

Towards Multi-task transformer based reconstruction for real- time high-energy neutrino alerts.

Aske Rosted¹ on behalf of the IceCube collaboration.

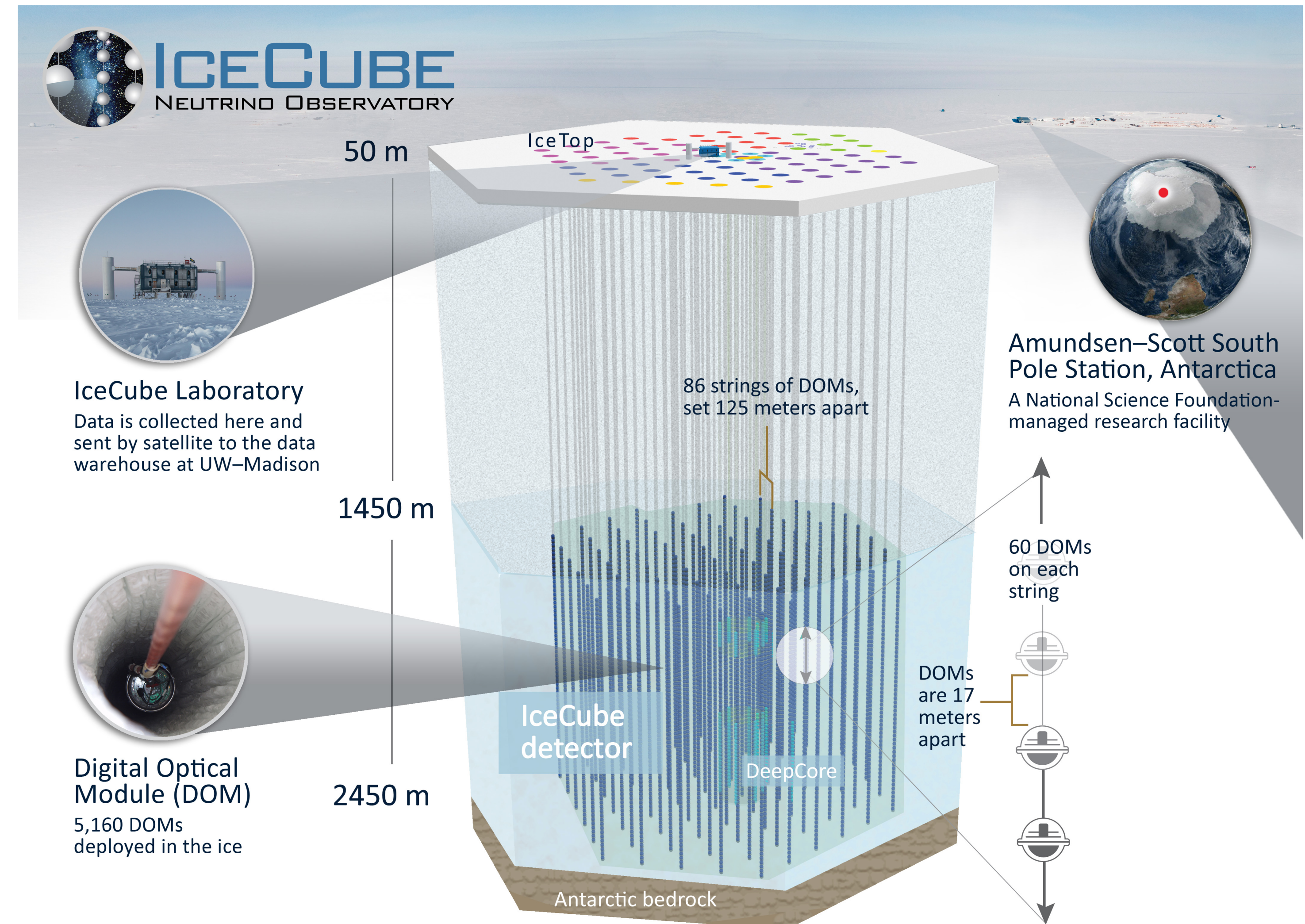
¹ICEHAP Chiba university

October 27, 2025

The IceCube experiment.

- Located in the clear ice below the surface of Antarctica
- Cubic-kilometer detector volume
- ~ 1.5 km under the ice surface.
- IceCube produces neutrino *alerts* to enable multi-messenger astronomy
- Currently produces ~10 (gold) alerts per year with 50% signal purity or ~20 (bronze) alerts with 30% signal purity

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The types of events that we see in IceCube.

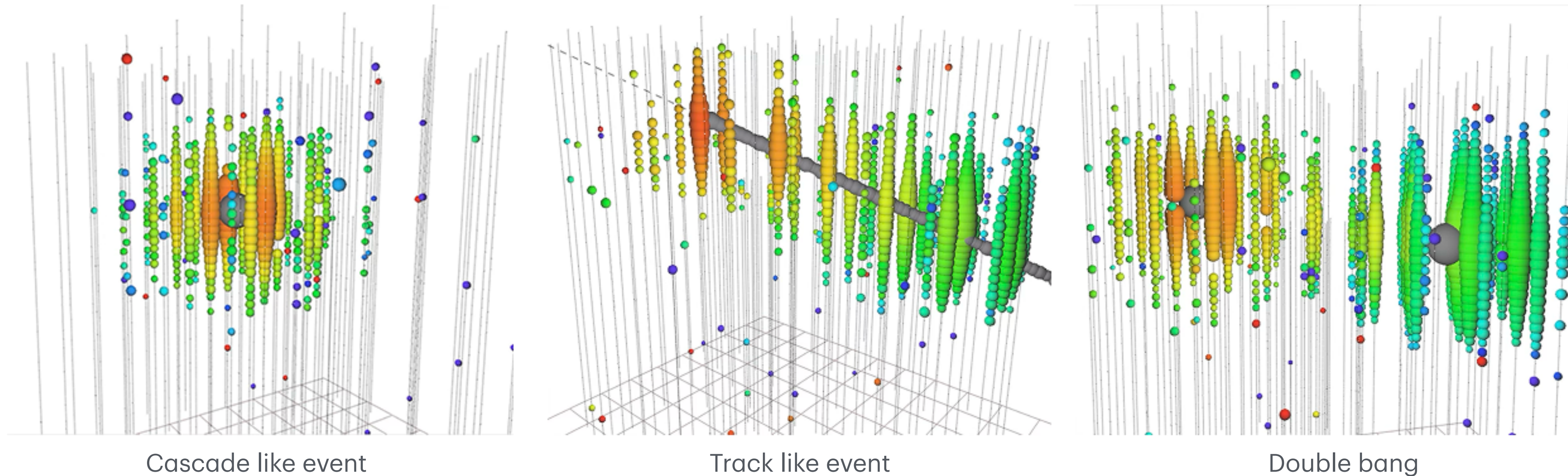


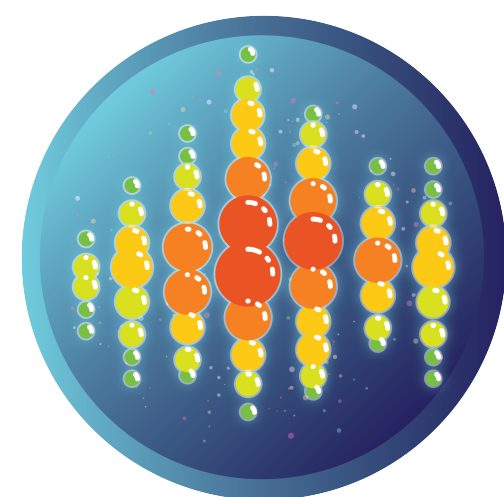
Figure altered from Usner, Marcel. (2017). Search for Astrophysical Tau Neutrinos in Six Years of High-Energy Starting Events in IceCube. 974. 10.22323/1.301.0974.

Tracks → starting, stopping, through-going.

Cascades → contained, uncontained.

Double bang → starting (contained/uncontained),
stopping

Fast event reconstruction & alerts in IceCube.



Event Triggered

Event splitter

Hit cleaning

Simple fitting algorithms

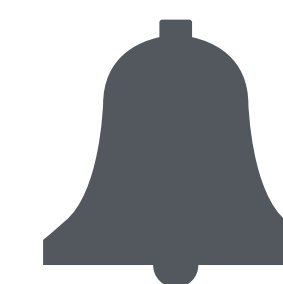


Low level cuts targeting
specific event morphology.

Based on convergence
of simple fit

Cuts on low level event
features

Reduce event rate



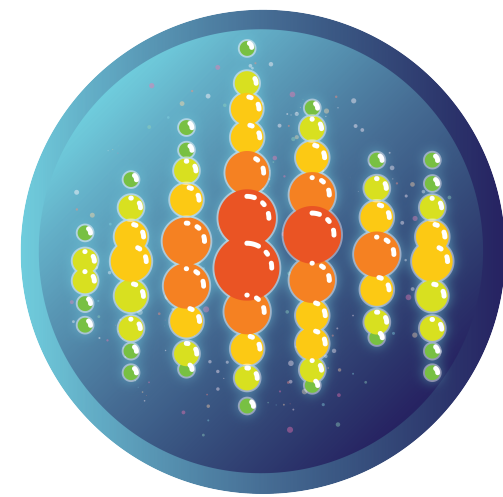
Alert

Reconstruction under
hypothesis

Use previous fit as seed

Final selection based
on reconstructed
features

Suggested approach for NN based alert

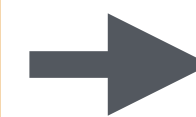


Event Triggered

Event splitter

Hit cleaning

Simple fitting algorithms



Simple cut on recorded charge

Reduce event rate



NN based alert

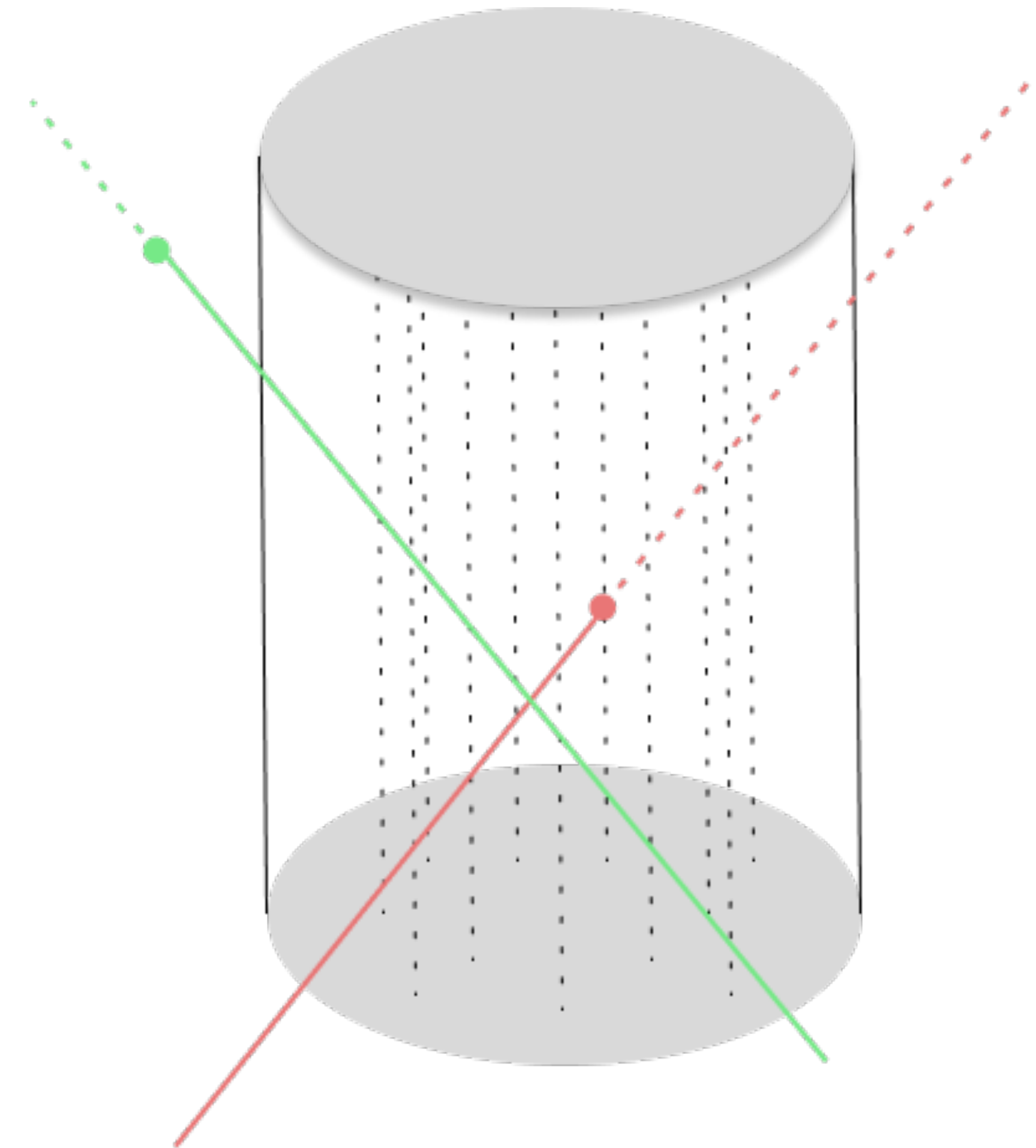
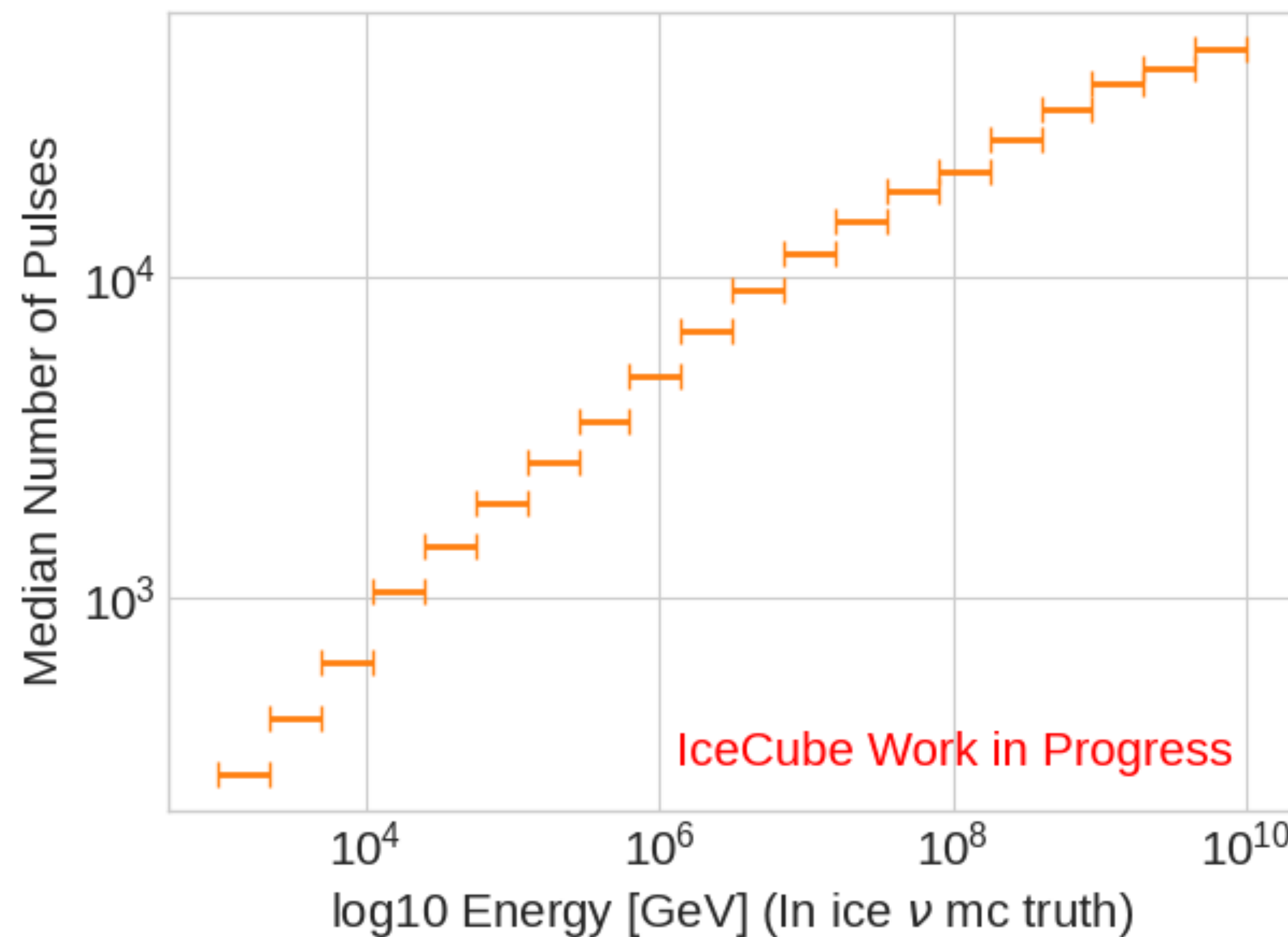
Use general NN based reconstruction

