IceCube - Recent Results, Upgrade, Gen2

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Yonsei University Lecture Series
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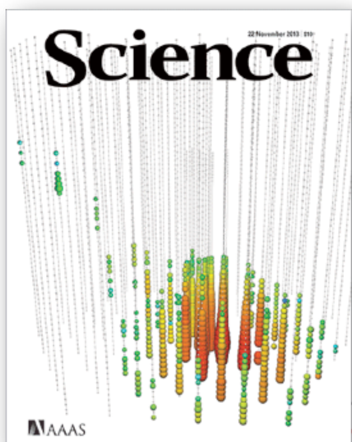
Motivation

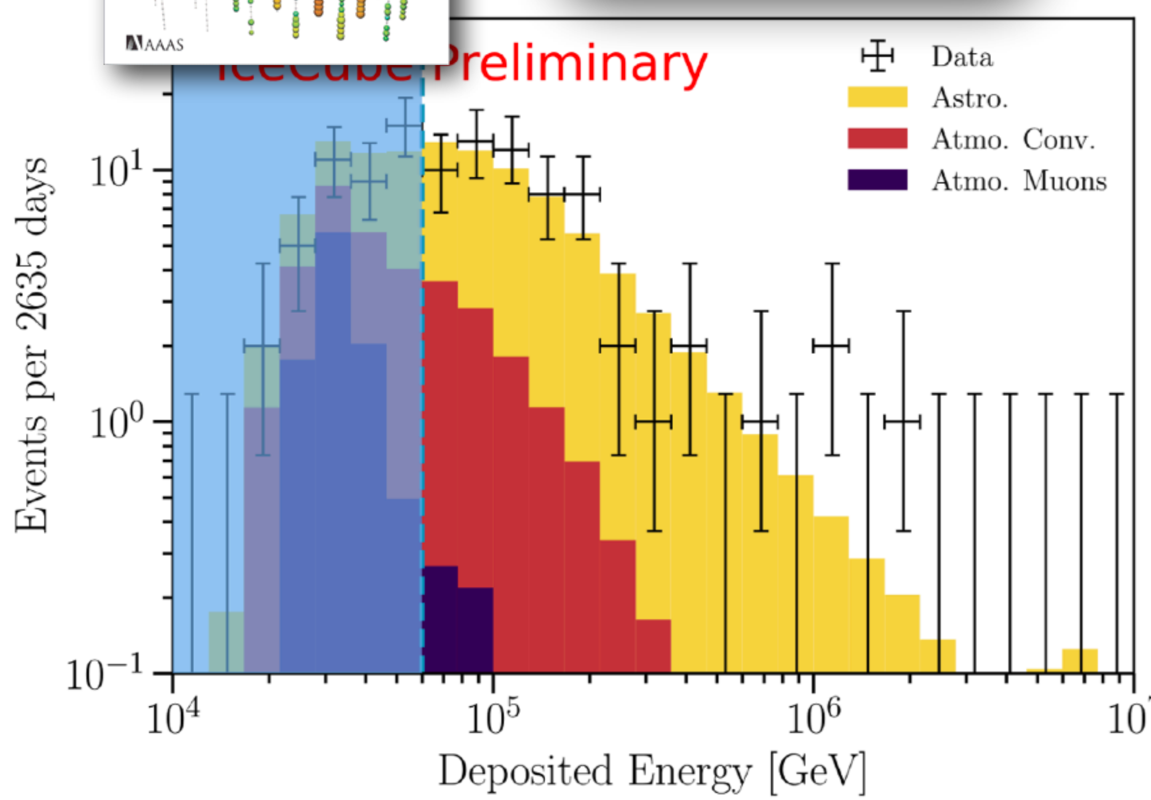
New Window to the Universe !

2002

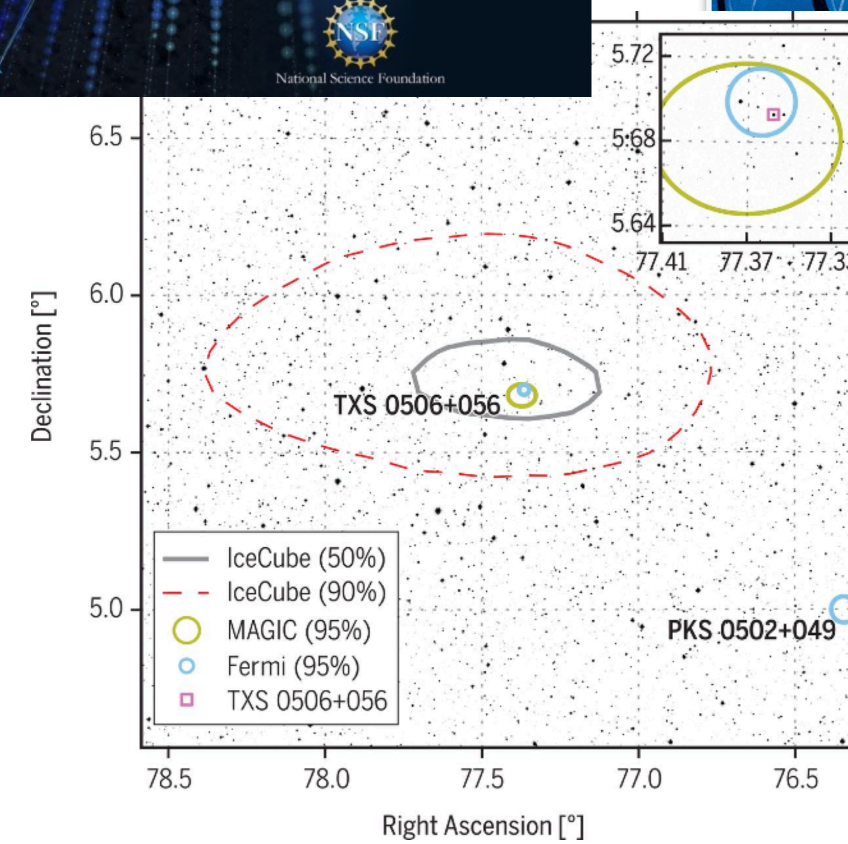
Following the observation of supernova burst neutrinos in 1987, *neutrino astronomy is becoming a reality quickly now …*

2013 Discovery of diffuse astrophysical neutrino flux



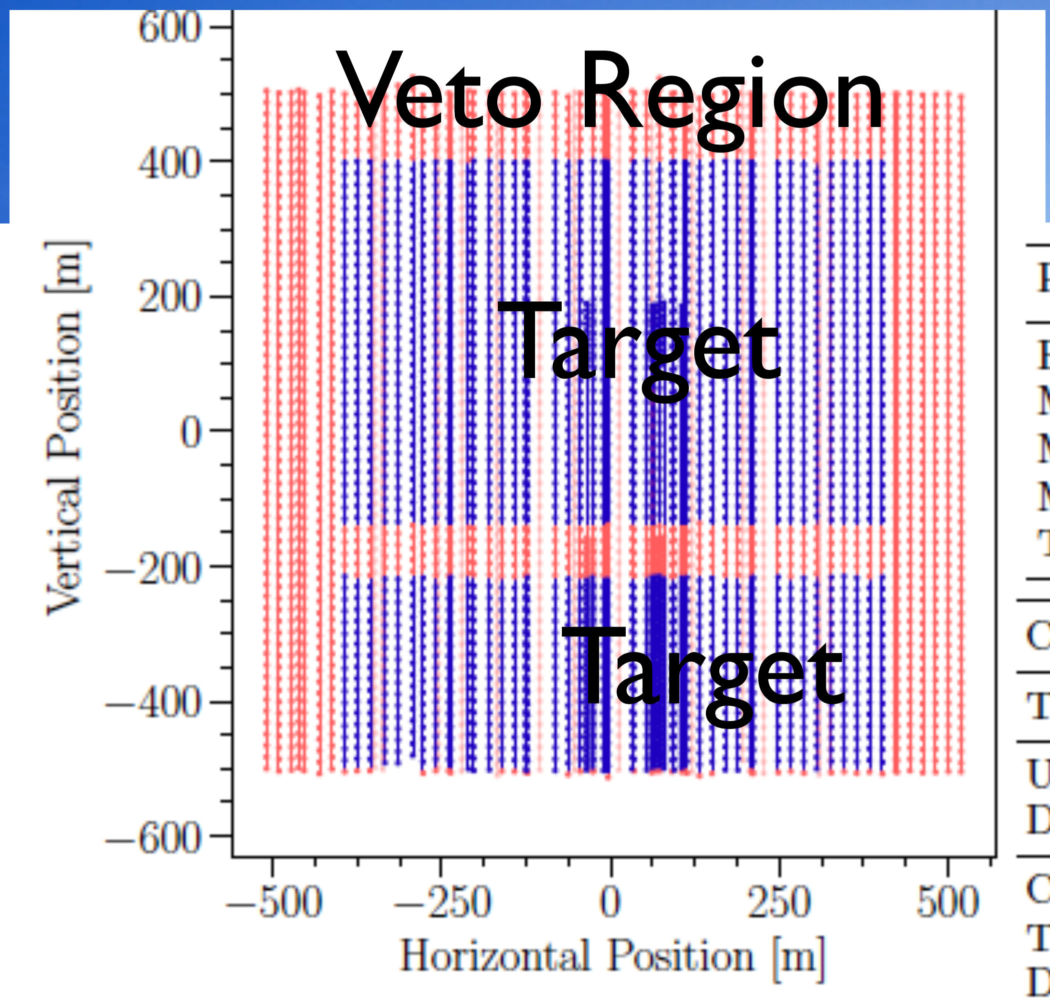


2018 Neutrino multi-messenger astroparticle physics



Astrophysical Neutrino Search

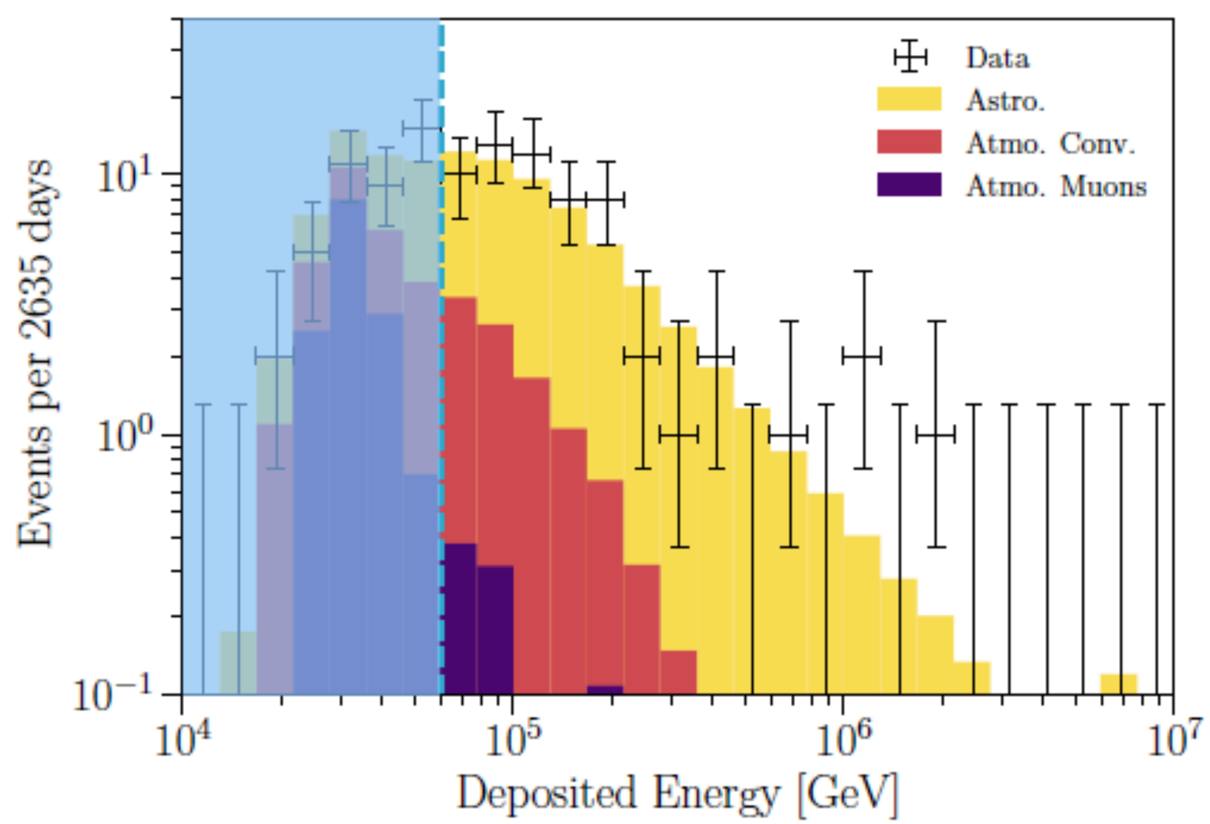
HESE 7.5 years

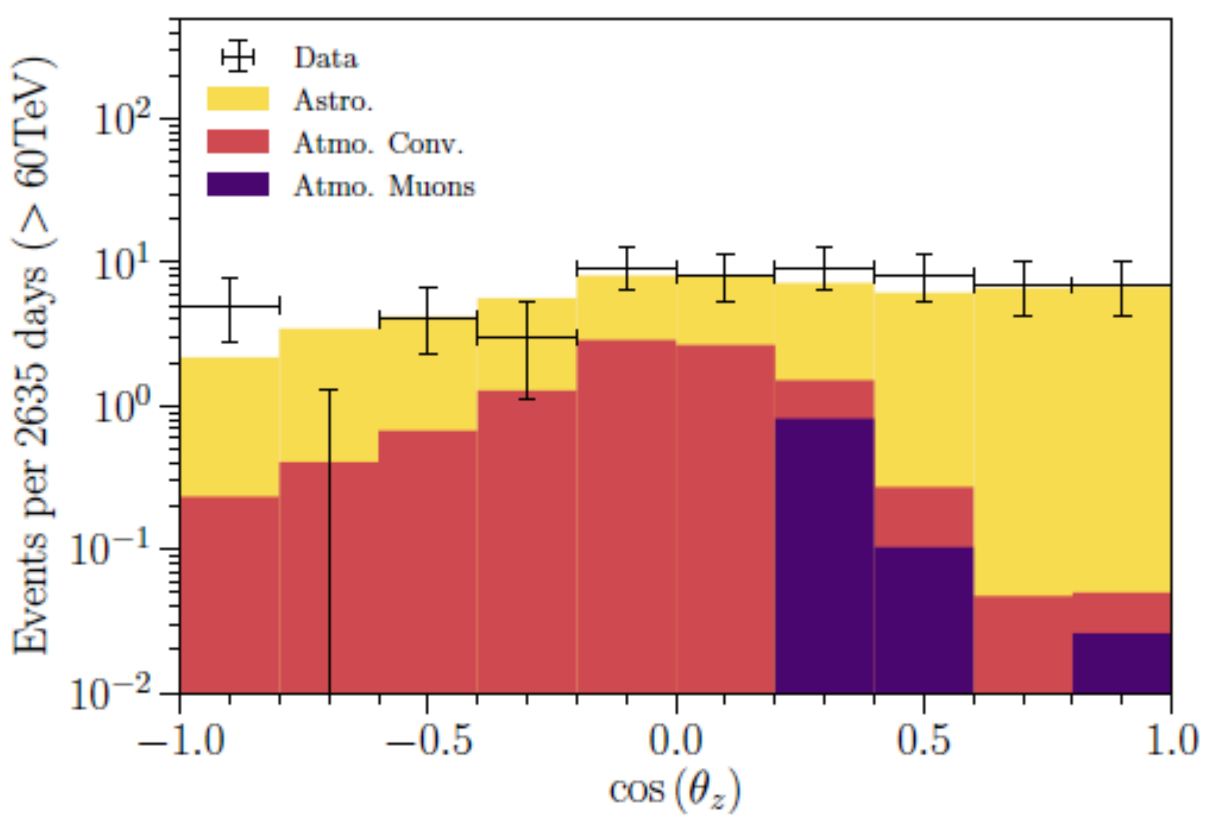


Parameter	Value
Event start time charge threshold	250 PE
Maximum veto charge	3.0 PE
Maximum DOMs with veto hits	2
Minimum total charge	6000 PE
Trigger time window	3 μs

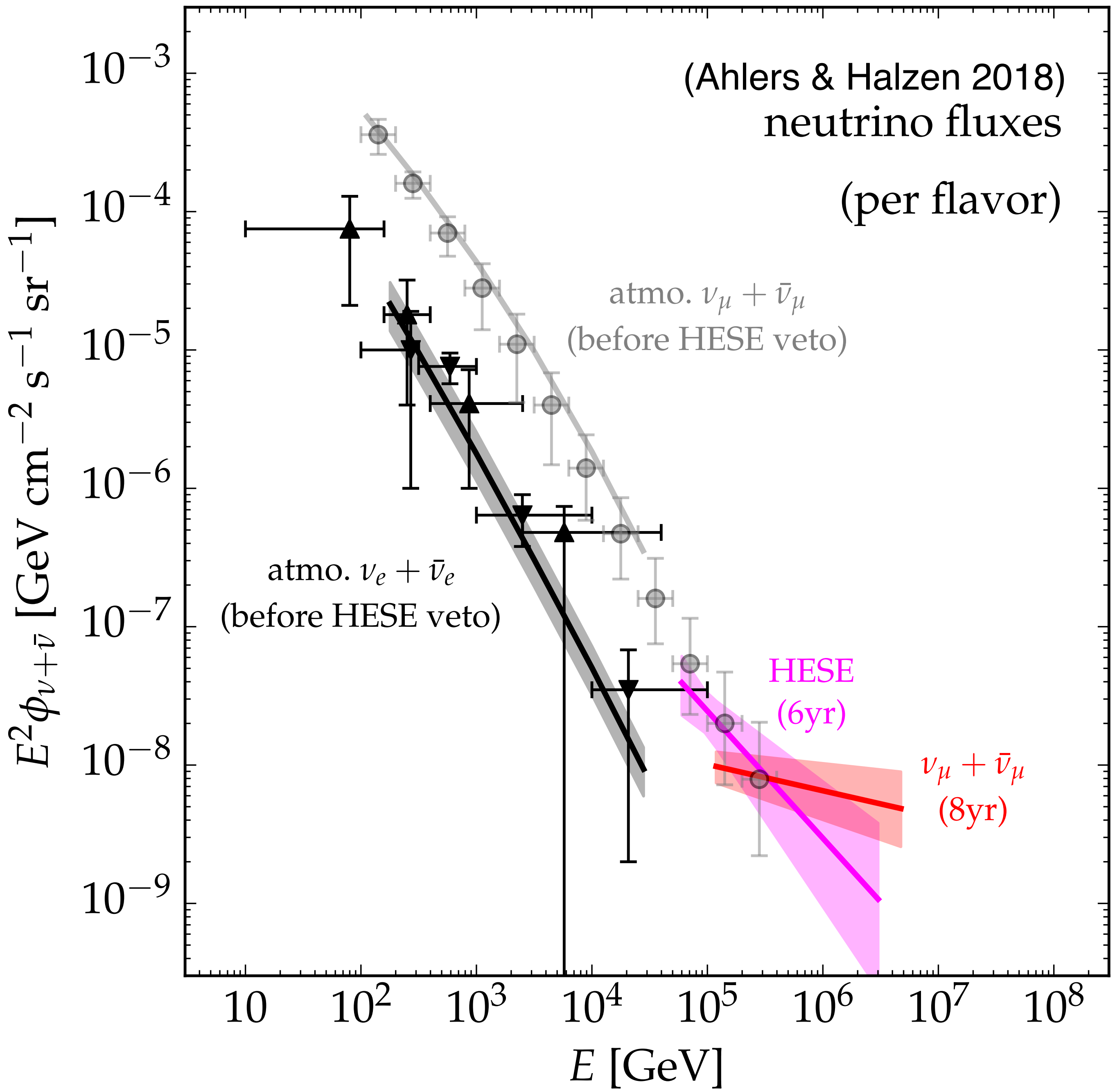
Category	$E < 60$ TeV	$E > 60$ TeV	Total
Total Events	42	60	102
Up	19	21	40
Down	23	39	62
Cascade	30	41	71
Track	10	17	27
Double Cascade	2	2	4

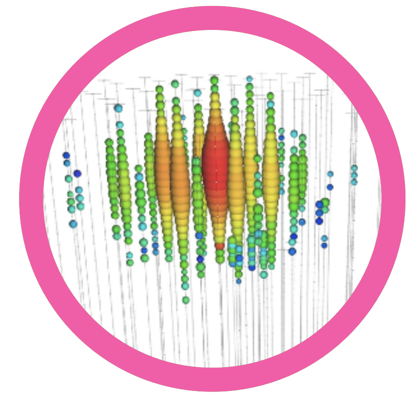
IceCube Collaboration
arXiv:2011.03545



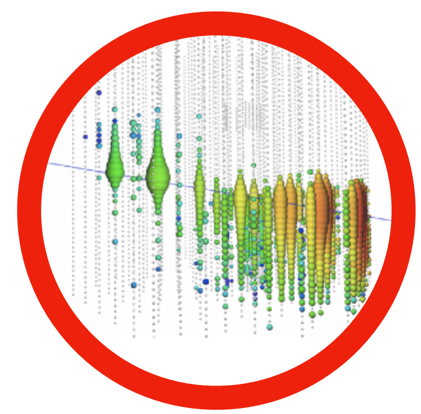


Astrophysical Neutrino Flux





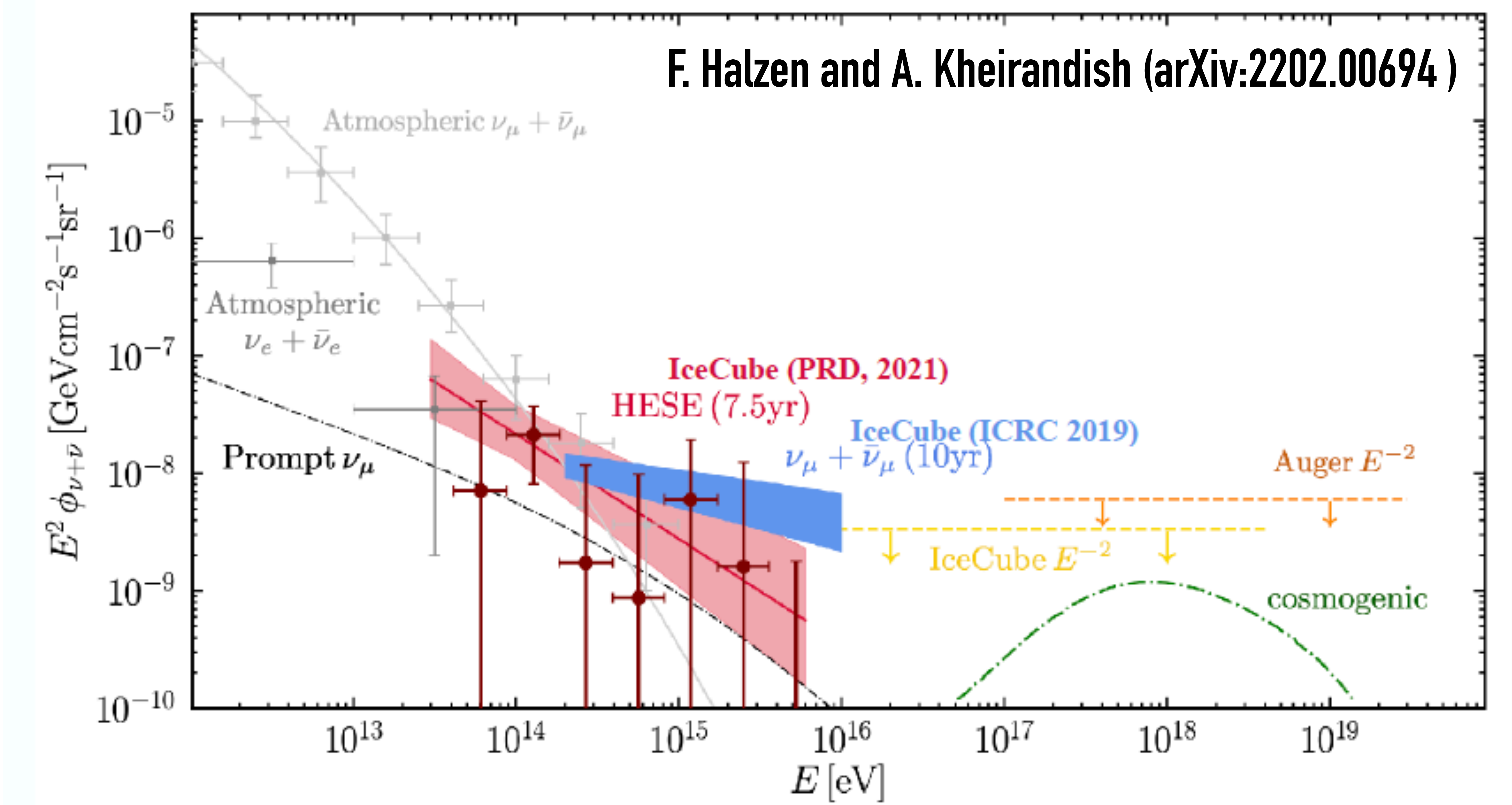
High-energy starting events (HESE)
Interaction vertex in the detector, All flavor, all sky



