Image Credit: Keith Vanderlinde, NSF

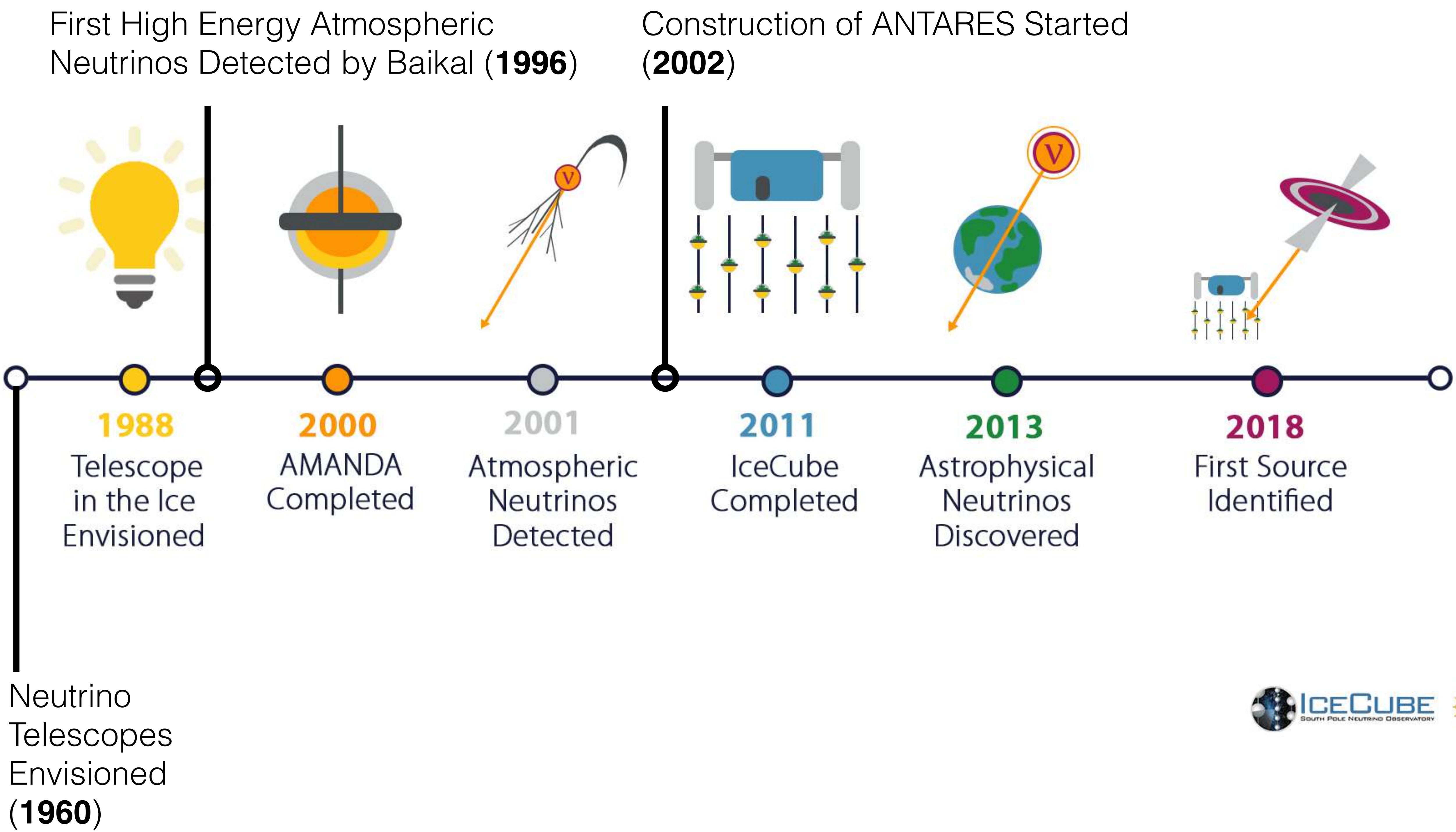
High-energy Neutrino Astronomy: Looking at the Universe through the Ice

Elisa Bernardini, University of Padova (Italy)

Virtual Seminar on Multimessenger Astronomy II, winter semester 20/21

https://www.sfb1258.de/graduate-school/virtual-seminar-on-multimessenger-astronomy/

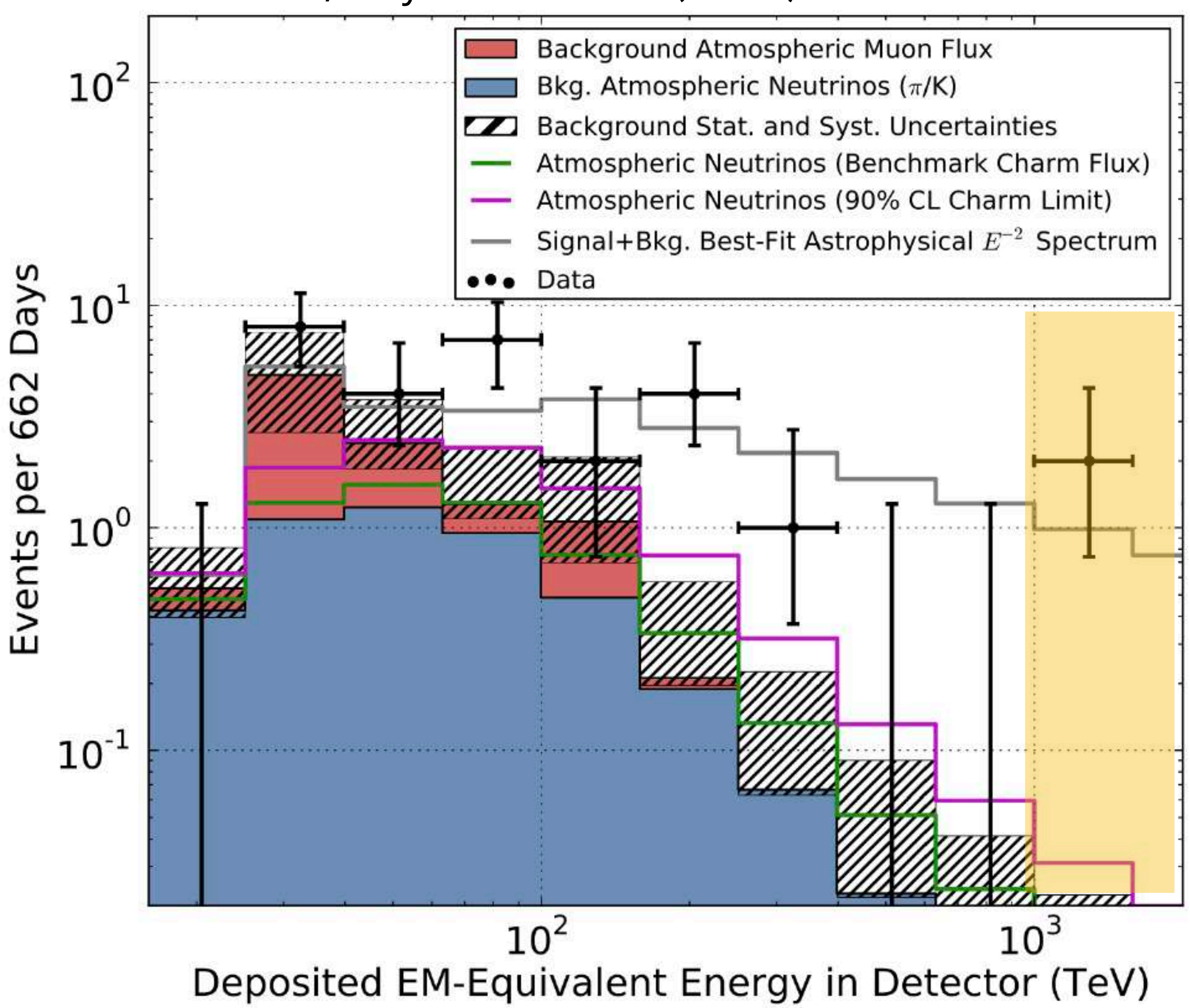
History of neutrino Astronomy in a nutshell

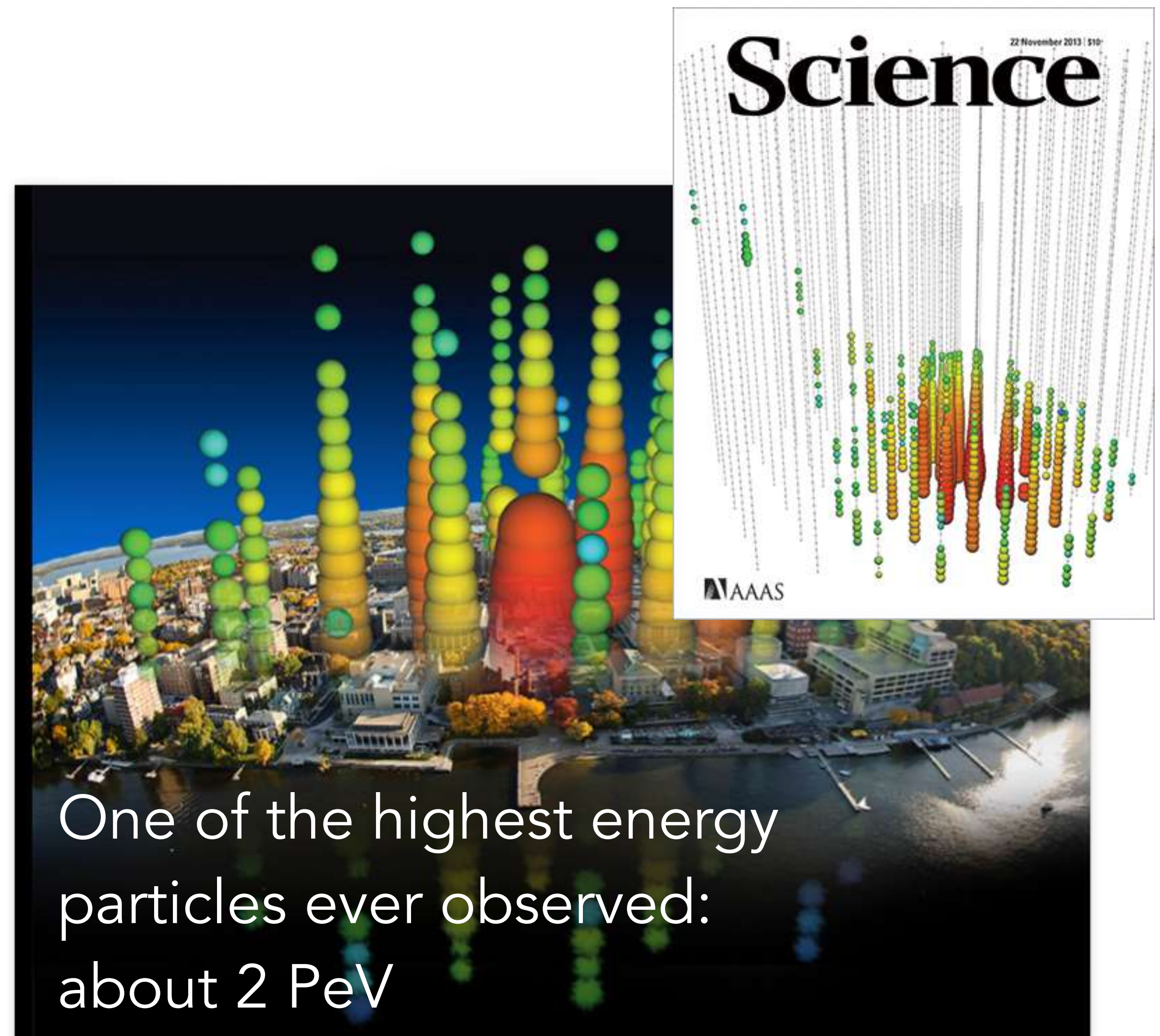


Astrophysical neutrinos discovered

A refined background rejecting analysis yielded the first evidence of neutrinos of astrophysical origin: flavors, directions, and energies inconsistent with those expected from the atmospheric muon and neutrino backgrounds

IceCube, Science 342, 1242856 (2013)
IceCube, Phys. Rev. Lett. (2015)

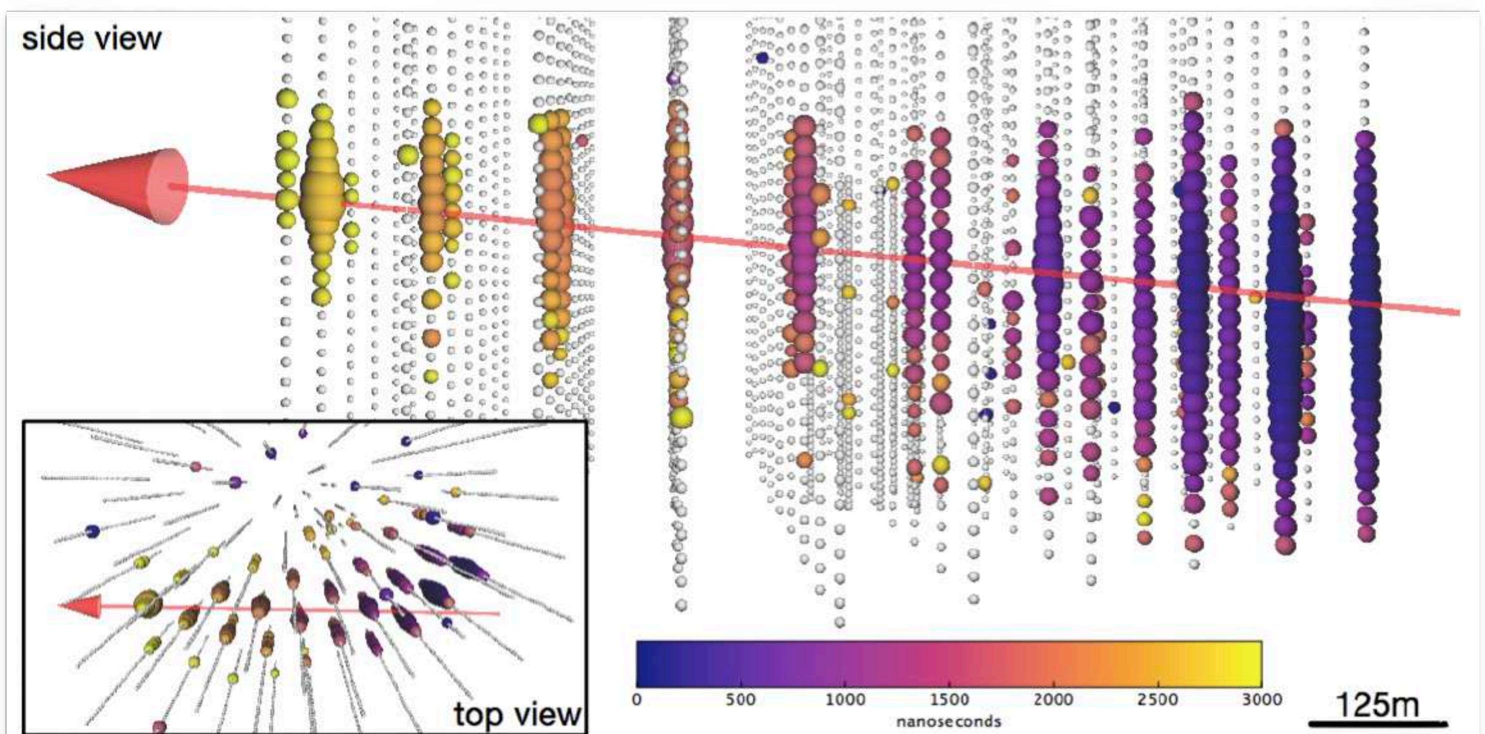


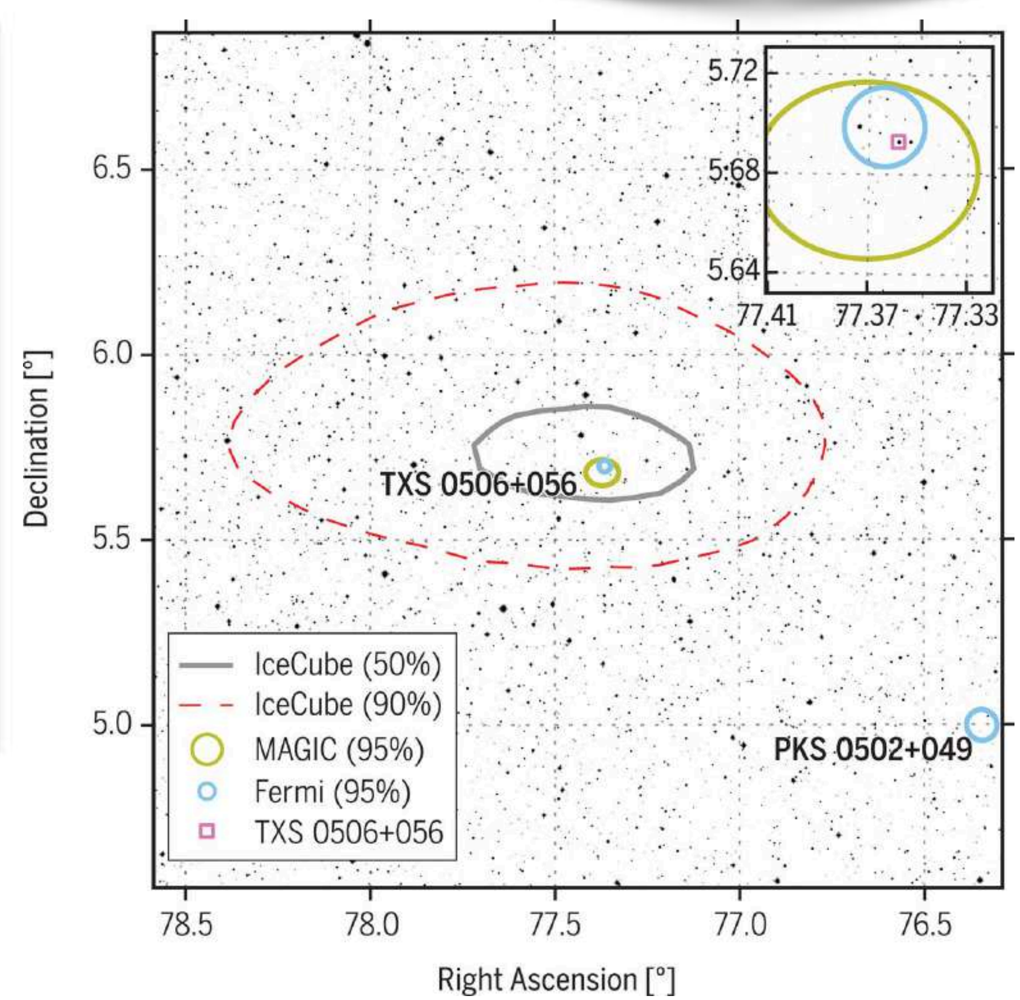


Breakthrough in Multi-Messenger Astronomy

Compelling evidence for high-energy emission from the Blazar TXS 0506+056 associated with the high-energy neutrino IceCube-170922A. Identification of a cosmic hadron accelerator with >PeV energies!

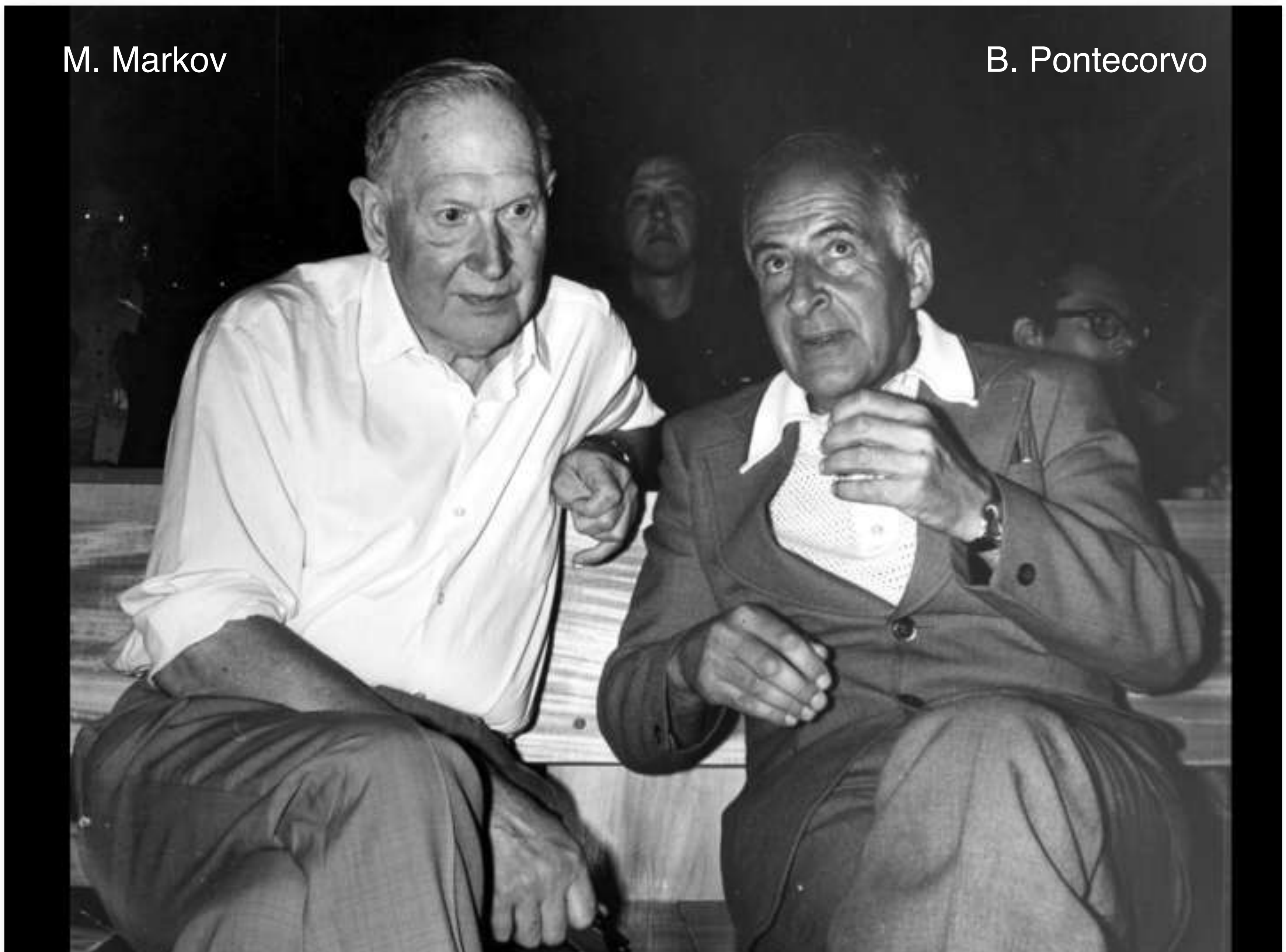
IceCube, FERMI, MAGIC, ++., Science 361, 146 (2018)





Envisioning a neutrino telescope

M.Markov (1960): *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*



A "Dio Volente" detector

F. Halzen & J. Learned 1988: *"this is a detector that requires a number of happy accidents to make it feasible. But if these should come to pass, it may provide the least expensive route to a truly large neutrino telescope. Exploratory studies may begin at the South Pole Station within the next few years."*

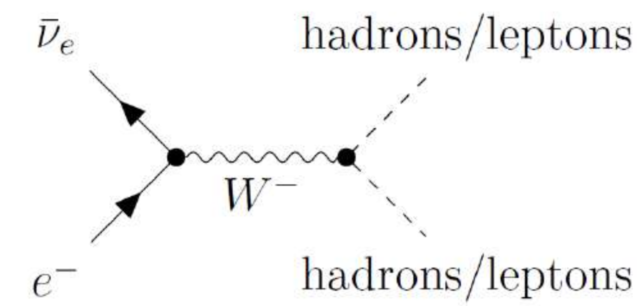
R. March, F. Halzen & J. G. Learned "Neutrino detection in clear polar ice" at The First "**International Venice Workshop on Neutrino Telescopes**" (1998)

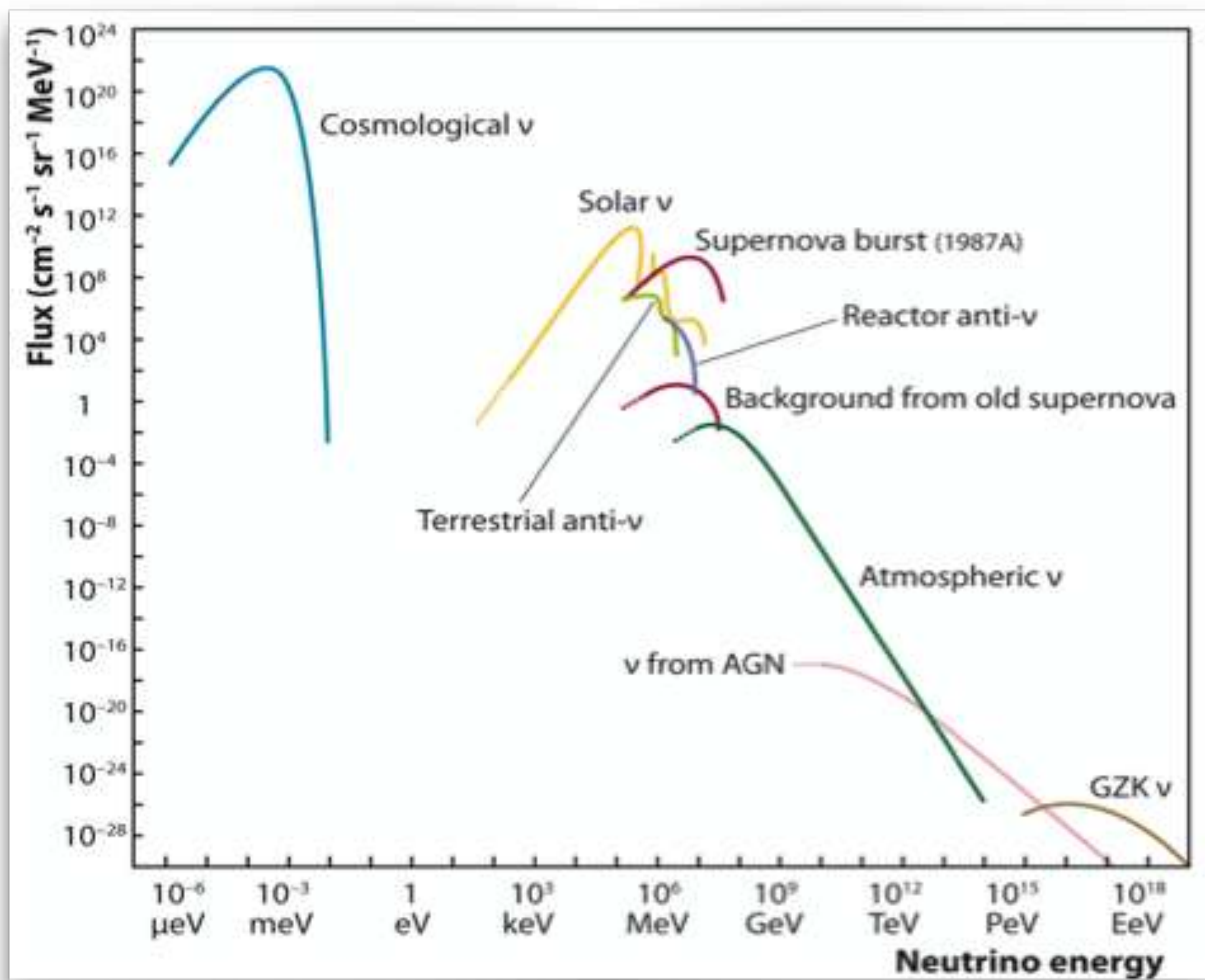
It must be emphasized that this is a "<u>Dio Volente</u>" detector, for to make it feasible three conditions must be met that are beyond our control:

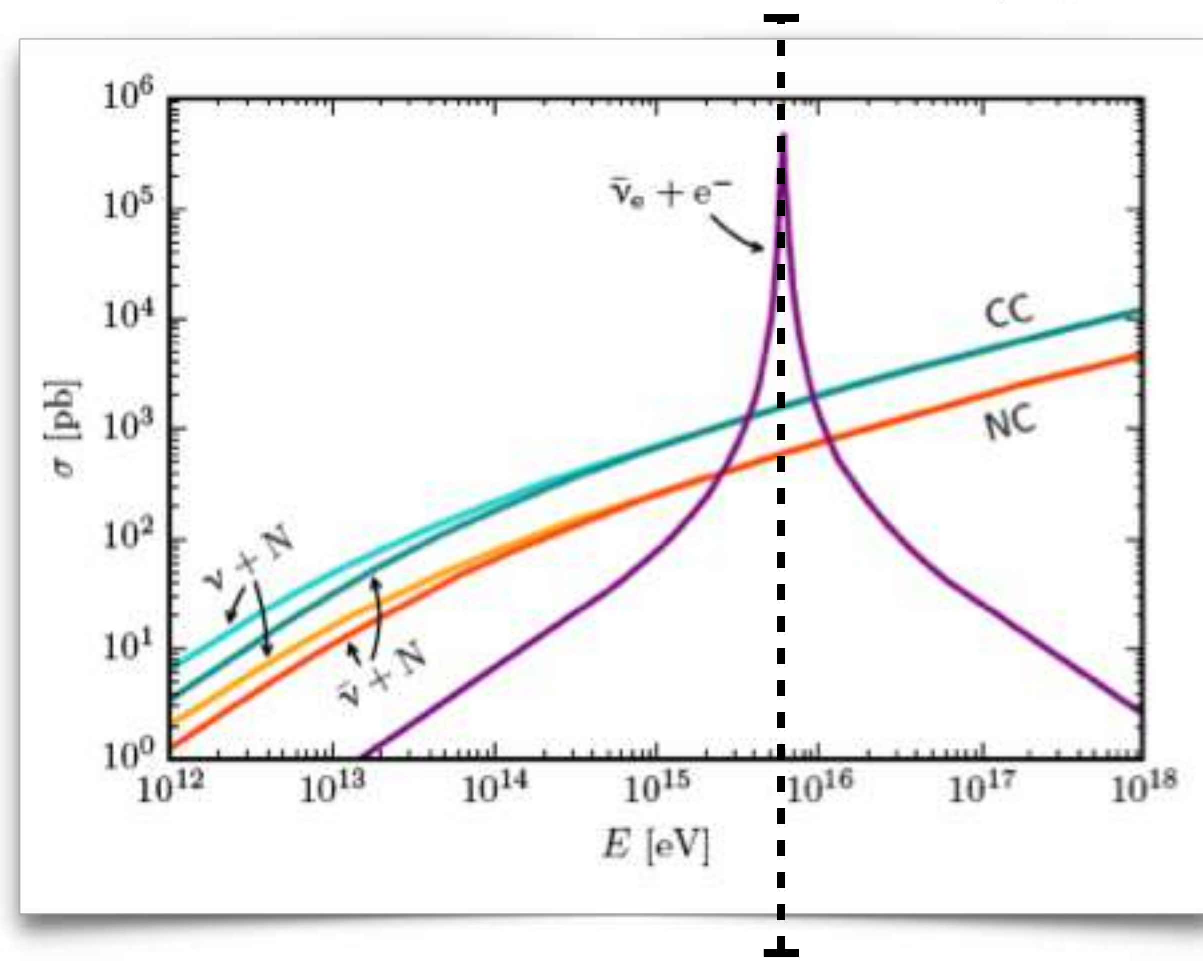
1. A natural body of clear ice, of area at least tens of thousands of square meters and thickness a few hundred meters, must exist somewhere within a kilometer or so of the surface;
2. The light transmission of the ice in the Cherenkov band (near 450nm) must be comparable to that of pure water, with attenuation (absorption and scattering) lengths of tens of meters;
3. The ice body must be situated near an existing permanent research station, for the cost of constructing, maintaining, and supplying a base would be prohibitive.

