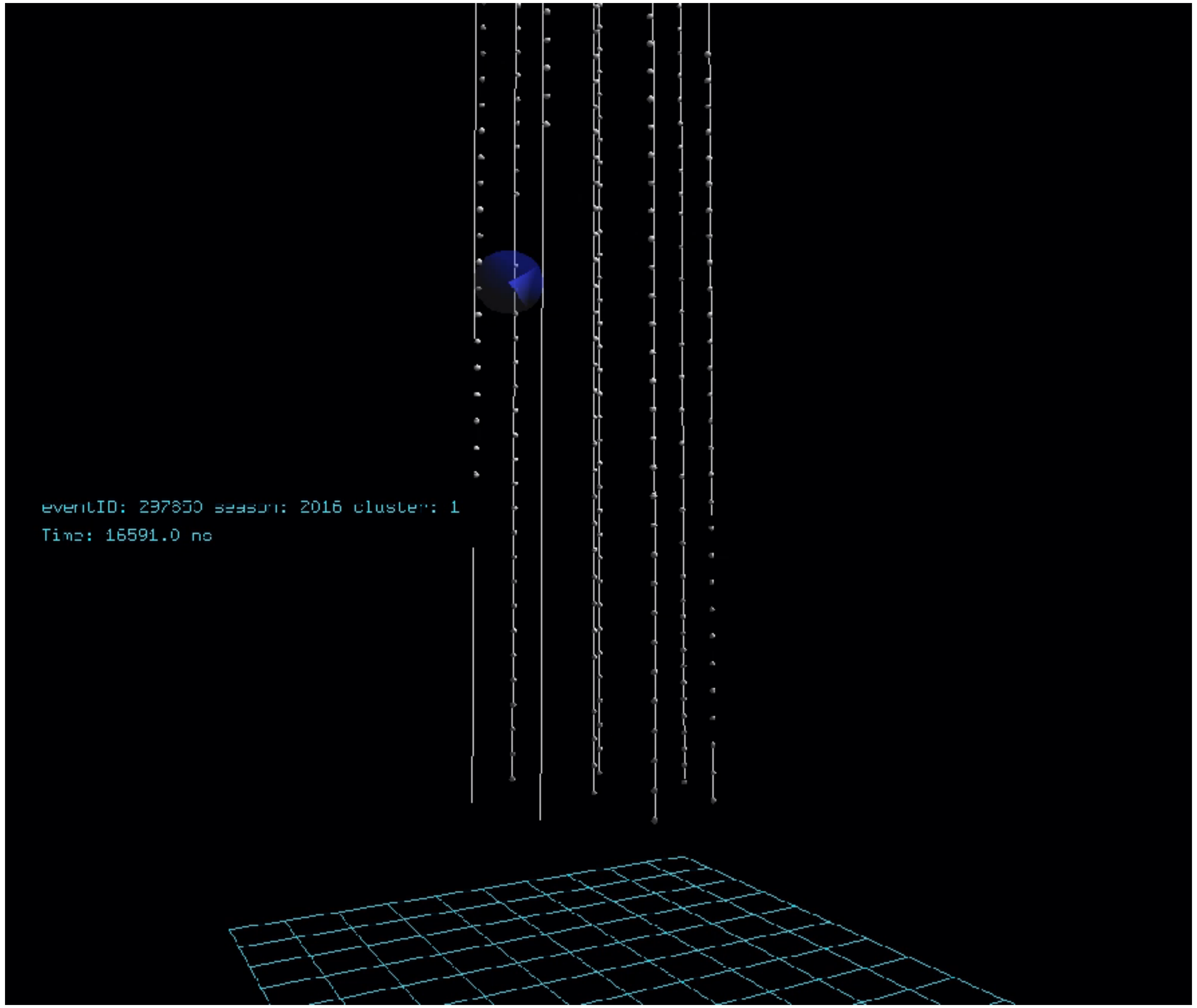
Track-like event $\nu_\mu + N \rightarrow \mu + N'$



- Large arrays of PMTs in deep water or ice
- Cherenkov light detected by PMTs
- Track-like events from ν_μ CC
- Cascade-like events from ν_e & ν_τ CC + NC
- Direction reconstructed from hit positions and times
- Energy reconstructed from hit charges
- Look downward through the Earth to suppress atmospheric muon background

Neutrino Telescope: Operation Principle

Cascade like event $\nu_{e,\tau} + N \xrightarrow{CC} e, \tau + N^{'}, \nu_{e,\mu,\tau} + N \xrightarrow{NC} \nu^{'}_{e,\mu,\tau} + N^{'}$



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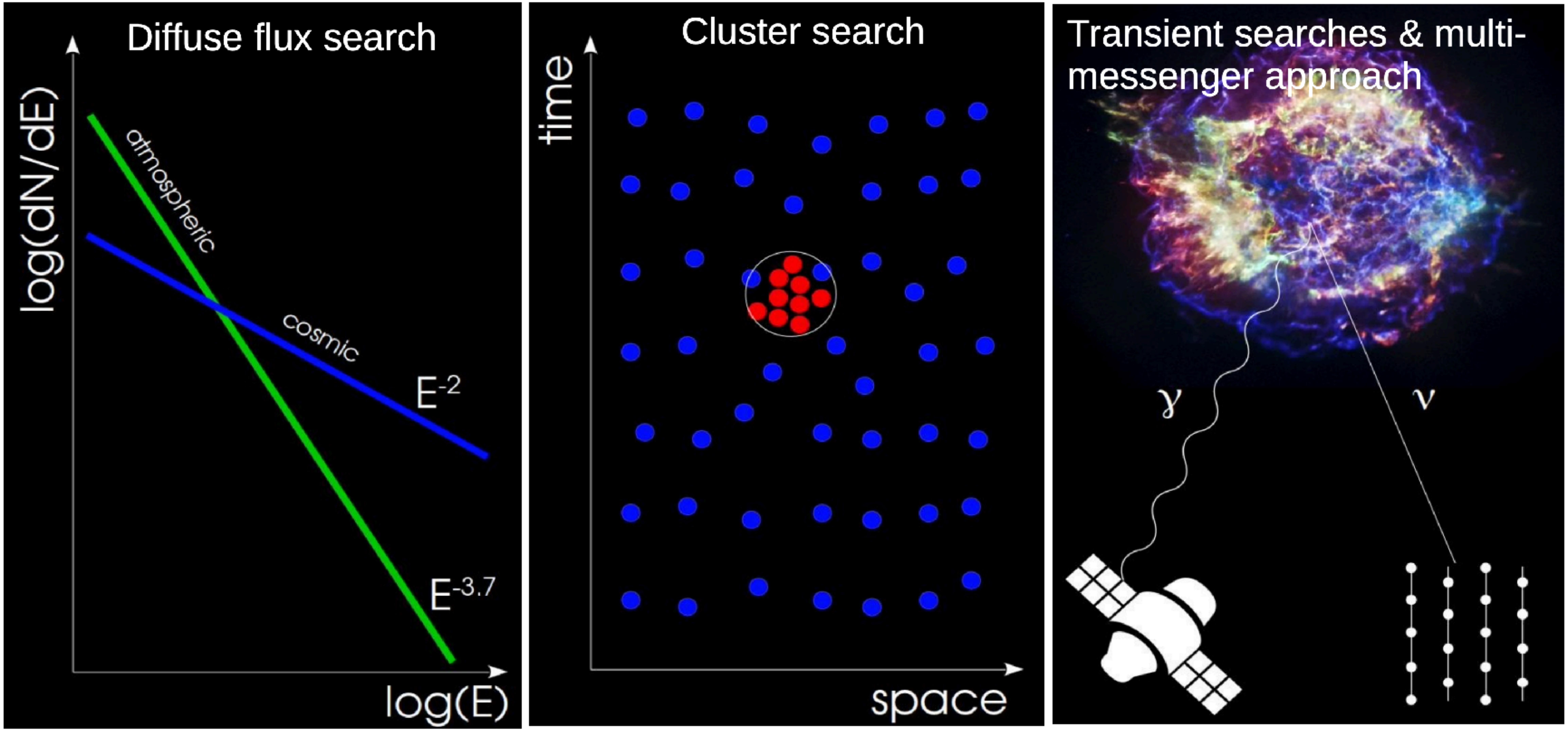
Methods of Background Suppression



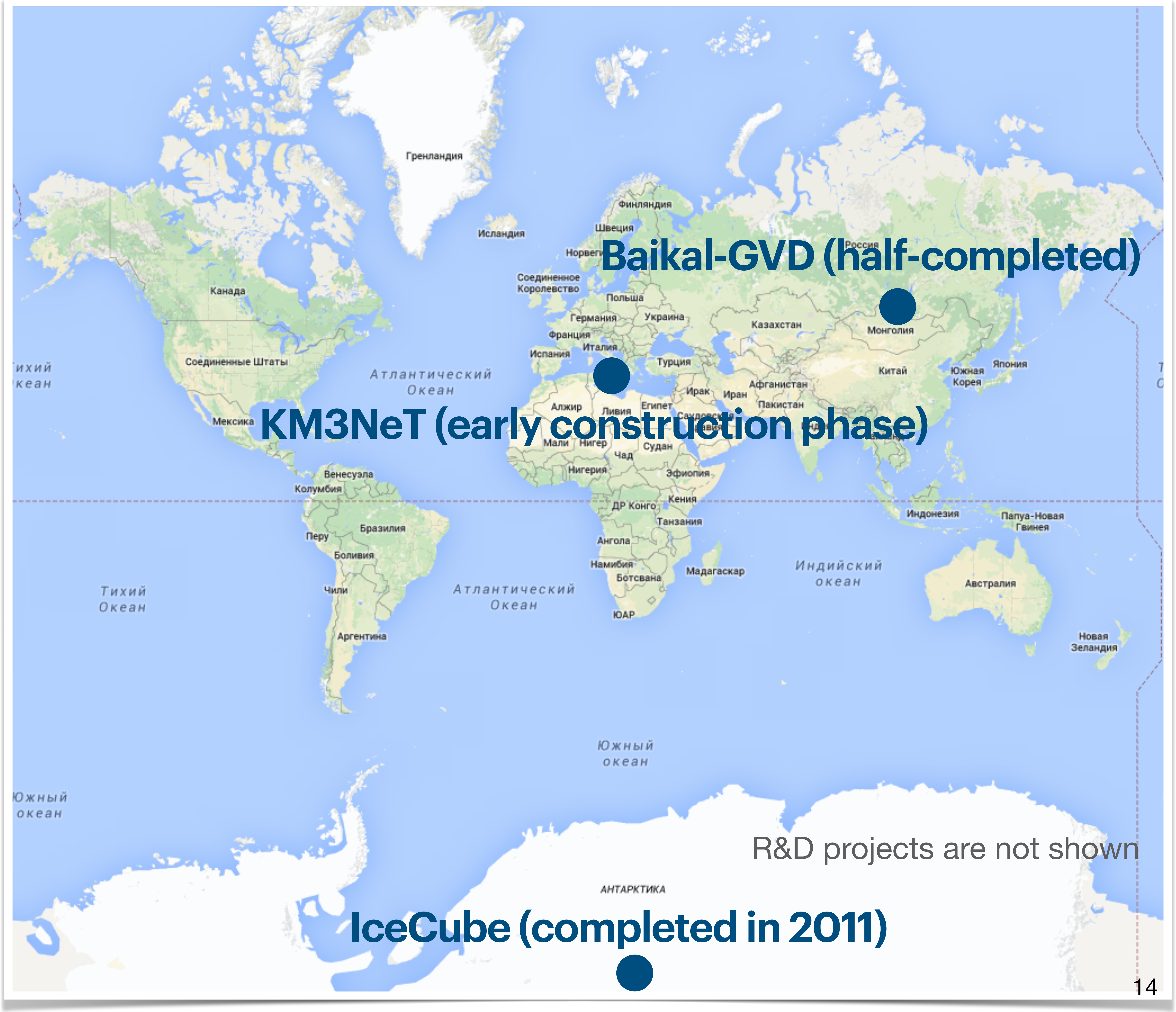
Pictures borrowed from talk by R. Ruiz

Neutrino Telescopes Worldwide

A difficult task both technically and scientifically:

- Detector volume should be 1 km^3 or more of natural environment
- Clear water or ice
- Deep underwater, under ice to suppress the background of other particles
- Located in both the Northern and Southern hemispheres to cover the entire celestial sphere

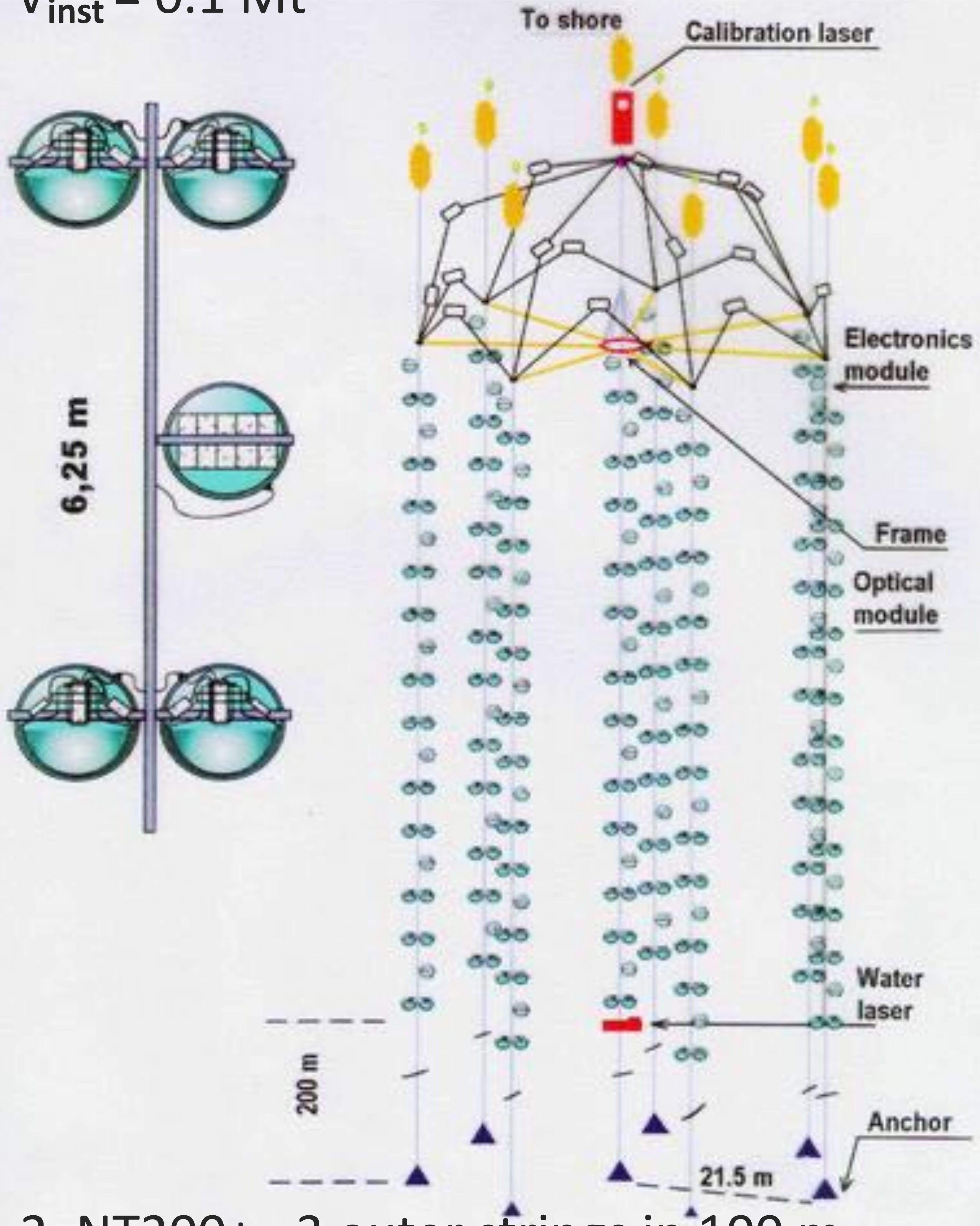
Combined into the global neutrino network (GNN)



Telescope NT200 (commissioned 1998)

Feasibility study

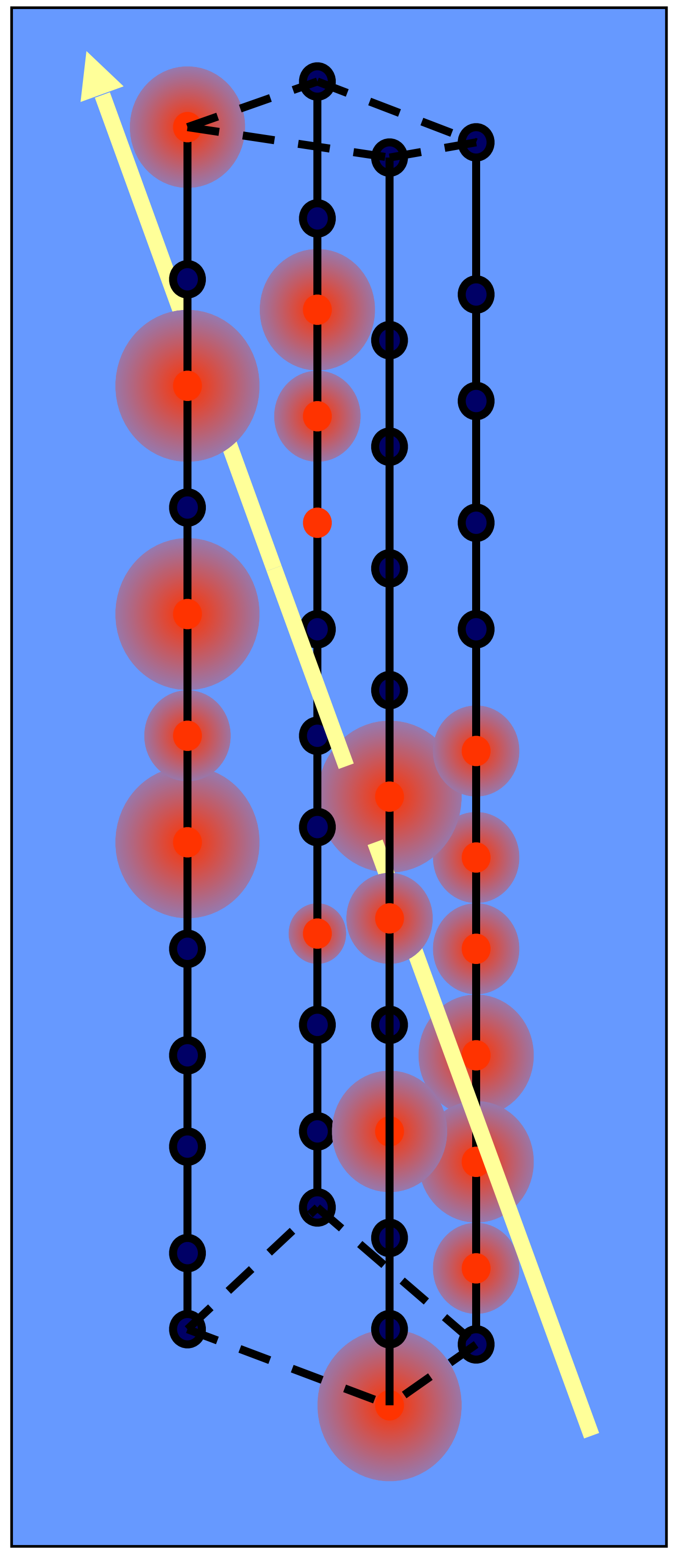
1. Height = 70м, Diameter = 42м
 V_{inst} = 0.1 Mt



2. NT200+ : 3 outer strings in 100 m

Hybrid PMT «Quasar»: 37cm (14.6"), mushroom-shaped, V = 15 kV

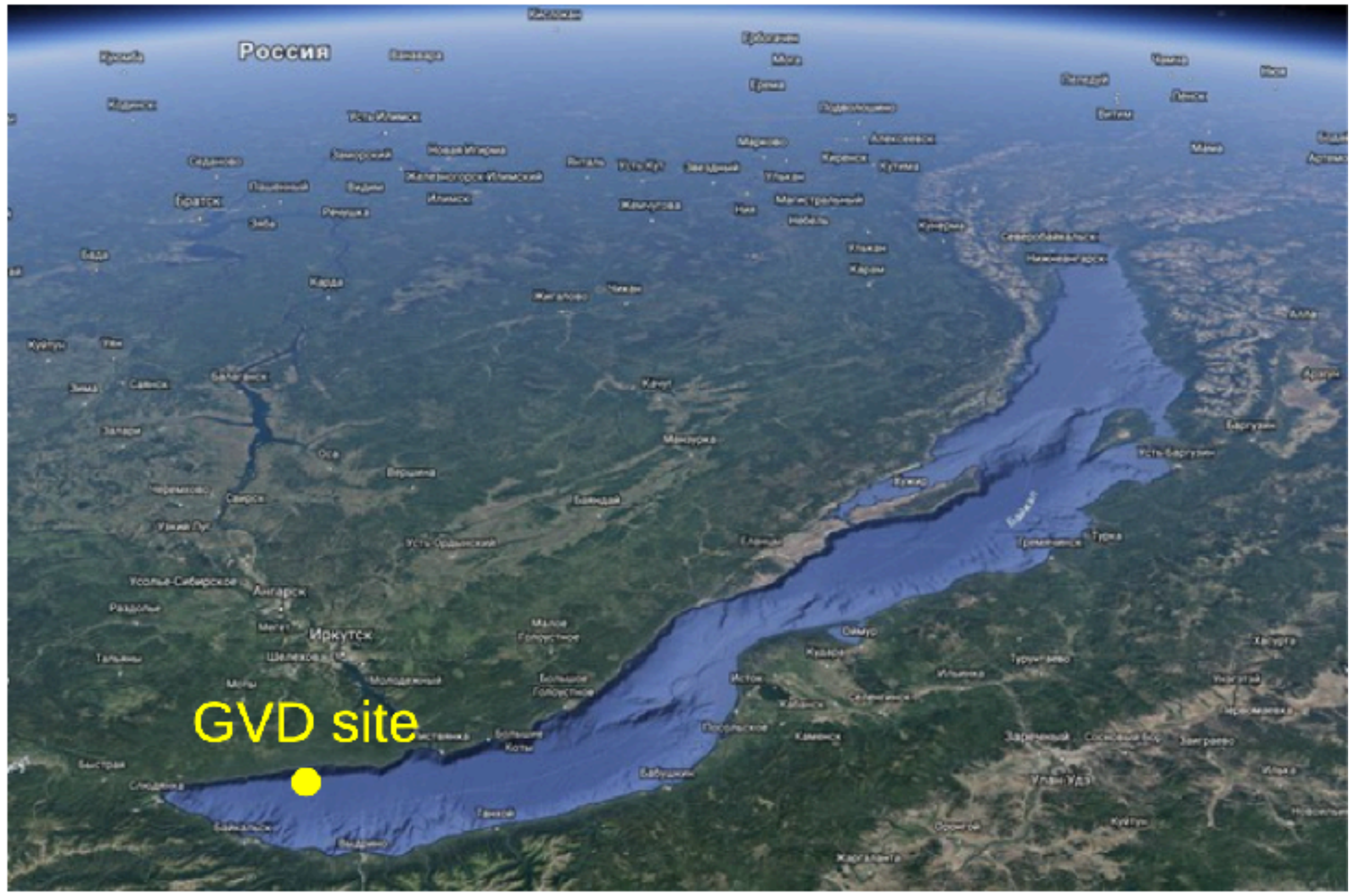
- 8 strings
- 192optical modules
- timing σ_T ~ 1 ns

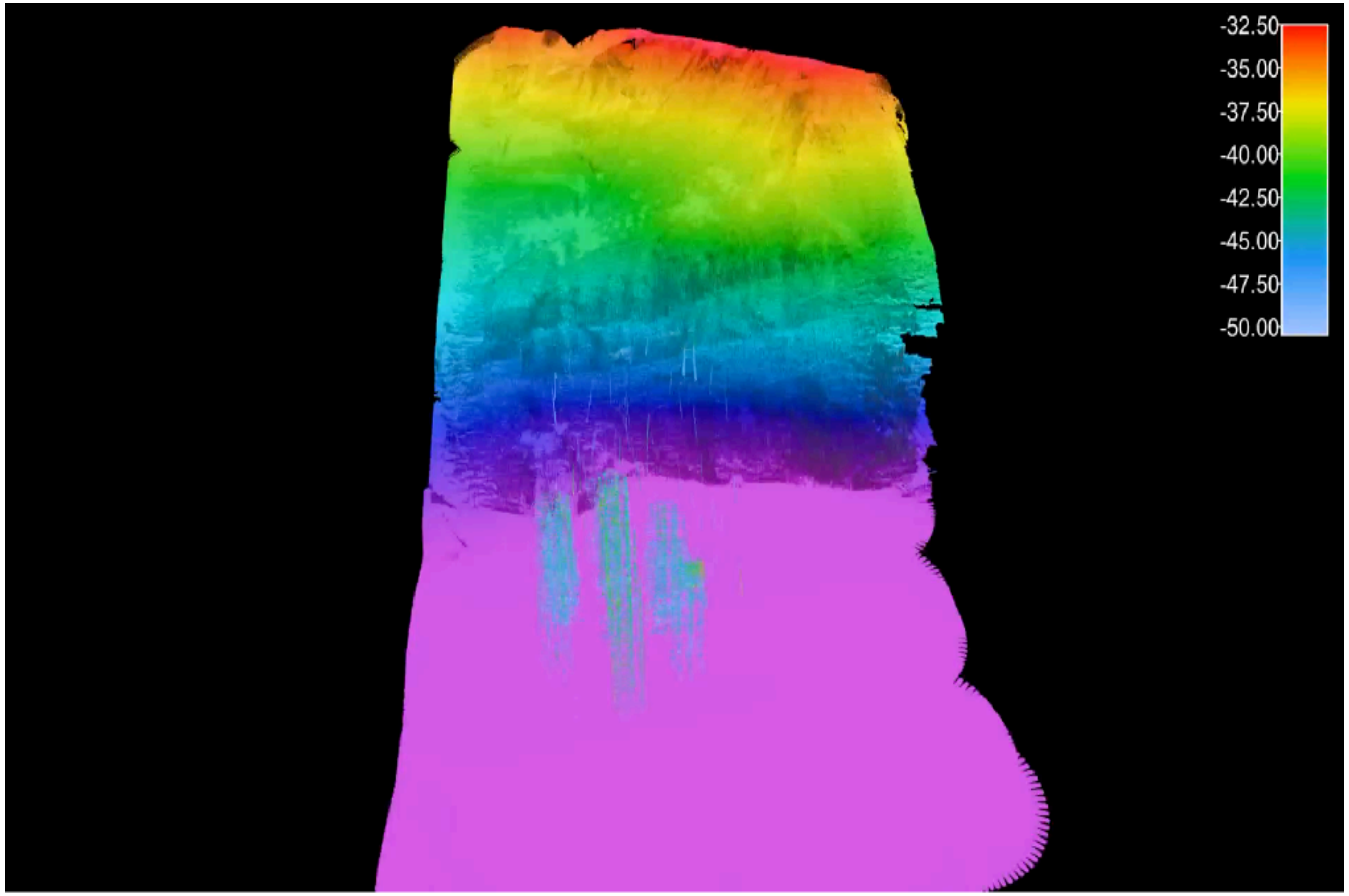


First underwater neutrino registered in the world

Energy threshold: ~ 15 GeV
Effective area: ~ 2000 m² (1 TeV)
Effective volume: ~ 0.2 Mt (10 TeV)
~ 1 Mt (1 PeV)

Baikal-GVD Site

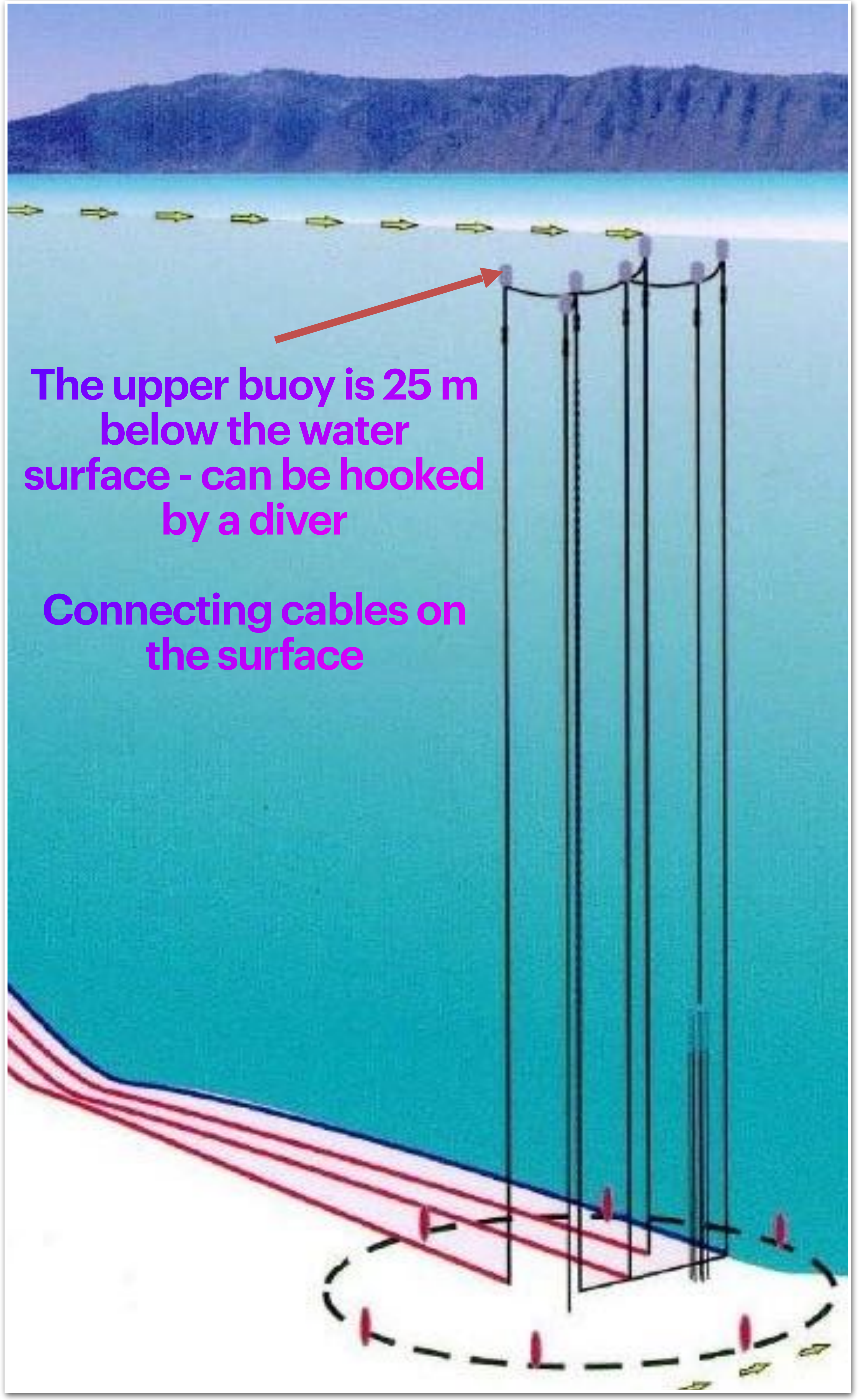


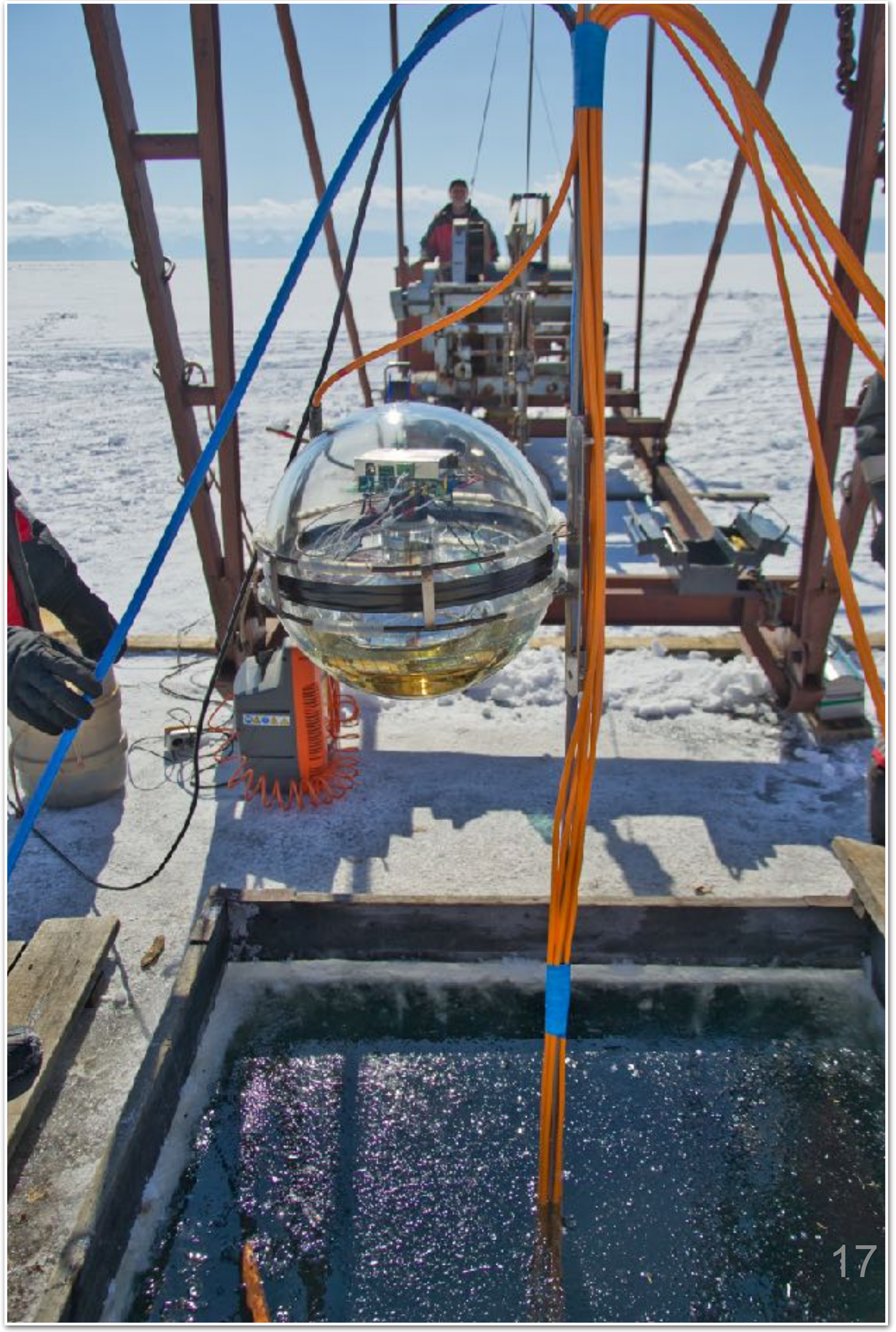


- Southern basin of the lake
- ~3.6 km offshore
- Flat area at depths 1366–1367 m
- High water transparency:
  - Absorption length: 22 m
  - Effective scattering length: 480 m
- Moderately low optical background: 15–50 kHz

