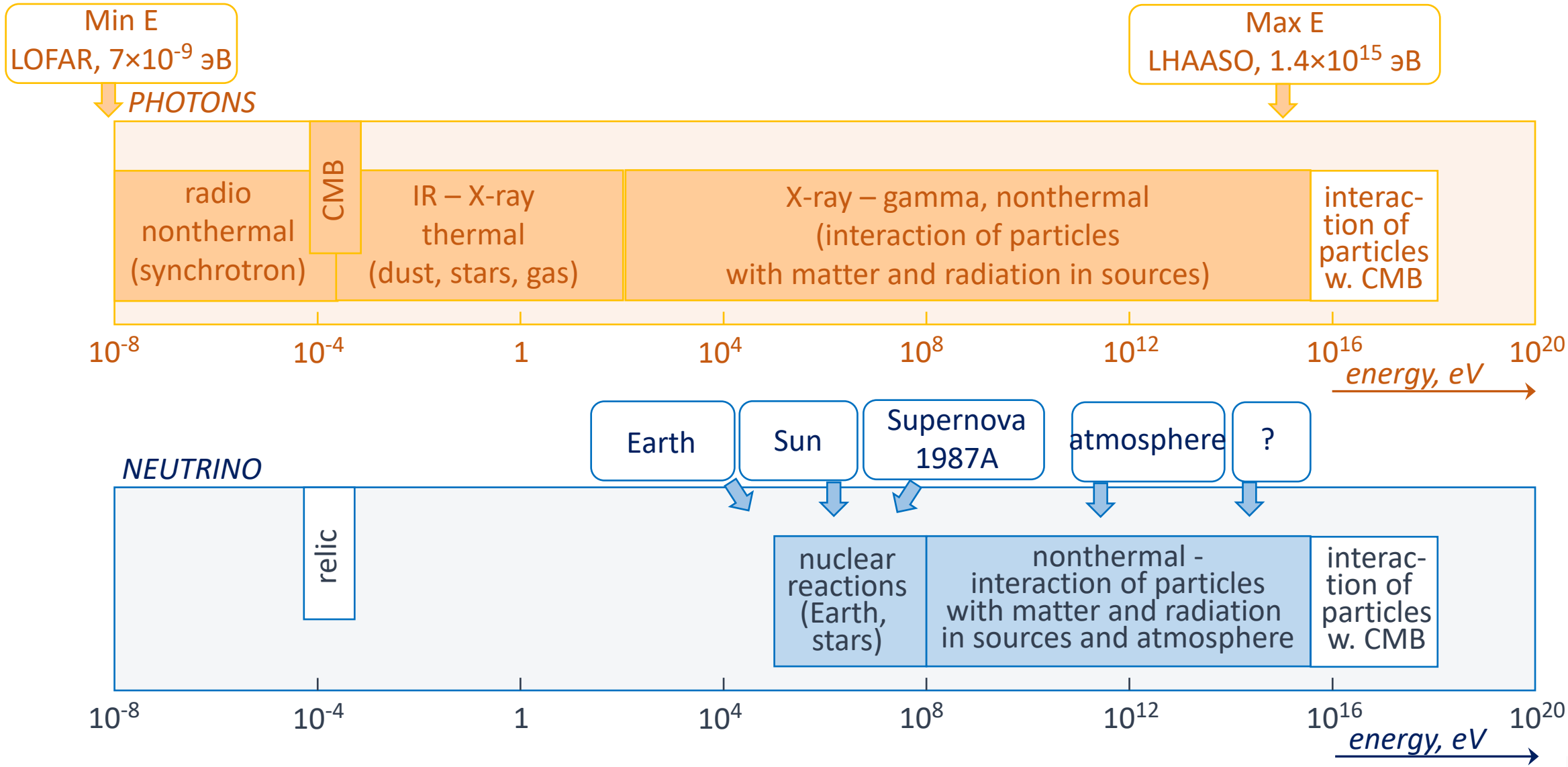
High-energy neutrino astrophysics

Sergey Troitsky
(INR, Moscow)

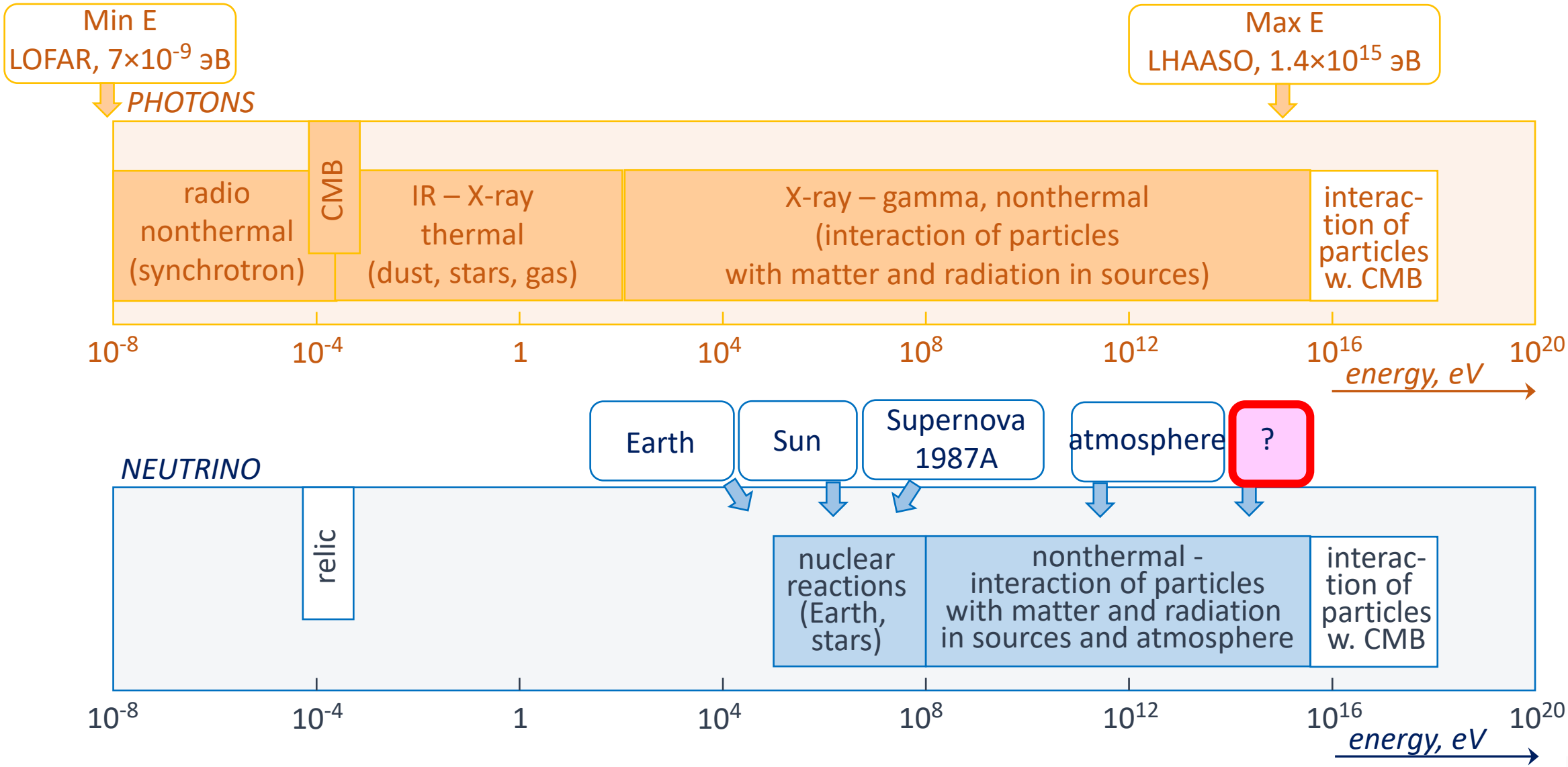
QFT, HEP, cosmology:

Dubna, 19.07.2022

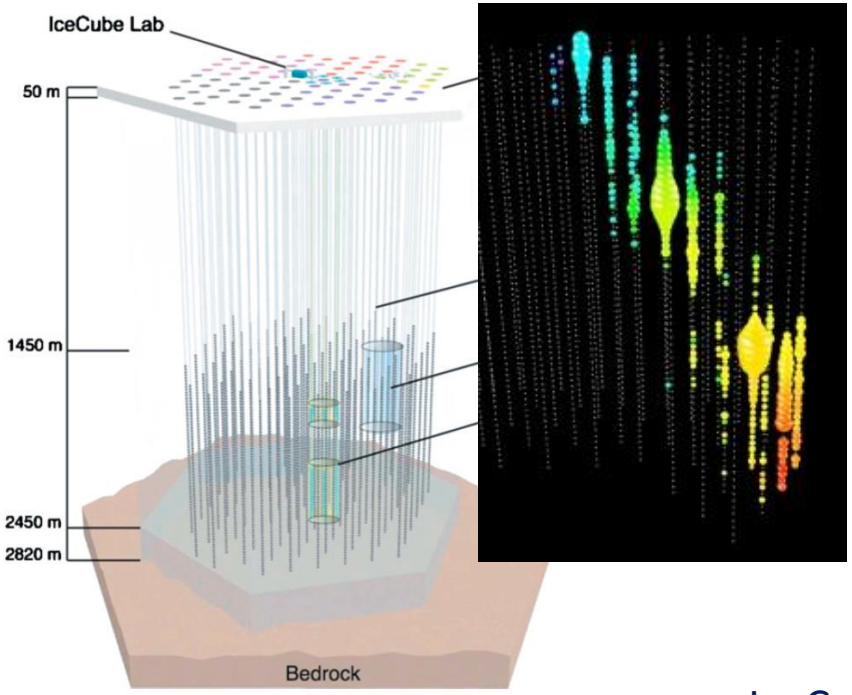
Natural sources of photons and neutrinos

