3D reconstruction of cavities by cosmic ray imaging

Hiroto Kodama, Kento Nakano, Kunihiro Morishima and Nobuko Kitagawa
School of Science, Nagoya University

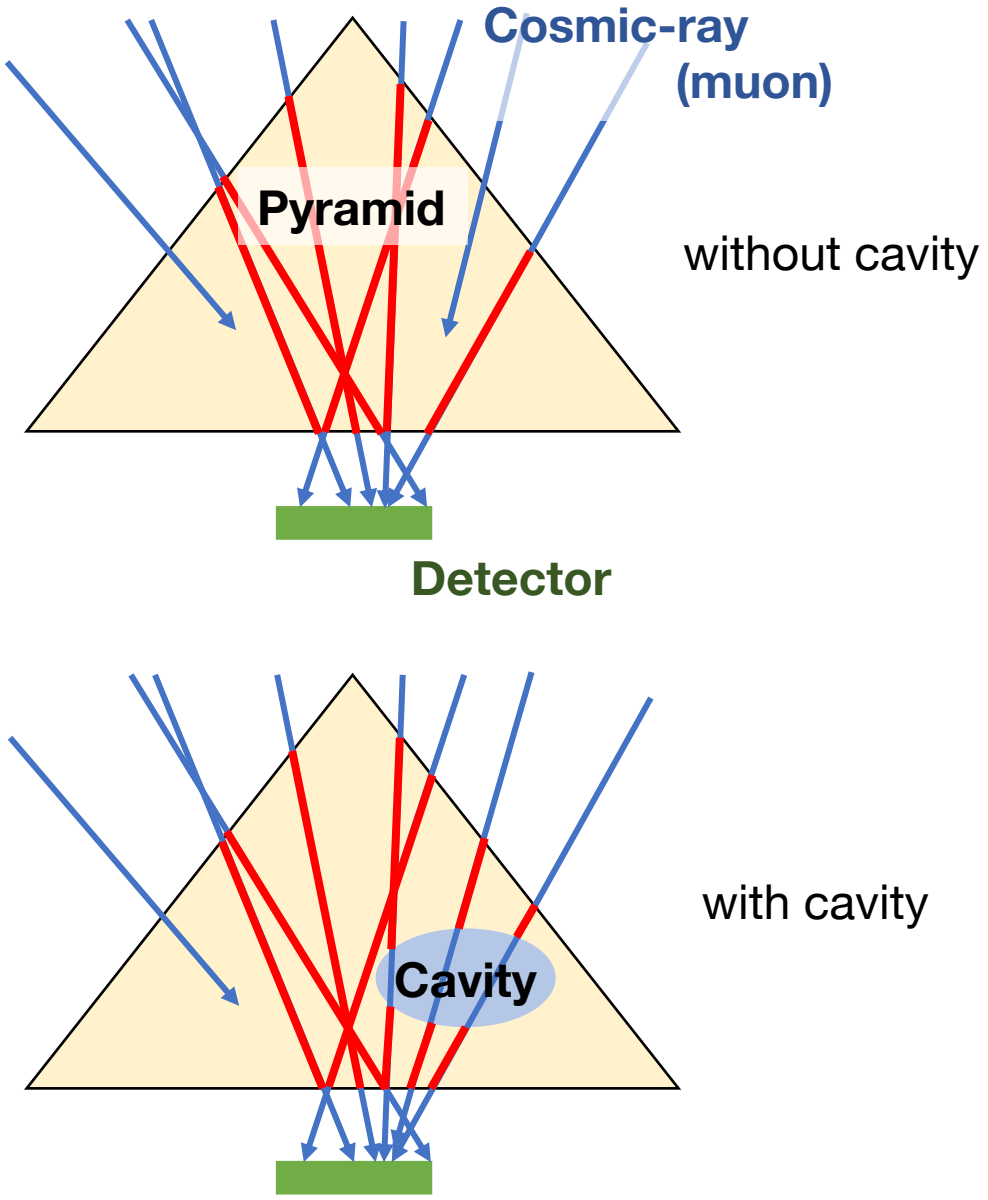
Cosmic ray Imaging

- By observing cosmic ray muons falling from various directions, **Visualize the internal structure** of objects

  →**Discover unknown structures**

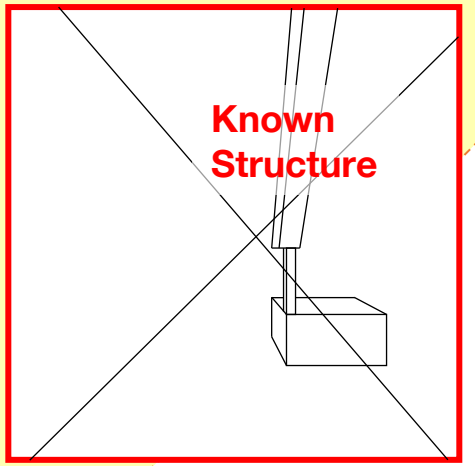
- The greater the product of (distance traveled through the object) and (density), the fewer muons penetrate.

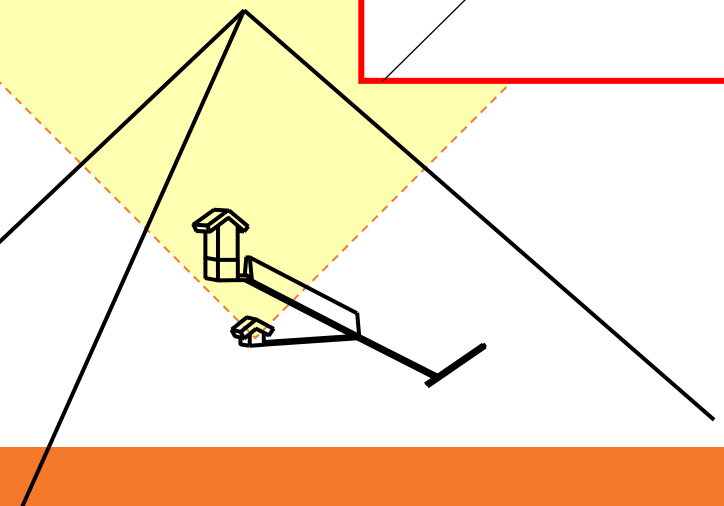
→ imaging through muon arrival frequencies (flux) at different angles, like X-ray imaging.



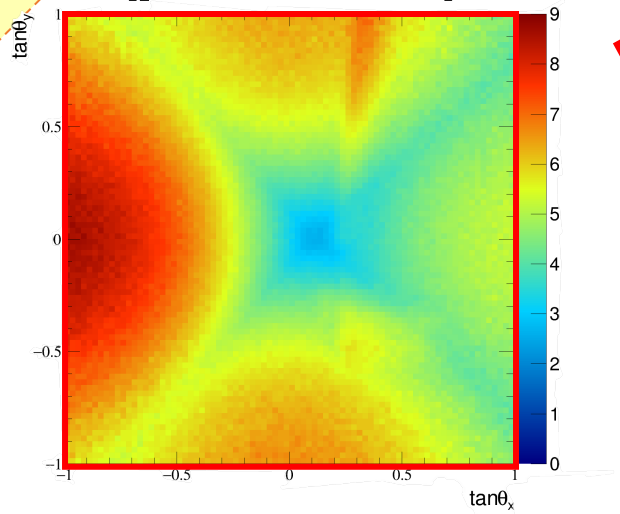
Example of application to pyramid

expected view

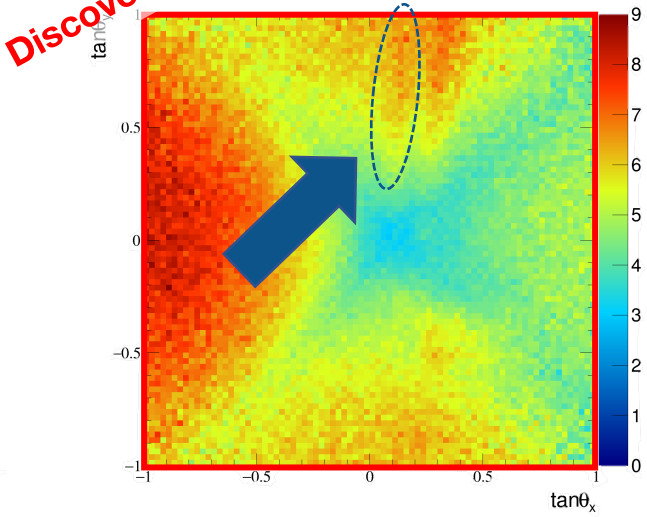




simulation (prediction)



observation (result)



