UPPSALA UNIVERSITET

# Deep Learning Reconstruction of in-ice Radio Neutrino Signals

Astroparticle School 2024, Obertrubach-Bärnfels

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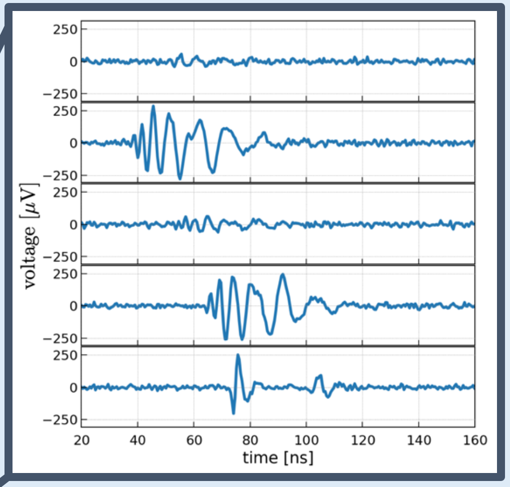
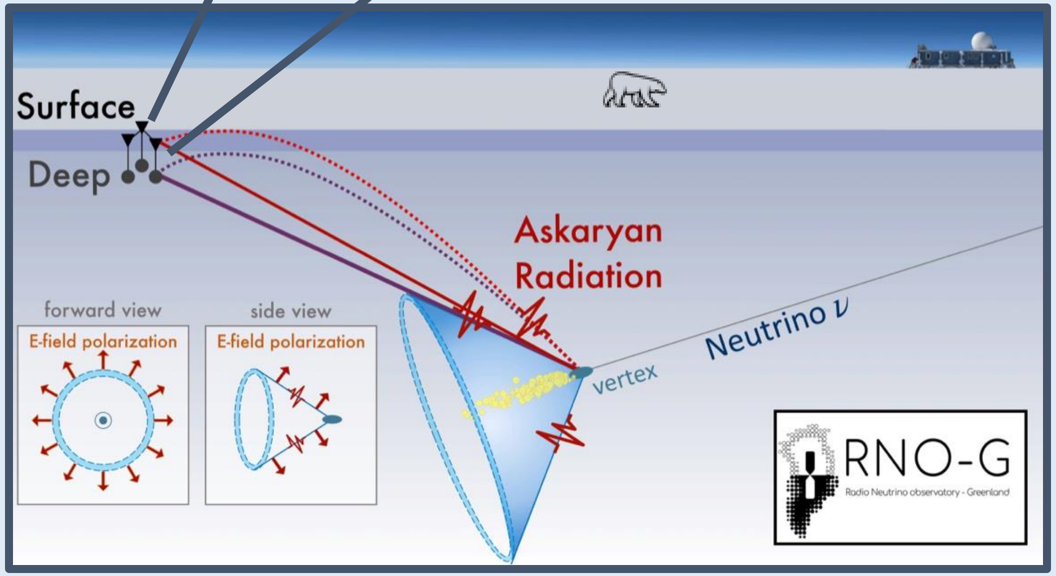
# Radio Detection of Cosmic Neutrinos

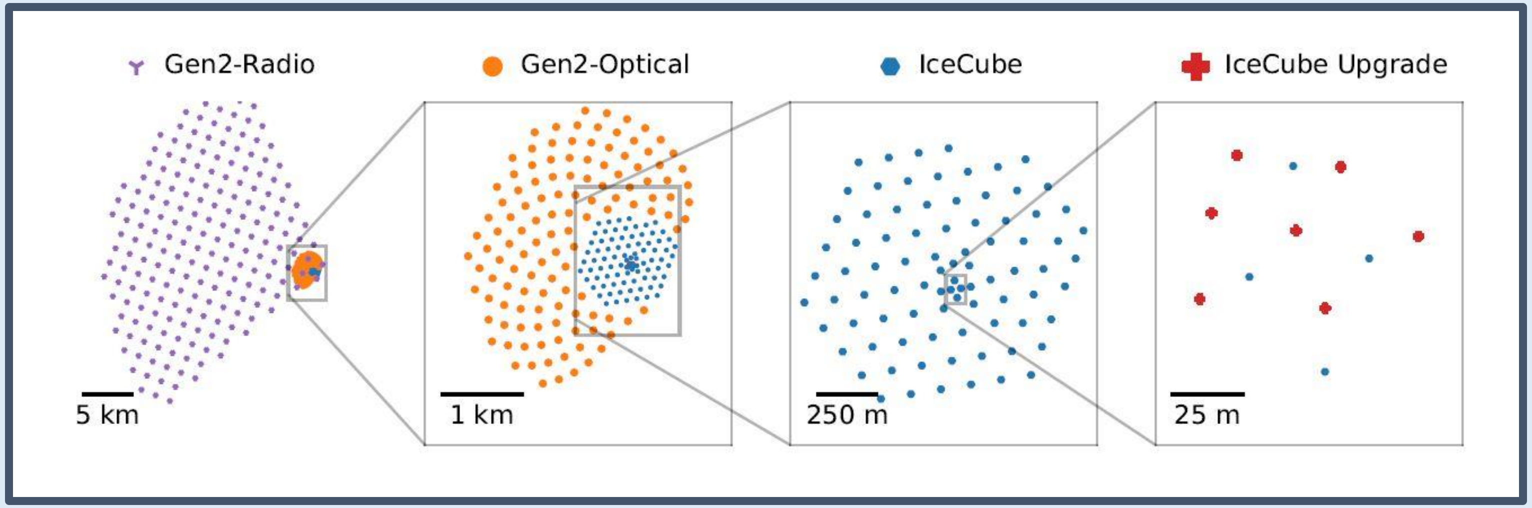
- The neutrino collides with a nucleus in the ice
- The collision induces a particle shower
- The particle shower creates a radio pulse via Askaryan emission
- The radio pulses propagate through the ice until reaching an antenna
- The pulse is measured by one or multiple radio antennas



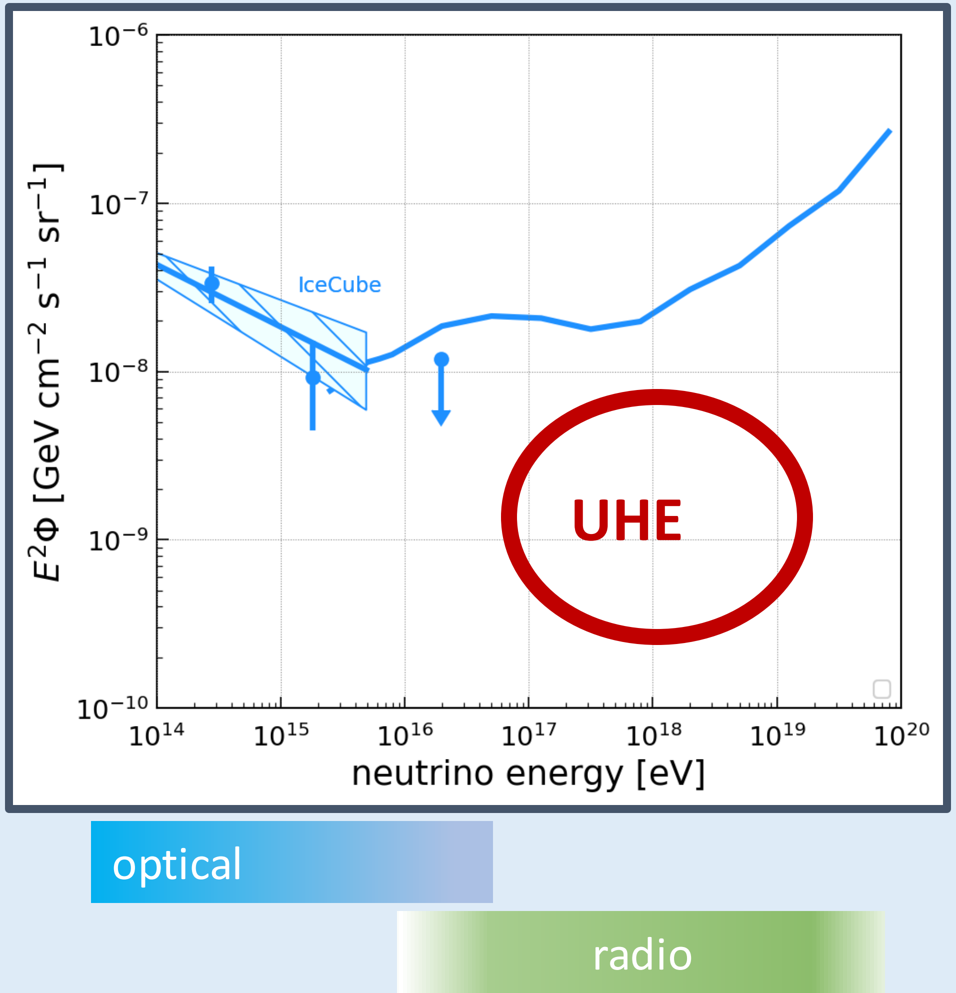



# IceCube - Gen2 Radio

- Is planned to instrument ~500 km³ of ice
- Its sensitivity is expected to tap into the predicted UHE neutrino flux
- Counting experiment or neutrino observatory?

