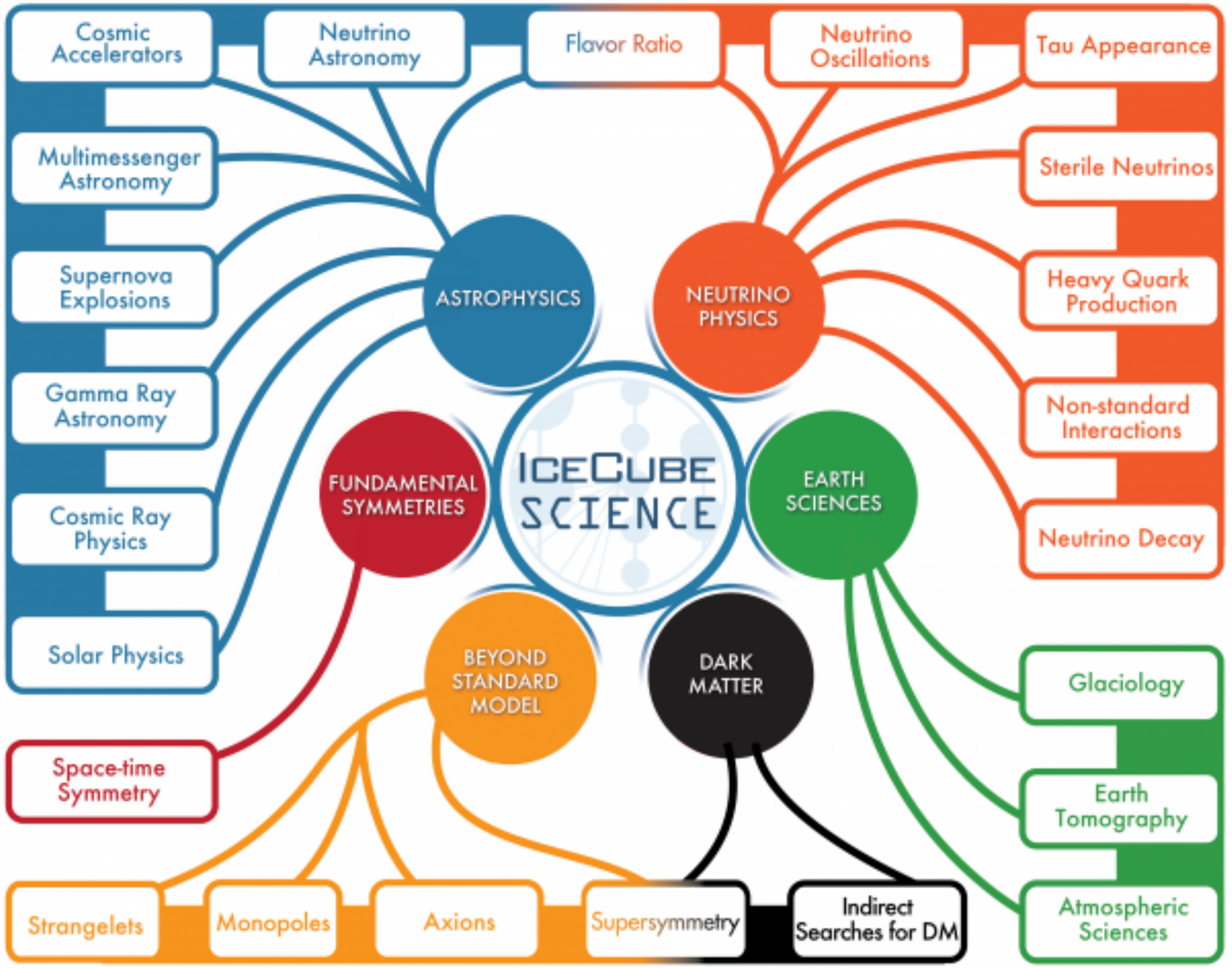
ICECUBE NEUTRINOS AT THE HIGH-ENERGY FRONTIER

S. Toscano on behalf of the IceCube Collaboration*

*Simona.Toscano@ulb.be

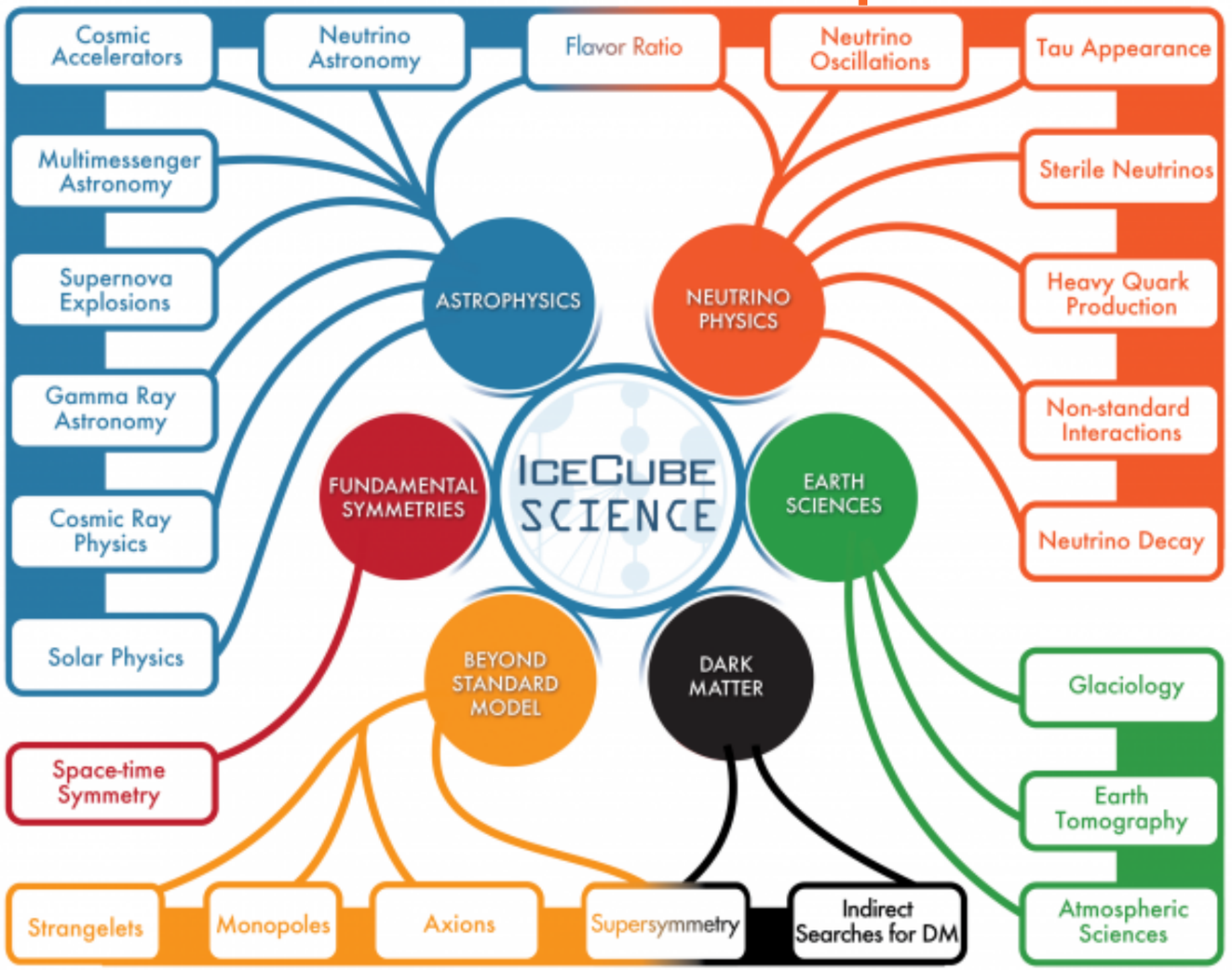
NOW 2022
Neutrino Oscillation Workshop

Physics reach

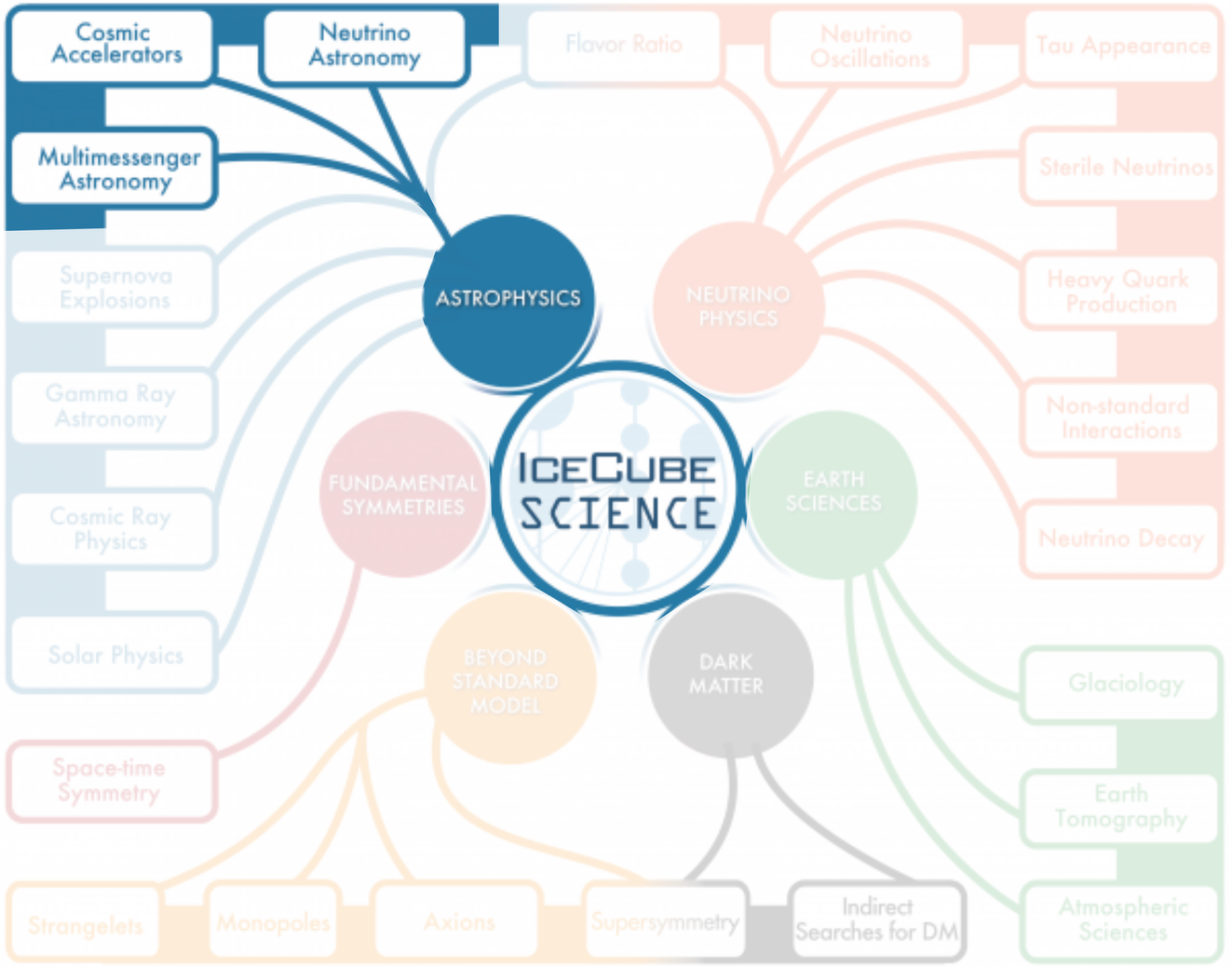


Physics reach

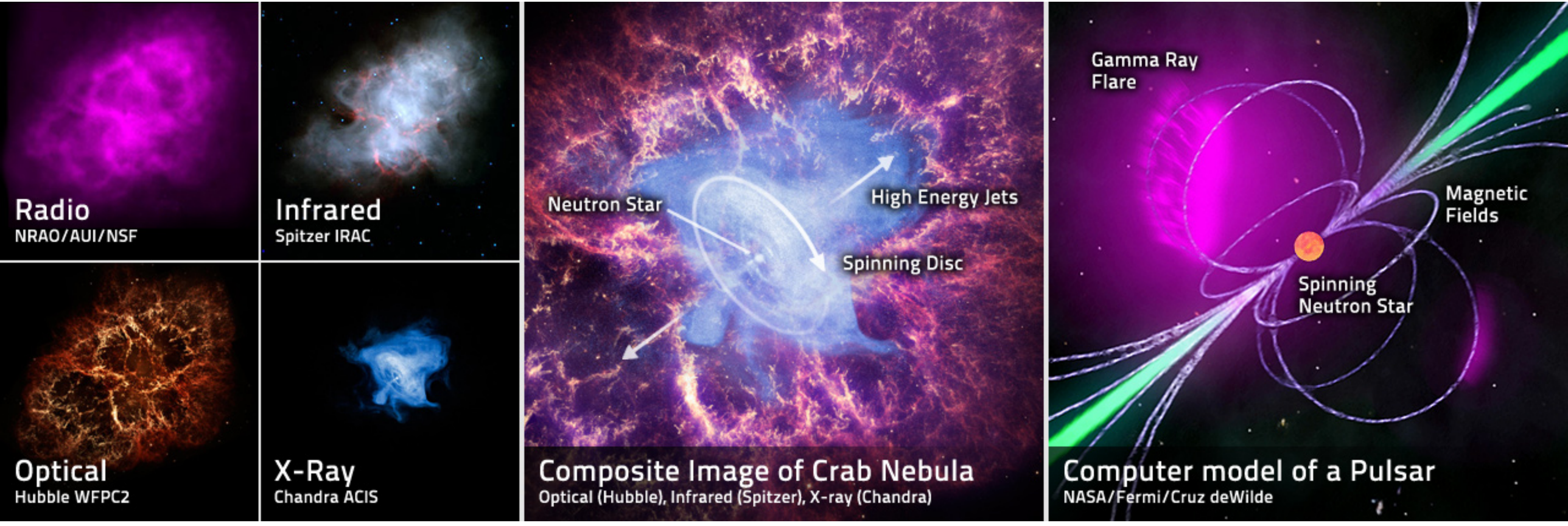
Talk by J.V. Mead on Monday parallel Session I
Atmospheric neutrino oscillations in IceCube-DeepCore



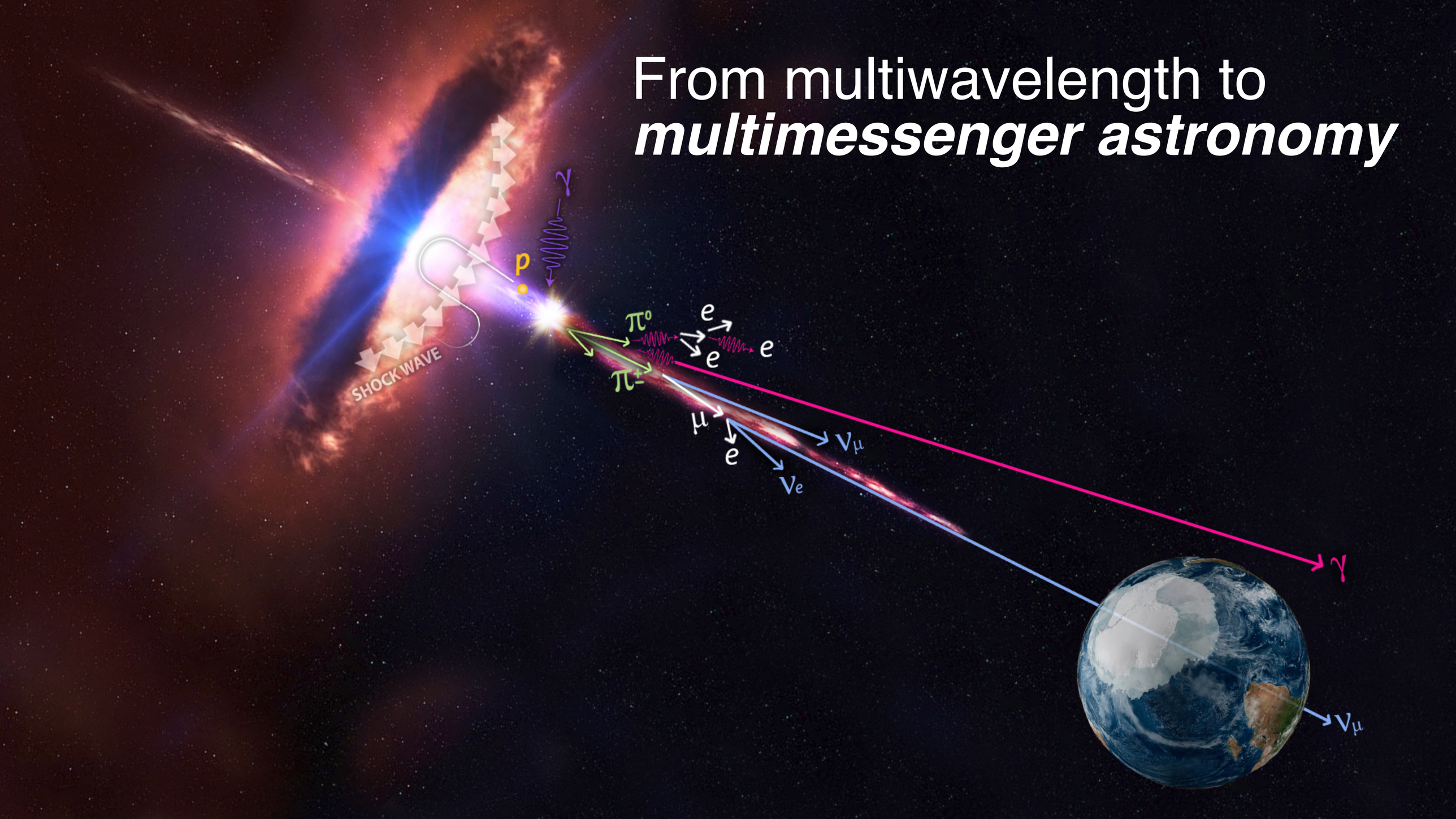
Physics reach



[Multiwavelength Crab]

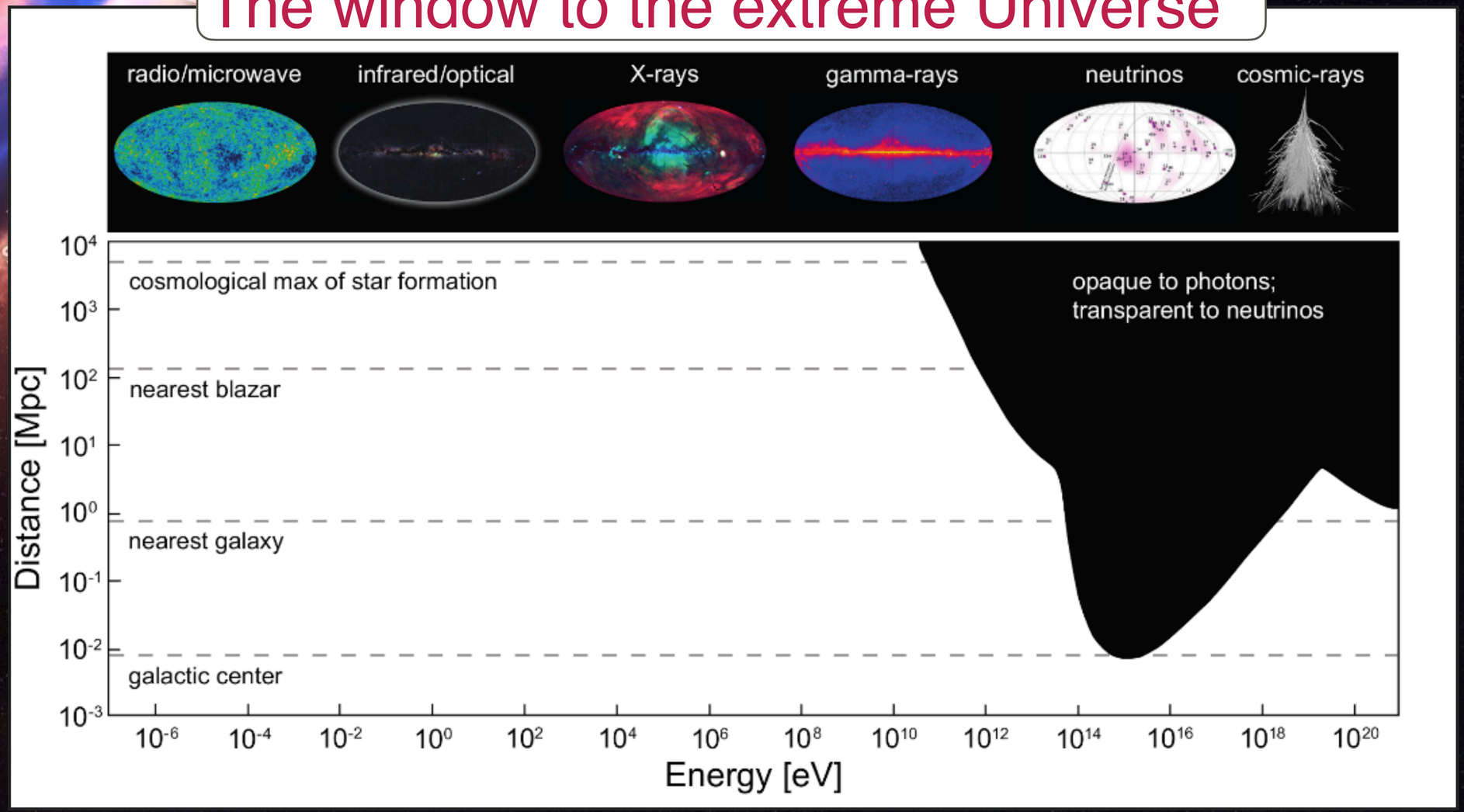


From multiwavelength to ***multimessenger astronomy***

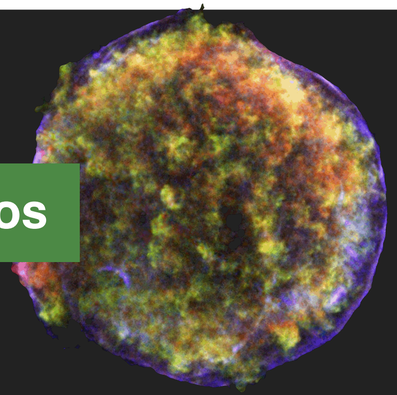


From multiwavelength to *multimessenger astronomy*

The window to the extreme Universe



Neutrino Detectors what are we hunting?



SN Neutrinos

Astrophysical

MeV

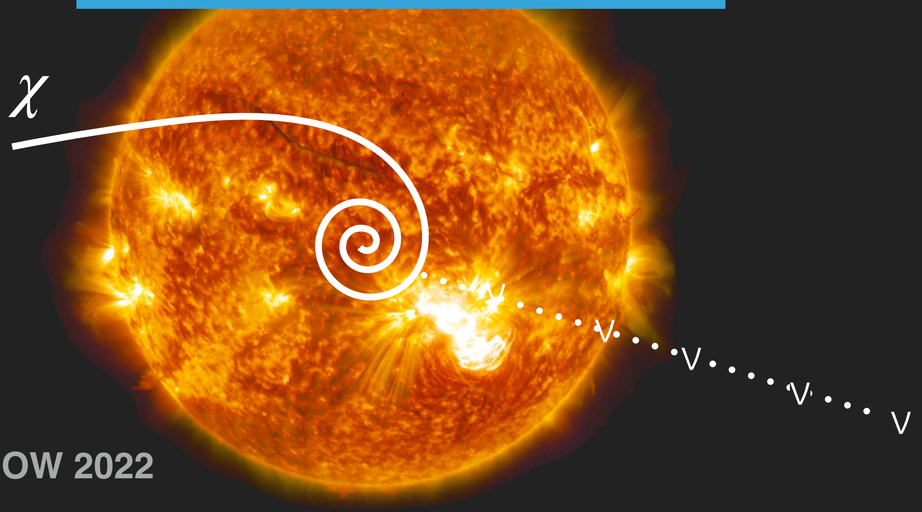
GeV-TeV

<100 TeV

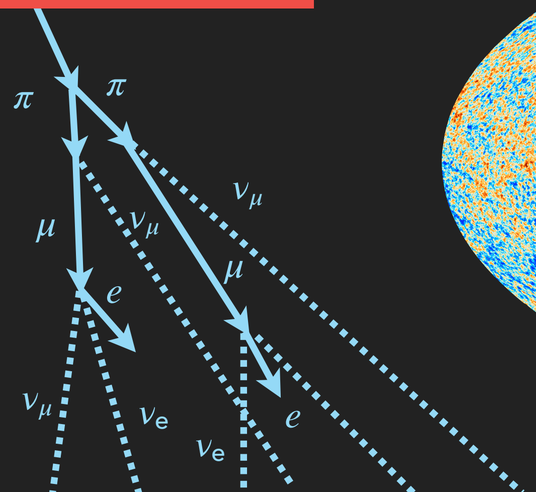
>100TeV

> 10^6 TeV

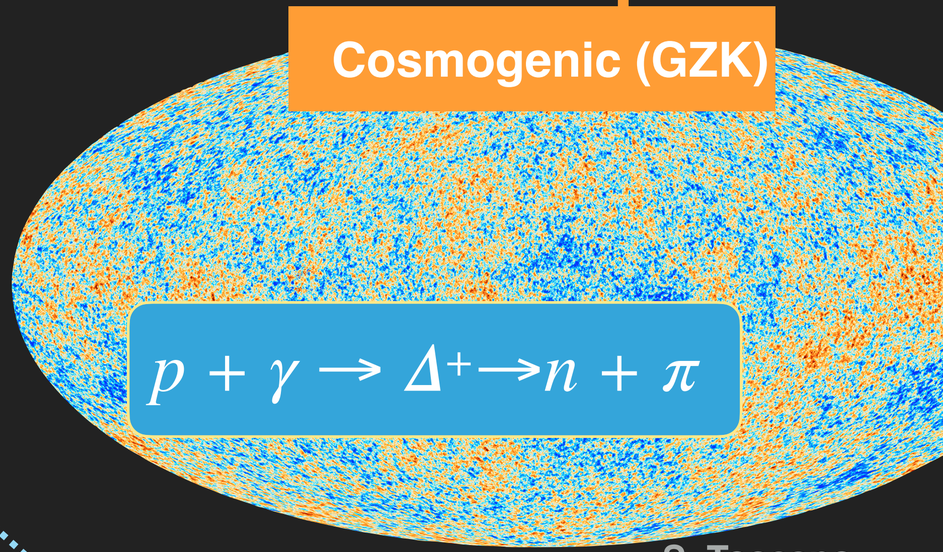
Solar Flares/Dark Matter



Atmos: Oscillations, sterile ν , Prompt



Cosmogenic (GZK)



$$p + \gamma \rightarrow \Delta^{+} \rightarrow n + \pi$$

Neutrino Detectors what are we hunting?

