Convolutional neural network neutrino reconstruction in IceCube

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The Standard Model of particle physics

What can't it explain?

- Gravity
- Dark matter
- Dark energy
- **Neutrino masses**
- **Matter-antimatter asymmetry**

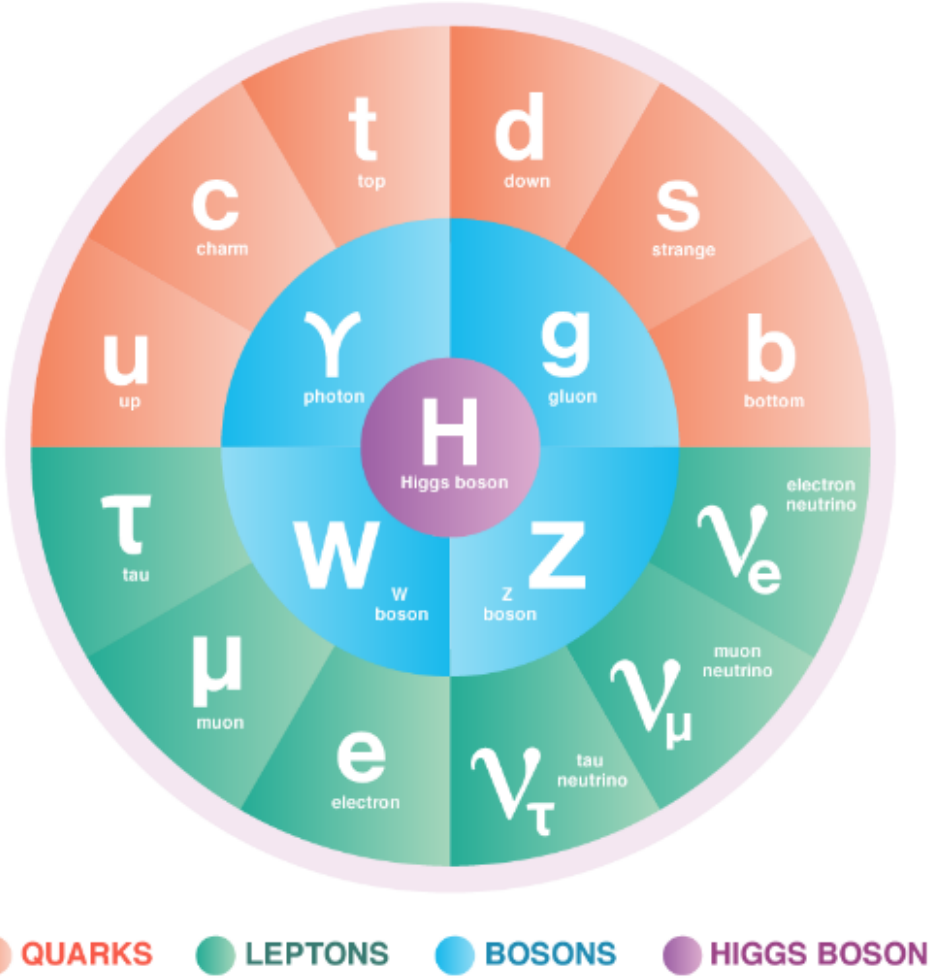


Image courtesy of Sandbox Studio, Chicago for Symmetry

Neutrinos

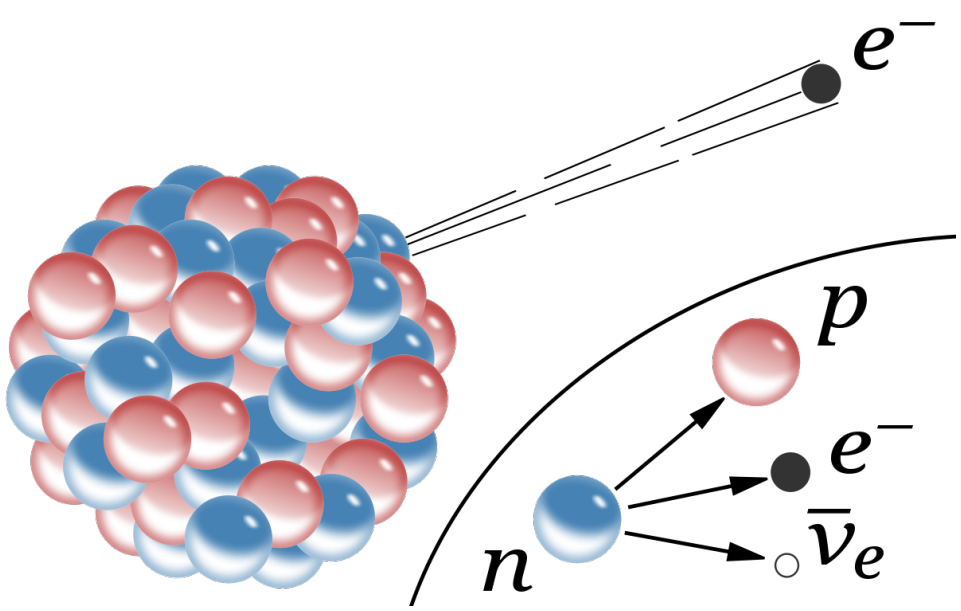


Image courtesy of Wikimedia

I have done a terrible thing, I have postulated a particle that cannot be detected.

—Wolfgang Pauli via C. Sutton

Neutrino used to explain

- Continuous energy spectra in beta decay
- Conservation of spin

Neutrinos

- Mass is necessary for oscillations
  - Does not follow from Standard Model
- CP-violation
  - Via CKM matrix (quarks)
  - Via PMNS matrix (neutrinos)

$$|\psi(L,T)\rangle = e^{-i\phi_1}\left(e^{i\Delta\phi_{12}} - 1\right)\cos\theta\sin\theta\,|\nu_e\rangle - e^{-i\phi_1}\left(e^{i\Delta\phi_{12}}\cos^2\theta + \sin^2\theta\right)|\nu_\mu\rangle$$

$$\Delta\phi_{12} = \phi_1 - \phi_2 \approx \frac{m_1^2 - m_2^2}{2\mathrm{p}}L$$

$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu) = 16\Im\left\{U_{e1}^* U_{\mu 1} U_{e2} U_{\mu 2}^*\right\}\sin\Delta_{12}\sin\Delta_{13}\sin\Delta_{23}.$$

Neutrino oscillations

Image courtesy of CBS News

The Homestake Experiment,

or: how to turn abject failure into a Nobel Prize in just 34 years!

$$|\psi(L,T)\rangle = e^{-i\phi_1}\left(e^{i\Delta\phi_{12}} - 1\right)\cos\theta\sin\theta\,|\nu_e\rangle$$
$$- e^{-i\phi_1}\left(e^{i\Delta\phi_{12}}\cos^2\theta + \sin^2\theta\right)|\nu_\mu\rangle$$

$$\Delta\phi_{12} = \phi_1 - \phi_2 \approx \frac{m_1^2 - m_2^2}{2\mathrm{p}}L$$

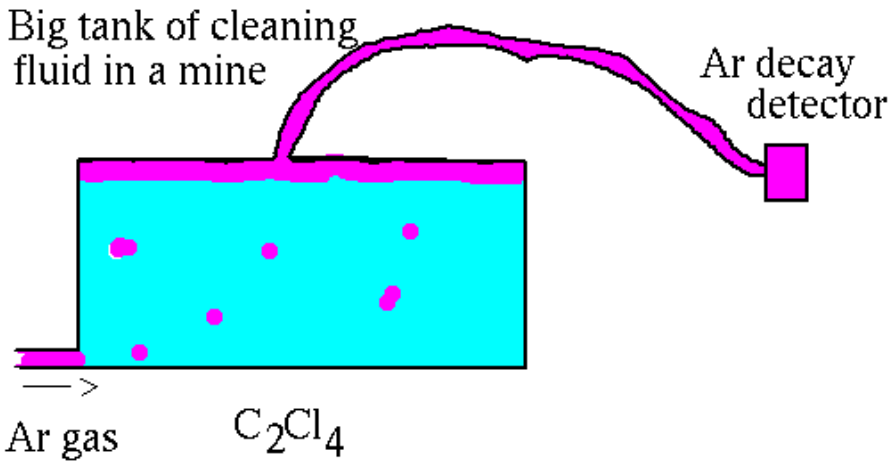


Image courtesy of University of Oregon

Why do we bother?

Precision

$$|U| = \begin{bmatrix} |U|_{e1} & |U|_{e2} & |U|_{e3} \\ |U|_{\mu 1} & |U|_{\mu 2} & |U|_{\mu 3} \\ |U|_{\tau 1} & |U|_{\tau 2} & |U|_{\tau 3} \end{bmatrix} = \begin{bmatrix} 0.801 \ldots 0.845 & 0.513 \ldots 0.579 & 0.143 \ldots 0.156 \\ 0.233 \ldots 0.507 & 0.461 \ldots 0.694 & 0.631 \ldots 0.778 \\ 0.261 \ldots 0.526 & 0.471 \ldots 0.701 & 0.611 \ldots 0.761 \end{bmatrix}$$

Values from NuFIT.org, June 2020

Multi-messenger astronomy

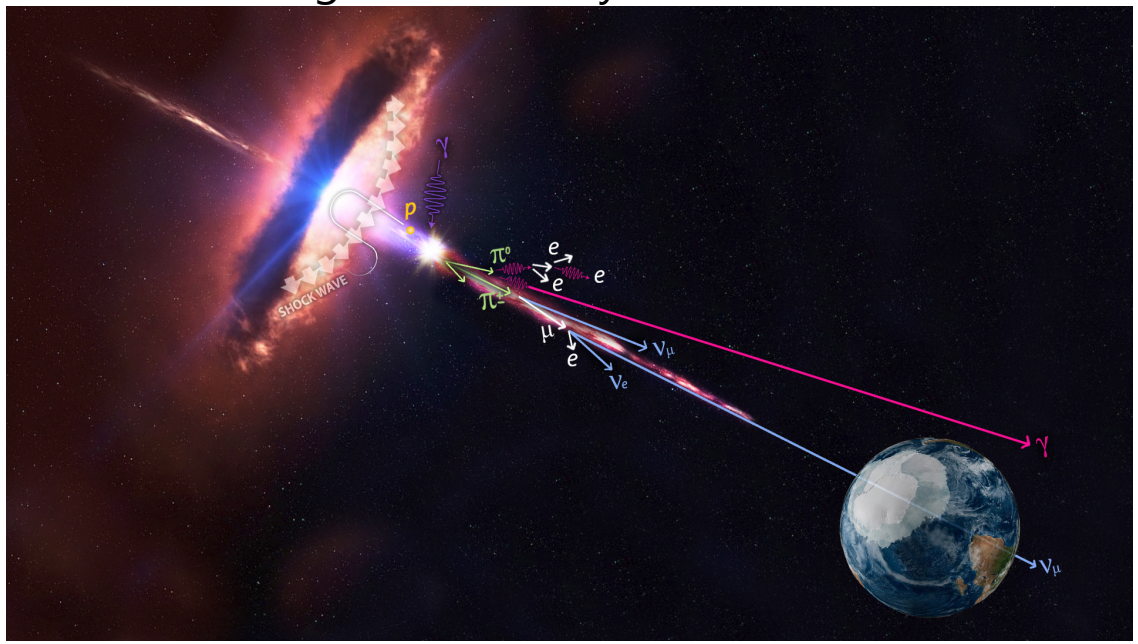


Image courtesy of IceCube/NASA

New particles

Desperately seeking sterile

The three known types of neutrino might be "balanced out" by a bashful fourth type

