Machine Learning in neutrino telescopes

Mostly deep convolutional neural networks

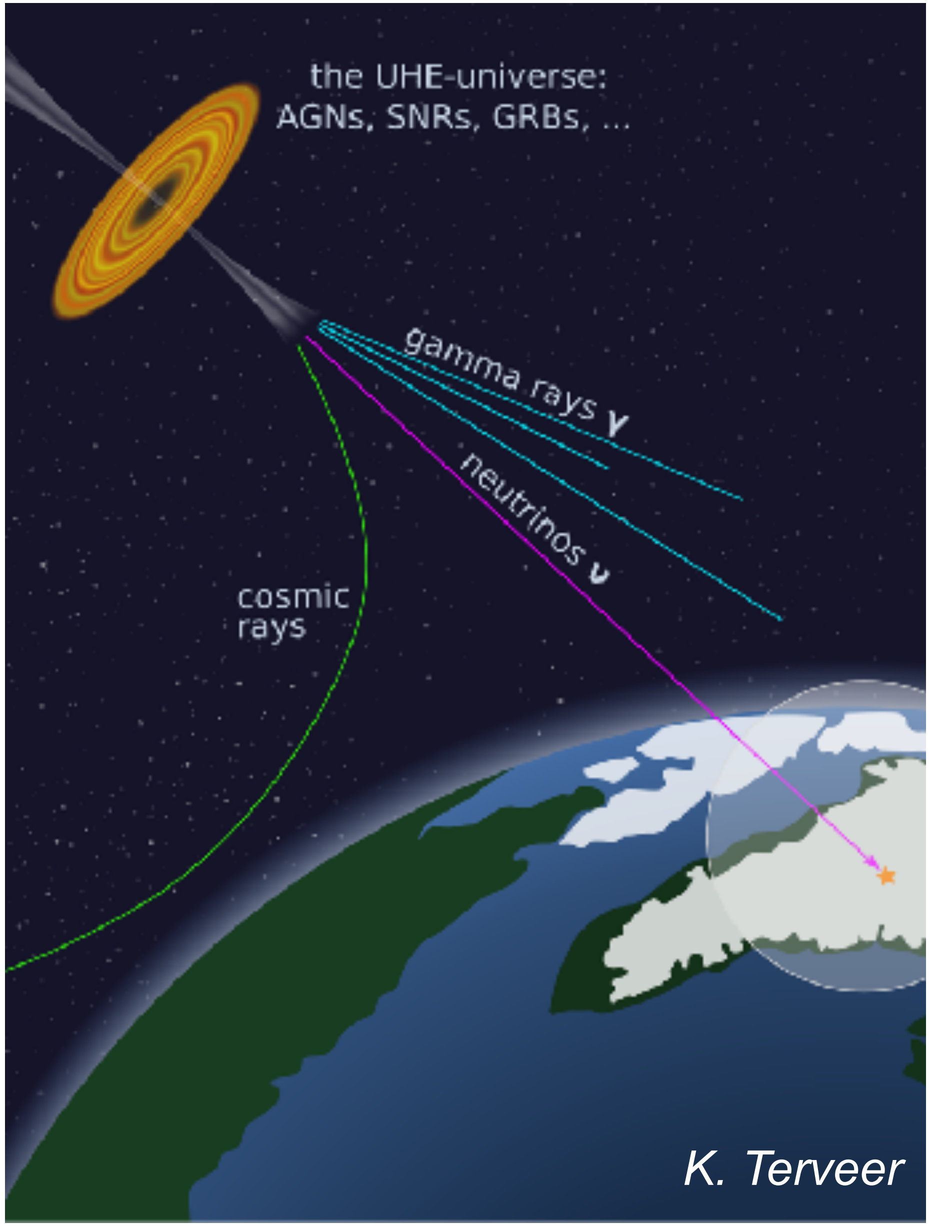
Jakob van Santen
APPP Workshop, Zeuthen, 2025-10-07

HELMHOLTZ

DESY.

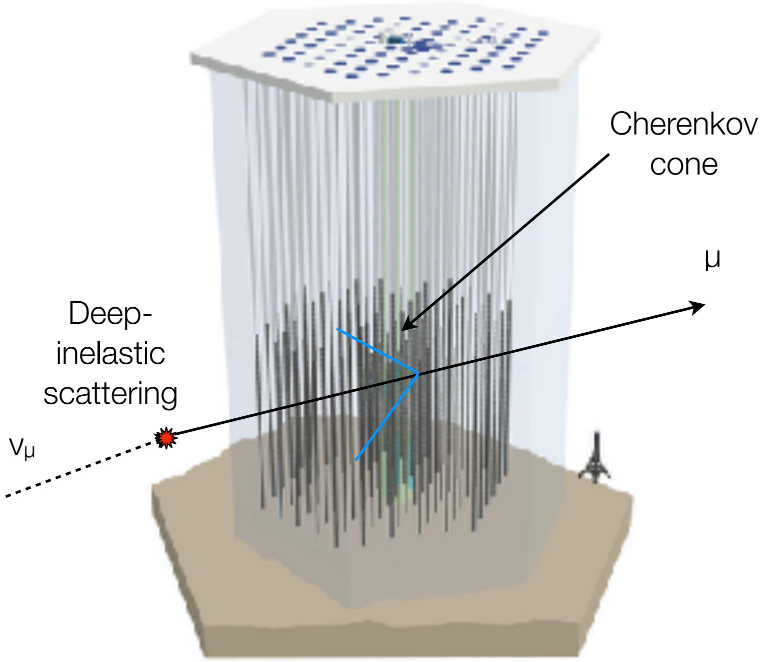
Why neutrino telescopes

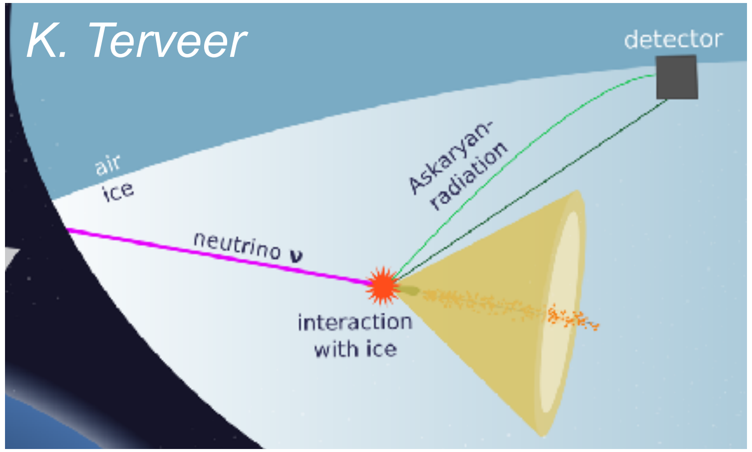
- Where are the sources of high-energy neutrinos?
- What are their properties?
- Along the way: what are the properties of the unresolved sources? (In IceCube jargon: "diffuse analysis")
- Small fluxes -> O(gigaton) target mass -> natural media
- While you're at it:
    - Neutrino properties with atmospheric neutrinos
    - Hadronic physics with air showers
    - [Dark matter, nonstandard interactions, Lorentz invariance violation, etc]



IceCube & Radio Neutrino Observatory Greenland

- **IceCube**: PMTs 125 (40-70, 20)* m apart
- Deep-inelastic scattering in the ice
- Relativistic charged particles induce Cherenkov radiation, detectable O(100 m) away
- Sensitive to neutrinos above ~1000 (100, 30)* GeV
- Completed in 2012 (Upgrade 2026)
- Cf. KM3NeT, Baikal-GVD, P-ONE
- **RNO-G**: radio antenna stations 1.25 km apart
- Deep-inelastic scattering in the ice
- Moving charge emits radio pulse, detectable O(1 km) away
- Sensitive to neutrinos above ~1e7 GeV
- Under construction (7/35 stations)
- Cf. ARA, ARIANNA





* IceCube DeepCore, IceCube Upgrade (2026) target lower-energy neutrinos with denser instrumentation

Tasks

From raw to analysis-ready data

Filter noise

Physics: high-energy charged particles in ice
Noise: everything else

Classify/select

Signal/Background
or
Interaction signature

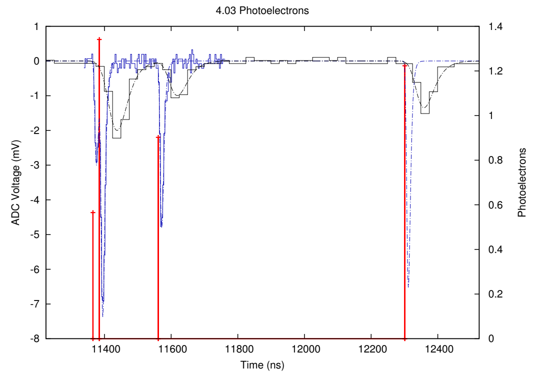
Reconstruct

Direction: resolve sources
Energy: separate from atmospheric backgrounds

Focus on IceCube for now

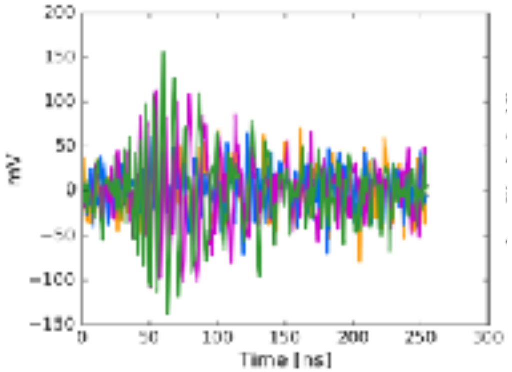
IceCube: photons

- Location, time
- Number



RNO-G: electric field

- Location, time
- Amplitude
- Polarization

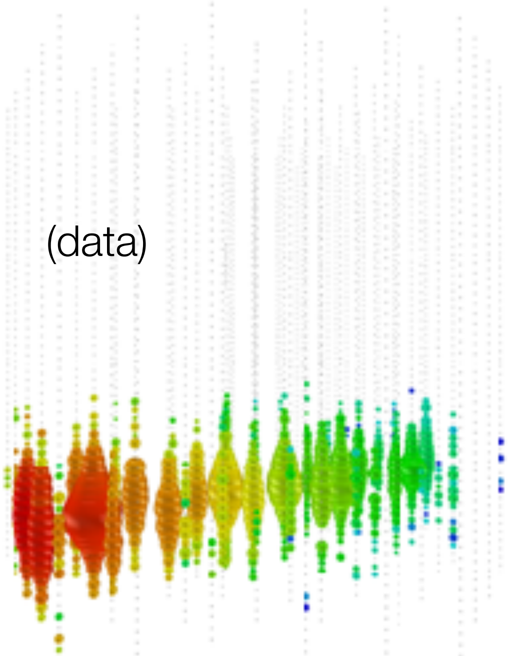


Event reconstruction in IceCube

Neutrino event signatures (in an optical detector)

Charged-current ν_μ

(data)