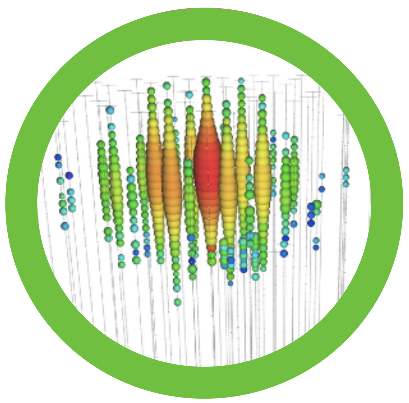
Up-going tracks
Muon-dominated Northern sky

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

Astrophysical Neutrino flux



Astrophysical Neutrino Flux



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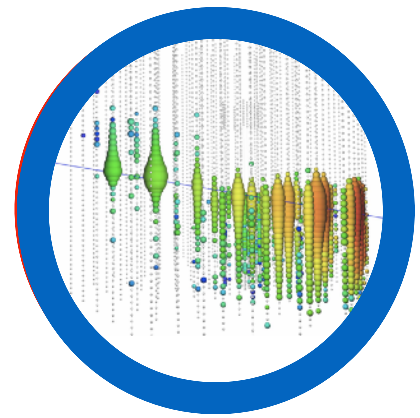
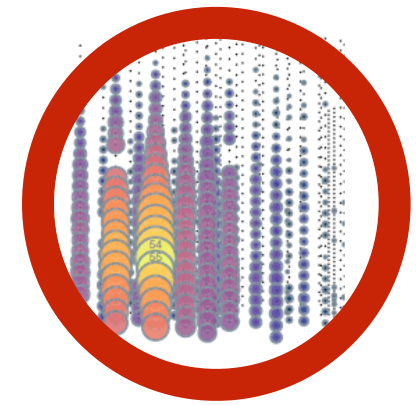
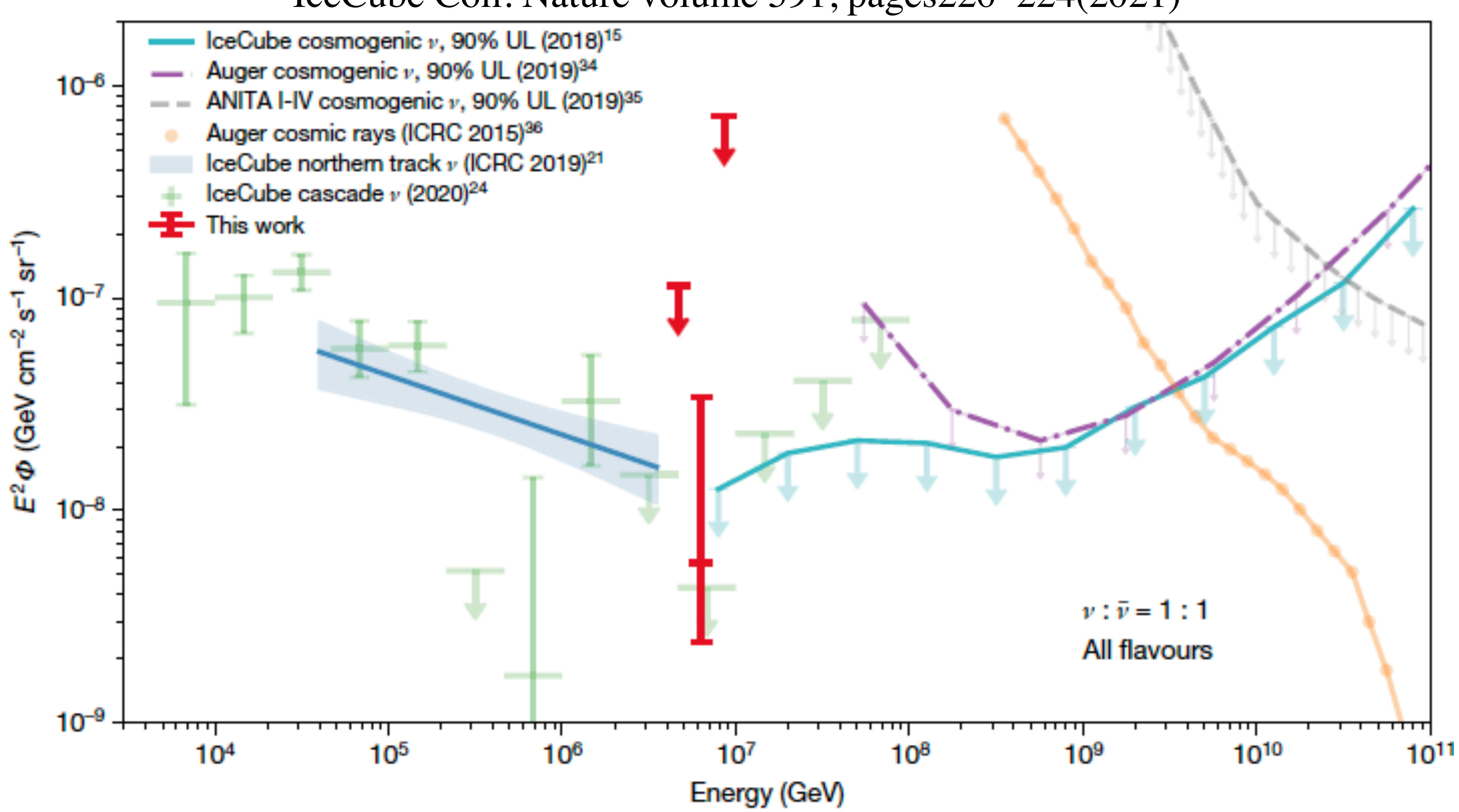


Up-going tracks
Muon-dominated
Northern sky



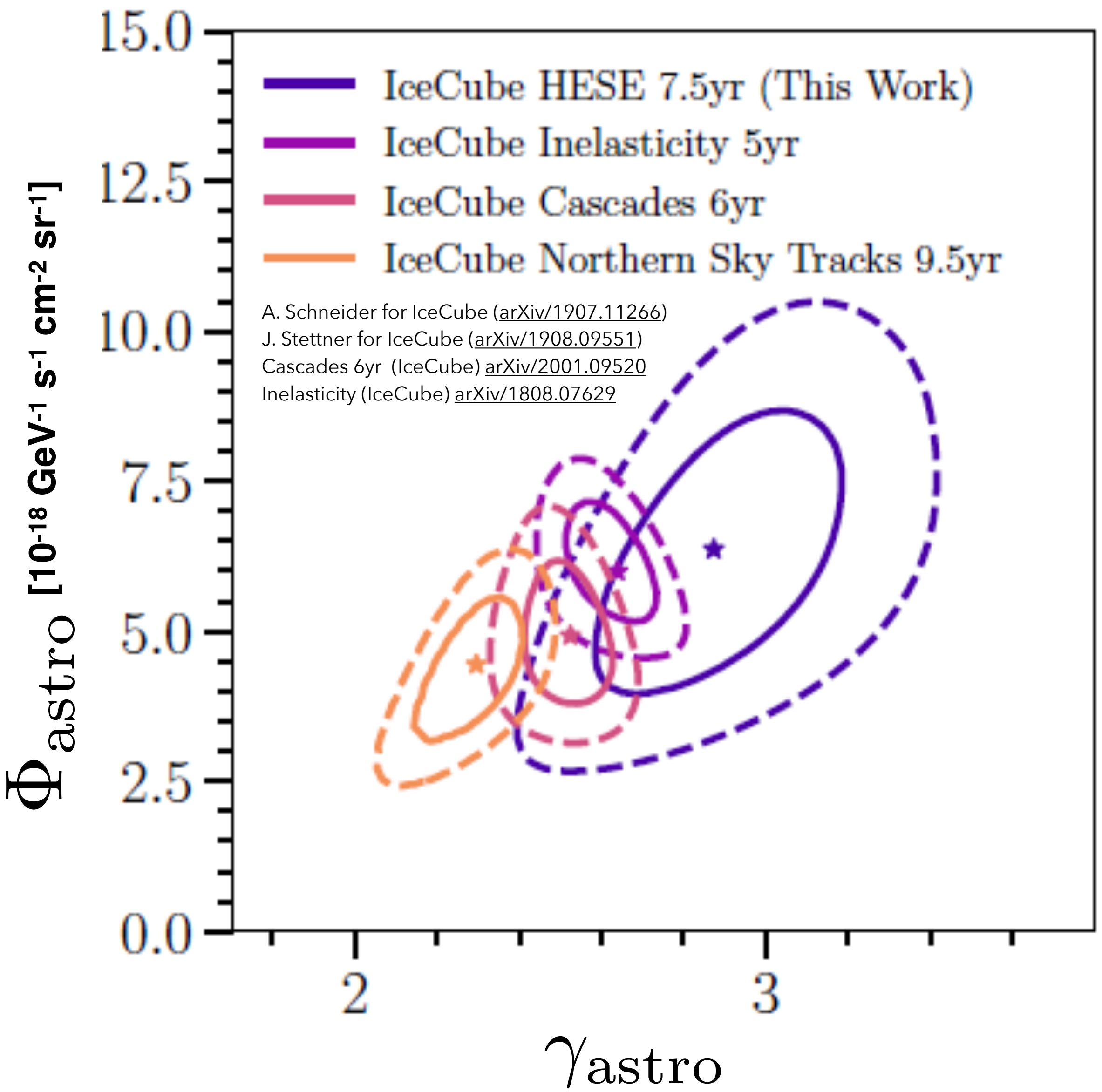
PeV energy partially contained events (PEPE)
Interaction vertex near the edge of the detector, All flavor, all sky

IceCube Coll. Nature volume 591, pages220–224(2021)



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

Neutrino energy spectrum



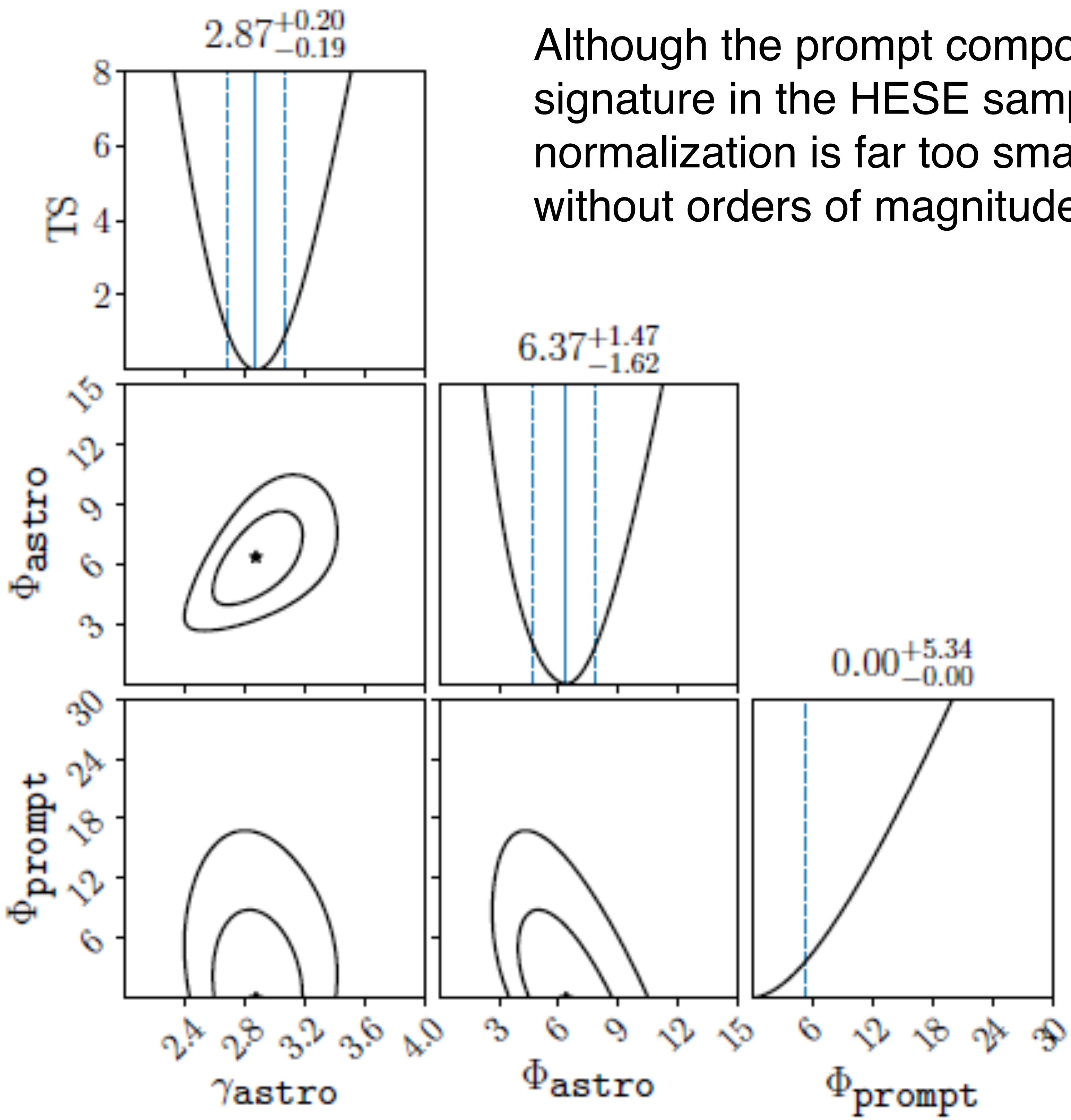
- Flux modeled with a simple power-law spectrum.

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

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

- Several independent analyses (on completely different samples and signatures) confirm diffuse astrophysical neutrino flux
- Single power law ("simplest" astrophysical source assumption) is not a good fit ! ⇒ Much more to learn !

Prompt neutrinos

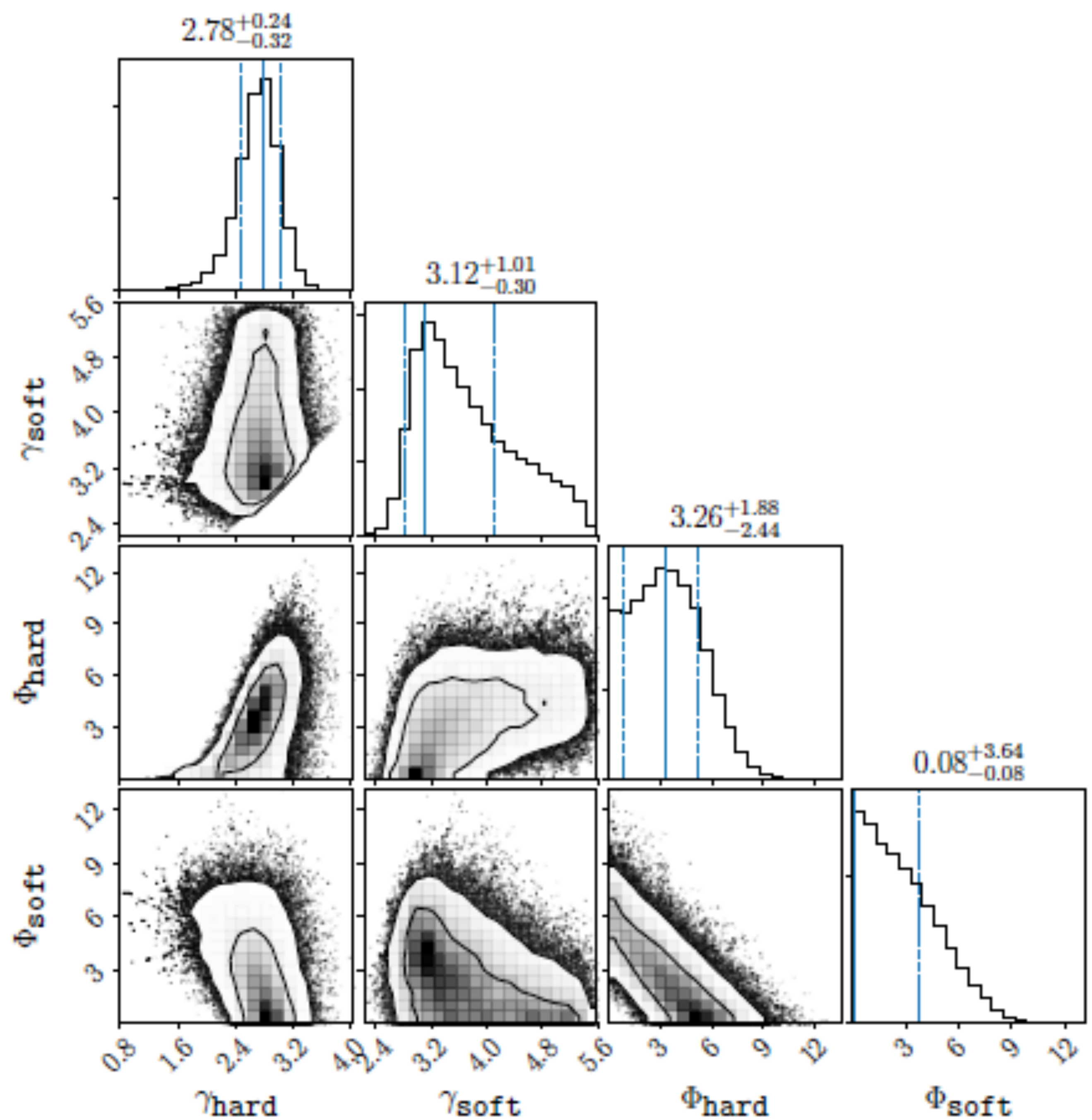


Although the prompt component has a distinct angular signature in the HESE sample, the component's normalization is far too small for this analysis to be sensitive without orders of magnitude more data.

Baseline Model: Atri Bhattacharya, Rikard Enberg, Mary Hall Reno, Ina Sarcevic, and Anna Stasto, "Perturbative charm production and the prompt atmospheric neutrino flux in light of RHIC and LHC," JHEP 06, 110 (2015), arXiv:1502.01076 [hep-ph].

Double power law

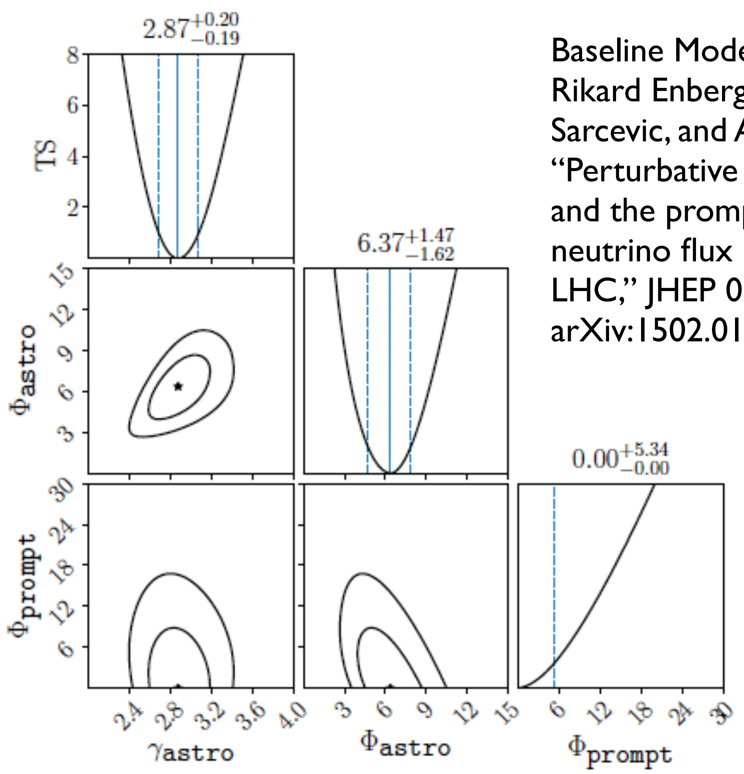
$$\frac{d\Phi_{6\nu}}{dE} = \left(\Phi_{\mathrm{hard}}\left(\frac{E_\nu}{100\,\mathrm{TeV}}\right)^{-\gamma_{\mathrm{hard}}} + \Phi_{\mathrm{soft}}\left(\frac{E_\nu}{100\,\mathrm{TeV}}\right)^{-\gamma_{\mathrm{soft}}}\right)$$



- Double power law fit finds:
  - hard index (γ_{hard}~2.8) close to single fit (γ_{astro}~2.9)
  - soft spectral index poorly constrained (γ_{soft}~2.1)
  - two components' normalizations are highly correlated, with either equal to zero allowed within the two-dimensional 68.3% highest probability density region

HESE conclusions

- Based on the 7.5yrs HESE data sample and it's sensitive energy range, the astrophysical neutrino flux is well described by a single power law
  - No evidence for additional spectral structure
  - Many models remain compatible with the data, and larger samples will be required to differentiate between the different proposed spectra



