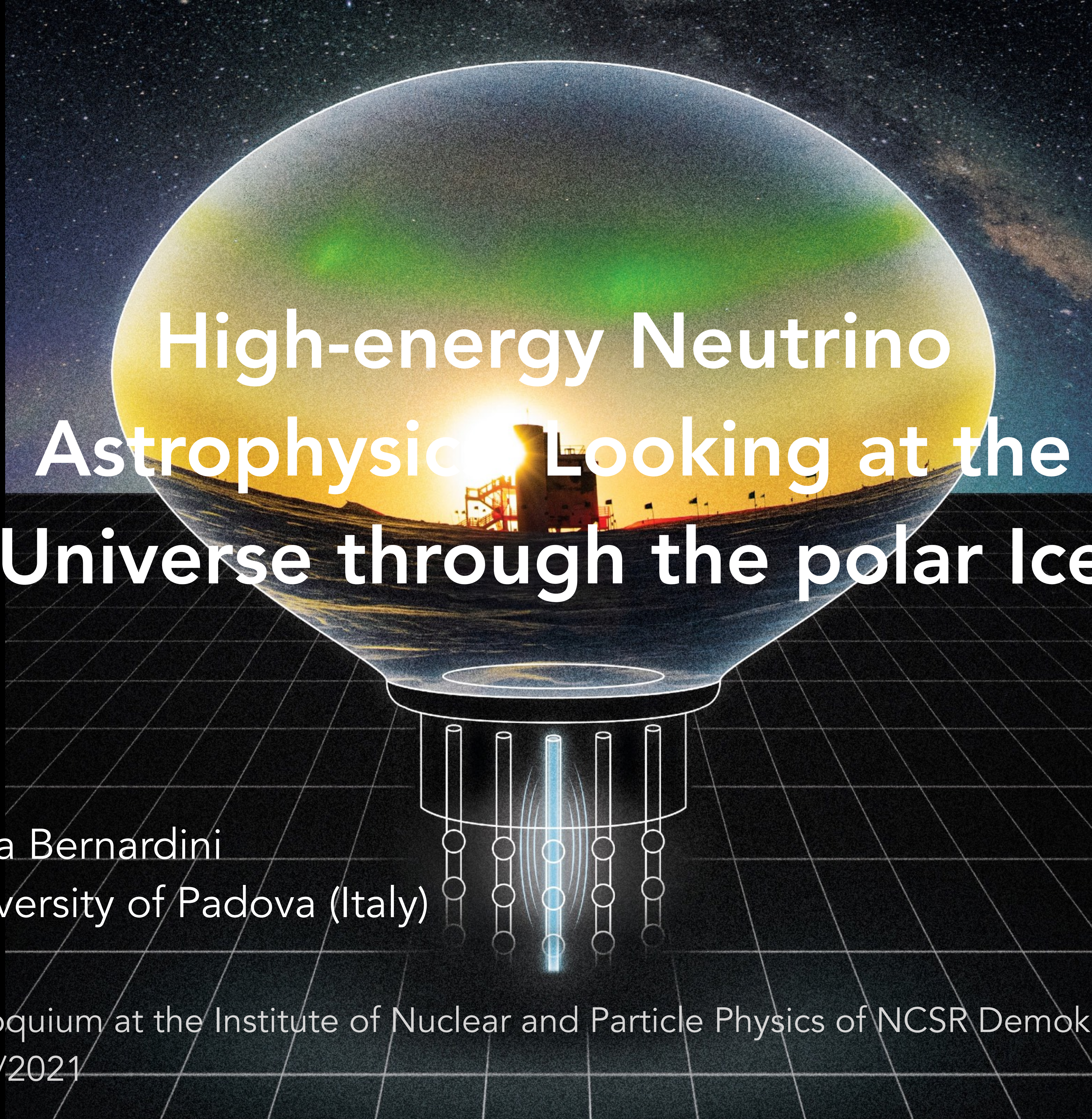
High-energy Neutrino Astrophysics: Looking at the Universe through the polar Ice



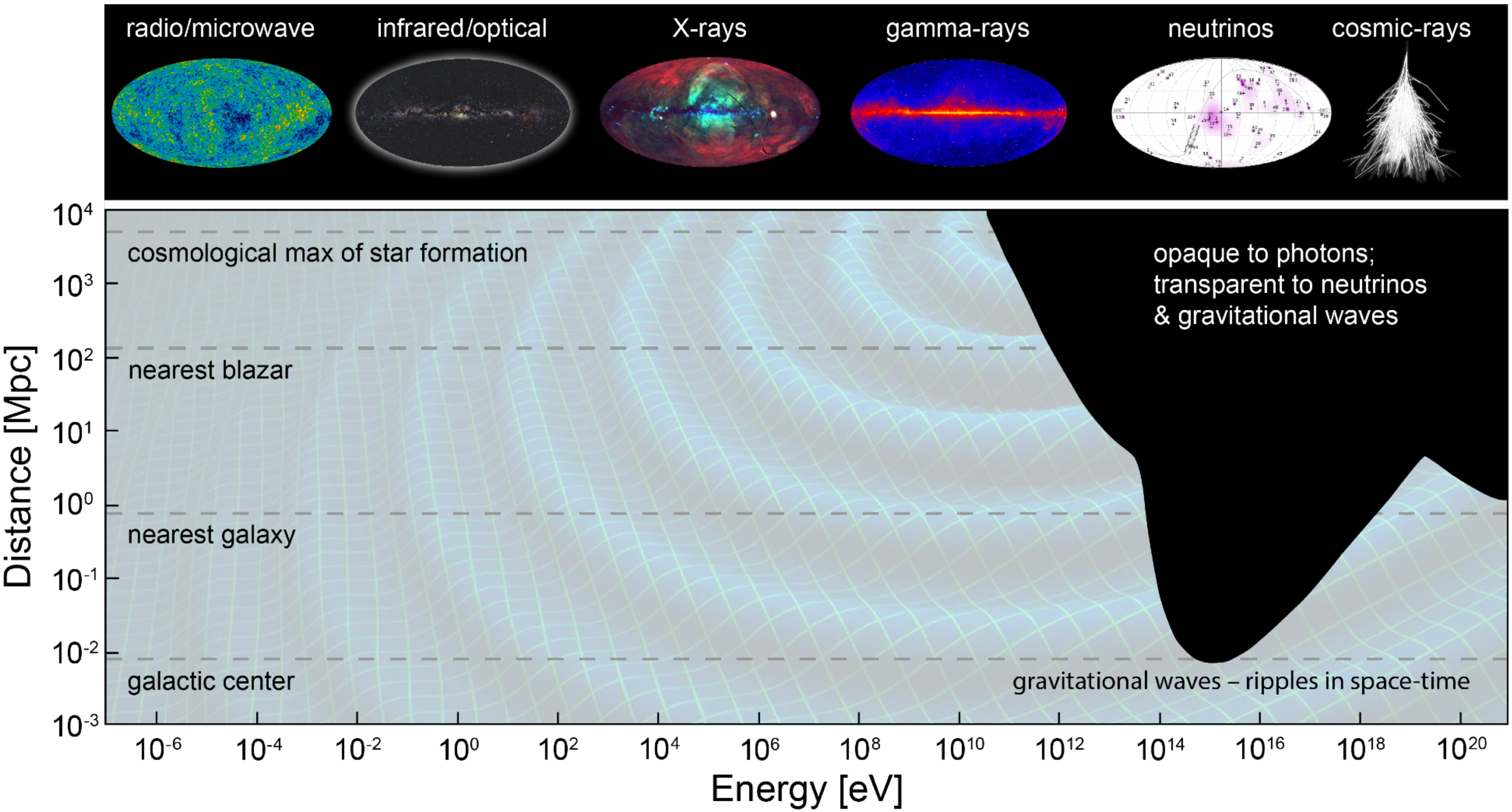
Elisa Bernardini
University of Padova (Italy)

Colloquium at the Institute of Nuclear and Particle Physics of NCSR Demokritos
9/11/2021

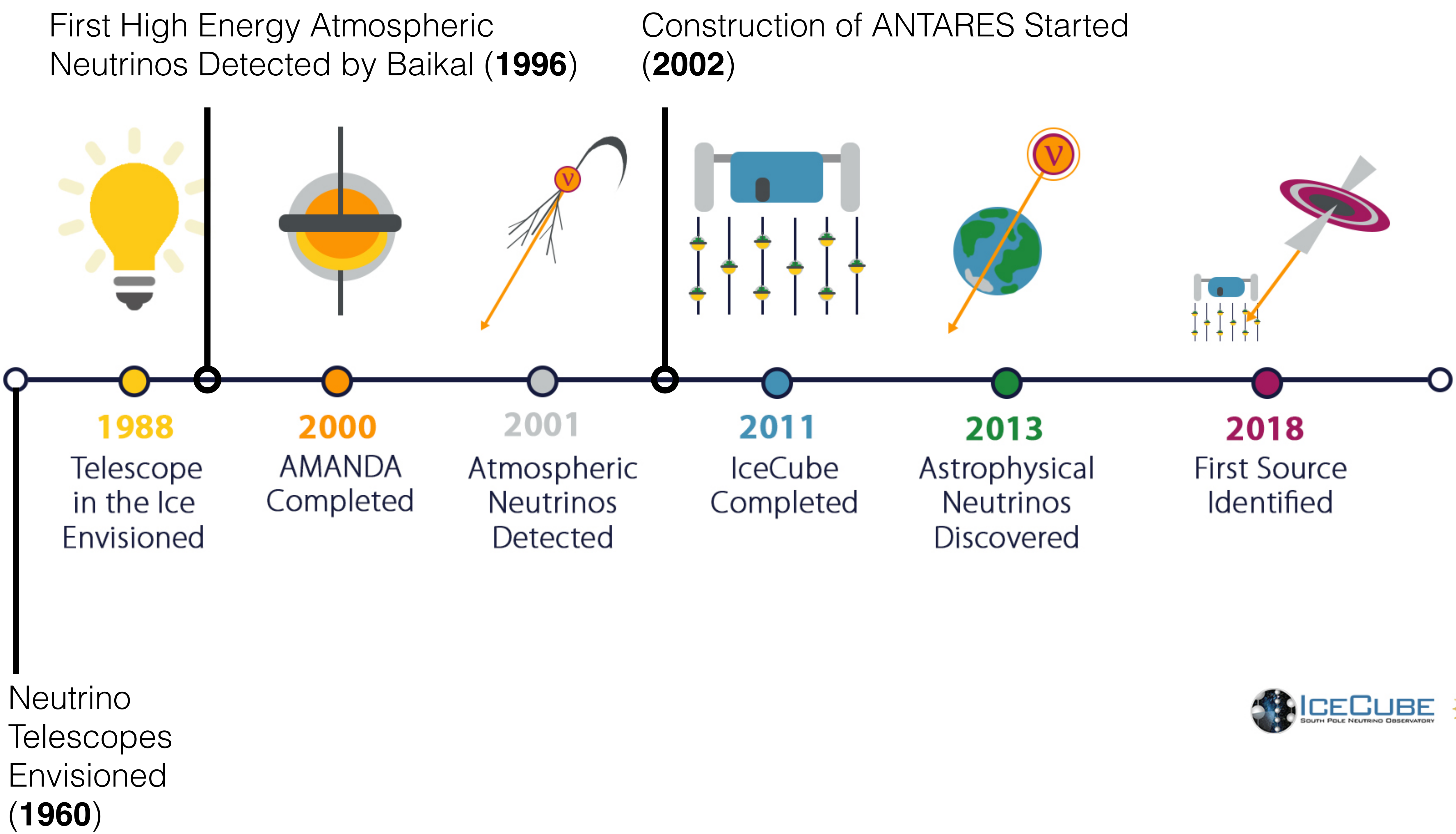
Why neutrino Astronomy?

Photons are absorbed in the Extragalactic Background Light (EBL)

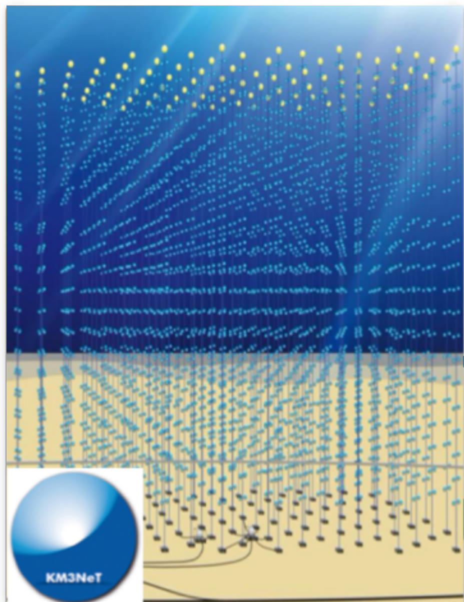
Protons ($E > 10^{20}$ eV) interact with the Cosmic Microwave Background (CMB)



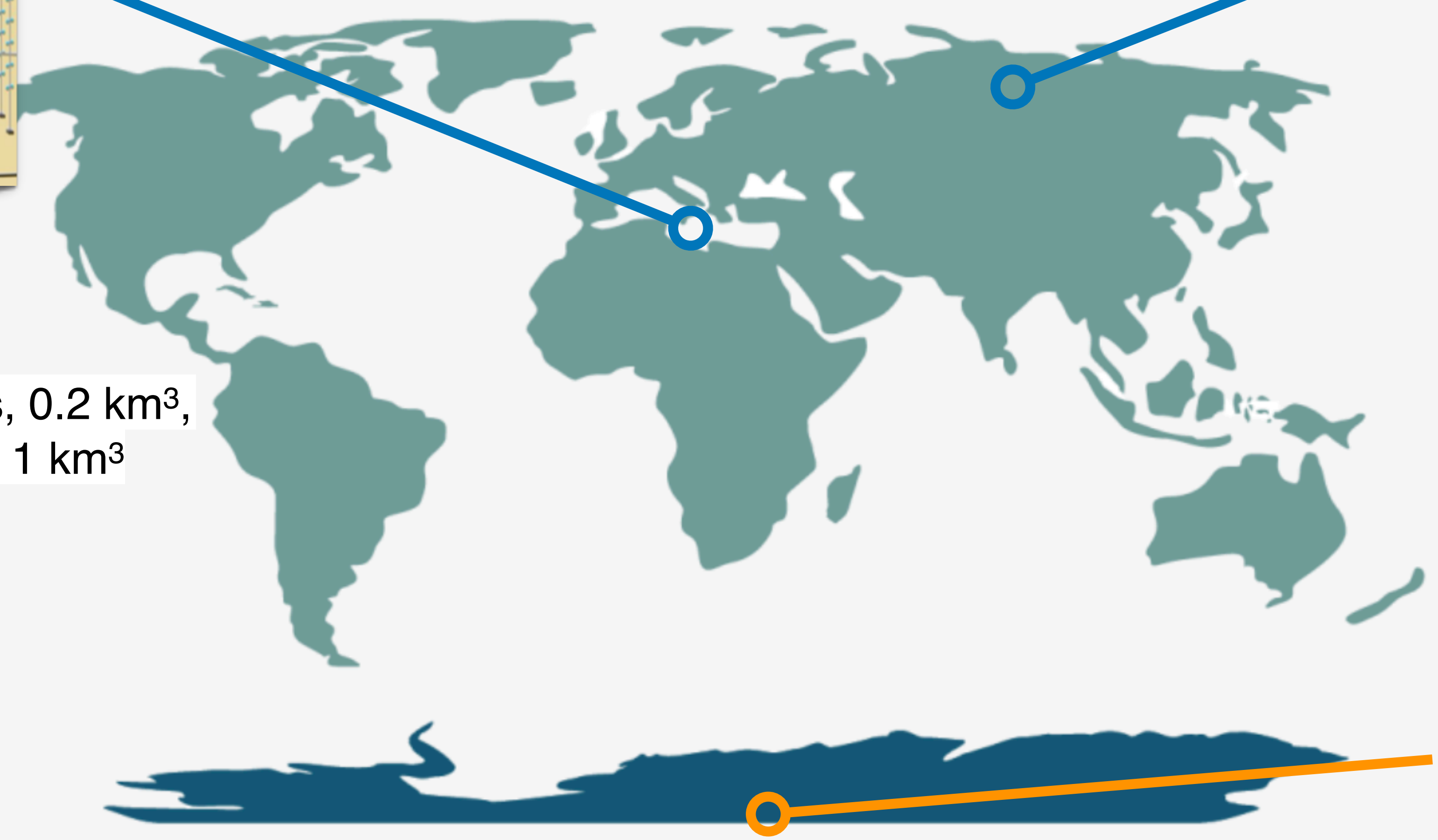
History of neutrino Astronomy in a nutshell



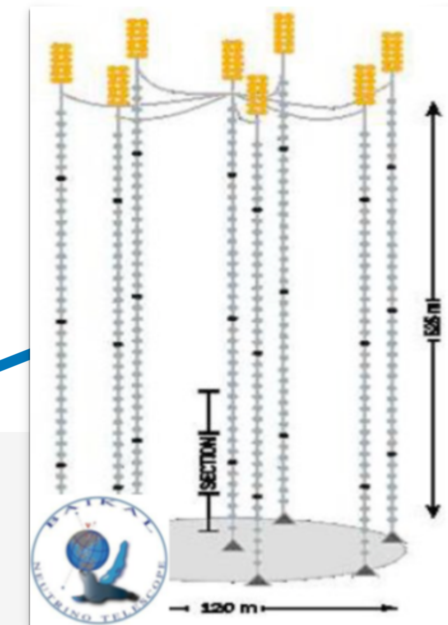
Neutrino telescopes around the world



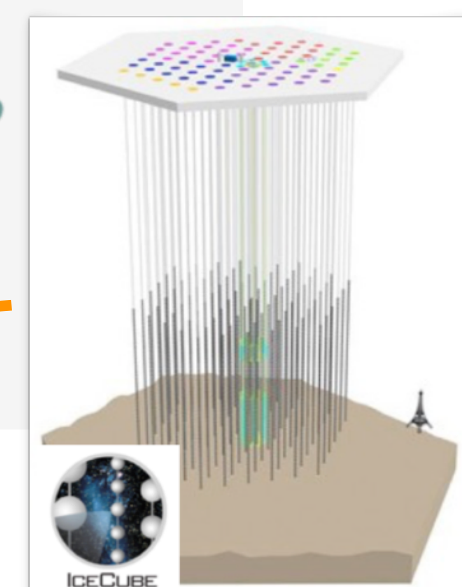
KM3NeT
Under construction
6 out of ~200 strings, 0.2 km^3,
target ~4100 OMs & 1 km^3



Baikal/GVD
Under construction
3 out of 8 clusters, 0.4 km^3,
target 2304 OMs & 1 km^3

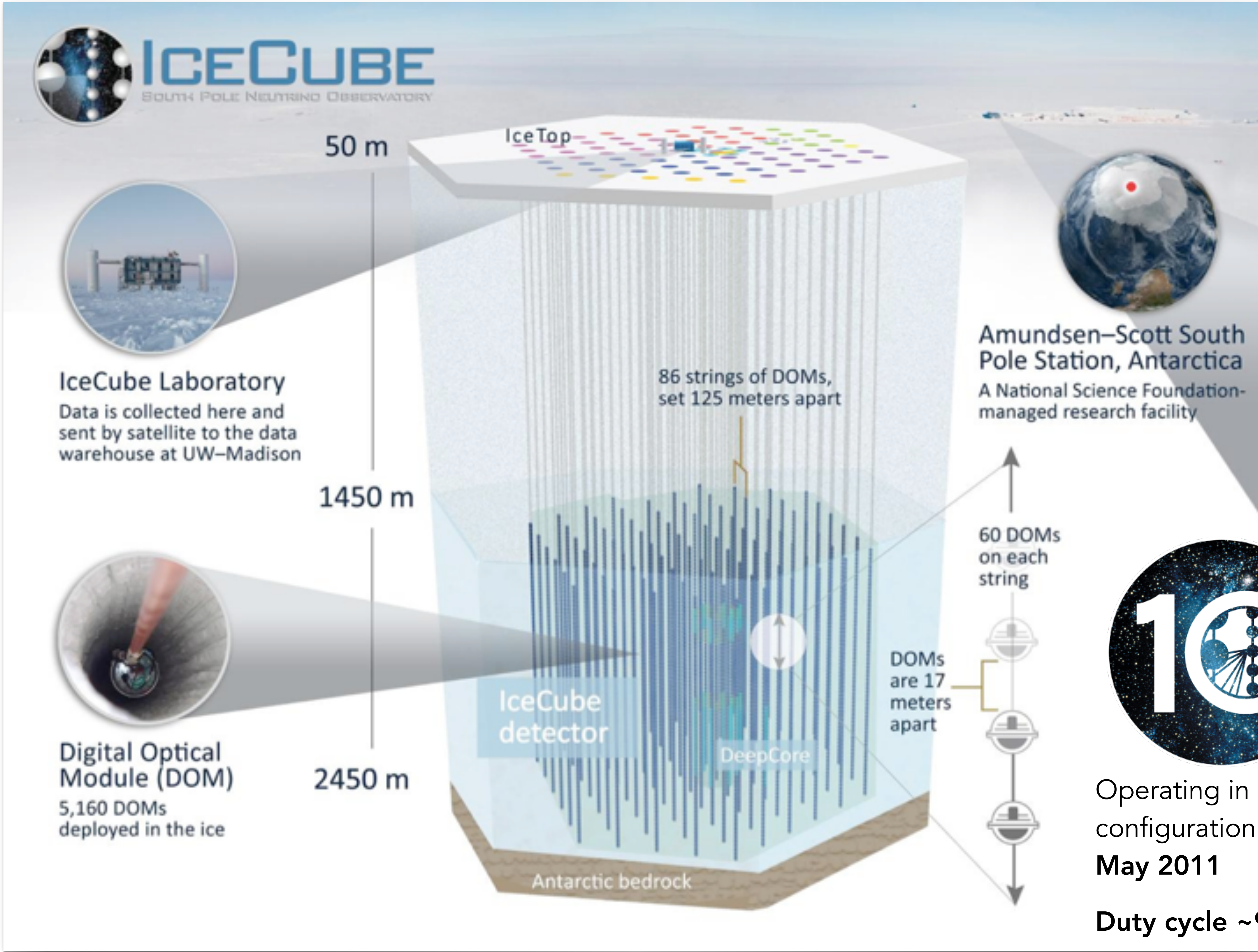


IceCube
completed in 2011
5160 OMs, ~ 1km^3



Elisa Bernardini — University of Padova (Italy)

The IceCube Neutrino Observatory



Operating in full configuration since **May 2011**

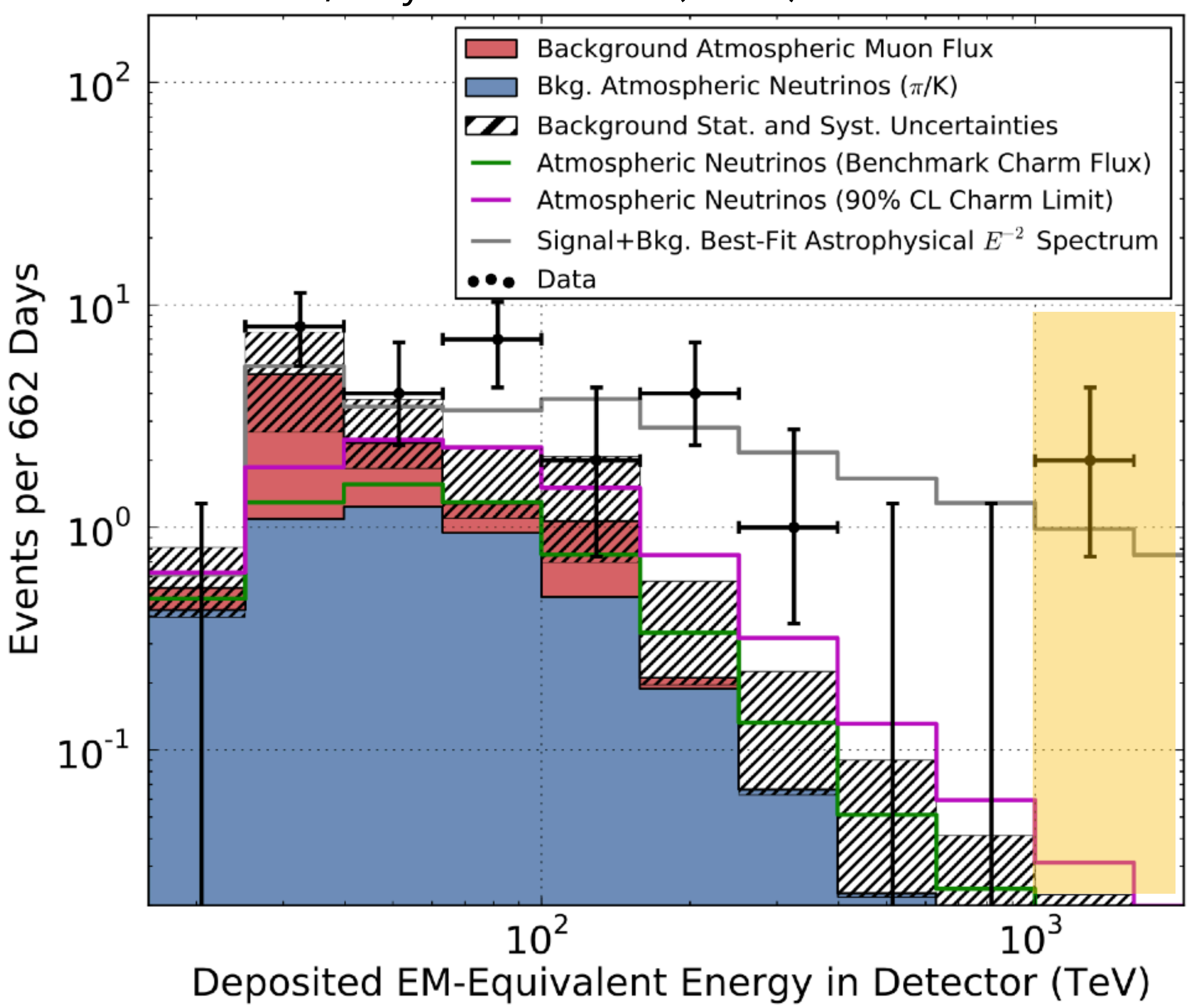
Duty cycle ~99%

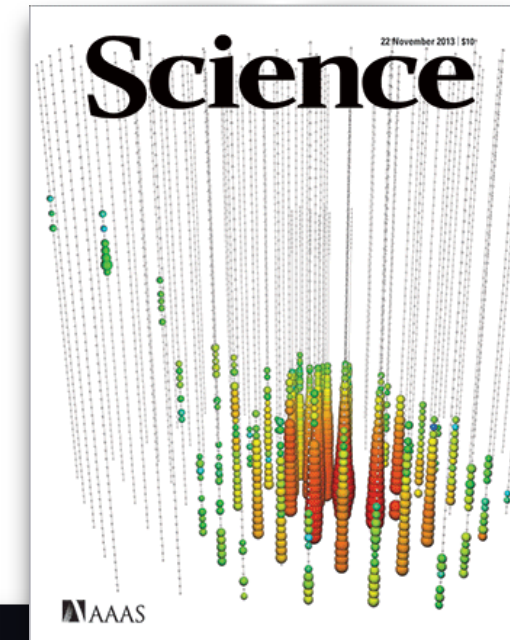
Astrophysical neutrinos discovered

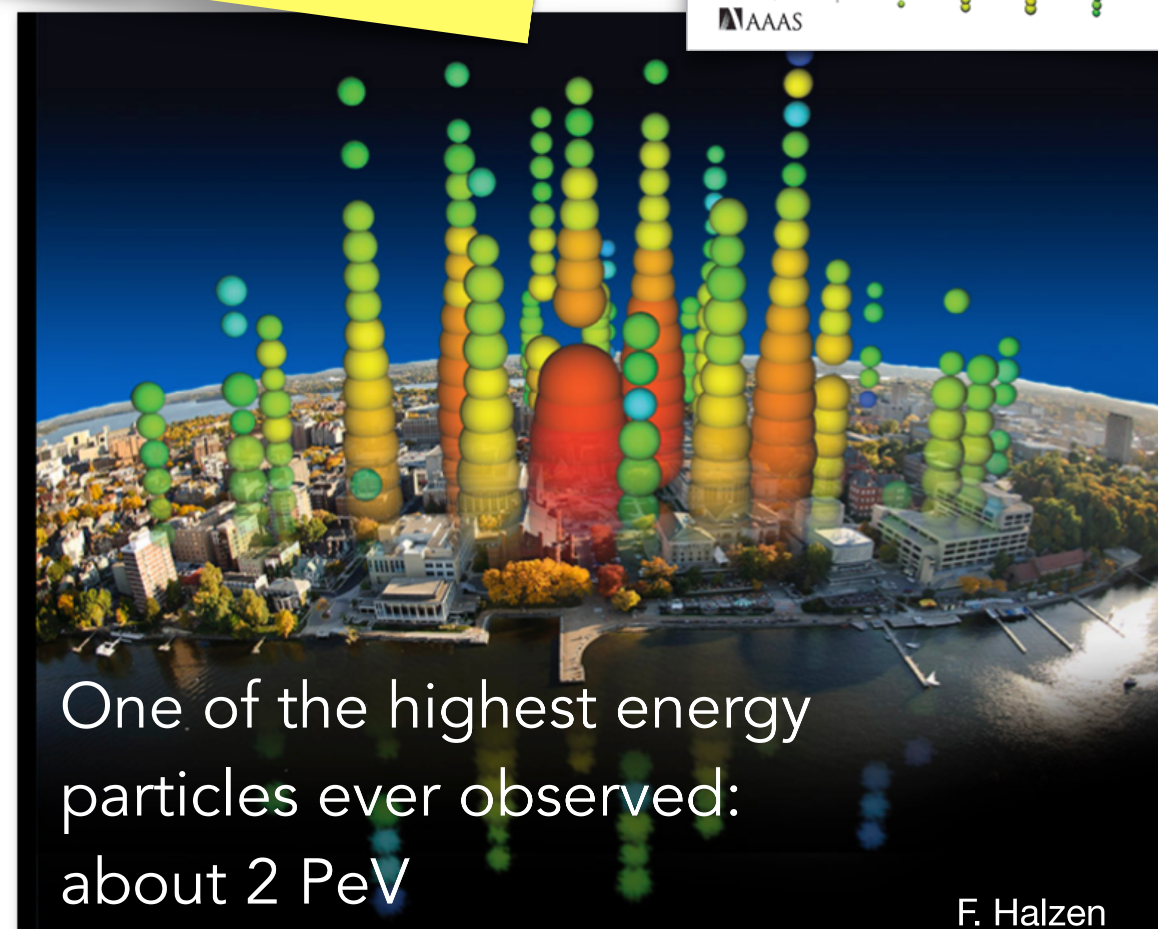
First evidence of neutrinos of astrophysical origin: flavors, directions, and energies inconsistent with those expected from the atmospheric muon and neutrino backgrounds

