Search for Unmodeled Rare Events with the IceCube Neutrino Observatory

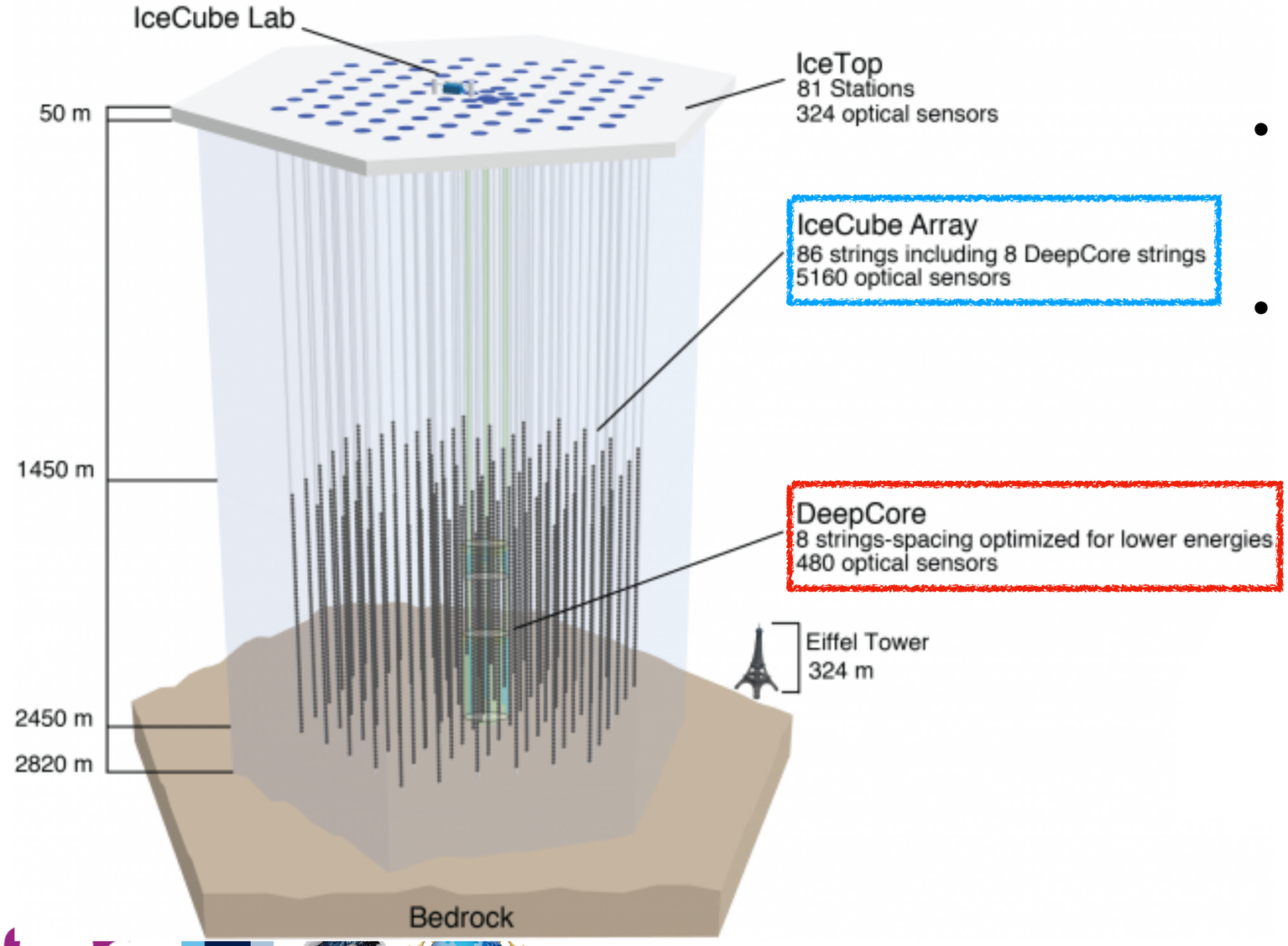
Jeffrey Lazar and Gwen de Wasseige for the IceCube Collaboration

31 Aug., 2026

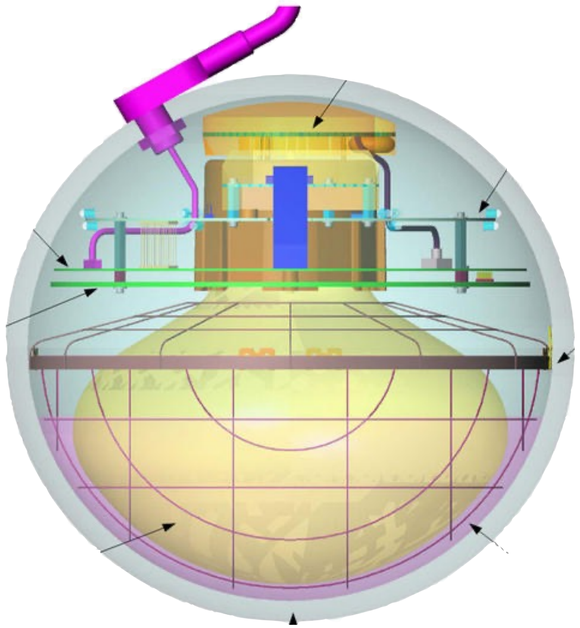
TeV Particle Astrophysics 2026

Tendo, Japan

The IceCube Neutrino Observatory



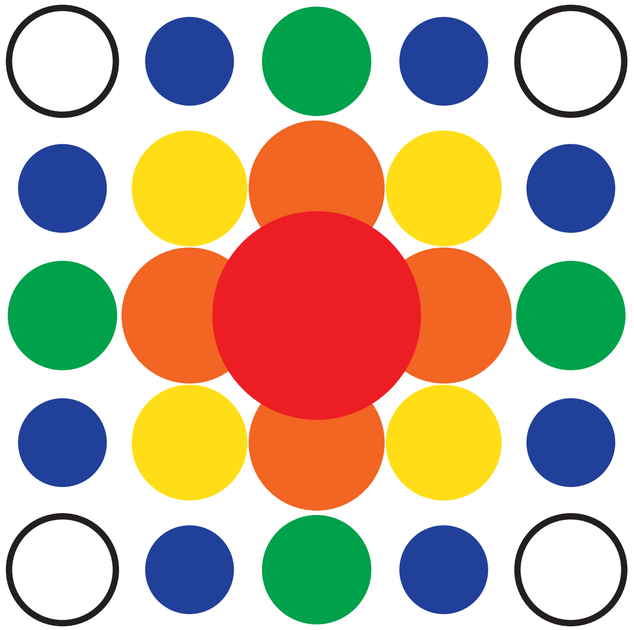
- Gigaton scale detector of 5,160 light detecting digital optical modules (DOMs)
- IceCube and DeepCore sensitive to high- and low-energy neutrinos



Event Morphologies

Cascades

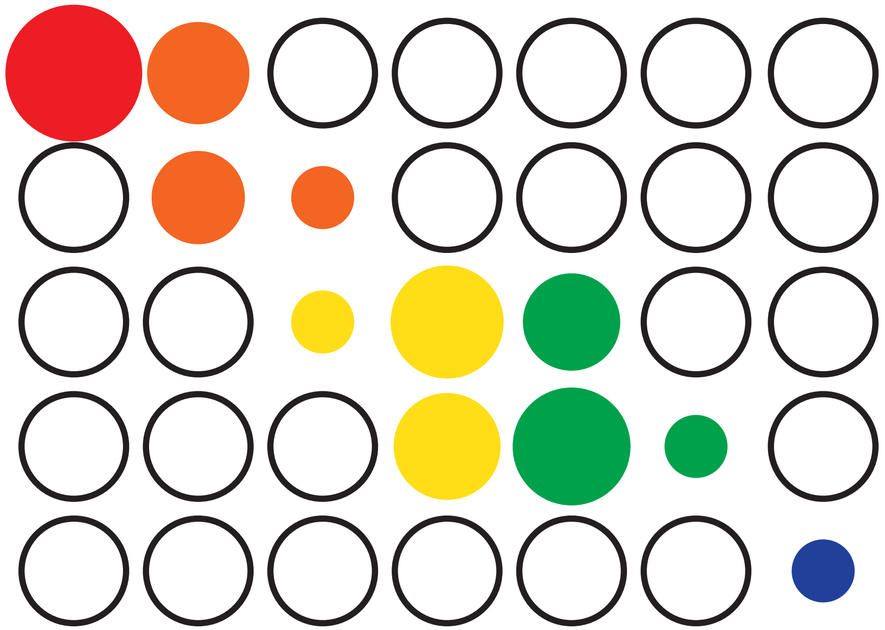
ν_e CC | ν_α NC



Great energy resolution, but angular reconstruction is challenging

Tracks

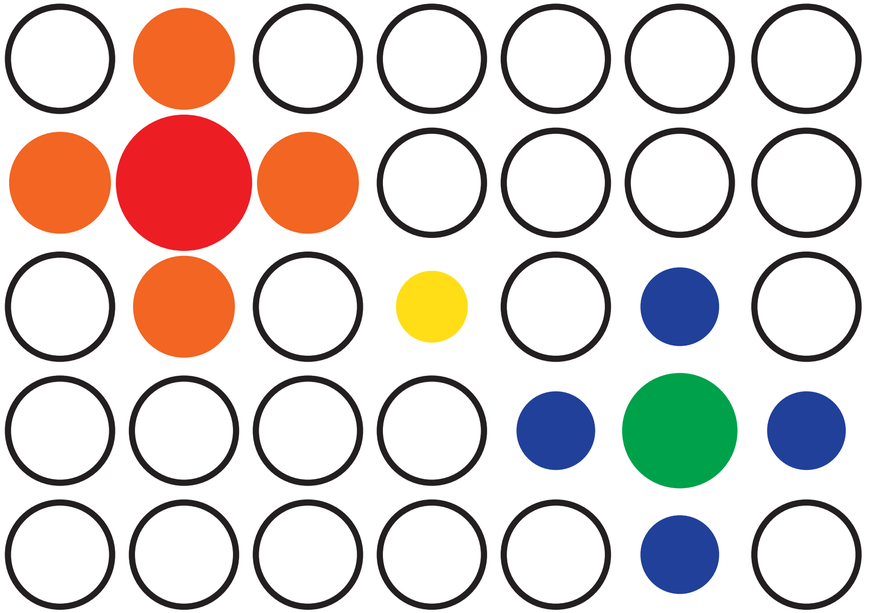
ν_μ CC



Great directional resolution, but deposited energy not proportional to E_ν

Double bangs

ν_τ CC



Signature of ν_τ CC events

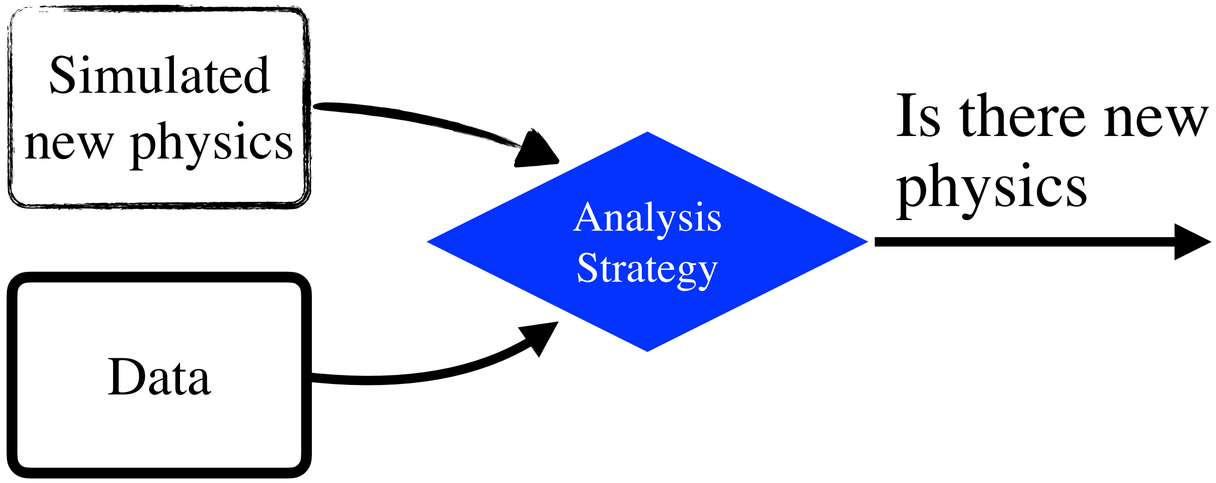
Looking for Who-Knows-What in a Haystack

