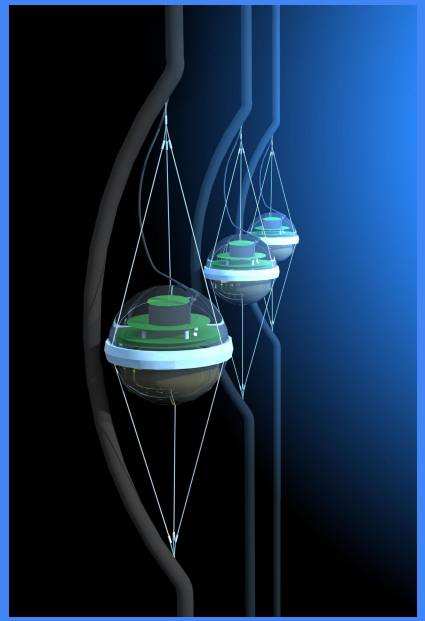
Deep learning in the IceCube detector status - prospects - challenges



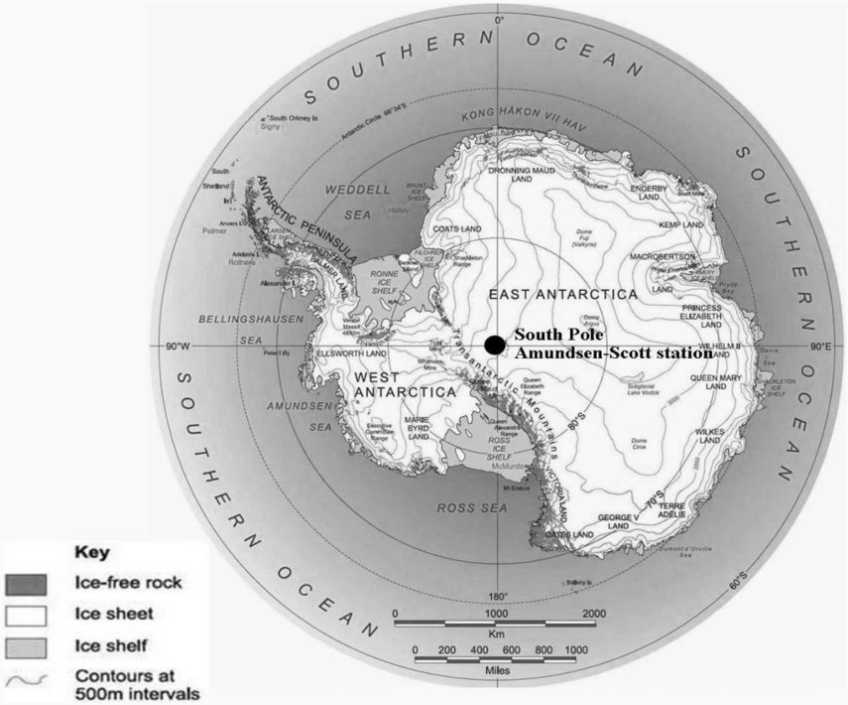
IceCube

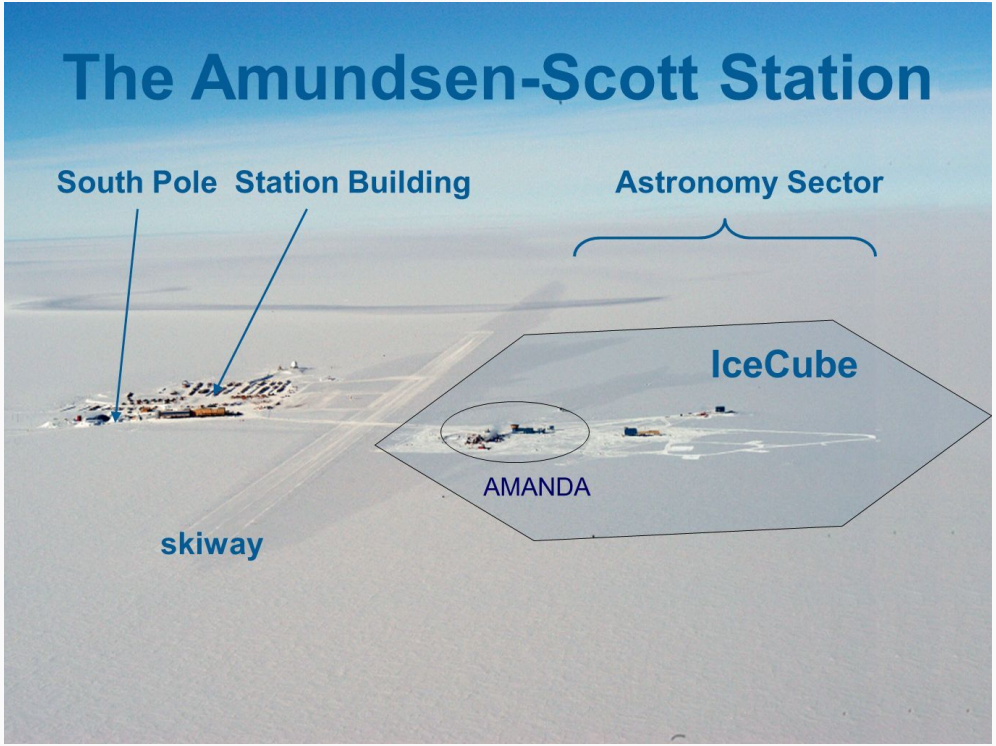
CARL TRYGGERS STIFTELSE
FÖR VETENSKAPLIG FORSKNING