SN Neutrinos

Astrophysical

MeV | GeV-TeV | <100 TeV | >100TeV | > 10^6 TeV

Solar Flares/Dark Matter

Atmos: Oscillations, sterile ν , Prompt

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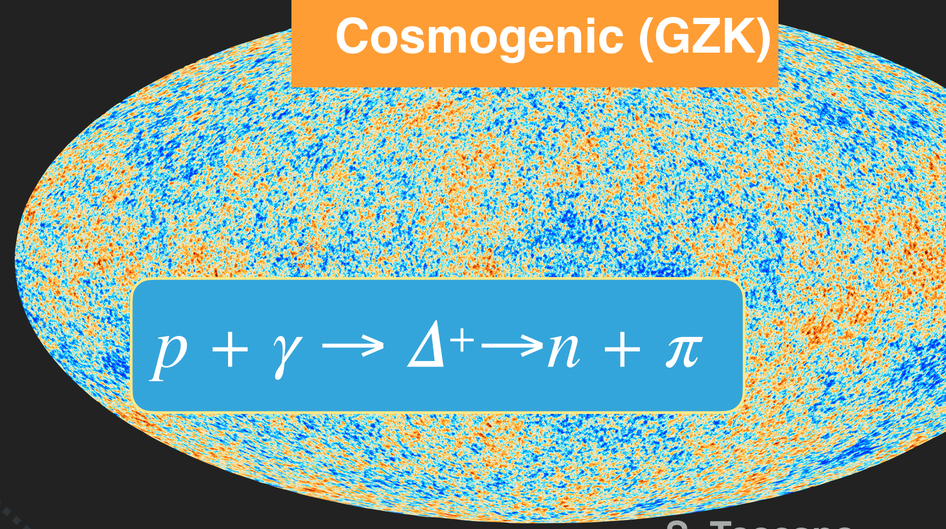
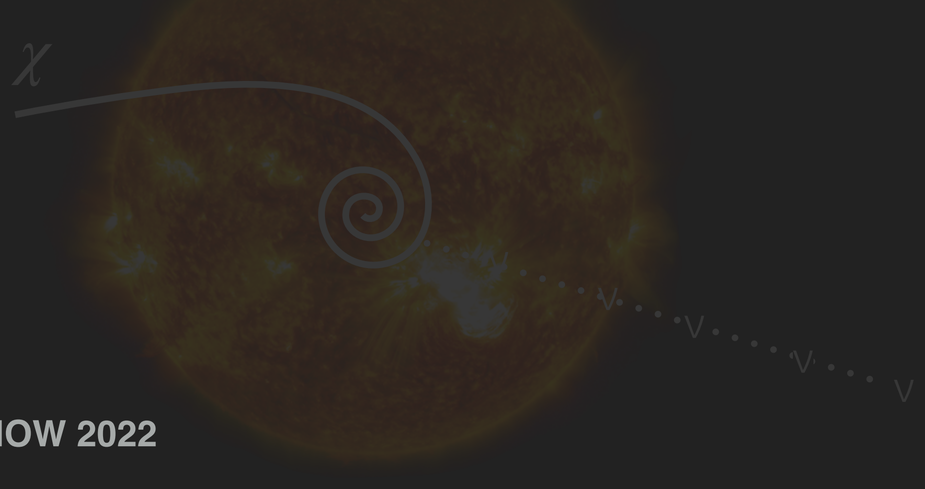
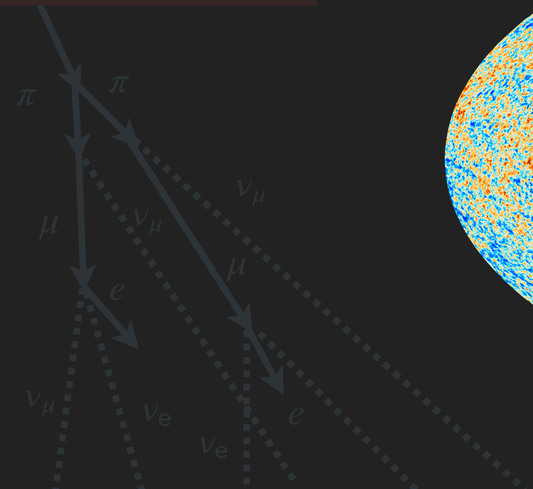
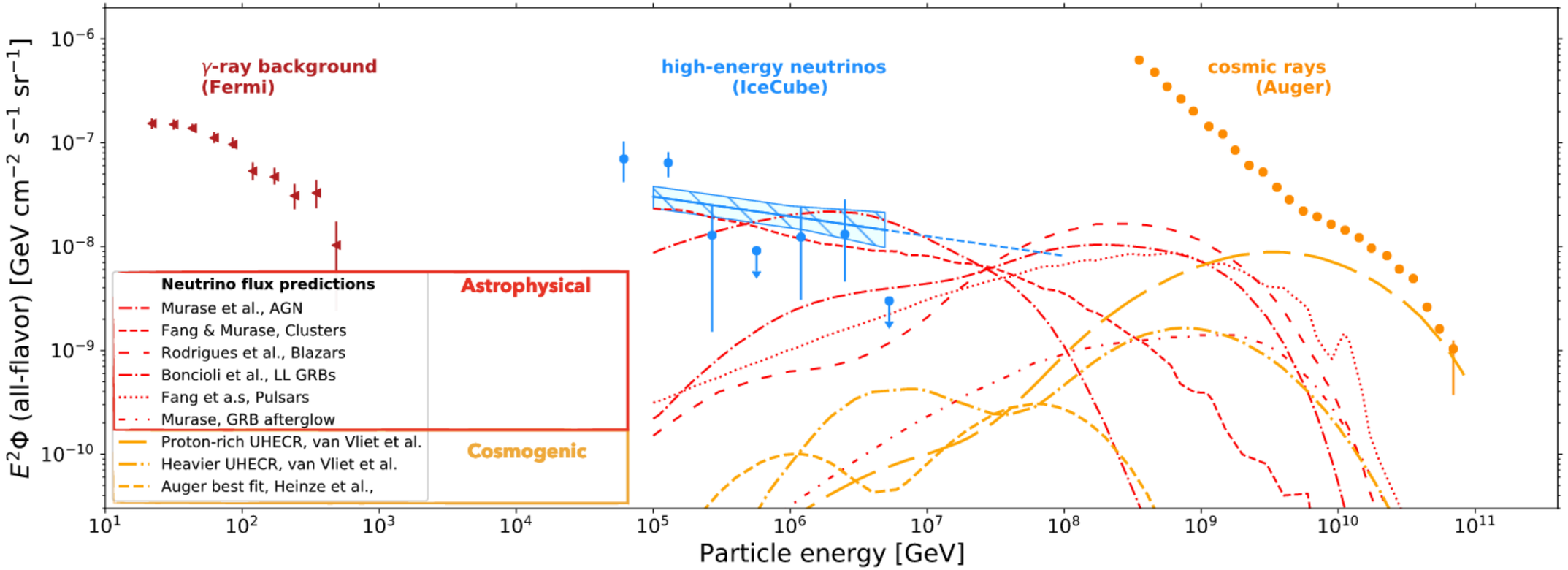






Neutrino astronomy: The multi-messenger connection

J. Aguilar et al, (RNO-G Collaboration),JINST 16 P03025 2021



$$p + \gamma_{target} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0, Br = 2/3 \\ n + \pi^+, Br = 1/3 \end{cases}$$

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

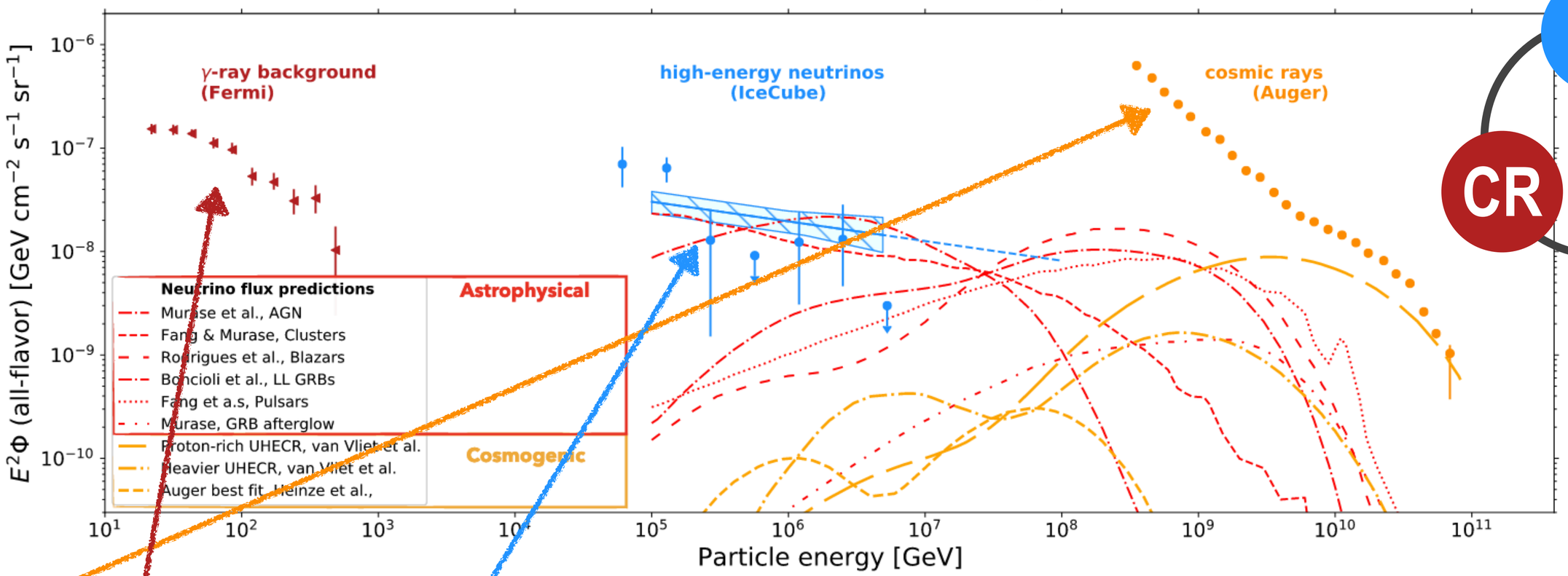
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow \overline{\nu}_\mu + e^+ + \nu_e + \nu_\mu$$

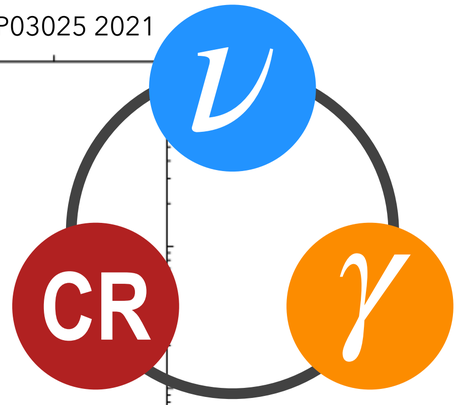
1 PeV **20 PeV**

Neutrino energy = Proton energy / 20

Neutrino astronomy: The multi-messenger connection

J. Aguilar et al, (RNO-G Collaboration),JINST 16 P03025 2021





$$p + \gamma_{target} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0, Br = 2/3 \\ n + \pi^+, Br = 1/3 \end{cases}$$

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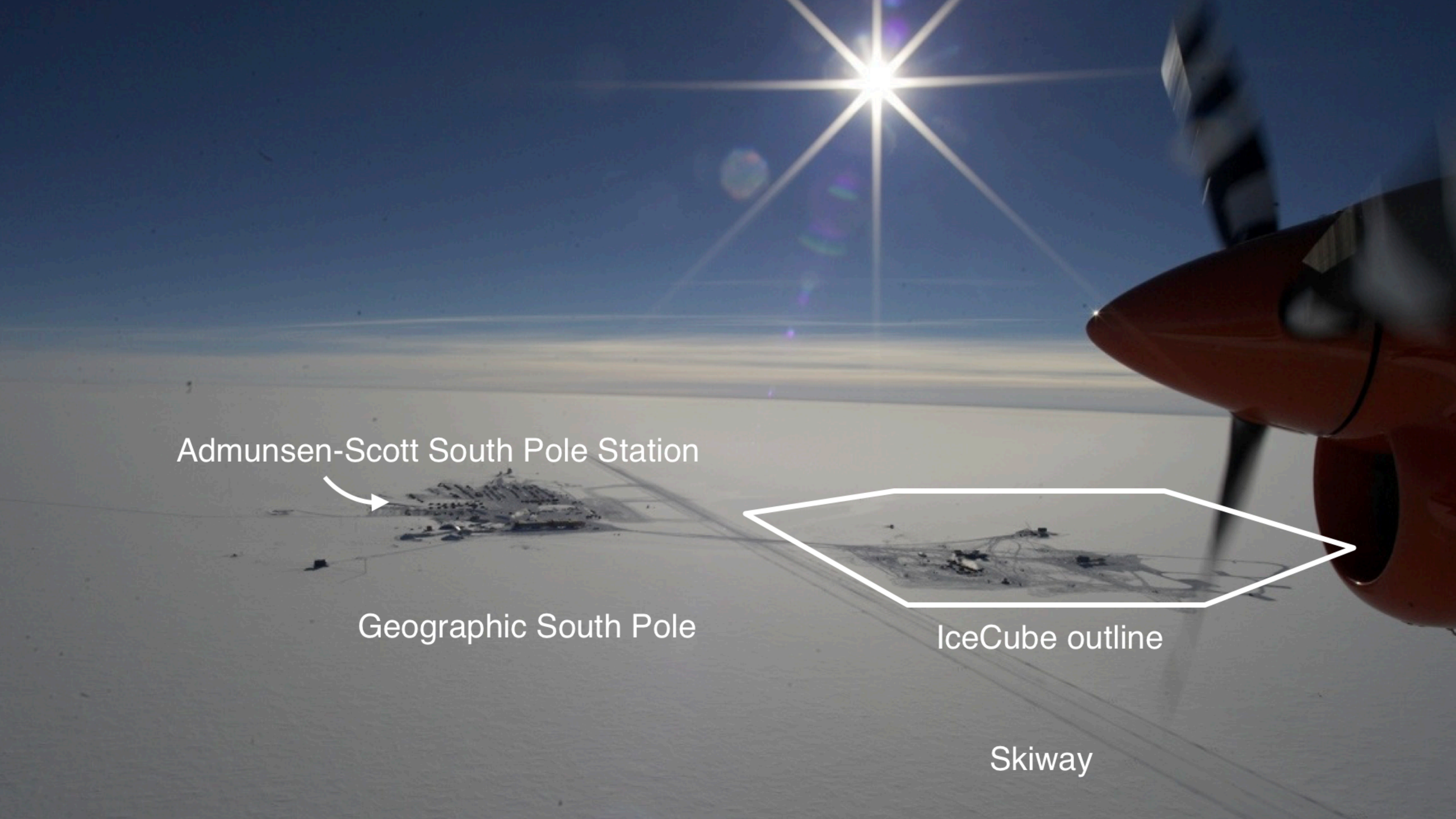
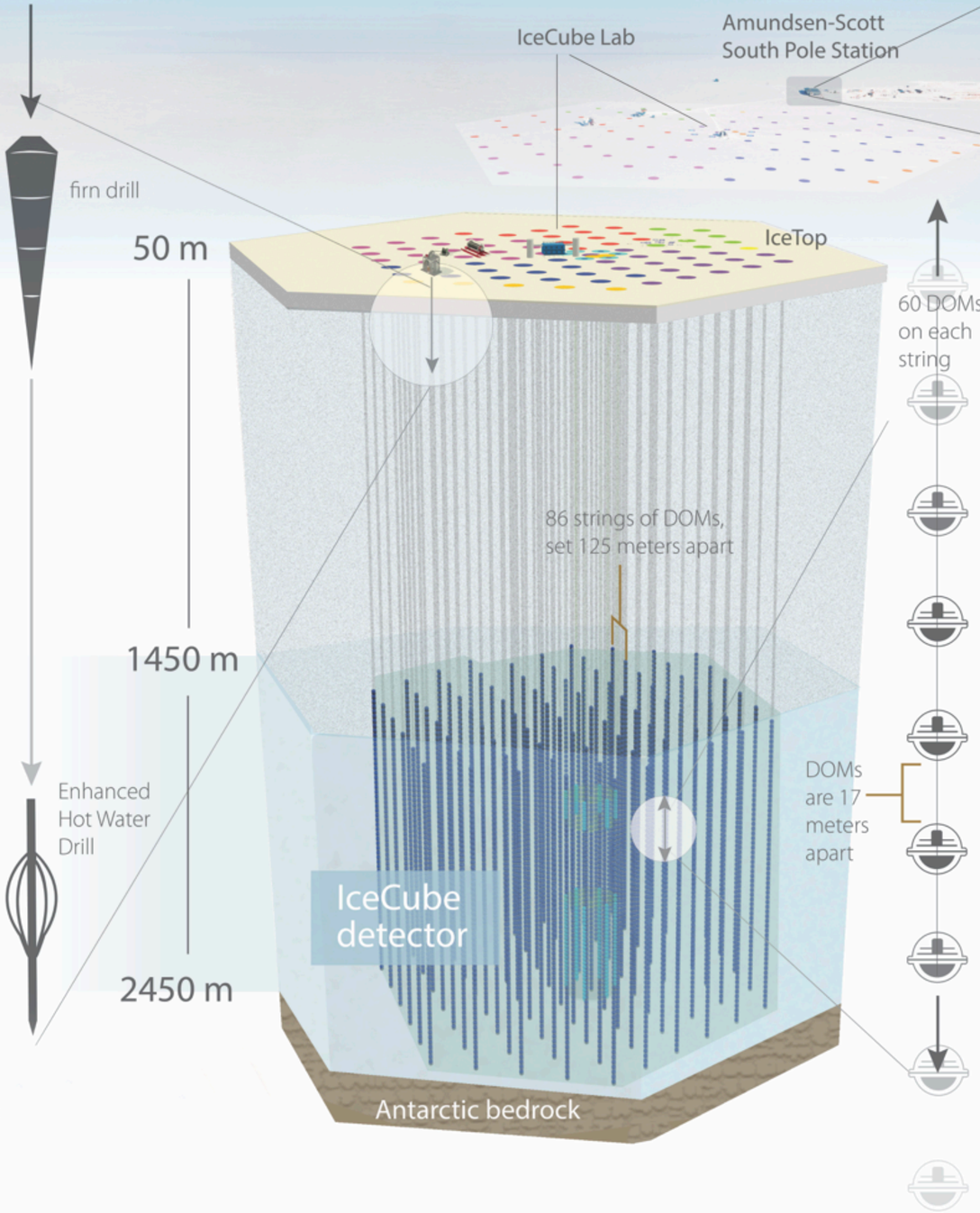
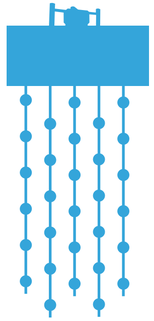

Admunsen-Scott South Pole Station
Geographic South Pole
IceCube outline
Skiway

IceCube Neutrino Observatory



5,160 Digital Optical Modules (DOMs)



86 string with 60 DOMs each

6 denser strings called **DeepCore**

1 km² surface array with 324 DOMs: **IceTop**

Completion in December 2010

THE ICECUBE COLLABORATION

AUSTRALIA
University of Adelaide

BELGIUM
UCLouvain
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
SNOLAB
University of Alberta–Edmonton

DENMARK
University of Copenhagen

GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Karlsruhe Institute of Technology
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
Westfälische Wilhelms-Universität Münster

ITALY
University of Padova

JAPAN
Chiba University

NEW ZEALAND
University of Canterbury

SOUTH KOREA
Sungkyunkwan University

SWEDEN
Stockholms universitet
Uppsala universitet

SWITZERLAND
Université de Genève

TAIWAN
Academia Sinica

UNITED KINGDOM
University of Oxford

UNITED STATES
Clark Atlanta University
Drexel University
Georgia Institute of Technology
Harvard University
Lawrence Berkeley National Lab
Loyola University Chicago
Marquette University
Massachusetts Institute of Technology
Mercer University
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines and Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of Delaware
University of Kansas
University of Maryland
University of Rochester
University of Texas at Arlington
University of Utah
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University

FUNDING AGENCIES

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
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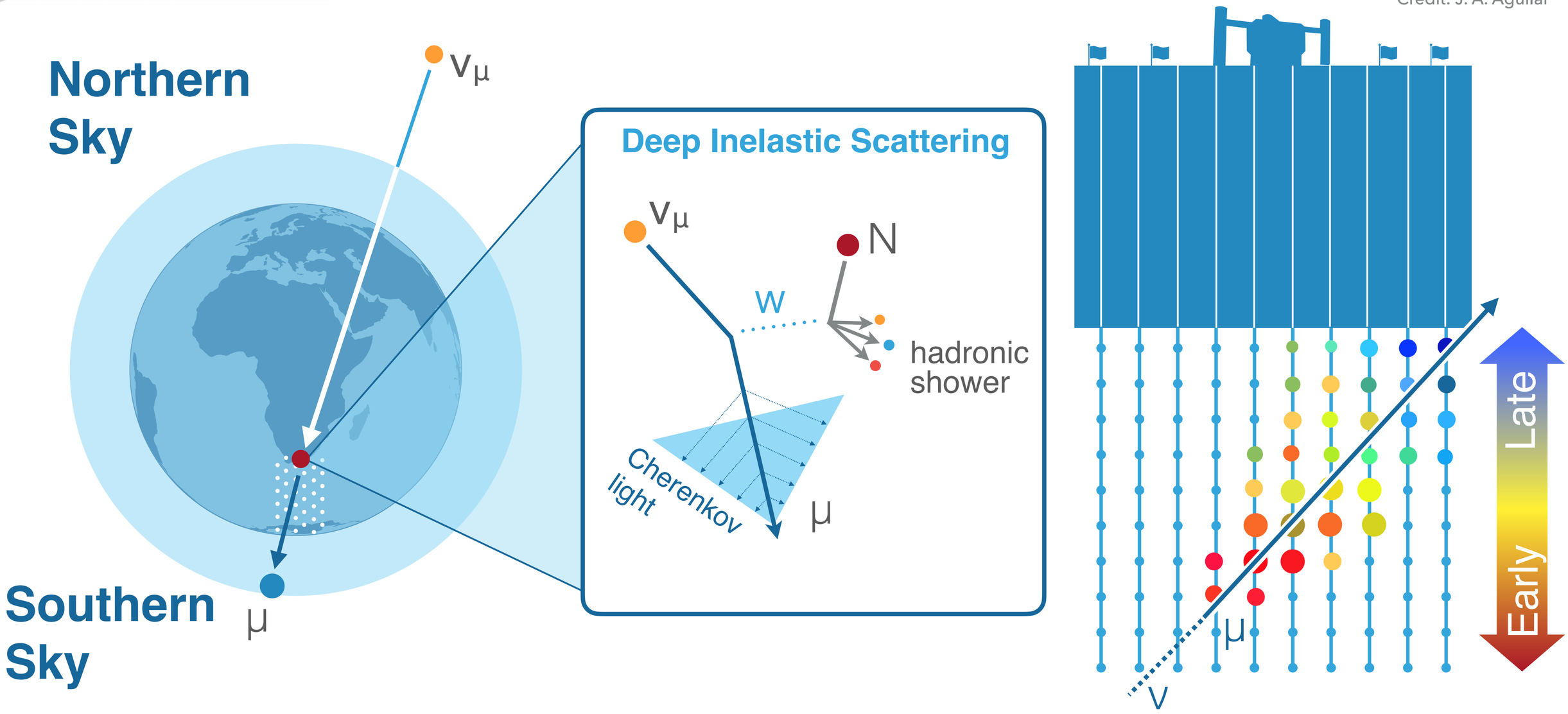
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

