Extracting "dark matter" volume density information at NIF

neutron imaging

P-23 Advanced Imaging Team, LANL

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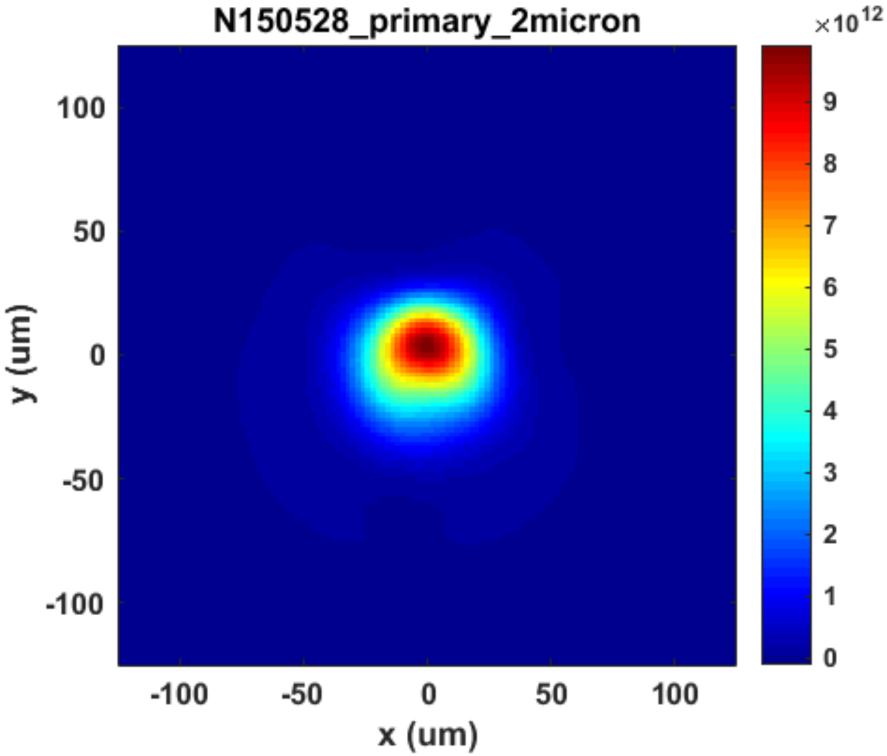
NNSA National Nuclear Security Administration

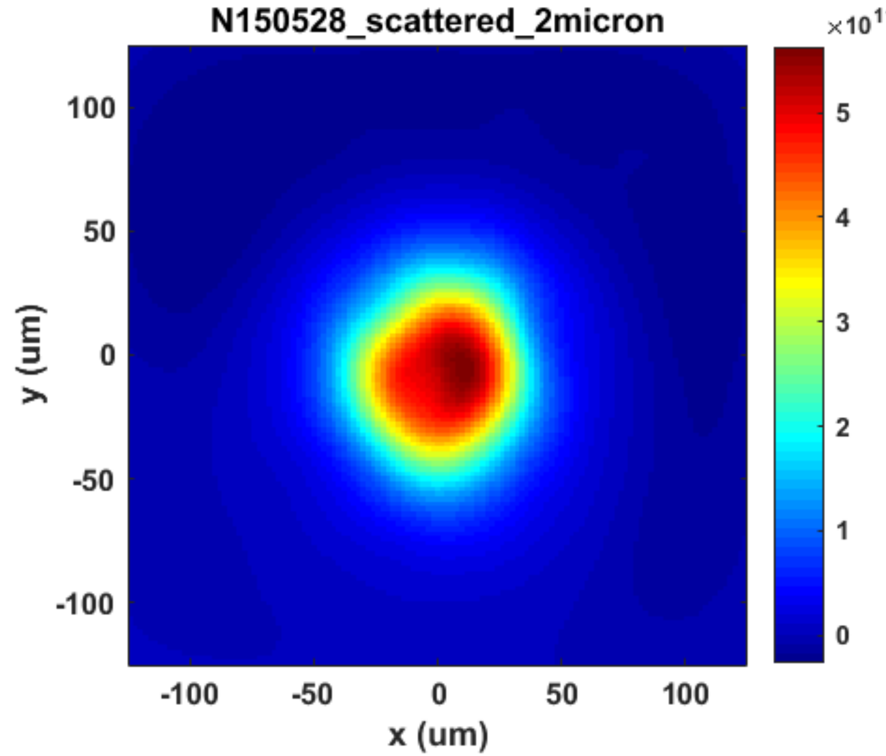
Outline

- **Cold fuel density reconstruction from primary and scattered neutron images**
  - Single scatter model
  - Experimental data reconstruction
  - 3D reconstruction
- **Gamma images analysis and reconstruction**
  - Noise analysis
  - Experimental data reconstruction
  - Statistical tests

