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Sandia National Laboratories

# Lessons Learned in the Development of a Hyperspectral Computed Tomography System

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U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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# CT Radiography at Sandia National Laboratories

- Over a dozen fixed and fieldable Computed Tomography and Radiography systems
  - Film
  - Computed Radiography
  - Digital Radiography
  - Computed Tomography

- Wide applications capability
  - 10 keV to 9 MeV
  - Mini-focus to nano-focus

- Our customers and stakeholders continue to push for richer and higher fidelity information
  - This is great!

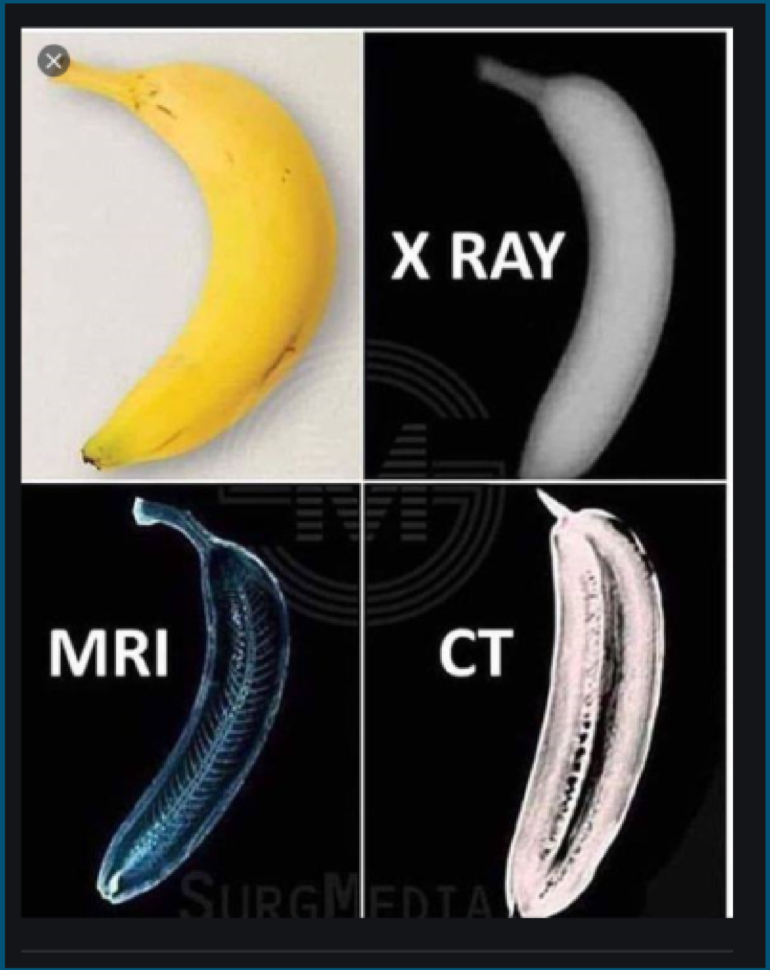
# Limitations of CT for Quantitative Digital Imaging

- Several types of metrics are desired for various NDE applications
  - Metrology
    - Part dimensions
    - Part deformations
    - Before/After event evaluations
  - Material Identification and Classification
  - Anomaly detection

  - PROBLEM: Traditional Computed Tomography is highly nonlinear!!
    - Beam hardening artifacts
    - Streaking due to photon starvation
    - Various materials can appear identical to other materials

# Unprecedented Insight

- **Goal: Novel X-ray CT Capability**
- Transform National Security Missions
- Unprecedented Imaging Resolutions
- Reliably Identify Material Composition
- **Revolutionize Industrial and Security-based Non-Destructive Evaluation**




# What is Hyperspectral CT?

**Traditional X-ray image**

**Traditional X-ray CT**

- Traditional X-ray Image –Single Gray-scale Image per Scan
- X-ray imaging is defined by a nonlinear mathematical operator!

# Hyperspectral Computed Tomography

- Traditional Computed Tomography almost always uses
  - Wide energy spectrum source
  - Scintillation-based detector material coupled with light sensors
  - Result: Integrating detector that indirectly measures averaged energy intensity

- CT vs. Hyperspectral CT
  - Measure the photon AND its energy
  - Hardware difference is only the type of detector that is used
  - Semiconducting material – typically Cadmium Telluride
  - Each detector pixel outputs a set of values instead of a single number per projection

# Data– Traditional vs. Spectral X-ray Input Data

**Bin 0 – 2 keV**

**Bin K – 150 keV**

**Bin N – 300 keV**

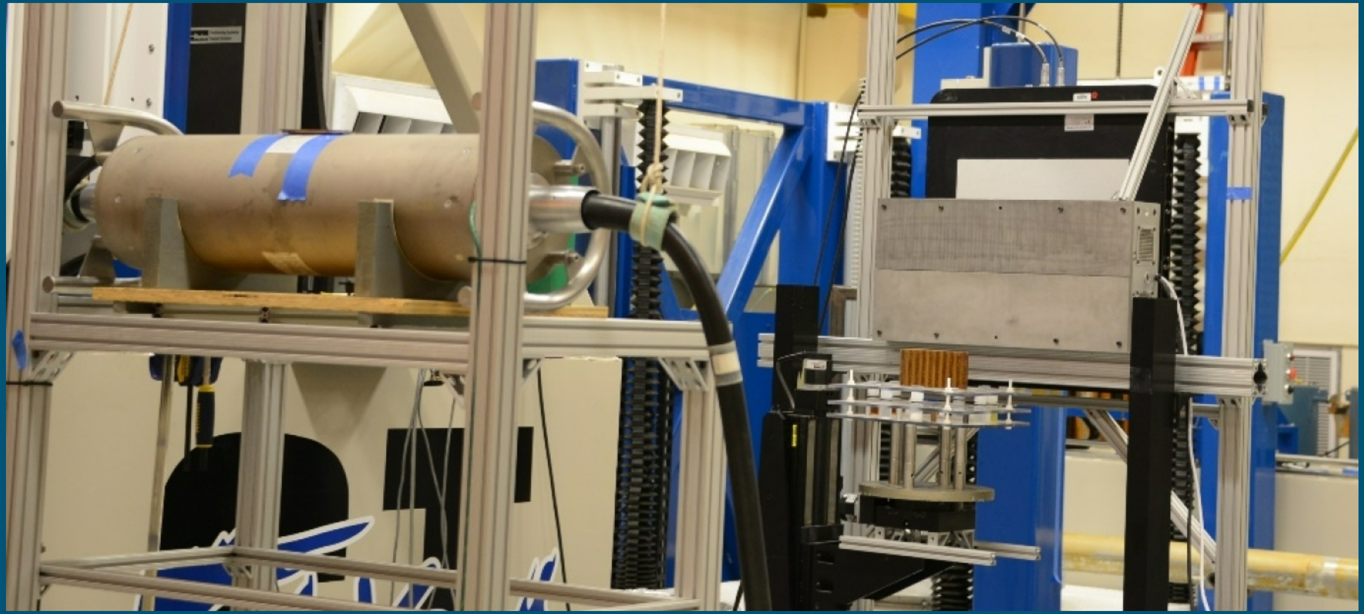
…

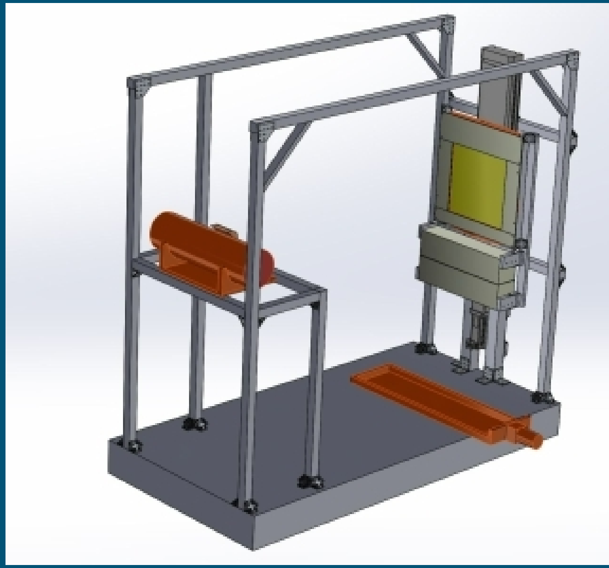
…

# Prototype System at Sandia

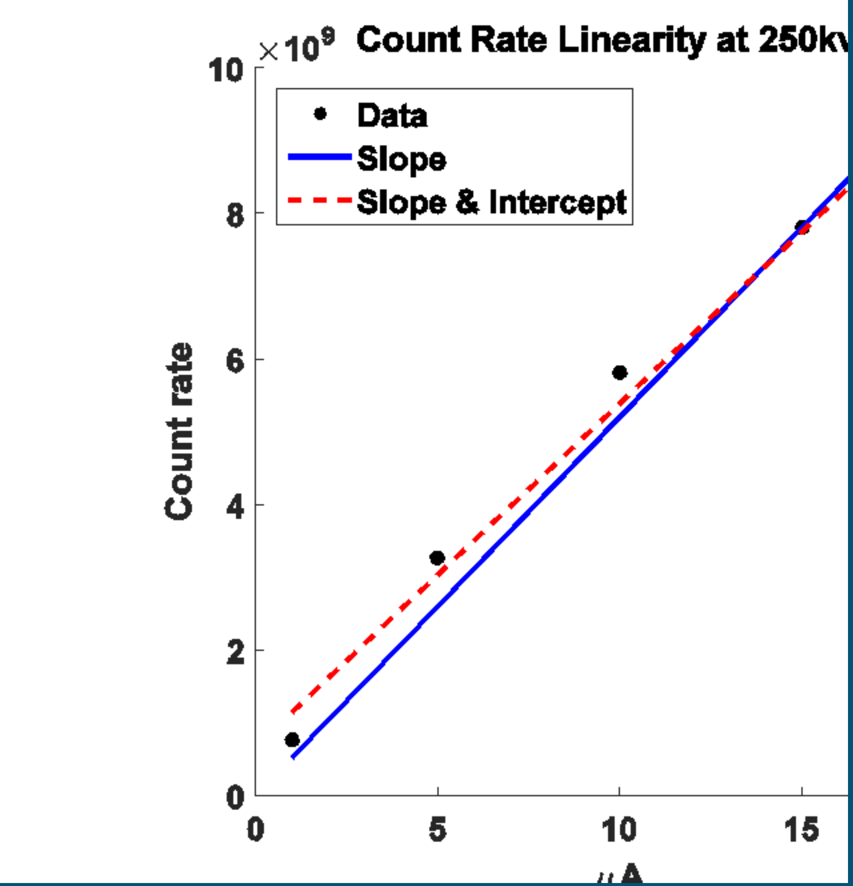
- In 2016, Sandia built a prototype system
  - 640 pixels at a 0.8 mm pitch
  - 128 Channels from 20 to 300 keV
  - Customized Multix ME100 modules
  - Comet 450 keV X-ray Source

