SIMULATION STUDY ON HIGH-RESOLUTION MUON TOMOGRAPHY OF A SPENT NUCLEAR FUEL STORAGE CASK

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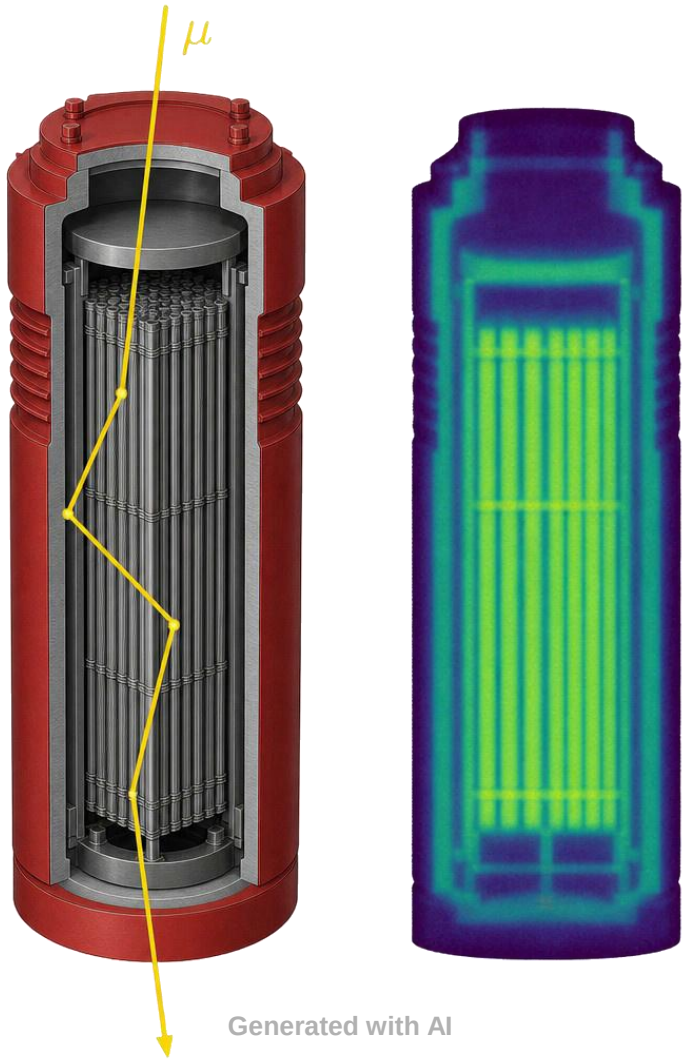
DLR

The story of muon tomography & nuclear storage casks

- Inspection of nuclear storage casks and its interior is difficult due to heavy shielding for radiation protection measures
- Muon tomography is currently only viable option to image the cask and its interior in a 3D and reliable way
- Previous studies successfully proved feasibility to reconstruct partial and full fuel assemblies using simulation and experimental data
- Complete and definite cask inspection however requires ability to reconstruct and detect single fuel rods
- Necessity for imaging resolution of less than 2 millimeters



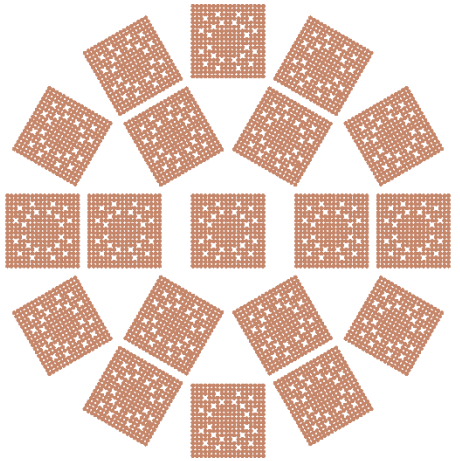
The CACTUS project

- **C**ask **A**nalysis with **C**osmic-ray **T**omography for **U**pgraded **S**afety
- Cooperation between BGZ and DLR
- Main goals of simulation-driven feasibility study:
  - Creation of detailed model of CASTOR V/19 nuclear storage cask suitable for simulations
  - Development of suitable muon scattering reconstruction method to allow for sufficient imaging resolution
  - Detection of single fuel rods with machine learning support

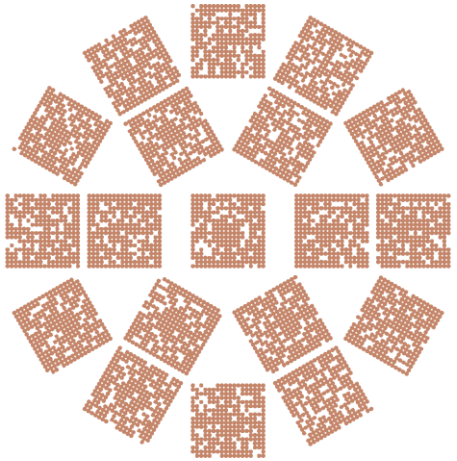
Source: GNS.de

The CASTOR model

- Goal: Keep as many details as possible without increasing simulation runtime
- Using DLR-developed B2G4 tool – see yesterday's talk of Felix Sattler [LINK]
  - Allows direct import of high-fidelity 3D models into Geant4 simulation framework
  - Optimizes simulation runtime by using native Geant4 object shapes
  - Options to randomize various parameters of scene
- Three test scenes:
  - Empty cask: no fuel rods
  - Full cask: all fuel rod positions occupied
  - Missing rods: 90% of fuel rod positions randomly occupied