Reconstruct multiple features of the event

Cut based on reconstruction

Designing a machine learning model for high energy all type events at IceCube.

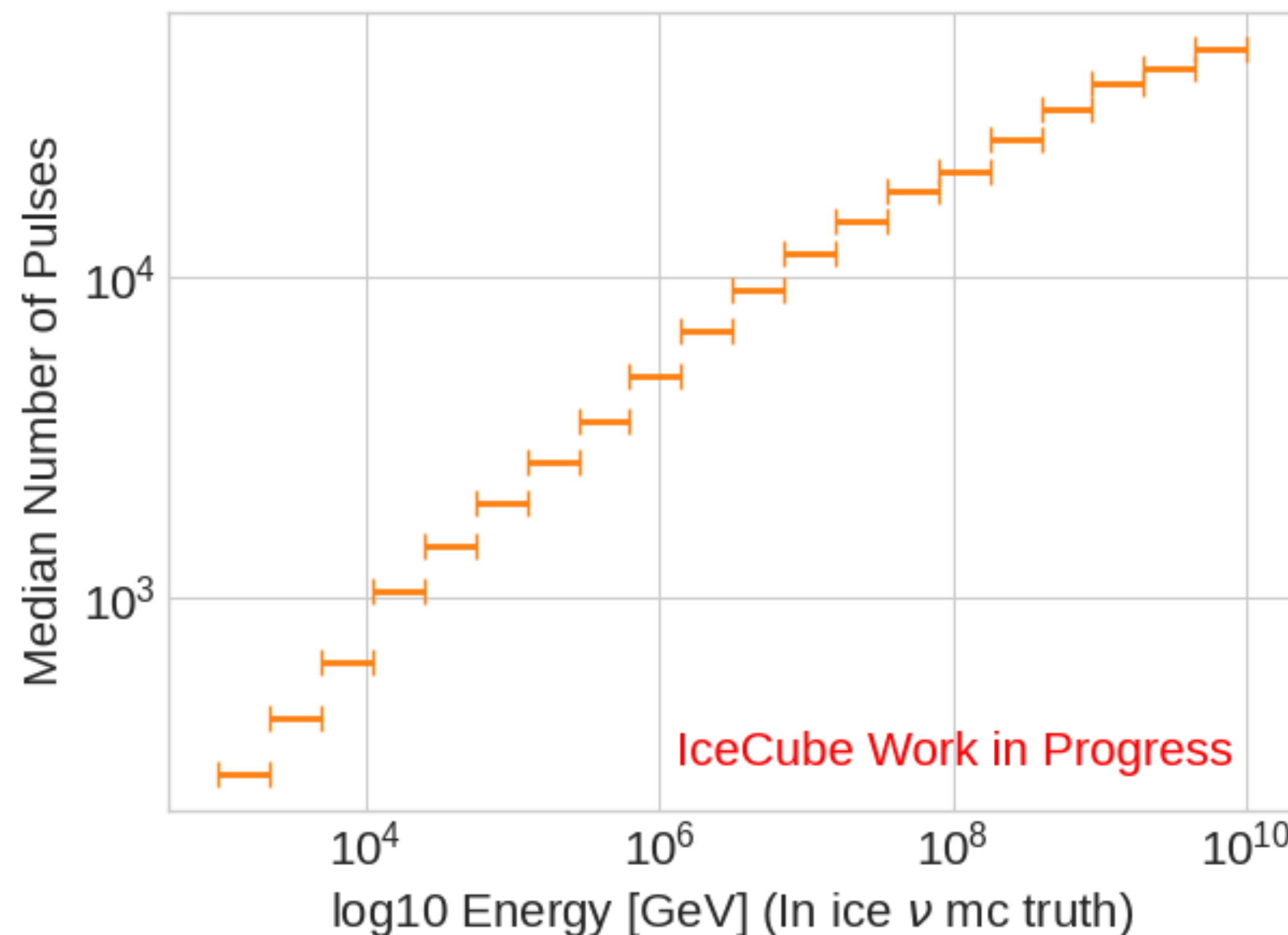
- Variable length input data. (Or extremely sparse or zero padded)
- Reconstructable features similar regardless of the event morphology.



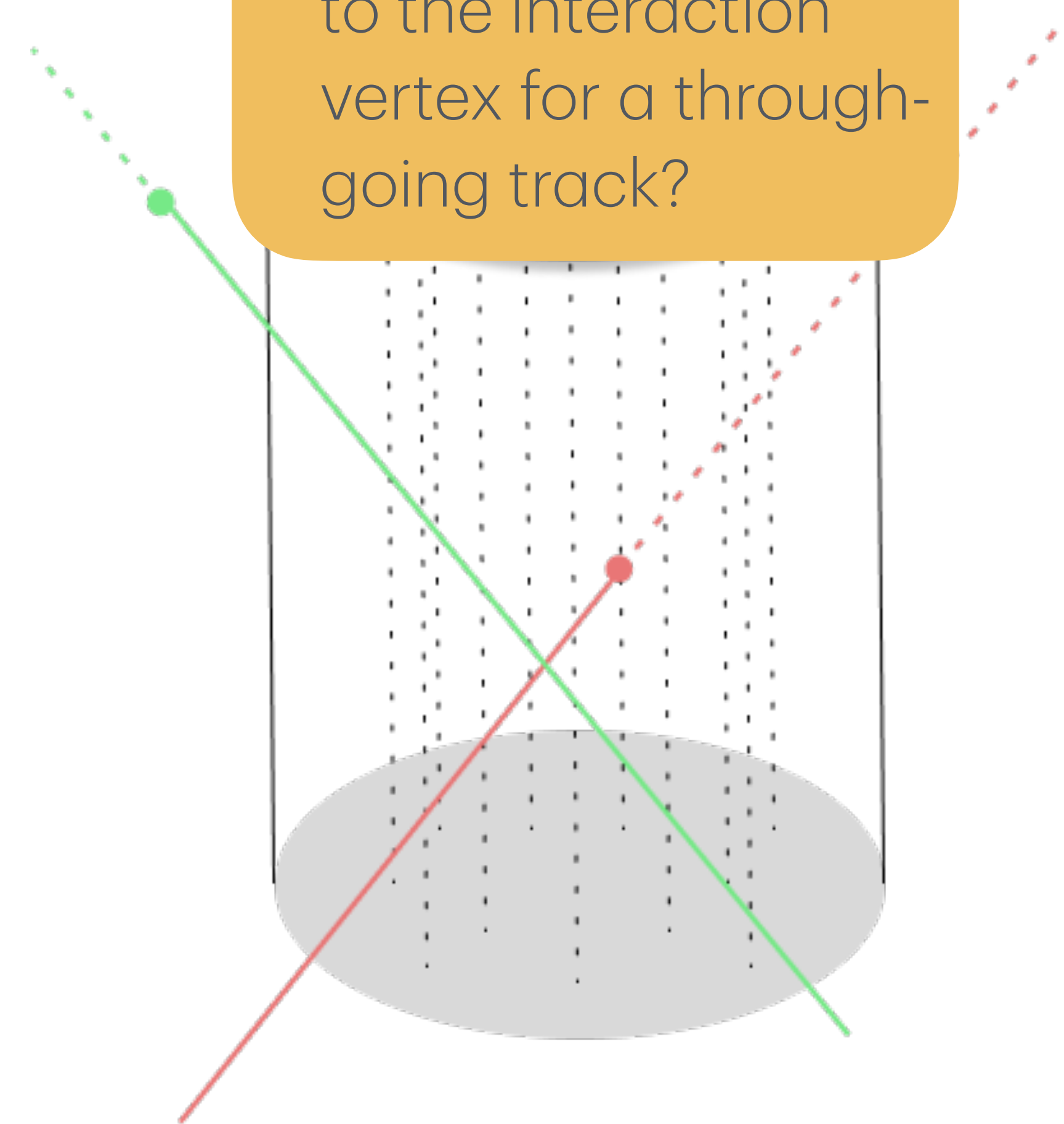
Designing a machine learning model for high energy all type events at IceCube.

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RAM usage scales with number of pulses $\mathcal{O}(n^2 \cdot d)$ for the chosen architecture



What is equivalent to the interaction vertex for a through-going track?



Target labels designed to be similar between event morphologies

Tasks

Interaction-vertex/closest approach: (x,y,z,t)

Trackness: The amount of energy deposited from tracks compared to the full energy deposit

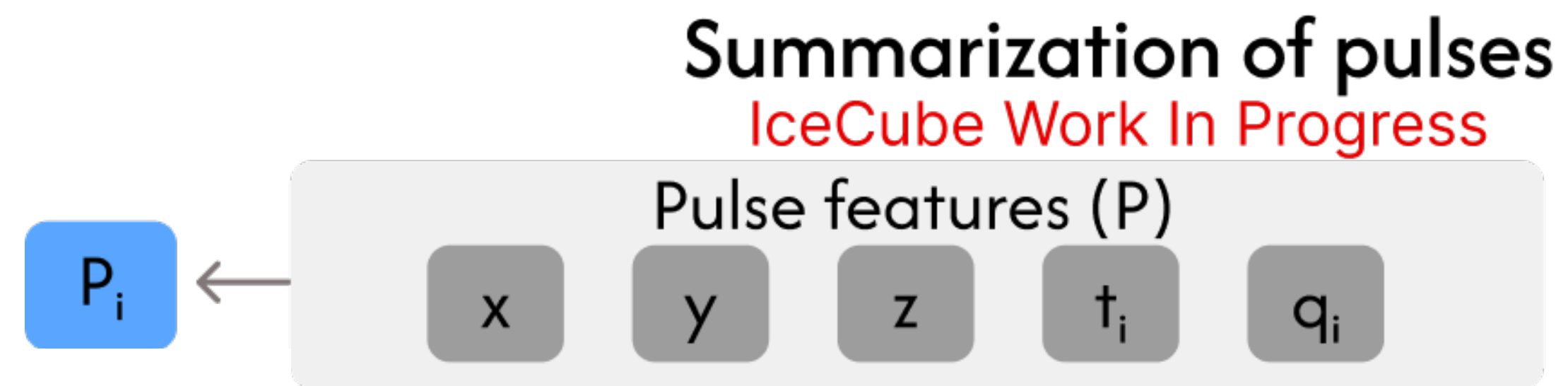
Visible length: length of the track or expansion of the cascade inside the detector volume

Deposited energy: Energy from the primary/daughters of the primary deposited inside the detector volume

