Astrophysical Neutrinos with IceCube

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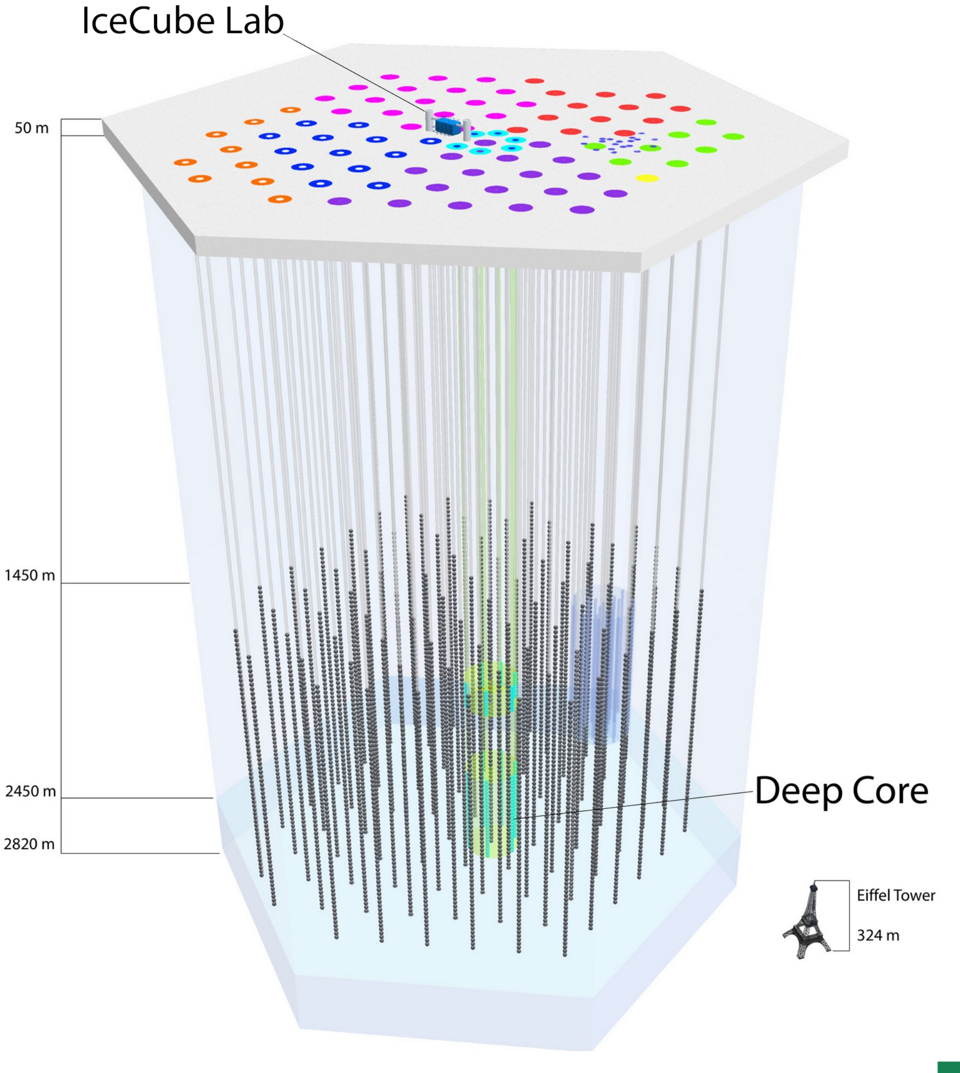
On behalf of the IceCube Collaboration

Questions about Neutrino Sources

- Where does the diffuse neutrino background we see come from?
- How is it made?
- What happens to it between there and here?

IceCube Observatory

- ~ 1 km^3 instrumented volume
- Completed in 2010
- 5160 phototubes
- Primarily sensitive in the northern sky
- Primarily sensitive to muon neutrinos for source searches, but similar sensitivities to all flavors for others

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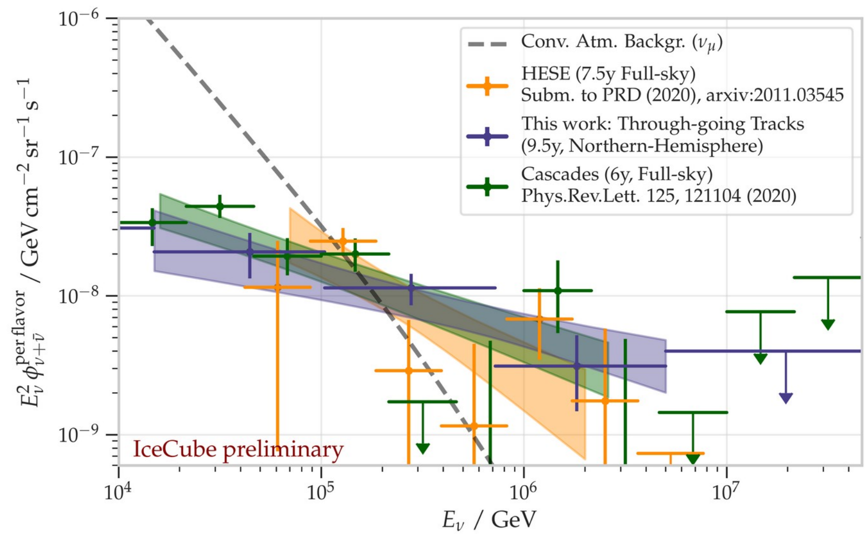
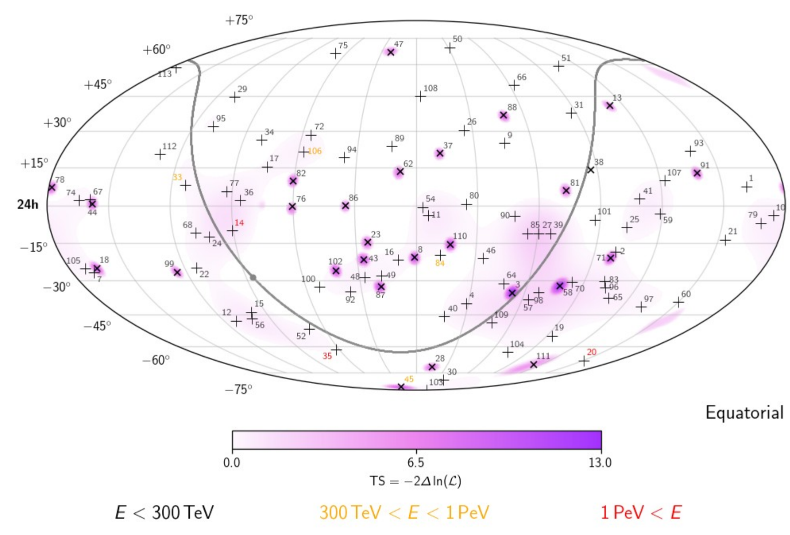
ICECUBE
icecube.wisc.edu

First-order State of Things

Since 2013:

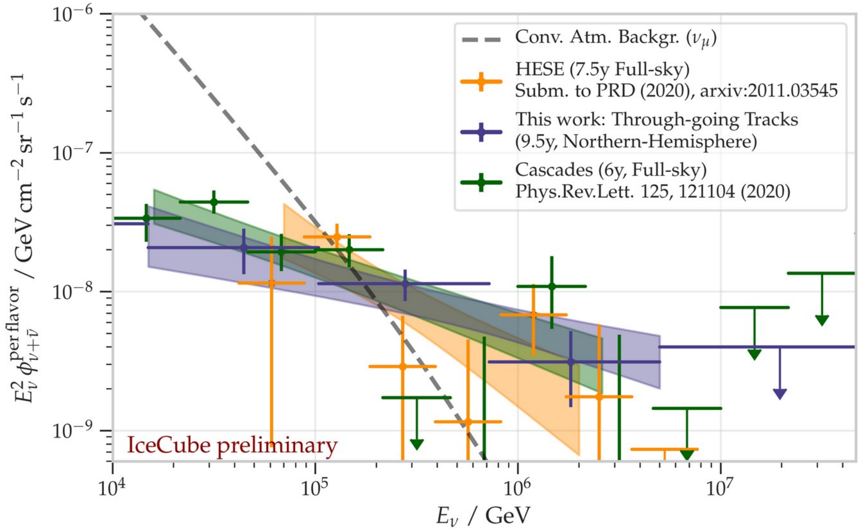
- **Bright diffuse background of high-energy neutrinos**
- **Roughly power-law shaped**
- **Nearly isotropic**
- **Apparently equal populations of all flavors of neutrinos**



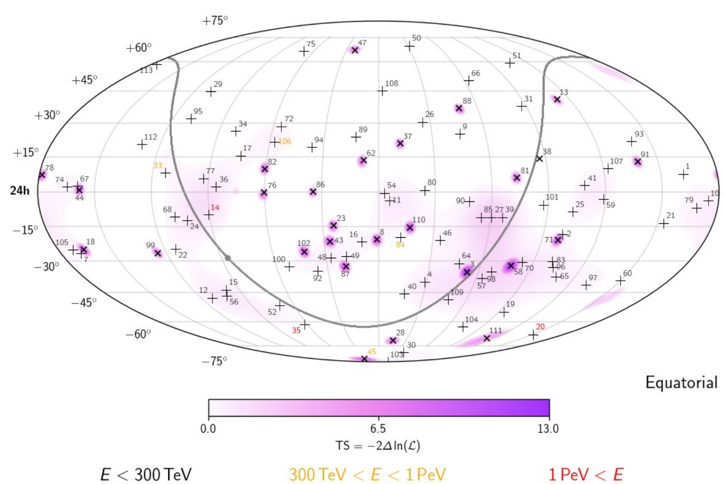


ArXiv:2011.03545

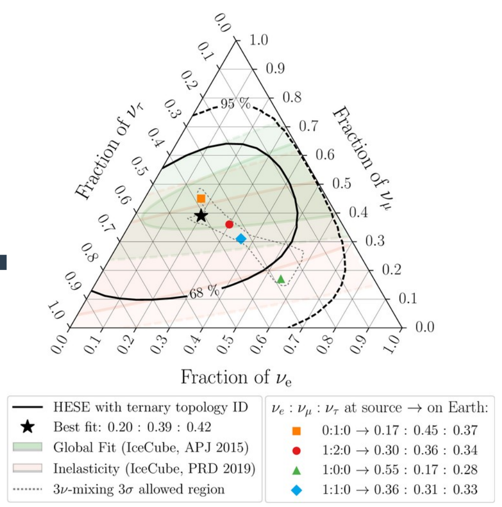
Measurement Triangle



Spectrum



Anisotropies

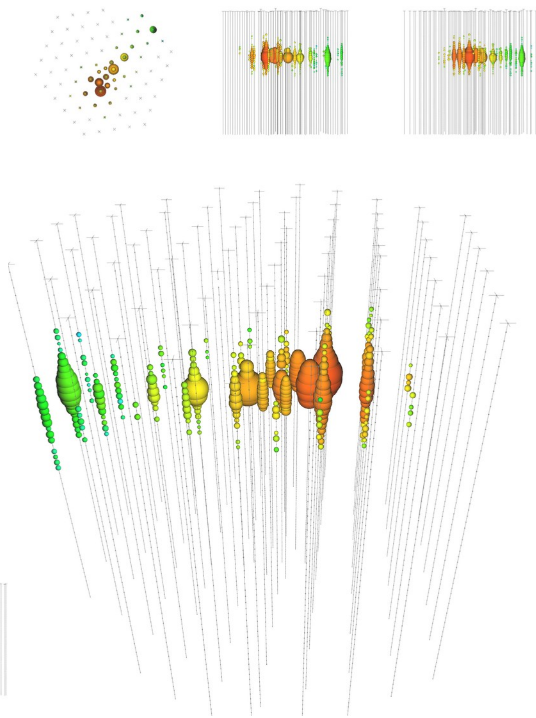


Flavor

Measurement Techniques

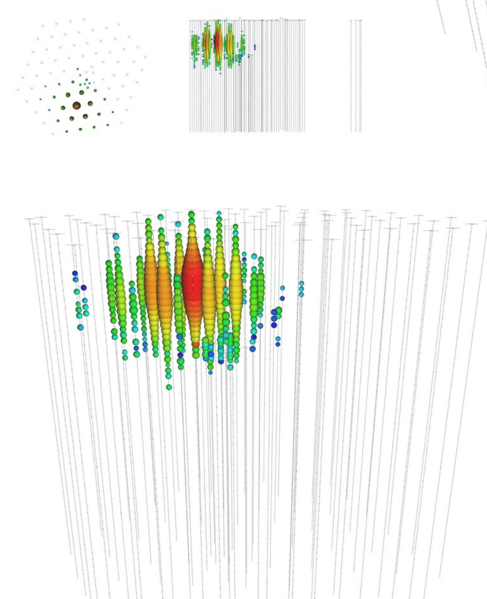
Astrophysical point sources:

- **Particle acceleration mechanism/source identification**
- **Indirect detection of dark matter**



Energy spectrum:

- **Direct detection of neutrinos from (ultra-)high-energy cosmic ray sources (concealed, internal dynamics)**
- **Probes of neutrino propagation over long distances**