UPPSALA UNIVERSITET

Thorsten Glüsenkamp, 16.6. 2023

IceCube - the detector





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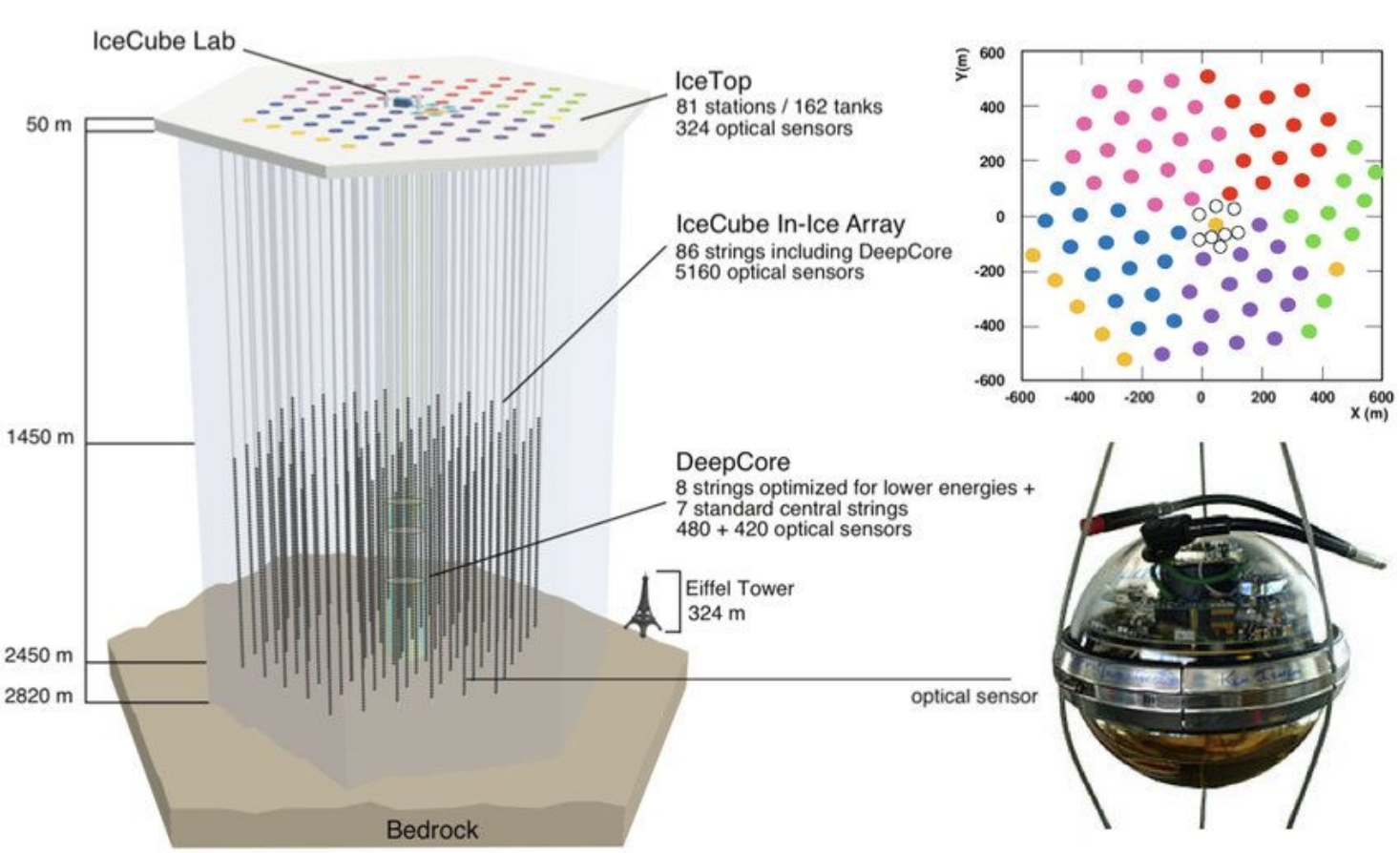
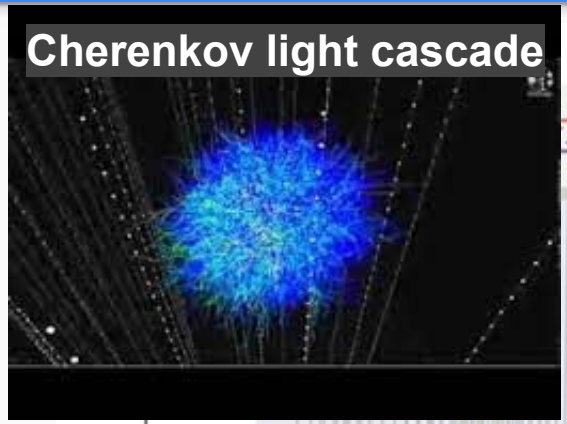
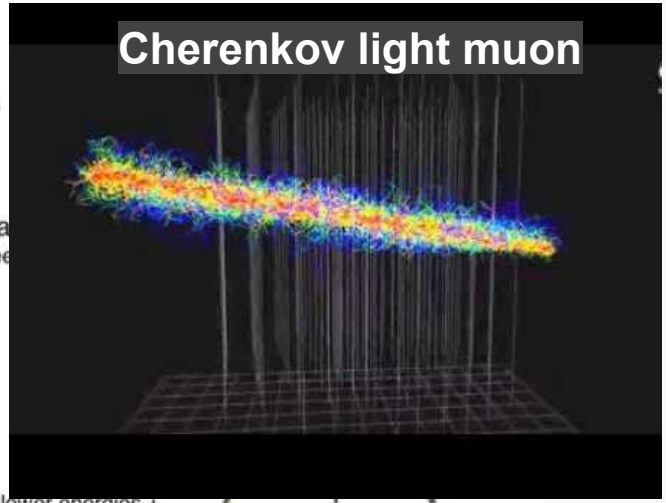


Digital Optical Module

IceCube - the detector

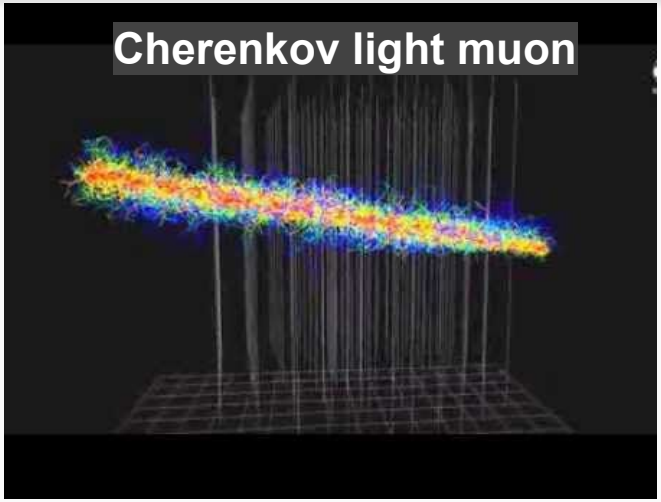




Digital Optical Module

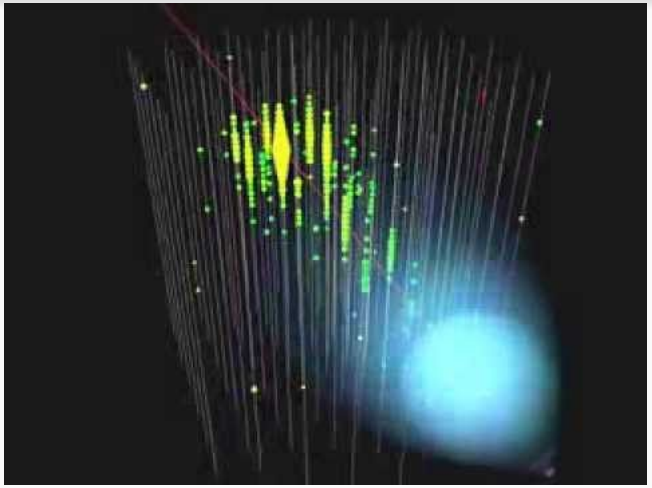
velocity of charged particle larger than speed of light in ice (~0.75 * c) -> emission of Cherenkov light