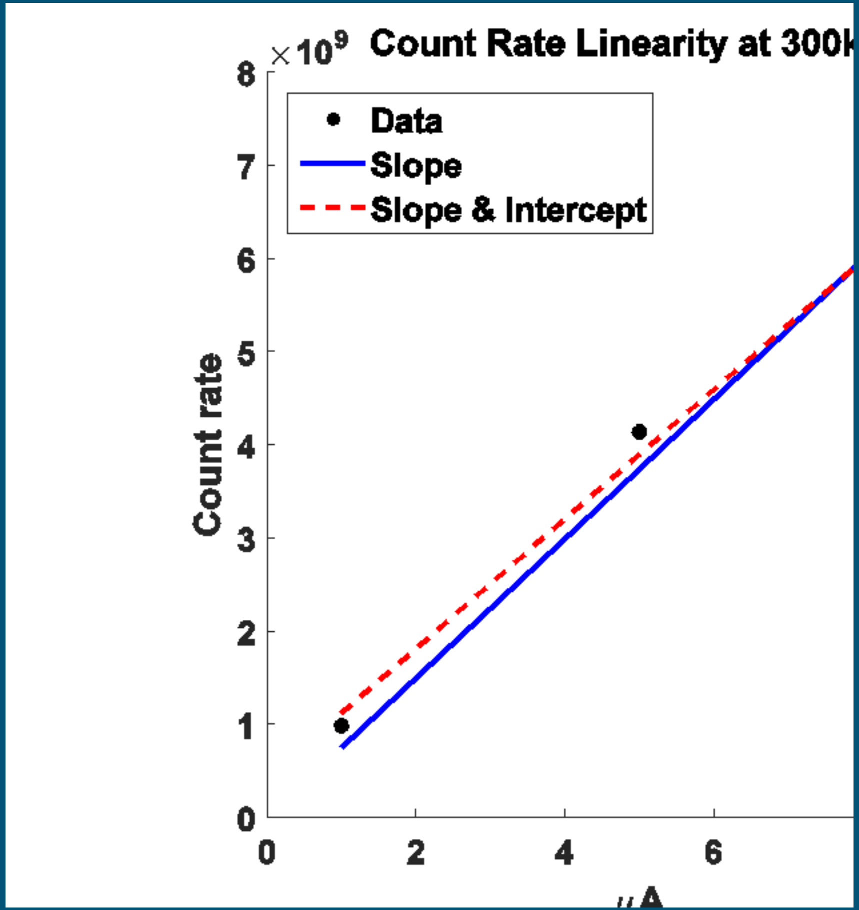
- Original Goal:
  - Improve image quality through bandpass filtering
  - Investigate big data challenges
    - 128 channels = 128x more data!





# ...250keV & 300keV



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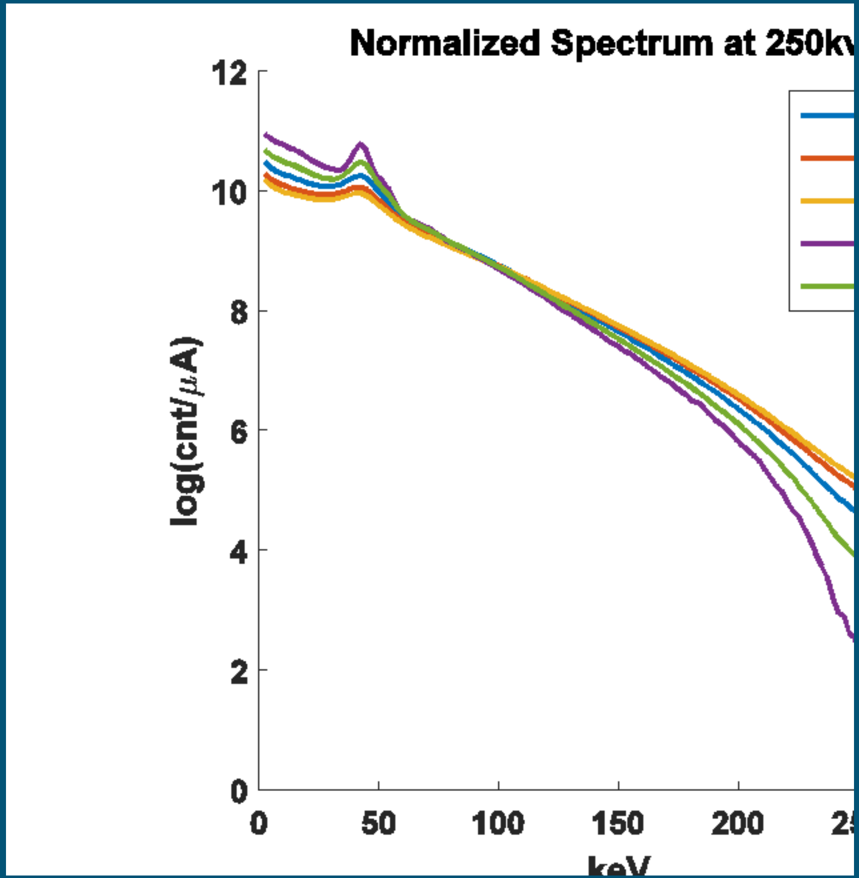
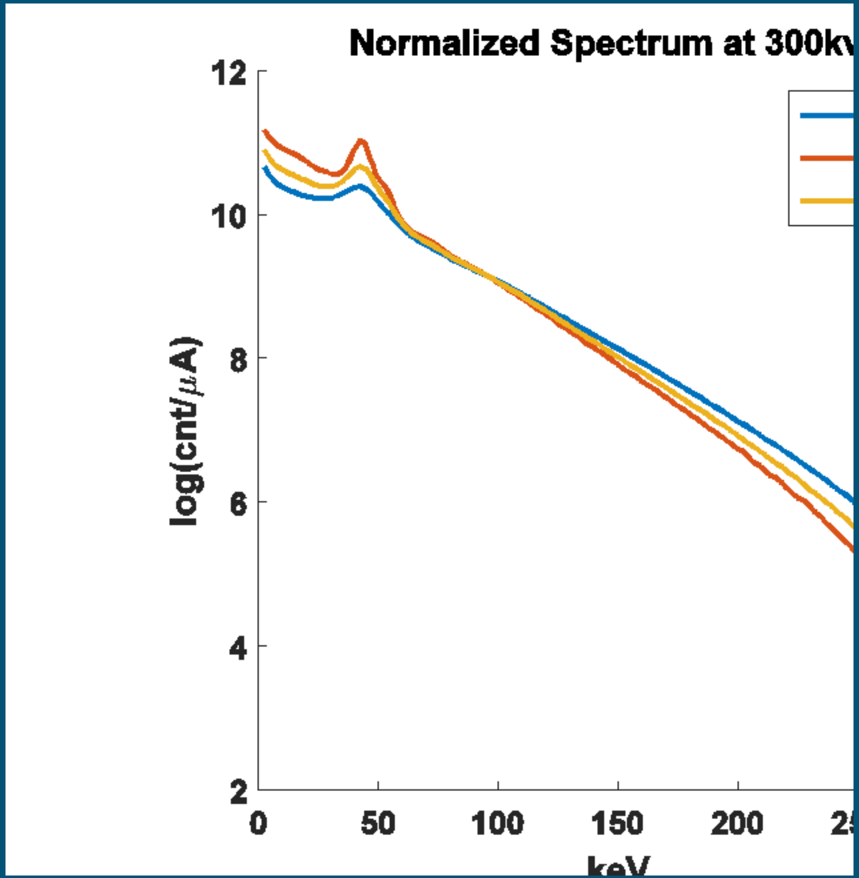


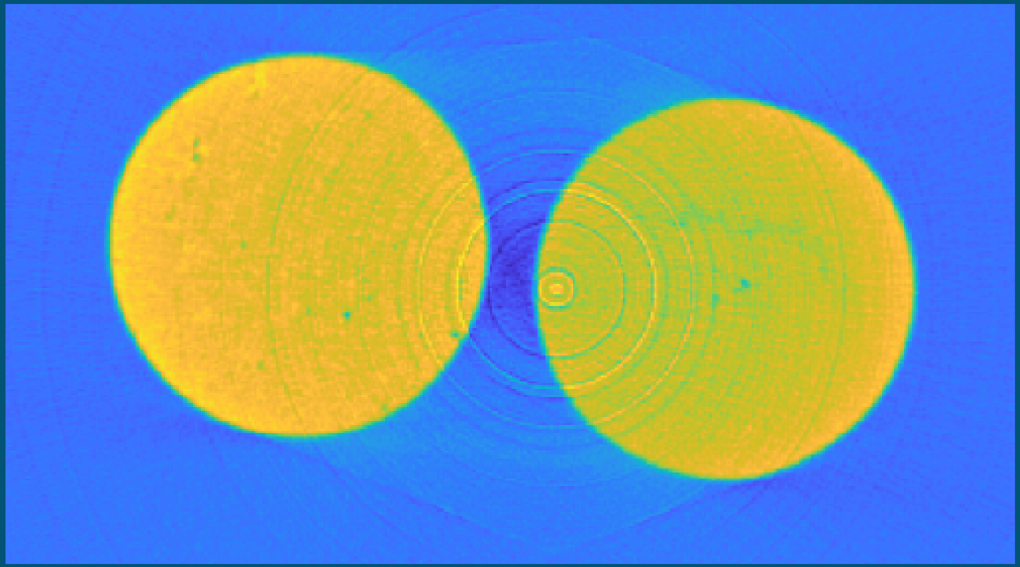
# Advantages of Hyperspectral CT

- Single-Channel for Effective Bandpass filter

- Linearizes the imaging system

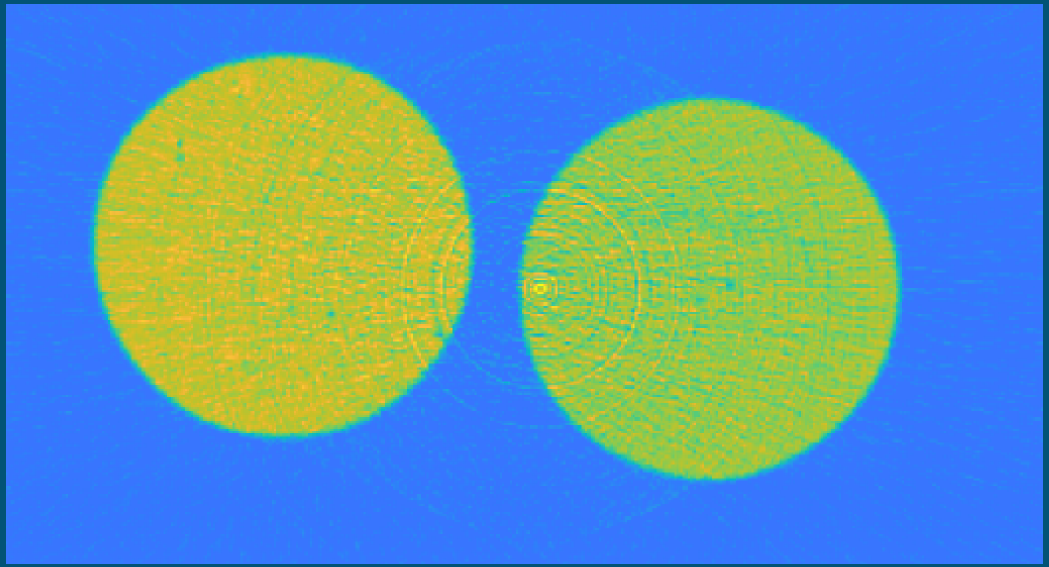
- Improved Reconstruction Quality through artifact reduction