NIS: Primary and down-scattered images



Energy range > 13 MeV

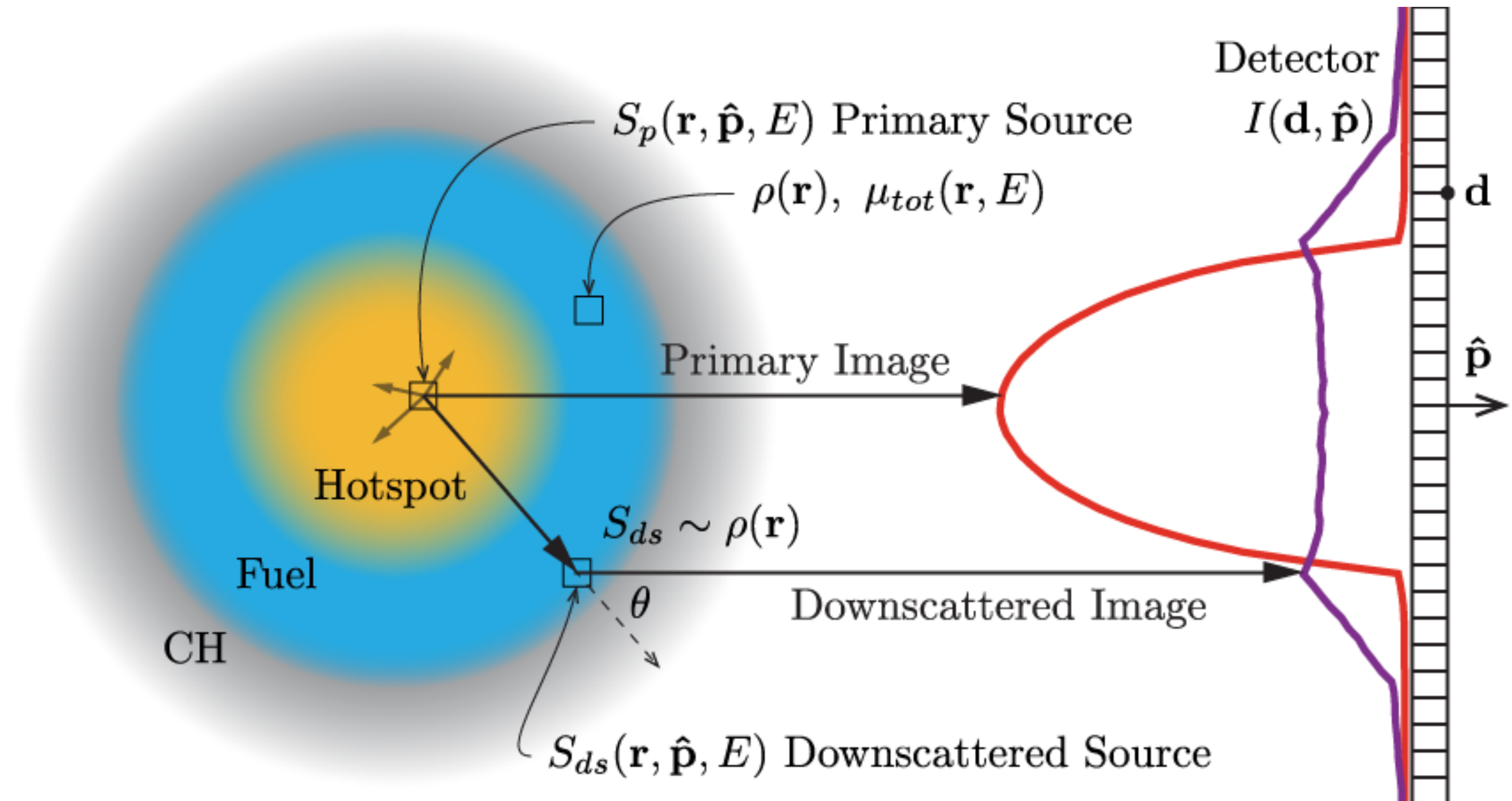


Energy range [6..12] MeV

Can we extract cold-fuel volume density from those images?

