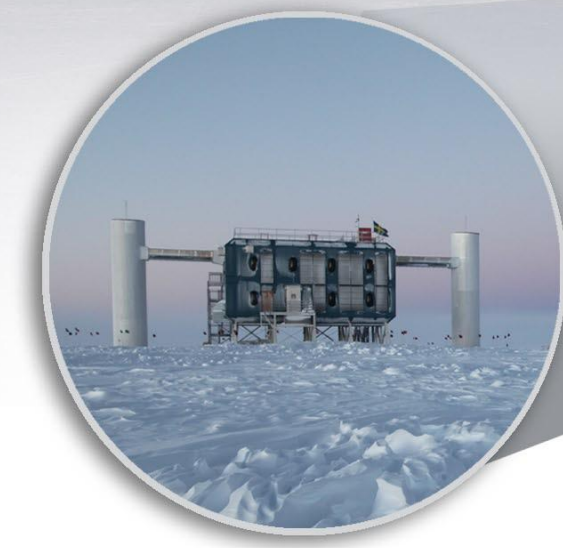

IceCube T1 Overview

Max, Omar

2026.09.28

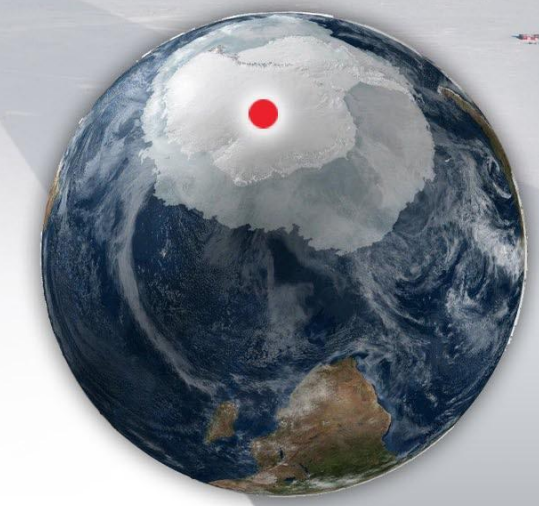
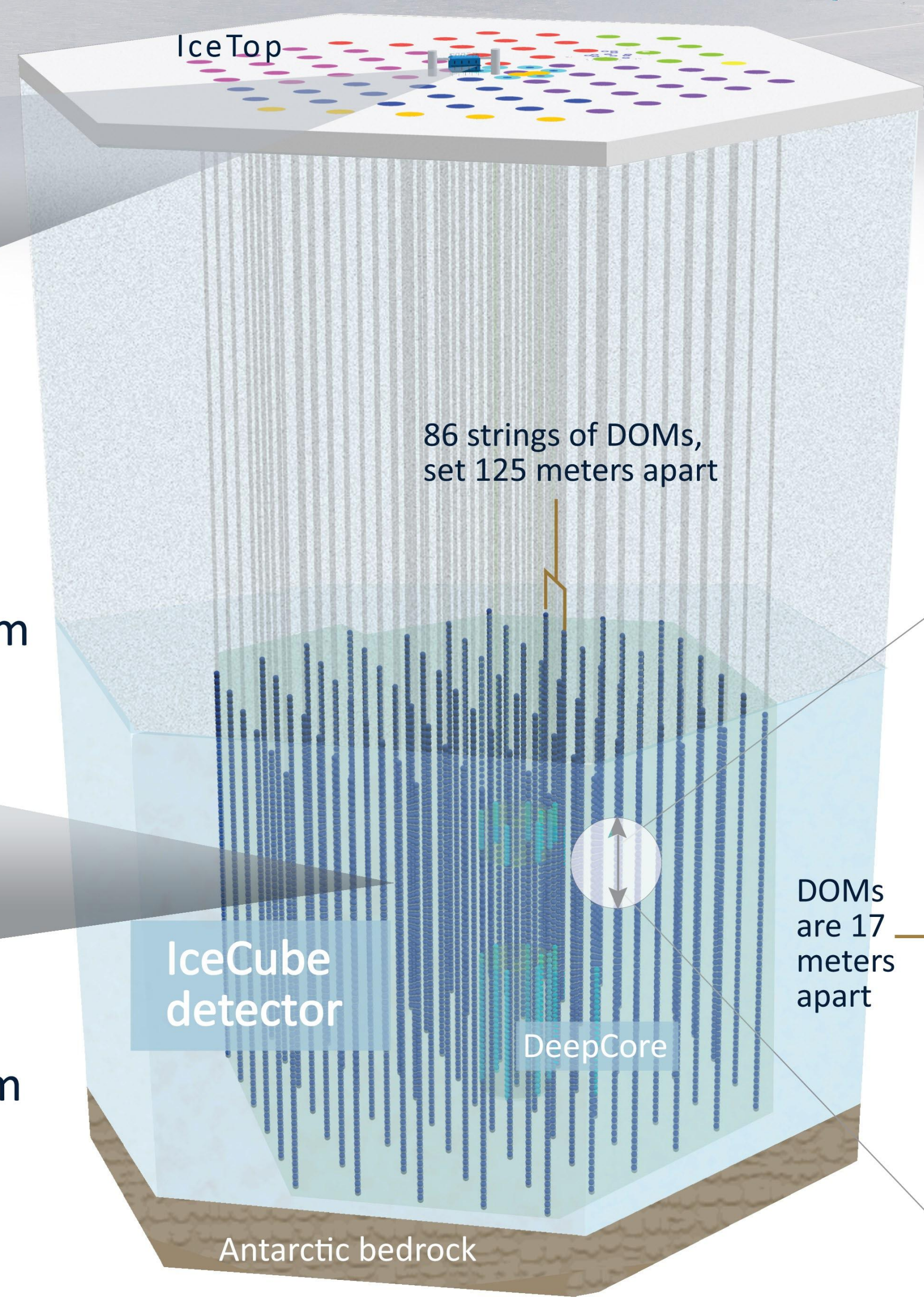


IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison



Digital Optical Module (DOM)
5,160 DOMs deployed in the ice

50 m
1450 m
2450 m



Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility

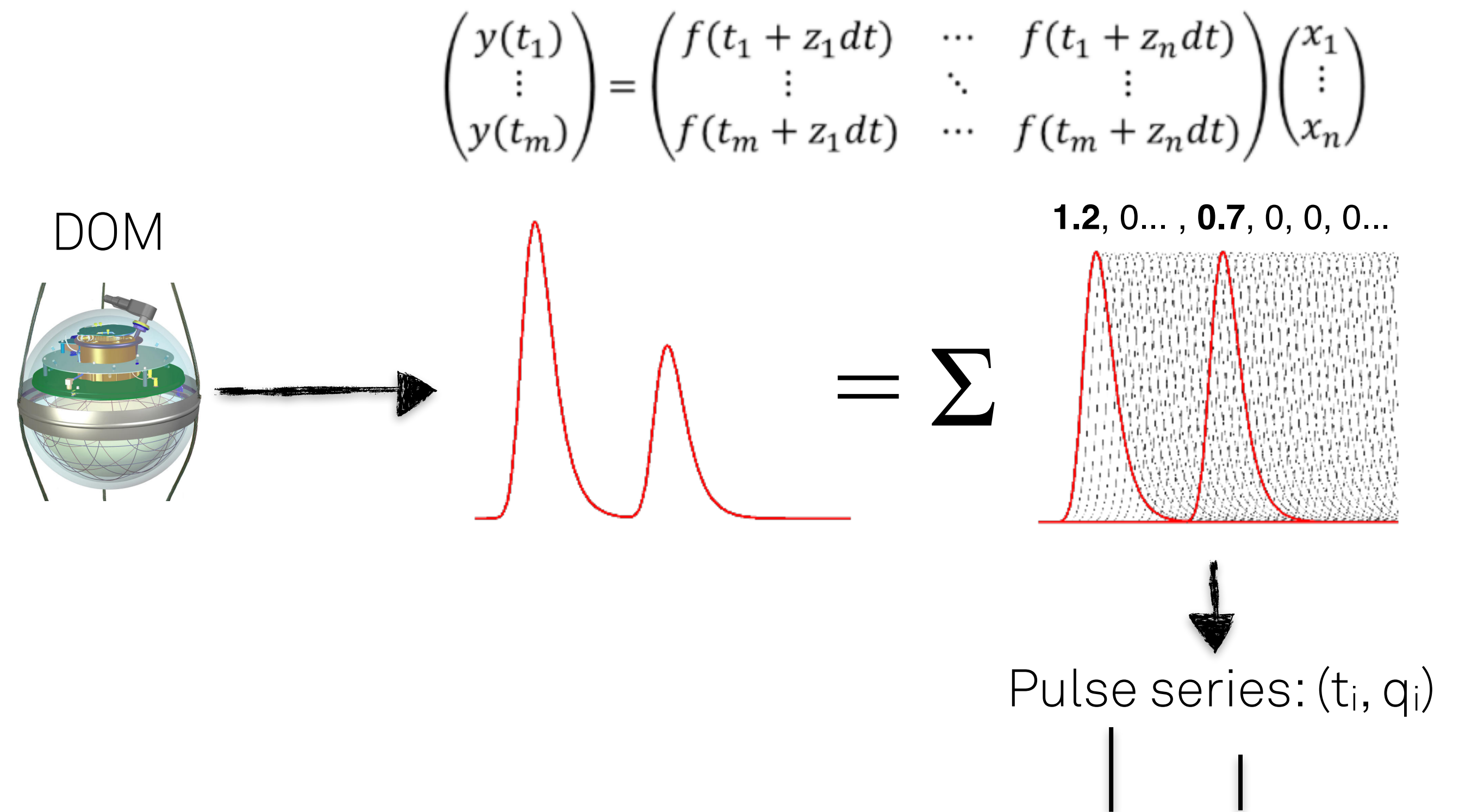


Detector Design

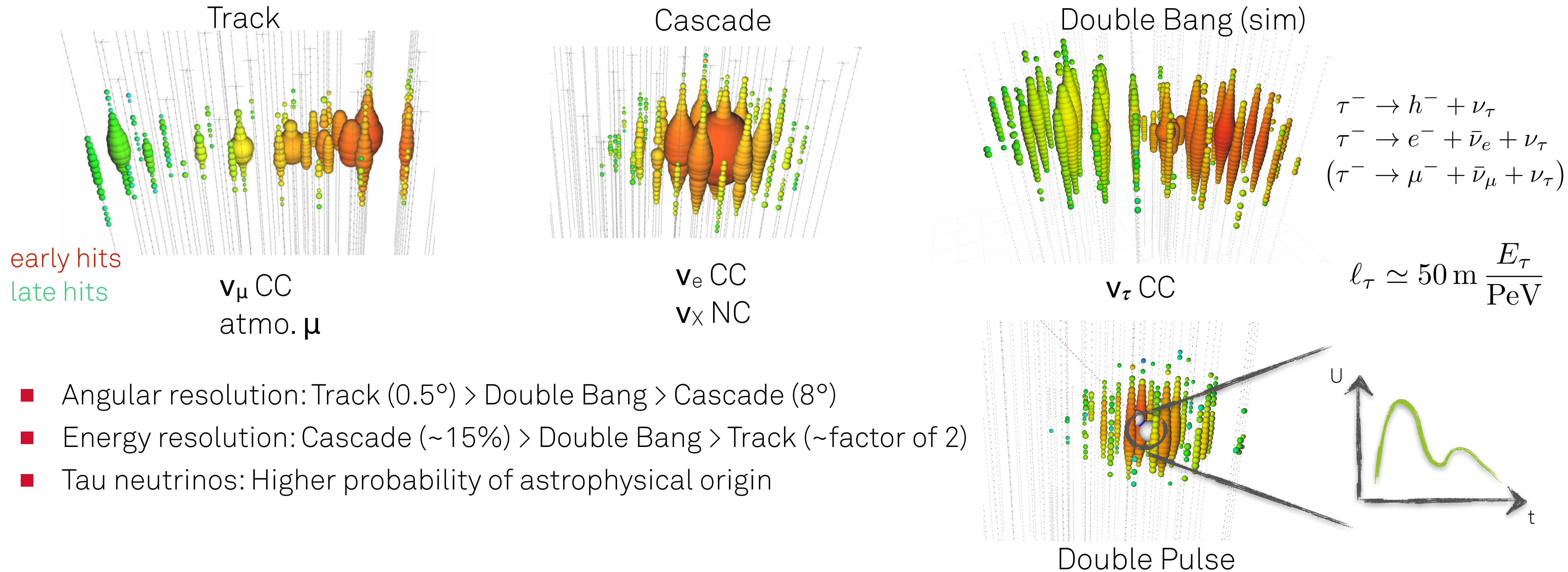
-  1 gigaton of instrumented ice
-  5,160 light sensors, or digital optical modules (DOMs), digitize and time-stamp signals
-  1 square kilometer surface array, IceTop, with 324 DOMs
-  2 nanosecond time resolution
-  IceCube Lab (ICL) houses data processing and storage and sends 100 GB of data north by satellite daily

IceCube data structure

- DOMs record waveforms (422ns)
- Typical waveform of a single photo-electron (SPE) event is well known
- Measured waveform = linear combination of time-delayed SPE waveforms



