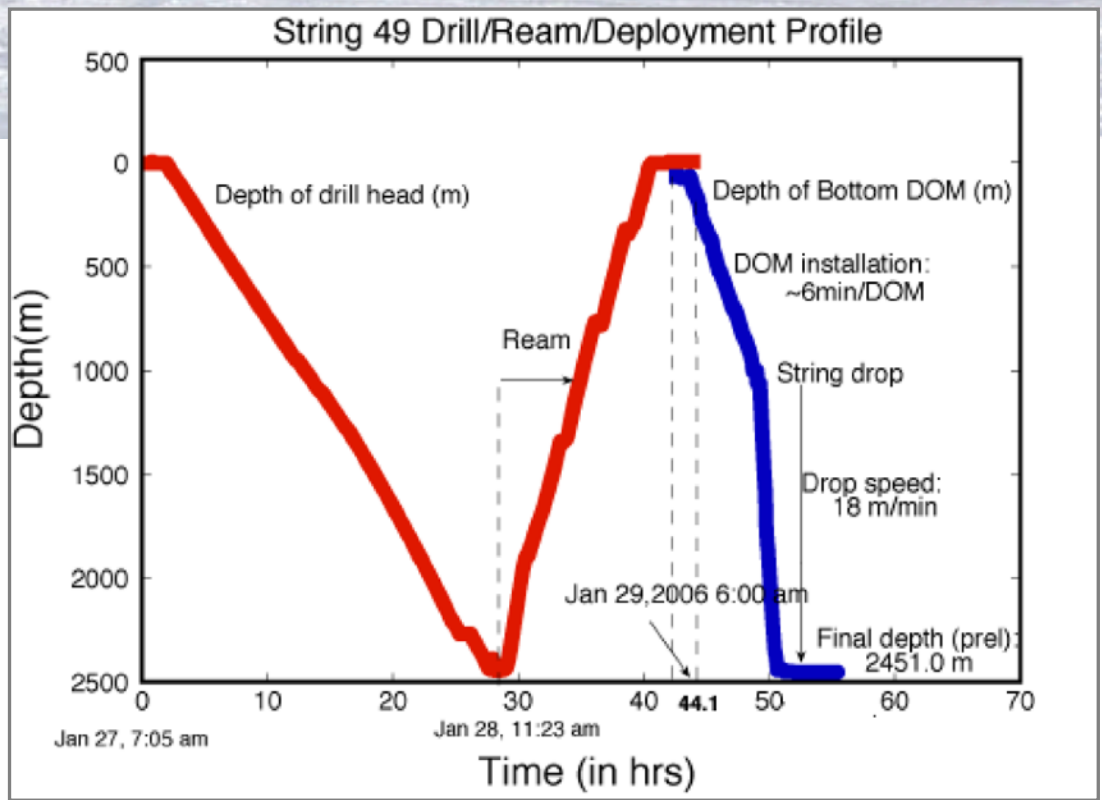
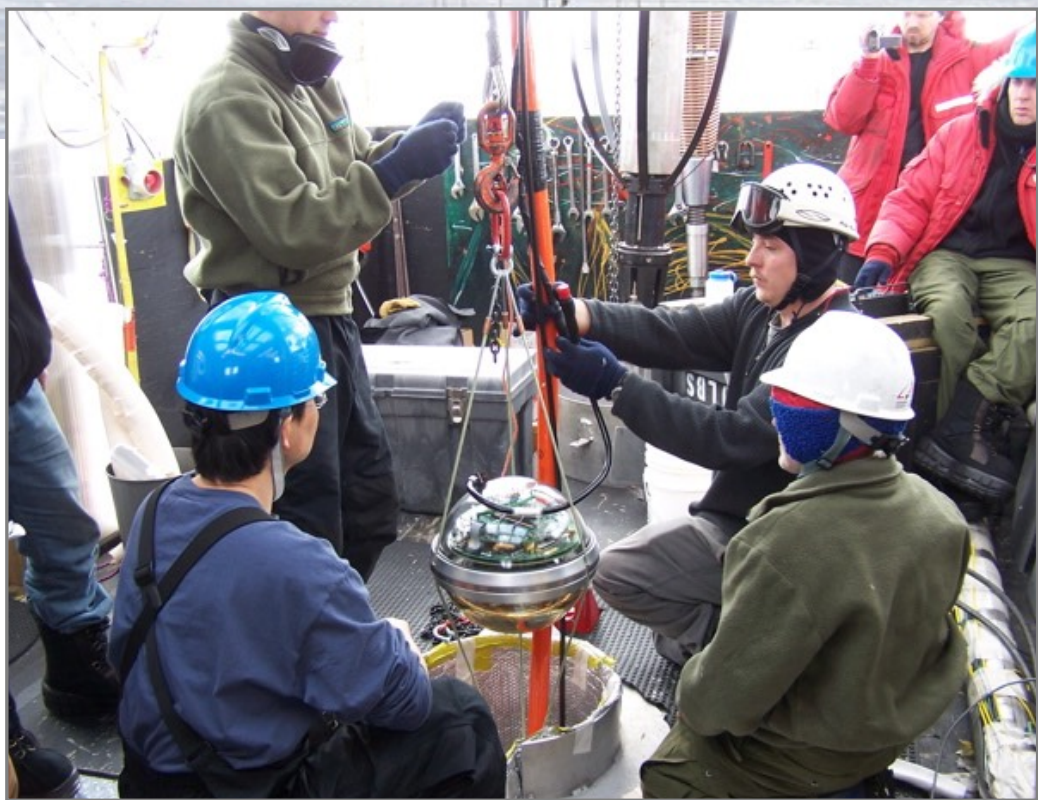


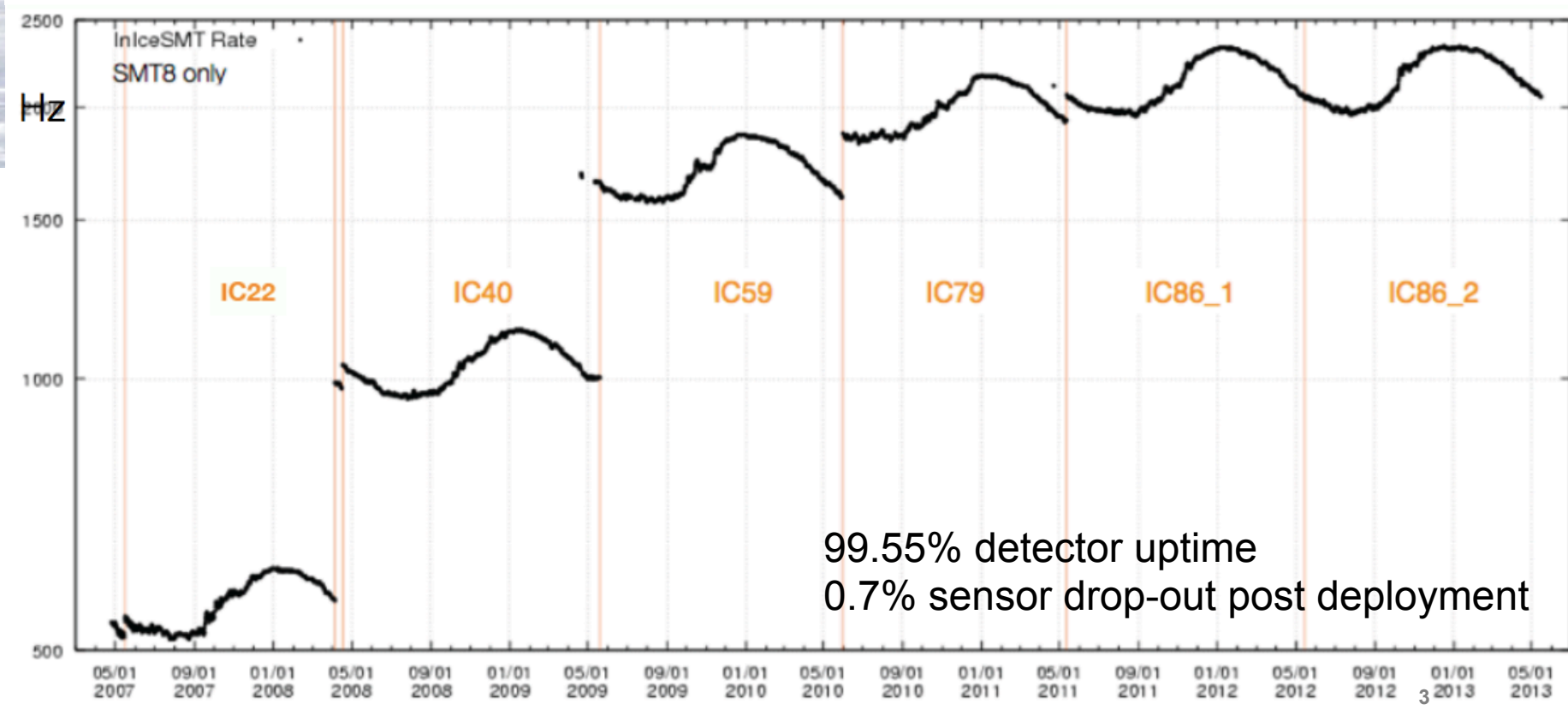
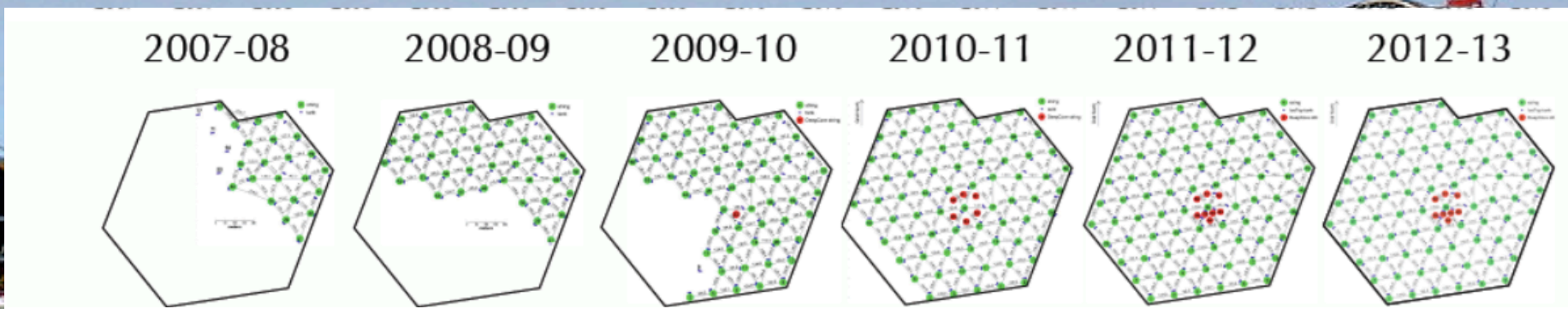
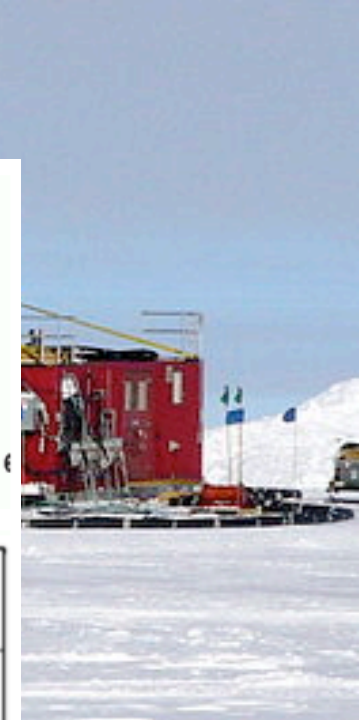
IceCube: The Window to the extreme Universe

Marek Kowalski (DESY & Humboldt University of Berlin)

for the IceCube and IceCube-Gen2 Collaboration

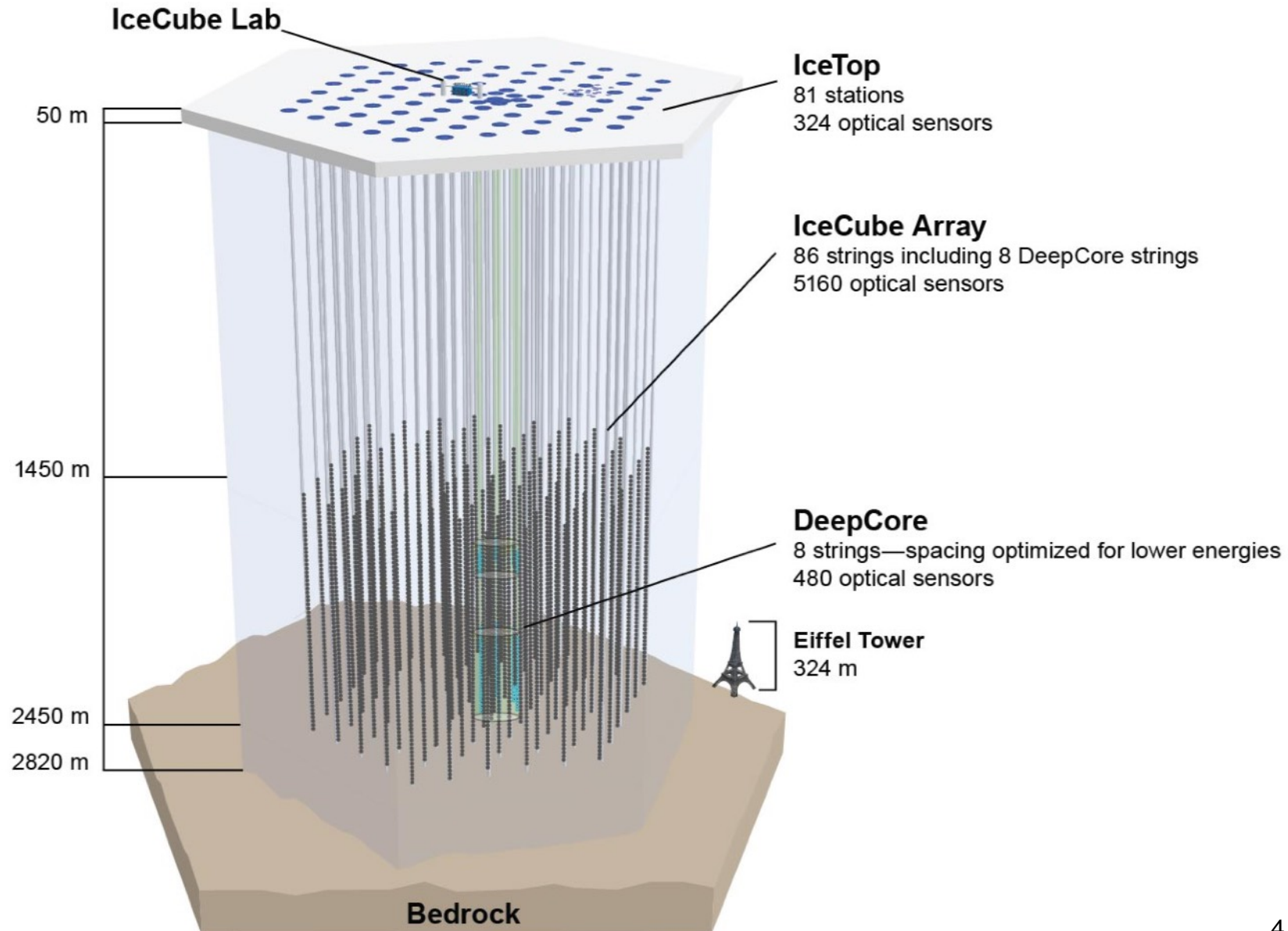
16.7.2021, ICRC 2021





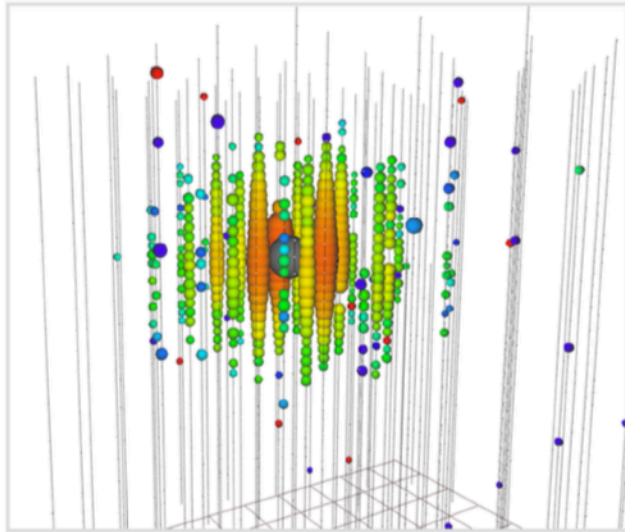
The IceCube Neutrino Observatory

- 5160 PMTs
- 1 km³ volume
- 86 strings
- 17 m vertical spacing
- 125 m string spacing
- Completed 2010
- Fully operational since 2011