- There are many hypotheses for what form new physics may take
- There is no proof that the current landscape is at all exhaustive
- We're not even at the point of looking for a needle in a haystack…

Casting a Wide Net

The Problem

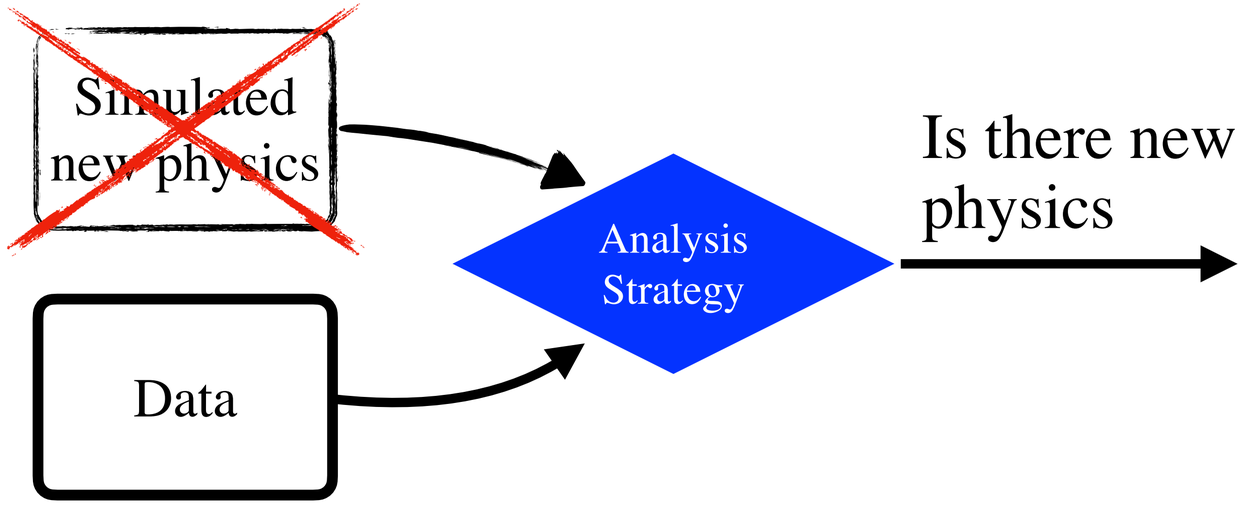
- Typically, you simulate some physics hypothesis and compare to data to get a result
- This is reliant on simulating the correct new-physics hypothesis
- Can we circumvent these challenges?



Casting a Wide Net

The Problem

- Typically, you simulate some physics hypothesis and compare to data to get a result
- This is reliant on simulating the correct new-physics hypothesis
- Can we circumvent these challenges?



Casting a Wide Net

Anomaly Detection

- Use unsupervised anomaly detection (AD) methods to look for “something weird”
- These methods allow us to cast a wide net, but with some tradeoffs

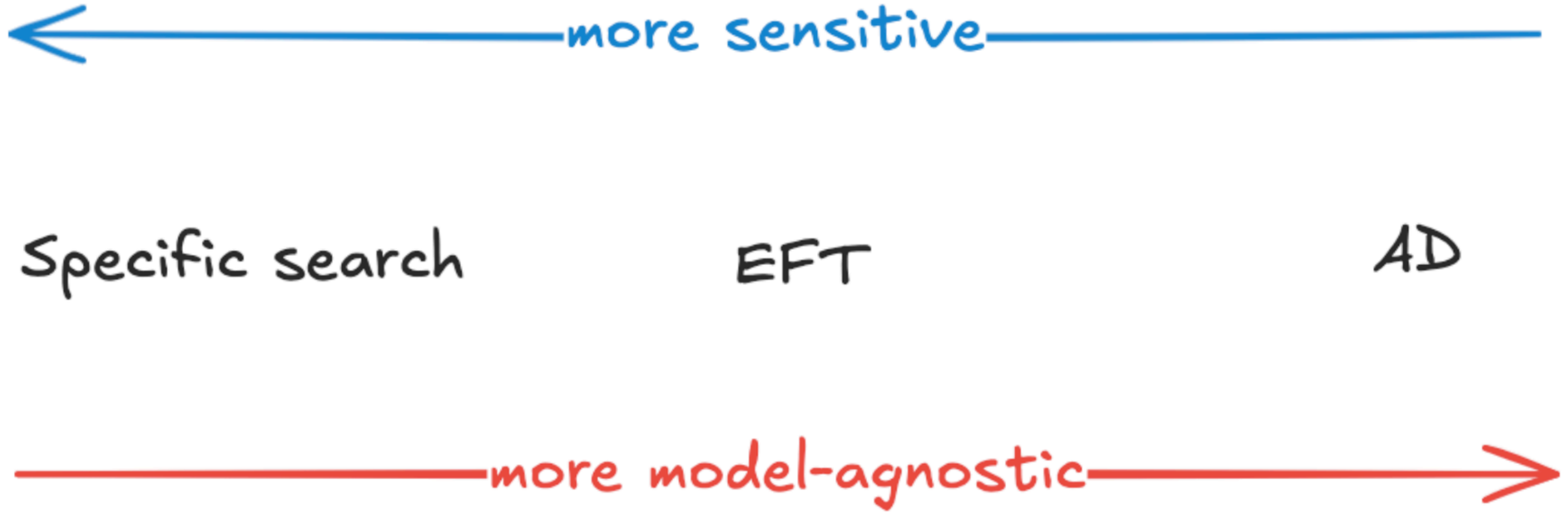
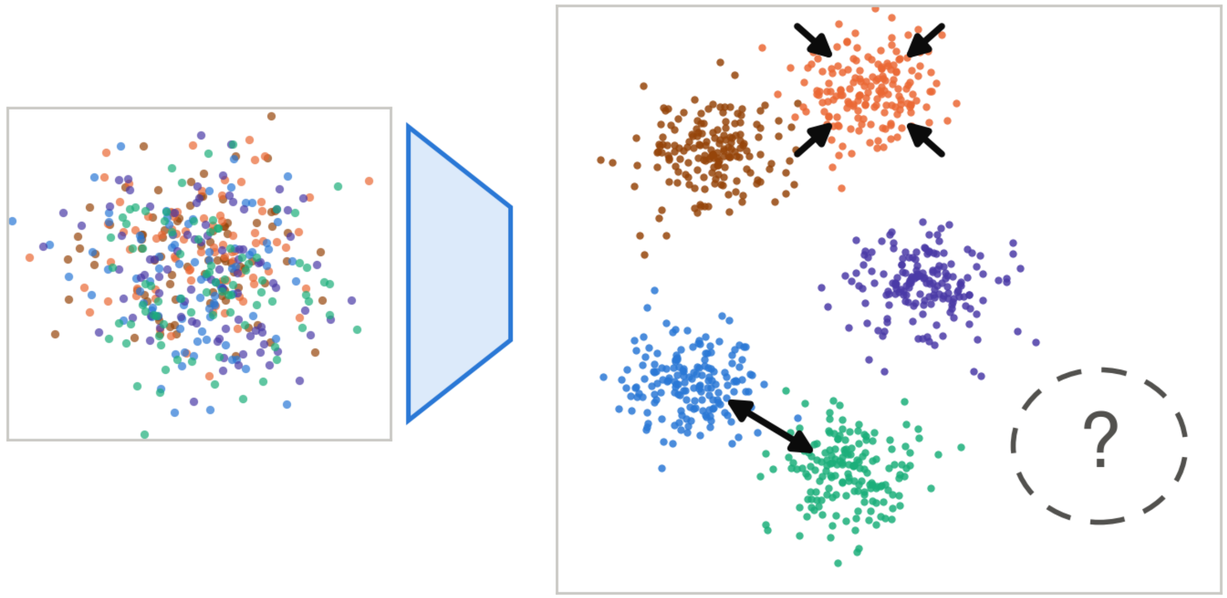