IceCube
South Pole Neutrino Observatory

icecube.wisc.edu

Detection principle

Credit: J. A. Aguilar



IceCube detects Cherenkov radiation from secondary charged particles

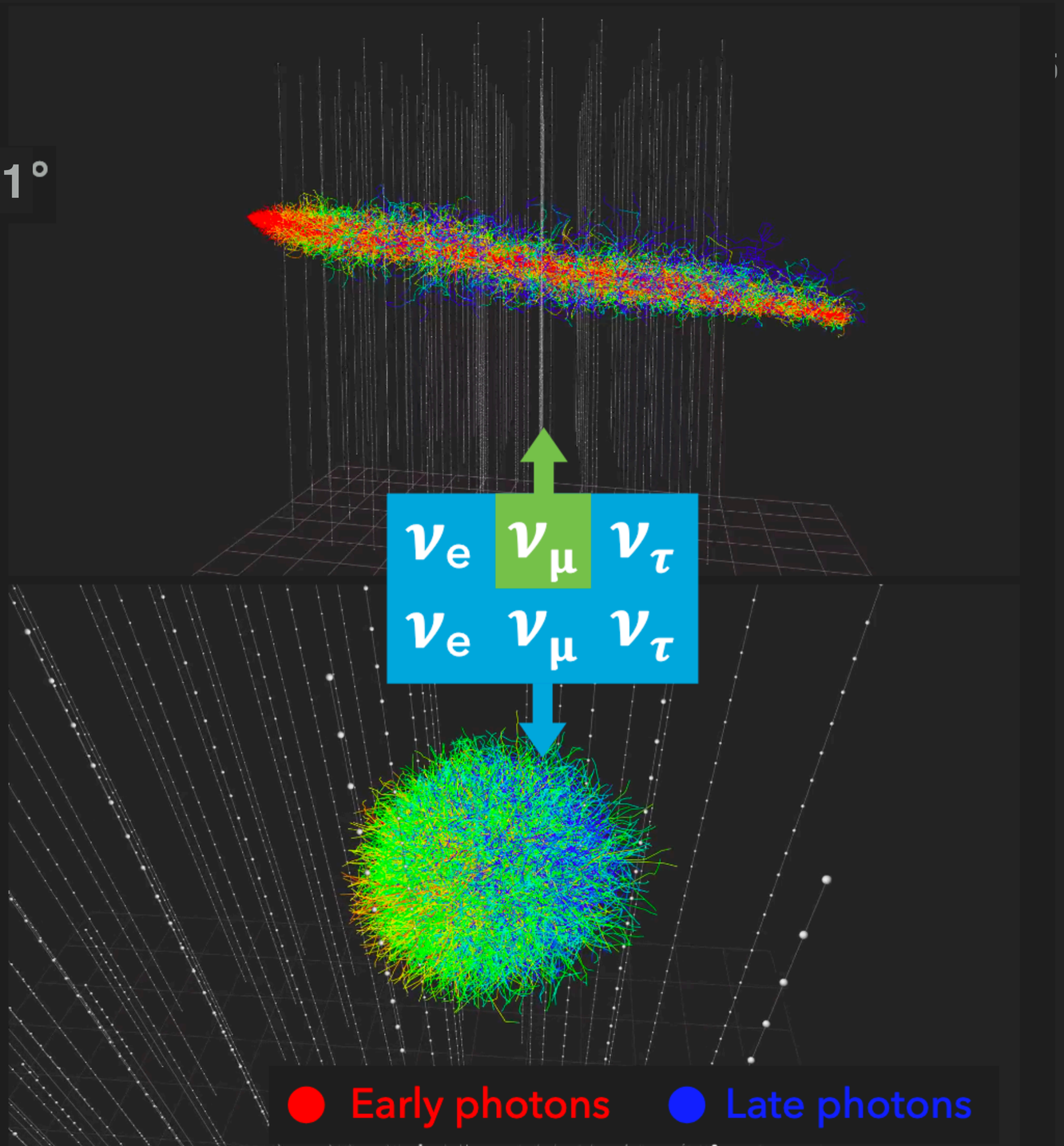
In-ice signatures

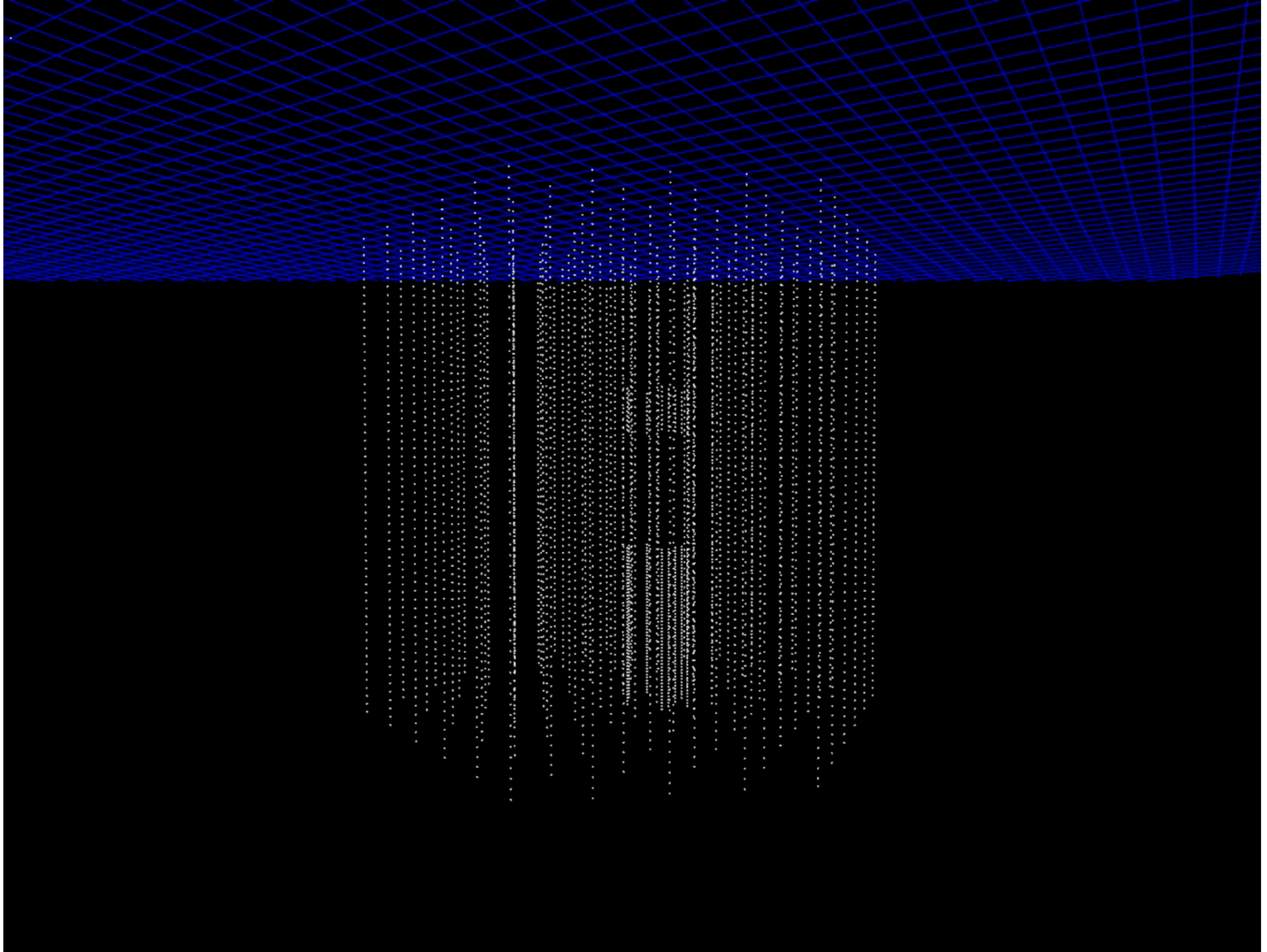
Track topology

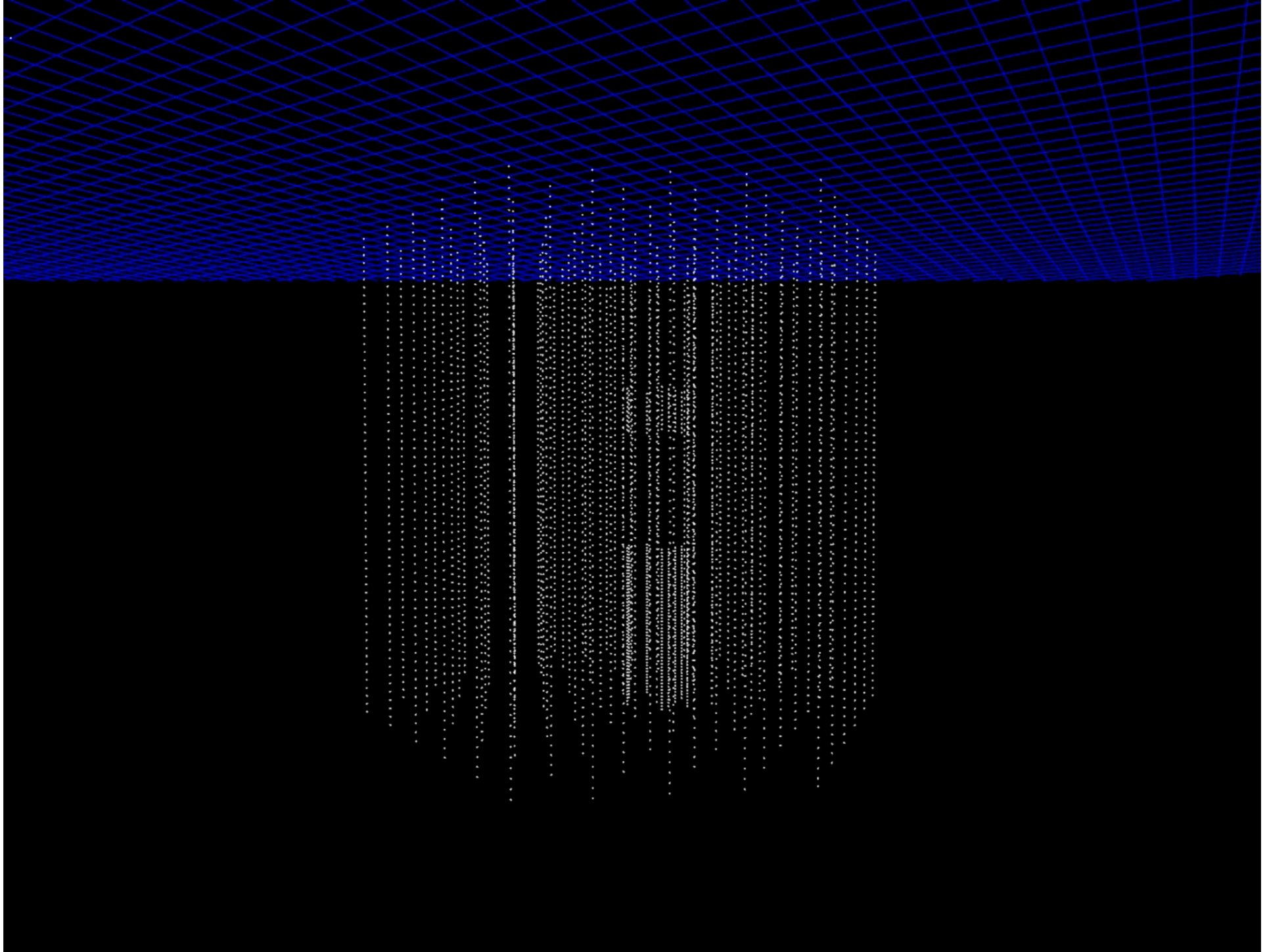
- Good angular resolution 0.2° - 1°
  ➜ **Neutrino Astronomy**
- Vertex can be outside the detector ➜ **Increased effective volume**

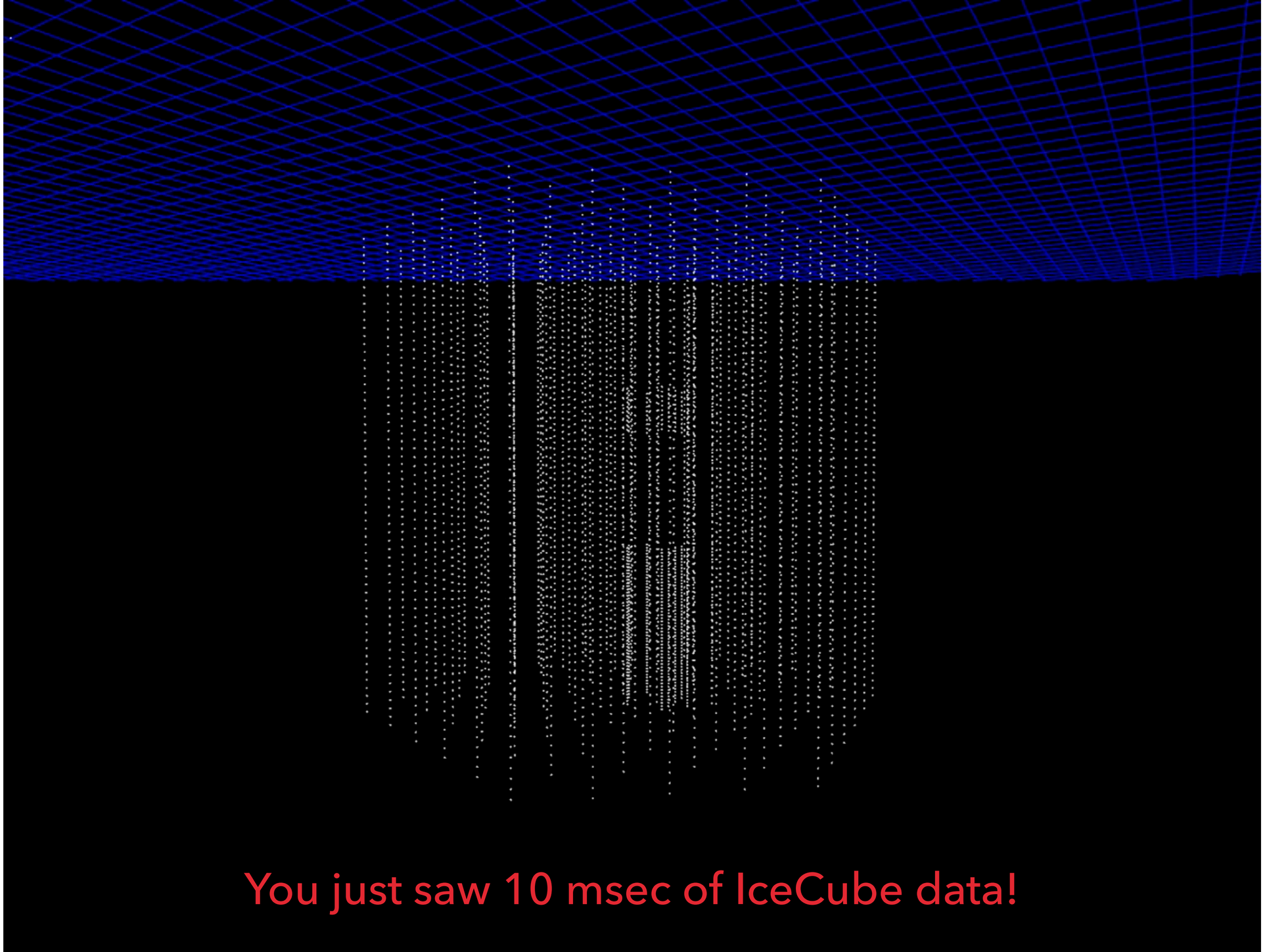
Cascade topology

- All flavors
- Fully active calorimeter ➜ **Good energy resolution ±15% deposited energy**
- Angular reconstruction possible ➜ **~10° > 100 TeV**





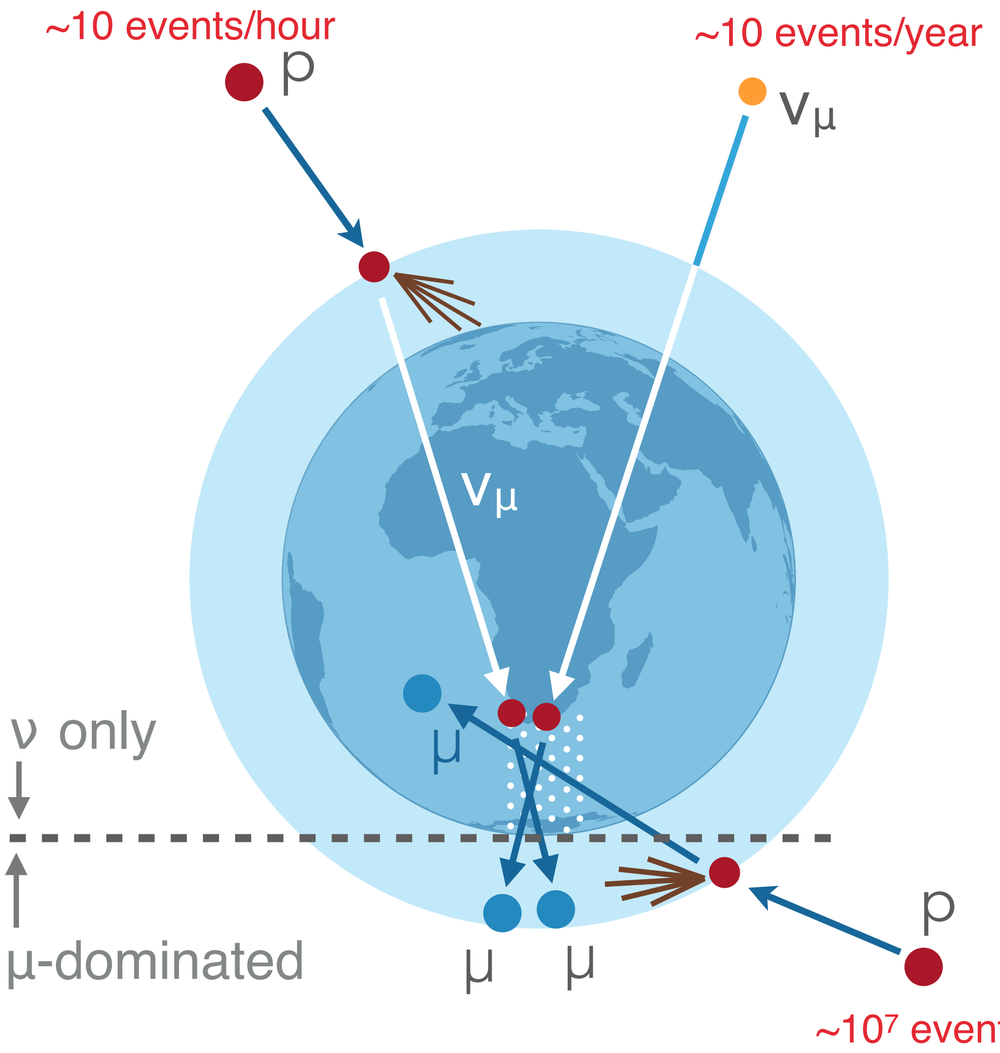


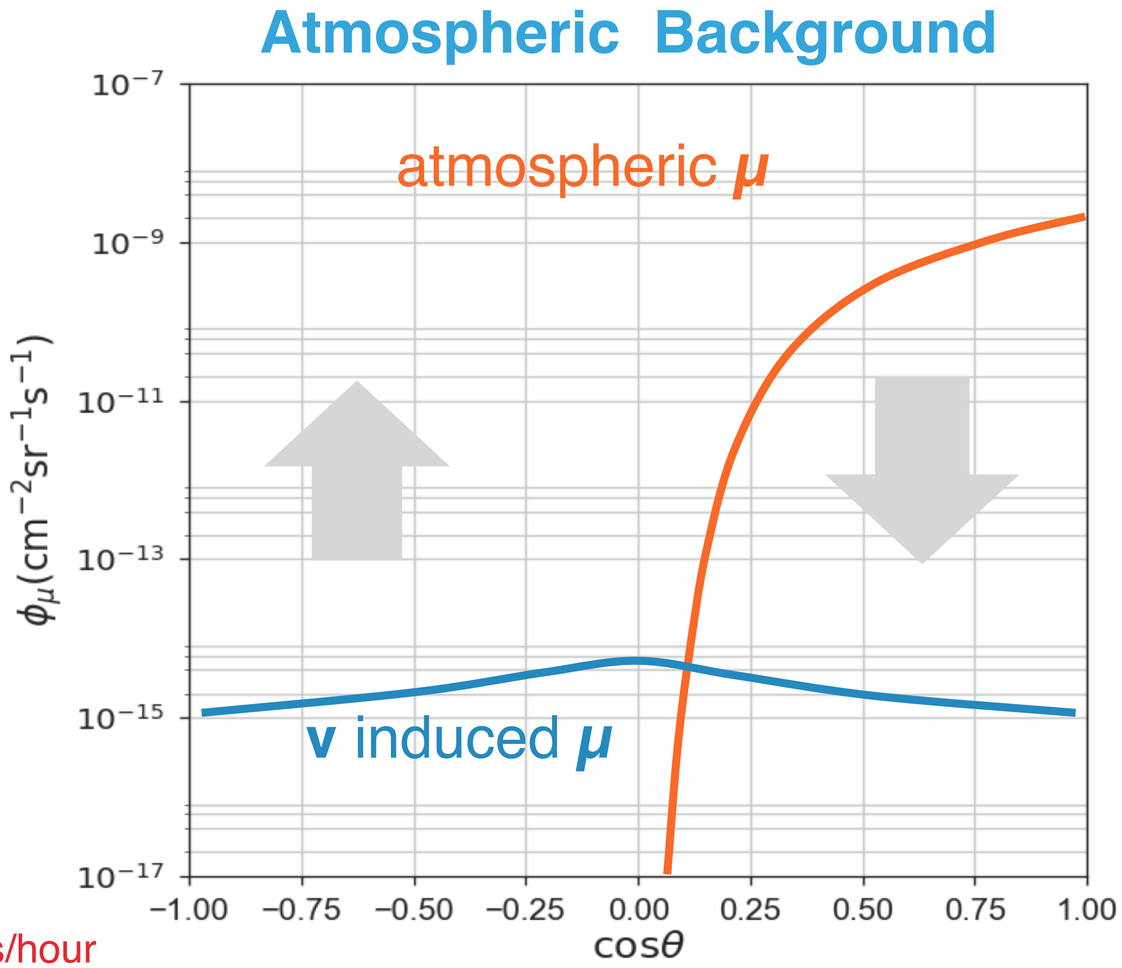


You just saw 10 msec of IceCube data!

The atmospheric background

Credit: J. A. Aguilar



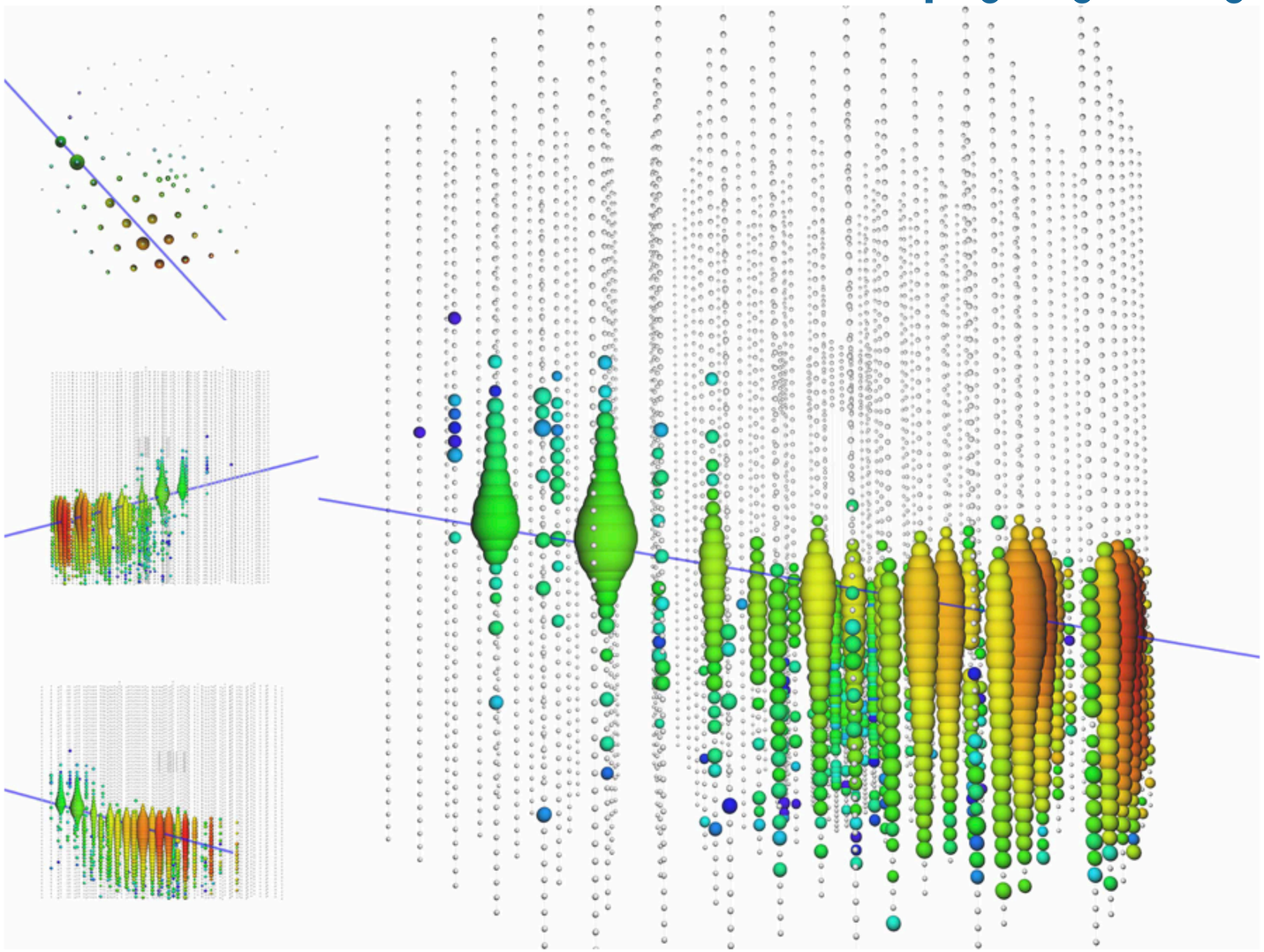


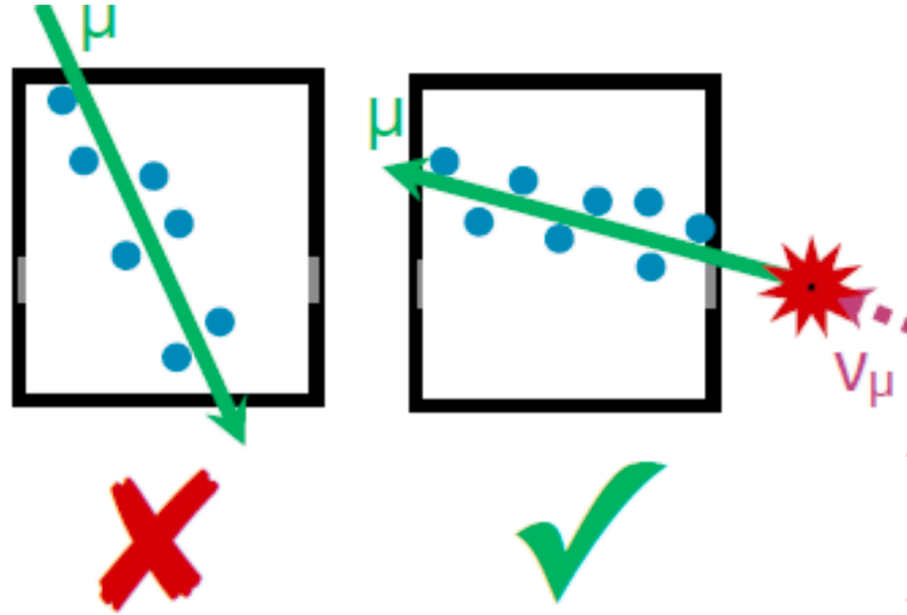
3kHz

2mHz

Searching for astrophysical neutrinos

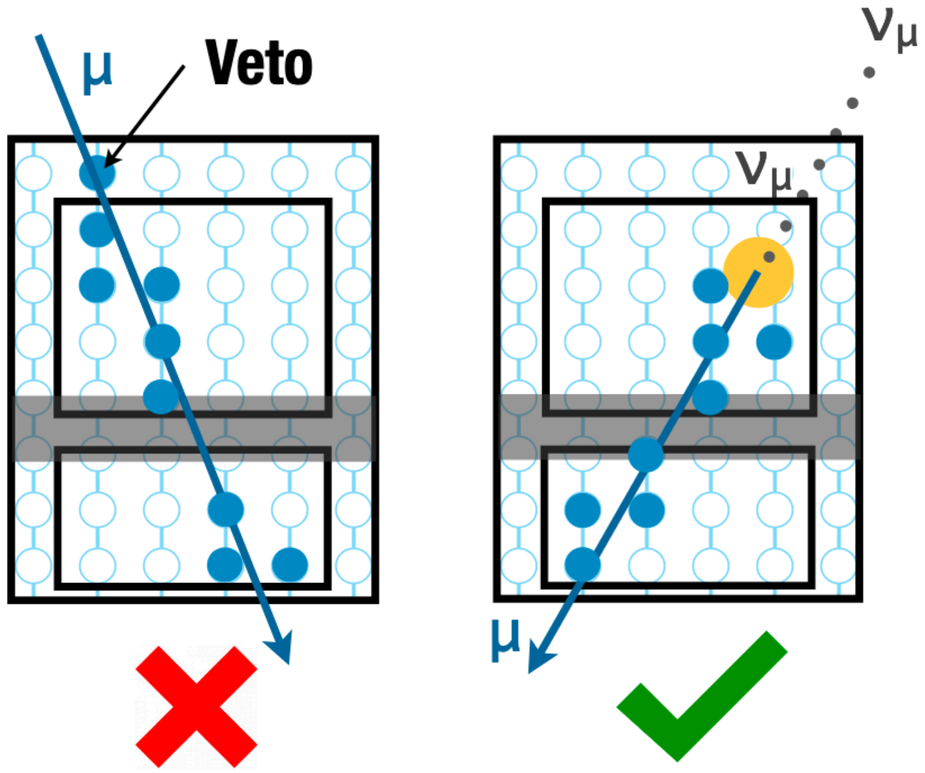
Up-going through-going muons travelled through the Earth

