# Diagnostic Imaging Using Contrast from Fission

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Los Alamos National Laboratory
FIESTA Fission School
and Workshop

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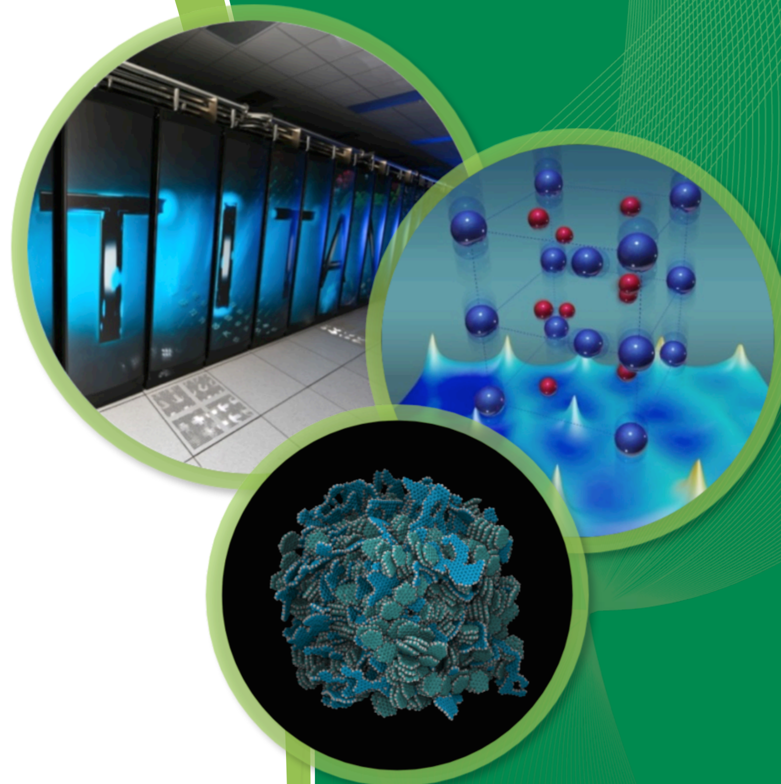



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# Elements of Imaging

Object

- Unknown object



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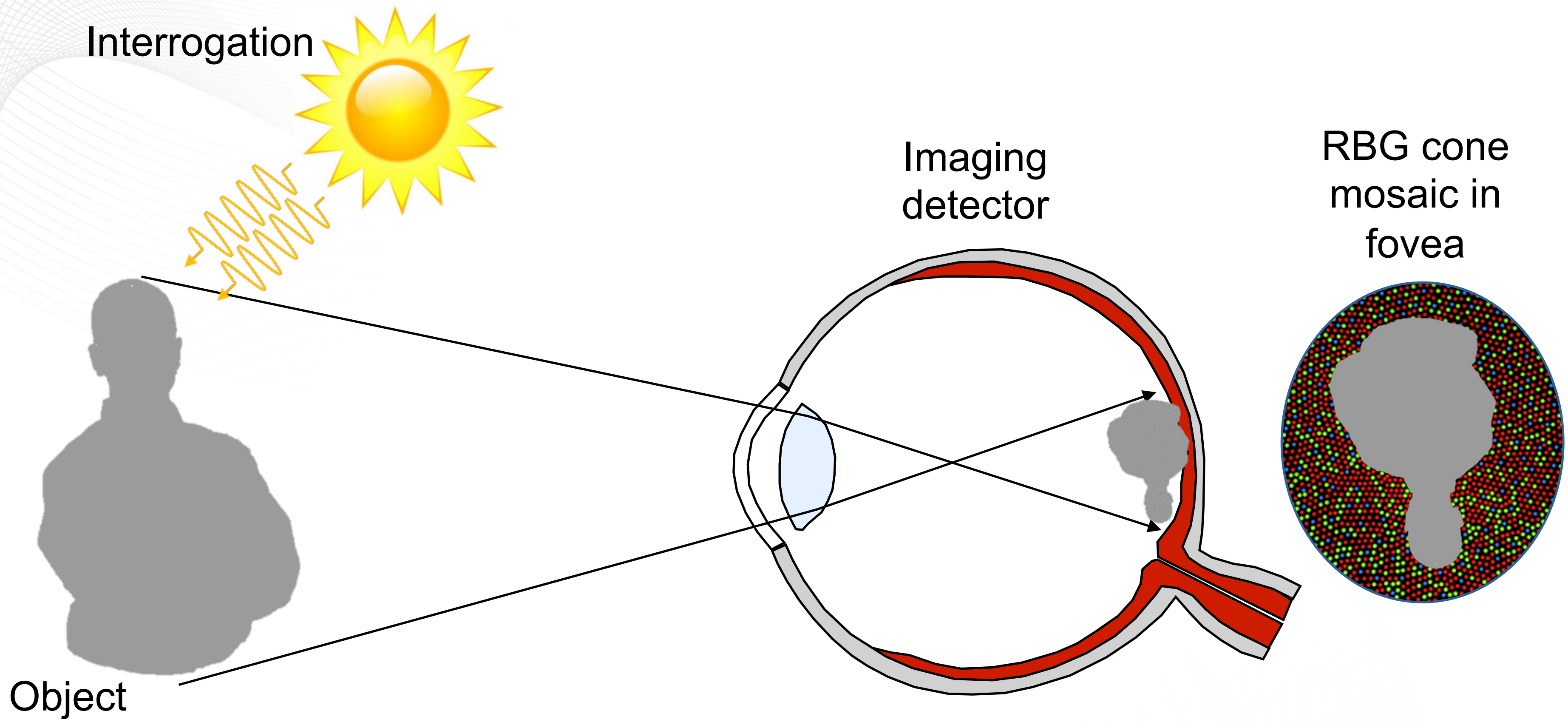
# Elements of Imaging

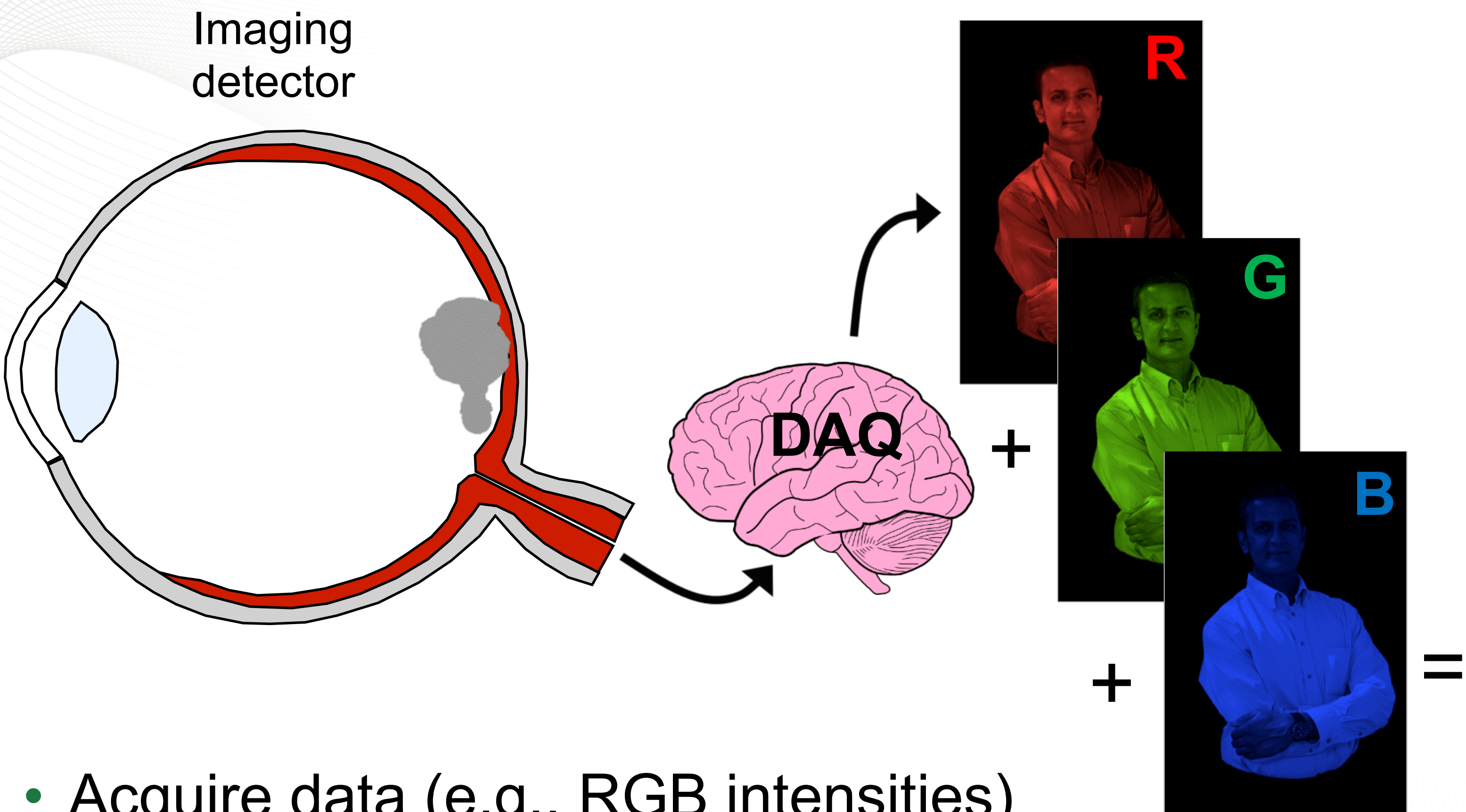

- Interrogate with photons (from the sun)

# Elements of Imaging



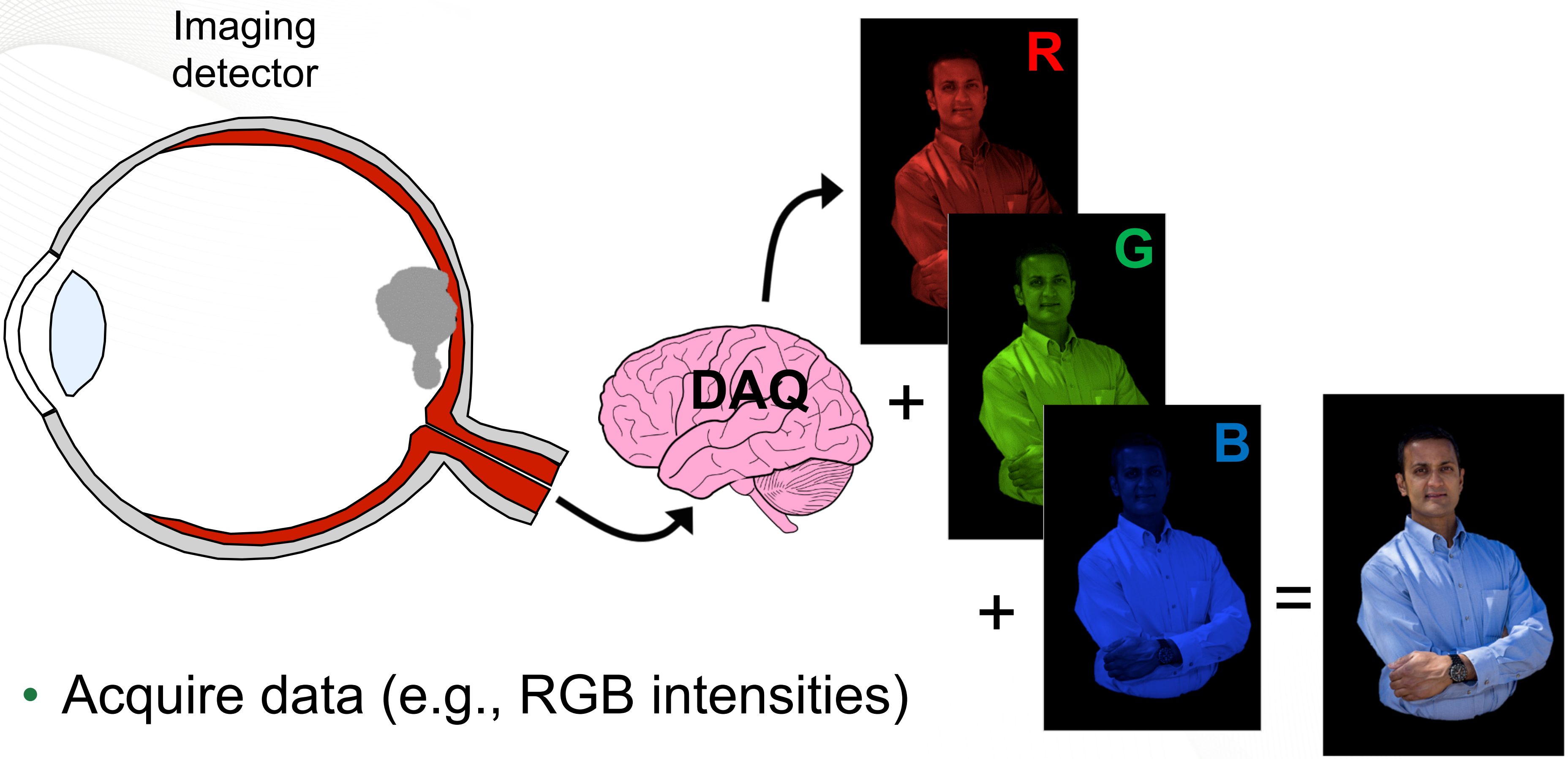

- Measure emitted radiation with an imaging detector (eye)
  - Position sensitive detector
  - Known mapping between detector pixel and object voxel