Telescope Deployment

From the ice cover of the lake (mid-February - early April)



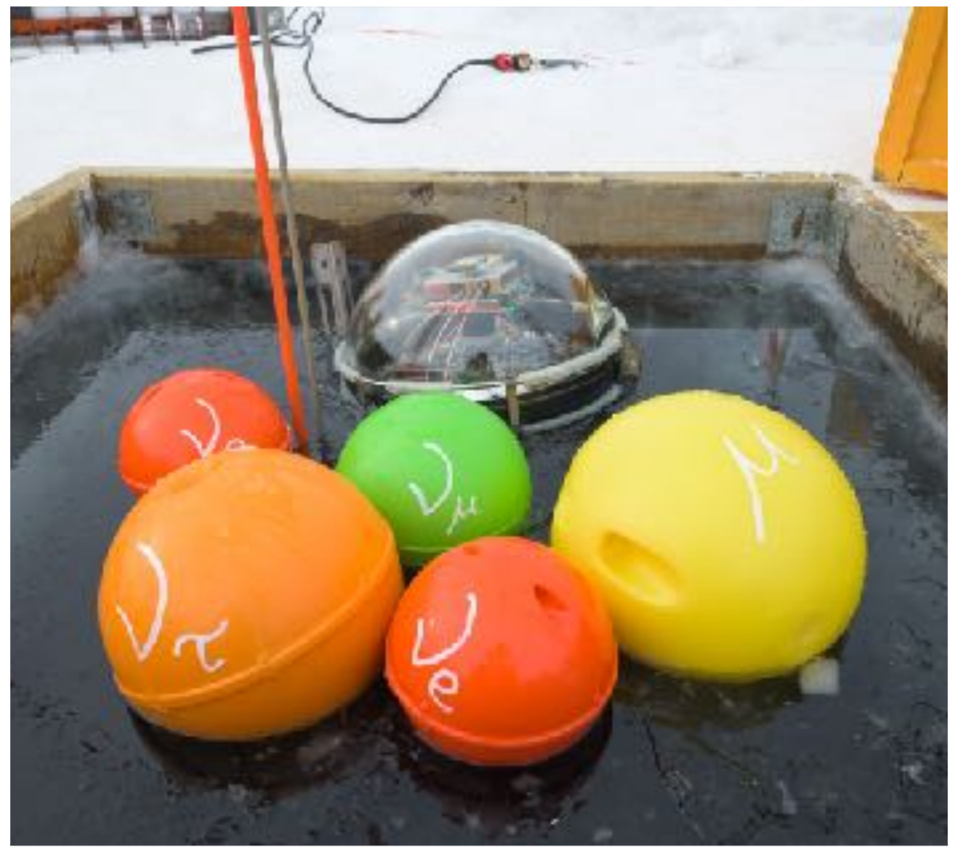


Winter Expedition 2023







Bottom Cable Laying

Optical Module - Basic Element of the Telescope

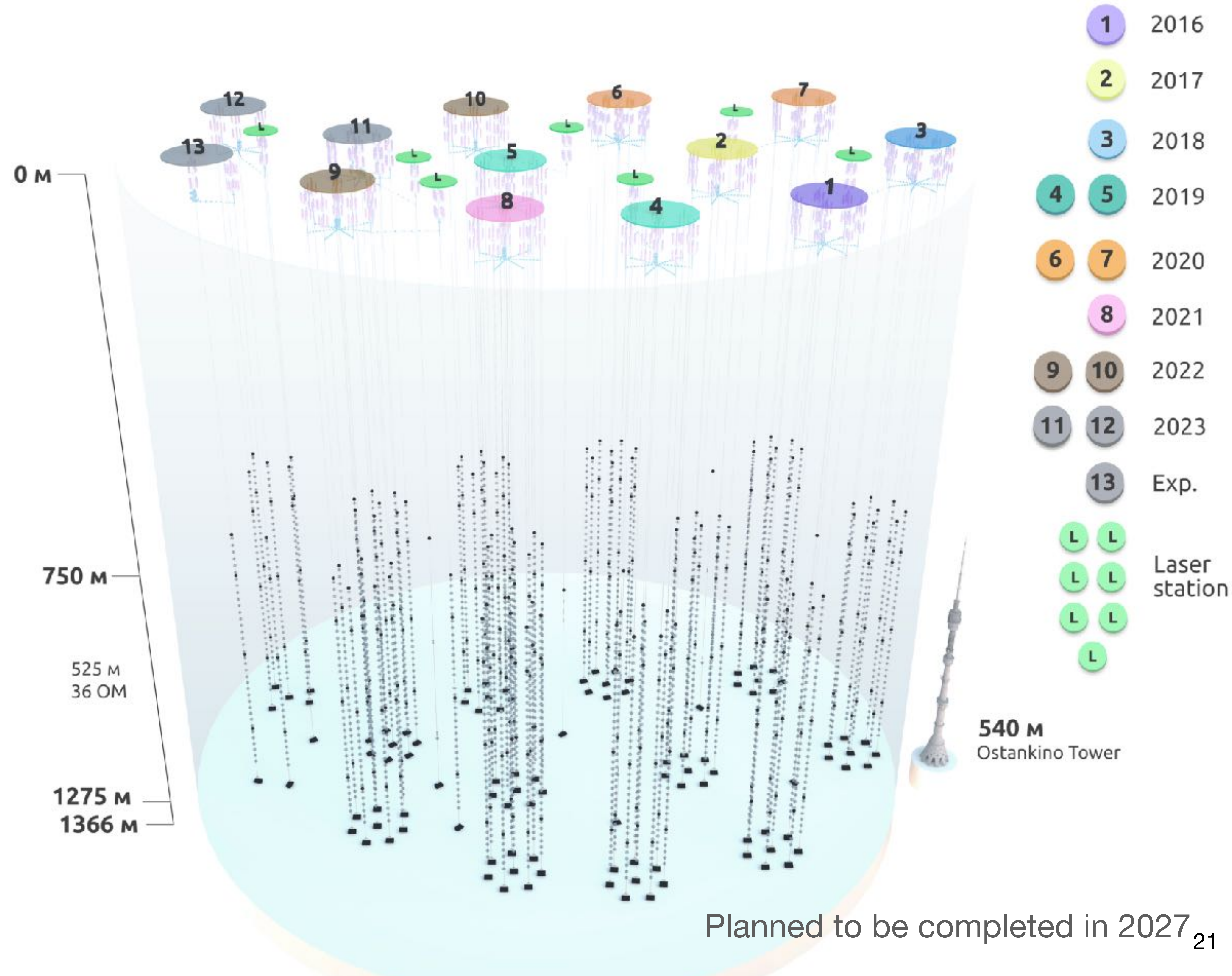
17 inches sphere
(42 cm)

10 inch Hamamatsu PMT
R7081-100

Baikal-GVD Status

April 2023

- 3456 Optical modules on 96 strings (12 clusters)
- 8 strings form a cluster - independent array of optical modules
- 36 optical modules per string
- 60 m between strings in a cluster, 250-300 m between clusters
- More than half of 1 km^3 of water volume
- 384 Acoustic modules for positioning
- 72 LED beacons and 11 powerful laser sources for calibration

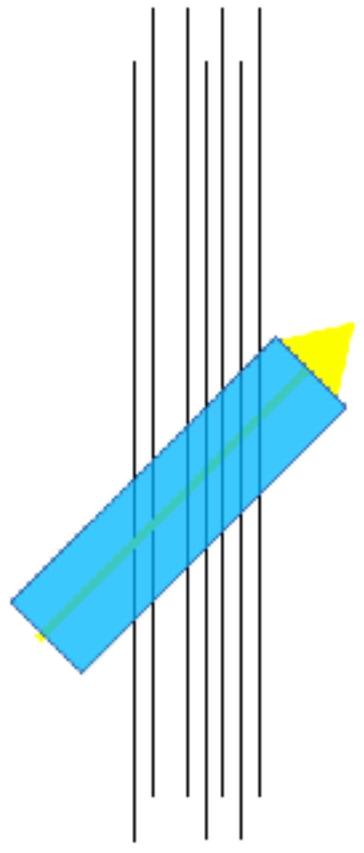


Planned to be completed in 2027

Event Types

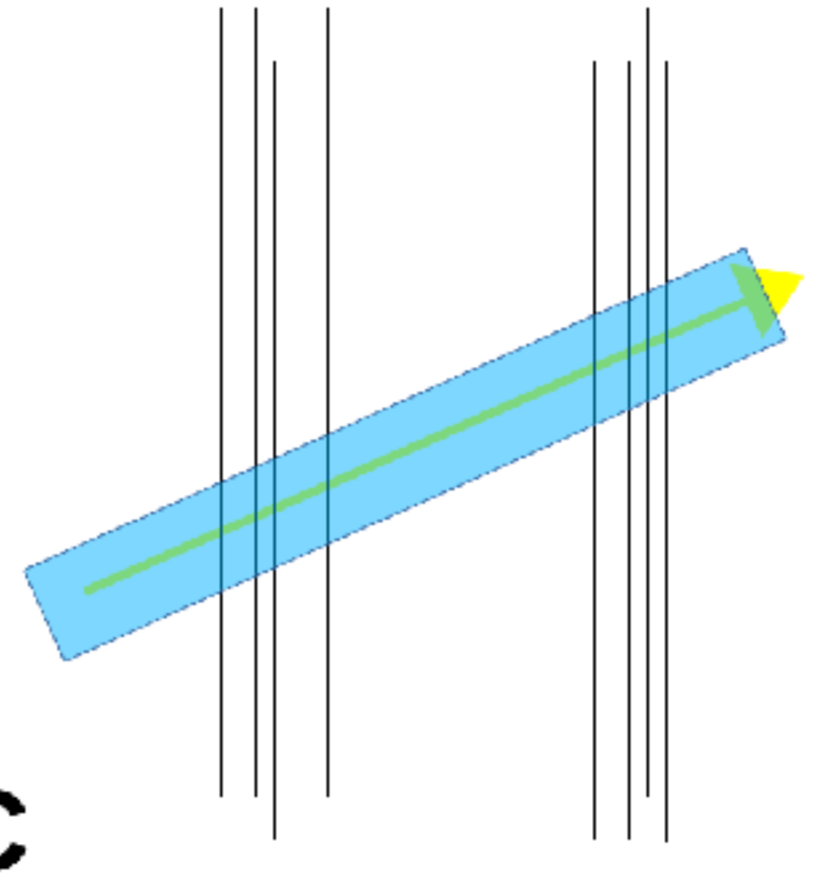
ν_μ CC

Single-cluster tracks



- Low energy threshold
- Optimal sensitivity to nearly vertical tracks
- 90% of recorded track events

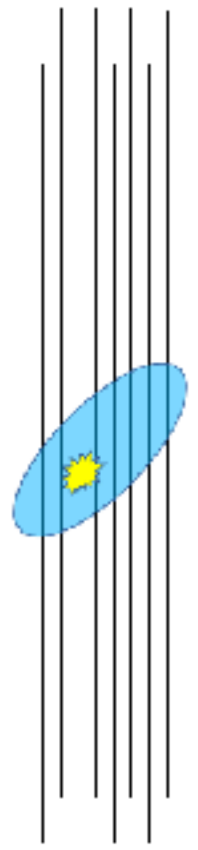
Multi-cluster tracks



- Moderately low energy threshold
- Optimal sensitivity to inclined tracks
- Best angular resolution

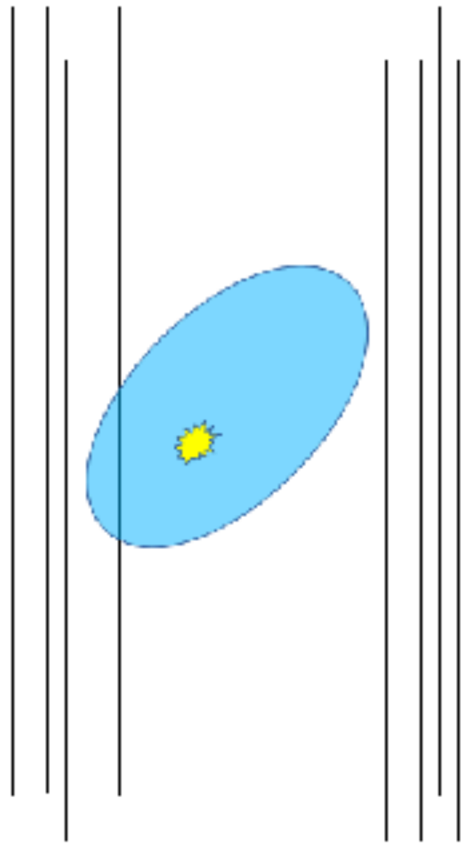
NC, ν_e ν_τ CC

Single-cluster cascades



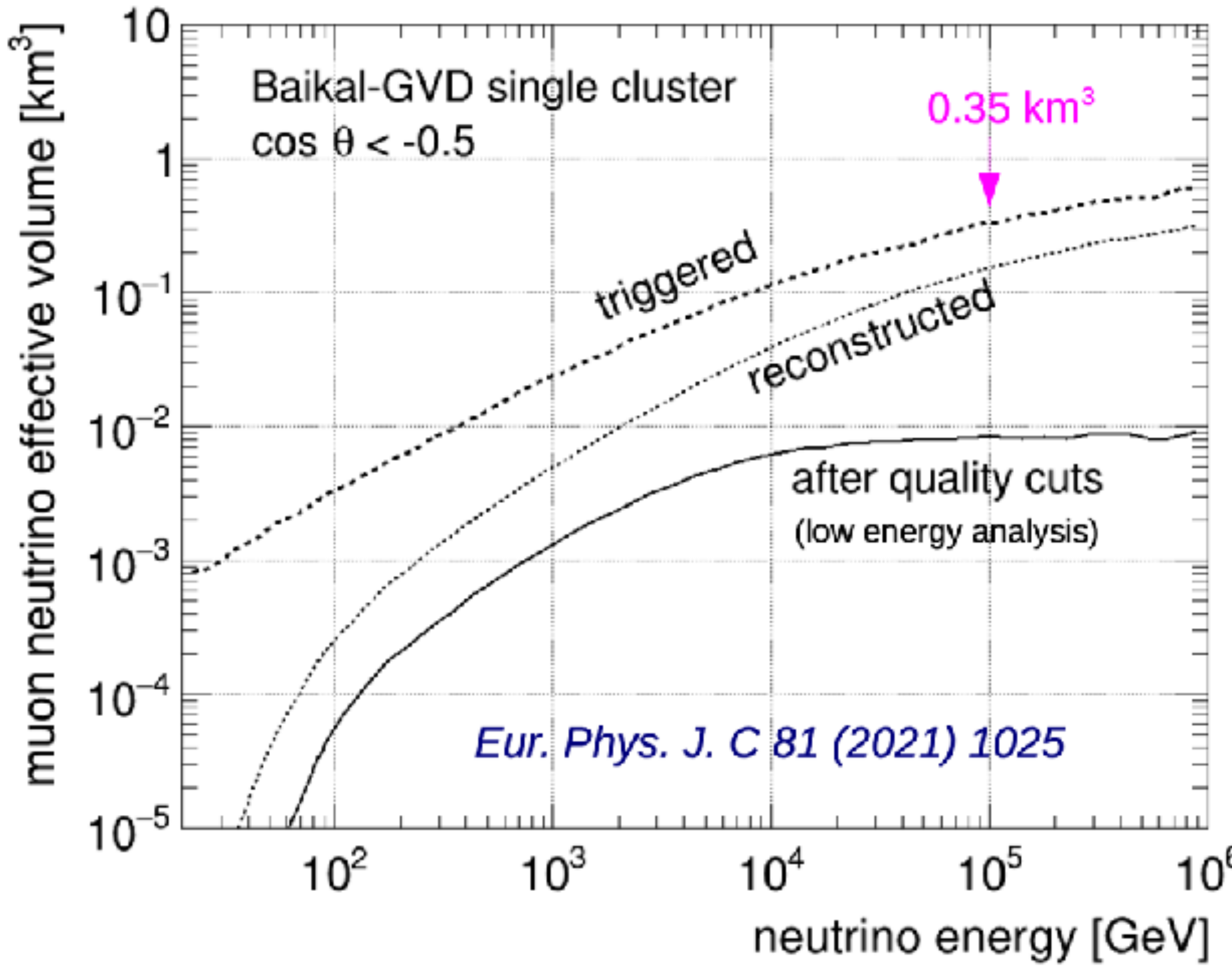
- High energy threshold
- Good energy resolution
- Relatively rare events

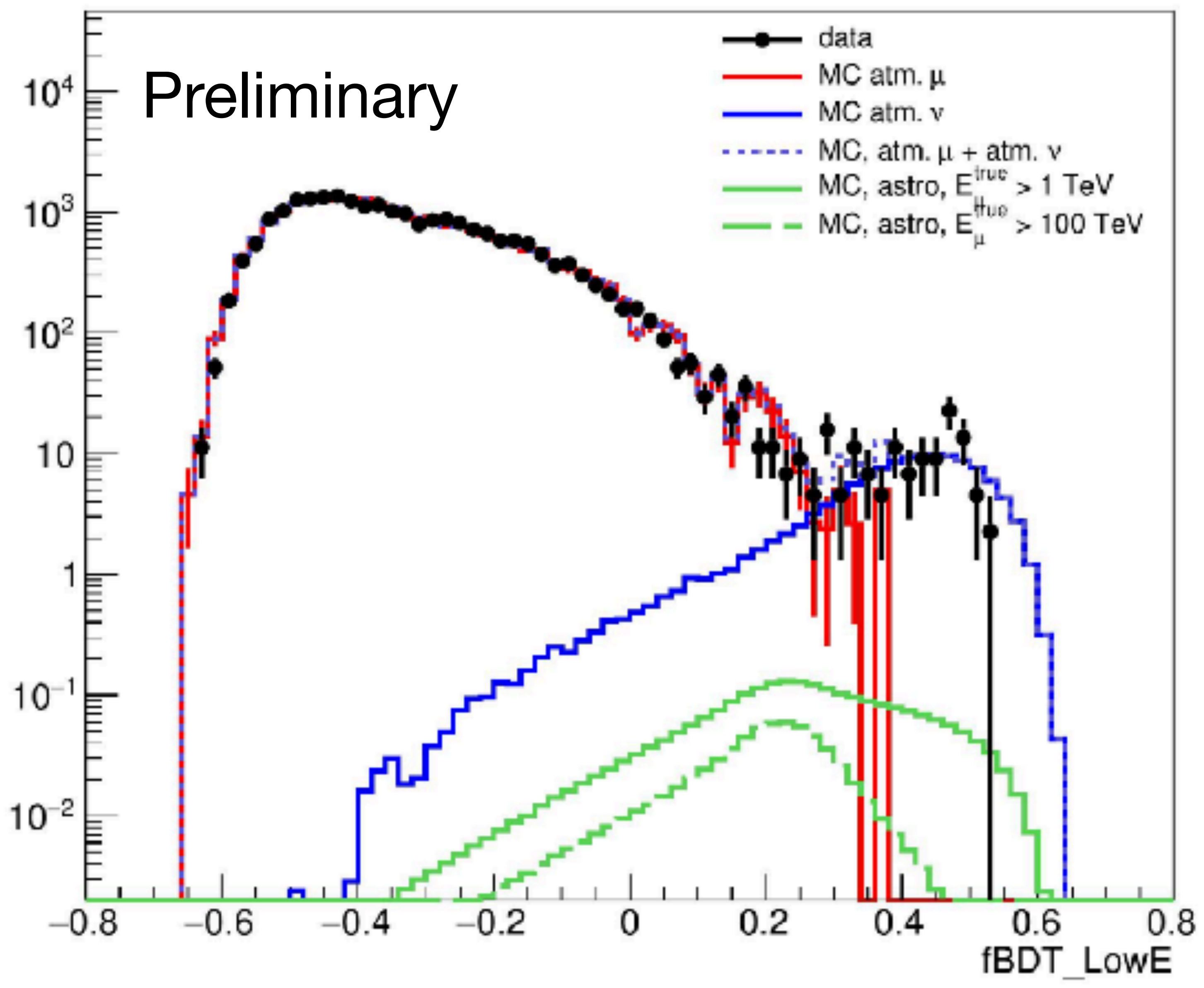
Multi-cluster cascades



- Very high energy threshold
- Excellent energy resolution
- Very rare events

Single-Cluster Muon-Track Analysis





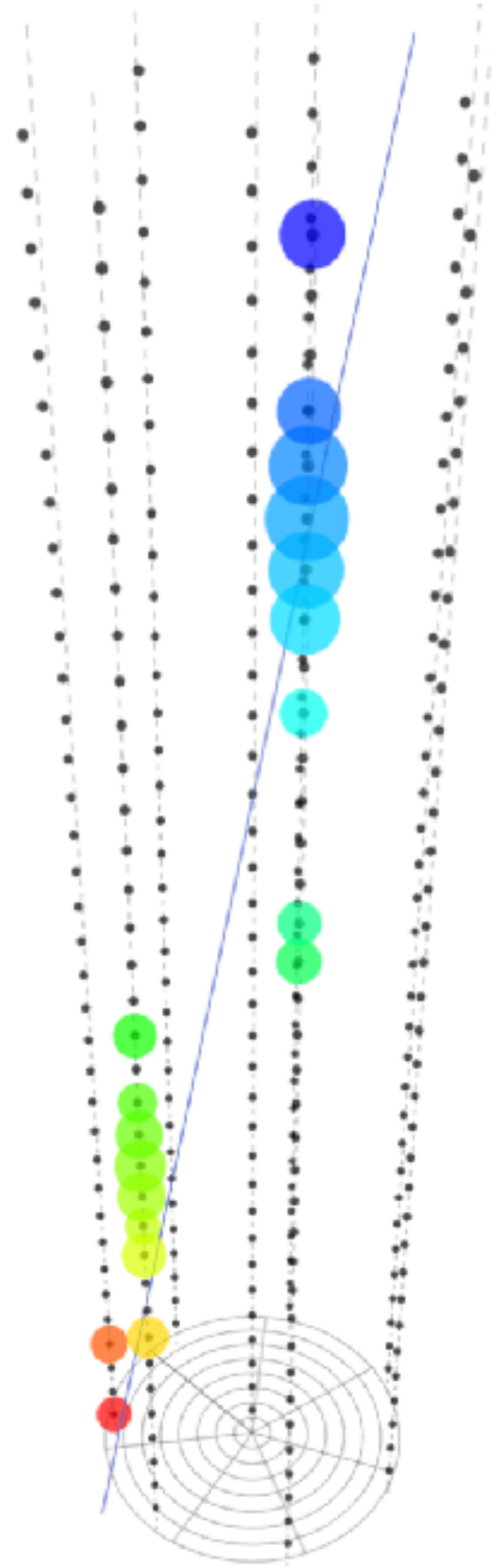
- Direction resolution: 0.3-1.0 degrees
- Energy resolution: factor of 3 or 2
- Work in progress towards higher sensitivity and resolution

Events per year per cluster

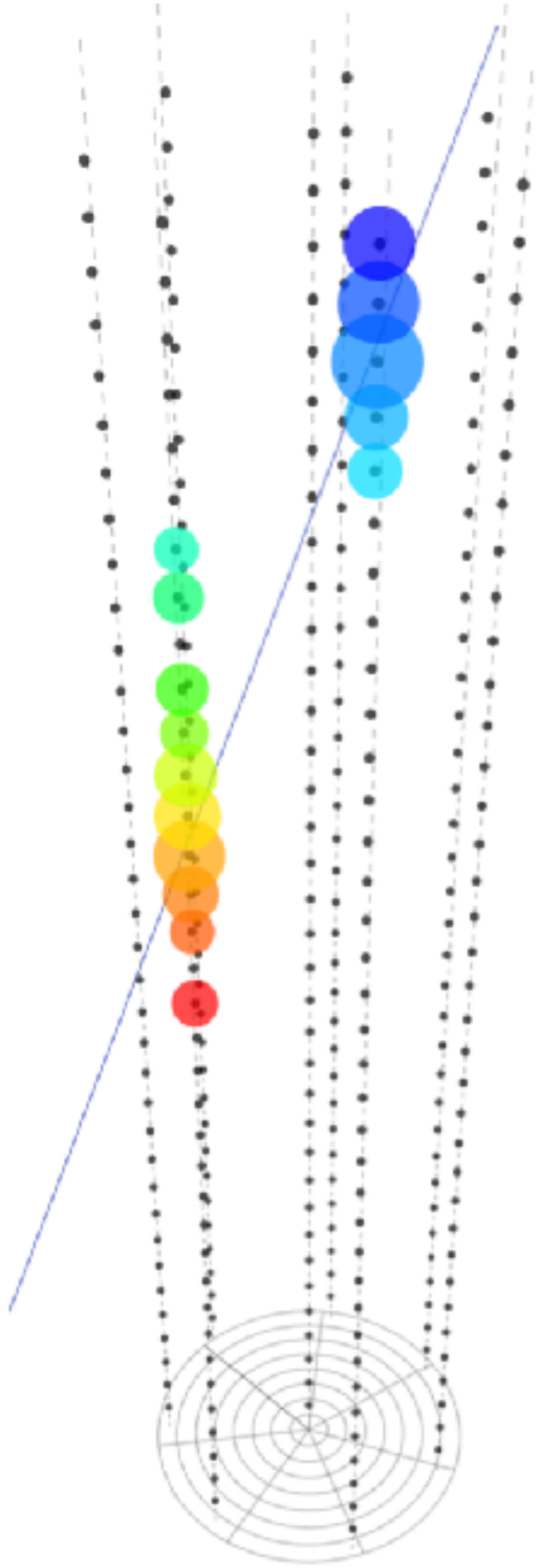
atm. nu	102.2
atm. mu	12.5
SUM:	**114.7**
data	**106.0**

Preliminary

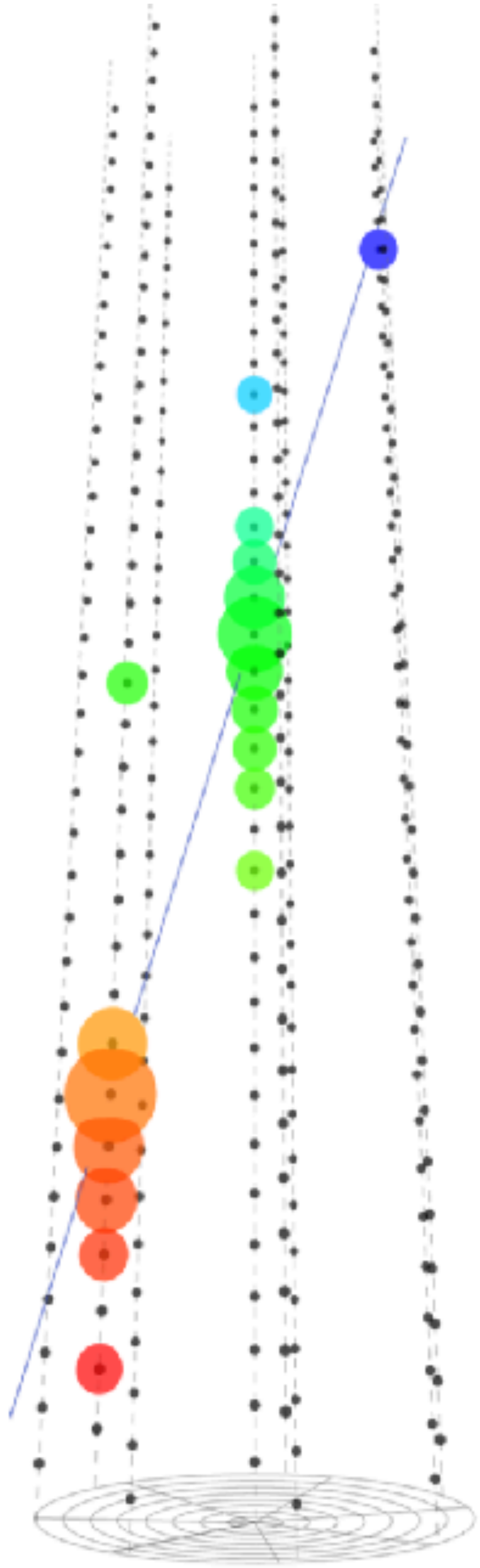
Muon Track Events



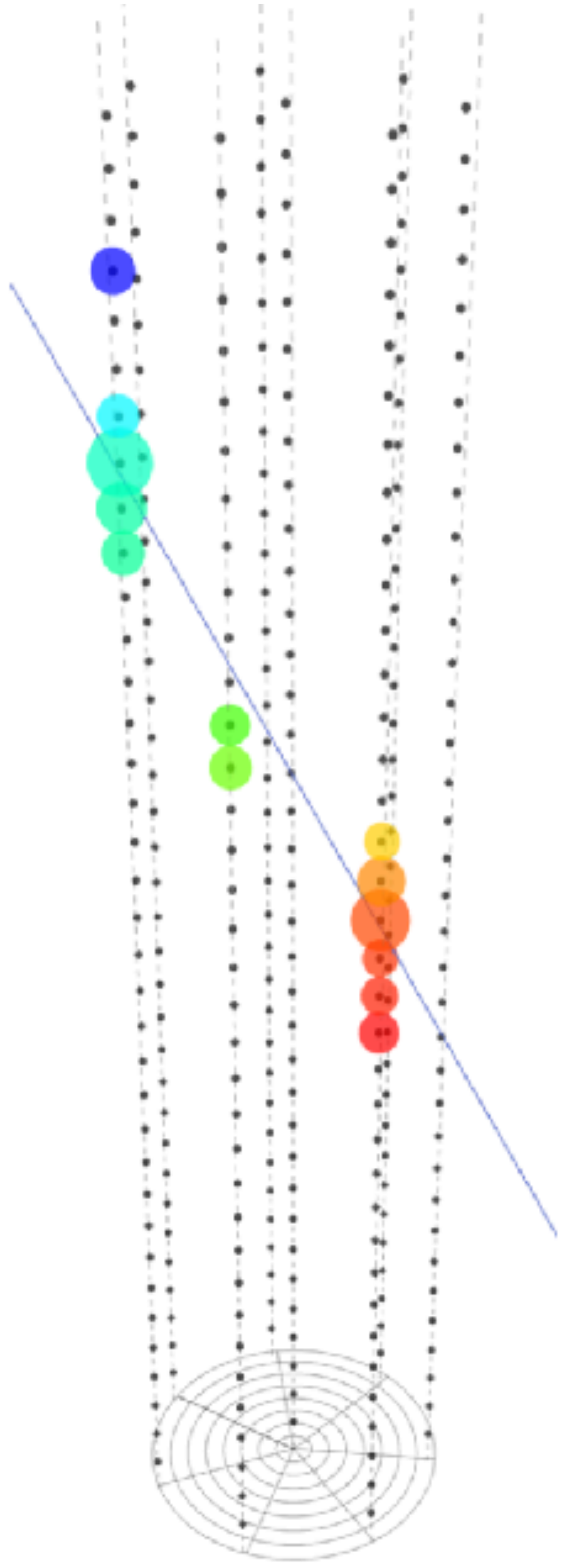
cluster 3, run 122
evt. 1549343
θ_{zenith} = 169.78°
$N_{strings}$ = 3
N_{hits} = 19



cluster 1, run 157
evt. 1414137
θ_{zenith} = 161.78°
$N_{strings}$ = 2
N_{hits} = 15