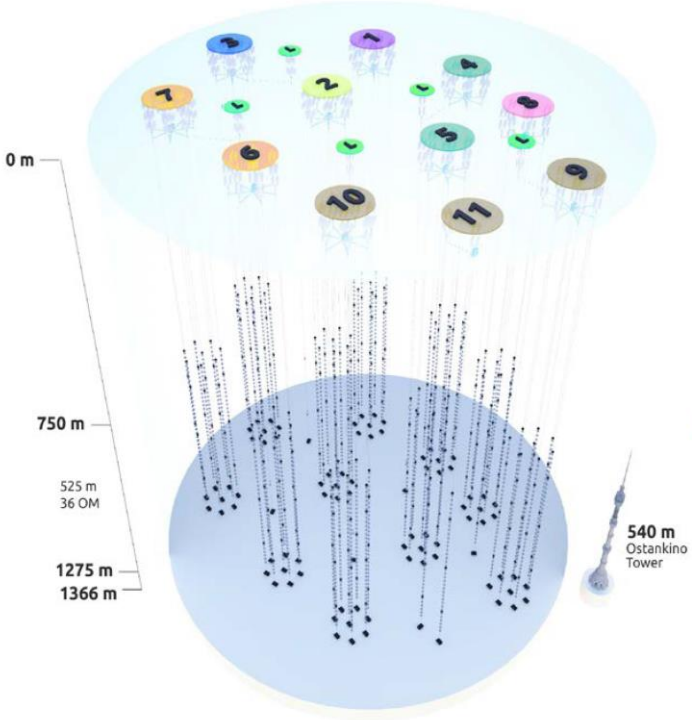


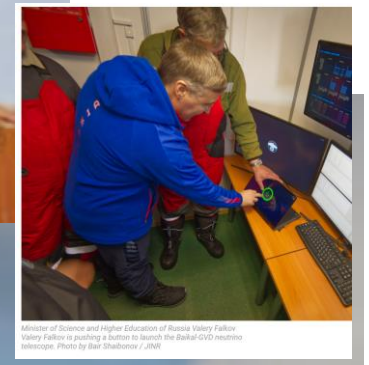
Natural sources of photons and neutrinos

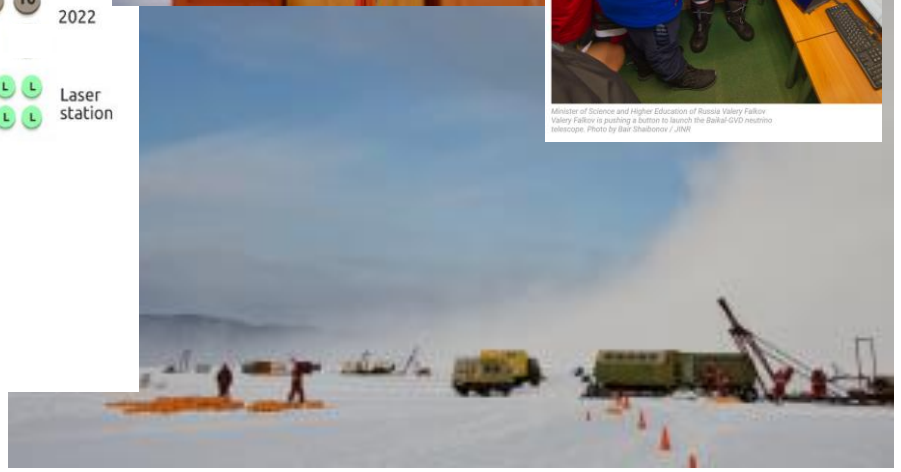


High-energy neutrinos









IceCube:

- South Pole, operates since 2008
- discovery of extraterrestrial neutrinos >60 TeV
- neutrino sources unknown!

KM3NeT:

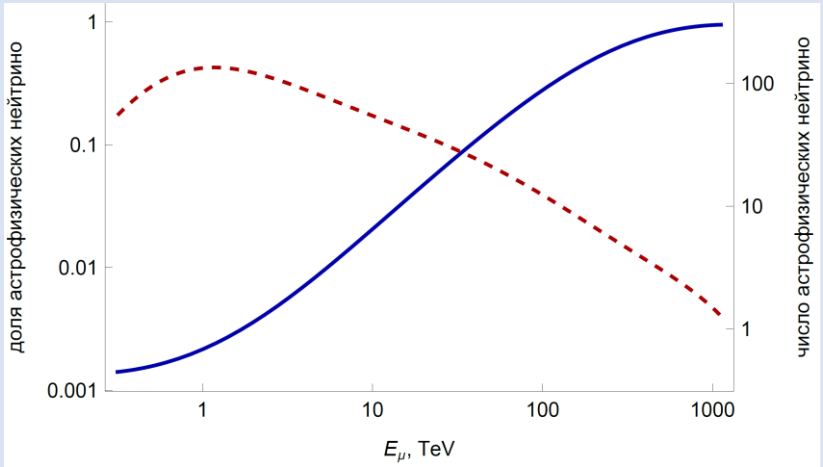
- Mediterranean Sea, developing

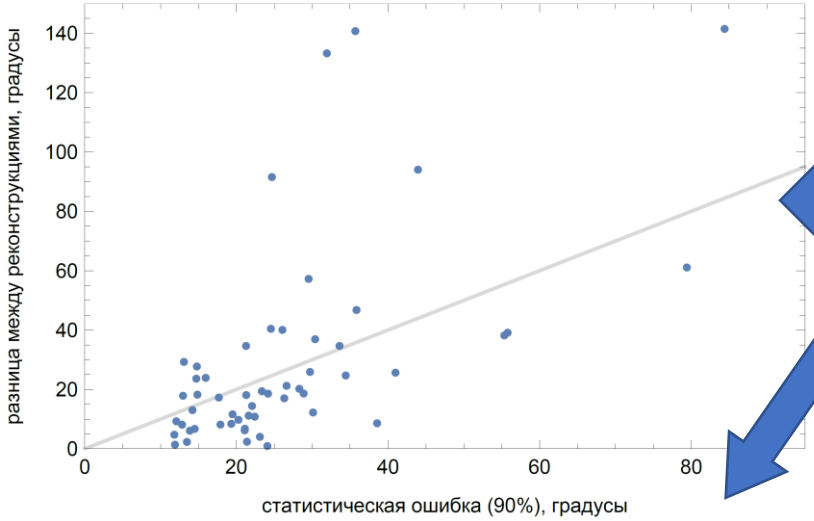
Baikal-GVD:

- neutrino arrival directions in water more precise than in ice
- commissioned in 2021, but data collection since 2017 in incomplete configuration
- Baikal-GVD effective volume in one of registration modes of order of IceCube effective volume
- South+North = full-sky observations in neutrino

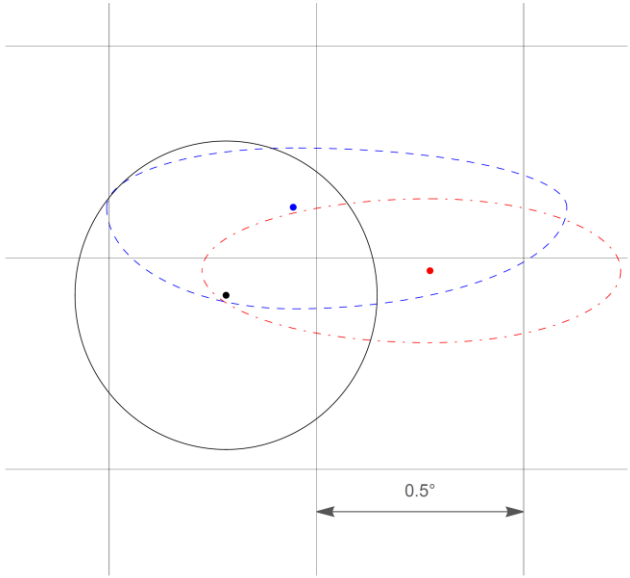
Complications...

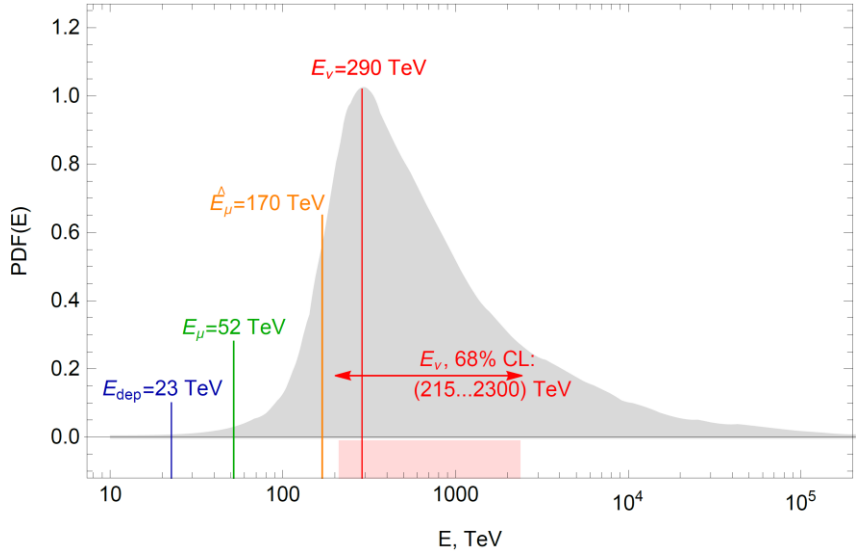
- Lots of neutrinos are born in the atmosphere, so it is complicated even to determine the astrophysical origin.