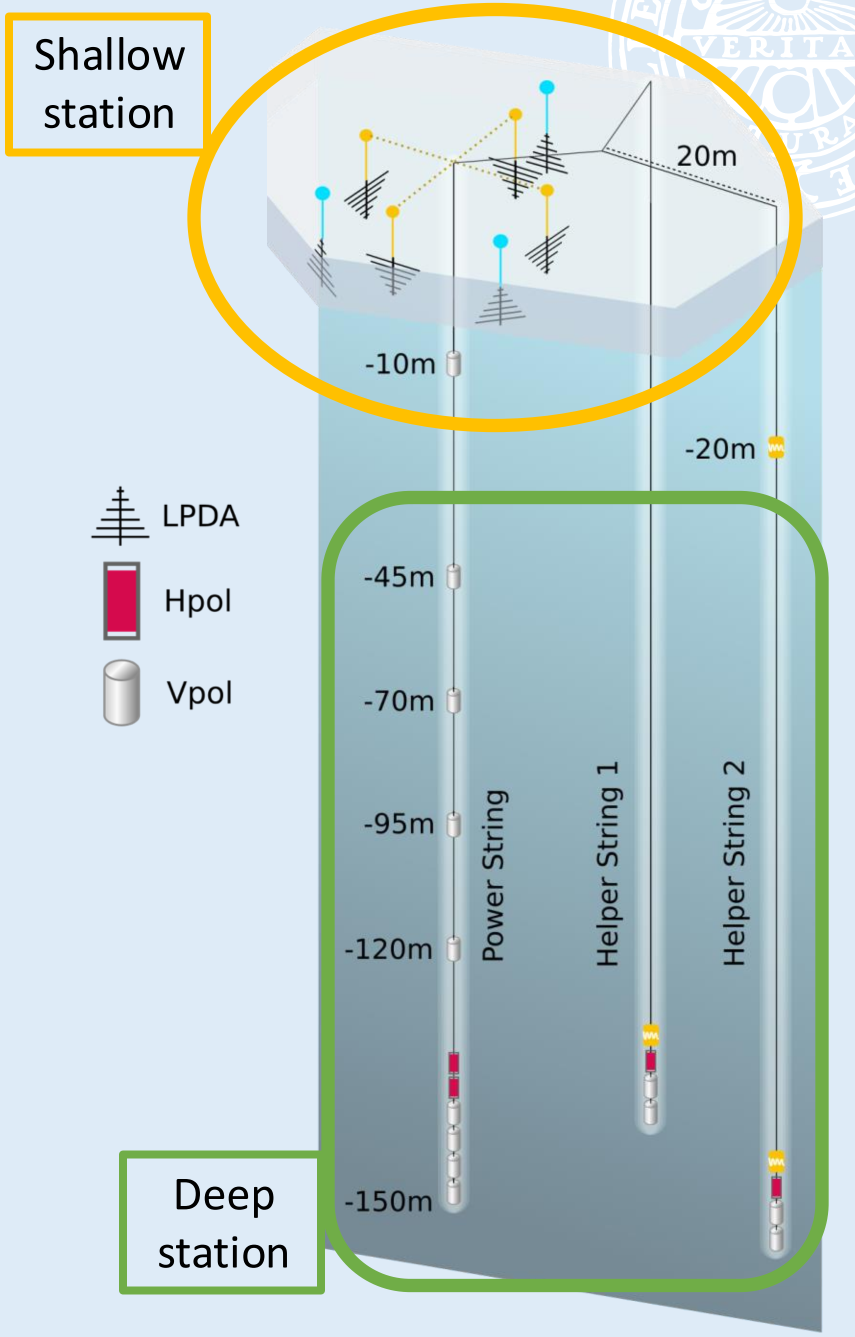



neutrino spectrum



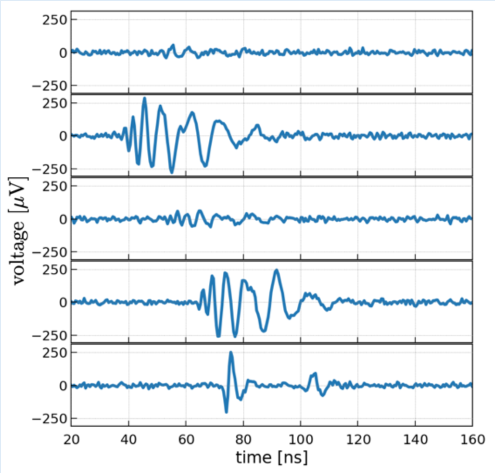
# Two Different Station Designs

- MC generated events for a single station @South Pole
- The events have a uniform shower energy distribution
- Single station event topologies:
  1. Hadronic shower ($\nu_{e,\mu,\tau} - NC$, $\nu_{\mu,\tau} - CC$ )
  2. Hadronic shower + EM shower ($\nu_e$ $- CC$ )
- The current IceCube Gen2 station:
  - Shallow – 5 antennas
  - Deep – 16 antennas
  - 2.1 million neutrino events for each station layout



# What will we do after measuring the first neutrino?

raw traces



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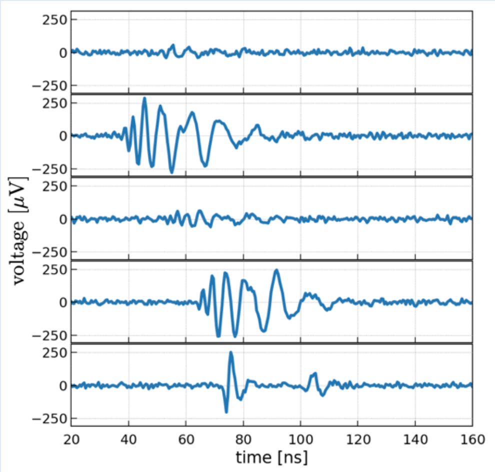
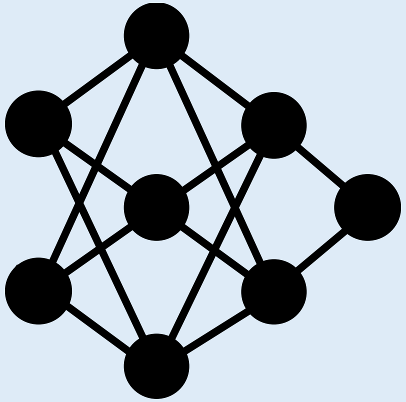



reconstruction algorithm



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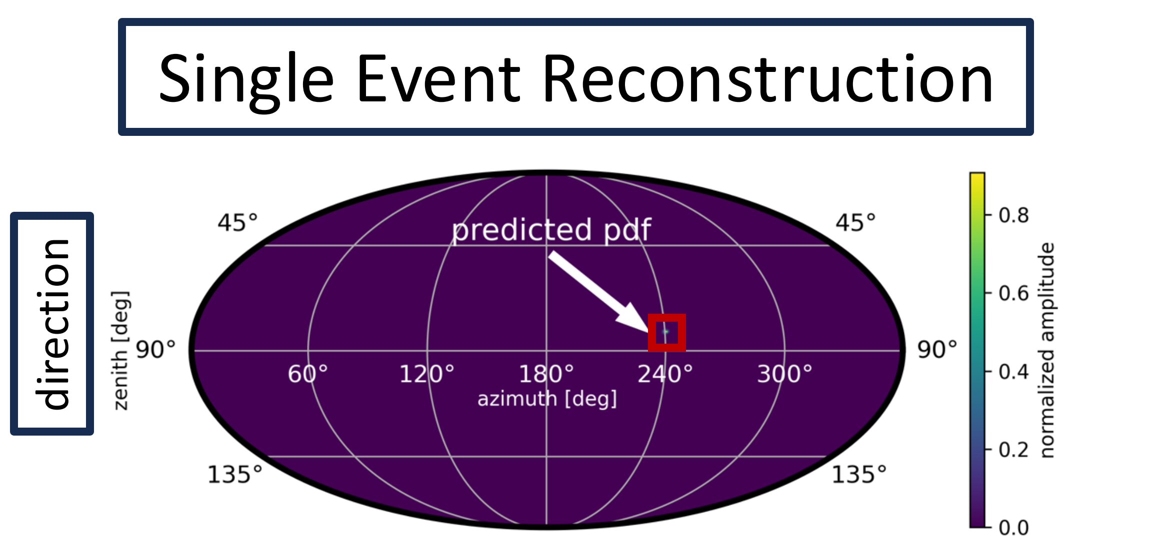
## Single Event Reconstruction

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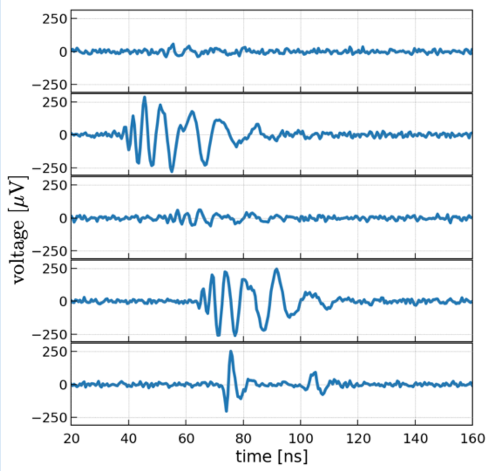


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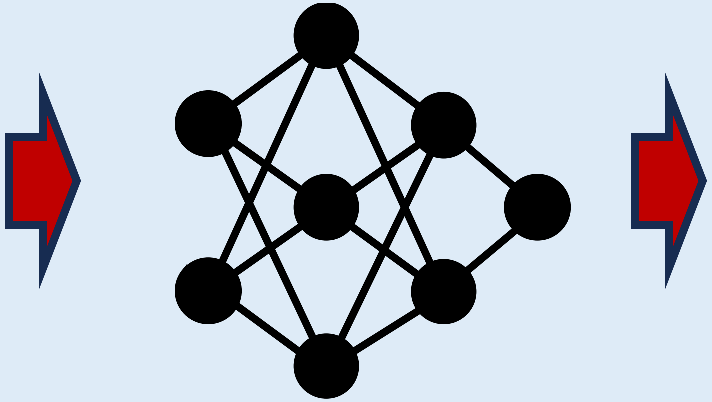