Breakthrough discovery

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





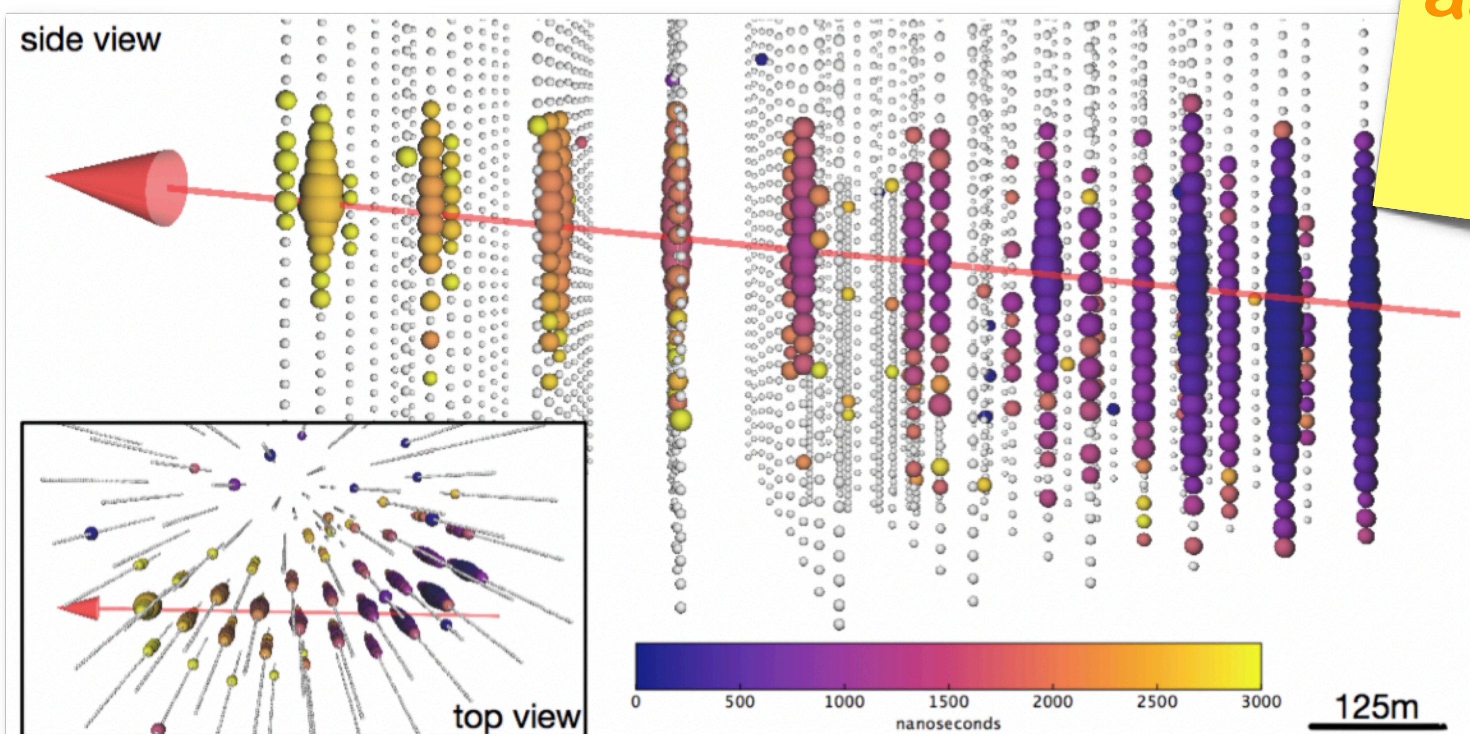


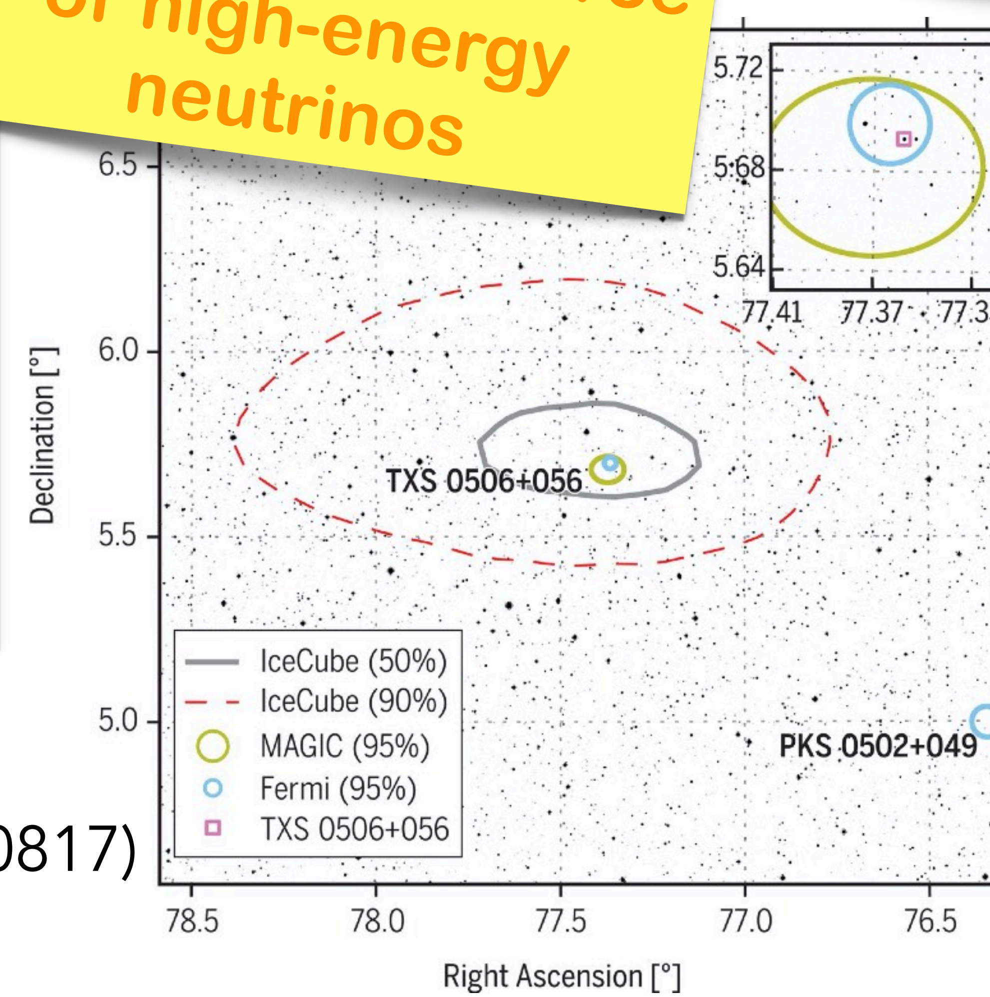
Breakthrough in Multi-Messenger Astronomy

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!

First evidence for an astrophysical source of high-energy neutrinos

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



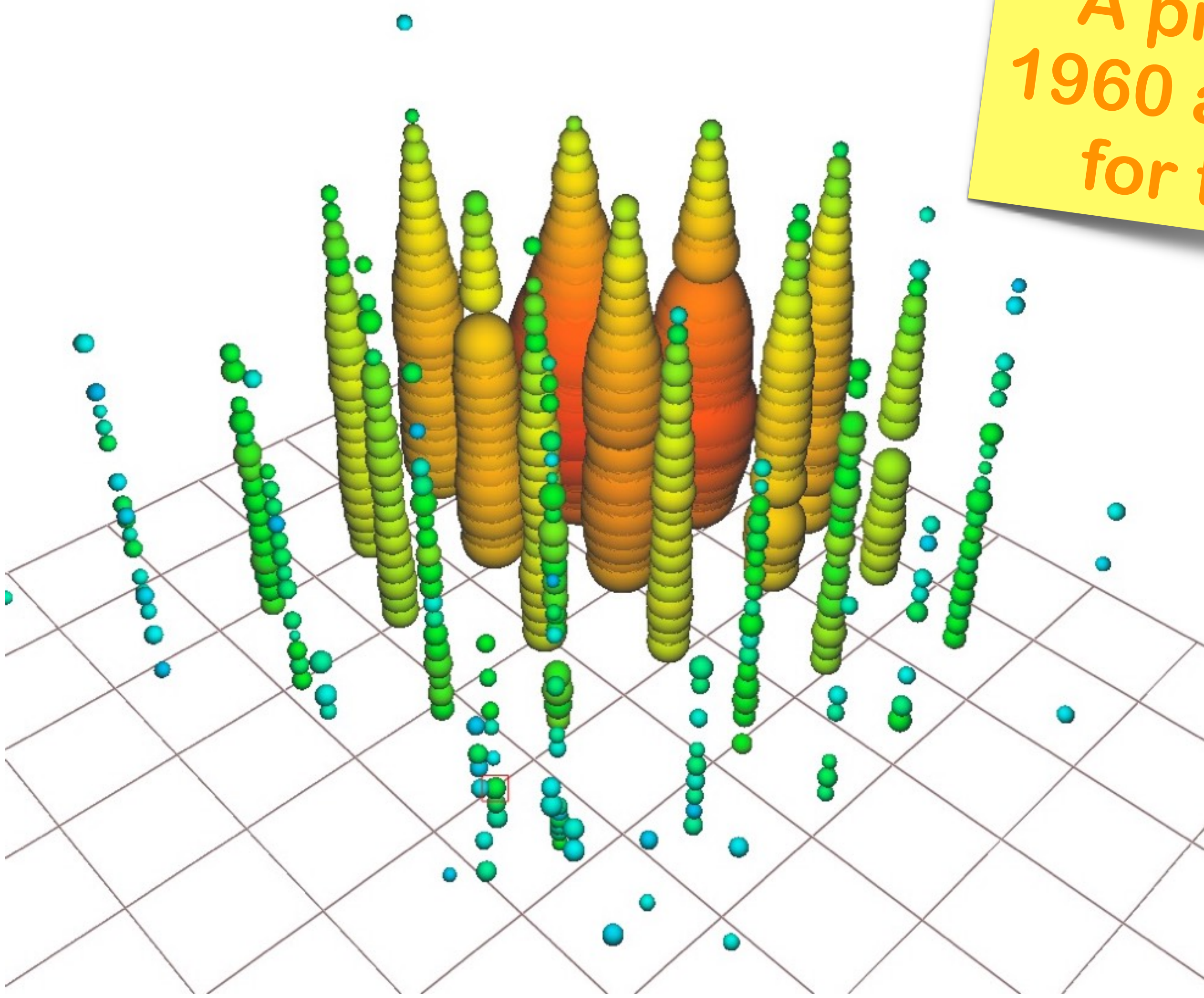


~1000 astronomers / 18 observatories!

(~3000 astronomers / 70 observatories was for GW170817)

A neutrino at the Glashow resonance energy

The resonant formation of a W^- boson from the interaction of a high energy anti-electron neutrino with an electron (Glashow resonance) is predicted at a peaking neutrino energy of 6.3 PeV. One such event found for the first time in 4.6 years of IceCube data!



M. G. Aartsen et al. [IceCube Collaboration], Nature 591, 220 (**2021**)

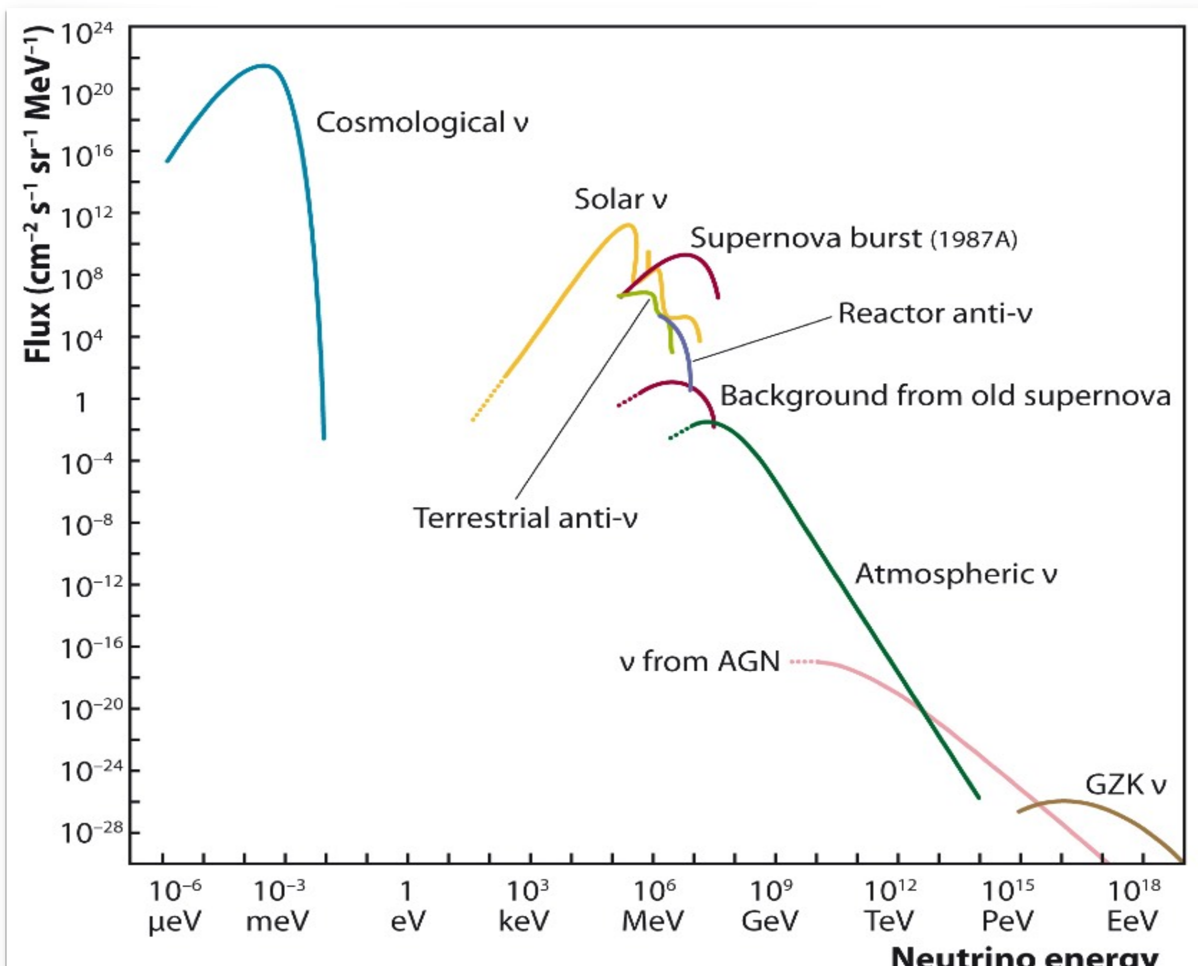
A prediction from 1960 accessible now for the first time

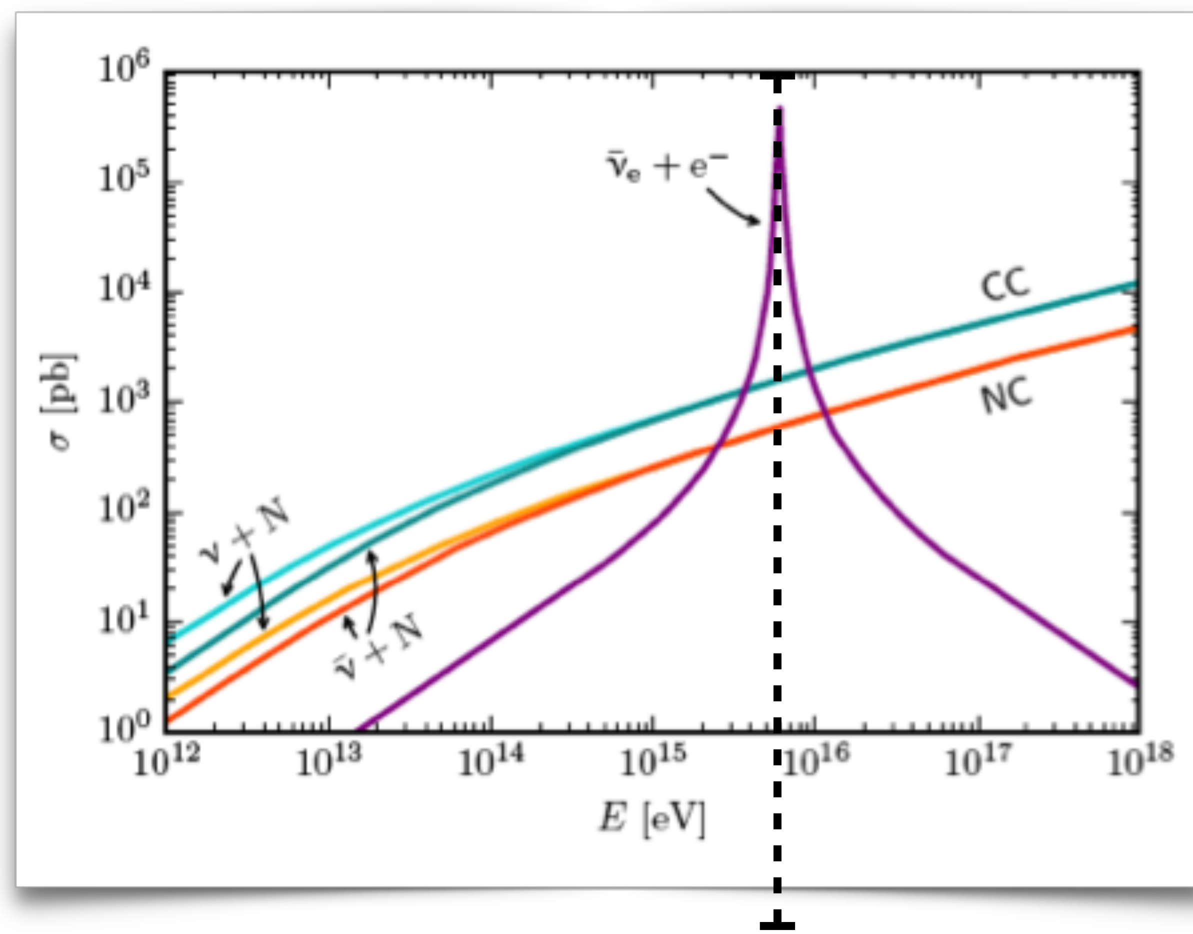
$$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow \begin{cases} \text{Hadrons (67\%)} \\ \text{Leptons (23\%)} \end{cases}$$

See also **Sheldon Glashow "The past and the future of neutrino science"** @ XIX International Workshop on Neutrino Telescopes, Venice (Italy) **2021**

Challenges: cross section & flux

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

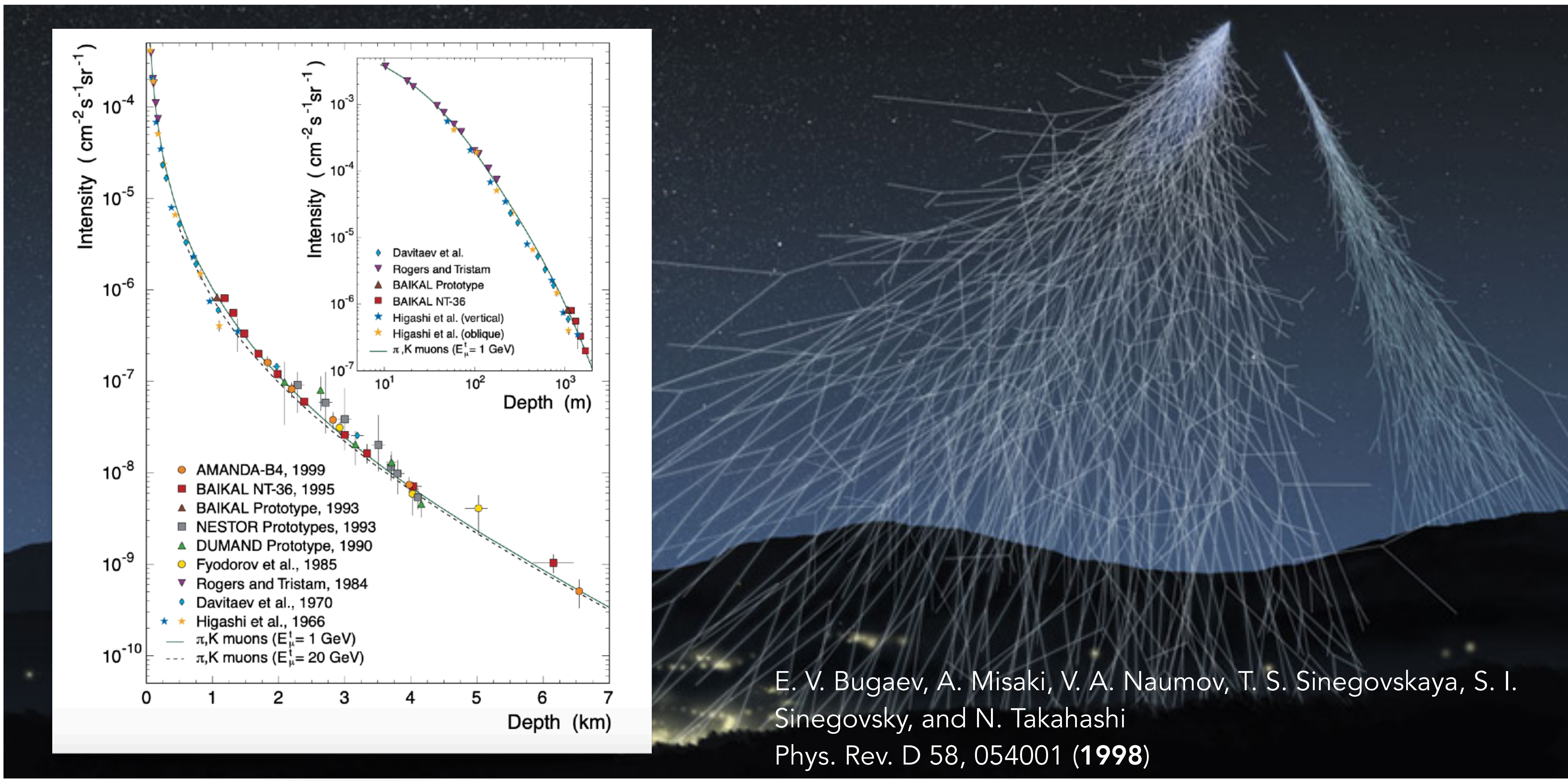




$E_{\overline{\nu}_e} = M^2_W /(2m_e) = 6.3$ PeV

Challenges: backgrounds

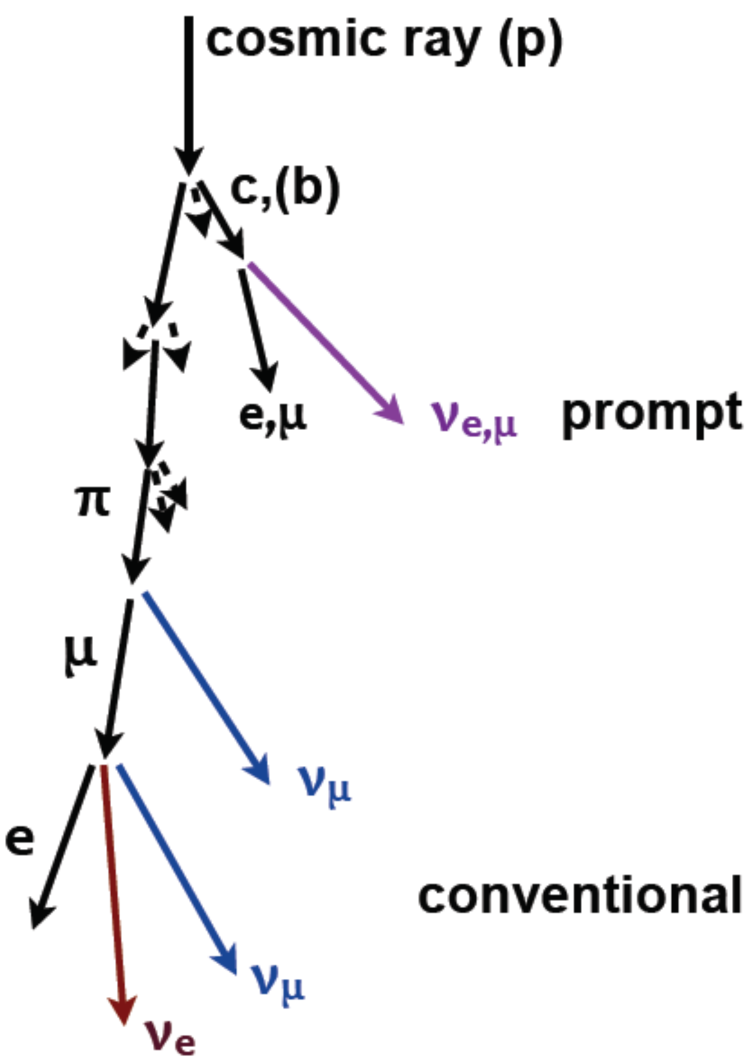
Large volumes beneath important mass overburdens are needed to suppress the background from interactions of cosmic rays in the Earth's atmosphere

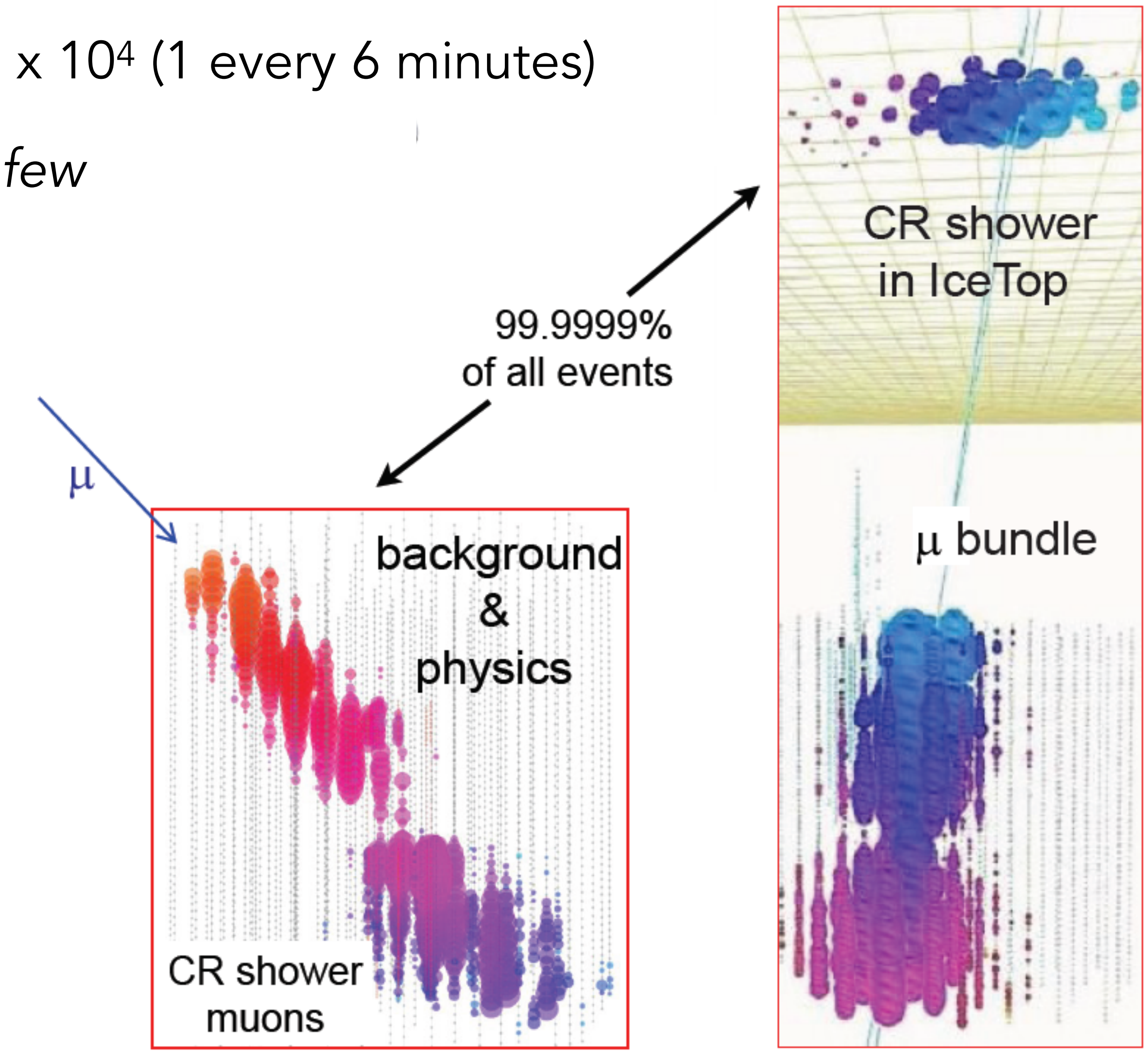


E. V. Bugaev, A. Misaki, V. A. Naumov, T. S. Sinegovskaya, S. I. Sinegovsky, and N. Takahashi
Phys. Rev. D 58, 054001 (**1998**)

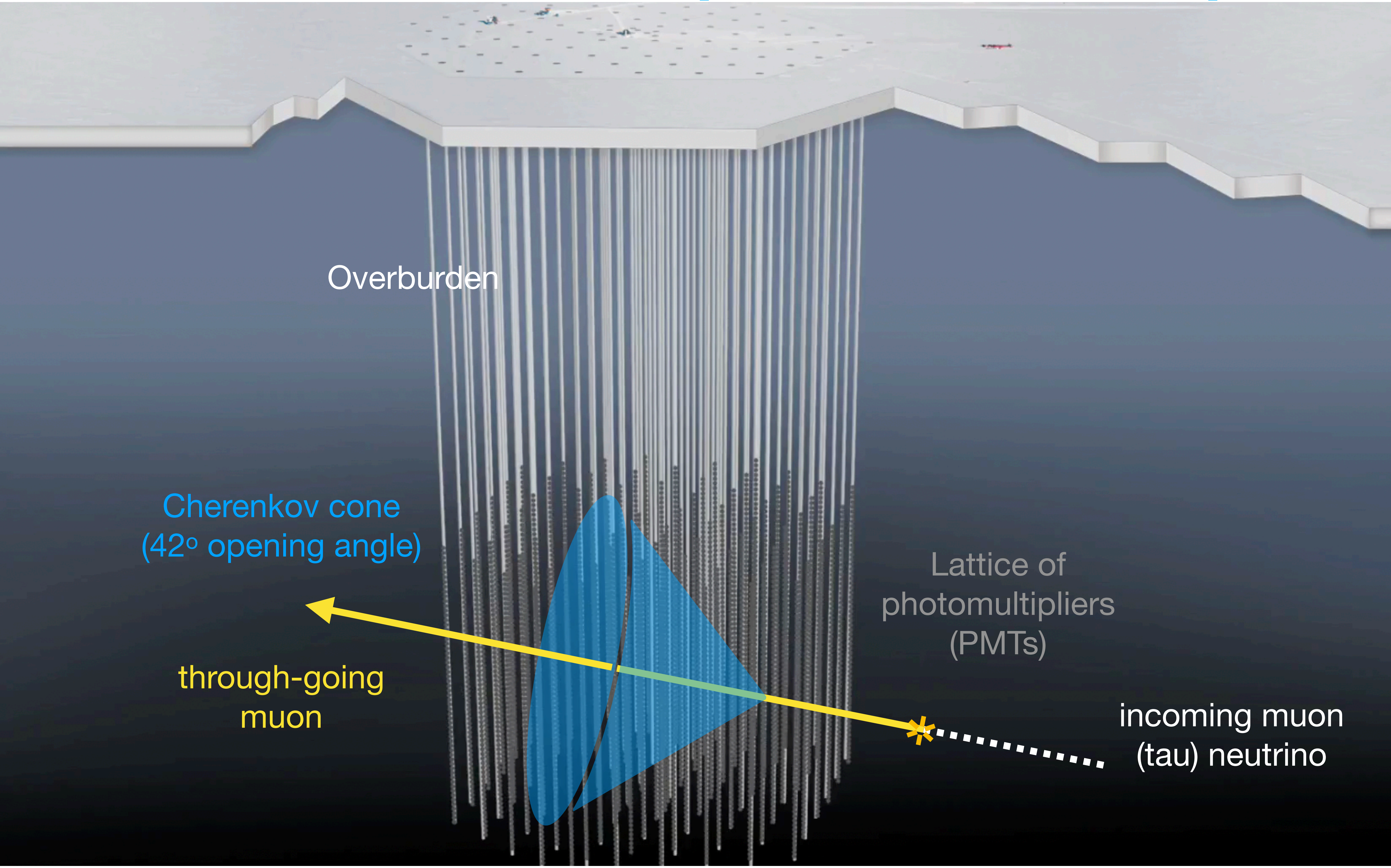
Signal and backgrounds

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

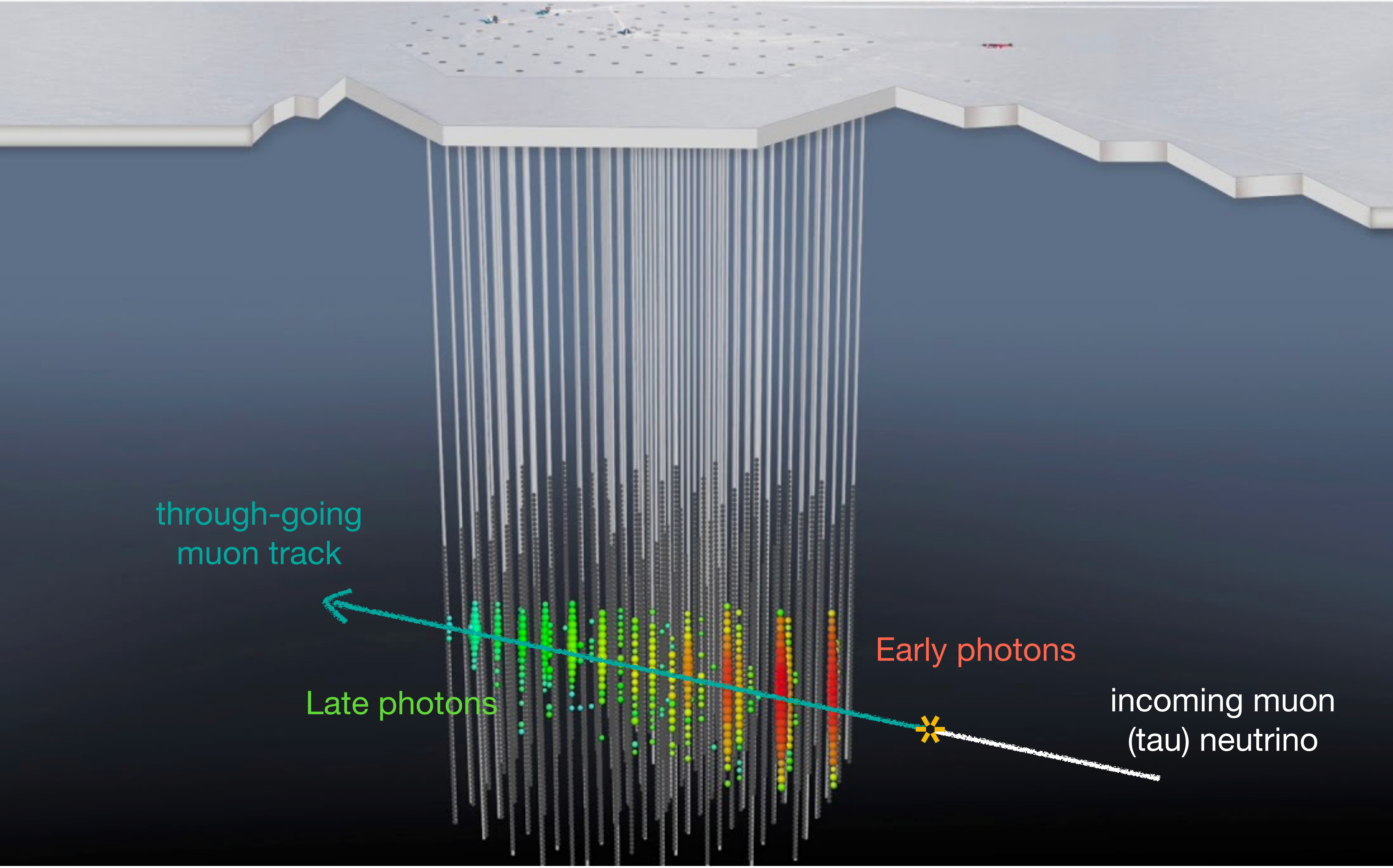




Neutrino telescopes: the concept



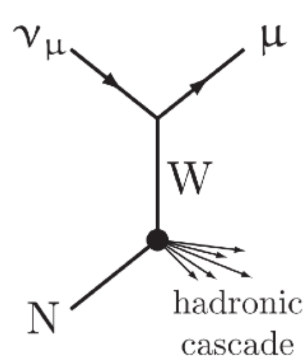
Neutrino telescopes: the concept



Event signatures

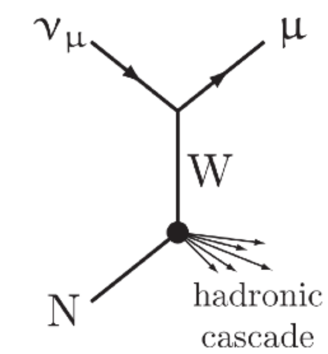
Through-going track (ν_μ)

