Universität Münster

PMT assigment of photons with Neural Networks

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Software call

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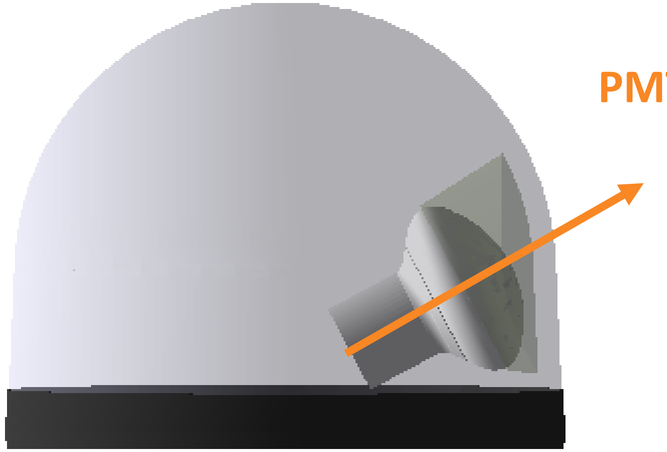
Motivation I

- Current IceCube simulation for Gen2 OMs (PPC) assumes:
  1. All PMTs within an OM are equivalent
  2. The angular acceptance of a PMT is symmetric with respect to its symmetry axis

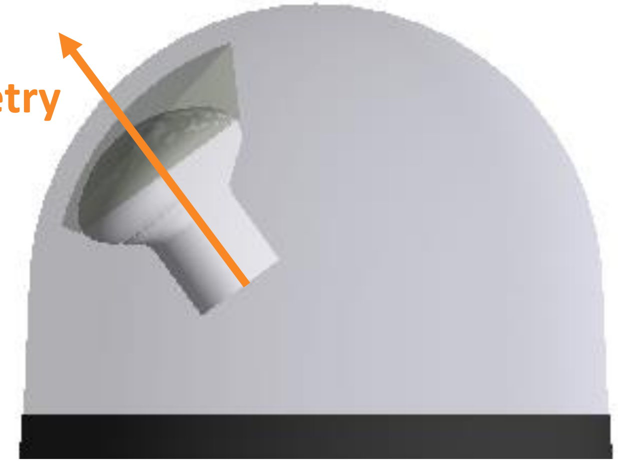
- These assumptions are not true → especially for LOM:
  - Gel Pads are not symmetric
  - PMT symmetry axis does not align with the pressure vessel normal vector
  - There are two “types” of PMT: **Polar and Equatorial**

IceCube-Gen2 LOM16

Equatorial PMT



Polar PMT



Motivation II: Why Neural Networks?

Challenging to find an analytical parametrization of angular acceptance → alternatives:

1. Direct Geant4 simulation (might be too slow/challenging to pipe)
2. Interpolation tables (e.g. DEgg)
3. Neural Network based parametrization of angular acceptance (today's talk):
    - NNs excel at high dimensional problems (LOM needs more degrees of freedom than D-Egg)
    - NNs provide fast inference times using a GPU

PMT assigment of photons with NN: Concept

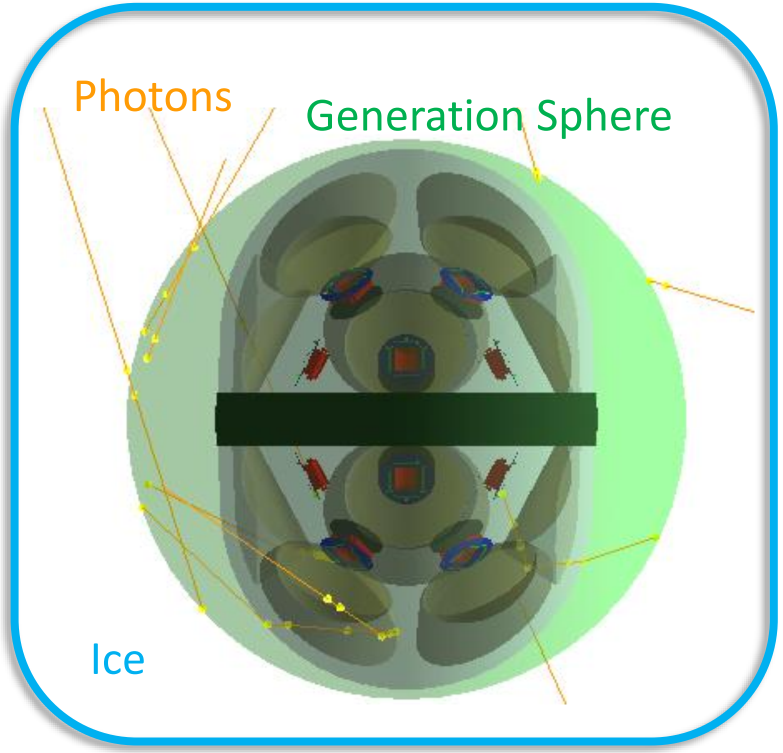
- Neural Networks (NNs) are essentially function approximators

Inputs:
Photon position
Photon direction
Wavelength

→ **NN** →

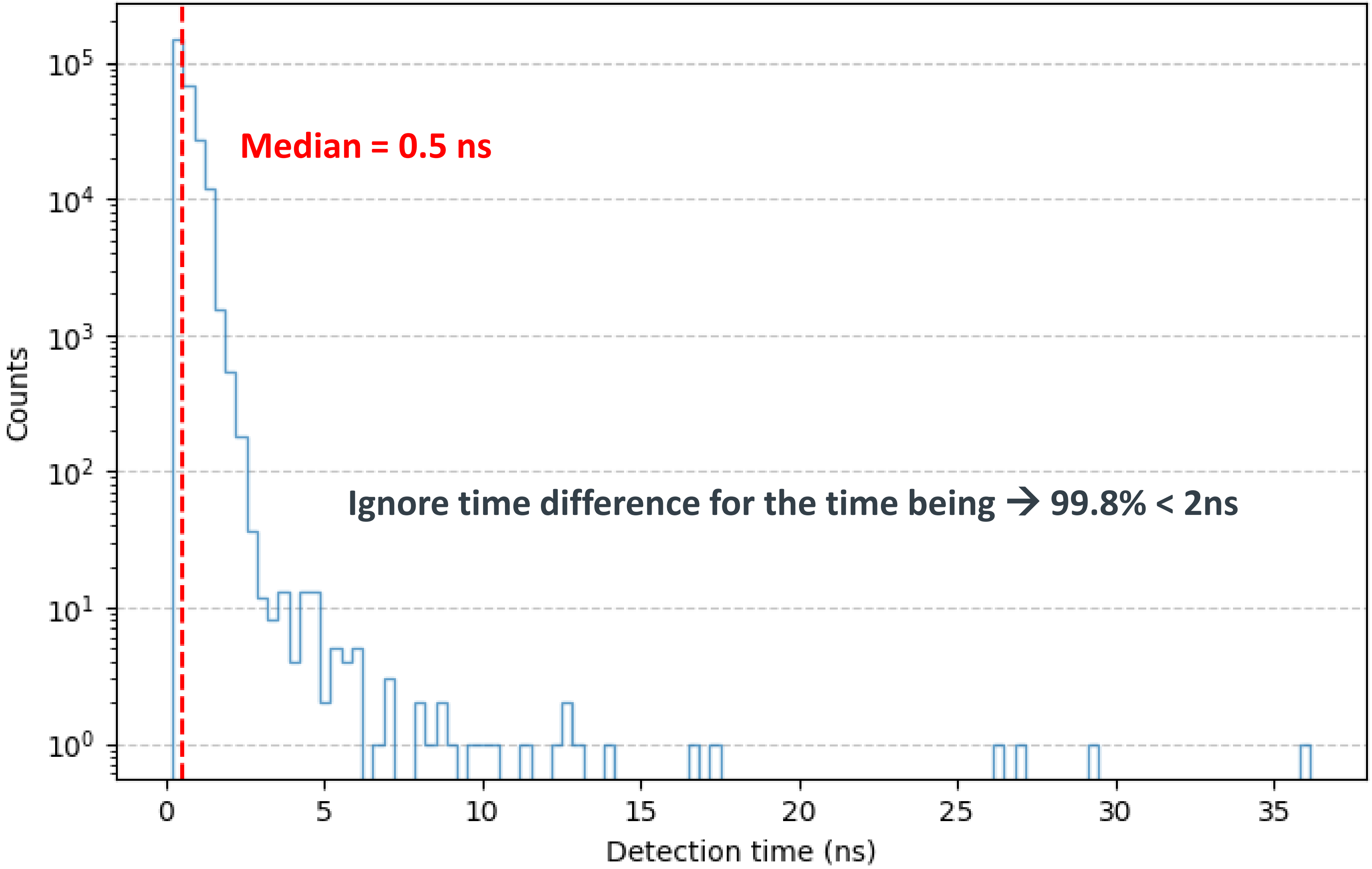
Output:
Detection prob.
in each PMT
+ no detection prob.