	ELECTRON NEUTRINO	MUON NEUTRINO	TAU NEUTRINO	STERILE NEUTRINO
	ν_e	ν_μ	ν_τ	ν_s
MASS	< 1 electronvolt			>1 electronvolt
FORCES THEY RESPOND TO	Weak force Gravity			Gravity
DIRECTION OF SPIN	All three "left handed"			"Right handed"

Image courtesy of quantumdiaries.org

IceCube Neutrino Observatory

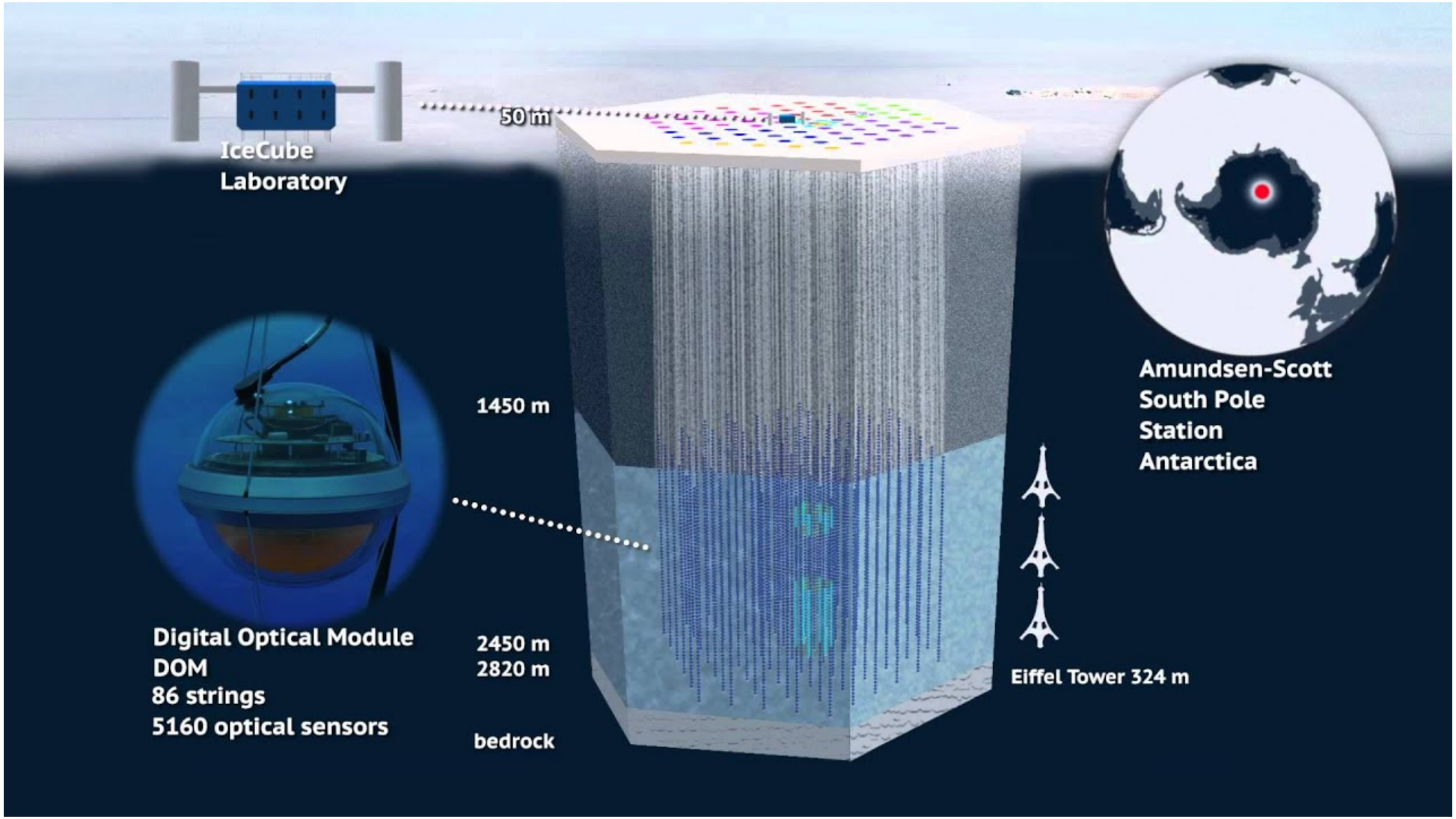


Image courtesy of IceCube

IceCube's past, present & future

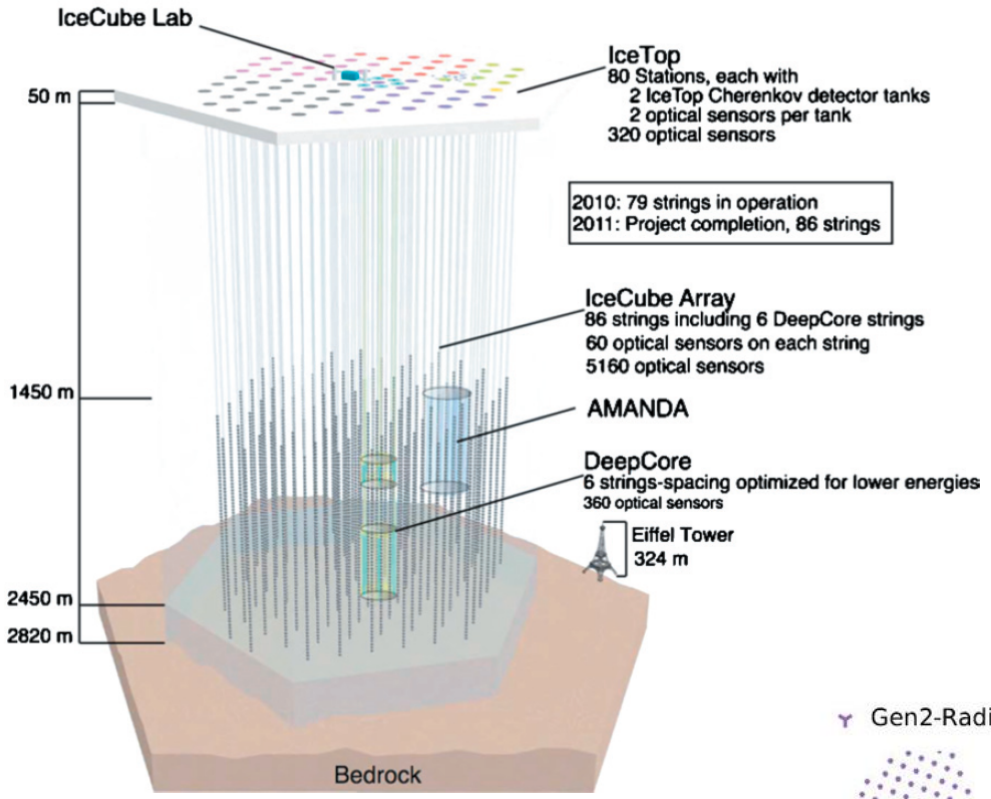


Image courtesy of IceCube

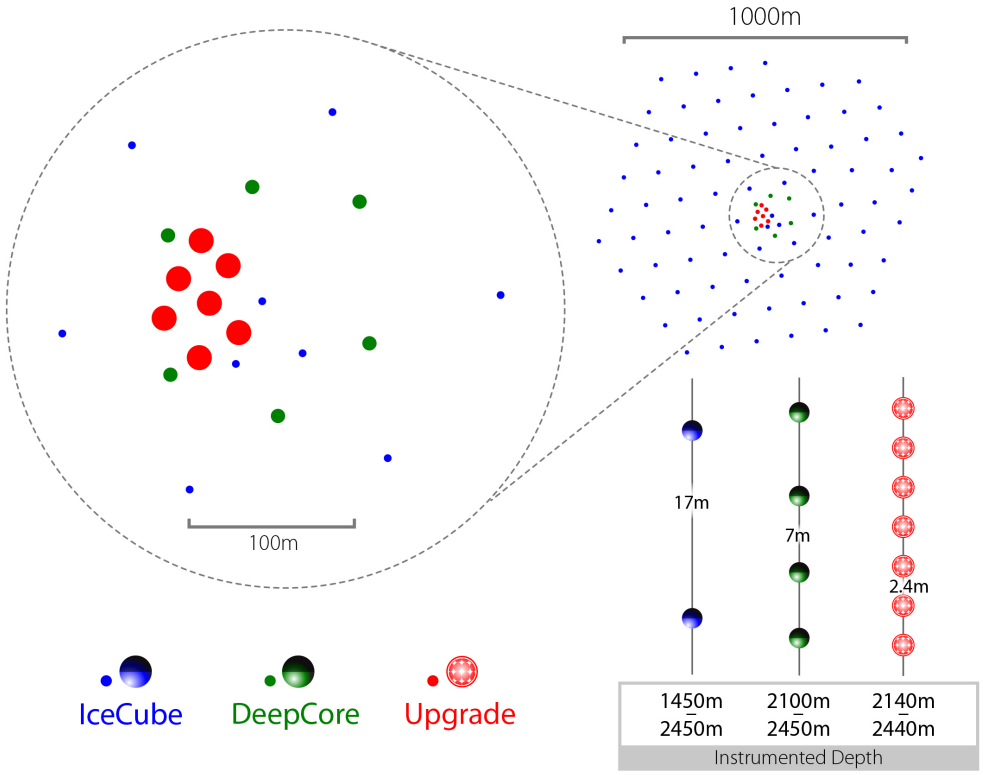


Image courtesy of IceCube

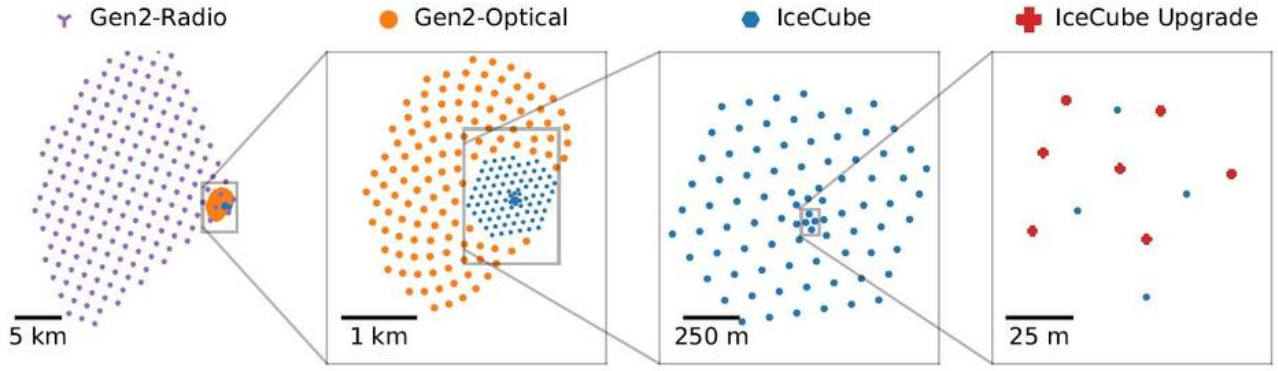


Image courtesy of DESY

Anatomy of an event

What makes up an event in data?

- Position of pulse
- Charge of pulse
- Timing of pulse
- …

MC truth

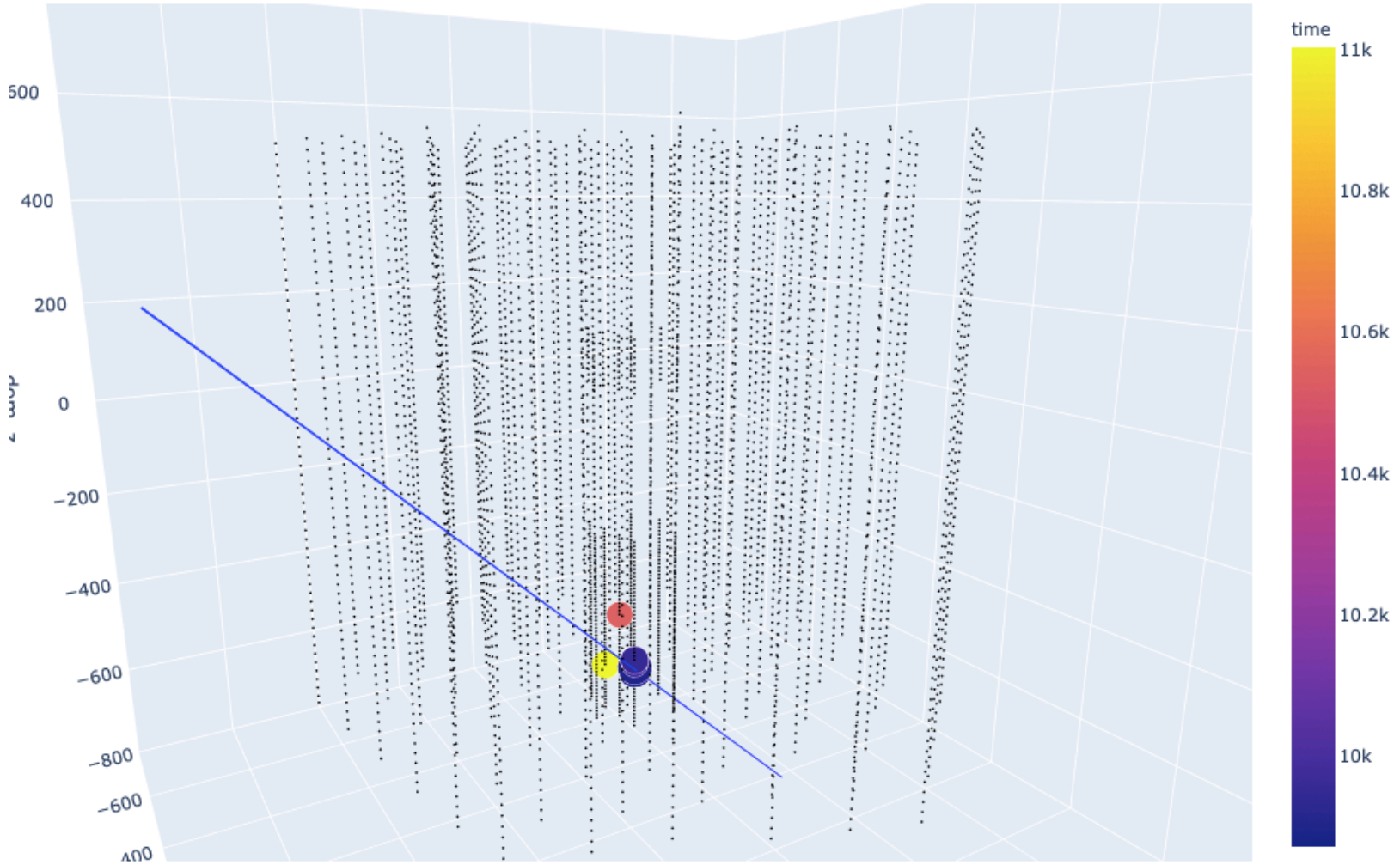
- Energy
- Timing
- Direction
- Vertex

event_no	dom_x	dom_y	dom_z	time	charge_log10
124340548	-2.09238972452156	-2.20391765059521	-0.20531792780969	-1.3965...	-0.621035408596312
124340548	0.271777194705254	0.8137652069211	0.476851509366702	-1.3856...	-0.181237923295411
124340548	2.39285113557912	1.08496075547179	0.802832762772986	-1.2309...	-0.499121097569611
124340548	-0.0336872398641...	-1.84865440274923	1.18720780690279	-1.1043...	-0.0880284366468398
124340548	-2.96864746768481	-1.04685643476376	0.02752918732120...	-1.0490...	-1.05577189763356
