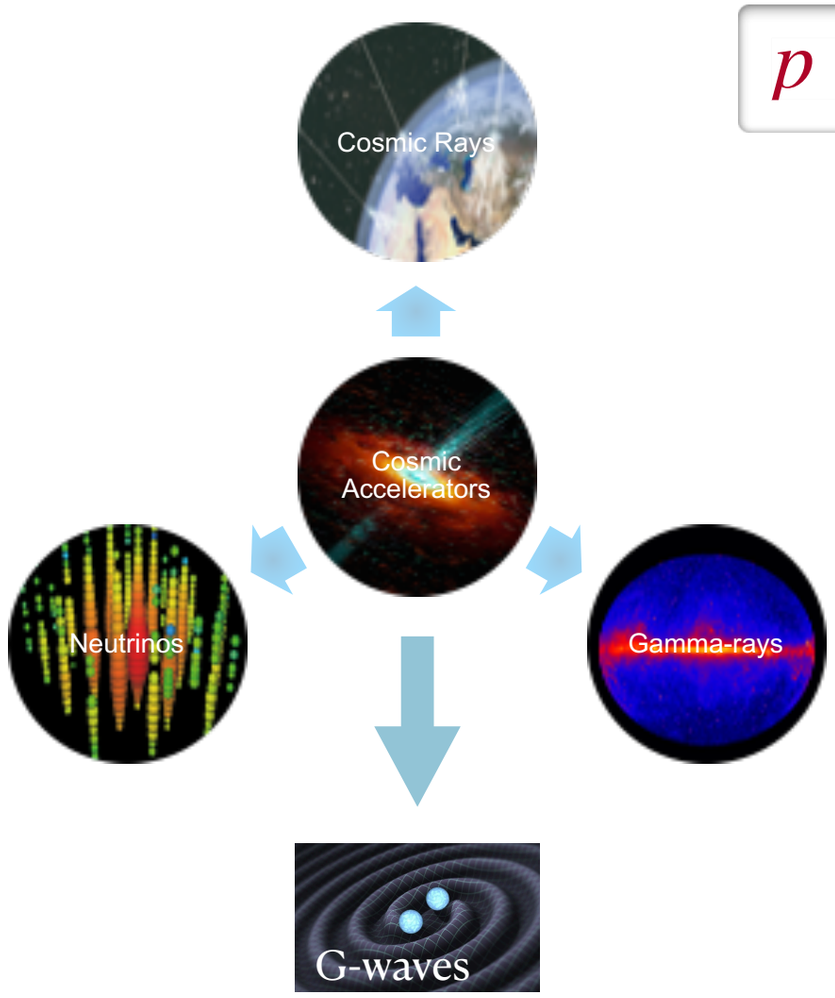
Probing the neutrino sky with IceCube: recent results and future outlook

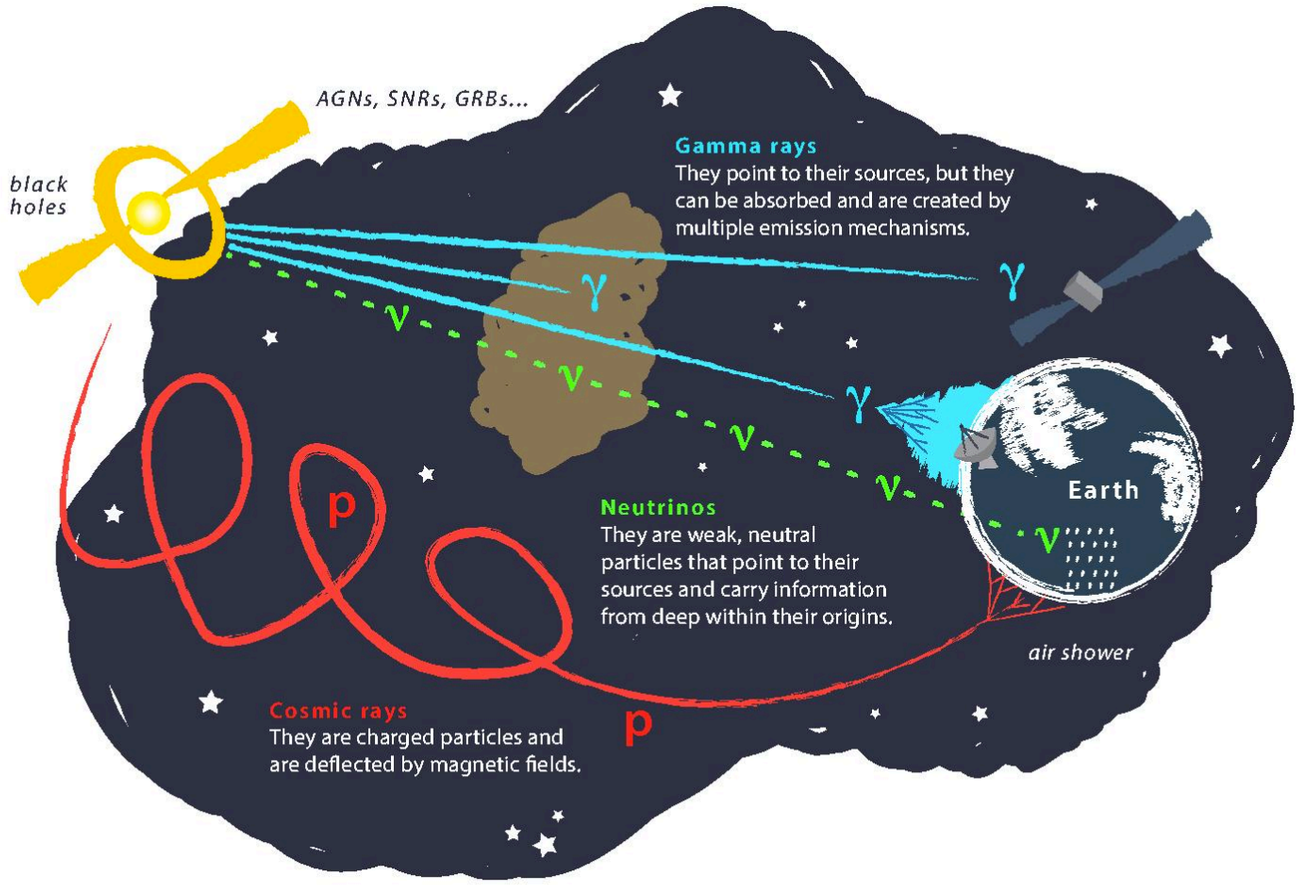
Ankur Sharma

on behalf of IceCube-Sweden

Interactions of accelerated cosmic rays simultaneously produce high energy ν and γ-rays

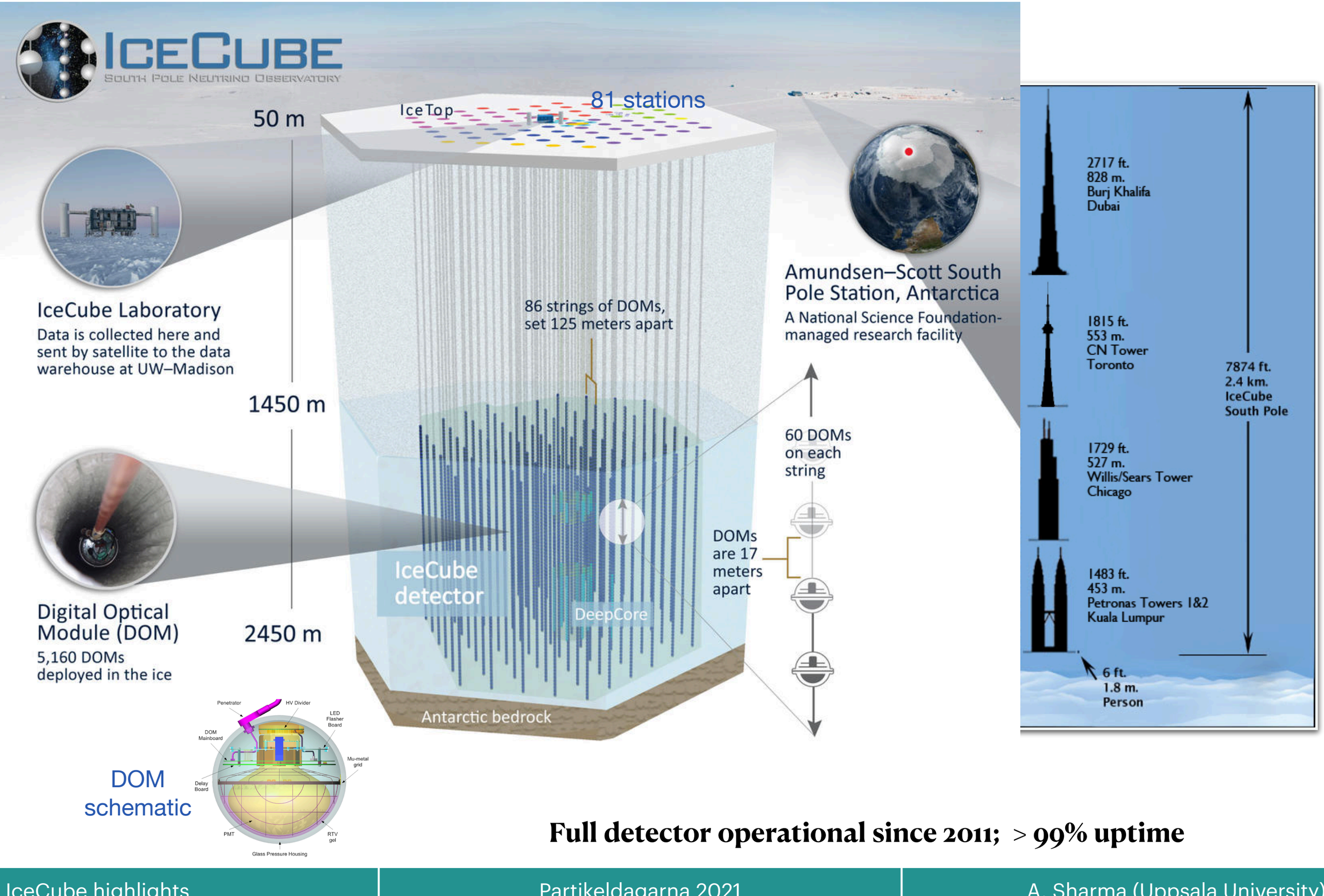


$$p + p/\gamma -> \nu + \gamma + X$$



Neutrinos are ideal messengers to peek far into the Universe and into its most extreme environments

IceCube Observatory



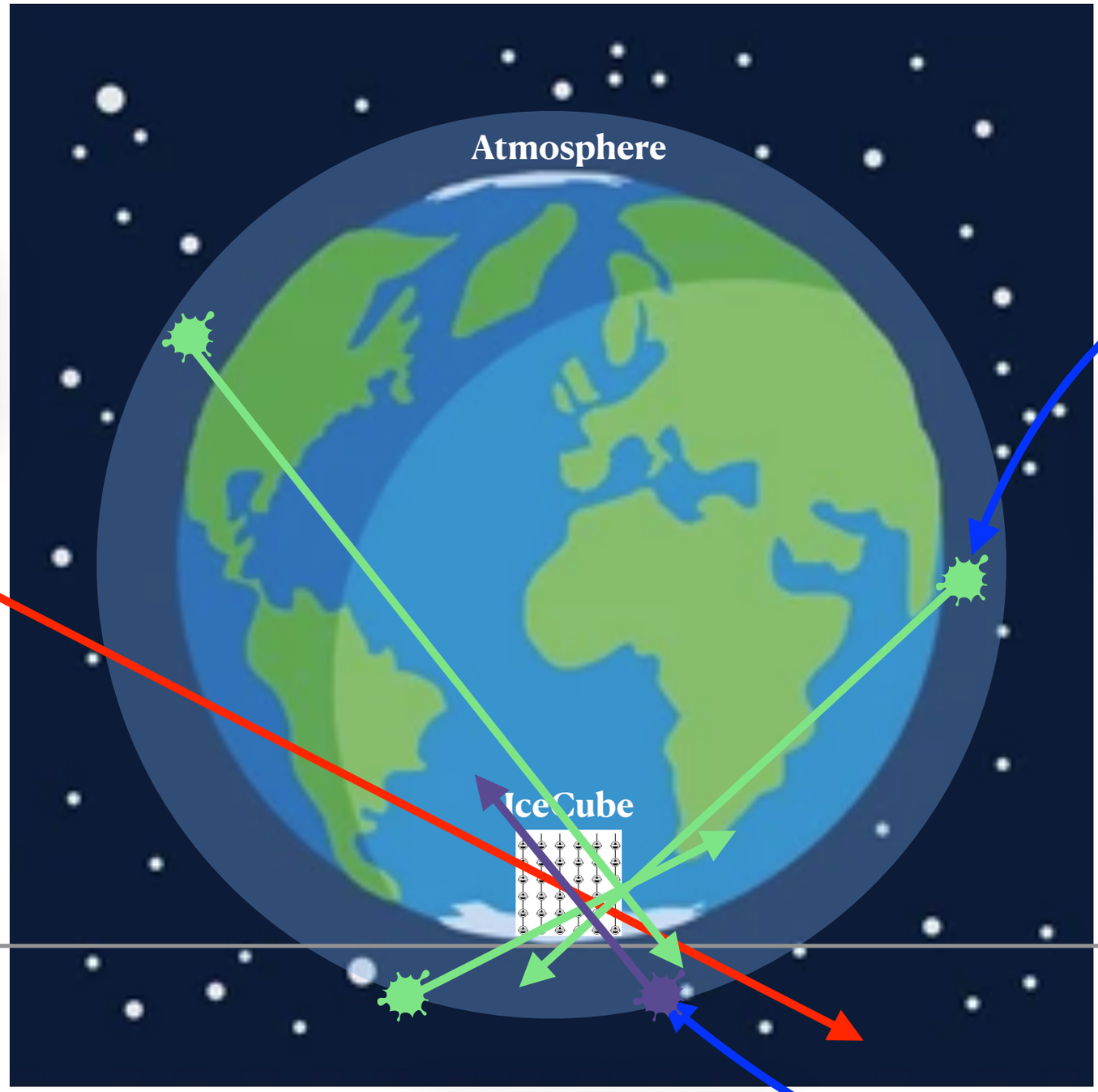
DOM schematic

Full detector operational since 2011; > 99% uptime

What we see....?

Signal:
Astrophysical ν
(~10 evts/yr above 100 TeV)

Up-going/down-going



Cosmic ray

Background:
Atmospheric ν
(> 10⁵ evts/yr)

Isotropic background

Up-going

Horizon

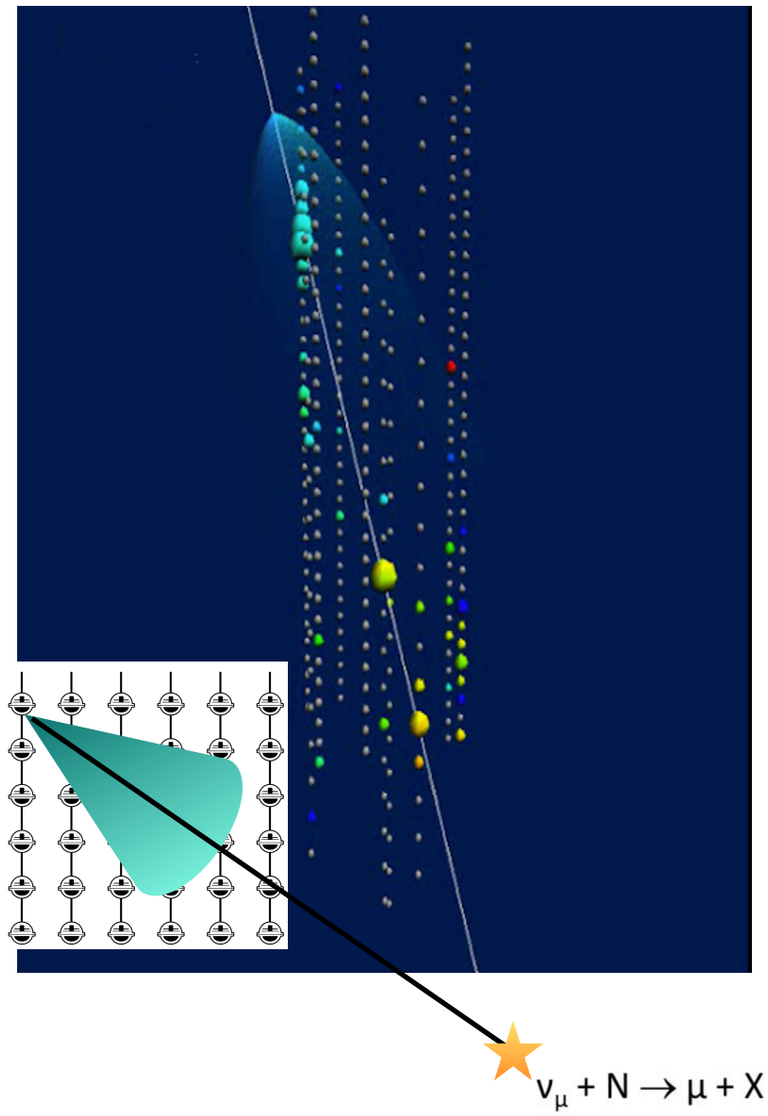
Down-going

Down-going

Background:
Atmospheric μ
(100 billion evts/yr)

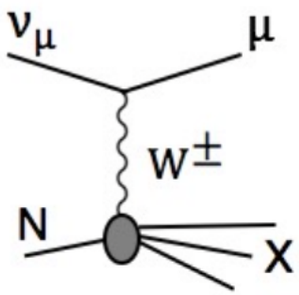
Cosmic ray

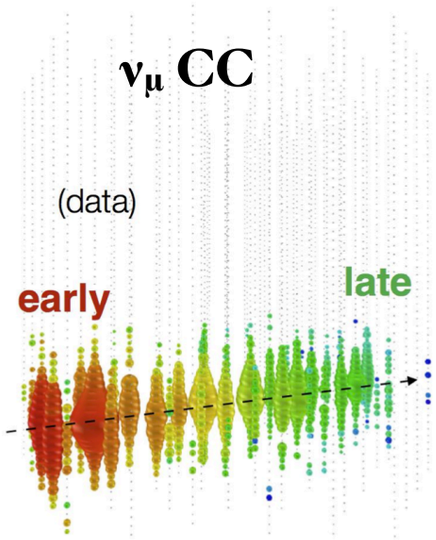
How do we see it....?



