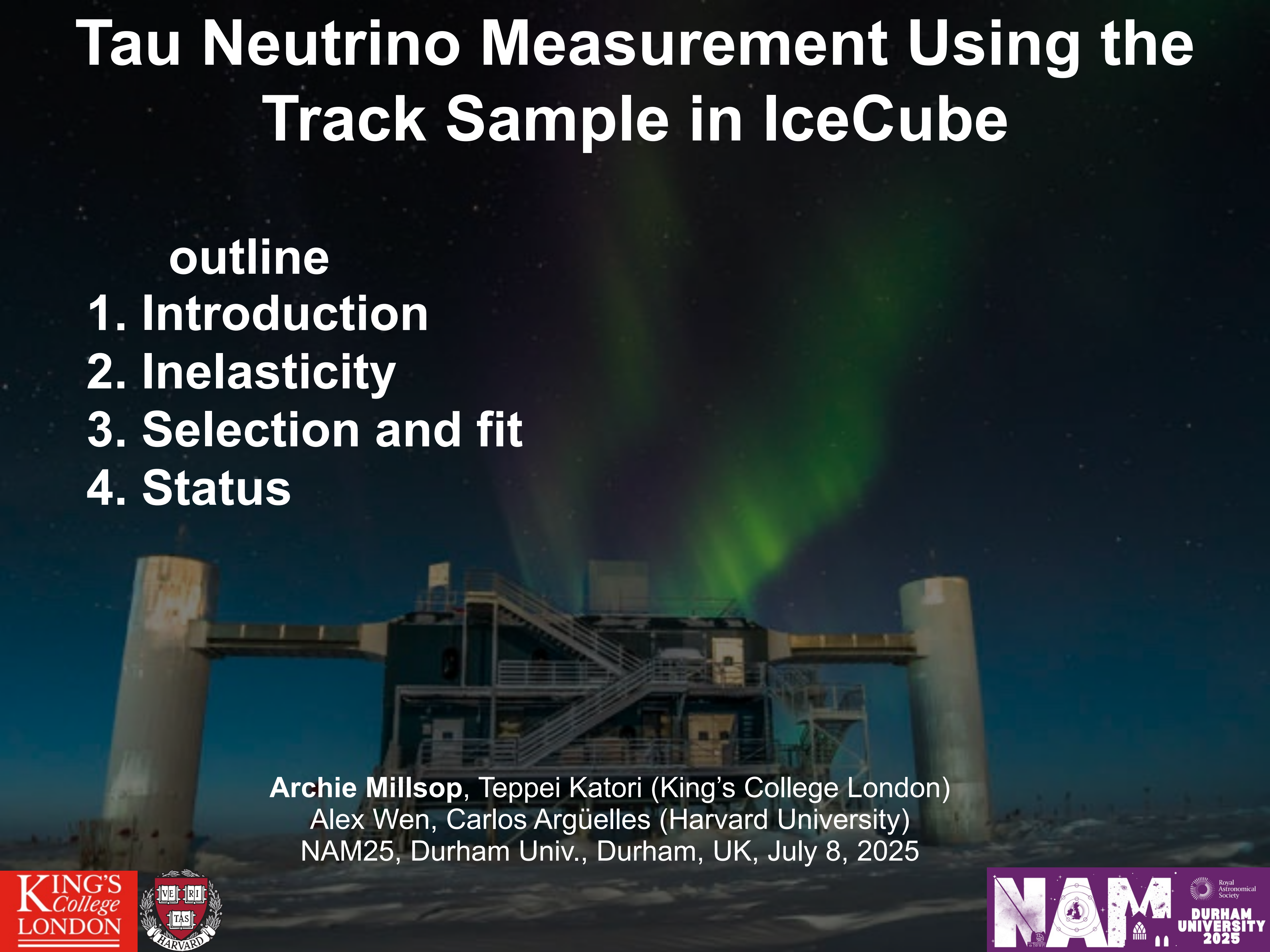
Tau Neutrino Measurement Using the Track Sample in IceCube

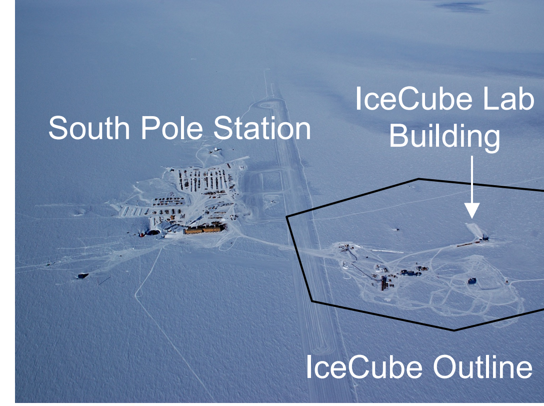


outline

1. Introduction
2. Inelasticity
3. Selection and fit
4. Status

Archie Millsop, Teppei Katori (King's College London)
Alex Wen, Carlos Argüelles (Harvard University)
NAM25, Durham Univ., Durham, UK, July 8, 2025