Event Signatures in IceCube



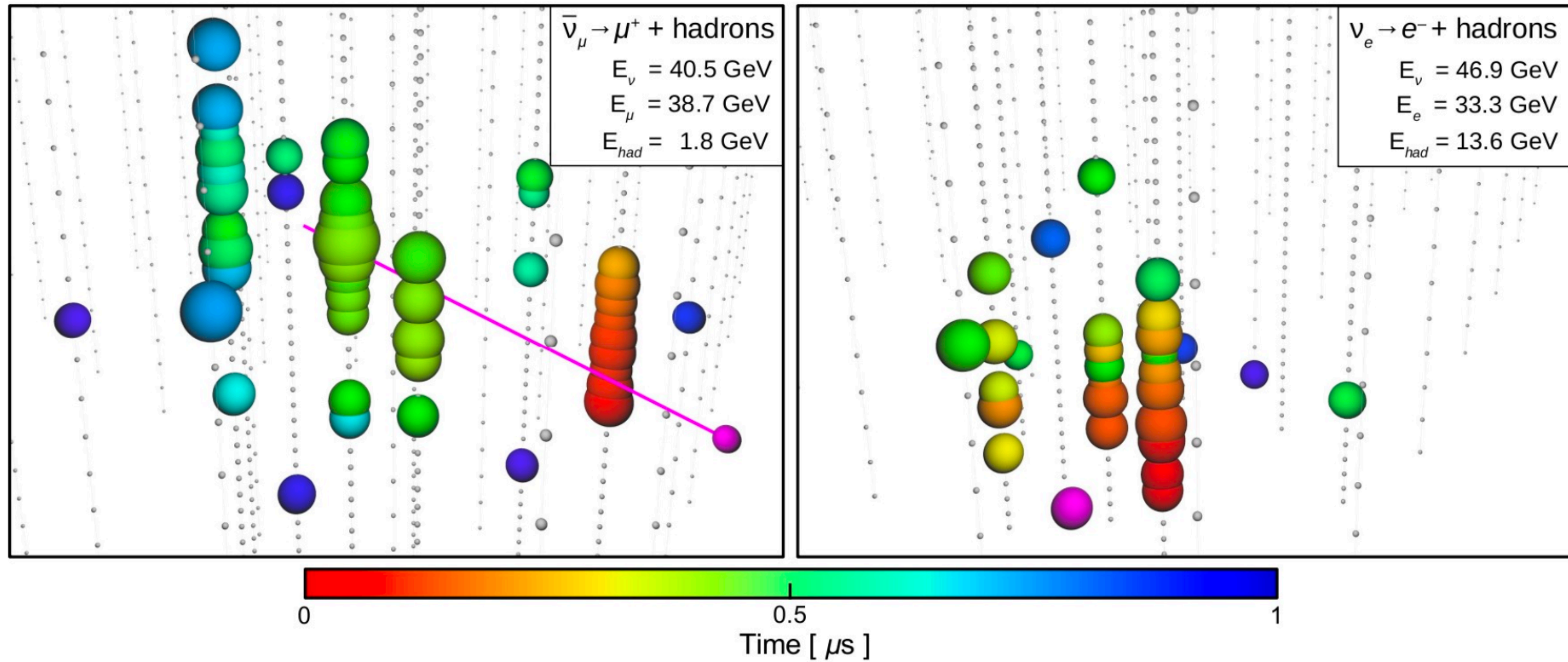
IceCube's highest energy neutrino event

March 2019

$$E_\nu = 11.4 \text{ PeV}$$



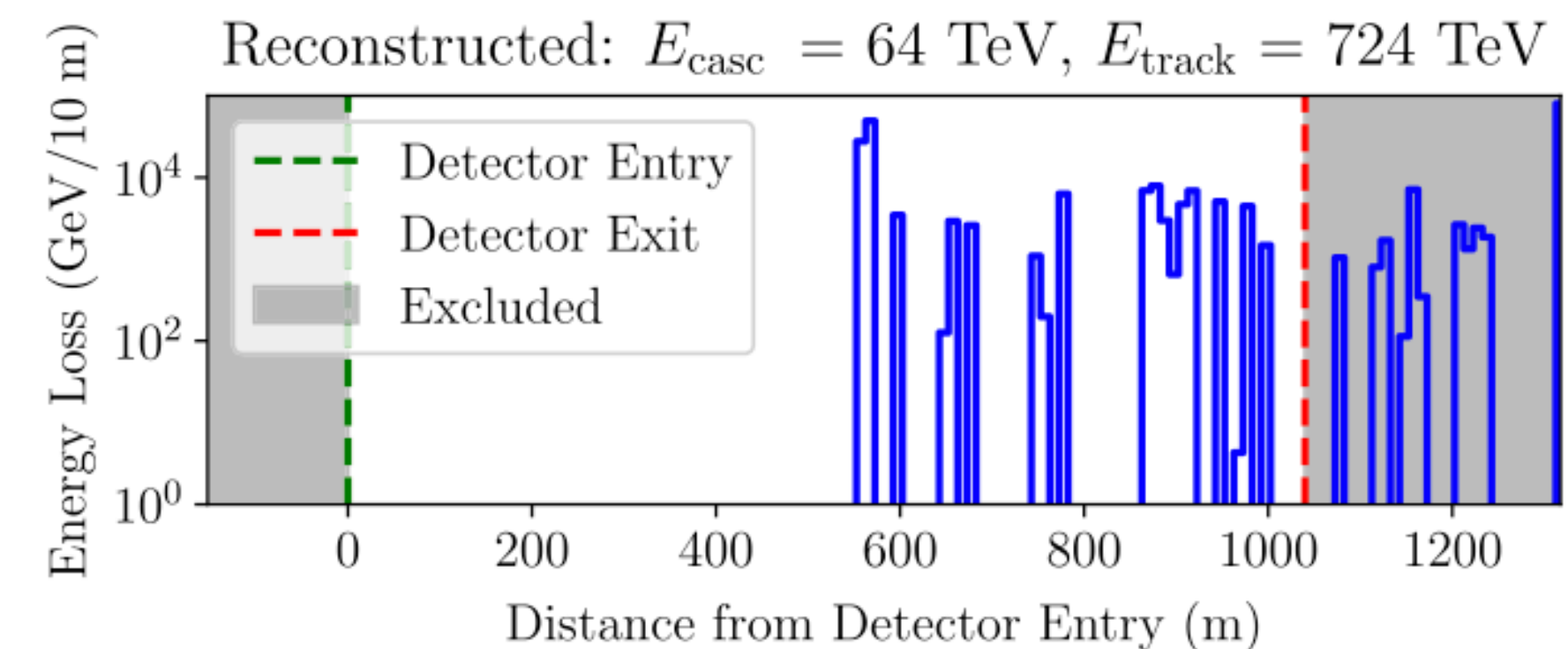
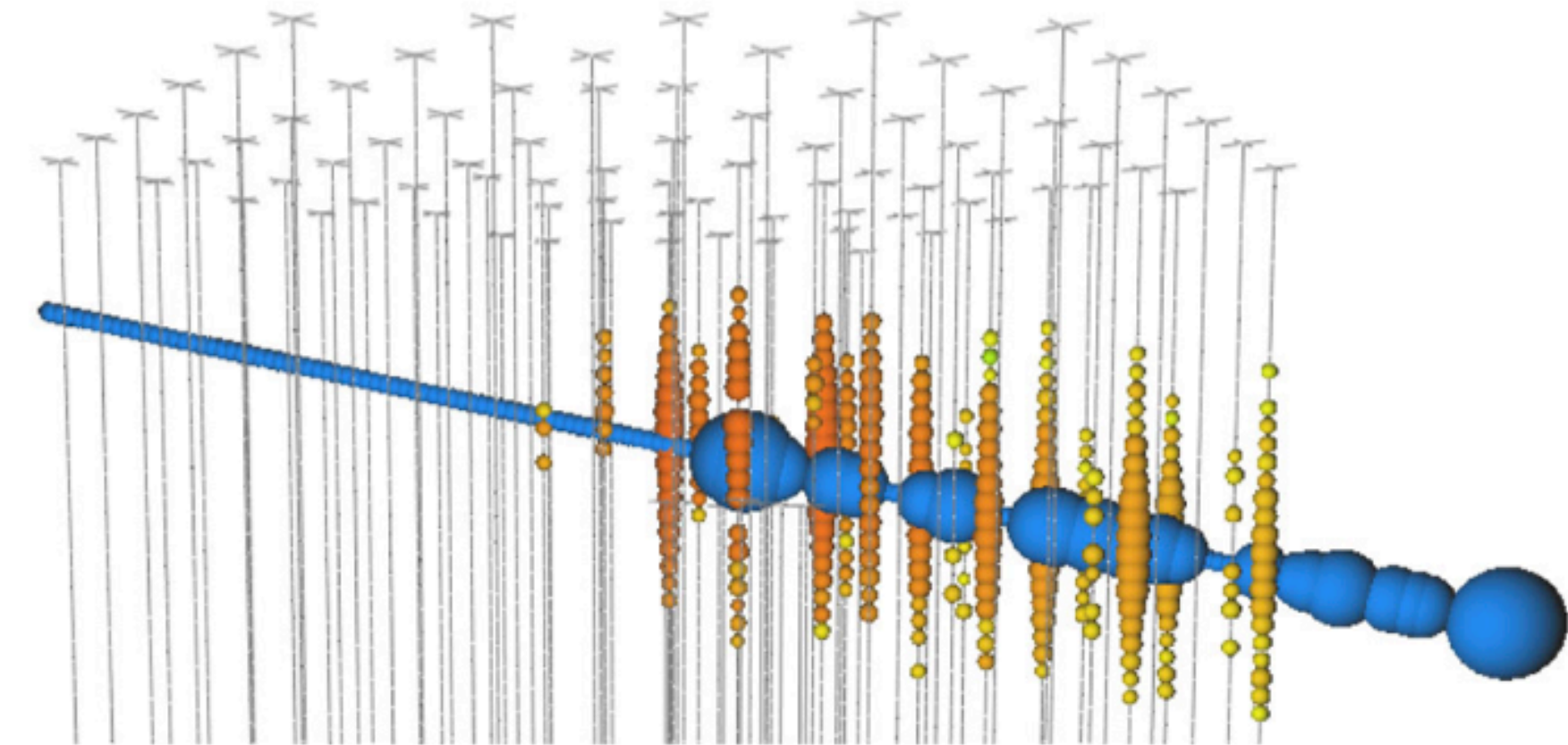
Low energy event topologies



Key challenges and AI tasks

- Directional reconstruction of parent neutrino
- Energy reconstruction
 - Total deposit (standard)
 - Individual cascades/energy losses (challenging)
- Neutrino interaction vertex/time
- PID
 - Track (ν_μ CC)
 - Cascade (ν_e CC, NC)
 - Double cascade (ν_τ CC / single cascades w/ charm, $E > 10$ s of TeV))
- Soft clustering of pulses into track pulses and pulses from (specific) cascades

PRD 99, 032004 (2019)

