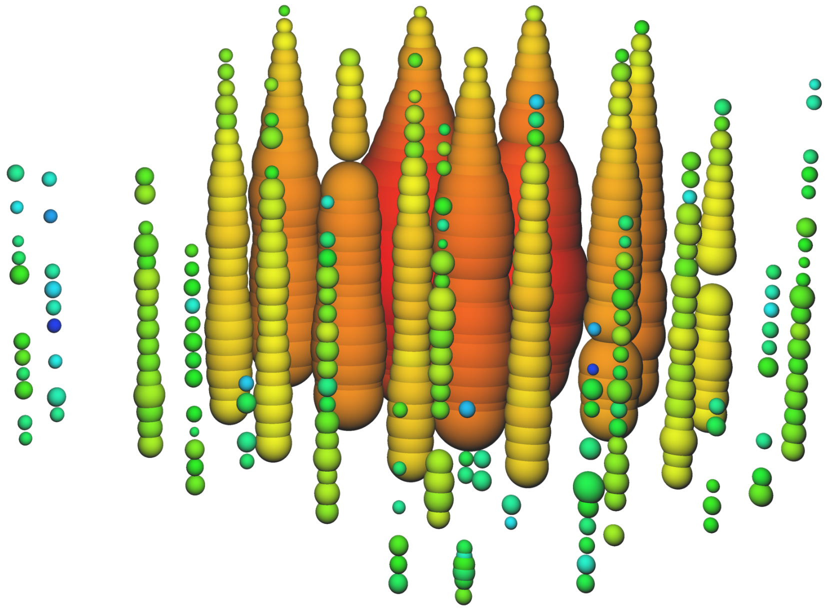
Detecting neutrinos in the South Pole ice with Cherenkov light in IceCube

Tianlu Yuan for the IceCube Collaboration

RICH2022, Edinburgh UK

12 September 2022



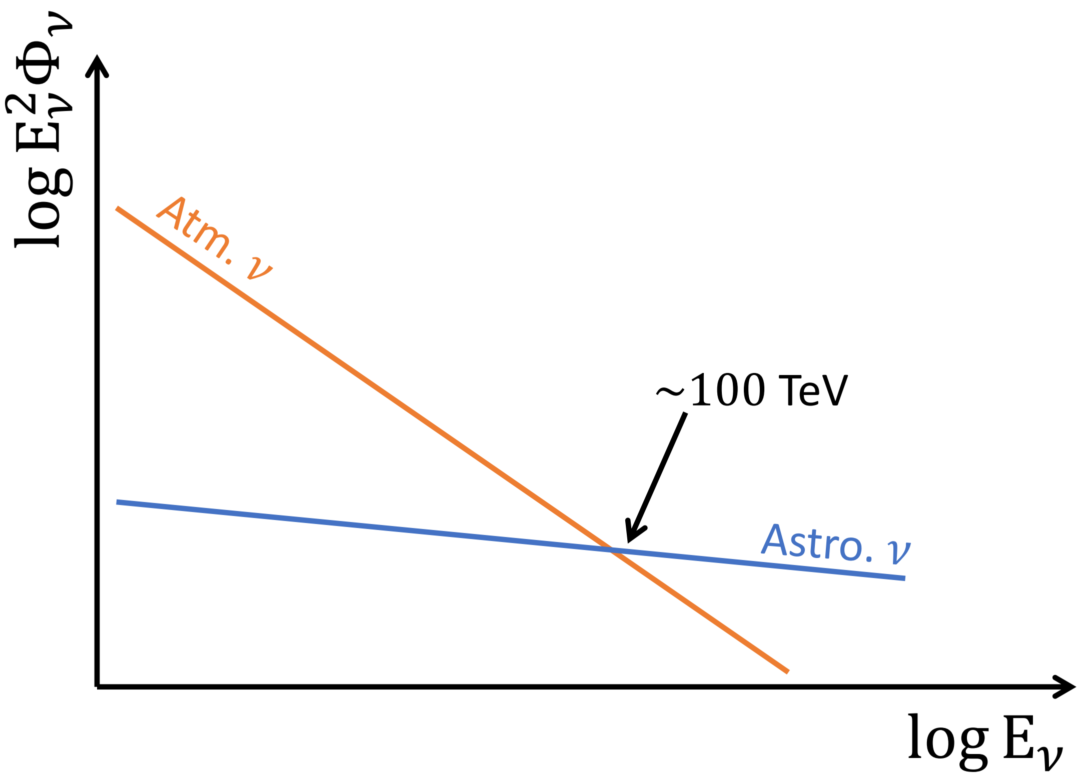
ICECUBE

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

Overview

- Motivation and background
- Highlight of IceCube results
- Ice modeling and calibration
- Event reconstruction
- New OM technologies

Neutrino fluxes



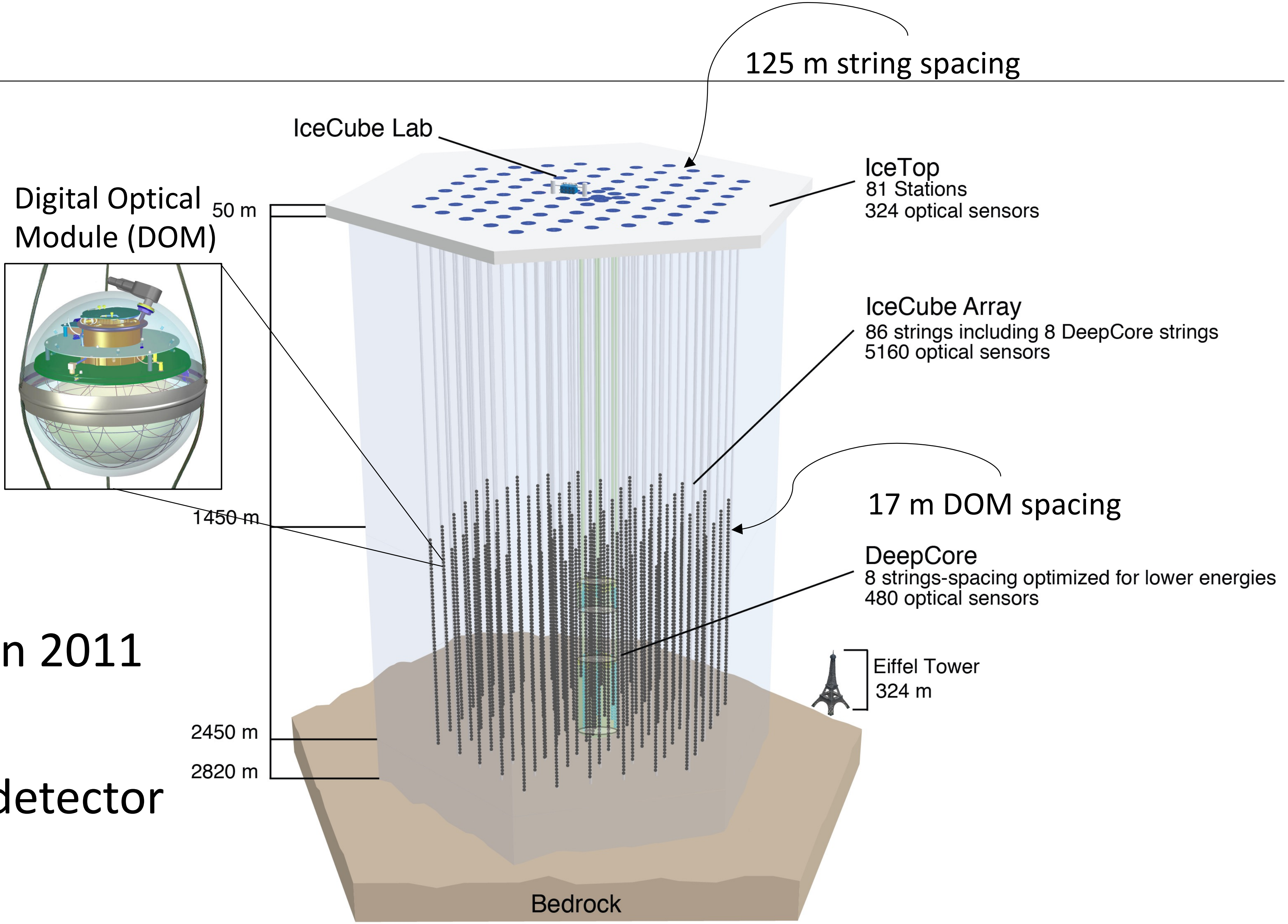
Power-law flux $\Phi_\nu = \Phi_0 E^{-\gamma}$

Flux falls off faster than cross section increases

→ Need **large** mass detector

South Pole ice is extremely clear and there is a lot of it

IceCube



5000+ DOMs

Fully operational in 2011

Natural neutrino detector

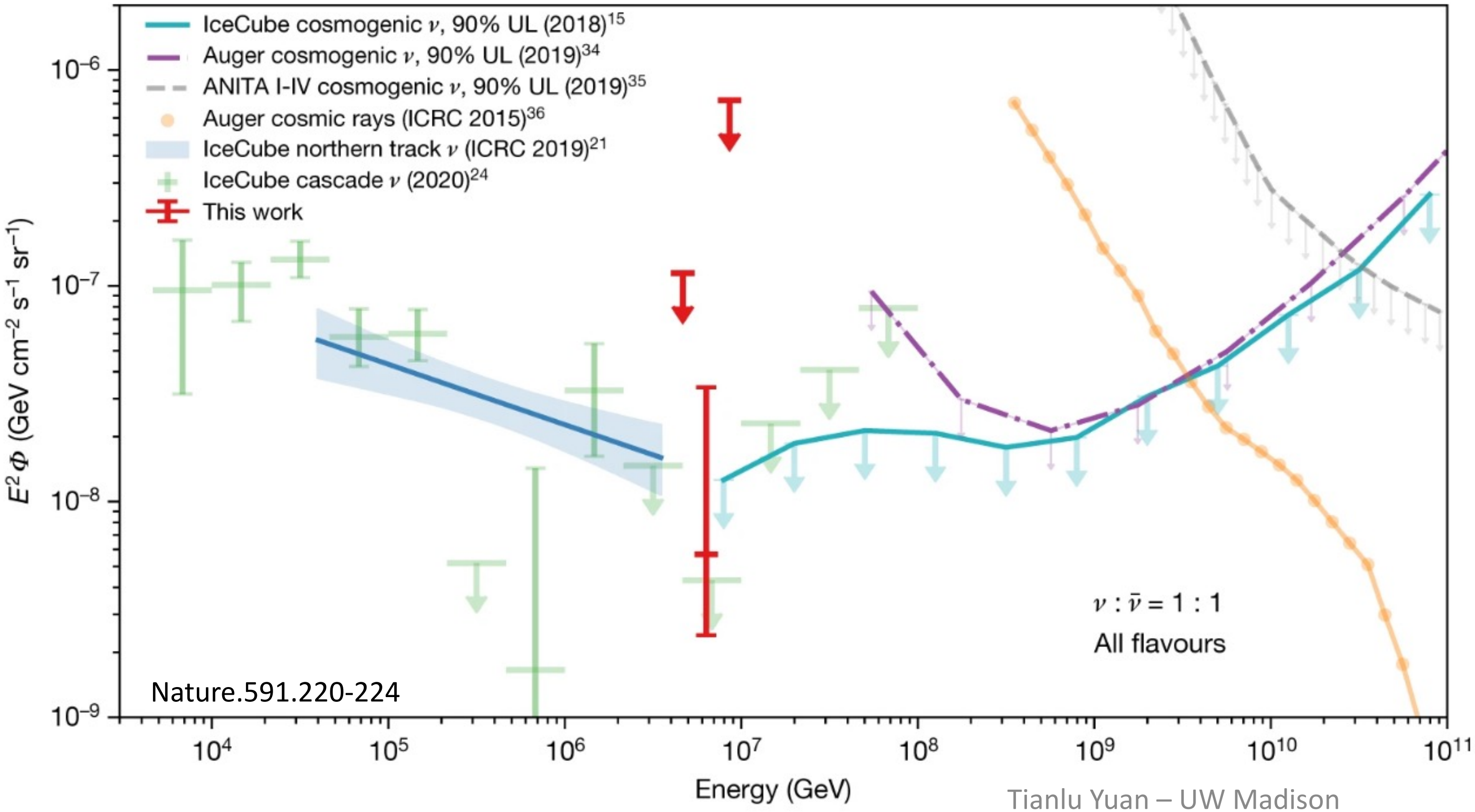
Results, a highlight

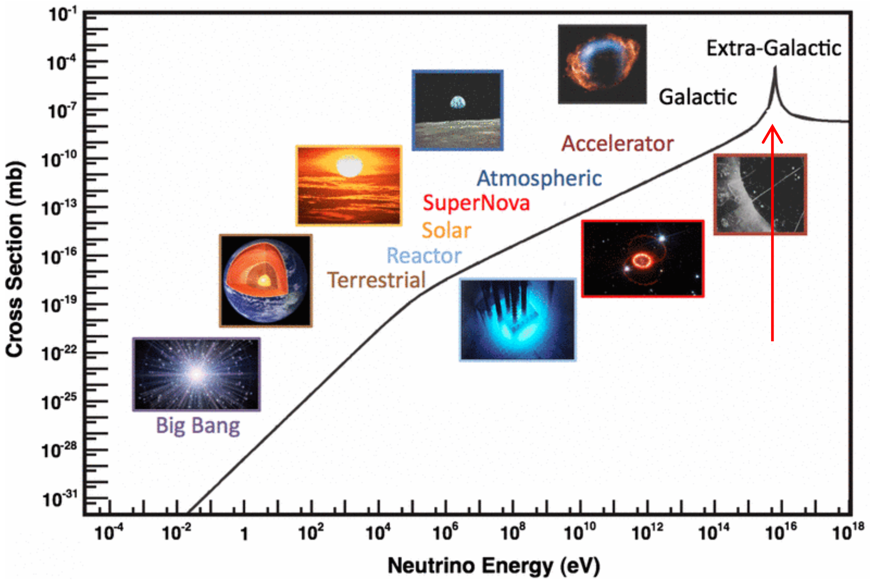
Glashow resonance

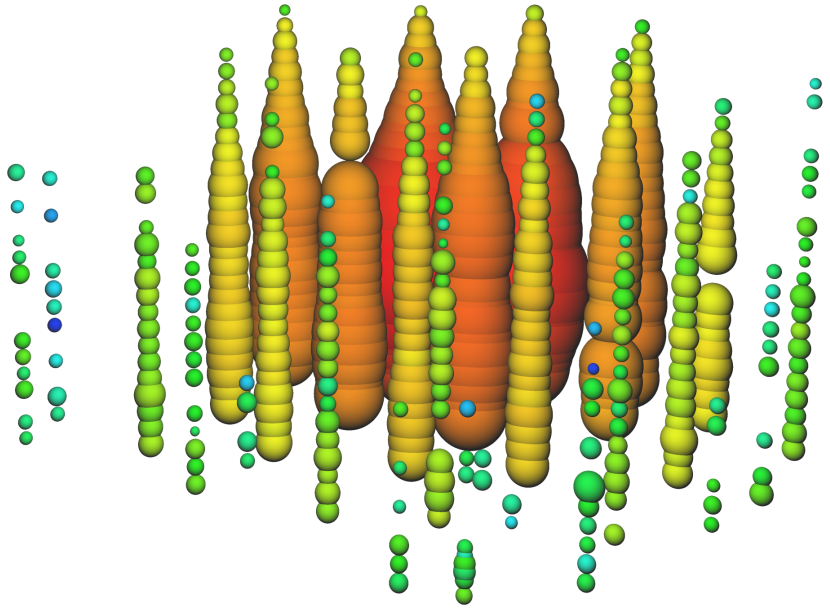
Partially-contained cascade with reconstructed energy:
$\mathbf{6.05 \pm 0.72}$ **PeV**

- Significance of astrophysical origin above 5σ

Consistent with resonant formation of on-shell W-boson







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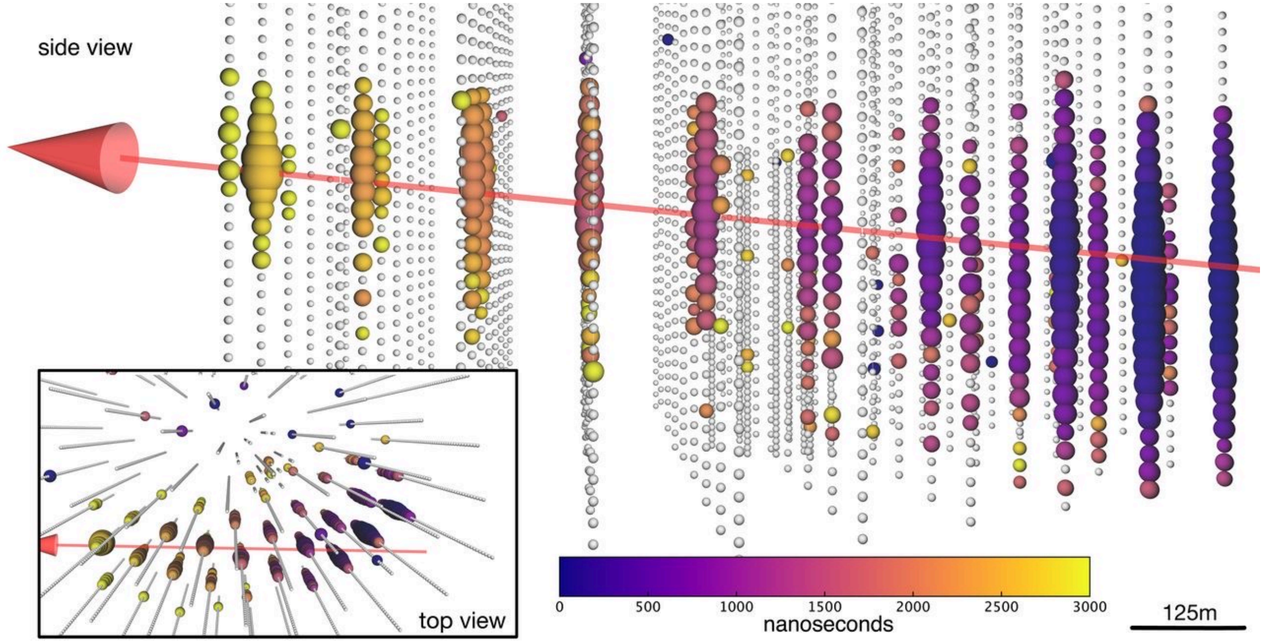
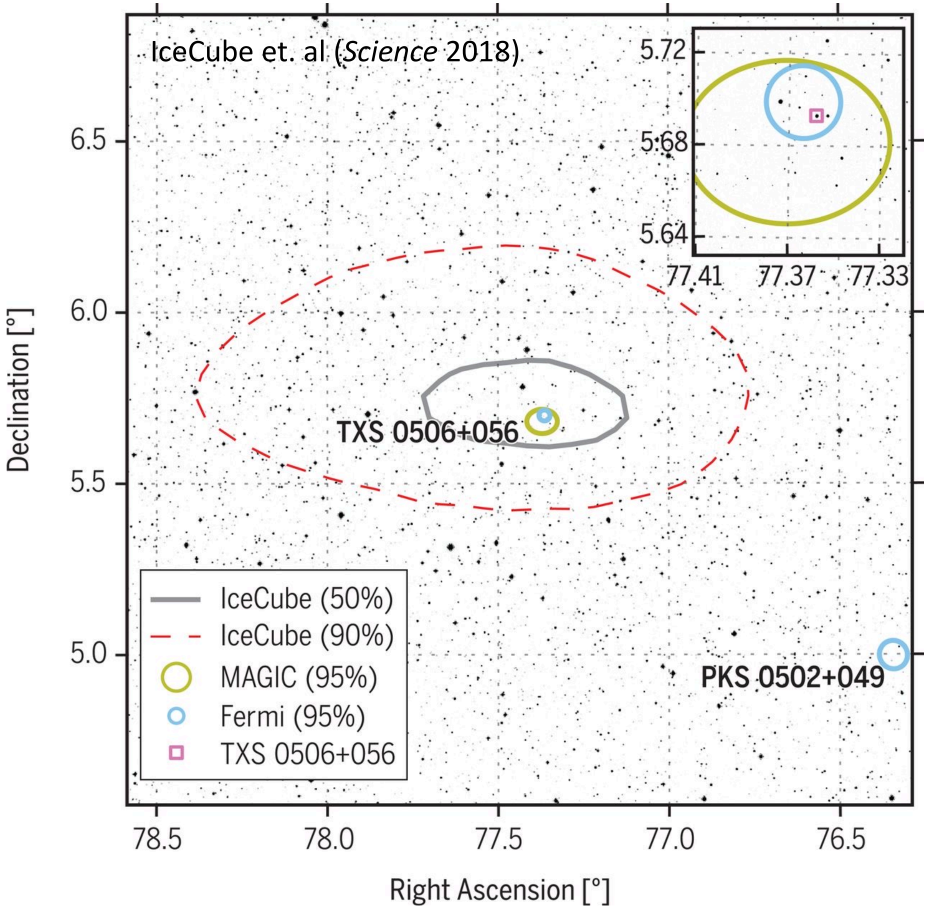


Realtime alert on Sept. 22, 2017

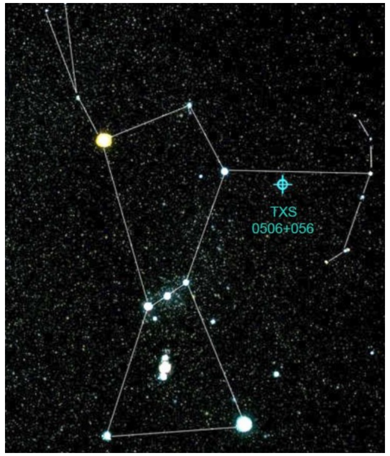
~5800 p.e. track, E~290 TeV



Significant excess seen by Fermi-LAT and MAGIC shortly after IC alert (3σ)

Independent neutrino flare in 2014-15 (3.5σ)

Summary: **first evidence** for very high-energy, astrophysical neutrino source. Implications for blazars as an origin of high-energy cosmic rays.