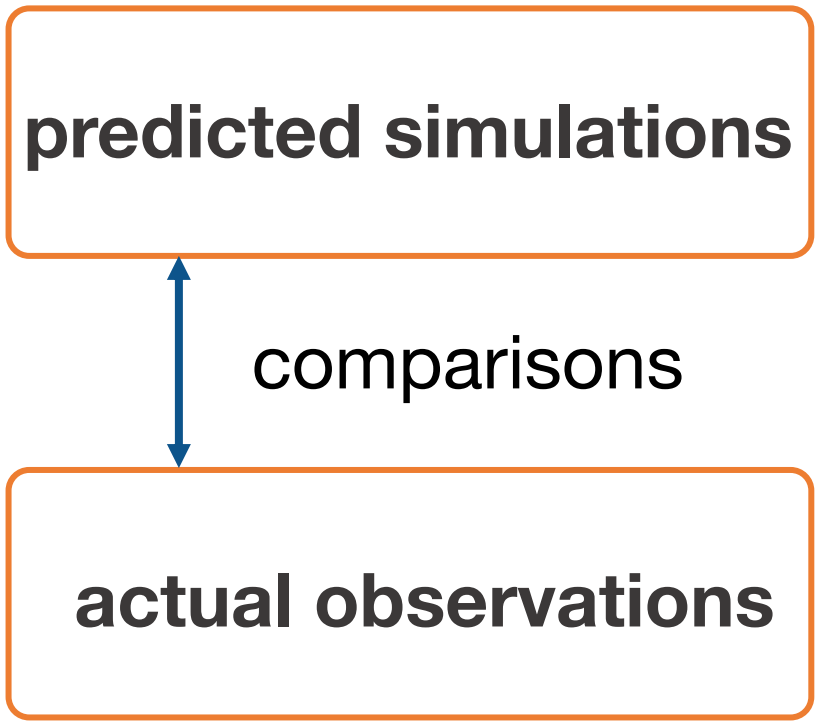
high

arrival frequency (flux)

low

Discovered unknown structures by comparing simulation data with observational data.

3D Reconstruction of Unknown Cavities



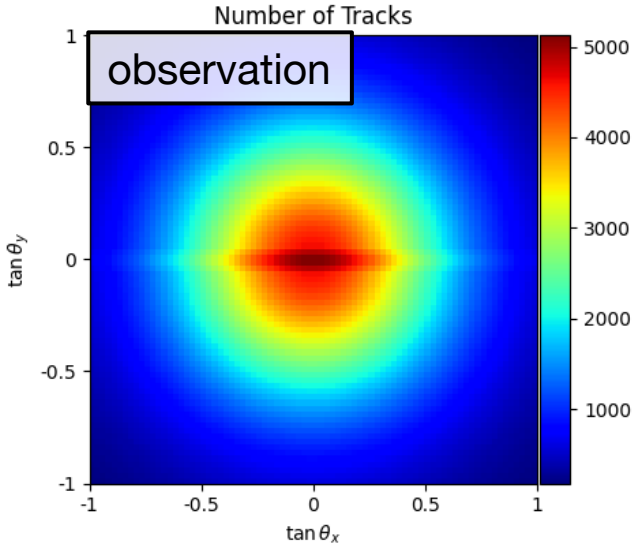
3DCG method

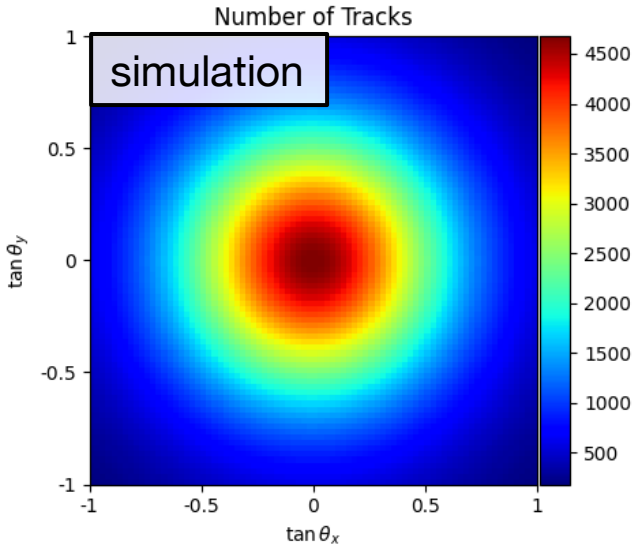
Estimation of Unknown Cavity's 3D Position and Shape

Visualization on 3D Model

Workflow of 3D Reconstruction for Unknown Cavities

1. Obtaining muon detection counts from observed data at different viewing angles.
2. Comparing the number with the predicted simulations by using subtraction.





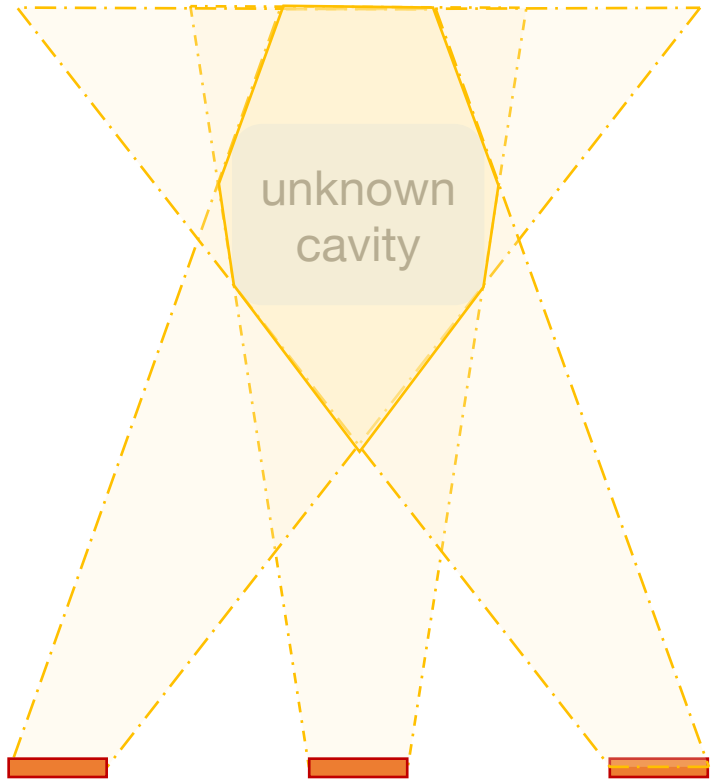
Workflow of 3D Reconstruction for Unknown Cavities

1. Obtaining muon detection counts from observed data at different viewing angles.
2. Comparing the number with the predicted simulations by using subtraction.
3. Displaying regions exceeding a defined threshold using a 3DCG software as potential cavity locations.

Performing these operations with detectors placed at multiple locations,

and extracting overlapping regions.

→**3D reconstruction for unknown cavity.**



Validation of the Proposed Methodology

Detection Area per Detector: 0.075 m^2
Field of View: 90 degrees
Observation Period: 60 days
Density of Target Material (Ground): 2.2 g/cm^3
Detector Spacing: 2m ~ 8m