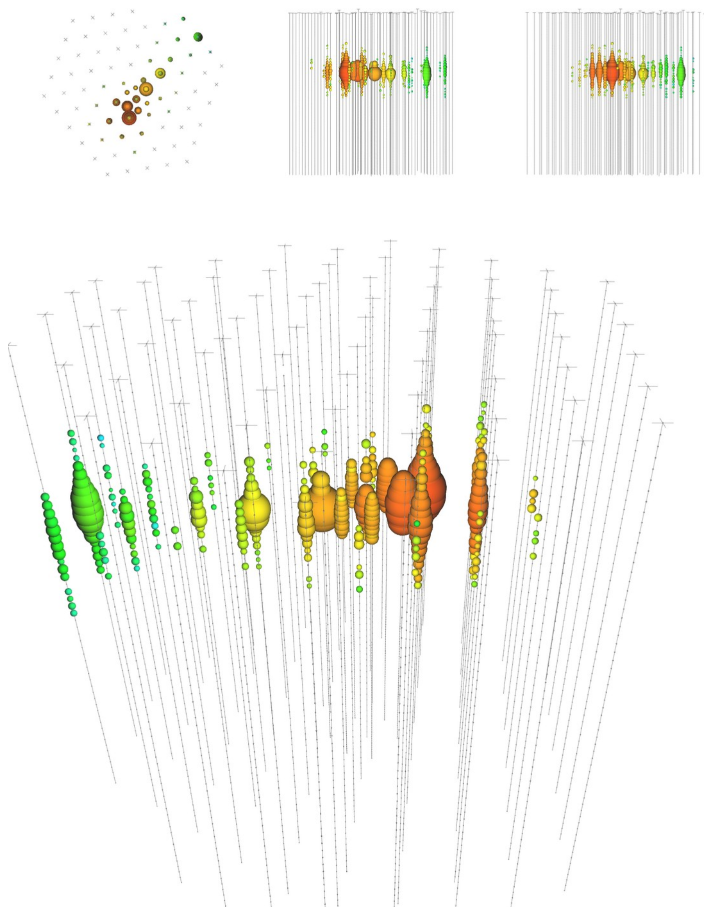
Flavor:

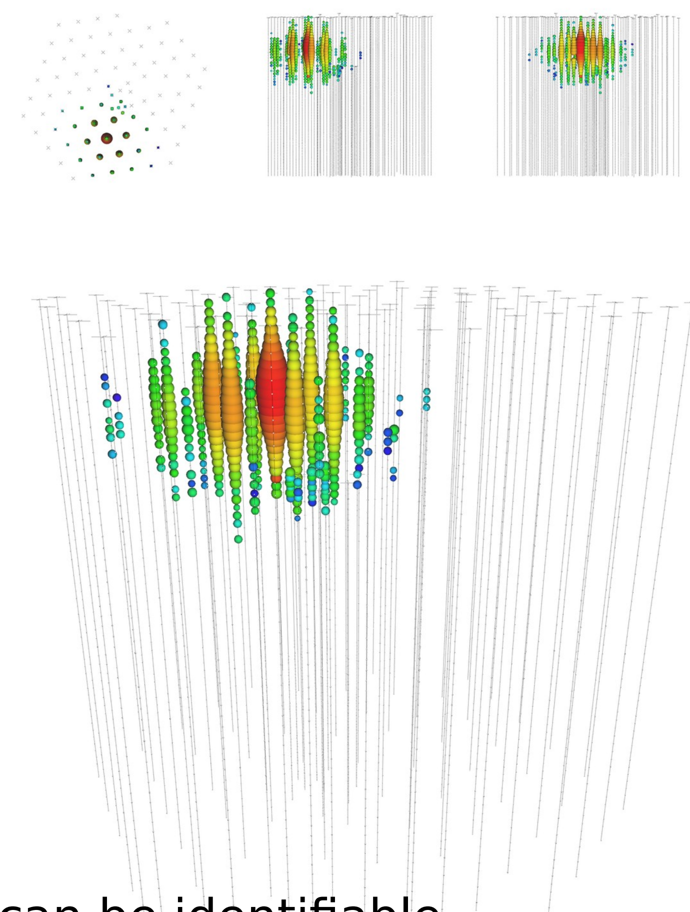
- **Non-standard propagation/interaction**
- **Astrophysical particle acceleration mechanism**

Tools: Topology and Flavor

“Track”: Almost entirely ν_μ CC
+ small amount $\tau \rightarrow \mu$

“Cascade”/“Shower”: Everything else





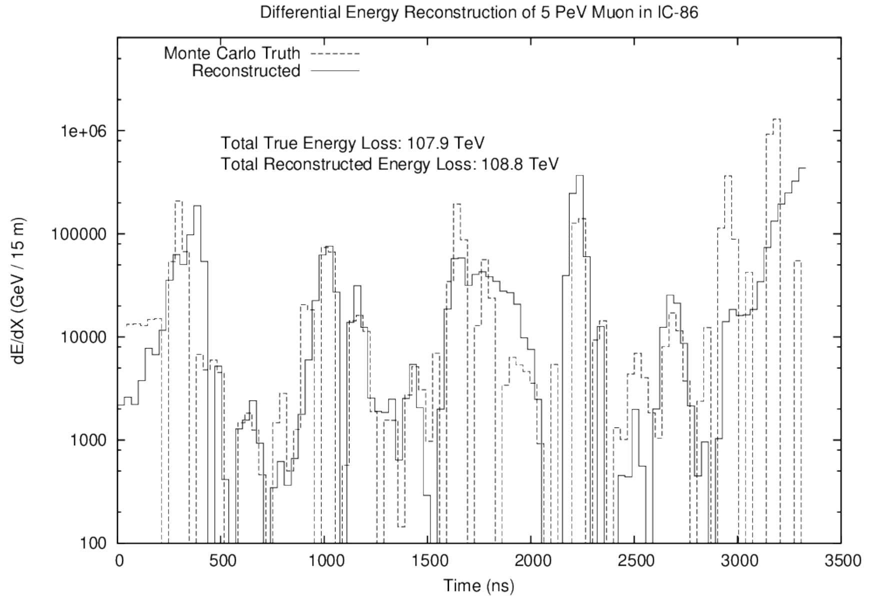
* High-energy taus (~ 500 TeV and up) can be identifiable
** At 6.3 PeV, statistical neutrino/anti-neutrino discrimination

Tools: Energy

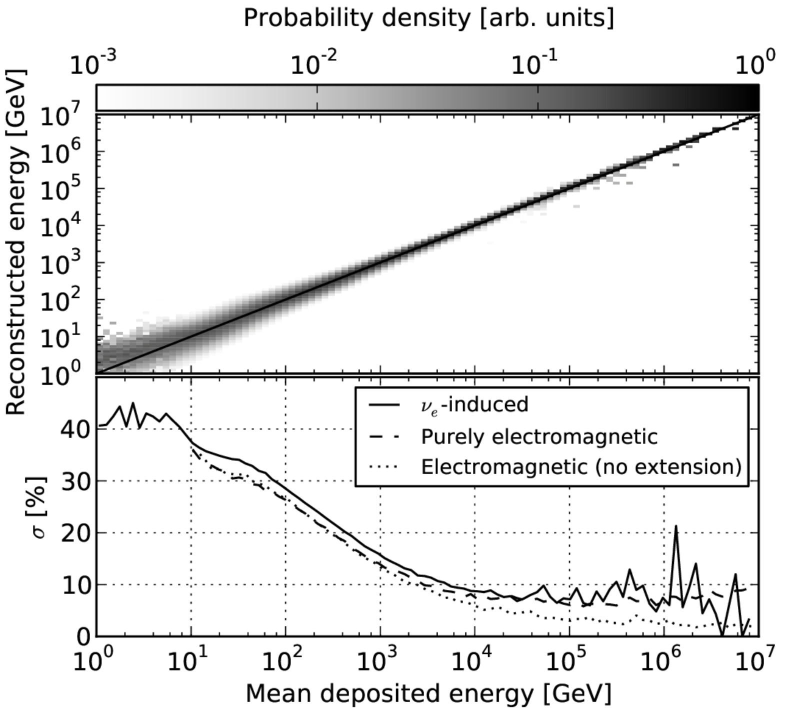
ArXiv:1311.4767

Tracks: Hard and lots of choices

- Muon energy? (where?)
- Neutrino energy? (high variance? Where did the neutrino interact?)
- Deposited energy? (limited information)