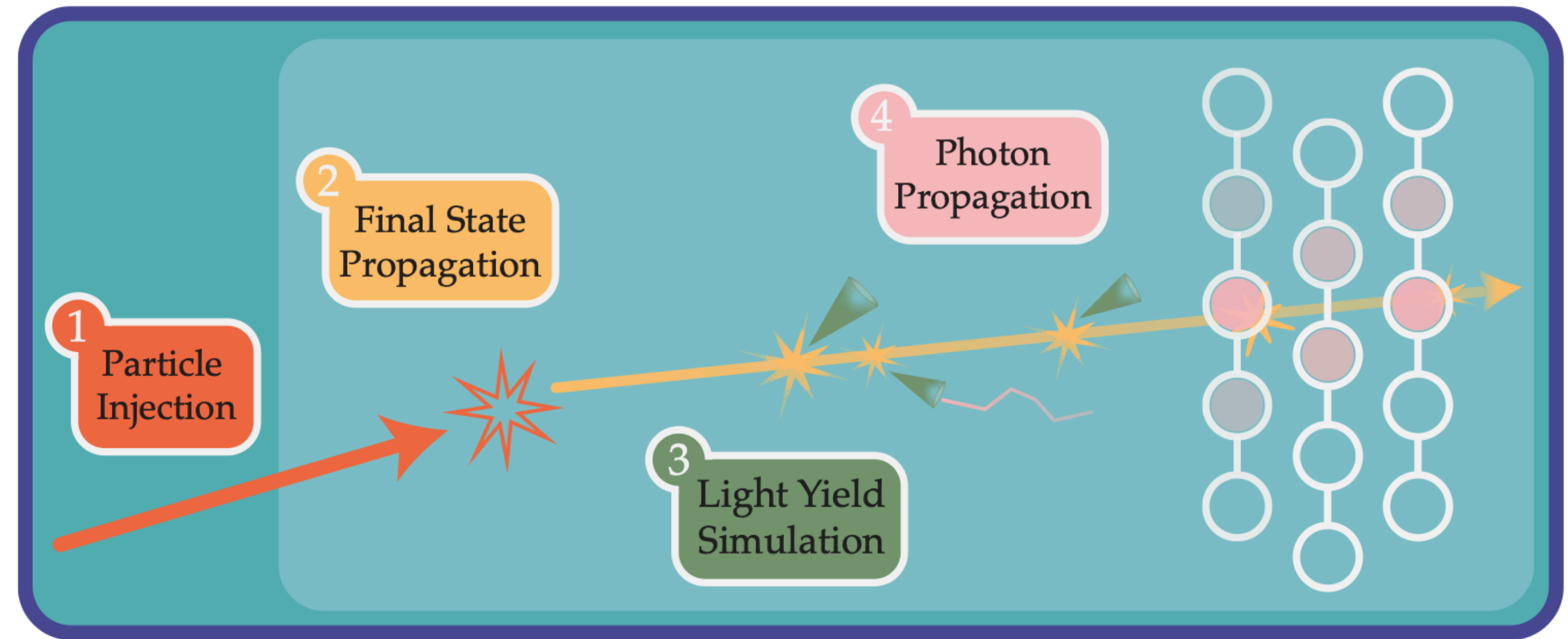


Target dataset

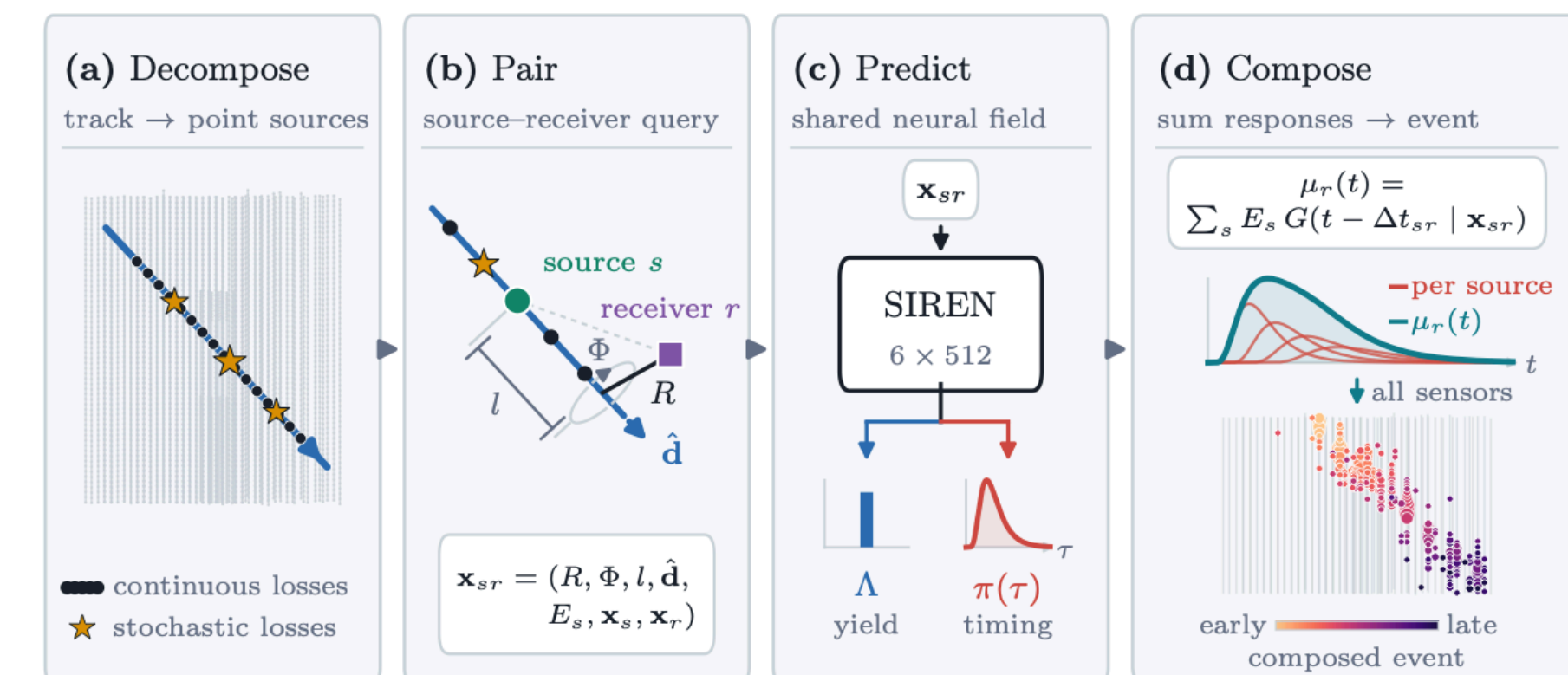
- All-flavor
- $E_\nu \in [100 \text{ GeV}, 1 \text{ PeV} \dots 100 \text{ PeV}]$
 - Upper bound constrained by resources/simulation technique
 - Dataset up to **100 PeV** will need $\mathcal{O}(100\text{k})$ GPUh
- Aim for dataset size comparable to IceCube datasets ($\sim 2 \cdot 10^8$ events, $\gamma \in [-1, \dots, -2]$)

Tools

- Prometheus
 - Open Source tool for neutrino telescope simulation (ice/water)
 - Currently uses `ppc` code for photon prop. in ice
- Simulation output
 - photons hitting sensors
- Need to add simple detector simulation as a post-processing step
 - Charge smearing
 - Time jitter
 - Hit merging



Surrogate model for photon propagation developed by Harvard group to be added to prometheus soon



potential ~100x speed-up

[arXiv:2609.04695](https://arxiv.org/abs/2609.04695)

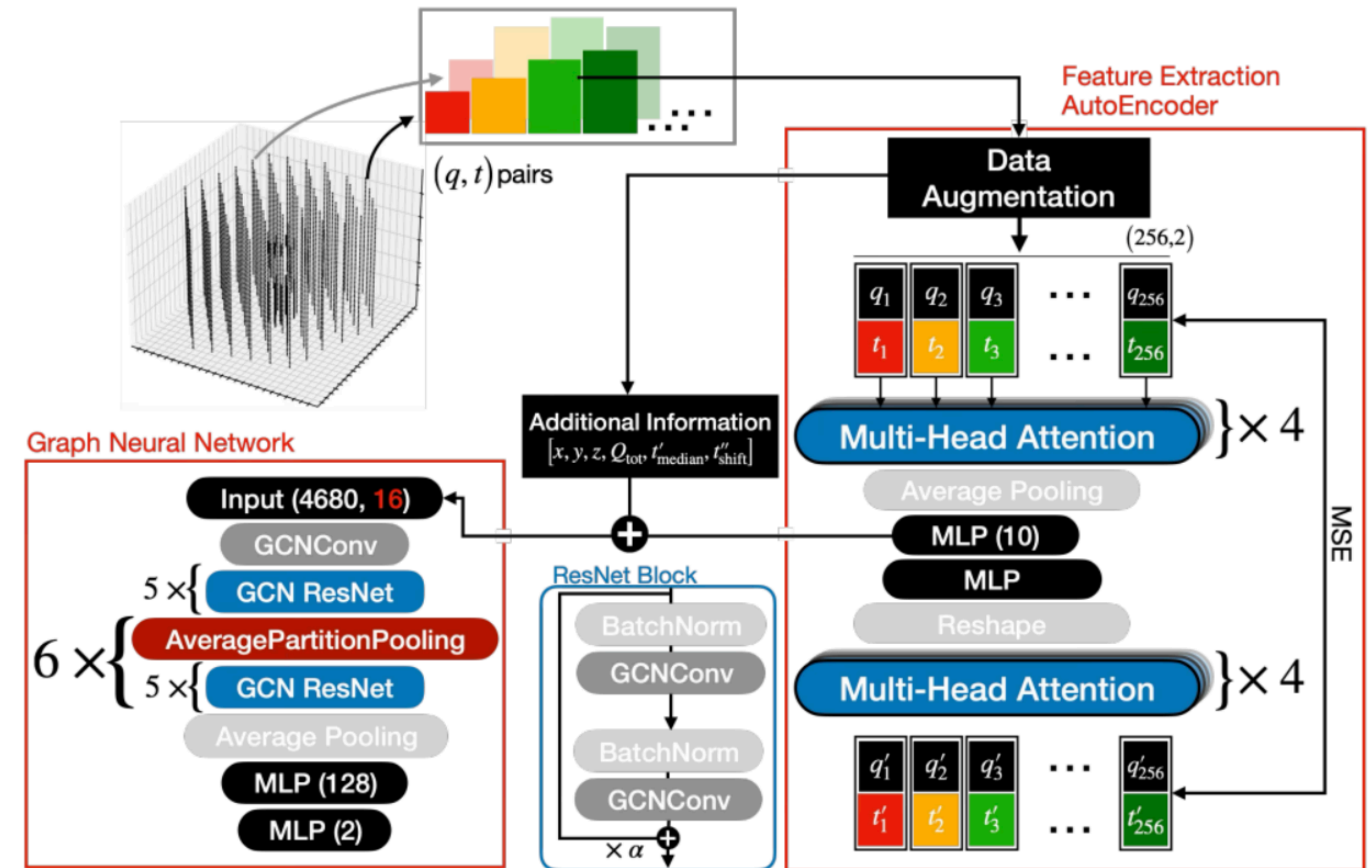
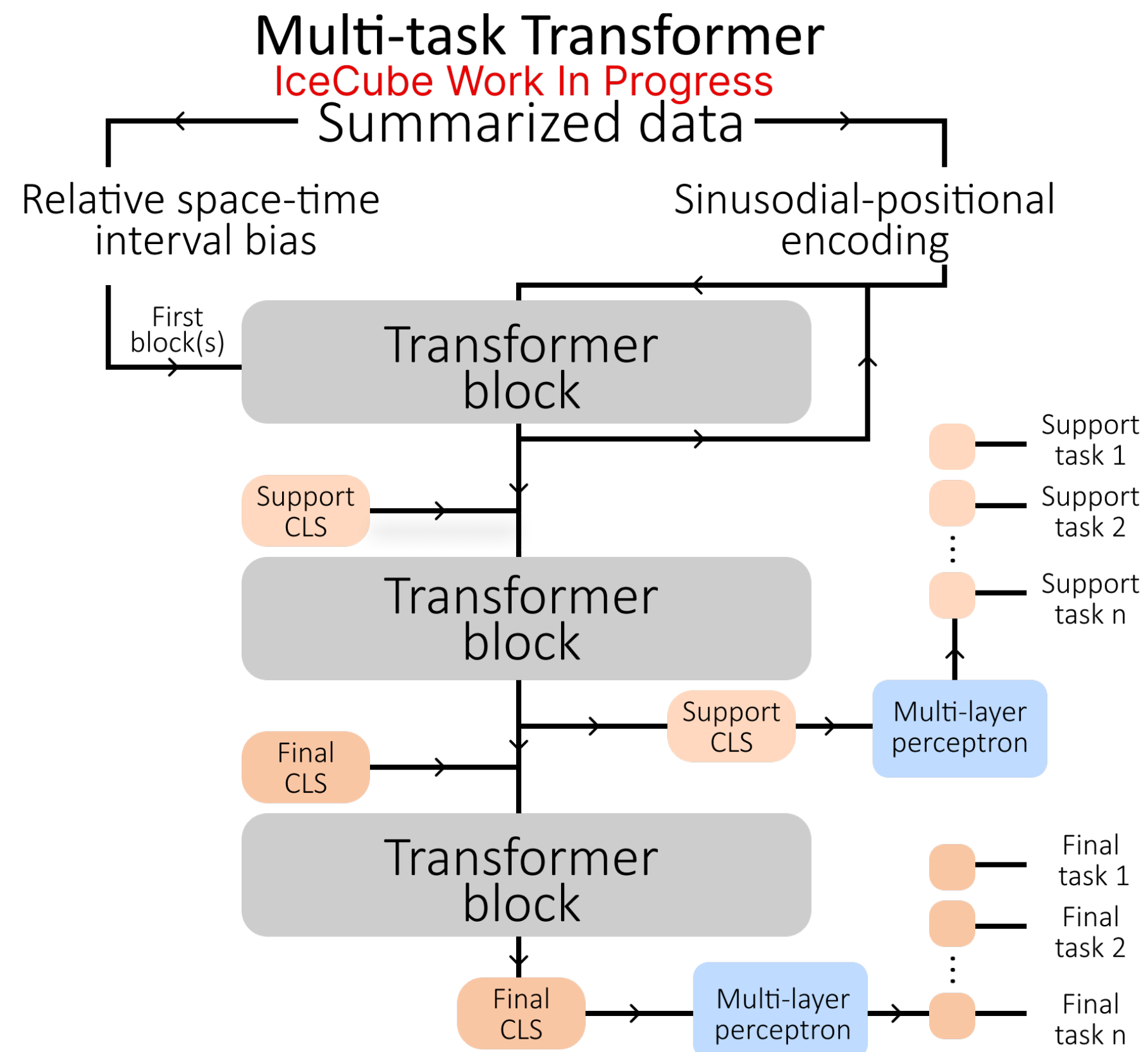
Potential AI solutions and plans for this week