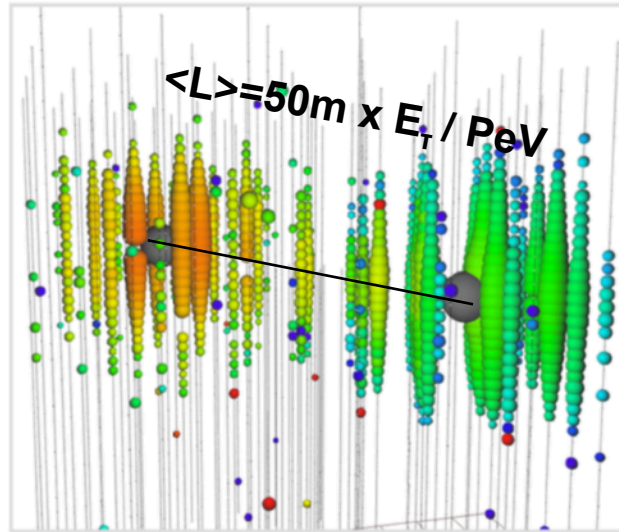


The first decade of discoveries

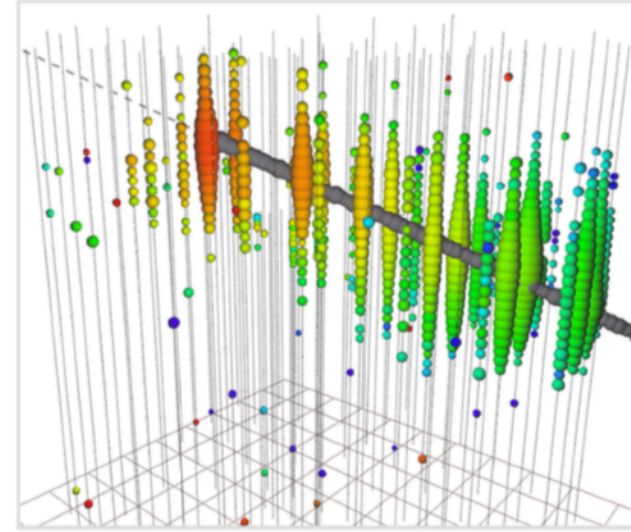
Neutrino Signatures in IceCube



Electron neutrinos:
isolated cascades



Tau neutrinos:
“double bang”

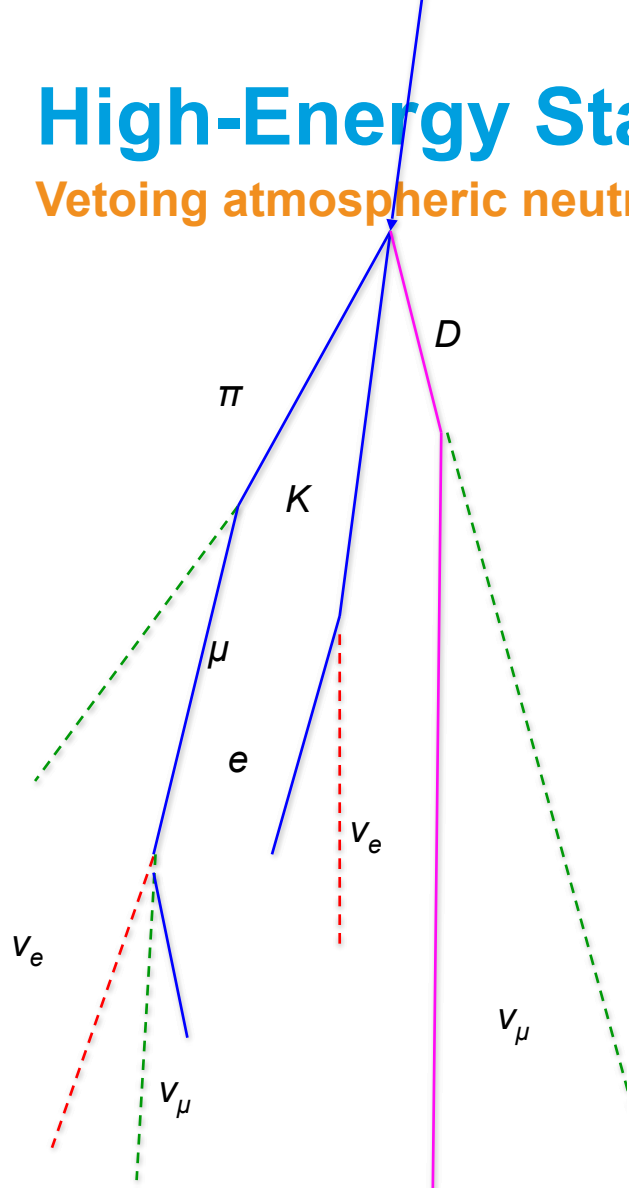


Muon neutrinos:
track-like events

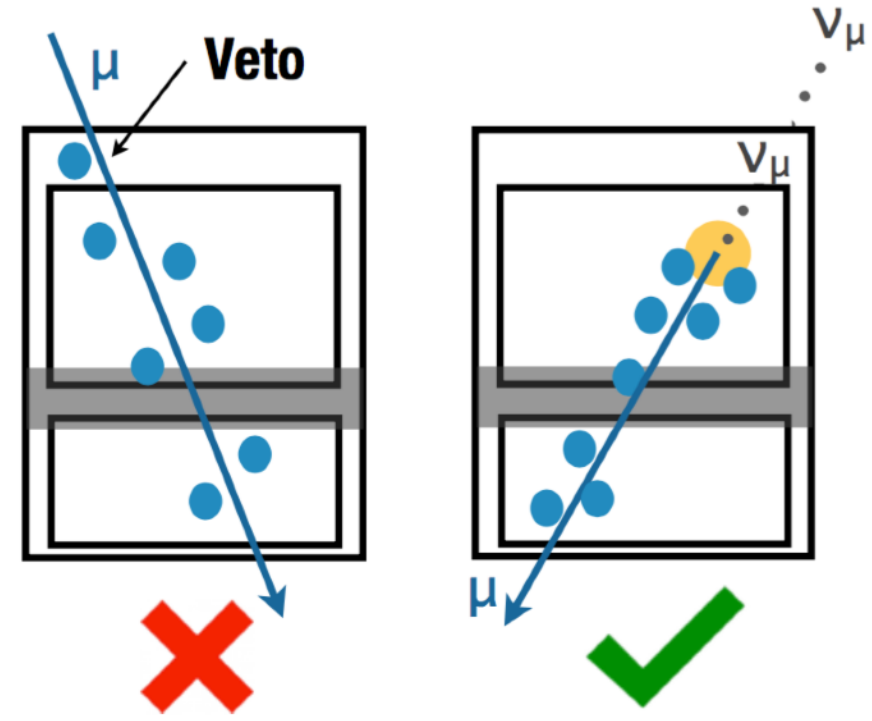


High-Energy Starting Events

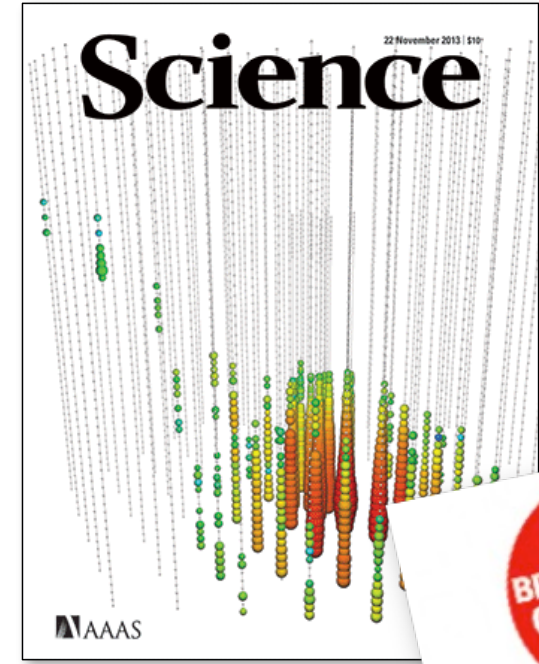
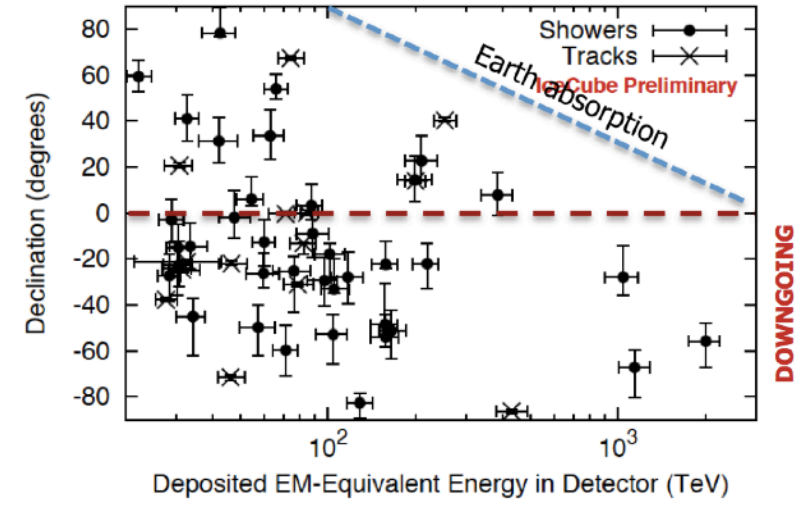
Vetoing atmospheric neutrinos



Veto technique: Schönert et al, 2009
Gaisser et al. 2014



PRL 2014, 3 years of data

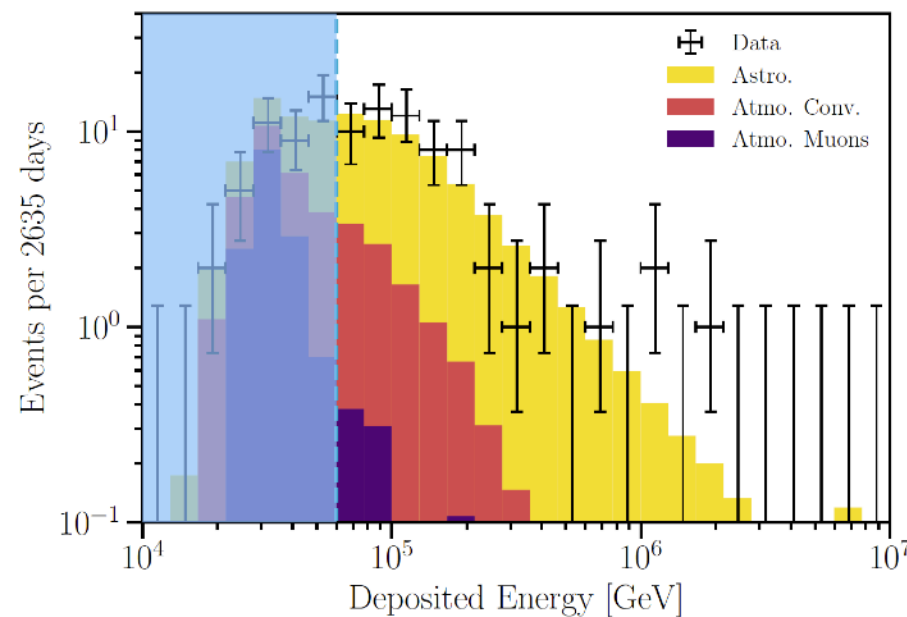
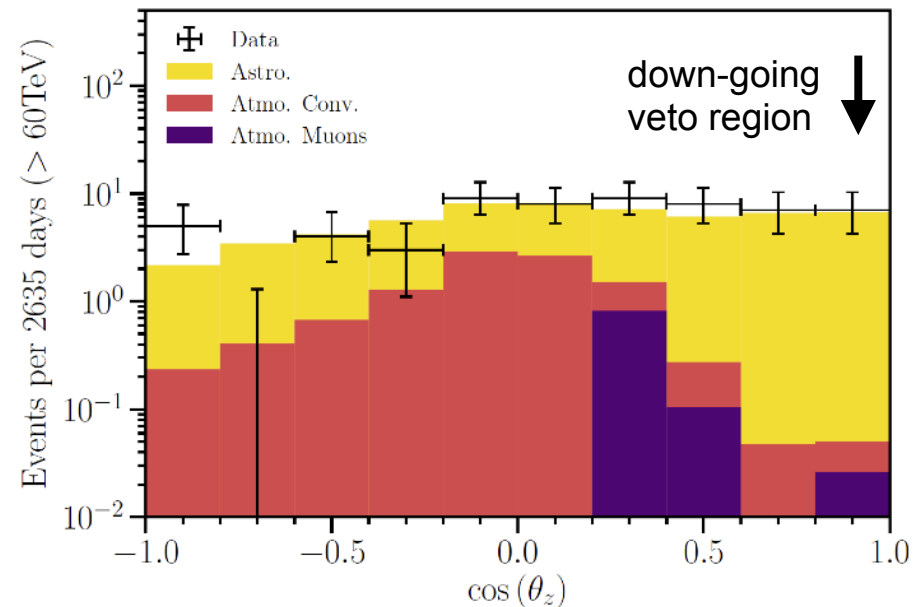
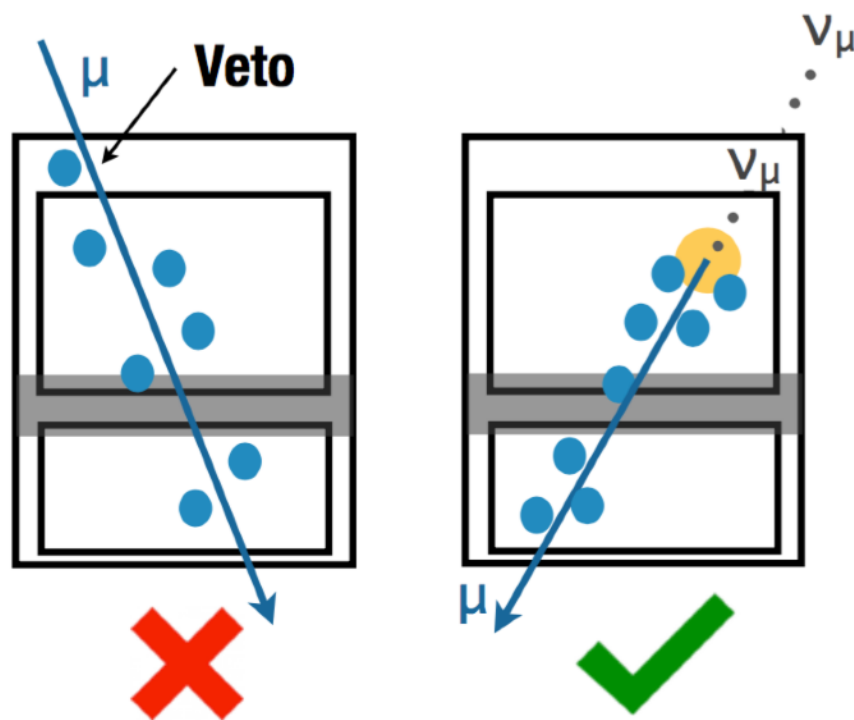
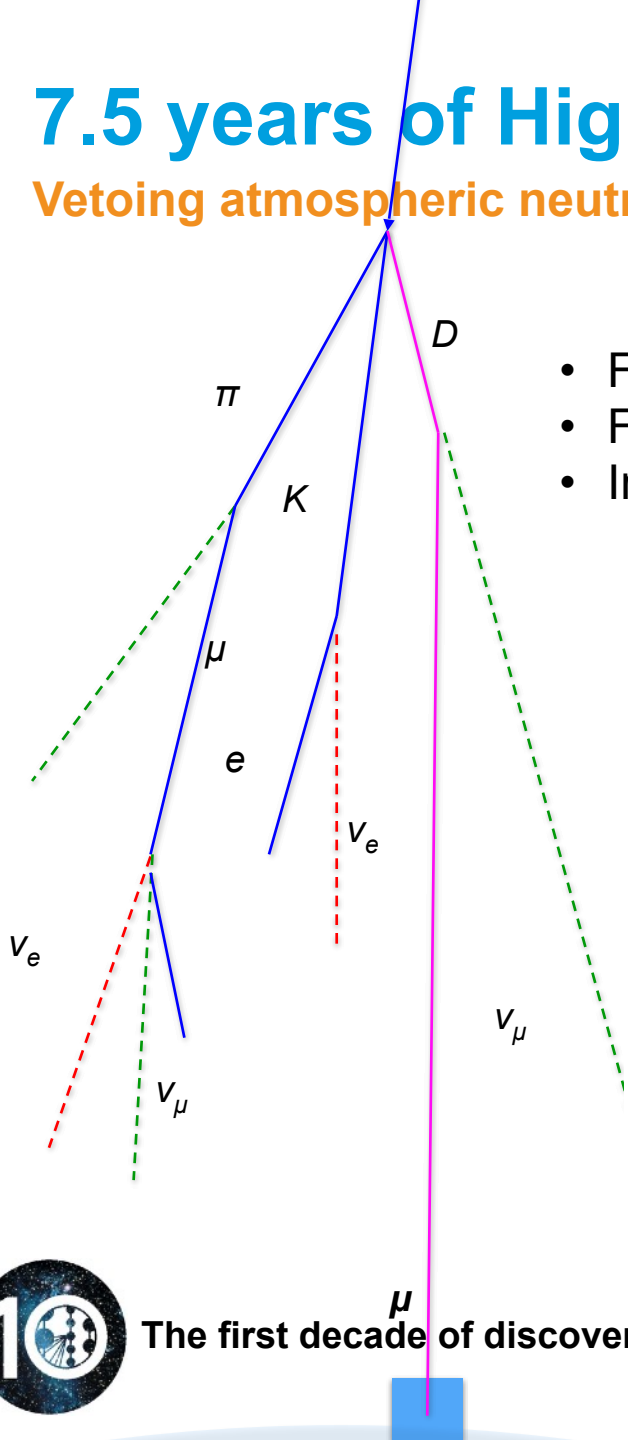