Challenges: cross section

For a benchmark astrophysical flux O(10^5)/km^2/year at energies > 100 TeV we need km^3-scale detectors! ⇒use natural water or ice



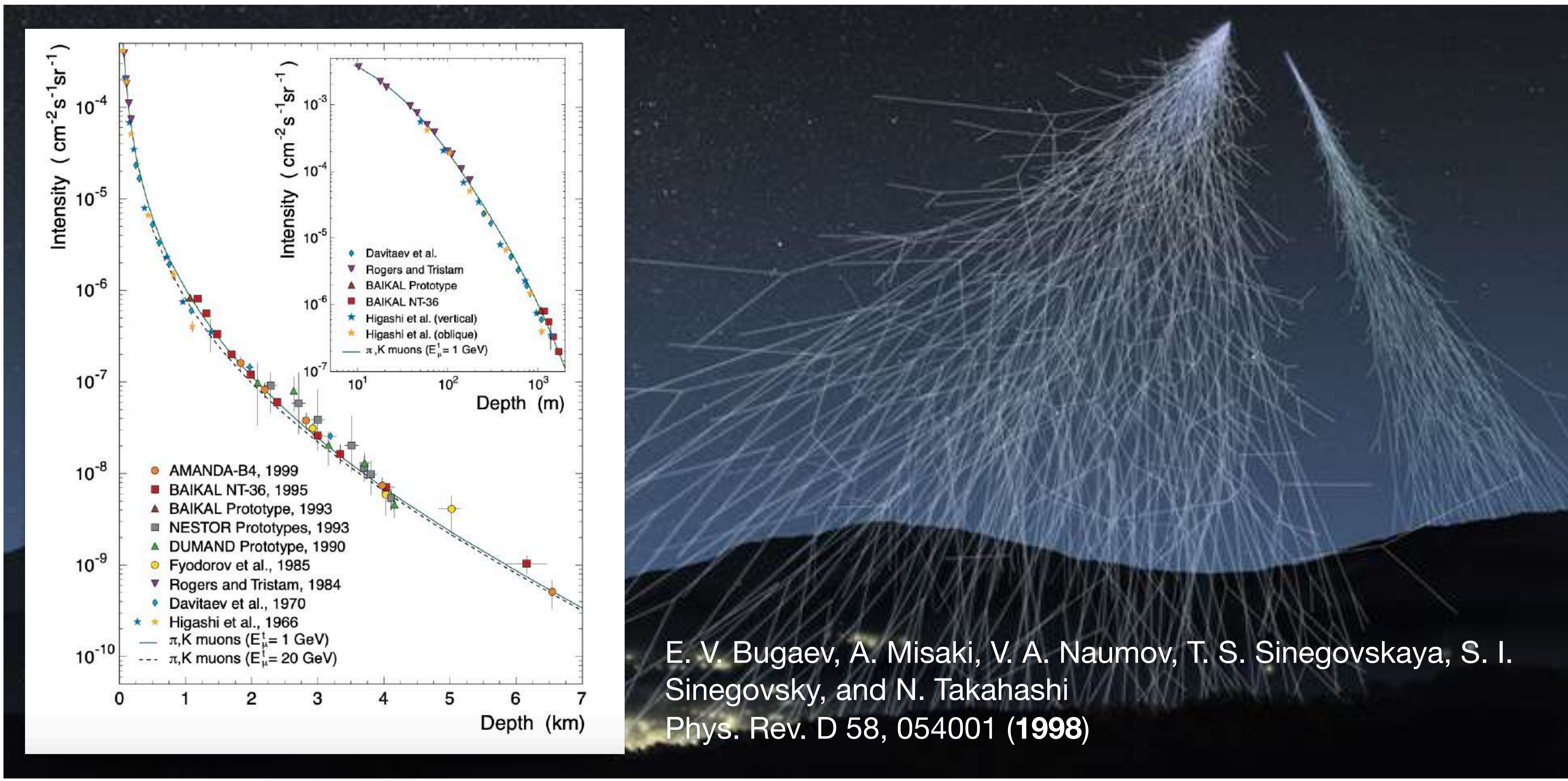




$E_{\overline{\nu}_e} = M^2_W/(2m_e) = 6.3$ PeV

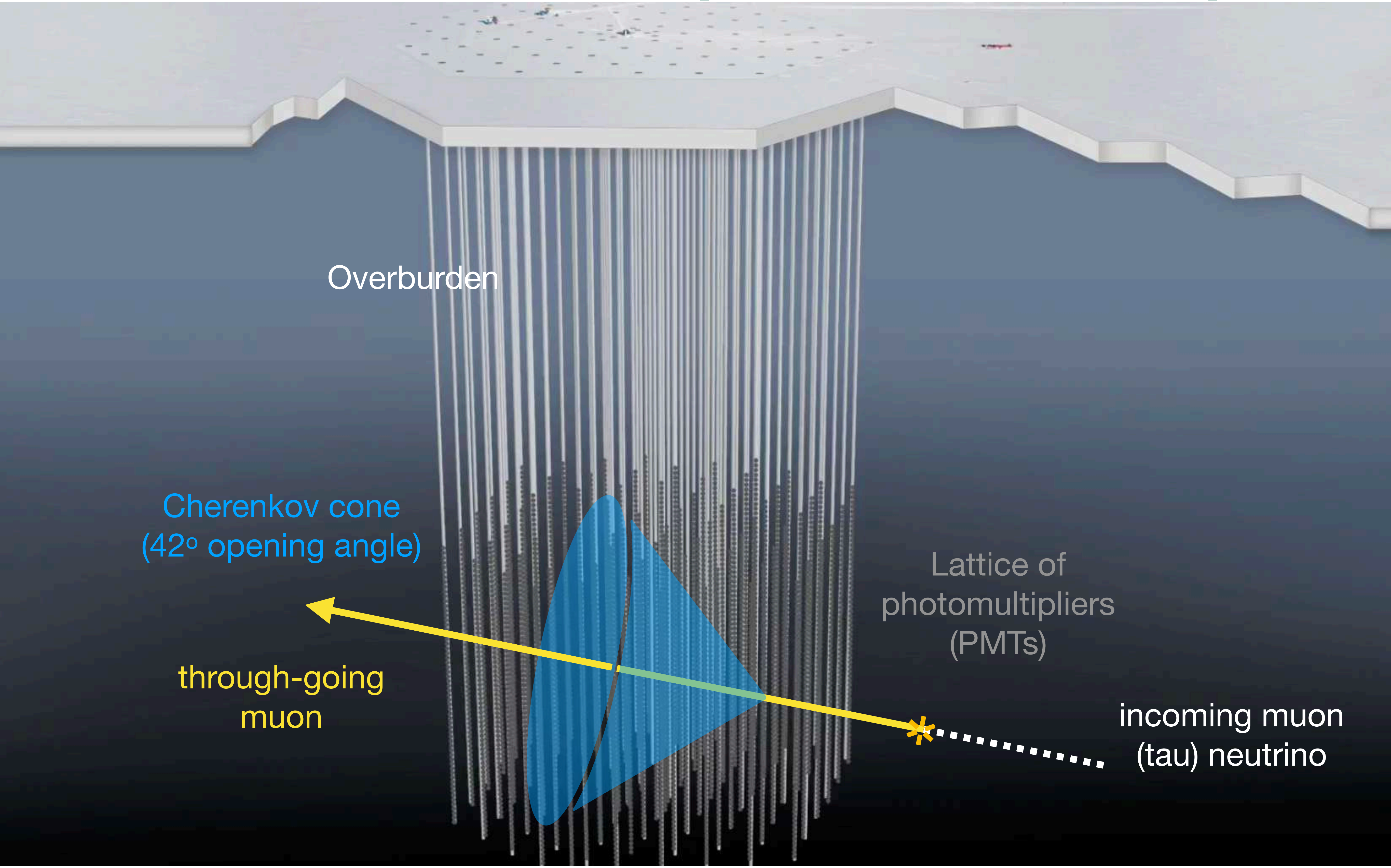
Challenges: backgrounds

Event rates in underwater experiment are **at least** of the order of **10^{10} events/ year**: need to instrument a volume surrounded by important mass overburden to suppress the background from cosmic rays

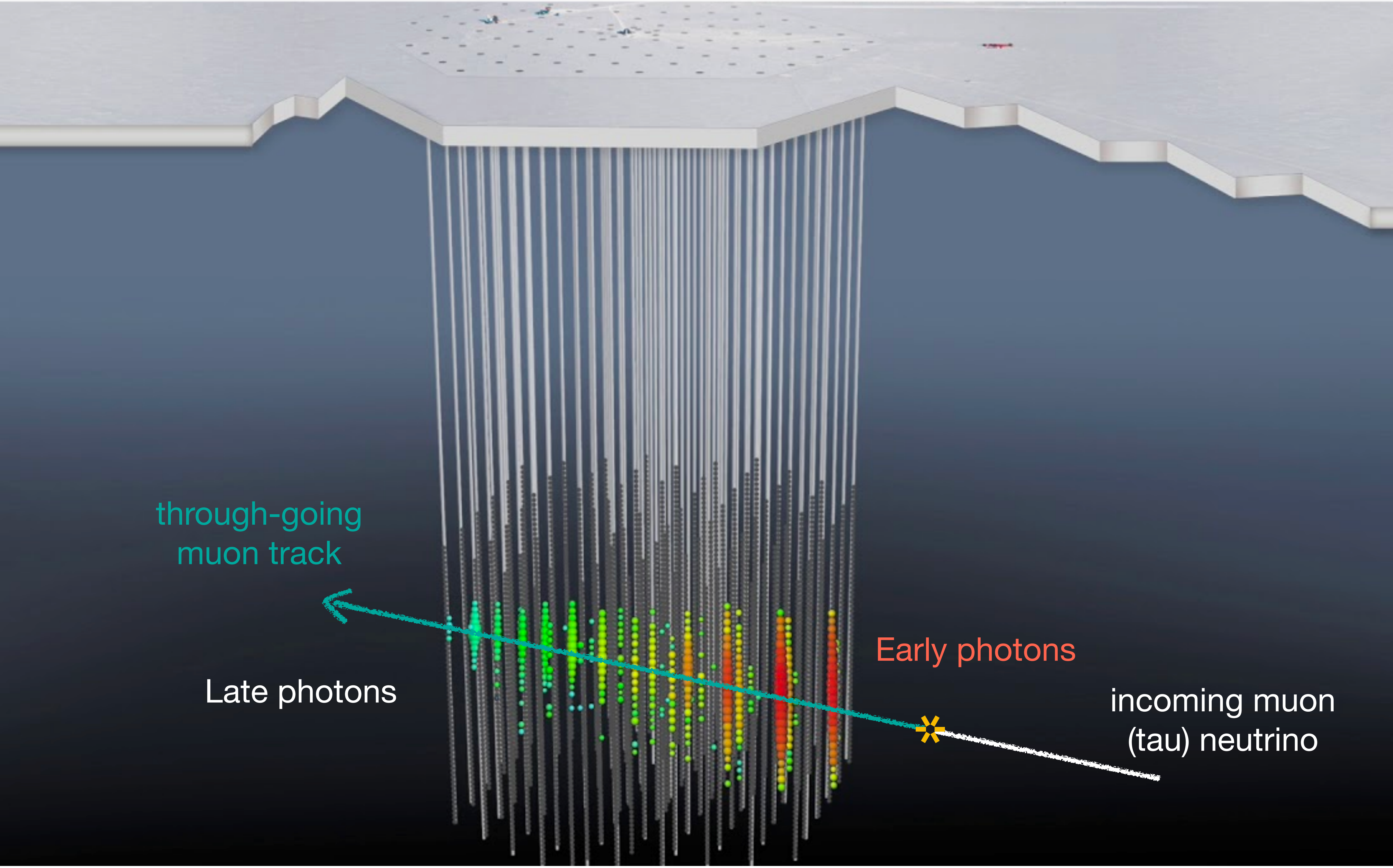


E. V. Bugaev, A. Misaki, V. A. Naumov, T. S. Sinegovskaya, S. I. Sinegovsky, and N. Takahashi
Phys. Rev. D 58, 054001 (**1998**)

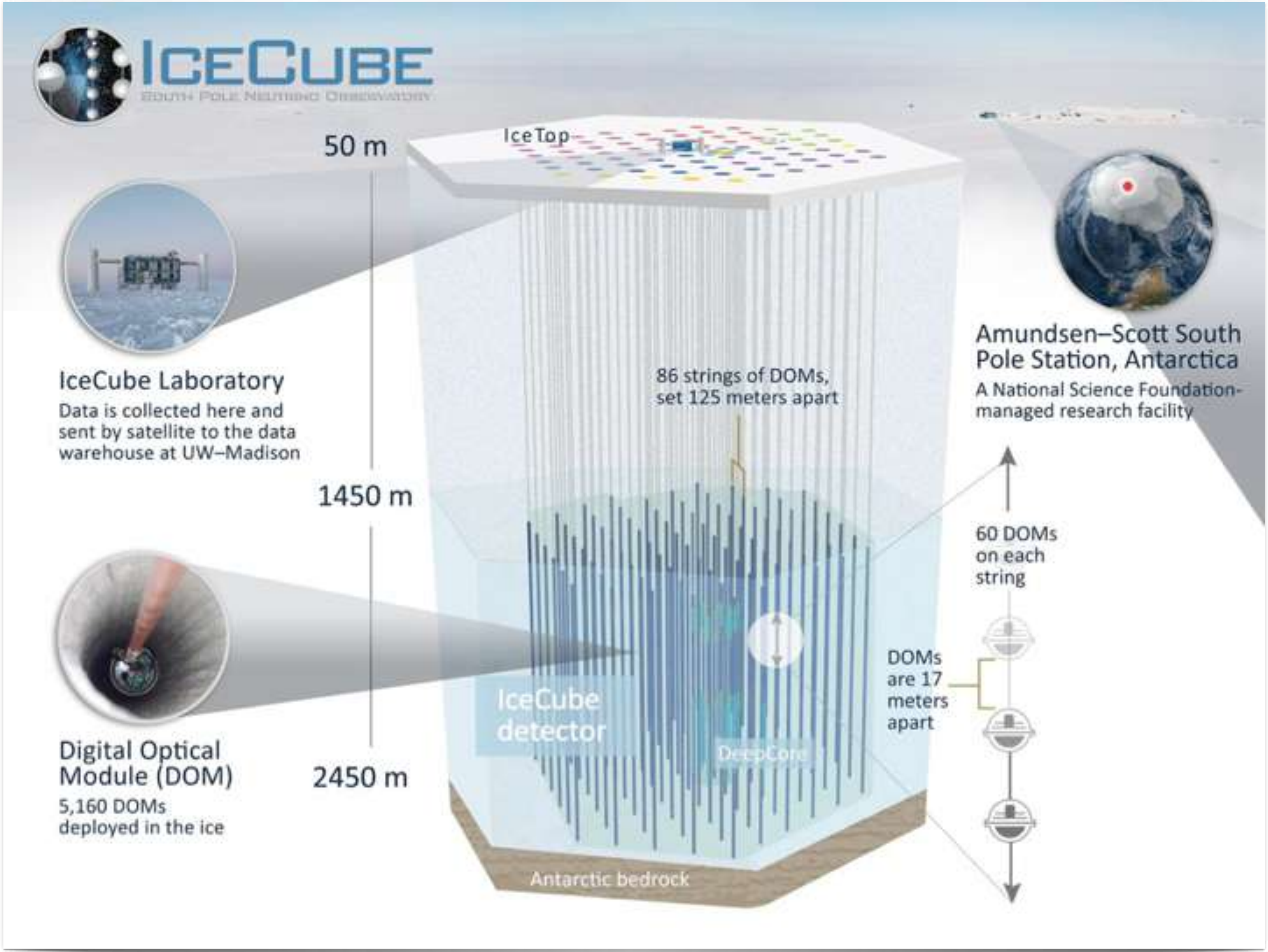
Neutrino telescopes: the concept



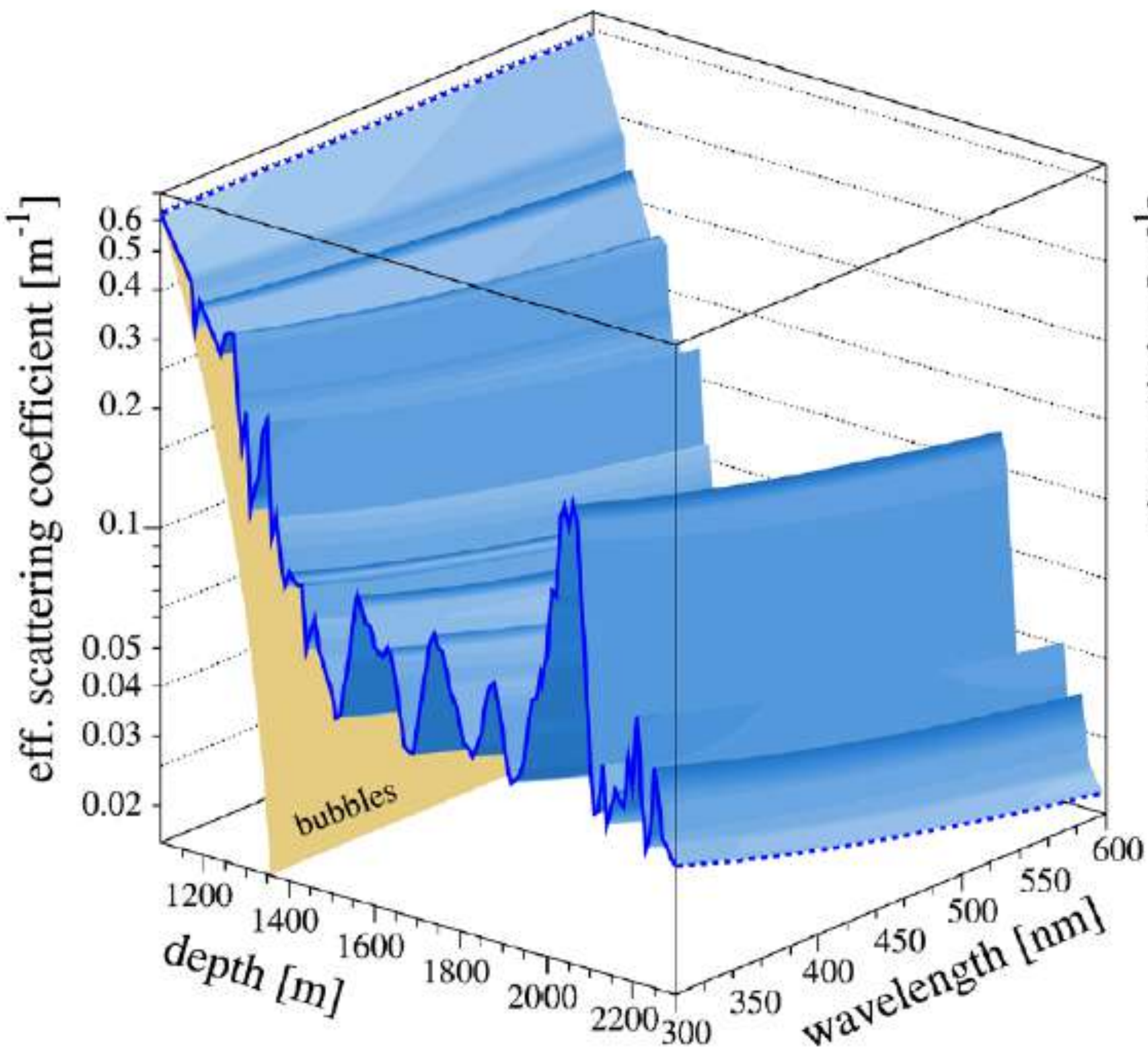
Neutrino telescopes: the concept

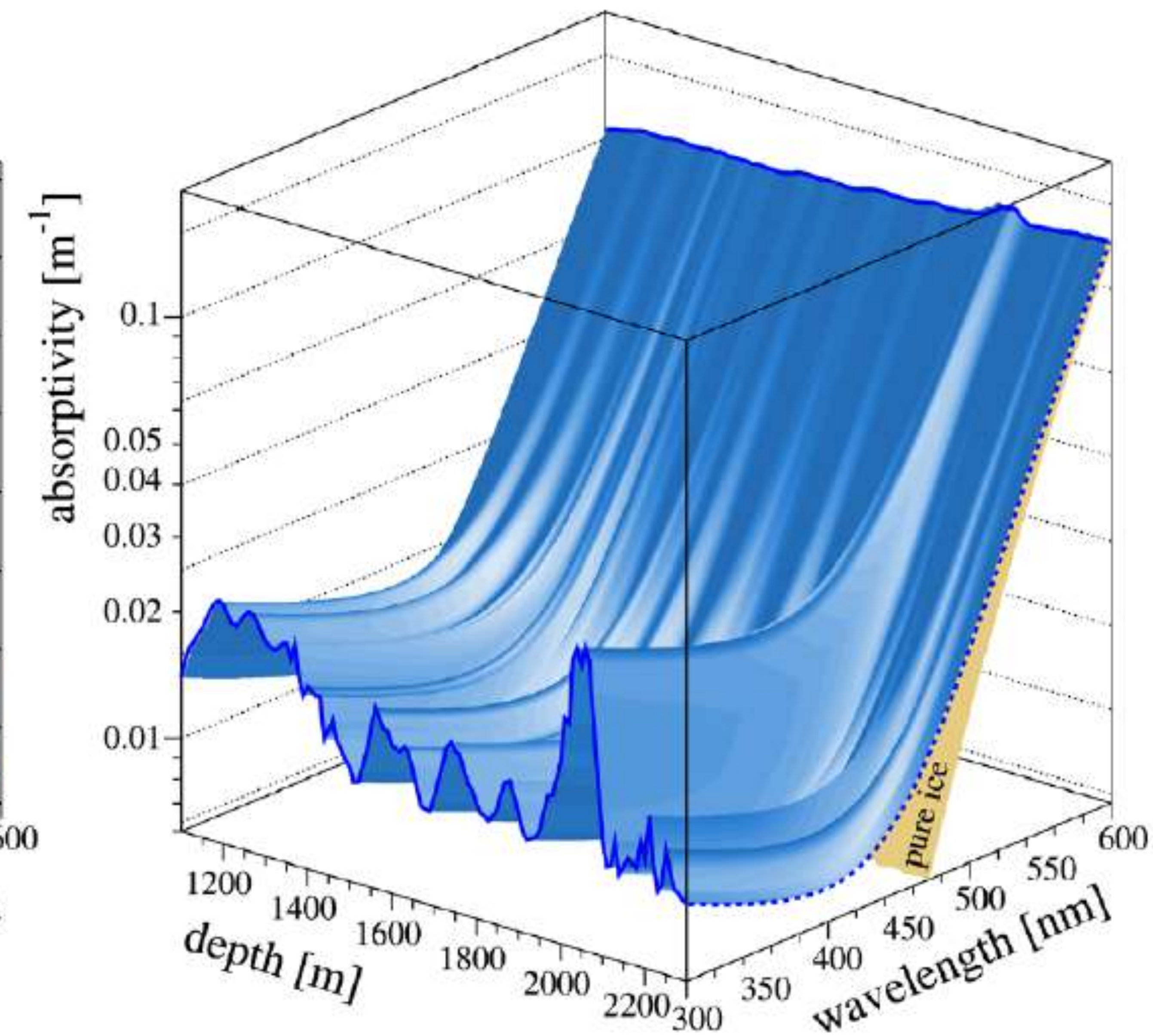


The IceCube Neutrino Observatory

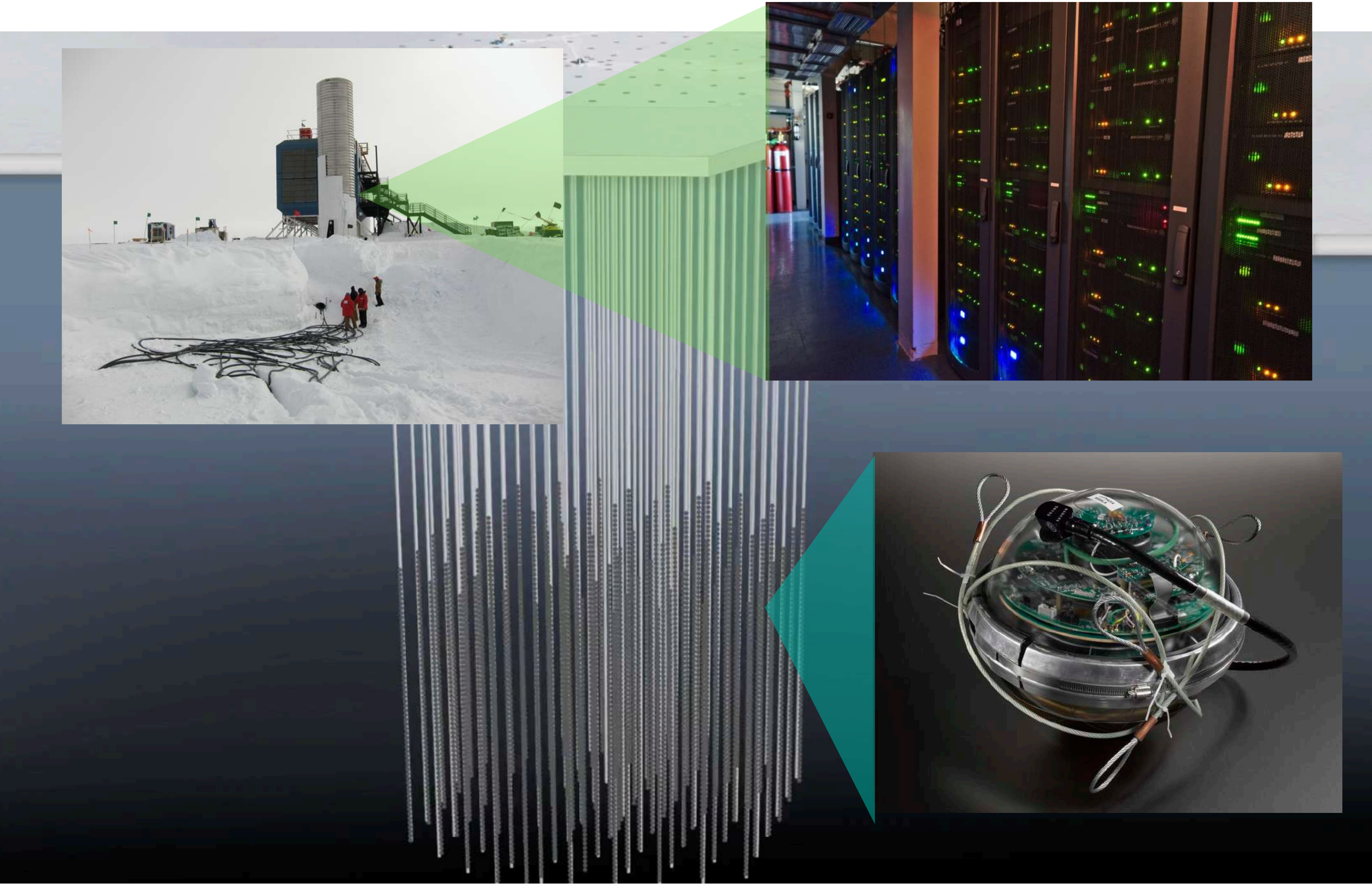


Properties of the medium





Digital Optical Modules



Neutrino detection probability

A high-energy neutrino has a reduced mean free path (λ_ν) and the secondary muon an increased range (λ_μ), therefore the probability for observing a neutrino-induced muon (λ_μ/λ_ν) increases with energy, being about 10^{-6} at an energy of 1 TeV

- Probability to detected a Neutrino (contained events):

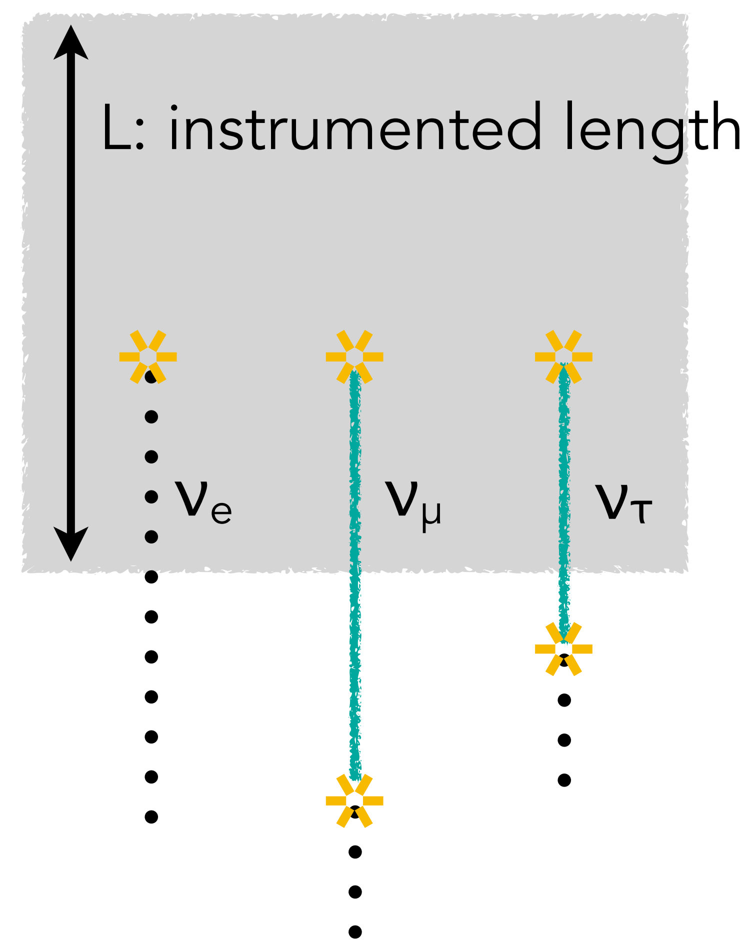
$$P(E_\nu) = 1 - \exp\left(-\frac{L}{\lambda_\nu(E_\nu)}\right) \cong \frac{L}{\lambda_\nu(E_\nu)}$$