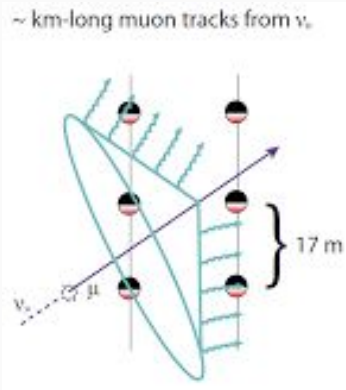
IceCube - the detector



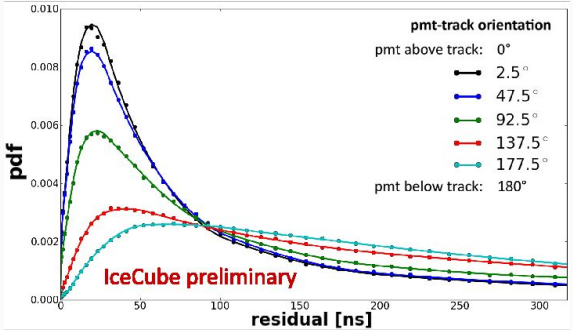
Blob size:
Number of photons

Blob color:
Photon arrival time

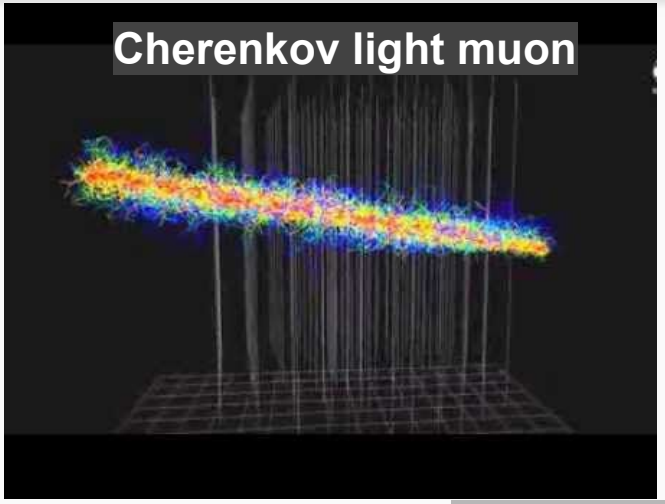




Track orientation determines photon arrival PDF



IceCube - the detector



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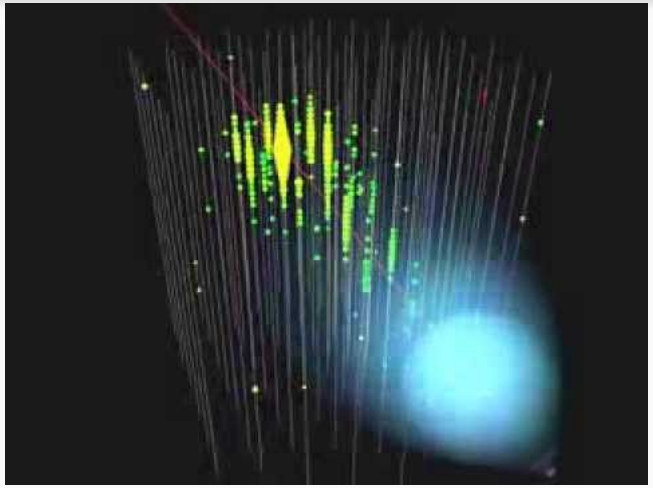
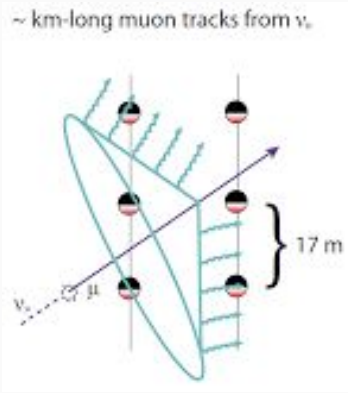
Blob color:
Photon arrival time

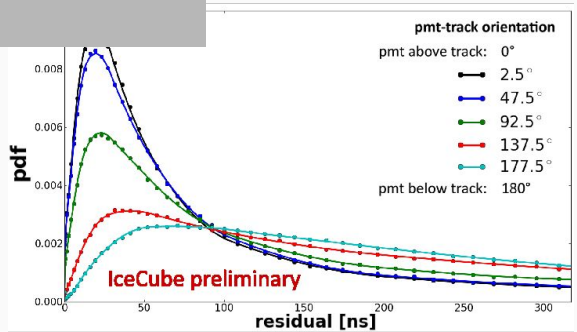


Use data + algorithm (typically likelihood Ansatz) to determine parameters



$$L_{ext} = \prod_{j}^{N_{DOM}} \frac{e^{-\lambda_j} \lambda_j^{q_j}}{q_j!} \prod_{i}^{N_{hit}} [p_j(t_i)]^{q_i},$$

Energy, Direction, …



The first point source - TXS 0506+056

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[Previous | Next | ADS]

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

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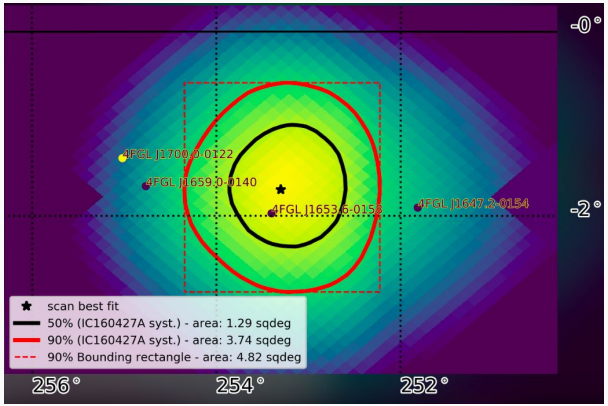
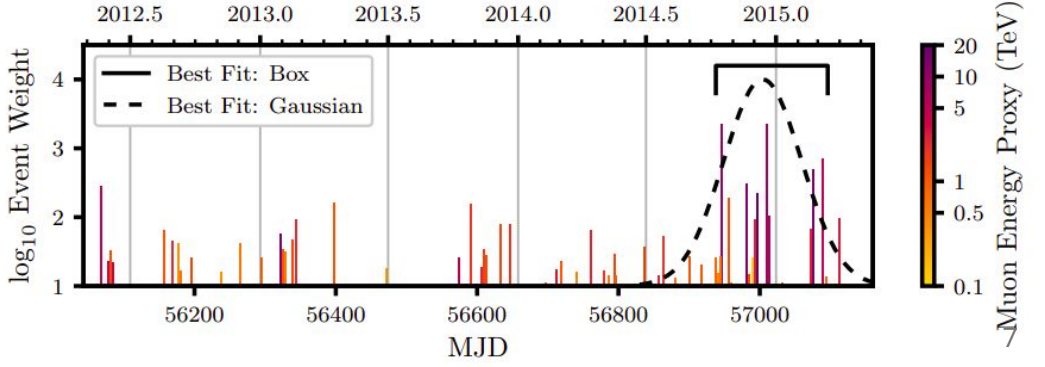
*on **28 Sep 2017; 10:10 UT***
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

Neutrino coincident with gamma rays (2017)