Cascades: Deposited Energy (10% resolution)



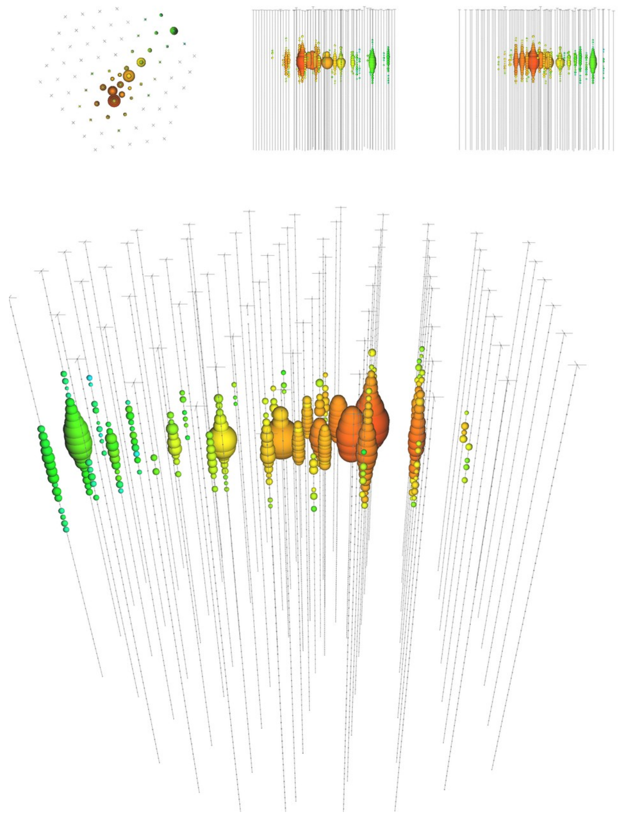
IMPORTANT PSA: For tracks, the number we quote can have the same units (GeV) but change meaning analysis to analysis and with time. Read the fine print!

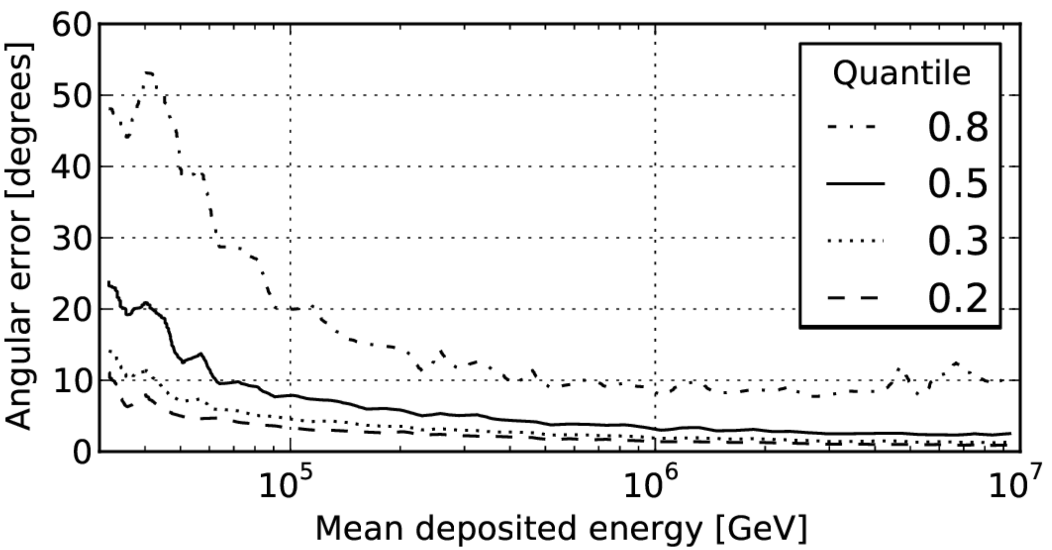
Tools: Direction

Tracks: Just look at the thing!

- Half a degree is easy
- Better gets hard, we're at ~ 0.3 degrees at high energy, still improving