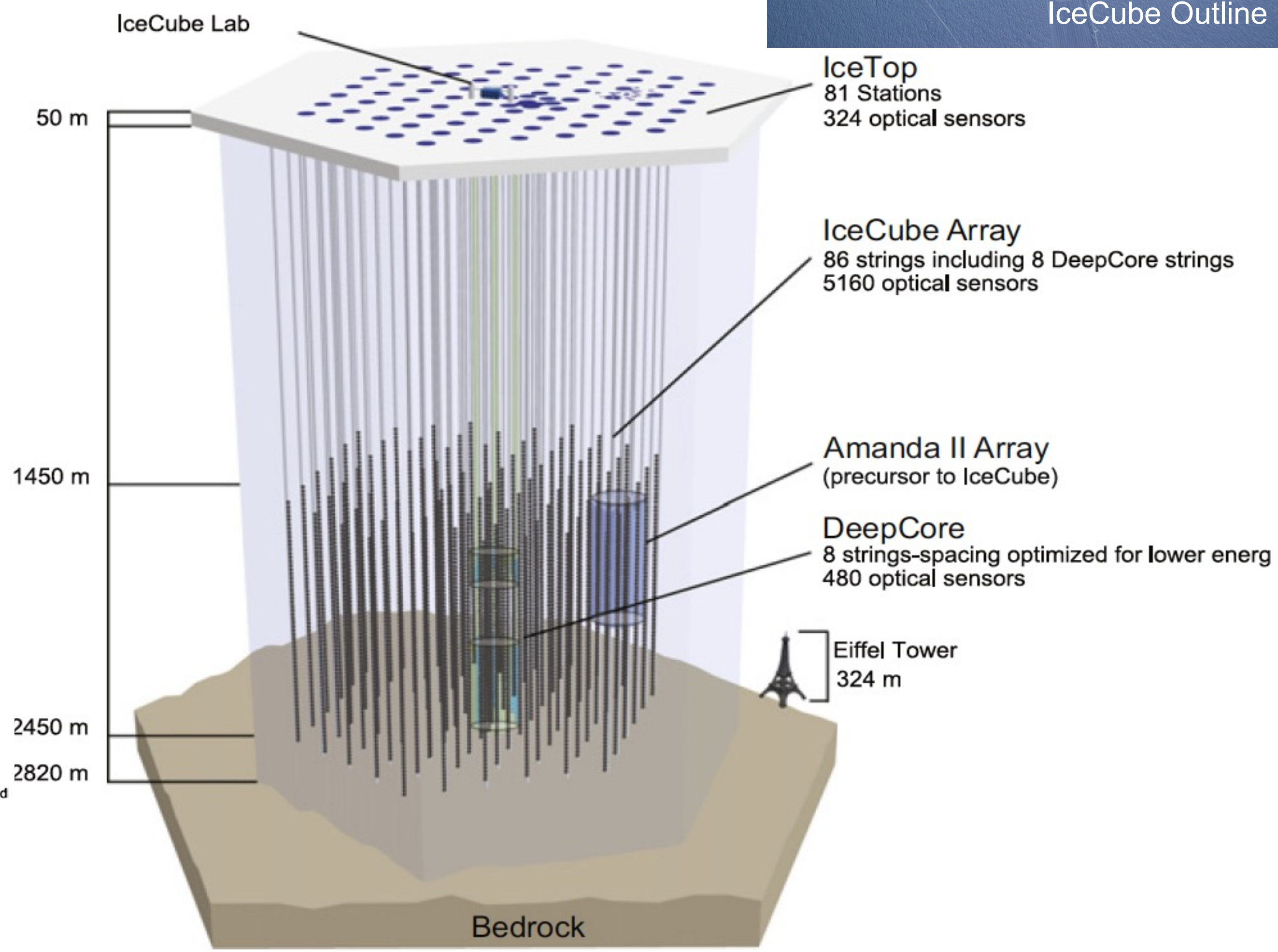
1. IceCube detector



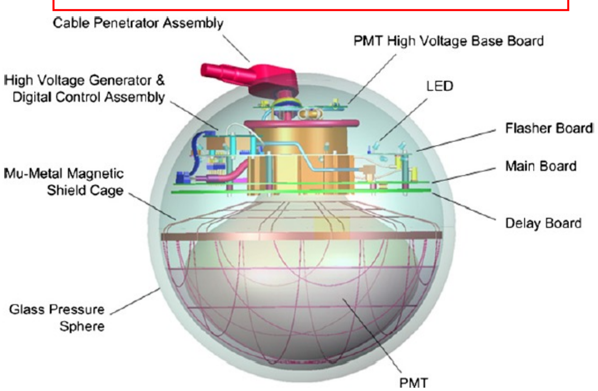
IceCube is a ~1km^3 ice-based Cherenkov detector, primarily designed to detect high energy astrophysical neutrinos.

Based at the south pole, kilometres under the ice.

Uses strings of downwards-facing PMTs in Digital Optical Modules (DOMs) to detect photons from neutrino events.



digital optical module (DOM)



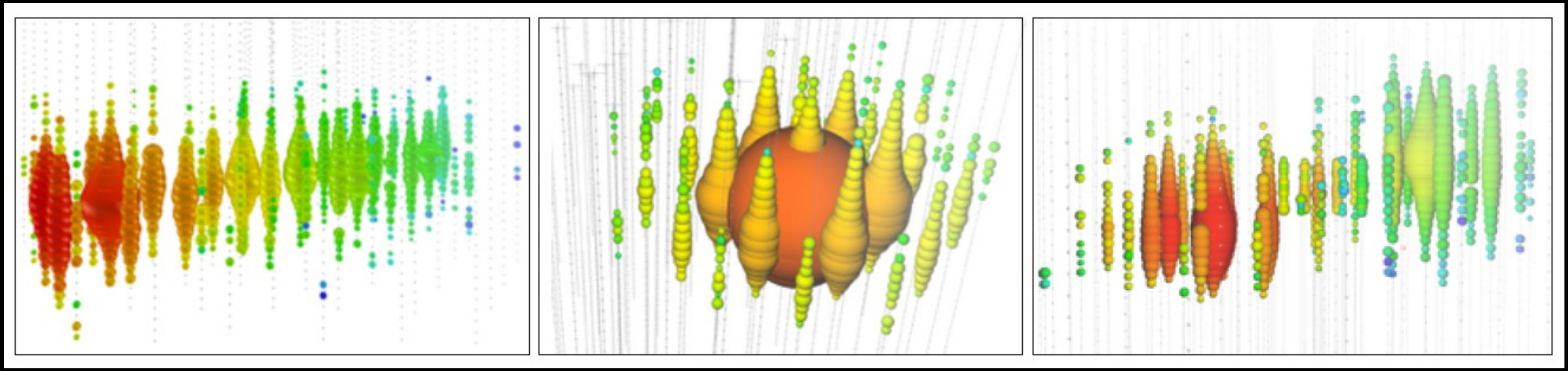
IceCube-Gen2, J.Phys.G.48(2021) 060501

1. IceCube event morphology

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

Cascade
ν_eCC, ν_τCC, NC
$$\nu_e + N \rightarrow e + X$$
$$\nu_\tau + N \rightarrow \tau + X$$
$$\nu_x + N \rightarrow \nu_x + X$$

Double cascade
ν_τCC (L~50m•E/PeV)
$$\nu_\tau + N \rightarrow \tau + X$$
$$\tau \rightarrow X' \text{ (62\%)}$$



1. Inelasticity-based PID

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

Cascade
ν_eCC, ν_τCC, NC
$$\nu_e + N \rightarrow e + X$$
$$\nu_\tau + N \rightarrow \tau + X$$
$$\nu_x + N \rightarrow \nu_x + X$$

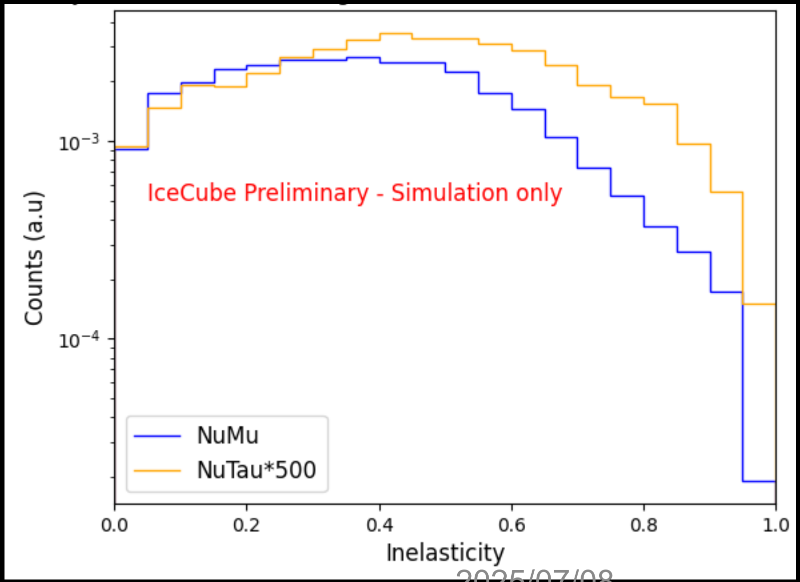
Double cascade
ν_τCC (L~50m•E/PeV)
$$\nu_\tau + N \rightarrow \tau + X$$
$$\tau \rightarrow X' \text{ (62\%)}$$

Trak from Tau decay
ν_τCC
$$\nu_\tau + N \rightarrow \tau + X$$
$$\tau \rightarrow \mu + \bar{\nu}_\mu + \nu_\tau \text{ (18\%)}$$

Relatively smaller track energy due to neutrino emissions.
→ Larger effective inelasticity

Tau decay track can be statistically separated

$$y_{eff} = \frac{E_{had}}{E_{vis}}$$



IceCube,EPJC82(2022)1031, PRL132(2024)151001

1. Tau neutrino measurements in IceCube

ICECUBE

Atmospheric neutrino oscillation length ~12700 km (earth diameter) at ~35 GeV
→ no tau neutrinos from conventional atmospheric neutrinos above ~35 GeV

Tau neutrino sources
1. Astrophysical tau neutrinos
2. Charm-decay tau neutrino (prompt atmospheric neutrino)
   → haven't observed yet
3. exotic process (new physics)

So far, tau neutrinos are only identified in cascade samples.