Geant4 simulation



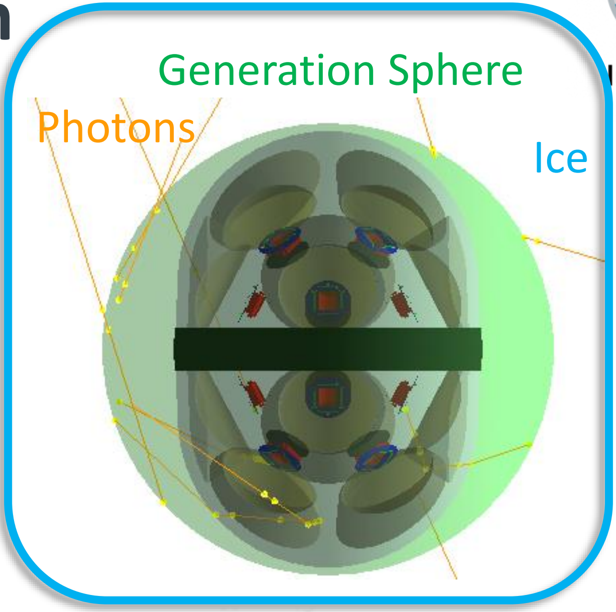
- Train NN on photons generated randomly on a sphere surrounding the LOM:
  → 30 billion photons simulated
  → Random uniform wavelength sampling (270 nm – 700 nm)
  → Radius of the sphere = 23 cm

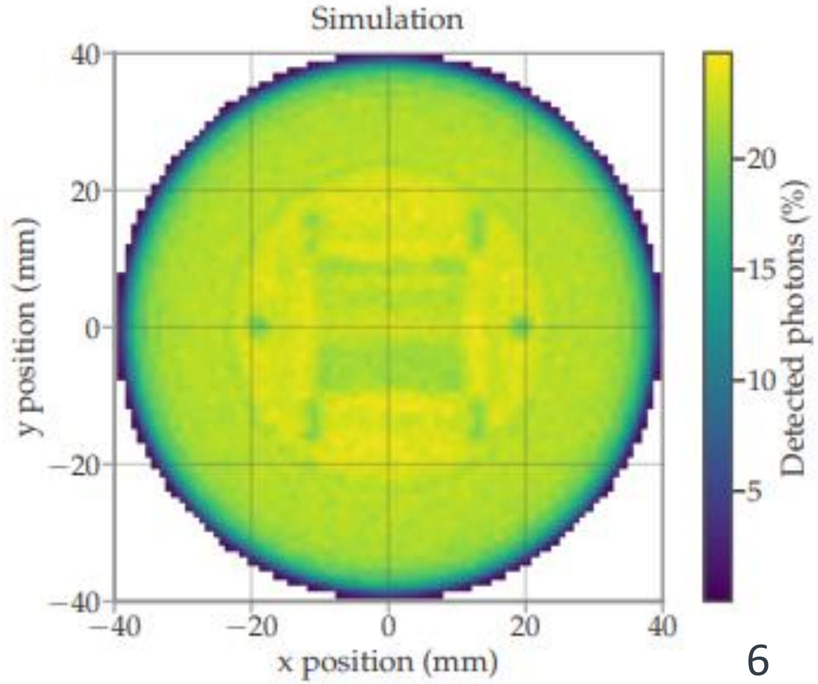
Relative Detection Time



LOM16 Geant4 Simulation

- Using Münster's OMSim framework
- Most current and next-gen OMs included
- Did not consider harness / internal components for the first study
  → Could include in next training iteration
- Ice properties considered:
  - ✓ Refractive index
  - ✗ Absorption length
  - ✗ Scattering length
- Possible to perform detailed PMT detection probability simulation:
  → Match simulation with PMT measurements
  → **Main difference with respect to DOUMEKI**





LOM Symmetries in NN Design

- Any kind of NN could approximate this task but not with the same accuracy
- All PMTs of a same kind (polar/equatorial) have the same properties

→ Leverage LOM symmetries for best performance

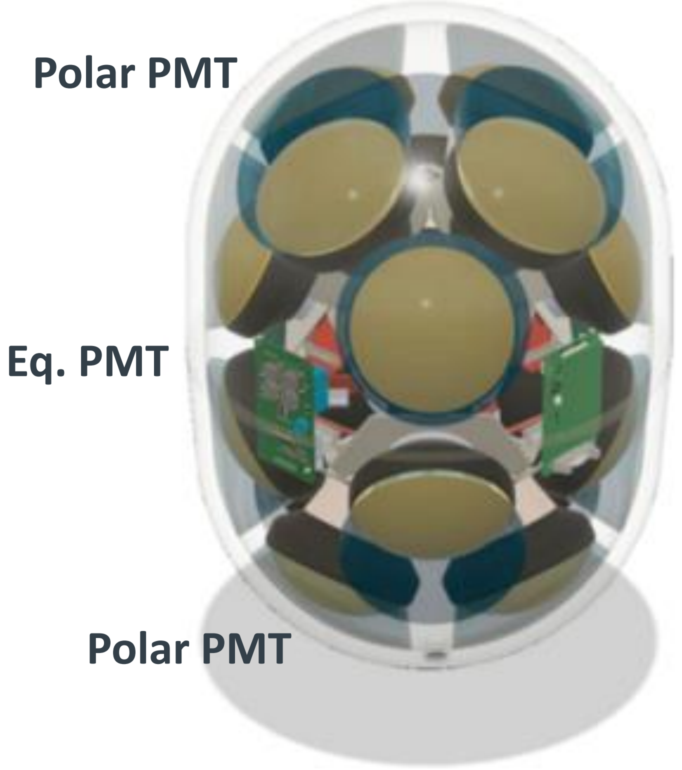
How?

1. Describe incoming photon properties based on relative values for each PMT
2. Identify symmetries within one PMT for equivalent scenarios:
   → azimuthal symmetry in XY plane
3. Use CNN layers with relative values as input for each PMT → [n_features,16]
4. One of the features must be a Polar/Eq. PMT identifier
5. Combine with linear layers for symmetry breaking properties e.g. penetrator cable