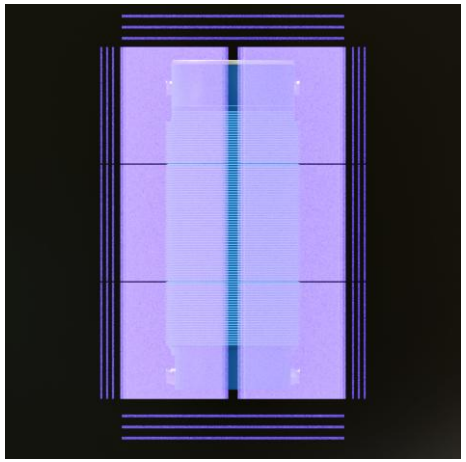
Full cask

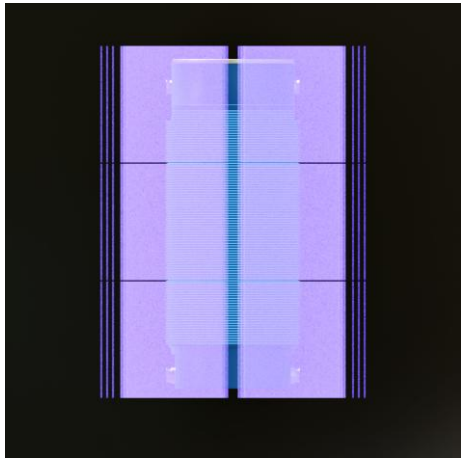


Missing rods

The simulation setup

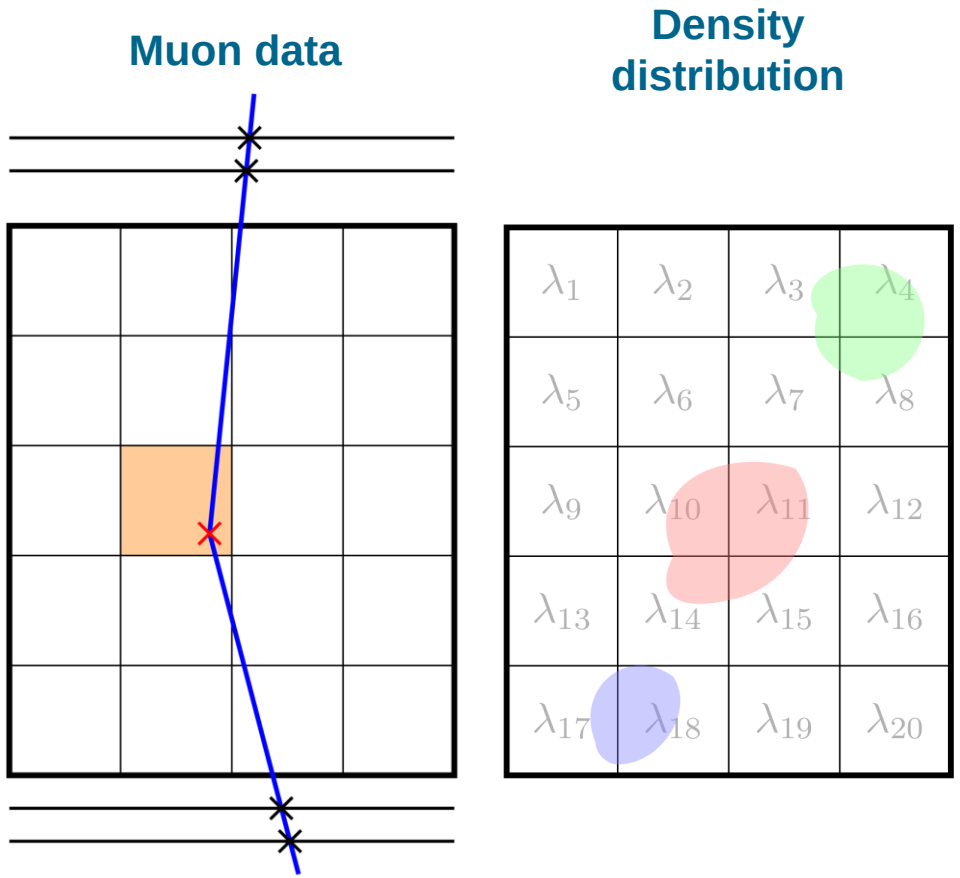
- Geant4 simulation toolkit with hemispherical EcoMug muon generator
- Effective measurement time of 75 h for each model scenario
- Detector setup:
  - Three configurations: top & bottom, sides only, top & bottom & sides
  - Following results will be based on top & bottom & sides setup for best possible measurement conditions
  - Side note: Side detectors seems to be more important than top & bottom detectors
  - Three detection layers per detector
  - Assumption of perfect detection efficiency and resolution in each layer





The reconstruction approach

- Common geometric reconstruction methods are not able to resolve sub-centimeter details
- Such fine resolution requires more sophisticated approaches, such as statistical methods
- Method works by maximizing likelihood function depending on density distribution model λ and data
- Millions of voxel require very efficient implementation of computing intensive algorithm
- Using automatic differentiation with gradient descent in PyTorch – see yesterday's talk of Jean-Marco Alameddine [LINK]