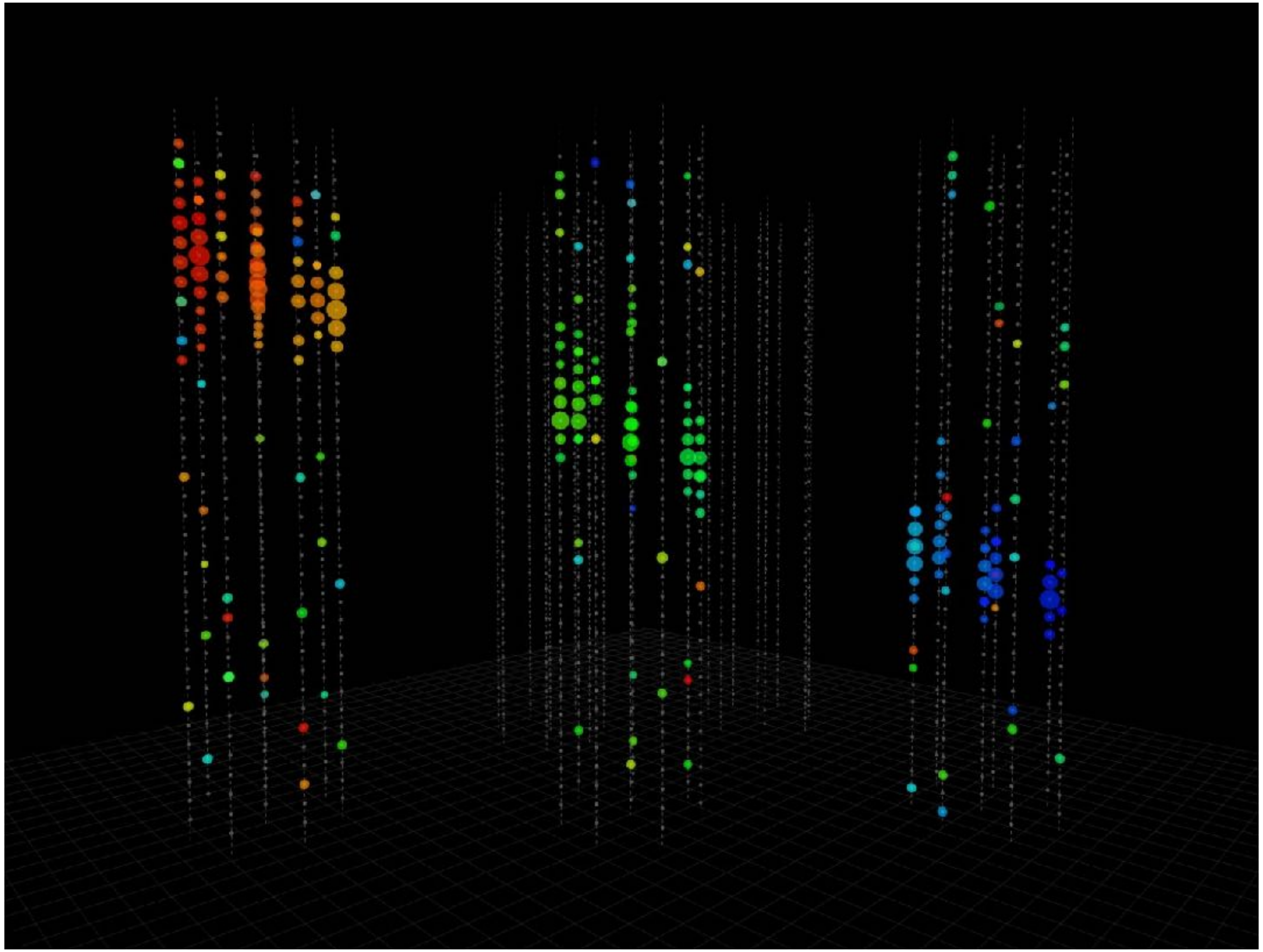


cluster 4, run 99
evt. 438088
θ_{zenith} = 162.22°
$N_{strings}$ = 3
N_{hits} = 18

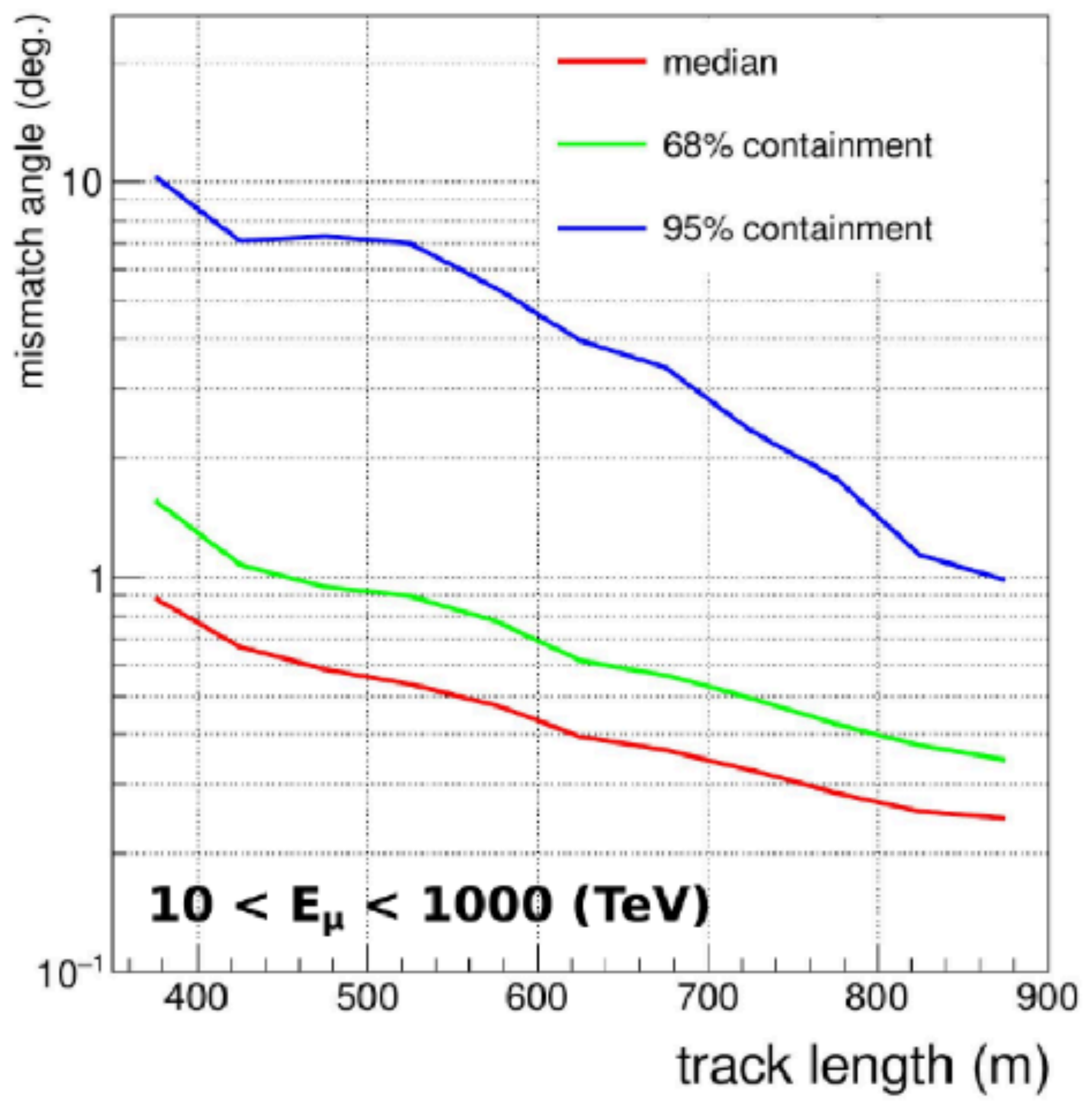


cluster 5, run 162
evt. 1939721
θ_{zenith} = 148.07°
$N_{strings}$ = 3
N_{hits} = 13

Multi-Cluster Track Event

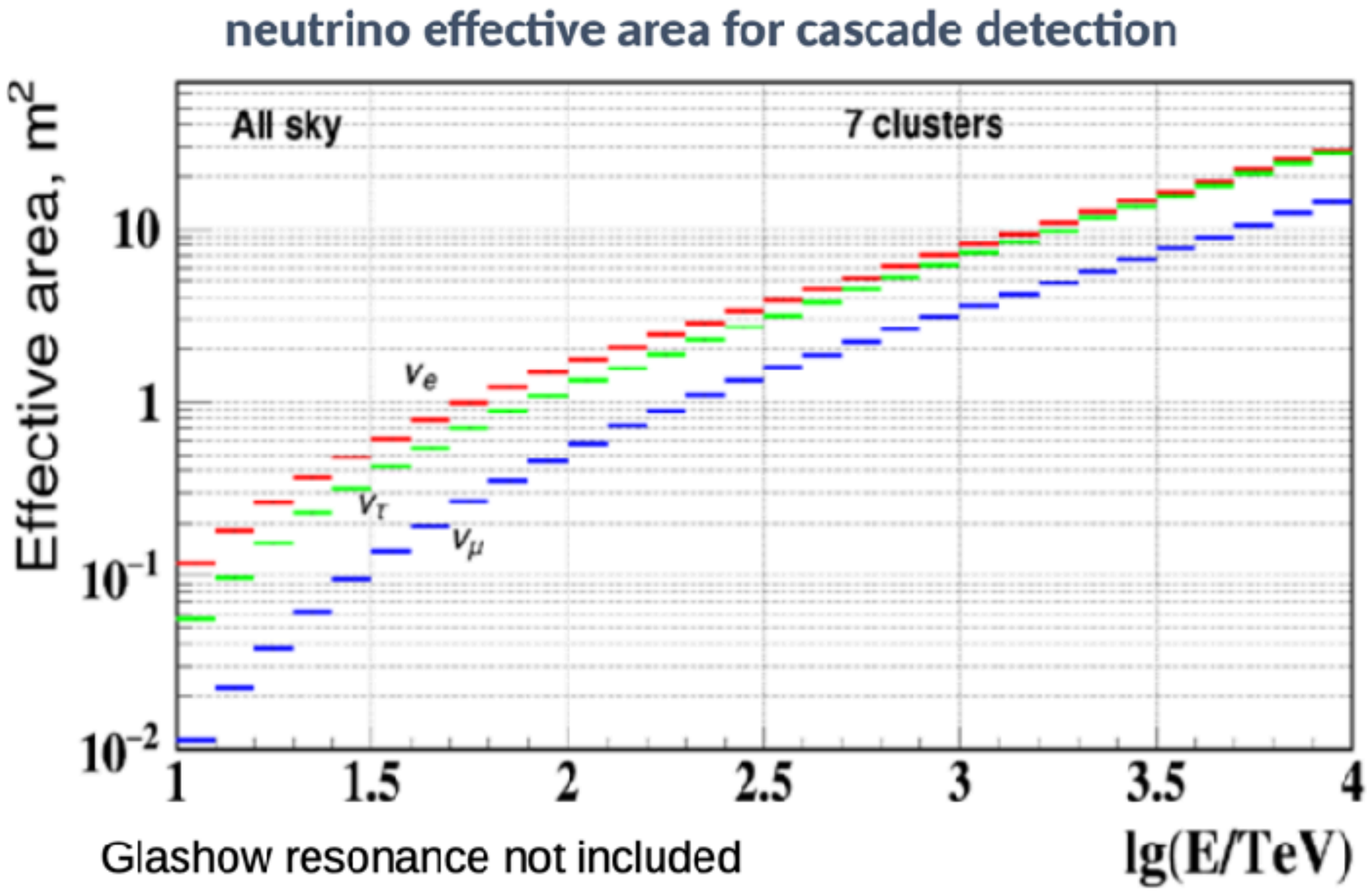


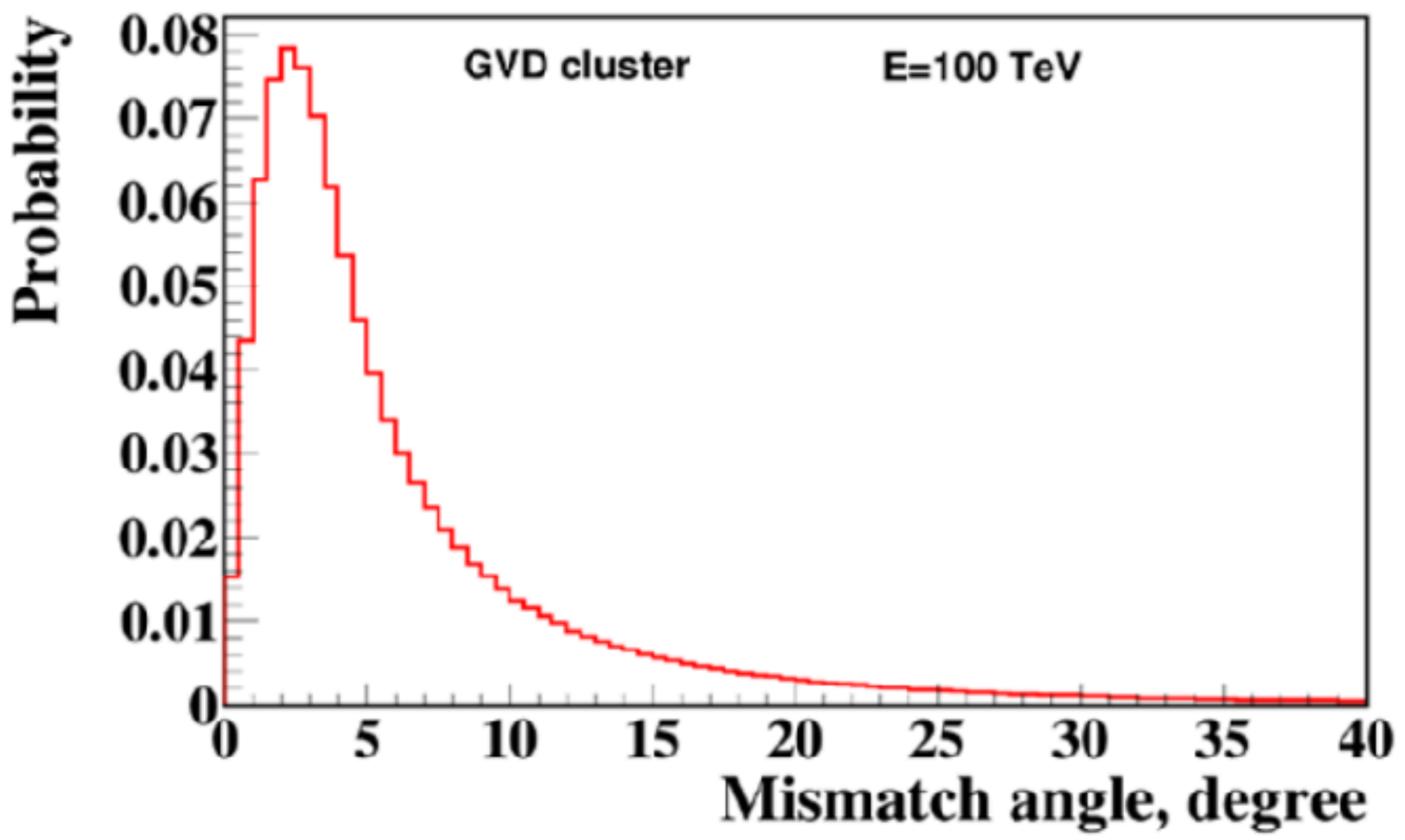
Real Multi-cluster event example



Median energy ~ 4 TeV
Work in progress

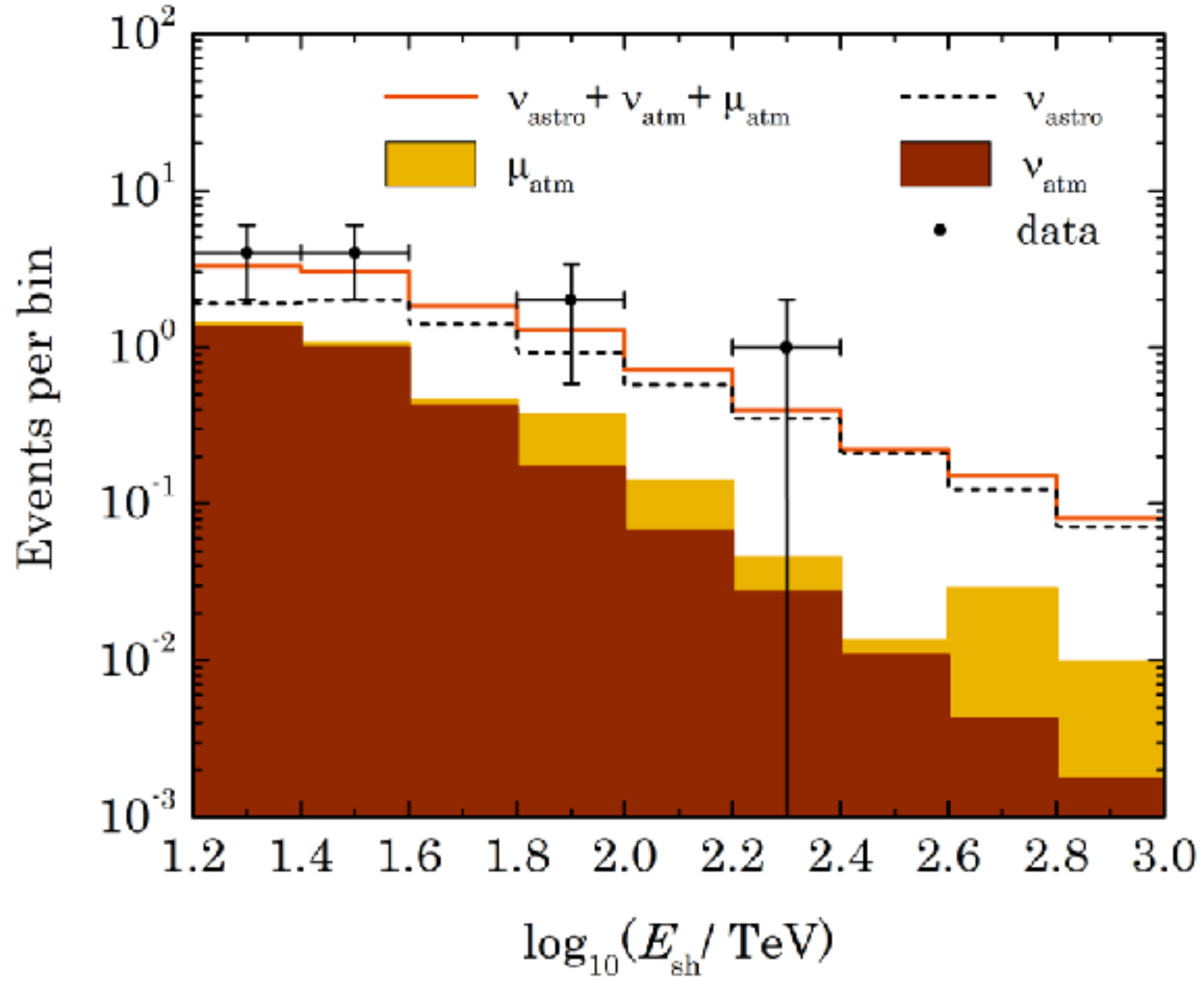
Cascade Event Analysis

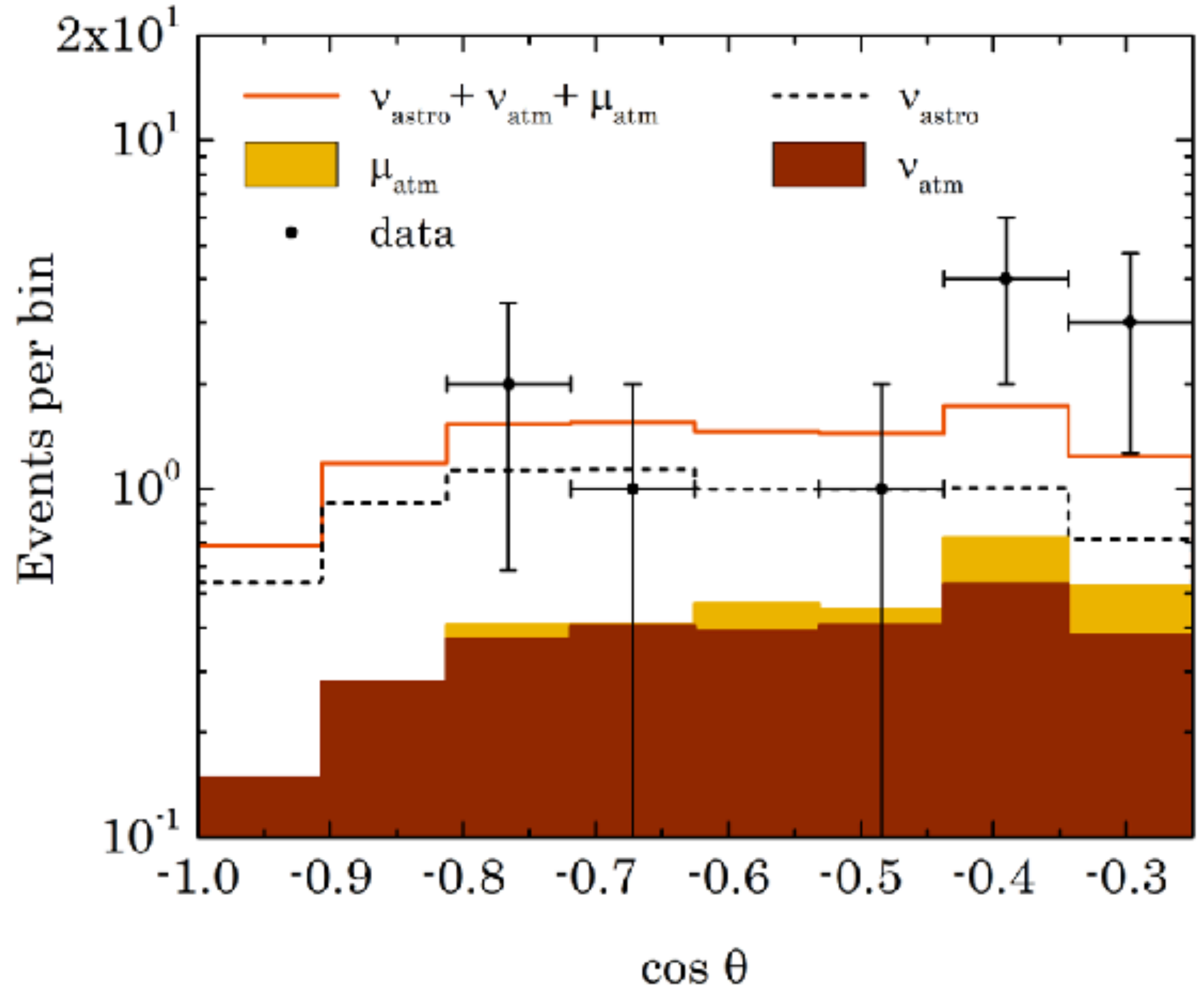




- Sensitive to all-flavour CC and NC interactions over the whole sky
- Effective volume for E > 100 TeV >0.5 km^3
- Directional resolution for cascades: ~ 2.0-4.5°
- Energy resolution: ~ 30%

Astrophysical Diffuse Neutrino Flux with Baikal-GVD





- Data analysed April 2018 - March 2022
- Cascade energy >15 TeV
- Upward going cascades

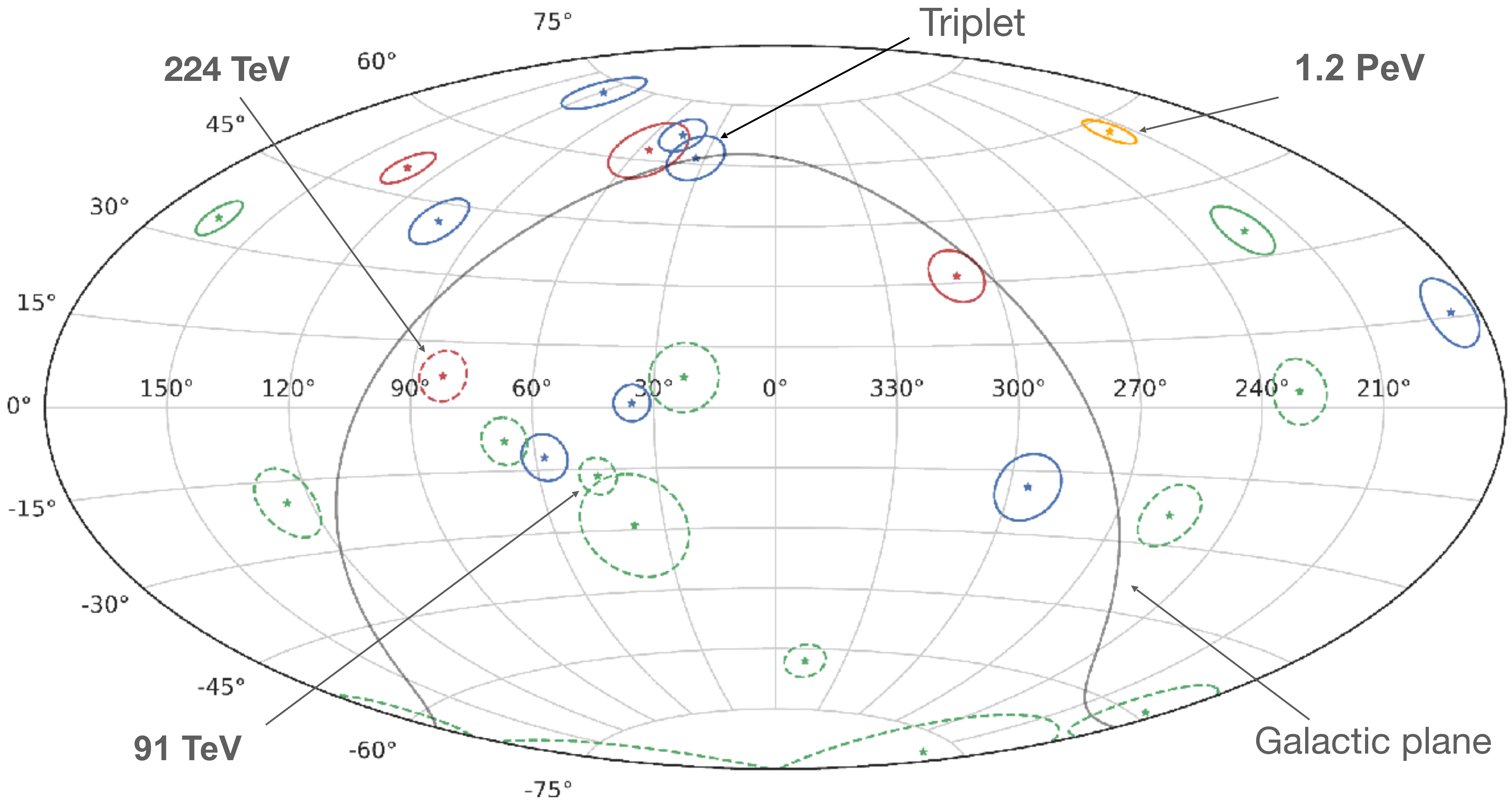
	Events
Atm. muons MC	0.5
Atm. neutrino MC	2.7
Astro neutrino MC best fit	6.3
Data	11

Excess over the atmospheric background: 3.05σ

Phys. Rev. D **107**, 042005, February 2023

High-Energy Cascade Sky Map

Most prominent downgoing and upgoing cascade events



Best fit positions and 90% angular uncertainty regions in equatorial coordinates

- dashed - upgoing events
- solid - downgoing events

Color represents energy:

E_{rec} < 100 TeV
100 TeV < E_{rec} < 200 TeV
200 < E_{reco} < 1000 TeV
E_{rec} > 1 PeV

Single Power-Law Model of Astrophysical Flux

All-sky events:

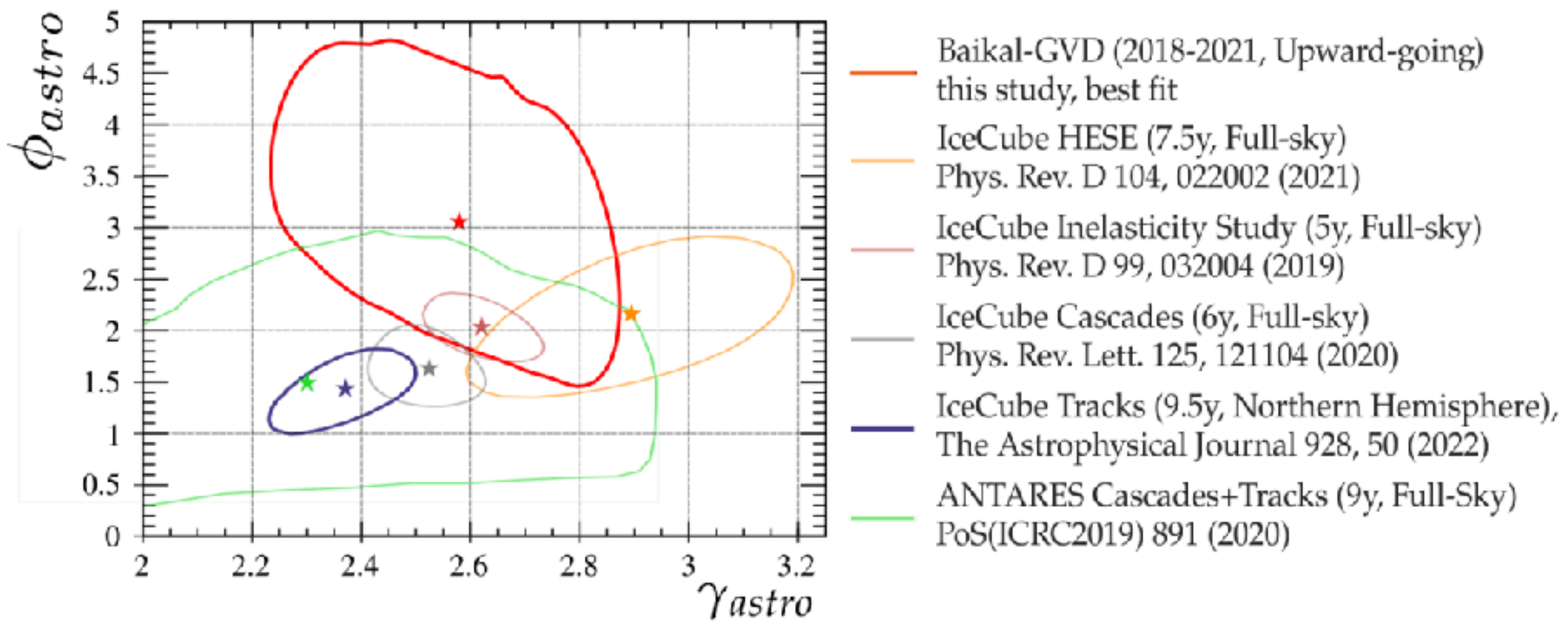
- 16 events: E > 70 TeV
- Expected background (atm. ν and μ) of 8.2 events
- Signal best fit 5.8 events
- Probability for the background-only hypothesis:
  - P-value = 0.026 (2.22 σ)

Under horizon events:

- 11 up-going cascades E > 15 TeV
- Expected background of 3.2 events
- Signal best fit 6.3 events
- Probability for the background-only hypothesis:
  - P-value = 0.0024 (3.05 σ)

The best fit parameters for the single power law model:

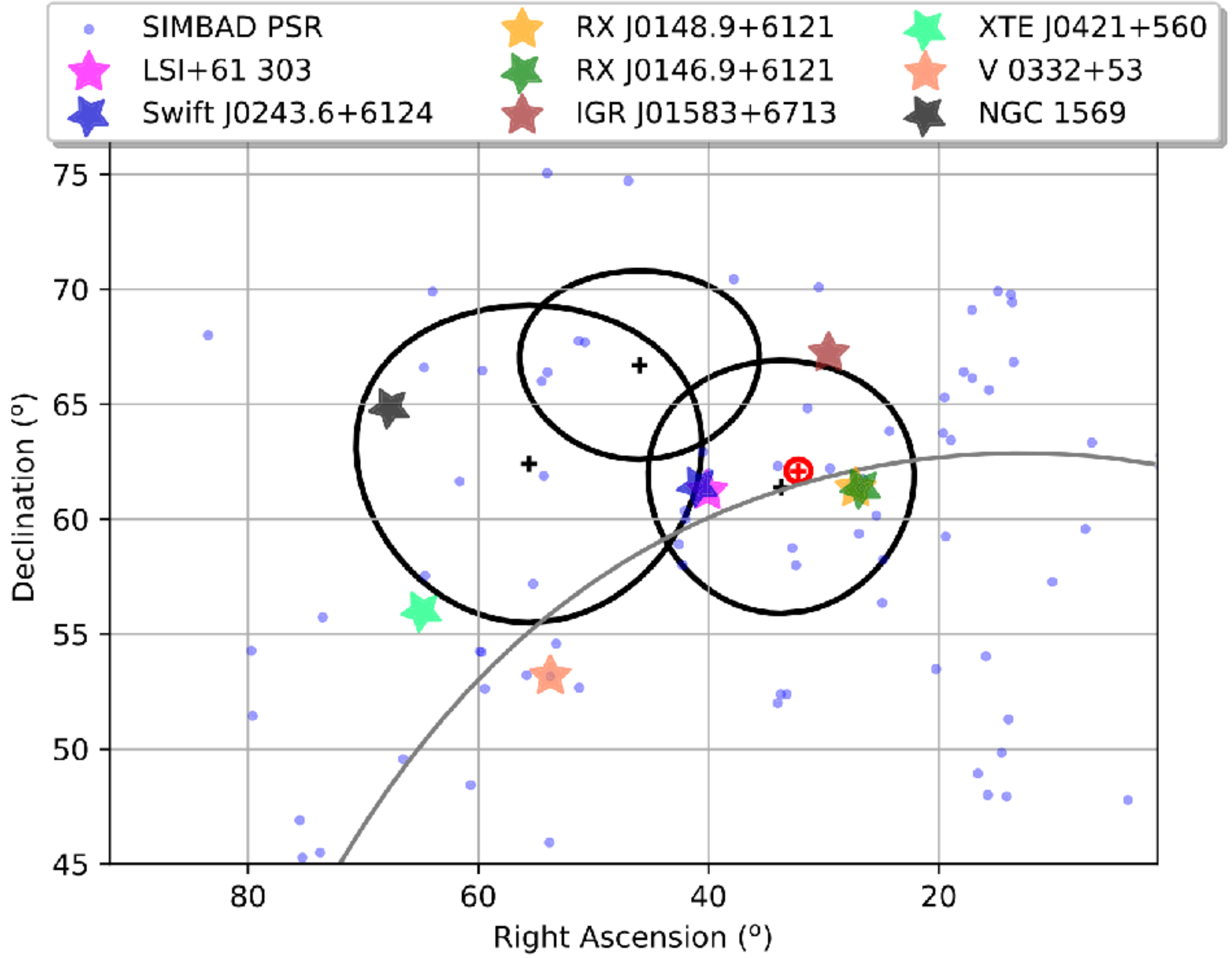
$$\Phi_{astro}^{\nu+\bar{\nu}} = 3 \times 10^{-18} \phi_{astro} \left(\frac{E_\nu}{E_0}\right)^{-\gamma_{astro}}$$



https://doi.org/10.1103/PhysRevD.107.042005

Event Triplet near Galactic Plane

Intriguing events



Chance probability to observe such a triplet was estimated as 0.024 (2.3 σ)

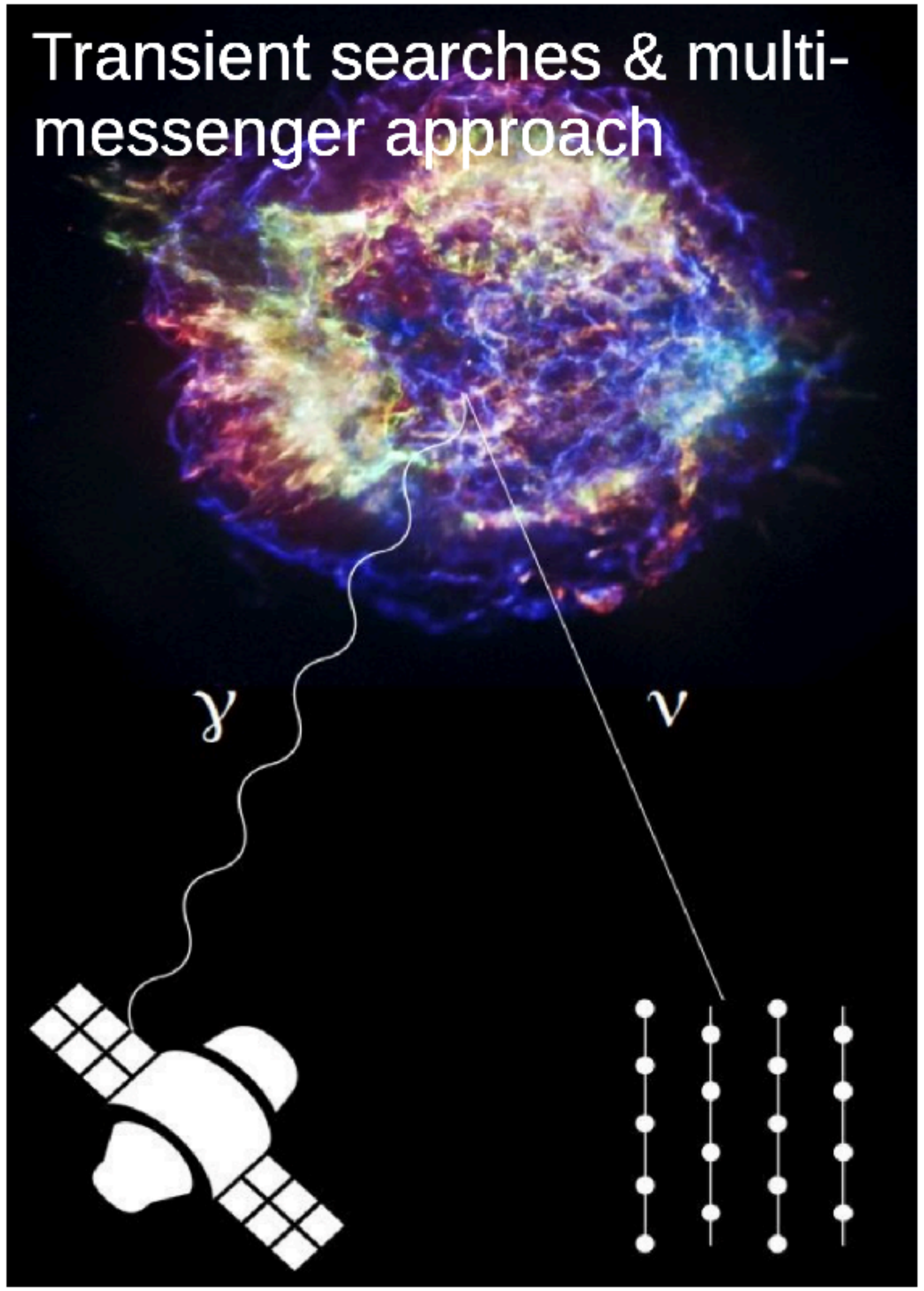
- γ-ray microquasar LS I +61 303 (very well known high energy Galactic source, only 2 kpc away) and the two Baikal-GVD events with 3.1° and 7.4° from the source (both are downgoing events)
- Highest significance IceCube persistent Northern hot spot (red plus and circle)

Monthly Notices of the Royal Astronomical Society, Volume 526, Issue 1, November 2023, Pages 942–951

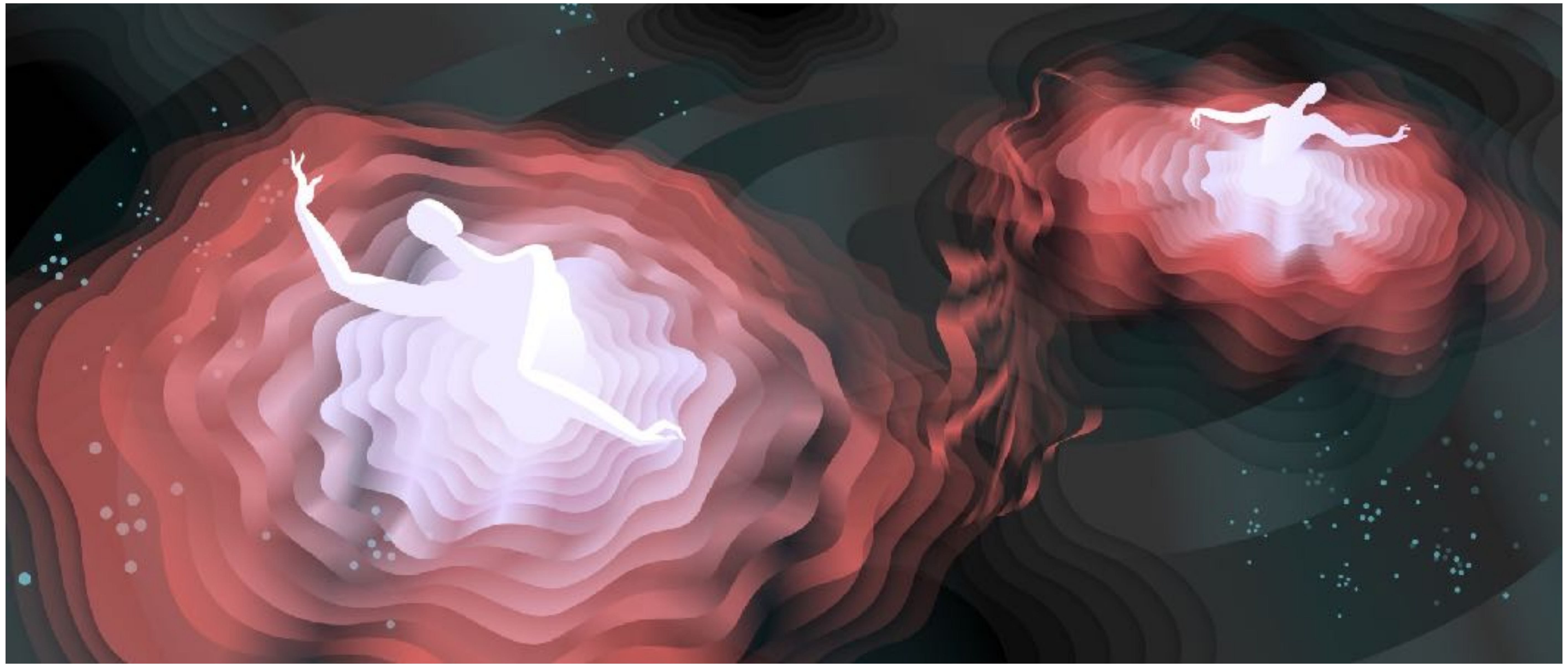
One More Thing…

Multimessenger astrophysics…

First example



See talk by Sergey Troitsky on Friday 03.11



First cosmic event seen in gravitational waves and light

2017 Astrophys. J. Lett. 848 L12 doi:10.3847/2041-8213/aa91c9

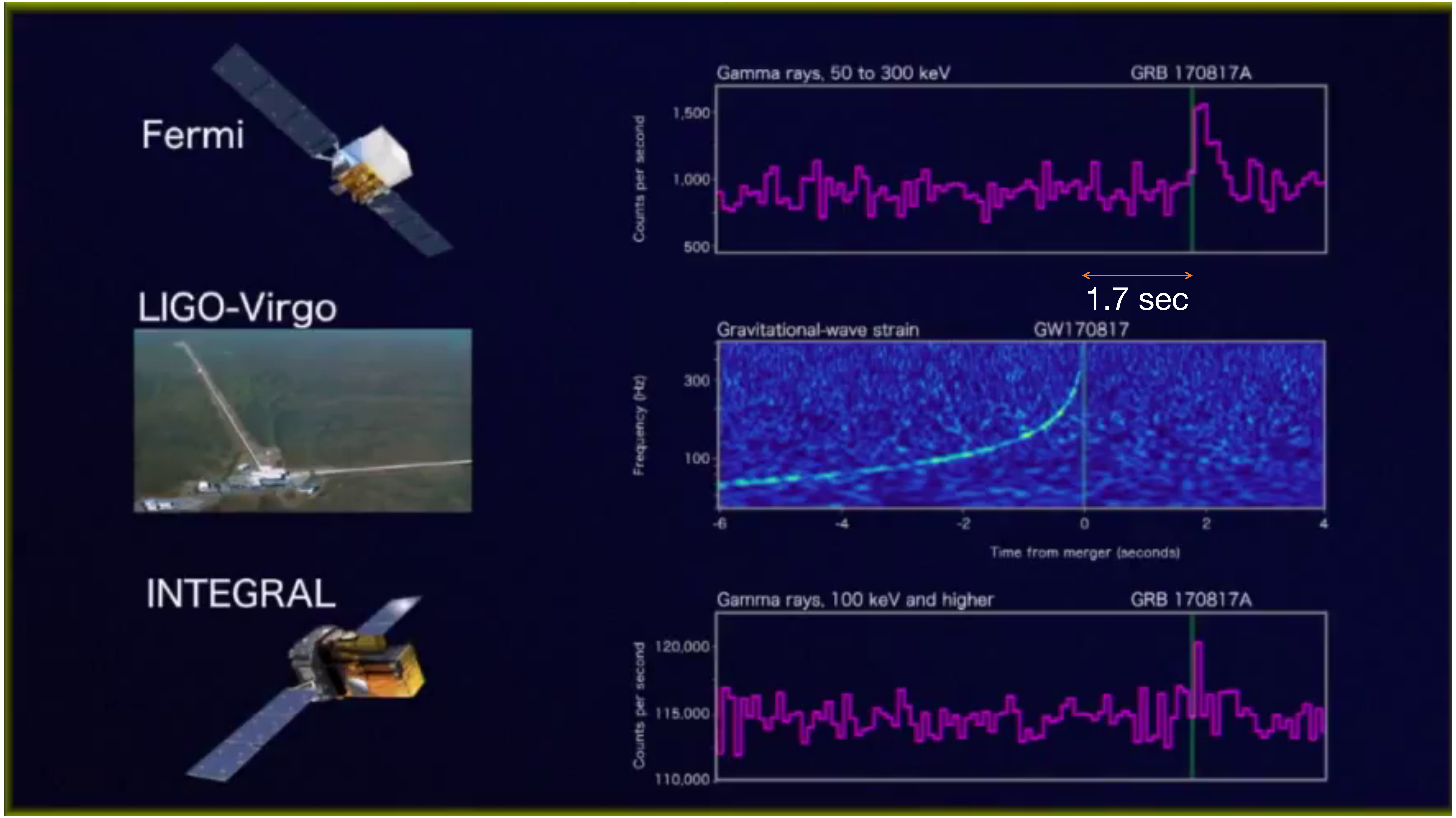
https://www.nature.com/news/colliding-stars-spark-rush-to-solve-cosmic-mysteries-1.22829

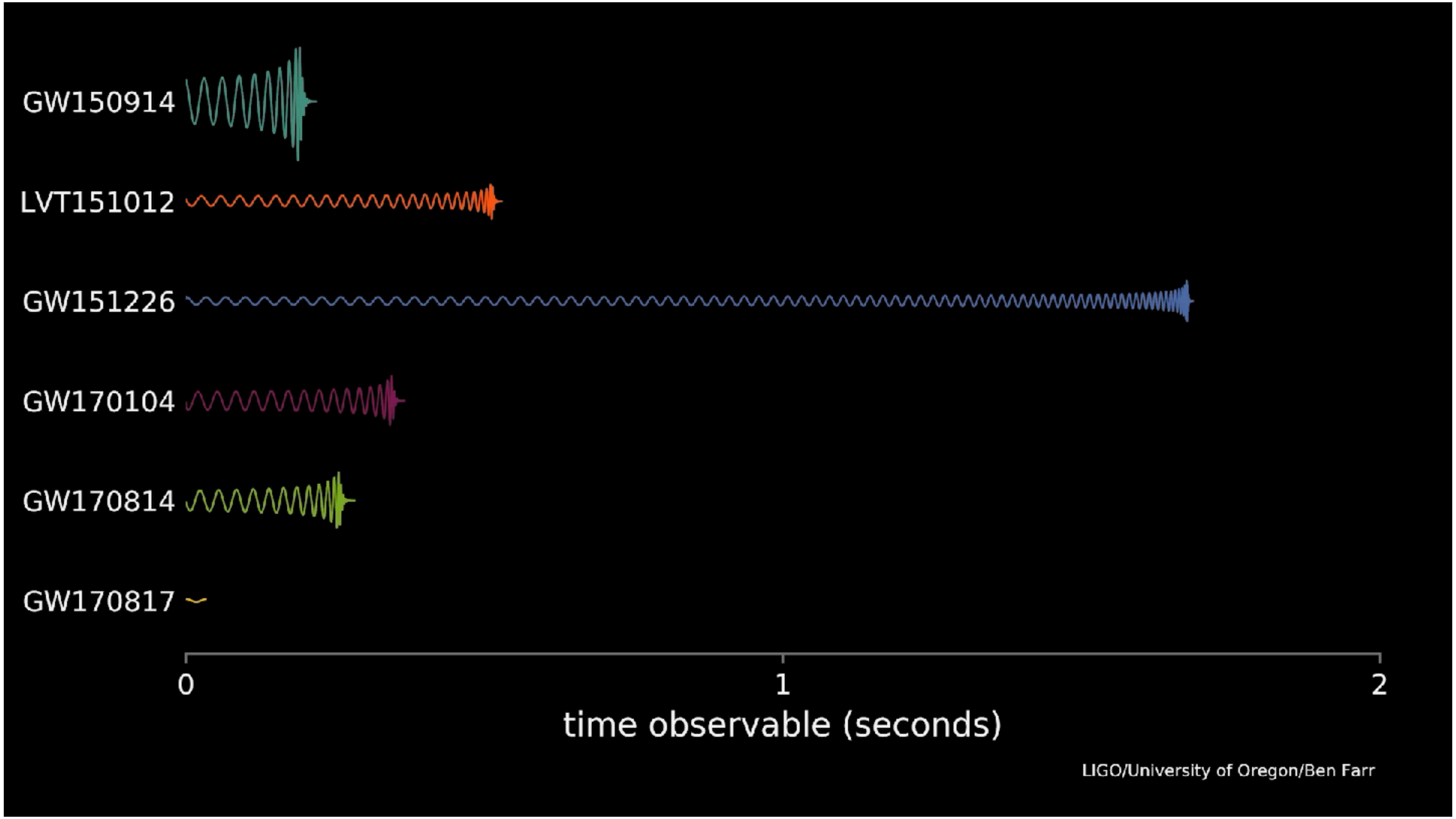
http://press.cosmos.ru/observatorii-ligovirgo-integral-i-fermi-vpervye-zaregistrirovali-moment-sliyaniya-dvuh-neytronnyh

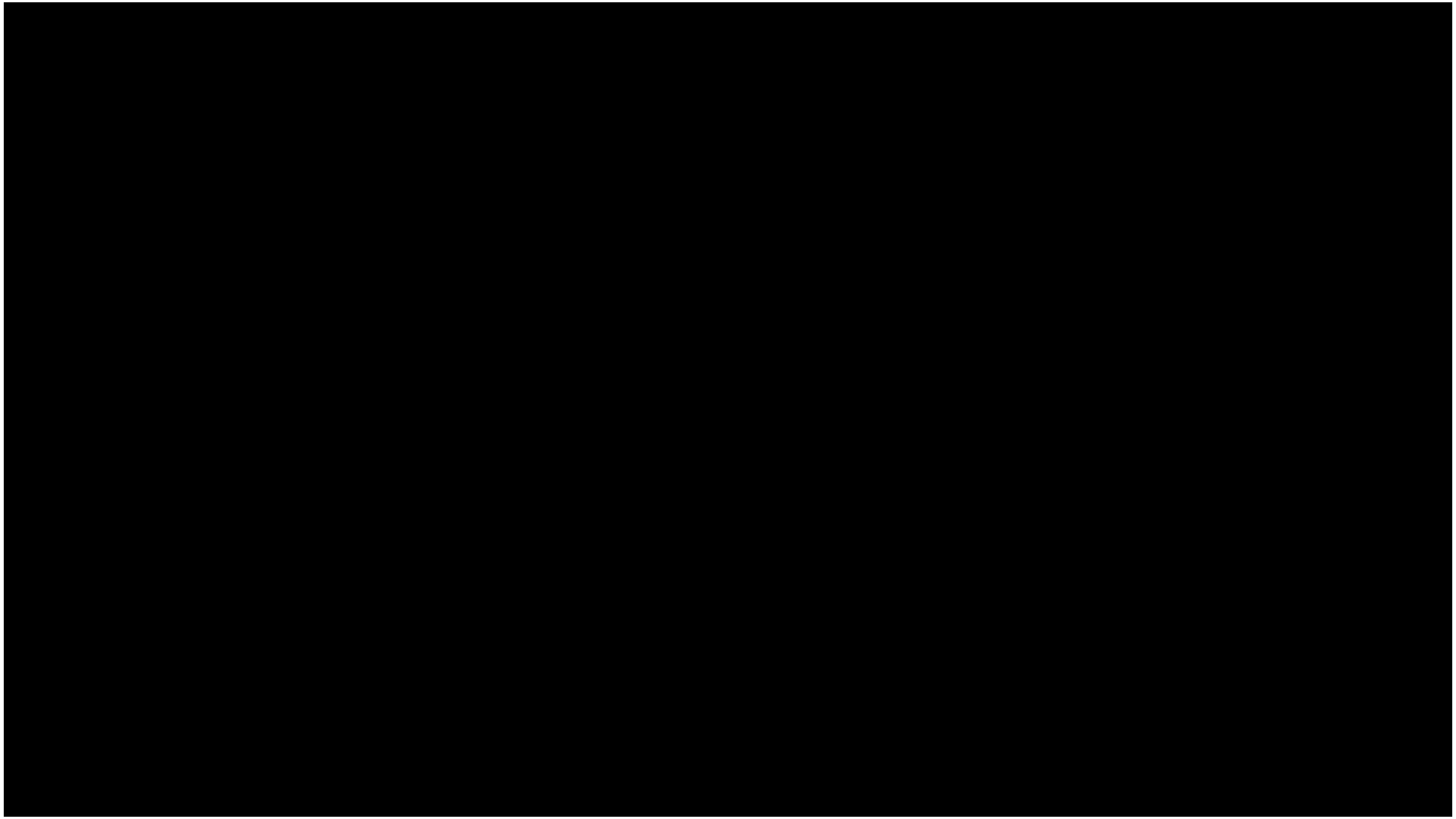
https://www.quantamagazine.org/neutron-star-collision-shakes-space-time-and-lights-up-the-sky-20171016/

National Science Foundation. Live https://www.youtube.com/watch?v=AFxLA3RGjnc

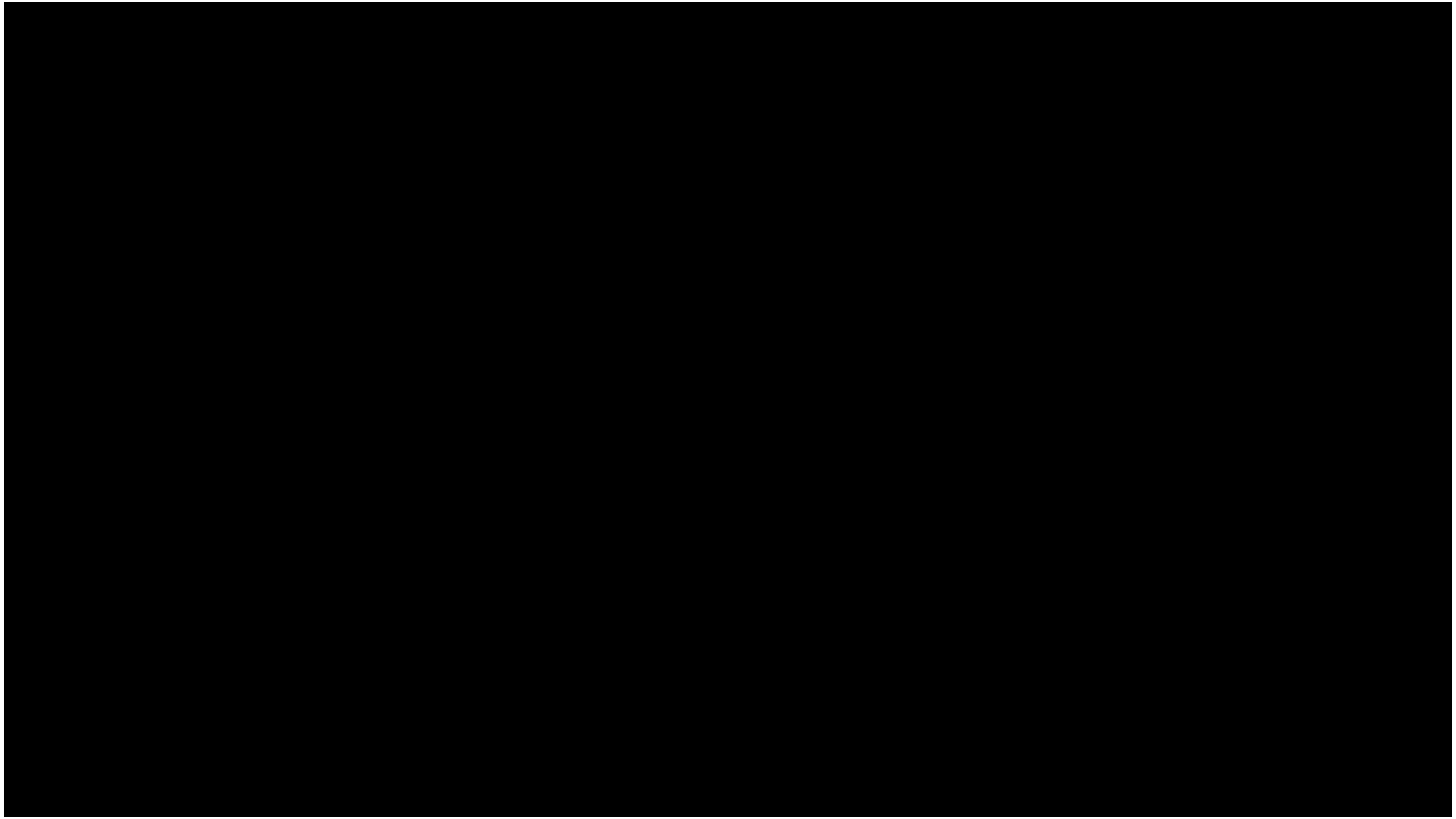
Campaign announced to the public on October 16, 2017
Event was registered on August 17, 2017

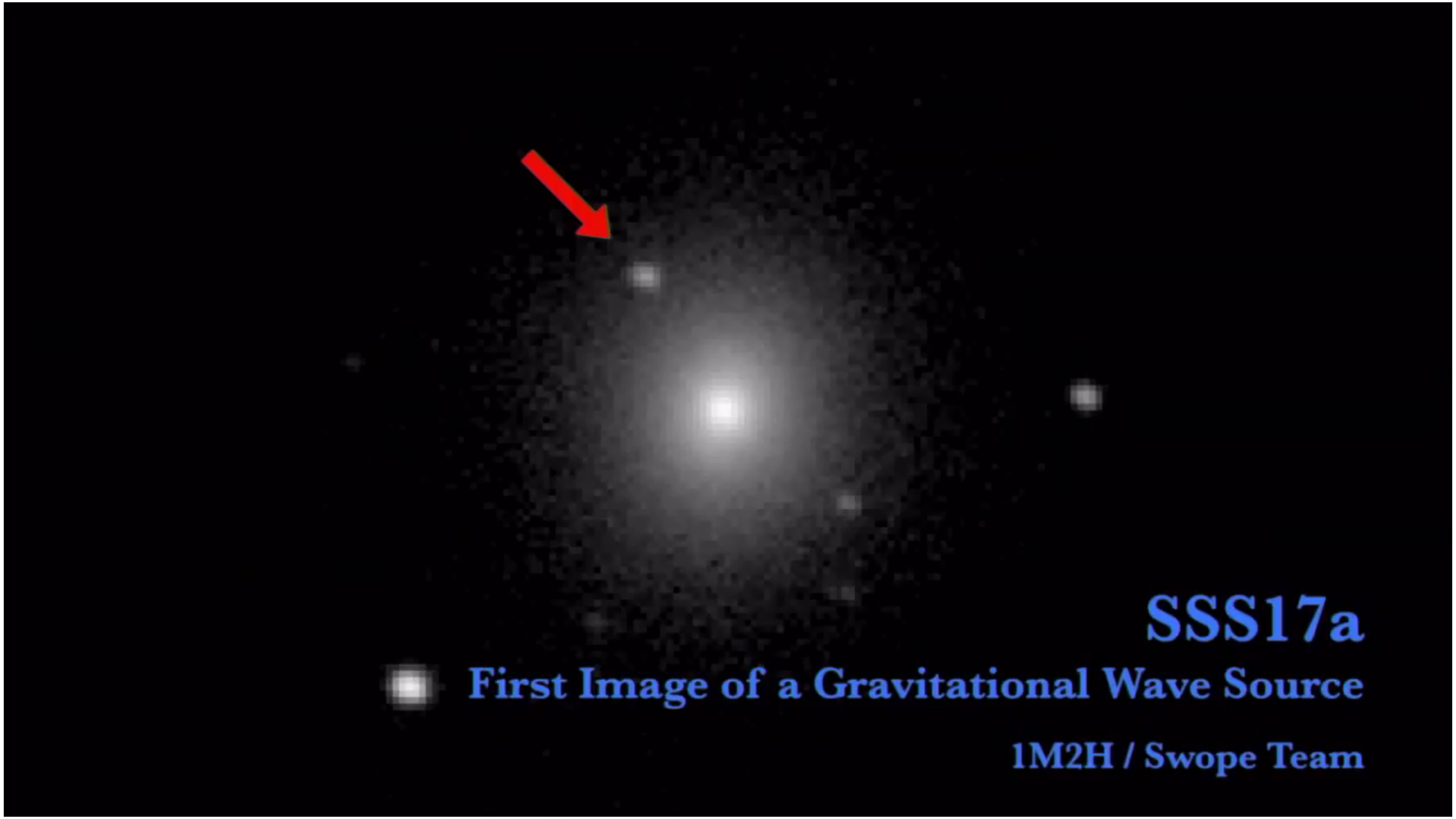

Fermi
LIGO-Virgo
INTEGRAL
Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
500
1.7 sec
Gravitational-wave strain
GW170817
Frequency (Hz)
300
100
-6
-4
-2
0
2
4
Time from merger (seconds)
Gamma rays, 100 keV and higher
GRB 170817A
Counts per second
120,000
115,000
110,000


GW150914
LVT151012
GW151226
GW170104
GW170814
GW170817
0
1
2
time observable (seconds)
LIGO/University of Oregon/Ben Farr



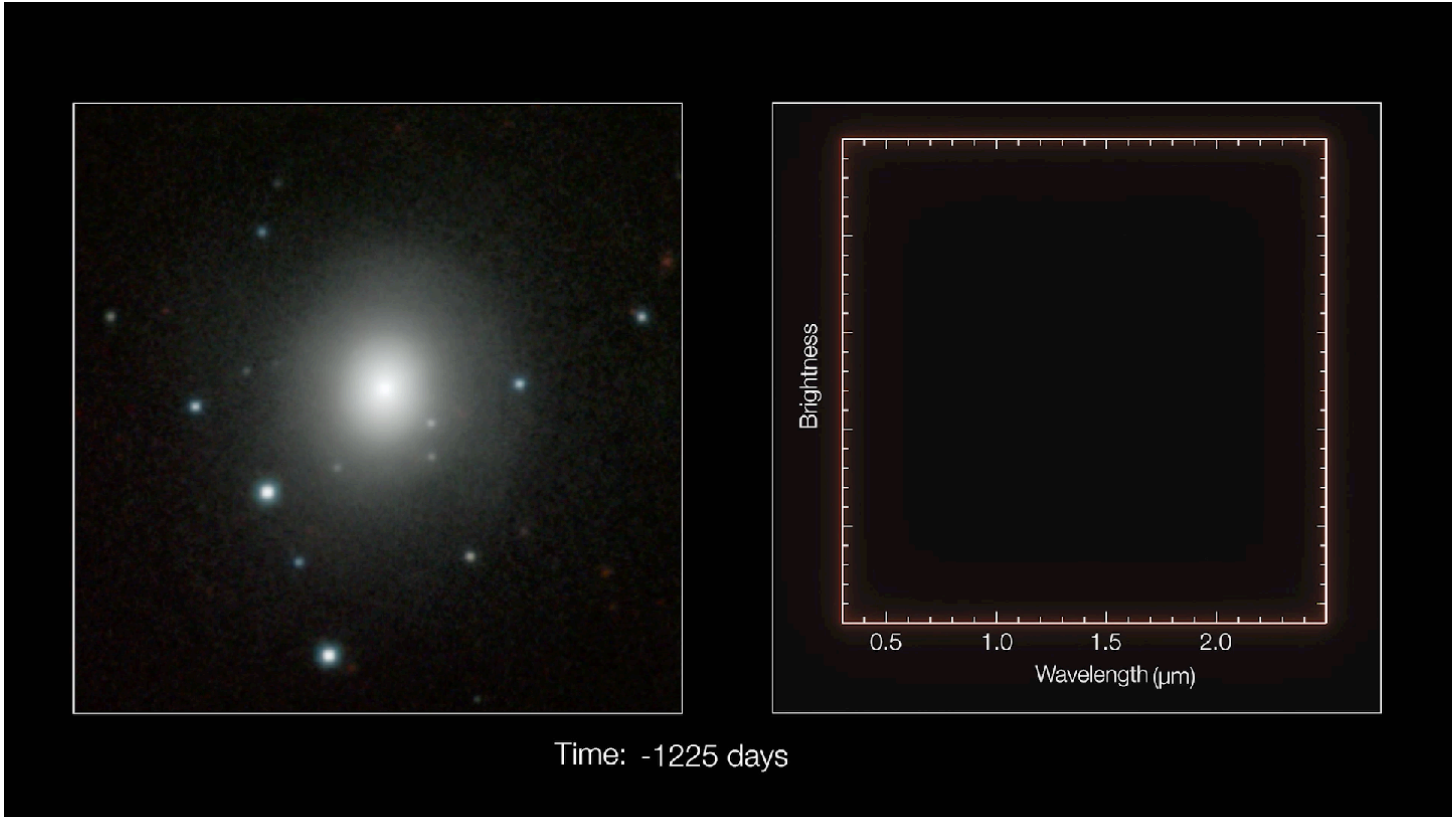
70 ground-based и 7 satellite observatories took part in this campaign