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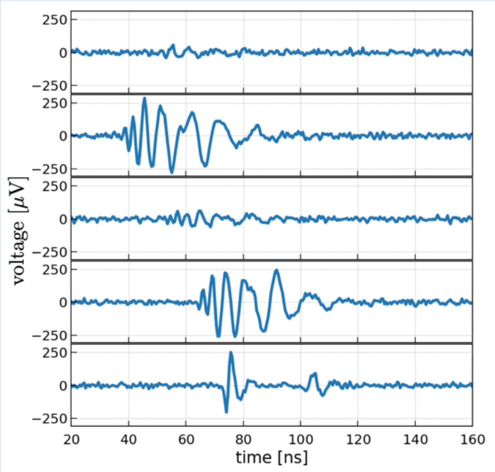


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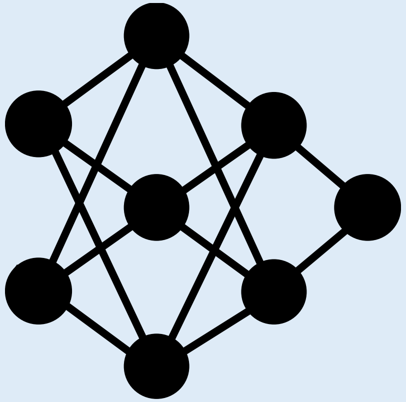
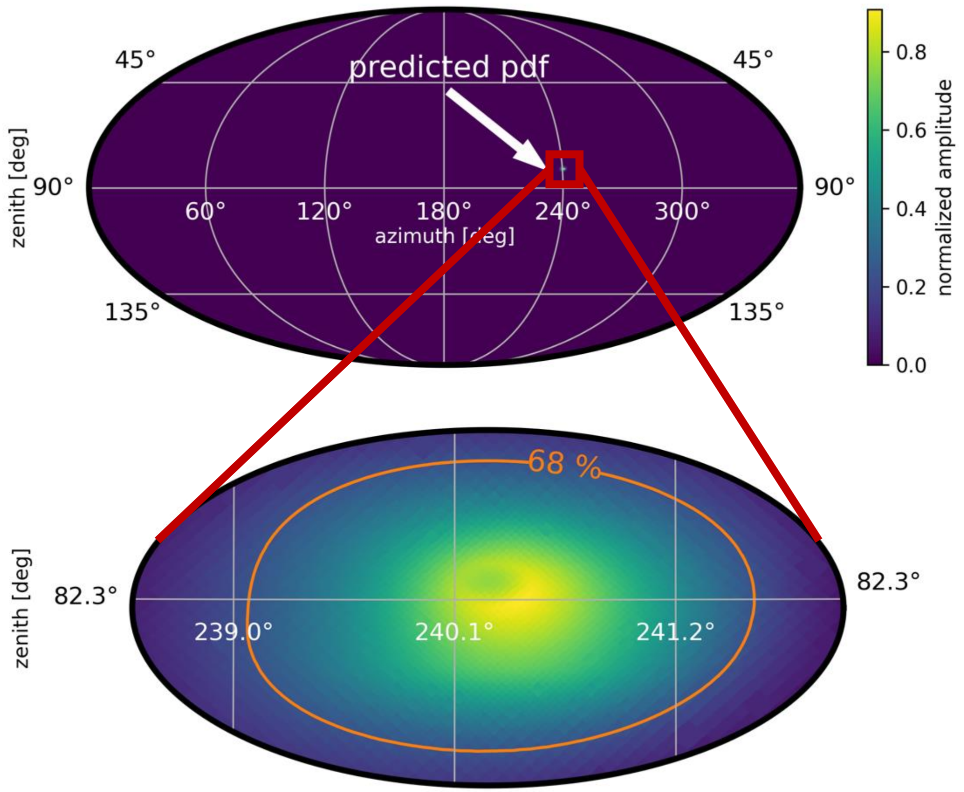


Single Event Reconstruction

direction



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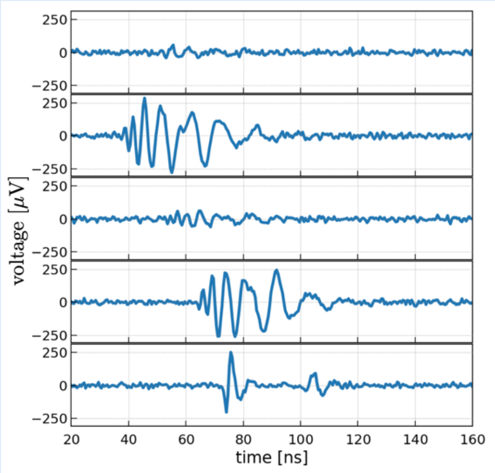


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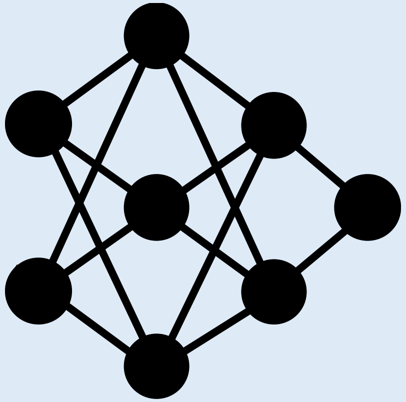

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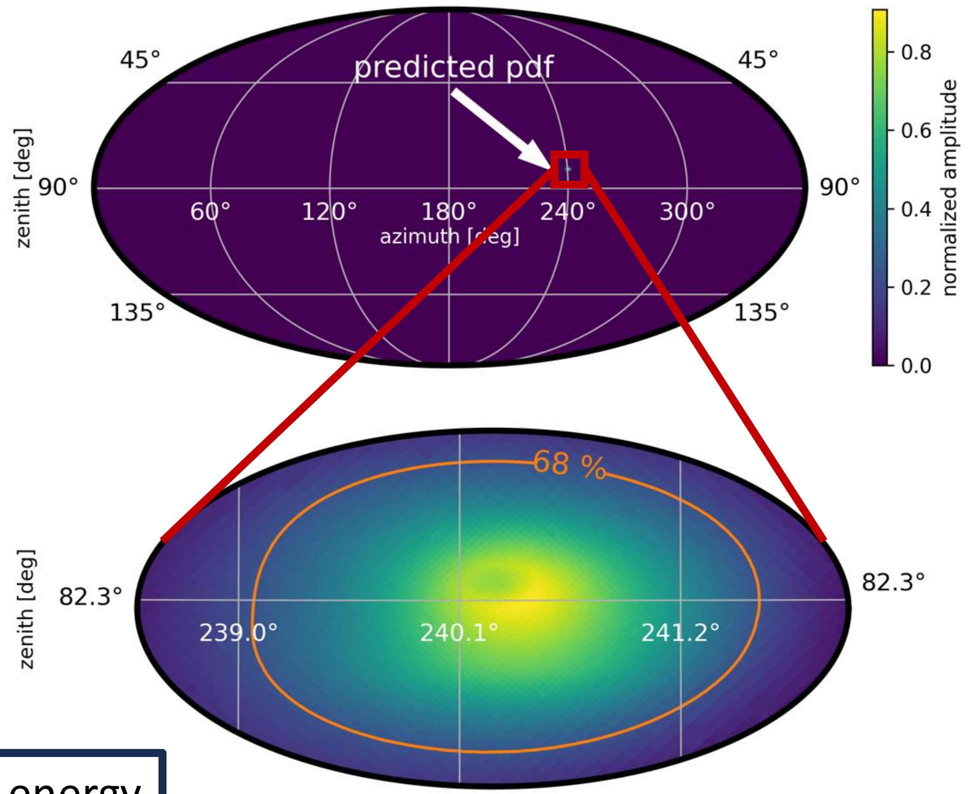
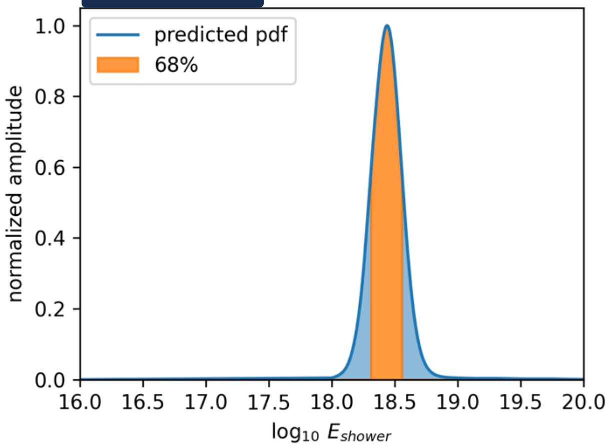