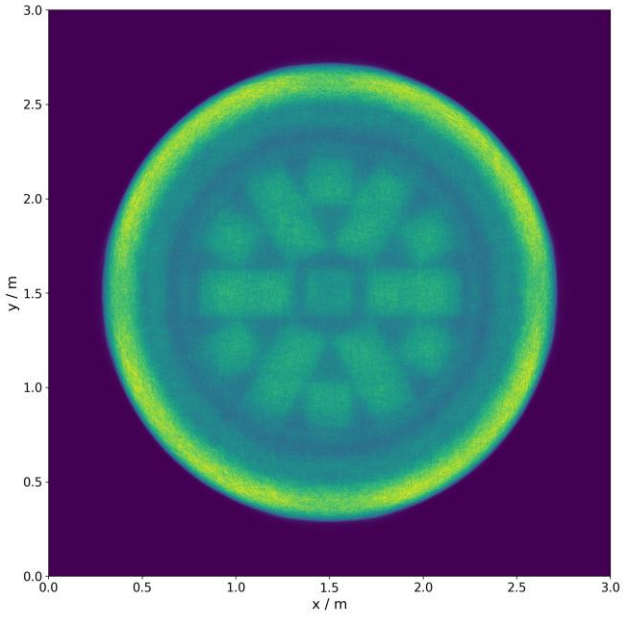


Muon path based on PoCA assumption

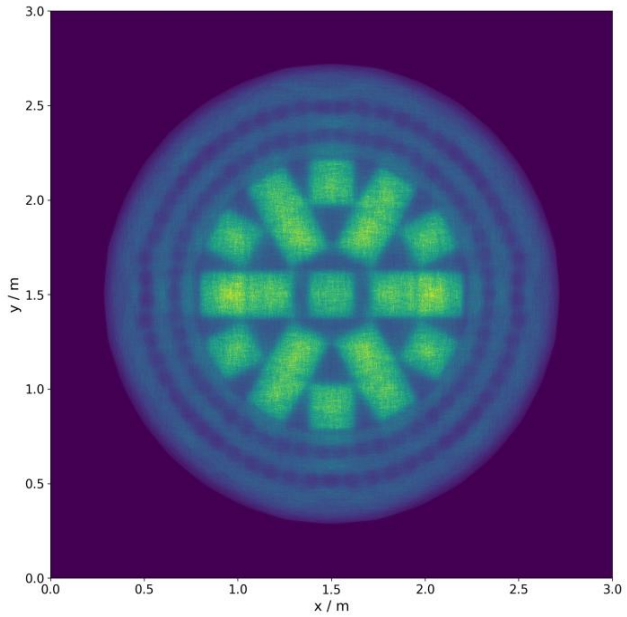
The reconstruction approach

- Voxel dimensions: 1.5 mm in X- & Y-direction, 50 cm in Z-direction
- Utilizing the muon momentum information to correct scattering angles for optimized results
- Clear depiction of detailed structures preserved through entire cask