THEORY/ALGORITHM

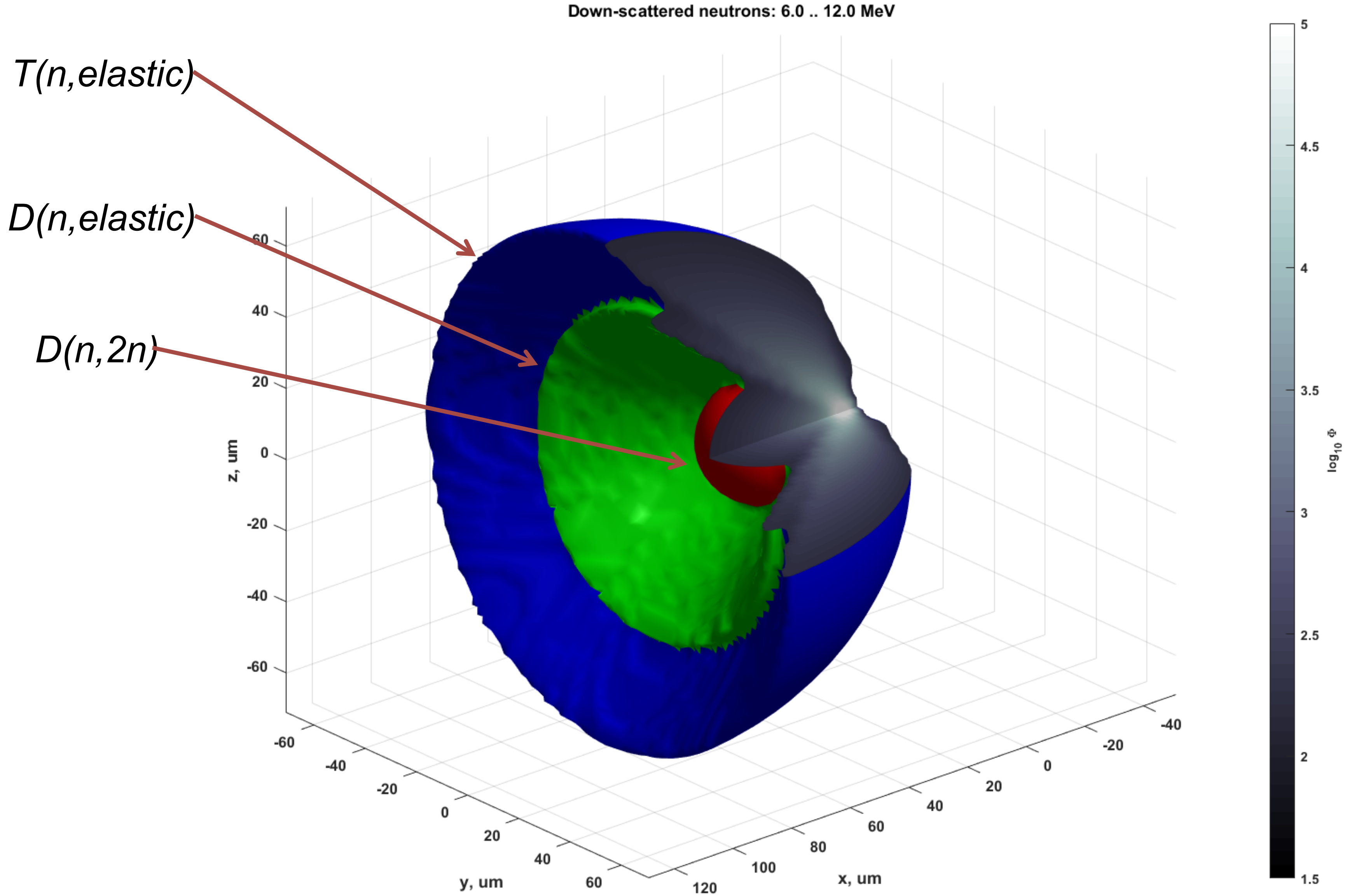
Down-Scattered Image Formation



$$I_{ds}(\mathbf{d},\hat{\mathbf{p}}) = \frac{\Delta a}{L^2}\int_{-\infty}^{\infty} \rho(\mathbf{d}+\xi\hat{\mathbf{p}})\,\Phi(\mathbf{d}+\xi\hat{\mathbf{p}},\hat{\mathbf{p}})\,S_{ds}\,d\xi$$

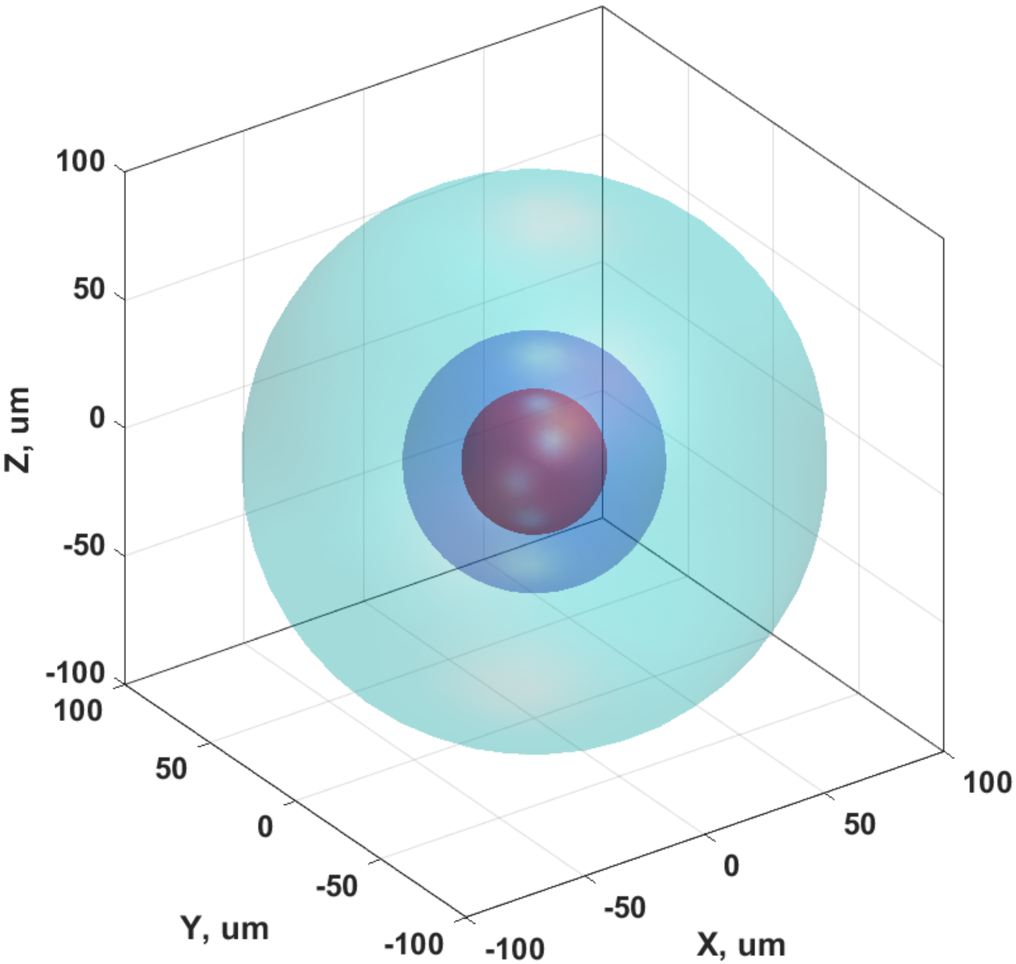
$$\Phi(\mathbf{r},\hat{\mathbf{p}}) = \frac{N_A}{m_a}\int_0^{\infty}\int_V S_p(\mathbf{r}',E)\int_0^{\infty} D(E')\,A(\mathbf{r},\hat{\mathbf{p}},E')\,\frac{d\sigma_{sc}(E,\theta,E')}{d\Omega}\,\frac{A(\mathbf{r},\mathbf{r}',E)}{|\mathbf{r}-\mathbf{r}'|^2}\,dE'\,d^3r'\,dE$$

Down-scattered image projection kernel $\Phi\,(\mathbf{r}, \mathbf{p}\,)$ for a point primary source