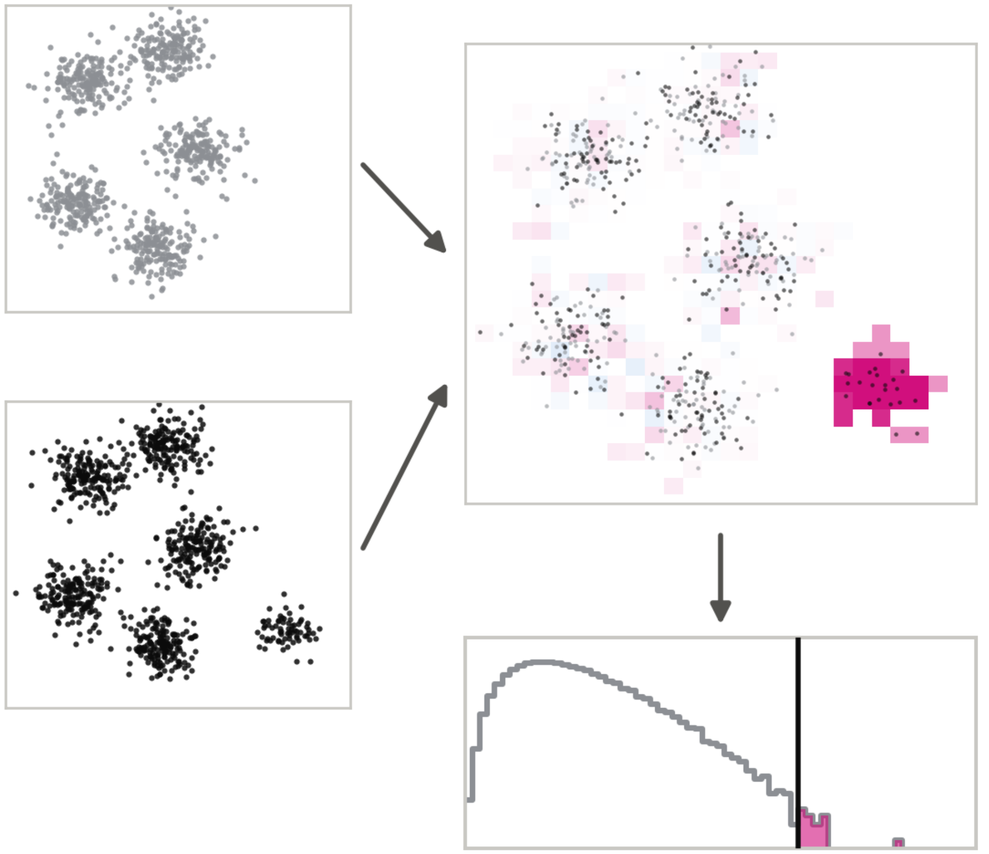
Figure courtesy of J. Ling

AutoSciDACT Framework

Supervised Contrastive (SupCon) Learning

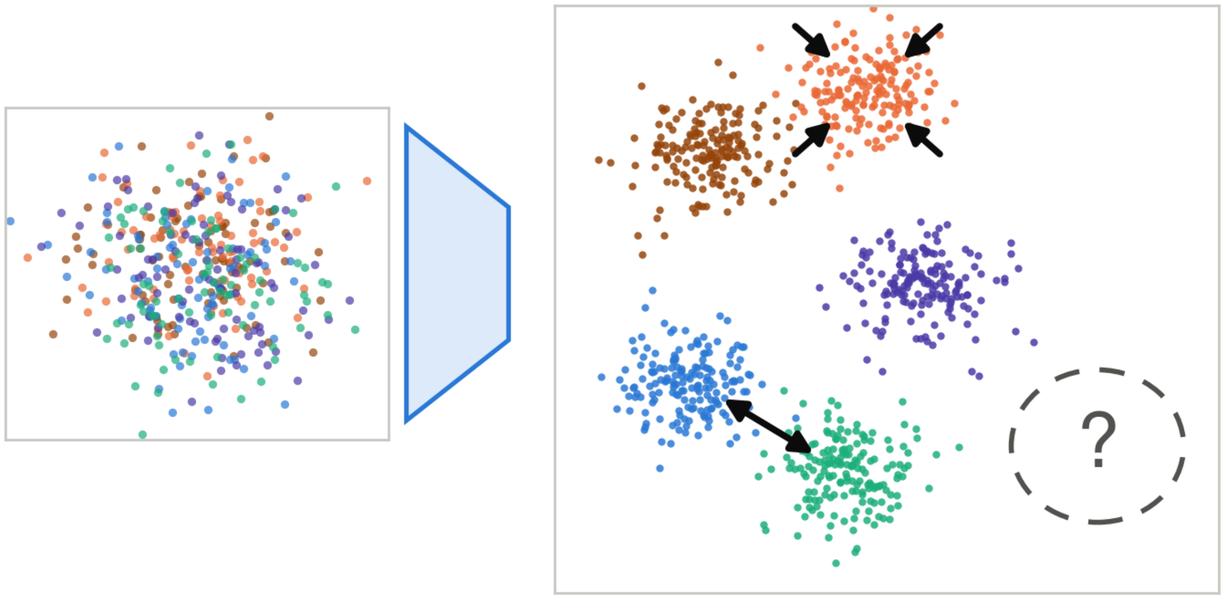


New Physics Learning Machine (NPLM)



AutoSciDACT Framework

Supervised Contrastive (SupCon) Learning



- Transformer-based NEPTUNE† framework projects event point cloud to low dimensional space
  - Per-DOM information with nine charge and timing features
- SupCon groups events with the same labels while separating events with different labels
  - Learned analysis-level features

†F. Yu, et al. (2025)

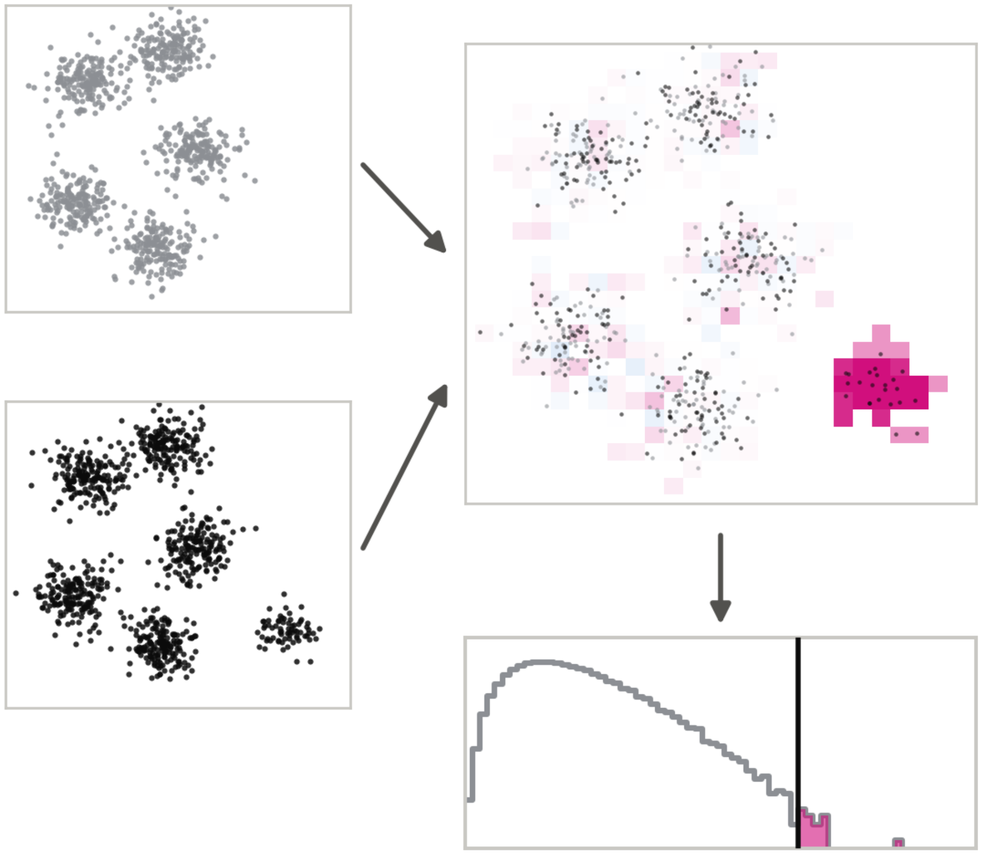
AutoSciDACT Framework

- "Are there places where simulation and data don't match"
- Train a classifier to differentiate reference and data $\rightarrow f(x) = \log[p(x)/q(x)]$
- Compute test statistic as

$$t = 2\Big[\underbrace{\sum_{i\in D} w_D^{(i)} f\left(x^{(i)}\right)}_{\text{shape}} - \underbrace{\tau \sum_{i\in R} w_R^{(i)}\left(e^{f\left(x^{(i)}\right)} - 1\right)}_{\text{rate}}\Big]$$

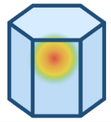
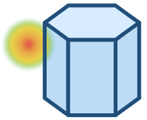
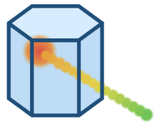
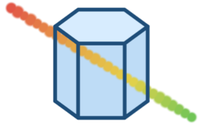
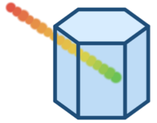
- Kernels at different scales can see anomalies at different resolutions

New Physics Learning Machine (NPLM)



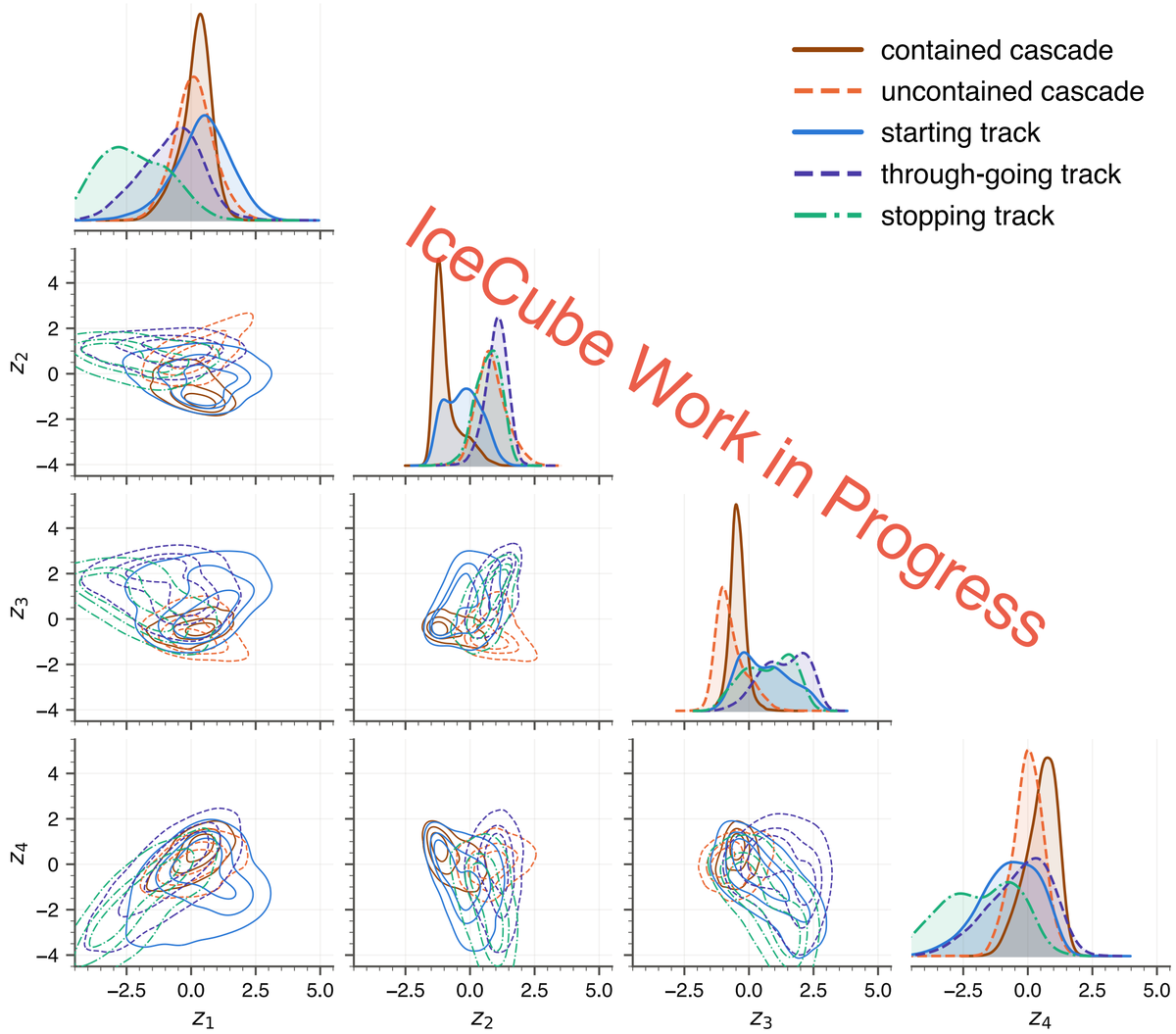
Demonstration on IceCube Simulation

- Take events at L2 that pass either MuonFilter, CascadeFilter, MeseFilter, or HeseFilter
- Cut on total charge, $Q_{\mathrm{tot}} \geq 100\,\mathrm{PE}$, and number of channels, $N_{\mathrm{DOM}} \geq 10$, to ensure reasonable events
- Currently only using neutrino simulation

Class		Description
Contained cascade		Nue CC, nux NC, and Glashow e with vertex inside detector
Uncontained cascade		Nue CC, nux NC, and Glashow e with vertex outside detector
Starting track		Muon from numu CC with vertex inside detector. Glashow mu
Throughgoing track		Muon from numu CC or atmospherics that passes through entire detector
Stopping track		Muon from numu CC or atmospherics produced outside detector and stops in detector
Exotic-tau		Nutau CC with non-muonic decay, Glashow tau (**Held out in training to act as anomaly**)