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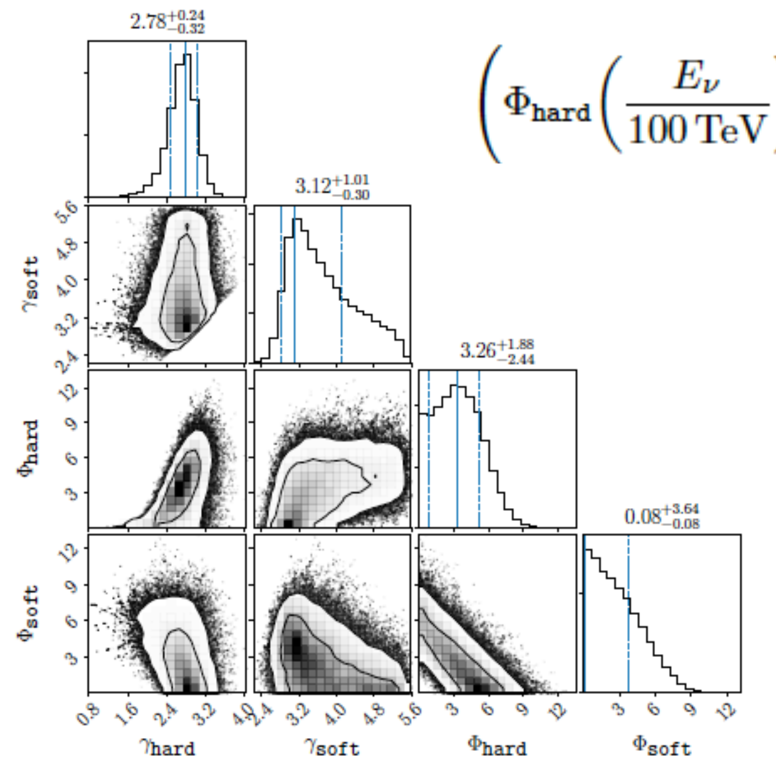
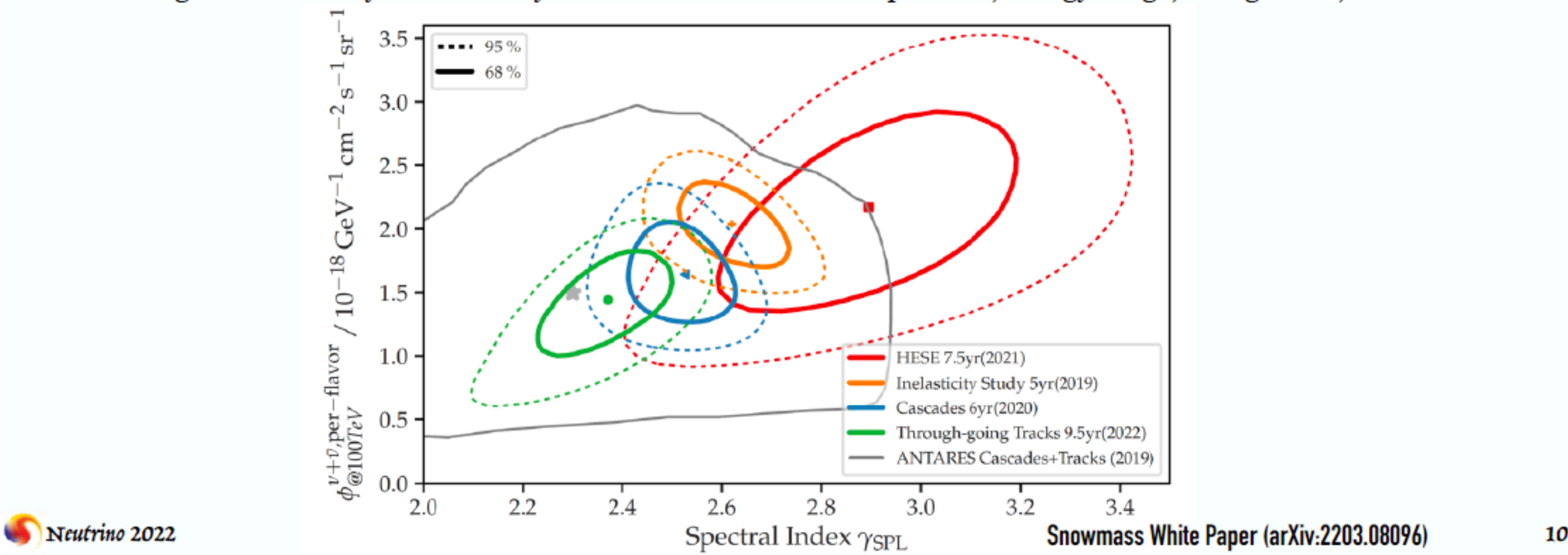


$$\left(\Phi_{\mathrm{hard}}\left(\frac{E_\nu}{100\,\mathrm{TeV}}\right)^{-\gamma_{\mathrm{hard}}} + \Phi_{\mathrm{soft}}\left(\frac{E_\nu}{100\,\mathrm{TeV}}\right)^{-\gamma_{\mathrm{soft}}}\right)$$

High-Energy Astronomical Neutrinos

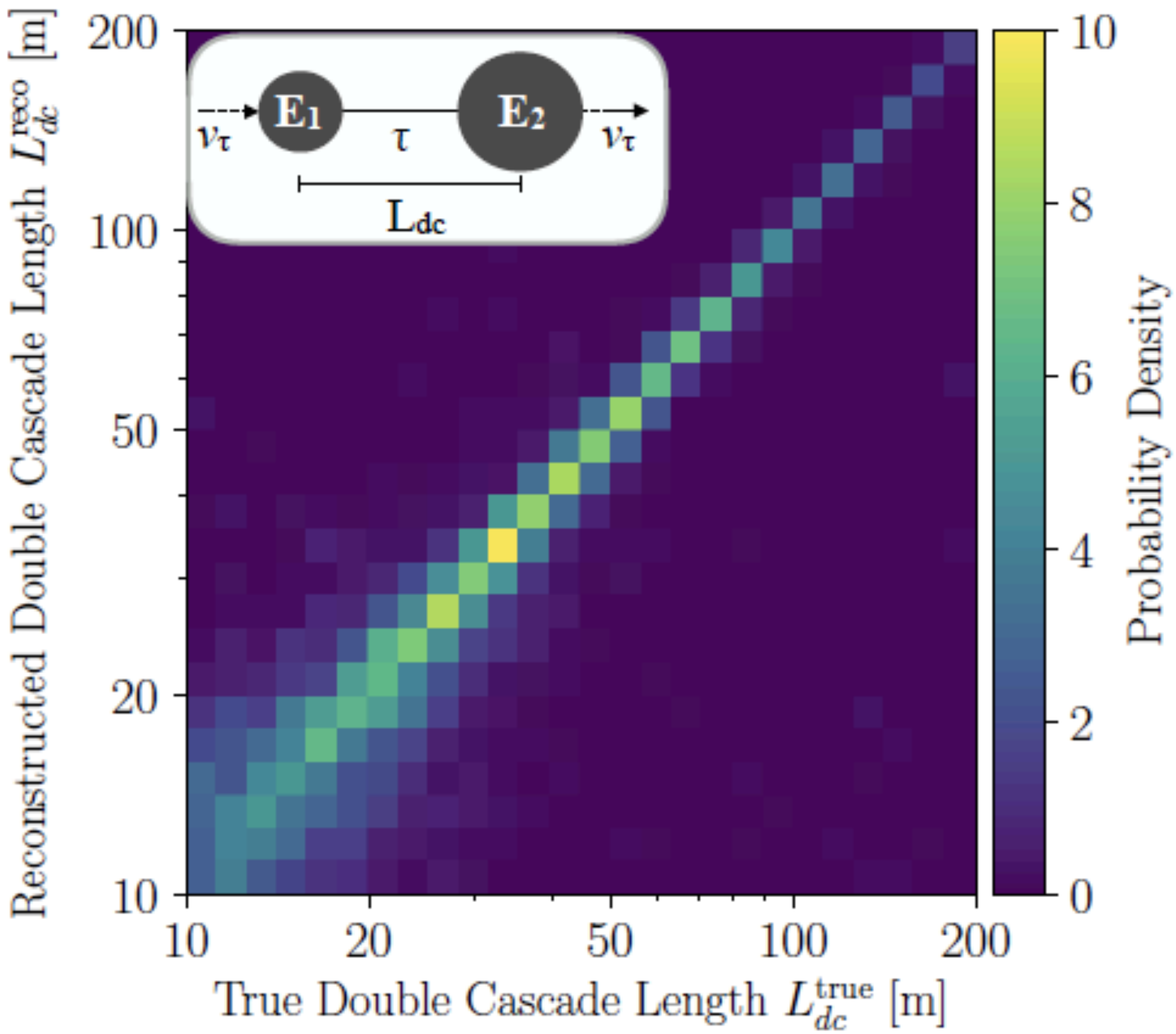
IceCube has measured the astrophysical neutrino flux with multiple independent analyses

- Independent event selection and analyses generally agree with the flux and index (assuming a single power-law distribution)
  - Slight tension may be caused by differences in flavour composition, energy range, background, …

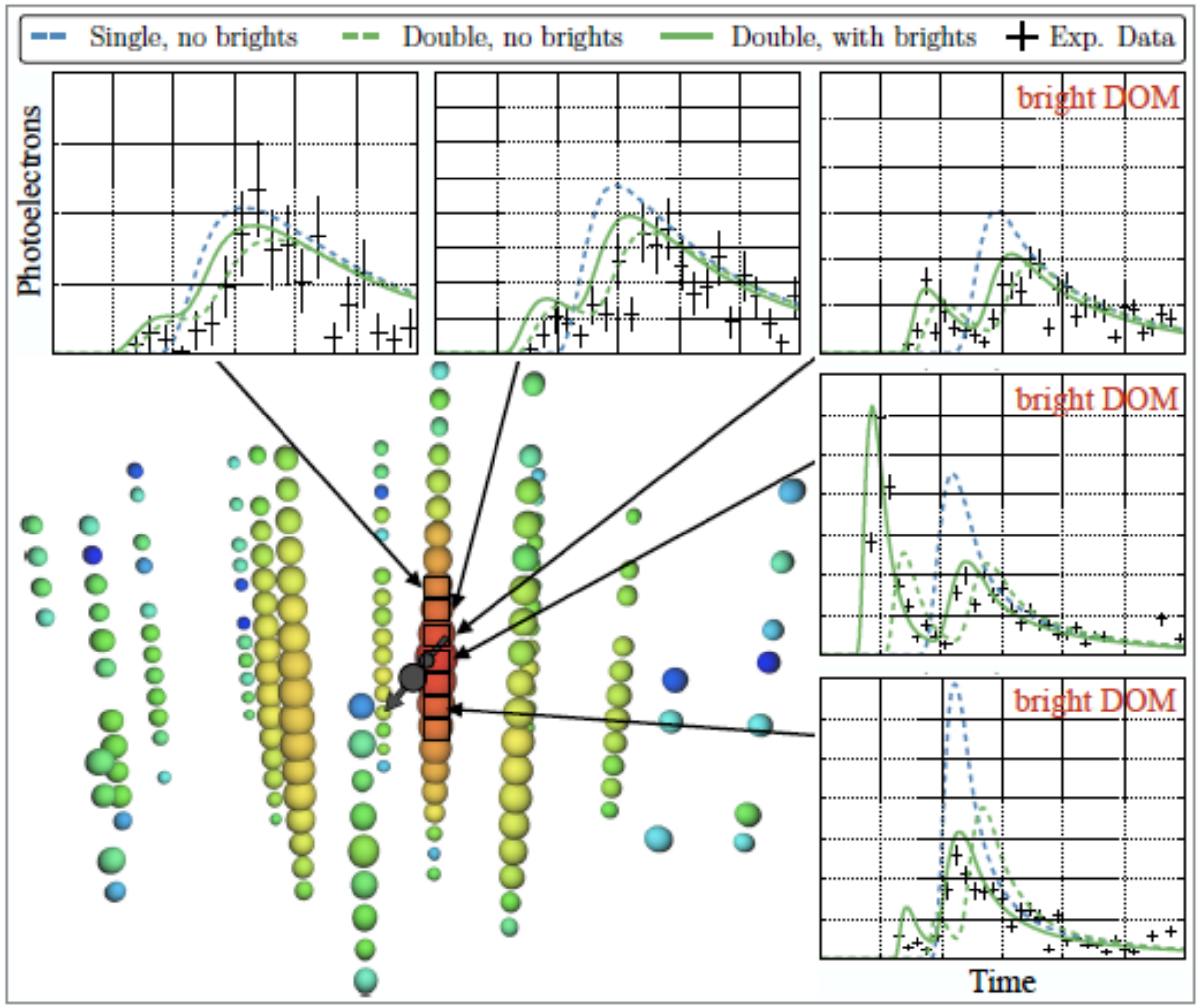


“Measurement of Astrophysical Tau Neutrinos in IceCube’s High-Energy StartingEvents” (IceCube Collaboration) arXiv:2011.03561

Tau Neutrinos



	Event #1	Event #2
Year	2012	2014
Energy of 1st cascade	1.2 PeV	9 TeV
Energy of 2nd cascade	0.6 PeV	80 TeV
Energy Asymmetry	0.29	-0.80
Length	16 m	17 m
	“Big Bird” 76%	“Double double” 98%



2 candidate events detected in HESE 7.5yr sample with E>60TeV
1PeV tau travel about ~50m

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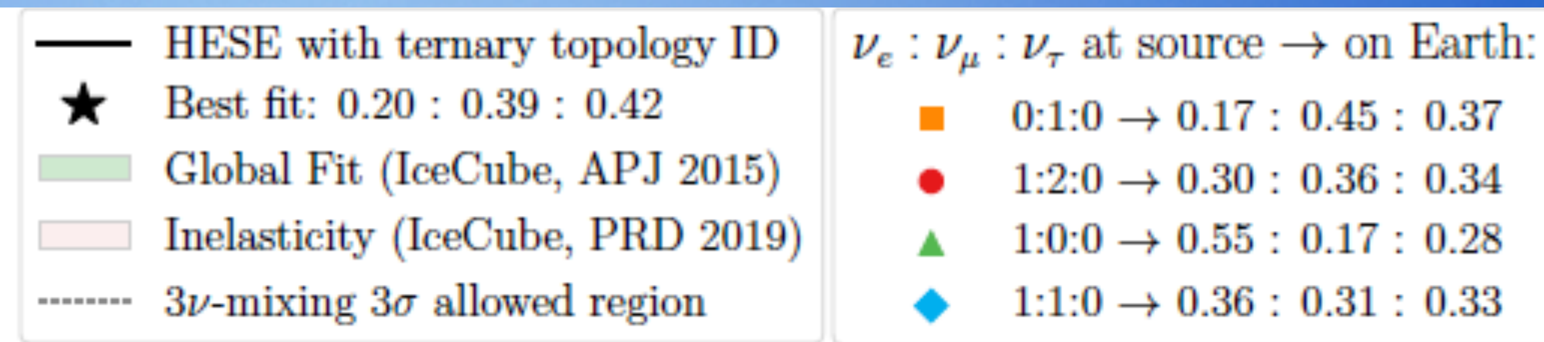
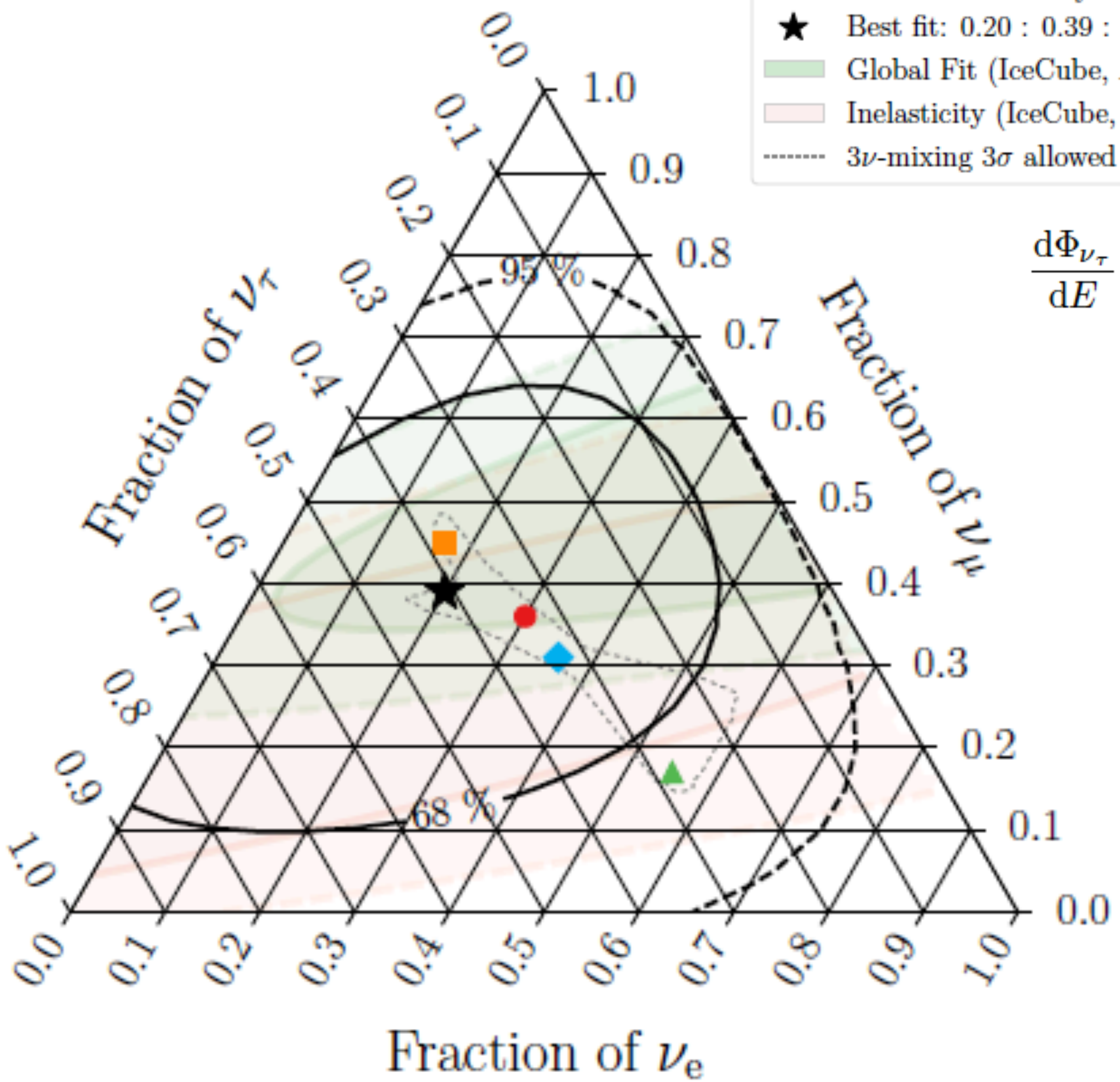
Tau Neutrinos





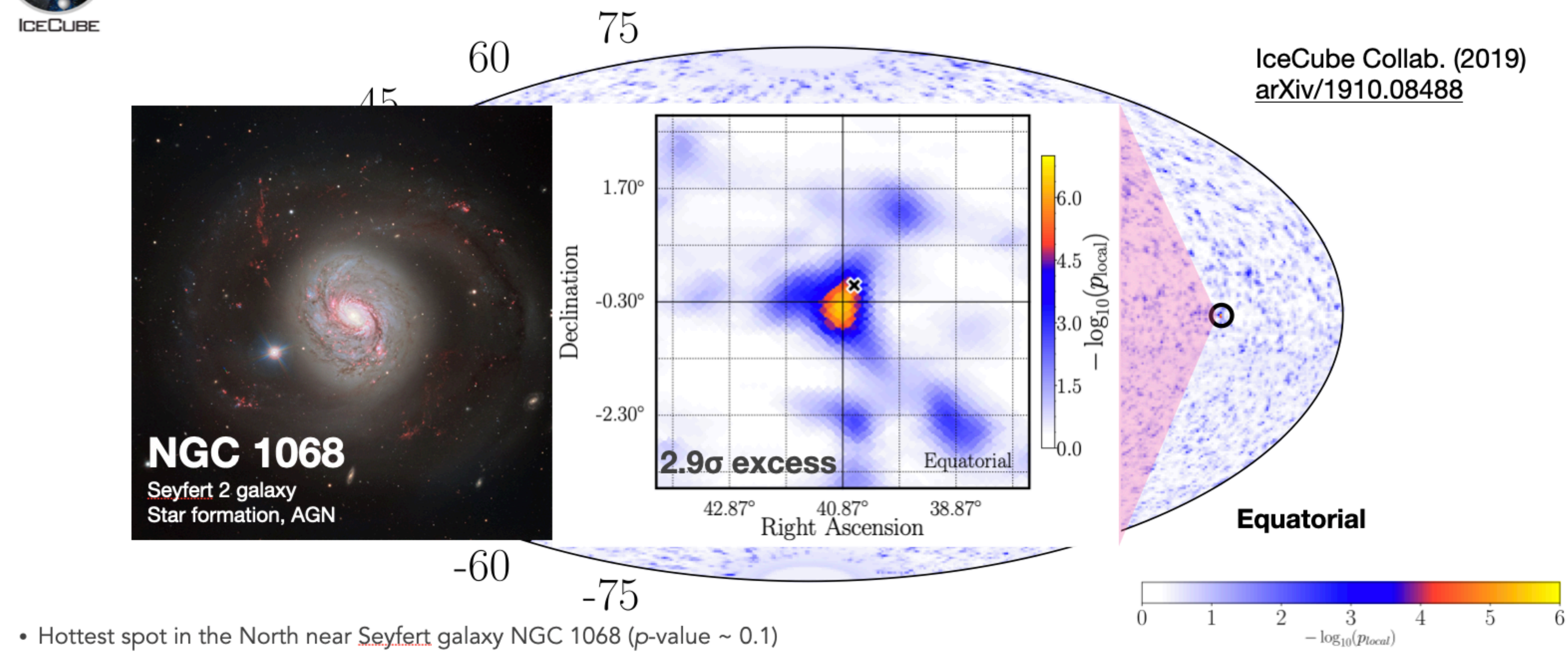
$$\frac{d\Phi_{\nu_\tau}}{dE} = 3.0^{+2.2}_{-1.8} \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-2.87[-0.20,+0.21]} \cdot 10^{-18} \cdot \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1},$$

disfavoring a no-astrophysical tau neutrino flux scenario with 2.8σ significance

Astrophysical Neutrino Sources

Point source search

Search for point sources in 10 years of IceCube data

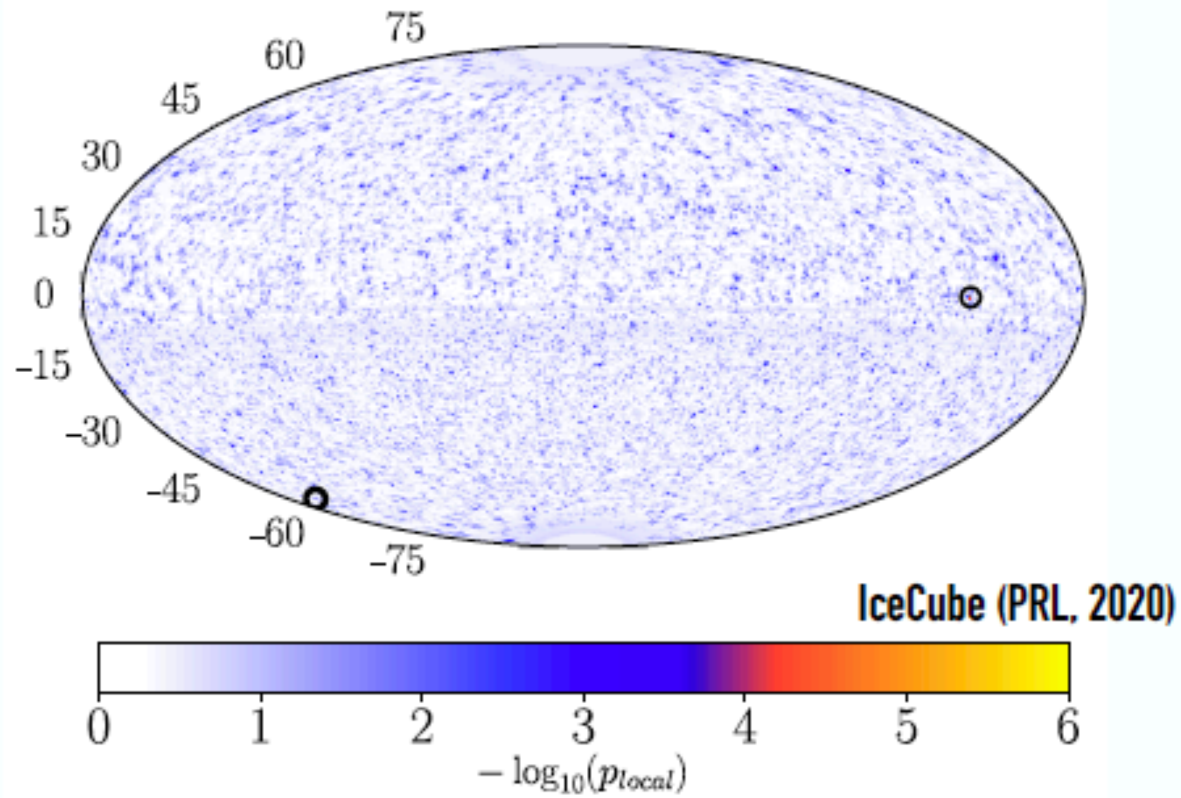


- Hottest spot in the North near Seyfert galaxy NGC 1068 (p-value ~ 0.1)
- Excess at NGC 1068 location: **2.9σ**
- **3.3σ** from a source catalog search