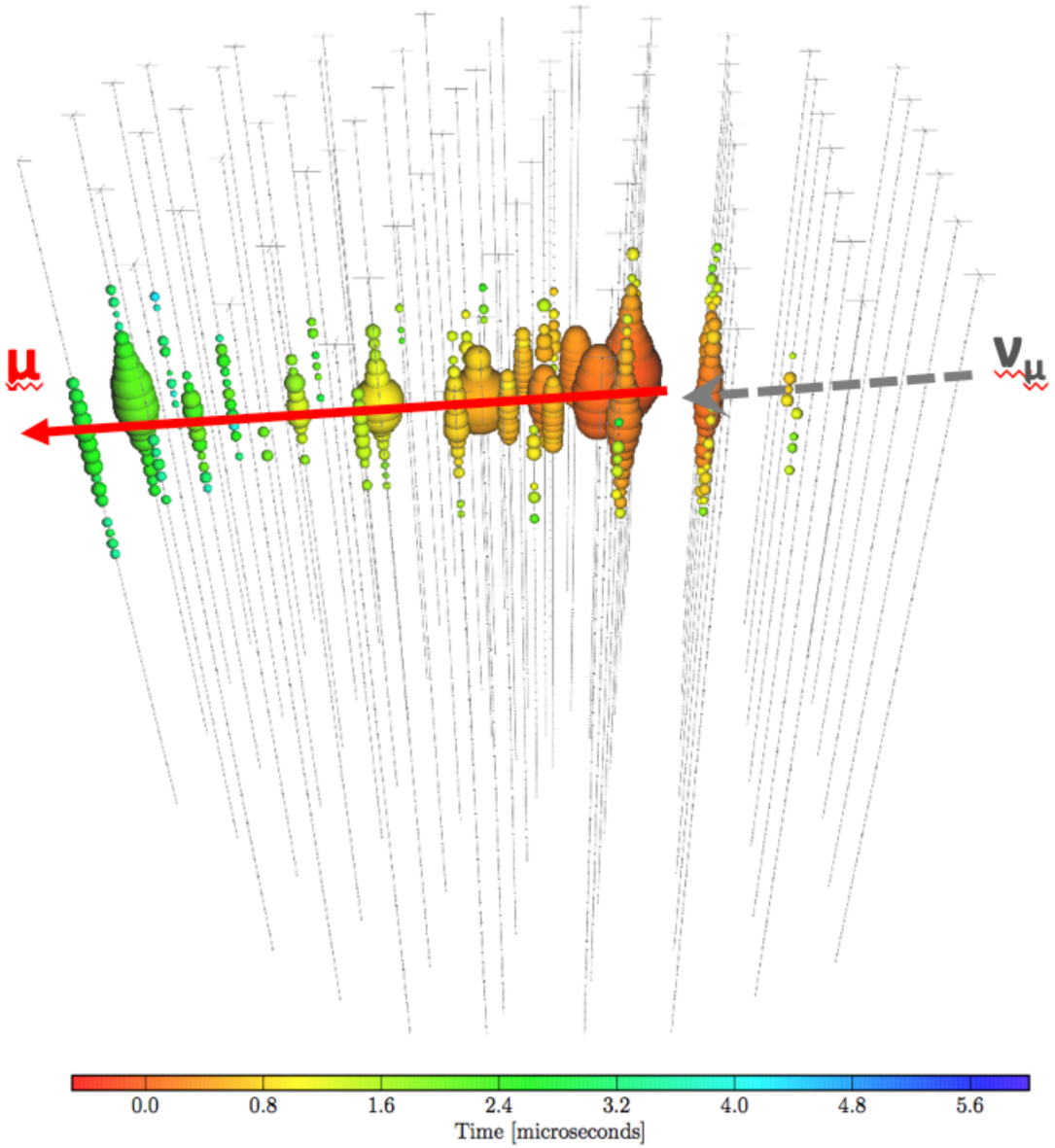




Diffuse-ν_μ sample (Northern Sky)

High Energy Starting Events (HESE)





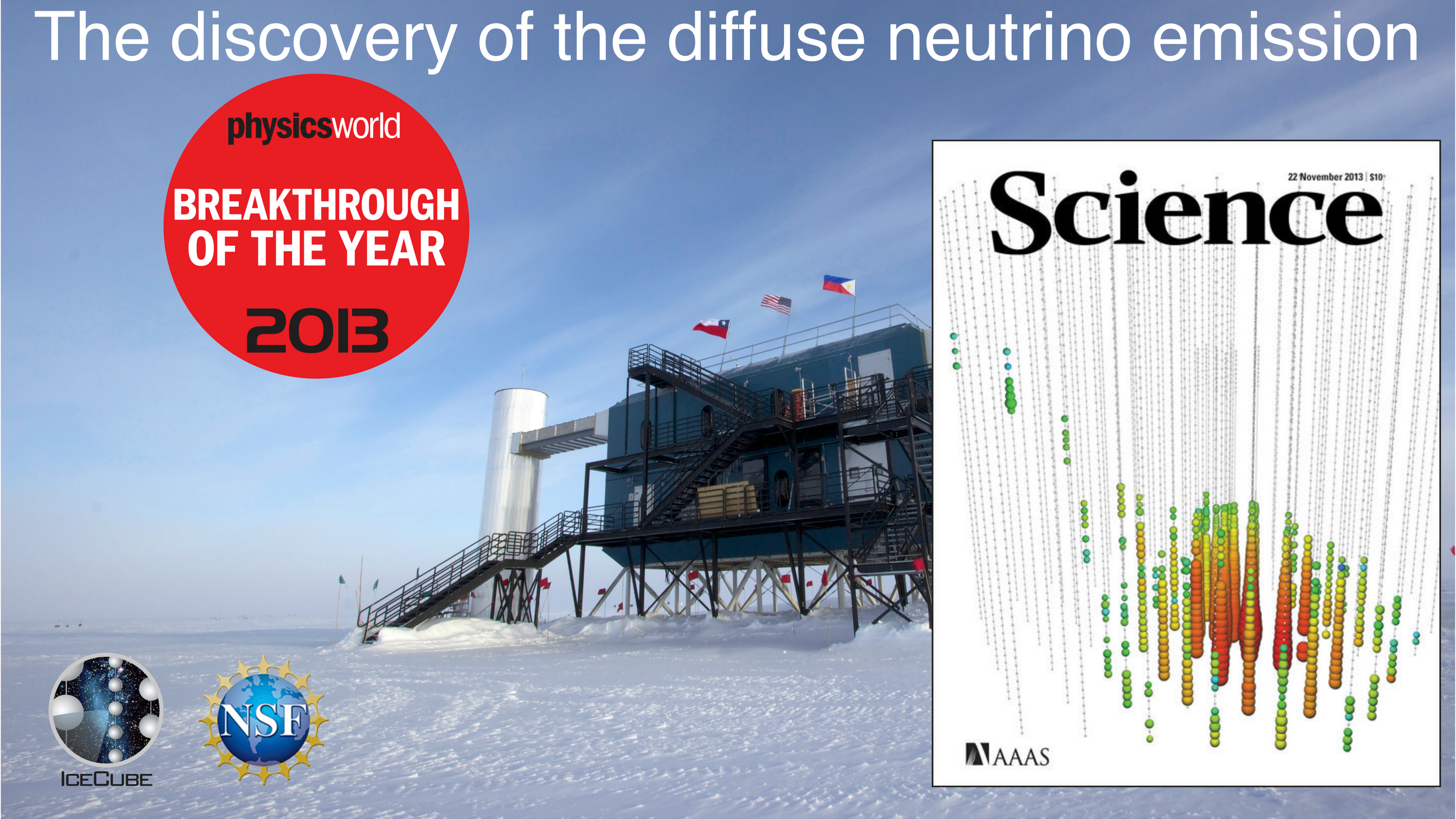
Hybrid (tracks and cascades) - 4π

The discovery of the diffuse neutrino emission

physicsworld

BREAKTHROUGH OF THE YEAR

2013



IceCube

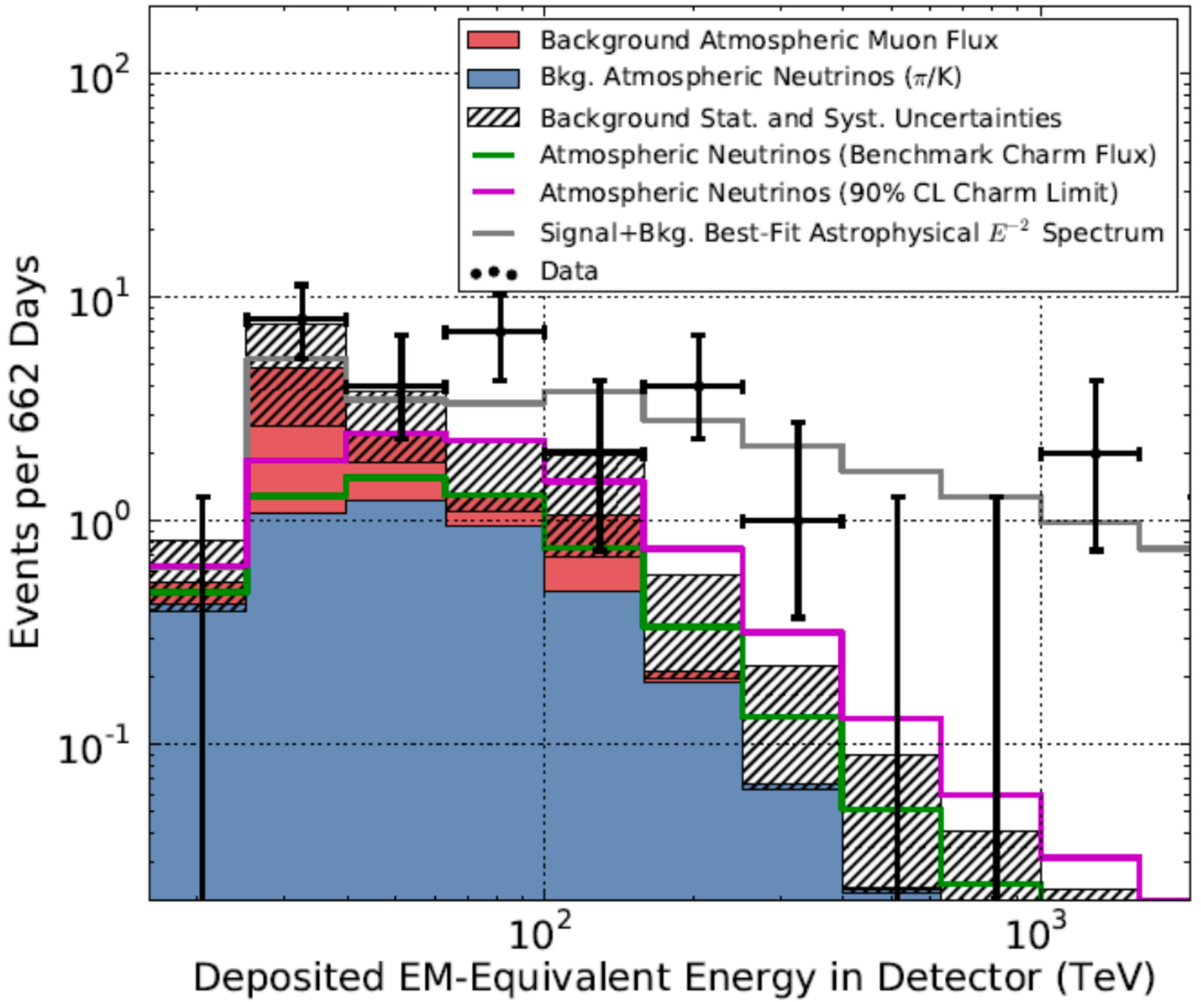
NSF

Astrophysical neutrinos: diffuse flux

Only 2 years of data to find evidence of astrophysical neutrinos!

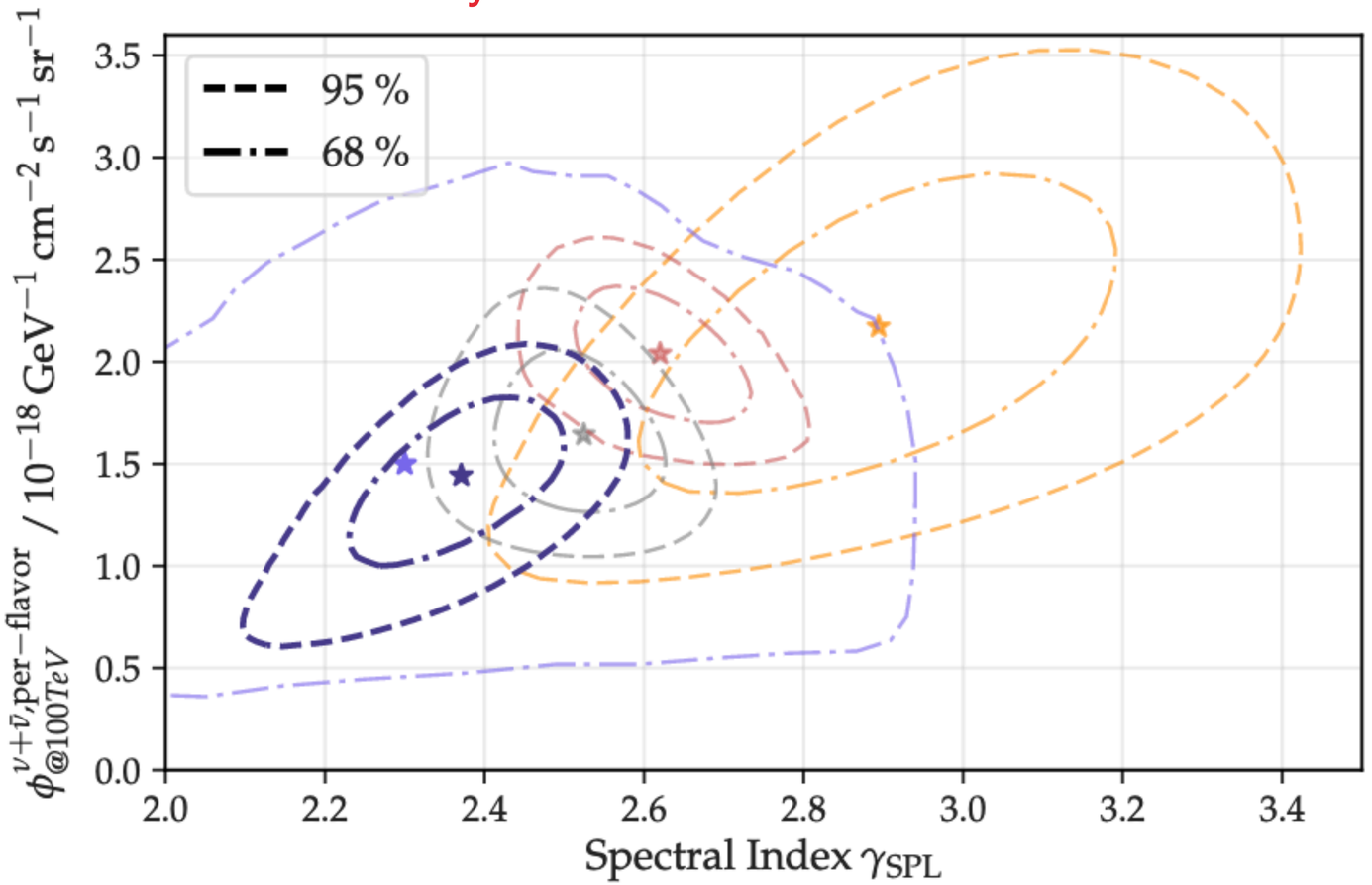
Aartsen et al (IceCube Coll.) Science 342, 1242856 (2013)

- Flux assuming E^{-2}: ~1.2 x 10-8 E-2 [/GeV/cm2/s/sr]
- Best fit spectral index: -2.2
- 28 events (expected ~ 10 background events)
- Significance ~ 4σ



Astrophysical neutrinos: power law

Several analysis confirm the detection at > 5σ



HESE (7.5y Full-sky)
Phys. Rev. D 104, 022002 (2021)

Inelasticity Study (5y, Full-sky)
Phys. Rev. D 99, 032004

Cascades (6y, Full-sky)
Phys. Rev. Lett. 125, 121104 (2020)

This work: Through-going Tracks
(9.5y, Northern-Hemisphere)

ANTARES Cascades+Tracks
(best-fit: 9y, Full-sky) PoS(ICRC2019)891

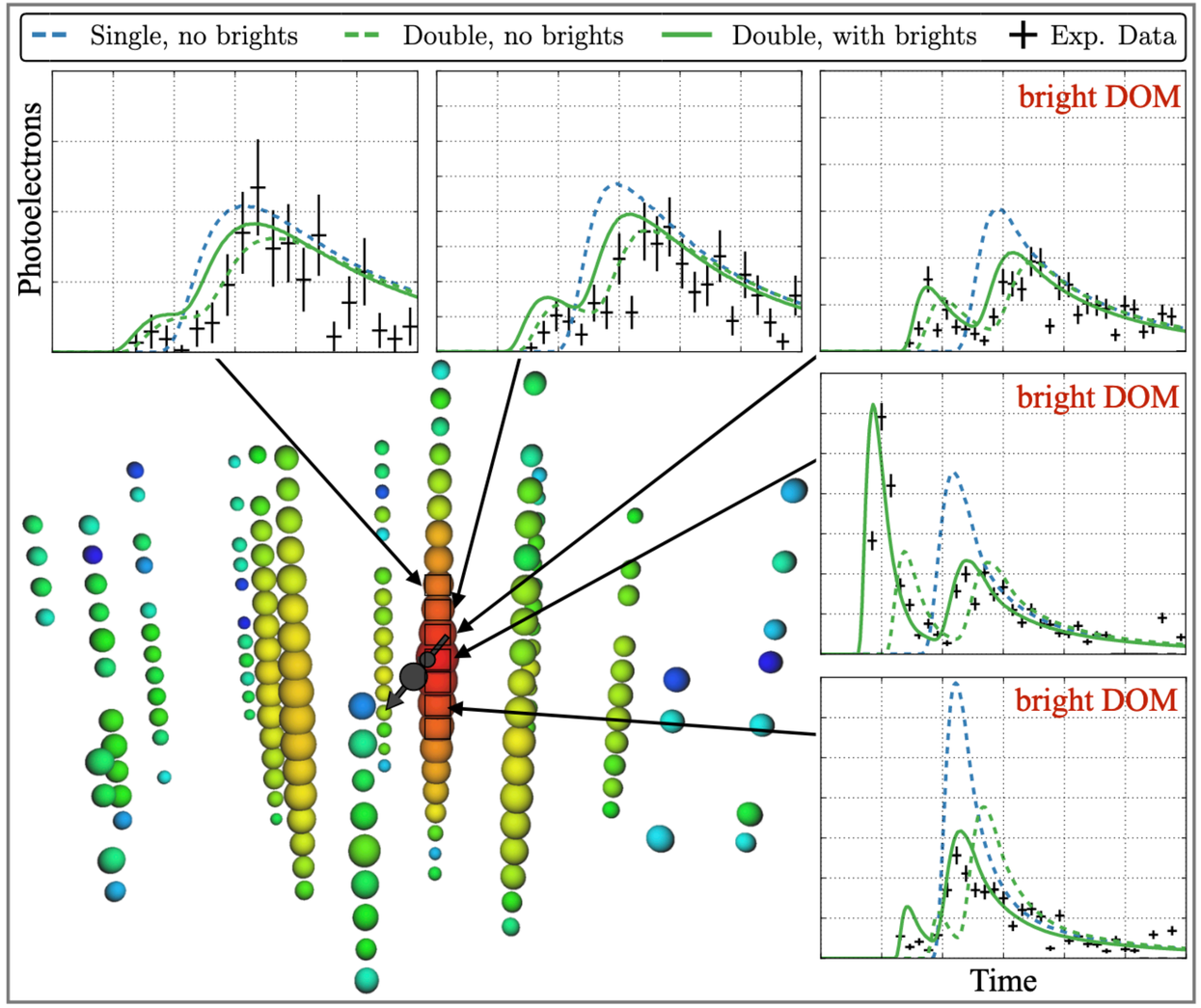
Abbasi et al (IceCube Coll), ApJ 928:50 (2022)

Comparison difficult since datasets have different energy cuts and select different morphologies (hemispheres)

Global fit to unify all detection channels and test tensions between results

ν_τ candidate

arXiv:2011.03561

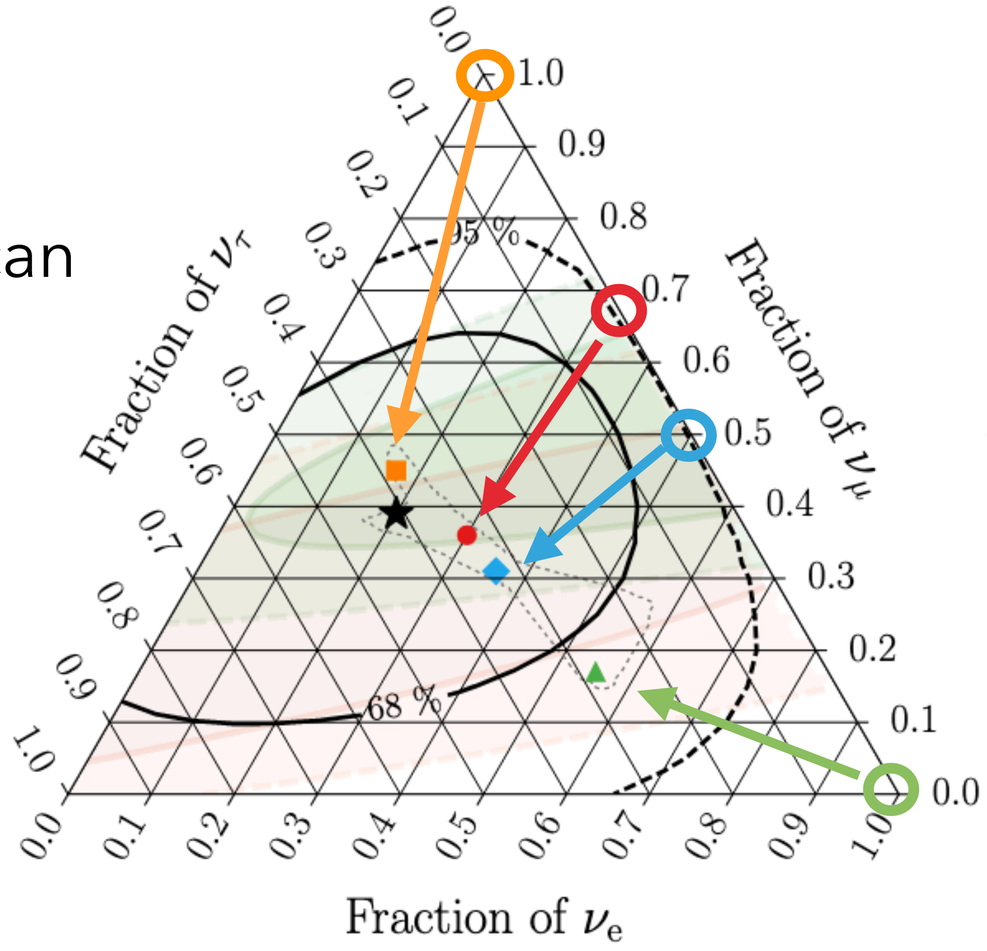


- Tau neutrinos selected using a double cascade hypothesis in reconstruction.
- Likelihood analysis finds two candidates: 76%, 98% probabilities of being ν_T.
- Null hypothesis (no astrophysical ν_T) rejected at 2.8σ.

Neutrino flavor triangle

arXiv:2011.03561

Flavor ratio at Earth can constrain source environment



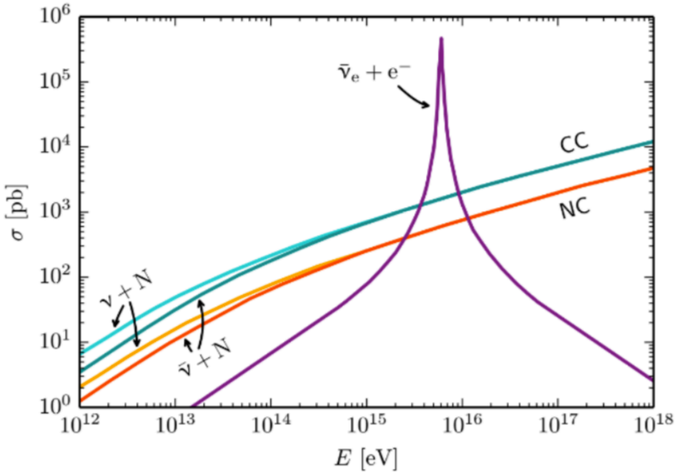
HESE with ternary topology ID
Best fit: 0.20 : 0.39 : 0.42
Global Fit (IceCube, APJ 2015)
Inelasticity (IceCube, PRD 2019)
3ν-mixing 3σ allowed region

$\nu_e : \nu_\mu : \nu_\tau$ at source $\rightarrow$ on Earth:

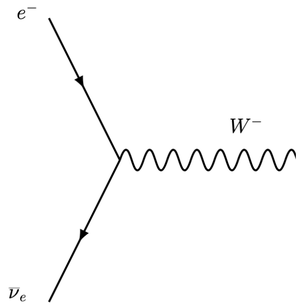
- 0:1:0 $\rightarrow$ 0.17 : 0.45 : 0.37
- 1:2:0 $\rightarrow$ 0.30 : 0.36 : 0.34
- 1:0:0 $\rightarrow$ 0.55 : 0.17 : 0.28
- 1:1:0 $\rightarrow$ 0.36 : 0.31 : 0.33

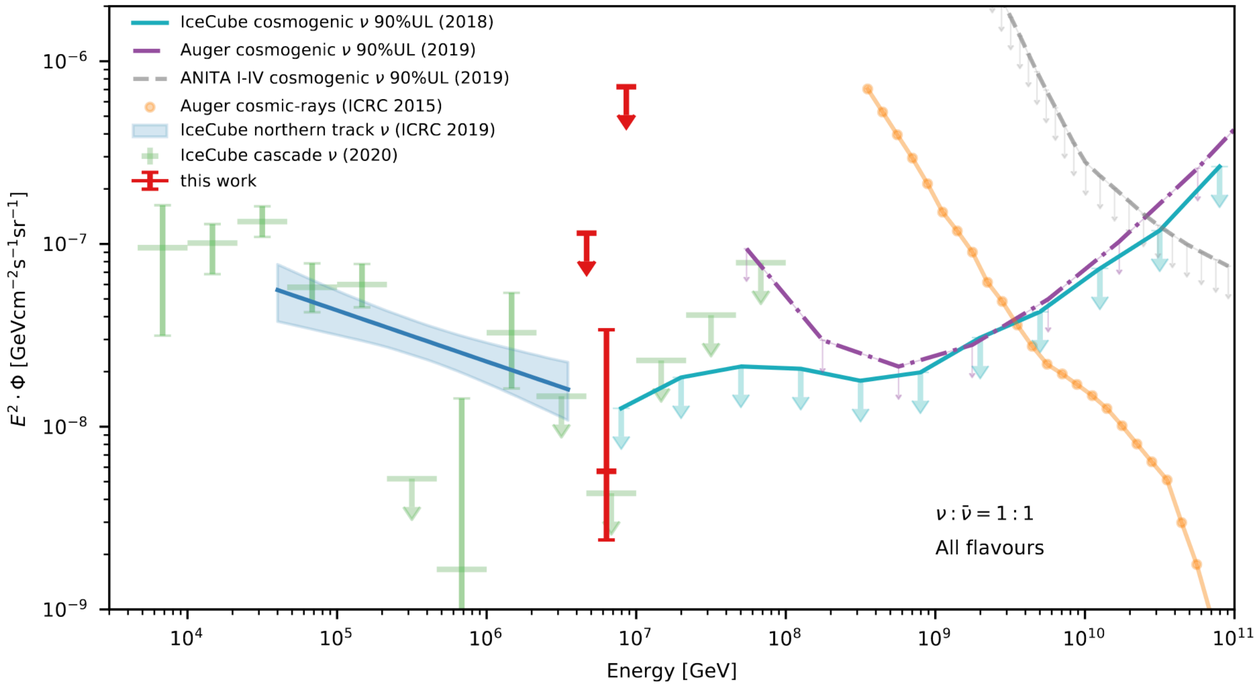
The Glashow resonance

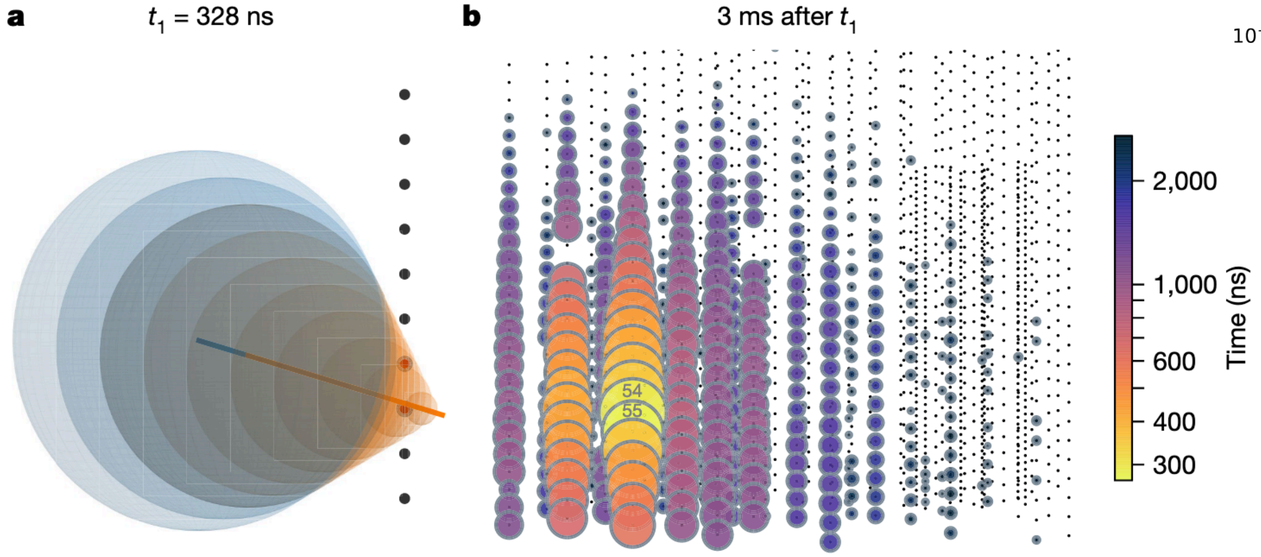
Nature volume 591, pages 220–224 (2021)



$E_R = 6.3$ PeV







Observed cascade: E ~6.3 PeV consistent with resonance energy.