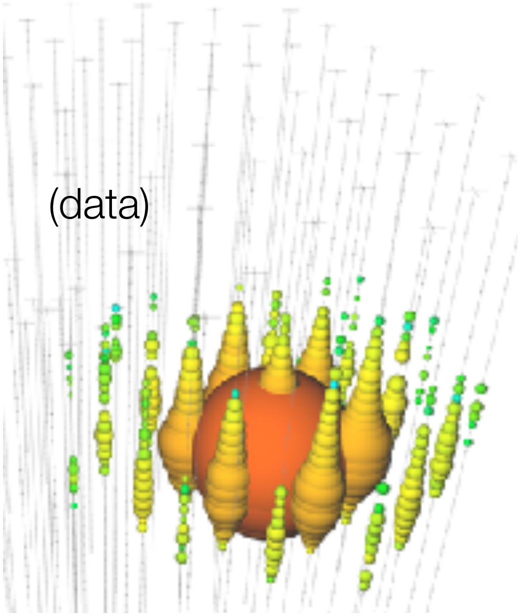


Up-going track

Factor of ~2 energy resolution
< 1 degree angular resolution

Neutral-current / ν_e

(data)

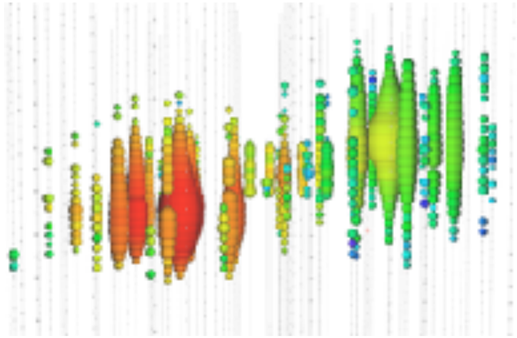


Isolated energy deposition (cascade) with no track

15% deposited energy resolution
10 degree angular resolution (above 100 TeV)

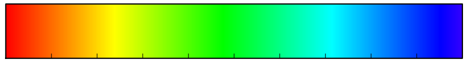
Charged-current ν_τ

(simulation)

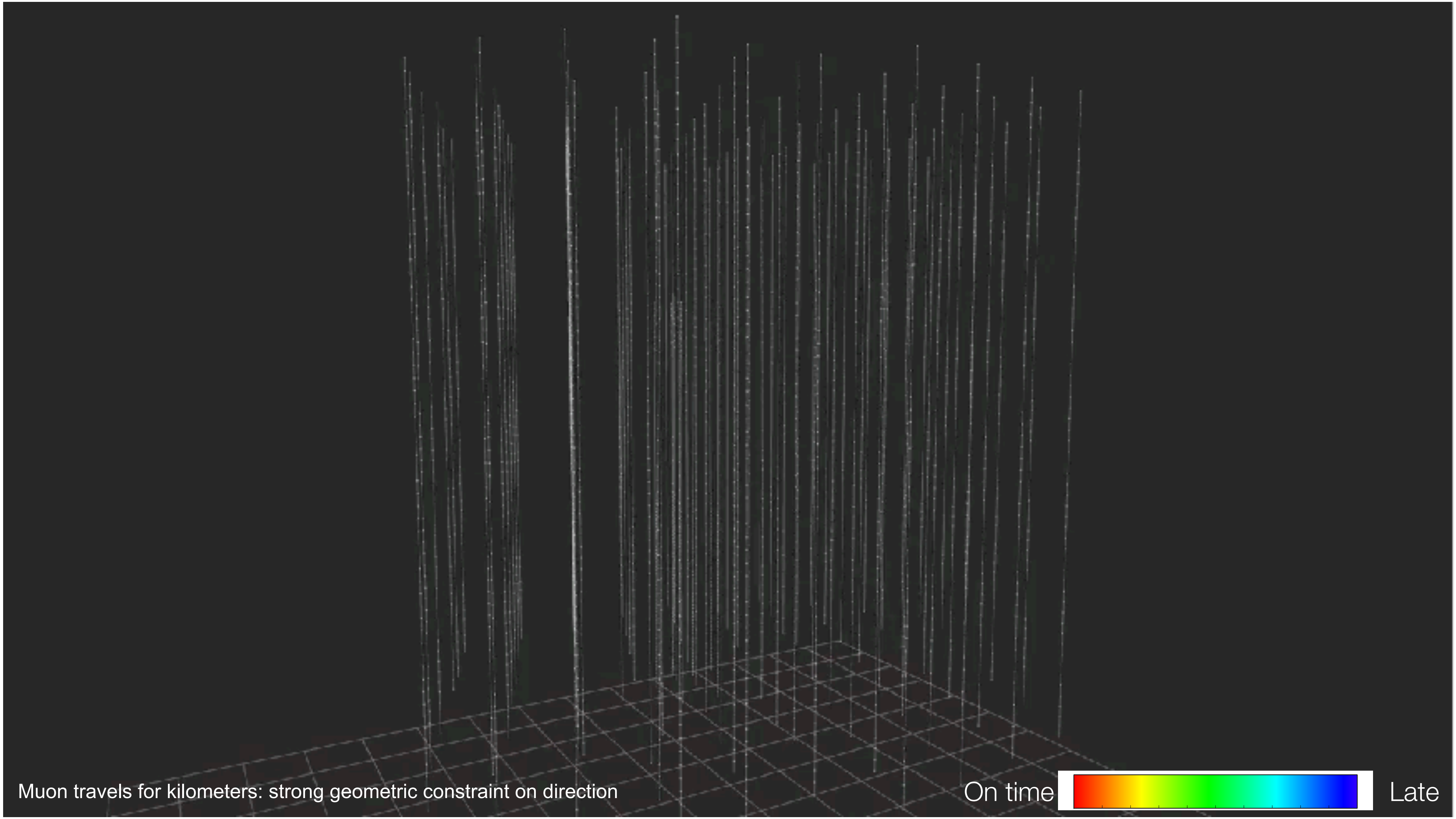


“Double-bang”

(none this clear observed yet: τ decay length is 50 m/PeV)

Early  Late

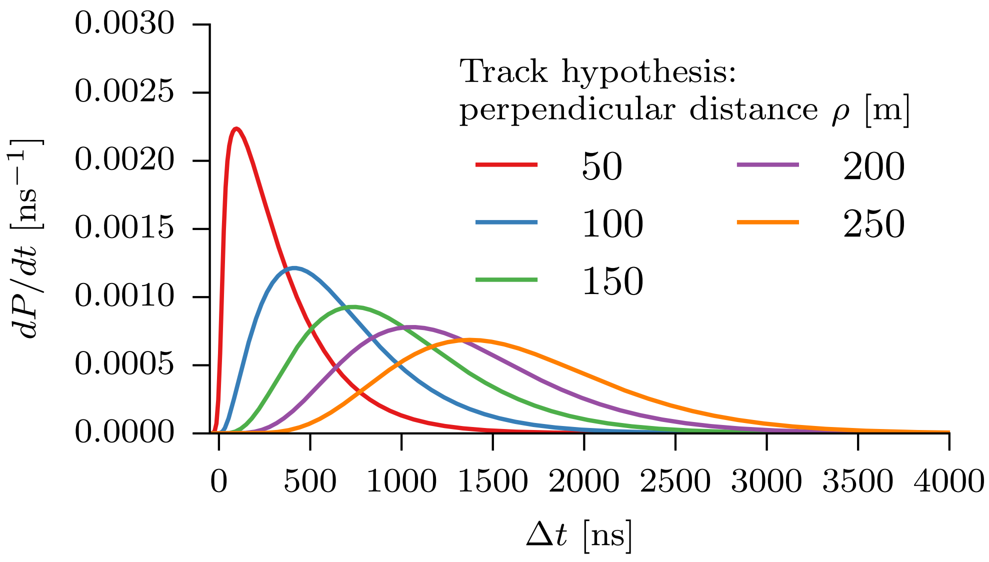
0.01% of Cherenkov photons from a 100 TeV muon in South Pole ice (   )



Accounting for scattering in reconstruction

Standard/legacy approach

- Use a model of the expected time-delay distribution *from a constant-intensity emitter* to construct a likelihood for the underlying muon track
- For single photon detection: time distribution of individual photons
- For multiple photon detections: time distribution for first of N photons (order statistic)
- "Easy" for kilometer-long muon tracks: <1 degree angular error

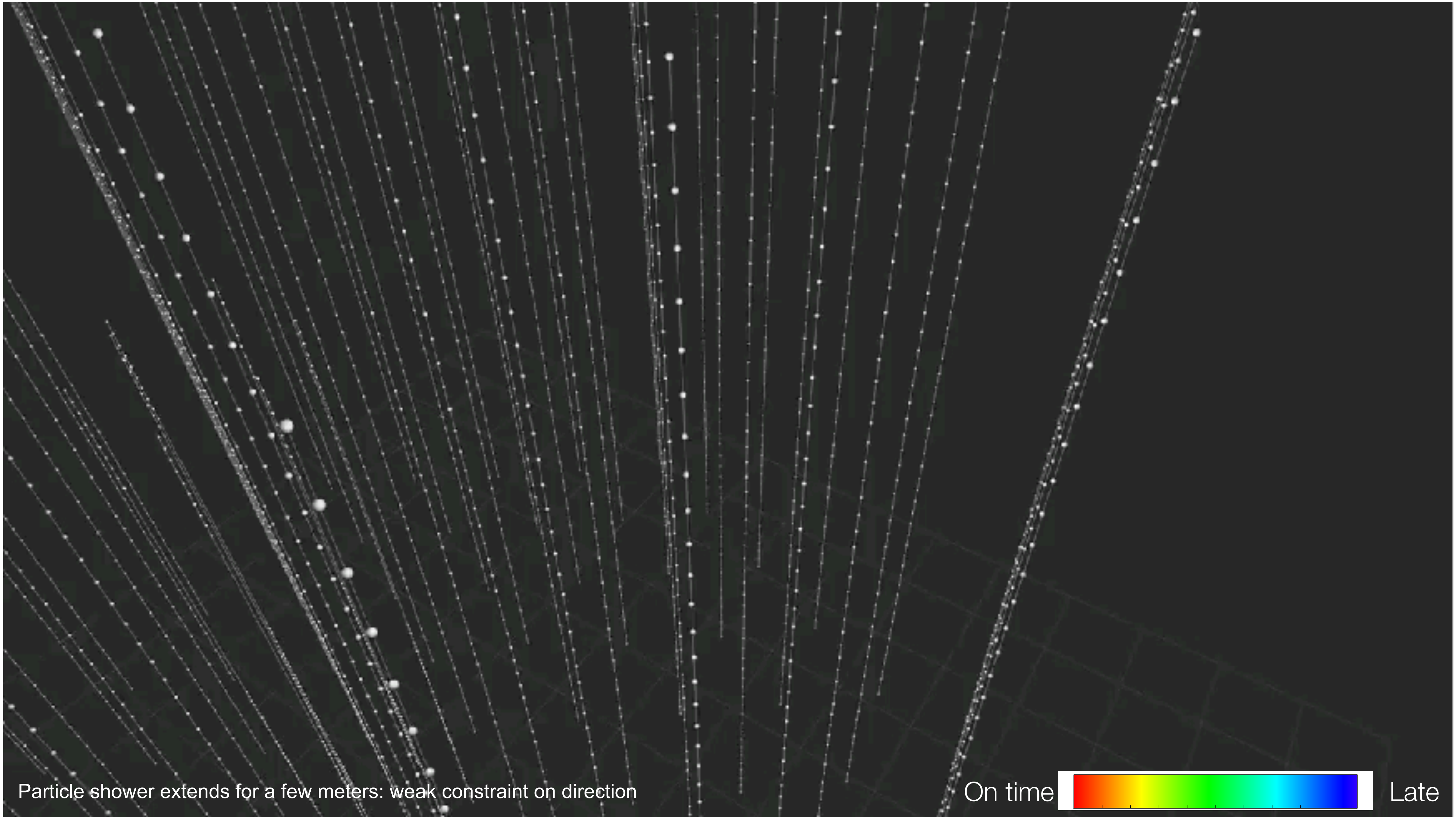


$$L_{\mathrm{SPE1st}}(x) = \prod_{i=1}^{N_{\mathrm{modules}}} dP(t_i - t_{\mathrm{geo},i})/dt$$

$$L_{\mathrm{MPE1st}}(x) = \prod_{i=1}^{N_{\mathrm{modules}}} N dP(t_i - t_{\mathrm{geo},i})/dt \cdot (1 - P(t_i - t_{\mathrm{geo},i}))^{(N-1)}$$