The first decade of discoveries

7.5 years of High-Energy Starting Events

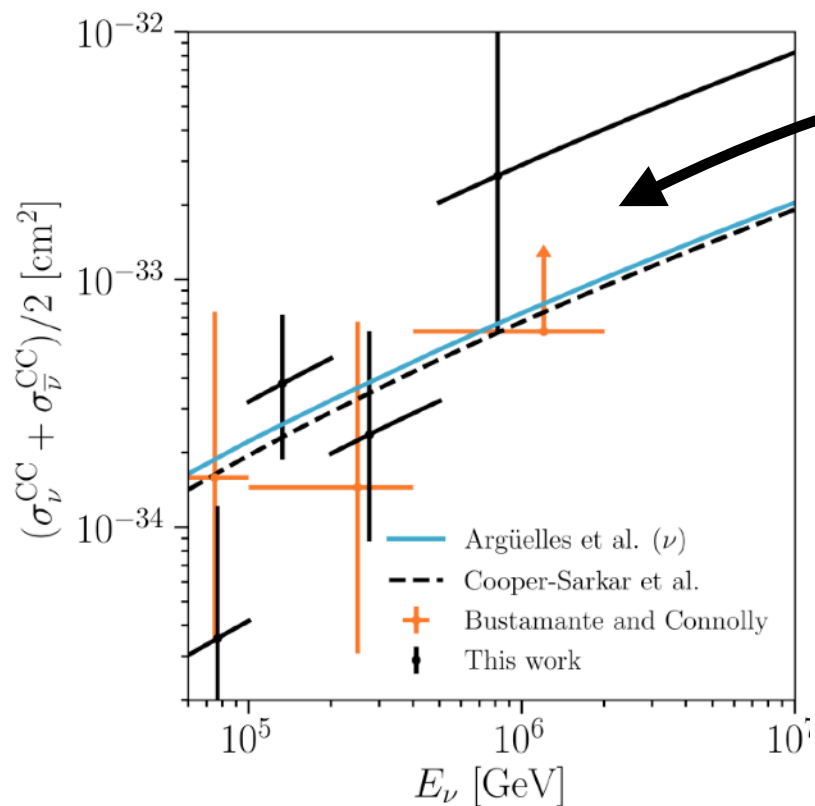
Vetoing atmospheric neutrinos

- From 3 to 7.5 years of data
- From 37 to 102 events
- Improved calibration and systematics



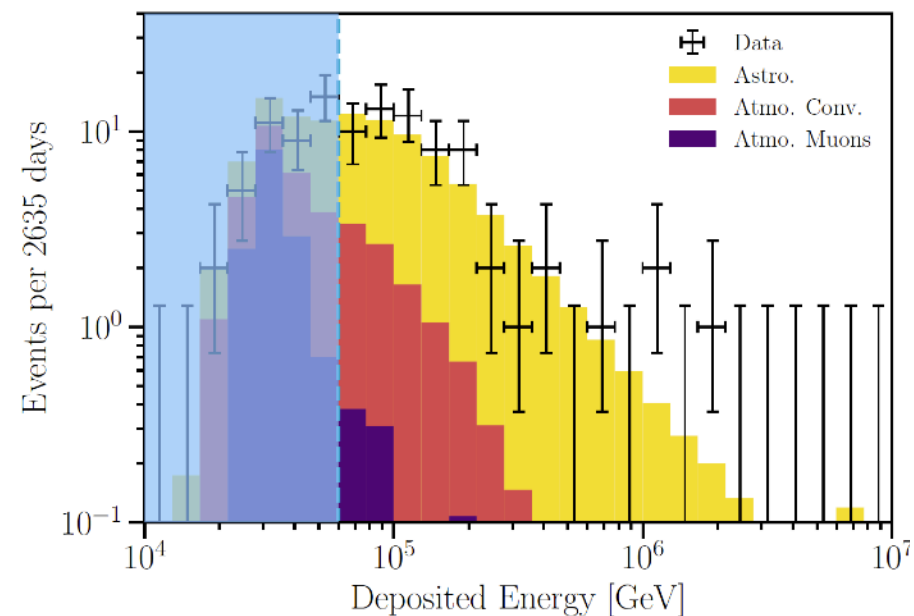
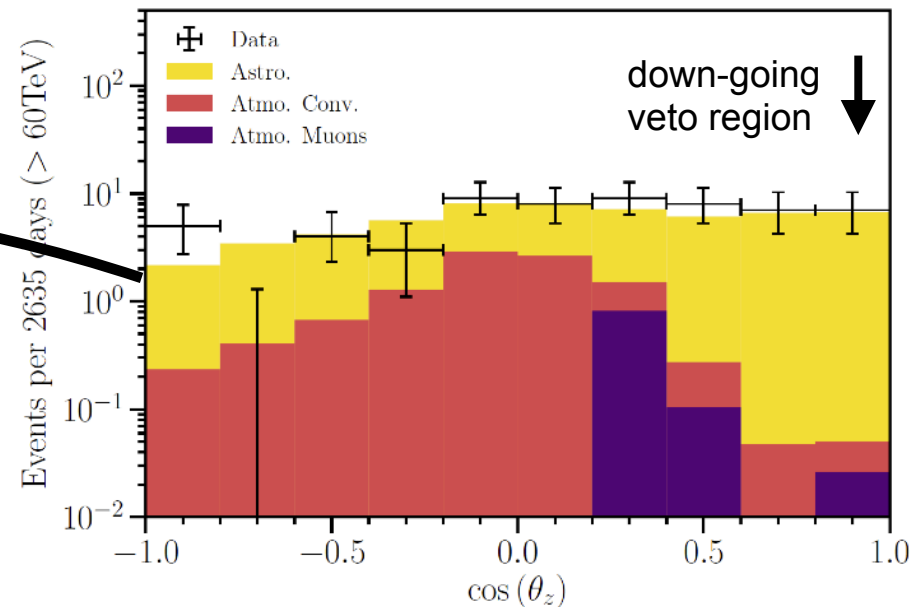
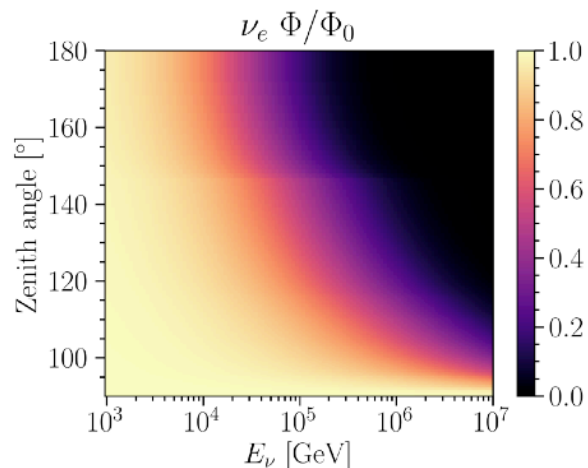
7.5 years of High-Energy Starting Events

Neutrino cross-section measurement



PRD (2021), <https://arxiv.org/abs/2011.03560>

up-going region:
cross-section dependent absorption



PRD (2021), <https://arxiv.org/abs/2011.03545> 8

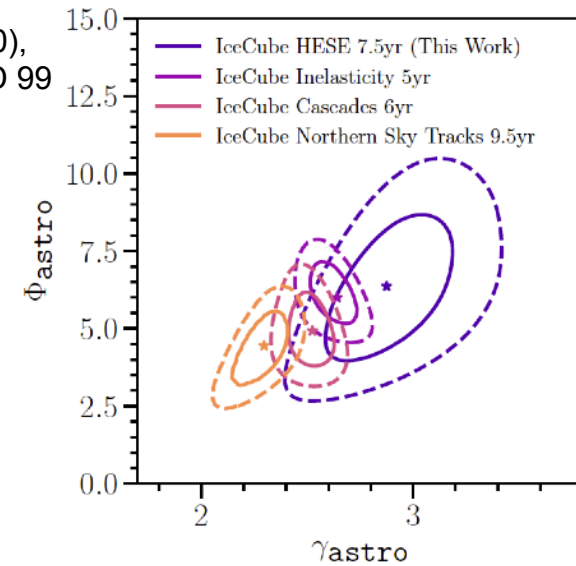
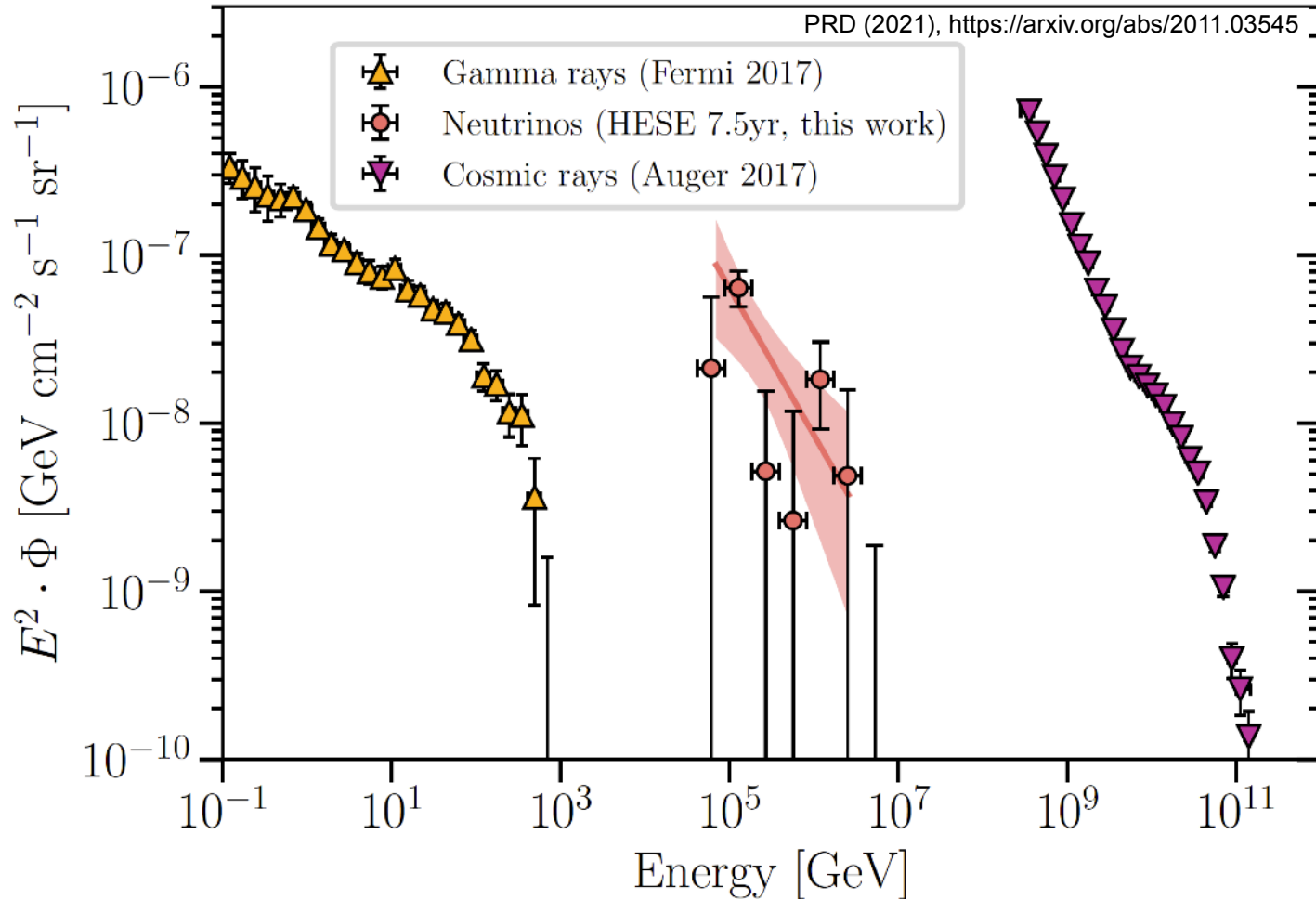


The first decade of discoveries

Multimessenger spectroscopy

with 7.5 years of High-Energy Starting Events

Other channels: Phys.Rev.Lett. 125 (2020),
PoS ICRC2019, 1017 (2020), Phys.Rev.D 99
(2019) 3, 032004



- Spectral index of astro. flux: $\gamma=2.3-2.9$ depends on analysis / energy range
- Similar energies among messengers ...
... but also evidence for different origin!
- Gamma-obscured sources?