energy



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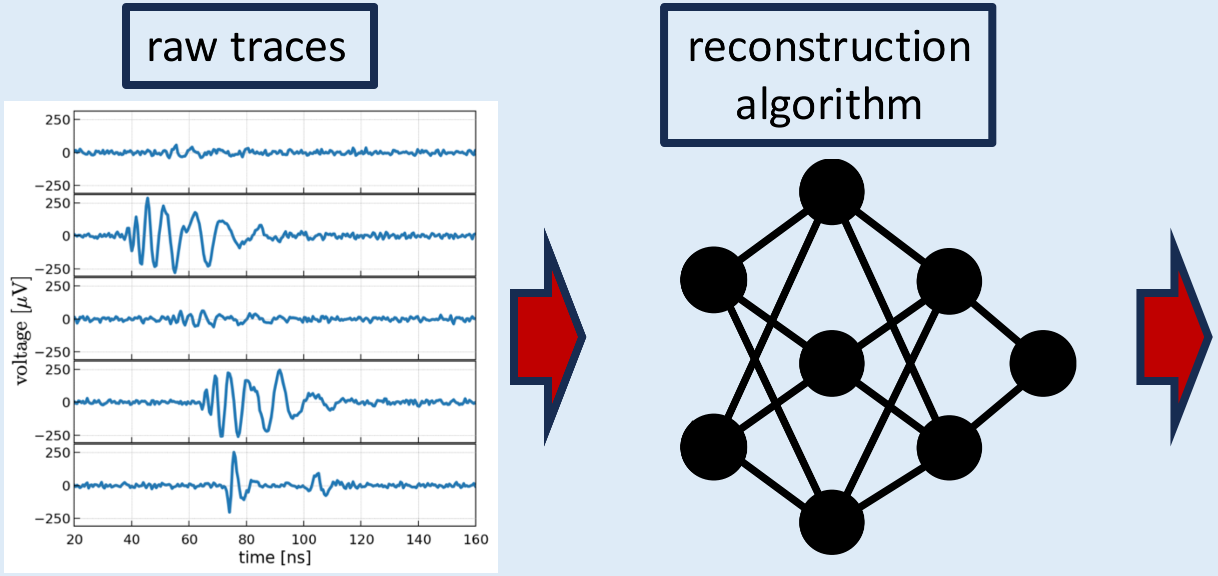


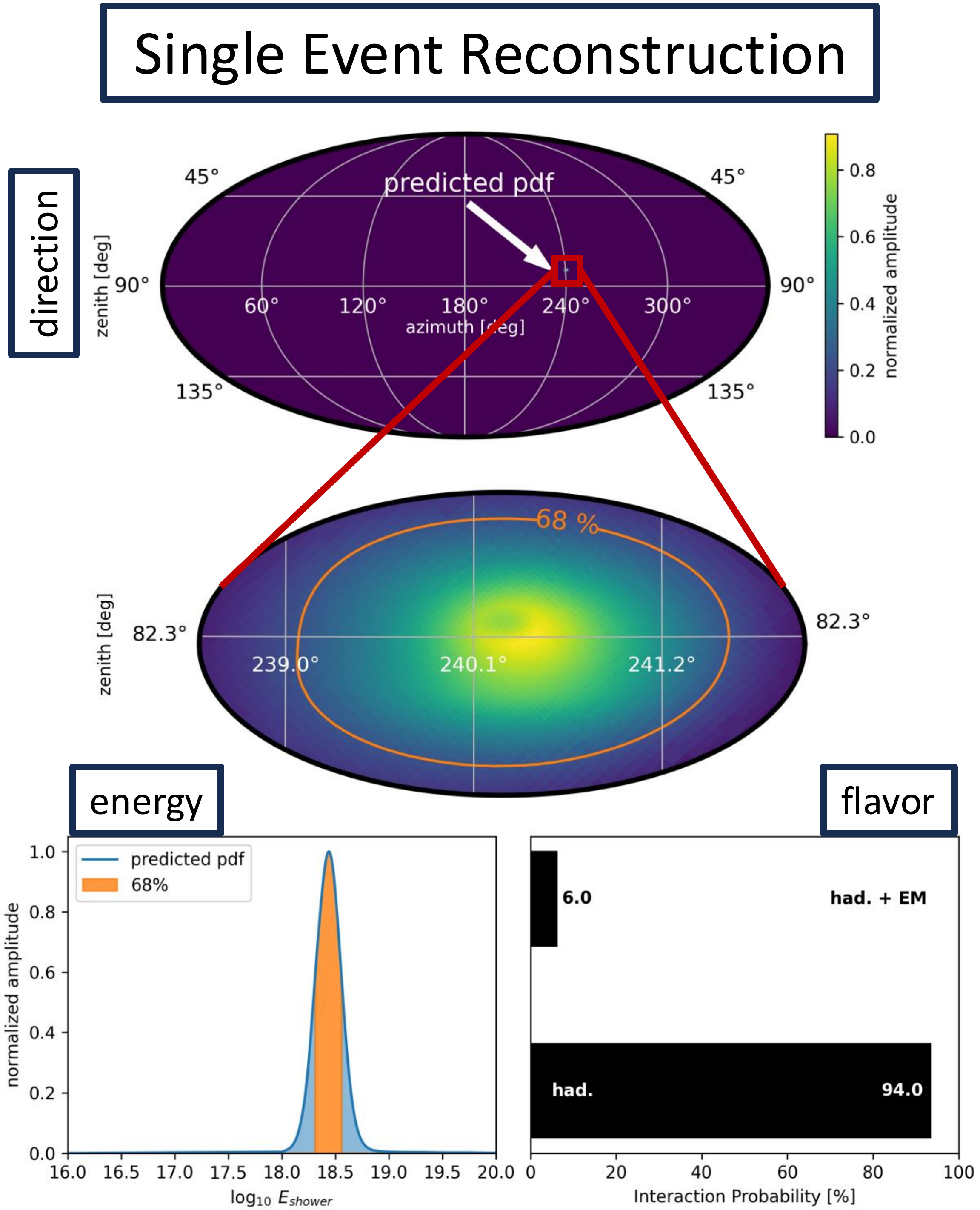

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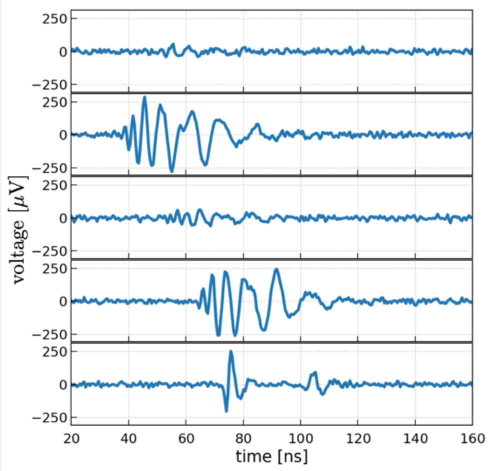


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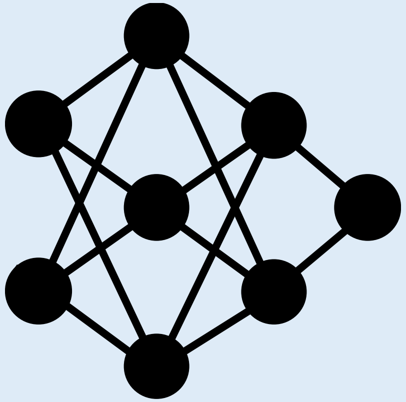

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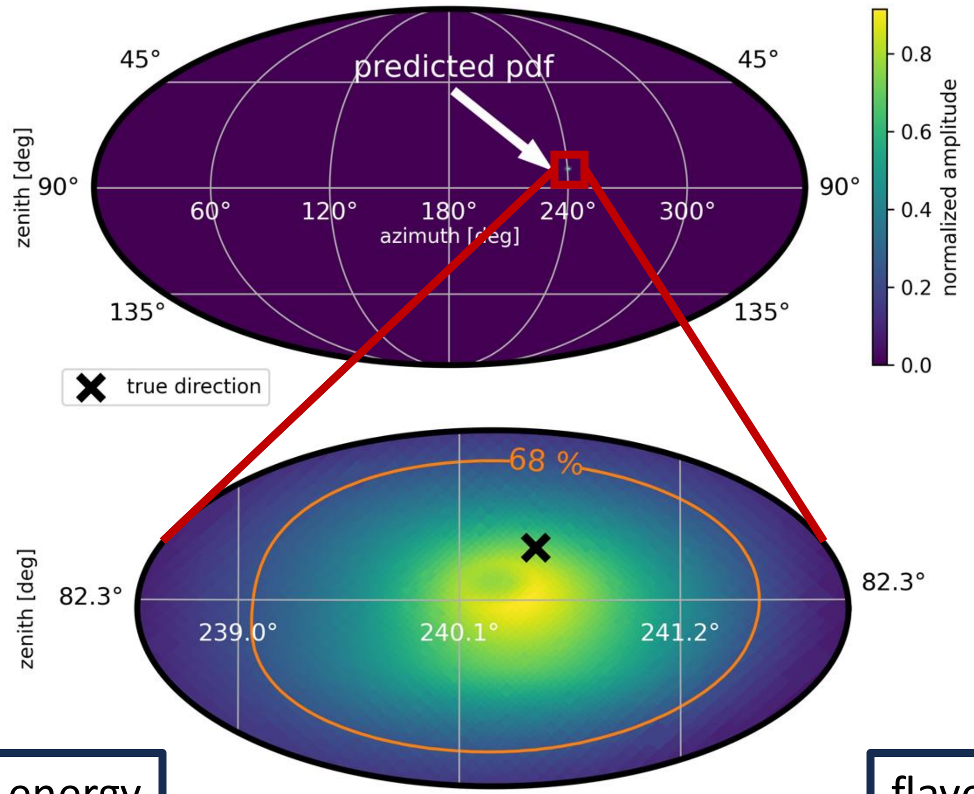
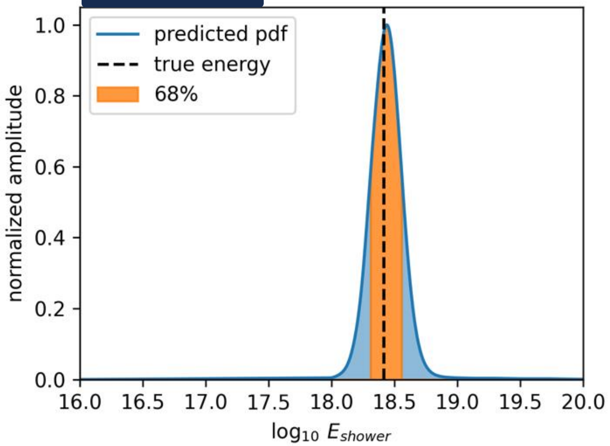
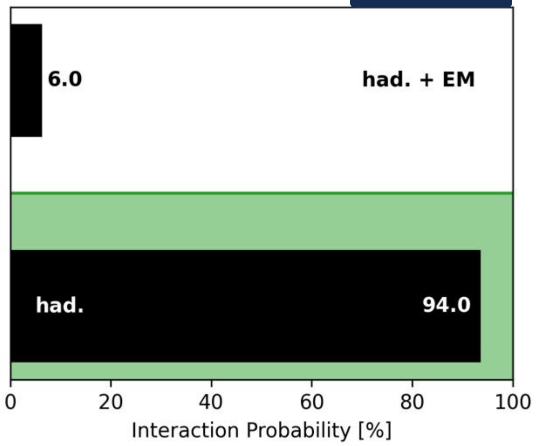