MCNP SIMULATION

MCNP Simulation



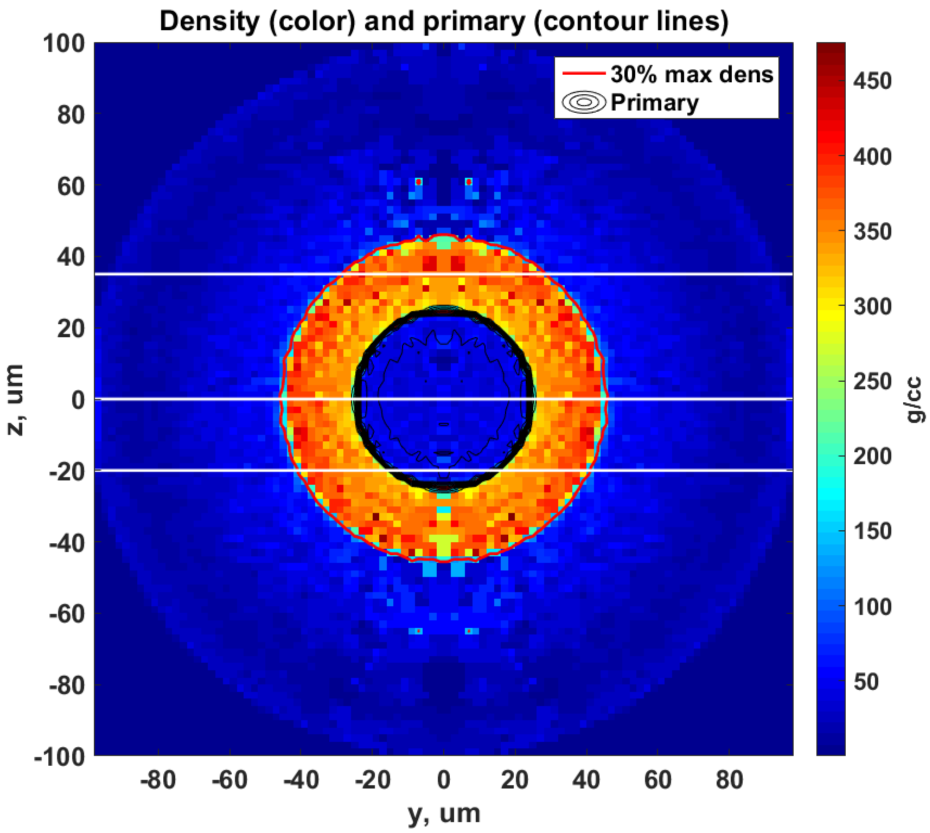
<u>"Hot spot" (magenta):</u>
radius = 25 μm,
material 50%D + 50%T,
density 25 g/cc,
emission = 1·TotalYield/Volume/4π

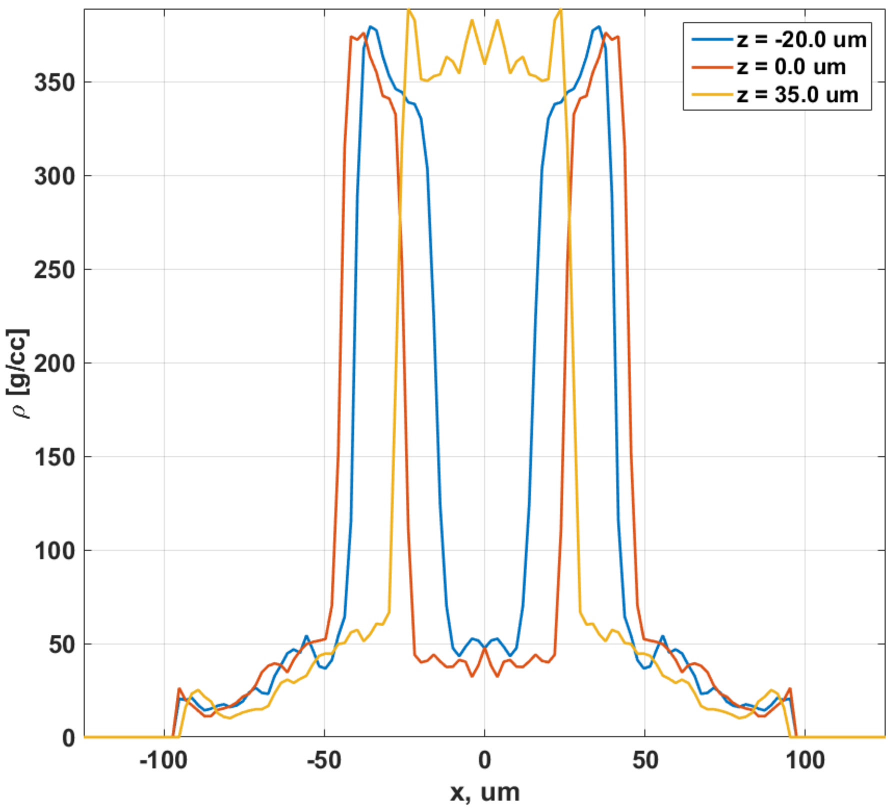
<u>DT shell (blue):</u>
thickness = 20 μm,
material 50%D + 50%T,
density 350 g/cc,
emission =0

<u>CH shell (cyan):</u>
thickness = 55 μm,
material 50%C + 50%H ,
density tapering from 150g/cc at 45 μm to 30g/cc at 100 μm,
emission =0