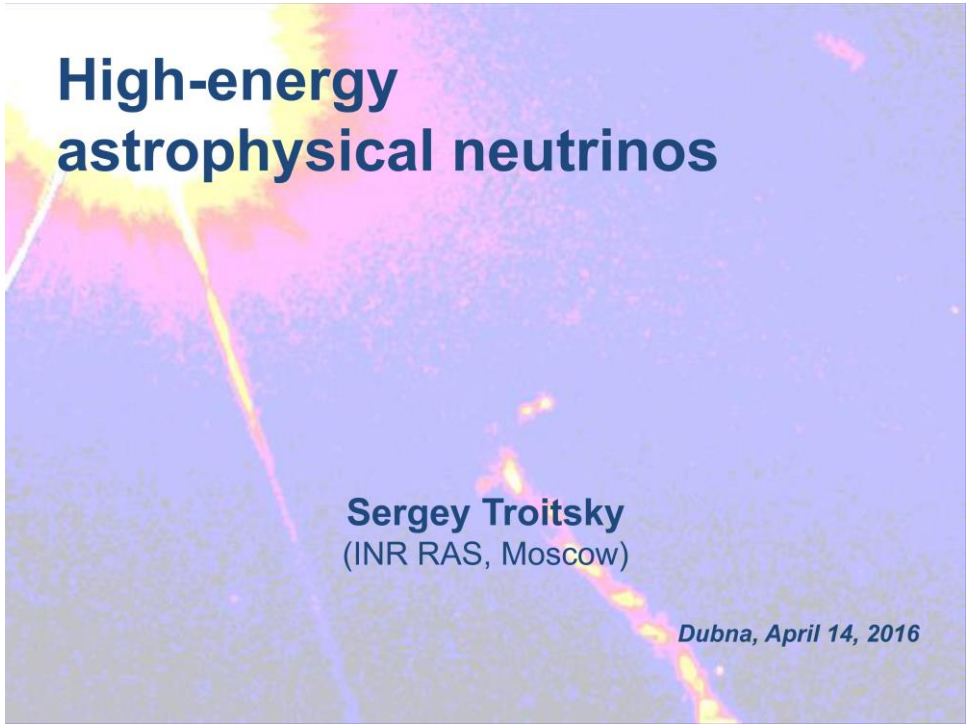


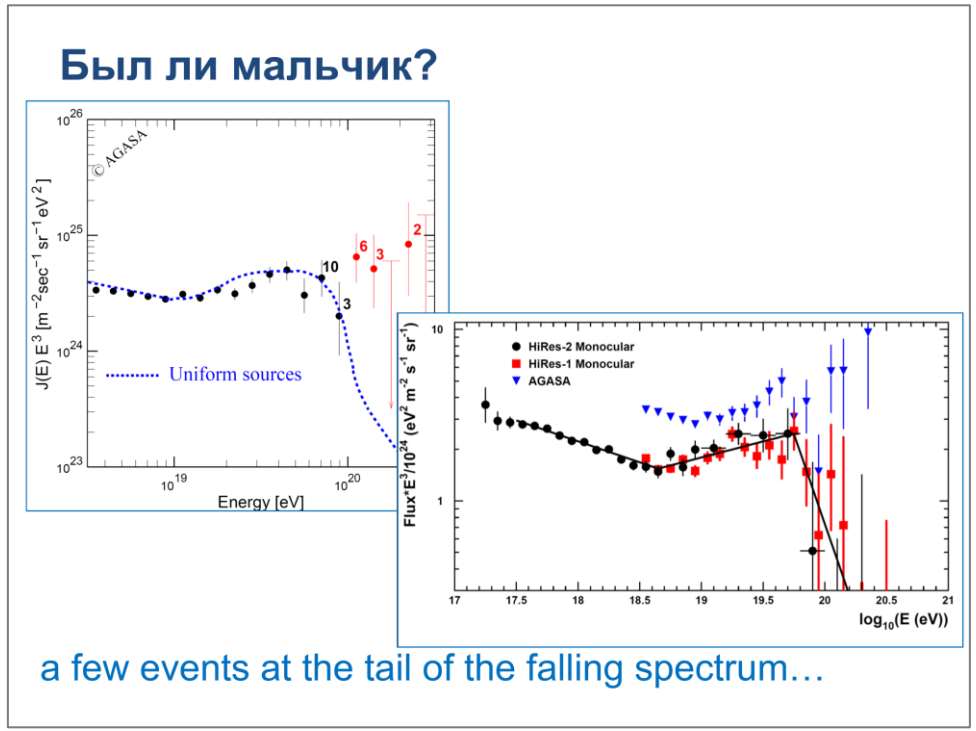
- Low accuracy of determination of arrival directions and energies of neutrinos.
- Large systematic errors.





High-energy astrophysical neutrinos 2016: evidence from a single experiment

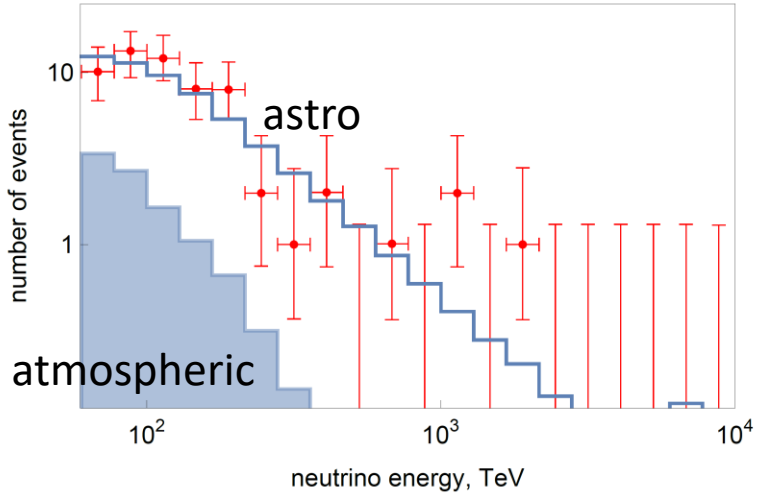


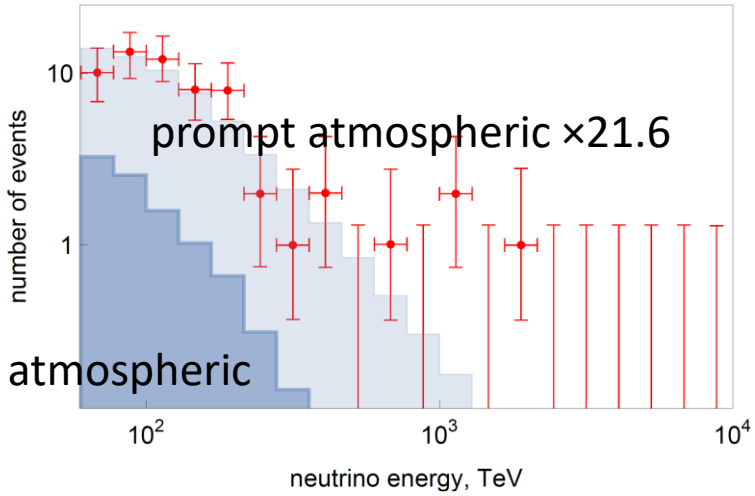


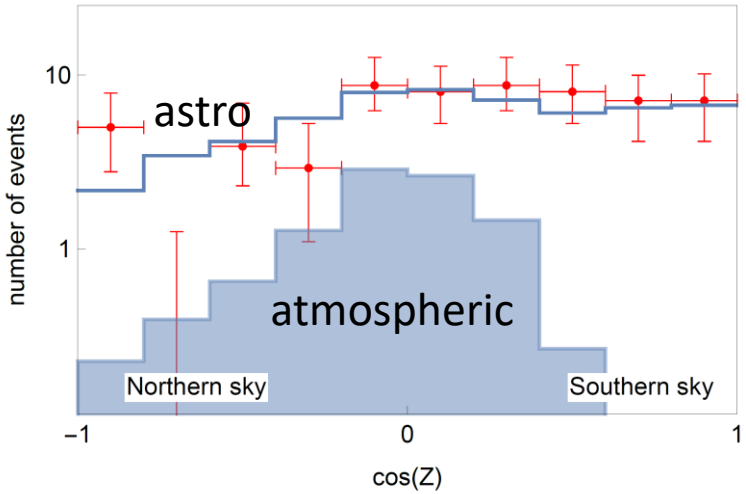
Until 2020, only one experiment (IceCube) claimed HE astrophysical neutrinos

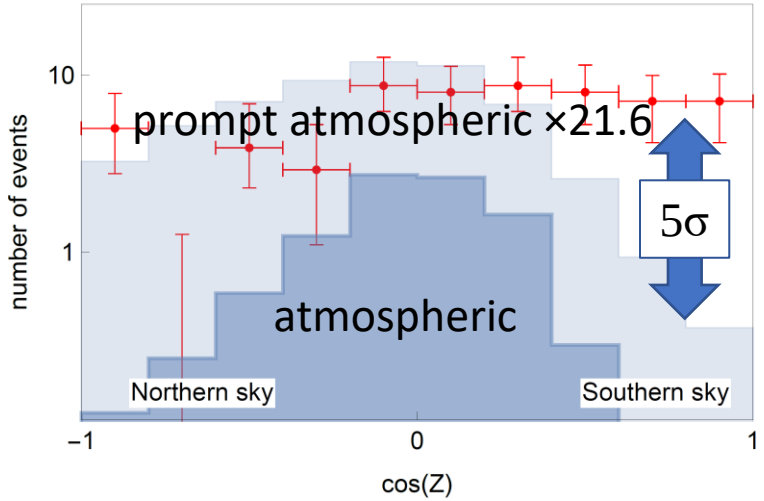
High-energy astro neutrinos: confirmations, 2020

- IceCube 2020, 5 sigma

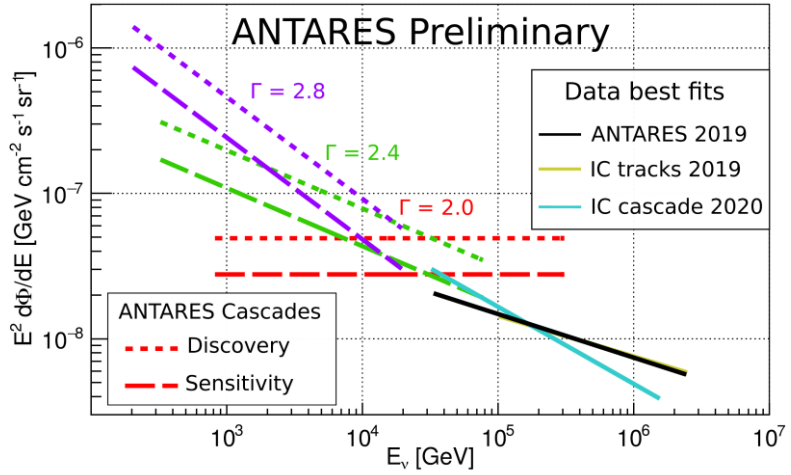








- ANTARES 2020, 2 sigma



High-energy astro neutrinos: Baikal-GVD confirmation (new!)

Search for upward moving events

Preliminary!

Additional selection requirements

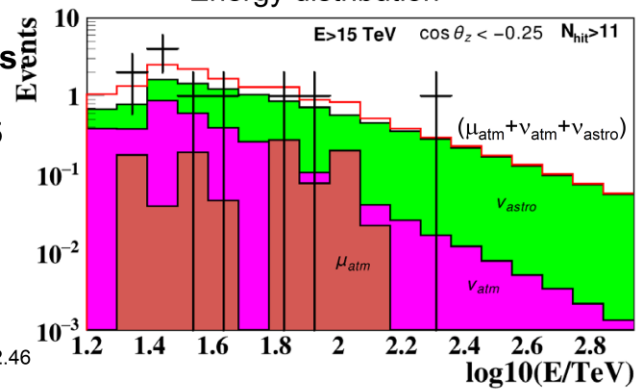
E > 15 TeV & N_{hit} >11 & $\cos\theta_z$ < -0.25

11 - data events have been selected
0.95 - events from atm. muons
3 - events from atm. neutrinos
10.3 - events are expected from IC $E^{-2.46}$ astrophysical flux

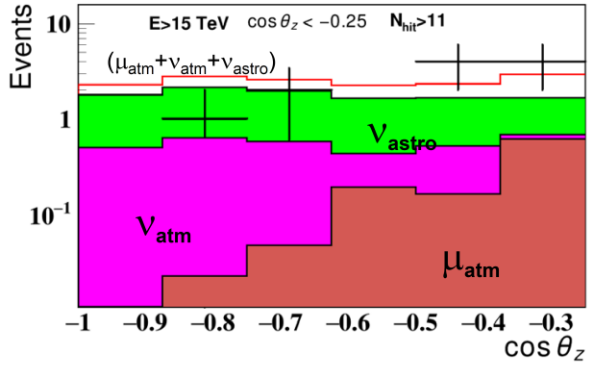
Probability for the background-only hypothesis (stat. errors only):

P-value = 0.00268 (3σ)

Energy distribution



Zenith angular distribution



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Combined analysis of upward moving events and downward moving HE cascades

Preliminary!