energy



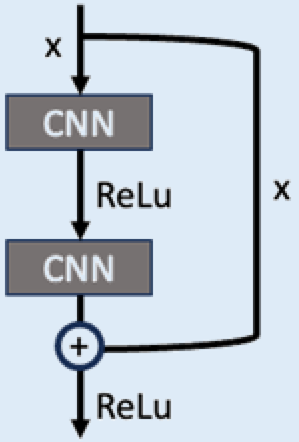

flavor



# Important Deep Learning Concepts

## ResNet

- Developed for **image classification**
- Allows for very deep networks **without vanishing gradients**
- Previously used for **GW detection**



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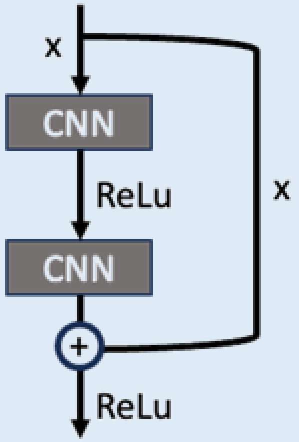
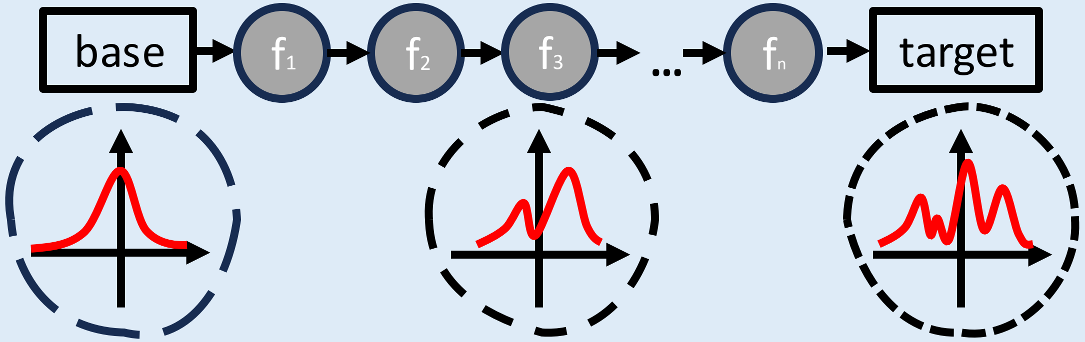



## Normalizing Flow

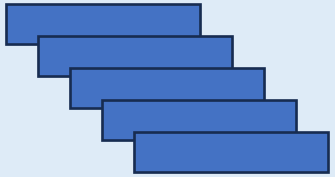
- A **function that maps** a gaussian PDF to a non-Gaussian target PDF
- Parameters of the flow can be learned by a **neural network**
- Can model **complex PDF shapes**



# Model architecture

**Model Shallow**:

1 x 5 x 512



**Model Deep**:

1 x 16 x 2046

# Model architecture

**Model Shallow:**

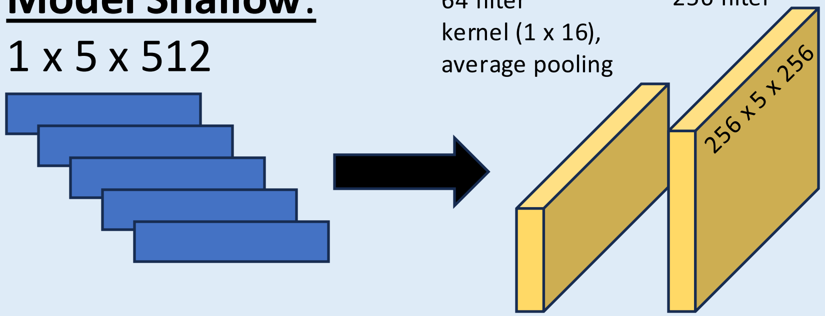
1 x 5 x 512

CNN1

4x 1d-conv
64 filter
kernel (1 x 16),
average pooling

CNN2

4x 1d-conv
kernel (1 x 16),
256 filter

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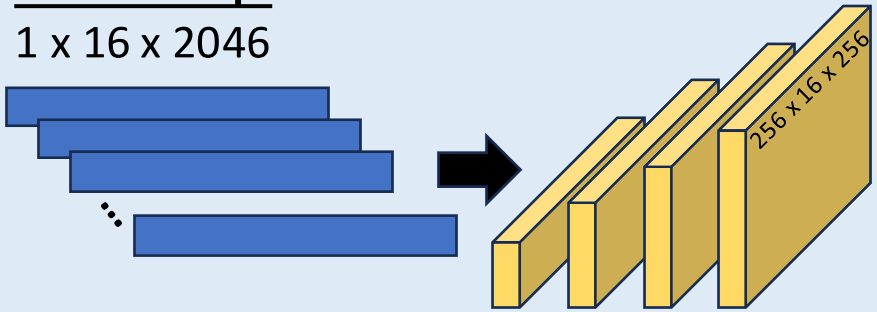


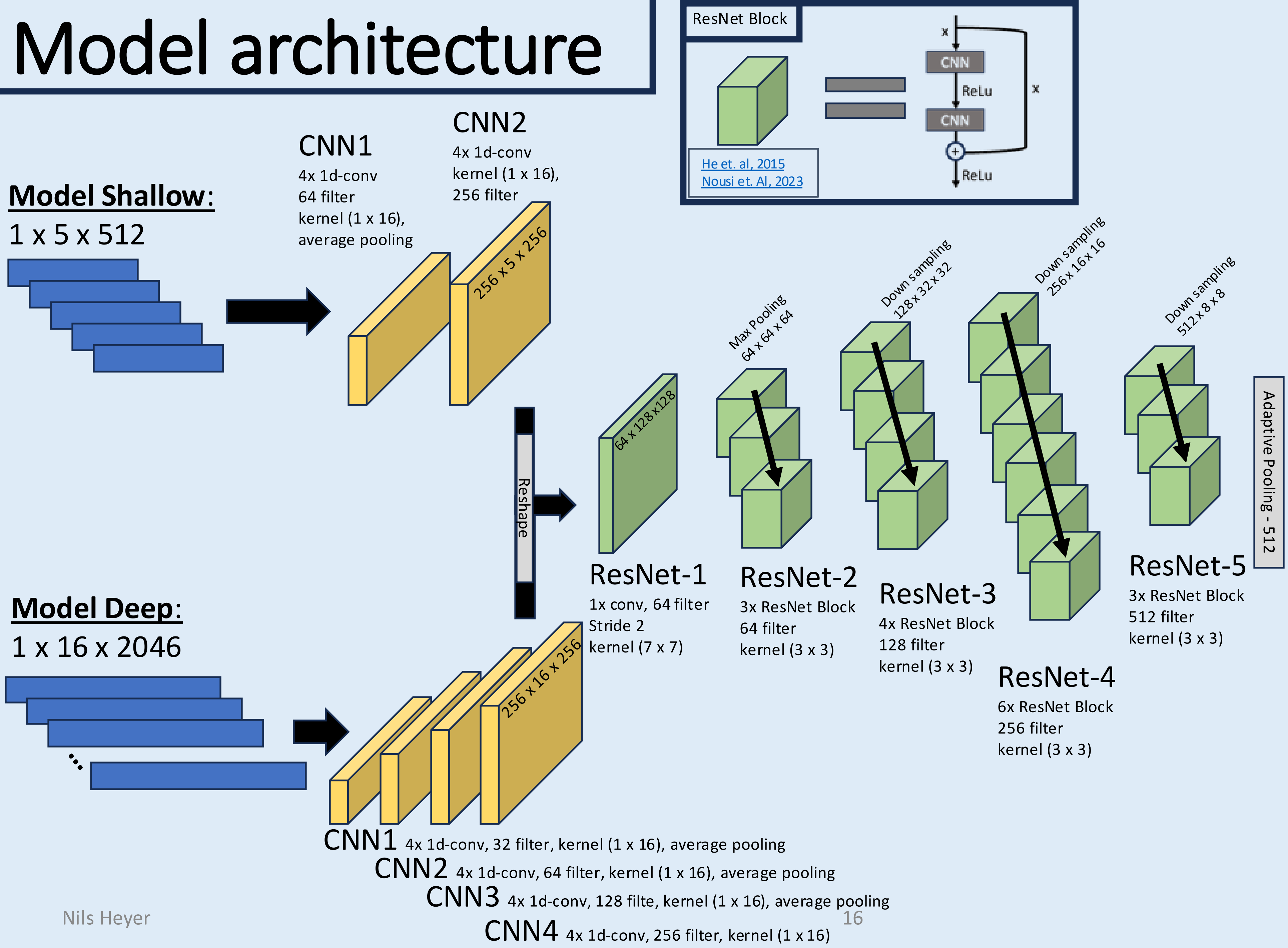

CNN1 4x 1d-conv, 32 filter, kernel (1 x 16), average pooling

CNN2 4x 1d-conv, 64 filter, kernel (1 x 16), average pooling

CNN3 4x 1d-conv, 128 filte, kernel (1 x 16), average pooling

CNN4 4x 1d-conv, 256 filter, kernel (1 x 16)