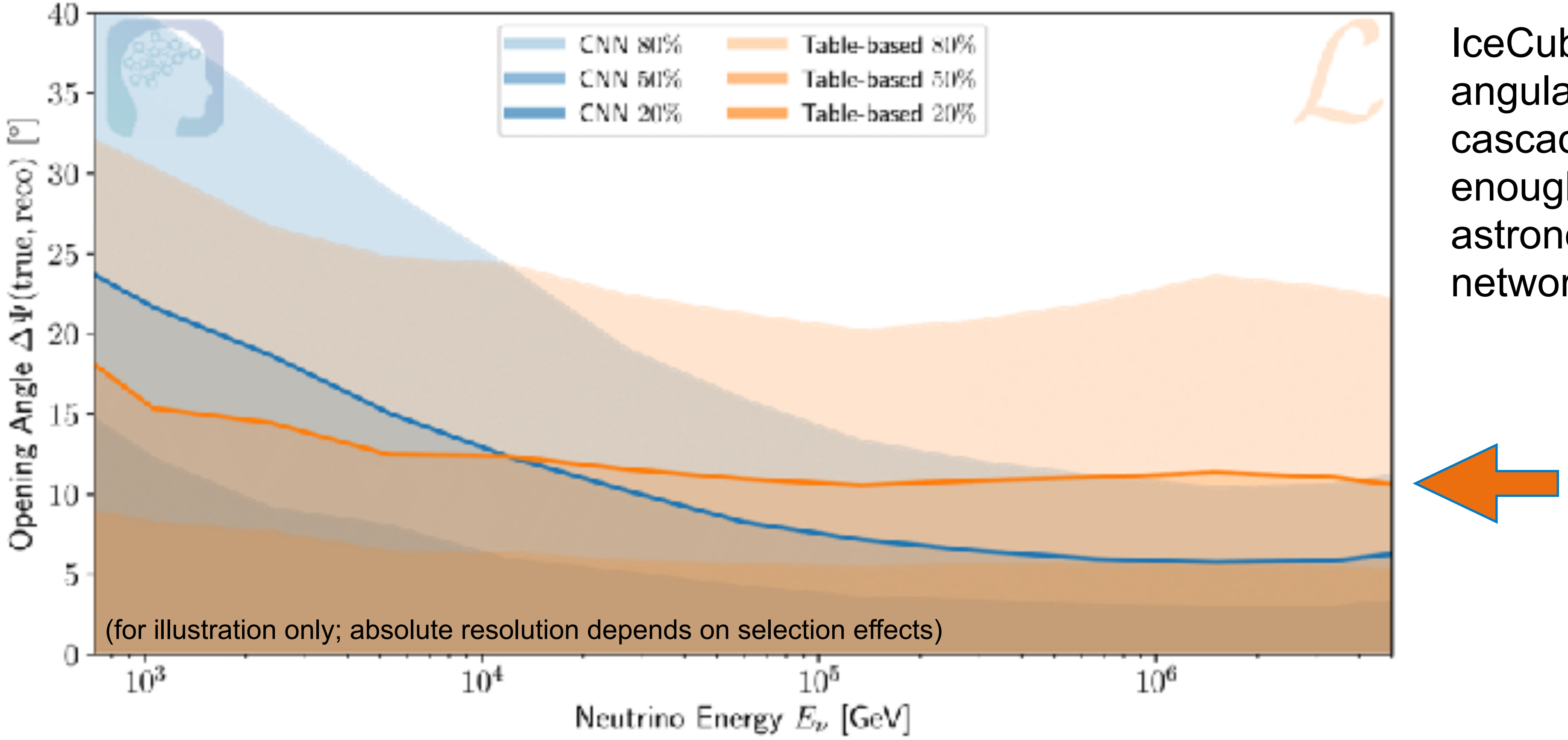
https://arxiv.org/abs/astro-ph/0407044v1

0.01% of Cherenkov photons from a 100 TeV EM shower in South Pole ice (   )



Cascade reconstruction with CNNs

Motivation



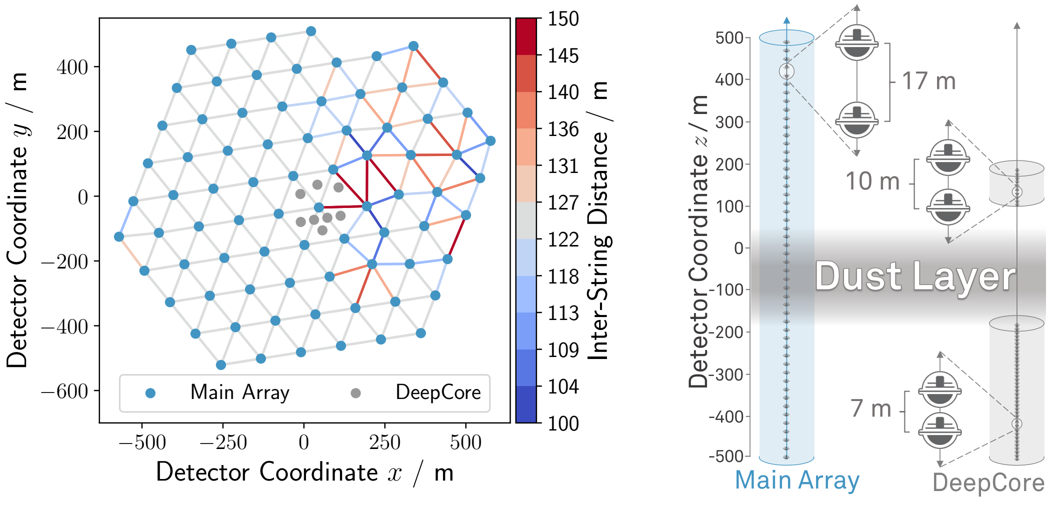
IceCube's likelihood-based angular reconstruction for cascades is not precise enough to be useful for astronomy. Can a deep neural network do a better job?