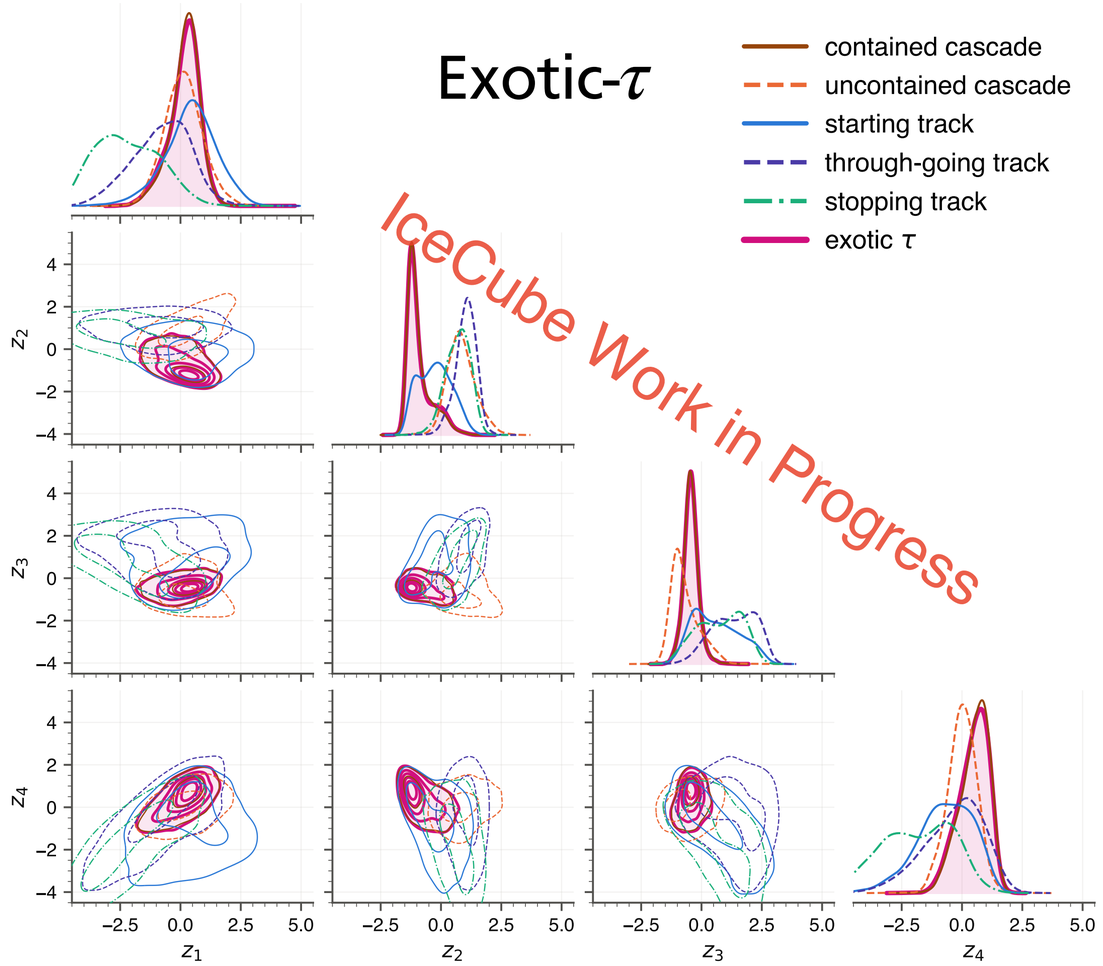
Low-Level Embedding

- SupCon embedding on all “track” and “cascade” categories
- Double cascade events held out to act as an “anomaly” class
- Some physics is legible
  - Cascades group along one axis
  - Starting tracks and cascades group along another



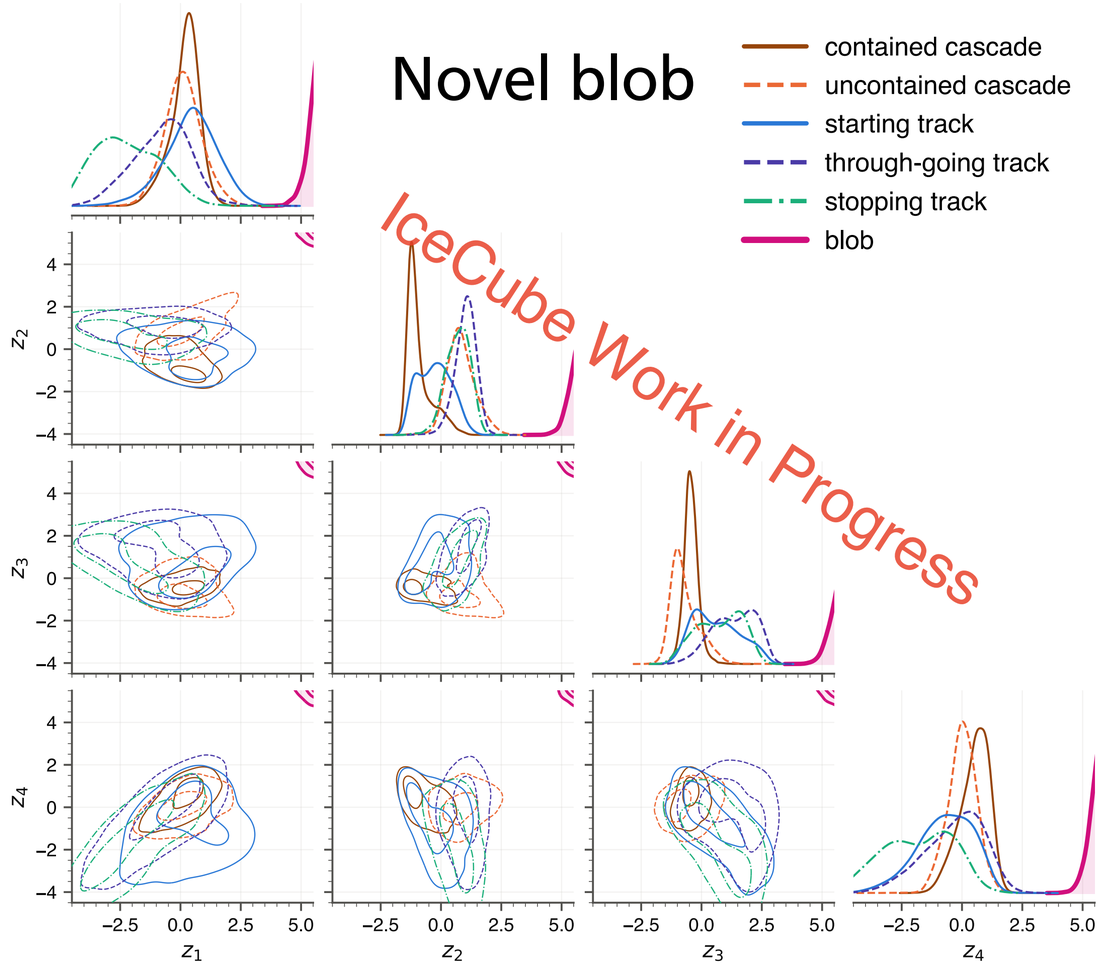
Adding Anomalies

- Exotic tau events mostly align with contained cascades with small divergences
  - Sensible since at most energies cascades overlap



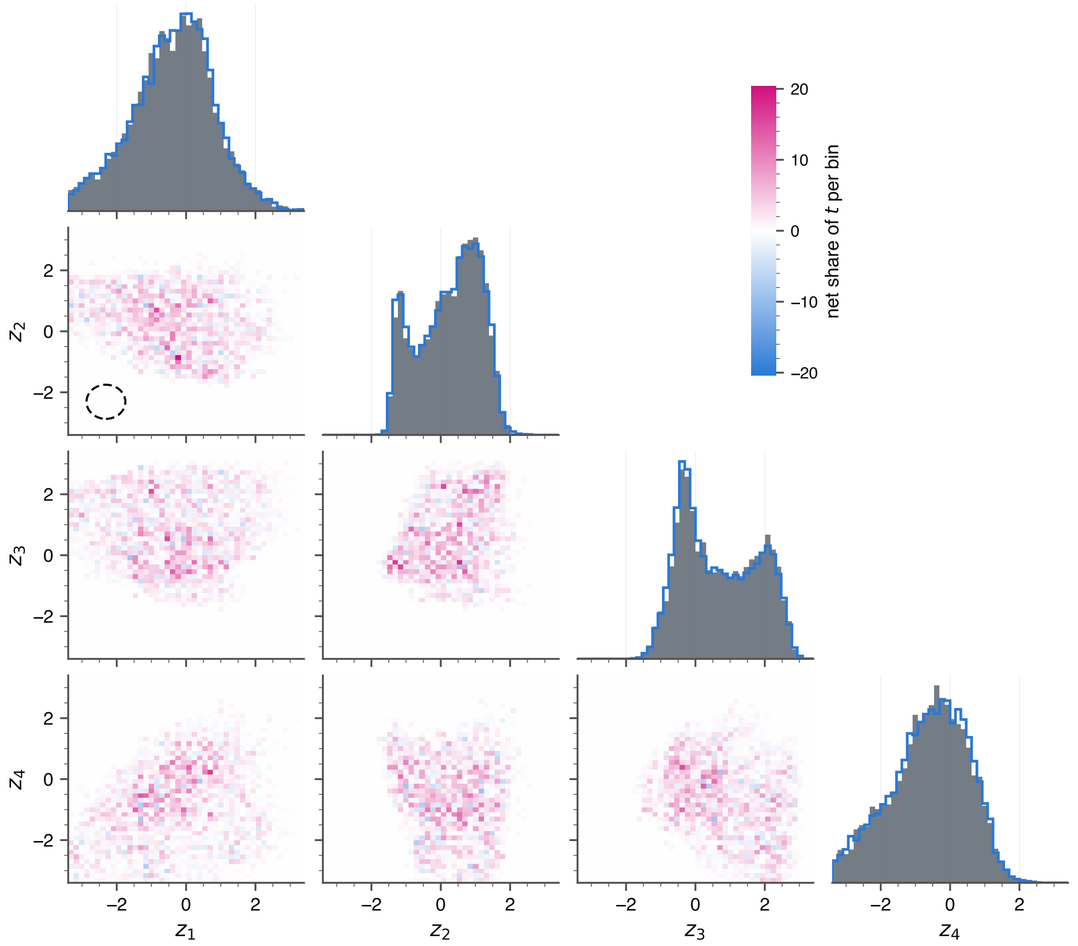
Adding Anomalies

- Exotic tau events mostly align with contained cascades with small divergences
  - Sensible since at most energies cascades overlap
- Also considered a Gaussian “novel blob” to act as a control



