PHYSICS ANALYSES
IN ICECUBE

Alex Pizzuto

*With many slides stolen from WG summaries and
from Kayla Leonard DeHolton's talk from last year

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

WIPAC
WISCONSIN ICECUBE
PARTICLE ASTROPHYSICS CENTER

*PC: Yuya Makino,
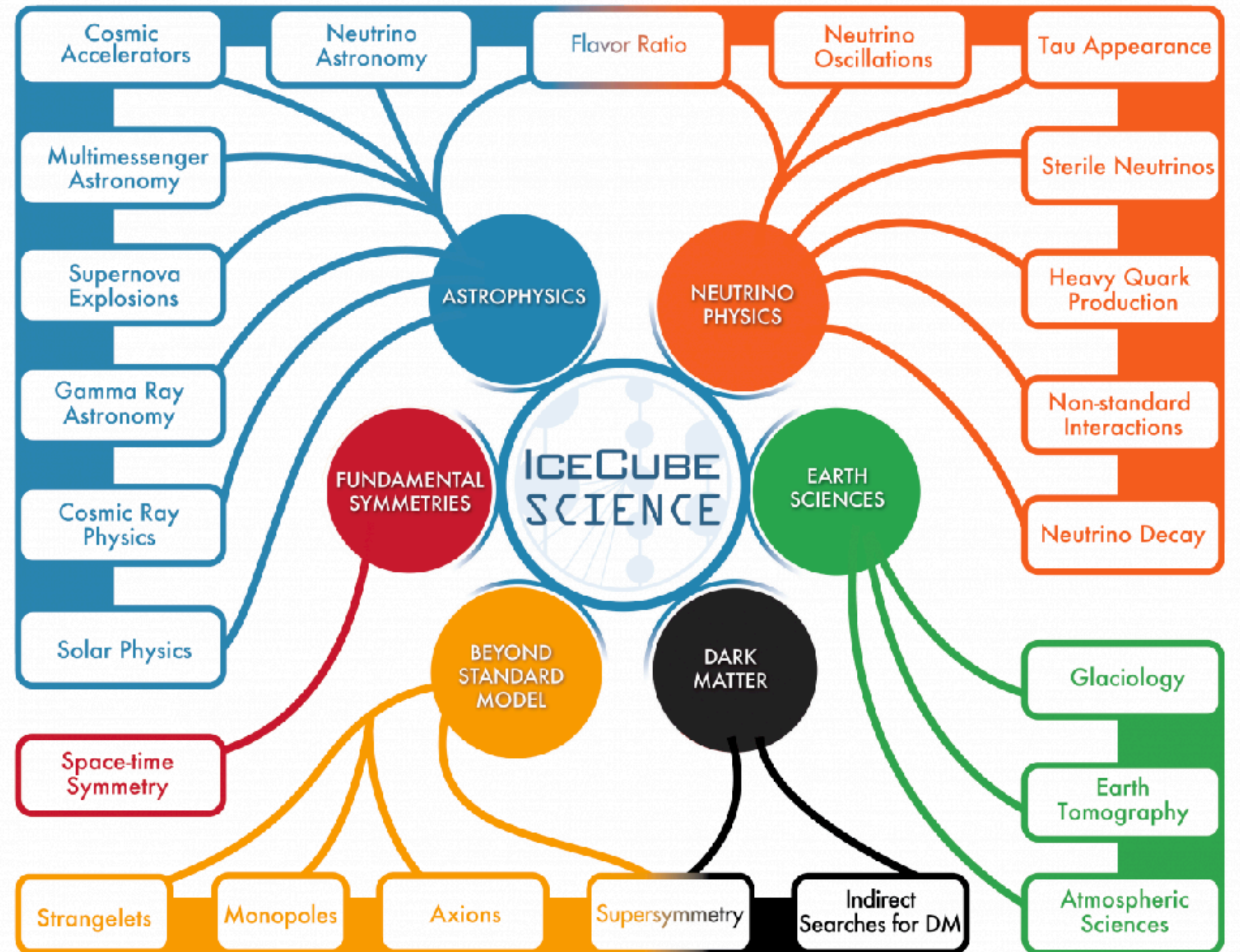IceCube Collaboration*

OVERVIEW

❯ Working groups

- ✦ What they are

- ✦ Software they use

- ✦ Commonly discussed analyses ("What's a HESE??")

❯ How to do your own analysis

- ✦ Getting started

- ✦ Unblinding

- ✦ Writing a paper in IceCube

IceCube Science

> **IceCube does A LOT of science**
> - ✦ It isn't feasible for all few hundred of us to hear about every step of every person's analysis

> **Large physics goals are broken into "working groups" (WGs)**
> - ✦ Working groups are the subsets of folks you'll interact with more frequently
> - ✦ When you have an update you want to show, you'll start to do these in your working group calls

> **Working groups answer different types of questions**
> - ✦ Analysis WGs: High-level physics analyses
> - ✦ Technical WGs: Technical projects
> - ✦ R&D WGs: Planning for Upgrade, Gen2, etc.

> **Analysis, Technical, and R&D WGs work together**

ICECUBE WORKING GROUPS

Analysis		
Oscillations	(calls)	(mail)
Cosmic rays	(calls)	(mail)
Diffuse/Atmospheric ν	(calls)	(mail)
Supernova	(calls)	(mail)
Beyond the Standard Model	(calls)	(mail)
Neutrino Sources	(calls)	(mail)

Technical Working Groups		
Reconstruction and Systematics	(calls)	(mail)
Realtime	(slack)	(mail)
Calibration	(calls)	(mail)

Detector & Simulation	
Simulation	(mail)
Simulation Production	

R&D projects		
Acoustic	(calls)	(mail)
AURA		
RASTA	(calls)	(mail)
PINGU		
Proton Decay Simulation		
IceCube Extensions		(mail)
IceAct	(calls)	

Legacy working groups		
Neutrino Oscillations	(calls)	(mail)
Low-energy ν	(calls)	(mail)
Extreme energies	(calls)	(mail)
Tau & Composites	(calls)	(mail)
Exotic particles	(calls)	(mail)
WIMPs/Dark Matter	(calls)	(mail)
Transients	(calls)	(mail)
Point sources	(calls)	(mail)
Cascades/Taus	(calls)	(mail)
Muons	(calls)	(mail)
Verification		(mail)

- All this info is on wiki.icecube.wisc.edu
  - Each WG has a page telling you when phone calls are, where materials are, etc.
  - WGs have "leads" as well as "technical leads"

Please refer to the wiki calendar or the upcoming meetings web page for times and dates of phone calls.

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Analysis working groups

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ANALYSIS IN ICECUBE: OVERVIEW

› **Analysis call: weekly on Thursdays (9:00 AM Central)**

  ✦ These are where nearly-finished analyses are presented to the entire collaboration

  ✦ High-level descriptions of the analyses

  ✦ Good way to start learning about other science that happens in IceCube

  ✦ Also present "WG Summaries" which are *super* helpful synopses of activities in an entire WG

› **https://wiki.icecube.wisc.edu/index.php/Analysis_calls_2021**

NEUTRINO SOURCES

› **Trying to pinpoint the sources of astrophysical neutrinos**

› **A few interesting hotspots so far**

› **Can only explain ~1% of the total flux of neutrinos, so the rest must be dim**

› **Group focuses on testing new hypotheses for correlating our data with possible sources and on building new tools to do these searches**

› **Most recent WG summary here**

bright

faint

Hubble horizon

AGNs, SNRs, GRBs...

black holes

Gamma rays
They point to their sources, but they can be absorbed and are created by multiple emission mechanisms.

γ

γ

γ

Neutrinos
They are weak, neutral particles that point to their sources and carry information from deep within their origins.

Earth

air shower

p

Cosmic rays
They are charged particles and are deflected by magnetic fields.

p

$-\log_{10}(p_{local})$

1   3   5   7

☆ NGC 1068   + Best-Fit

0.6

0.4

0.2

0.0

−0.2

−0.4

Dec. (degrees)
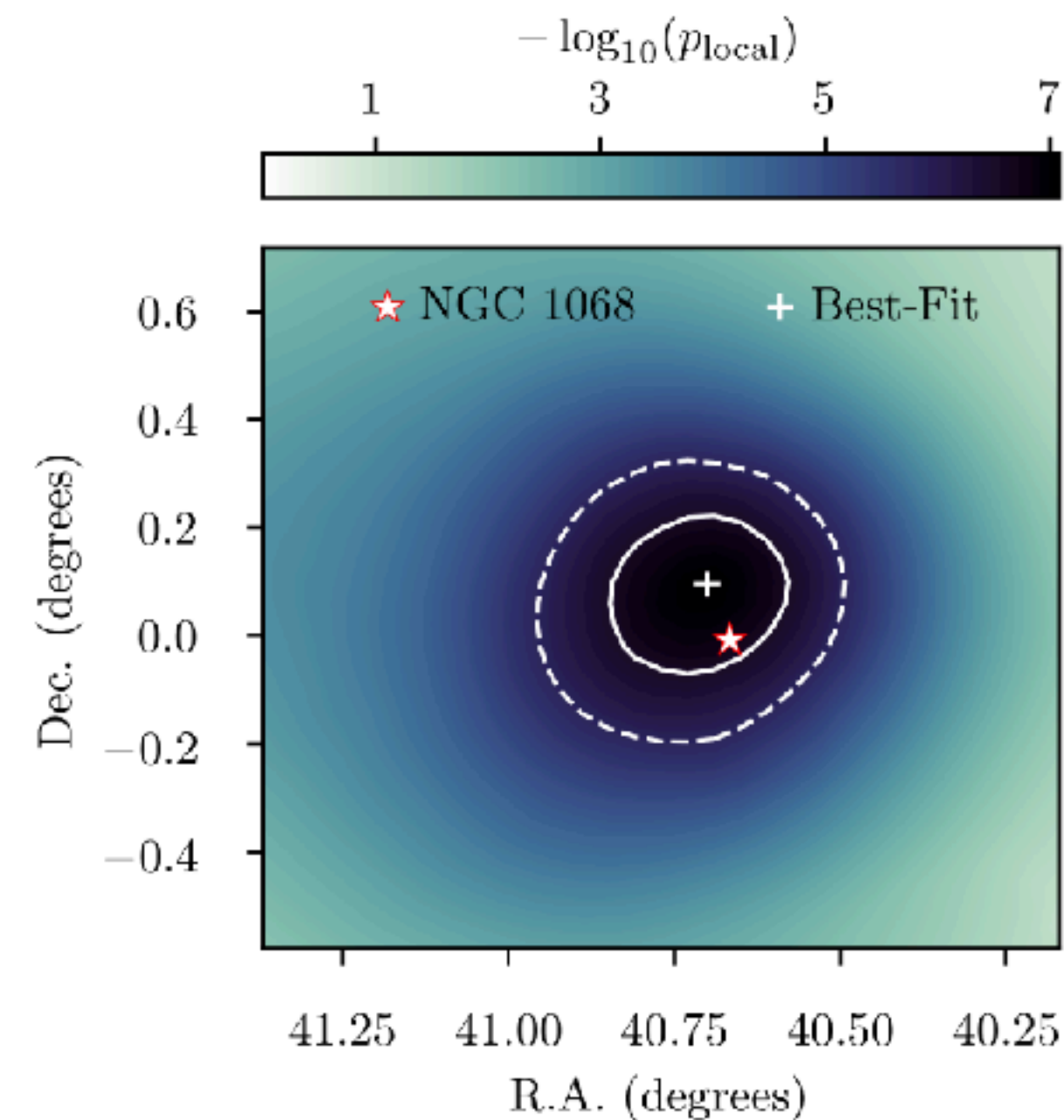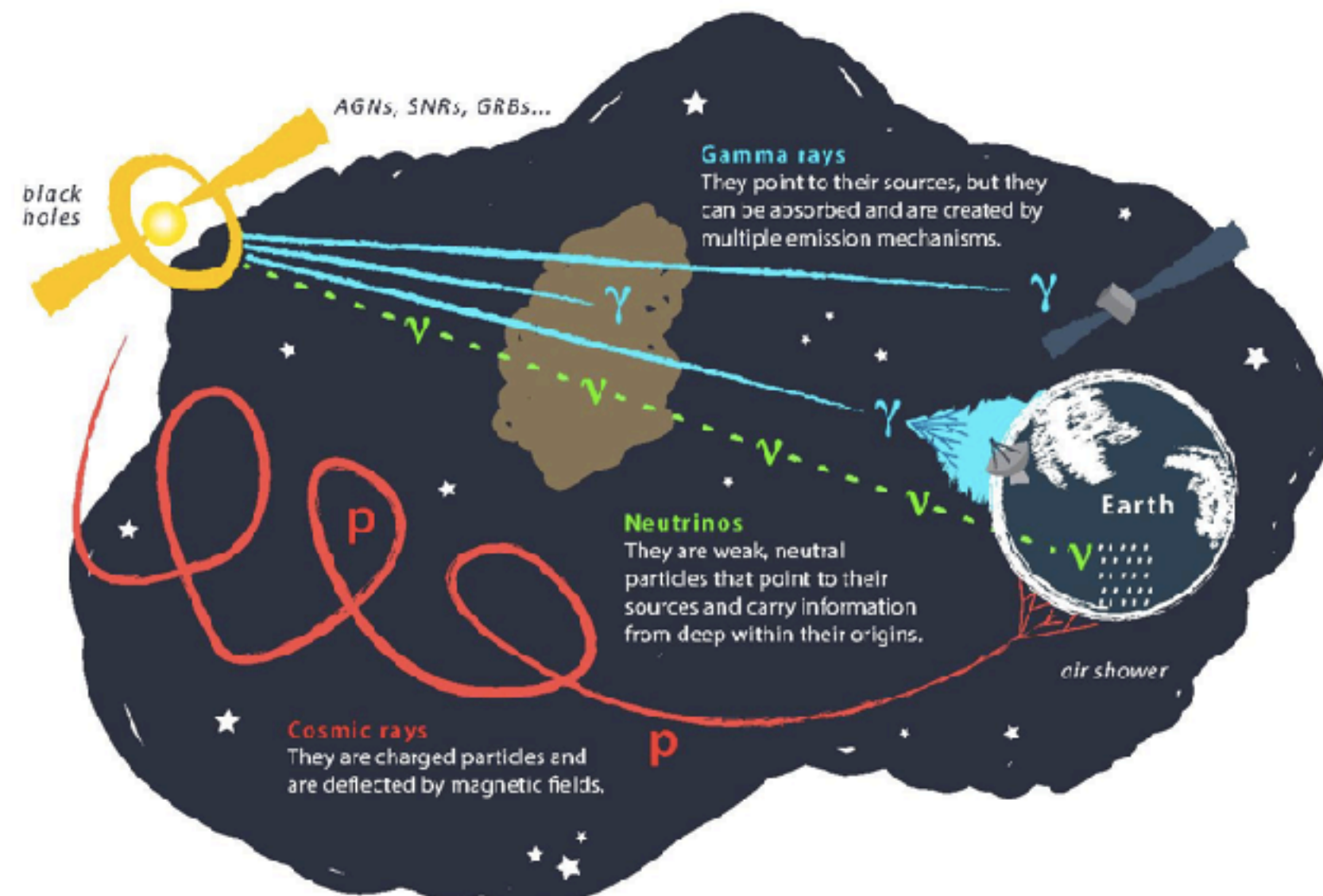
41.25   41.00   40.75   40.50   40.25
R.A. (degrees)