Identifying tau neutrinos are difficult,
but tau neutrino measurement has many interesting topics!

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2. Inelasticity

Inelasticity y is defined

$$y = \frac{\nu}{E}$$

Experimentally,

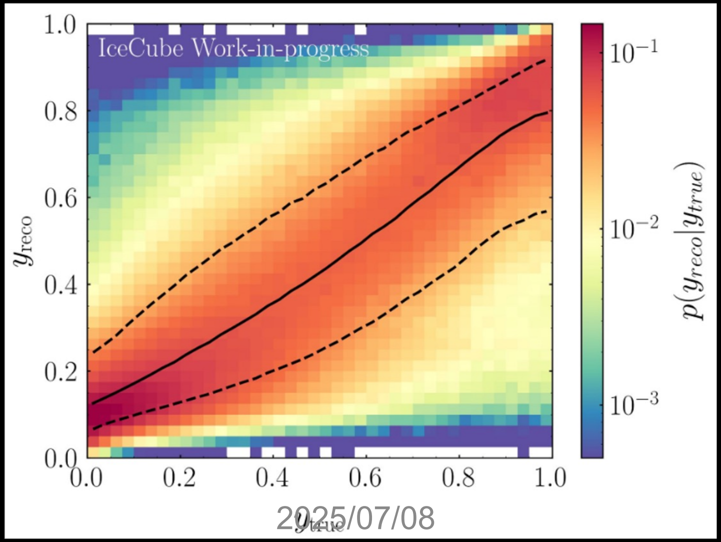
$$E = E_{vis} = E_{track} + E_{had}$$
$$\nu = E_{vis} - E_{track} = E_{had}$$

Effective y is defined

$$y_{eff} = \frac{E_{had}}{E_{vis}}$$

MAMBA-based y-reconstruction is underway

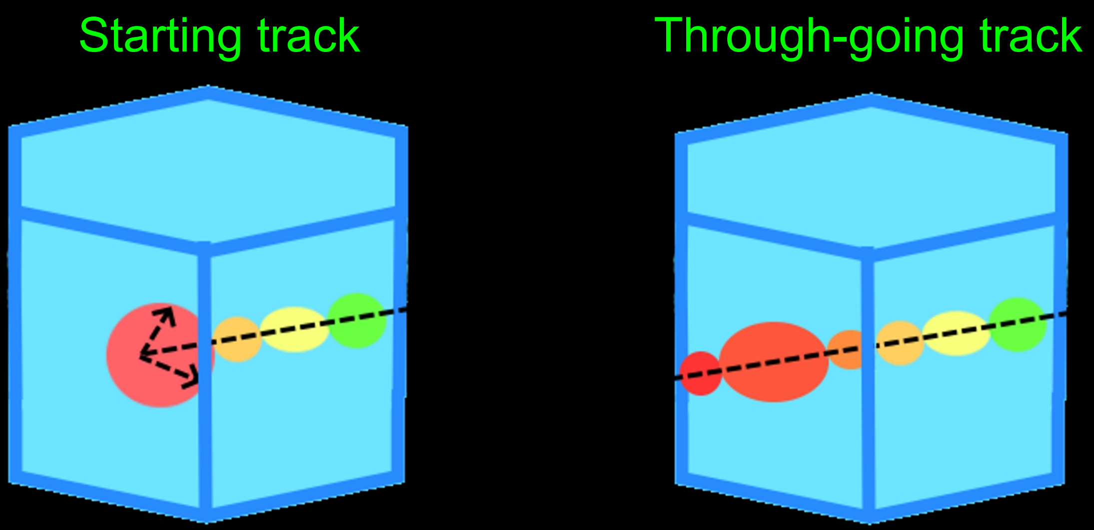
- Inelasticity is also useful to nu/nubar separation



Icecube, PRL133 (2024) 201804

3. Selection

MEOWS (Matter-enhanced oscillations with steriles)
- Developed for sterile neutrino search analysis
- BDT-based selection
- 99.9% pure muon track sample
  - 0.5-100 TeV
  - -1 < cosθ < 0 (upgoing)
  - Starting track ~25%