124340548	1.01717718593457	2.89759479424175	-0.4535033996708...	-0.6379...	-0.181237923295411
124340548	-1.97454002881094	1.73713986954943	-0.5237592023868...	-0.5571...	-0.0880284366468398
124340548	0.363221992267376	0.484758301242309	1.03276720299124	-0.5022...	1.62182309520387
124340548	0.363221992267376	0.484758301242309	1.03276720299124	-0.4850...	-0.621035408596312
124340548	-0.0336872398641...	-1.84865440274923	-0.4519766247672...	-0.3761...	0.310079721608181
124340548	1.6033687324687	1.08079306913367	1.67437100551306	-0.2345...	-1.92155384342976
124340548	-0.2850630882944...	-0.1498571021541...	0.201042900733252	-0.2236...	-1.43023625575038
124340548	-0.2850630882944...	-0.1498571021541...	0.233974580226505	-0.2050...	0.378964591403688
124340548	-0.2850630882944...	-0.1498571021541...	0.217508758400613	-0.1842...	-0.753120570788277

event_no	energy_log10	time	position_x	position_y	position_z	direction_x	direction_y
124340548	-1.00068738072728	-0.795841750621981	-0.456637495020781	0.123421517285253	0.93328190601528	-0.442319276010738	-0.890548542605657

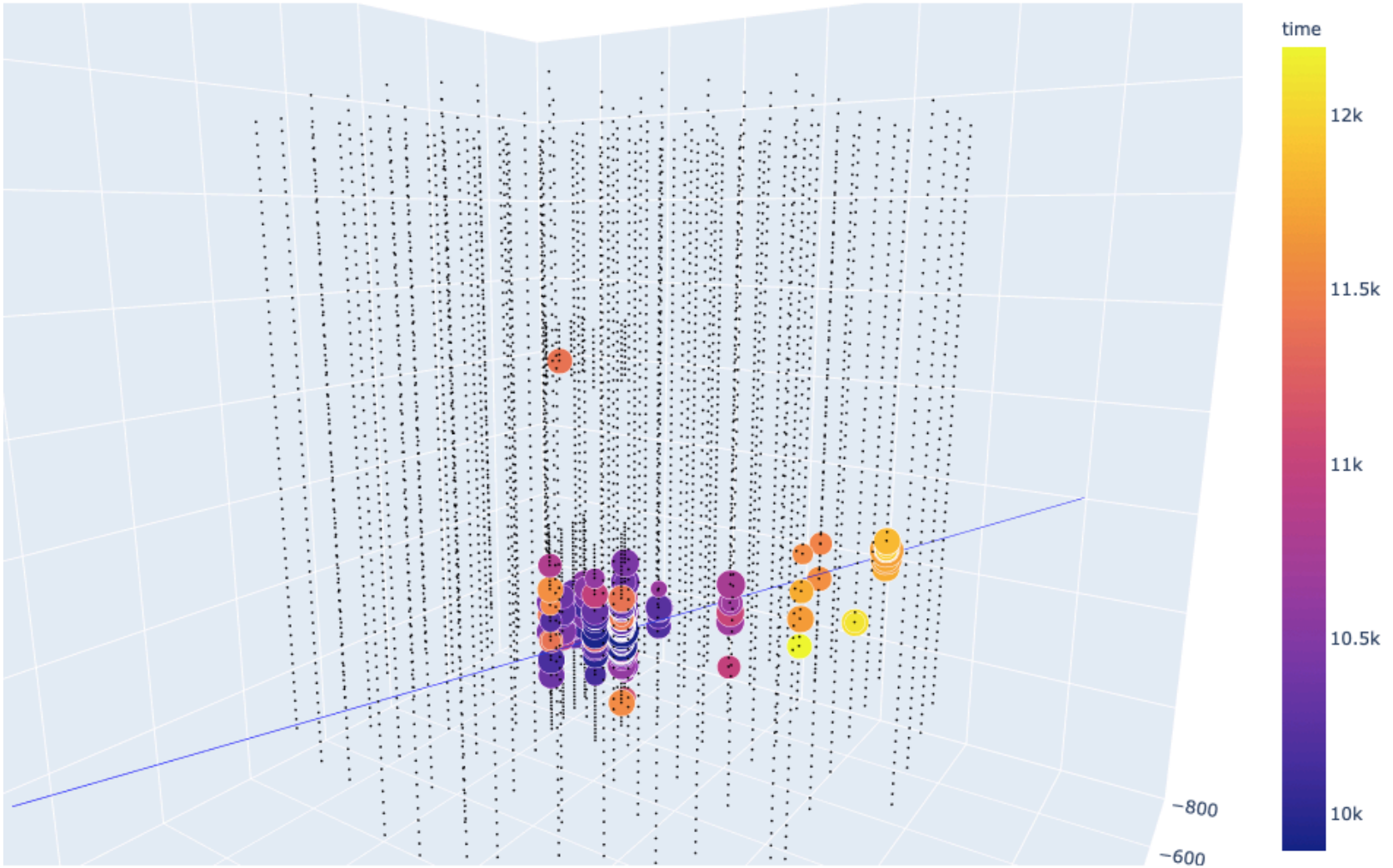
The challenge of reconstruction

$$E = 1.3 \text{ GeV}$$



The challenge of reconstruction

$$E = 677 \text{ GeV}$$



Machine learning in physics

Pros:

- Fast
- Generalizable
- Works with simulated data
- Research momentum

Cons:

- Black box
- Not trusted by the establishment
- Black box (yes, twice!)

Convolutional neural networks

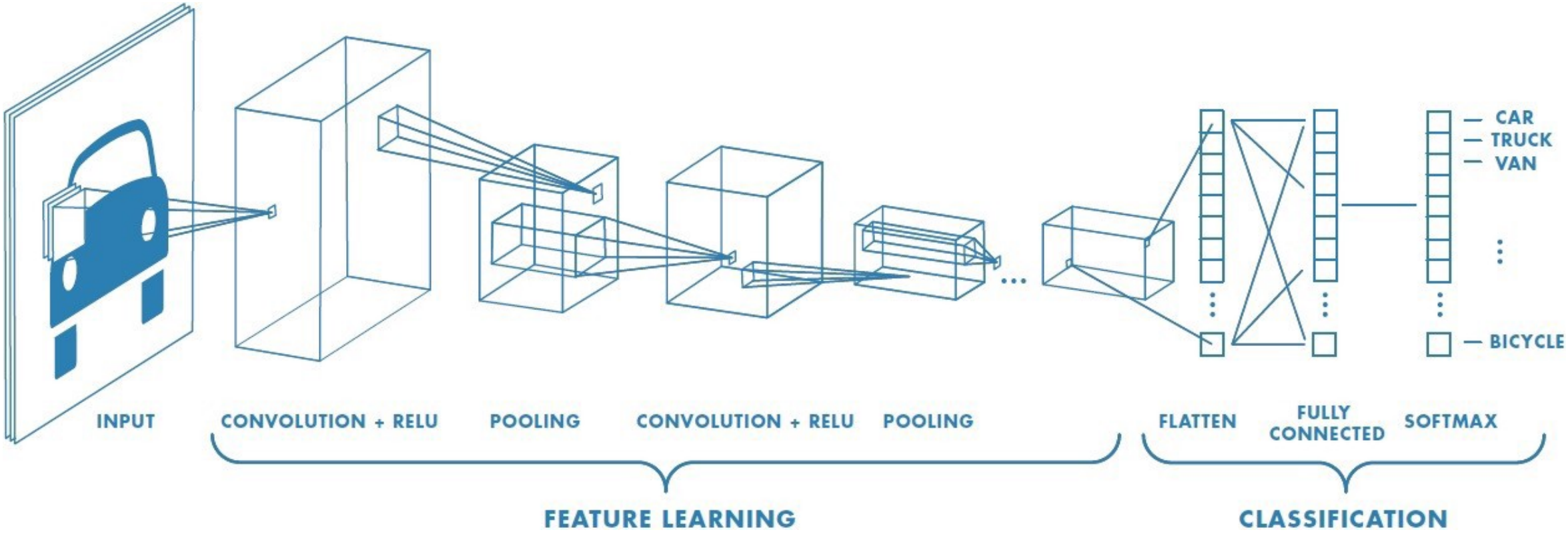


Image courtesy of towards data science

Temporal convolutional networks

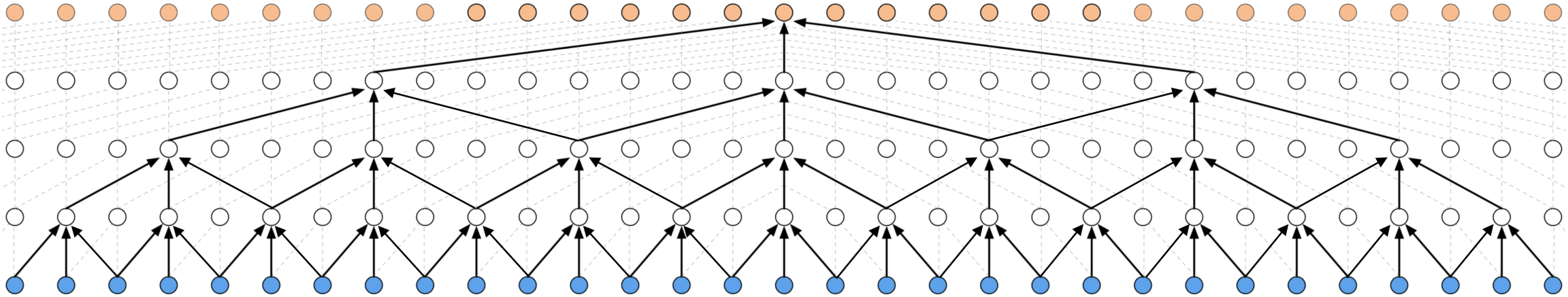


Image courtesy of keras-tcn

IceCube tooling & data

Mature software stack

- Hard to install
- Event viewer next to impossible

I3 data format

- Tape-like sequential format
- Efficient
- Not ML ready

CubeDB - https://github.com/ehrhorn/cubedb

Meta database

- One source of truth for all events
  - Event numbers
  - Train / test set
- SQLite format
  - Great query language to build your dataset

```
select *
from (select
    meta.event_no,
    meta.level,
    meta.pid,
    meta.unix_start_time,
    meta.energy_log10,
    meta.max_size_bytes,
    meta.raw_event_length,
    meta.event_id,
    meta.sub_event_id,
    reconstruction_names.reconstruct
    gcd_file_paths.gcd_file_path ||
    i3_file_paths.i3_file_path || '/
    run_types.run_type
from
    meta
    inner join reconstruction_names
    inner join i3_file_paths on meta
    inner join i3_file_names on meta
    inner join gcd_file_paths on met
    inner join gcd_file_names on met
    inner join run_types on meta.run
where
    run_types.run_type in ('genie')
    and abs(meta.pid) = 14
    and meta.reconstruction = 2
    and meta.train = 1
    and meta.energy_log10 <= 3
limit 2e5)
```

CubeDB - https://github.com/ehrhorn/cubedb

Training data

- Create dataset from meta
- Dataset SQLite as well
  - Indexable == fast
  - One file, many (many!!) events
- Agree on blinded data with whole collaboration

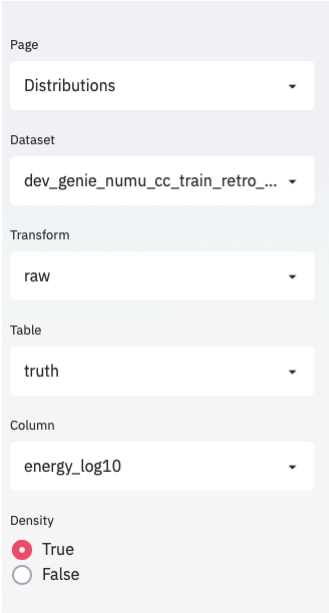
```
select *
from (select
    meta.event_no,
    meta.level,
    meta.pid,
    meta.unix_start_time,
    meta.energy_log10,
    meta.max_size_bytes,
    meta.raw_event_length,
    meta.event_id,
    meta.sub_event_id,
    reconstruction_names.reconstruct
    gcd_file_paths.gcd_file_path ||
    i3_file_paths.i3_file_path || '/
    run_types.run_type
from
    meta
    inner join reconstruction_names
    inner join i3_file_paths on meta
    inner join i3_file_names on meta
    inner join gcd_file_paths on met
    inner join gcd_file_names on met
    inner join run_types on meta.run
where
    run_types.run_type in ('genie')
    and abs(meta.pid) = 14
    and meta.reconstruction = 2
    and meta.train = 1
    and meta.energy_log10 <= 3
limit 2e5)
```

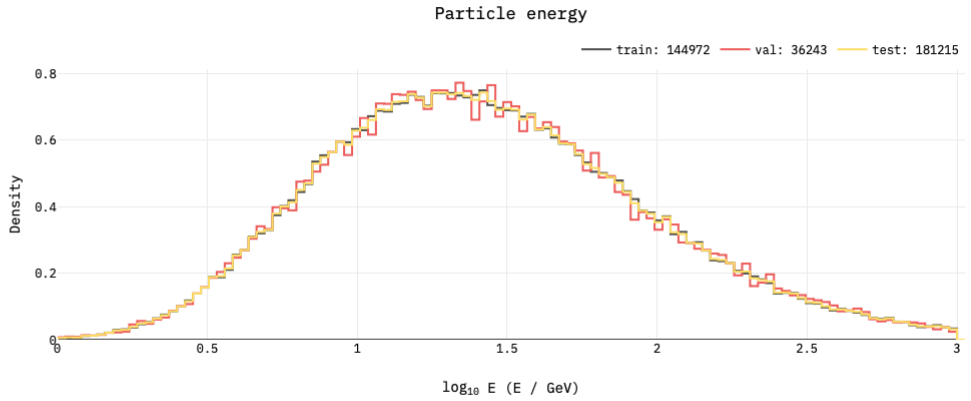
Powershovel - https://gitlab.com/ehrhorn/powershovel