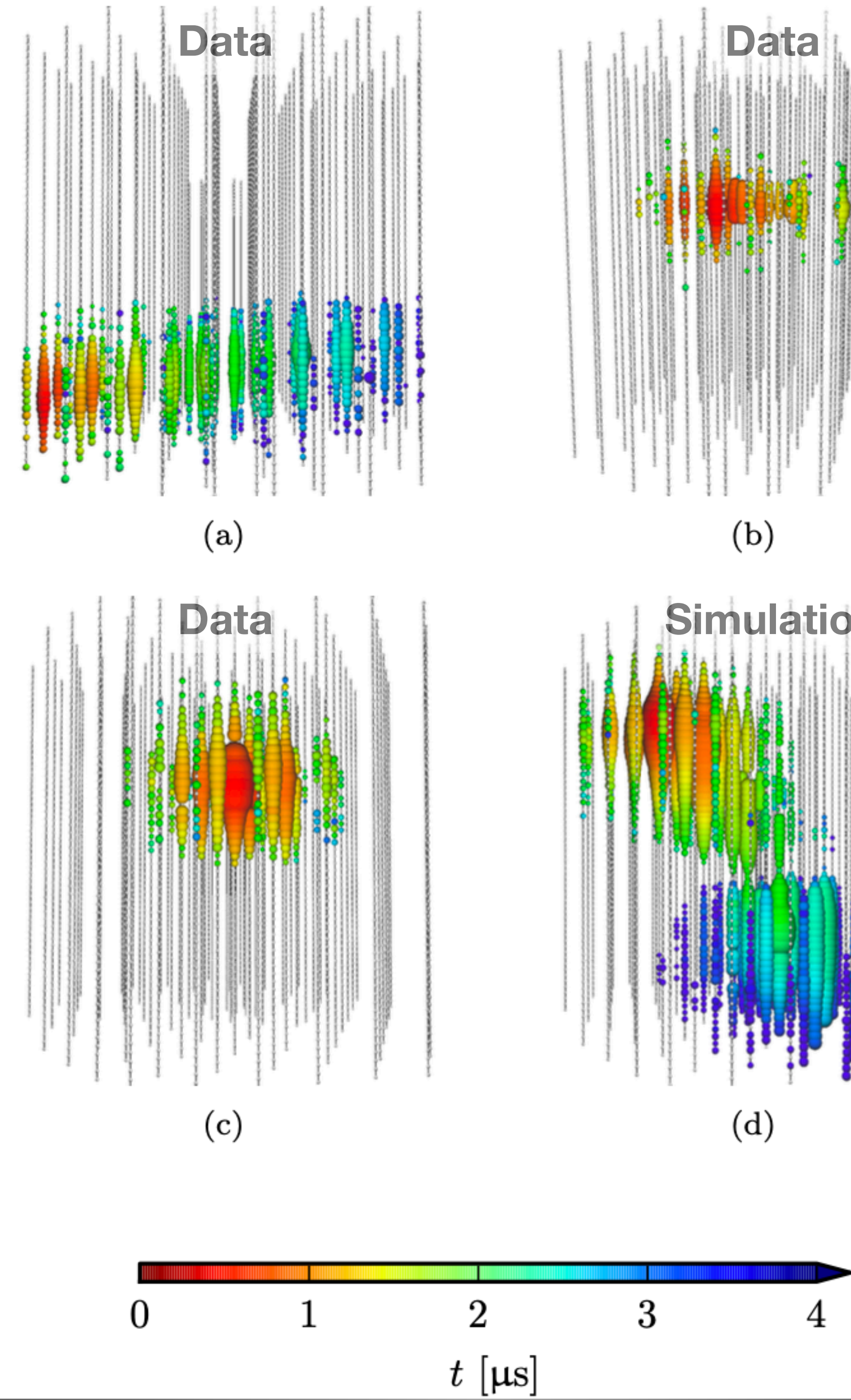
angular resolution < 1°
energy resolution ~ factor of 2



Starting track (ν_μ)

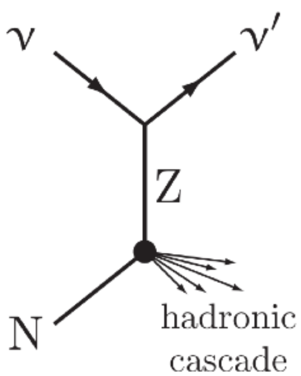
angular resolution < 1°
dE/dx + energy at vertex

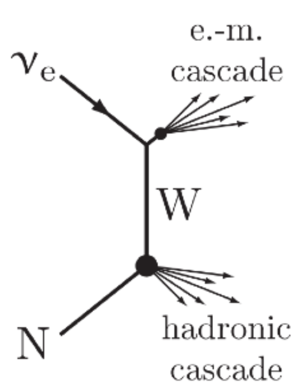




Cascade (ν_e, ν_μ, ν_τ)

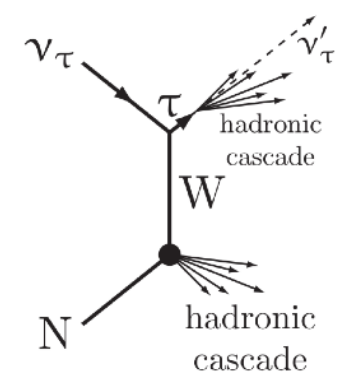
angular resolution 10° - 40°
energy resolution ~ 10%





Double-Bang (ν_τ)

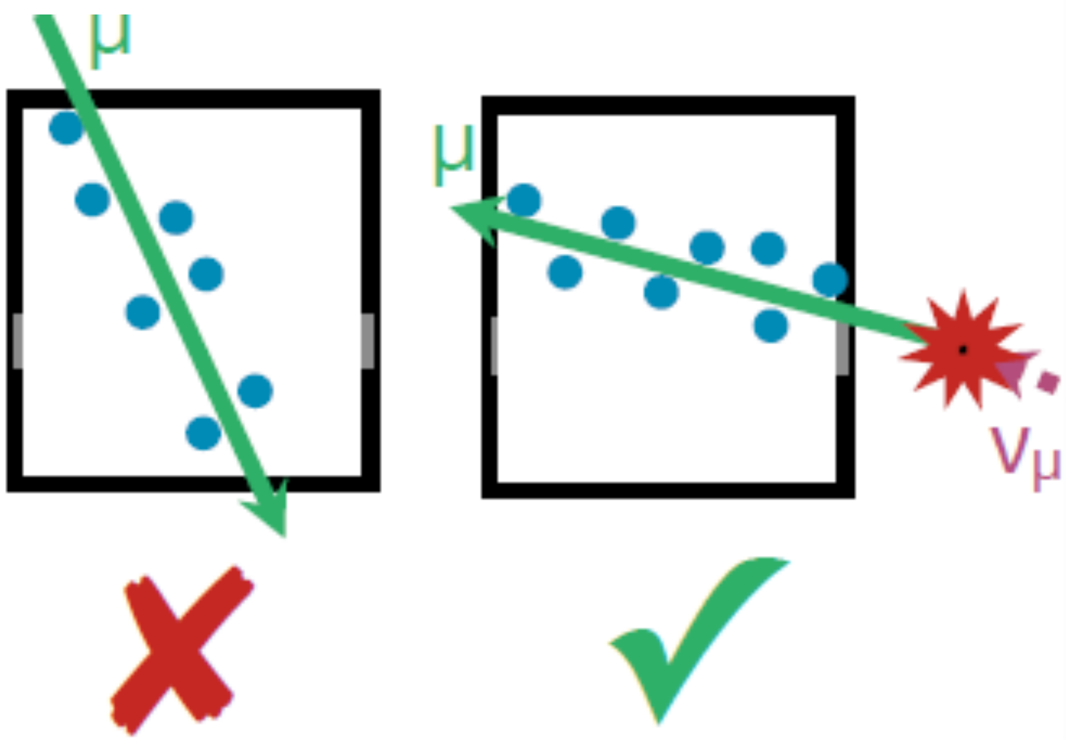
E > O(PeV)

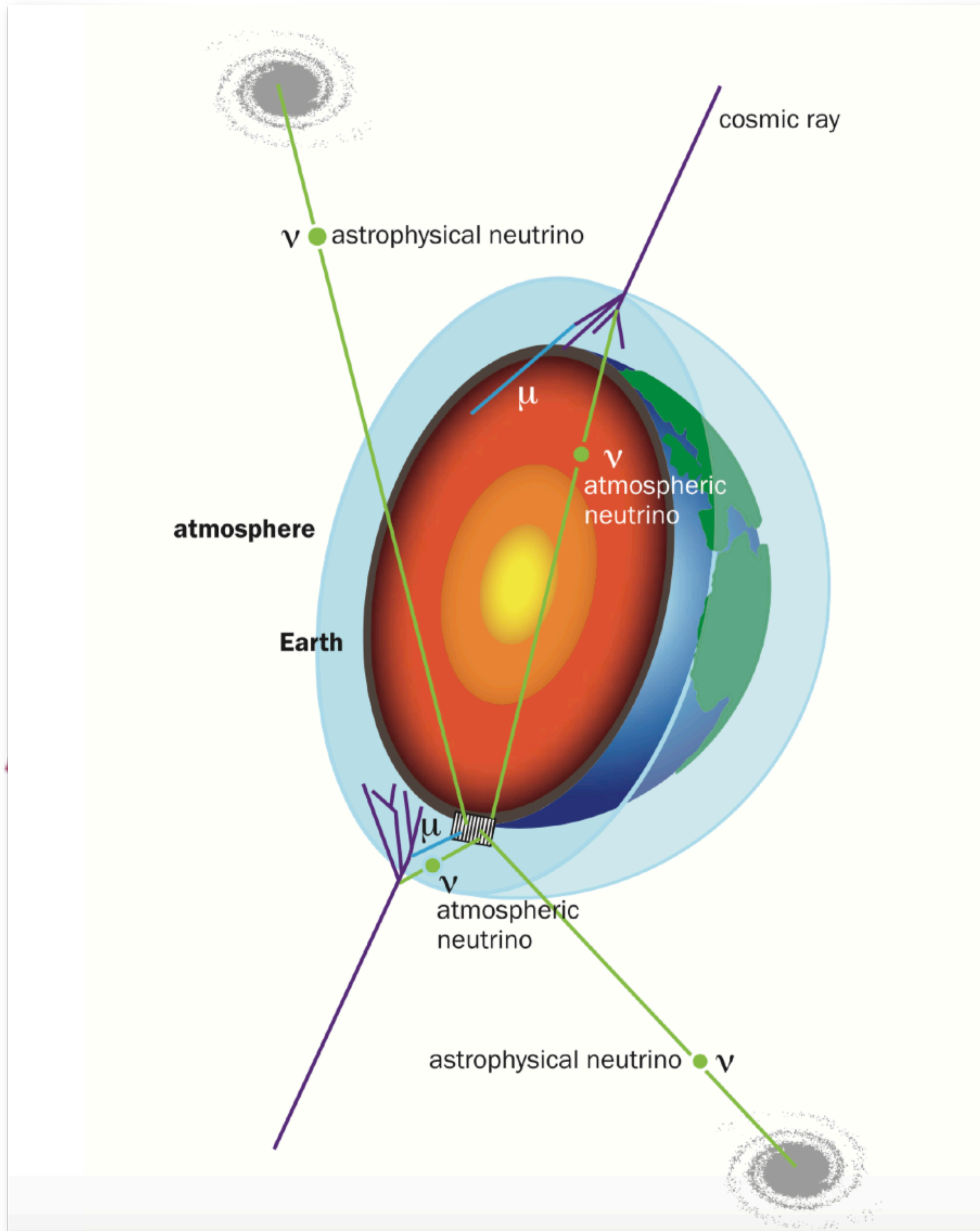


$<L>=50\ m \times E_\tau$ /PeV

Reducing the background

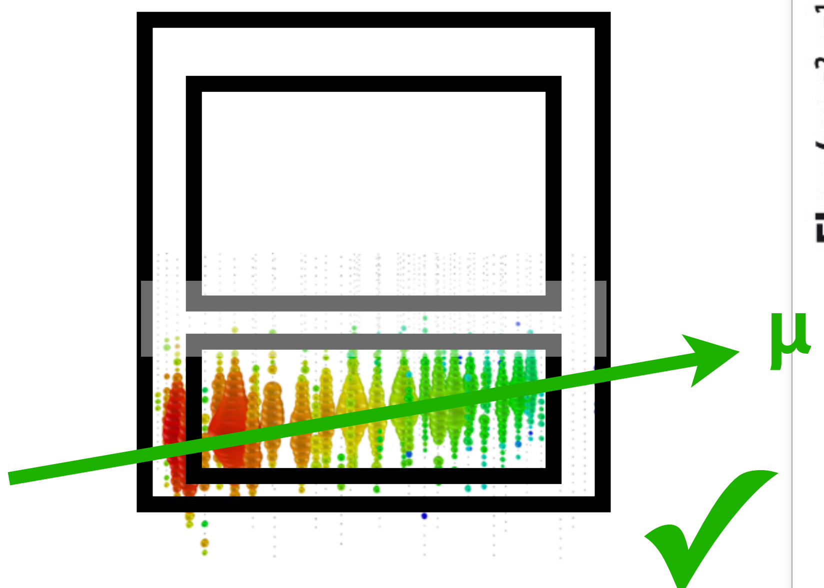
Select up-going events travelled through earth: Sensitive to ν_μ, ν_τ, Northern Sky only

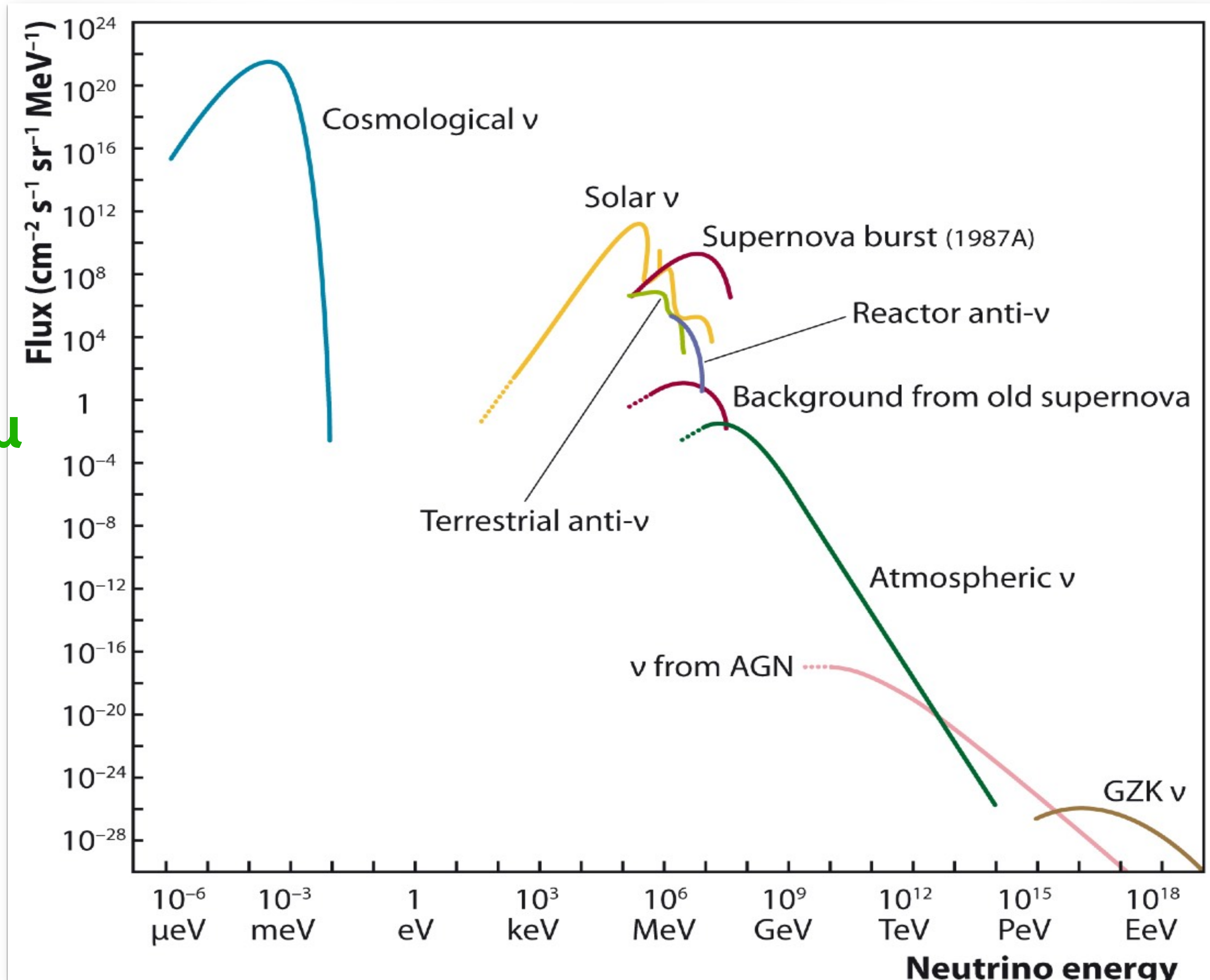




Reducing the background

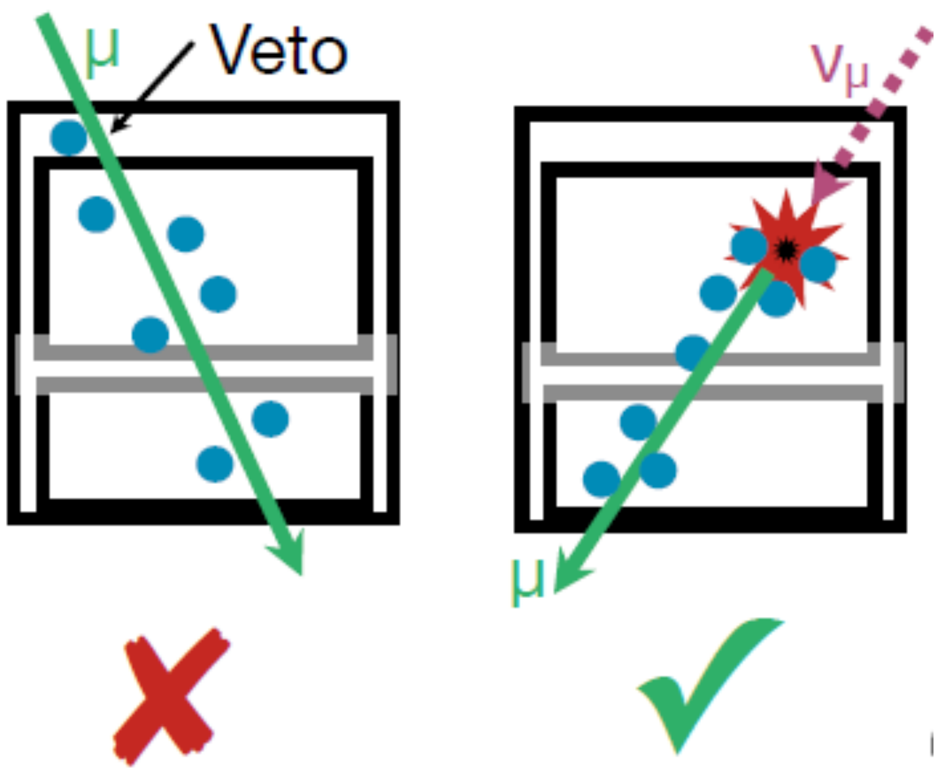
Select Extreme High Energy events (EHE): Sensitive to ν_e, ν_μ, ν_τ in energy range from few 100 TeV to few EeV. Around horizon with very good angular resolution for tracks

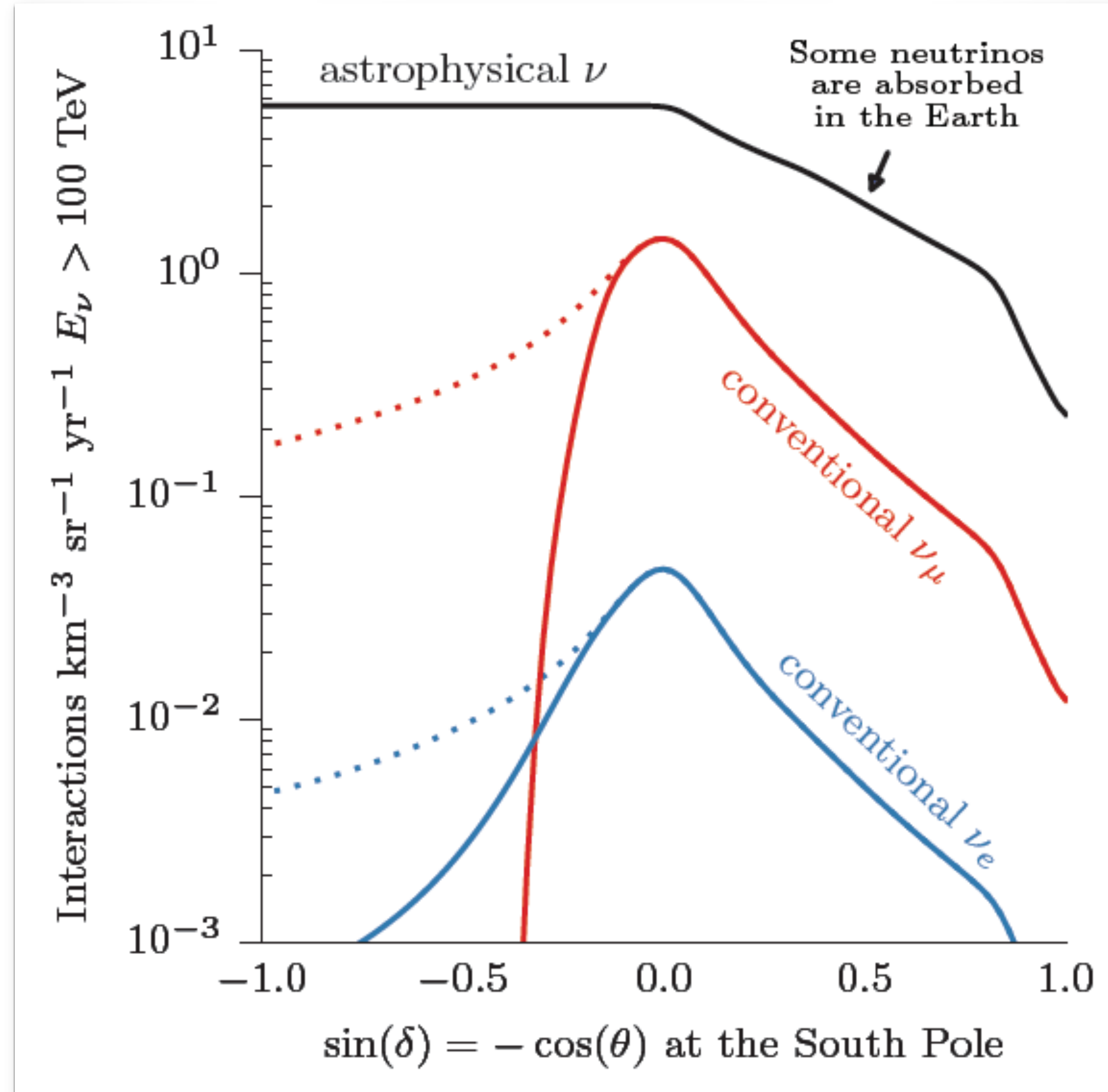




Reducing the background

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

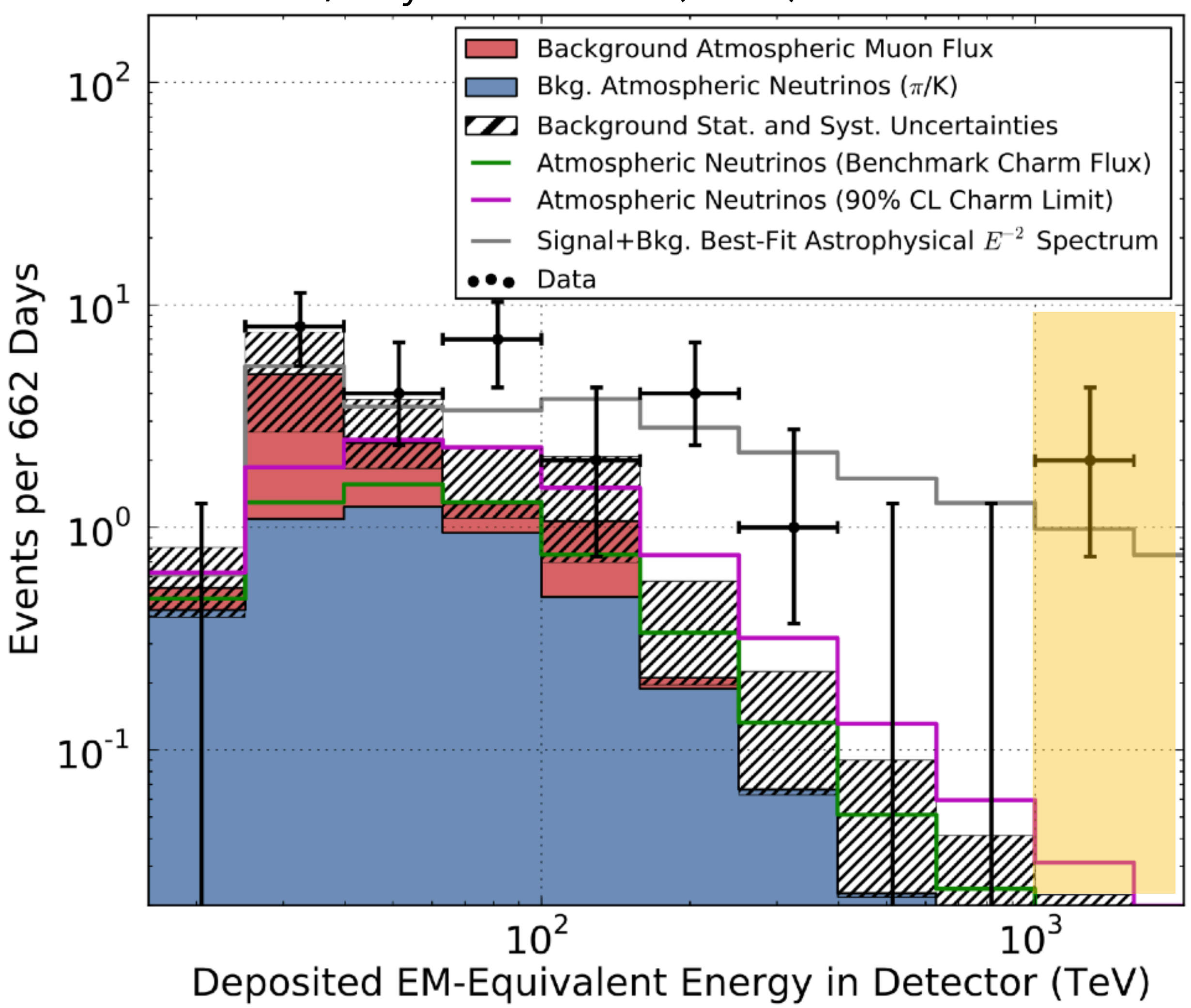
Wandkowsky, N., & Weaver, C. 2018, PoS, ICRC2017, 976

