Neutrino Astrophysics Overview, High Energy

Topics in Cosmic Neutrino Physics

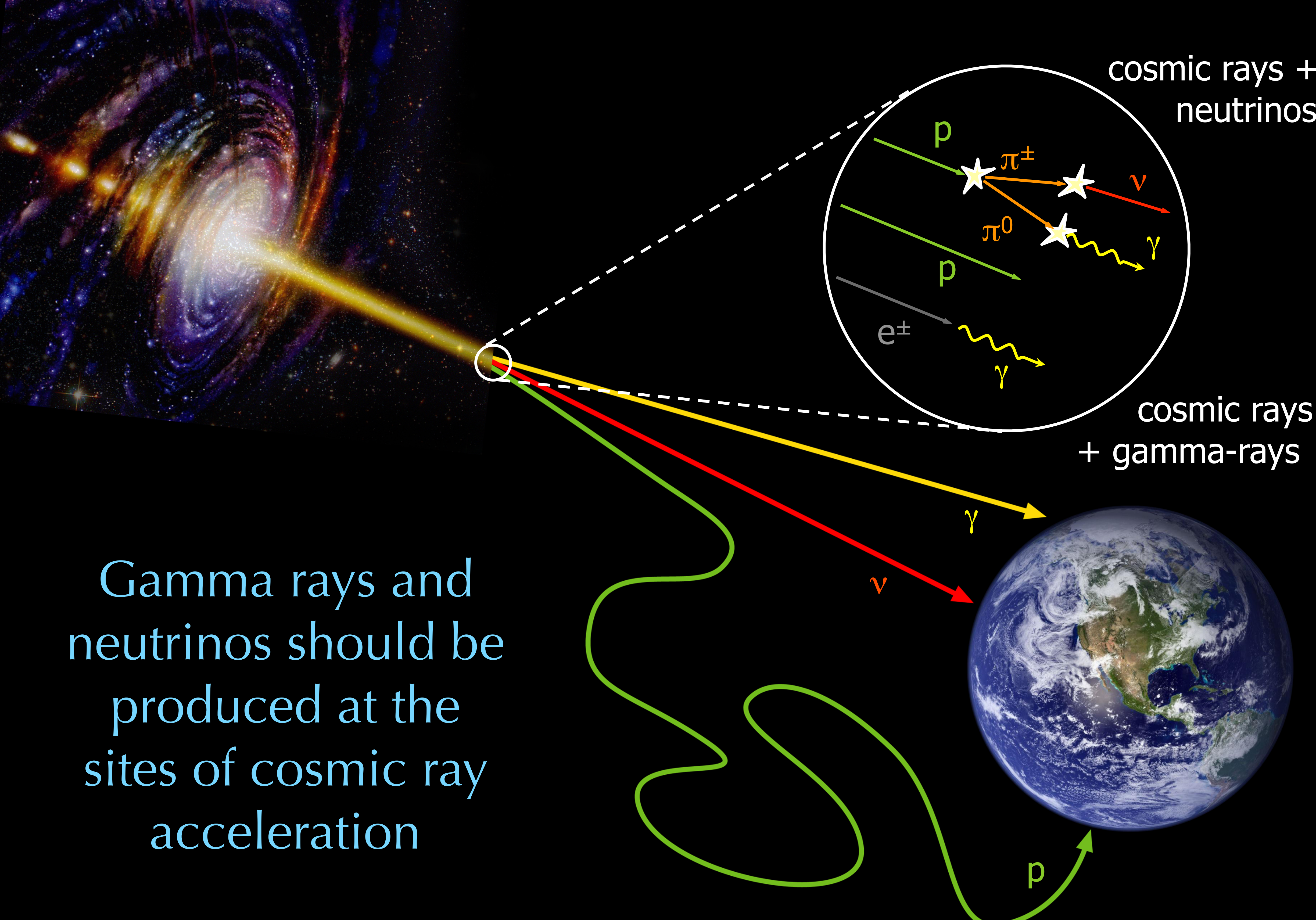
October 11, 2019

Fermilab

Darren R Grant

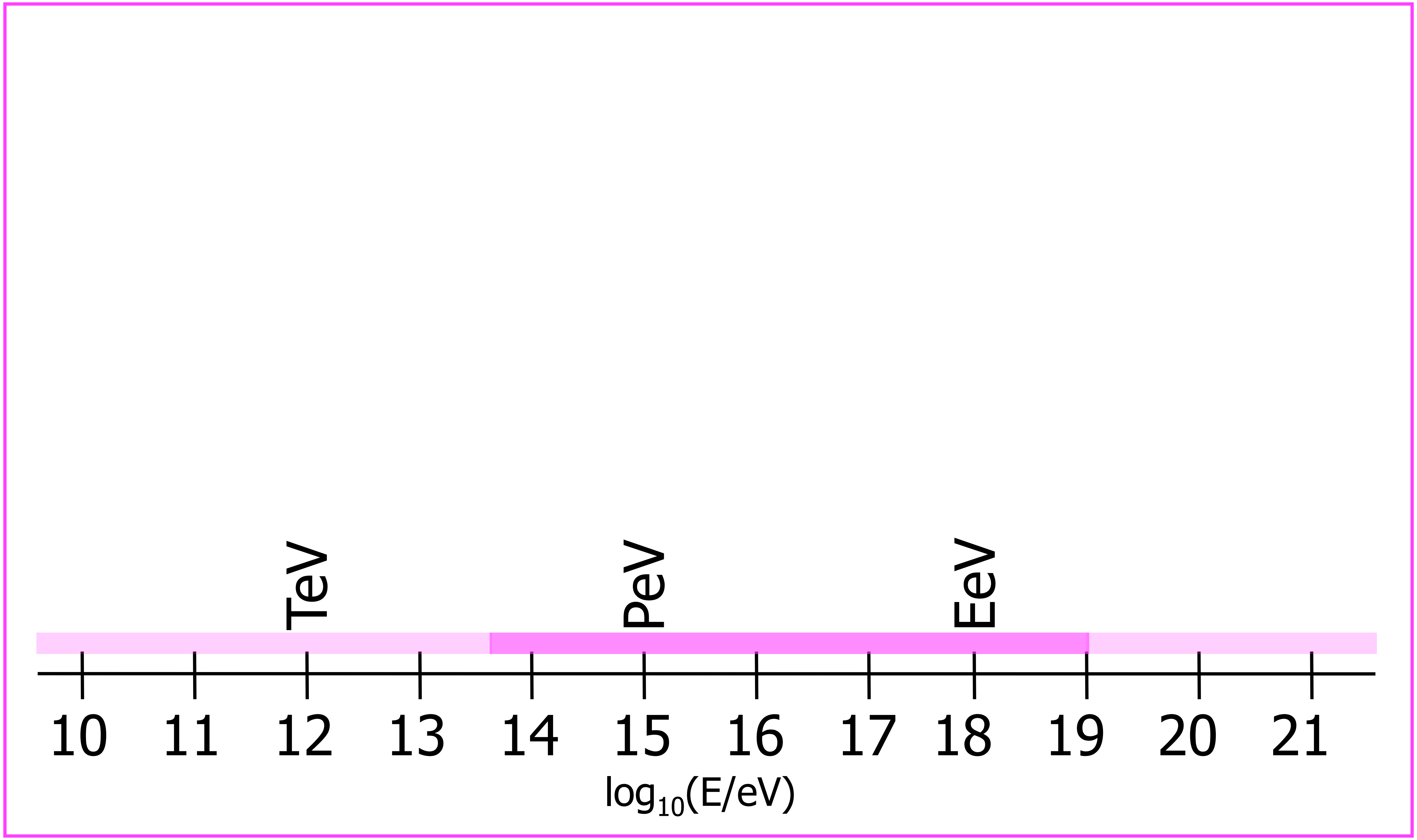
MICHIGAN STATE UNIVERSITY

Multimessenger Astronomy

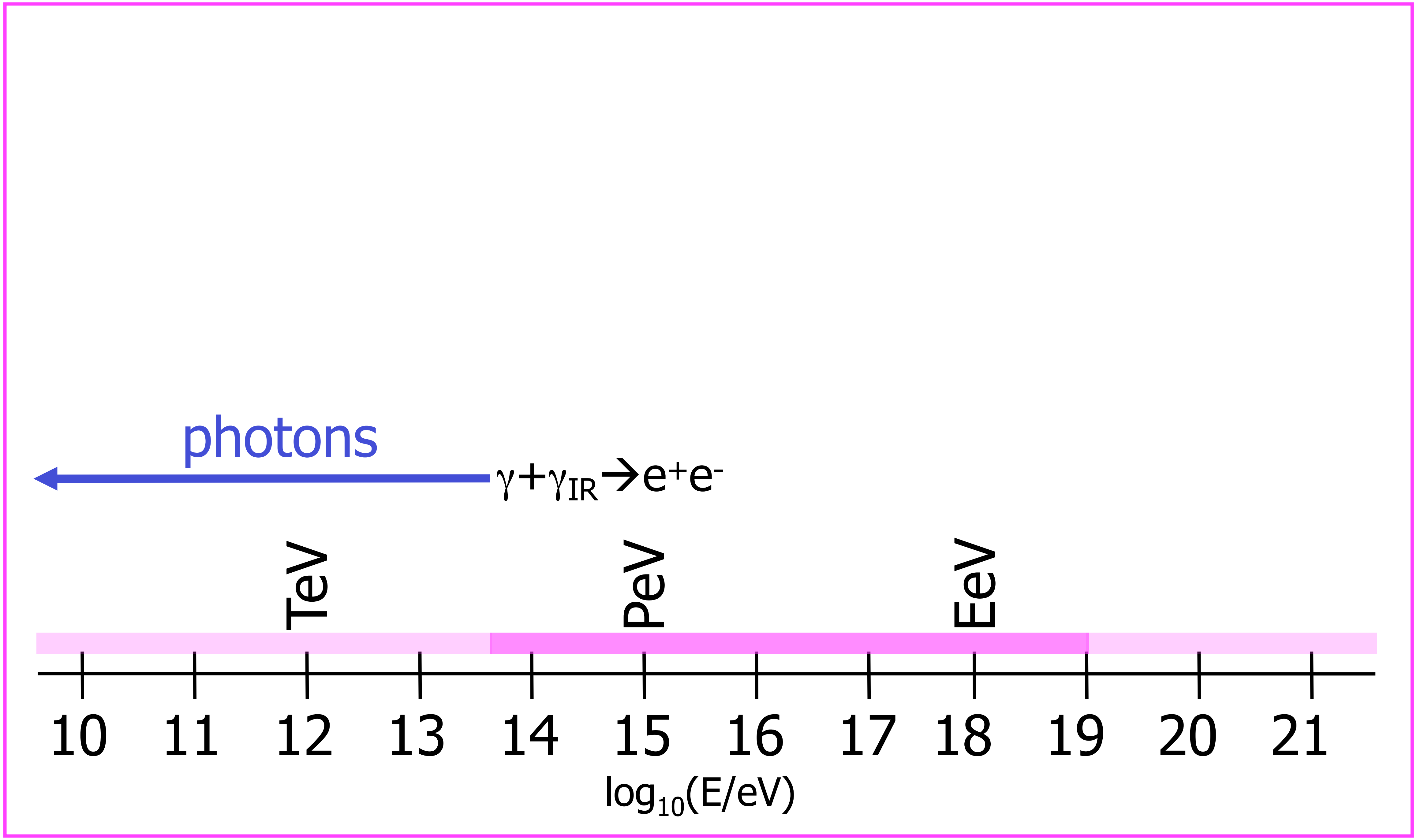


Gamma rays and neutrinos should be produced at the sites of cosmic ray acceleration

