Friedrich-Alexander-Universität
Erlangen-Nürnberg

SWGO The Southern Wide-field Gamma-ray Observatory

ecap Erlangen Centre for Astroparticle Physics

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Energy reconstruction for SWGO with Graph Neural Networks

Franziska Leitl

High-energy astrophysics in the multi-messenger era

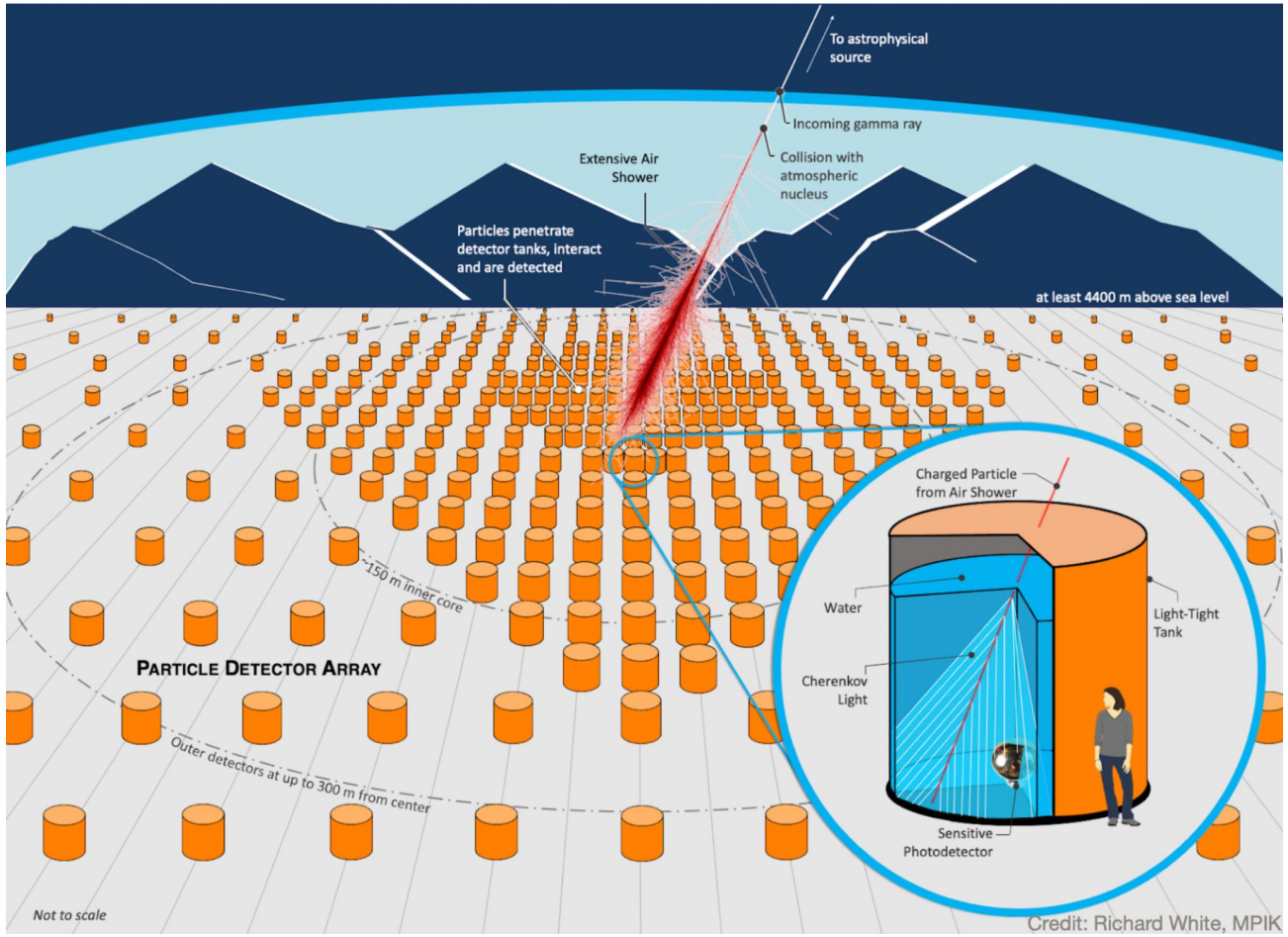
Erlangen Centre for Astroparticle Physics (ECAP)

08.04.24

The Southern Wide-field Gamma-Ray Observatory (SWGO)

- Future particle detector array located in South America
- Ground-level water-Cherenkov detector array
- Energy range from hundreds of GeV up to PeV
- Altitude above 4.4 km and latitude between 10° and 30° South