# Elements of Imaging



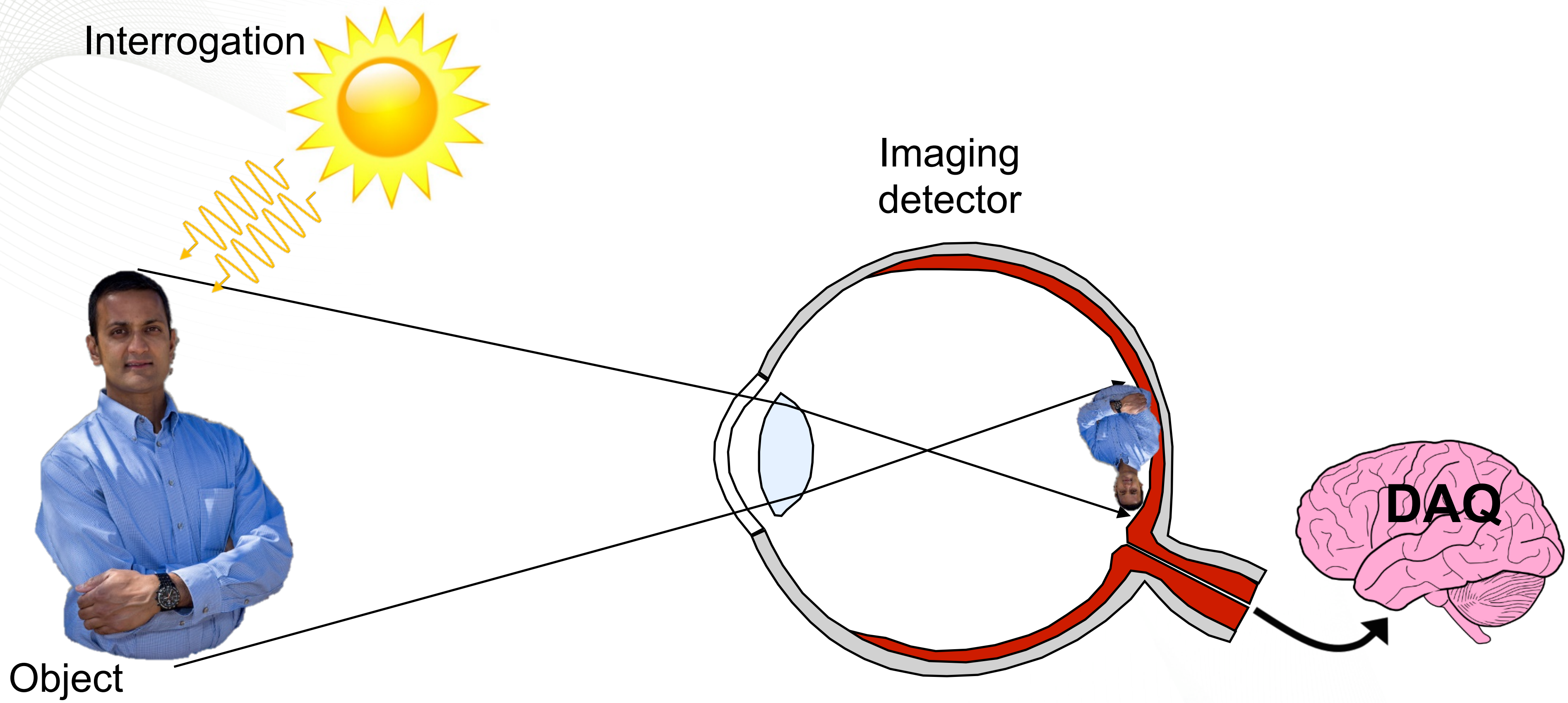

- Acquire data (e.g., RGB intensities)
- Process detector signals in data acquisition

# Elements of Imaging

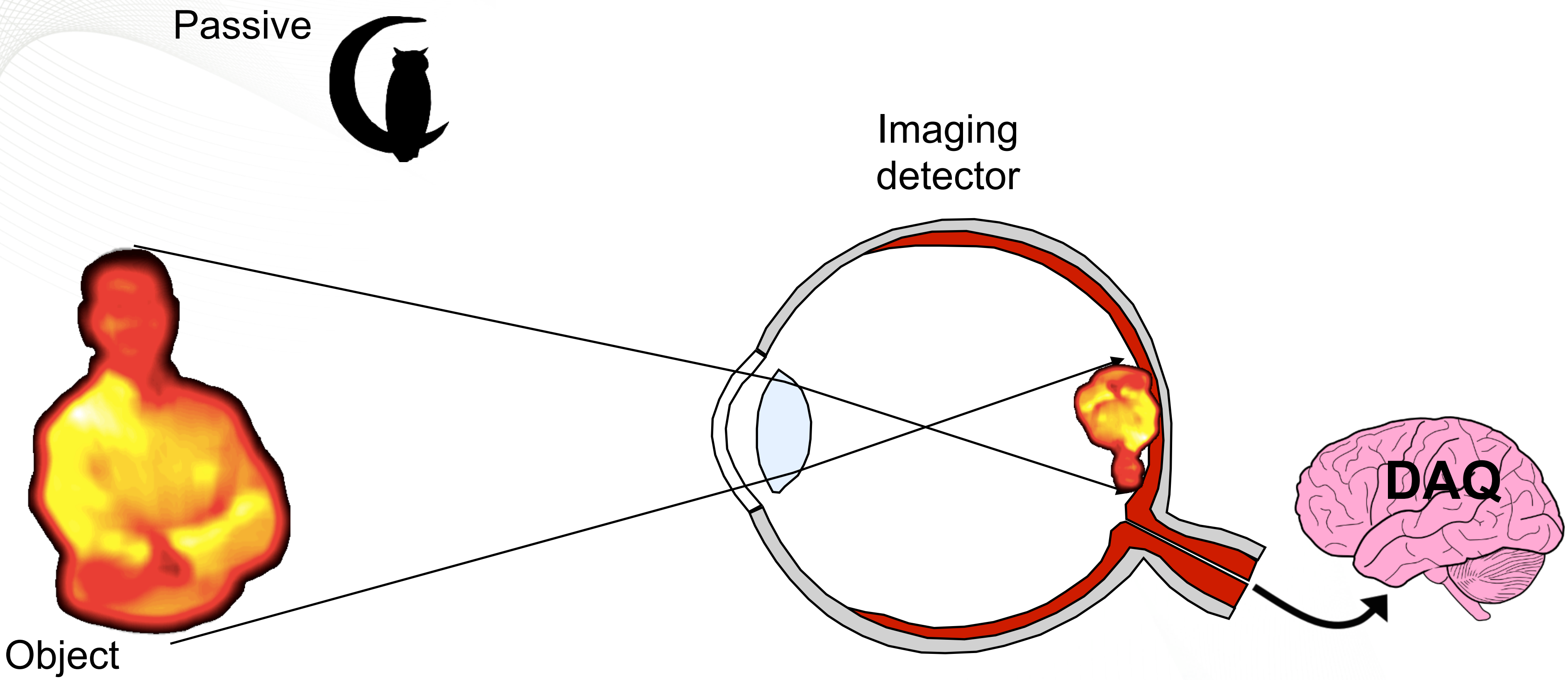



- Acquire data (e.g., RGB intensities)
- Process detector signals in data acquisition
- Then, do something with the information (e.g., recognize Avneet)

# Active Imaging



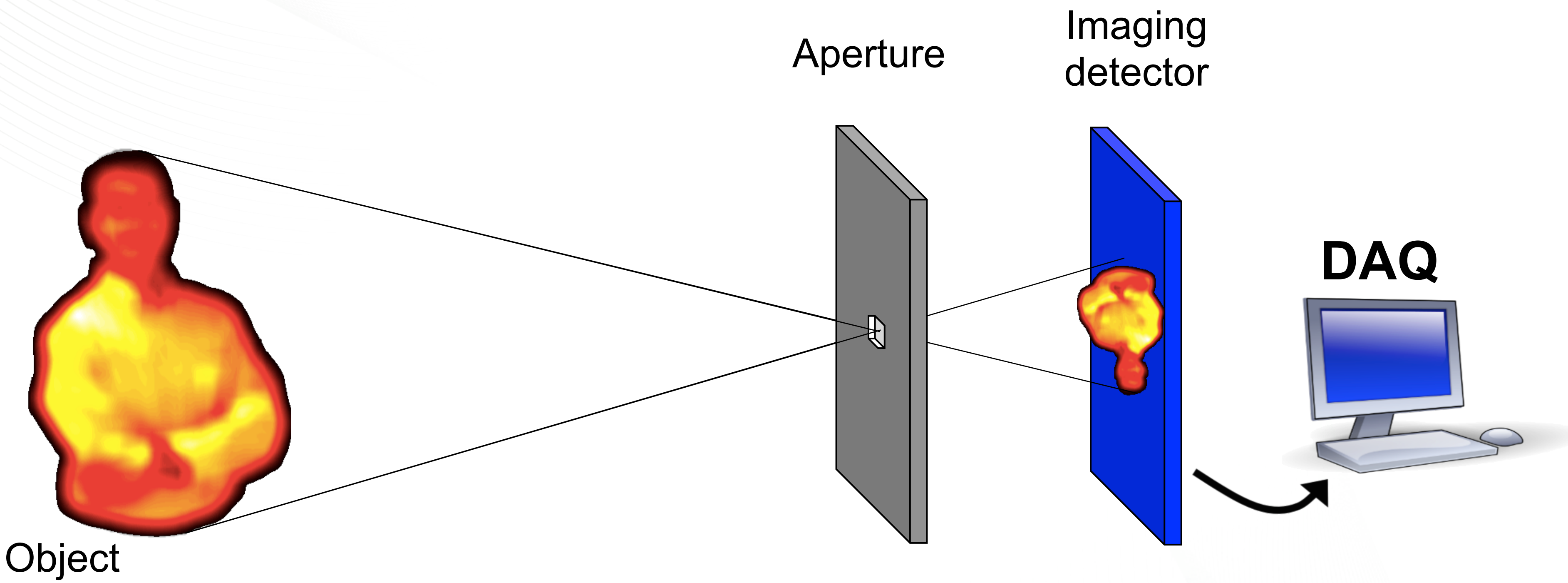
# Passive Imaging




- If Avneet emits radiation, then passive measurements are possible without interrogation

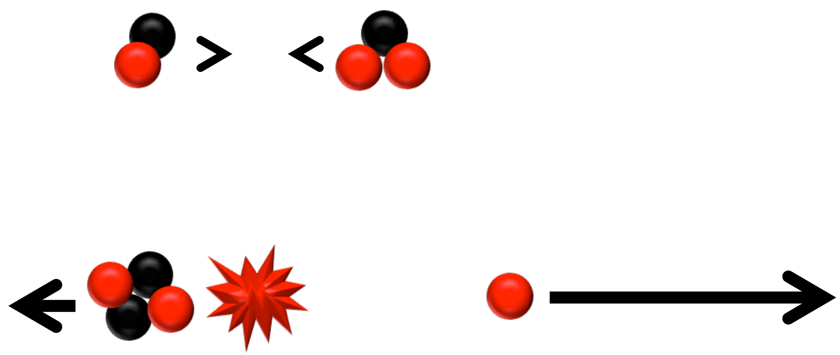
# Imaging Fission: Idea

- In principle, the process for imaging fission is the same




- Use stimulated or spontaneous fast-neutron emission to indicate fission
- Use collimation of source or detector to achieve mapping between each neutron and a unique path though object

# Stimulated Emission: Associated-Particle Technique Using D-T Neutrons



- Interrogate using fast (14 MeV) neutrons produced by the $d + t \rightarrow \alpha + n$ reaction
- The $\alpha$ and $n$ are emitted simultaneously in opposite directions
- Detection of the alpha particle determines the time and direction of emitted neutron



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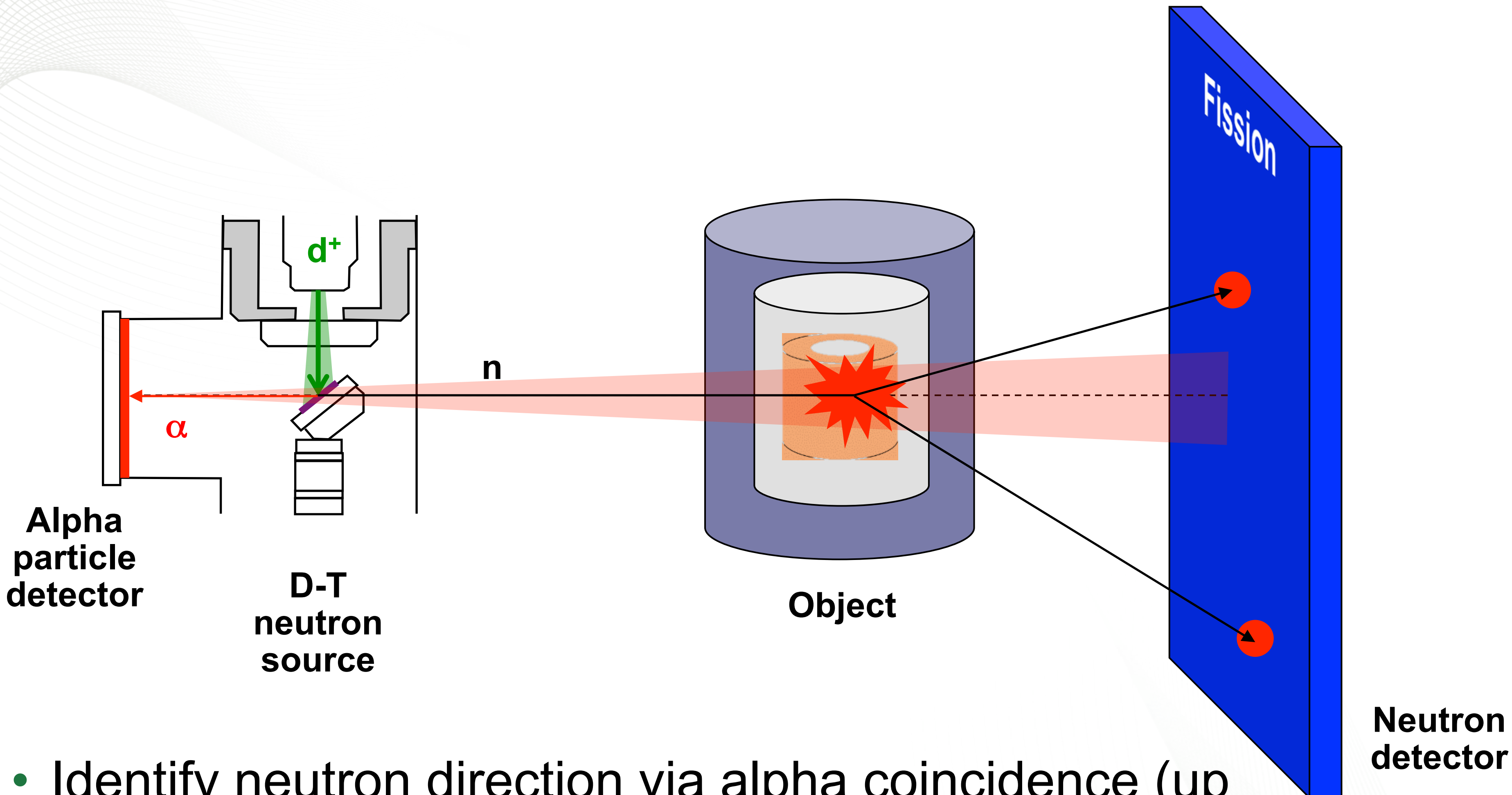
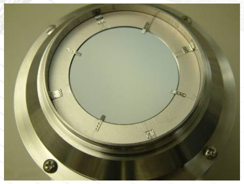
# Stimulated Emission Imaging