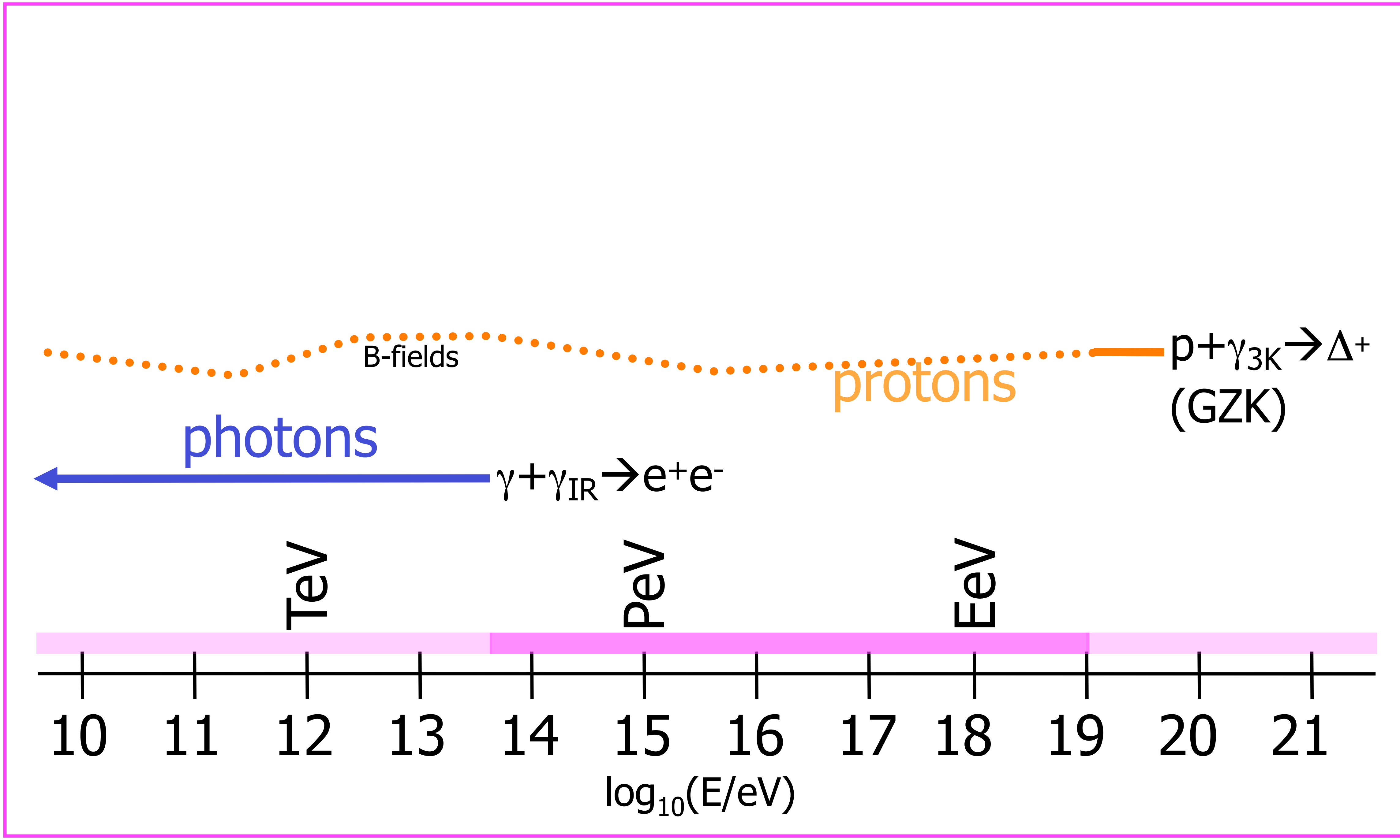
Astronomical messengers



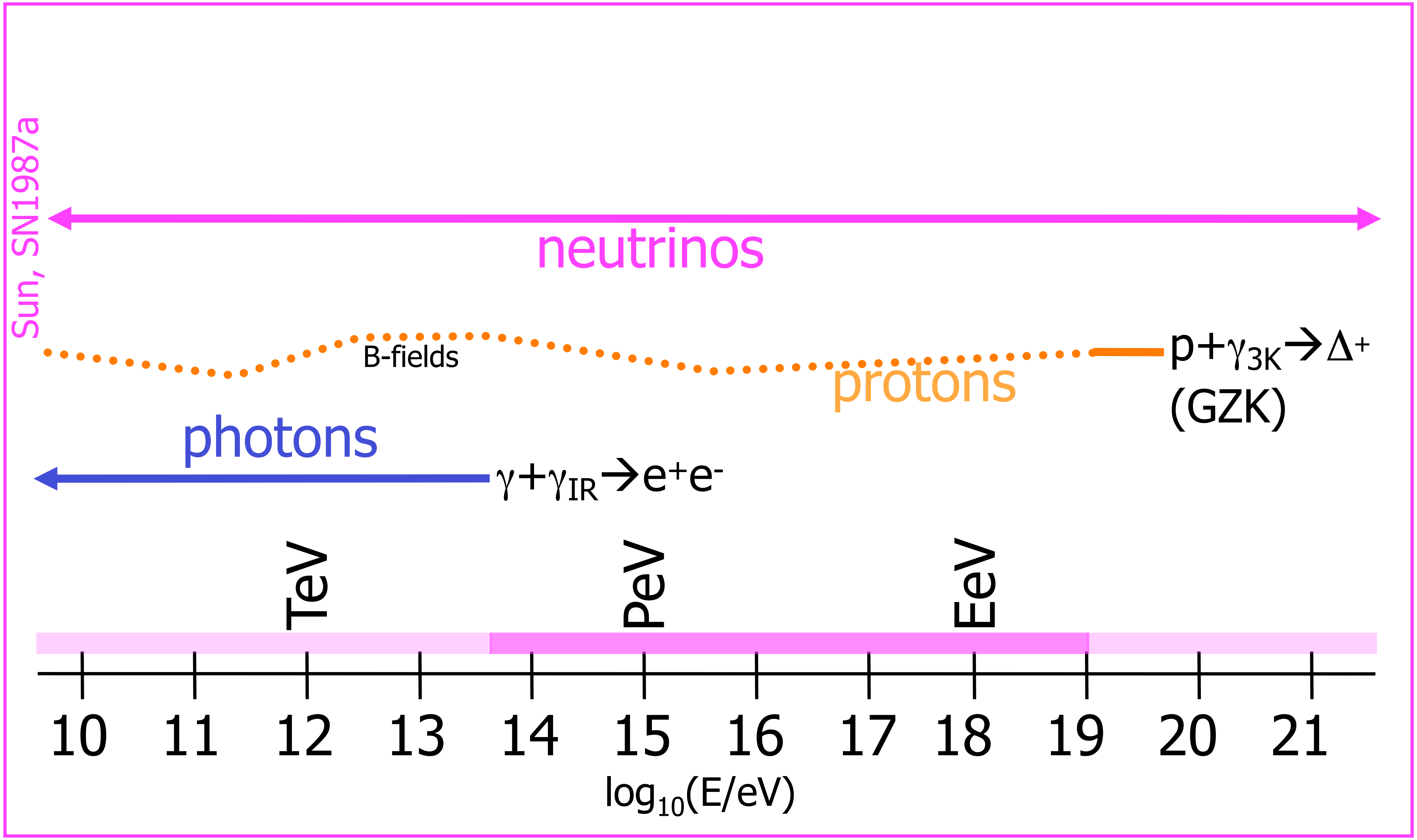
Astronomical messengers



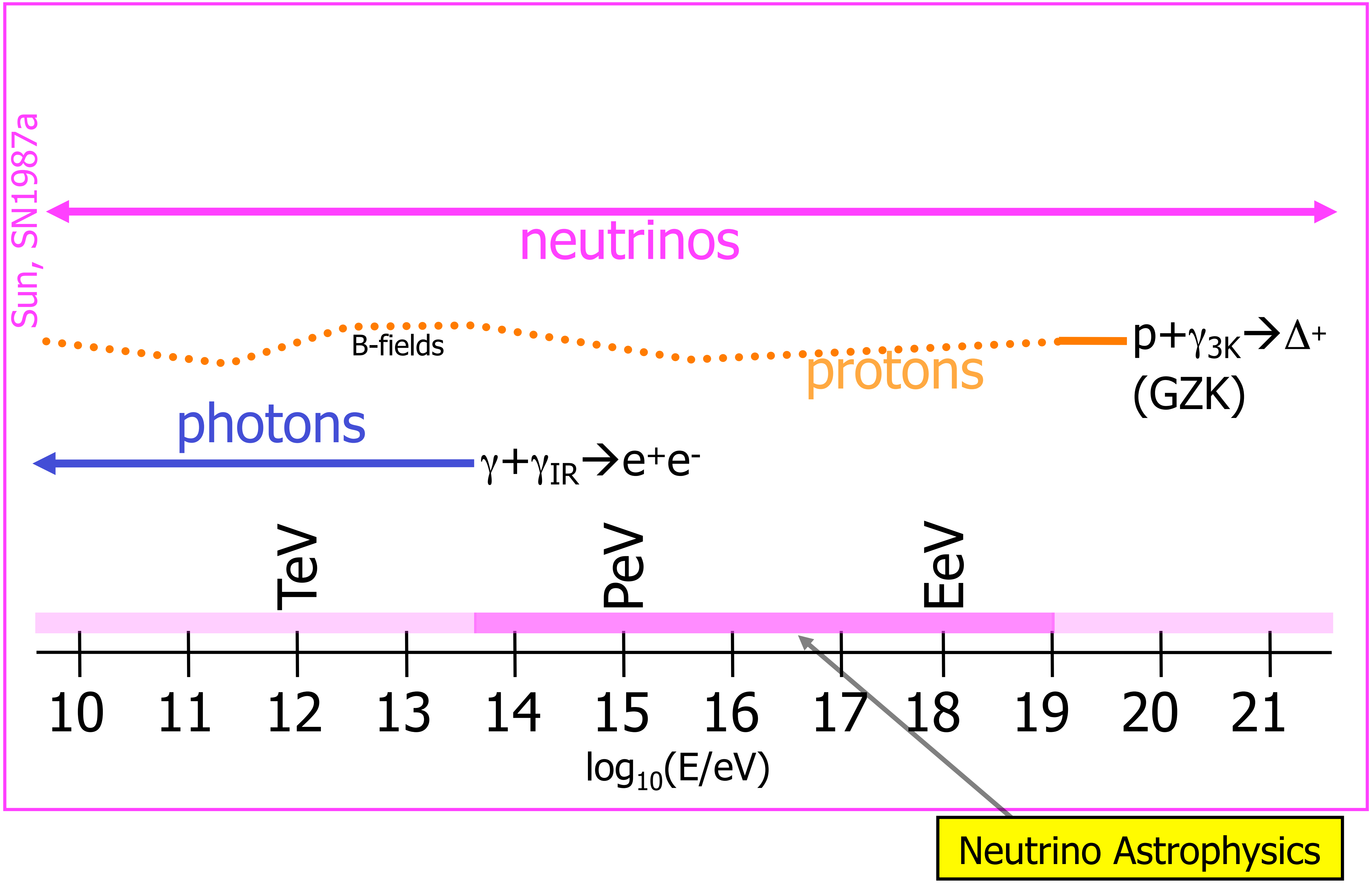
Astronomical messengers



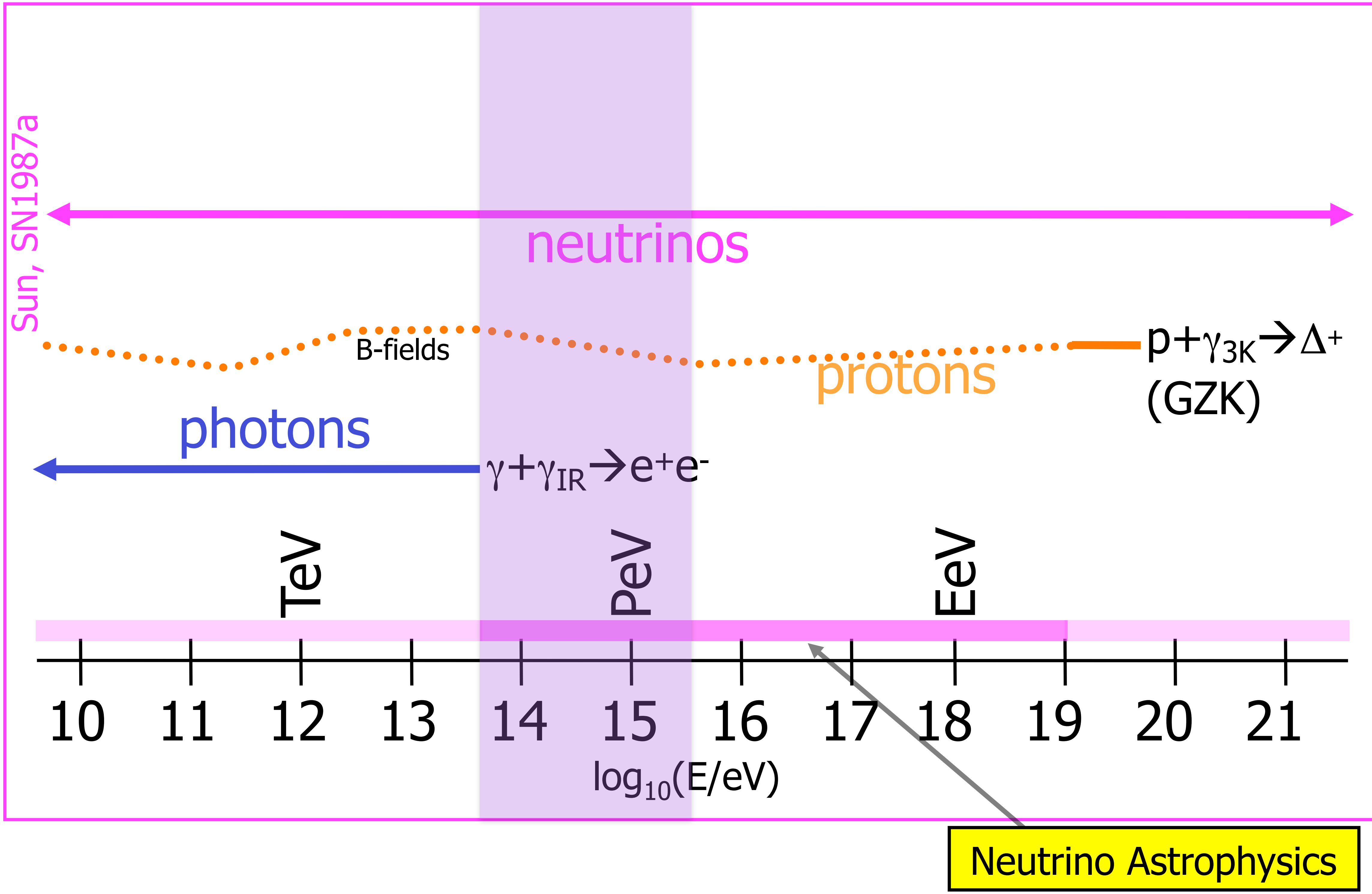
Astronomical messengers



Astronomical messengers



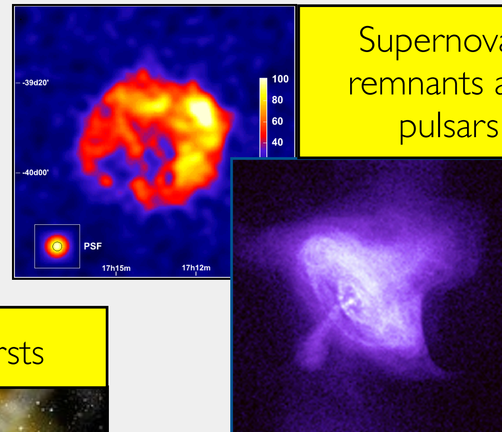
Astronomical messengers



Astronomical messengers - sources

Active Galactic Nuclei

Supernovae, remnants and pulsars

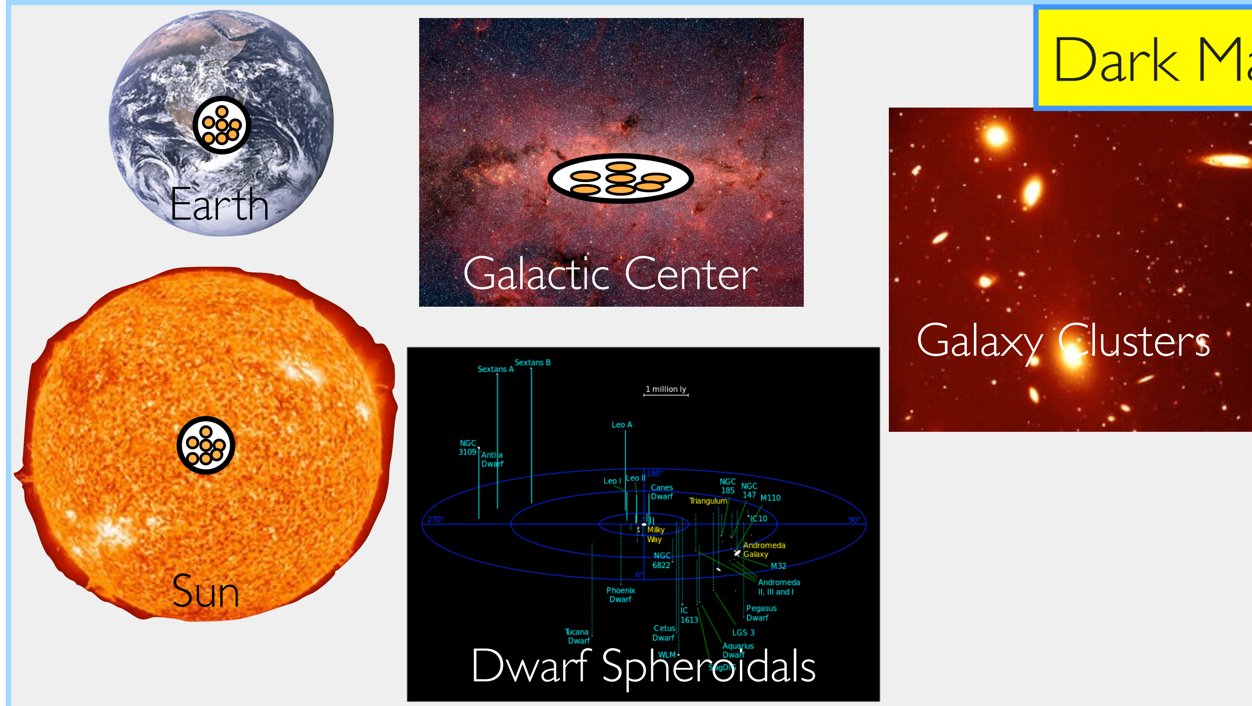


Gamma-ray Bursts

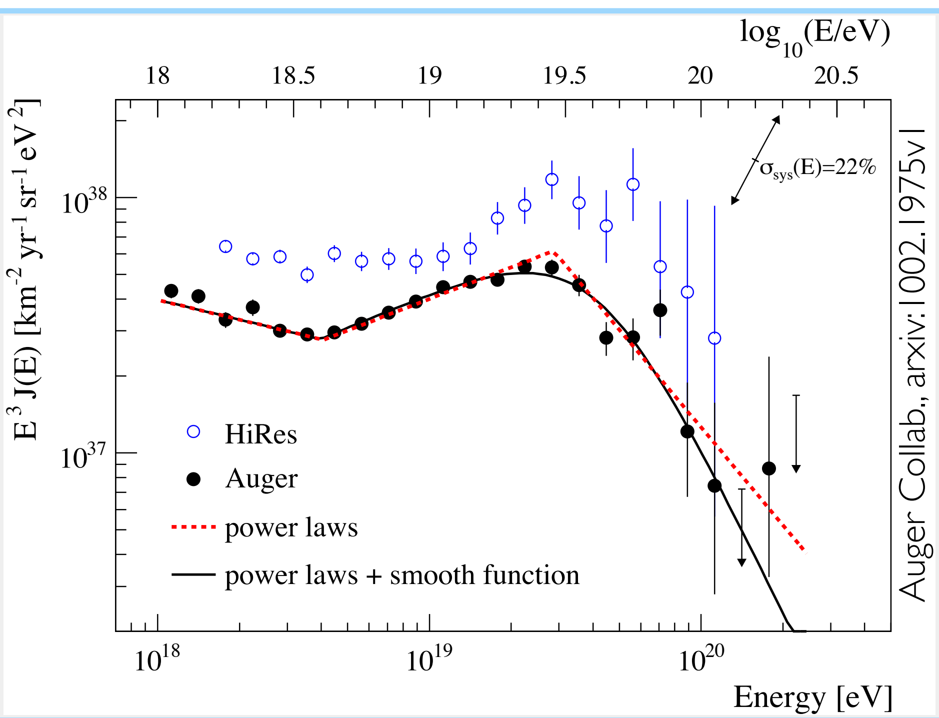
Starburst Galaxies

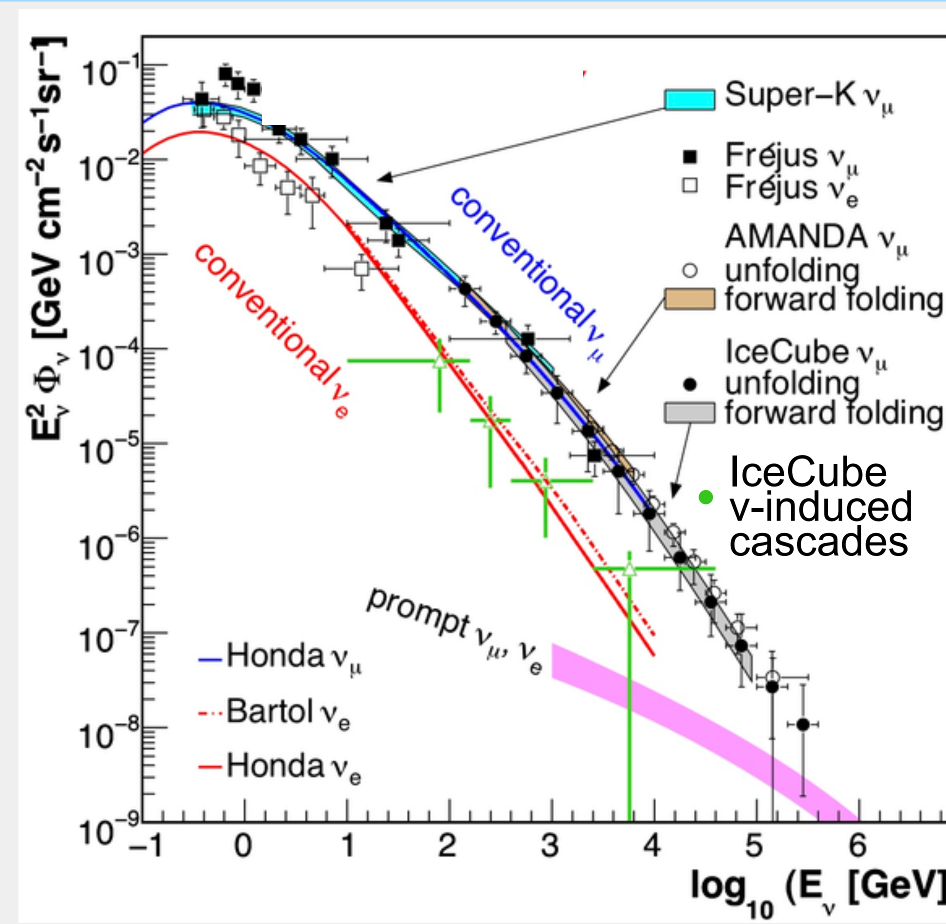
$p + (p,\gamma) \rightarrow \pi^{\pm} \rightarrow \nu$

Dark Matter



$p+\gamma_{3K} \rightarrow \Delta^{+}$ (GZK)





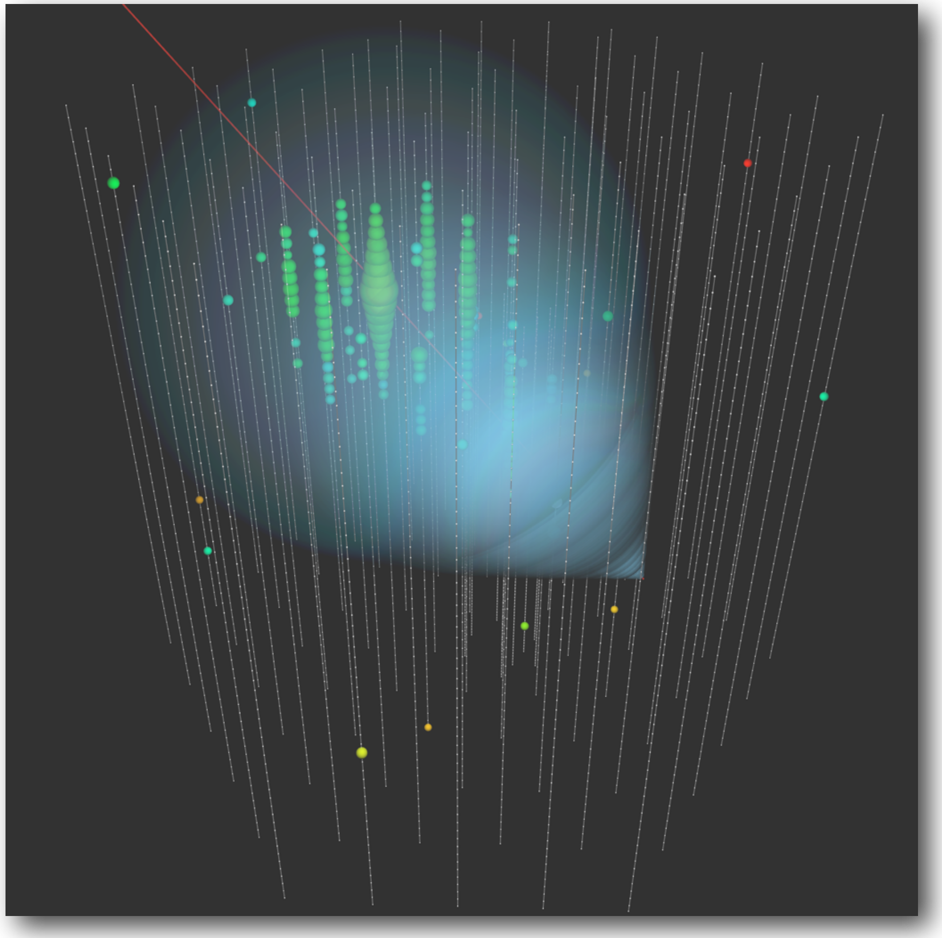
Atmospheric interactions

Principles of high-energy ν detection

- Water Cherenkov
  - ν-induced charged particles emit a detectable pattern of Cherenkov radiation
  - backgrounds from cosmic ray μ and atmospheric ν reduced via event timing, direction, energy and vetoing techniques
- Radio (Askaryan)

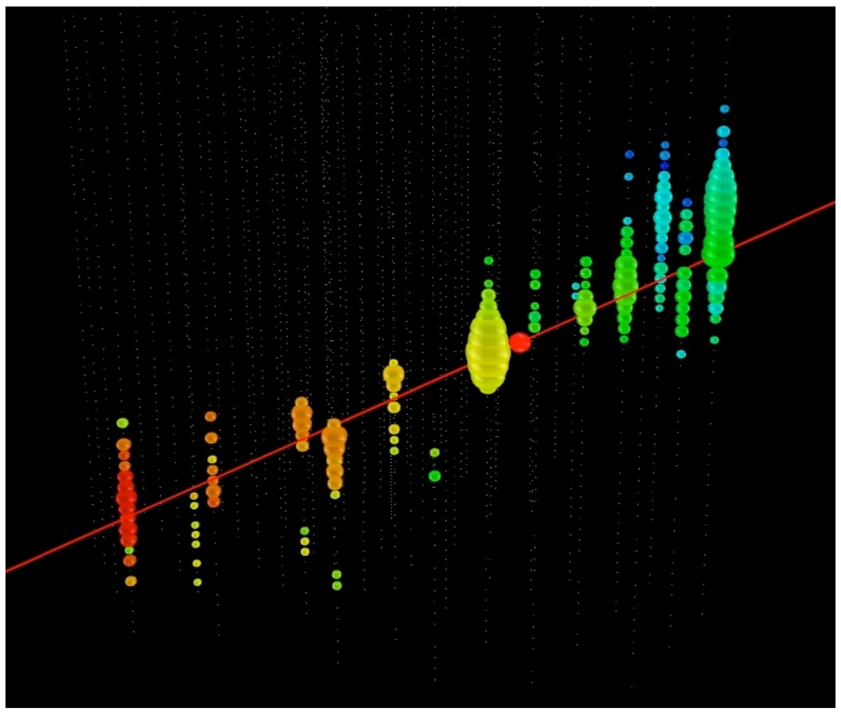
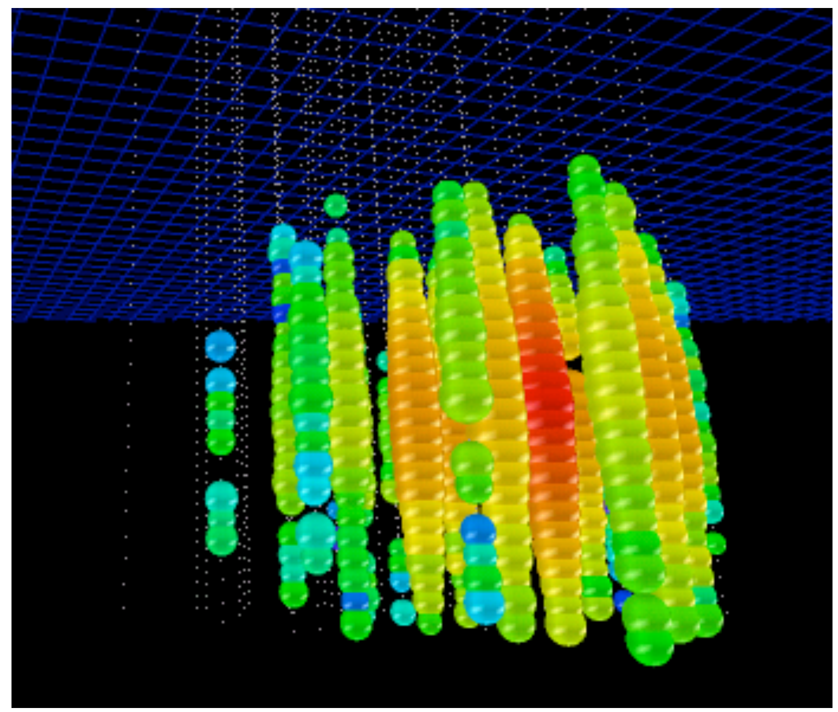
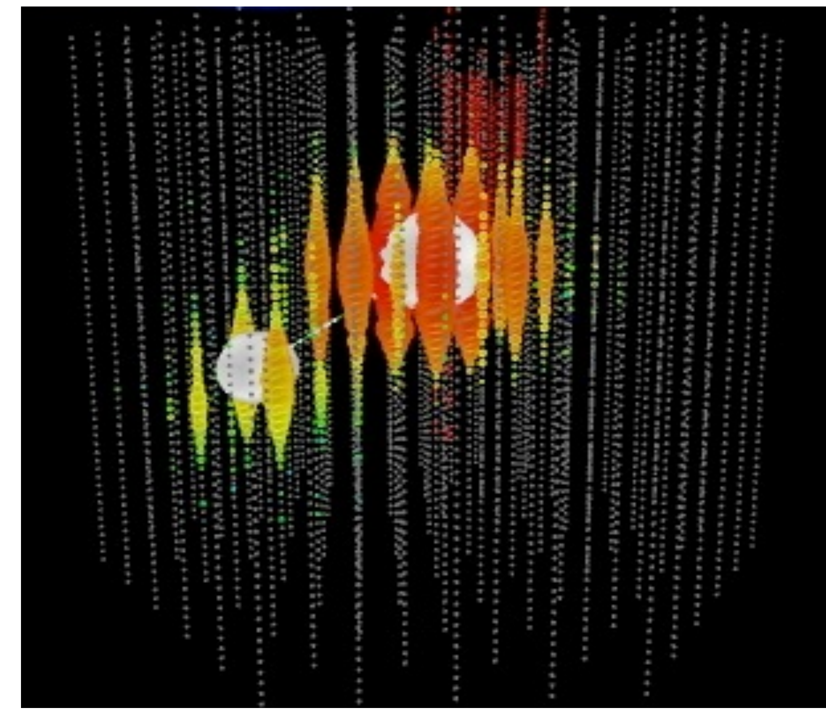
see talk Cosmin Deaconu this afternoon

  - radio λ's are comparable to size of ν-induced shower of charged particles; resulting coherent radiation can be very powerful
- Penetrating or upward-going air shower
  - air Cherenkov (e.g. Auger)
- Acoustic
  - localized ν-induced heating: sharp sonic pulse
  - tests in polar icecap yielded too small λ_{att}
    - water could be better (the Dead Sea?)

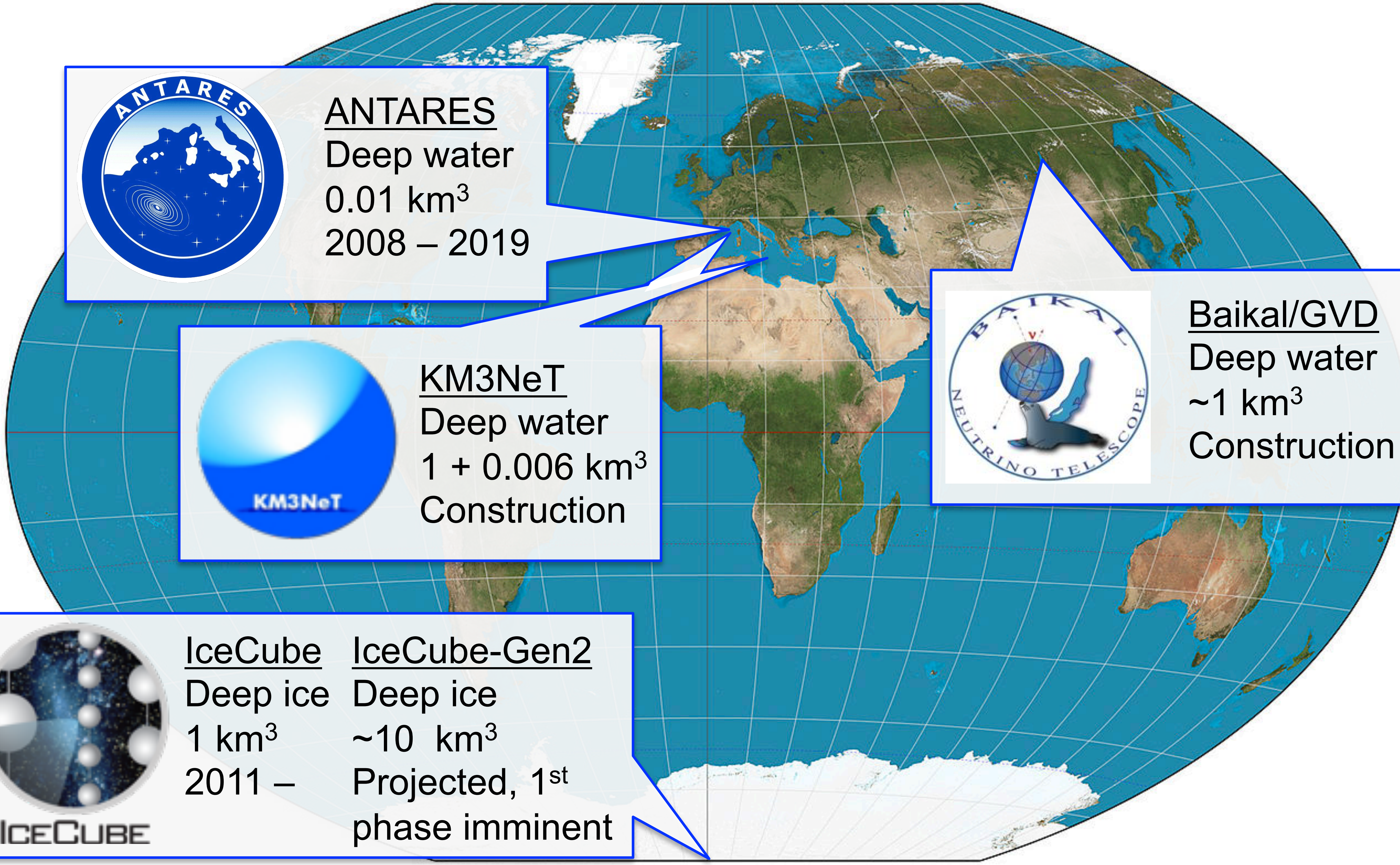


Simulated downward-going cosmic-ray muon in IceCube

Principles of high-energy ν detection - water Cherenkov

CC Muon Neutrino	Neutral Current / Electron Neutrino	CC Tau Neutrino
		
track (data)	cascade (data)	"double-bang" (≳10PeV) and other signatures (simulation)
factor of ≈ 2 energy resolution < 1° angular resolution at high energies	≈ ±15% deposited energy resolution ≈ 10° angular resolution (at energies ≳ 100 TeV)	(τ decay length is 50 m/PeV)

Ice/water Cherenkov neutrino telescopes - global view



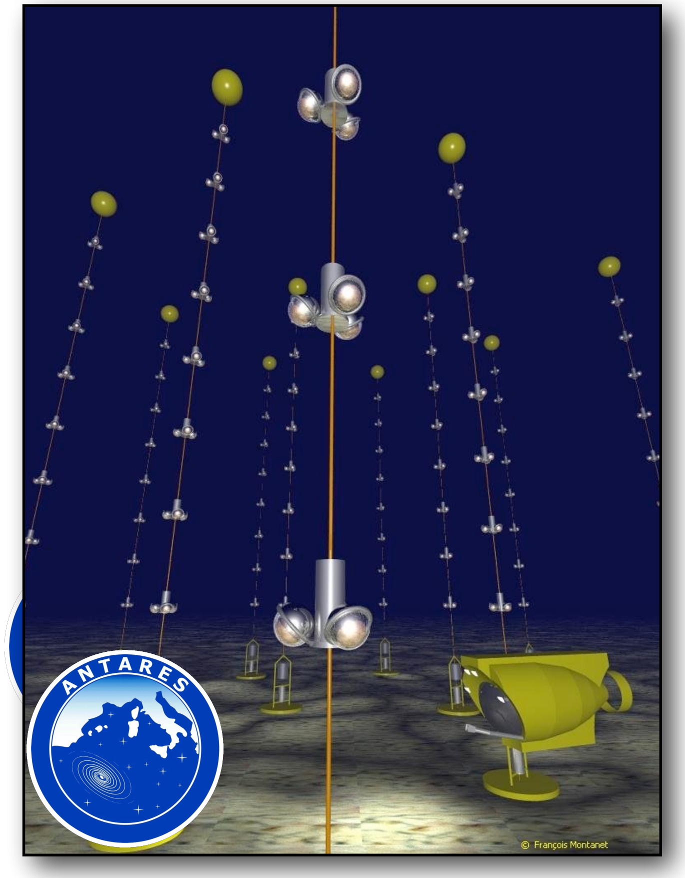
ANTARES
Deep water
0.01 km^3
2008 – 2019

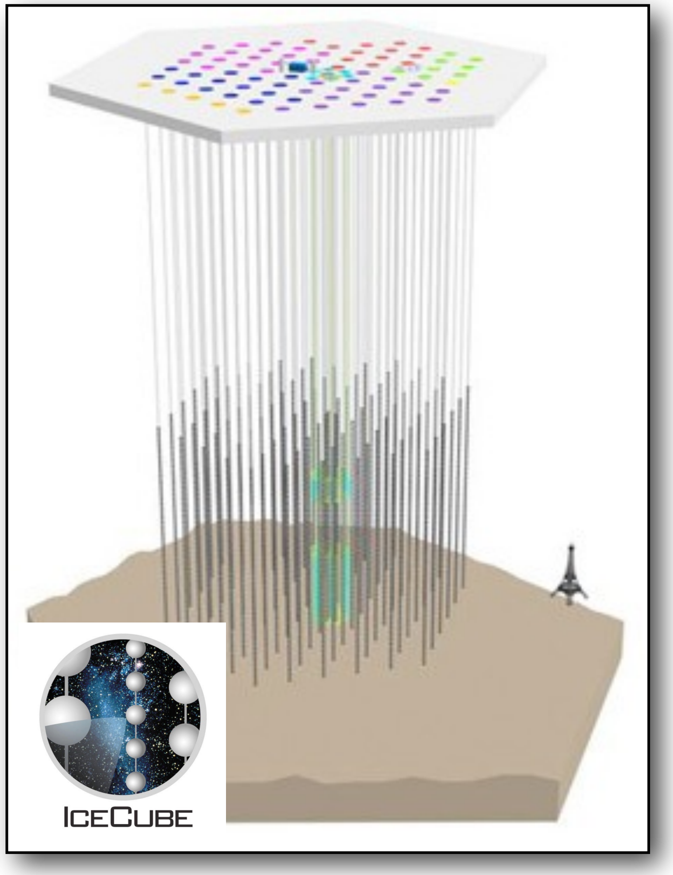
KM3NeT
Deep water
1 + 0.006 km^3
Construction

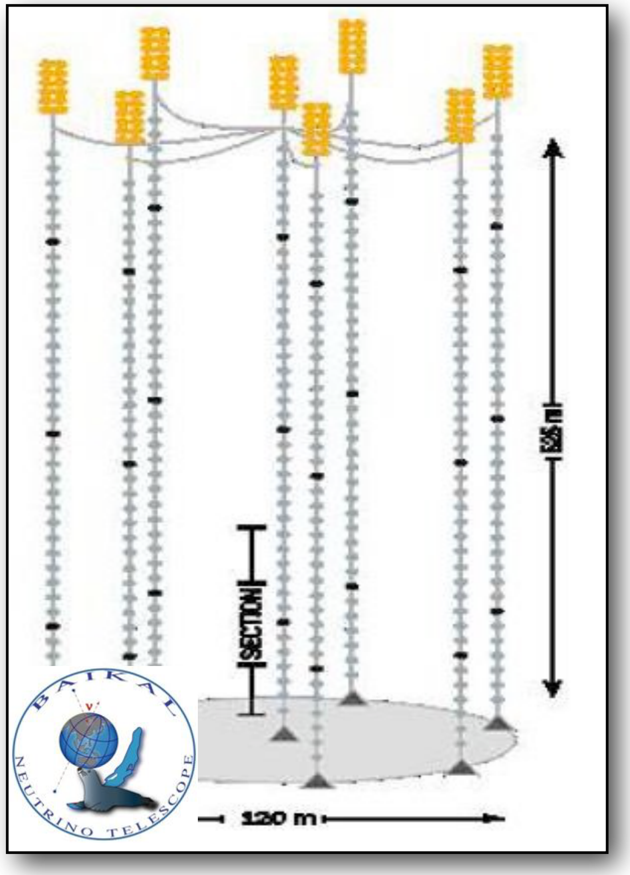
Baikal/GVD
Deep water
~1 km^3
Construction

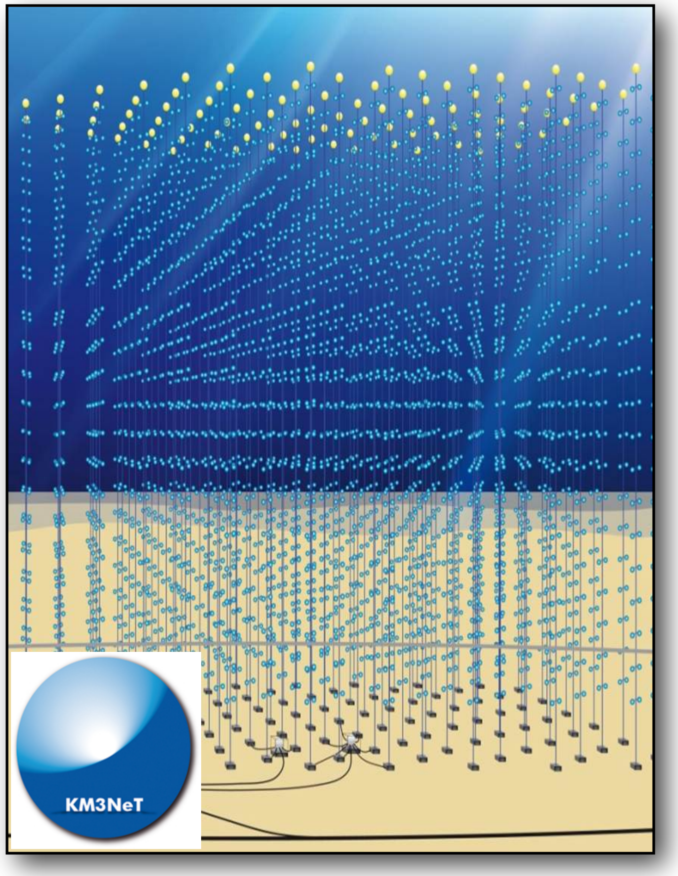
IceCube	IceCube-Gen2
Deep ice	Deep ice
1 km^3	~10 km^3
2011 –	Projected, 1st phase imminent

