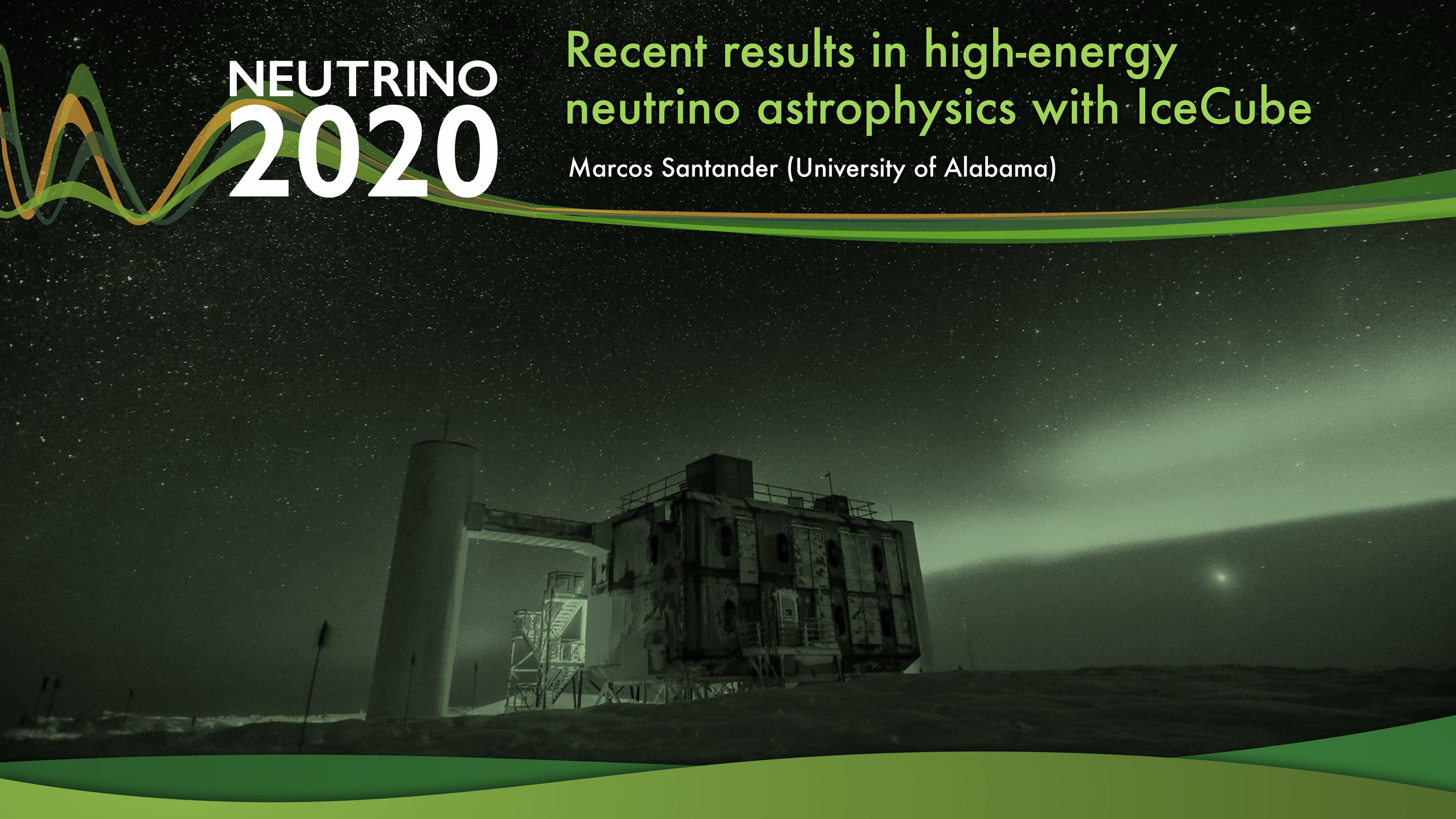
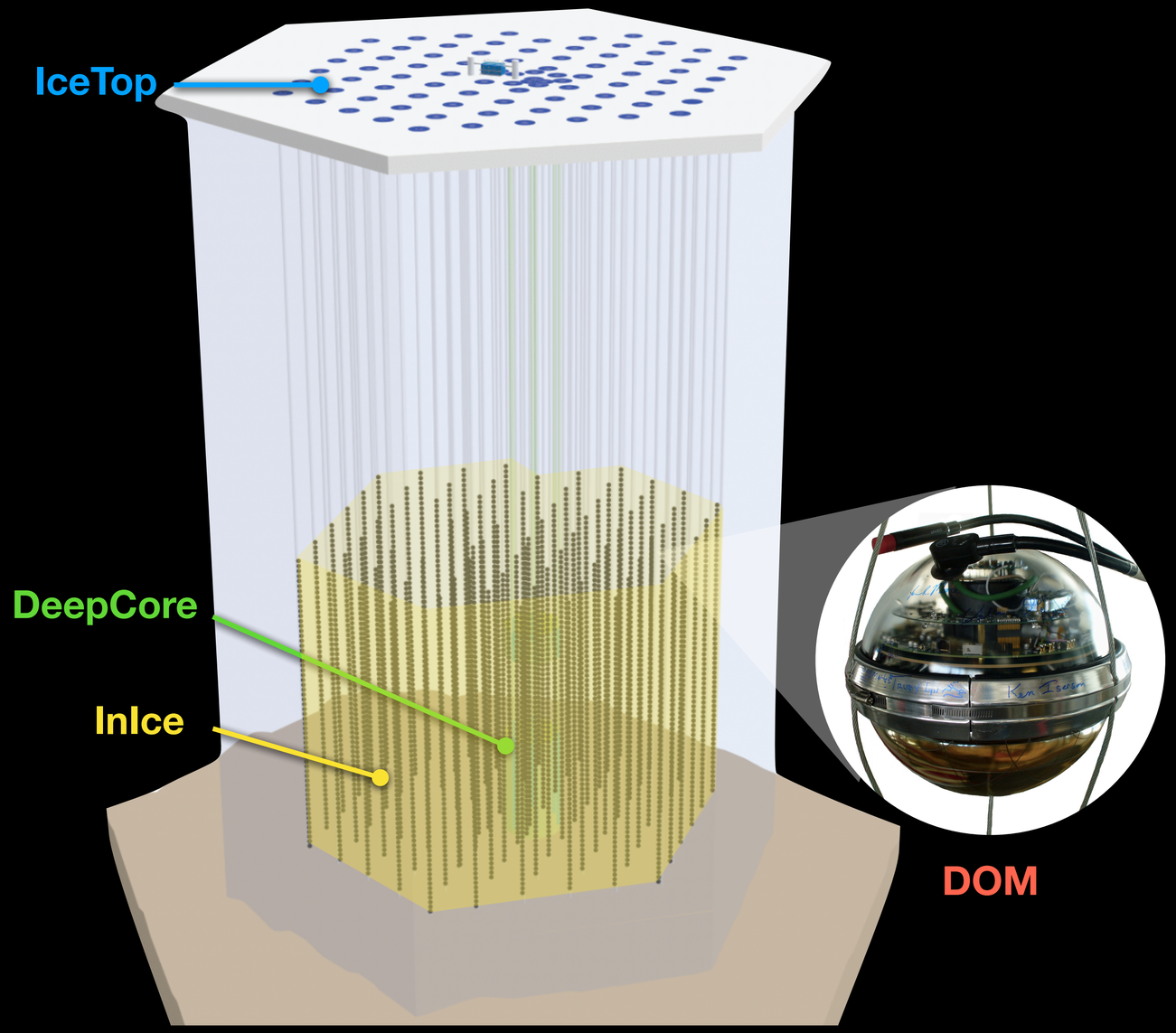
NEUTRINO 2020

Recent results in high-energy neutrino astrophysics with IceCube

Marcos Santander (University of Alabama)



The IceCube Neutrino Observatory



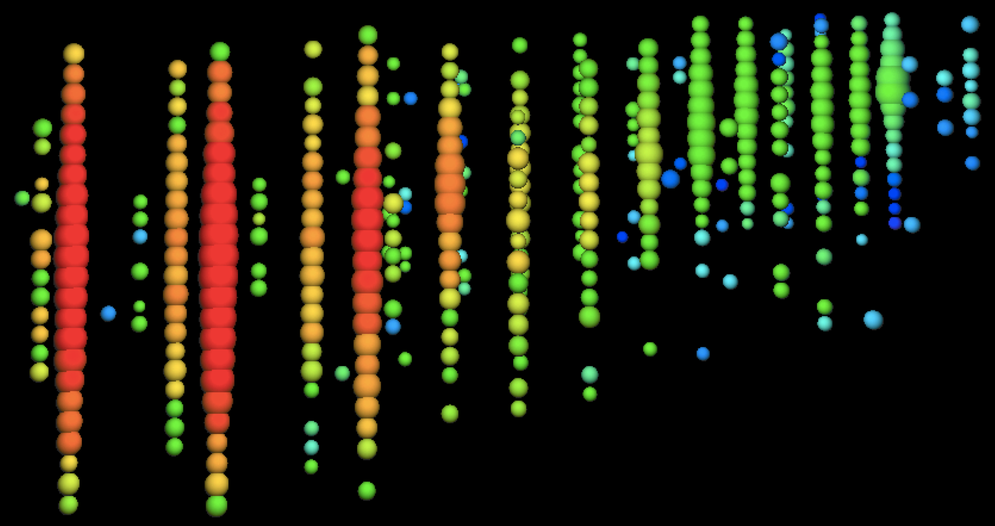
- **First km³-scale neutrino detector**
- 5160 digital optical modules (DOMs) deployed at depths between ~1.5-2.5 km
- Construction finished in Dec 2010
- Surface air shower array (IceTop)
- Denser in-fill for O(10) GeV neutrinos (DeepCore)

Neutrinos in the multi-messenger era (F. Halzen)
Neutrino oscillations with DeepCore (S. Blot)

Neutrino event topologies

Muon tracks

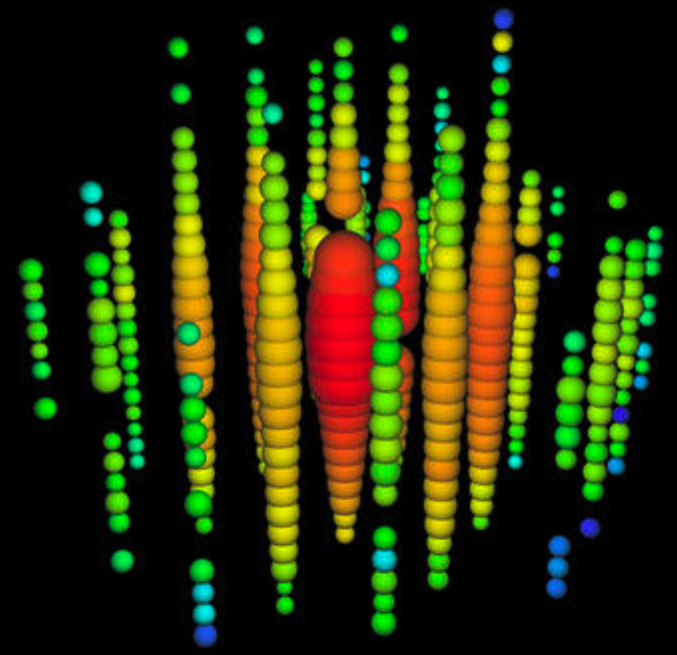
CC ν_μ interactions



Factor of ~2 energy resolution on neutrino energy
(~15% on deposited visible muon energy)
Angular resolution **0.5° @ 10 TeV**, 0.3° @ 100TeV

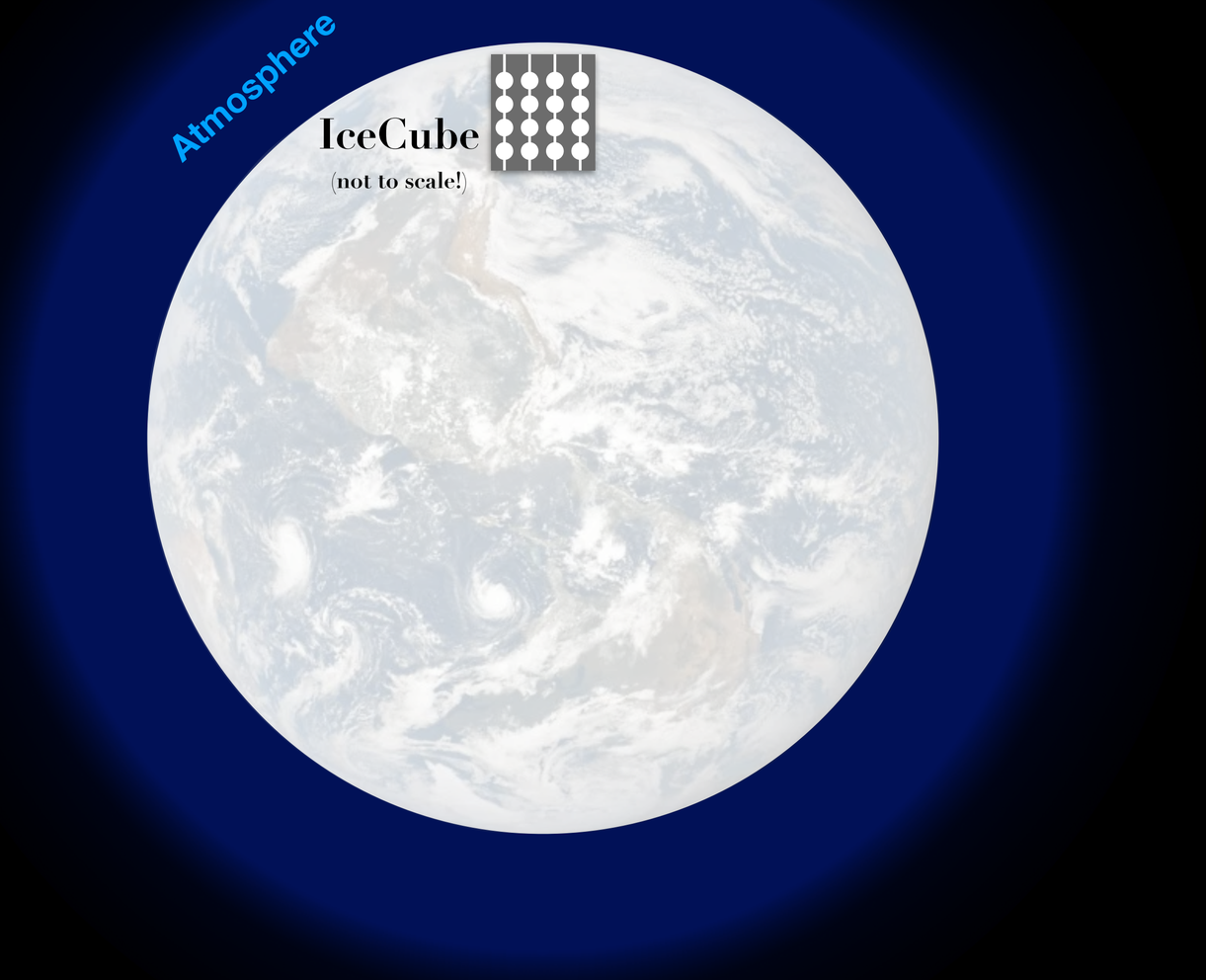
Cascades

NC / CC ν_e, most ν_τ



15% deposited energy resolution
~15° median angular resolution @ 10 TeV (8° @ 100 TeV)

Backgrounds



Dominated by cosmic ray interactions. CR spectrum softens above a few PeV ("knee")

Rates

- Atmospheric **μ**: **10^3 Hz**
- Atmospheric **ν**: **10^{-3} Hz** (> 100 GeV)
  - From CR meson decays. Mostly **ν_μ**, soft spectrum.
  - Potential contribution from charmed mesons (still unmeasured, harder spectrum, $\nu_\mu + \nu_e$).
- HE astrophysical **ν**: **10^{-7} Hz** (>100 TeV)
- **x10^{10} bkg suppression**

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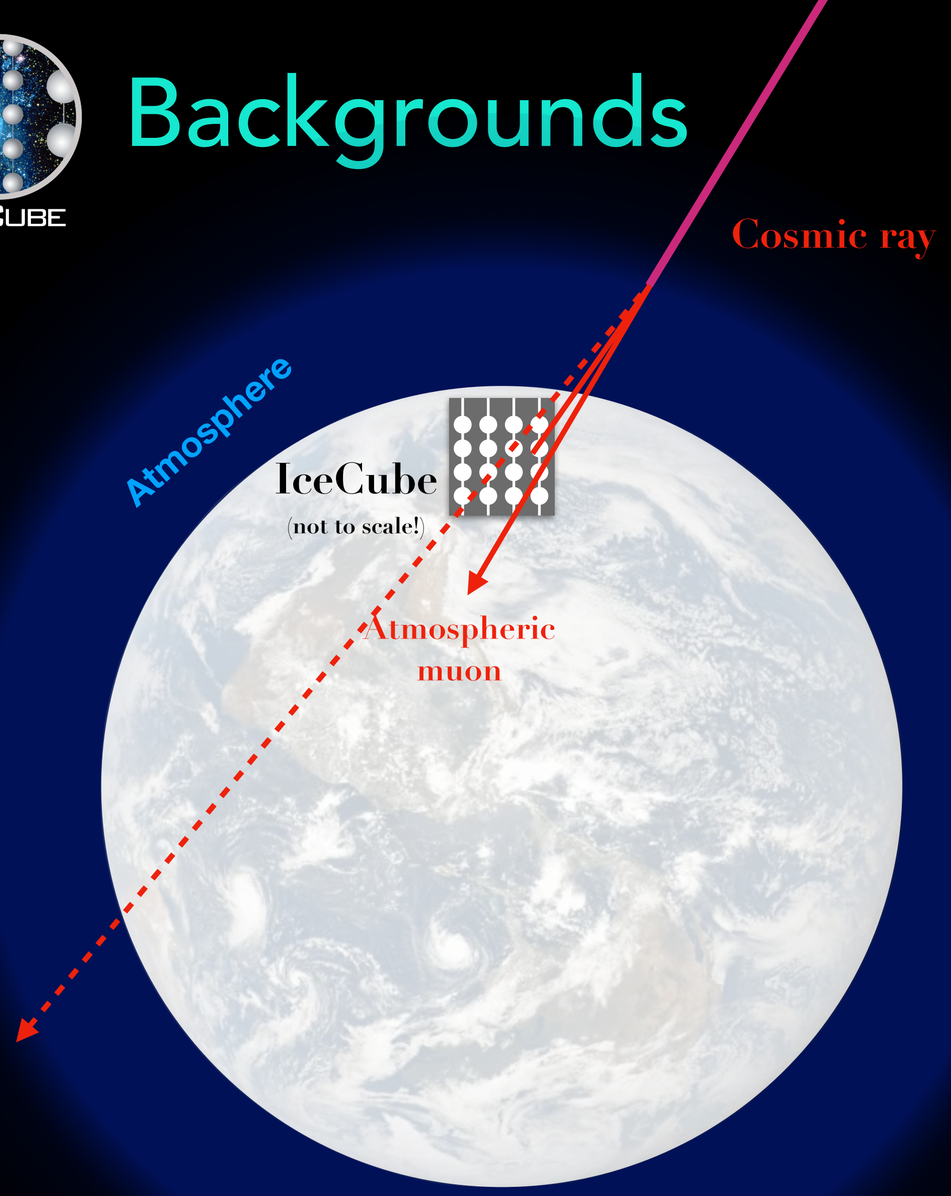

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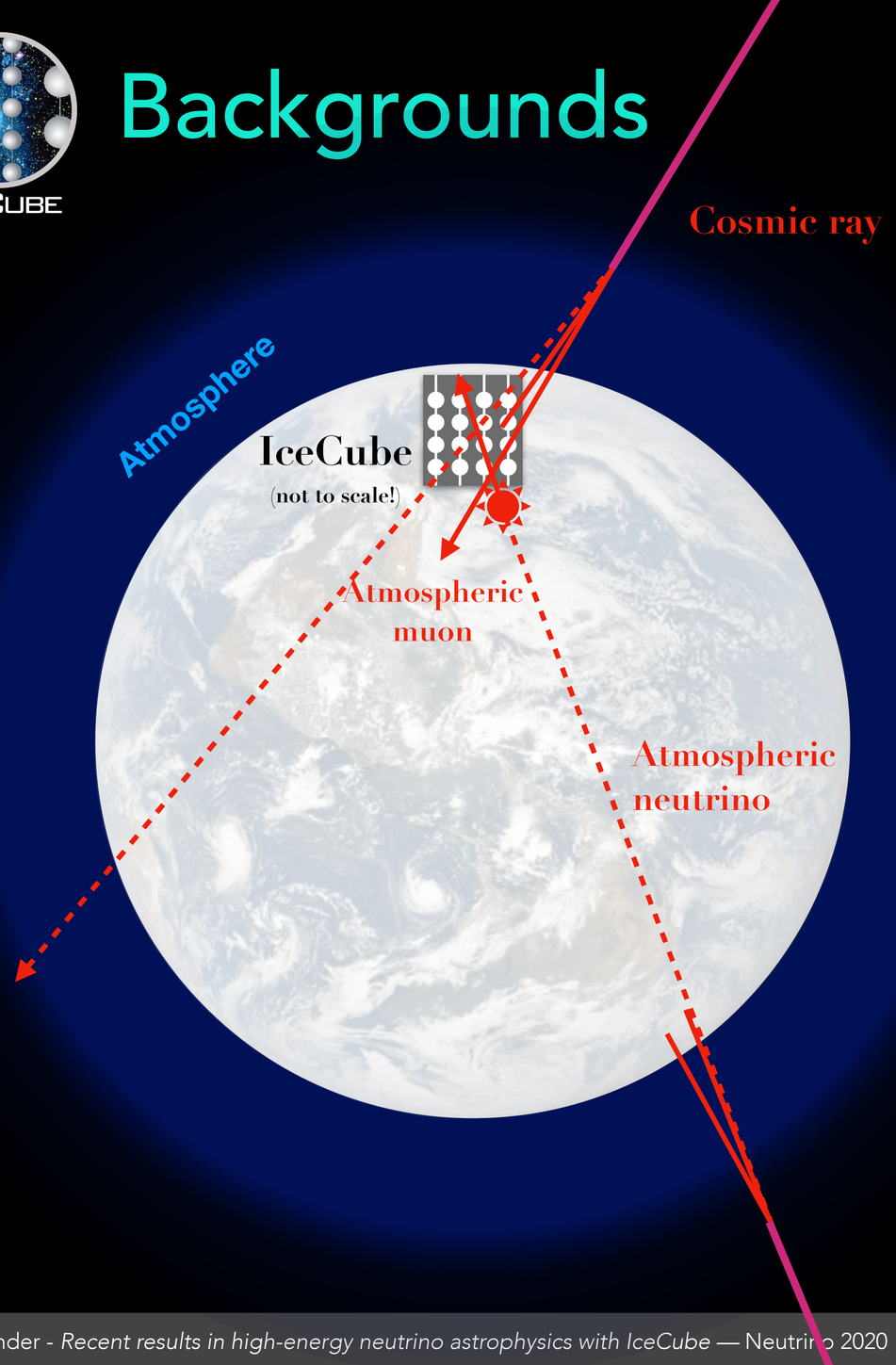

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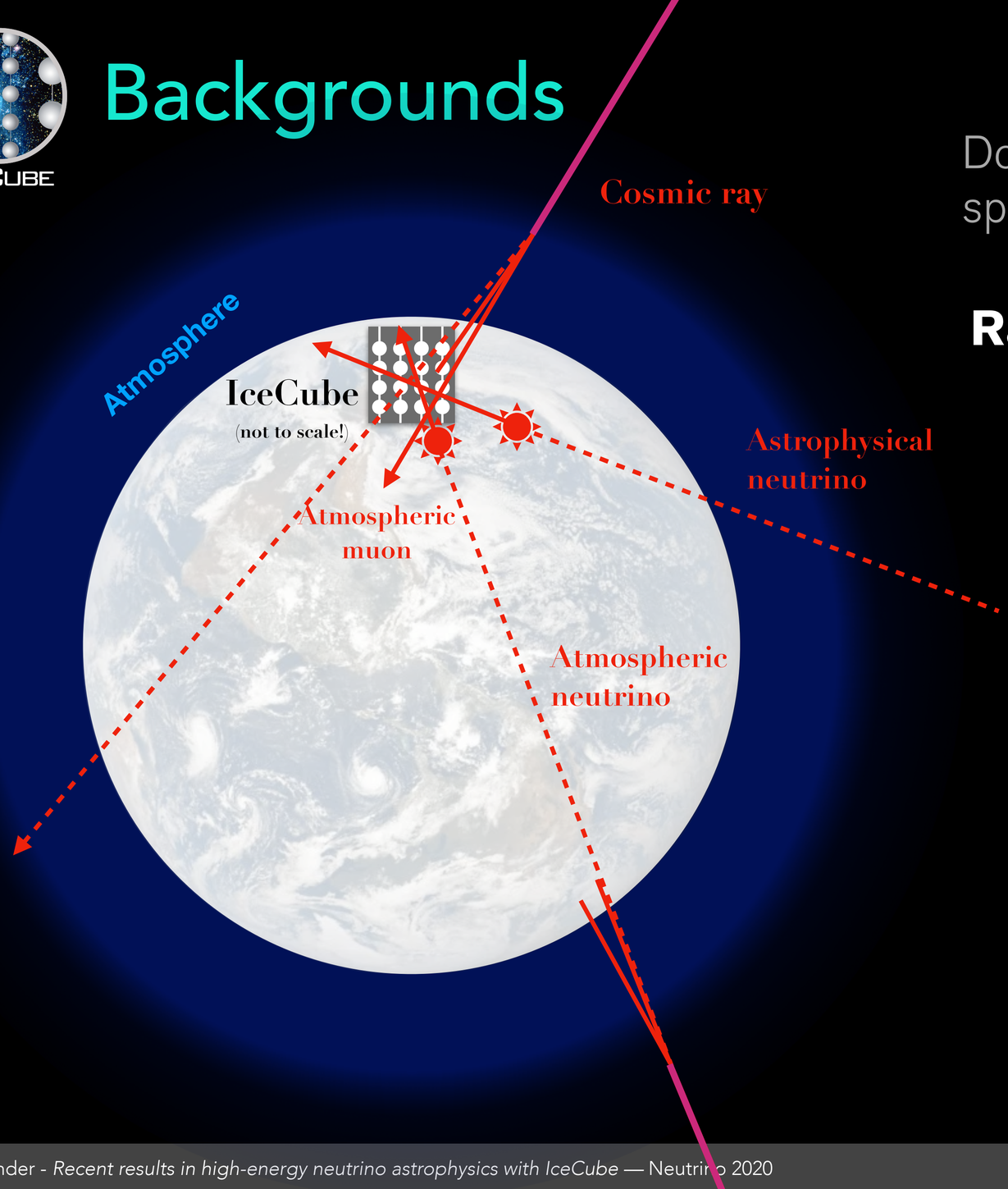

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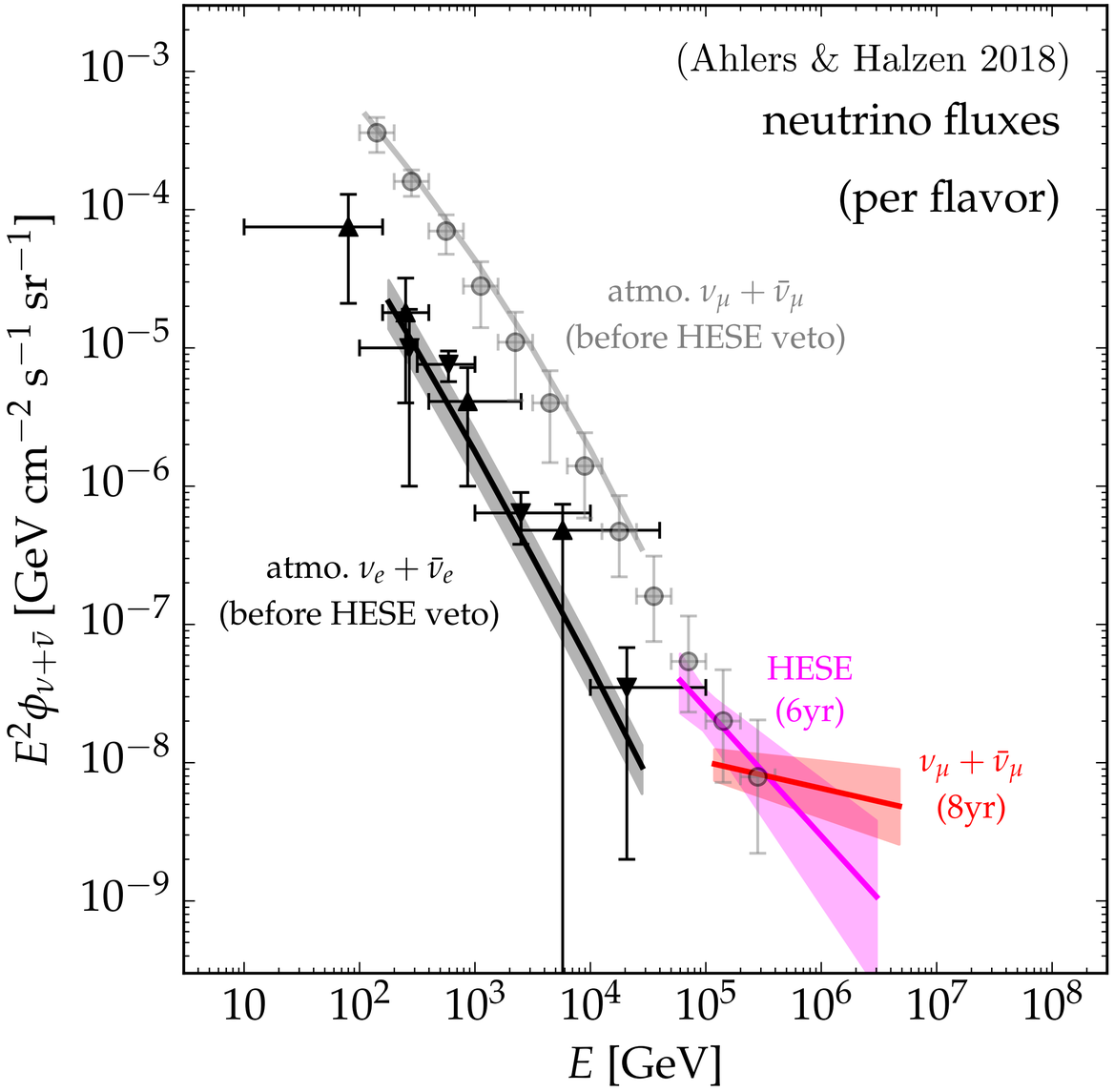
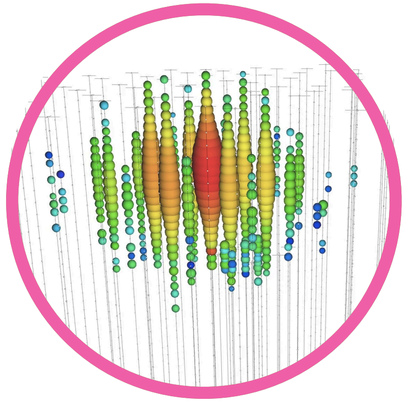
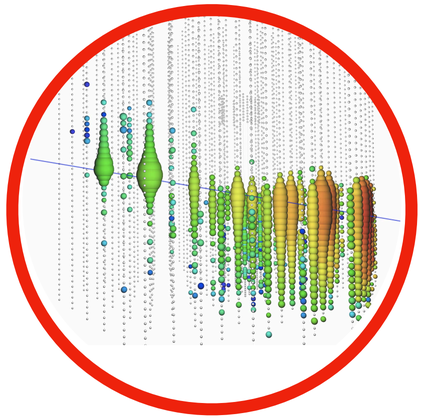
Astrophysical neutrino flux