- For ν_μ:

$$L \to \lambda_\mu \qquad P = \frac{\lambda_\mu}{\lambda_\nu}$$

- For ν_τ:

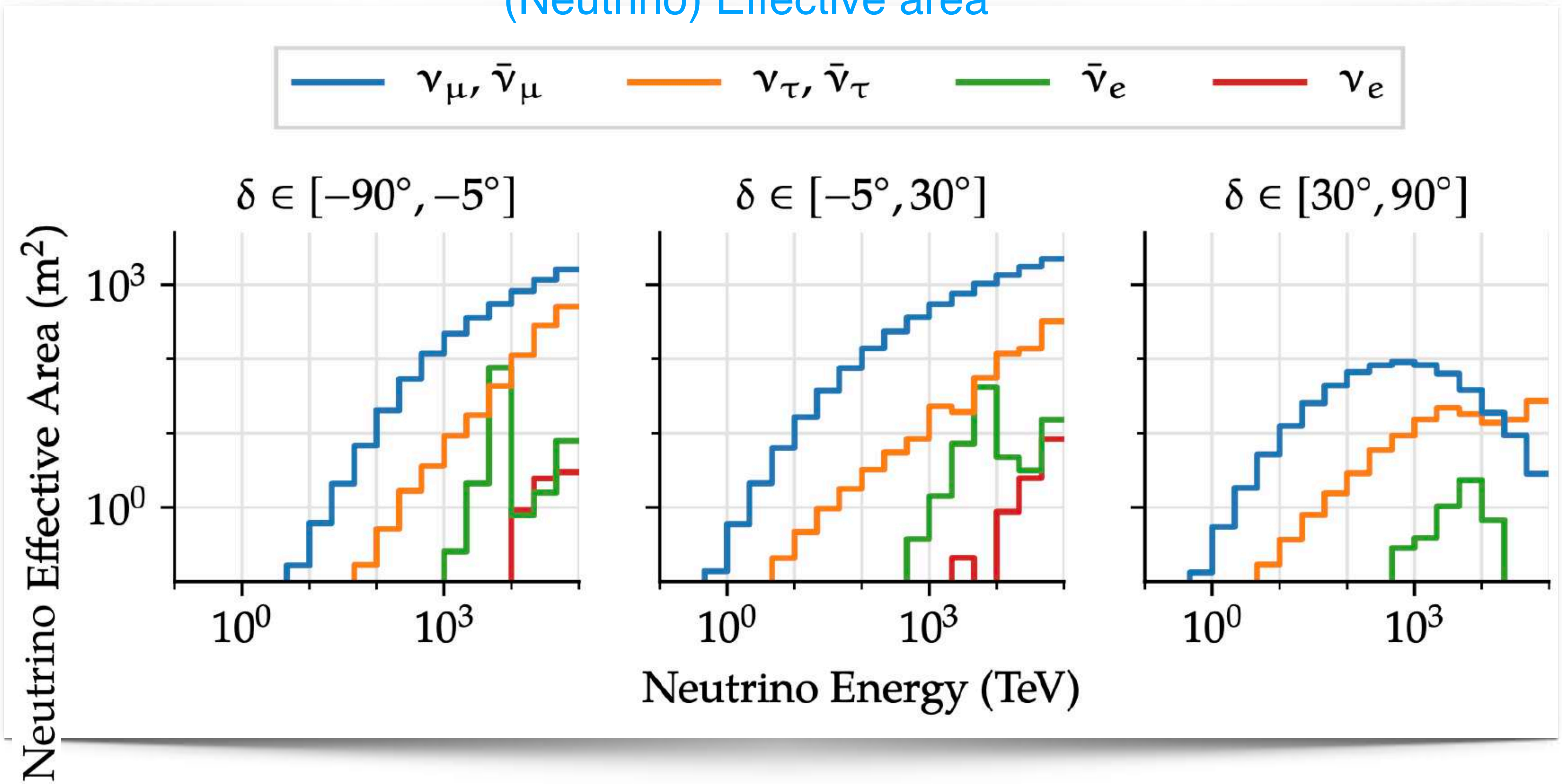
$$L \to \gamma c \tau$$



The neutrino and the muon effective areas

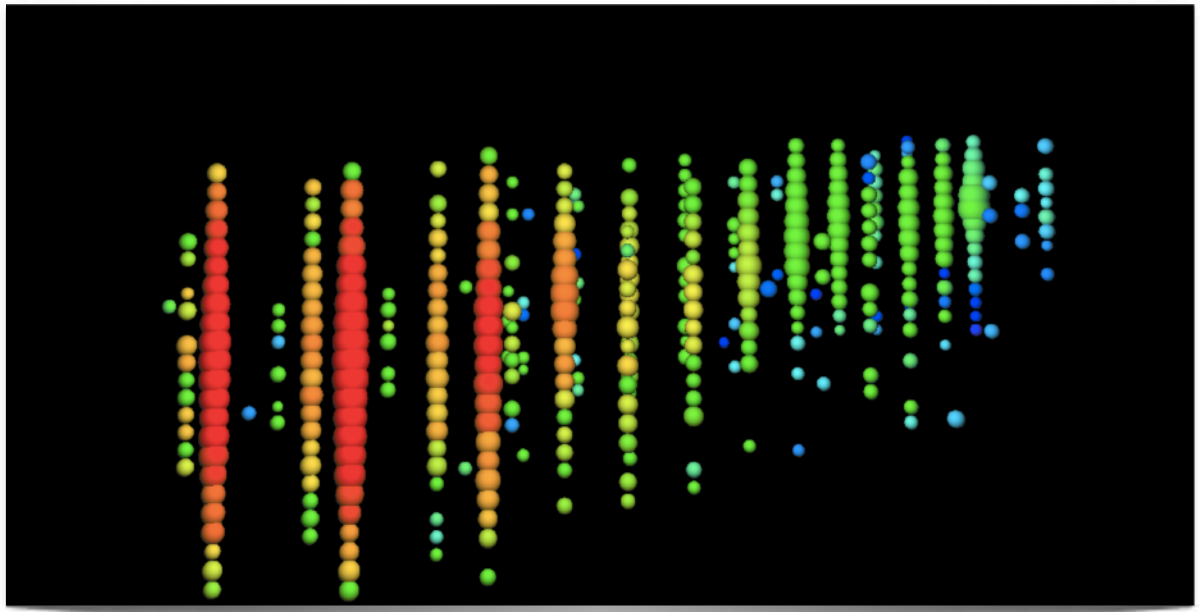
Neutrinos may not reach the detector and be absorbed in the Earth on their journey, with a probability depending upon their flavour and energy

$$N_{ev} = T \int_{E_\nu^{th}} \underbrace{A(E_\nu) P(E_\nu)}_{\text{(Neutrino) Effective area}} \frac{dN}{dE_\nu} dE_\nu$$

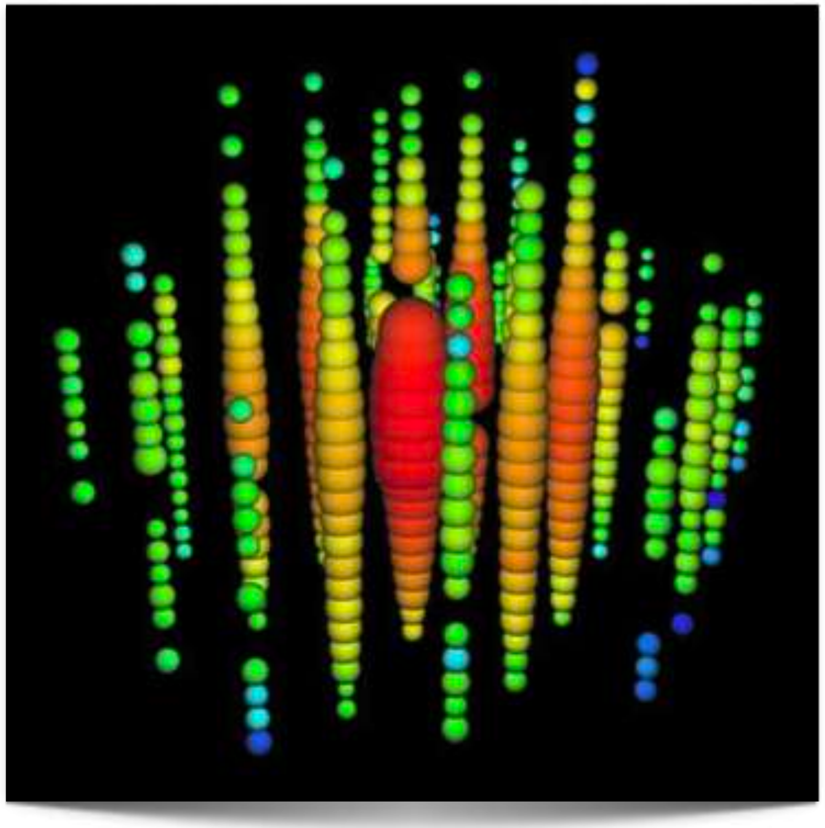


Measuring the Direction

The arrival times of photons at the optical sensors, whose positions are known, determine the particle's trajectory. These photon arrival times are used in maximum-likelihood fitting event reconstruction with different hypotheses on the event topology (flavour)



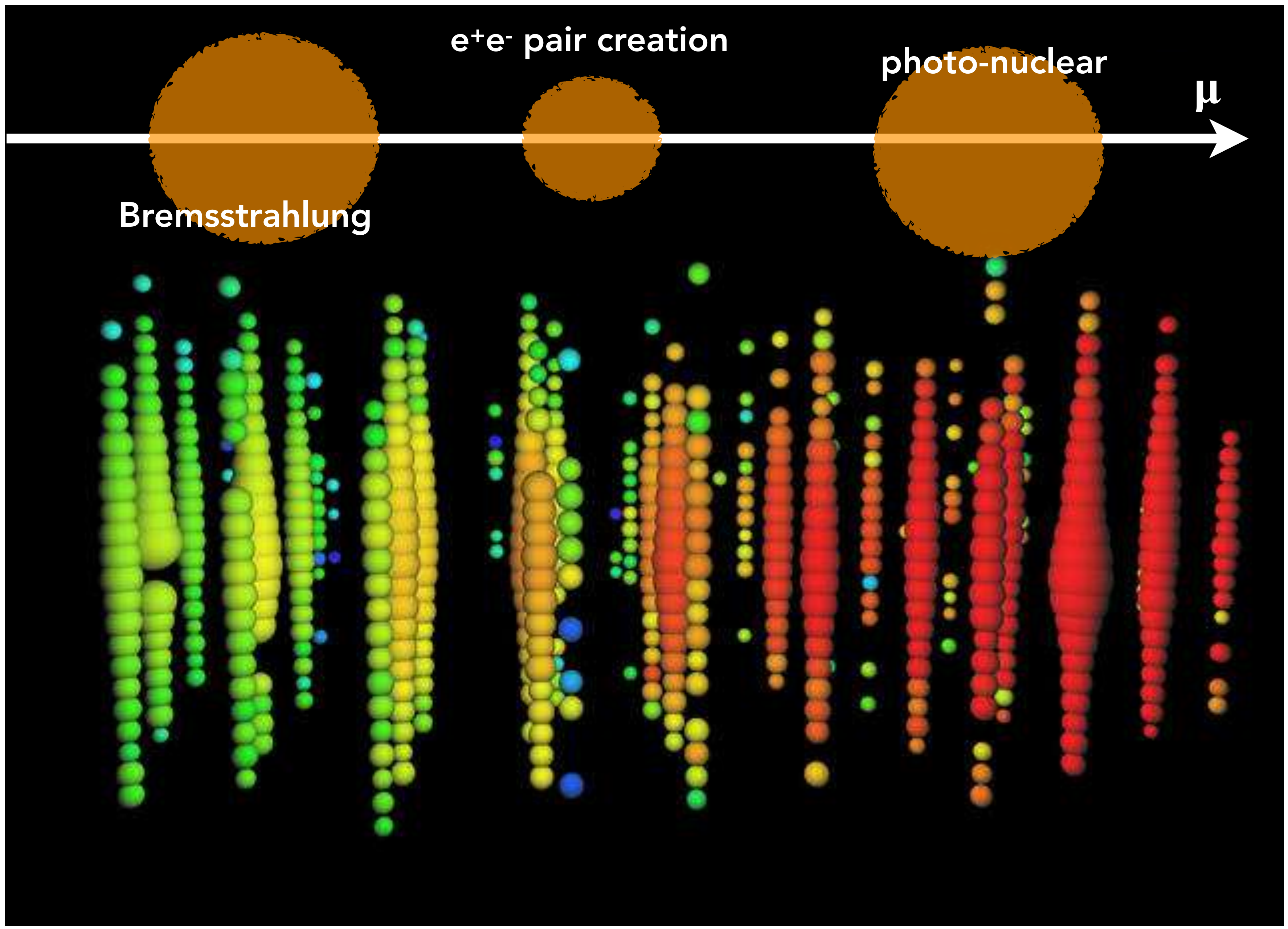
Muon tracks
angular resolution **0.5°** @ 10 TeV (0.3° @ 100 TeV)



Cascades
~15° median angular resolution @ 10 TeV (8° @ 100 TeV)

Measuring the Energy

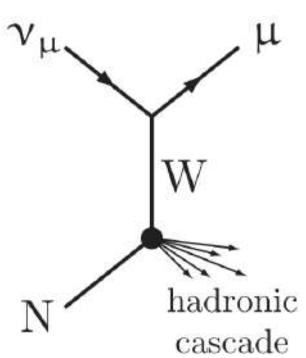
Most Cherenkov light from a muon traveling through ice is radiated through stochastic processes, resulting in a dense series of cascade-like signatures. The mean distance between these energy deposits decreases with increasing energy.



Event signatures

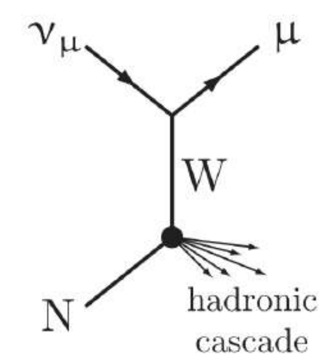
Through-going track (ν_μ)

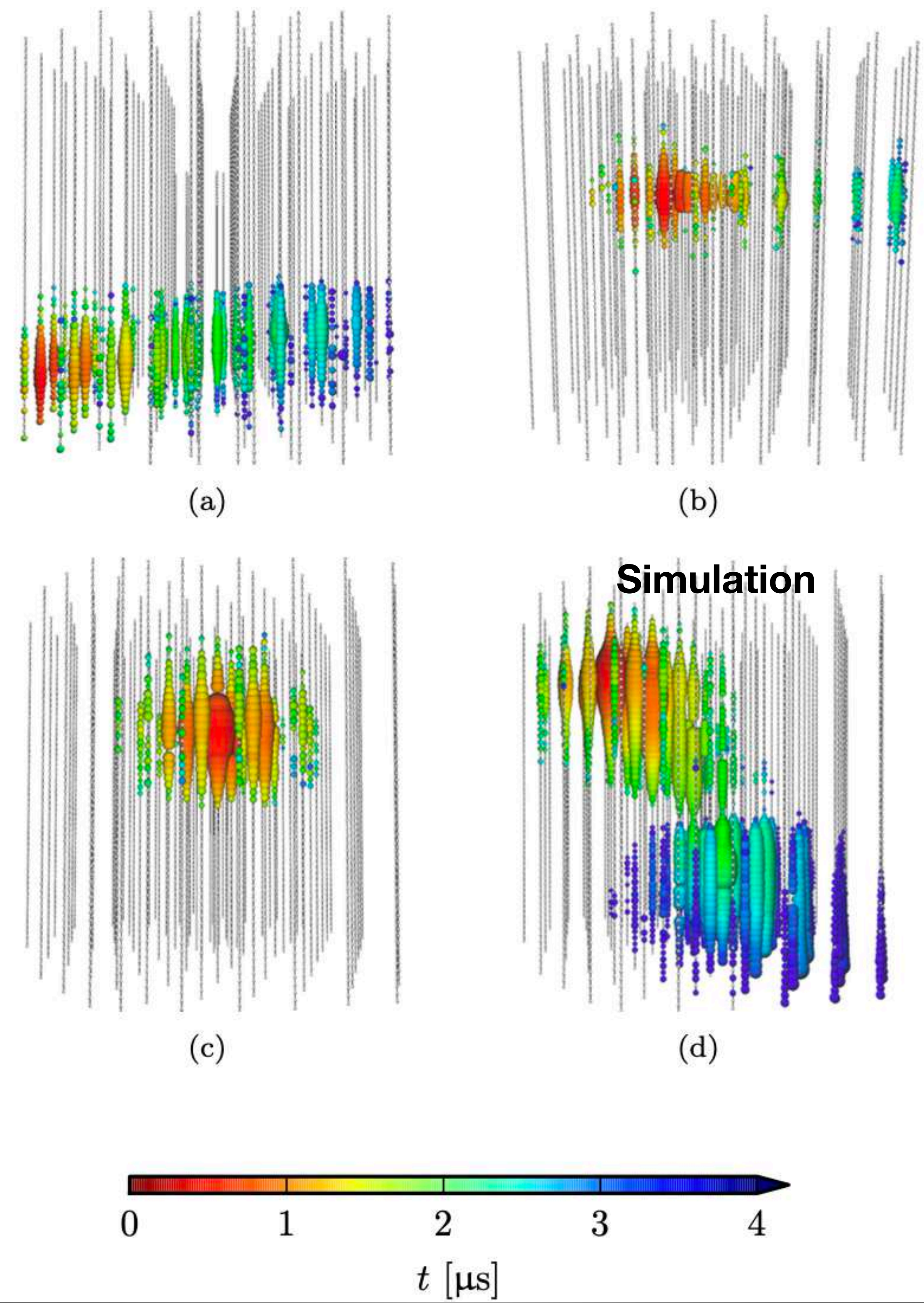
angular resolution < 1°
only dE/dx



Starting track (ν_μ)

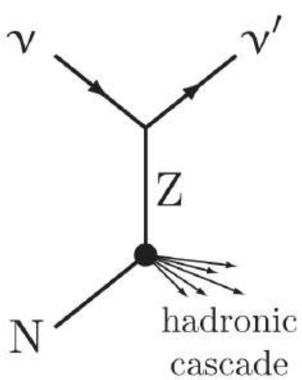
angular resolution < 1°
dE/dx + energy at vertex

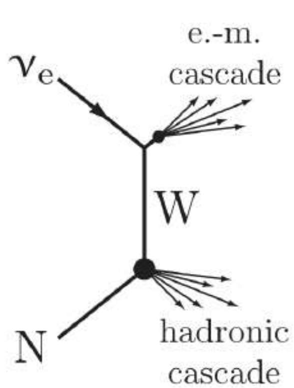




Cascade (ν_e, ν_μ, ν_τ)

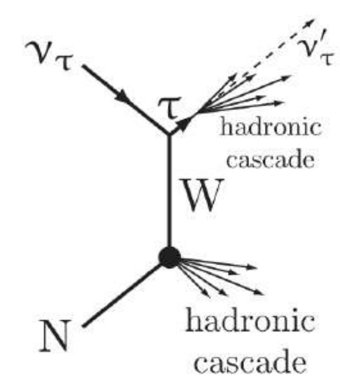
angular resolution > 10°
energy resolution ~ 15%



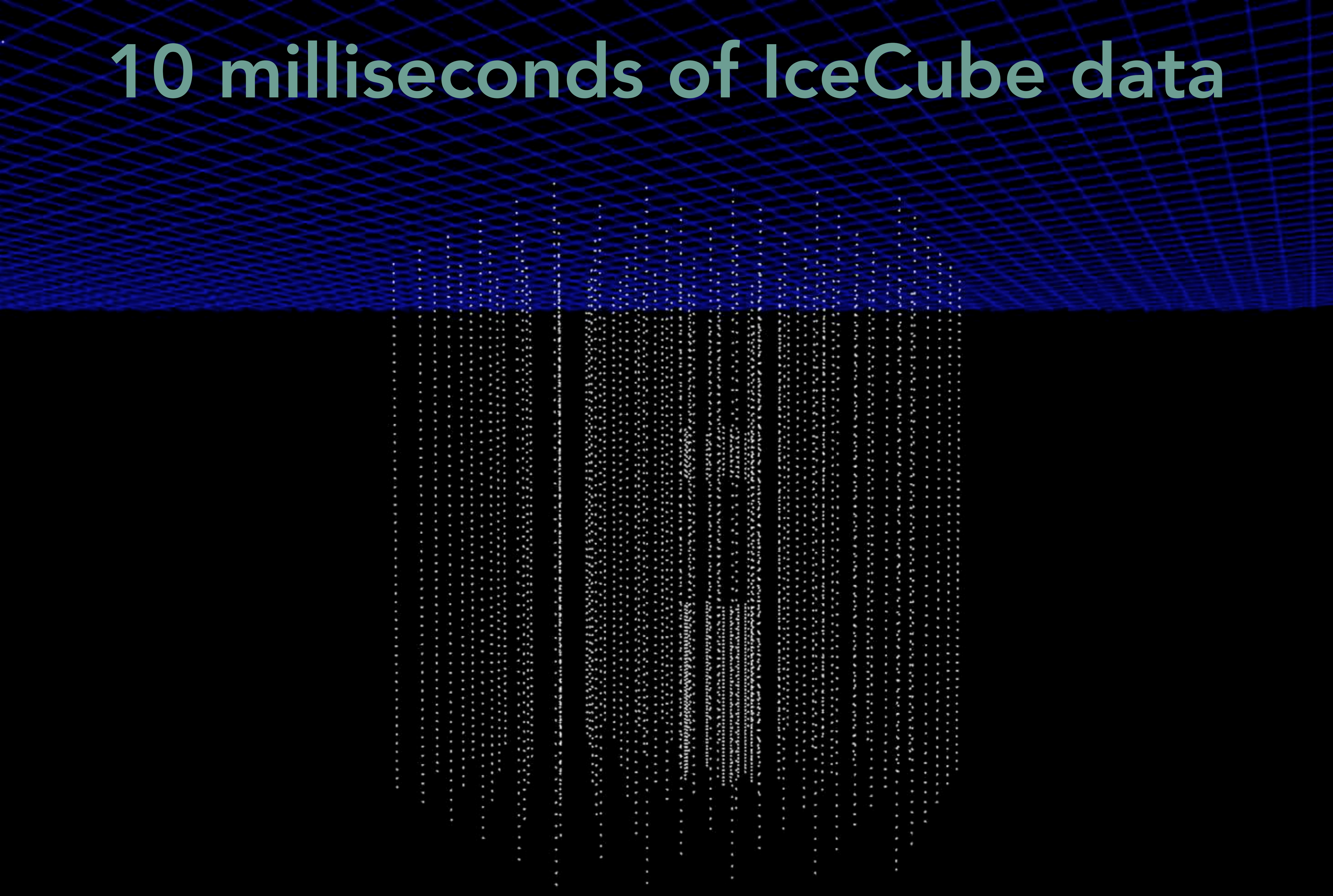


Double-Bang (ν_τ)

E > O(PeV)



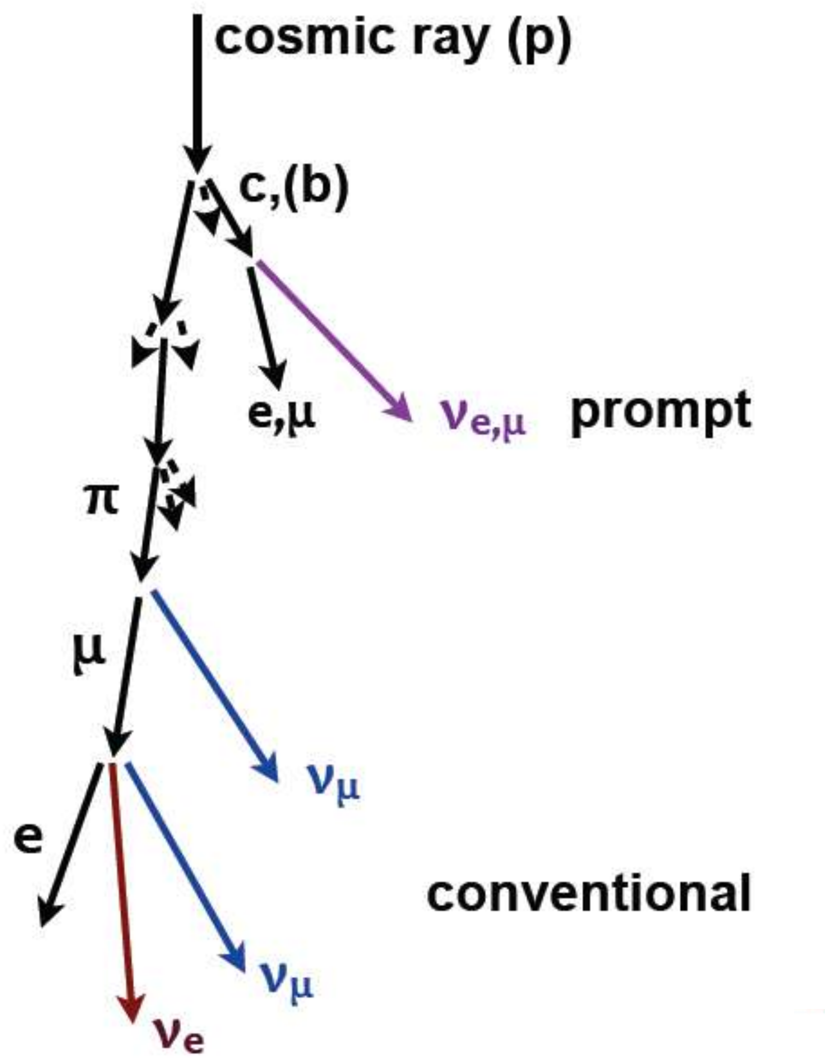
10 milliseconds of IceCube data

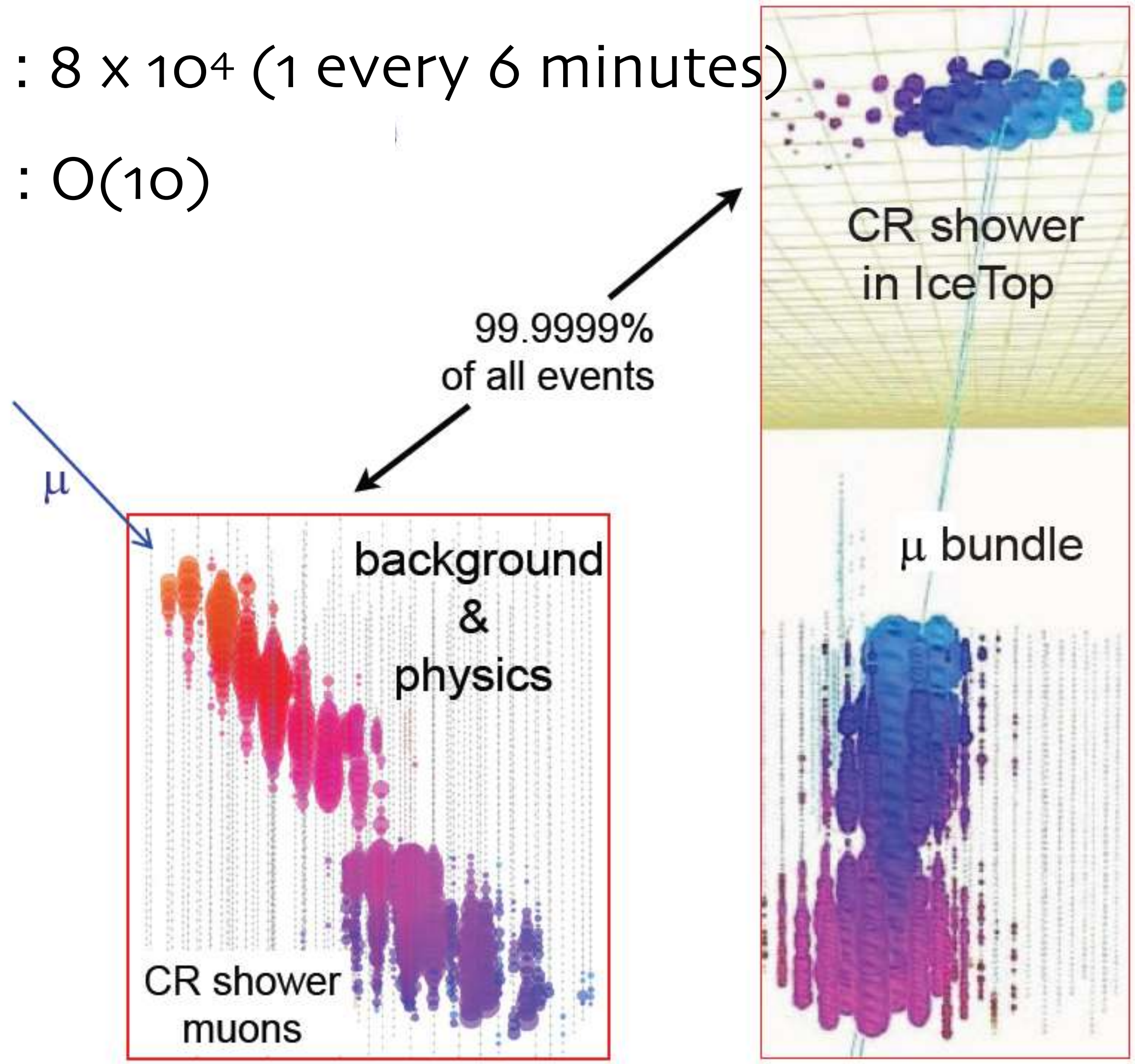


https://www.youtube.com/watch?v=IPzk2ZGUOB0

Signal and backgrounds

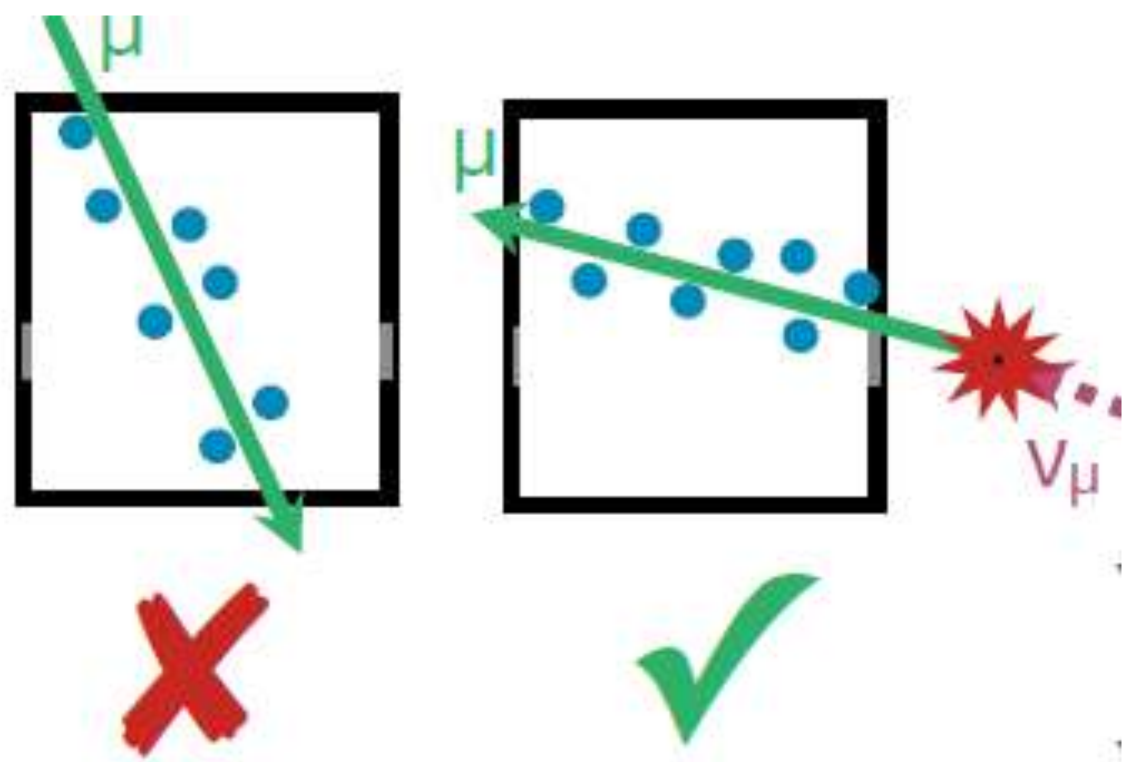
- Event rates in IceCube (year^{-1}):
  - atmospheric muons : 9×10^{10} (3000 per second)
  - atmospheric neutrinos : 8×10^{4} (1 every 6 minutes)
  - astrophysical : O(10)