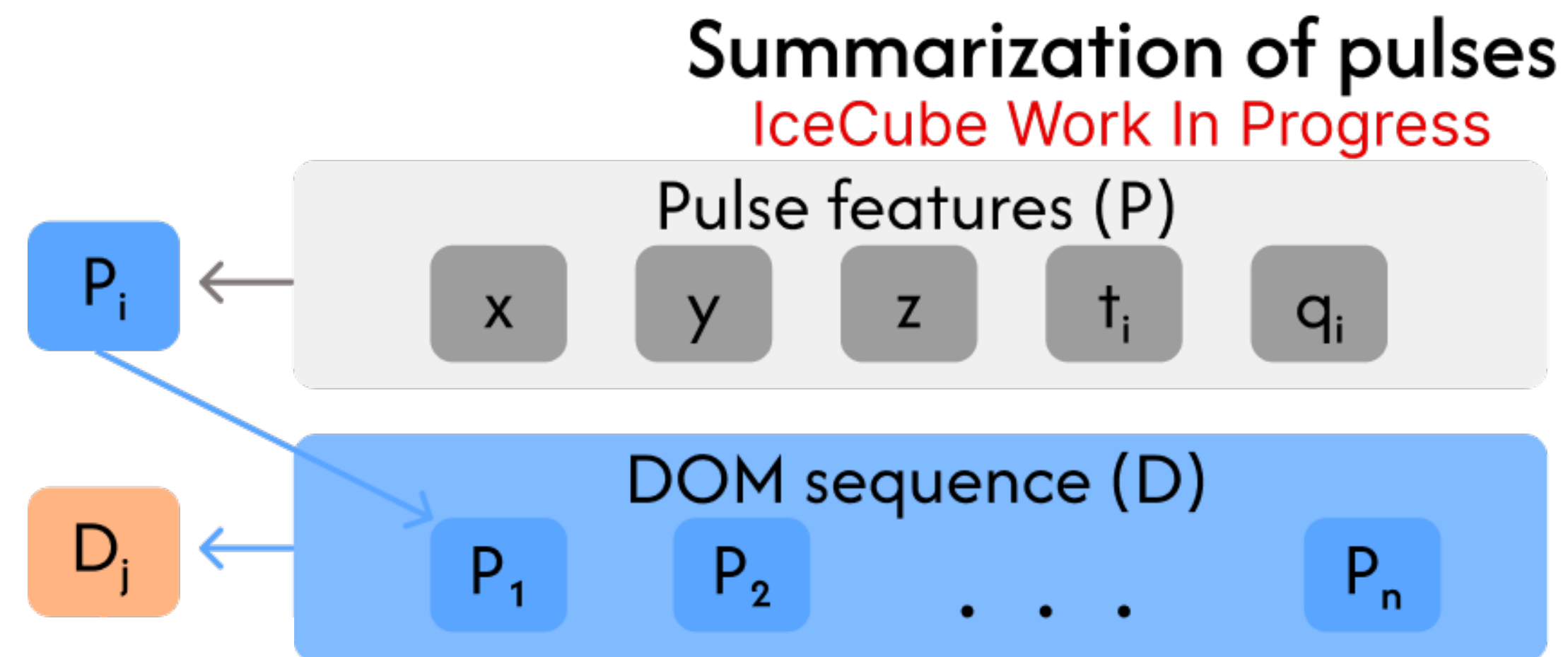
Energy on entrance: The energy of the highest energy pseudo-particle as it enters the detector volume.

Direction: x,y,z -vector of the direction of the particle along with an confidence metric κ

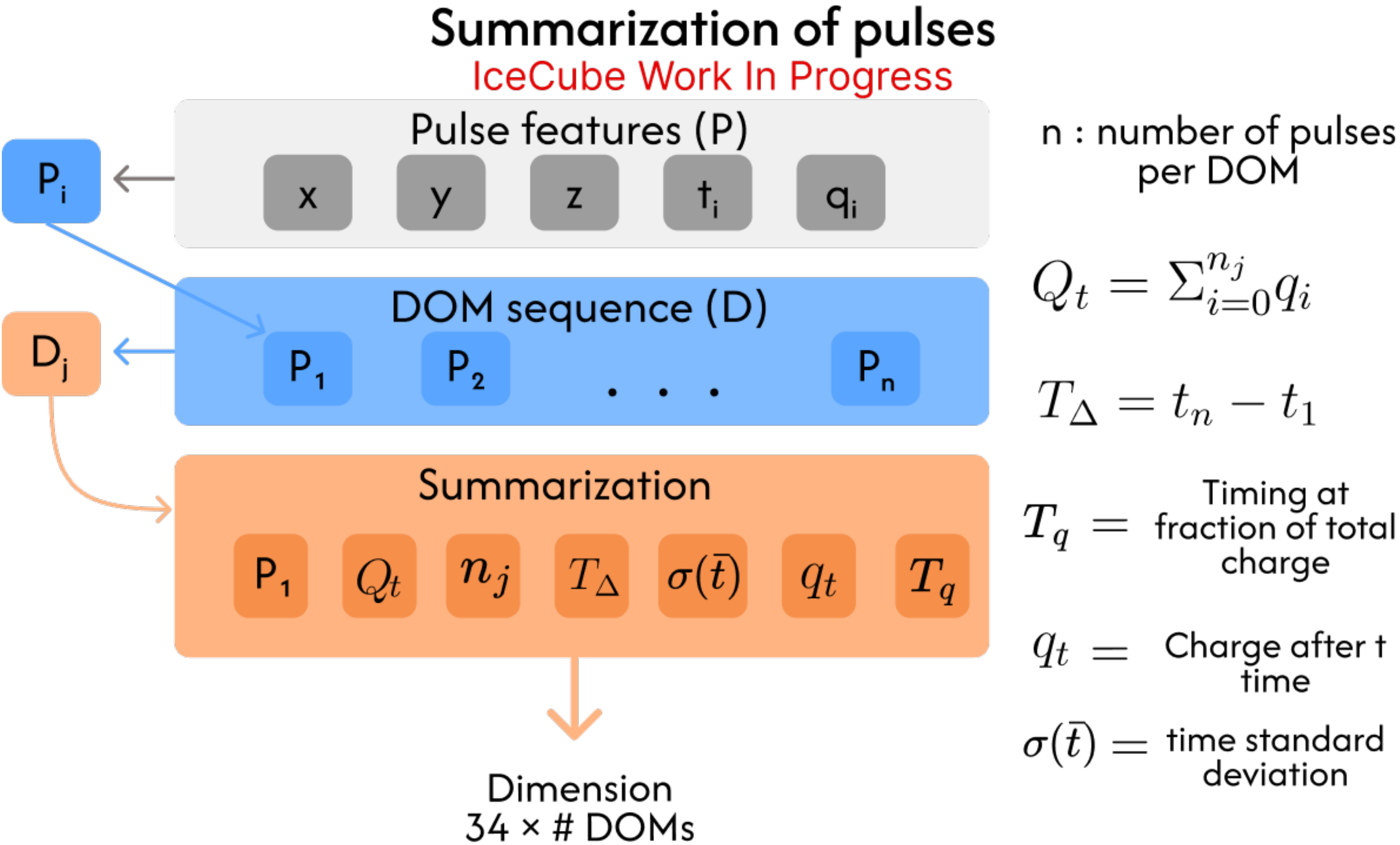
Summarization of the input pulses.



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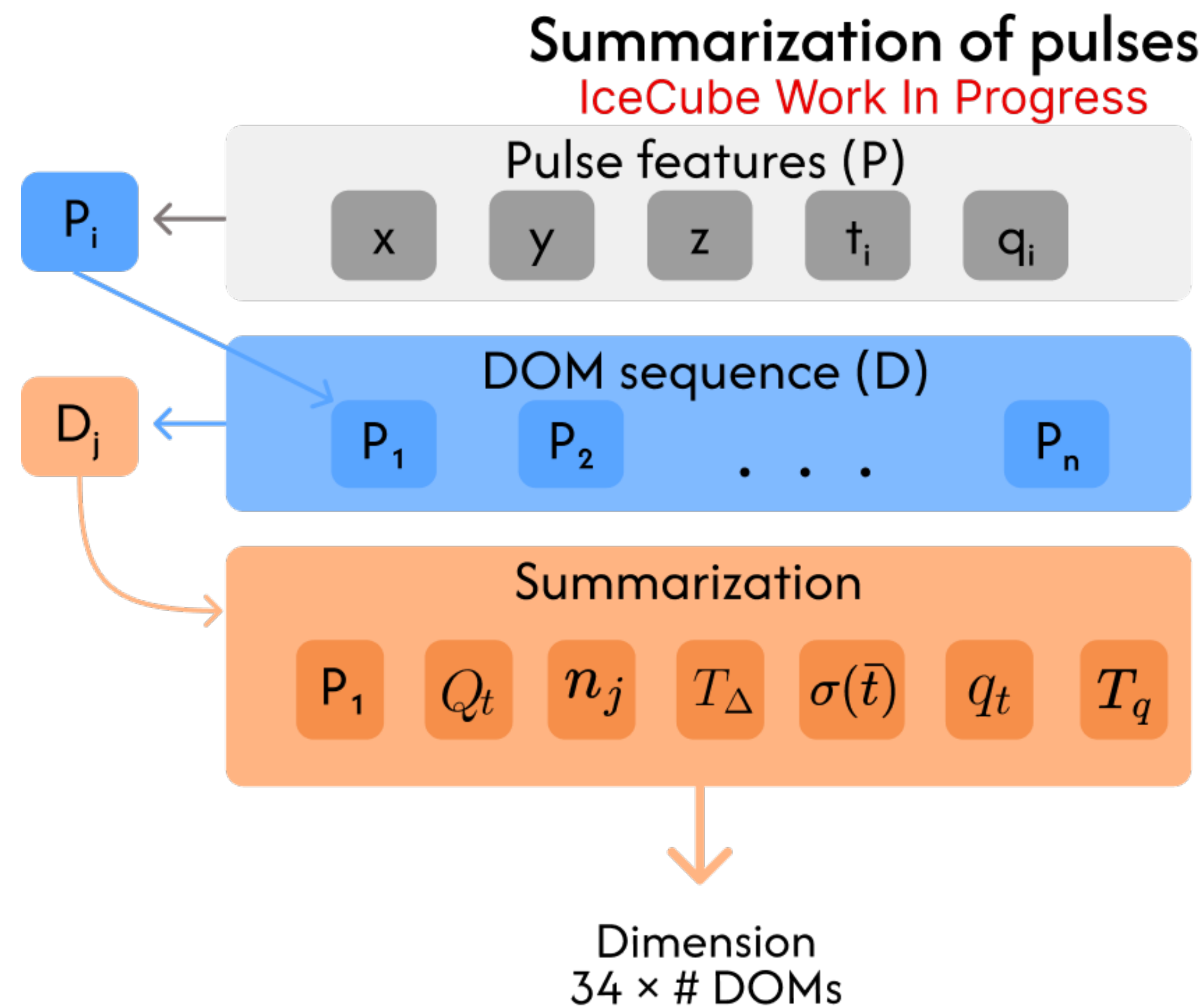


Summarization of the input pulses.



Summarization of the input pulses.

- Summarizing the pulses effectively reduces the RAM requirement.
- The initial pulse timings are the most important for reconstructing the direction of the particle.
- Similar methods used for the CNN reconstruction for cascades in IceCube (<https://arxiv.org/pdf/2101.11589>)



n : number of pulses
per DOM

$$Q_t = \sum_{i=0}^{n_j} q_i$$

$$T_{\Delta} = t_n - t_1$$

$$T_q = \text{Timing at fraction of total charge}$$

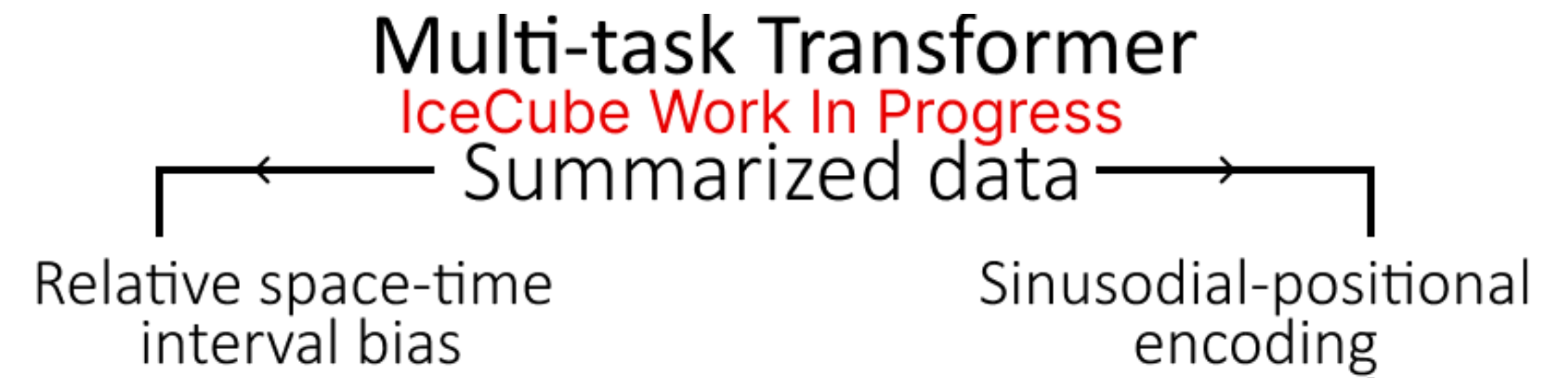
$$q_t = \text{Charge after } t \text{ time}$$

$$\sigma(\bar{t}) = \text{time standard deviation}$$

Model architecture

Transformer based model

- Based on the second place solution from the Kaggle competition organized by IceCube.*