Different event selections have different strength for neutrino searches

10 Year track-like events (E>10 TeV, $\mu+\nu_\mu$)

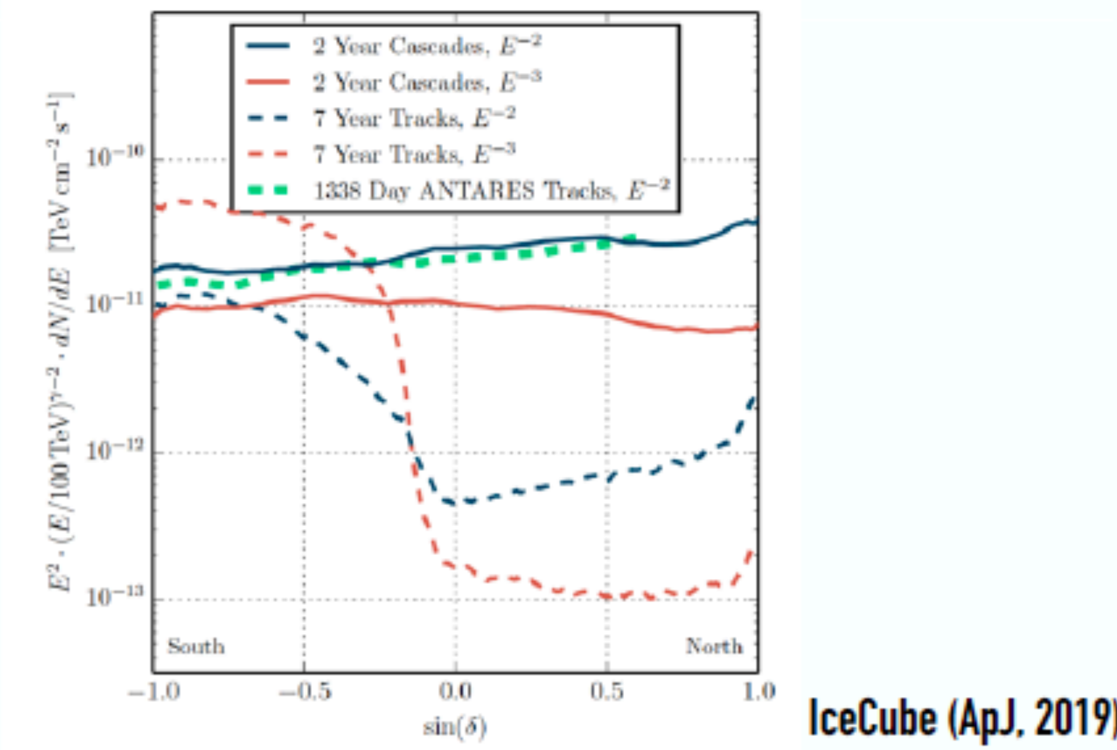
(https://icecube.wisc.edu/data-releases/2021/01/all-sky-point-source-icecube-data-years-2008-2018/)



→ Good angular resolution

→ Best sensitivity at Northern sky

7 Year Cascade events (E>1 TeV, all flavour)

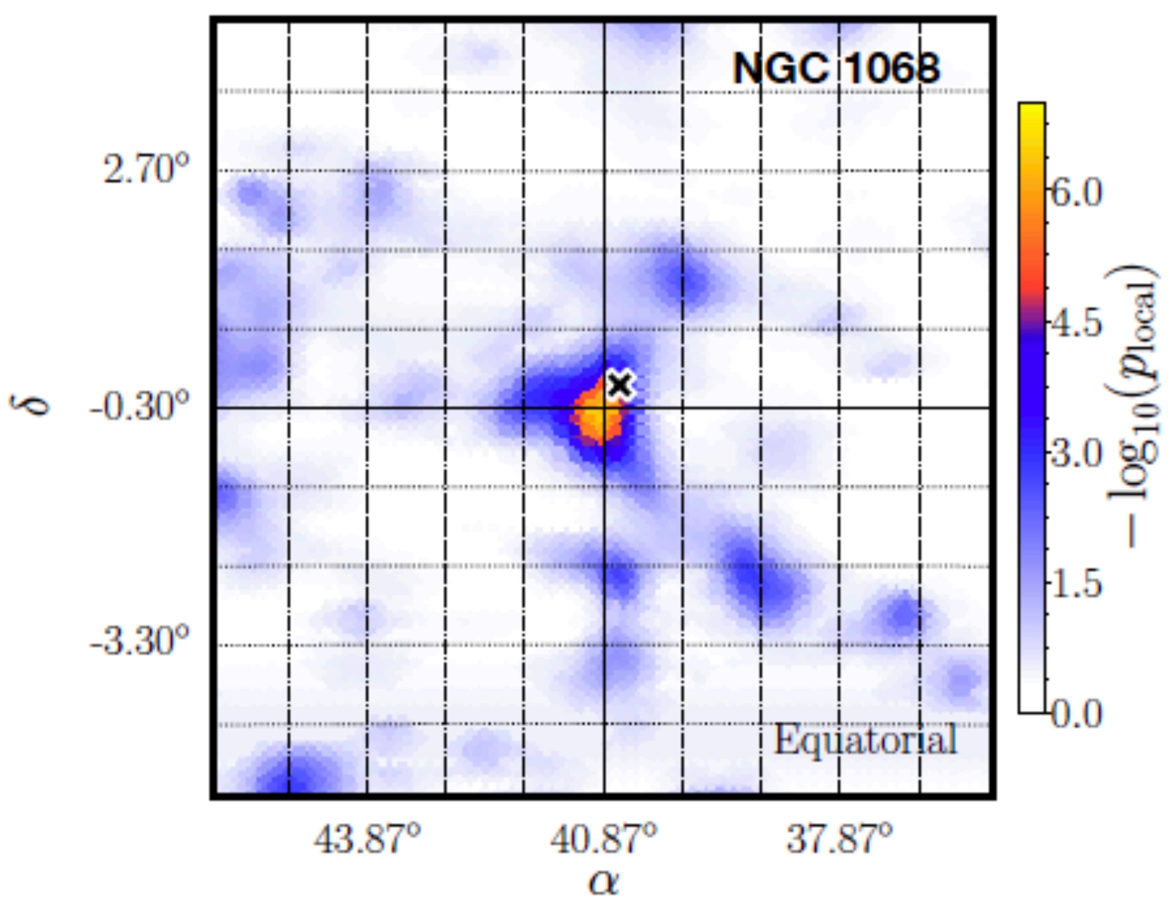


→ Lower energy coverage

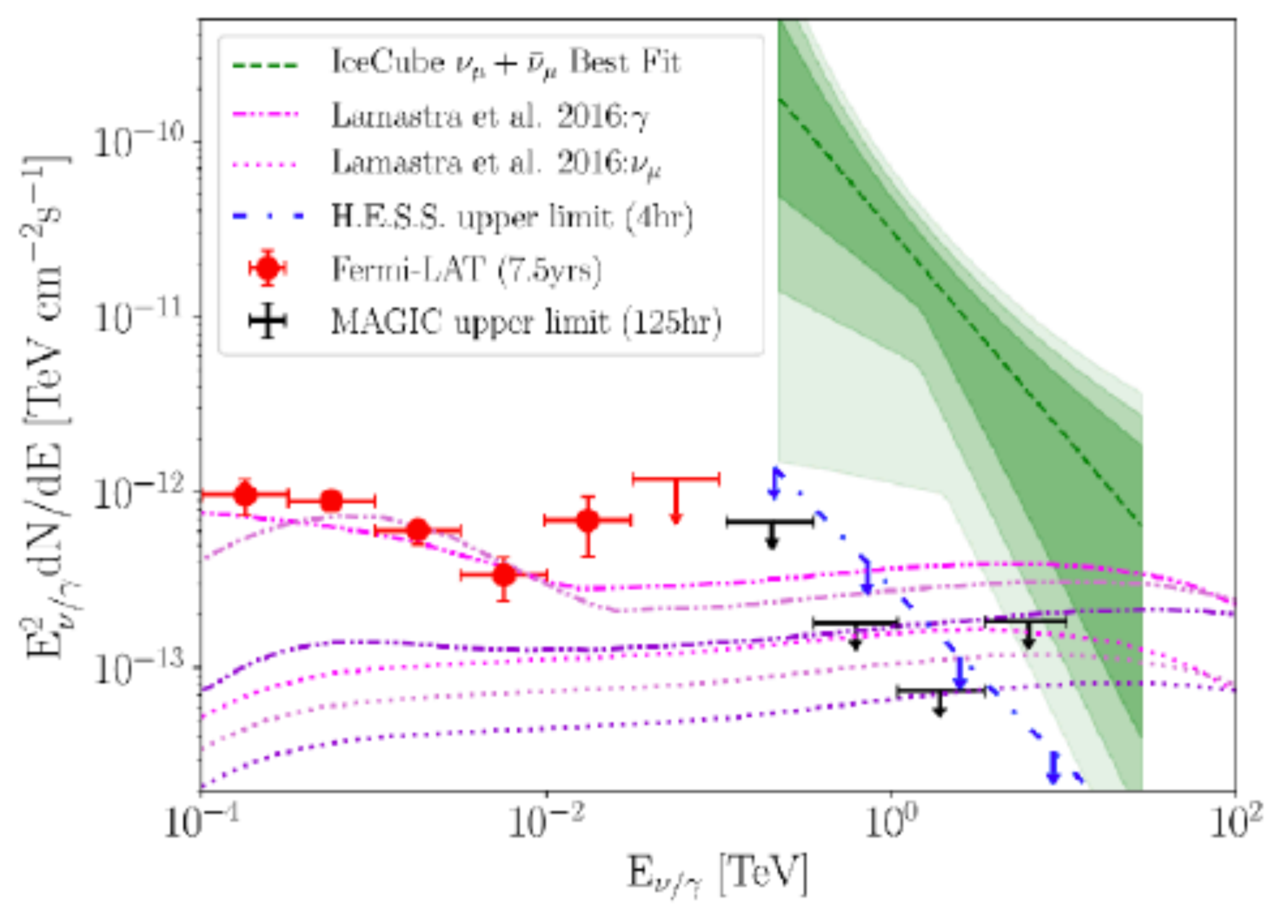
→ ~Uniform sensitivity for all-sky

The most significant source in the Nothern hemisphere: nearby Seyfert galaxy NGC 1068 w/ significance of 2.9σ

- GeV gamma-ray based catalogue search inconsistent with background w/ 3.3σ



“Searches for neutrinos from hard X-ray AGNs”

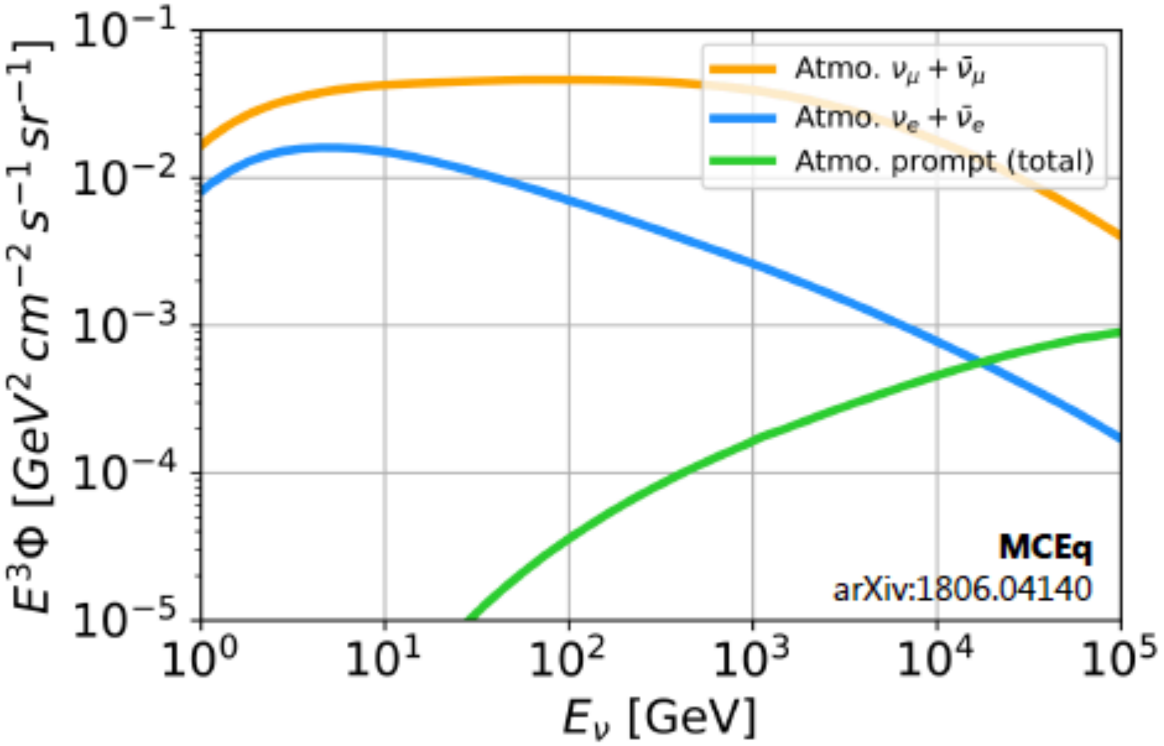


IceCube (PRL, 2020)

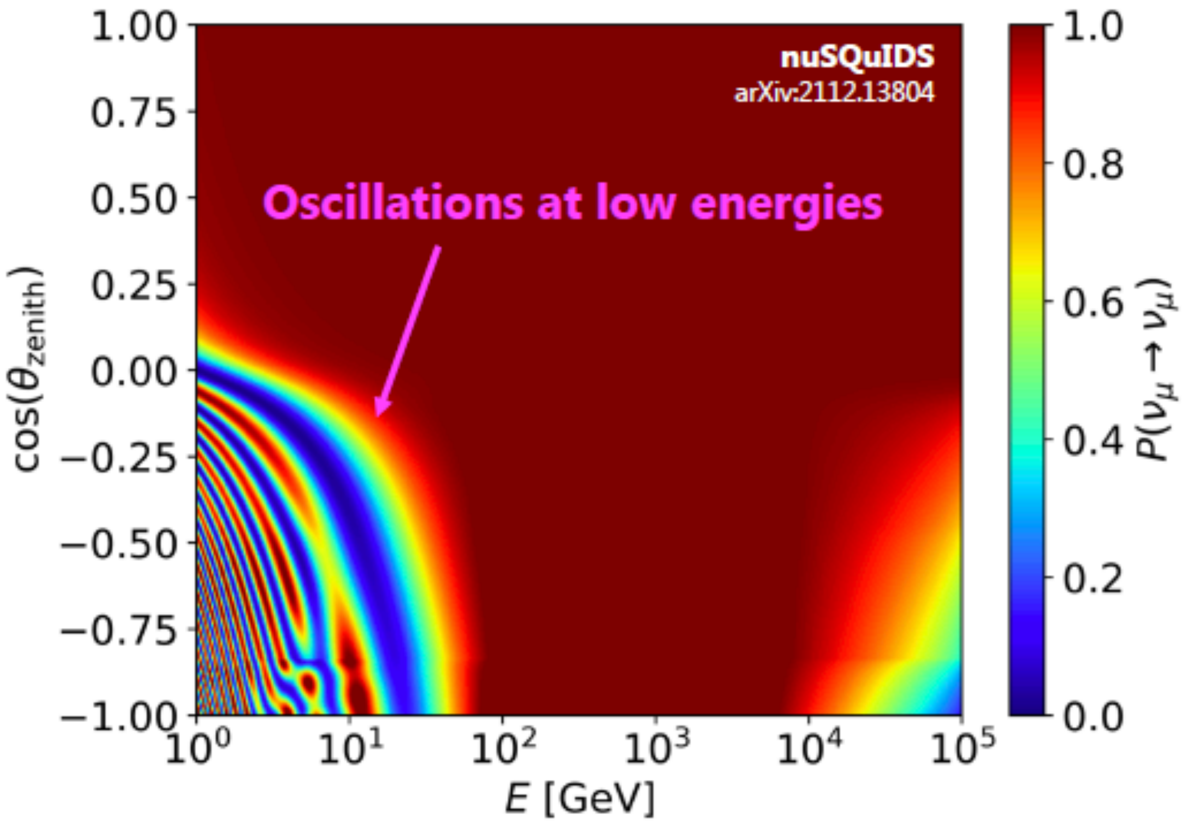
Oscillations

(1) Cosmic rays interact in the atmosphere and produce air showers

→ **Large flux of high energy neutrinos**

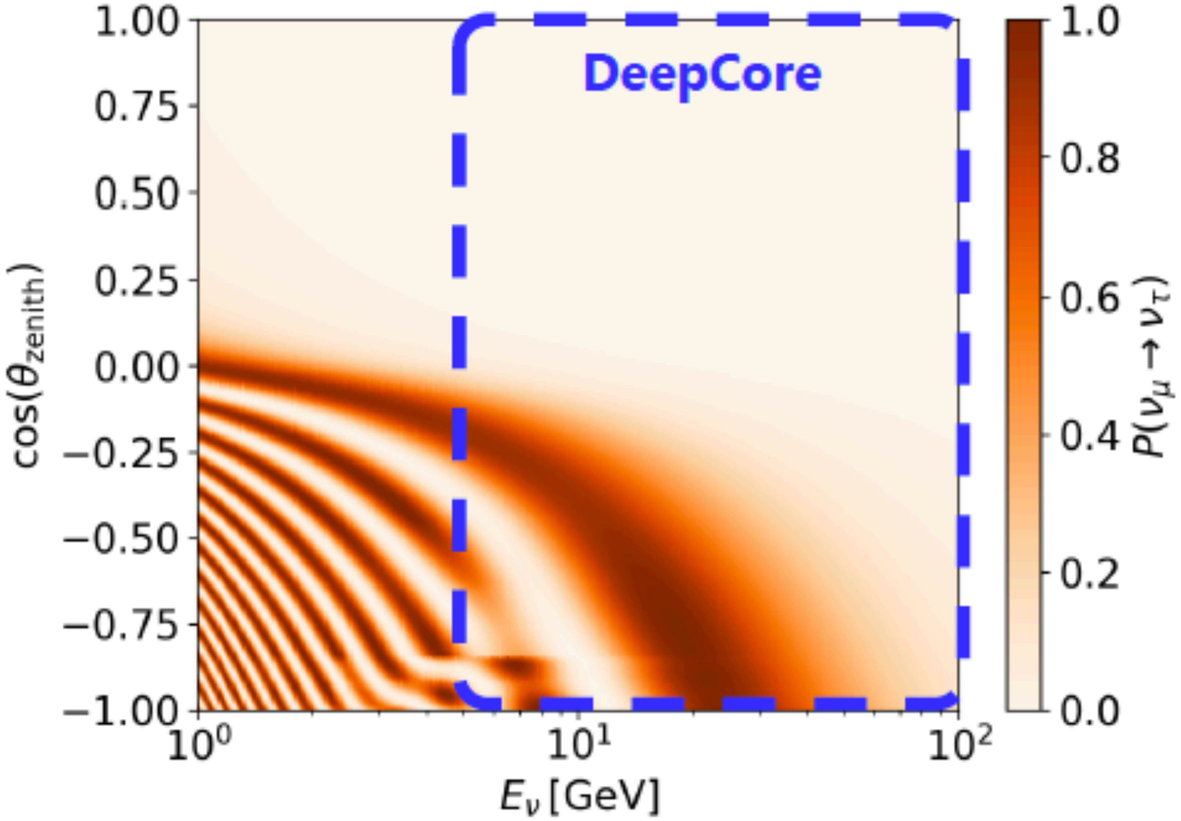


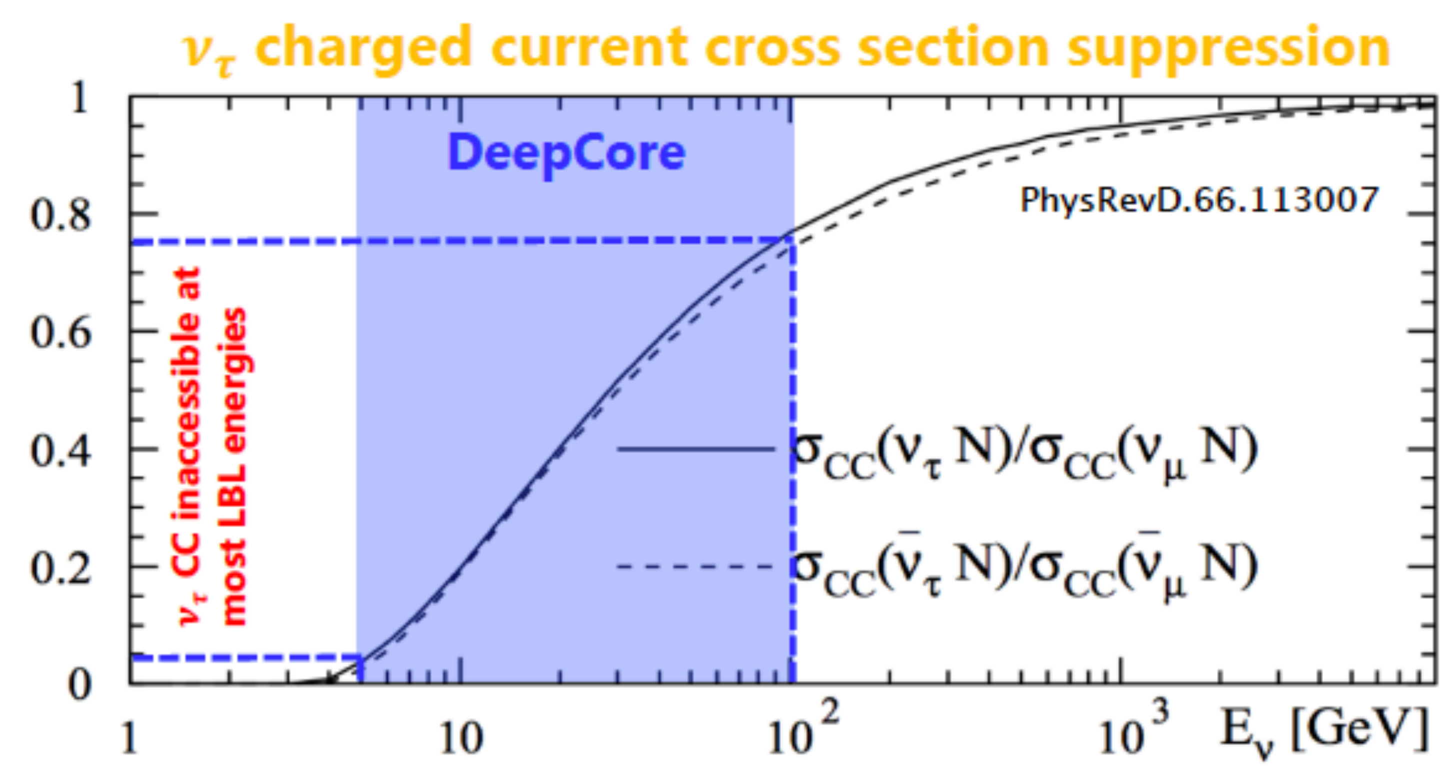
(2) Neutrinos propagate across the Earth