Validation of Accuracy in Estimating the Position and Shape of Unknown Cavities

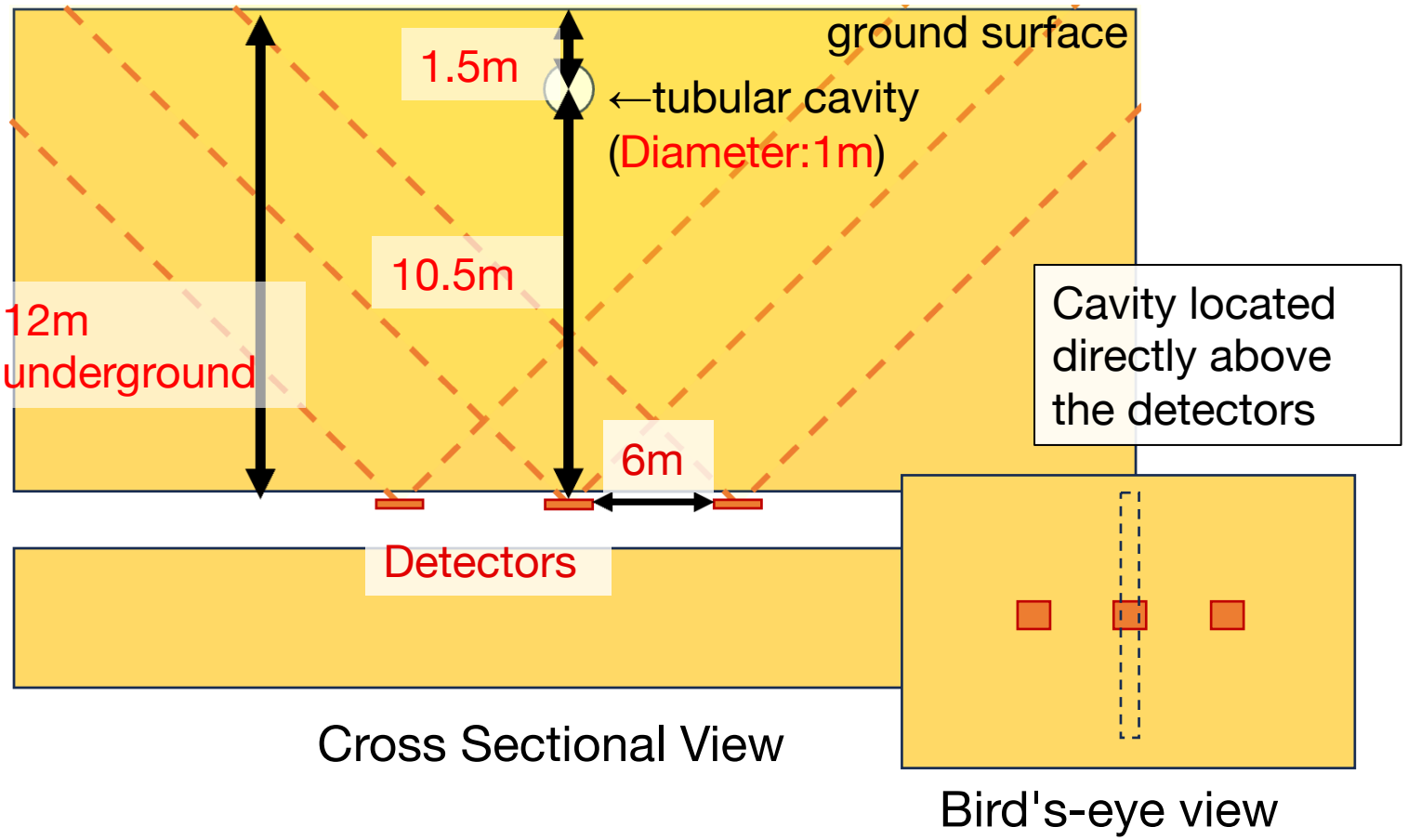
<u>For simulation data:</u>

simulations(without cavity)

<u>For observational data:</u>

imitative observational data

(simulations(with cavity) +random noise)



Validation of the Proposed Methodology

Detection Area per Detector: 0.075 m^2
Field of View: 90 degrees
Observation Period: 60 days
Density of Target Material (Ground): 2.2 g/cm^3
Detector Spacing: 2m ～ 8m

Detector Spacing :

2m to 8m (1m interval)

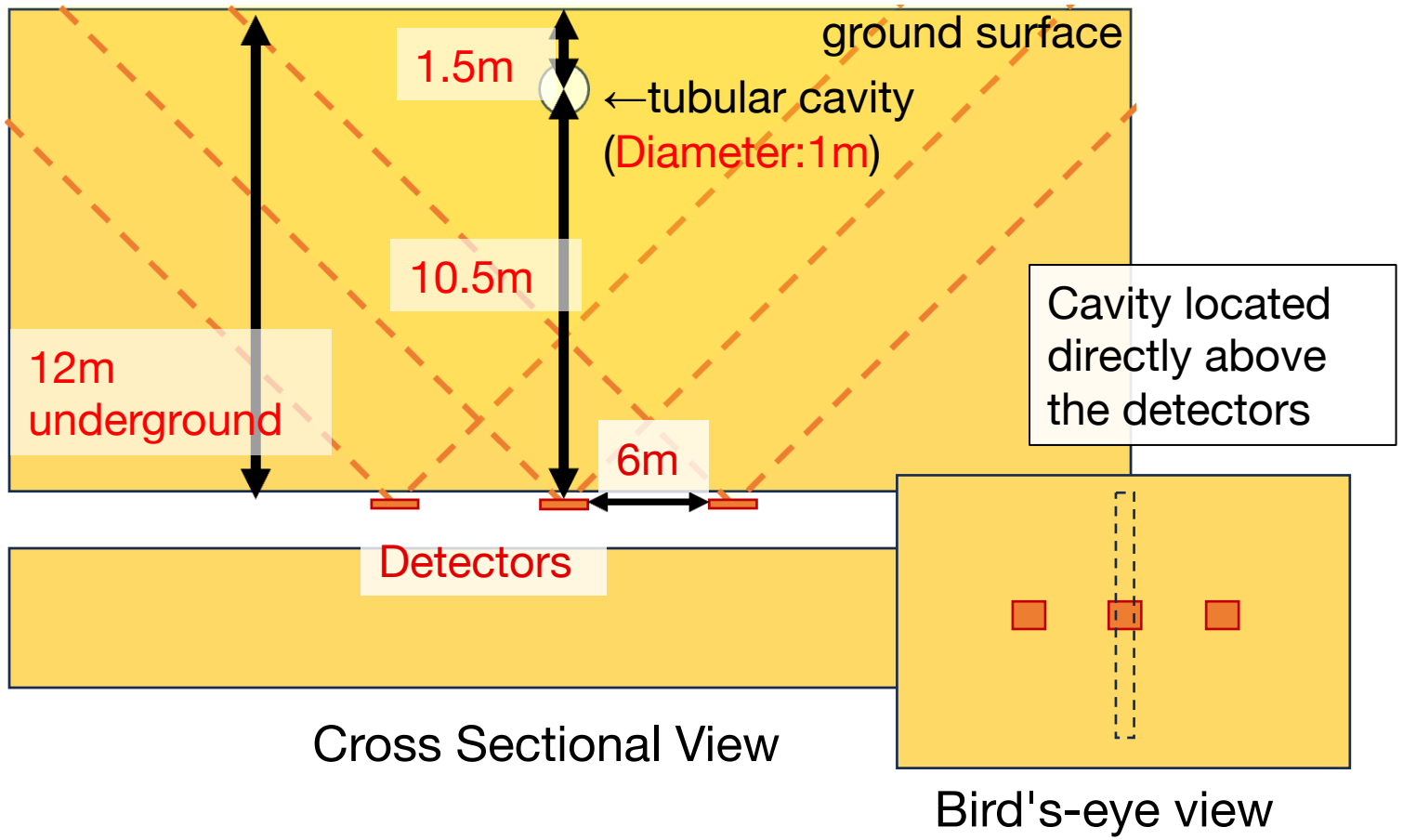
Threshold for Cavity Detection:

1.5σ, 2σ, and 3σ

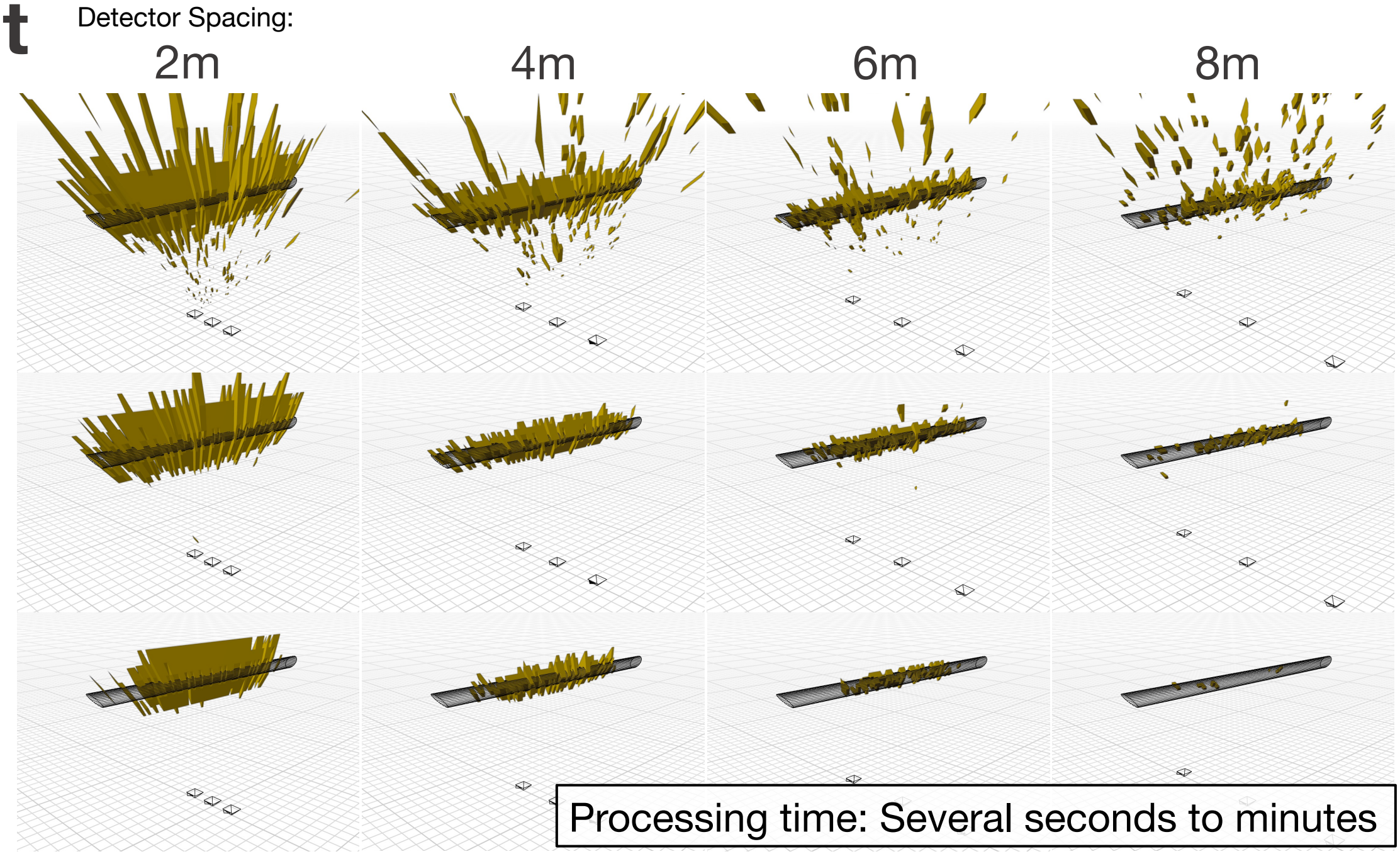
(Using the standard deviation (σ) of simulation data (results without cavity).)