Time-independent source search

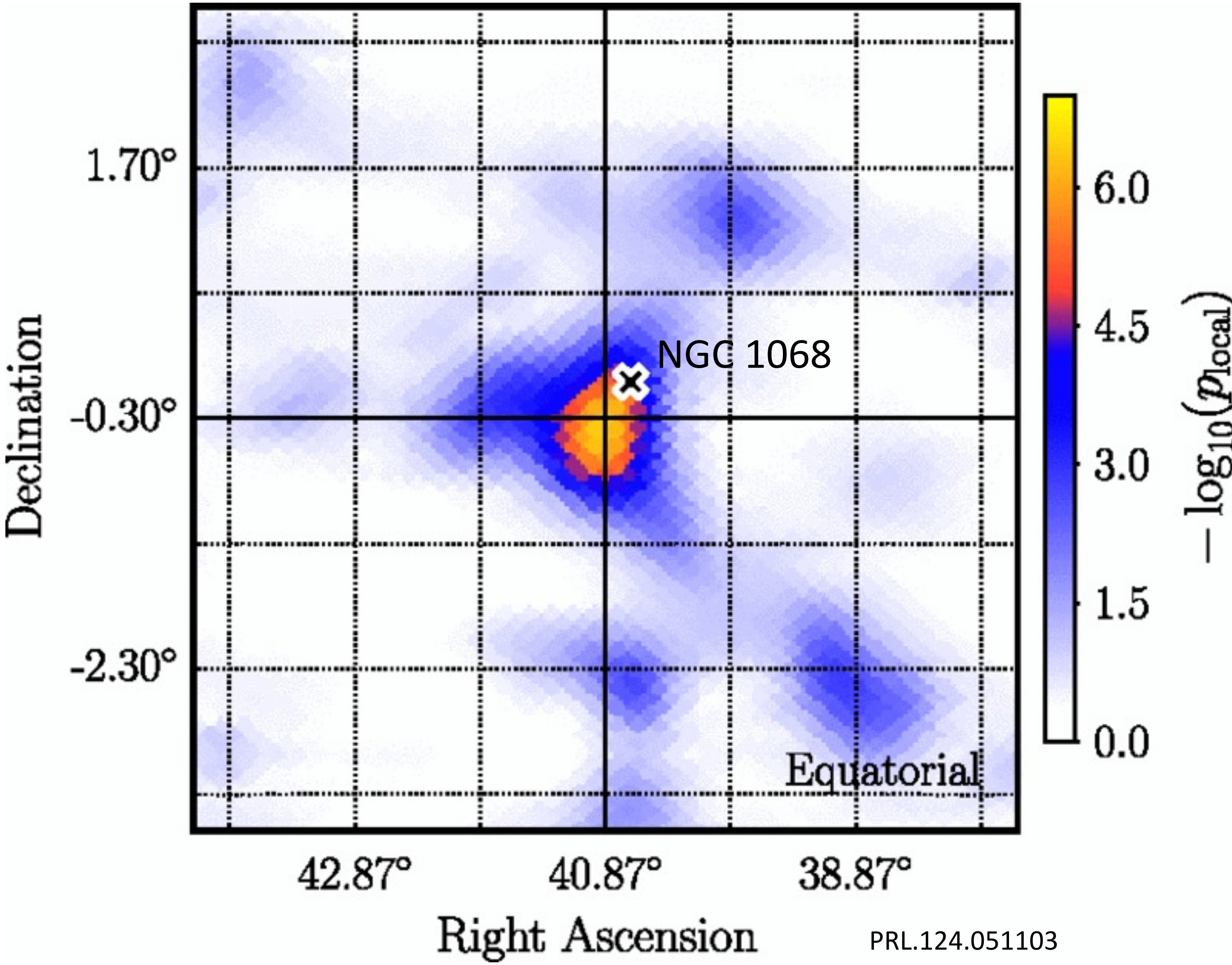
110 sources selected *a priori*

- 97 N. sky; 13 S. sky

Hottest spot in N. Sky ~ NGC 1068

- 4.1σ (pretrial), 2.9σ (posttrial)

TXS 0506 at 3.6σ (pretrial)
consistent with previous results



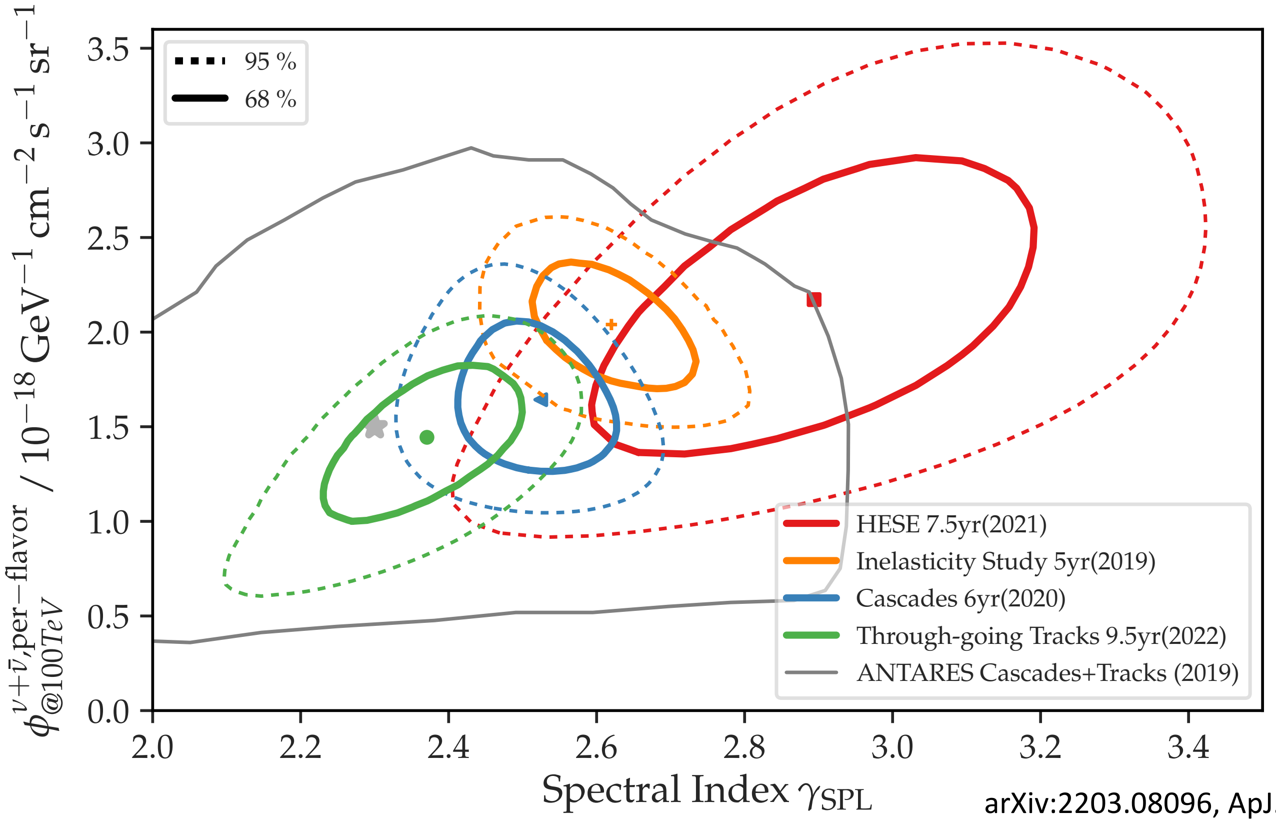
PRL.124.051103

Current landscape of the diffuse astrophysical flux

Assuming single-power-law flux

All results consistent at 2 sigma level

All results consistent with SPL hypothesis



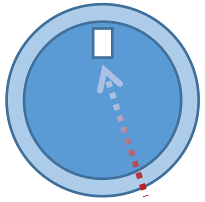
arXiv:2203.08096, ApJ.928.50

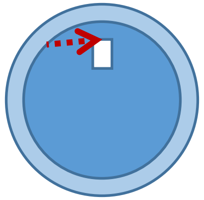
Neutrino cross sections at high energies

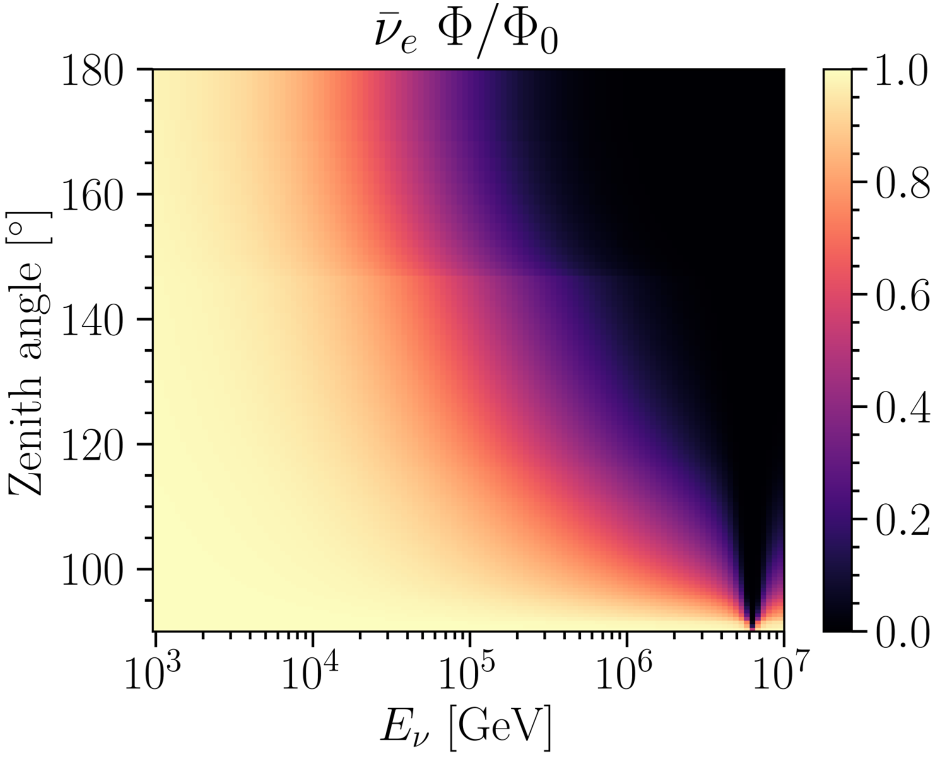
Utilize in-Earth attenuation to measure neutrino cross sections

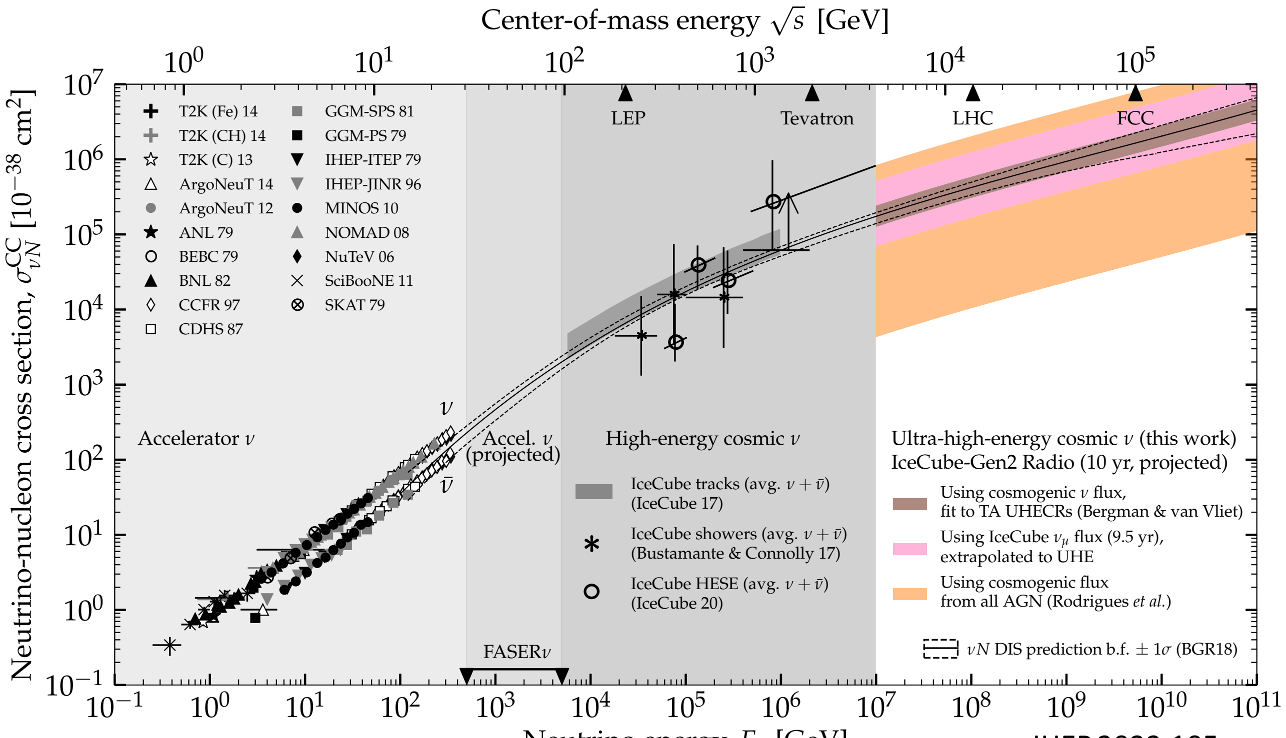
- Expected arrival flux depends on cross section

Probe of BSM physics at PeV+ energies









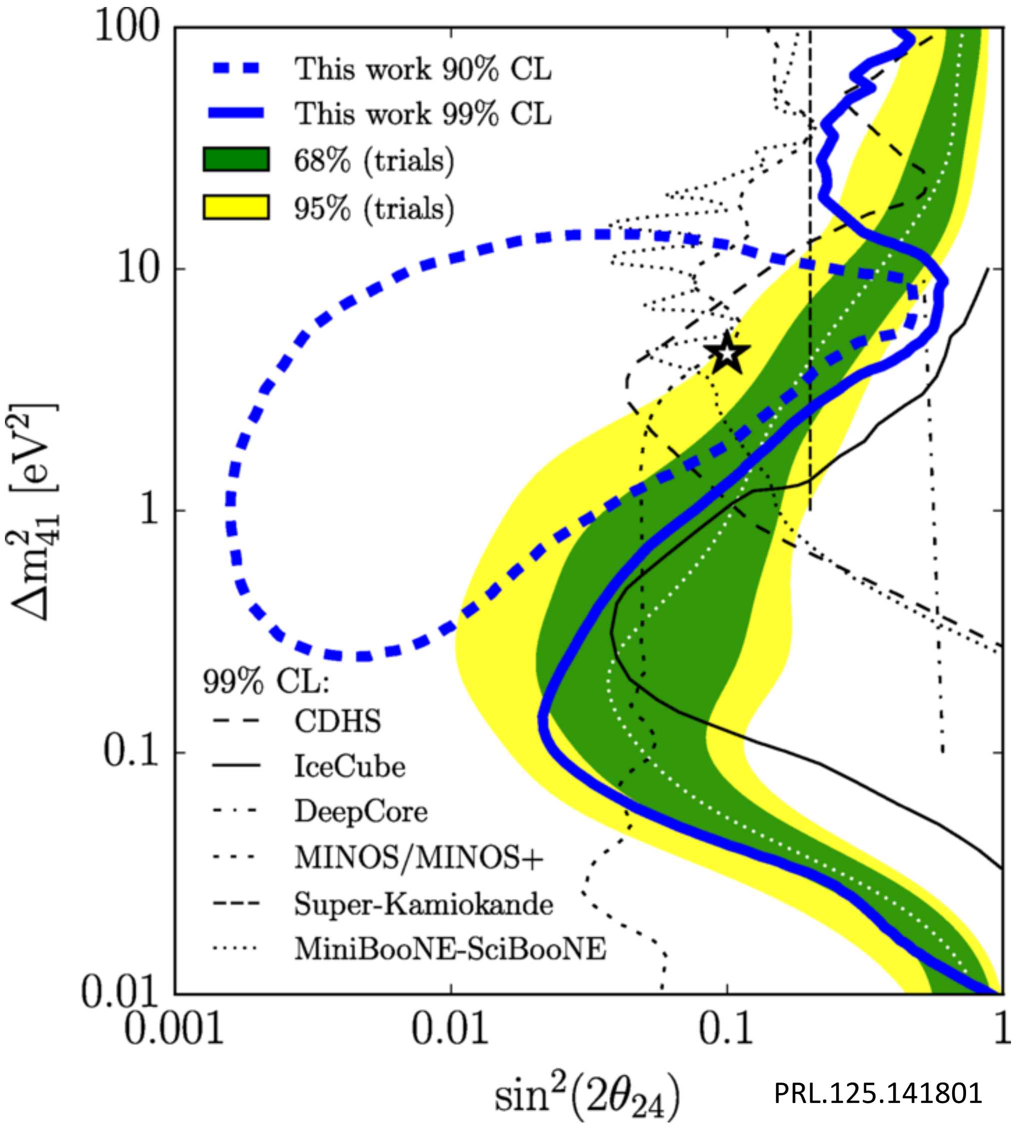
JHEP.2022.105

Sterile neutrinos?