Ice/water Cherenkov neutrino telescopes - global view

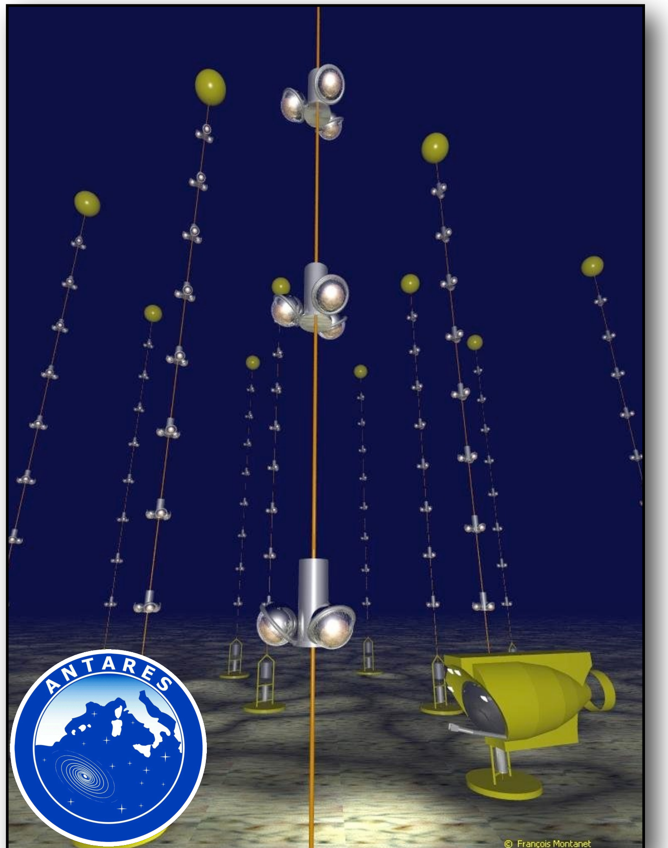


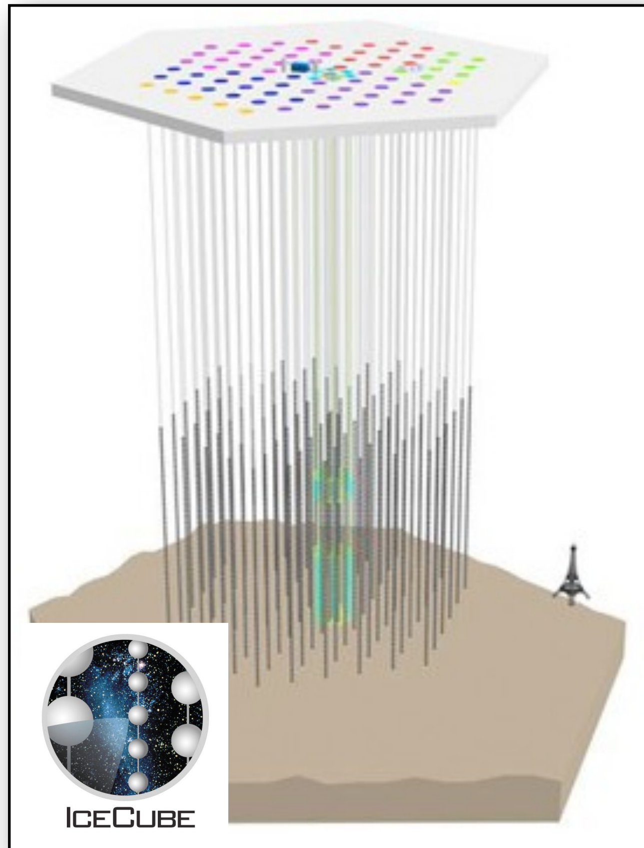


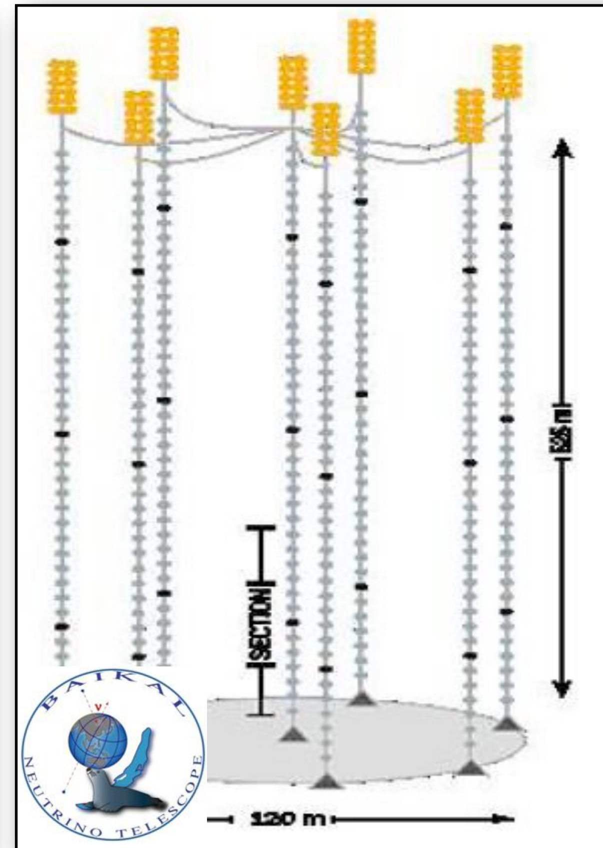


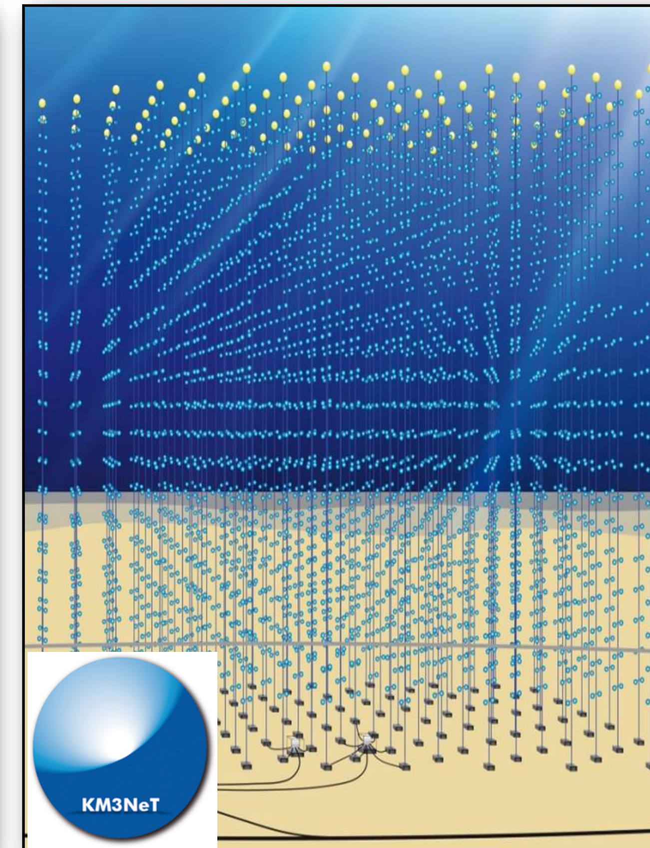


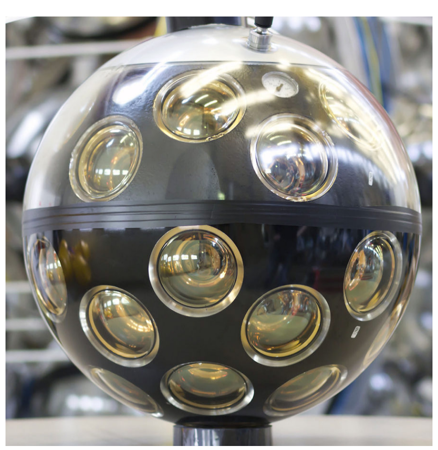
Ice/water Cherenkov neutrino telescopes - global view







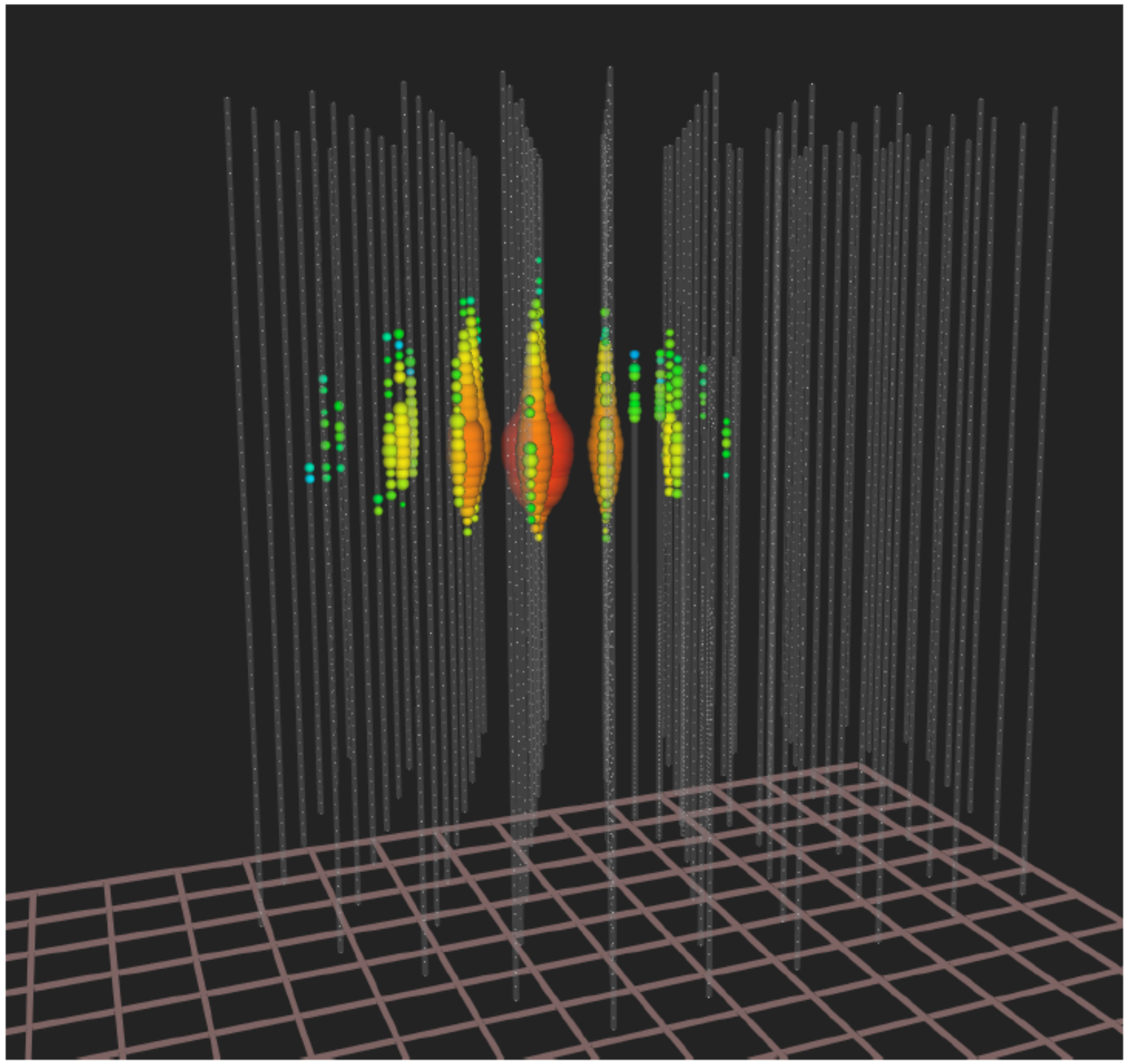




Astrophysical ν signal

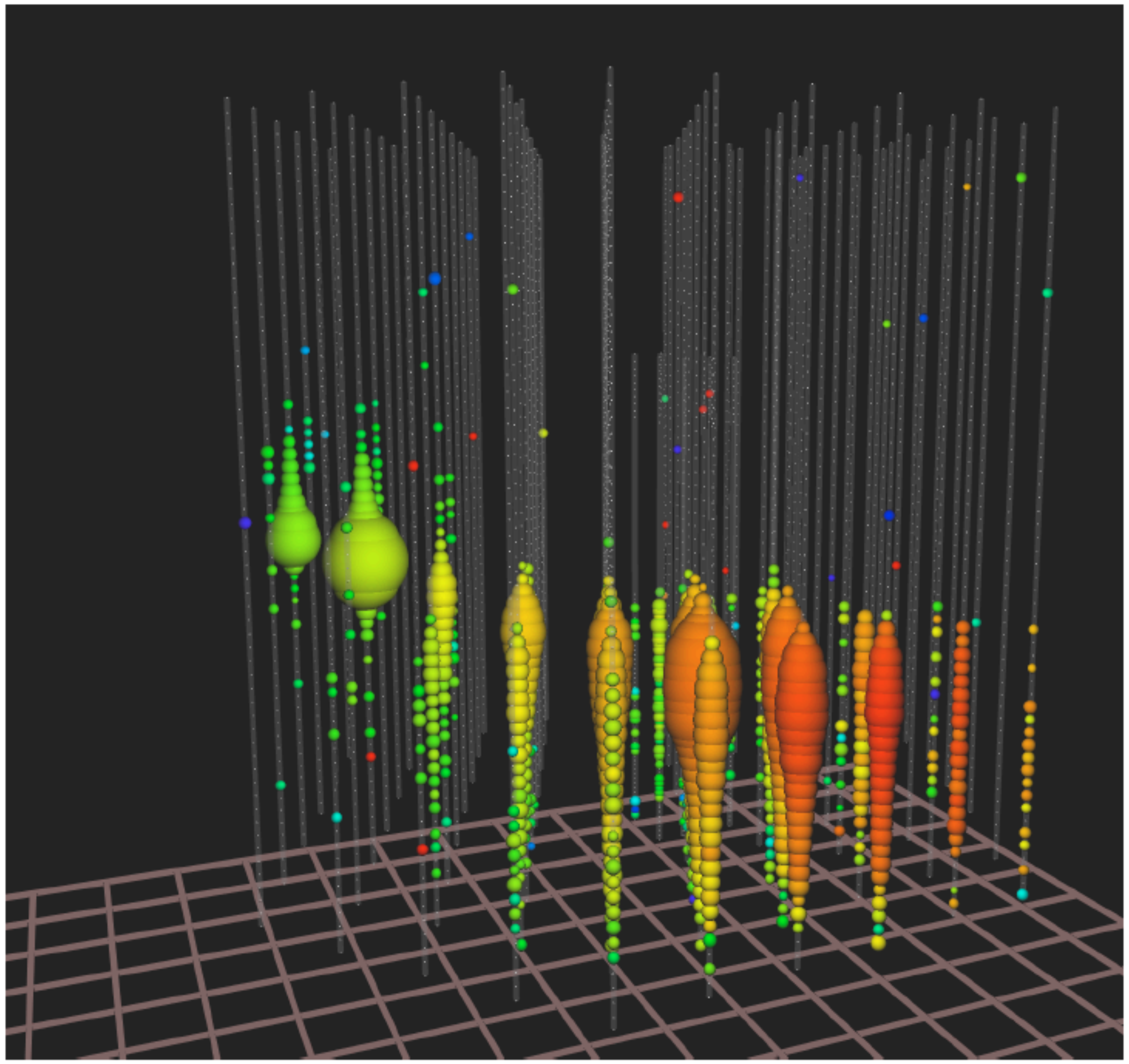
Two independent observations of cosmic neutrinos

Isolated neutrinos interacting inside the detector (HESE)



provides total energy measurement; all flavours, all sky

Up-going muon tracks

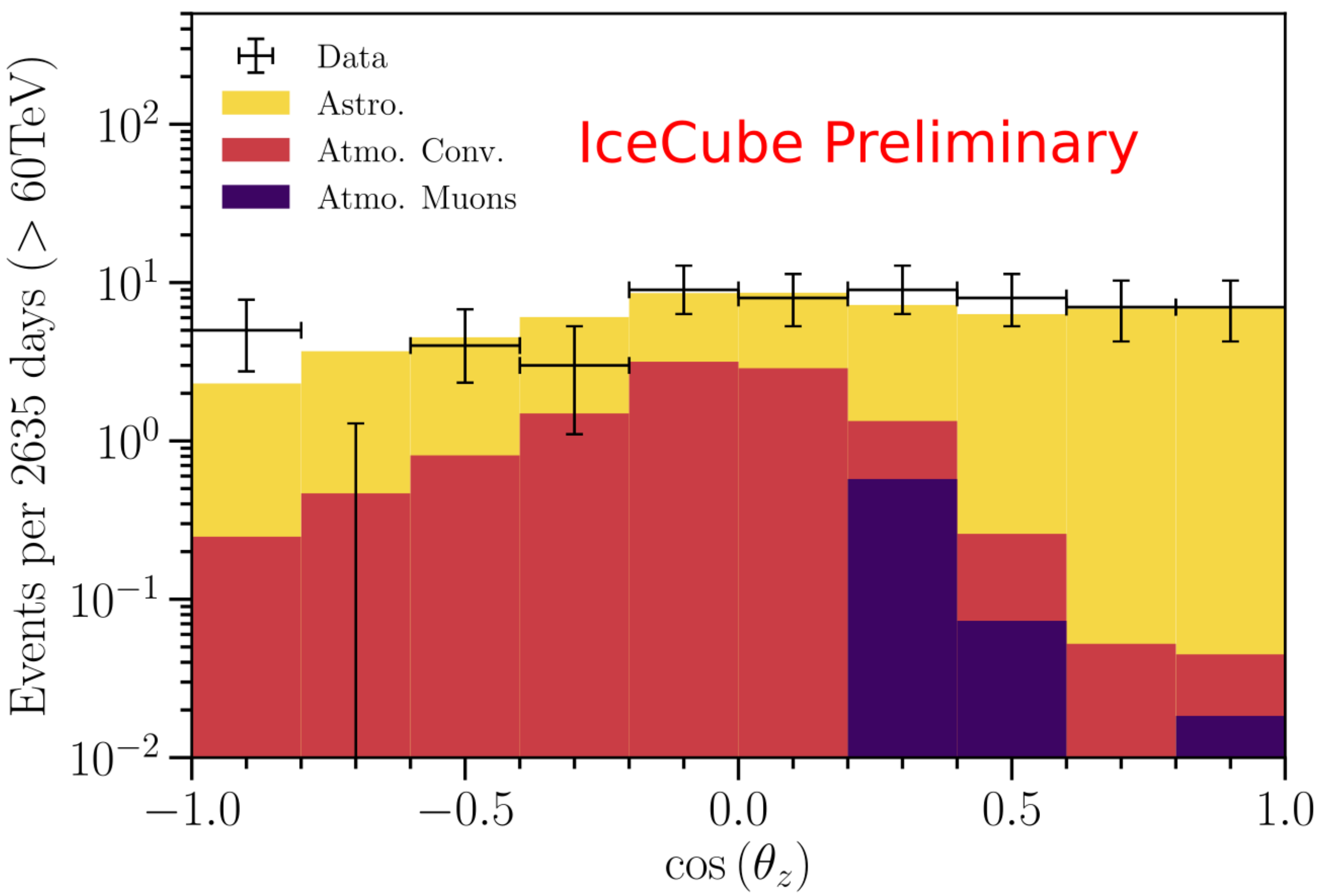


ideal for astronomy; angular resolution < 0.5°

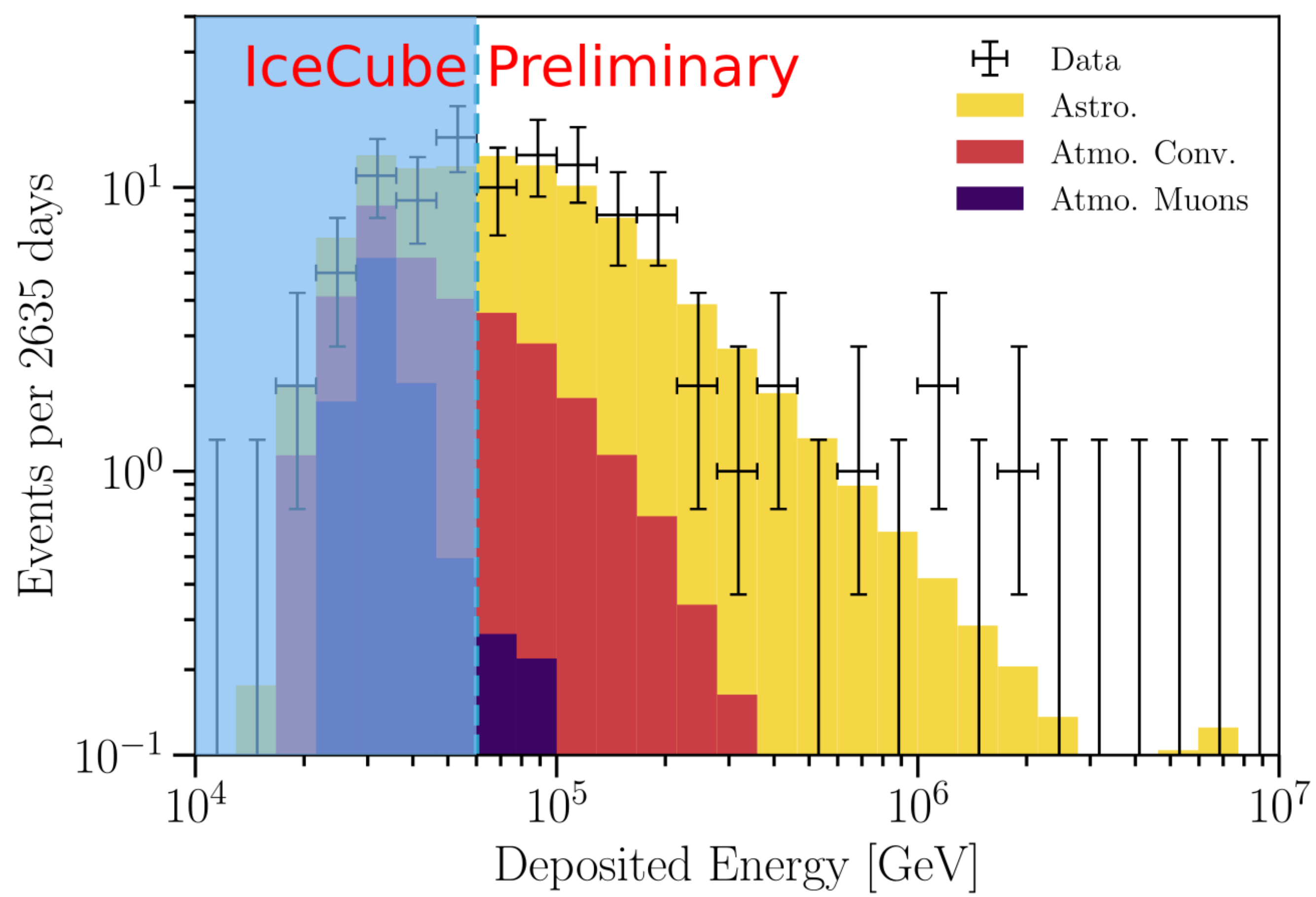
Astrophysical ν signal

HESE

Starting Event Angular Distribution



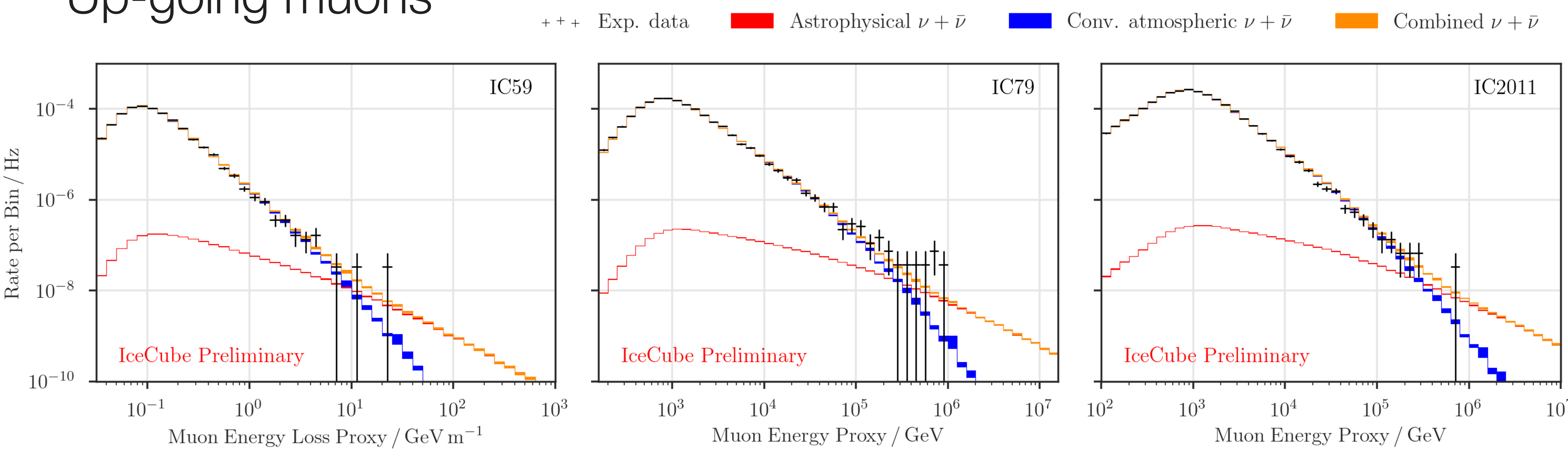
Starting Event Spectrum

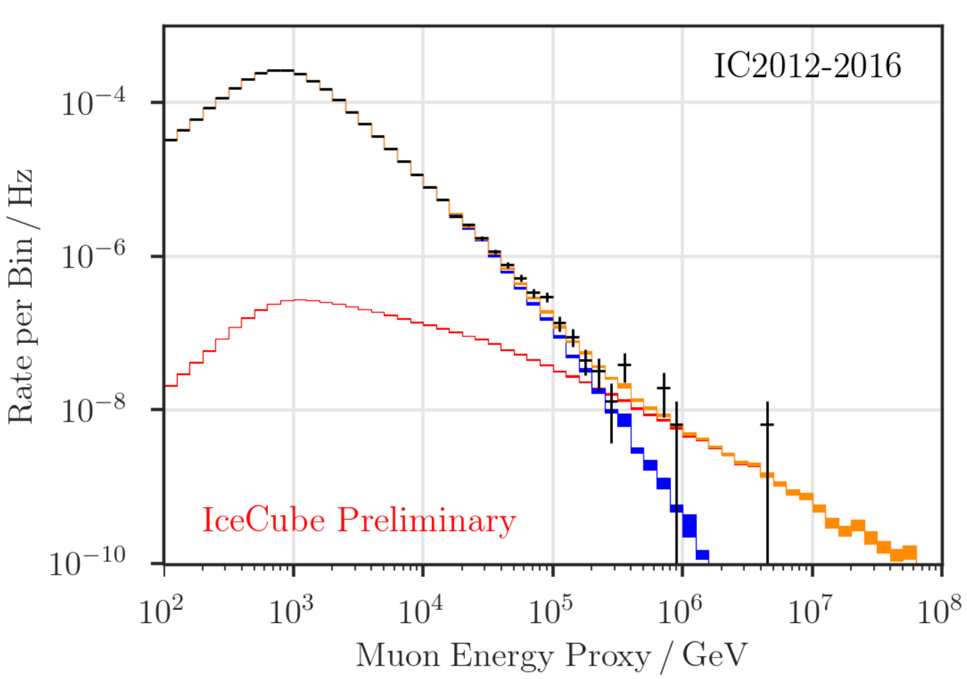


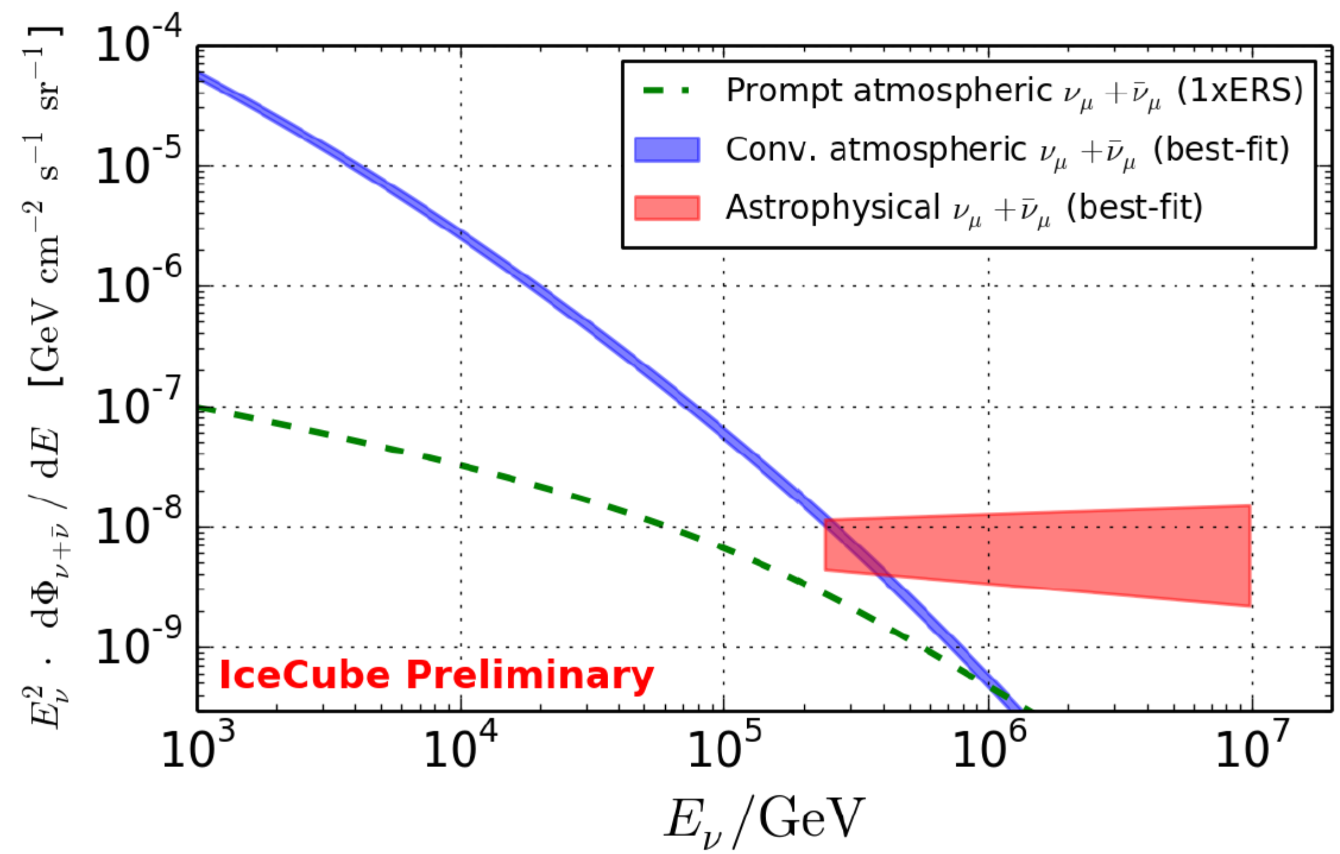
7.5 year dataset; atmospheric-only hypothesis excluded by more than 7σ