Evaluation of reconstruct：

Two custom-defined evaluation metrics

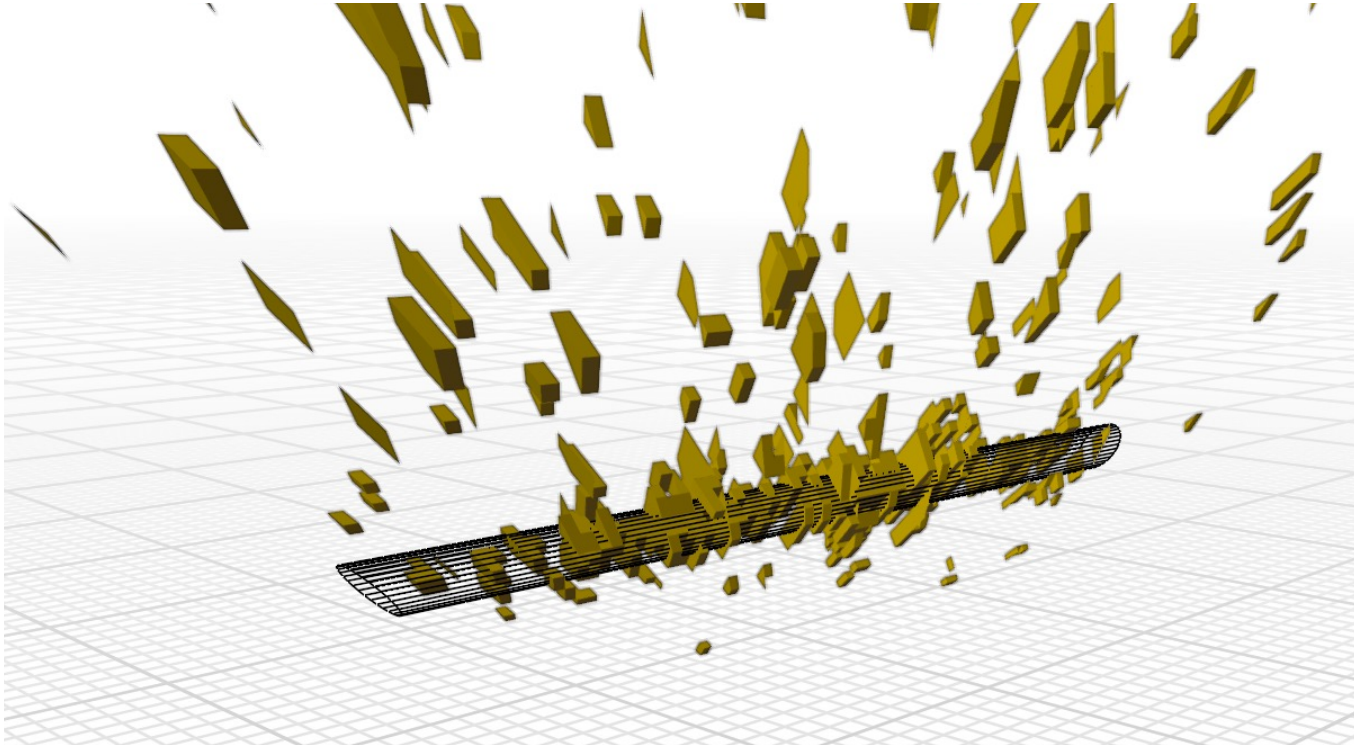


Result



Processing time: Several seconds to minutes

Evaluation



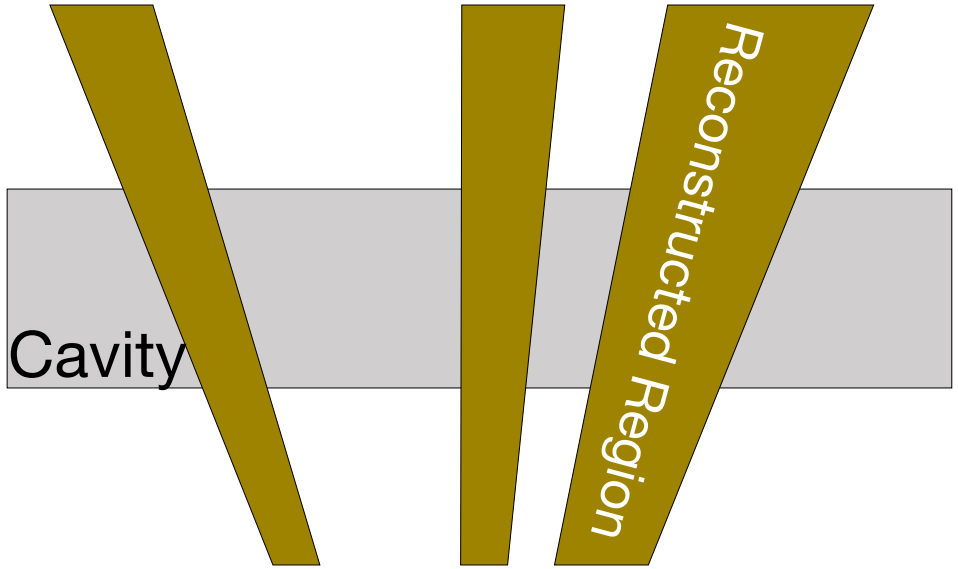
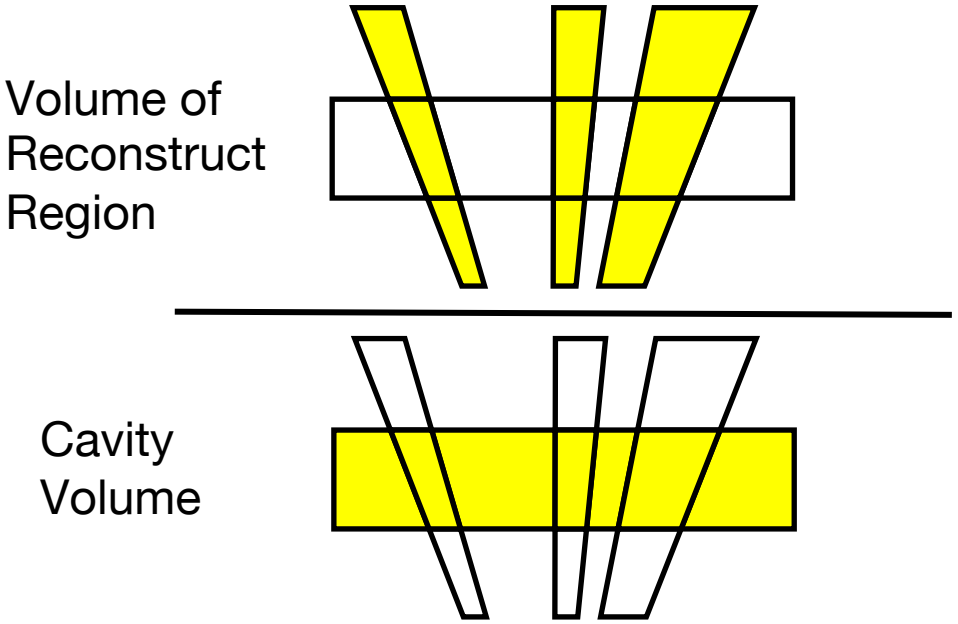