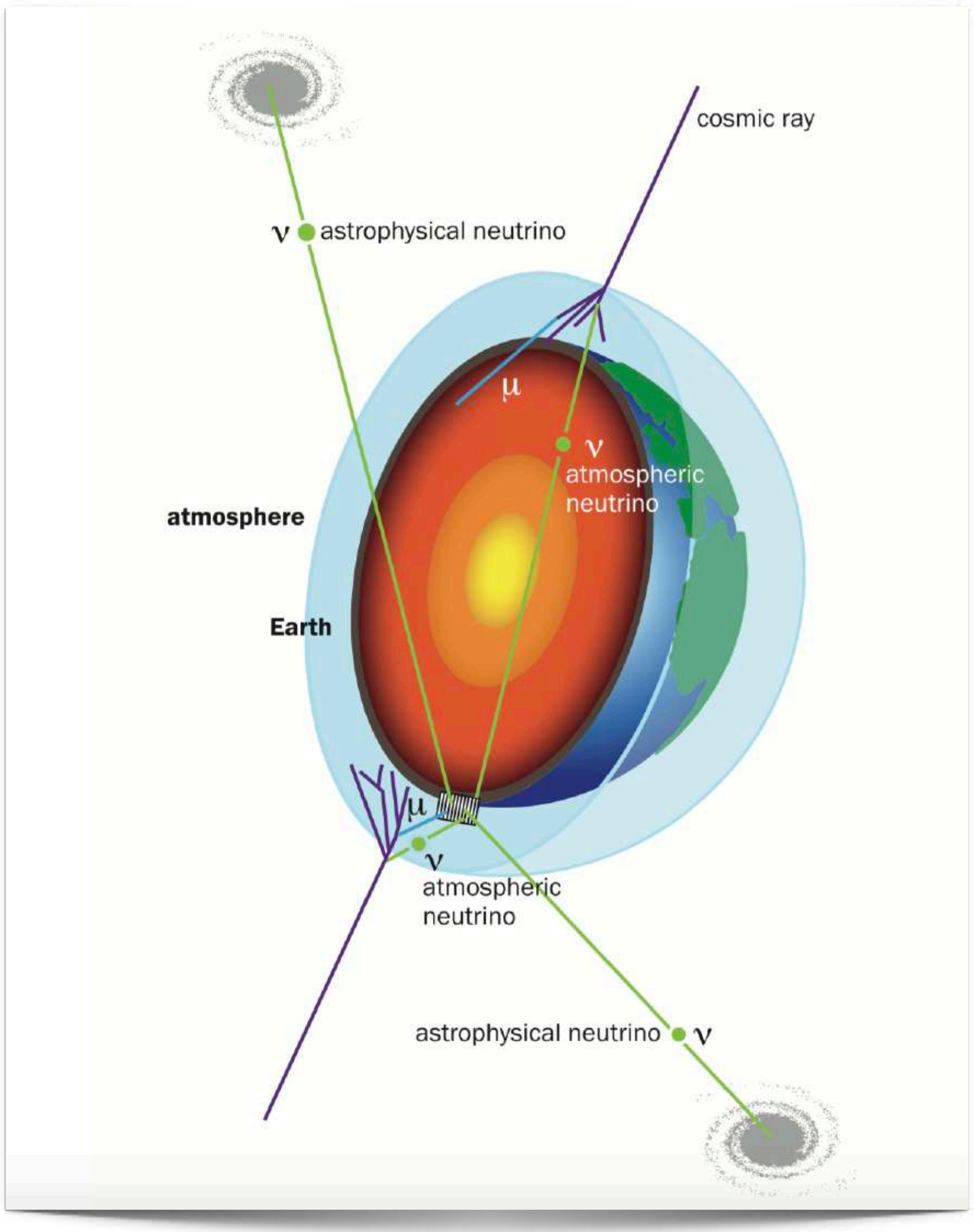




Reducing the background

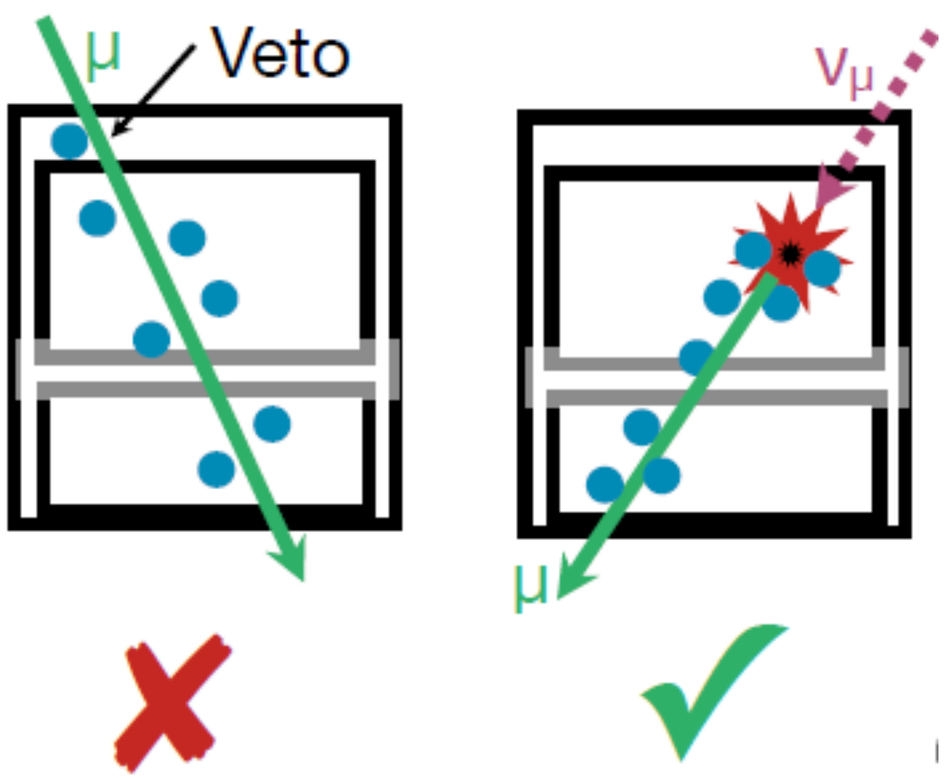
Selecting up-going events travelled through earth: Sensitive to ν_μ, ν_τ, Northern Sky only

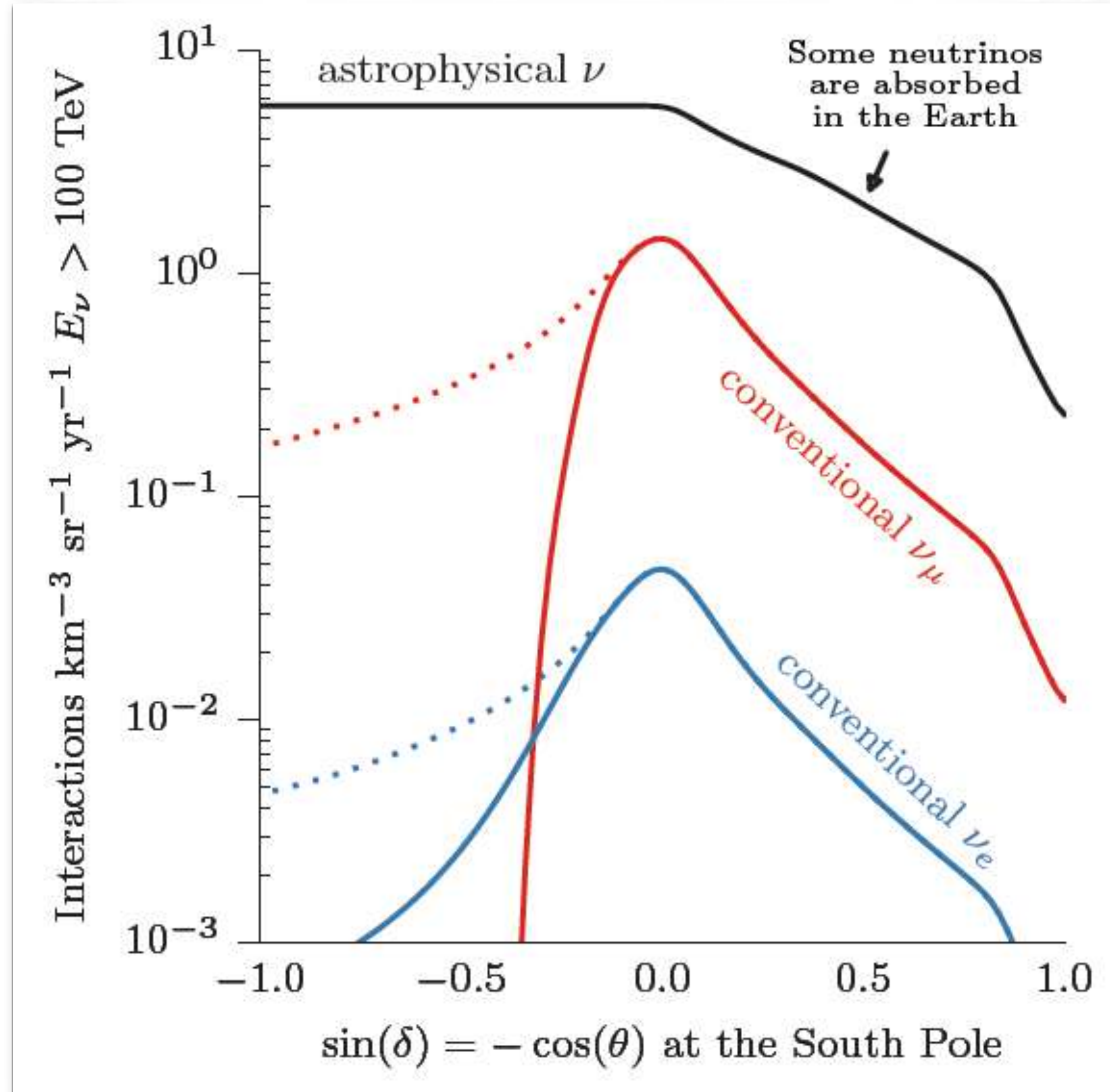




Reducing the background

Select High Energy Starting Events (HESE): Sensitive to ν_e, ν_μ, ν_τ from ~60 TeV to few PeV, Full Sky





Schonert, S., Gaisser, T. K., Resconi, E., & Schulz, O. Phys. Rev., D79, 043009

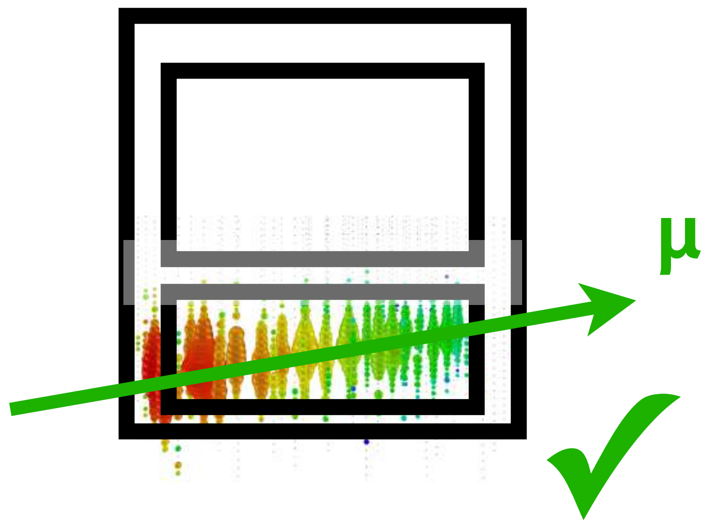
Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

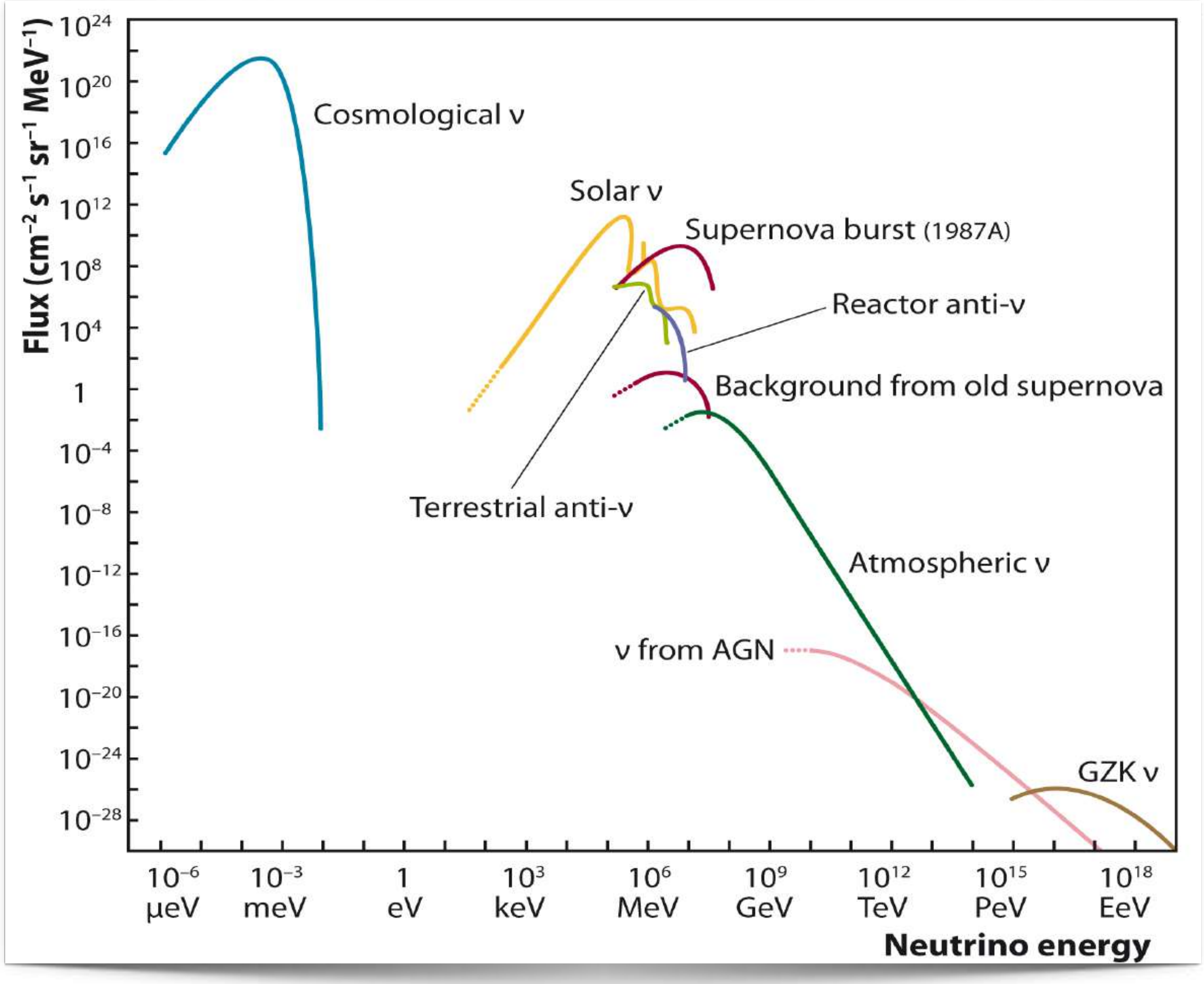
Aartsen, M. G., 2017d, Astrophys. J., 846, 136

Wandkowsky, N., & Weaver, C. 2018, PoS, ICRC2017, 976

Reducing the background

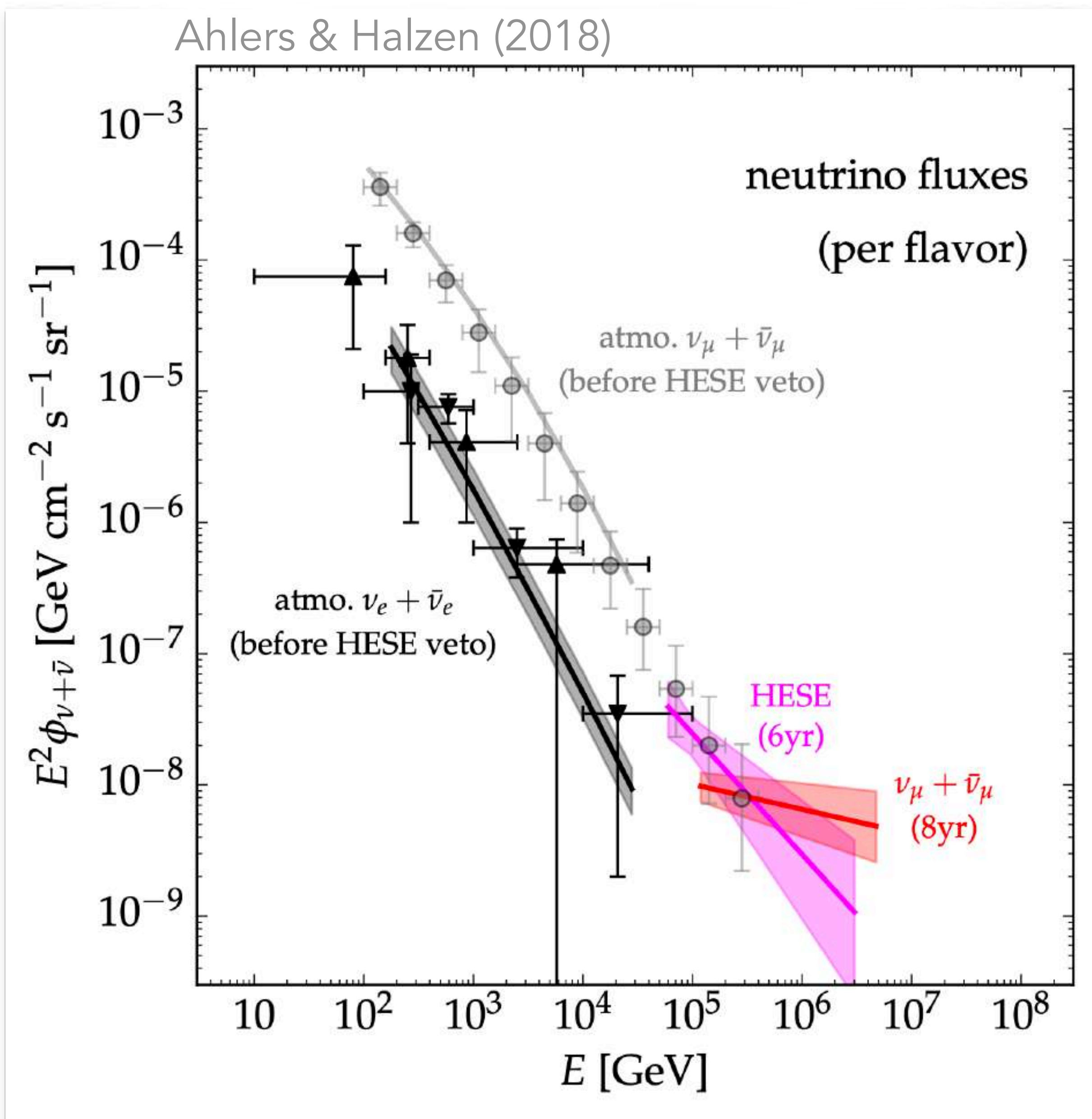
Select Extreme High Energy events (EHE): Sensitive to ν_e, ν_μ, ν_τ in energy range from few 100 TeV to few EeV, Around horizon with very good angular resolution for for tracks



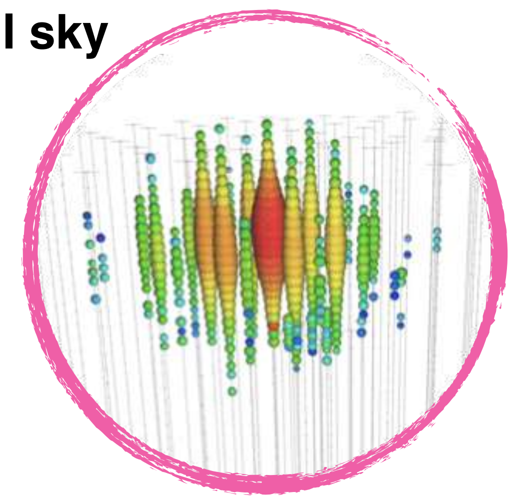


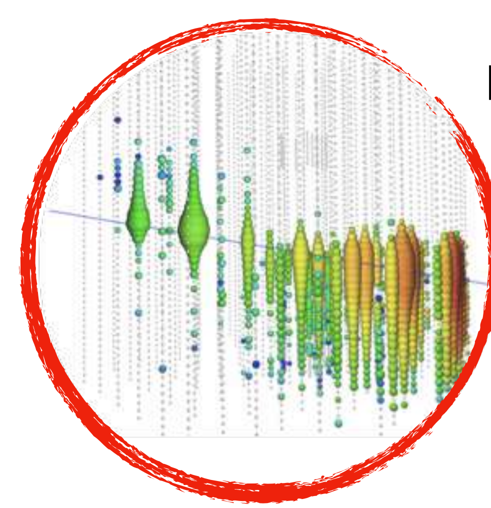
Astrophysical neutrino flux

At high energies an excess of events is observed excluding an atmospheric-only origin. An astrophysical flux in the energy range from 20 TeV and 9 PeV is testified by various channels and analysis methods



High-energy starting events (**HESE**)
Interaction vertex in the detector
All flavor, **all sky**



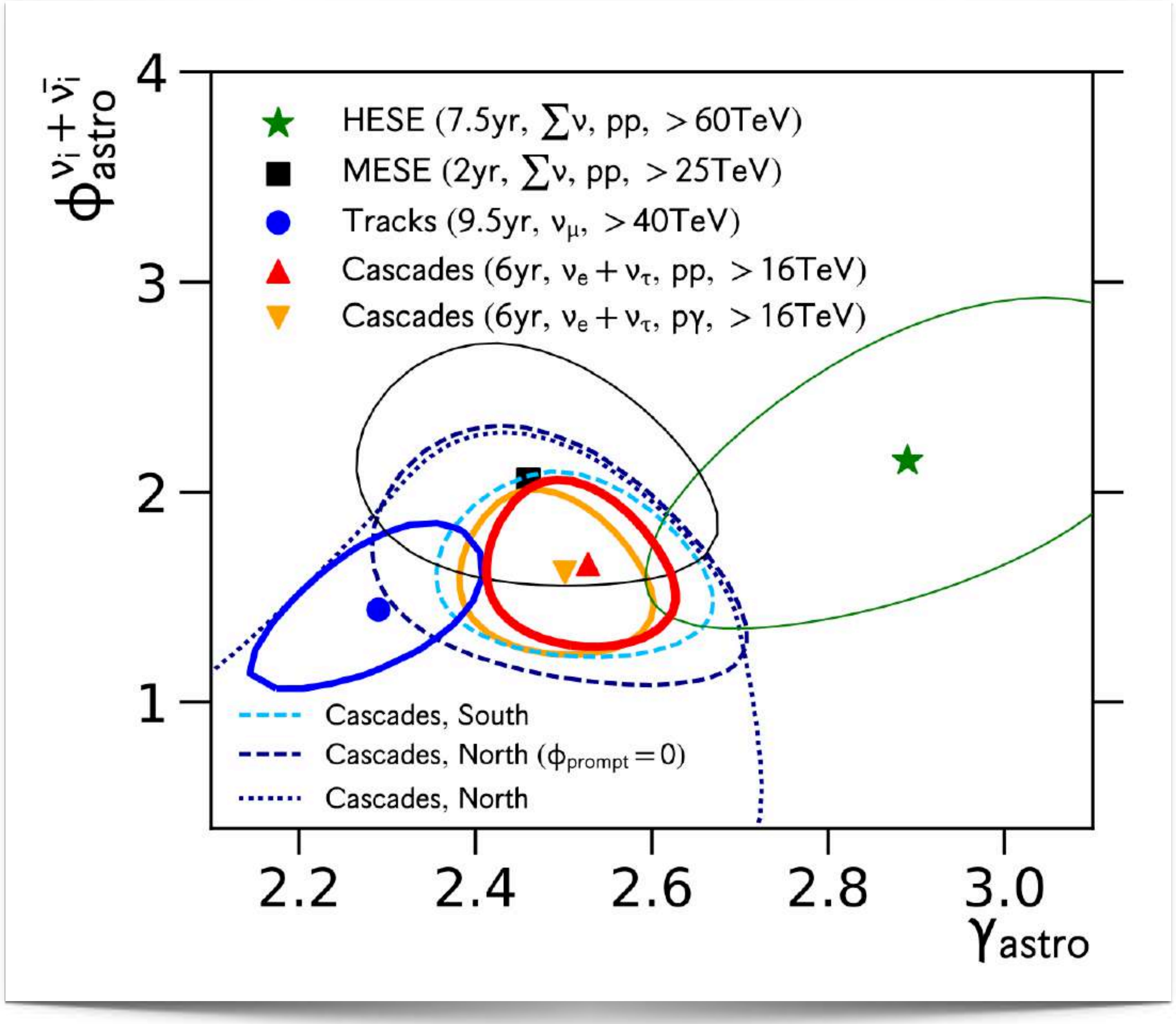


Up-going tracks
Muon-dominated
Northern sky

Astrophysical neutrino flux

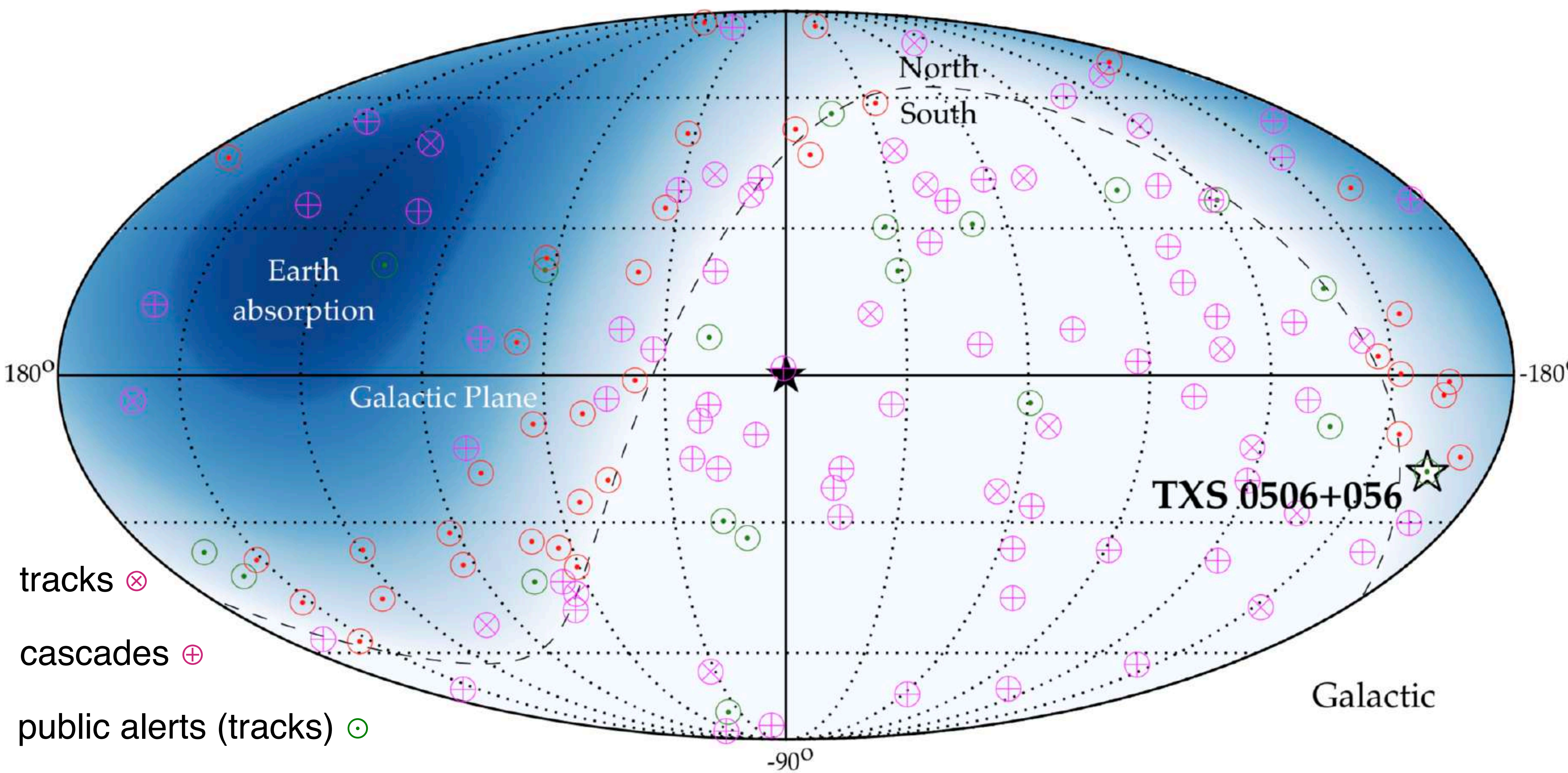
The energy spectrum is compatible with a power-law with a spectral index of 2.5 between 16 TeV and 3 PeV. Independent channels (cascades: ν_e+ν_τ) and tracks (ν_μ)

IceCube Col.. Phys. Rev. Lett. 125, 121104 (2020)



The high-energy Neutrino Sky

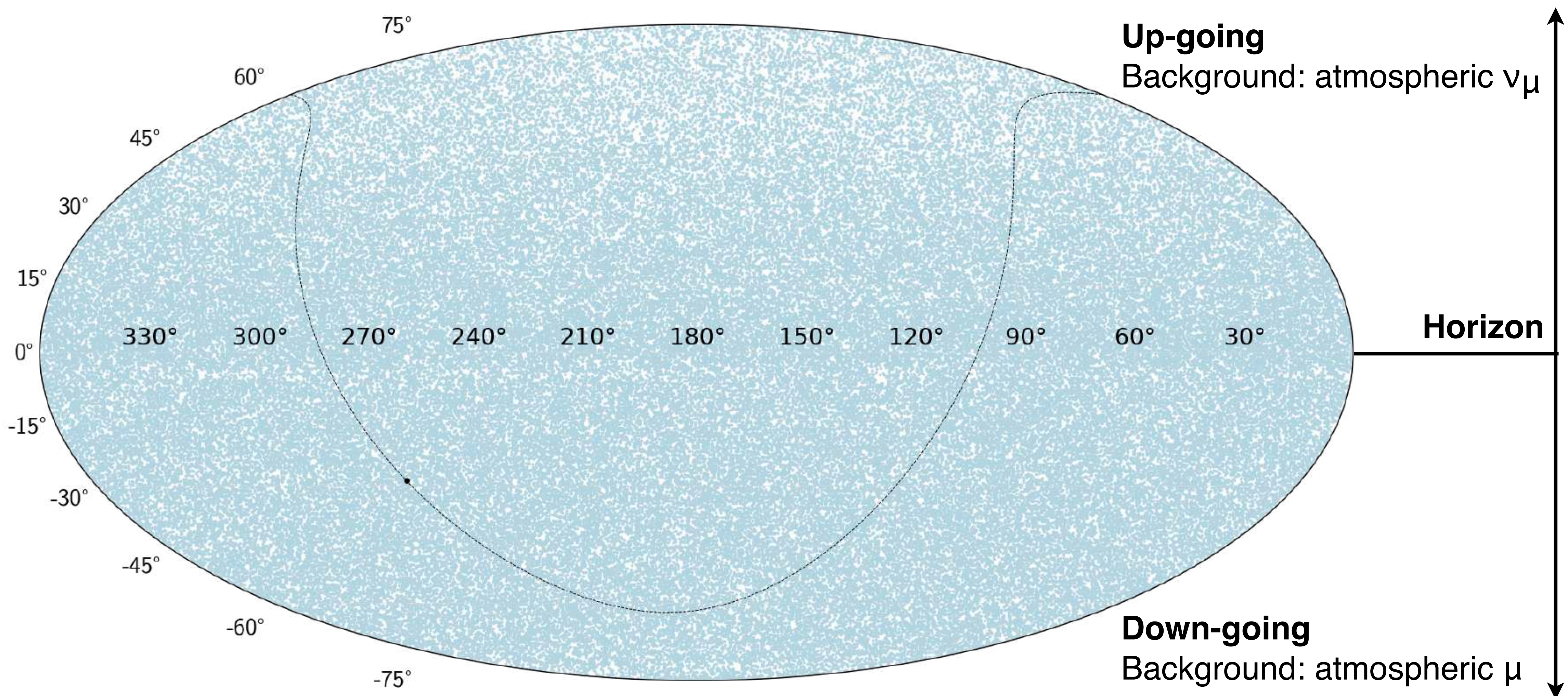
At high energies (few tens TeV) a clear excess of events is observed excluding an atmospheric-only origin. Directions show no obvious accumulation either around individual sources or the Galactic plane



M. Ackermann et al., Astro2020 Science White Paper 2019

Searching for Neutrino Point Sources

Allowing for more background and larger signal efficiencies it is possible to search for individual astrophysical sources as local event excesses. From the first year of full IceCube operations 138,322 neutrino candidates (**muon tracks**) recorded!