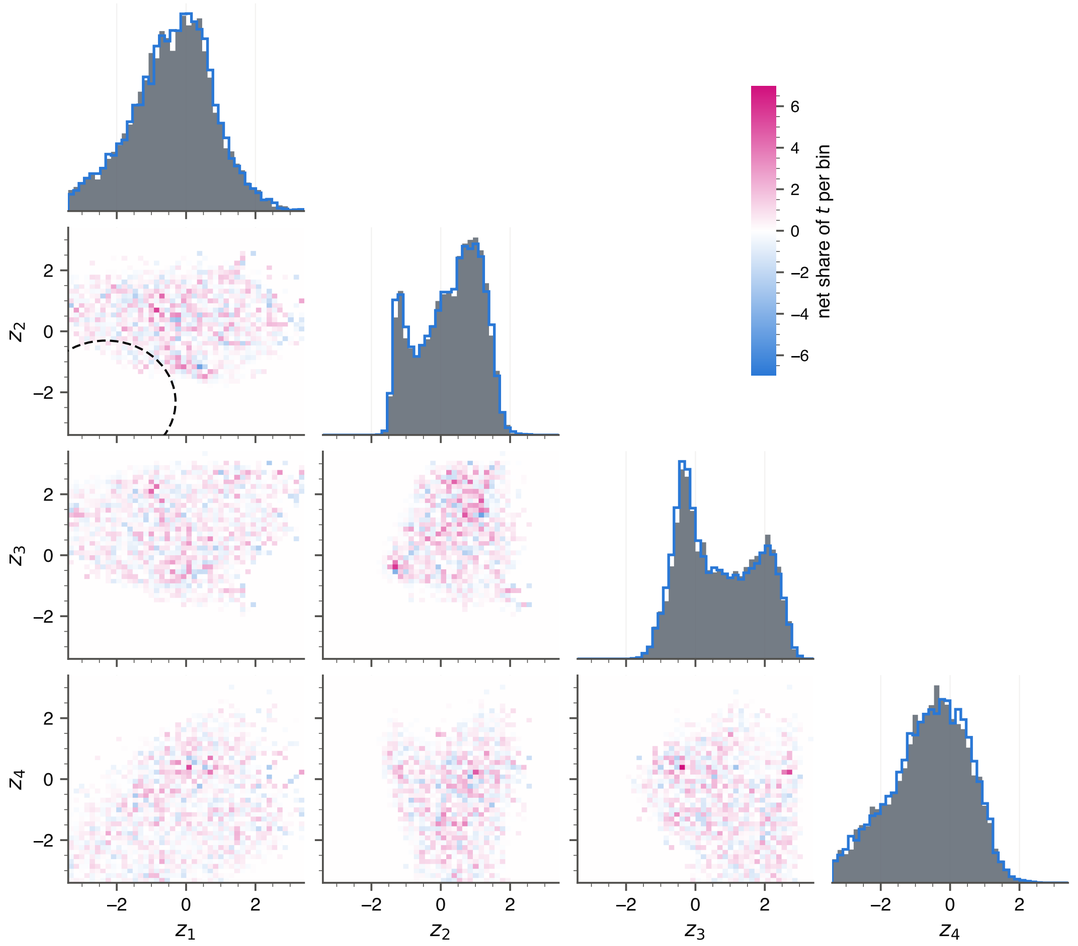
Null Trials

- Inject 8,100 simulated events drawn uniformly according to their rate
- Run the NPLM procedure withholding anomalies to build “null distributions”
- Repeated at six different kernel widths to probe differences at many scales
- Marginals show data (grey) and reference (blue), while heat maps show TS contribution



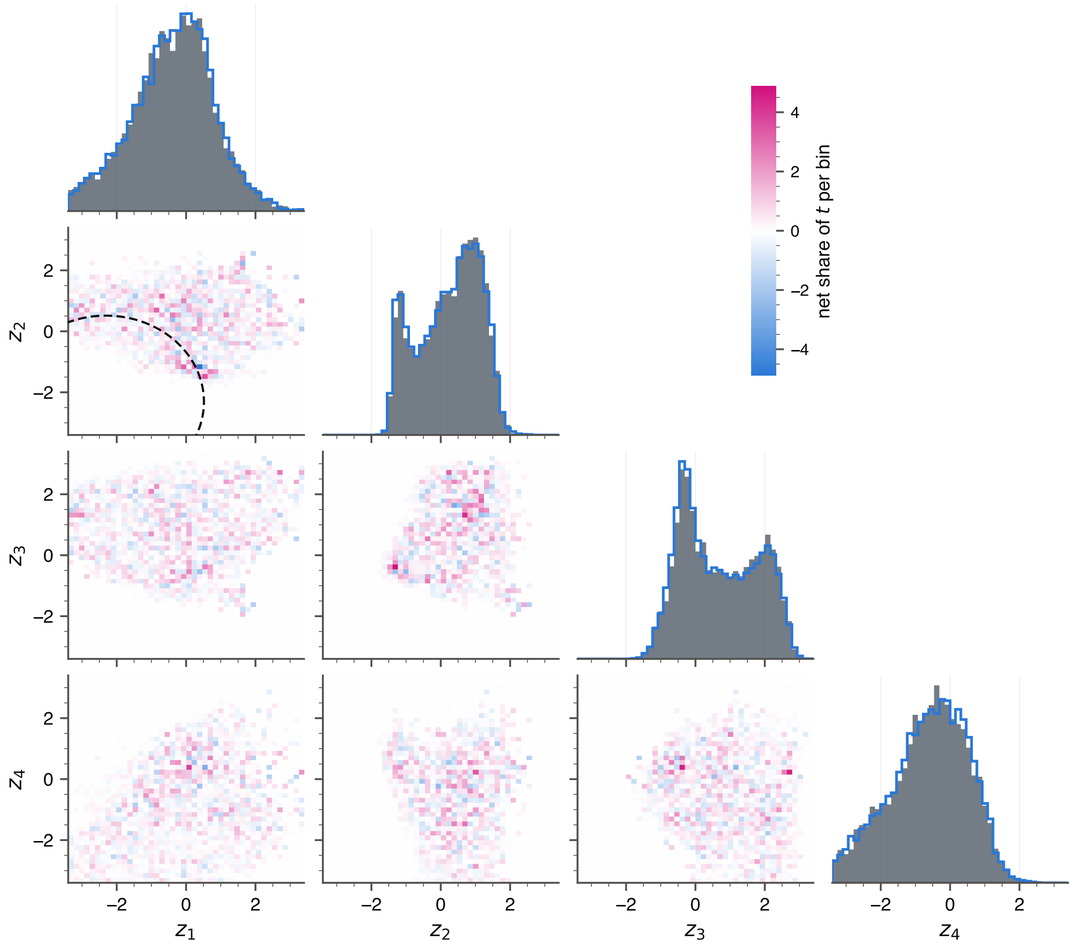
Null Trials

- Inject 8,100 simulated events drawn uniformly according to their rate
- Run the NPLM procedure withholding anomalies to build “null distributions”
- Repeated at six different kernel widths to probe differences at many scales
- Marginals show data (grey) and reference (blue), while heat maps show TS contribution



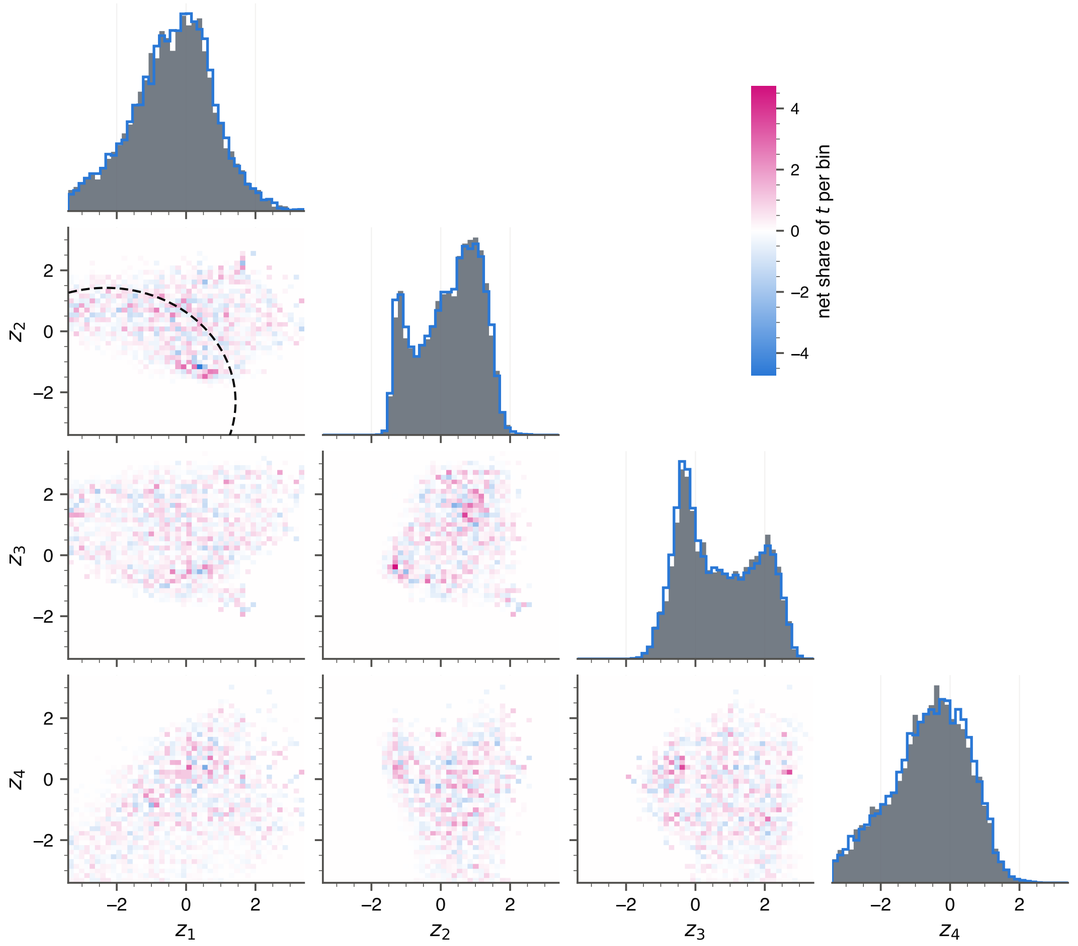
Null Trials

- Inject 8,100 simulated events drawn uniformly according to their rate
- Run the NPLM procedure withholding anomalies to build “null distributions”
- Repeated at six different kernel widths to probe differences at many scales
- Marginals show data (grey) and reference (blue), while heat maps show TS contribution