Steamshovel was impossible to install

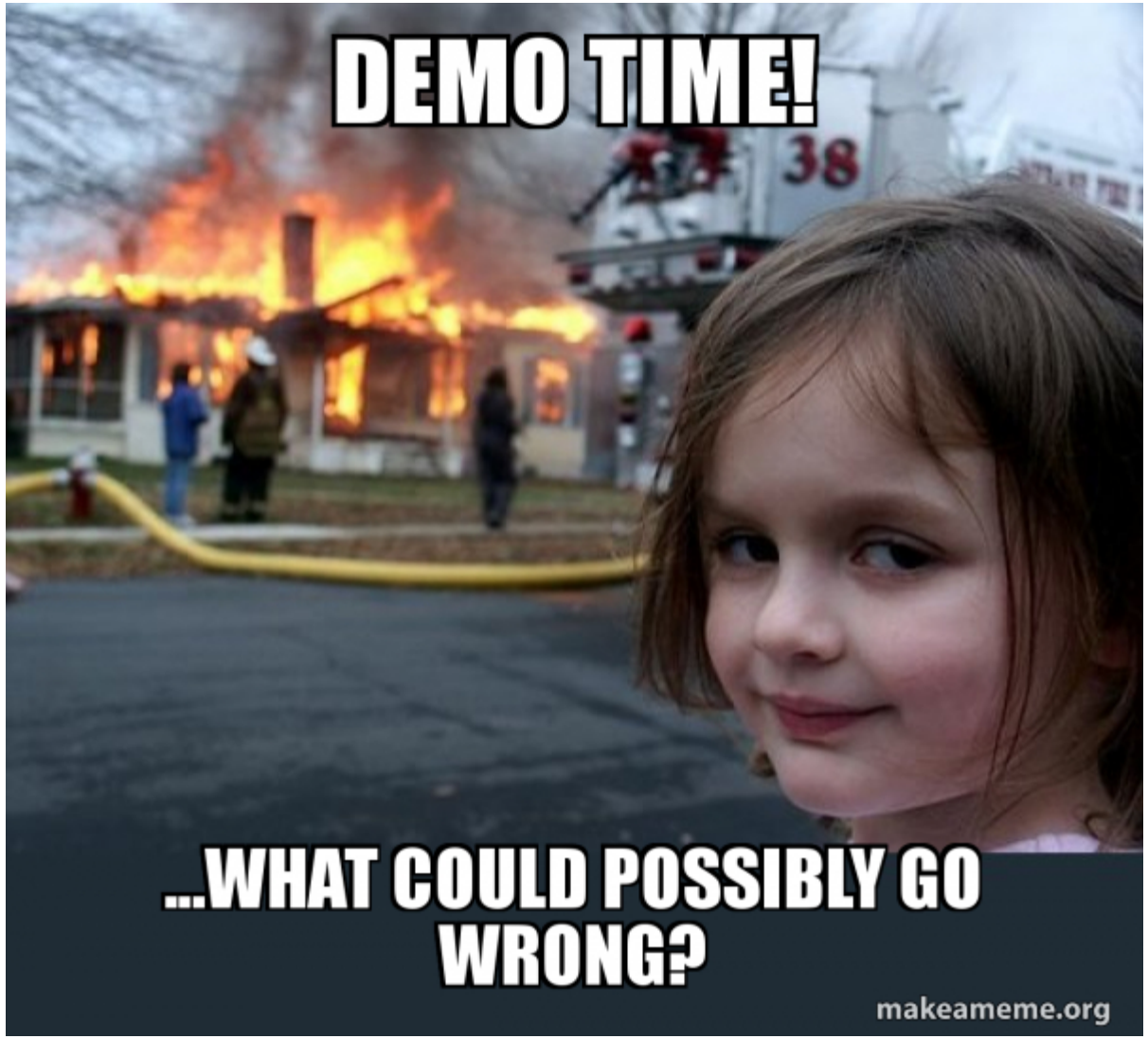
Built Powershovel as replacement

- Using modern web technologies
- Capable of more than event viewing
  - Dataset distributions
  - Run comparisons





Powershovel - https://gitlab.com/ehrhorn/powershovel



CubeFlow - https://gitlab.com/ehrhorn/cubeflow

Training and inference “framework”

- Python + TensorFlow
- Calculates metrics for Powershovel
  - Pre-made histograms for performance

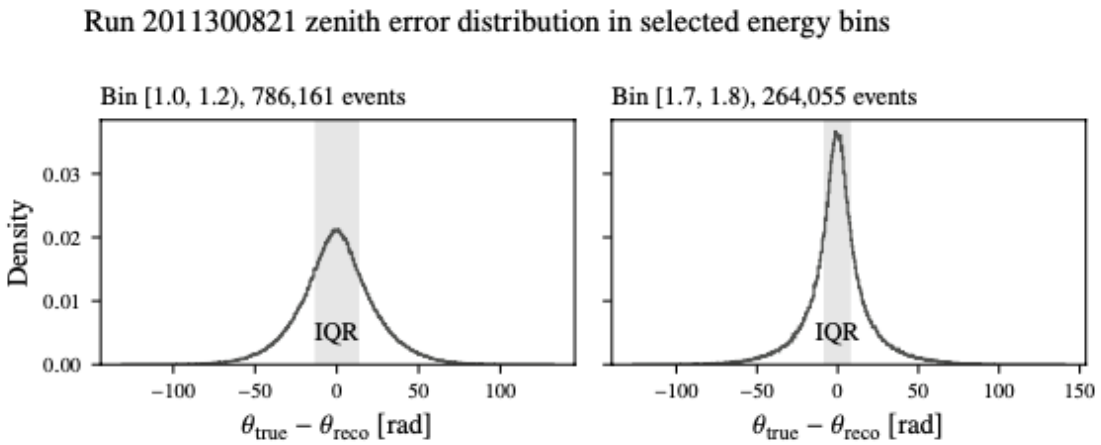
Results – metric

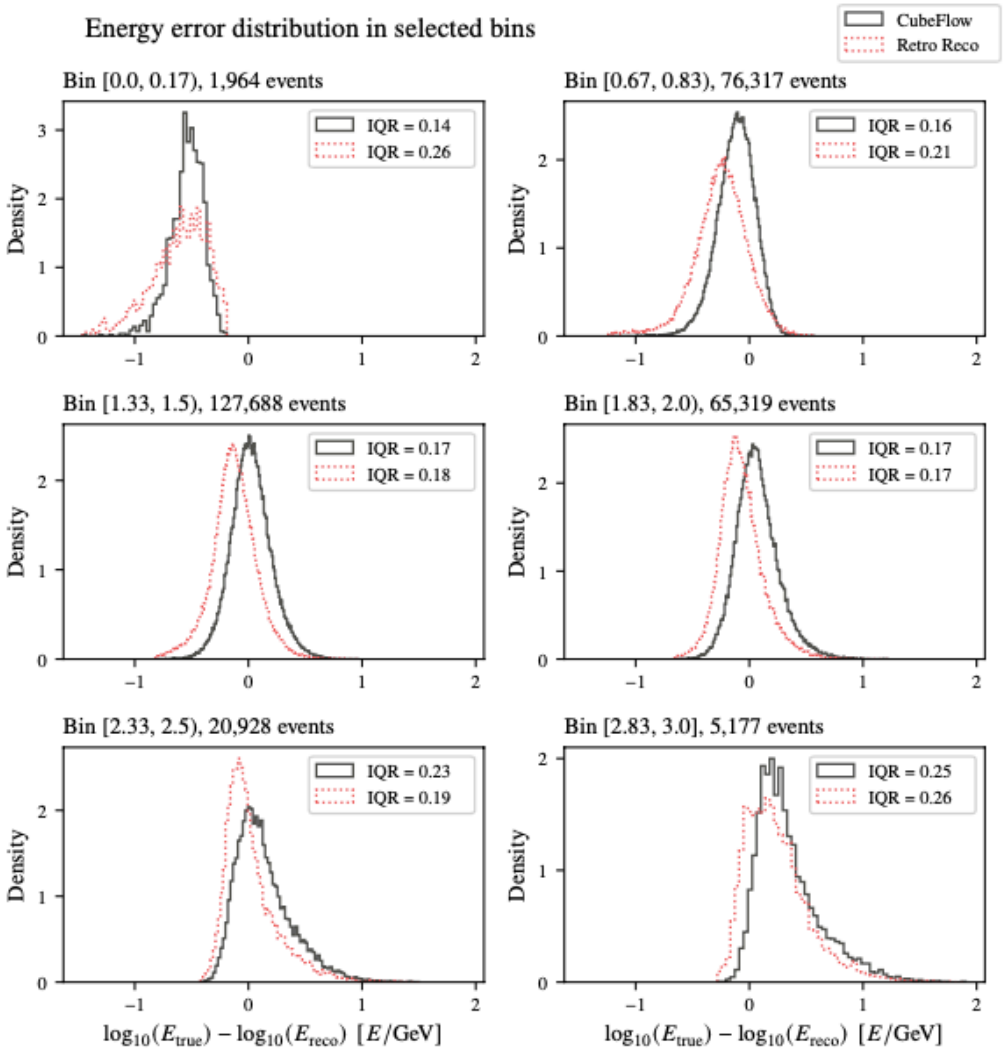
Comparison metric is the IQR in given bins (6 bins per order of magnitude)

$$\mathrm{IQR} = Q_3 - Q_1$$

For normal distribution:

$$\mathrm{IQR} \approx 1.349\sigma \Rightarrow \sigma \approx \frac{\mathrm{IQR}}{1.349}$$