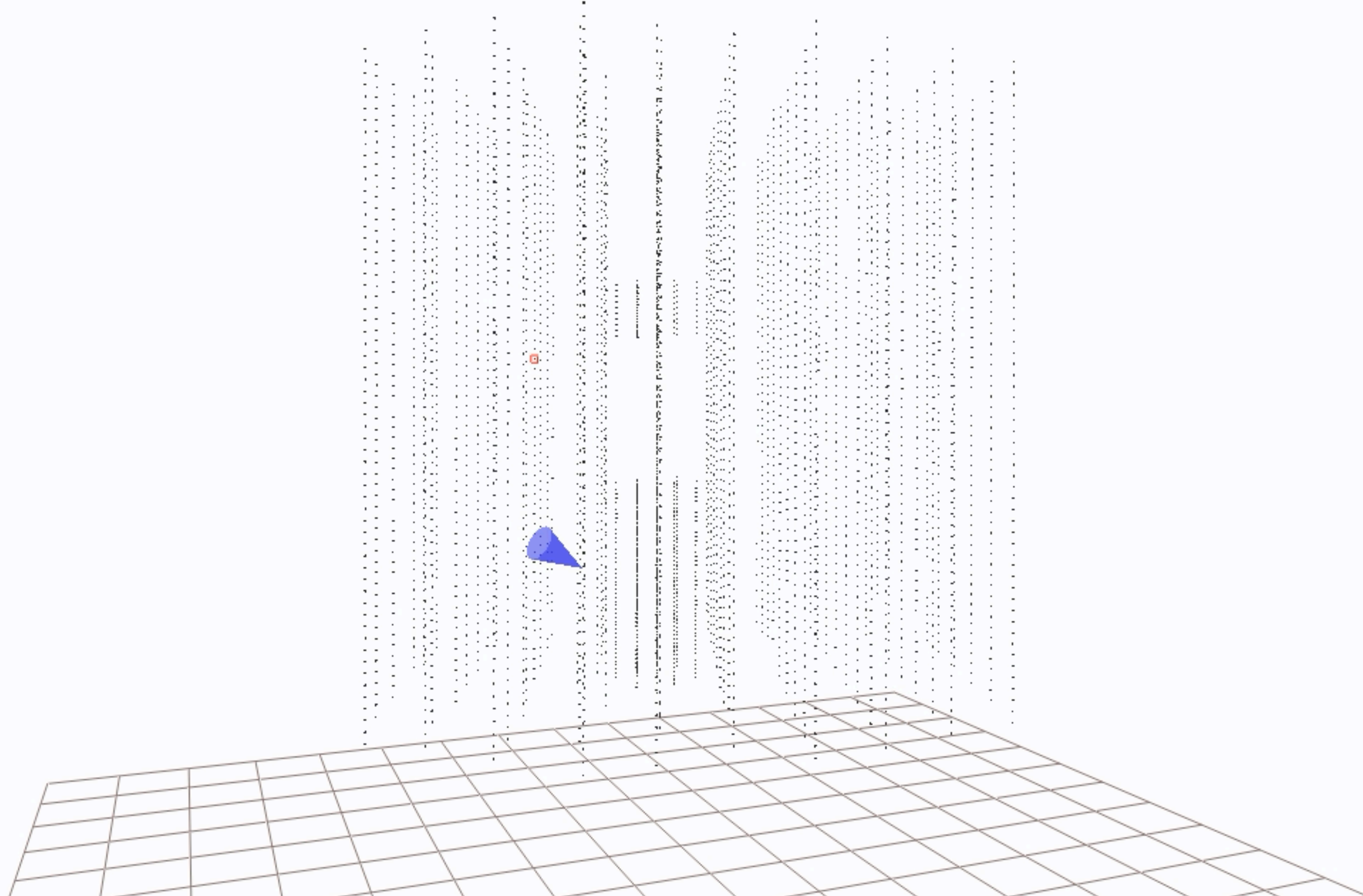
- Suggestion from Kazu: Train a Panda-style model
 - Would like to discuss with Sam
- Not discussed intensively yet
- Goal for this week:
 - Run initial production end-to-end
 - Inspect output
 - Measure / estimate / extrapolate resource needs
 - Document pilot production work flow
- Discuss available computing resources
- Finalize task list & discuss relevant metrics

Timeline & Prospects

- Start dataset production in the coming weeks
- Finish dataset production by EoY
- Produce lower energy range datasets first
 - If/when surrogate model becomes available high energy simulation can be sped up
- If time permits, it should be straightforward to also add a water-based „KM3NeT-like“ detector
 - Photon propagation in water needs fewer resources