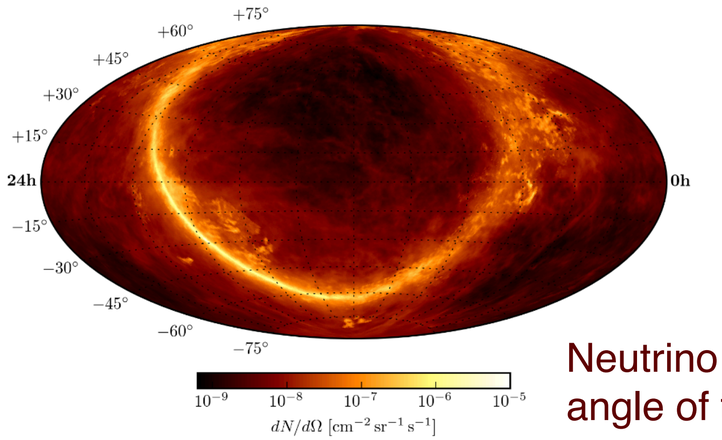
Nu/nubar ratio constrain production mechanism (pp/ pγ) of astro neutrinos.

Diffuse galactic emission (joint with ANTARES)

- Contribution much smaller than total detected diffuse neutrino flux (<10%)
- It is a guaranteed source:

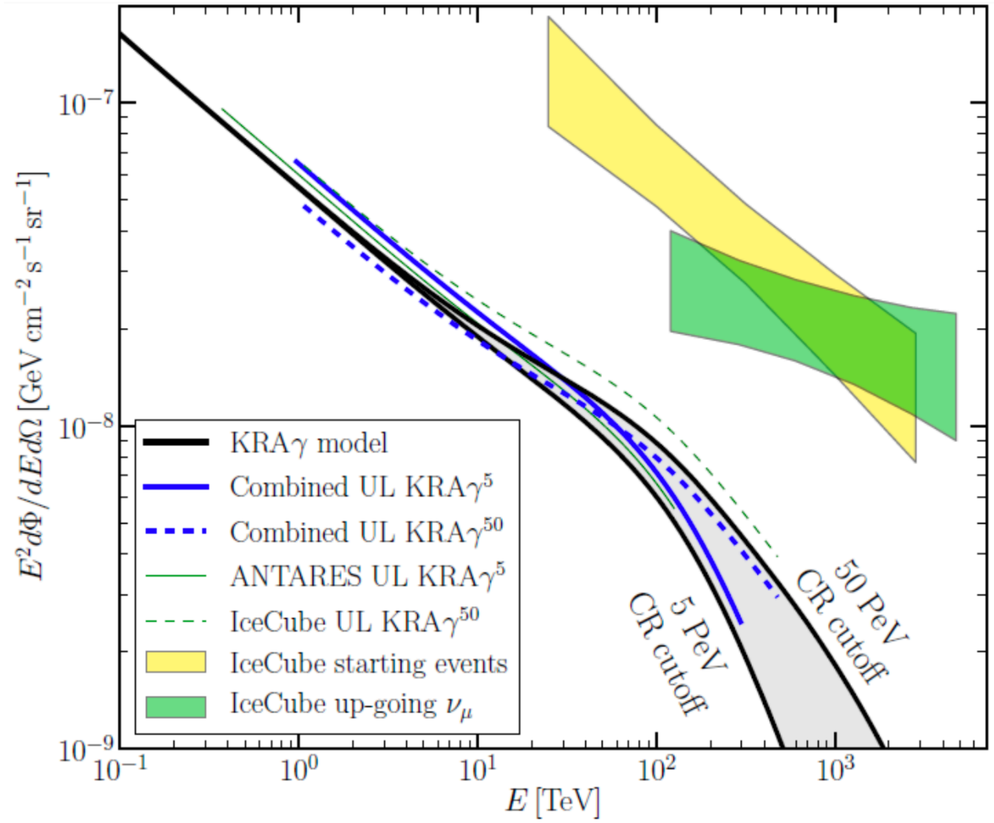
$$p + \text{gas} \rightarrow \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow \pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu)$$

- Upper limits close to the expected diffuse Galactic neutrino component



Neutrino flux per unit of solid angle of the KRAγ5 model.

ANTARES and IceCube Coll. A. Albert *et al* 2018 *ApJL* **868** L20



Template	*p*-value
KRA_γ^5	0.021
KRA_γ^{50}	0.022
Fermi-LAT π^0	0.040

7-years cascades GP analysis

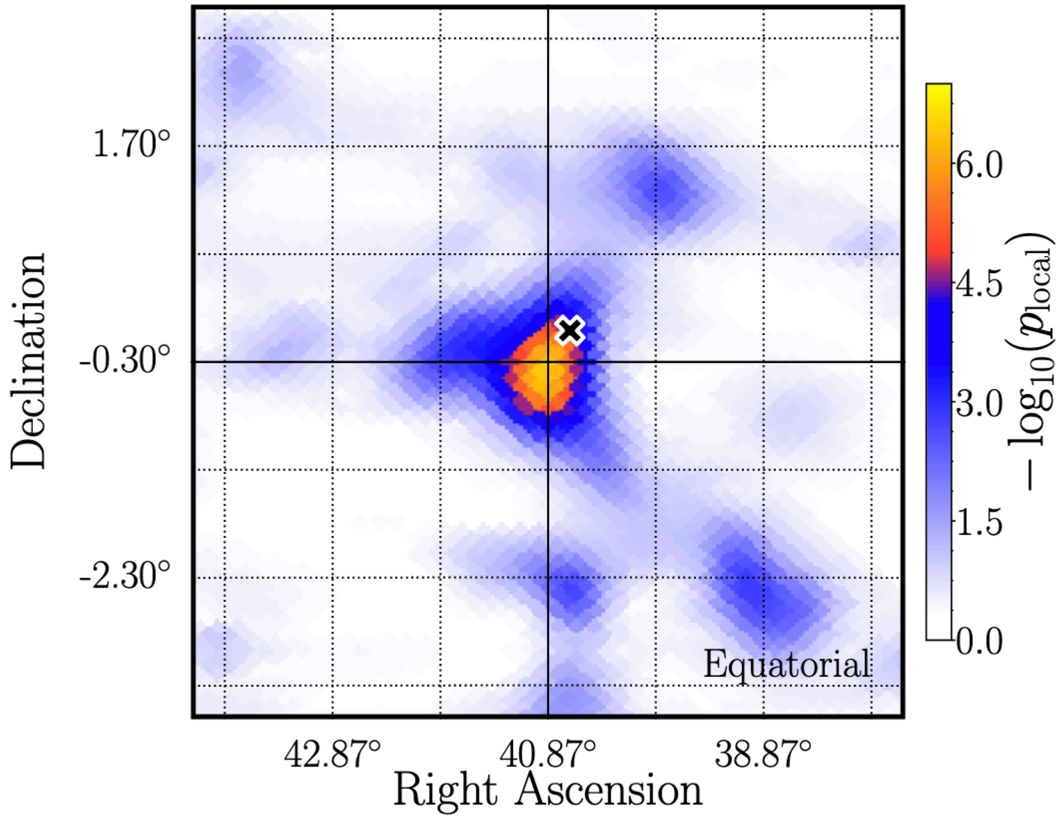
M. G. Aartsen *et al* 2019 *ApJ* **886** 12

S. Toscano

10 years all sky point sources

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

Using high energy through-going tracks and tracks optimized for point source searches



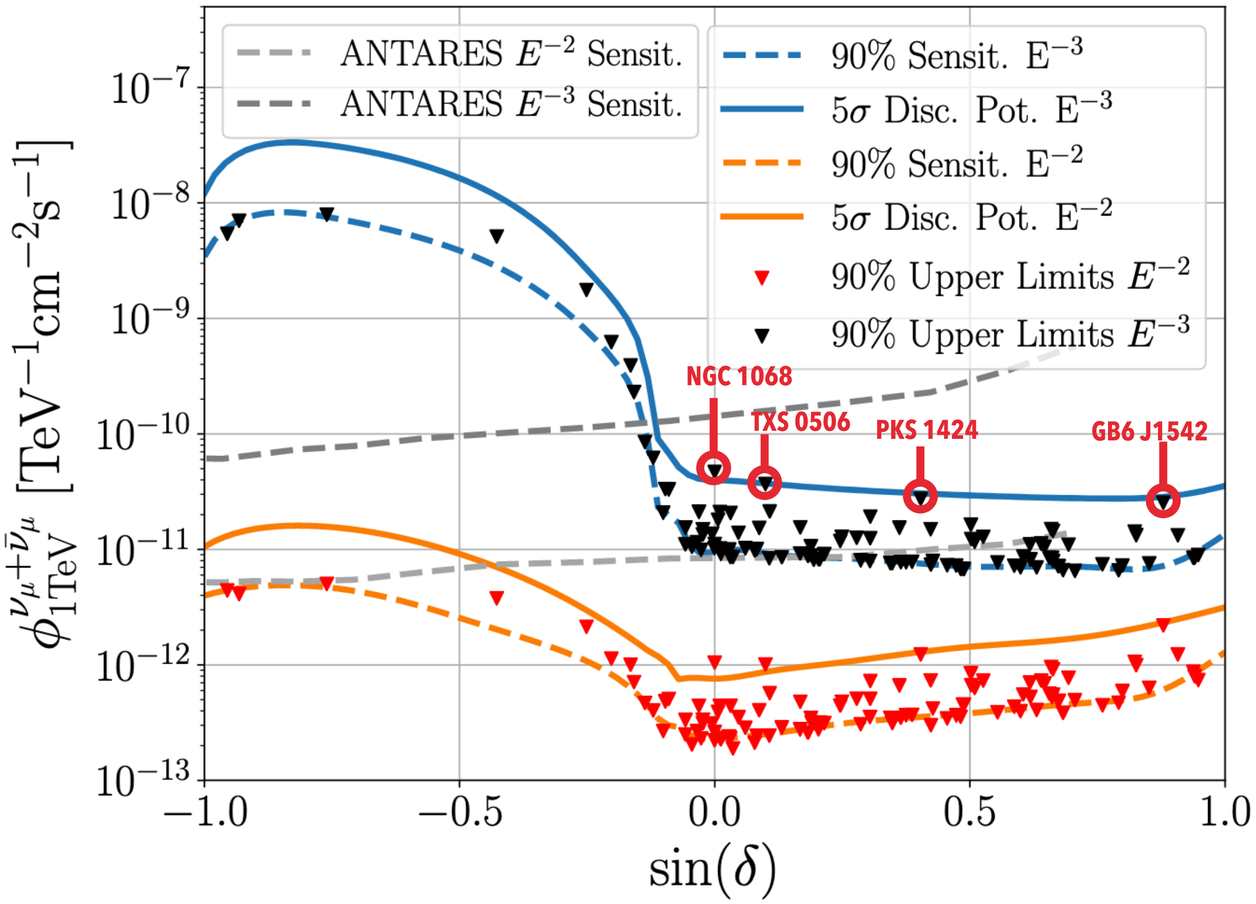
Hottest spot in Northern Hemisphere coincides with 2.9σ excess at the position of **NGC 1068**

10 years of IceCube data now publicly available at NASA's HEASARC archive

10 years all sky point sources

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

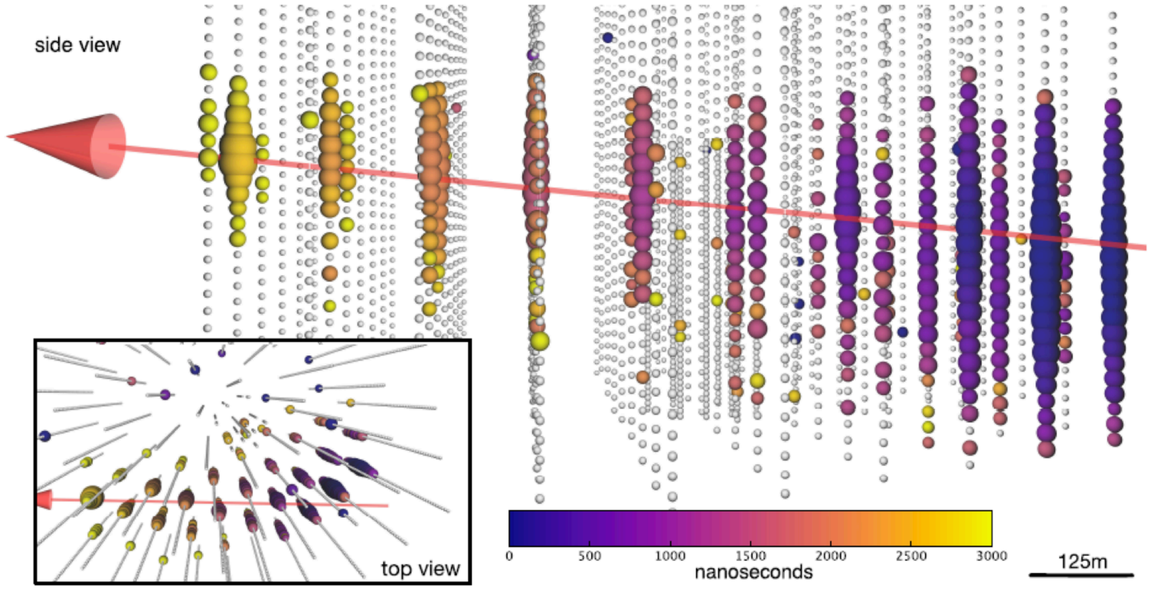
Source list search is incompatible with background at 3.3σ (2.25σ without TXS 0506)

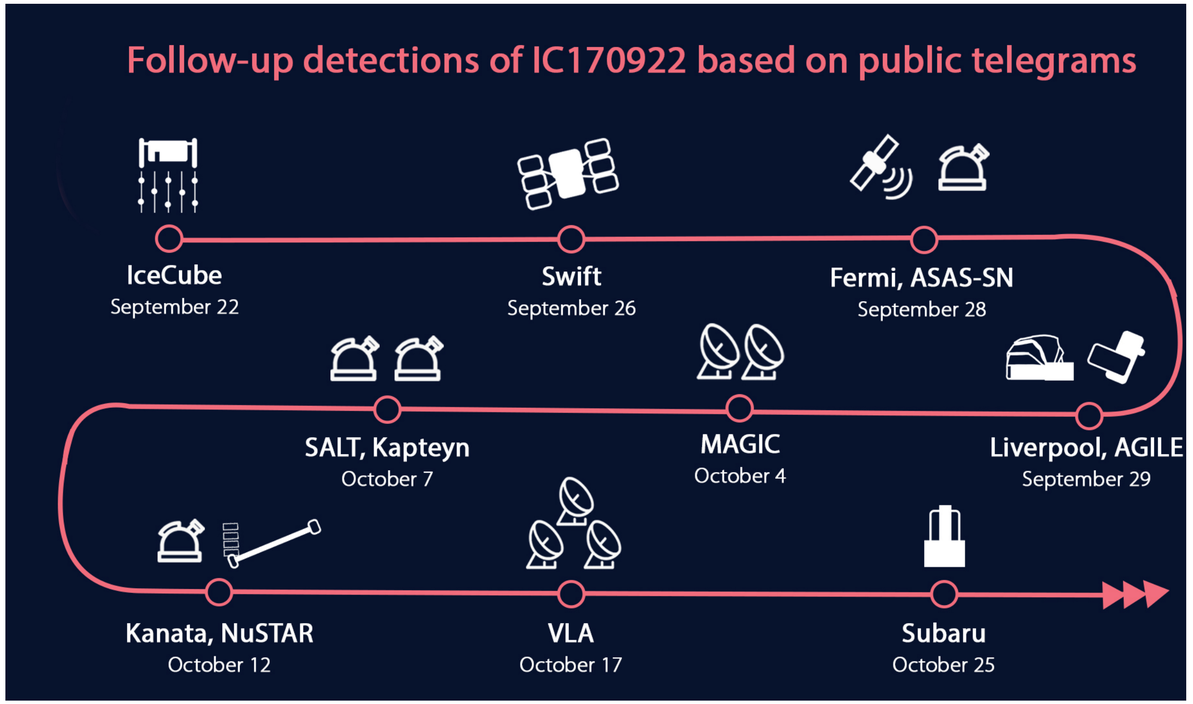


10 years of IceCube data now publicly available at NASA's HEASARC archive

Neutrino emission from TXS 0506+056

IceCube-170922A E = 290 TeV





Science 13 Jul 2018: Vol. 361, Issue 6398

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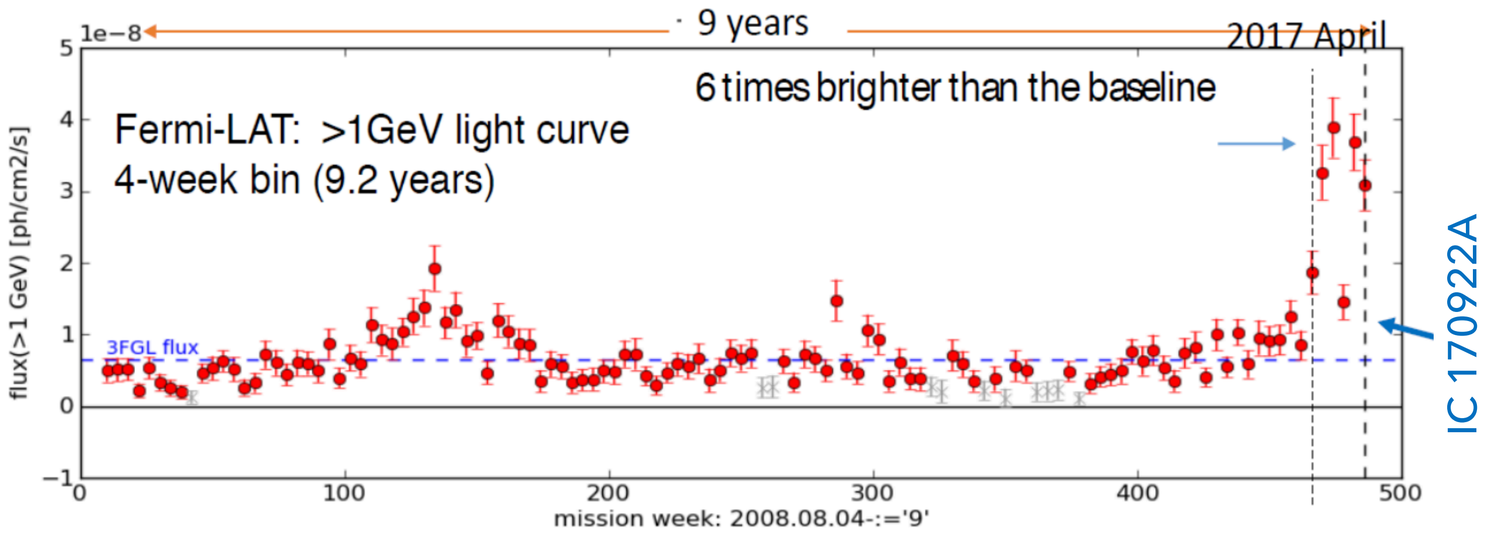
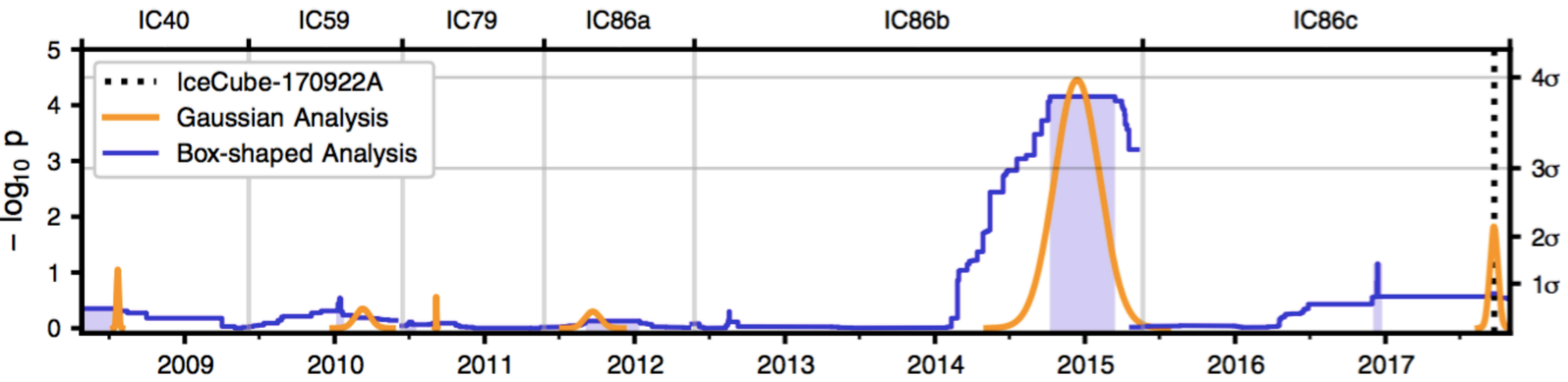
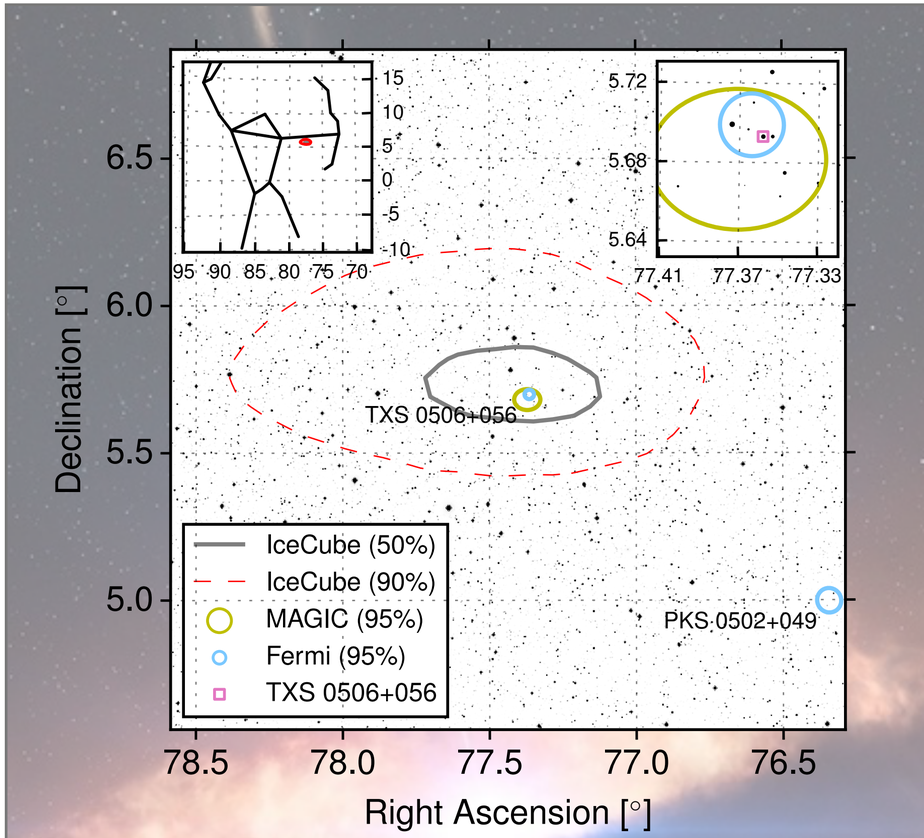
Multimessenger coincidence: p-value = 3σ. [Science 361 (2018) eaat1378]



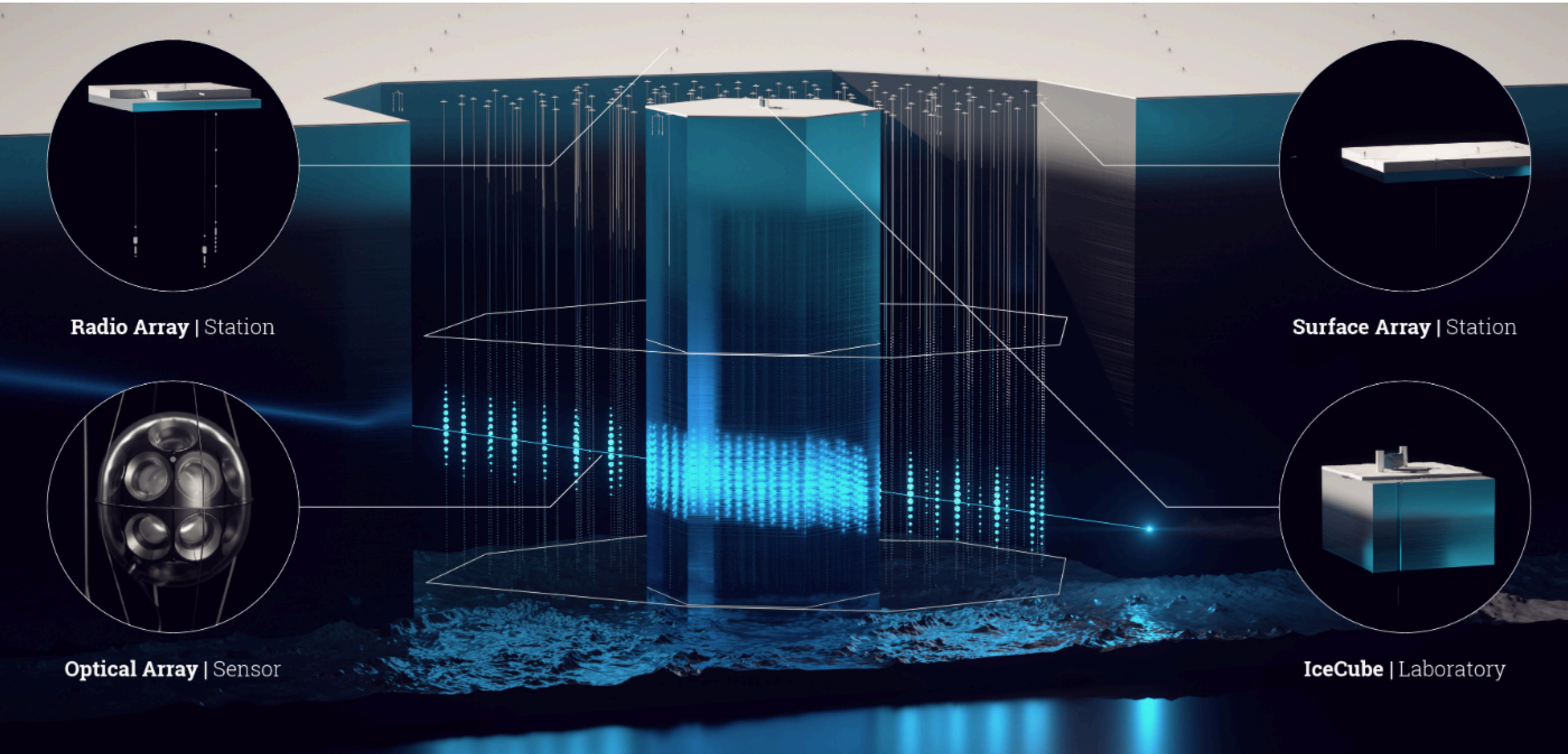




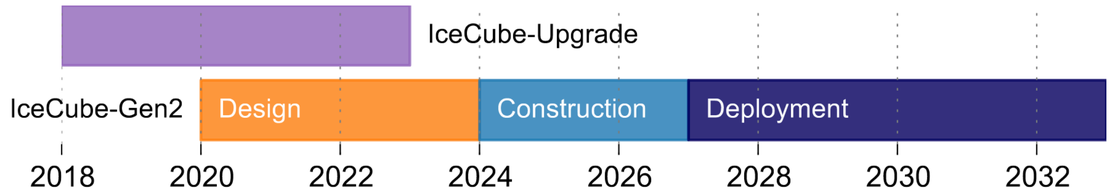
Archival neutrino search find an excess between September 2014 and March 2015: background only hypothesis rejected at 3.5σ [Science 361 (2018) 147-151].