SWGO
The Southern Wide-field
Gamma-ray Observatory



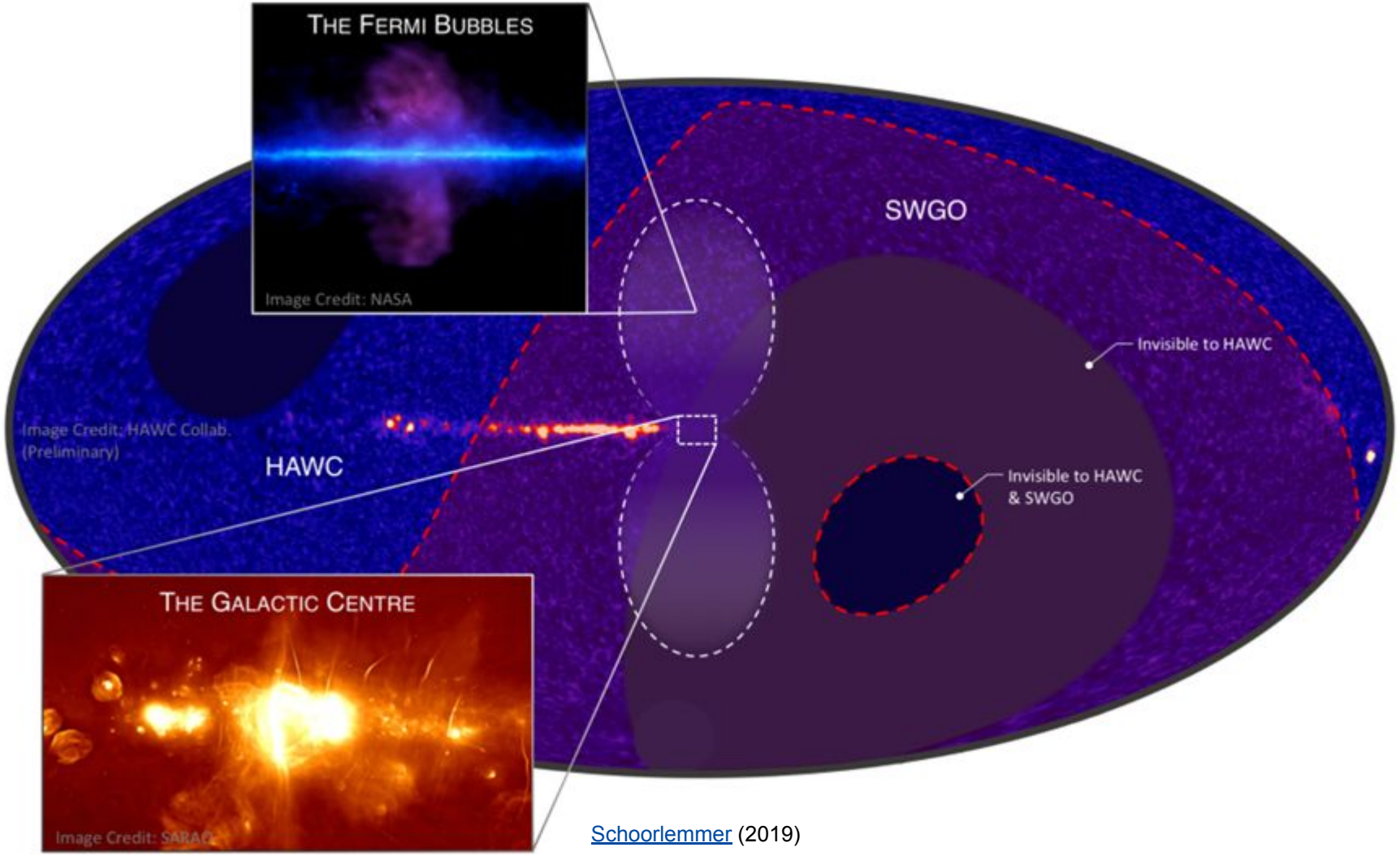
SWGO (2024)

The Southern Wide-field Gamma-Ray Observatory (SWGO)

Scientific prospects:

- Very extended gamma-ray emission sources
- Transient sources
- Primordial black holes
- Galactic accelerators
- And many more

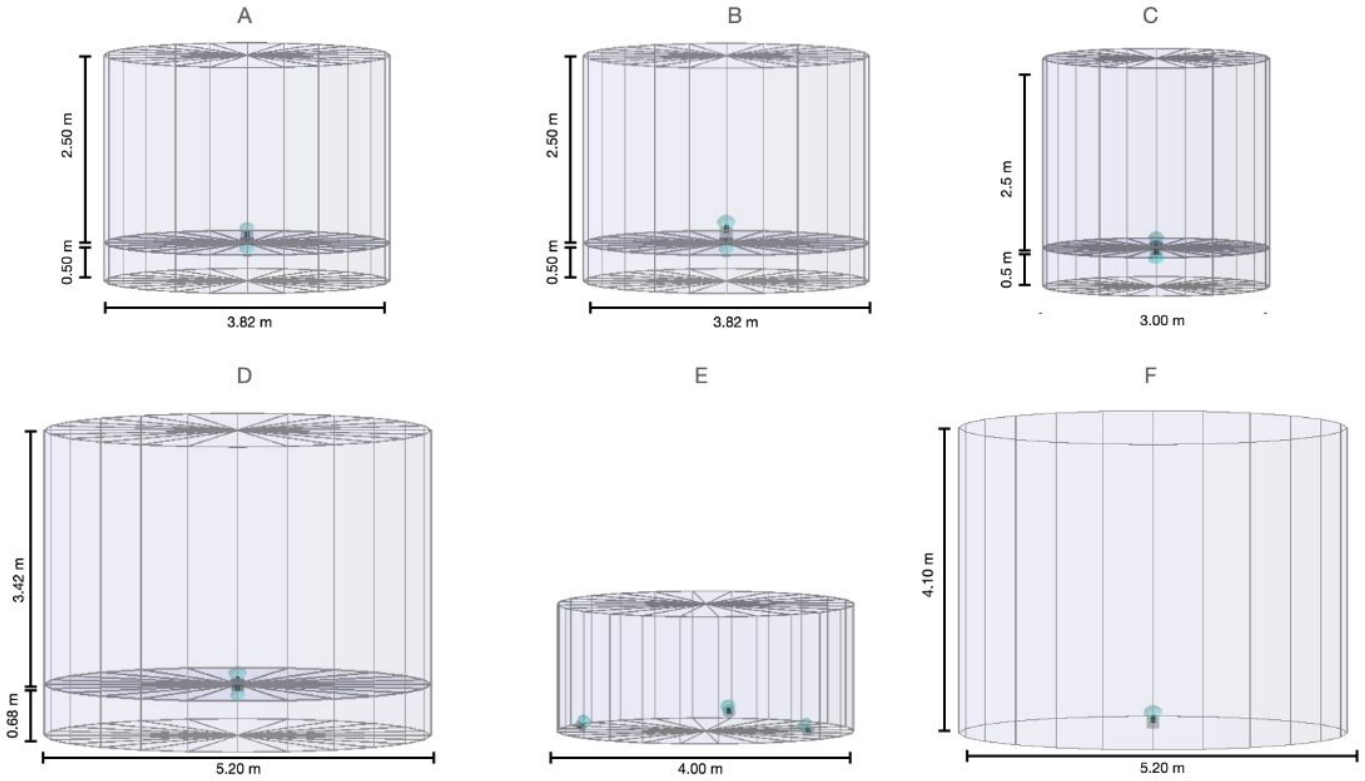
→ Extending current generation instruments to the Southern hemisphere