Atmospheric Neutrino Oscillations

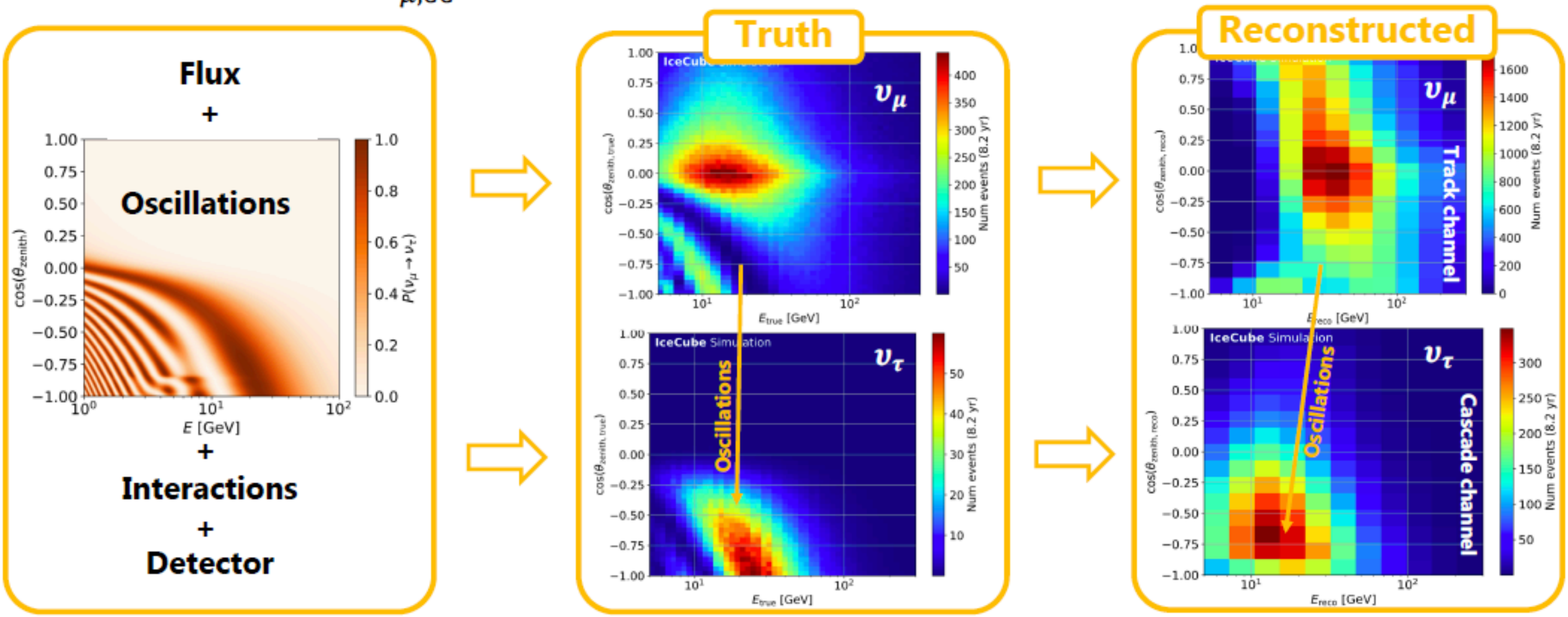
- $\mathcal{O}$(20 GeV) Earth-crossing $\boldsymbol{\nu_\mu}$ **near maximally oscillate to** $\boldsymbol{\nu_\tau}$
  - Same L/E as LBL accelerators but in DIS regime and with very different systematics
  - Observe both ν_μ and ν_τ **(above the $\boldsymbol{\nu_{\tau,CC}}$ kinematic threshold, ~3.5 GeV)**





Measuring Oscillations

- Measure **3D distortions in reconstructed [energy, zenith, PID]**
  - Robust against systematic uncertainties
  - PID discriminates $\nu_{\mu,CC}$ interactions vs all other flavours/channels



8+ years Oscillation Analysis @ Neutrino 2022

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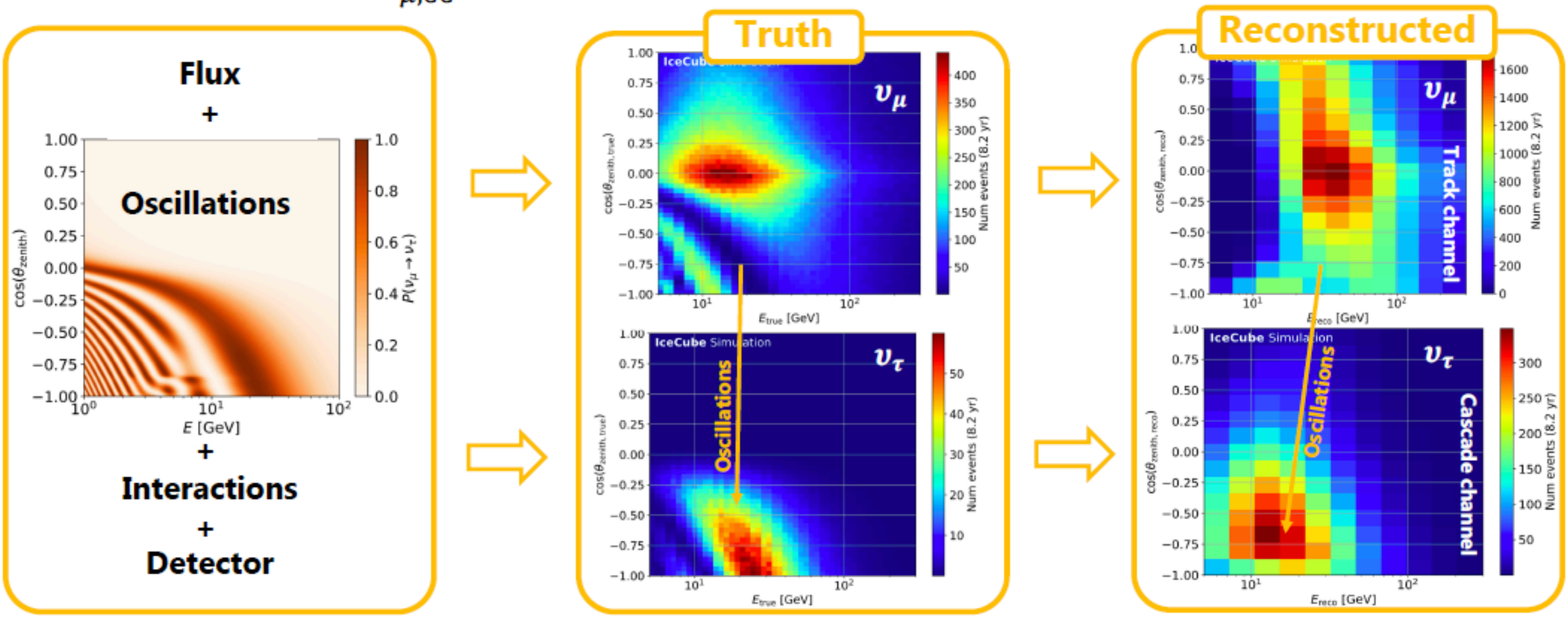
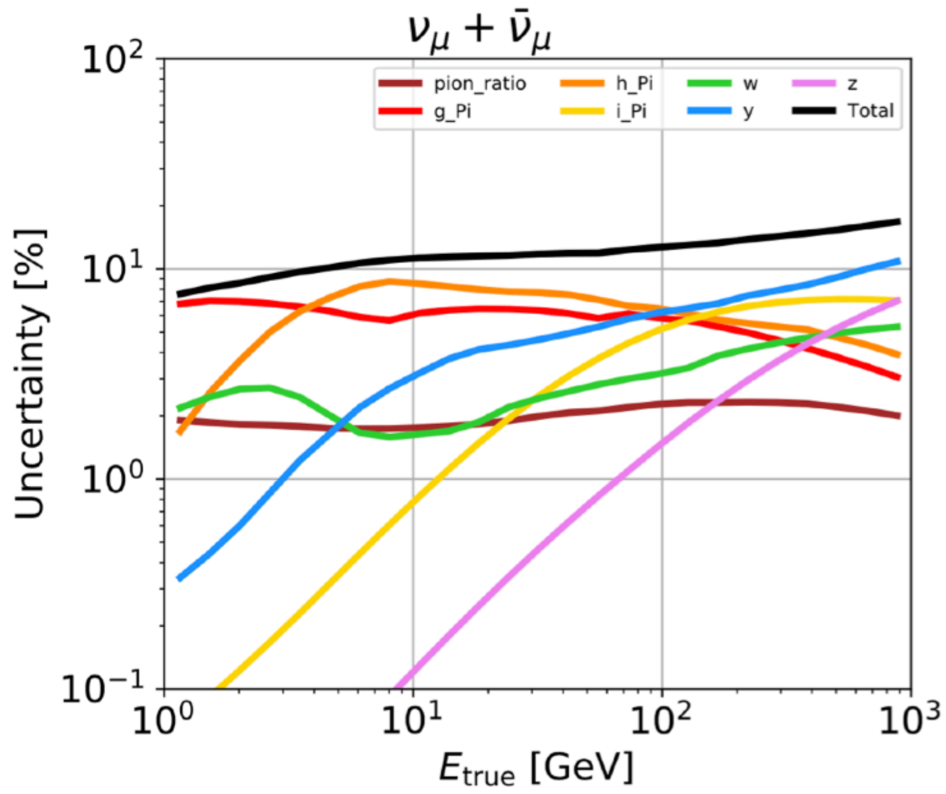
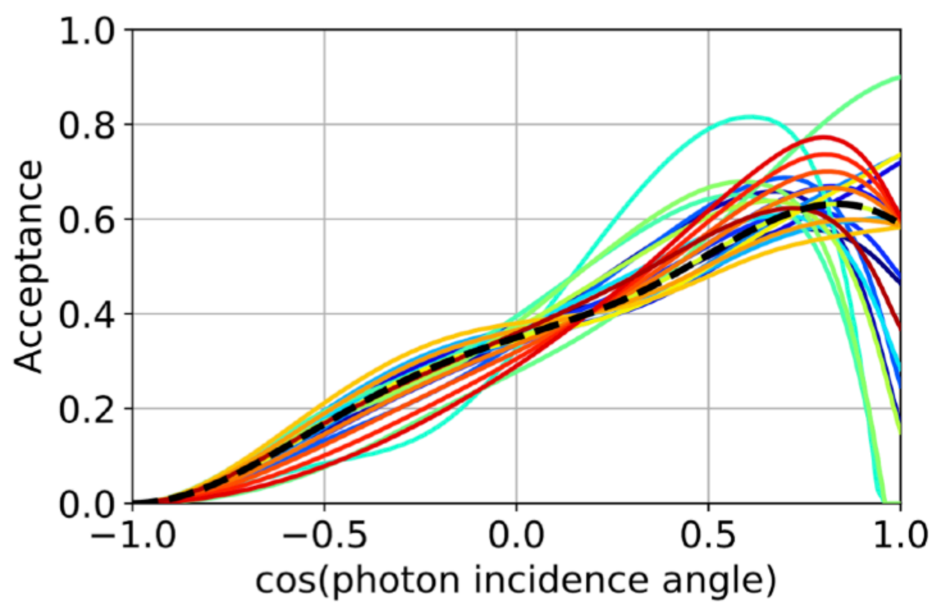


Systematic uncertainties

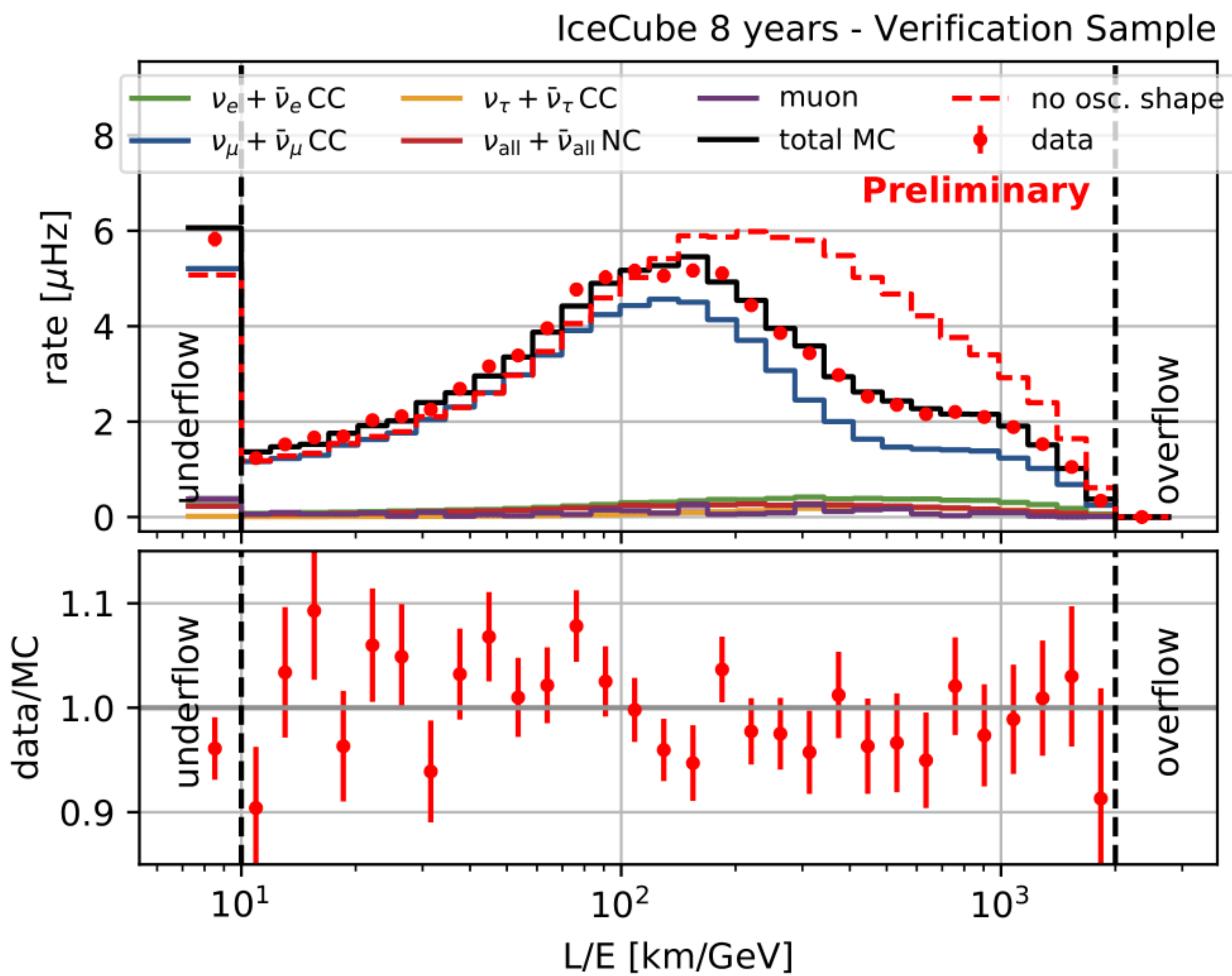




- **Flux**
  - Account for primary CR spectrum and hadronic model uncertainties
  - Use MCEq to re-compute flux with modified meson production
  - Meson re-interaction and atmospheric density variations uncertainties
- **Cross sections** → *smallest impact*
  - Axial mass uncertainty for resonance and quasielastic events
  - Continuous transformation between GENIE and CSMS DIS cross sections
  - Propagation of PDF uncertainties to DIS cross sections
- **Detector/ice properties** → *largest impact*
  - Individual charge calibration for every PMT
  - Detailed modelling of ice stratigraphy and anisotropy
  - Dedicated MC perturbing PMT and ice properties (bulk and drill column)
    - 6-D hypersurfaces fitted per analysis bin to give continuous distributions
  - Radioactive decay noise and charge calibration uncertainties
- **~40 systematic uncertainties in total**

Muon Neutrino Disappearance

- New measurement of ν_μ **disappearance with 8 years of IceCube data**
  - Uses a "**golden" sub-sample of ~23,000 track-like events**
  - Clean events with low levels of photon scattering → robust to ice modelling



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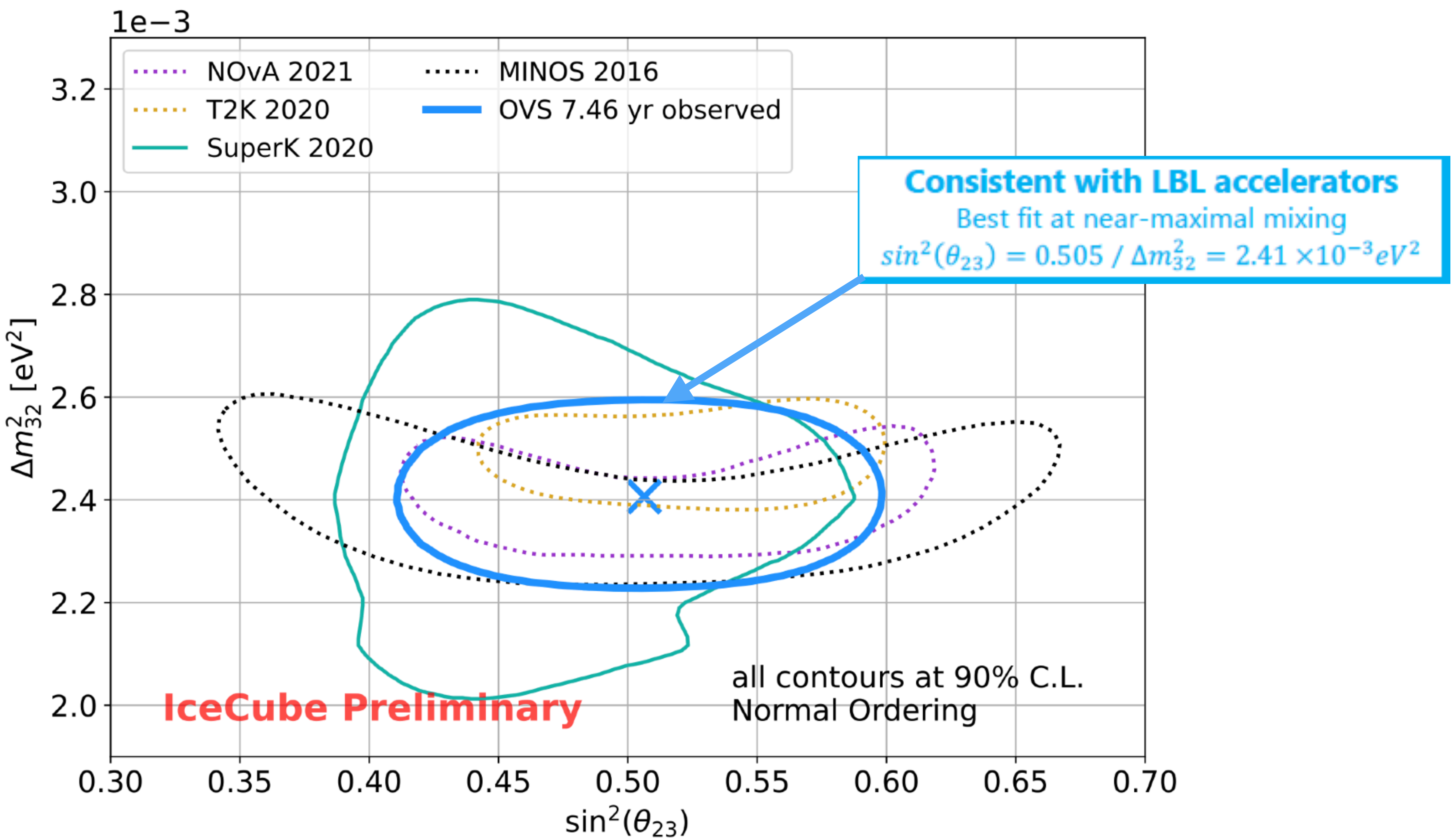
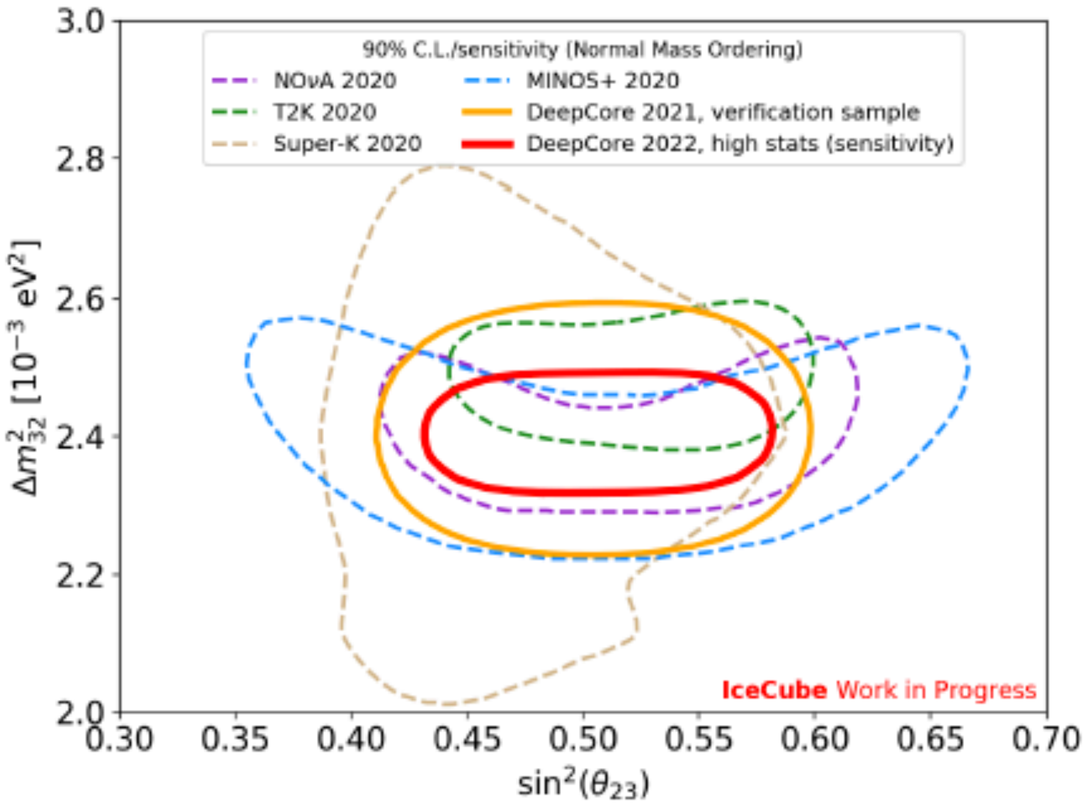


On-going analyses

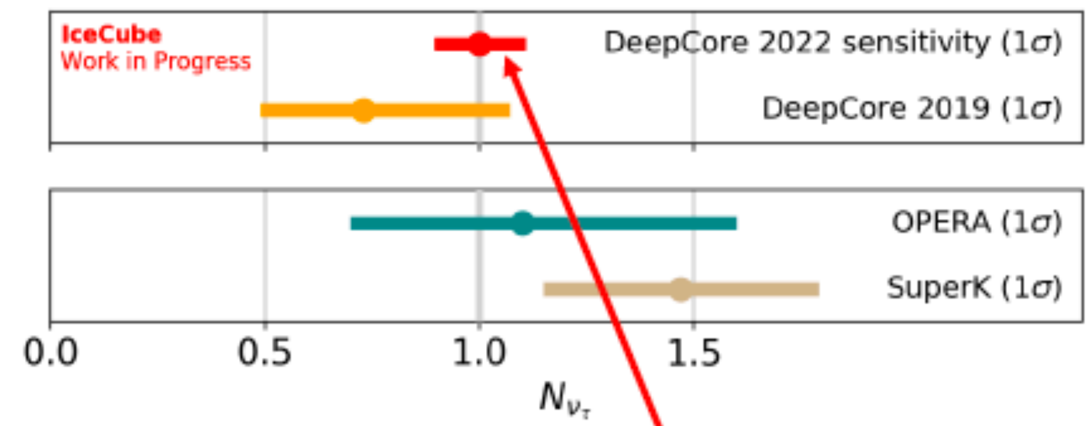
- Suite of analyses underway with a **new, high statistics data sample**
  - All flavours, state-of-the-art reconstruction and background rejection
- Observe ν_μ **disappearance and corresponding** ν_τ **appearance**

Atmospheric mixing parameter sensitivity



Sensitivity competitive with LBL accelerators
~210,000 neutrinos (0.7% background) → high stats and purity

ν_τ normalization sensitivity



Expecting world-leading 11% precision
~9,700 $\nu_{\tau,CC}$ events expected
Signal is statistical excess of upgoing cascades with suppressed cross section
Tests PMNS unitarity and $\nu_{\tau,CC}$ cross section