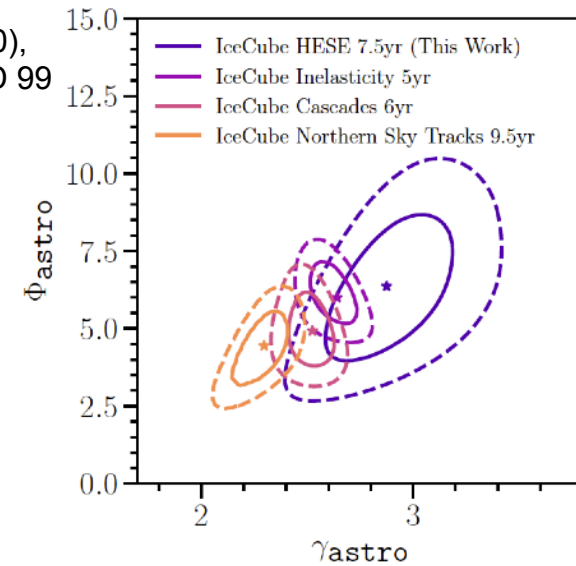
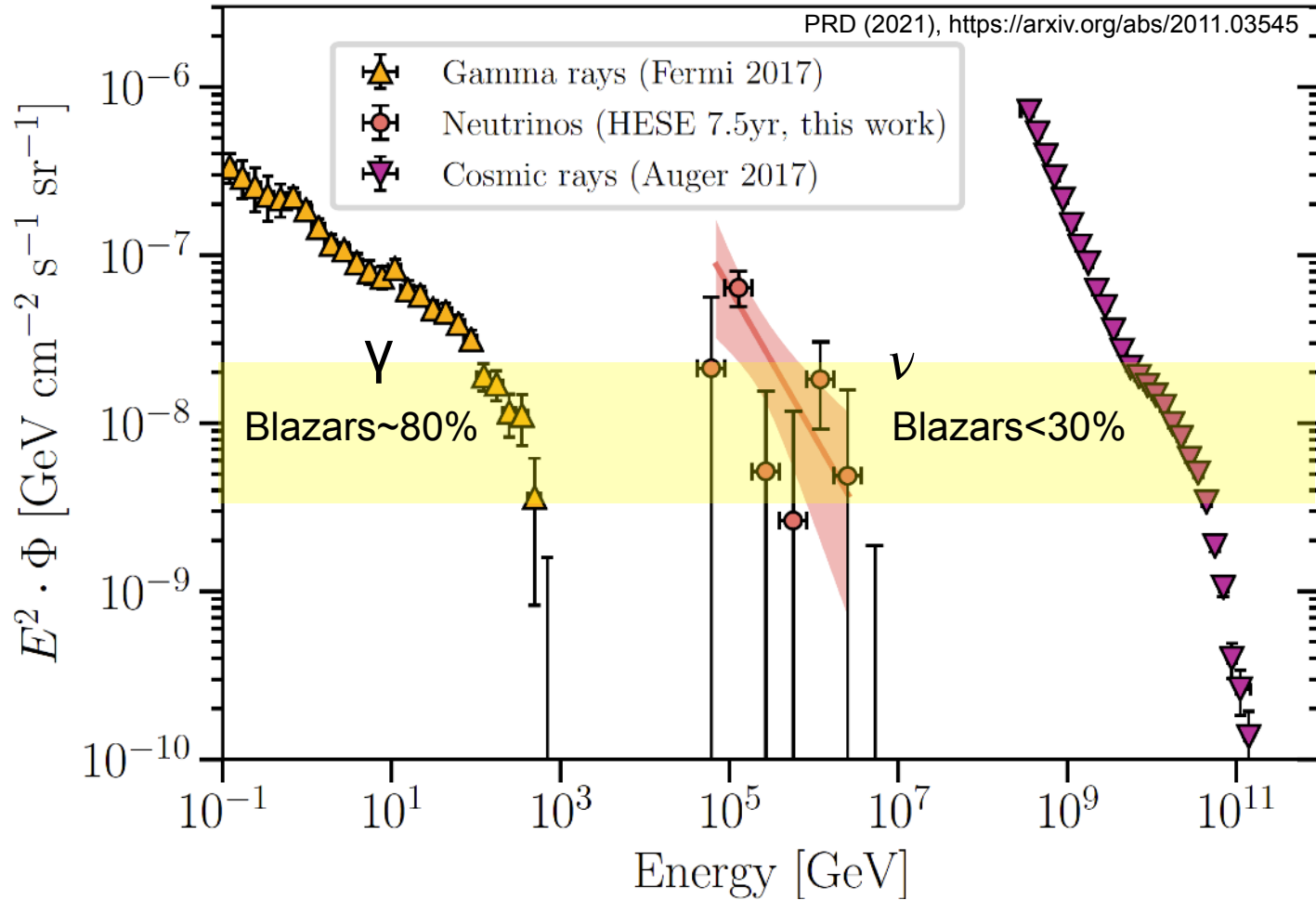


The first decade of discoveries

Multimessenger spectroscopy

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Other channels: Phys.Rev.Lett. 125 (2020),
PoS ICRC2019, 1017 (2020), Phys.Rev.D 99
(2019) 3, 032004



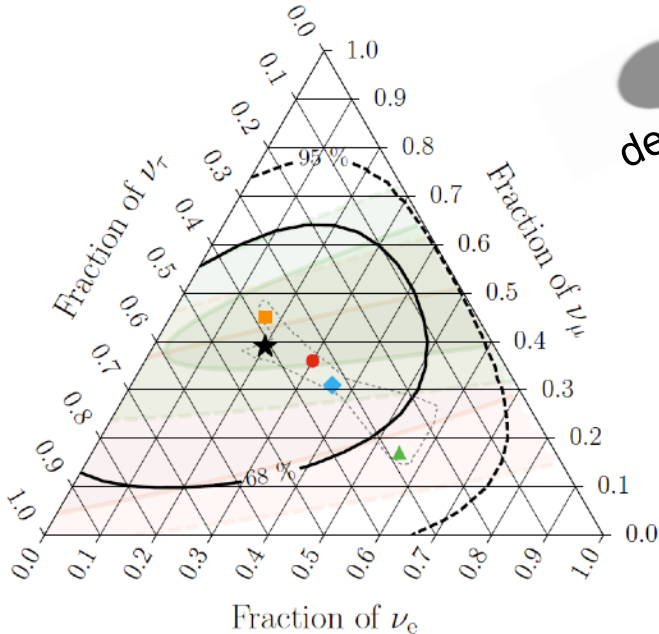
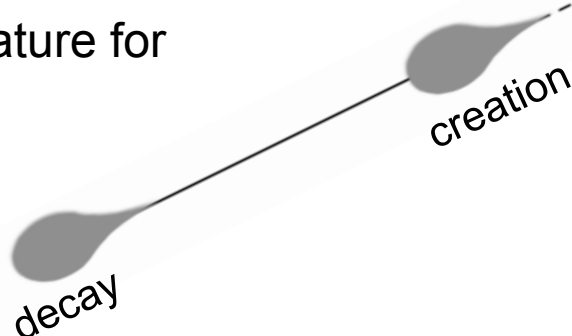
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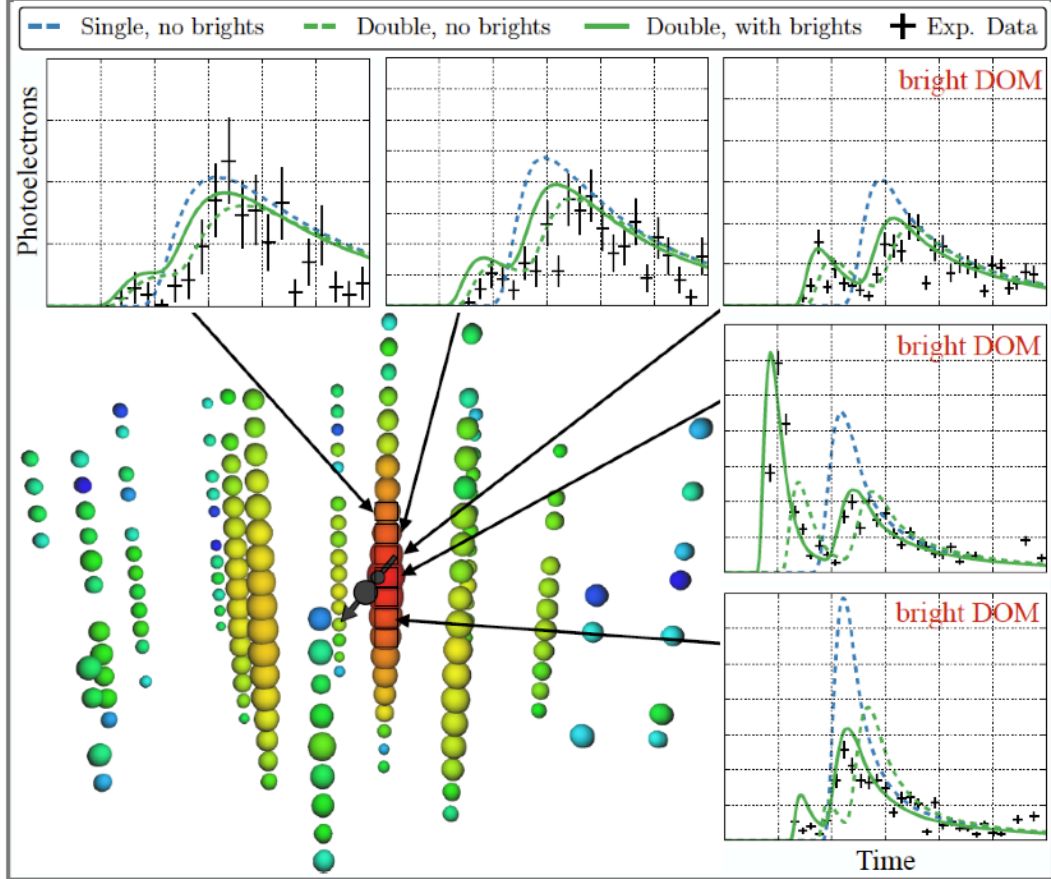
The first decade of discoveries

First cosmic tau-neutrino event(s) candidate in IceCube

- First convincing “Double-Bang” event signature detected by IceCube
- Tau-neutrinos smoking gun signature for astrophysical origin



— HESE with ternary topology ID	$\nu_e : \nu_\mu : \nu_\tau$ at source \rightarrow on Earth:
★ Best fit: 0.20 : 0.39 : 0.42	■ 0:1:0 \rightarrow 0.17 : 0.45 : 0.37
■ Global Fit (IceCube, APJ 2015)	● 1:2:0 \rightarrow 0.30 : 0.36 : 0.34
■ Inelasticity (IceCube, PRD 2019)	▲ 1:0:0 \rightarrow 0.55 : 0.17 : 0.28
⋯ 3 ν -mixing 3 σ allowed region	◆ 1:1:0 \rightarrow 0.36 : 0.31 : 0.33

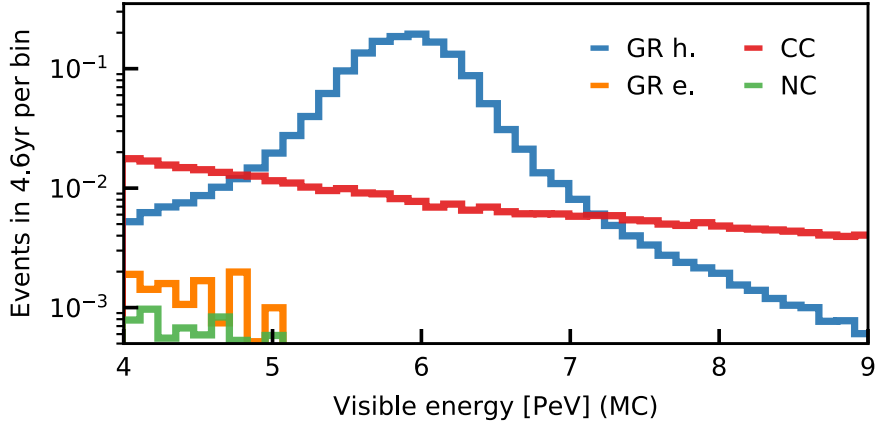
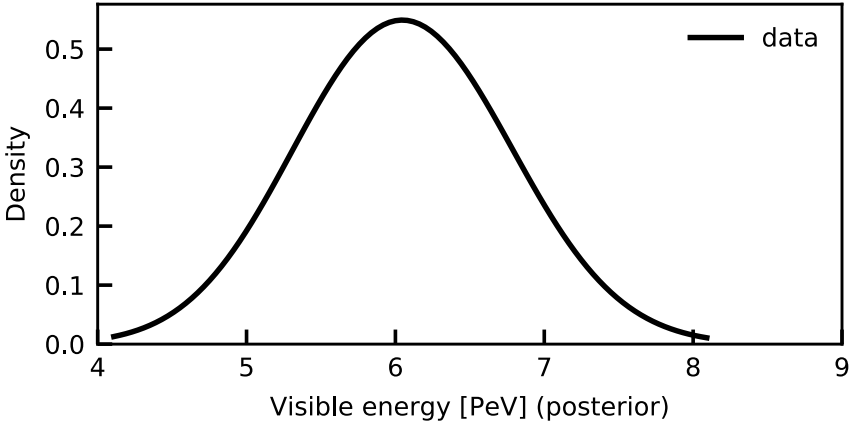
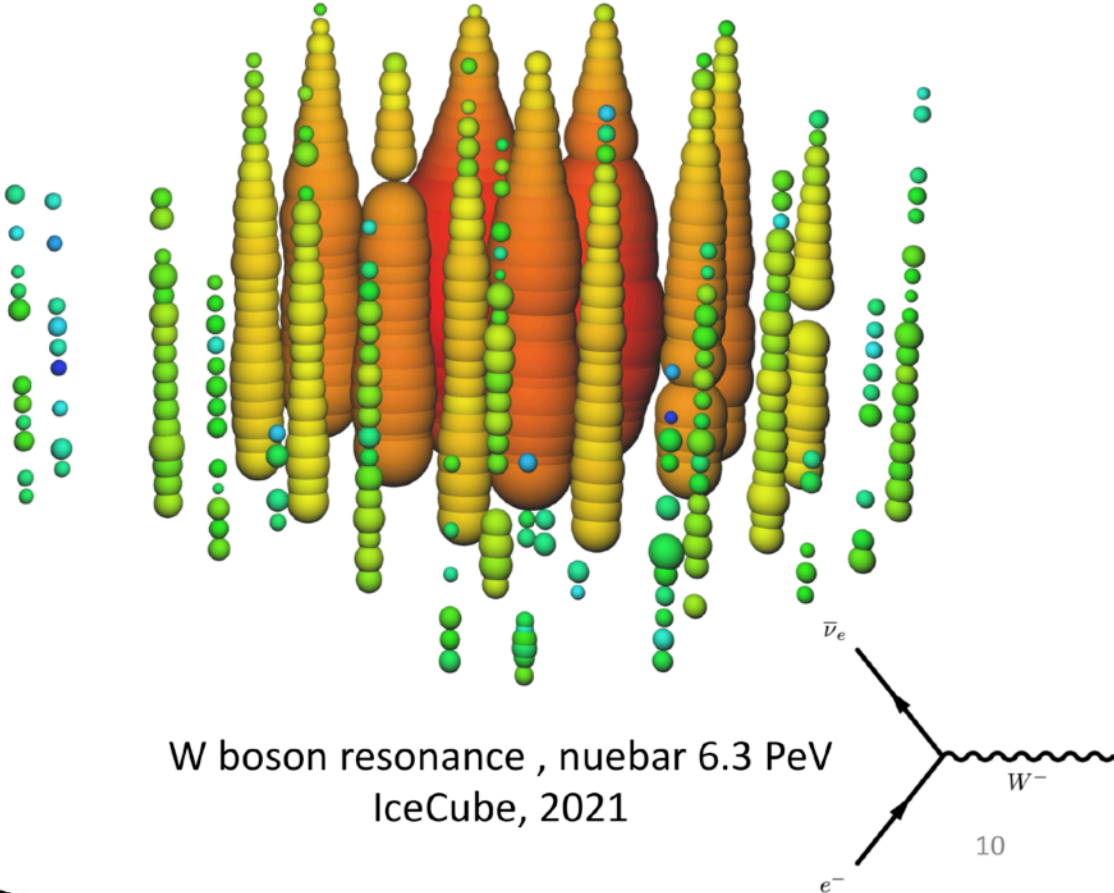