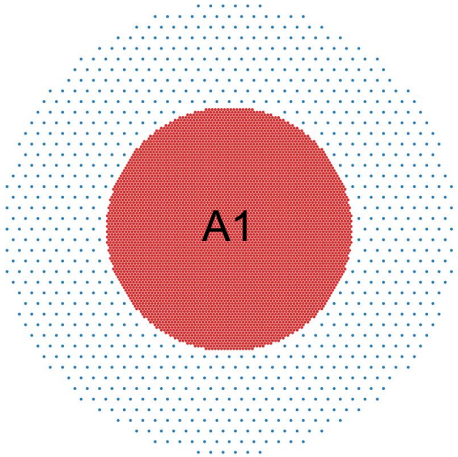
Schoorlemmer (2019)

R&D phase: detector design and array layout

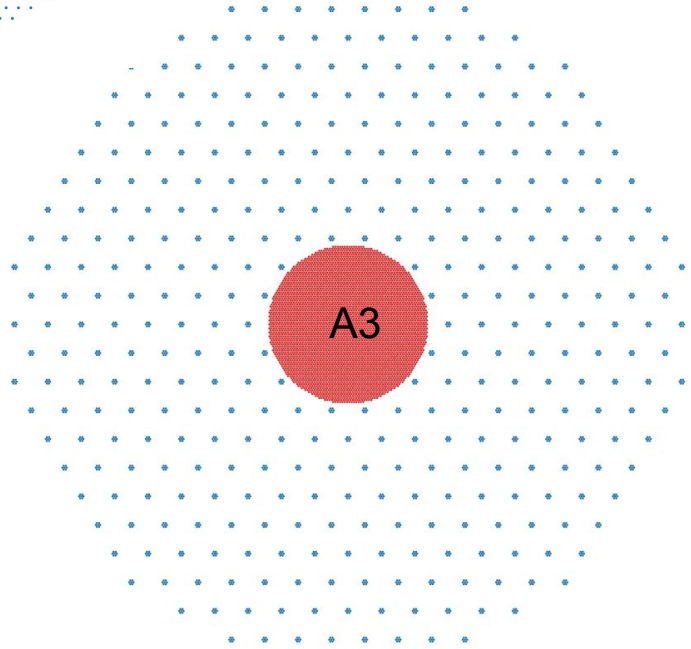
→ Explore design phase-space to find the optimal design for SWGO given fixed costs



SWGO internal document (2022)



and more …



Energy reconstruction for SWGO

Throwback to last time

Current standard method to reconstruct the energy and core for SWGO

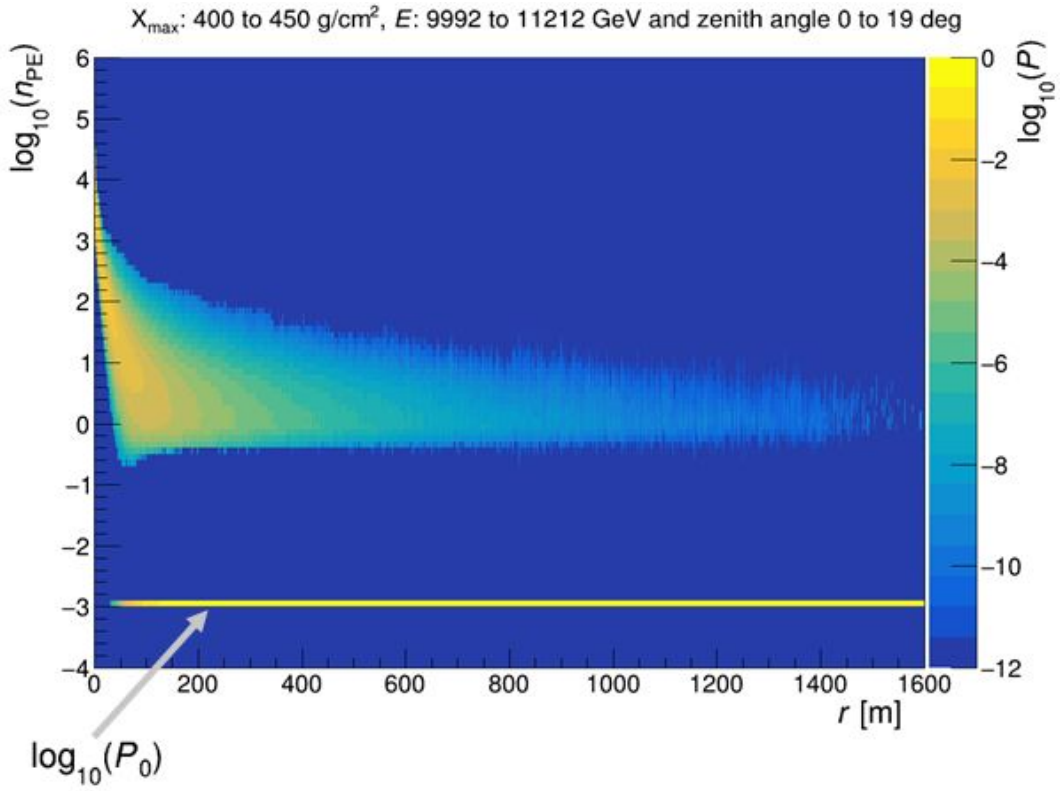
Template-based reconstruction:

- Templates:
  MC simulations of gamma-induced EAS binned in E, X_{max}, θ

- Reconstruct incoming shower:
  Fit LDF of the shower to the templates

- Minimise log-likelihood to get best fit parameters

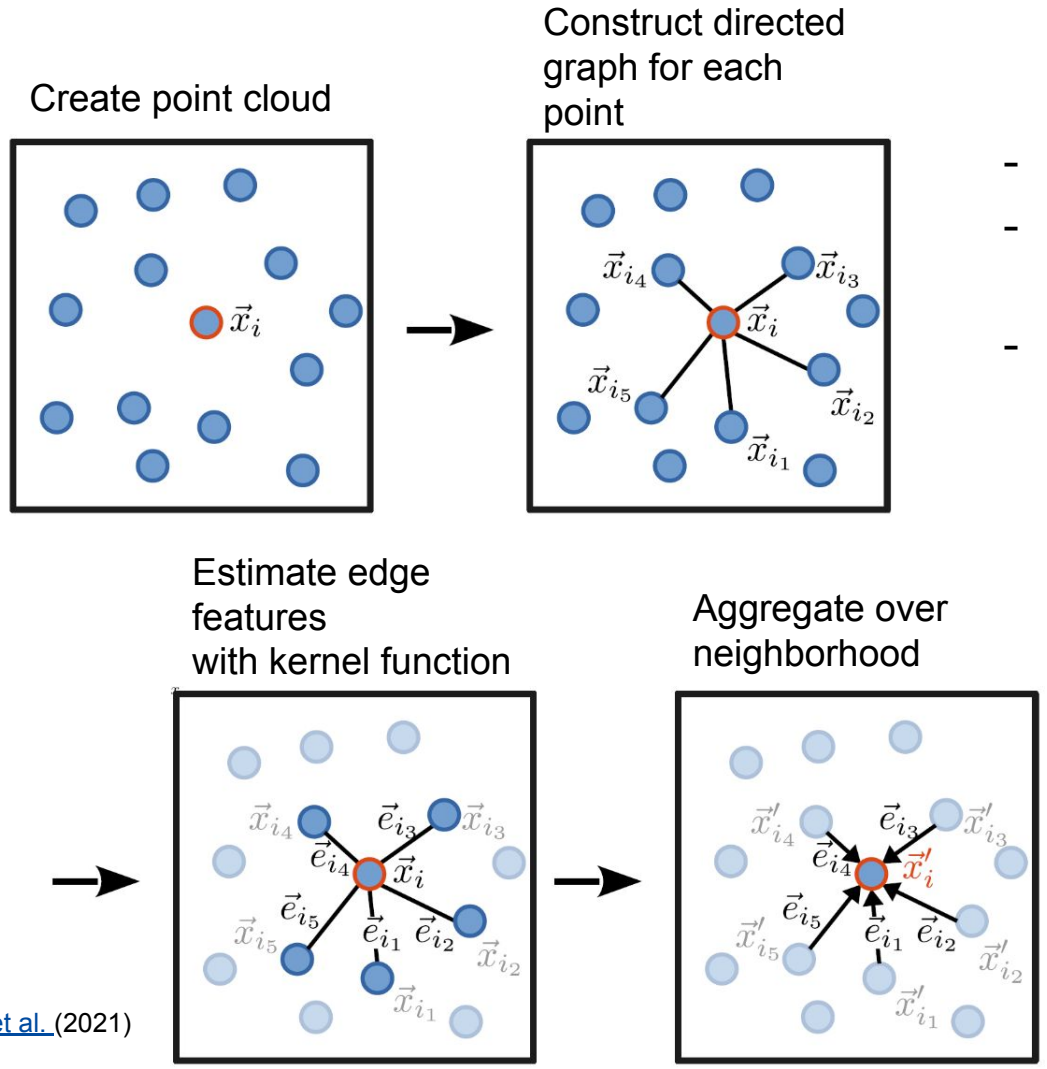
$$\log L = -2 \sum_i \log(F(\log_{10}(N_{\mathrm{PE}})_i, r_i, X_{\mathrm{max}}, E|\theta, \phi))$$



→ Successfully implemented the module as current standard method to reconstruct energy for SWGO

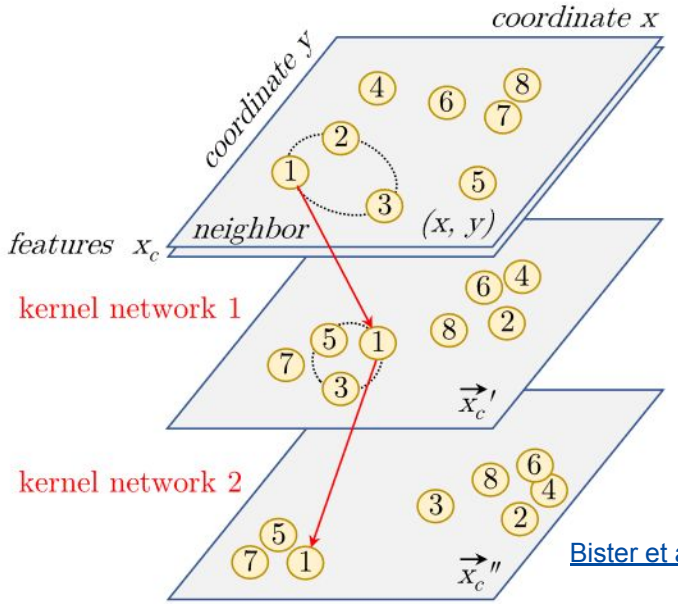
Energy reconstruction with Graph Neural Networks (GNNs)

Graph Neural Networks (GNNs)



Erdmann et al. (2021)

- Machine learning approach
- GNN as state-of-the-art method to analyze data distributed on non-regular domains/grids
- Utilize EdgeConvolutions and DynamicEdgeConvolutions

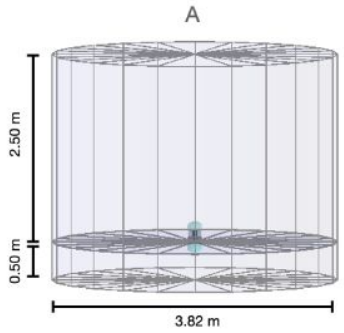


Bister et al. (2021)

Energy reconstruction with GNNs

Network structure

- Network based on ParticleNet
- Features: x_{pos}, y_{pos}, t_{low}, t_{up}, S_{low}, S_{up}
- EdgeConvolution block (nearest neighbours: k = 6)
- DynamicEdgeConvolution blocks (nearest neighbours: k = 16)