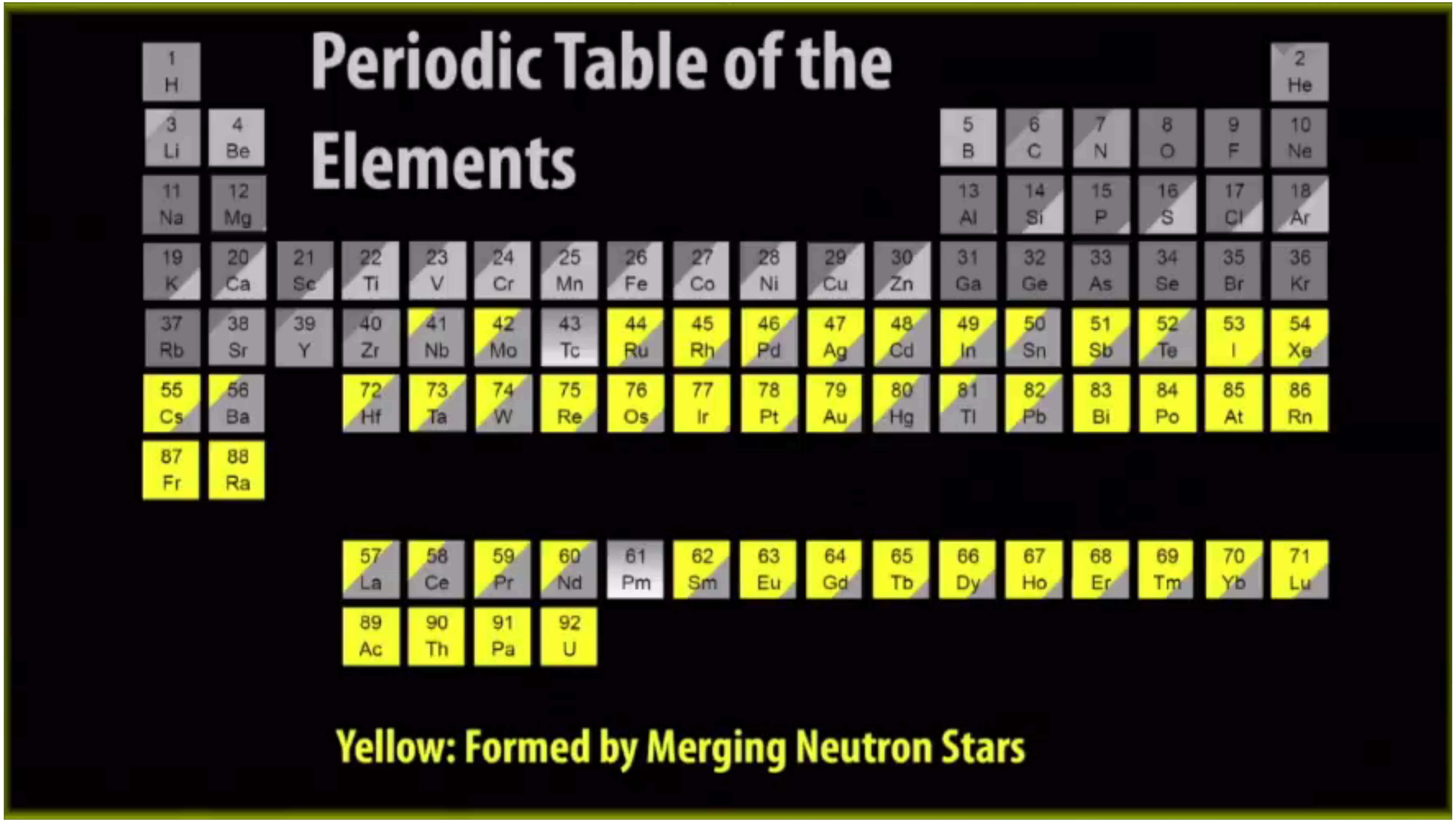


11 hours after the gravitational wave

Within an hour, many other telescopes registered the signal



- The source: Kilonova
- Attenuation in the UV range after 48 hours
- In the optical and IR range lasted 10 days
- In the X–ray was seen after 9 days
- In the radio - after 16 days

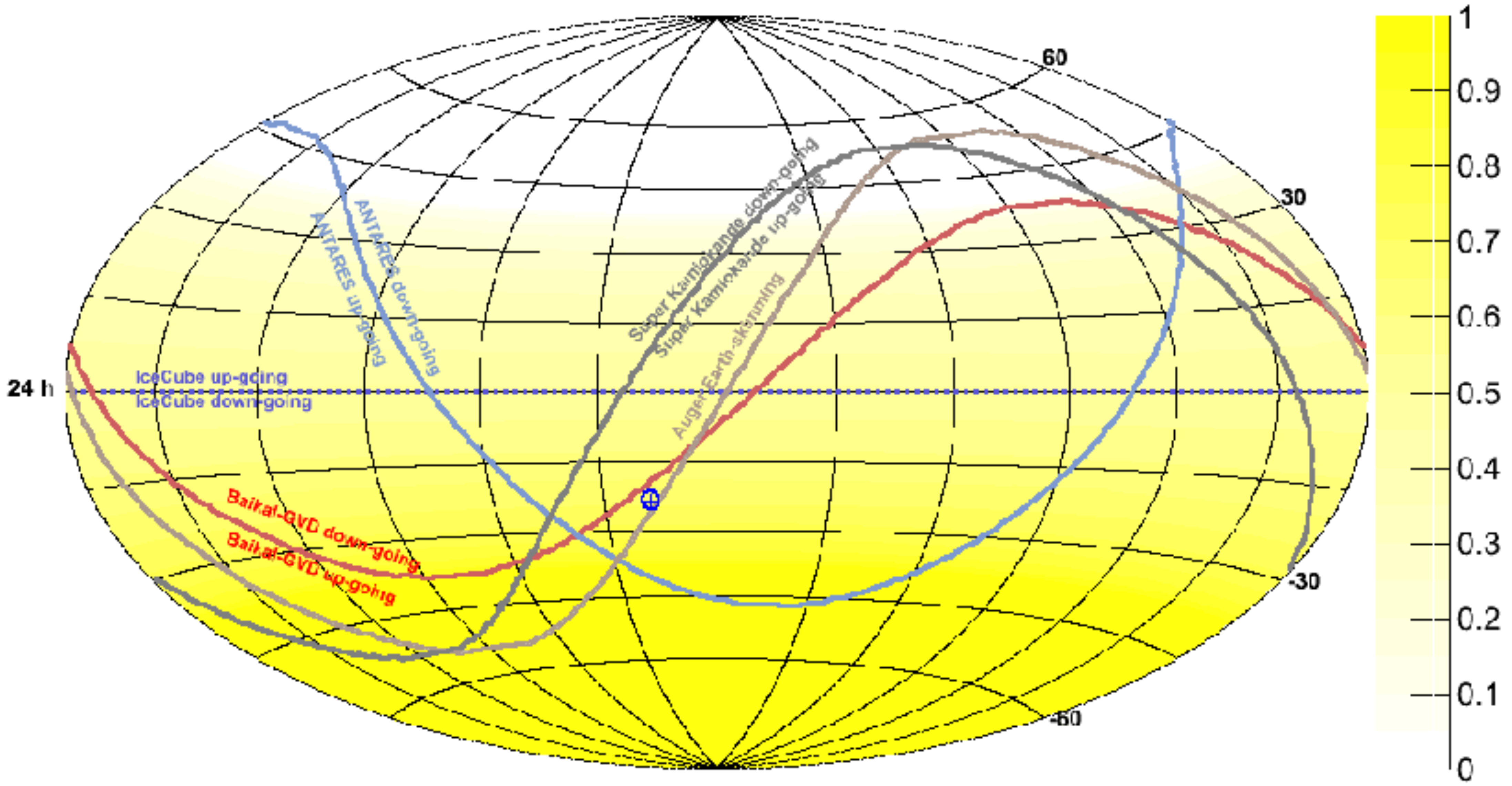


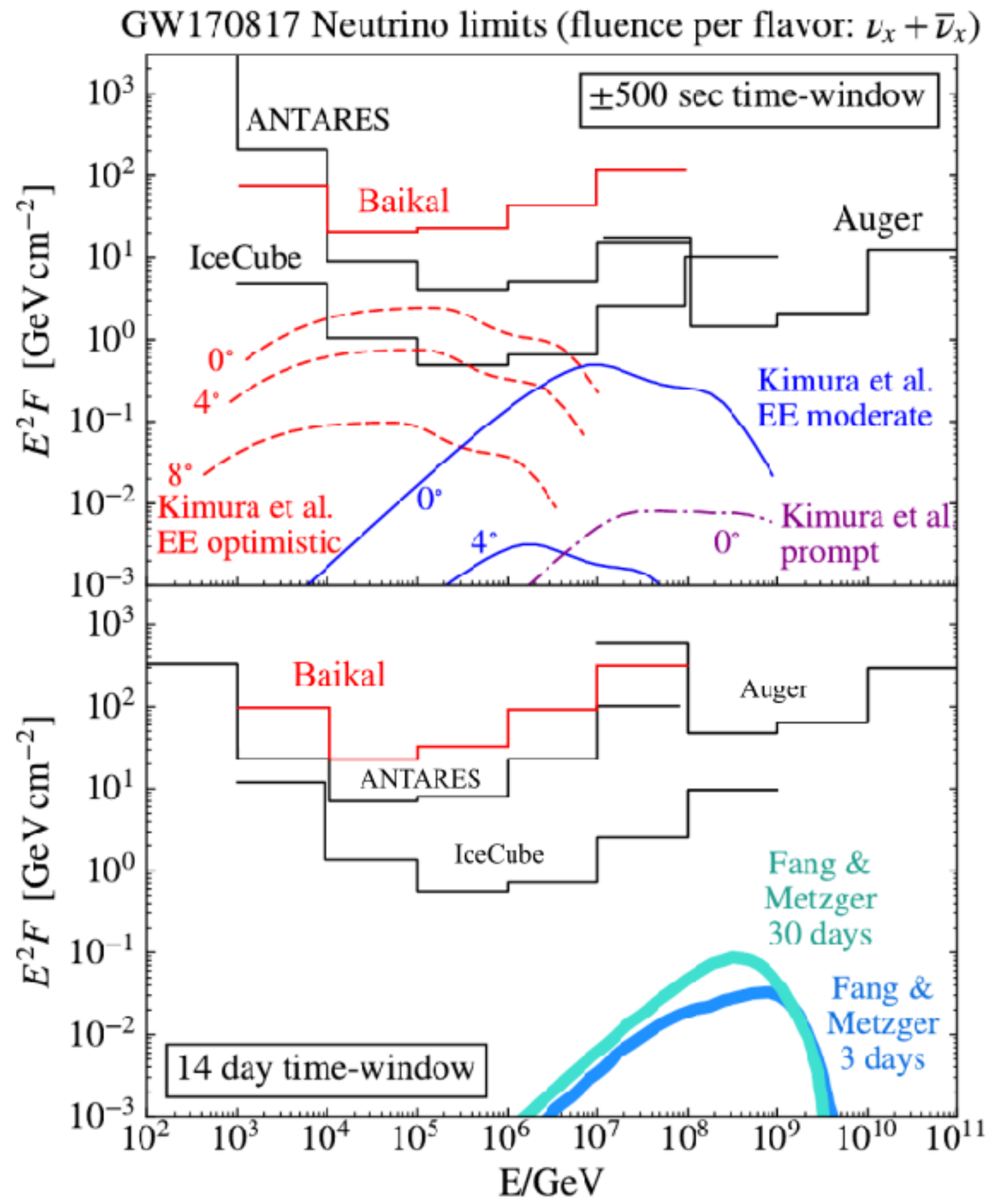
Only gold produced more than the mass of the Earth

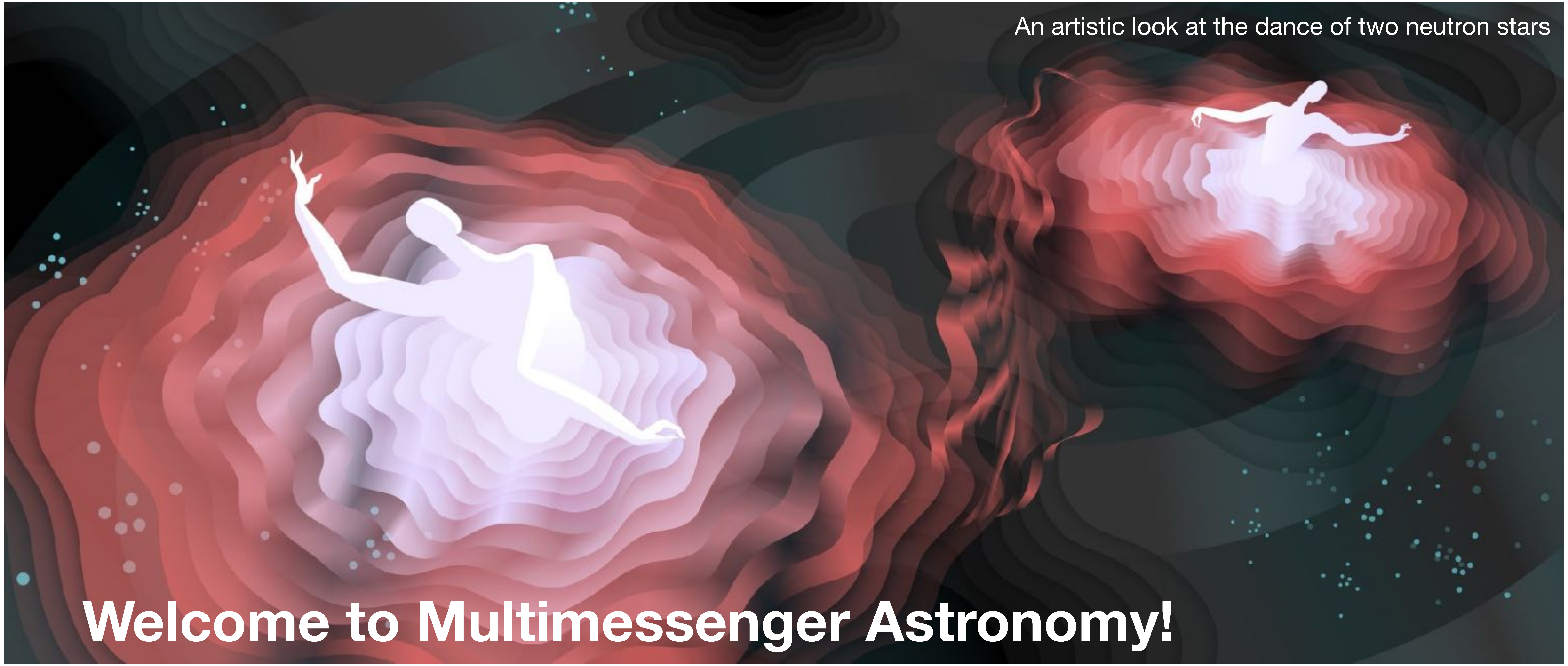

Dave Reitze
Executive Director, LIGO Laboratory, Caltech

Search for high-energy neutrinos associated with the GW170817

- The source is under horizon at registration time: 93.3°
- No neutrino events associated with GW170817 using **cascade** mode within both ± 500 sec and 14 days are observed
- Assuming E-2 spectral behaviour and equal fluence in all flavours the upper limits at 90% C.L. are obtained on the neutrino fluence from GW170817 for each energy decade



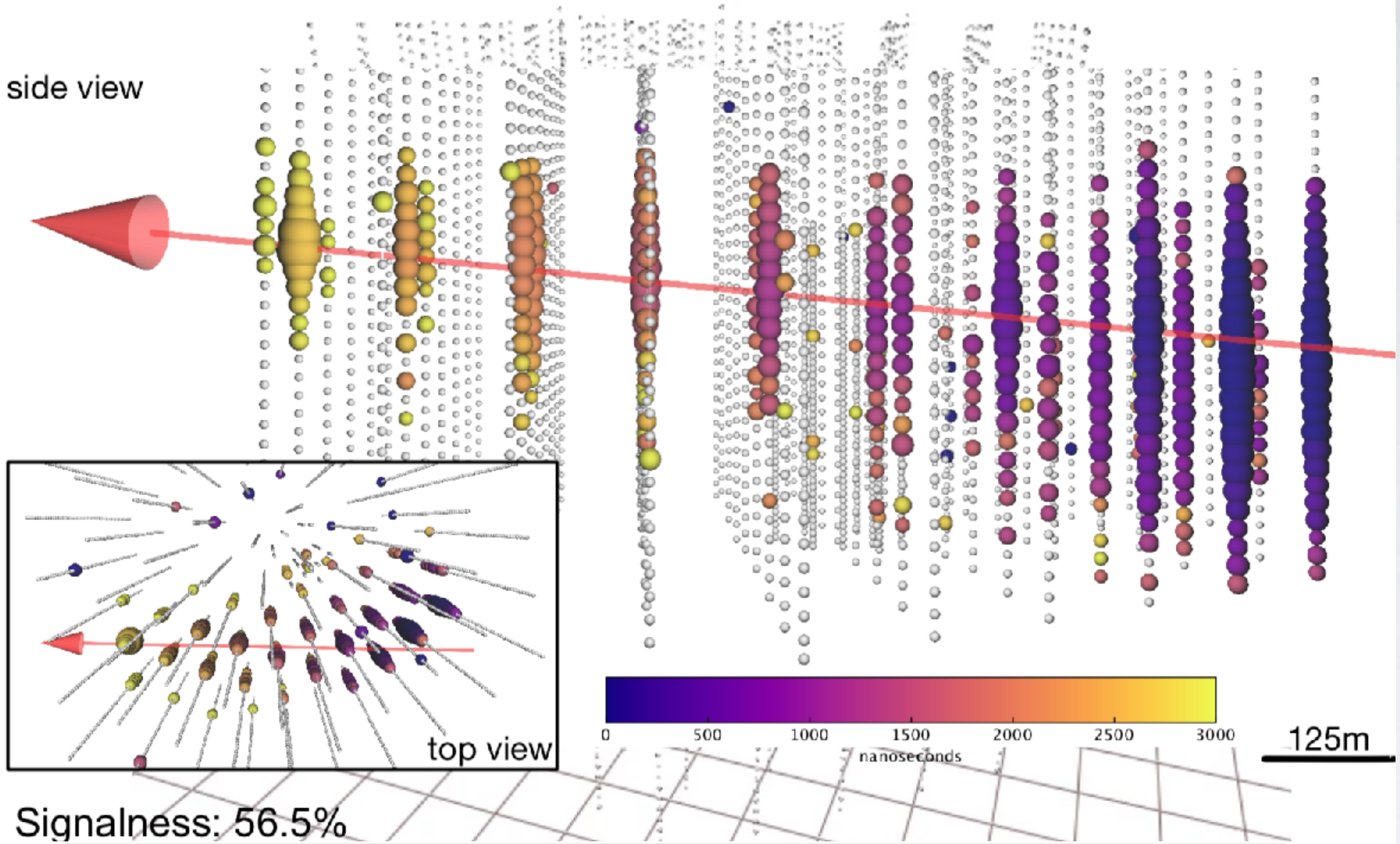




A new era in astrophysics has begun!

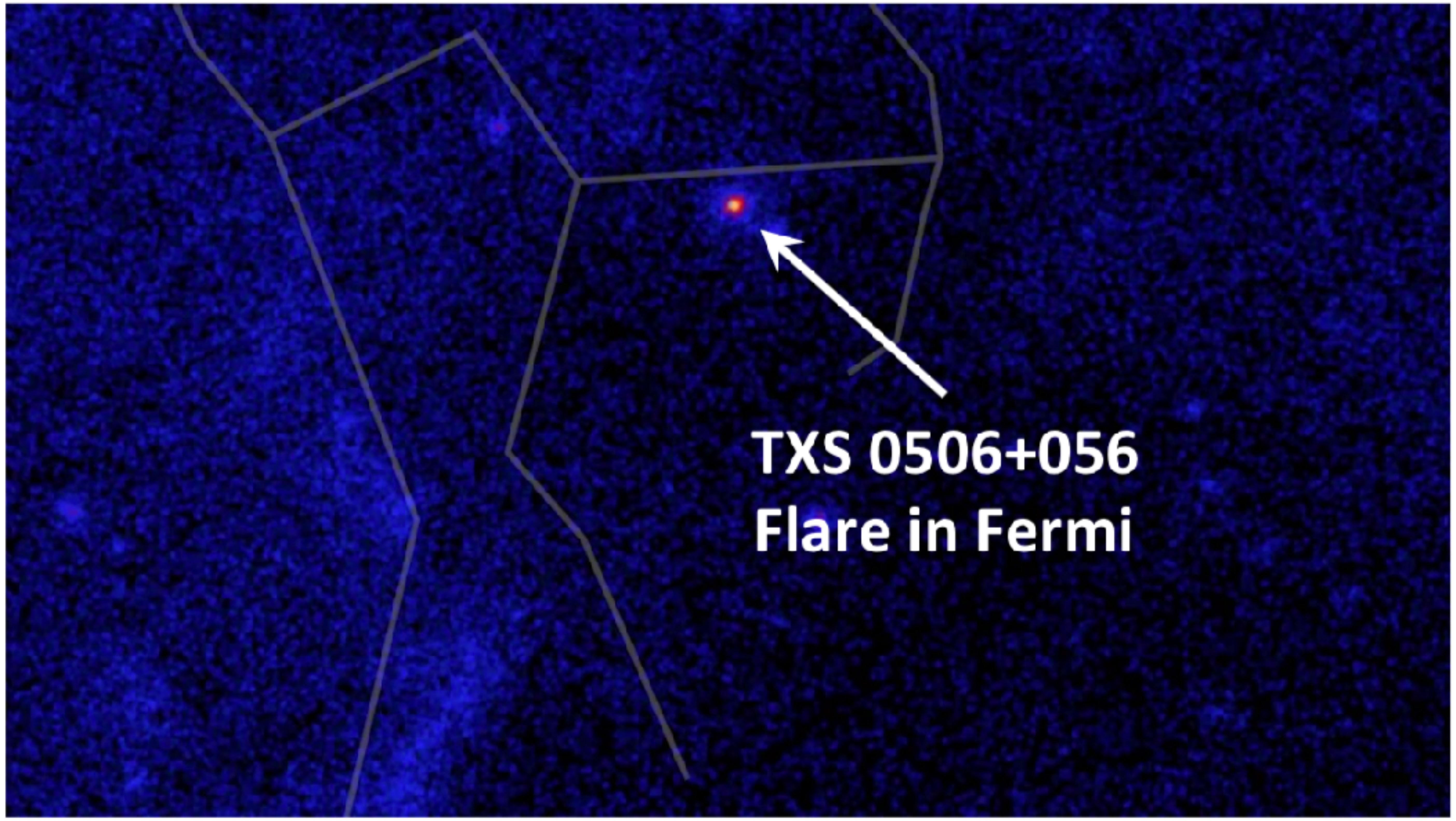
The results of this campaign demonstrate the importance of collaborative gravitational wave, electromagnetic and neutrino observations and mark a new era in multi-messenger, time-domain astronomy

IC-170922A – a 290 TeV Neutrino



IceCube EHE ("extremely-high energy") alert IC-170922A
Up-going muon track (5.7° below horizon) observed on September 22, 2017.
The best-fit neutrino energy for a power-law spectrum is 290 TeV.

TXS 0506+056: First evidence of a ν source

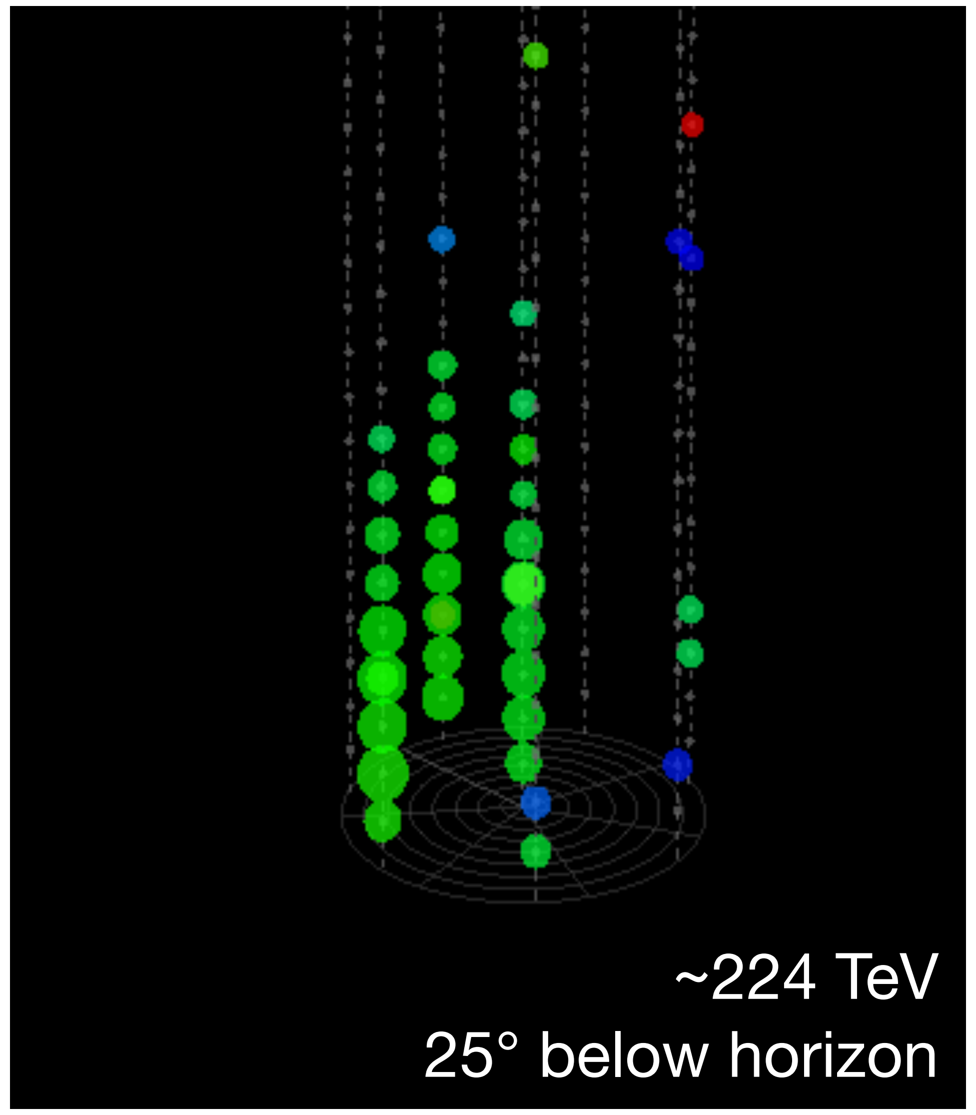


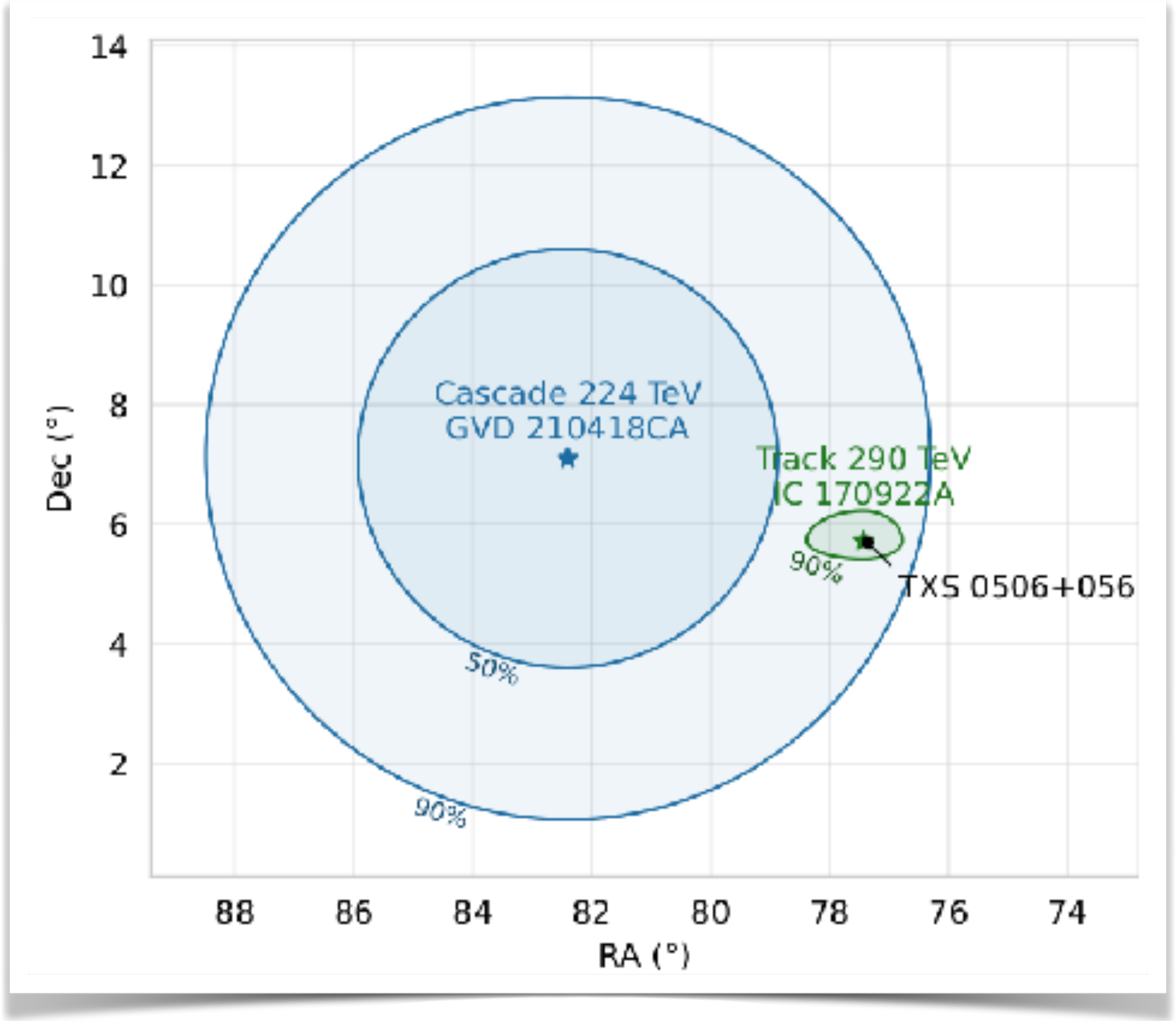
Science 361 (2018) eaat1378
Science 361 (2018) 147-151