Anomalies from other experimental results challenging 3-flavor paradigm

Test of 3+1 mixing at eV-scale mass splitting with IceCube upgoing tracks

Consistent with 3-flavor oscillations (p=0.08)



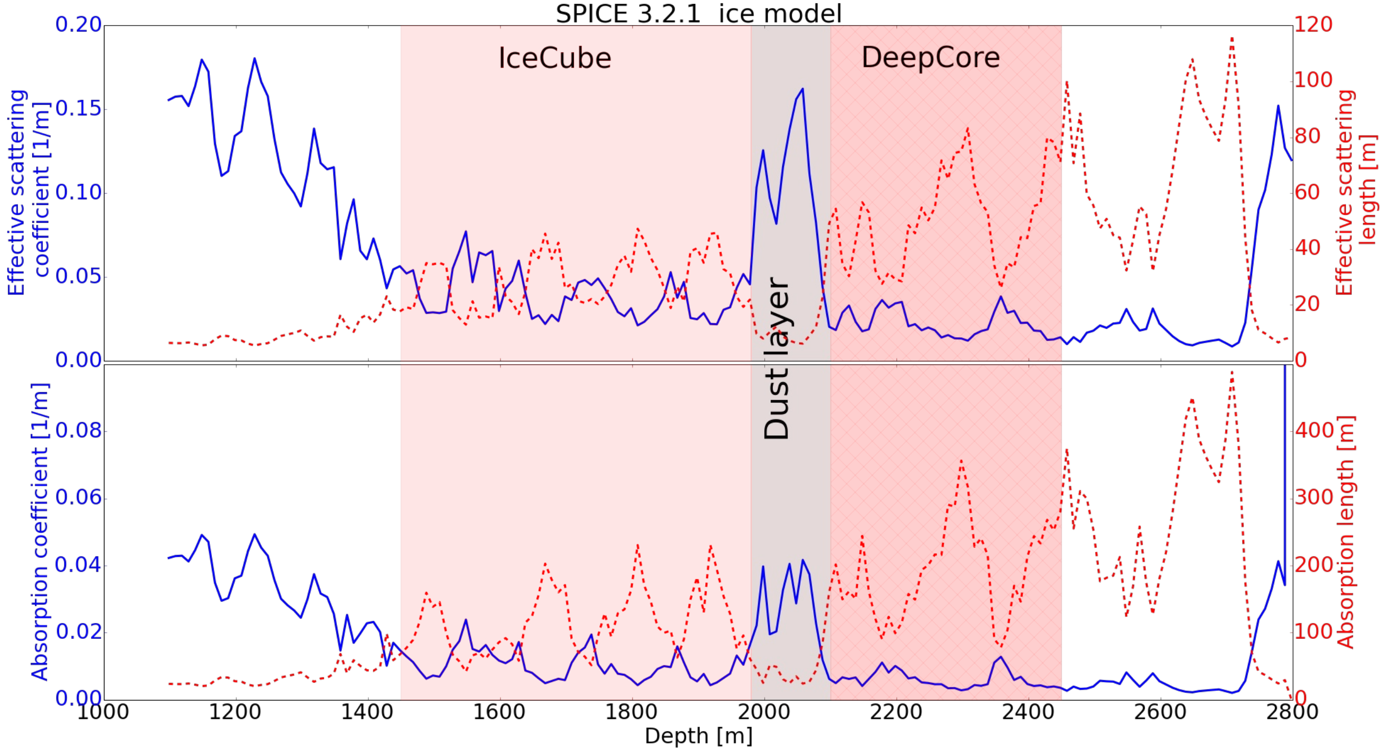
PRL.125.141801

Ice modeling

Ice calibration

Bulk ice described by scattering and absorption coefficients as a function of depth → these have been refined over time

- Governs how far a photon goes before scatter or absorption



Ice layers not perfectly flat

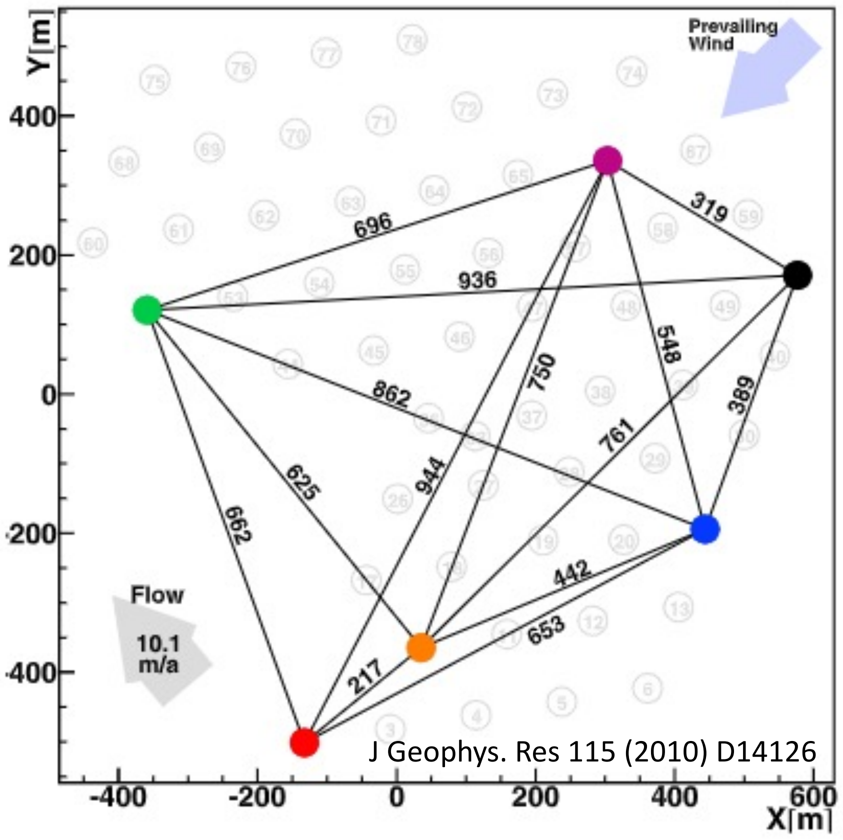
[NIM A711:73,2013]

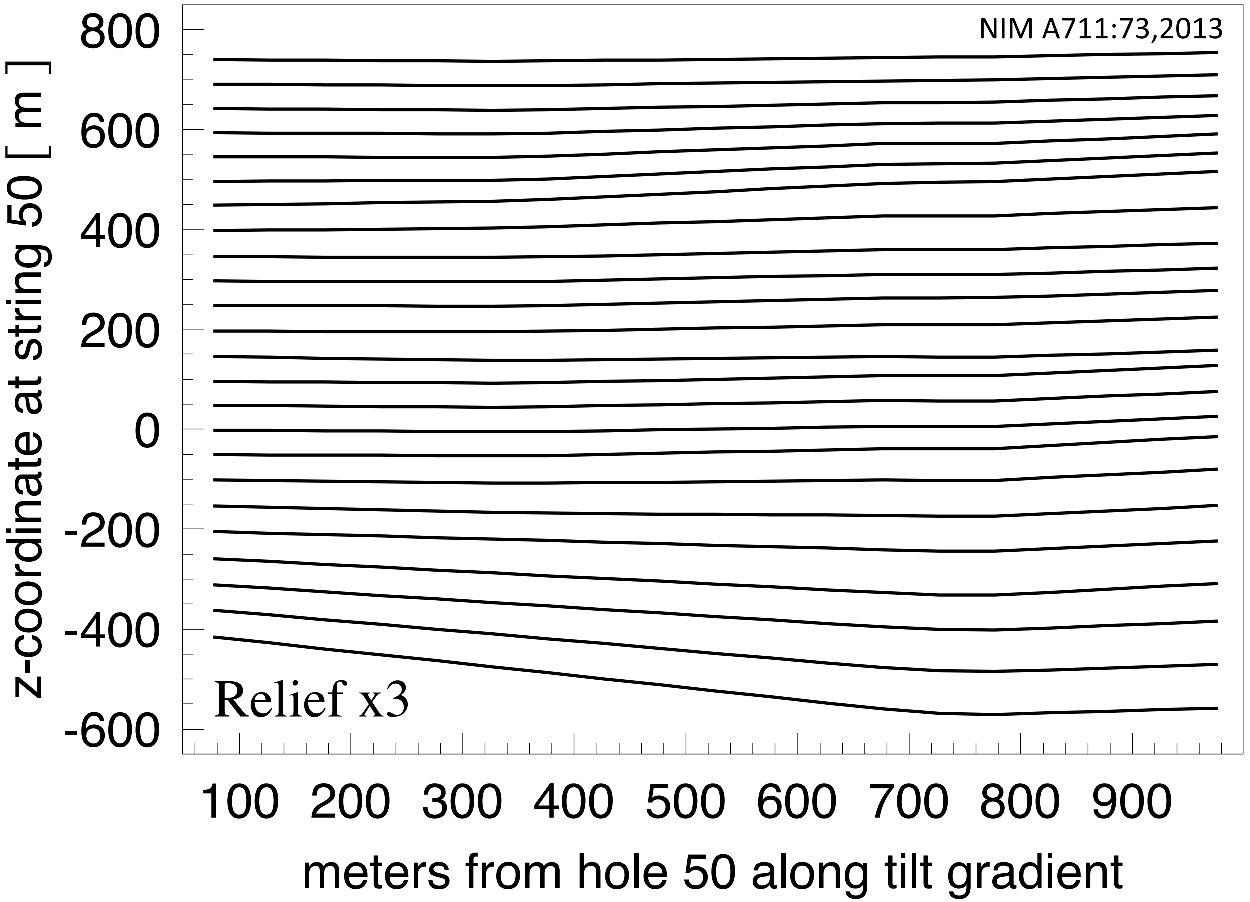
Ice was also discovered to be anisotropic

[ICRC 2013 0580, ICRC 2019 854, ICRC 2021 1119]

Ice layer tilt

Derived from laser dust logger data deployed in 5 IC boreholes

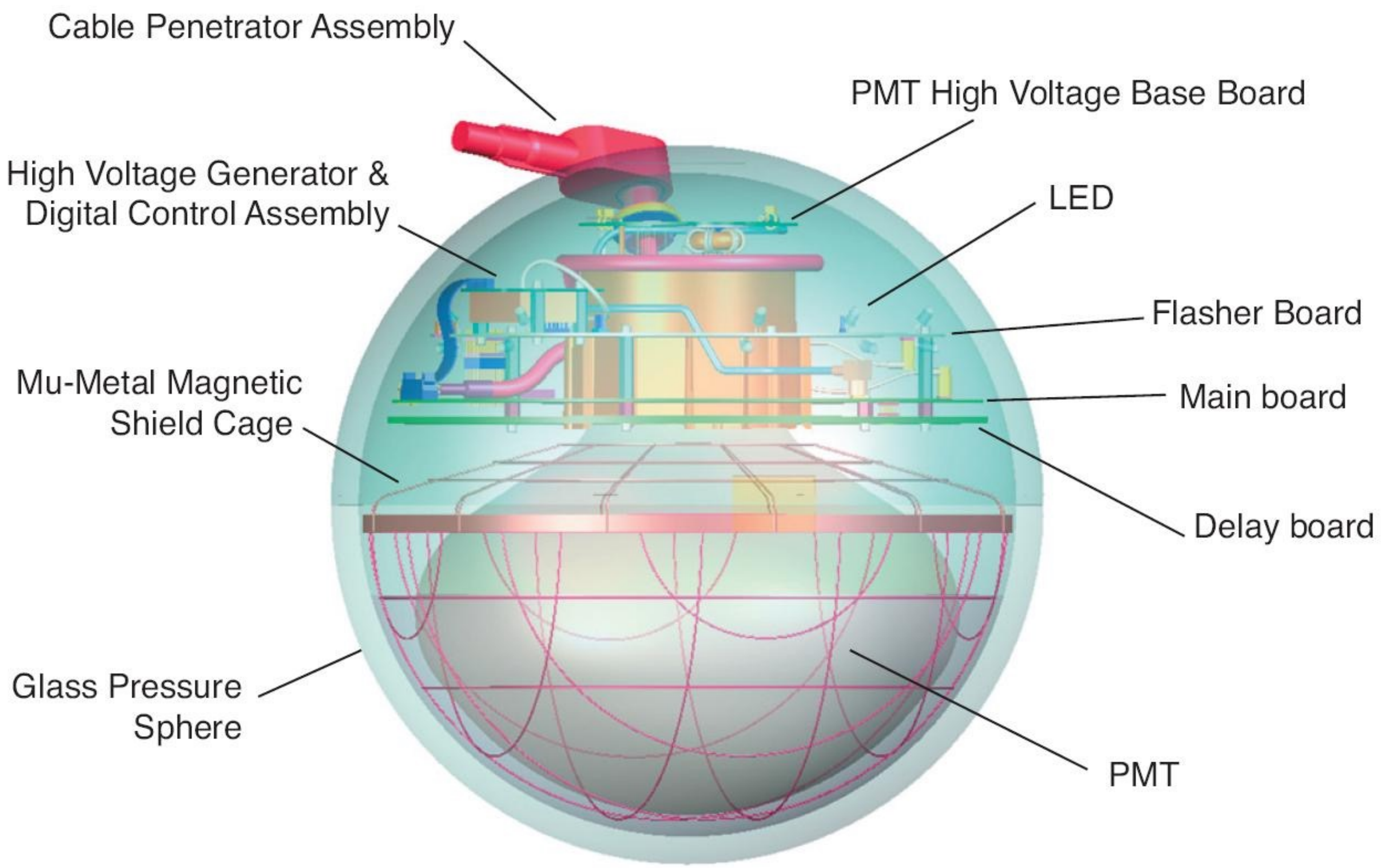




In-situ calibration

Each IceCube DOM contains 12 LEDs arrayed on its mainboard

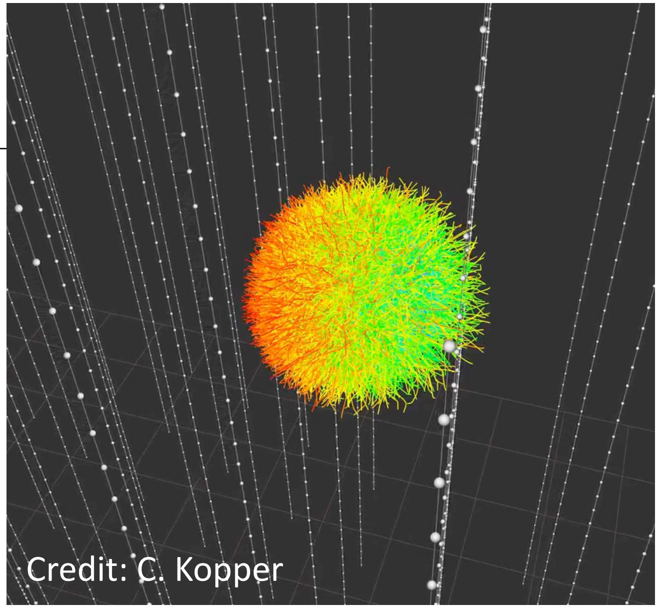
Produces in-situ calibration “flasher” data

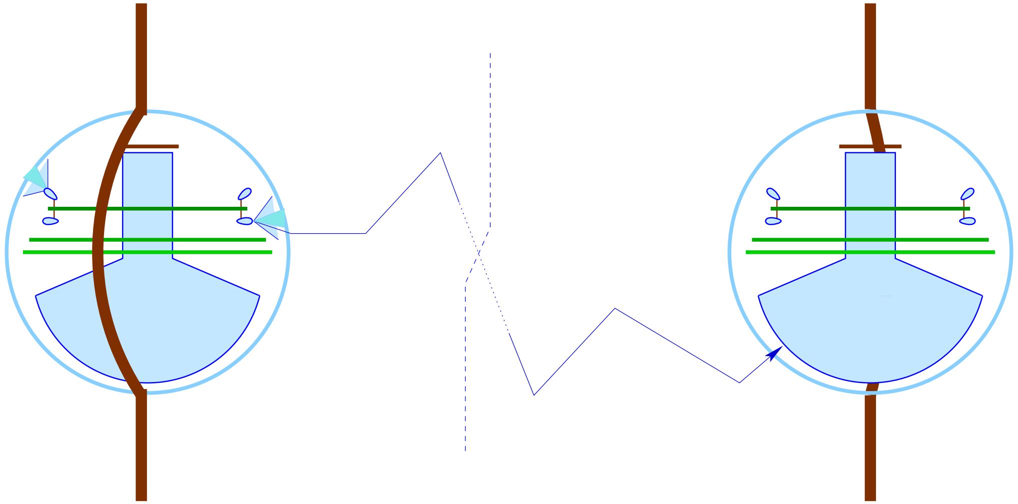


Photon propagation simulation

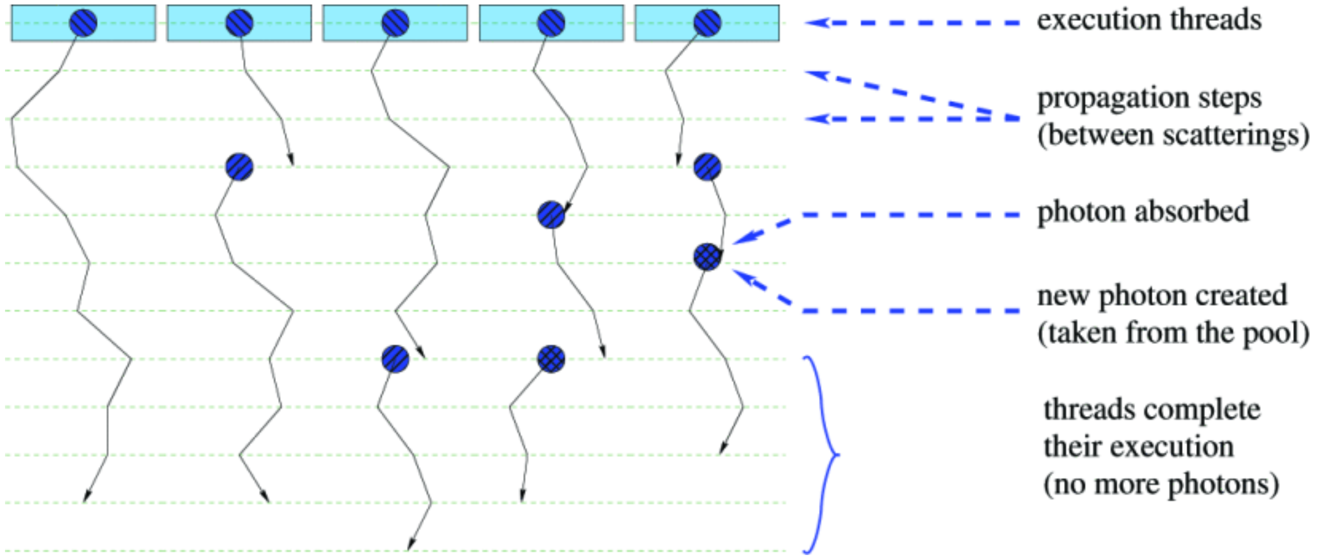
Parallelize photon propagation with GPUs