Non-standard interactions

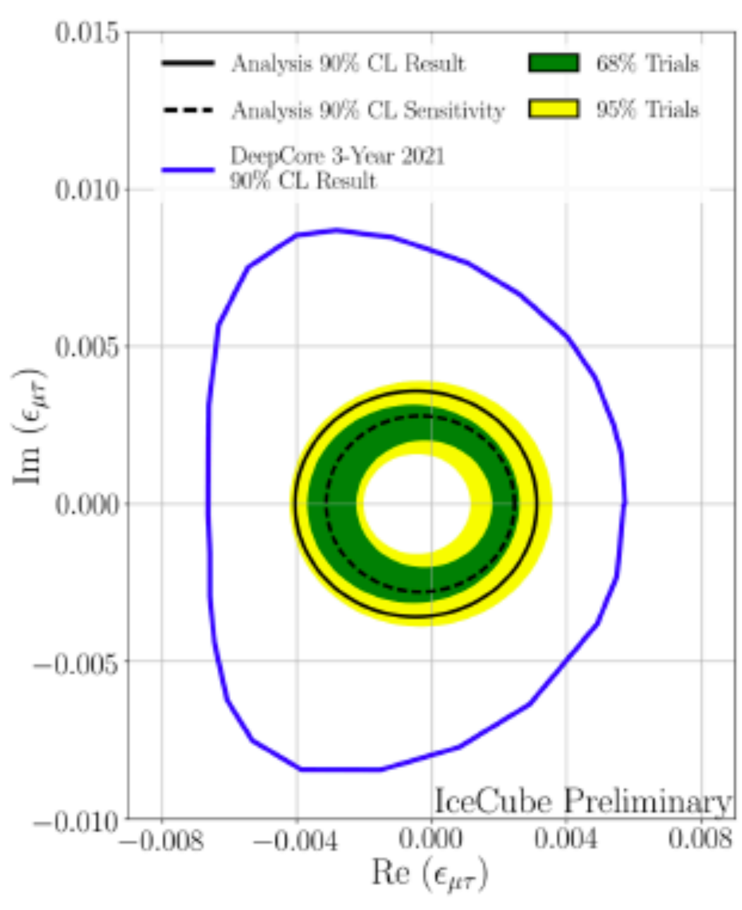
arXiv:2201.03566

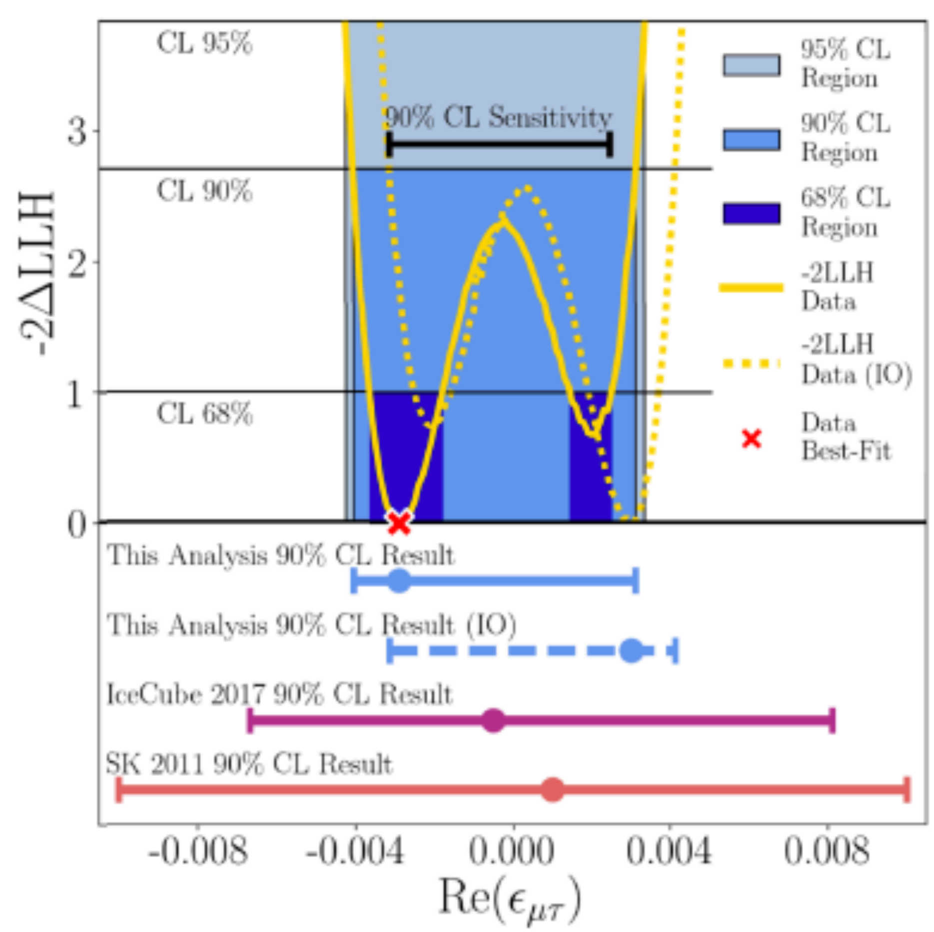
New neutrino-quark interactions could result in **additional matter effects**

Can parameterise via a **generic matter potential matrix**

$$H_{\mathrm{mat+NSI}} = V_{CC}(x)\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

- Recent NSI search using 300,000 ν_μ events in the 0.5 – 10 TeV energy range
  - Results consistent with no NSI
  - **Strong limits set on $\epsilon_{\mu\tau}$ (real and imaginary components)**



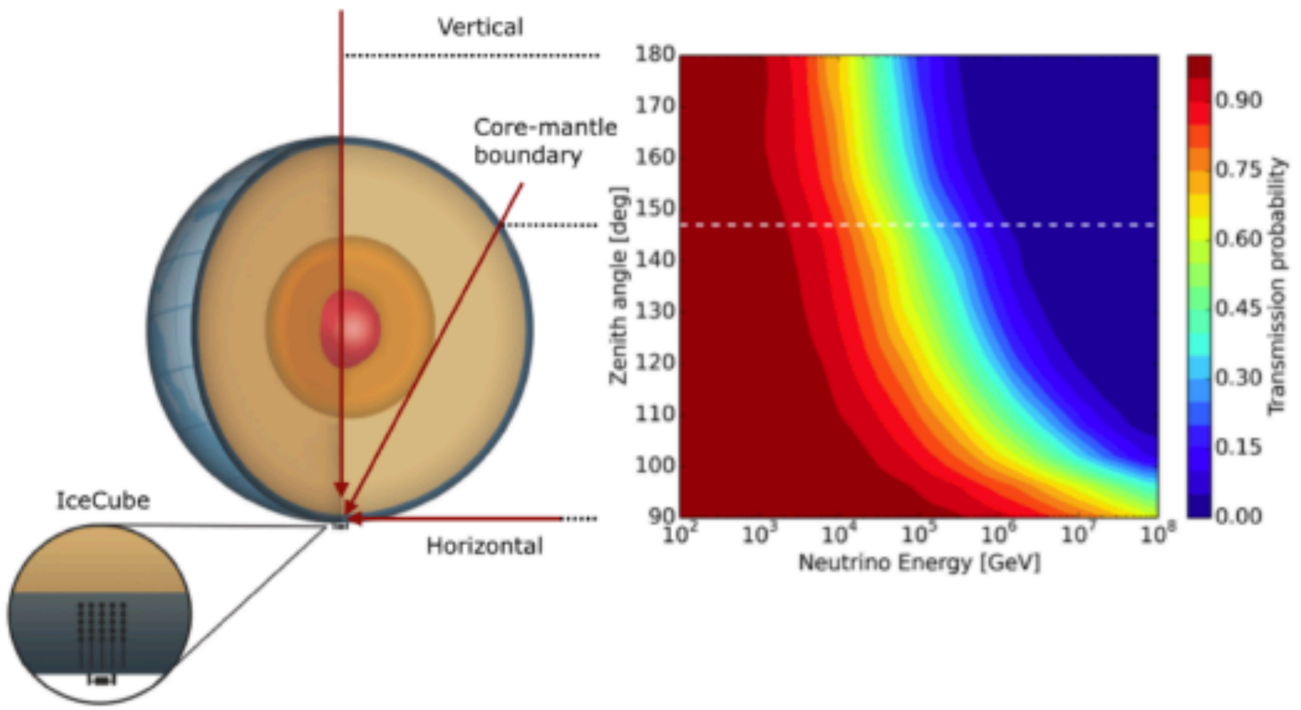


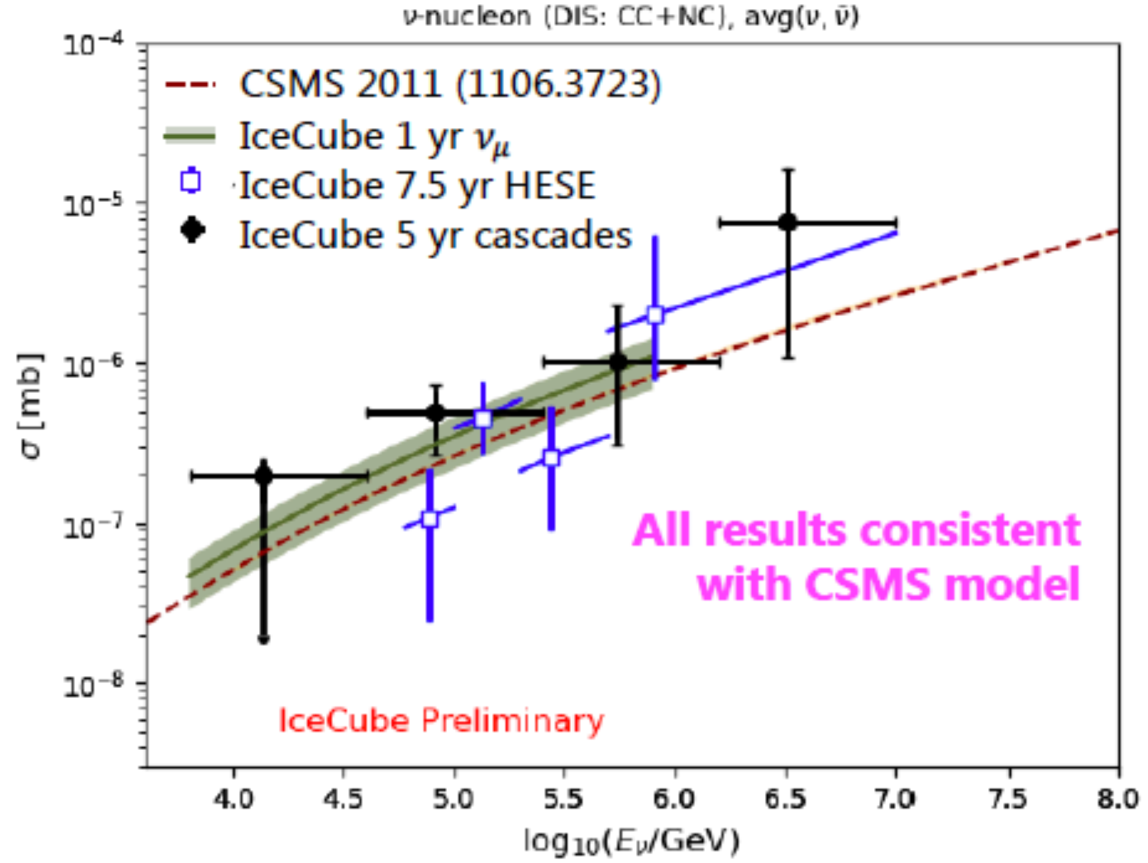
$$\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \boxed{\epsilon_{\mu\tau}} \\ \epsilon^*_{e\tau} & \boxed{\epsilon^*_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix}$$

Neutrino Absorption

Neutrino Absorption

- Absorption becomes significant for ν crossing the Earth when E $\gtrsim 10^4$ GeV
- Can measure the $\nu - N$ DIS cross section by observing this deficit
  - Orders of magnitude above accelerator measurement energies
  - Range of IceCube measurements: TeV-PeV, all flavours, CC and CC+NC





NuFact 2022
Salt Lake City, Utah, United States
July 31st – Aug. 6th, 2022
The 23rd International Workshop on Neutrinos from Accelerators
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Jian Tang (Sun Yat-Sen University, China)
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Tatsuya Kikawa (Kyoto University, Japan)
Raúl González Jiménez (Complutense University of Madrid, Spain)
WG3: Accelerator Physics
Natalia Milas (ESS, Sweden)
Tsunayuki Matsubara (J-PARC, KEK)
Kastsuya Yonehara (FNAL, USA)
WG4: Muon Physics
Yuki Fujii (University of Monash, Australia)
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WG5: Neutrinos beyond PMNS
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Richard Ruiz (UC Louvain, Belgium)
Ian Shoemaker (Virginia Tech, USA)
WG6: Detectors
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Davide Sgalaberna (CERN, Switzerland)
Nishimura Yasuhiro (Keio University, Japan)
WG7: Inclusion, Diversity, Equity, Education, & Outreach
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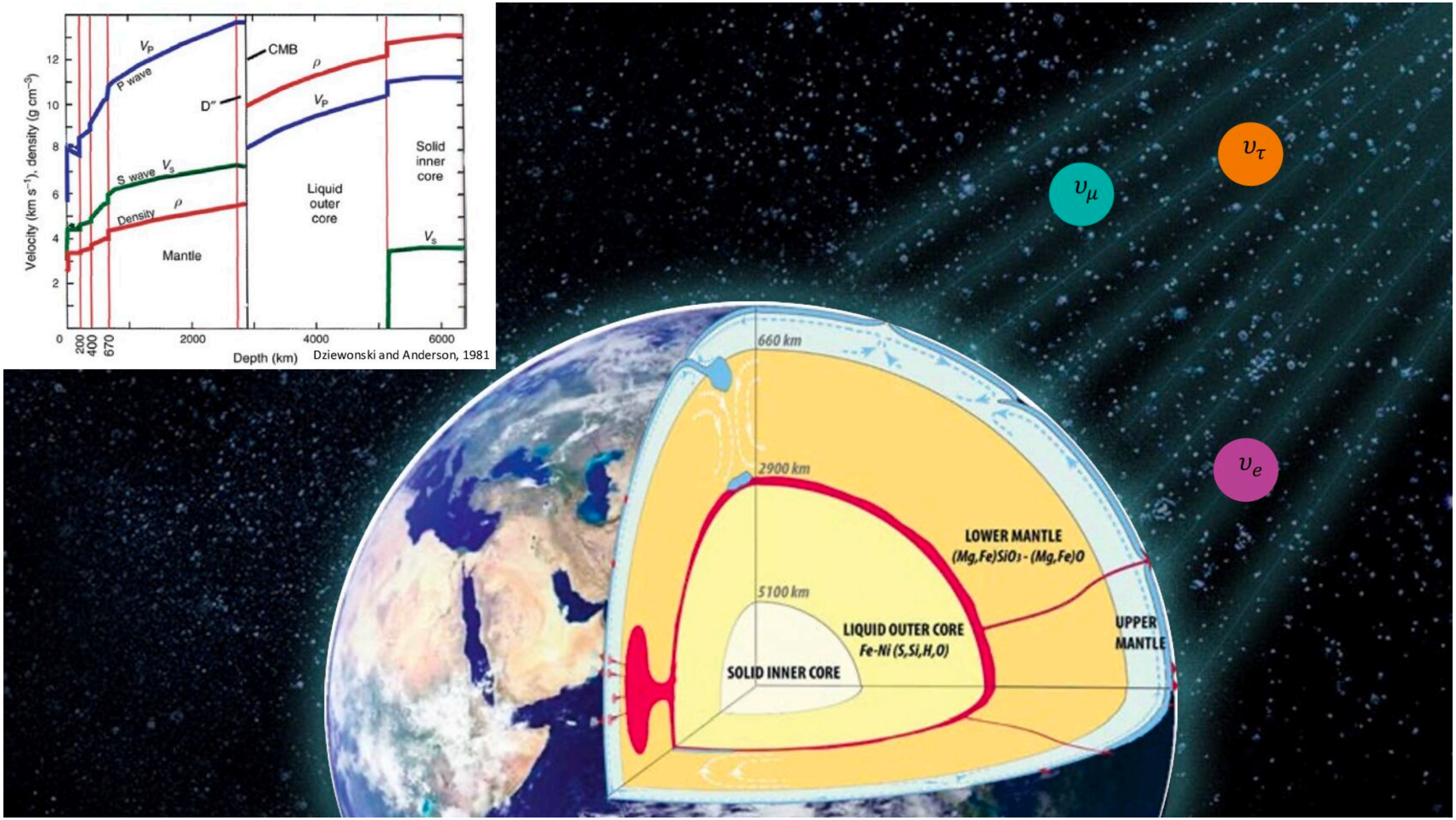
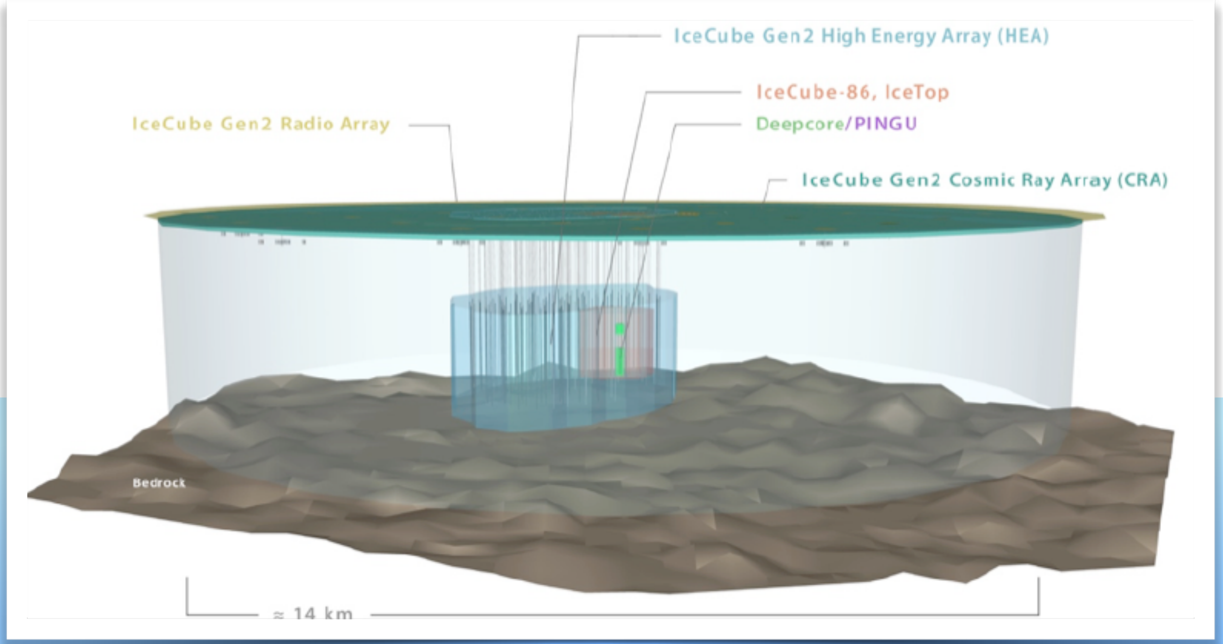
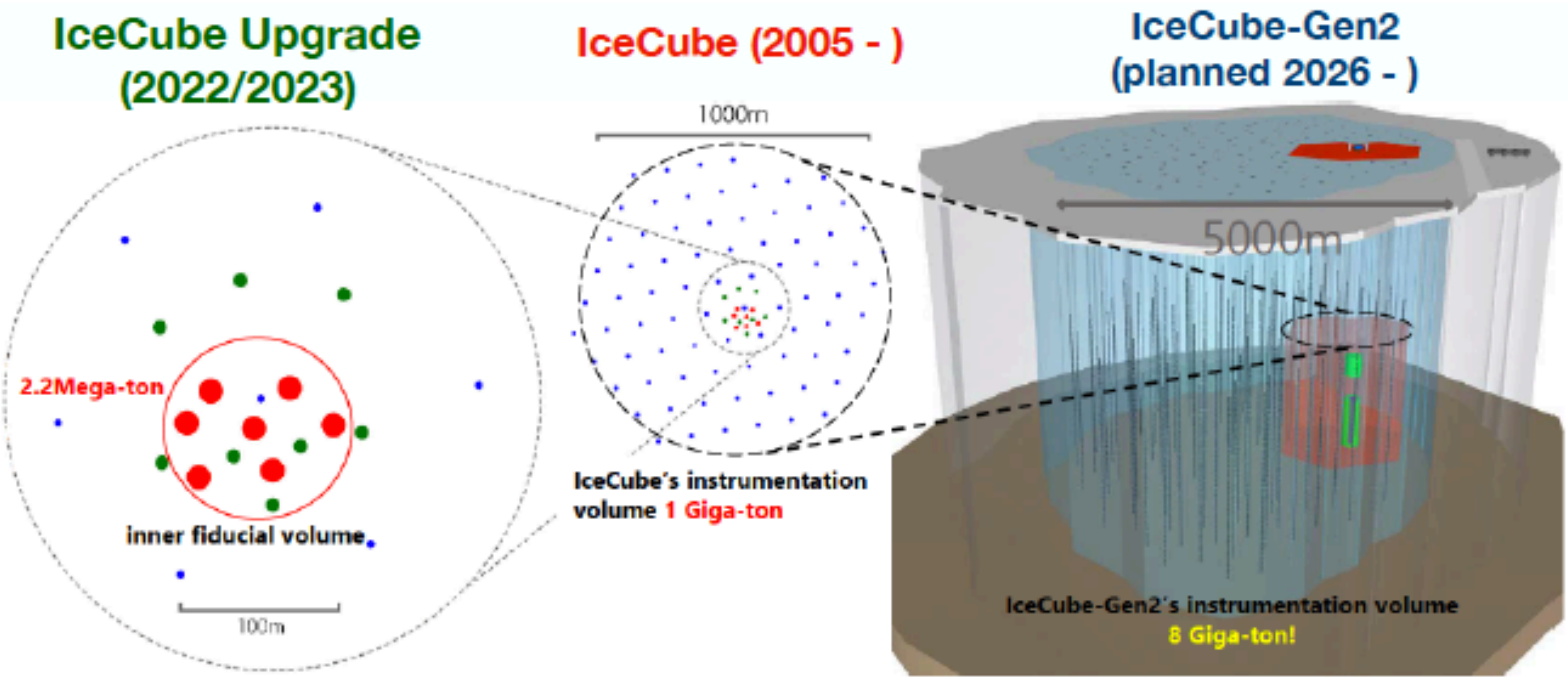


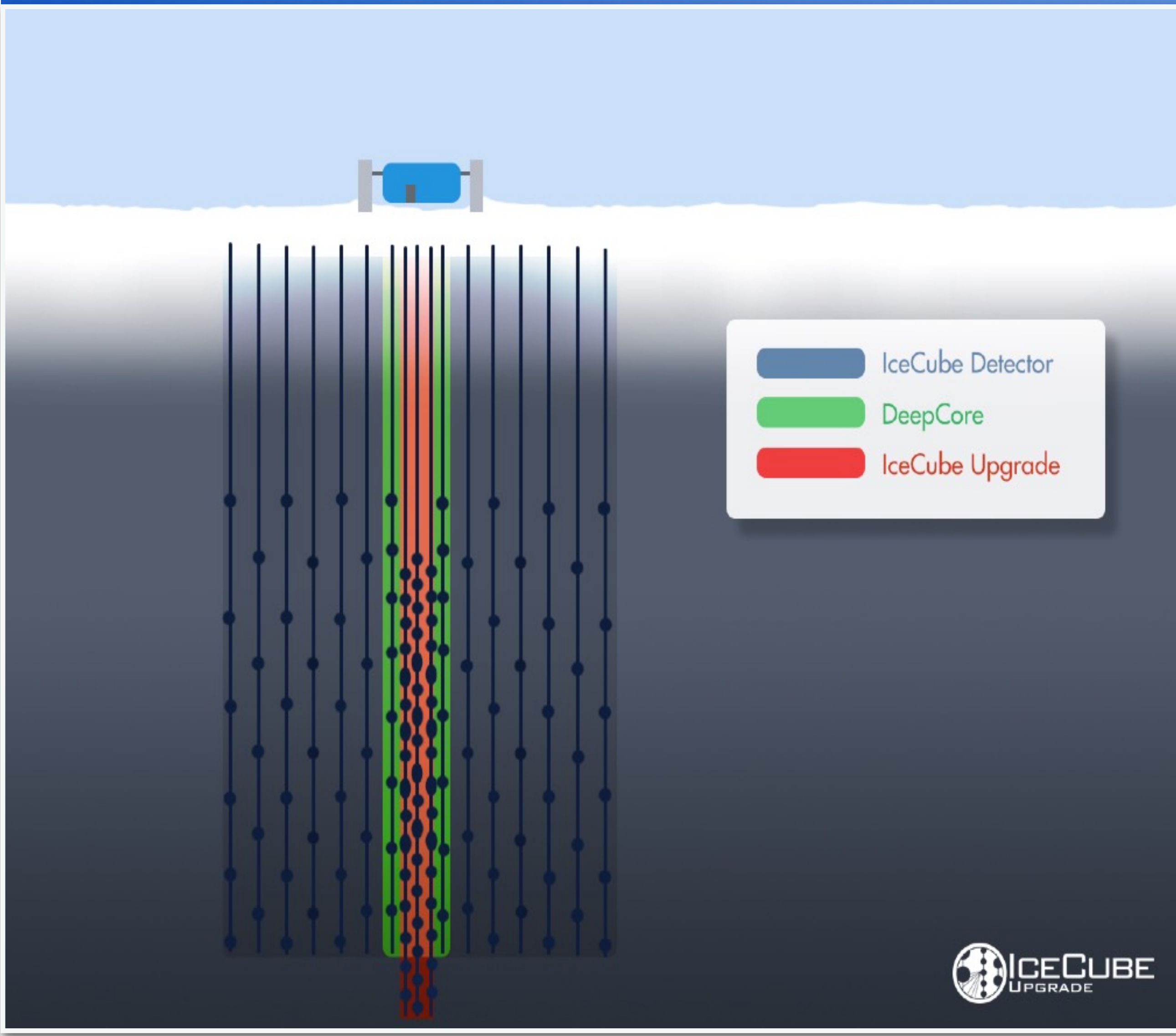

IceCube Gen2 High Energy Array (HEA)
IceCube-86, IceTop
IceCube Gen2 Radio Array
Deepcore/PINGU
IceCube Gen2 Cosmic Ray Array (CRA)
Bedrock
≈ 14 km

What's next ?