More recent WIP architectures used in IceCube



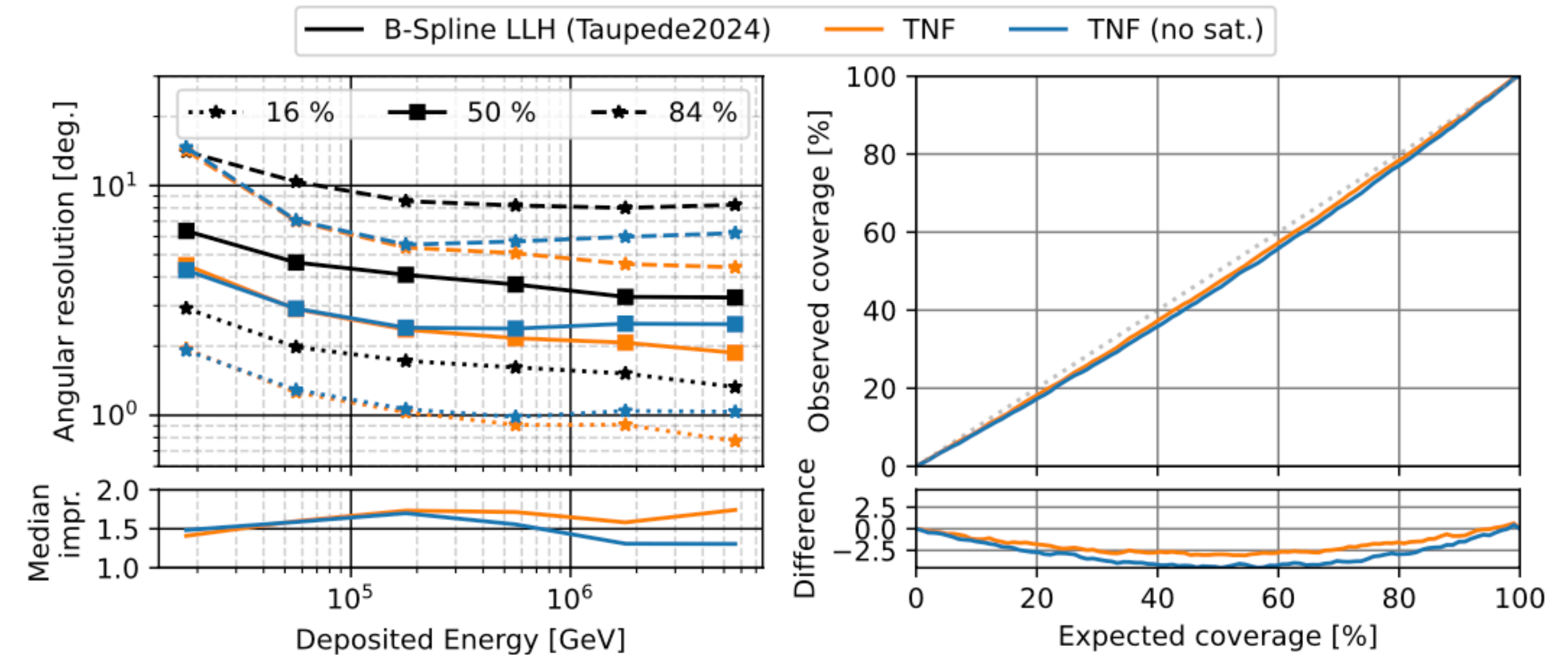


More challenging // exotic signatures

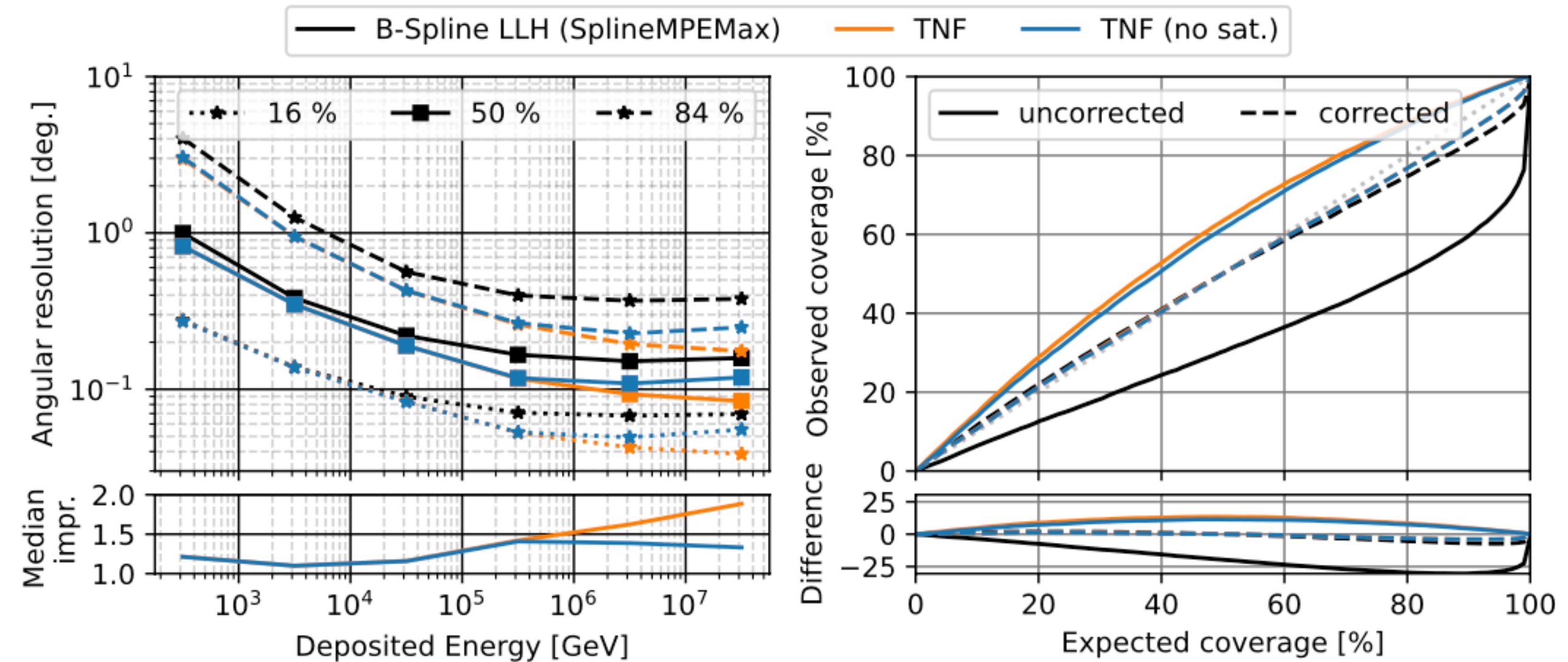
- Charm production in hadronic cascades
- Dimuon events
- Single muons // Atmospheric muon bundles

Normalizing flows performance

- Comparison of normalizing flows' performance to traditional likelihood reconstructions



(a) Neutrino-induced showers



(b) Throughgoing tracks (at least 300m distance within detector)

[arXiv:2604.19846](https://arxiv.org/abs/2604.19846)

Wavedeform (Waveform → Hit Converter)

- Typical waveform of a single photo-electron (SPE) event is well known

- Measured waveform = linear combination of time-delayed SPE waveforms

- Problem to solve:

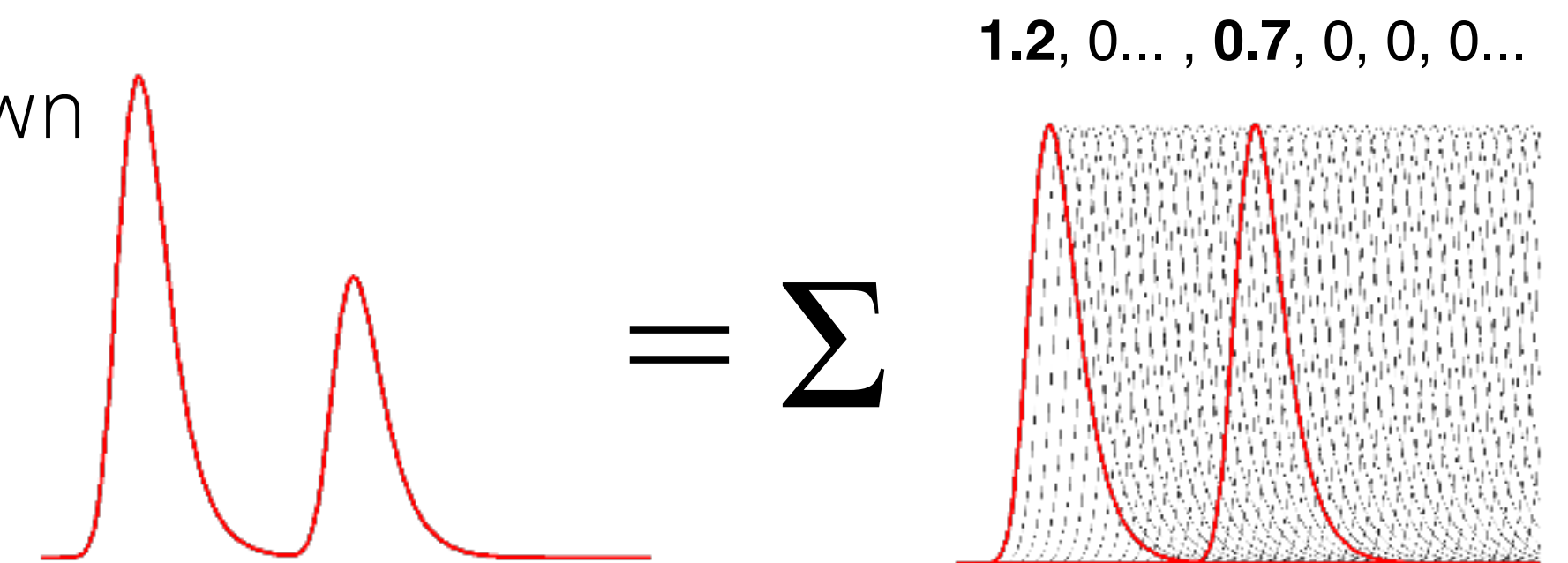
$$A^T A x = A^T y \quad \text{with sparse } x \geq 0$$

- y = waveform, x = pulse series

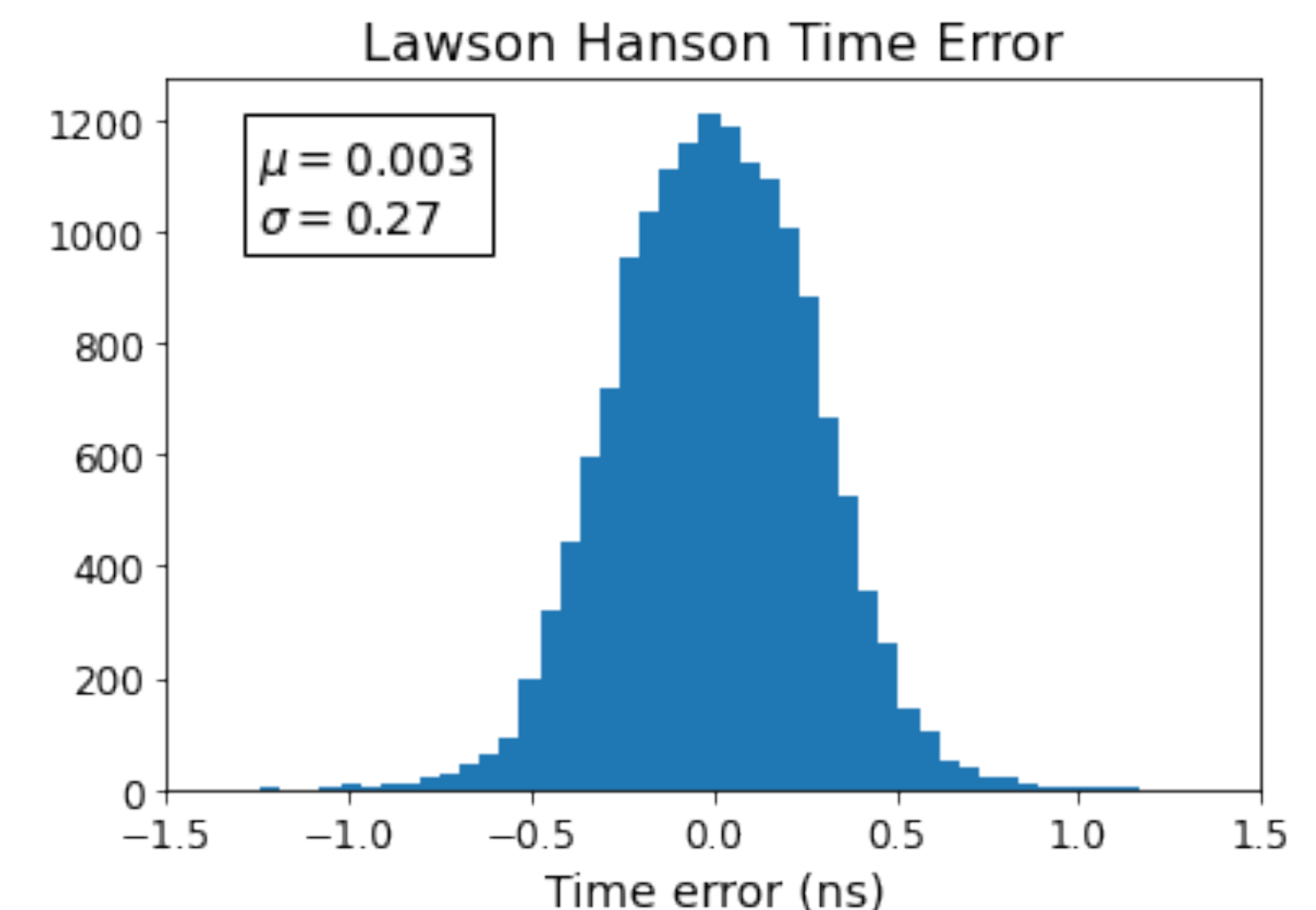
- IceCube currently uses Lawson-Hanson NNLS algorithm to solve this