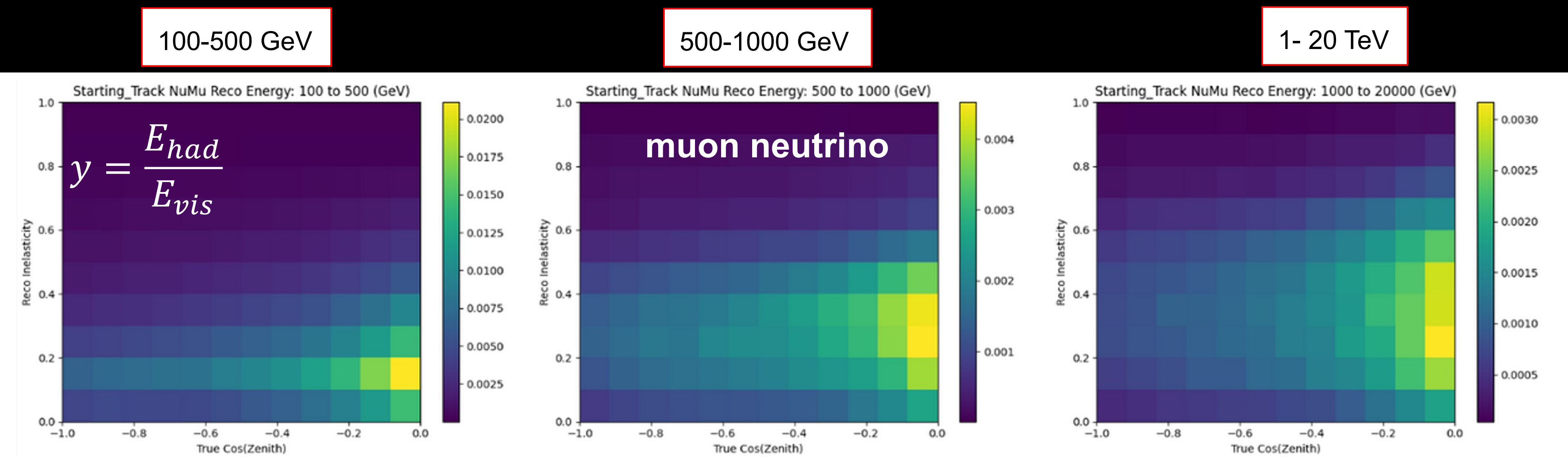


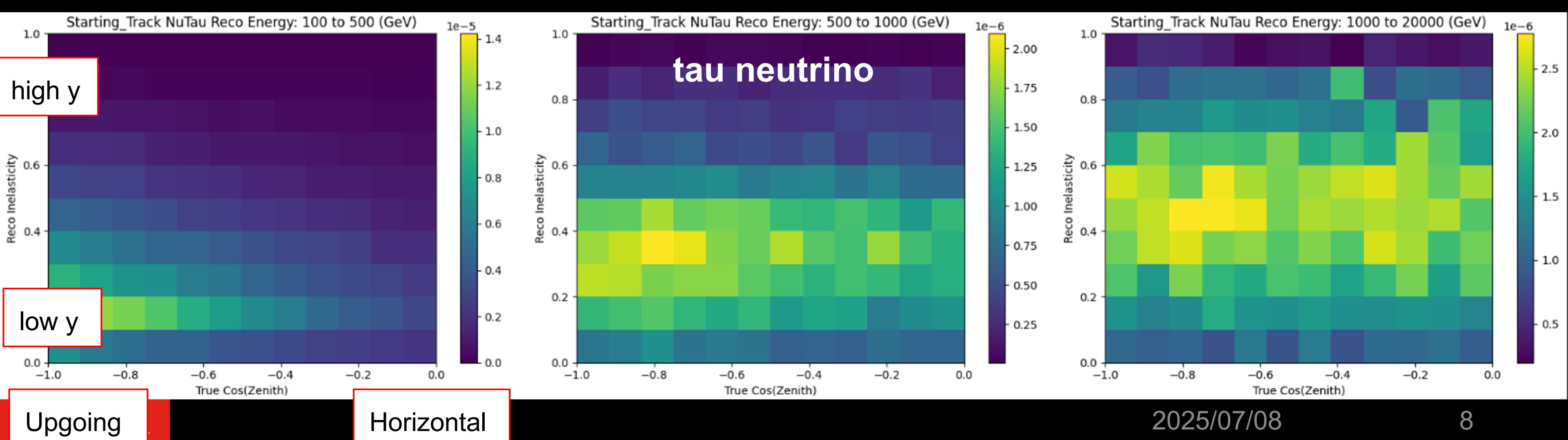
Muon neutrino MC sample

- Mostly horizontal events → atmospheric
- Inelasticity peak at low

Tau neutrino MC sample

- From all direction → astrophysical
- Inelasticity peak is higher





Icecube, ArXiv:2506.04491

3. Fit

GollumFit
- Developed for high-energy neutrino analysis
- Public software of binned likelihood fit
- 3-dimension (energy, angle, morphology)
- 37 nuisance parameters
  - Normalization
  - Conventional atmospheric neutrino flux
  - Prompt atmospheric neutrino flux
  - Astrophysical neutrino flux
  - Cross section
  - Detector response
  - Bulk ice model

We added the 4th fitting dimension (inelasticity) and a new nuisance parameter (numu/nutau ratio)

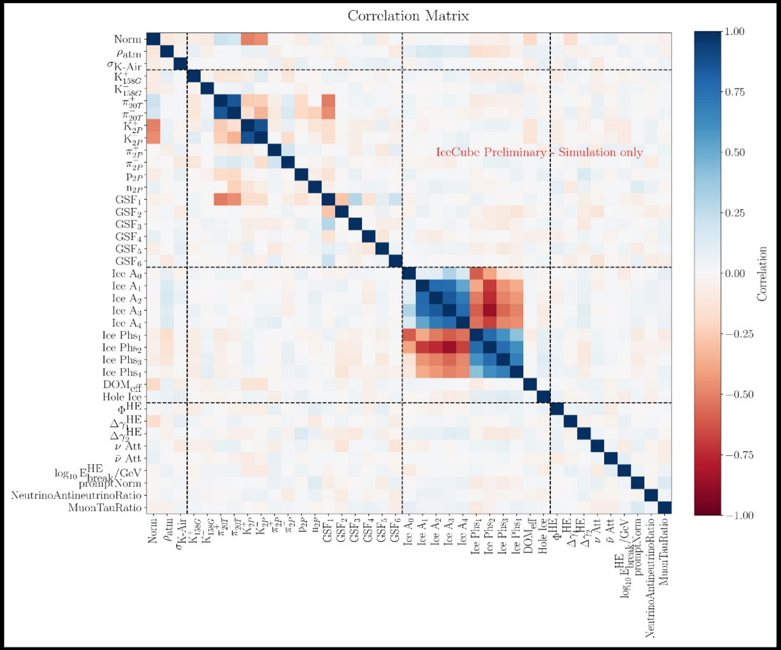
Key	Variable	Value ± Width
Common to all neutrino telescopes		
convNorm	convNorm	1.0 ± 0.2
ρ_{atm}	zenithCorrection	0.0 ± 1.0
$\sigma_{\text{K-Air}}$	kaonLosses	0.0 ± 1.0
K^+_{158G}	hadronicHEkp	0.0 ± 1.0
K^-_{158G}	hadronicHEkm	0.0 ± 1.0
π^+_{20T}	hadronicVHE1pip	0.0 ± 1.0
π^-_{20T}	hadronicVHE1pim	0.0 ± 1.0
K^+_{2P}	hadronicVHE3kp	0.0 ± 1.0
K^-_{2P}	hadronicVHE3km	0.0 ± 1.0
π^+_{2P}	hadronicVHE3pip	0.0 ± 1.0
π^-_{2P}	hadronicVHE3pim	0.0 ± 1.0
p_{2P}	hadronicVHE3p	0.0 ± 1.0
n_{2P}	hadronicVHE3n	0.0 ± 1.0
GSF_1	cosmicRay1	0.0 ± 1.0
GSF_2	cosmicRay2	0.0 ± 1.0
GSF_3	cosmicRay3	0.0 ± 1.0
GSF_4	cosmicRay4	0.0 ± 1.0
GSF_5	cosmicRay5	0.0 ± 1.0
GSF_6	cosmicRay6	0.0 ± 1.0
$\Phi^{\text{HE}}/10^{-18}\text{GeV}^{-1}\text{sr}^{-1}\text{s}^{-1}\text{cm}^{-2}$	astroNorm	0.787 ± 0.36
$\Delta\gamma_1^{\text{HE}}$	astroDeltaGamma	0.0 ± 0.36
$\Delta\gamma_2^{\text{HE}}$	astroDeltaGammaSec	0.0 ± 0.36
$\log_{10}(E^{\text{HE}}_{\text{break}}/\text{GeV})$	astroPivot	5.0 ± 1.0
promptNorm	promptNorm	1.0 ± 1.0
$\nu/\bar{\nu}$	NeutrinoAntineutrinoRatio	1.0 ± 1.0
ν Att	nuxs	1.0 ± 0.1
$\bar{\nu}$ Att	nubarxs	1.0 ± 0.1
IceCube Monte Carlo parameters		
DOM eff	domEfficiency	1.27 ± 0.123
Hole Ice	holeiceForward	-1.0 ± 10.0
Ice A_0	icegrad0	0.0 ± 1.0
Ice A_1	icegrad1	0.0 ± 1.0
Ice A_2	icegrad2	0.0 ± 1.0
Ice A_3	icegrad3	0.0 ± 1.0
Ice A_4	icegrad4	0.0 ± 1.0
Ice Phs_1	icegrad5	0.0 ± 1.0
Ice Phs_2	icegrad6	0.0 ± 1.0
Ice Phs_3	icegrad7	0.0 ± 1.0
Ice Phs_4	icegrad8	0.0 ± 1.0