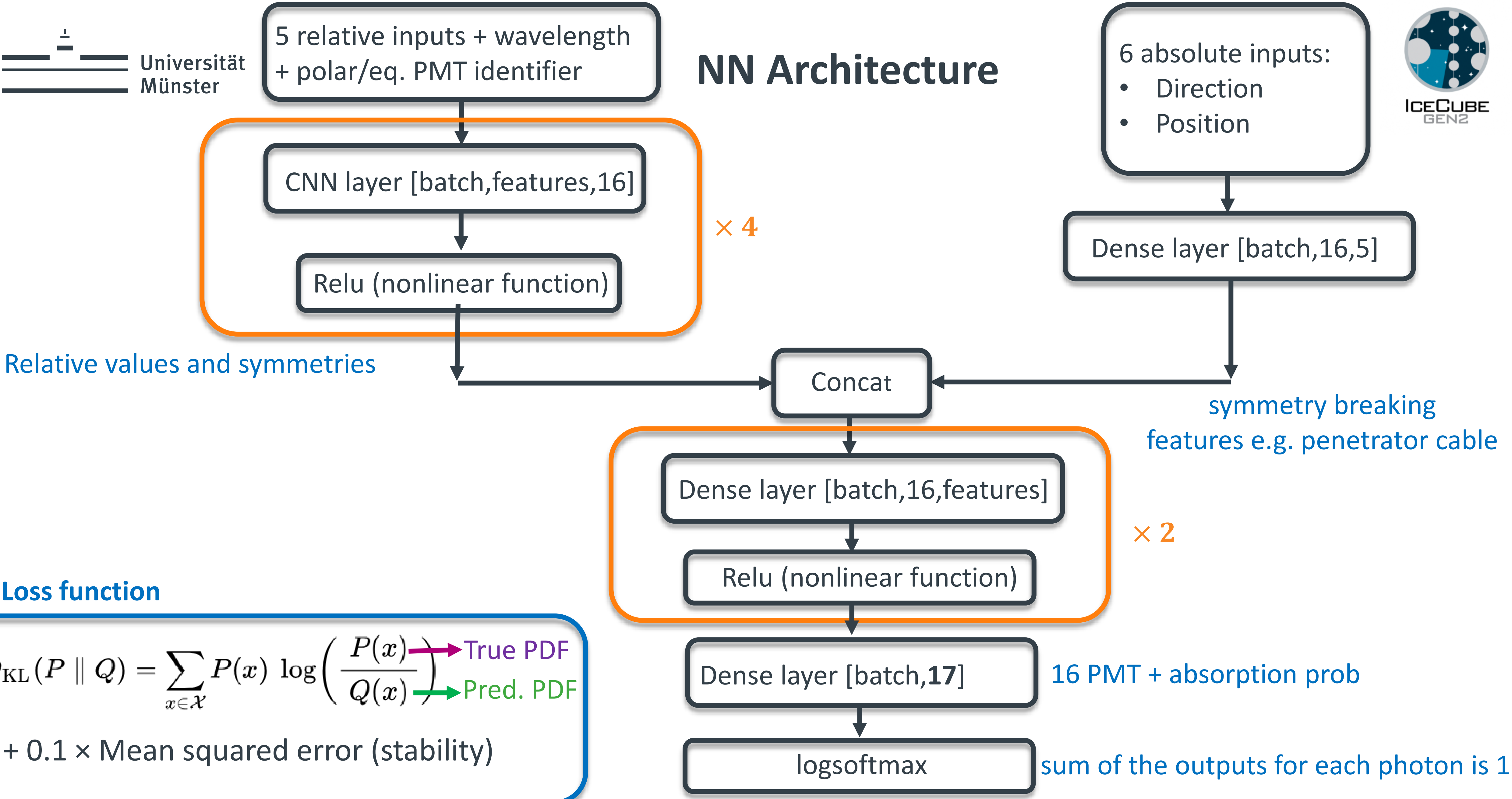
If one PMT sees some relative values:

→ CNN with kernel size 1×1 can map the outcome to any other PMT

→ Inspired by Event-Generator



NN Architecture



Loss function

$$D_{\mathrm{KL}}(P \parallel Q) = \sum_{x \in \mathcal{X}} P(x) \, \log\left(\frac{P(x)}{Q(x)}\right)$$

$P(x)$ → True PDF

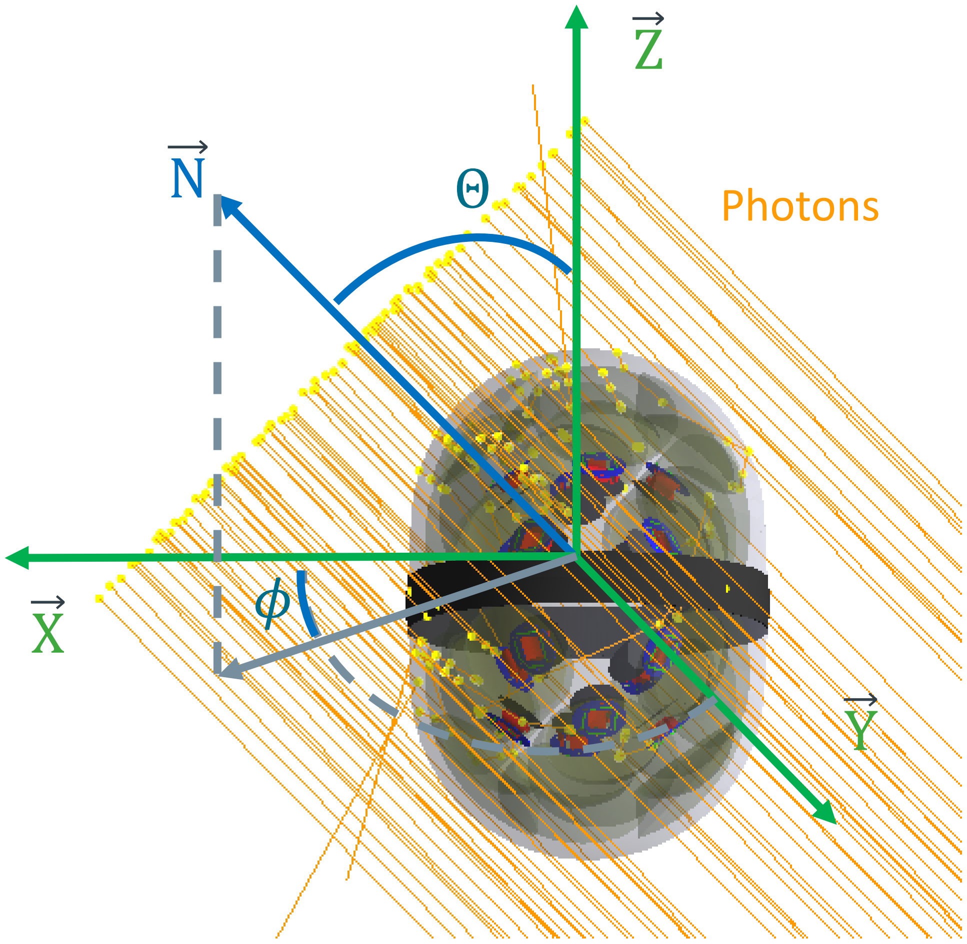
$Q(x)$ → Pred. PDF

+ 0.1 × Mean squared error (stability)