- Timescale here is much smaller than the PMT transit time spread ($\sim 2.2\text{ns}$)

- Side note: This makes labels for individual pulses fuzzy

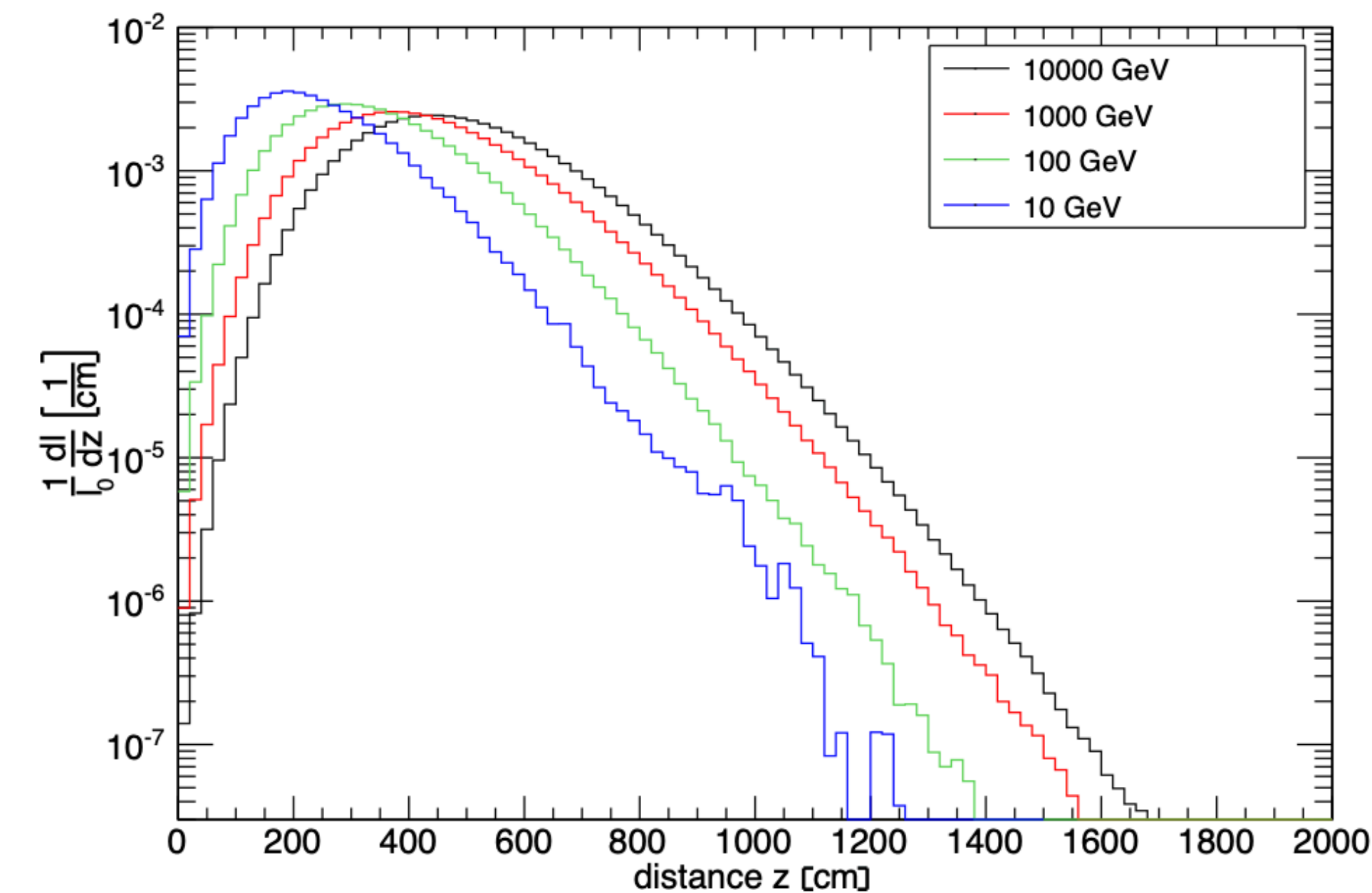


$$\begin{pmatrix} y(t_1) \\ \vdots \\ y(t_m) \end{pmatrix} = \begin{pmatrix} f(t_1 + z_1 dt) & \cdots & f(t_1 + z_n dt) \\ \vdots & \ddots & \vdots \\ f(t_m + z_1 dt) & \cdots & f(t_m + z_n dt) \end{pmatrix} \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix}$$



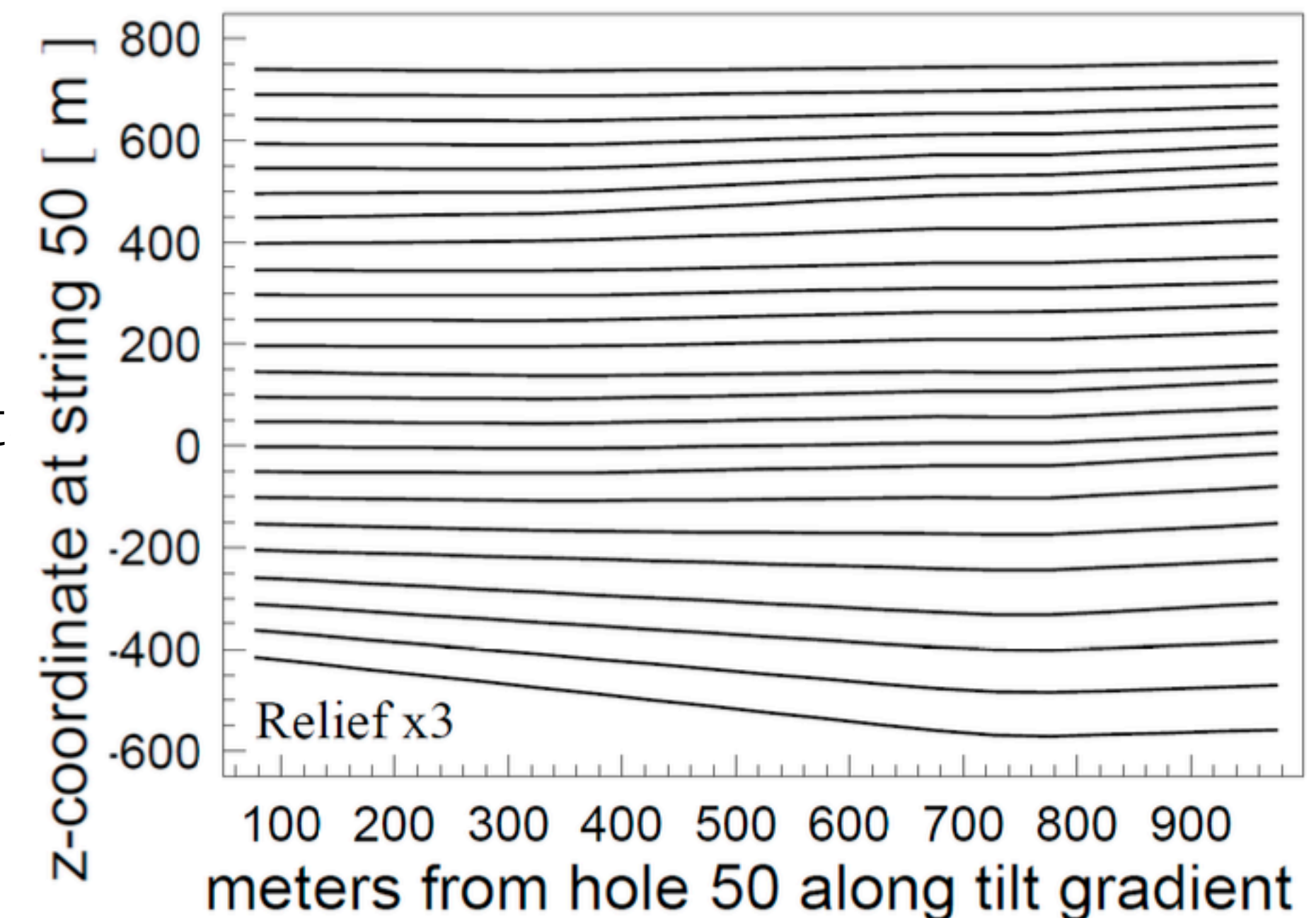
Light yield in Prometheus

- photon propagation code ([ppc](#)) is used to simulate light yield and to propagate photons to modules
- Light yield parametrization from [Calculation of the Cherenkov light yield from electromagnetic cascades in ice with Geant4](#)
 - Simulated EM-showers from 1 GeV to 10 TeV in ice with GEANT
 - Hadronic showers are re-scaled EM showers (energy dependent)
 - Longitudinal profile is modeled by a Γ -distribution
- Same parametrization is used by IceCube simulations
- Separate implementation in Prometheus: fennel
 - Used for water based detectors by default
 - Can also be used for Ice, uses same light yield parametrization as ppc
 - Easier to use standalone, compared to just using parts of ppc