25 data events have been selected
9.7 events are expected from atm. muons
3.4 events are expected from atm. neutrinos
16 events are expected from IC $E^{-2.46}$ diffuse astrophysical neutrino flux

P-value = 0.0022 (3σ)

Baikal-GVD confirms IceCube observation of astrophysical diffuse neutrino flux at 3σ level !

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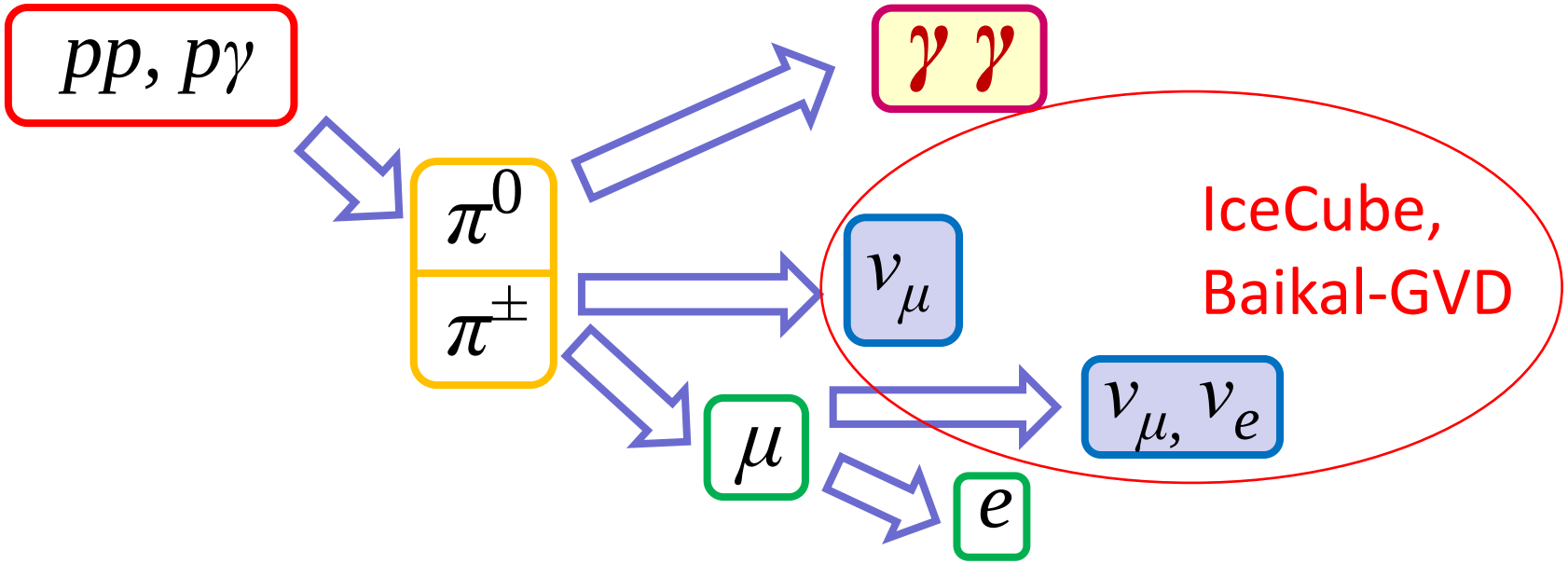
slides from Zh.-A. Dzhilkibaev's invited talk at Neutrino-2022 (June) – paper in preparation

мальчик был

High-energy neutrinos require relativistic protons



- ✓ Energies above 1 ТэВ – nonthermal origin
- ✓ Standard physics – only processes with accelerated hadrons

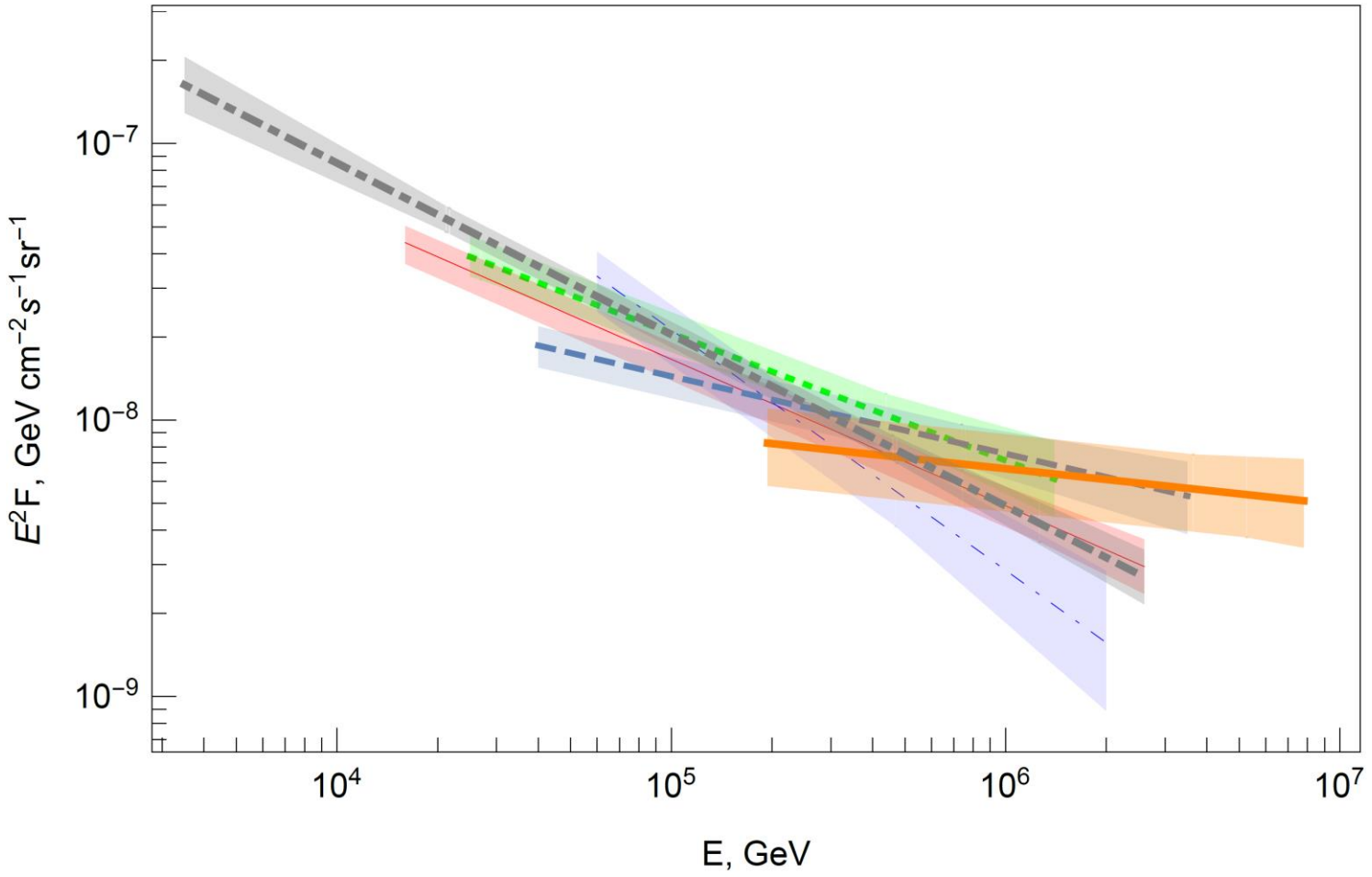
Neutrino is a marker of relativistic protons and nonthermal processes

Spectral measurements suggest two components

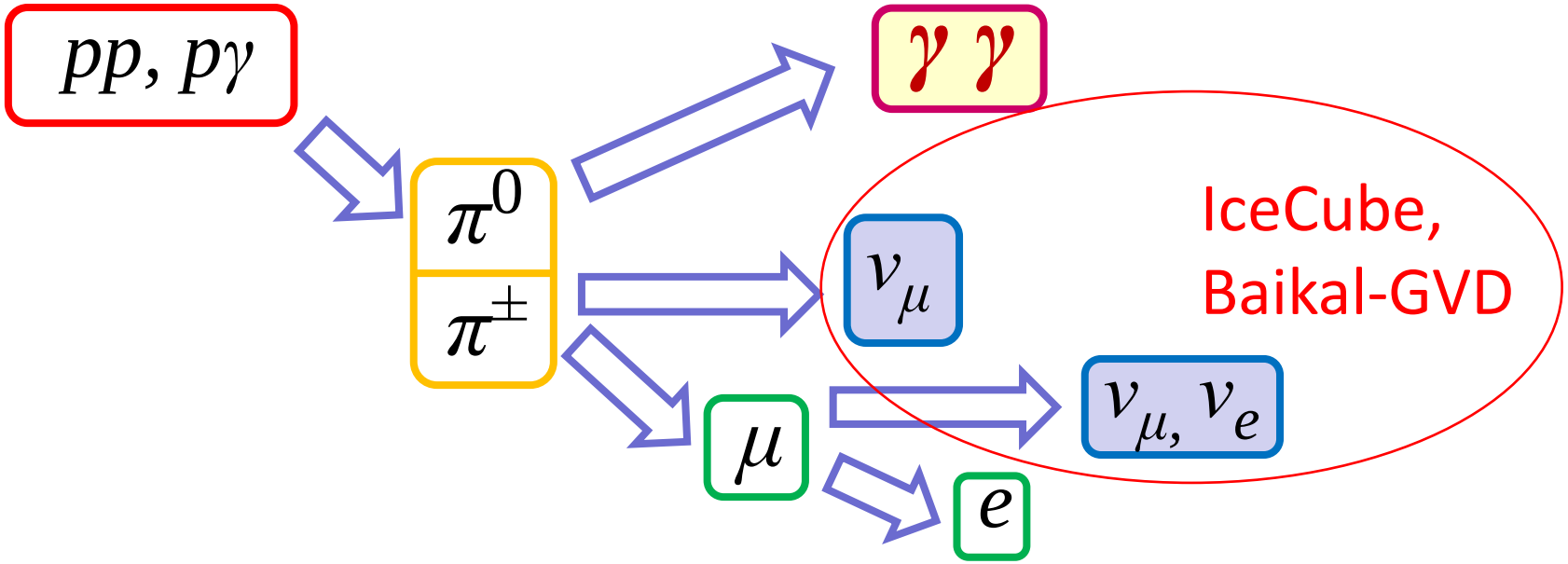
IceCube: multiple analyses

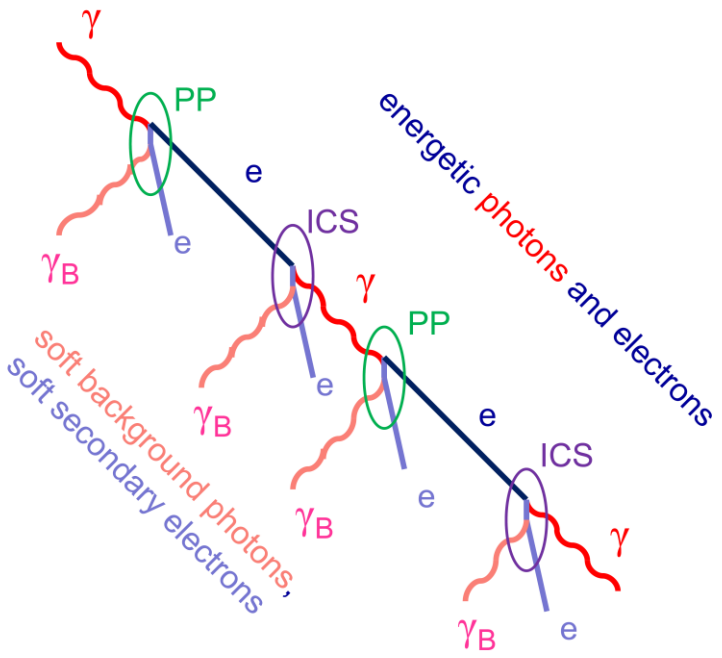
- in every analysis, best-fit is power-law
- but slopes disagree...