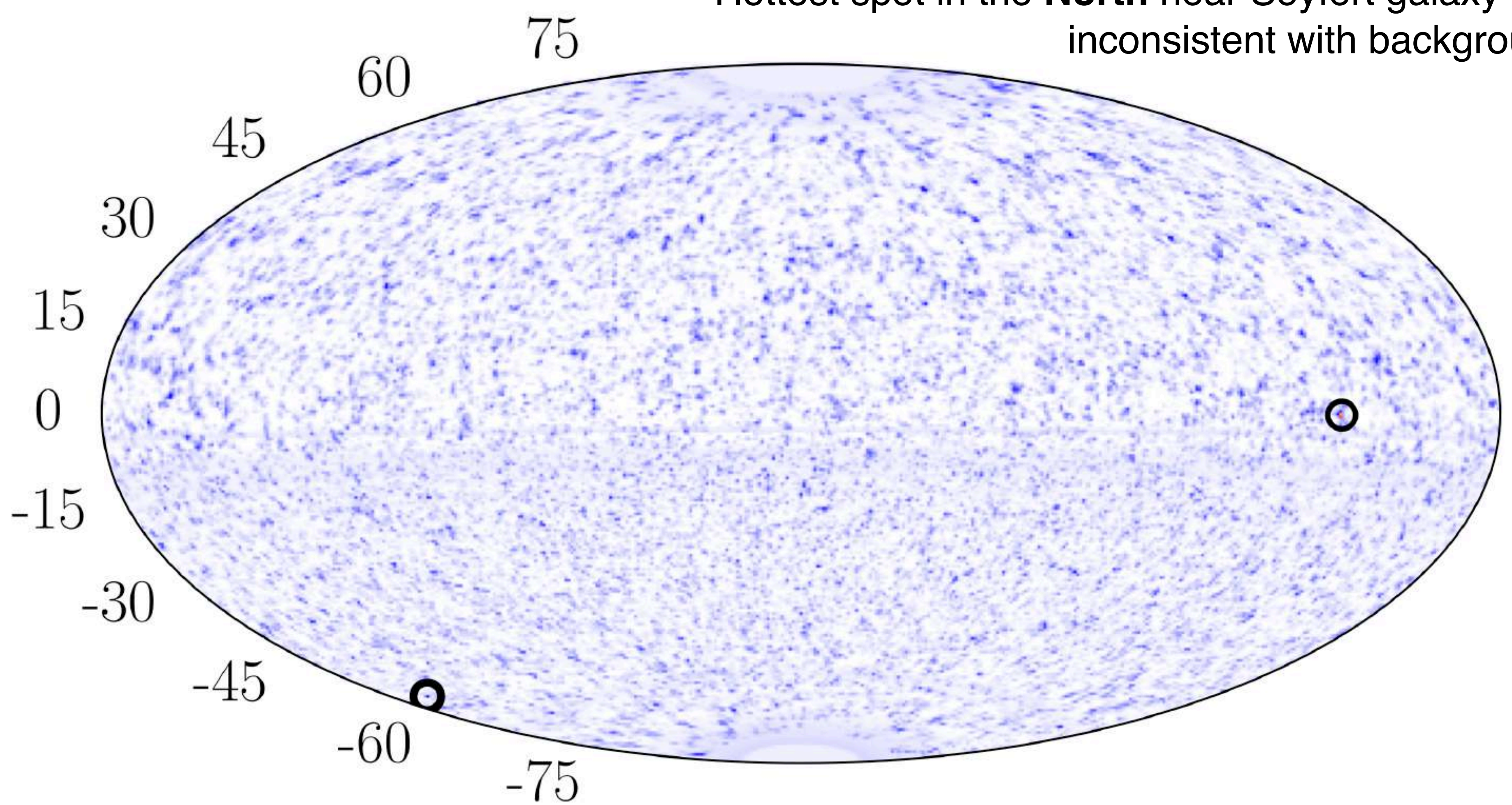


Equatorial coordinates

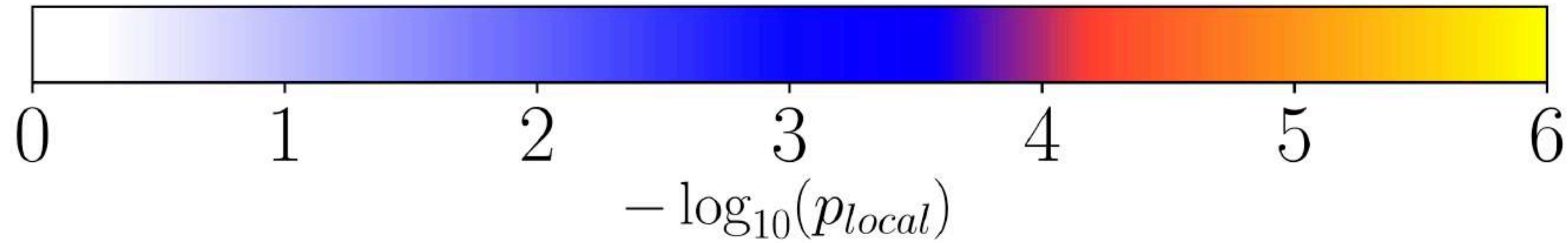
Searching for Neutrino Point Sources

A sample of ~1x10^6 neutrinos recorded by IceCube in 10 years provides no evidence for neutrino sources in the full sky and in locations motivated by gamma-ray observations

Hottest spot in the **North** near Seyfert galaxy NGC 1068, inconsistent with background at **2.9σ**

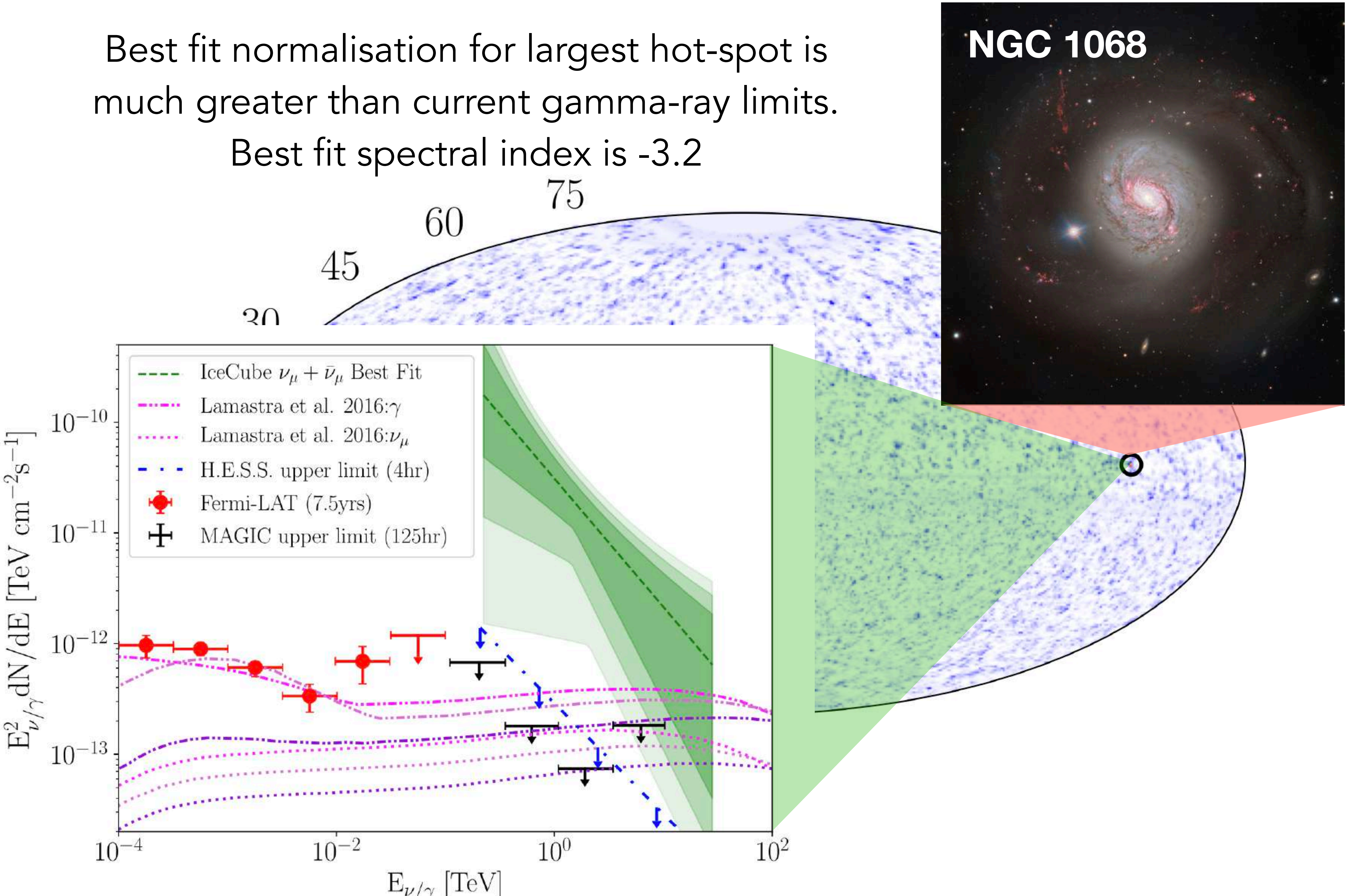


Hottest spot in the **South** post-trial probability 75%



Searching for Neutrino Point Sources

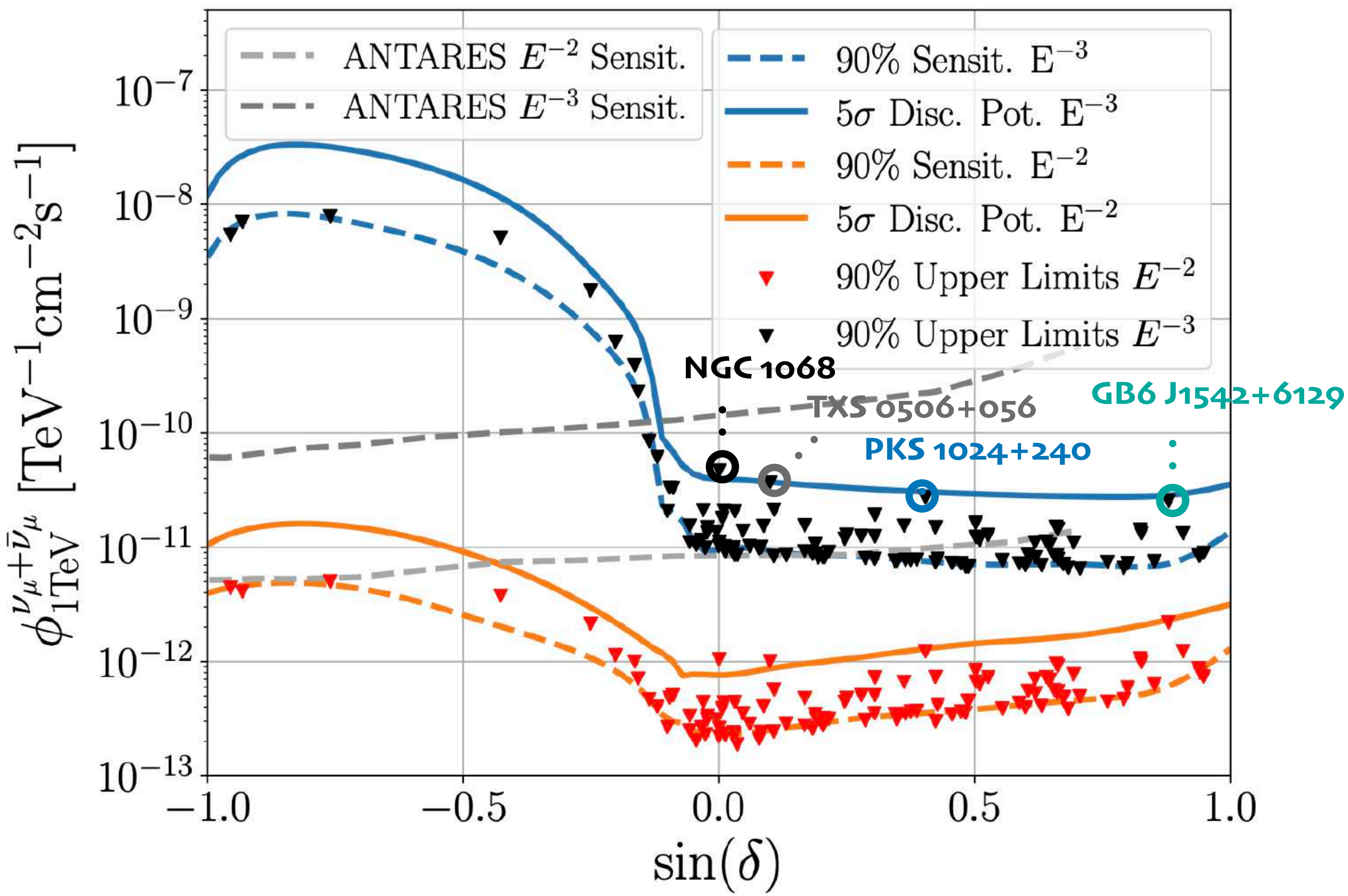
Best fit normalisation for largest hot-spot is much greater than current gamma-ray limits.
Best fit spectral index is -3.2



MAGIC Coll., The Astrophysical Journal 883 (2019) 135

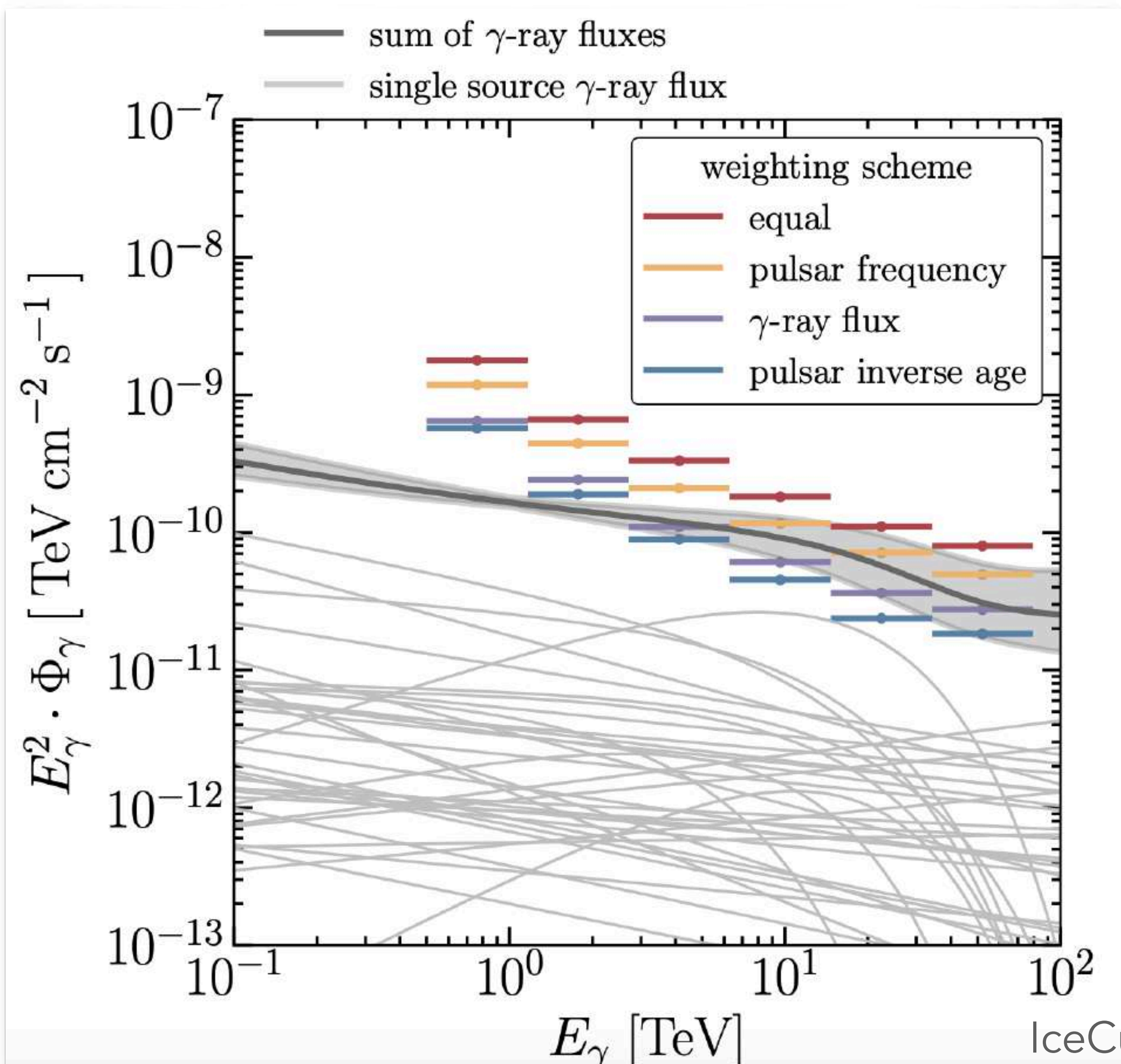
Searching for Neutrino Point Sources

Collectively, correlations with sources in the Northern catalog are inconsistent with background at 3.3 σ significance.



Neutrinos from PWNe

Galactic cosmic ray accelerators are expected to contribute at a subdominant level to the observed high-energy cosmic neutrino flux. Pulsar Wind Nebulae are the most abundant population of gamma-ray emitters, motivating dedicated searches

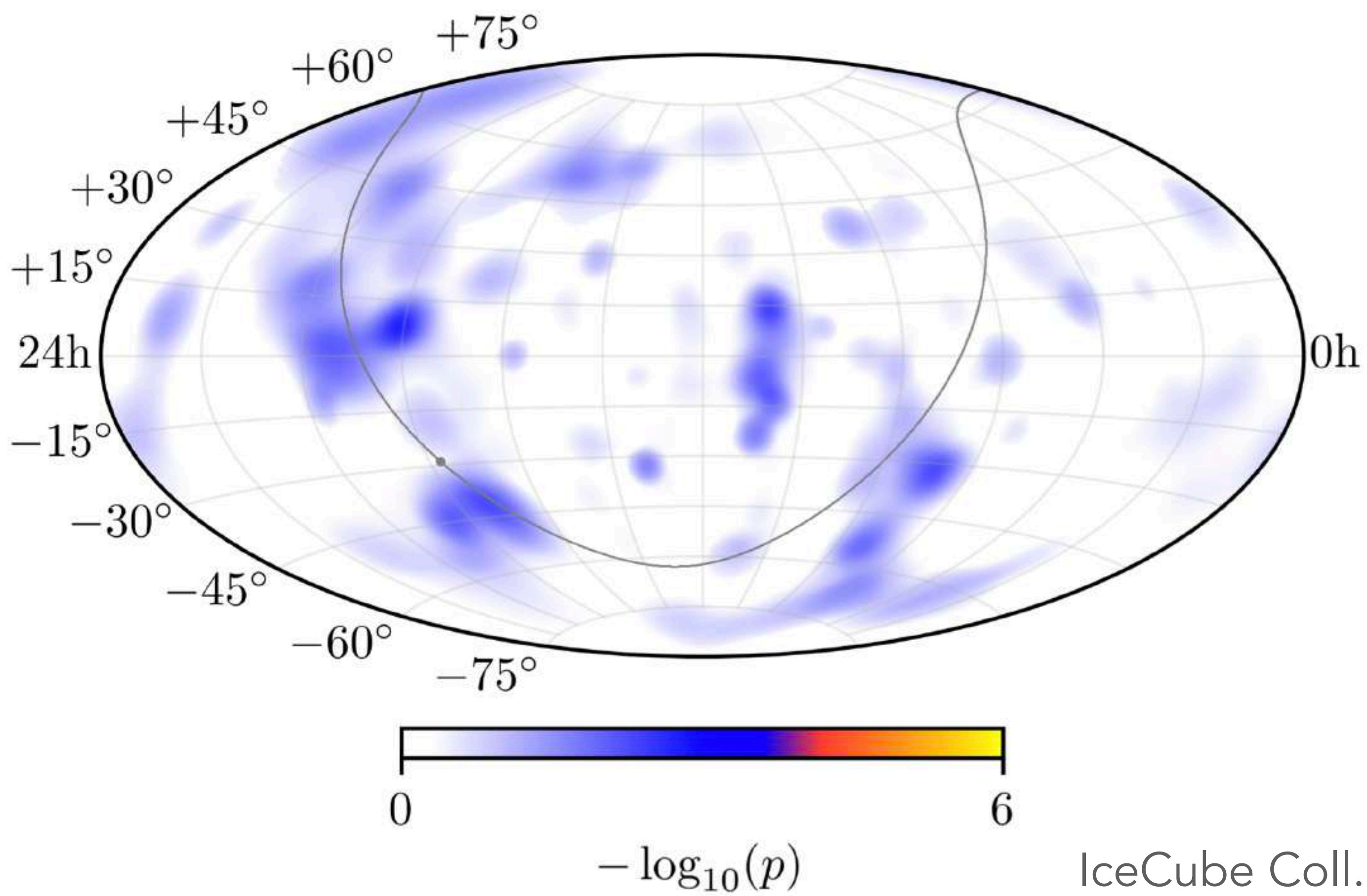


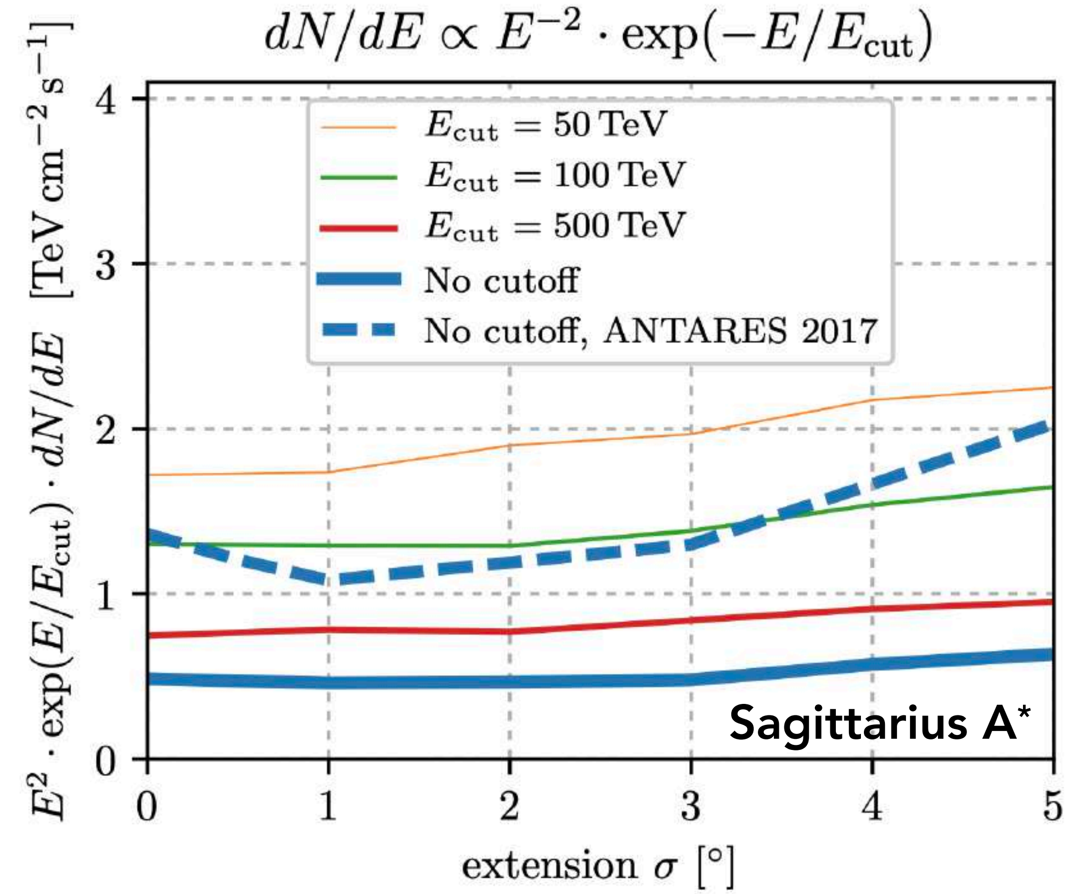
PWNe can be strong neutrino emitters if the neutrino flux is correlated with the gamma-ray flux or if correlated with the pulsar's age

IceCube Coll. Astrophys. J. 898 (2020) 117

Using cascade events

Cascade events allow for low background searches for point sources of neutrinos with energies as low as 1 TeV anywhere in the sky