IceCube detects Cherenkov radiation from the secondary particles produced in charged-current (CC) and neutral-current (NC) interactions of neutrinos in the vicinity of the detector

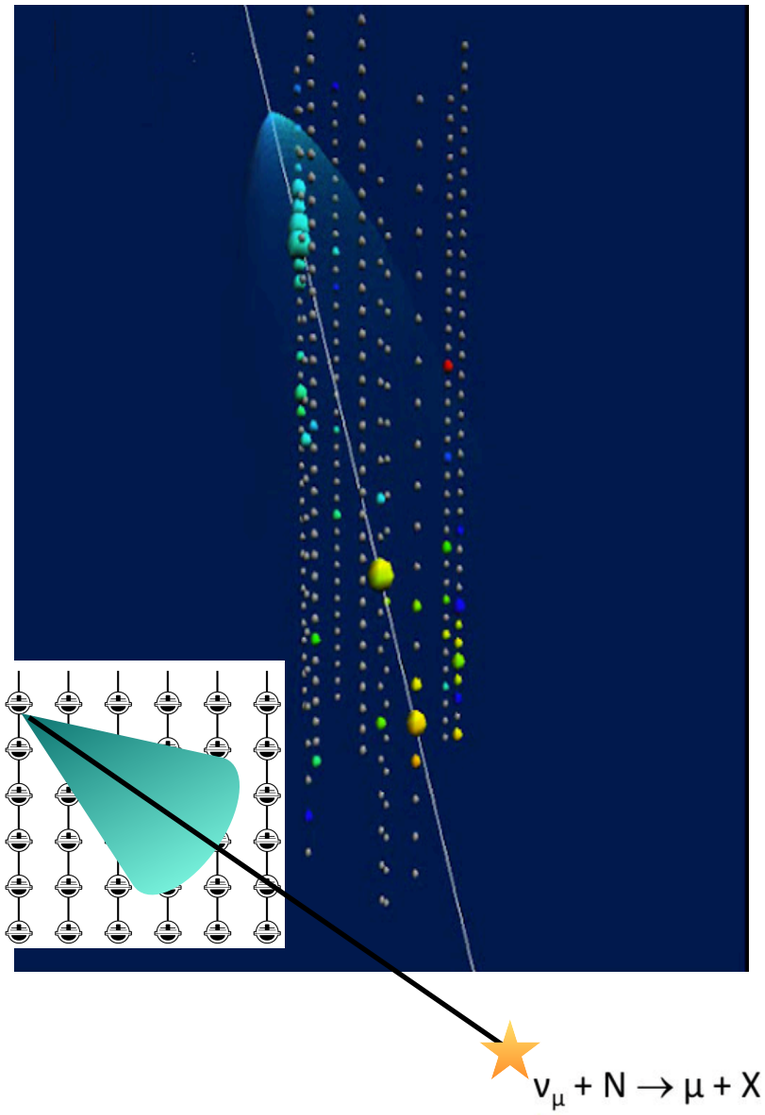
How do we see it....?

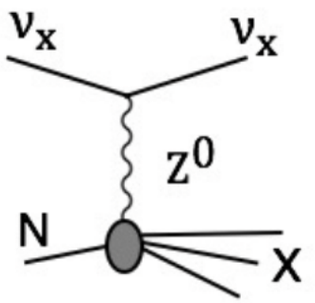


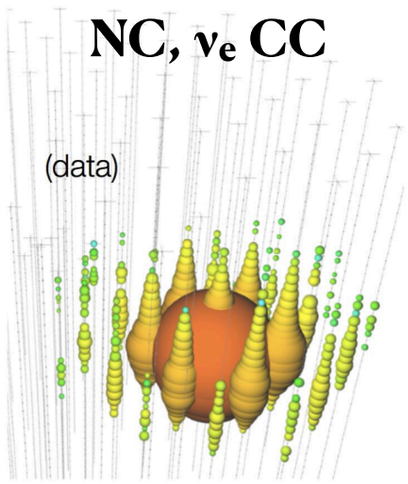


Tracks:

- Starting tracks and through-going
- Energy resolution: factor of ~2
- Angular resolution < 1 deg

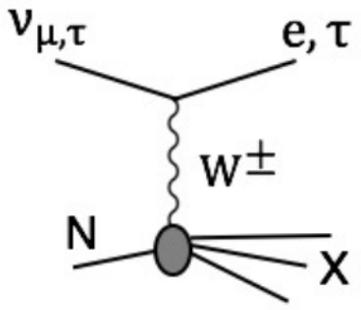


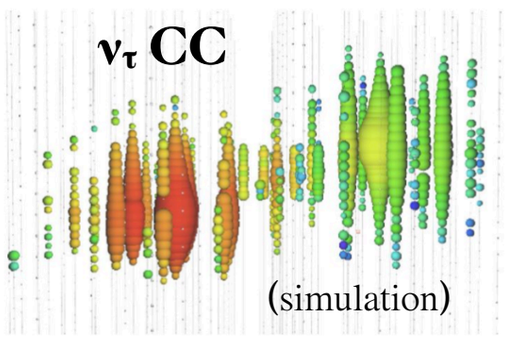




Cascades:

- EM and hadronic cascades
- Energy resolution: ~ 10-15%
- Angular resolution > 10 deg





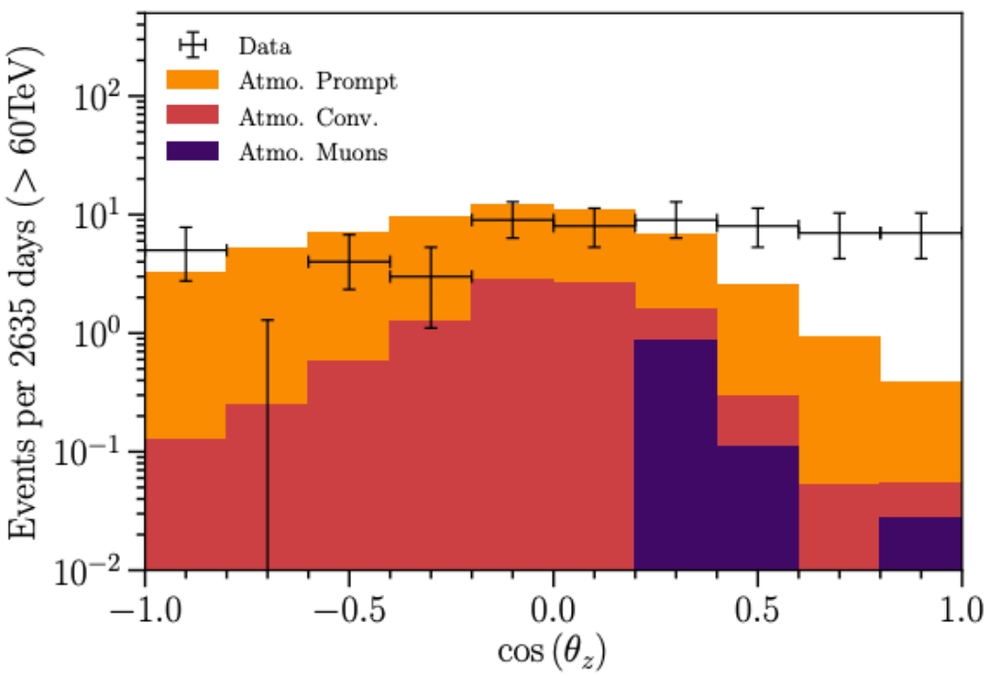
Double Cascades:

- τ hadronic decay (double bang)
- Resolvable above ~ 100 TeV

IceCube detects Cherenkov radiation from the secondary particles produced in charged-current (CC) and neutral-current (NC) interactions of neutrinos in the vicinity of the detector

Recent highlights

$$\Phi(E_\nu) = \Phi_{\text{astro}} \left(\frac{E_\nu}{100\ \text{TeV}} \right)^{-\gamma_{\text{astro}}}$$



RESEARCH

RESEARCH ARTICLE SUMMARY

NEUTRINO ASTROPHYSICS

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

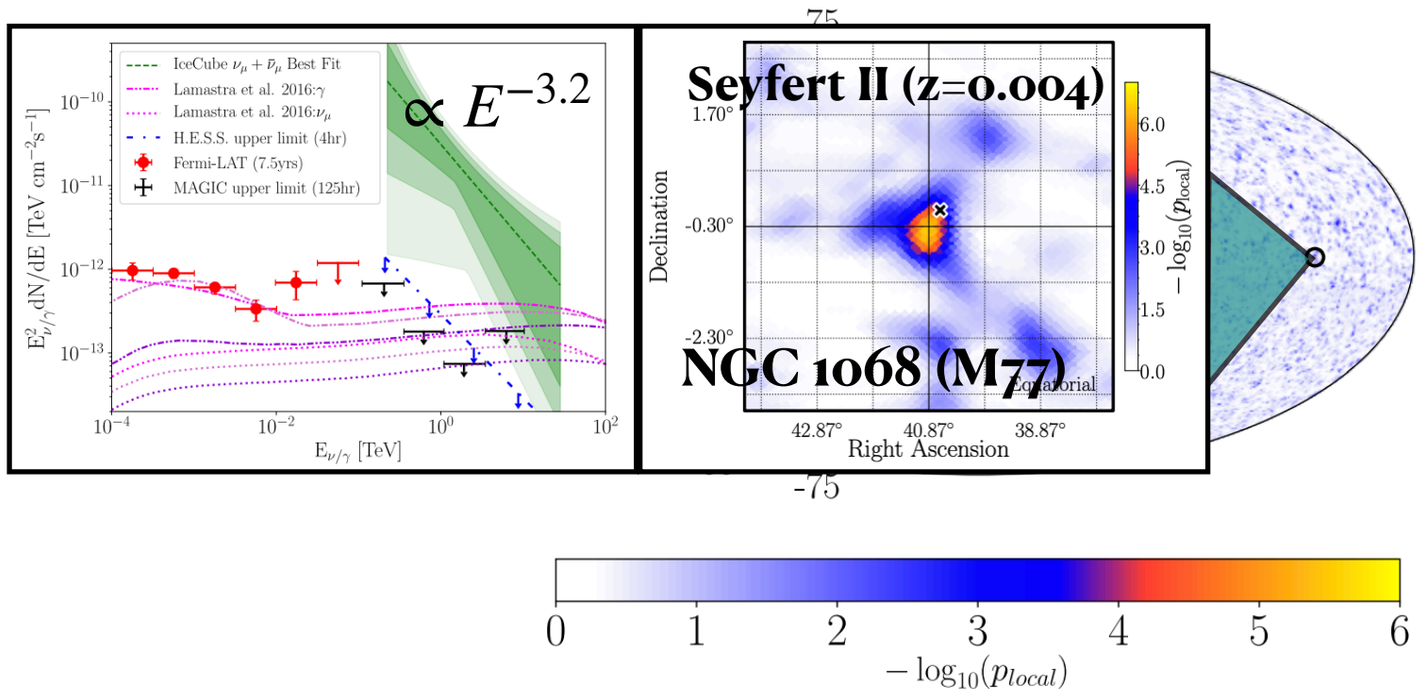
trinos, IceCube provides real-time triggers for observatories around the world measuring γ-rays, x-rays, optical, radio, and gravitational waves, allowing for the potential identification of even rapidly fading sources.

RESULTS: A high-energy neutrino-induced muon track was detected on 22 September 2017, automatically generating an alert that was distributed worldwide within 1 min of detection and prompted follow-up searches by telescopes over a broad range of wavelengths. On 28 September 2017, the *Fermi* Large Area Telescope Collaboration reported that the di-

ON OUR WEBSITE

Read the full article at http://dx.doi.org/10.1126/science.aat1378

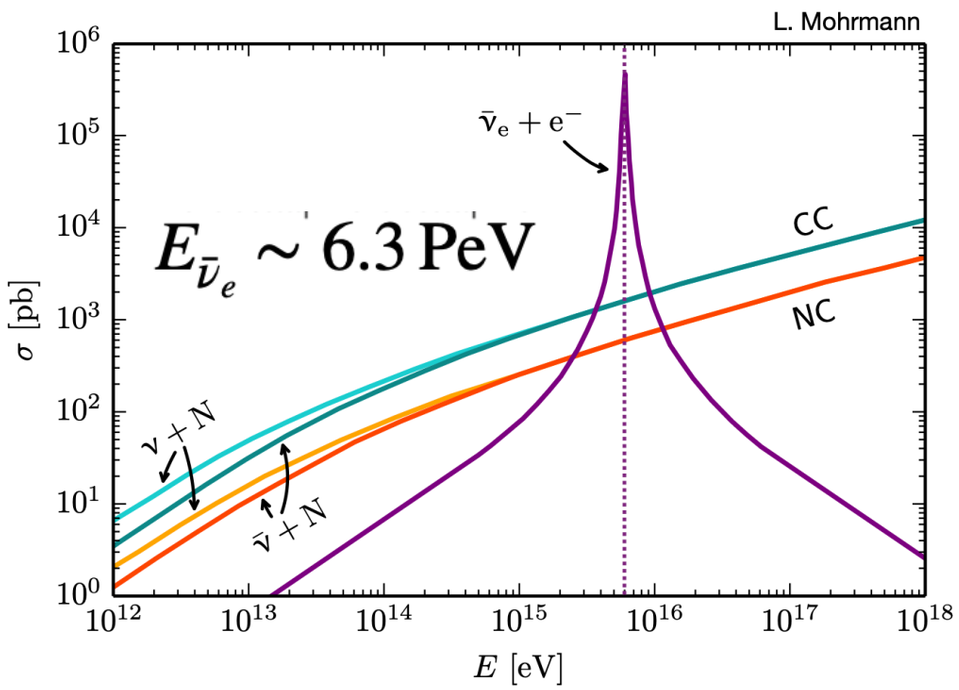
- ~290 TeV neutrino from the direction of blazar **TXS 0506+056** (**z =0.336**); Observed by MAGIC and Fermi in increased activity (flaring) state in the following days

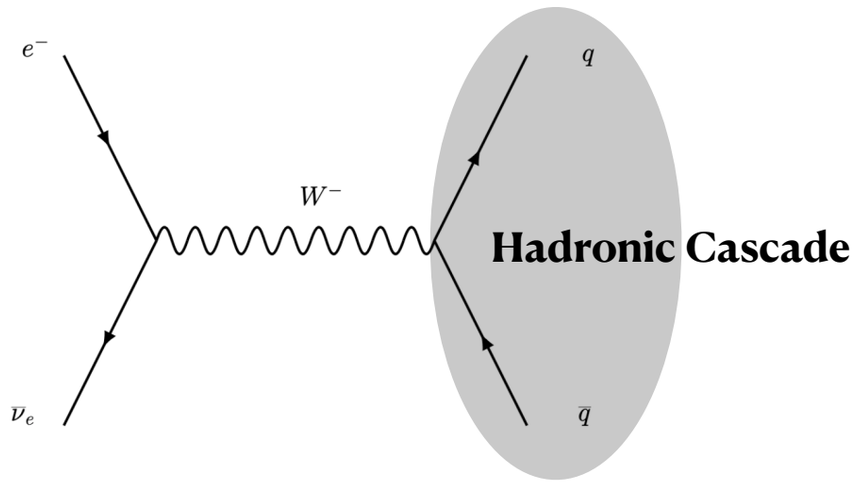


- Most significant Northern sky hotspot in 10 year all-sky scan coincident with **NGC 1068**; at 2.9σ above bkgd (post-trial)

Glashow Resonance Candidate

Resonant formation of a W⁻: $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow X$