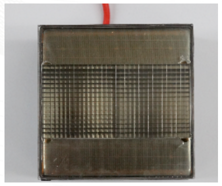



- Identify neutron direction via alpha coincidence (up to uncertainty from "spot size," detector resolution)
- Identify stimulated fission via multiple late neutrons

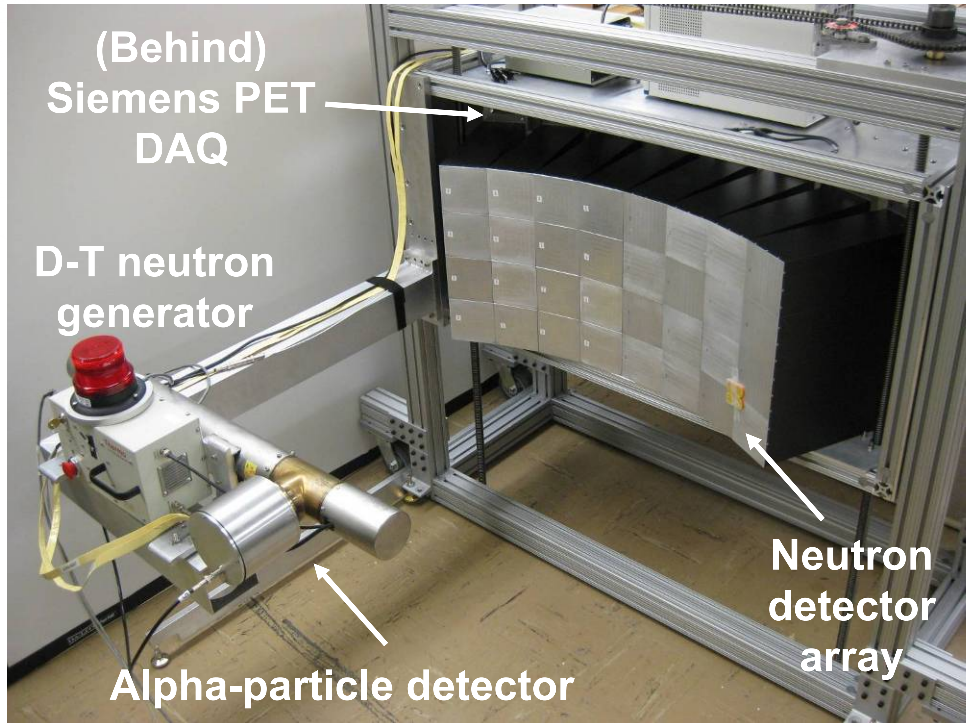
# Experimental Imaging System



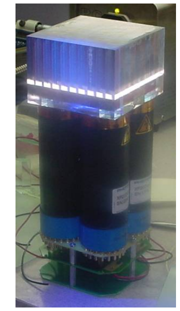
YAP:Ce alpha detector



Segmented readout



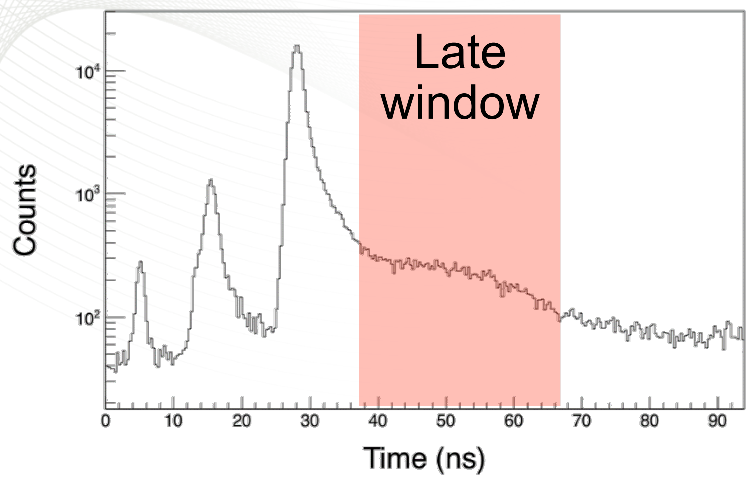

*Left*, D-T neutron generator with alpha detector (512 initial neutron directions).



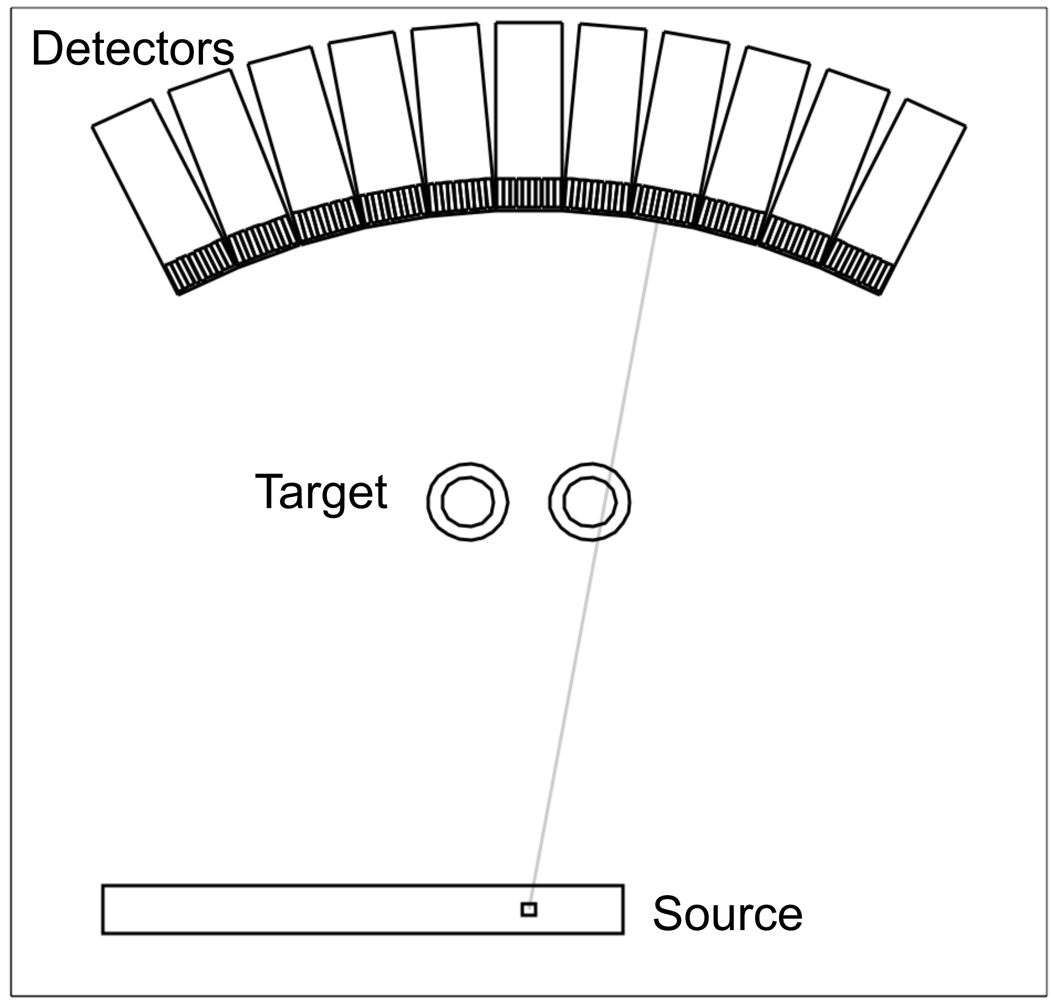
Plastic scintillator block detector. Fast, position-sensitive neutron detectors (3,200 total pixels).

- Imaging system has a D-T neutron generator with alpha detector, highly segmented neutron detectors, and commercial data acquisition system (Siemens Inveon preclinical position emission tomography [PET] system)

# Stimulated Emission Simulation



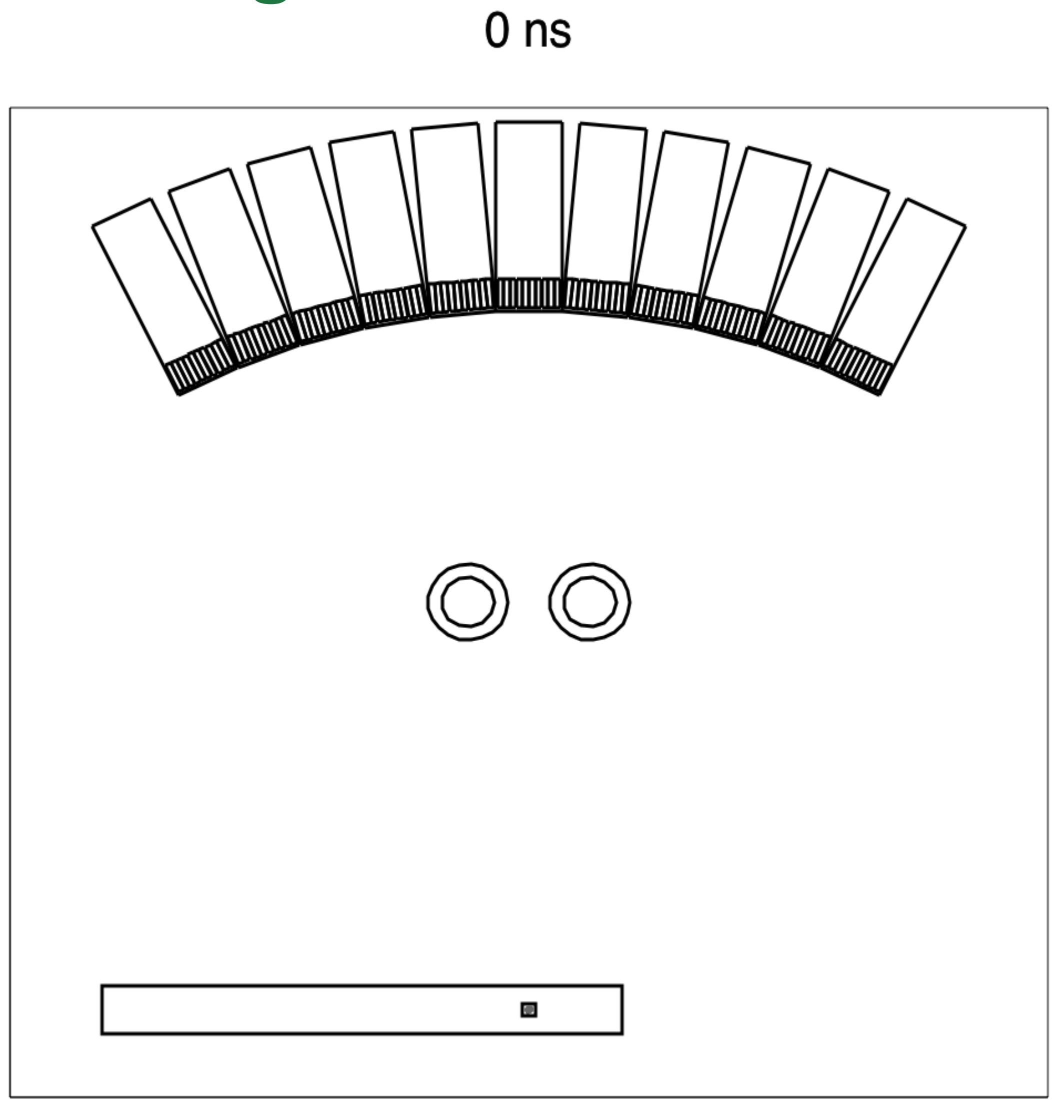

0 ns




- Instances of stimulated fission identified by detection of multiple late neutrons
- Instances of stimulated fission associated with interrogating neutron direction

# Stimulated Emission Backgrounds

- Fission competes with other reaction backgrounds as well as scattering between detectors



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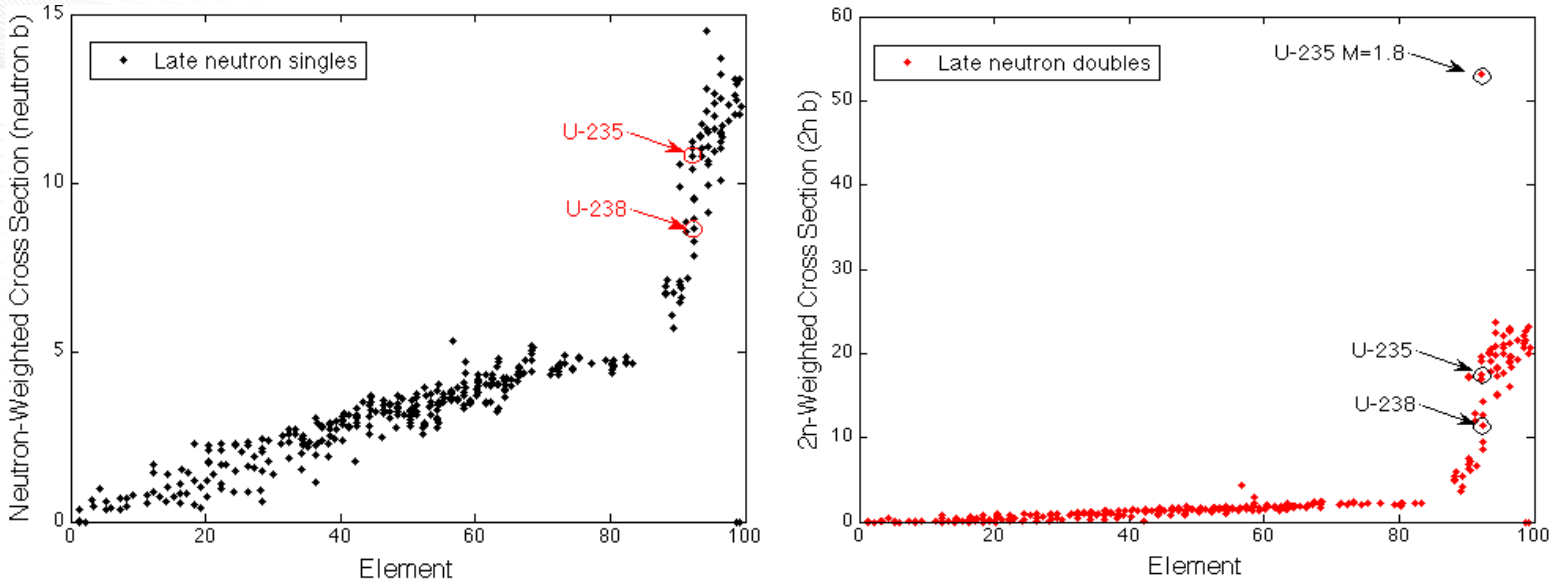
# Contrast for Fission