https://user-web.icecube.wisc.edu/~mhuennefeld/docs/dnn_reco/html/index.html

Cascade reconstruction with CNNs

Challenge: geometry

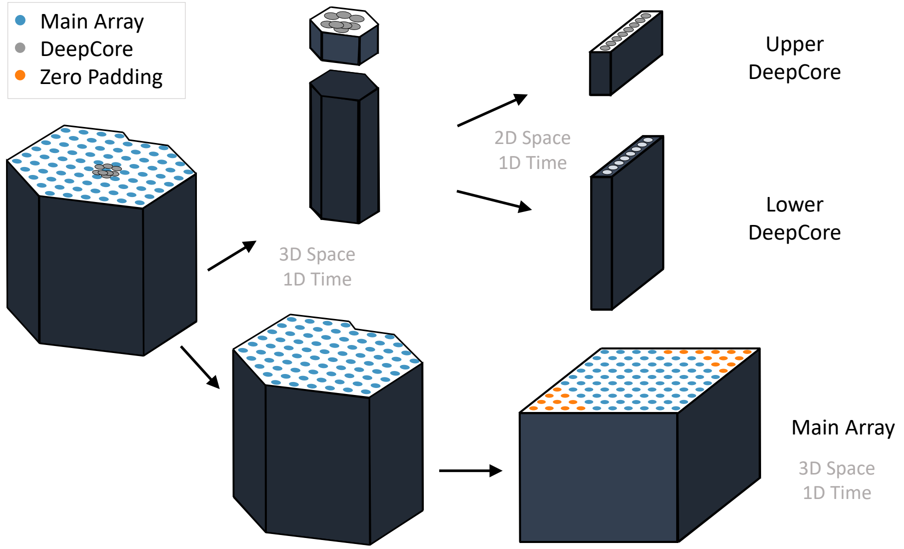
Detector is not a cartesian grid



(a) Top view of IceCube

(b) Side view of Strings

Approximate main array as cartesian grid, flatten dense infill



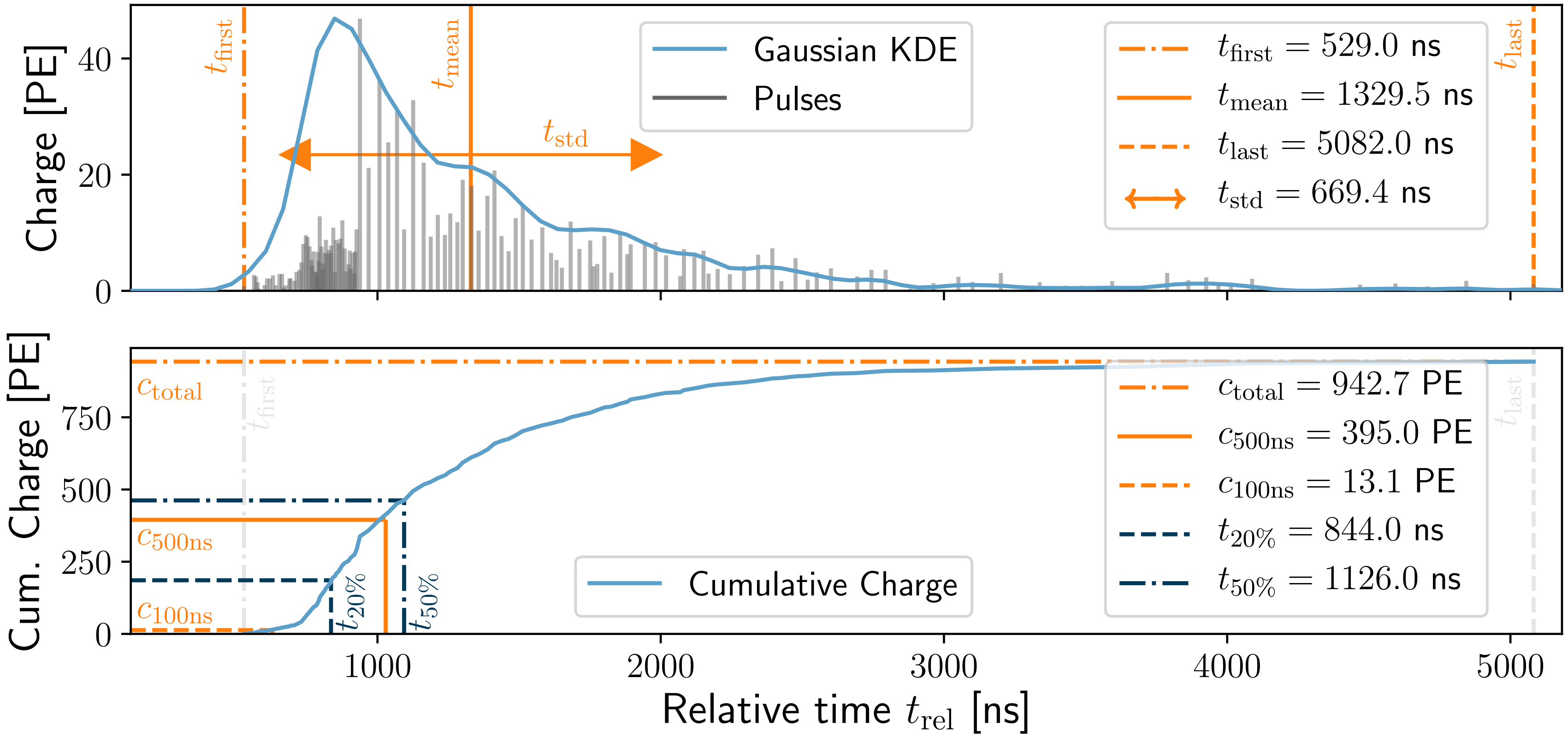
doi:10.1088/1748-0221/16/07/P07041

Cascade reconstruction with CNNs

Challenge: variable-sized input data

Multiple photon arrival times measured per module

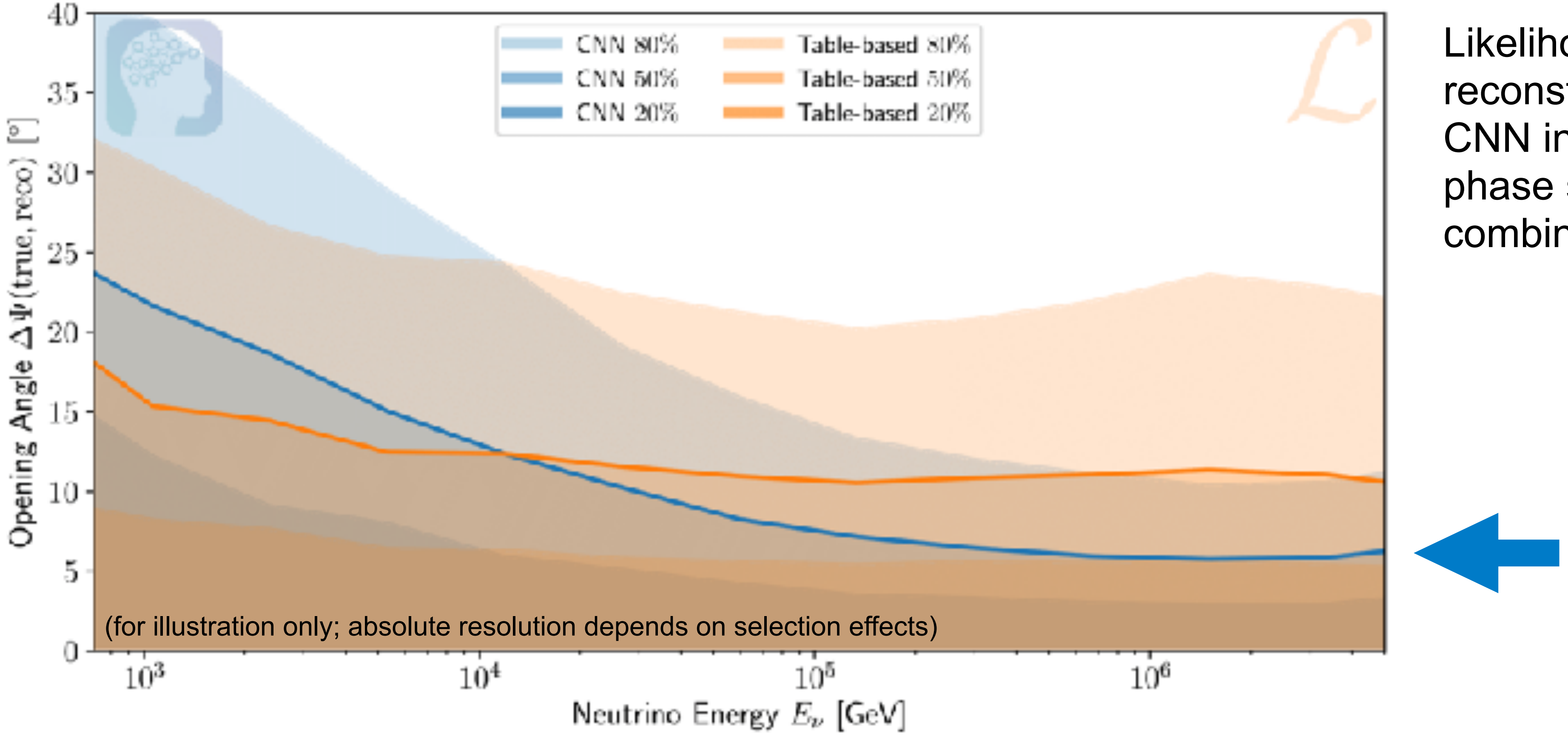
9 summary statistics per module



doi:10.1088/1748-0221/16/07/P07041

Cascade reconstruction with CNNs

Potential for improvement



Likelihood-based reconstruction still outperforms CNN in some parts of the phase space. Can they be combined?

Injecting domain knowledge

$\vec{\Theta} = f(\vec{t}\,)$

Point predictor

Maximum likelihood
(Learned PDF parameters)

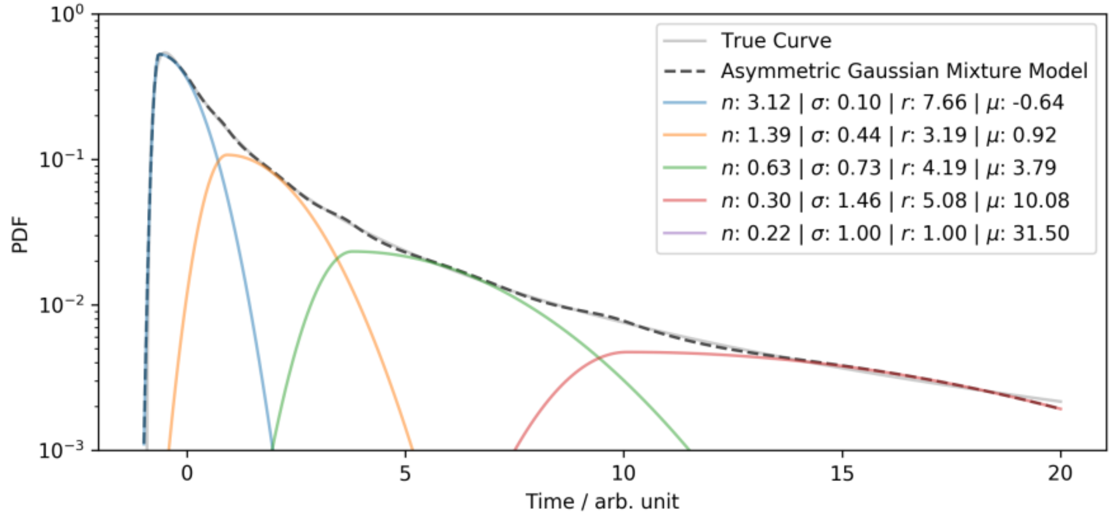
$$\vec{\Theta} = \max_{\vec{\theta}} \prod_{i} dP(t_i | \vec{\Theta})/dt$$

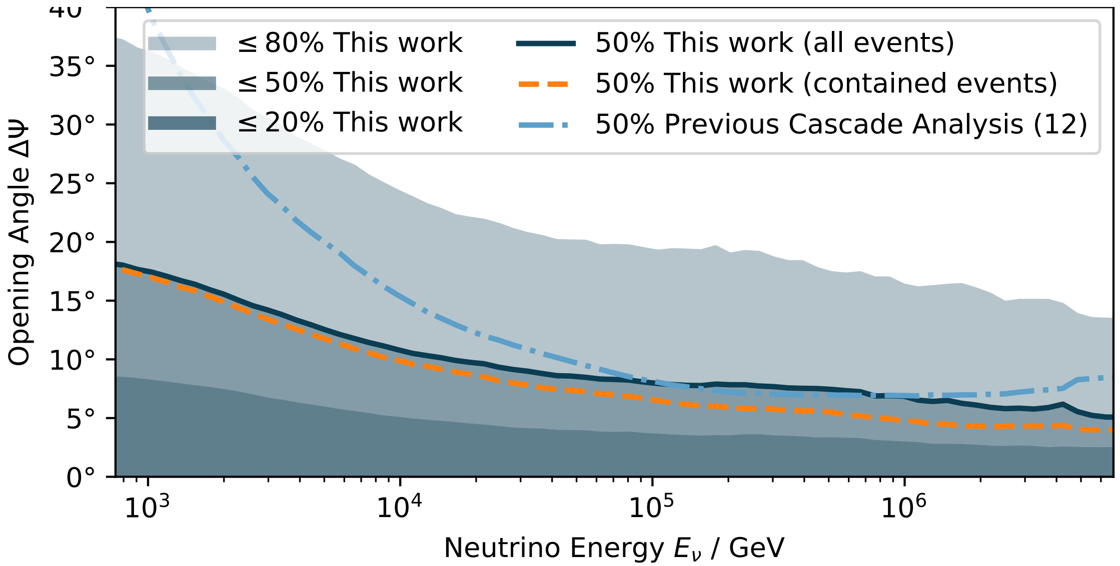
Maximum likelihood
(Fixed PDF parameters)