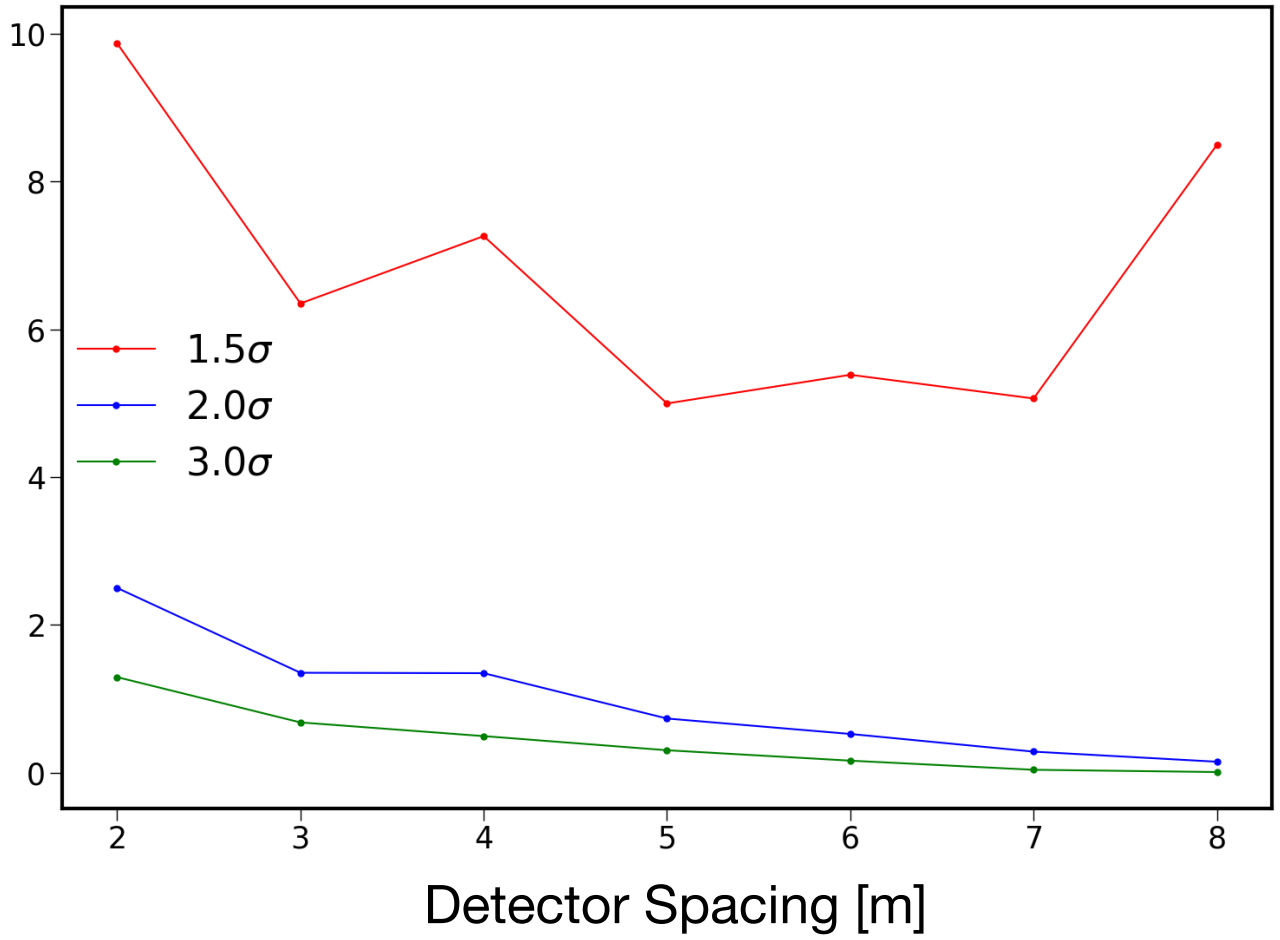
Illustration Depicting the Reconstructed Region and Cavity

Evaluation index1 $\left(\frac{\text{Volume of Reconstruct Region}}{\text{Cavity Volume}}\right)$

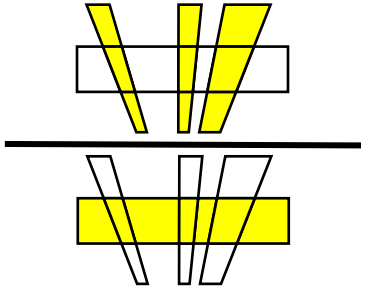


Reconstructed Region Size

Relative to Cavity.



Evaluation index1 $\left(\frac{\text{Volume of Reconstruct Region}}{\text{Cavity Volume}}\right)$



- Detector Spacing: **Large**

  Vertical Positioning of Cavities Determined

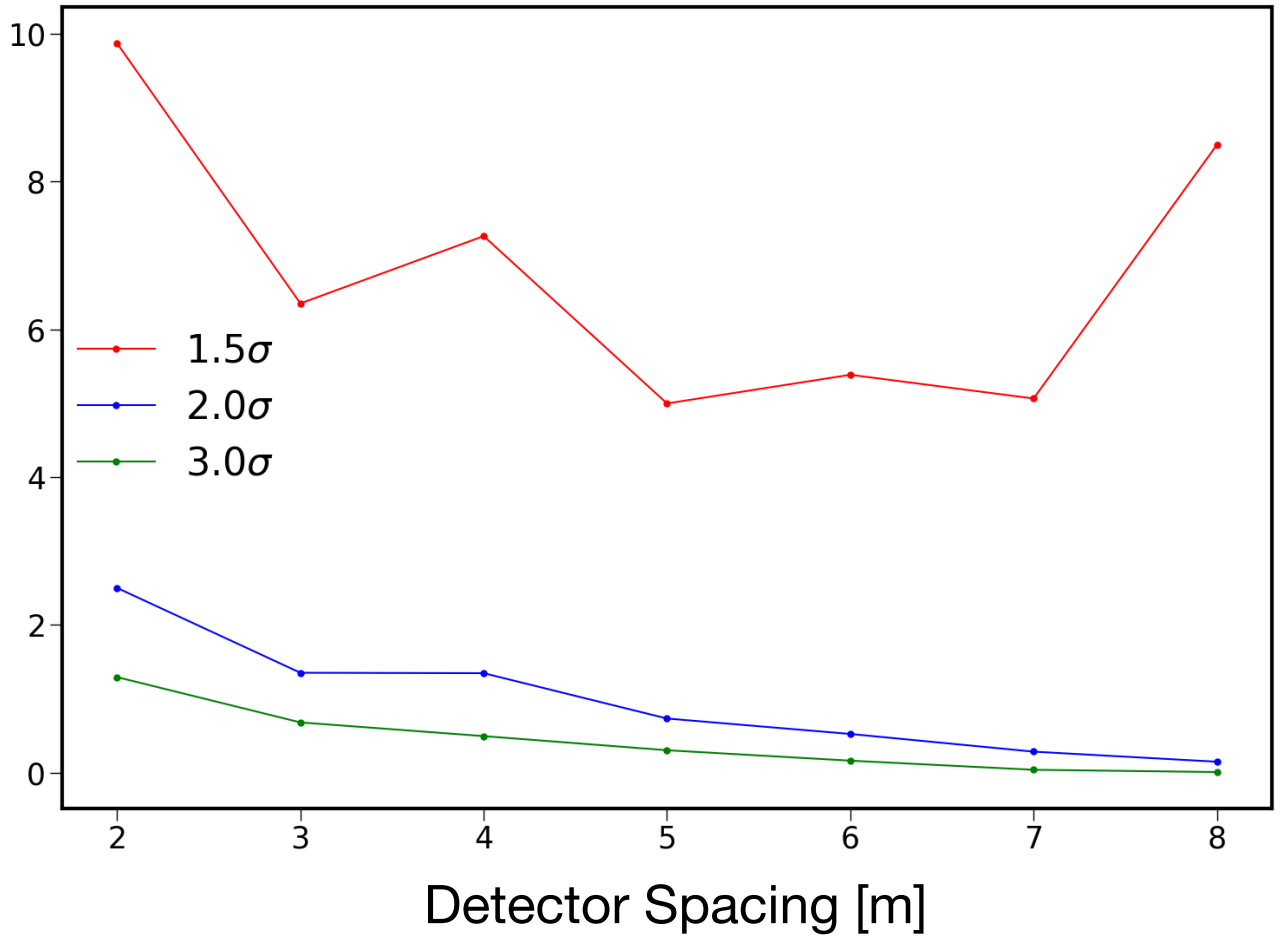
  →Reconstruct Region: **Decreased**

- Large zenith angles

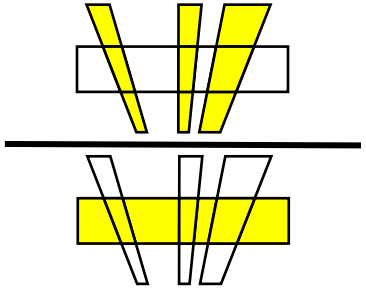
  fewer muons coming

  → Statistical Errors increase

  → Noise **Increase** at 1.5σ



Evaluation index1 $\left(\frac{\text{Volume of Reconstruct Region}}{\text{Cavity Volume}}\right)$