- Almost all materials yield some amount of late-arriving singles and doubles from incident 14-MeV neutrons
- Estimate of yield for all materials from tabulated (n,n$\gamma$), (n,np), (n,nd), (n,nt), (n,n$^3$He), (n,n$\alpha$), (n,n2p), (n,np$\alpha$), (n,n2$\alpha$), (n,nd2$\alpha$), (n,nt2$\alpha$), (n,n3$\alpha$), and (n,f) cross sections in evaluated nuclear data



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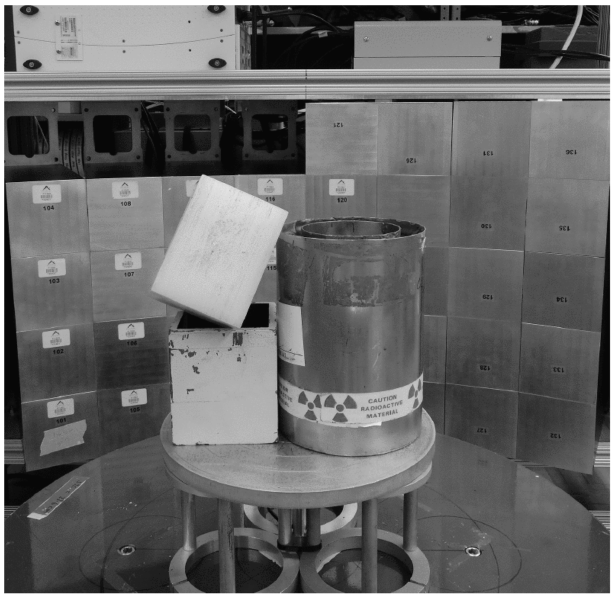
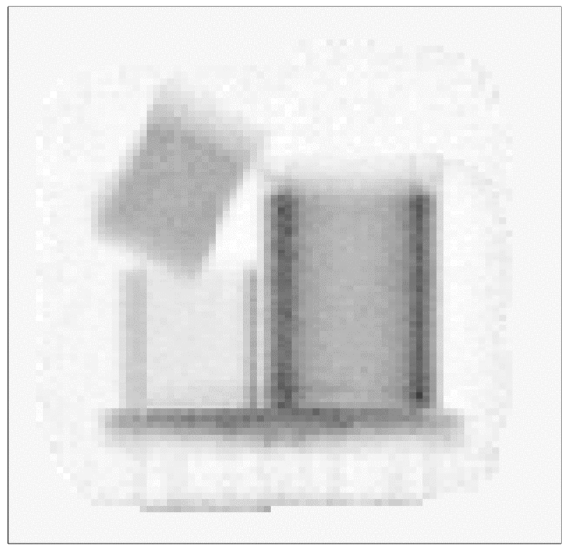
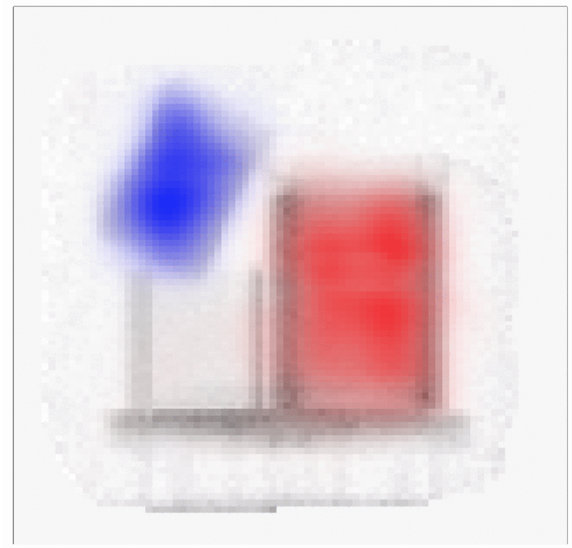
# Example Experimental Data (1)

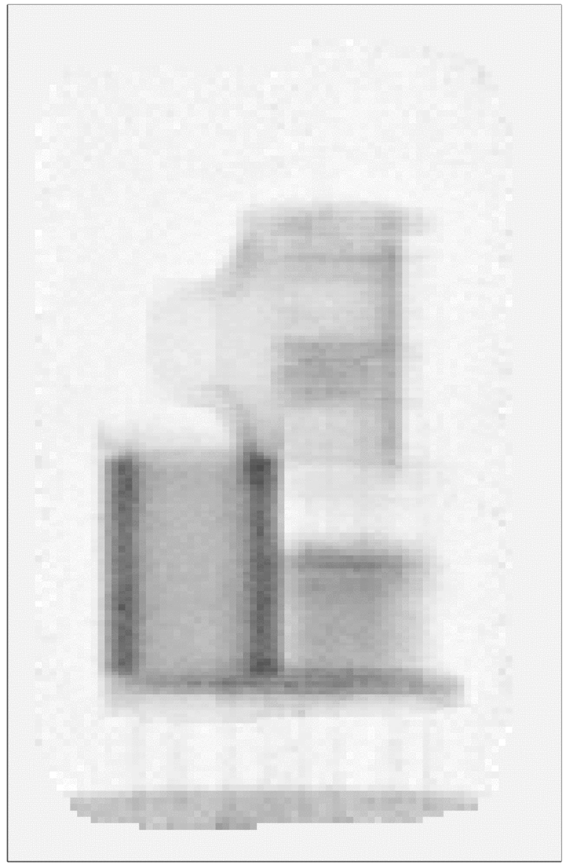






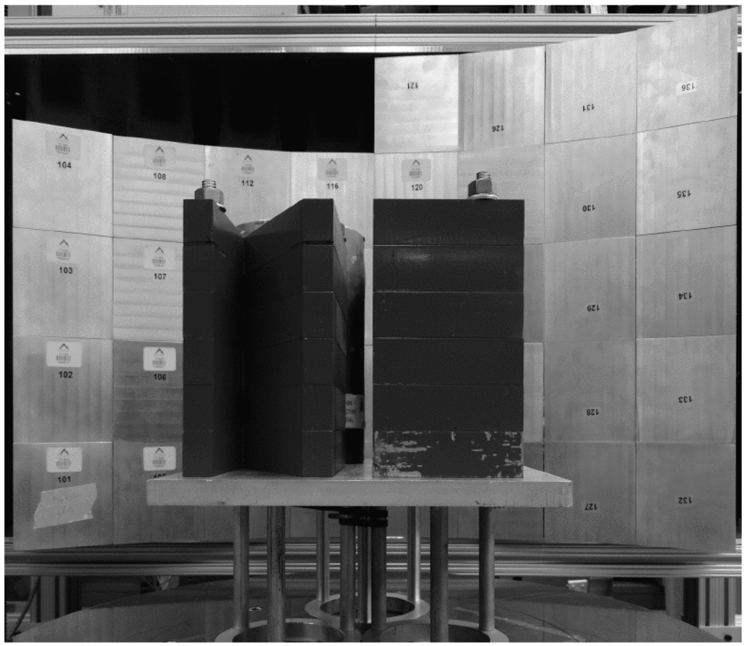
- Photographs and projection data where transmission is shown in grayscale, induced neutron doubles are shown in red, and hydrogen scatter is shown in blue

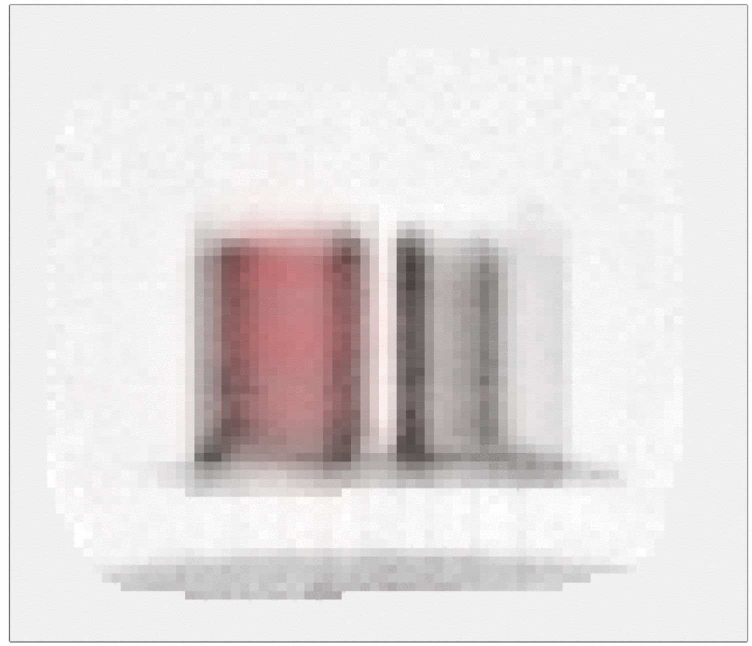
# Example Experimental Data (2)



- Photographs and projection data where transmission is shown in grayscale, induced neutron doubles are shown in red, and hydrogen scatter is shown in blue

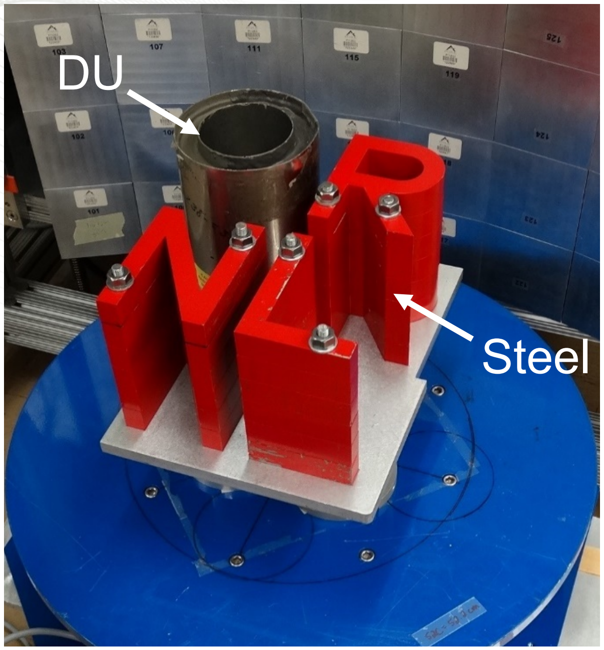
# Example Experimental Data (3)





- Photographs and projection data where transmission is shown in grayscale, induced neutron doubles are shown in red, and hydrogen scatter is shown in blue

# Reconstructed Images of (3)




Object

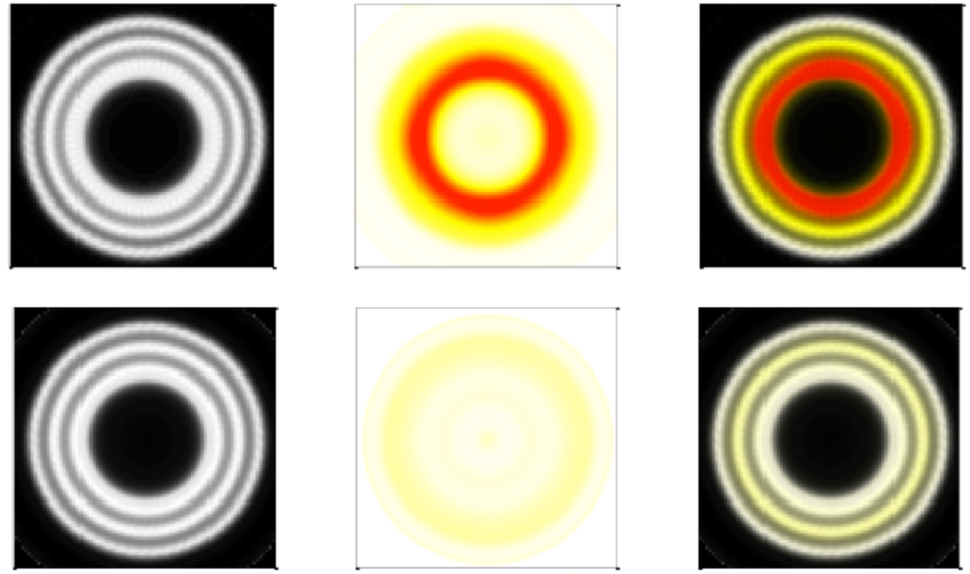
Transmission

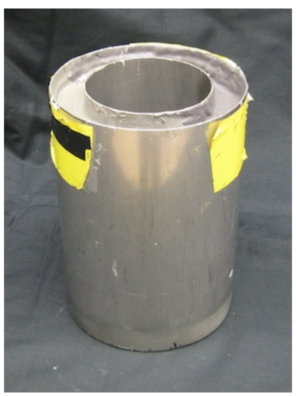
Fission
(neutron doubles)

- Tomographic reconstruction of induced neutron doubles (fission) identifies depleted uranium (DU) storage casting