# Reconstruction - Even Simple Objects have Artifacts!



Traditional Reconstruction

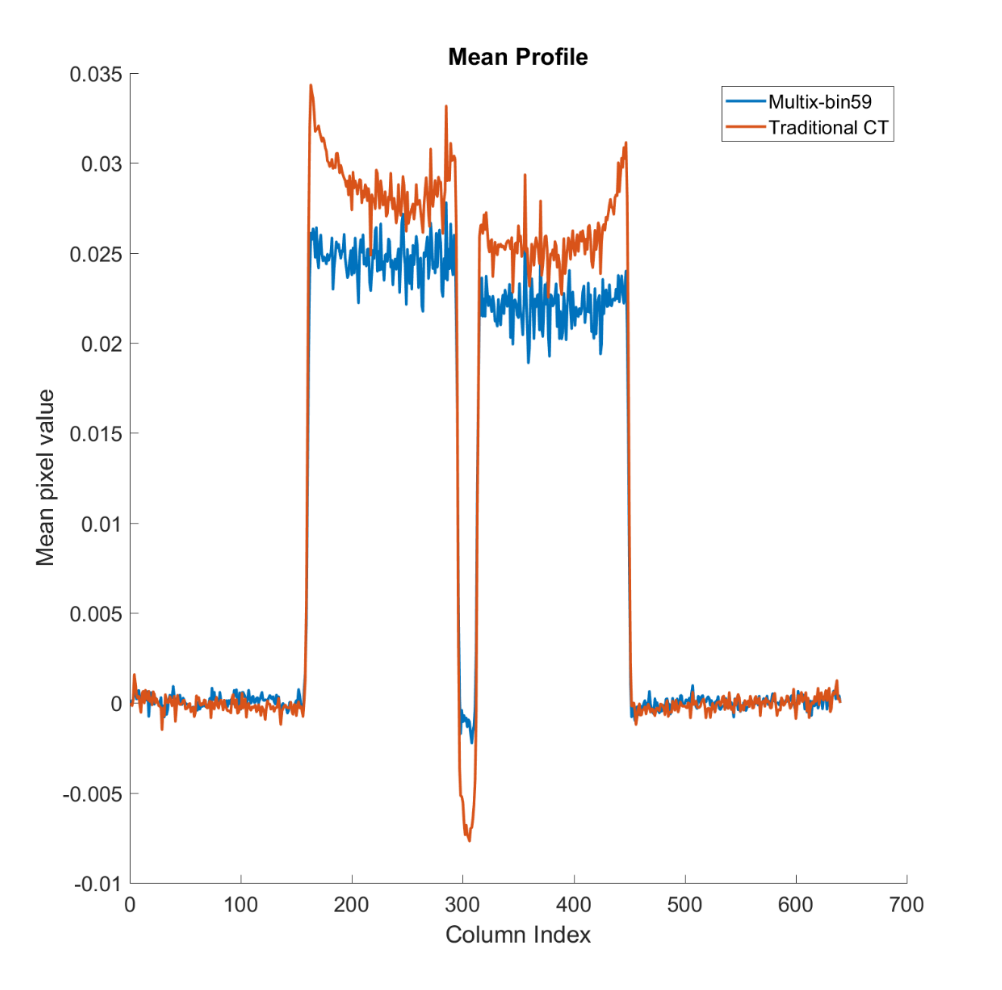
- Summed bin data
- Streaking emanating from objects
- Beam hardening

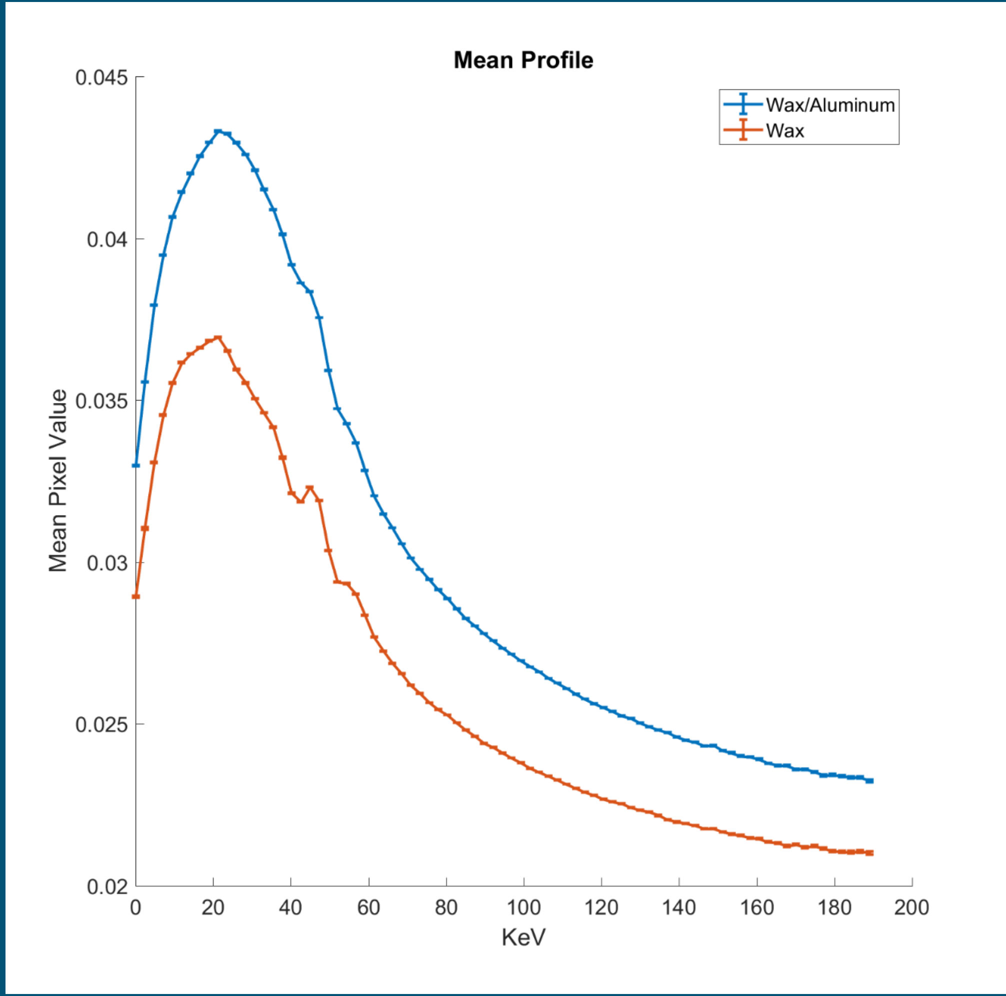


Single Bin Reconstruction

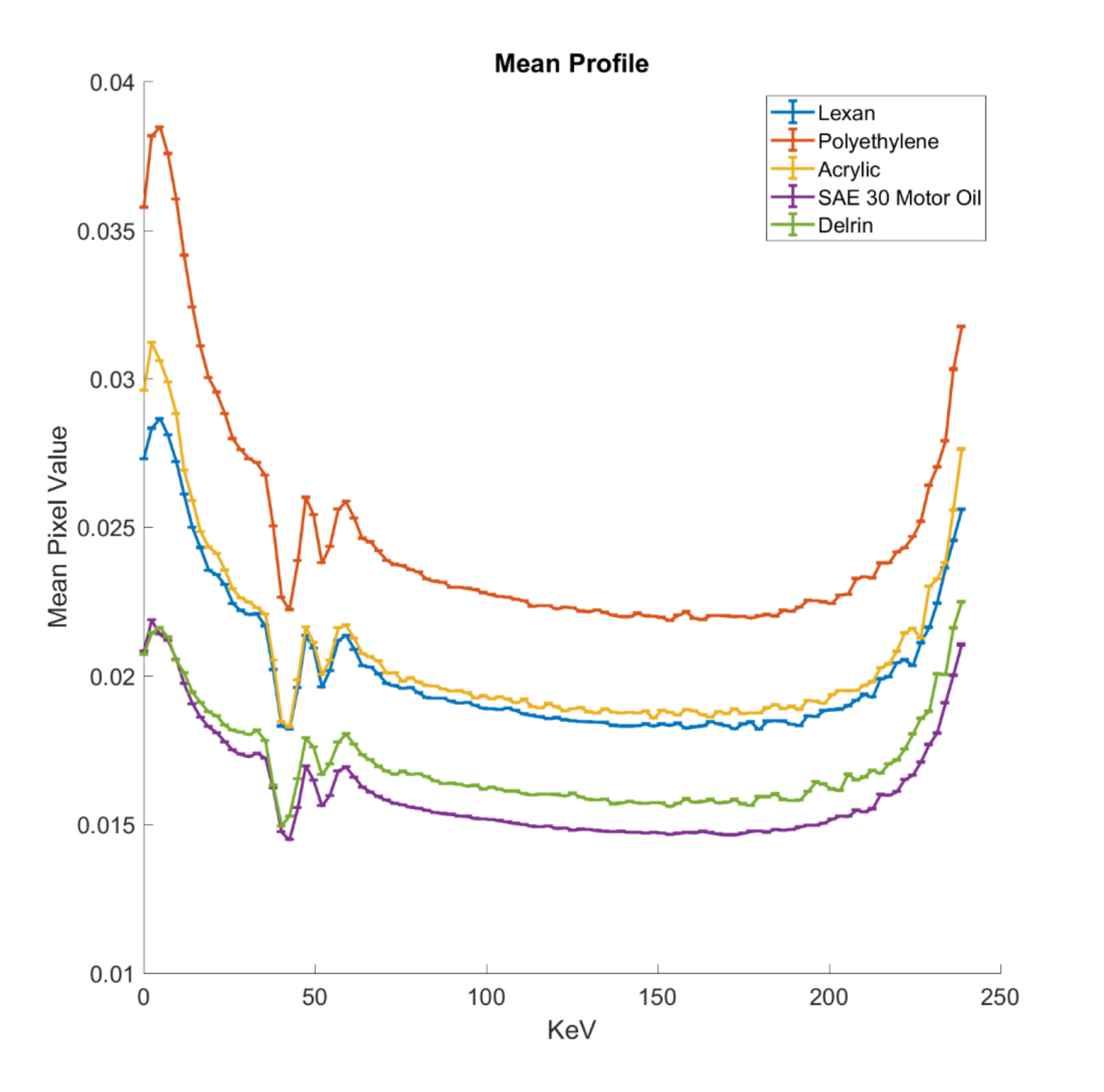
- Identical Reconstruction Algorithm
- Reduced Artifacts
- Uniform Sample Value