INGREDIENTS FOR A NU-SOURCE ANALYSIS

Where are you looking?

1. Individual source
2. List of EM sources (stacking or catalog)
3. List of neutrino alerts (self-triggered)
4. Over an entire region of the sky (template)
5. Not exactly sure, but I have a spatial PDF (spatial prior)
6. The whole sky

When are you looking?

A. The whole dataset (time-integrated)
B. Correlating with EM observations (lightcurve)
C. Around a specific time (transient)
D. Fitting the time of a neutrino burst (flare)
E. Fitting multiple neutrino bursts (multi-flare)

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a non-exhaustive list of recent analyses

1D: TXS 0506+056

1B: PKS 1502+106 Lightcurve

1C: Fast Response analysis

2A: 10 year time-integrated catalog

2A: MOJAVE stacking

2E: Multi-flare blazar stacking

3D: TXS 0506+056

4A: Galactic plane (MESE, MESC, ESTES)

5C: GW followup (UMLLH & LLAMA)

5A: UHECR correlation

6A: Improved PS analysis

2A: Improved PS analysis

6E: All-sky multiflare analysis

And so many more . . .

Nu-Sources: Code & Analyses

> **nu-sources code**

- ✦ Skylab / csky / SkyLLH / FlareStack: likelihood frameworks to do point source analysis

- ✦ grbllh / psLab: Legacy LLH code

- ✦ FIRESONG: simulating populations of neutrino sources

> **nu-sources jargon**

- ✦ TXS / "Texas" / TXS 0506+056: blazar coincident with an alert event and flaring in 2014-2015

- ✦ NGC / NGC 1068 / M77: Hotspot from most recent update of the point source analysis

- ✦ PSTracks: An all-sky muon neutrino dataset optimized for point source analyses

- ✦ NorthernTracks: A northern hemisphere tracks dataset for diffuse and point source analyses

- ✦ GFU: Gamma-ray followup dataset for realtime source searches

REALTIME

> **Technical WG that works closely with nu-sources**

> **Focused on rapidly identifying neutrino sources**

> **Group not only sends alerts to the community but also responds to interesting alerts from the astronomical community**

> **Most recent WG summary here**

Event 135363/69917294-0
Time 2021-06-08 03:41:00 UTC
Duration 19207.6 ns
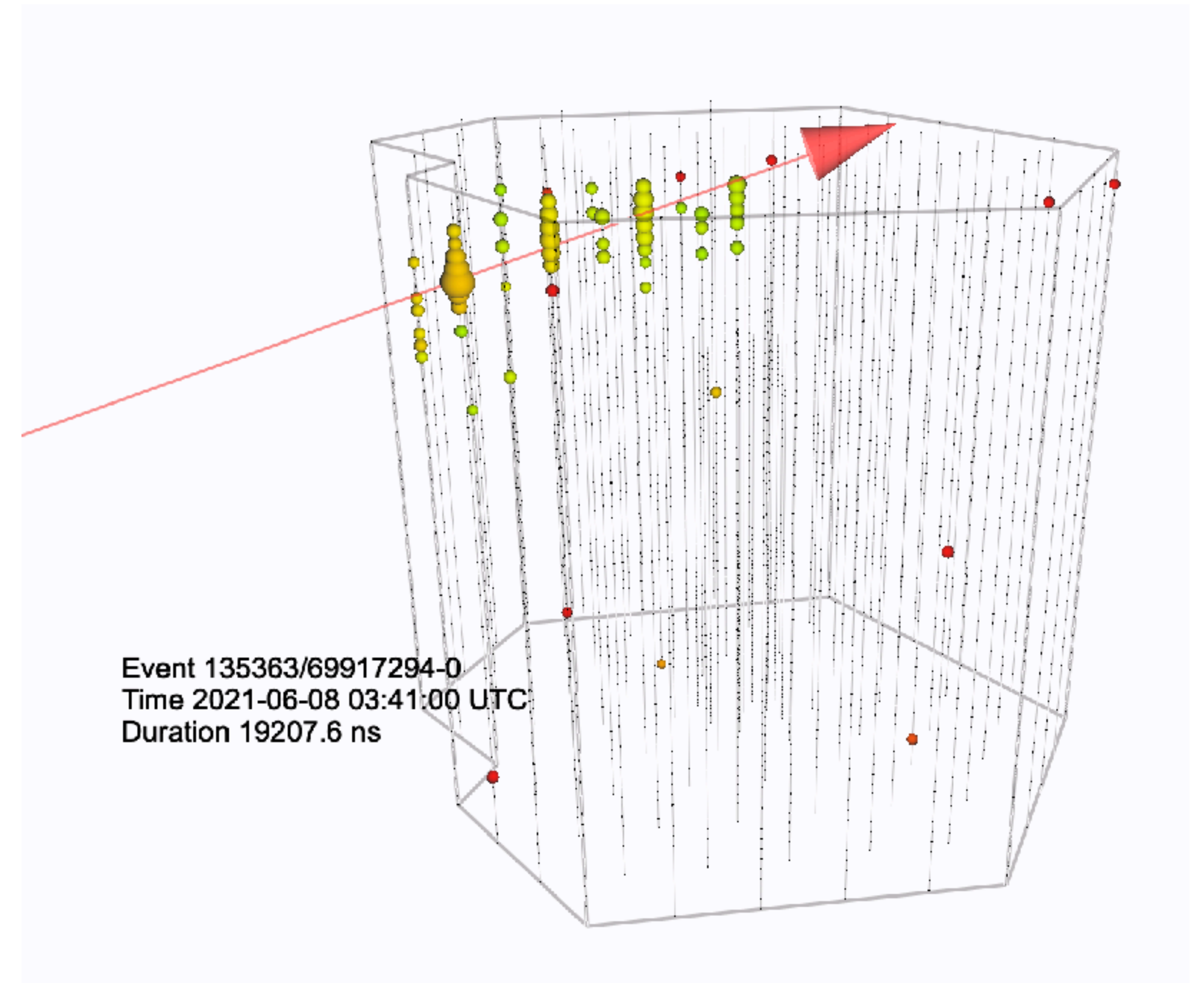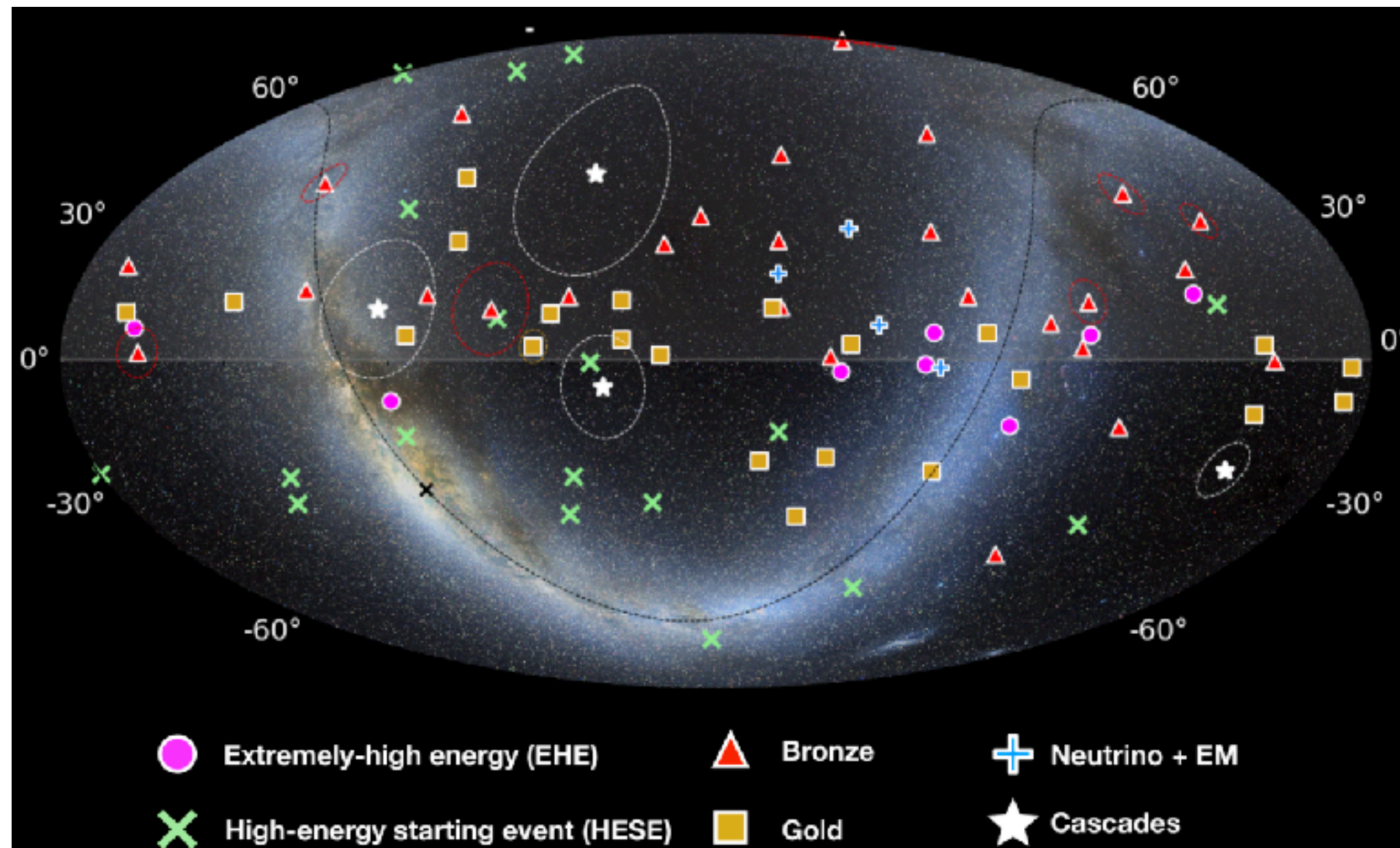
REALTIME ANALYSES