Performance Checks: Effective Area

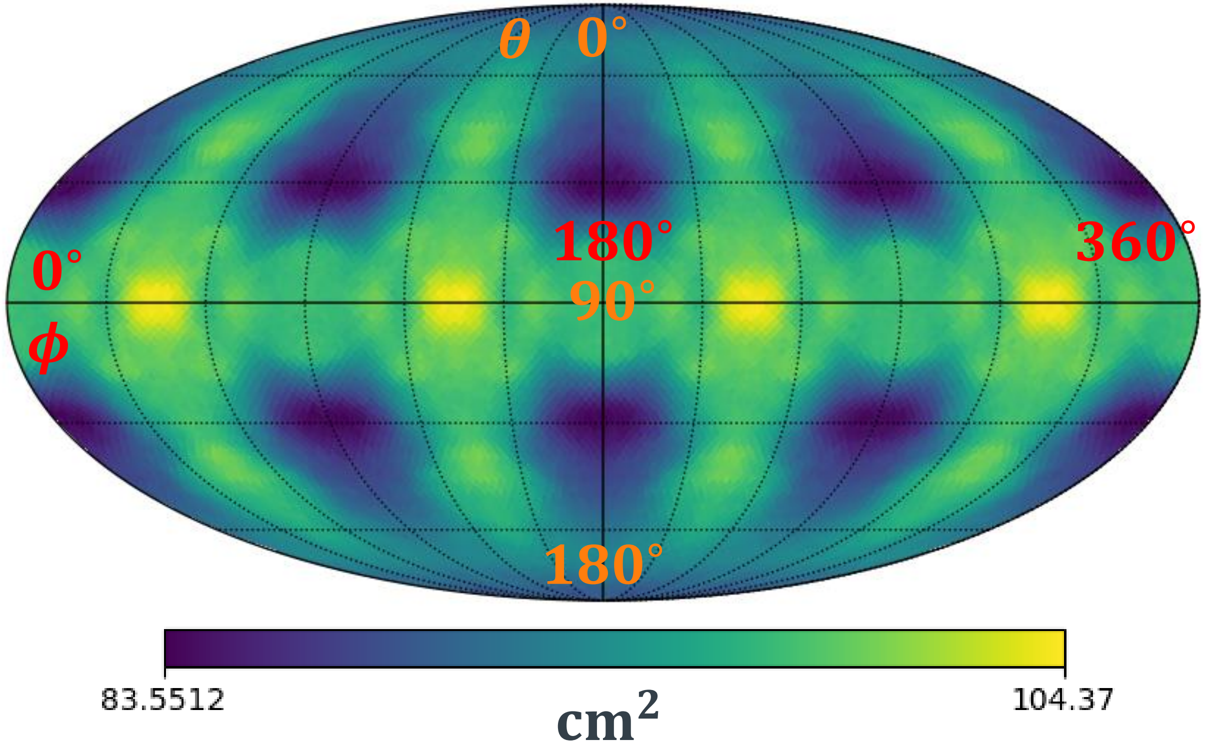
$$\boxed{A_{eff}(\lambda, \theta, \phi) = \frac{N_{det}}{N_{emit}} \cdot A_{beam}}$$