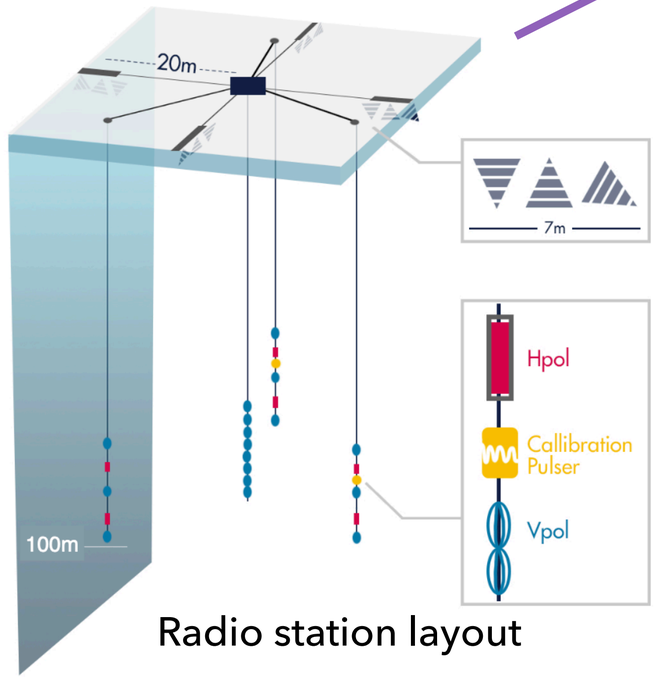
S. Toscano

The future IceCube-Gen2 Observatory

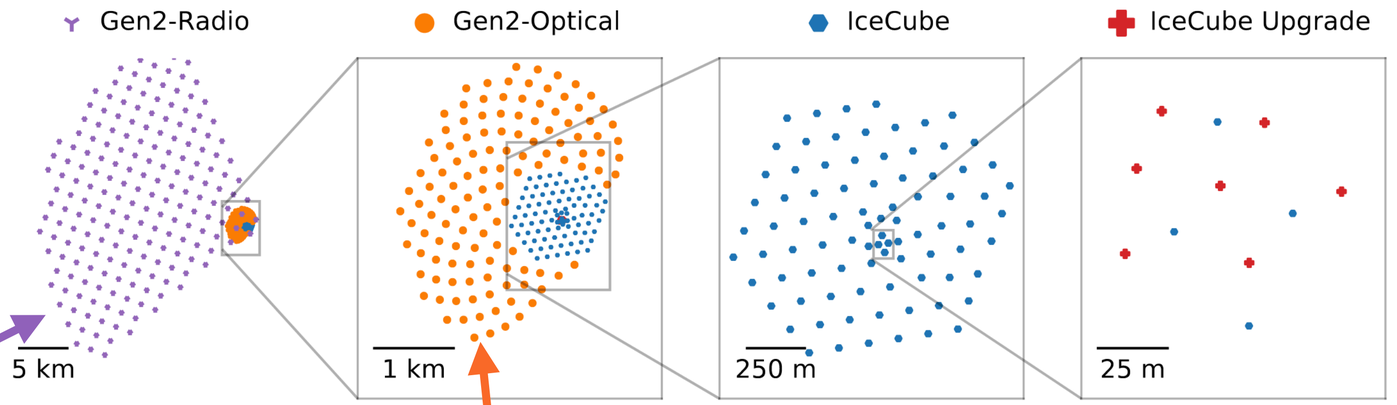


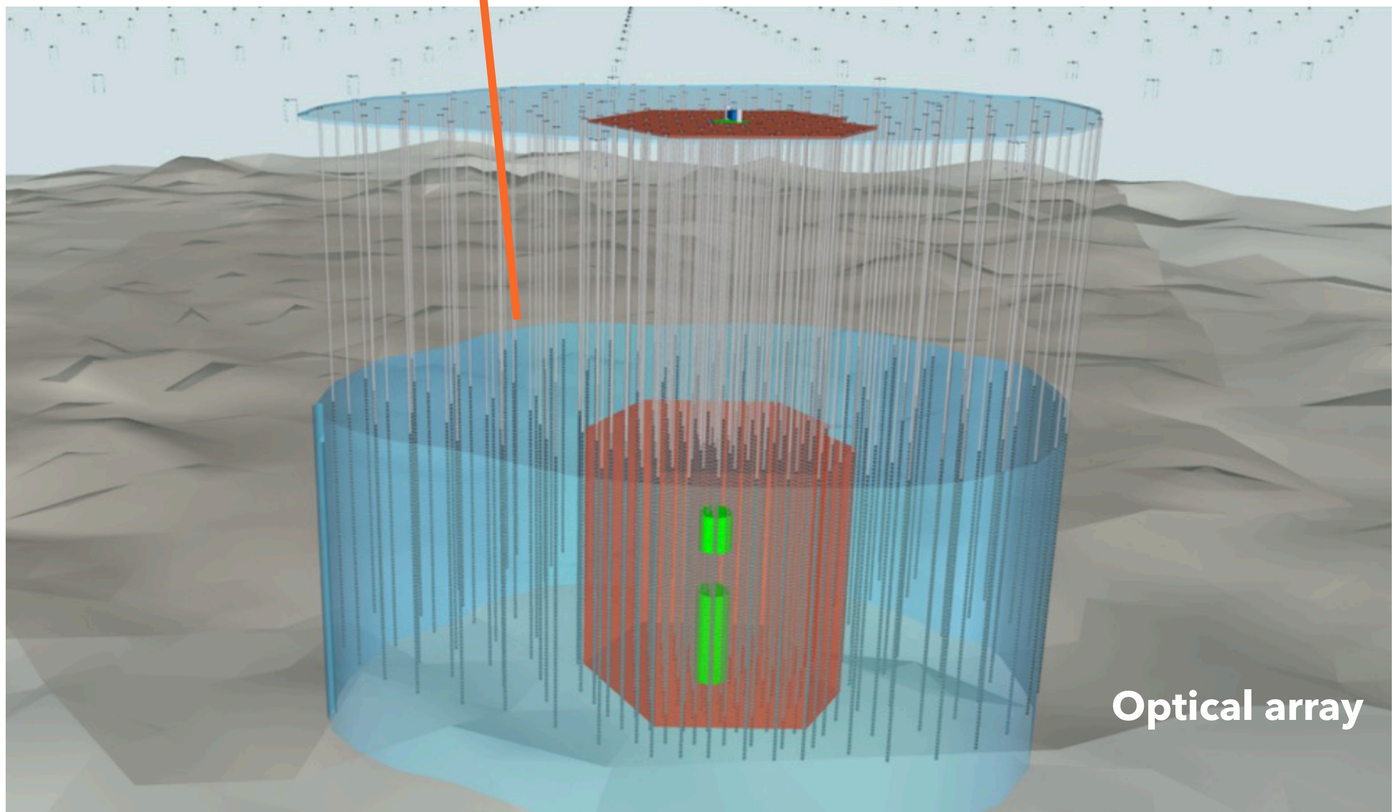
Neutrino astronomy from GeV to EeV



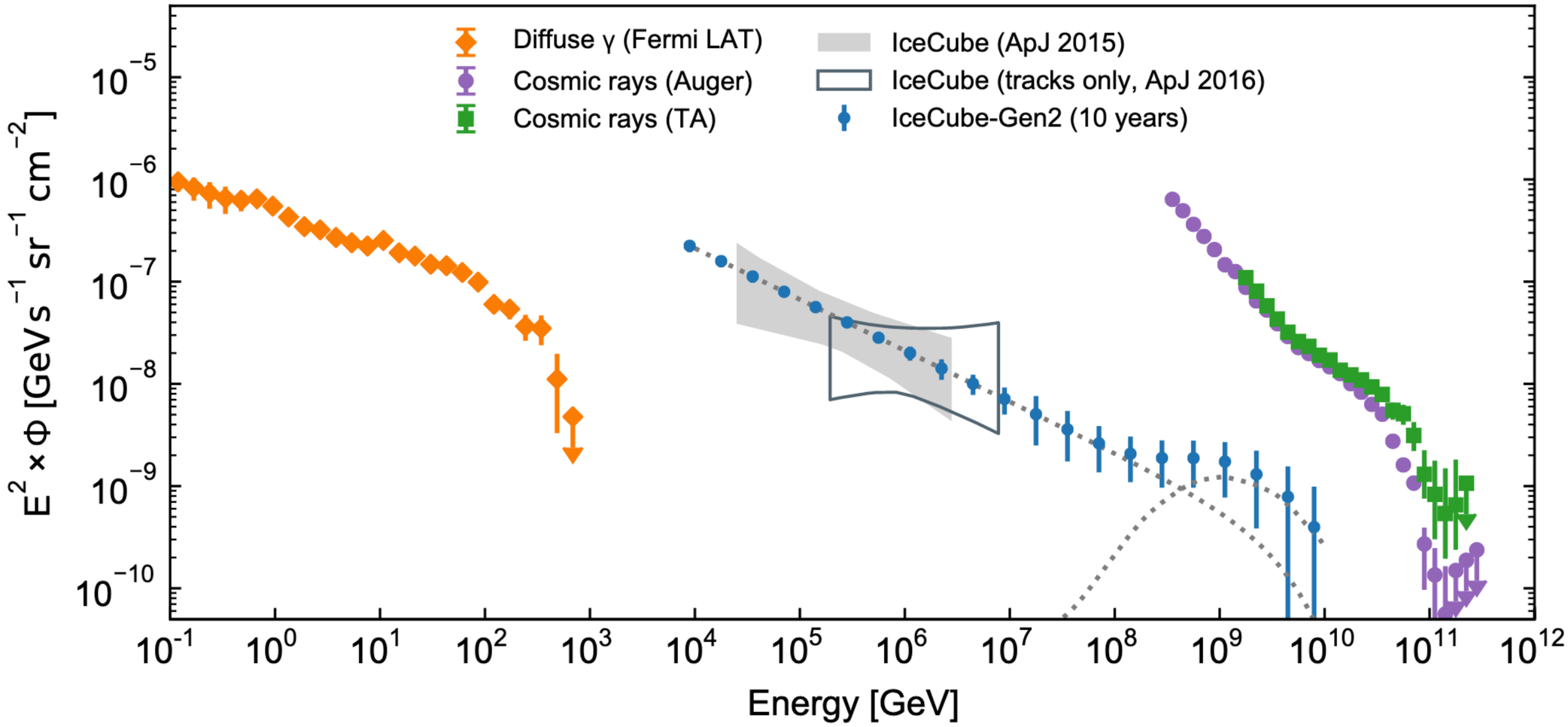


Radio station layout





Projection for IceCube-Gen2: spectrum



SUMMARY

Credit: SPT/Aman Chokshi

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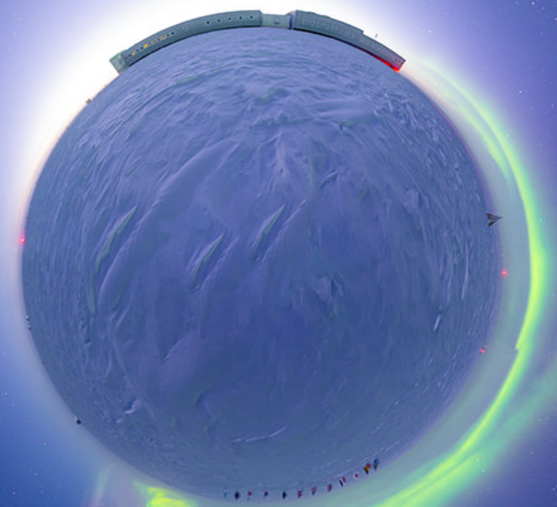

Credit: SPT/Aman Chokshi

SUMMARY

- Neutrino astronomy has opened a **new window** on the Universe: spectral studies important to understand production mechanism.

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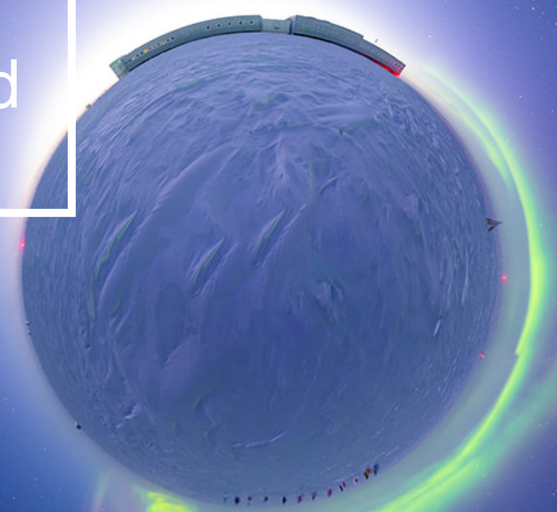

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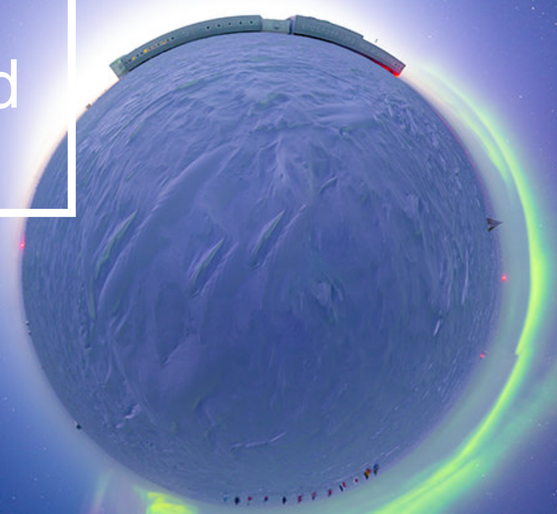

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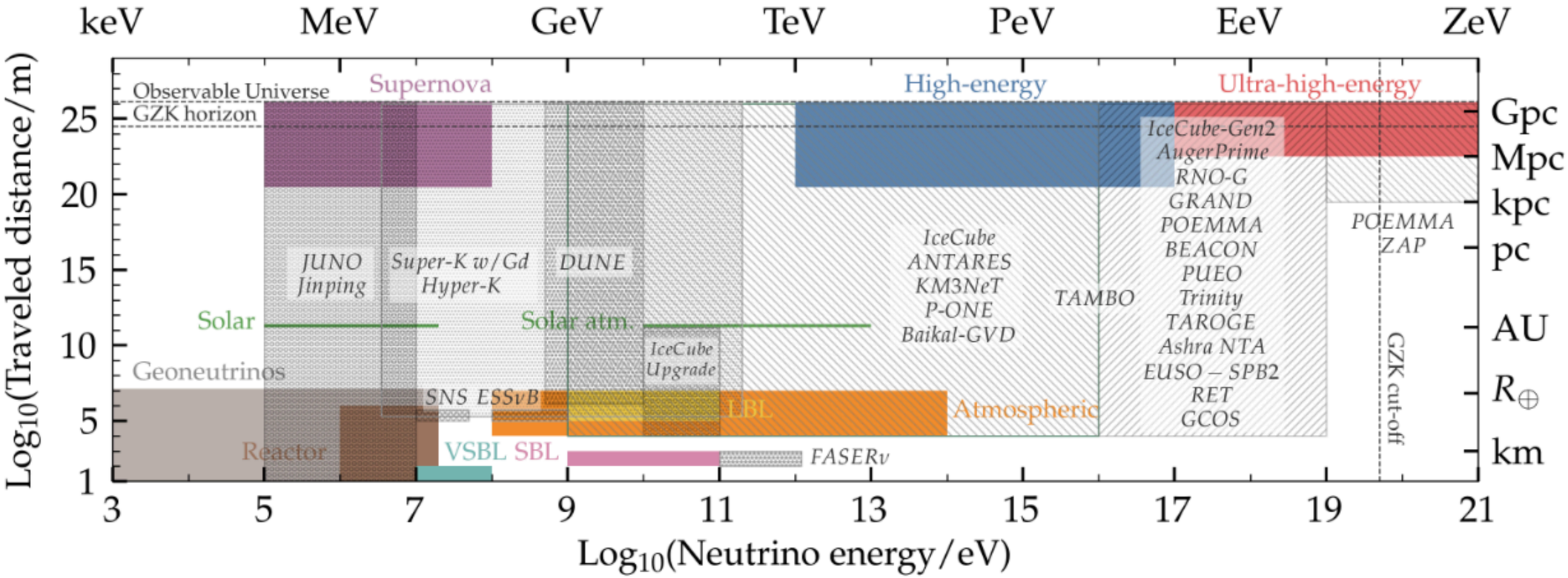
THANK YOU

Credit: SPT/Aman Chokshi

Neutrino astronomy: The multi-messenger connection

M. Ackermann, M. Bustamante, L. Lu et al., Journal of High Energy Astrophysics



The radio detector for the highest energies

Radio antennas detect particle showers in the ice through the Askaryan effect

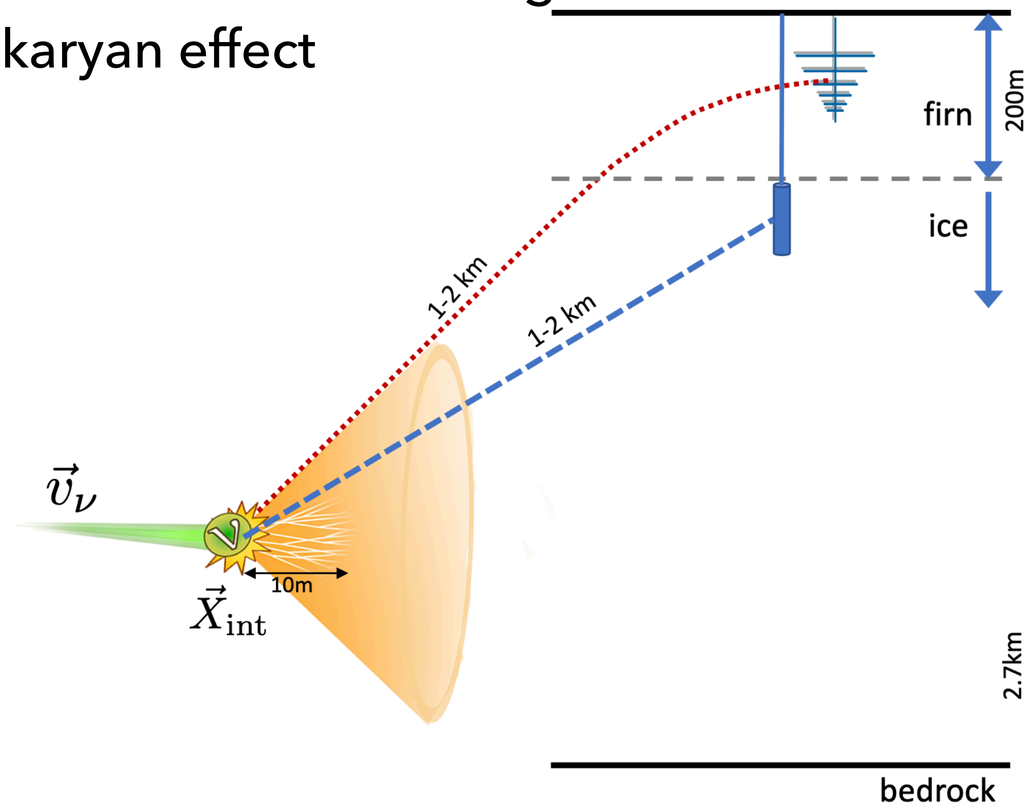
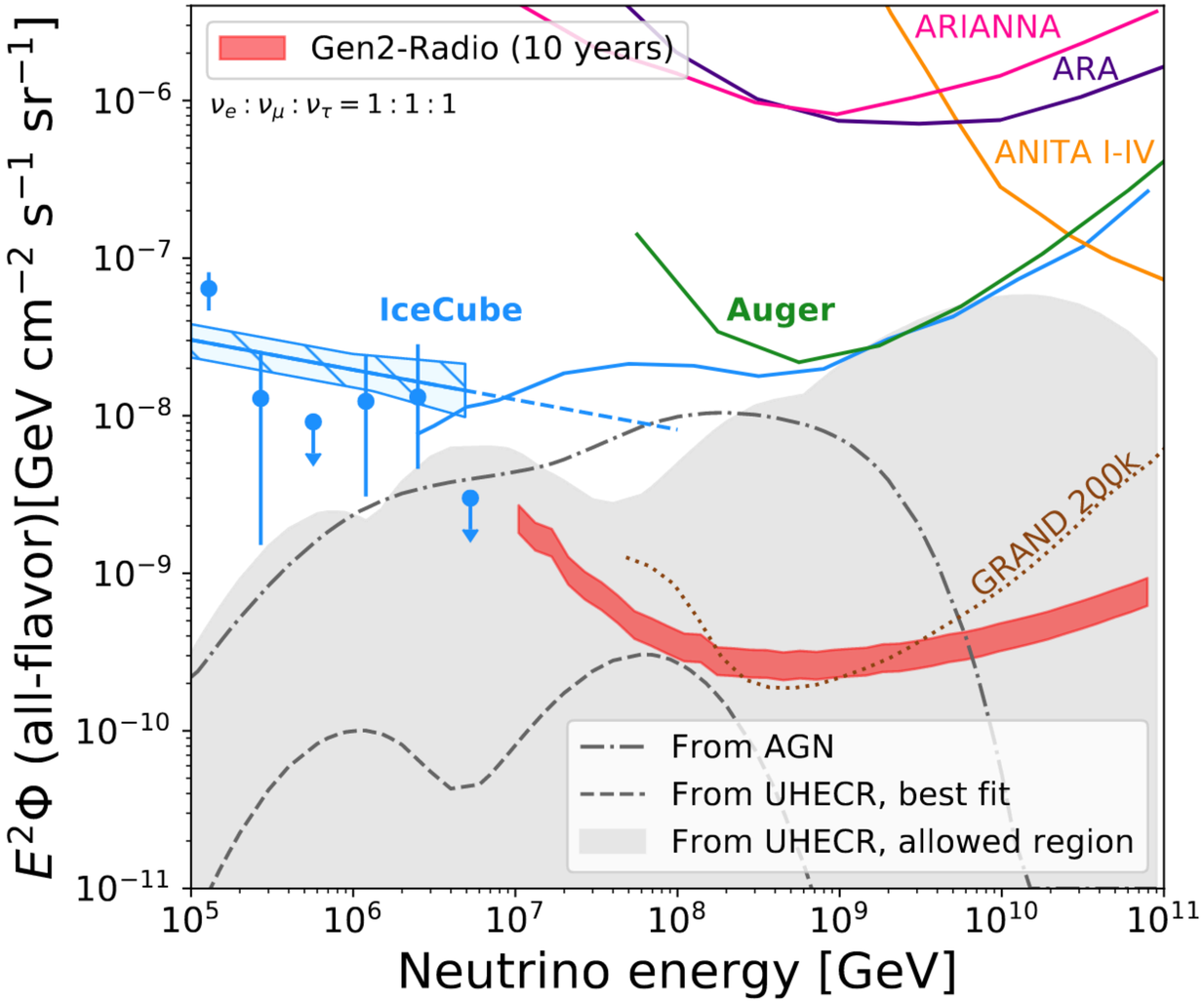