Cascades: Tricky! Can get to ~ 10 degrees, enough for large-scale anisotropy

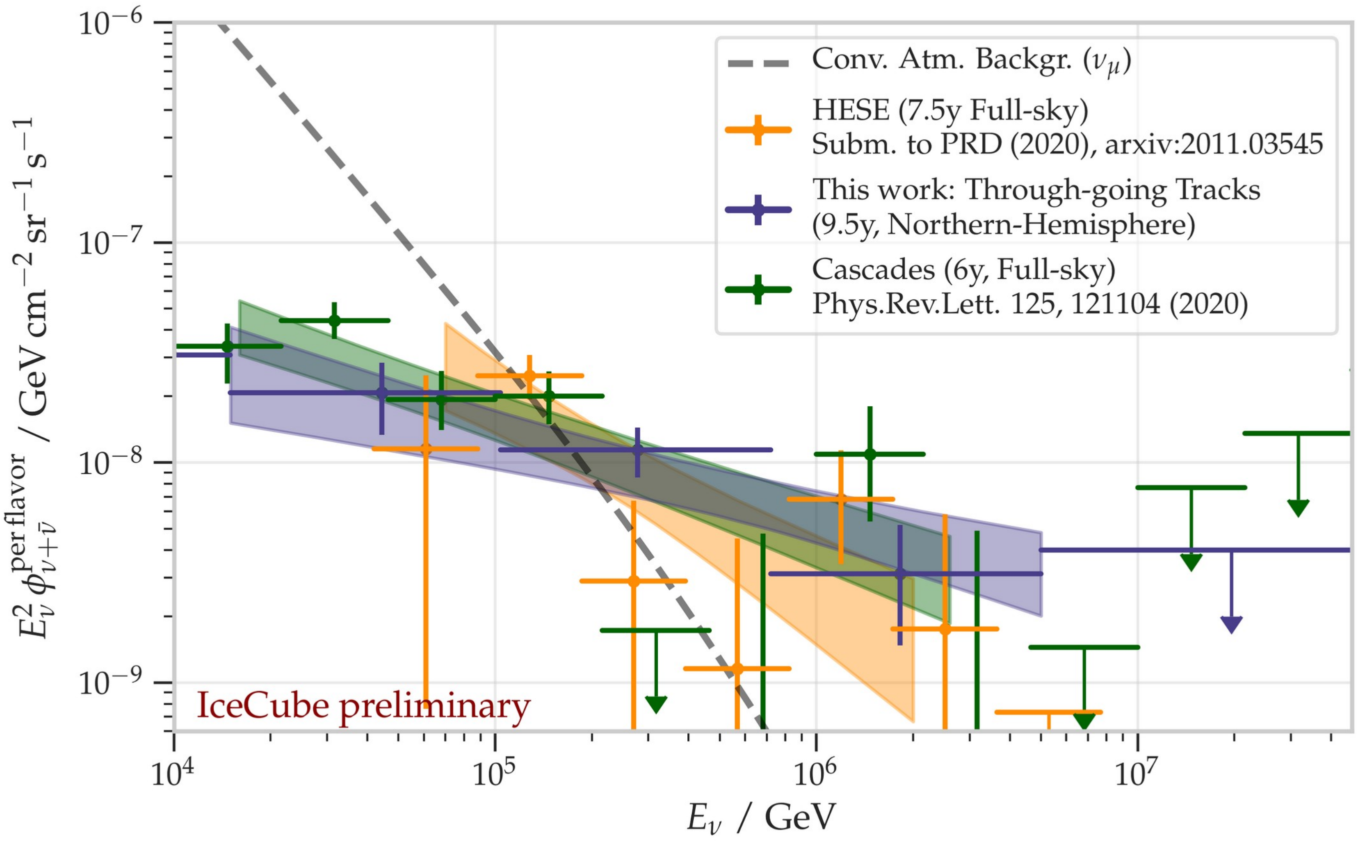




ArXiv:1311.4767

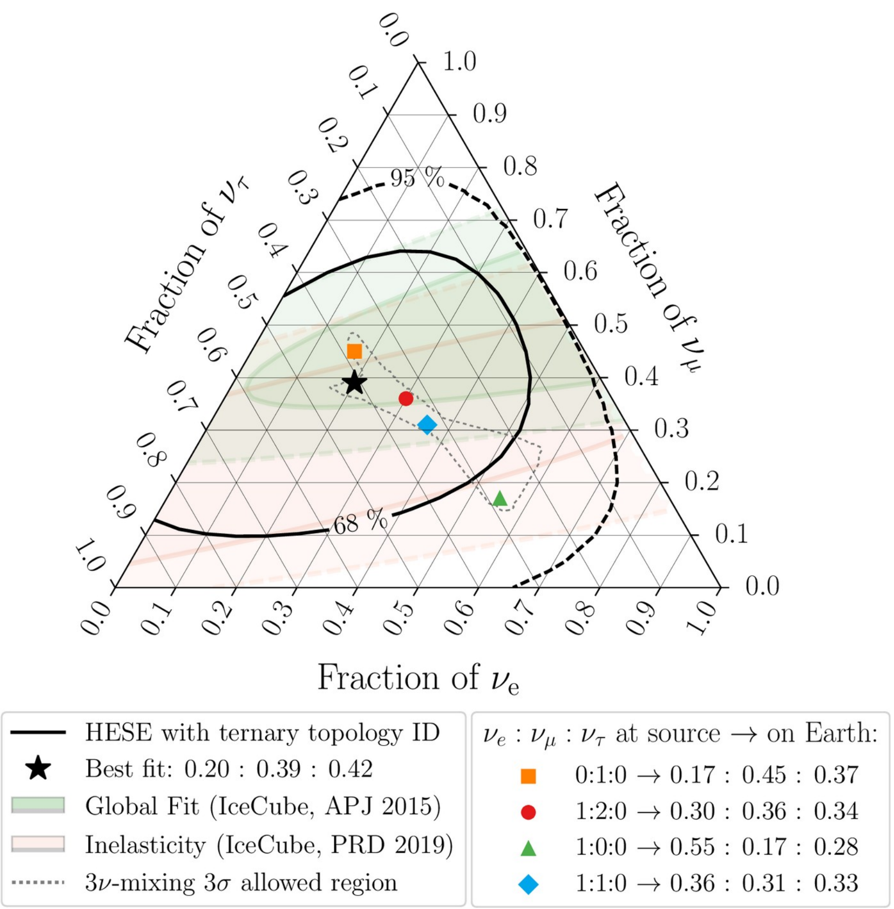
Spectrum

- **Roughly E$^{-2.4}$**
- **Seems compatible with a single power-law spectrum**
- **Limited statistical power except around 100 TeV**



Flavor

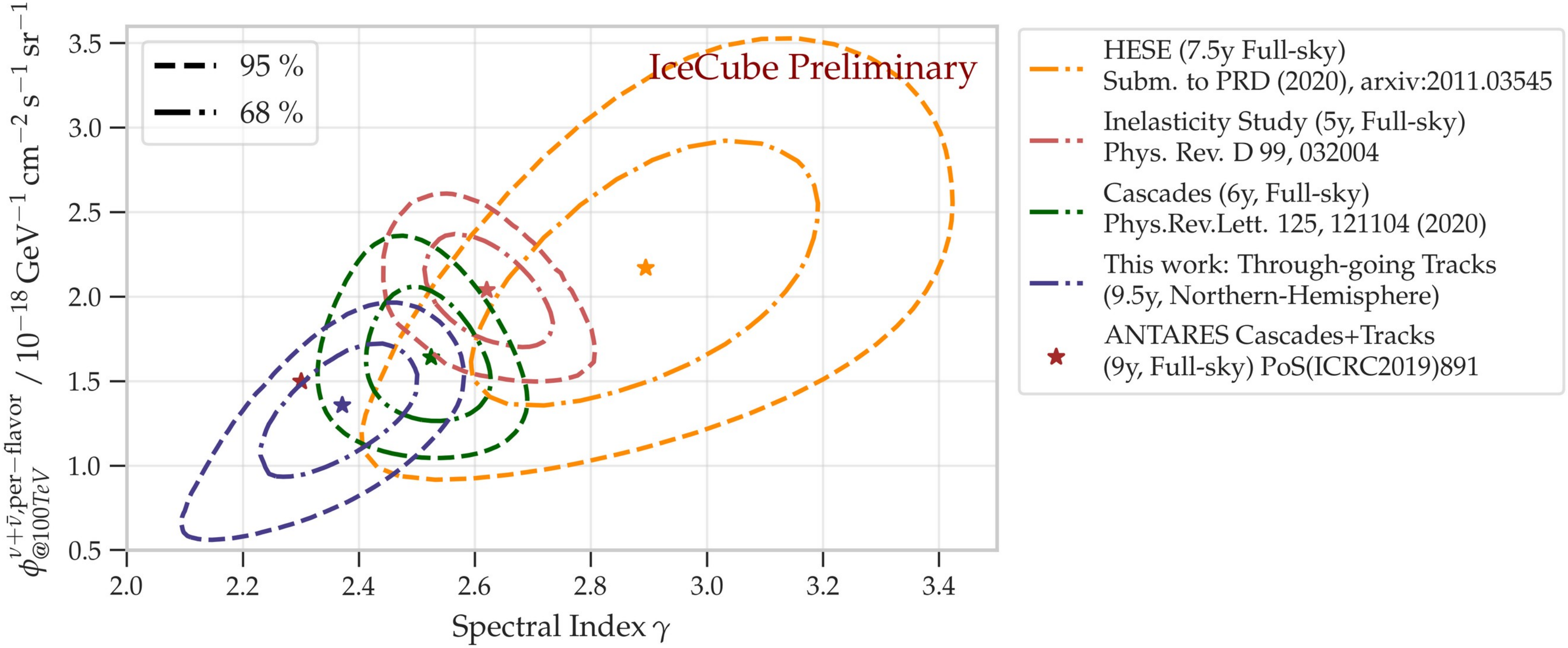
- **Use in-detector topology to determine neutrino flavor**
- **Tells you about:**
  - Neutrino production mechanism in the unknown sources
  - Possible non-standard behavior on the way
- **Sensitivity to neutrinos vs. anti-neutrinos at the Glashow resonance too**



ArXiv:2011.03561

Hints of structure?