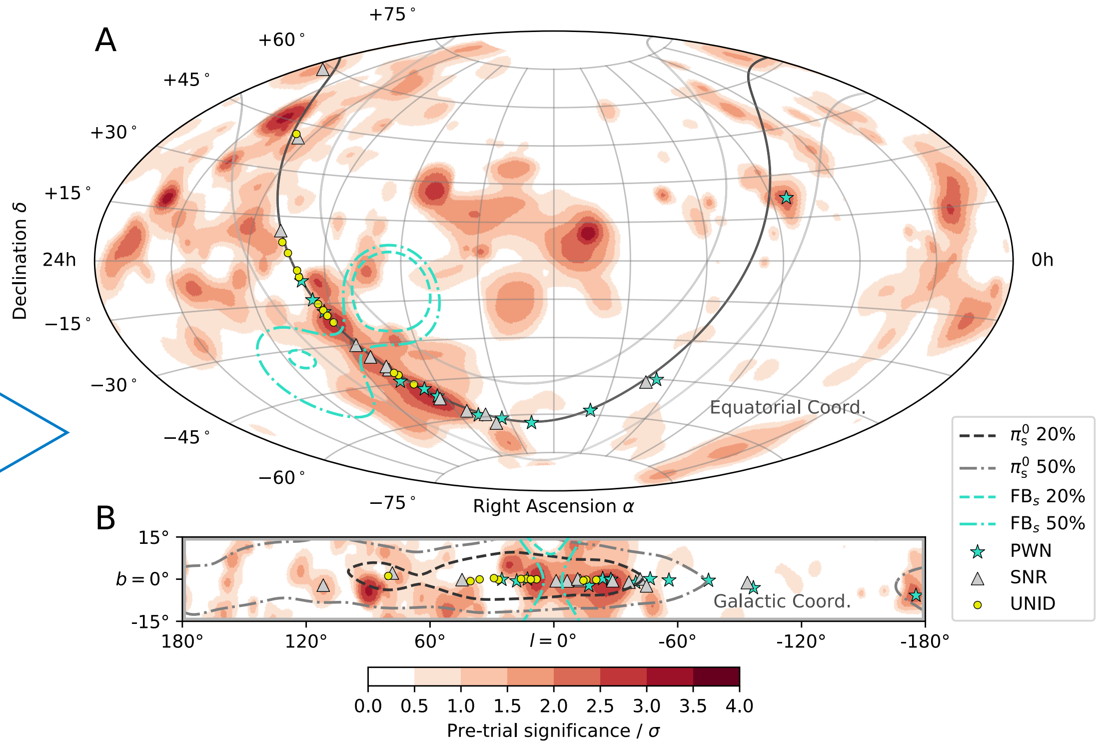
More domain knowledge

Hybrid reconstruction with CNN-backed likelihood

Train a mixture density network to predict time-delay PDFs





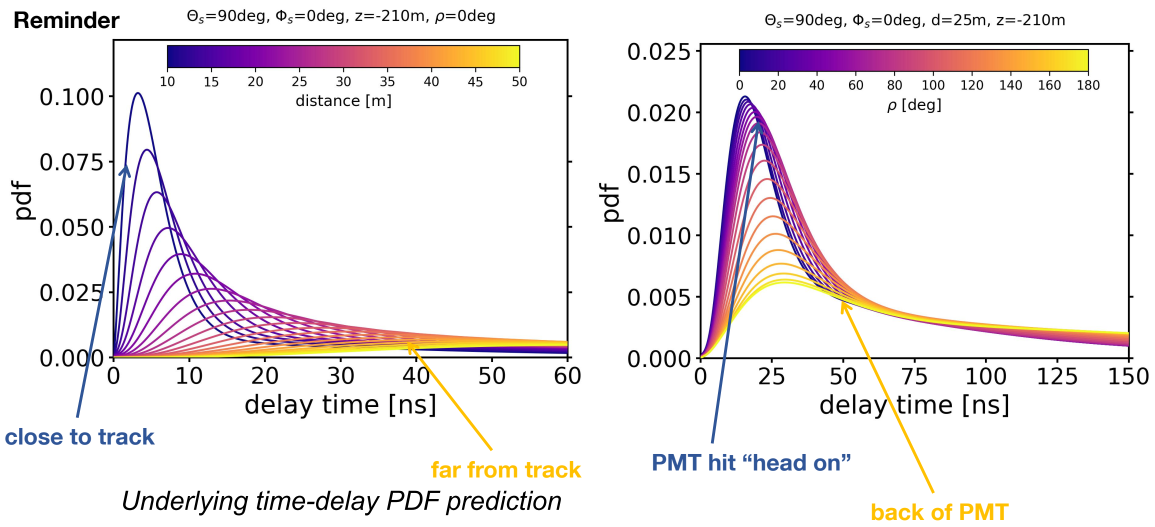


First detection of high-energy neutrino emission from the galactic plane
https://doi.org/10.1126/science.adc9818

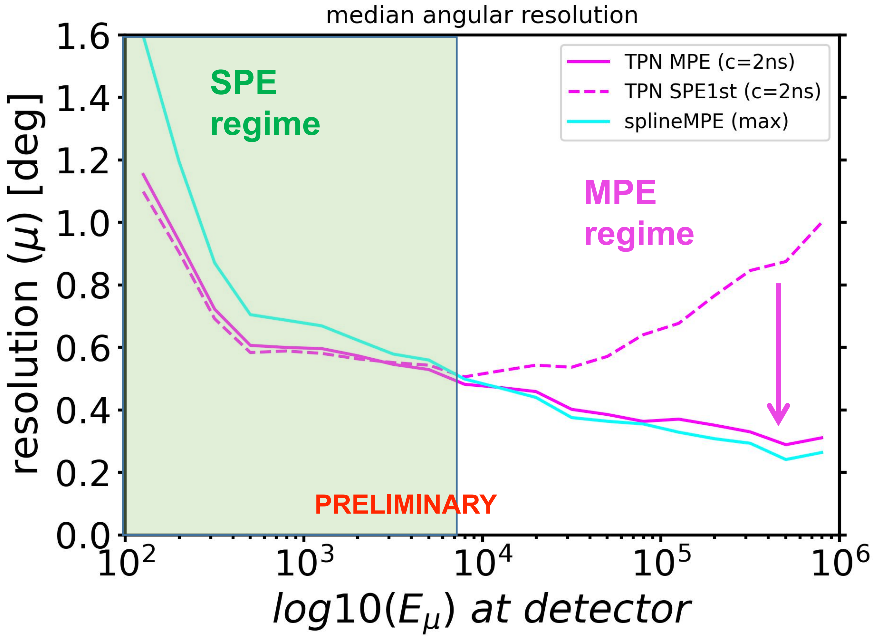
DESY.

What about tracks?

- Kilometer-long tracks are the most important sensitive channel for [optical] neutrino telescopes, **but**
- CNN-based point predictors have **worse** resolution than classical maximum-likelihood reconstruction for track events
- Hybrid likelihood backed by a mixture density network is likely the way forward here, too
- (Work continues)



Underlying time-delay PDF prediction



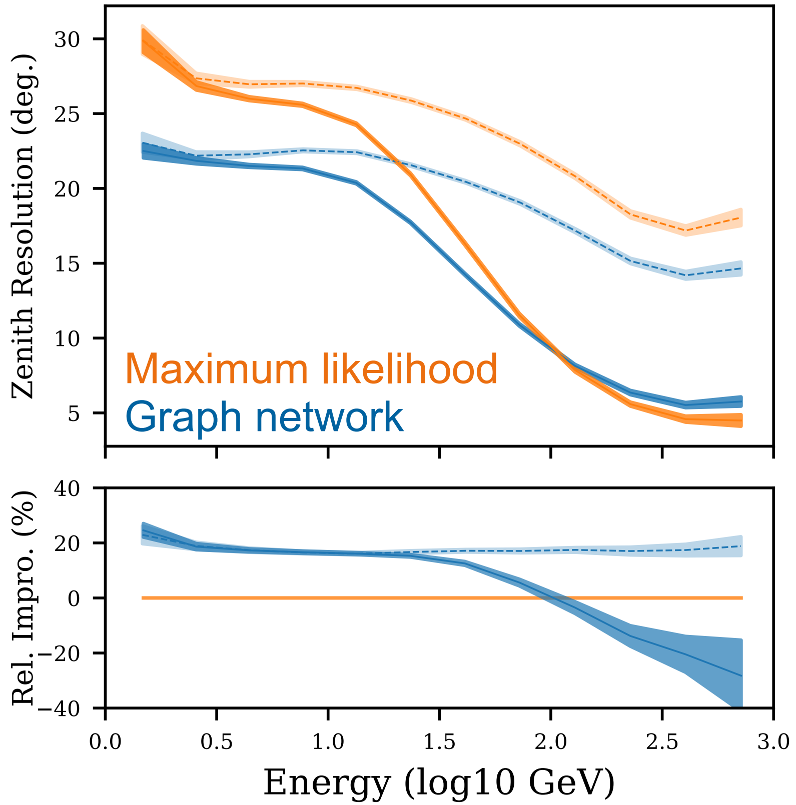
First example of ML-assisted track reconstruction beating legacy method
H. Niederhausen, M. Jansson, R. Babu, B. Henke, M. Nisa

What about low energies?

- Most sensitivity below ~300 GeV comes from DeepCore infill array (soon: IceCube Upgrade)
- Special challenges: very sparse data, noise, **even more irregular geometry**
- **Graph CNNs**: convolutions with arbitrary (learnable) neighbors
- Graph networks outperform previous maximum-likelihood method
- Multiple applications: noise suppression, segmentation, classification, reconstruction

GraphNeT
Deep Learning for Neutrino Telescopes

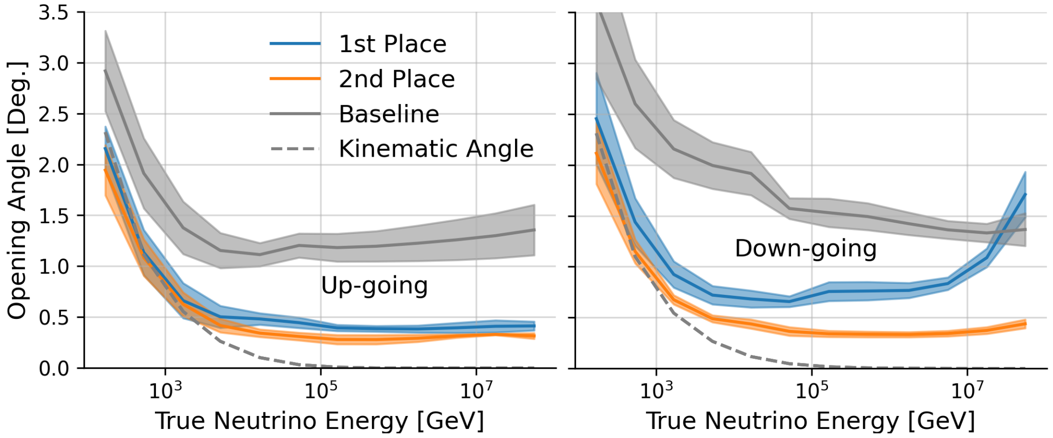
https://github.com/graphnet-team/graphnet