# Model architecture



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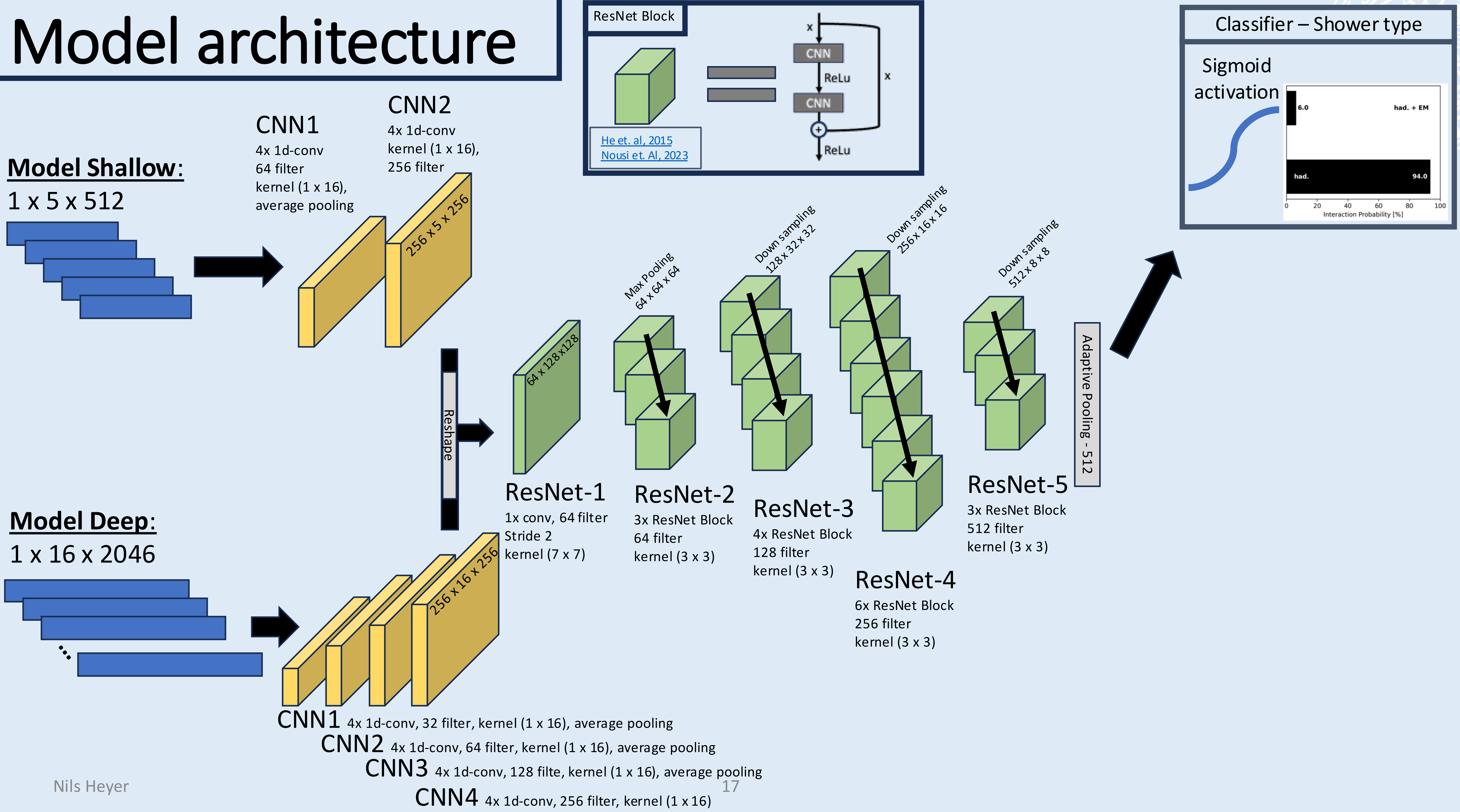

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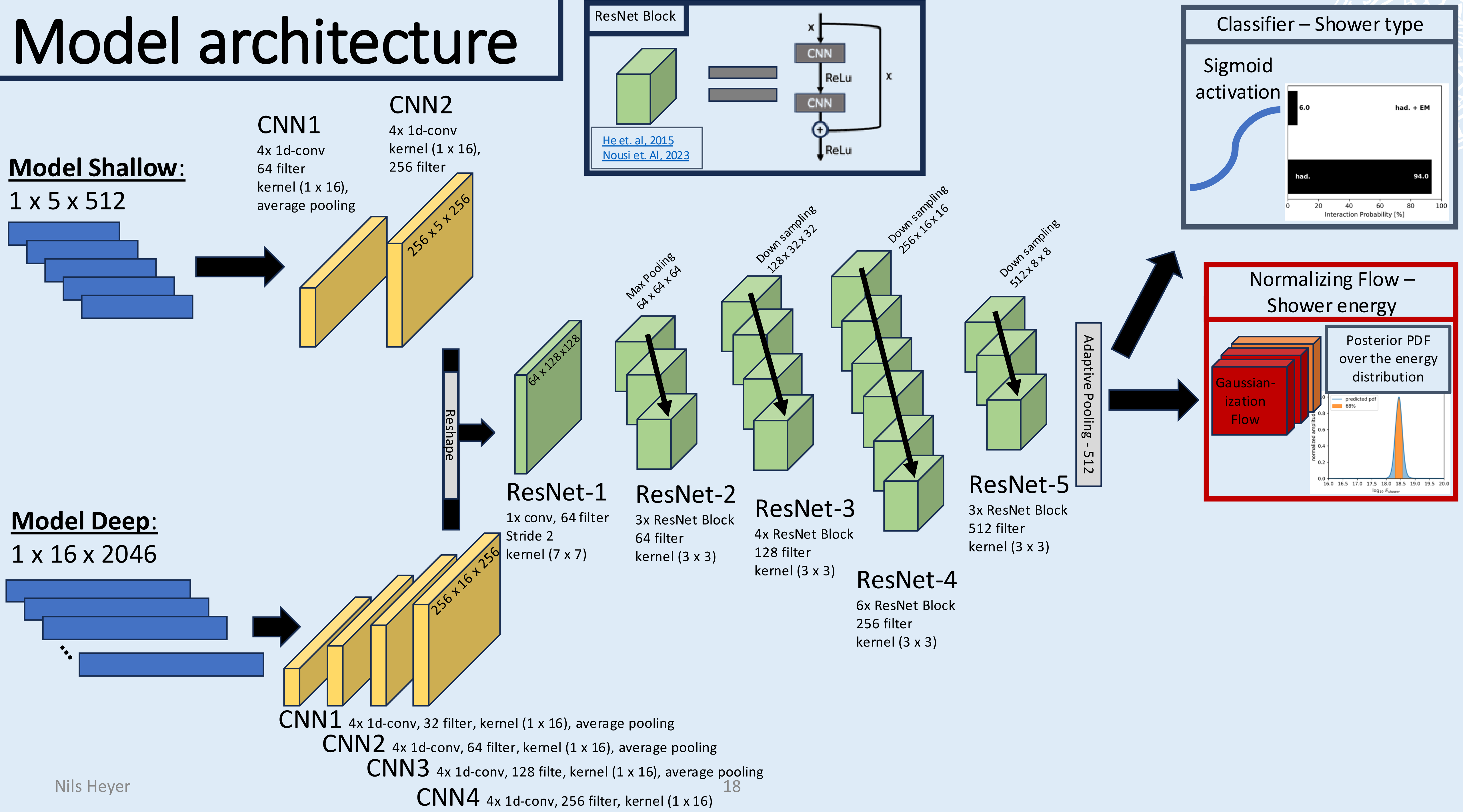