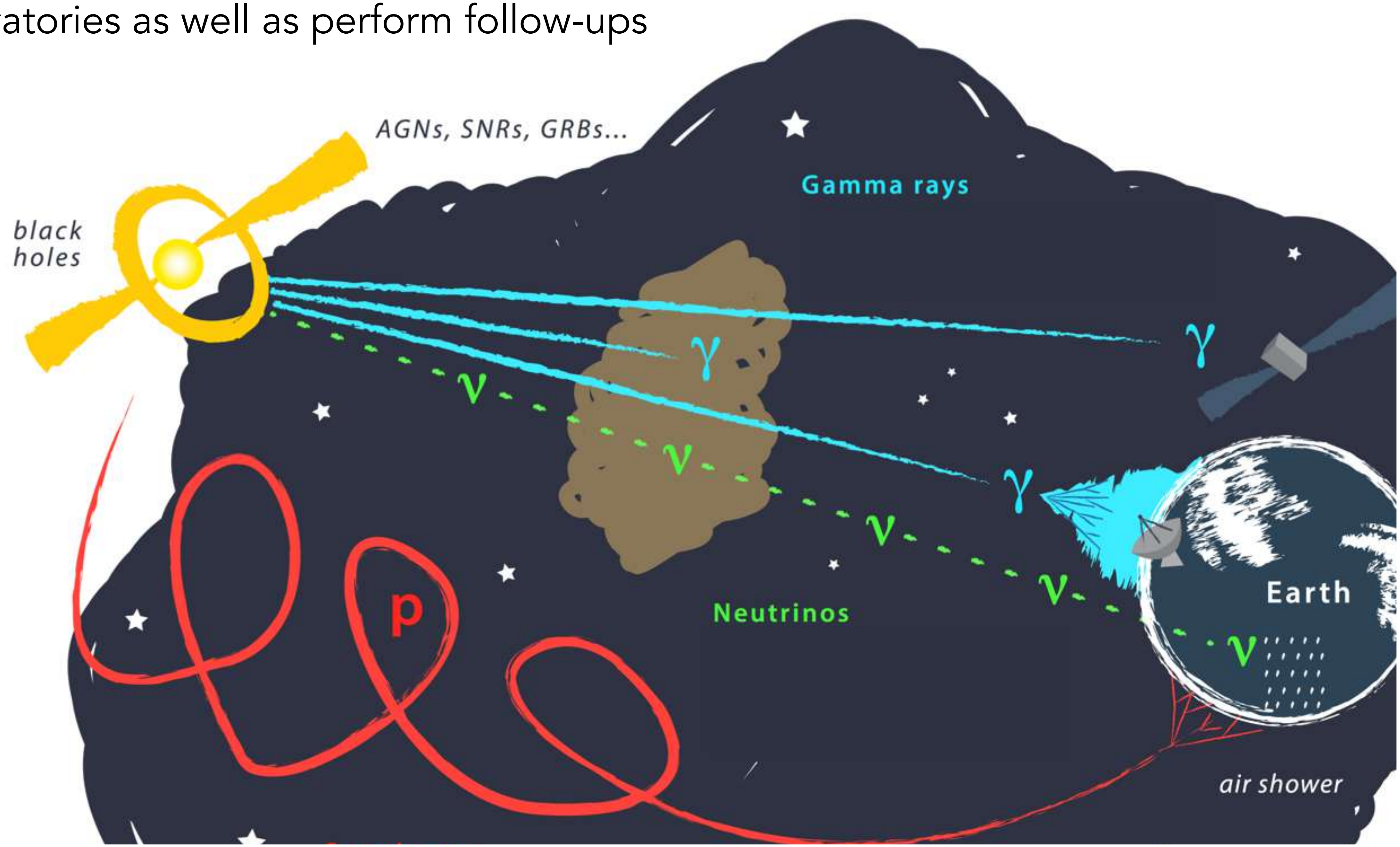




IceCube Coll. Astrophys. J. 886 (2019) 12

Realtime Neutrino Astronomy

IceCube's nearly 100% uptime and continuous 4π steradian field of view make it an ideal observatory for multi- messenger programs, both to trigger other observatories as well as perform follow-ups



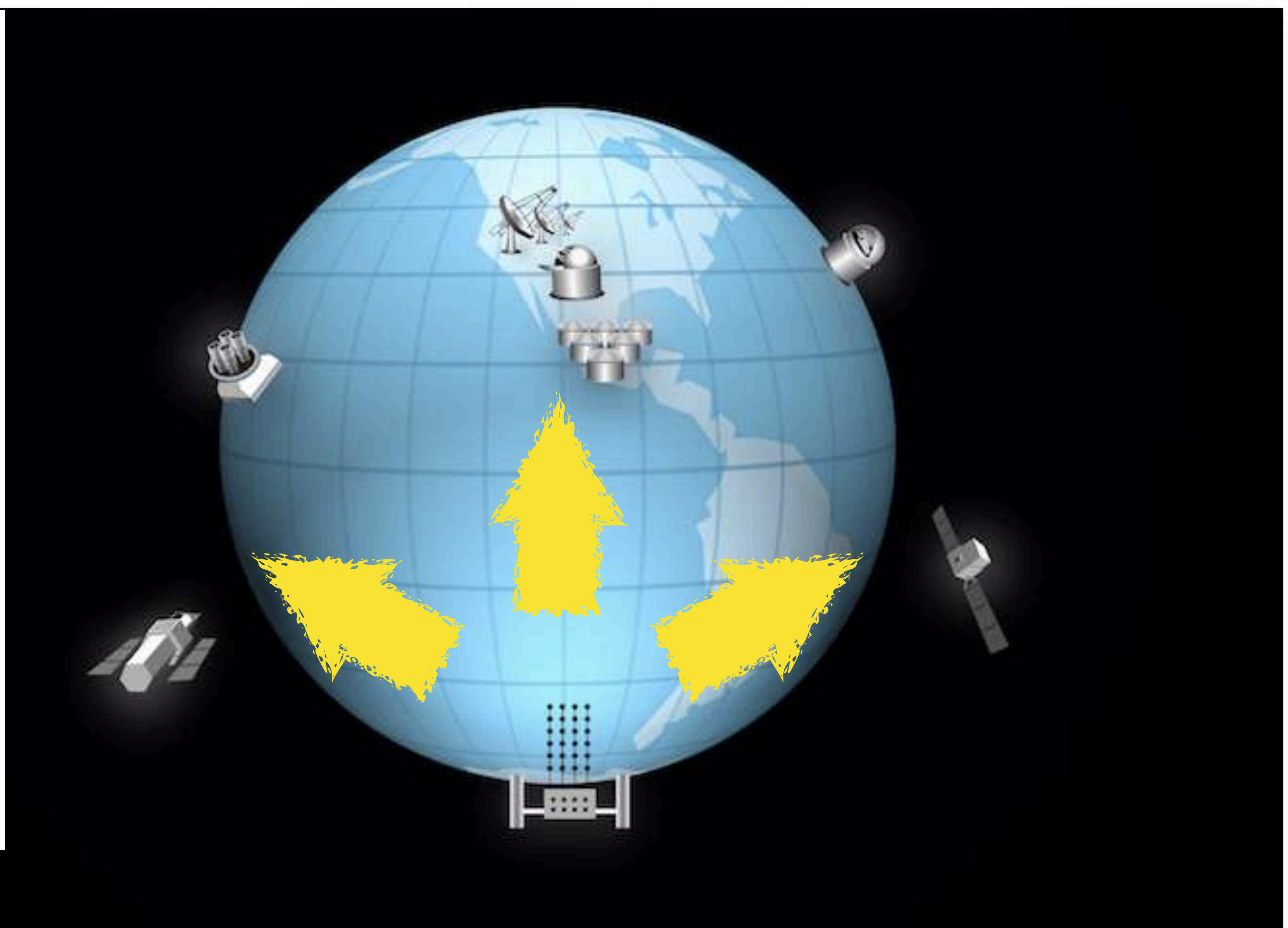
Neutrino triggered target of Opportunity

The first application of a **Target of Opportunity strategy** to collect simultaneous data of high energy neutrinos and gamma-rays. Neutrino events with coordinates close to preselected candidate sources are used to alert gamma-ray observations. The detection of a positive coincidence can enhance the neutrino discovery chance or more generally increase the availability of simultaneous observations

E.B "Multi-messenger approaches to search for point sources of high energy neutrinos with AMANDA/IceCube" @ The Multi-Messenger Approach to High-Energy Gamma-Ray Sources, Barcelona (**2005**)

E.B "Multi-messenger Studies with AMANDA/IceCube: Observations and Strategies" @ Cherenkov 2005, Palaiseau (**2005**)

M. Ackermann, E.B., et al., Neutrino Triggered Target of Opportunity (NToO) test run with **AMANDA-II and MAGIC**, arXiv:0709.2640 (**2007**)



Trigger types before 2019

IceCube Coll., The IceCube Realtime Alert System, Astropart. Phys., 92, 30 (2017)

Event multiplets (**PRIVATE, since 2008/2012**):

ɣ-ray follow-up (**GFU**) timescales up to three weeks, 2 (background) alerts/yr [also @ M. G. Aartsen, et al., JINST 11 (2016)]

optical and X-ray follow-up (**OFU**) timescales up to 100 s, 7 (background) alerts/yr [also @ M. G. Aartsen, et al., Astrophys. J. 811 52 (2015)]

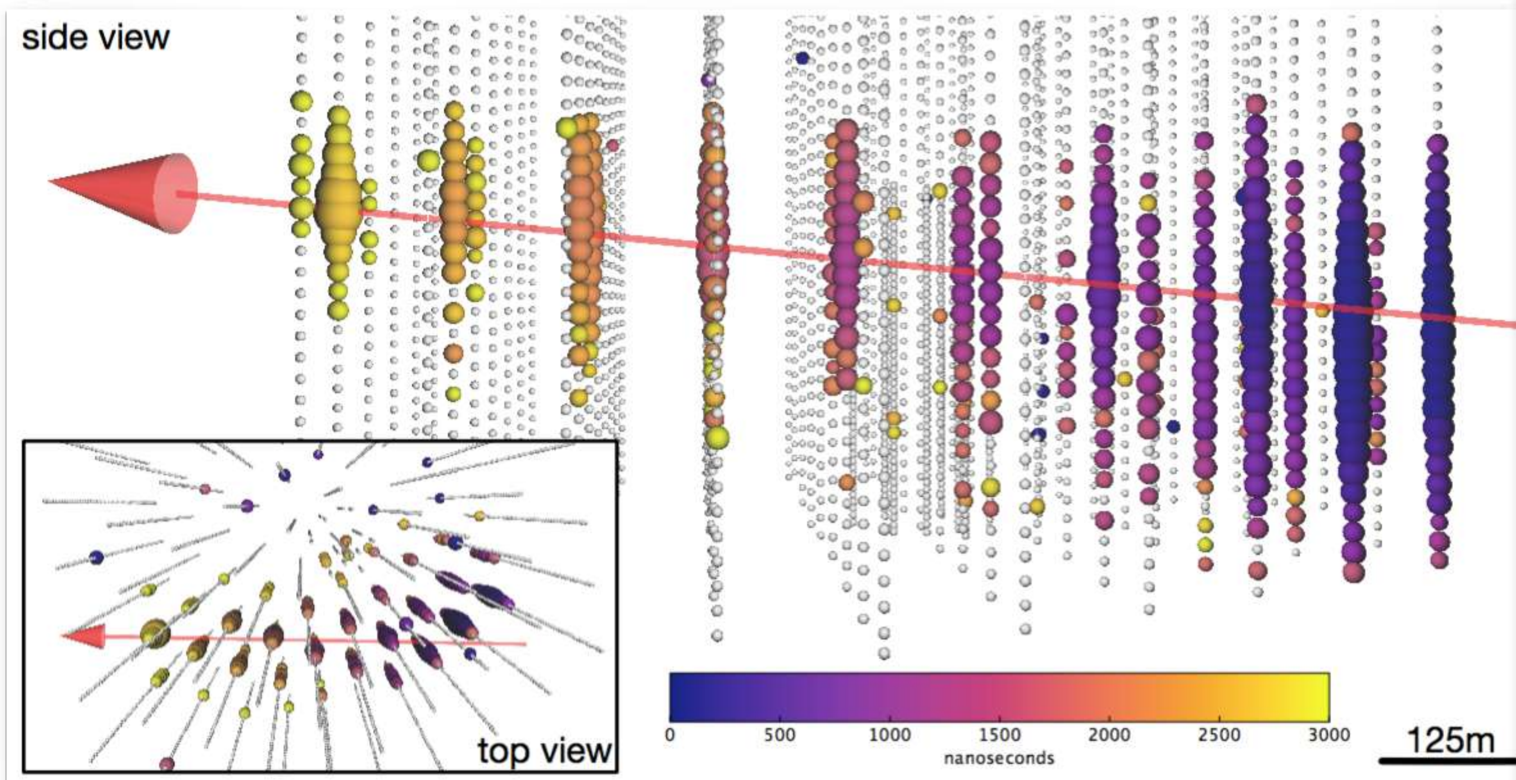
Single events (**PUBLIC, since 2016**)

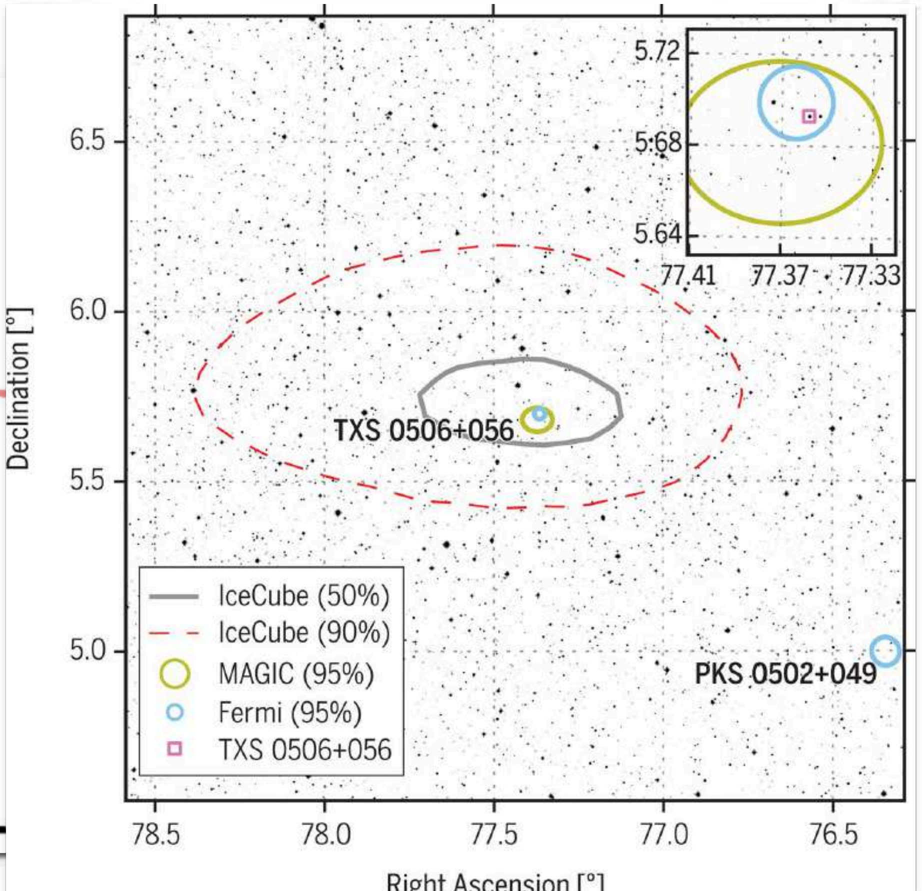
Track-like high-energy starting events (**HESE**): single events, 4 alerts/yr, 1/yr signal expected

Extremely high-energy through- going tracks (**EHE**): single events, 4 alerts/yr, 2/yr signal expected

IceCube-170922A

Compelling evidence for neutrino emission from the **Blazar TXS 0506+056.** Identification of a cosmic hadron accelerator with >PeV energies!



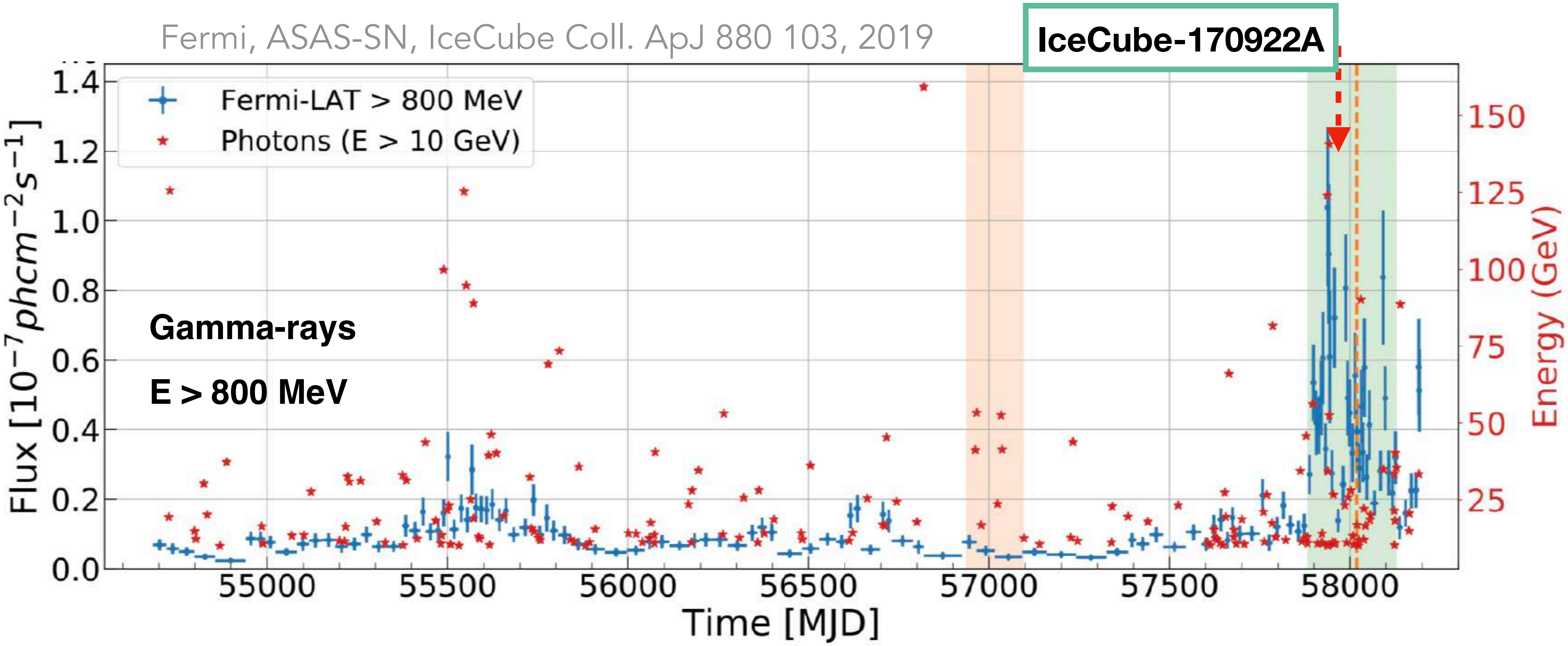


- Publicly distributed 43 seconds after trigger, refined direction 4 hr later
- At 6 arc-minutes from the direction of TXS 0506+056
- Most probable energy between 250 and 300 TeV and probability of astrophysical origin 56.6%

IceCube-170922A

Compelling evidence for neutrino emission from the **Blazar TXS 0506+056.**
Identification of a cosmic hadron accelerator with >PeV energies!

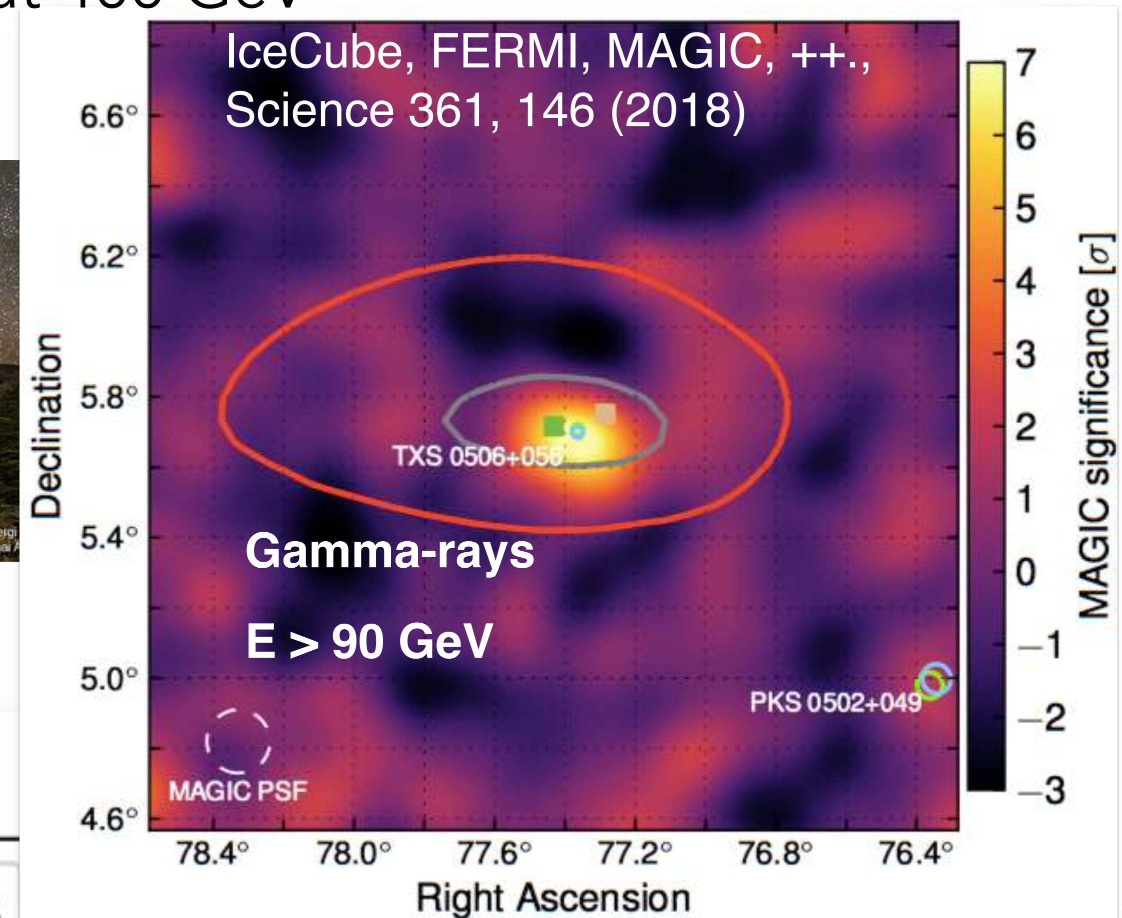
Fermi, ASAS-SN, IceCube Coll. ApJ 880 103, 2019

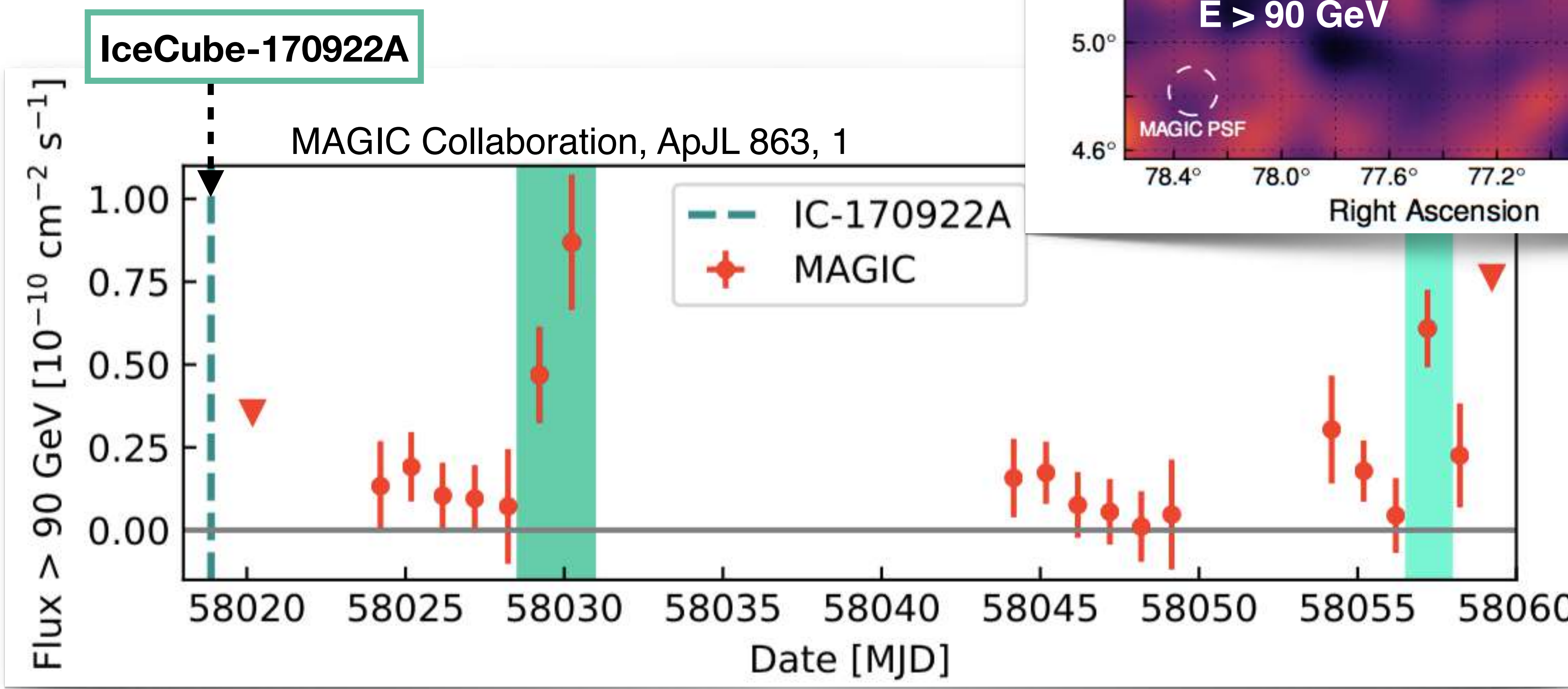


- Consistent with the direction of IceCube-170922A there is the Blazar TXS 0506+056
- The source was found in a state of enhanced gamma-ray activity lasting several months
- Coincidence probability after trials (10 public alerts and 40 archival events): 3 σ

Very high energy gamma-rays from TXS 0506+056

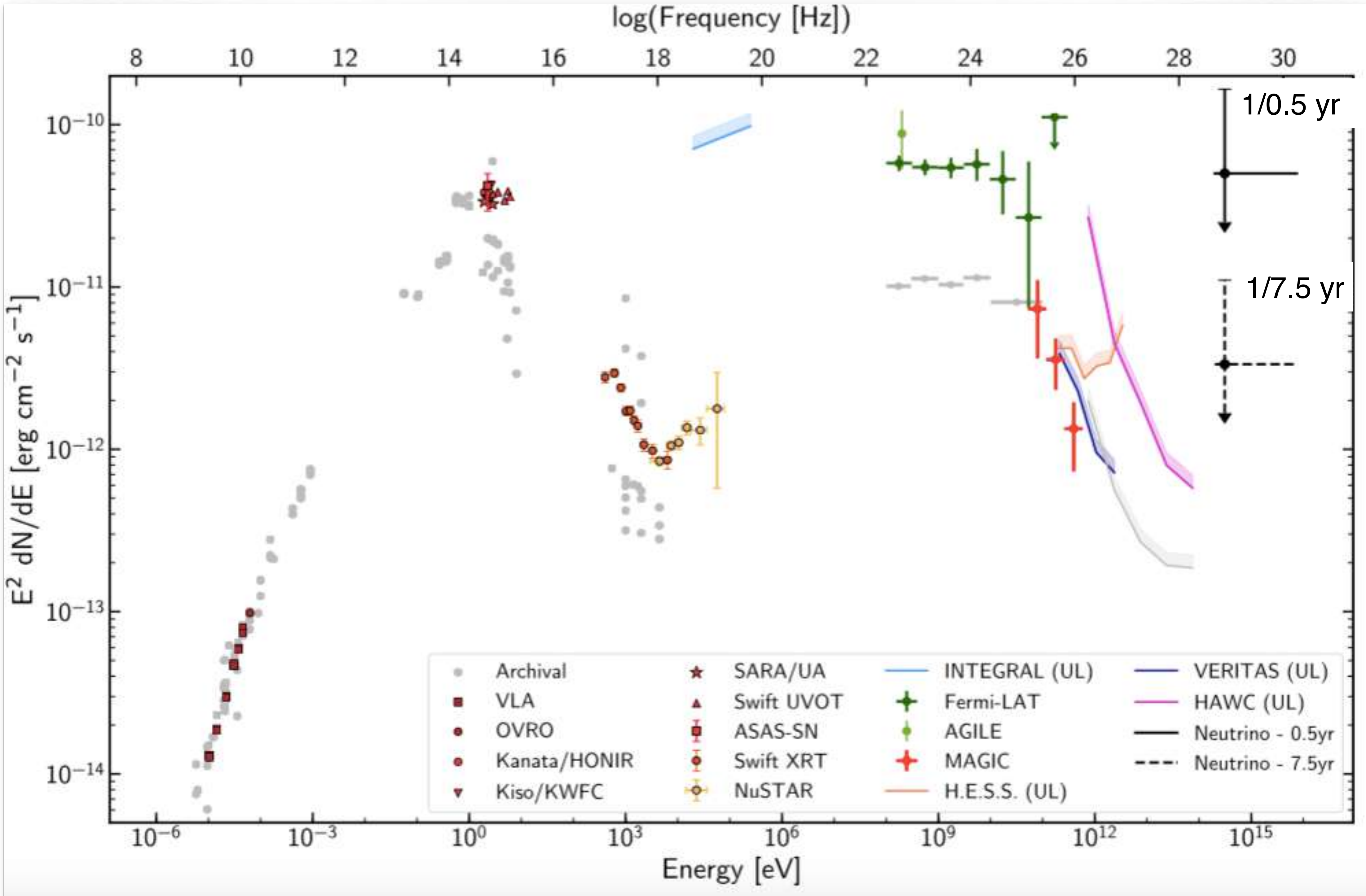
MAGIC detected ɣ-rays with energies up to about 400 GeV with strong day-to-day variations





The first multi-messenger SED

IceCube, FERMI, MAGIC, ++., Science 361, 146 (2018)



A neutrino emitter?

For $E_\nu \sim 300$ TeV, **interacting protons shall have energies $E_p \geq 6$ PeV** and must interact with photons with energies in the UV to soft X-ray range. Getting all the elements of this puzzle to **fit together is not easy**. Blazars seem to contain important clues on the origin of cosmic neutrinos and cosmic rays.

C. Righi, F. Tavecchio, and S. Inoue. Neutrino emission from BL Lac objects: the role of radiatively inefficient accretion flow

S. Ansoldi et al. The Blazar TXS 0506+056 Associated with a High-energy Neutrino: Insights into Extragalactic Jets and Cosmic

M. Cerruti, A. Zech, C. Boisson, G. Emery, S. Inoue, and J. P. Lenain. Leptohadronic single-zone models for the electromagnetic and neutrino emission of TXS 0506+056. *Mon.*

Shan Gao, Anatoli Fedynitch, Walter Winter, and Martin Pohl. Modelling the coincident observation of a high-energy neutrino and a bright blazar flare. *Nature Astronomy*, 3:88–92, 2019.

A. Keivani et al. A Multimessenger Picture of the Flaring Blazar TXS 0506+056: Implica- tions for High-energy Neutrino Emission and Cosmic-Ray Acceleration. ApJ, 864:84, 2018.