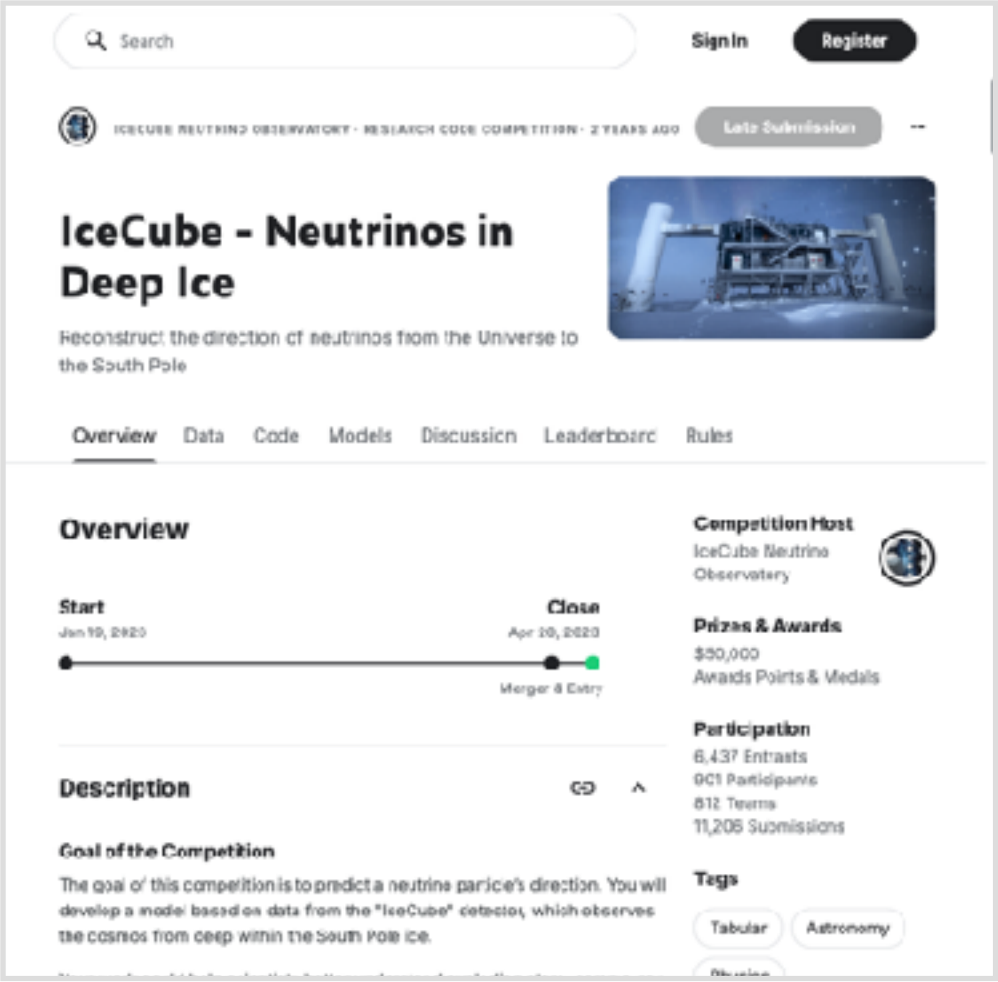
https://doi.org/10.1088/1748-0221/17/11/P11003

IceCube Kaggle competition

- Public competition to improve IceCube reconstruction
- Provided training data, documentation, baseline solution
- Ran in early 2023, generated 11k submissions from 900 participants
- 1st and 2nd-place solutions implemented in GraphNeT



https://arxiv.org/abs/2501.03817



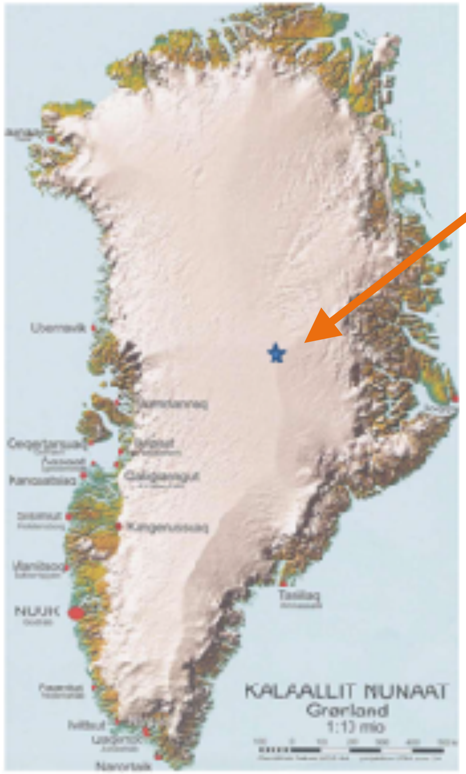
Led by P. Eller (TUM)
https://www.kaggle.com/competitions/icecube-neutrinos-in-deep-ice
https://doi.org/10.22323/1.444.1609

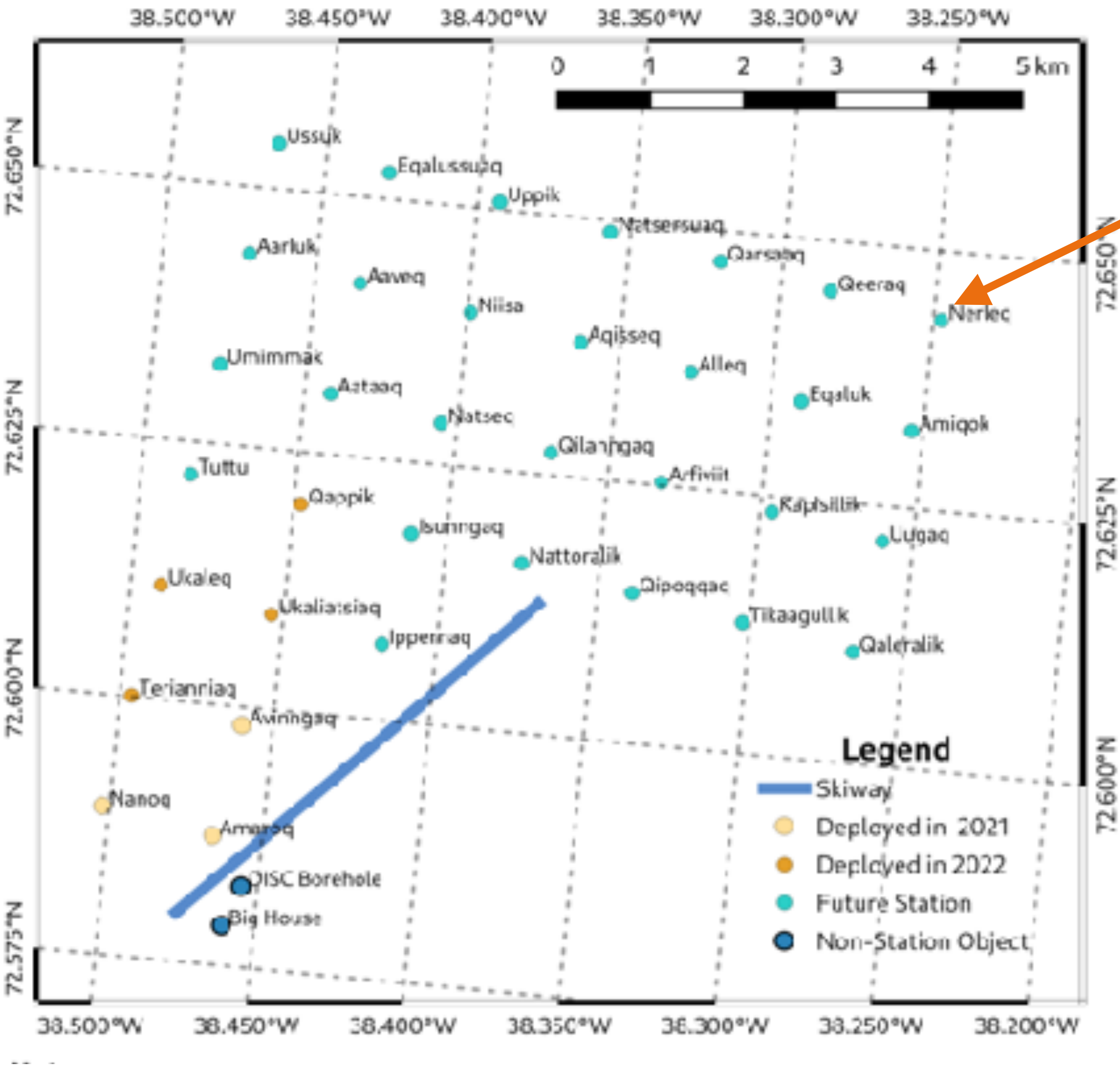
cf. https://www.kaggle.com/c/trackml-particle-identification
cf. https://www.kaggle.com/competitions/g2net-gravitational-wave-detection

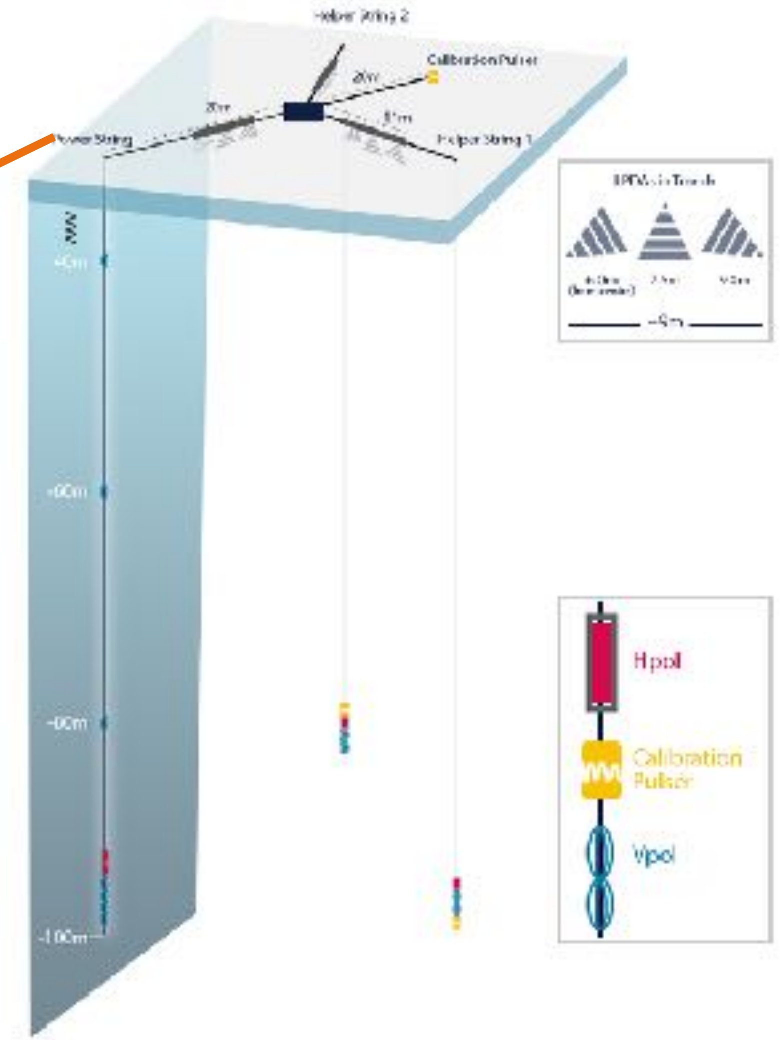
RNO-G

The Radio Neutrino Observatory in Greenland (RNO-G)