Analysis	Energy	Φ_0	γ
HESE 2020 [24]	69.4 TeV–1.9 PeV	$2.12^{+0.49}_{-0.54}$	$2.87^{+0.20}_{-0.19}$
Cascades $\nu_e + \nu_\tau$ 2020 [30]	16 TeV–2.6 PeV	$1.66^{+0.25}_{-0.27}$	2.53 ± 0.07
MESE 2014 [31]	25 TeV–1.4 PeV	$2.06^{+0.4}_{-0.3}$	2.46 ± 0.12
Inelasticity 2018 [32]	3.5 TeV–2.6 PeV	$2.04^{+0.23}_{-0.21}$	2.62 ± 0.07
ν_μ 2016 [17]	194 TeV–7.8 PeV	$0.90^{+0.30}_{-0.27}$	2.13 ± 0.13
ν_μ 2019 [25]	40 TeV–3.5 PeV	$1.44^{+0.25}_{-0.24}$	$2.28^{+0.08}_{-0.09}$
ANTARES 2019 [28]		1.5 ± 1.0	2.3 ± 0.4



Neutrino astronomy and gamma rays





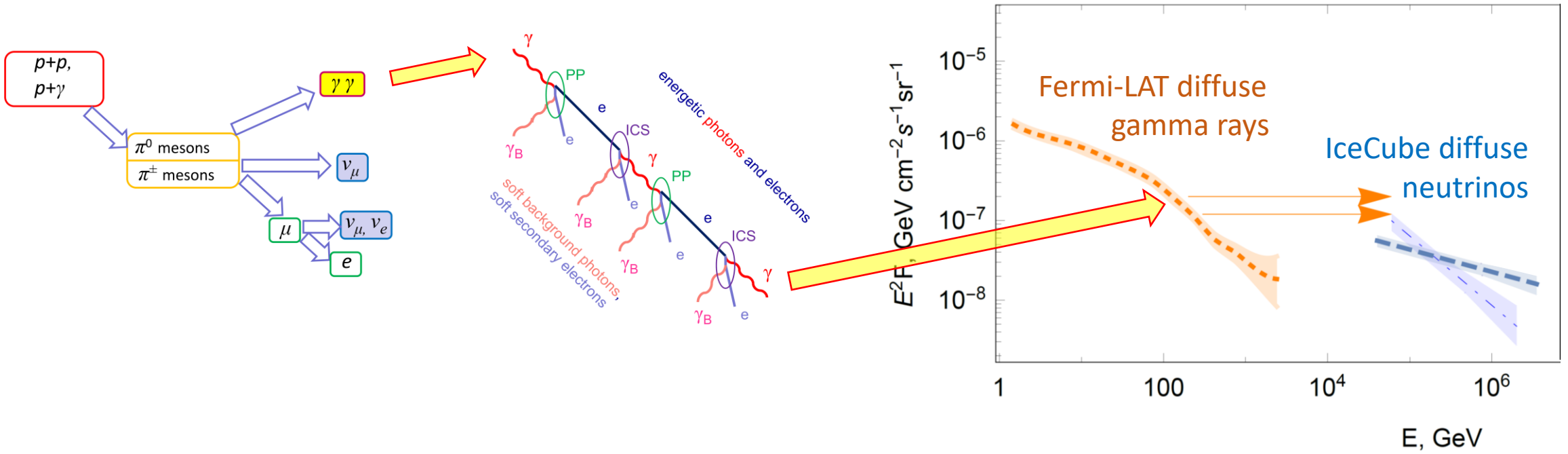
✓ High-energy (E>100 TeV) astrophysical neutrinos are accompanied by high-energy photons, if they are born in π-meson decays

✓ Cascades on CMB ⇨ (for extragalactic sources) the energy is transferred to the GeV band

✓ Nonthermal radiation (radio and gamma) accompanies the acceleration of particles to the required energies

Search for high-energy photons = a tool to understand the neutrino origin

A Galactic component at low energies?



- Thanks to cascades, accompanying photons reemit their energy at TeV and overshine Fermi-LAT measured fluxes
- Galactic sources are too close, no time to develop cascades – no tension

Blazars: motivation and “the gamma-ray story”

- ✓ Active galactic nuclei (AGN) are powerful astrophysical accelerators, potential sources of high-energy neutrinos

  Berezinsky 1978, Eichler 1979, Berezinsky&Ginzburg 1981, ...

- ✓ Blazars = AGN with relativistic jets pointing to the observer (Doppler boosting of the neutrino flux is possible)

- ✓ Coincidence of one IceCube event (22.09.2017, E>200 TeV) with a gamma-ray flare of the TXS 0506+056 blazar *IceCube 2018a [Science]*
- ✓ Lower-energy neutrino flare from the same direction (2014, no gamma-ray flare) *IceCube 2018b [Science]*

- ✓ Population studies of gamma-ray-loud blazars: they **cannot** be the sources of the dominant part of events detected by IceCube *Ptitsyna et al. 2016, Murase et al. 2018, ...*

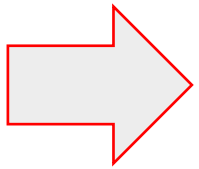
collective opinion of “the neutrino community”:
- *blazars = gamma-ray loud blazars,*
- *TXS 0506+056 = a miraculous, unique source*

High-energy neutrinos from radio blazars?

- ✓ TXS 0506+056 is a typical gamma- and radio-loud blazar *Kovalev et al. 2019, …*
- ✓ Blazars are AGN with relativistic jets pointing to us, they can be selected by their VLBI flux (compact cores)
- ✓ Not all blazars are gamma-ray loud, but TXS 0506+056 is bright both in VLBI and gamma

~~*collective opinion of "the neutrino community":*~~
~~- *blazars = gamma-ray loud blazars,*~~
~~- *TXS 0506+056 = a miraculous, unique source*~~

a possible way to the solution:
- *neutrino sources = VLBI-bright blazars,*
- *TXS 0506+056 = a typical radio blazar*



- ✓ catalog of blazars: a complete isotropic sample, selected by the VLBI flux *(note there are >3500 of them, while only <500 of gamma-ray loud)*
  - coincidence of neutrino arrival directions with blazar positions?
  - relation to the VLBI flux?
  - neutrino arrival times and radio flares?

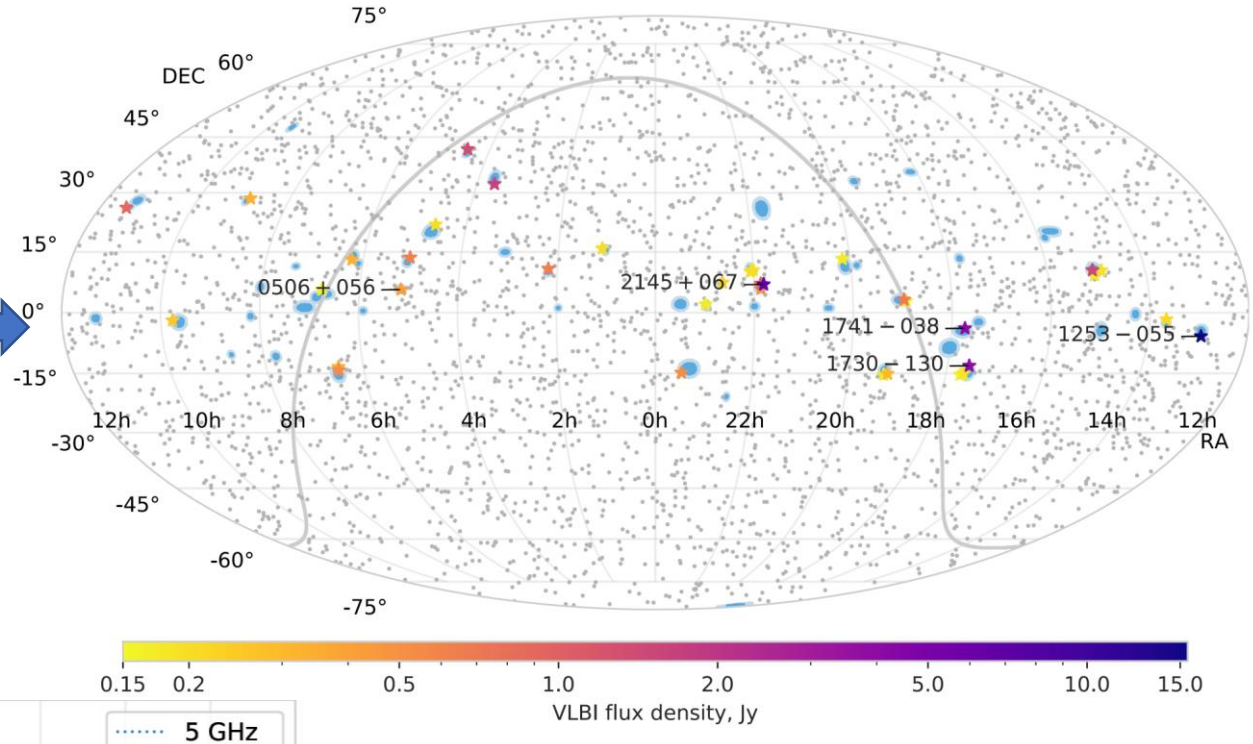
High-energy neutrinos from radio blazars!