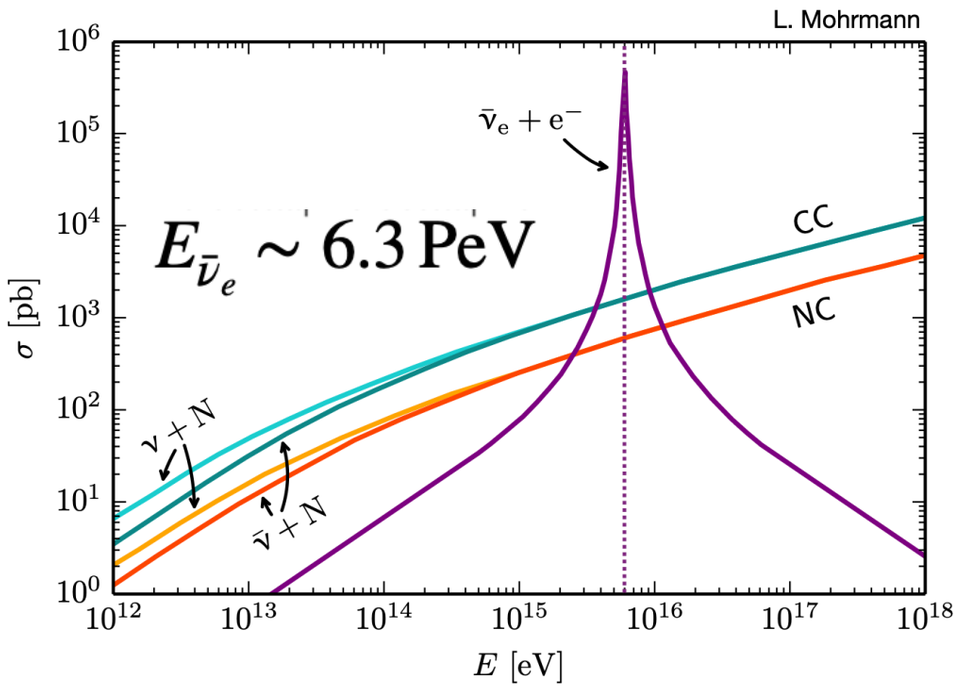


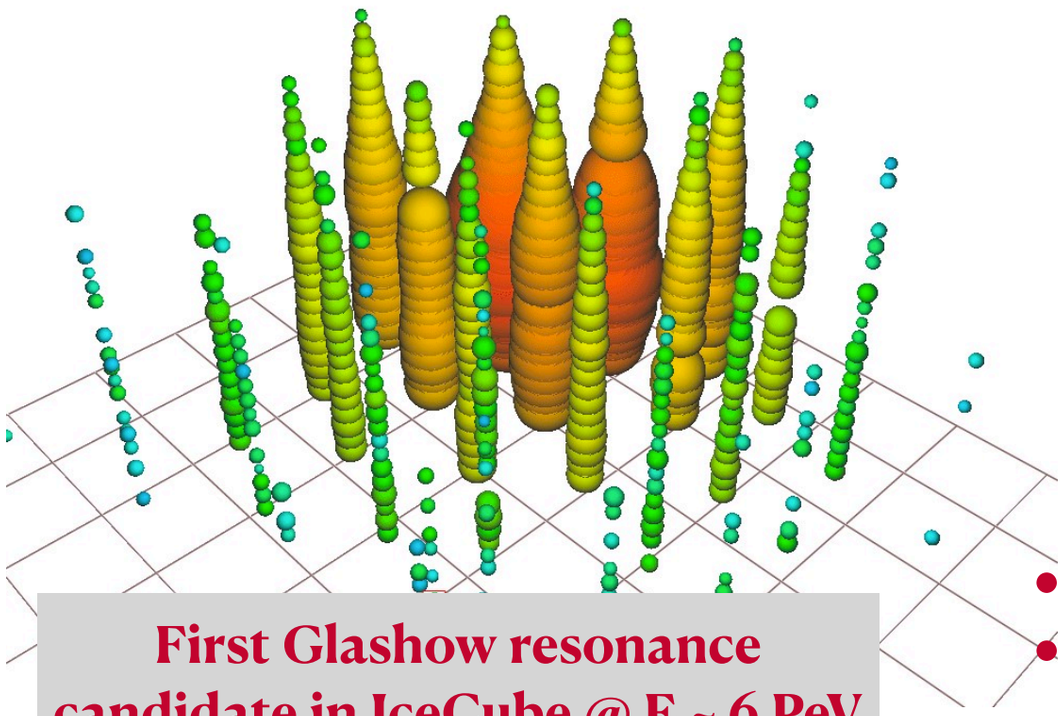


Nature 591 (2021) 220–224

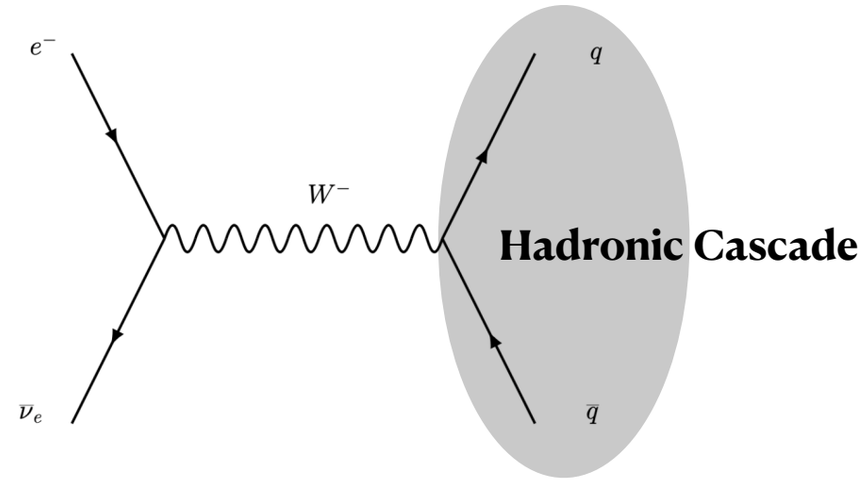
Glashow Resonance Candidate

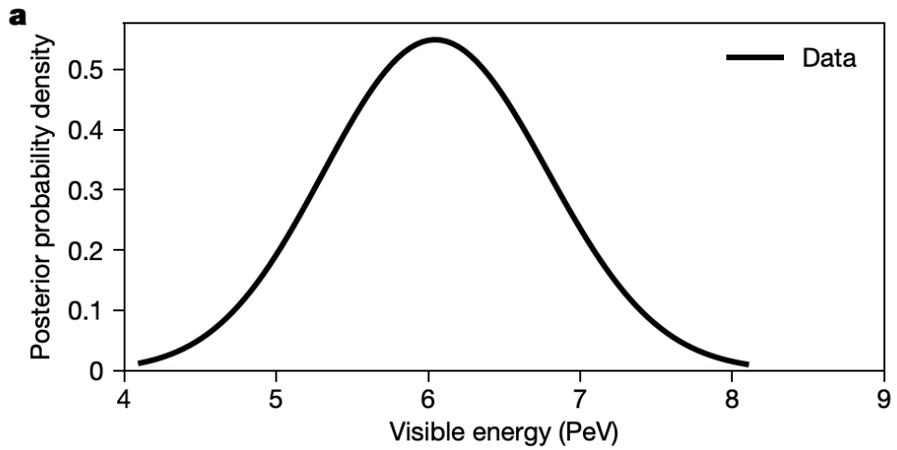
Resonant formation of a W⁻: $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow X$

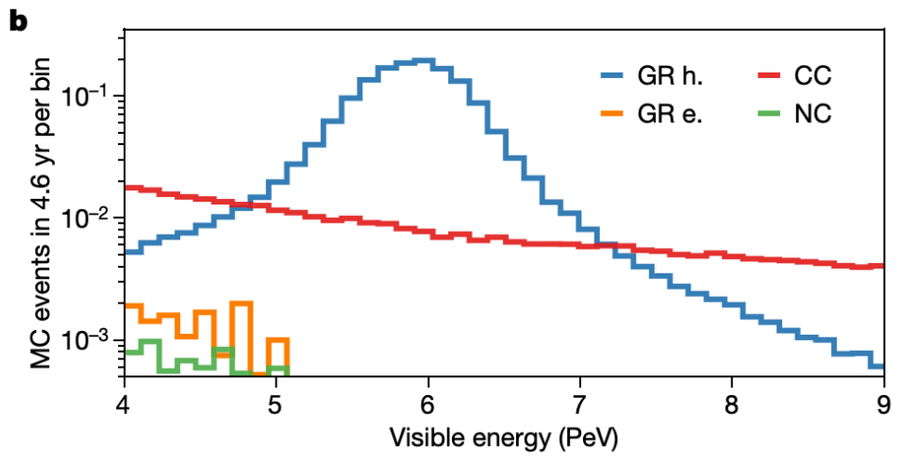




First Glashow resonance candidate in IceCube @ E ~ 6 PeV



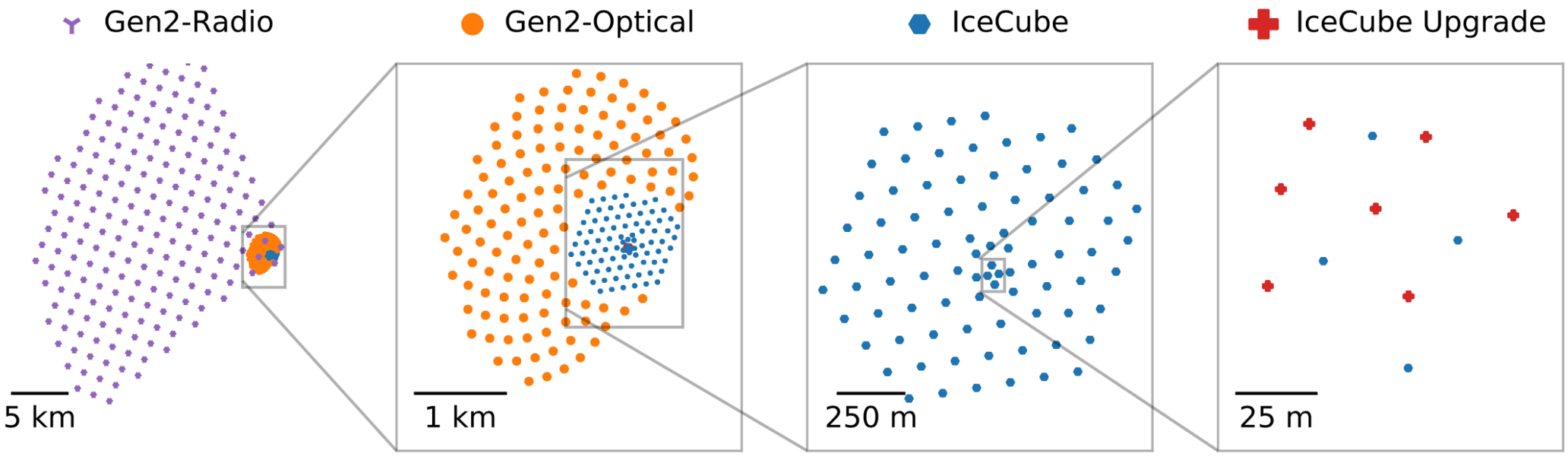




- **New analysis has an increased sensitivity to PeV cascades**
- **Allows disentangling of neutrinos and anti-neutrinos!**

Nature 591 (2021) 220–224

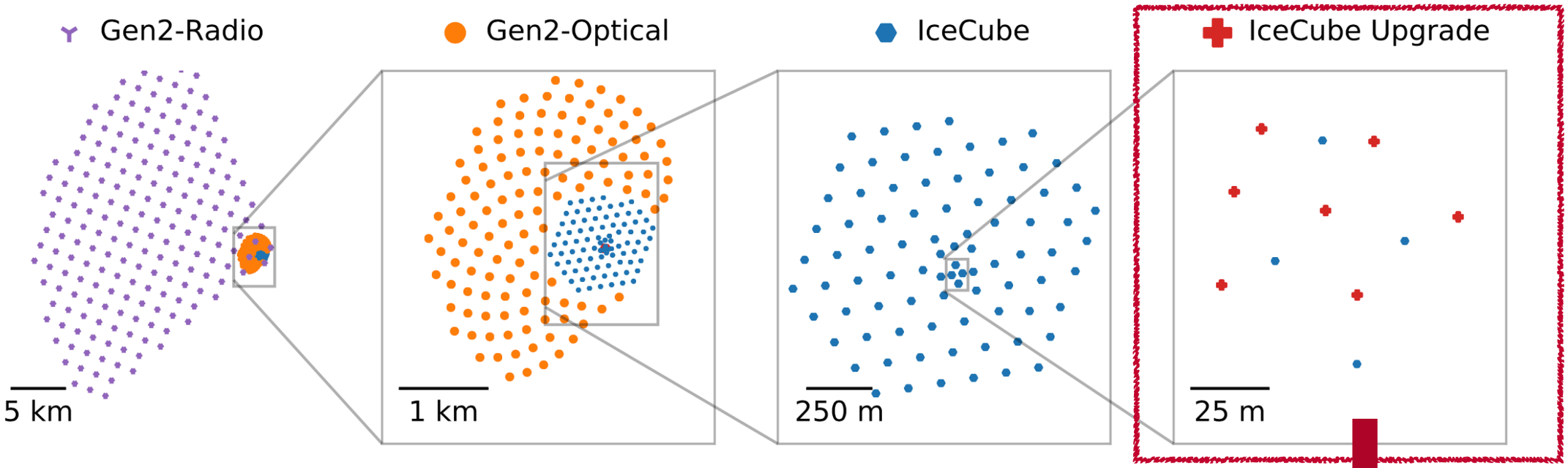
The future of IceCube



sparsely spaced strings

closely spaced strings

The future of IceCube



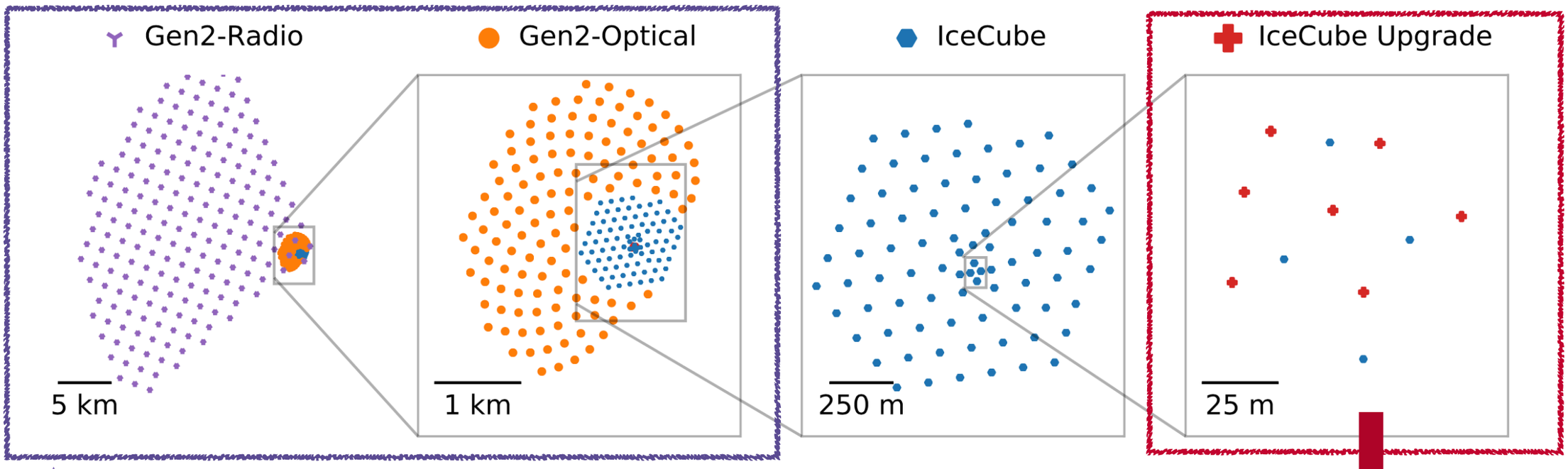
- Approved and funded (construction in 2024-25)
- 7 closely-spaced strings at the bottom-centre of the detector
- New calibration devices to study ice properties and detector response; expected to improve reconstruction resolution and provide increased sensitivity in a re-analysis of 15 year data
- Precision measurement of neutrino oscillations
- New DOM designs to be tested

m-DOM

D-Egg

PoS ICRC(2019) 1031

The future of IceCube



IceCube Gen-2:

- **Gen2-Optical** will increase the rate of astrophysical neutrinos observed by a factor ~ 10
- **Gen2-Radio** will extend the energy range by a factor of ~ 1000 (UHE ν)

(See next talk by Christian Glaser!)

- Approved and funded (construction in 2024-25)
- 7 closely-spaced strings at the bottom-centre of the detector
- New calibration devices to study ice properties and detector response; expected to improve reconstruction resolution and provide increased sensitivity in a re-analysis of 15 year data
- Precision measurement of neutrino oscillations
- New DOM designs to be tested

m-DOM

D-Egg

PoS ICRC(2019) 1031

The Collaboration Map

THE ICECUBE COLLABORATION

AUSTRALIA
University of Adelaide

BELGIUM
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

JAPAN
Chiba University

NEW ZEALAND
University of Canterbury

REPUBLIC OF KOREA
Sungkyunkwan University

SWEDEN
Stockholms universitet
Uppsala universitet

SWITZERLAND
Université de Genève

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)
Federal Ministry of Education and Research (BMBF)
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

IceCube @Sweden

Stockholm University

UPPSALA UNIVERSITET

Stockholm Group:

Klas Hultqvist
Chad Finley
Christian Walck
Matti Jansson
Kunal Deoskar

Uppsala Group:

Olga Botner
Allan Hallgren
Carlos de los Heros
Erin O'Sullivan
Christian Glaser
Ankur Sharma
Nora Valtonen-Mattila
Jakob Beise

Research interests:

- ν source searches
- BSM physics
- SN ν
- Machine learning for radio detection of ν
- Detector development
- Calibration studies

8 Faculty
1 Postdoc
4 PhDs
+ Masters

IceCube @Sweden

Position calibration of IceCube DOMs

Stockholm Group:

Klas Hultqvist
Chad Finley
Christian Walck
Matti Jansson
Kunal Deoskar

Uppsala Group:

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Jakob Beise

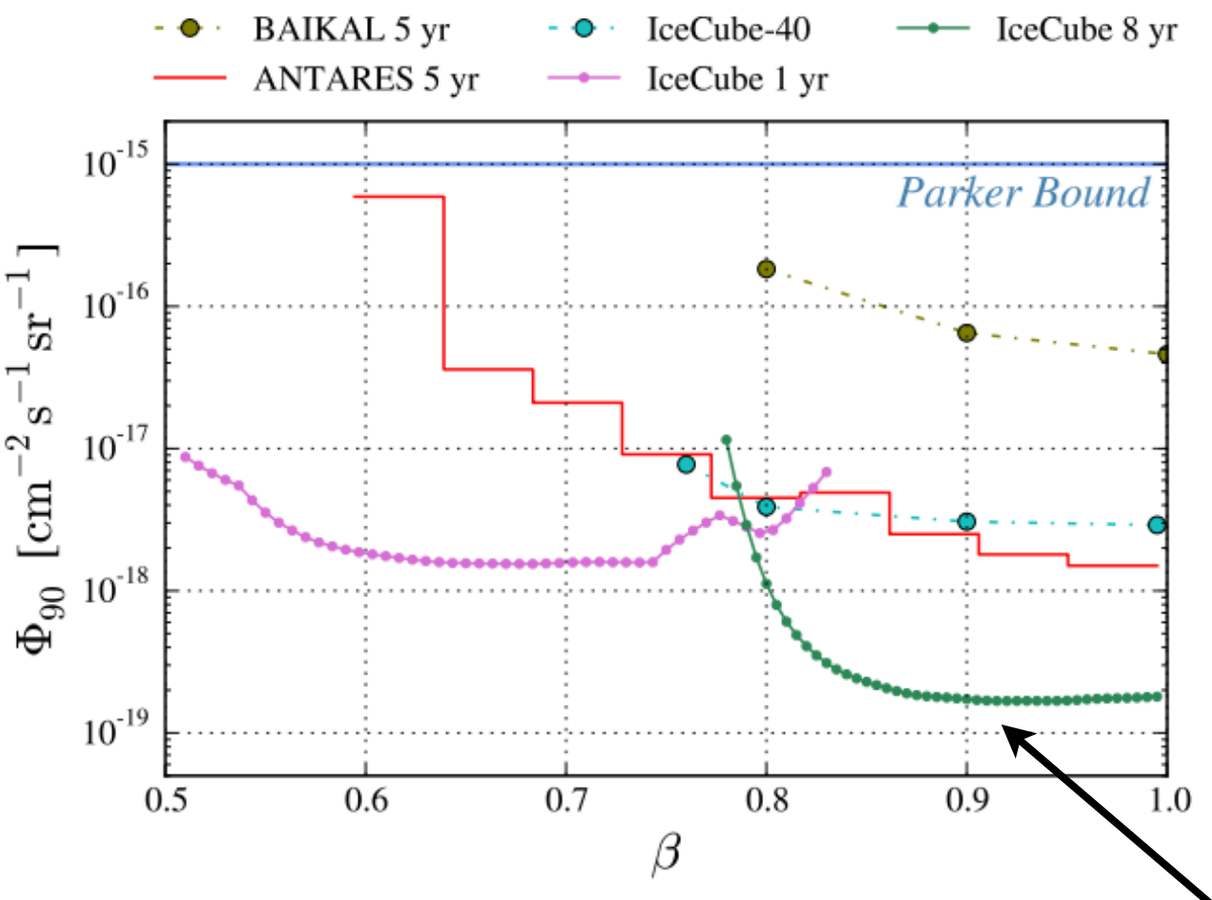
Wavelength-shifting modules For Gen2

ν searches from GRBs

High energy ν from SN

Magnetic Monopoles

Search for relativistic magnetic monopoles above Cherenkov threshold



Speed: $0.750 < \beta < 0.995$

Monopole mass:

$$10^{8-11}\,GeV < m_M < 10^{14-15}\,GeV$$

Limited by Earth absorption

Limited by strength of IGMF

No candidates observed; stringent upper limit at the level of

$$\sim 2 \times 10^{-19}\,cm^{-2}s^{-1}sr^{-1}$$

(recent result from Sweden)