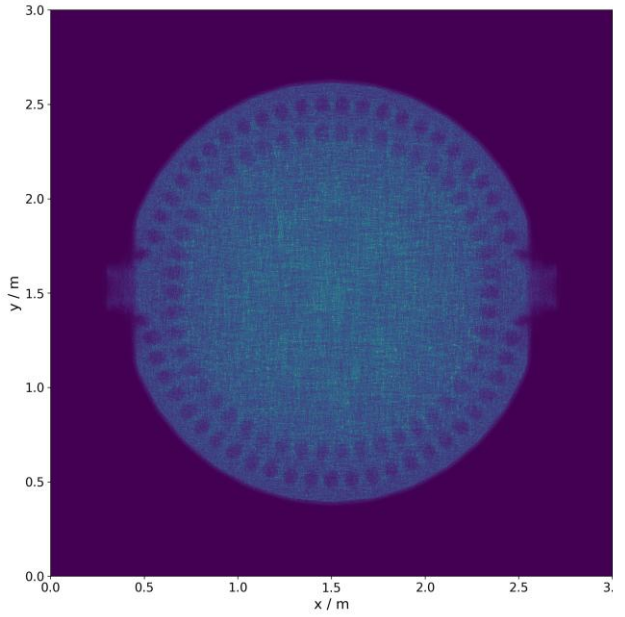
No momenta



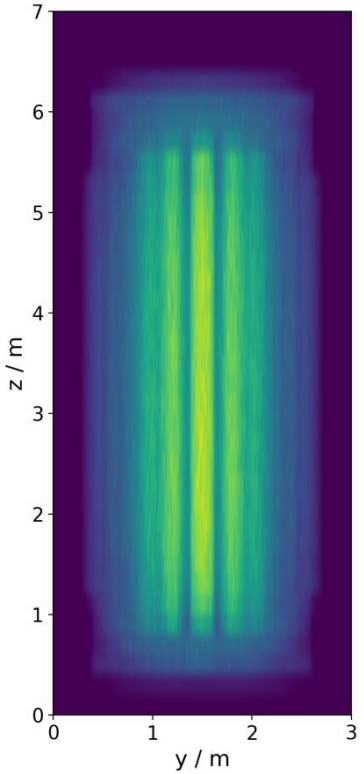
With momenta



Cask bottom



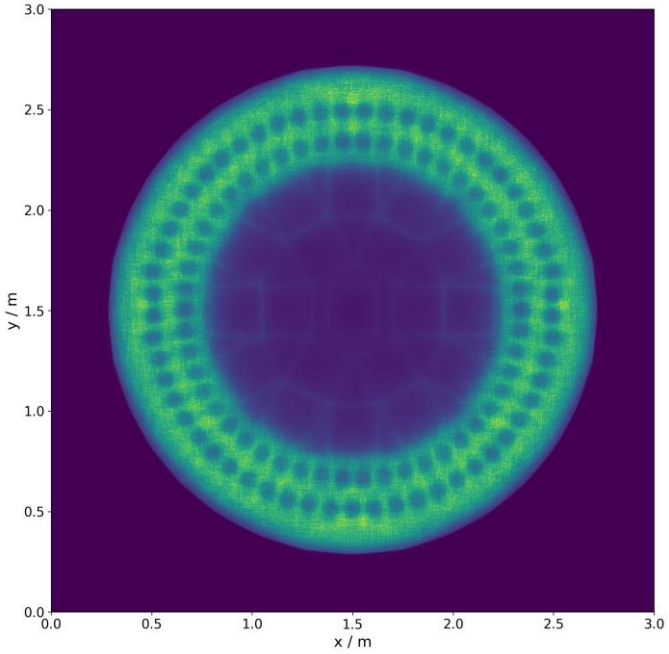
Full cask



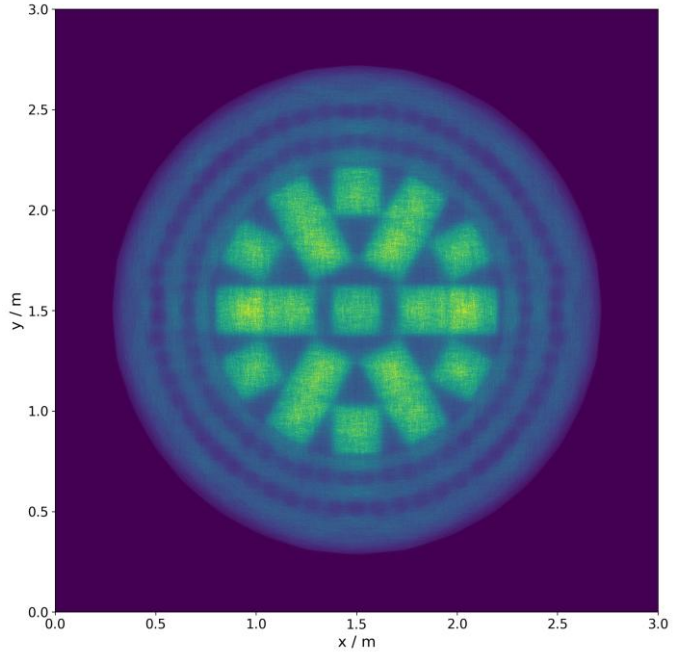
The reconstruction approach

- Voxel dimensions: 1.5 mm in X- & Y-direction, 50 cm in Z-direction
- Utilizing the muon momentum information to correct scattering angles for optimized results
- Clear and by eye visible differences between the three scenarios

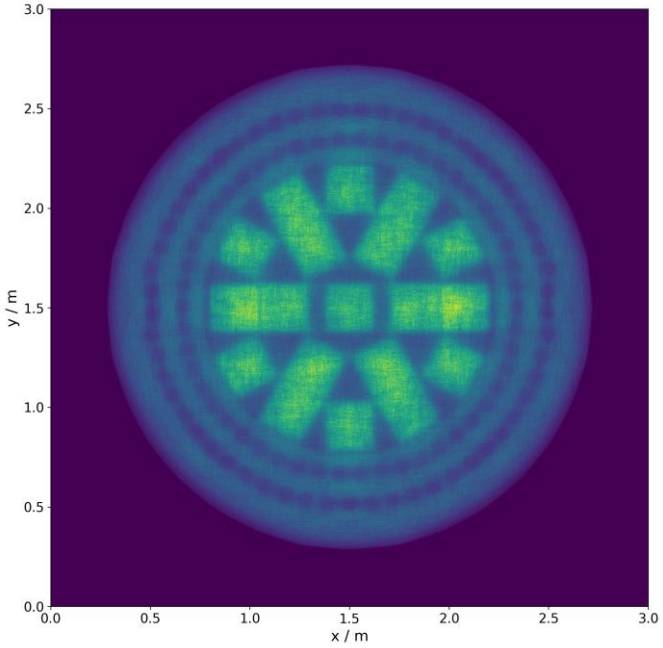
Empty cask



Full cask



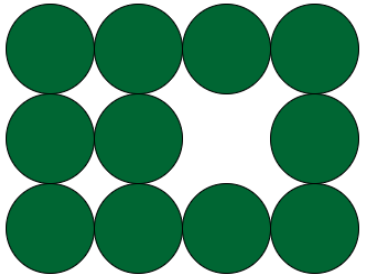
Missing rods

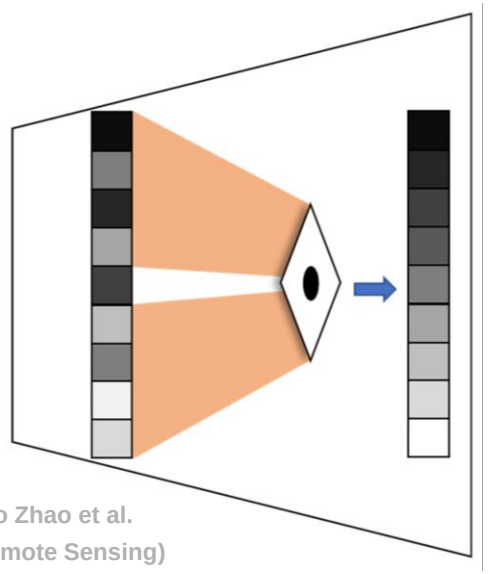


The single rod detection

- Maps from gradient descent-based reconstruction are high resolution, but still contain noise and artefacts to some degree
- Scarce data is challenging for analyzing images and improving image quality with machine learning methods
- Problem can be solved with self-supervised Noise2Void method:
  - Based on U-Net architecture – see today's talk of Angel Bueno Rodriguez [LINK]
  - Pixel prediction using blind-spot network
  - Learns to separate the noise from the consistent and frequent structure of the single rods
  - No requirement for ground truth or reference dataset
- Rods can be detected by overlaying ground truth rod pattern