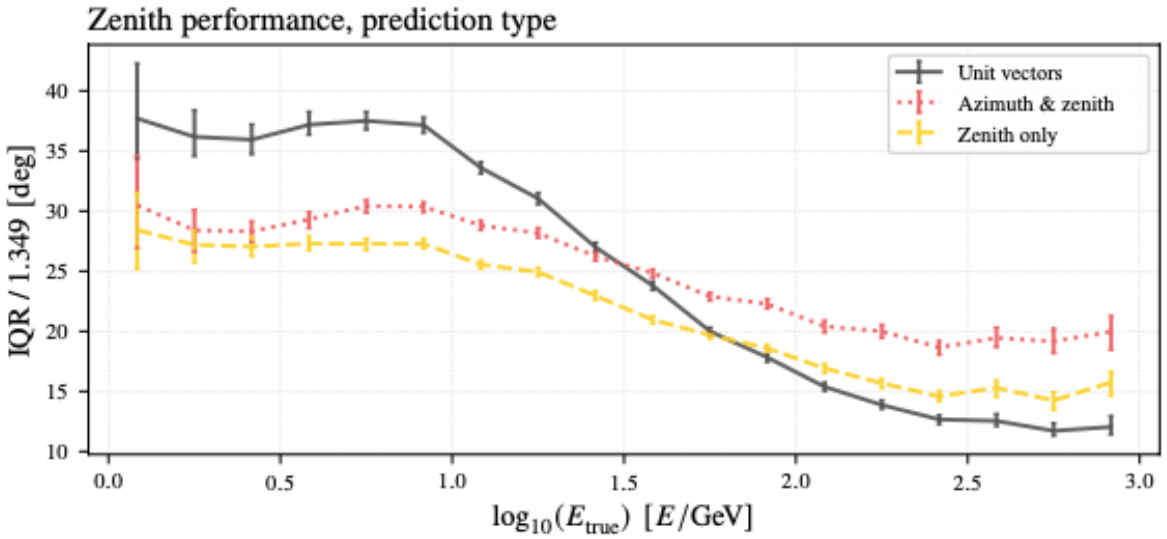




Results – reconstruction type

Reconstruct:

- Azimuth and zenith angles
  - Problematic because $2\pi = 0$; how should the network know?
- x, y, z unit direction vectors
  - Penalize loss such that length is unity
- Best performance from zenith alone
  - No spherical statistics
  - Zenith most important for many studies

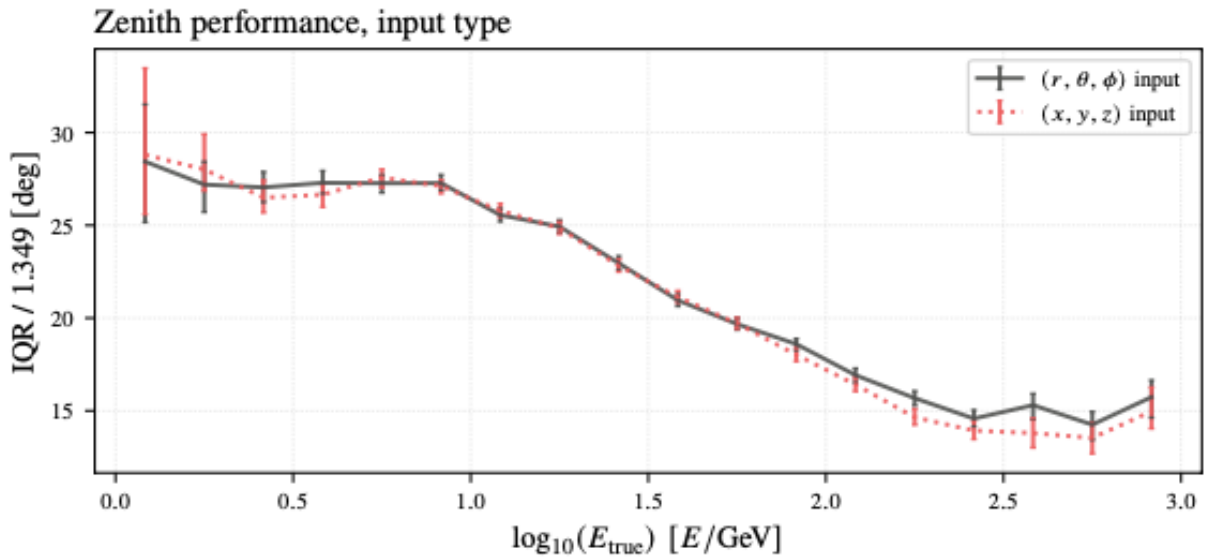


Results – input type

Features:

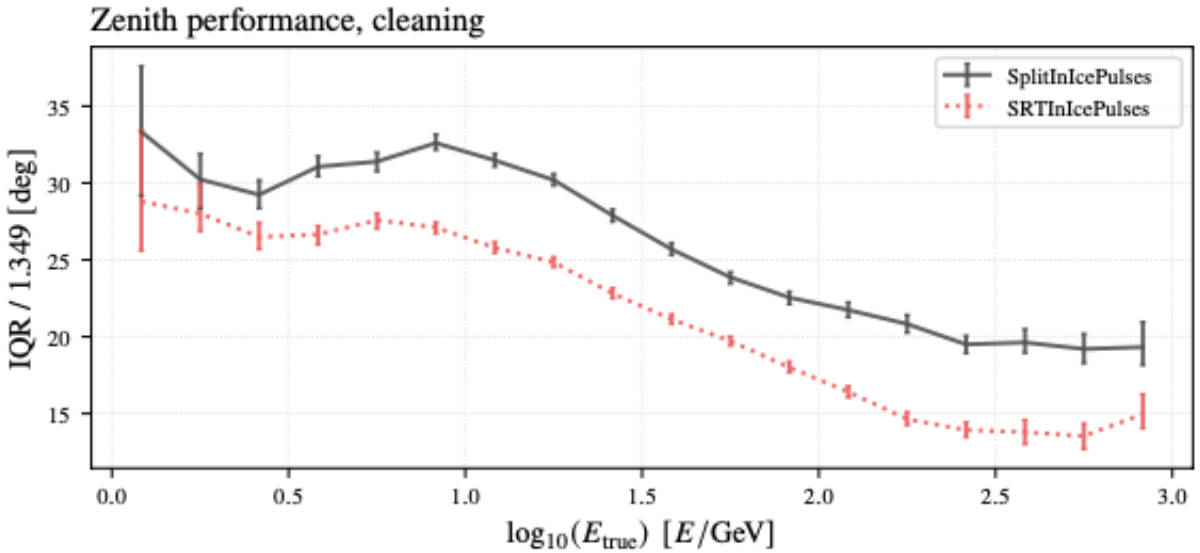
- Cartesian
  - "Natural" features, IceCube coordinate system
  - Useful for predicting zenith angle?
- Spherical
  - Transformation may help network predict zenith angle

No real difference, network figures it out!