# "Huh…well that's interesting…"



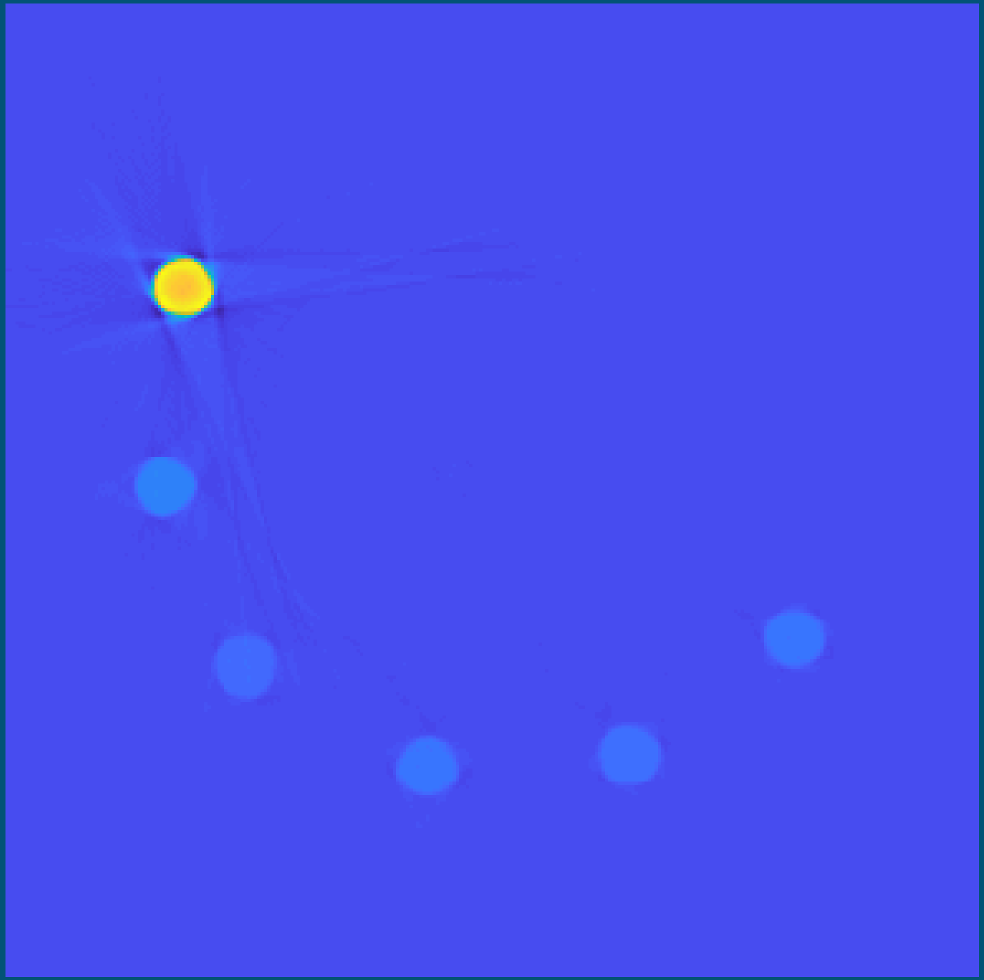



# "Curiouser and curiouser…"



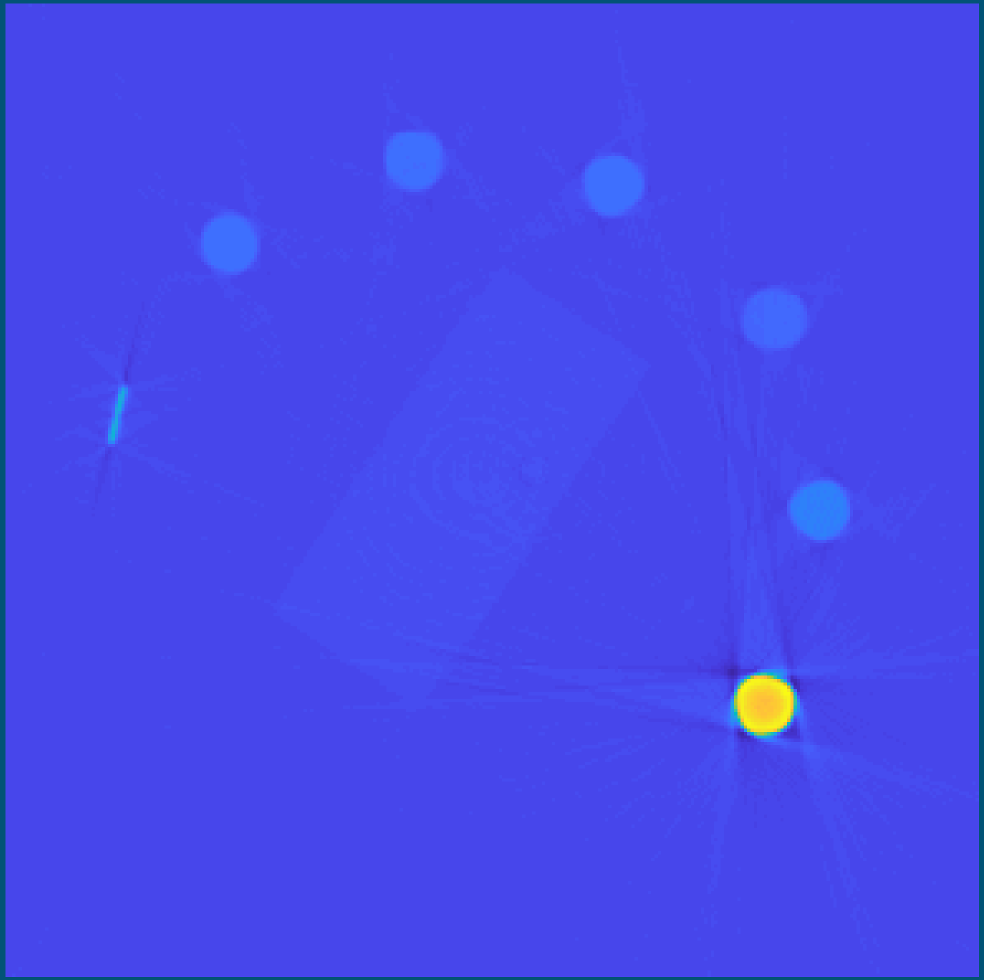
# Unsupervised Learning...quick excursion!

- Six materials
- Isolated
- Artifacts on edges of cylinders
- Highly similar spectral data



# DATASETS: CERAMIC CYLINDERS WITH COIN AND BLOCK

- Permuted material positions
- Added steel penny and wood
- Penny and block absorb signal, create additional artifacts
- Increased difficulty in material identification task



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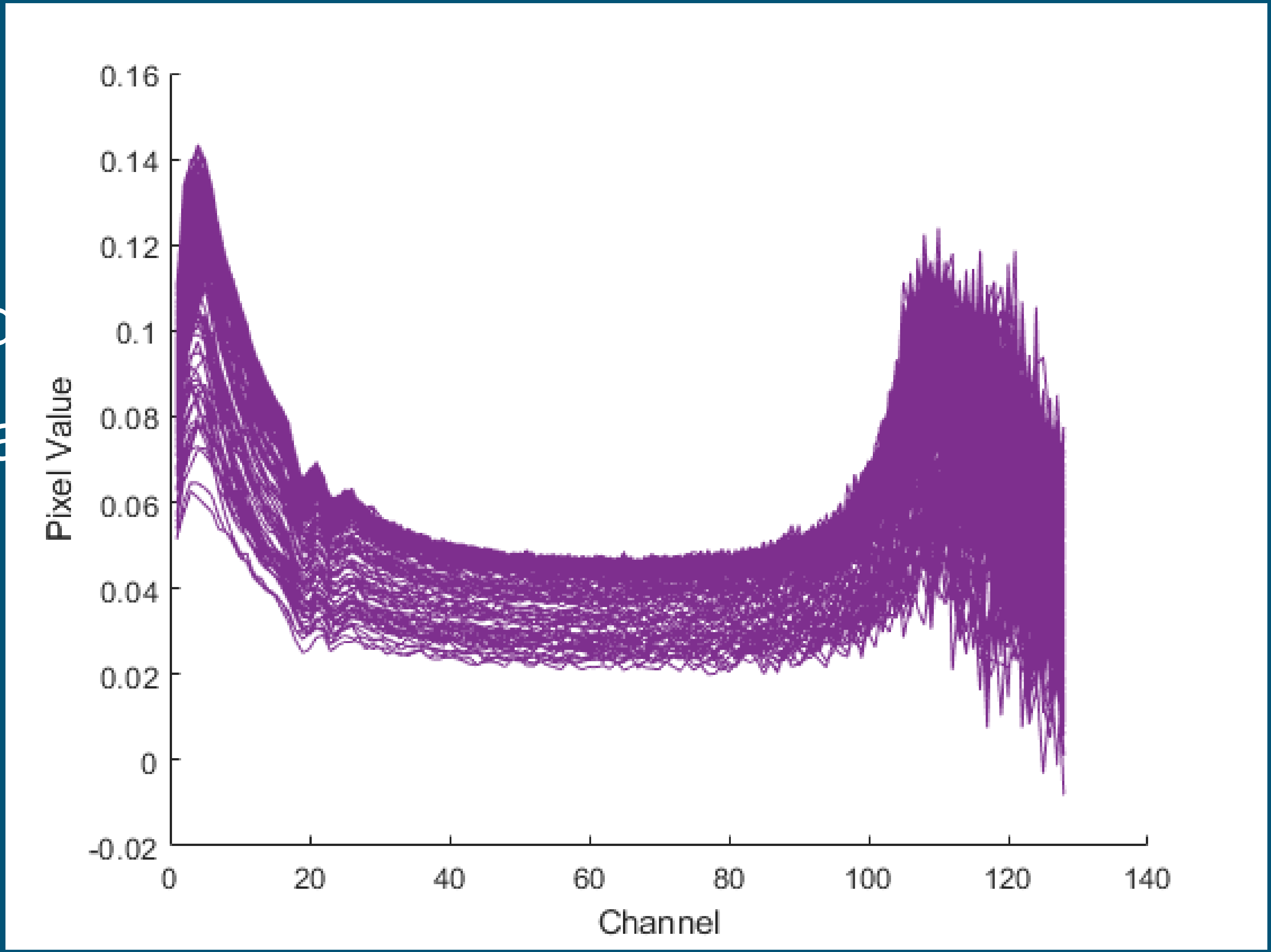