Missing rods

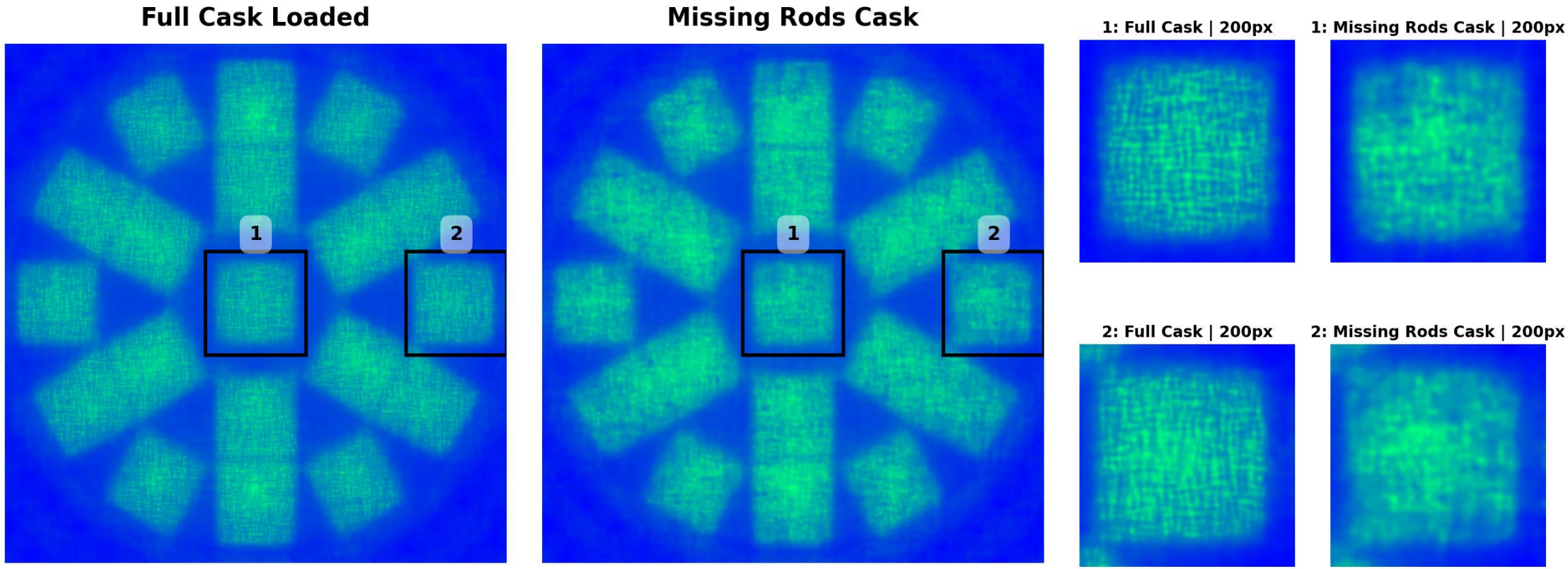




Source: Yao Zhao et al. (MDPI – Remote Sensing)