Interpretation: Area of the module if it were 100% efficient

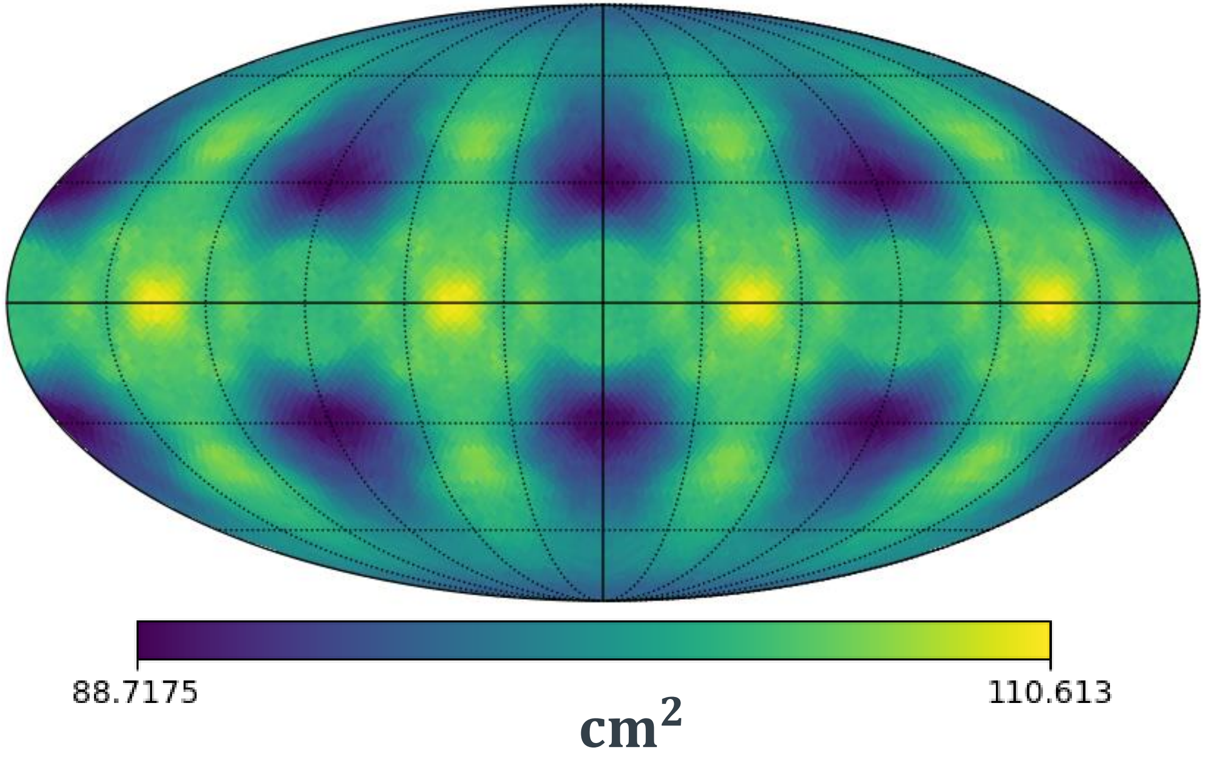


Effective Area: Comparison at 400 nm

NN $\overline{\mathrm{A}}_{\mathrm{eff}}$ =94.2 cm^2

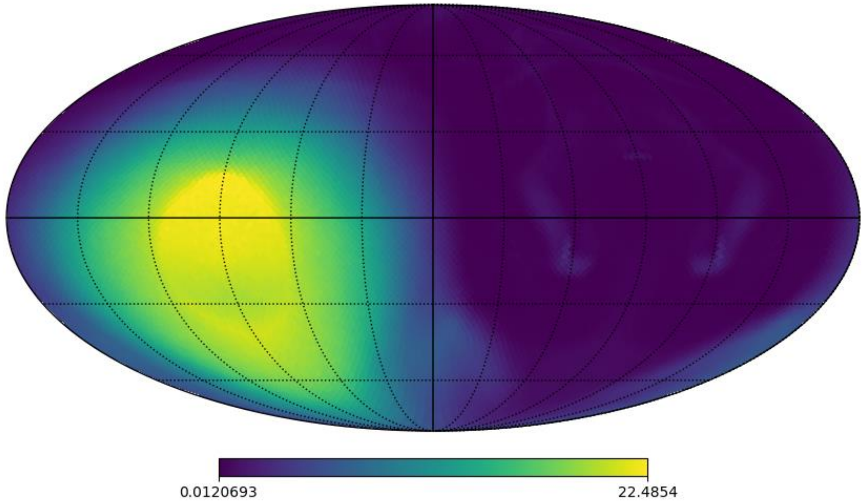


Geant4 $\overline{\mathrm{A}}_{\mathrm{eff}}$ =100.2 cm^2

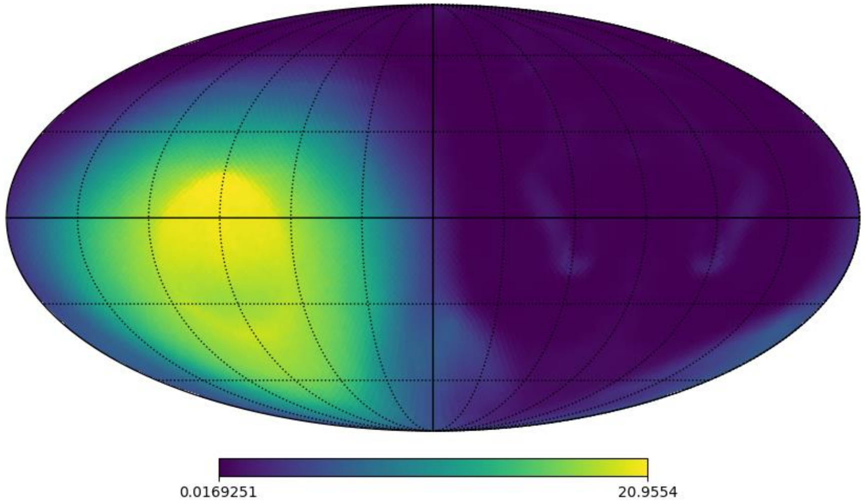


Single PMT Effective Area: Comparison at 400 nm

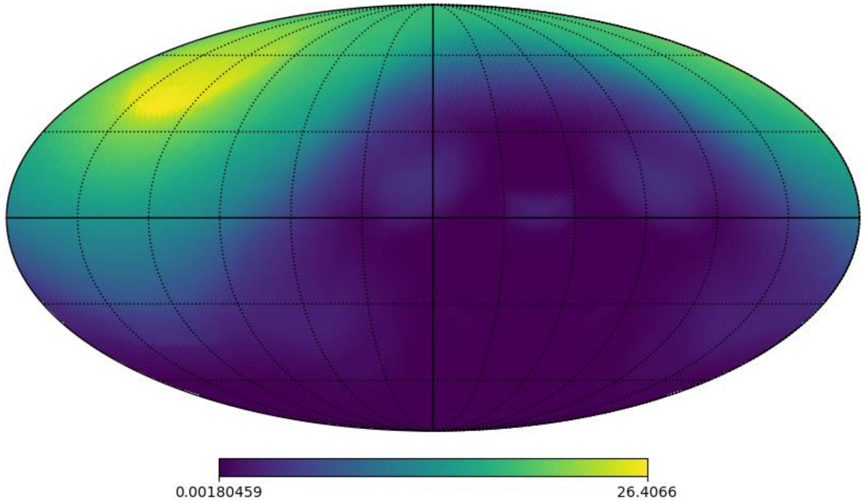
Geant4 Equatorial $\overline{\mathrm{A}}_{\mathrm{eff}} = 5.9\ \mathrm{cm}^2$



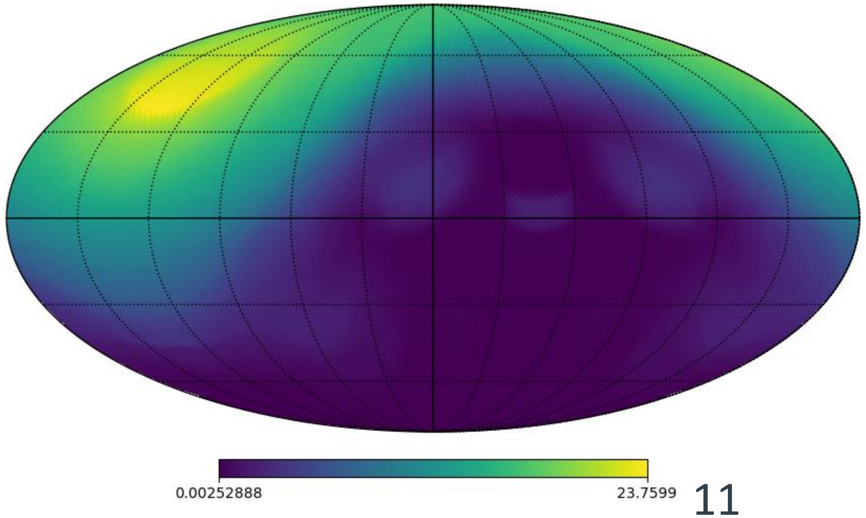
NN Equatorial $\overline{\mathrm{A}}_{\mathrm{eff}} = 5.55\ \mathrm{cm}^2$



Geant4 Polar $\overline{\mathrm{A}}_{\mathrm{eff}} = 6.62\ \mathrm{cm}^2$

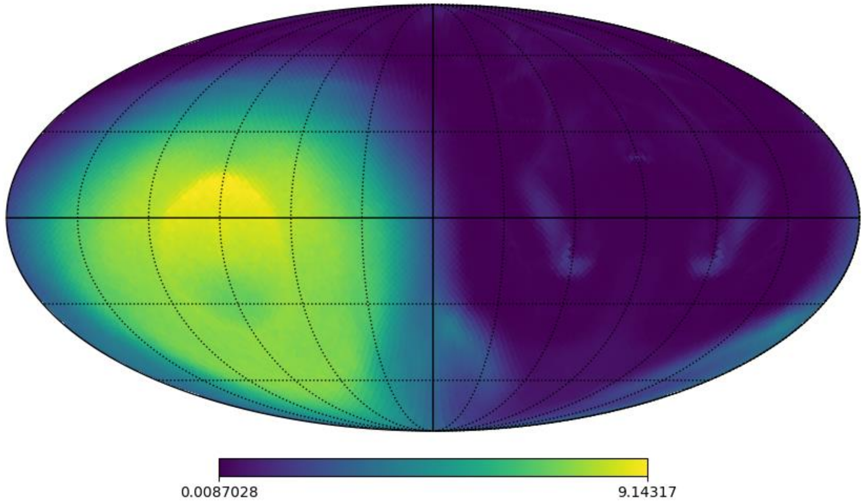


NN Polar $\overline{\mathrm{A}}_{\mathrm{eff}} = 6.23\ \mathrm{cm}^2$

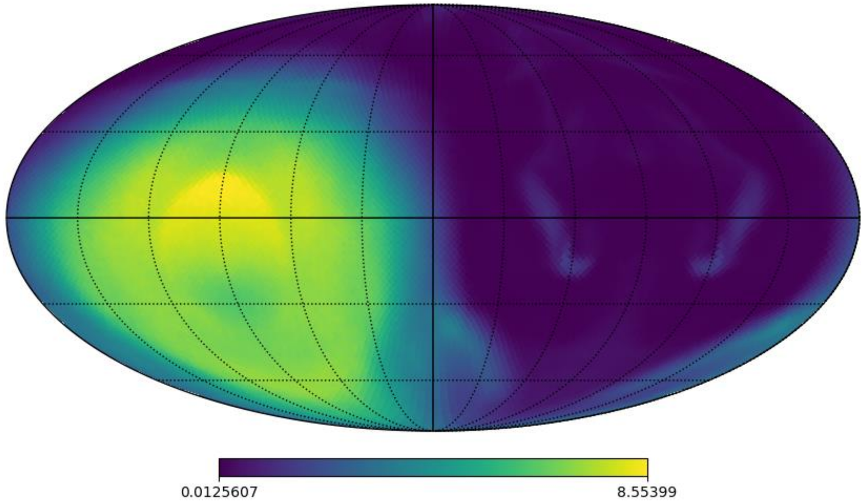


Single PMT Effective Area: Comparison at 550 nm

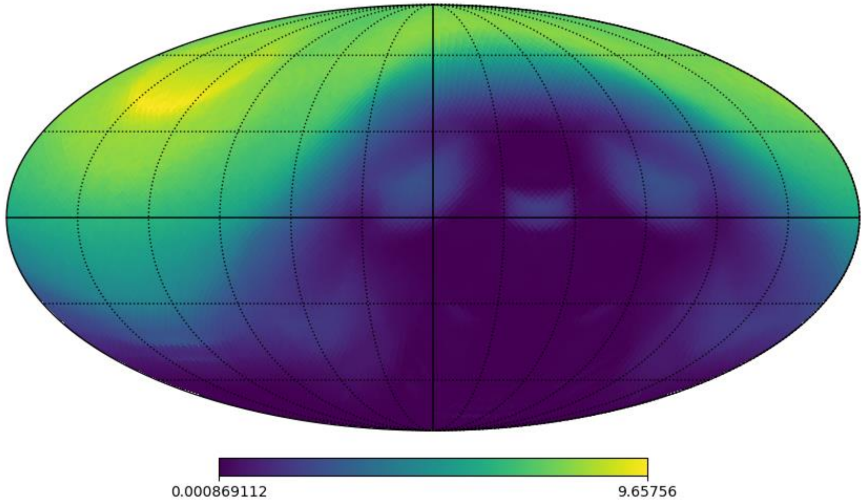
Geant4 Equatorial $\overline{\mathrm{A}}_{\mathrm{eff}} = 2.78\ \mathrm{cm}^2$