Corresponding author: **Alexander Burgman**, PhD (Uppsala University)
Supervisor: **Carlos de los Heros**

arXiv:2109.13719

Upgrade efforts in Sweden

IceCube-Sweden group majorly involved in IceCube Upgrade and Gen2 development efforts:

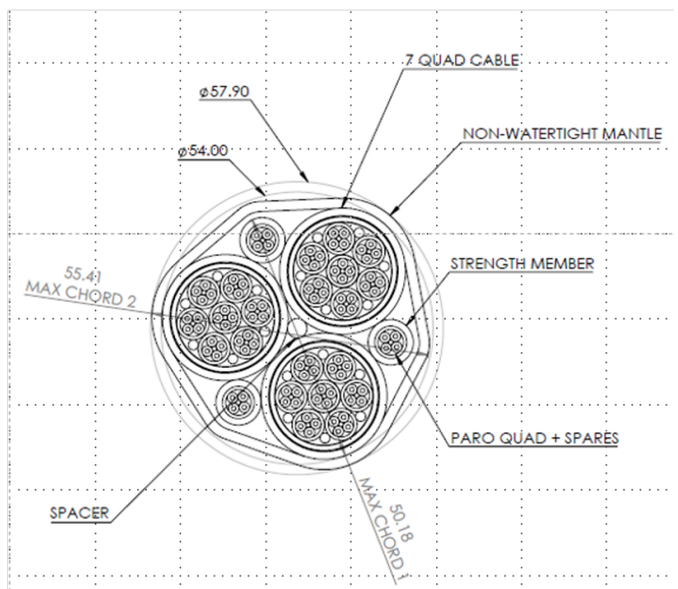
1. **Sweden Camera 2.0 for the Upgrade** ← (see next slide)
2. **Optical module development for the Upgrade and Gen2**
3. **Wind turbines (Autonomous power) for Gen2 Radio array**

   ] ← (see Gen2 talk)

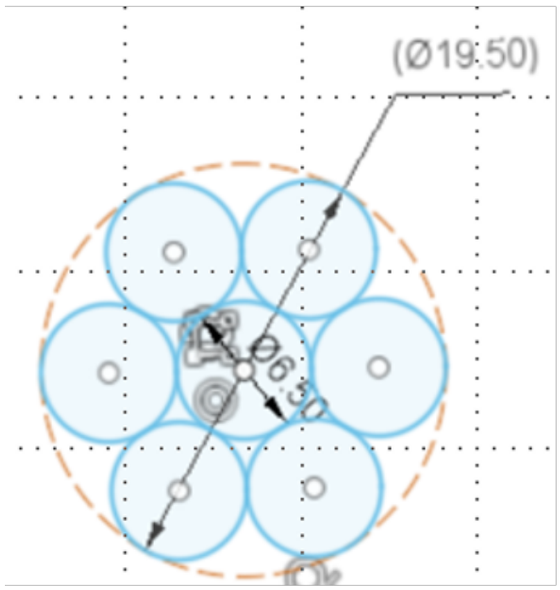
4. **Cable development for Upgrade and Gen2 (in-ice)**
5. **Support system for the Upgrade**

   ] ← (not covered here)

Support System in IceCube



IceCube Upgrade cable



Cable for IceCube Gen2 (in-ice)

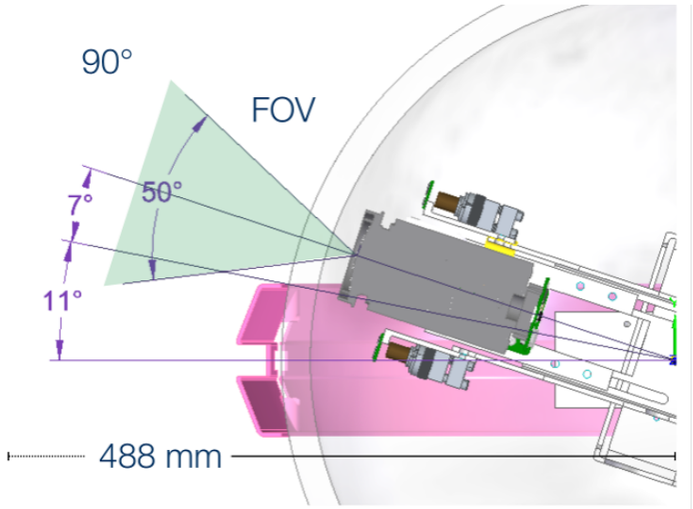
Sweden Camera 2.0

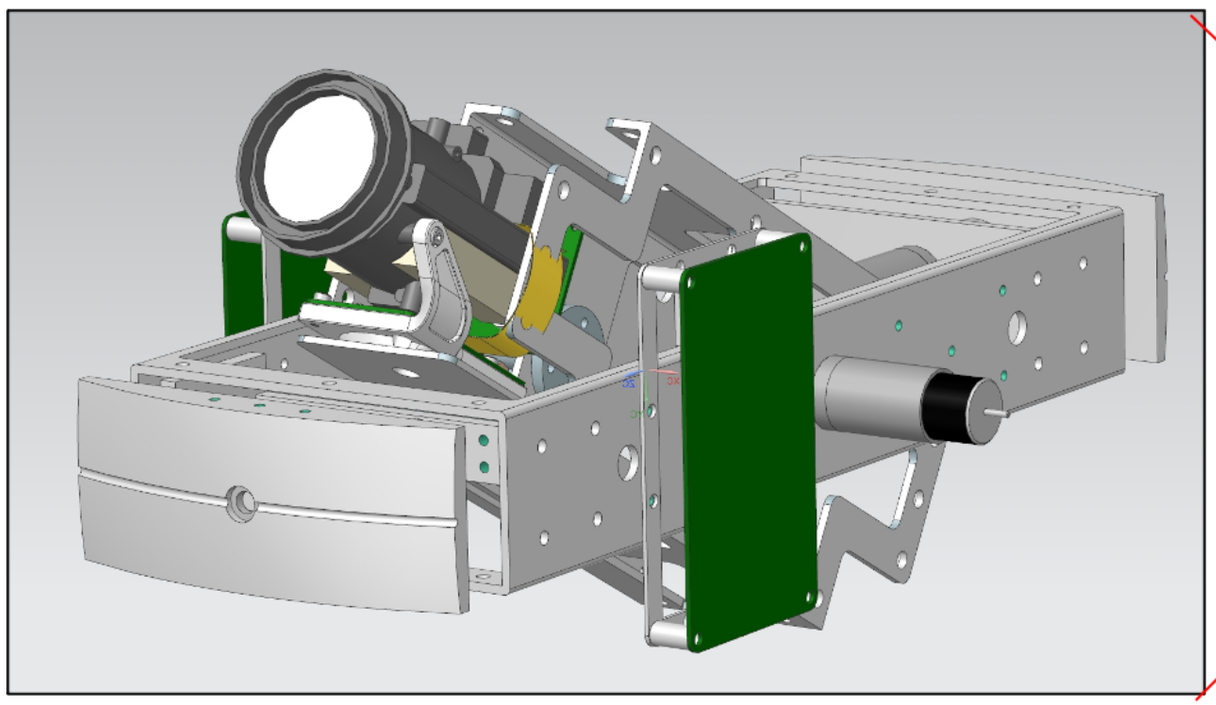
- Ice properties at site have been the biggest source of systematic uncertainties in IceCube event reconstruction

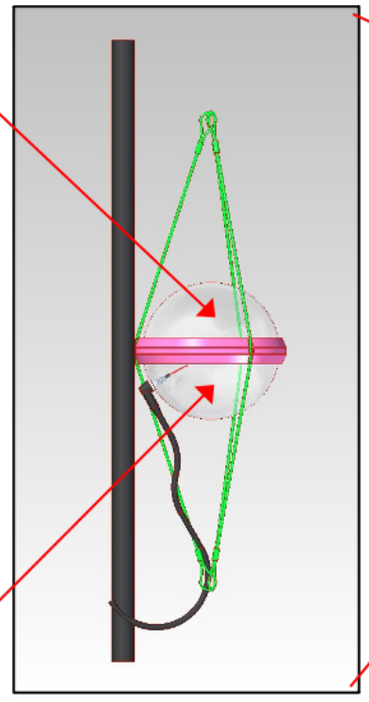
- Bubbles in hole ice near DOMs make the scattering worse, requiring precision position calibration

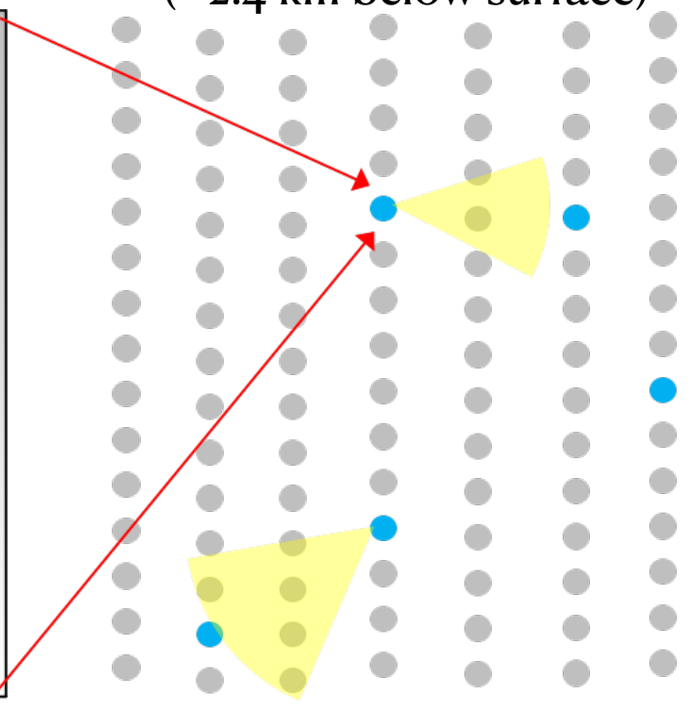
Sweden Cameras for the **Upgrade**:

- 5 modules with steerable video camera + LED and laser illumination
- Manual and autonomous operation
- Currently in design phase; collaboration b/w UU and SU





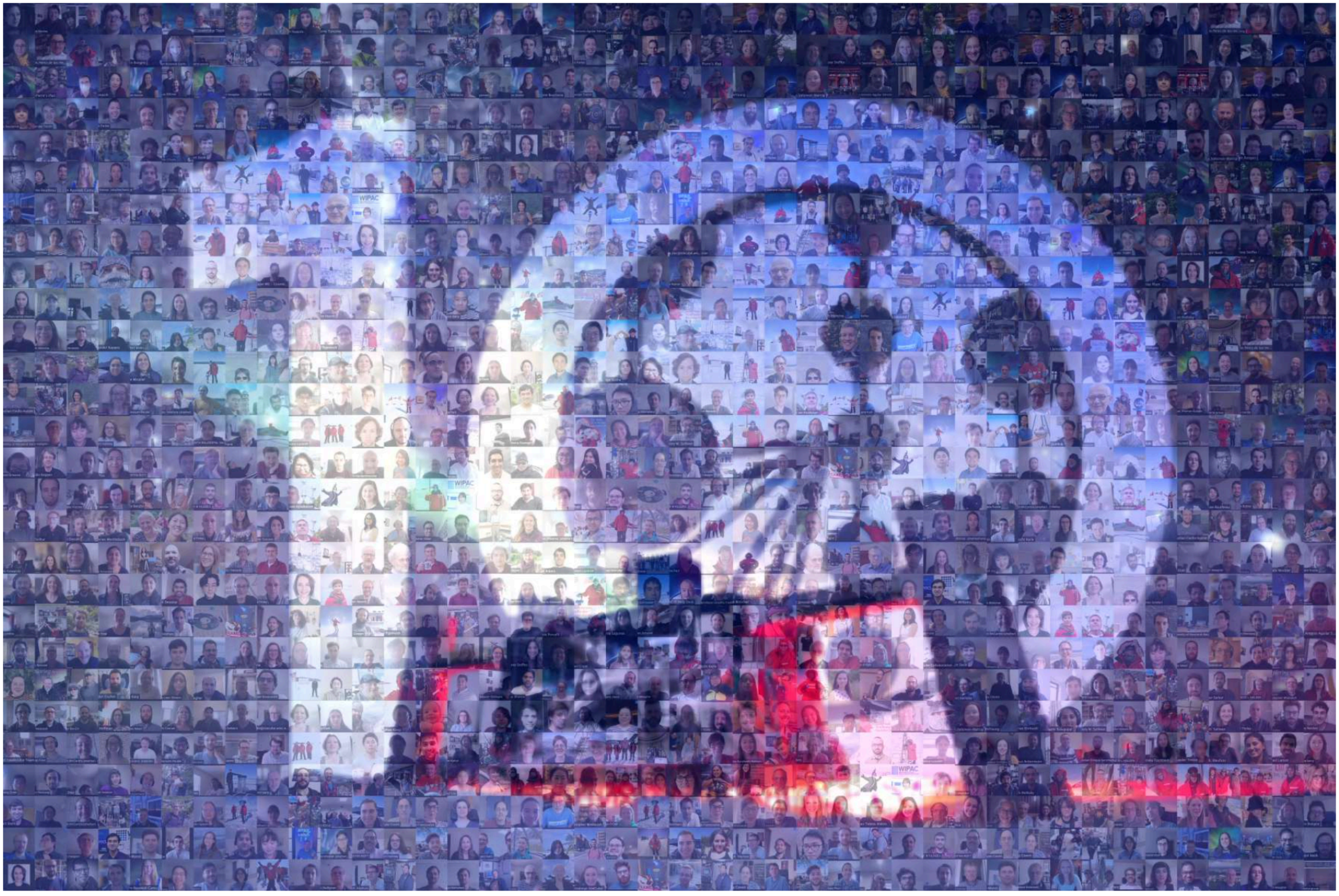




Conclusions

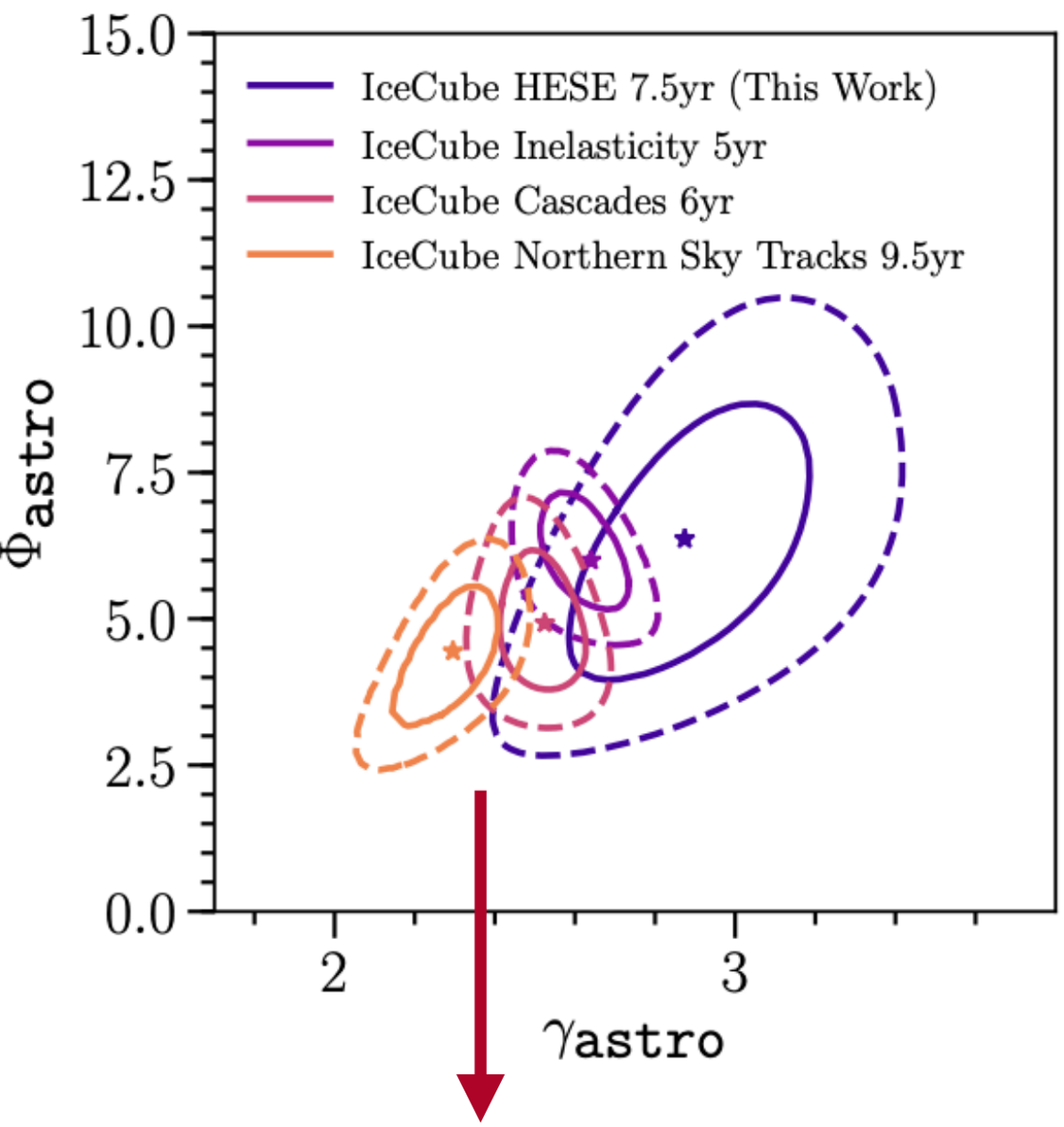
- Robust measurements of the cosmic neutrino flux at > 6σ confidence; slight tension between Northern sky and all-sky spectrum
- First potential source (TXS 0506+056) identified in 2017 through a strong multi-messenger campaign
- Have seen likely candidates for astrophysical τ and Glashow resonance; all SM cosmic messengers observed?
- No strong correlation with any source class in data, but interesting individual candidates (NGC 1068) and tighter constraints on populations emerging from new analyses
- Upcoming improvements (IceCube-Upgrade) and proposed expansion (IceCube-Gen2) will enable neutrino astronomy with an unprecedented sensitivity in the decades ahead; Sweden group providing crucial contributions to this progress!

Thank You!