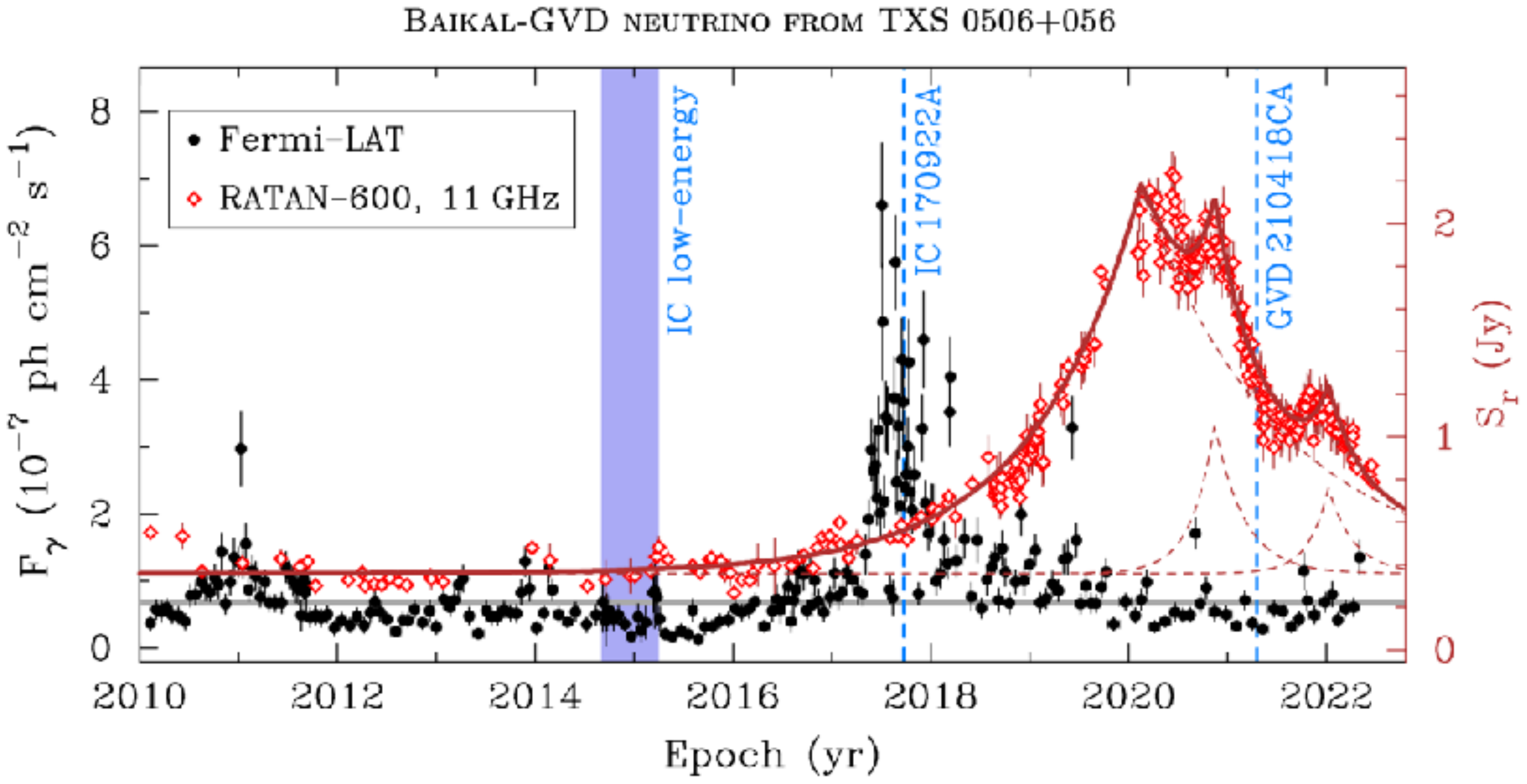
IceCube-170922: a neutrino alert issued by IceCube
Fermi and MAGIC identify a spatially coincident flaring blazar (TXS 0506+056)
A ν-flare was found in archival IceCube data (10/2014 – 03/2015)

Most energetic upgoing cascade events

Best candidates for neutrino events of astrophysical origin







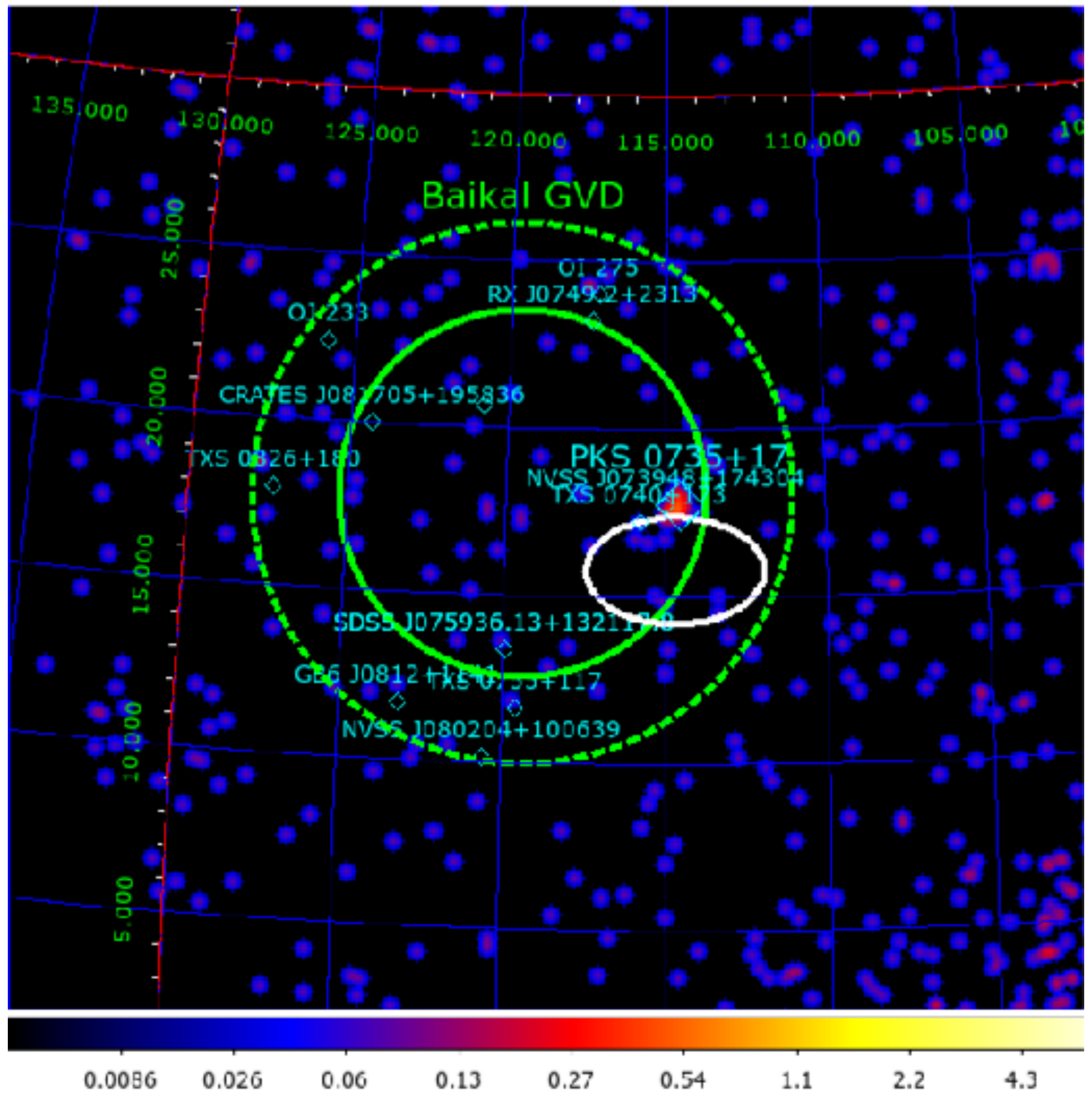
Closest sources (in 6 degrees):

- TXS 0506+056 Blazar (BL Lac) at z= 0.34 (5.7 Gly) is IceCube neutrino source observed at 3.7σ
- This event is probably of astrophysical origin (signalness = 97%).

arXiv:2210.01650

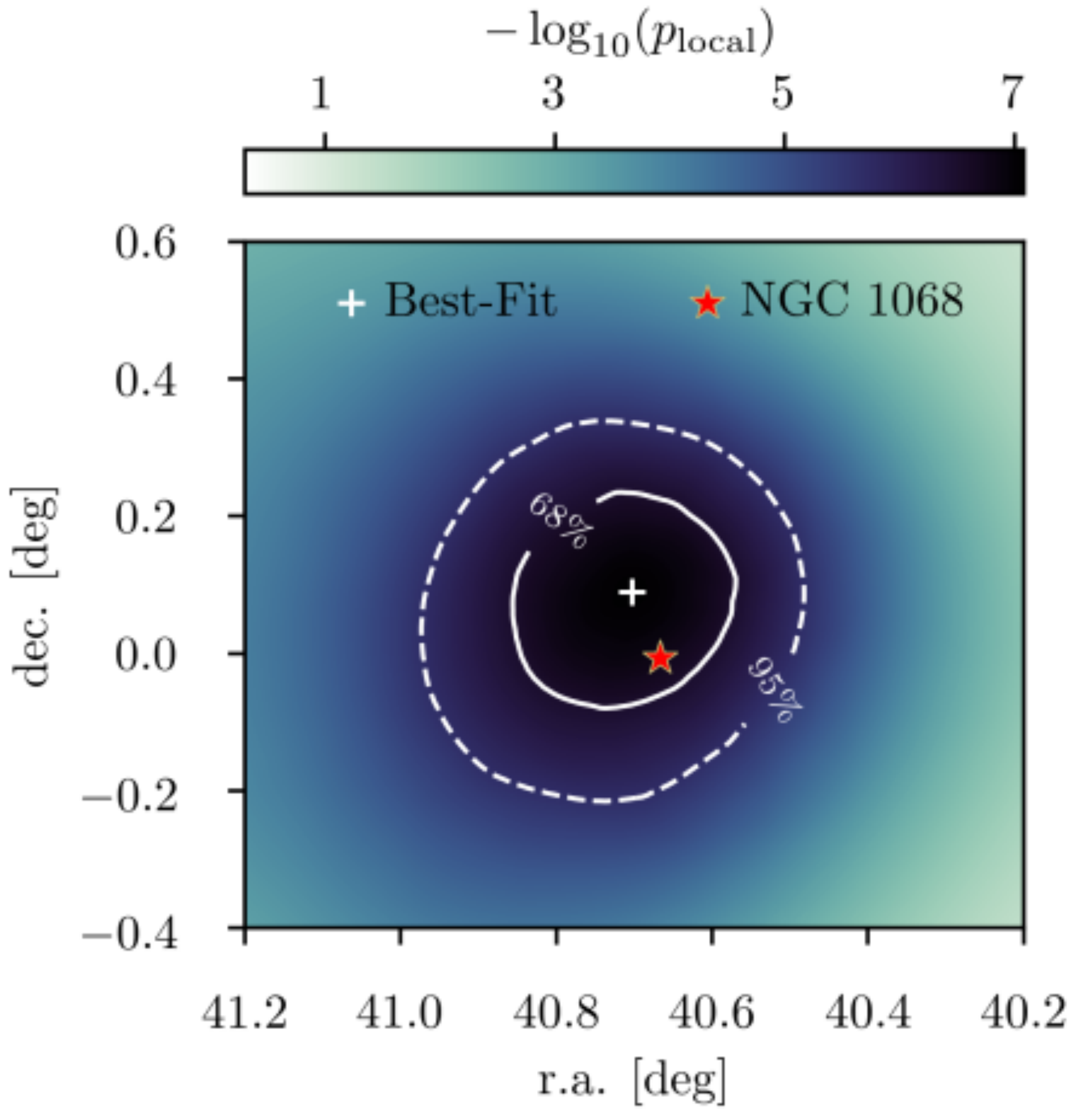
Baikal-GVD follow up of IceCube-211208A / PKS 0735+17

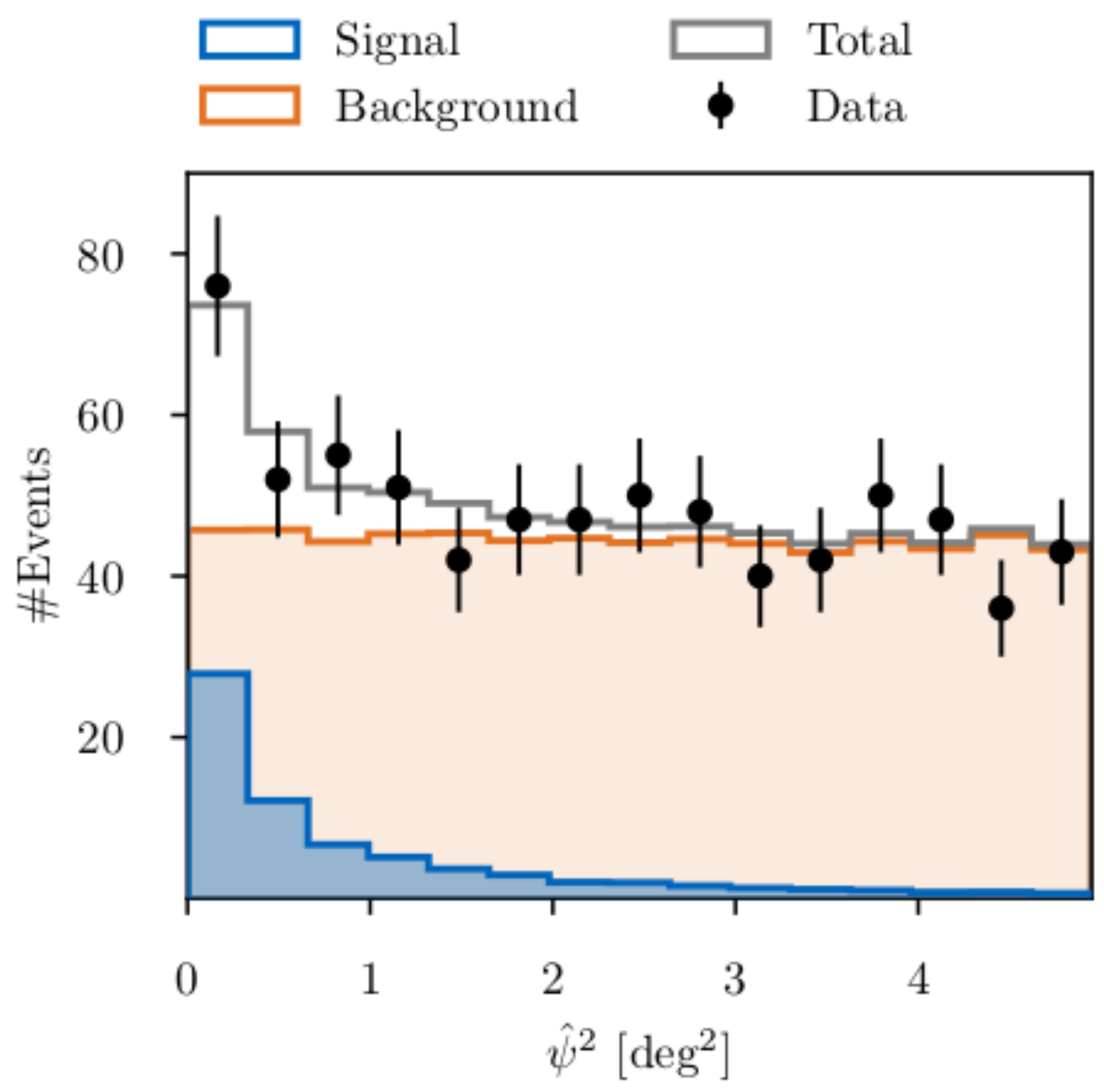
- Dec 8, 2021 20:02: IceCube “Astrotrack Bronze” neutrino event in vicinity of bright blazar PKS 0735+17
- Active state of PKS 0735+17 reported in optical (MASTER), HE gamma-rays (Fermi LAT), X-rays (Swift XRT) and radio
- Baikal-GVD found a downward-going (30° above horizon) cascade-like event 4 hours after the IceCube alert and in 5.3° from it and 4.7° from PKS 0735+17
    - E ≈ 43 TeV
    - PSF 50% (68%) containment radius = 5.5 deg (8.1 deg)
    - Pre-trial p-value = 0.0044 (2.85 σ) [24 hr, 5.5 deg cone]
    - Trial factor ~ 40 (total number of IceCube alerts analyzed)



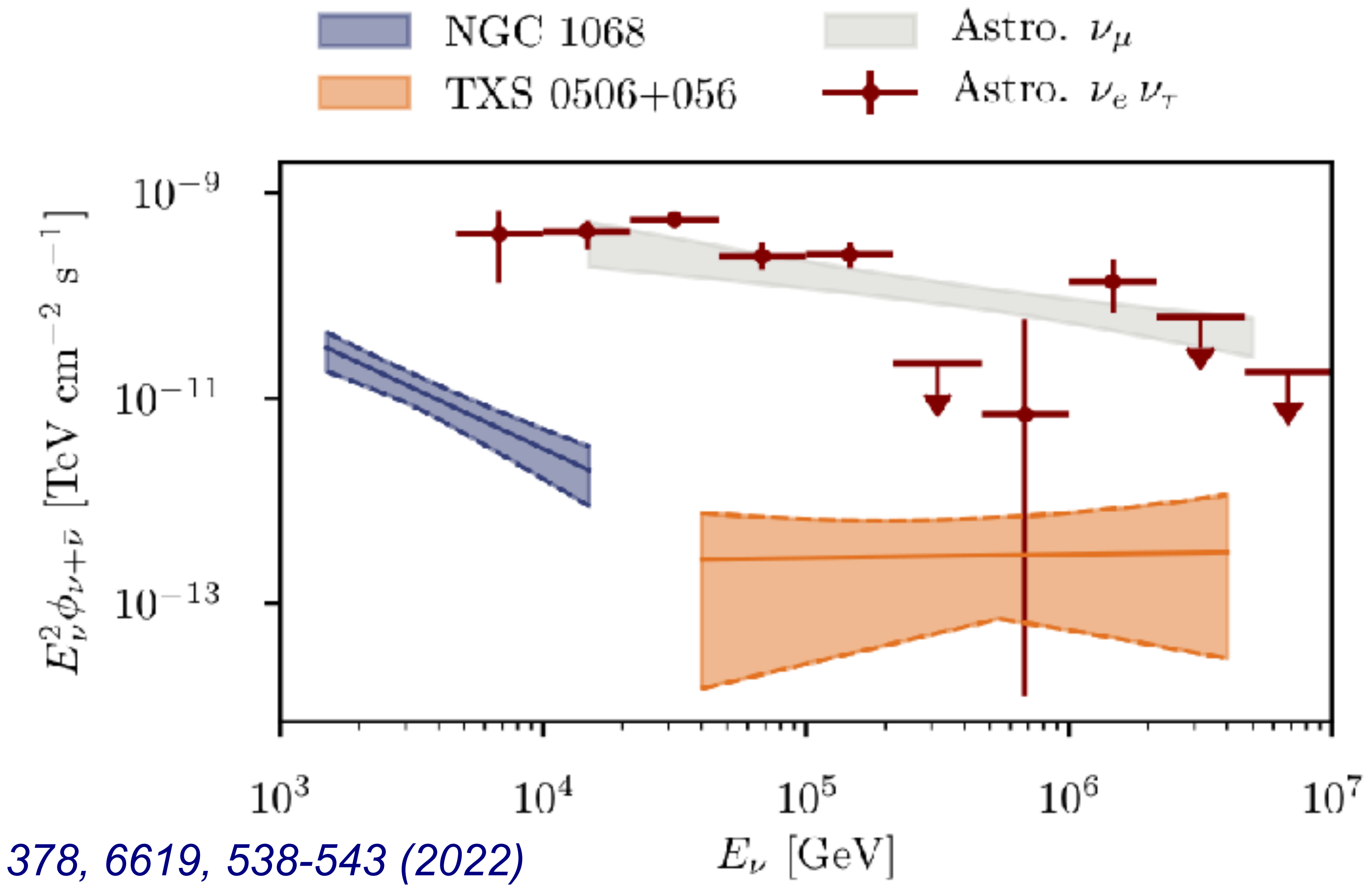
Astronomy telegram ATeL 15112

Permanent neutrino source: Galaxy NGC 1068





- NGC 1068 is a nearby active galaxy (Seyfert II)
- NGC 1068 is also known as a “starburst” galaxy
- 14.4 Mpc (47 Mly) from Earth
- Detected at 4.2 σ with 10 yr of IceCube data
- Permanent, seen in low-energy band



Messier 77 (**M77**), also known as **NGC 1068** or the **Squid Galaxy**

Science 378, 6619, 538-543 (2022)

Seyfert galaxies with the highest X-ray fluxes

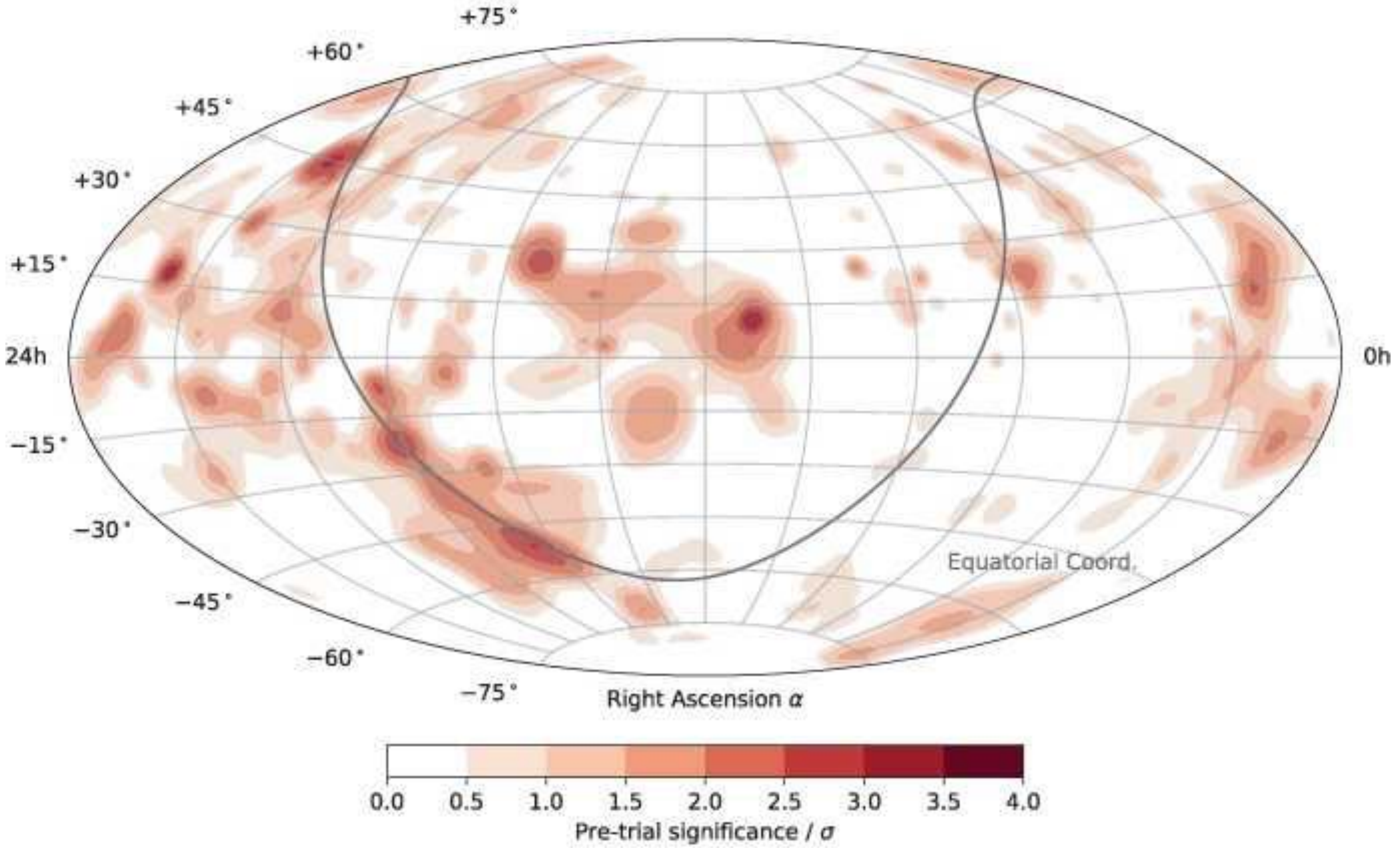
Source	Declination [deg]	z	d_L [Mpc]	Intrinsic flux [10^{-12}erg cm^{-2} s^{-1}]	log(Intrinsic luminosity) [erg s^{-1}]
Circinus Galaxy	-65.34	0.0014	4.2*	984.4	42.31
ESO 138-1	-59.23	0.0091	39.2	671.3	44.09
NGC 7582	-42.37	0.0052	22.4	507.6	43.48
Cen A	-43.02	0.00136	3.8*	347.3	42.39
NGC 1068	-0.013	0.00303	13.0	268.3	42.93
NGC 424	-38.08	0.0118	51.0	188.1	43.77
CGCG 164-019	27.03	0.0299	131.0	179.5	44.57
UGC 11910	10.23	0.0267	116.7	157.5	44.41
NGC 4945	-49.47	0.0019	3.6*	149.4	41.36
NGC 1275	41.51	0.0176	76.4	132.8	43.98

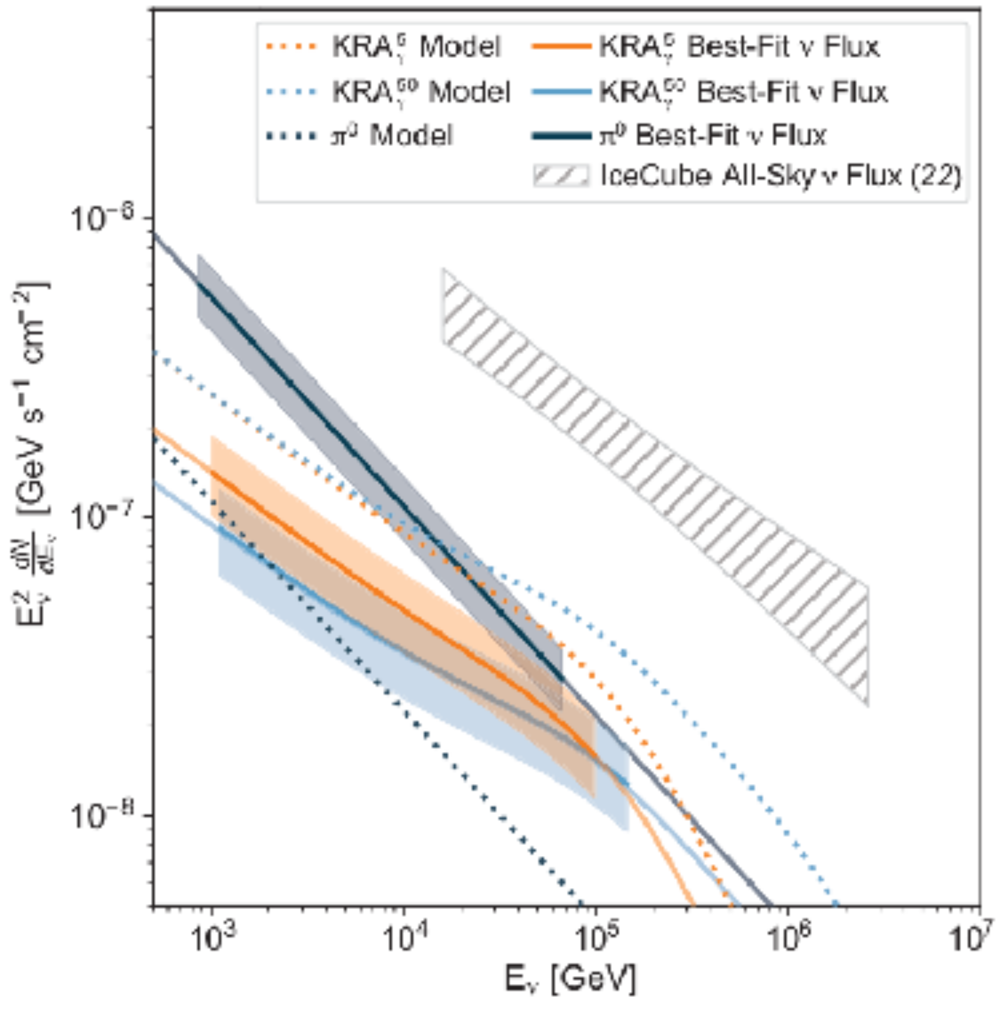
arXiv:2102.04475

Galactic Diffuse neutrino flux observed by IceCube

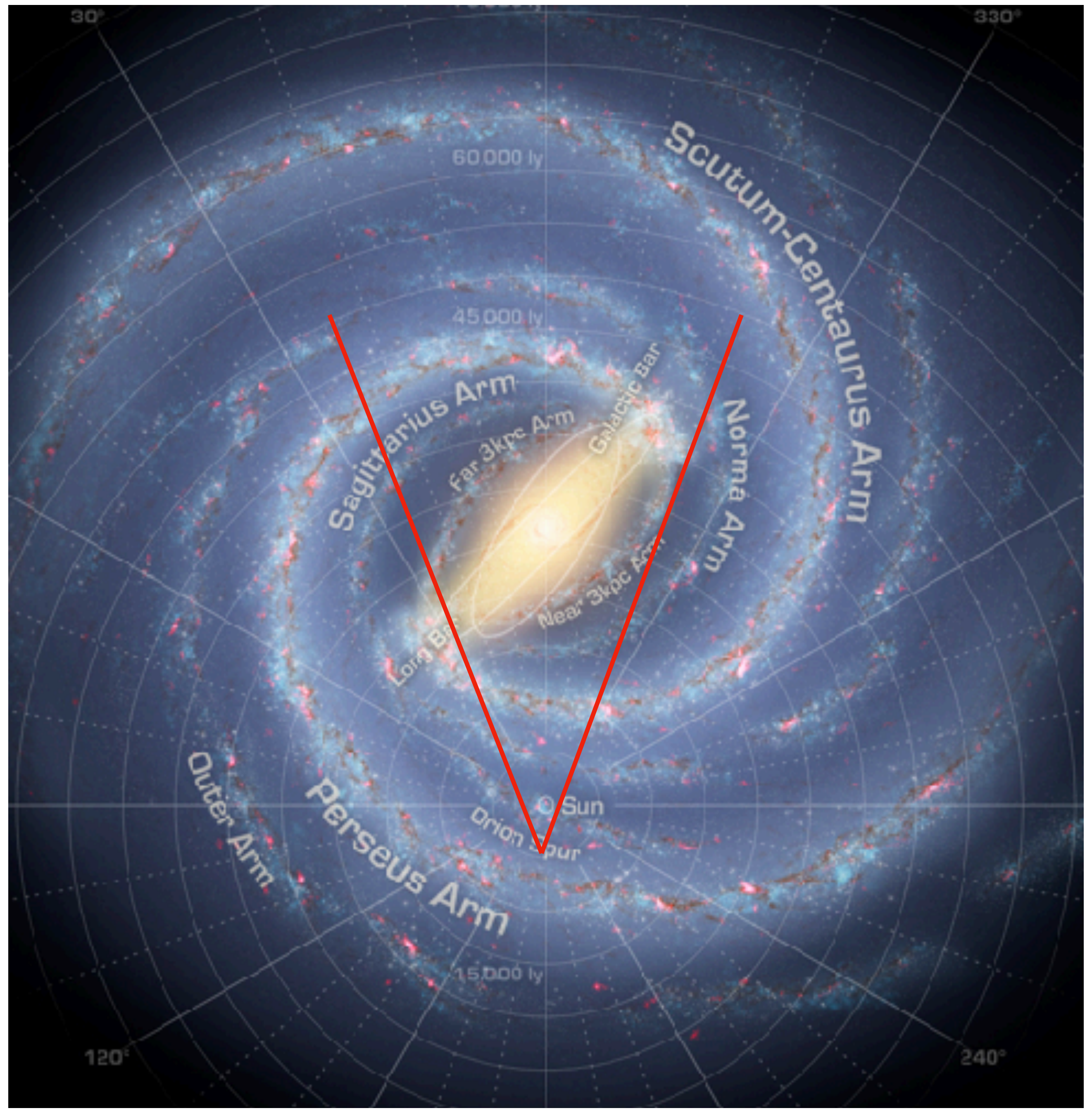
NEW!

4.5 σ excess!