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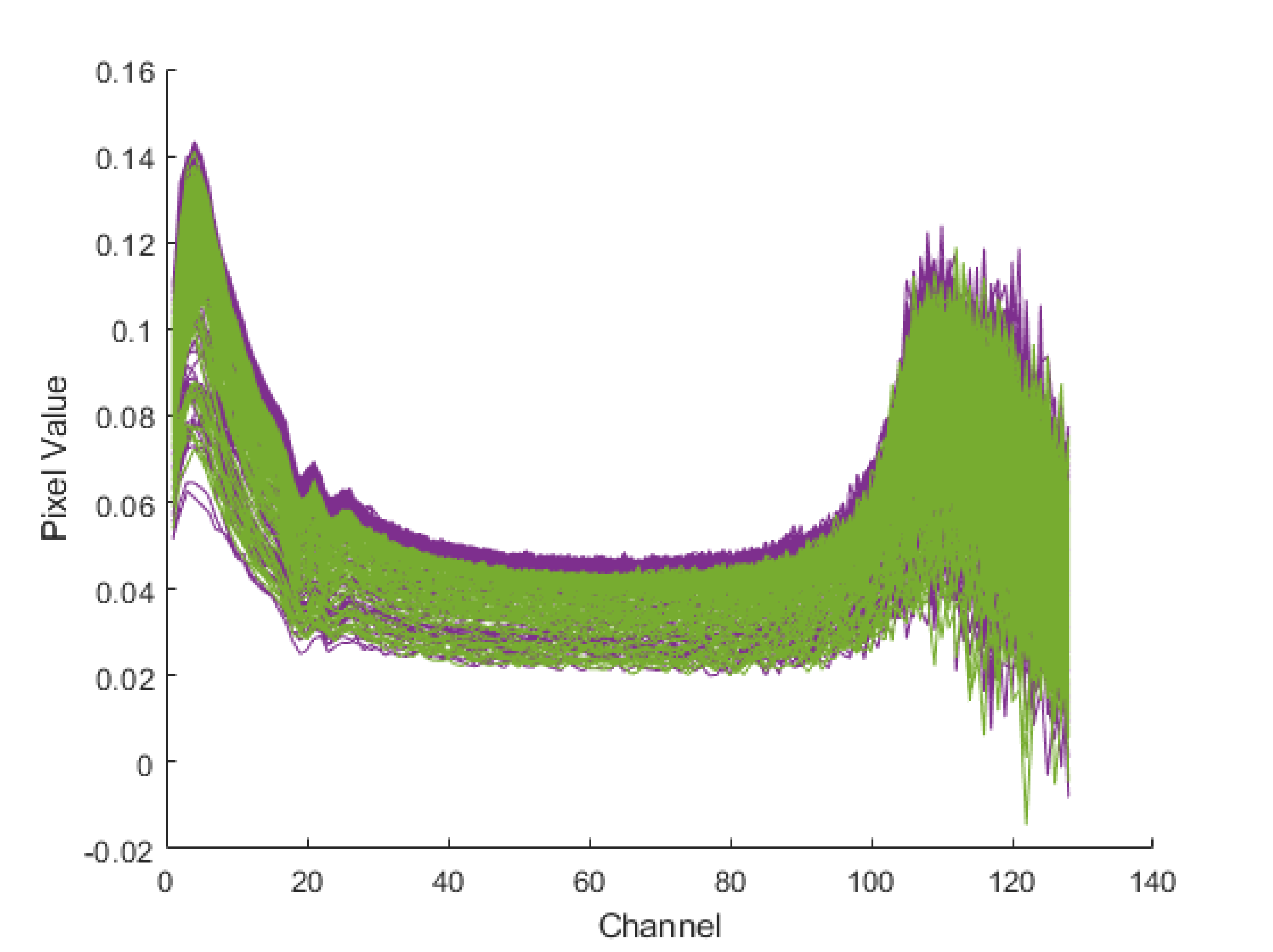

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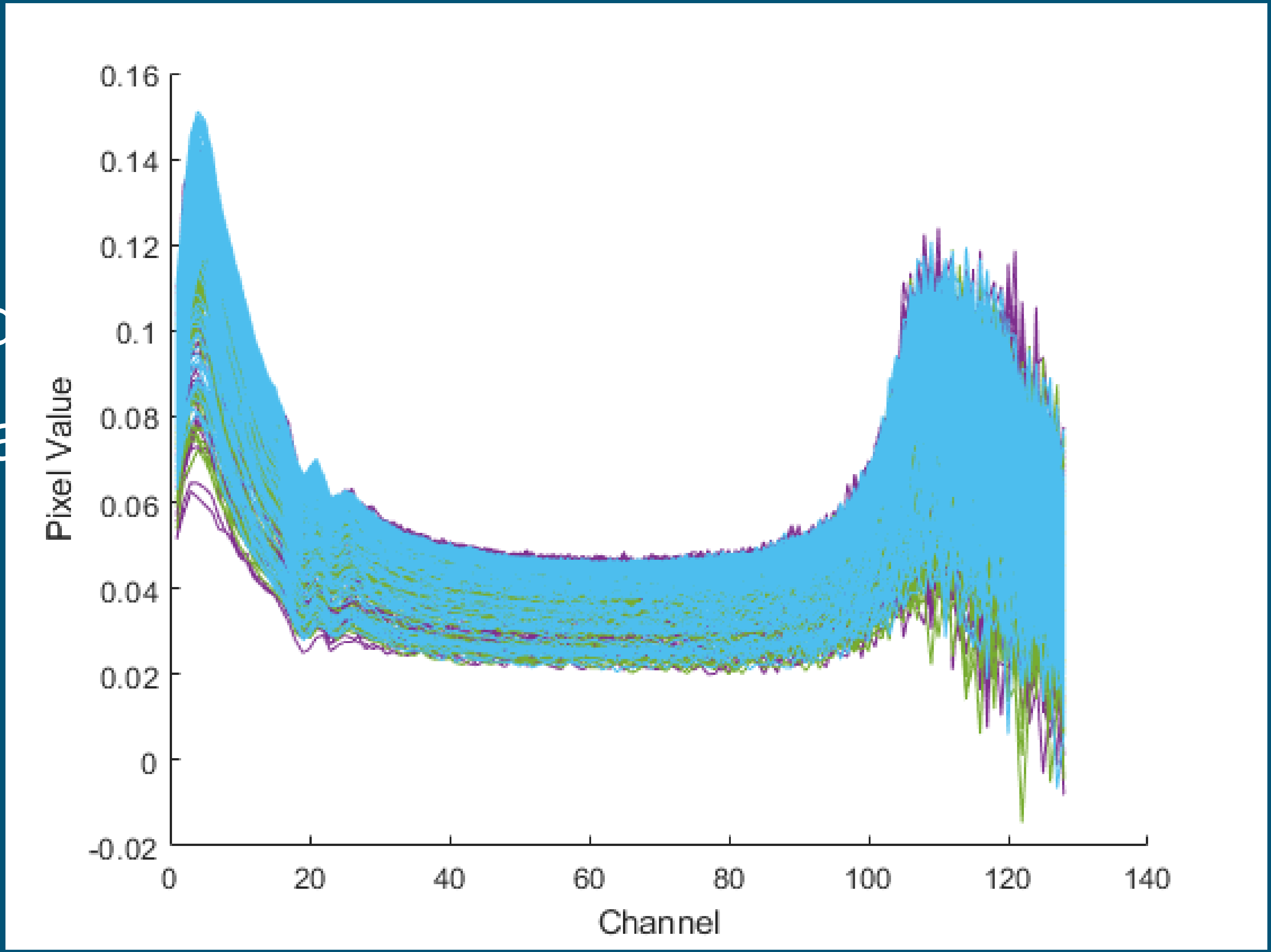


# Achievements of H-CT Effort

- Beam hardening artifact reduction through band passed spectral data.

- Demonstrated material identification capability.
  - Supervised Learning
    - Koundinyan et. Al. – Perform Machine Learning based Material Identification of various liquids, metals, and plastics
  - Unsupervised Learning
    - Gallegos et. Al. – Performed Classification of various ceramics of similar density and molecular composition

- Four patents filed
  - 3 granted
  - 1 in review

# We're not out of the woods yet…What did we learn?

- Temperature sensitivity
  - Detector pixel responses seem to be temperature dependent
  - Fixed sensitivity bias was also observed
  - Calibrating was a huge challenge!
  - Ring artifacts is the main consequence

- Photon starved even with long exposures
  - Poor quality reconstructions
  - For single channels, some have poor penetration, low photon signal, or both!

- Partial voxel occupancy is significant for this system
  - Affects the edges of objects as their spectral signature will represent 2 or more materials

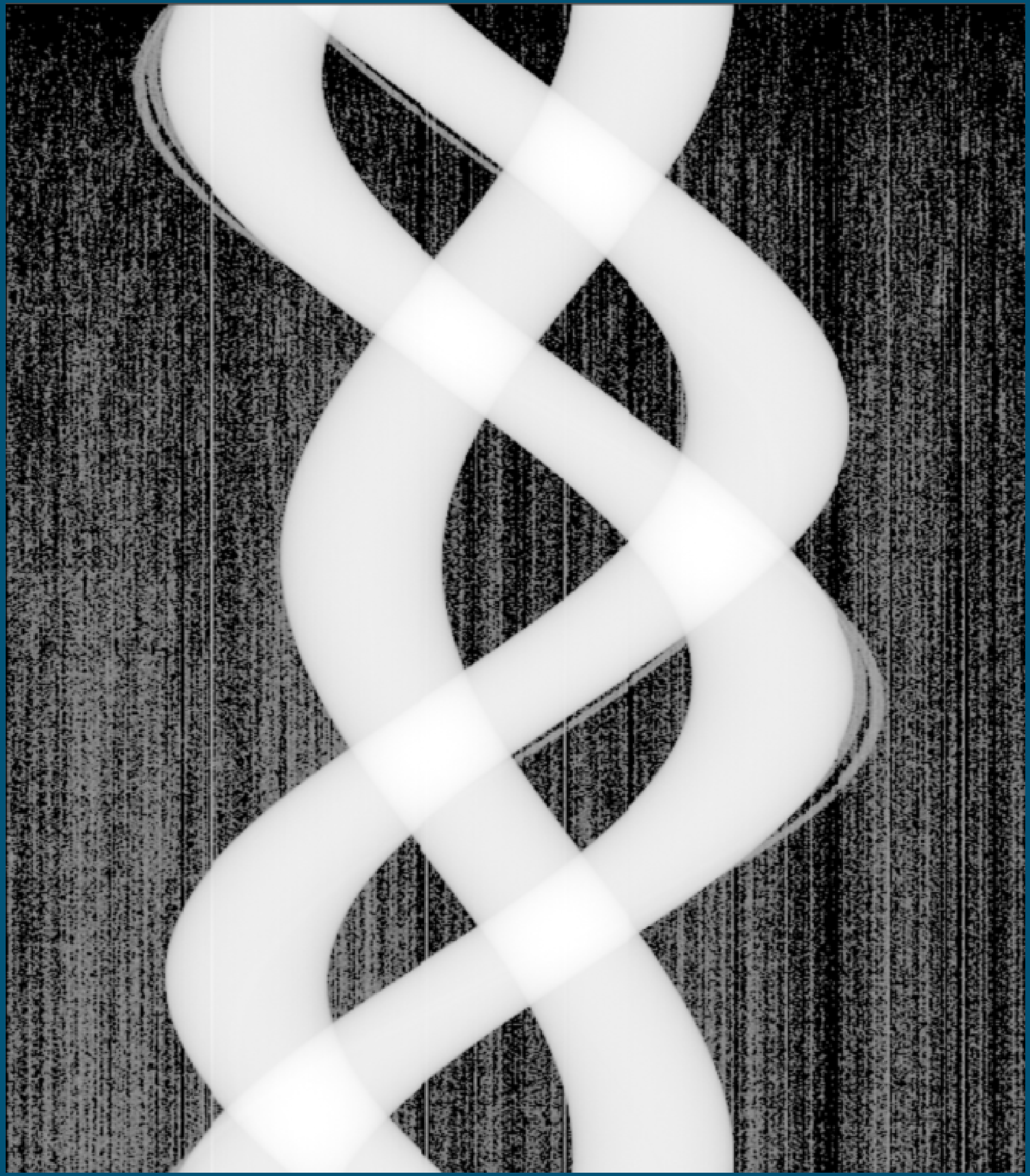
# Temperature Sensitivity

- For every data acquisition:
  - Severe ring artifacts were observed
  - Beyond typical ring removal
  - Detector responses changed over time
  - Virtually impossible to calibrate!

- Although temperature can be queried, it may be difficult to do in practice in a robust manner.

- As the electronics are run, the equipment heats up over time.

- Additionally, environmental changes may affect the sensitivity.