Backup

Diffuse Neutrino Flux and Spectrum



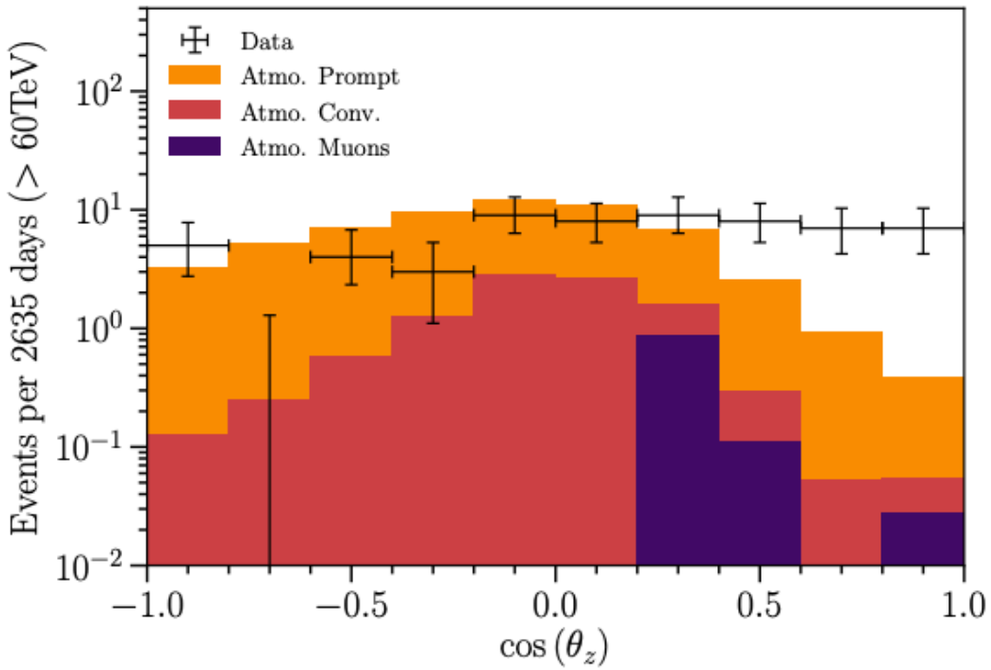
$$\Phi(E_\nu) = \Phi_{\text{astro}} \left(\frac{E_\nu}{100\ \text{TeV}} \right)^{-\gamma_{\text{astro}}}$$

Simple power-law flux assumption for the astrophysical flux

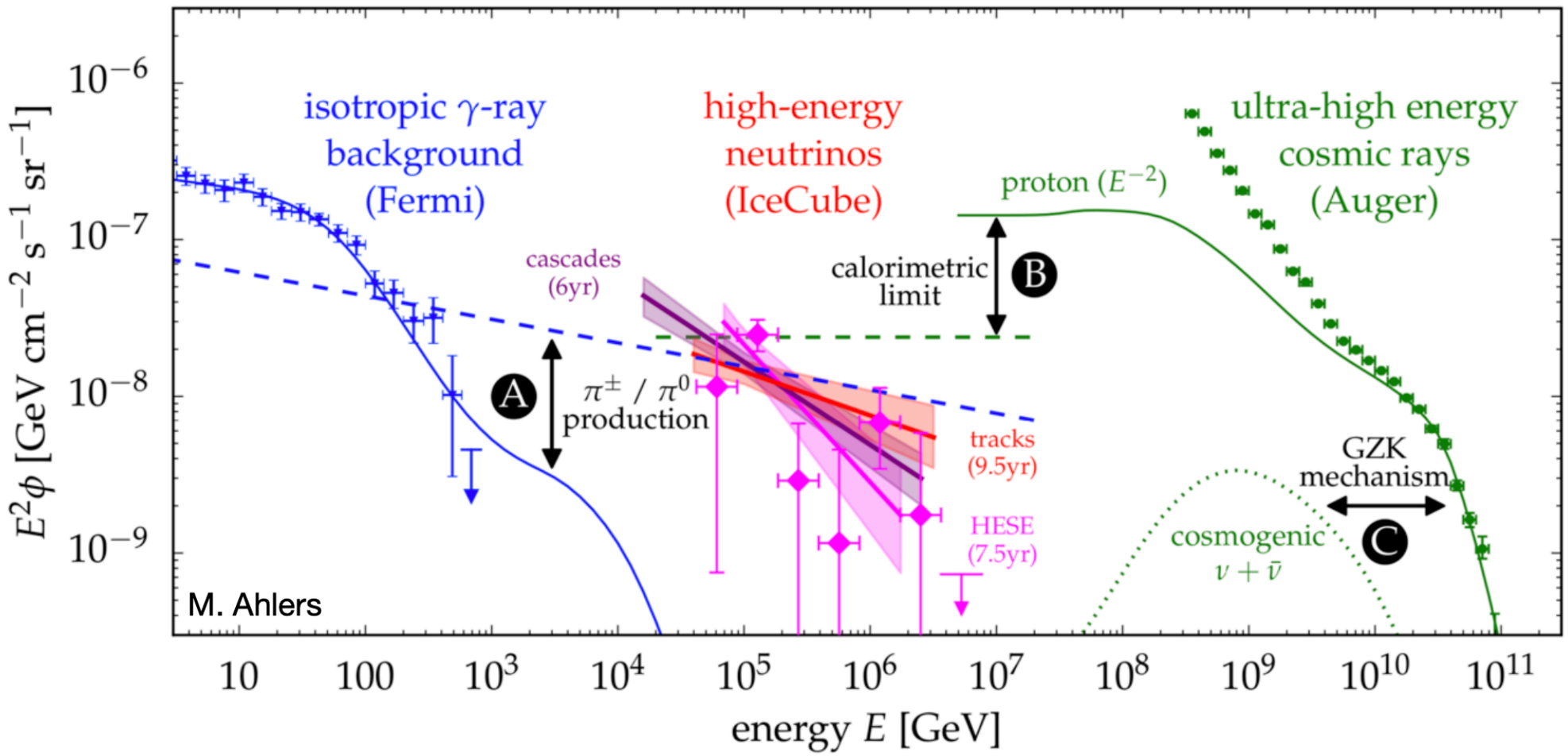
- Spectral index in the Northern hemisphere (~ 2.3) is harder than the fully-sky index measured with starting track events (~ 2.9); but non-negligible uncertainties

Possible explanations:

- Spectral change at source ($\propto E$)
- Galactic/extra-galactic turnover
- (Unidentified) systematic uncertainty ??



10.1103/PhysRevD.104.022002



Similar energy density in GeV gamma-rays [Fermi-LAT], TeV-PeV neutrinos [IceCube] and ultra-high energy cosmic rays (UHECR) [Pierre-Auger] indicating a correlation at source

F. Halzen & A. Kheirandish, 2019

Real-time Alerts

AMON - Astrophysical Multi-messenger Observatory Network

- IceCube releases public alerts in real time (~ 1 min) for ν-events of probable astrophysical origin through the Gamma-ray Coordinates Network (GCN)
- Followed-up by observatories like Fermi, MAGIC, SWIFT, ZTF etc. for coincident activity
- Since 2016; ~ 10 **Gold** (> 50% signalness) and ~30 **Bronze** (> 30% signalness) alerts/year
- First positive follow-up: **TXS 0506+056** ; observed in a gamma-ray flaring state

AMON ICECUBE_GOLD and _BRONZE EVENTS

EVENT				OBSERVATION								
RunNum_EventNum	Rev	Date	Time UT	NoticeType	RA [deg]	Dec [deg]	Error90 [arcmin]	Error50 [arcmin]	Energy	Signalness	FAR [#/yr]	Comments
134751_31476488	1	20/11/30	20:21:46.47	GOLD	30.5399	-12.0999	70.79	41.39	2.0347e+02	1.4696e-01	1.3222	IceCube Gold event. The position error is statistical only, there is no systematic added.
134751_31476488	0	20/11/30	20:21:46.47	GOLD	30.4950	-11.6137	42.65	16.61	2.0347e+02	1.4696e-01	1.3222	IceCube Gold event. The position error is statistical only, there is no systematic added.
134715_65785778	1	20/11/20	09:44:40.55	BRONZE	307.5299	+40.7700	280.79	158.40	1.5396e+02	5.0338e-01	0.2947	IceCube Bronze event. The position error is statistical only, there is no systematic added.
134715_65785778	0	20/11/20	09:44:40.55	BRONZE	307.8471	+40.1903	30.80	12.00	1.5396e+02	5.0338e-01	0.2947	IceCube Bronze event. The position error is statistical only, there is no systematic added.

The AMON network enables multi-messenger discoveries ($\nu + \gamma$ and also GW $+\gamma$) by bringing together Gamma-ray, Neutrino and GW observatories and vastly improving the significance of observations by any single experiment/instrument

First HE neutrino source....

RESEARCH

RESEARCH ARTICLE SUMMARY

NEUTRINO ASTROPHYSICS

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

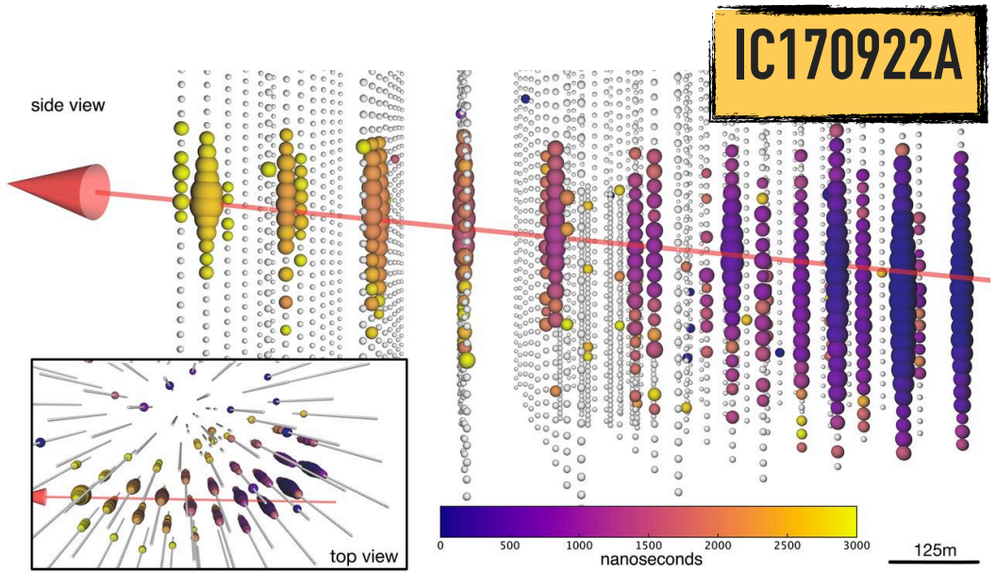
The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

trinos, IceCube provides real-time triggers for observatories around the world measuring γ-rays, x-rays, optical, radio, and gravitational waves, allowing for the potential identification of even rapidly fading sources.

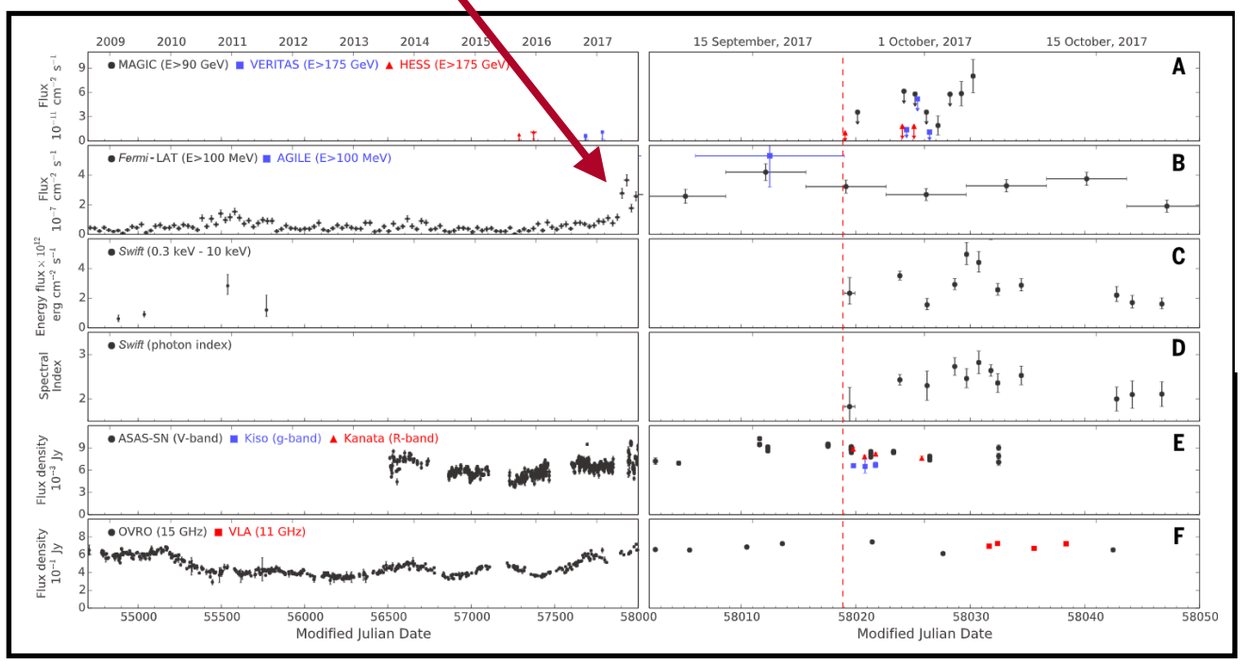
RESULTS: A high-energy neutrino-induced muon track was detected on 22 September 2017, automatically generating an alert that was distributed worldwide within 1 min of detection and prompted follow-up searches by telescopes over a broad range of wavelengths. On 28 September 2017, the *Fermi* Large Area Telescope Collaboration reported that the di-

ON OUR WEBSITE

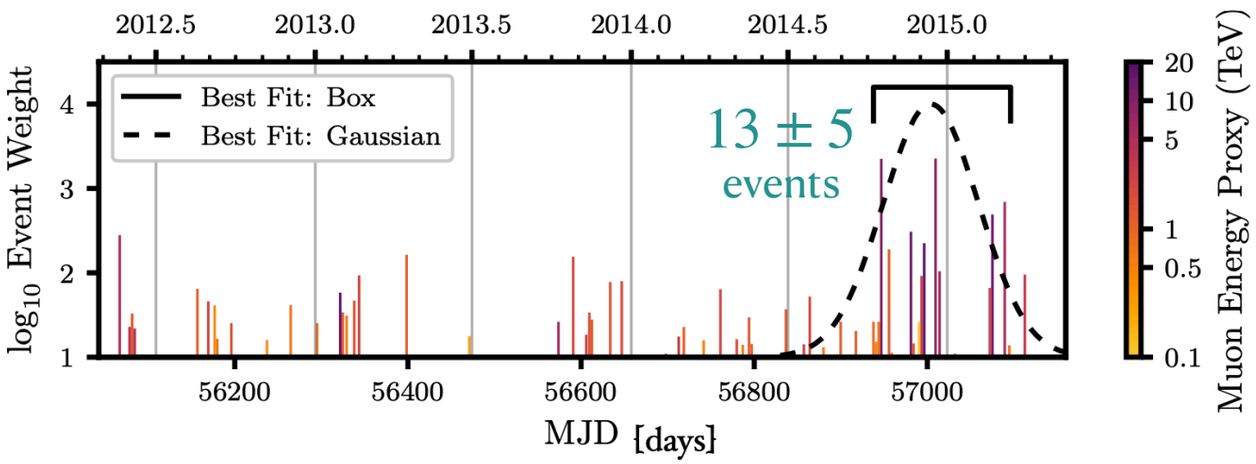
Read the full article at http://dx.doi.org/10.1126/science.aat1378



- ~290 TeV neutrino from the direction of blazar TXS 0506+056 (**z =0.336**)
- Observed by MAGIC and Fermi in increased activity (flaring) state in the following days



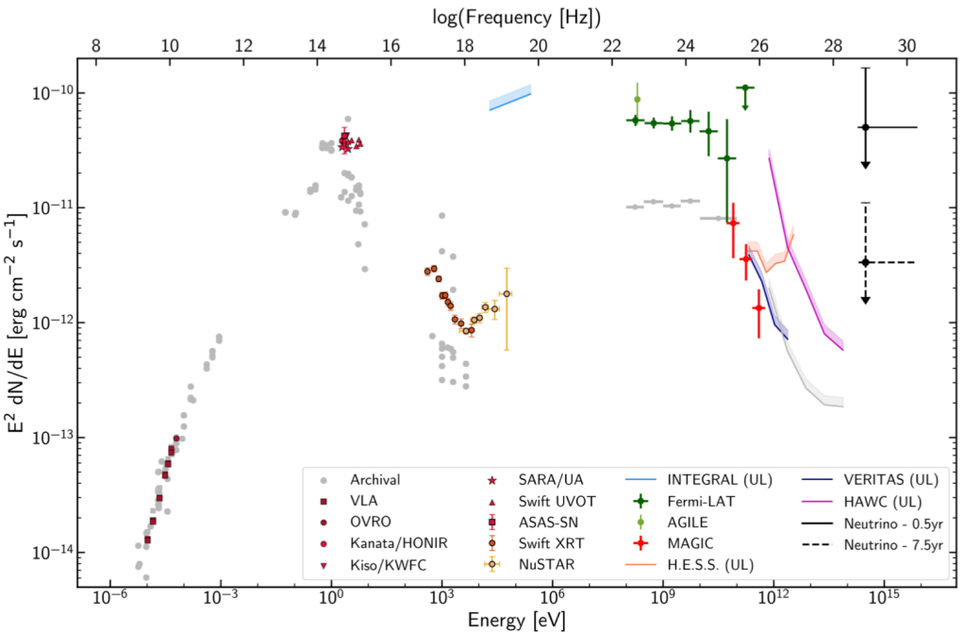
Analysis of archival IceCube data confirmed a 3.5σ excess over ~110 days in 2014-15



First successful multi-messenger follow-up campaign for a real-time alert!