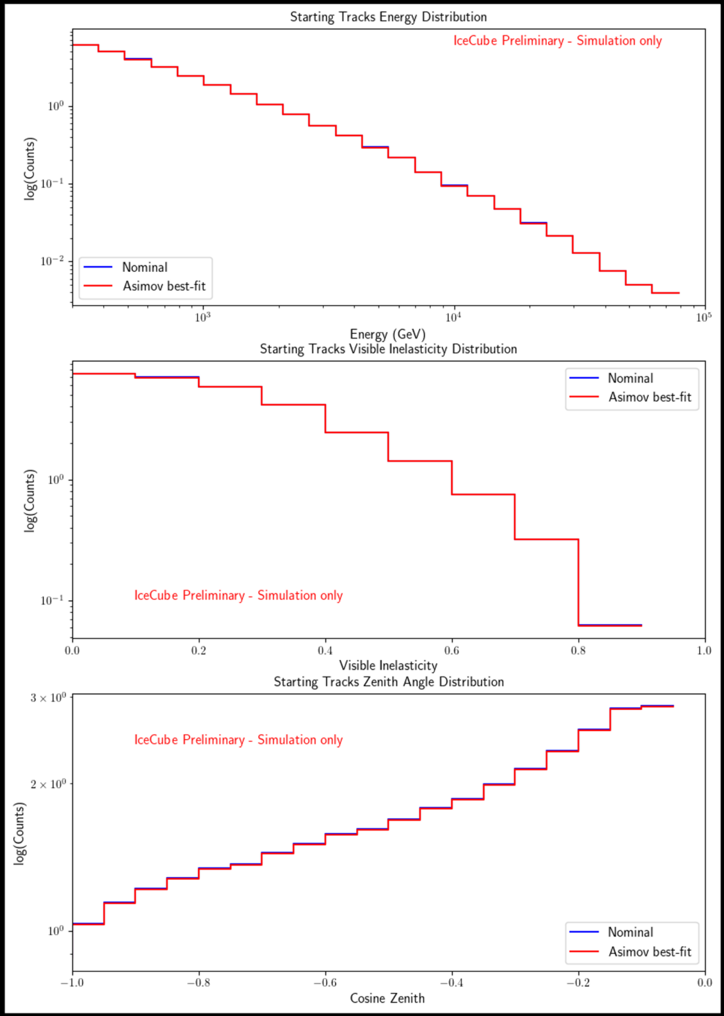
Icecube, ArXiv:2506.04491

3. Fit

Fit results

- Asimov fit returns the expected values
- Correlations between ice model parameters
- Correlations between atmospheric neutrino flux parameters.
- MuonTauRatio parameter has no strong correlations





Icecube, ArXiv:2506.04491

3. Fit

Fit results
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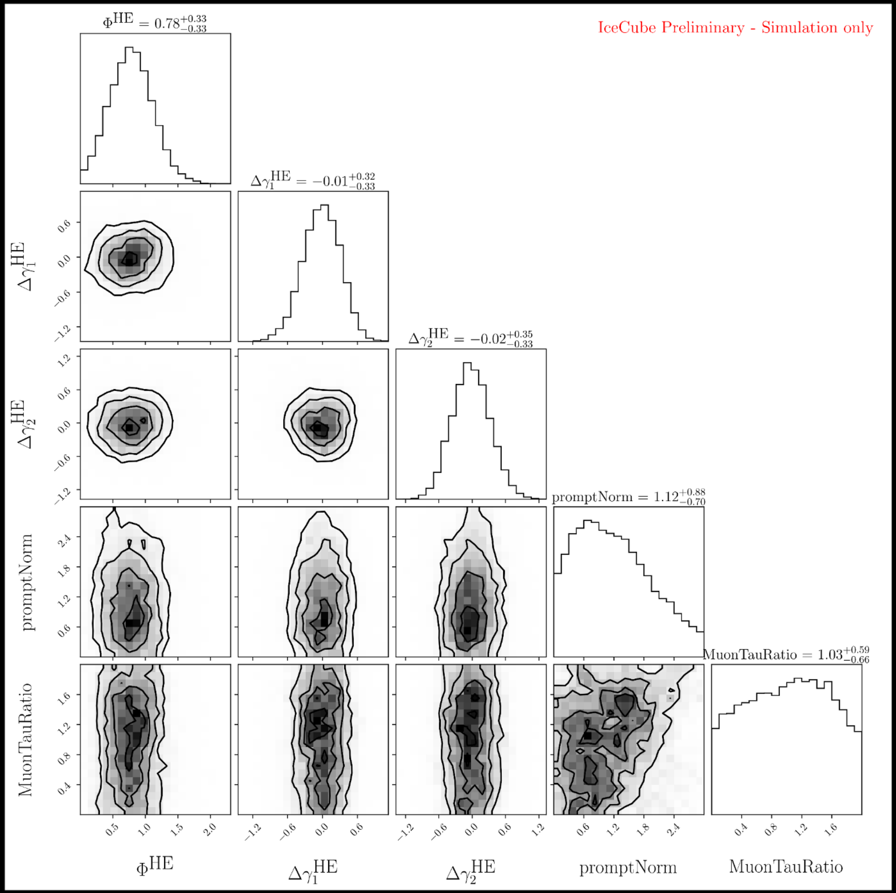
Nuisance parameters correlations
- astro norm, 2 astro spectral indices, prompt flux norm, MuonTauRatio.
- MuonTauRatio not correlated with astro parameters, but positive correlation to the prompt flux normalisation.

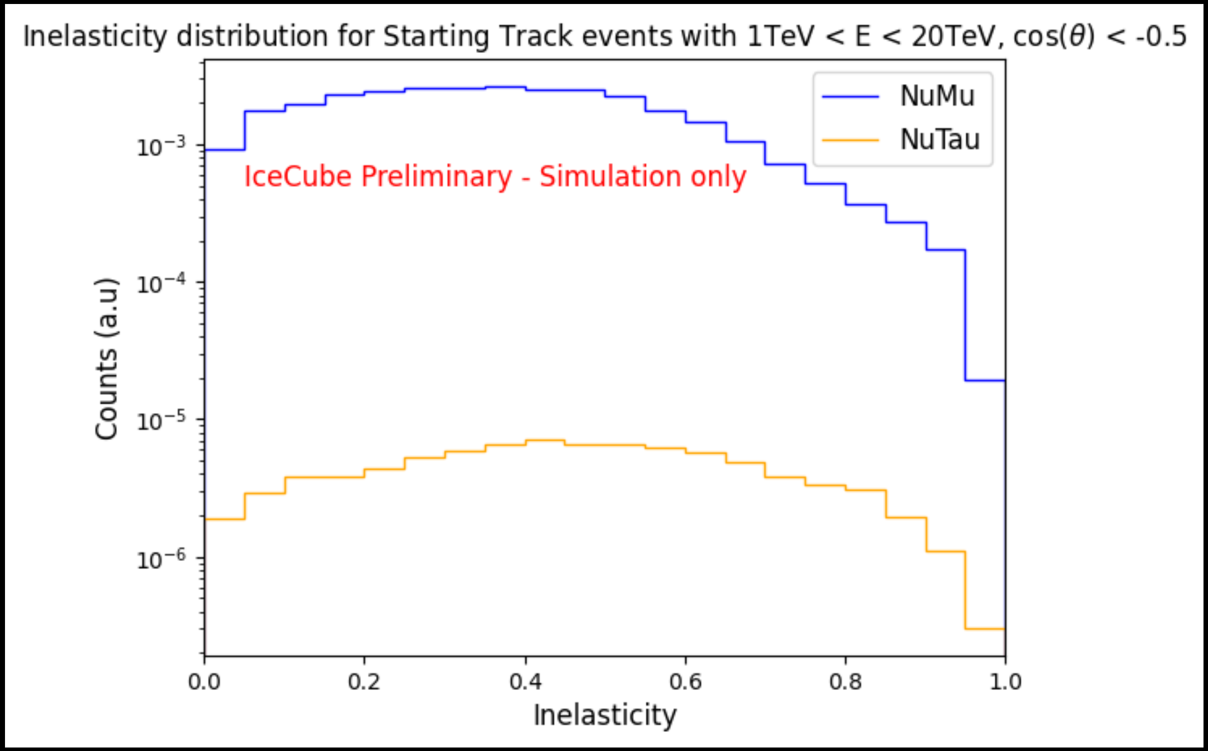


3. Fit

Inelasticity distribution
There are overwhelming amount of muon neutrinos
- Energy cut (1-20 TeV)
- Angle cut (cosθ < -0.5)

Expected tau neutrino events are ~1% of muon neutrino events.