Historical data at same loc. shows excess in 2014/2015



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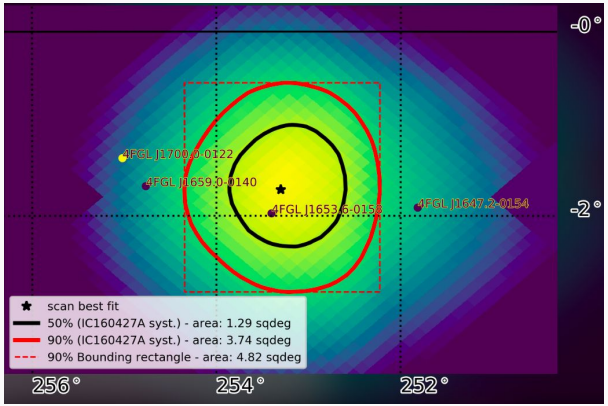
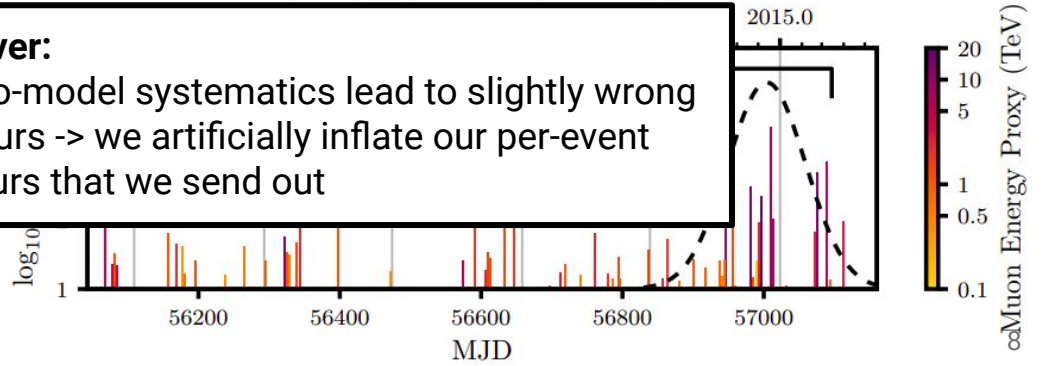


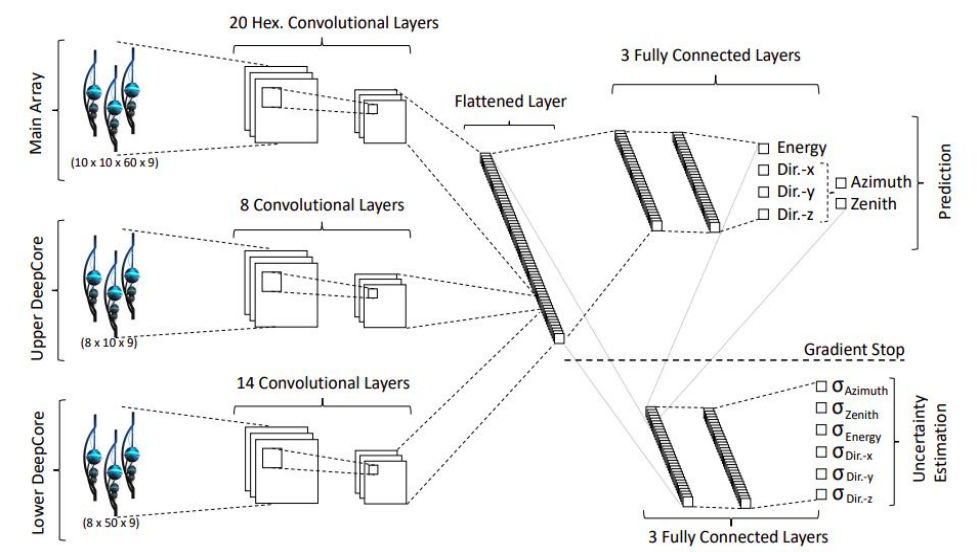
Historical data at same loc. shows excess in 2014/2015

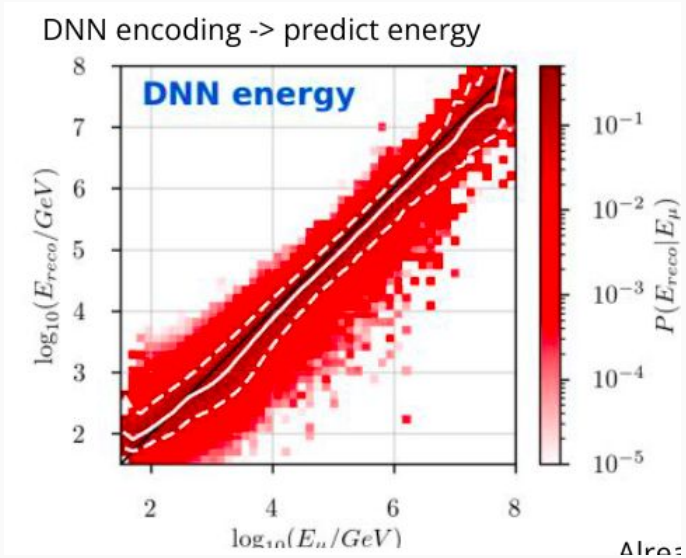
However:
hard-to-model systematics lead to slightly wrong Contours -> we artificially inflate our per-event contours that we send out



New track processing in 2021

Neural-network based muon energy prediction
was part of processing





New track processing in 2021 -> some changes in contours

Neural-network based muon energy prediction
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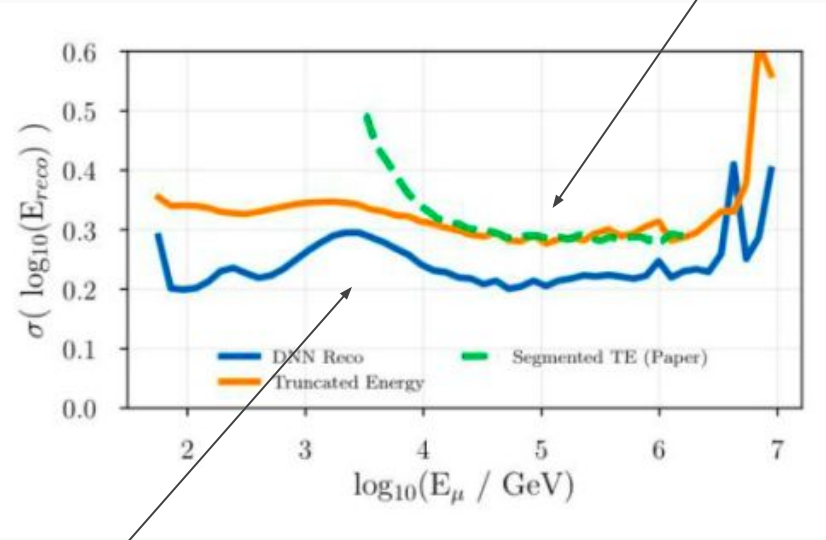
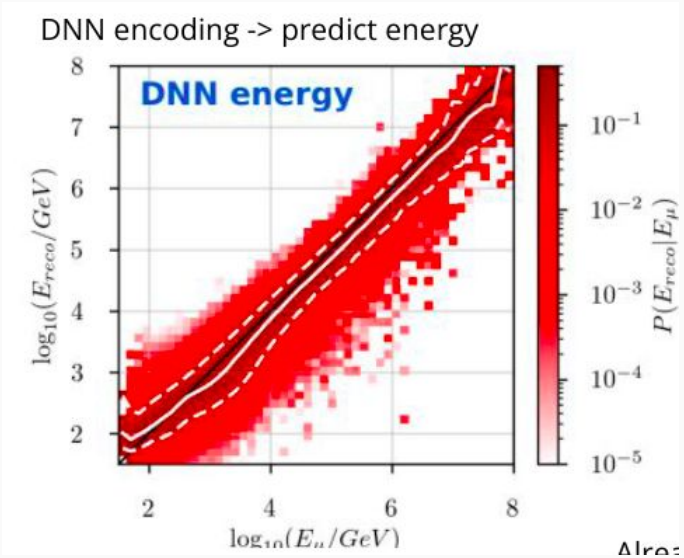
Likelihood based