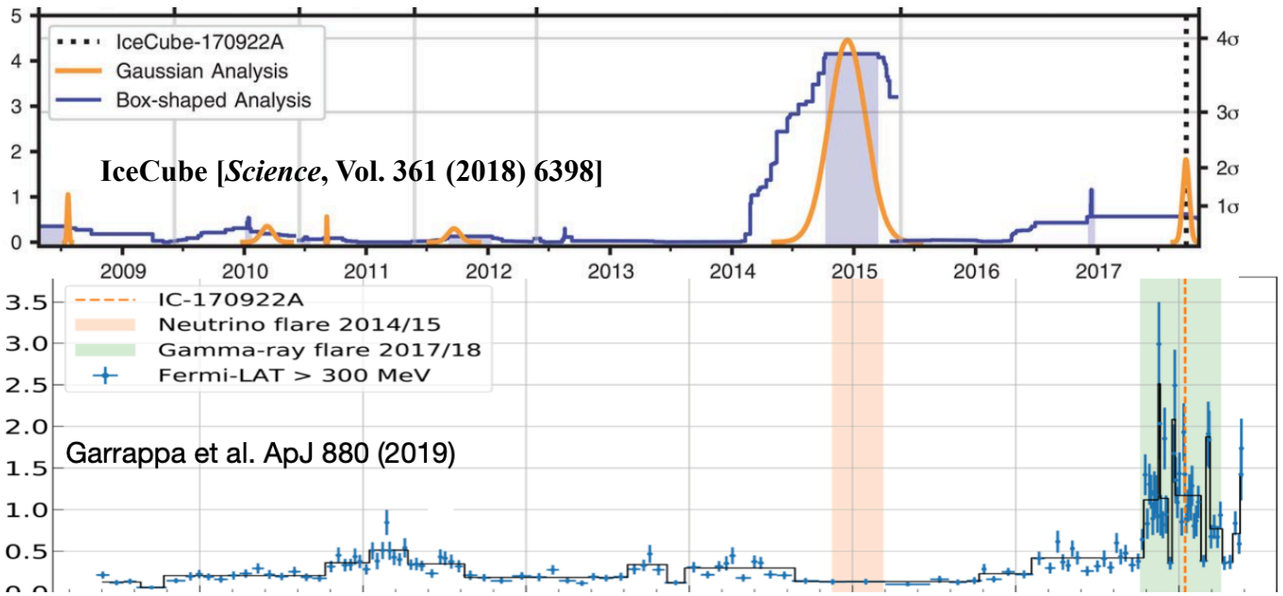
IceCube [*Science*, Vol. 361 (2018) 6398]
IceCube++ [*Science*, Vol. 361 (2018) 6398]

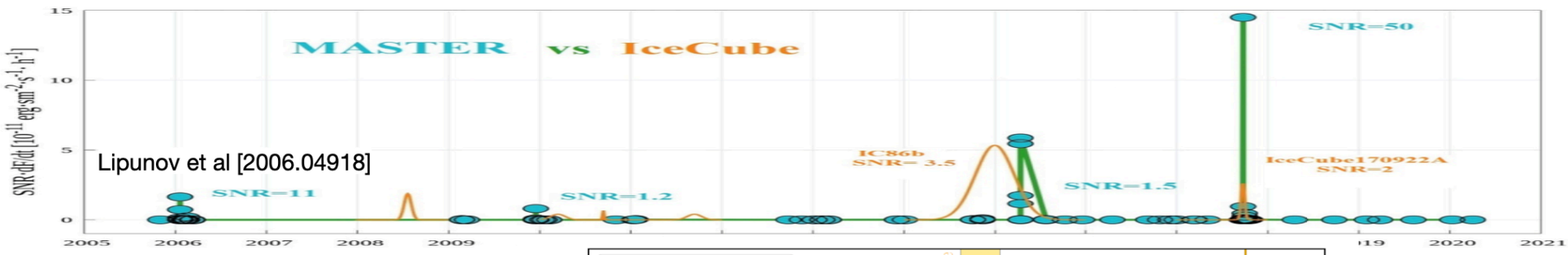
TXS 0506+056

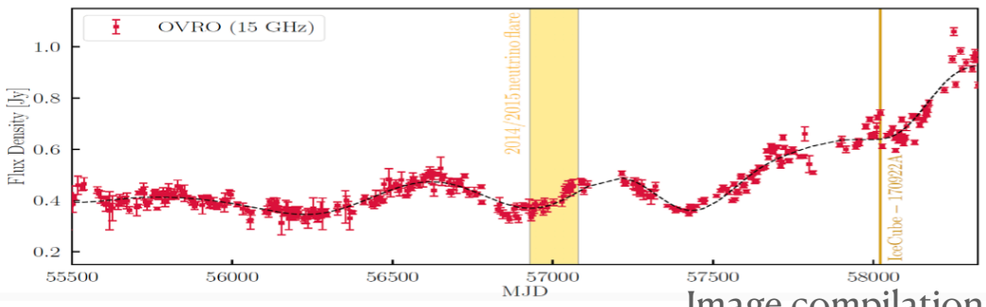


IceCube++ [*Science*, Vol. 361 (2018) 6398]

SED of TXS 0506+056 around the time of IC170922A, with neutrino flux expectation for 1 event in 6 months and 7 years





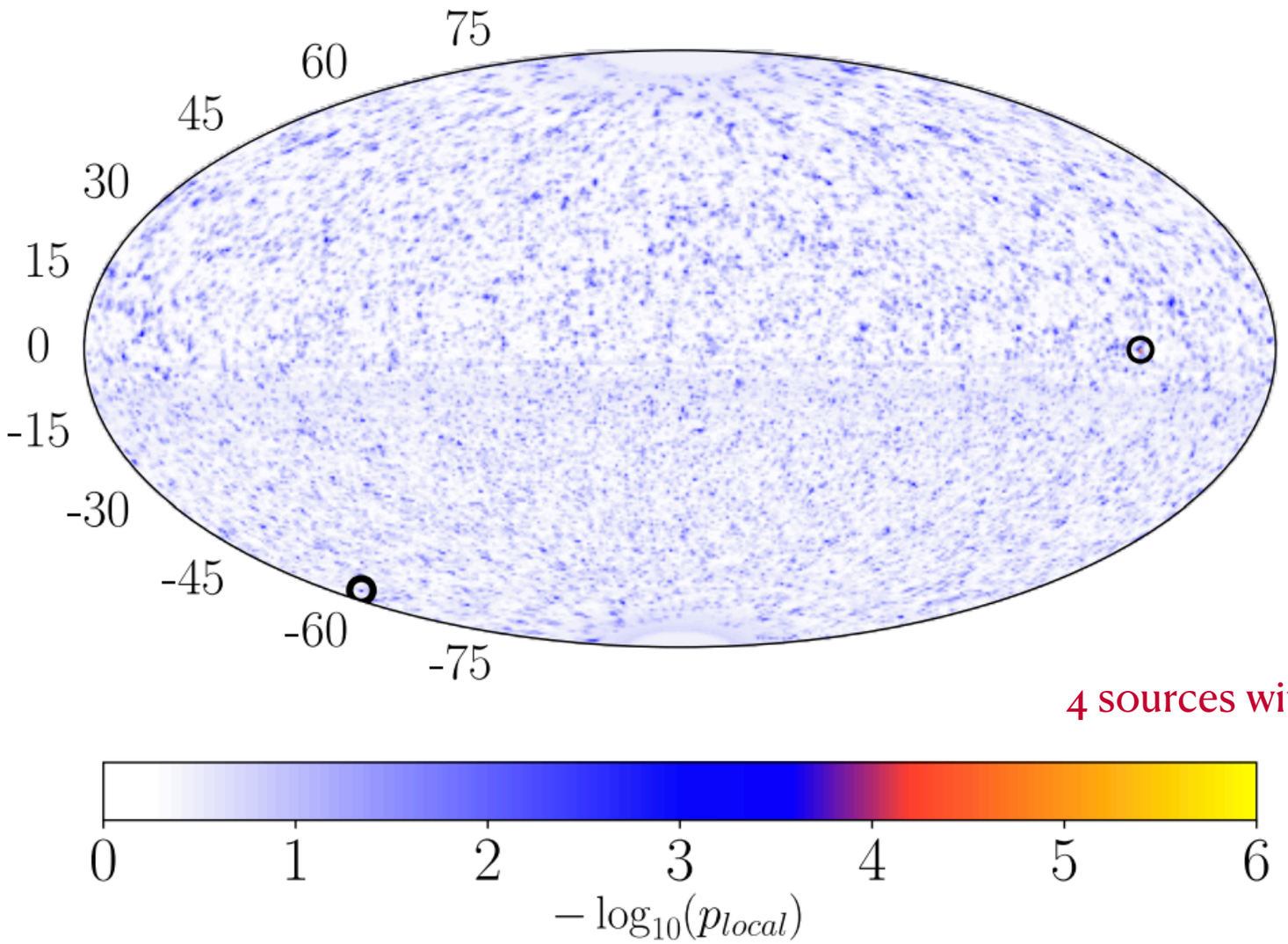


Neutrino alert and archival flare duration as observed by different instruments

Image compilation Credit: Qinrui Liu

All-sky point source search

All-sky scan to search for self-clusterings of neutrinos in 10 year IceCube data



NGC 1068
TXS 0506+056
PKS 1424+240
GB6 1542+6129

4 sources with pre-trial p-value < 0.01

- Northern source catalog search inconsistent with background at 3.3σ; might hint at correlations with observed neutrinos

IceCube (PRL,**124**, 051103)

All-sky point source search

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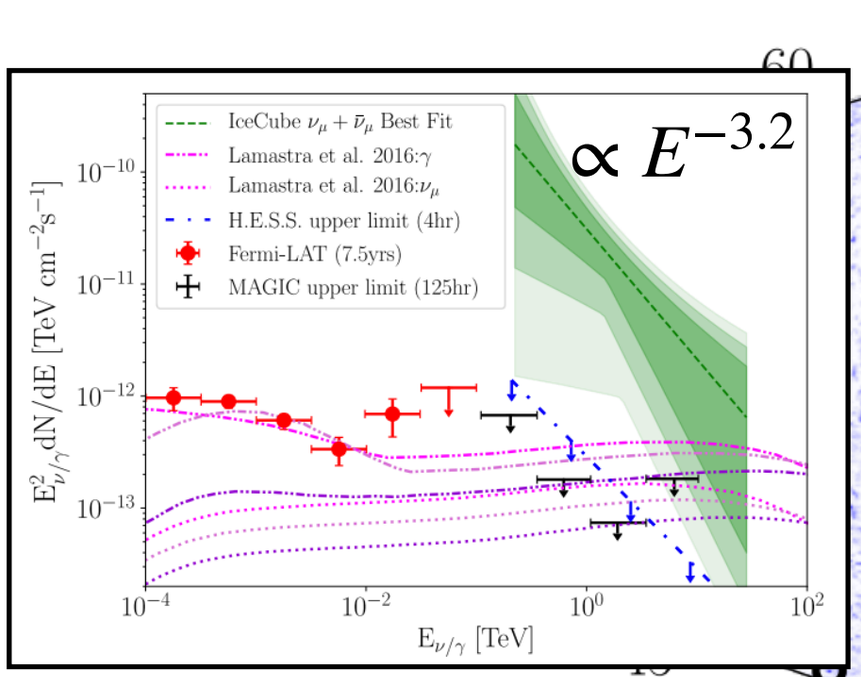
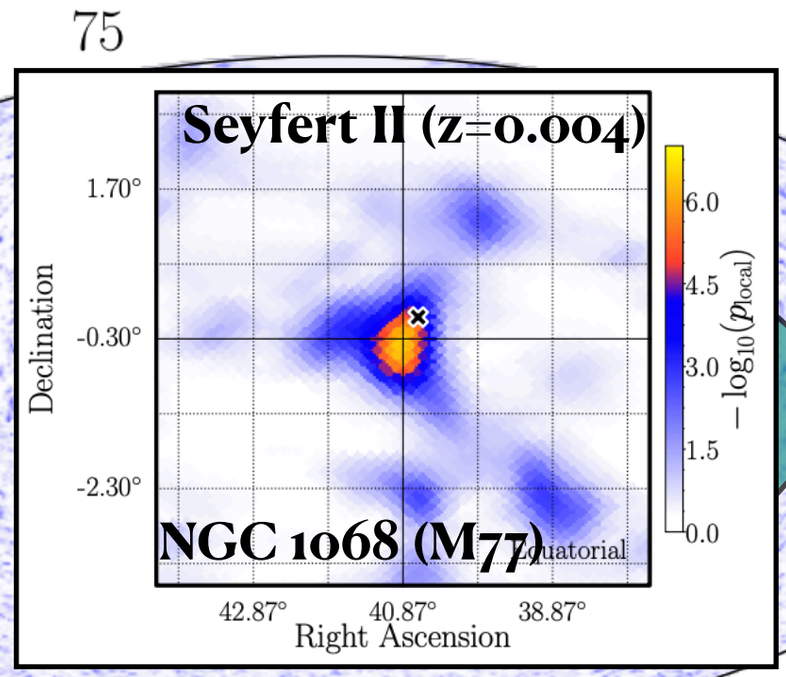




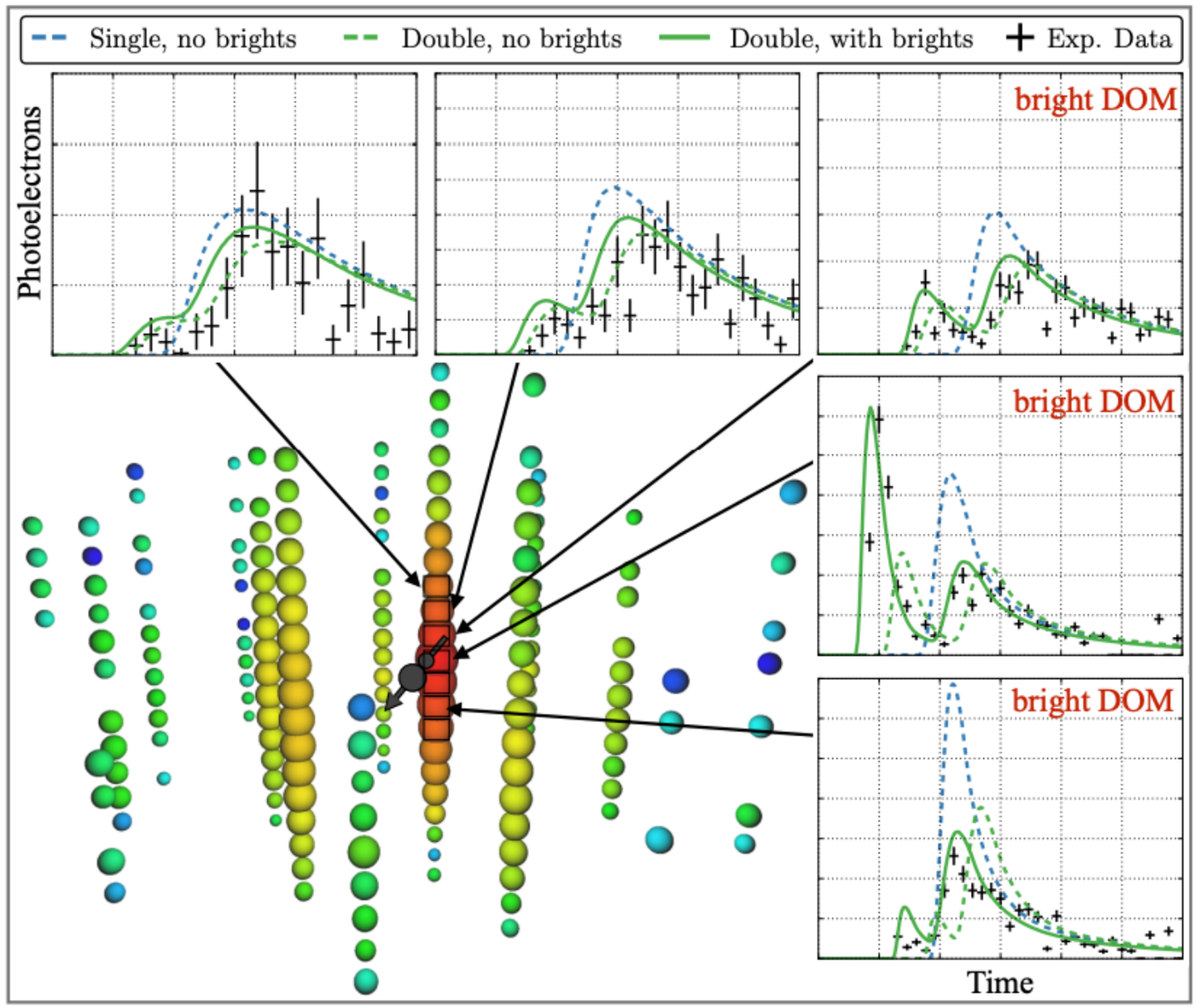
NGC 1068
TXS 0506+056
PKS 1424+240
GB6 1542+6129

4 sources with pre-trial p-value < 0.01

- Northern source catalog search inconsistent with background at 3.3σ; might hint at correlations with observed neutrinos
- Most significant Northern sky hotspot coincident with **NGC 1068**; at 2.9σ above bkgd (post-trial)

IceCube (PRL,**124**, 051103)