The first large scale implementation







ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Machine Learning for Radio Detection

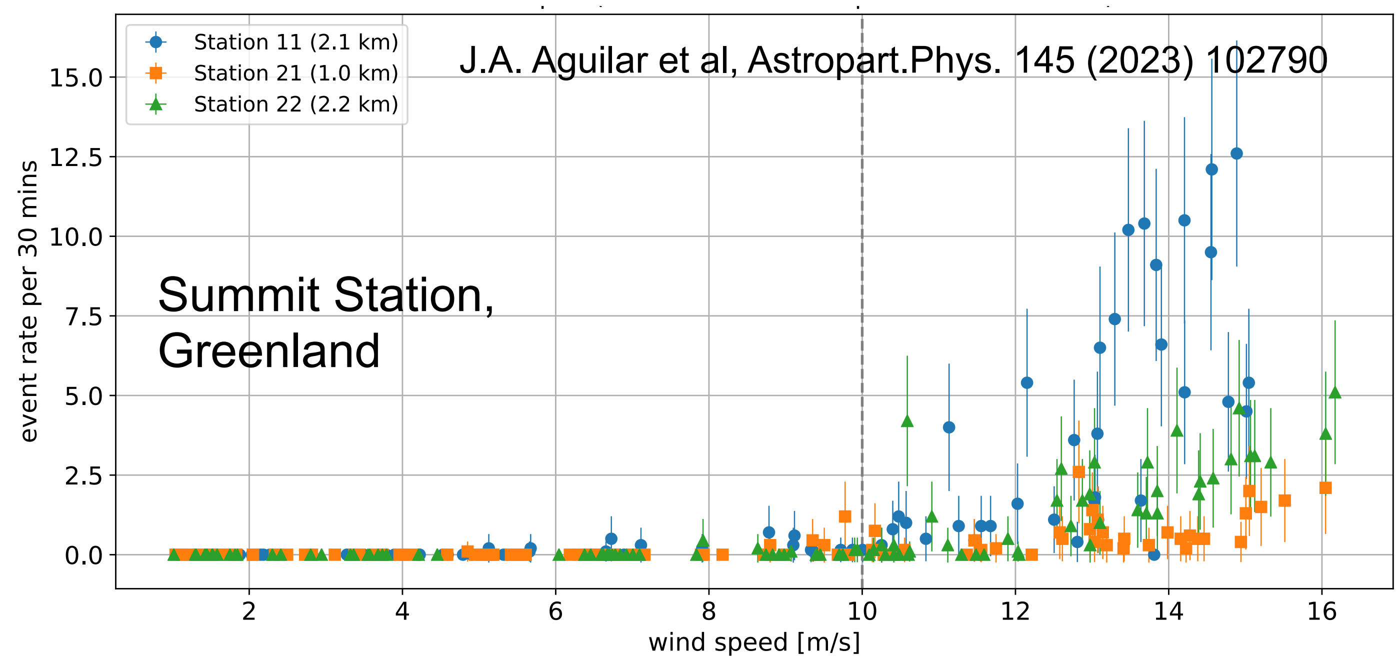
Mostly used for two things

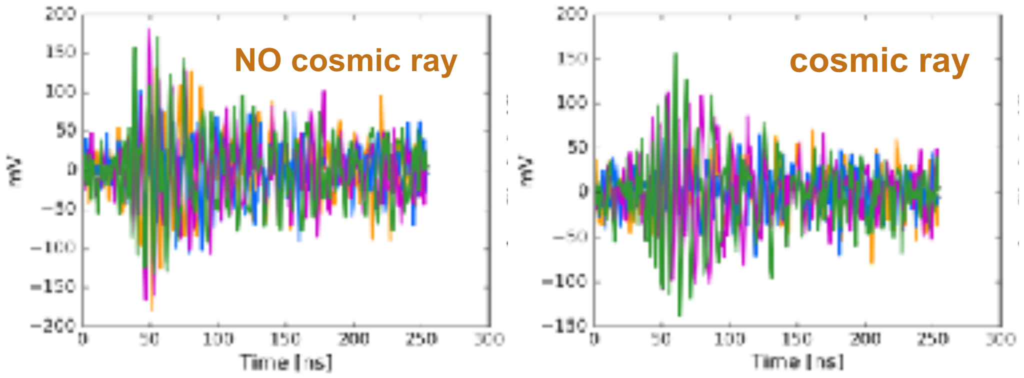
- Background
  - Our triggers are 99.999% useless (little pulses from thermal noise, airplanes, humans, wind, ….)
  - Classify backgrounds, understand backgrounds, mitigate them in instrument
  - Smarter triggering (reduce background at trigger level)

- Reconstruction
  - Signal propagation in ice is complicated and ice not perfectly understood
  - Use ML to reconstruct signals (a bit hypothetical at this point, because not radio emission from a neutrino has been detected)

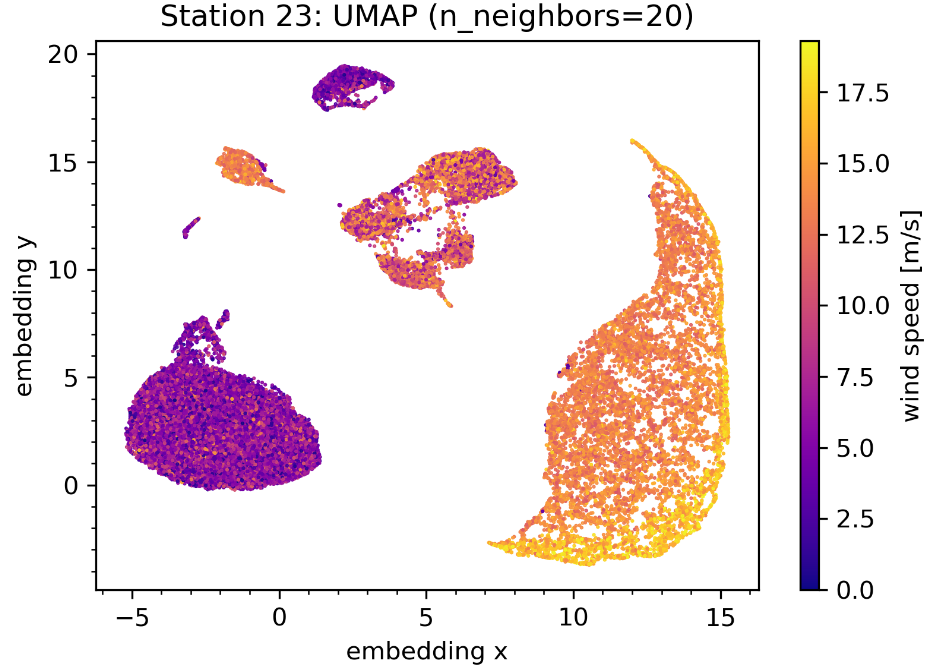
Wind noise tagging for RNO-G

- Train variational autoencoder to describe individual waveforms
- Wind-triggered events cluster in latent space





Noise waveforms are very similar to real triggers, but can be distinguished



P. Laub, MSc FAU Erlangen

Summary

- Machine learning is becoming a workhorse for difficult reconstruction problems in IceCube
- Will likely play a larger role in RNO-G as it grows
- Interesting opportunities for outreach via open data
- Some common challenges:
  - Irregular spatial data
  - Sparse, variable-sized data
  - Industry-standard solutions often need adaptation to our problem domain
  - No calibration source or off-beam data: need to train on simulation

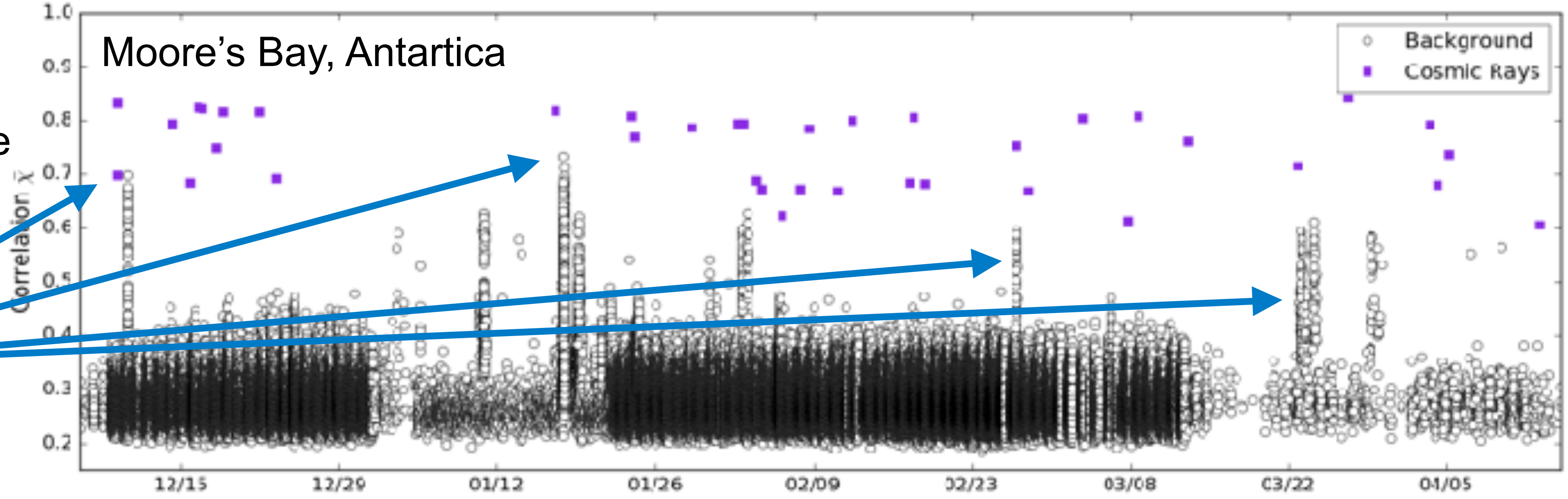
Backup

Wind and radio detection

Background events pose a threat to neutrino detection

ARIANNA Coll. (AN)., Astropart. Phys. 90 (2017) 50

No weather information at site
But
bad weather
at Mc Murdo

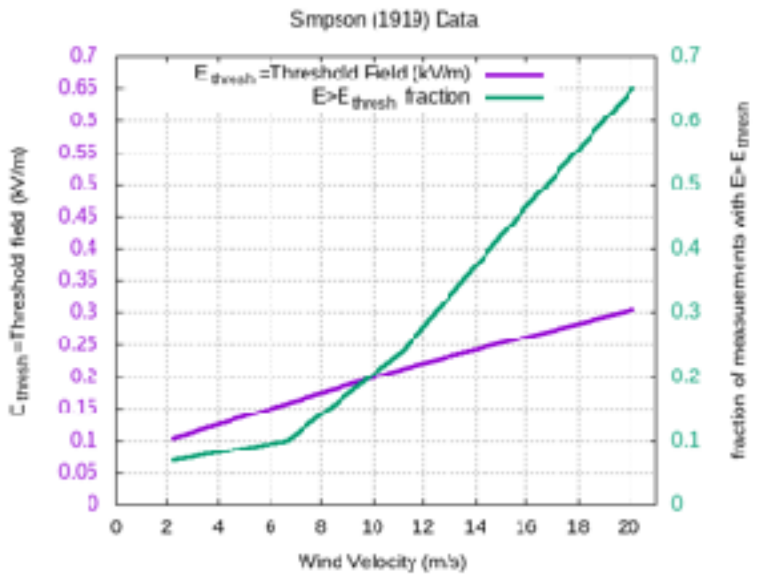


- During periods of bad weather the ARINNA experiment saw an increase in background mimicking neutrino and cosmic ray signals
- Hypotheses: problems with our power or communication system in bad weather