- Some minor tension between analyses in different energy ranges/flavors
- More complex spectrum?
- Not clear yet



Summary of Diffuse Measurements

Things we know:

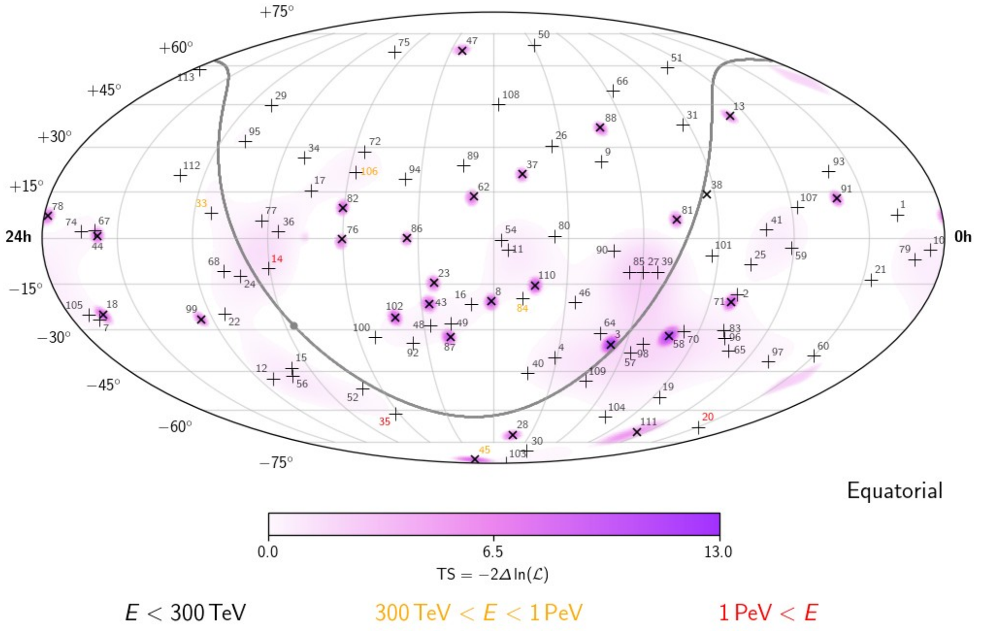
- **Bright neutrino background**
- **Nearing flavor sensitivity to distinguish between production mechanisms**
- **Compatible with a hard power law, expected from shock acceleration of protons**

Things we don't:

- **Is there any structure in the spectrum, suggesting multiple source classes?**
- **Is the flux actually iso-flavor?**
- **What interaction creates the neutrinos?**

Anisotropy

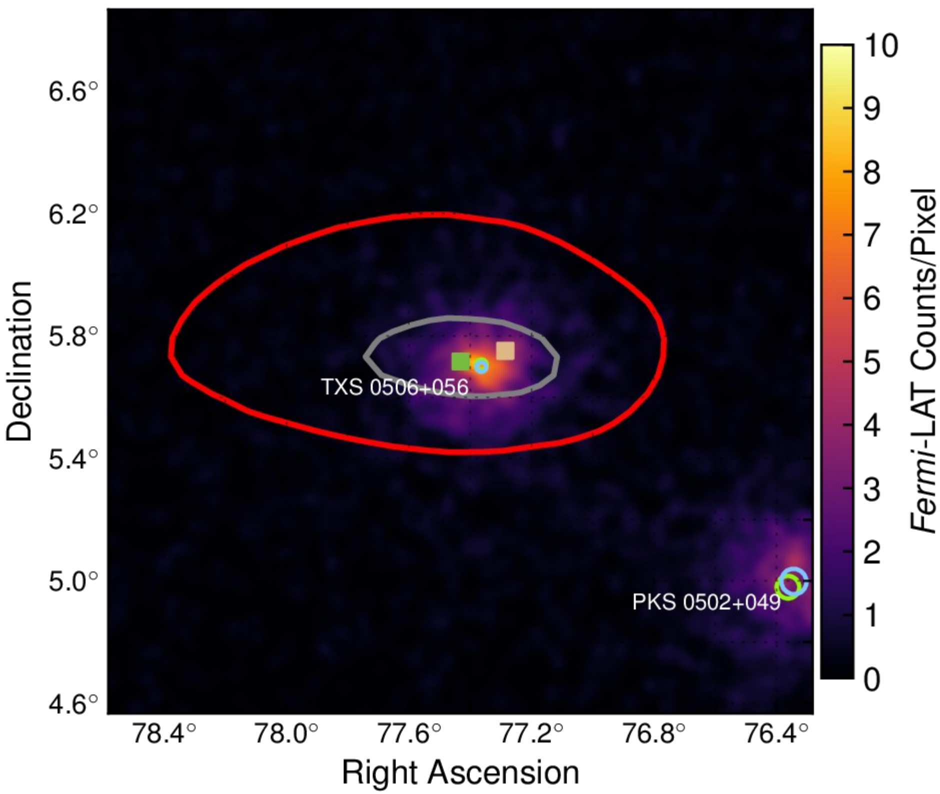
- **If we can find specific sources, provides insight into the acceleration mechanism**
- **Sensitivity related to pointing for small-scale anisotropies: dominated by muon neutrinos**



ArXiv:2011.03545

Real-time Searches

- **Follow up IceCube neutrinos with other instruments**
- **First source from a 2017 alert: TXS 0506+056, a distant blazar**
- **Fast (minutes) turnaround on IceCube events**



ArXiv:1807.08816

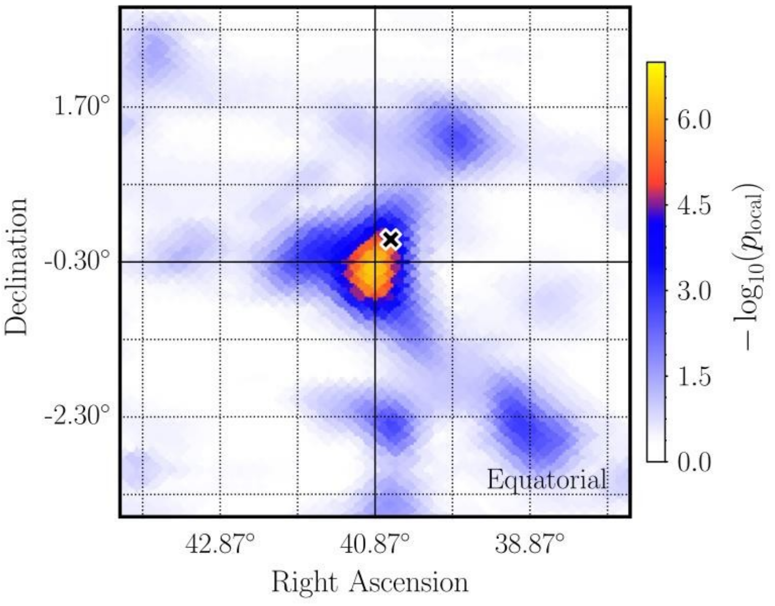
See also: talk by C. Boscolo Meneguolo

Offline Searches

- **Autocorrelation to find excesses in our data**
- **Cross-correlation to look from specific, likely places**