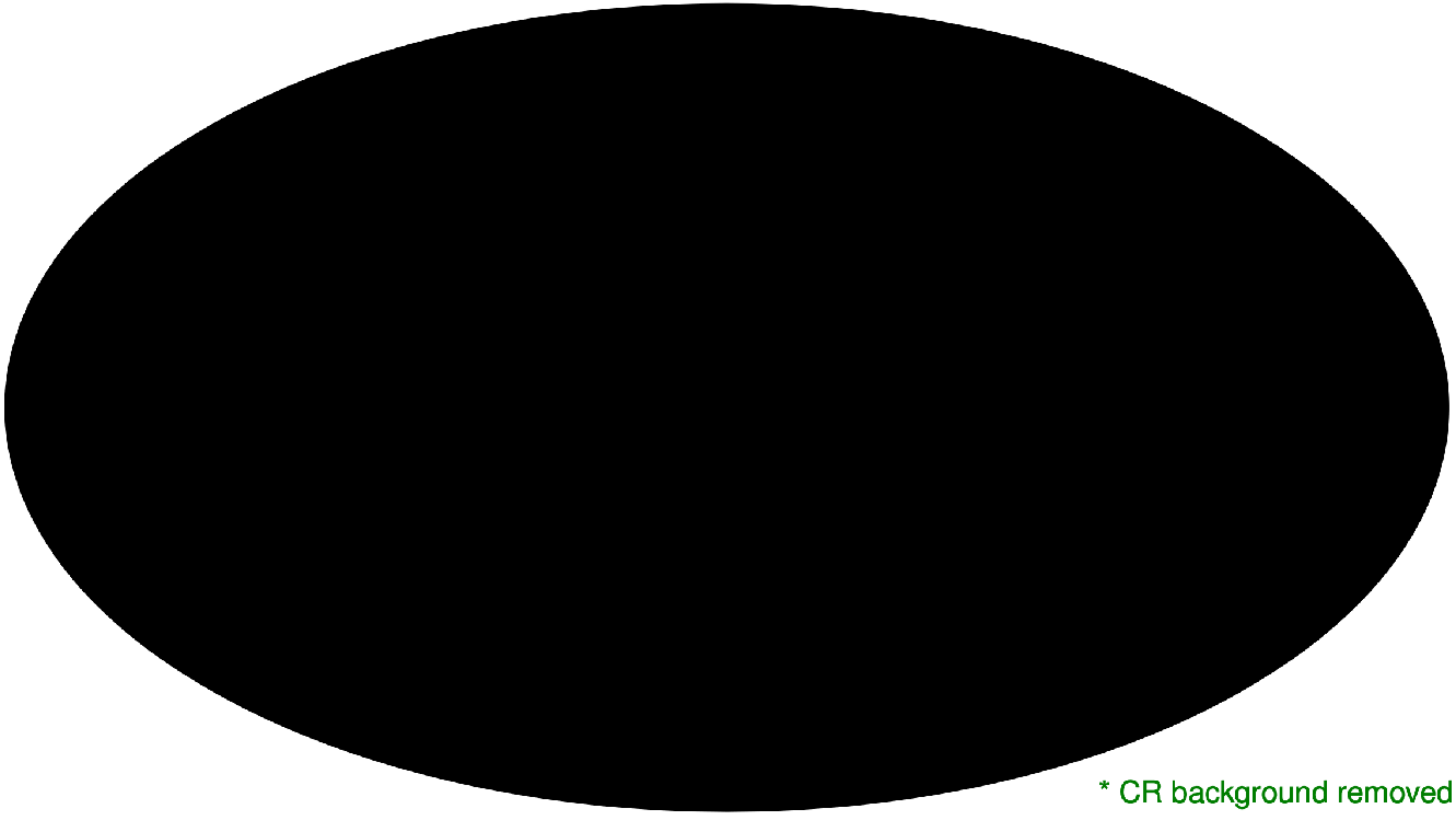
The signal is consistent with diffuse emission of neutrinos from the Milky Way but could also arise from a population of unresolved point sources



galactic longitudes |*l*| < 30°, galactic latitudes |*b*| < 2°

Science, 380 (6652)

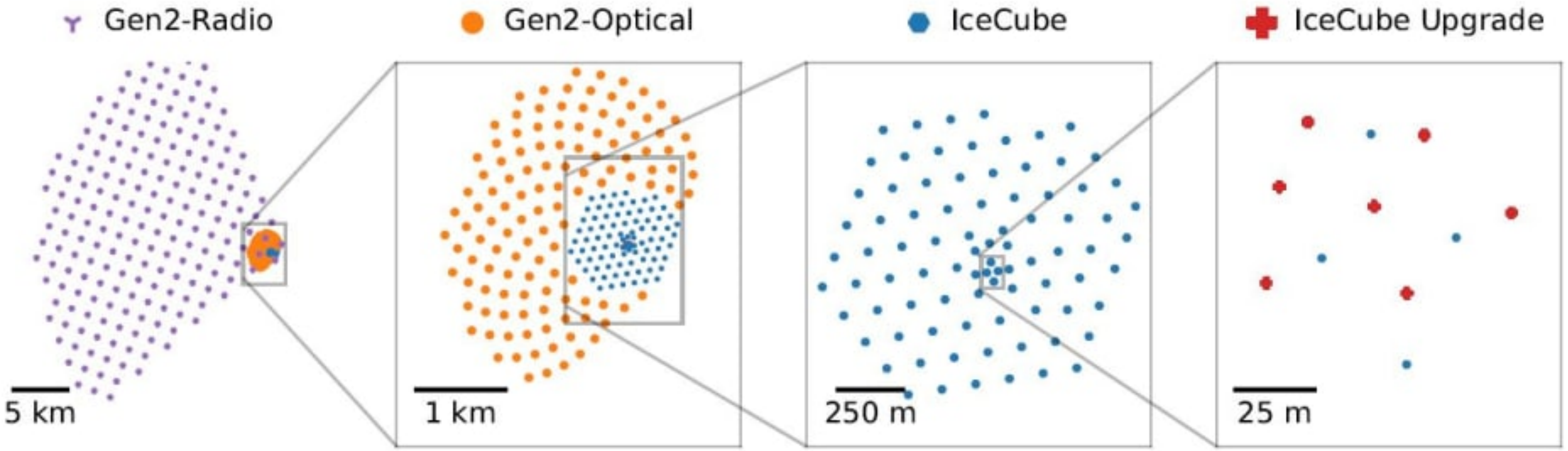
Neutrino sky map* at very high energies



* CR background removed

Prospects

- IceCube: plan to build ~8 km^3 optical array
- KM3NeT: finish construction
- Baikal-GVD: discussions on for further detector extensions (10 km^3?)



Conclusion

- A lot of discoveries are happening right now
- Baikal-GVD is the second largest neutrino telescope and the first one in the Northern Hemisphere
- Baikal-GVD has already an effective volume of above 0.5 km^3 and grows every year
- Cascade analysis shows the astrophysical neutrino flux (3.05 σ) and some intriguing events
- Muon track analysis is under way. Stay tuned
- Baikal-GVD is entering the discovery game

Thank you for attention!

BACK-UPS

Origin of High-Energy Gamma Rays

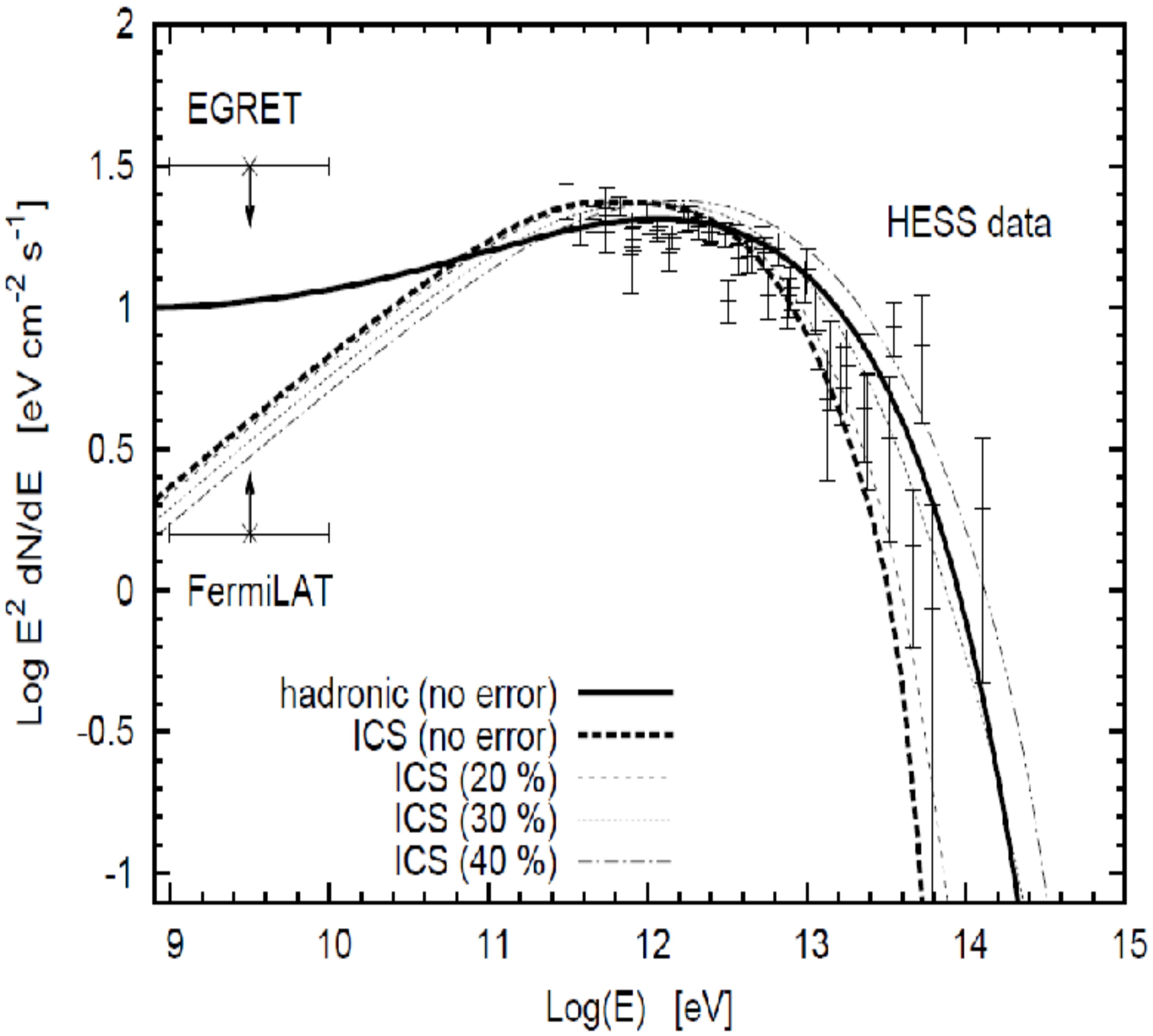
1. Hadronic :

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} \pi^0 + p \\ \pi^+ + n \end{cases}$$

$$\pi^0 \rightarrow \gamma\gamma$$

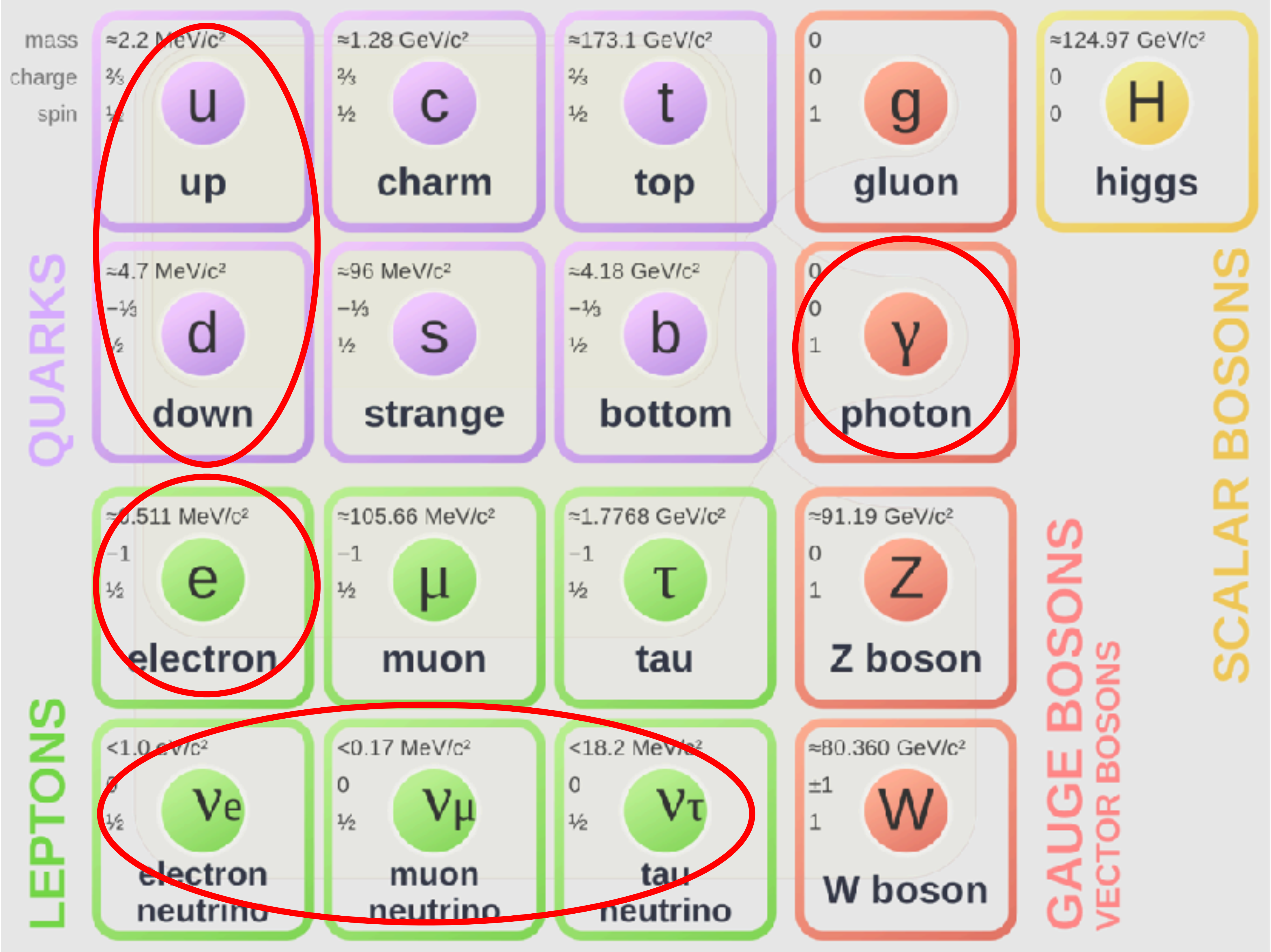
2. Electromagnetic (inverse Compton scattering):

$$e^- + \gamma_{\text{low energy}} \rightarrow e^- + \gamma_{\text{high energy}}$$



RX J1713.7-3946

In addition to photons, there are other stable particles that carry information about the cosmos



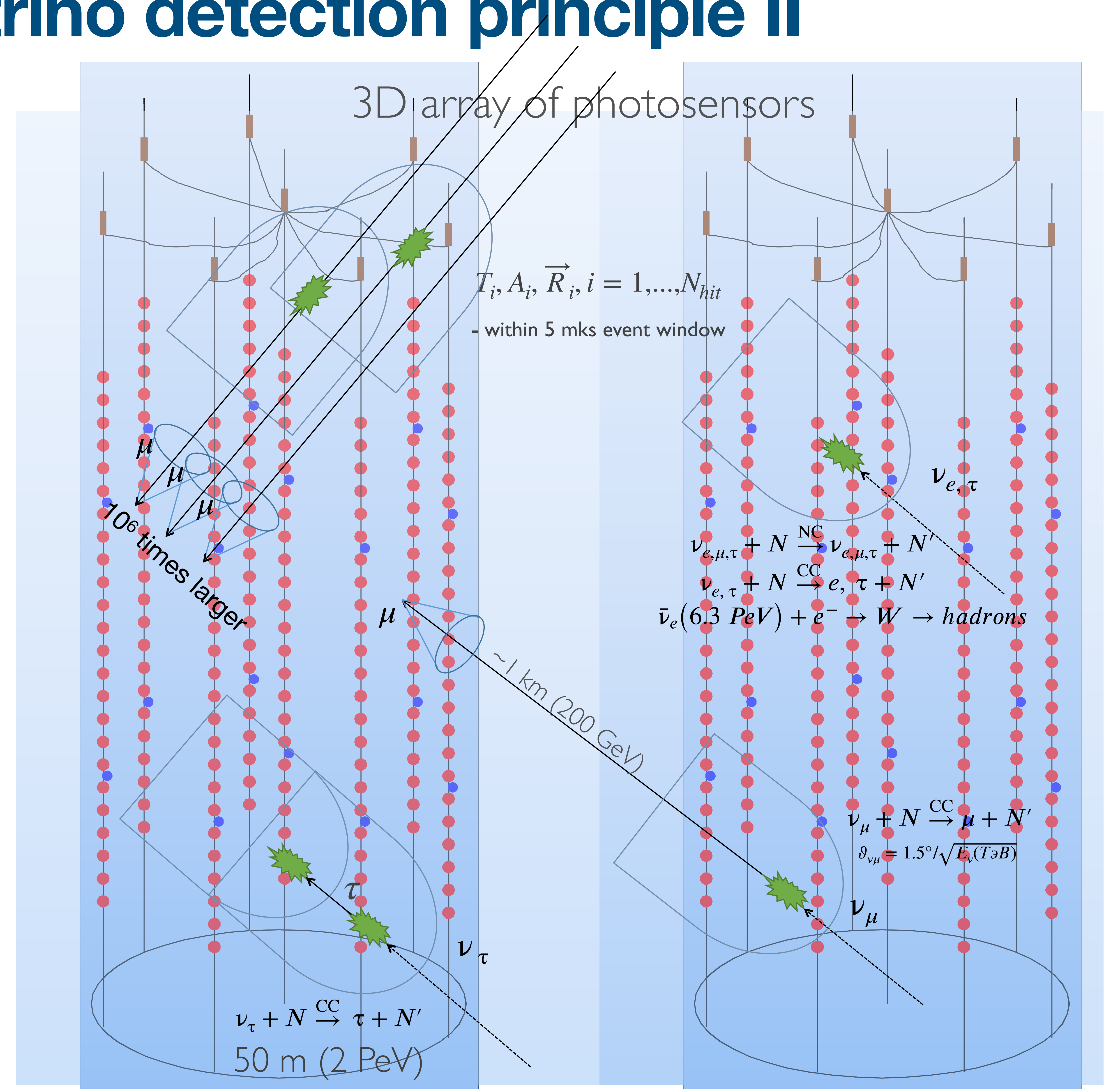
Stable particles:

protons, nuclei, electrons,

photons, neutrinos

+ gravitational waves

Neutrino detection principle II



Atmospheric muons

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

Neutrino induced muons

- Long track in the detector
- Good angular resolution < 1°
- Neutrino interaction vertex can be located at several km from the detector → large detection volume

Neutrino induced showers

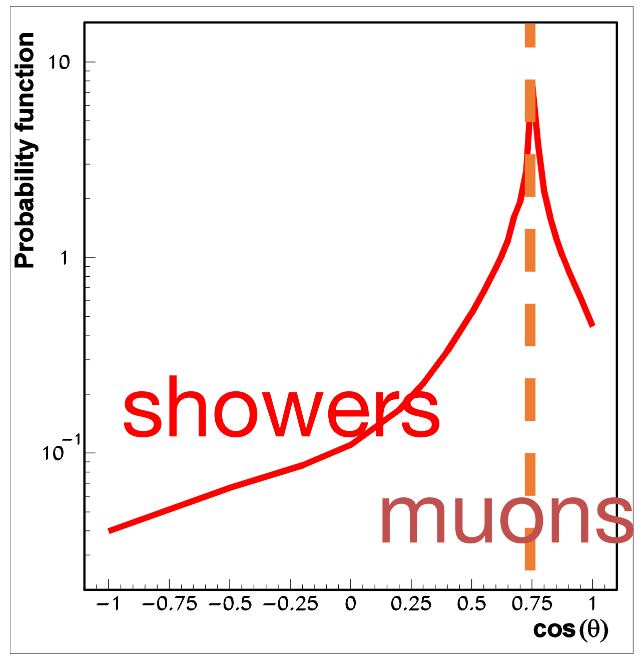
- Showers are produced in all neutrino interaction channels and by all neutrino flavors
- Bright anisotropic point-like source of Cherenkov light
- Moderate angular resolution
- Good energy resolution

relative cross sections

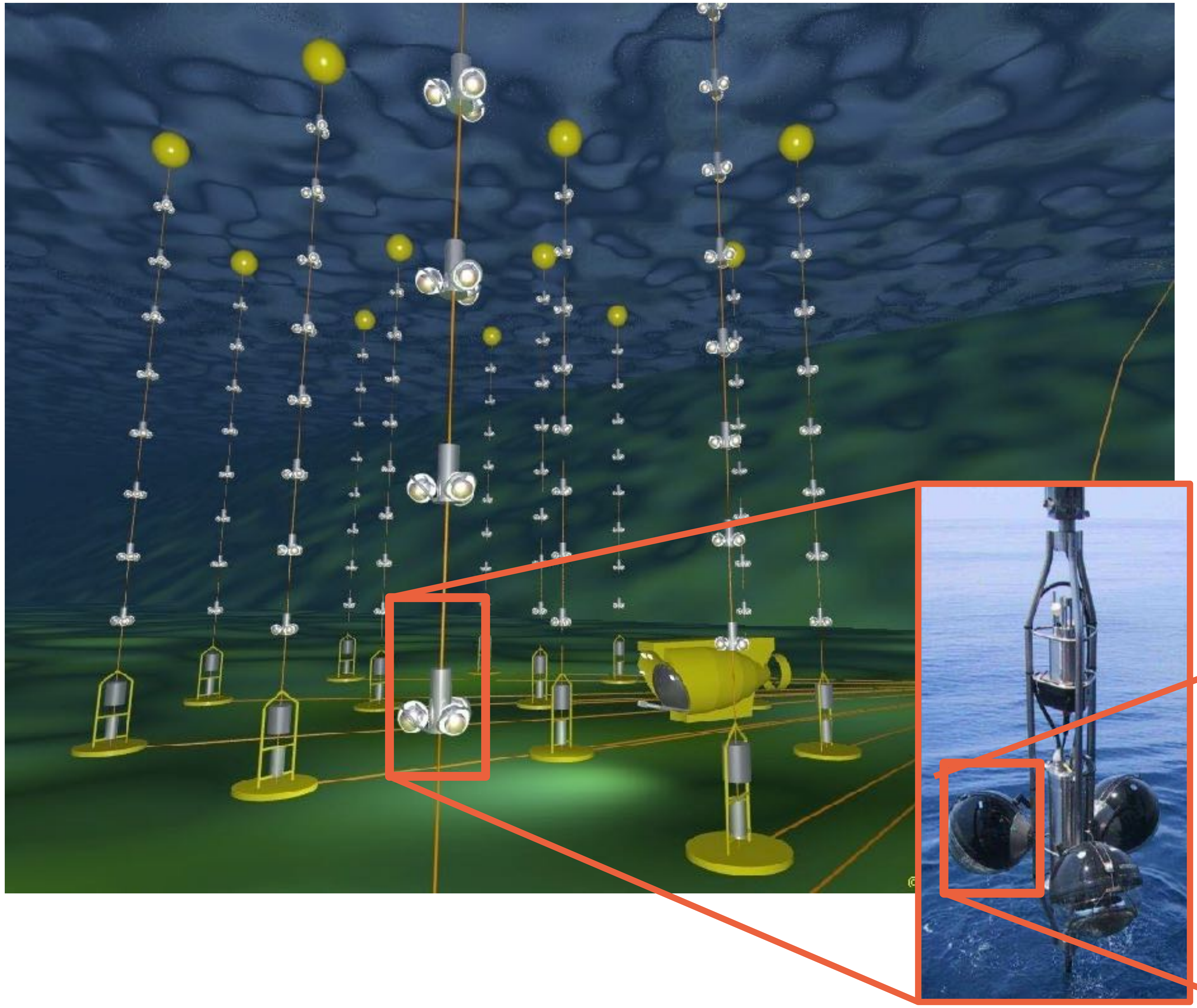
	ν_e	ν_μ	ν_τ
NC	1	1	1
CC	2	2	2

cascades tracks

3.5:1



ANTARES in Mediterranean sea (decommissioned in 2023)

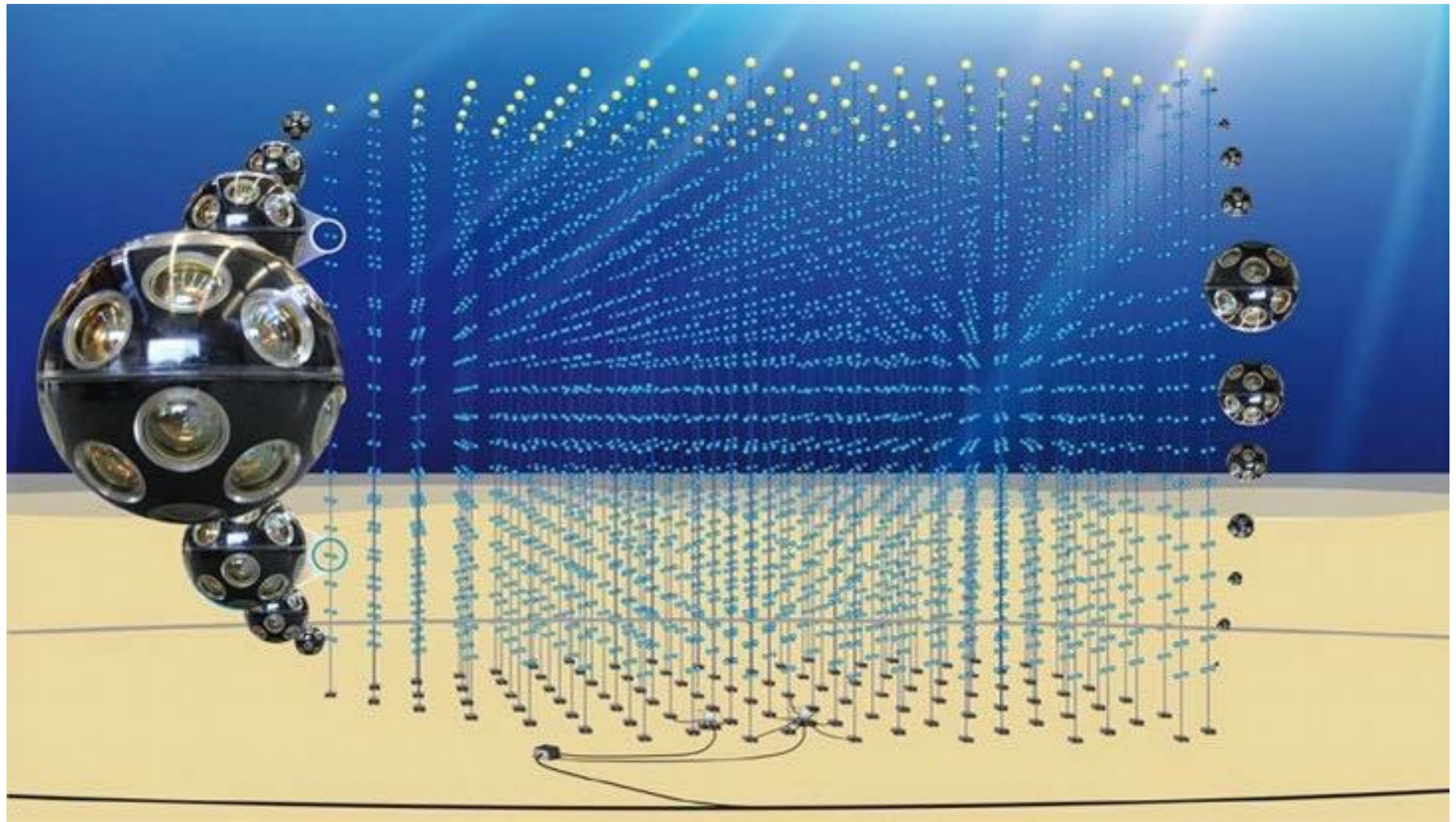


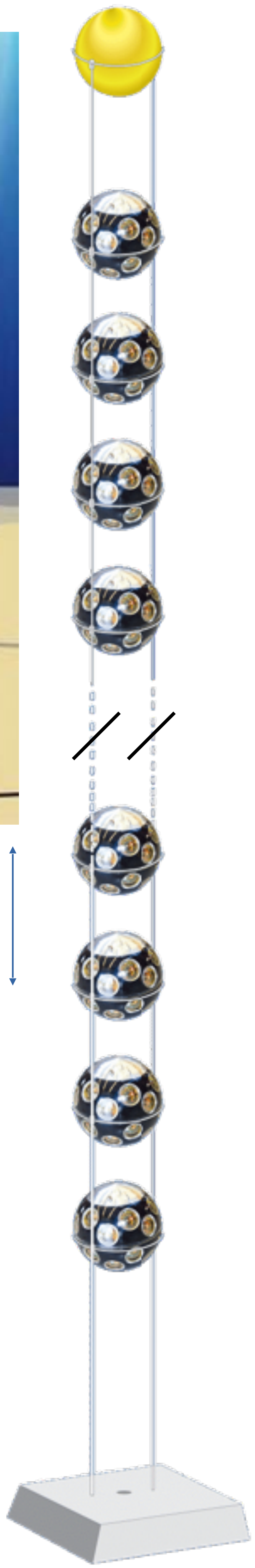
- 40 km offshore Toulon, France
- 2.5 km depth
- 885 optical modules on 12 strings
- ~ 12 Mton instrumented volume

ANTARES OM:
10” Hamamatsu PMT

- Array completed in 2008
- Dismantled in Feb 2022

KM3NeT – ARCA (under construction)





Mediterranean sea, 80 km offshore Sicily
Depth 3500 m

2 x 115 strings
18 DOMs / string
31 PMTs / DOM
Total: **128 000 PMTs (3”)**

36 m

Vertical spacing: 36 m
Horizontal spacing: 90 m

Digital Optical Module

17”

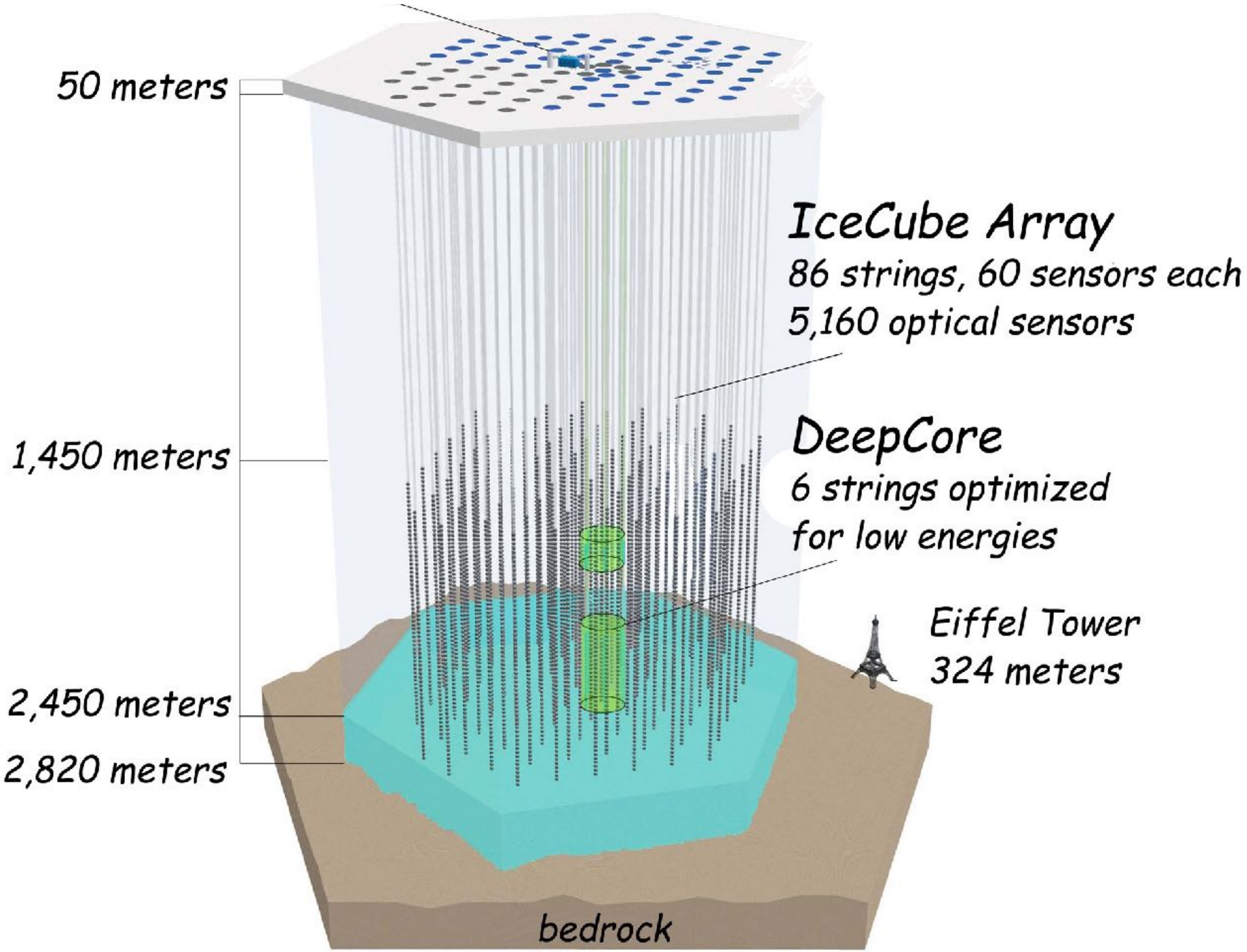
- 31 x 3” PMTs
- PMT HV
- LED & piezo
- FPGA readout
- DWDM

photocathode area similar to a 17” PMT

✓ Uniform angular coverage
✓ Directional information
✓ Digital photon counting
✓ All data to shore

Optical background (mainly ^{40}K): 5-10 kHz

IceCube under-ice neutrino telescope



- Construction started in 2005
- Complete in 2010
- 1 km^3-scale neutrino detector
- Still fully operational as of 2023