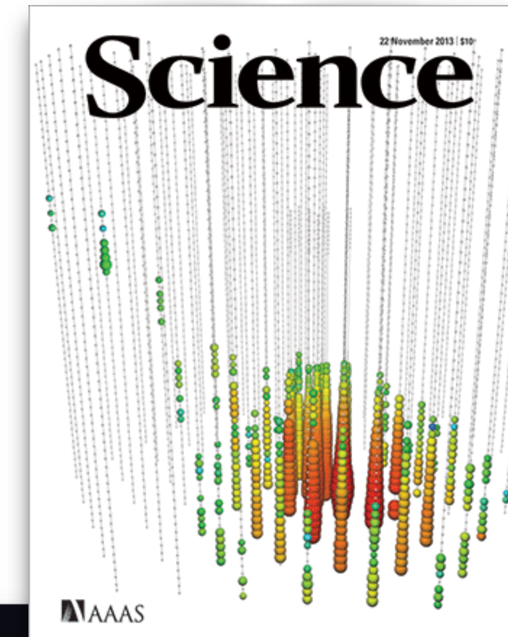
Astrophysical neutrinos discovered

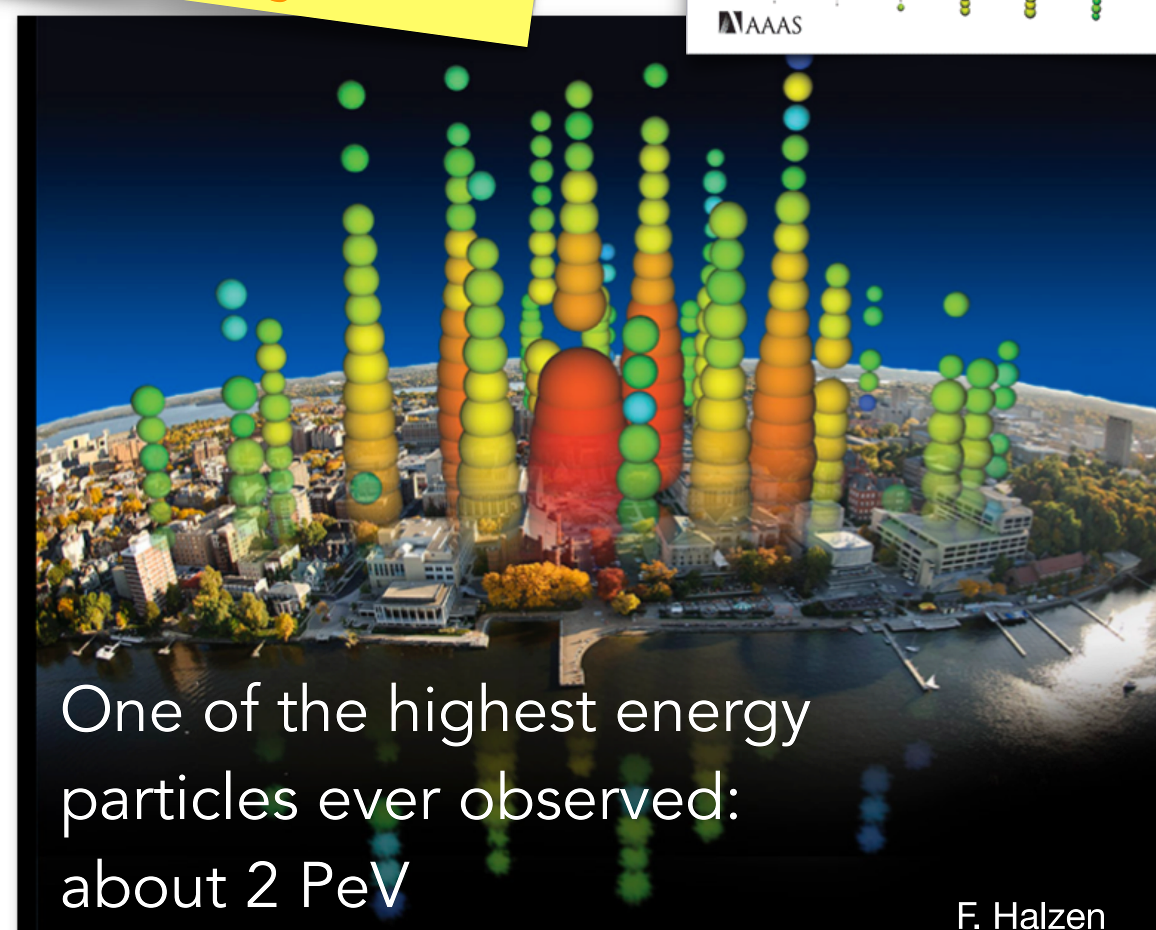
First evidence of neutrinos of astrophysical origin: flavors, directions, and energies inconsistent with those expected from the atmospheric muon and neutrino backgrounds

Breakthrough discovery

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



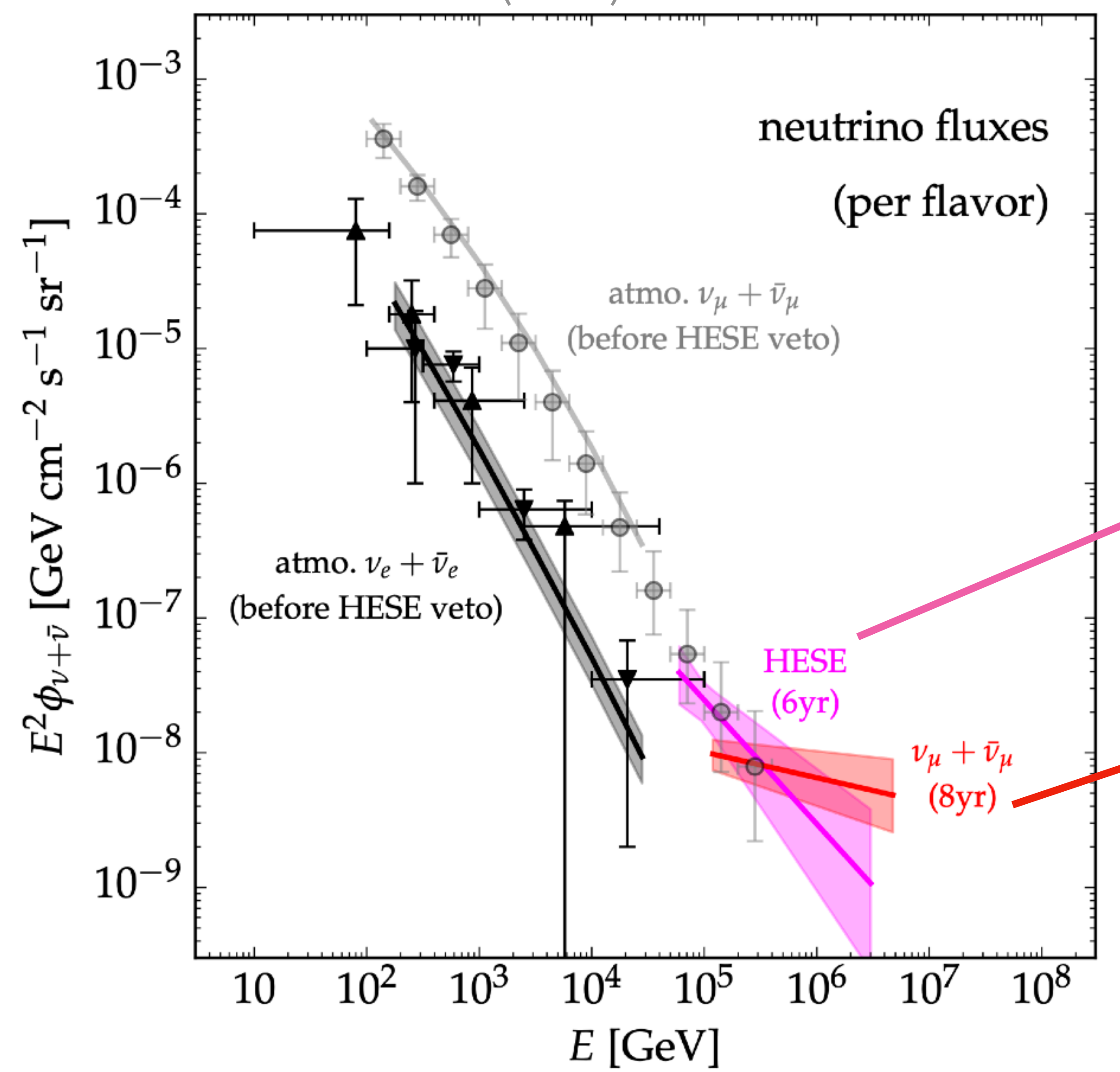




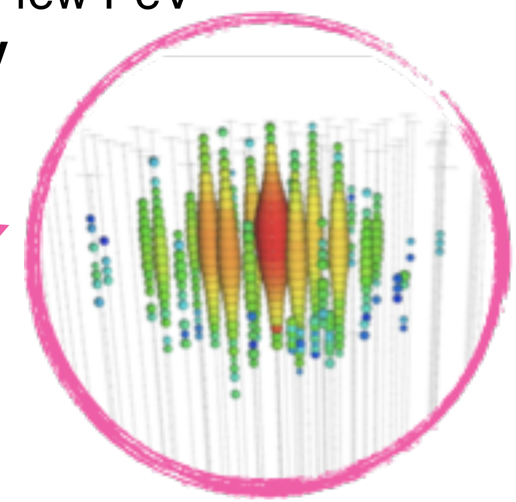
Astrophysical neutrino flux

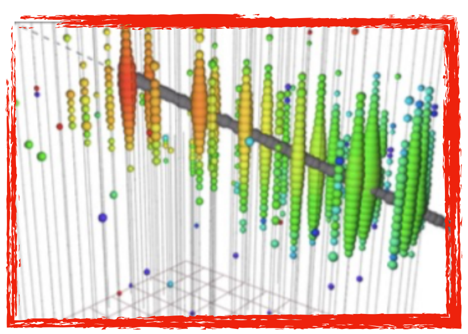
At high energies an excess of events is observed excluding an atmospheric-only origin. An astrophysical flux in the energy range from ~10 TeV and ~10 PeV is testified by various channels and analysis methods

Ahlers & Halzen (2018)



High-energy starting events (**HESE**)
Interaction vertex in the detector
Energy ~70 TeV - few PeV
All flavor, all sky

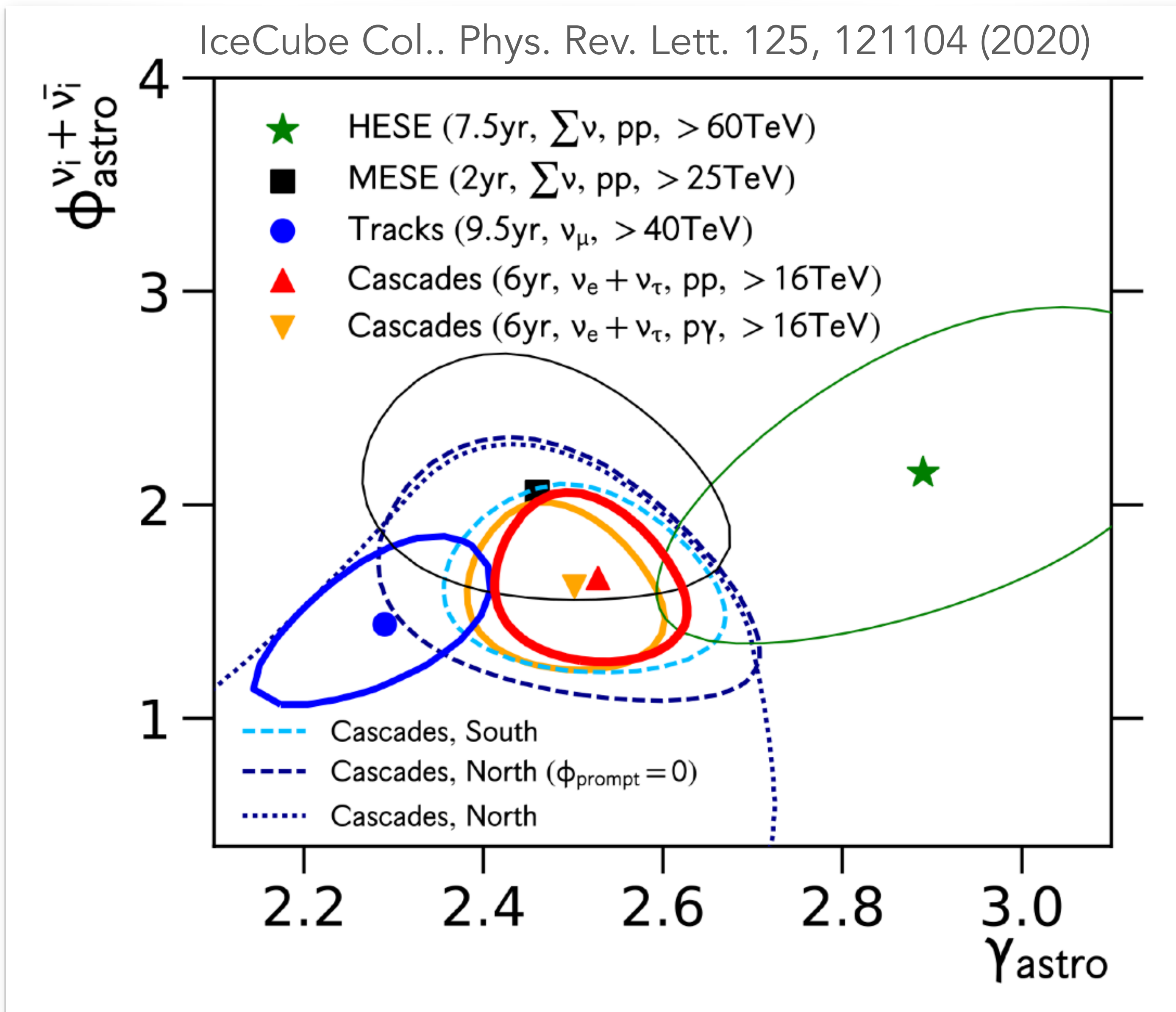




Up-going tracks
Muon-dominated
Energy 100 GeV - 10 PeV
Northern sky

Astrophysical neutrino flux

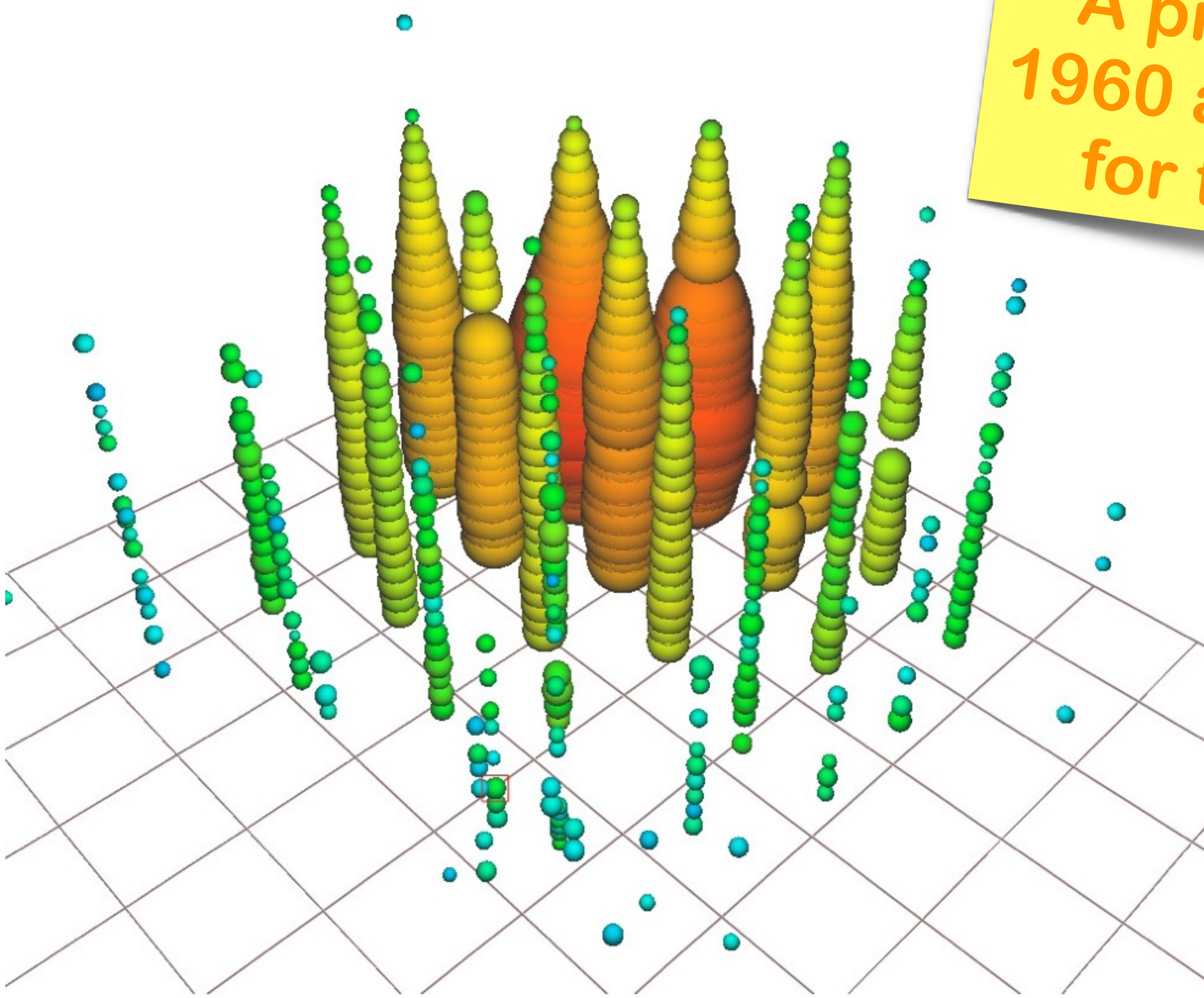
The energy spectrum is compatible with a single power-law with a spectral index of 2.5 between 16 TeV and 3 PeV. No event observed so far with energy > 10 PeV. Flavor composition compatible with standard scenarios.



A neutrino at the Glashow resonance energy

The resonant formation of a W^- boson from the interaction of a high energy anti-electron neutrino with an electron (Glashow resonance) is predicted at a peaking neutrino energy of 6.3 PeV. One such event found for the first time in 4.6 years of IceCube data!

A prediction from 1960 accessible now for the first time



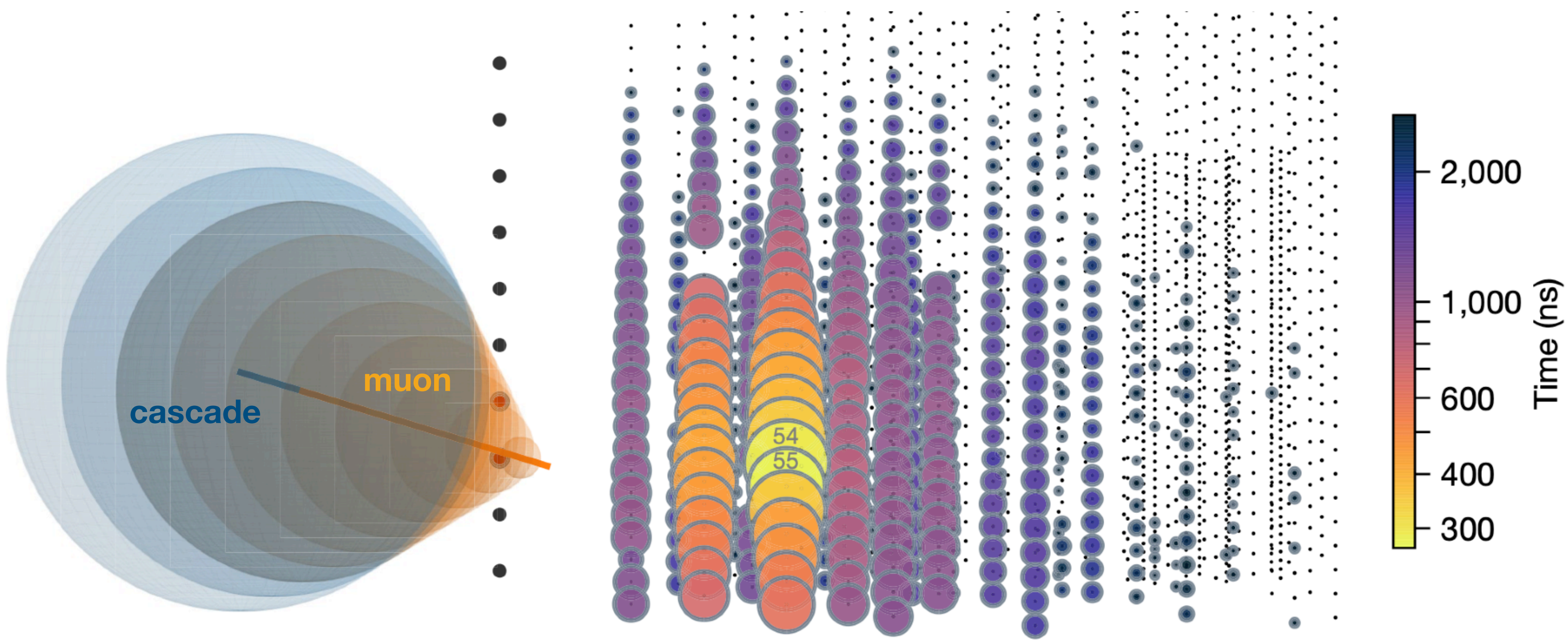
M. G. Aartsen et al. [IceCube Collaboration], Nature 591, 220 (**2021**)

$$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow \begin{cases} \text{Hadrons (67\%)} \\ \text{Leptons (23\%)} \end{cases}$$

See also **Sheldon Glashow "The past and the future of neutrino science"** @ XIX International Workshop on Neutrino Telescopes, Venice (Italy) **2021**

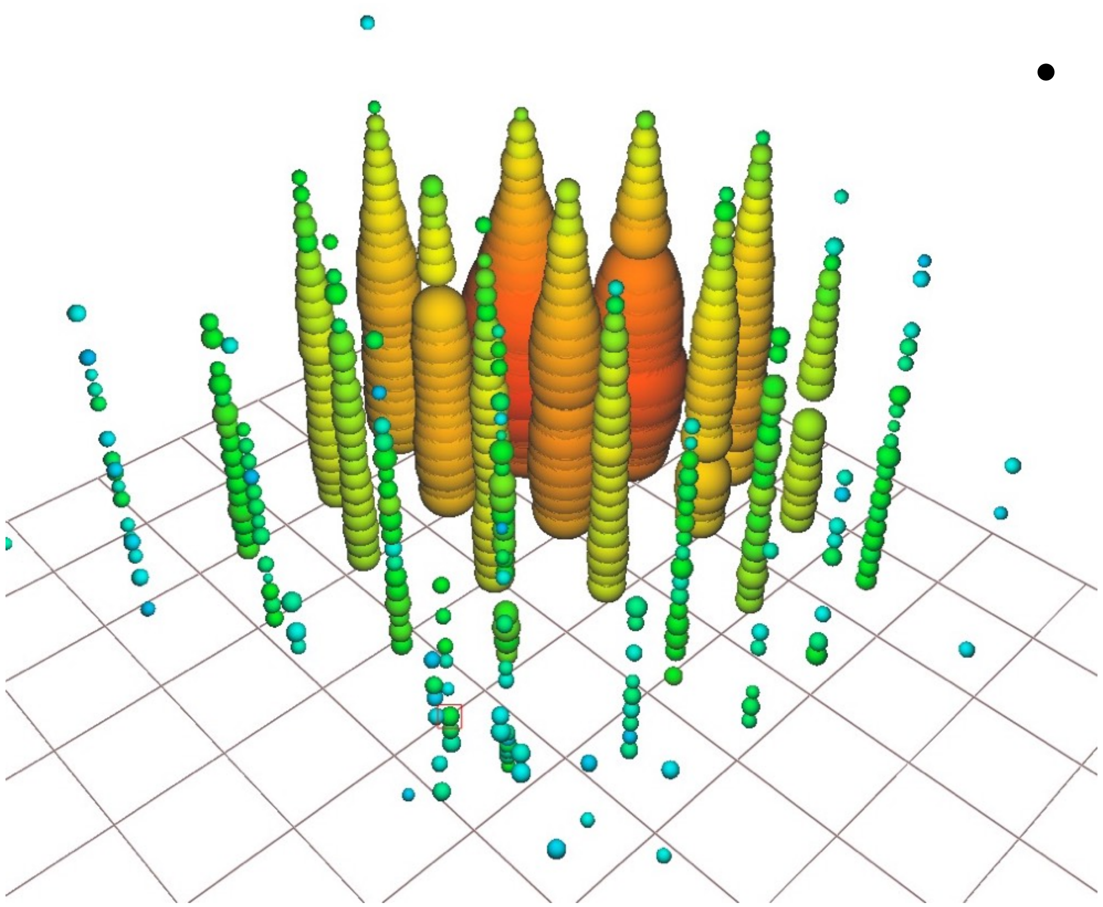
A neutrino at the Glashow resonance energy

Early pulses are consistent with with an outgoing muon from the hadronic shower (with reconstructed energy ~ 26 GeV) and allow to conclude that the event is very likely to be of astrophysical origin.



A neutrino at the Glashow resonance energy

Simplified source models can already be tested with one Glashow resonance. Future facilities and multi-messenger associations will enable differentiating between different scenarios.

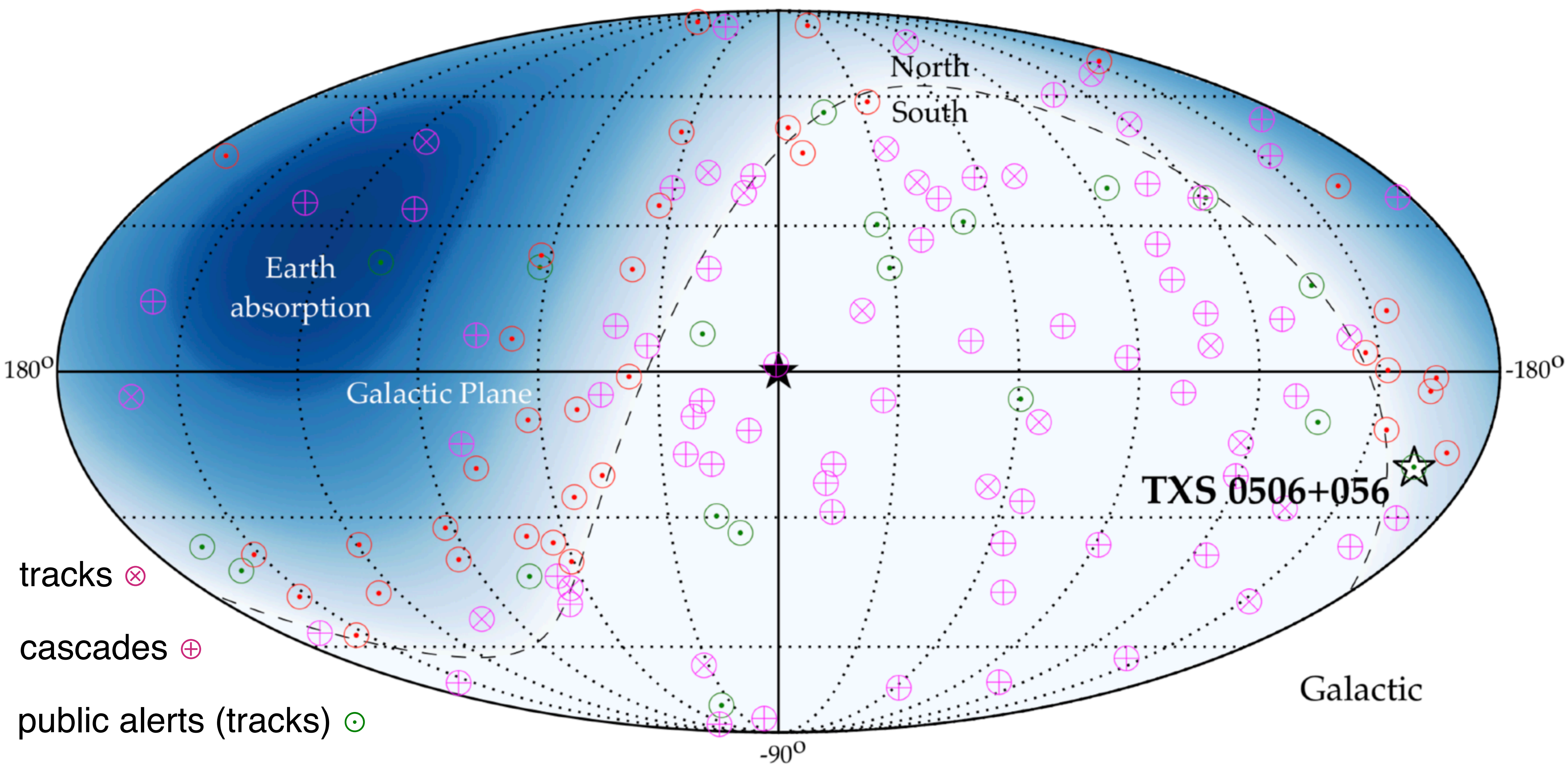


M. G. Aartsen et al. [IceCube Collaboration], Nature 591, 220 (2021)

- Expected ratio anti-ν_e / ν_e:
  - proton-proton
    - $(pp)\ \ \bar{\nu}_e : \nu_e = 1:1$
  - proton-photon
    - $(p\gamma)\ \ \bar{\nu}_e : \nu_e = 1:3.5$
    - $(p\gamma,$ strong B-field$)\ \ \bar{\nu}_e : \nu_e = 0$

The high-energy Neutrino Sky

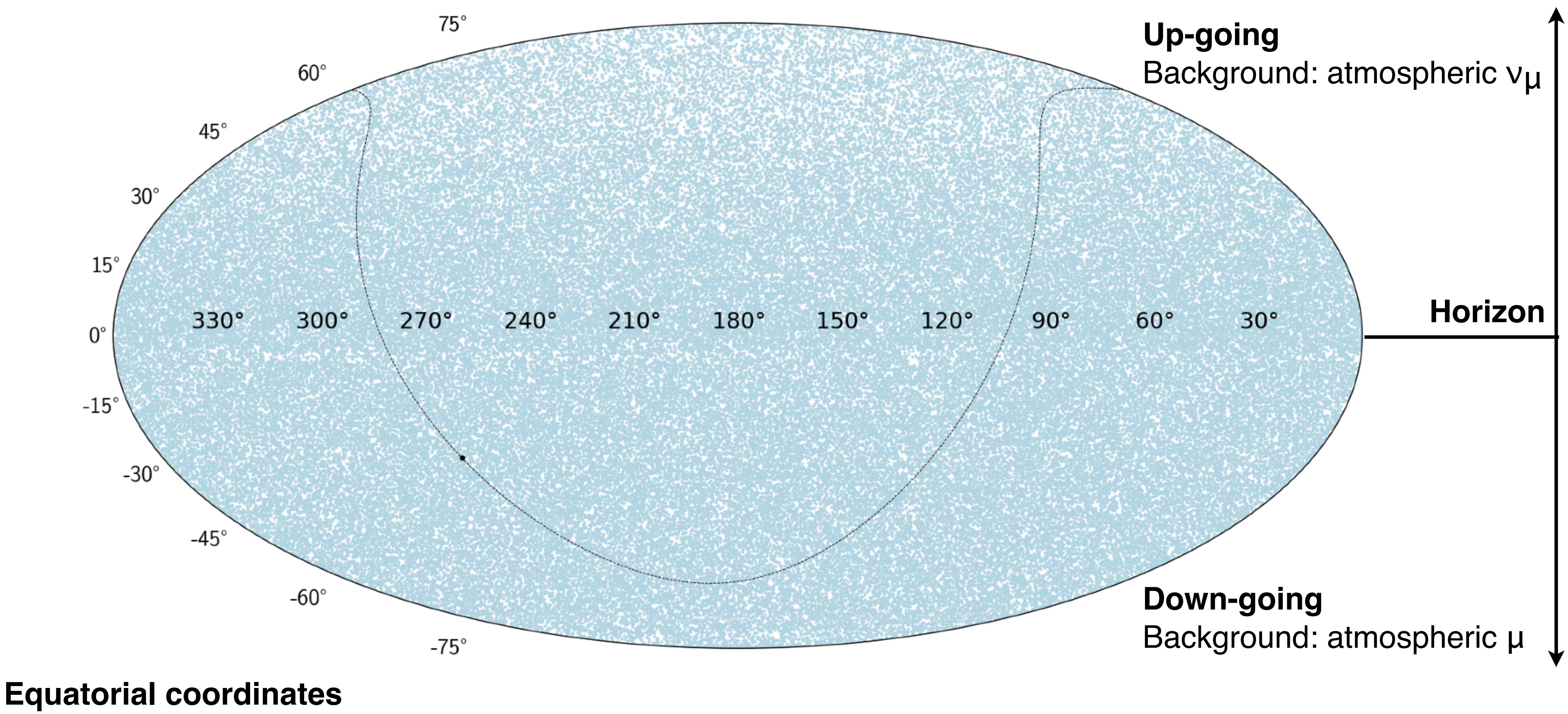
At high energies (few tens TeV) a clear excess of events is observed excluding an atmospheric-only origin. Directions show no obvious accumulation either around individual sources or the Galactic plane



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

Searching for Neutrino Point Sources

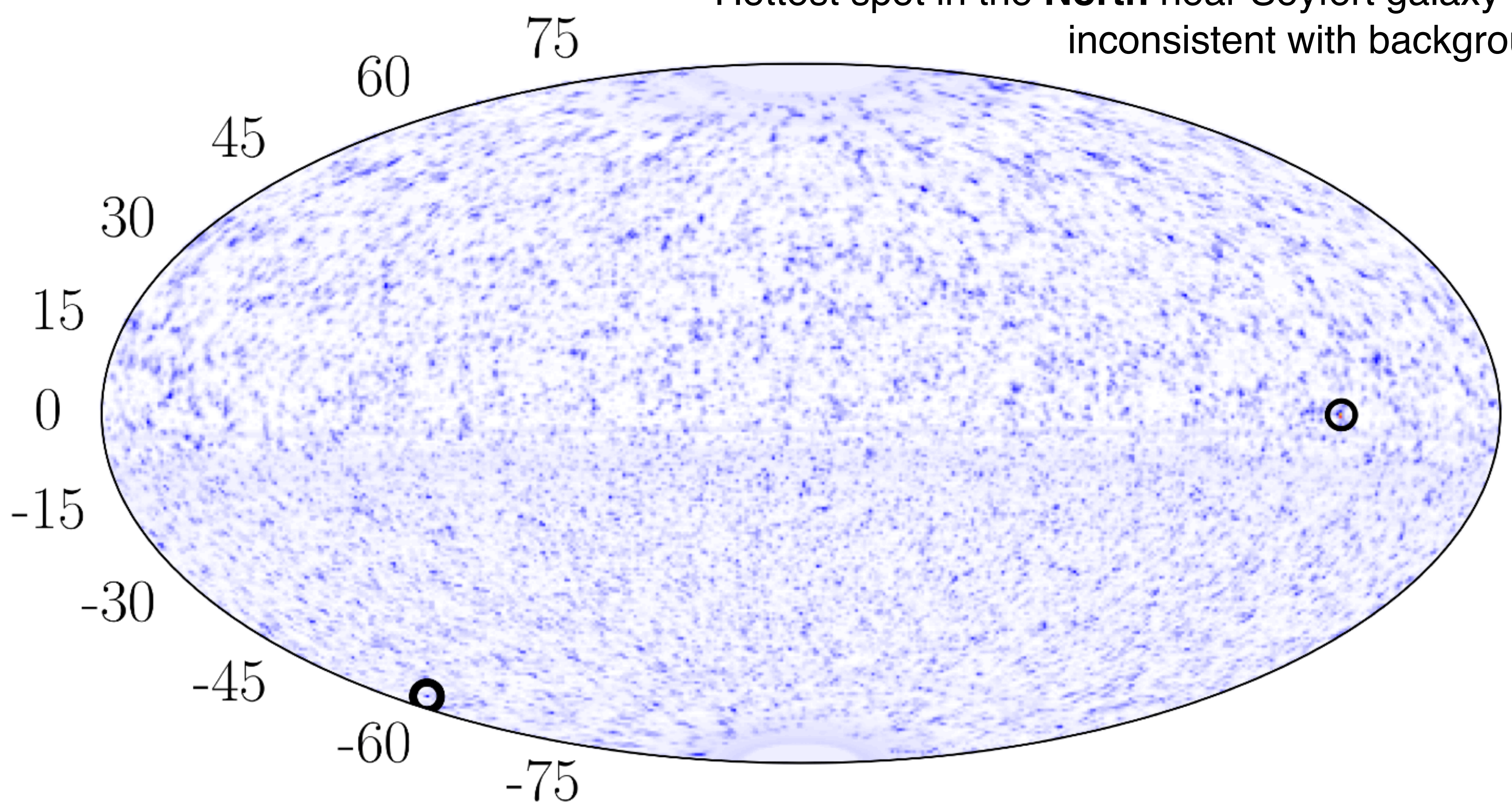
Allowing for more background and larger signal efficiencies it is possible to search for individual astrophysical sources as local event excesses. From the first year of full IceCube operations 138,322 neutrino candidates (**muon tracks**) recorded!