Tau neutrino particle identification method is being constructed.

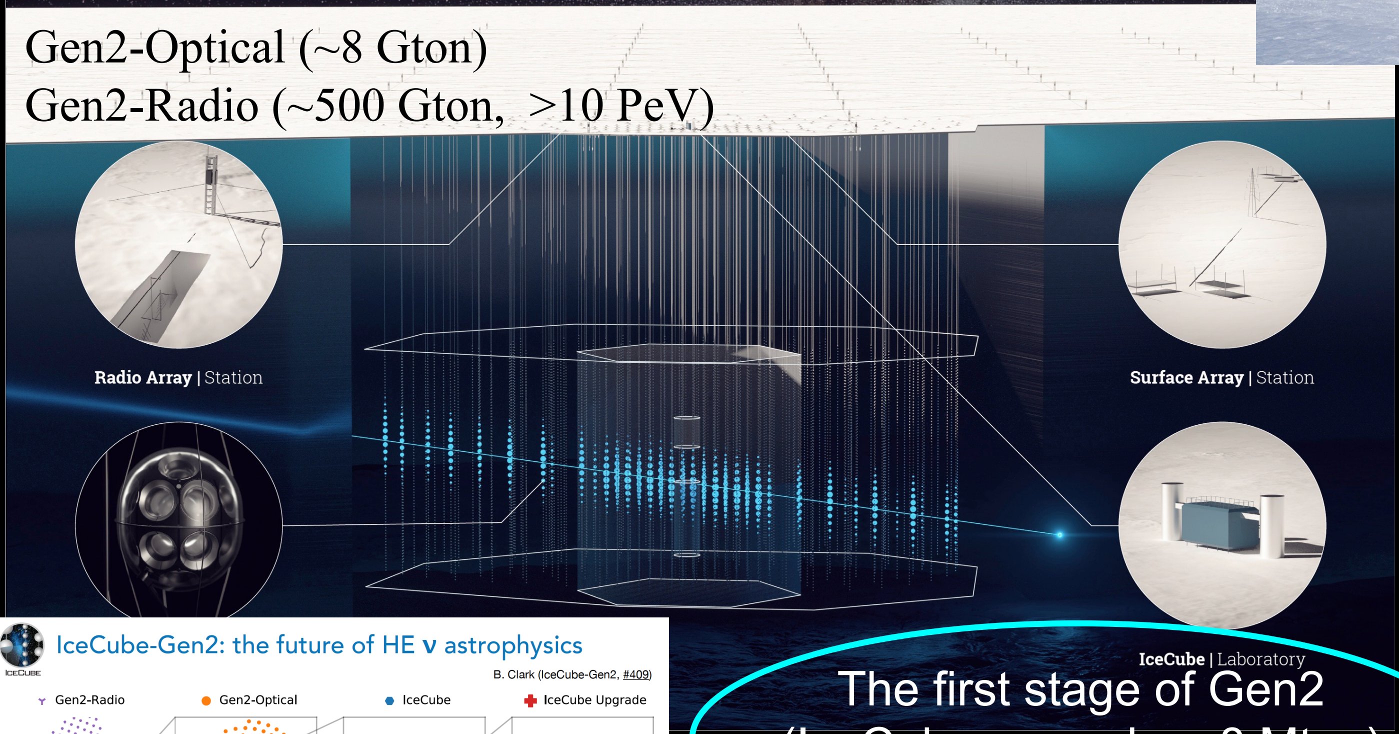


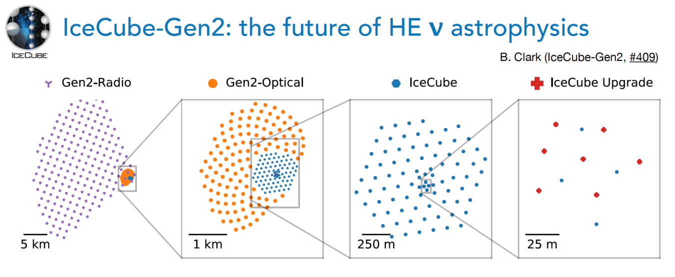
IceCube-Gen2

Summer 2024-2045
IceCube team

New international neutrino astronomy projects around the world
- Best astrophysical neutrino flavour measurement

Gen2-Optical (~8 Gton)
Gen2-Radio (~500 Gton, >10 PeV)