> Sending alerts to the community and improving our alert quality

> Follow up of gravitational wave events

> Multiplet alerts

> Coordinating with IACT observations

> Responding to astrophysical transients
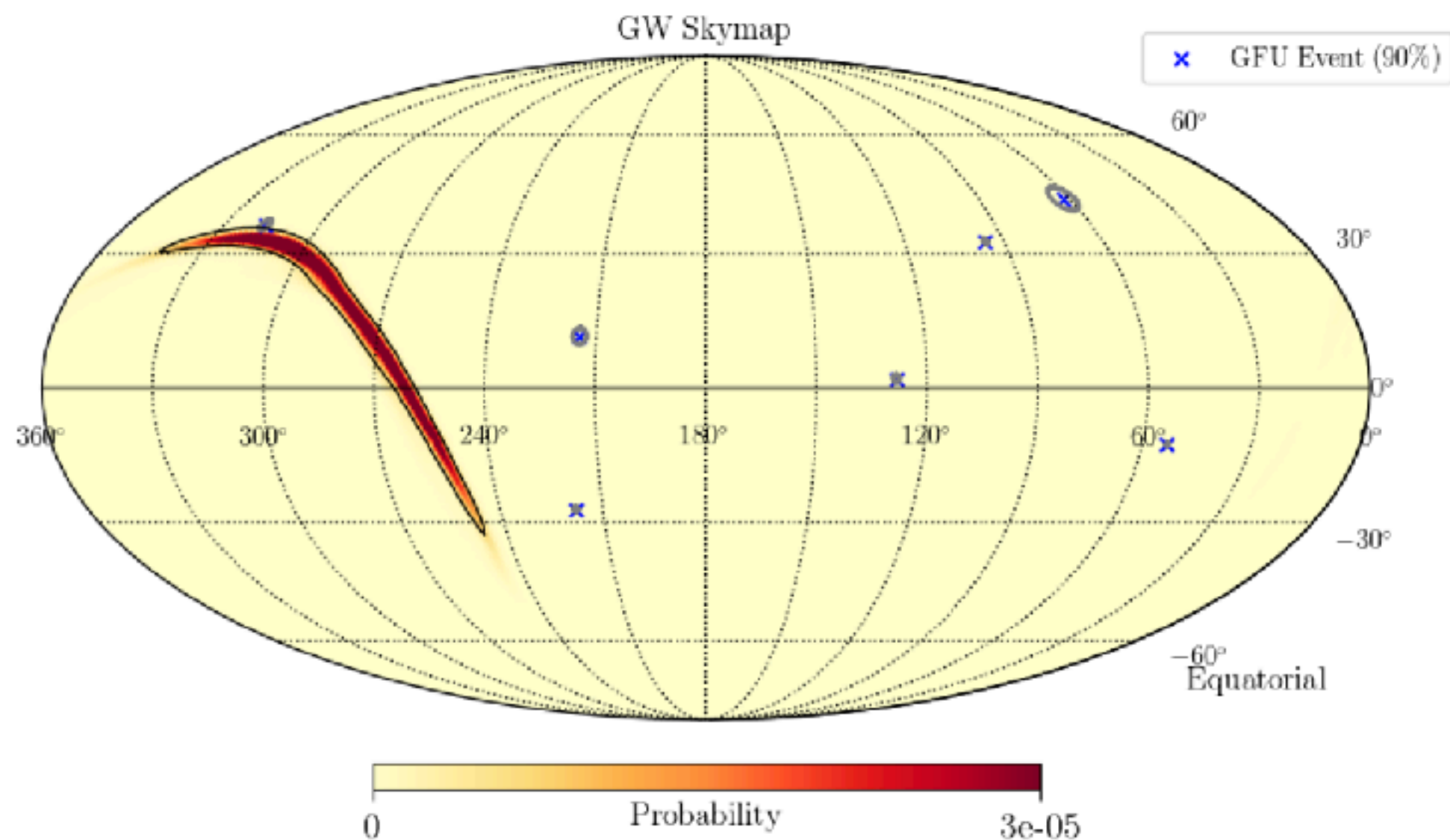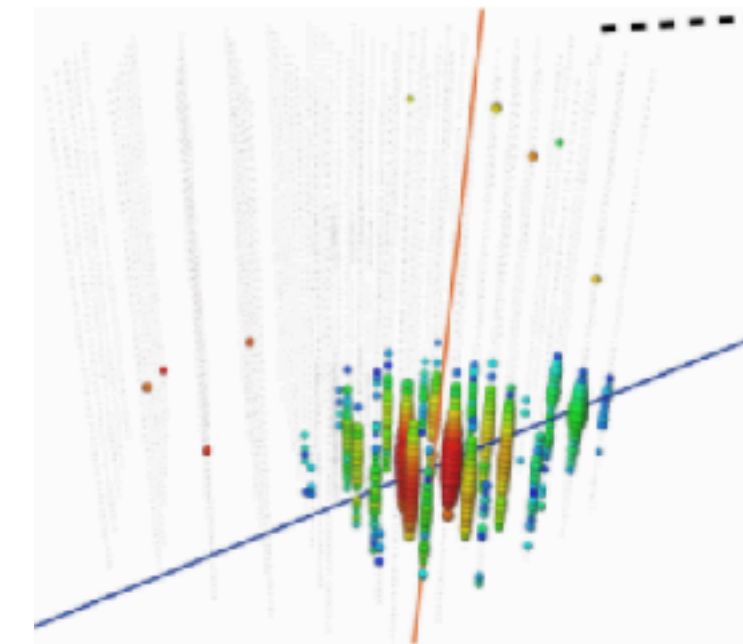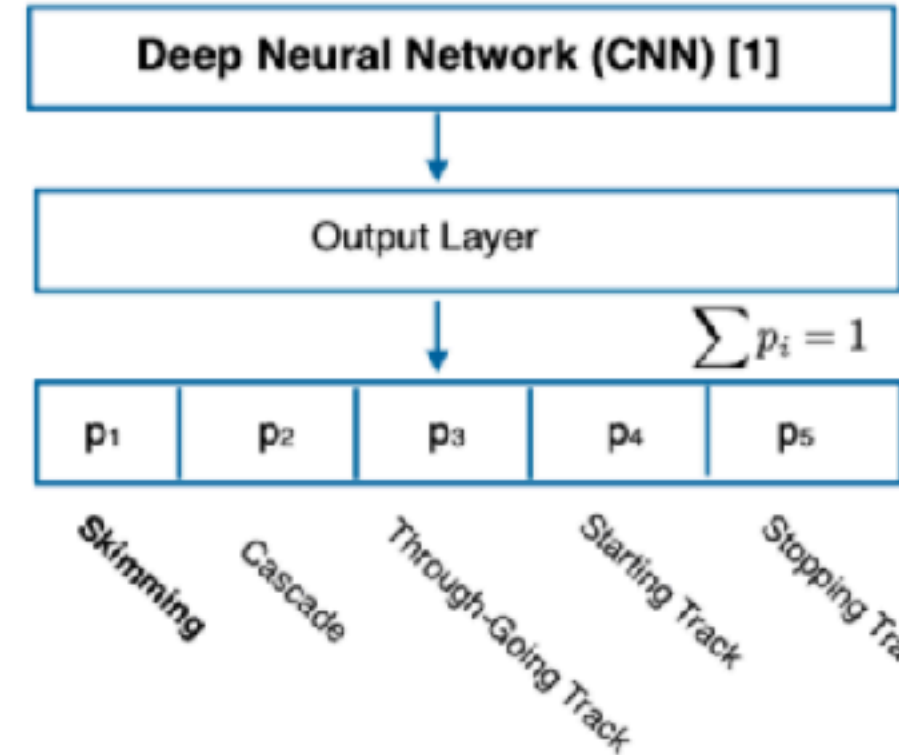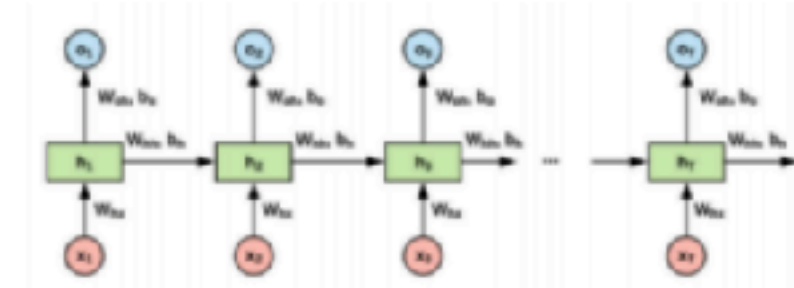
DIFFUSE

> **Characterizing the neutrino fluxes at Earth**

   ✦ Atmospheric neutrino: Unfolding, seasonal variation, prompt?, Earth core

   ✦ Astrophysical neutrino: Flux - bump? power law? Flavor ratio?

   ✦ Cosmogenic neutrino: Direct and indirect (tau secondaries)

> **Inelasticity,**

> **Cross-section**

> **Nu/Nubar ratio**

> **Most recent WG summary here**
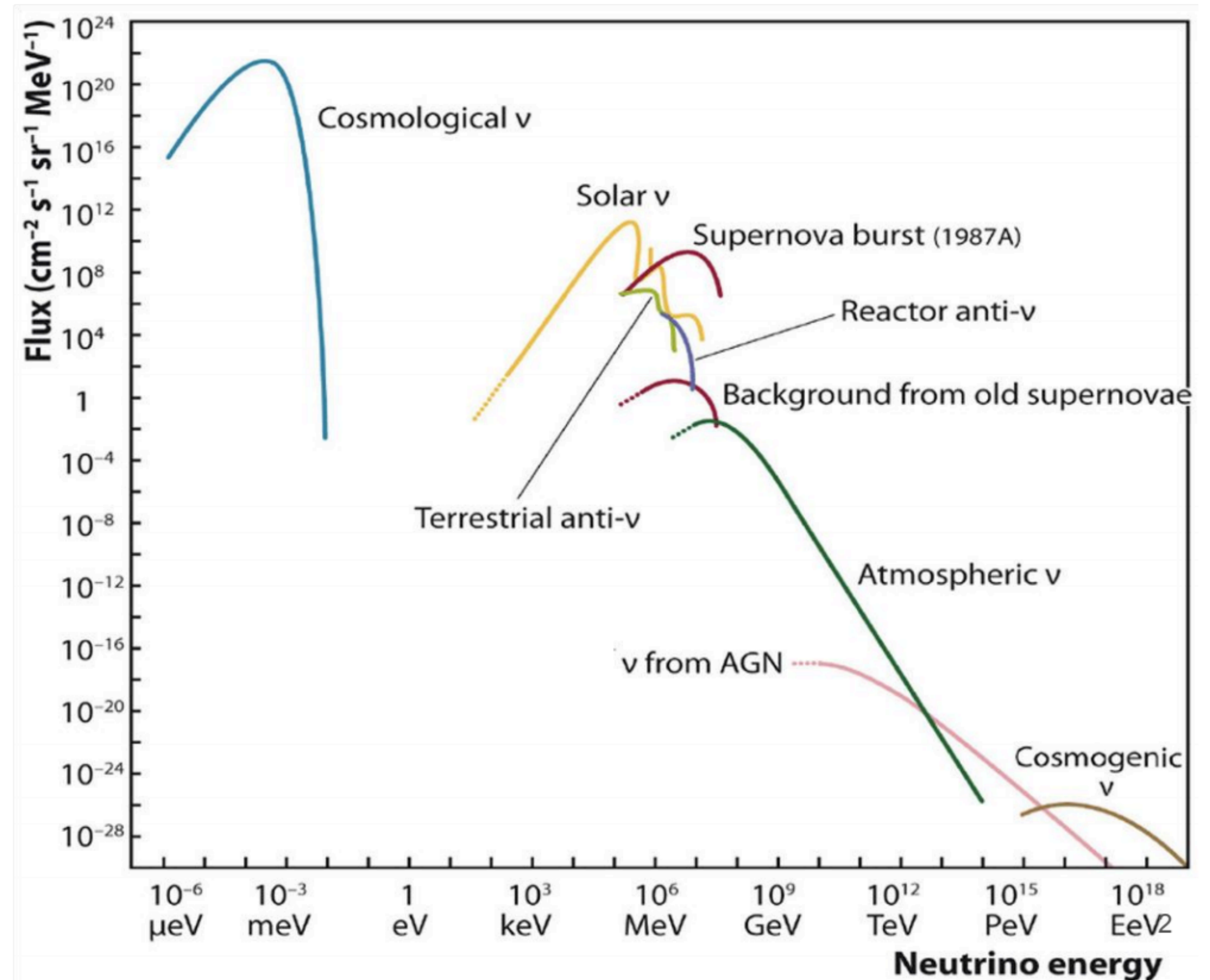
DIFFUSE: ANALYSES