Total mass of DT = 112 μg

Density reconstruction

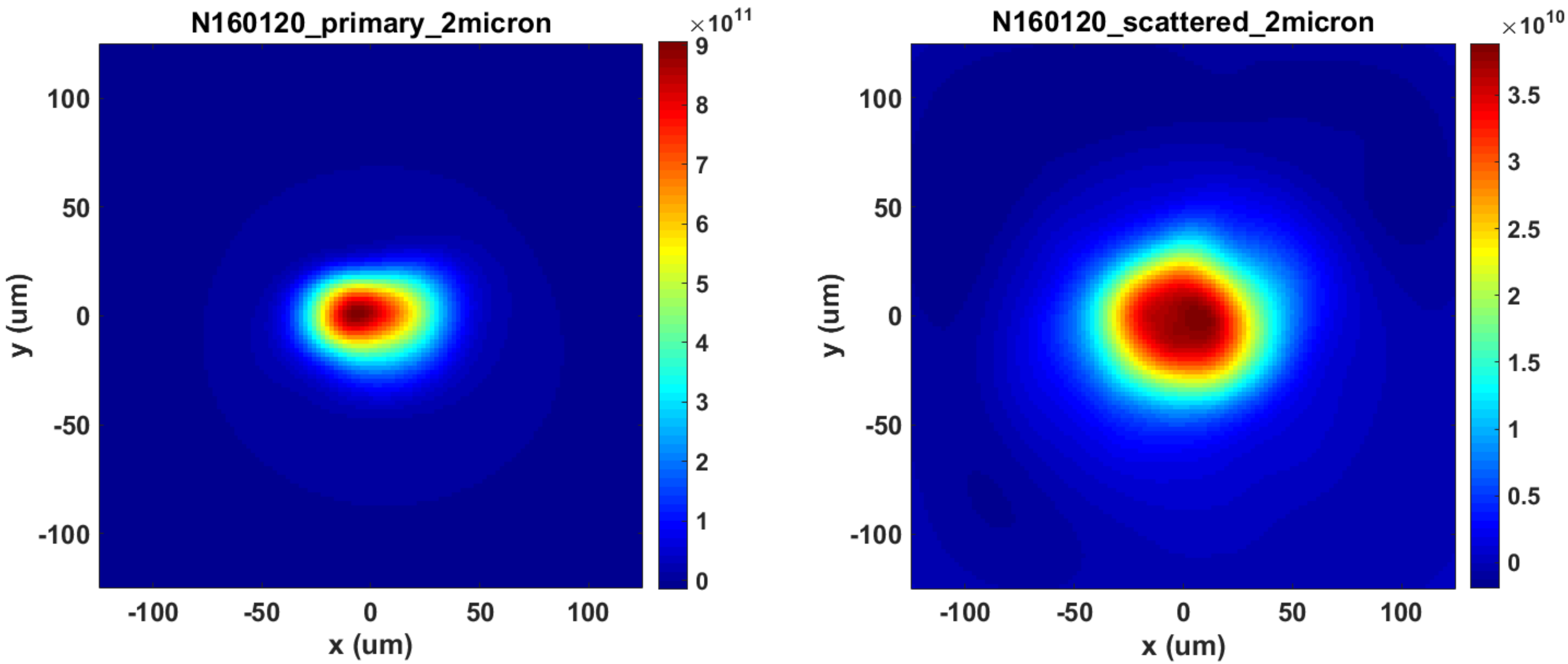




Total reconstructed mass of DT (inside 30% level) = 114 μg (exact value 112 μg)

EXPERIMENTAL DATA RECONSTRUCTION

N160120



	P_0 (μm)	P_2/P_0 (%)	P_3/P_0 (%)	P_4/P_0 (%)
Primary (13..17 MeV)	33.40	-23%	-6%	1%
Down-scattered (6..12 MeV)	49.58	-12%	-2%	2%

Attempt to account for L-R asymmetry

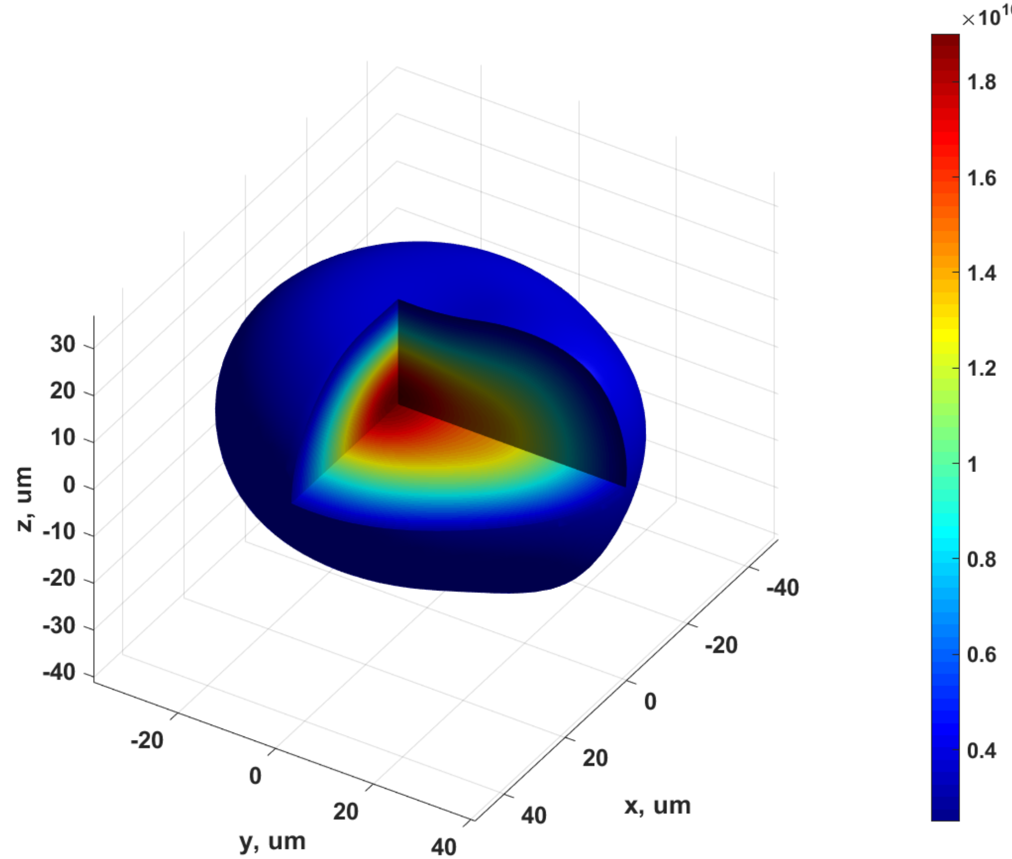
The method requires inferring 3D distribution of the primary source.