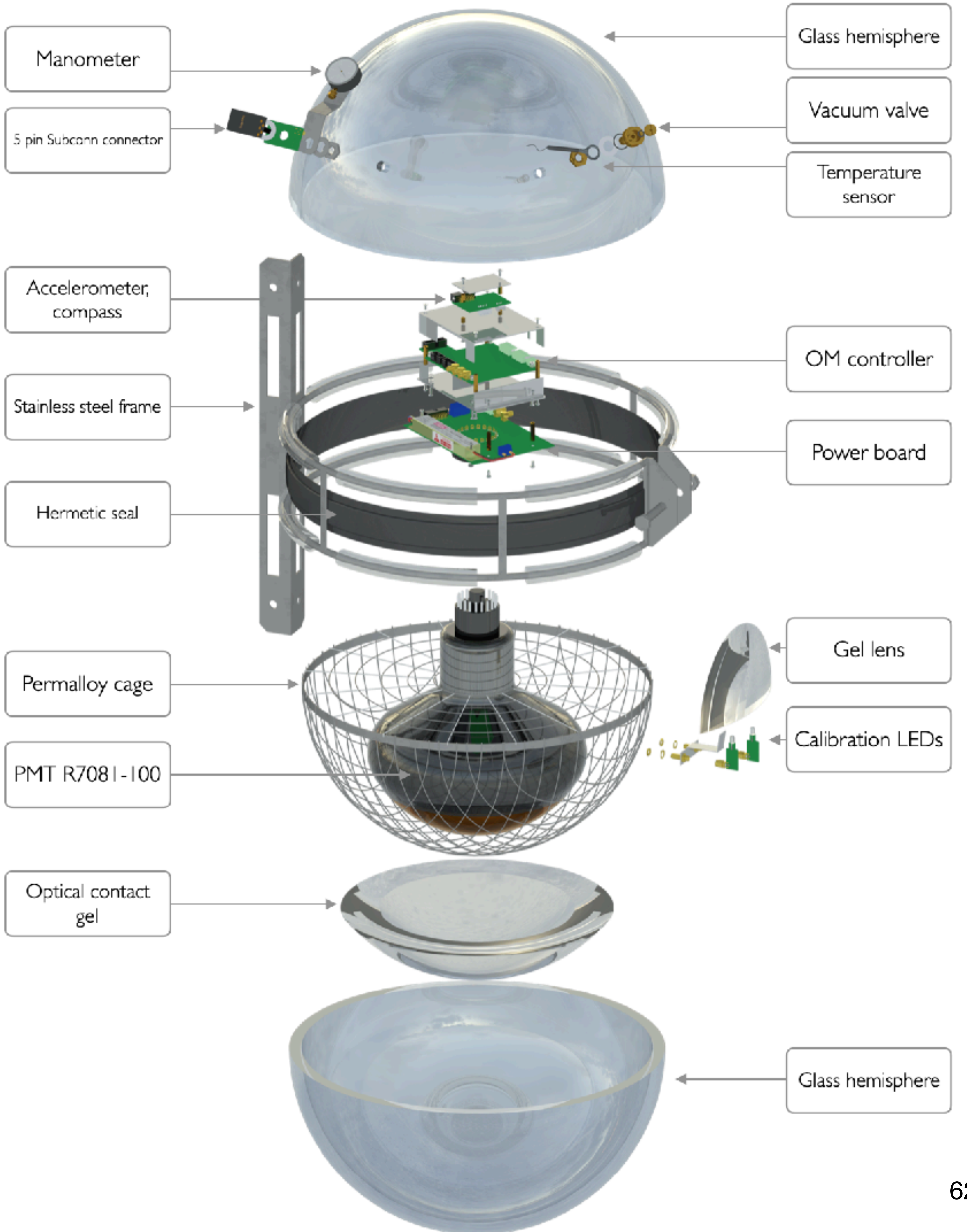
Evidence for High-Energy Extraterrestrial Neutrinos with IceCube (*Science* 2013, 342, 1242856)

Neutrino emission from the direction of the blazar TXS 0506+056 (*Science* 2018, 361, 147)

Optical module

internal structure

- 10” (25.4 cm) Hamamatsu R7081HQE, Qeff~0.35
- 17” (43 cm) VITROVEX glass sphere
- 5-pin deep-sea industrial Subconn connector
- 2-channel amplifier, controller, high voltage unit
- 2 calibration LEDs: 108 p.e., 430 nm, 5 ns
- Metal mesh
- Optical transparent gel
- Control: RS485 (monitoring of the rate of calculation of the PMT, values of high voltage, temperature)
- Consumption: max 0.3A x 12V
- Calibration of the signal transmission delay in the PMT (the difference between the test and LED pulses)

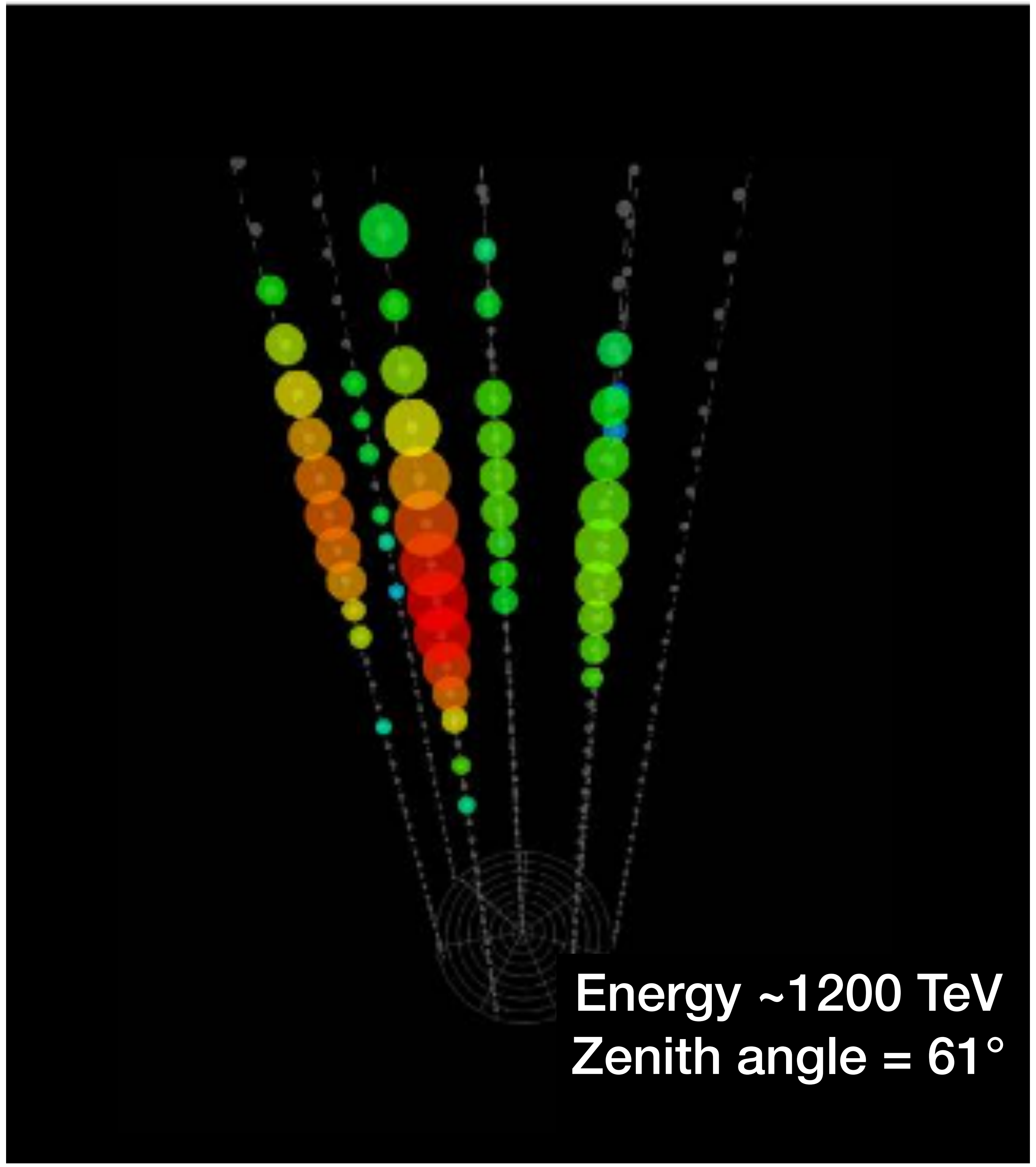


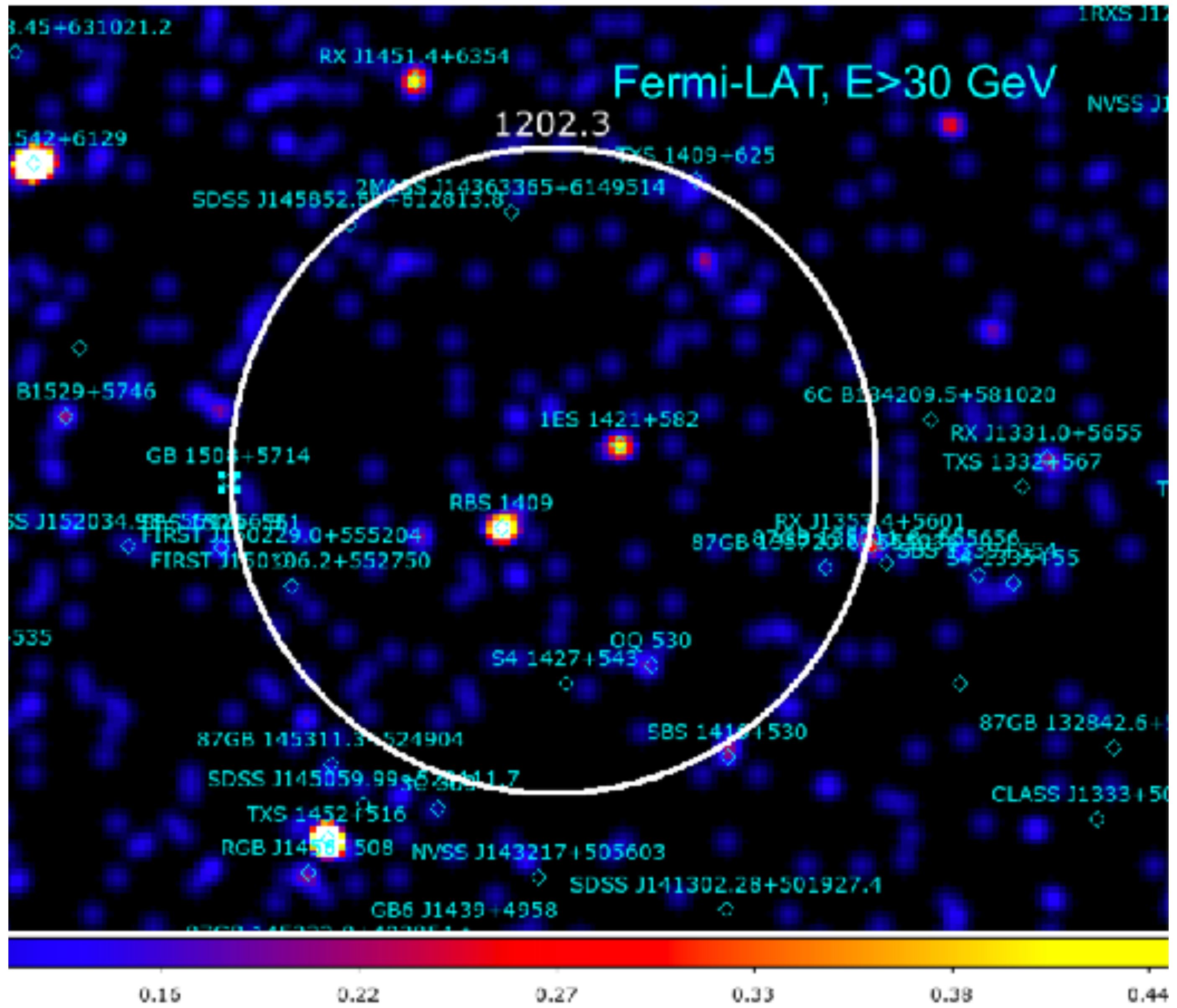
Infrastructure

1. New lab for long-term tests of the detector parts is operating in Dubna.
2. New OM production line started in Dubna. 12 OM per day
3. The control center at the Baikal shore installed in August 2016.
4. The building in Baikalsk town is prepared as a local lab and OM storage

PeV downgoing cascade

Most energetic cascade so far





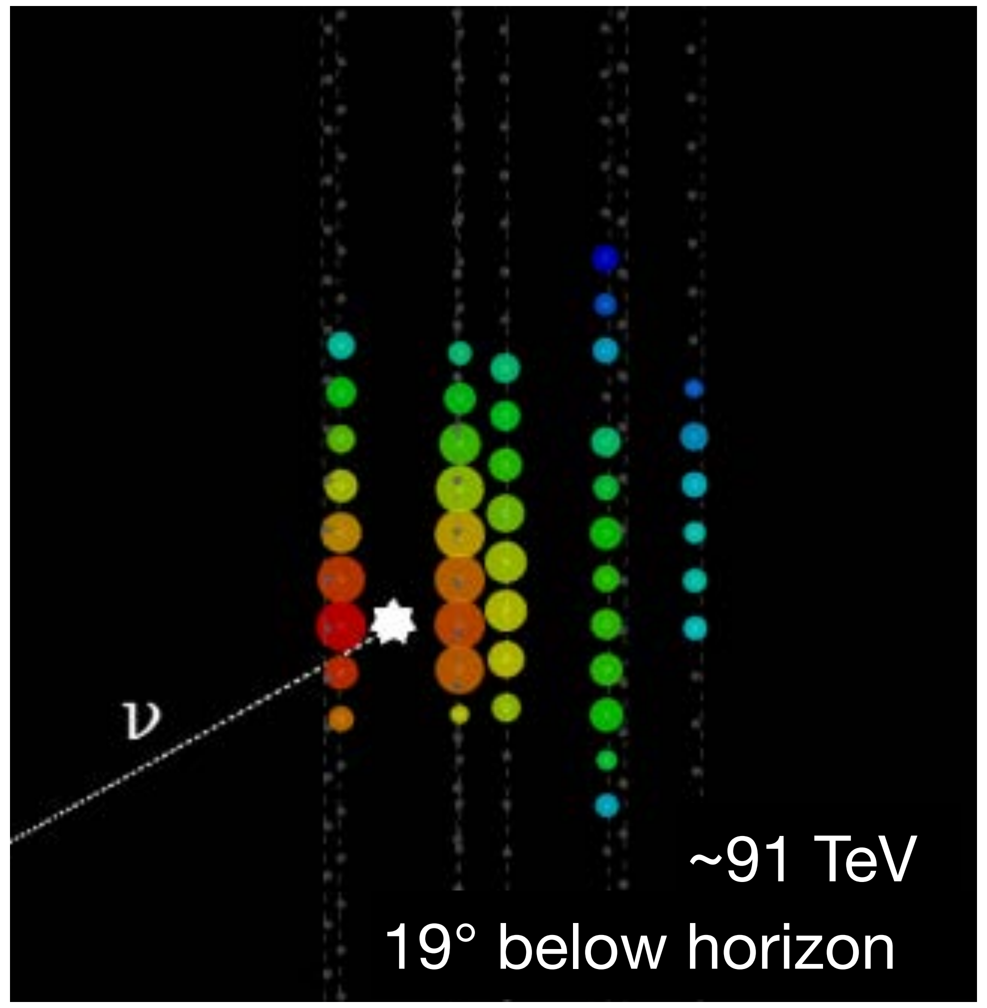
Sky plot of γ-ray sources and event uncertainty circle

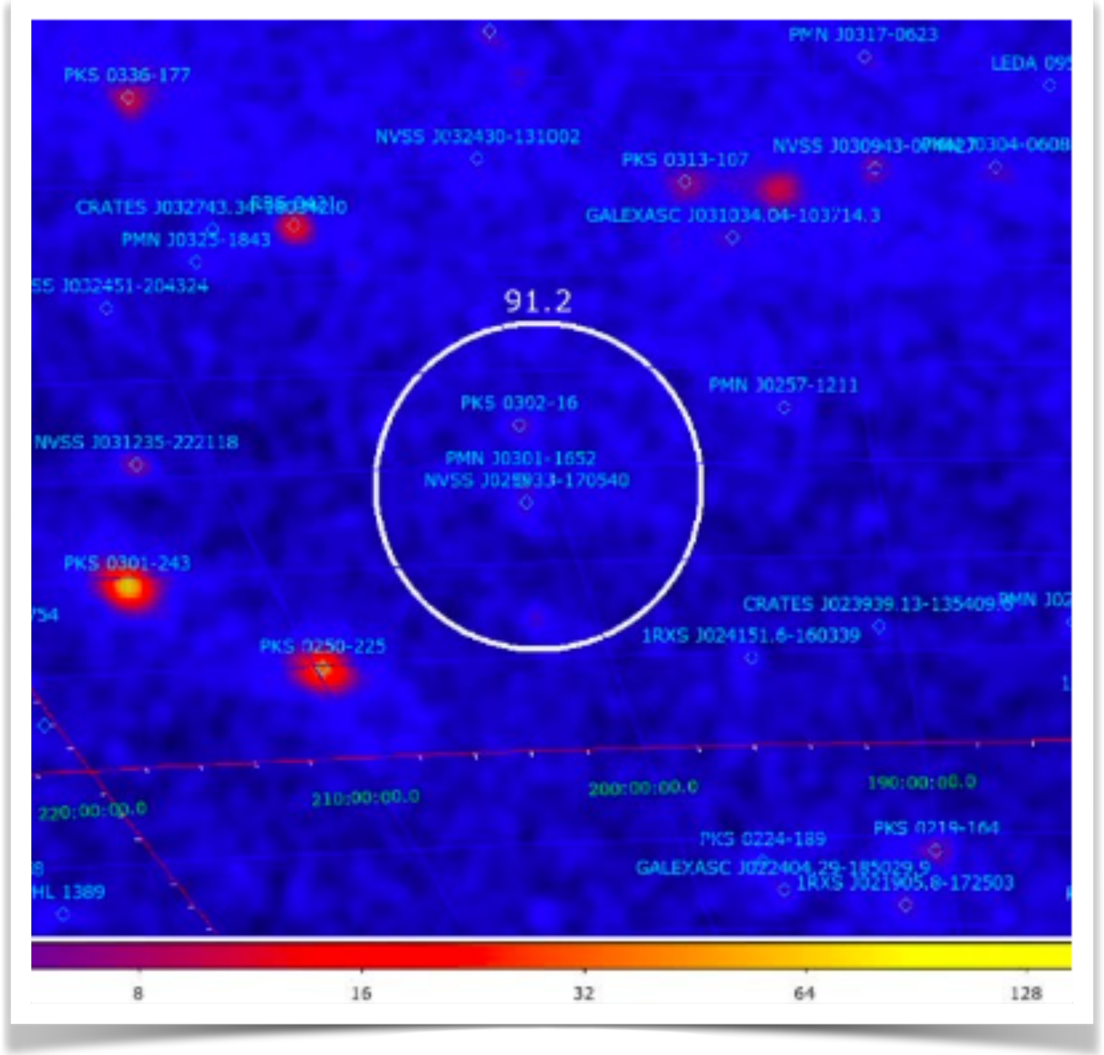
Closest sources (in 5 degrees):

- RBS 1409 BL Lac z=unknown
- 1ES 1421+582 z=unknown

Most energetic upgoing cascade events II

Best candidates for neutrino events of astrophysical origin



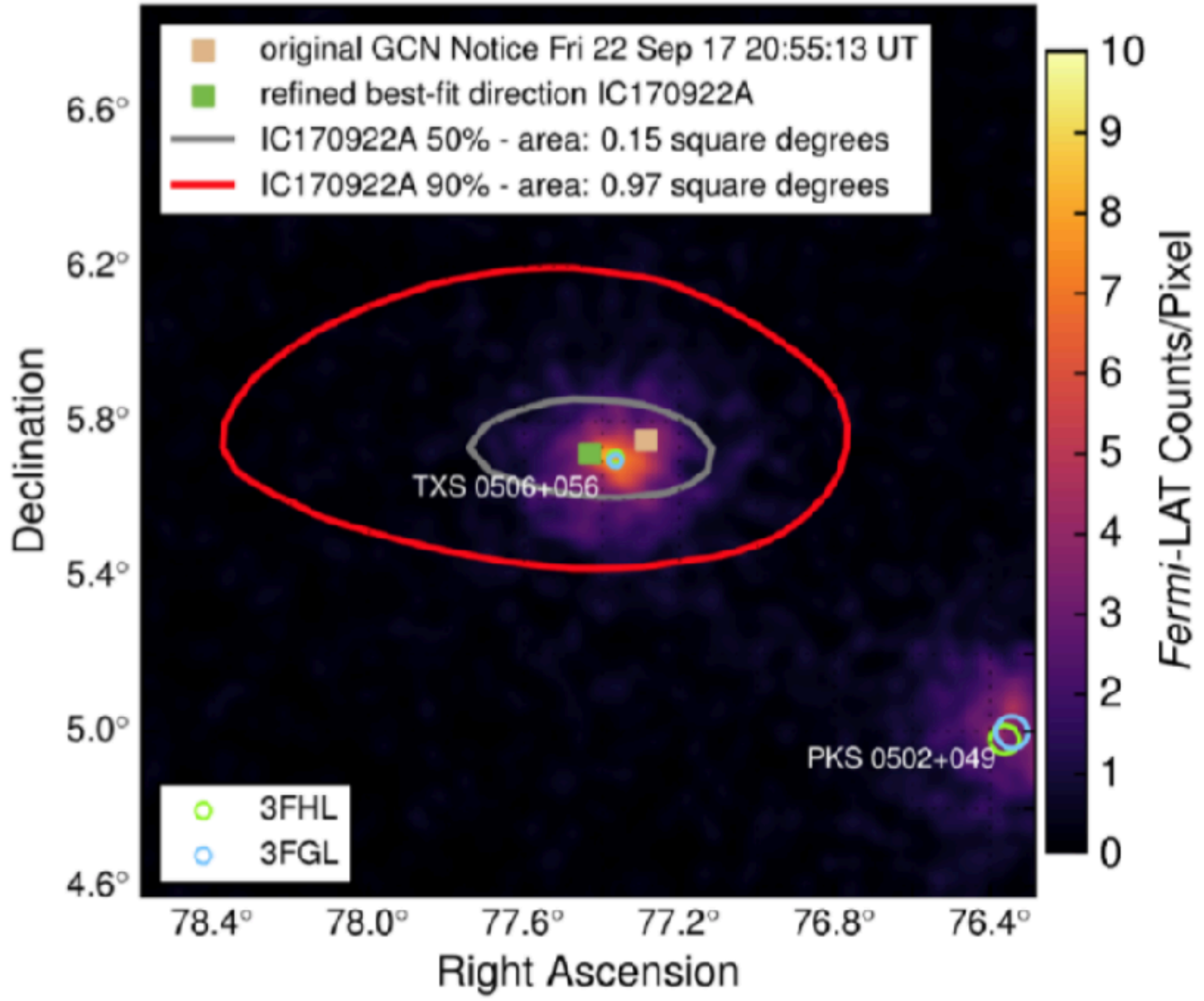


Sky plot of γ-ray sources and event uncertainty circle

Closest sources (in 3 degrees):

- PKS 0302-16 : unknown type of source
- PMN J0301-1652 : unknown type of source

TXS 0506+056: First evidence of a ν source



Science 361 (2018) eaat1378
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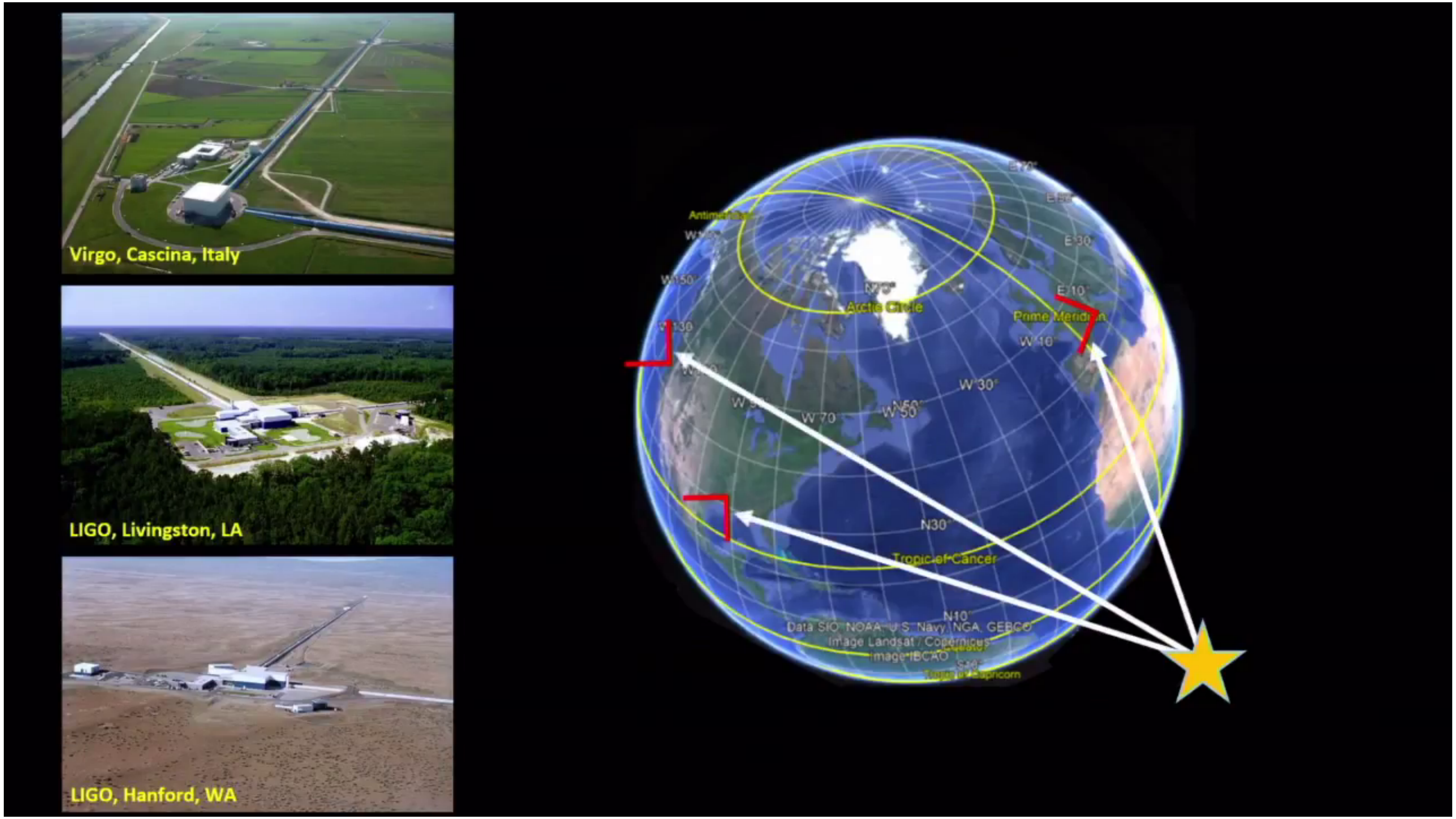
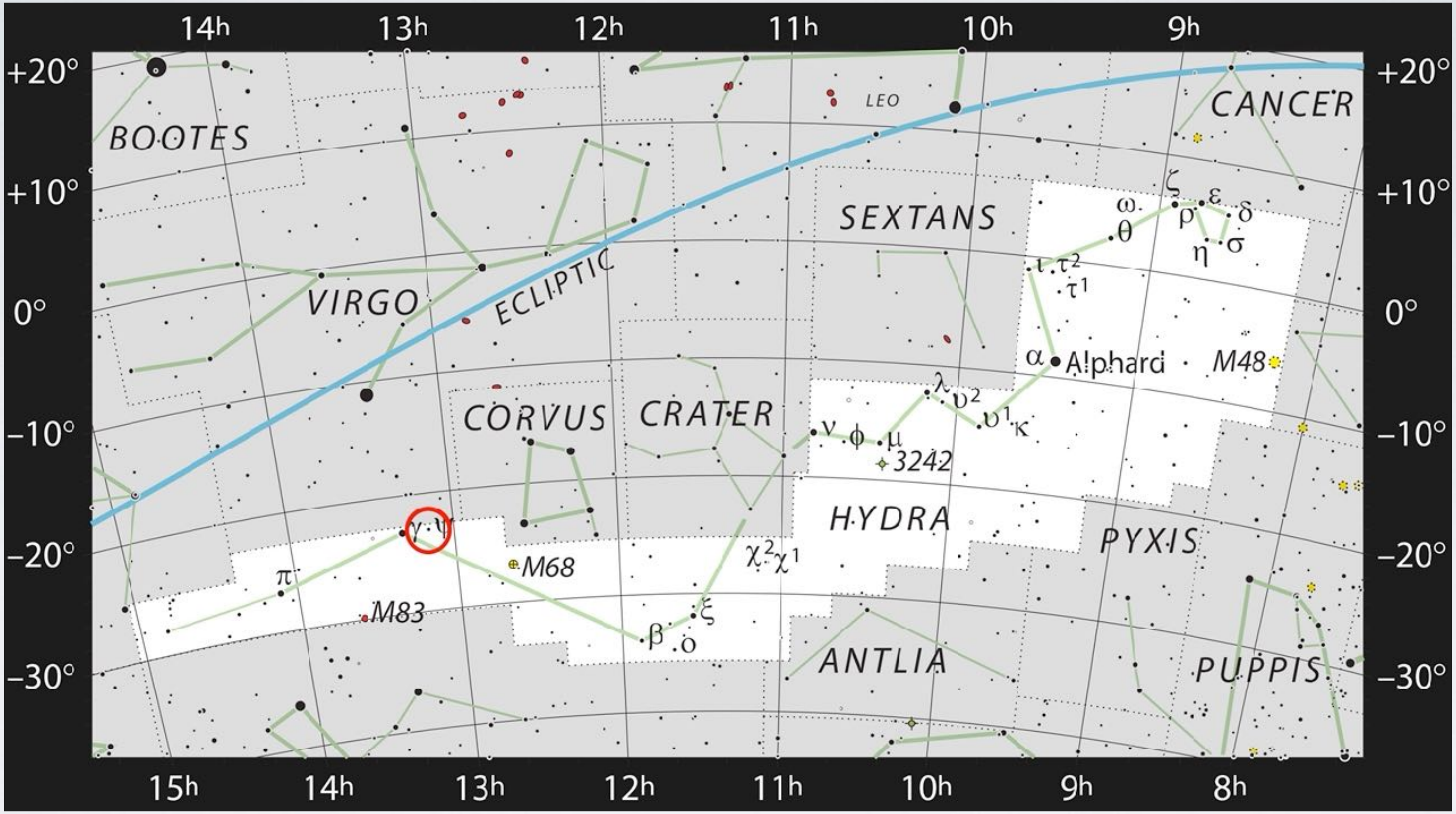
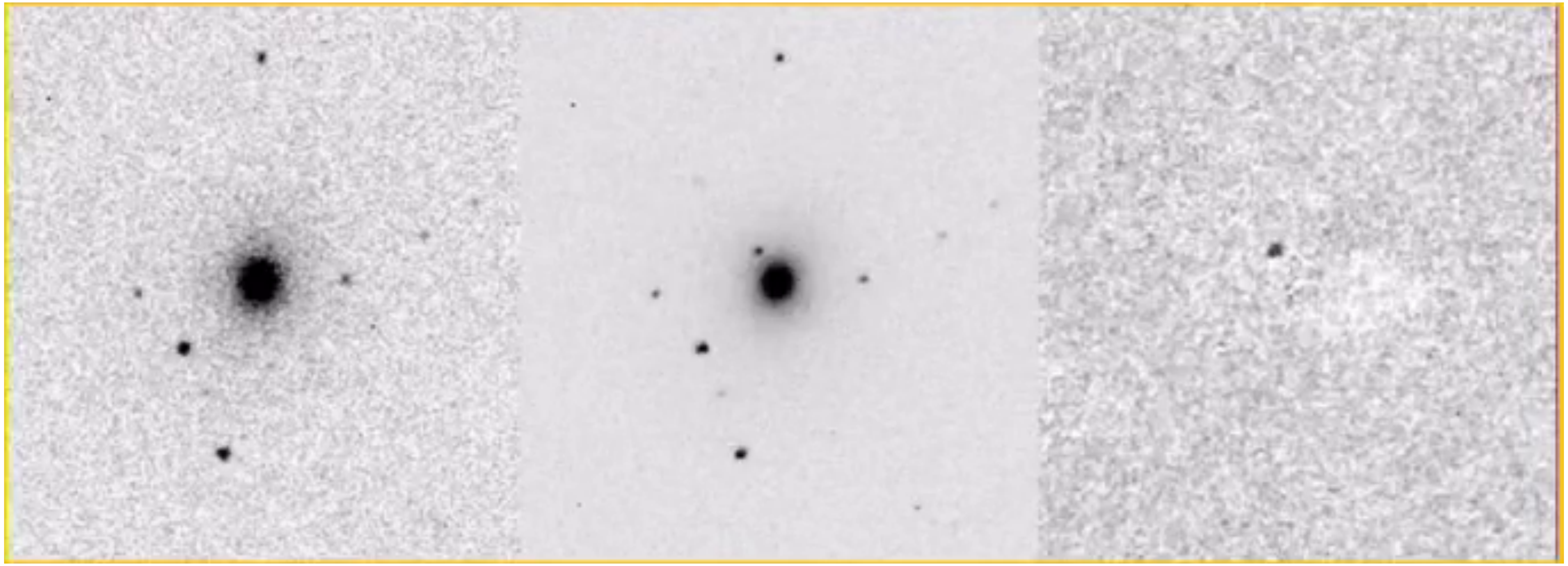

Virgo, Cascina, Italy
LIGO, Livingston, LA
LIGO, Hanford, WA
Arctic Circle
Tropic of Cancer
W 30°
W 70°
N30°
N10°
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat / Copernicus
Image IBCAO


14h 13h 12h 11h 10h 9h
+20° +10° 0° −10° −20° −30°
15h 14h 13h 12h 11h 10h 9h 8h
BOOTES
LEO
CANCER
SEXTANS
VIRGO
ECLIPTIC
Alphard
M48
CORVUS
CRATER
3242
HYDRA
PYXIS
M68
M83
ANTLIA
PUPPIS



Before After Difference

Hubble telescope