Astrophysical ν signal

Up-going muons



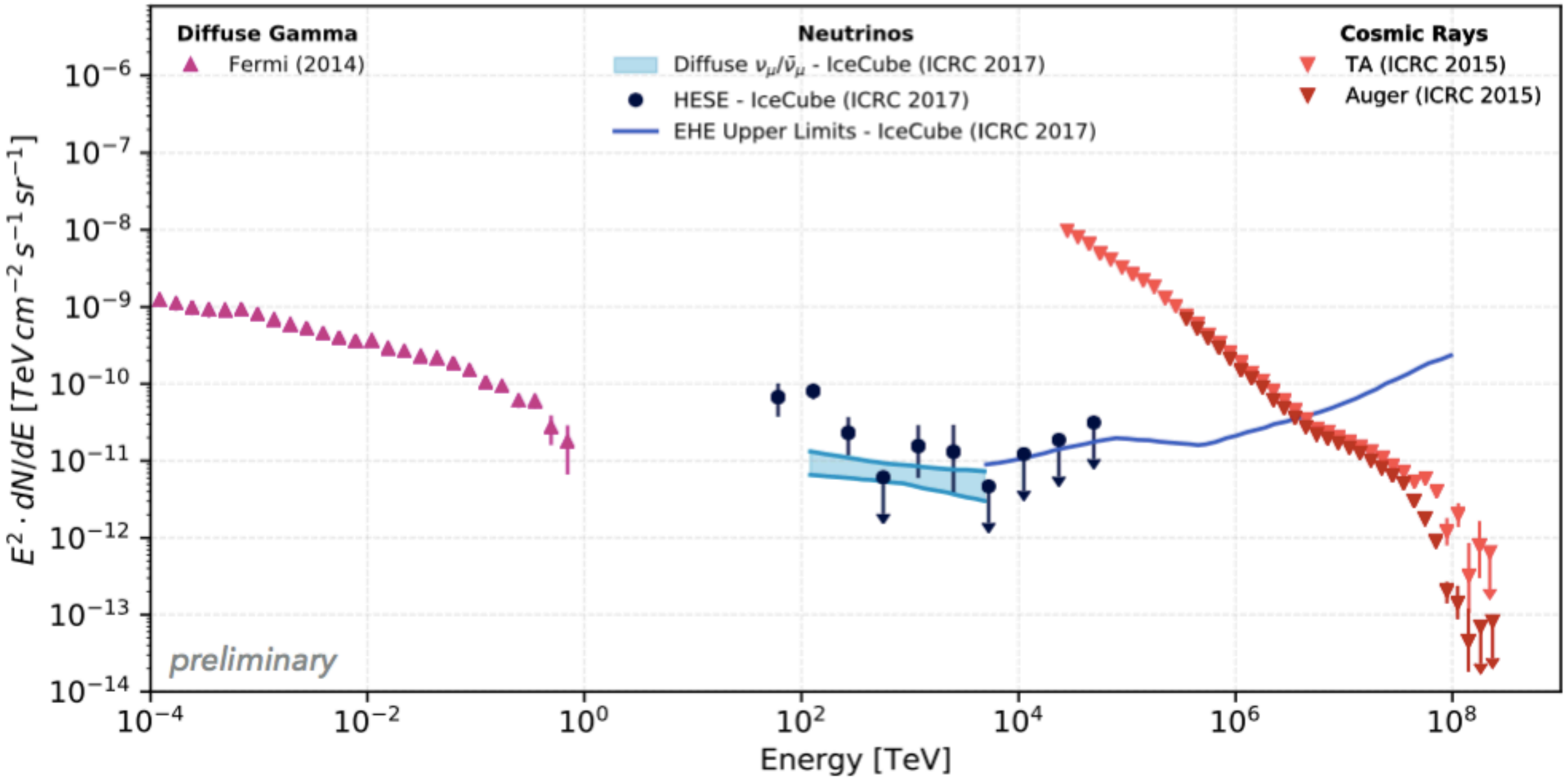




Atmospheric-only hypothesis excluded by more than 6σ; best fit spectral index 2.16 +/- 0.11

Astrophysical ν signal

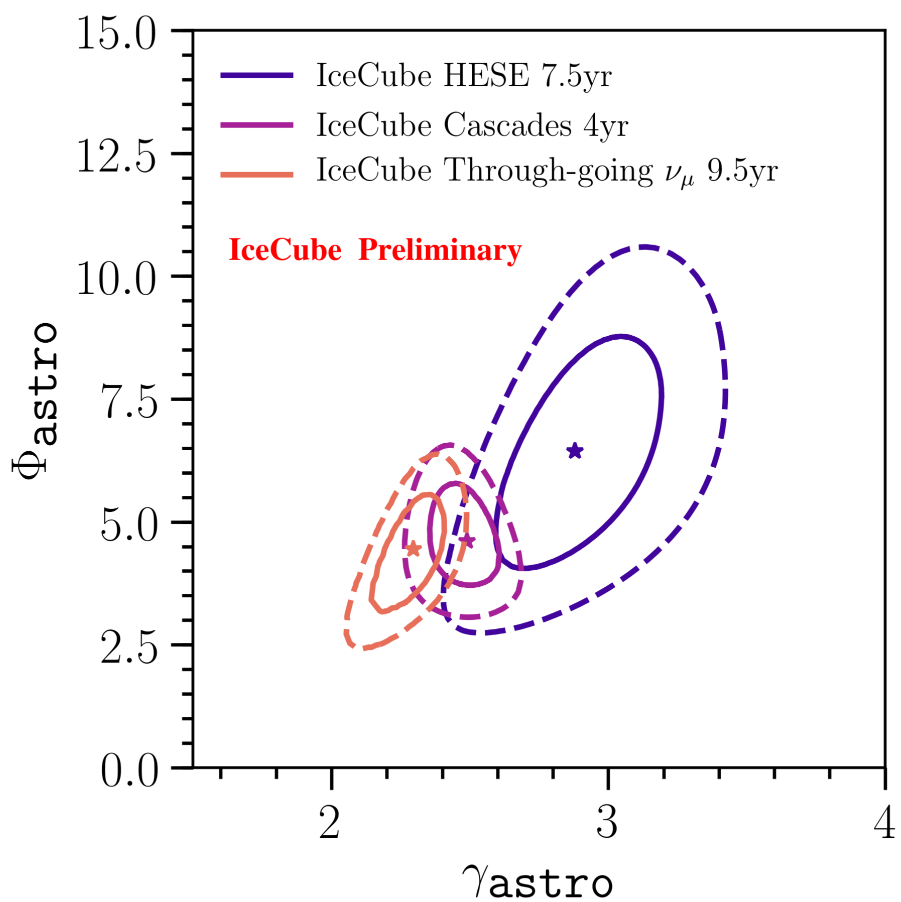
A. Turcati, modified from L. Mohrmann, PhD Thesis (2015)

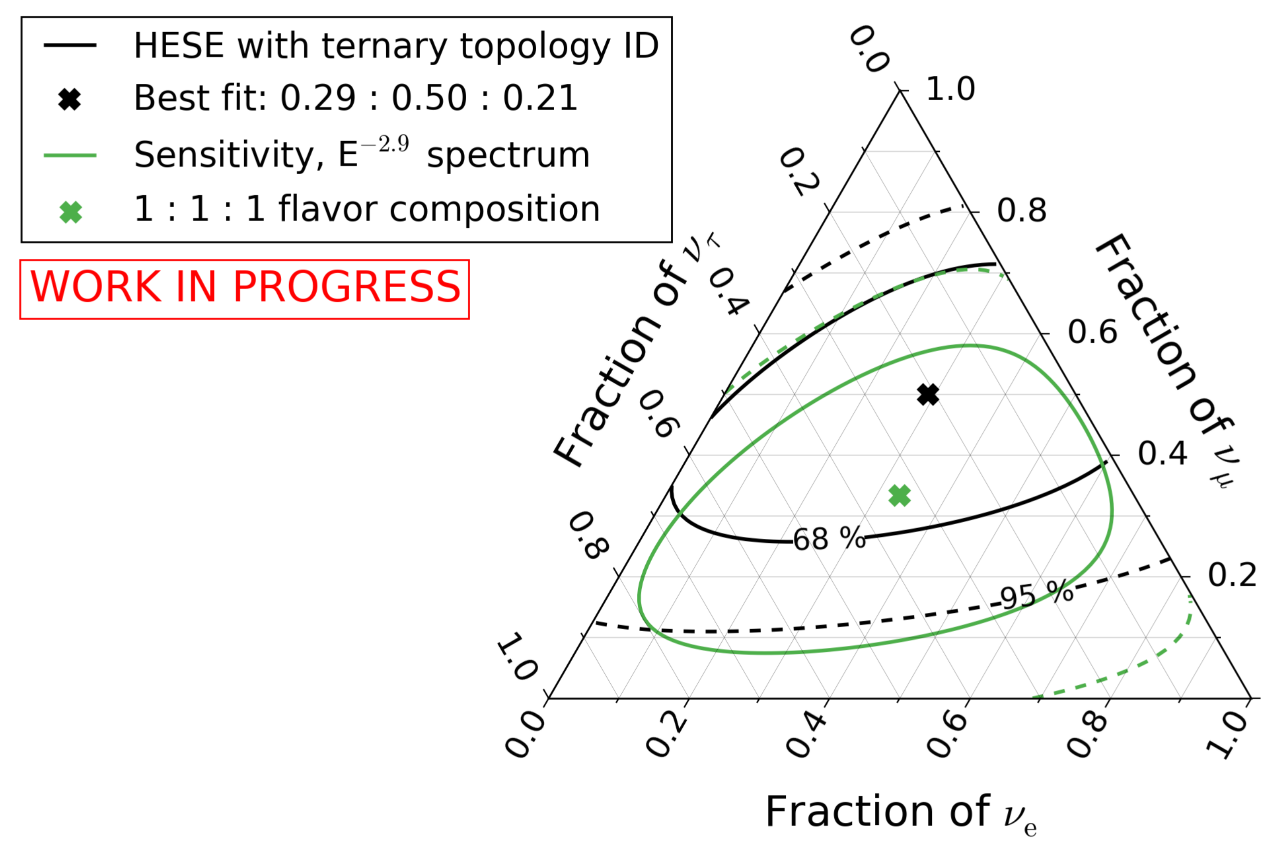


Similar energy injected into the Universe in gamma-rays, neutrinos & extragalactic cosmic rays

Spectrum for the observed neutrino signatures are largely consistent with a single power-law.

First indications of "tauness" have emerged in most recent global fit of flavor ratio (see backup slides)

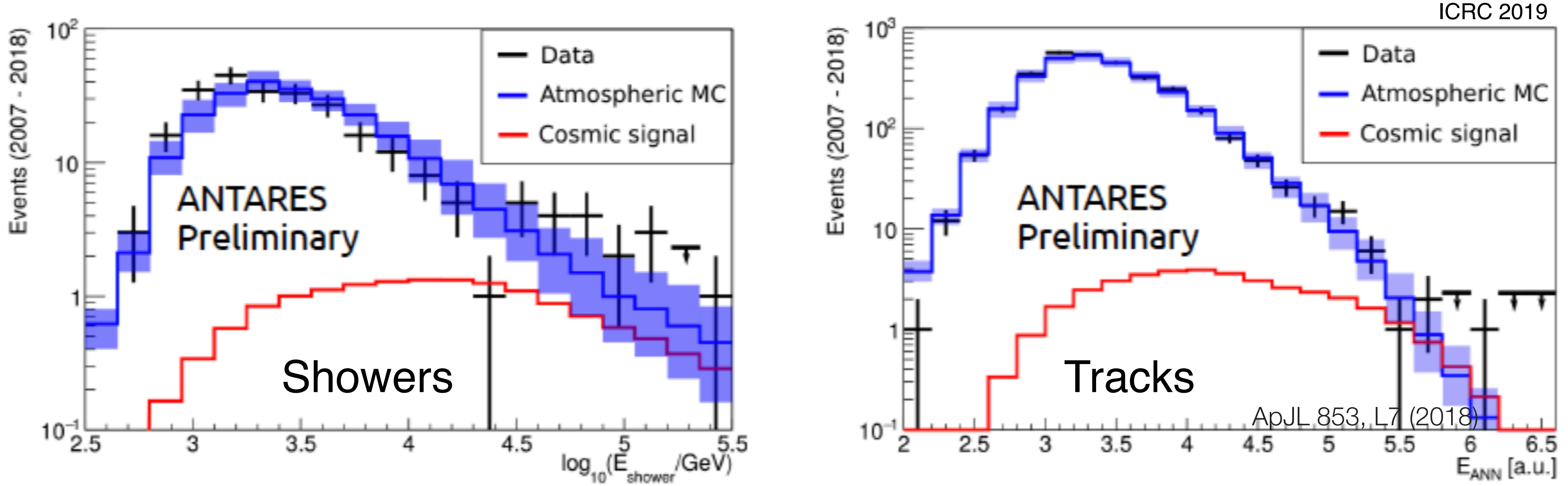


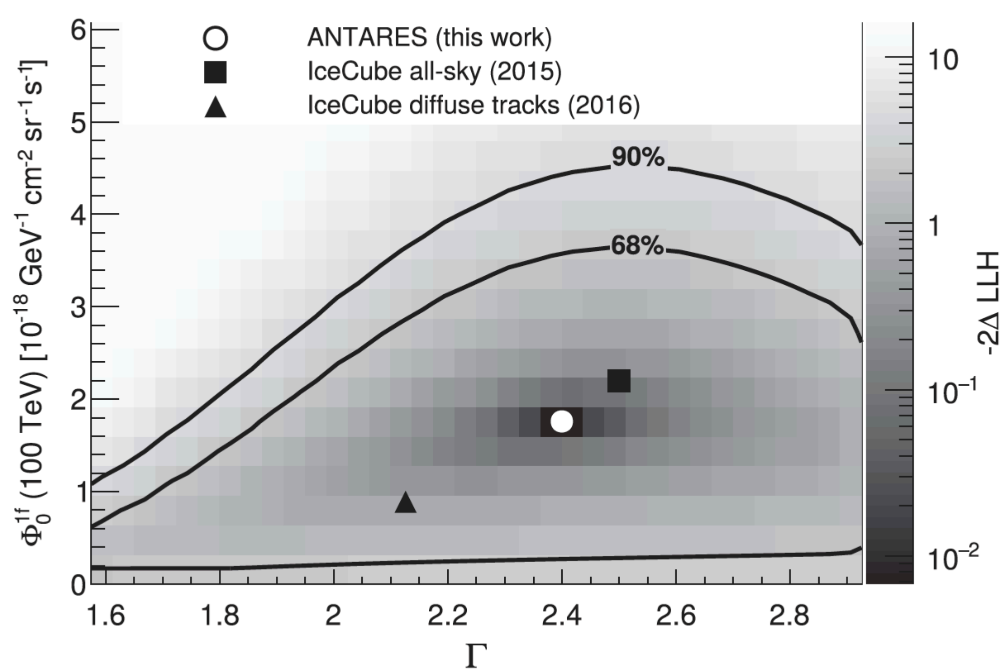


Astrophysical ν signal

Reconstructed events after quality cuts provide 1.6σ excess over background expectations.

ICRC 2019

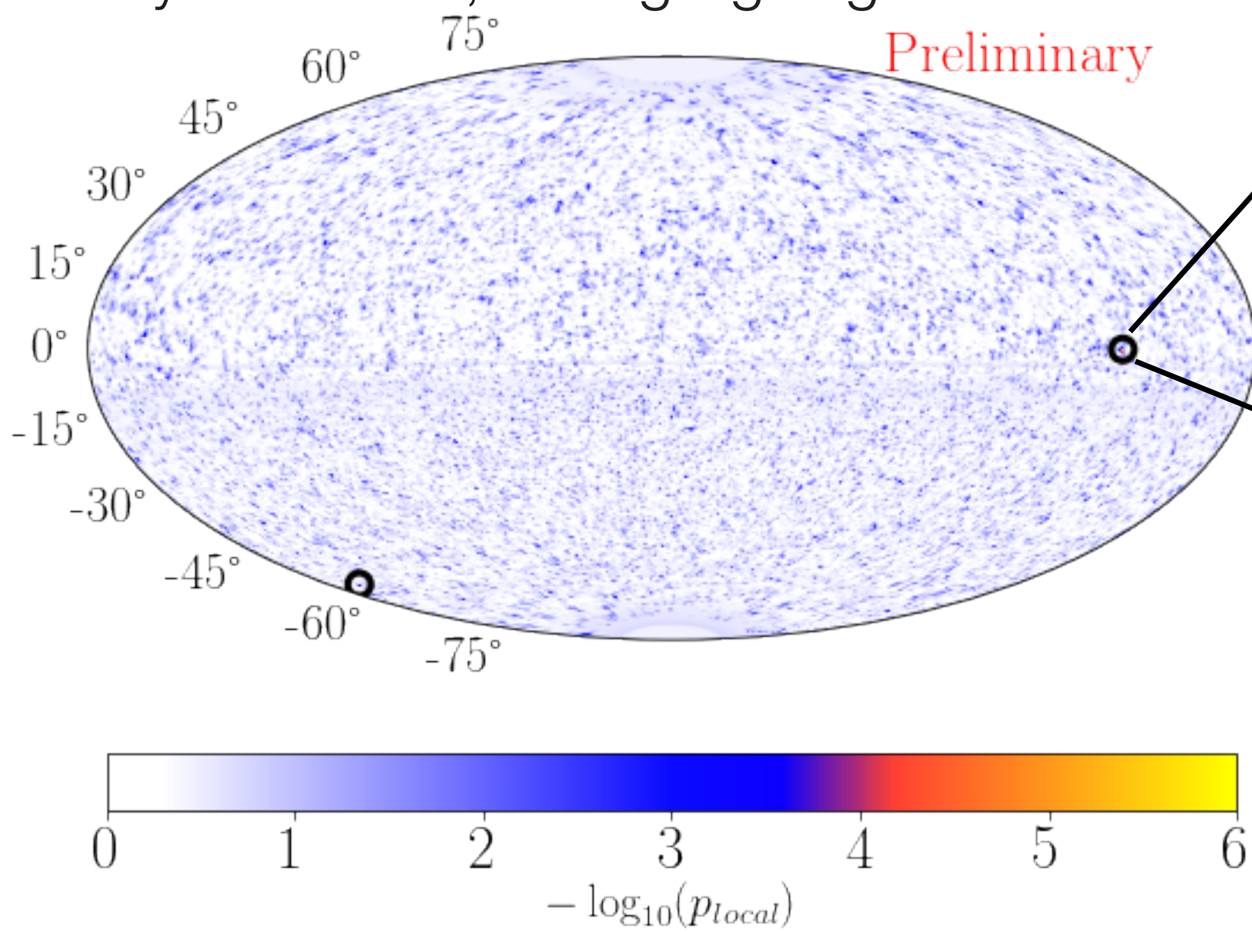


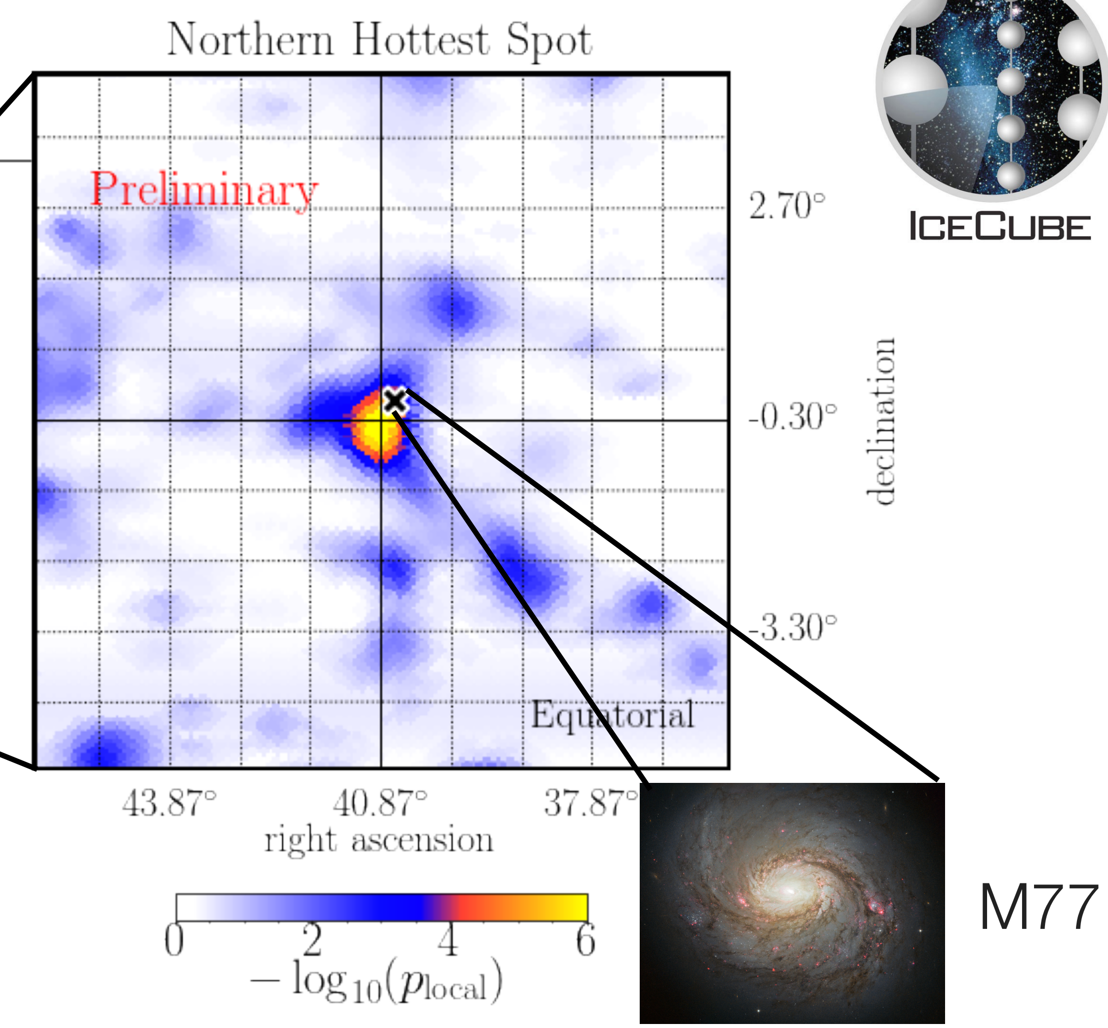


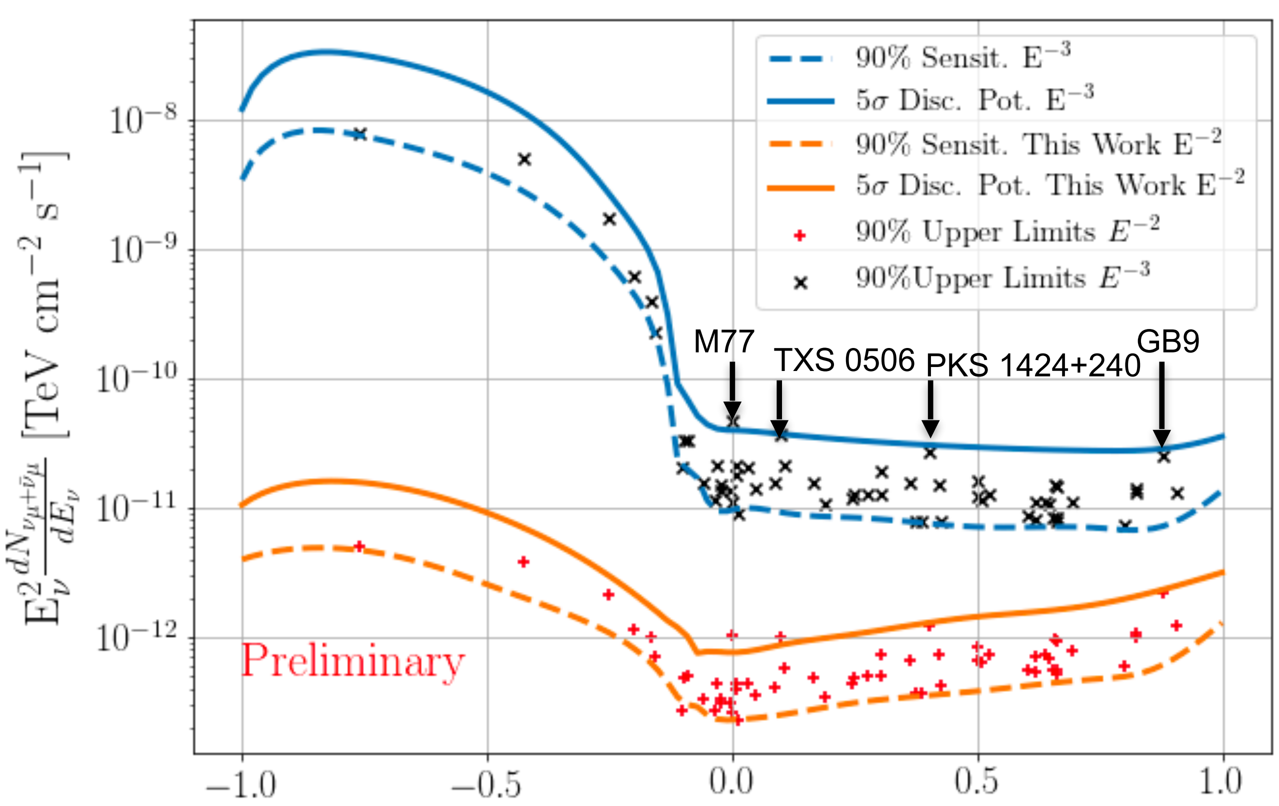
Results are compatible with the measured IceCube diffuse flux.

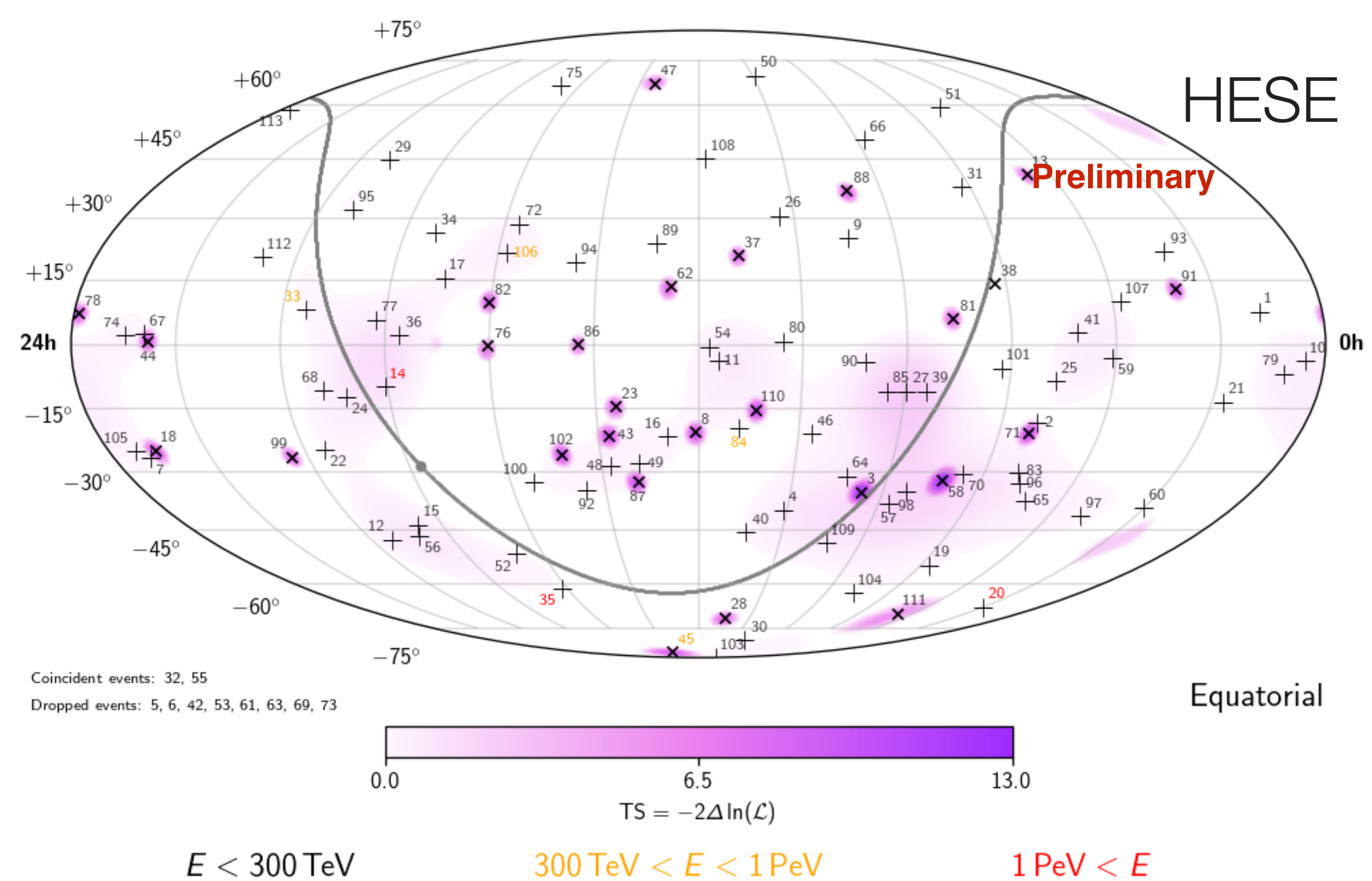
Astrophysical ν signal sources?