- Detector Spacing: **Large**

  Vertical Positioning of Cavities Determined

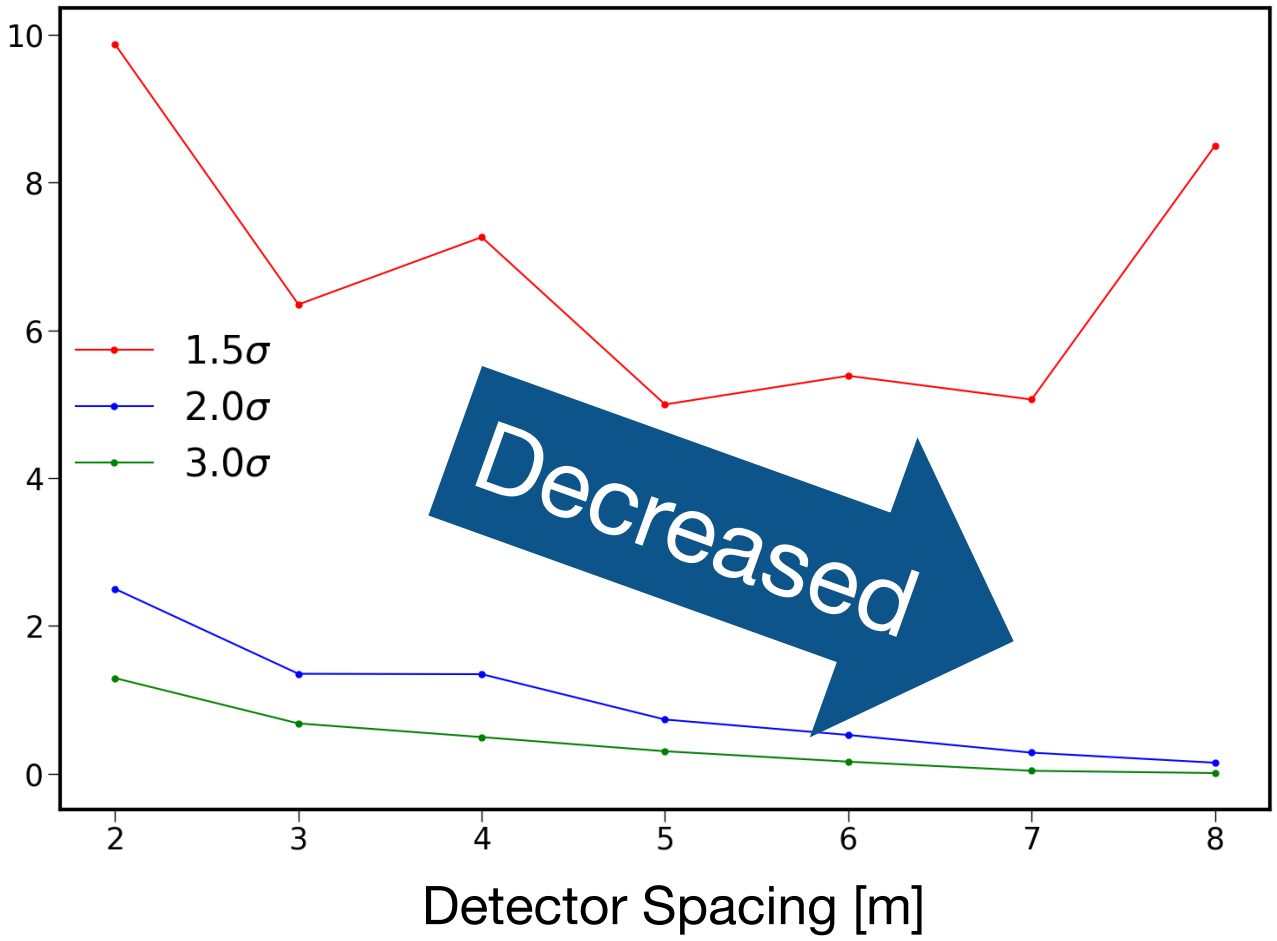
  →Reconstruct Region: **Decreased**

- Large zenith angles

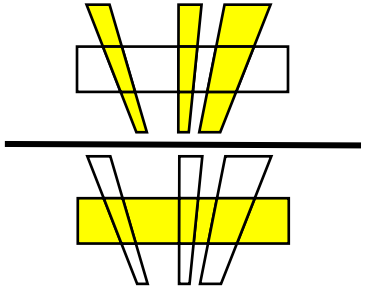
  fewer muons coming

  → Statistical Errors increase

  → Noise **Increase** at 1.5σ



Evaluation index1 $\left(\frac{\text{Volume of Reconstruct Region}}{\text{Cavity Volume}}\right)$



- Detector Spacing: **Large**

  Vertical Positioning of Cavities Determined

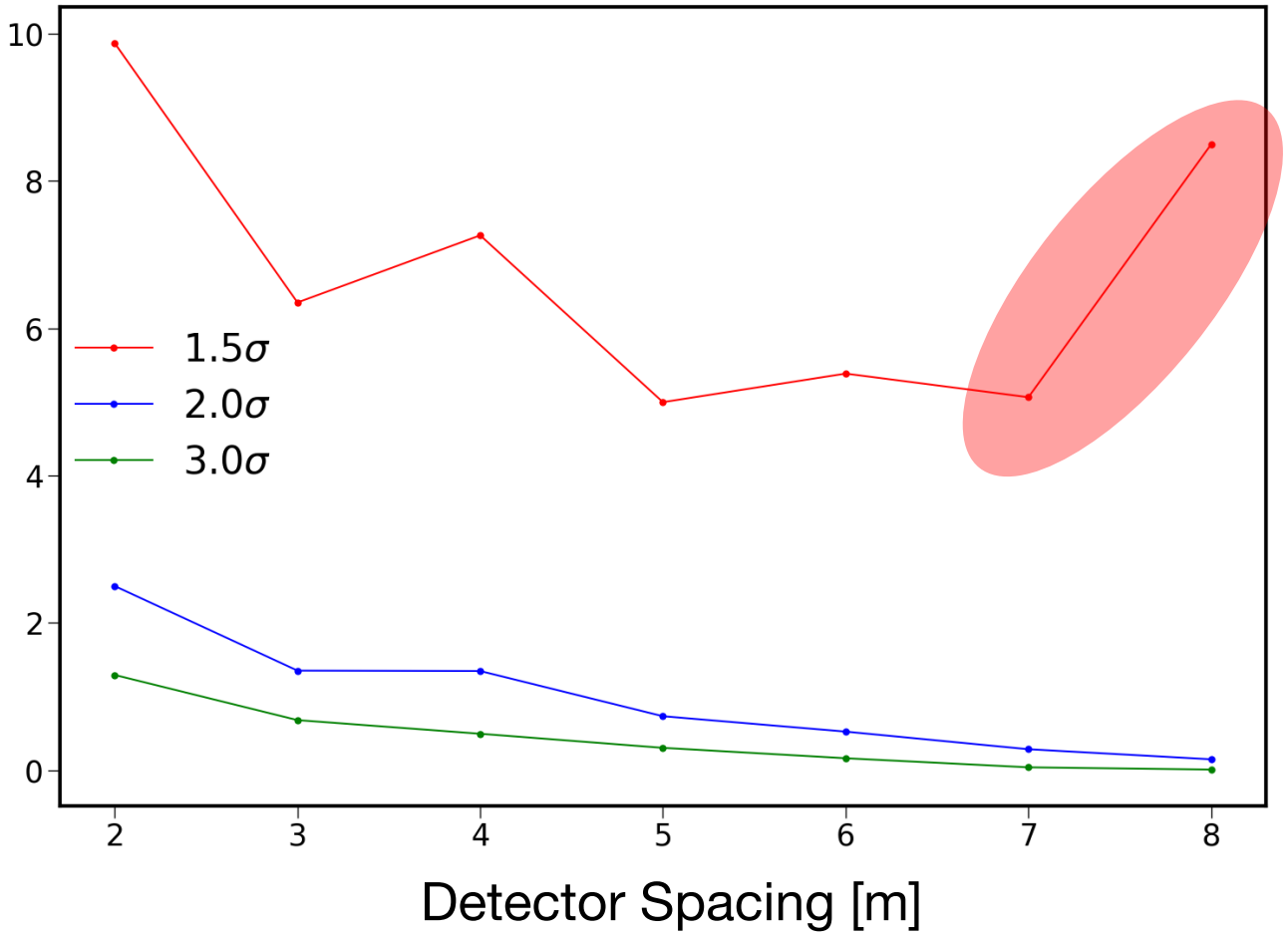
  →Reconstruct Region: **Decreased**

- Large zenith angles

  fewer muons coming

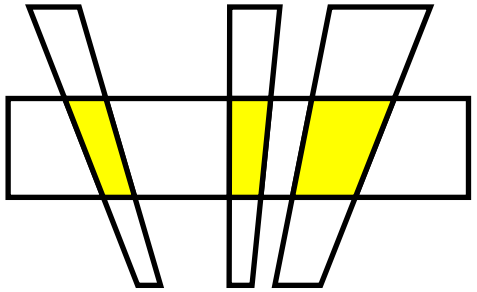
  → Statistical Errors increase

  → Noise **Increase** at 1.5σ

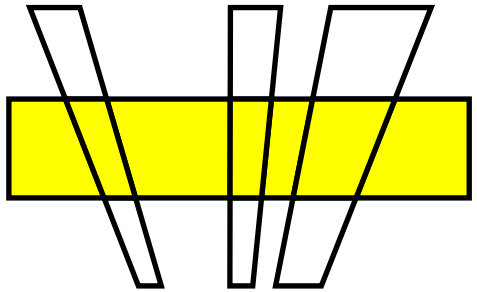


Evaluation index2 $\left(\frac{\text{Volume of Reconstruct Region within Cavity}}{\text{Cavity Volume}}\right)$