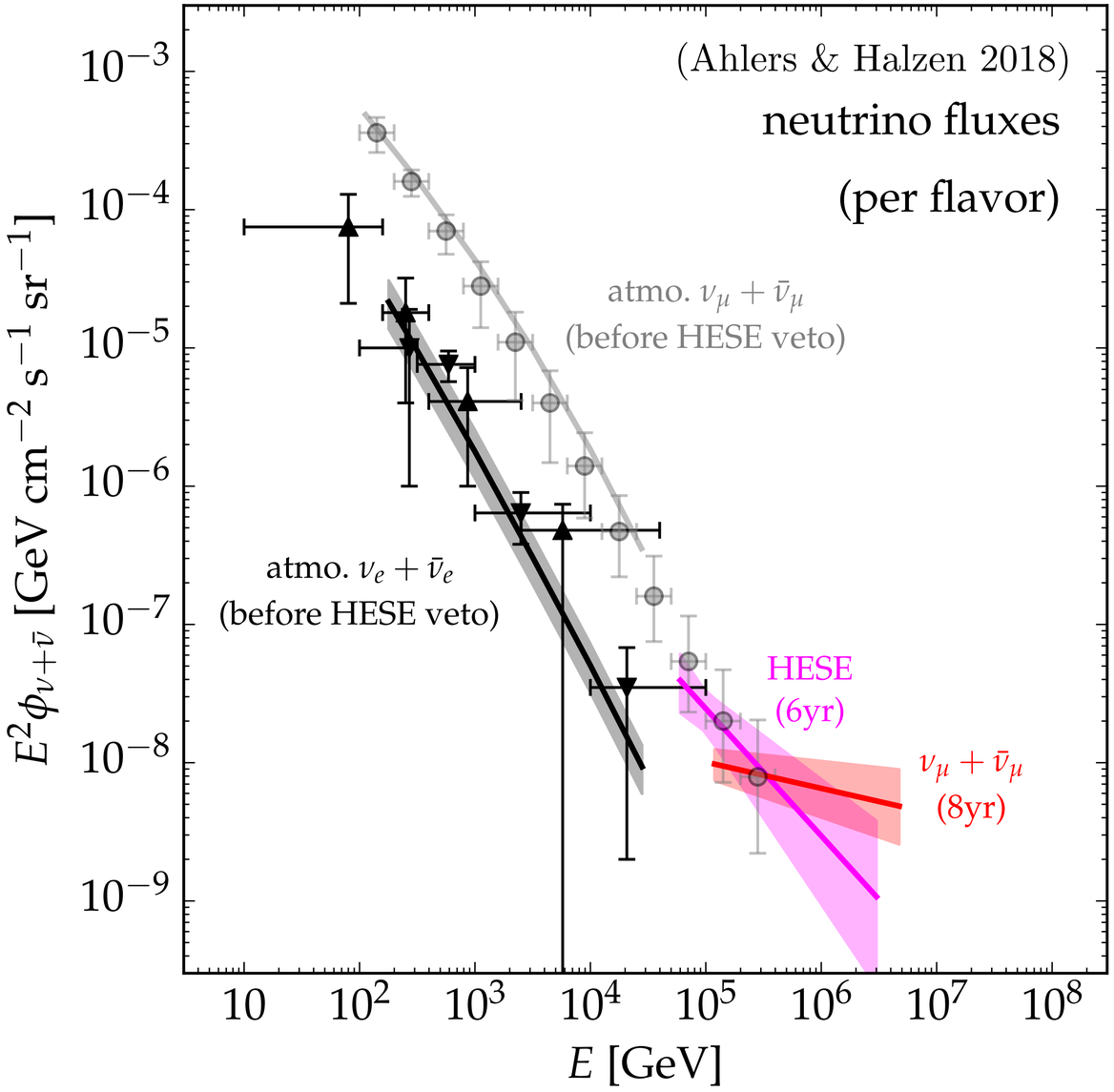


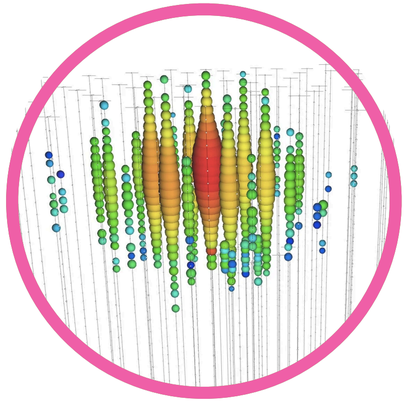
High-energy starting events (HESE)
Interaction vertex in the detector
All flavor, all sky



Up-going tracks
Muon-dominated
Northern sky

Astrophysical neutrino flux





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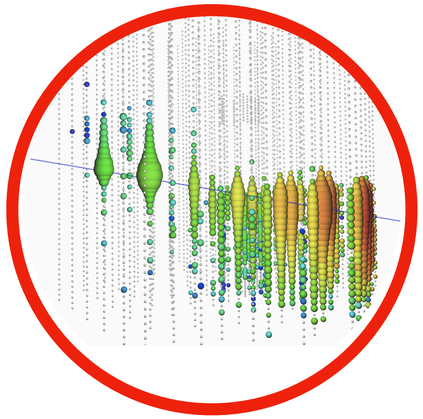

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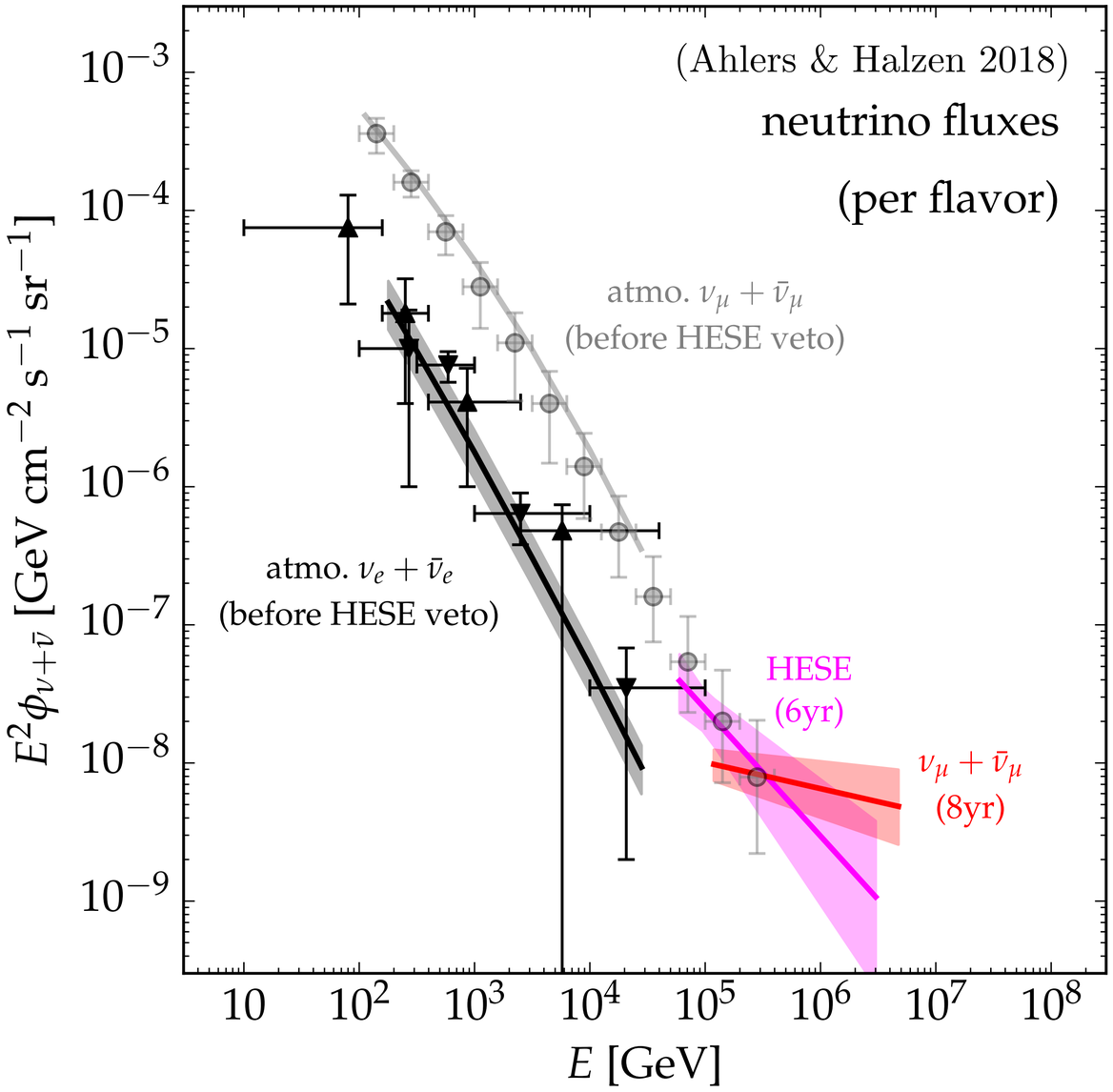
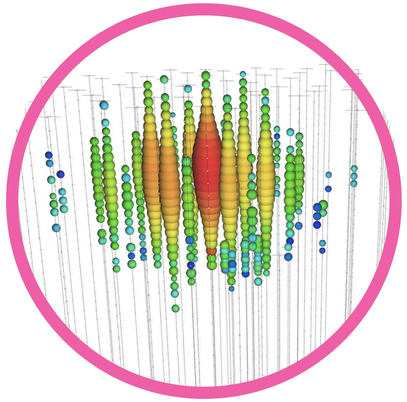
- **Astrophysical flux in the 20 TeV - 9PeV range**

Astrophysical neutrino flux





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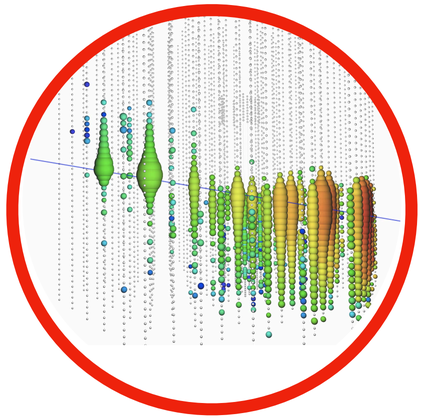

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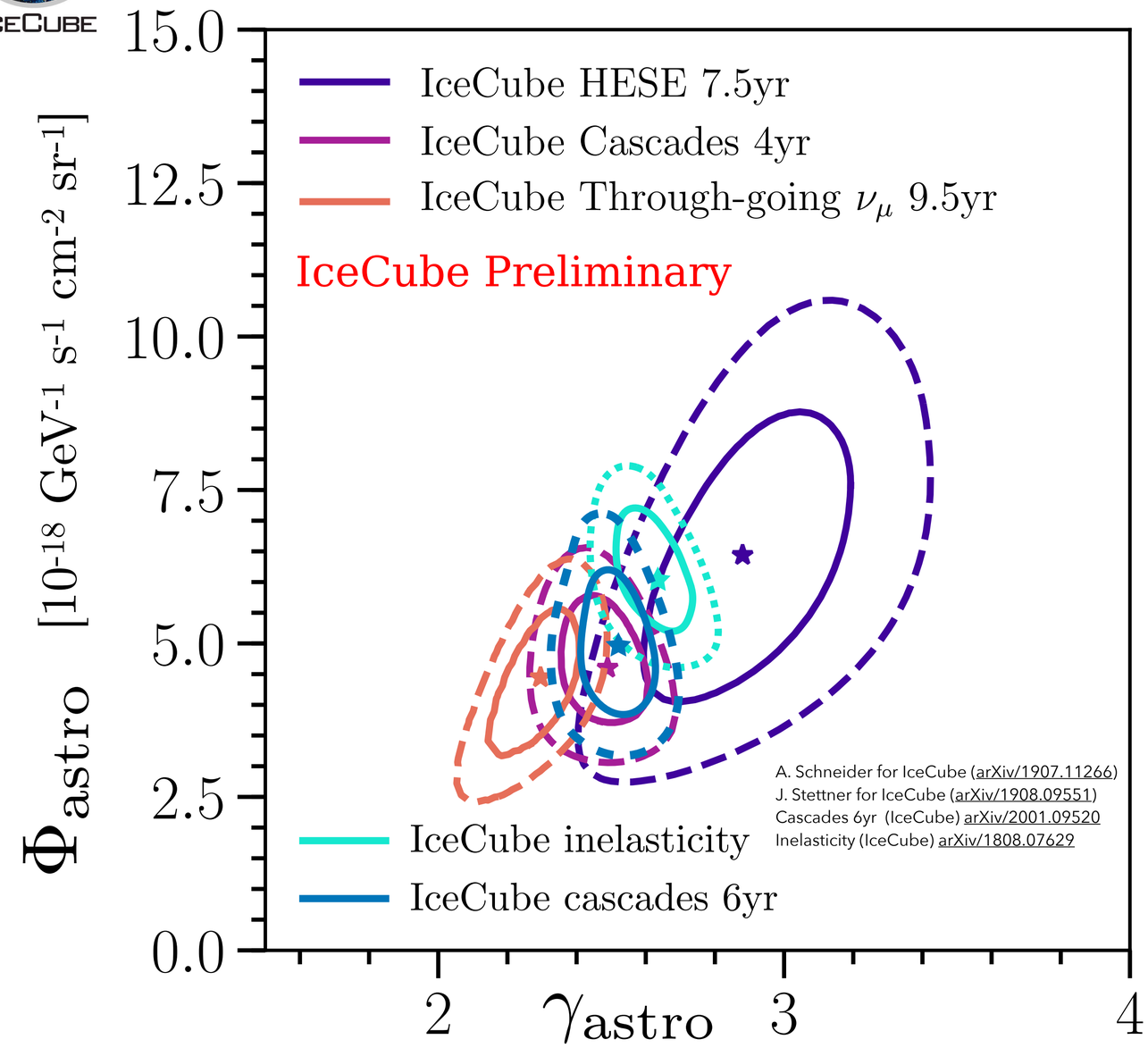
- **Astrophysical flux in the 20 TeV - 9PeV range**
- **Various channels and analysis methods**

Astrophysical neutrino flux



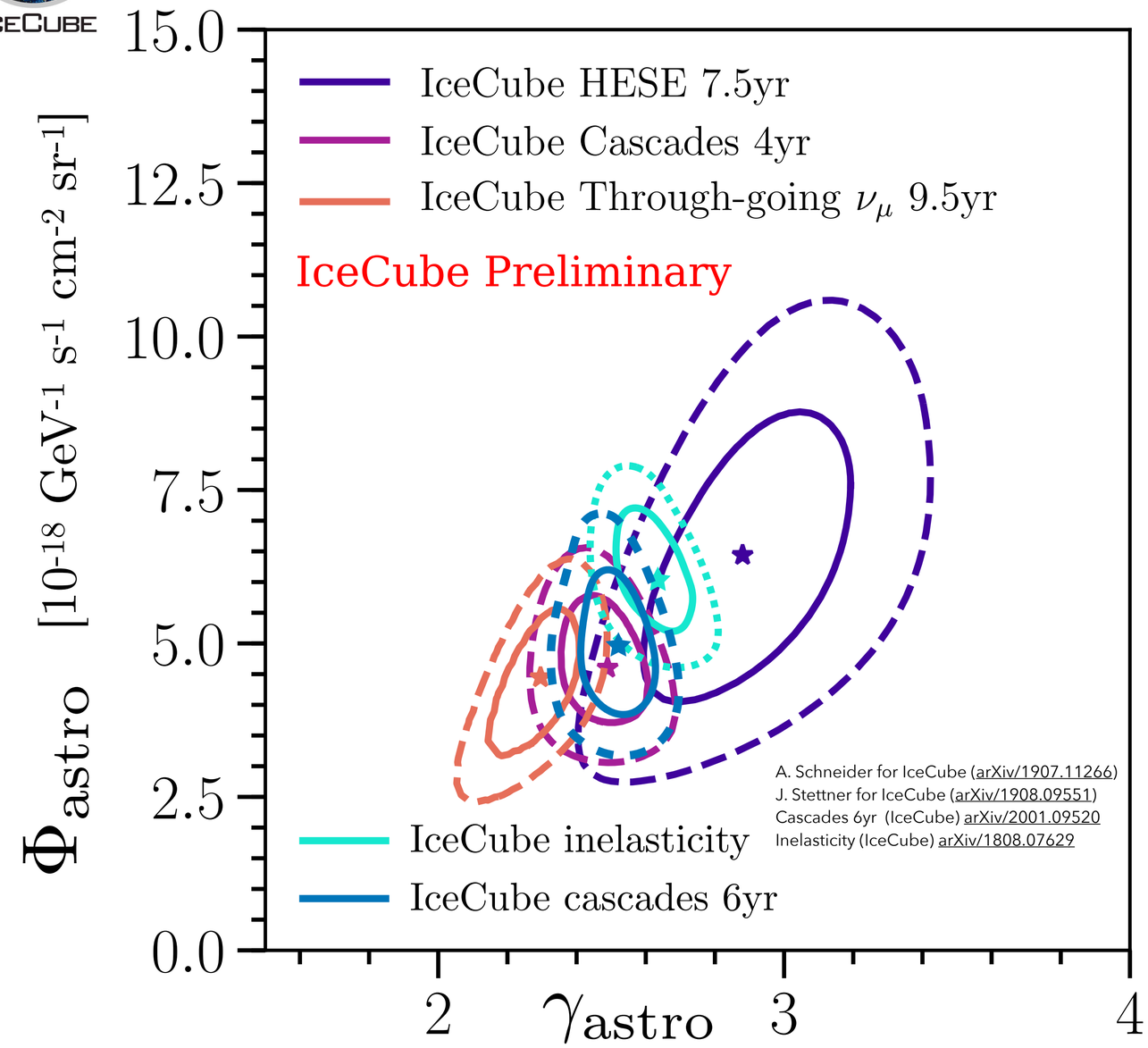
- Flux modeled with a simple power-law spectrum.

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

- Different event samples (covering different energy ranges, topologies, or sky hemispheres) favor slightly different indices, normalizations.

- **HESE 7.5 year papers coming soon!**

Astrophysical neutrino flux



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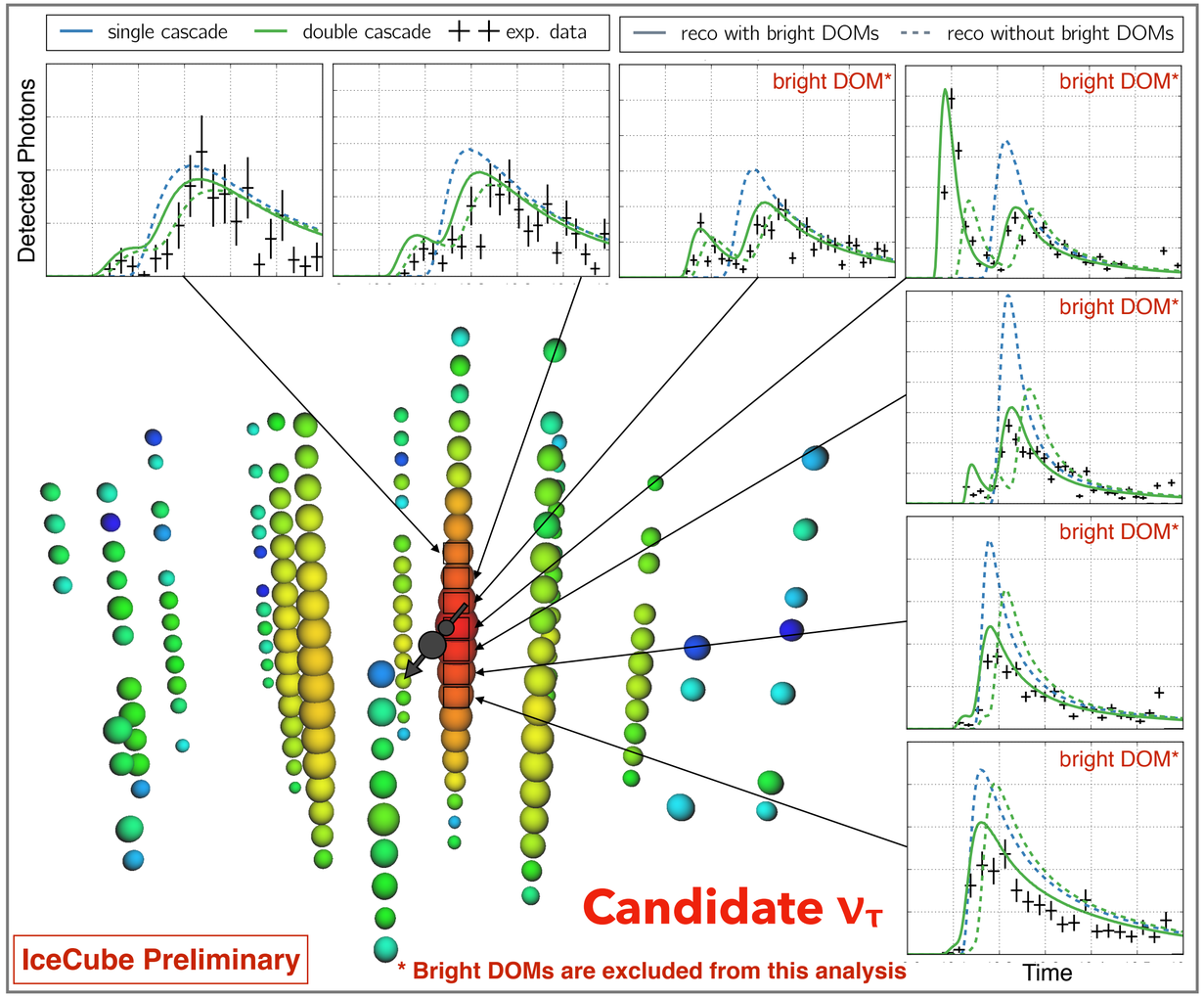
New methods to measure the astrophysical flux using starting tracks
M. Silva & S. Mancina (IceCube)
Poster 159

Tau neutrino searches



J. Stachurska (IceCube) arXiv/1908.05506
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τ decay length is 50 m/PeV

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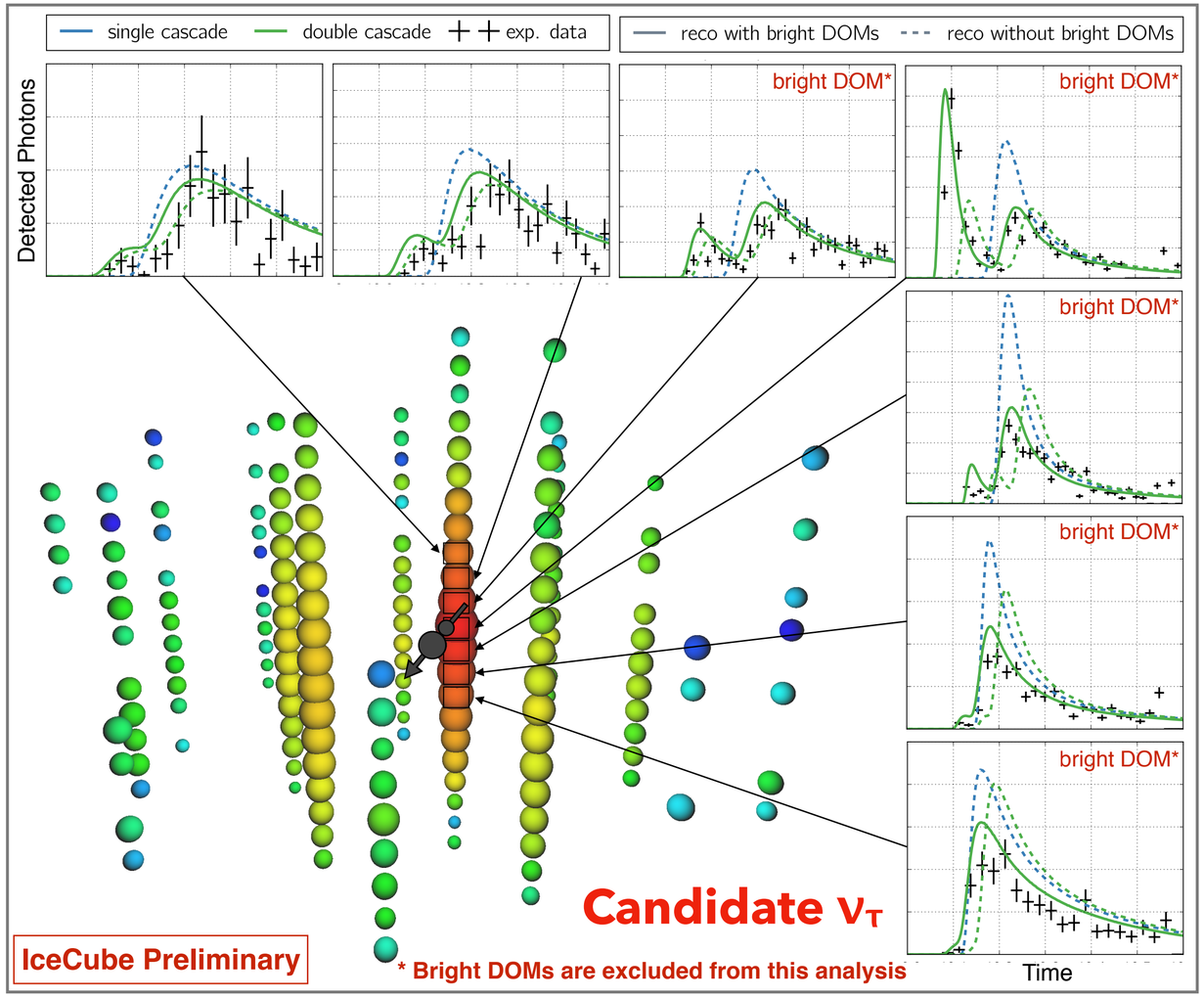

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- One event passes a double-cascade selection, as well as two complementary double-pulse selections.
- Data consistent with flavor equipartition.
- **Paper coming soon!**

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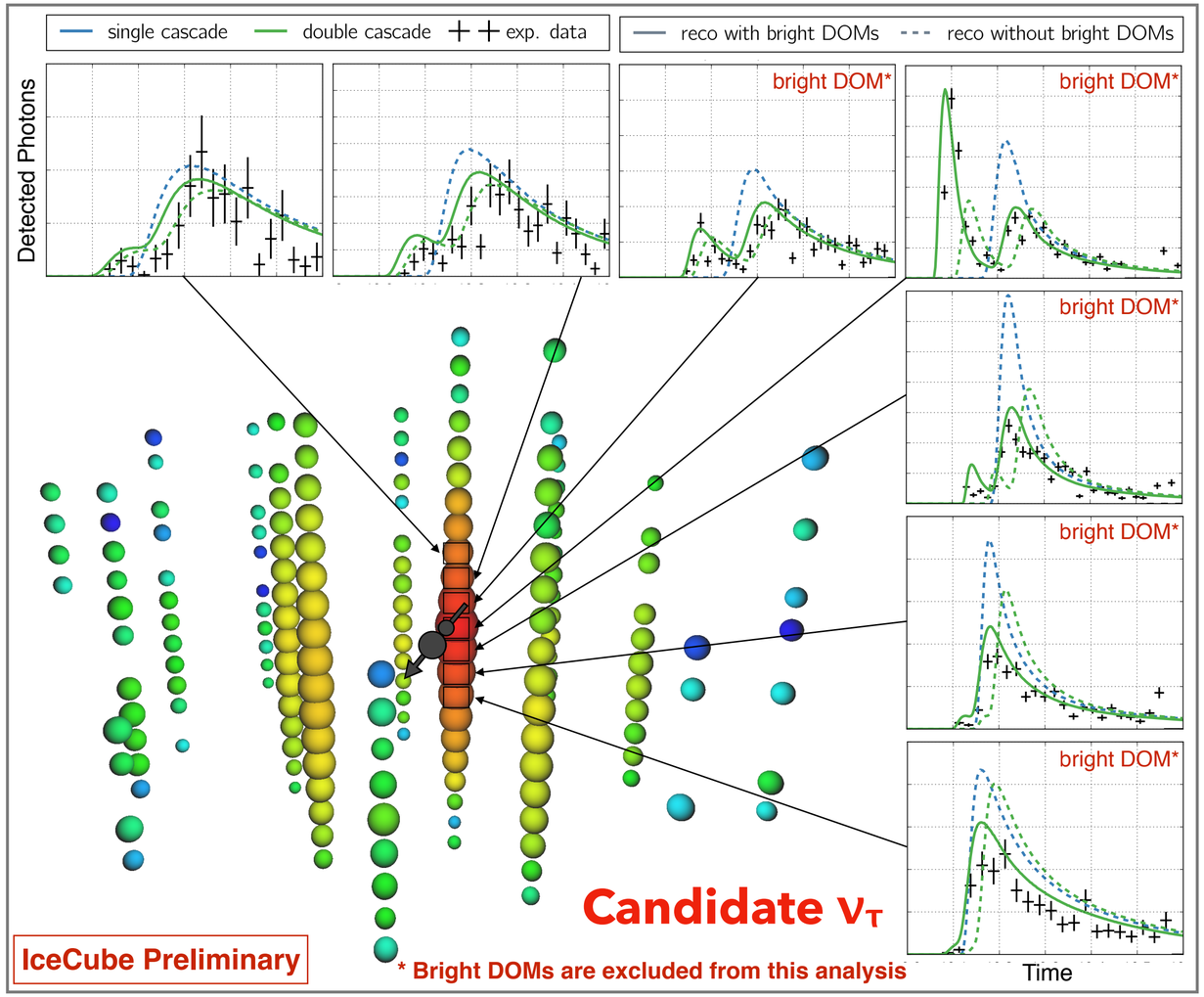

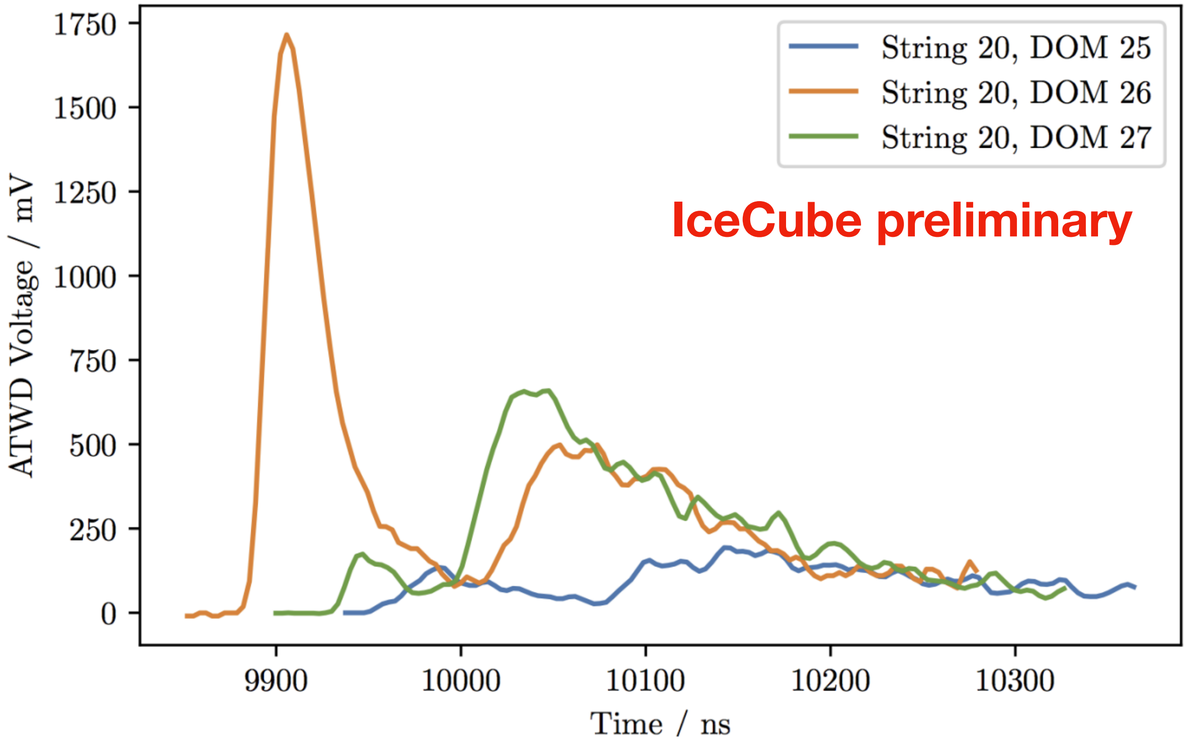

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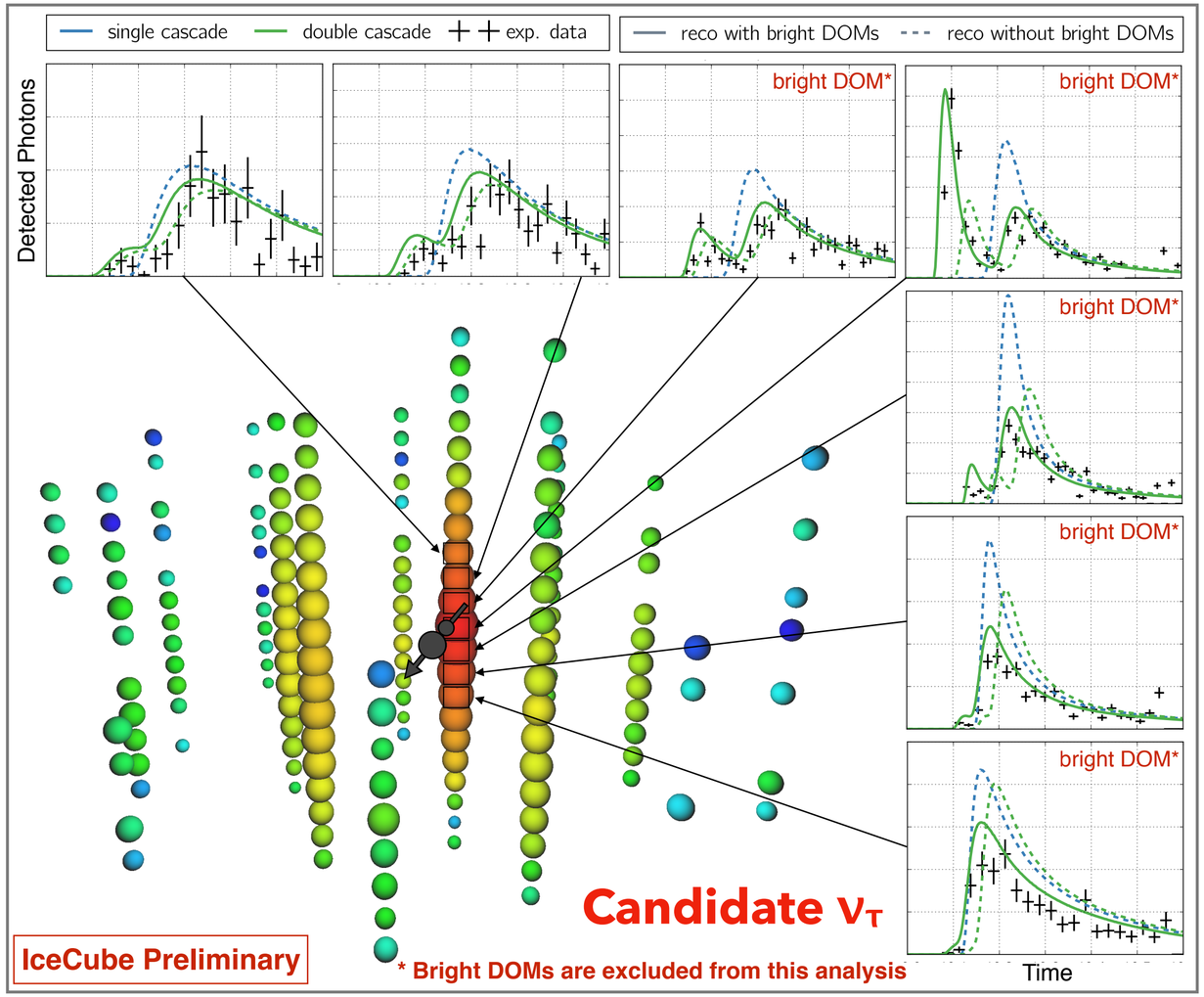