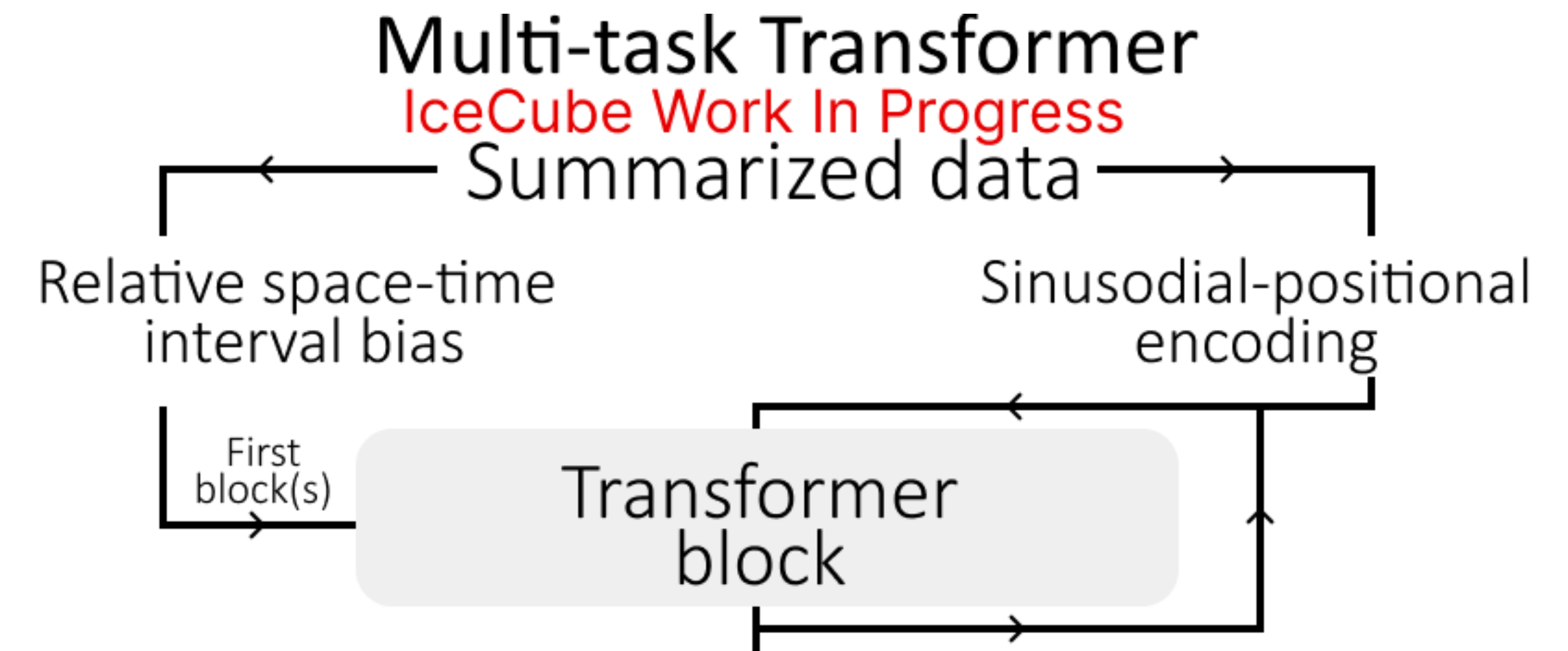


*<https://www.kaggle.com/competitions/icecube-neutrinos-in-deep-ice>

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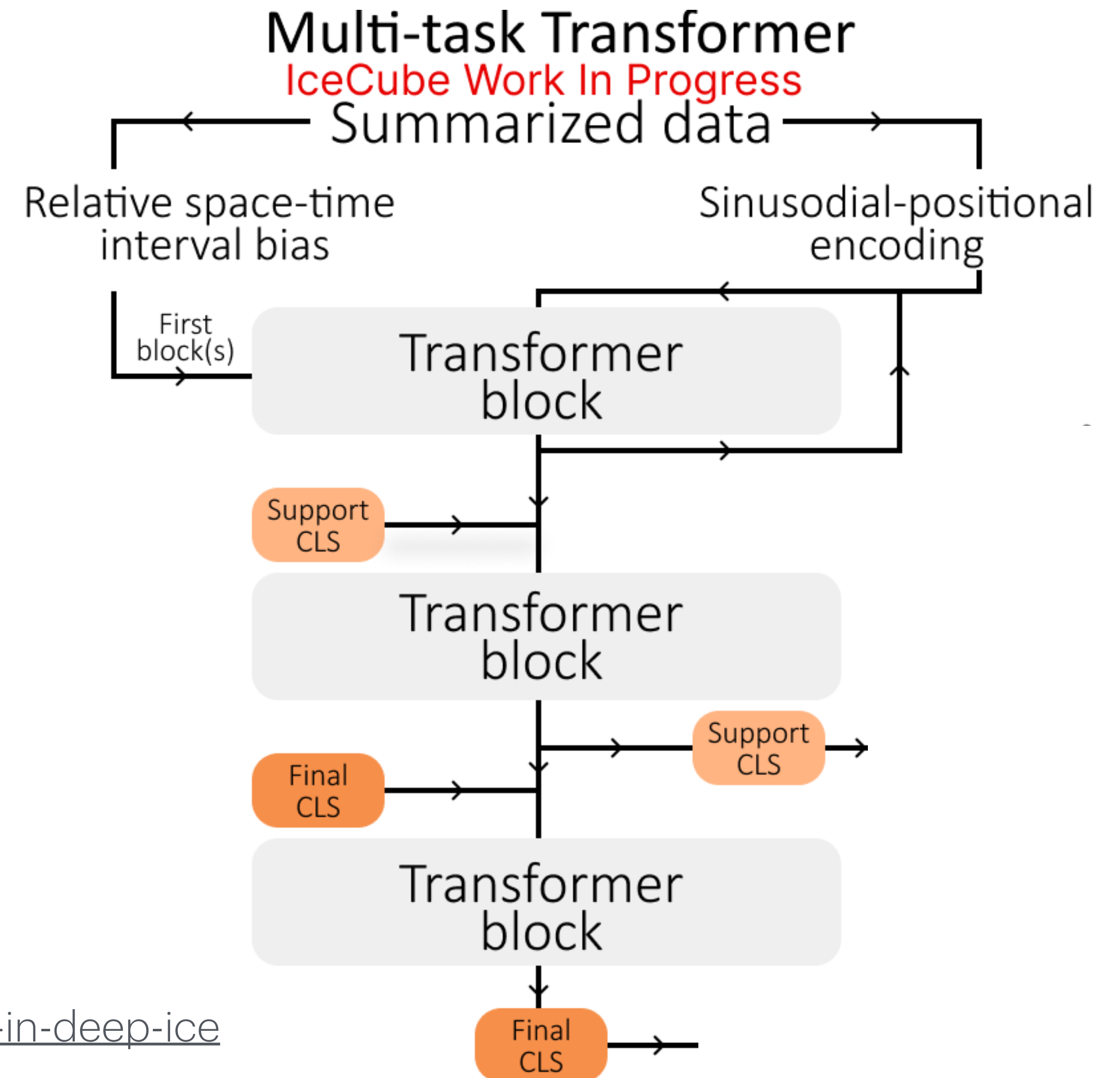
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- CLS tokens for regularizing output dimensions.
- Last transformer blocks reserved for *primary tasks*.

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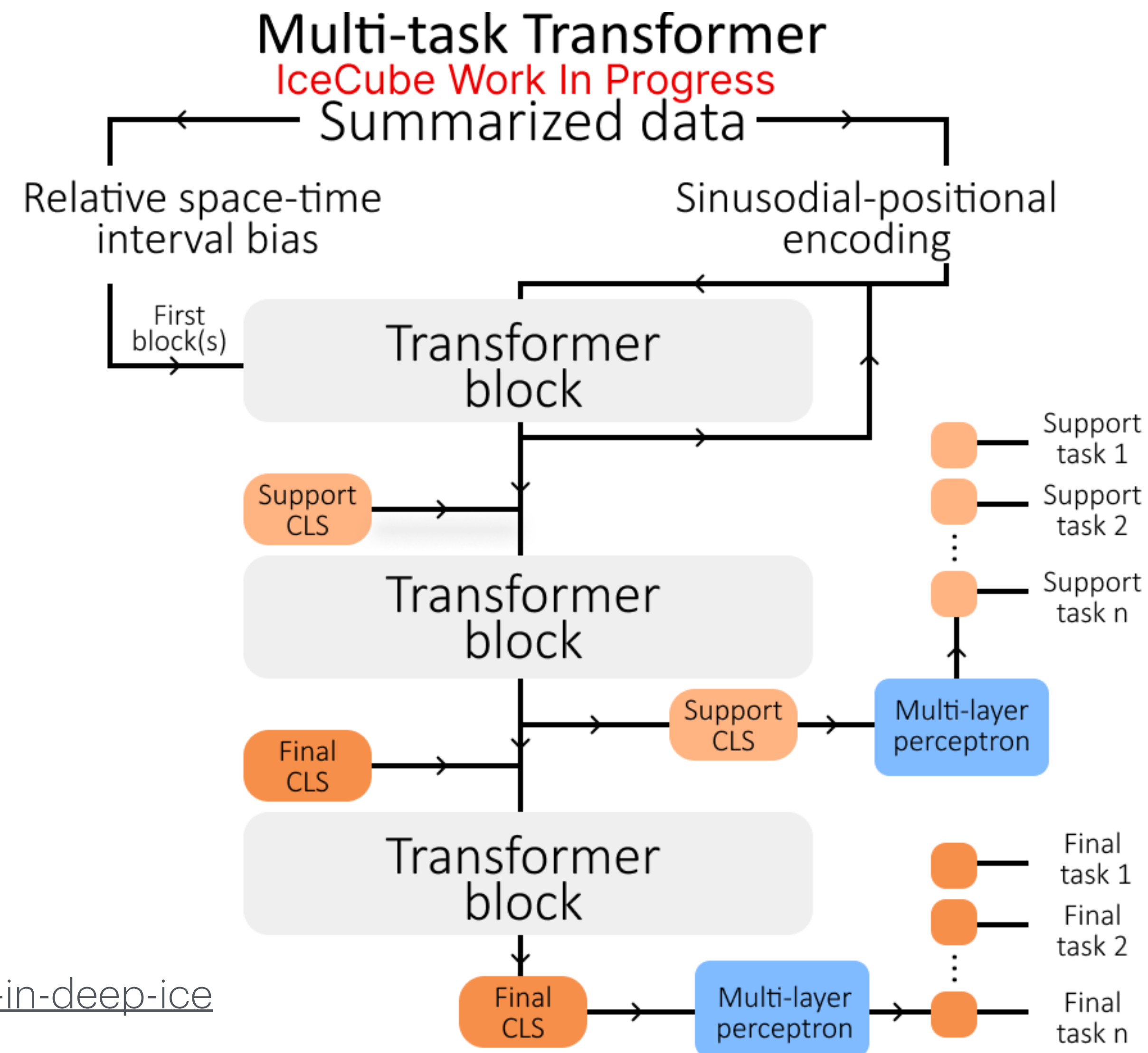


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Initial results and comparisons to previous work

Please keep in mind that this analysis is a work in progress and results are therefore subject to change

In the following a selection based on the reconstructed interaction vertex and *trackness* of the event has been applied. Removing cascade like events and events at the border of the detector.

Model confidence

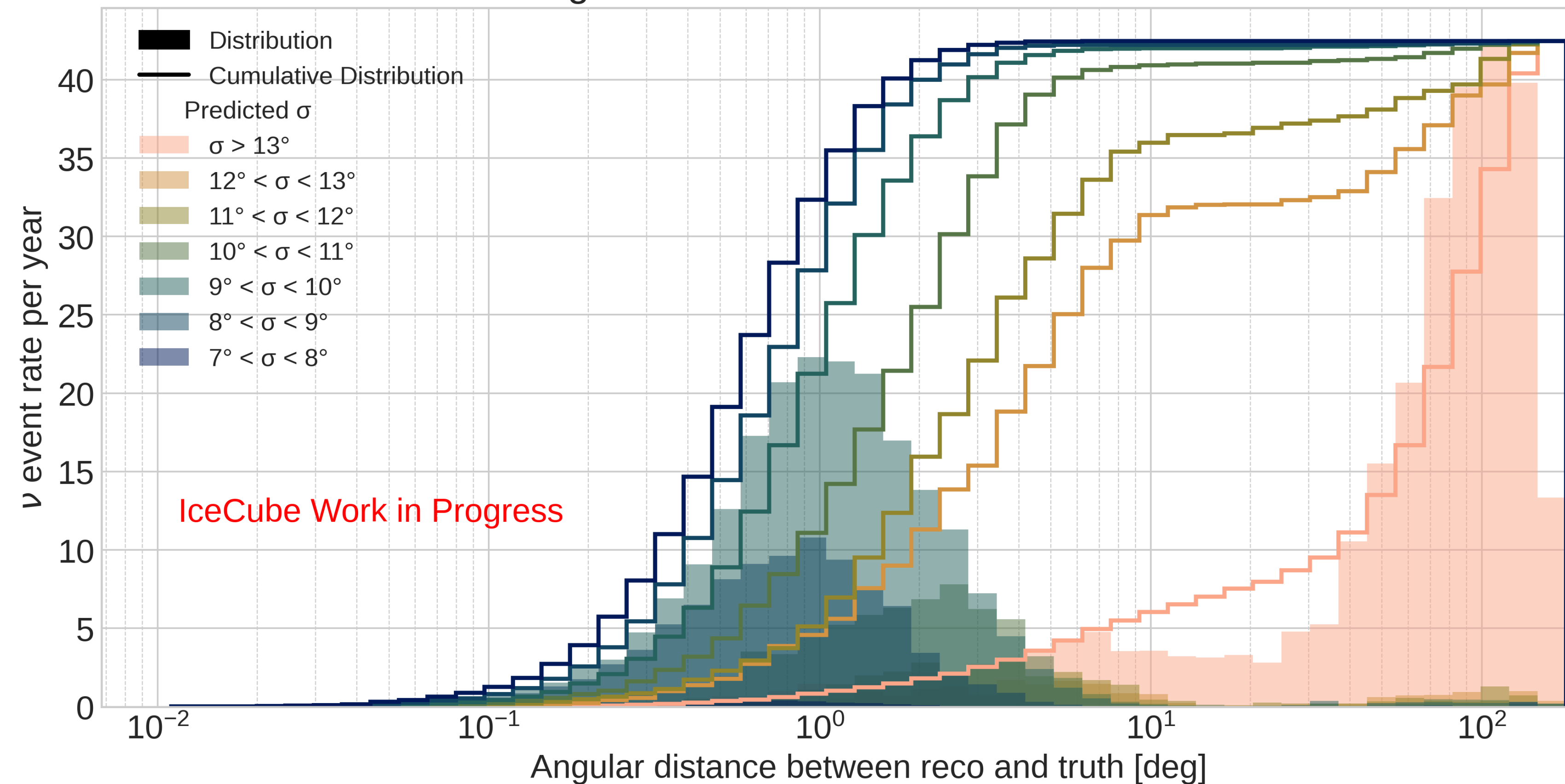
Transformer based

- The κ produced by using the von Mises Fisher loss is related to the uncertainty through:

$$\sigma \propto \frac{1}{\sqrt{\kappa}}$$

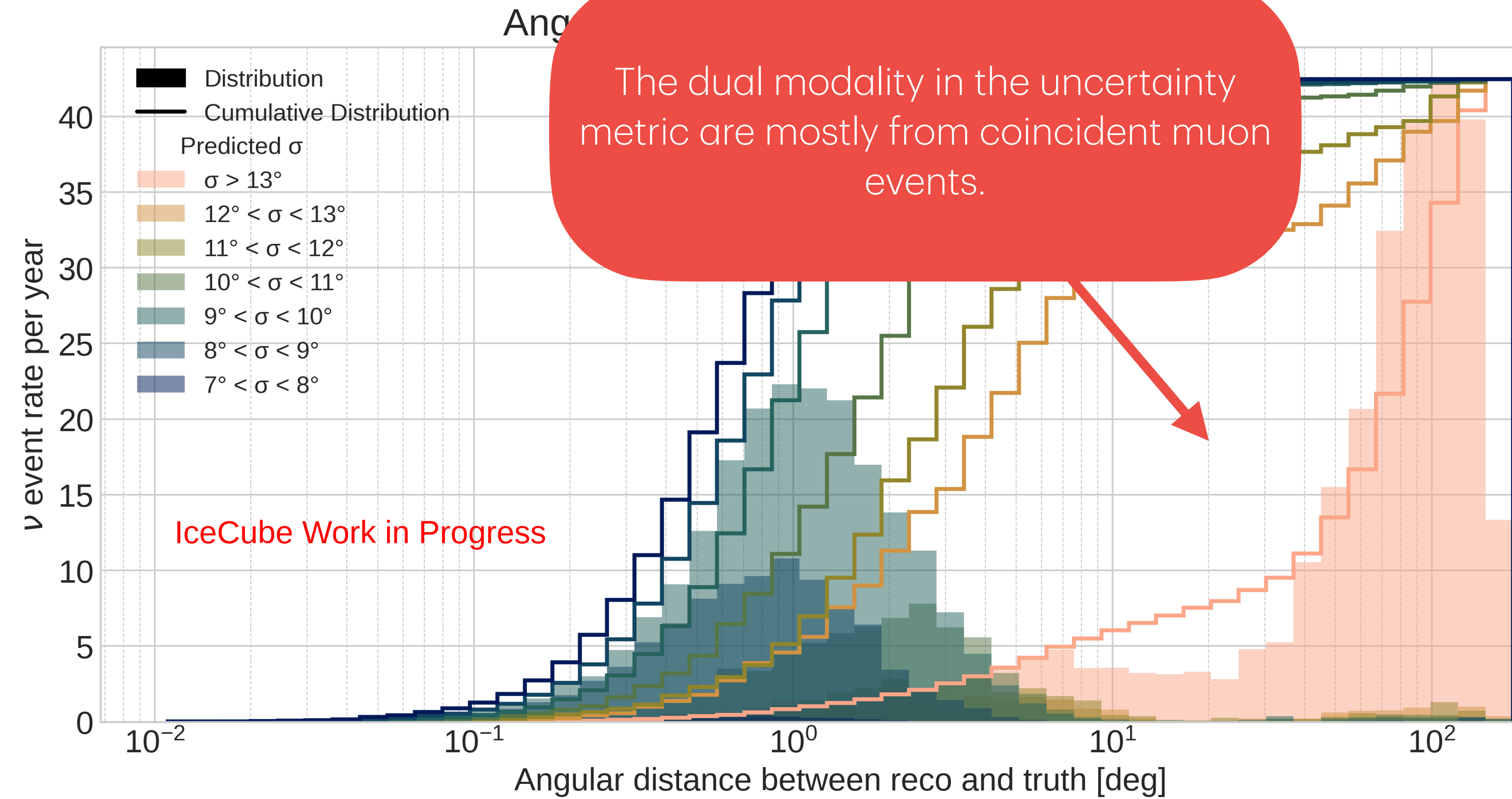
- angular distance (reconstructed/true)
- We are reliant on being able to effectively remove mis-reconstructed events.

Angular distance distribution ν track-like



While the value of the uncertainty does not align with the median it can be used to effectively remove poorly reconstructed events.

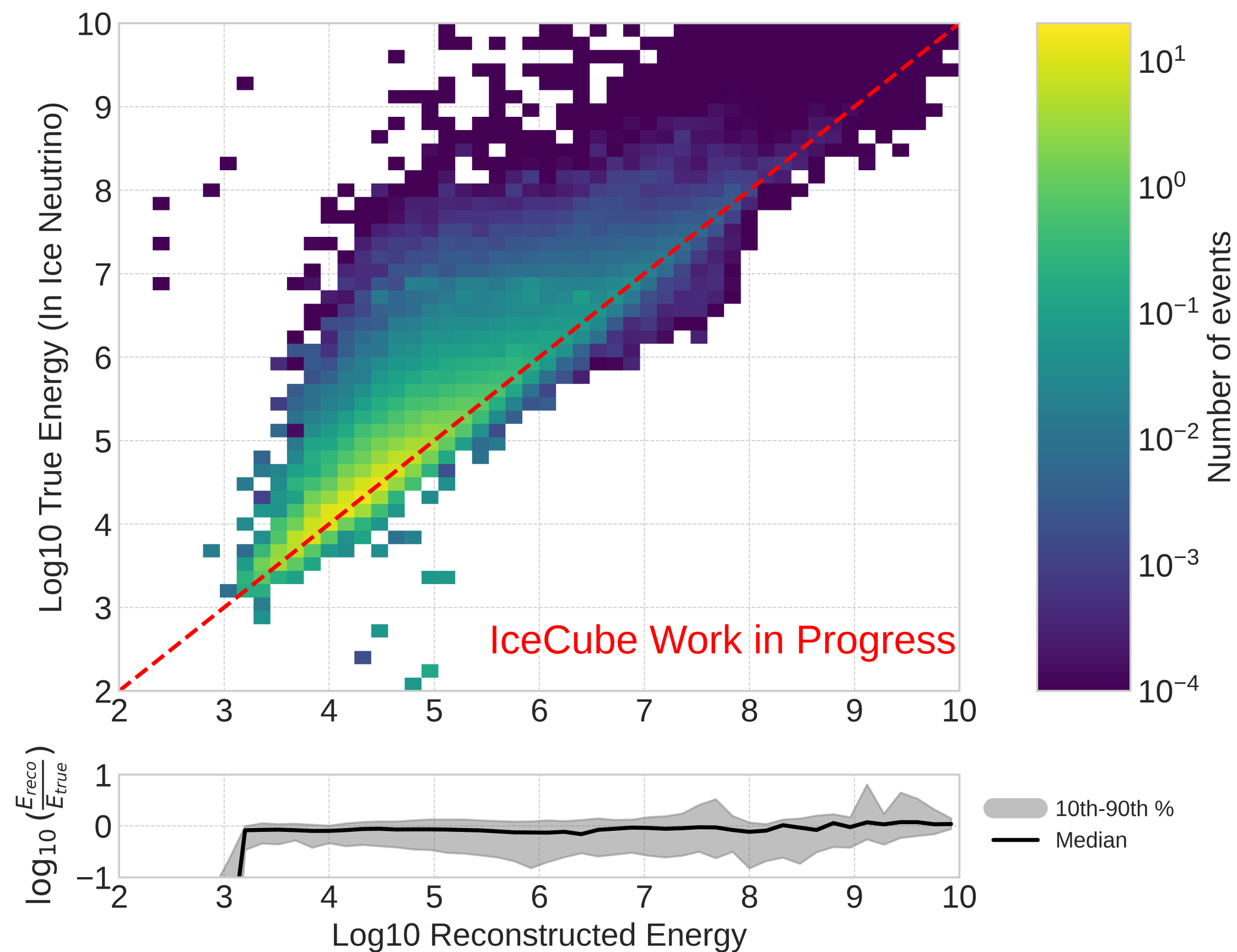
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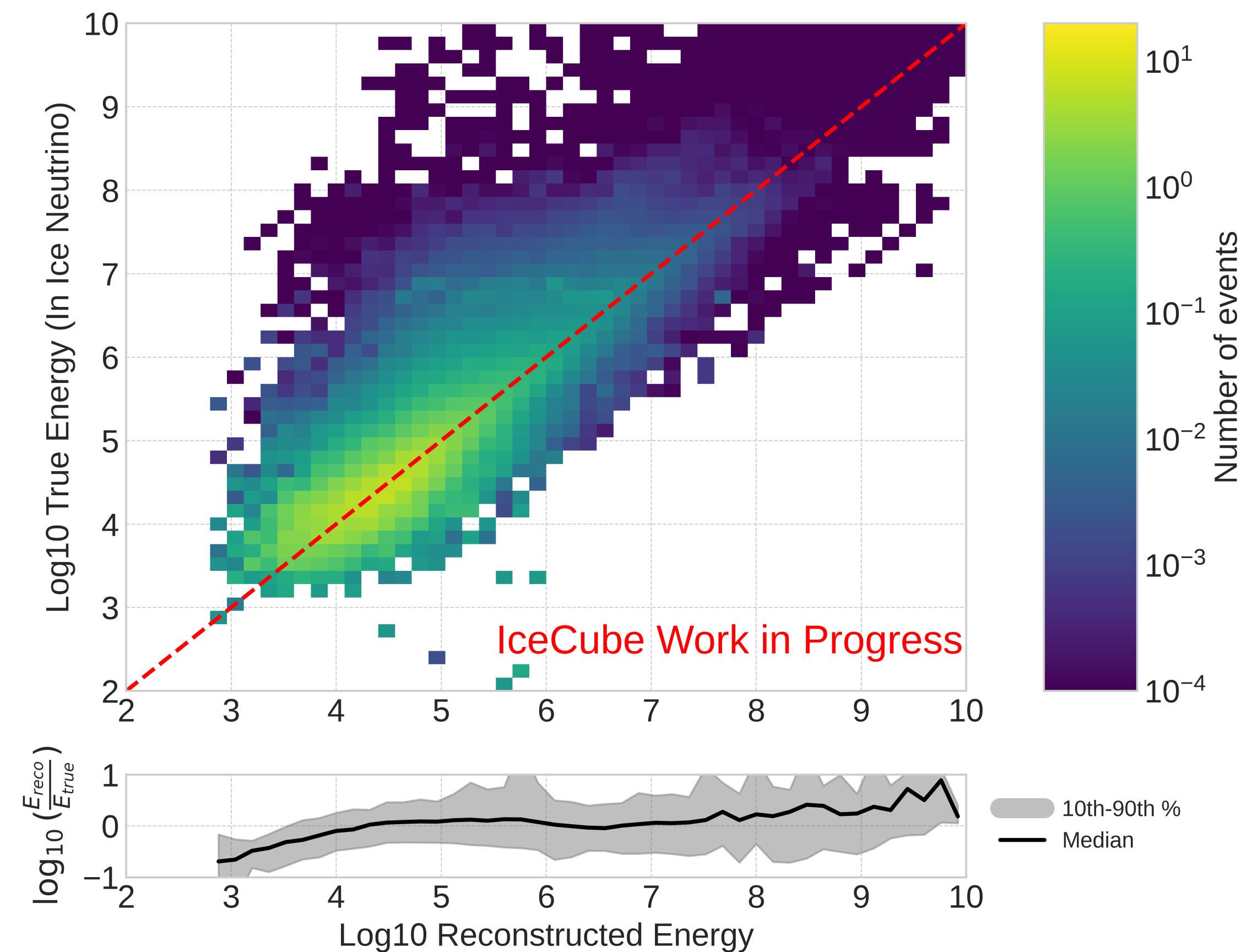
Performance of the energy reconstruction

Compared on events passing the previous GFU selection.