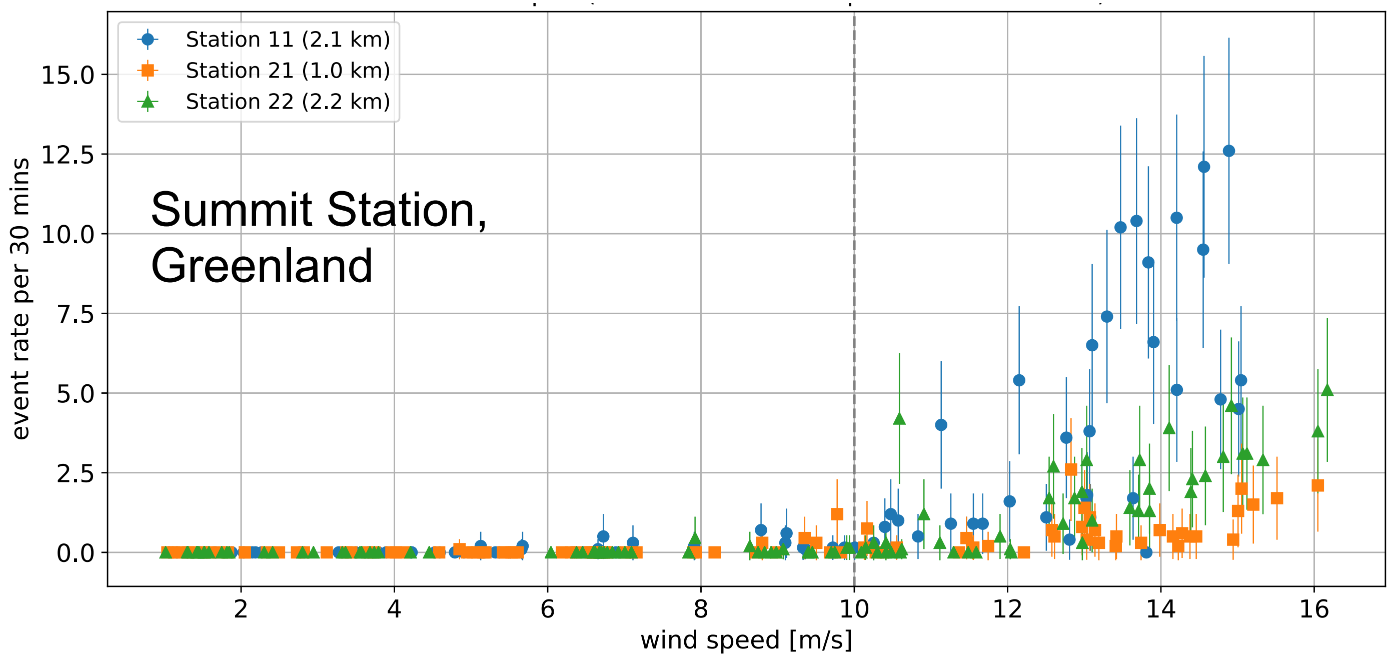
Triboelectricity

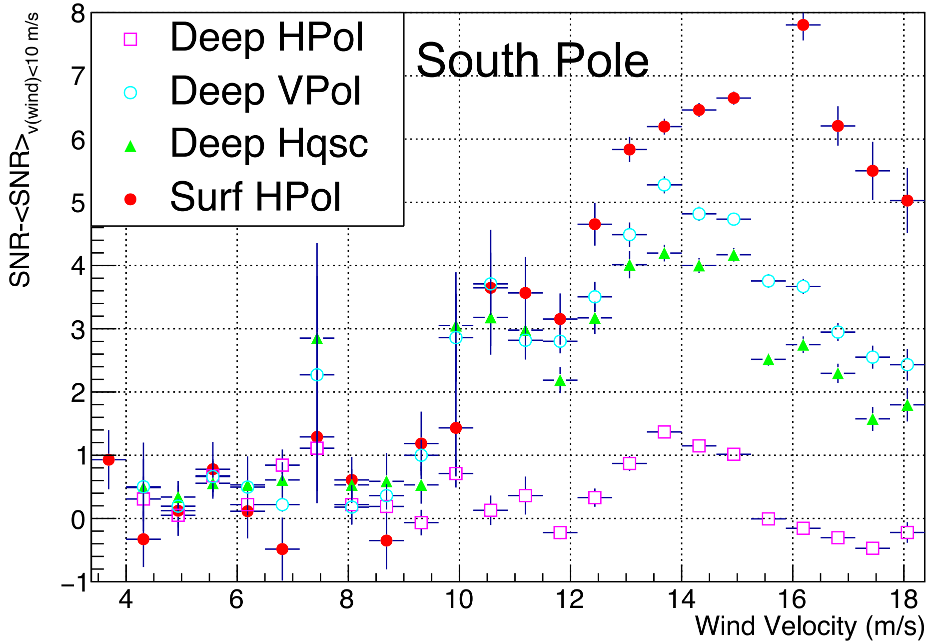
But the same all around the world

- All prototypes for neutrino detectors see and increase in triggers as function of wind-speed
- Anecdotal evidence from radio glaciologists: If the weather is bad, we just don't go out, the data is bad anyway …
- Even the expedition from Scott to South Pole saw this already



J.A. Aguilar et al, Astropart.Phys. 145 (2023) 102790



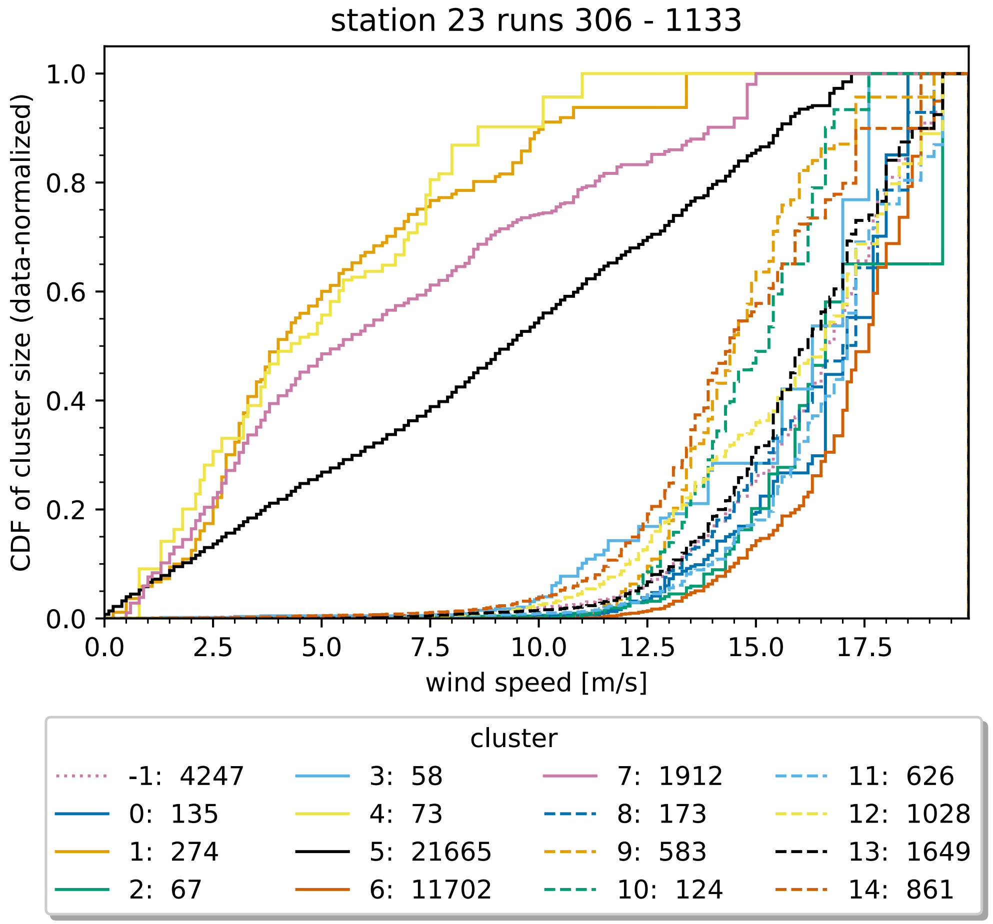


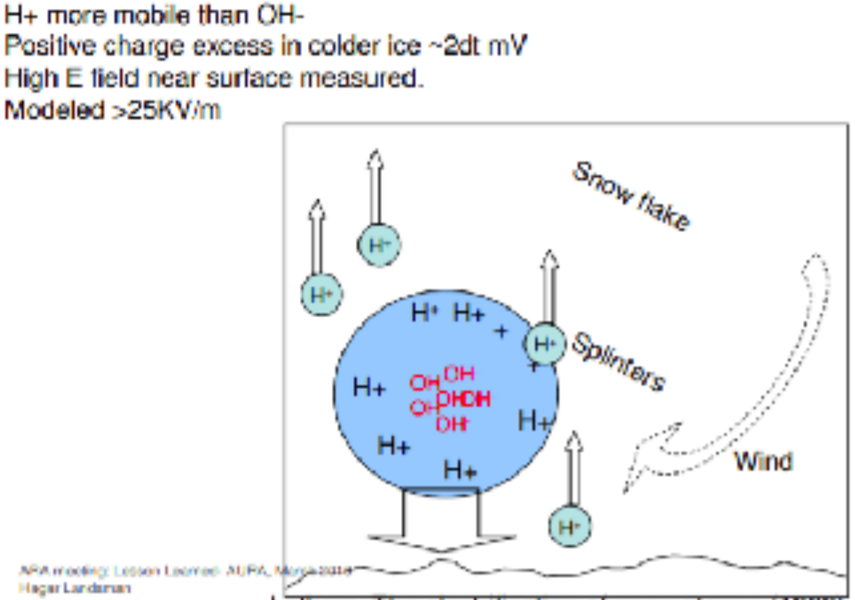
Triboelectricity

But what actually causes it?

Master Thesis, P. Laub, FAU

- If we want to make sure that we can reduce these backgrounds, we need to be able to model them
- Lacks & Shinbrot (2019): *We may never be able to model triboelectric charging*
- Then we need to understand better, what causes them and what they correlate with





Latham, The electrification of snow storms (1963)

Clustering using Variational Auto Encoders

There are clearly different event characteristics

So we probably need more than just wind