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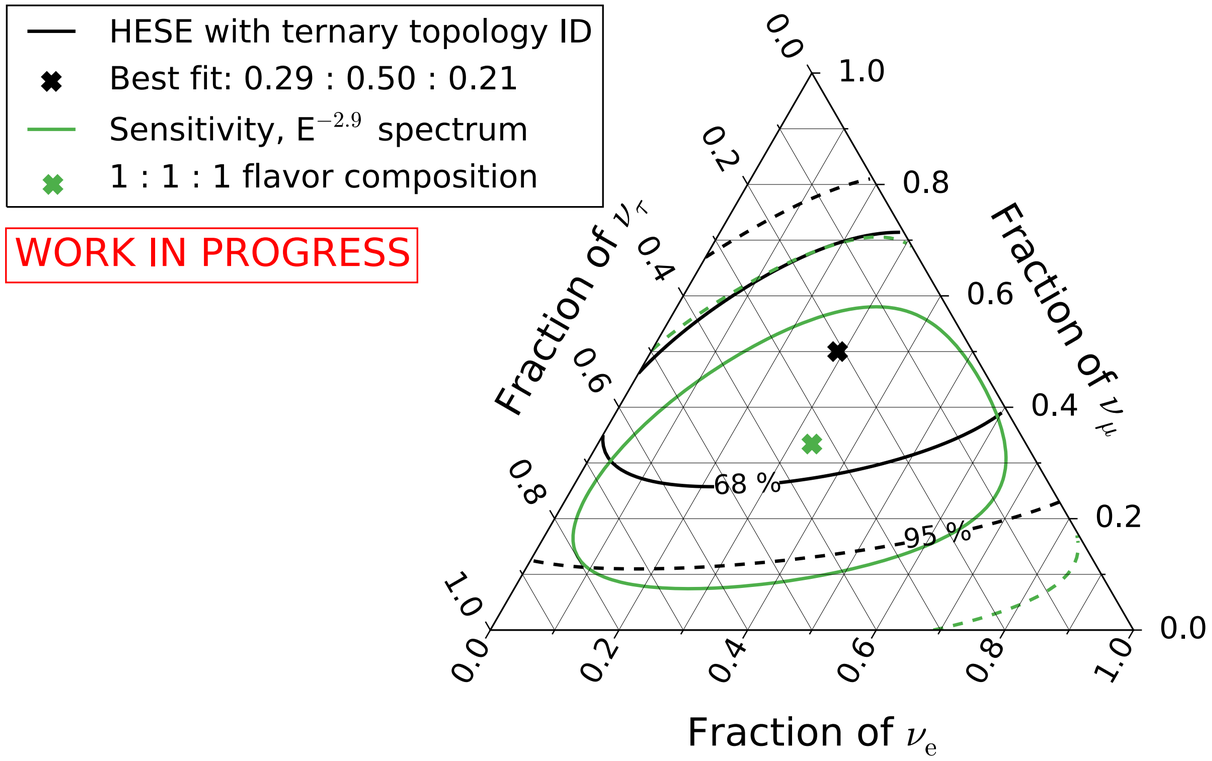

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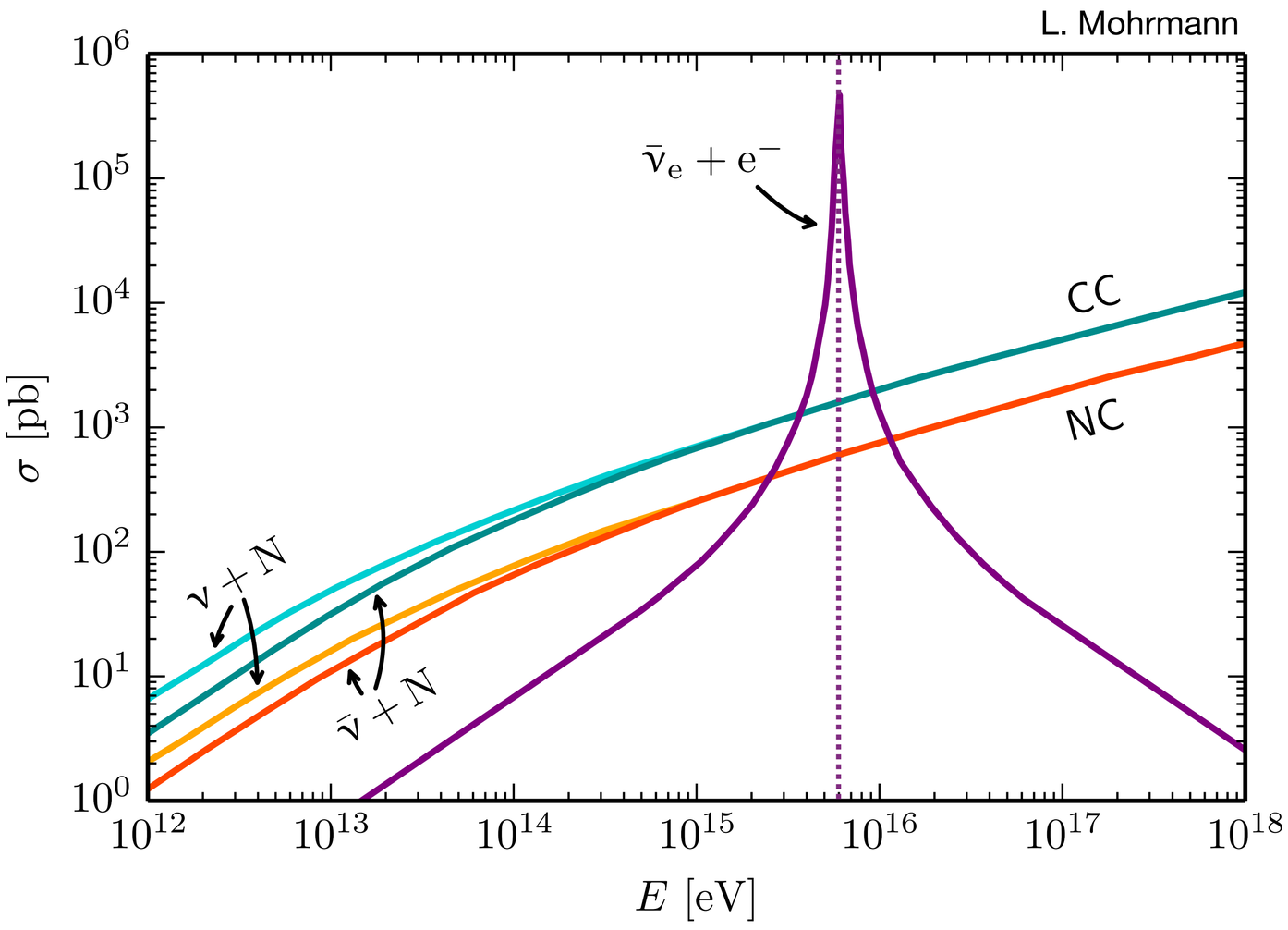
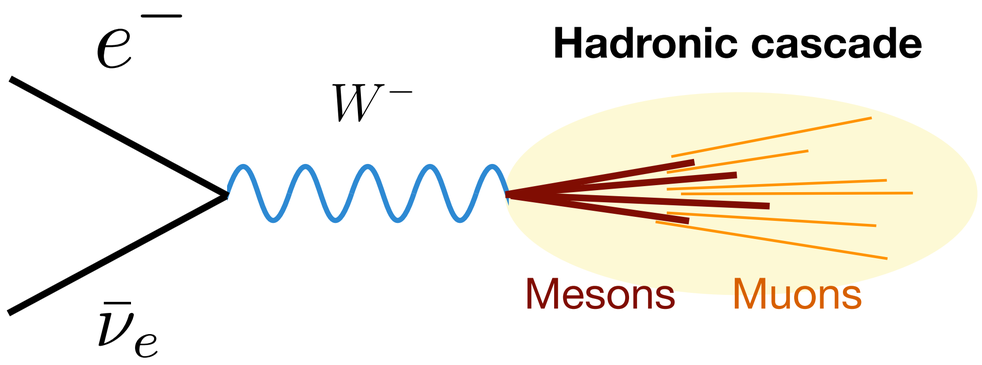
Partially-contained cascades





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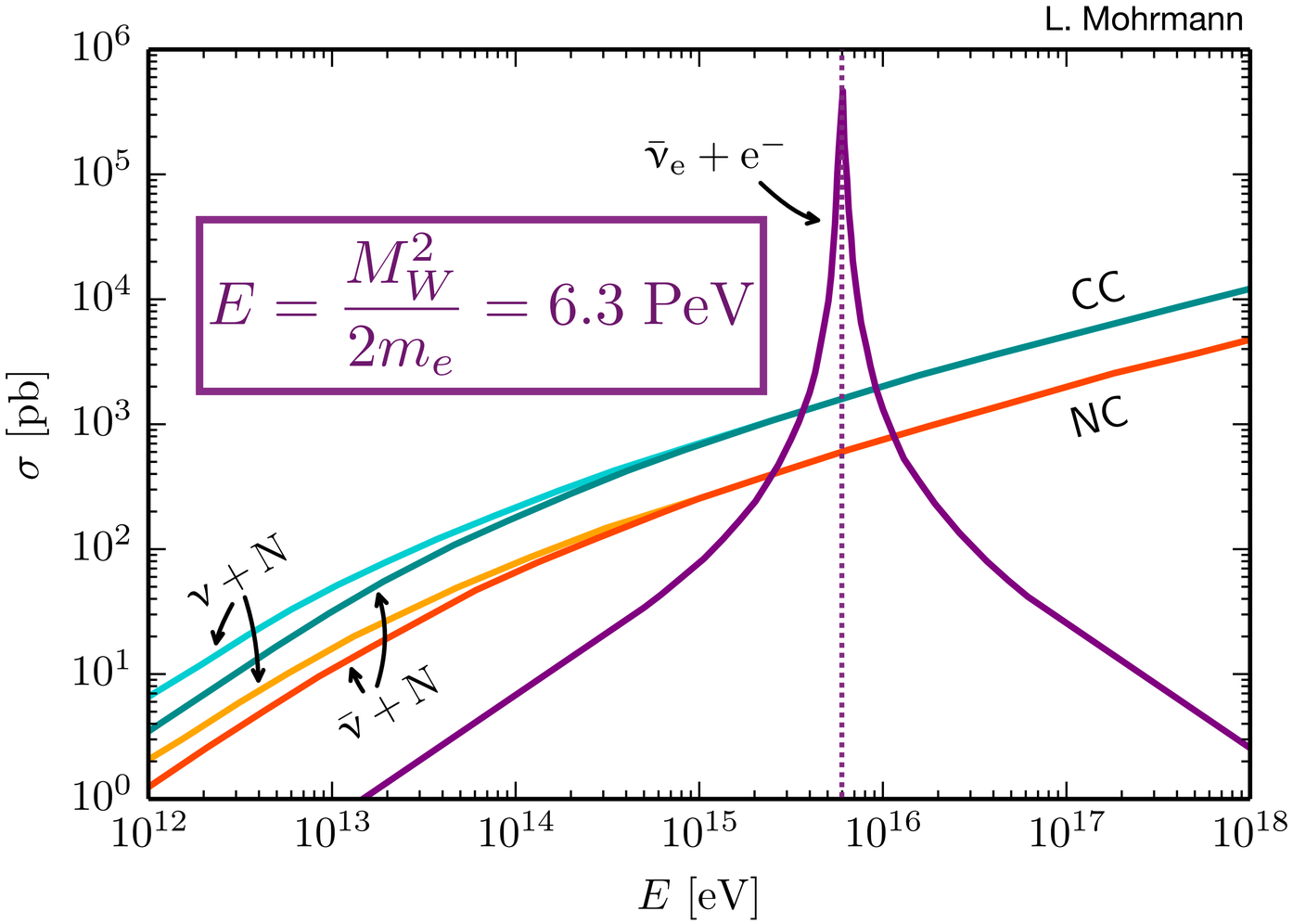
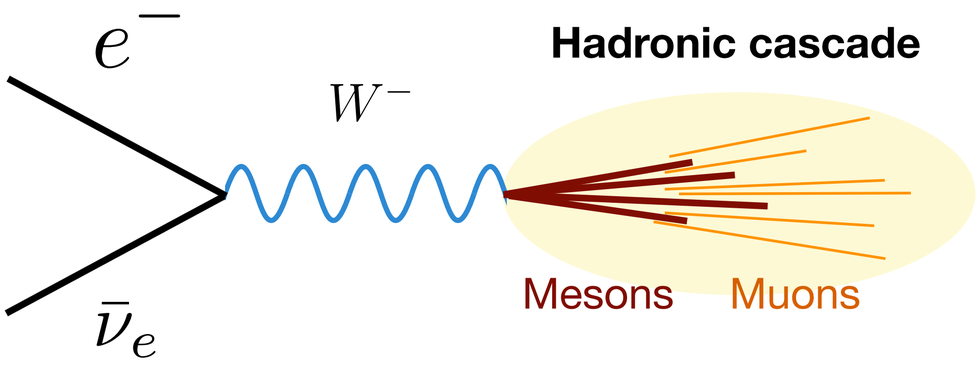
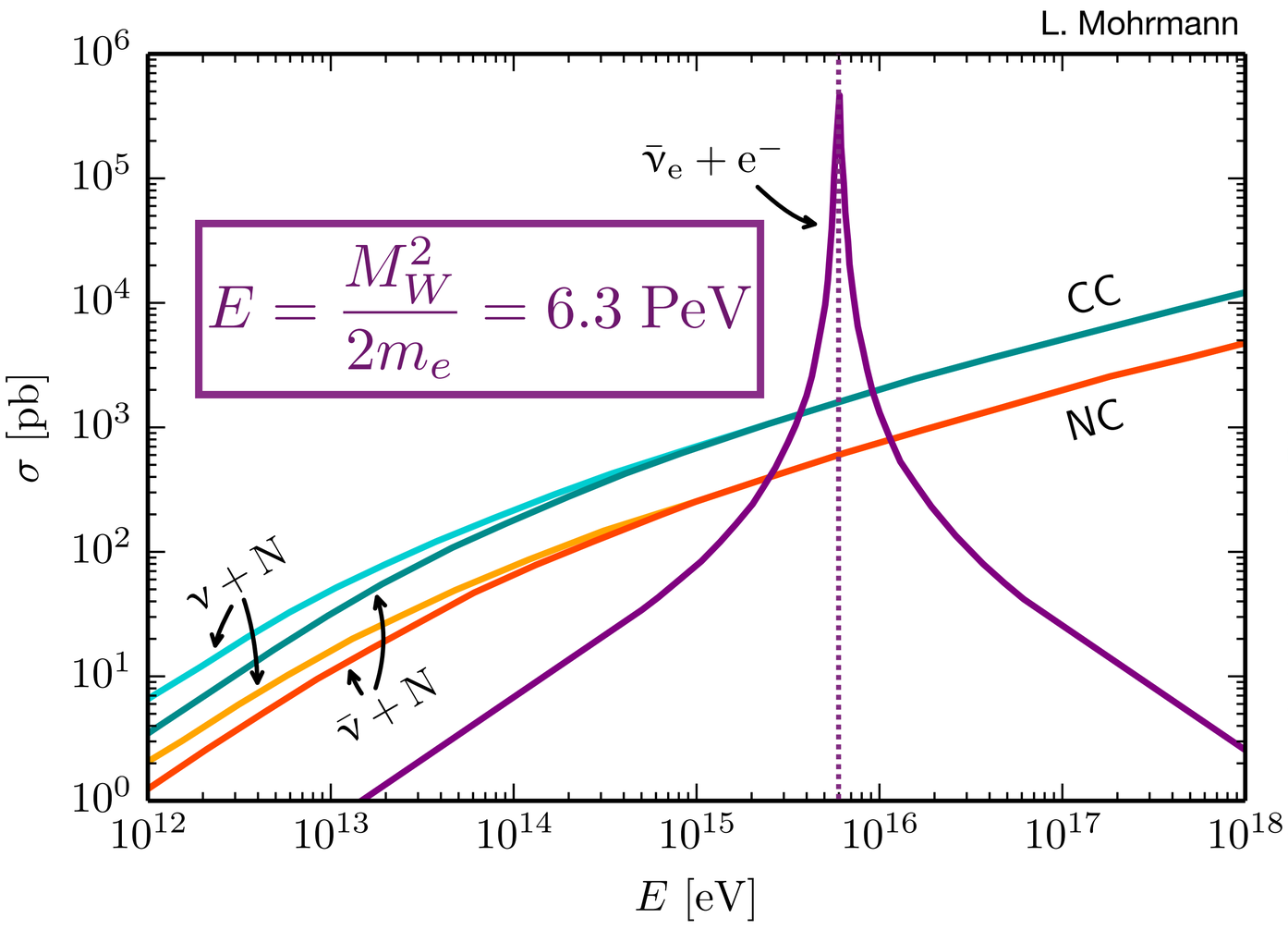


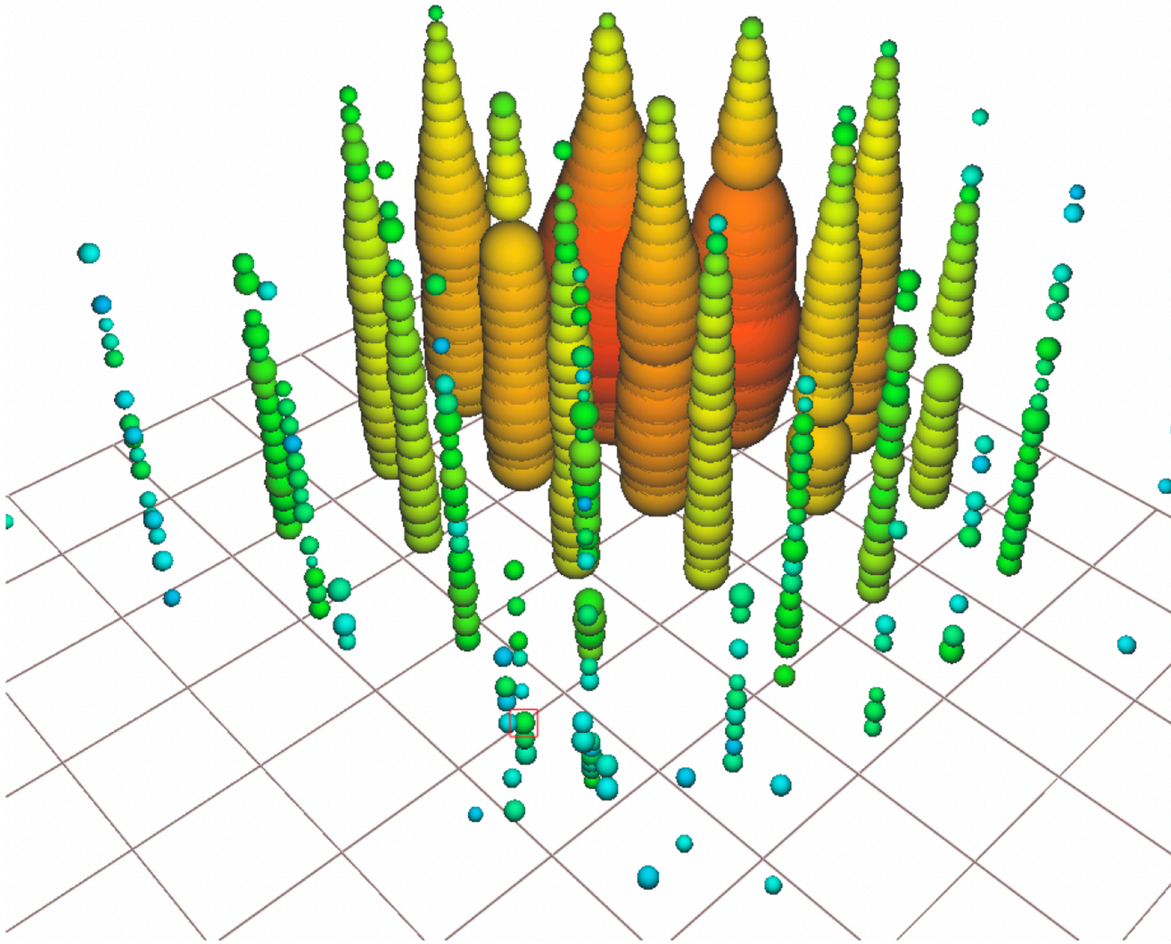


Partially-contained cascades

First Glashow candidate event ~6 PeV

Paper coming soon





New analysis with increased sensitivity to multi-PeV hadronic cascades

Partially-contained cascades

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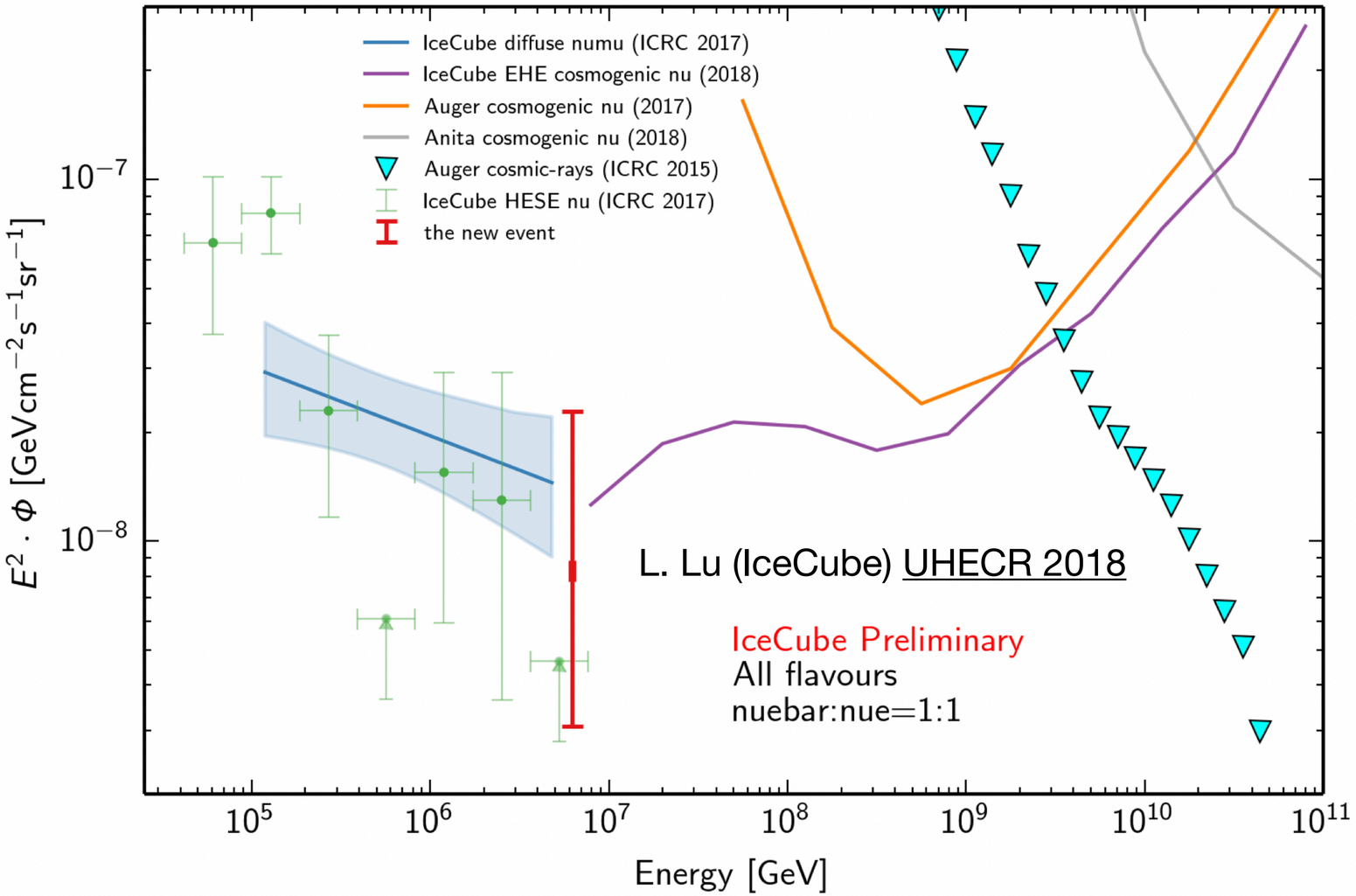

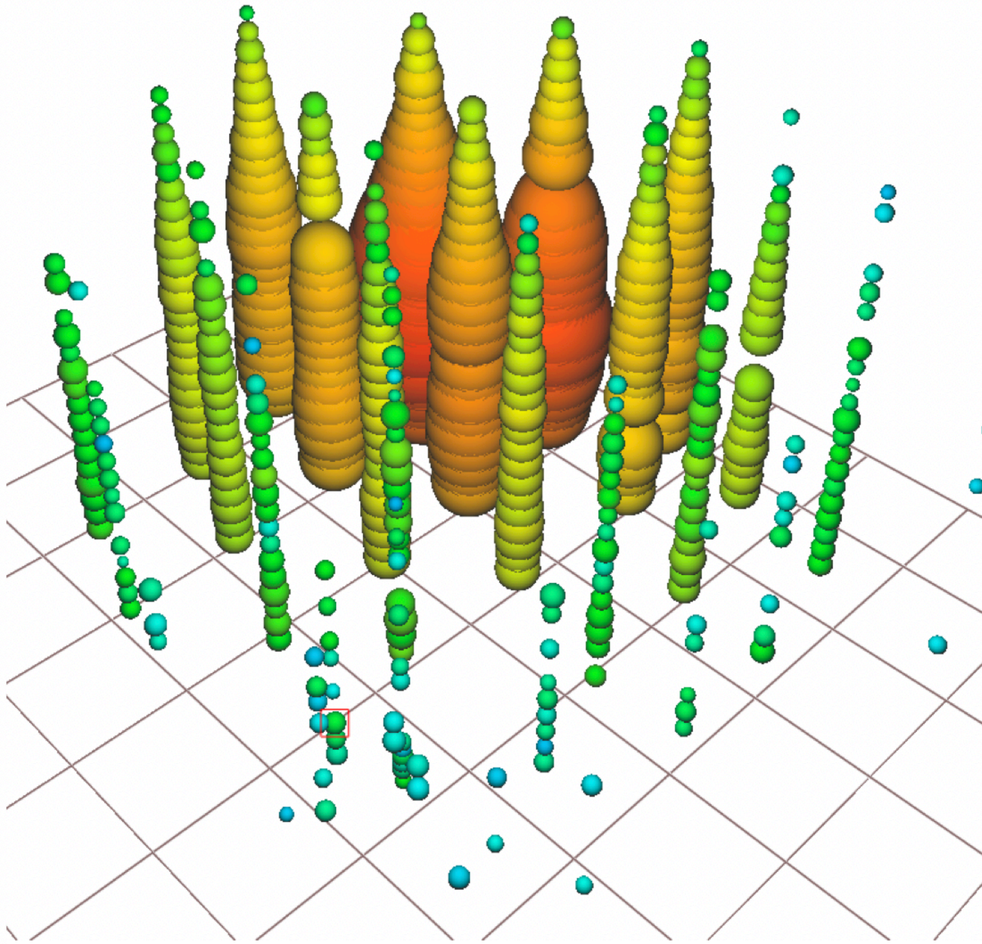

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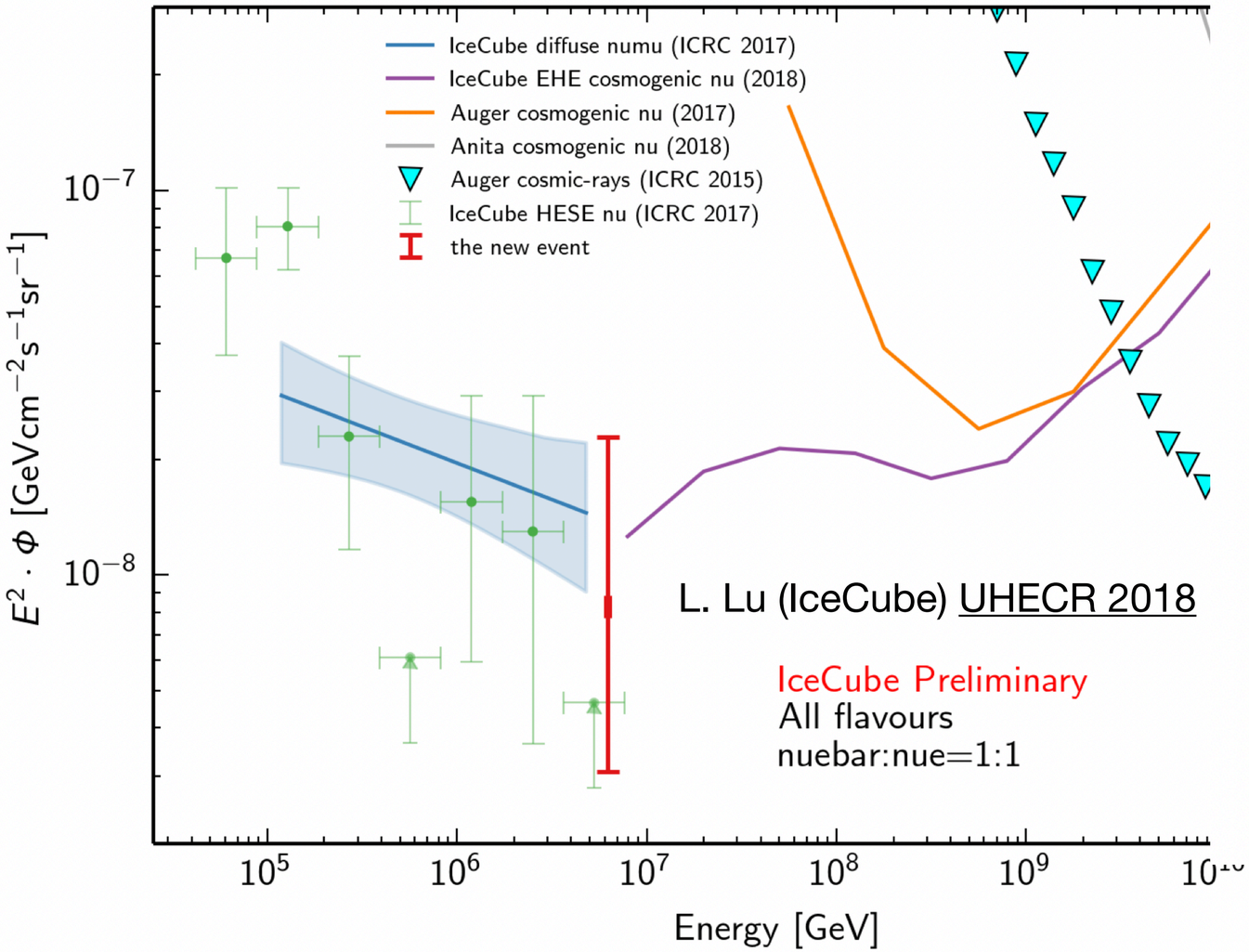