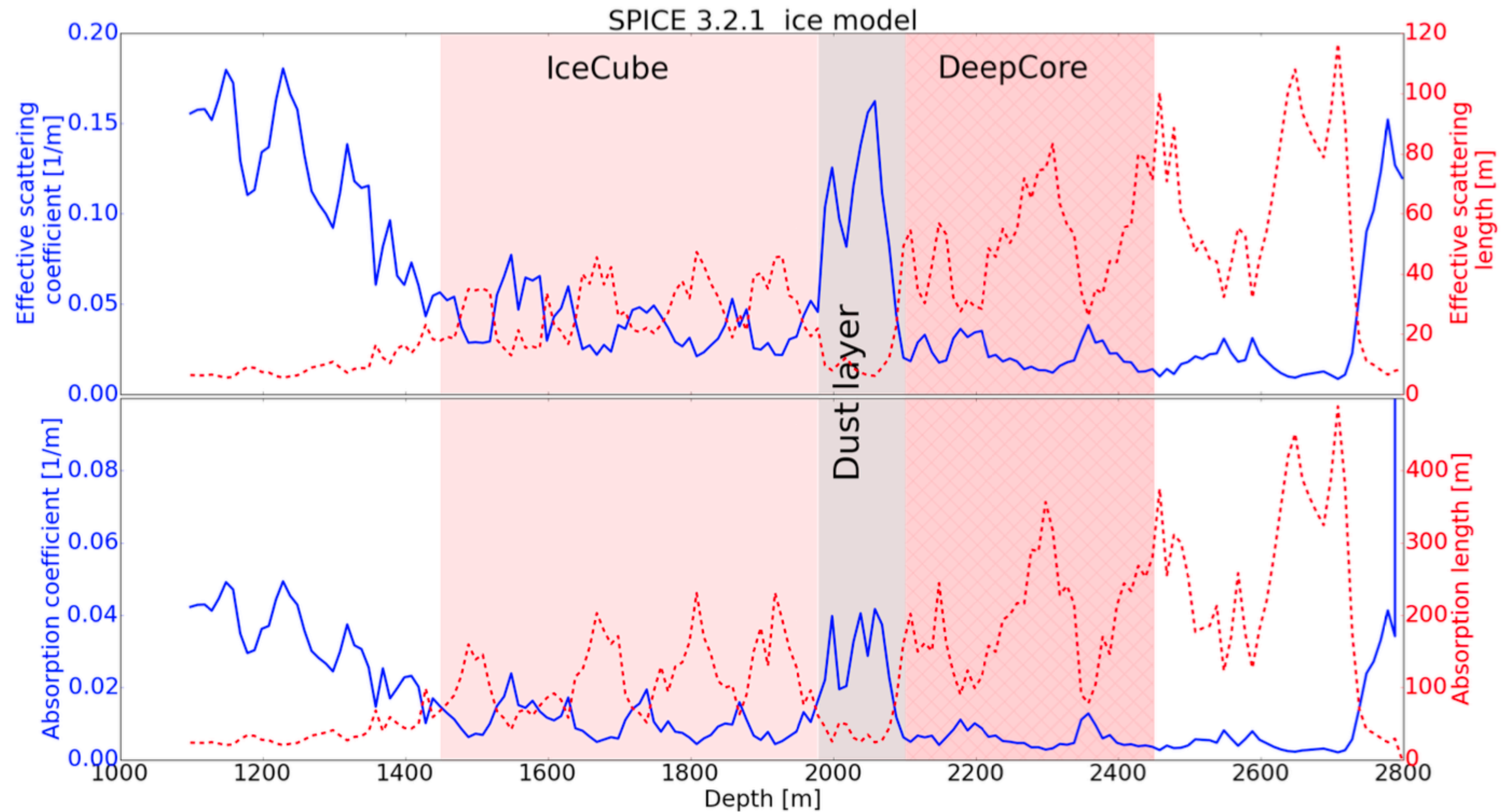


Ice Model Overview

- Modeled in layers with 10m width
- Absorption and scattering coefficients tabulated for each layer @400nm (1100 - 2800m depth)
- Wavelength and temperature dependence described by global parameters
- Scattering function also described by global parameters
- Global parametrization of ice layer tilt (from dust logger data)
- Ice anisotropy described 1 directional & 2 strength coefficient (only works as an effective model)
- Newest ice model describes anisotropy by modeling ice as birefringent crystals
 - Not reconstructable with public information



Ice Model Overview

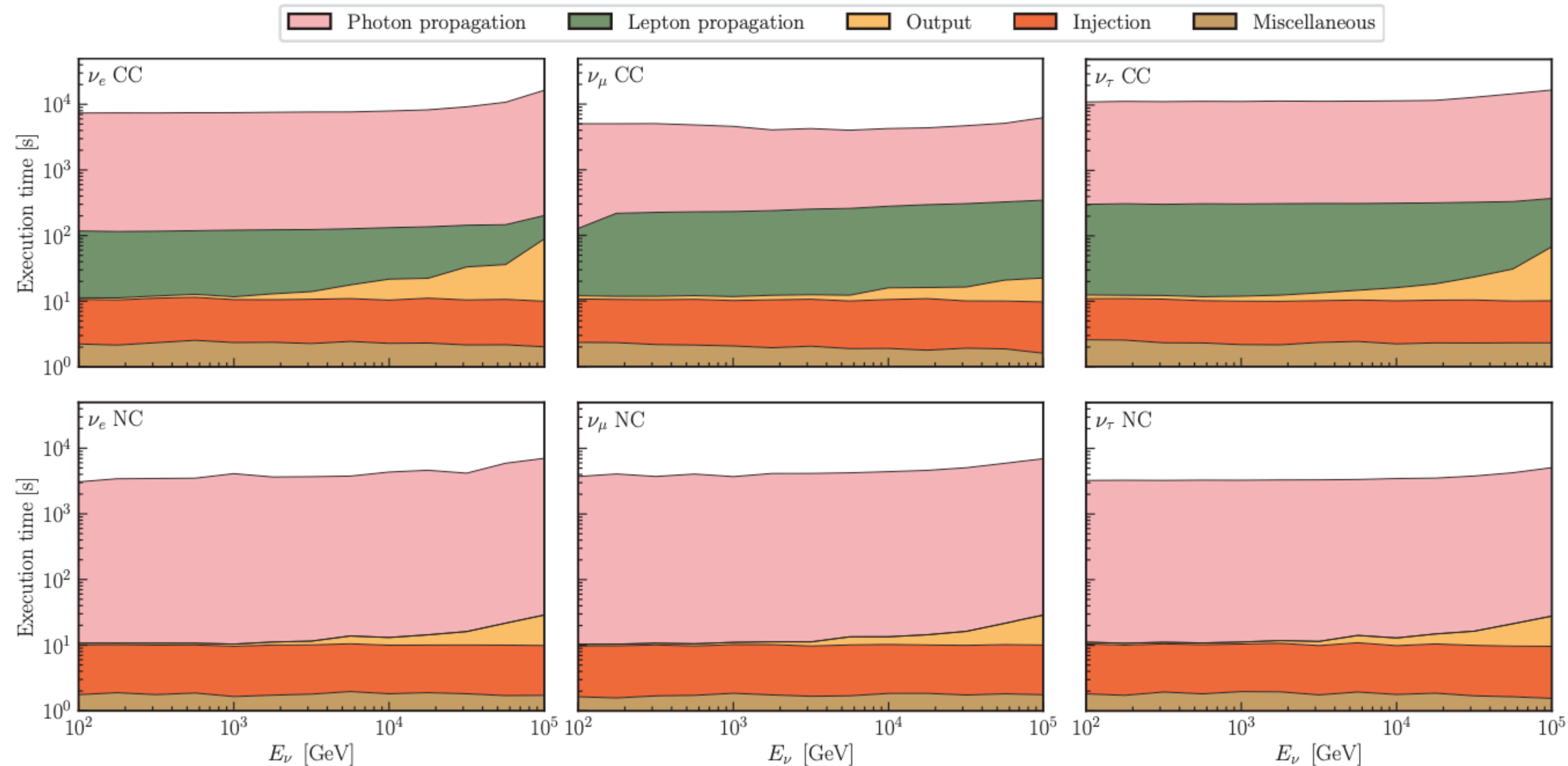


Ice Model in Prometheus

- Ice model passed to ppc described here: [resources/PPC_tables/south_pole](#)
- Uses scattering/absorption values from previous slide
- Ignores:
 - Ice tilt
 - Ice anisotropy

Wall time of Prometheus

Stacked histograms for ice-like detector
Photon propagation done by ppc



10^5 GeV is
somewhat low

Rough wall time estimates based on IceCube datasets

Energy range	Simulated power law index	DOM oversizing	CPU kh / flavor	GPU kh / flavor	N Events generated
10^2 - 10^4 GeV	-1.5	1	1.2	3.1	$2\text{E}+08$
10^4 - 10^6 GeV	-1.5	1	0.6	5.1	$4\text{E}+07$
10^6 - 10^8 GeV	-1.0	3	3.2	25.2	$4\text{E}+06$

NuBench

[arXiv:2511.13111](https://arxiv.org/abs/2511.13111)

- <https://github.com/graphnet-team/NuBench>
- Open benchmark sets for ML in Neutrino telescopes
- Using prometheus
- Many caveats
 - Almost exclusively focusing on water-based detectors since it's easier to simulate
 - Only ν_μ CC+NC simulation
 - Energy limited to $< 100 \text{ TeV}$
 - PID only possible between tracks (ν_μ CC), cascades (ν_μ NC)
- Using simple detector simulation
 - Merging hits (within a few ns based on TTS)
 - Smearing charge and arrival time
 - (No waveform simulation + pulse unfolding)
 - No PMT saturation