For equatorial views spherical harmonics decomposition reduces to polar Fourier transform:

$$S(\rho,\varphi,z)=\sum_{m=-N}^{N} S_i(\rho,z)e^{im\varphi}$$

Given one projection direction this results in first order polar Fourier transform:

$$S(\rho,\varphi,z)==S_l(\rho,z)(1-\sin\phi)/2+S_r(\rho,z)(1+\sin\phi)/2$$

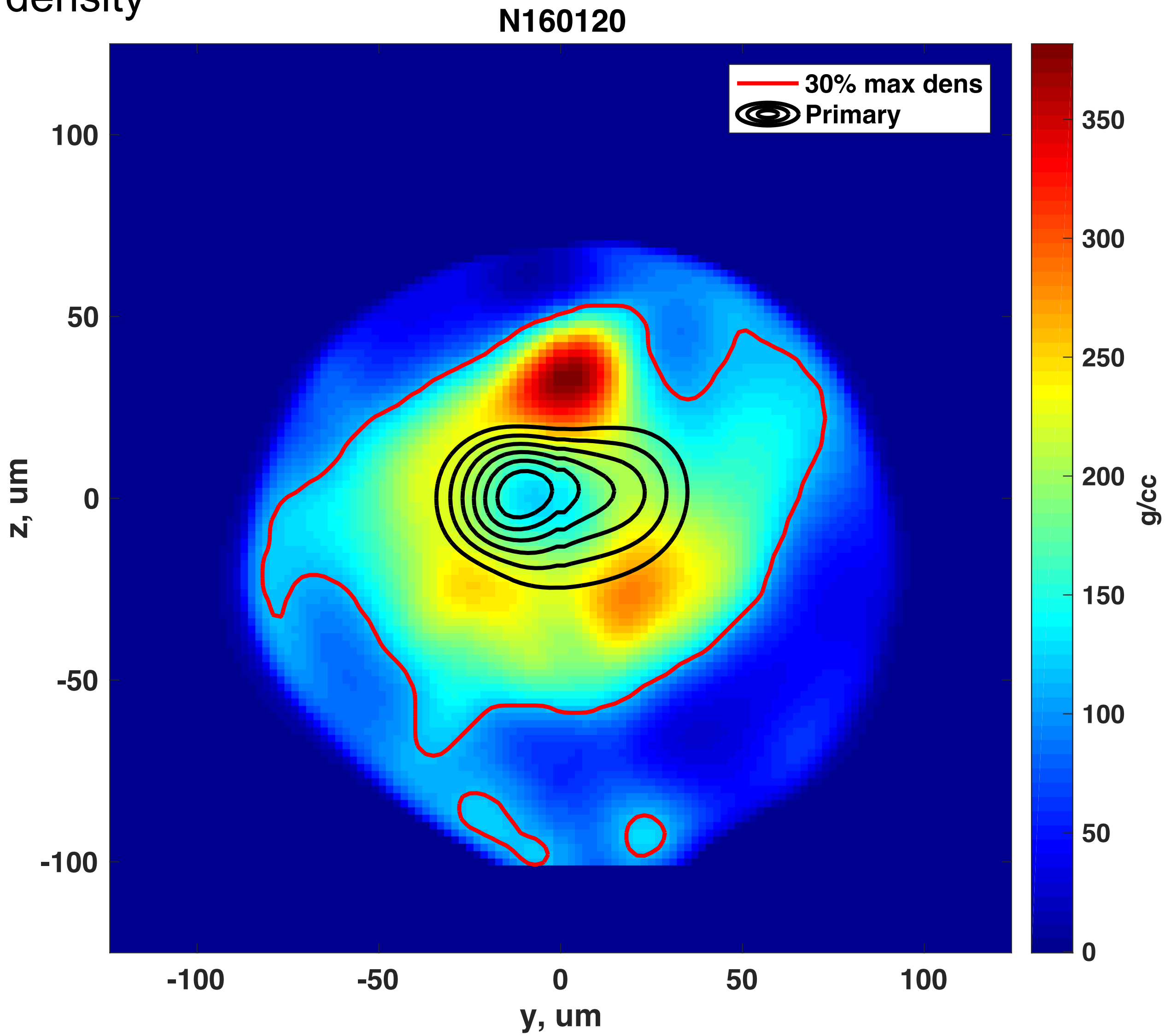


N160120: Reconstructed ”hot spot”

N160120: Reconstructed density

Reconstructed density with overlaid reconstructed primary contour.

Reconstructed Mass: 313 µg (total), 174 µg (inside 30% level)



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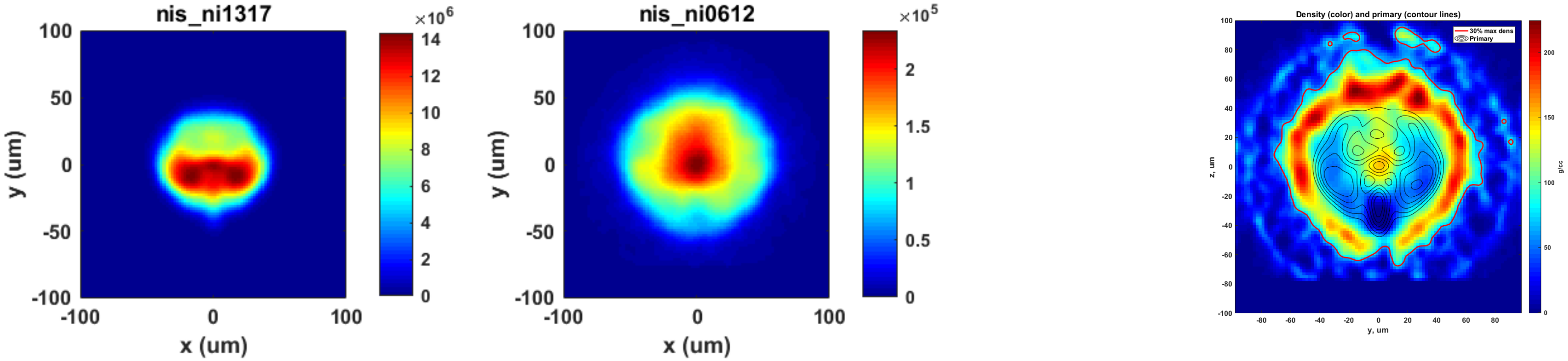
$S(x,y,z)$