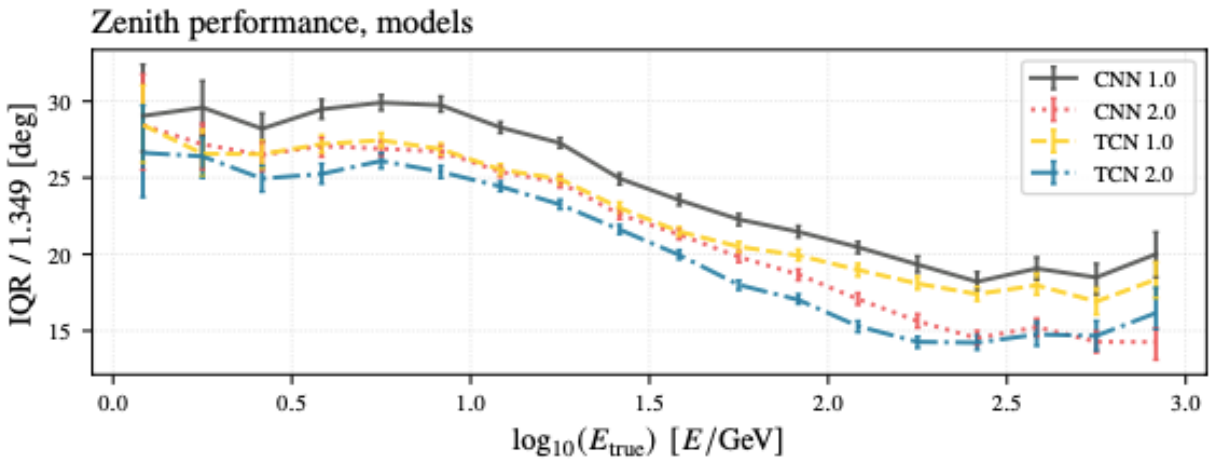
Results – cleaning type

SRT (cleaned pulse series) performs better

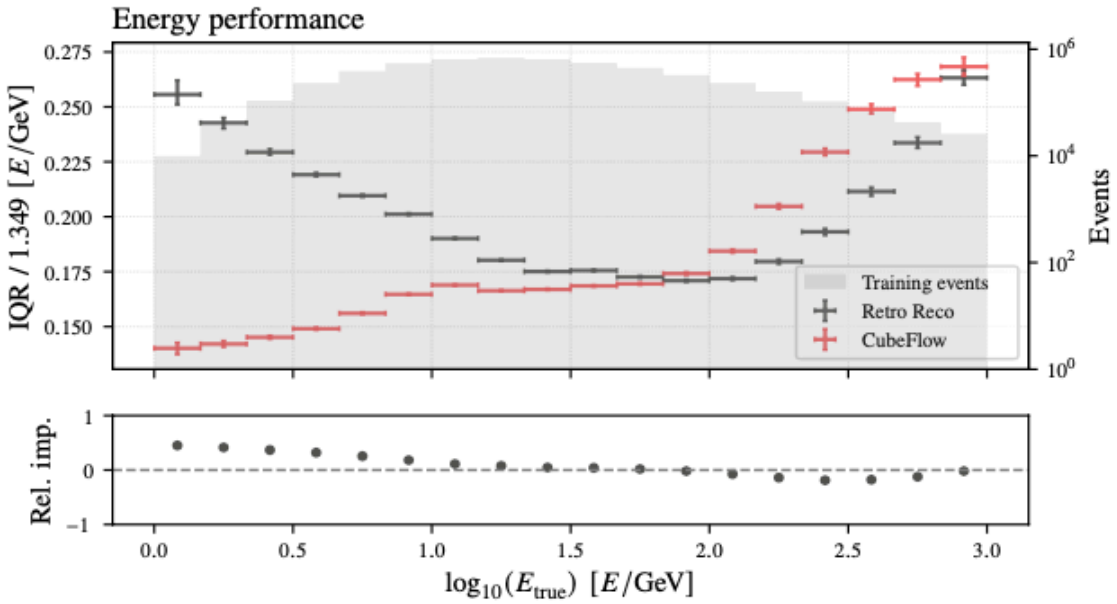


Results – models

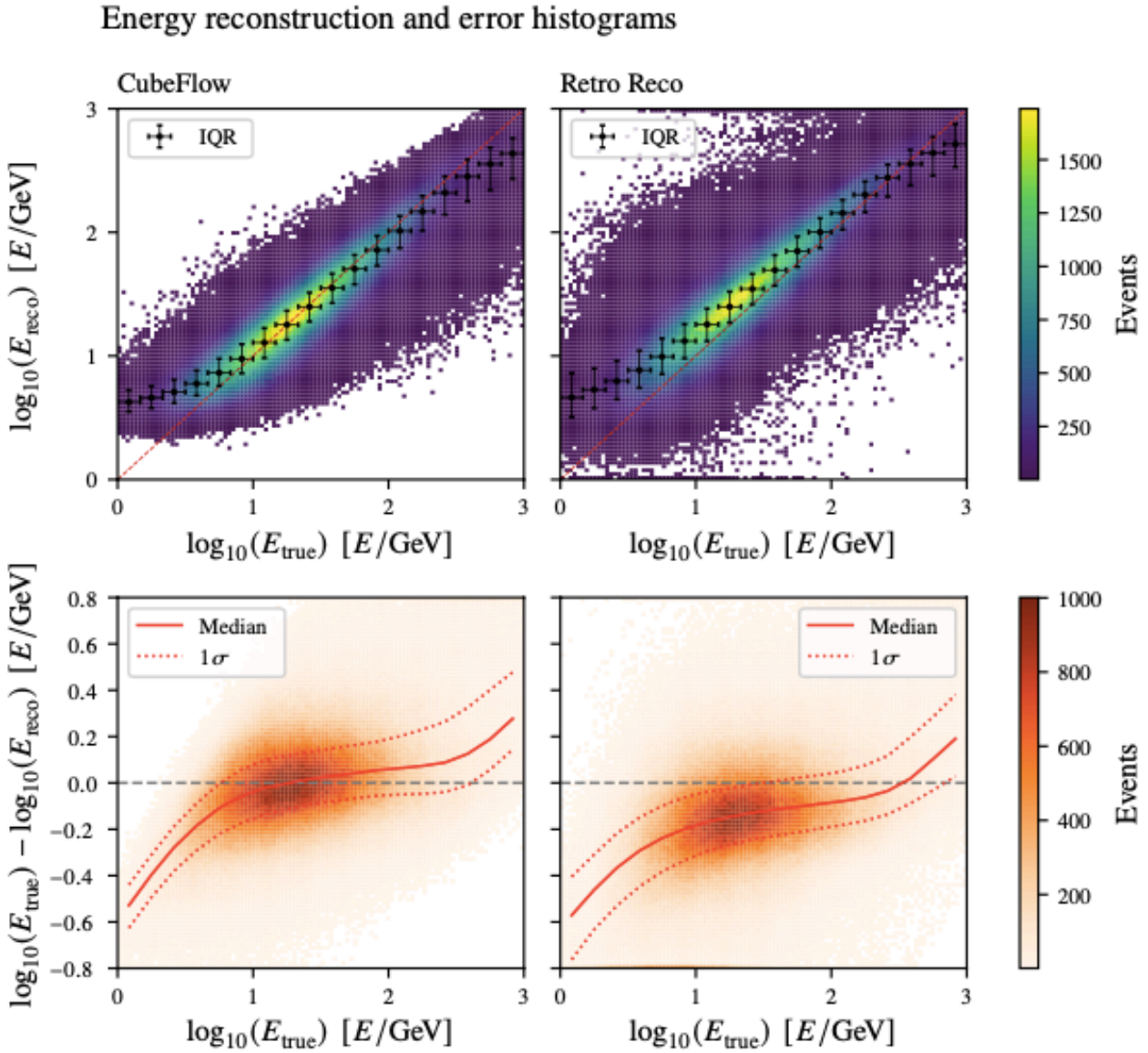
- CNN
  - Convolutional layers
  - FCN layers
- TCN
  - Dilated convolutions
  - Residual block



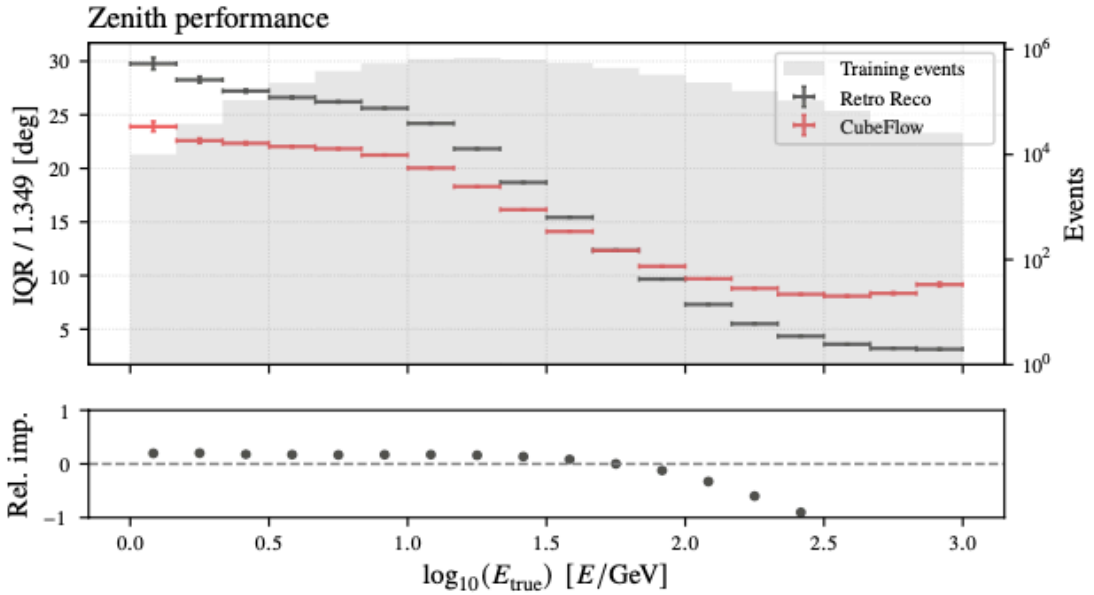
Results – energy



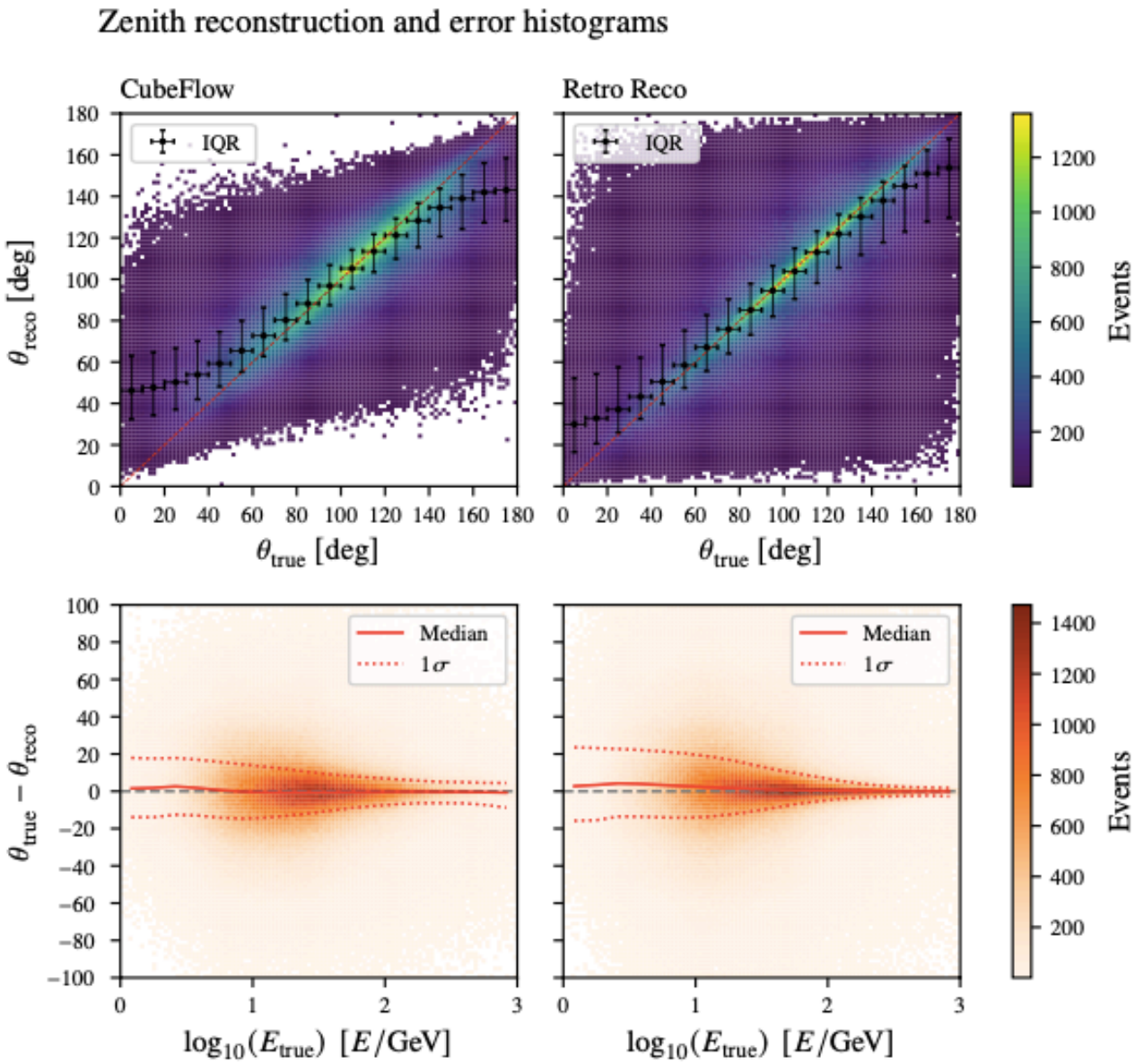
Better performance than IceCube's current algorithm at low energy