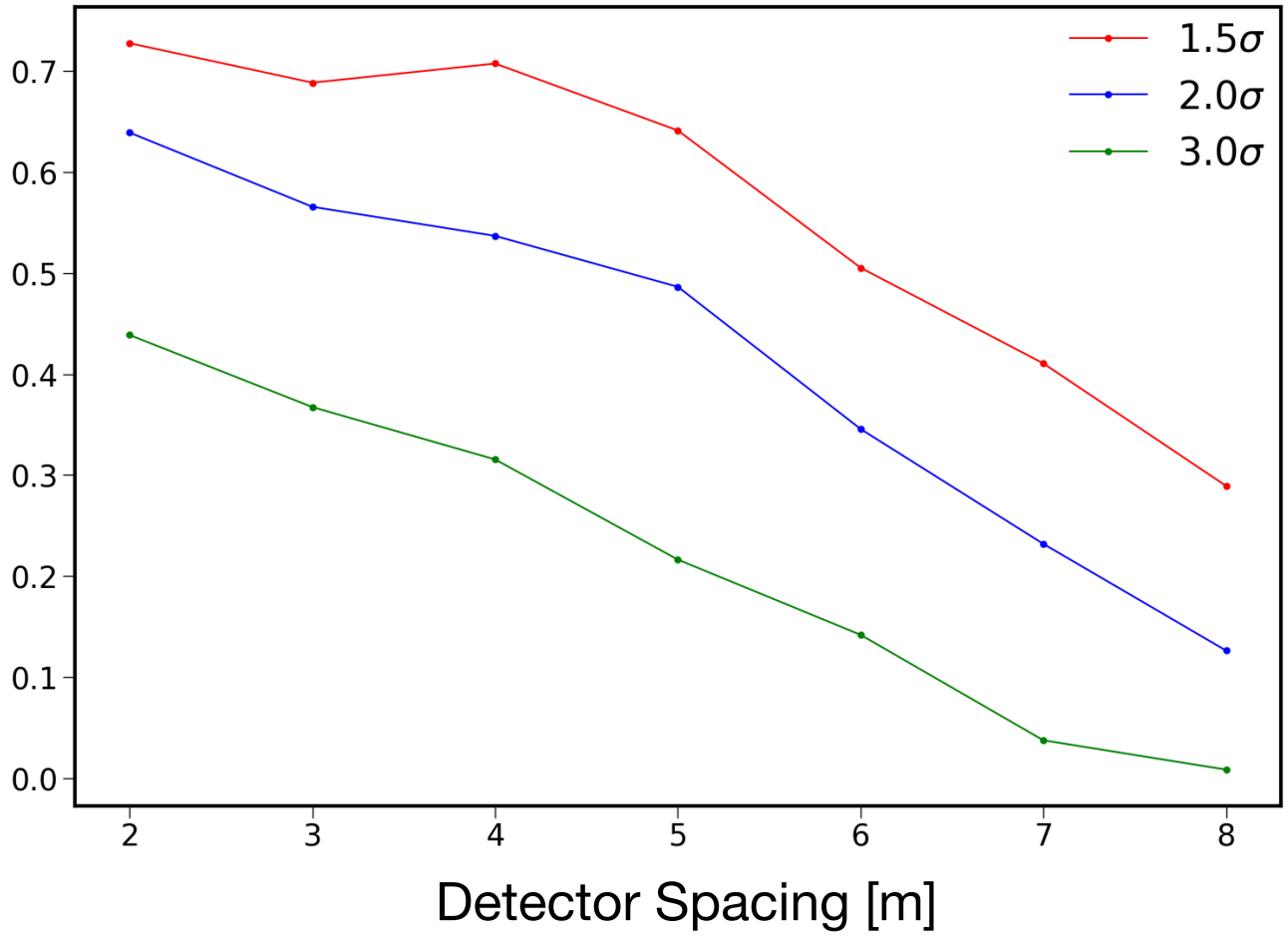
Volume of Reconstruct Region within Cavity



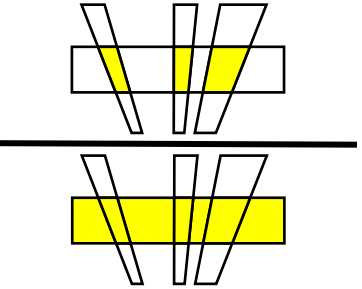
Cavity Volume



Percentage of Detected Cavity



Evaluation index2 $\left(\frac{\text{Volume of Reconstruct Region within Cavity}}{\text{Cavity Volume}}\right)$

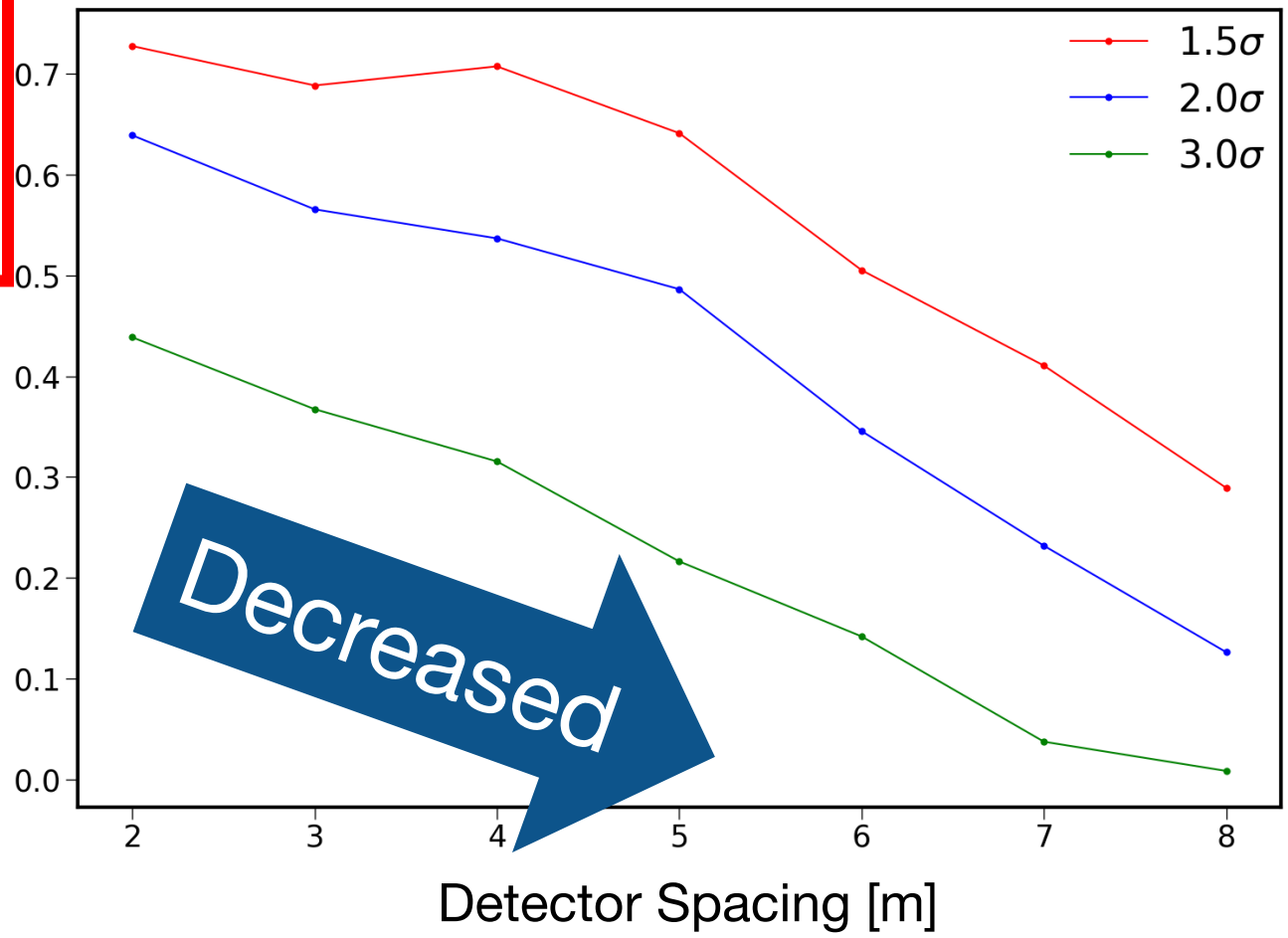


- Detector Spacing: **Large**

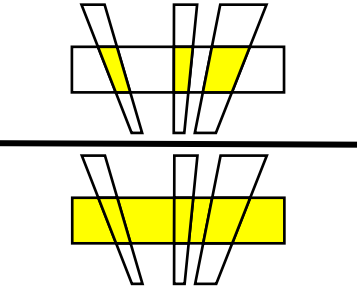
  →Decrease in index2

- High Threshold (3σ)