Energy reconstruction by the new model



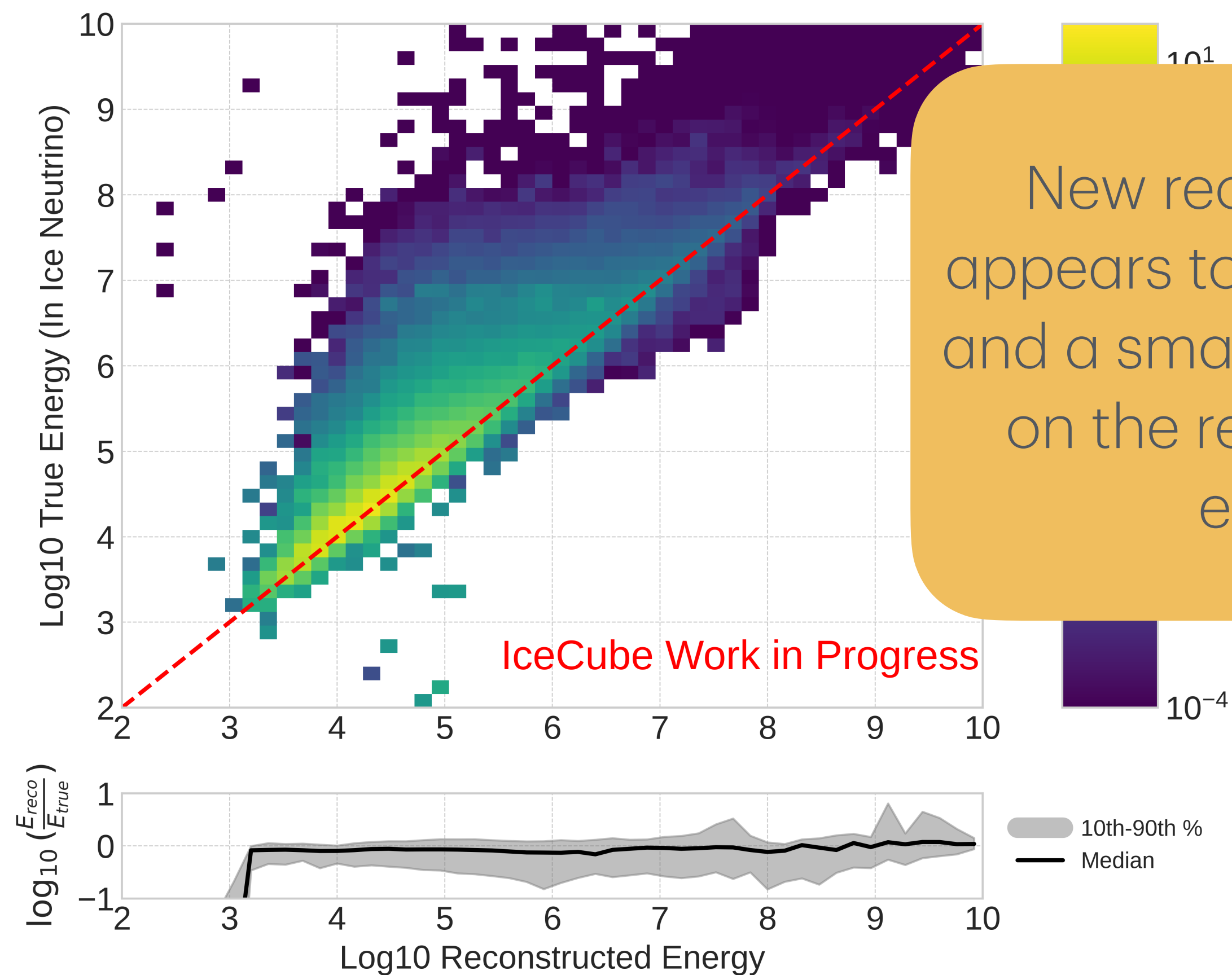
Energy reconstruction used by the GFU selection.



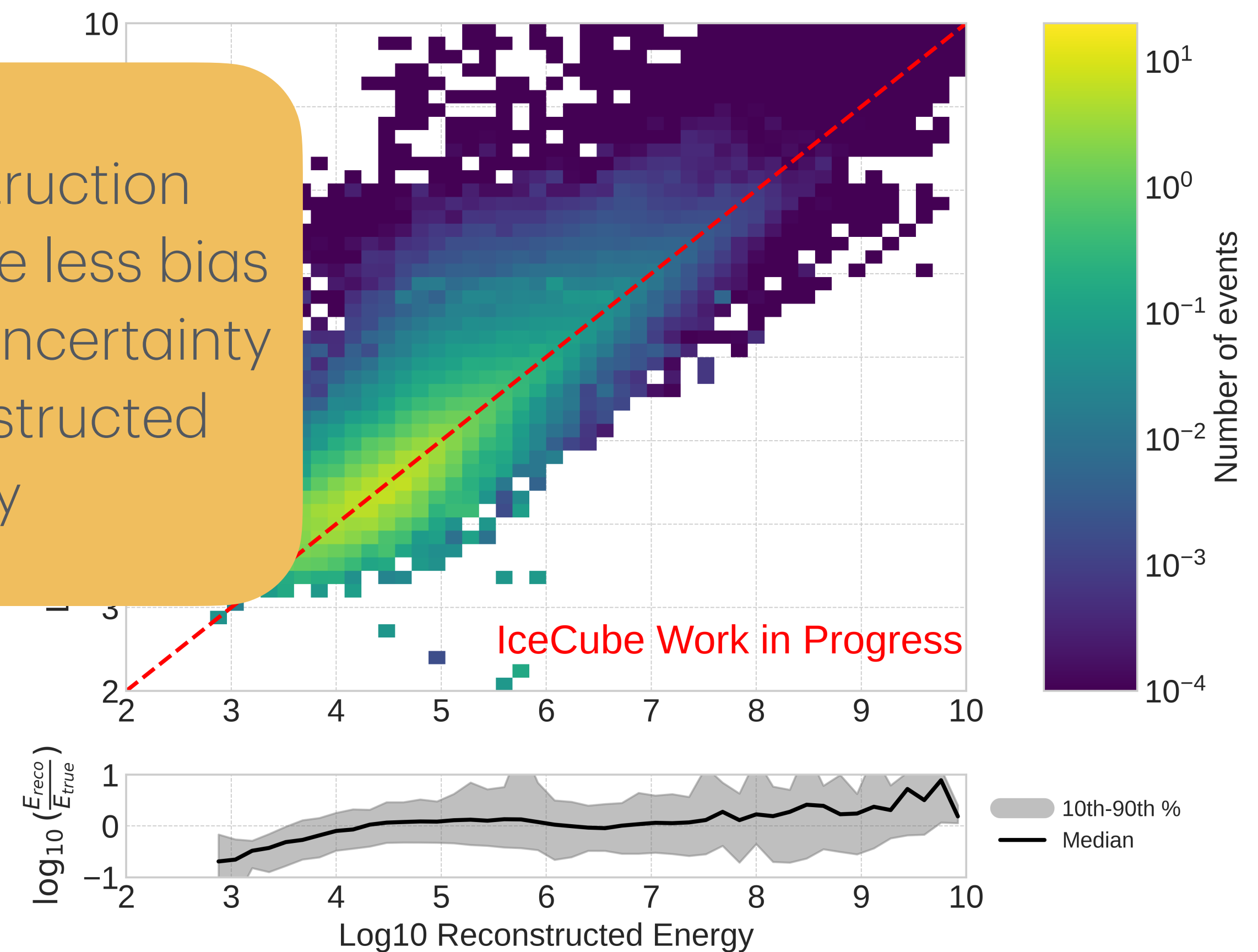
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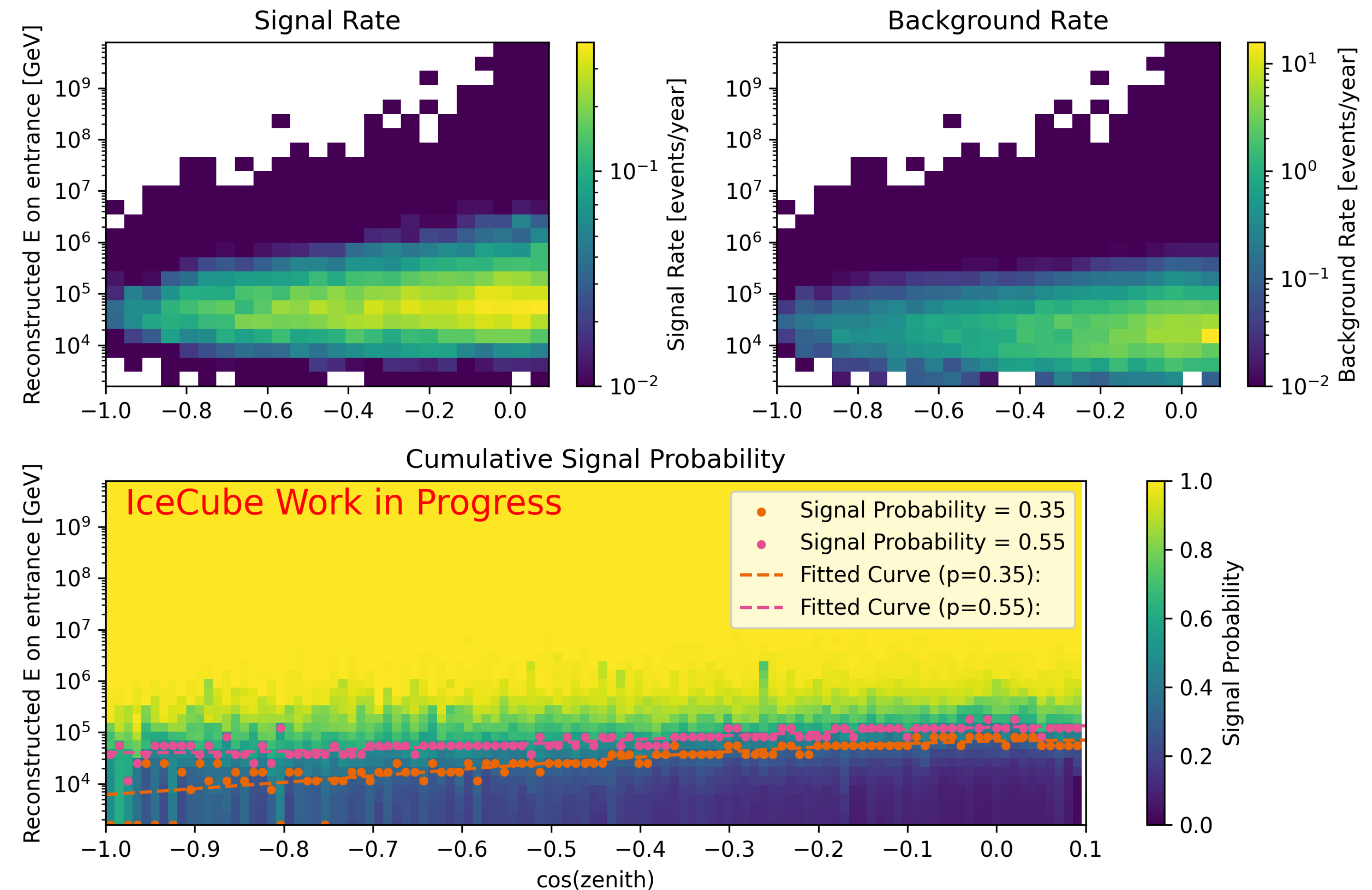
Energy reconstruction used by the GFU selection.



Selection of high energy astrophysical neutrino events

Up-going region

- In the up-going region the reconstructed energy and $\cos(\text{zenith})$ angle can be used to separate the atmospheric neutrinos from the astrophysical.
- Fit of the signal probability is a 4 parameter polynomial fit.
- From this we can construct a selection similar to the gold and bronze selections.

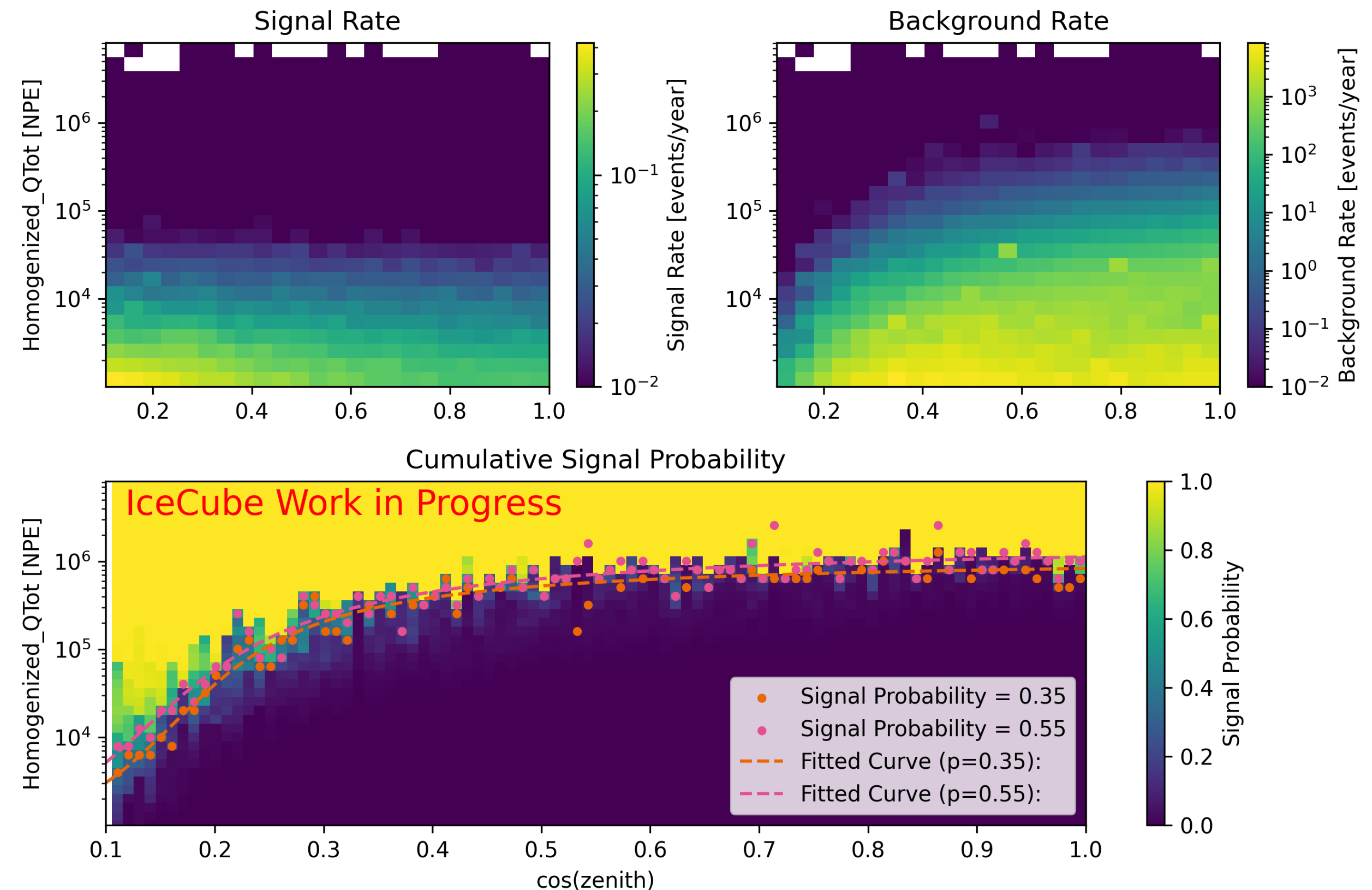


Selection of high energy astrophysical neutrino events

down-going region

- In the down-going region the Homogenized Q_{tot} [NPE] is more effective at separating atmospheric muons from the astrophysical neutrinos.
- The fit is an arctan function with 4 parameters.