A. Gokus, S. Richter, F. Spanier, M. Kreter, M. Kadler, K. Mannheim, and J. Wilms. Decom- posing blazar spectra into ... 31,

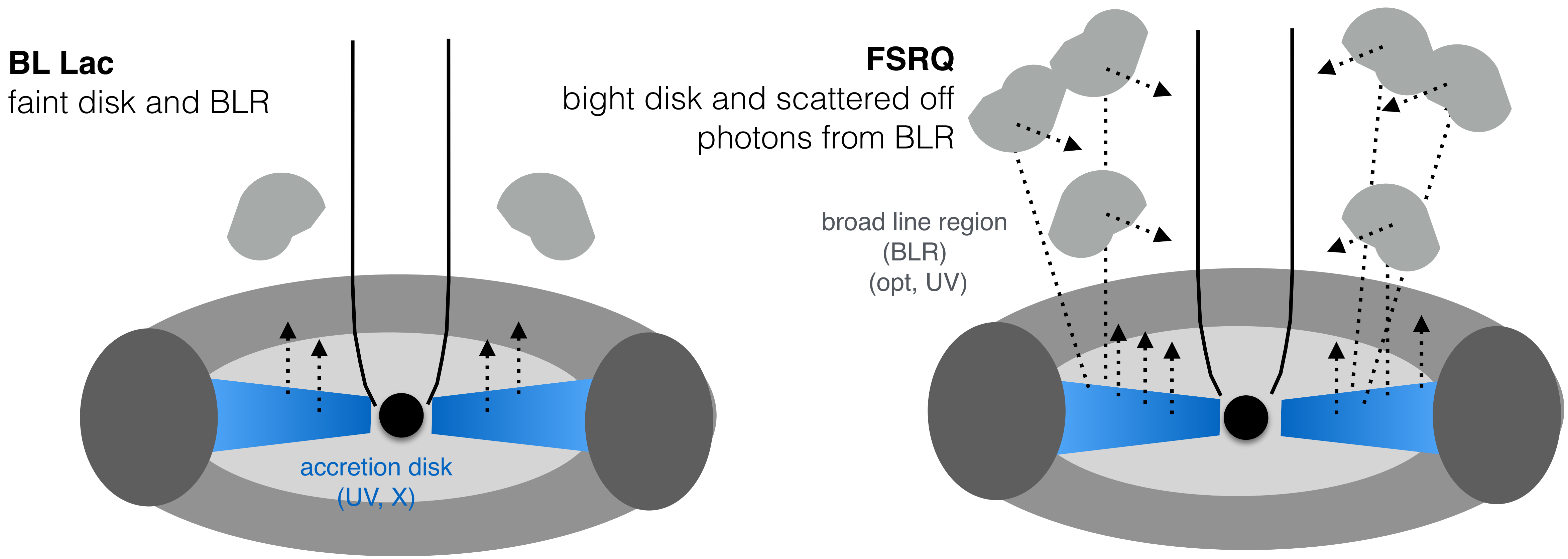
P. Padovani, P. Giommi, E. Resconi, T. Glauch, B. Arsioli, N. Sahakyan, M. Huber. Dissecting the region around IceCube-170922A: the blazar TXS 0506+056 as the first cosmic neutrino source. *Monthly Notices of the Royal Astronomical Society, Volume 480, Issue 1*

Ruo-Yu Liu, Kai Wang, Rui Xue, Andrew M. Taylor, Xiang-Yu Wang, Zhuo Li, and Huirong Yan. Hadronuclear interpretation of a high-energy neutrino event coincident with a blazar flare. *Phys.*

N. Sahakyan. Lepto-hadronic γ-ray and neutrino emission from the jet of TXS 0506+056. *Astrophys. J.*, 866(2):109, 2018.

Interpreting the multi-messenger data in a nutshell

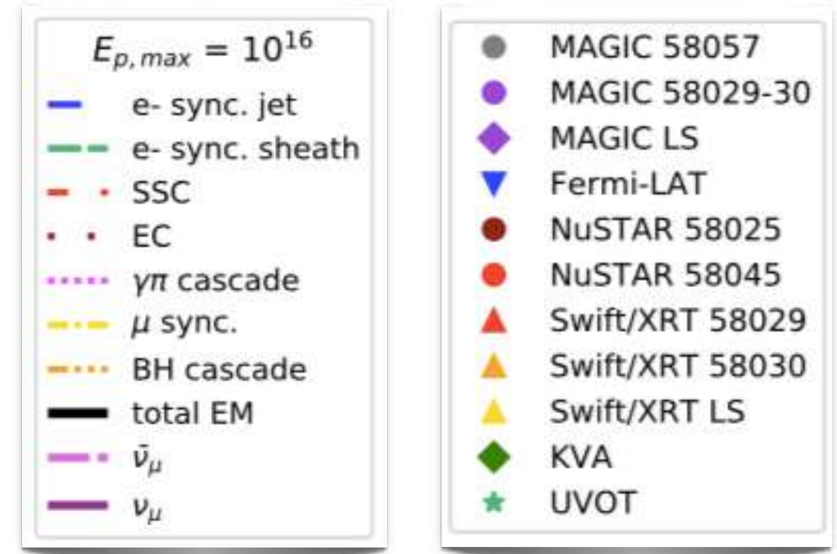
Most Blazar emission models assume that high-energy particles (electrons, protons, nuclei) are injected into the jet where they encounter target radiation (non-thermal emission by the high-energy particles, or external photons from the accretion disk, clouds or dust torus.

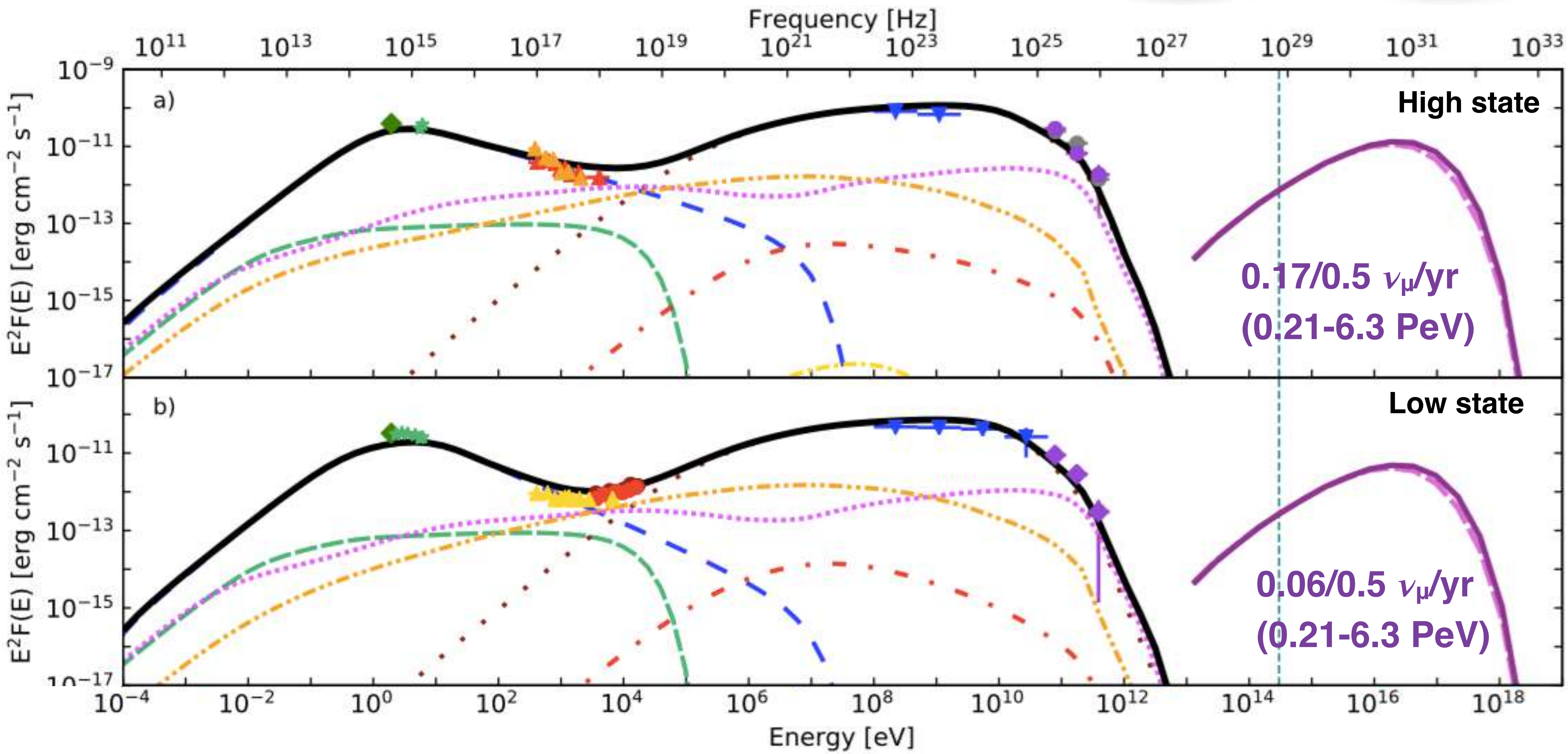


An example from MM models

- Photopion efficiency $f_{p\gamma}(E_p\sim 6\ \mathrm{PeV})\sim O(10^{-4})$
- $\tau_{\gamma\gamma}(E_\gamma\sim 12\ \mathrm{GeV})\sim 0.1 \Longrightarrow \tau_{\gamma\gamma}(E_\gamma\sim 100\ \mathrm{GeV})\sim 1$
  Consistent with observed GeV-TeV break

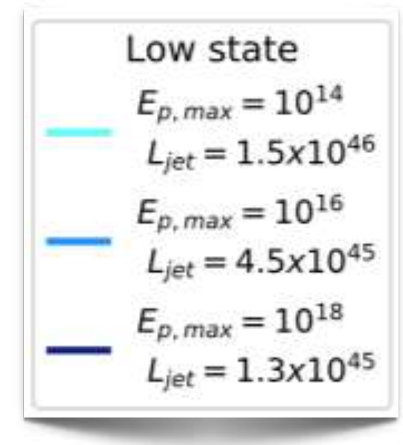
The MAGIC Coll. The Astrophysical Journal Letters, 863 (2018) L10



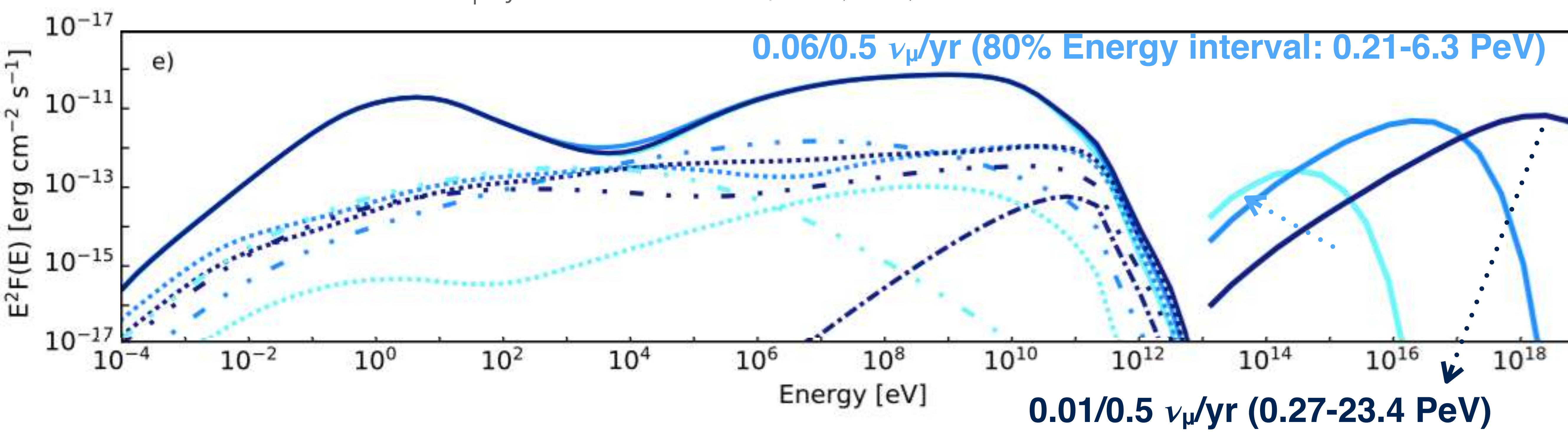


An example from MM models

- Results similar to purely leptonic models without protons
- Jet power 4x10^{45} to 10^{46} erg/s
- Highest neutrino rate found for E_{pmax} = 10^{16} eV

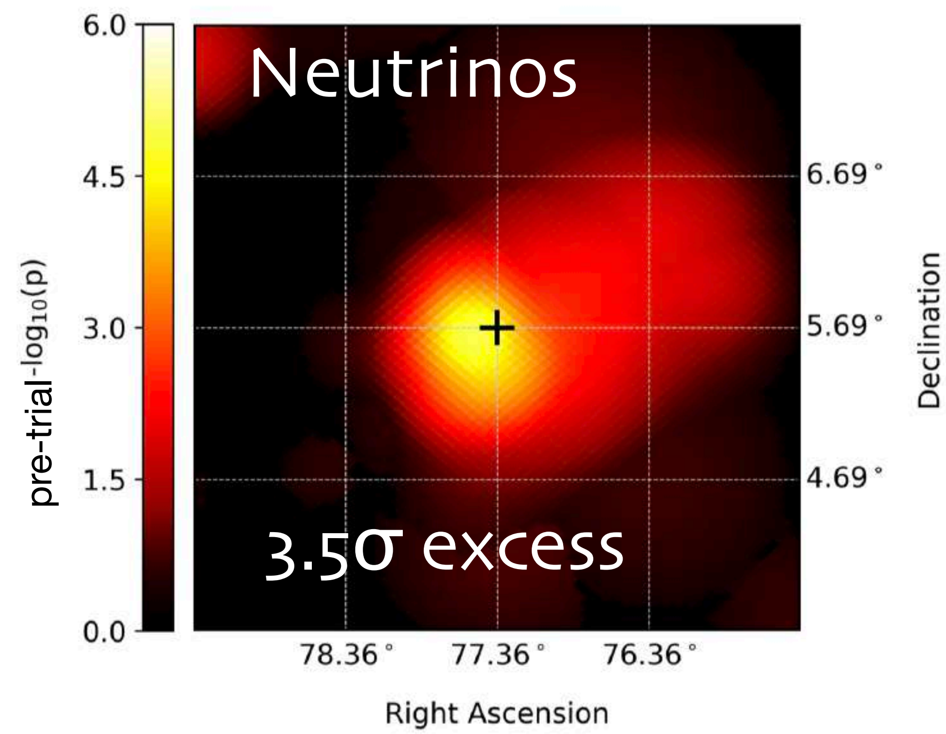


The MAGIC Coll. The Astrophysical Journal Letters, 863 (2018) L10



IceCube archival data on TXS 0506+056

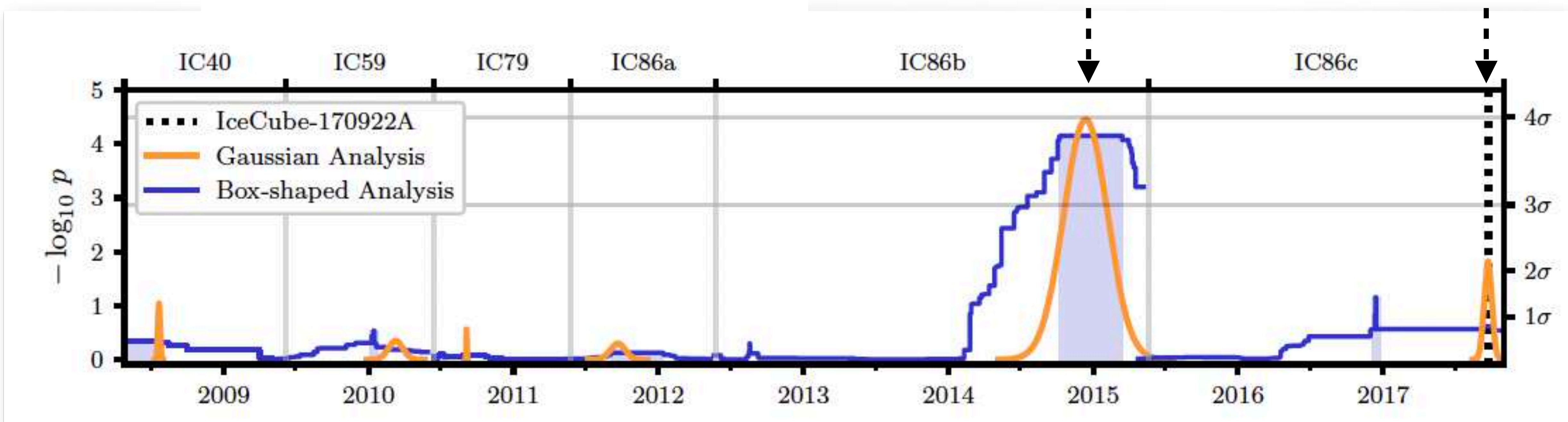
The observation of an excess of neutrino events in ~5 months (2014-2015) together with IceCube-170922A provides a strong evidence against the background hypothesis



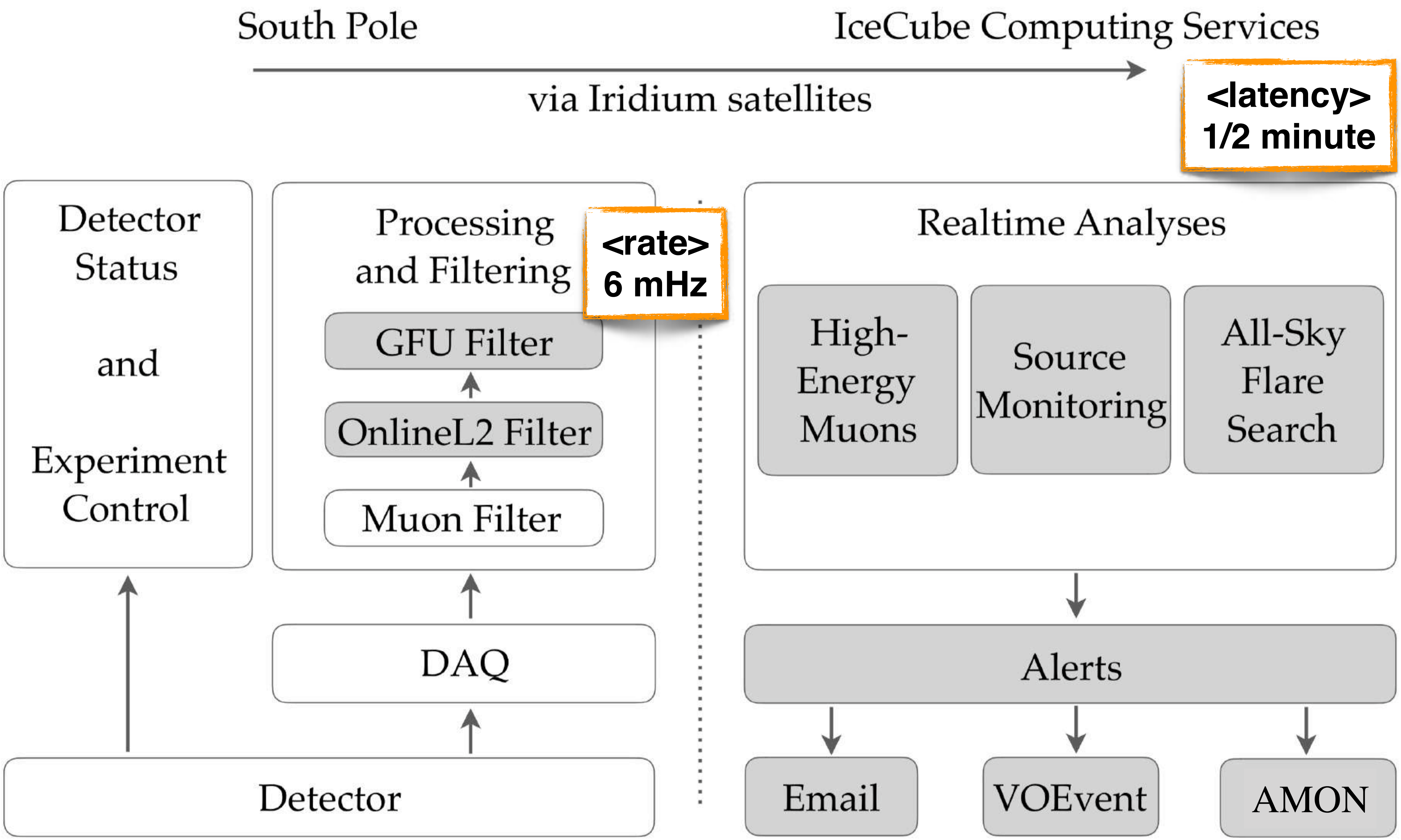
IceCube Coll. Science 361, eaat1378 (2018)

Spectral index ~2

Spectral index ~1.7



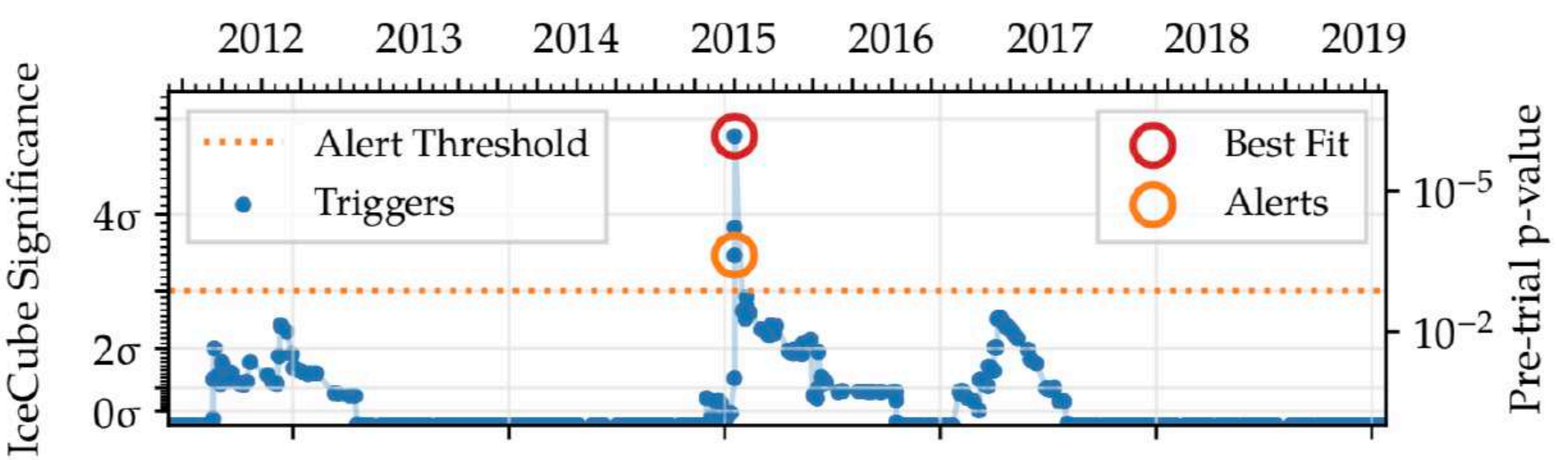
Realtime IceCube pipeline: GFU



Thomas Kintscher, PhD, Humboldt University of Berlin (2020)

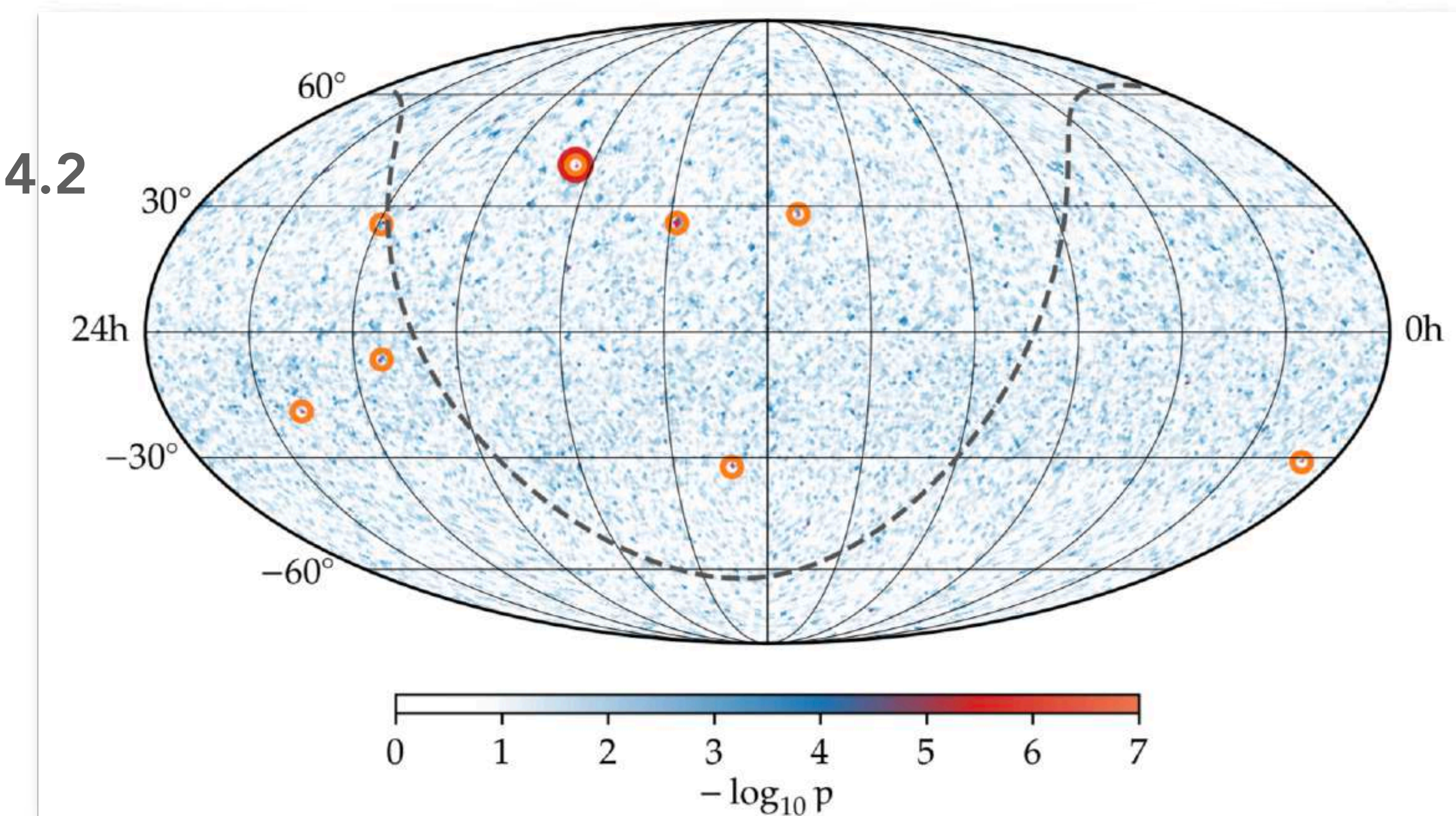
Gamma-ray follow-up (GFU) alerts

Alerts are being sent to Imaging Air Cherenkov telescopes H.E.S.S., MAGIC and VERITAS through **PRIVATE** channels regulated under dedicated MoUs



Triggers for a list of pre-selected sources (promising for TeV detections) **above 3 σ** (pre-trial)

Triggers from all-sky **above 4.2 σ** (pre-trial, 6.8 needed for discovery)



Thomas Kintscher, PhD, Humboldt University of Berlin (2020)

Fast response analysis: TXS 0506+056

[Previous | Next | ADS]

MAGIC detects enhanced flux of VHE gamma rays from TXS 0506+056

ATel #12260; *Razmik Mirzoyan (Max-Planck-Institute for Physics) on Behalf of the MAGIC Collaboration*
on 3 Dec 2018; 22:22 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Gamma Ray, >GeV, TeV, VHE, AGN, Blazar

Referred to by ATel #: 12267, 12274

Tweet

We report an enhanced emission of VHE gamma-rays from the direction of the blazar TXS 0506+056 (05 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 arcmin from the estimated direction of the high energy IceCube neutrino event IceCube-170922A (ATel #10791). On Dec 3rd 2018 the MAGIC telescopes observed this source for about 2 hours under good weather conditions. The source was detected at VHE gamma-rays above 90 GeV with a significance larger than 5 sigma. The preliminary analysis yields an estimate of the VHE gamma-ray flux above 90 GeV of ~10-15% of the flux from the Crab Nebula above the same energy threshold, and a spectral index of ~4. This flux is consistent with the emission level integrated between September 28th 2017 to October 3rd 2017, when the source was discovered at VHE gamma-rays (ATel #10817). The MAGIC telescopes will continue monitoring the VHE gamma-ray emission of TXS 0506+056. Soft-X-rays and ultraviolet ToO observations with the Neil Gehrels Swift Observatory have been approved for the next three nights (PI: Cerruti, on behalf of MAGIC), to occur within the time-window 00:00 to 04:00 UTC. NuSTAR ToO observations have also been approved (PI: Satalecka). Multi-wavelength observations (quasi)-simultaneous with MAGIC in this time-window are strongly encouraged.

The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de), E. Bernardini (elisa.bernardini@desy.de), K.Satalecka (konstancja.satalecka@desy.de).

MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.