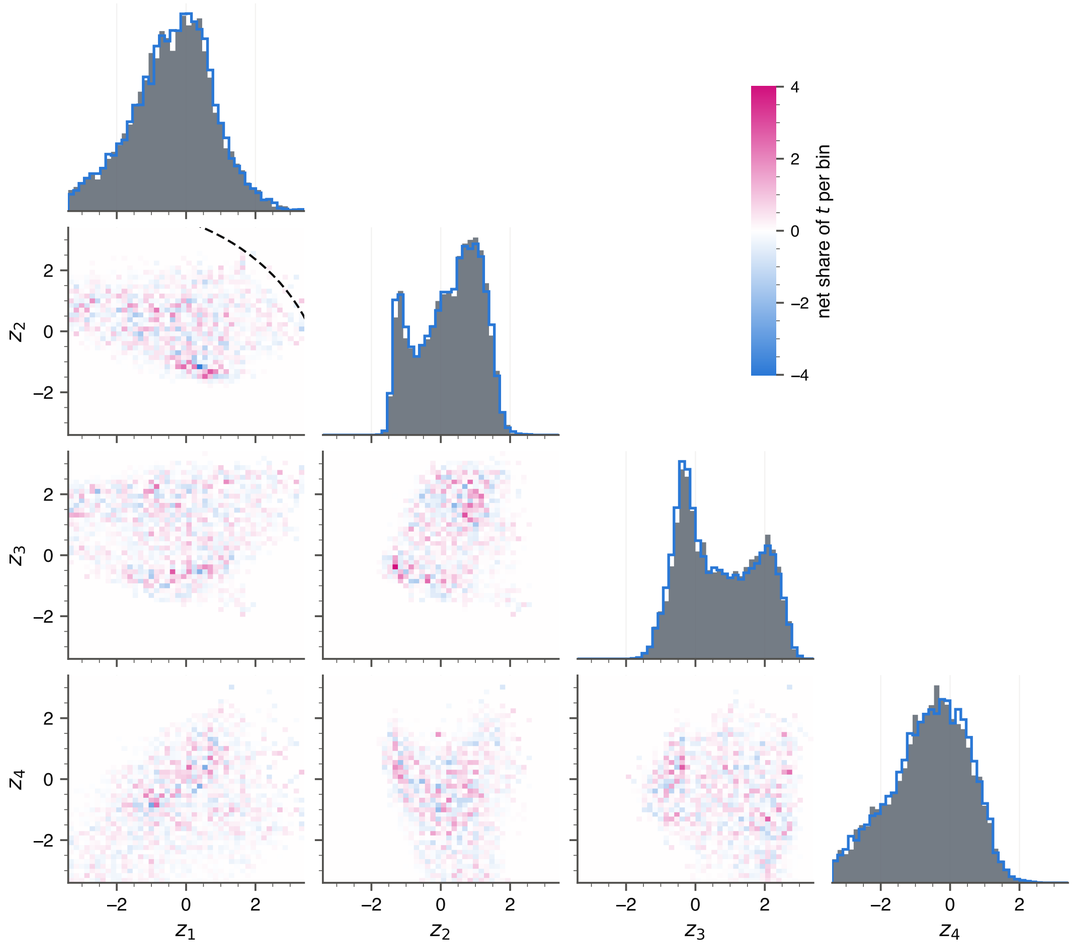
Null Trials

- Inject 8,100 simulated events drawn uniformly according to their rate
- Run the NPLM procedure withholding anomalies to build “null distributions”
- Repeated at six different kernel widths to probe differences at many scales
- Marginals show data (grey) and reference (blue), while heat maps show TS contribution



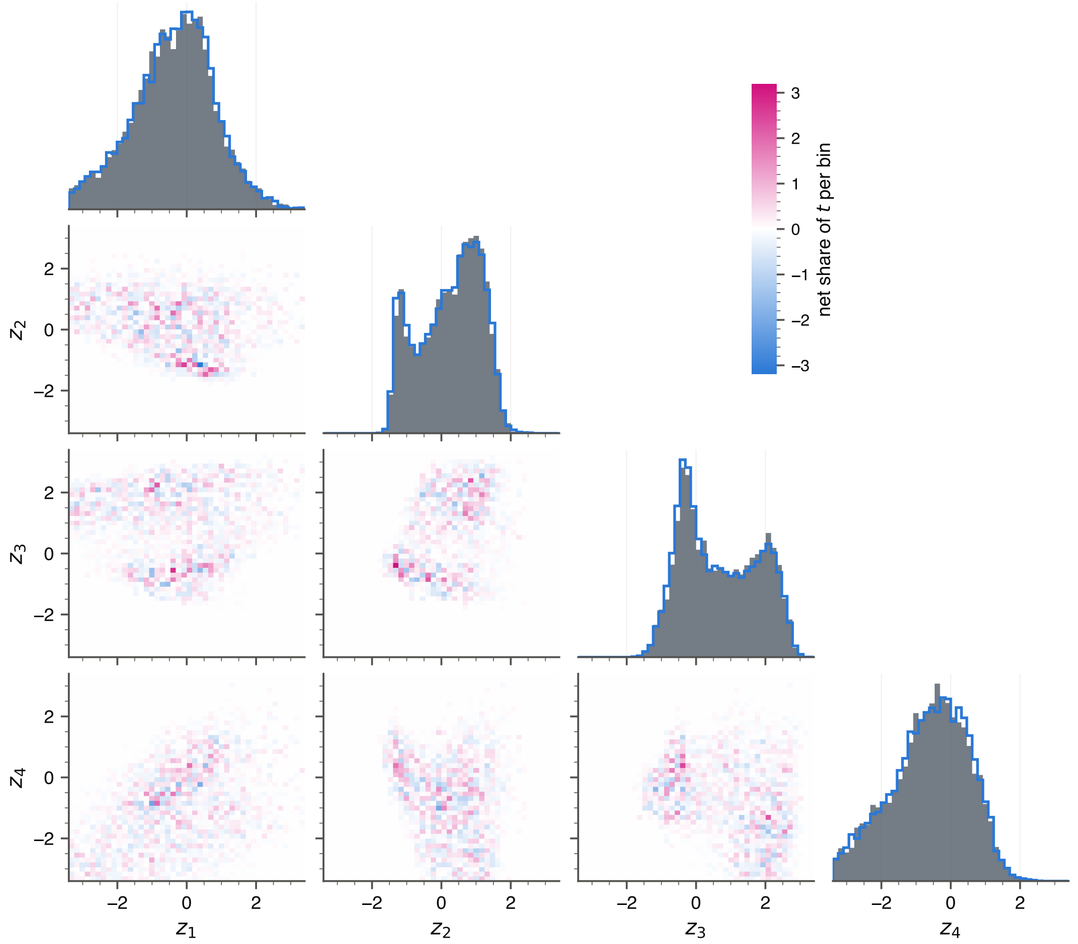
Null Trials

- Inject 8,100 simulated events drawn uniformly according to their rate
- Run the NPLM procedure withholding anomalies to build “null distributions”
- Repeated at six different kernel widths to probe differences at many scales
- Marginals show data (grey) and reference (blue), while heat maps show TS contribution



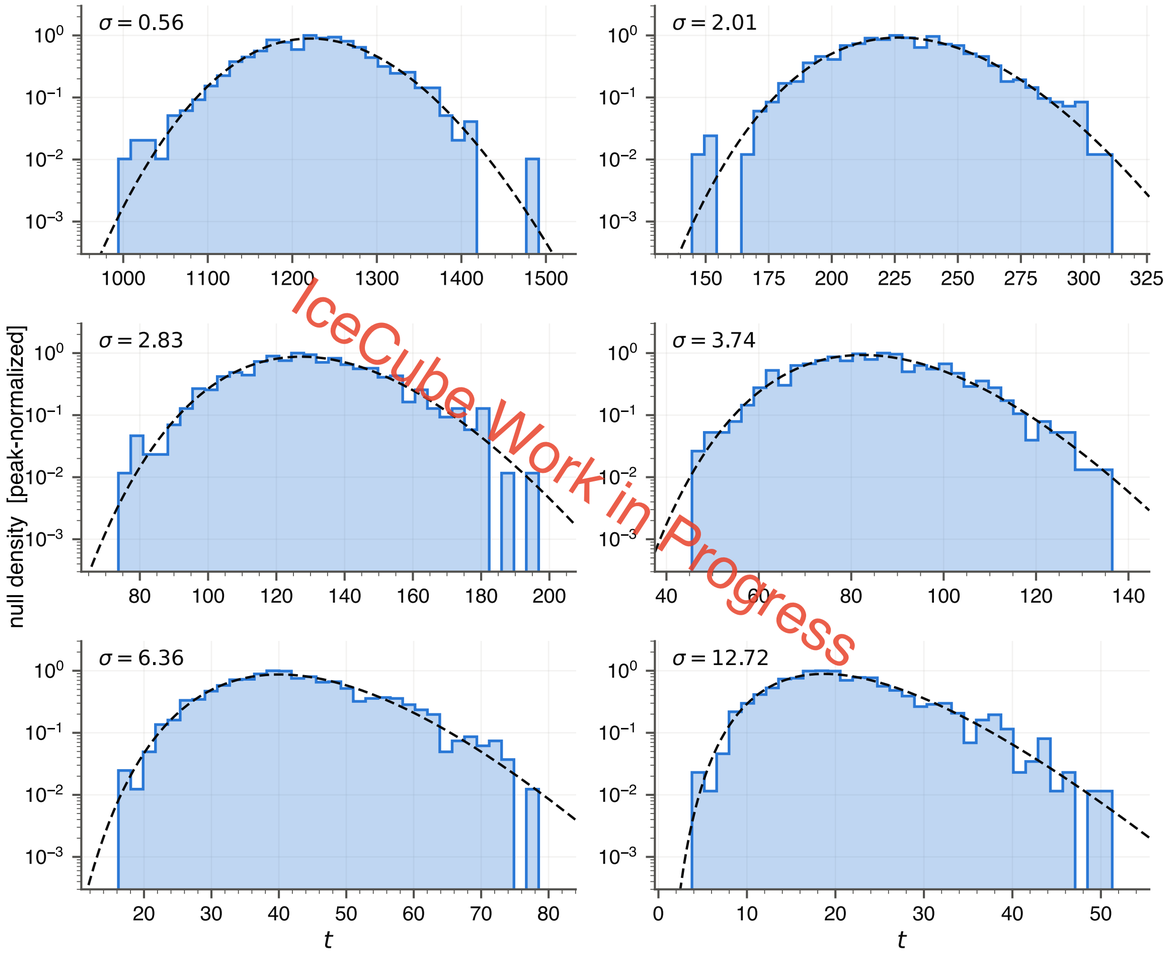
Null Trials

- Inject 8,100 simulated events drawn uniformly according to their rate
- Run the NPLM procedure withholding anomalies to build “null distributions”
- Repeated at six different kernel widths to probe differences at many scales
- Marginals show data (grey) and reference (blue), while heat maps show TS contribution



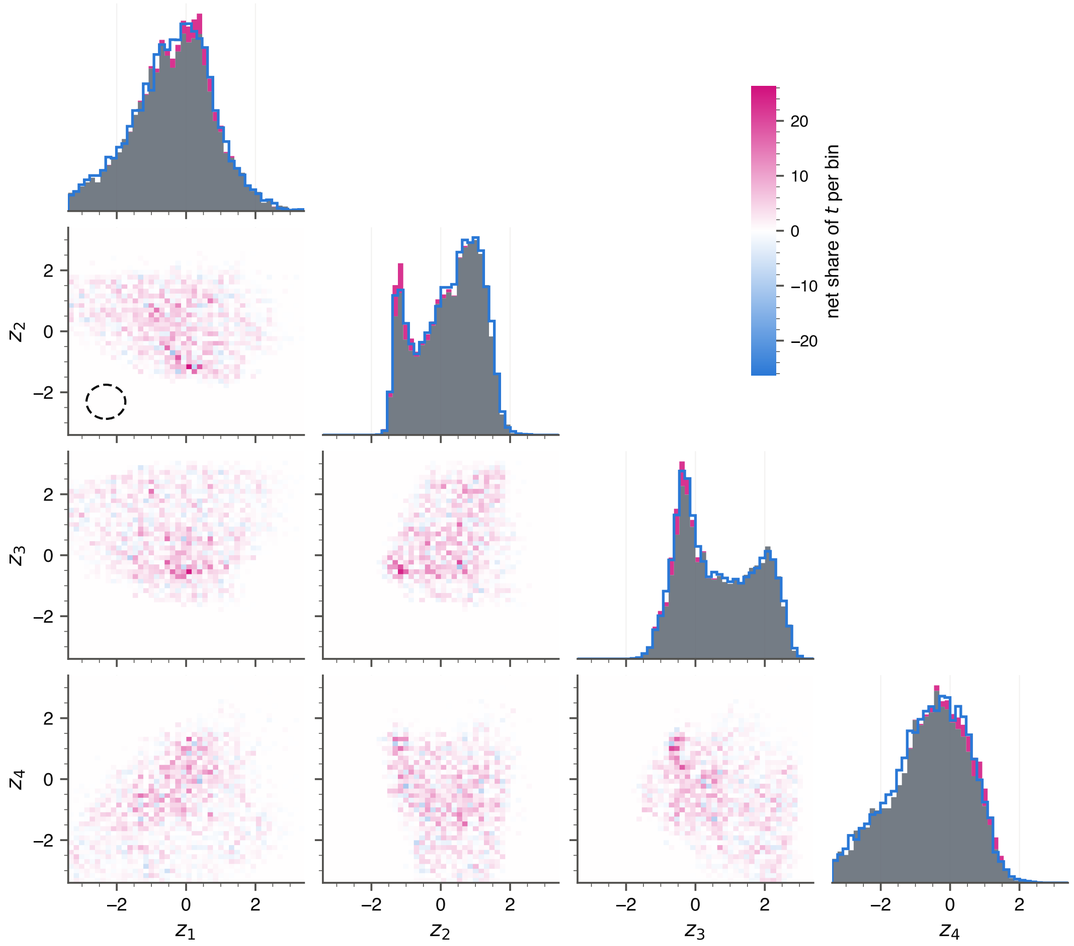
Null Trials

- Background trials are fitted to gamma distribution, i.e, a generalization of the χ^2
- Smaller kernel widths tend to give larger values
  - Easier to see confuse noise for divergence at smaller scales
- Fits generally look good