IceCube (2005 - ...)	1 Giga-ton	• Diffuse astrophysical neutrinos • Optimized for TeV Neutrinos
IceCube Upgrade (2022/2023)	2.2 Mega-ton	• GeV neutrinos, PMNS unitarity • Calibration of the IceCube detector
IceCube-Gen2 (planned 2026 -)	~ 8 Giga-ton	• Astrophysical neutrino sources • GZK neutrinos, PeV Neutrinos

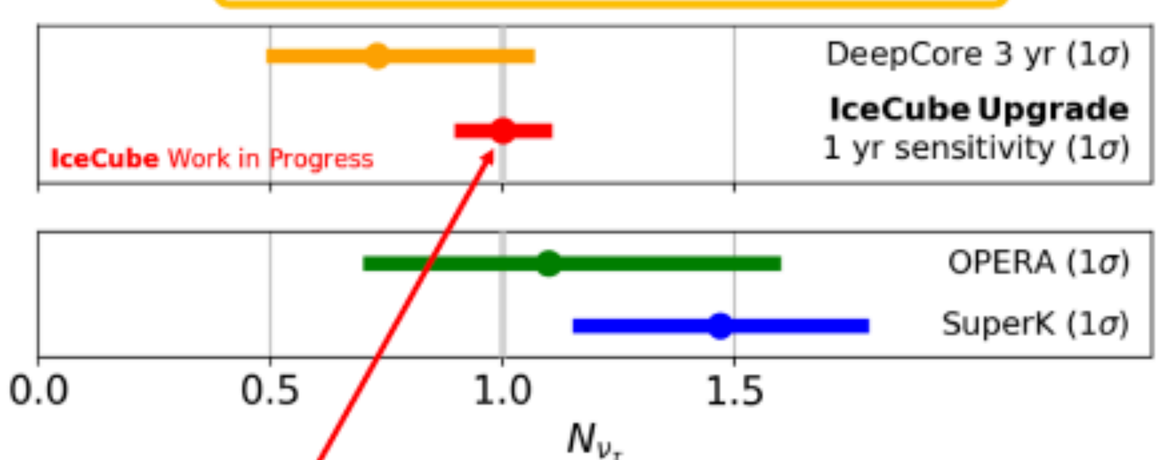
IceCube Upgrade



Science goals and objectives

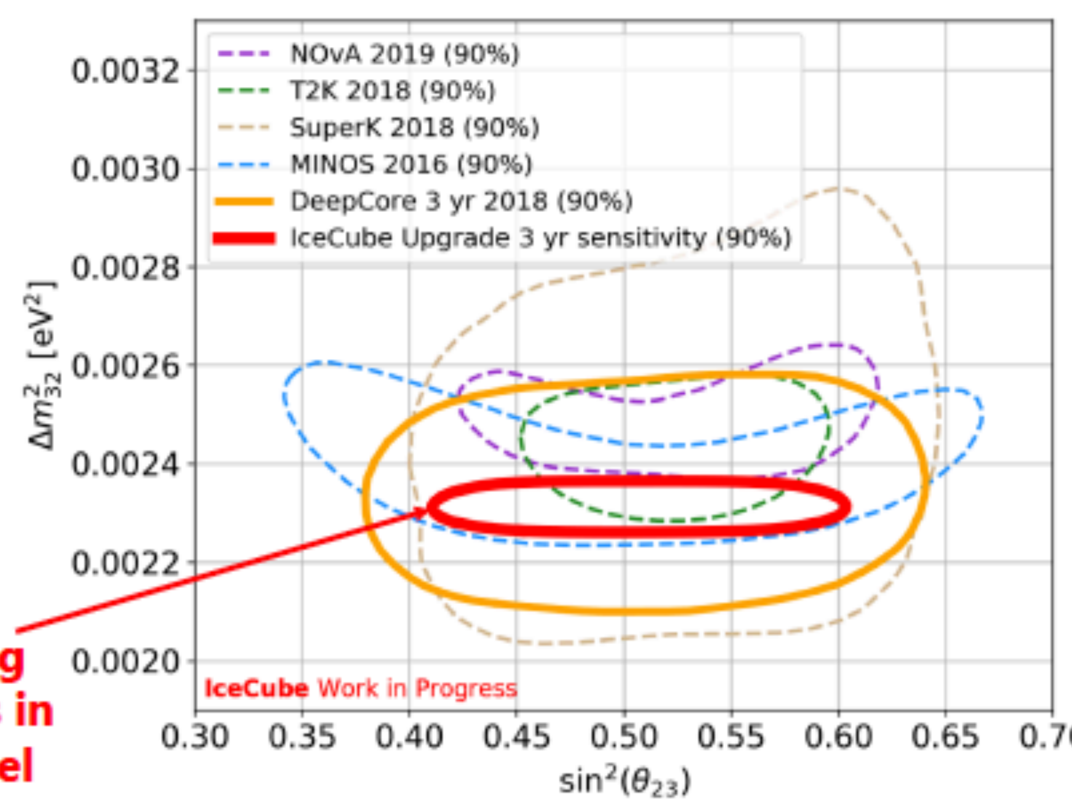
- Tau neutrino appearance - Test unitarity of the PMNS matrix
- Recalibration campaign - Retroactively apply improved ice-model to archival data (since 2010)

ν_τ appearance sensitivity (1 yr)



10% precision after 1 year
(6% after 3 years)

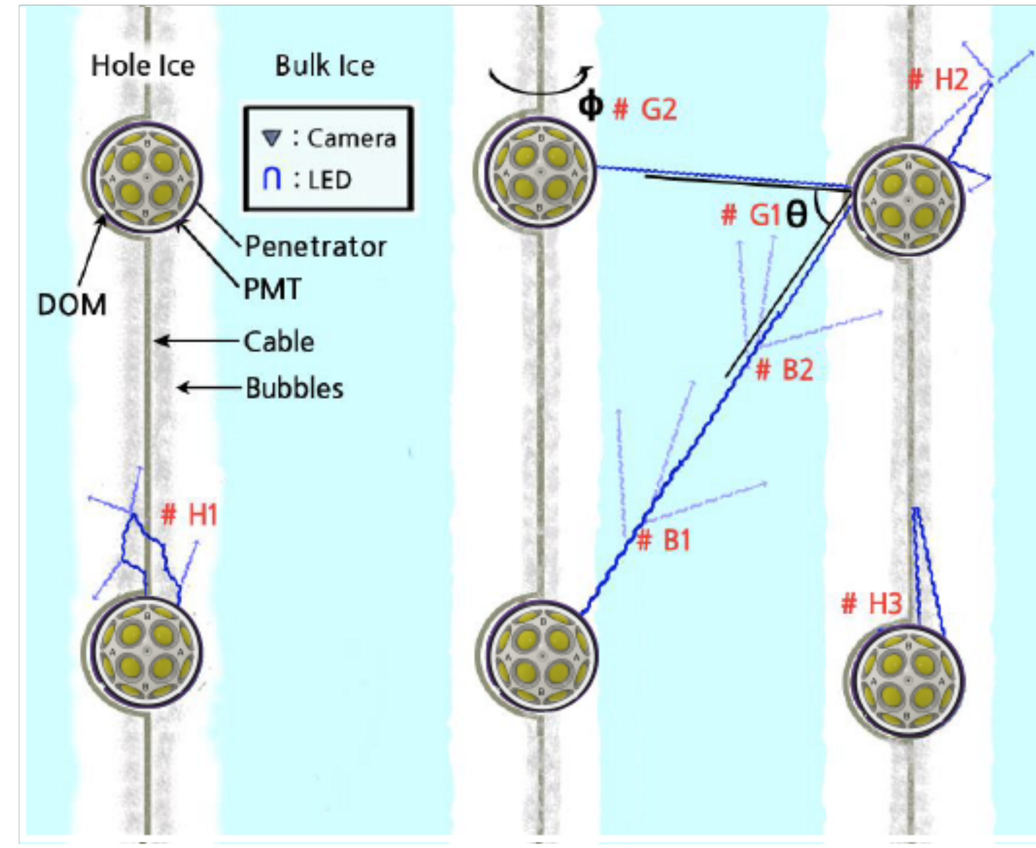
ν_μ disappearance sensitivity (3 yr)

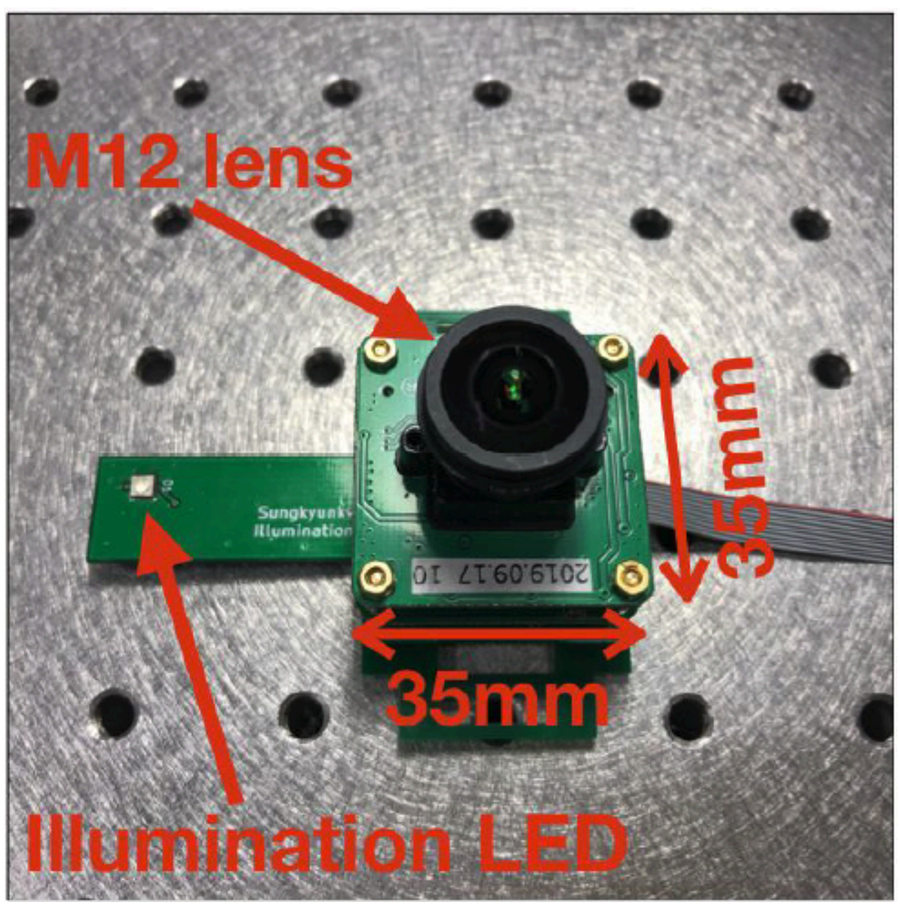


Competitive with long baseline experiments in disappearance channel

Ice Camera System

- Limited understanding of Antarctic ice properties dominant source of sys. uncertainties for most analyses
  - ⇒ better characterize detector medium
- Solution: Camera-based calibration system
  - Monitor freeze in
  - Hole ice studies
  - Local ice environment
  - Position of the sensor in the hole
  - Geometry calibration
  - Survey capability





Customized **camera module** consisting of 2 PCBs: One with the Image sensor (Sony IMX225) , M12 lens mount and lens, and second with CPLD and connectors.

Hole ice	Geometry (Positioning)	Geometry (DOM Orientation)
Mapping local hole profile (hole ice / bulk ice)	DOM position relative to adjacent DOMs	Orientation of camera DOM
Location of bubble column	Cable position	Orientation of neighbouring DOM on adjacent string
Impurities / cracks / ...		Orientation of neighbouring DOM on same string
transmission / reflection at interface hole/bulk ice		

Freeze in process	Bulk ice properties	Others
Dust / contanimants deposition on the surface	Measurement of scattering length	Survey capability
Formation / crushing of bubbles /degasing worked ?	Measurement of absorption length	
Formation of cracks	Hole/Bulk ice interfaces	
Triboluminescence	Anisotropy of light propagation	

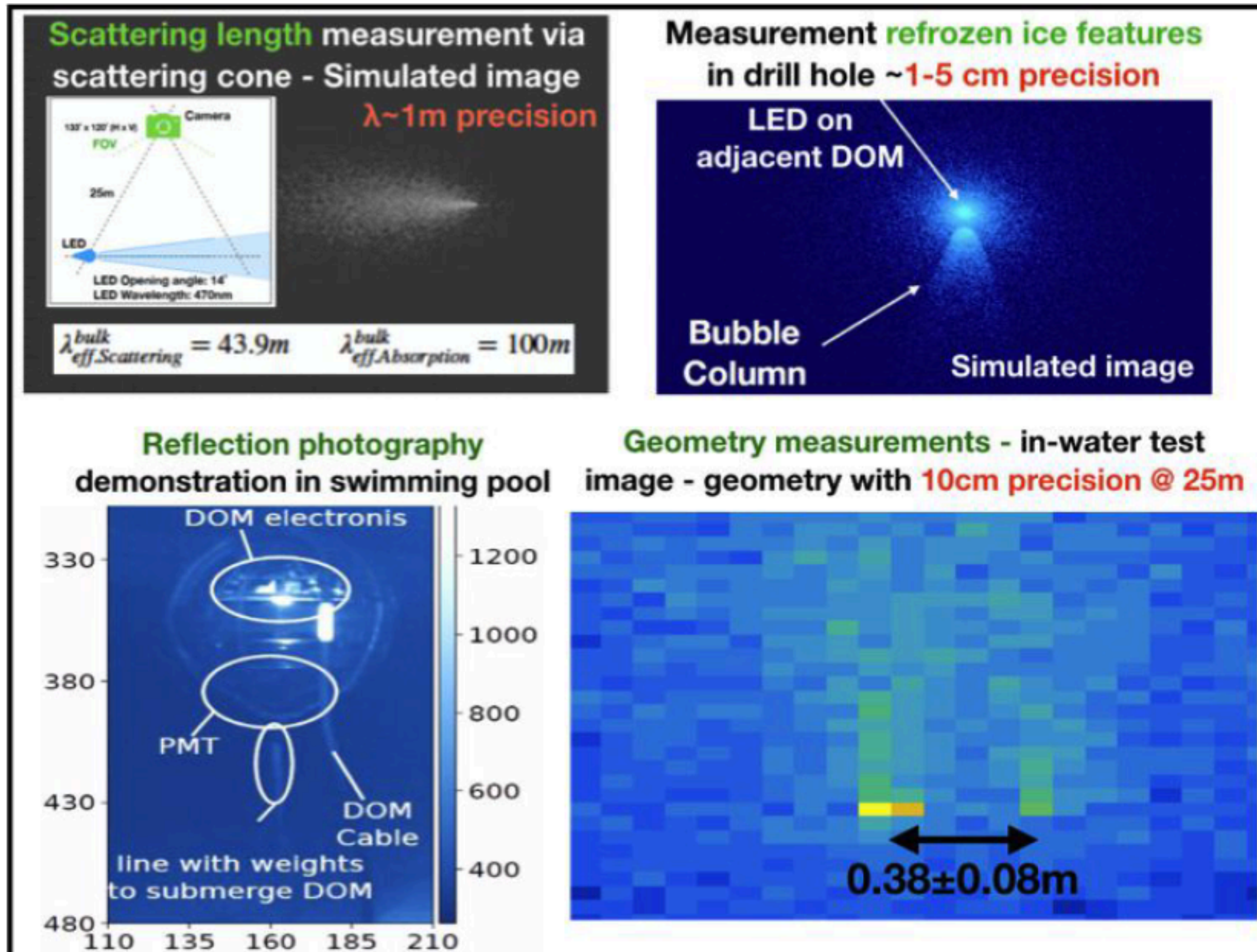
Complementary
Important
Highest Priority

Camera sensitivity and Field Test

Work at local high school swimming pool on IceCube camera system testing

Swimming pool at Gyeonggi Physical Education High school

Demonstrated camera abilities in dedicated simulations and lab tests (incl. swimming pool measurements)



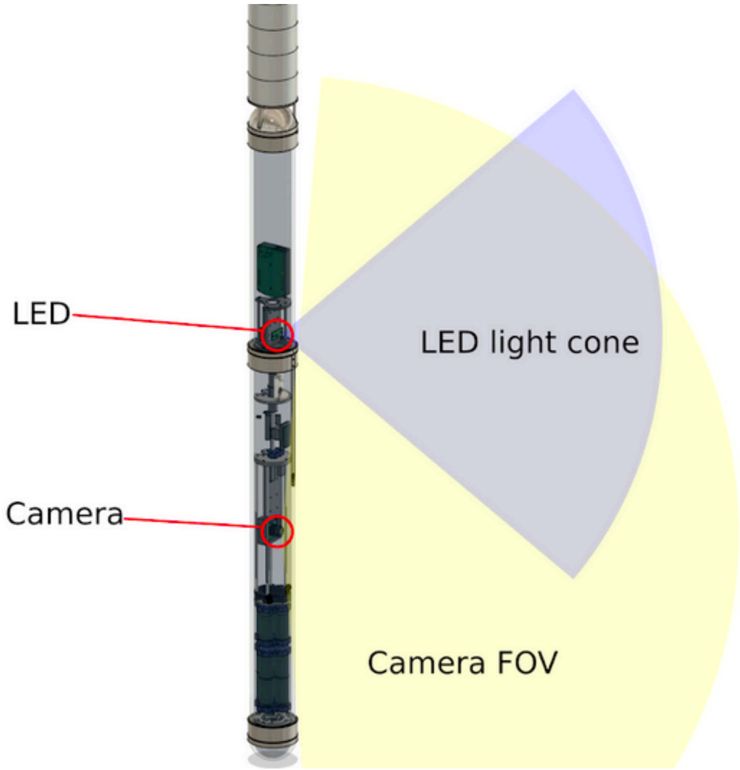
- Verified successful operations under polar conditions and demonstrated ability to measure ice properties with cameras
- **Camera system successfully passed IceCube Internal Final Design Review (FDR) in September 2019**

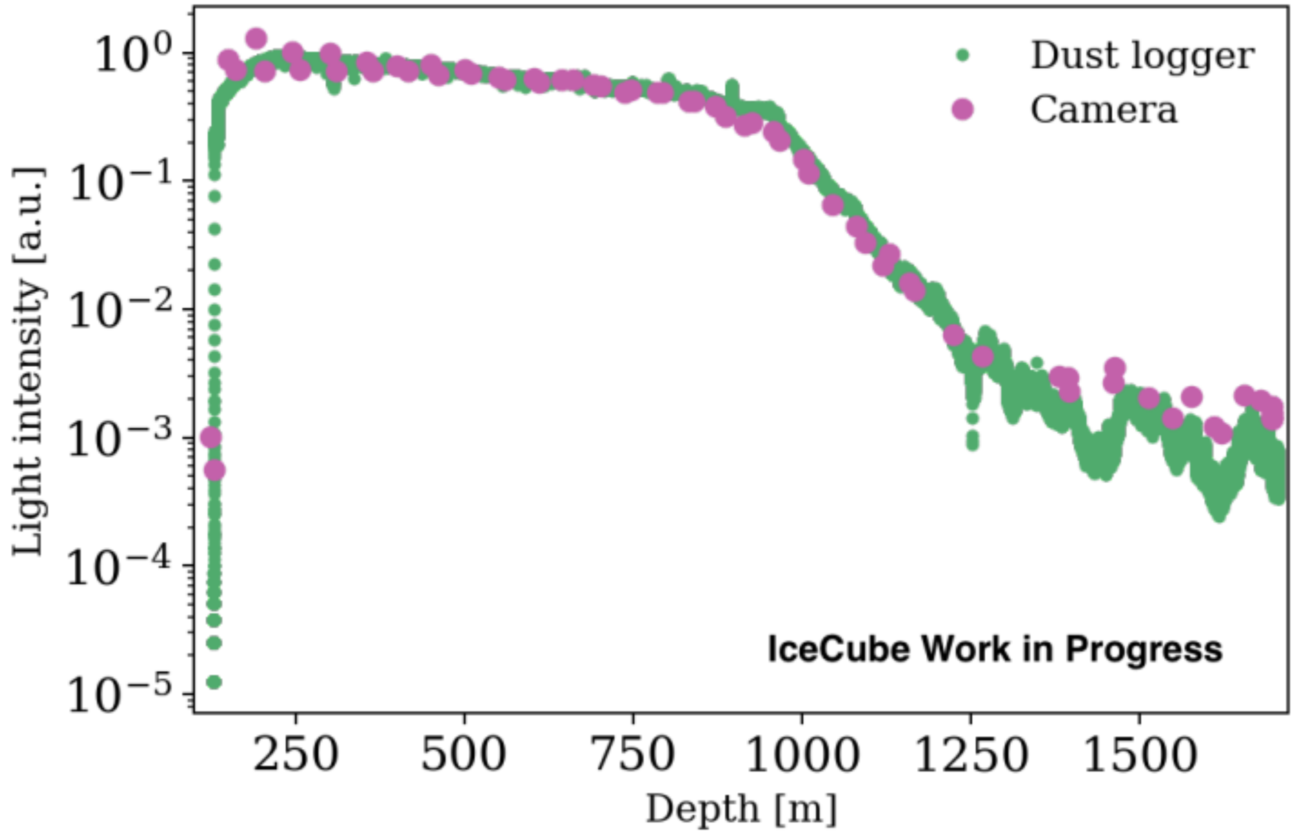
Camera sensitivity and Field Test

Successful South Pole Deployment of Test System

PoS(ICRC2019)926

- After the main deployment of the Luminescence logger a ICU camera and an LED used for the ICU camera system were installed in the logger
- The camera was installed on a special holding structure where the mirror of the logger would otherwise be
- The LED is installed below the RED pitaya pointing in the same direction as the camera
- The distance between LED and camera is 38.5cm
- The camera measures the backscattered light from the LED
- From the distribution and amount of light, we expect to estimate the scattering length in ice

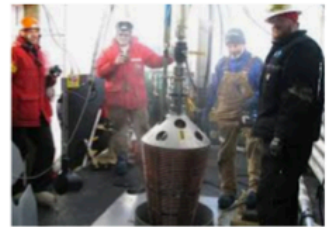




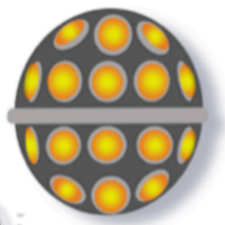
Group photo after successful passing of the camera preliminary design review (Madison May 2019)