<https://arxiv.org/abs/2011.03561>
 Also @ ICRC 2021: PoS ID 1146

First hint of electron anti-neutrino

W boson (Glashow) resonance

Nature 591, 220–224 (2021)

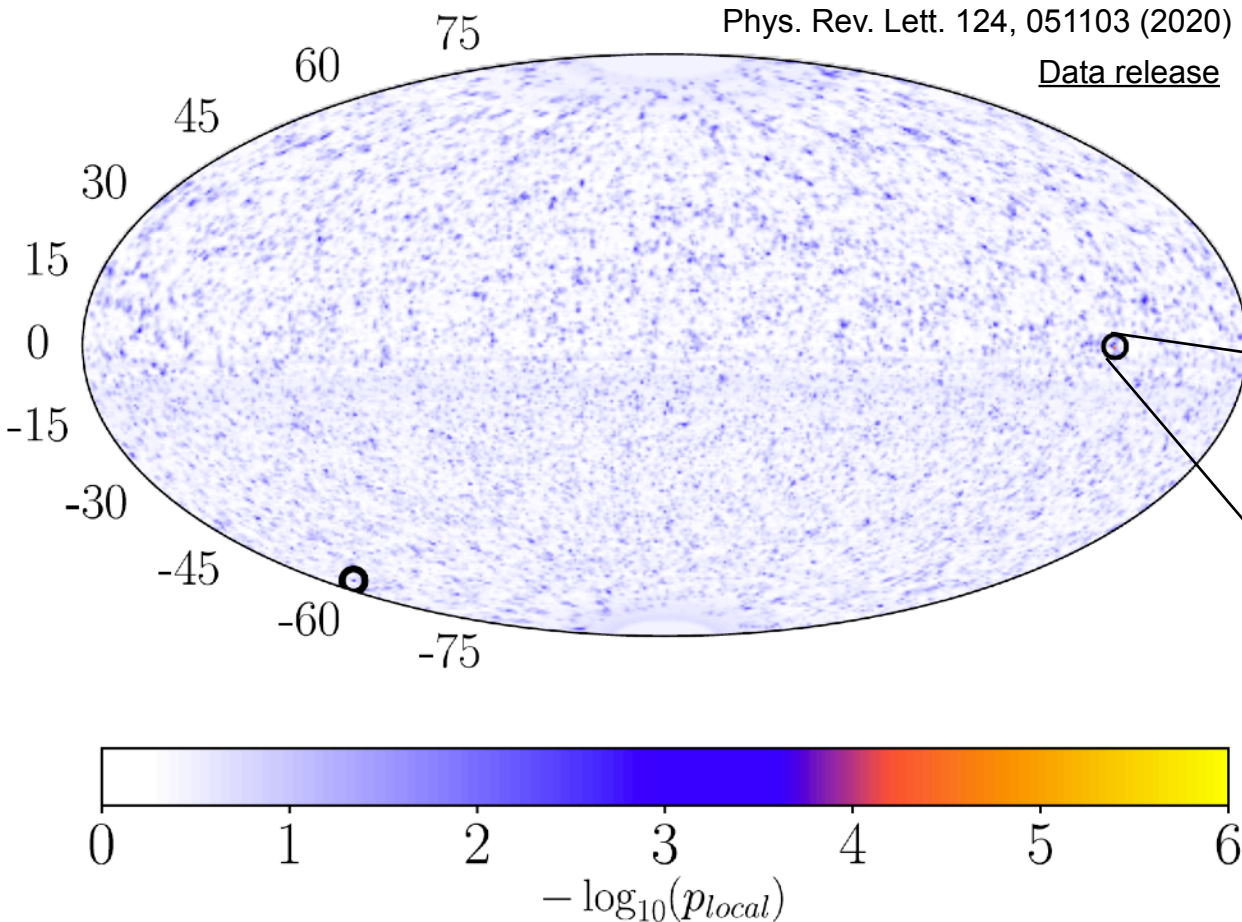


The first decade of discoveries

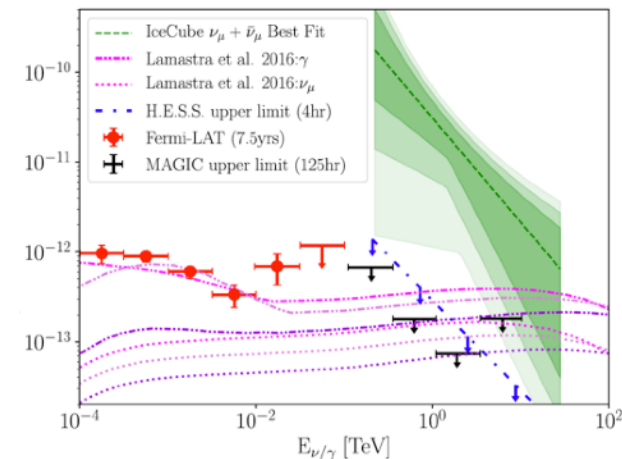
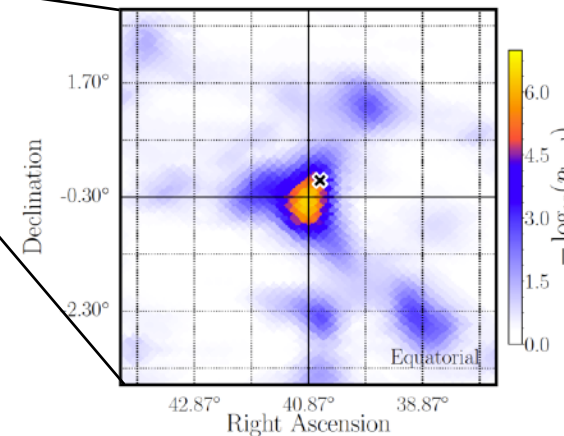
Time-integrated point source searches with 10 years of data

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

Data release



Most significant excess:
NGC1068 @ 2.9 sigma



Improved point source analysis on the way
(PoS ID 1138, 1073)

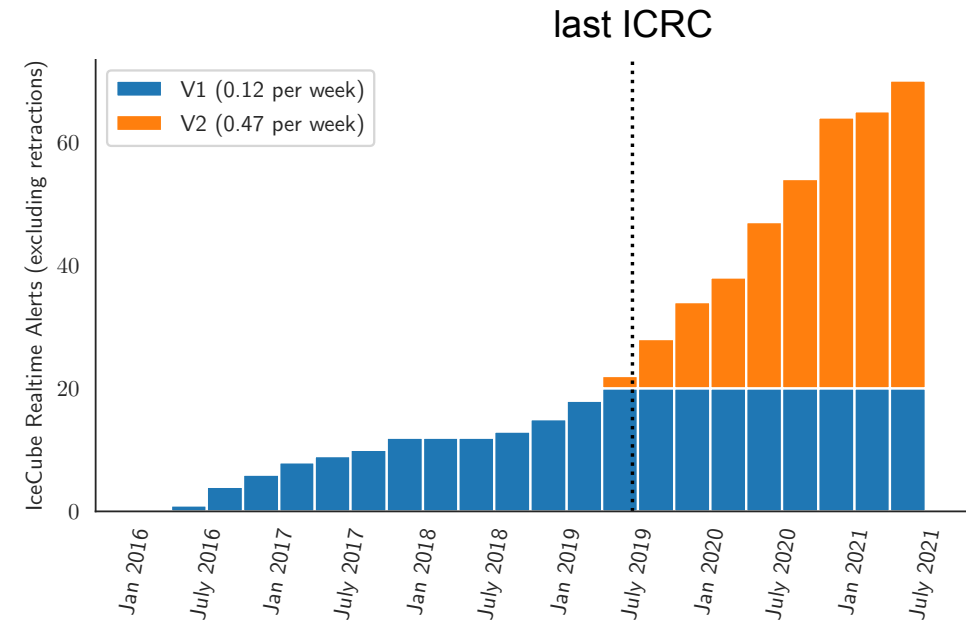
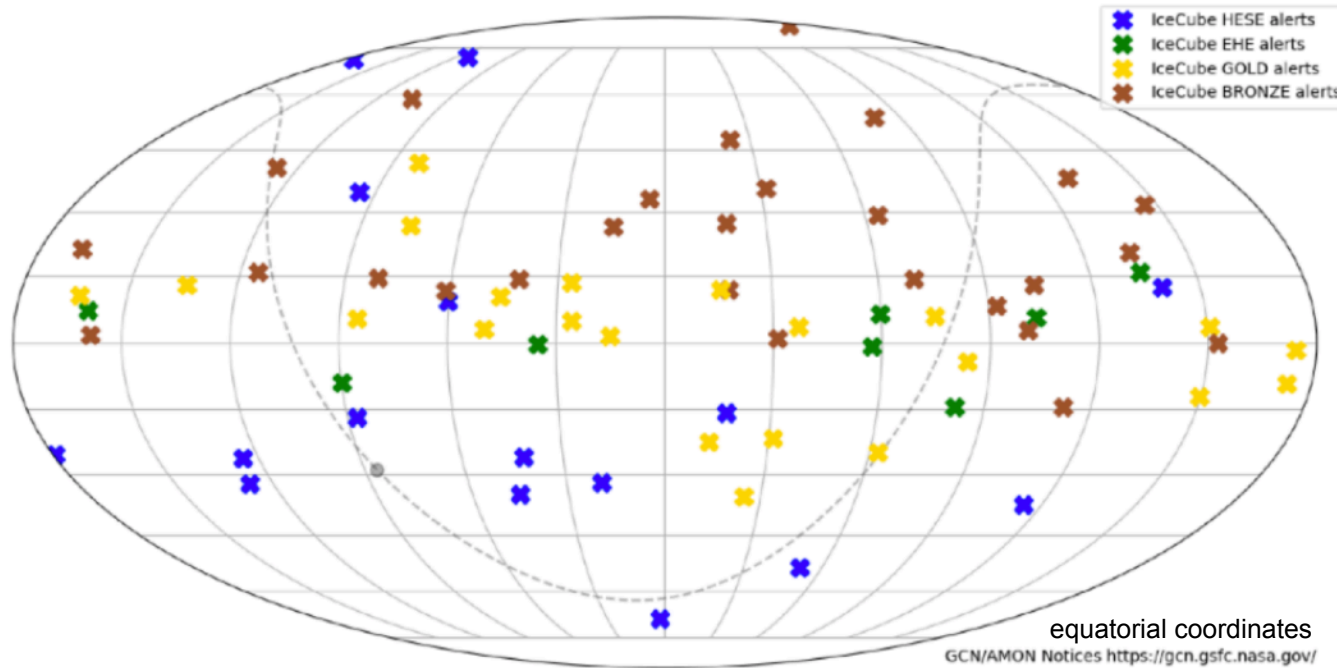
[Searches for other sources: SNe (PoS ID 1116), GRBs (PoS ID 1118), Ultra Luminous IR galaxies (PoS ID 1115), Radio AGNs (PoS ID 949), X-ray AGNs (PoS ID 1142), Galaxy Clusters (PoS ID 1133), X-ray binaries (PoS ID 1136), Magnetars (PoS ID 1135), GW sources (PoS ID 950)]



The first decade of discoveries

Realtime high-energy neutrino alerts

Public alert stream running since April 2016, >80 alerts so far



[K. Satalecka et al., ICRC2021 (PoS ID 1138), other realtime activities: PoS ID 1045, 952]

V1: HESE/EHE stream [Astropart. Phys., 92, 30 (2017)]

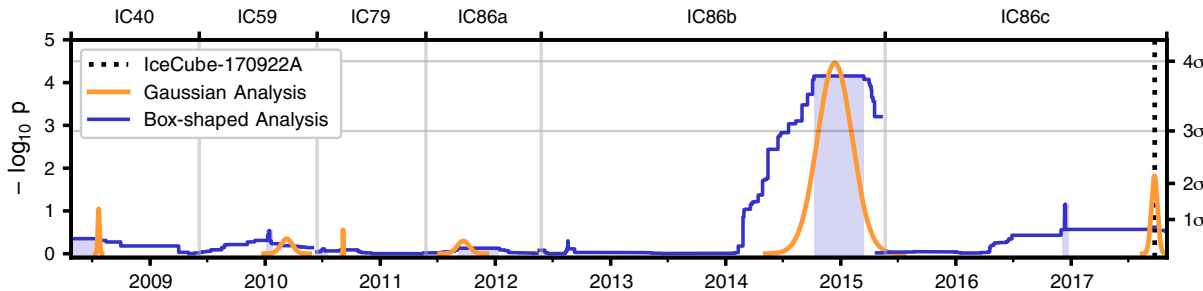
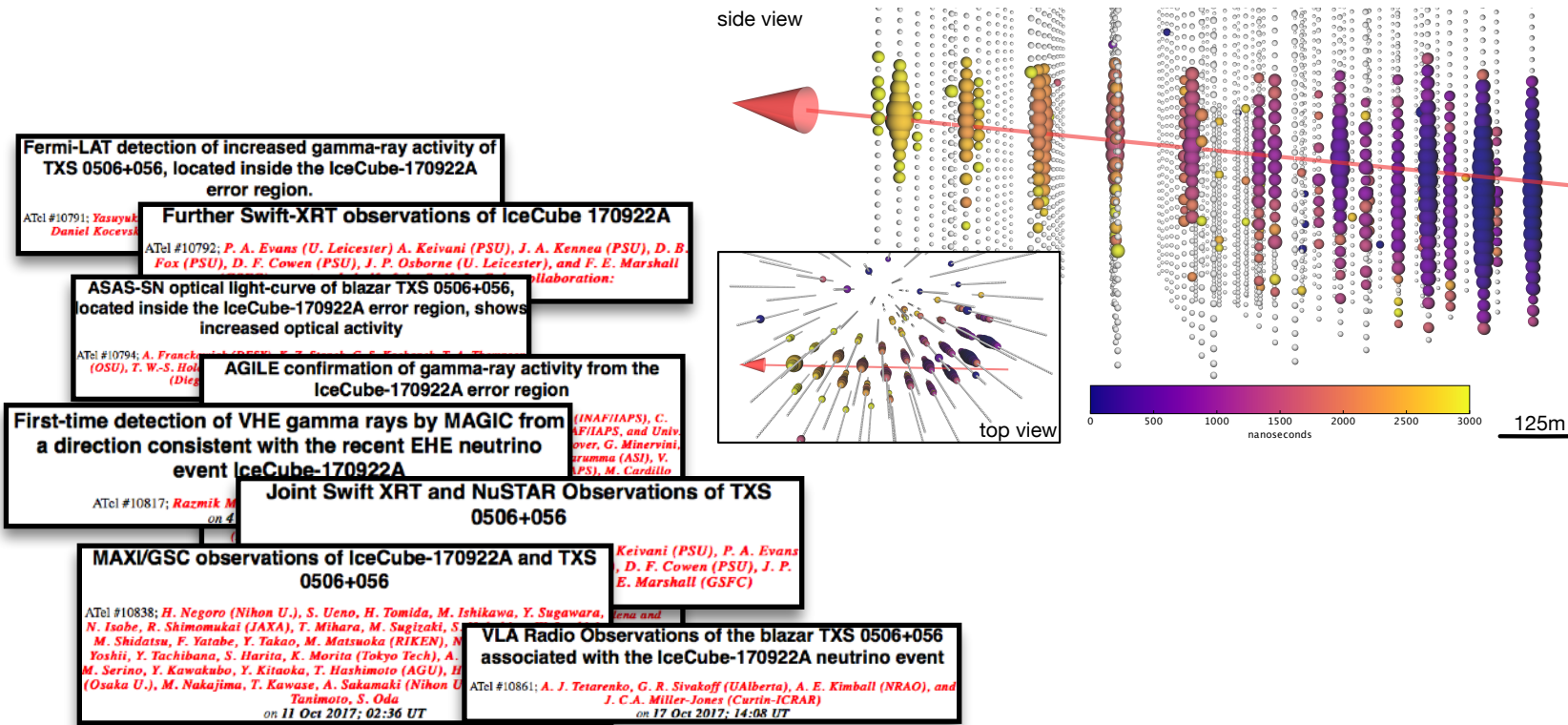
V2: Improved and unified stream with Gold/Bronze classification
($> 0.5/0.3$ probability for astro. origin) [PoS-ICRC2019-1021]