The first stage of Gen2
(IceCube upgrade, ~8 Mton)
is ongoing

Status

Tau neutrinos are the new signal of astrophysical neutrinos

New starting track sample reconstruction and selection is in progress

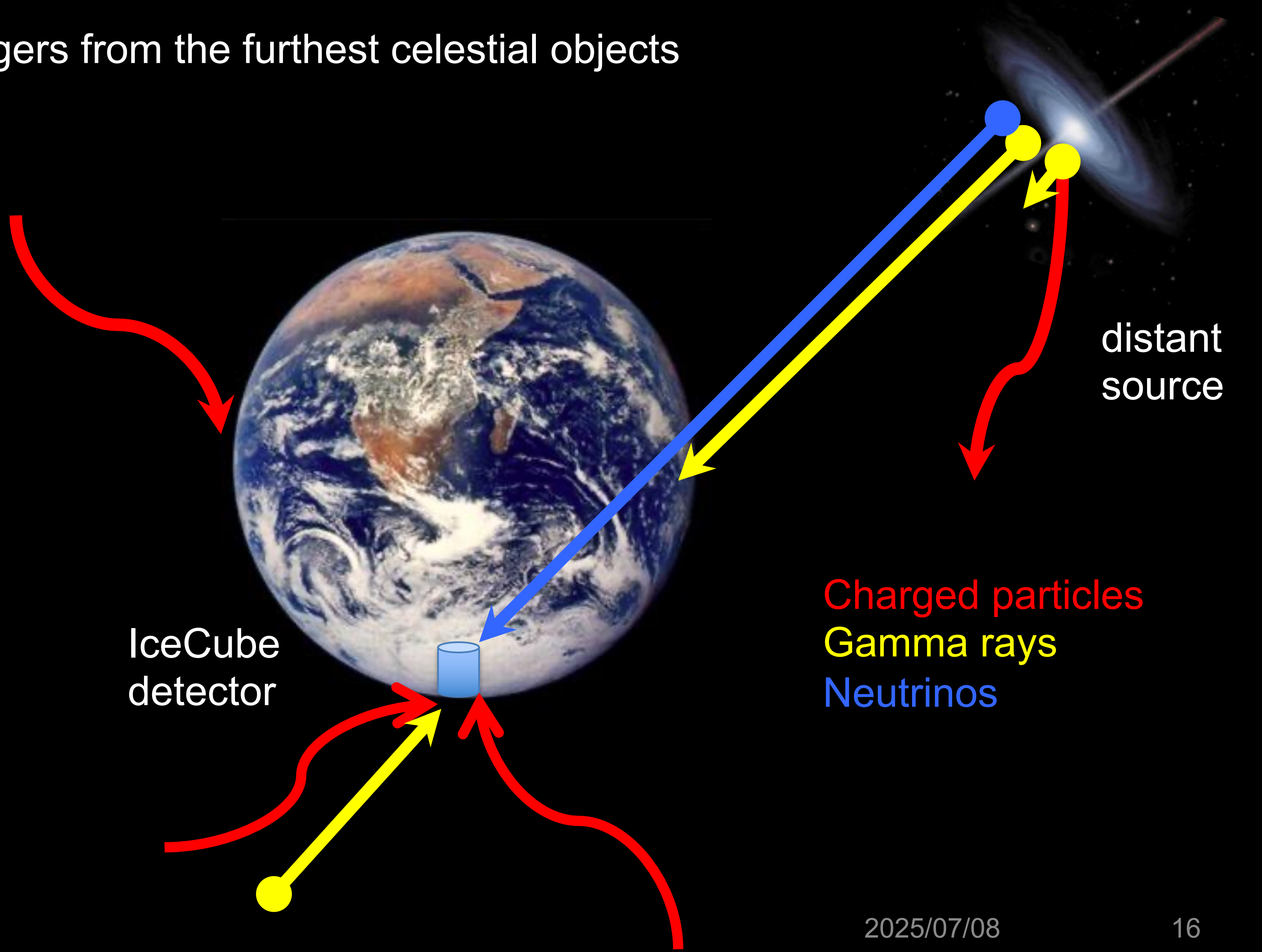
New inelasticity-based tau track PID is being made

Thank you for your attention!