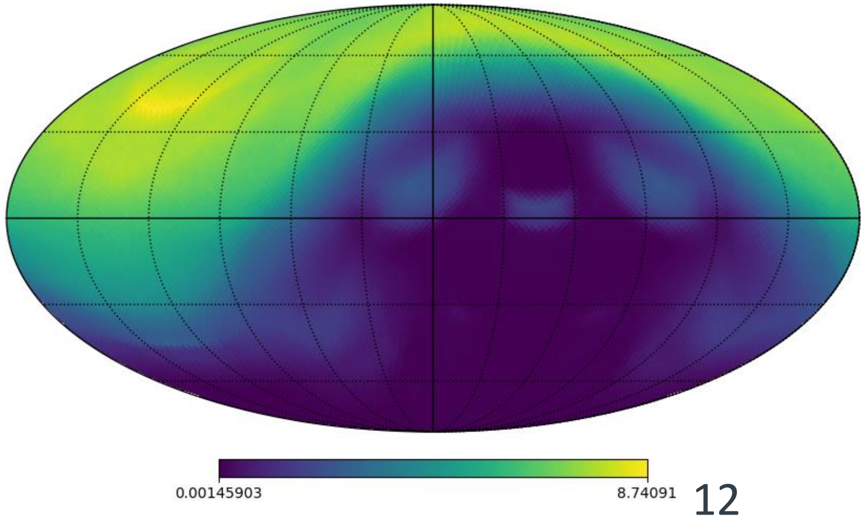
NN Equatorial $\overline{\mathrm{A}}_{\mathrm{eff}} = 2.70\mathrm{cm}^2$



Geant4 Polar $\overline{\mathrm{A}}_{\mathrm{eff}} = 3.18\ \mathrm{cm}^2$

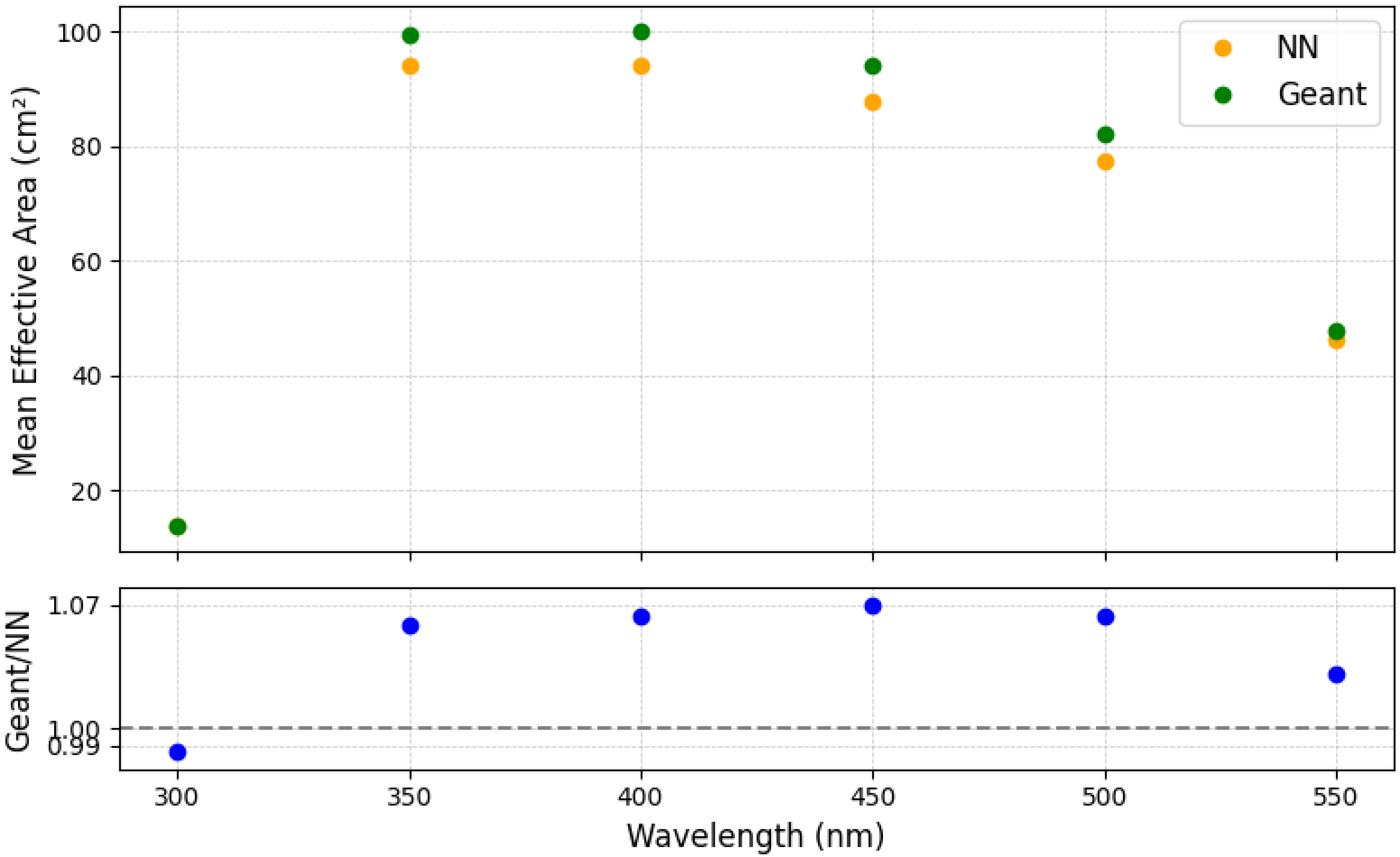


NN Polar $\overline{\mathrm{A}}_{\mathrm{eff}} = 3.09\ \mathrm{cm}^2$



Mean Effective Area vs Wavelength

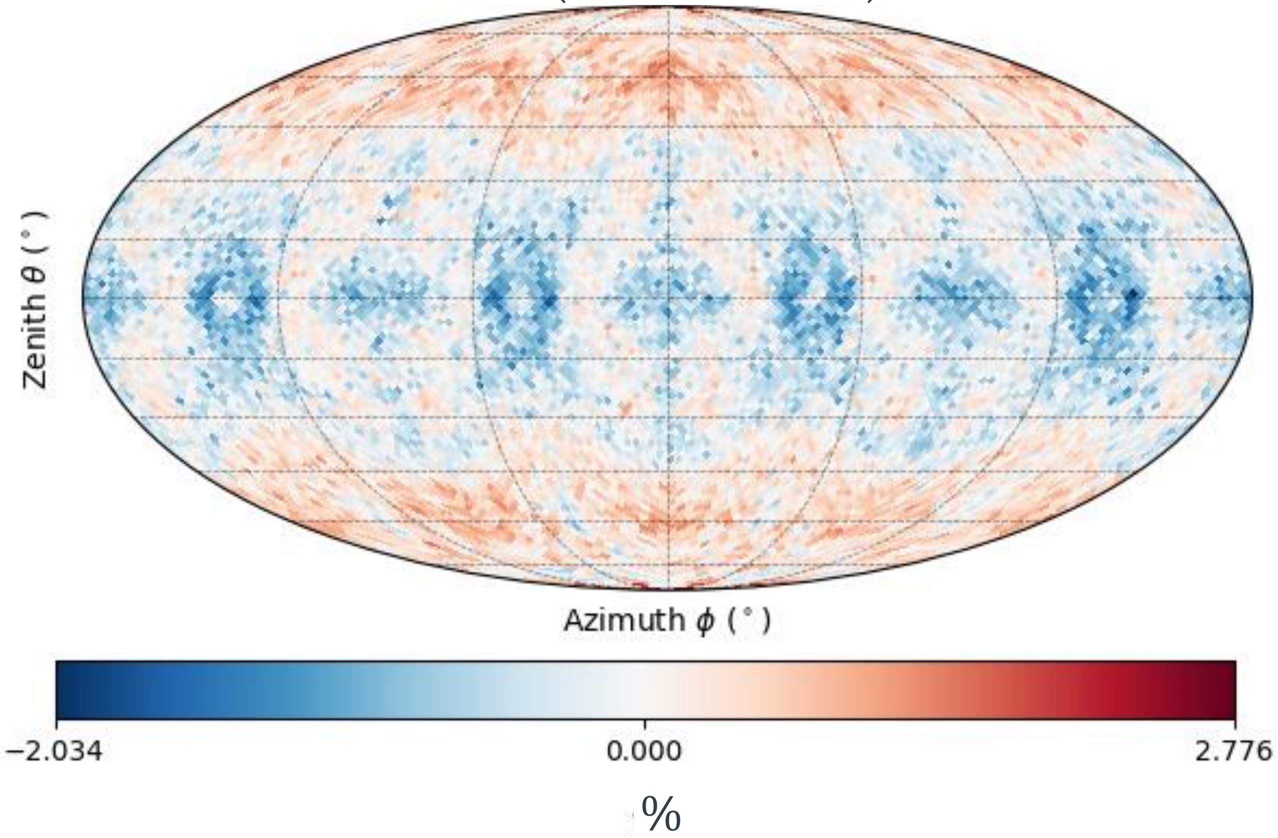
- NN underestimates probability
- Still not clear why
- Relative probability seem okay
- Scale NN predictions?