Enables large-scale simulations of high-energy events *and* flasher LEDs





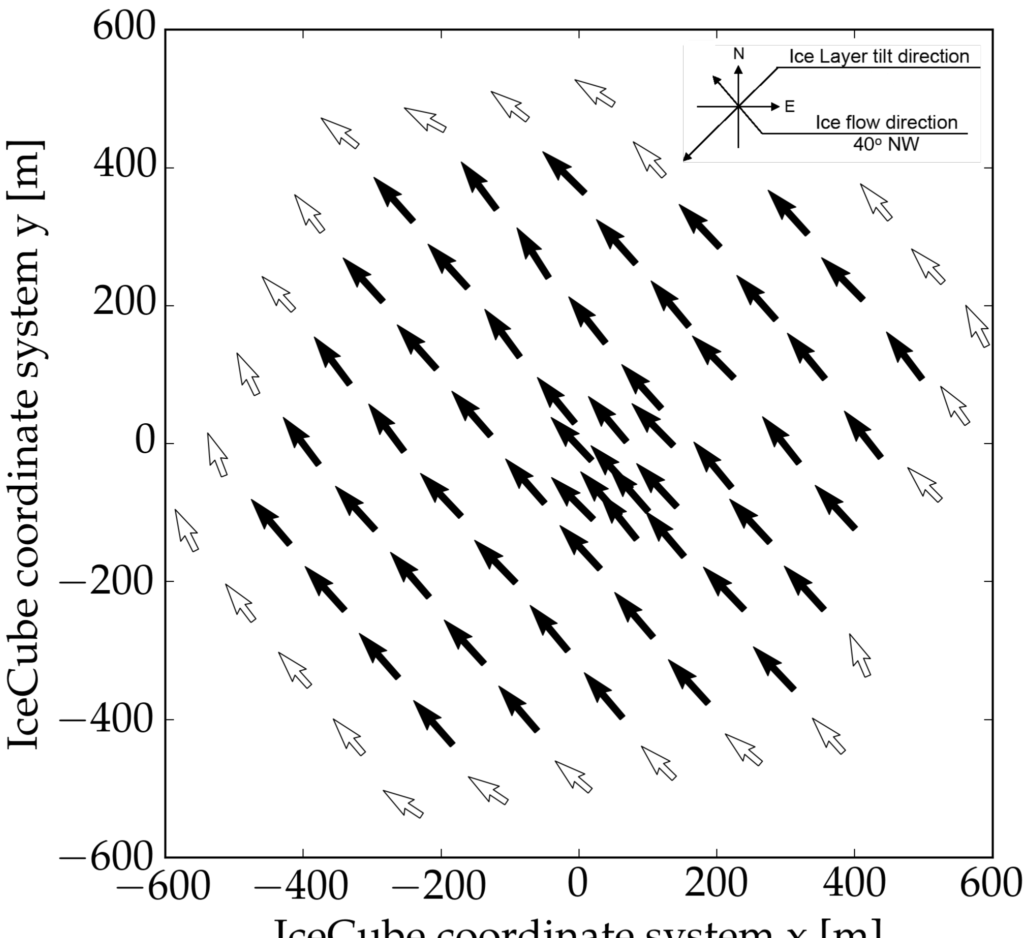
NIM A711:73,2013

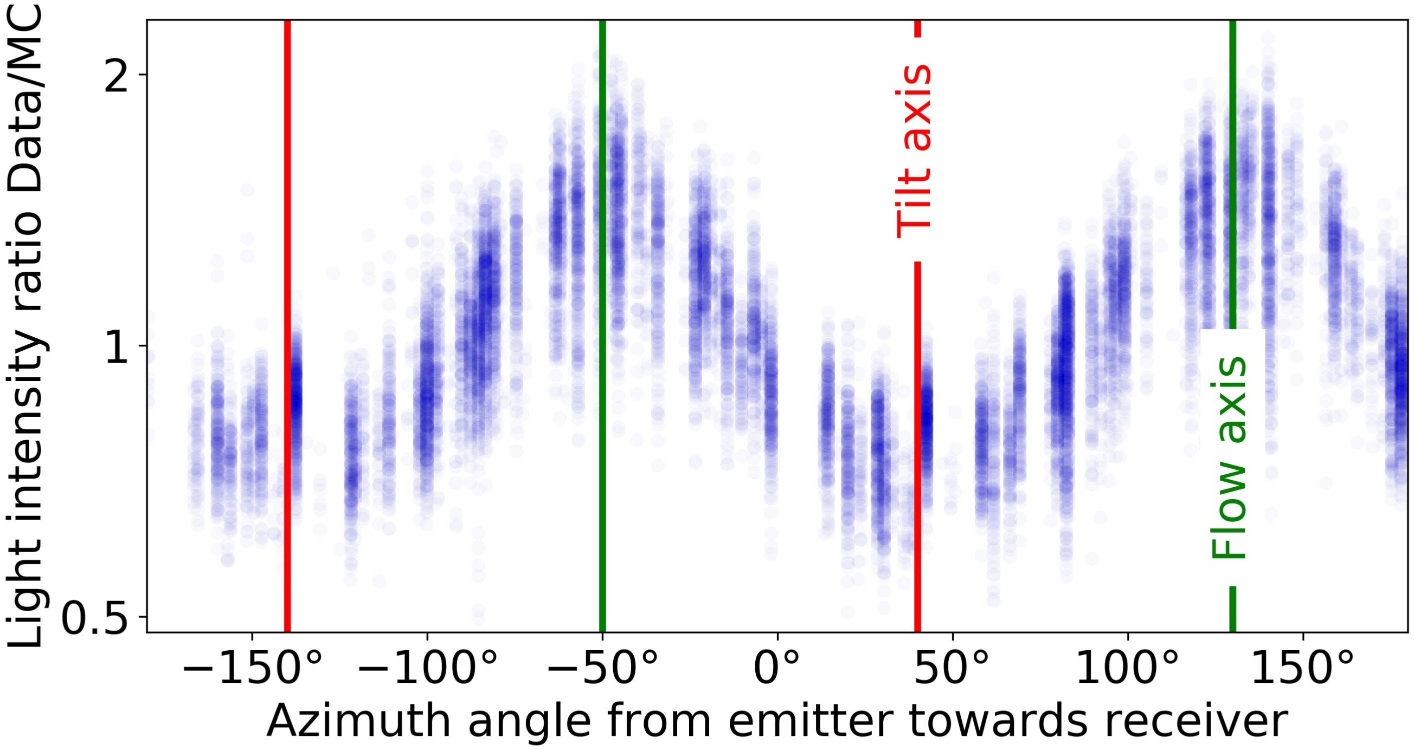


doi:10.1109/eScience.2019.00050

Ice anisotropy

Comparison of flasher data to simulation indicated an azimuthally dependent light-intensity profile





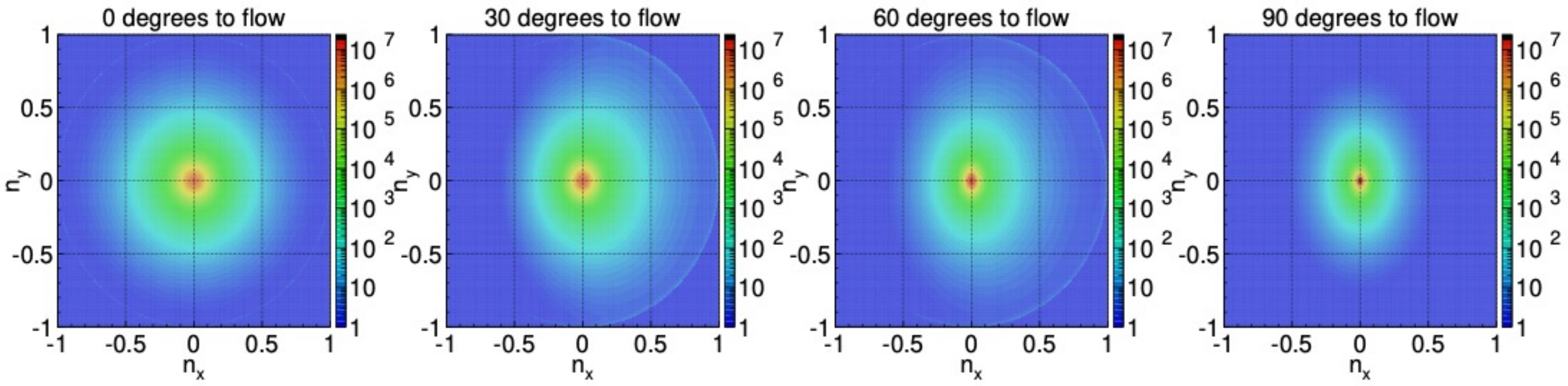
Submitted to *the Cryosphere*

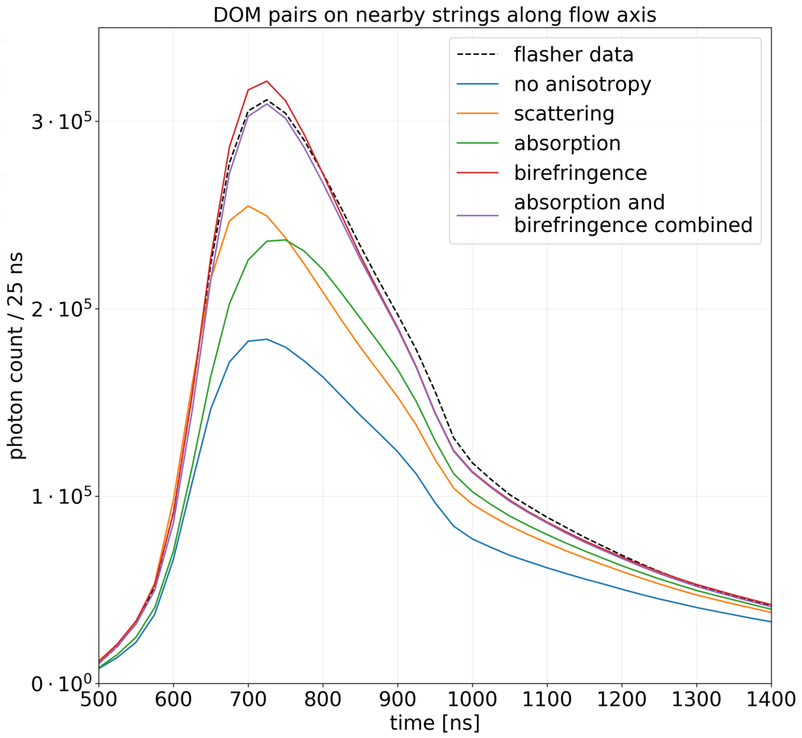
Birefrigence

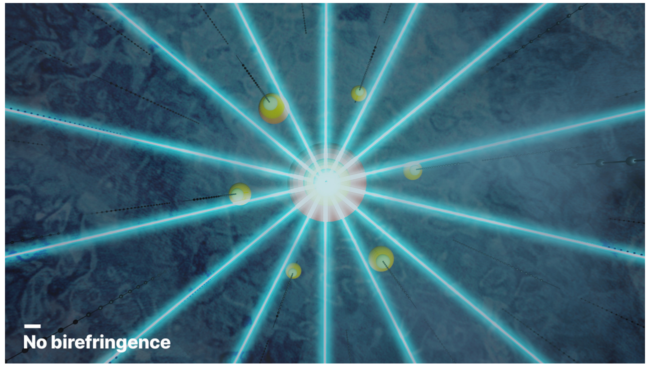
Index of refraction dependent on polarization and direction of EM waves

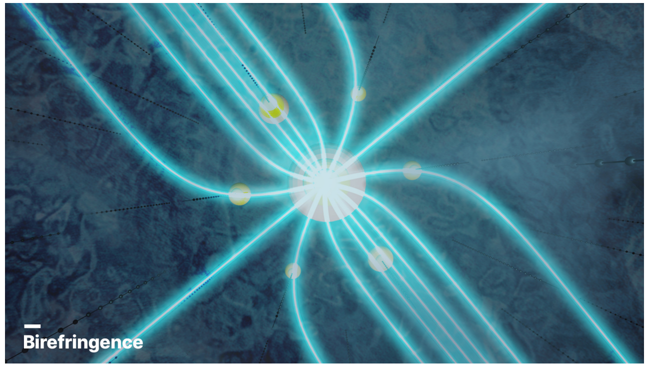
Crystals with non-cubic crystal structures are often birefringent… -Wikipedia

Modeling ice crystals on microscopic scale improves agreement to observed macroscopic anisotropy







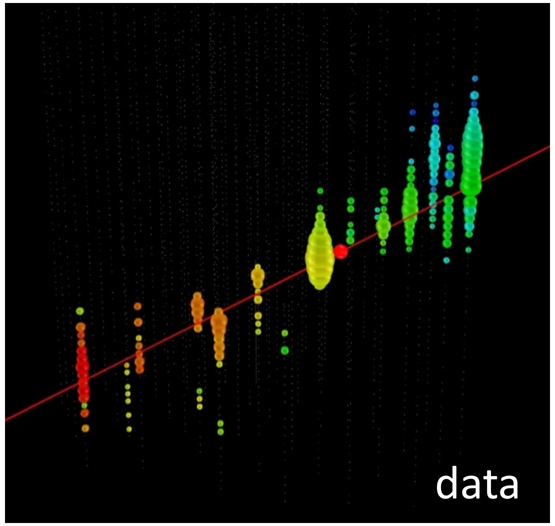


Submitted to *the Cryosphere*

Event reconstruction

Neutrino PID

CC muon neutrino

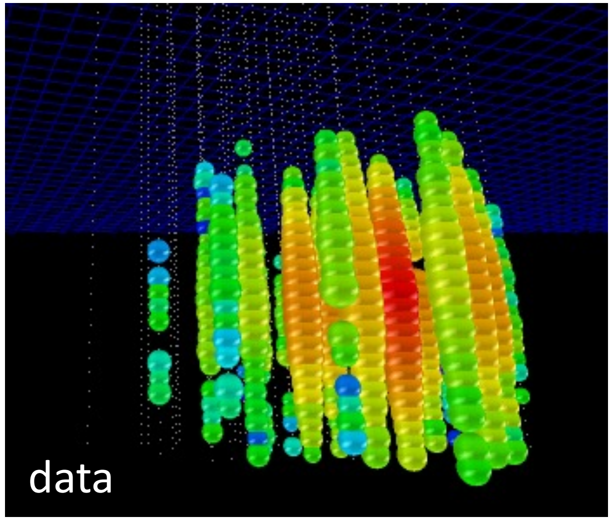


$$\nu_\mu + N \rightarrow \mu + X$$

track

angular resolution ~ 0.5°
energy resolution ~ x2

NC or CC electron neutrino

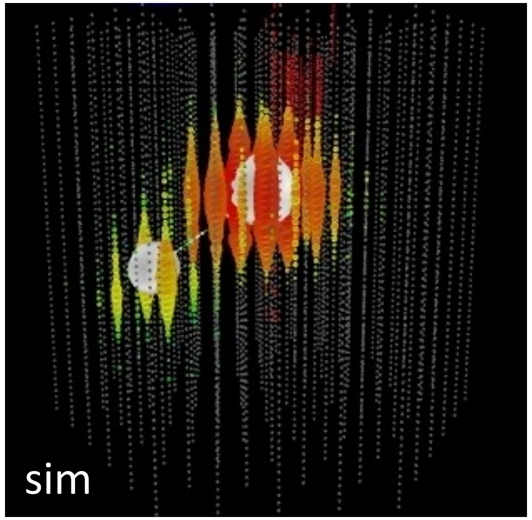


$$\nu_e + N \rightarrow e + X$$
$$\nu_x + N \rightarrow \nu_x + X$$

cascade

angular resolution ~ 8°
energy resolution ~ 10%

CC tau neutrino



$$\nu_\tau + N \rightarrow \tau + X$$

double cascade

~2 expected in 6 years

Earlier  Later

Notable quantities

Typically interested in **energy, direction, and time**

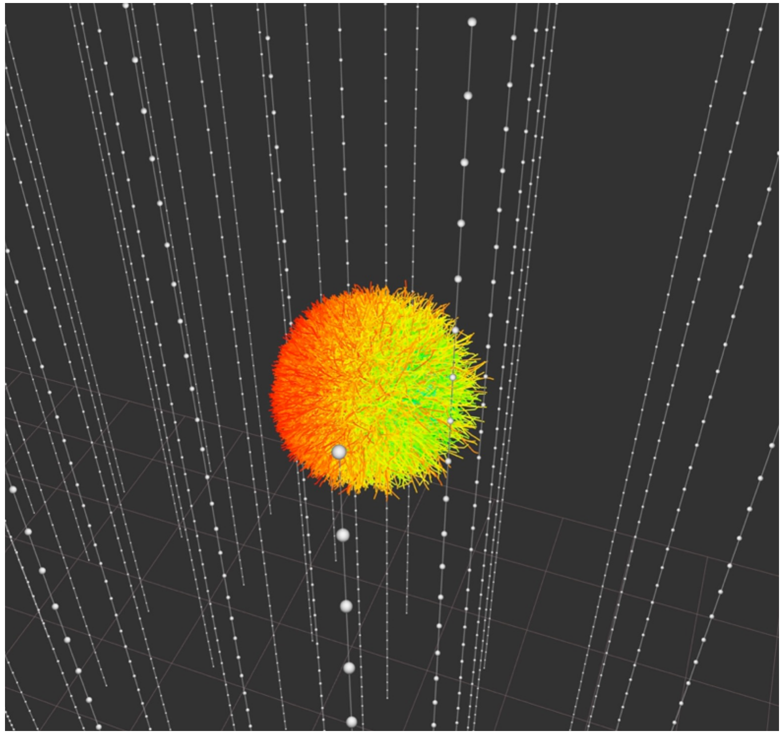
Reconstructed energy is a proxy for E_ν

Direction $(\theta_{zen}, \phi_{azi})$ tells us where the neutrino came from in local coordinates

Time allows us to translate that into celestial coordinates

Constructing a model

Emitted

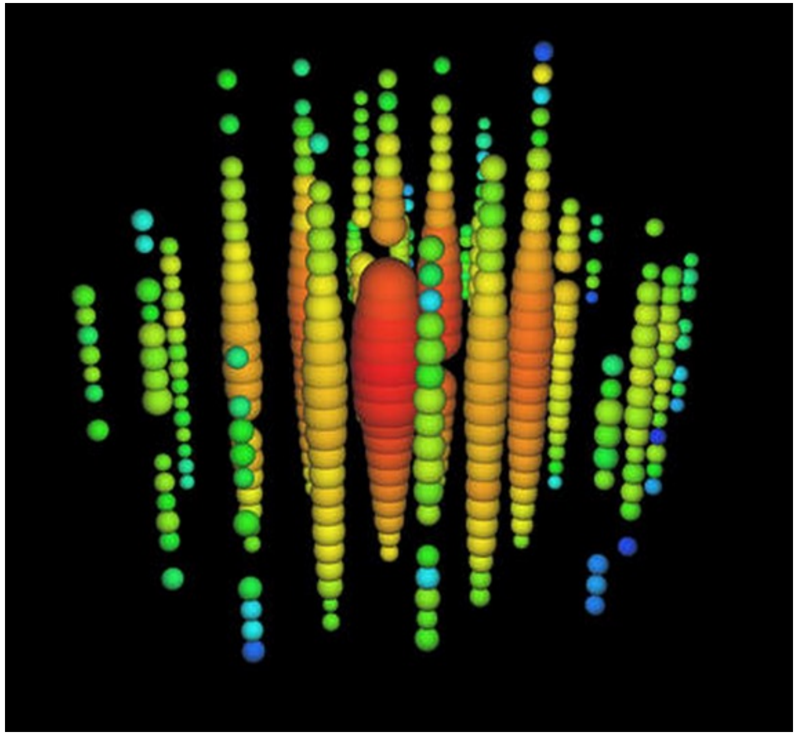


Asymmetry in photon emission helps with directional reconstruction

Information loss

$$\nu_e + N \rightarrow e + X$$
$$\nu_l + N \rightarrow \nu_l + X$$

Detected



Model photon yields: ideally fast and accurate

$$\mathbf{\Theta} = (x, y, z, \theta, \phi, E, t)$$

$$X = q_{DOM}\ (t)$$

Maximize $\mathcal{L}(\mathbf{\Theta}|\mathrm{X}_{\mathrm{Data}})$ or train ML on MC

Approaches for reconstruction

Tracks

- Use **first-hit times** for *directional* reconstruction
- Use **full-waveform** information by fitting predicted light yields to what is actually seen
  - **High-energy track** can be approximated by multiple cascades along its length

Cascades

- Use **full-waveform** information by fitting predicted light yields to data
- Focus for remainder of talk

Model expectations with B-splines or NN

- Simulate physics and tabulate/interpolate

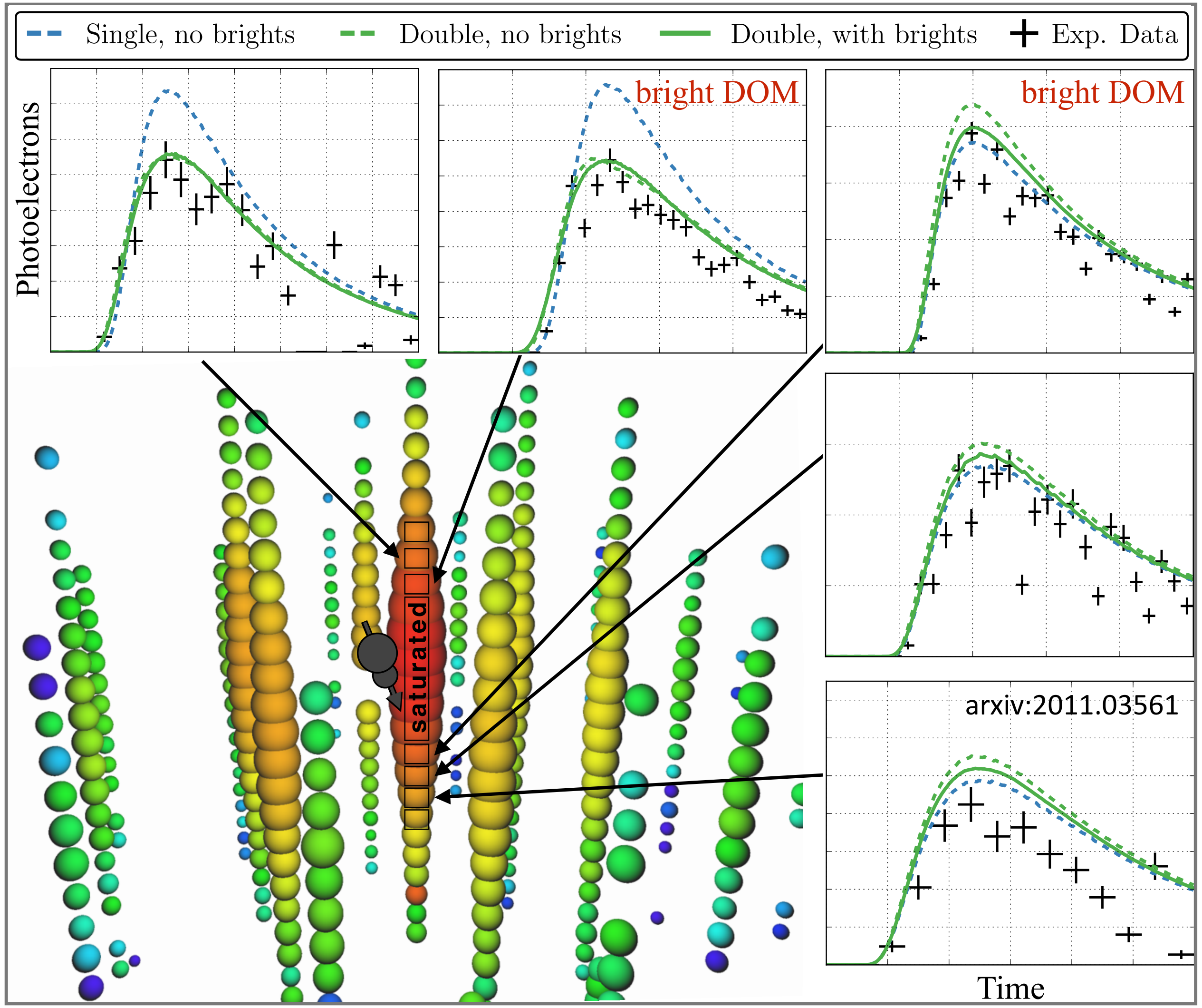
Photoelectron distributions

An example of an observed event in data

- PeV cascade
- Nearest O(10m) PMTs can be saturated

Expectations under different hypotheses shown

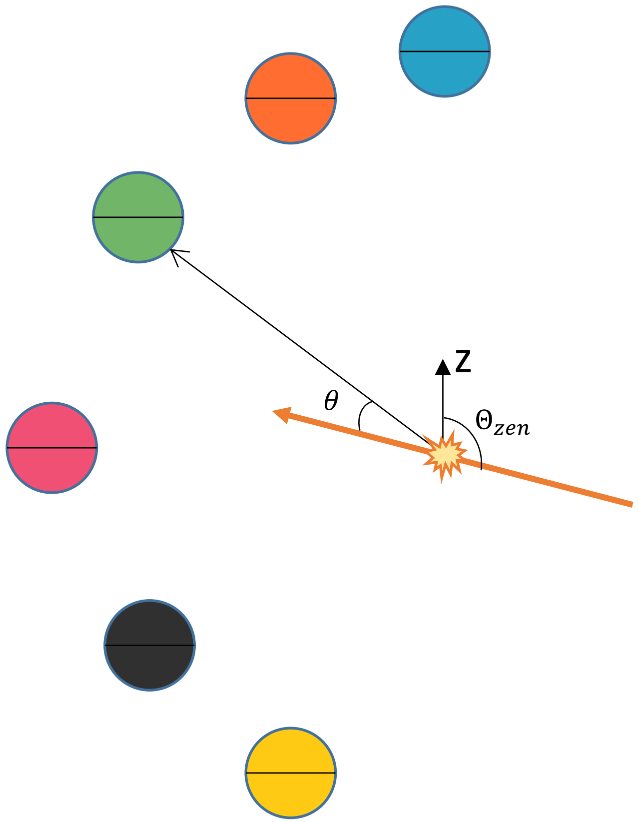
- “Bright DOM” can be unsaturated but still difficult to model