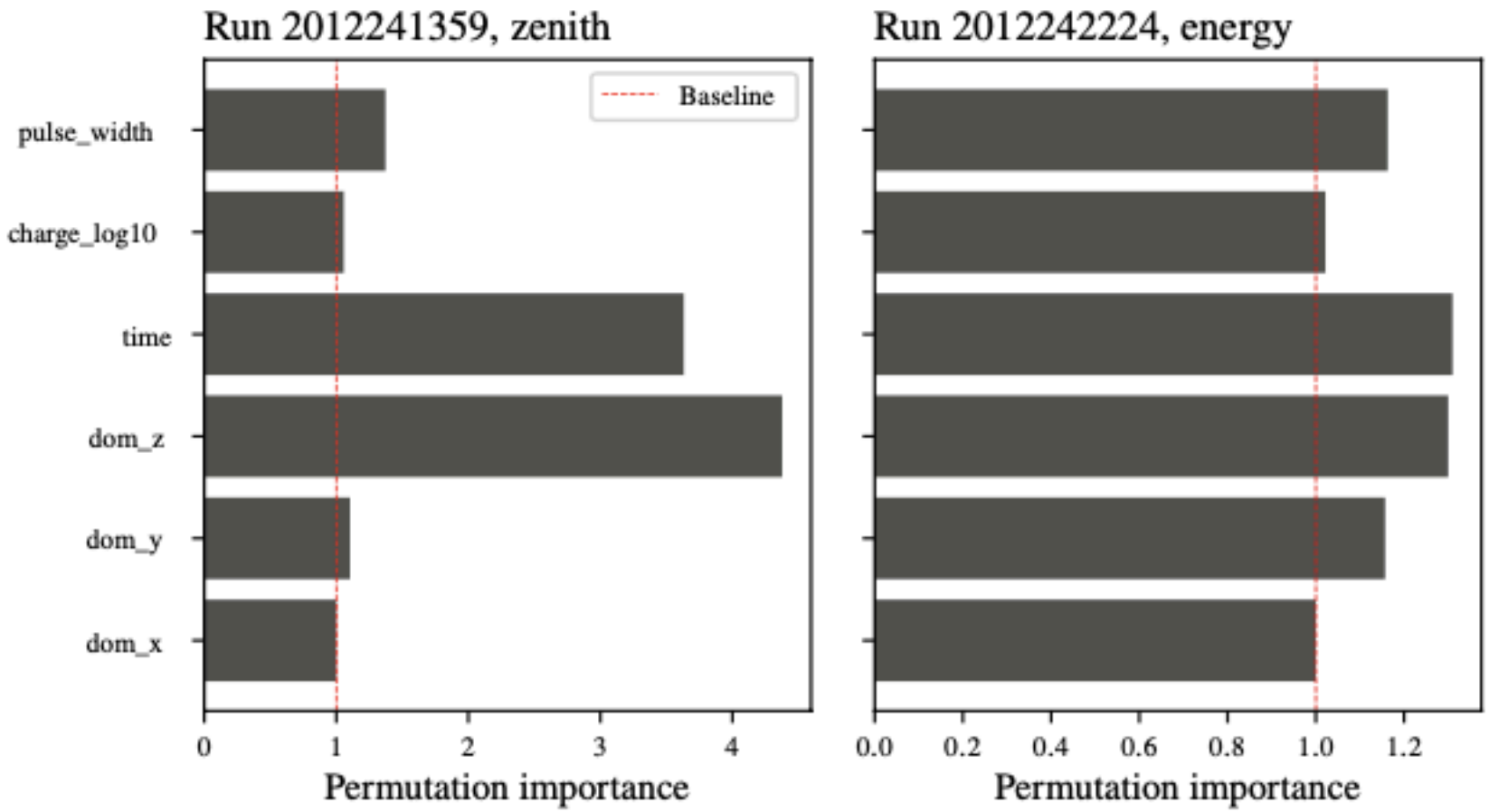
Results – zenith



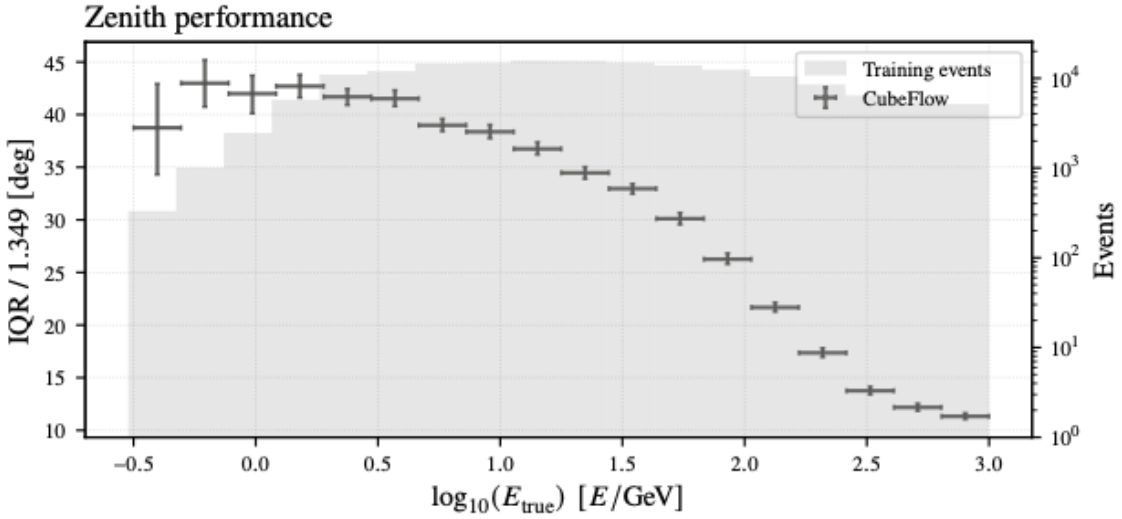
Better performance than IceCube's current algorithm at low energy

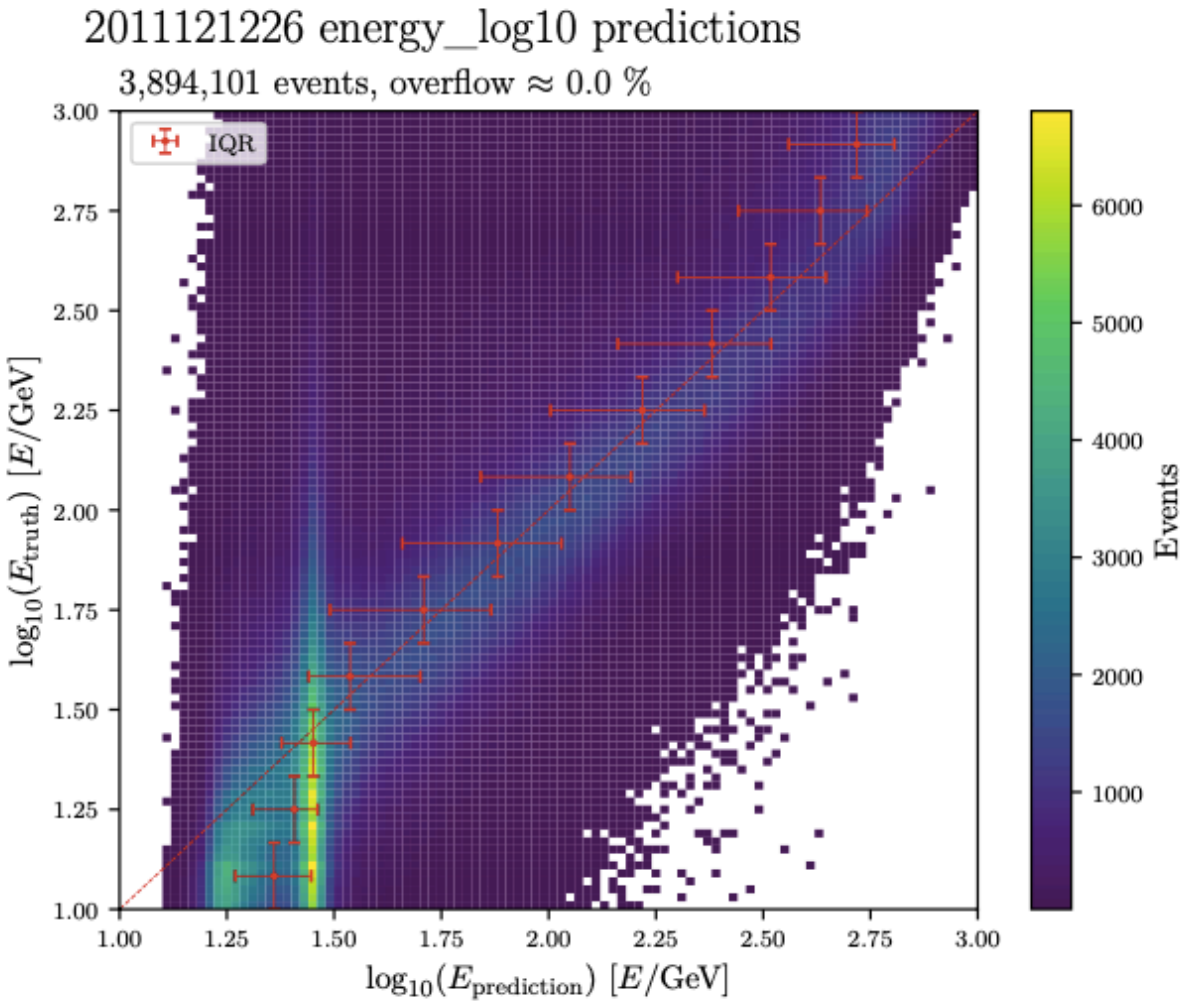


Results – permutation importance



Results – upgrade





Too much noise to be useful

The future

- Cleaning pipeline for upgrade
- Further work on architecture
- CubeDB collaboration-wide
  - Or just the idea
- GPUs on the Pole
  - Fast response, high precision
  - Early warning system
- Better weighting
- Different datasets

Thank you for listening

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Image references

- Slide 2: https://www.energy.gov/science/doe-explainsthe-standard-model-particle-physics
- Slide 4: https://commons.wikimedia.org/wiki/File:Beta-minus_Decay.svg
- Slide 5: https://www.cbsnews.com/news/south-dakota-mine-gets-repurposed-as-underground-science-lab/
- Slide 5: https://pages.uoregon.edu/soper/Sun/homestake.html
- Slide 6: https://www.quantumdiaries.org/2014/07/27/sterile-neutrinos/
- Slide 6: https://www.space.com/41156-cosmic-ray-source-multimessenger-astronomy.html
- Slide 7: https://www.youtube.com/watch?v=iv-Rz3-s4BM
- Slide 8: https://commons.wikimedia.org/wiki/File:Icecube-architecture-diagram2009.PNG
- Slide 8: https://icecube.wisc.edu/news/view/605
- Slide 8: https://www.desy.de/news/news_search/index_eng.html?openDirectAnchor=1916
- Slide 13: https://towardsdatascience.com/a-comprehensive-guide-to-convolutional-neural-networks-the-eli5-way-3bd2b1164a53
- Slide 14: https://github.com/philipperemy/keras-tcn