Scaled difference @ 400 nm

- NN underestimates probability
- Still not clear why
- Relative probability seem okay
- Scale NN predictions?
- Differences less than 3%:
→ Within expected module to module variations

$$(\mathrm{Geant4} - \mathrm{NN} \cdot \left(\frac{\mathrm{mean(Geant4)}}{\mathrm{mean(NN)}}\right)/\mathrm{Geant4}$$



Summary & Outlook

Summary

Gen2 OM NN-based simulation seems promising:

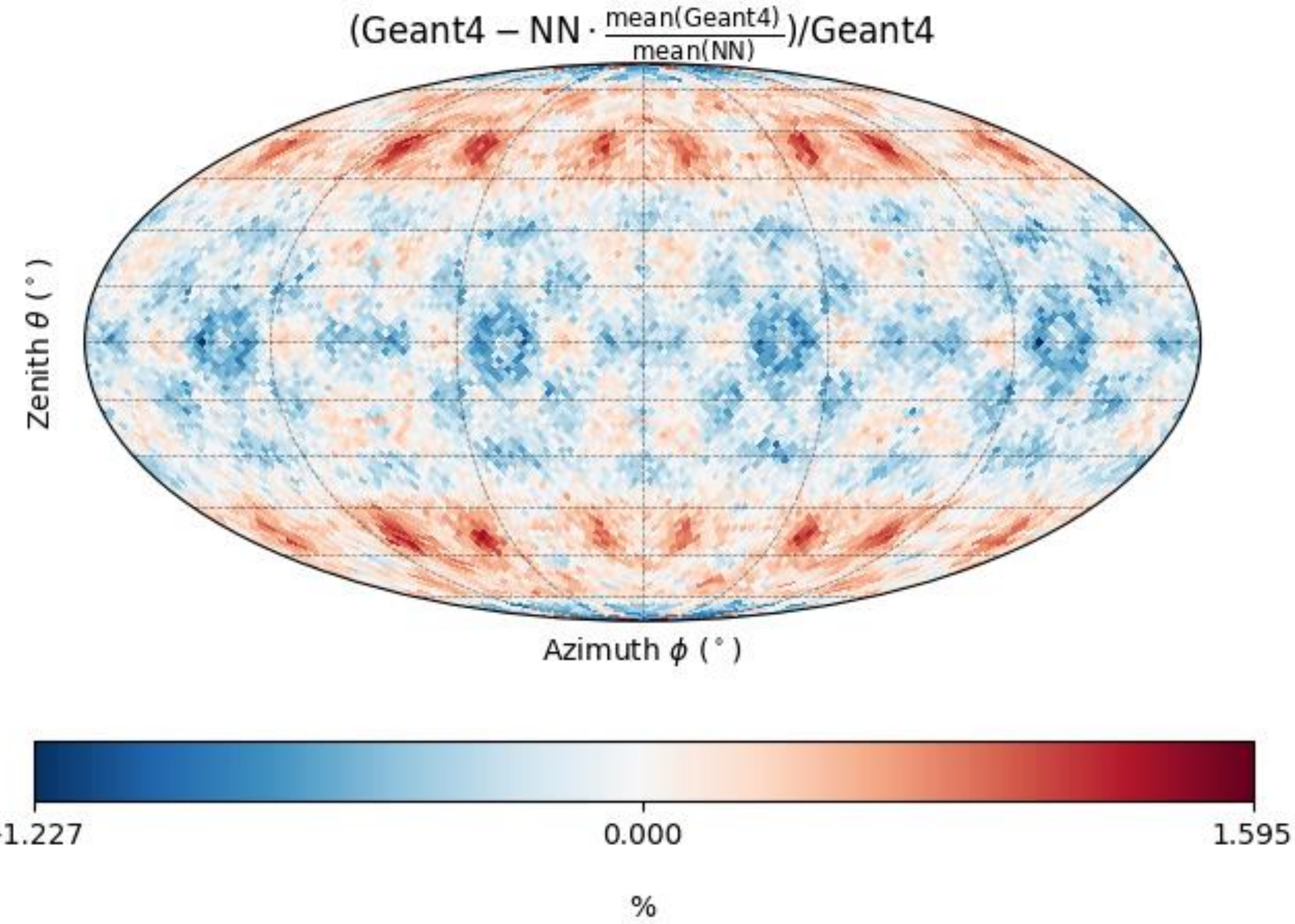
- NNs excel at interpolation of high-dimensional problems
- Use CNN with kernel size 1×1 to leverage symmetries
- Fast inference times in GPU (0.3 s / 1 million photons → expect to reduce at least by 2)

Outlook

- Take Yukiho's PR as a reference for implementation in clsim
- Optimize NN hyperparameters and architecture
- Think how oversize / hole ice could be considered
- Any feedback is very welcome

Back-Up

Scaled difference @ 550 nm

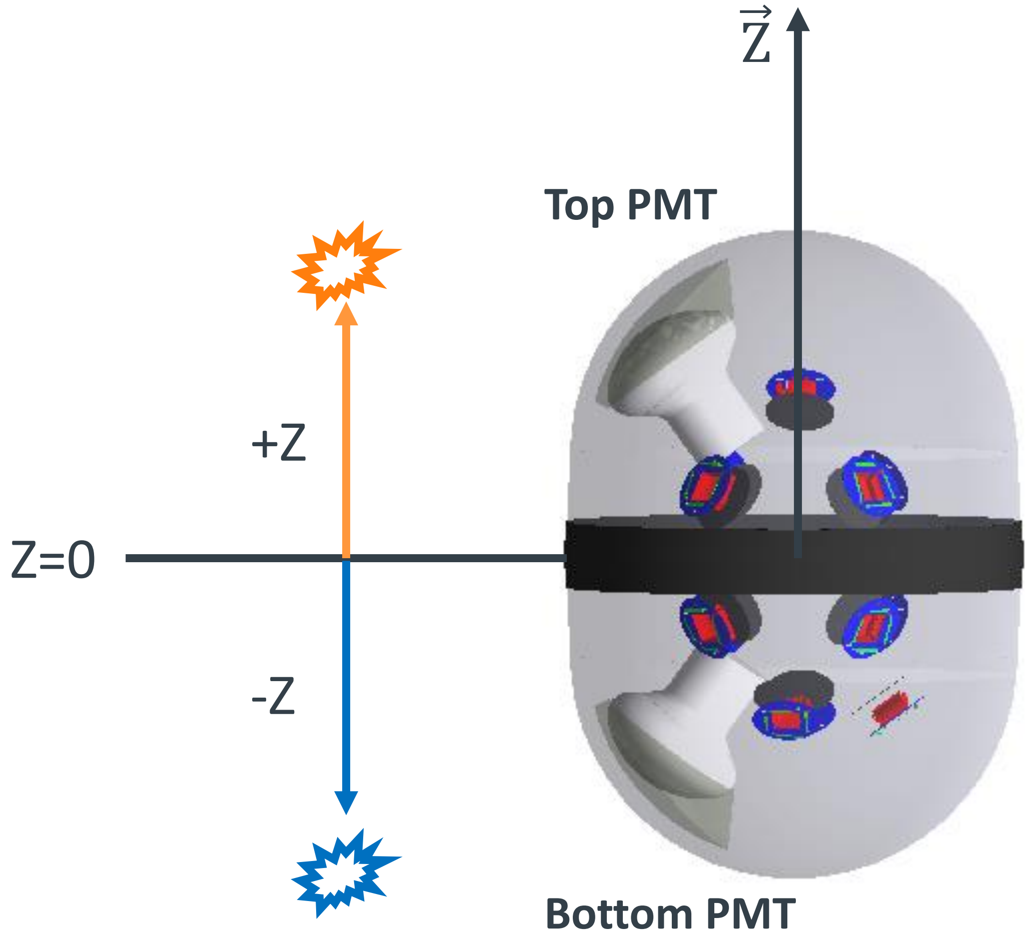


LOM16 PMT Relative Values and Symmetries

Photon Position (at least 2 values required):