Searching for Neutrino Point Sources

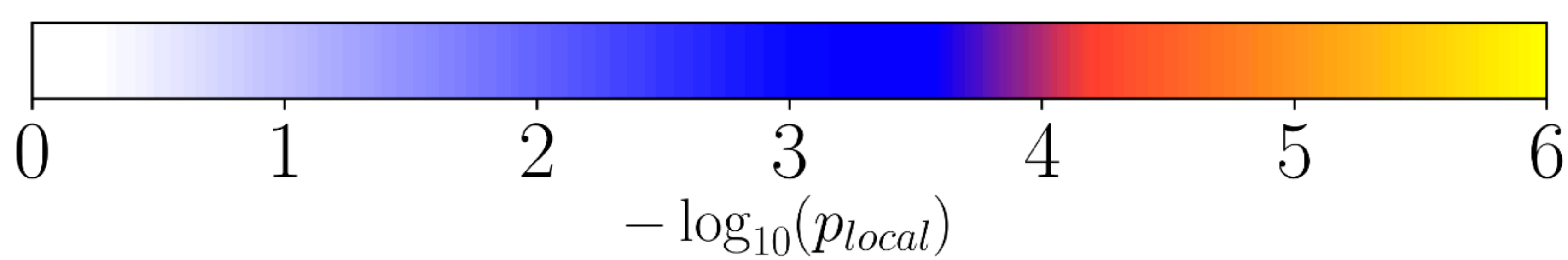
A sample of ~1x10[6] neutrinos recorded by IceCube in 10 years provides no evidence for neutrino sources in the full sky and in locations motivated by gamma-ray observations

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



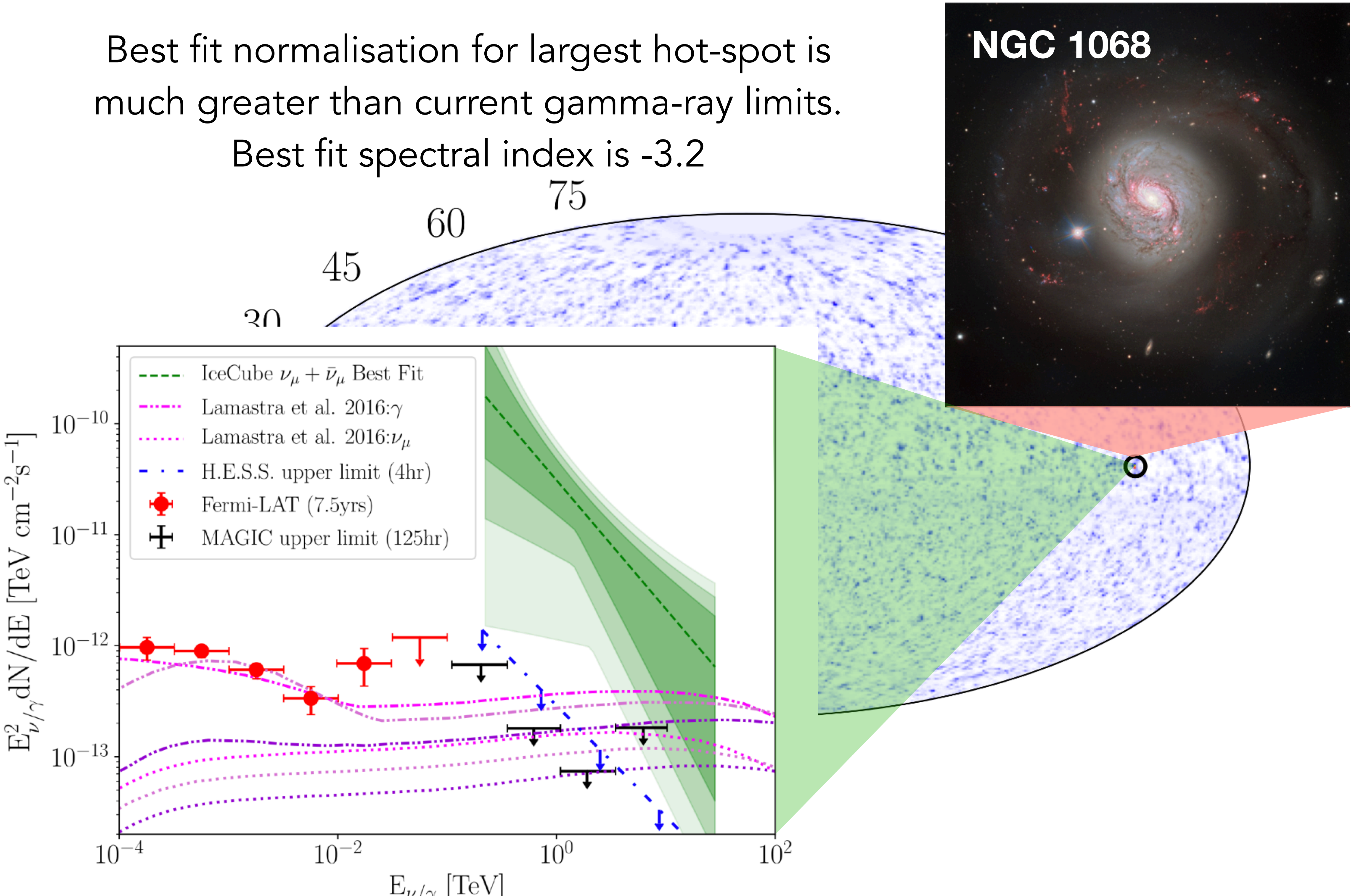
Hottest spot in the **South** post-trial probability 75%

IceCube Coll. Phys. Rev. Lett. 124, 051103 (2020)



Searching for Neutrino Point Sources

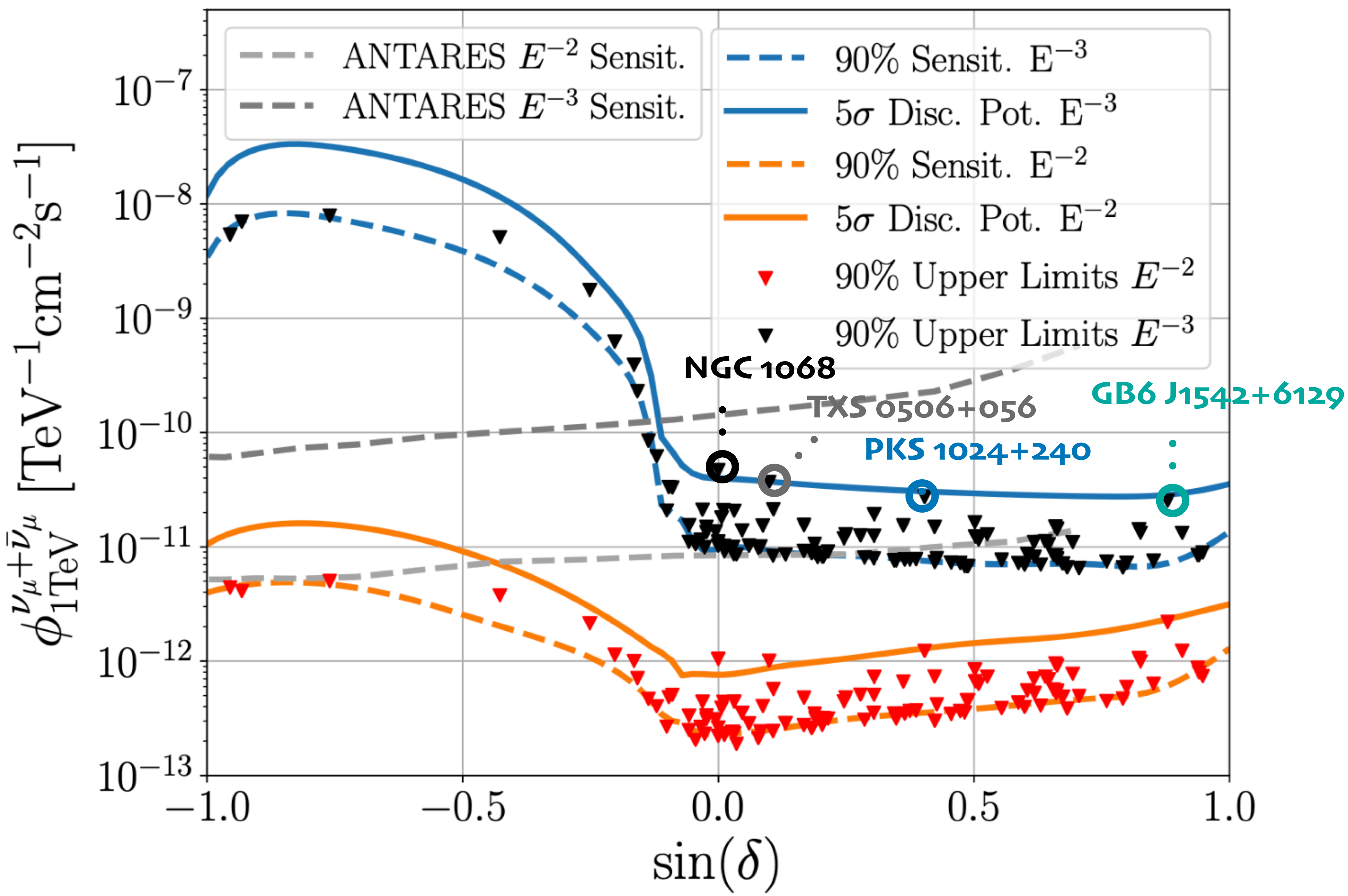
Best fit normalisation for largest hot-spot is much greater than current gamma-ray limits.
Best fit spectral index is -3.2



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

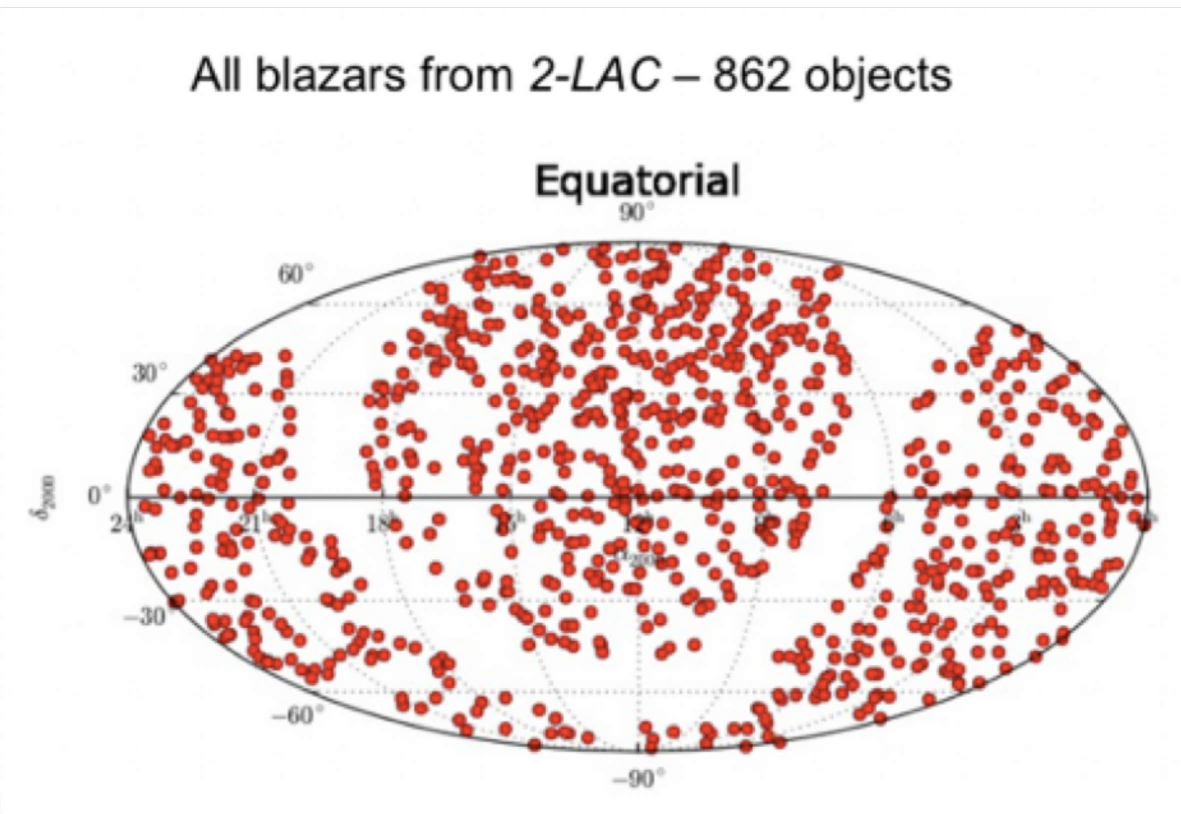
Searching for Neutrino Point Sources

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

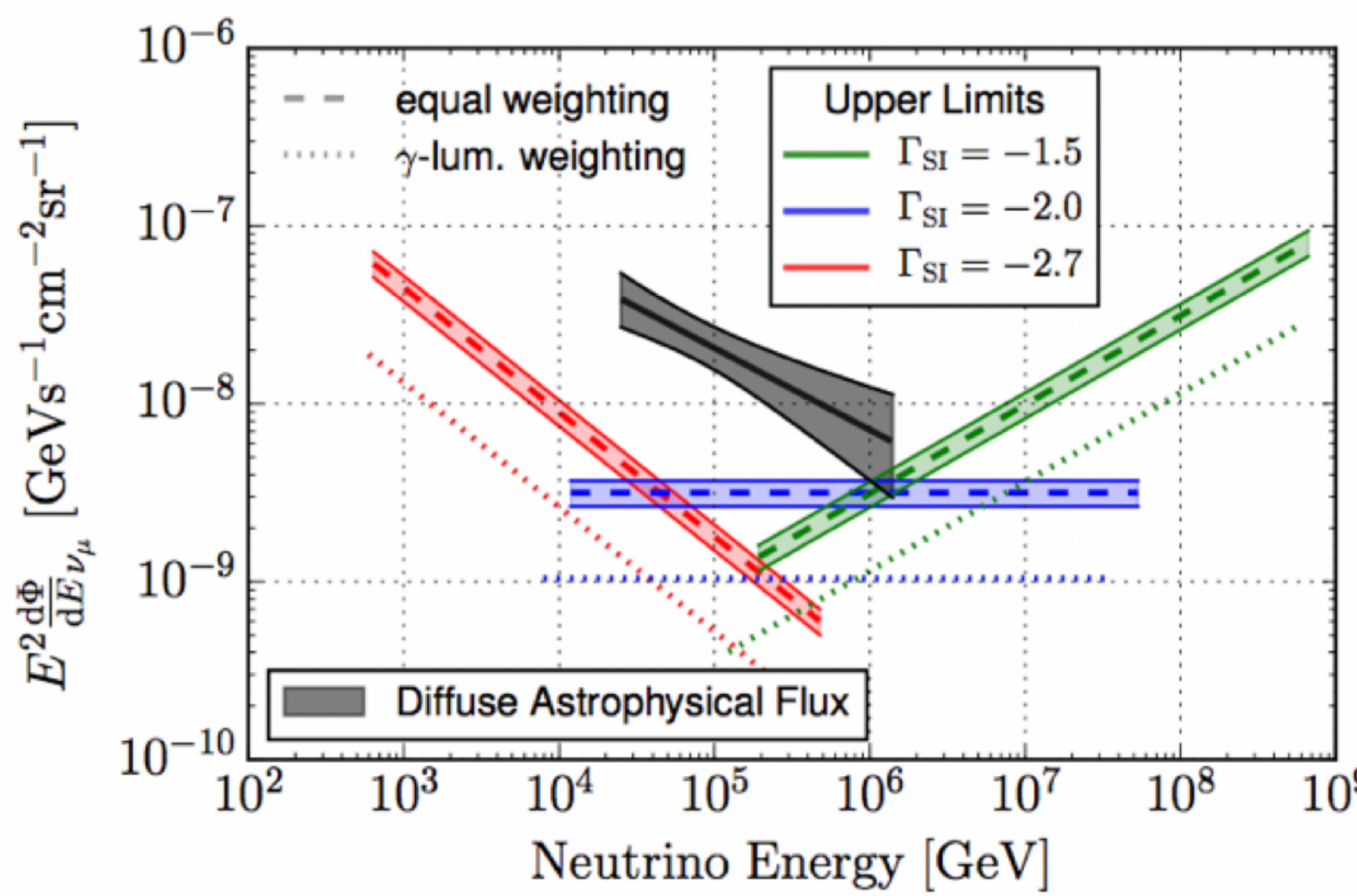


Contribution from γ-ray Blazars

Blazars dominate the diffuse γ-ray background above 10 GeV. A Stacking analysis allows to evaluate the contribution of Fermi-LAT Blazars to the diffuse neutrino flux. Fermi LAT blazars can only be responsible for a small fraction of the observed neutrinos. Similar conclusions are derived for different source populations, e.g. Gamma-ray Bursts.

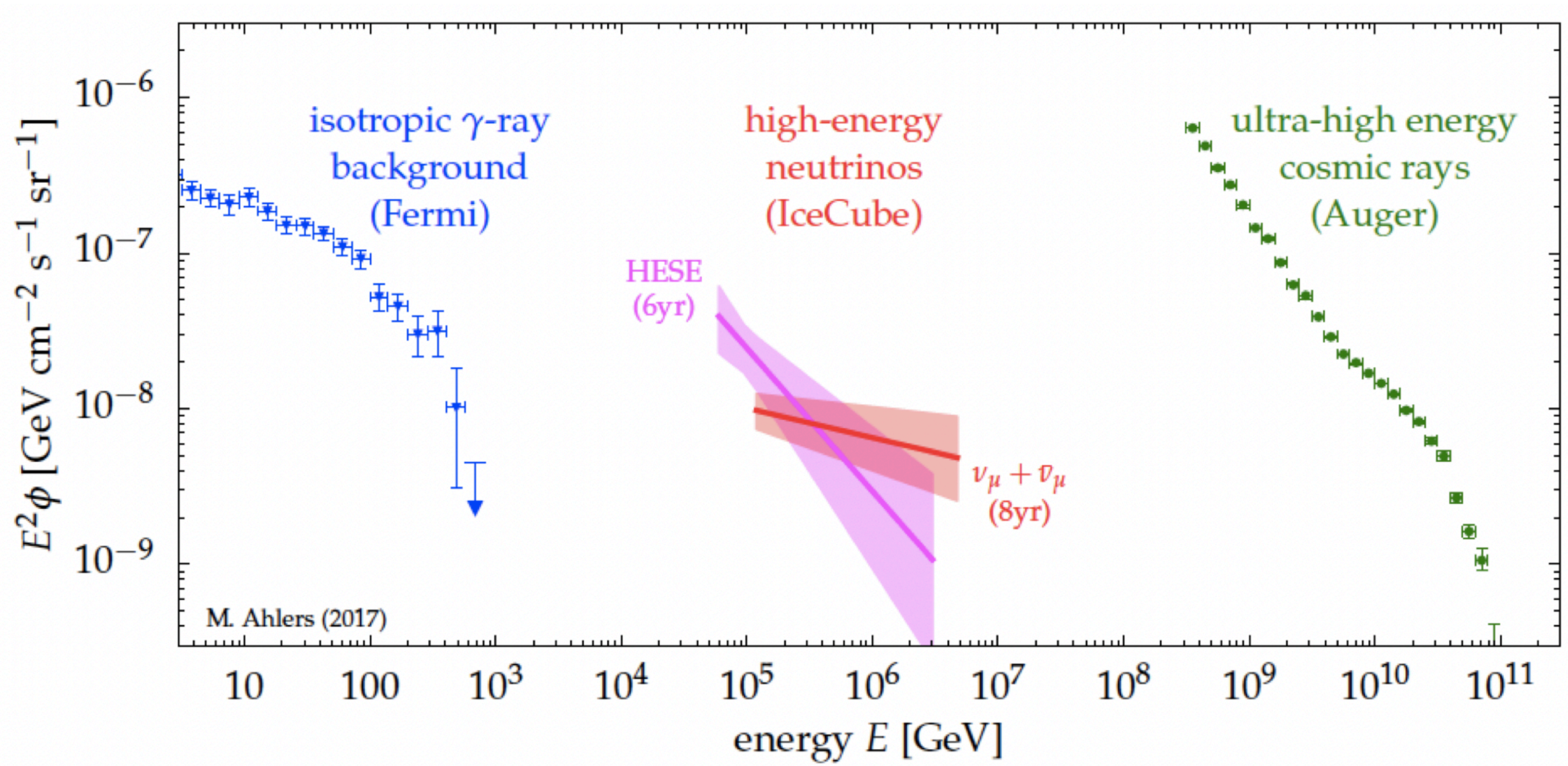


IceCube, ApJ, 835 (2017)



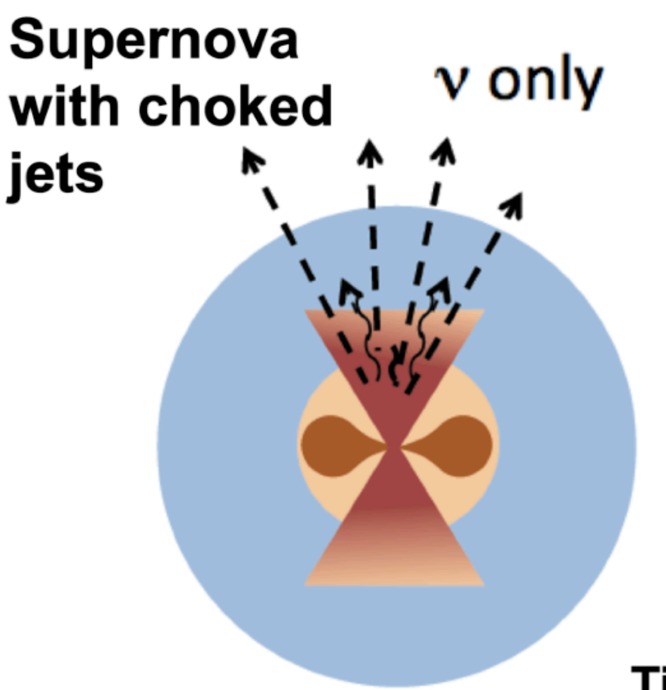
Multi-Messenger backgrounds

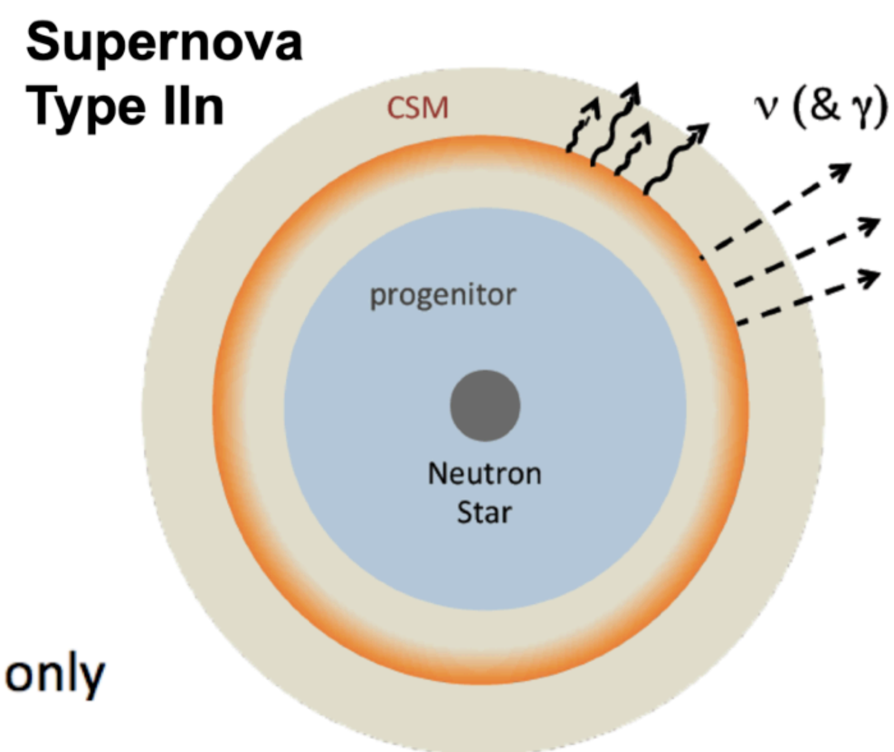
Diffuse cosmic ray, γ-ray, and neutrino fluxes show similar energy content despite their different energy regimes. This correspondence suggests an intriguing multi-messenger relationship.

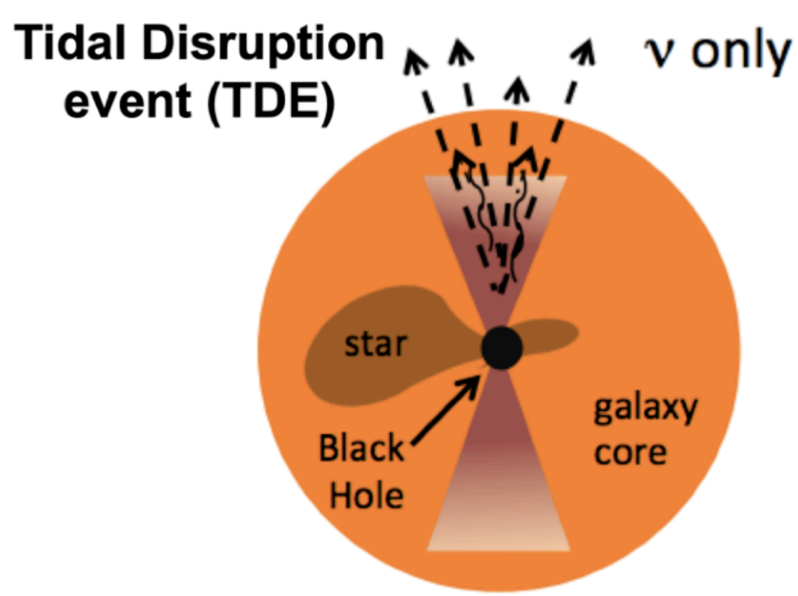


Other interesting transients

Different source populations might dominate in different energy regions, for example AGN cores, Starbursts Galaxies, Low-luminosity GRBs, TDE etc. emitting at low energies, while Blazars emit at high energies.





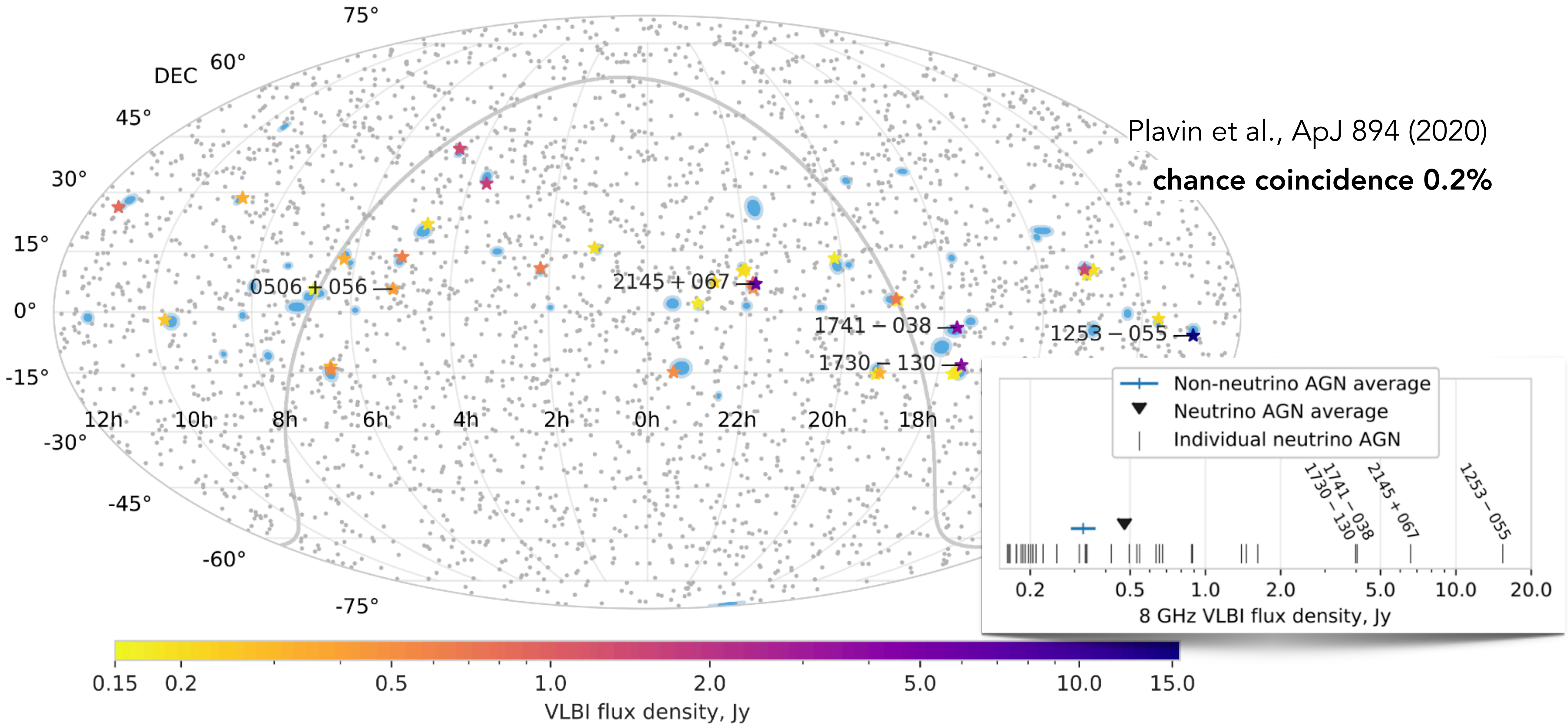


Blazars in enhanced radio emission

Two of the highest energy IceCube events found during bright radio flares of Blazars (TXS 0506+056, PKS 1502+106). A study of the correlations of high-energy neutrinos and AGNs based with radio data suggest correlations with location of bright blazar and neutrino emission during radio enhanced emission.