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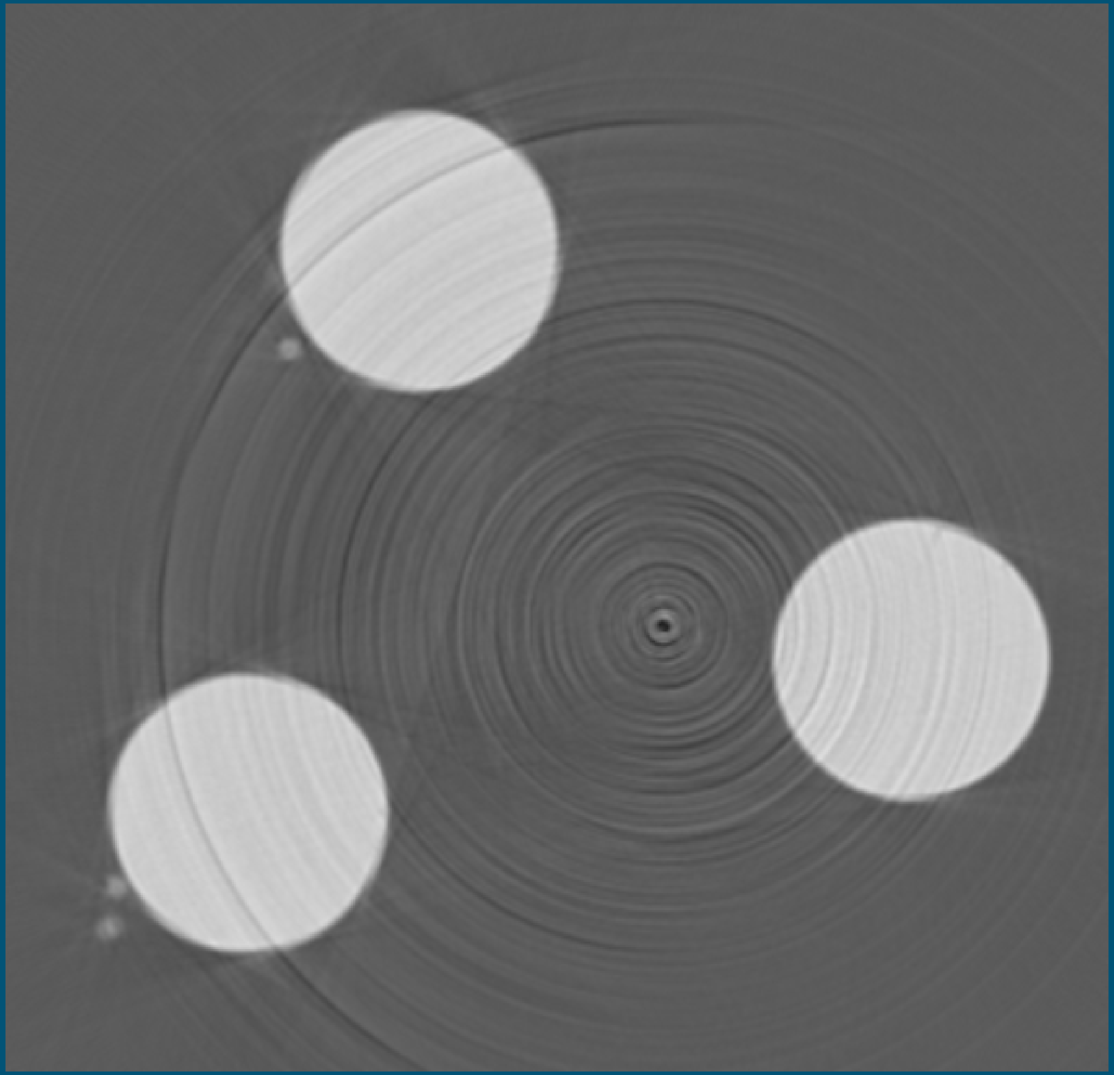
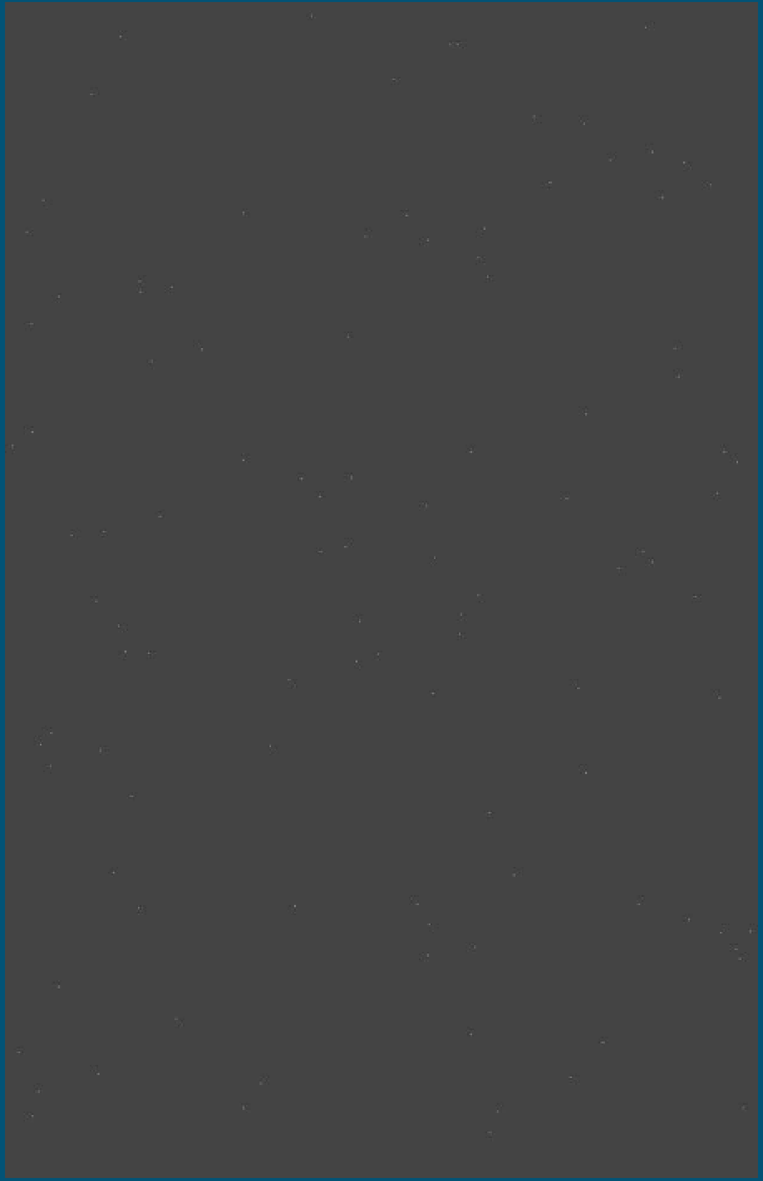


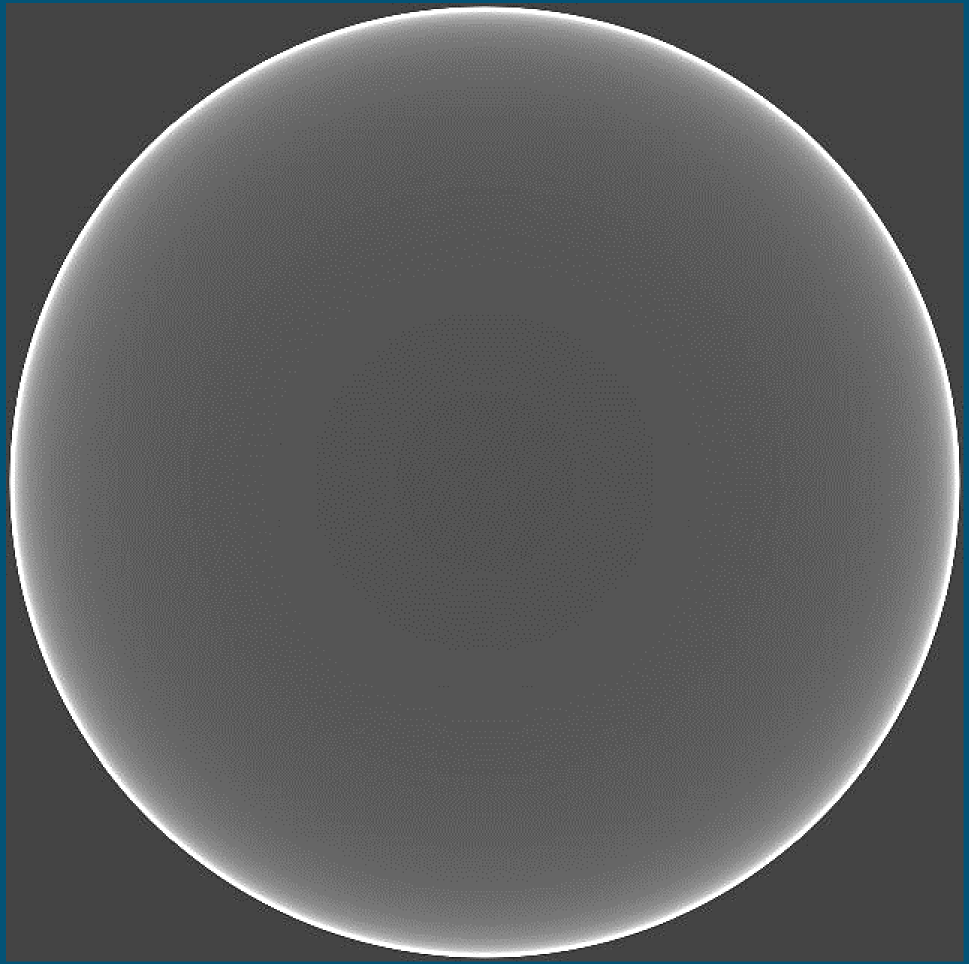
# Photon Starvation – Simulation of Sugar Water

- Question:
  - For a given allocation of photons, are all channels sufficiently saturated?
- Experiment:
  - Monte-Carlo simulation of typical Bremsstrahlung Radiation profile through samples of sugar water at various concentrations.
  - Eliminate other sources of noise, purely photon signal dependent.
- Goal:
  - Determine if every (or almost every) channel can provide a CT reconstruction of sufficient quality.



# Photon Starvation – Simulation of Sugar Water

- Traditional Feldkamp Reconstruction
  - Even for simple objects and arrangements, streaking artifacts dramatically affect image quality.
  - To be expected for low and high index channels.
  - Streaking is dramatic at every channel!