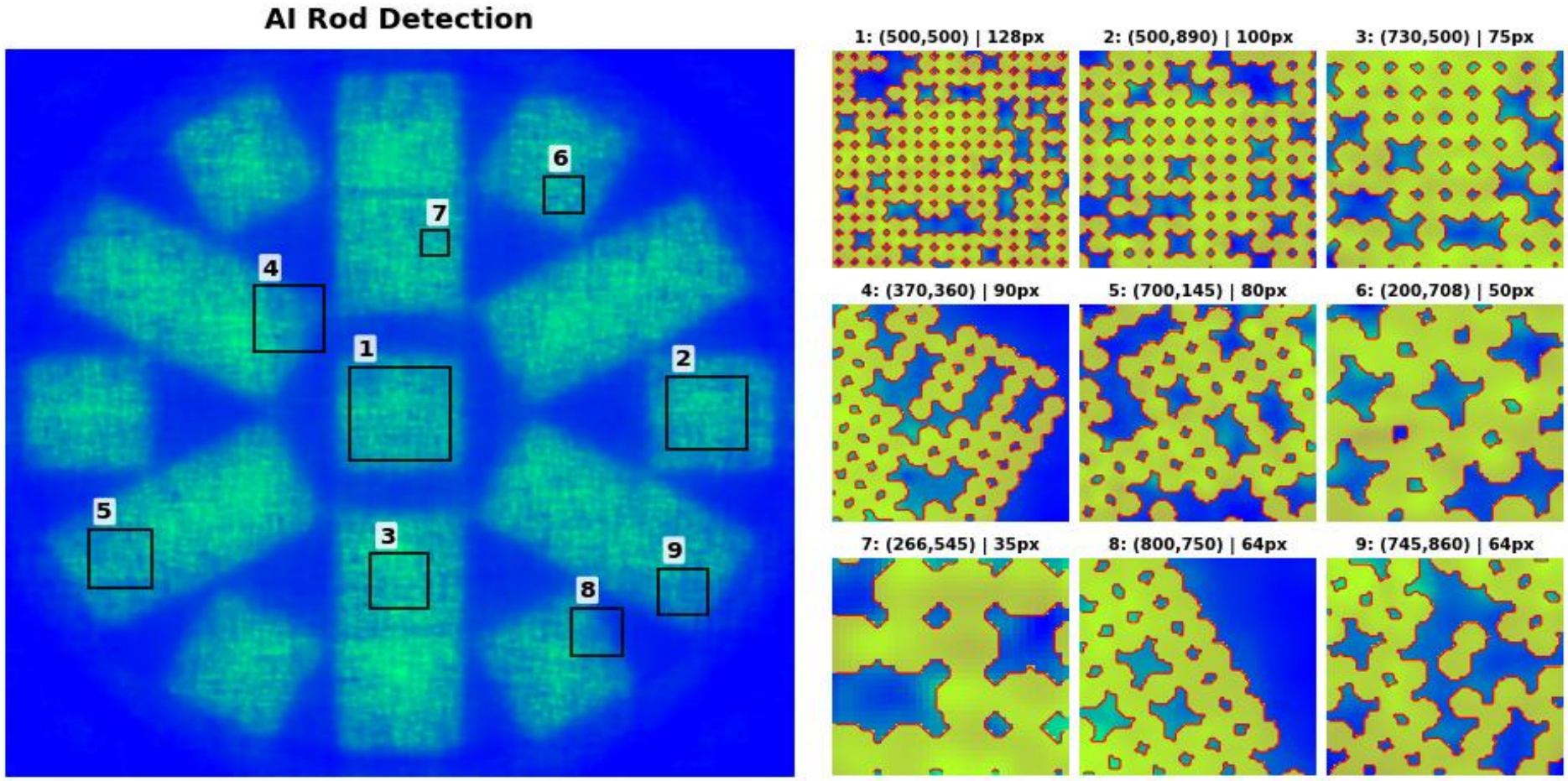
The single rod detection

- Denoised image allows for reliable differentiation between different cask scenarios



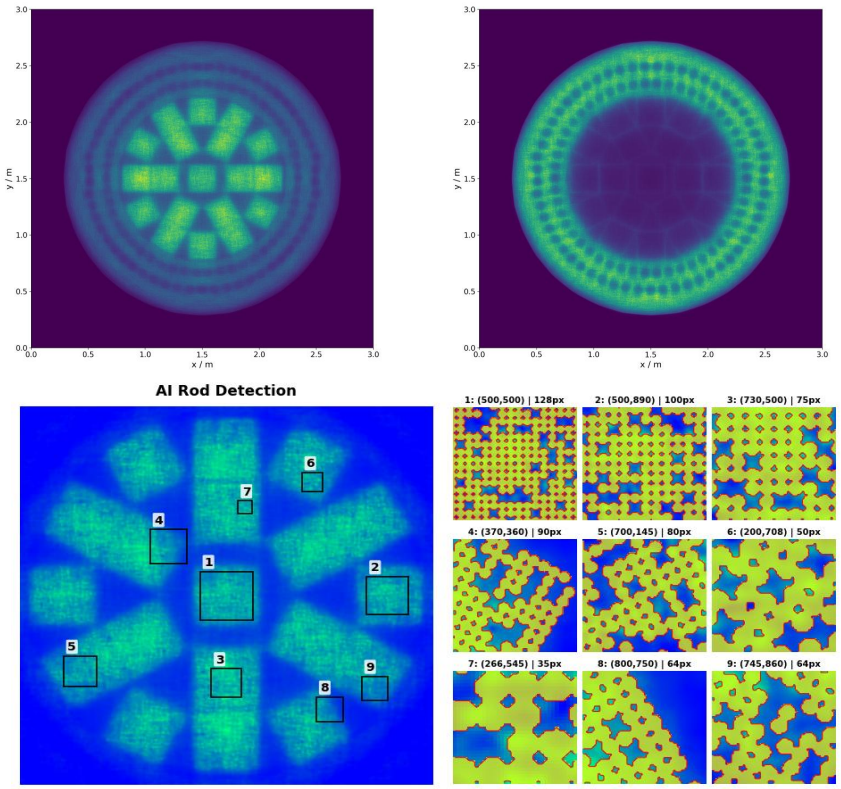
The single rod detection

- Overlaying ground truth clearly highlights missing rods and inter-rod spacings



The overview

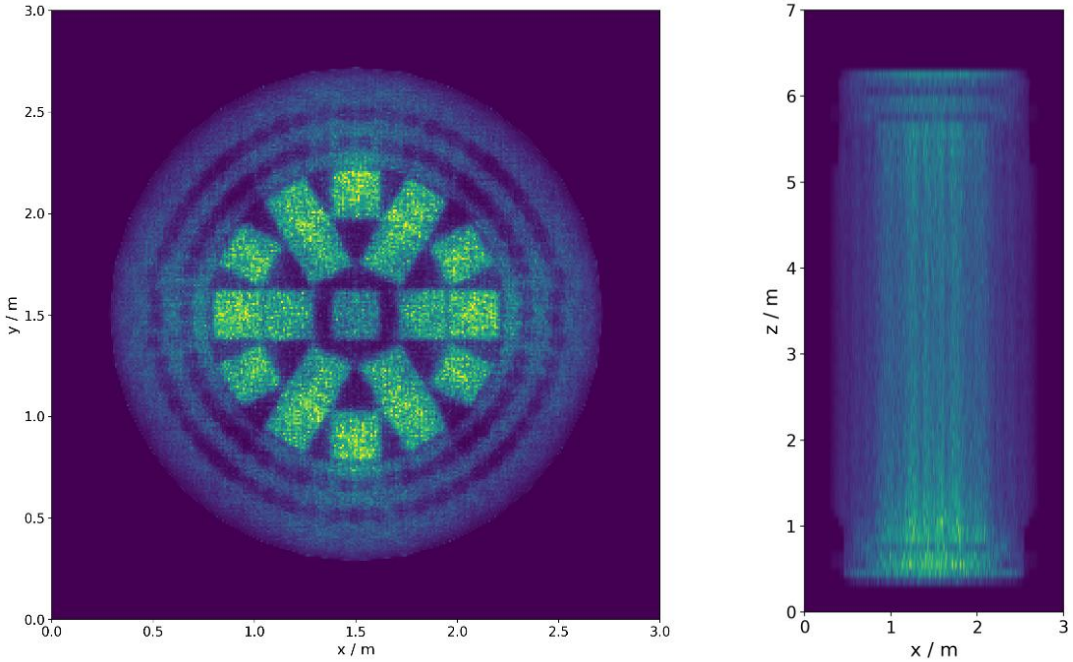
- High-resolution muon tomography of nuclear storage casks is challenging, but feasible
- Reconstruction method using gradient descent approach delivers high-resolution results
- Self-supervised denoising method enables single rod detection
- Next steps:
  - Testing more cask scenarios: different cask models, various rod configurations
  - Improving reconstruction method: incorporation of templates or dynamic voxelization schemes
  - Refining automatic detection analysis method
  - Experimental validation