The first decade of discoveries

TXS 0506+056 - first neutrino point source

A flaring Blazar in spacial and temporal coincidence with IC170922A

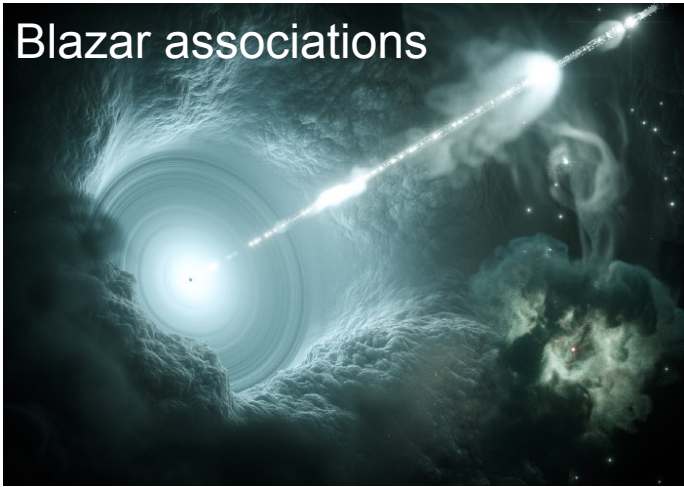


Archival analysis: Inconsistent with bkg-only at 3.5σ
 (In addition of the 3σ flaring Blazar coincidence)

Science 361 (2018) no.6398, 147-151

Realtime high-energy neutrino alerts

Other selected follow-up observations

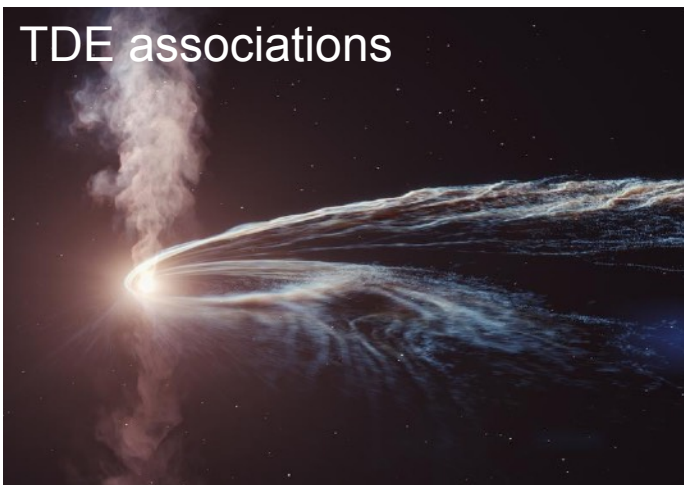


IC190730A → PKS 1502+106

15th brightest GeV Blazar, with strong radio flare [e.g. Britzen et al, Plavin et al, Rodriguez et al]

IC 200107A → BZB / 3 HSP J0955+3551

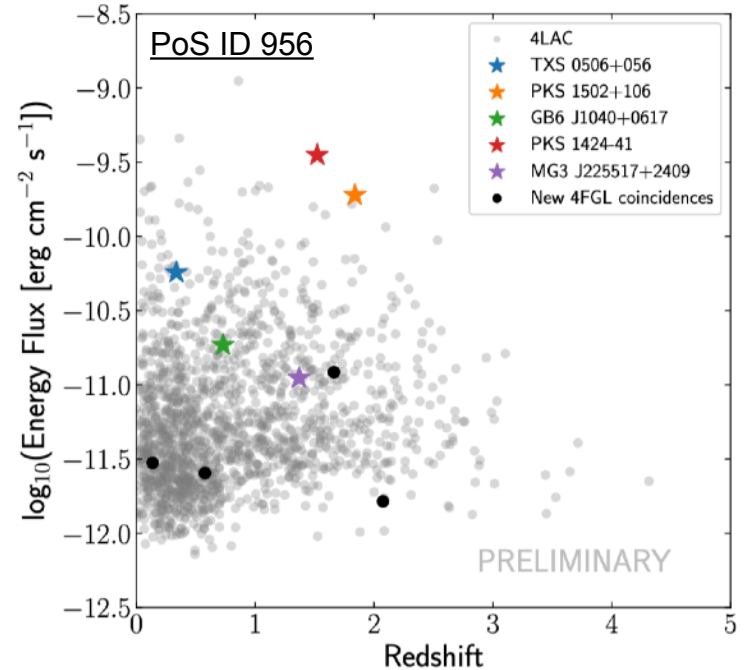
strong X-ray flare [e.g. Giommi et al, Paliya et al, Petropoulou et al]



IC191001A → AT2019dsg

Bright TDE with evidence for outflows from radio observations [Stein et al]

We need more cosmic neutrinos!



Neutrino astronomy with single neutrino associations:

- Single neutrinos probe the full Universe, limited by follow-up capacities and source confusion.
- p-value $\geq 10^{-3}$ for long duration counterparts.
- # found sources \propto # neutrinos.

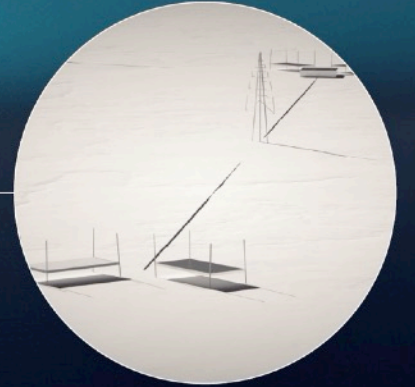


The first decade of discoveries

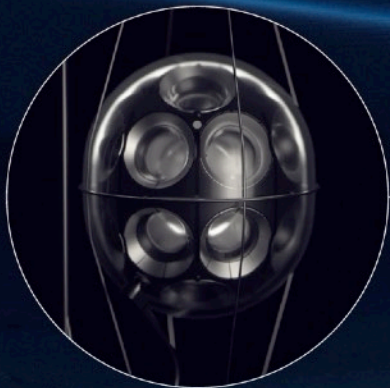
ICECUBE GEN2



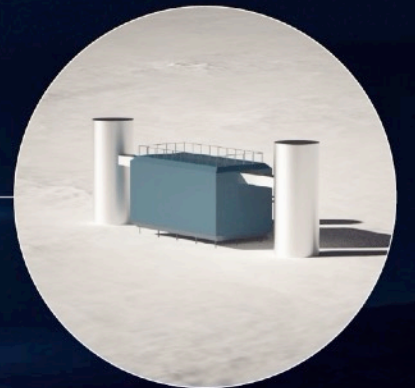
Radio Array | Station



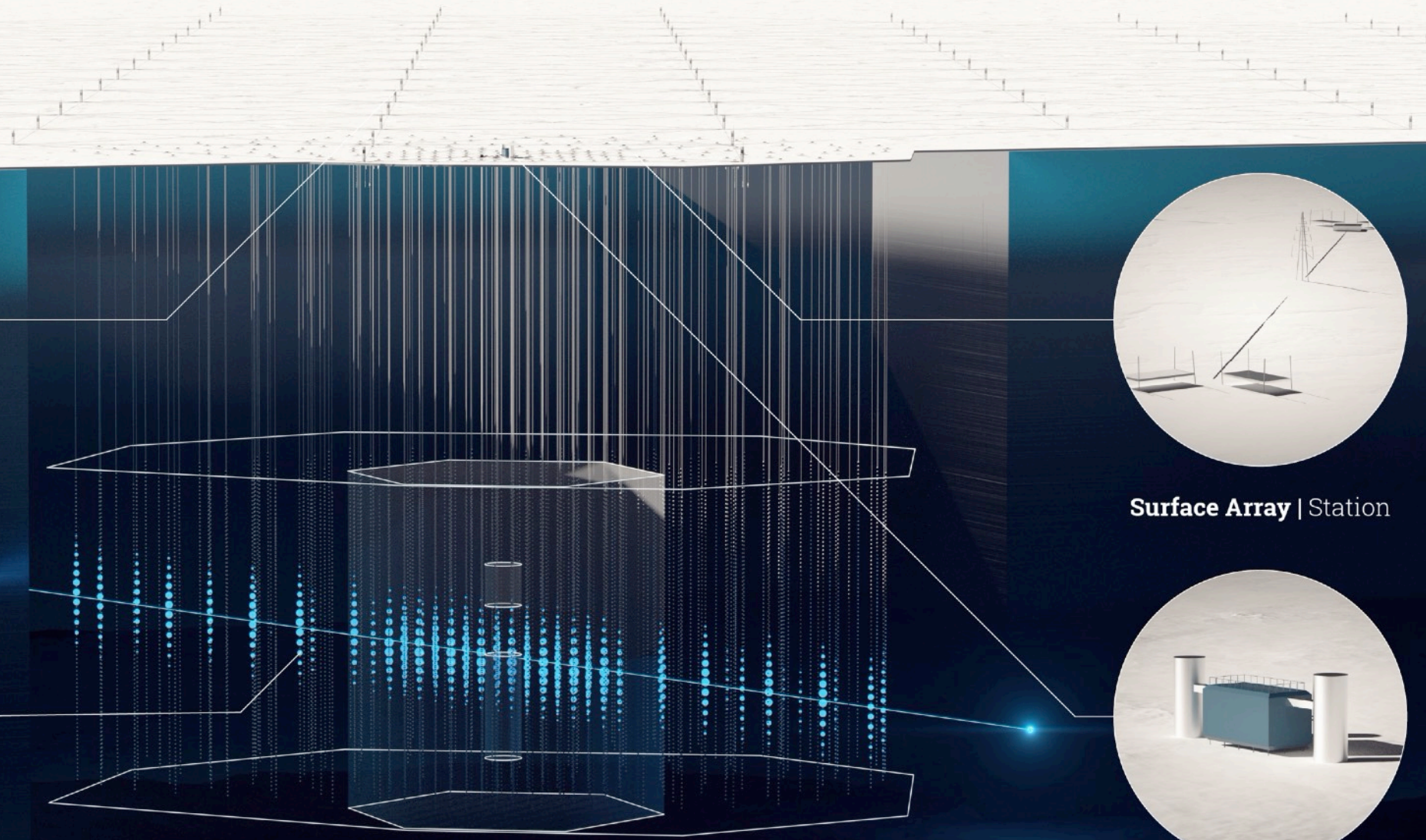
Surface Array | Station



Optical Array | Sensor

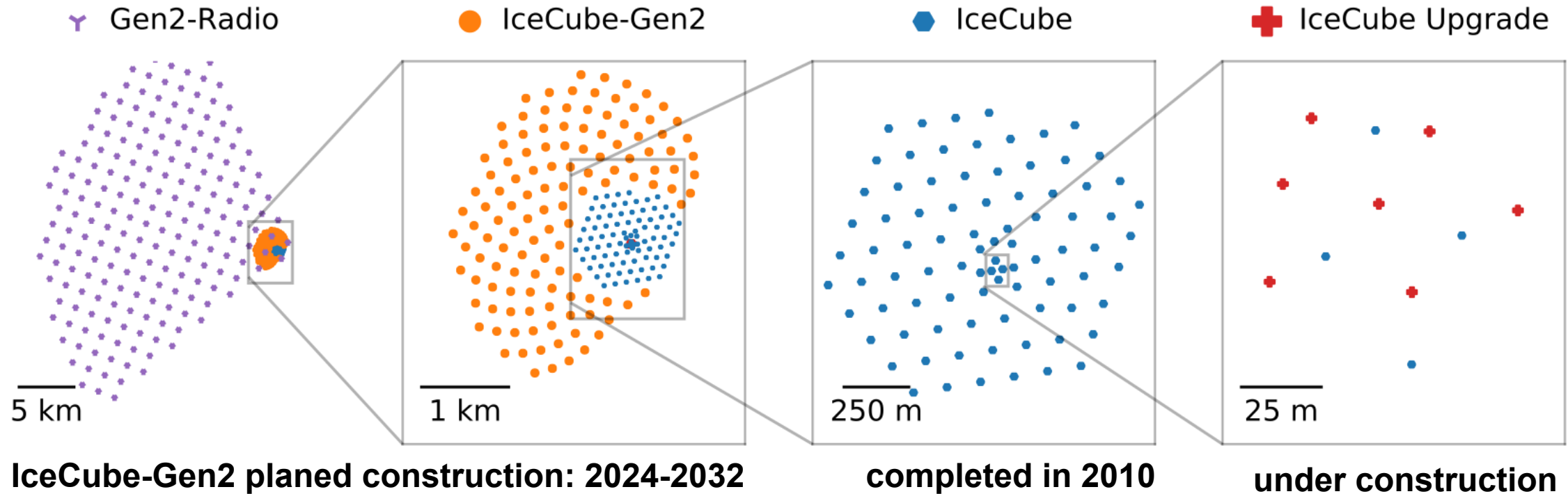


IceCube | Laboratory



The IceCube Gen2 facility at the South Pole

Wide-band observatory: Optimizing scales for leading sensitivity from 10^9 to 10^{20} eV



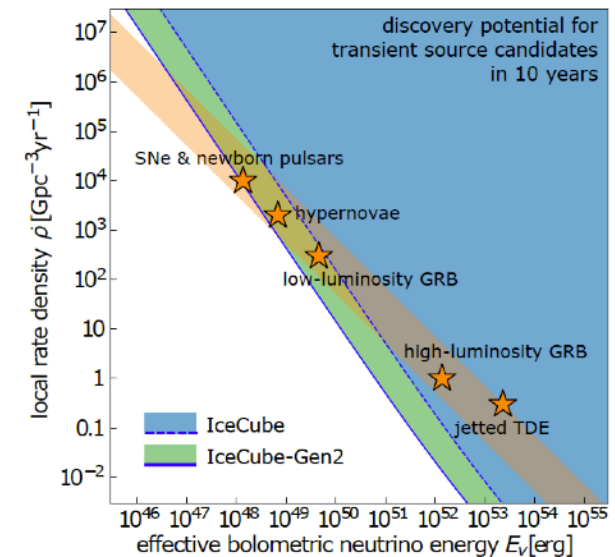
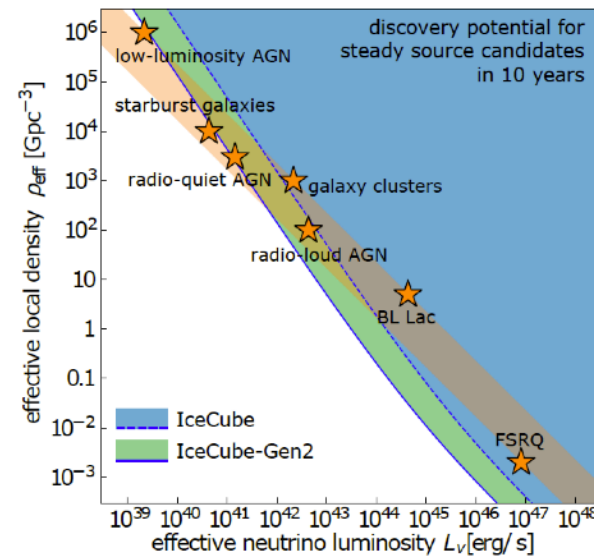
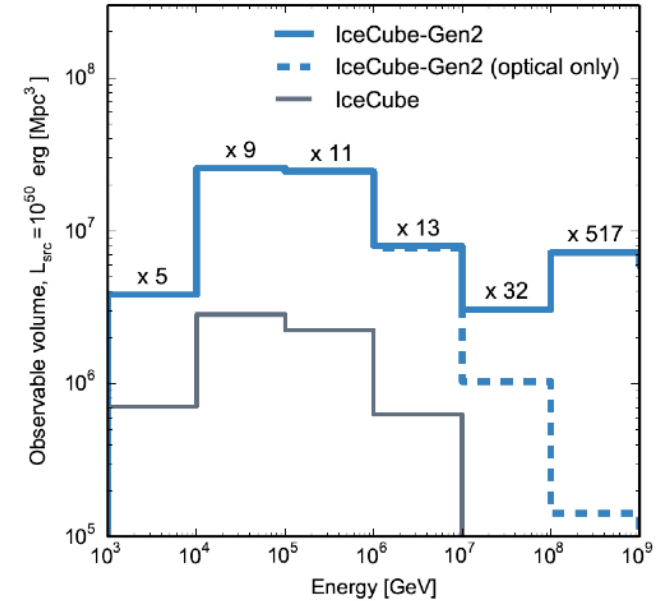
[Gen2 white paper: 2008.04323](#)