$$f(x) = a \cdot \arctan(b \cdot (x - x_0)) + c$$

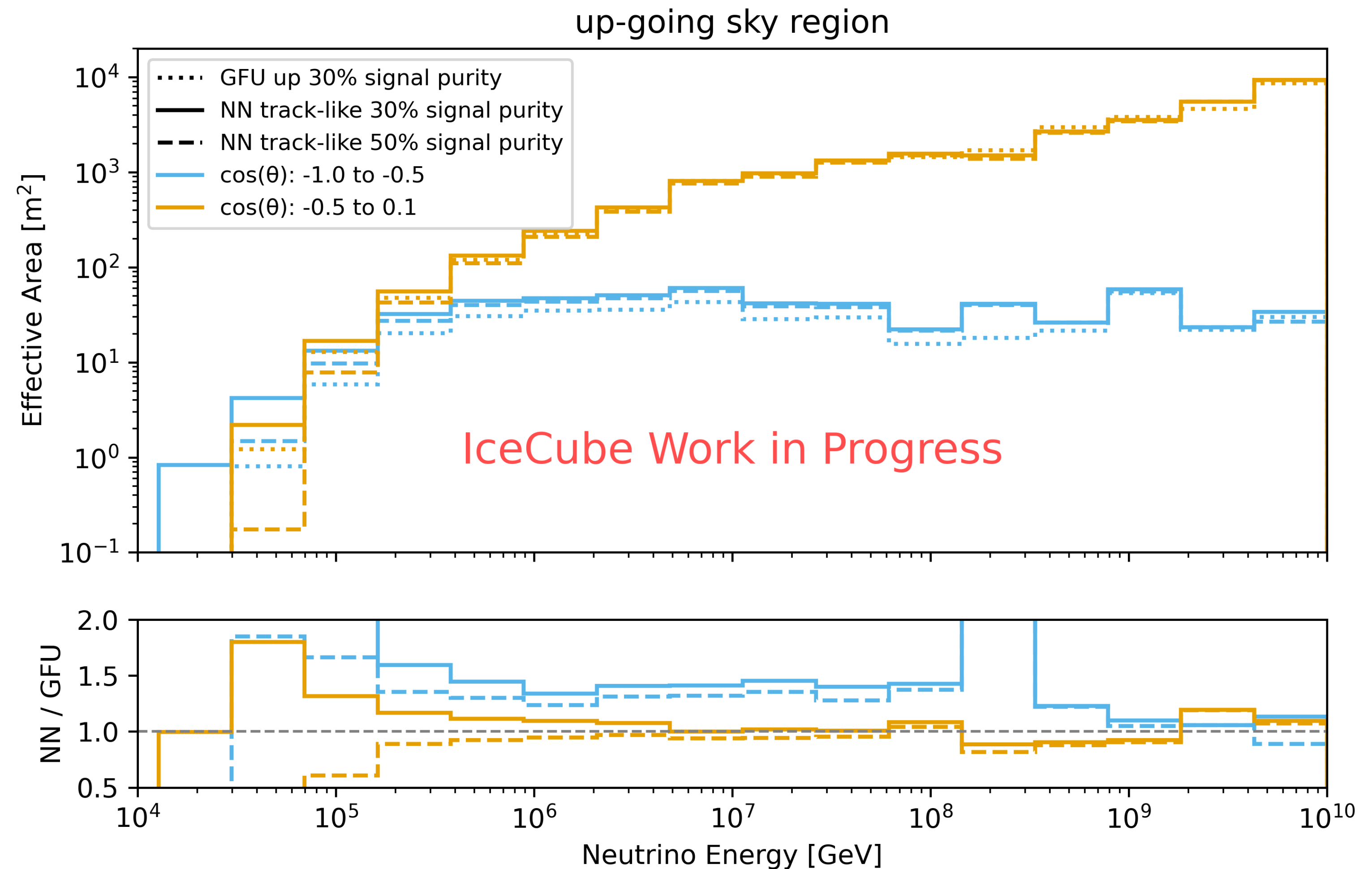


Resulting effective area comparison

up-going region

- Increase in number of signal events of ~ 50% at the same level of signal purity (30%) for the loose selection.
- Angular distance median and 90th percentile are slightly degraded.
- ~50% of events are also present in the GFU selection.

	This work	GFU
Median	0.29	0.22
90th	2.69	1.70

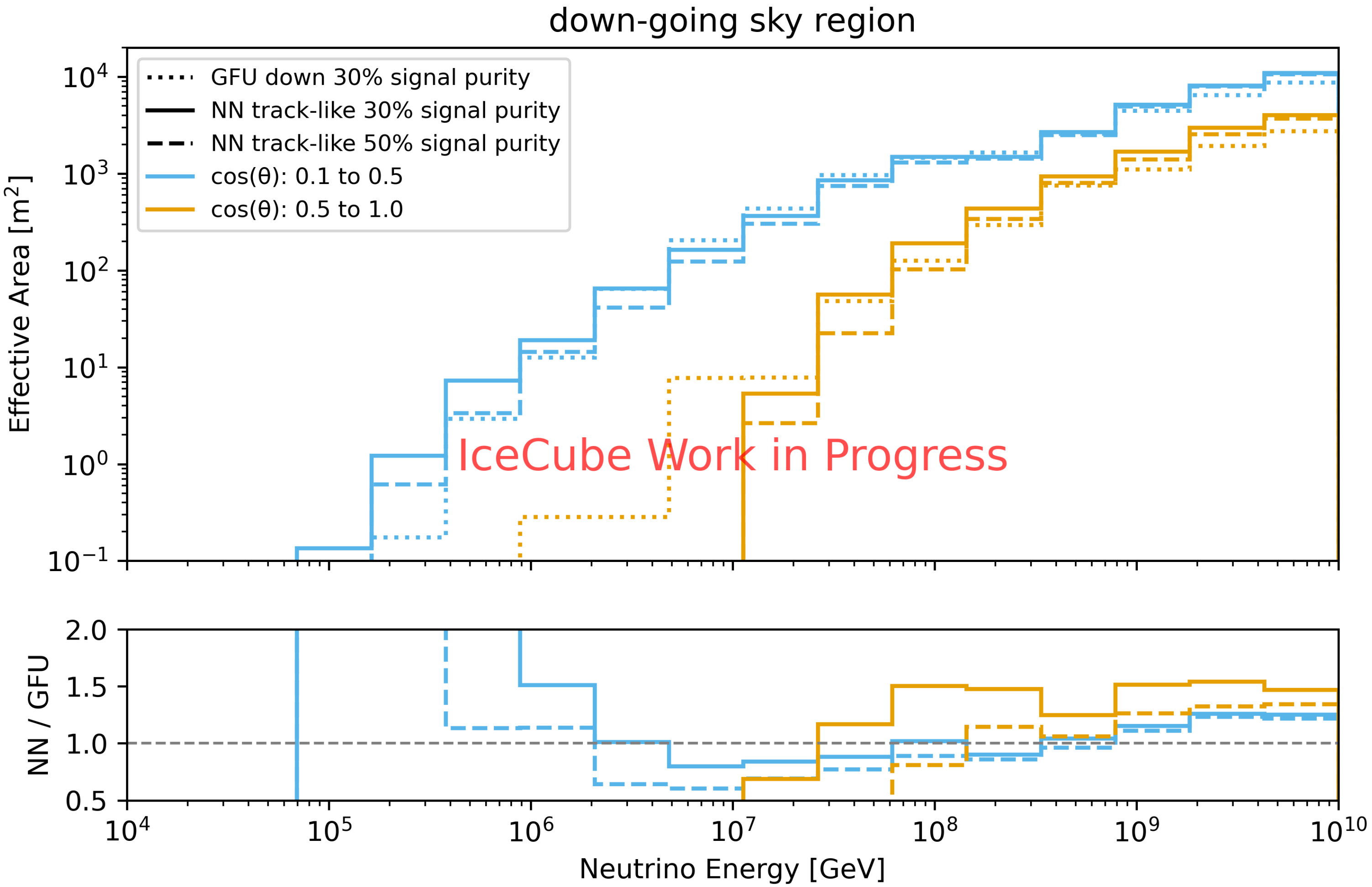


Resulting effective area comparison

down-going region

- Increase in number of signal events of ~ 200% — 300% However this number is quite dependent on the astrophysical flux assumed.
- Angular distance median is slightly worse.
- ~20% of the events are also present in the GFU selection

	This work	GFU
Median	0.34	0.25
90th	1.70	2.17



Summary slide

Summary

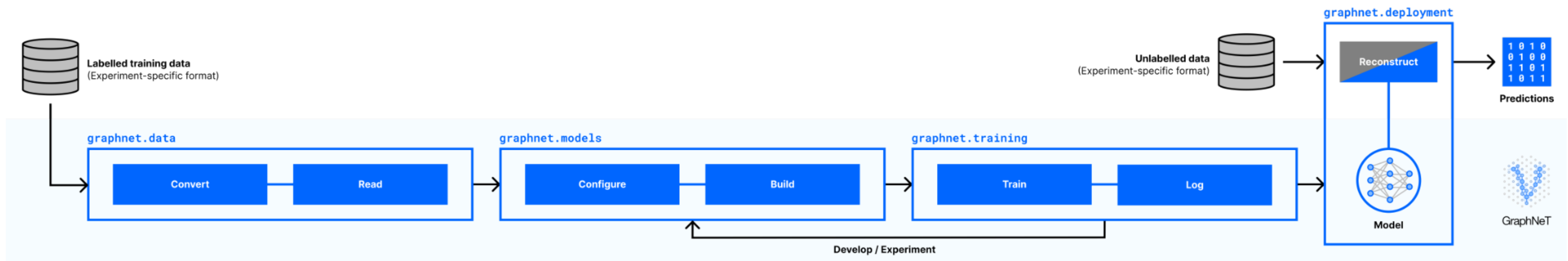
- The multitask model can be used create robust directional and energy estimation for any event type.
- For selections targeting through-going events previous methods provide more precise reconstructions.
- Can be used to increase the number of alerts at the same level of purity with similar angular distance between reconstructed direction and truth.

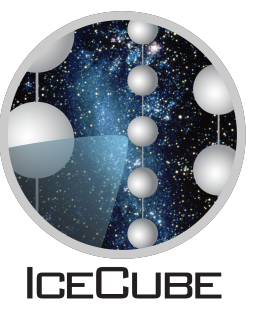
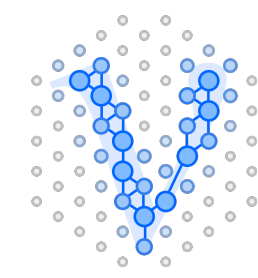
Future work

- Produce accurate uncertainty estimation and possible event by event posterior distribution.
- Characterize the reconstruction performance of cascade-like events.
- Can a selection be created for cascade like-events with a guaranteed *good* directional reconstruction?