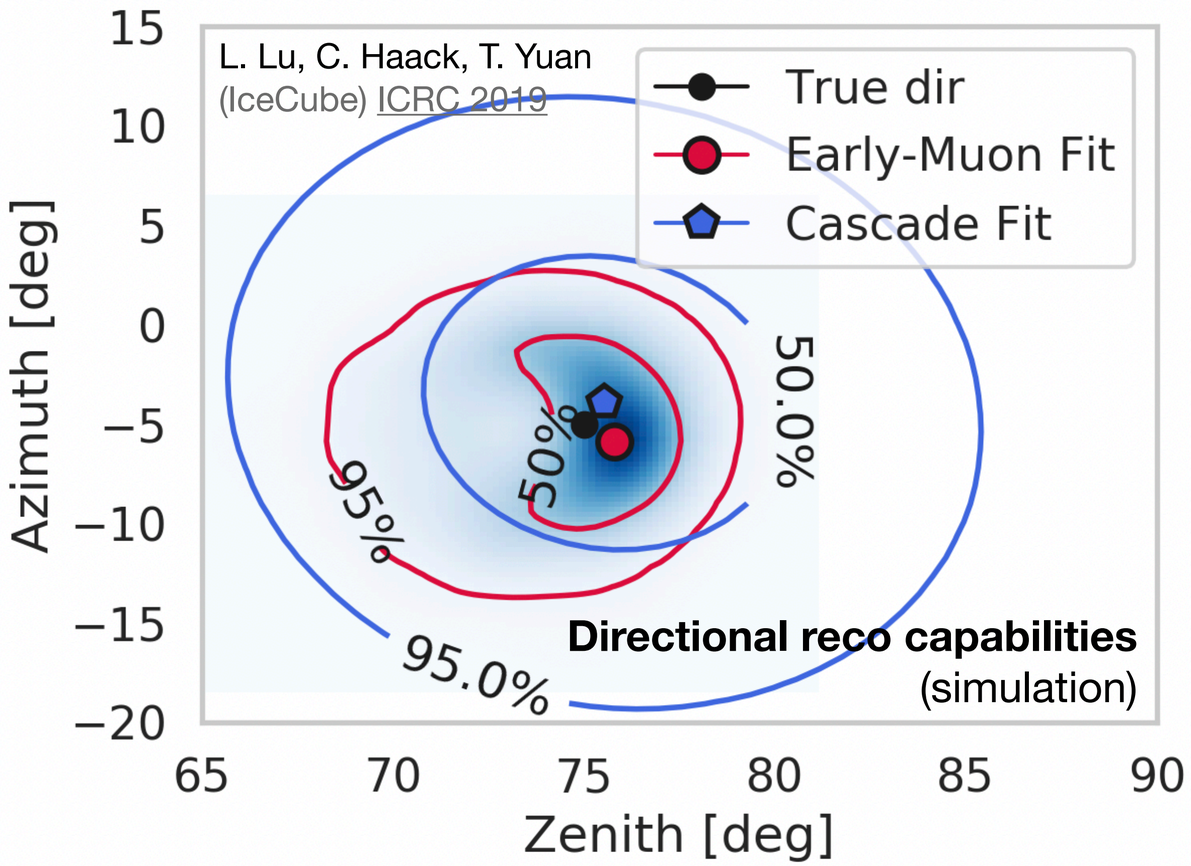

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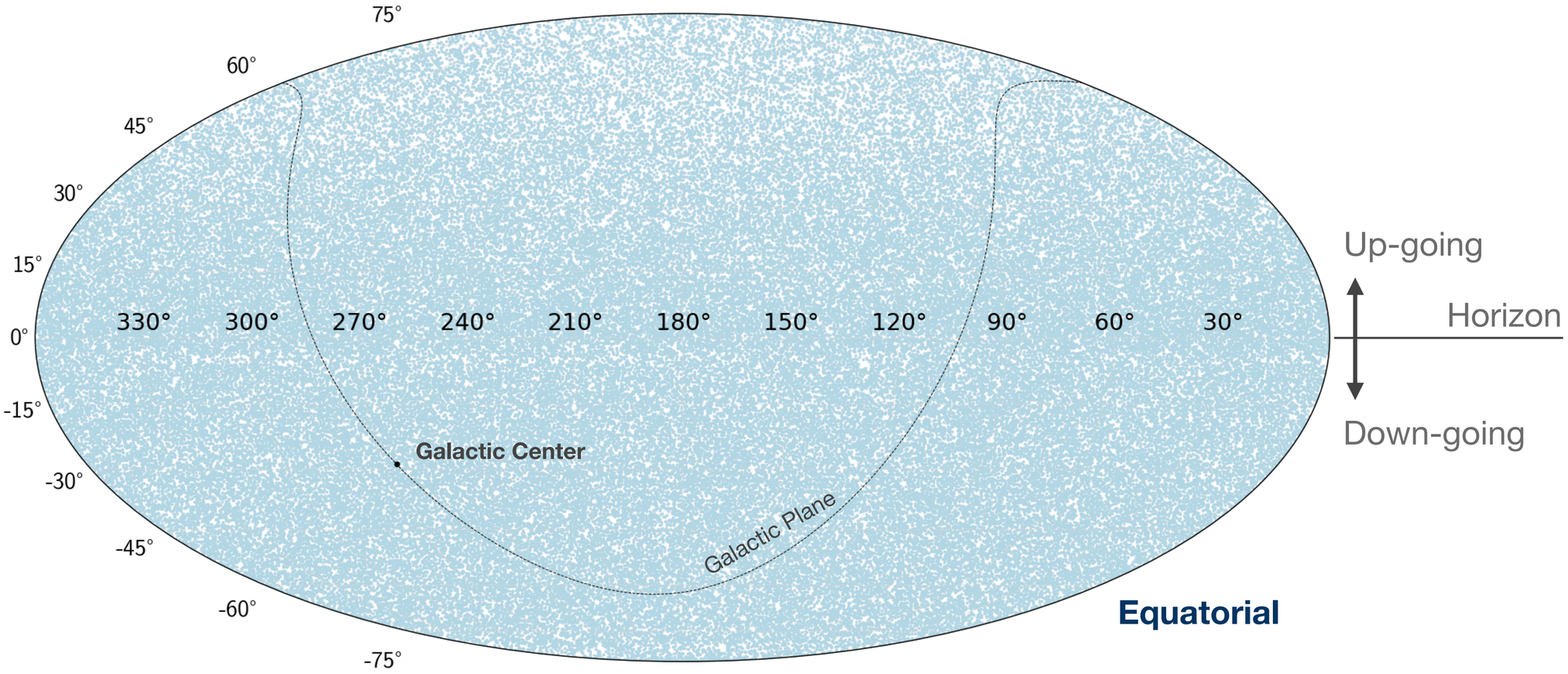
One year of IceCube neutrinos

https://icecube.wisc.edu/science/data/PS-IC86-2011



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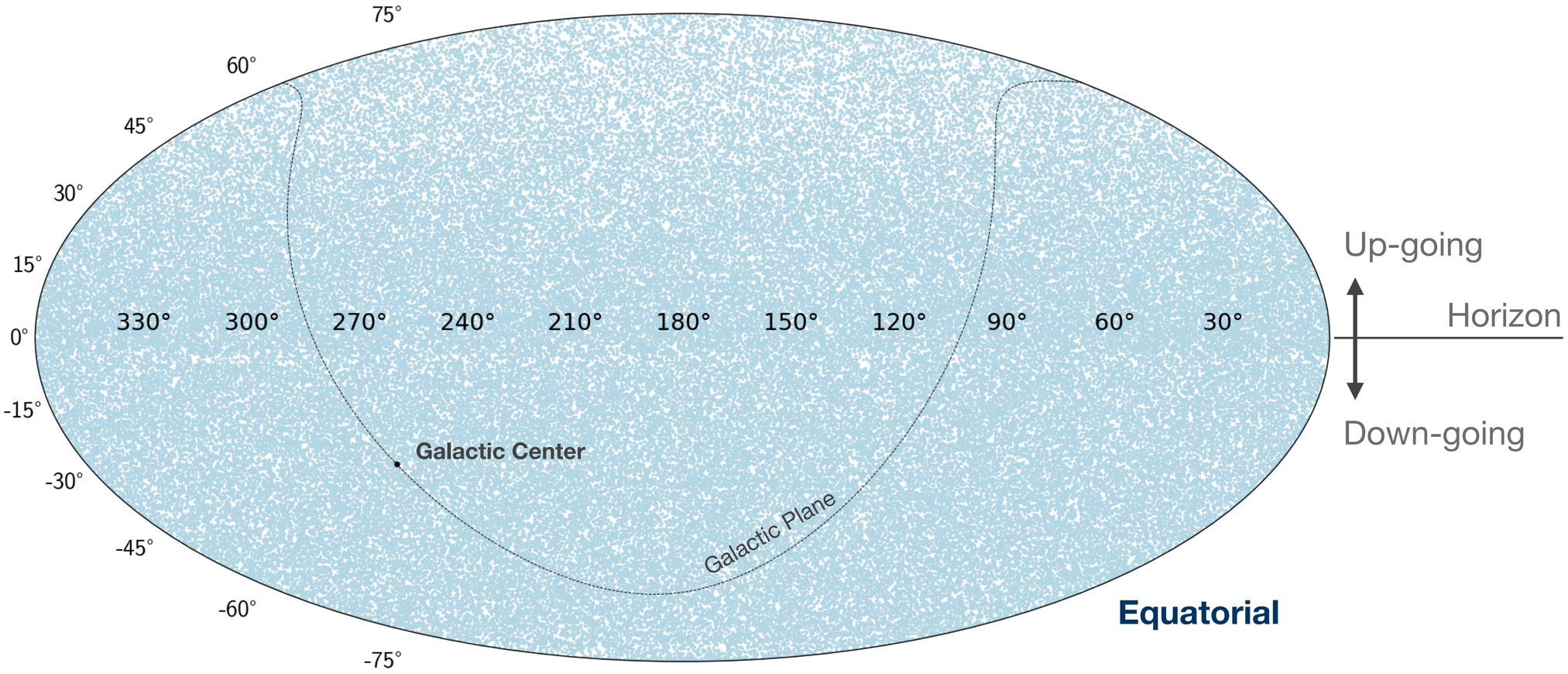

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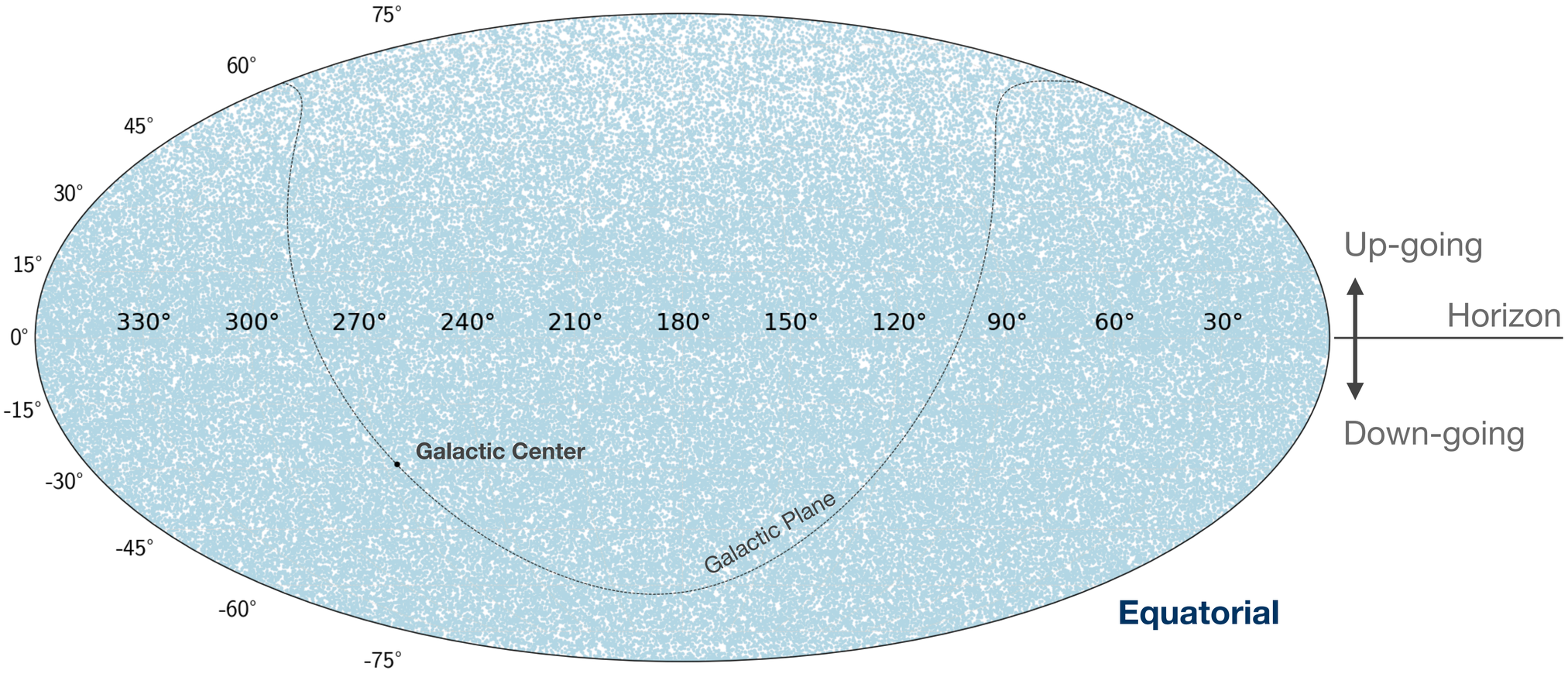

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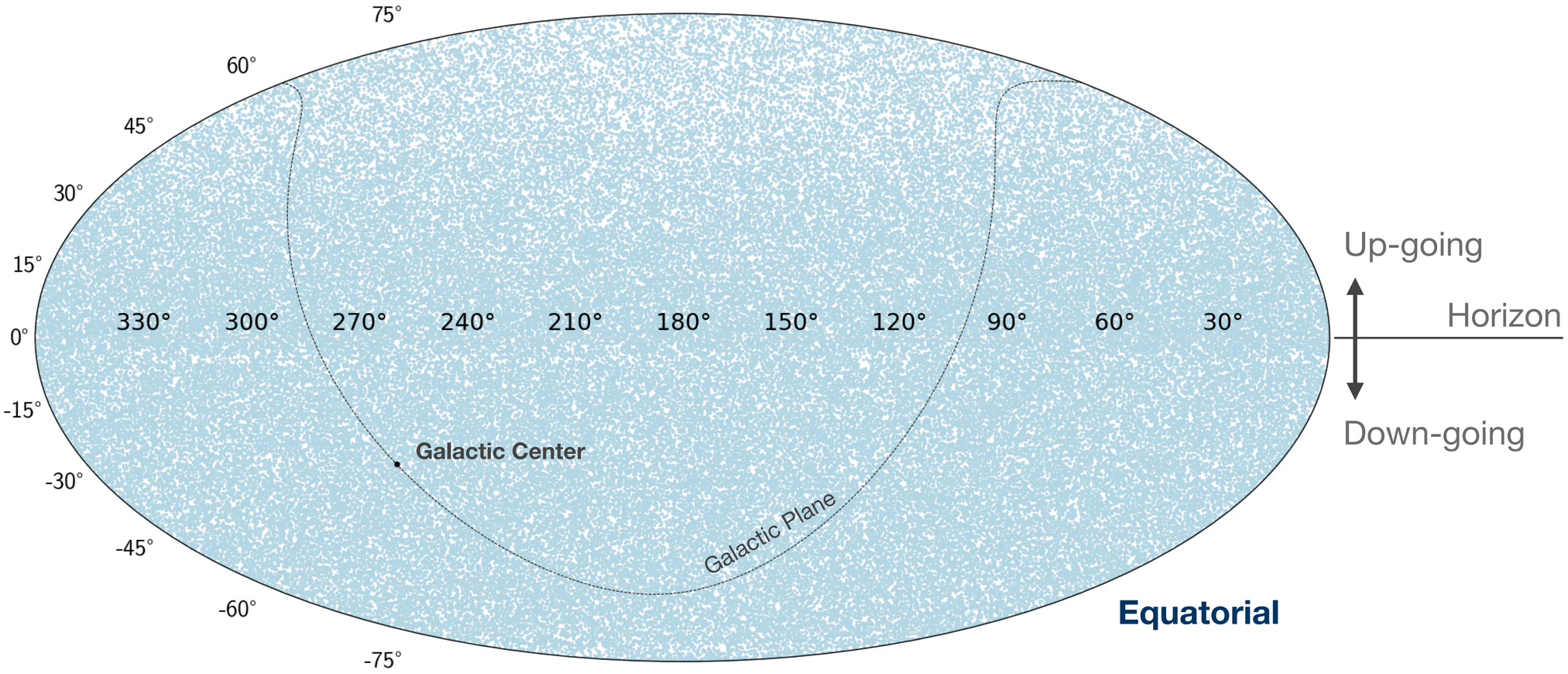

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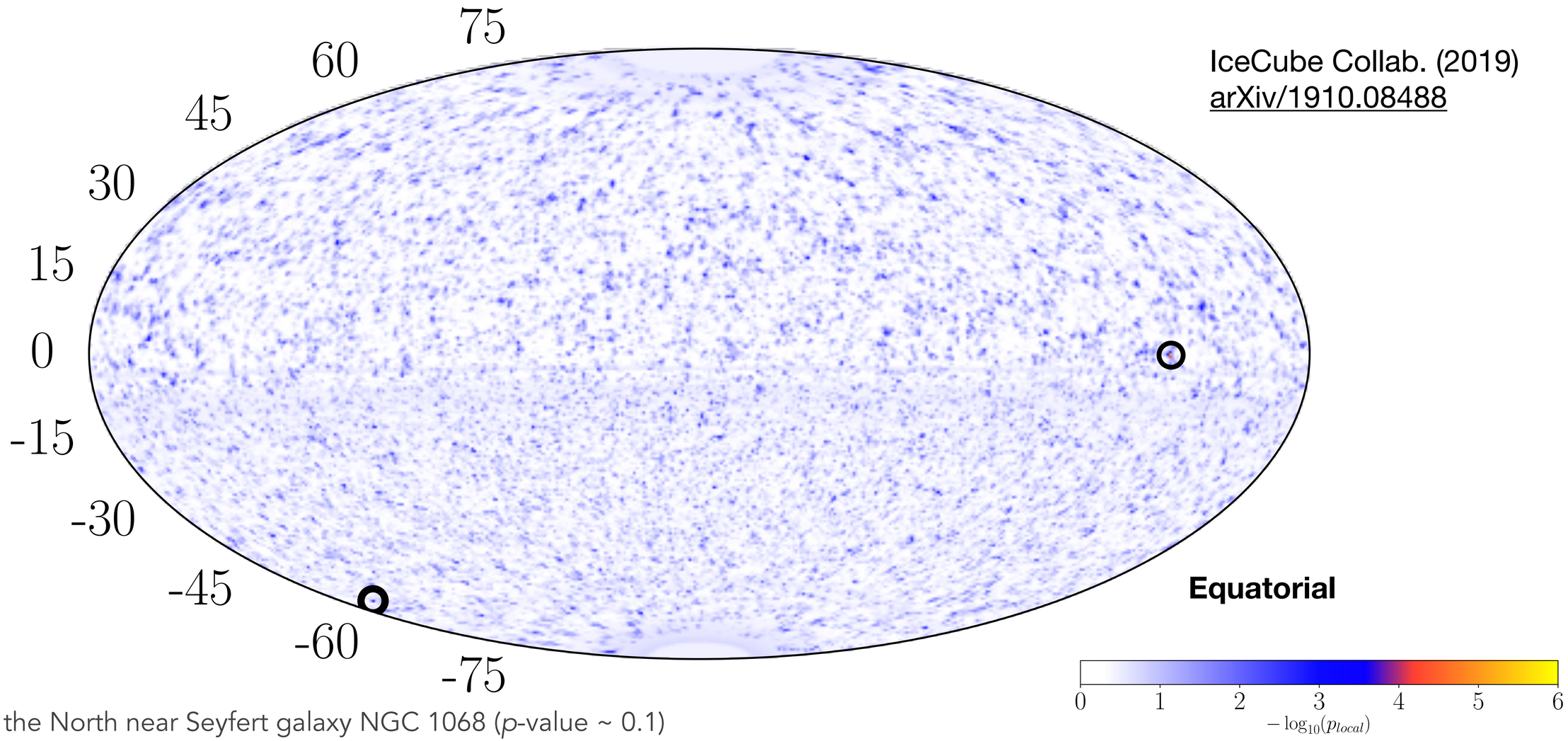
- **Search for neutrino self-clusterings that evidence a point source.**

Search for point sources in 10 years of IceCube data

IceCube Collab. (2019)
arXiv/1910.08488



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- Excess at NGC 1068 location: **2.9σ**
- **3.3σ** from a source catalog search

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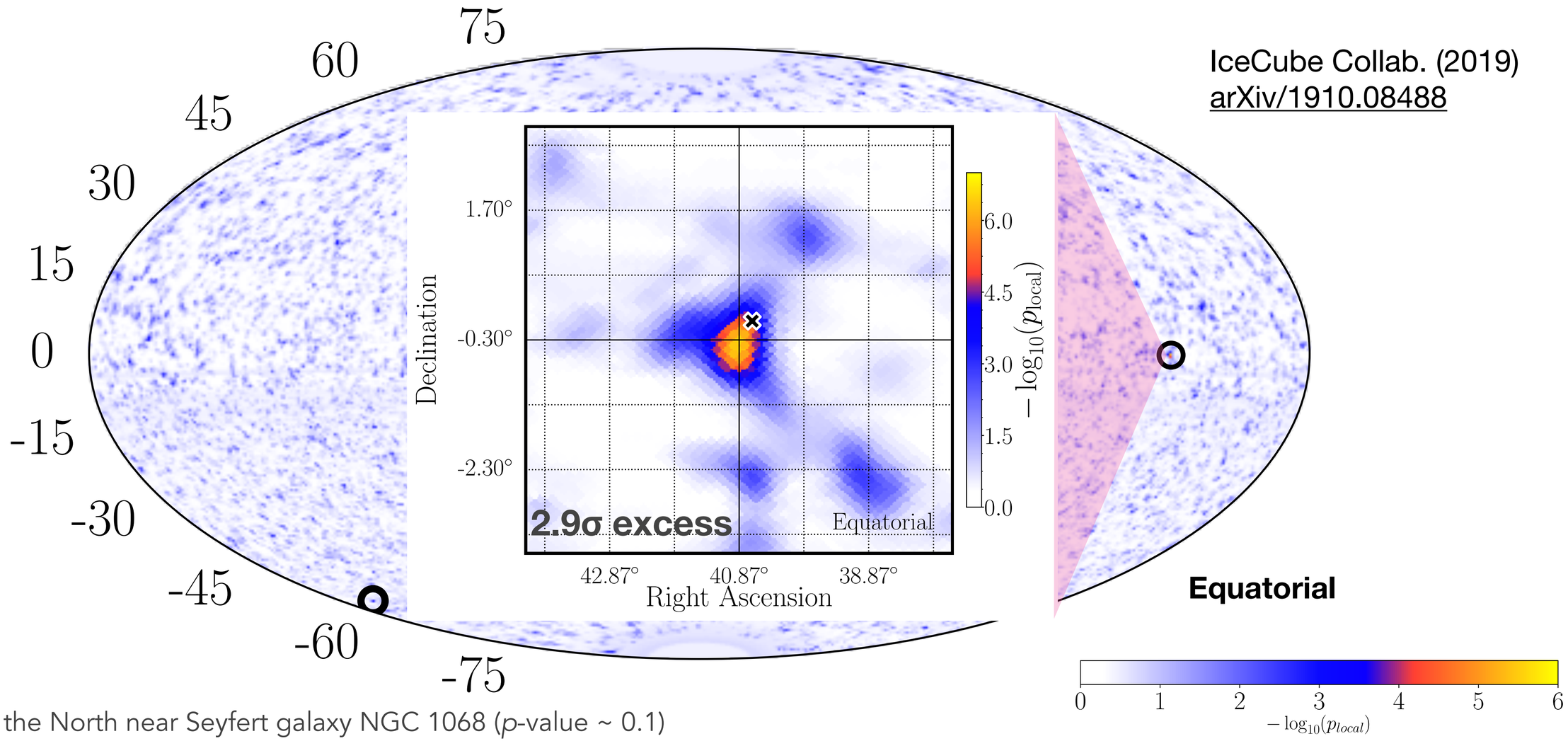

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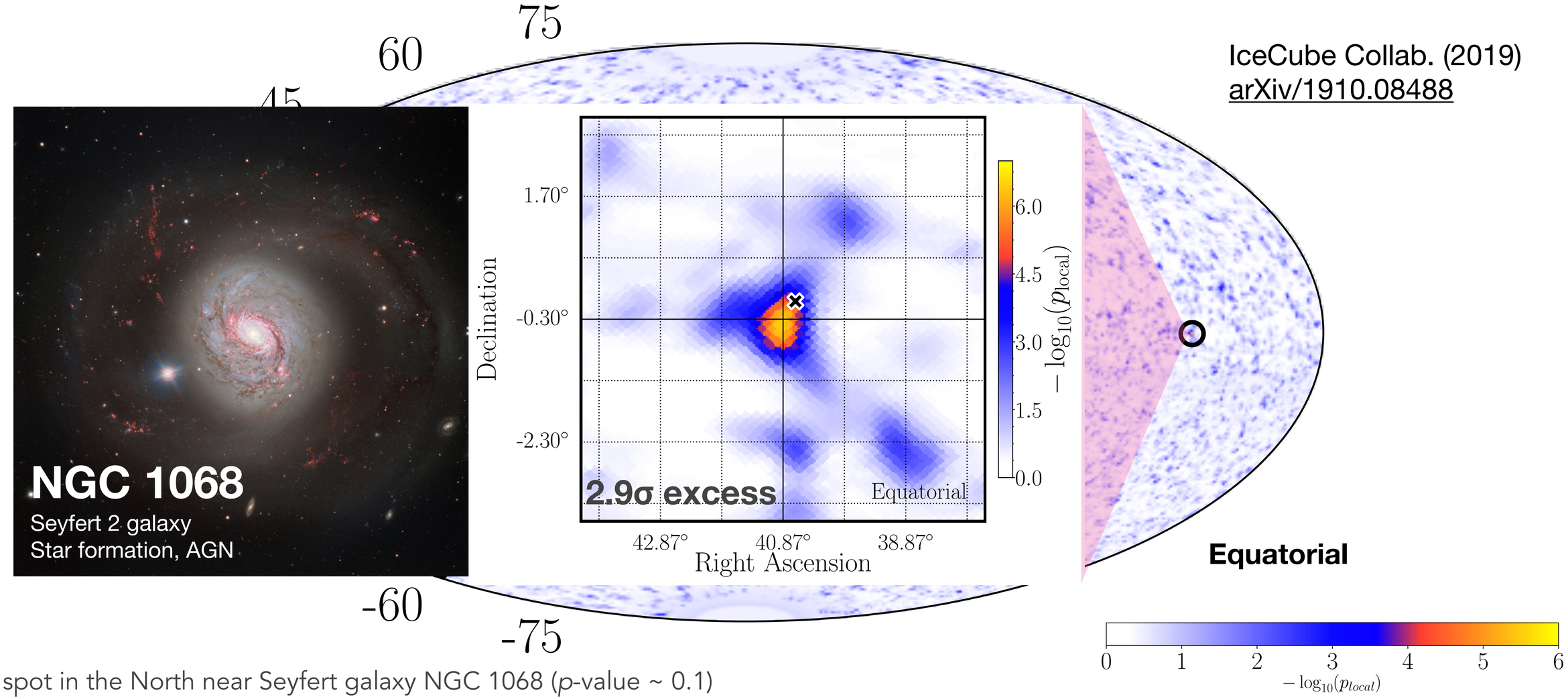
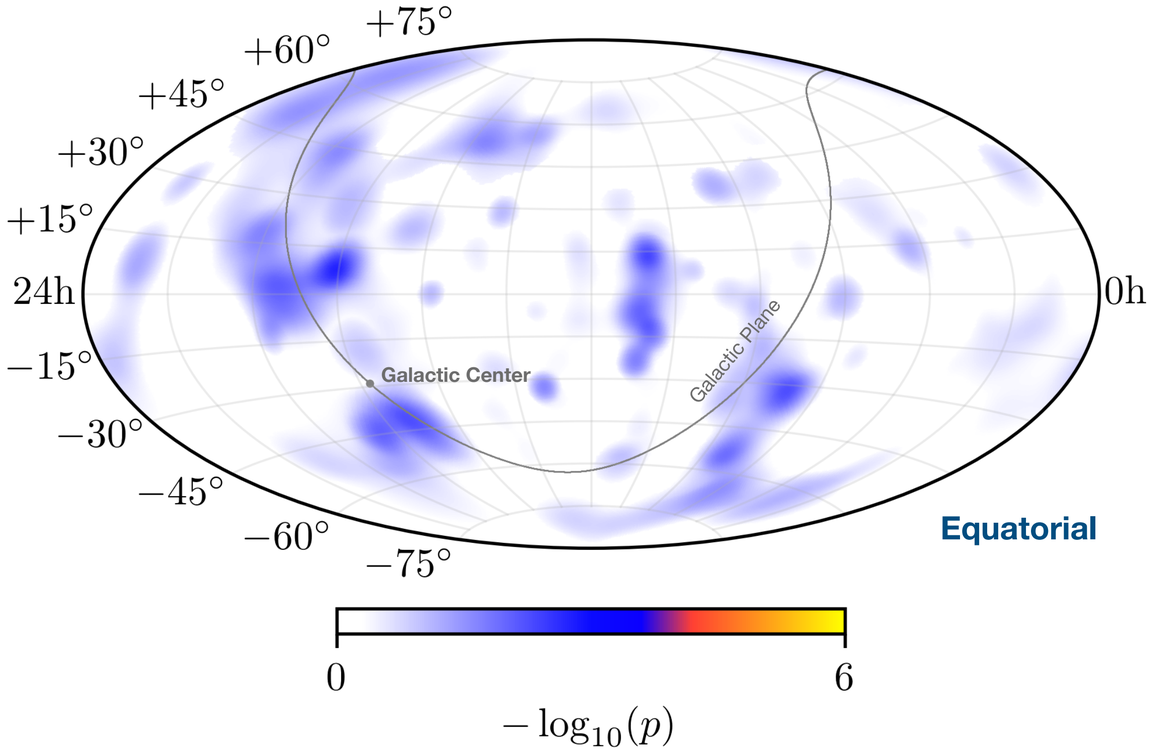


- Hottest spot in the North near Seyfert galaxy NGC 1068 (*p*-value ~ 0.1)
- Excess at NGC 1068 location: **2.9σ**
- **3.3σ** from a source catalog search