- **Found early evidence for a bright neutrino flare from TXS 0506+056 when gamma-dark in 2014**
- **May be hinting at other sources too (see talk by F. Lucarelli)**

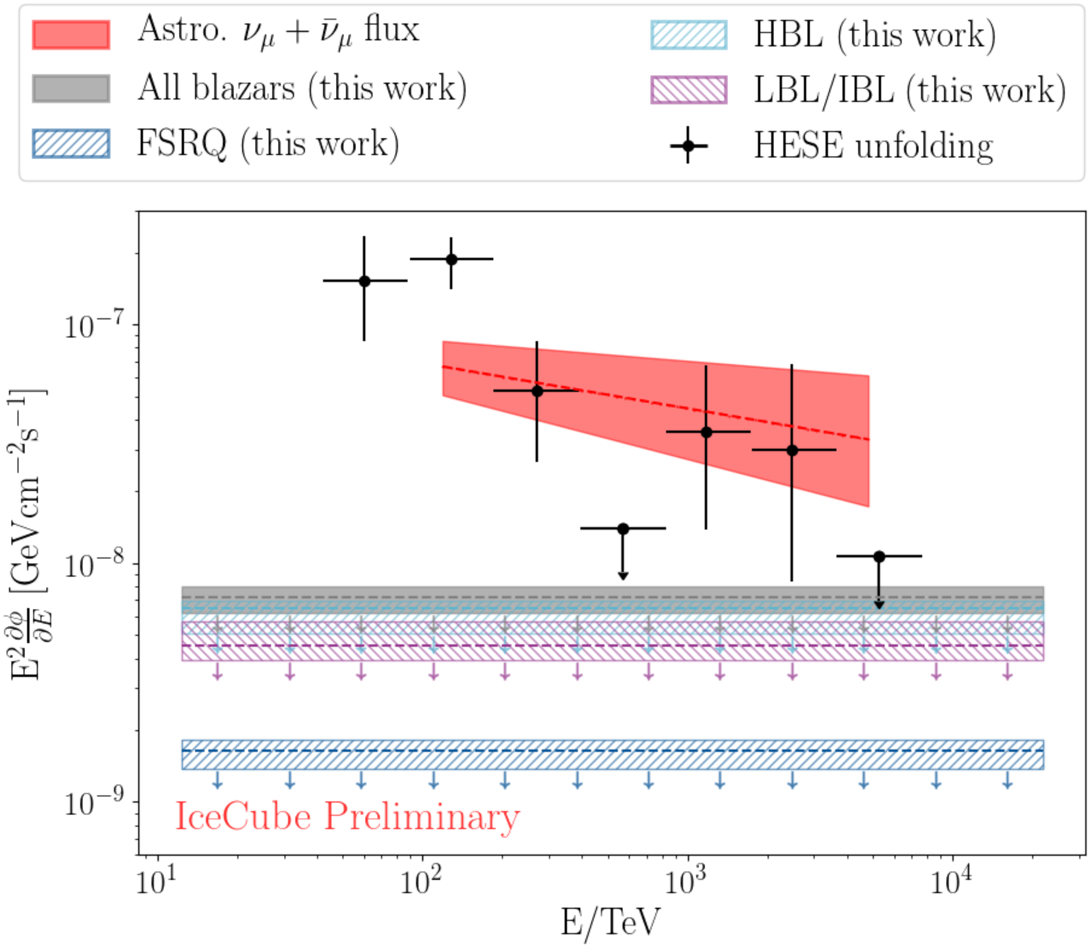
NGC 1068



ArXiv: 1910.08488

Population Studies

- **With sources peeking out, can correlate with catalogs to see what fraction of the diffuse flux comes from a class of sources**
- **Tested source catalogs in general (blazars, right) don't add up to anywhere close to the diffuse flux!**



ArXiv:1611.03874

Summary of Anisotropy Measurements

Things we know:

- **At least some of the diffuse flux comes from blazars**
- **Which ones are not obvious and simple models don’t explain the whole flux**
- **Neutrino emission sometimes, but not always, correlated with gamma rays**

Things we don’t:

- **Why is TXS brighter in neutrinos than nearer galaxies?**
- **Are other sources starting to peek through?**
- **If so, what common thread links them?**
- **Are those sources, if real, representative of the sources of the bulk of the diffuse flux?**

New Questions

With signals come new questions:

- **Where is the GZK flux?**
- **What makes the diffuse TeV background? How?**
- **Why is the brightest spot on the sky (TXS) 4 billion light years away?**
- **What (if anything) happens to neutrinos when they fly for a billion years?**
- **How we increase precision of the measurements?**

Very different focus for next generation of analyses and detectors!

Keys to improve: the measurement regime

Effective area

- 1^{st} generation targeted the first events
- More required, scaling between sqrt(N) and linear
- 1 km^3 → 5-10 km^3

Angular resolution

- Limits source searches (dark matter and astrophysics)
- Scaling linear
- .5 degree → .1 degree

Systematics

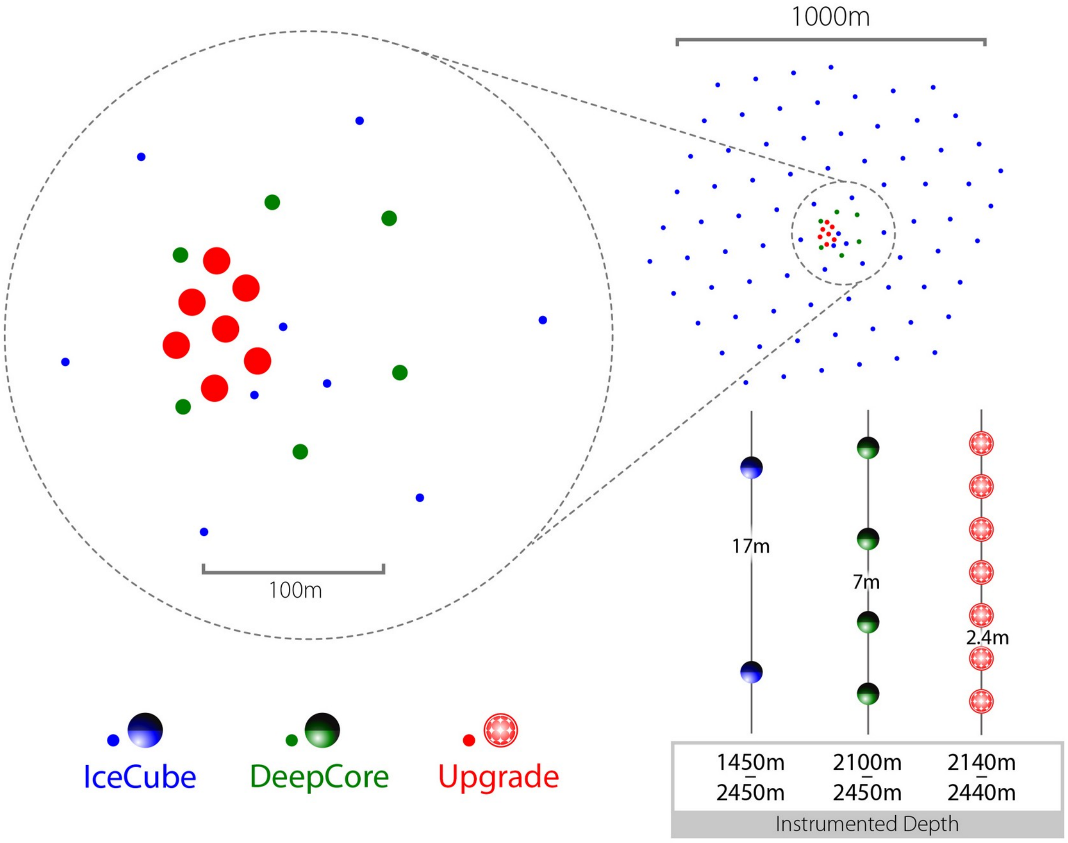
- Limits spectral measurement, low energies