# Shielded HEU

Measuring at Y-12



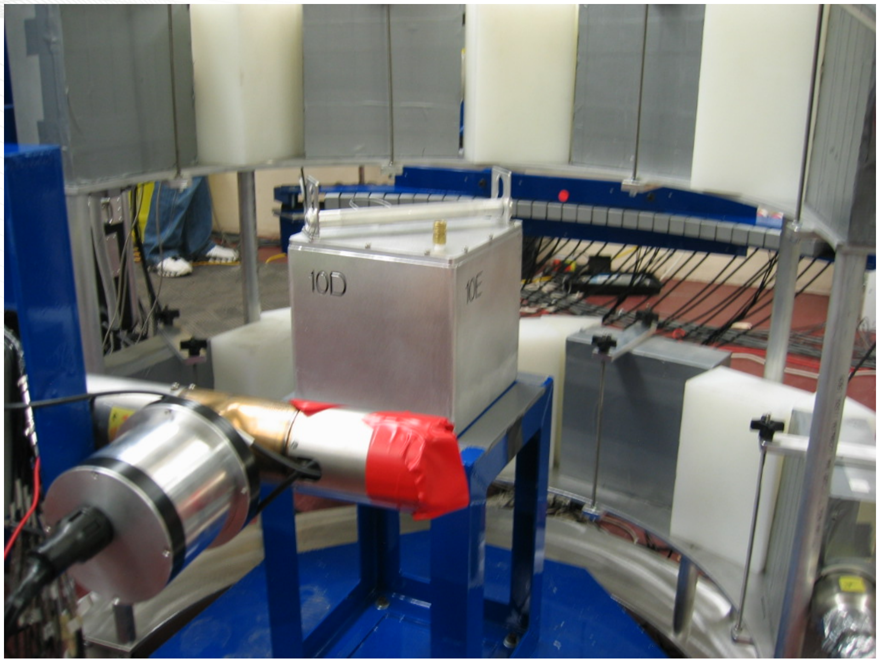



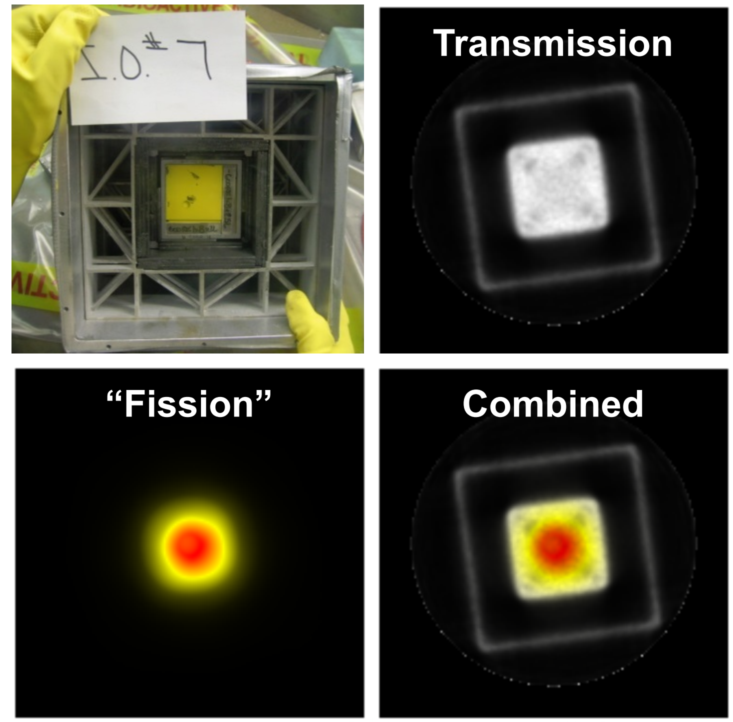
18 kg HEU or DU

3 DU shields

- Fission imaging can identify HEU, even shielded by DU
- Not distinguishable via transmission measurements

# Shielded HEU




- Idaho National Laboratory inspection object (IO) #7 contains HEU (yellow) shielded by DU (black/gray)
- Induced-fission tomography identifies HEU portion



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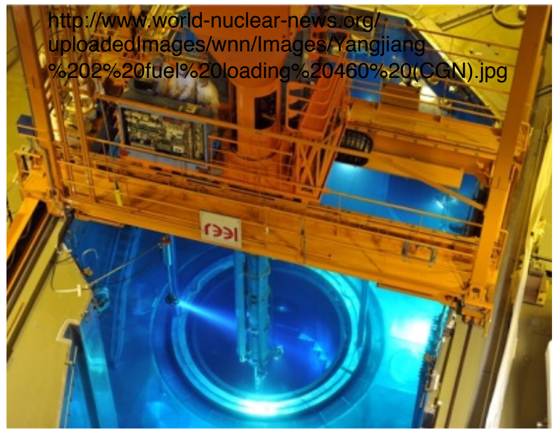
# Emission Tomography

- ORNL developing a new capability to perform passive fast-neutron emission tomography for spent nuclear fuel
- Why? To support item accountability by verifying the integrity of spent fuel assemblies before transfer to difficult to access storage
- Challenges
  - Sufficient spatial resolution to identify individual fuel pins
  - Sufficient efficiency to measure on an appropriate time scale (~1 h)
  - Sufficient insensitivity to gamma rays to handle the relevant gamma dose rates

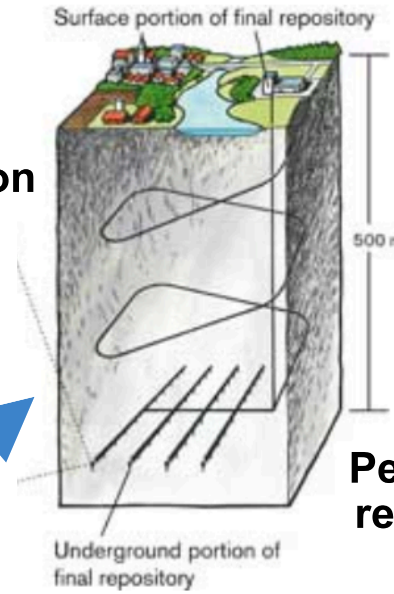
# Point of Verification


Nuclear fuel assembly




Irradiation in reactor (makes Pu)

Disposition

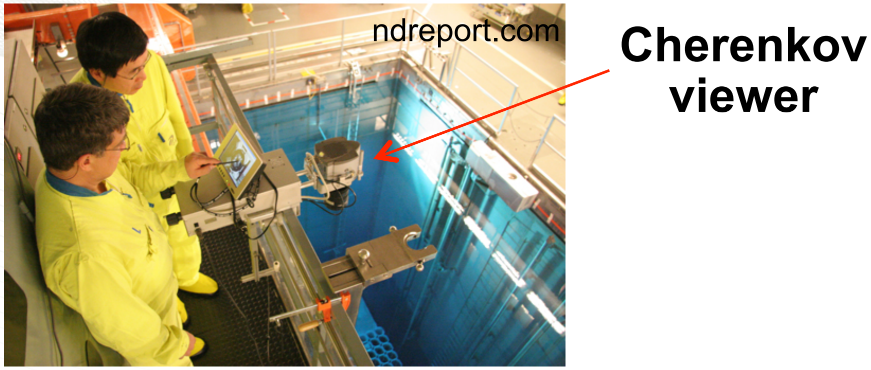


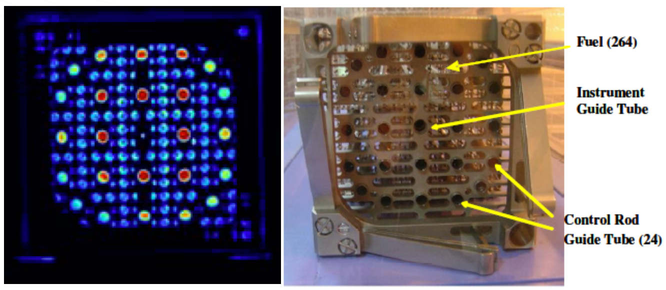

Permanent repository


Dry cask storage

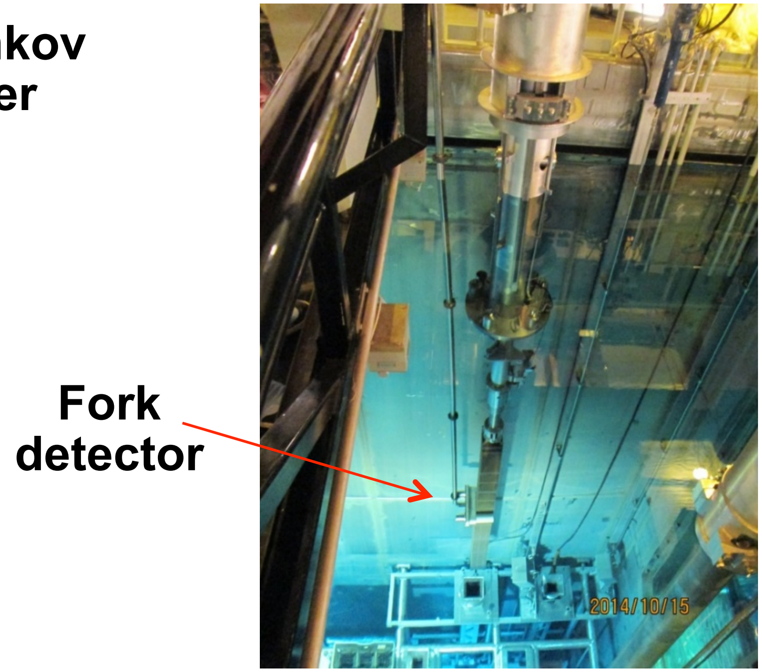
- Assemblies safeguarded as items, but some assemblies have damaged rods stripped out or replaced
- Verify integrity before disposition

# Present Integrity Verification



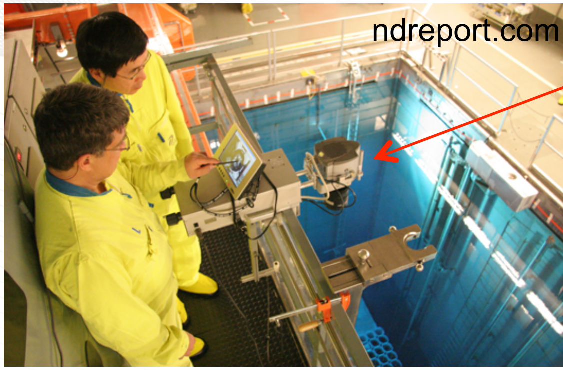




17 x 17 PWR Westinghouse Type

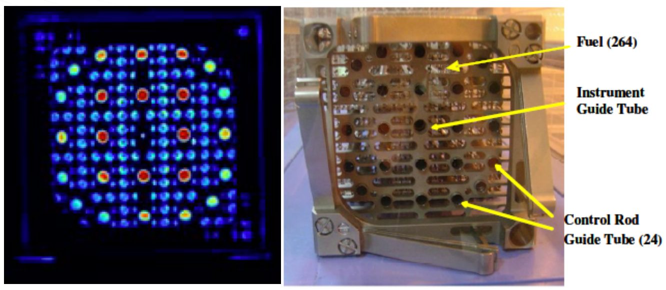



- Primary tools for verifying assemblies are the Digital Cherenkov Viewing Device (DCVD) and fork detector (FDET)
  - DCVD provides quantitative measure of amount of Cherenkov light induced in water channels between fuel rods
  - FDET measures combined total gamma and neutron activity

# Present Integrity Verification

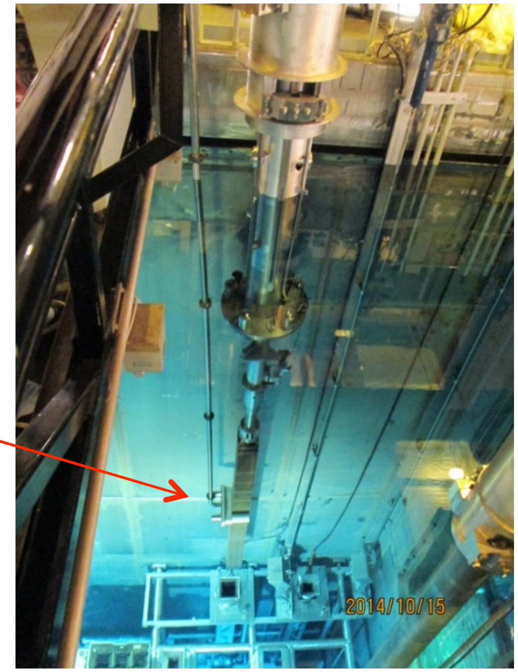



**Cherenkov viewer**



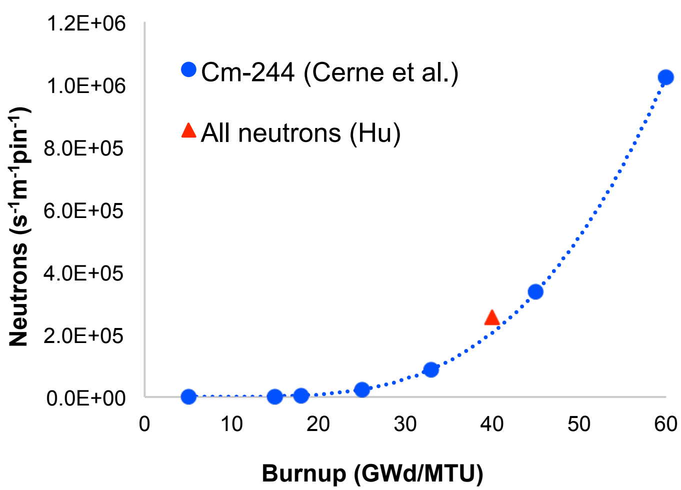

17 x 17 PWR Westinghouse Type

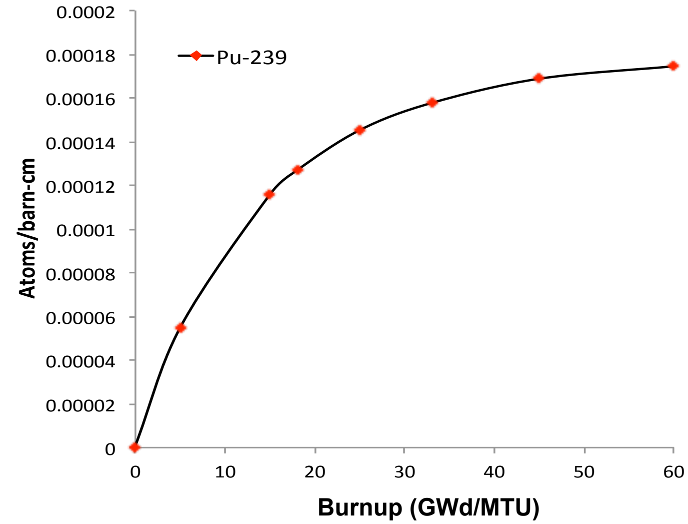
**Fork detector**




"The major common weaknesses of the DCVD and FDET is that **the detection probability is null** for carefully designed low-level diversions of a few fuel rods in each fuel assembly within a large population."
–A. Lebrun, IAEA Nondestructive Analysis Section Head

# Basis of Verification Using Neutron Imaging




- Verifying integrity (i.e., all fuel pins are present)
- Use fast neutrons (primarily from $^{244}$Cm spontaneous fission)
- Neutron intensity as a function of burnup gives sensitivity to replacement pins that are subsequently irradiated

- NOT confirming Pu
  – Pu content only known to a few percent from burnup codes
  – Pu content saturates with exposure (minimally sensitive to pin replacements made after first cycle in reactor)



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# Imaging Approach

- **Imaging** (emission tomography) fully uses available information to account for complicated geometries and identify emissions from individual fuel pins.
- Would you detect the absence of a single star in the night sky by measuring the total brightness of the night sky?

http://rsaa.anu.edu.au/news-events/mt-stromlo-observatory-public-astronomy-nights-5

- **Fast neutrons** enable penetration of high–atomic number shielding to verify an entire volume rather than its surface, providing the highest sensitivity to diversion with subsequent irradiation of substituted pins.