E>200 TeV

Plavin et al., Astrophys.J. 894 (2020) 101

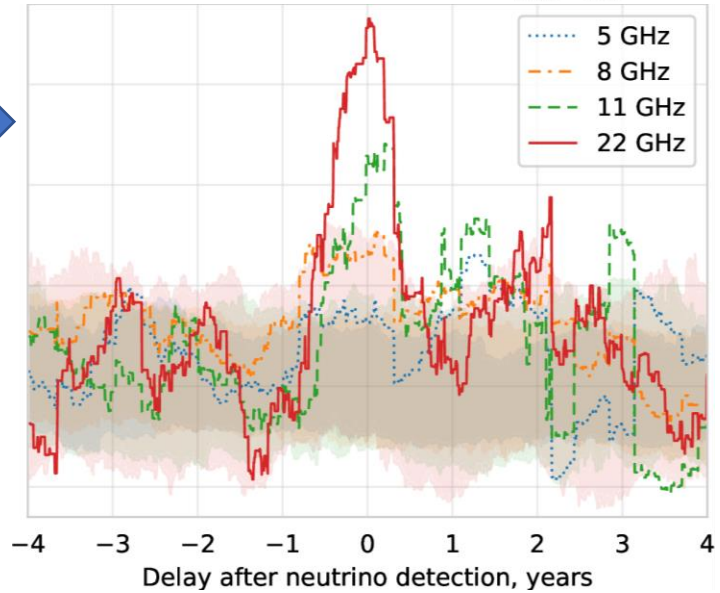
- Neutrino arrival directions coincide with radio blazars with higher VLBI flux

statistical effect,
but dominated by 4 strong sources:
1253-055 = 3C 279, 1730-130, 1741-038, 2145+067
statistical significance = 3.1σ post trial



- Neutrino arrival times coincide with radio flares

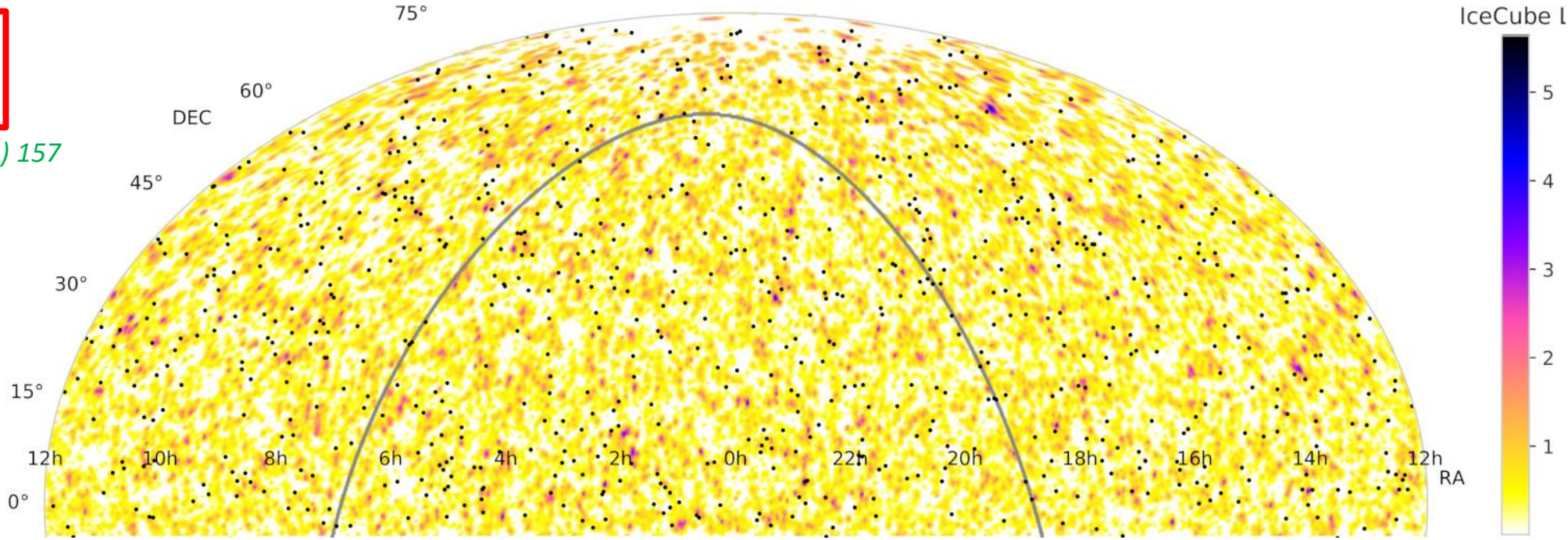
statistical effect,
radio flux enhancement over average
(RATAN-600 data)
statistical significance = 2σ post trial



High-energy neutrinos from radio blazars!

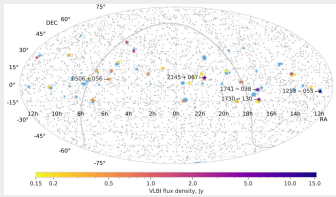
all IceCube tracks for
7 years: TeV – PeV

Plavin et al., Astrophys.J. 908 (2021) 157



statistical effect,
individual events not known,
statistical significance = 3.0σ post trial

- Neutrino arrival directions coincide with radio blazars
- About 25% of astro track-like neutrino events – from blazars in the catalog
- All astro track-like neutrino events – from radio blazars *(taking into account weaker sources not in the catalog)*



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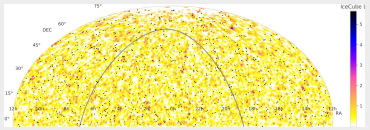


combined statistical significance
below and above 200 TeV:
4.1σ post trial

Neutrino and (radio) blazars, tests

✓ robust test with independent IceCube data requires a similar statistics, wait for 10 years...

✓ confirmation of RATAN temporal correlations with OVRO and Metsahovi data *Hovatta et al. 2021*
(neutrino data: significant overlap, radio data: independent)

✓ ANTARES (~1/10 IceCube): directional correlations, 2.2σ post trial preliminary *ANTARES ICRC 2021*
(independent data)

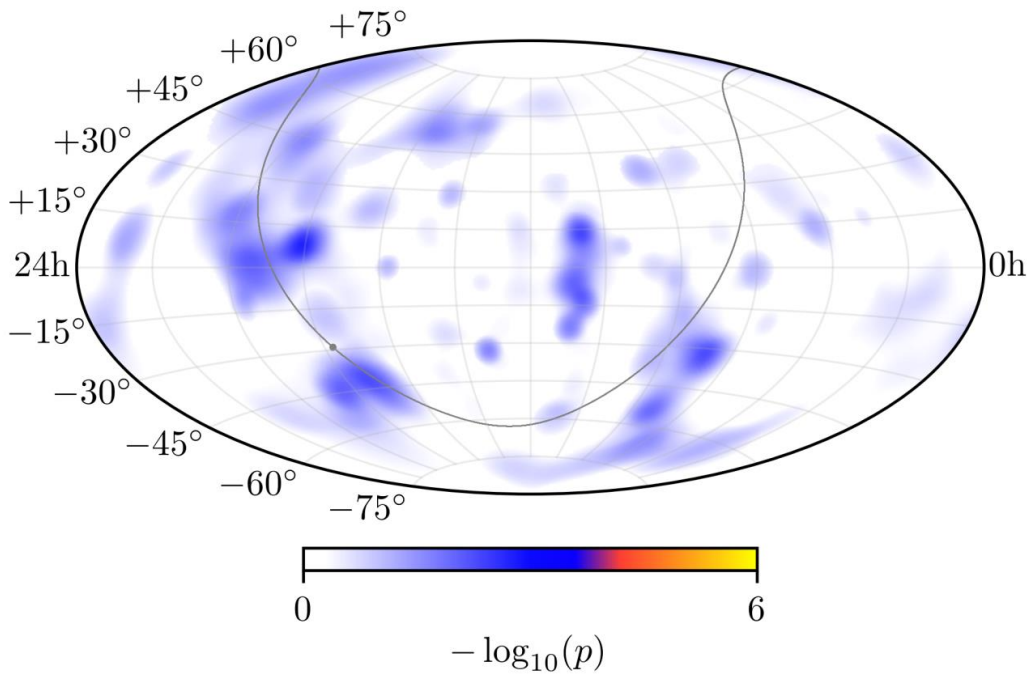
✓ other analyses of (significantly overlapping) IceCube data:

- high energies, “extreme blazars”, 3.2σ post trial *Giommi et al. 2020* – correlation dominated by VLBI sources
- high energies, “GOLD alerts”, CRATES 8 ГГц, 2.3σ *Kun et al. 2022*
- all energies, 10-year public catalog – correlation not found *Zhou et al. 2021*
  - from VLBI blazars <30% (*Plavin et al.* : 25%, agrees)
  - (?) poor data quality (NB: TXS 0506+056 also disappeared...) – discussed in *Plavin+ ICRC 2021*
- (NEW!) southern IceCube skymap – 7 years, 5BZCat blazars, 5σ (???) - *Buson et al. arXiv:2207.06314*

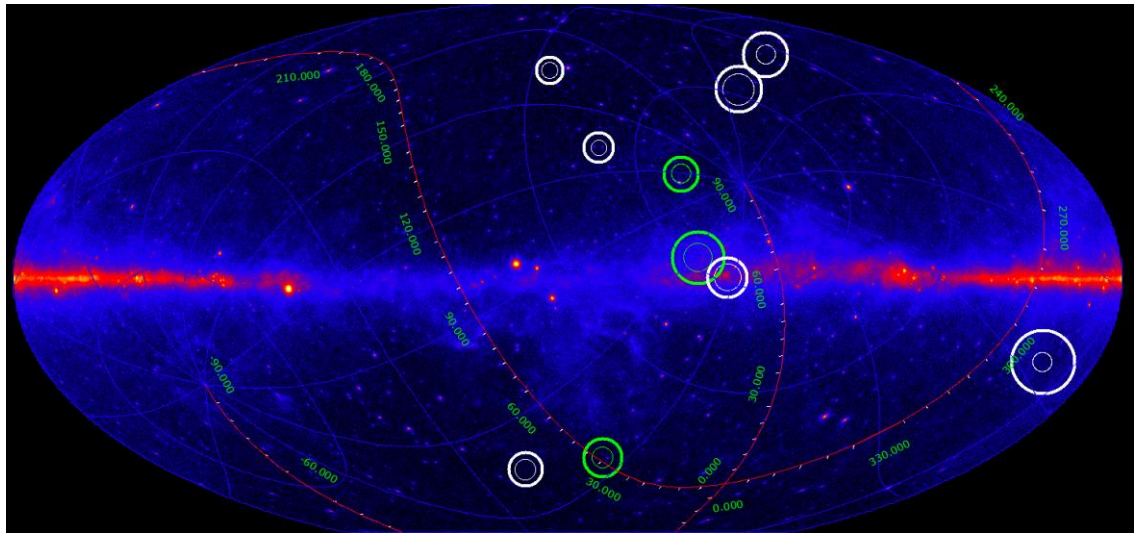
✓ particular interesting cases in independent data – ANTARES, Baikal-GVD, new IceCube alerts

Galactic component?