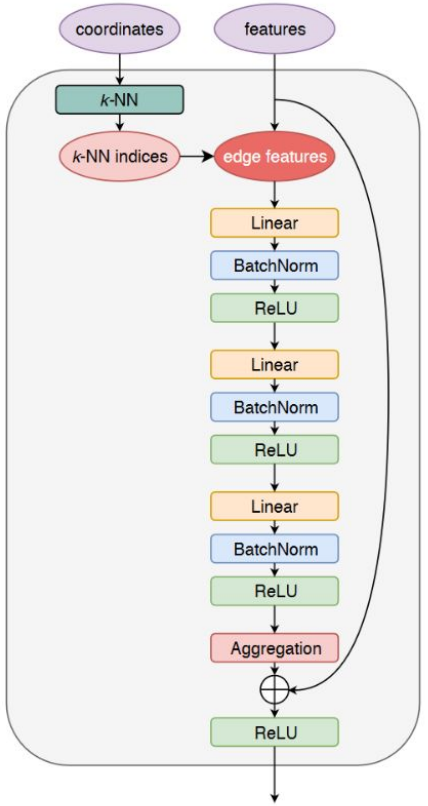
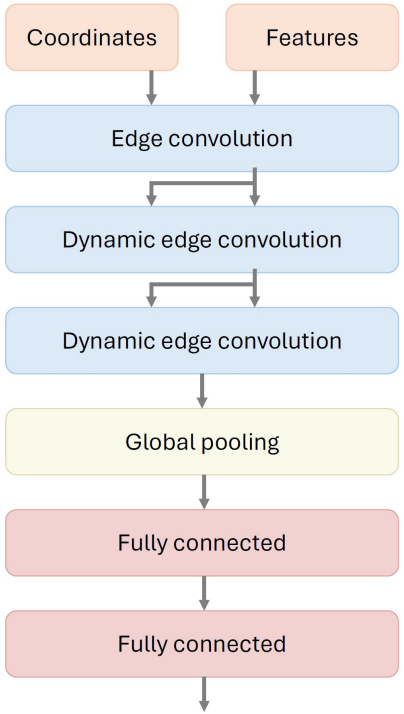


FIG. 1: The structure of the EdgeConv block.

Qu, Gouskos (2020)

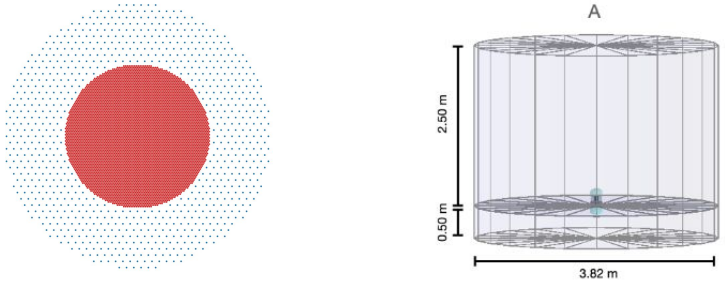


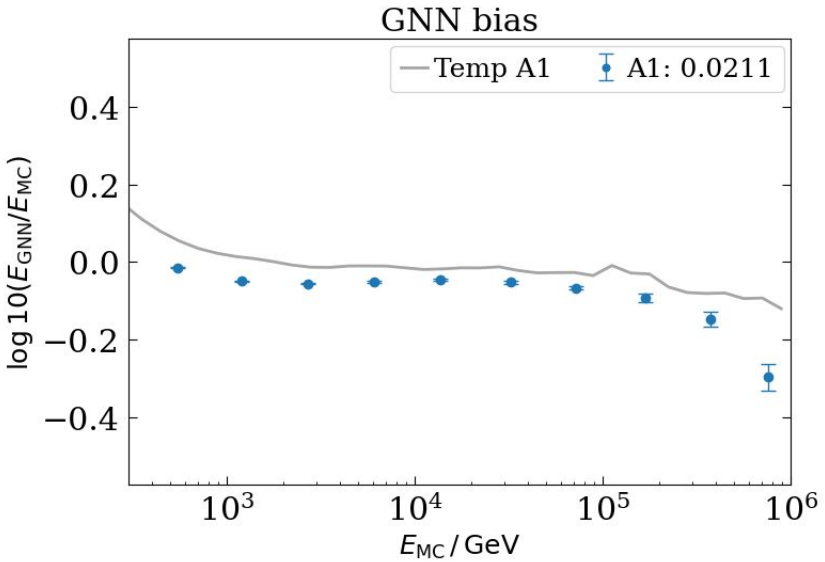
Energy reconstruction with GNNs

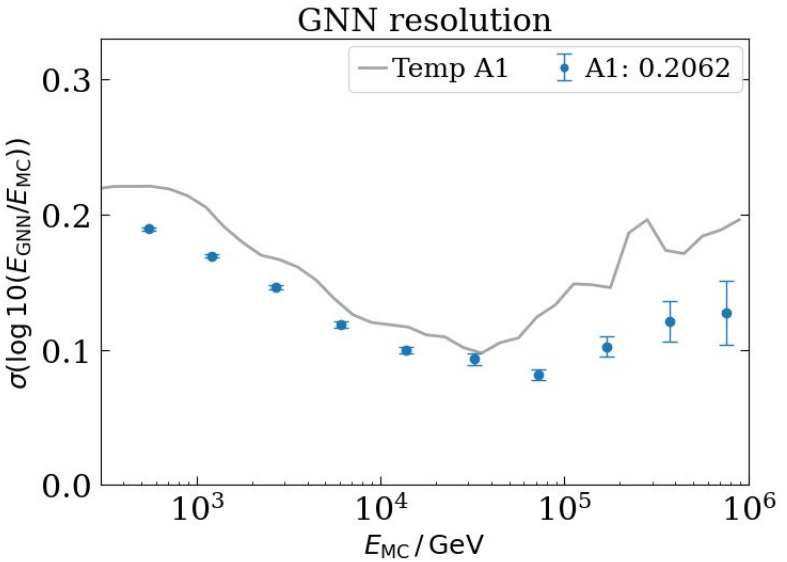
Results for one test configuration

Cuts applied after reconstruction:

- $r < 300$ m
- $\theta < 45$ deg
- $N_{hit} > 25$
- Additional cut on likelihood value for template results



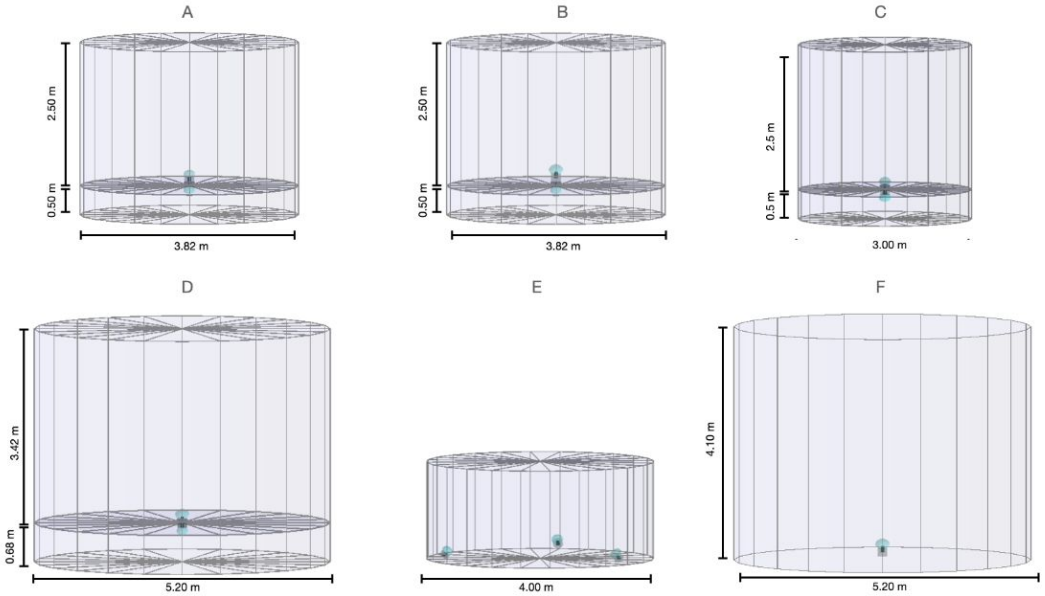


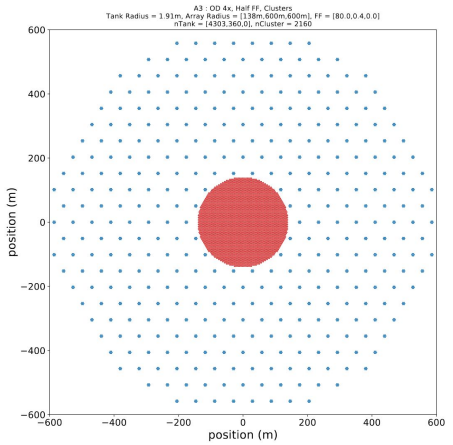


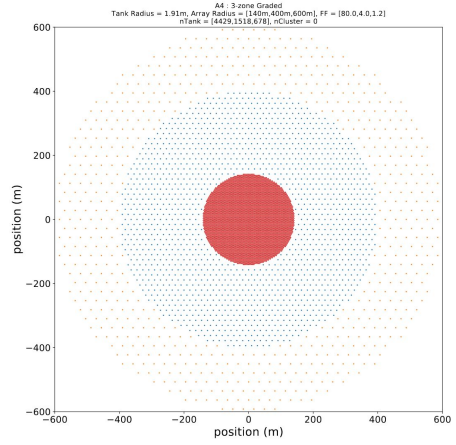
→ Successful energy reconstruction with GNNs for the first test configuration

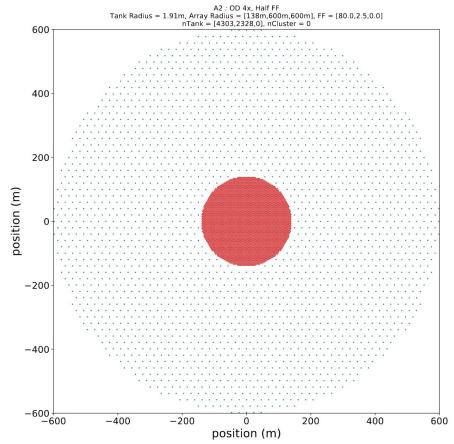
→ Performance comparable to standard method / seems to show improvements especially in the higher energies

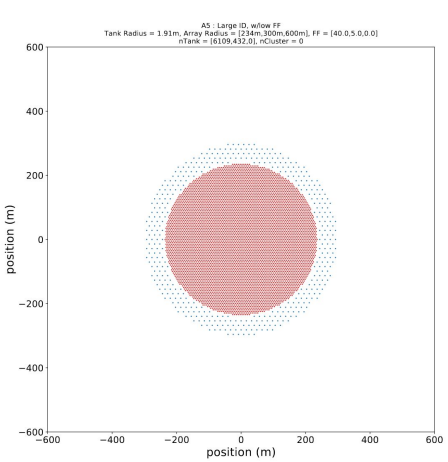
R&D phase: detector design and array layout