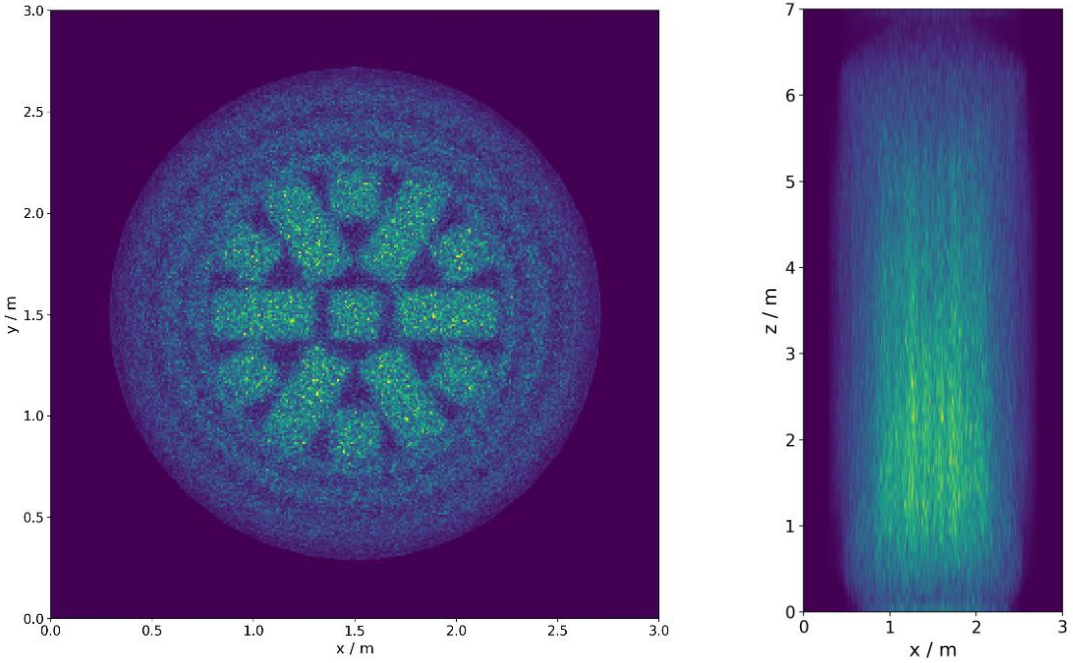
BACKUP

More on simulation setup

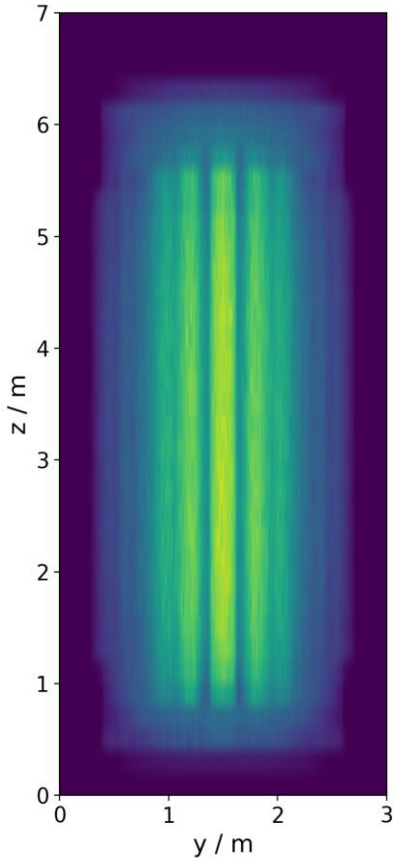
Only side detectors

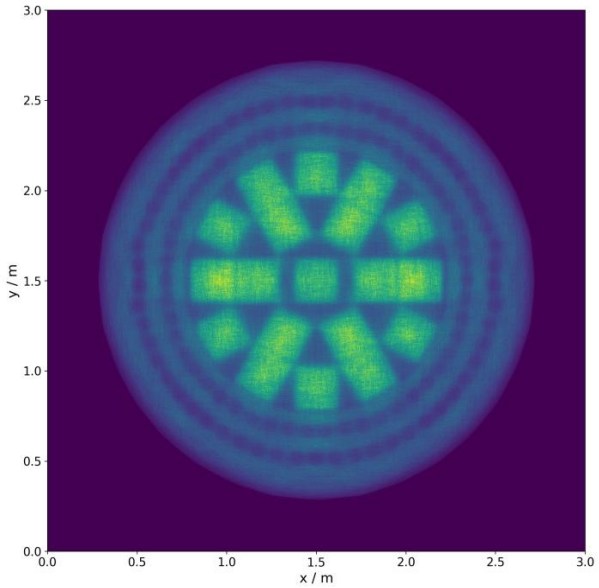


Only top & bottom detectors



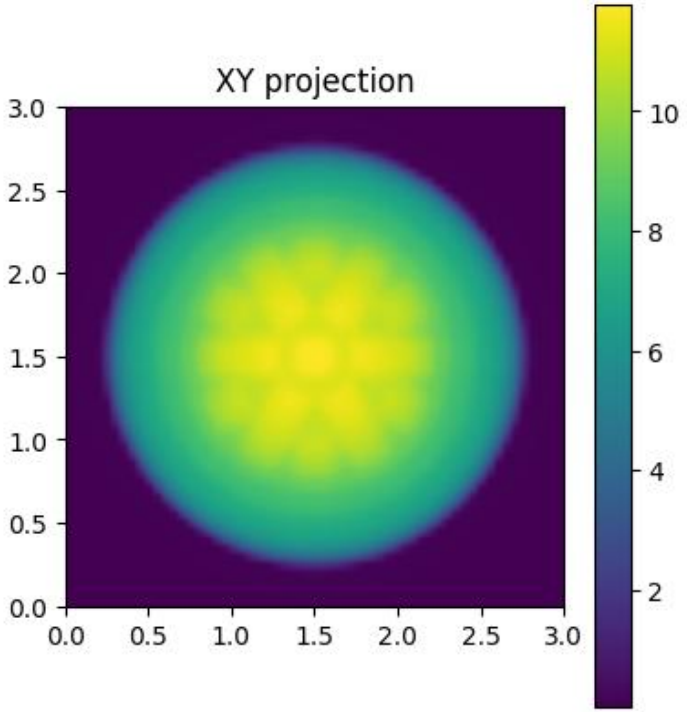
More on reconstruction approach