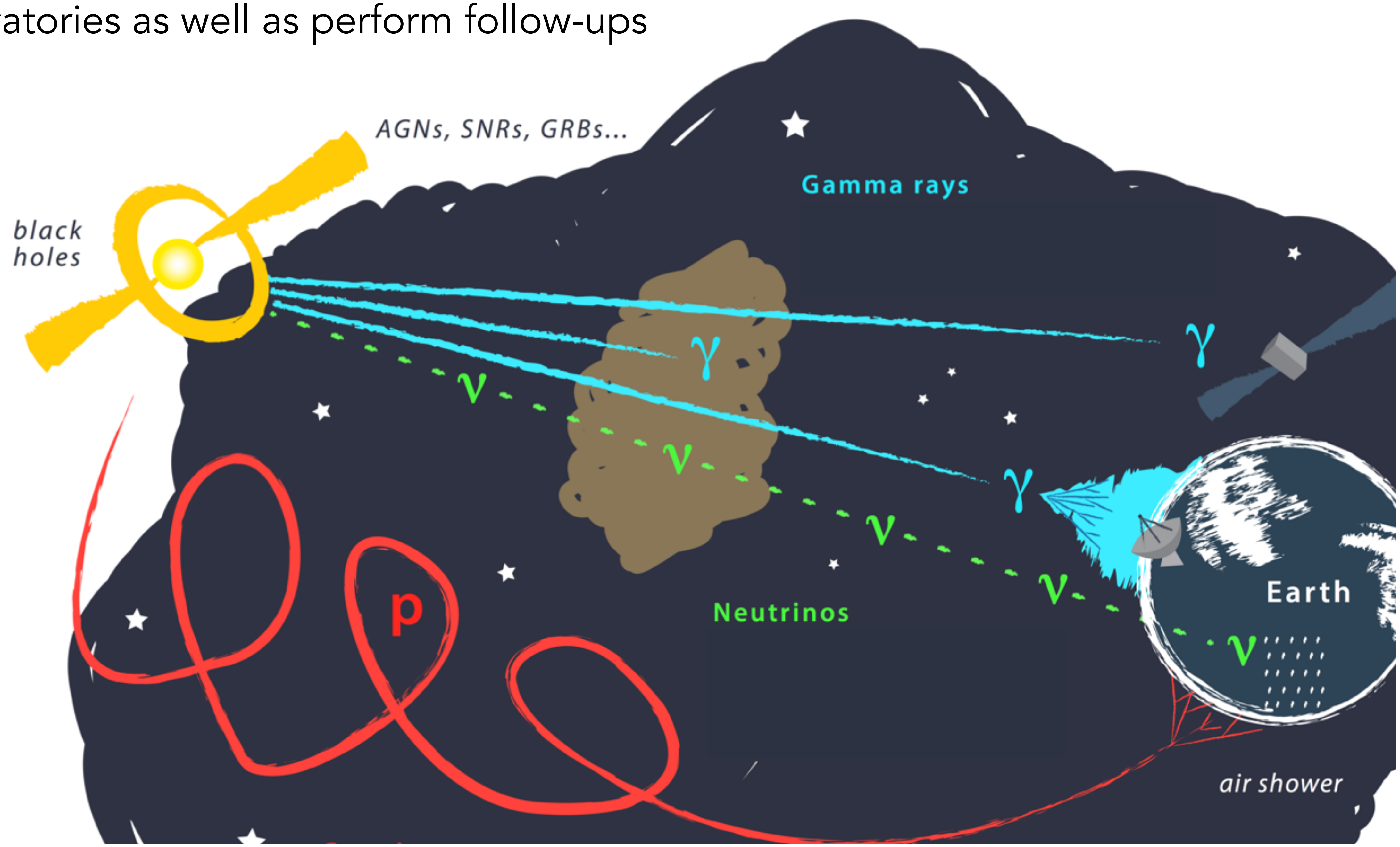
Plavin et al., ApJ 894 (2020)

chance coincidence 0.2%



Realtime Neutrino Astronomy

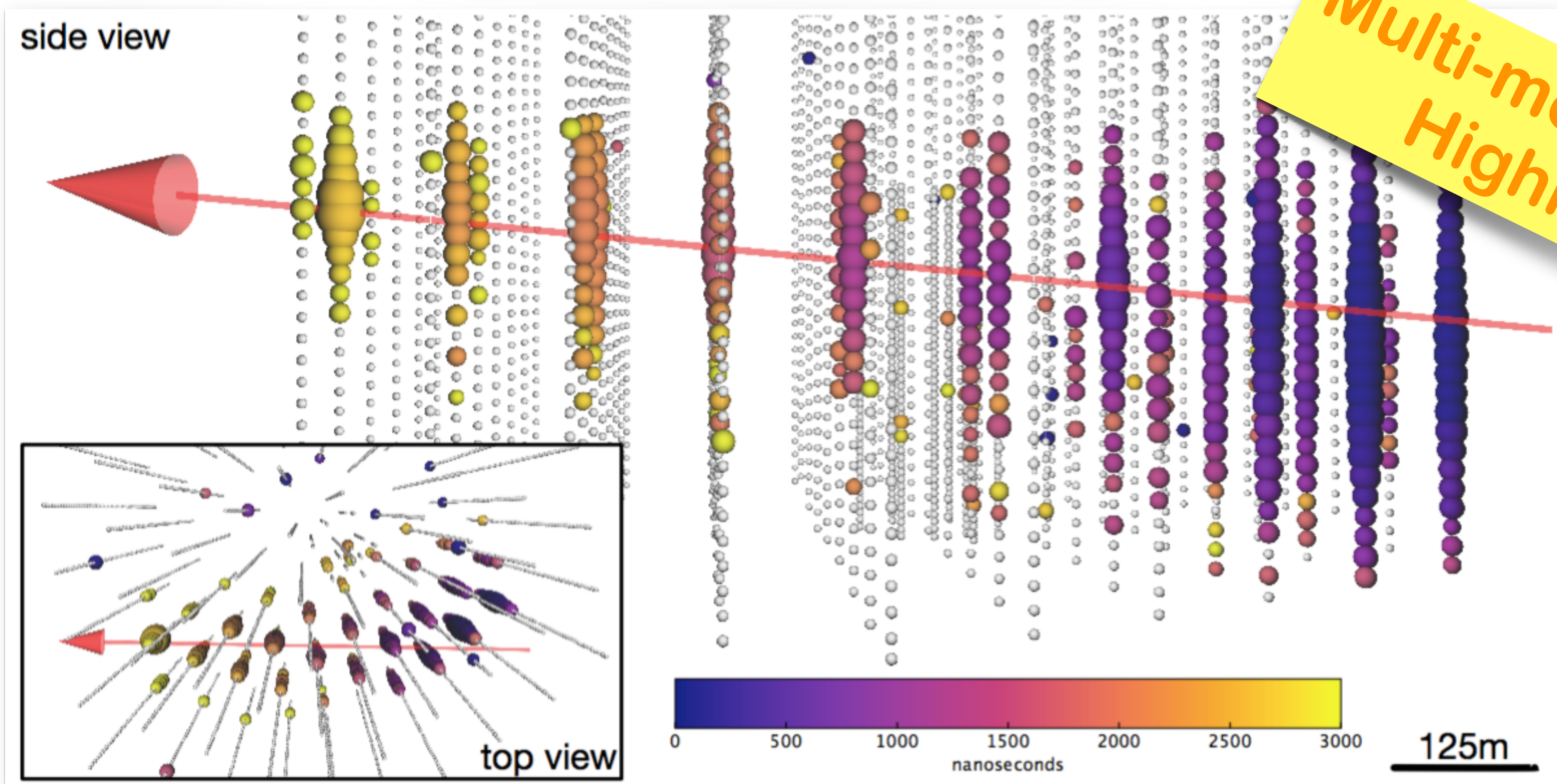
IceCube's nearly 100% uptime and continuous 4π steradian field of view make it an ideal observatory for multi-messenger programs, both to trigger other observatories as well as perform follow-ups



IceCube-170922A

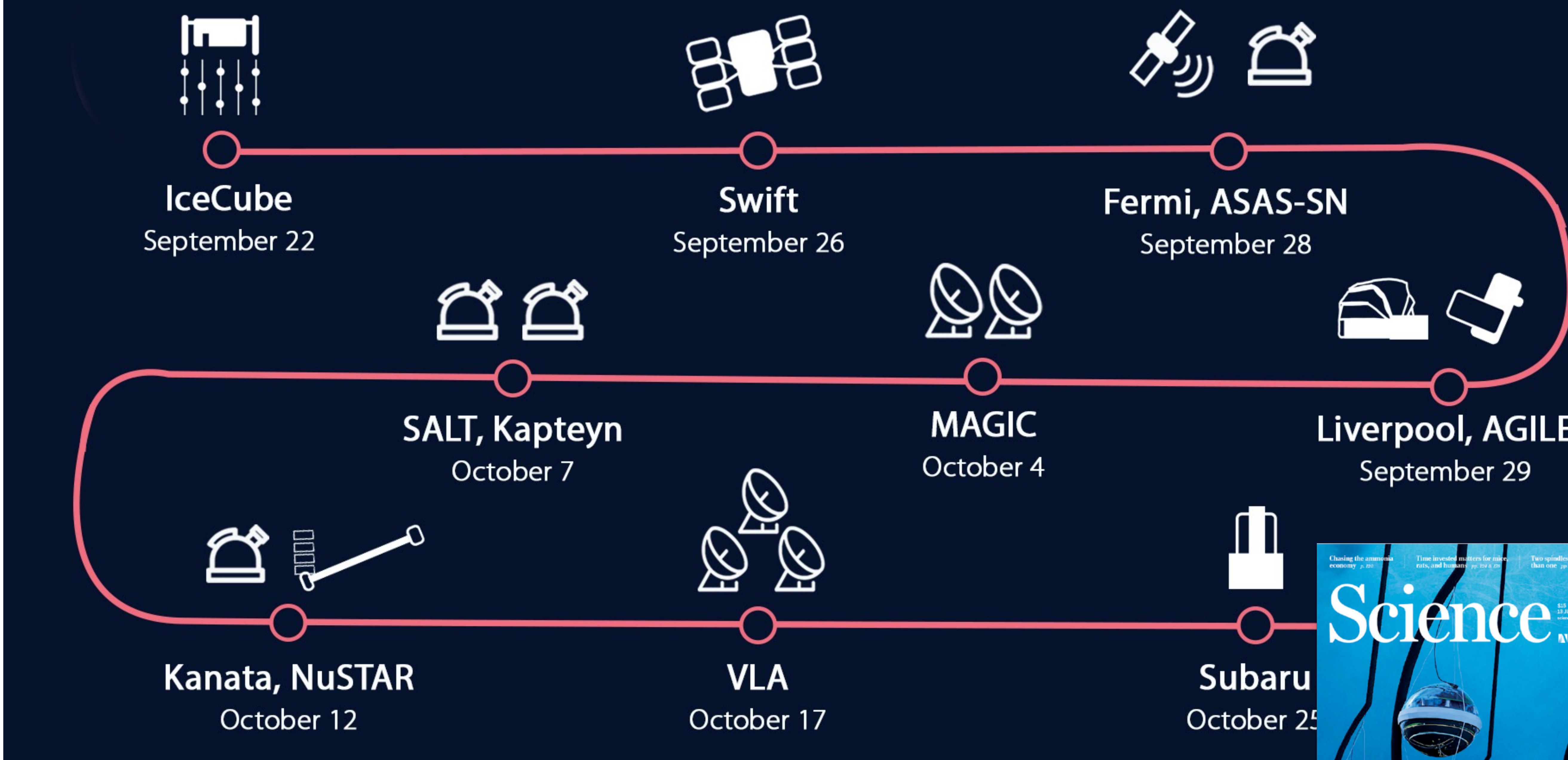
Compelling evidence for neutrino emission from the **Blazar TXS 0506+056.** Identification of a cosmic hadron accelerator with >PeV energies!

Multi-messenger Highlight



- Publicly distributed 43 seconds after trigger, refined direction 4 hr later
- Most probable energy between 250 and 300 TeV and probability of astrophysical origin 56.6%

Follow-up detections of IC170922 based on public telegrams

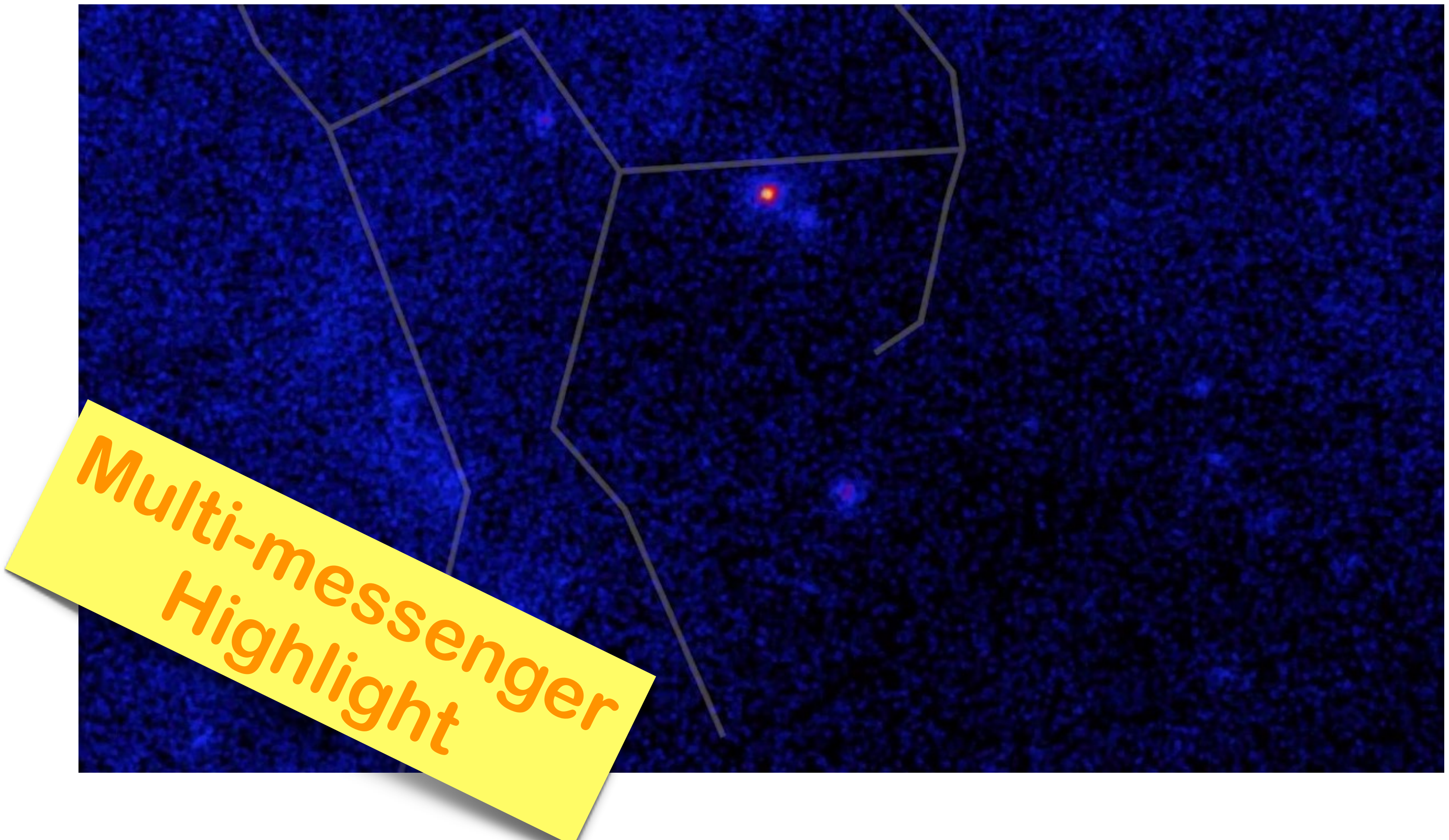


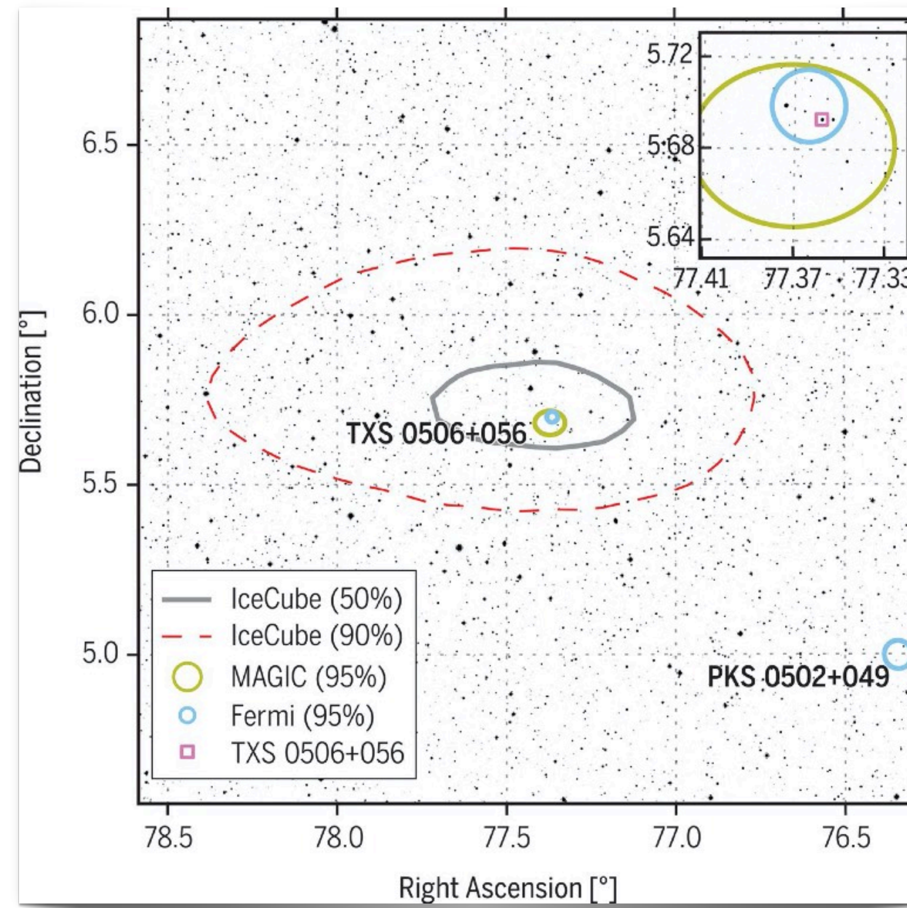
~1000 astronomers / 18 observatories!

(~3000 astronomers / 70 observatories was for GW170817)

IceCube-170922A

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

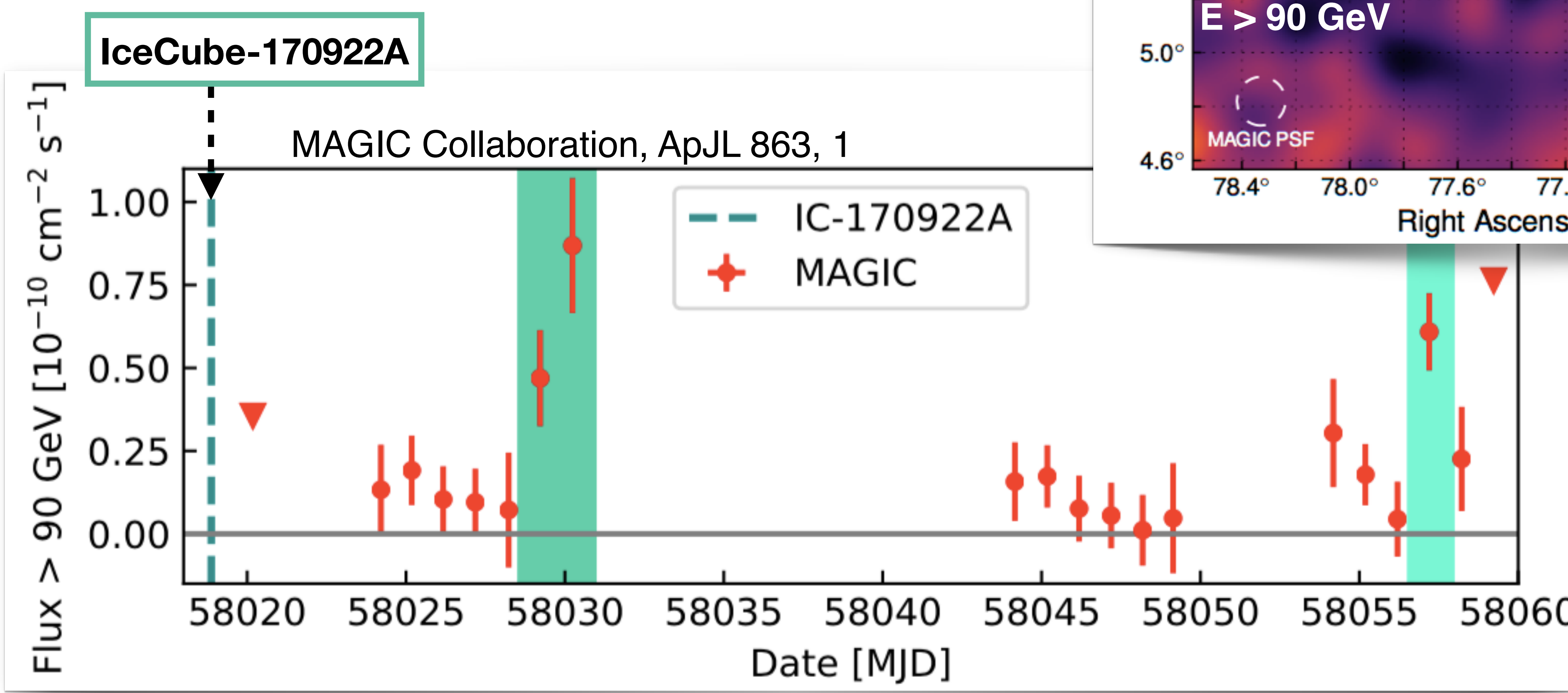


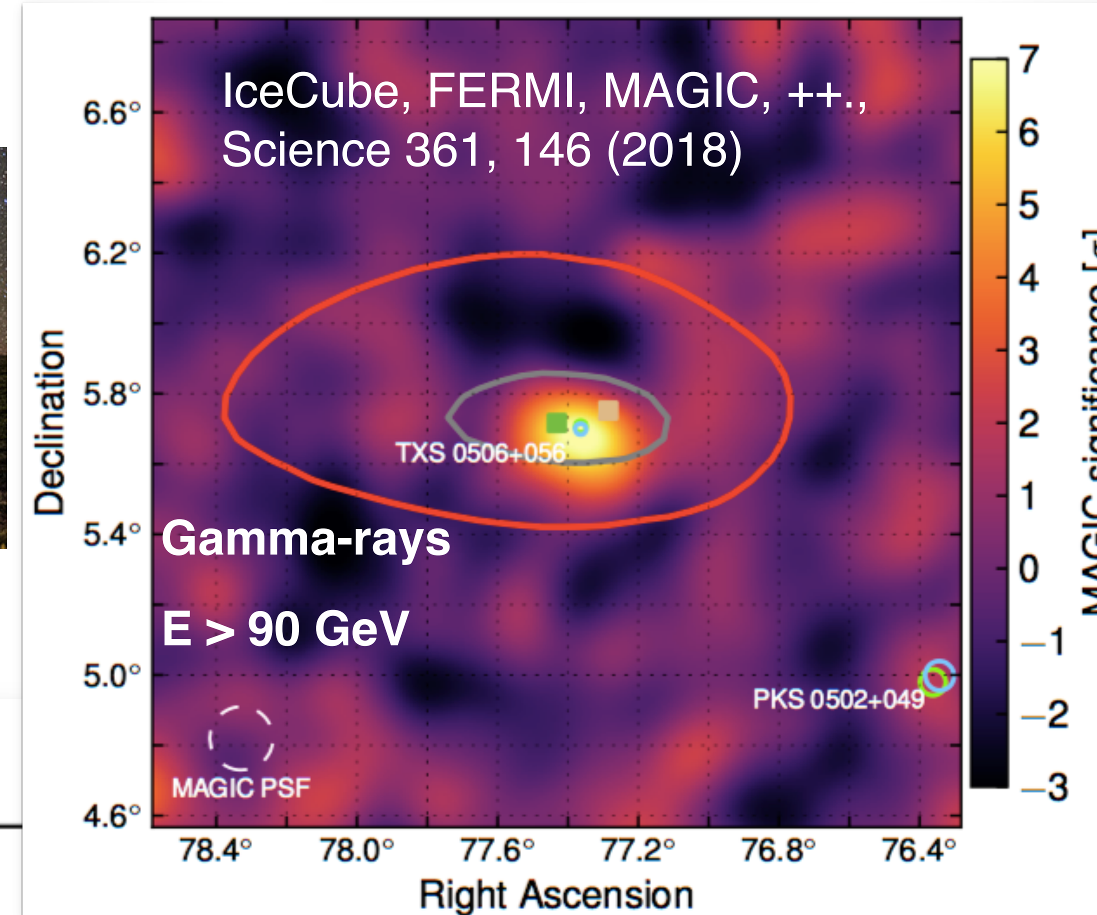


- At 6 arc-minutes from the direction of the Blazar TXS 0506+056
- Source was found in active emission state in gamma-rays
- Accidental correlation ruled out at 3σ.

Very high energy gamma-rays from TXS 0506+056

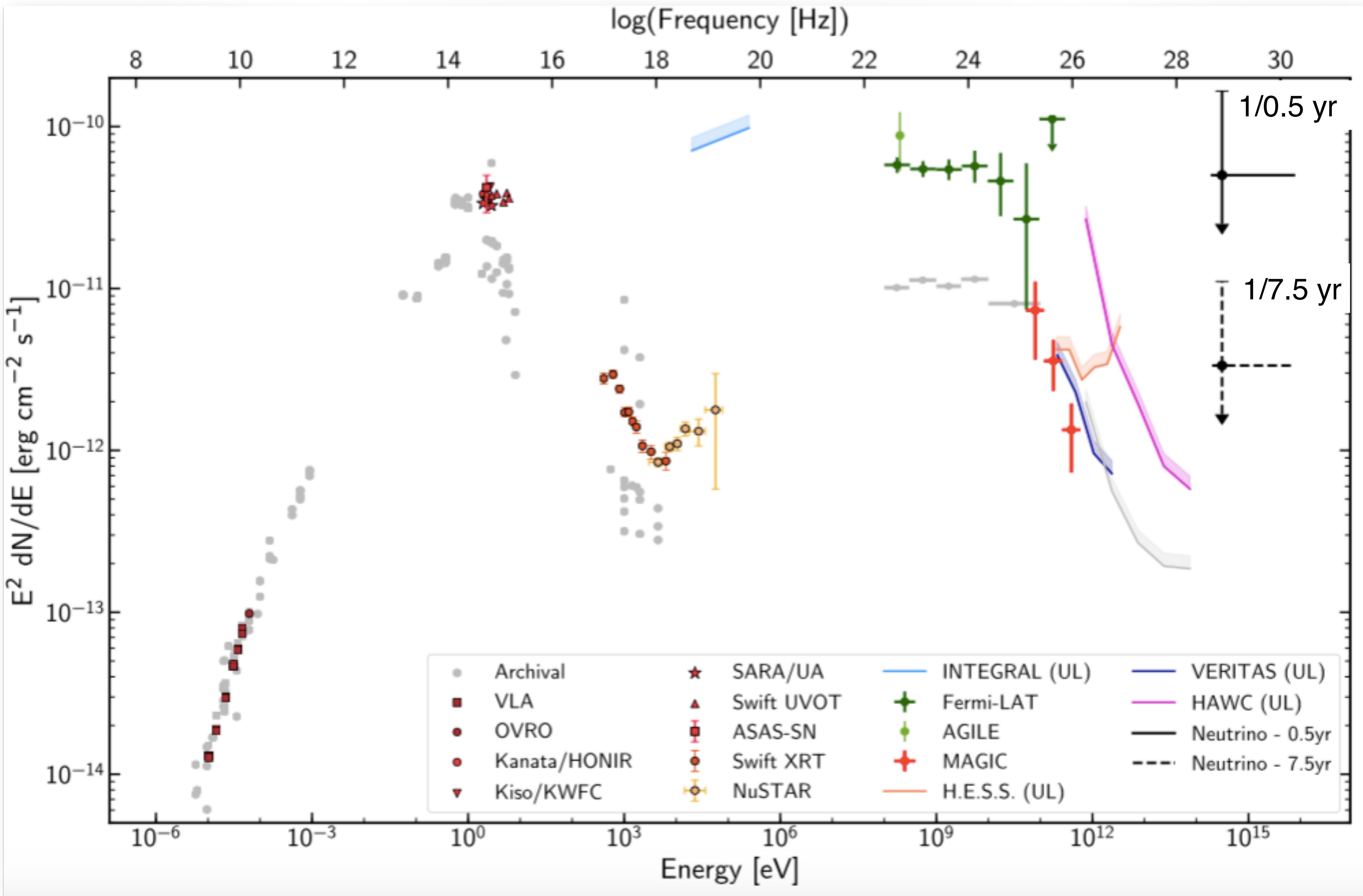
MAGIC detected ɣ-rays with energies up to about 400 GeV with strong day-to-day variations





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*

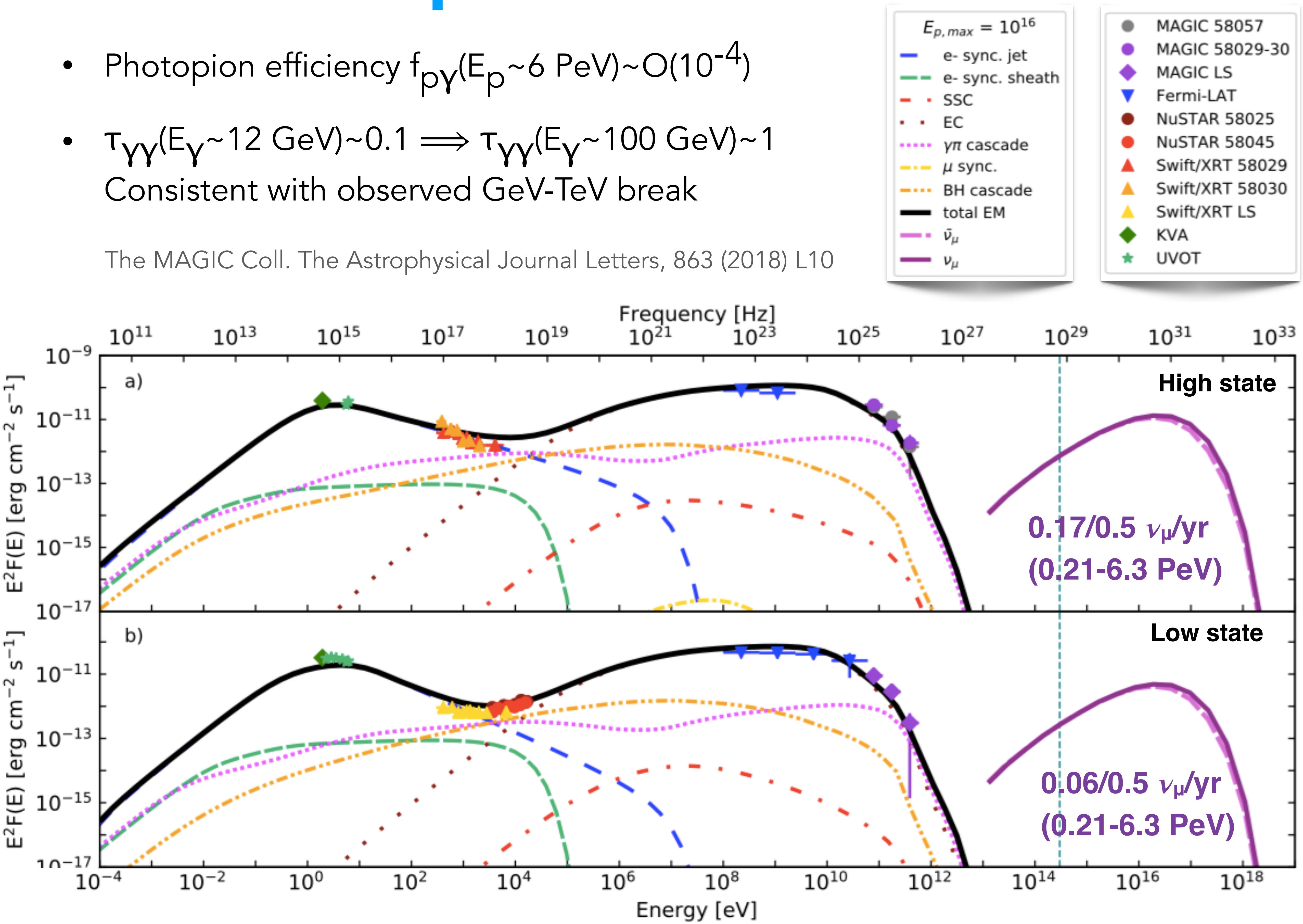
Ruo-Yu Liu, Kai Wang, Rui Xue, Andrew M. Taylor, Xiang-Yu Wang, Zhuo Li, and Huirong Yan. Hadronuclear interpretation of a high-energy neutrino event coincident with a blazar flare. *Phys.*