Neural network prediction

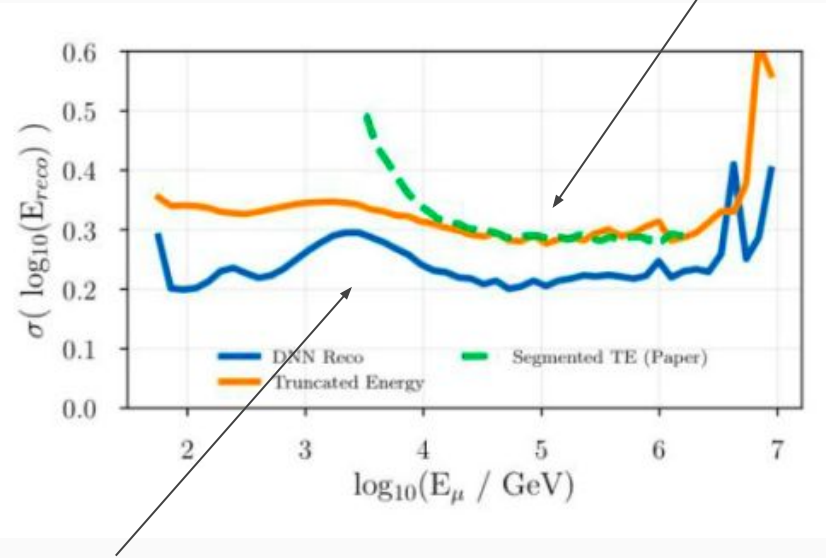


New track processing in 2021 -> some changes in contours

Neural-network based muon energy prediction was part of processing

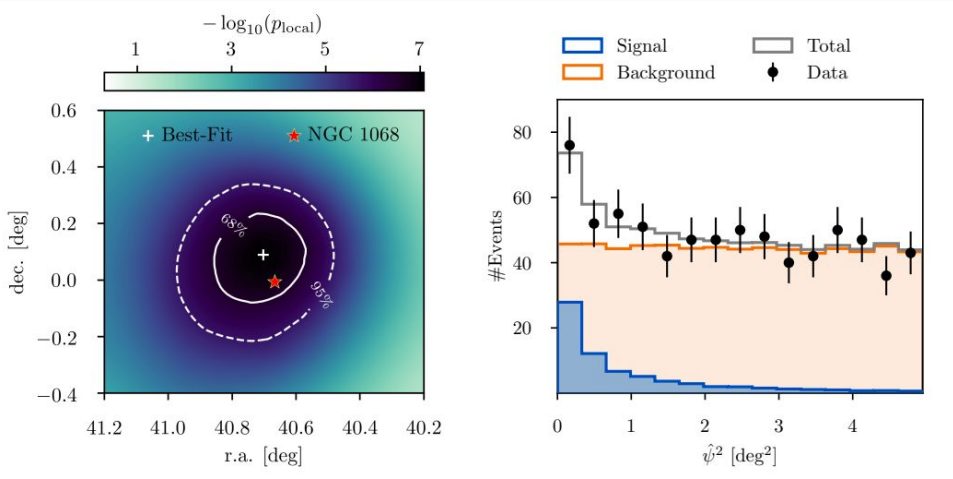
\+ improved likelihood formalism

Likelihood based

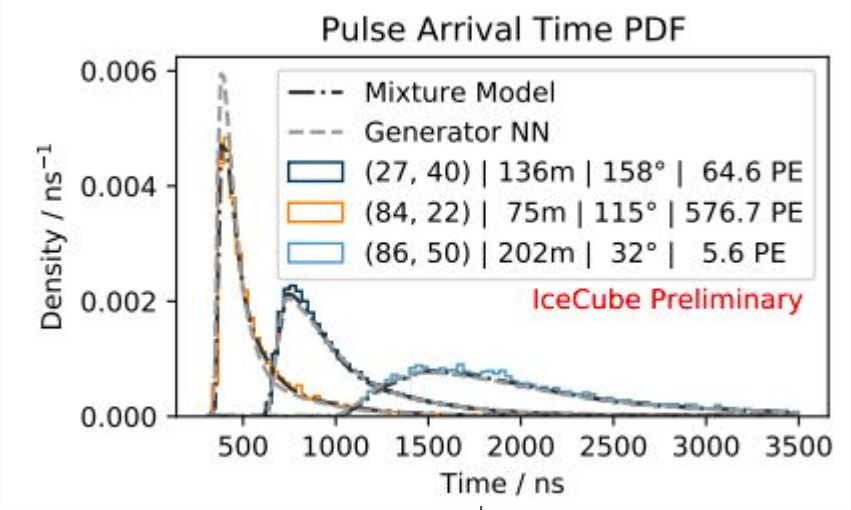


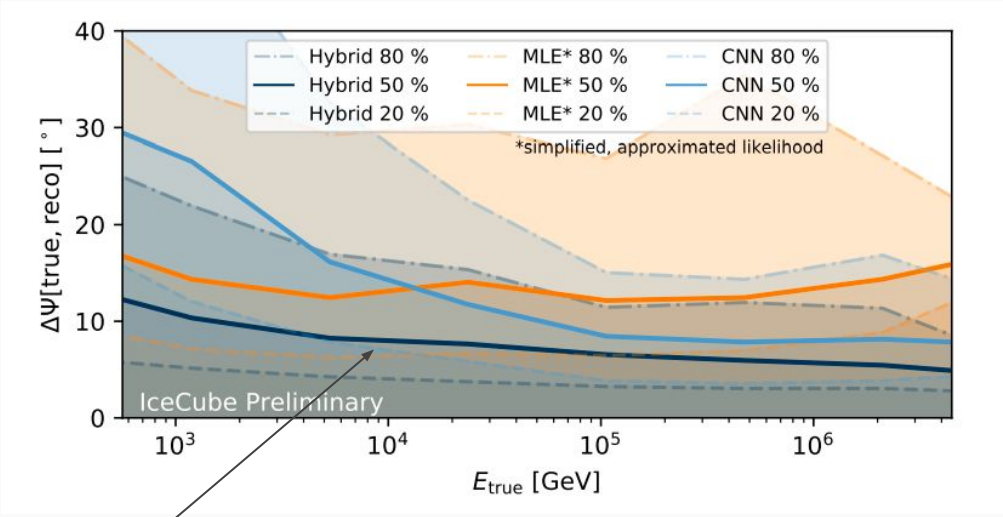
Neural network prediction

Frist time-independent point source: NGC 1068 (Science, Nov. ‘22)