Backup

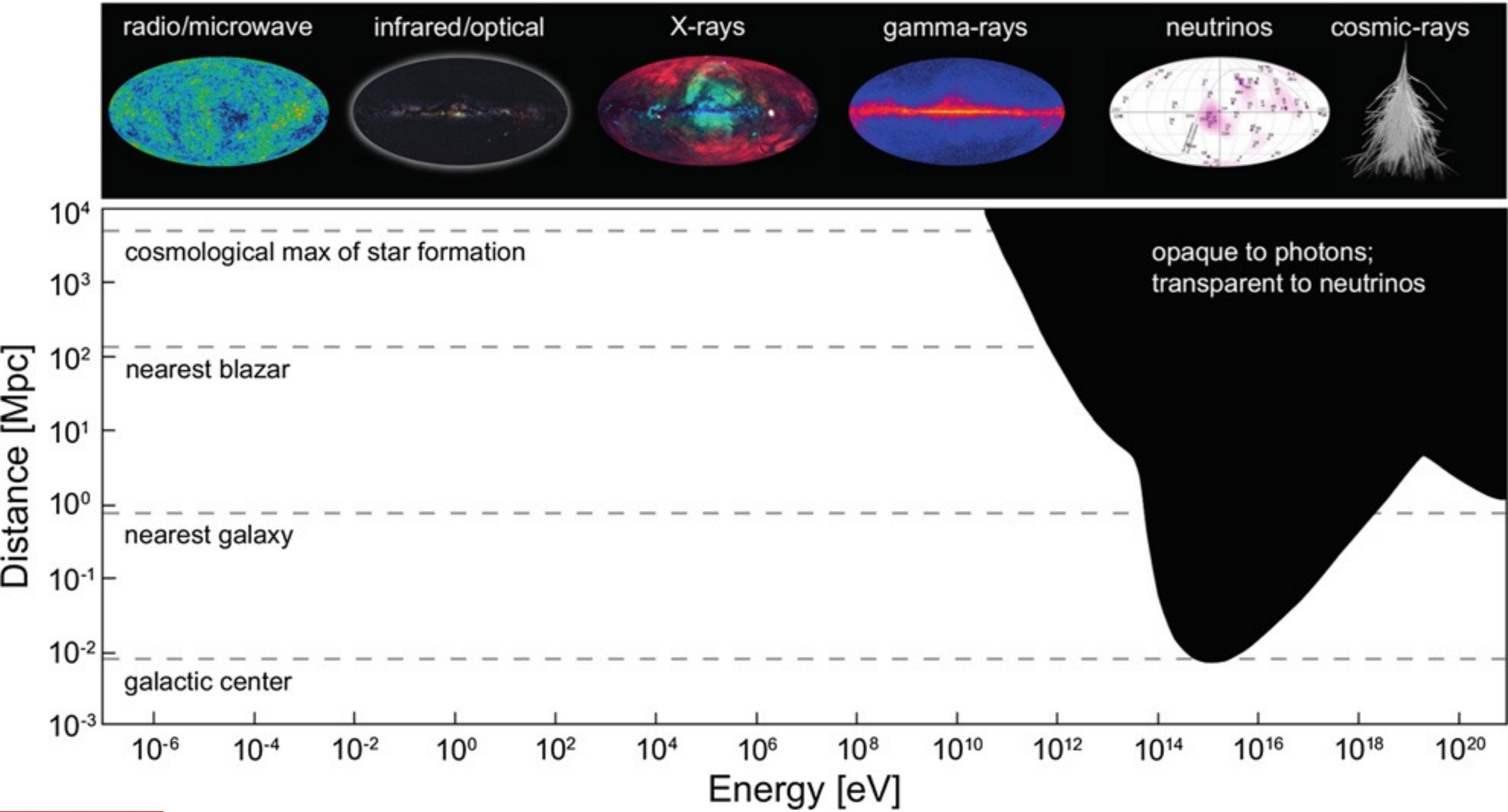
1. High-Energy Astrophysical Neutrinos

Direct messengers from the furthest celestial objects



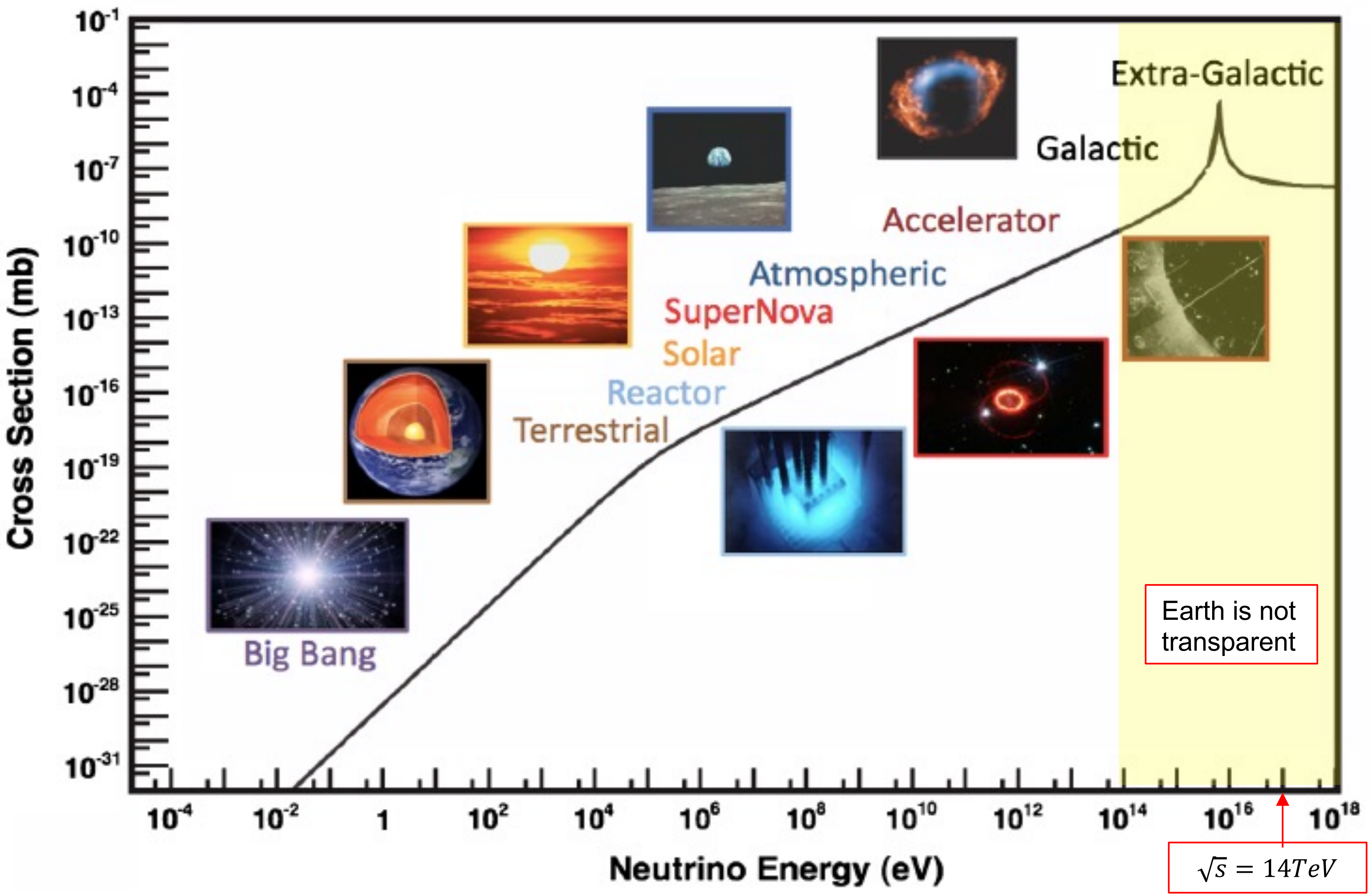
1. High-energy astrophysics

Above ~10-100 TeV neutrinos are only direct extra-galactic messengers



1. High-Energy Astrophysical Neutrinos

Above ~10-100 TeV neutrinos are only direct messengers

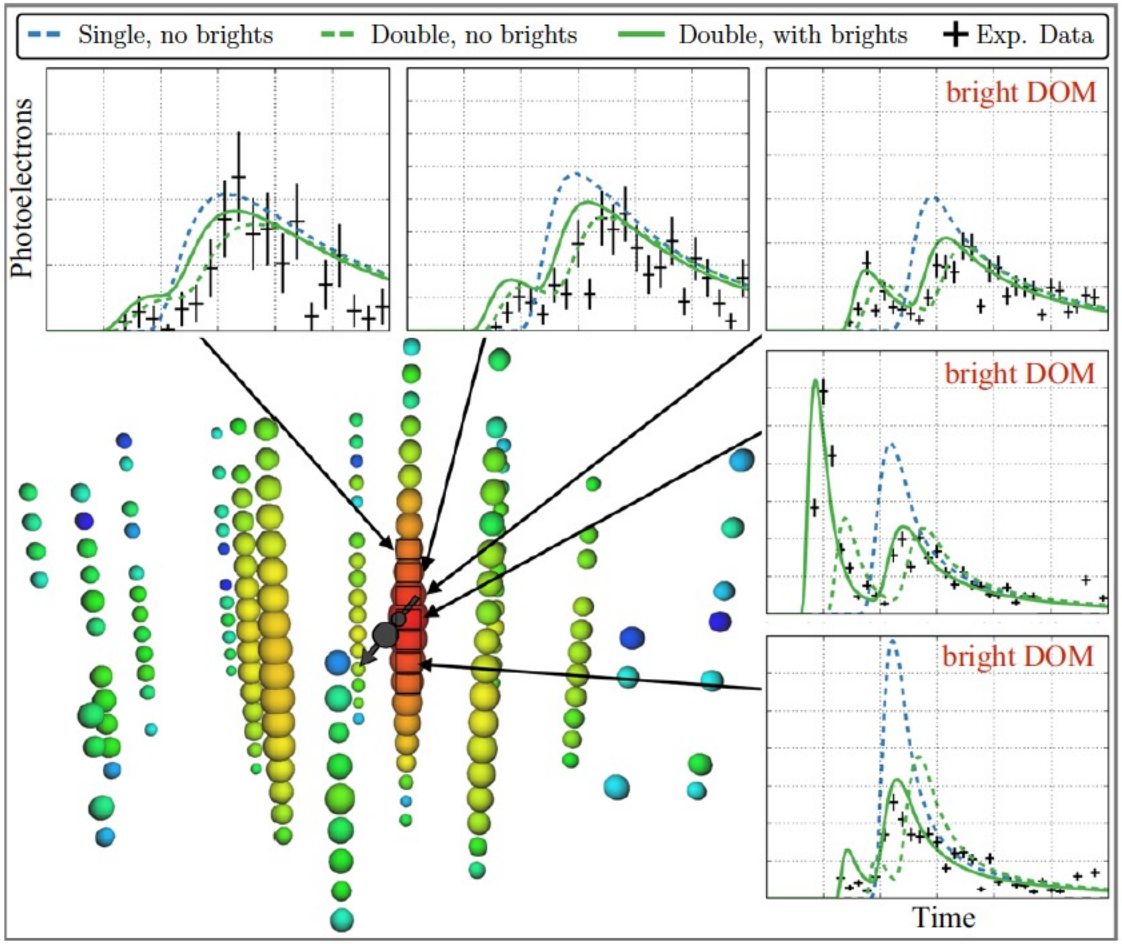


1. Astrophysical tau neutrinos

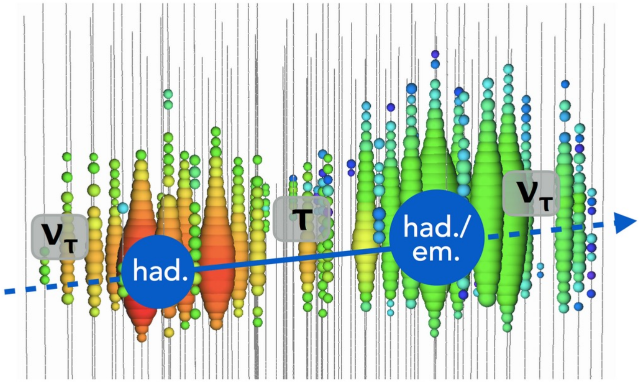
ICECUBE

Double Double

- newly discovered tau neutrino candidate



"Double bang" is rare (~50m•E/1PeV)



Double pulse can be found using timing information.

Improved tau PID algorithm is used for the flavour ratio

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