IceCube 2 sigma



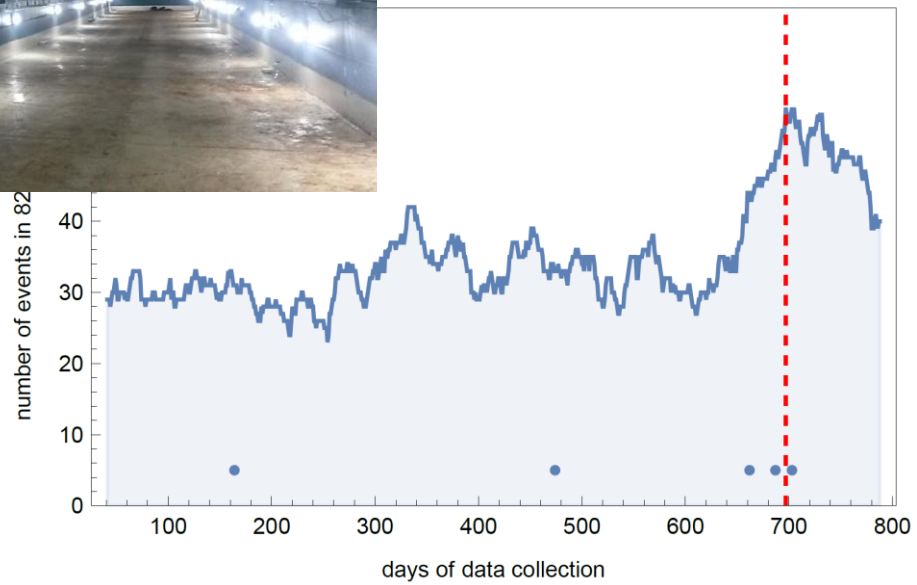
Baikal impressions



- constrained by the lack of strong Galactic anisotropy, but some hints to a moderate contribution
- there exist Galactic models without Galactic anisotropy!
- decisive: search for (sub)-PeV Galactic gamma rays (LHAASO, HAWC, TAIGA, Carpet)

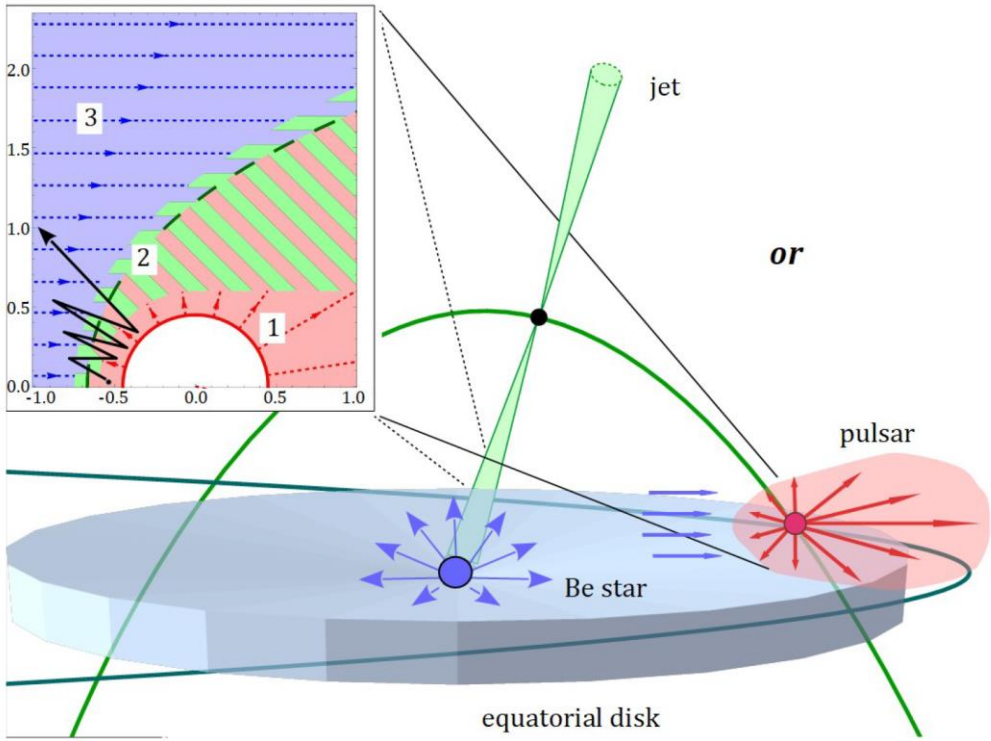
High-energy neutrinos from Galactic sources? neutrino + gamma rays of very high energy

- IceCube: 150 TeV neutrino
- Carpet-2: flare of gamma rays >300 TeV



Dzhappuev et al., Astrophys.J.Lett. 916 (2021) L22

- Cygnus region: many sources
- theory: binary system PSR J2032+4127?



Bykov et al., Astrophys.J.Lett. 921 (2021) L10

Conclusions:

- ✓ high-energy astrophysical neutrinos observed by >1 instruments
- ✓ observations: more precise Northern detectors (Baikal-GVD, KM3NeT) enter the game
- ✓ astrophysics: HE neutrinos mark nonthermal processes with relativistic protons, not opaque sources
- ✓ many astrophysical sources, various populations, extragalactic+Galactic
- ✓ extragalactic: evidence for neutrinos from blazars, strong and growing
- ✓ Galactic: less mature...
- ✓ lots of excitement expected in coming years (months? weeks?) – stay tuned

Thank you!

general constraints and results before mid-2021: UFN 2021 = arxiv:2112.09611

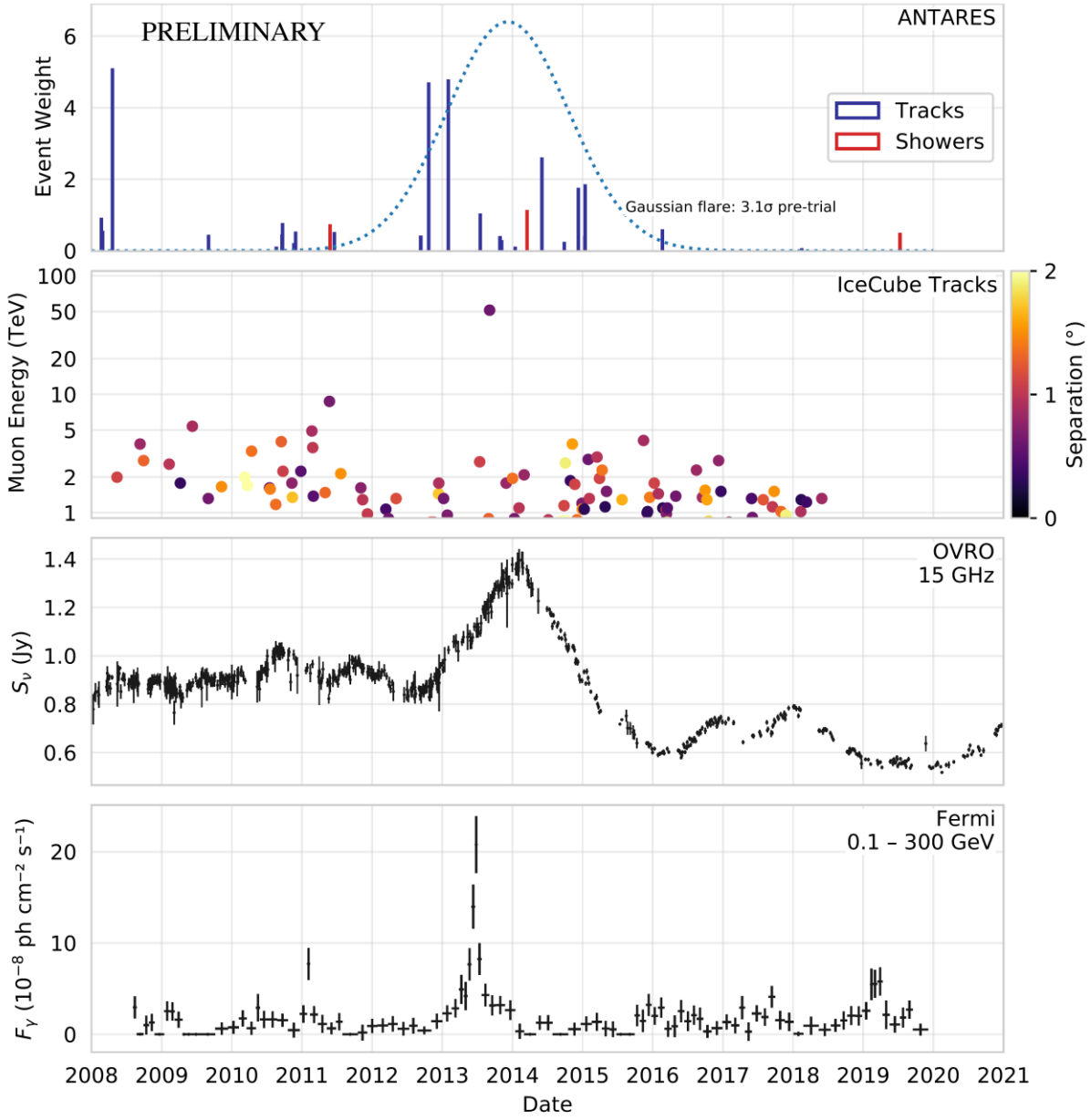
support: RF Ministry of science and high education, contract 075-15-2020-778

Backup slides
(new interesting cases)

Нейтрино и радиоблазары, новое
J0242+1101, многоканальная вспышка

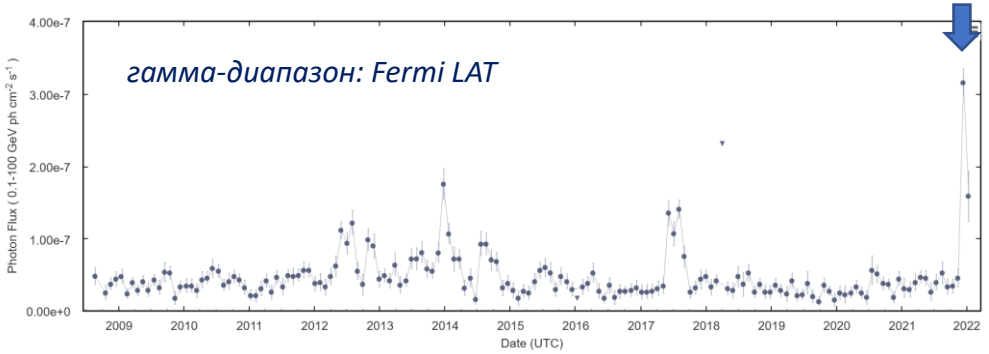
- ✓ слепой поиск нейтринных вспышек от RFC блазаров в данных ANTARES – нейтрино
- ✓ совпадающее нейтрино высокой энергии в публичных данных IceCube
- ✓ радиовспышка, OVRO 15 ГГц
- ✓ гамма-вспышка Fermi LAT