Flavor ID

- Powerful constraint on particle physics, source dynamics
- Better reconstruction, more fine-grained data

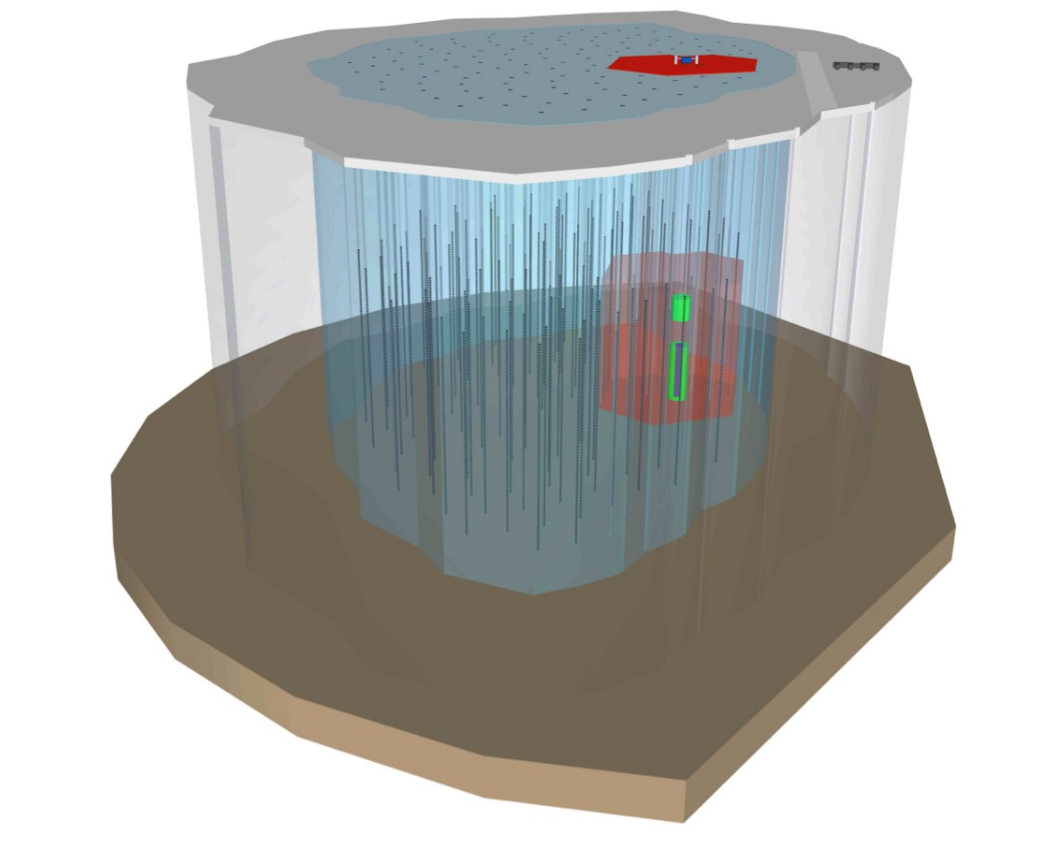
On the Horizon: IceCube Upgrade

- Small in-fill of IceCube
- Better calibration
- Improves all of IceCube's angular resolution
- Sensitivity enhancement at low energies
- R&D Opportunity
- Funded!



On the Horizon: IceCube Gen2

- **8 km³**
- **0.1 degree resolution**
- **Design stage**
- **New photo-detector designs**
- **PLUS: Large-scale high-energy Askaryan-effect radio array**



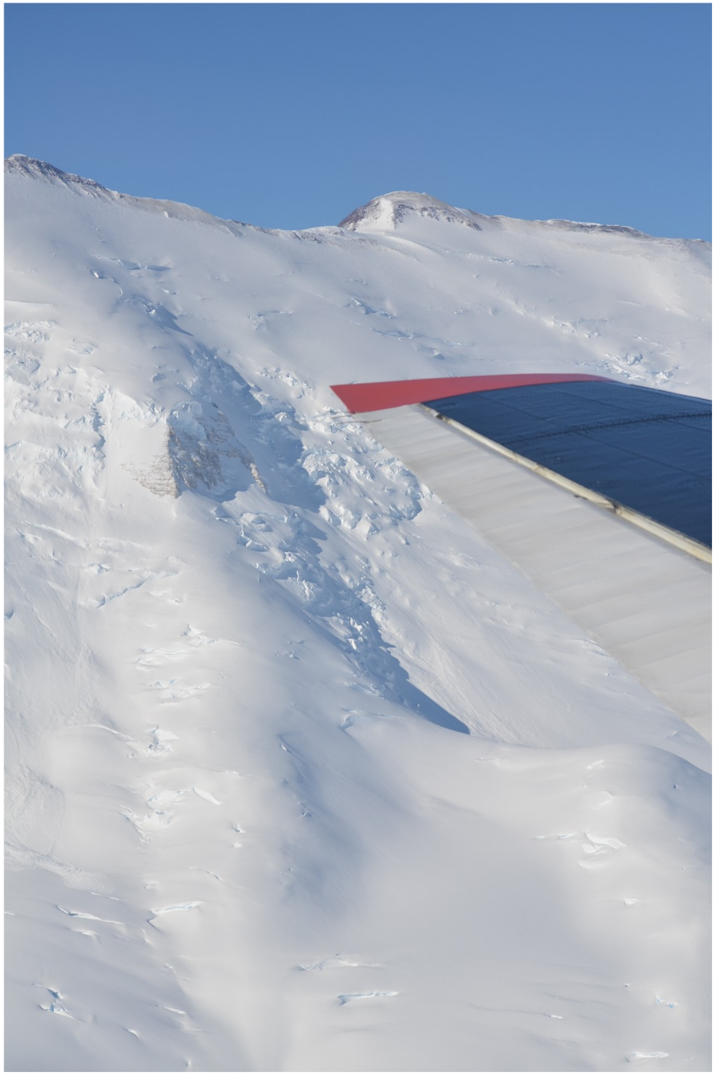
ArXiv:2008.04323

Prospects for the Next Decade

This decade, we stopped measuring zero:

- **First source – distribution normalized, know what to target**
- **At models for GZK**
- **Diffuse background detected**

Next 10 years, many new instruments coming online – learn what these things have to tell us



The Beginning