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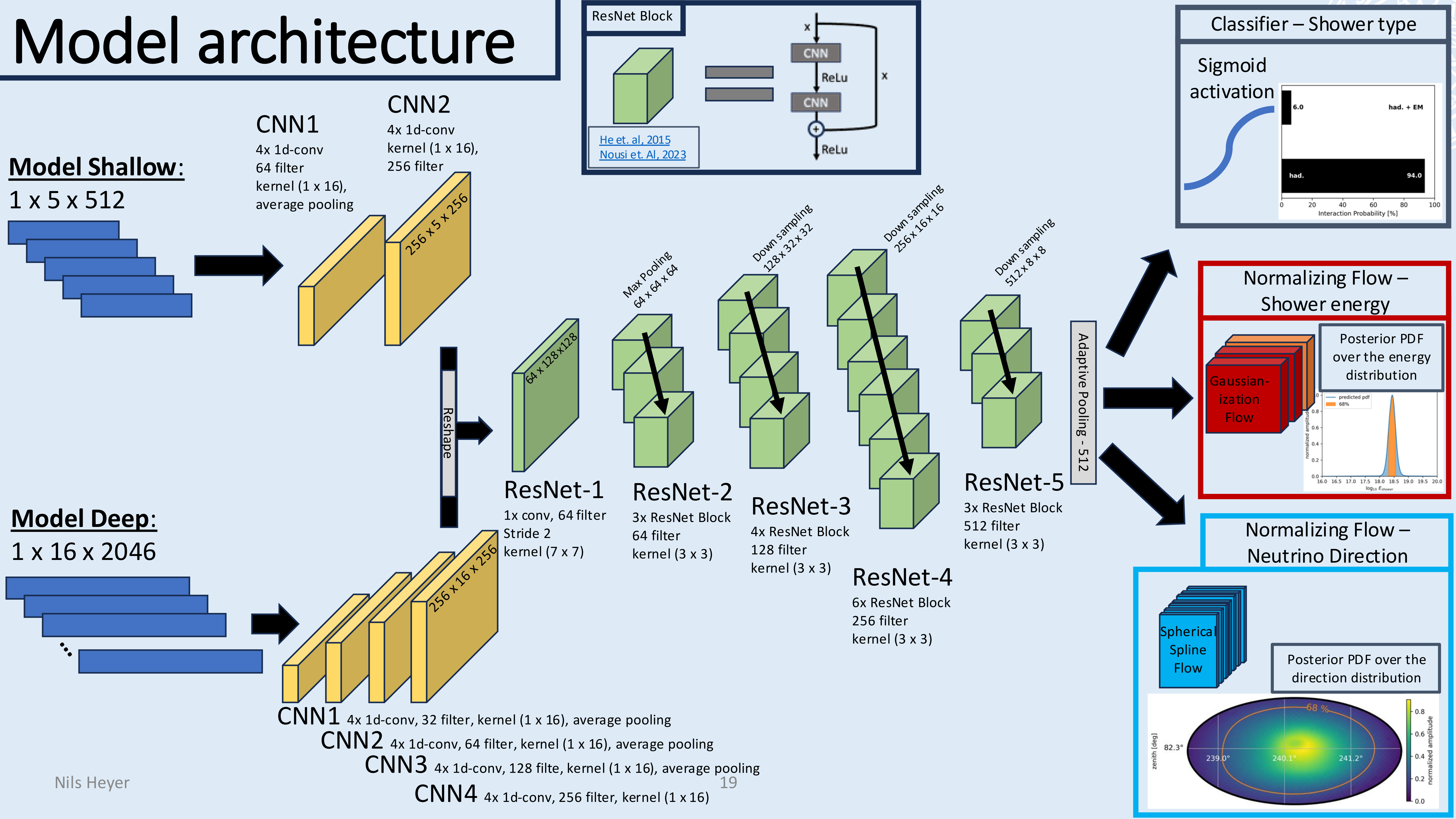

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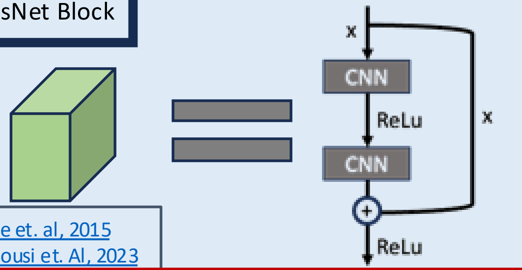


[He et. al, 2015](#)
[Nousi et. Al, 2023](#)

**Model Shallow:**
1 x 5 x 512

## Improvements to previous reconstructions:

1. One model (per station type) to predict all parameters
2. Normalizing flows return full posterior PDFs allowing for event-by-event uncertainties
3. The model has no prior knowledge of the shower type
4. No analysis cuts are needed – all neutrino events can be used

**Model Deep:**
1 x 16 x 2046

CNN1 4x 1d-conv, 32 filter, kernel (1 x 16), average pooling
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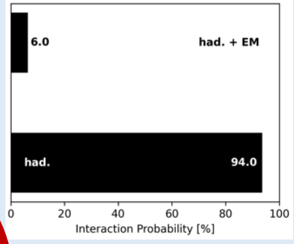
CNN4 4x 1d-conv, 256 filter, kernel (1 x 16)

kernel (3 x 3)

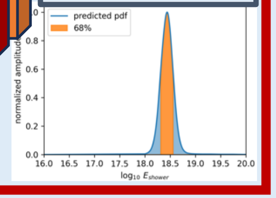
Classifier – Shower type

Sigmoid activation




malizing Flow –
ower energy

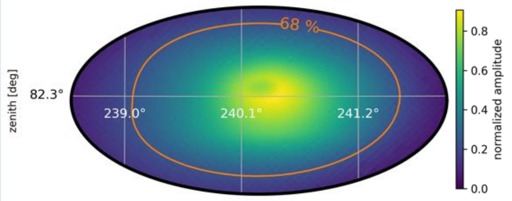
Posterior PDF over the energy distribution




malizing Flow –
trino Direction

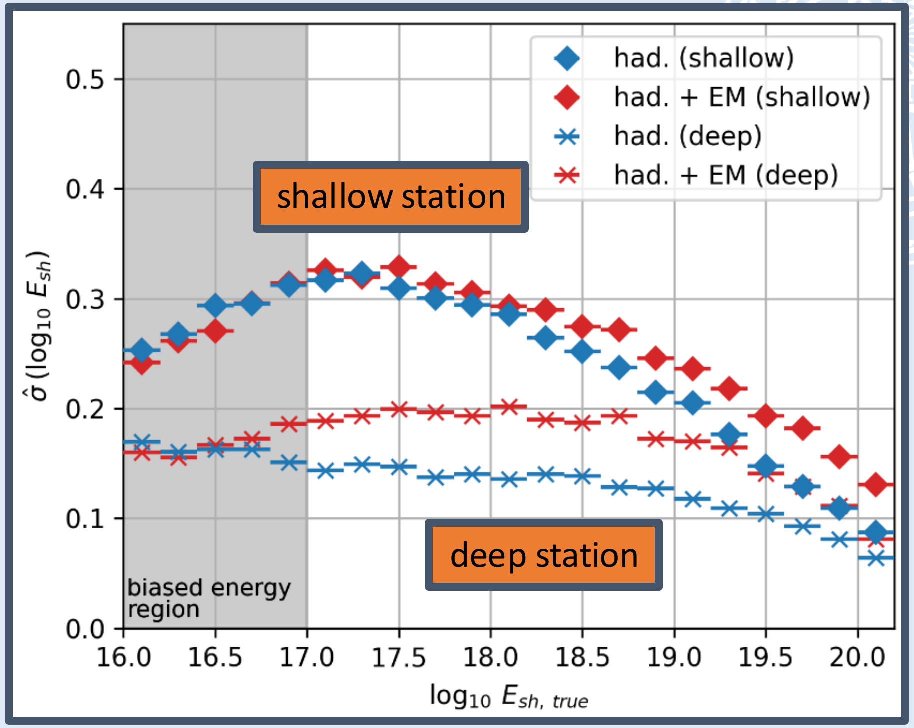
Spherical Spline Flow

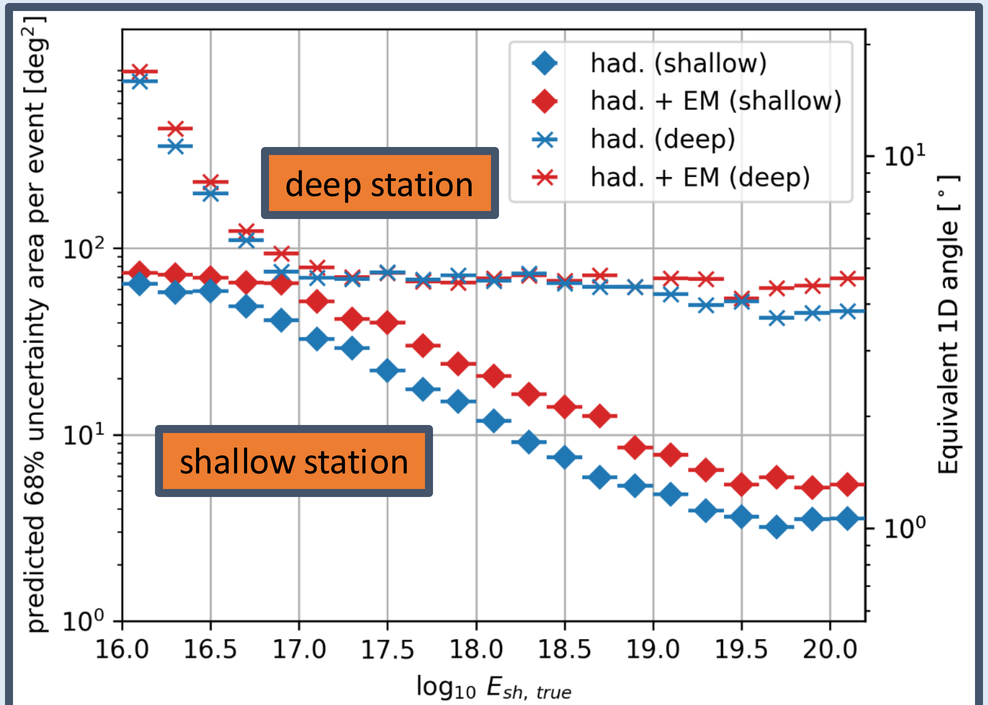
Posterior PDF over the direction distribution