3D RECONSTRUCTION

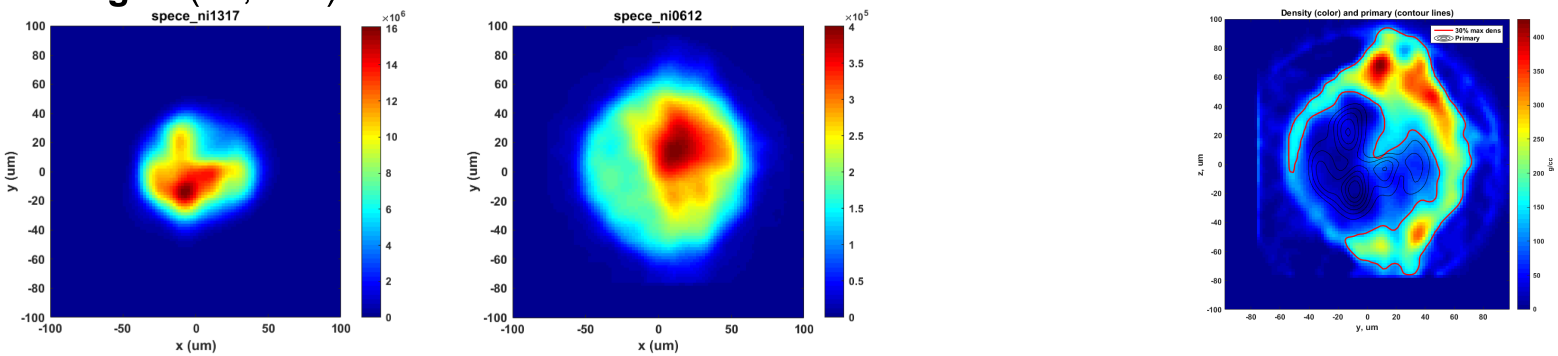
LLNL: Brian's "Turkey shot" 3D simulation

NIS line-of sight: (90, 315)

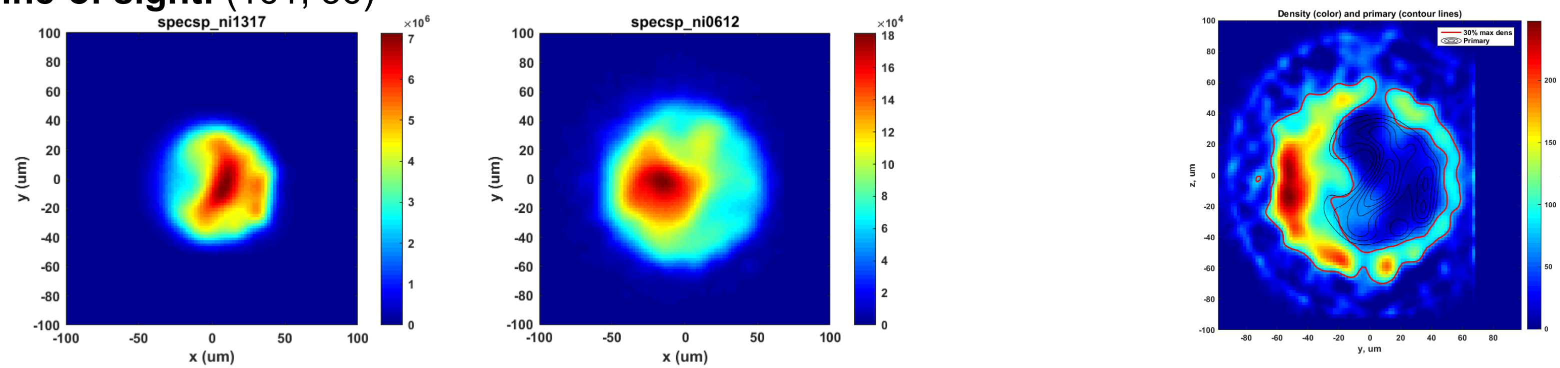
Density



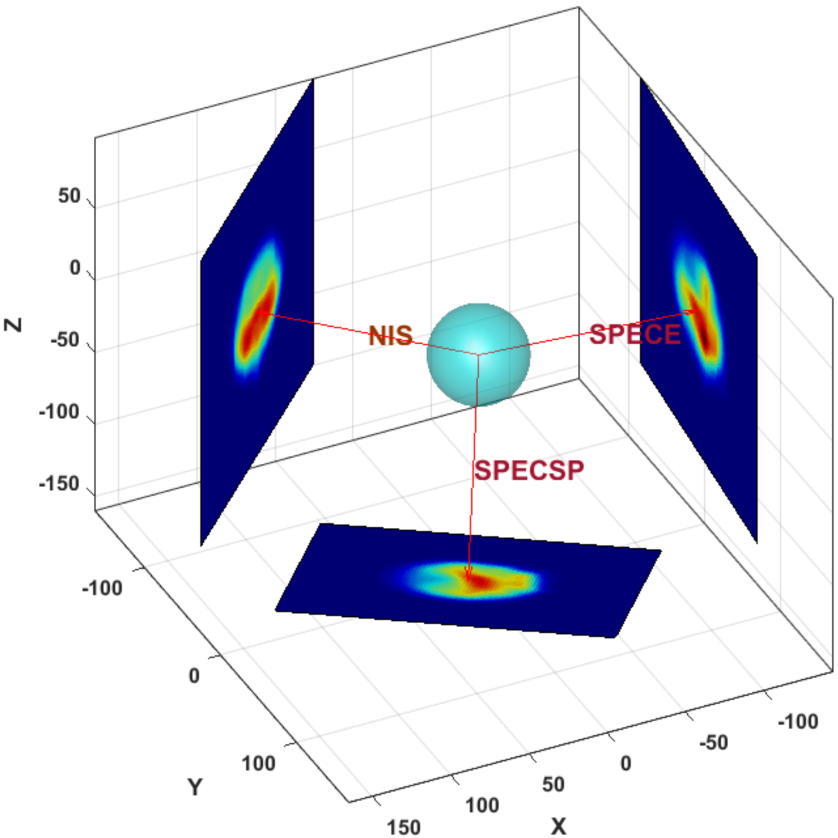
SPECE line-of sight: (90, 174)