Figure from S. Barwick, C. Glaser, arXiv:2208.04971



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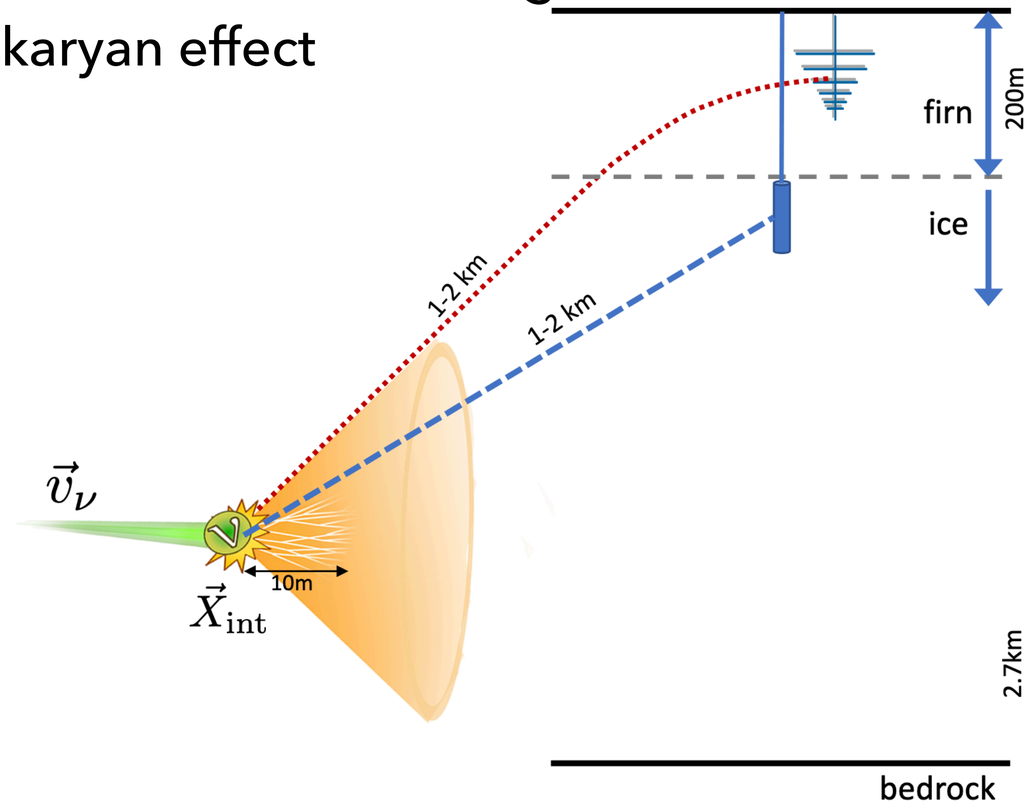

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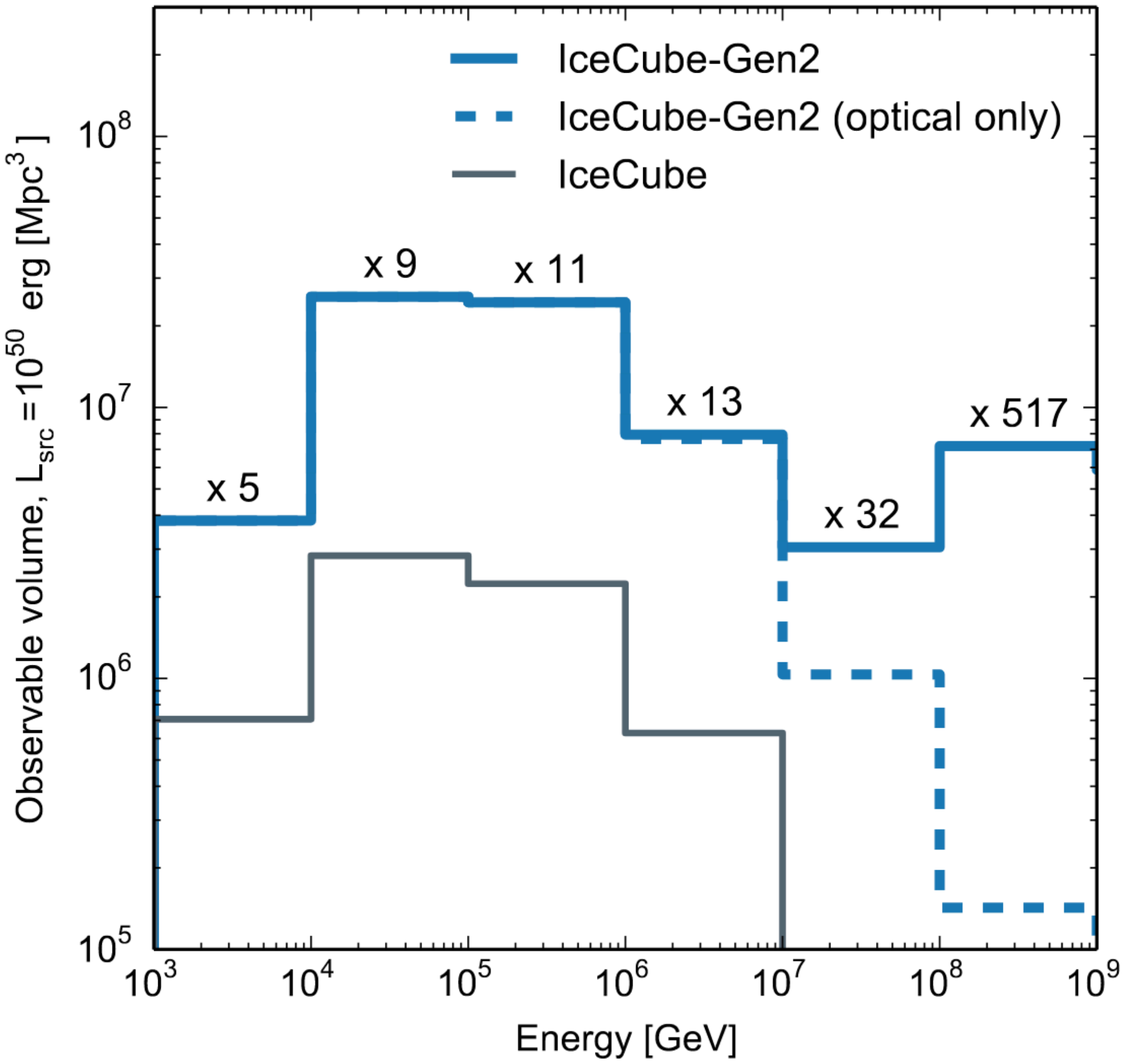
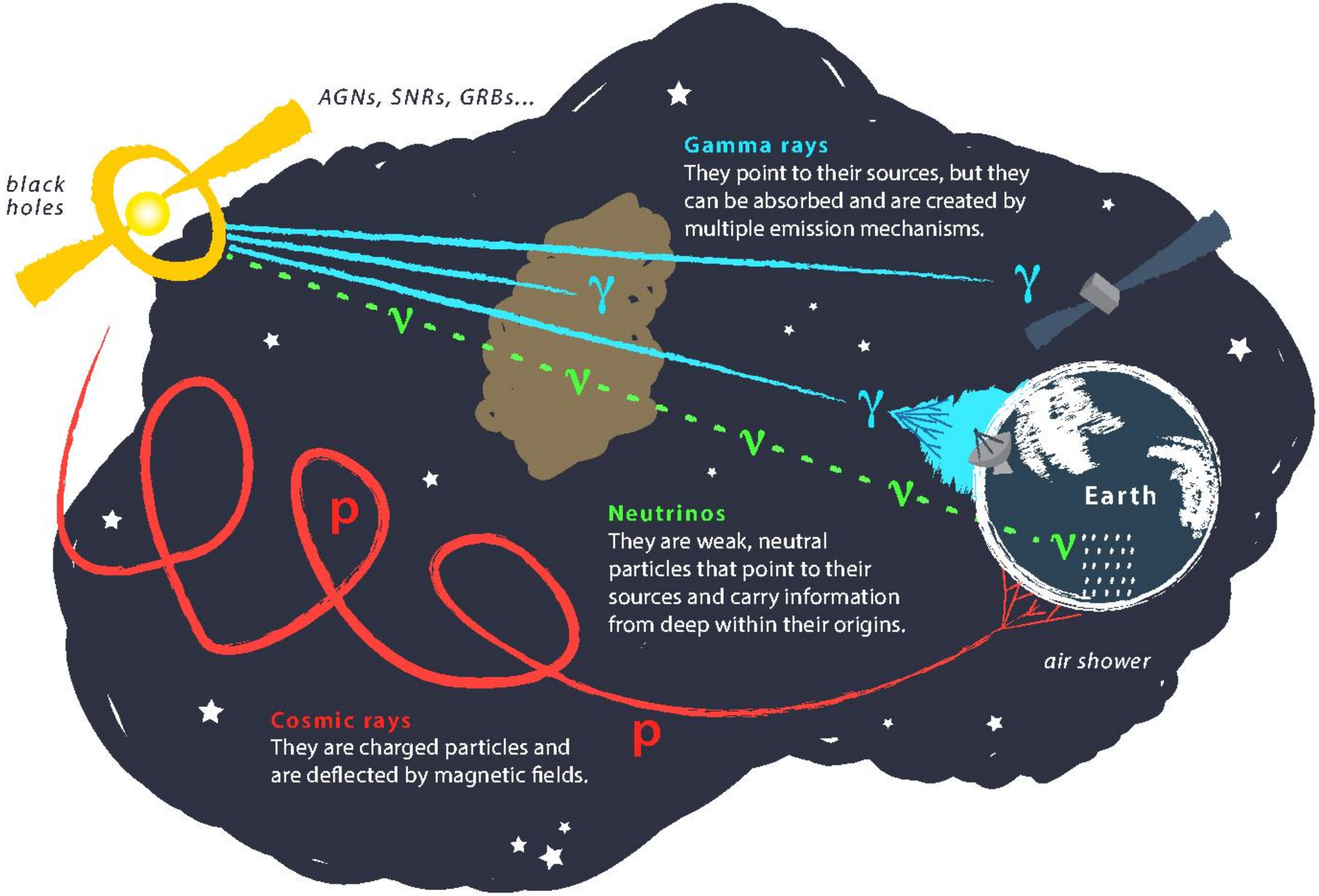
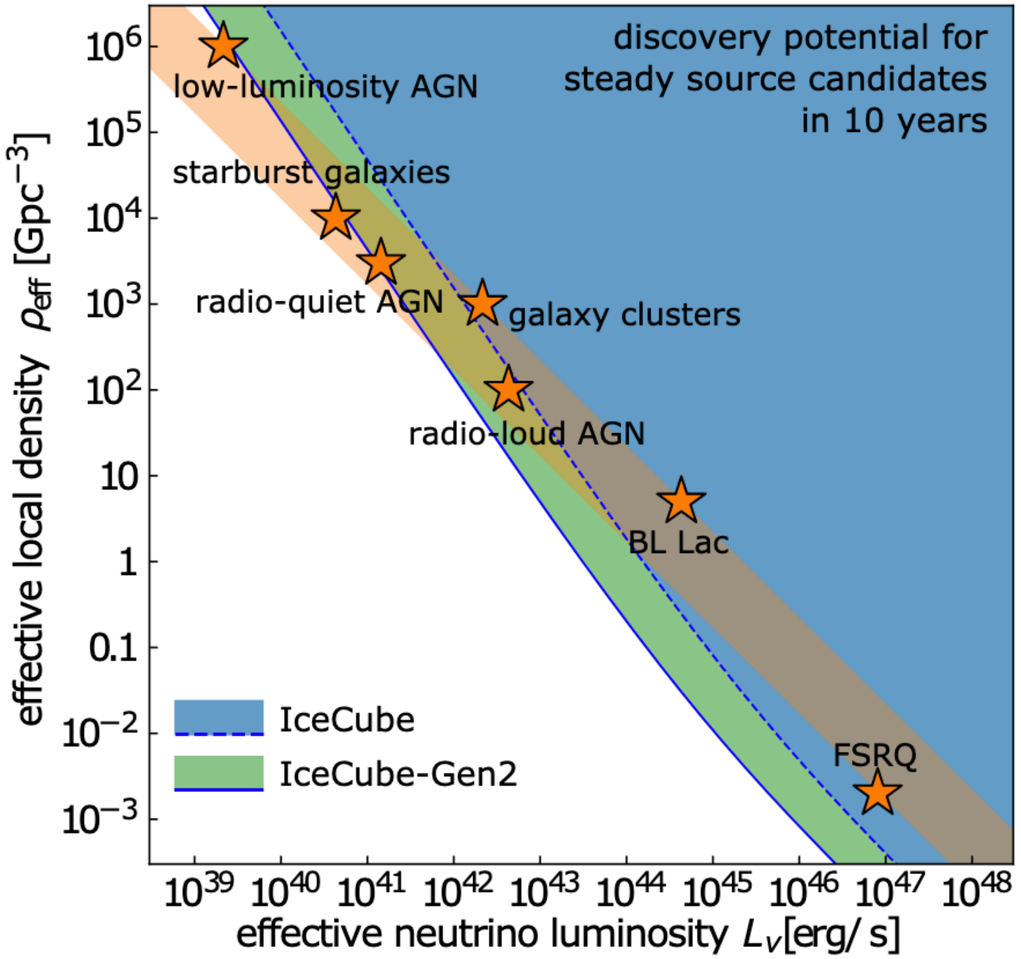


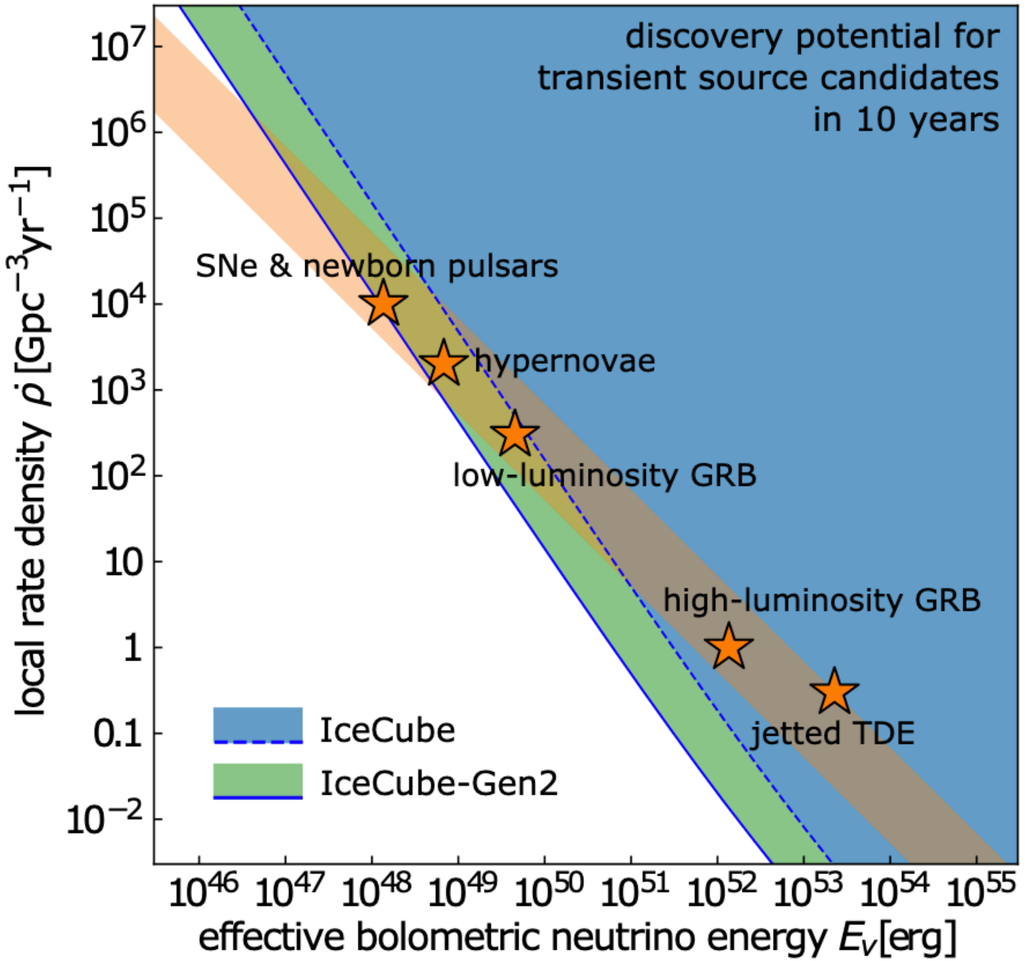
Neutrino astronomy: the physics case



Neutrino astronomy: what are the sources

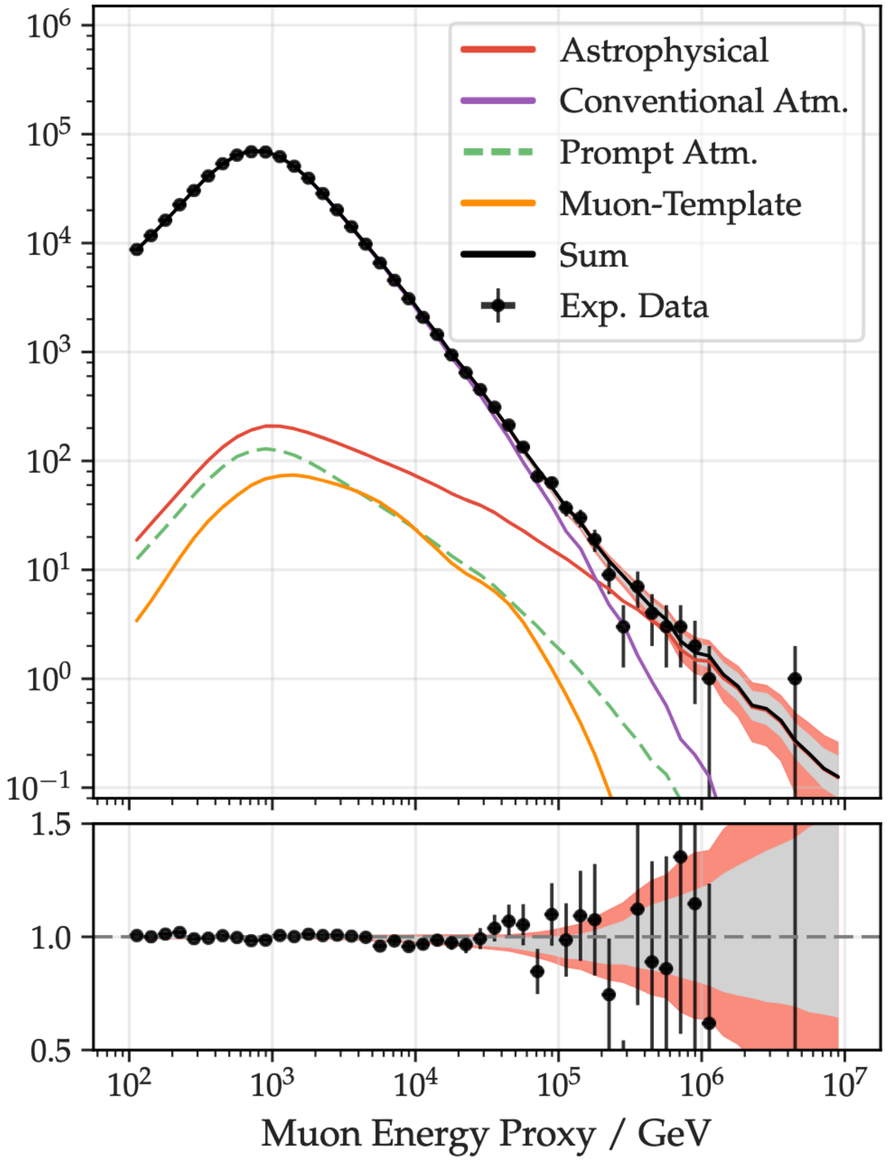
Aartsen et al. (IceCube-Gen2 Collaboration) J.Phys.G 48 (2021) 6, 060501

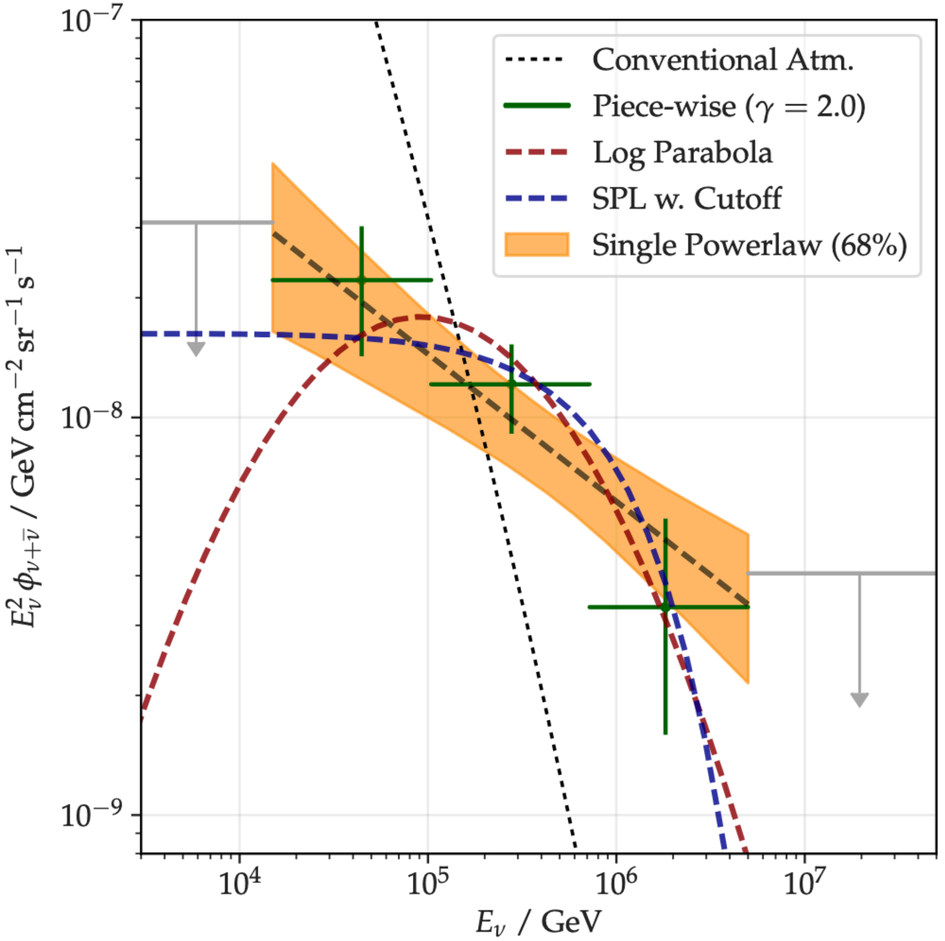




Astrophysical neutrinos: diffuse flux

R. Abbasi et al., Astrophysical Journal 928 (2022) 50





Astrophysical Norm. $\phi_{\text{astro.}}/C_{\text{units}}$	$1.44^{+0.25}_{-0.26}$
Spectral Index γ_{SPL}	$2.37^{+0.09}_{-0.09}$

Neutrino astronomy: what kind of neutrinos are we hunting?

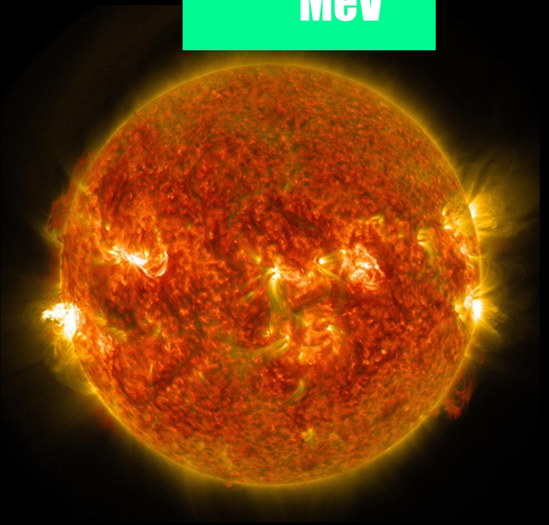
Solar/SN | Atmospheric | Astrophysical | Cosmogenic

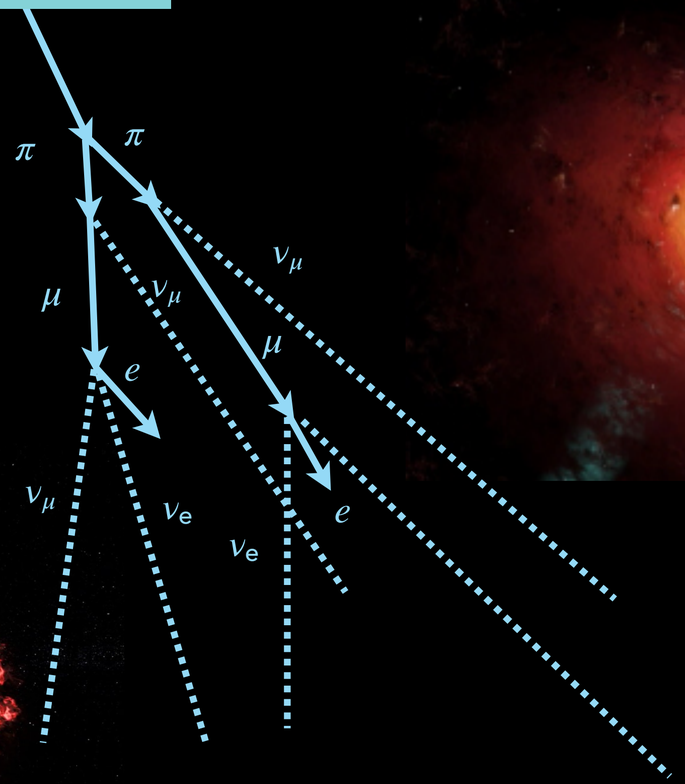
MeV

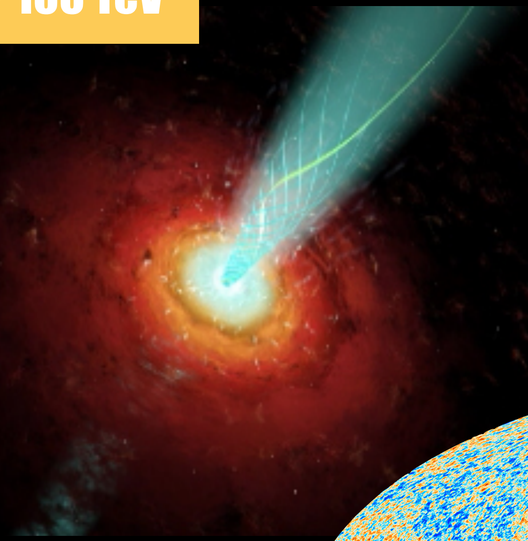
< 100 TeV

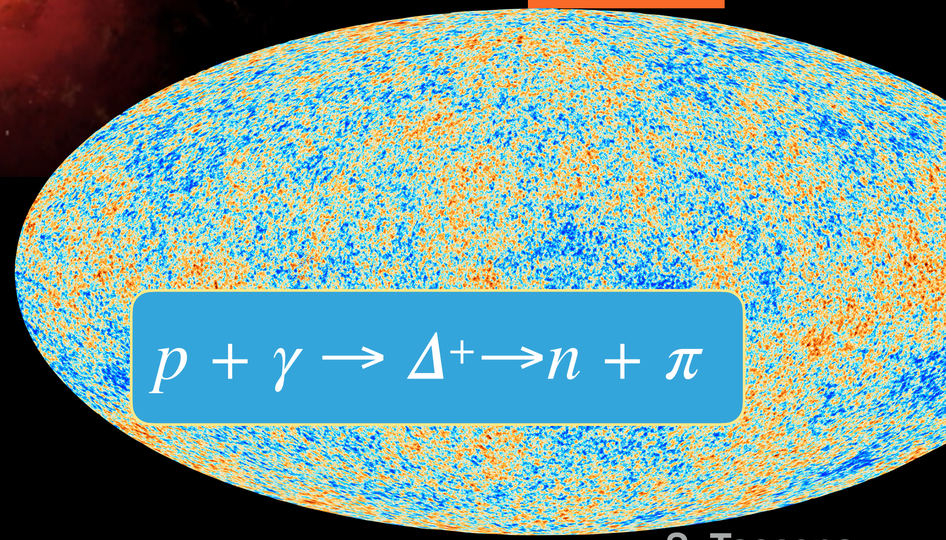
> 100 TeV

1 EeV









$$p + \gamma \rightarrow \Delta^{+} \rightarrow n + \pi$$

Neutrino astronomy: what kind of neutrinos are we hunting?