> **Diffuse Analyses**

- ✦ HESE: High-energy starting events sample

- ✦ MESE: Medium-energy starting events sample

- ✦ Northern Tracks / Diffuse NuMu: Through-going tracks sample

- ✦ ESTES: Enhanced Starting Track Event Selection

- ✦ Diffuse "GlobalFit": Upcoming measurement to combine datasets

- ✦ Searches for tau neutrinos ("double pulse", "double cascade")

- ✦ Cosmogenic neutrino searches: direct or via tau secondaries

- ✦ Glashow Resonance search
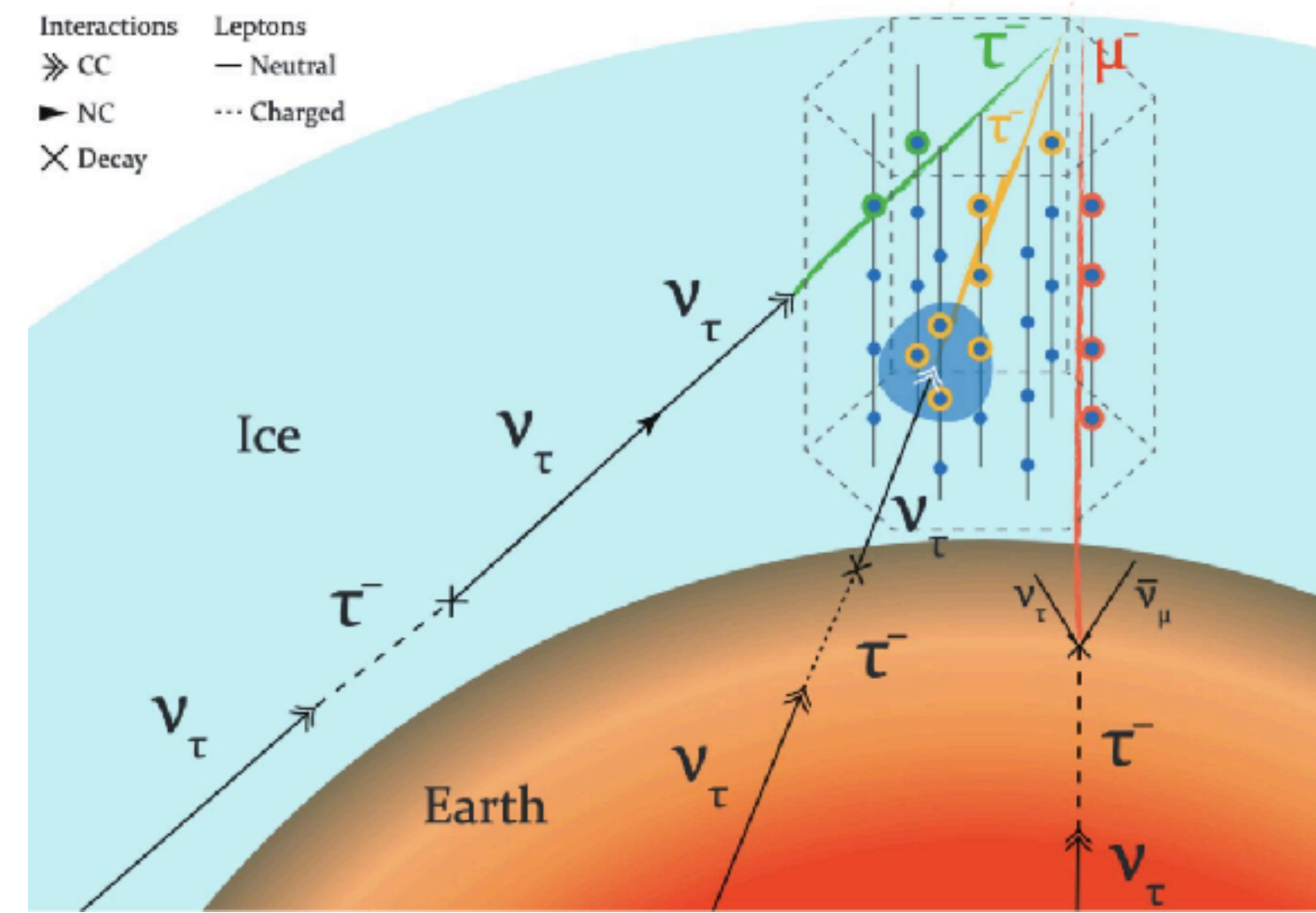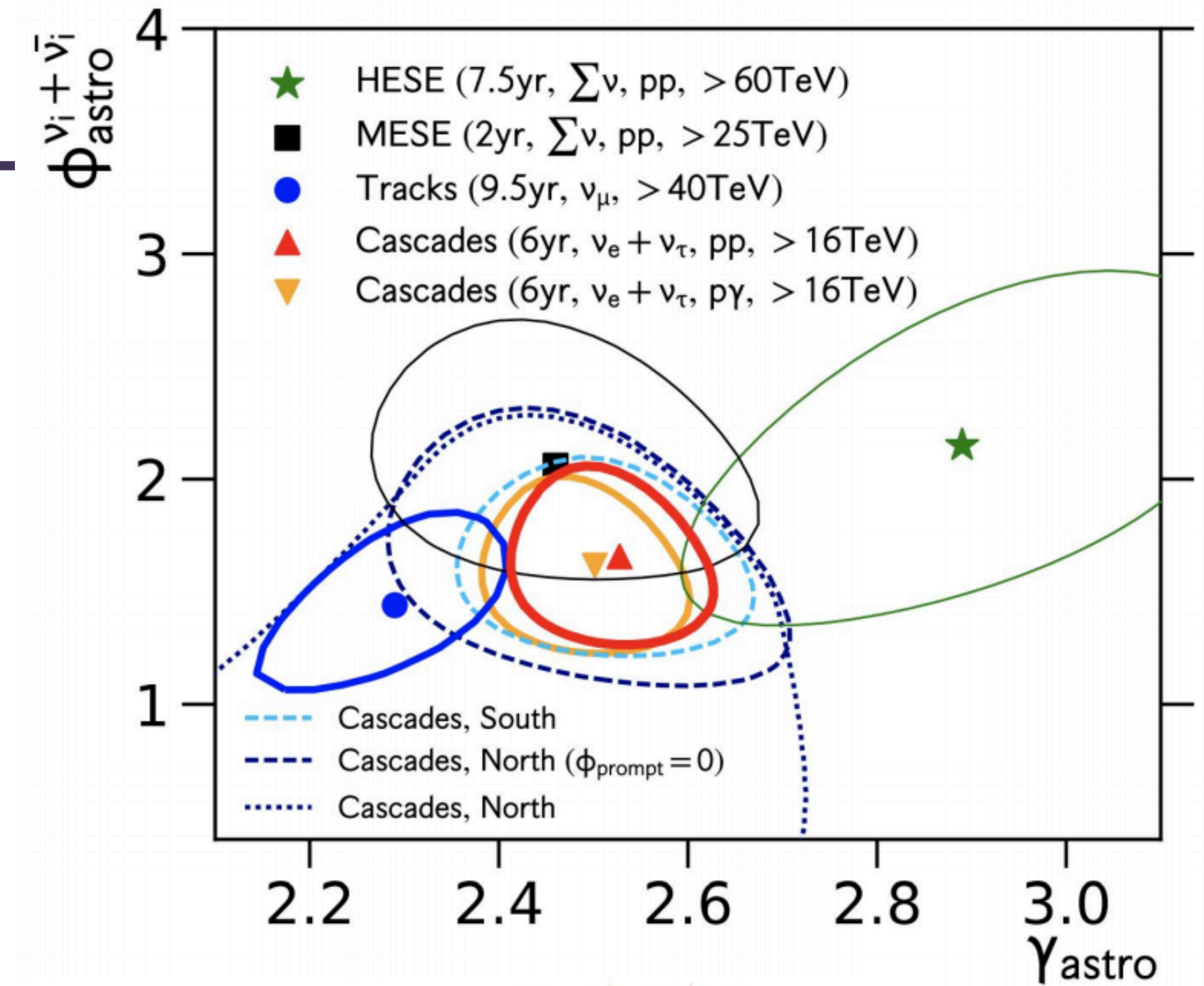
OSCILLATIONS

> If we know what the flavor a neutrino was created as, we can calculate the probability of it being measured as a certain flavor at another point in time

> "All analyses that focus on neutrinos changing flavor as they Cross the Earth"

> "Big-team" collaborative structure for large detailed analyses

> <u>Most recent WG summary here</u>

$$P_{\alpha \to \beta, \alpha \neq \beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Oscillation probabilities for an initial electron neutrino

13
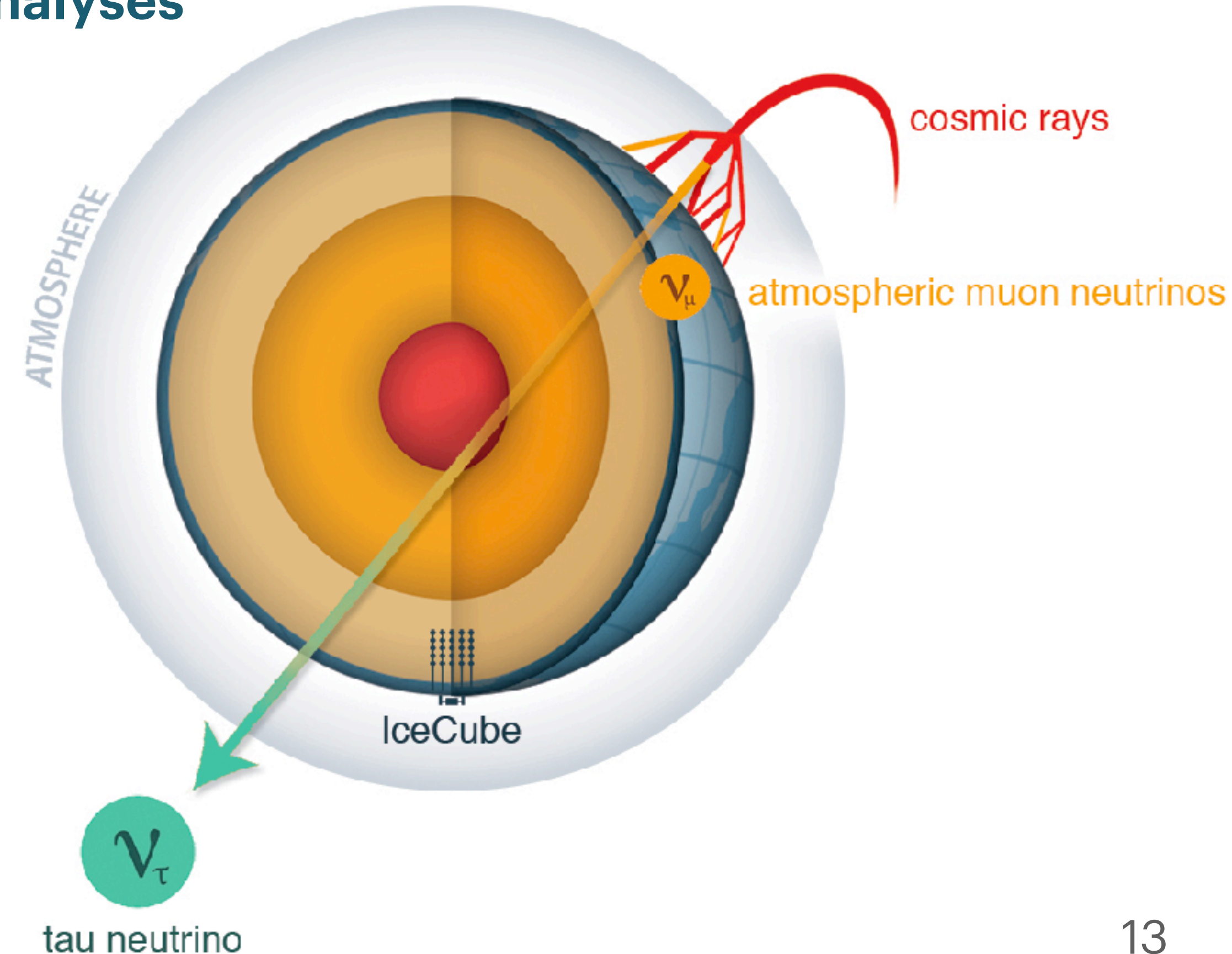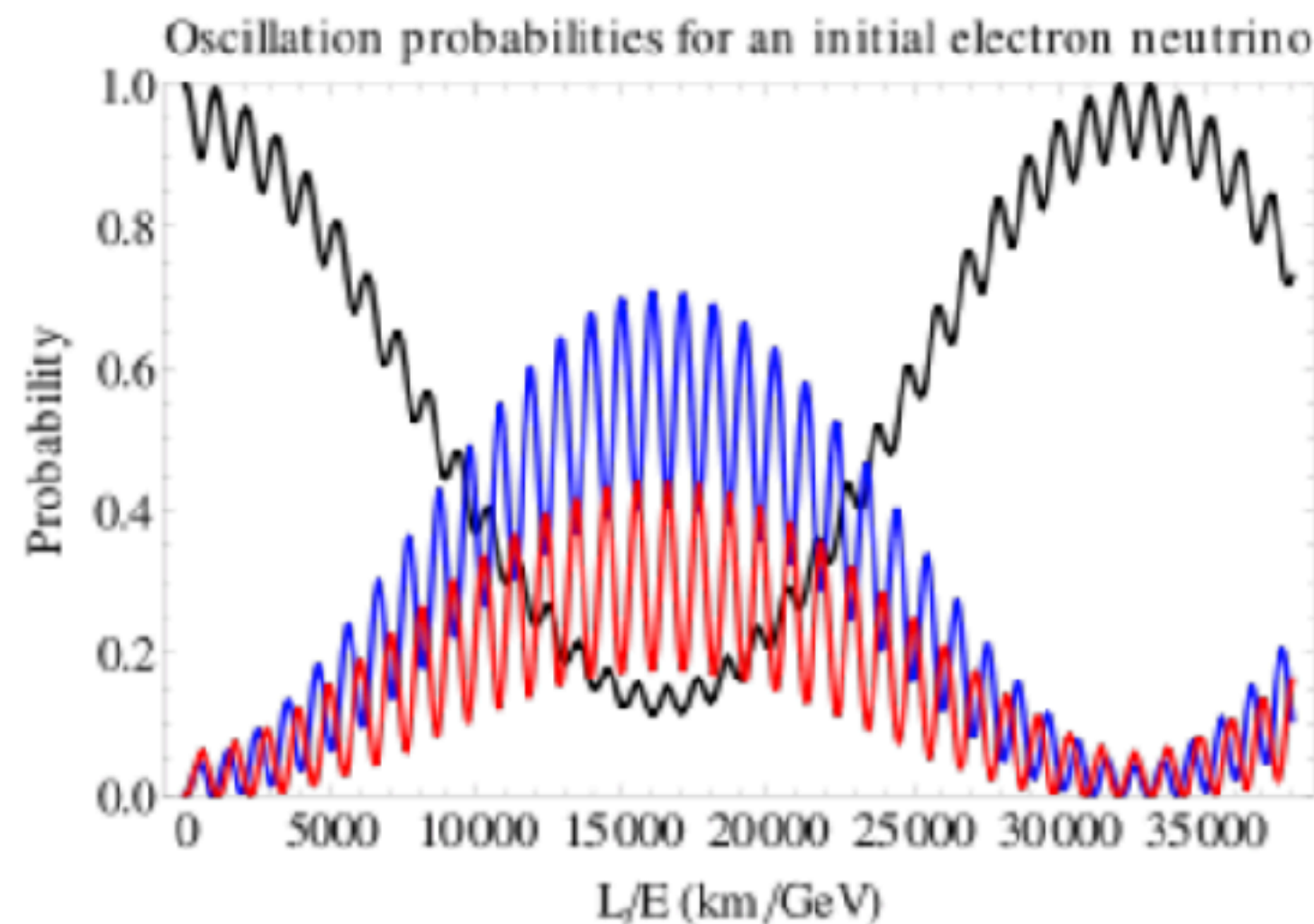
OSCILLATIONS ANALYSES