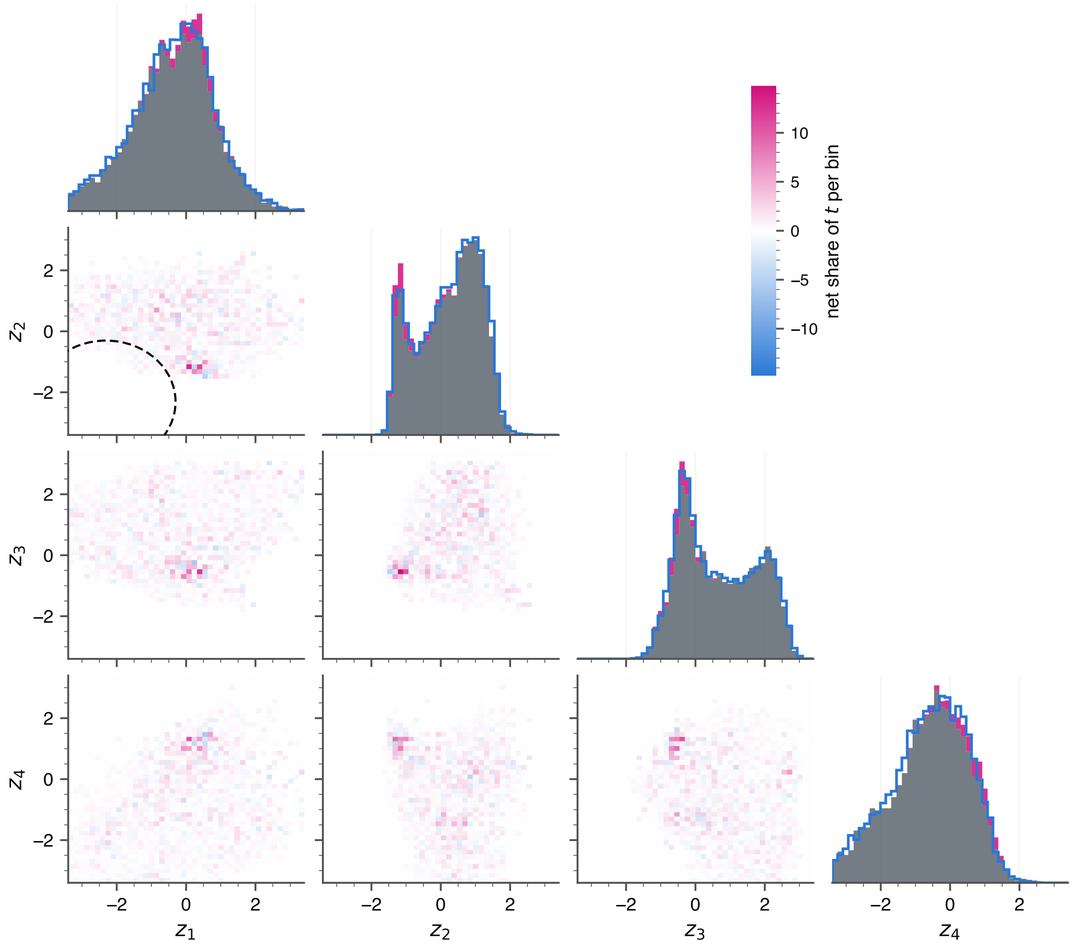
Exotic Tau Anomalies

- When adding exotic tau anomalies, structure begins to appear in the heat maps
- As expected, it is aligned



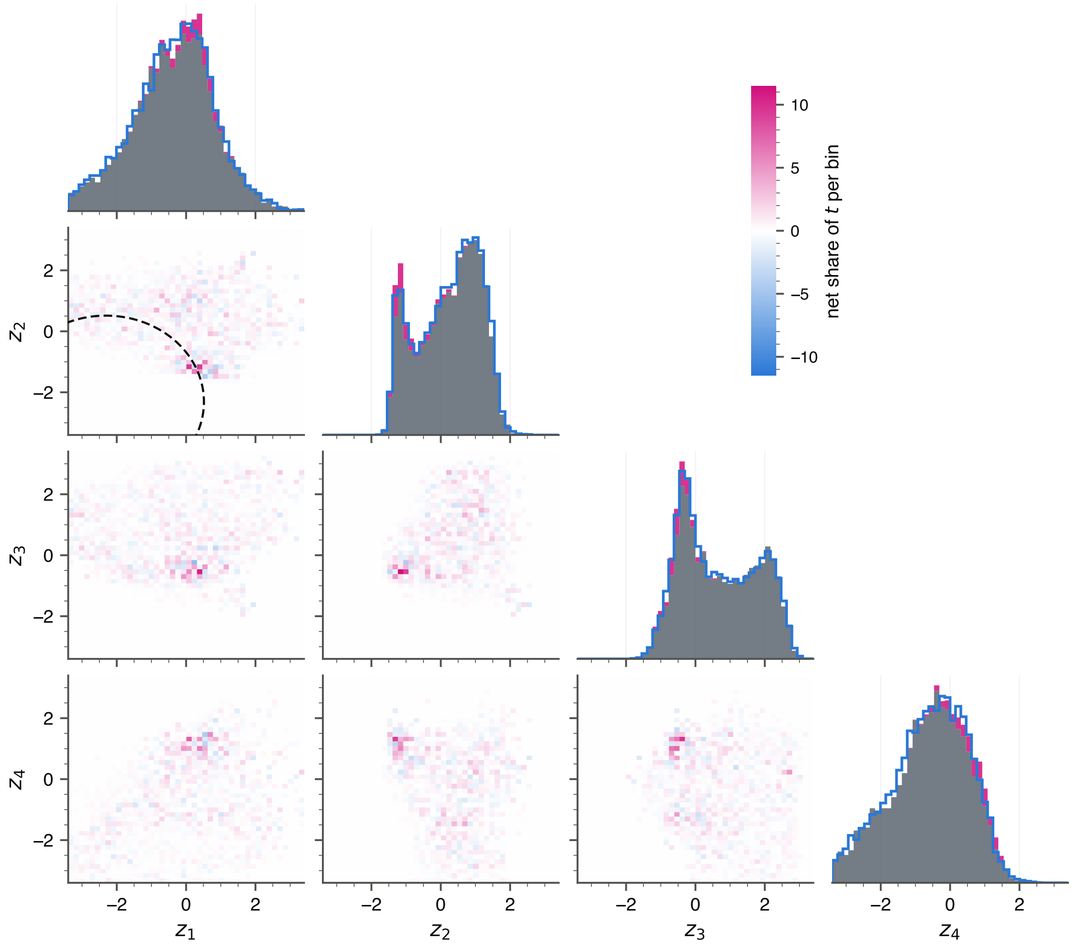
Exotic Tau Anomalies

- When adding exotic tau anomalies, structure begins to appear in the heat maps
- As expected, it is aligned



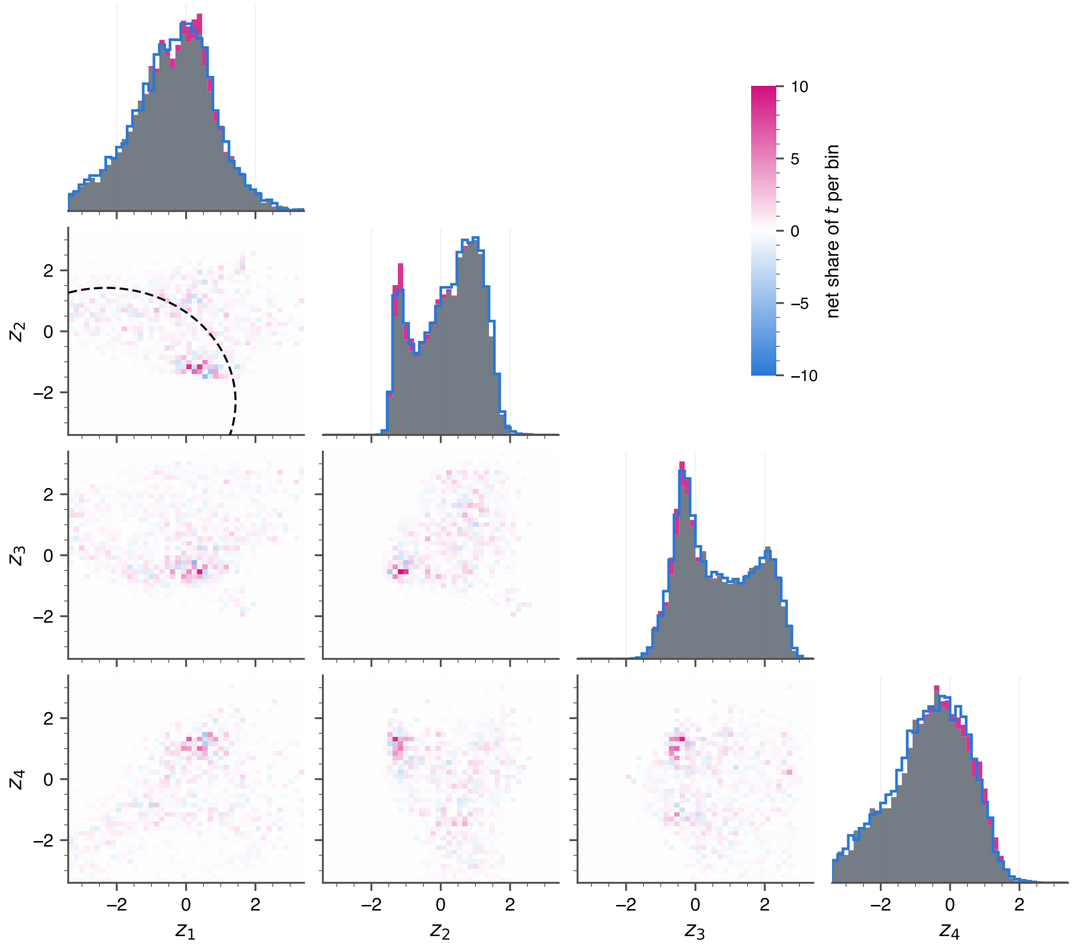
Exotic Tau Anomalies

- When adding exotic tau anomalies, structure begins to appear in the heat maps
- As expected, it is aligned