10-year search; through-going tracks



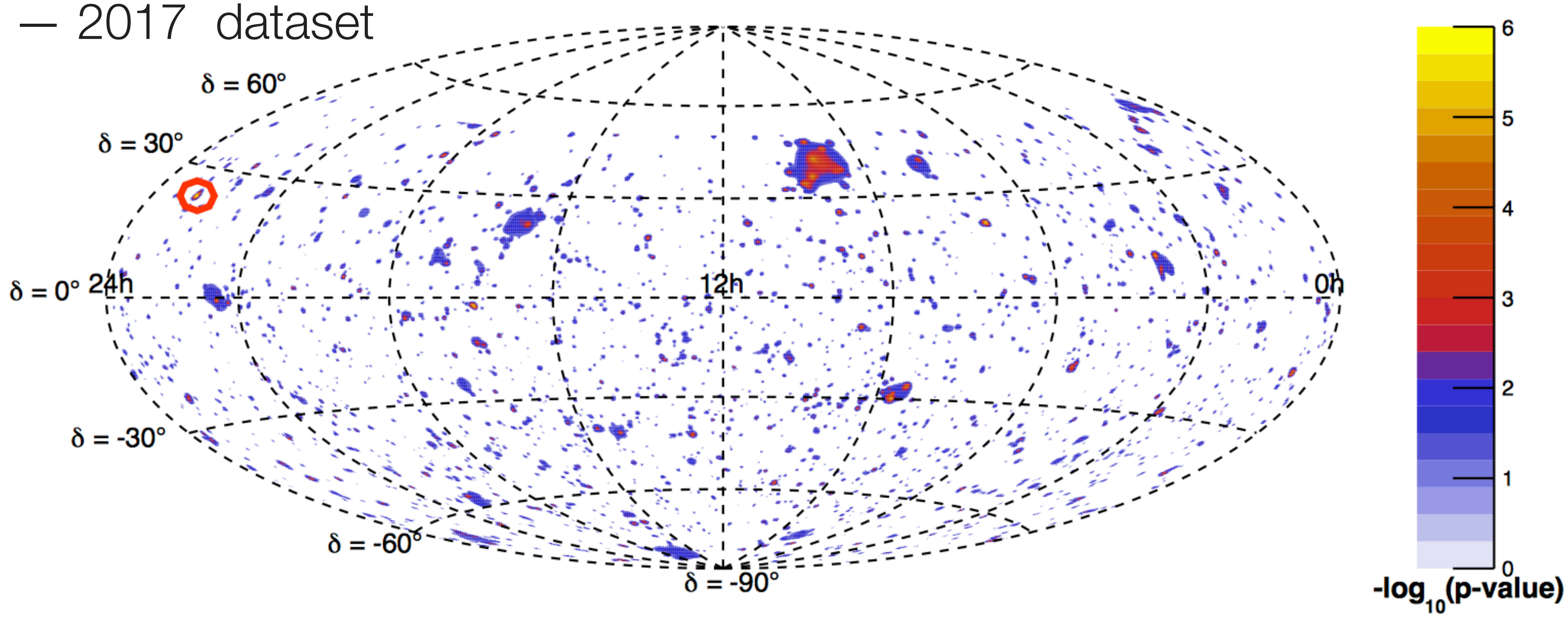




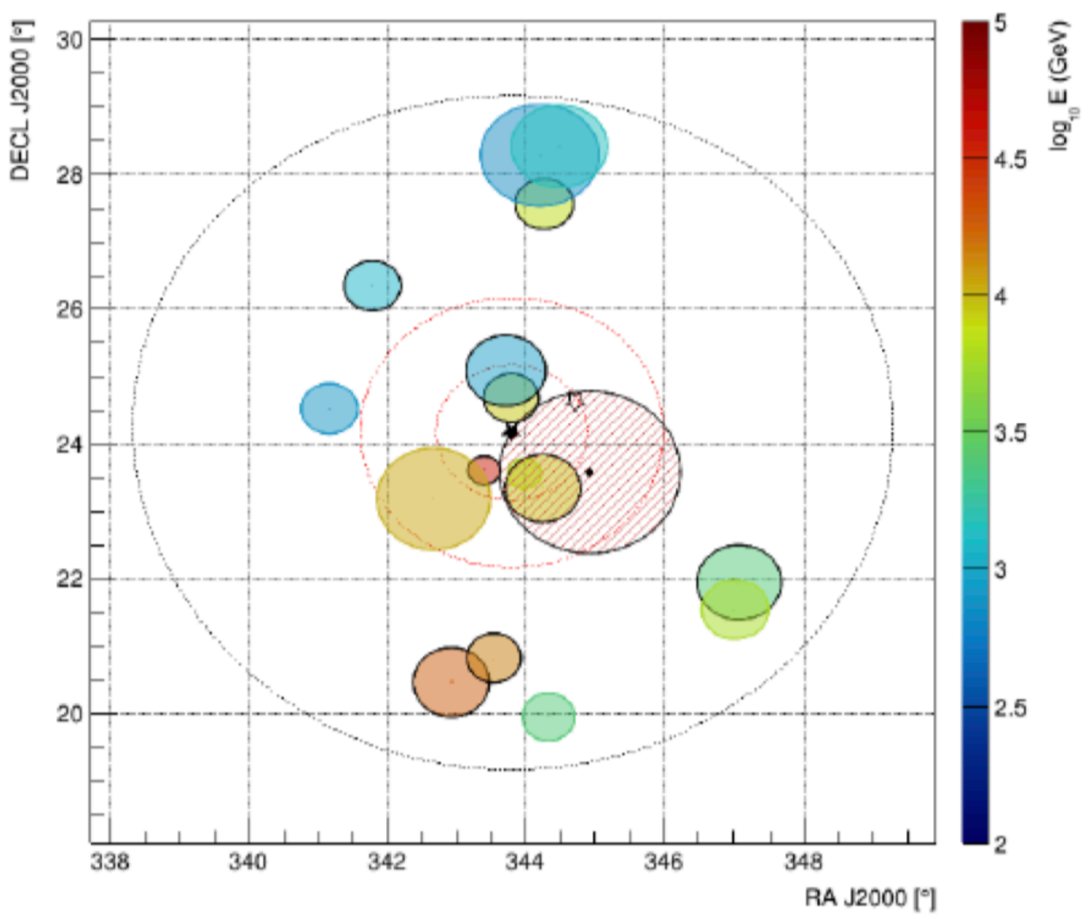


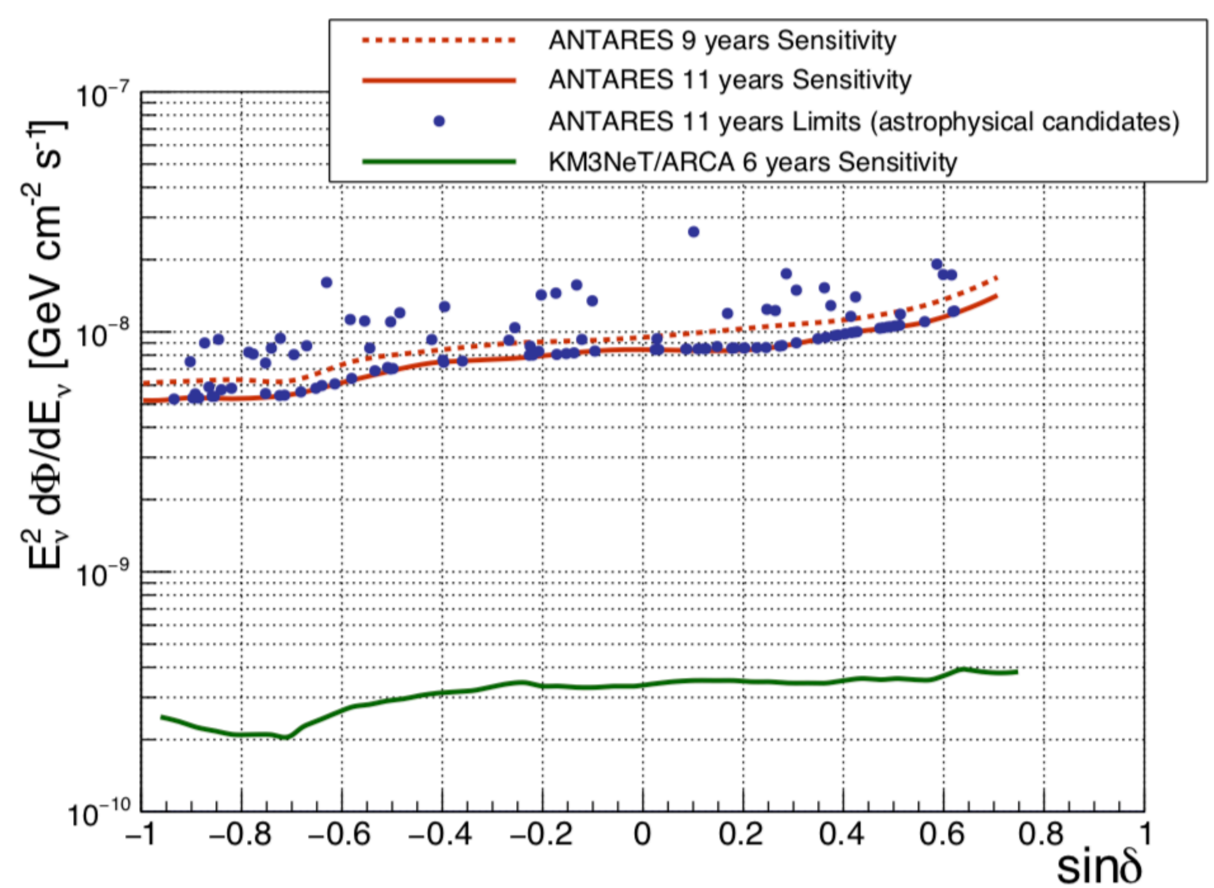
Astrophysical ν signal sources?

2007 — 2017 dataset



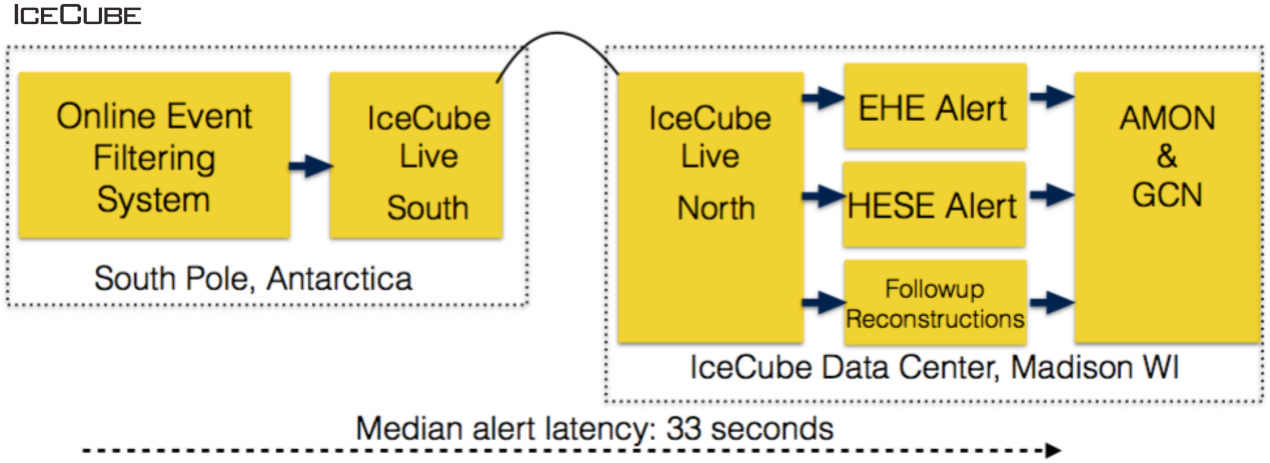
Blazar MG3 J225517+2409



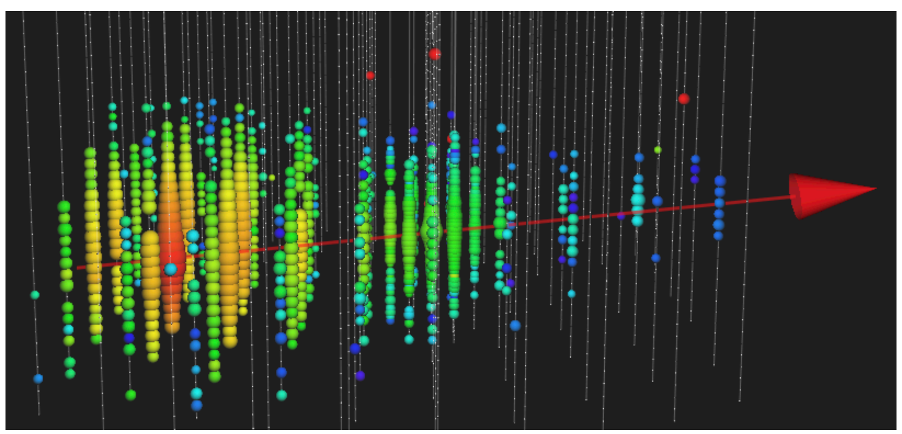


Multi-messenger Astronomy - realtime ν alerts

ICECUBE



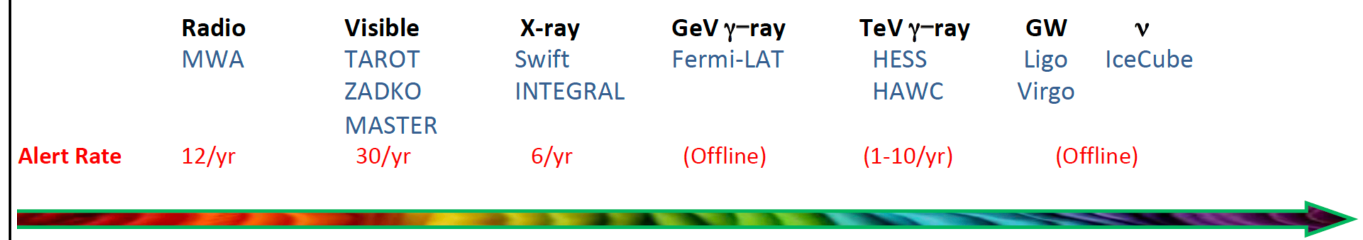
First public alert: IceCube-160427



Improved selection (Summer 2018):

- angular resolution between 0.5 — 2 degrees at 90%
- 50% astrophysical neutrino fraction

	Starting Tracks	Throughgoing tracks
Energy	**> 60 TeV**	**> 500 TeV**
Alerts per year	**4.8**	**4 - 5**
Signal events per year	**1.1**	**2.5 - 4**



Operating since July 2009 (314 alerts sent as of February 2018)

Performance:

- time to issue alert ~5s
- First image of the follow-up < 20s
- Median angular resolution ~0.5 degrees

Rates (approximate):

Neutrino doublets: 0.04 evts/yr

Single neutrinos; direction close to local galaxies (~1 TeV): 10 evts/yr

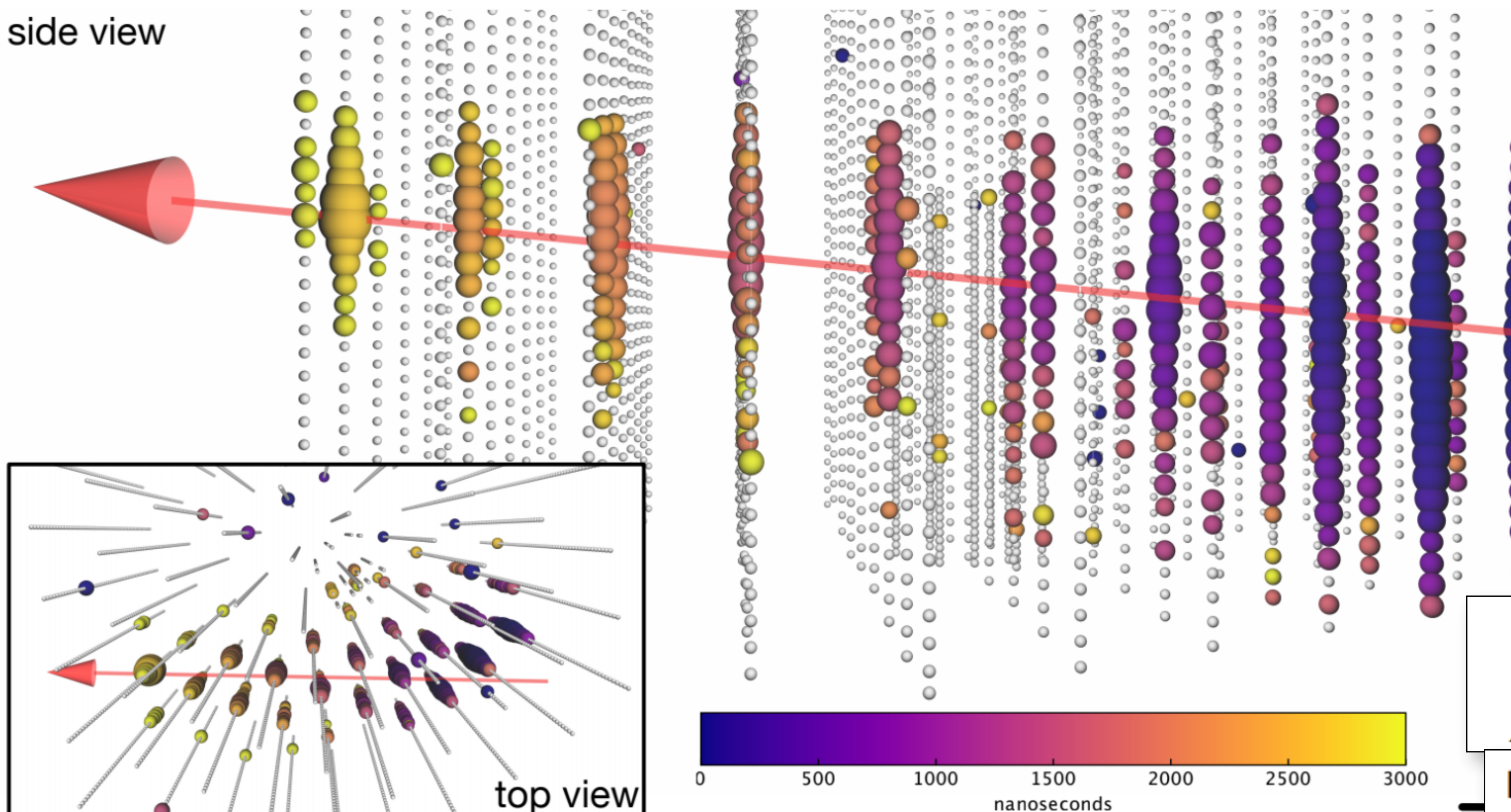
High-energy singles (~5 TeV): 20 evts/yr

Very-high-energy singles (~30 TeV): 3 — 4 evts/yr

Multi-messenger Astronomy - realtime ν alerts

ICECUBE

IceCube-170922A and TXS 0506+056



Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2017; 10:10 UT

Further Swift-XRT observations of IceCube 170922A

ATel #10792; *P. A. Evans (U. Leicester) A. Keivani (PSU), J. A. Kennea (PSU), D. B. Fox (PSU), D. F. Cowen (PSU), J. P. Osborne (U. Leicester), and F. E. Marshall (GSFC) report on behalf of the Swift-IceCube collaboration:*
on 28 Sep 2017; 11:57 UT
Credential Certification: Phil Evans (pae9@star.le.ac.uk)

ASAS-SN optical light-curve of blazar TXS 0506+056, located inside the IceCube-170922A error region, shows increased optical activity

ATel #10794; *A. Franckowiak (DESY), K. Z. Stanek, C. S. Kochanek, T. A. Thompson (OSU), T. W.-S. Holoien, B. J. Shappee (Carnegie Observatories), J. L. Prieto (Diego Portales; MAS), Subo Dong (KIAA-PKU)*

AGILE confirmation of gamma-ray activity from the IceCube-170922A error region

ATel #10801; *F. Lucarelli (SSDC/ASI and INAF/OAR), G. Piano (INAF/IAPS), C.*

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT

Joint Swift XRT and NuSTAR Observations of TXS 0506+056

ATel #10845; *D. B. Fox (PSU), J. J. DeLaunay (PSU), A. Keivani (PSU), P. A. Evans (U. Leicester), C. F. Turley (PSU), J. A. Kennea (PSU), D. F. Cowen (PSU), J. P. Osborne (U. Leicester), M. Santander (UA) & F. E. Marshall (GSFC)*

MAXI/GSC observations of IceCube-170922A and TXS 0506+056

ATel #10838; *H. Negoro (Nihon U.), S. Ueno, H. Tomida, M. Ishikawa, Y. Sugawara, N. Isobe, R. Shimomukai (JAXA), T. Mihara, M. Sugizaki, S. Nakahira, W. Iwakiri, M. Shidatsu, F. Yatabe, Y. Takao, M. Matsuoka (RIKEN), N. Kawai, S. Sugita, T. Yoshii, Y. Tachibana, S. Harita, K. Morita (Tokyo Tech), A. Yoshida, T. Sakamoto, M. Serino, Y. Kawakubo, Y. Kitaoka, T. Hashimoto (AGU), H. Tsunemi, T. Yoneyama (Osaka U.), M. Nakajima, T. Kawase, A. Sakamaki (Nihon U.), Y. Ueda, T. Hori, A.*

VLA Radio Observations of the blazar TXS 0506+056 associated with the IceCube-170922A neutrino event