1. Revert Z sign for bottom PMTs:

- Orange is to bottom PMT what blue is to top PMT
- Orange is to top PMT what blue is to bottom PMT



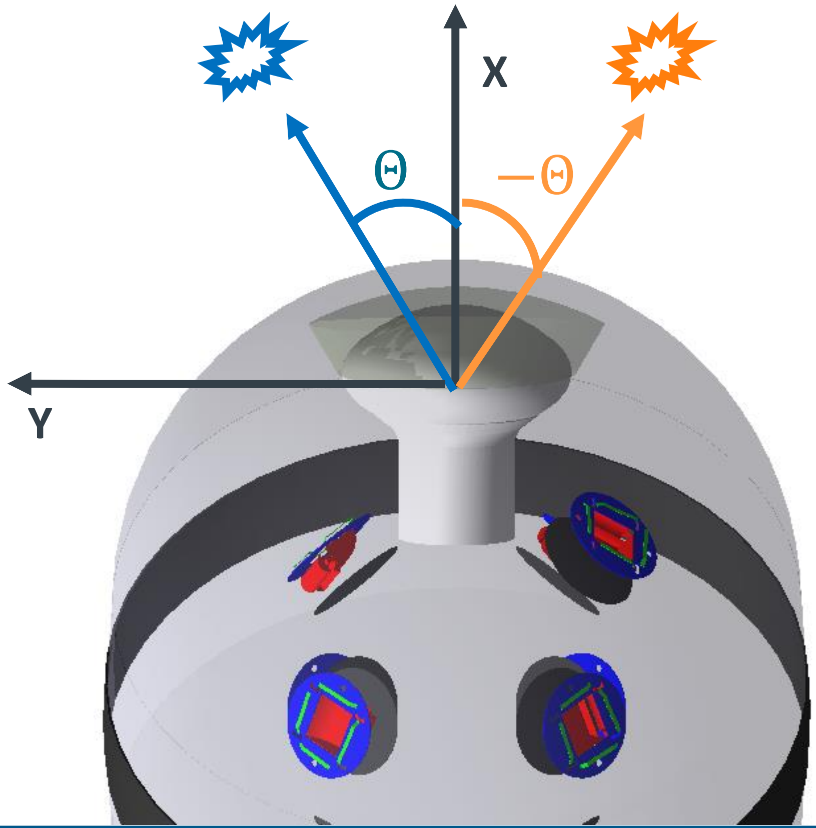
LOM16 PMT Relative Values and Symmetries

Photon Position (at least 2 values required):

1. Revert Z sign for bottom PMTs
2. Azimuth symmetry with respect to PMT symmetry axis in XY plane:

- Blue and orange are equivalent
- Give cosine of relative azimuth as an input

PMT symmetry axis



LOM16 PMT Relative Values and Symmetries

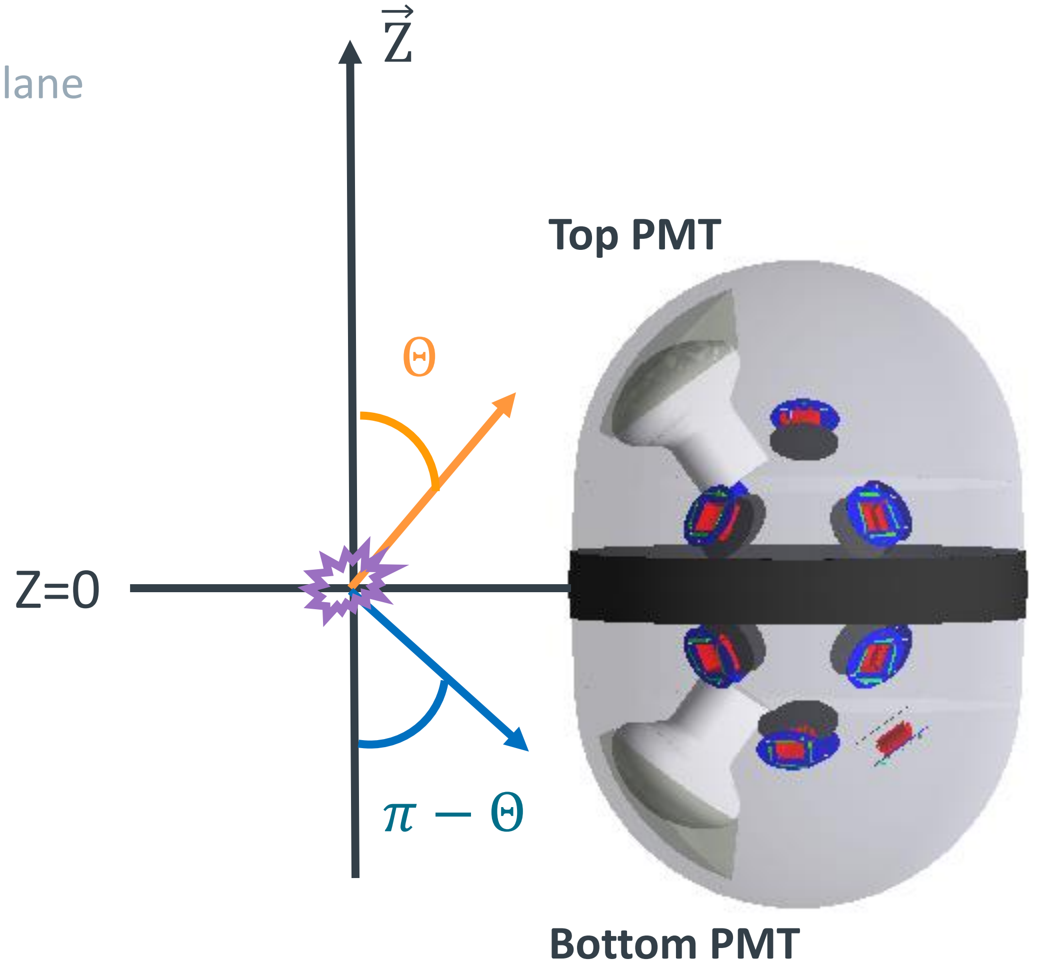
Photon Position (at least 2 values required):

1. Revert Z sign for bottom PMTs
2. Azimuth symmetry with respect to PMT symmetry axis in XY plane

Photon Direction (at least 2 values required):

1. Revert cos(zenith) sign for bottom PMTs:

- Orange is to bottom PMT what blue is to top PMT
- Orange is to top PMT what blue is to bottom PMT



LOM16 PMT Relative Values and Symmetries

Photon Position (at least 2 values required):
1. Revert Z sign for bottom PMTs
2. Azimuth symmetry with respect to PMT symmetry axis in XY plane

Photon Direction (at least 2 values required):
1. Revert cos(zenith) sign for bottom PMTs
2. Mirror symmetry in azimuth

- 1 and 3 have same azimuth, different from 2 and 4
- 2 and 3 are equivalent, same goes for 1 and 4
- Give cosine of relative azimuth as input
- Identifier telling whether direction points to PMT as input

→ will the photon get closer to PMT's "y" in the next step?

PMT symmetry axis