Model framework by GraphNeT

- Open-source codebase for deep-learning methods for reconstruction tasks at neutrino telescopes
- Covers everything from model development to deployment.
- Meant to share experience between collaborations and enable contribution from machine learning domain experts.
- <https://github.com/graphnet-team/graphnet>

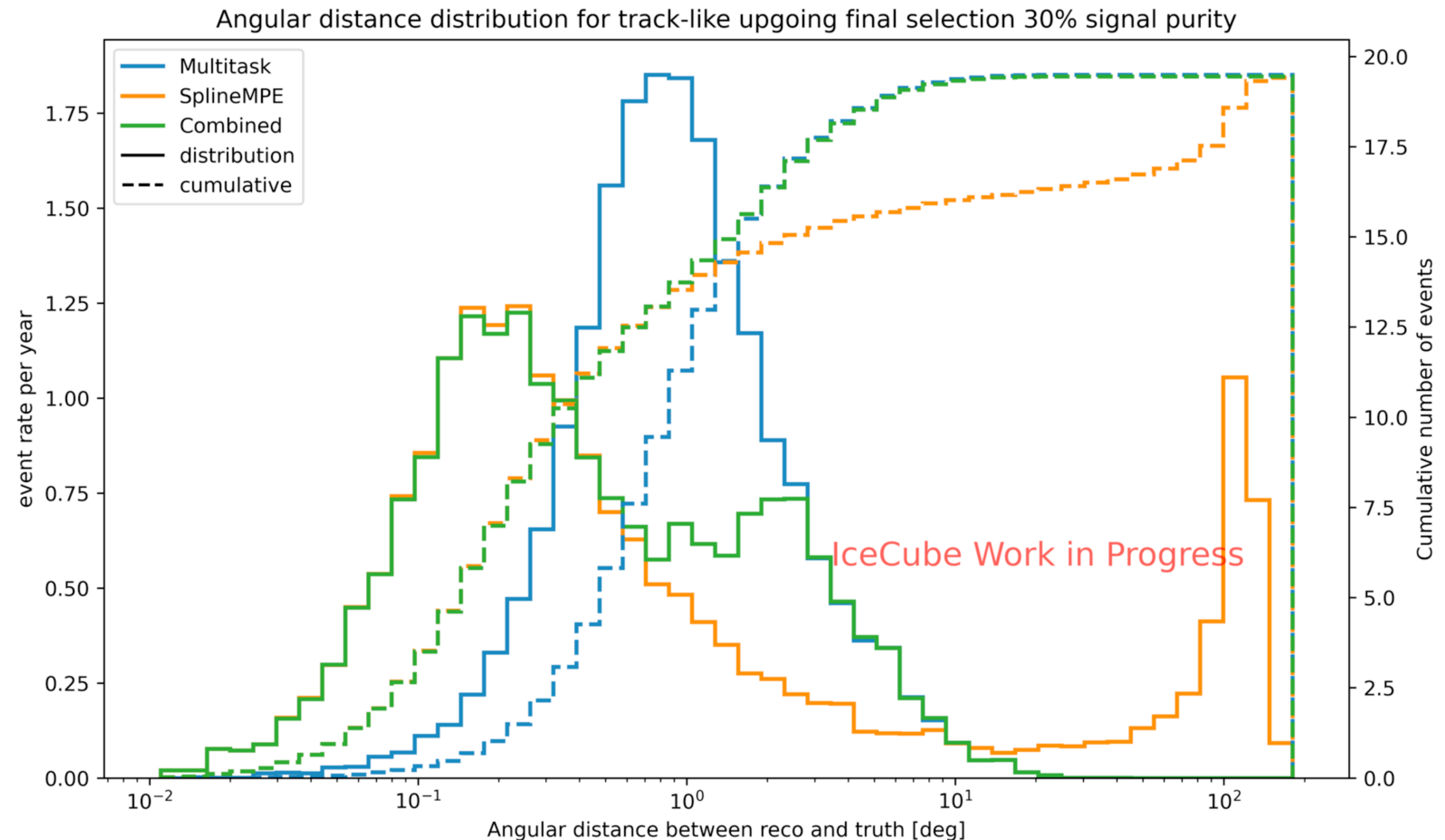




Backup

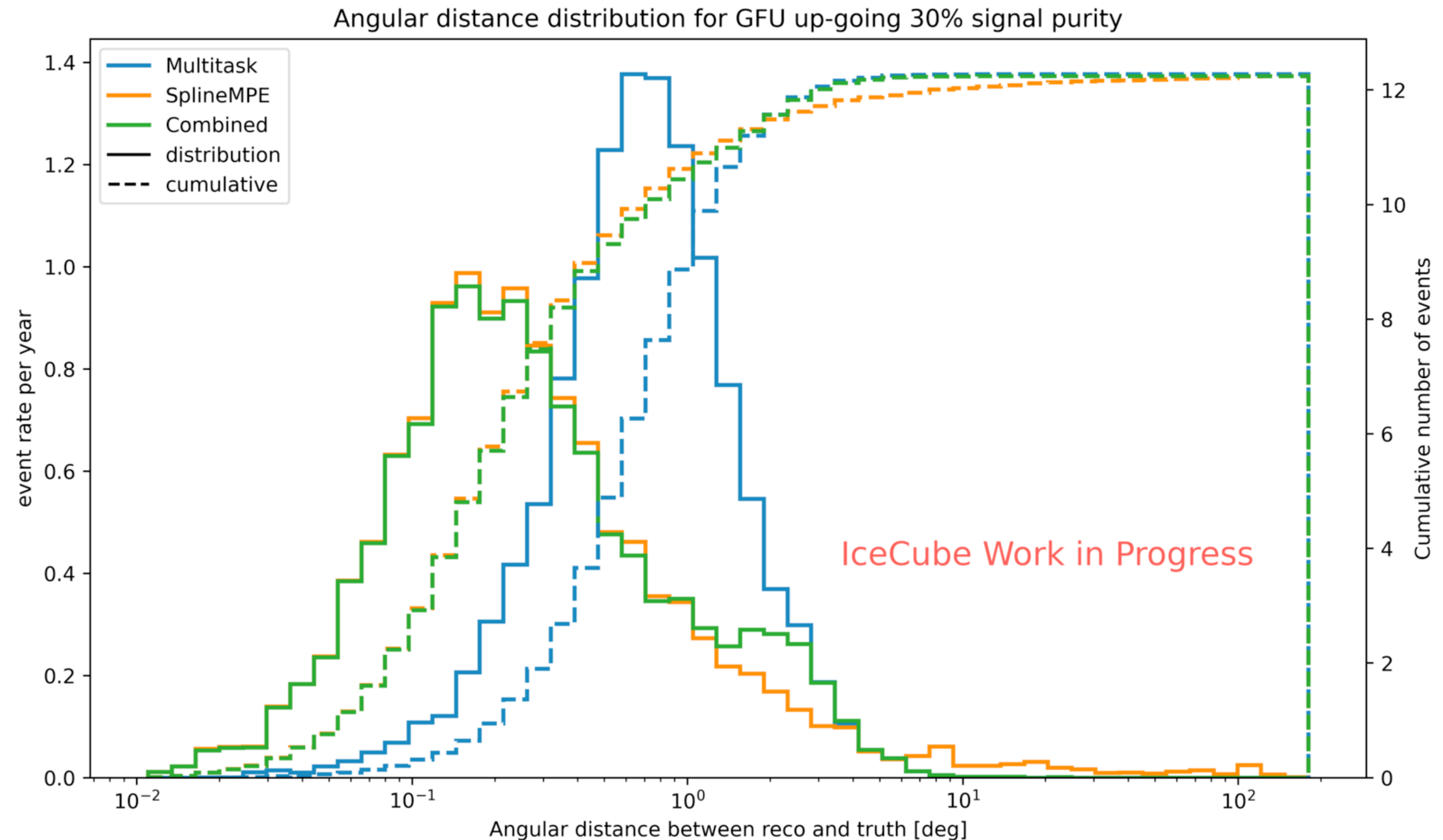
Angular distance (reco/truth) distributions of the final selections

NN selection up-going



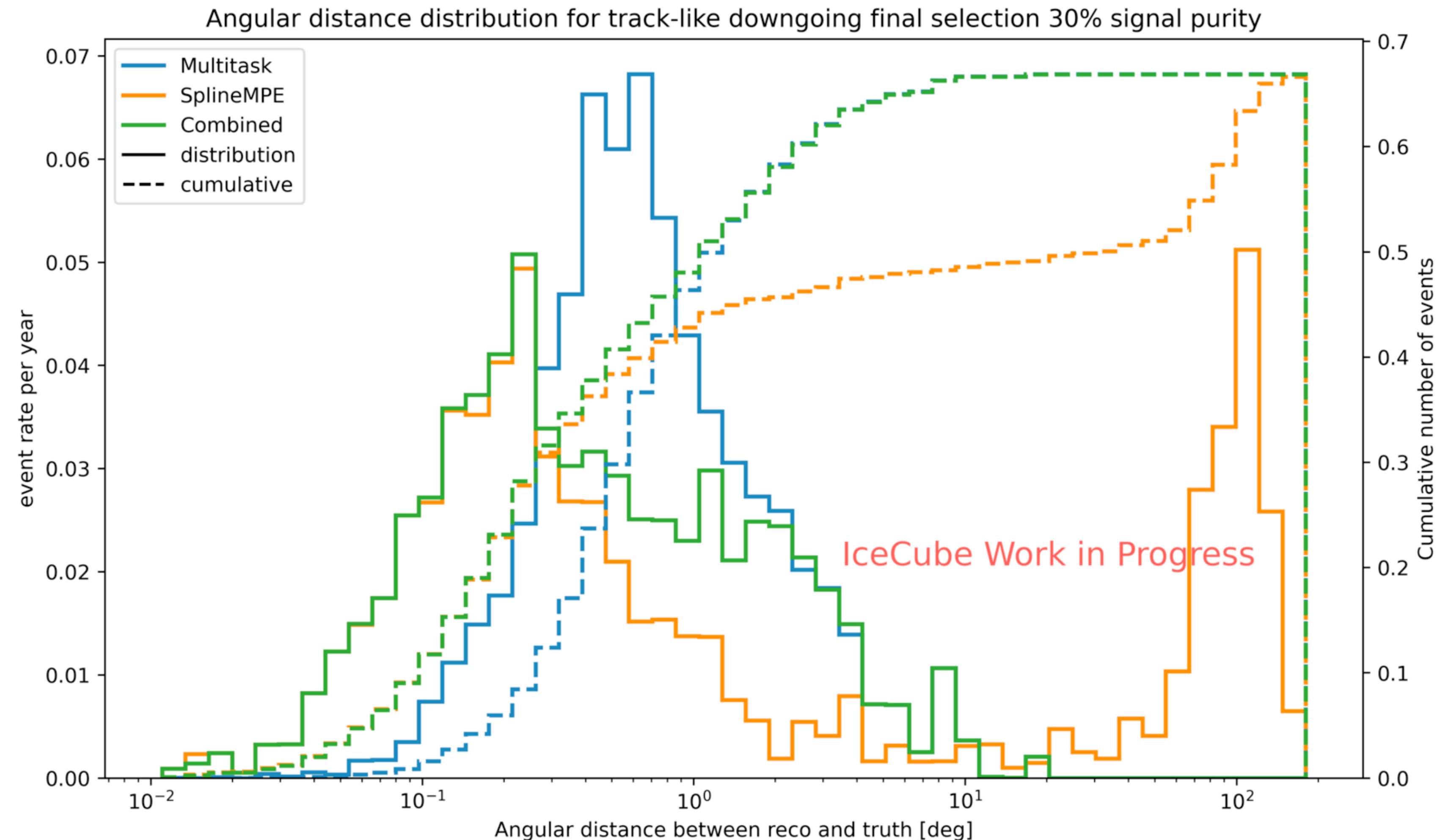
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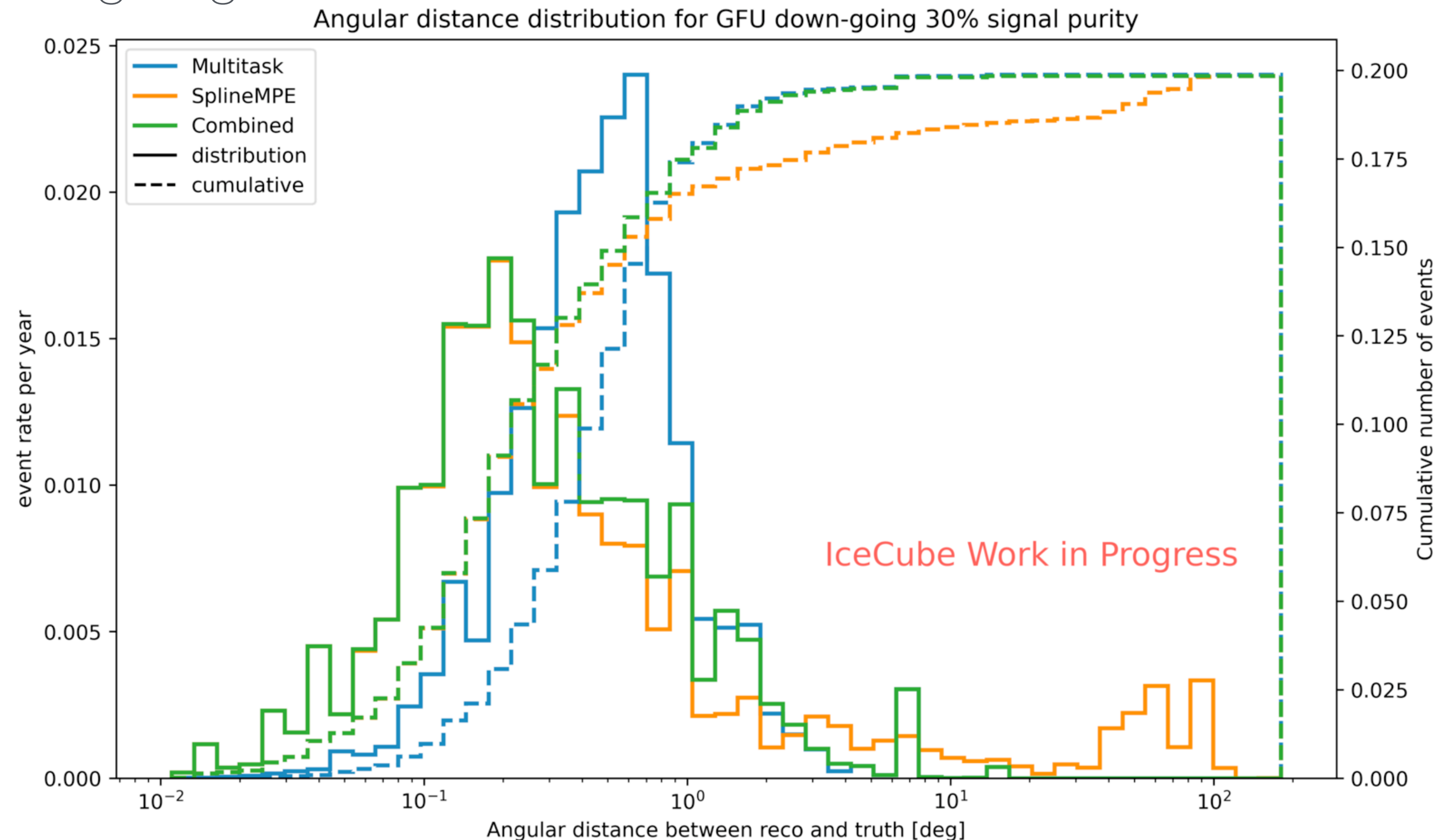


Angular distance (reco/truth) distributions of the final selections

NN selection up-going



Angular distance (reco/truth) distributions of the final selections GFU selection down-going



Performance of the uncertainty estimator with coincident events removed.