Neural-network based likelihood prediction: v_e direction reconstruction



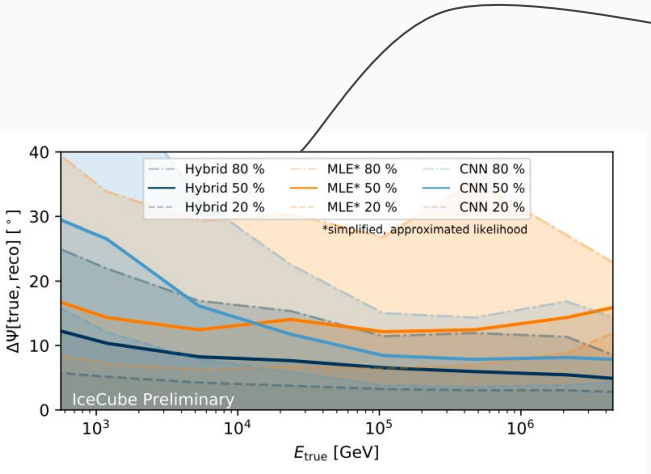


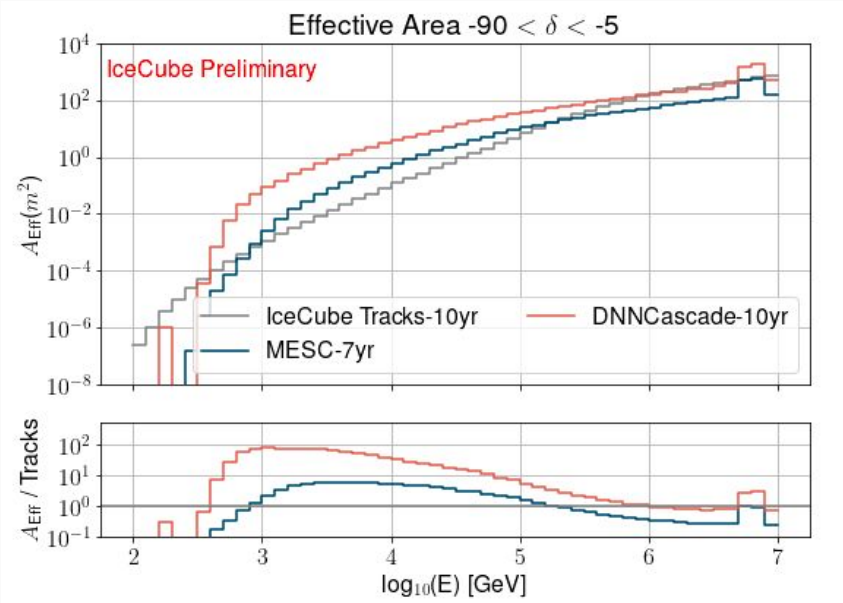
$$\mathcal{L}_{\text{event}}\left(\vec{x}=\{\vec{c},\vec{t}\}\,|\,\vec{\xi}\right)=\prod_{d}^{D}\text{Poisson}\left(\sum_{i}^{N_d}c_{d,i}\,|\,\lambda_d\left(\vec{\xi}\right)\right)\cdot\prod_{i}^{N_d}P_d(t_{d,i}\,|\,\vec{\xi})^{c_{d,i}}$$

PoS-ICRC2021-1065

Neural-network based likelihood prediction: v_e direction reconstruction

Deep Learning **crucial** in a new analysis pipeline (**see press conference on June 30 for more details on result**)





Multiple deep learning
Reconstructions in event selection
-> **Factor X 10-100** more signal events than preceeding event selections at low energies

Another promising direction: conditional normalizing flows

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Per-Event contours often systematically wrong…
Is there a better way?

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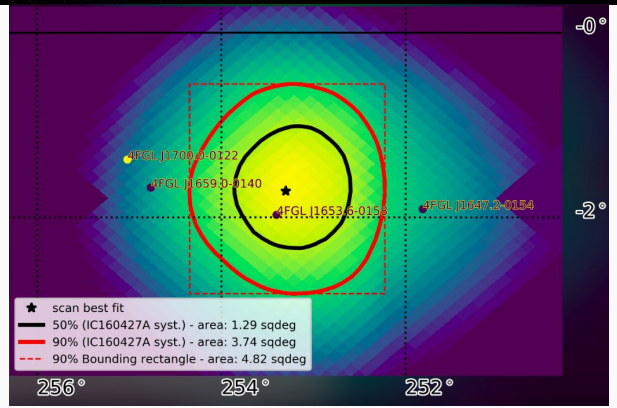
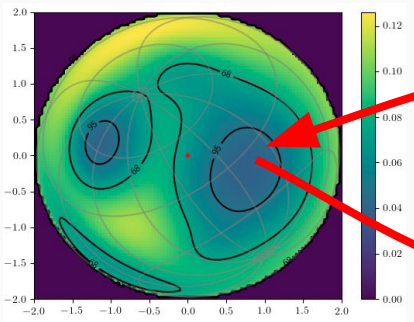
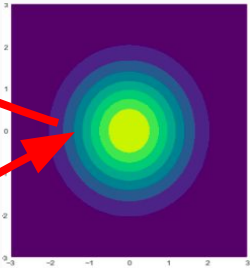


$$p_\theta(x|y) = p_0(f^{-1}_{g_\theta(y)}(x)) \cdot |\det J^{-1}_{g_\theta(y)}(x)|$$



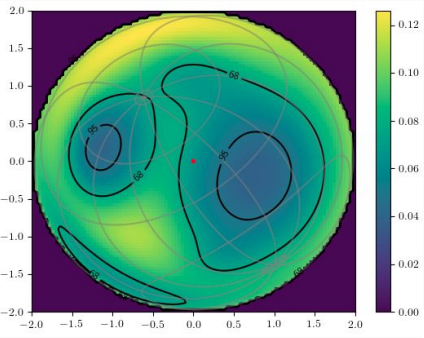
f(x)

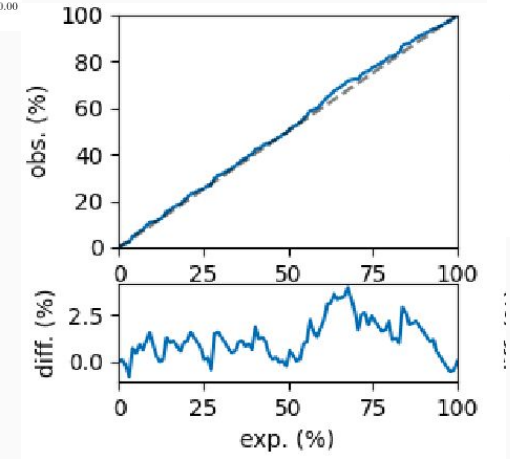
f^-1(x)