  → **30% Lower** Than 1.5σ



Evaluation index2 $\left(\frac{\text{Volume of Reconstruct Region within Cavity}}{\text{Cavity Volume}}\right)$

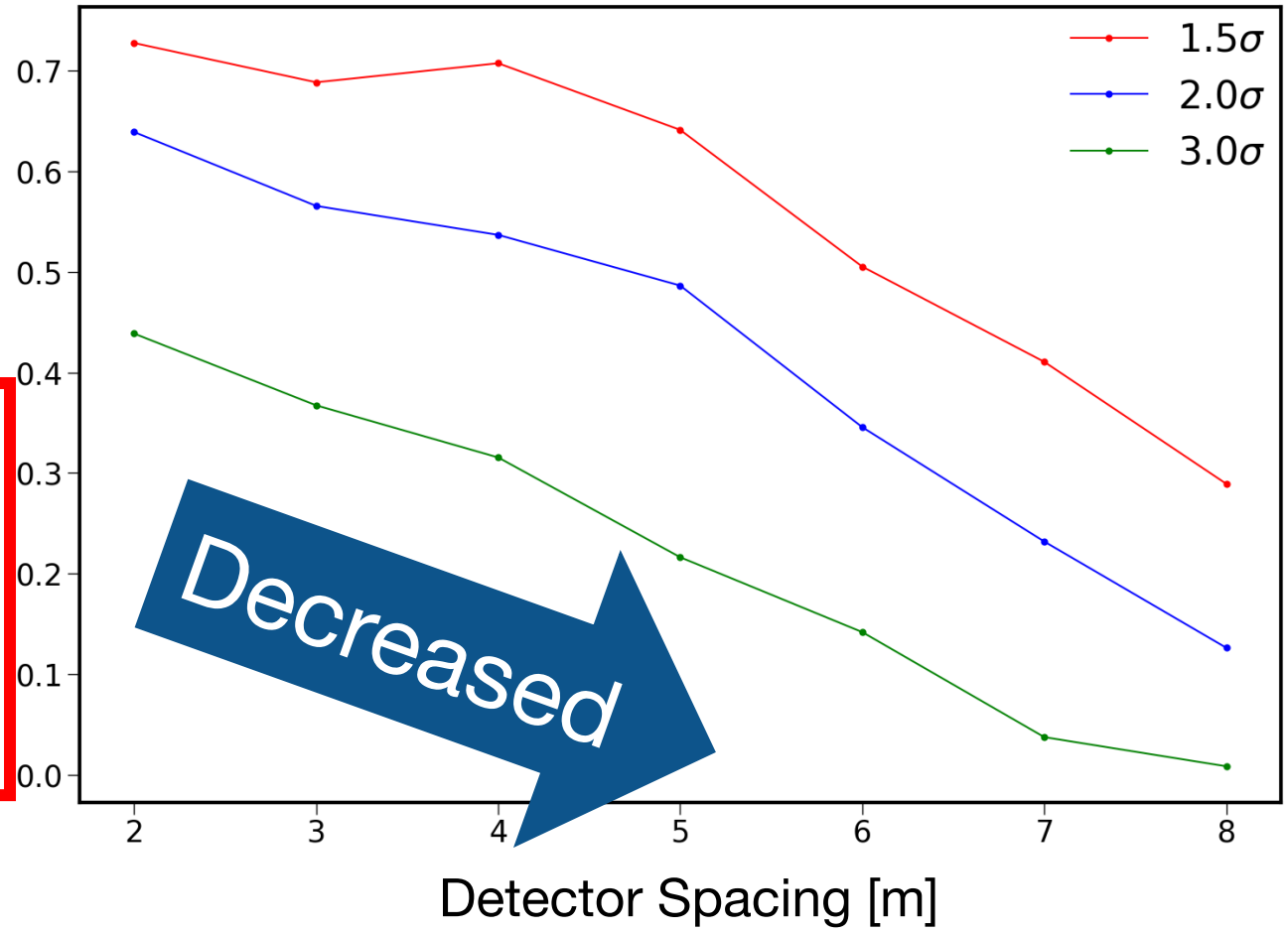


- Detector Spacing: **Large**

  →Decrease in index2

- High Threshold (3σ)

  → **30% Lower** Than 1.5σ



Summary of Current Content

We developed **a 3D Reconstruction Program for unknown cavities** using 3DCG software.

- Conducted practical application-oriented validation and **confirmed effectiveness**.
- Effective for:
  - **Quick confirmation** of observation results
  - **Planning detector positions**

Problems with this method

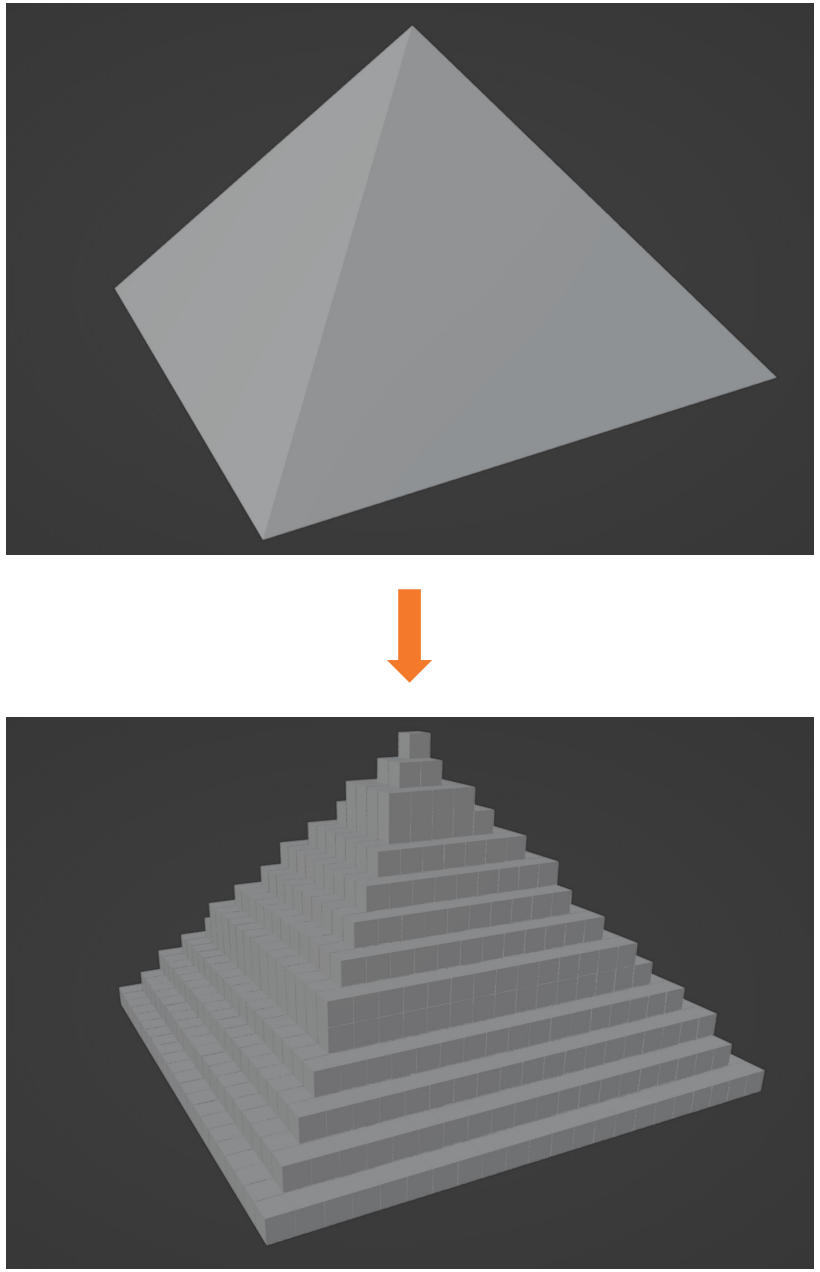
- Changing the threshold necessitates recalculations.
  →time-consuming processes
- It is challenging to remove isolated regions (considered to be noise).
- **Only** the "regions detected by **all detectors**" are output
  - In the previous example, There must be a region that is detected by only two of the three detectors but is still reliable as a signal

- By **voxelizing** the reconstructed area, we aim to address these issues.

Understanding Voxel

- Voxel is:
  - short for “Volume Pixel”
  - three-dimensional unit that represents a volumetric element in space, (like how a pixel represents a two-dimensional unit in an image.)

- Representing Reconstructed Regions with Voxels.



Benefits of Voxelization

- The region (voxel) itself can hold information.
  - Voxels can have continuous values rather than binary 0/1 based on threshold crossing.
  - It allows outputting reconstructed regions for various combinations of detection counts and thresholds in a single calculation.
- Easy clustering and isolation deletion.

Expectations include enhancing the signal while suppressing noise.

Future Directions

- A voxel-based version of the 3D reconstruction program is currently under development.

- Utilizing voxels, we aim to establish a method for more detailed analysis of cavities while minimizing noise.