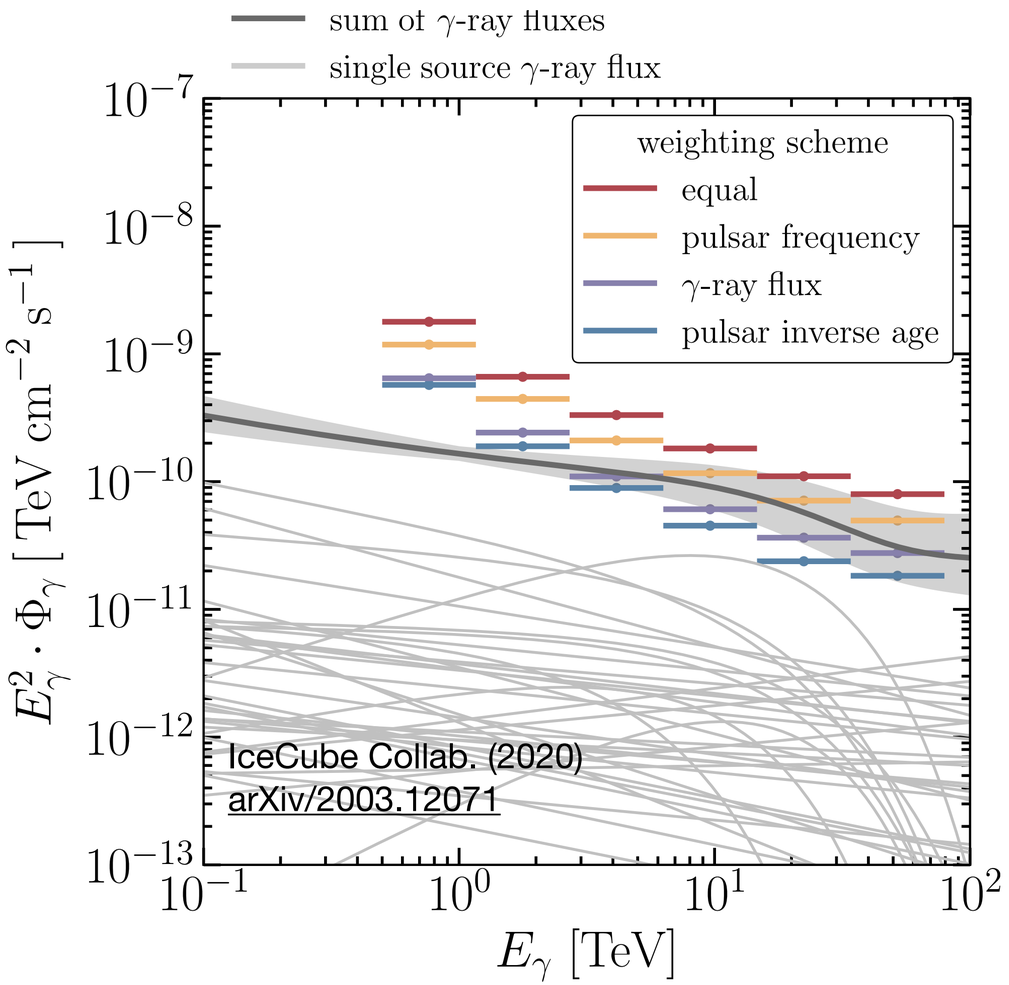
Targeted searches & new methods

Search for sources using 7 years of cascade

IceCube Collab. (2019)
arXiv/1907.06714

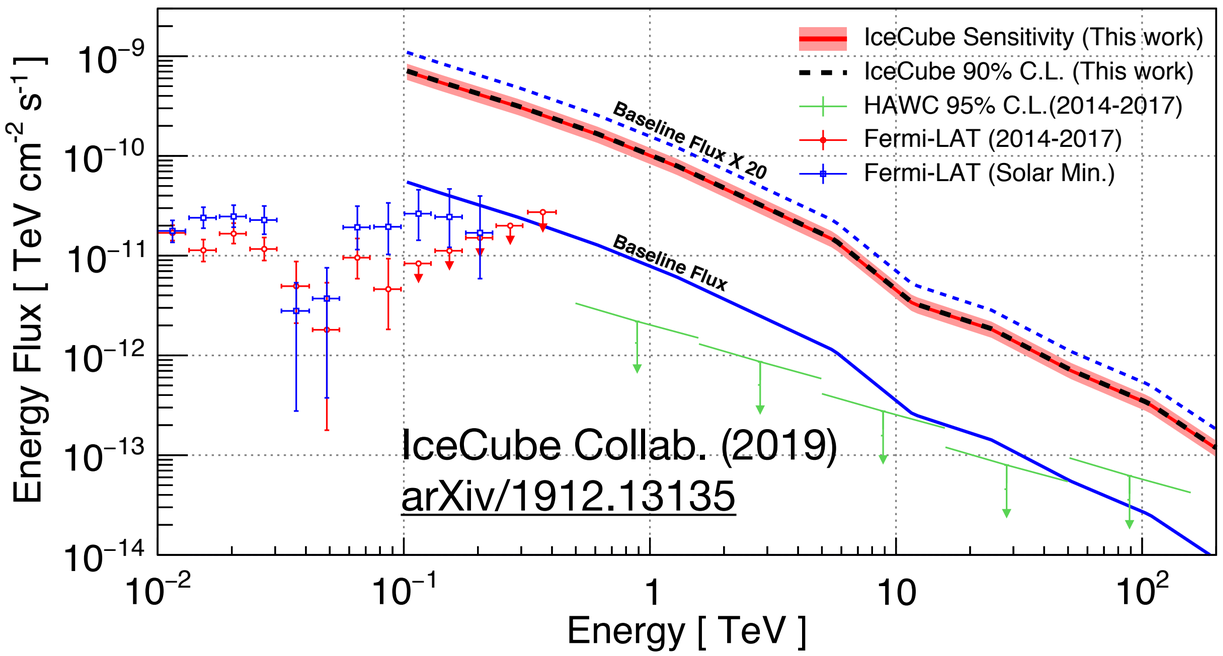


Limits on neutrinos from pulsar wind nebulae



Targeted searches & new methods

Search for neutrinos from CR interactions in the Sun



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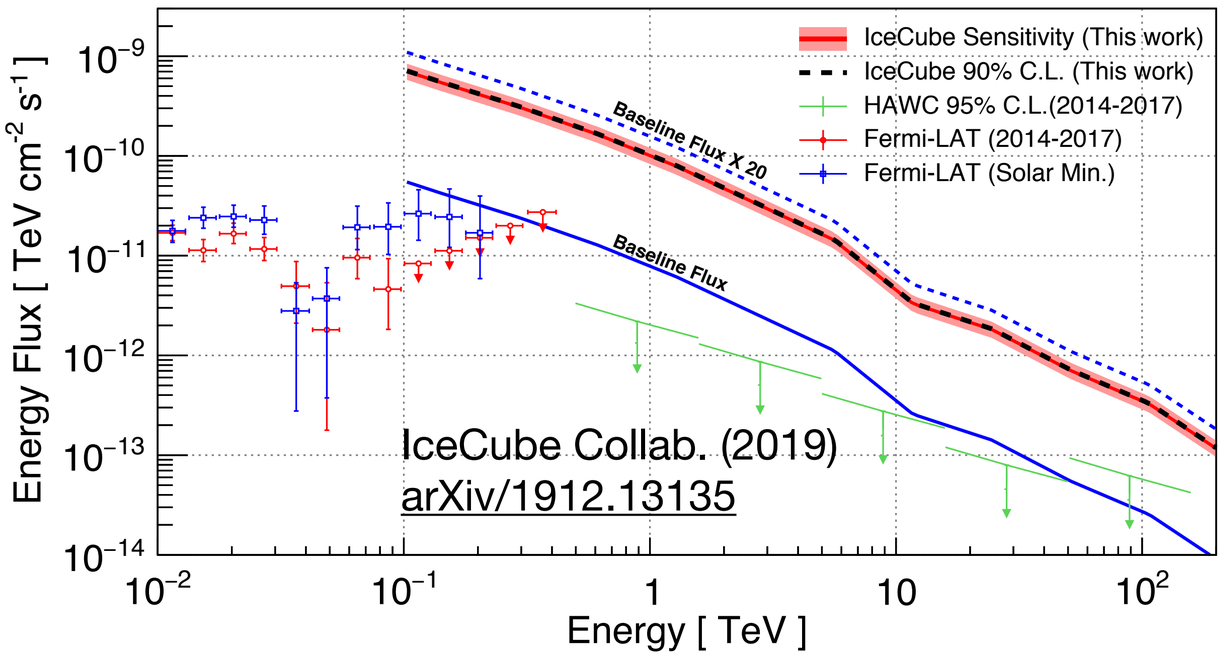

Many recent results not shown!

Many ongoing searches for neutrino emission from known Galactic and extragalactic objects.

Constraints on the contribution of known sources to the all-sky flux.

New searches. **Check out our posters!**

Targeted searches & new methods

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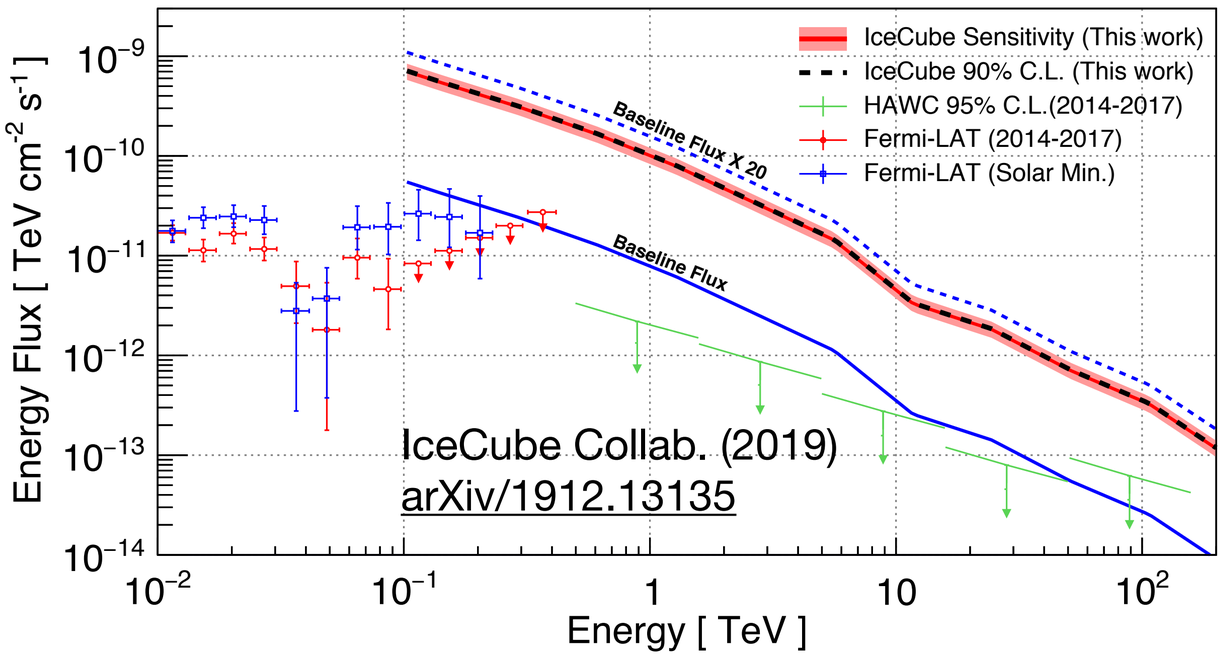

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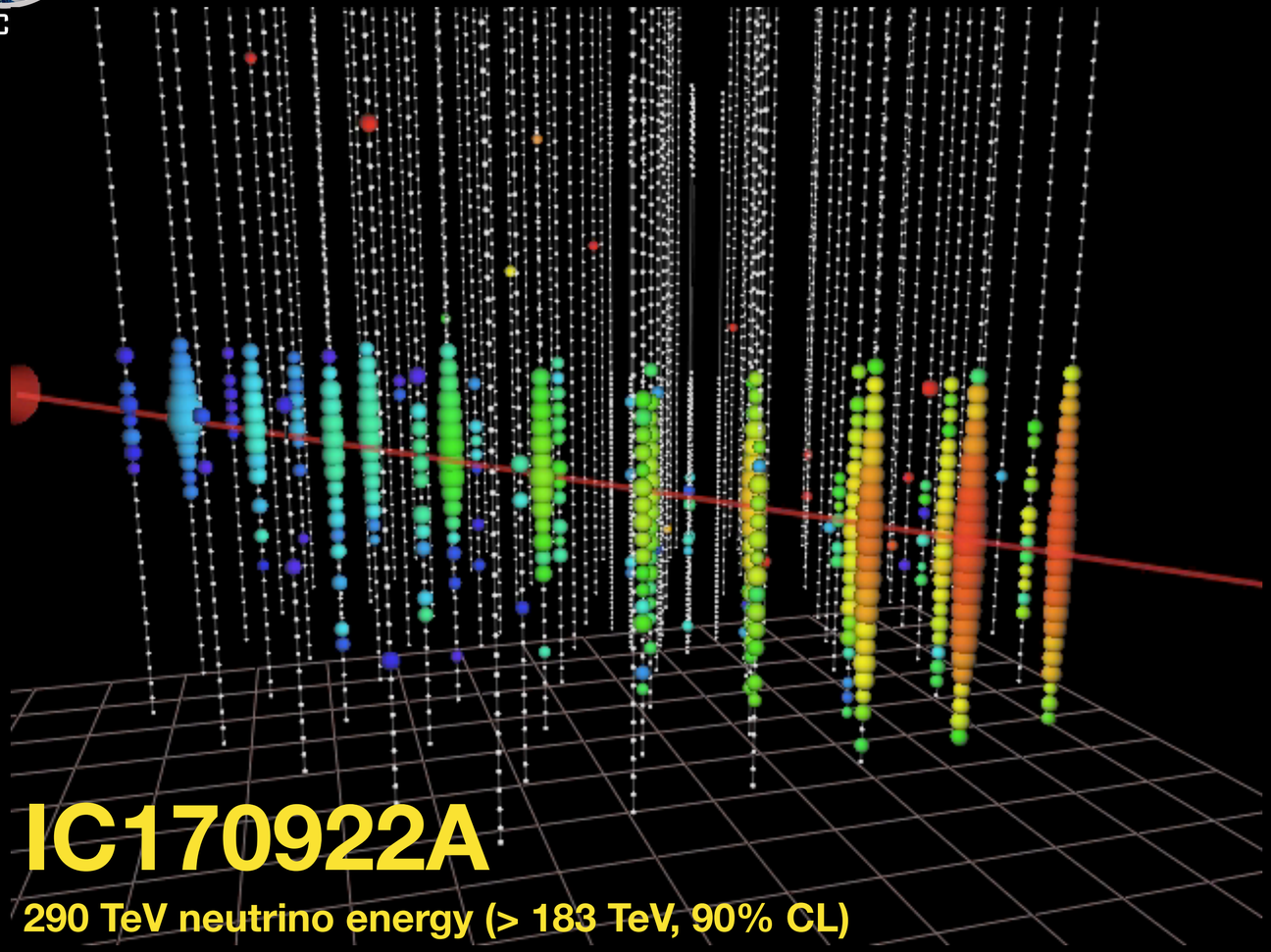
New searches. **Check out our posters!**

- Galactic SN: S. Griswold (#162)
- Searches using starting southern tracks: S. Mancina & M. Silva (#165)
- Sources in the local universe: E. Bourbeau & S. Sclafani (#168)
- GeV transients in DeepCore: C. Chen & I. Taboada (#266)
- Gamma-ray bursts: E. Friedman (#279)
- Low-energy transients: M. Larson (#280)
- Radio AGN: A. Desai et al. (#305)
- Rapid response with IceCube (E. Bernardini et al. (#339)
- Fast optical transients (R. Naab, #359)
- X-ray binaries (Q. Liu et al., #402)
- CCSNe (J. Necker, #458)
- Galactic Center DM with ANTARES and IceCube (S. Gozzini et al. #466)
- ANITA events (A. Pizzuto et al., #476)
- Variability search (P. Dave & I. Taboada, #539)

IceCube realtime alerts



- Alert system implemented in **2016**
- Automatically circulated to the astronomical community a few minutes after detection at the South Pole.

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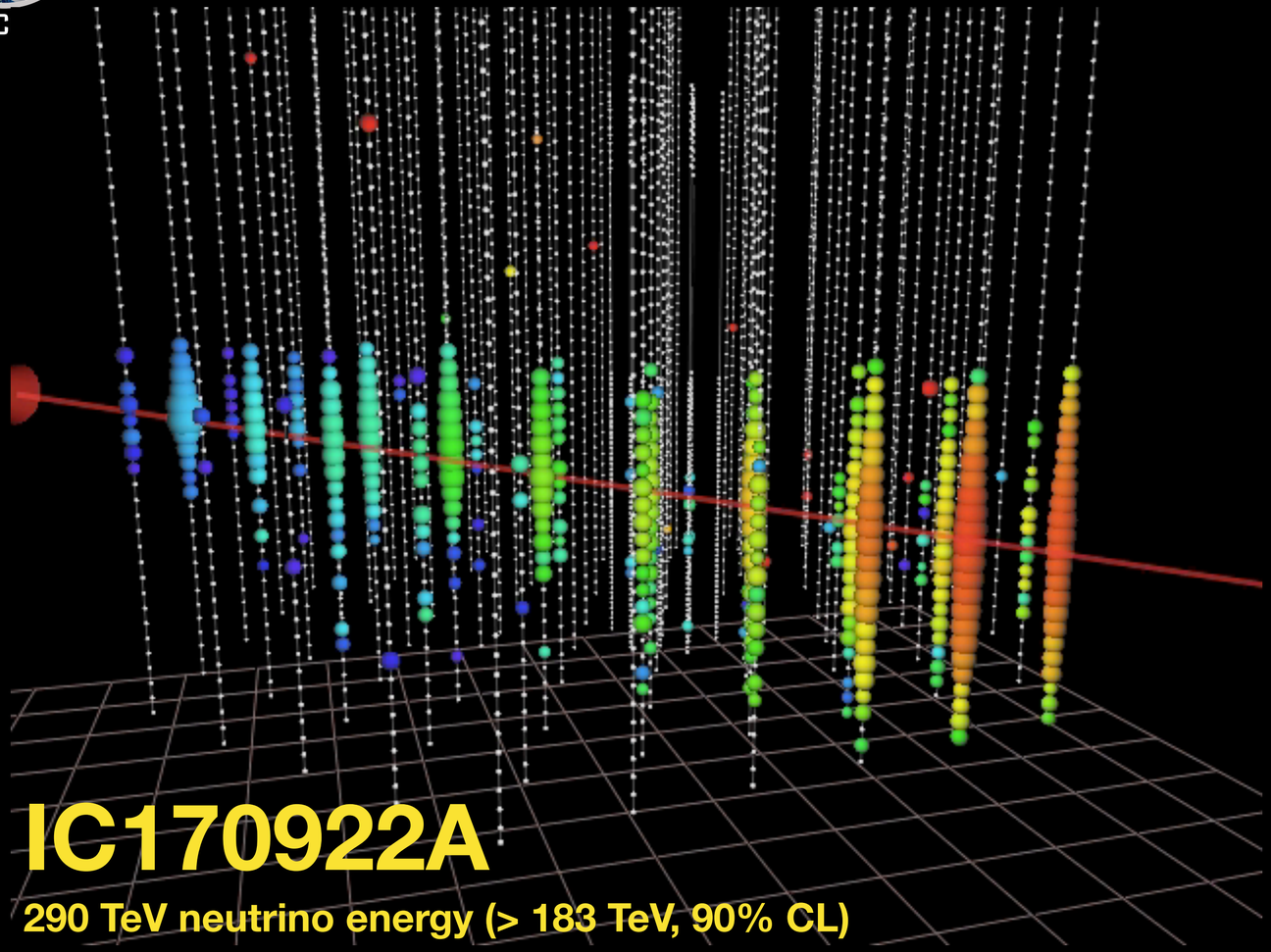

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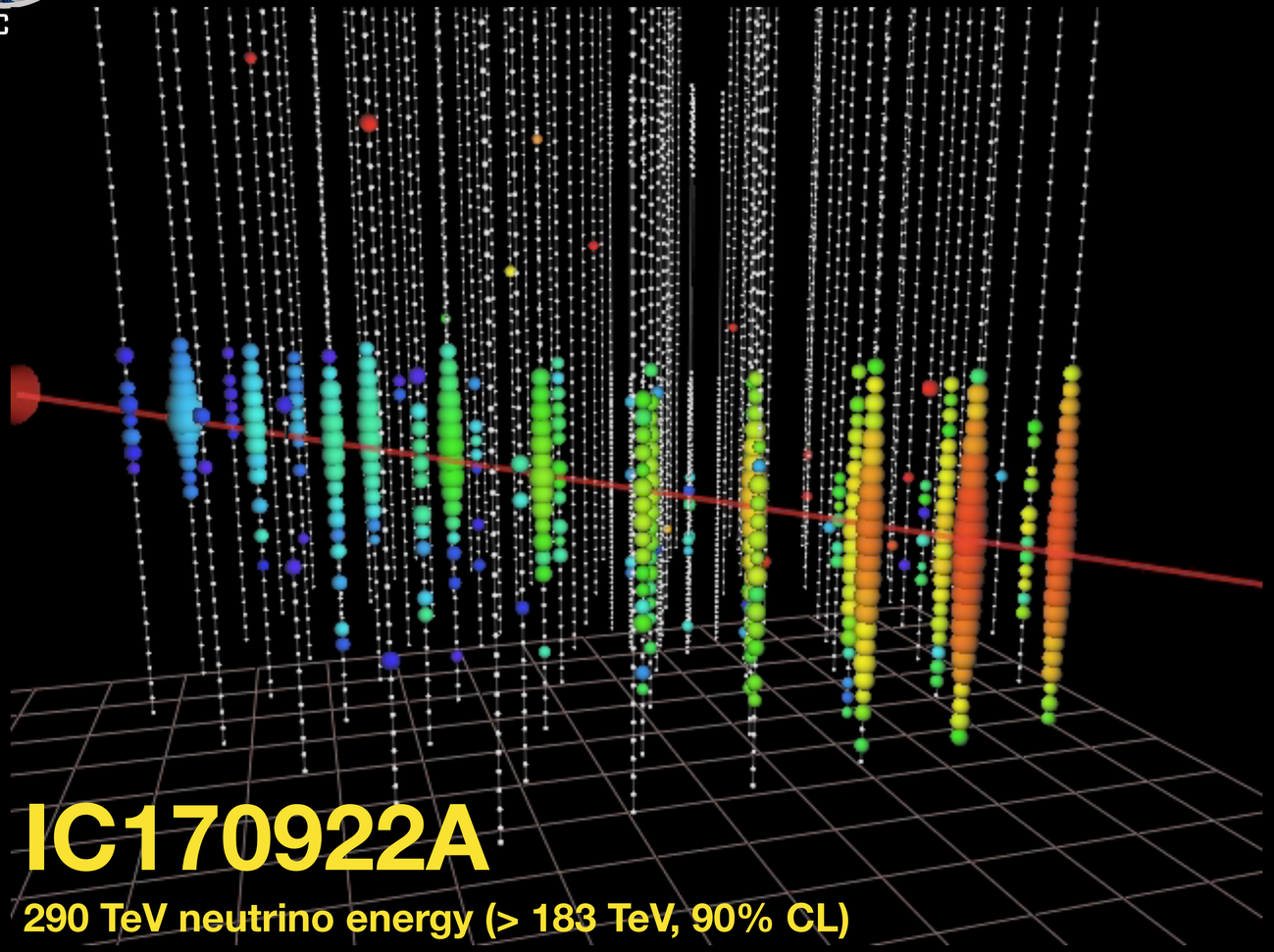

IC170922A

290 TeV neutrino energy (> 183 TeV, 90% CL)

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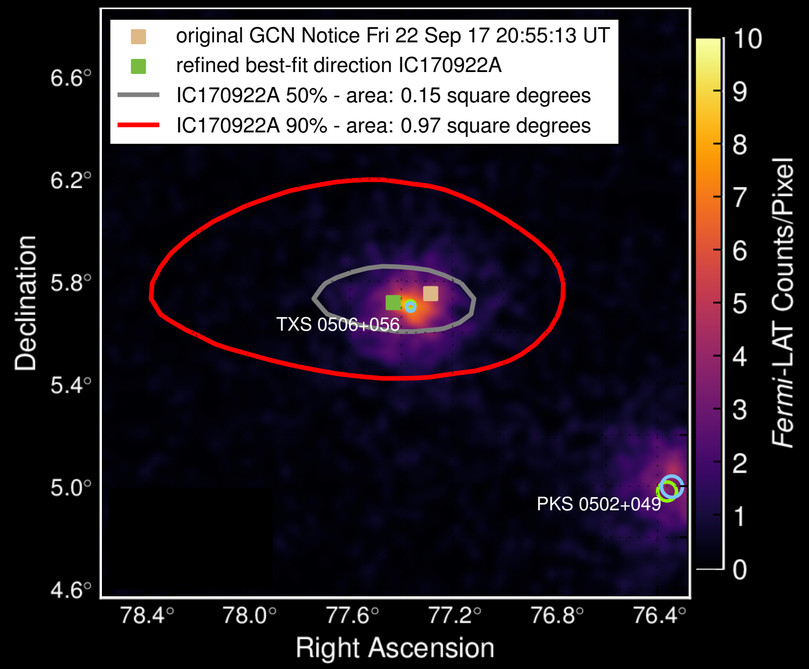
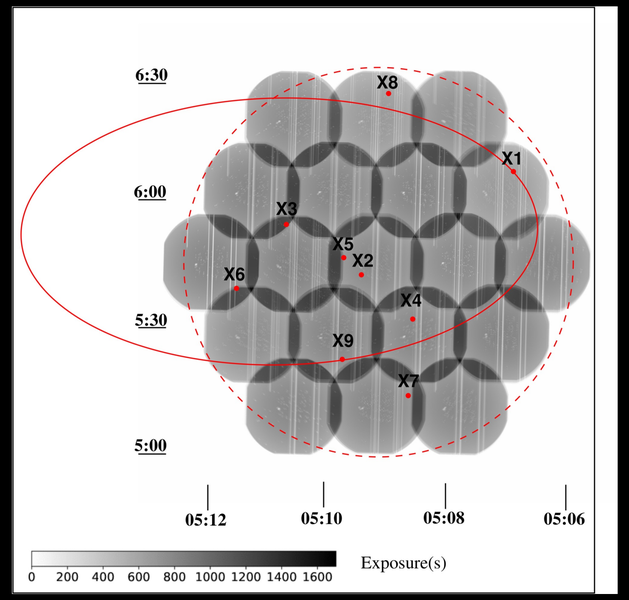
0.1 - 300 GeV



Fermi-LAT

0.3 - 10 keV



Swift-XRT

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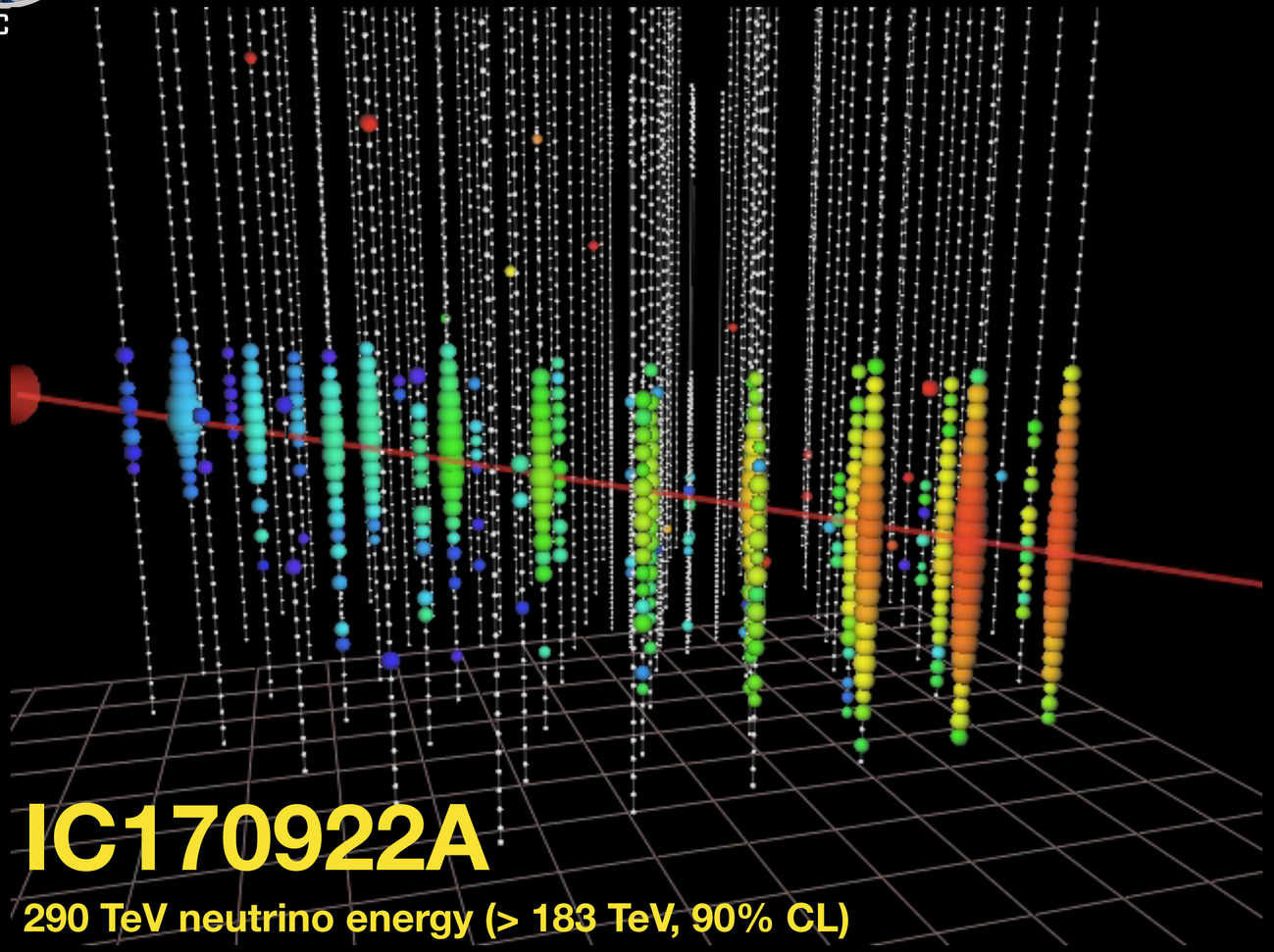

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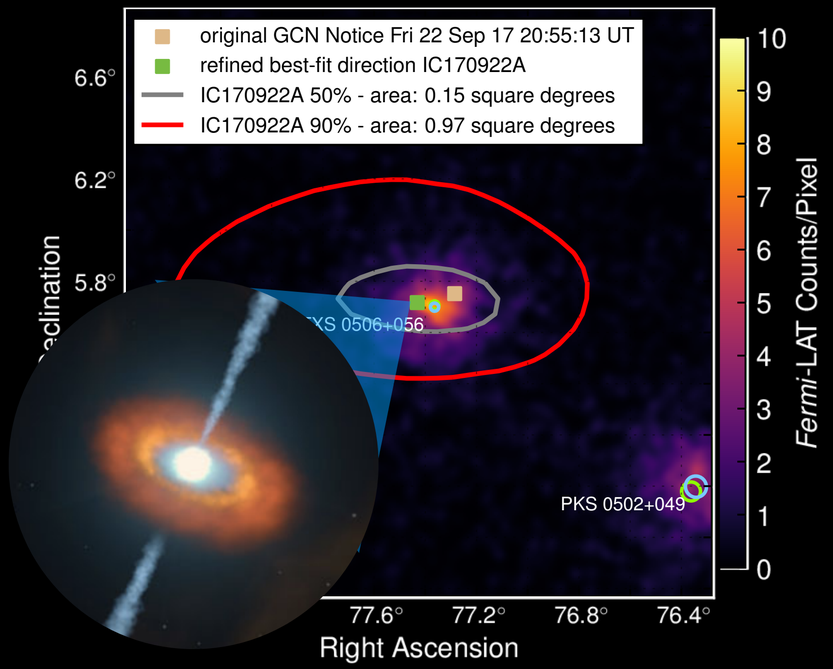

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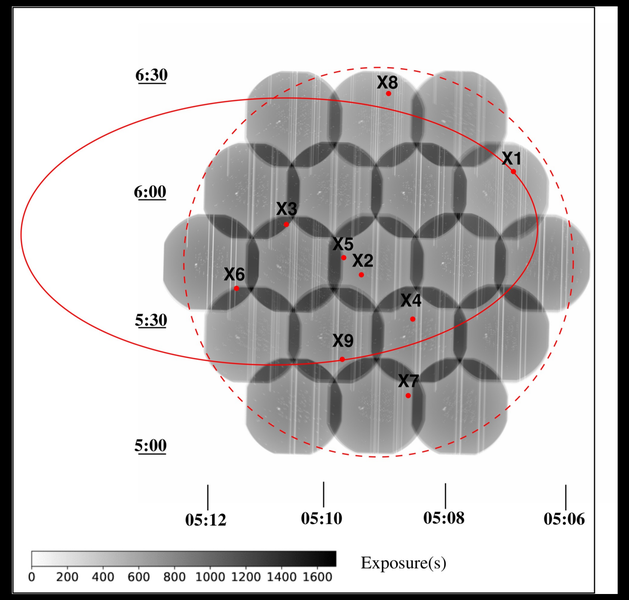
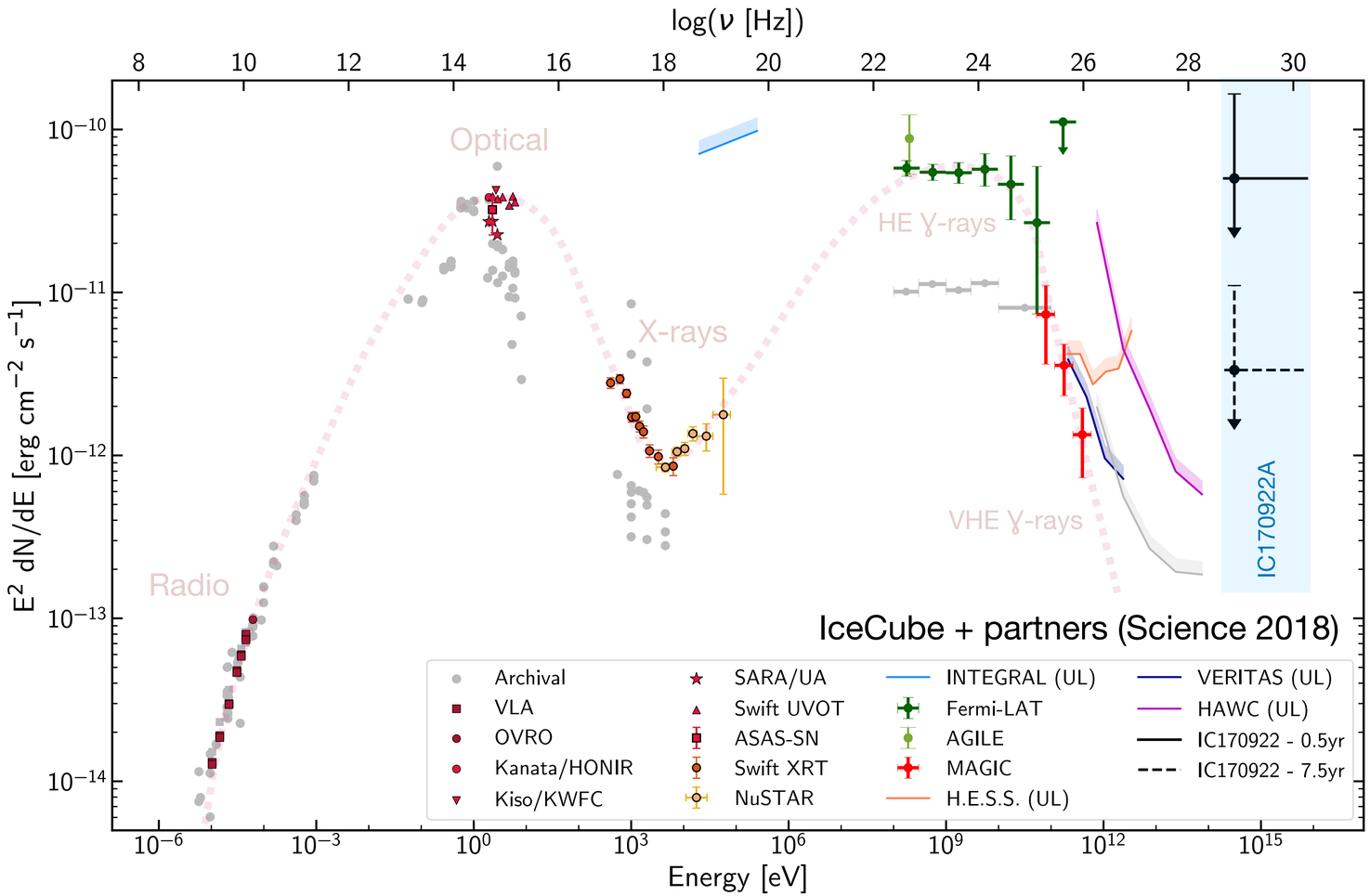
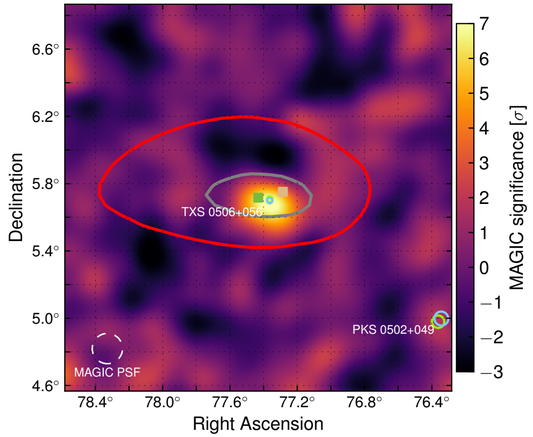