Astrophysical τ appearance

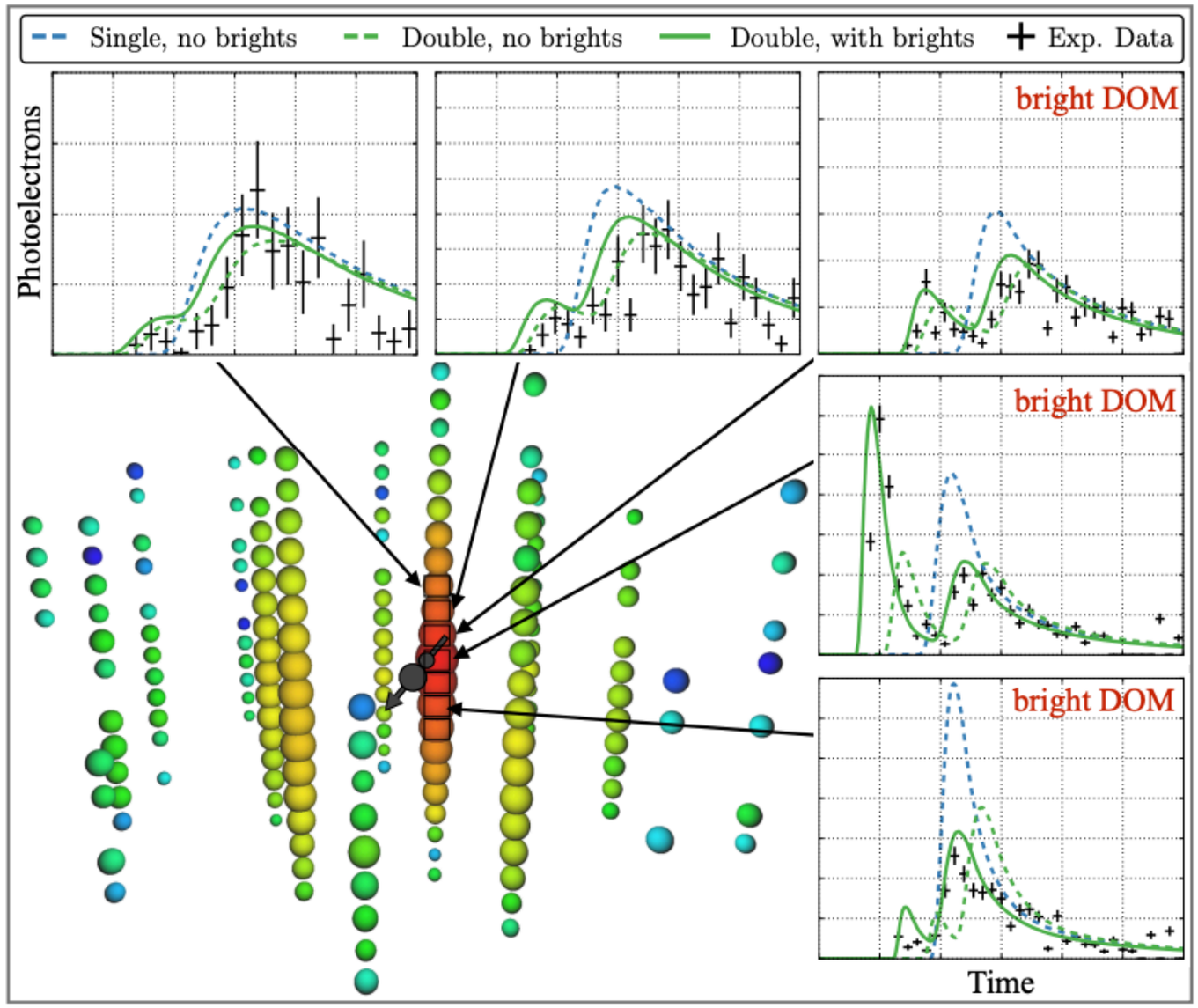


τ decay length: 50m/PeV

- 2 candidate events (above 60 TeV) in 7.5 years
- Double cascade and double pulse: shower (first-bang) + τ decay (second-bang)
- > 75% and > 97% probabilities of being astrophysical τ respectively

arXiv:2011.03561

Astrophysical τ appearance



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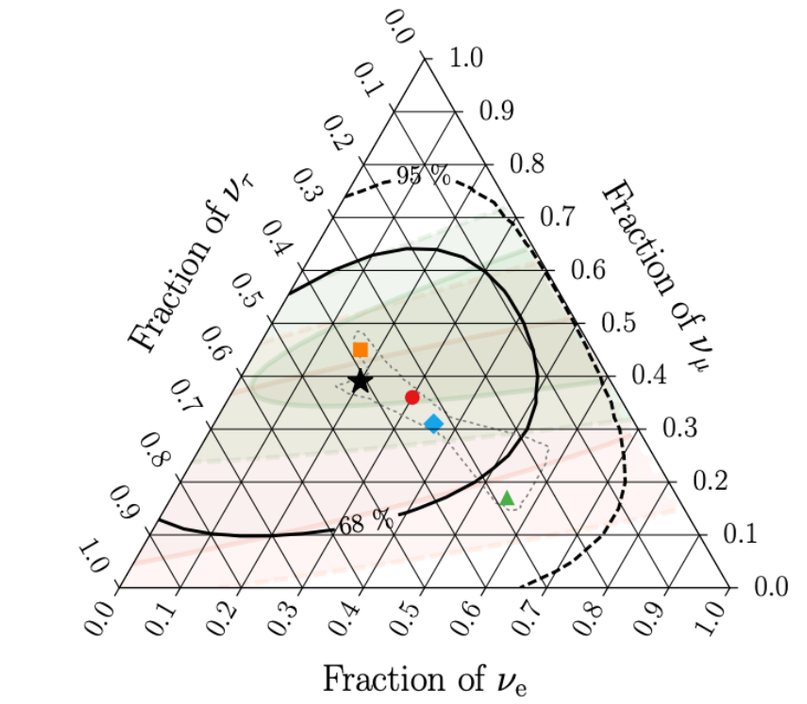
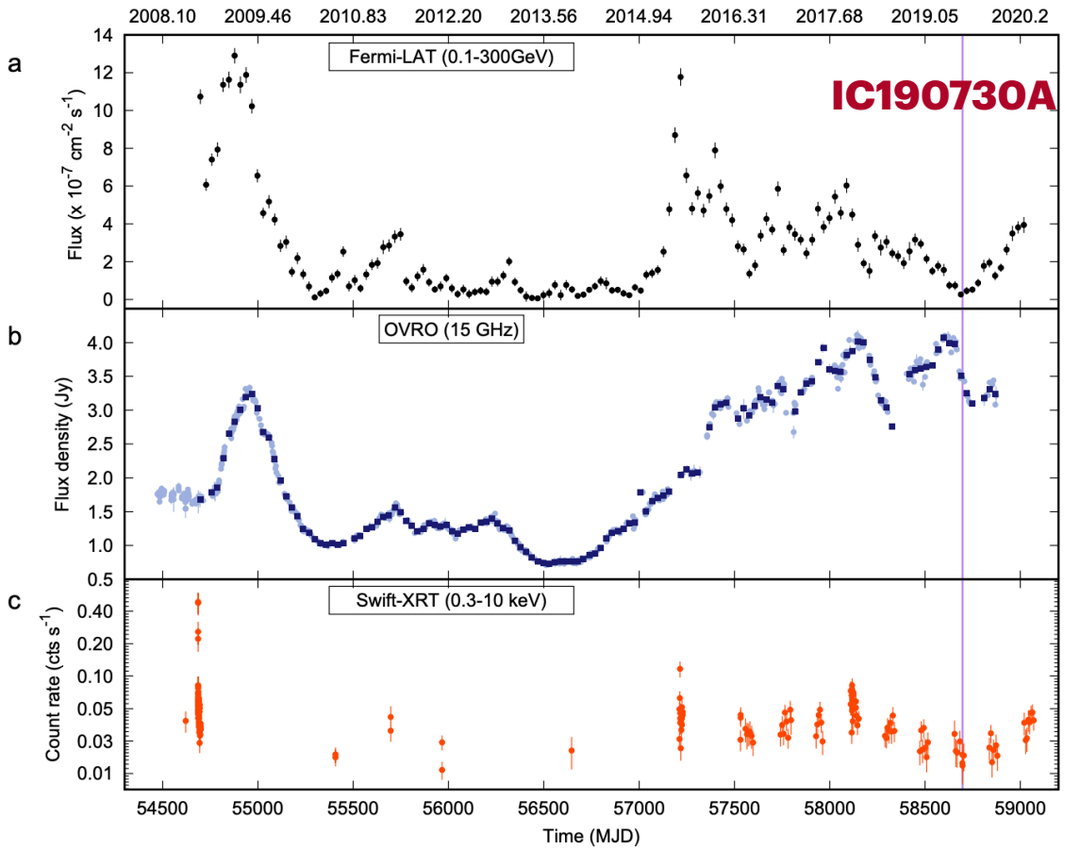


Data consistent with flavour equipartition

- 2 candidate events (above 60 TeV) in 7.5 years
- Double cascade and double pulse: shower (first-bang) + τ decay (second-bang)
- > 75% and > 97% probabilities of being astrophysical τ respectively

arXiv:2011.03561

Interesting alerts



IC190730A

Kun et al. ApJL 911 (2021) 2

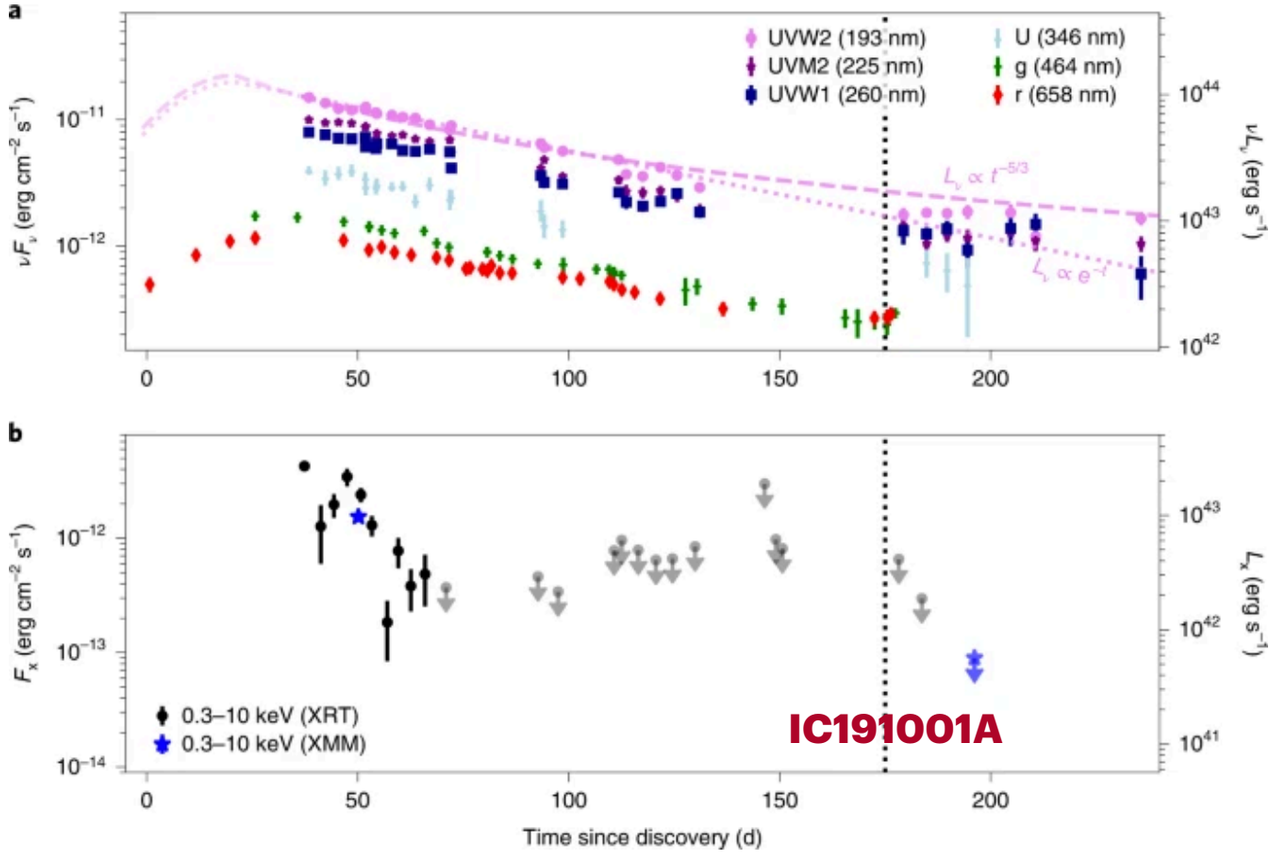
Coincident with blazar PKS 1502+106

Gamma-ray suppressed but flaring in radio at the time of neutrino alert

Coincident with radio emitting TDE AT2019dsg identified by ZTF

Taking into account bolometric flux, chance coincidence probability ~ 0.2%

IC191001A

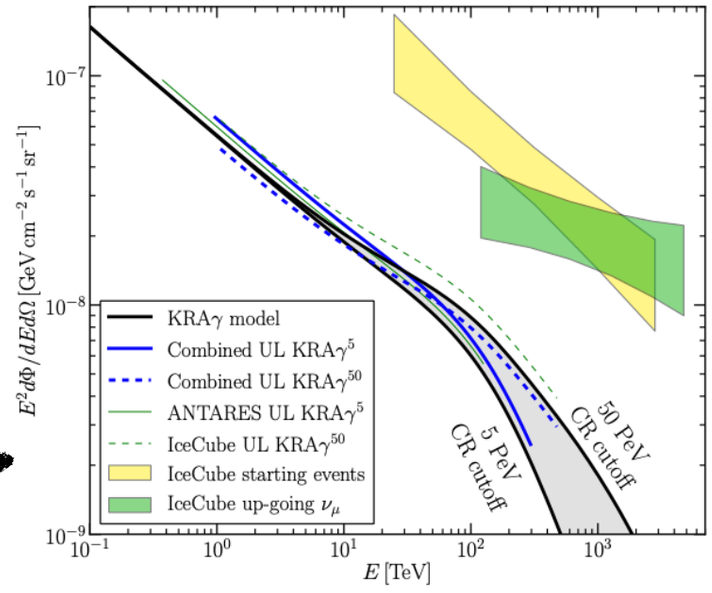


Stein et al. Nature Astron. 5 (2021) 5

Galactic Sources

TeV γ-ray sources and PeV cosmic rays in the galaxy hint at possible hadronic emission and a subsequent diffuse Galactic neutrino flux

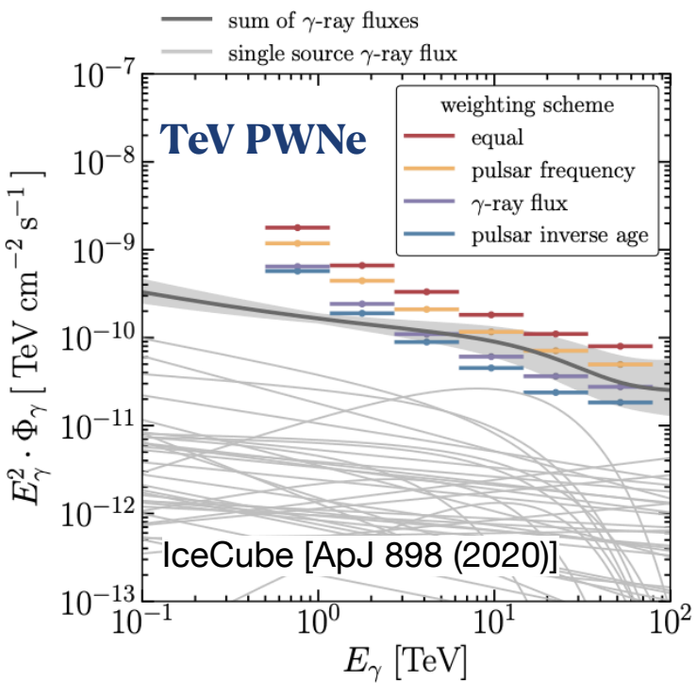
Galactic contribution to diffuse ν flux already constrained by IceCube to ~ 10% (E > 1 TeV)

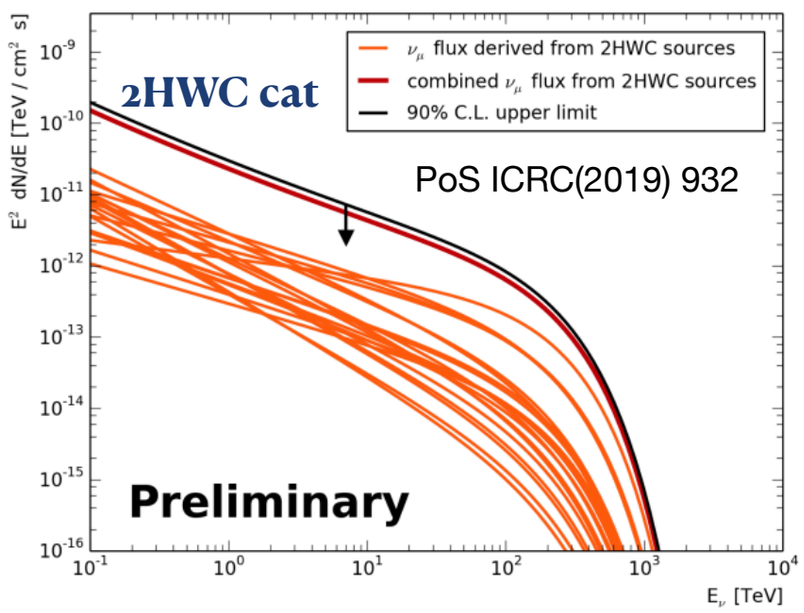


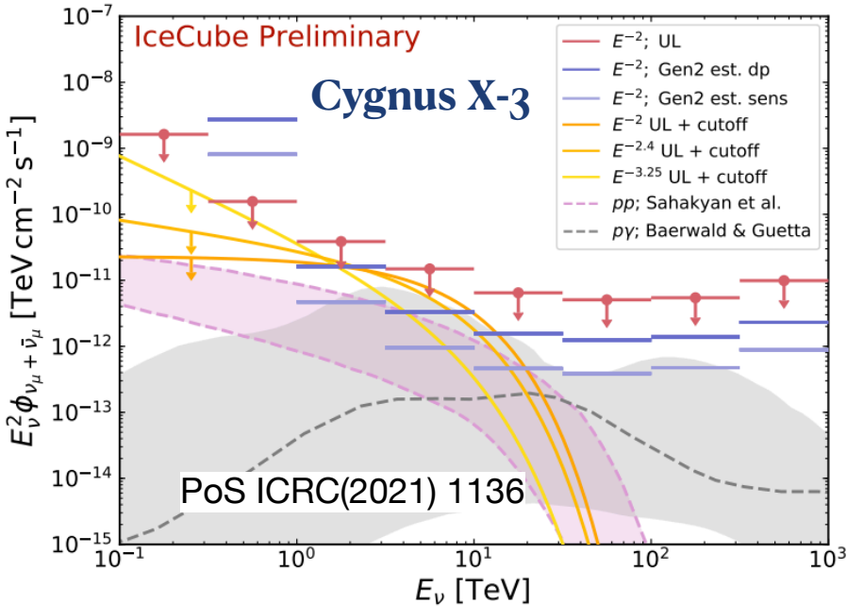
IceCube+ [ApJ 868 (2018) 2]

Recent stacking searches with Galactic source catalogs show no strong correlation with extended or point sources

Strong individual source upper limits!







However, few local hotspots (< 3σ) identified: Cygnus X-3, MGRO 1908+06, RX J1713.7-3946 ....