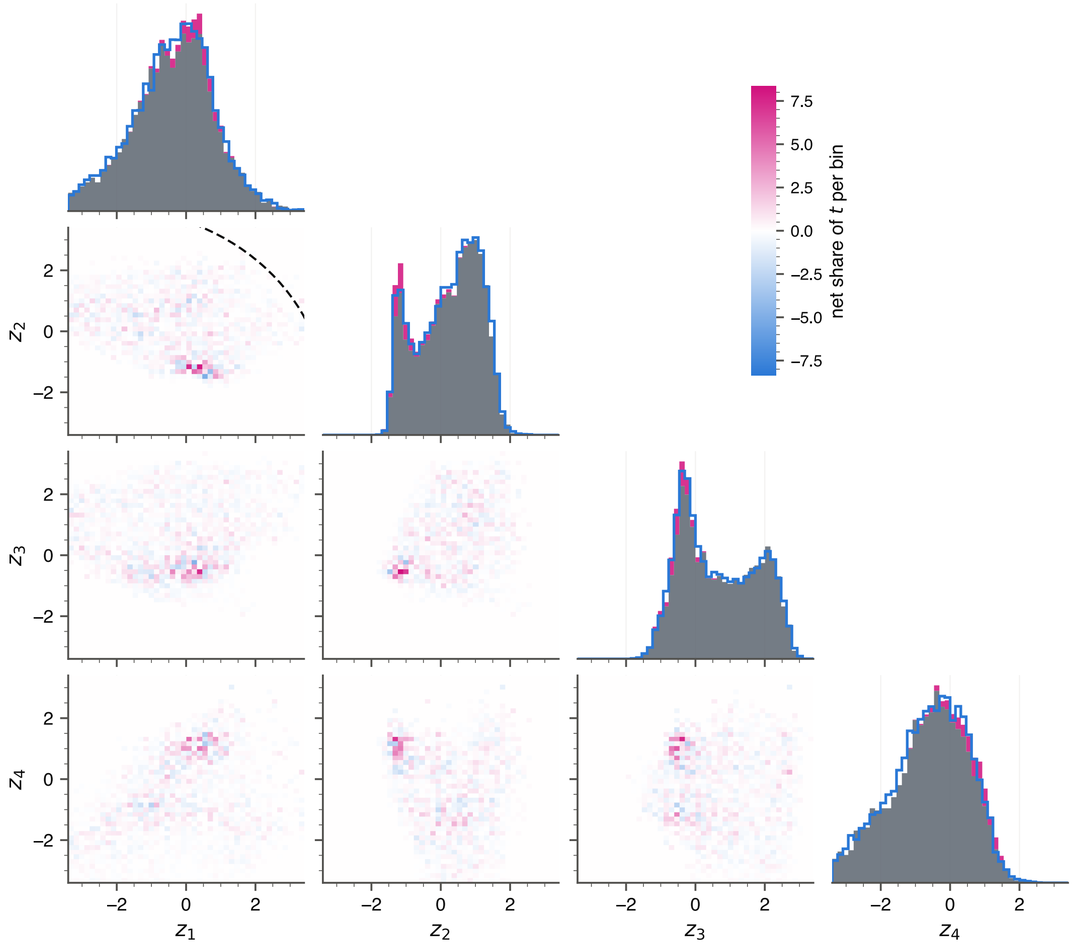
Exotic Tau Anomalies

- When adding exotic tau anomalies, structure begins to appear in the heat maps
- As expected, it is aligned



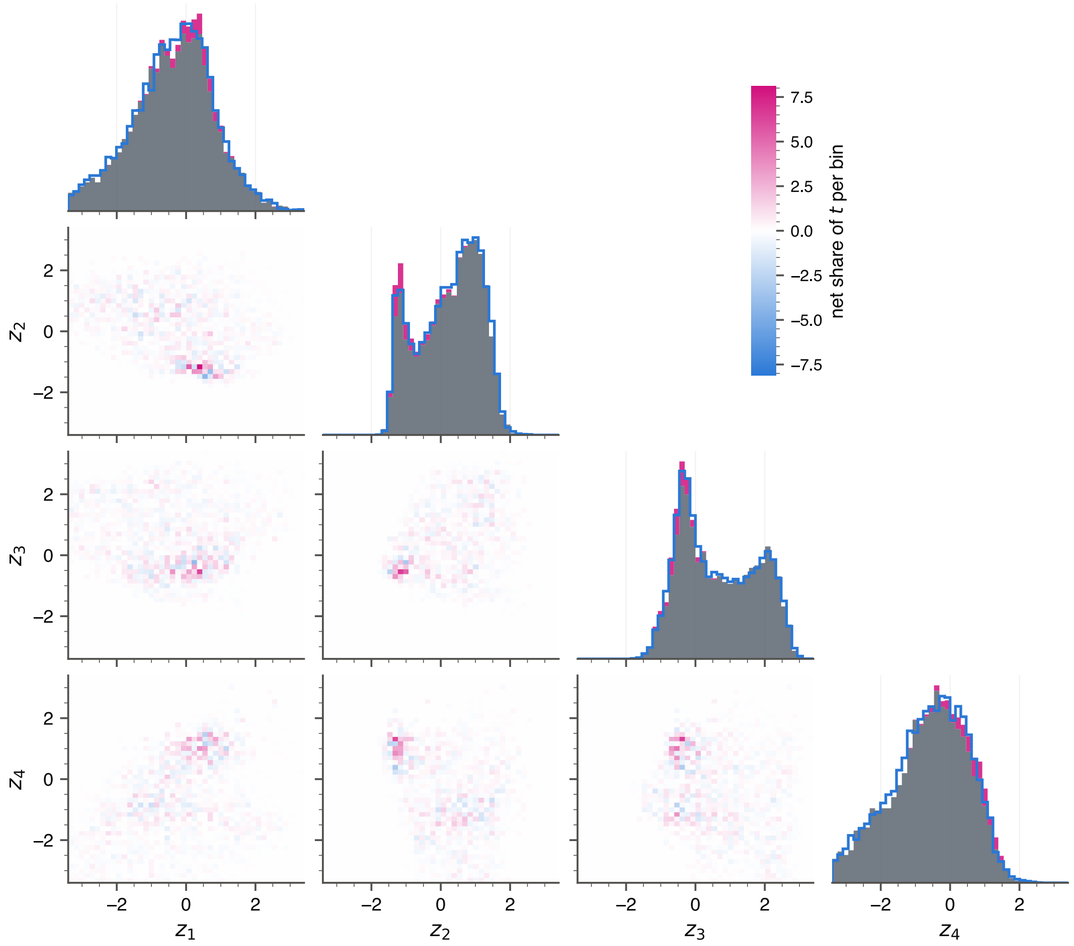
Exotic Tau Anomalies

- When adding exotic tau anomalies, structure begins to appear in the heat maps
- As expected, it is aligned



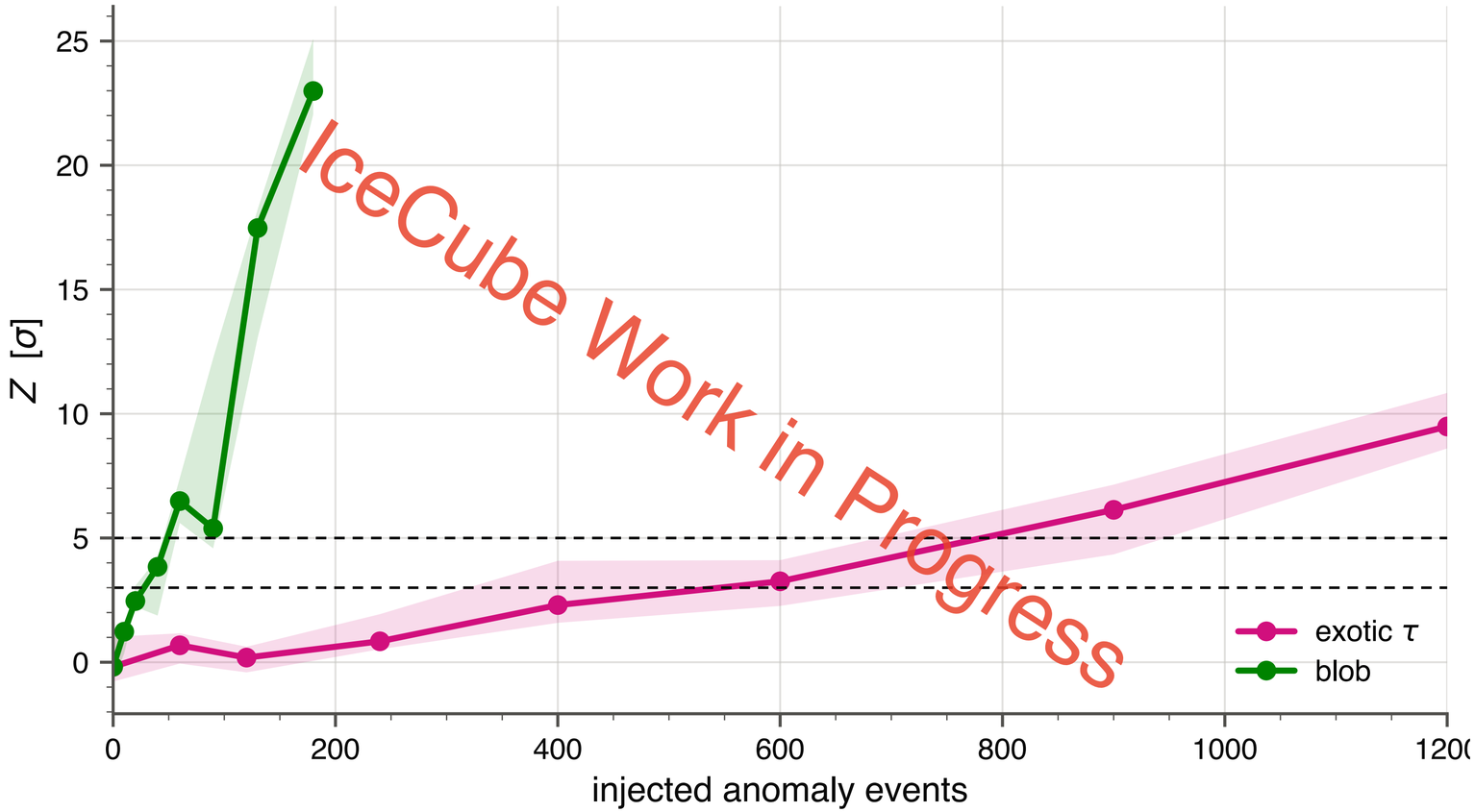
Exotic Tau Anomalies

- When adding exotic tau anomalies, structure begins to appear in the heat maps
- As expected, it is aligned



Detection Sensitivity

- Novel blob anomaly is more significant, reaching discovery at around 1.0% of total data
- Exotic tau detection scales more slowly, reaching discovery around 9% of total data



Summary and Conclusions

- **AutoSciDACT framework is able to find unmodeled anomalies in simulated IceCube neutrino events at the few-percent level**
  - Both tau neutrino and synthetic “blob” have been detected using this method
- Atmospheric muons neglected in current work and must be removed via event selection going forward
- Systematic studies will be critical, as well as estimation of the effects of detector mismodeling
- Many tests are necessary to make sure we understand the underlying behavior of this mechanism

Thank you :-)