❯ **OscNext: "This year's headline act for the IceCube neutrino oscillations program"**

✦ Two samples with semi-independent analyses

✦ OscNext "verification" sample and the OscNext High Stats sample

❯ **Sterile Neutrino searches**

❯ **Non-Standard neutrino-nucleus Interactions (NSIs)**

❯ **Searches for Lorentz Invariance Violation and Decoherence connected with quantum gravity**

❯ **Most recent WG summary here**
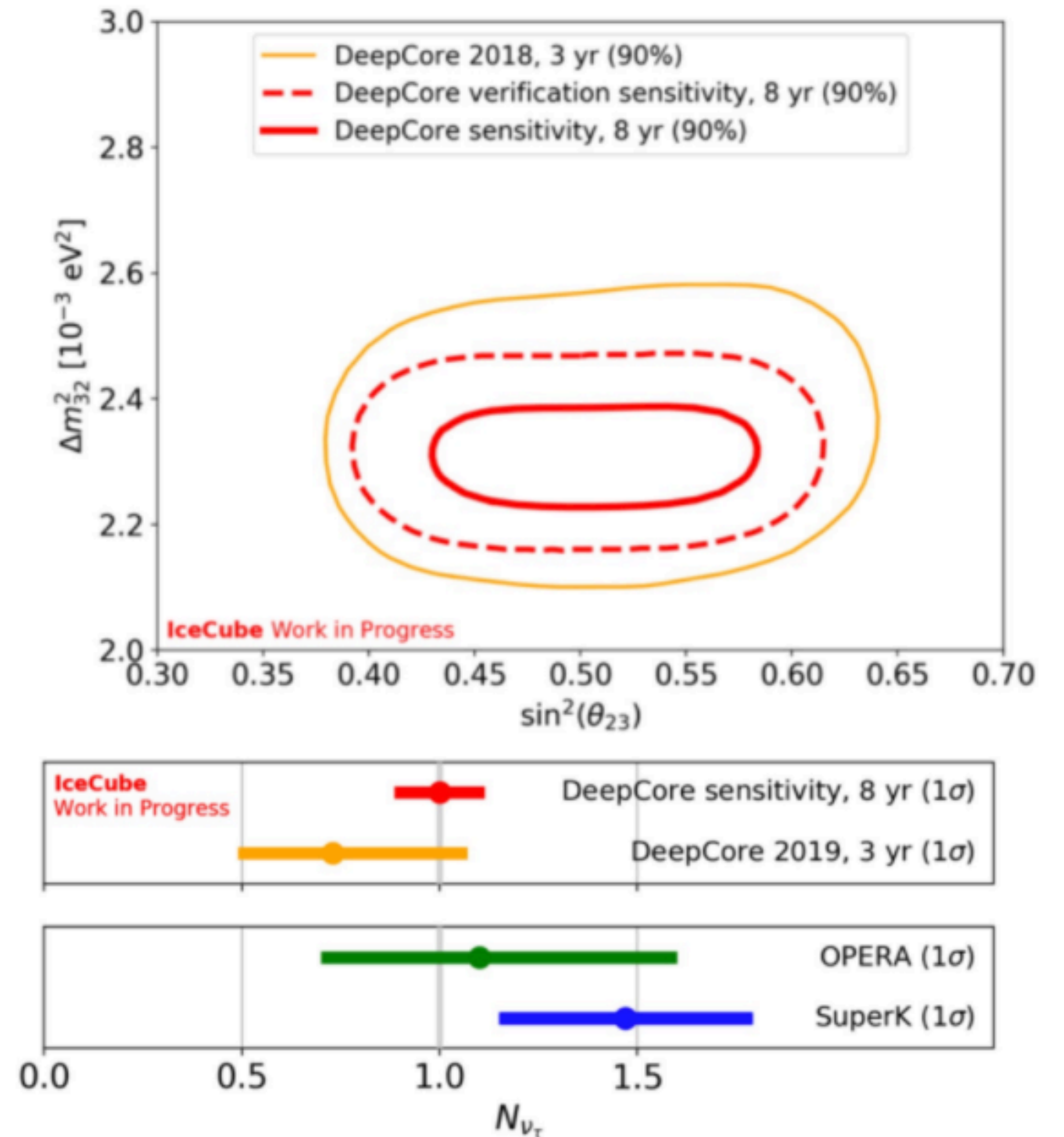
OSCILLATIONS: CODE & ANALYSES

> **Oscillations Analyses and jargon**

- ✦ OscNext: Two samples with semi-independent analyses for oscillations

- ✦ MEOWS: Dataset for recent sterile neutrino search

- ✦ NSI: **N**on-**S**tandard neutrino-nucleus **I**nteractions

- ✦ FLERCNN: New reconstruction tool being developed for low energies

- ✦ PISA: Software tool for doing oscillations analyses

COSMIC RAYS

> When cosmic rays hit Earth's upper atmosphere, they produce particle showers

> IceTop is a detector situated on top of IceCube that is designed to look for these air showers

> CR WG measures:

- ✦ Cosmic ray spectrum & composition

- ✦ Cosmic ray anisotropy

- ✦ Sun/Moon shado

- ✦ Seasonal variations

> **Most recent WG summary**

CR: ANALYSES

All-particle Cosmic Ray Energy Spectrum

measuring the shape of the flux

Sun & Moon Shadow

Anisotropy
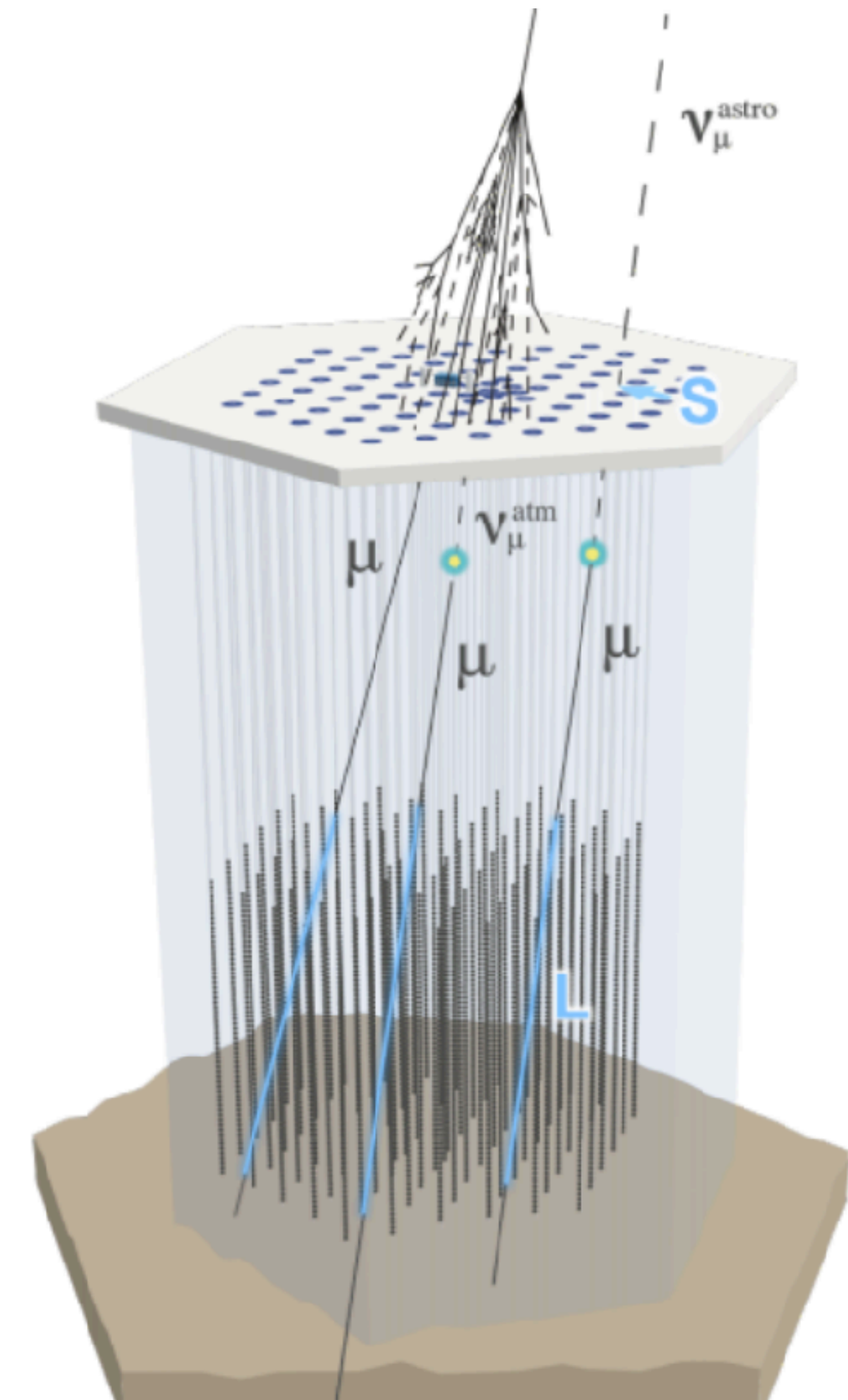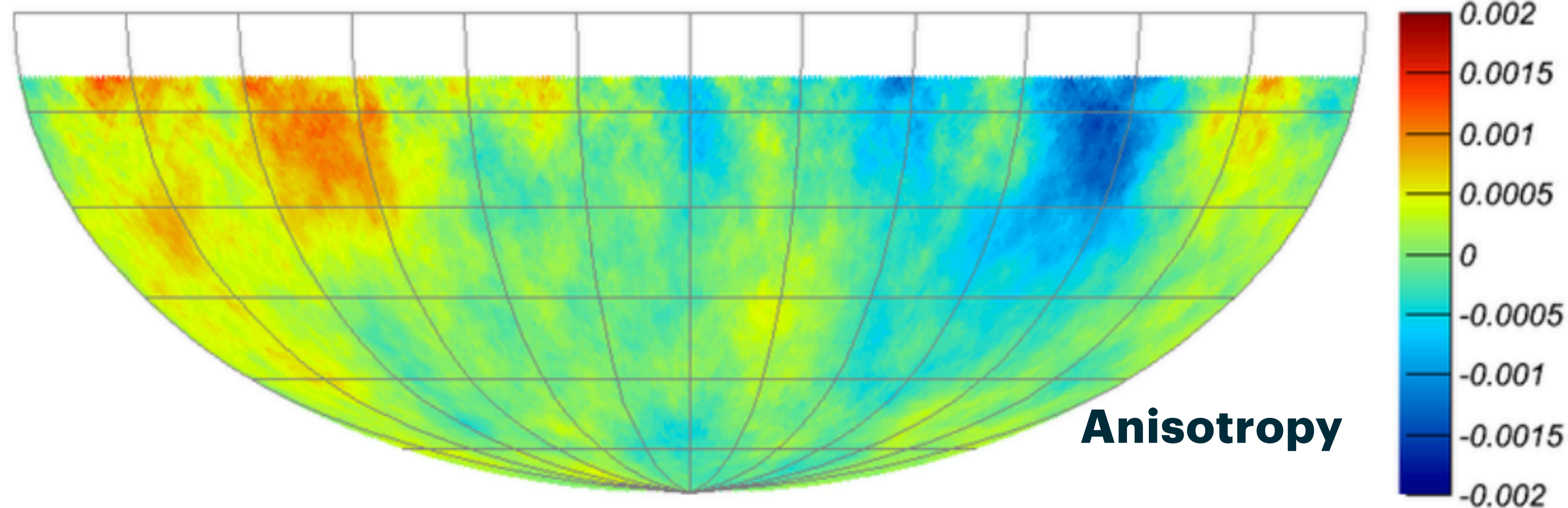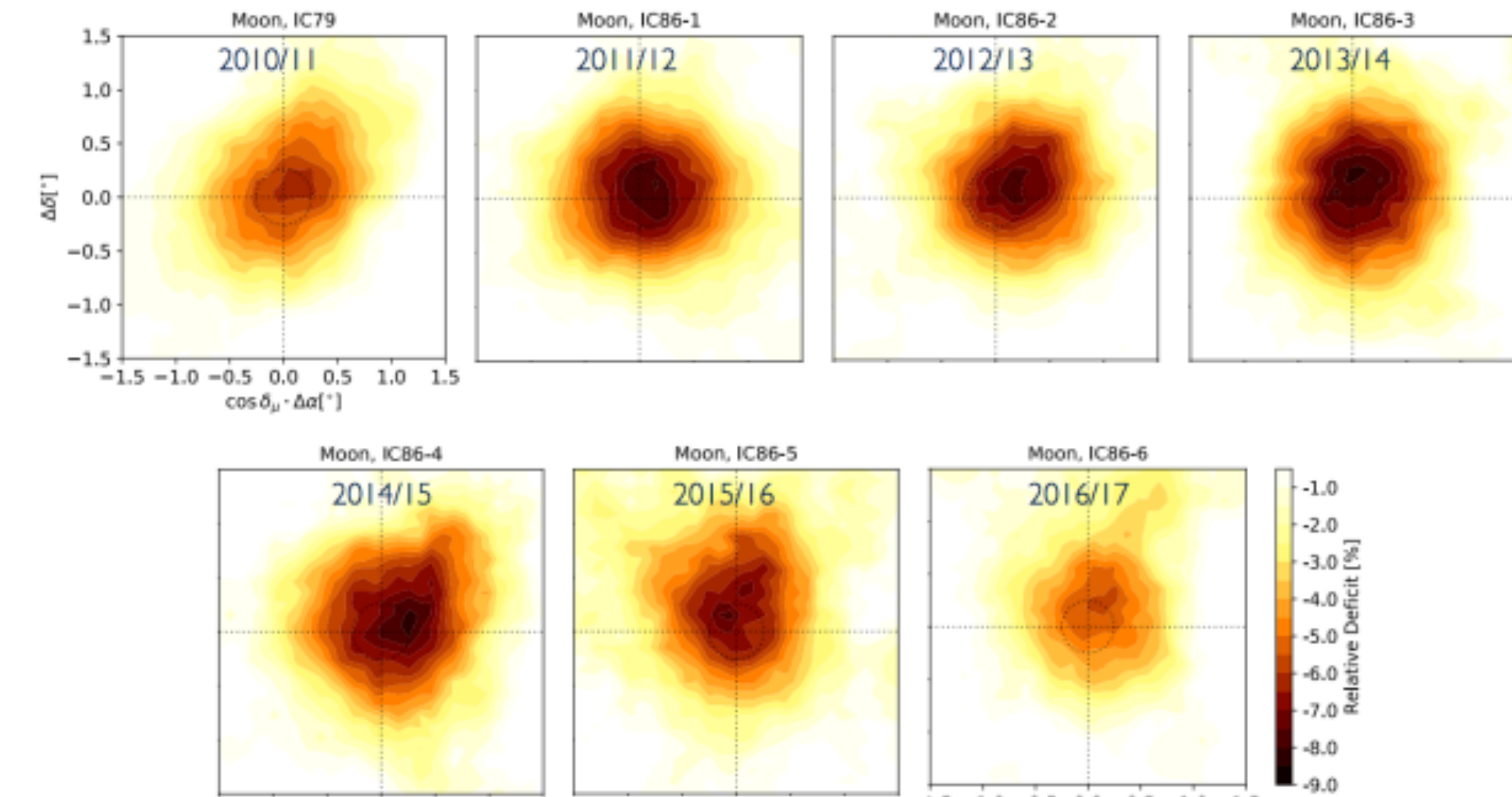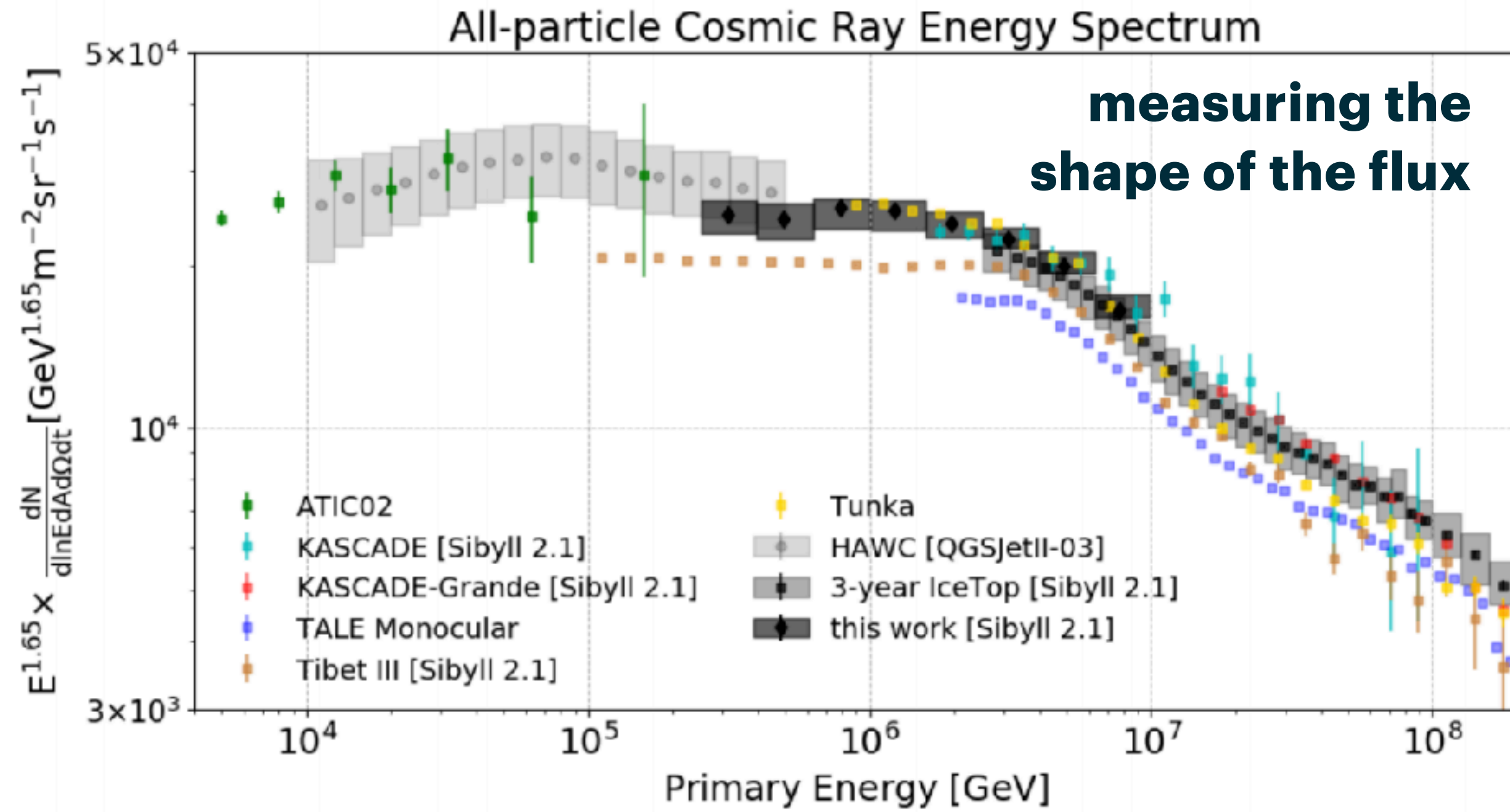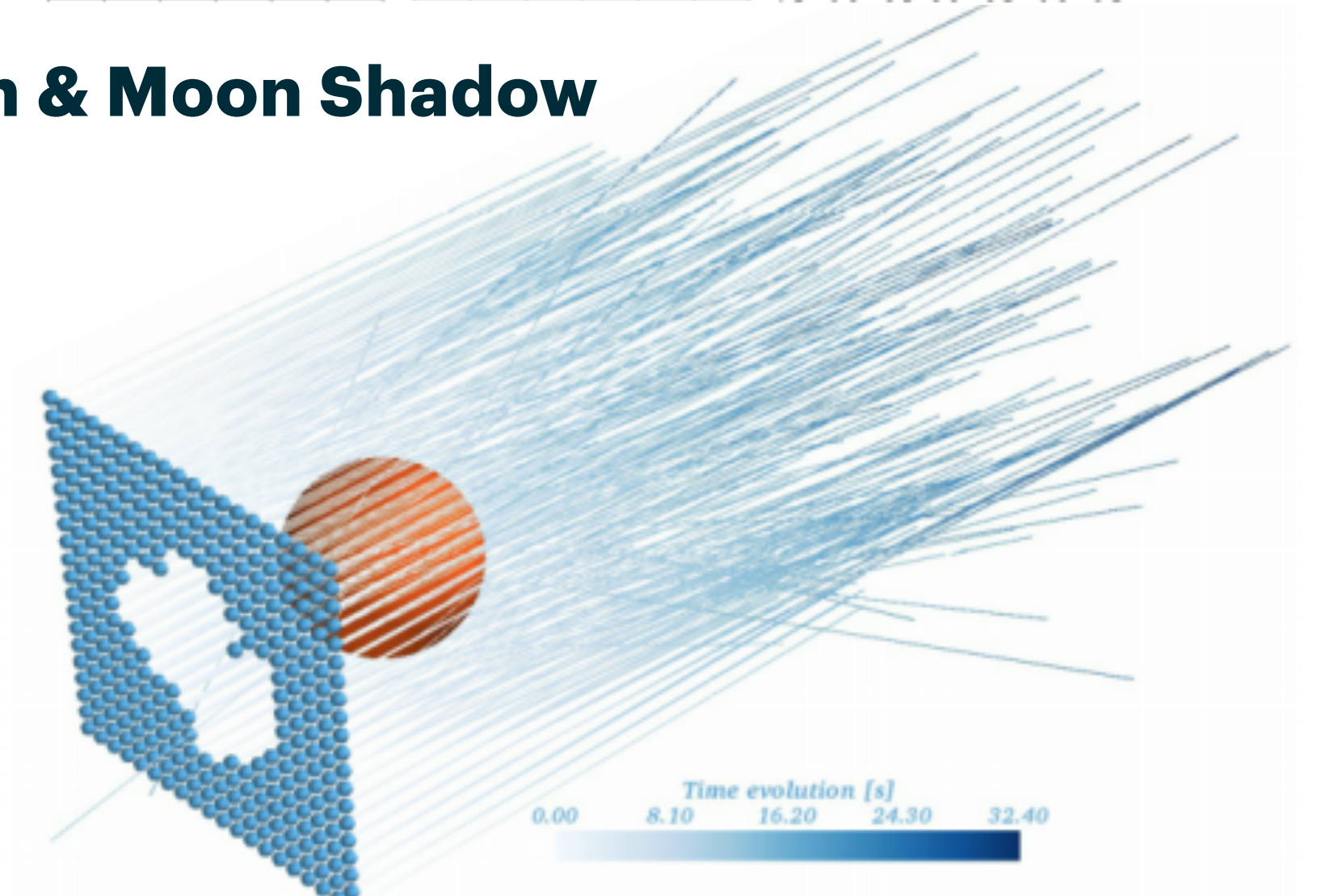
Beyond the Standard Model

> The Standard Model with the 3-Flavor Model of neutrino oscillations is widely accepted, but what if it's not the whole story?