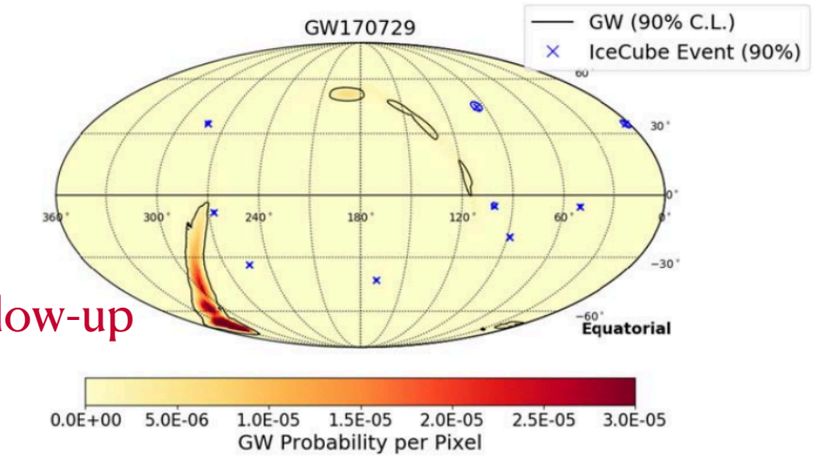
Ongoing investigations

Multi-messenger searches:

Multi-wavelength connections:

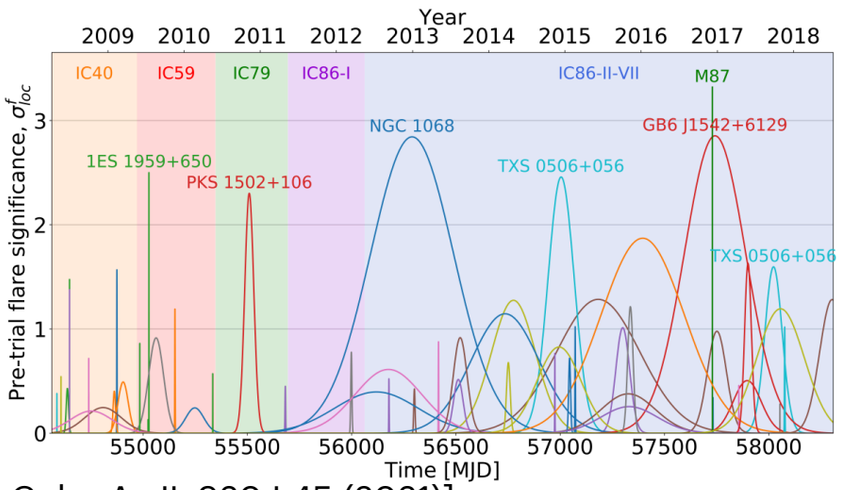
- Radio AGN [PoS ICRC(2021) 949]
- ULIRGs [PoS ICRC(2021) 1115]
- X-ray AGN [PoS ICRC(2021) 1142]
- VHE Gamma with alerts [PoS ICRC(2021) 960]

GW follow-up

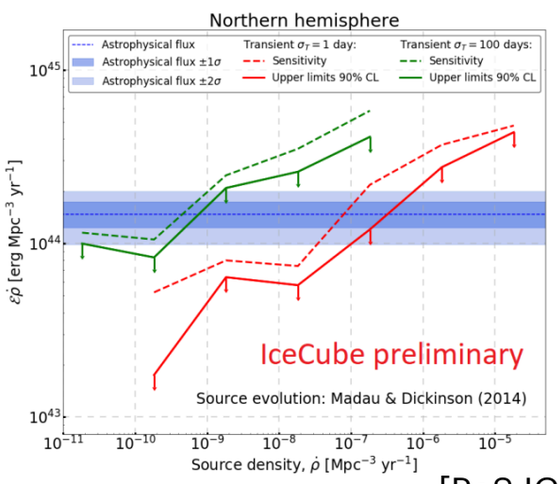


[IceCube ApJL 898 (2020) 1]

Time-dependent/multi-flare searches: all-sky scan and source catalog search



[IceCube ApJL 920 L45 (2021)]



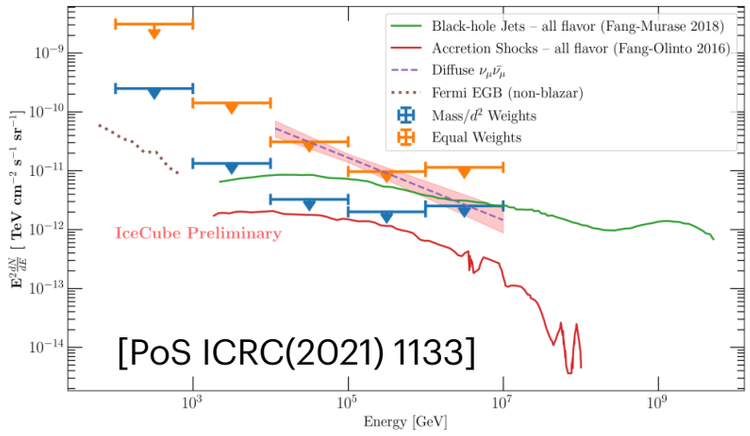
[PoS ICRC(2021) 1128]

Transients:

- GRBs [PoS ICRC(2021) 1118]
- sub-TeV transients [arXiv:2011.05096]

Galactic:

- X-ray binaries [PoS ICRC(2021) 1136]
- Magnetars [PoS ICRC(2021) 1135]

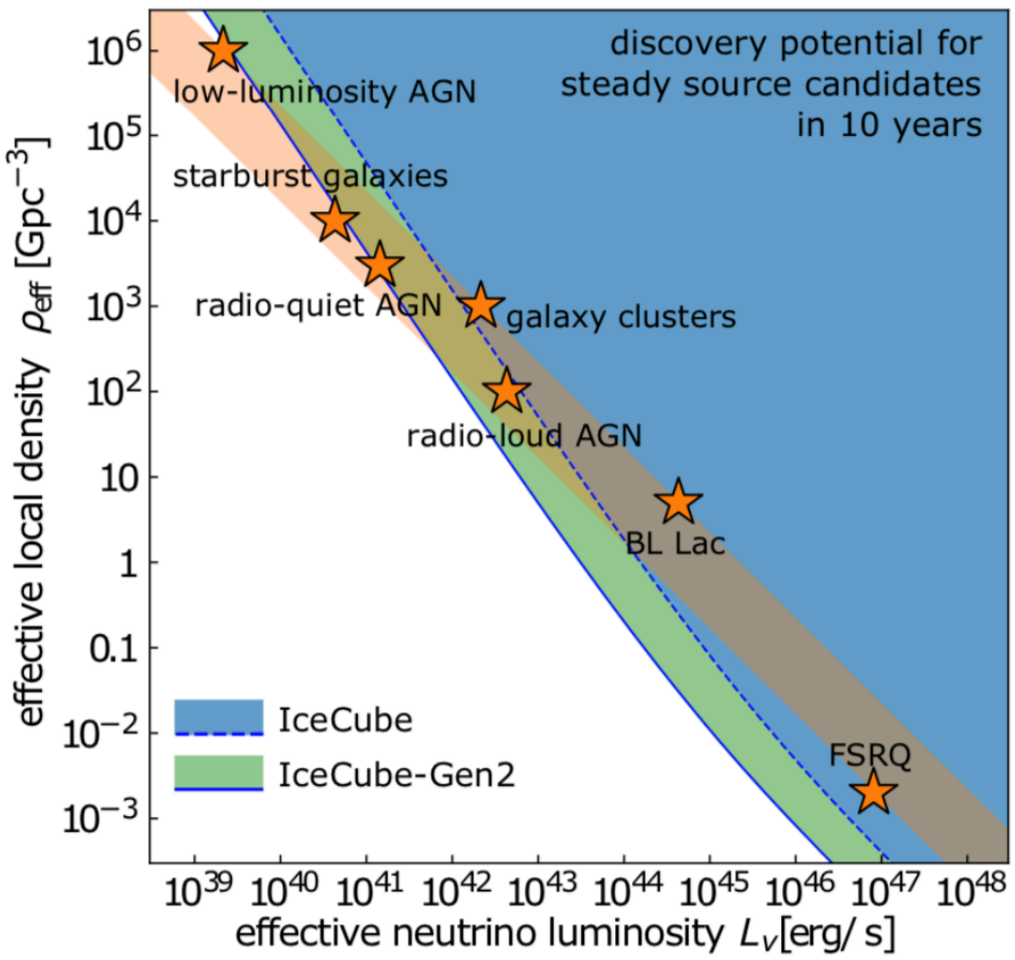


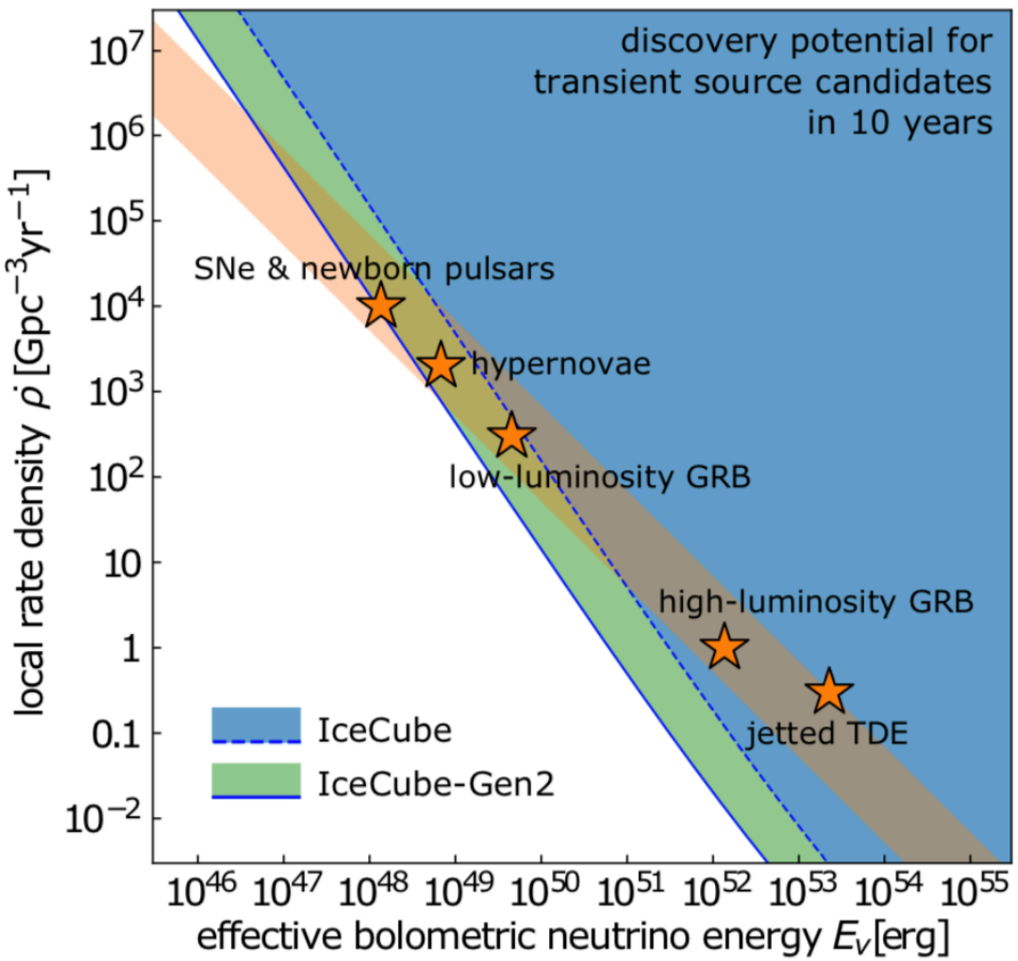
[PoS ICRC(2021) 1133]

Galaxy clusters

and many more....

Resolving source populations with IceCube and IceCube-Gen2

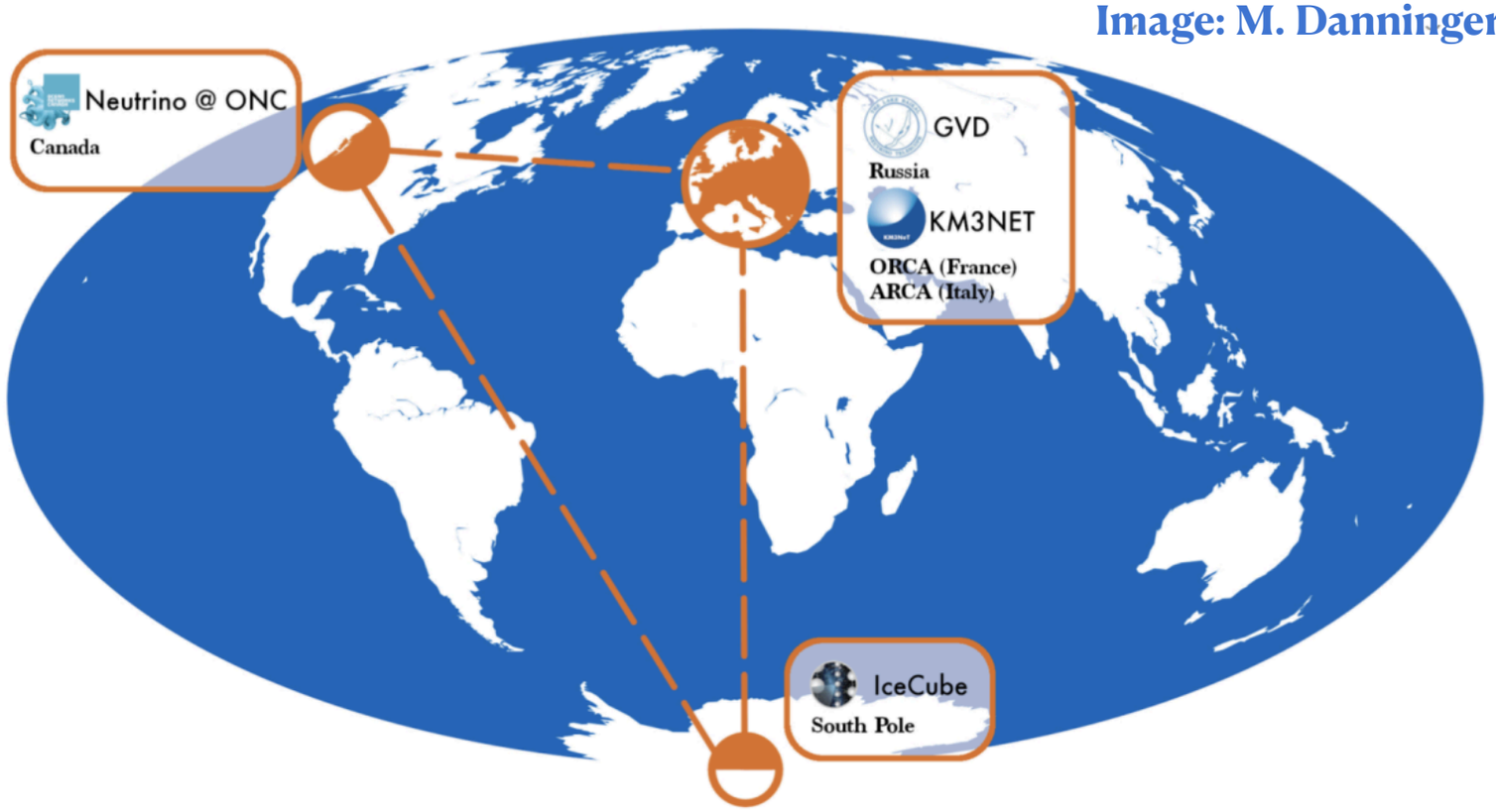


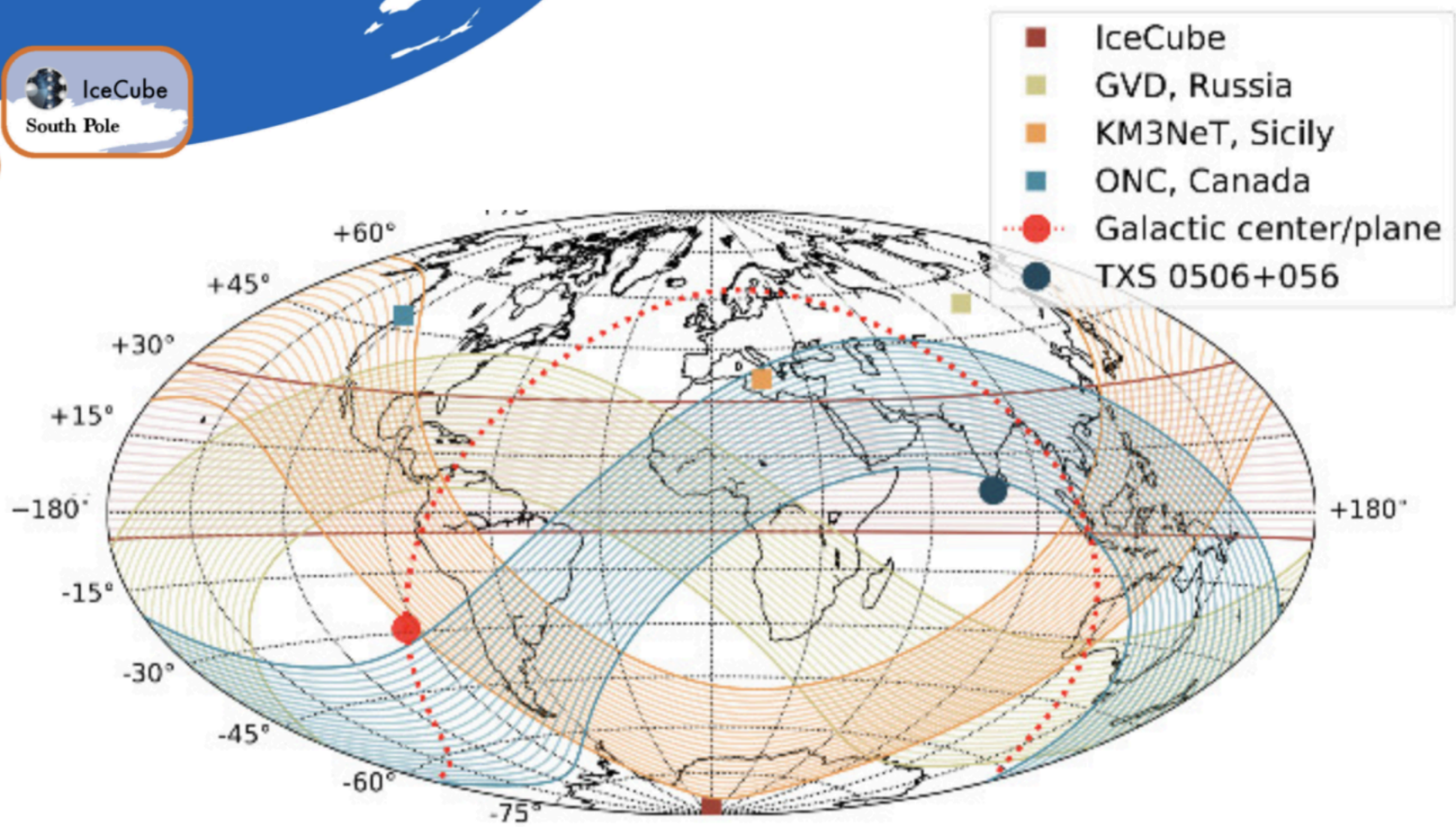


IceCube Gen-2 [2021 *J. Phys. G: Nucl. Part. Phys.* **48** 060501]

Global Neutrino Network

Image: M. Danninger/P-ONE





IceCube Science Map