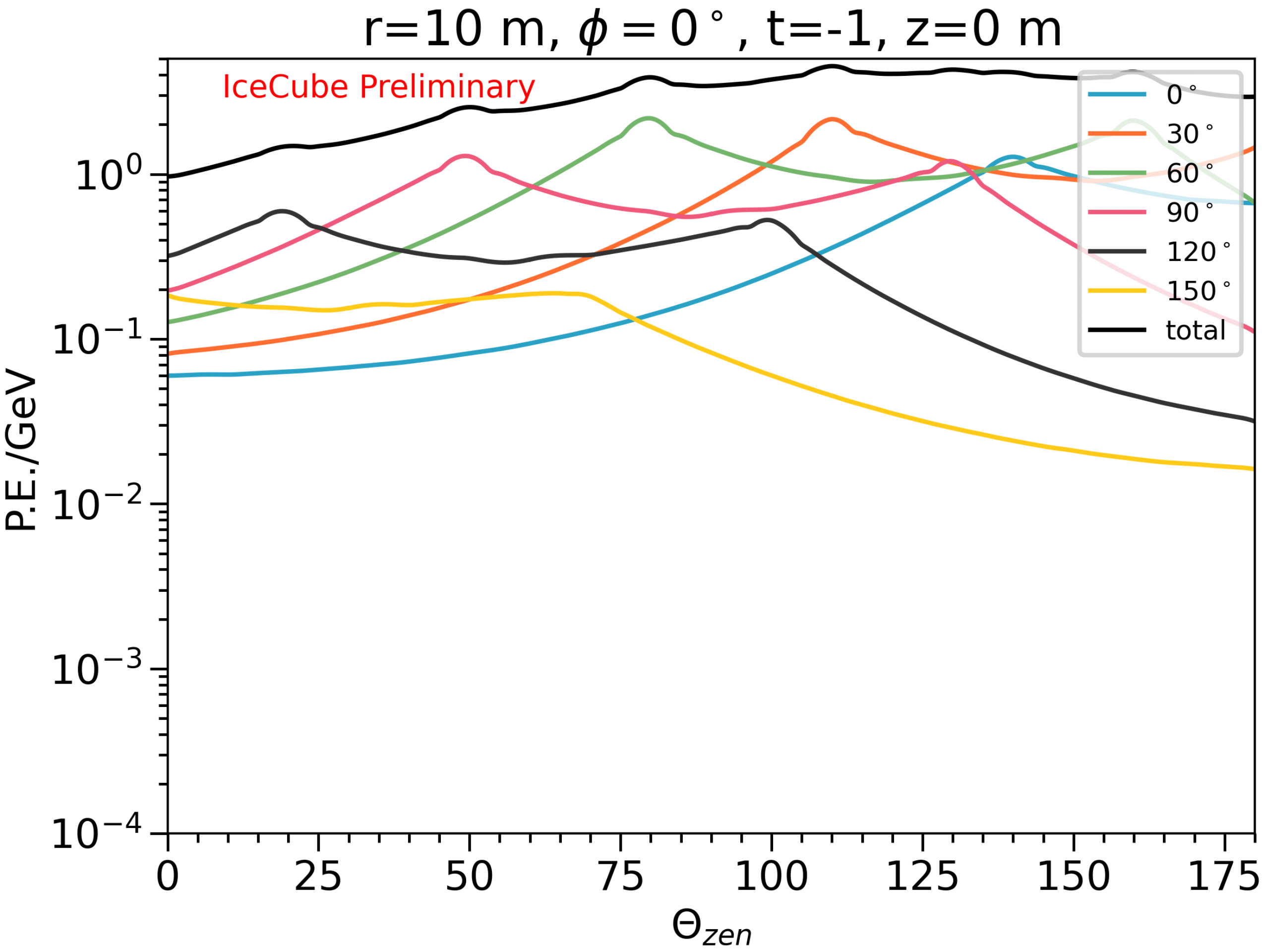


Cherenkov yield (integrated over t)

Photon yields for six receivers each located at a different zenith angle

Cherenkov peak smears out ~50m

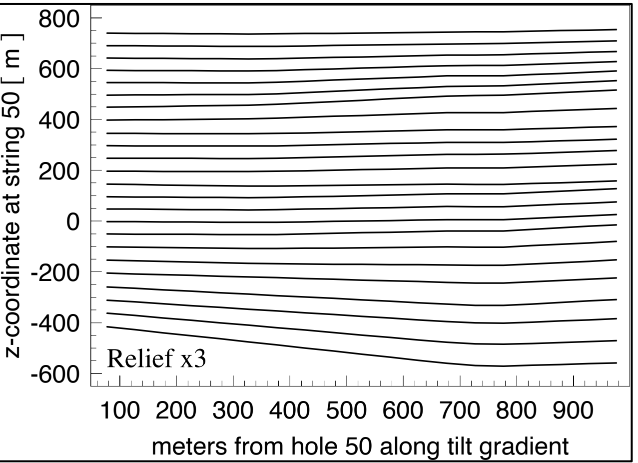


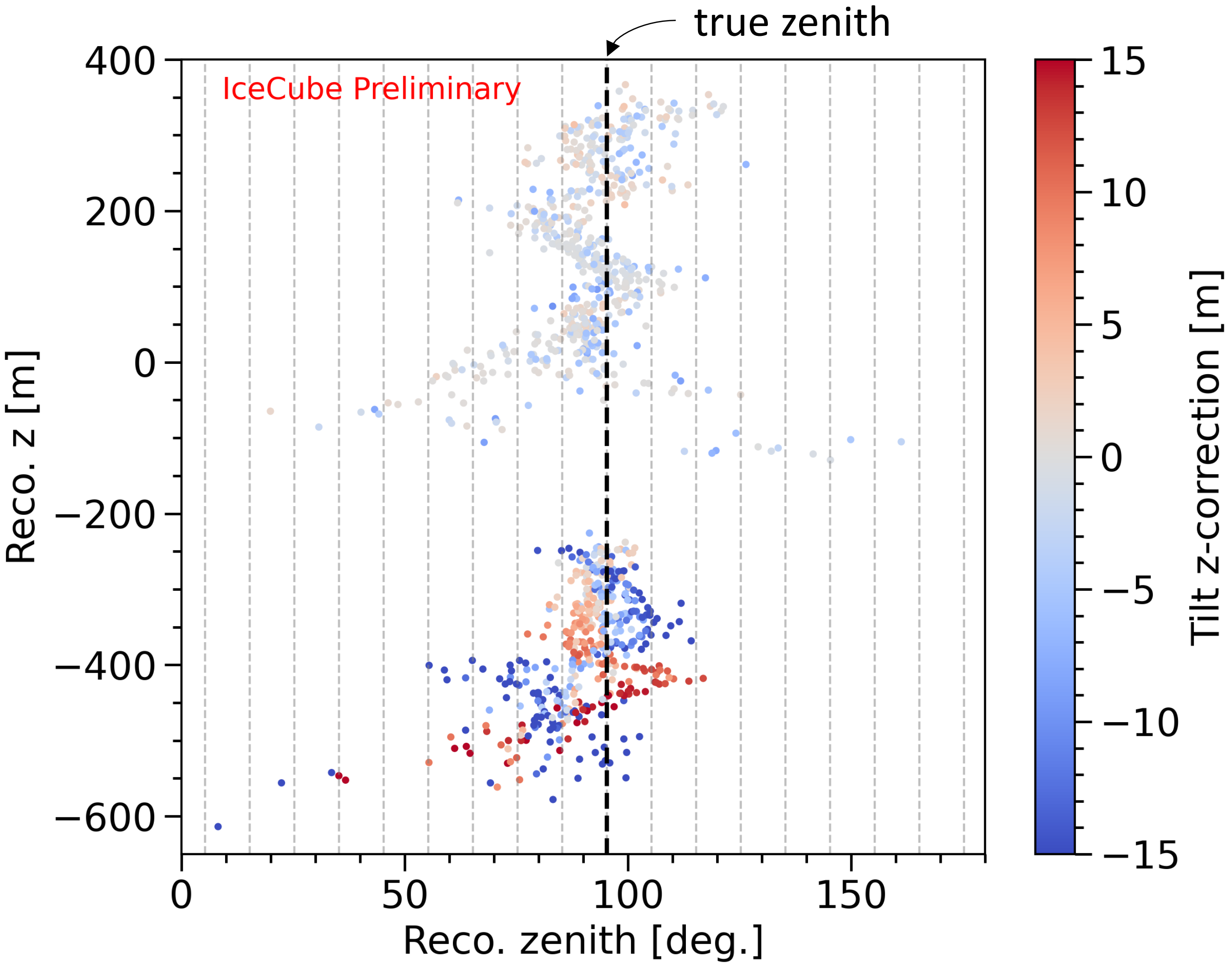


Impact of ice tilt and other mismodeling

Reconstructed zenith assuming ice is flat exhibits large pulls off truth

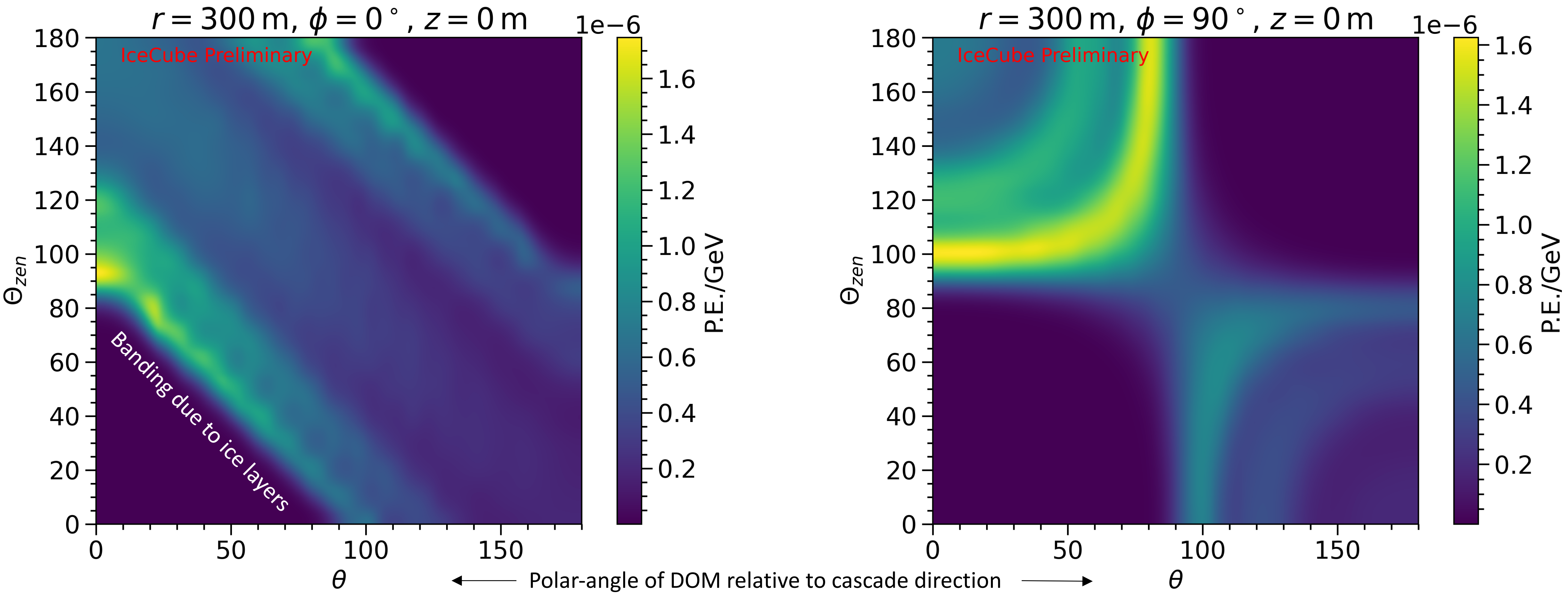
Clustering seen above and below truth





Reducing spline artifacts

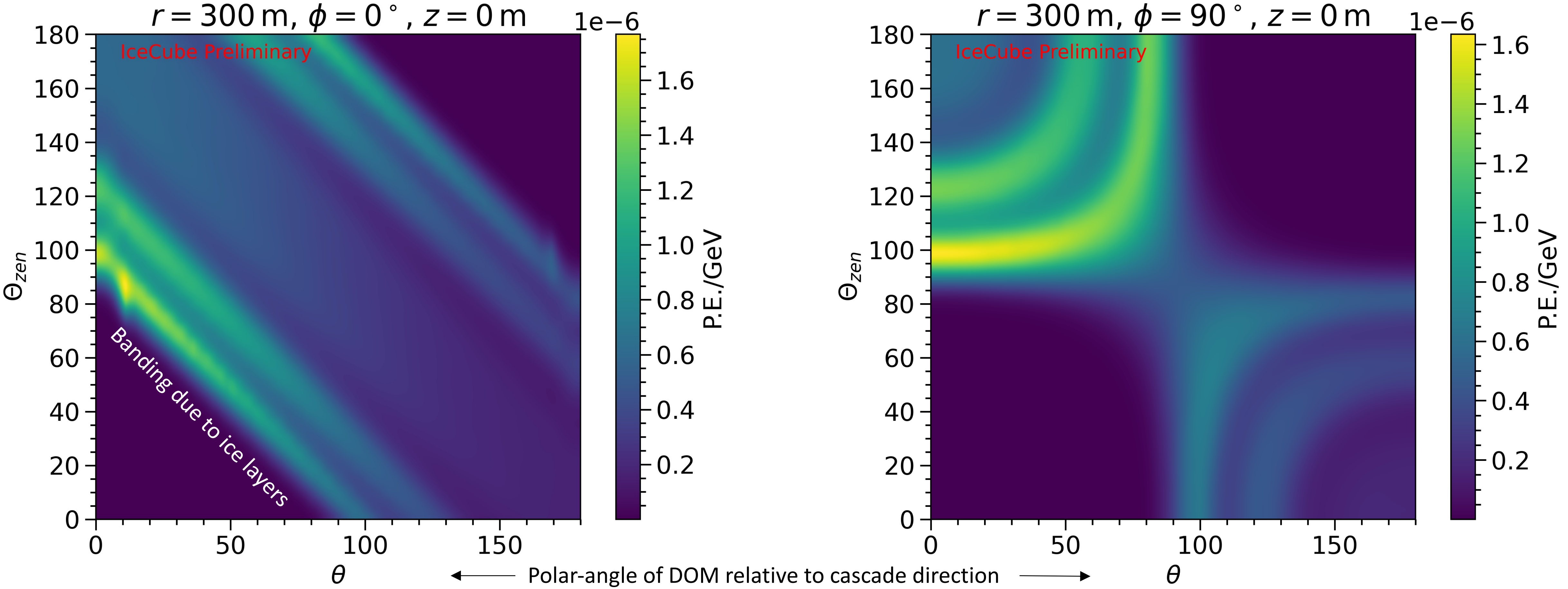
Model constructed from tensor-product B-splines has difficulty capture strong features along *diagonals* smoothly



Reducing spline artifacts

Adding more support points improves interpolation along diagonals

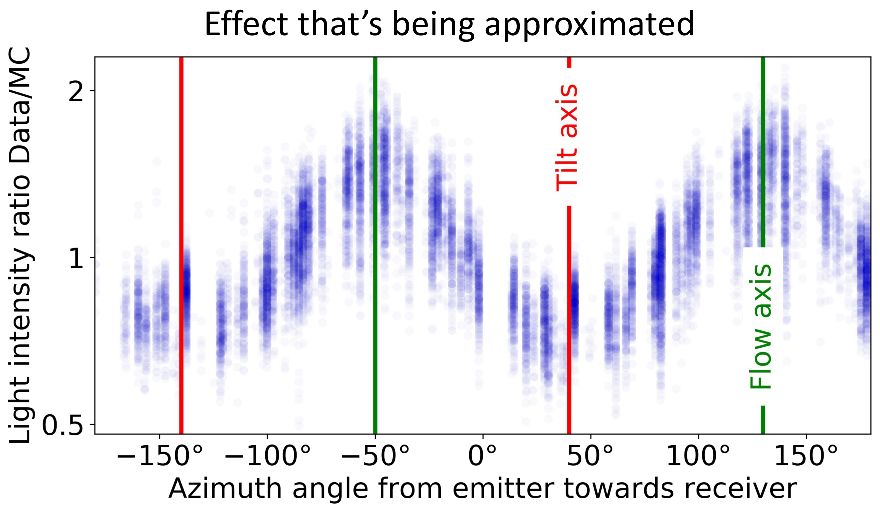
Update ice model, fix boundary conditions