> Interactions with new physics can cause distortions in the spectrum and flavor of both astrophysical and atmospheric neutrinos

> Most recent WG summary
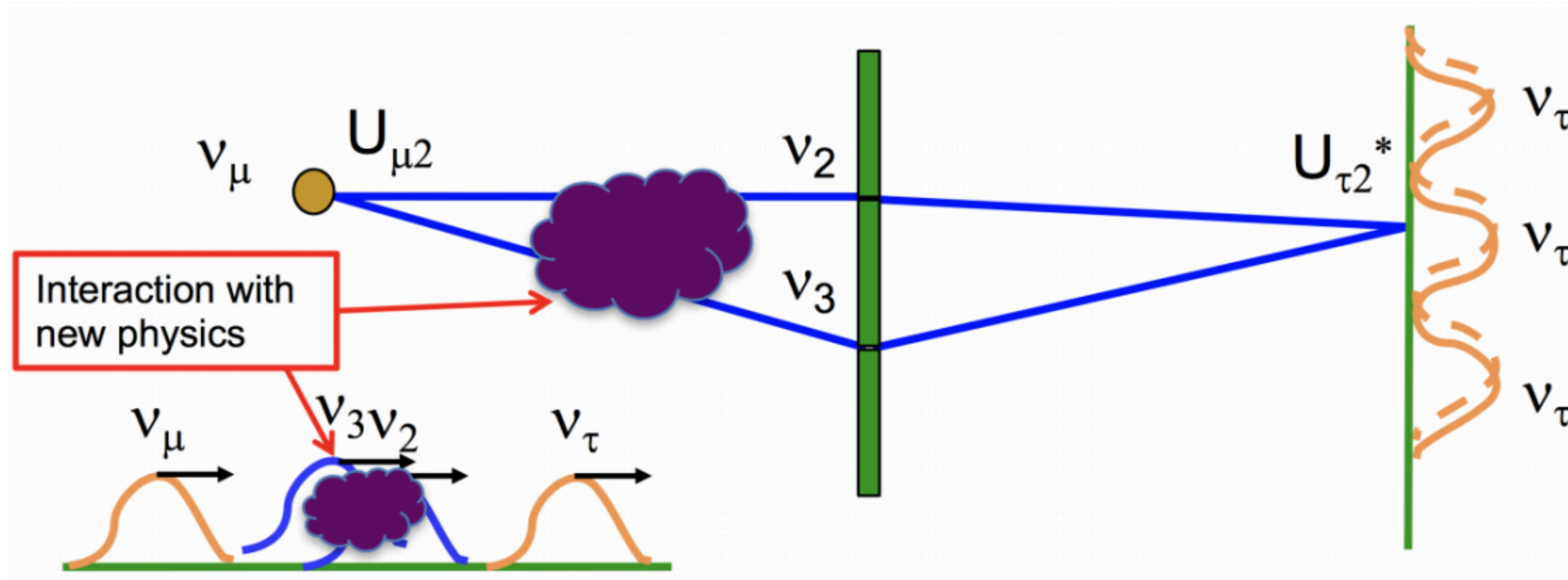
BSM ANALYSES

> **Analyses**

- ✦ Diffuse DM: could part of the diffuse spectrum be due to DM?

- ✦ Solar/Earth DM: Do we see an excess of neutrinos from the Sun/center of the Earth that could be from DM?

- ✦ Magnetic monopoles: Is there evidence for slow non-relativistic monopoles?

- ✦ Sterile-neutrinos (w/ decay): Do we see a signal consistent with that from a 4th neutrino flavor

- ✦ And many more! Search for staus, heavy neutral leptons, long-lived particle decay in the earth, etc.
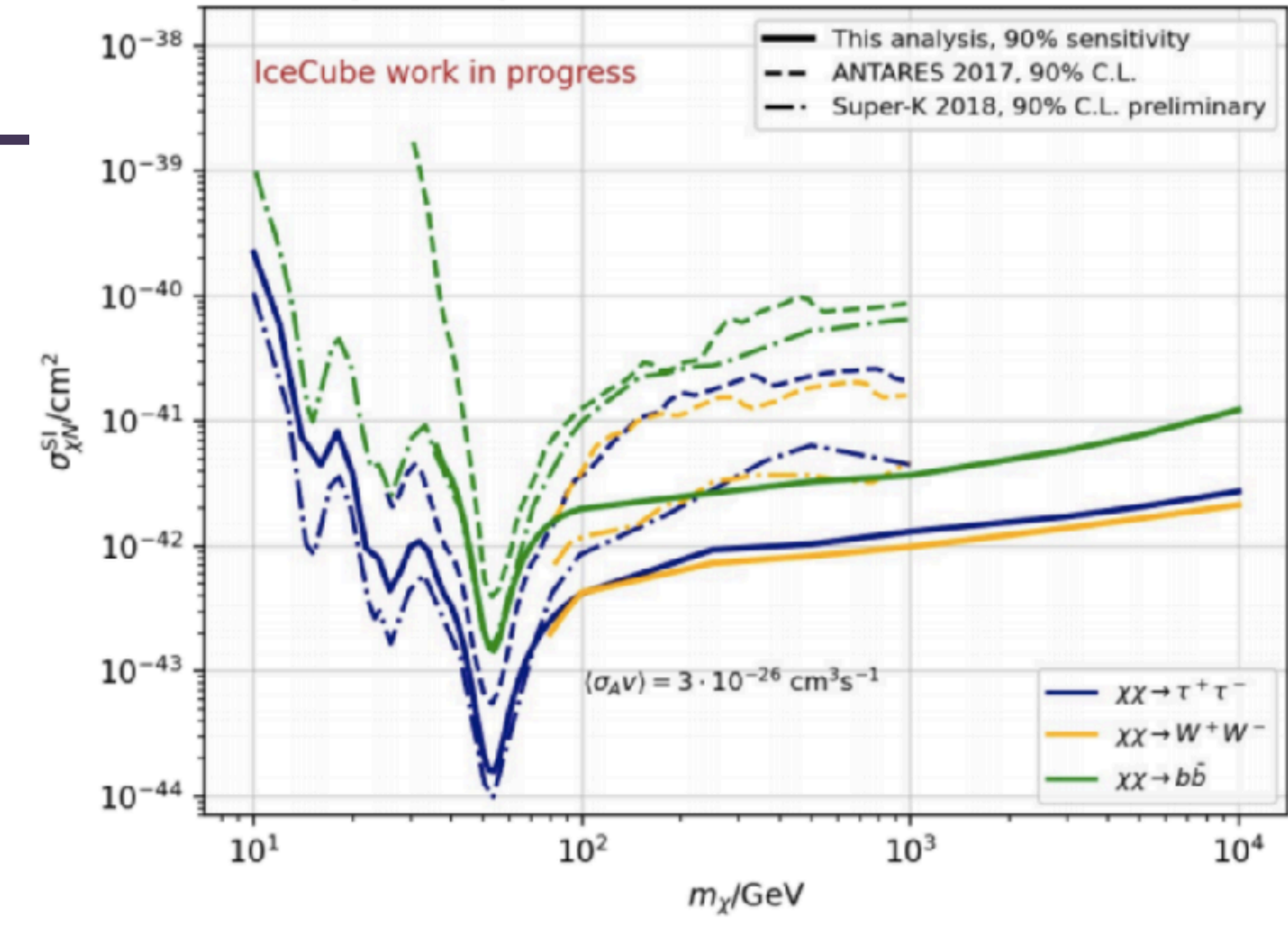
RECONSTRUCTIONS AND SYSTEMATICS