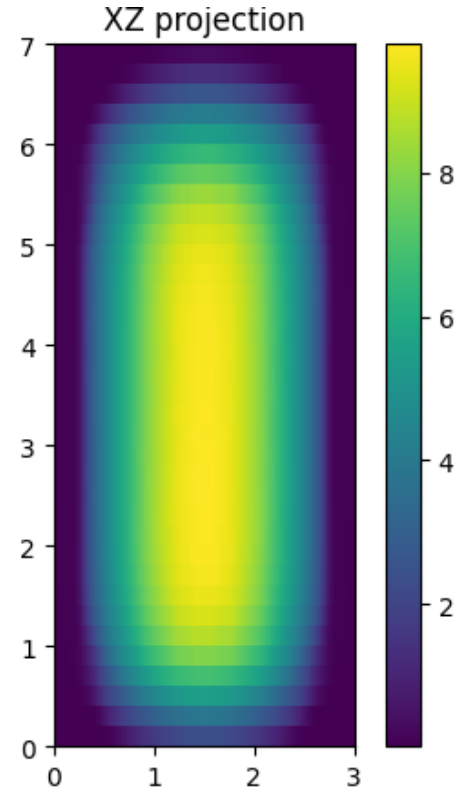




Max. Likelihood (with mom.)

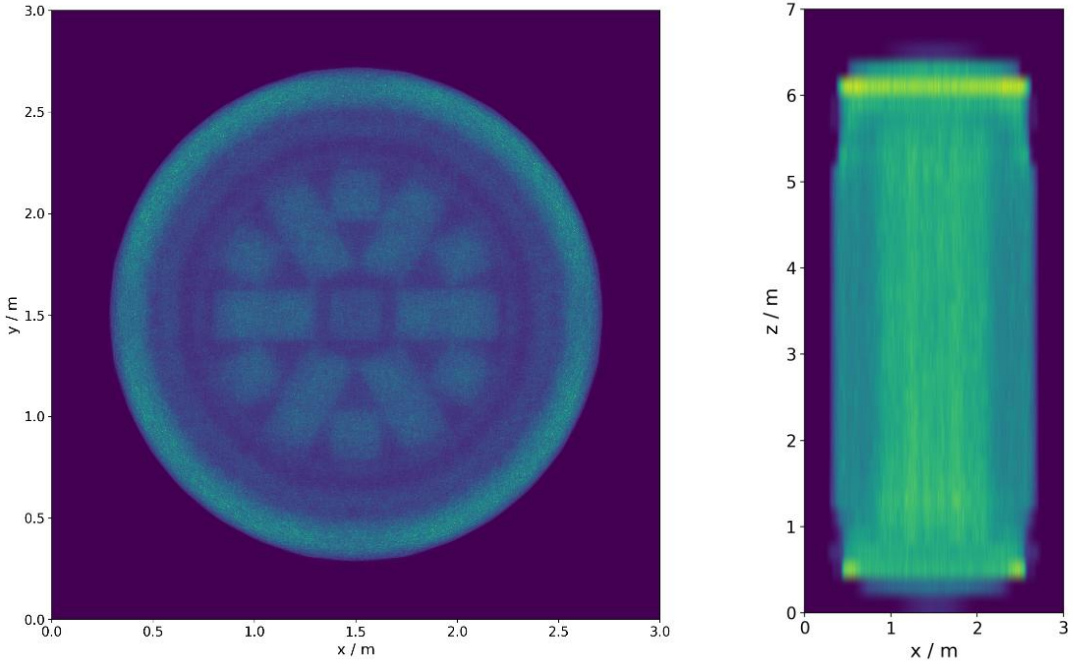
ASR (with momentum)





More on reconstruction approach

Muon momentum set to 3 GeV in reco.



Muon momentum is set to three groups in reconstruction: 200 MeV / 400 MeV / 600 MeV