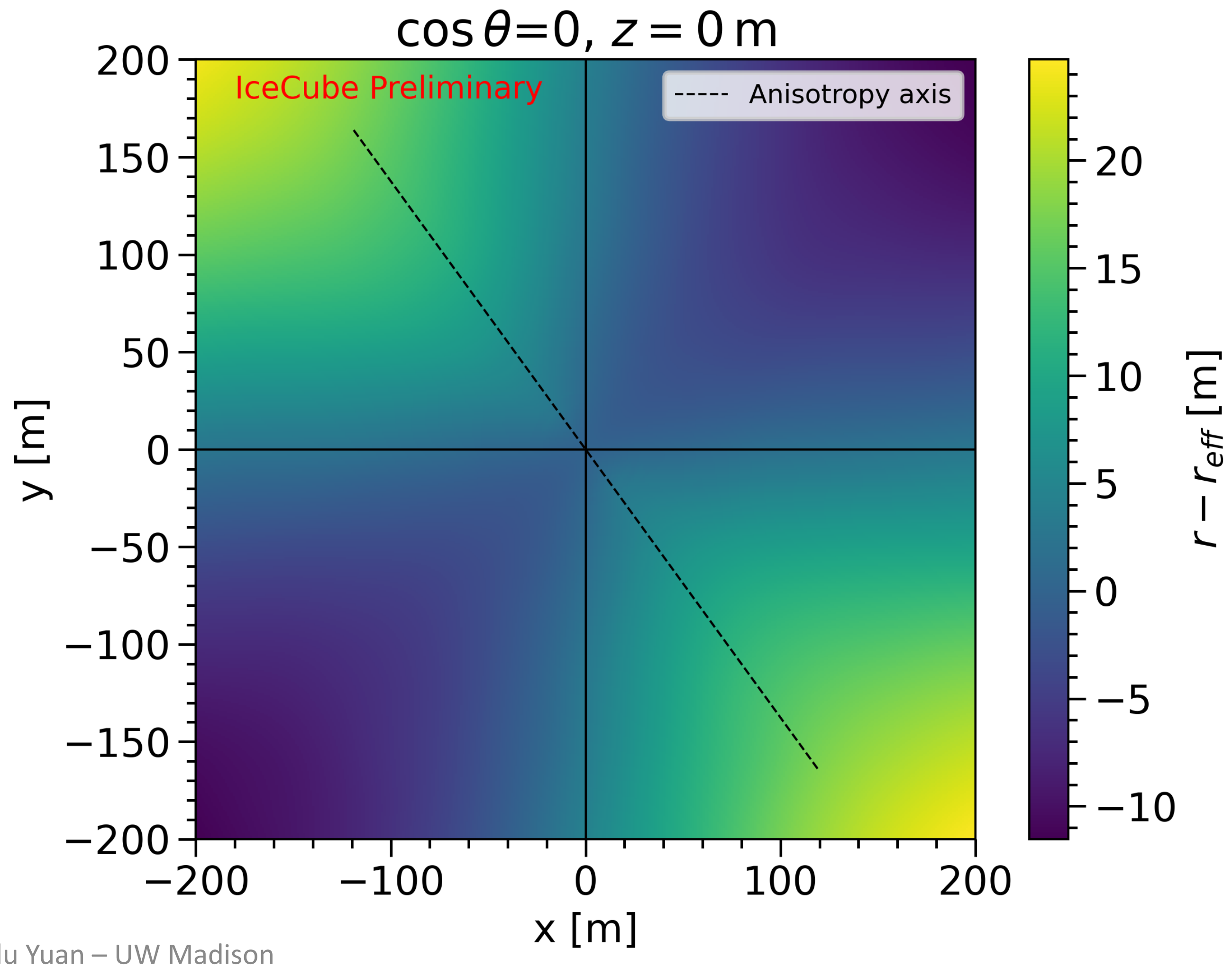


Anisotropy modeling

Difficult to capture with full grid scan due to dimensionality constraints

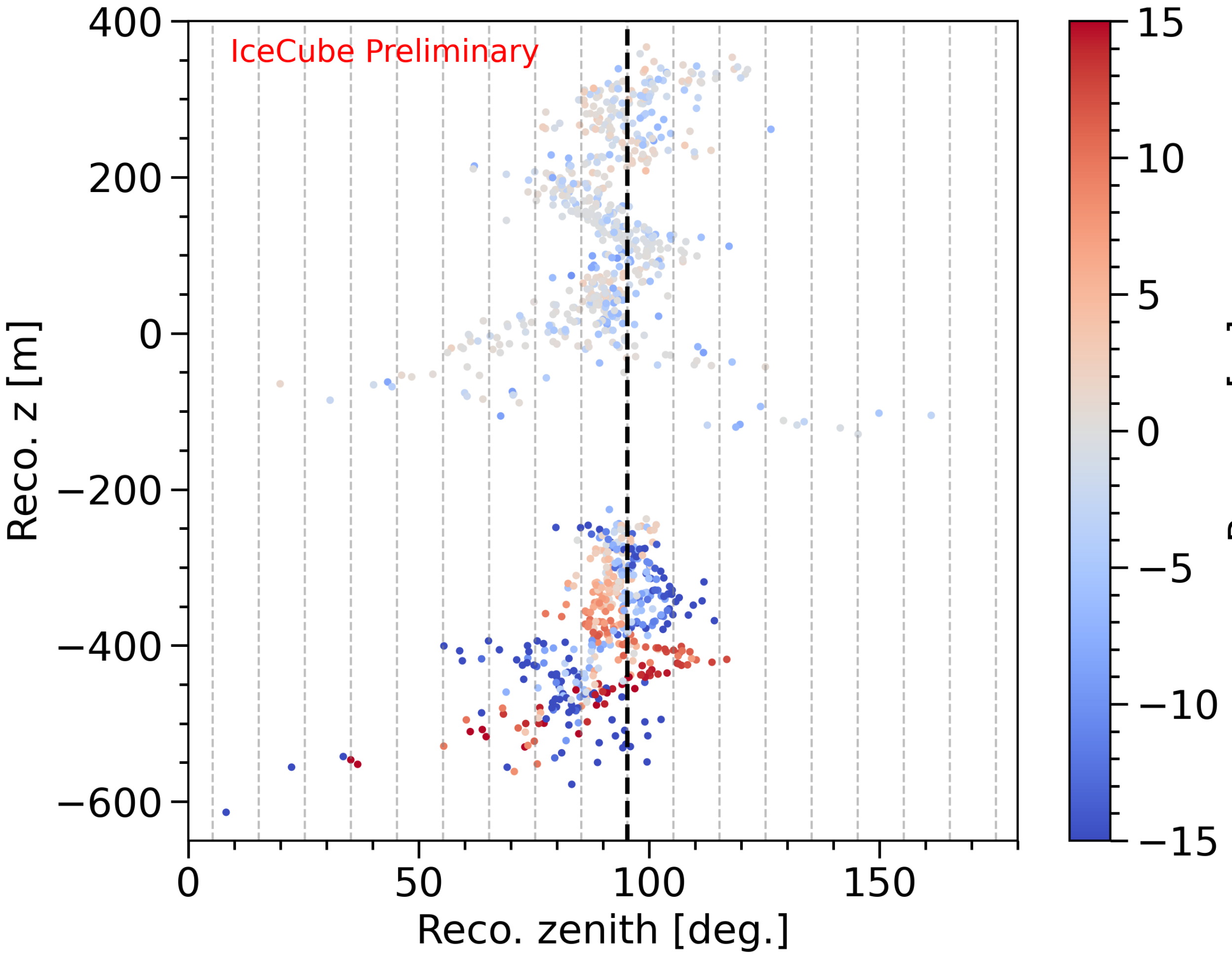
Approximate with radial distance correction



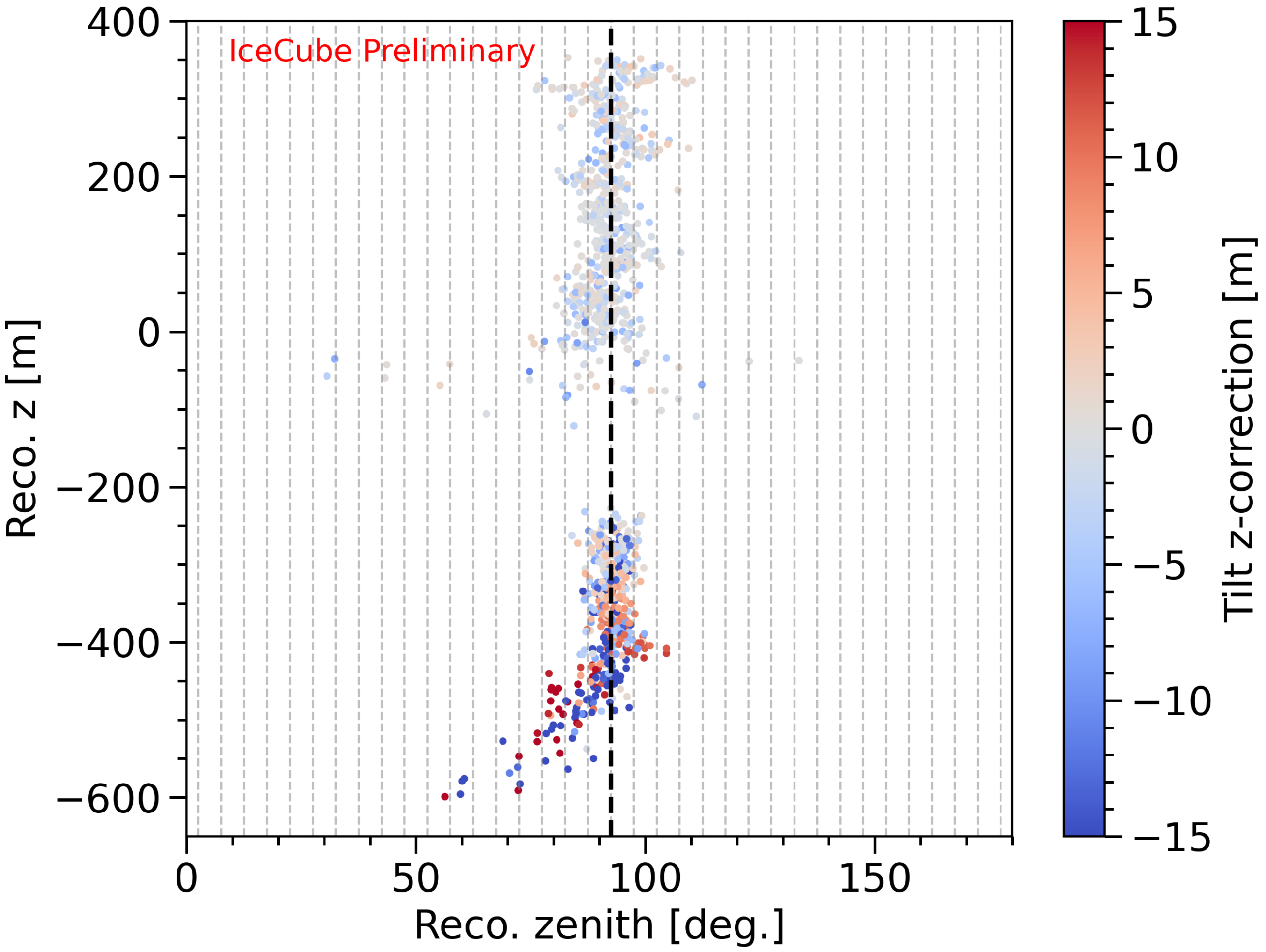


Improved zenith reco.

Older ice model

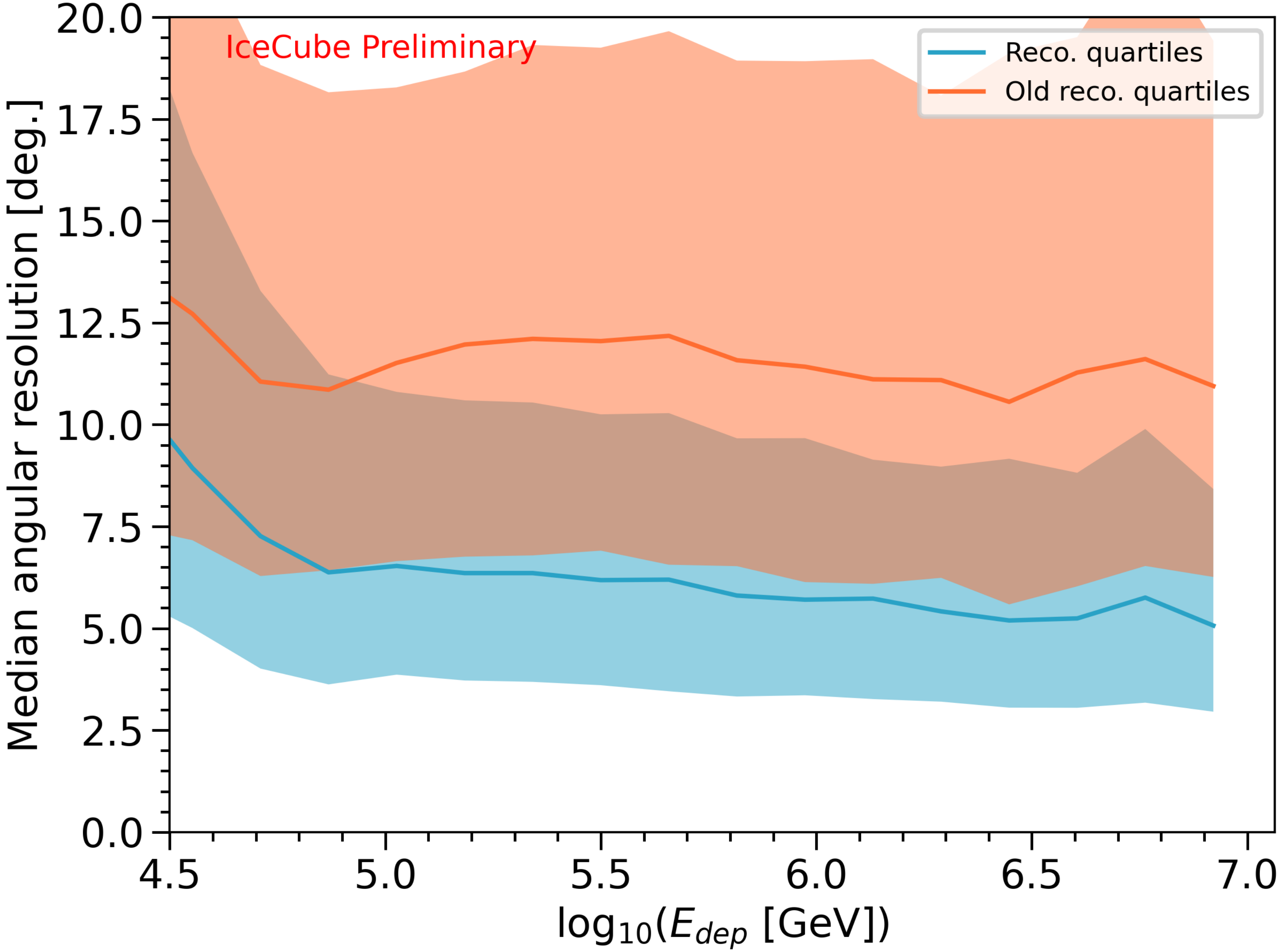


Updated ice modeling



Cascade angular resolution

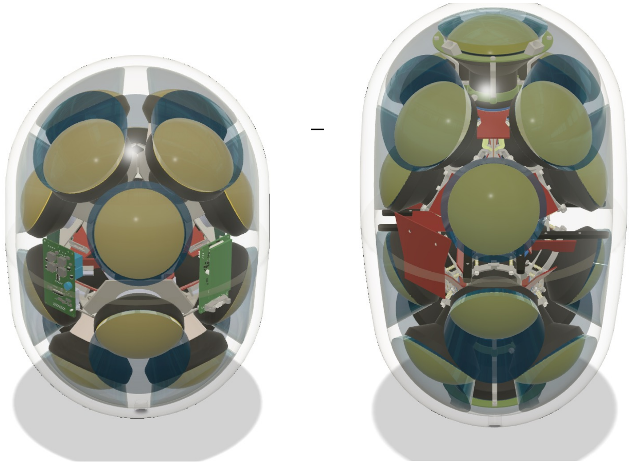
Space angle also improved between reconstructed and true direction



New OM technologies

MultiPMT modules and new readout

See talk by C. Spiering



Credit: Y. Makino [ICHEP22]

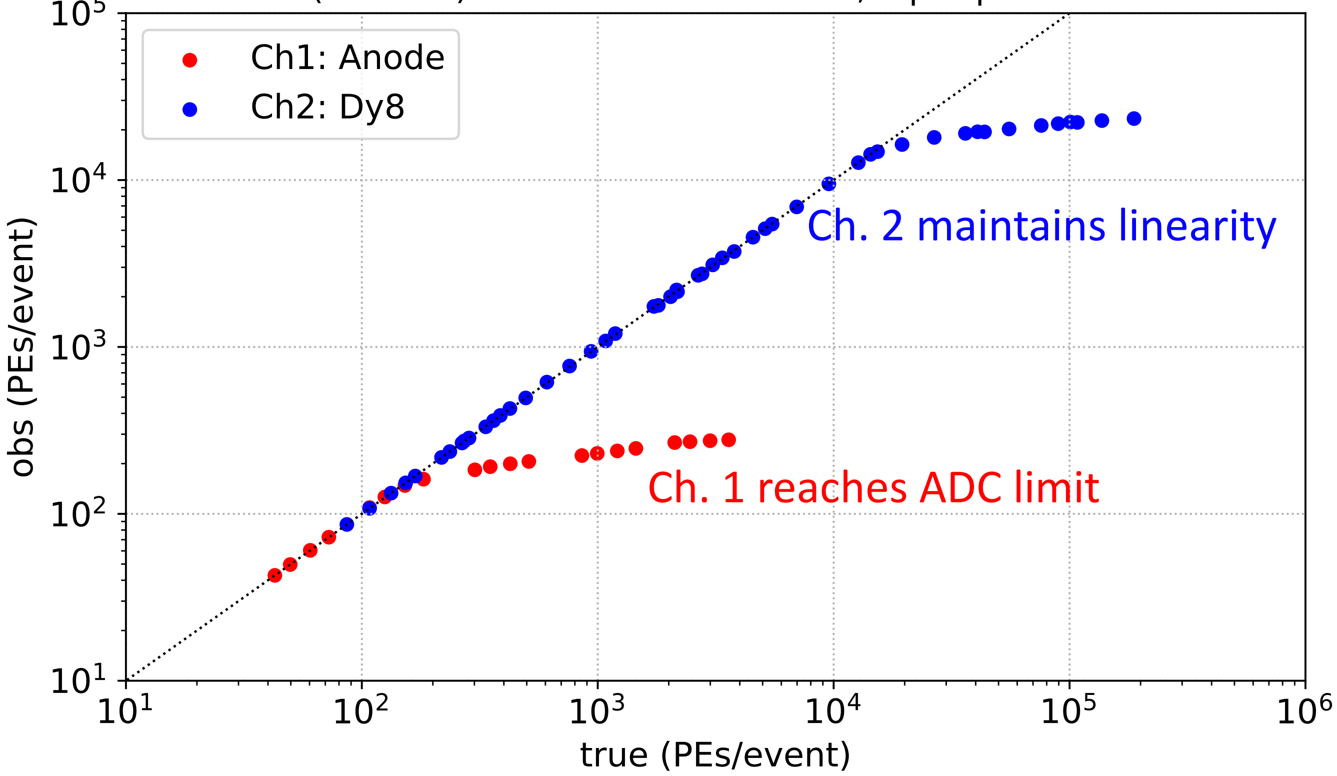
Anode + 8th dynode readout improves performance

- IC DOM channels all at anode

Should help with making use of highest-charge Gen2 OMs nearby source

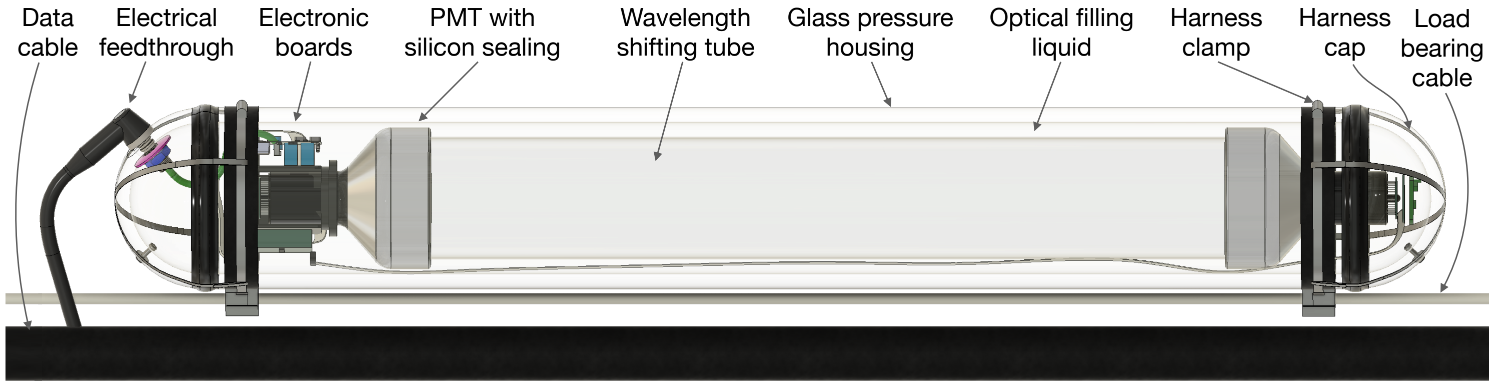
- Improve reconstruction performance for PeV events