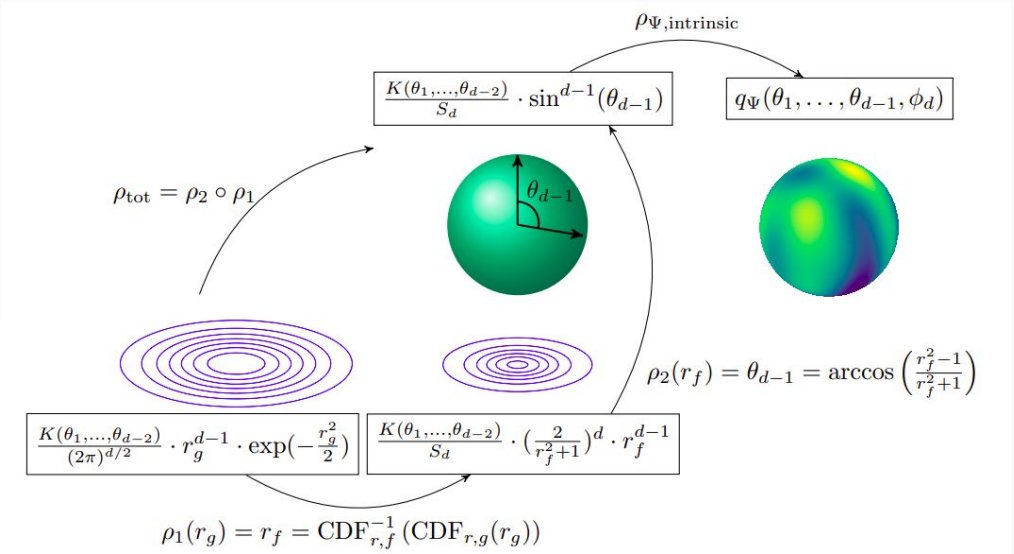


Another promising direction: conditional normalizing flows

- Coverage can be checked **without numerical integration**
  (for arbitrary shaped contours, including distributions on the sphere)



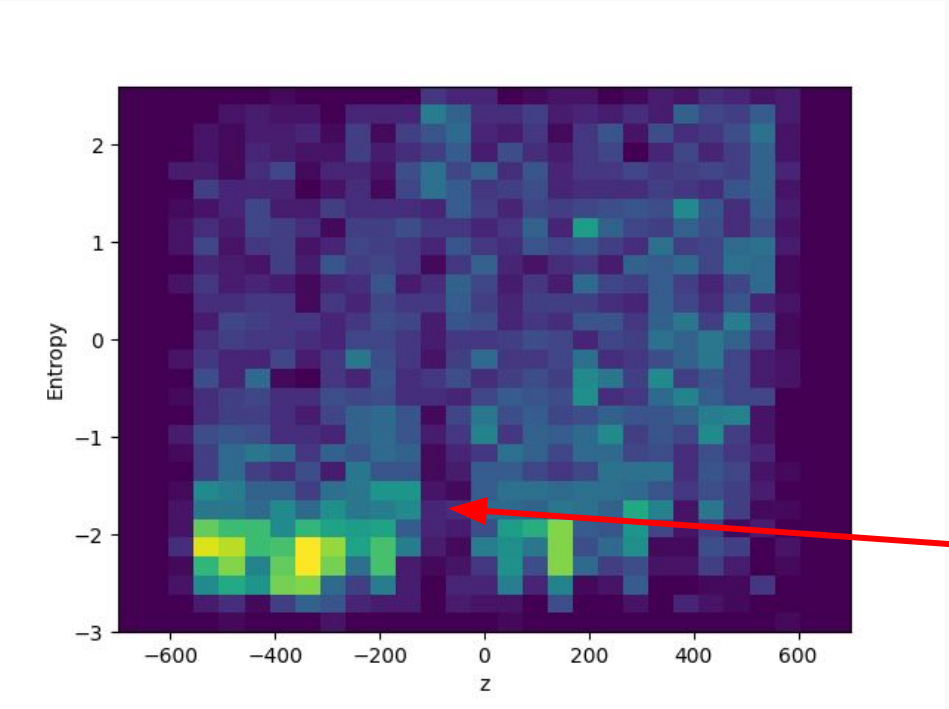


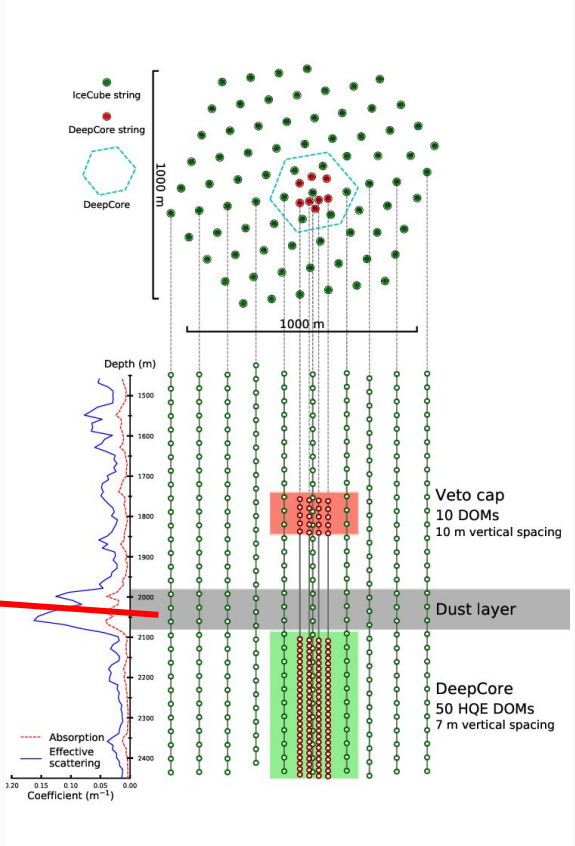


arXiv:2008.05825

Another promising direction: conditional normalizing flows

- The normalizing flow **picks up ice structure** (we have dust layers in the Antarctic ice)