Novel calibration system production lead by SKKU group

South Pole Operations



mDOM



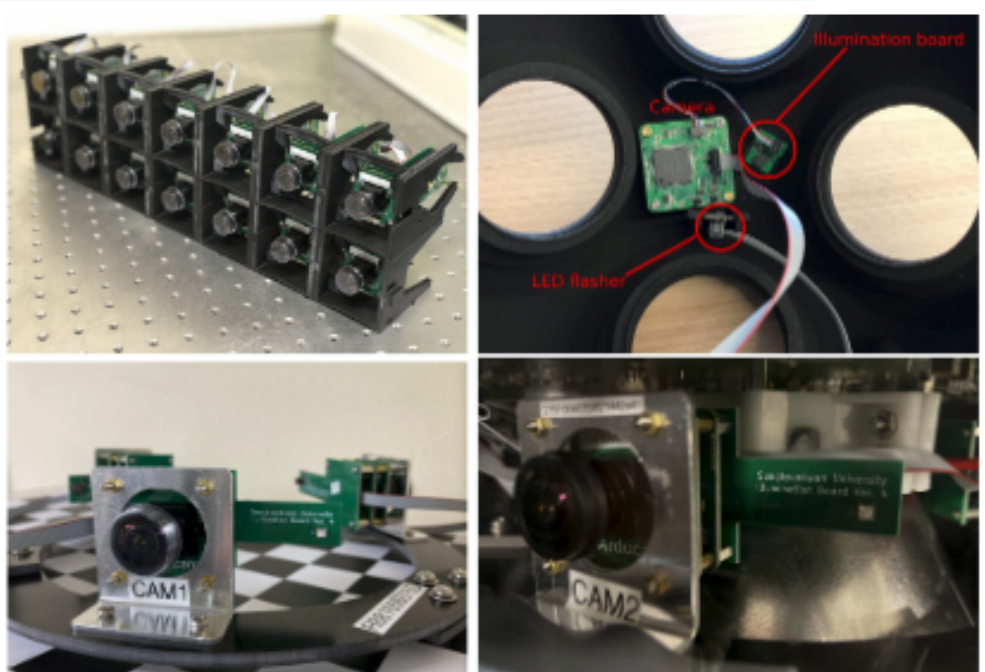
~650 sensor modules

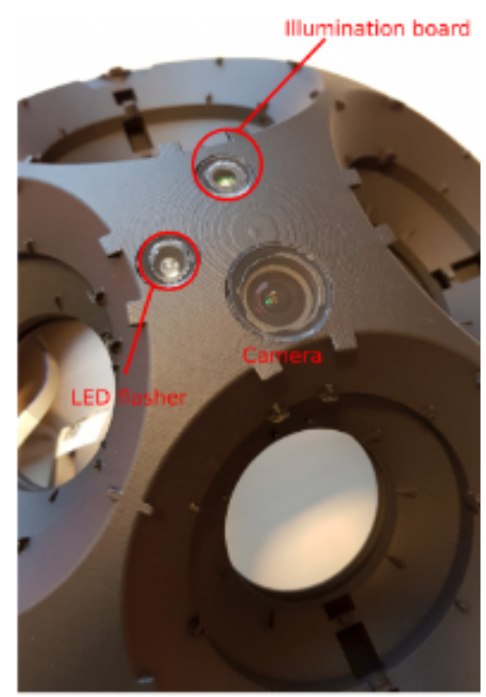
D-EGG

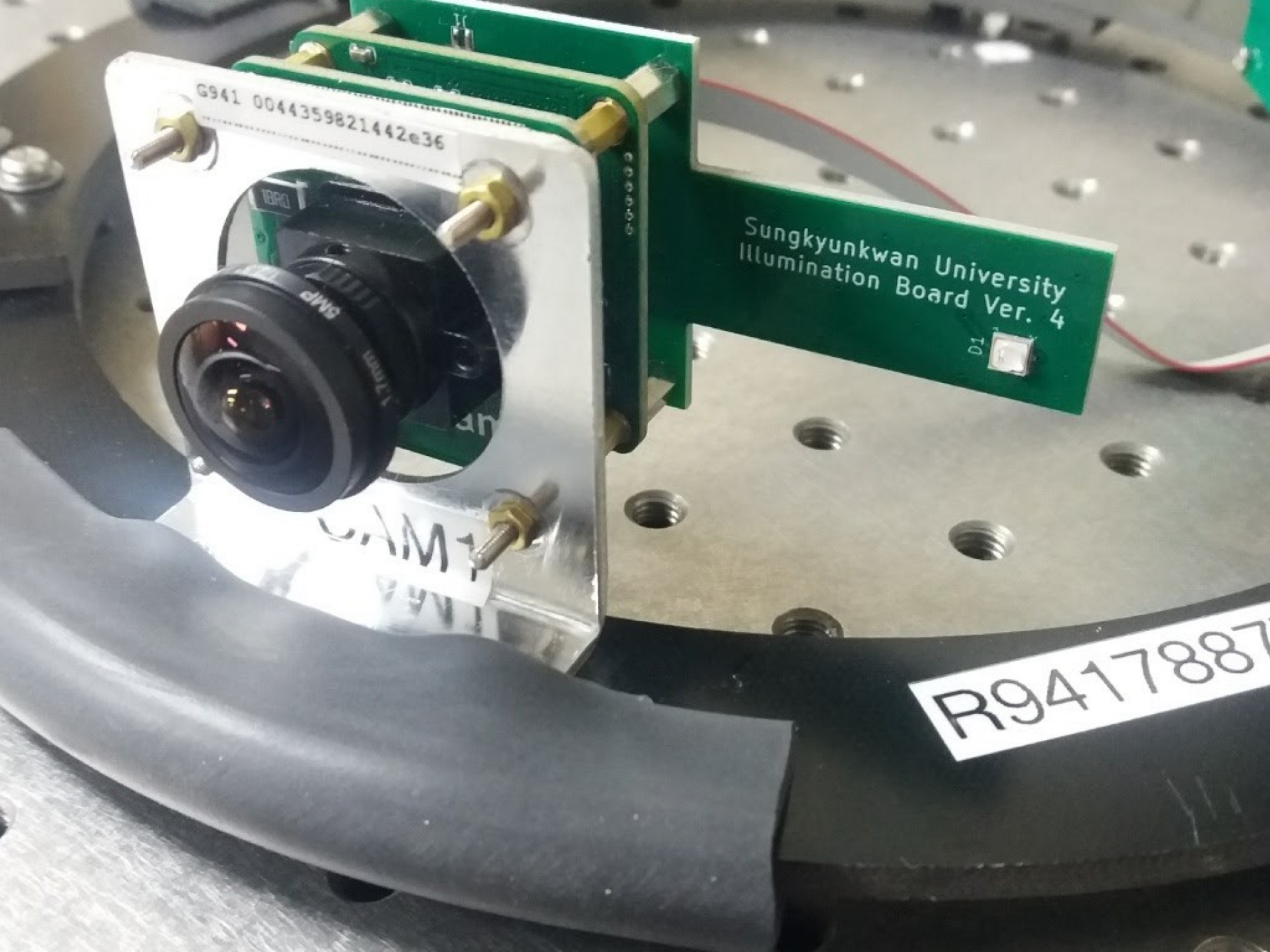
Novel calibration

~3 camera systems / module

Graduate student Jiwoong Lee (left) assembling mDOM cameras with trainee undergraduate assistants Youbin Oh (right, front) and Minji Shin (right, back). Inset shows a box being packed with camera-LED systems protected in ESD bags.



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Current status of camera production

- IceCube Upgrade deployment has been moved to 2024/2025 due to COVID-19 accessibility to pole
- Camera production well within the schedule to meet all the production and testing targets
  - D-EGG cameras integrated ~900 cameras
  - mDOM cameras tested and or shipped to production centers ~ 650 cameras
  - mDOM cameras remain to be tested at SKKU ~ 500 cameras

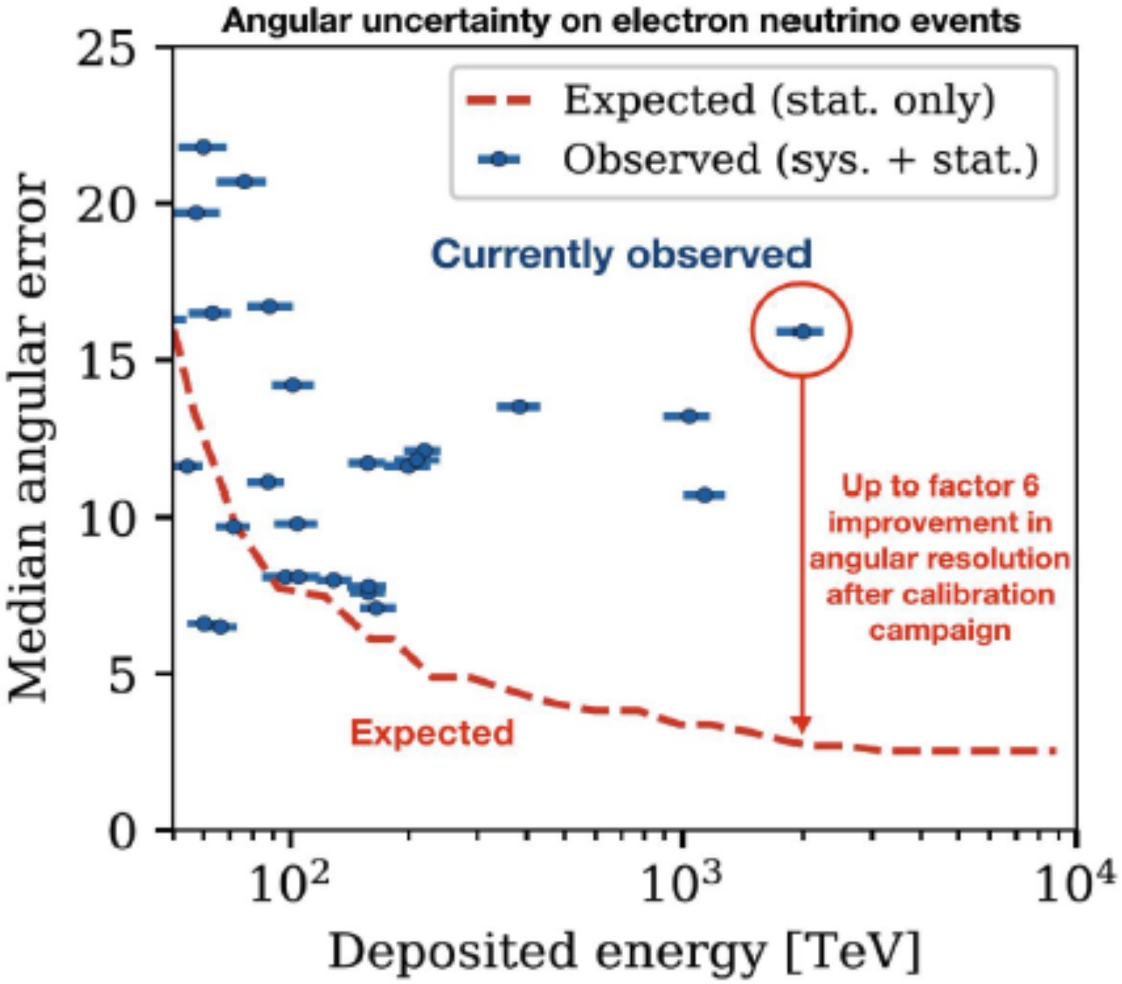
Camera status July 2022

Cameras that are at SKKU and are undergoing testing and calibration measurements

Cameras completed testing and shipped to integration centers or awaiting shipping

Cameras integrated in IceCube Upgrade optical modules

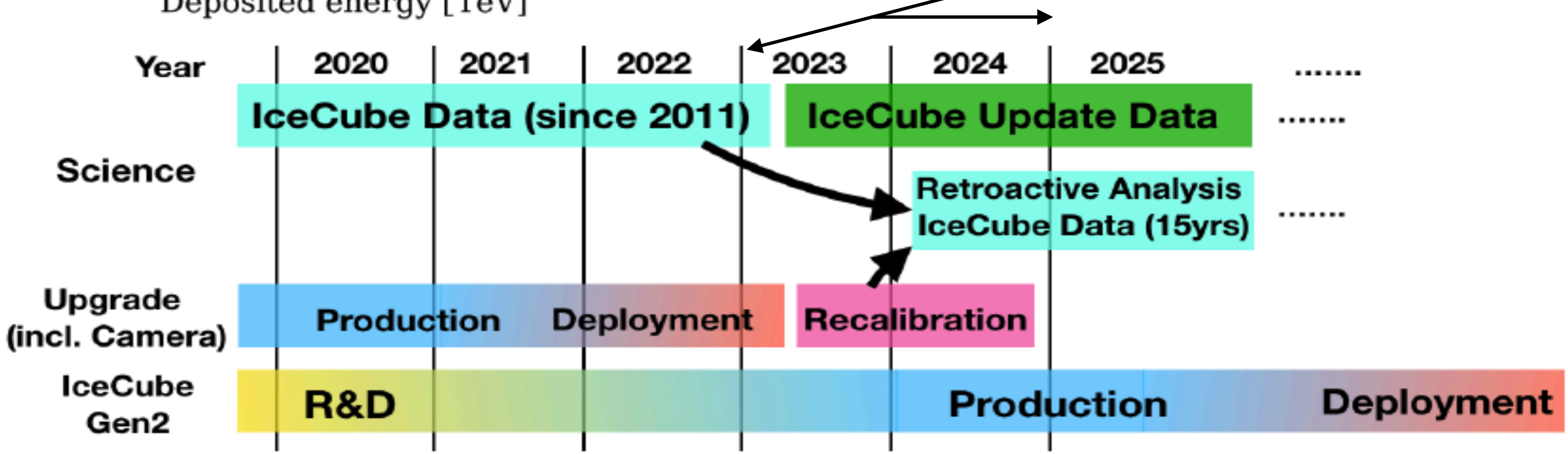
Camera system impact



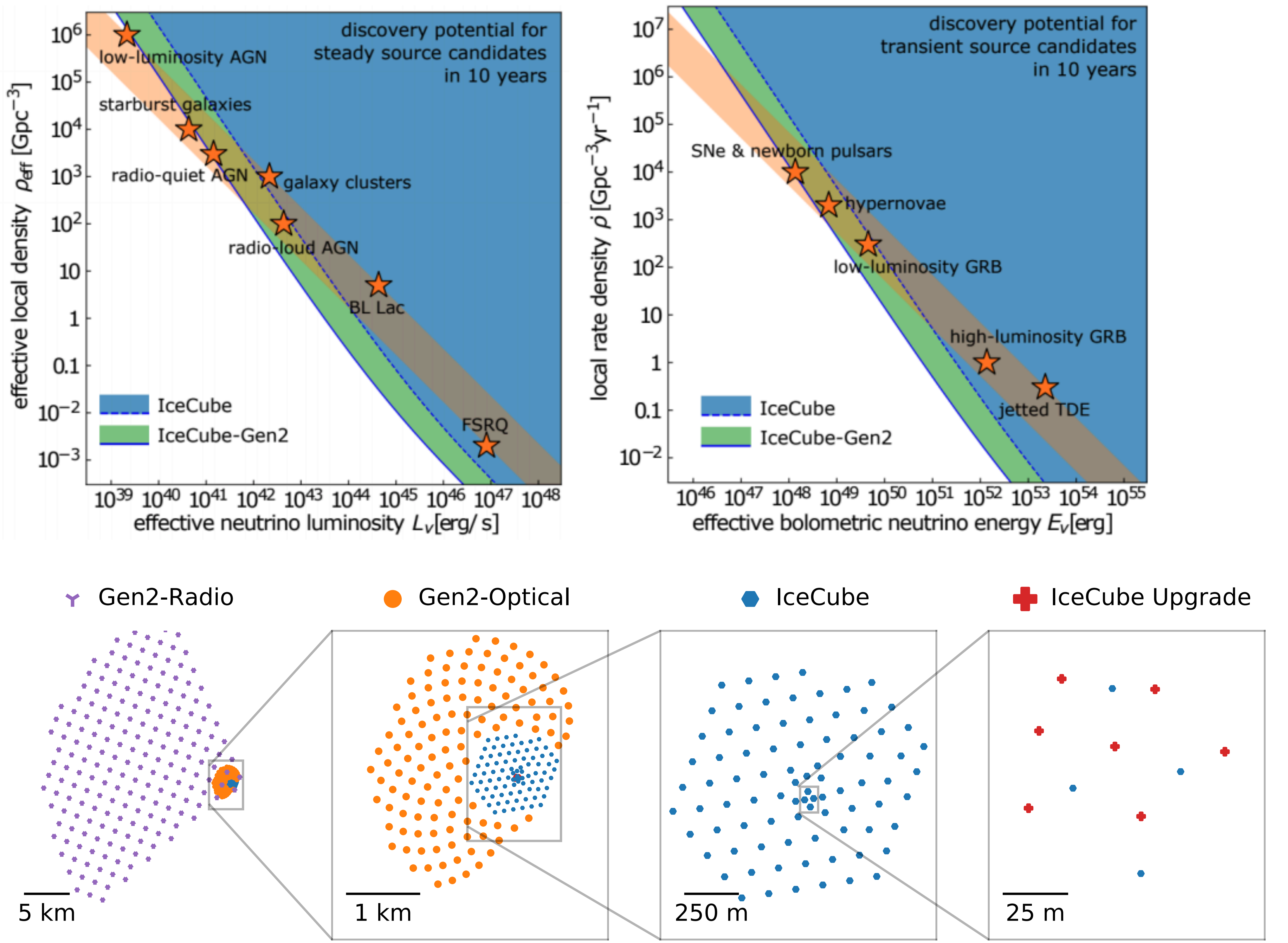
Camera system key to comprehensive understanding of the detector medium

- ***Science multiplier*** Retroactively analyze more than 15 years of IceCube data with substantially improved angular and energy resolution
- ***Improved neutrino event pointing*** critical for multi messenger science

Upgrade deployment delayed by two years due to COVID-19

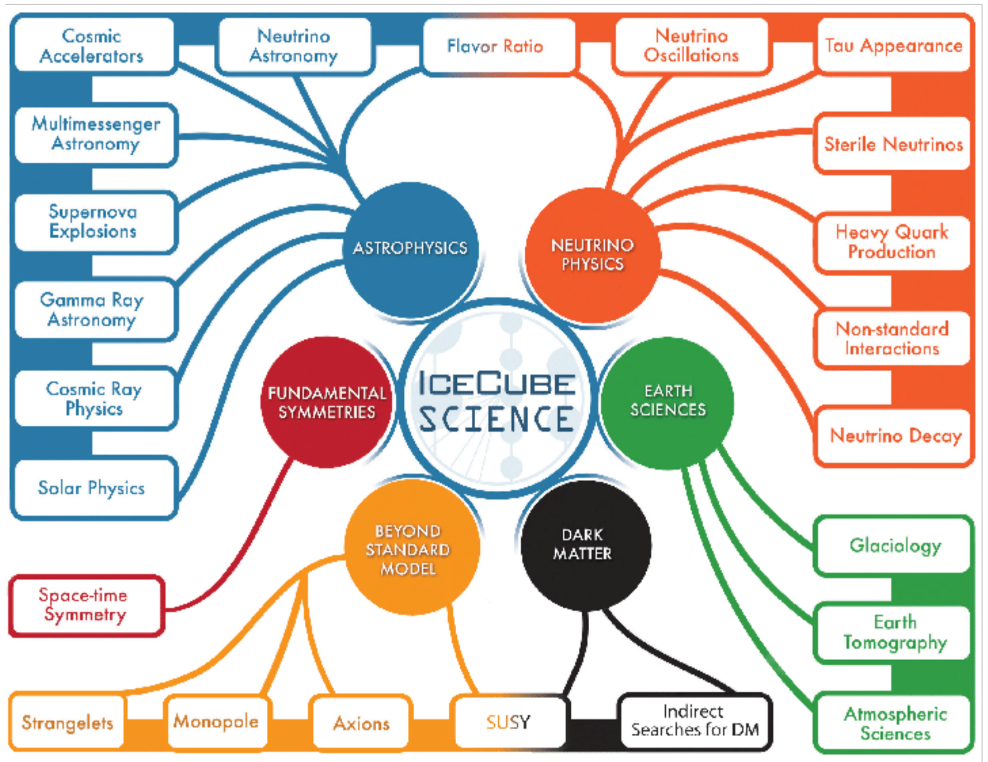


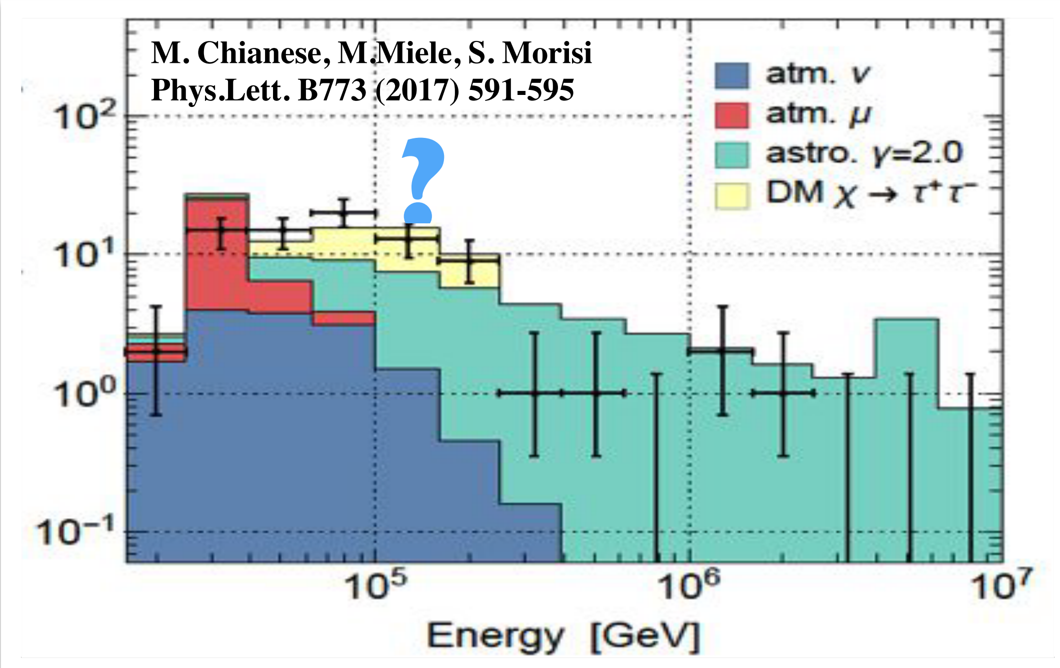
IceCube-Gen2



Complementarity & Outlook

- Neutrino Telescopes are discovery experiments, exploring the unknown, with a tremendous potential for BSM physics searches
  - Guaranteed science for dark matter searches & discovery potential
  - Observed astrophysical neutrino spectrum remains to be understood
    - Guaranteed discoveries, including potential to observe dark matter
  - BSM physics searches at neutrino telescopes come at essentially no additional costs (highly leveraged)
  - Independent from direct detection or other indirect searches
  - Rapidly evolving field that can provides unexpected new opportunities (example observation of new astrophysical sources or transient events)





High-energy astrophysical neutrino flux can only be understood with significantly higher event statistics (x10)

Conclusions

- Striking signatures provide high discovery potential for indirect searches for dark matter with neutrinos
- Stringent limits on dark matter self-annihilation cross section set using neutrino telescopes
- Lifetimes of heavy decaying dark matter has be constrained to 10^{28}s using neutrino signals
- Neutrino Telescopes/Detectors provide world best limits on the Spin-Dependent Dark Matter-Proton scattering cross section
- A new neutrino floor for solar dark matter searches has been calculated and might be observable in the near future
- Efforts underway to expand searches beyond WIMP hypothesis