ATel #10861; *A. J. Tetarenko, G. R. Sivakoff (UAlberta), A. E. Kimball (NRAO), and J. C.A. Miller-Jones (Curtin-ICRAR)*
on 17 Oct 2017; 14:08 UT

```
TITLE:   GCN CIRCULAR
NUMBER:  21916
SUBJECT: IceCube-170922A - IceCube observation of a high-en
neutrino candidate event
[…]
On 22 Sep, 2017 IceCube detected a track-like, very-high-ener
event with a high probability of being of astrophysical origi
event was identified by the Extremely High Energy (EHE) track
selection. The IceCube detector was in a normal operating state
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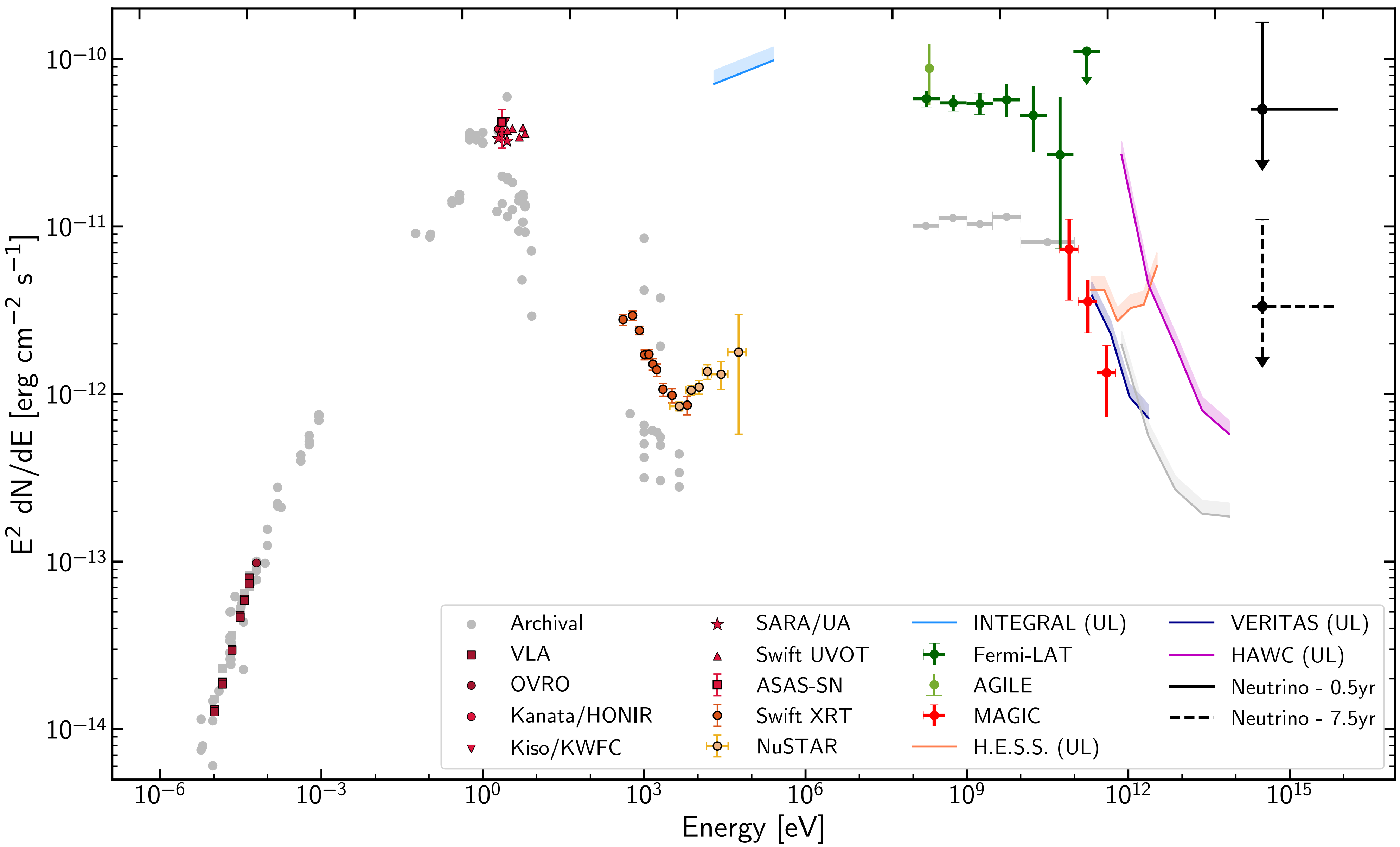
Multi-messenger Astronomy - realtime ν alerts

Spectral Energy Distribution — Sept/Oct 2017

Science 361, eaat1378 (2018)

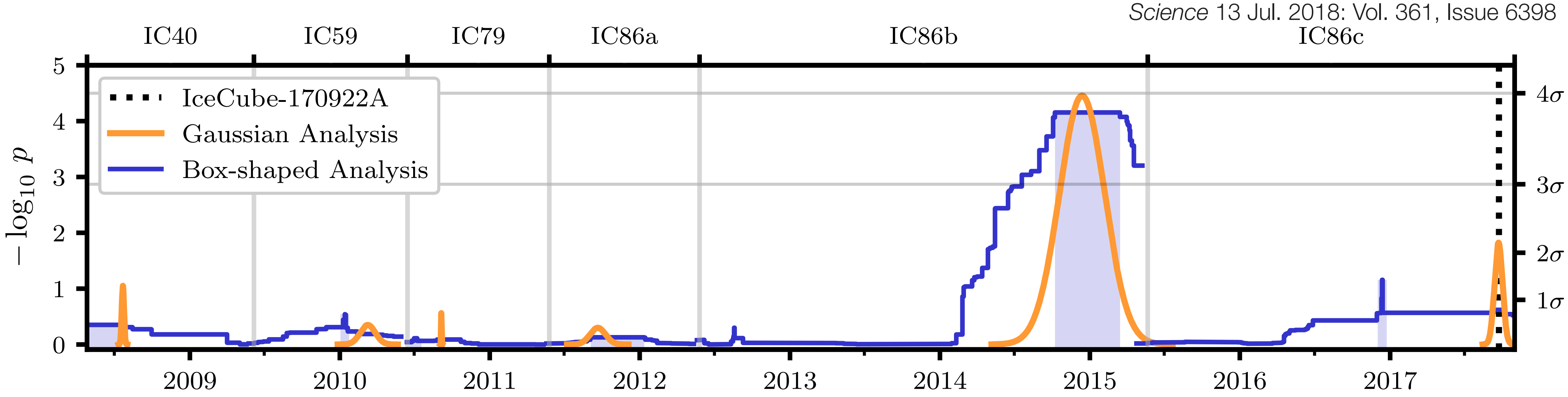


- Extensive broad-band follow-up measurements
- Inferred ~300 TeV neutrino emission has νF_ν of same order as HE / VHE gamma rays
- NB: observations <u>not</u> strictly contemporaneous

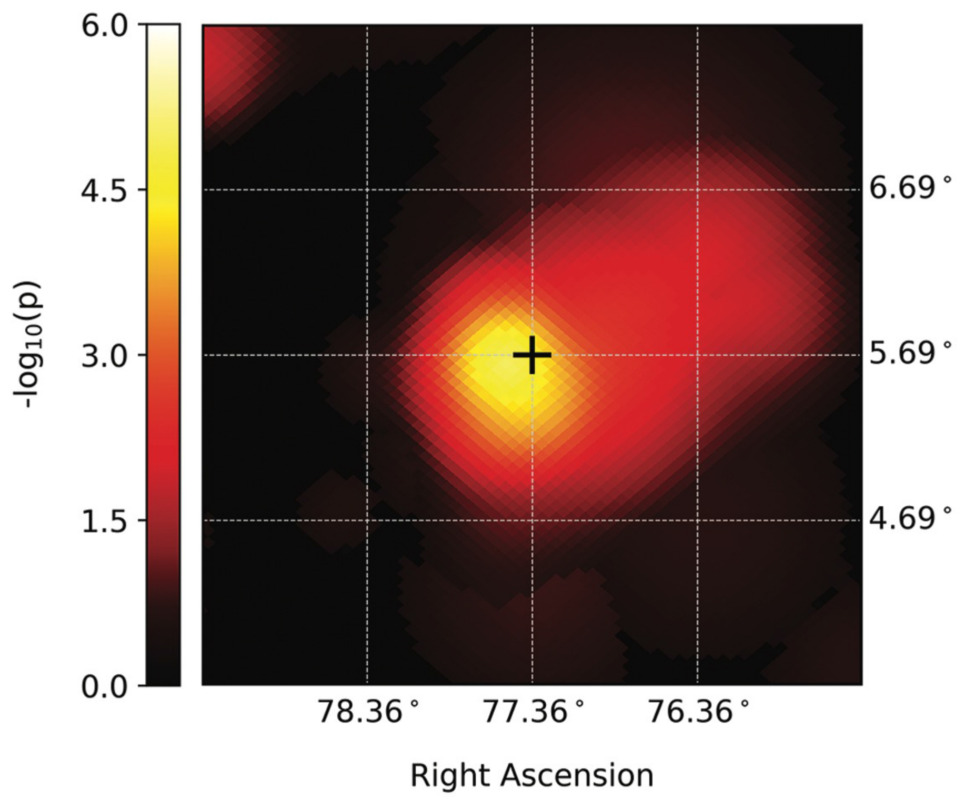
Multi-messenger Astronomy - realtime ν alerts

IceCube-170922A and TXS 0506+056

Science 13 Jul. 2018: Vol. 361, Issue 6398



- IceCube evaluated 9.5 years of archival data in the direction of TXS 0506+056
- 13 +/- 5 events excess compared to background expectations in 150 day period (September 2014 thru March 2015)
- Inconsistent with background only hypothesis at 3.5σ level (Gaussian window)
- Time-integrated neutrino spectrum is approximately E-2.1; flux over 9.5 years corresponds to ~ 1% of the diffuse neutrino flux
- Indications of gamma ray spectrum hardening during that time (Padovani *et al.*)

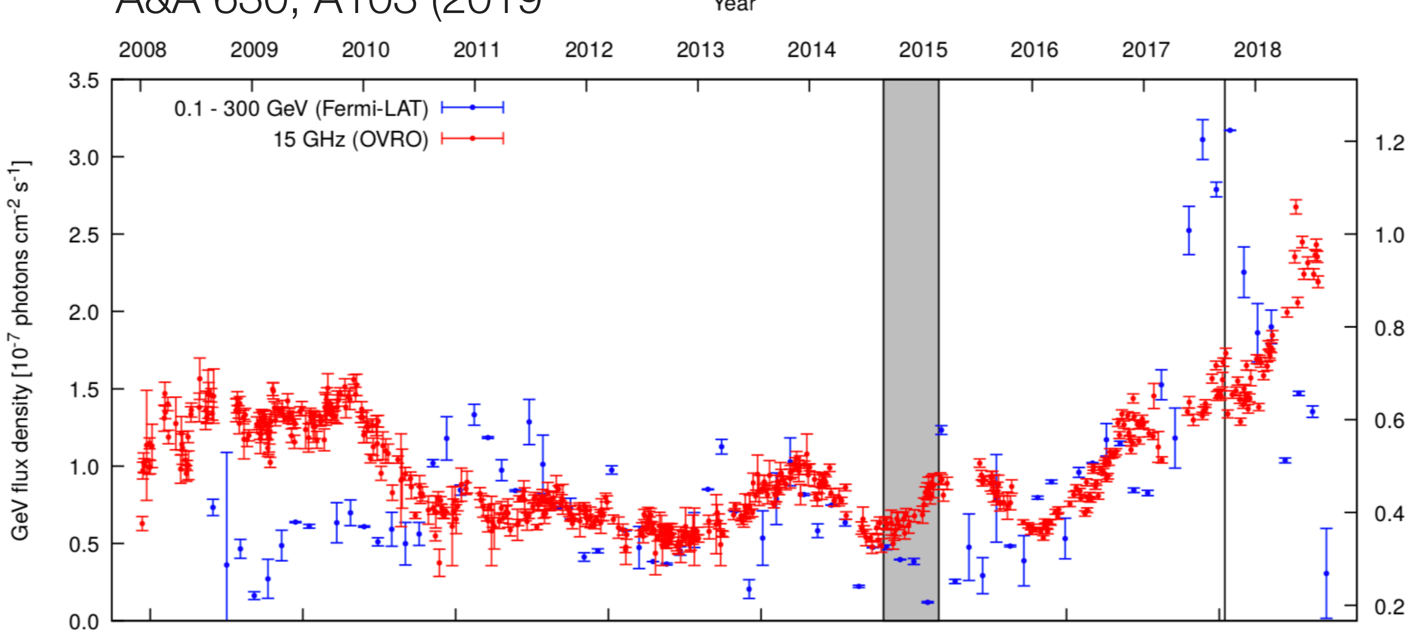


Multi-messenger Astronomy - realtime ν alerts

IC-170922A/TXS 0506+056

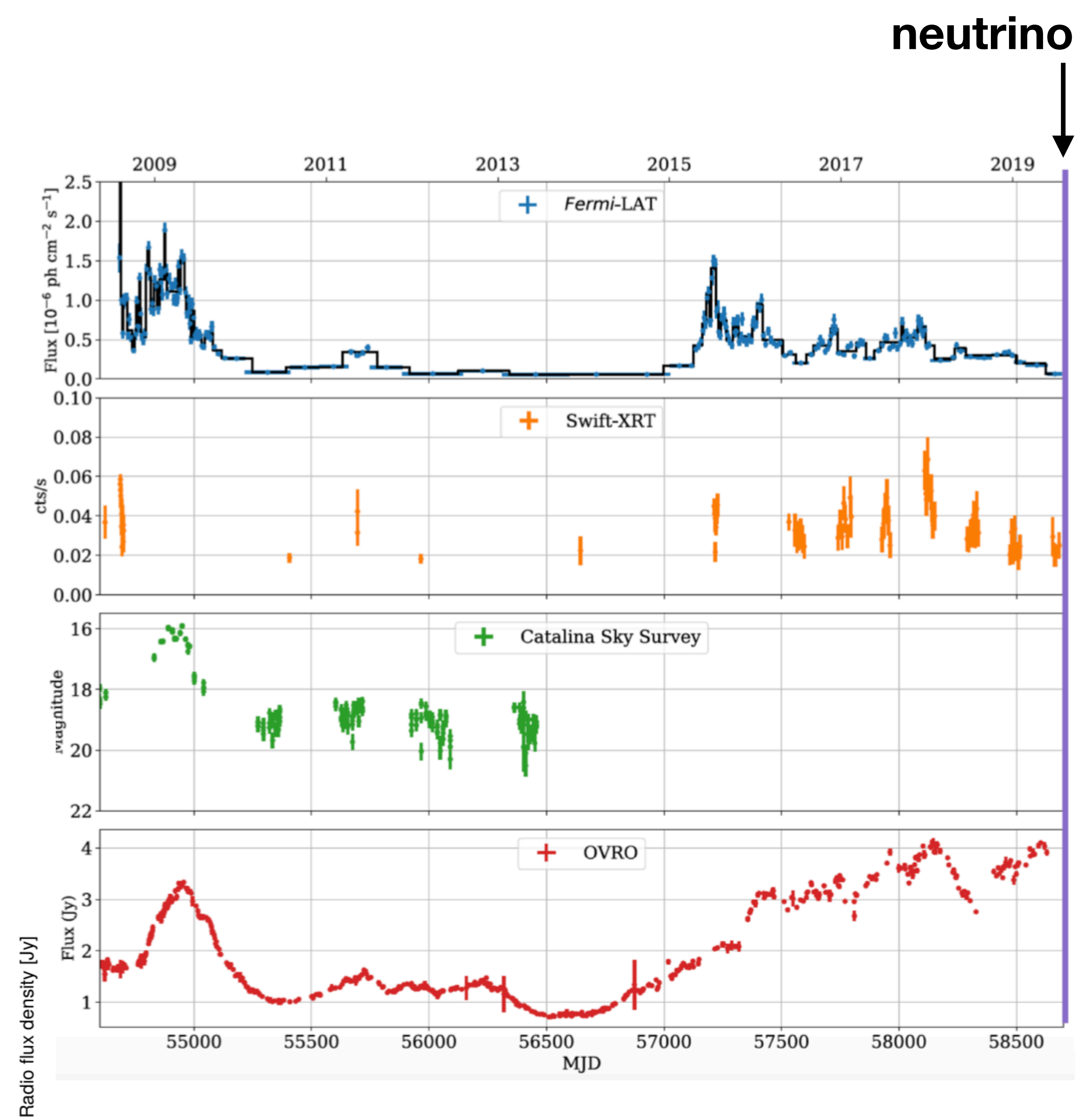
- TXS 0506+056 redshift of z = 0.3365
  (S. Paiano *et al.* ApJL 854, L32 (2018).)
- time-averaged luminosity an order of magnitude higher than Mkn 421, Mkn 501, or 1ES 1959+605
- VLBA high resolution measurements indicate TXS may be a rare pc-scale 2-jet AGN formed following a merger

A&A 630, A103 (2019



IC-190730A/PKS 1502+106

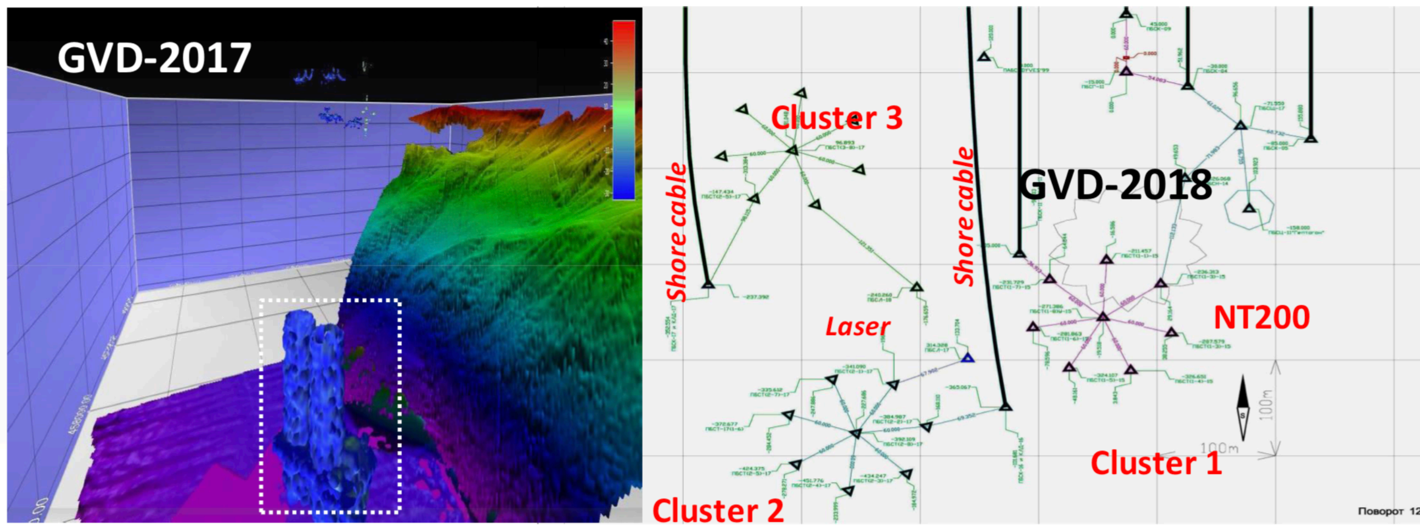
- 11th brightest blazar in the GeV sky

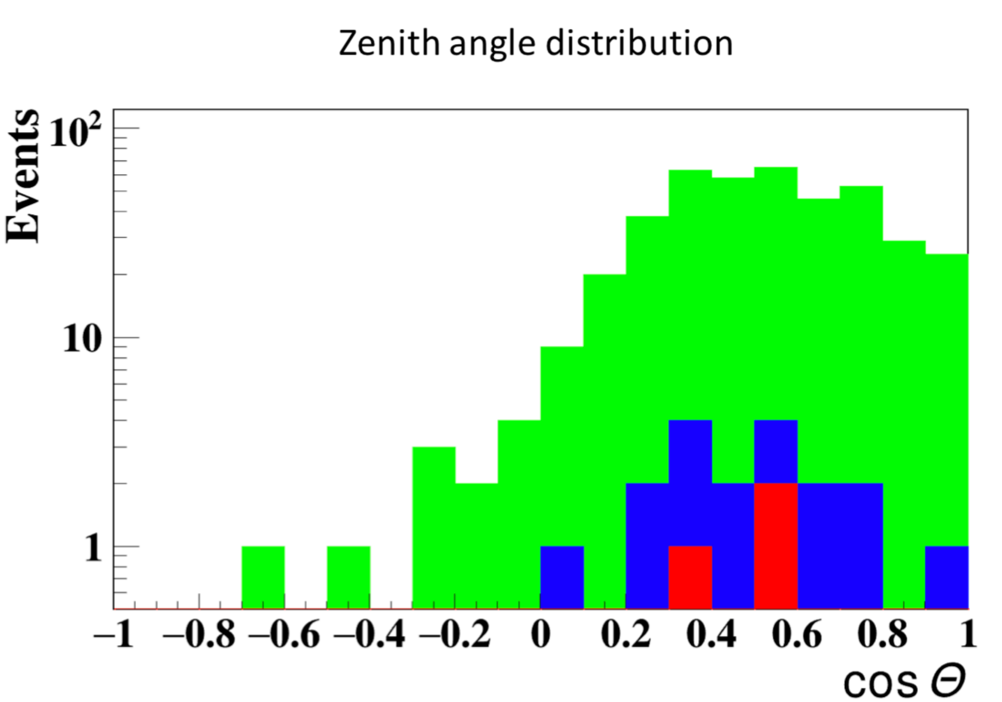


Future outlook

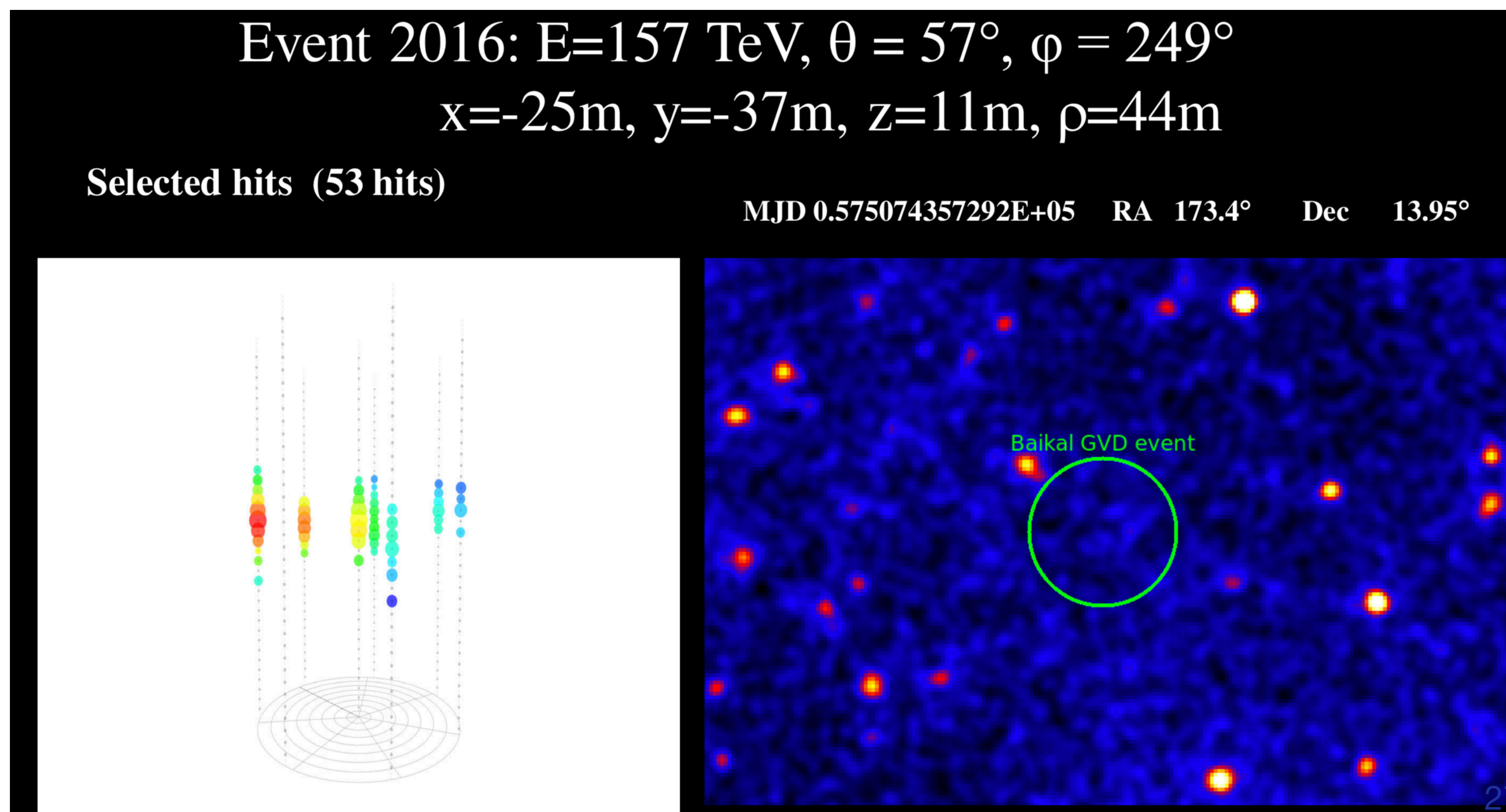
ICRC 2019

Configuration	2016	2017	2018	2019
The number of OMs	288 (8str×36)	576	864	1 440
Geometric sizes	∅120m×525m	2×∅120m×525m	3×∅120m×525m	5×∅120m×525m
Eff. Vol. (E > 100TeV)	0.05 km^3	0.1 km^3	0.15 km^3	0.25 km^3

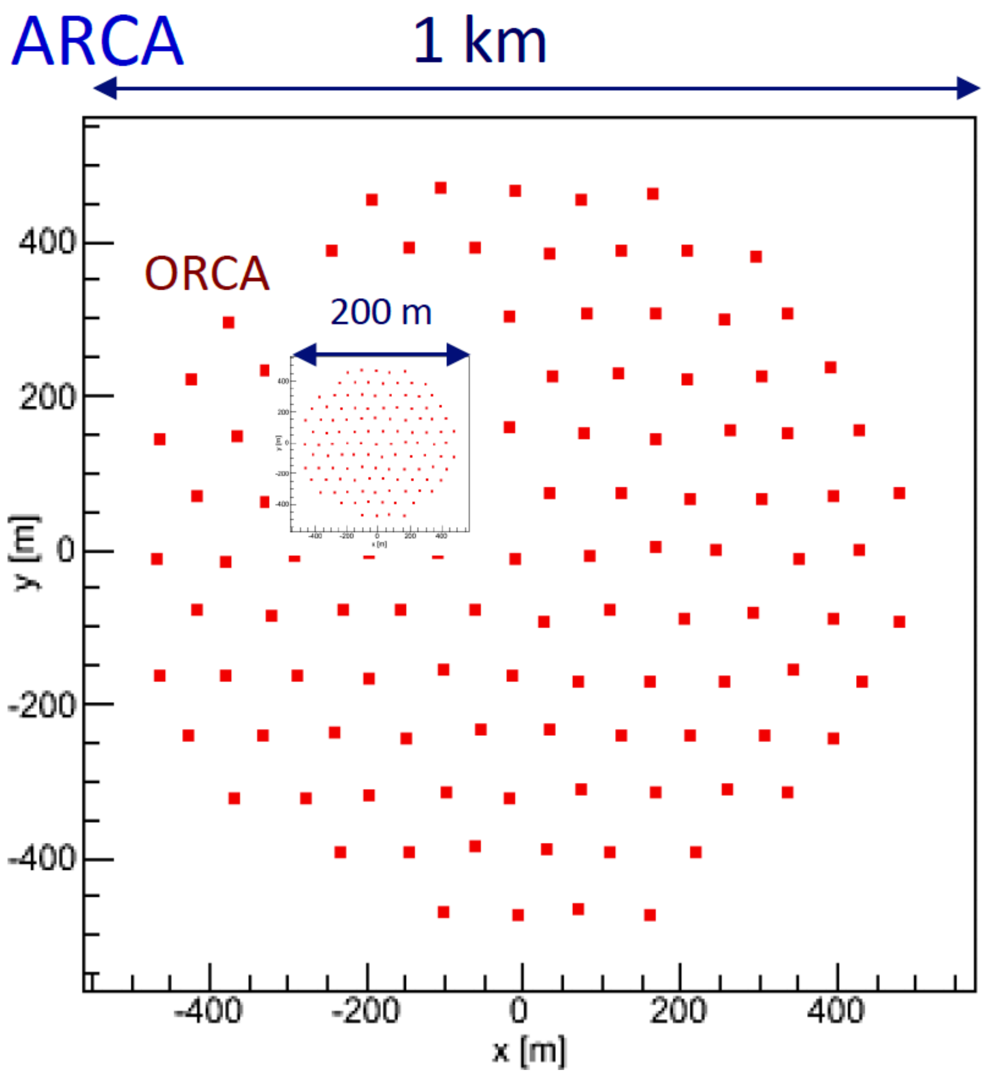




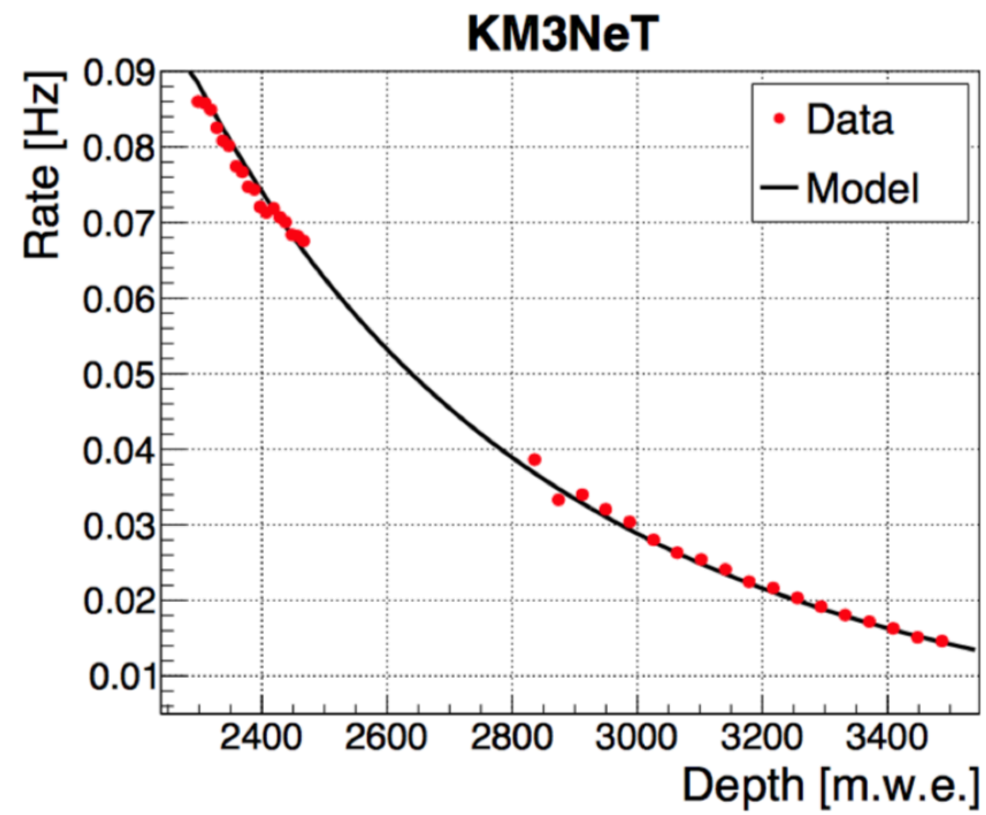
https://www.icrc2019.org/uploads/1/1/9/0/119067782/gvd_cascades_2019_dvornicky.pdf