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

An example from MM models

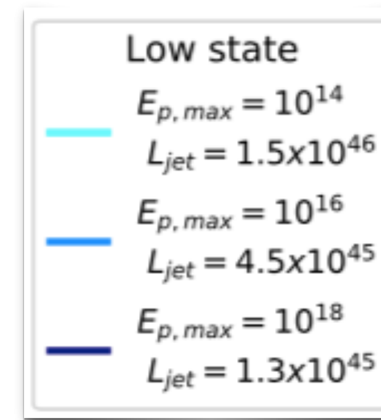
- Photopion efficiency $f_{p\gamma}(E_p \sim 6\ \mathrm{PeV}) \sim O(10^{-4})$
- $\tau_{\gamma\gamma}(E_\gamma \sim 12\ \mathrm{GeV}) \sim 0.1 \Longrightarrow \tau_{\gamma\gamma}(E_\gamma \sim 100\ \mathrm{GeV}) \sim 1$
  Consistent with observed GeV-TeV break

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

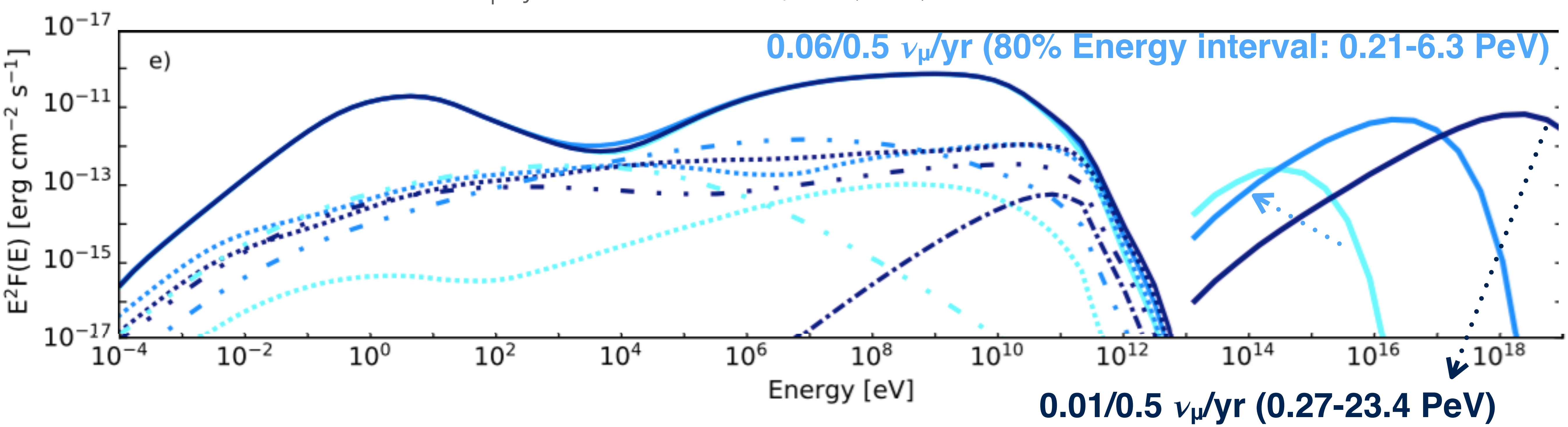


An example from MM models

- 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

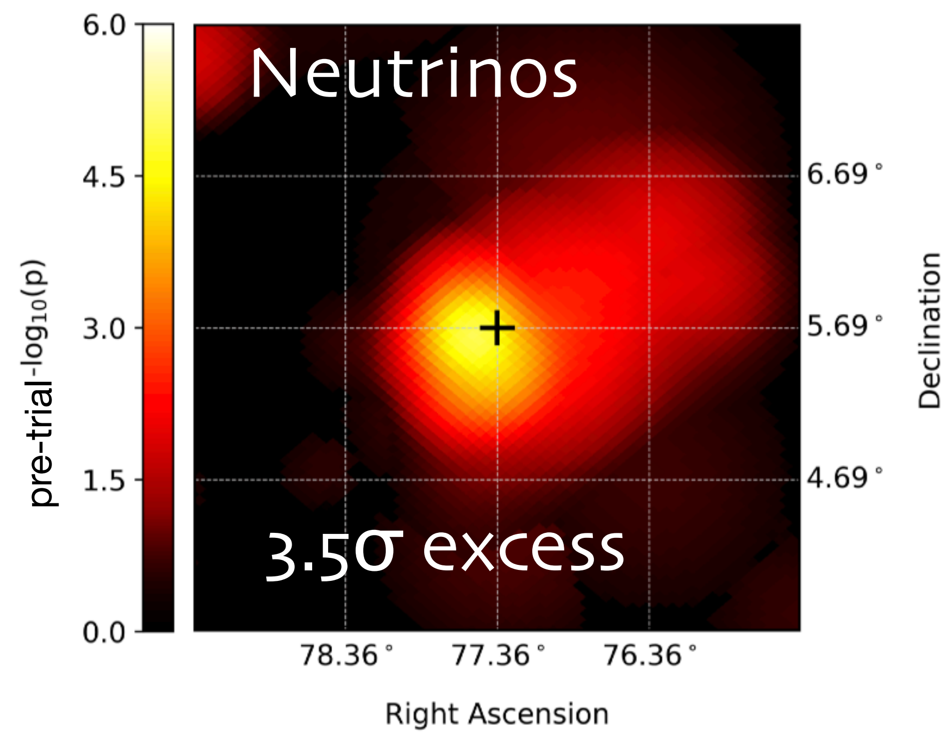


The MAGIC Coll. The Astrophysical Journal Letters, 863 (2018) L10



IceCube archival data on TXS 0506+056

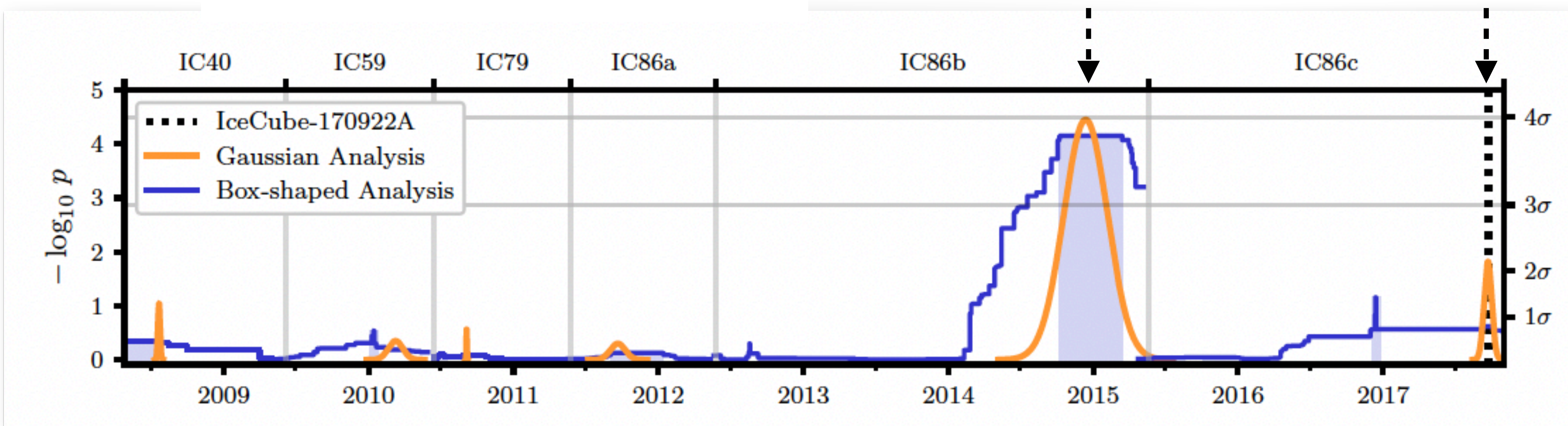
The observation of an excess of neutrino events in ~5 months (2014-2015) together with IceCube-170922A provides a strong evidence against the background hypothesis



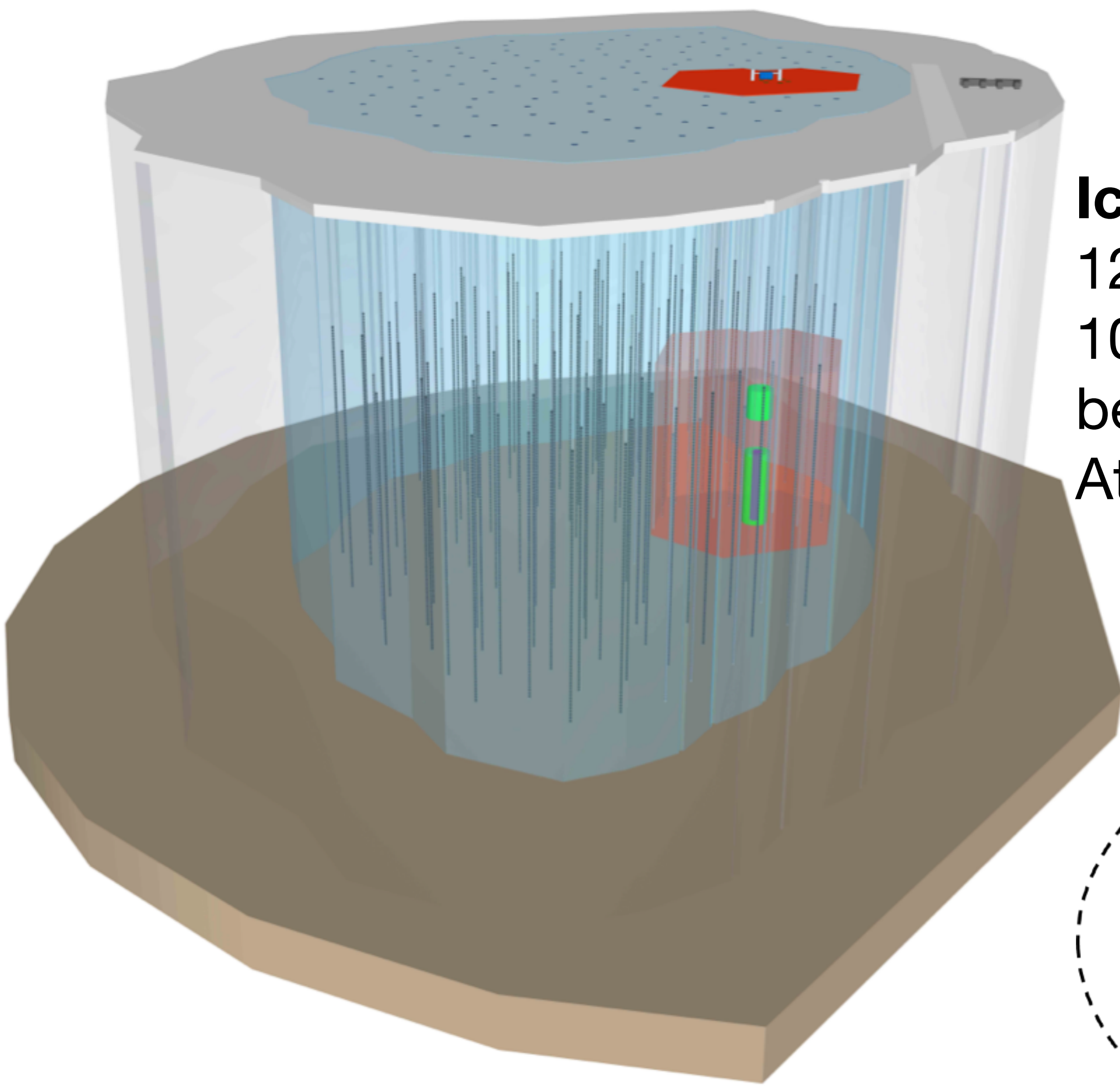
IceCube Coll. Science 361, eaat1378 (2018)

Spectral index ~2

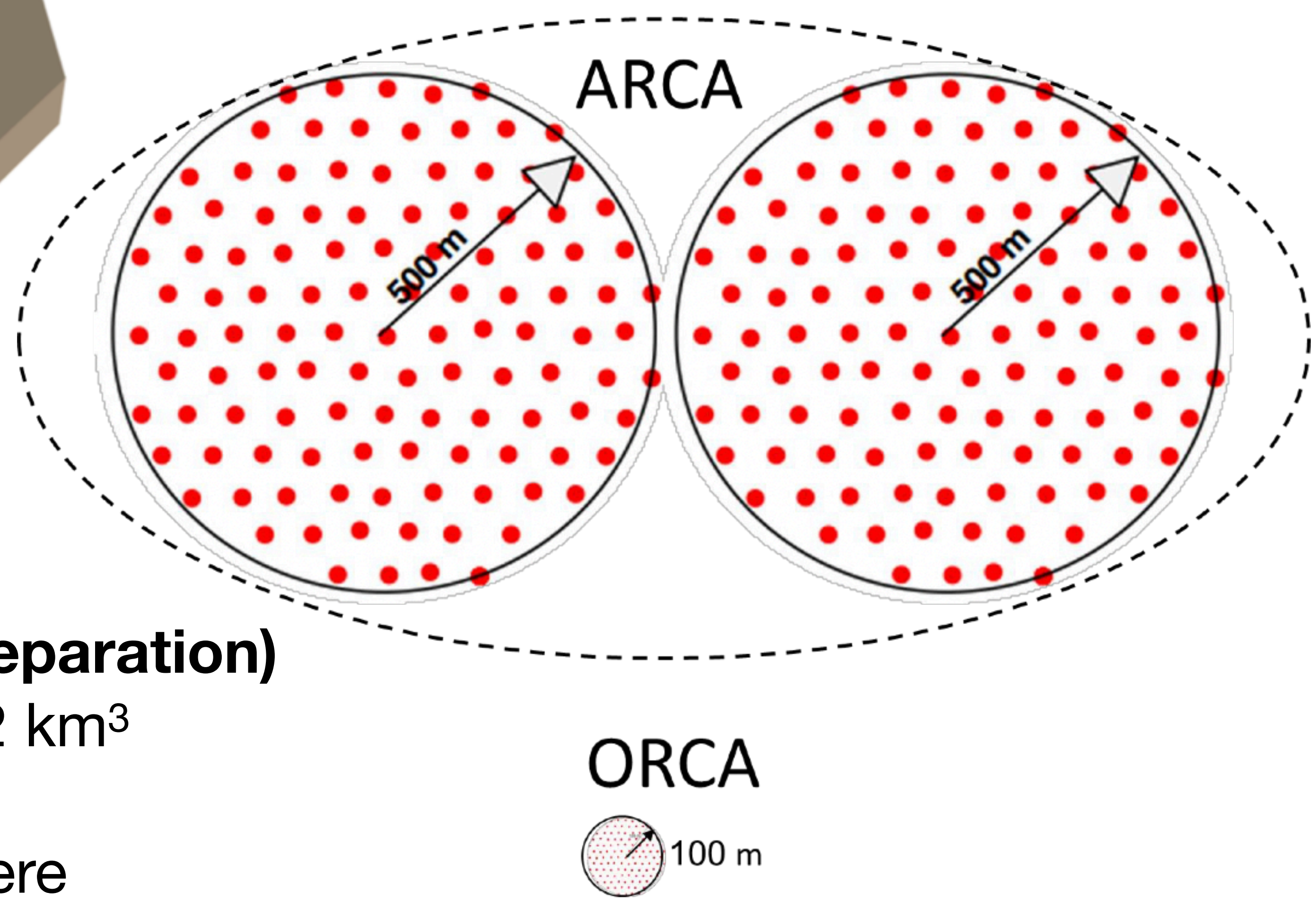
Spectral index ~1.7



Future



IceCube-Gen 2 (in preparation)
120 strings with 80 DOM/string, 1.35 to 2.7 km deep
10 times the instrumented volume of IceCube
better angular resolution
At the South Pole



KM3NeT Phase 2 (in preparation)
2 x 115 ARCA strings 1.2 km^3
1 x 115 ORCA strings
In the Northern hemisphere

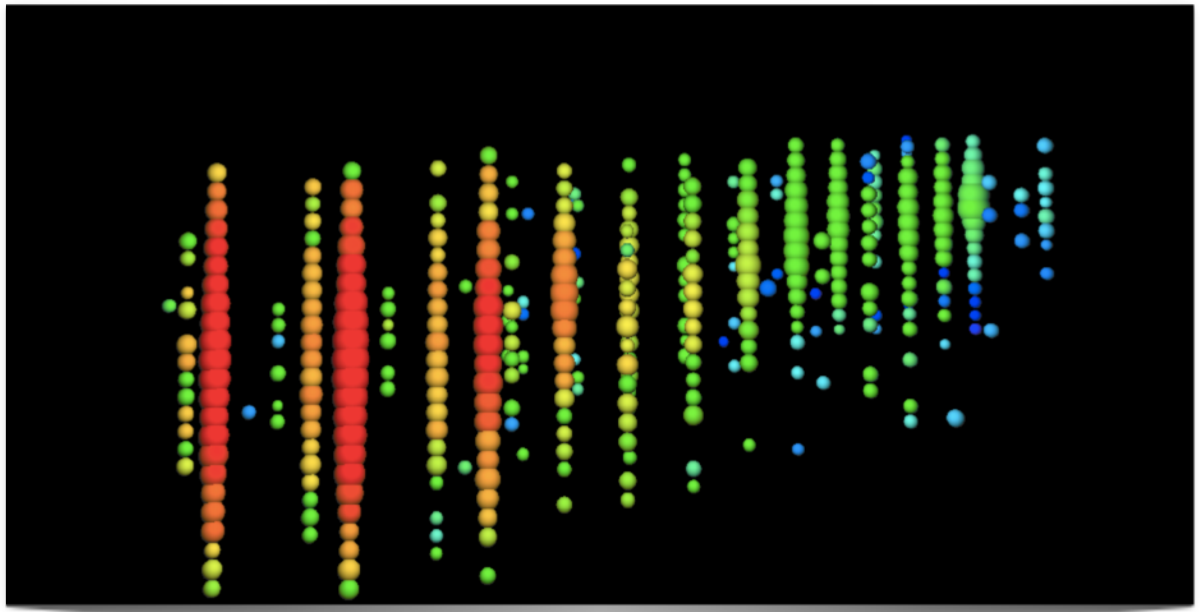
In Summary

- High Energy Neutrinos **opened a new window onto the Universe**:
  - Diffuse cosmic neutrinos: a well established signal
  - Compelling evidence for the first non-stellar neutrino source: a Blazar
- **Multi-messenger studies are essential for the identification of sources**
- Better understanding of the potential sources and relevant data can help the way to new breakthroughs
- Looking forward to upcoming ten times more sensitive instruments!

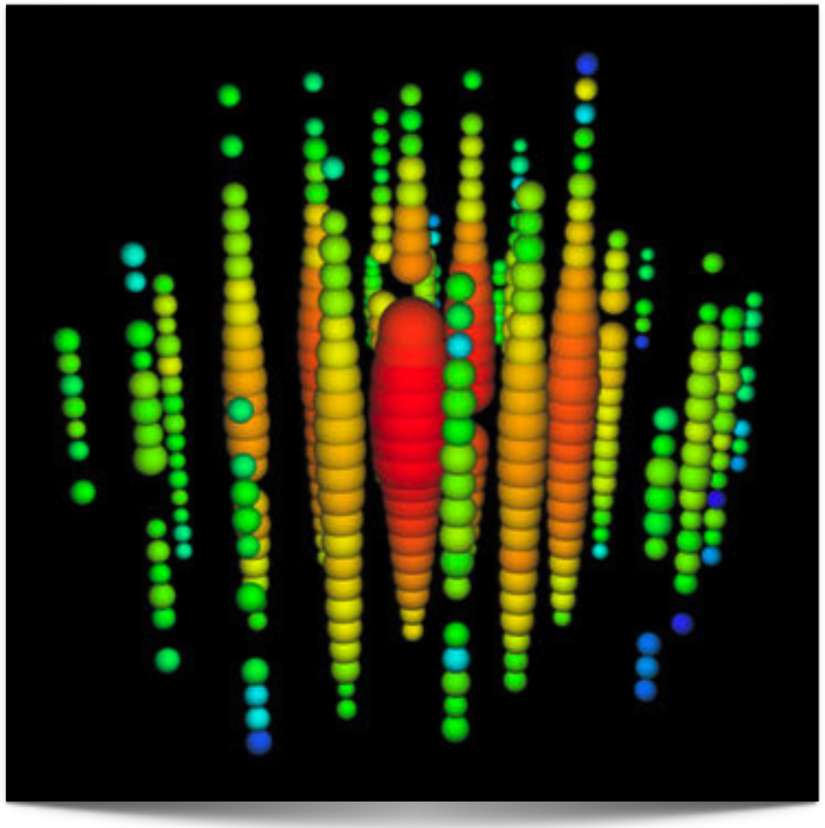
Back-up

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)



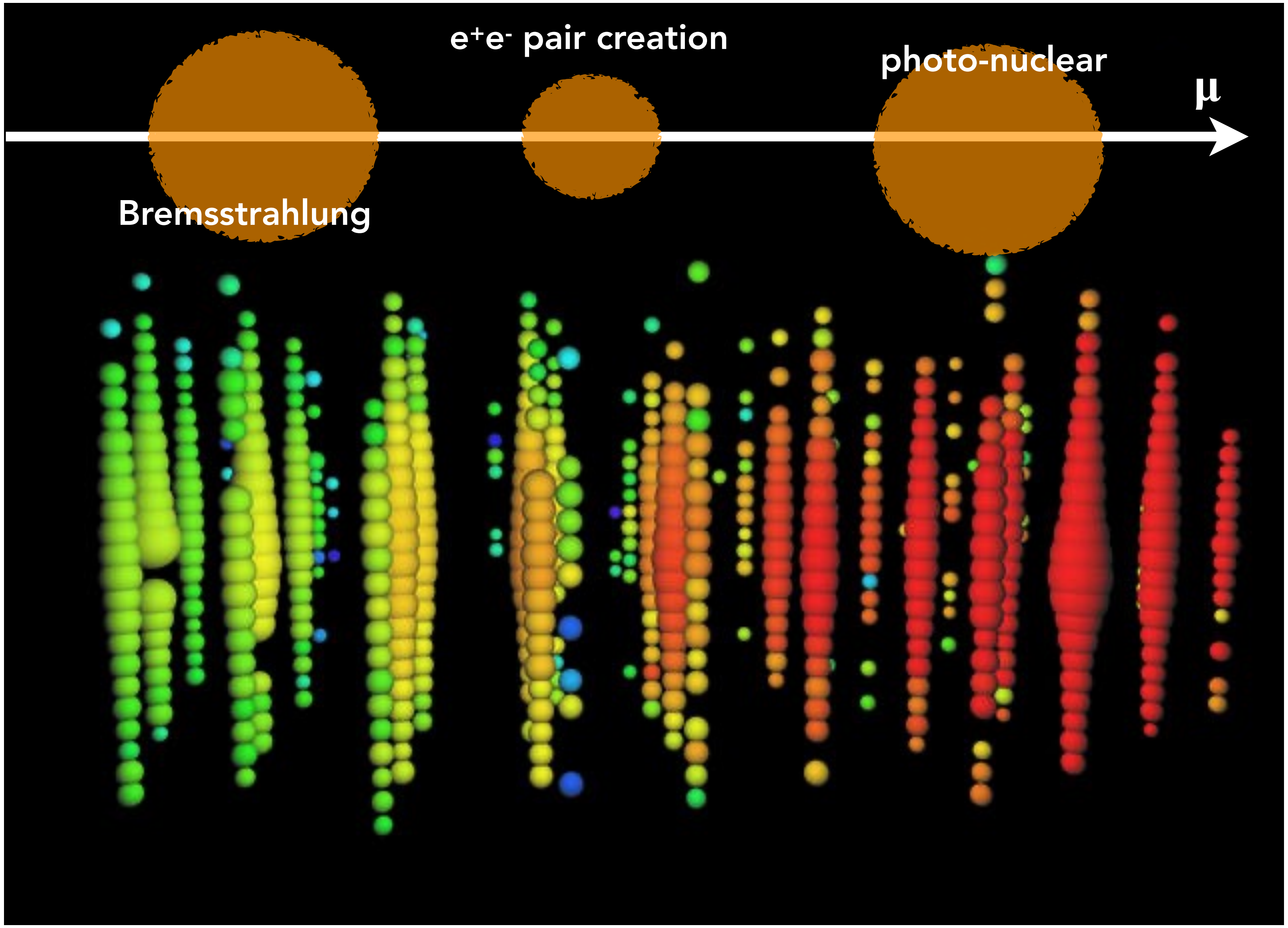
Muon tracks
angular resolution **0.5**° @ 10 TeV (0.3° @ 100 TeV)



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

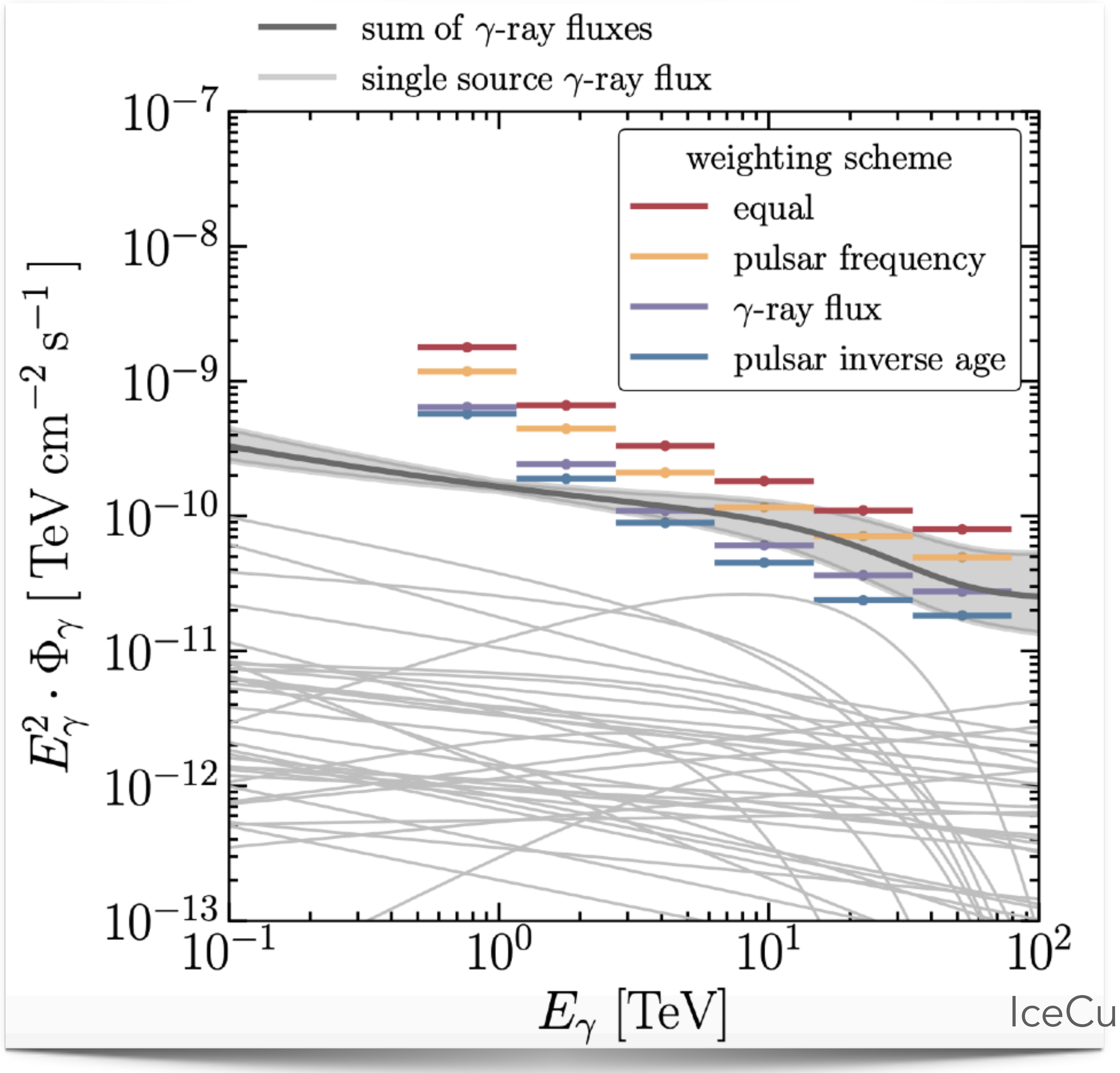
Measuring the Energy

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.