# Maybe H-CT isn't so simple?

- Implementing a Hyperspectral System likely involves a more significant deviation from traditional CT than just swapping out the detector?
  - Calibration
  - Acquisition time
  - Sparse signal

- What if we swapped out reconstruction algorithms?
  - Iterative reconstruction
    - Robust with sparse signals
    - Could shorten acquisition time
    - Could alleviate calibration requirements (sort of…)

# Iterative Reconstruction – A Possible Solution

PARENTAL
ADVISORY
EXPLICIT CONTENT

# Iterative Reconstruction – A Possible Solution

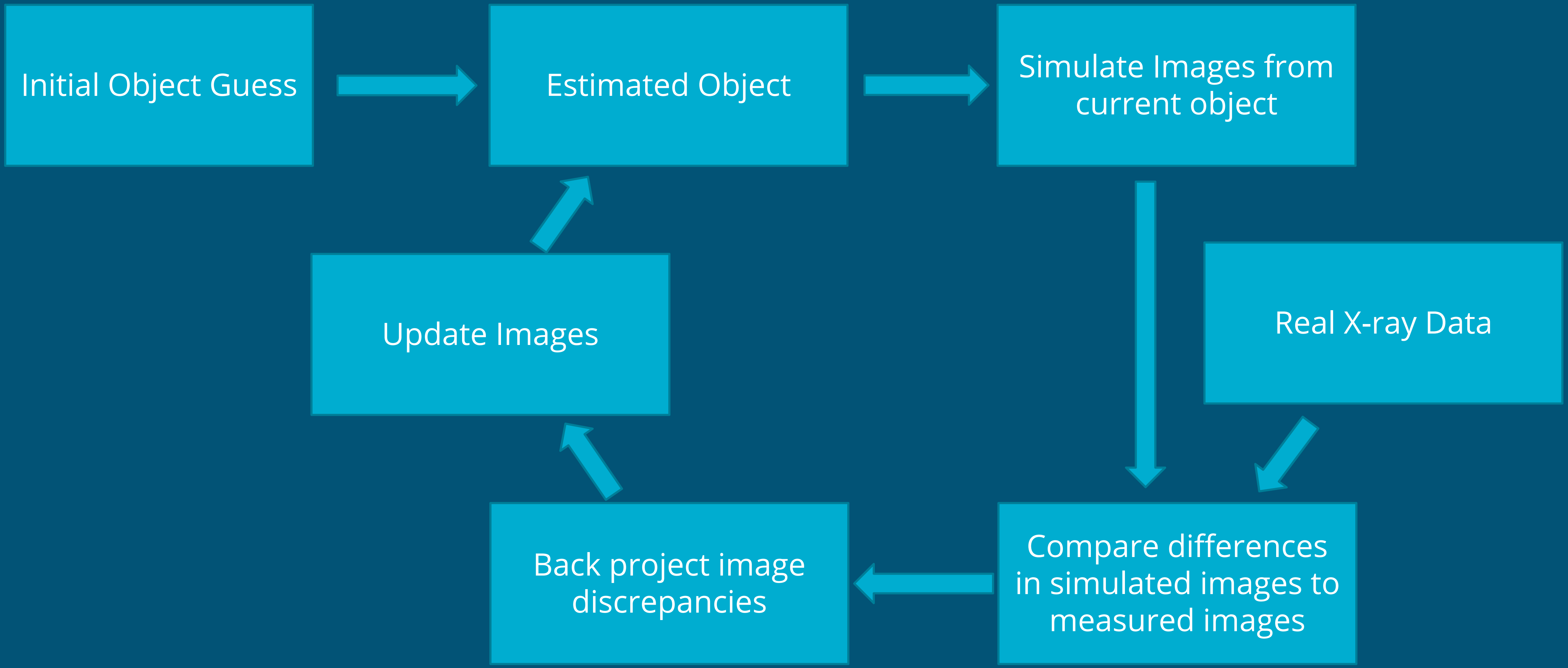
- Iterative Reconstruction
  - Prohibitive in the past
  - Challenge 1: 10x to 100x more computationally expensive than direct reconstruction
  - Challenge 2: 100x more data!

- We developed an implementation using multiple graphics processors in parallel for a high-performance computing solution.

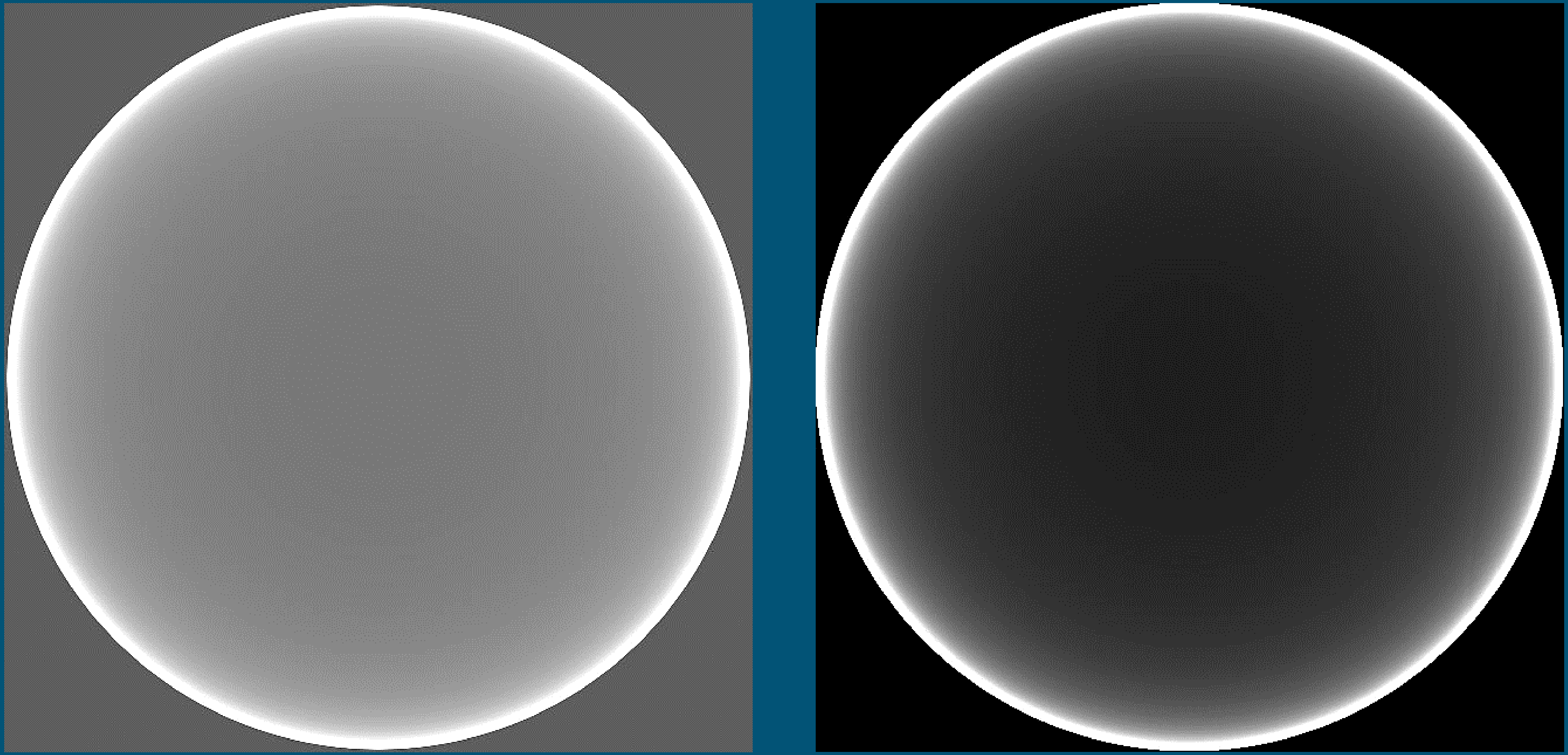
- Maximum Likelihood Expectation Maximization:

$$\hat{\theta}^{(k+1)} = \hat{\theta}^{(k)} \frac{1}{s_n} \sum_{m=0}^{M} \frac{g_m}{\left(H\hat{\theta}^{(k)}\right)_m} H_{mn} \cdot$$

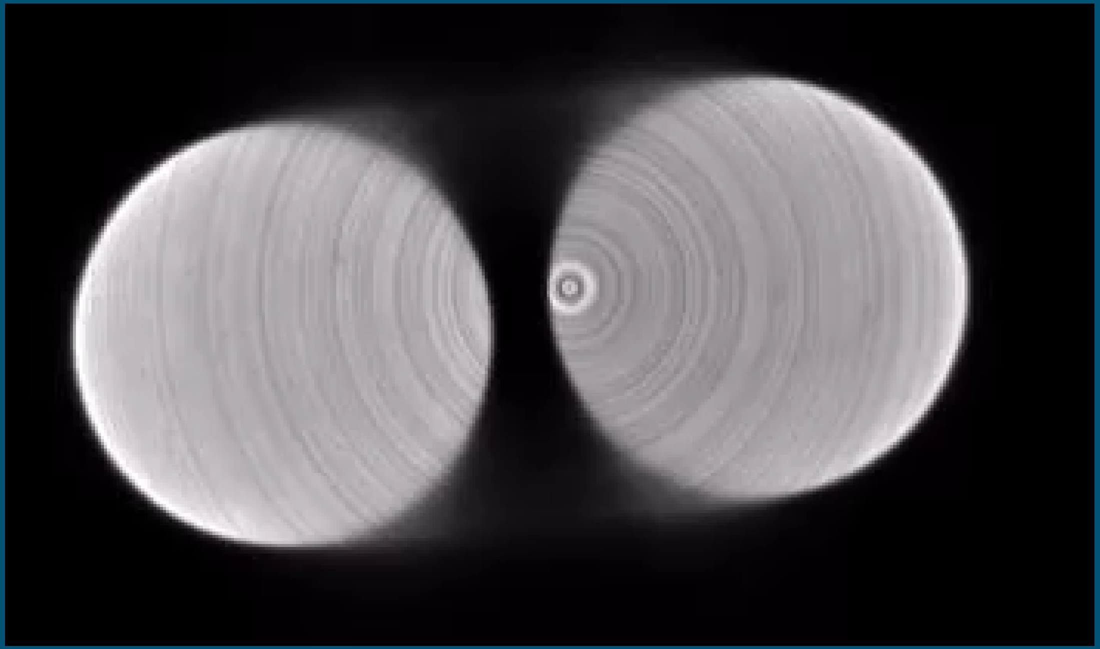
# Maximum Likelihood Expectation Maximization