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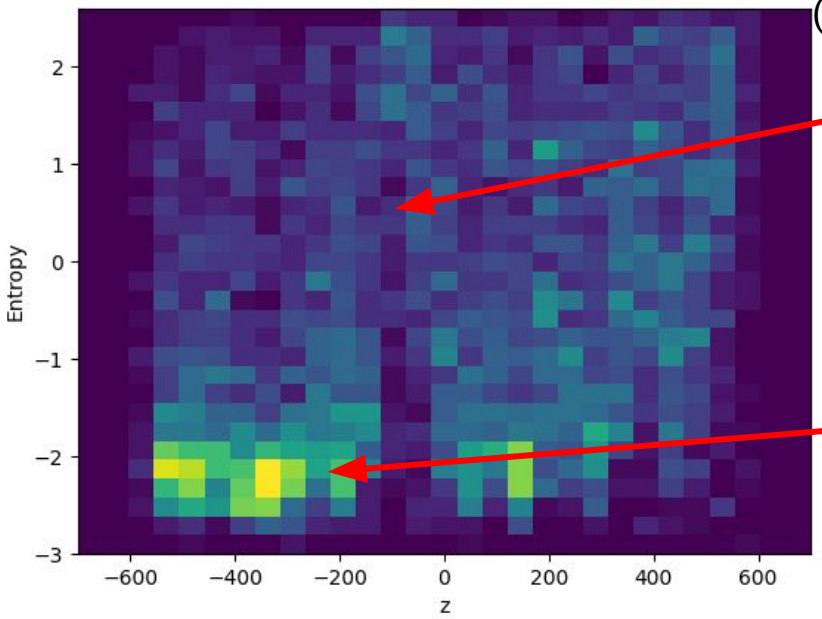
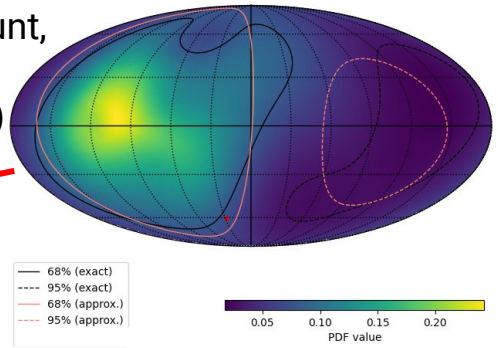
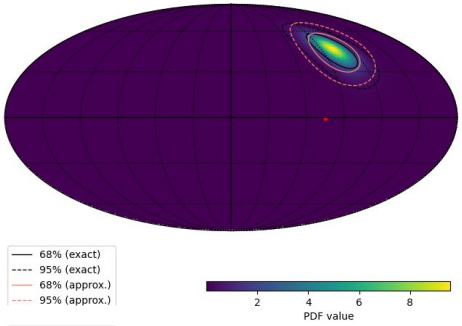


Low photon count,
High entropy
(large contours)



high photon count,
low entropy
(small contours)



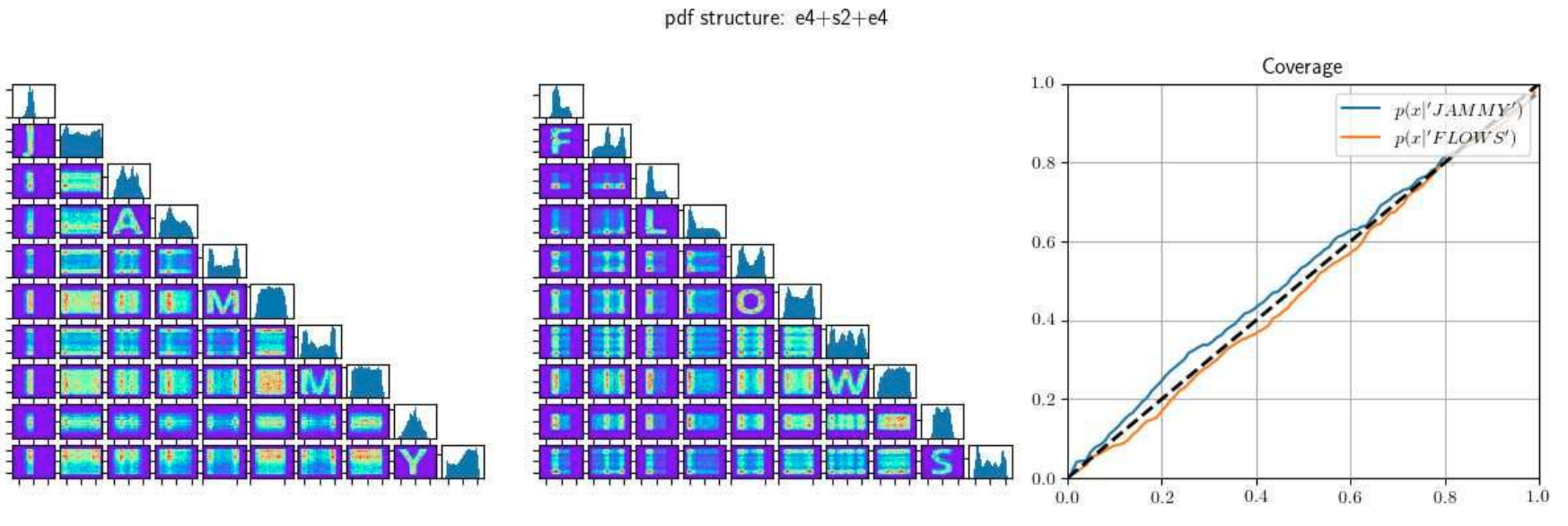
jammy_flows

https://github.com/thoglu/jammy_flows

import jammy_flows

pdf=jammy_flows.pdf("e4+s2+e4", "gggg+n+gggg")

"A generic pdf on a tensor product of manifolds"

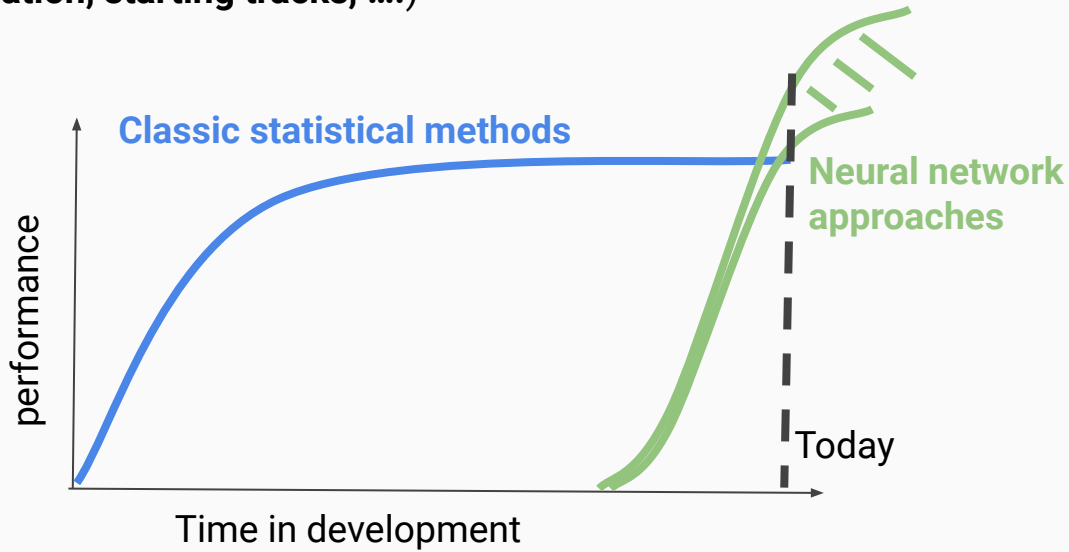


Summary

- More than 80% of technical effort in IceCube by now involves neural network and deep learning
- Already offers faster and more precise reconstructions for a large number of use cases (**cascade-type topologies, energy estimation, starting tracks, ….**)

Classical llh approaches run into bottleneck
(20+ years of history in IceCube/Amanda)

New Machine learning methods
(only ~2-3 years of investigation)
already better in many areas



New physics results and improvements of existing results guaranteed in the next years !