Swift-XRT

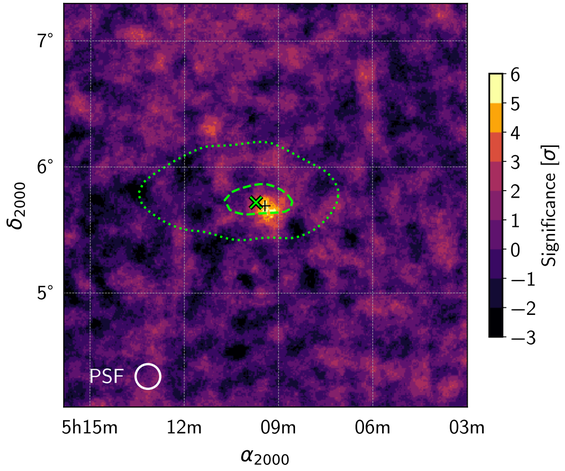
Photons from TXS 0506+056



VHE gamma rays



MAGIC (ApJL 2018)



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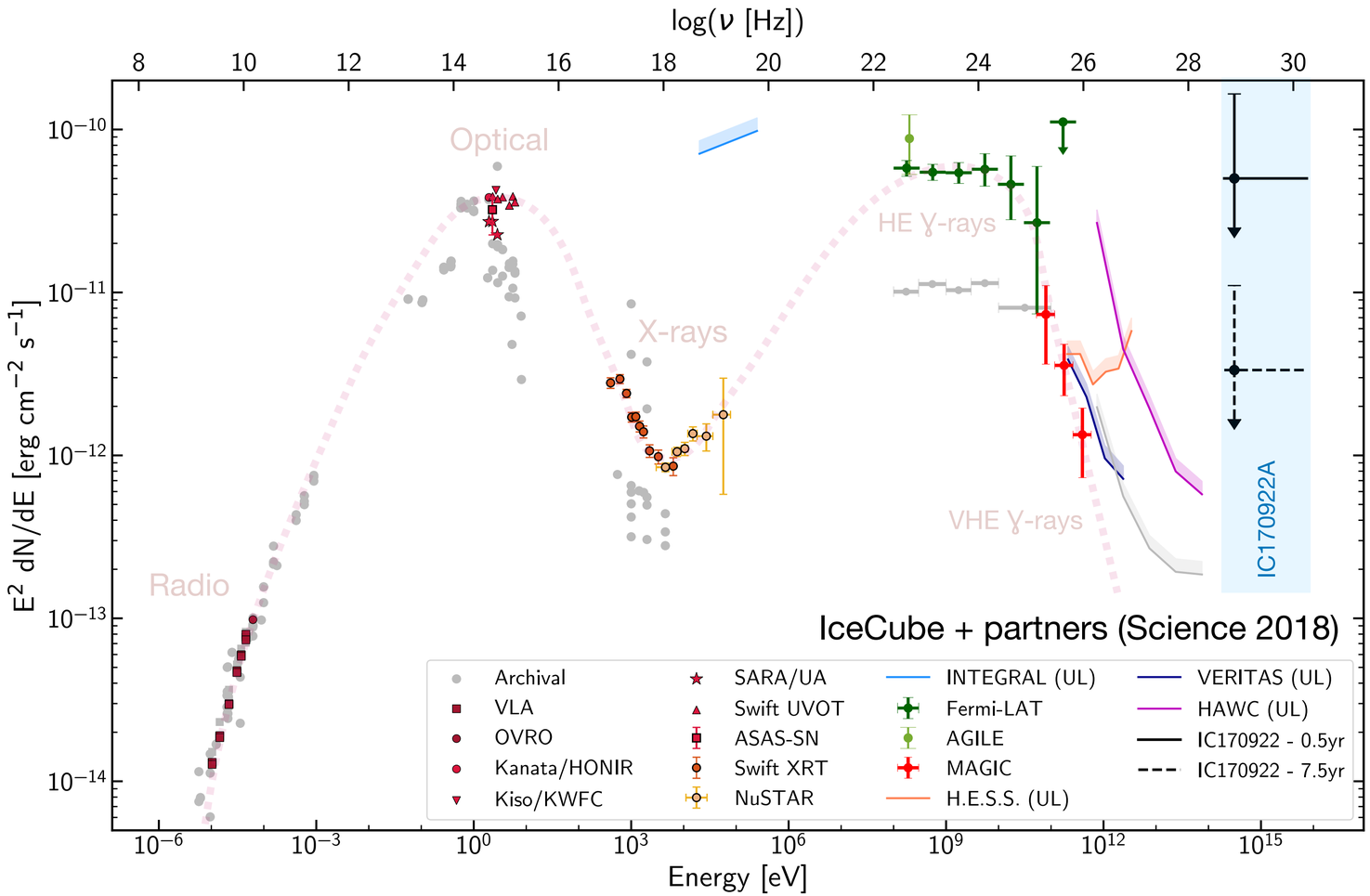

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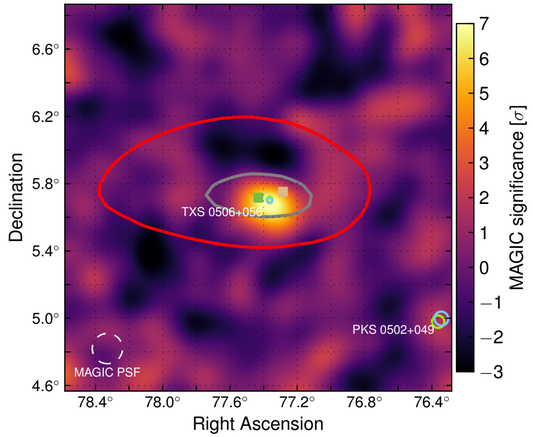

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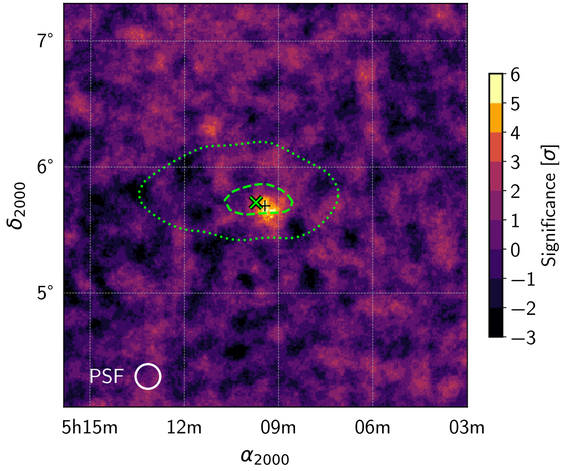

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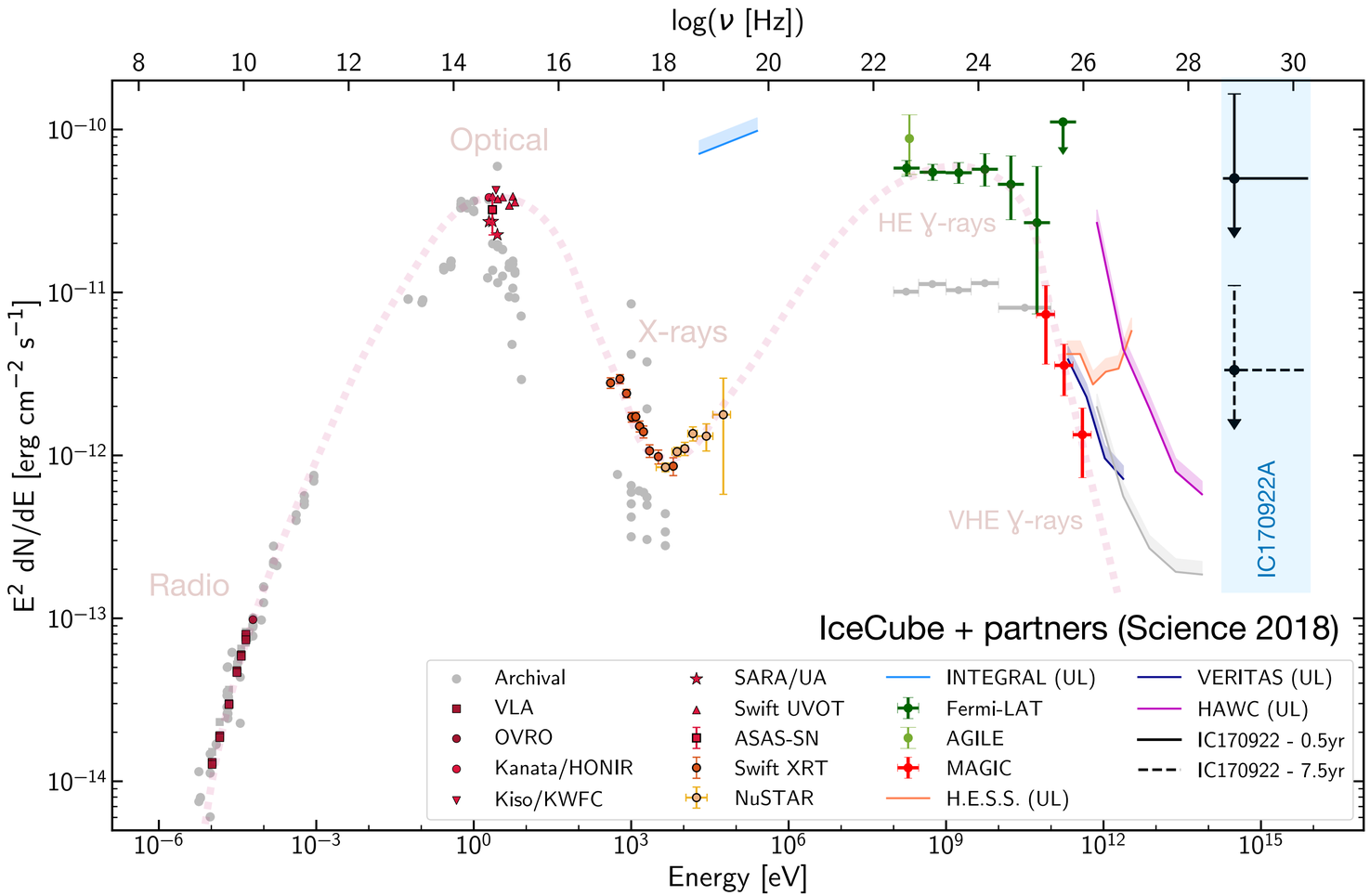

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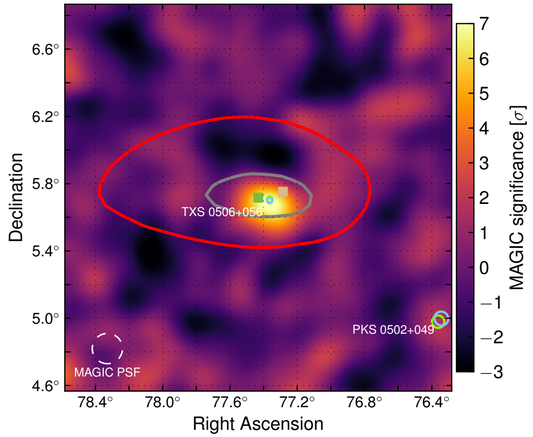

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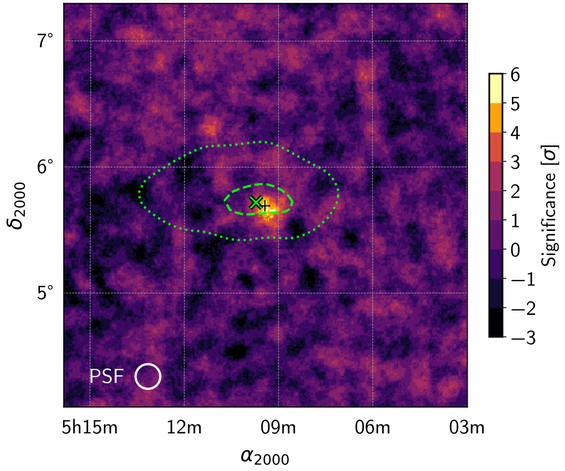

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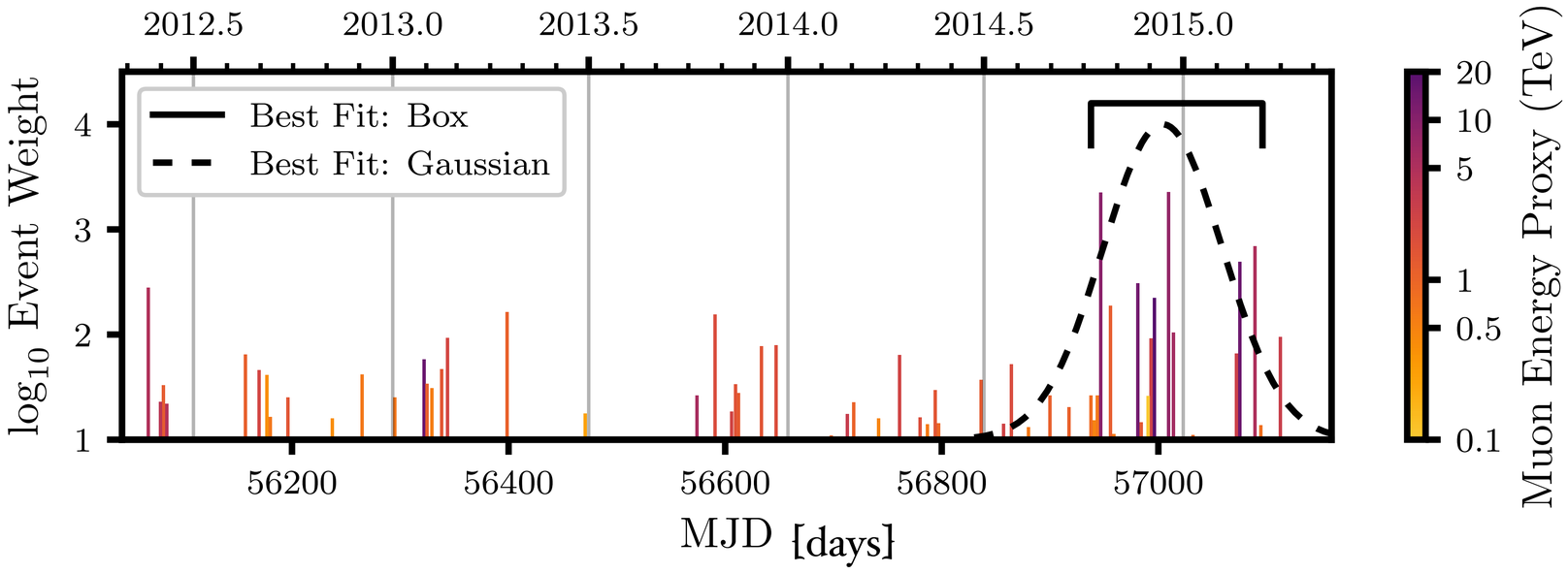
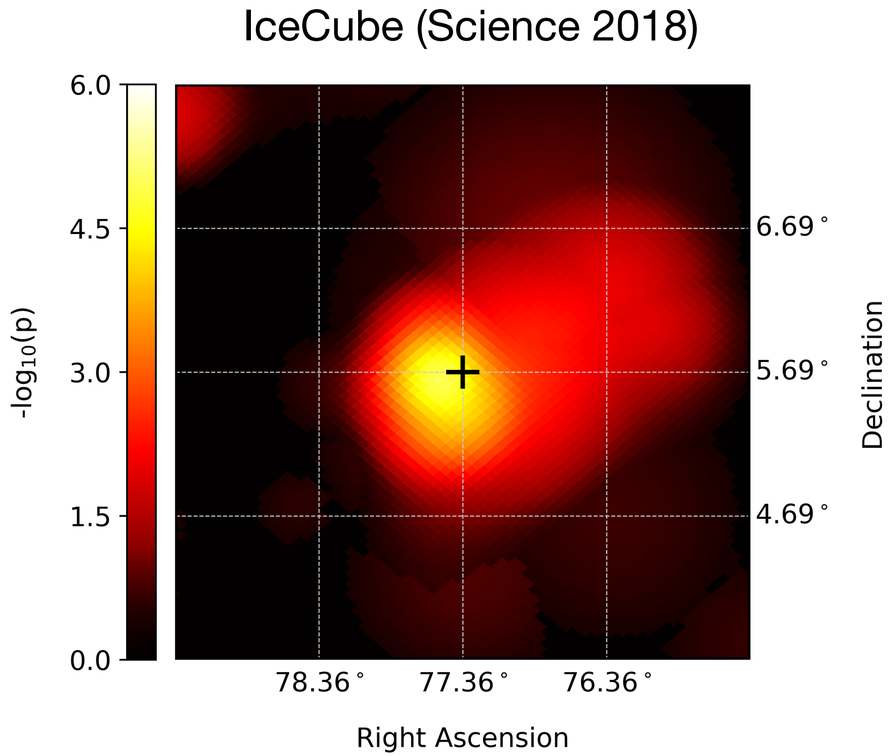
- **3σ chance coincidence correlation. Evidence for a connection between TXS 0506+056 and IC170922A.**

Archival neutrino search around TXS 0506+056





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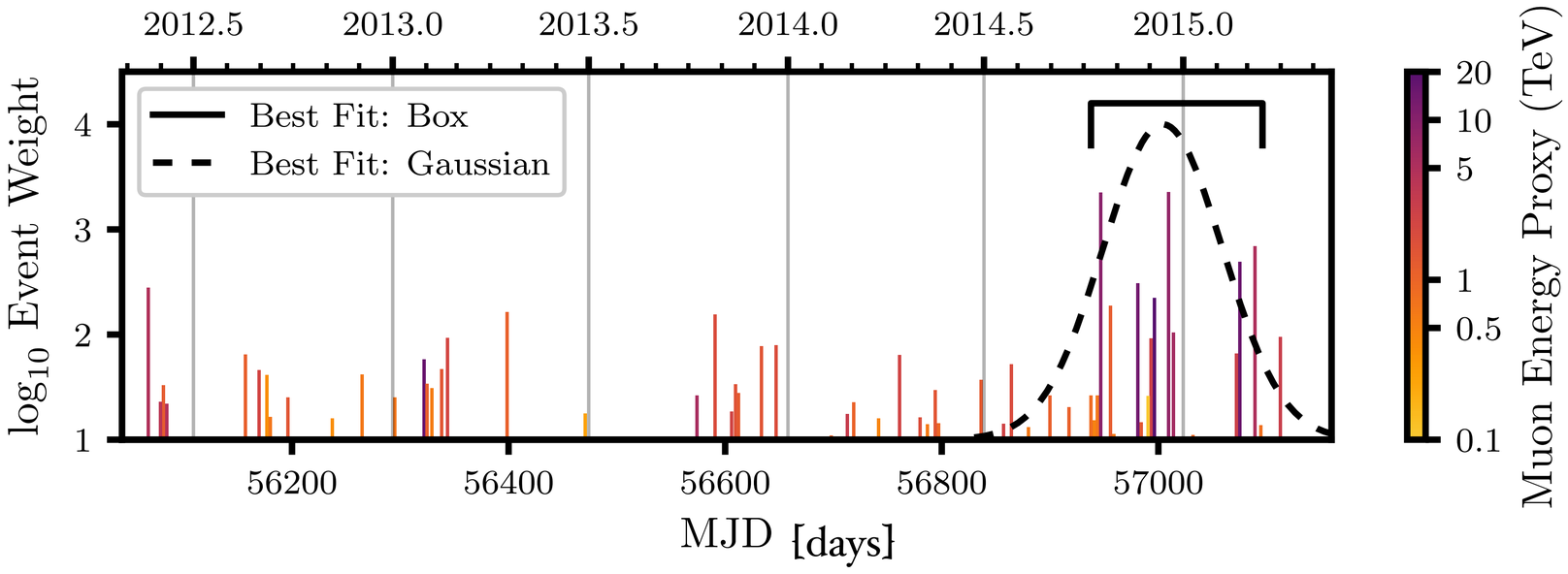

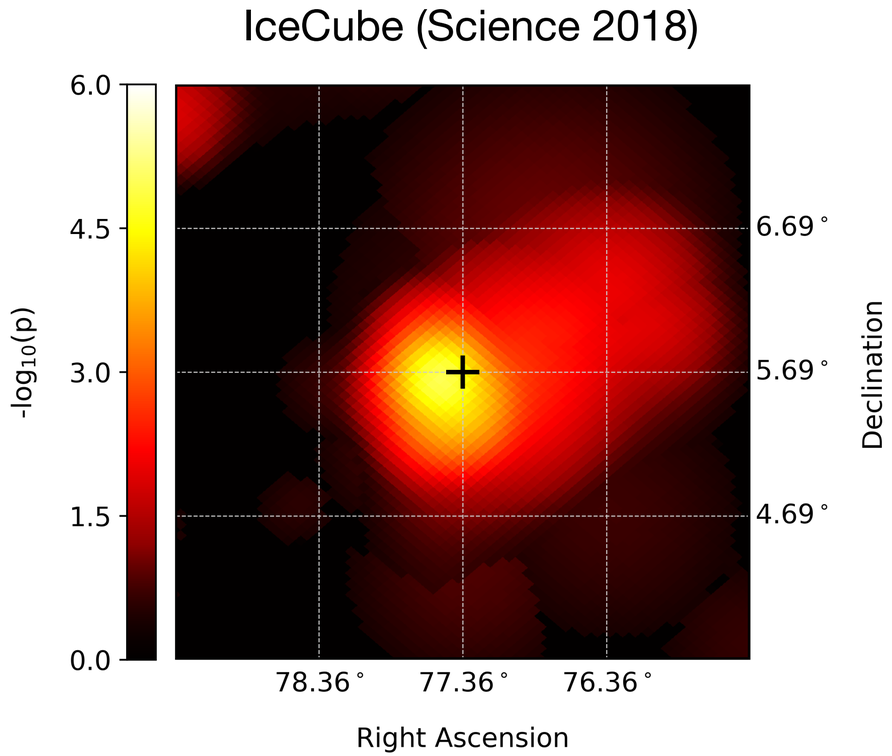

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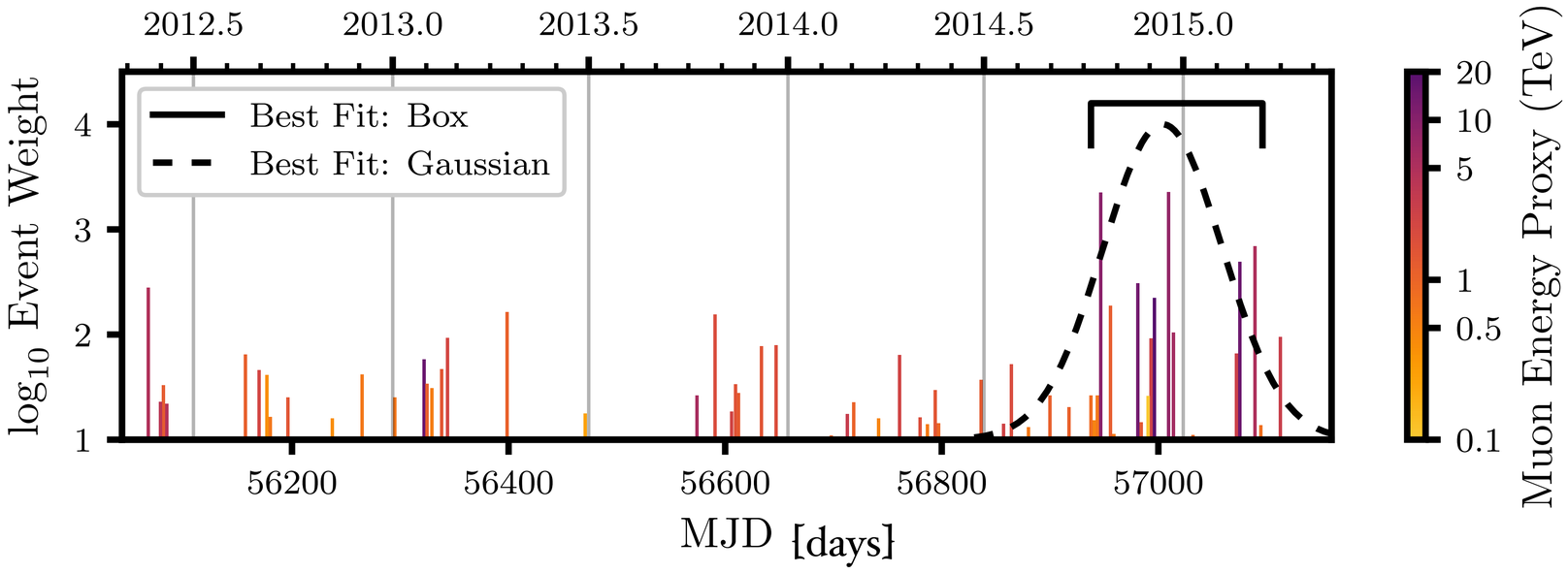

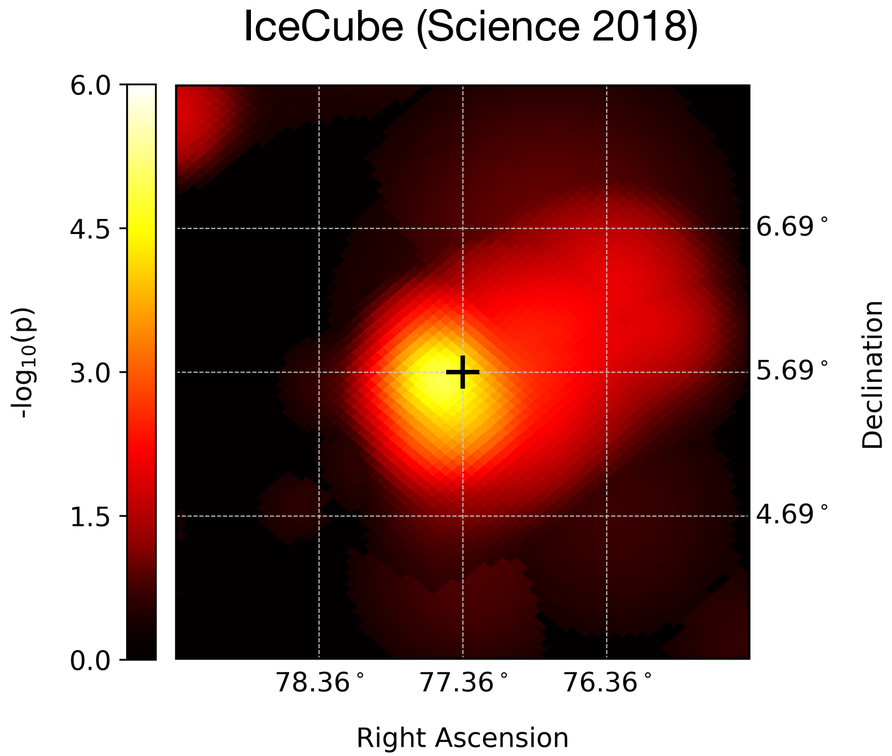

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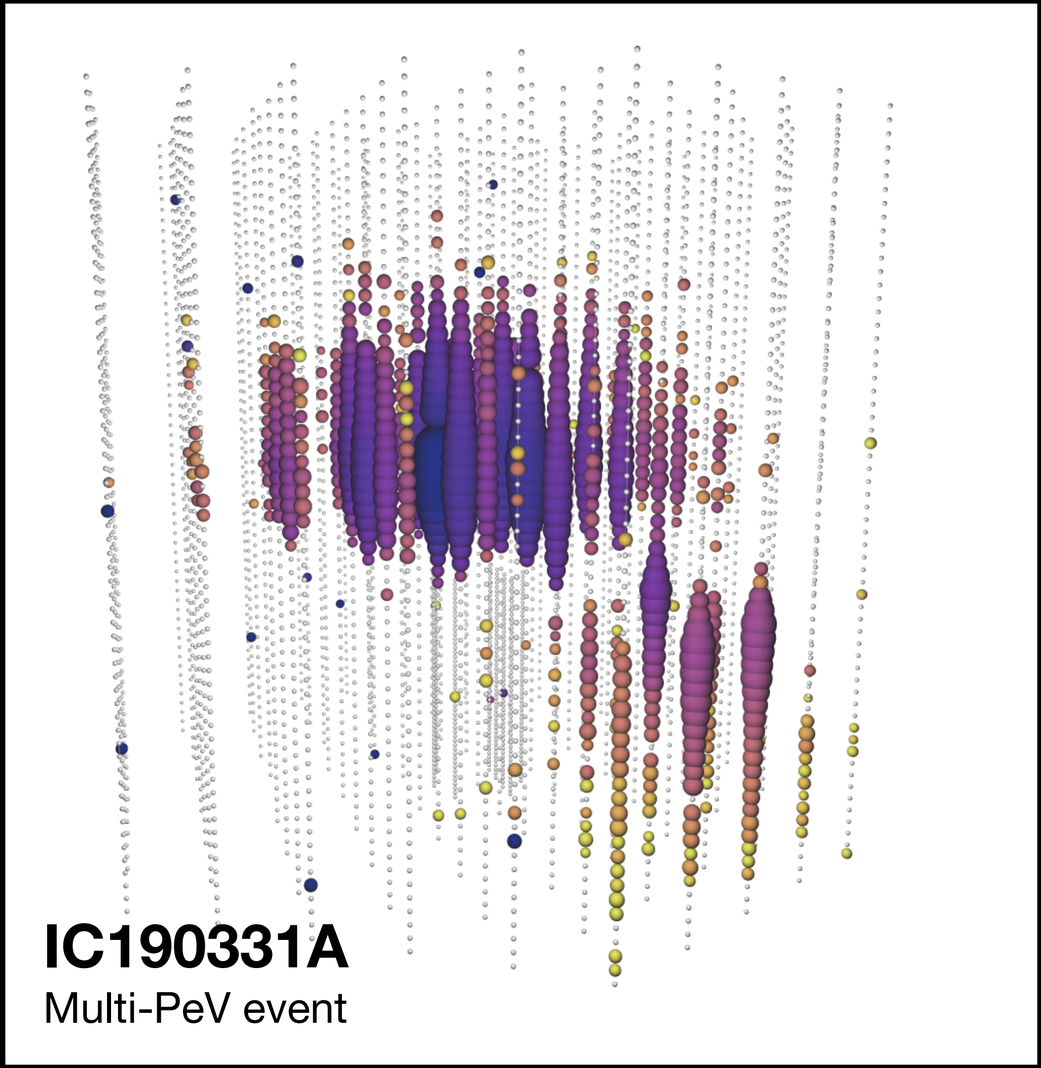
- No evidence of EM activity from the source during this period.