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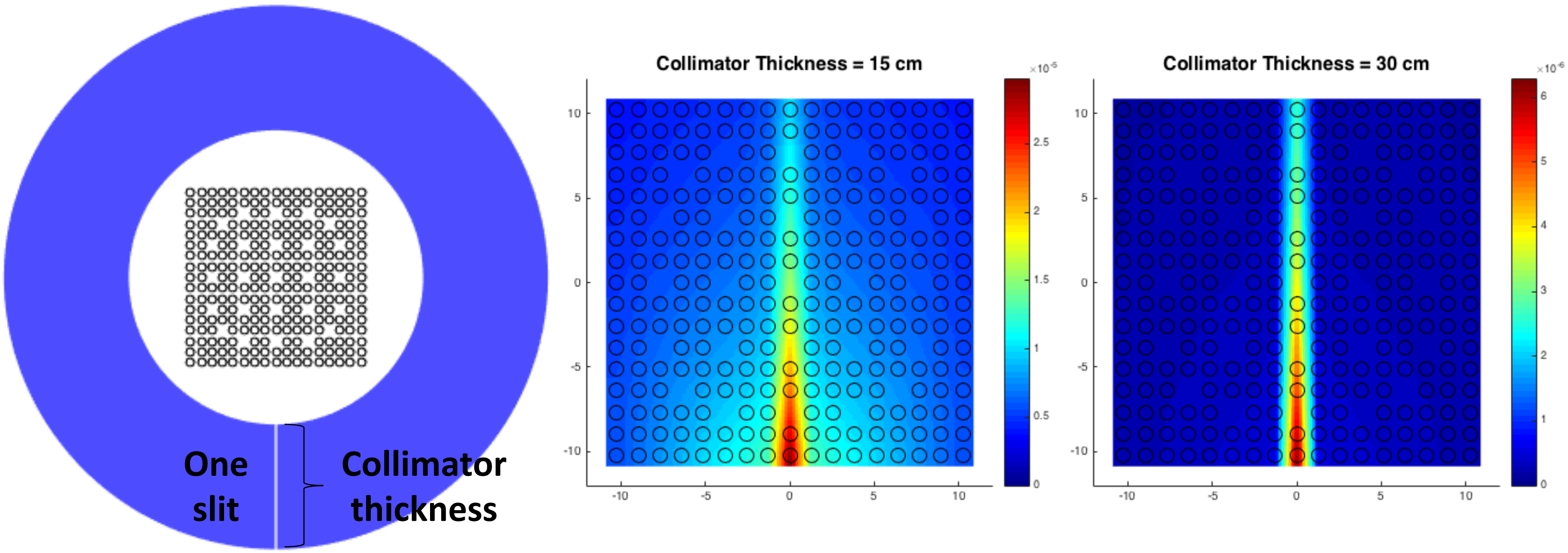
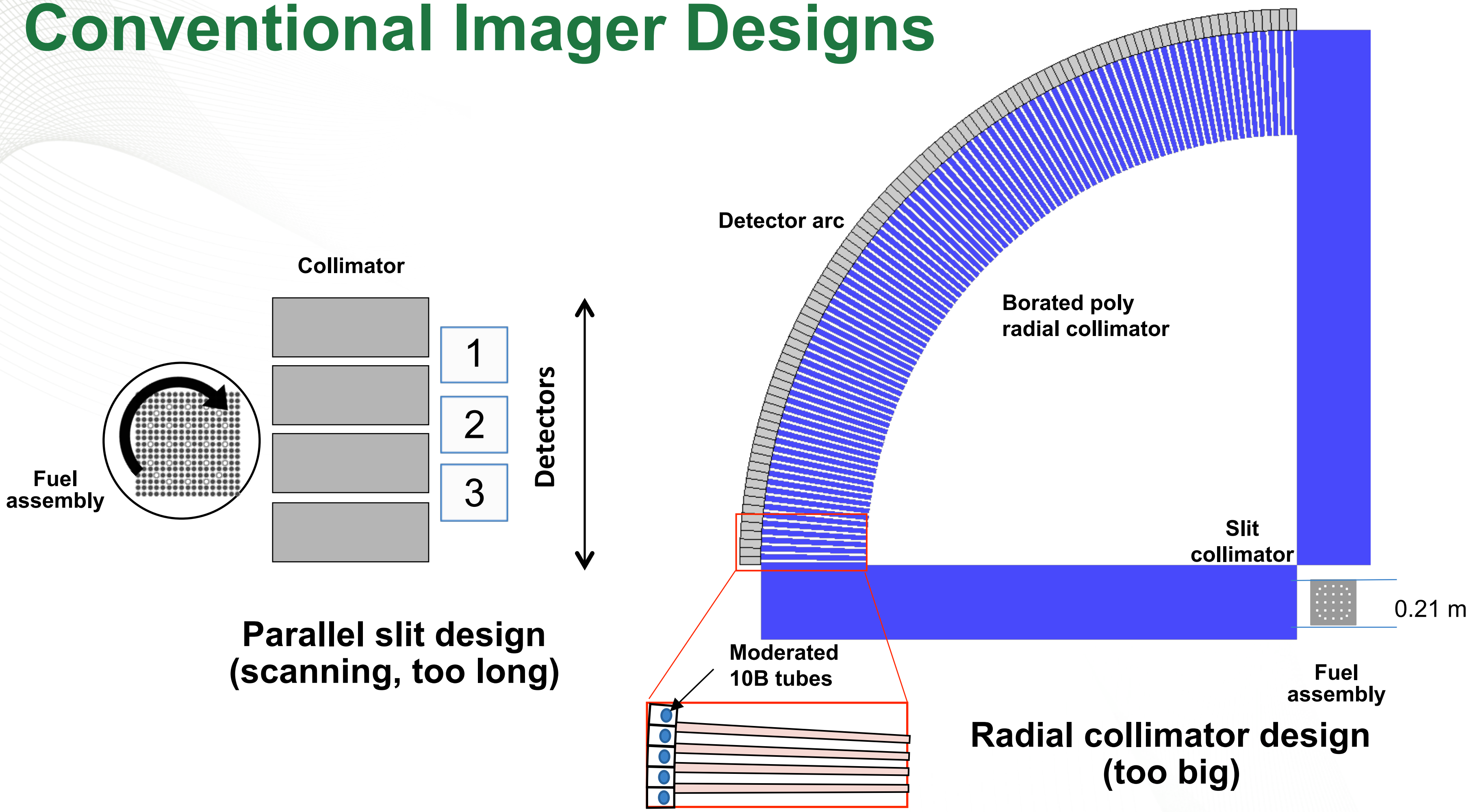
# Line of Response via Collimation




- Imaging depends on isolating lines of response through an object, where neutrons originate along a known path
  - Achieved via collimation
- Expect the scale of the collimator to be ~30 cm thick (will not work if substantially smaller)

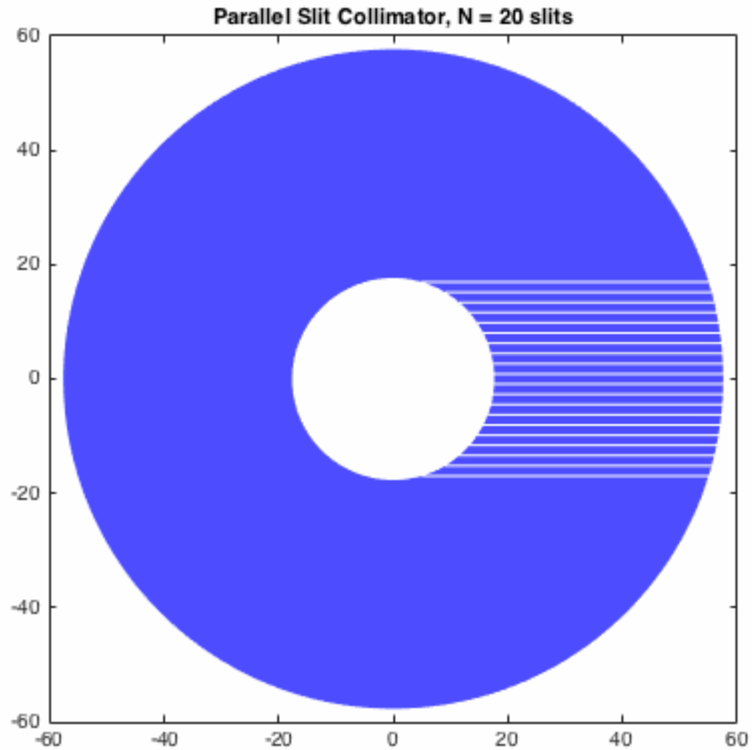
# Conventional Imager Designs




- To work, detector pixels and collimator slit spacing need to be large (~5 cm), especially for moderated detectors
- Two conventional options: parallel slit requires scanning, pinhole requires large size

# Novel Collimator Design

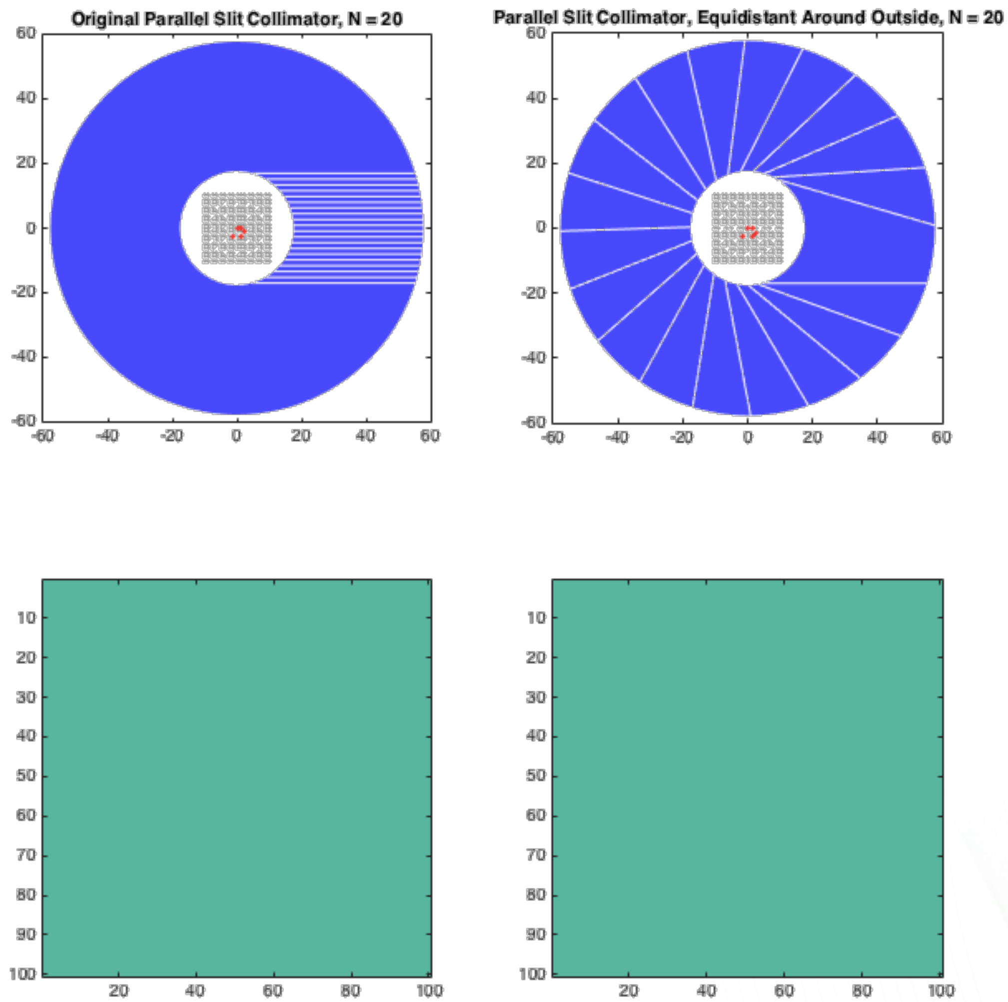
- There is a non-scanning and compact design option that uses many detectors




**For clarity,**
**20 slits shown**
**(actual number is ~100)**

- Equivalent to a parallel slit collimator, but each slit position is rotated to distribute endpoints evenly over outer diameter to make space for large detectors and spacing between slits