# Results
# – Energy and Direction

- Quantifying the size of our uncertainties
- Performance gets better with shower energy
- Hadronic showers are easier to reconstruct but don’t tell us as much about the neutrino
- ‘deep’ stations have better energy resolution
- ‘shallow’ stations have better direction resolution



# Summary & Outlook

- Radio Neutrino Detectors can instrument enormous volumes of ice
- After the first detection reconstruction will become a priority
- I created a model that can reconstruct all relevant properties
- Resolution at 1EeV shower energy:

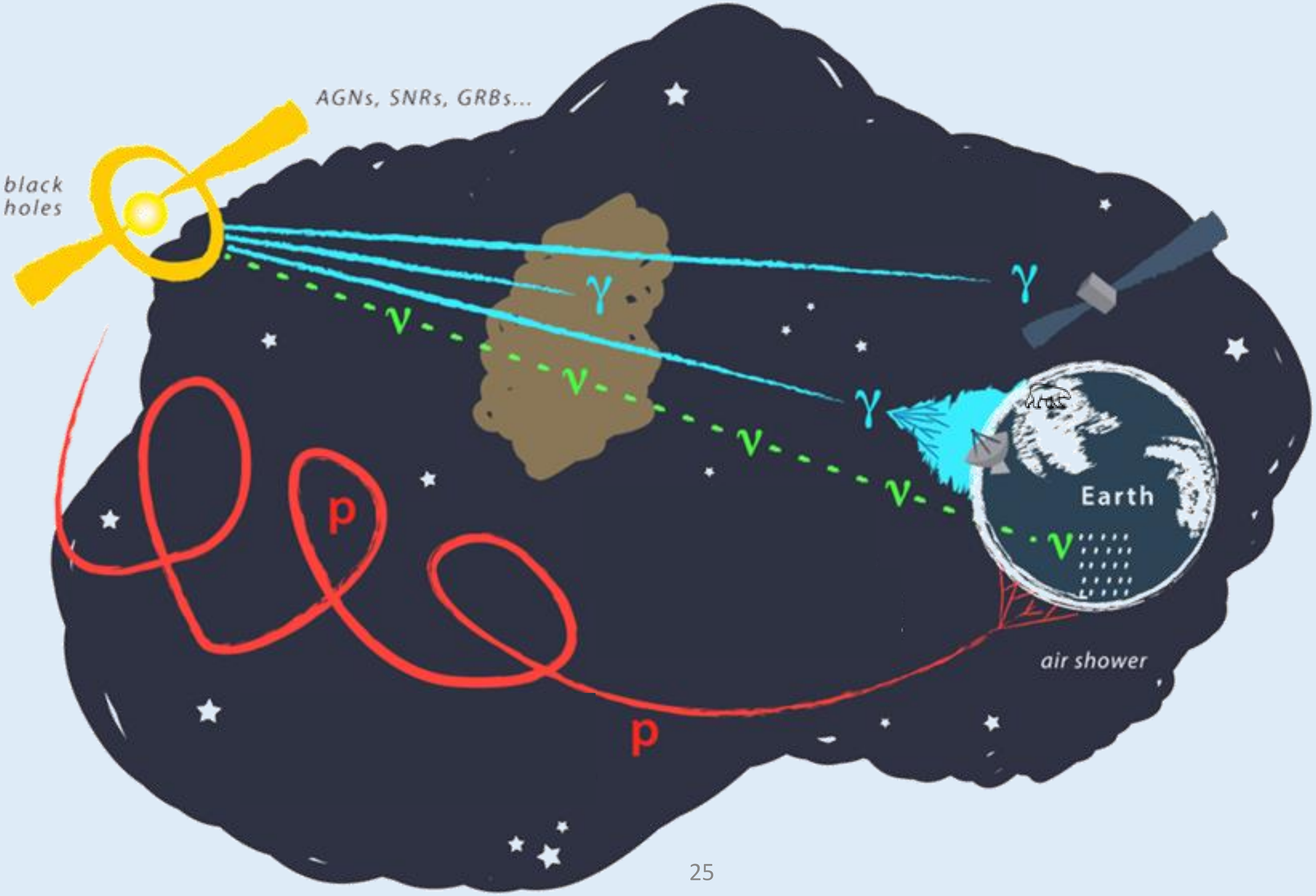
| Resolution at 1EeV (had.) | Shallow Station | Deep Station |
|---|---|---|
| Shower Energy | 0.3 log E | 0.15 log E |
| 68% Uncertainty size | ~10 $deg^2$ | ~70 $deg^2$ |

- Next up:
  - Nice statistical uncertainties, but what about systematics?
  - How similar is a measured event to our Monte Carlo simulations?
  - What are the effects of birefringence?

# Thank you!

# Usually we attack the science, but sometimes science strikes back

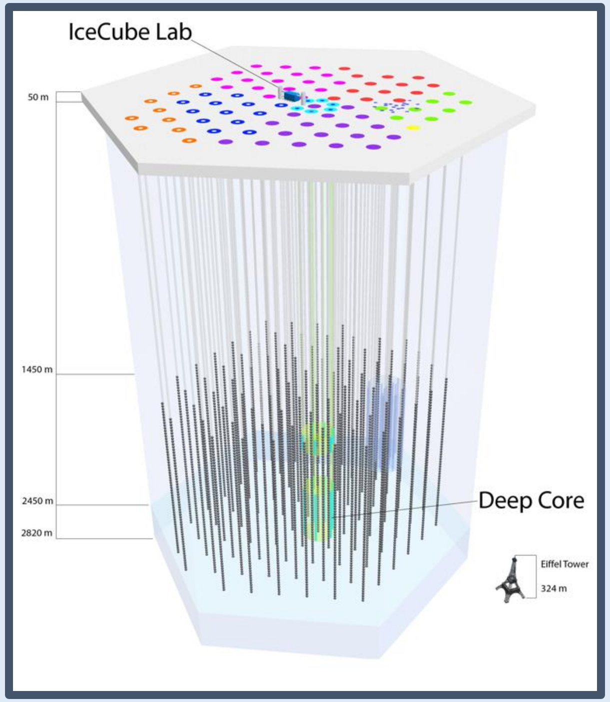
# Why measure Cosmic Neutrinos?



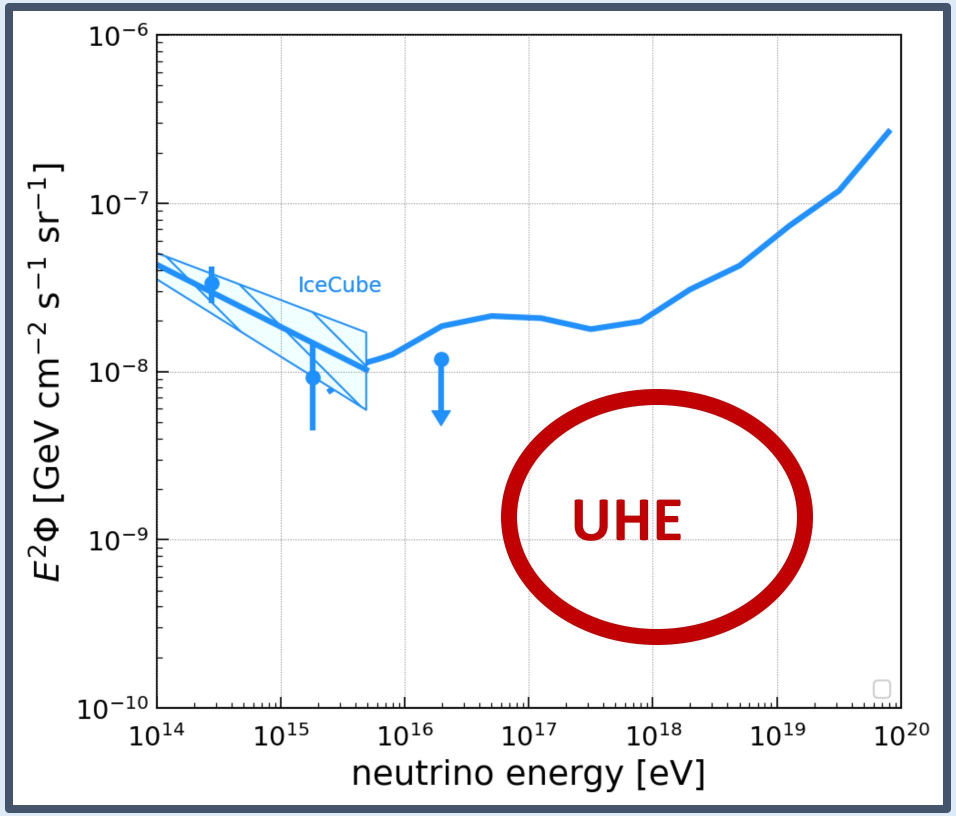
# IceCube – The km3 Neutrino Telescope

- Instruments a cubic kilometre of ice
- Successfully measured the cosmic neutrino flux in the TeV-PeV range
- Detected point sources of neutrinos (NGC1068, TXS 0506+056)

But there is more…




**neutrino spectrum**




optical

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But there is more…

- Radio neutrino detection extends the reach into the EeV range
- Can cost effectively instrument hundreds of cubic kilometres of ice