More recent alerts



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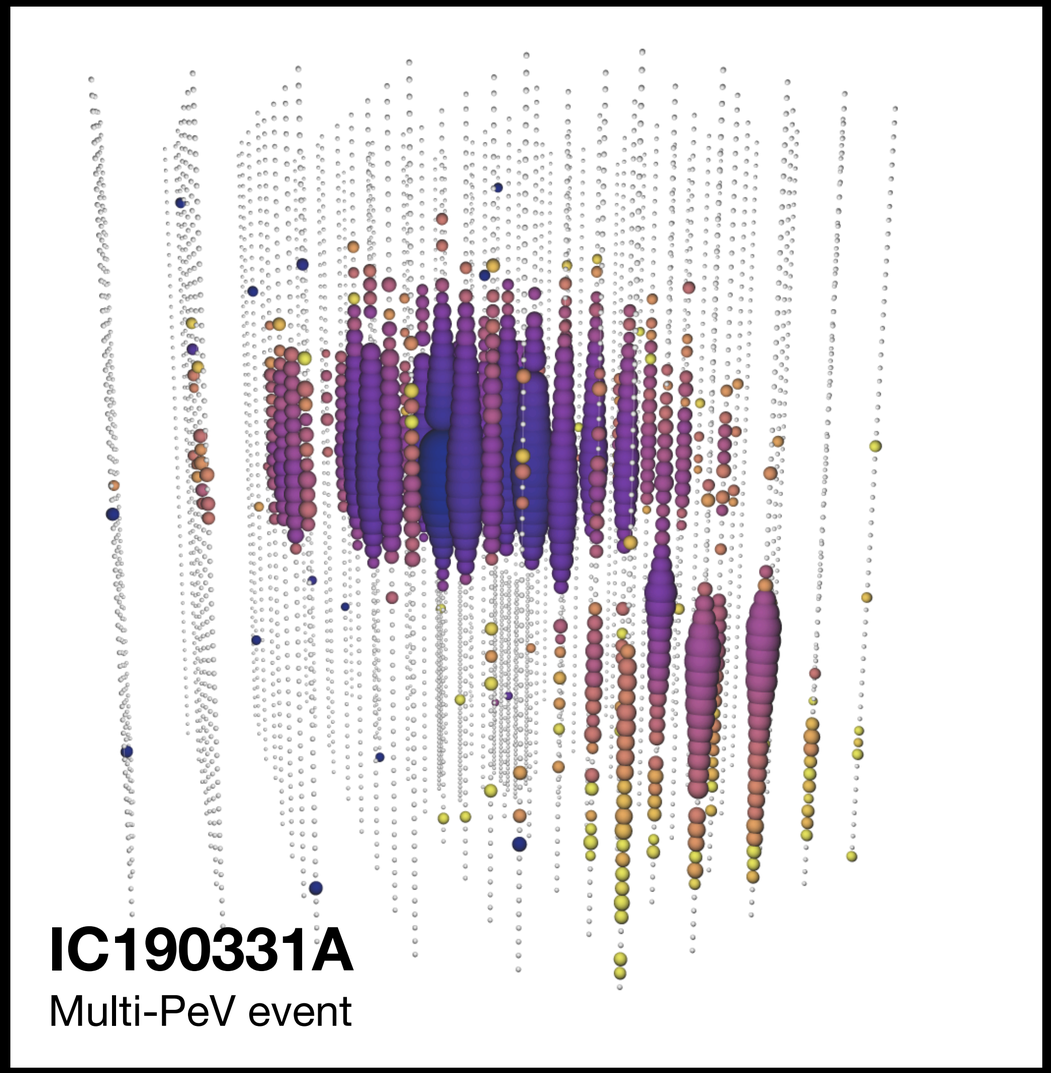
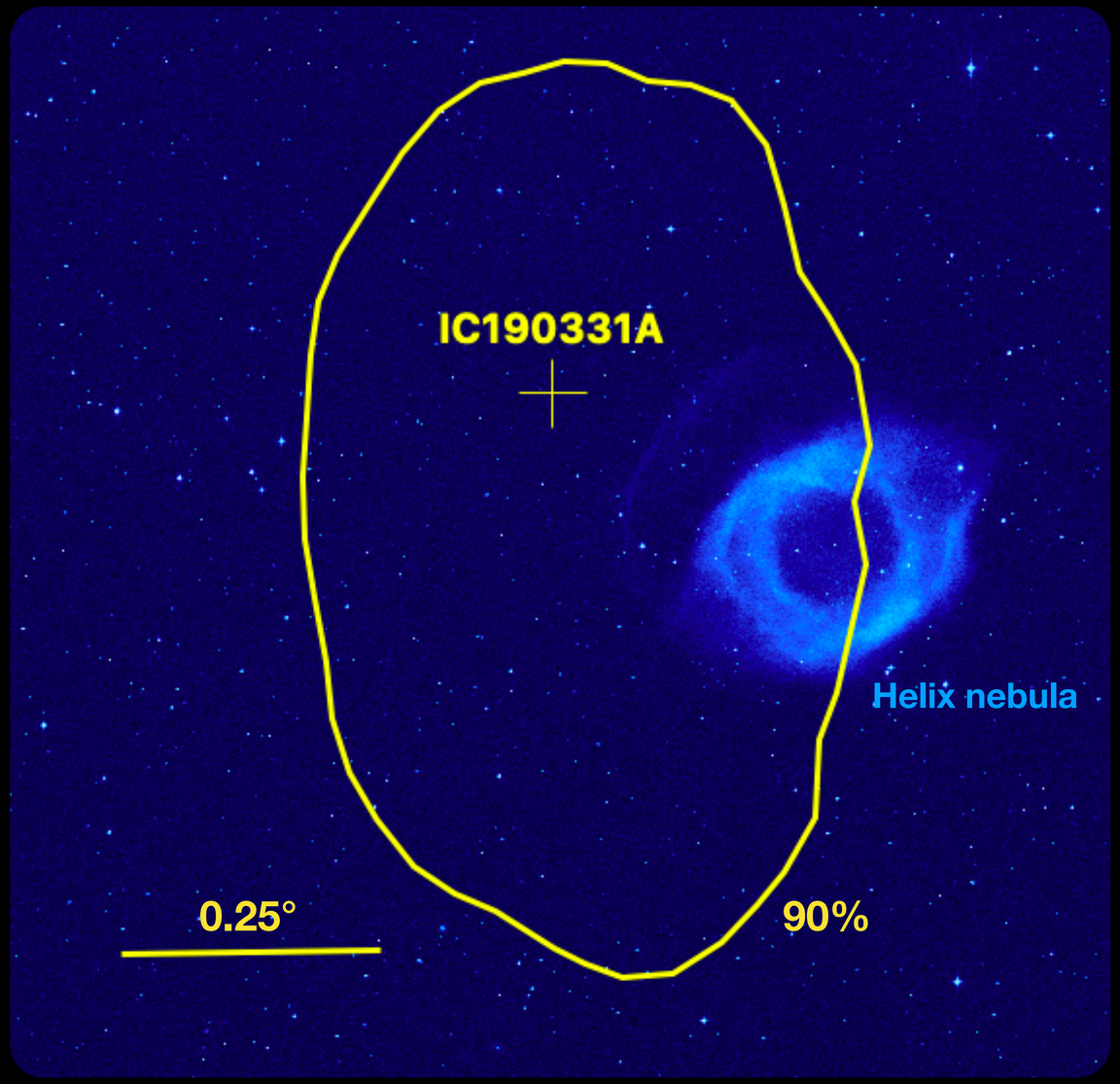


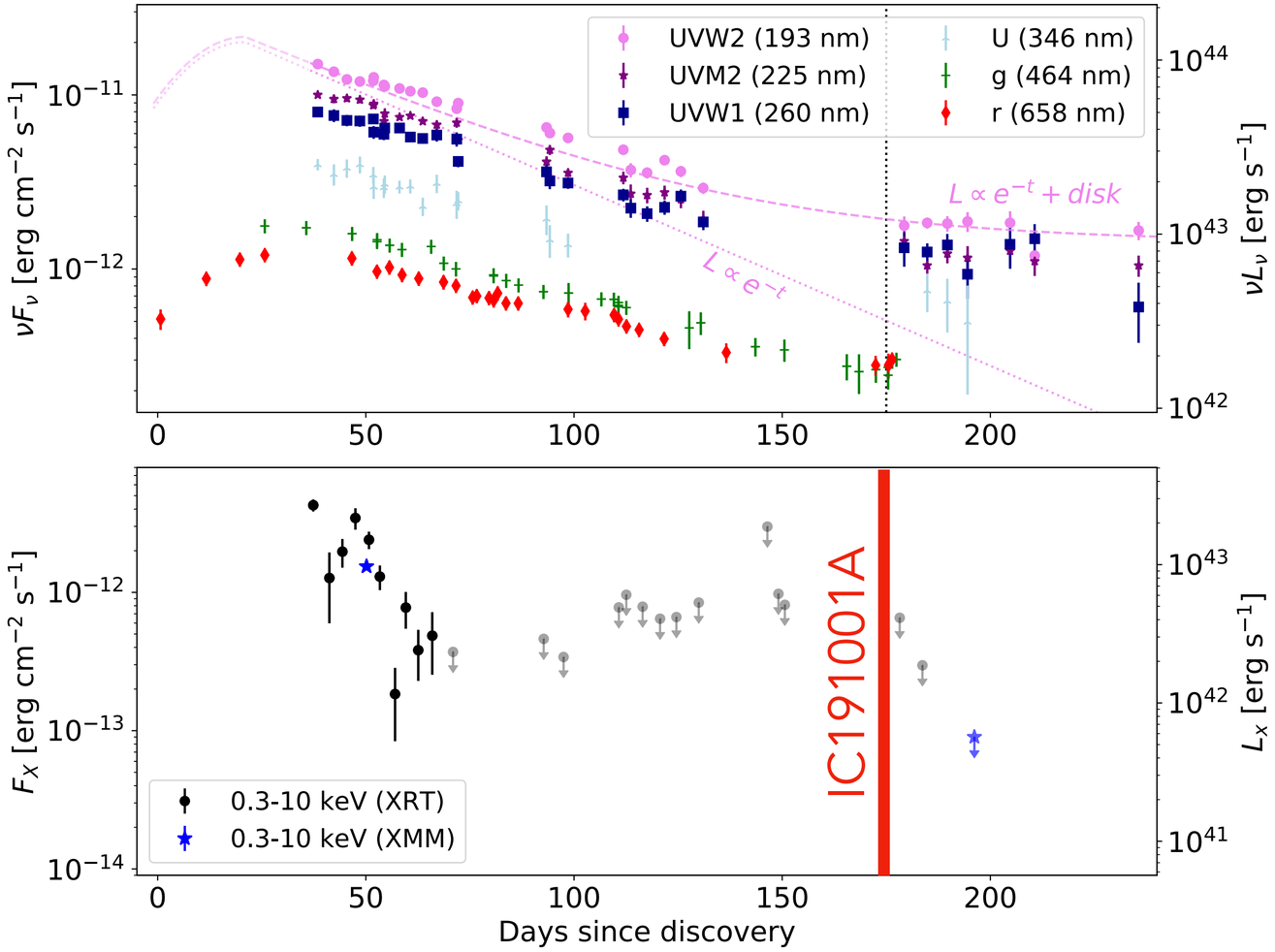
Digitized Sky Survey (optical)



No obvious high-energy EM counterparts

More recent alerts - Enabling multimessenger studies

R. Stein et al. (ZTF)
arXiv/2005.05340, Poster #347



A high-energy neutrino coincident with a tidal disruption event

Robert Stein*[1,2], Sjoert van Velzen*[3,4], Marek Kowalski*[1,2,5], Anna Franckowiak[1,2], Suvi Gezari[4,6], James C. A. Miller-Jones[7], Sara Frederick[4], Itai Sfaradi[8], Michael F. Bietenholz[9,10], Assaf Horesh[8], Rob Fender[11,12], Simone Garrappa[1,2], Tomás Ahumada[4], Igor Andreoni[13], Justin Belicki[14], Eric C. Bellm[15], Markus Böttcher[16], Valery Brinnel[2], Rick Burruss[14], S. Bradley Cenko[6,17], Michael W. Coughlin[18], Virginia Cunningham[4], Andrew Drake[13], Glennys R. Farrar[3], Michael Feeney[14], Ryan J. Foley[19], Avishay Gal-Yam[20], V. Zach Golkhou[15,21], Ariel Goobar[22], Matthew J. Graham[13], Erica

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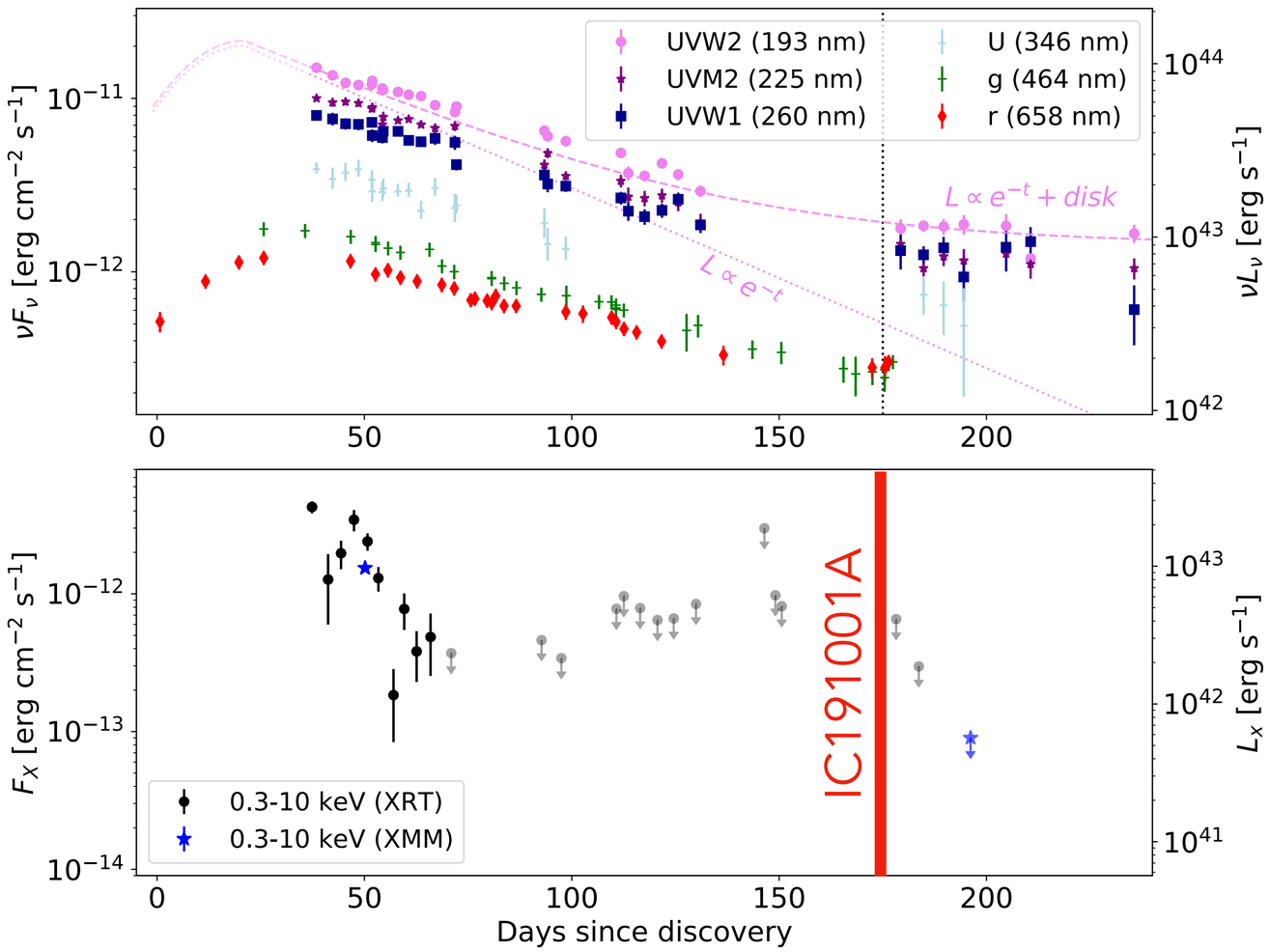

A high-energy neutrino coincident with a tidal disruption event

Radio TDE coincident with IC1901001A
0.5% chance probability

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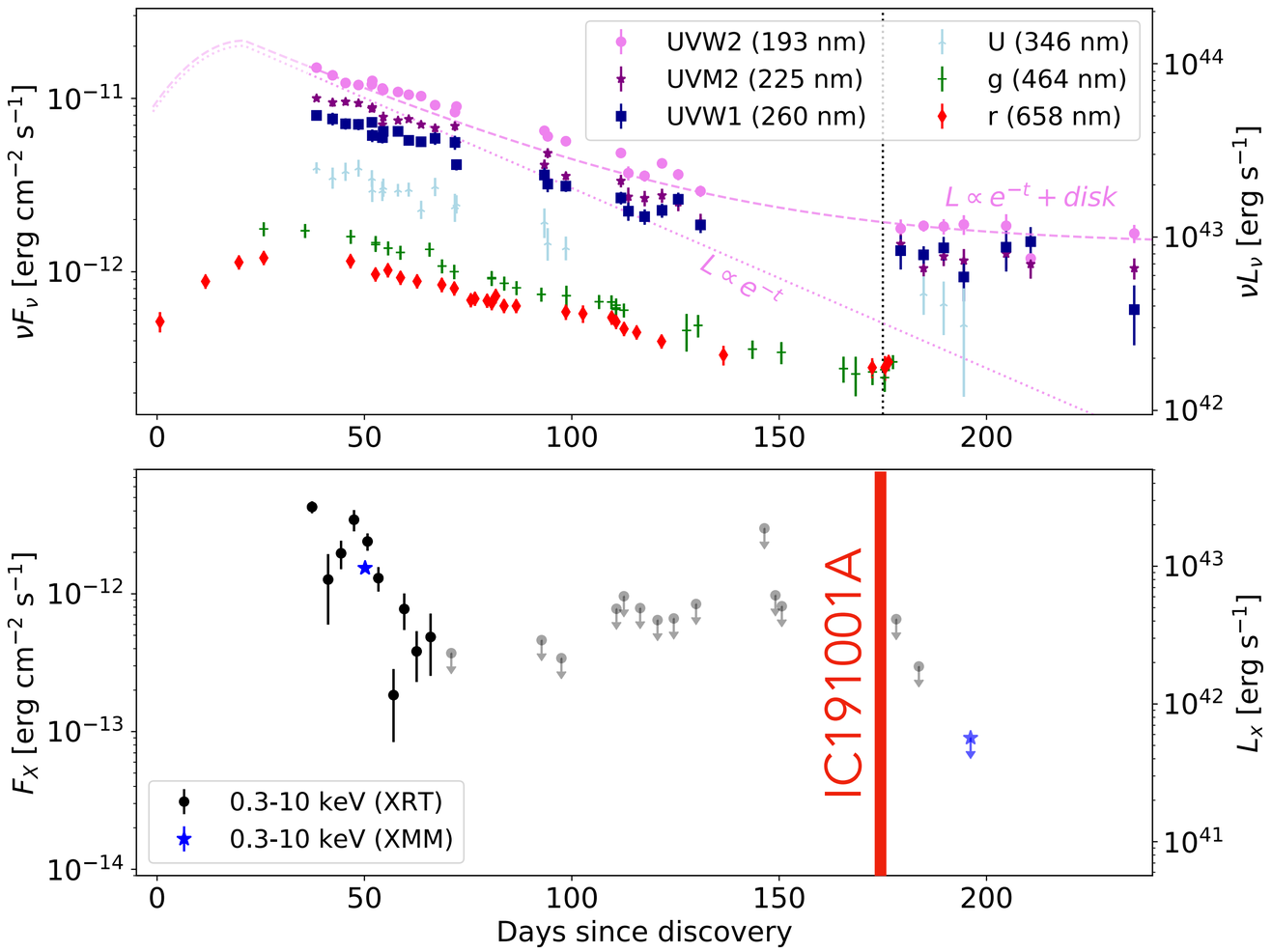

A high-energy neutrino coincident with a tidal disruption event

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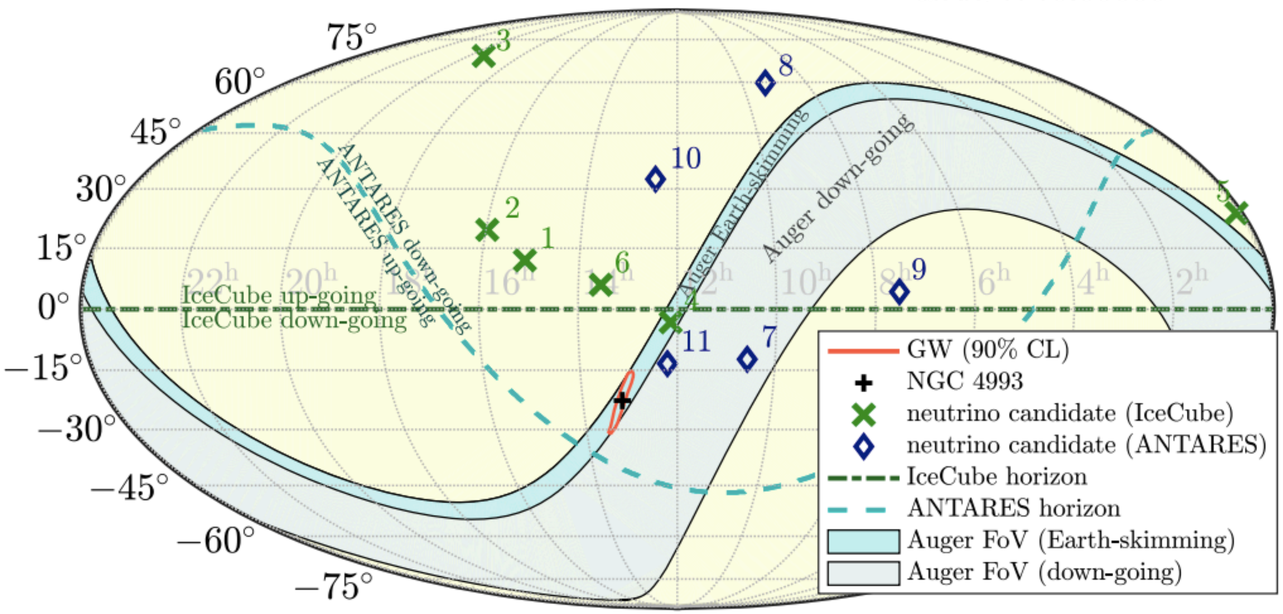
Highlights IceCube's capability as a multimessenger facility.

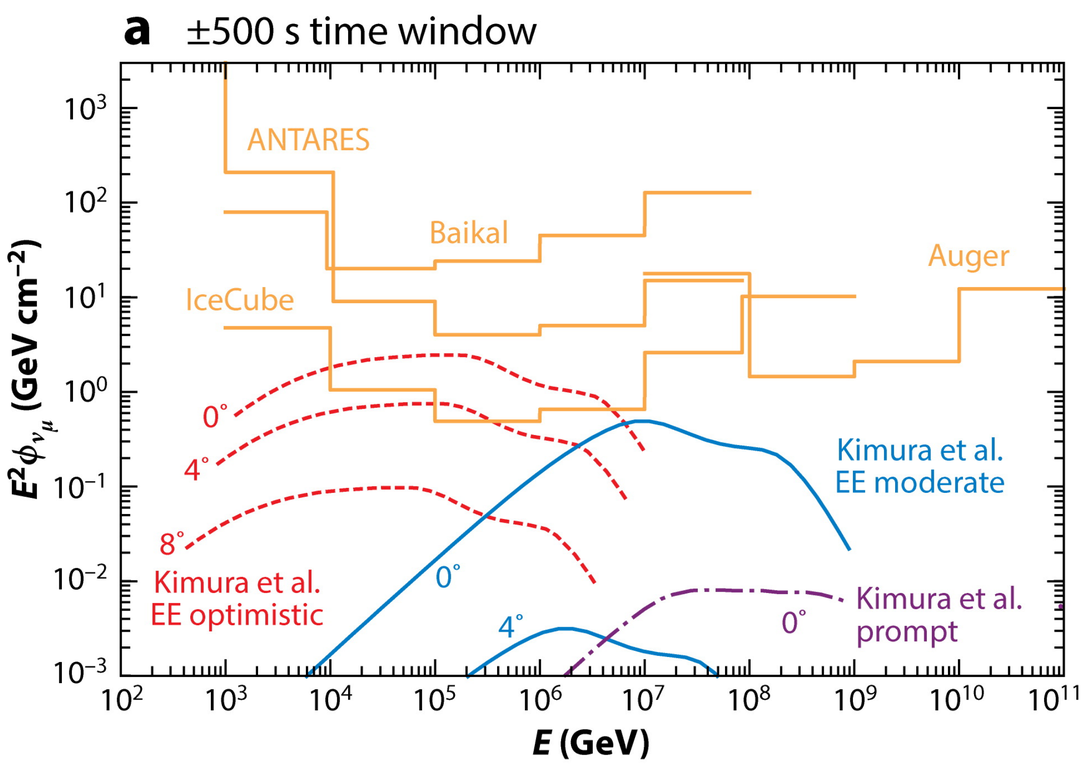
More alerts! we will soon start circulating alerts for cascade events via GCN.

Gravitational-wave followups

GW170817

ANTARES / Auger / IceCube
arXiv/1710.05839

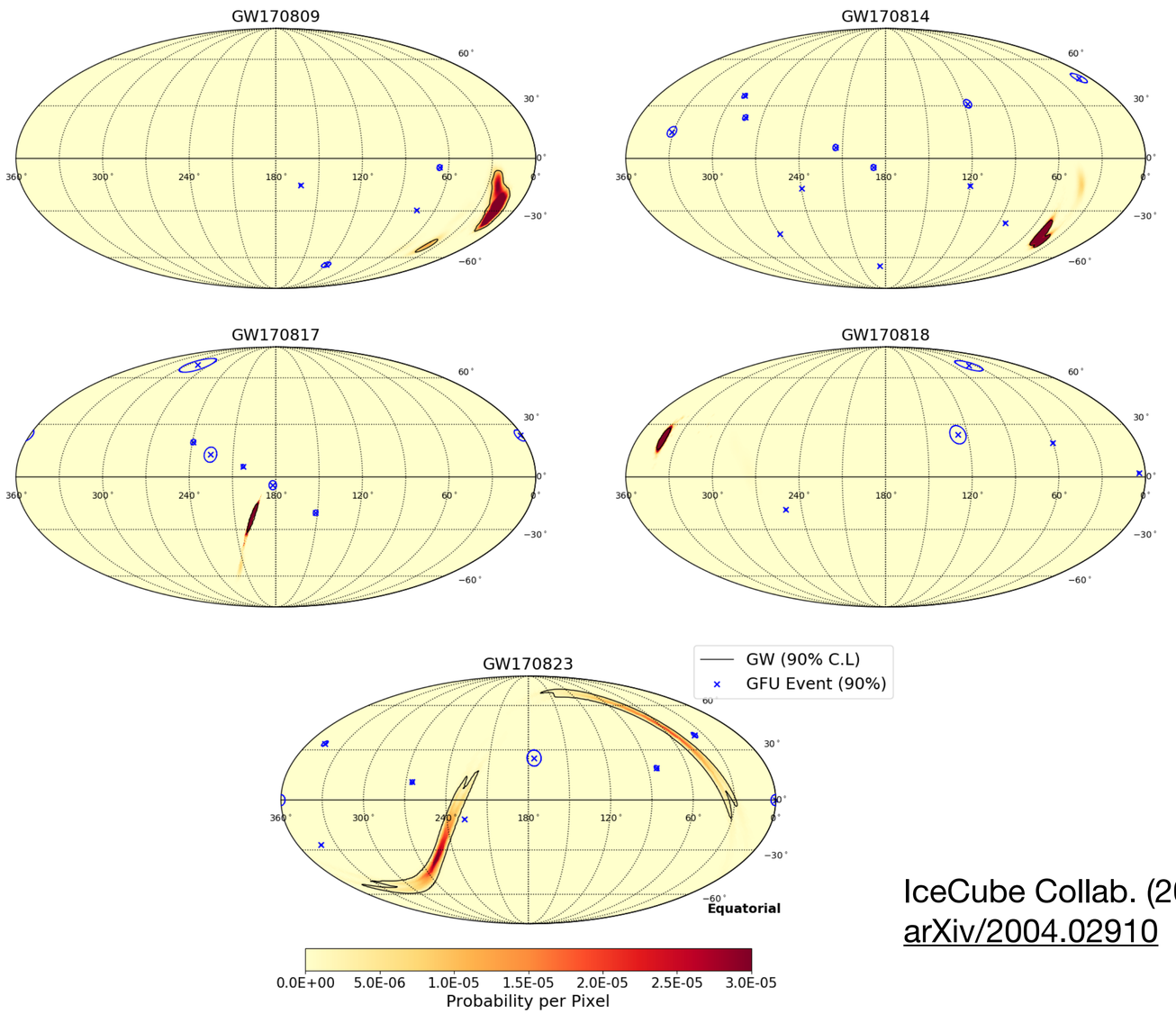




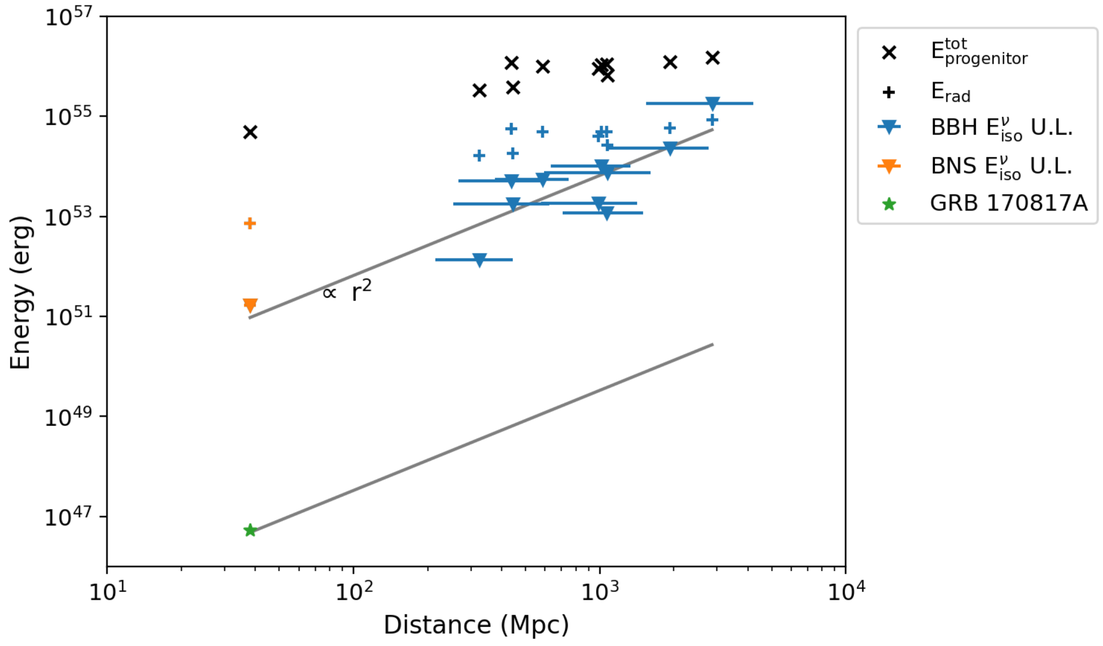
Murase K, Bartos I. 2019.
Annu. Rev. Nucl. Part. Sci. 69:477–506

Most sensitive searches for high-energy neutrino counterparts to GW events.