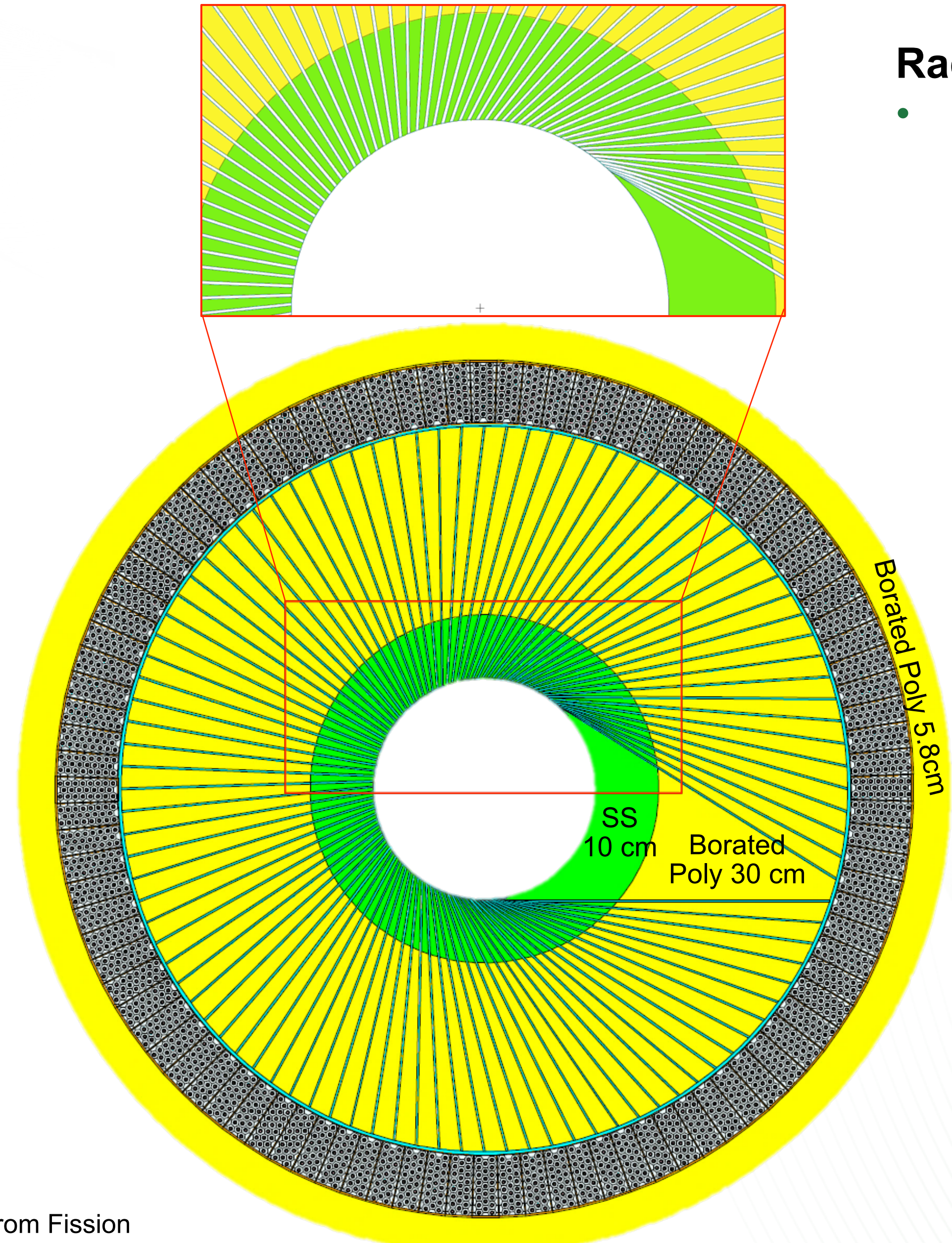
# Parallel-slit versus Radial Collimator




- Acquires same data as parallel-slit collimator but in a different order

# Imager Concept

- Steel and borated polyethylene (BP) collimator with 100 slits to isolate lines of response
- Stainless steel (SS) for structural integrity and shield detectors from gammas
- Annulus of 100 detectors that wrap around the fuel detects neutrons
- Fuel and detectors stationary, collimator rotates to perform tomography
- Annular design gives compact size




**Radiation resistant**

- Boron straw detectors (instrumented singly) can handle fields as high as 1,000 R/h

**Efficient**

- Large detectors
- Close to source
- No scanning, all lines of response measured simultaneously



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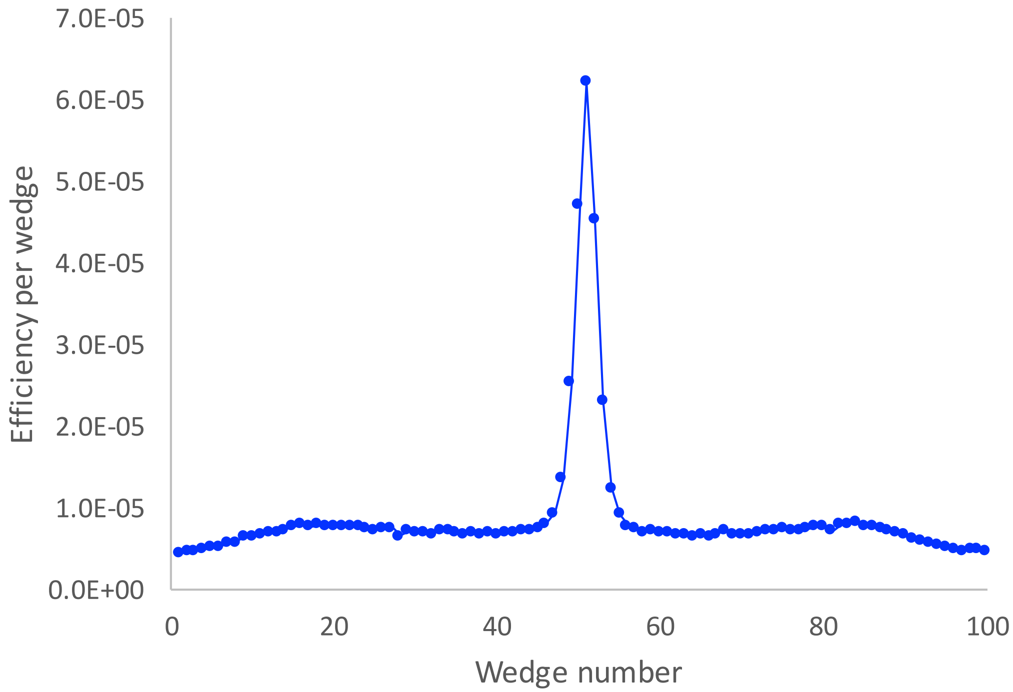
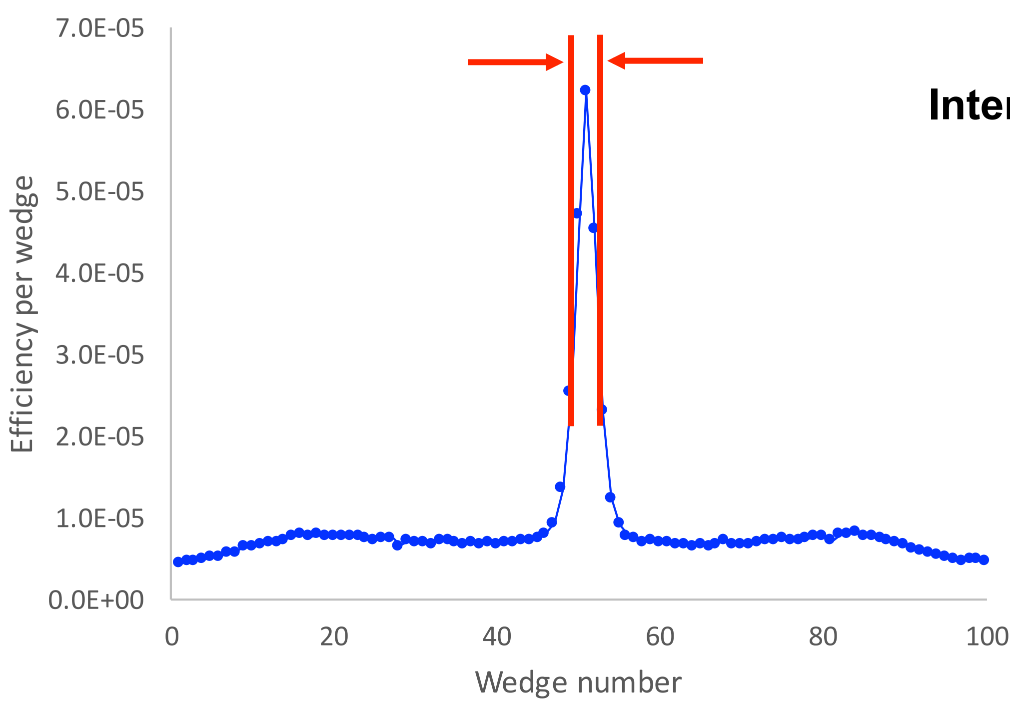
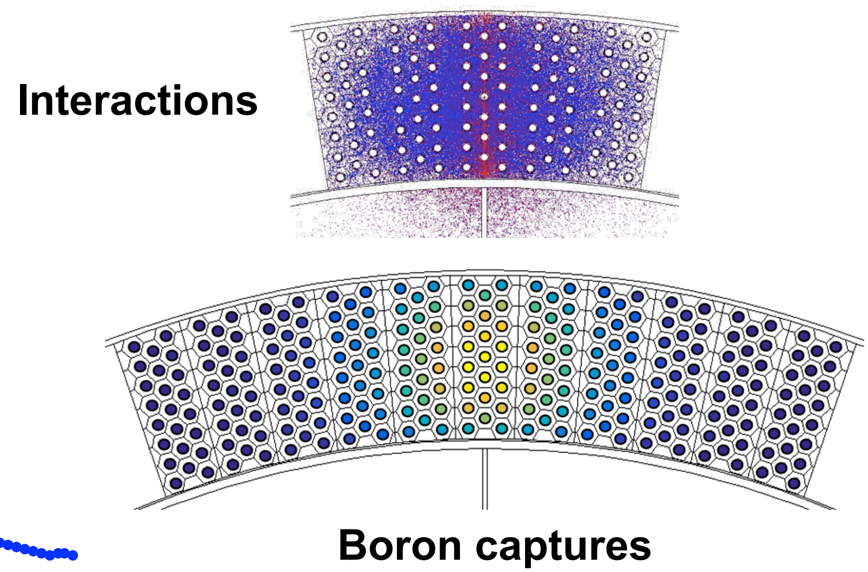
# Point-source Response




- Performance of collimator encoded in the point spread function (PSF) that quantifies line of response to a point source
- Vary slit width, collimator materials, and collimator thickness to maximize signal to noise ratio (SNR) for individual pins

# Point-source Response




- Resolution is limited by slit width, slit bore scattering, and scattering in detectors
- Dominant limitation is scattering of neutrons into neighboring detectors before capture



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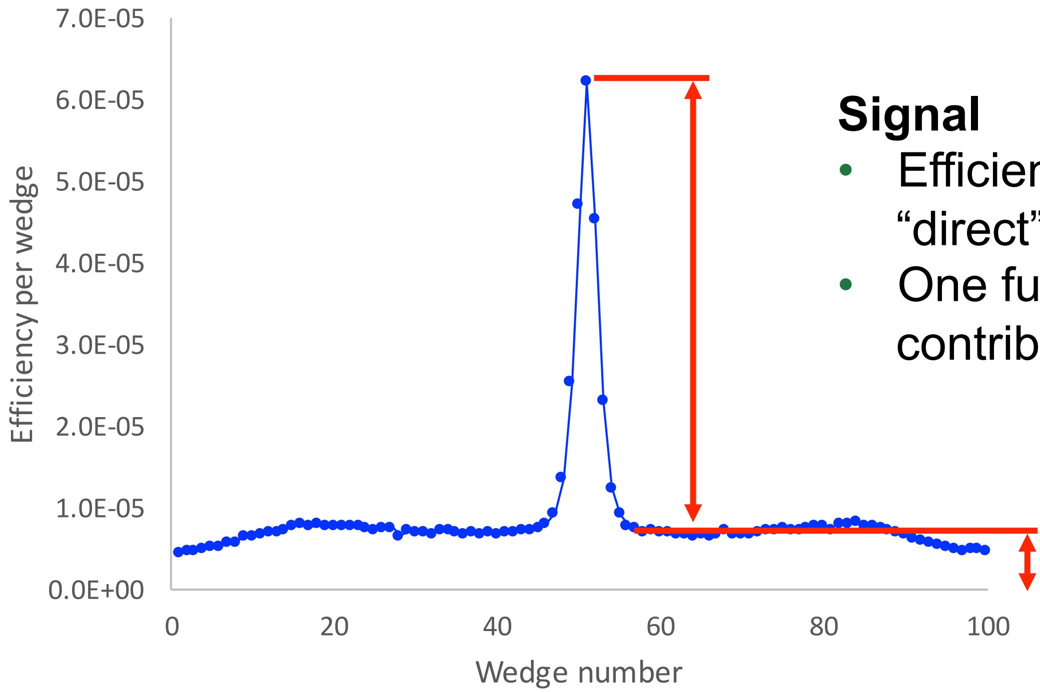
# Point-source Response