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

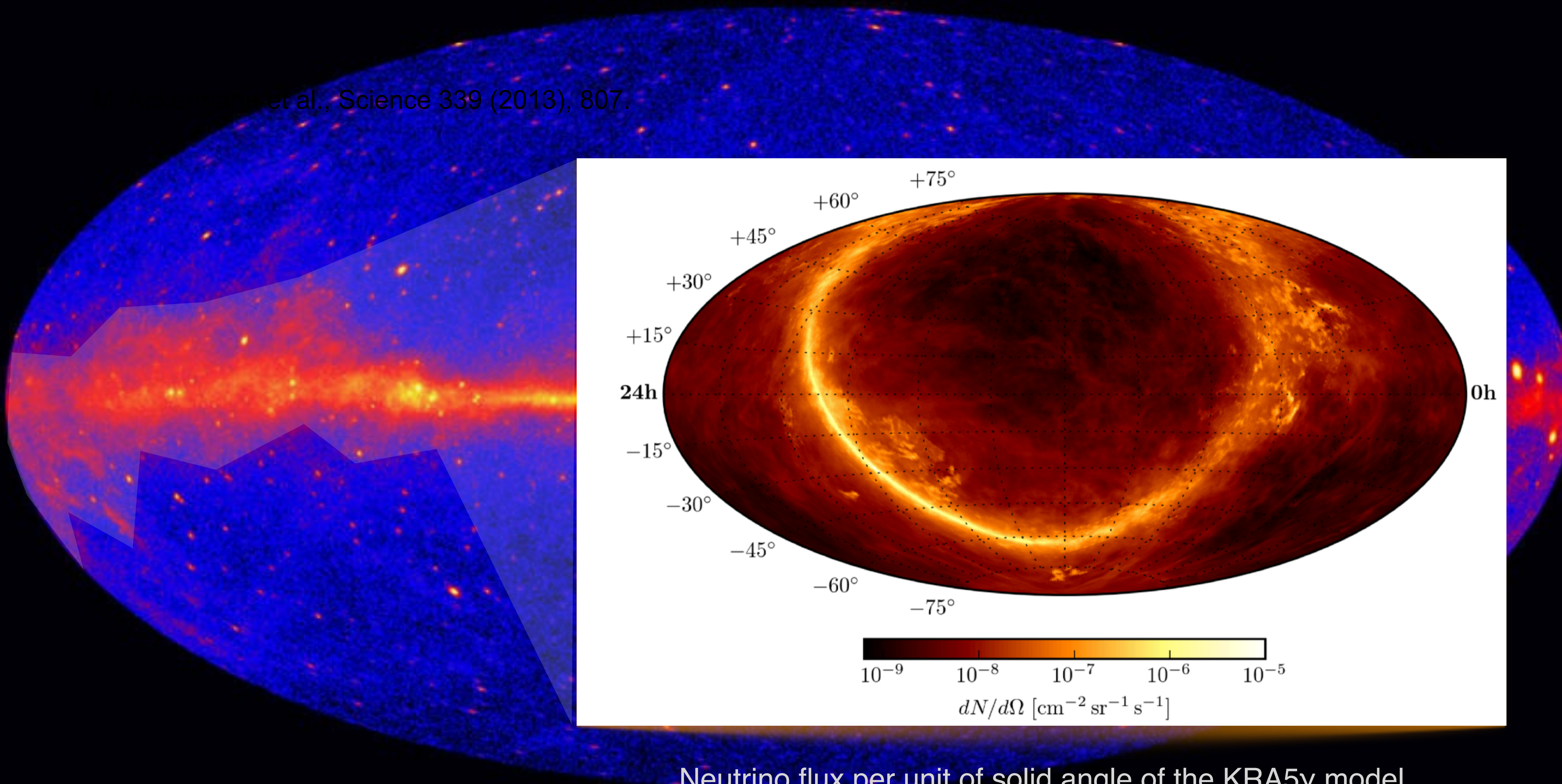


PWNe can be strong neutrino emitters if the neutrino flux is correlated with the gamma-ray flux or if correlated with the pulsar's age

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

Galactic Cosmic Rays

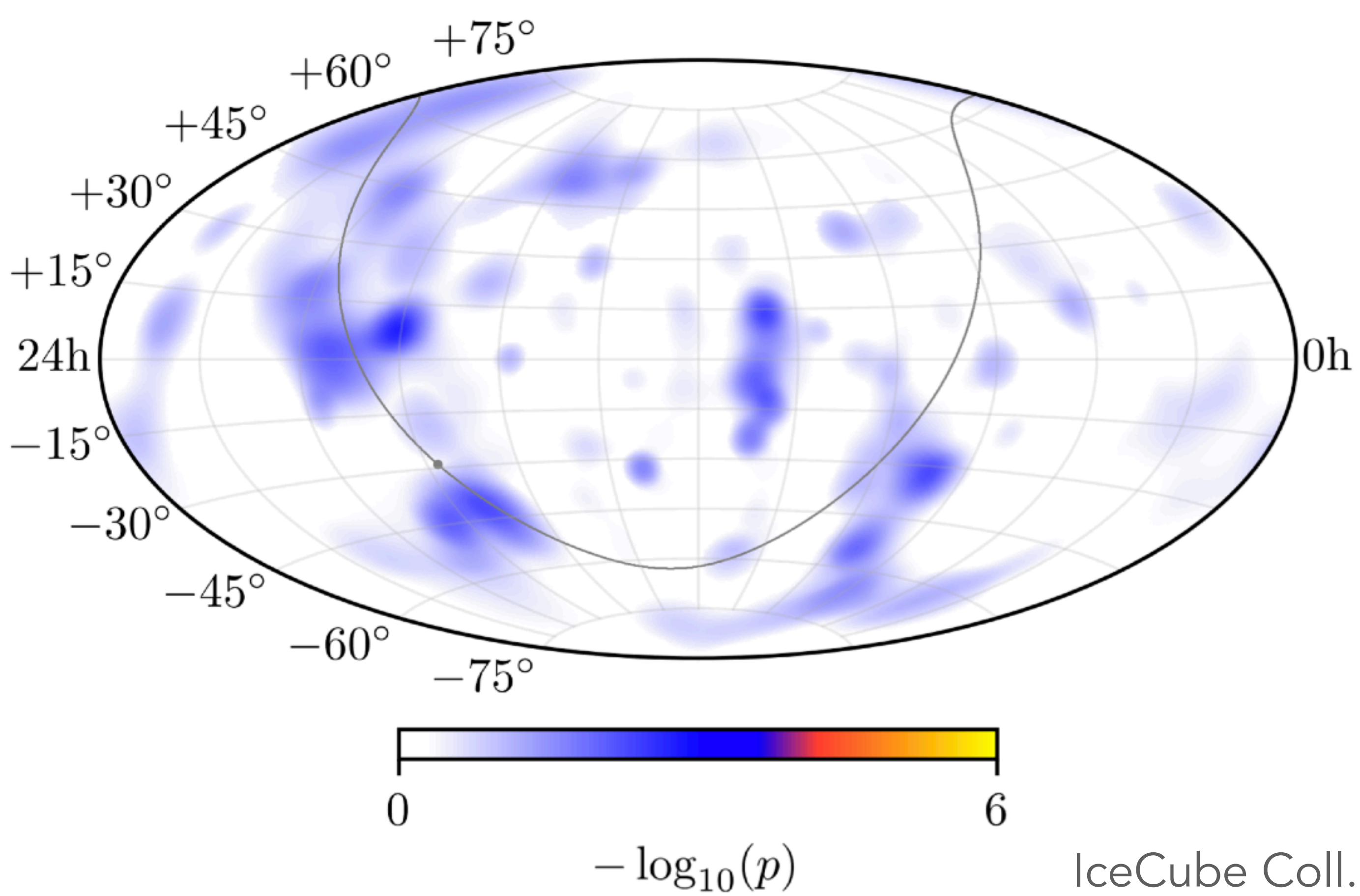
Cosmic rays interact with interstellar gas and radiation leading to the diffuse gamma-rays **observed** by Fermi-LAT and the **predicted** diffuse neutrinos

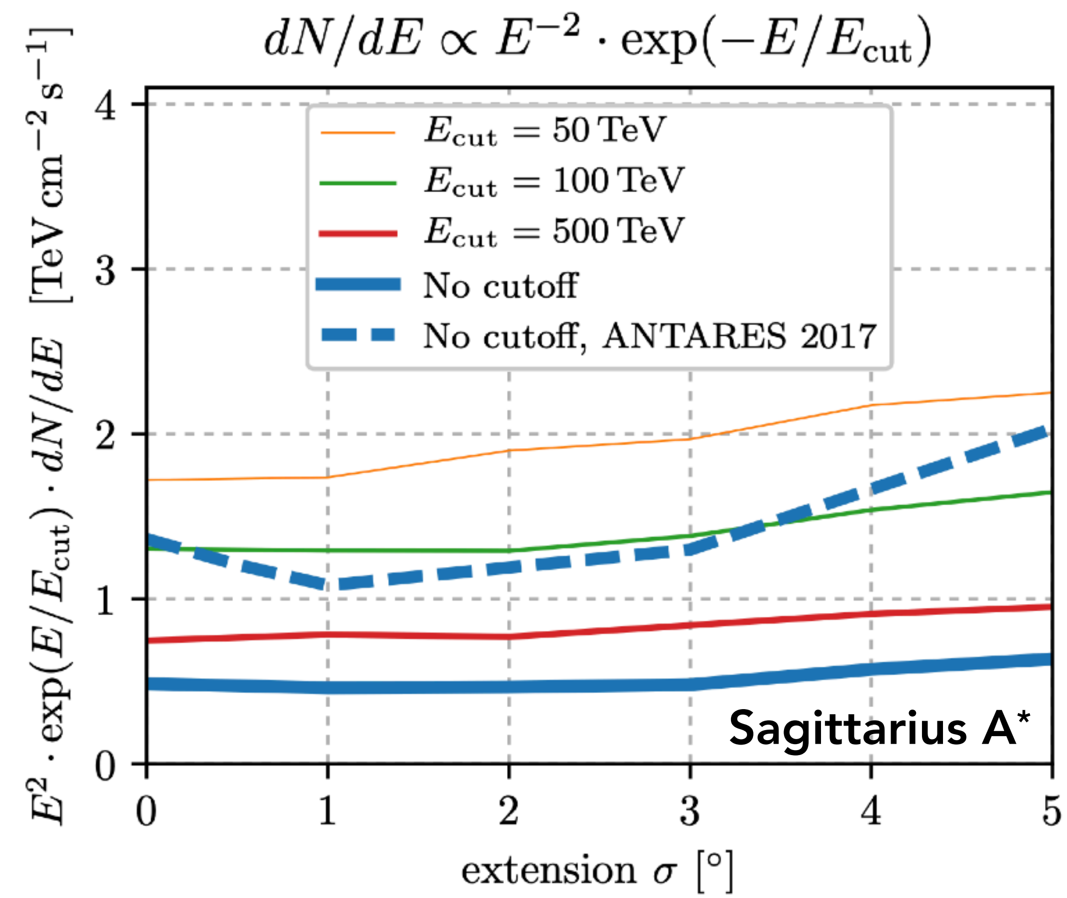


Neutrino flux per unit of solid angle of the KRA5γ model (Gaggero et al. 2015a), shown in equatorial coordinates.

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

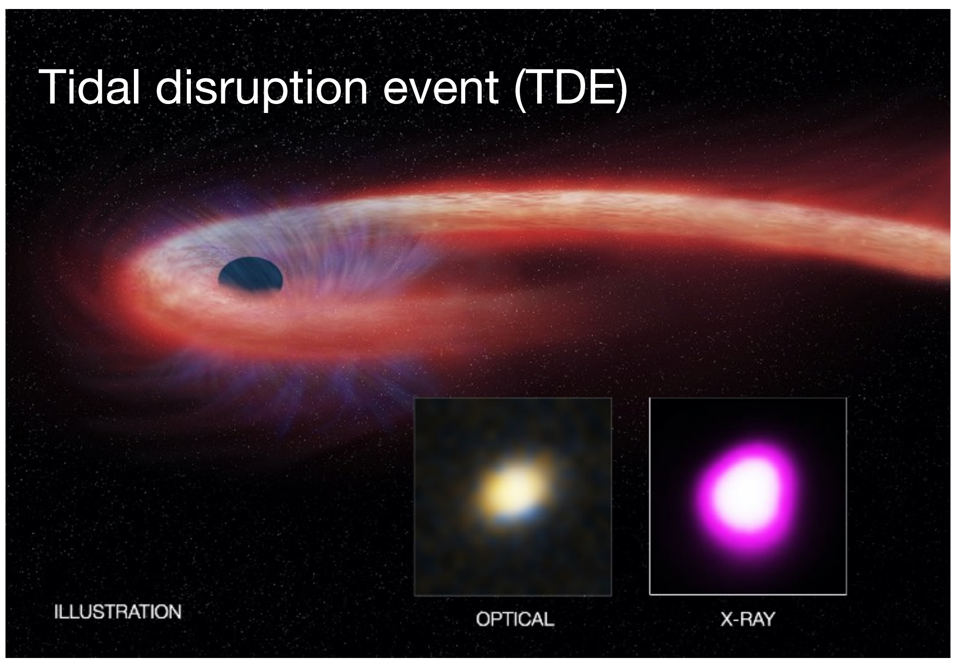




IceCube Coll. Astrophys. J. 886 (2019) 12

Tidal Disruption Events

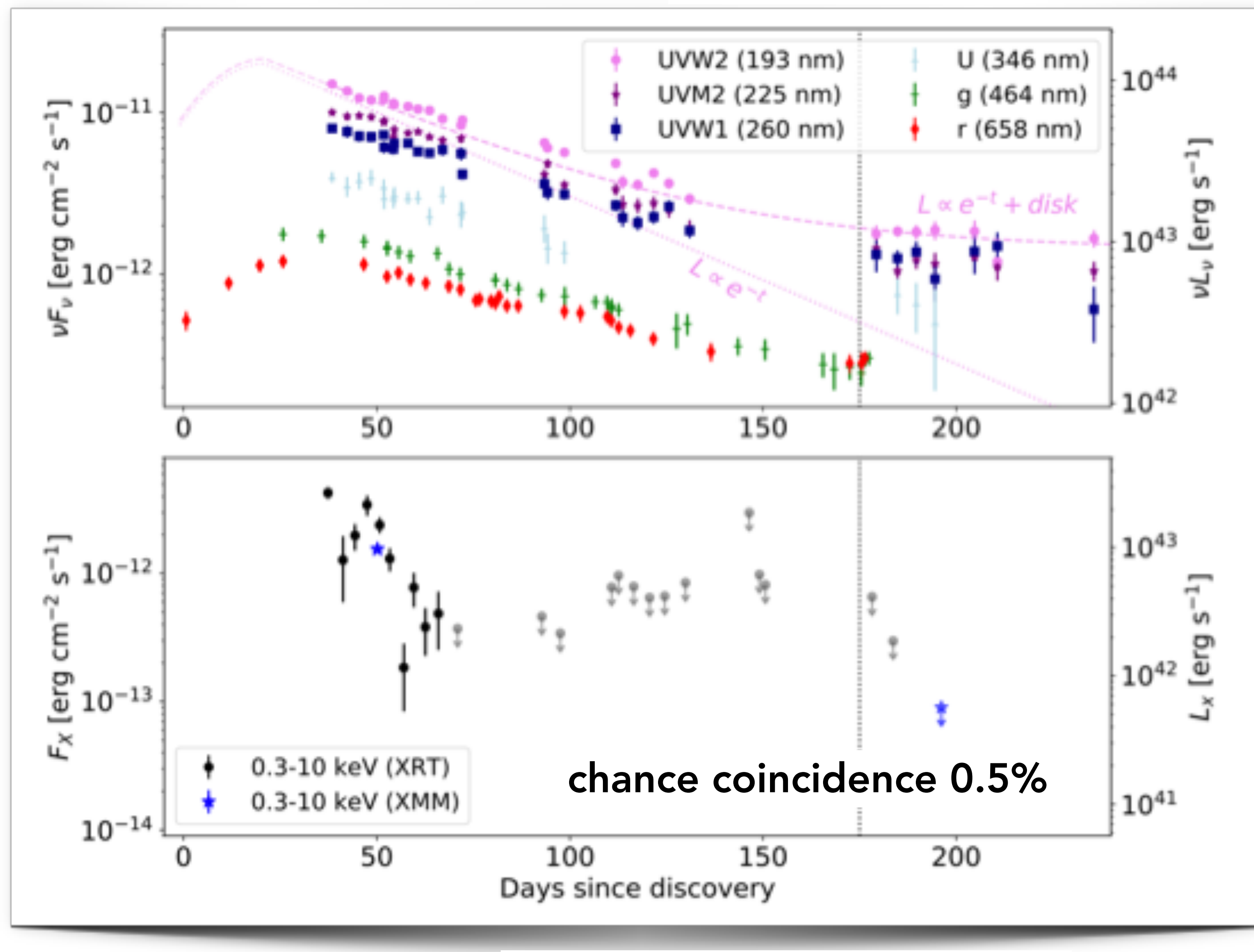
Stars torn apart by tidal forces in the vicinity of a supermassive black hole can launch jet-like outflows: tidal disruption events (TDE). Possible contribution to the total diffuse high-energy neutrino flux not conclusive yet but estimated to be sub-dominant.



e.g. Biehl, Boncioli, Lunardini & Winter 201

Murase et al Astrophys.J. 902 (2020)

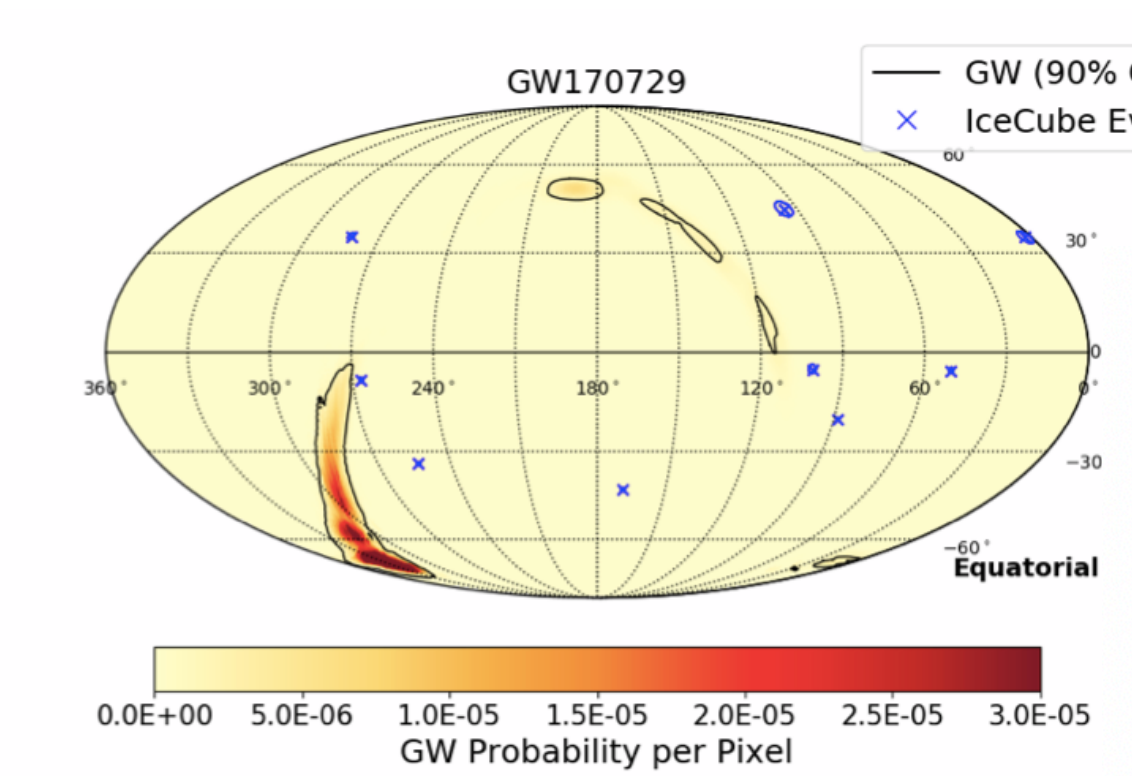
IceCube-191001A



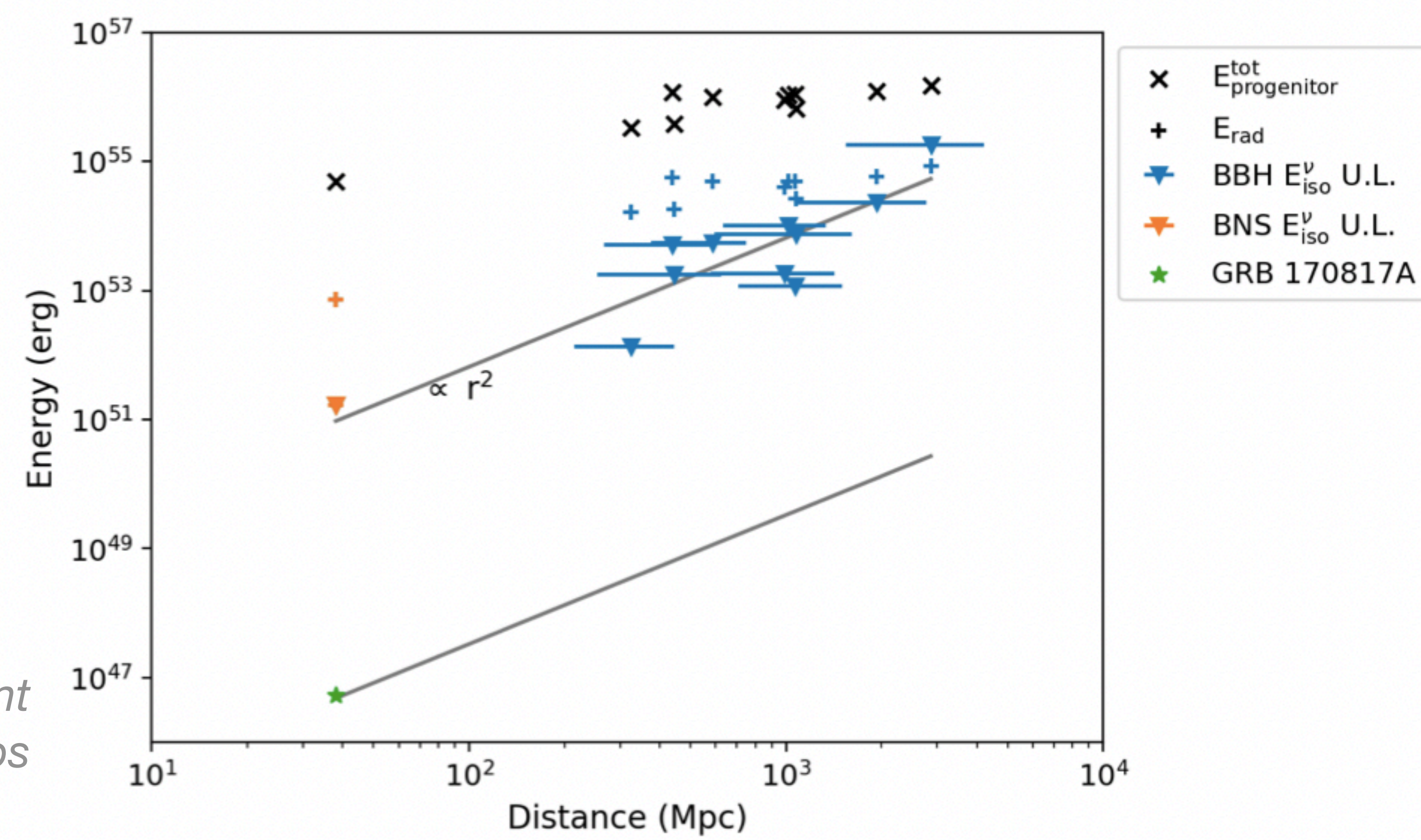
R. Stein et al. arXiv:2005.05340

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



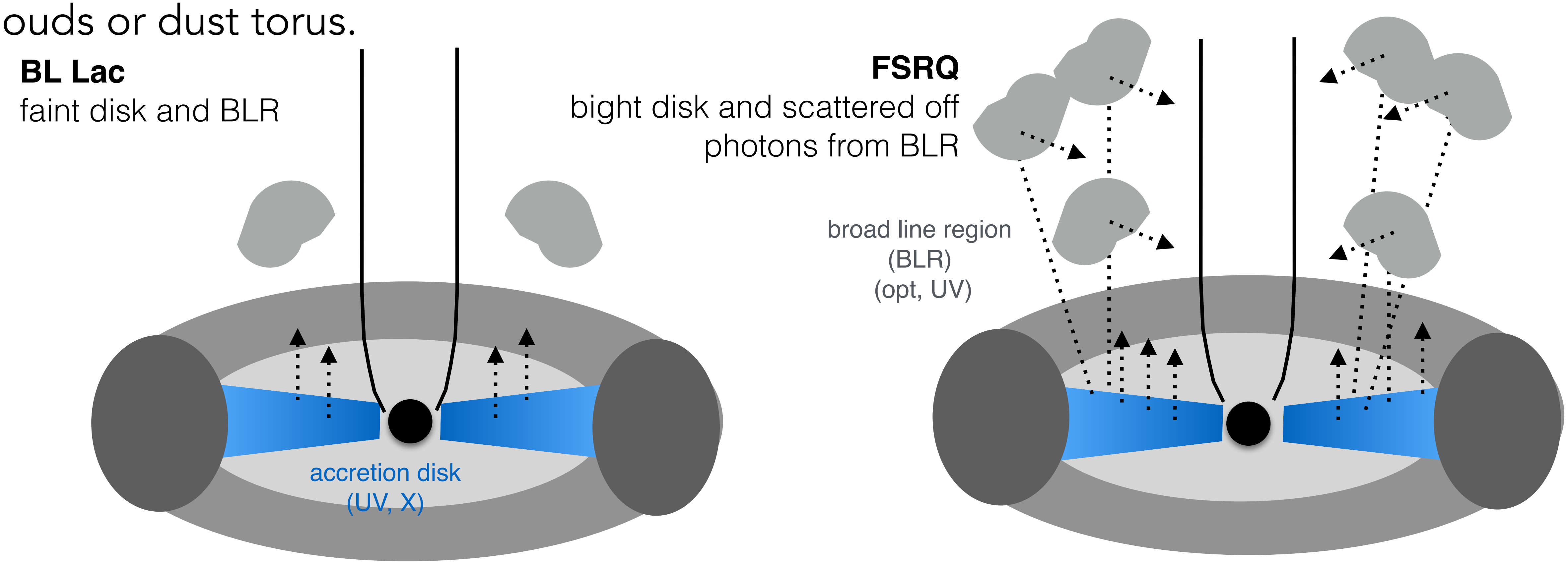
Left: *ν follow up to GW170729 (in a 1000 seconds time window)*



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

Interpreting the multi-messenger data in a nutshell

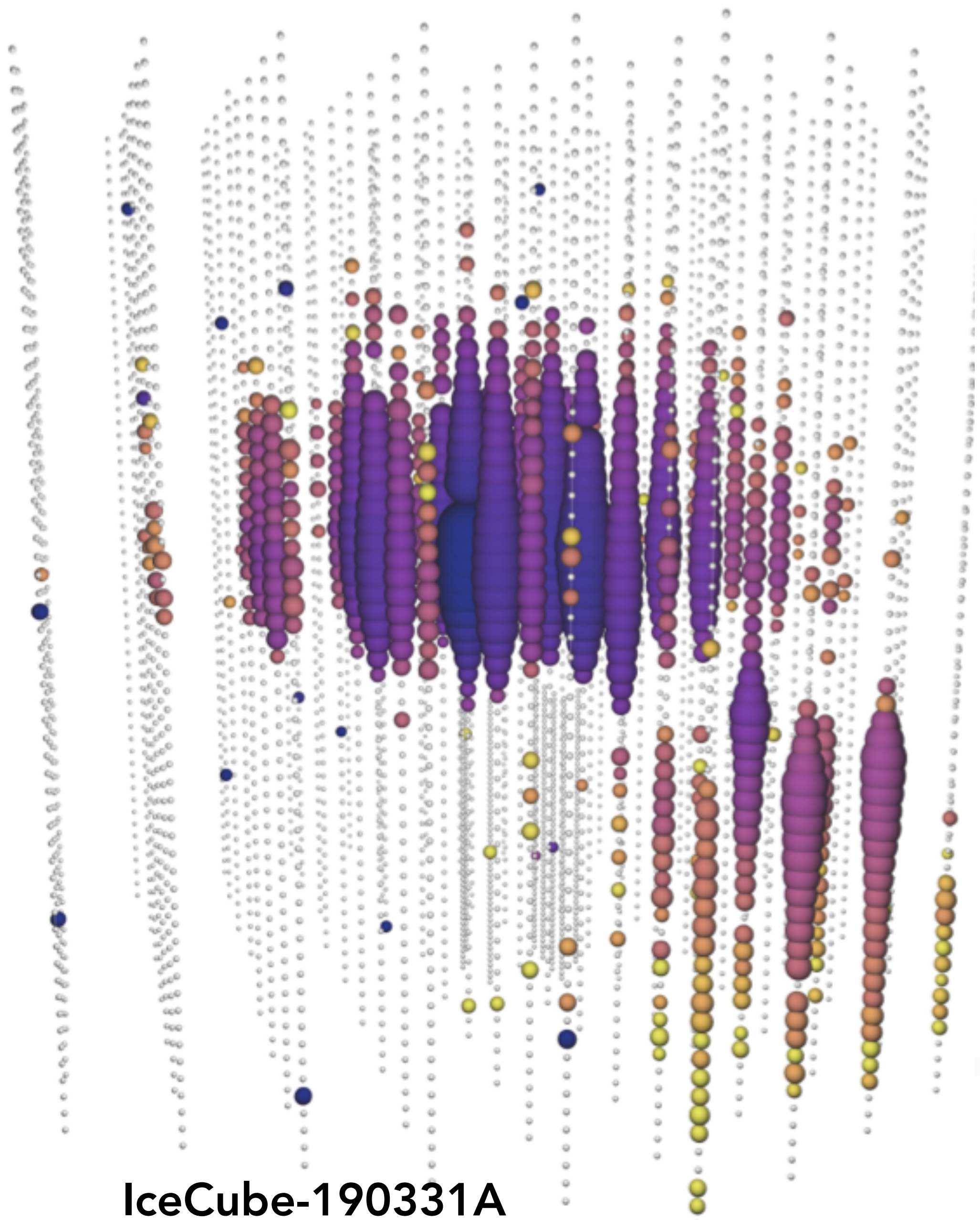
Most Blazar emission models assume that high-energy particles (electrons, protons, nuclei) are injected into the jet where they encounter target radiation (non-thermal emission by the high-energy particles, or external photons from the accretion disk, clouds or dust torus.



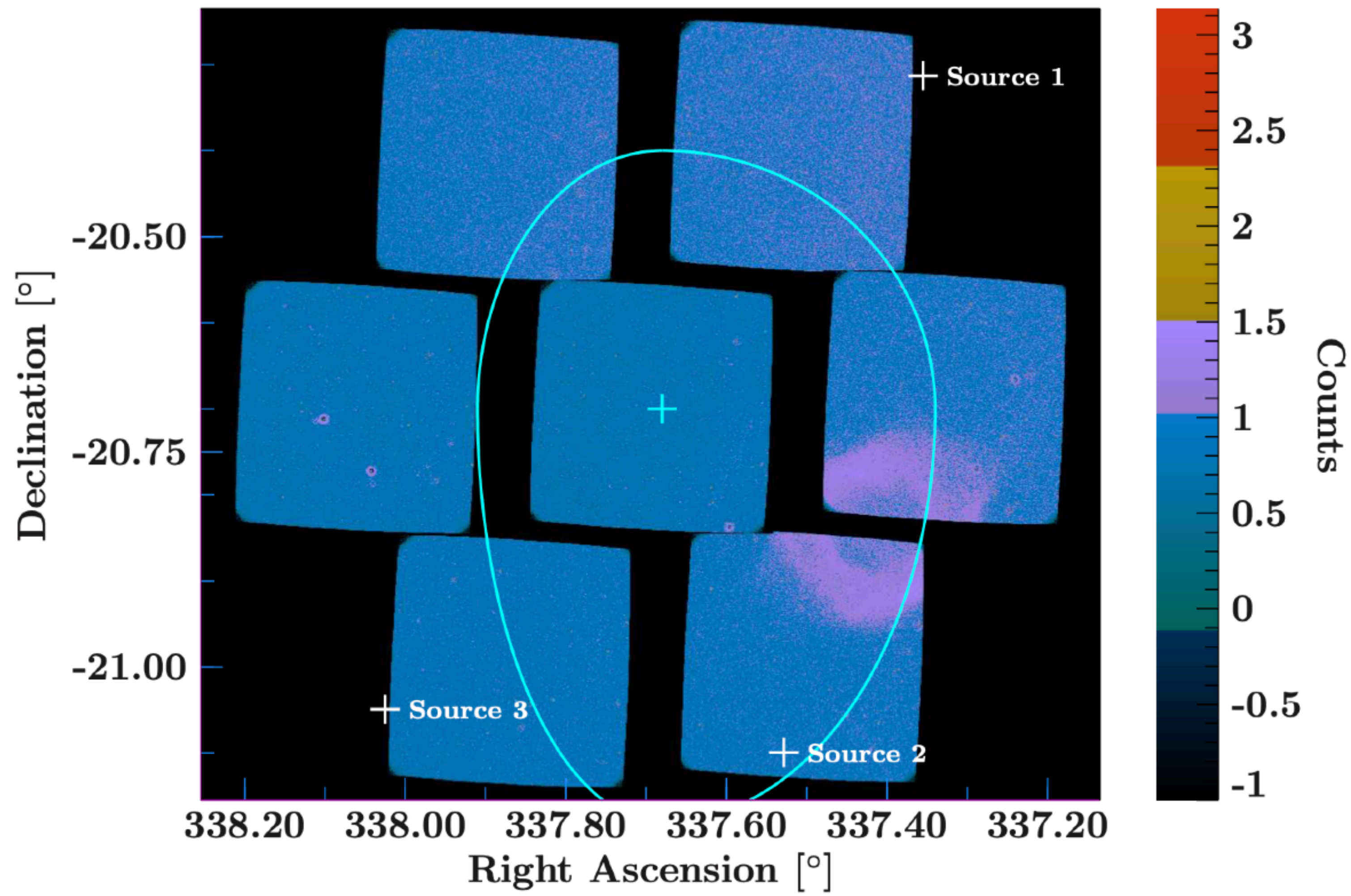
- A typical blazar of BL Lac type, z= 0.34 [Paiano et al., 2018]
- High energy neutrinos can be generated through pɣ interactions in the jet, for Eν ~ 300 TeV: protons with Ep ≥ 6 PeV must interact with photons with energies in the UV to soft X-ray range
- BL Lac objects generally disfavoured compared 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]

More alerts

For most cases, no obvious electromagnetic counterparts



IceCube-190331A



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