Solar/SN | **Atmospheric** | **Astrophysical** | **Cosmogenic**

MeV

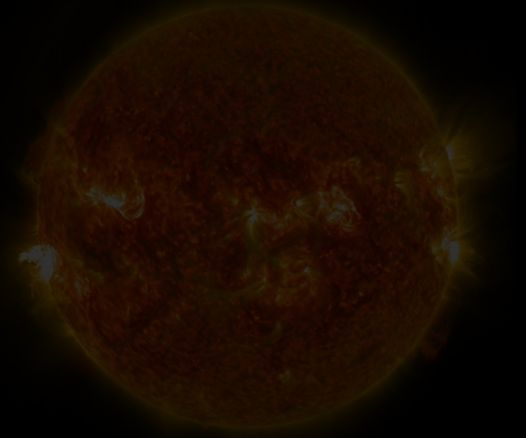
< 100 TeV

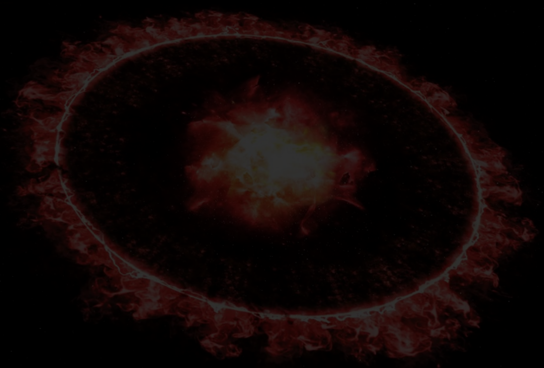
> 100 TeV

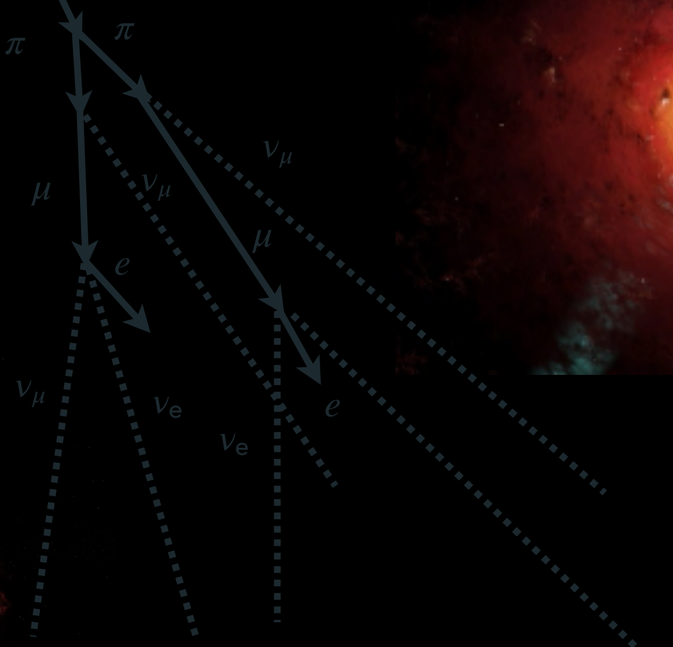
Discovered by IceCube

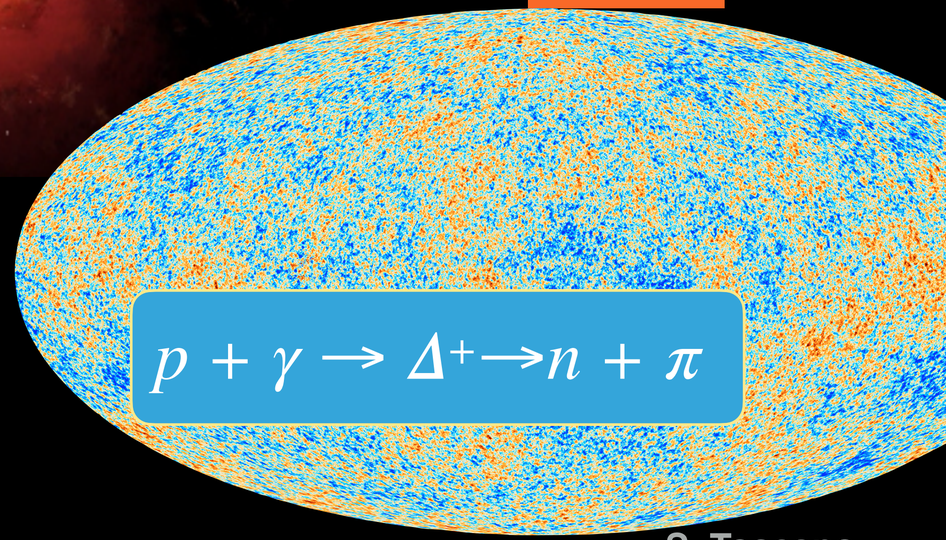
Guaranteed but not yet observed

1 EeV



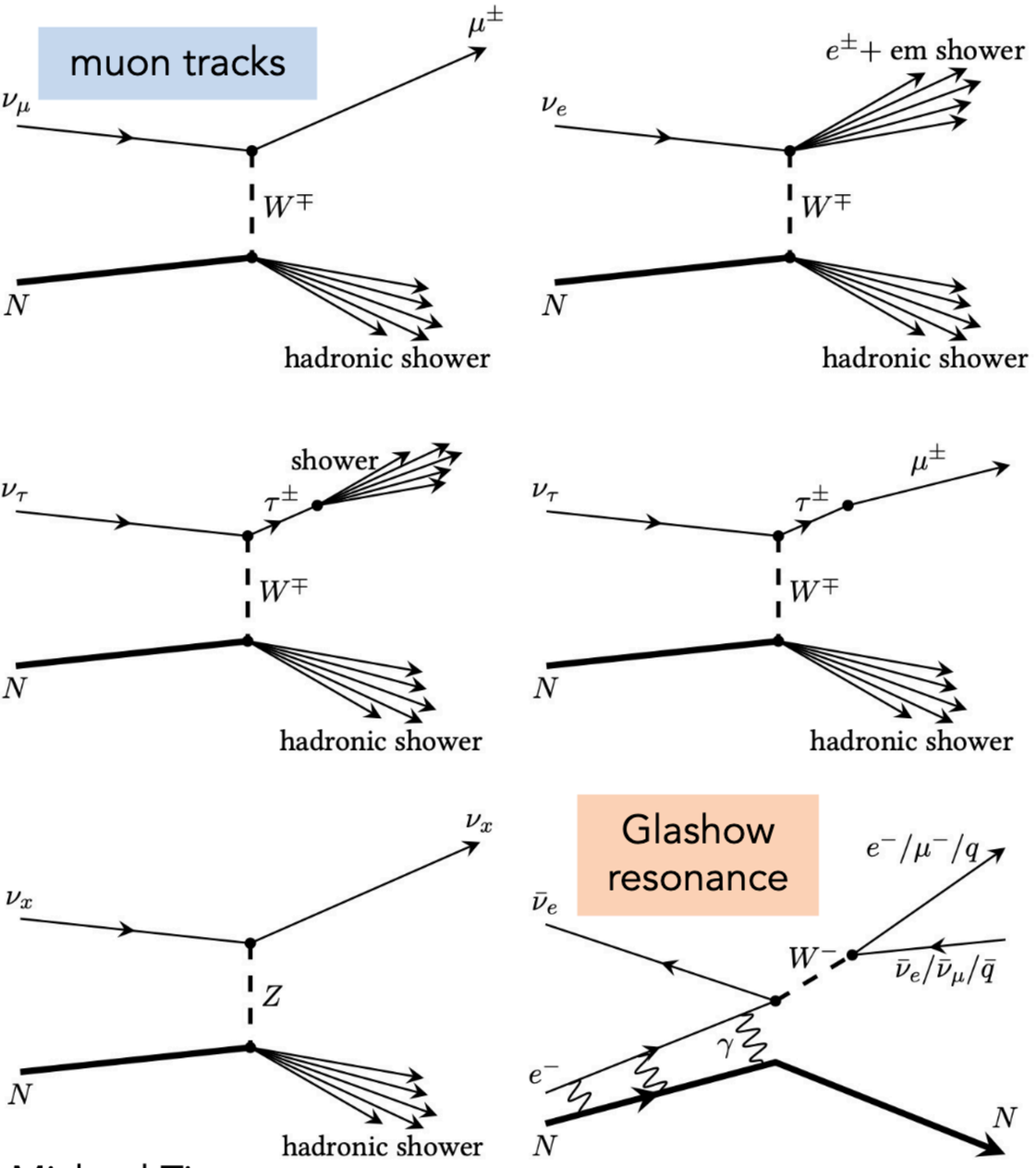






$$p + \gamma \rightarrow \Delta^{+} \rightarrow n + \pi$$

High-energy Neutrino Interaction Signatures



Tracks:

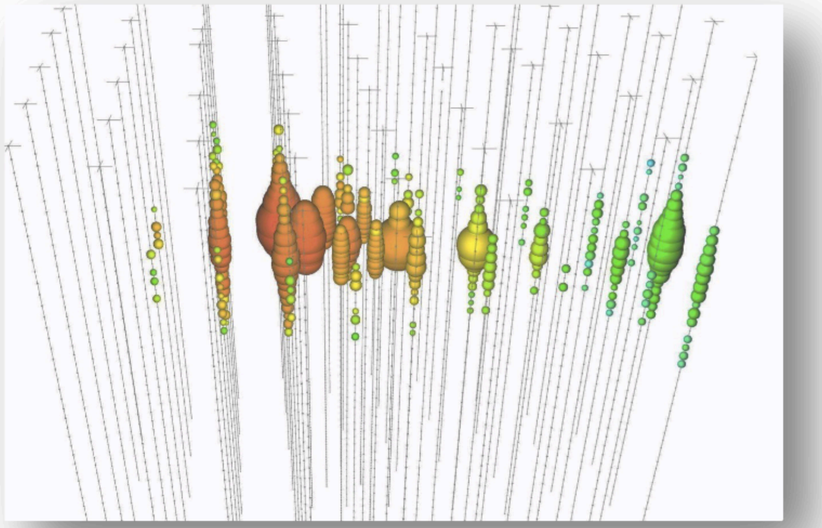
Charged-current muon neutrino interaction

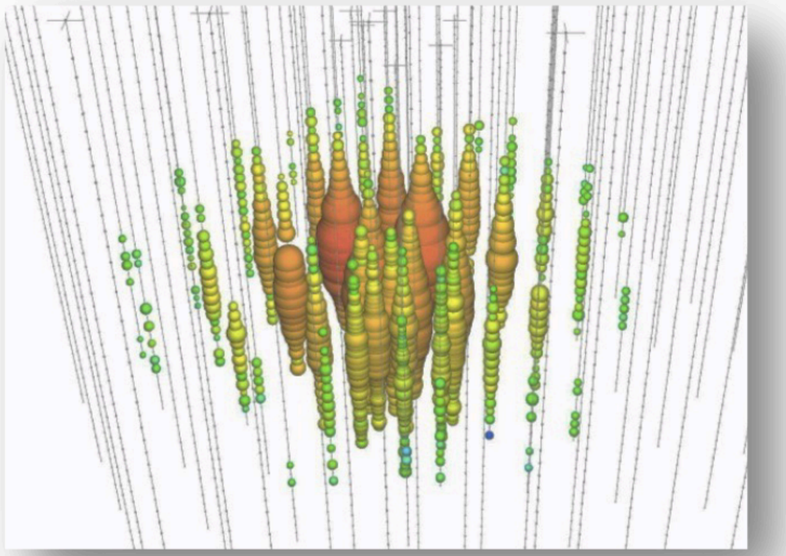
Cascades:

Nearly all other CC and NC neutrino interactions

Glashow resonance interactions (except if W decays to muon)

Event Topologies





Credits: Chad Finley

Neutrino emission from TXS 0506+056

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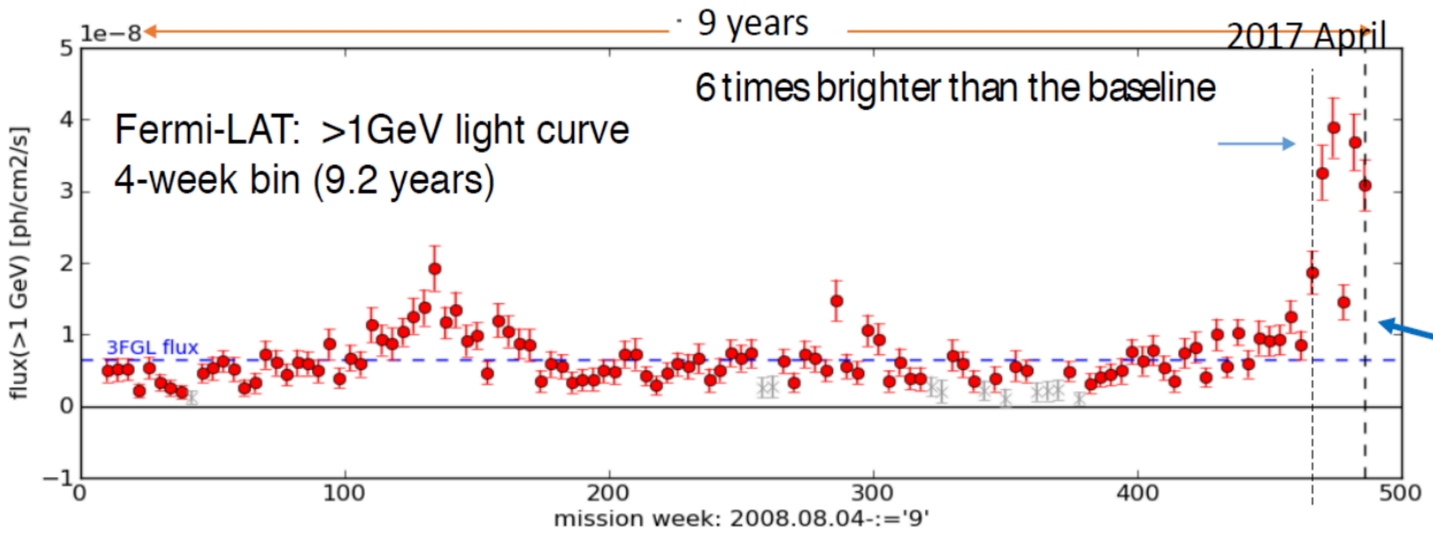
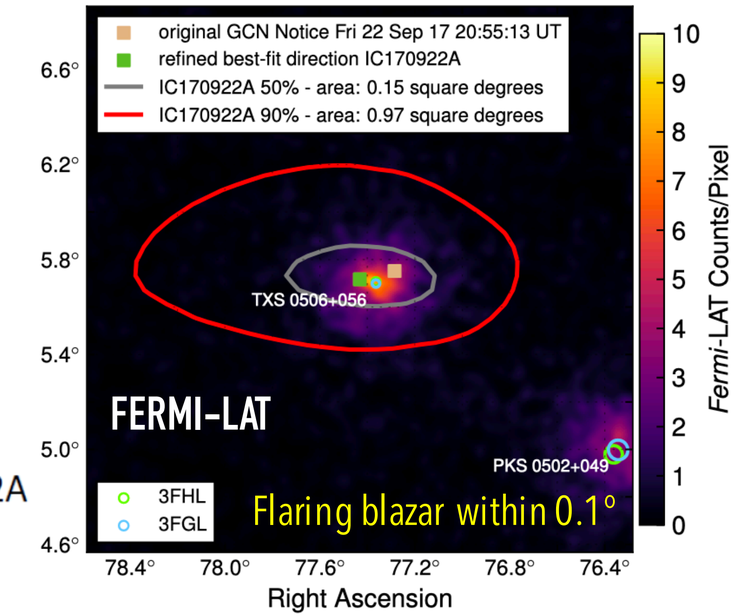
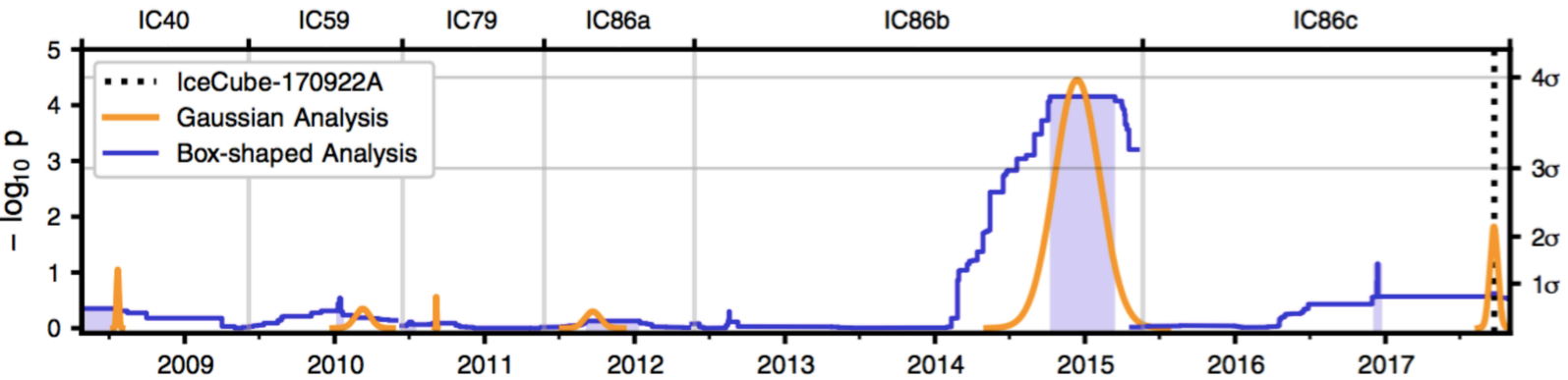
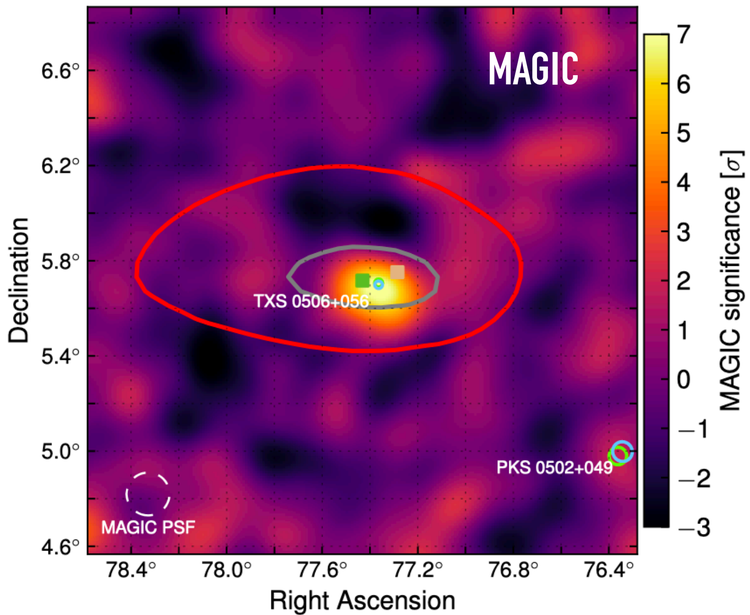


IceCube 170922A



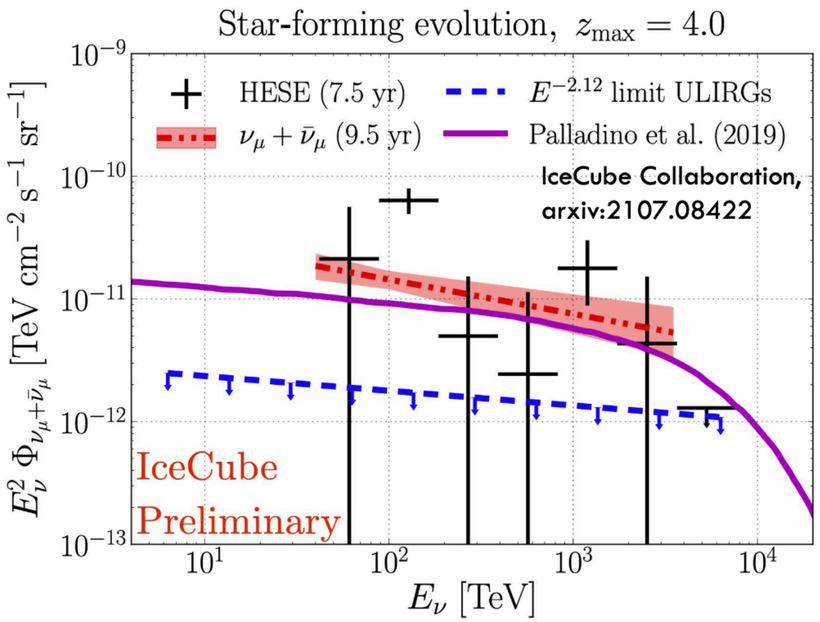


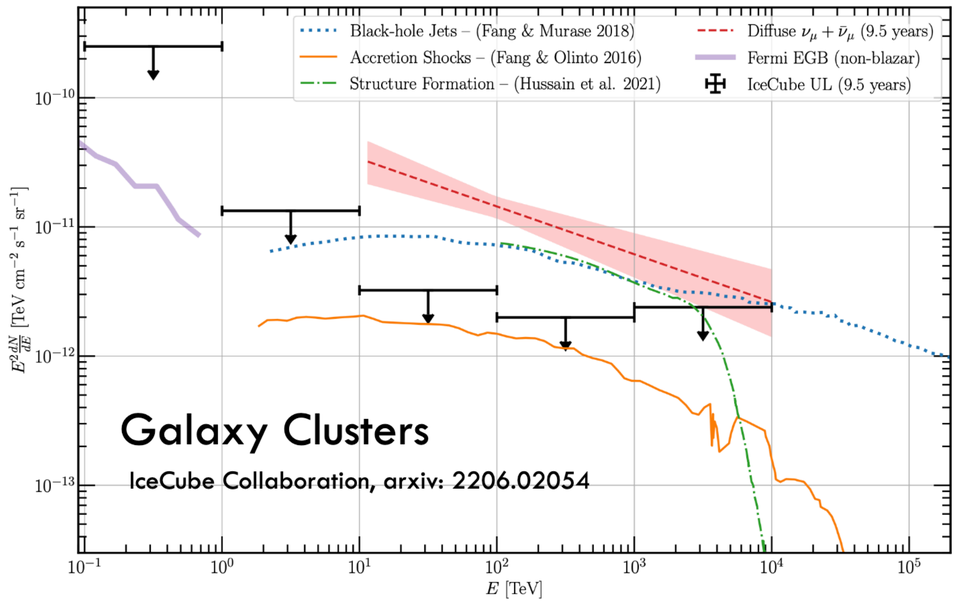


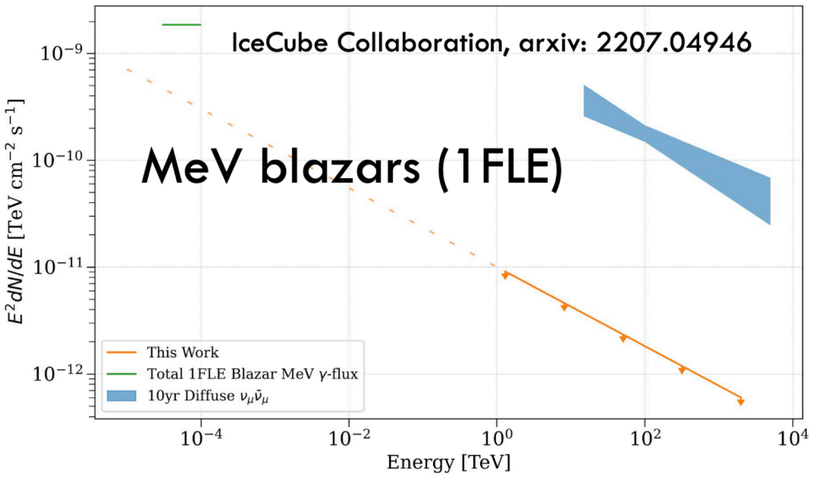
Archival neutrino search find an excess between September 2014 and March 2015: background only hypothesis rejected at 3.5σ [Science 361 (2018) 147-151].

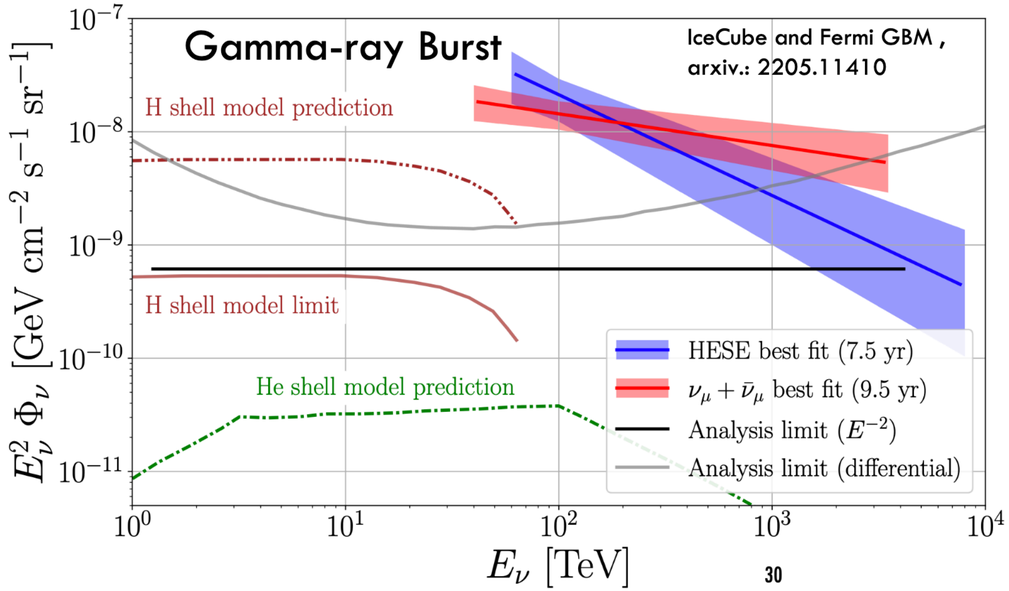
Catalogue searches

Credit: LuLu, TeVPA 2022









Neutrino interactions

T. K. Gaisser, R. Engel, and E. Resconi, Cosmic Rays and Particle Physics. Cambridge University Press, 2 ed., 2016.