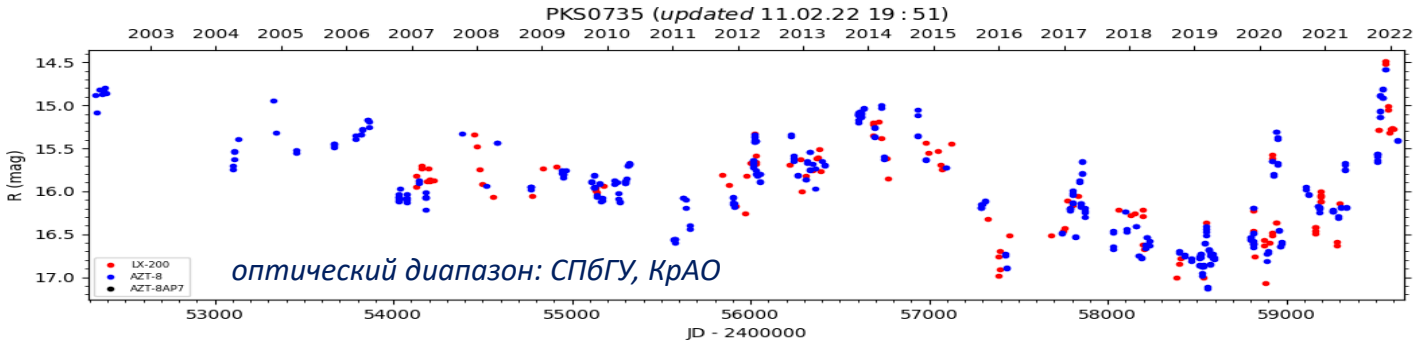
preliminary, *ANTARES ICRC 2021*

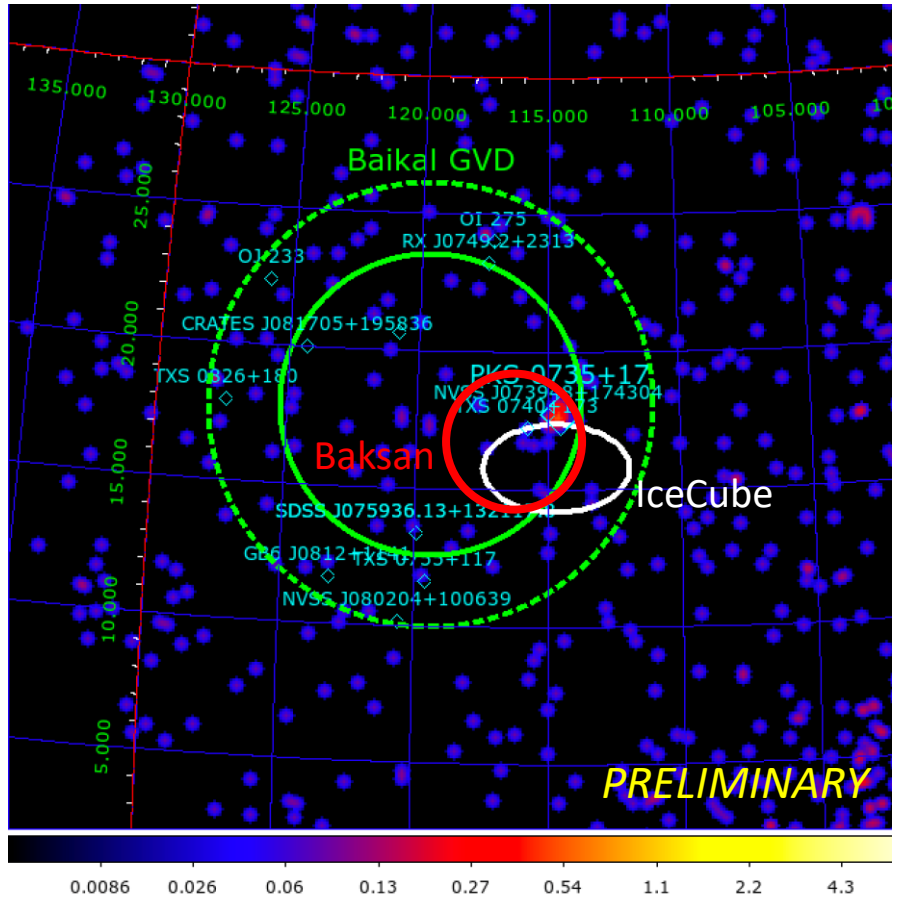


Нейтрино и радиоблазары, новое
PKS 0735+17, события декабря 2021

04-21.12: историческая вспышка радиоблазара PKS 0735+17
(оптика, рентген, гамма, начало вспышки в радио)
08.12: нейтрино 170 ТэВ, IceCube
08.12: нейтрино 43 ТэВ, Байкал-ГВД
04.12: нейтрино ~ТэВ, Баксан *(см. доклад В.Б. Петкова)*

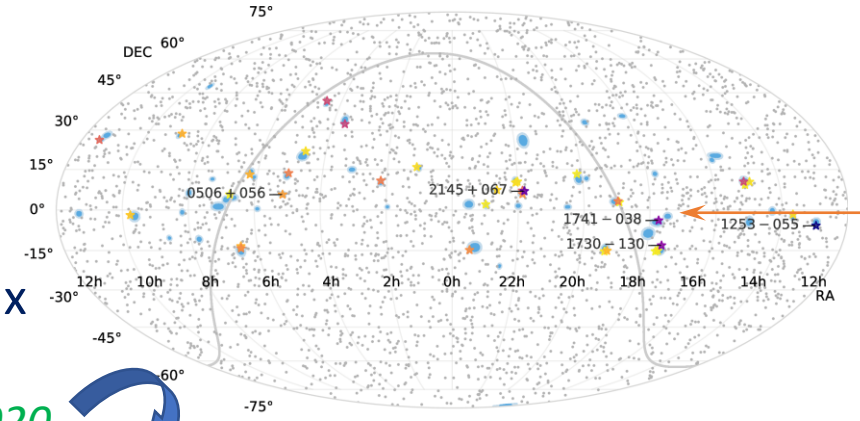


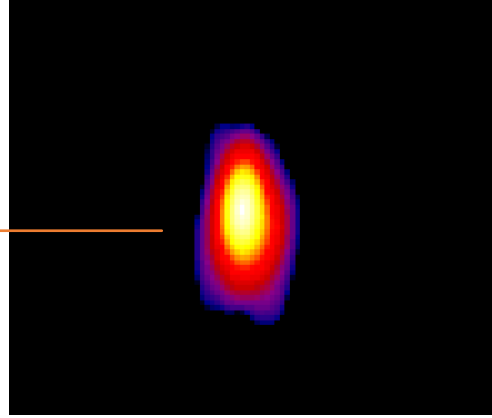




Нейтрино и радиоблазары, новое

PKS 1741-03, повторяющиеся нейтрино





- ✓ выделен как один из 4 наиболее вероятных источников нейтрино IceCube, E>200 ТэВ

Plavin et al. 2020

rest of the sample. The posttrial probability of a chance coincidence is 0.2%. We select the four strongest AGNs as highly probable associations: 3C 279, NRAO 530, PKS 1741−038, and OR 103. Moreover, we find an increase of

- ✓ выделен как один из 3 наиболее вероятных источников нейтрино ANTARES

preliminary, *ANTARES ICRC 2021*

Blazars		Neutrinos			
Source name	S_{8GHz} (Jy)	Arrival time	Separation [°]	β	Estimated energy (TeV)
J0609-1542	3.76	2011-01-30	0.15	0.47	70
J1743-0350	3.99	2019-03-08	0.05	0.43	2.3
J0538-4405	4.2	2011-08-09	0.39	0.93	45
	4.2	2018-03-20	0.34	0.82	6.0

- ✓ совпадение с радиовспышками

- ✓ новый алерт IceCube 5 февраля 2022 ! *IceCube GCN #31554*

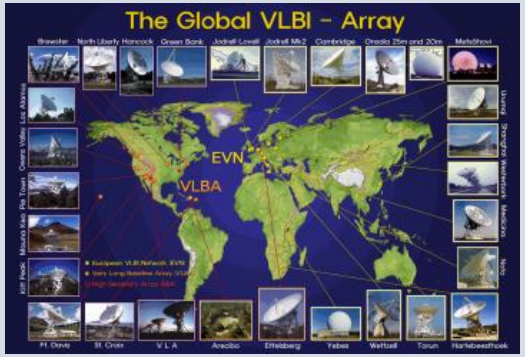
> Several gamma-ray sources listed in the 4FGL Fermi-LAT catalog are located near the best-fit neutrino candidate position, 3 of them within a 1 degree radius. These sources are: 4FGL J1747.8-0316 (0.34 deg away), 4FGL J1744.2-0353 (0.81 deg, associated with the source PKS 1741-03) and 4FGL J1749.8-0303 (0.84 deg).

- ✓ примечание: один из ярчайших радиоблазаров на небе, но скромный гамма-источник

Многоканальная астрономия, нейтрино+электромагнитная: будущее

- нетепловое излучение, радио и гамма

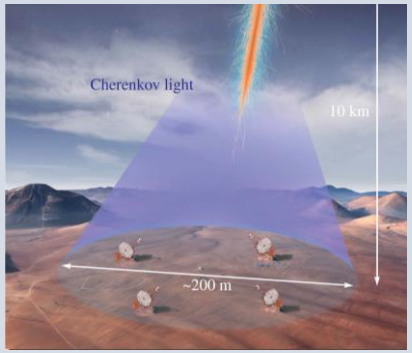
постоянный мониторинг обычными радиотелескопами (идентификация источников нейтрино и их вспышек)
РАТАН-600, OVRO, Metsahovi...



радиоинтерферометрия со сверхдлинными базами (идентификация и изучение процессов, приводящих к излучению нейтрино в конкретных источниках)

слайд из доклада на Президиуме РАН 22.02.2022

гамма-телескоп Fermi LAT:
на орбите с 2008 г.,
нет даже проекта спутника ему на смену



будущее этого диапазона - за «недорогими» наземными инструментами?
ALEGRO, ФТИ им. Иоффе РАН

галактические источники:
ПэВная гамма-астрономия
Ковер-3 (Баксан), TAIGA (Бурятия)
LHAASO, Tibet, HAWC, SWGO, ALPACA,...