Scientific objectives for IceCube-Gen2

Questions emerging after 10 years of IceCube operations

1. Resolving the high-energy sky from TeV to EeV energies
2. Understanding cosmic particle acceleration through multimessenger observations
3. Revealing the sources and propagation of the highest energy particles in the universe
4. Probing fundamental physics with high-energy neutrinos

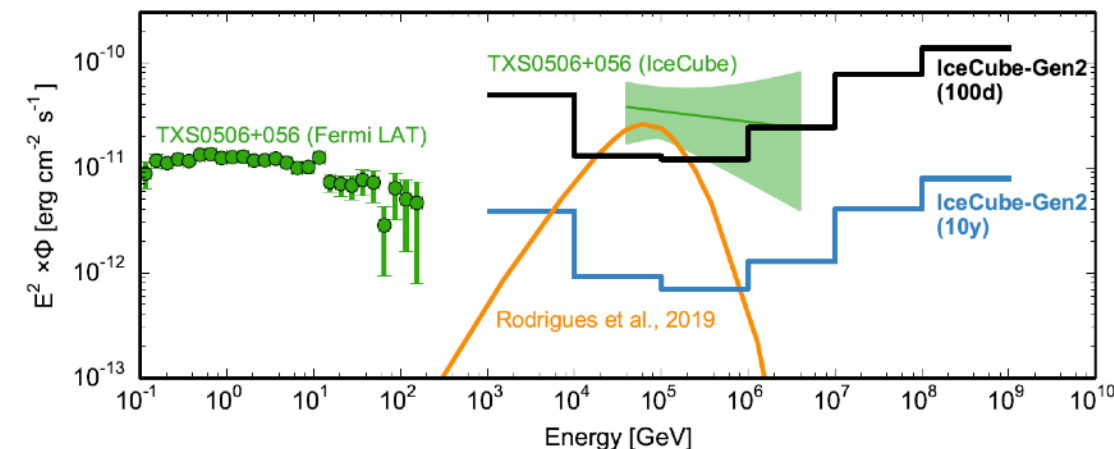
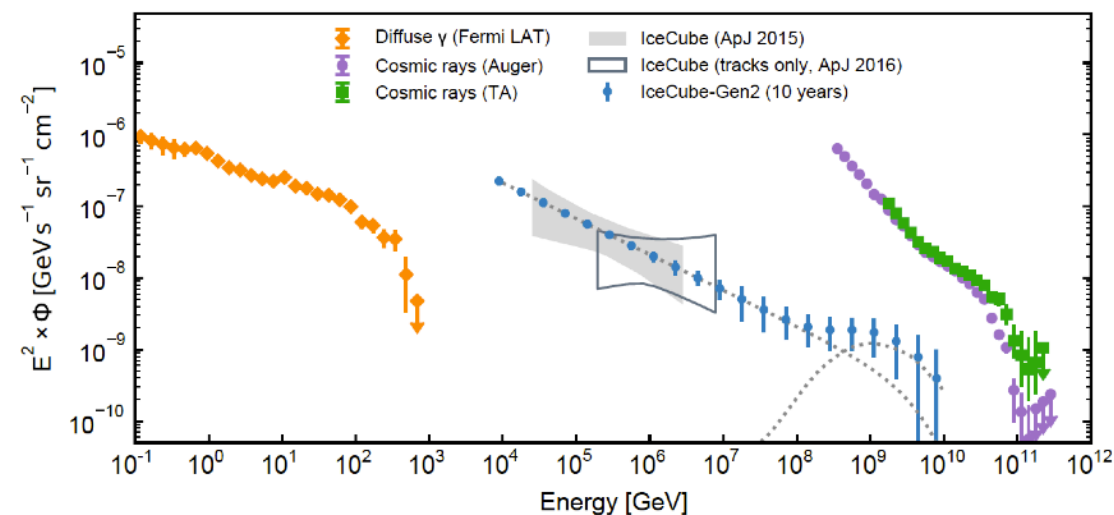
~10 x the number of sources



Scientific objectives for IceCube-Gen2

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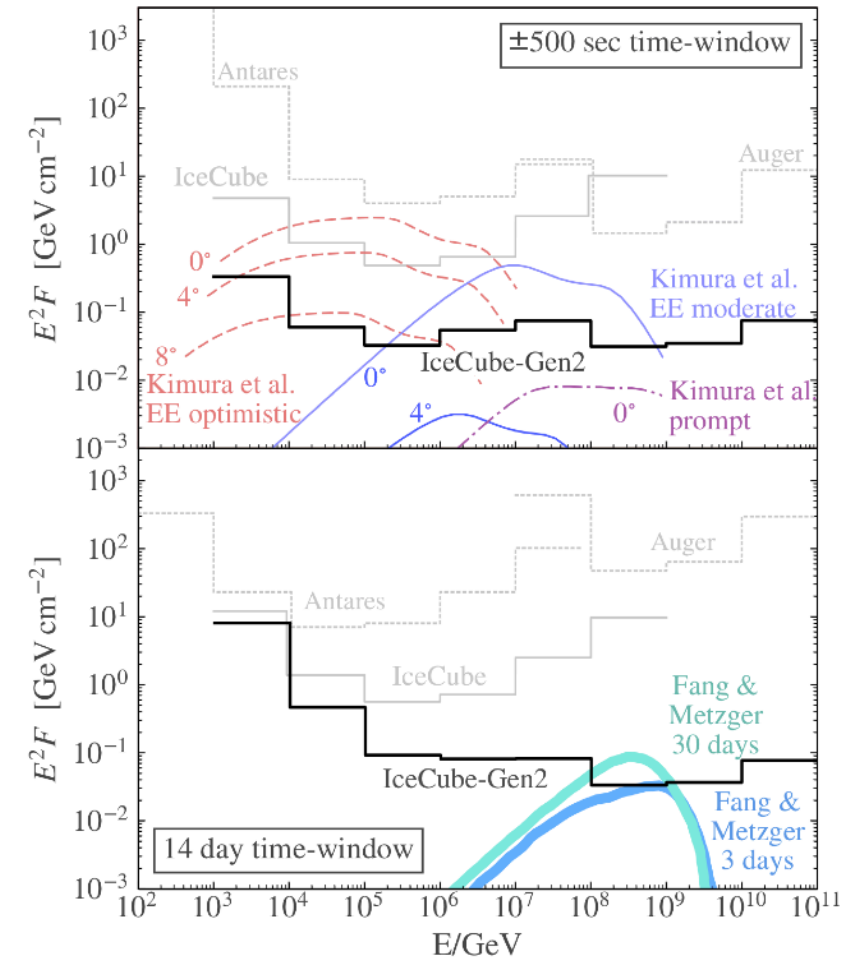


Scientific objectives for IceCube-Gen2

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Neutrinos from Kilonovae / GW sources

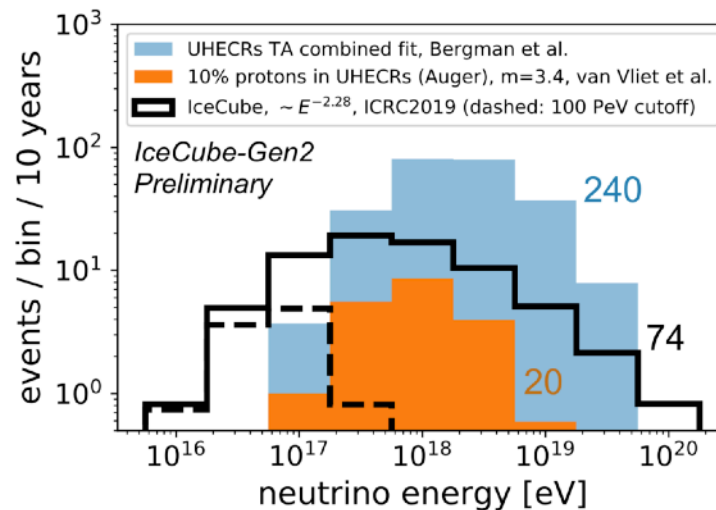


Sufficient sensitivity to test models for neutrino production in BNS mergers, observed in coincidence with next-generation GW detectors

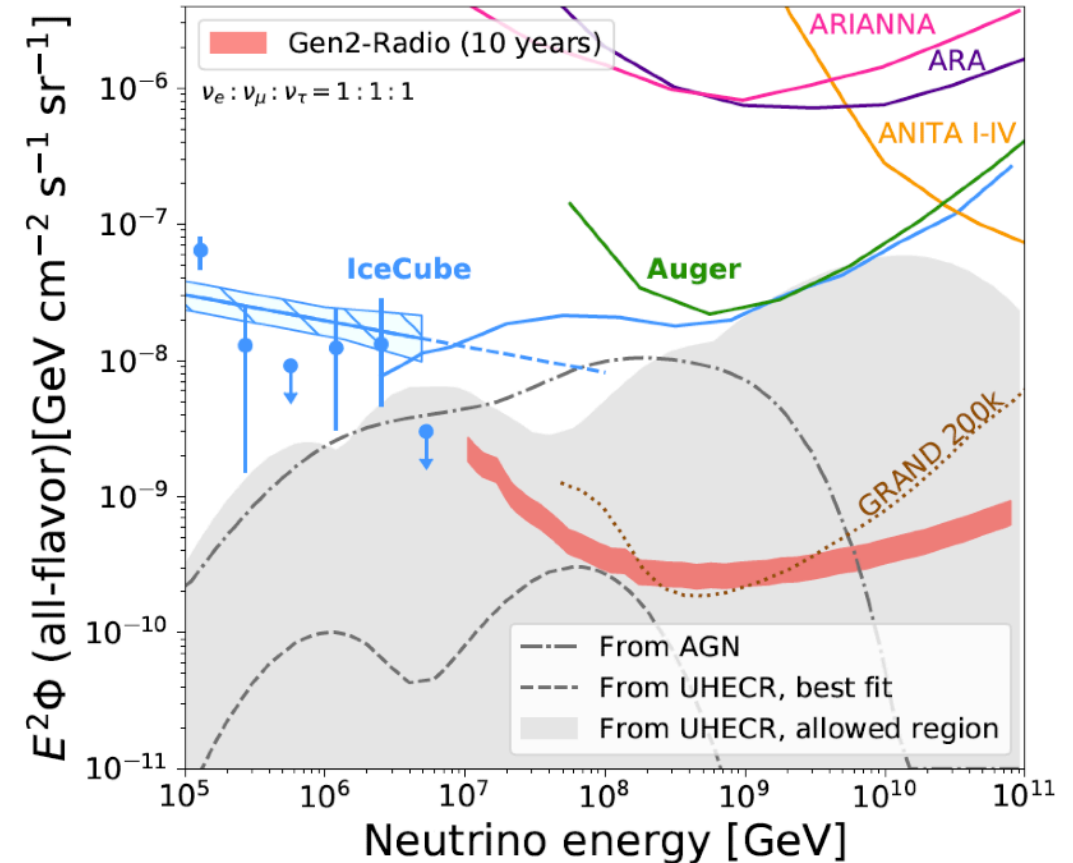
Scientific objectives for IceCube-Gen2

Questions emerging after 10 years of IceCube operations

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2. Understanding cosmic particle acceleration through multi-messenger observations
3. **Revealing the sources and propagation of the highest energy particles in the universe**
4. Probing fundamental physics with high-energy neutrinos



The EHE window: GZK and neutrino sources



Left: event rates for Gen2-Radio (see [presentation](#) by Hallmann)

Scientific objectives for IceCube-Gen2

Questions emerging after 10 years of IceCube operations

1. Resolving the high-energy sky from TeV to EeV energies
2. Understanding cosmic particle acceleration through multimessenger observations
3. **Revealing the sources and propagation of the highest energy particles in the universe**
4. Probing fundamental physics with high-energy neutrinos

Understanding CR gal.-extragal. transition

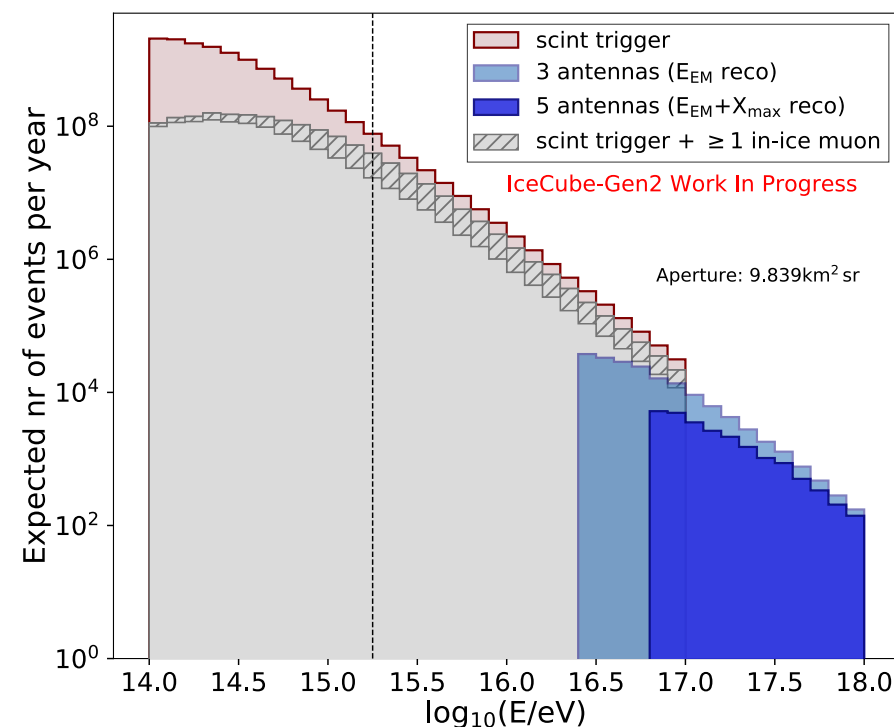
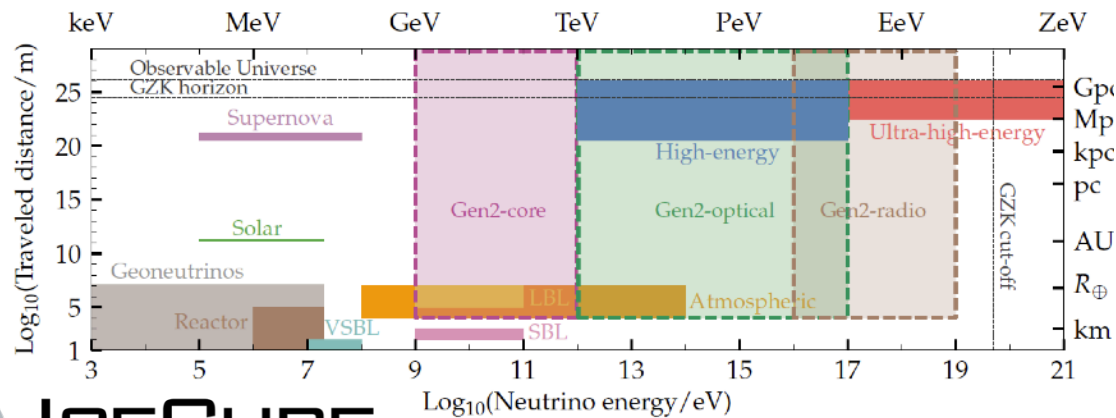