4inch PMT (BB9734) with wuBase v1.2revD, Input pulse width: 128 ns

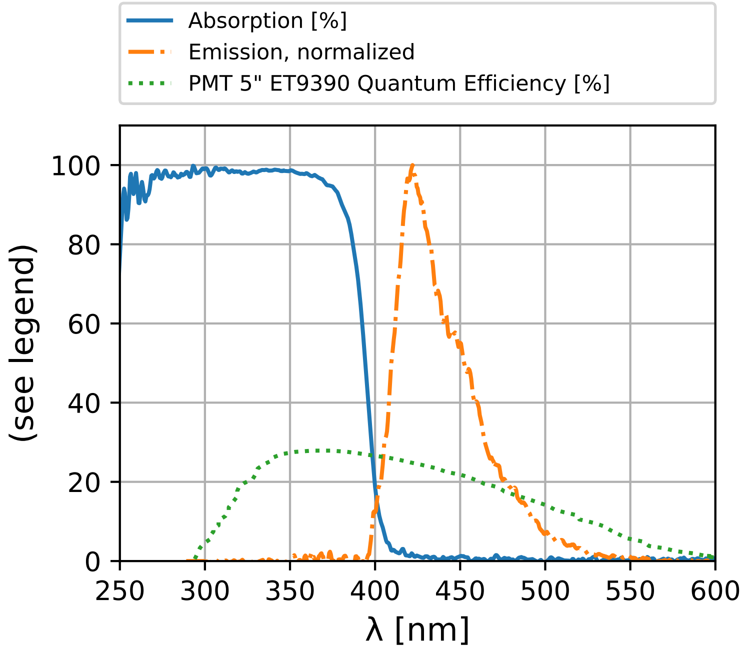


Prototype light sensors

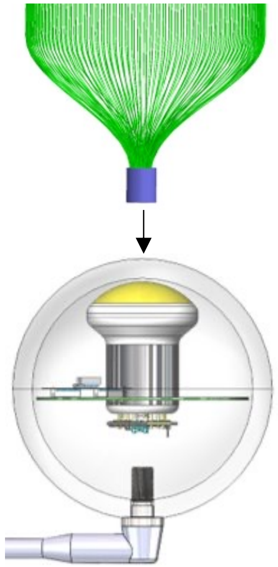
Wavelength-shifting optical module (WOM)

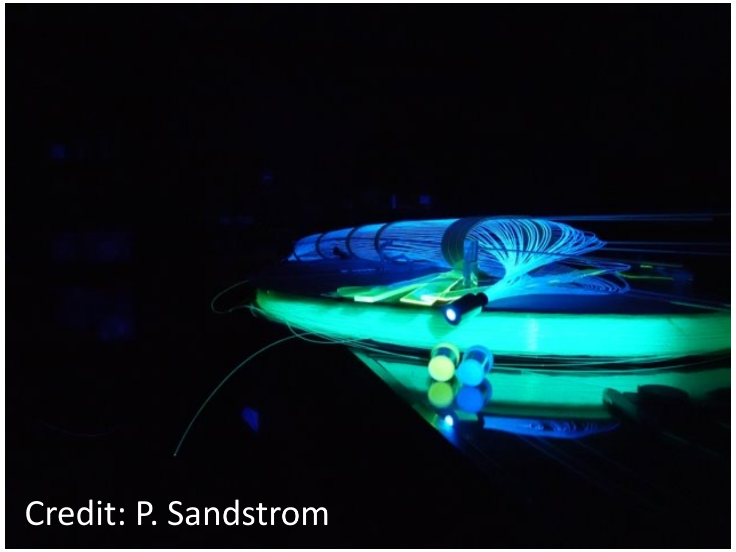


PoS-ICRC2021-1038



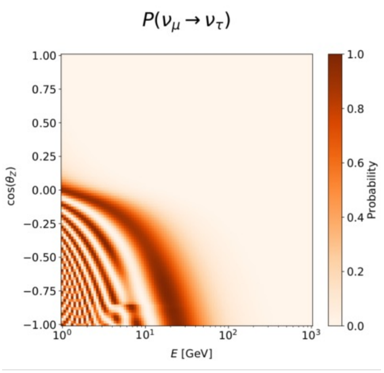
Fiber optical module (FOM)

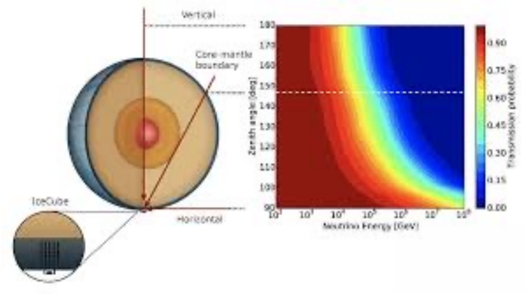


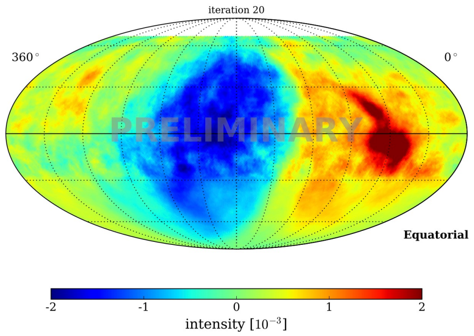


Summary

https://icecube.wisc.edu/science/publications/







IceCube energy range spans over **6 orders** of magnitude

Broad physics reach

Astrophysical flux and sources

Particle physics at the **highest energies**

Atmospheric neutrino **oscillations**

Supernova Early Warning System

CR physics with IceTop

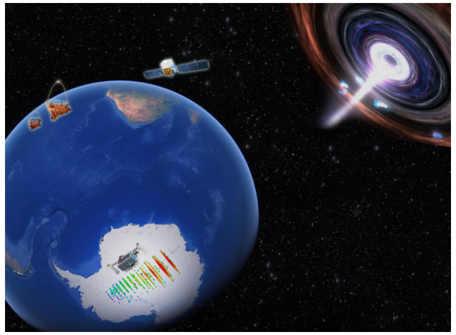
Ice modeling continually improving

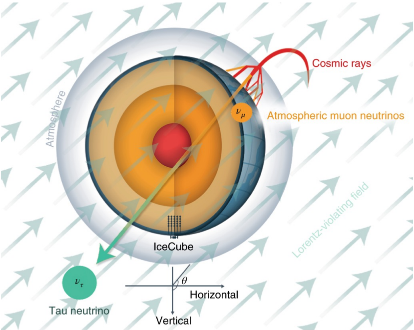
Calibration with **flasher** data

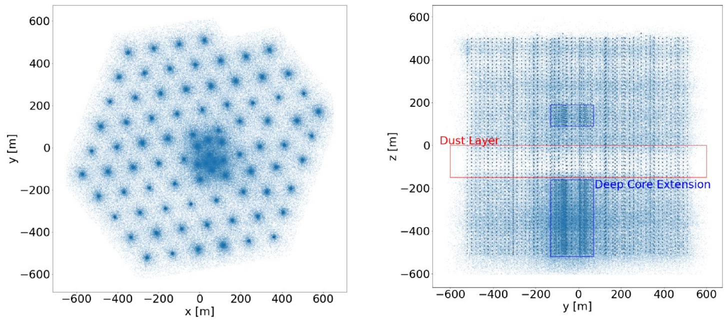
Birefringent ice describes anisotropies

Improved **reconstructions** possible

More to come, keep looking!







Thank you!

Backups

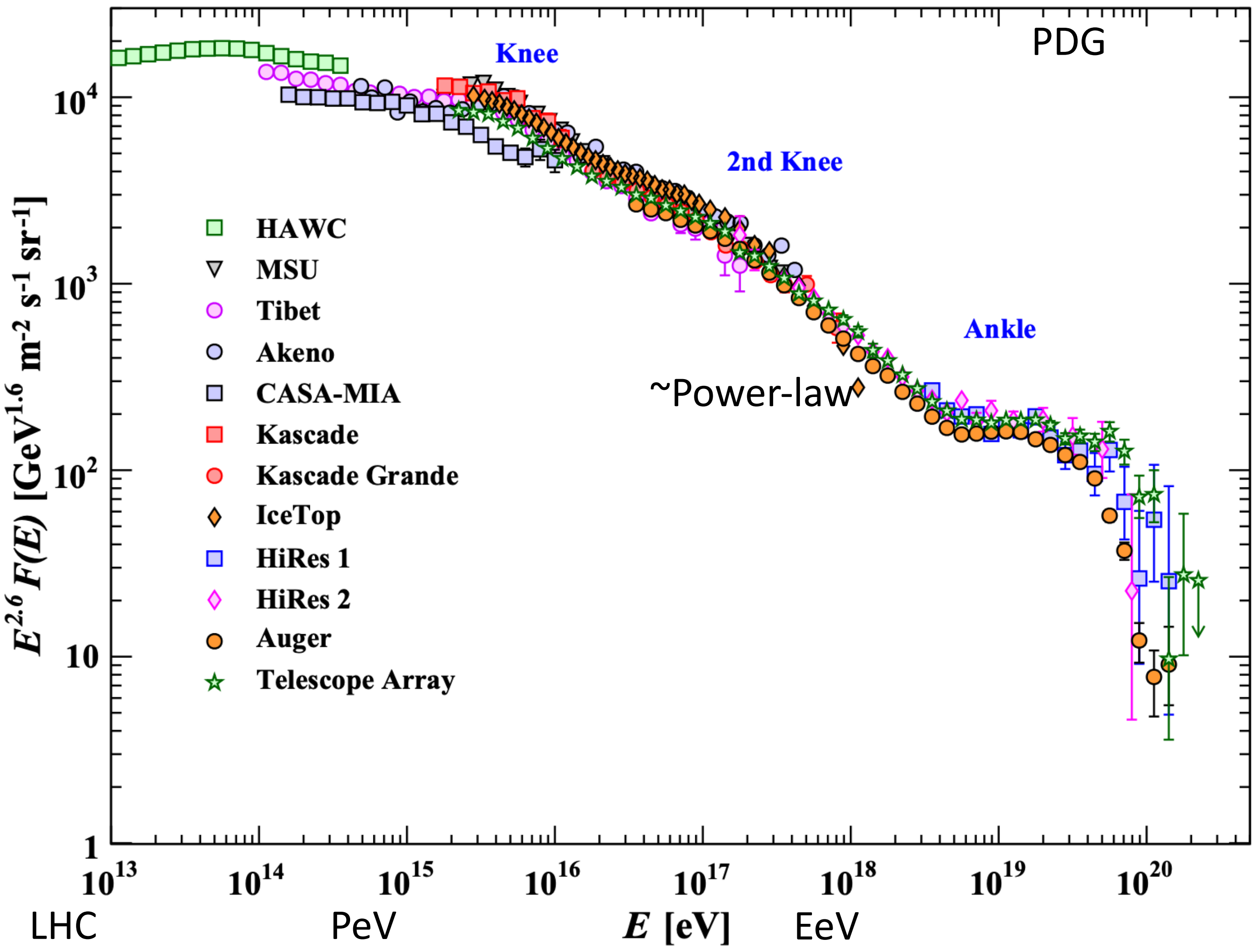
All-particle spectrum

What are the origins of (high-energy) cosmic rays?

Massive accelerator

Particles connected at source

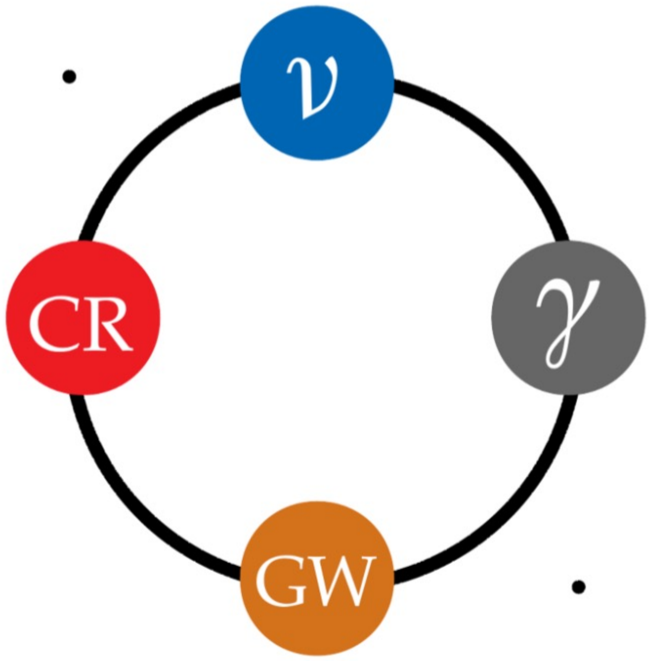
Neutrinos can probe

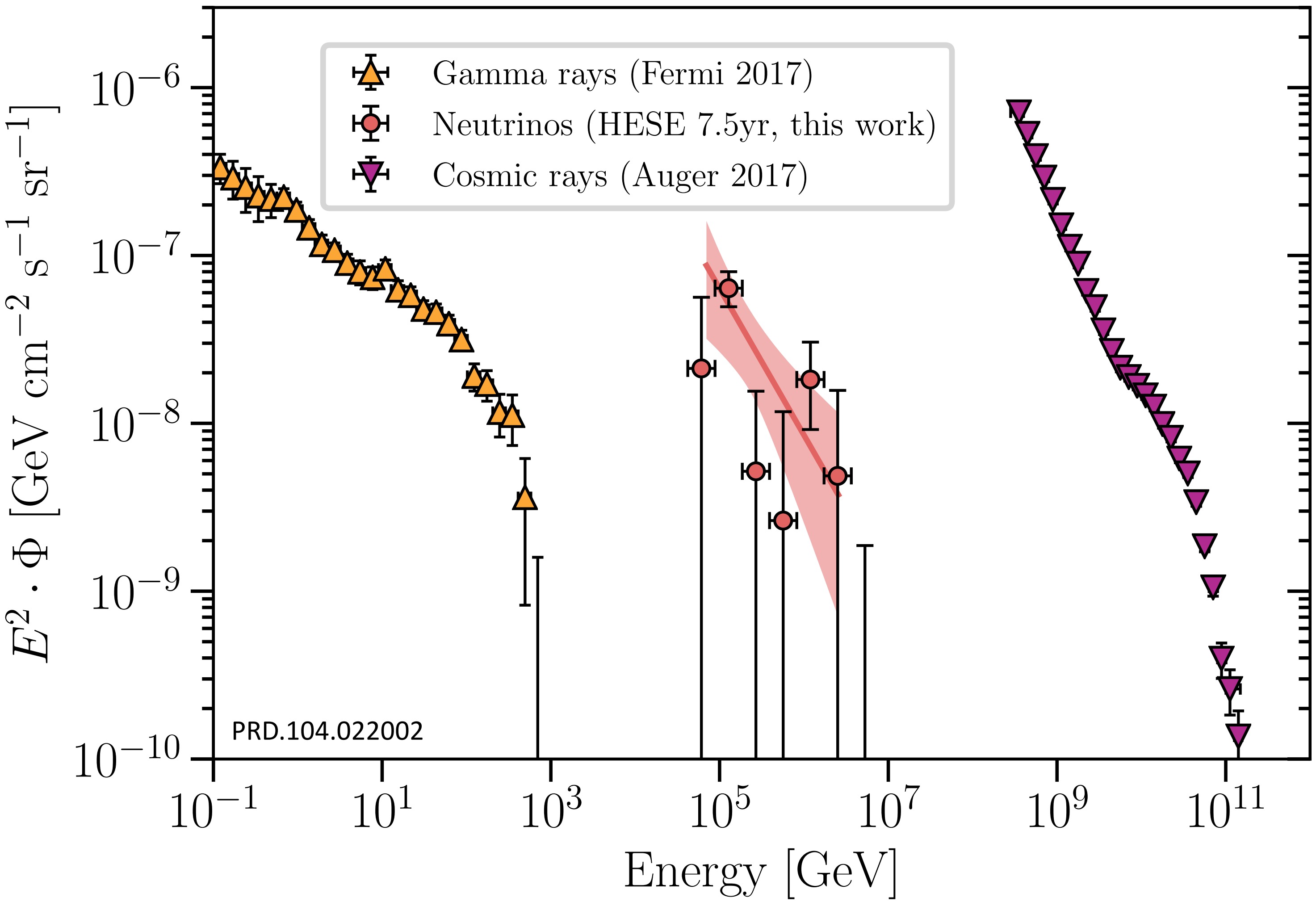


Multiple cosmic messengers

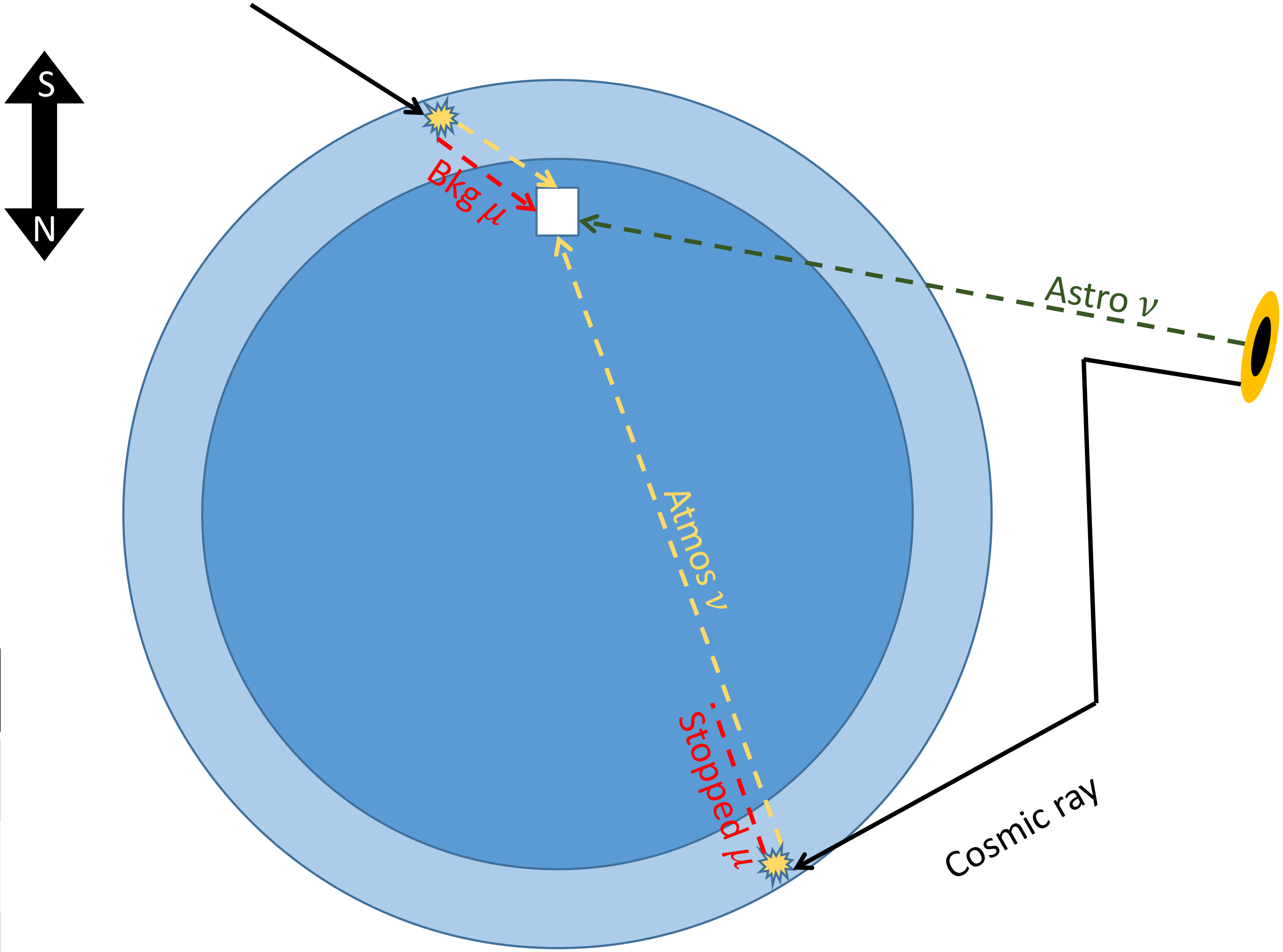
These particles are connected at the source