**Signal**

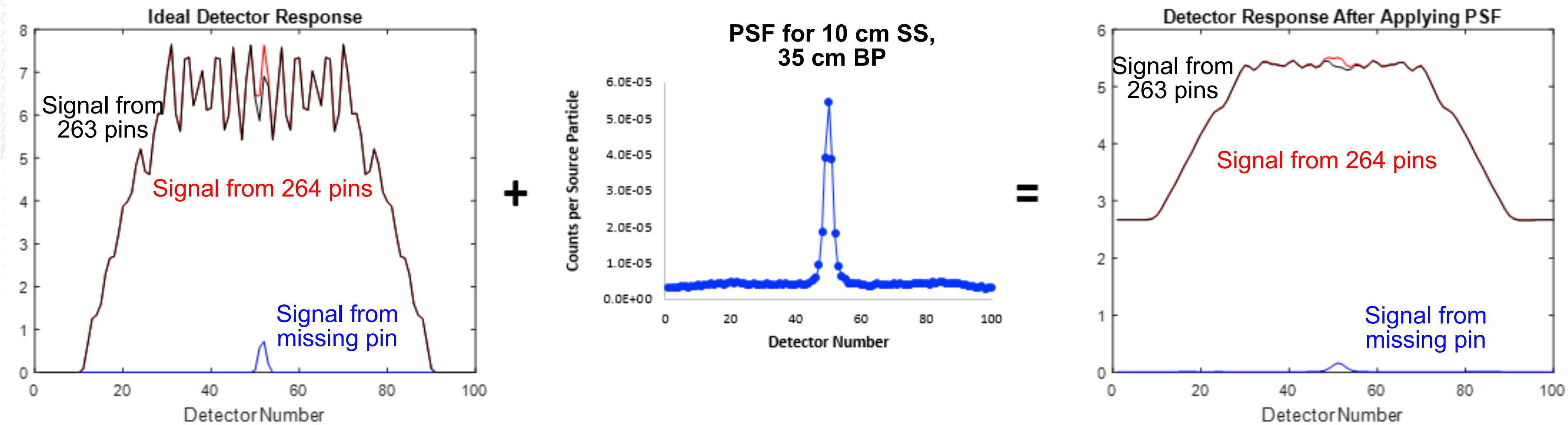
- Efficiency for "direct" neutrons
- One fuel pin contributes

**Background**

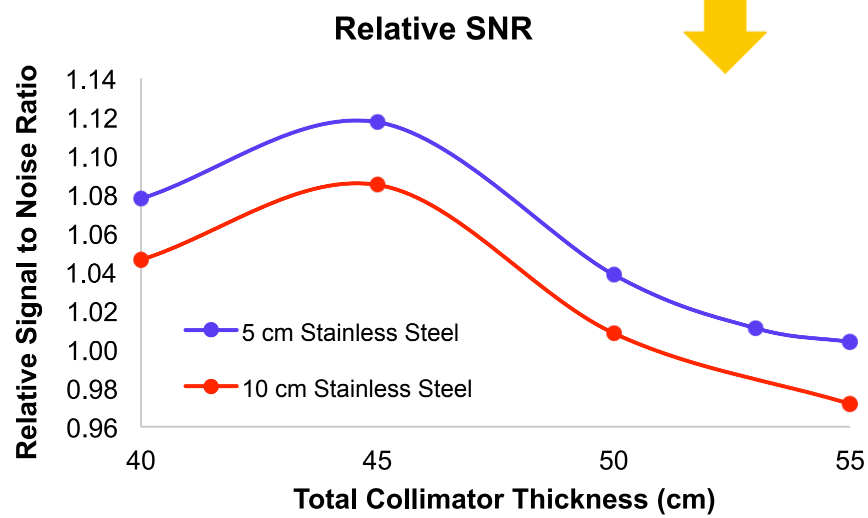
- Penetration of collimator
- All 264 fuel pins contribute

- SNR is limited by penetration of the collimator
- Note all (264 pins) contribute to background
- Additional background from nearby pins and poor resolution

# SNR Estimate

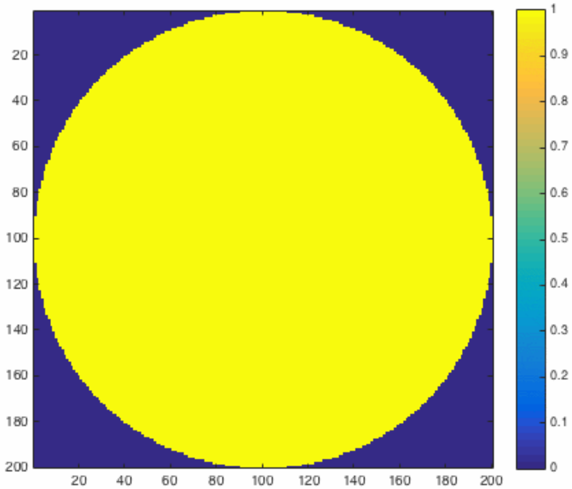



- SNR depends on the PSF
  - Goes to 0 with a collimator that is too thin (no modulation) or too thick (no counts)
  - Goes to 0 with slits that are too wide (no resolution) or too narrow (no counts)
  - Somewhere in the middle is optimal
- SNR estimate's assumptions
  - $2.55 \times 10^5$ n/s/m/fuel pin
  - Neglects scatter and self-attenuation within the spent fuel assembly

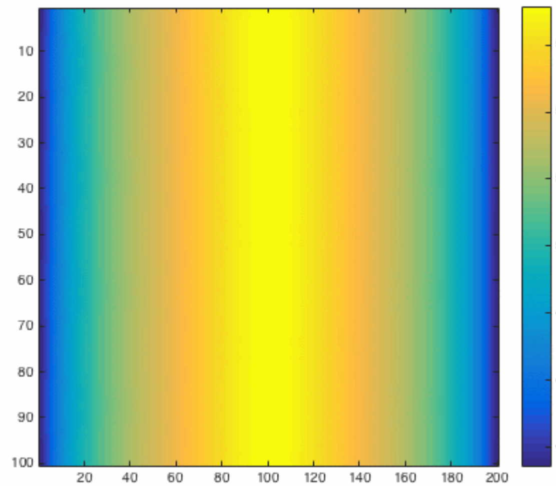


# Sample Reconstruction of Five Sources

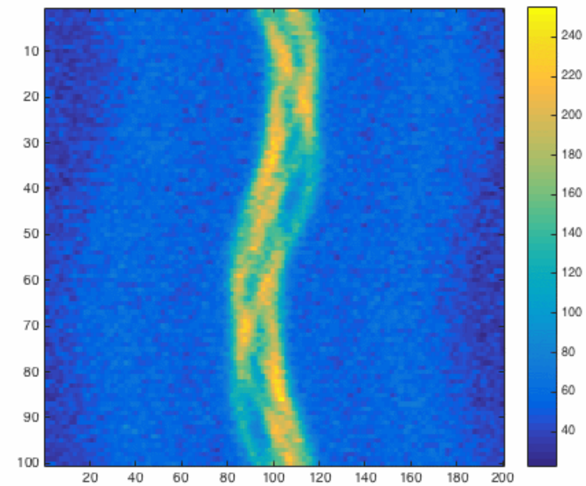
Reconstructed Image

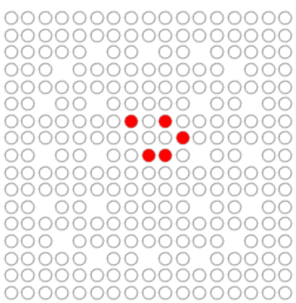



Calculated Sinogram



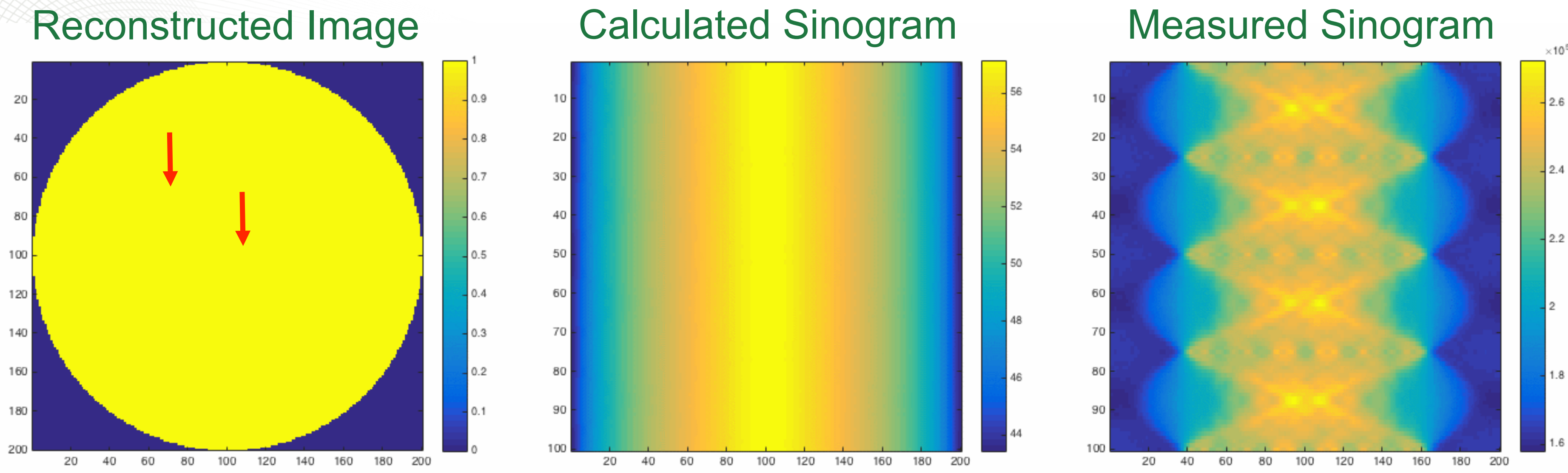

Measured Sinogram

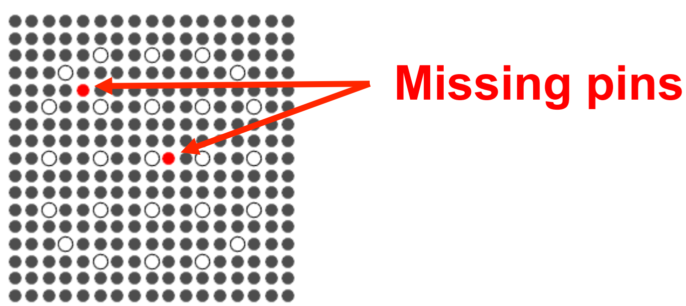


- Calculated PSF is consistent with resolving neighboring fuel pins (40 GWd/tU, 10 min)

# Reconstruction of Many Sources

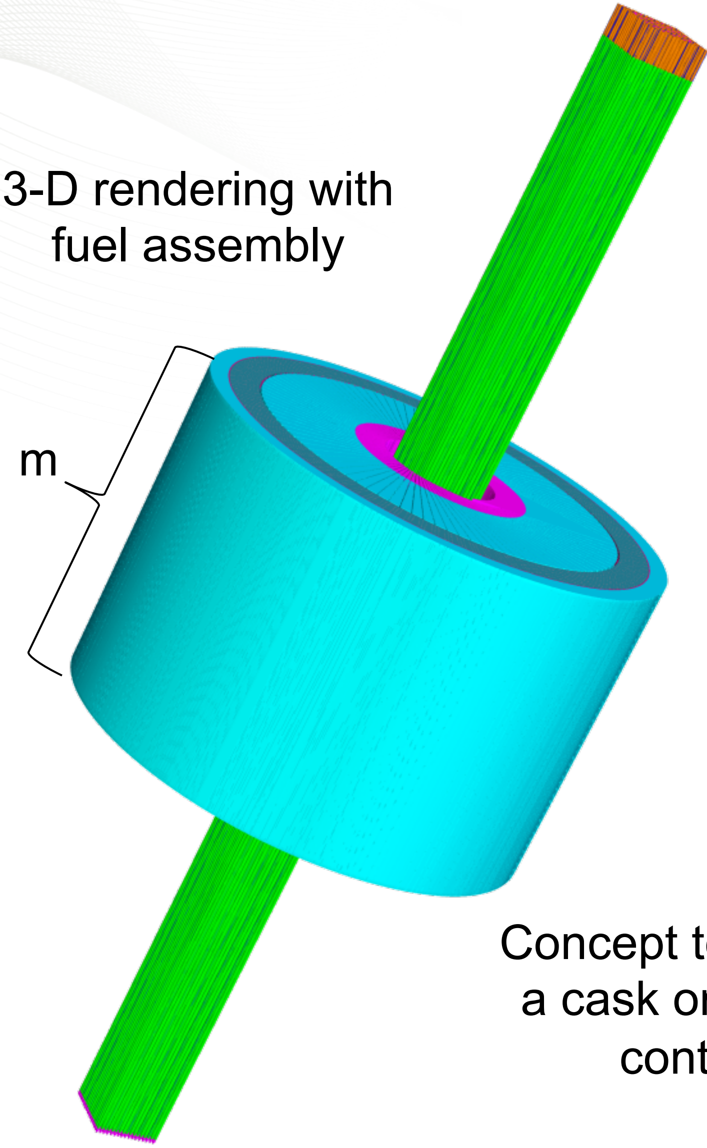


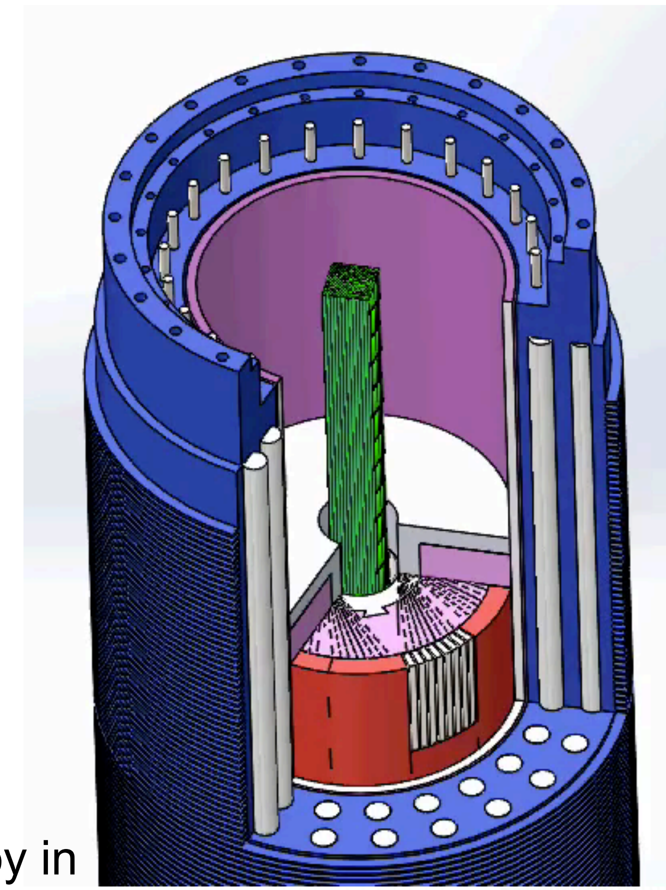




- Calculated PSF is consistent with identifying missing fuel pins

# Deployment Concept

3-D rendering with
fuel assembly



Concept to deploy in
a cask or cask-like
container

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