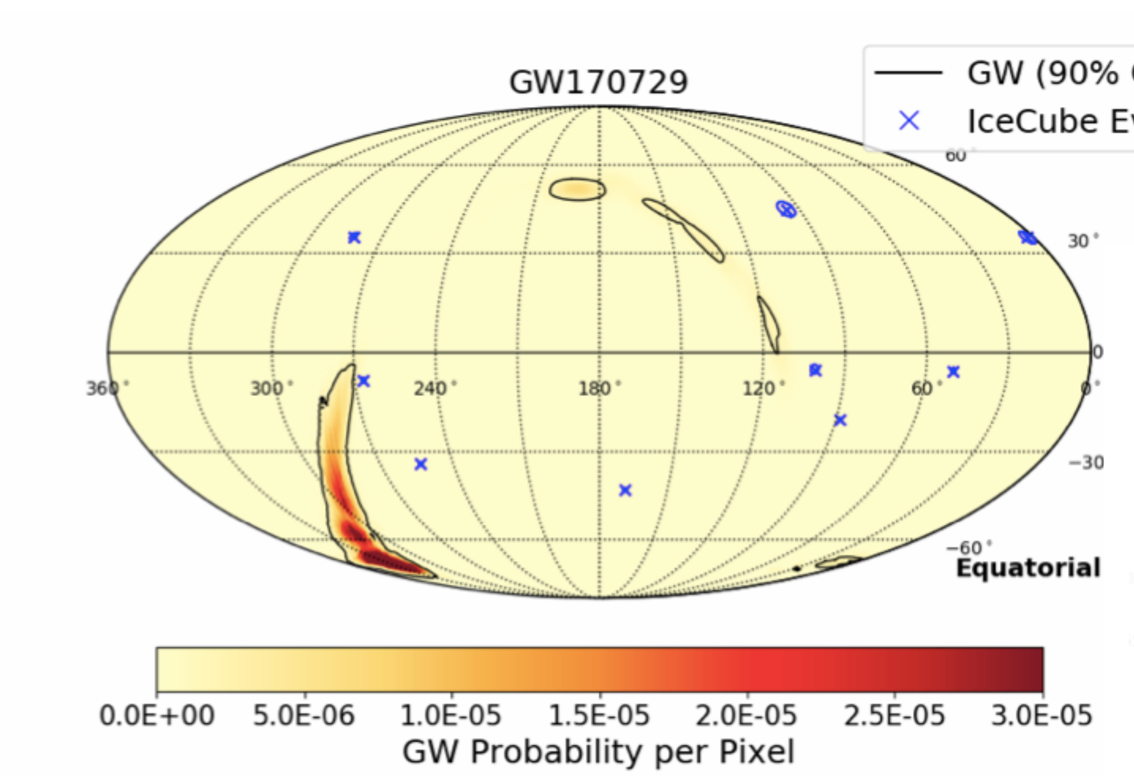
IceCube follow-up analysis:

- one week time window
- one event found, compatible with background

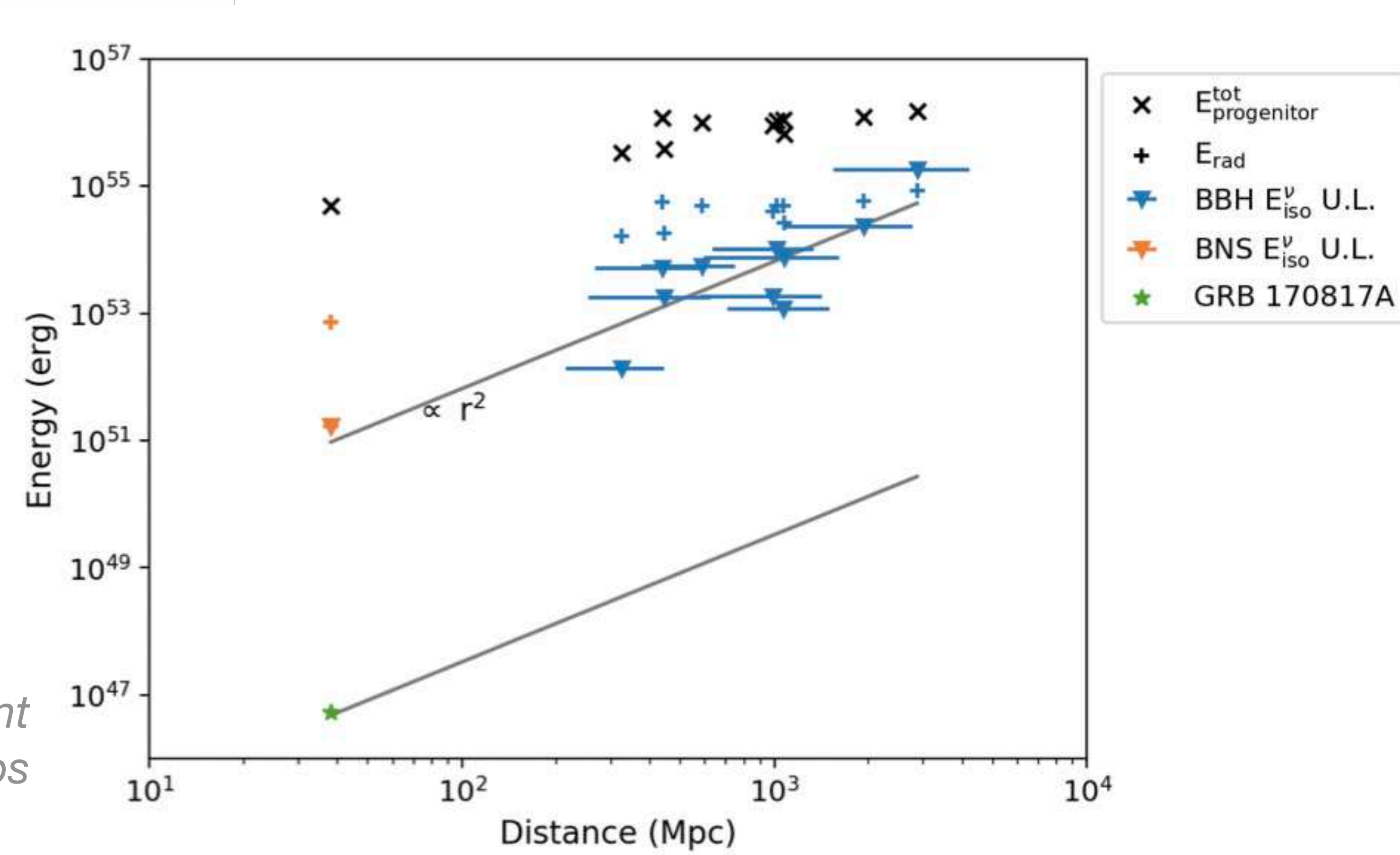
J. Vanderbroucke et al.
PoS(ICRC2019)1026

Neutrinos and Compact binary mergers

A joint neutrino and gravitational wave observation would shed light on the sources of high-energy neutrinos, investigate the connection between interaction of compact objects and associated energetic outflows, shed light on opaque sources



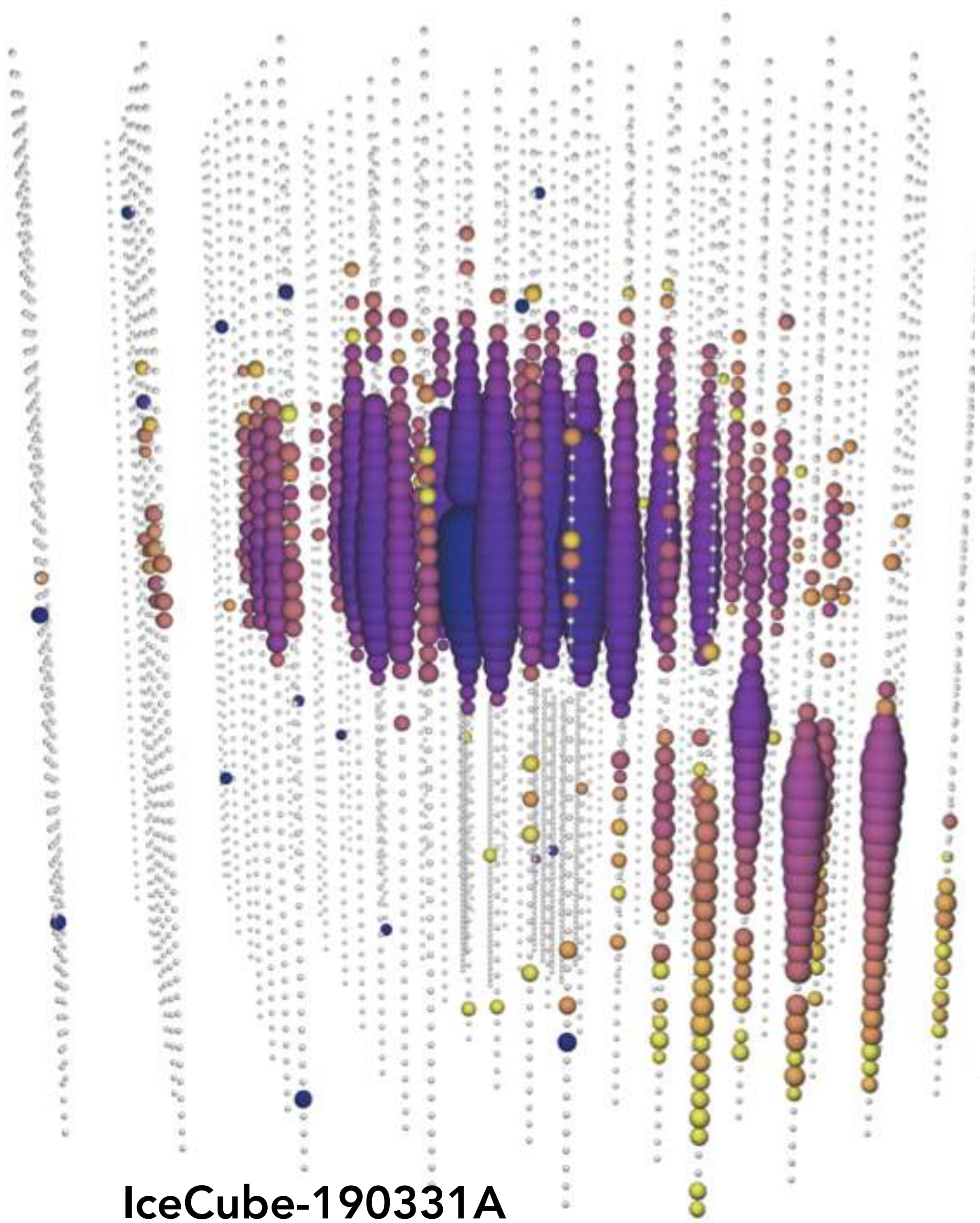
***Left**: ν follow up to GW170729 (in a 1000 seconds time window)*



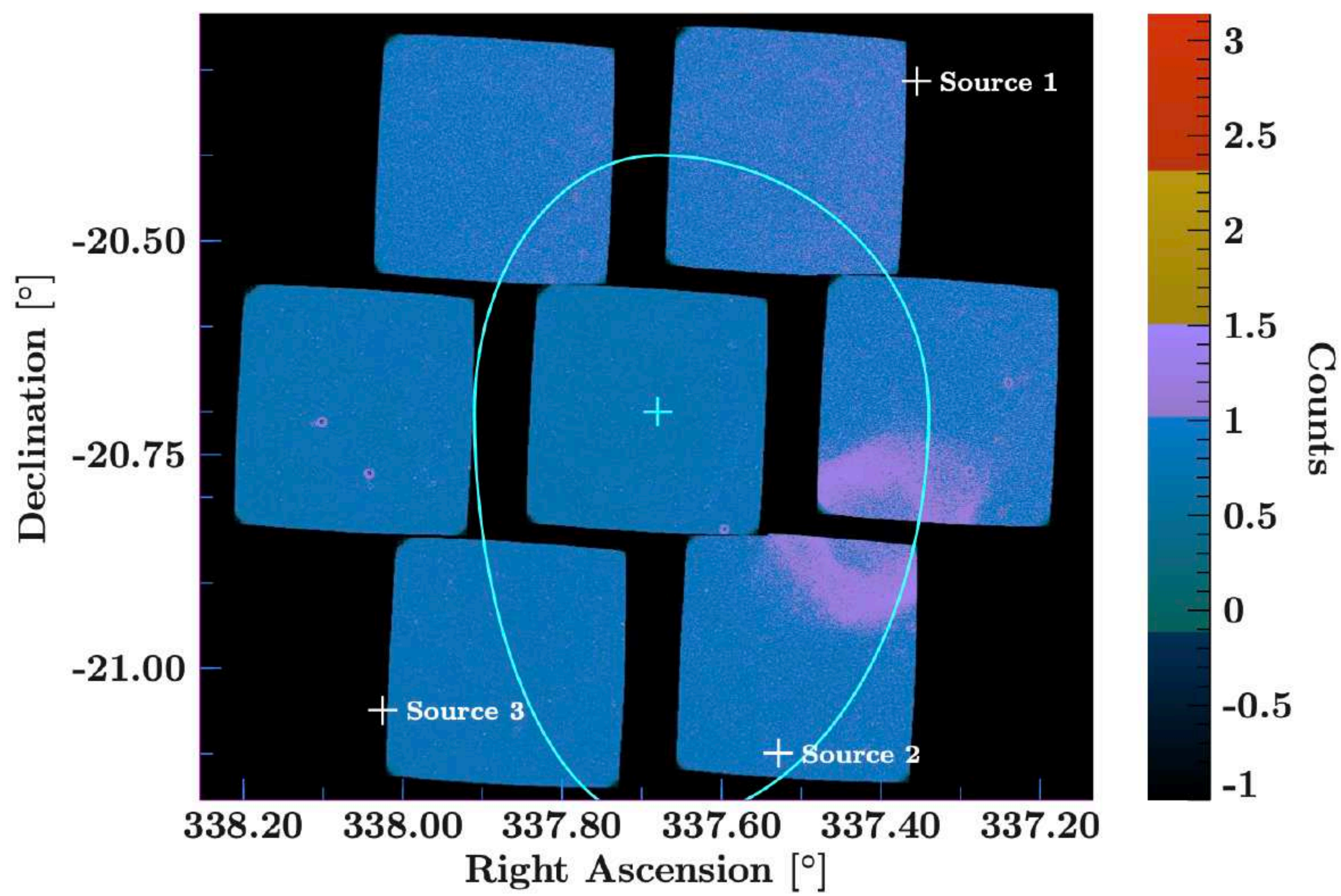
***Right**: UL on the isotropic equivalent energy emitted by BBH & BNS in neutrinos*

More alerts

For most cases, no obvious electromagnetic counterparts



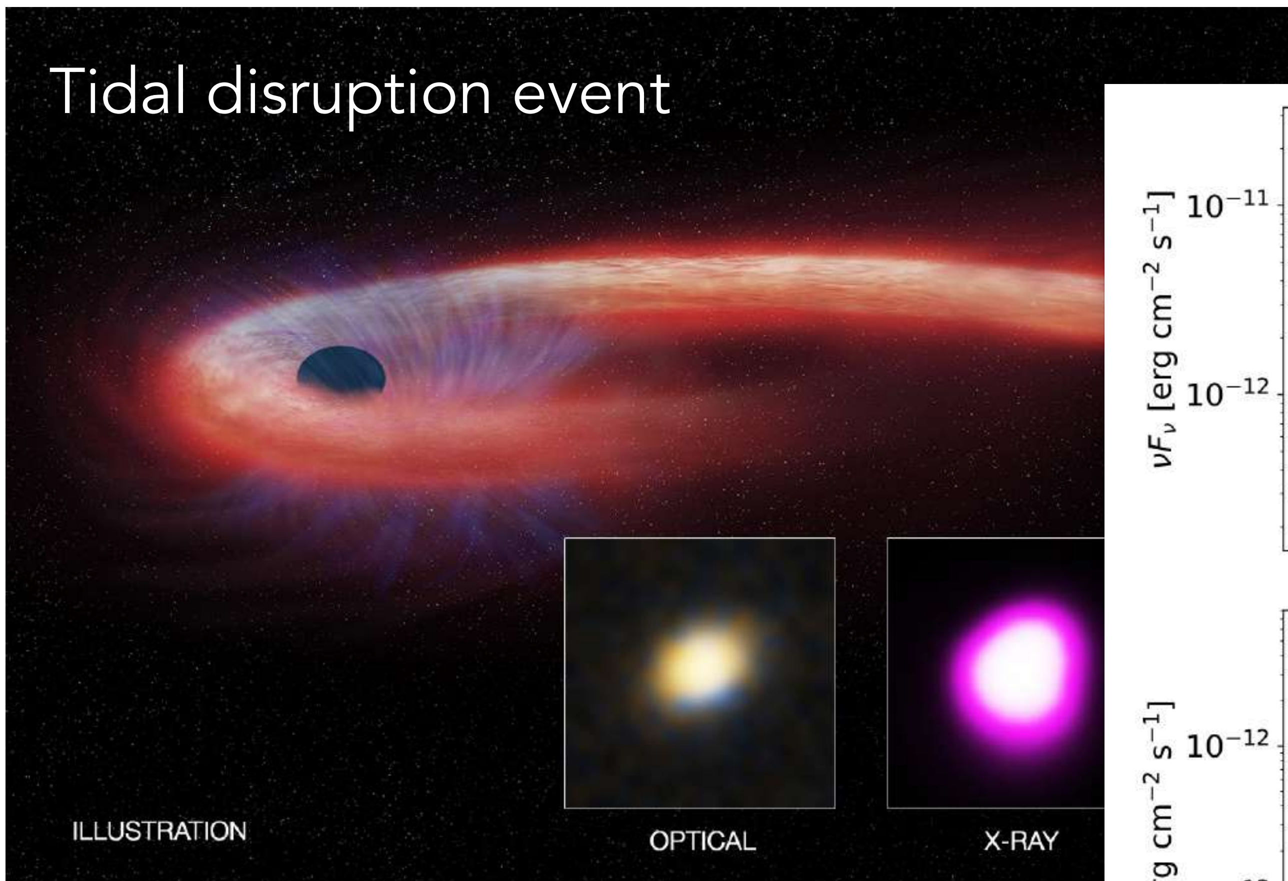
IceCube-190331A



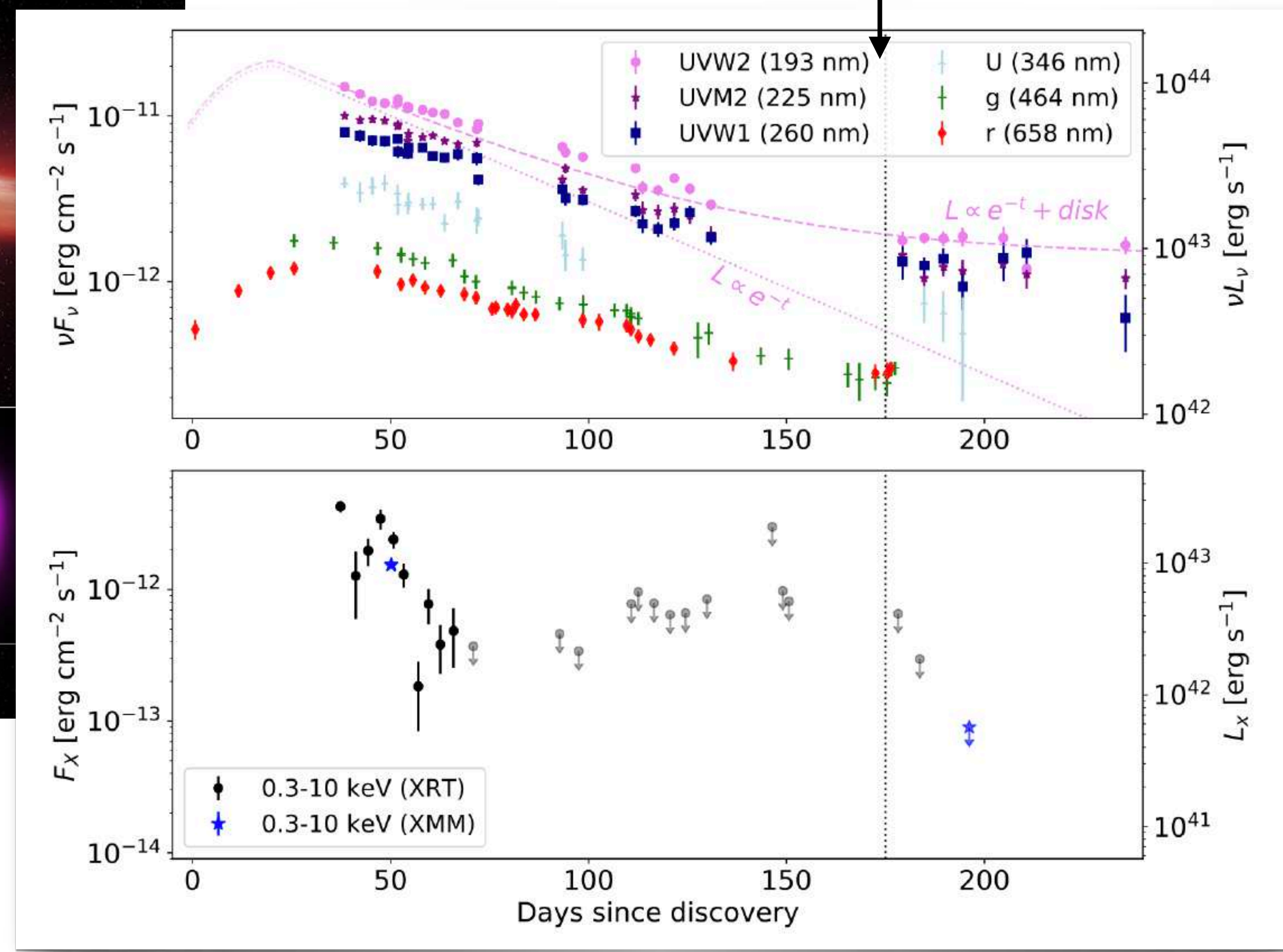
F. Krauß et al. Mon.Not.Roy.Astron.Soc. 497 (2020) 2553

More alerts

For most cases, no obvious electromagnetic counterparts



IceCube-191001A



R. Stein arXiv:2005.05340
W. Winter & C. Lunardini arXiv:2005.06097

In Summary

- High Energy Neutrinos **opened a new window into the Universe**:
- Diffuse cosmic neutrinos well established (more than 8 sigma by two channels)
- Compelling evidence for the first non-stellar neutrino source: a Blazar
- **Multimessenger studies are essential for identification of sources**
- Better (theoretical) understanding of the potential sources and relevant data can help the way to new breakthroughs
- Looking forward to upcoming ten times more sensitive instruments!

Back-up

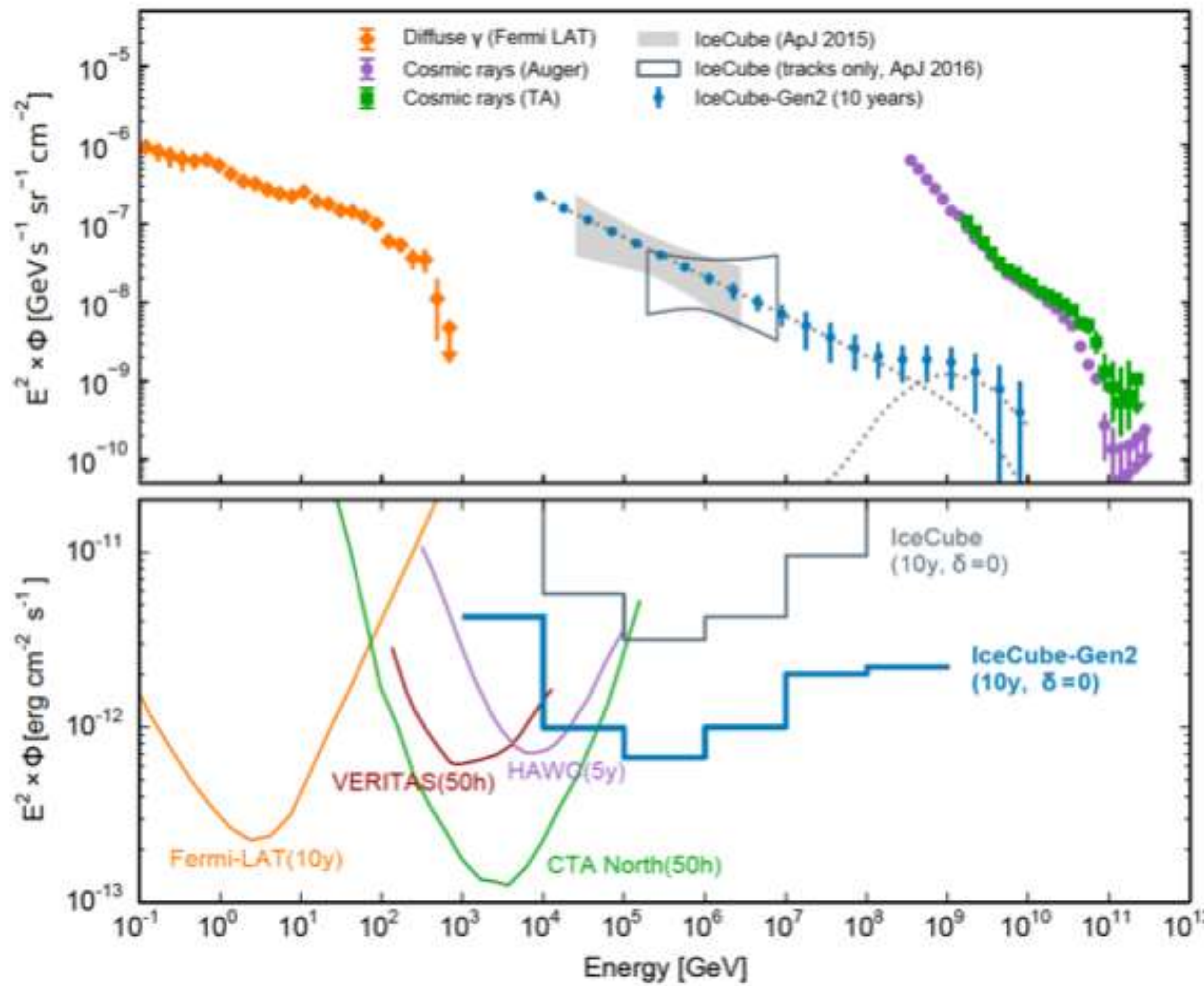
Public alerts before June 2019

EVENT			OBSERVATION		
EventNum_RunNum	Date	Time UT	NoticeType	RA	Dec
41485283_132628	19/05/29	01:55:22.21	HESE	287.3190	+78.1432
766165_132518	19/05/04	18:25:18.39	HESE	65.7866	
15947448_132379	19/03/31	06:55:43.44	HESE	355.6349	
66688965_132229	19/02/21	08:25:39.71	HESE	267.3650	
36142391_132143	19/02/05	21:21:10.50	HESE	128.6959	
9759013_132077	19/01/24	03:43:54.79	HESE	307.1920	
68269692_131999	19/01/04	08:34:38.23	HESE	359.3299	
66412090_131680	18/10/31	02:02:51.41	HESE	182.7920	
12296708_131624	18/10/14	11:52:19.07	HESE	225.1839	
71165249_130949	18/04/23	02:28:40.98	HESE	294.8820	
34032434_130171	17/10/28	08:28:14.81	HESE	275.0760	
56068624_130126	17/10/15	01:34:30.06	HESE	162.5790	
32674593_129474	17/05/06	12:36:55.80	HESE	221.6750	
65274589_129281	17/03/12	13:49:39.83	HESE	304.7300	
38561326_128672	16/11/03	09:07:31.12	HESE	40.8252	
38561326_128672	16/11/03	09:07:31.12	HESE	40.8740	
58537957_128340	16/08/14	21:45:54.00	HESE	199.3100	
6888376_128290	16/07/31	01:55:04.00	HESE	215.1090	
6888376_128290	16/07/31	01:55:04.00	HESE	214.5440	
67093193_127853	16/04/27	05:52:32.00	HESE	240.5683	
67093193_127853	16/04/27	05:52:32.00	HESE	239.6639	
67093193_127853	16/04/27	05:52:32.00	HESE	239.6639	
67093193_127853	16/04/27	05:52:32.00	HESE	239.6639	+6.8528

IceCube-170922A

EVENT			OBSERVATION		
EventNum_RunNum	Date	Time UT	NoticeType	RA	Dec
42419327_132508	19/05/03	17:23:08.72	EHE	120.3040	+6.3568
53411354_131653	18/10/23	16:37:32.65	EHE	269.8360	-8.8863
34507973_131475	18/09/08	19:59:31.84	EHE	145.7729	-2.5178
17569642_130214	17/11/06	18:39:39.21	EHE	340.2500	+7.3140
50579430_130033	**17/09/22**	**20:54:30.43**	**EHE**	**77.2853**	**+5.7517**
80305071_129307	17/03/21	07:32:20.69	EHE	98.3268	-14.4861
80127519_128906	16/12/10	20:06:40.31	EHE	46.5799	+14.9800
80127519_128906	16/12/10	20:06:40.31	EHE	45.8549	+15.7851
26552458_128311	16/08/06	12:21:33.00	EHE	122.7980	-0.7331
6888376_128290	16/07/31	01:55:04.00	EHE	214.5440	-0.3347
6888376_128290	16/07/31	01:55:04.00	EHE	215.0929	-0.4191

Comparing effective areas



Interpreting the multi-messenger data in a nutshell

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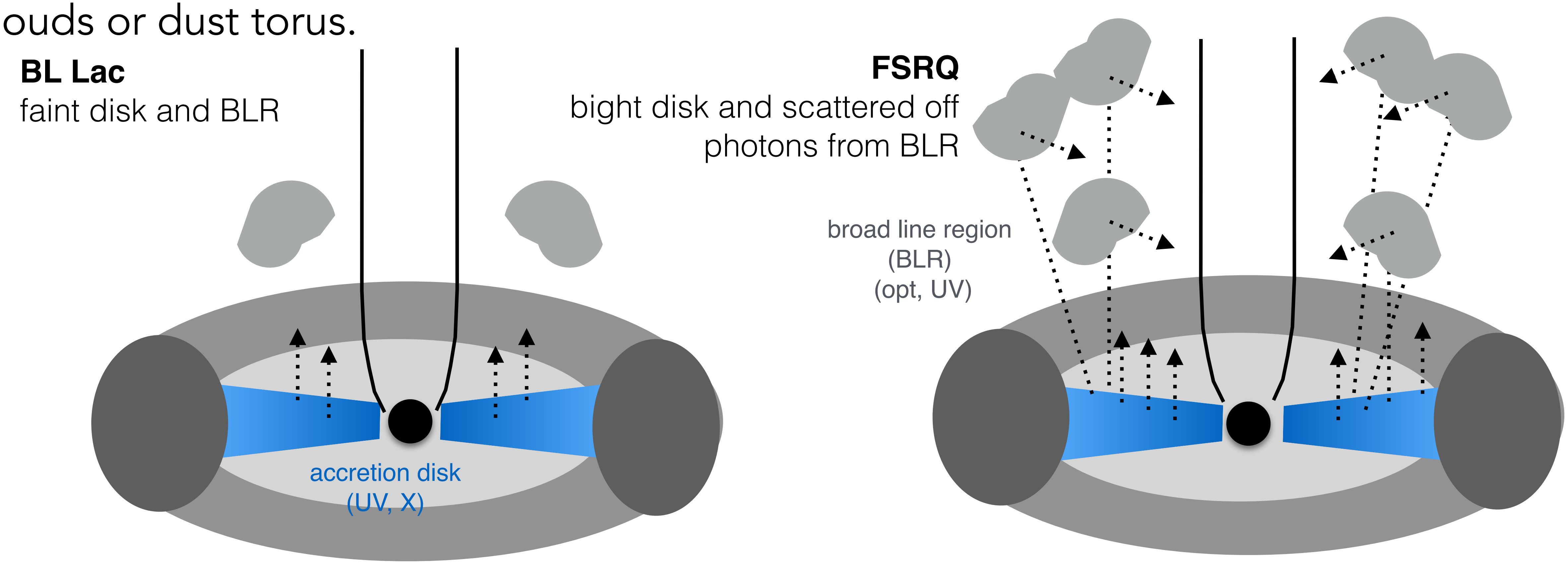

- A typical blazar of BL Lac type, z= 0.34 [Paiano et al., 2018]
- High energy neutrinos can be generated through pɣ interactions in the jet, for Eν ~ 300 TeV: protons with Ep ≥ 6 PeV must interact with photons with energies in the UV to soft X-ray range
- BL Lac objects generally disfavoured compared to FSRQs due to low density of target photon fields [e.g. Murase et al., 2014, Phys. Rev. D, 90, 023007]
- A Flat Spectrum Radio Quasar? [Padovani et al, 2019]