Figure: Event rate of cosmic-ray air showers

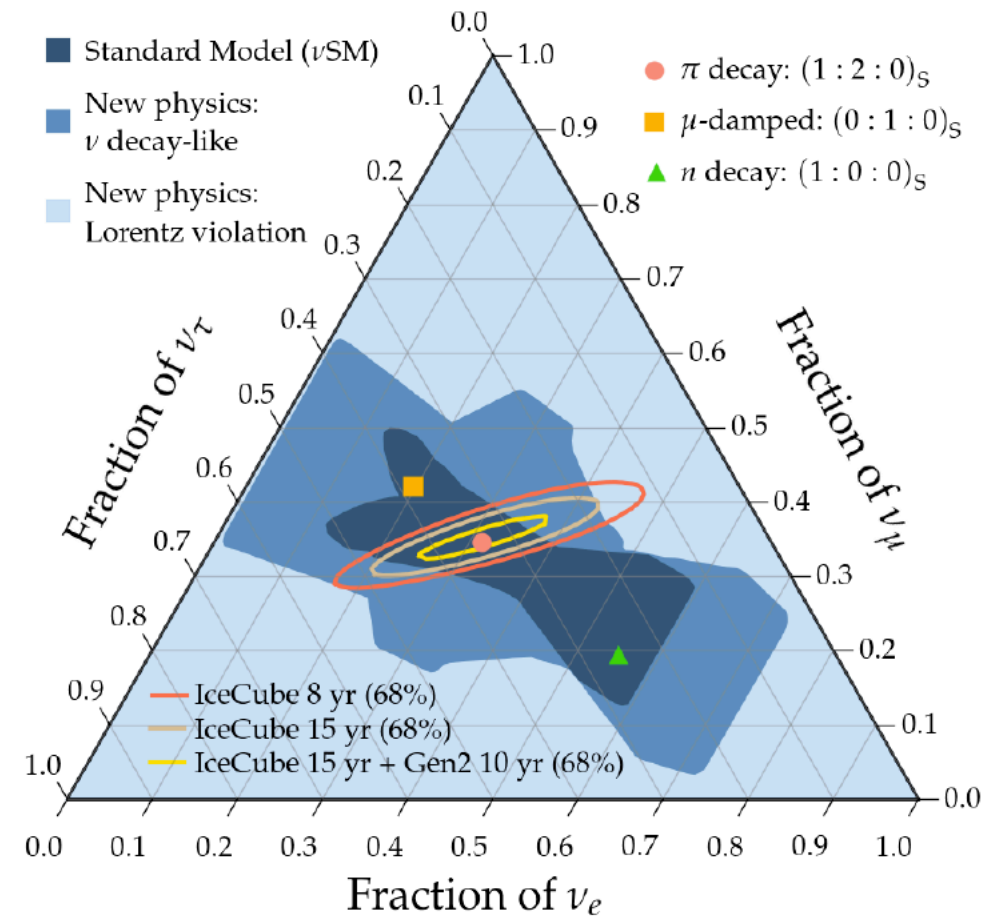
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Questions emerging after 10 years of IceCube operations

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2. Understanding cosmic particle acceleration through multimessenger observations
3. Revealing the sources and propagation of the highest energy particles in the universe
4. **Probing fundamental physics with high-energy neutrinos**



Flavor physics over cosmic base lines



Developments towards IceCube-Gen2

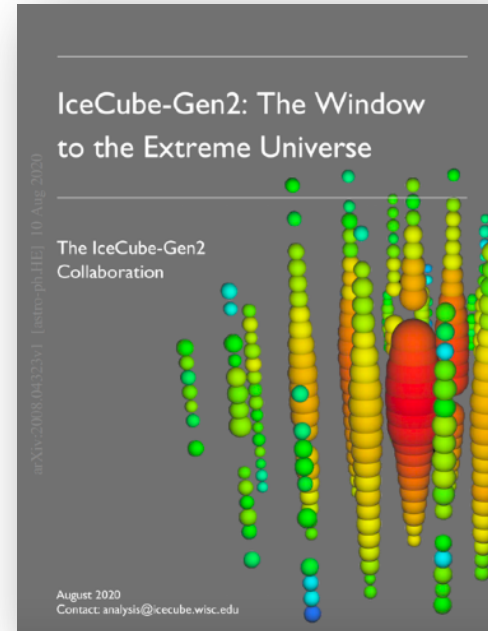
Project status & timeline

- Project office assembled / working groups formed
- CDR phase completed and published along scientific goals in our White Paper
- Preparation towards PDR ongoing

2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
IC Upgrade, RNO-G construction				IceCube / RNO-G Operation							
IceCube- Gen2 preparation				IceCube-Gen2 construction							

*preliminary schedule

Extended Gen2 White Paper: 2008.04323



>30 related contributions to Snowmass 2021, Astro2020 Decadal Survey

Snowmass2021 - Letter of Interest

IceCube-Gen2: the next generation wide band neutrino observatory

Thematic Areas

- (IF2) Instru
- (IF10) Instr
- (UF01) Und
- (UF03) Und
- (NF1) Neutr
- (NF4) Neutr
- (NF10) Neu
- (CF7) Cosm

Snowmass2021 - Letter of Interest

Monitoring Galactic core-collapse supernova neutrinos with IceCube and IceCube-Gen2

NF Topical Groups: (check all that apply)

Snowmass2021 - Letter of Interest

Highest Energy Galactic Cosmic Rays

Thematic Areas: (check all that apply)

- (CF1) Dark Matter: Particle Like
- (CF2) Dark Matter: WaveLike
- (CF3) Dark Matter: Cosmic Probes
- (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
- (CF5) Dark Energy and Cosmic Acceleration: Theoretical Foundations
- (CF6) E
- (CF7) C
- (EF06)

Snowmass2021 - Letter of Interest

Letter of Interest on Dark Matter Physics with the IceCube Neutrino Observatory

Contact:
Andreas H
Authors:
(RU Boch
Irkutsk, IR
nois (U W

Topical Groups: (check all that apply)

- (NF1) Neutrino oscillations

Snowmass2021 - Letter of Interest

IceCube-Gen2: The Window to the Extreme Universe

Thematic Areas:

- (NF1) Neutrino oscillations
- (NF2) Sterile neutrinos
- (NF3) Beyond the Standard Model
- (NF4) Neutrinos from natural sources
- (NF5) Neutrino properties
- (NF6) Neutrino cross sections
- (NF8/TF1.1) Theory of neutrino physics
- (NF10) Neutrino detectors
- (CF7) Cosmic Probes of Fundamental Physics

Contact Information:

Albrecht Karle (Univ. of Wisconsin-Madison) karle@icecube.wisc.edu
Marek Kowalski (DESY) marek.kowalski@desy.de

Authors: IceCube-Gen2 Collaboration

Abstract:

The discovery of cosmic neutrinos, announced by IceCube in 2013, has opened a new window to the high energy Universe. The observations made to date have already brought us one step closer to answering key questions, such as: what are the sources in the PeV sky and how do they drive particle acceleration; where are cosmic rays of extreme energies produced and on which paths do they propagate through the universe; and are there signatures of new physics at TeV-EeV energies? IceCube-Gen2, a next generation neutrino observatory, is designed to address these questions. In conjunction with continued progress in multi-messenger astrophysics, IceCube-Gen2 promises to elevate the cosmic neutrino field from the discovery realm to the precision era and to a survey of the sources in the neutrino sky. IceCube-

Developments towards IceCube-Gen2

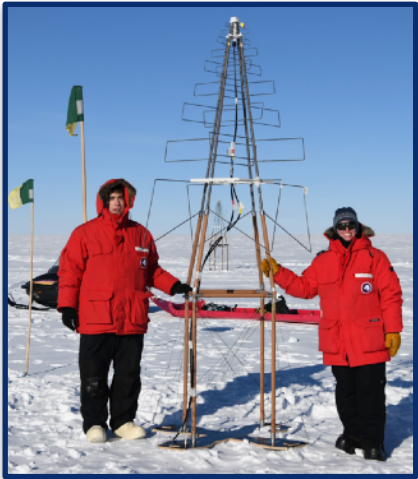
Building on experience and new technology

IceCube Installation



Operating sensors in the ice since 2006, with no evidence for aging

New surface technology



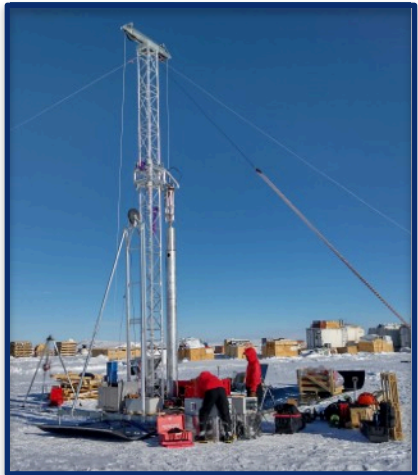
Scintillator / radio station deployed at South Pole (2019) (PoS ID 314)

IceCube Upgrade / Gen2 Phase 1



Deployment of next generation sensors (see next slide)

Radio-Tests in Greenland



Radio technology deployed in Greenland (2021, see S. Wissel et al., PoS ID 001)

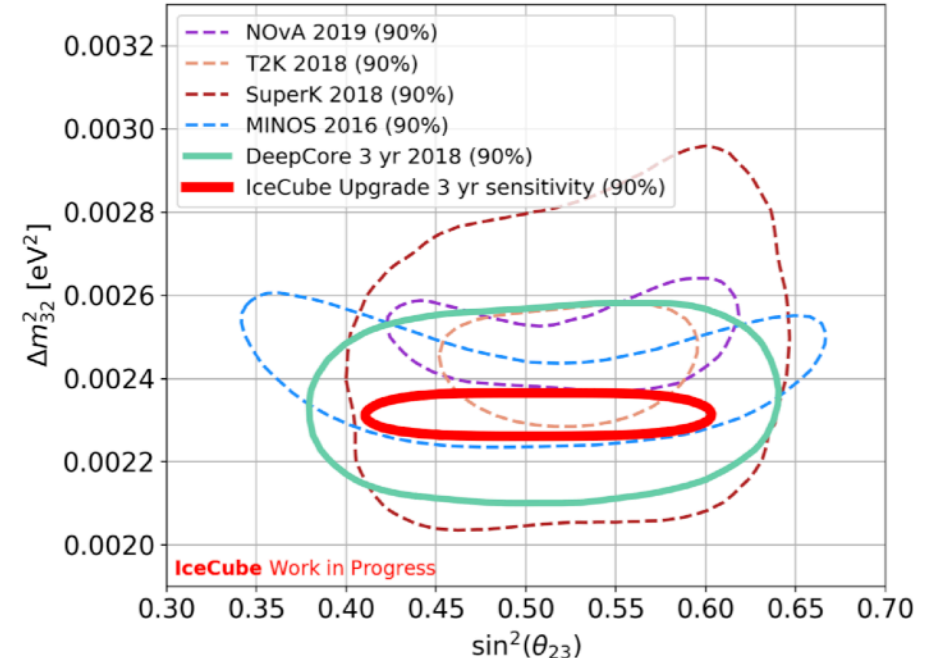
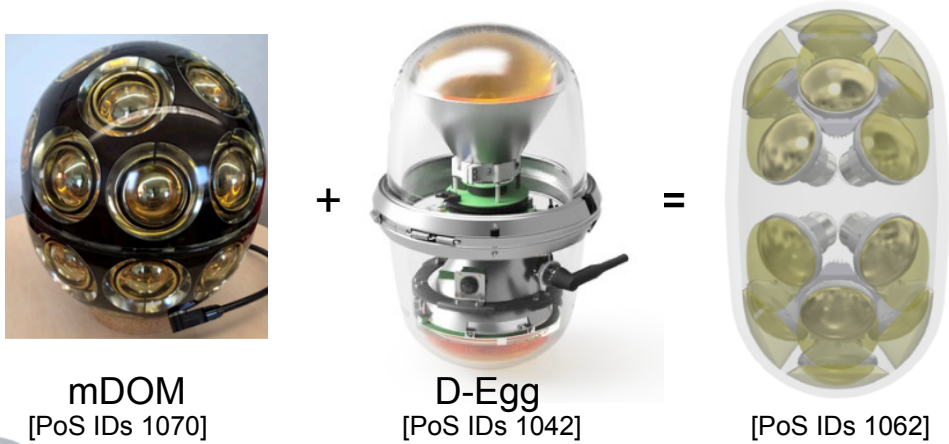
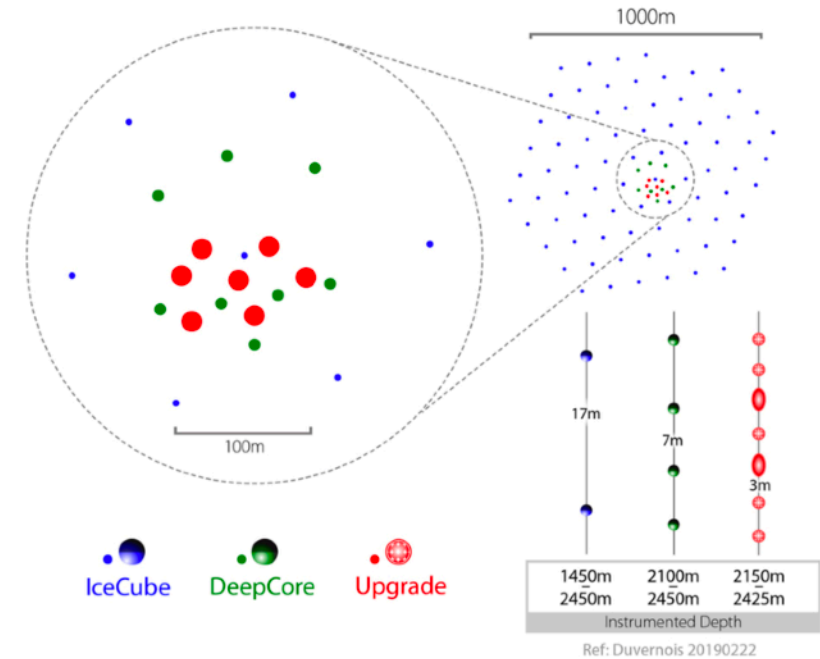



ICECUBE
GEN2


Developments towards IceCube-Gen2

IceCube Upgrade / IceCube Gen2-Phase I

- 7 string in-fill array in IceCube/DeepCore
- Unprecedented sensitivity to atmospheric neutrino mixing parameters and neutrino mass ordering
- Calibration of ice properties (e.g. [1049](#), [1064](#), [1059](#))
- Essential R&D for IceCube-Gen2
- Fully funded. Construction ongoing but COVID-related delays force us to re-baseline



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THE ICECUBE-GEN2 COLLABORATION

Conclusion

- IceCube, operating since 10 years, identified a strong flux of high-energy cosmic neutrinos and also pushes the boundaries in cosmic ray science as well as neutrino physics.
- First evidence of sources is emerging through multi-messenger observations.
- IceCube-Gen2 designed to harvest the emerging scientific opportunities, e.g. a uniquely sensitive neutrino observatory, ranging from GeV to beyond EeV in energy.
- Getting ready to start IceCube-Gen2 construction soon!