❯ **Technical WG that oversees development of reconstruction algorithms**

✦ Many of these are machine learning / deep learning based

❯ **Systematics tools (e.g. SnowStorm) discussed in this WG**

❯ **Current projects:**

✦ Segmented Spline Reco, FreeDOM, Cascade Event Generator, including an energy loss prior in Millipede, Muon angle distribution from multiple scattering, MCEq, . . .
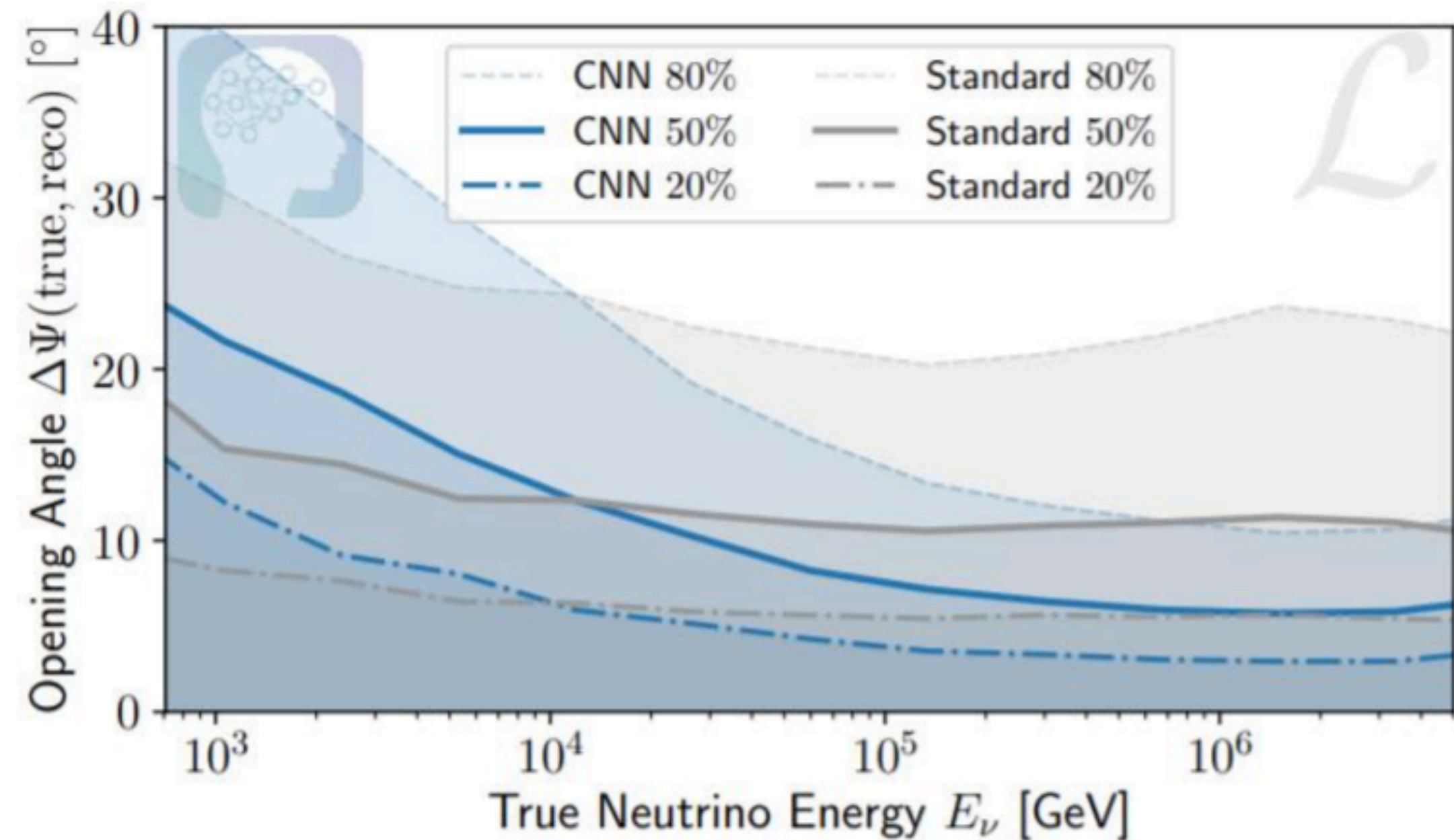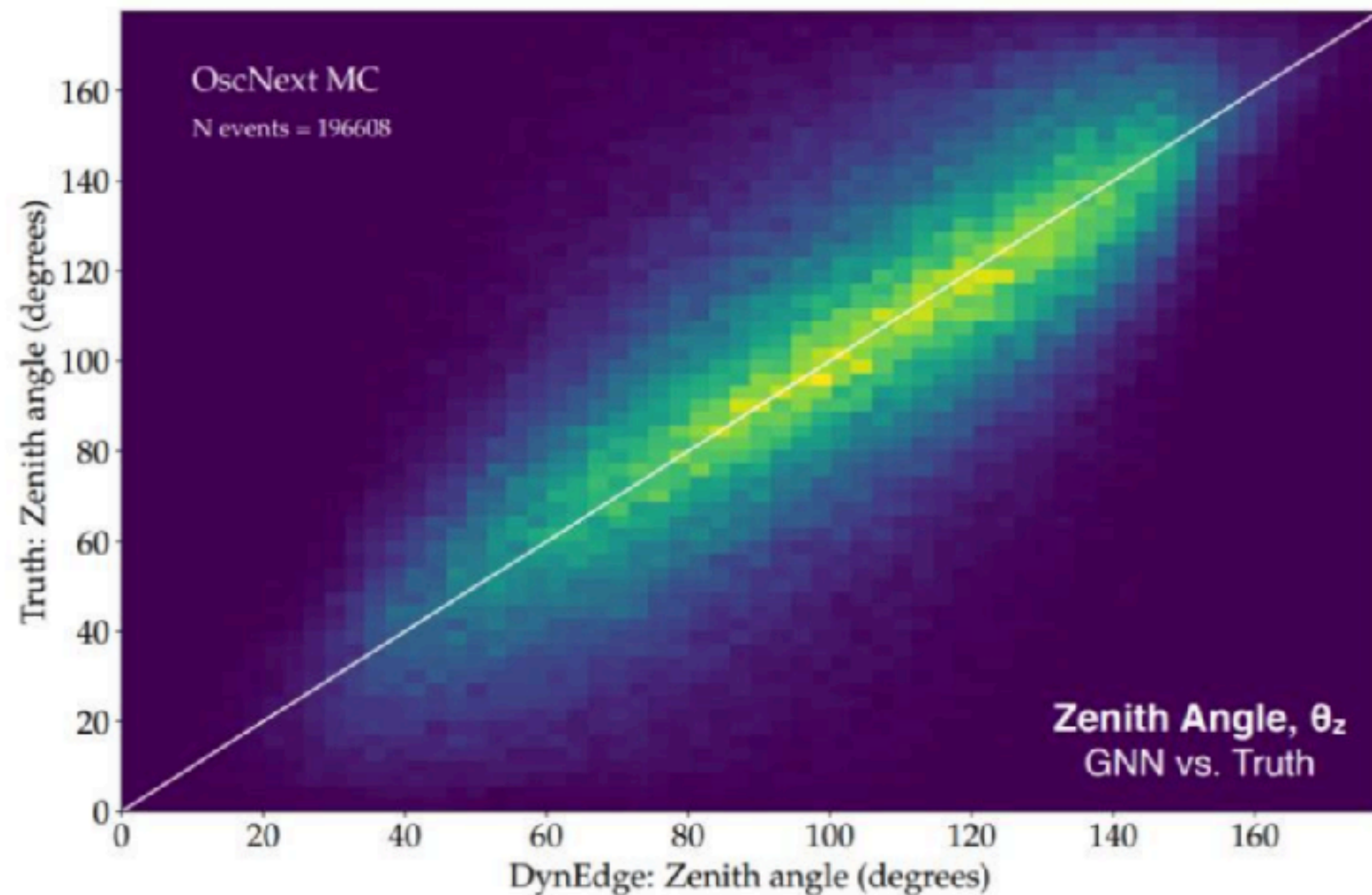
SUPERNOVA

> Supernova neutrinos are much lower energy (O(MeV)) compared to what IceCube normally sees

> With a SN, we might expect to see an overall rise in the "noise" of the detector instead of a clear single event

> SN WG does online and offline SN analyses

> Full "fire drills" underway

> ELOWEN analyses for GeV neutrinos

> Most recent WG summary

IceCube Preliminary
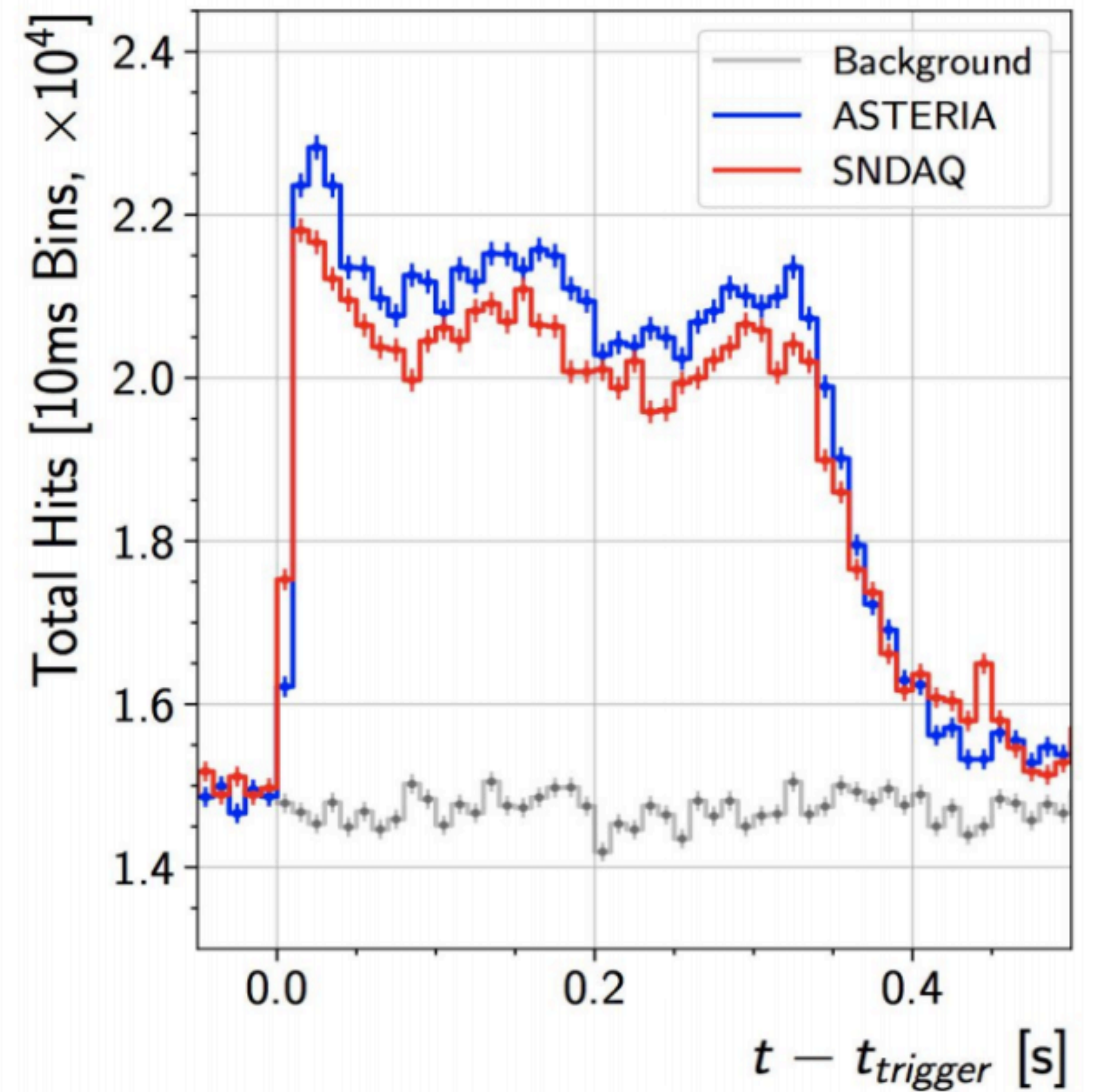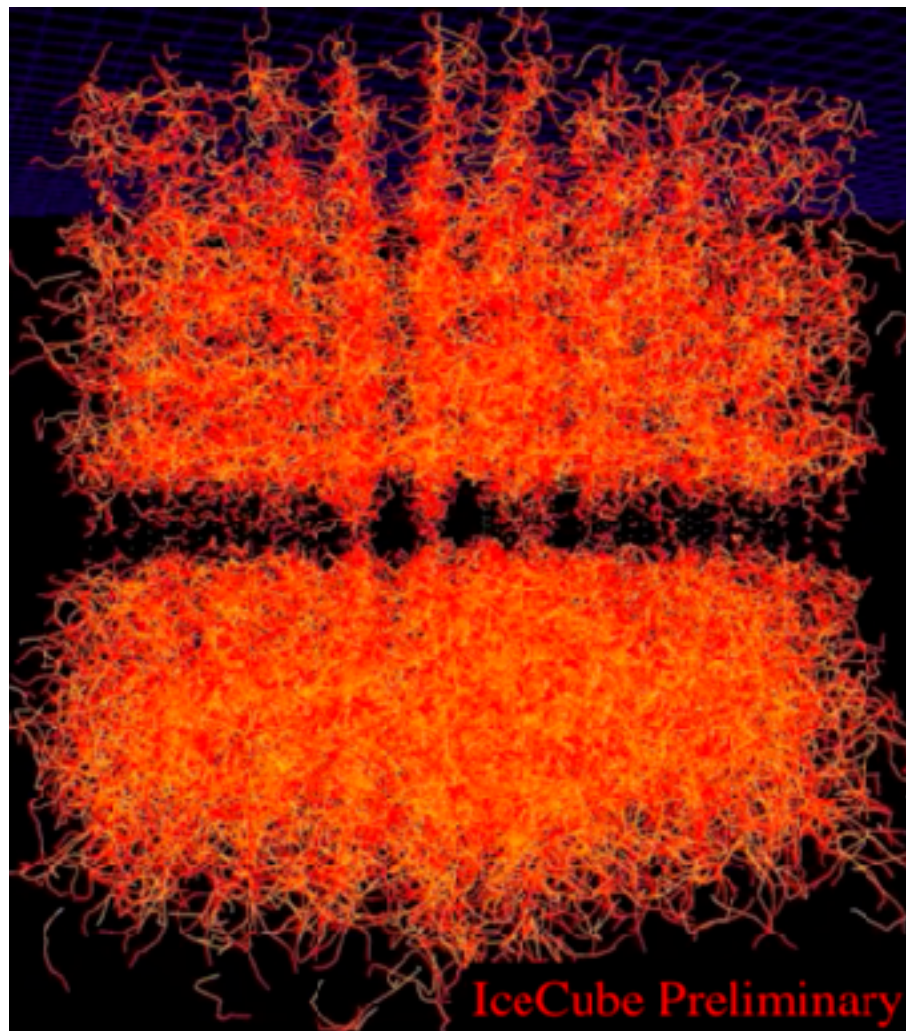
WG Misc.

> **I didn't mention Simulation (we heard about this from Juan Carlos)**

> **I left out R&D WGs**
> - Because the Upgrade and Gen2 aren't built yet, we don't have data for them, and they don't need to go through the same unblinding procedures

> **Besides attending WG calls, a good way to learn about WGs is at collaboration meetings**

HOW TO WRITE A PAPER

Develop analysis with simulation or scrambled data

→

Submit paper to journal 🎉

23

HOW TO WRITE A PAPER

Develop analysis with simulation or scrambled data ➡ Unblind Analysis ➡ Write paper outline ➡ Write Paper ➡ Submit paper to journal 🎉

HOW TO WRITE A PAPER

Develop analysis with simulation or scrambled data

Unblind Analysis

Write paper outline

Write Paper

Submit paper to journal 🎉

Unblinding approval from WG

Unblinding approval by analysis reviewers

Unblinding request on analysis call

HOW TO WRITE A PAPER

Develop analysis with simulation or scrambled data → Unblinding approval from WG → Unblinding approval by analysis reviewers → Unblinding request on analysis call → Unblind Analysis → Present results on WG call → Write paper outline → Write Paper → Submit paper to journal 🎉

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        ↓
Unblinding approval from WG
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        ↓
Unblinding request on analysis call
        →
Unblind Analysis
        ↓
Present results on WG call
        →
Write paper outline
        ↓
Outline approval by WG
        ↓
Outline approval request on analysis call
        →
Write Paper
        ↓
Paper approval from WG
        ↓
Paper approval from paper committee
        ↓
Paper circulated to icecube-c
        →
Submit paper to journal 🎉
```

23

THANK YOU!