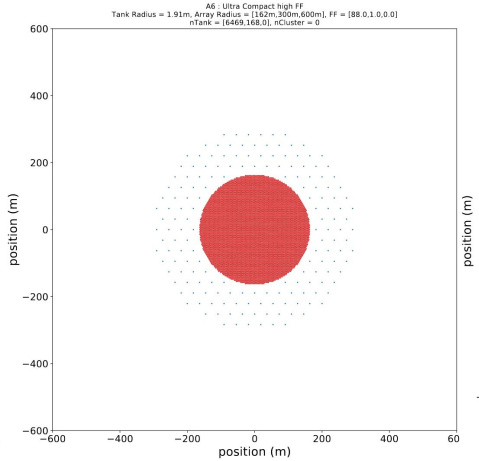


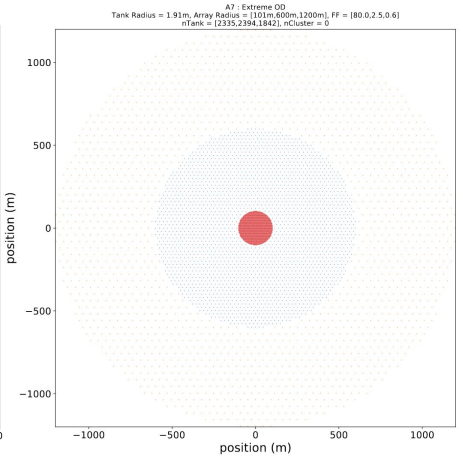


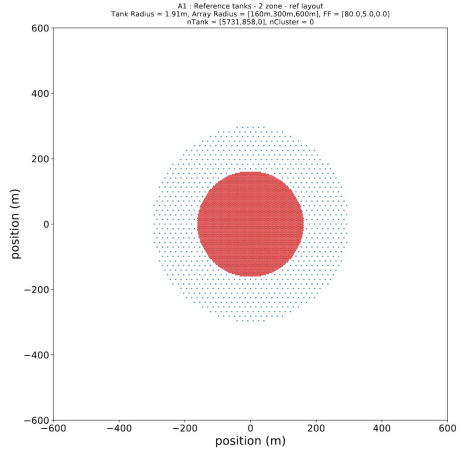












SWGO internal document (2022)

Energy reconstruction with GNNs

Hyperparameter search for all test configurations

- Features: x_{pos}, y_{pos}, t_{low}, t_{up}, S_{low}, S_{up}
- EdgeConvolution block(s) (nearest neighbours: k = 6)
- 2 DynamicEdgeConvolution block(s) (nearest neighbours: k = 16)
- Vary:
  - Dropout
  - Number of EdgeConvolution
  - kNN for DynamicEdgeConvolutions

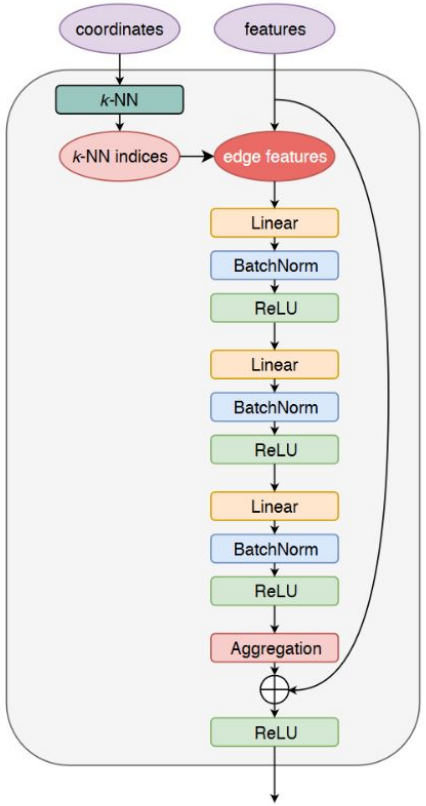
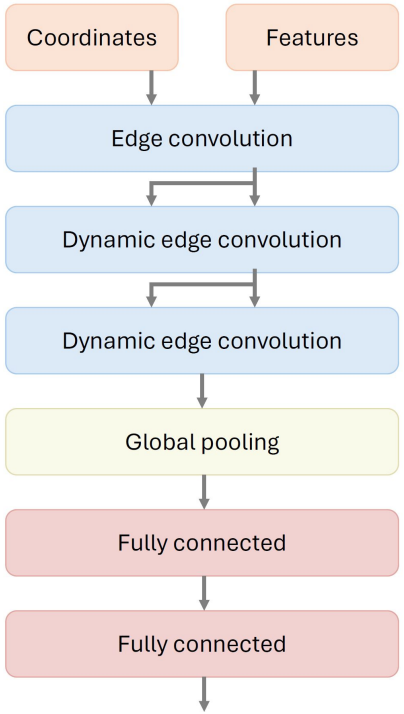


FIG. 1: The structure of the EdgeConv block.

Qu, Gouskos (2020)



Energy reconstruction with GNNs

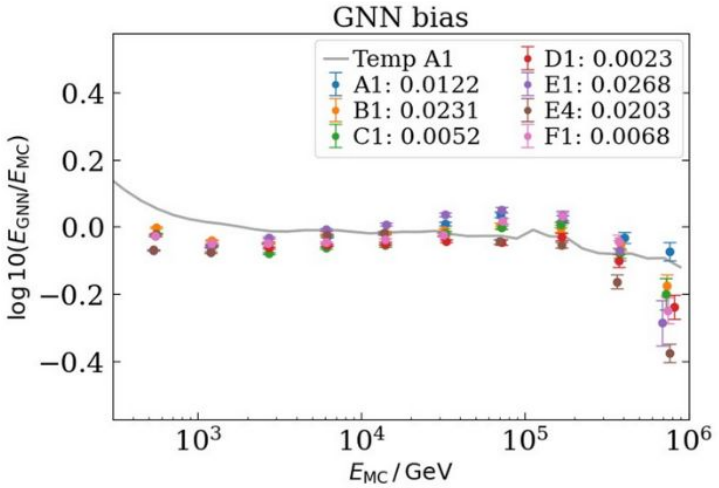
Results of hyperparameter search

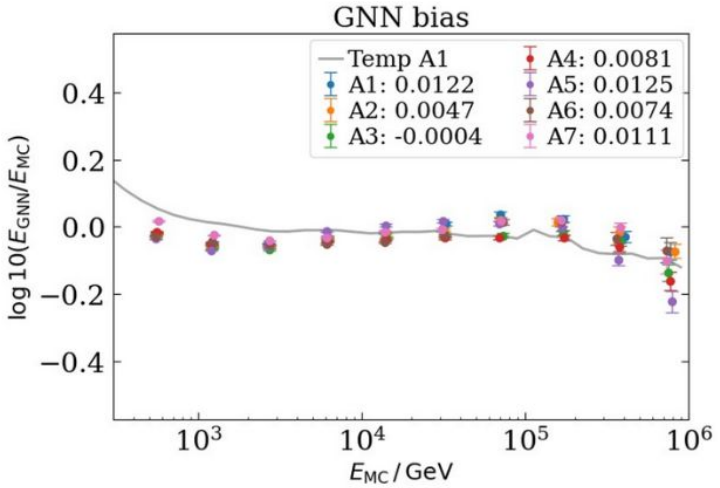
Cuts applied after reconstruction:

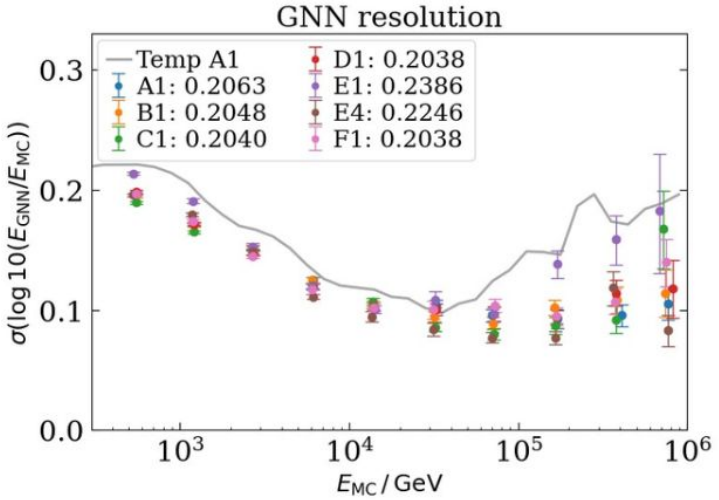
- $r < 300$ m
- $\theta < 45$ deg
- $N_{hit} > 25$
- Additional cut on likelihood value for template results

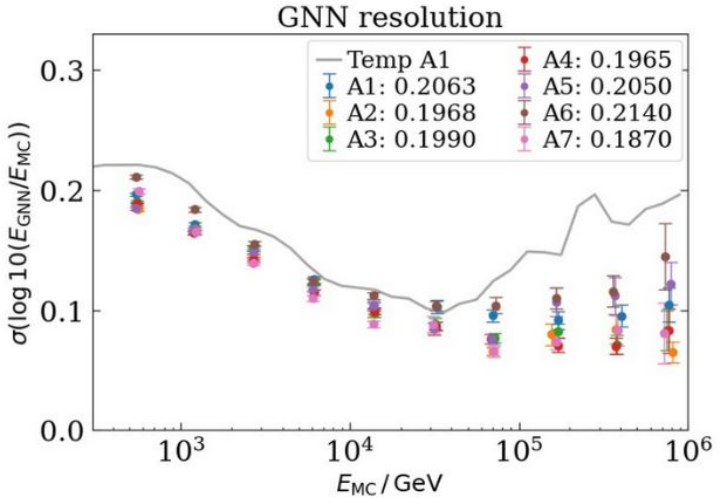
→ Template-based and GNN methods provide reliable reconstruction over 4 magnitudes of energy

→ GNN exhibits improvements particularly at high energies for all current test configurations







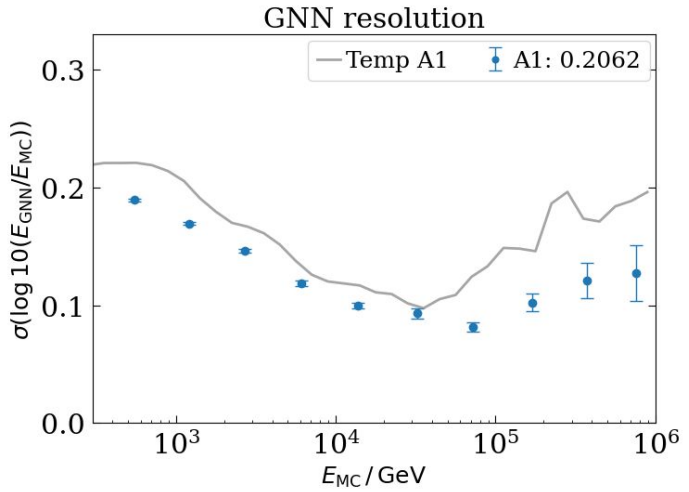


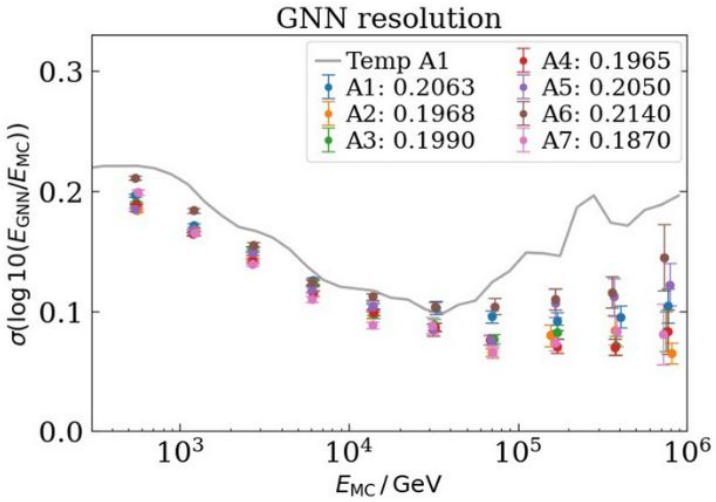
Energy reconstruction with GNNs

Summary:

- Investigation of event reconstruction for SWGO
- Developed template-based method for SWGO
- Developed graph neural network for SWGO energy reconstruction
- Implemented GNN and templates for all given designs and layouts
  → will support finding optimal observatory design

→ GNN shows promising improvements over template-based methods





Outlook:

- Refine GNN architecture
- Implement direction and core reconstruction for GNN
- Investigate event-by-event uncertainty estimates for GNN reconstruction

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Thank you for your attention!

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