Gravitational-wave followups

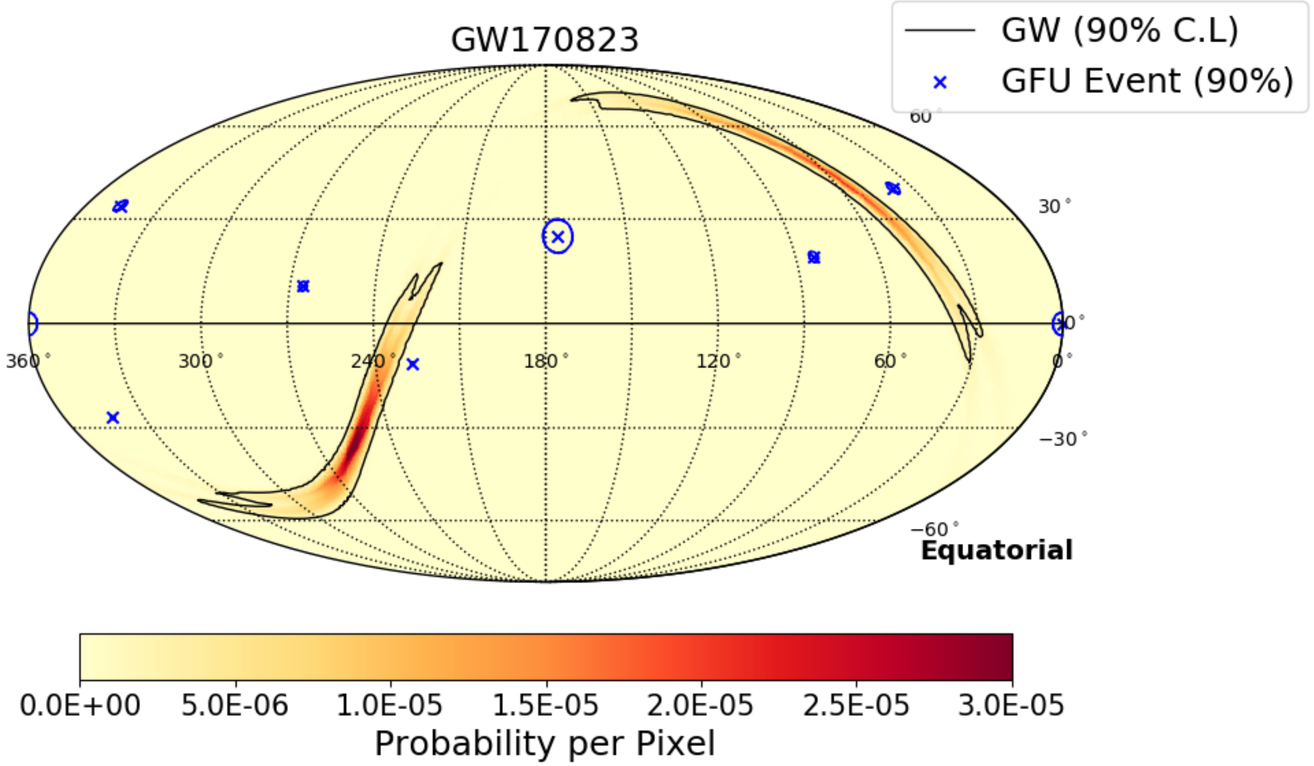


- Low-latency search for neutrinos from GW progenitors.
- Results promptly disseminated to the astrophysics community via GCN.
- **Constraints on neutrino luminosity of GW progenitors.**



IceCube Collab. (2020)
arXiv/2004.02910

Gravitational-wave followups



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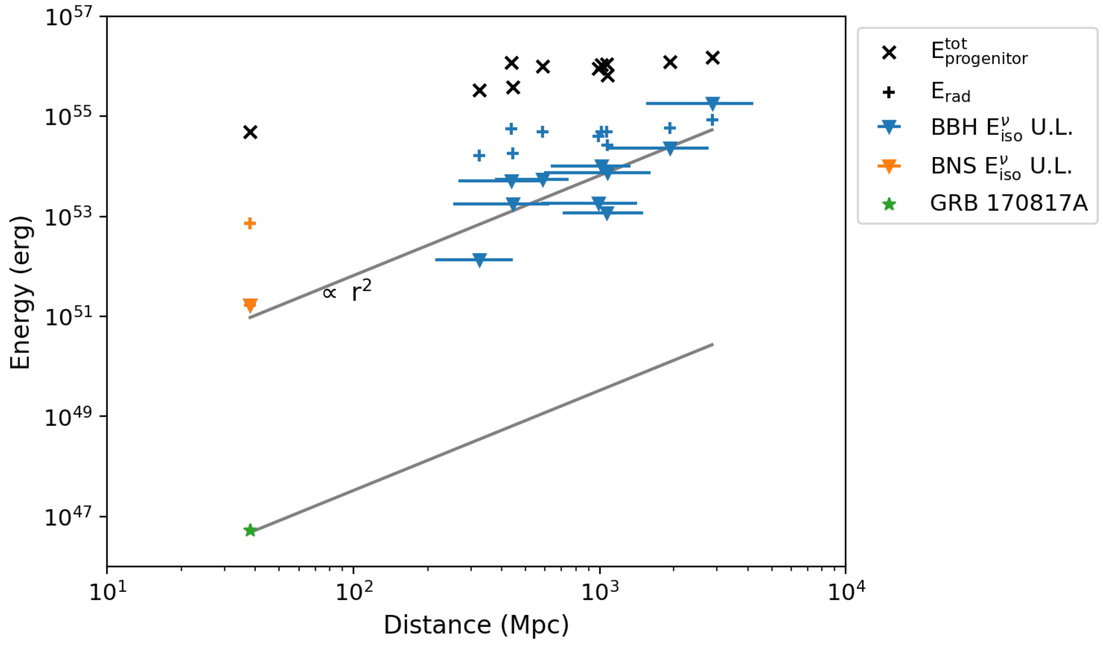
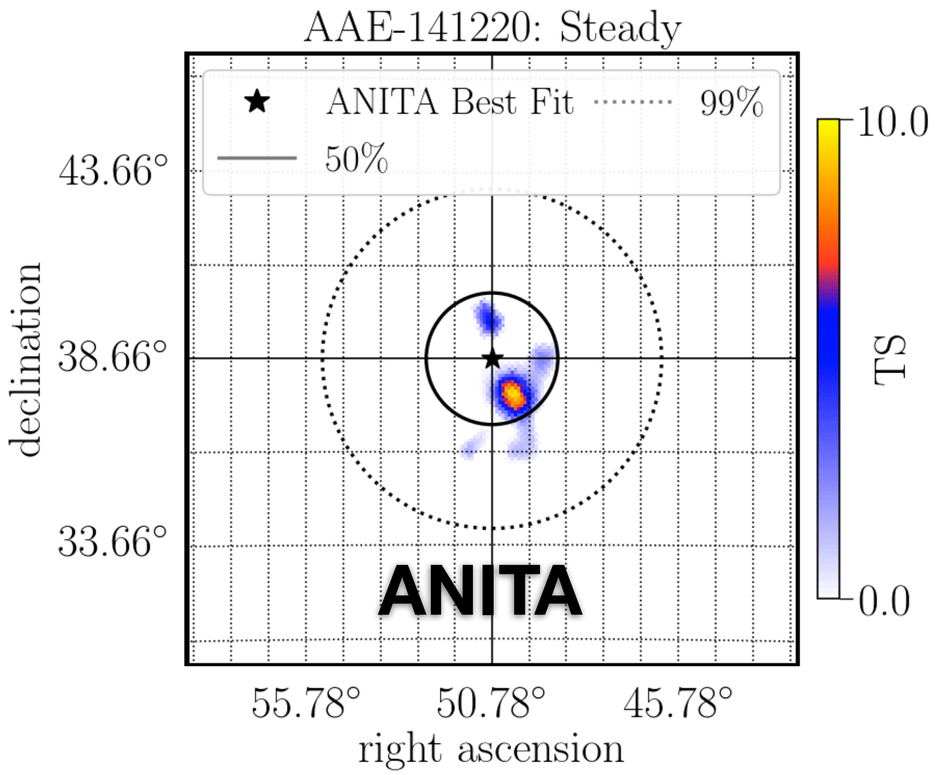
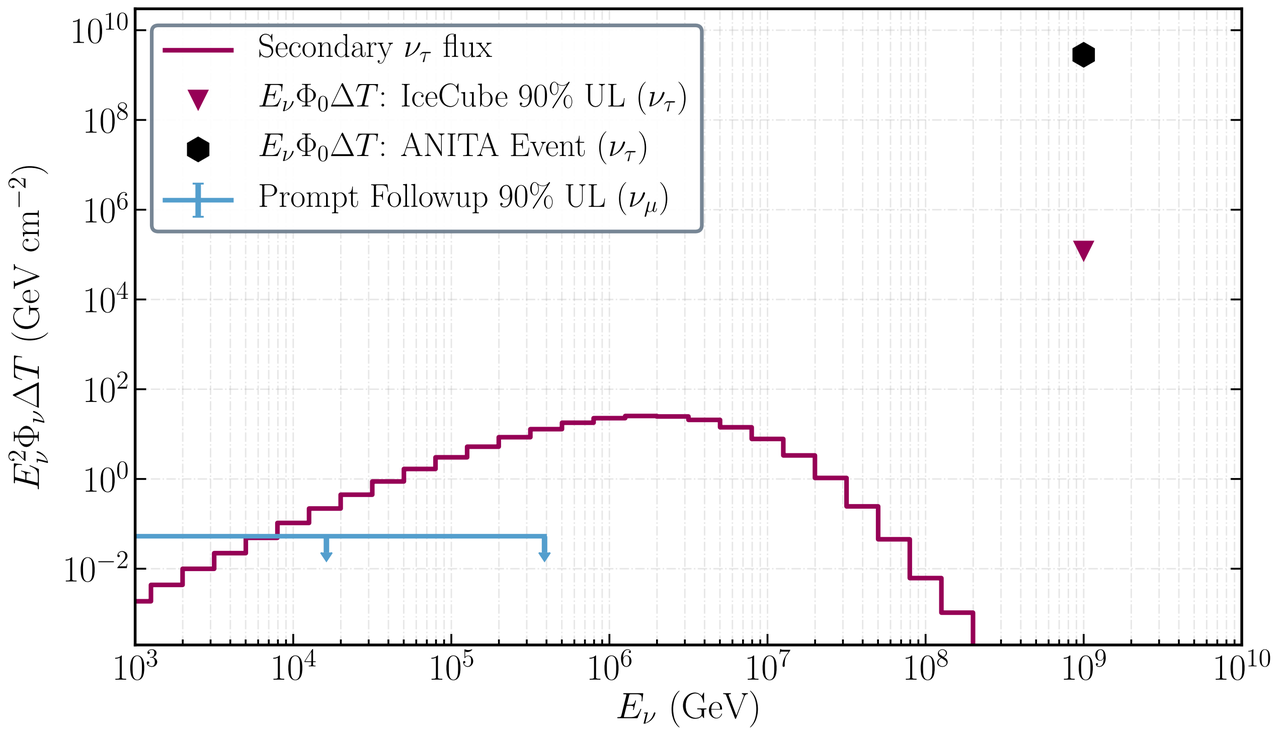


IceCube Collab. (2020)
arXiv/2004.02910

“Multi-wavelength” neutrino searches

IceCube Collab. (2020)
arXiv/2001.01737

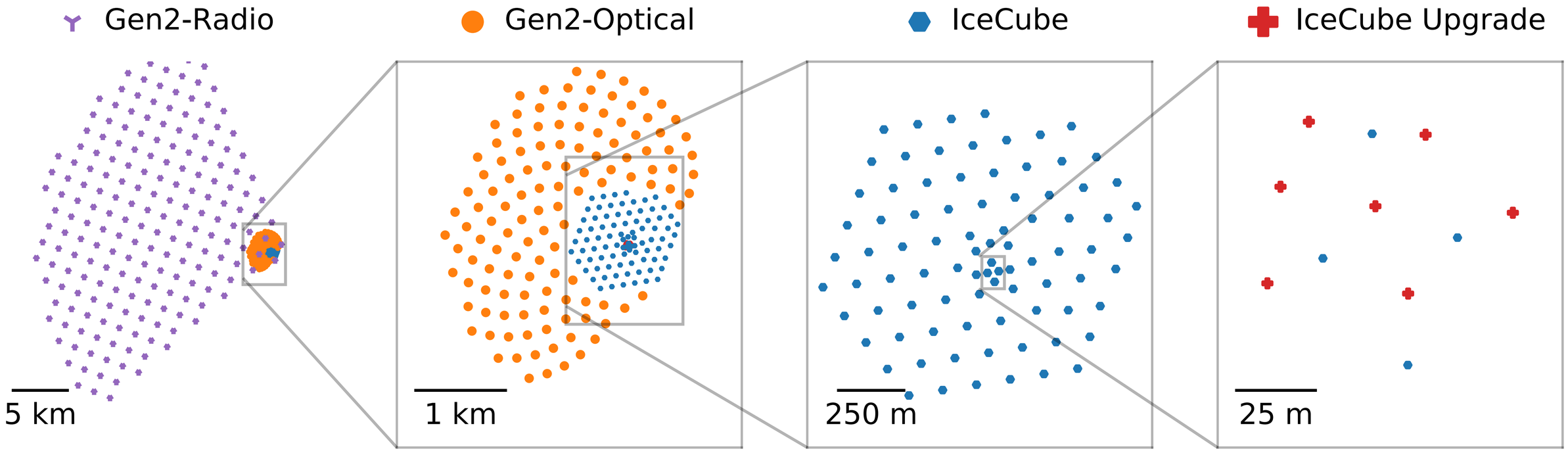




- **ANITA** reported the observation of two anomalous ~EeV neutrino candidate events.
- IceCube search for associated neutrino events on multiple timescales.
- IceCube constraints rule out astrophysical interpretations of the events under Standard Model assumptions.

IceCube-Gen2: the future of HE ν astrophysics

B. Clark (IceCube-Gen2, #409)



- Unprecedented sensitivity to astrophysical neutrinos in the GeV to >EeV range.
- 8 km^3 for optical array, 500 km^2 for radio.

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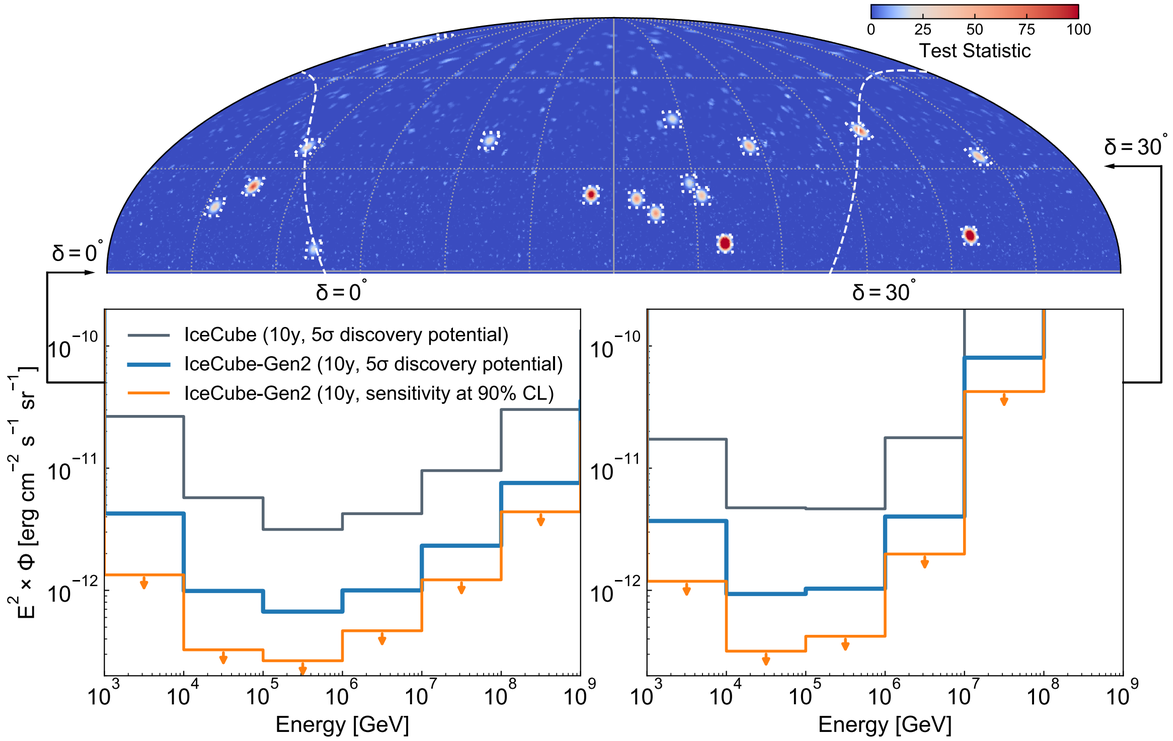
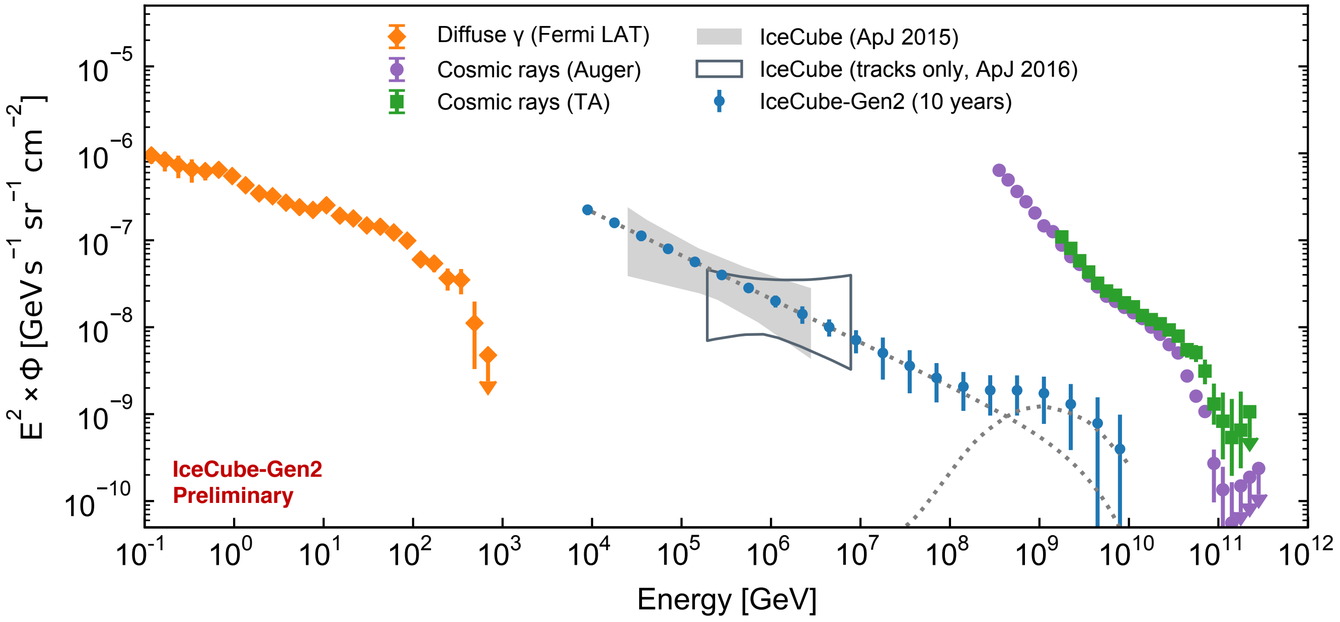
IceCube-Gen2 (Astro2020)





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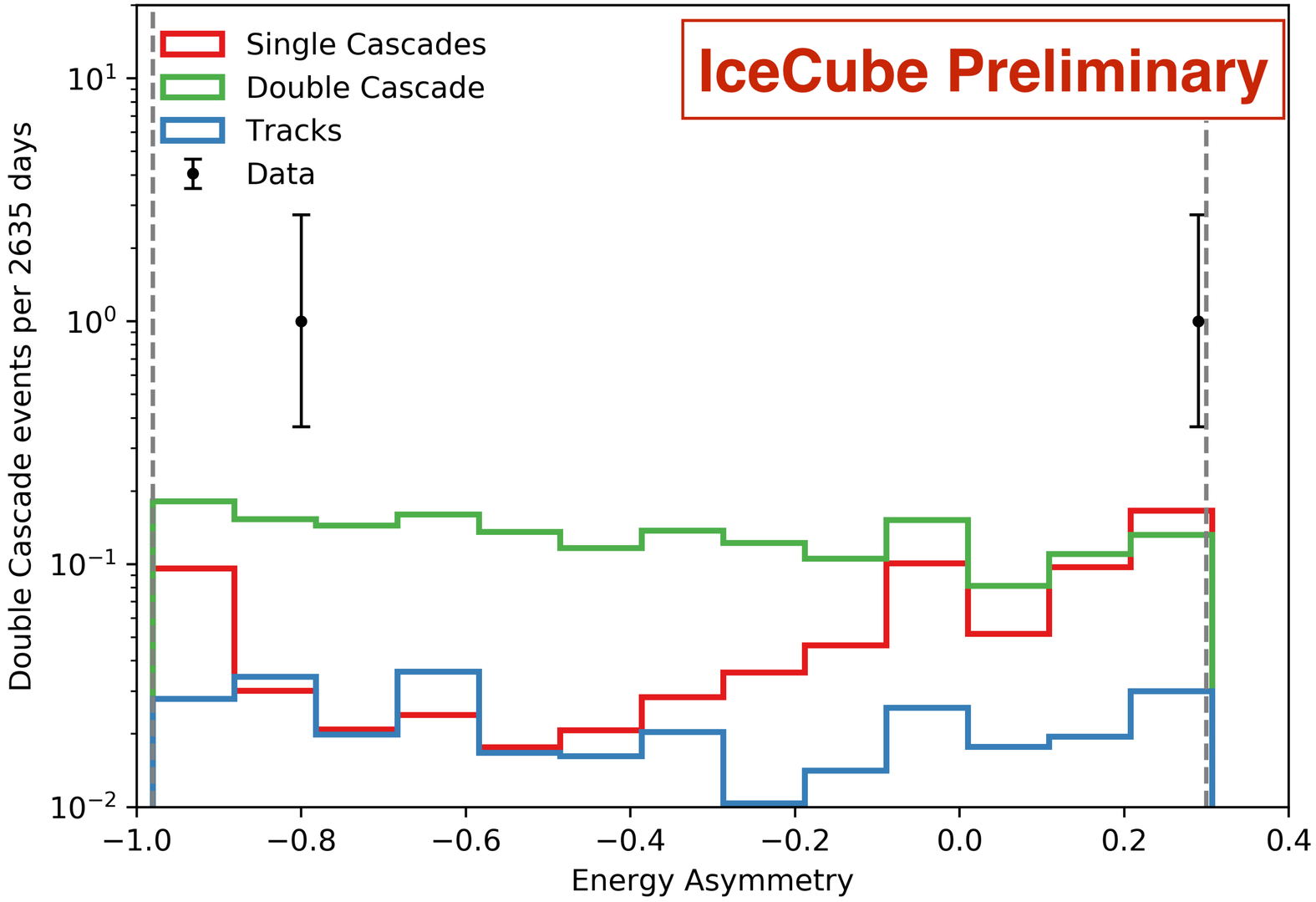
Conclusions

- Major results in the last few years
  - First detection of an astrophysical nu flux in 2013.
  - Evidence for the first HE astrophysical neutrino source in 2017.
- Continuing search for neutrino sources, either standalone or by identifying temporal/spatial correlations with EM and GW signals.
- The construction of IceCube-Gen2 will fully enable neutrino astronomy in the coming decades.

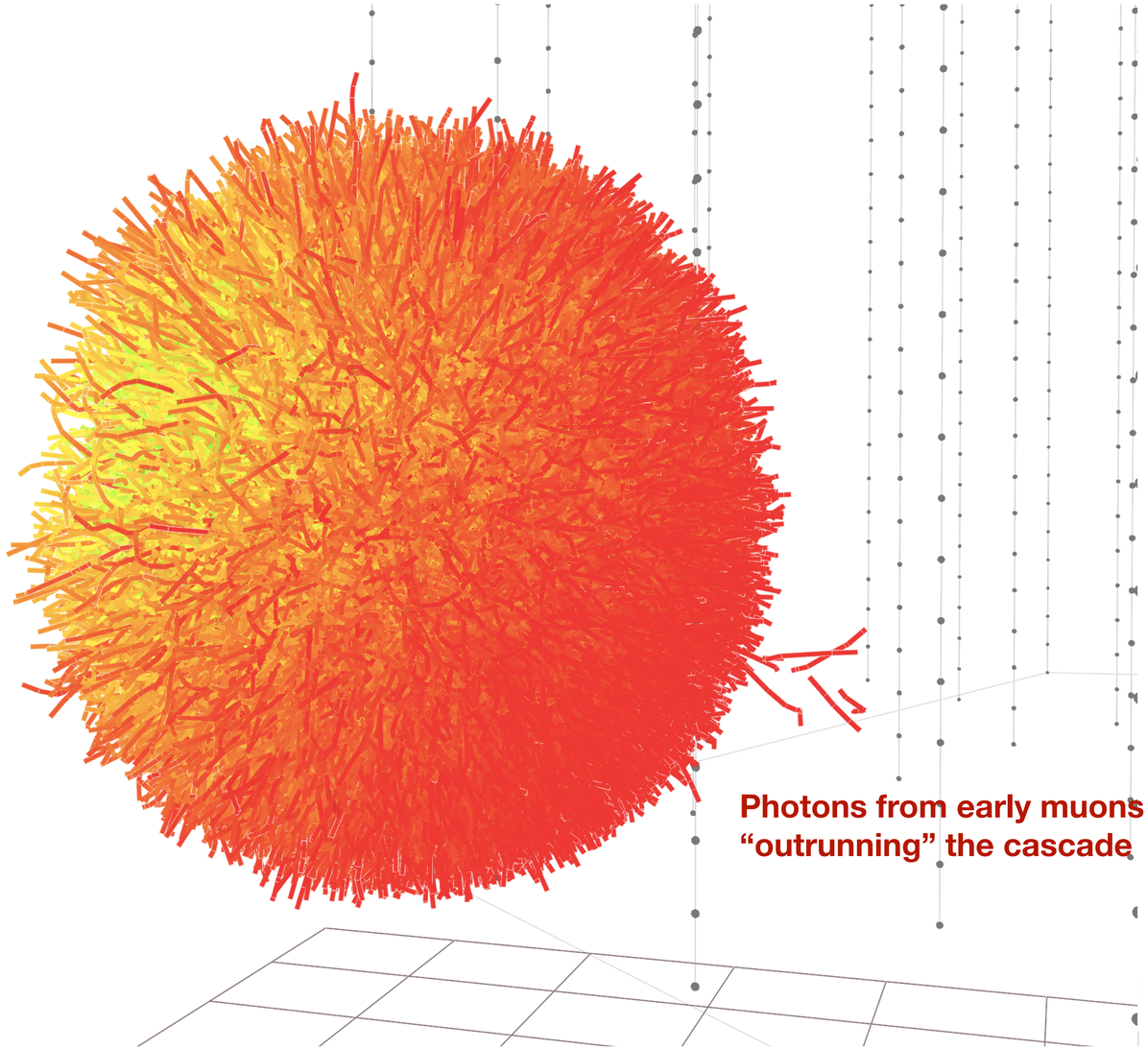
Thank you

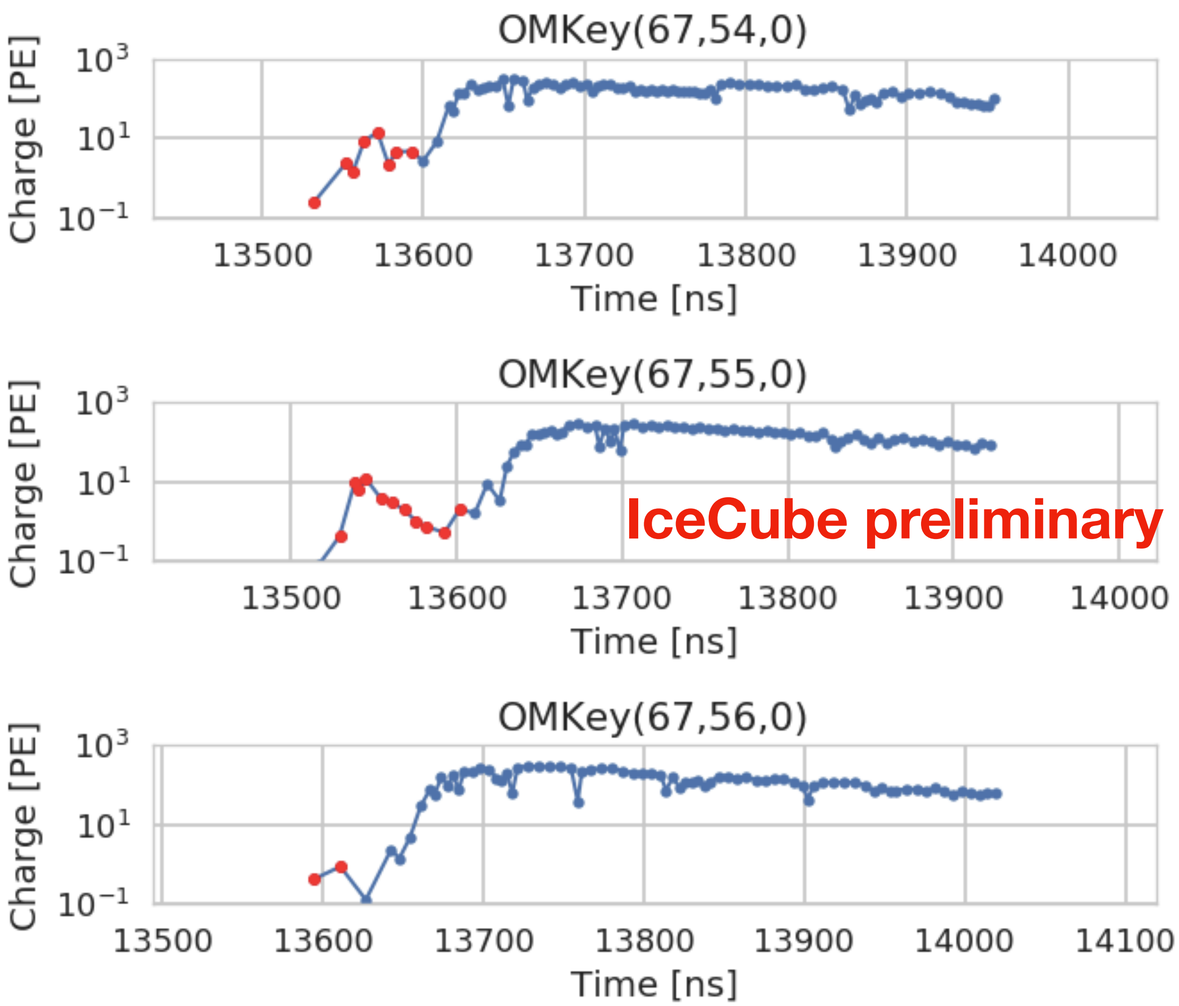
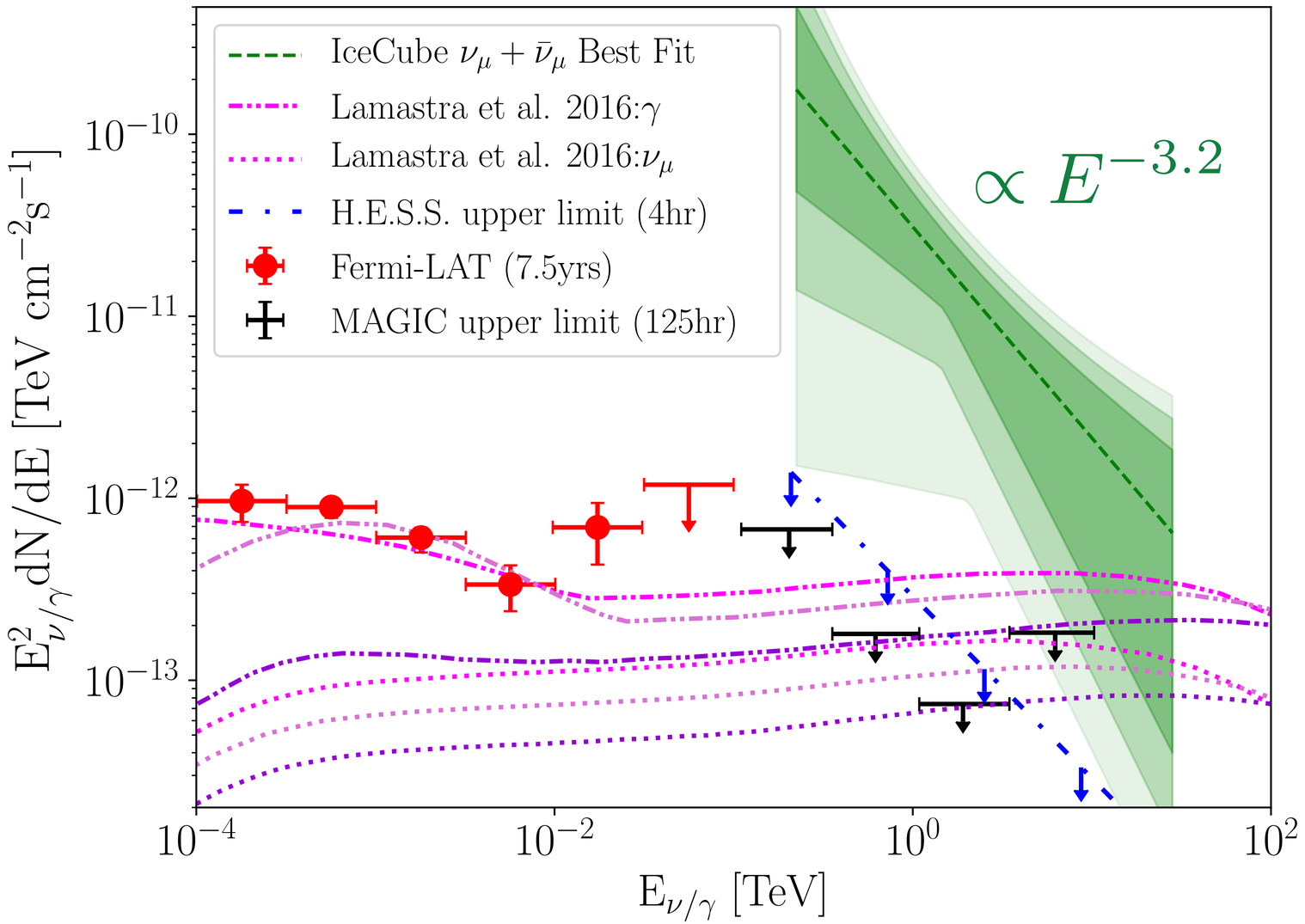
Backup

Tau candidates - energy asymmetry



Hadronic cascade signatures





NGC 1068 spectrum