Each fills a piece of the puzzle for production mechanisms





Muons and neutrinos

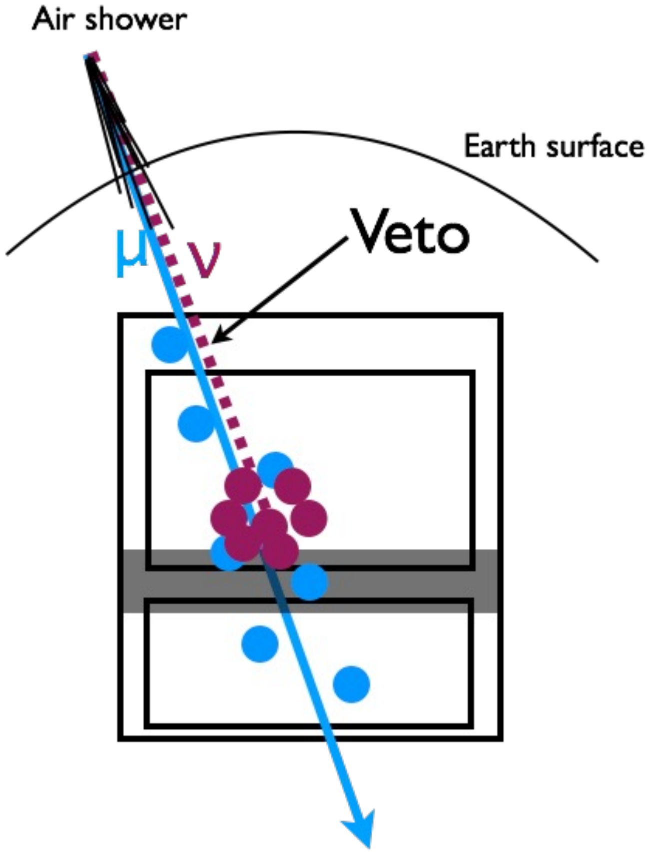


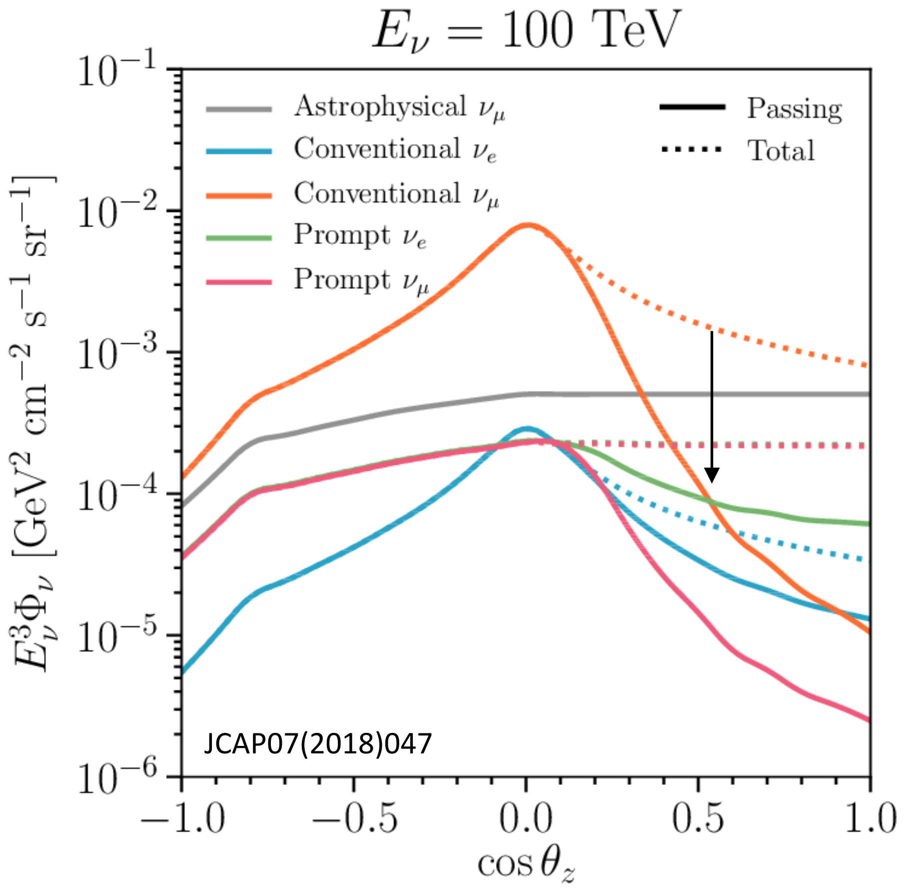
Event type	Rate
Atmospheric μ	~3 kHz
Atmospheric ν	~100k per year
Astrophysical ν	~100 per year

Atmospheric vs astrophysical neutrinos

Expect different energy spectra

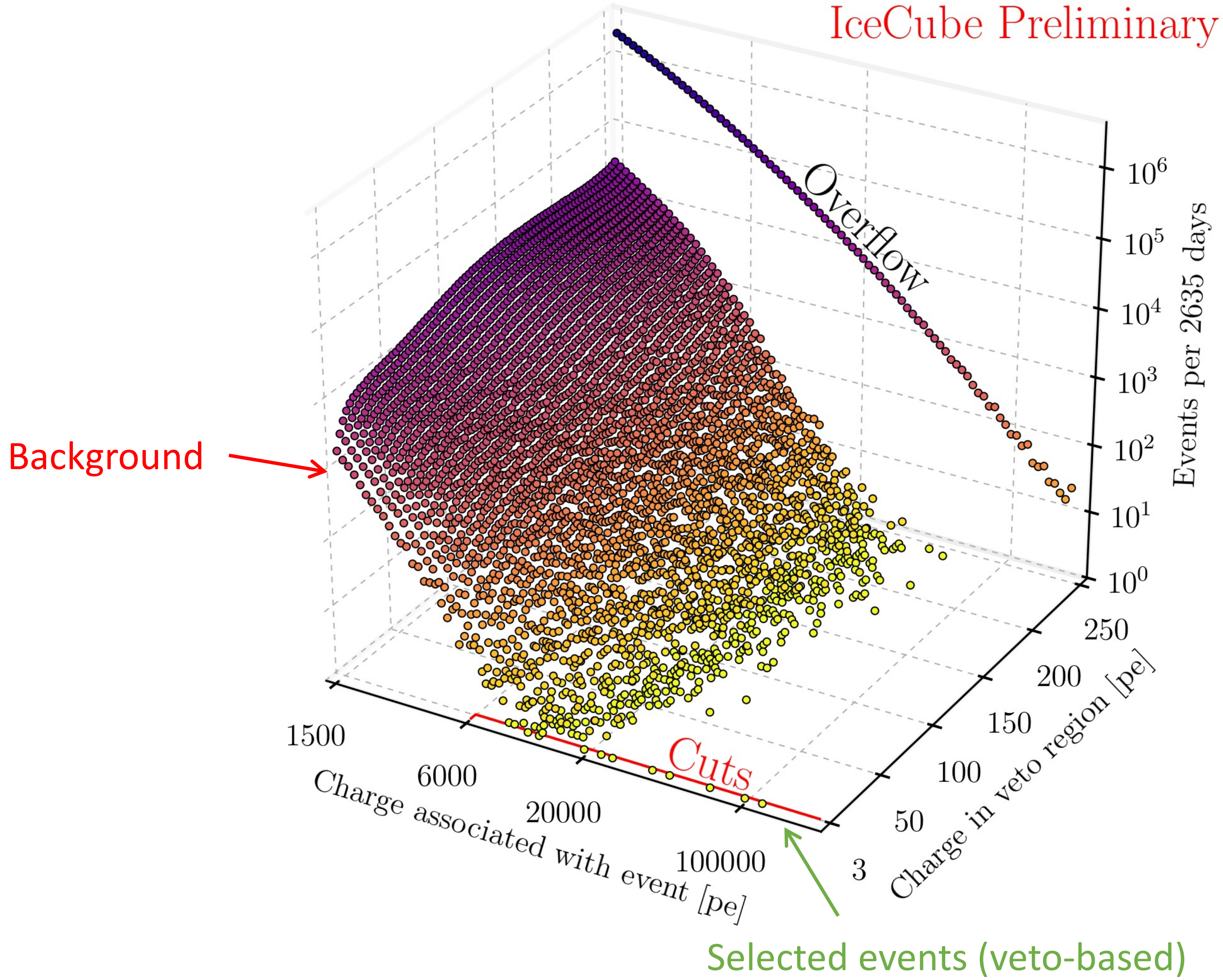
Can also distinguish via "self-veto"





Neutrinos in a haystack

Large muon background – suppress by veto or by looking down

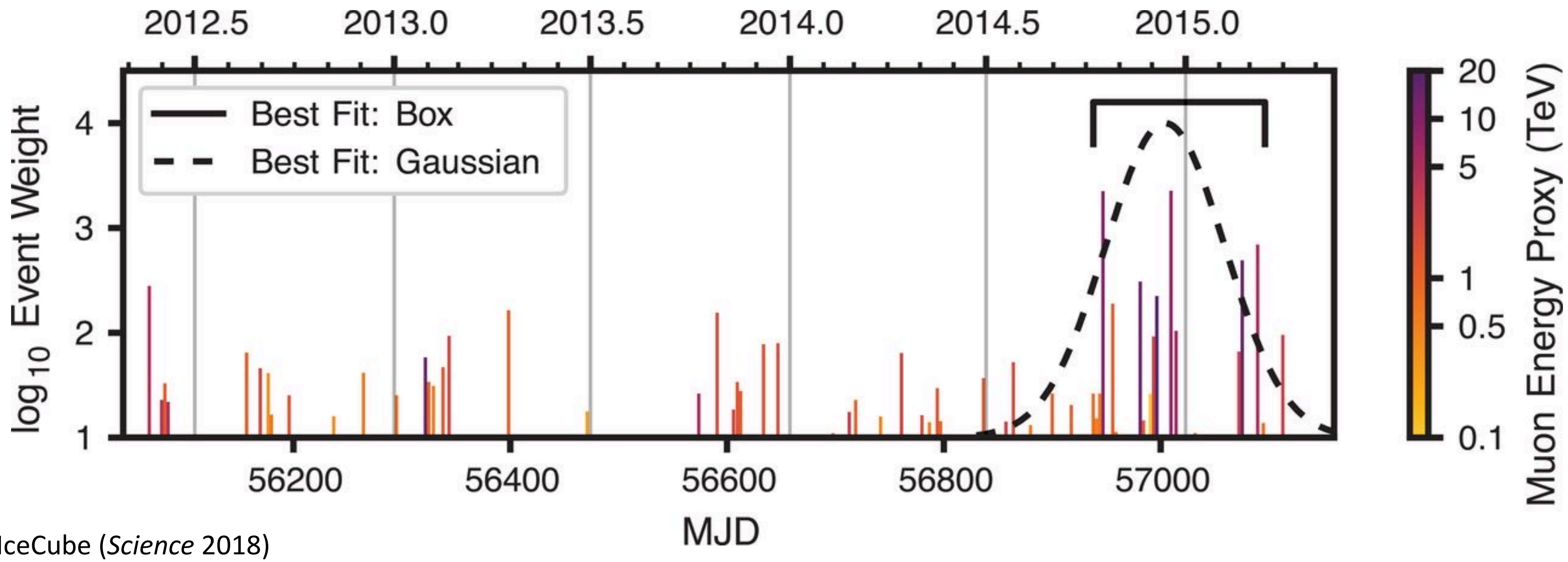


Time dependence in historical IceCube data

13 ± 5 tracks clustered in space and time in 2014, $E^{-2.1}$ spectrum

- No additional significant events were seen in 2017 around the time of IC170922A
- **Independent neutrino flare** in 2014-15 (3.5σ)

Summary: first evidence for very high-energy, astrophysical neutrino source. Implications for **blazars** as an origin of high-energy cosmic rays.



IceCube (*Science* 2018)

Indirect detection

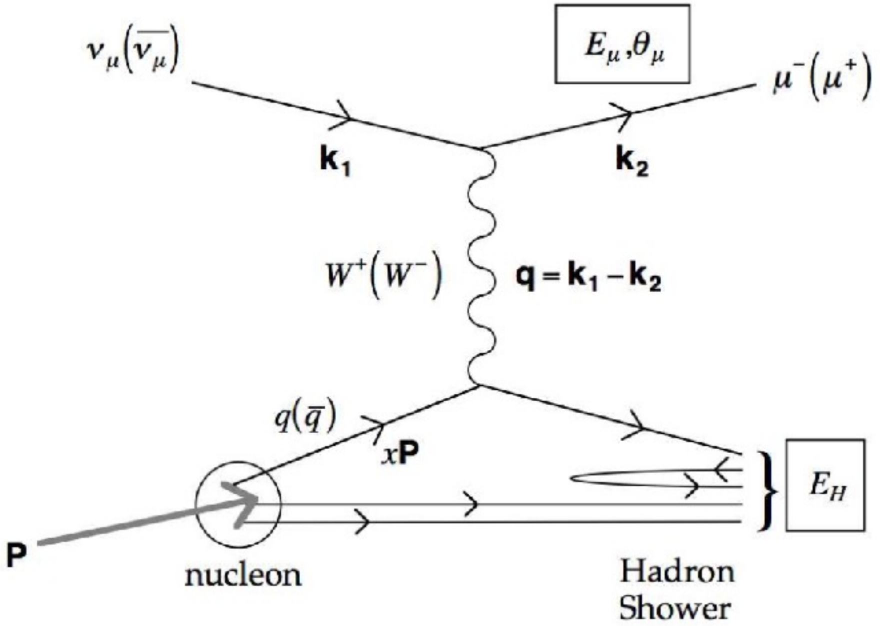
Neutrino interacts with targets in ice

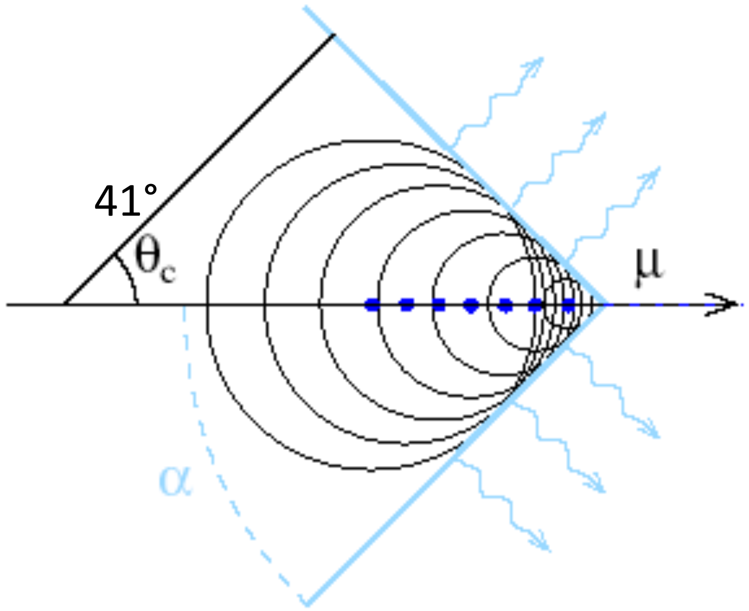
- Besides at resonance, primarily deep-inelastic scattering (DIS) off nucleons

Charged outgoing particles emit Cherenkov radiation detectable by PMTs

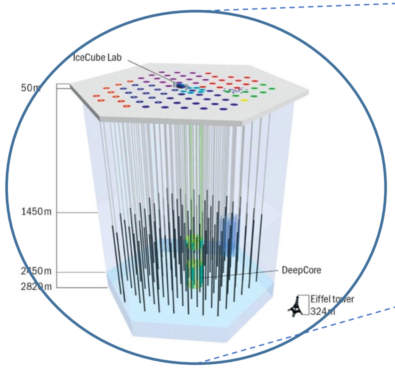
See talk by C. Spiering

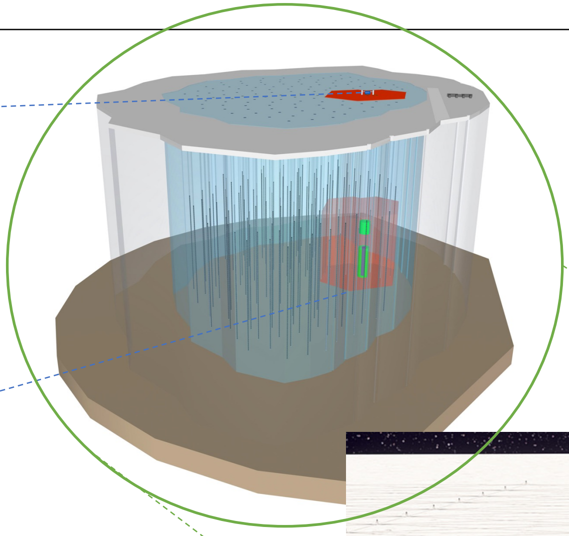
Rev. Mod. Phys. 84, 1307





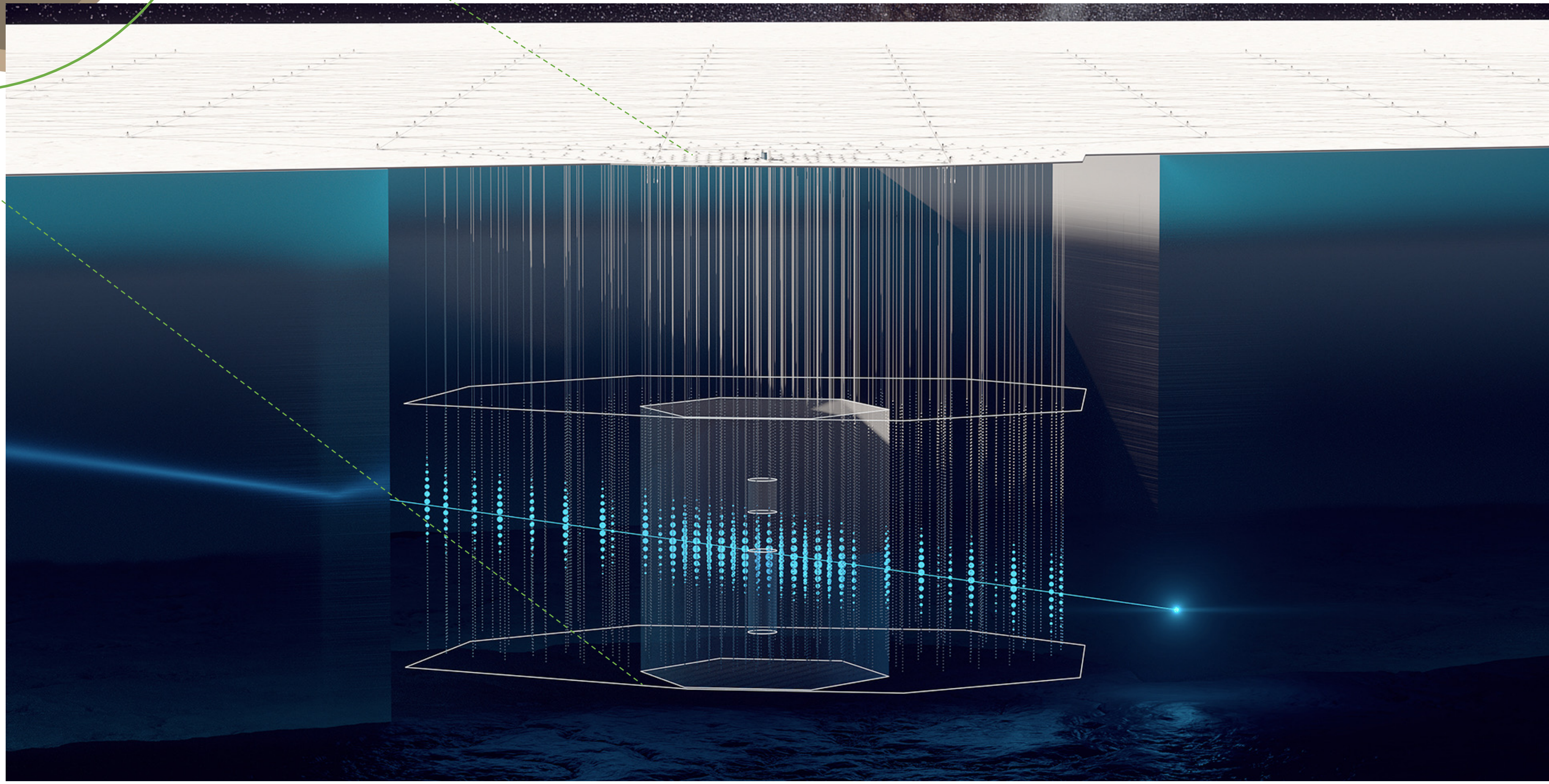
Envisioned detector





IceCube Gen2 Array

- Sparse radio array for ~EeV neutrino detection (c.f. talk by C. Glaser)
- 500 km^2 instrumented area with 300+ radio stations
- Scintillation panels part of surface array for CR physics and veto



Gen2-optical

- 120 new strings
- New OMs
- Order of magnitude larger instrumented volume
- 10x more showers
- Better angular resolution

See talk by C. Spiering