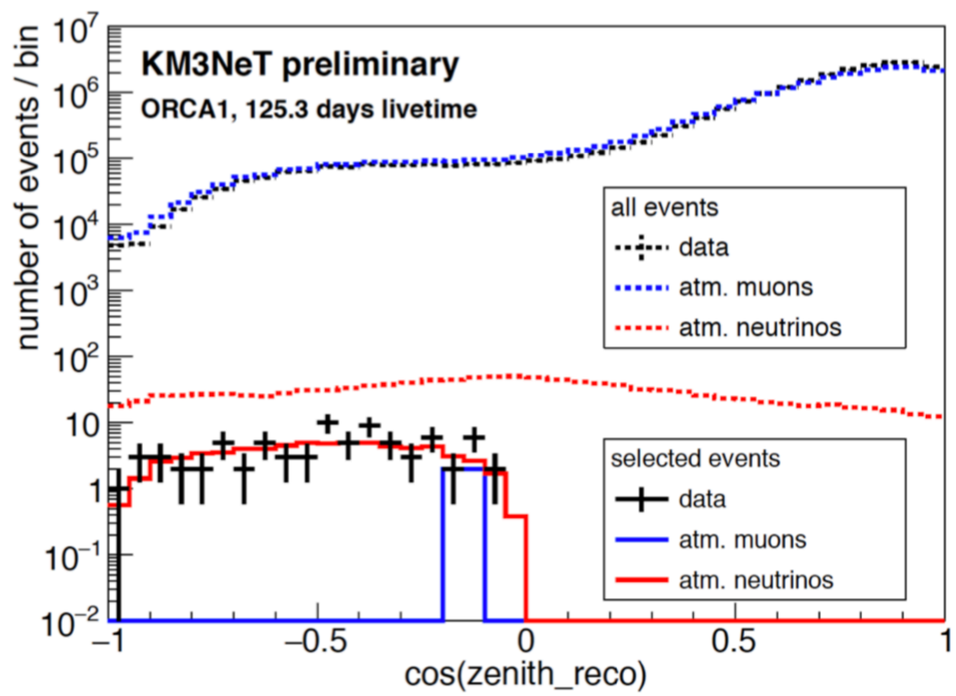


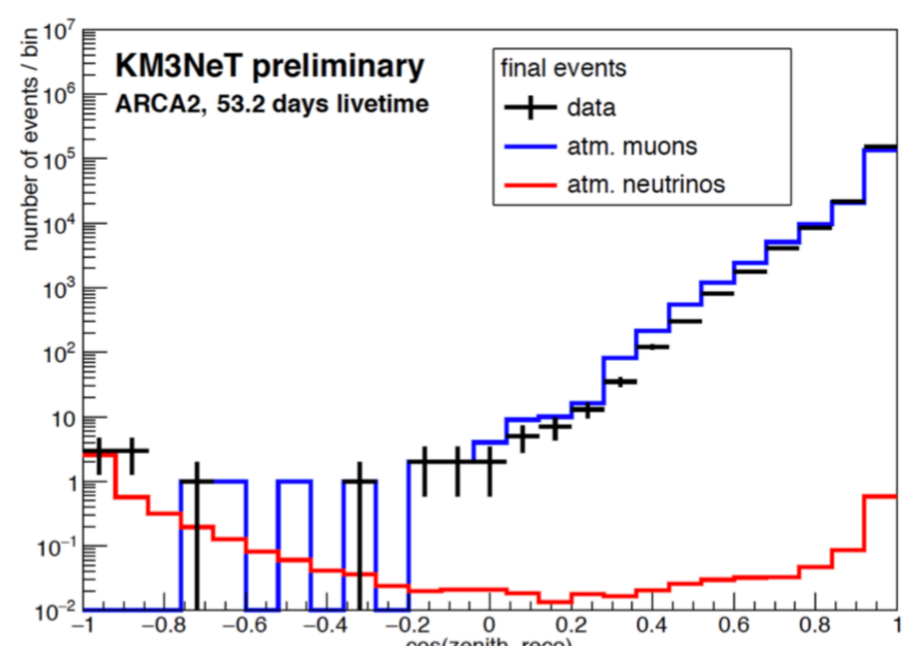
Future outlook



- Anticipated deployment of full project scope 2019 — 2021.



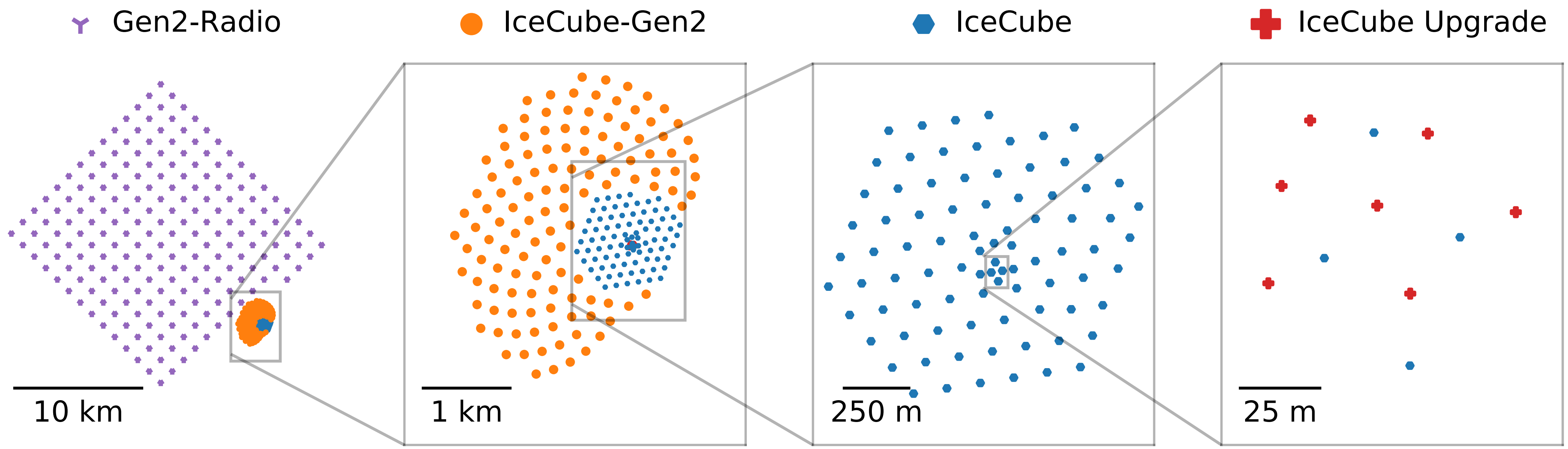




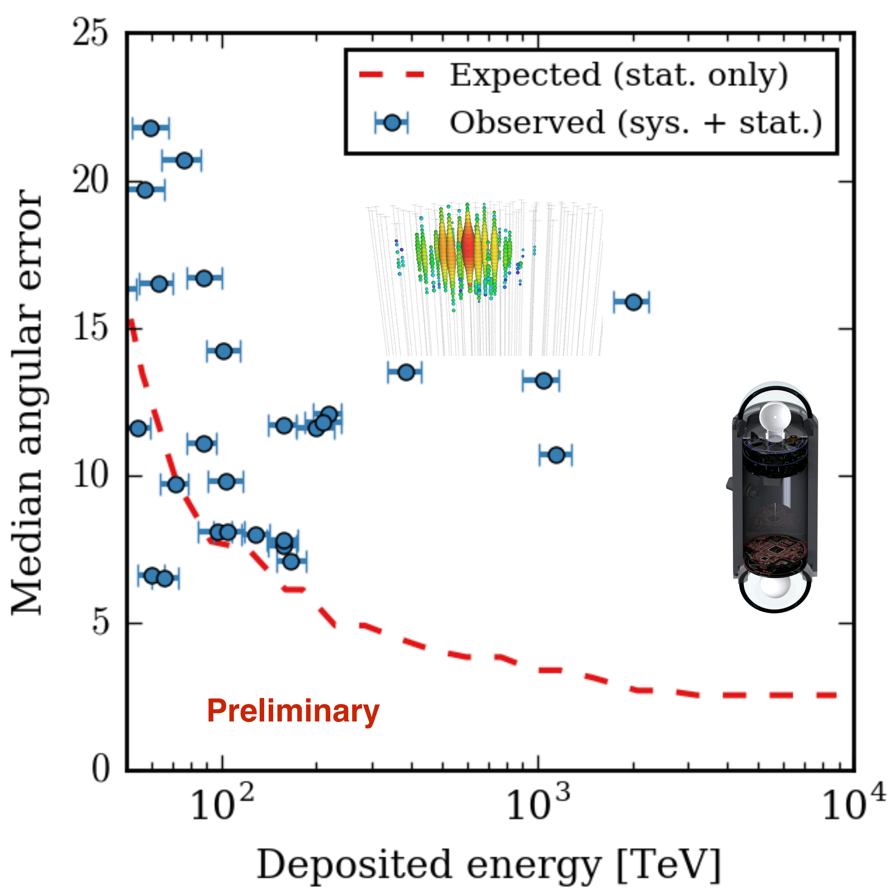
https://pos.sissa.it/358/006/pdf

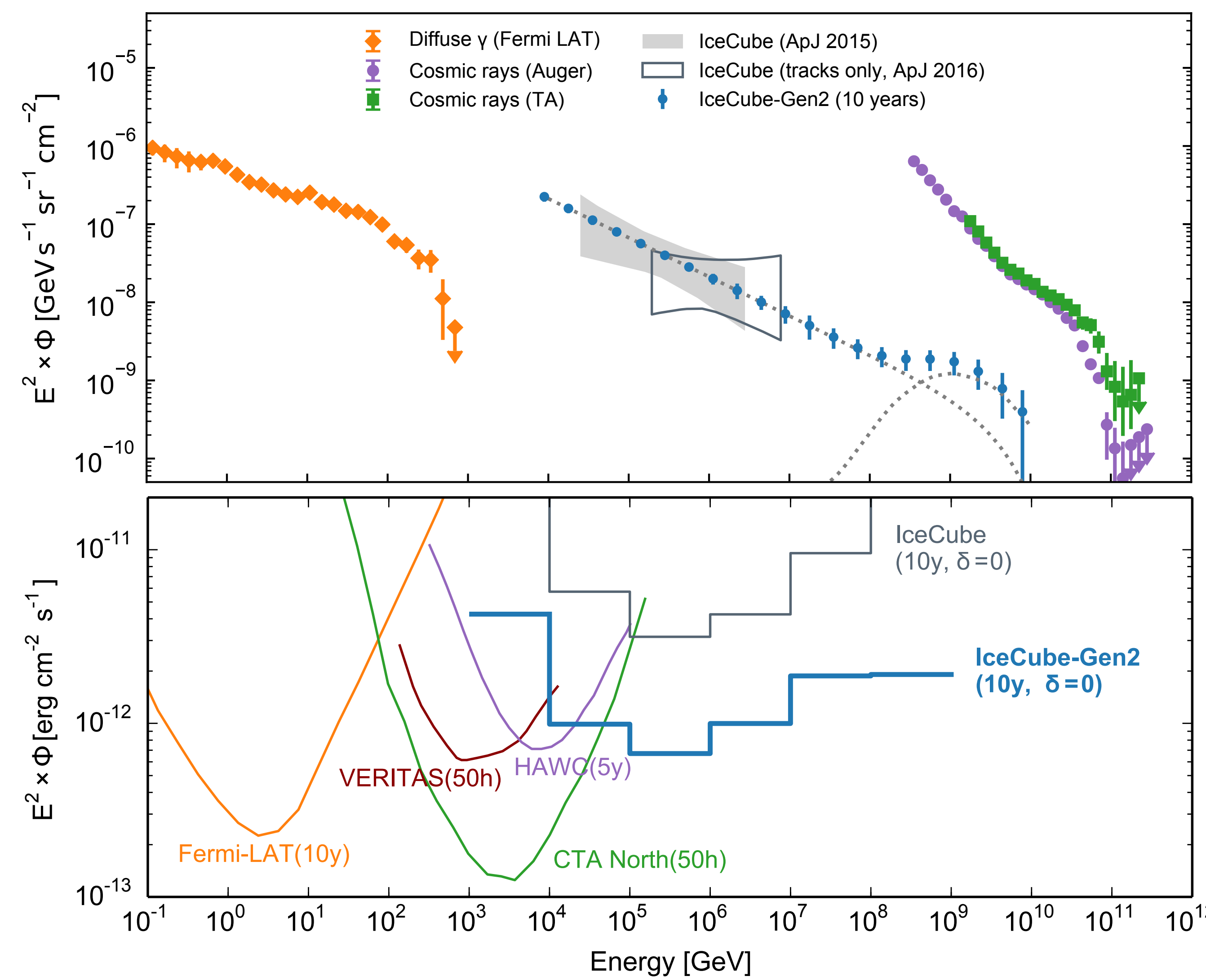
Future outlook

The IceCube Gen2 Facility



The Upgrade precision re-calibration program





Summary

From discovery to astronomy…

Photo credit: R. Busse/NSF

Summary

From discovery to astronomy…

The discovered high-energy cosmic neutrino flux is robust

- energy density similar to that of gamma rays and cosmic rays

Neutrinos have entered the game of multi-messenger astronomy

- a broad multi-wavelength followup campaign of IC-170922A provided evidence identifying a cosmic ray accelerator

Global program underway to develop new and enhanced neutrino observatories*

- opening a new window through which to study the extreme universe; from fundamental neutrino properties to cosmic accelerators

*including new exploration of a deep ocean via the P-ONE project associated with Ocean Networks Canada

Photo credit: R. Busse/NSF

Thank you for your attention!

DESY Science Communication Lab

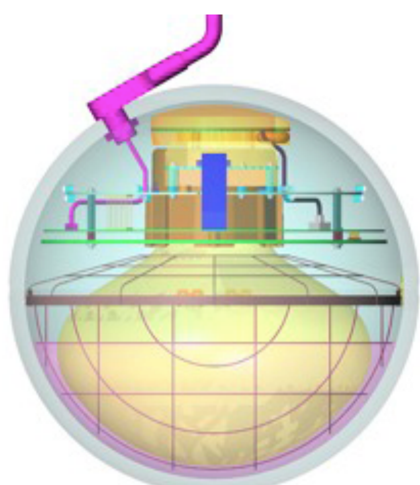
Backup Slides

The IceCube Neutrino Observatory

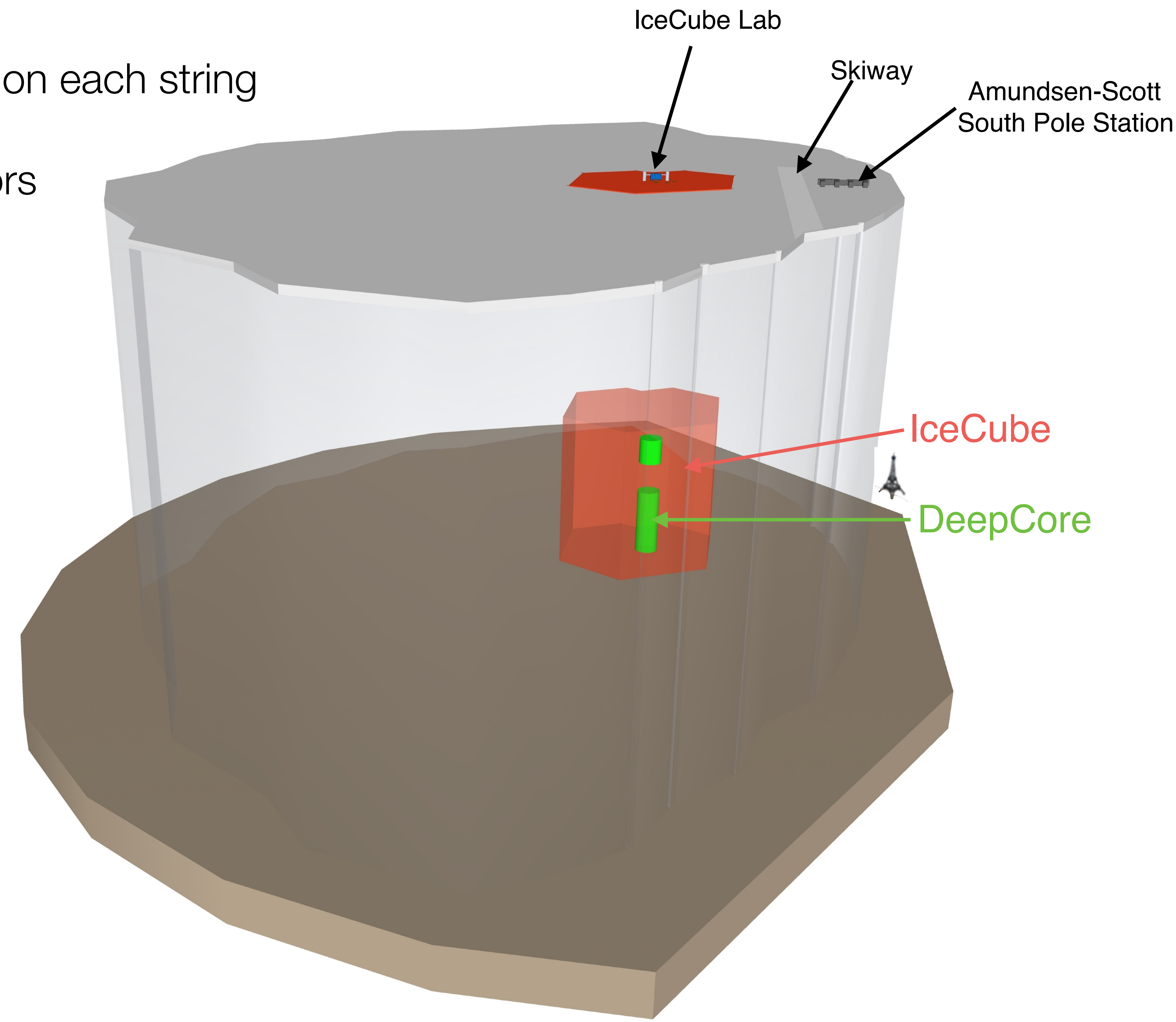
IceCube Array
86 total strings, including 8 DeepCore strings

60 optical sensors on each string

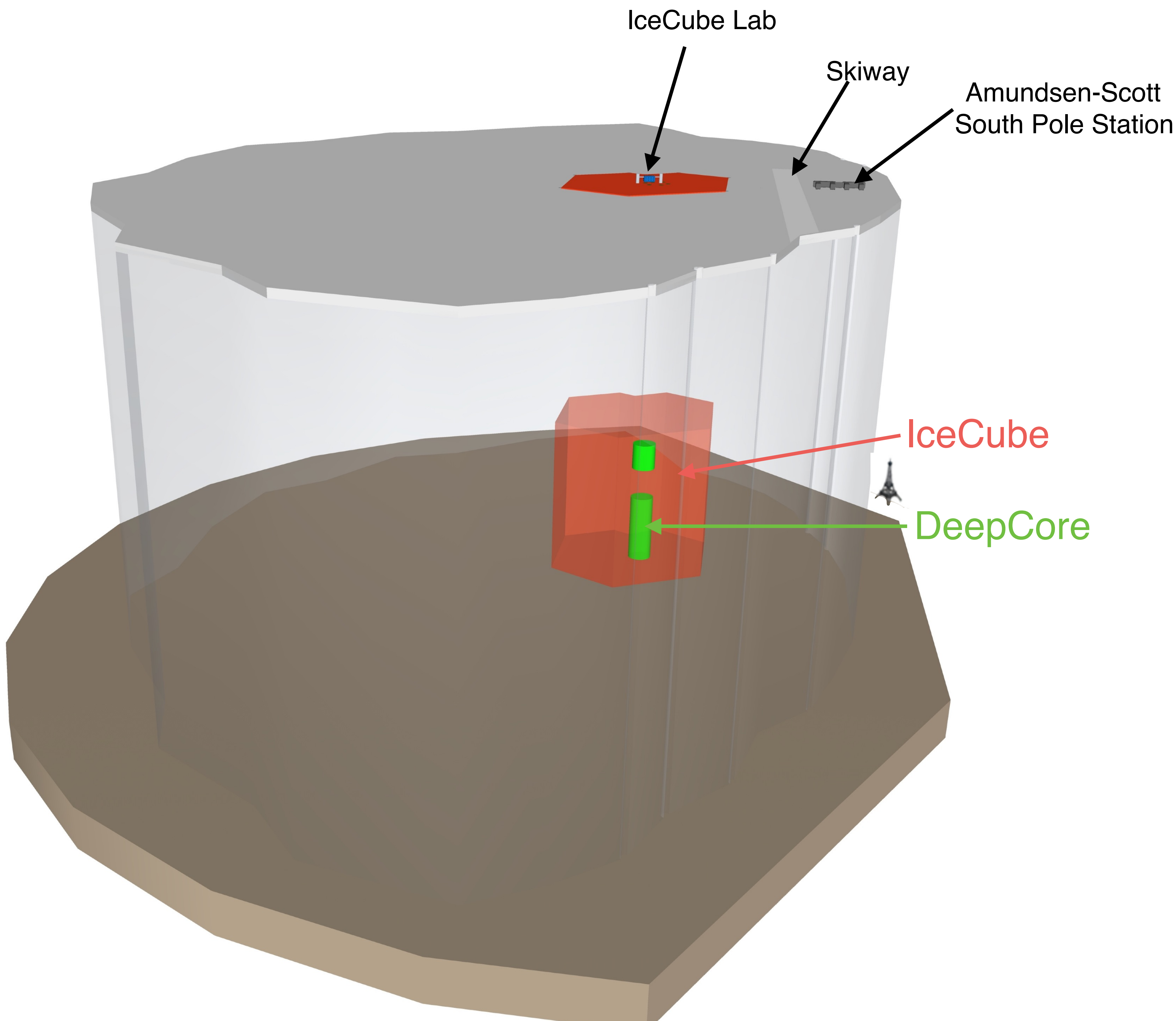
5160 optical sensors



Digital Optical Module

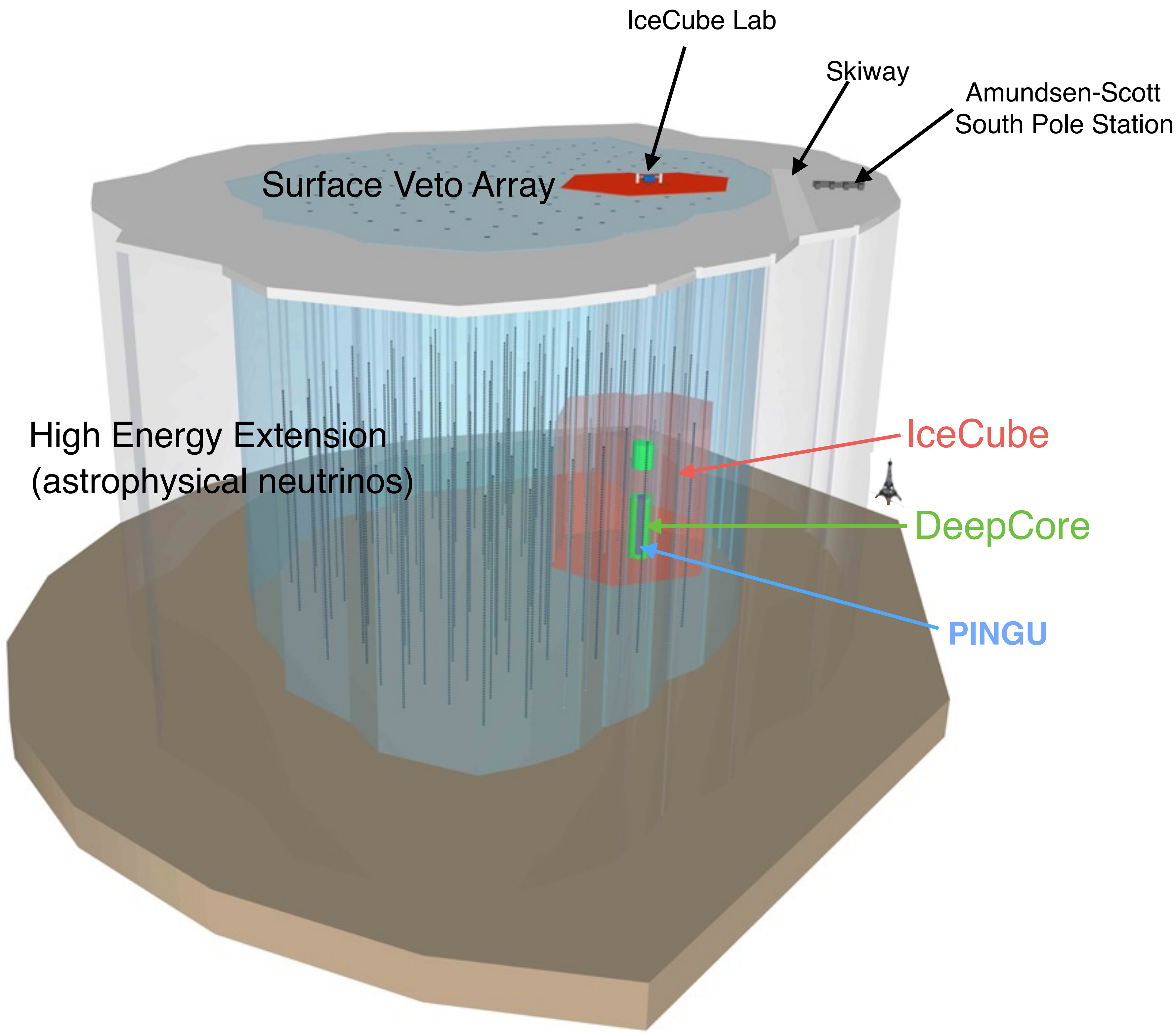


The IceCube Neutrino Observatory



X

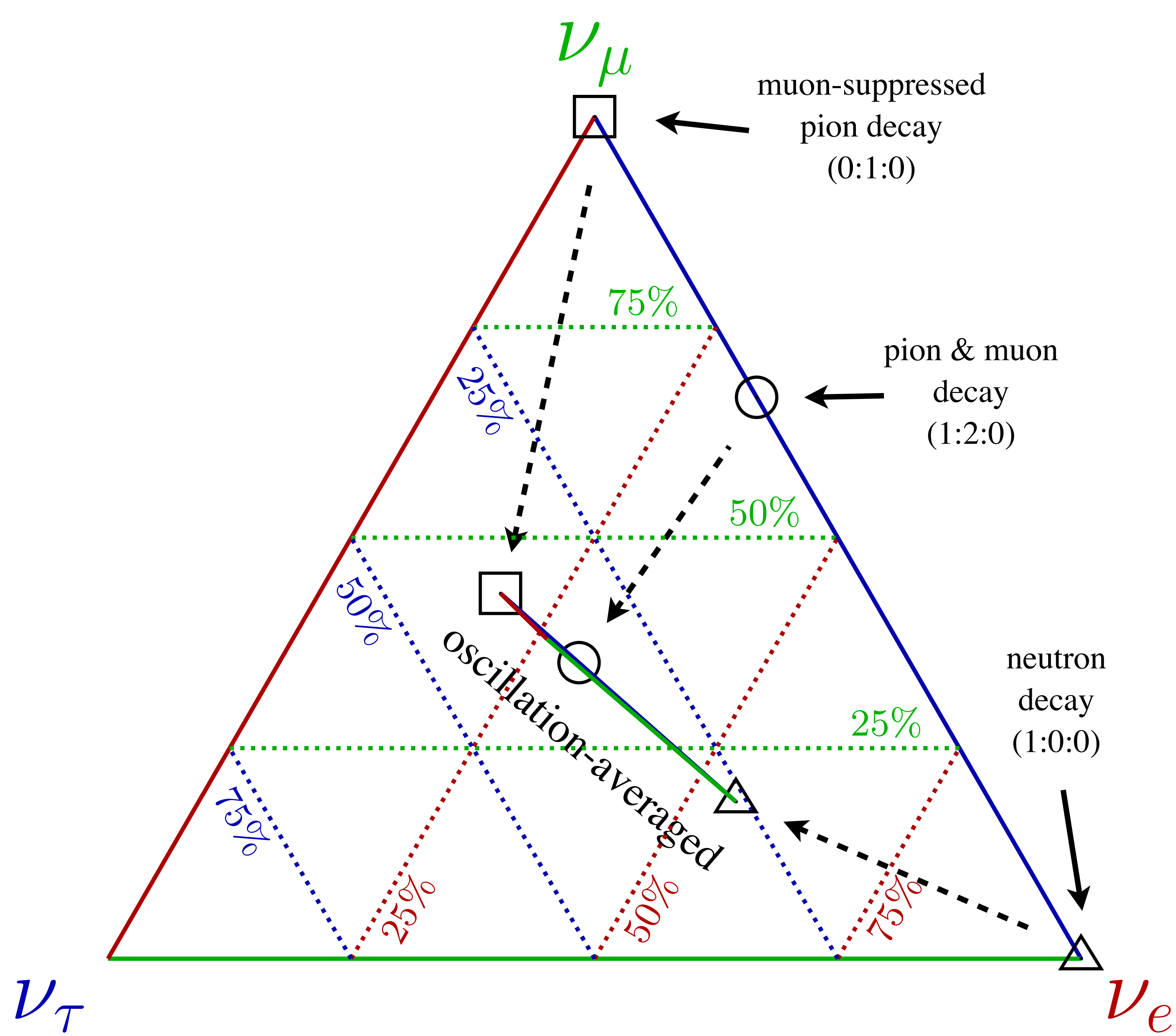
The IceCube Neutrino Observatory - Generation 2



x

Astrophysical ν signal - flavour component

- Studying the flavour components of the neutrino signal can tell you about neutrino production in the source environment
  - Neutrino oscillations complicate this



Astrophysical ν signal - flavour component

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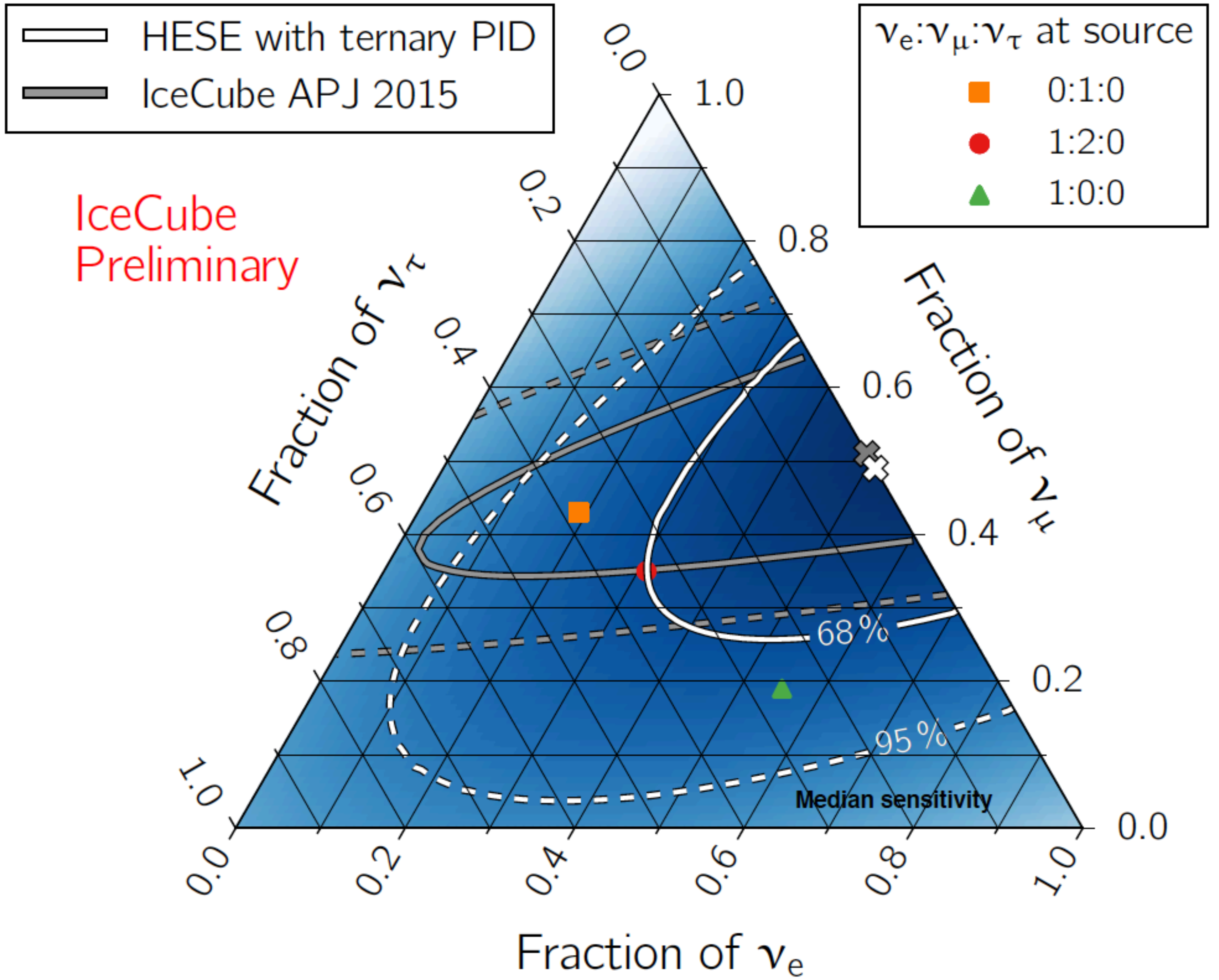
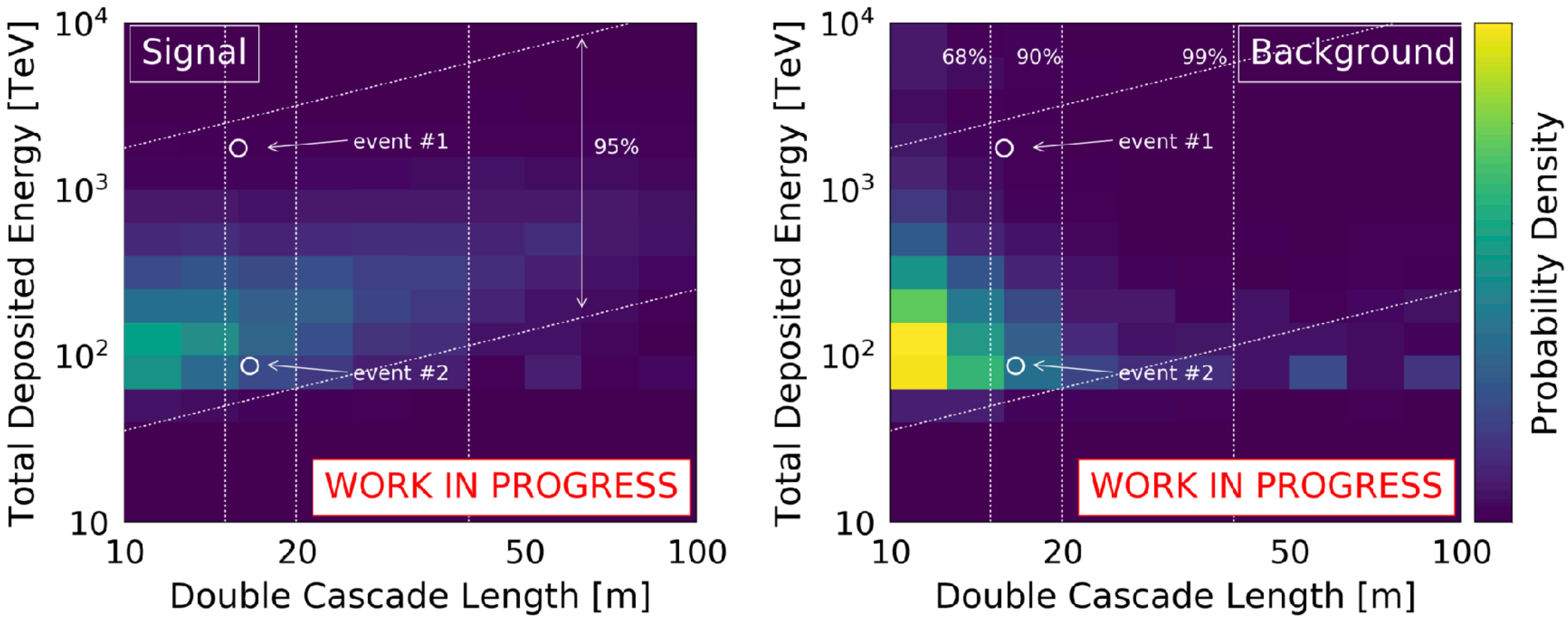


Astrophysical ν signal - flavour component

From the most recent 7.5 year HESE analysis…



Events reconstructed looking for evidence they contain 2 cascades

Two double cascade events have been identified

Double cascades can arise from ν_τ or mis-identified background (astro ν or atmospheric).

Separate study of "tauness" of the double cascade events ongoing

Astrophysical ν signal - flavour component

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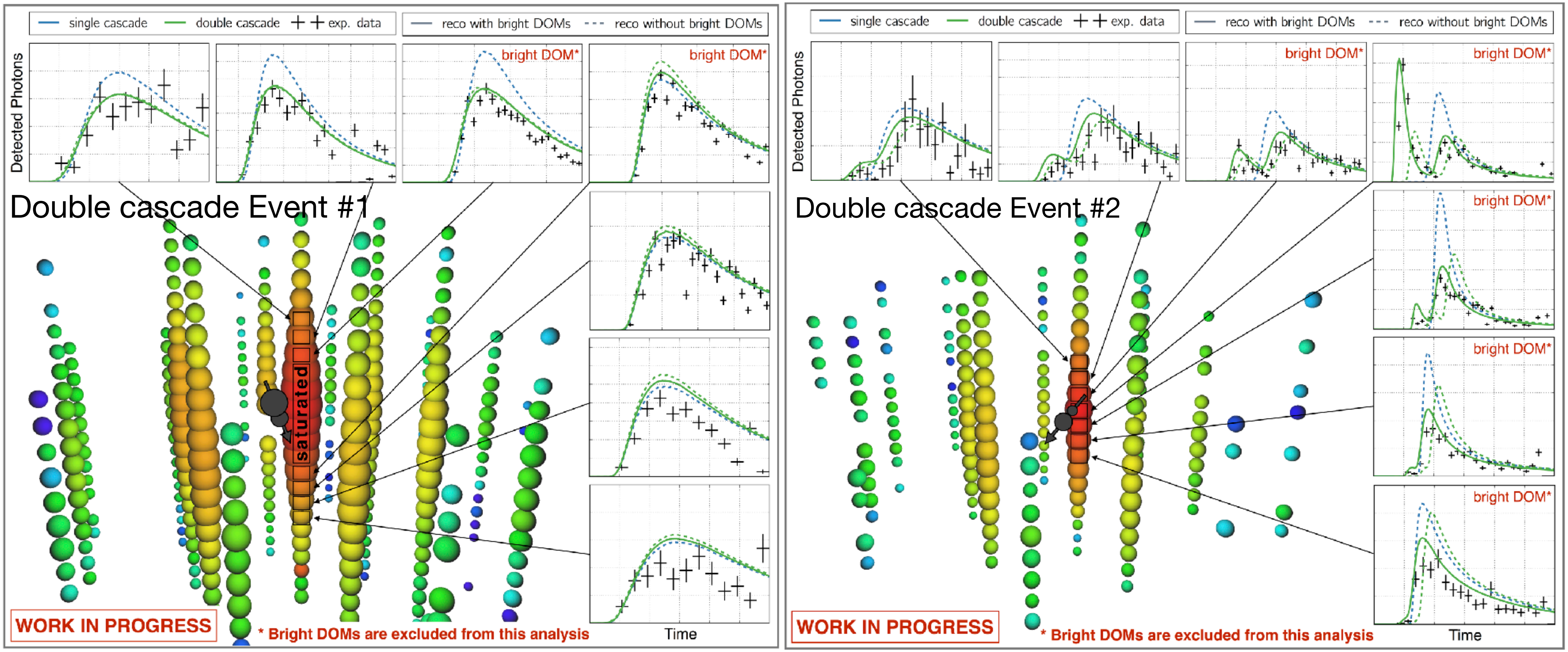