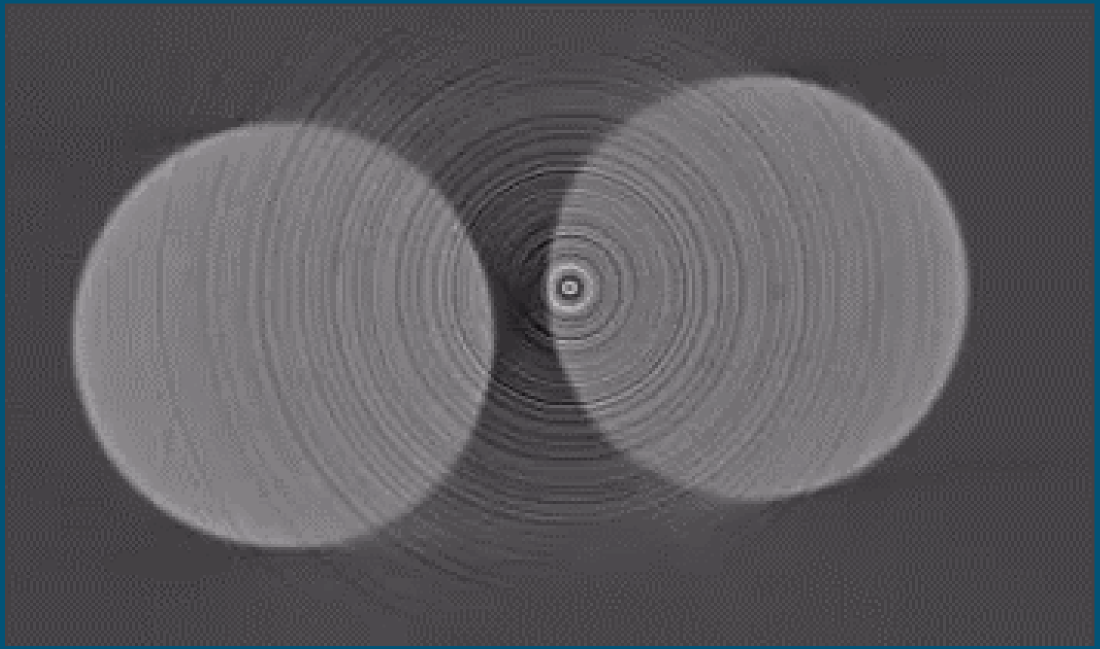


# FDK vs. MLEM – Monte Carlo Simulations

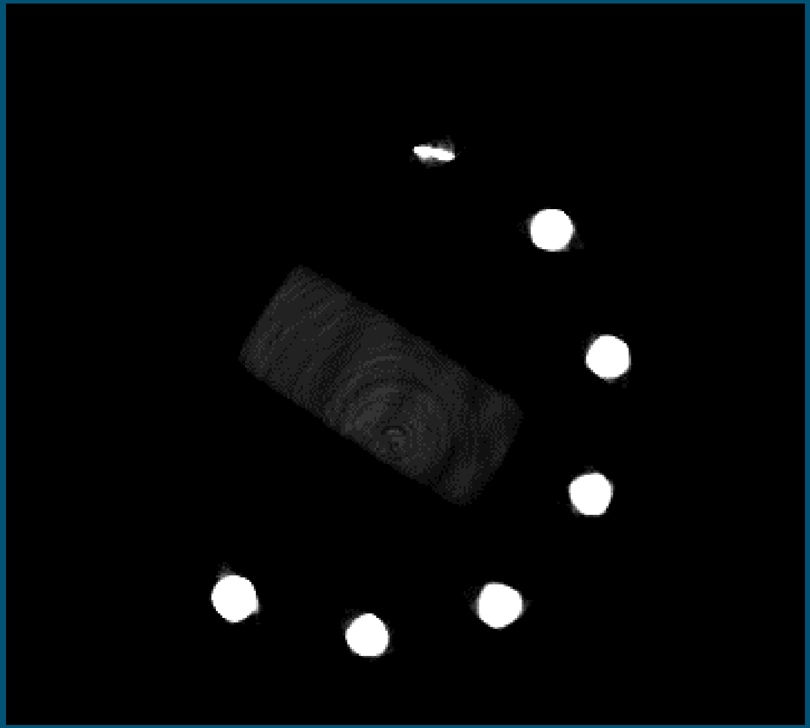


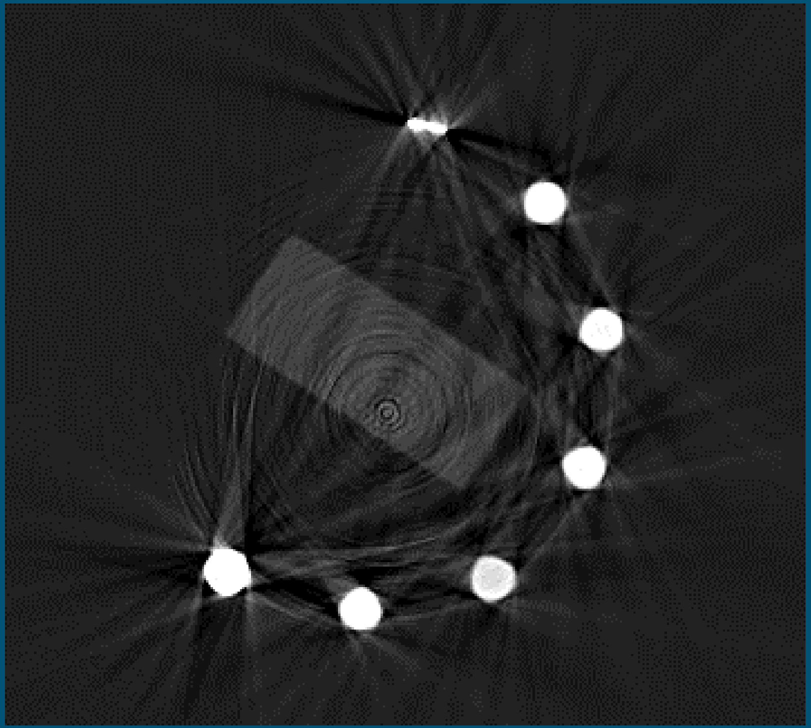
# FDK vs. MLEM – Wax Samples



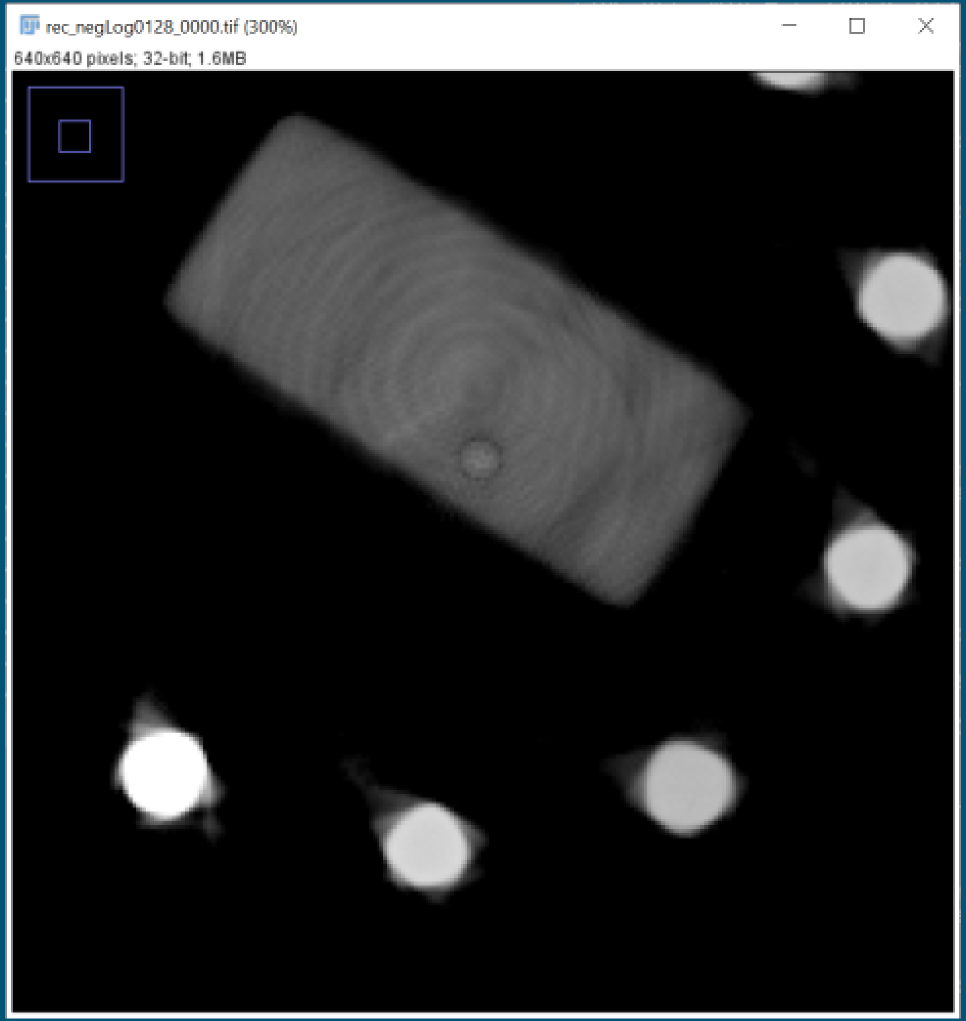


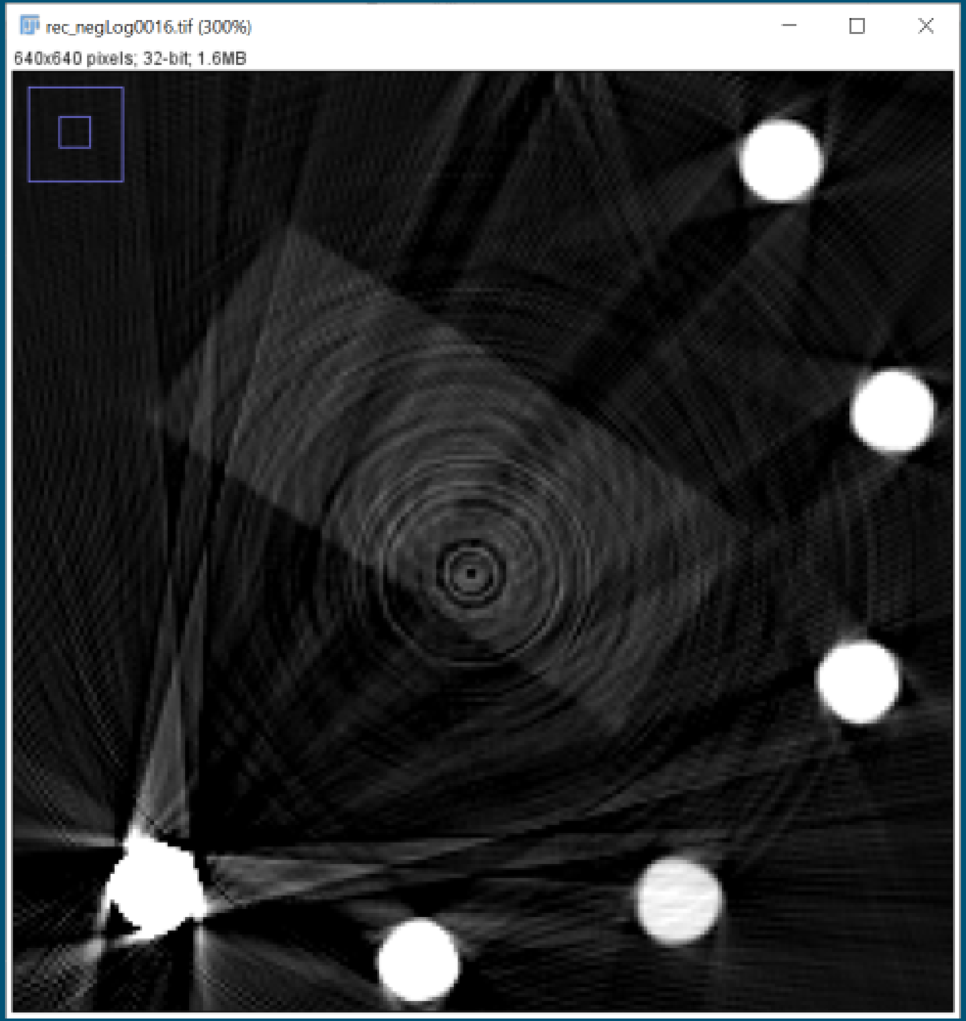
# FDK vs MLEM – Ceramic Samples – Wood with Steel





# FDK vs MLEM – Ceramic Samples – Wood Region



# Looking to the Future

- This year, we are building a new system
  - Current generation detector technology
  - Better thermal regulation – more robust detector response?
  - High count rates – High flux system output for faster acquisition

- Investigating Multi-metal patterned anodes
  - Preferential spectrum shape for maximum signal quality
  - Improved system resolution

- Expand application spaces
  - Counterfeit detection
  - Spectral decomposition to chemical composition