Events reconstructed looking for evidence they contain 2 cascades

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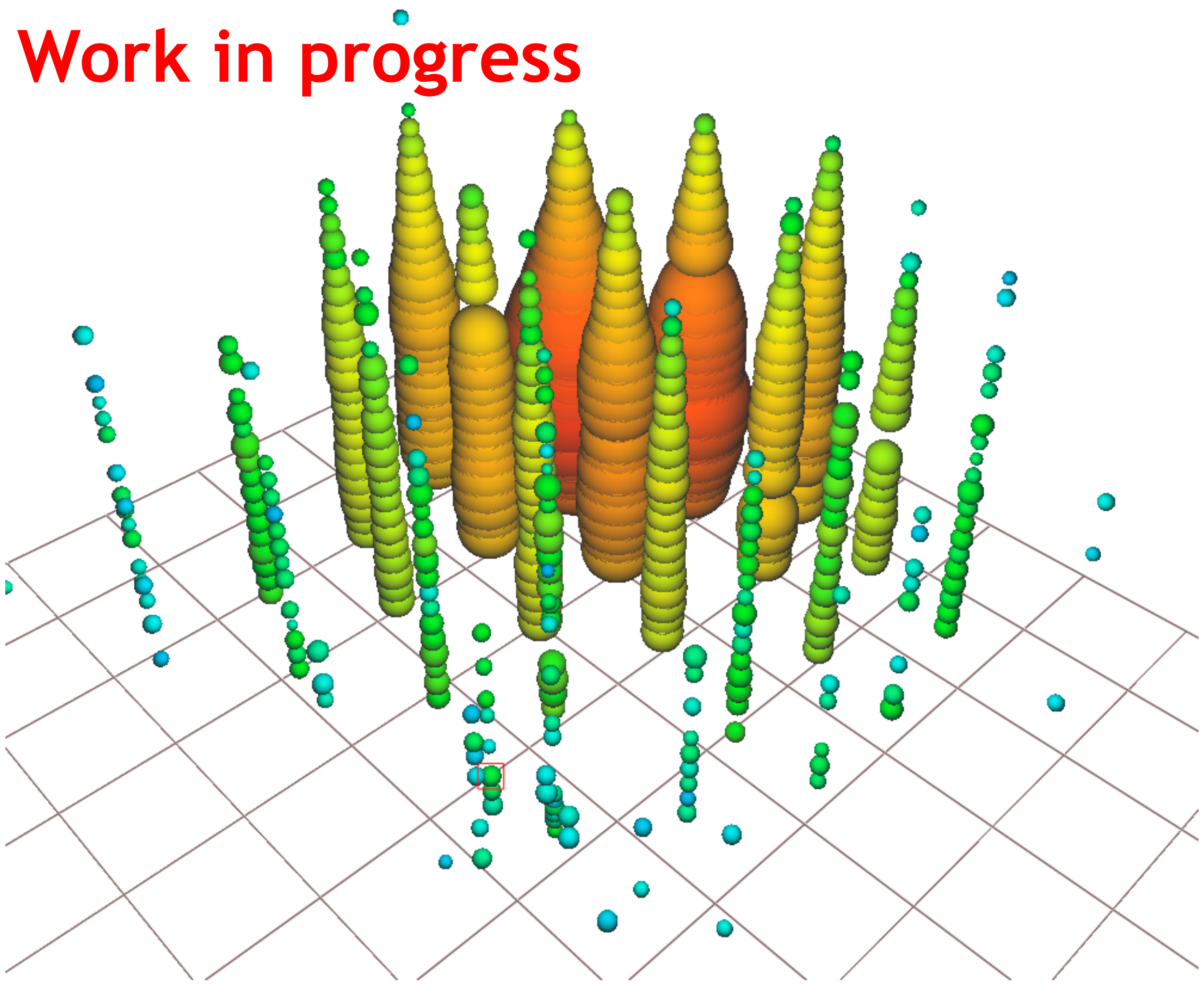
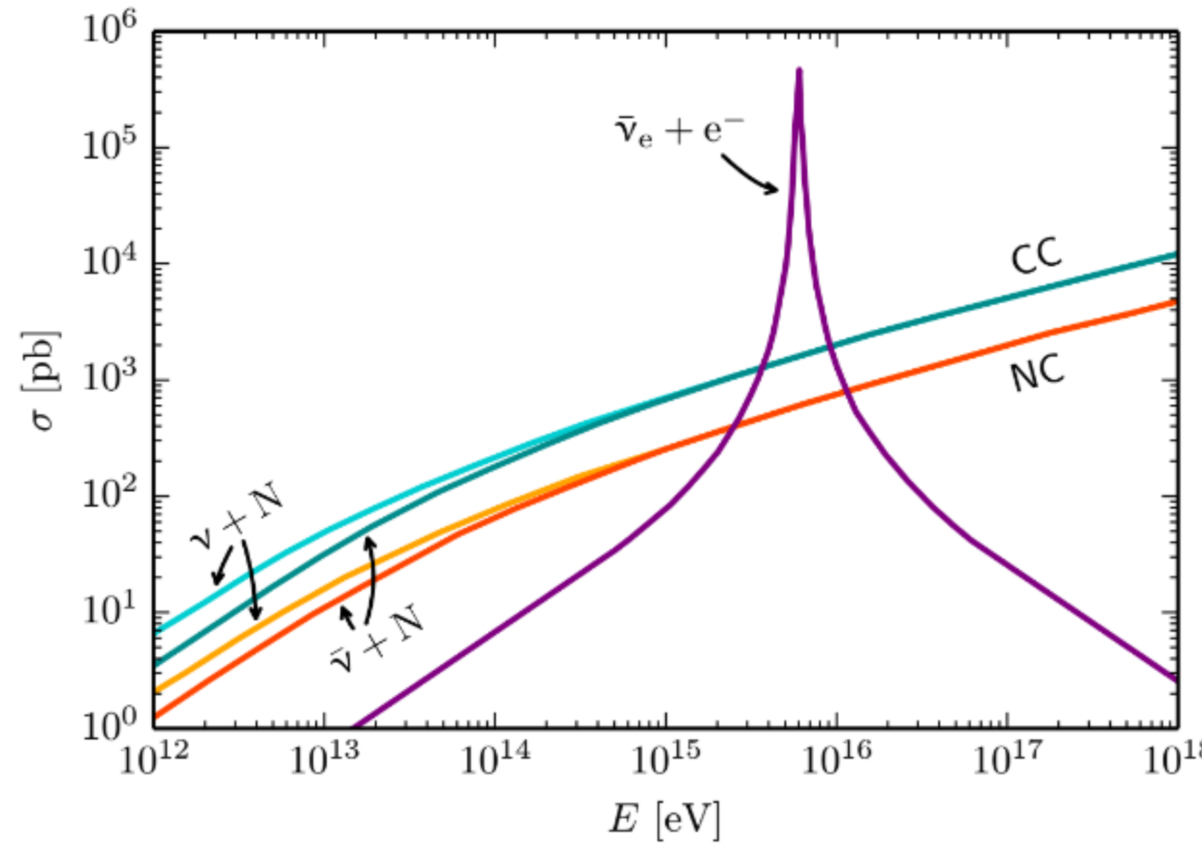
IceCube high energy events search

Work in progress

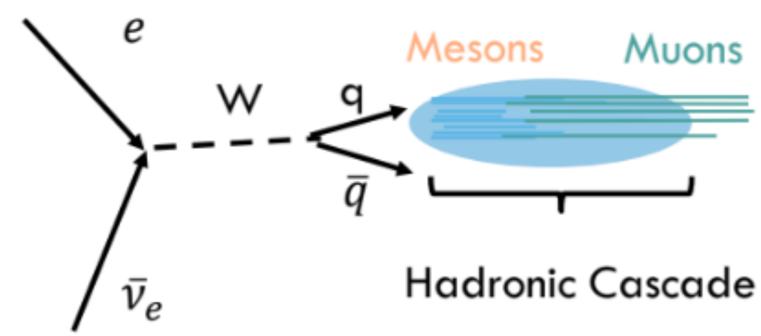


Event identified in a partially-contained PeV search (PEPE)
Deposited energy: 5.9±0.18 PeV (stat only)
ICRC 2017 arXiv:1710.01191

Potential hadronic nature of this event is being investigated



Glashow Resonance



Resonance: E_ν = 6.3 PeV
Typical visible energy is 93%

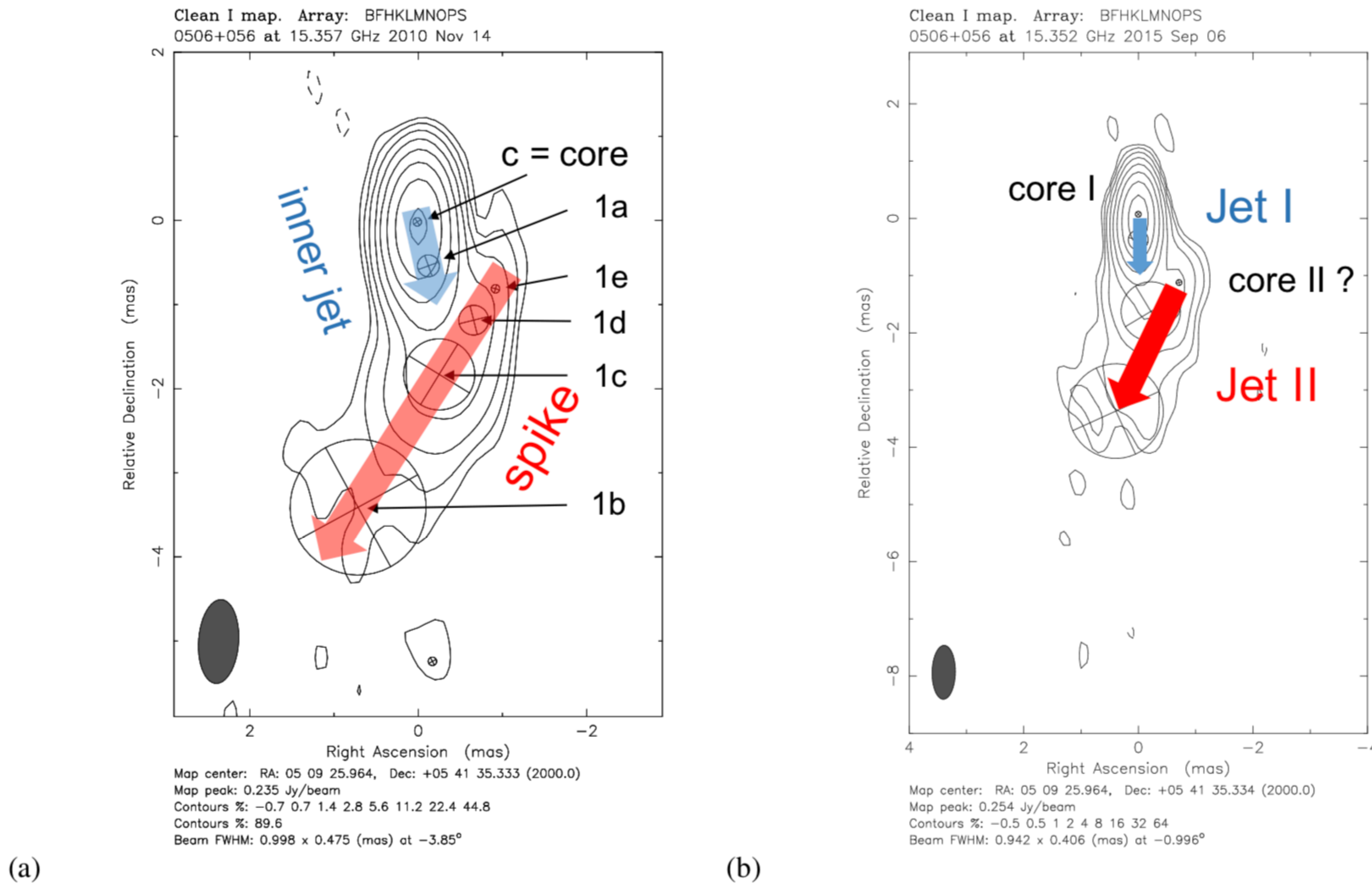
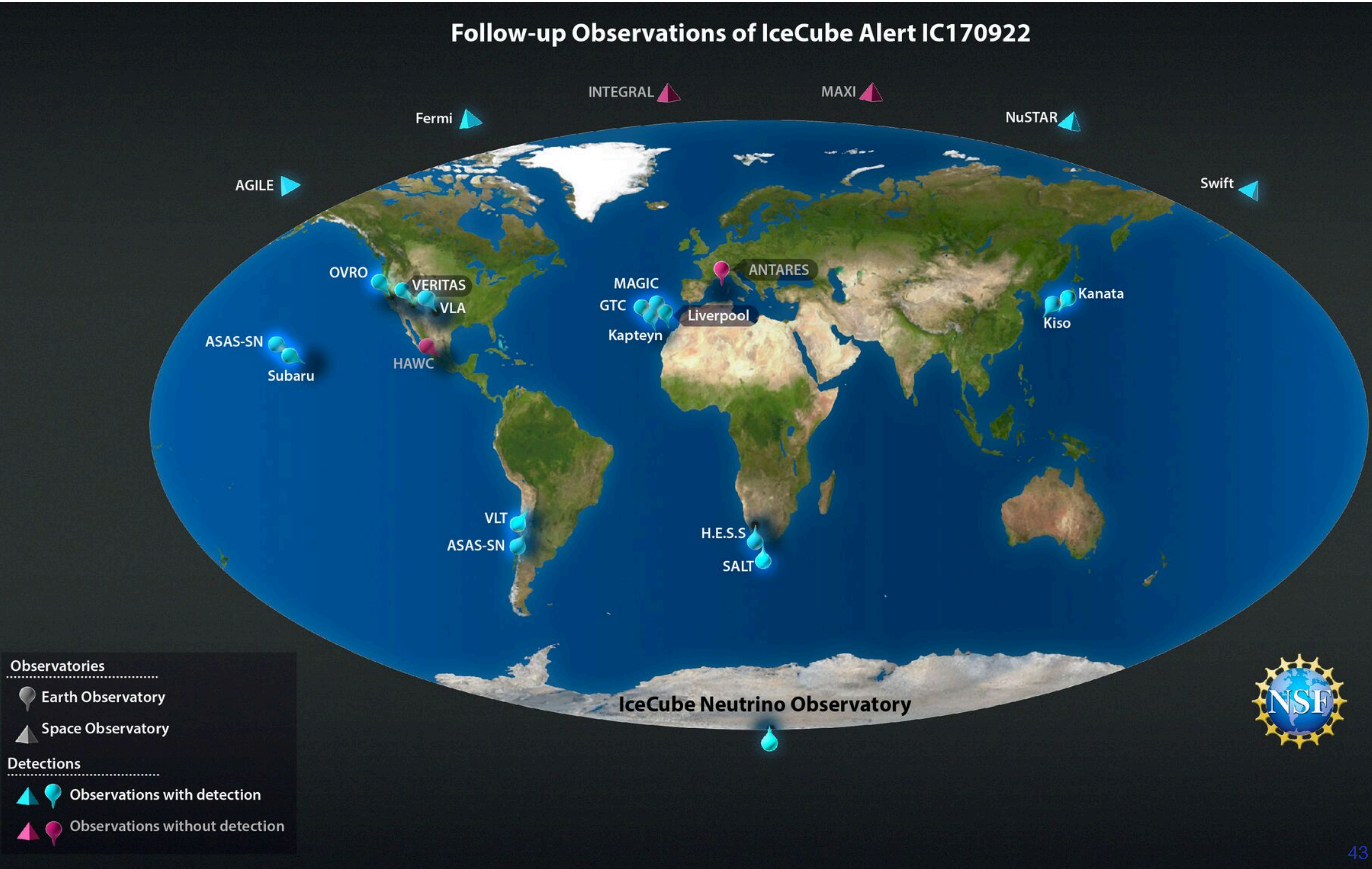


Fig. 1. *Panel a*: one of 16 epochs reanalyzed with the components identified in this epoch (Nov. 14, 2010) marked. Shown is an image with the *difmap* modelfit components superimposed (circles) and the components belonging to the inner jet (light blue arrow) and those features that seem to belong to the spike (red arrow). The arrows indicate the dominant direction of motion. The filled ellipse in the bottom left corner gives the beam size (point spread function). *Panel b*: image from a later epoch. The two potential jet scenarios are indicated (see text for details). The physical nature of the spike is unclear. The spike in the two-jet scenario might be the jet of a potential second black hole. The second core (core II) is therefore marked with a question mark.

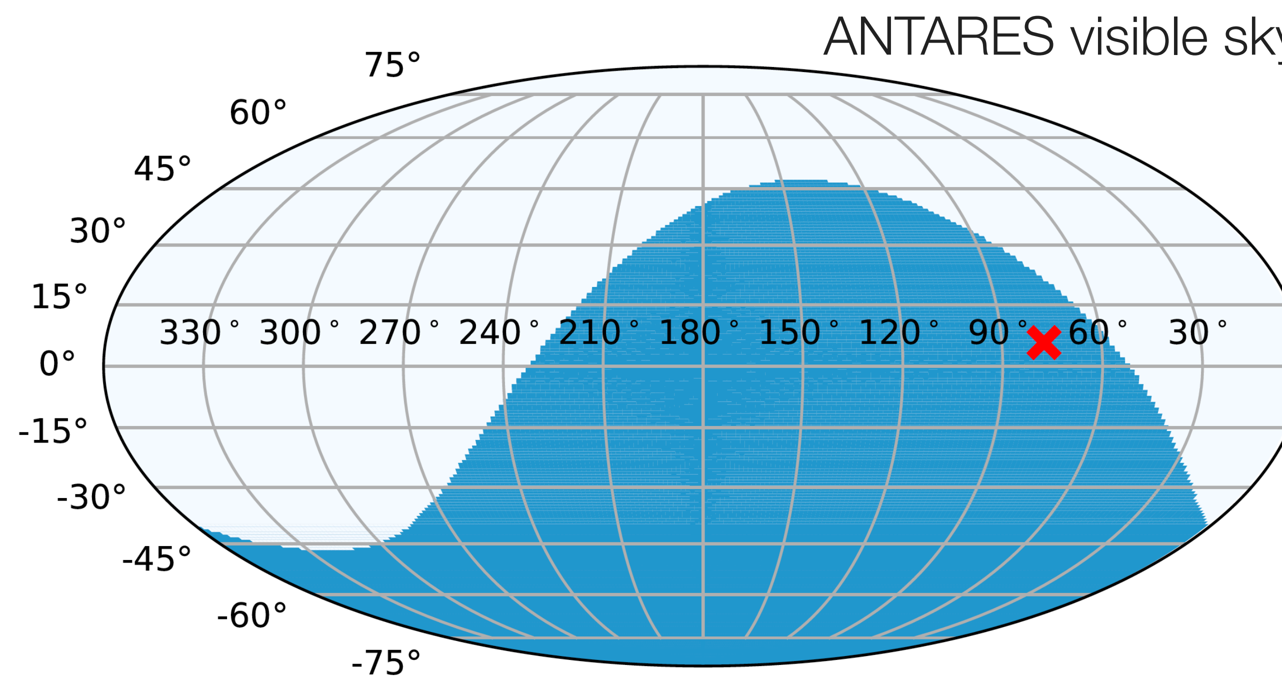
Multi-messenger Astronomy - realtime ν alerts

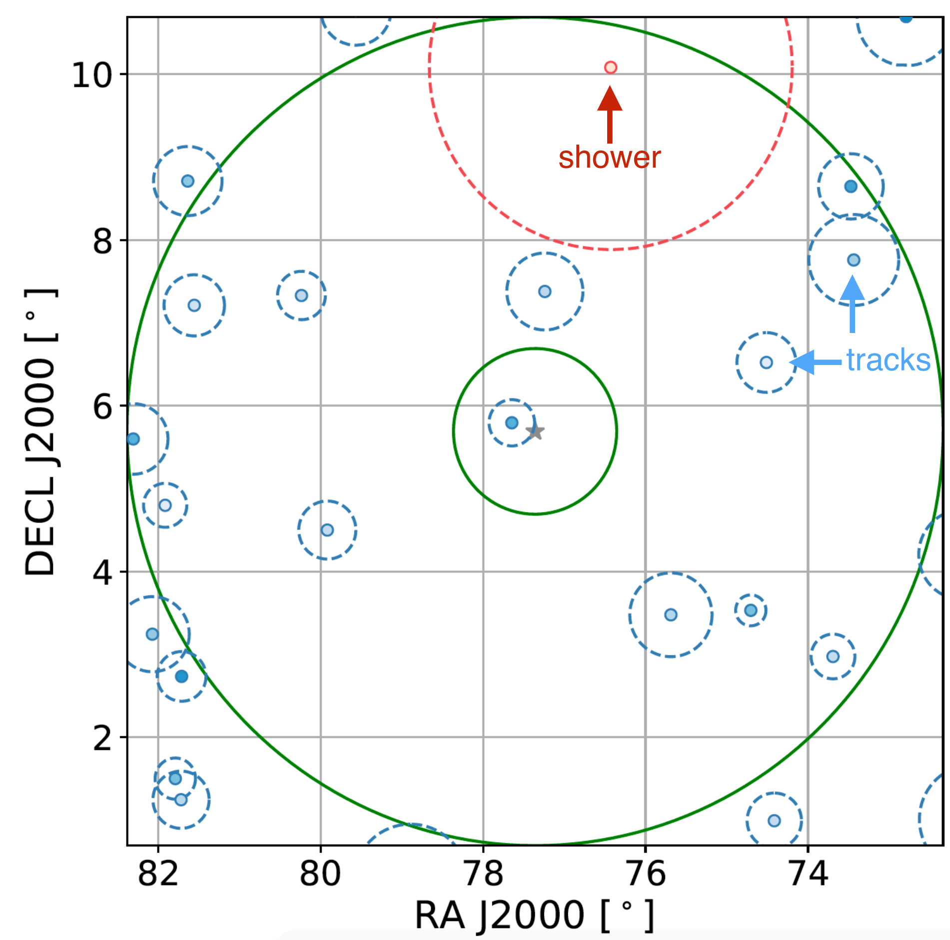


The story of a neutrino and a blazar…

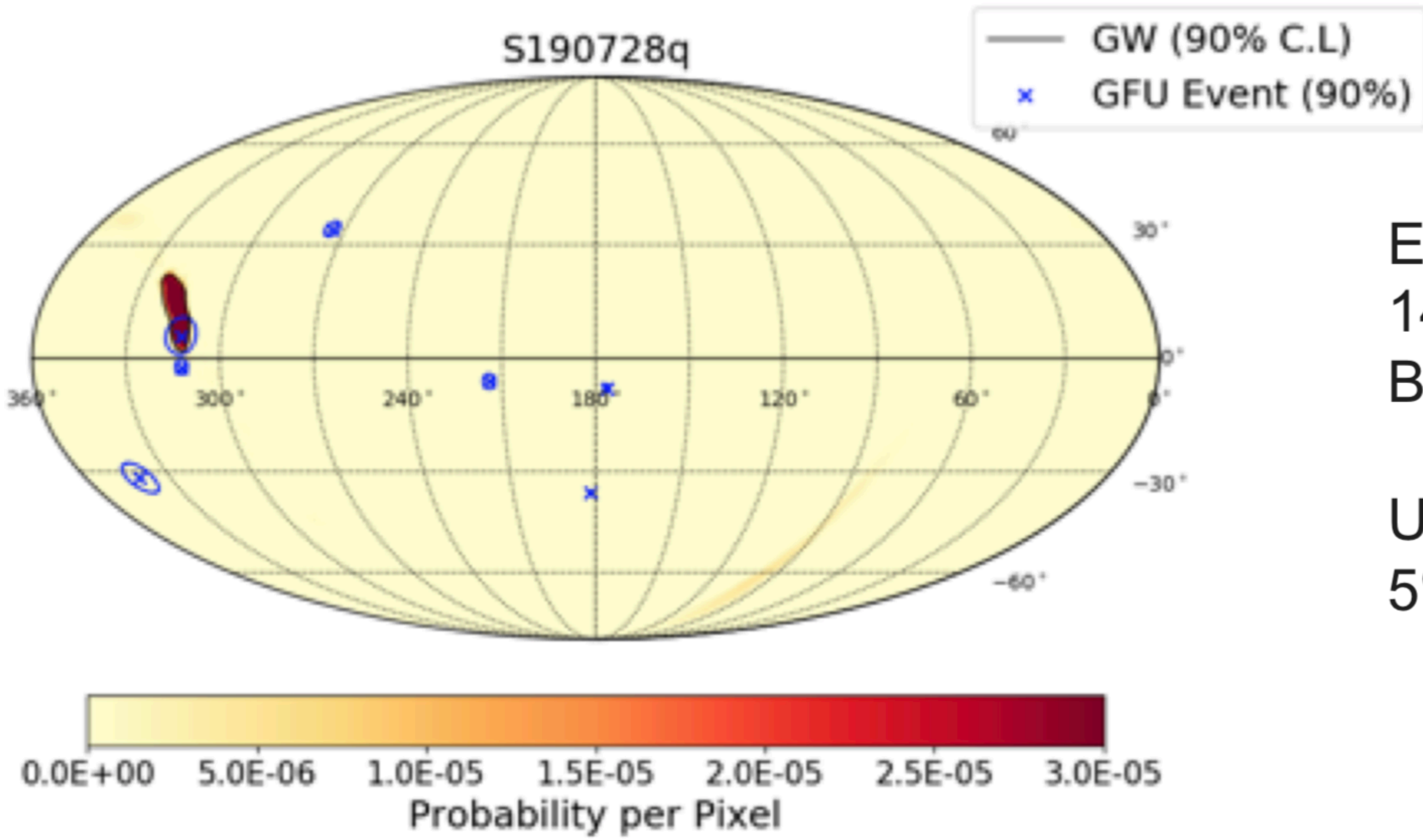
- **“online data stream”** search with fast reconstruction (3 degree cone for +/- 1 hr and 1 day time windows around the source provided 0 up-going muon neutrino candidates
- **“time-integrated”** search for 3136 live day (2007 — 2017)
    - 0.18 track-like events per square-degree
    - 0.004 shower-like events per square degree
    - number of signal events fitting likelihood function for the source = 1.03
    - pre-trial p-value = 2.6%; compatible with background
- **“2015 burst period search”** - time dependent
    - Gaussian (550 days) and box (158 days) time window shapes (flares) centred on MJD57004
    - relaxed selection criteria gave 0 events in the flaring periods

Joint IceCube-ANTARES analysis is under development.





Gravitational wave follow-up



Early classification: 14.4% NS/BH, 34.0% BH/BH, 51.6% Mass gap

Updated to: 95% BH/BH. 5% Mass gap

dt (ns)	RA (deg)	Dec (deg)	Ang. Uncert. (deg)	P-value (Bayesian)	P-value (generic transient)
-360	312.87	5.85	4.81	0.010 (2.33 σ)	0.016 (2.21 σ)