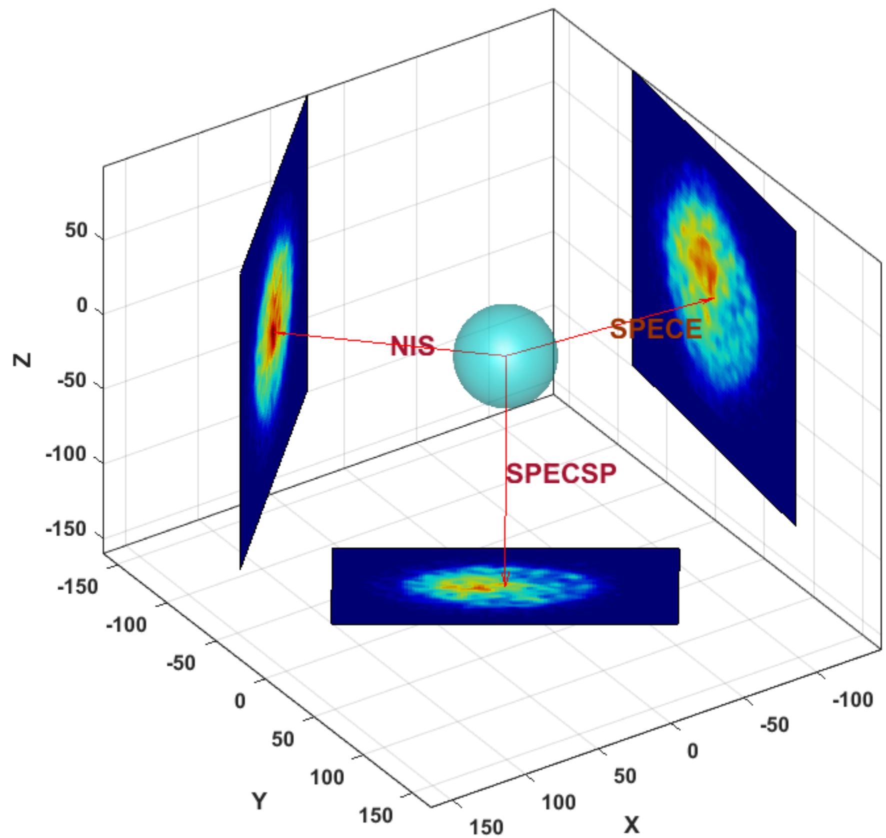
SPECSP line-of sight: (161, 56)



3D projections

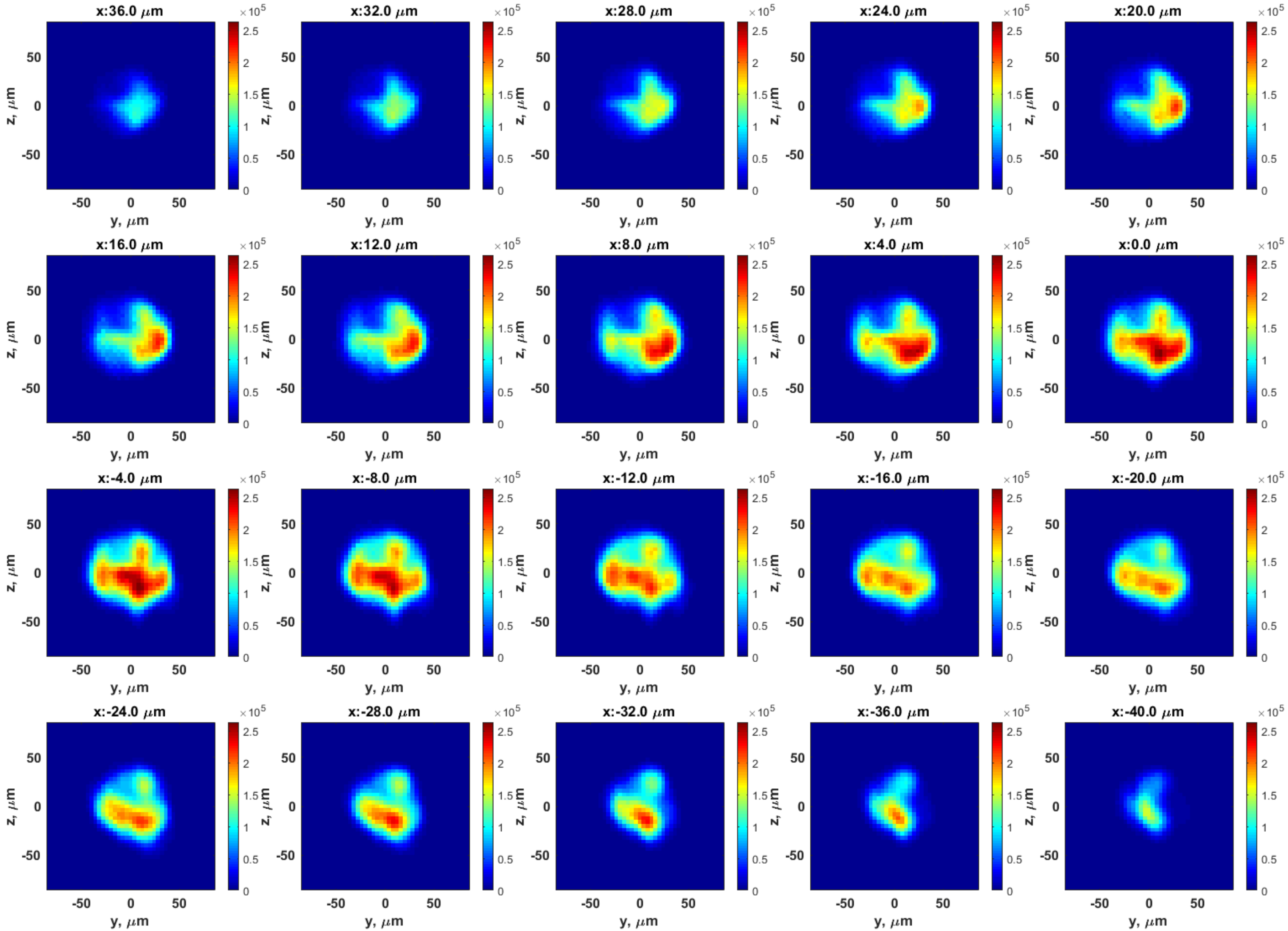


Primary

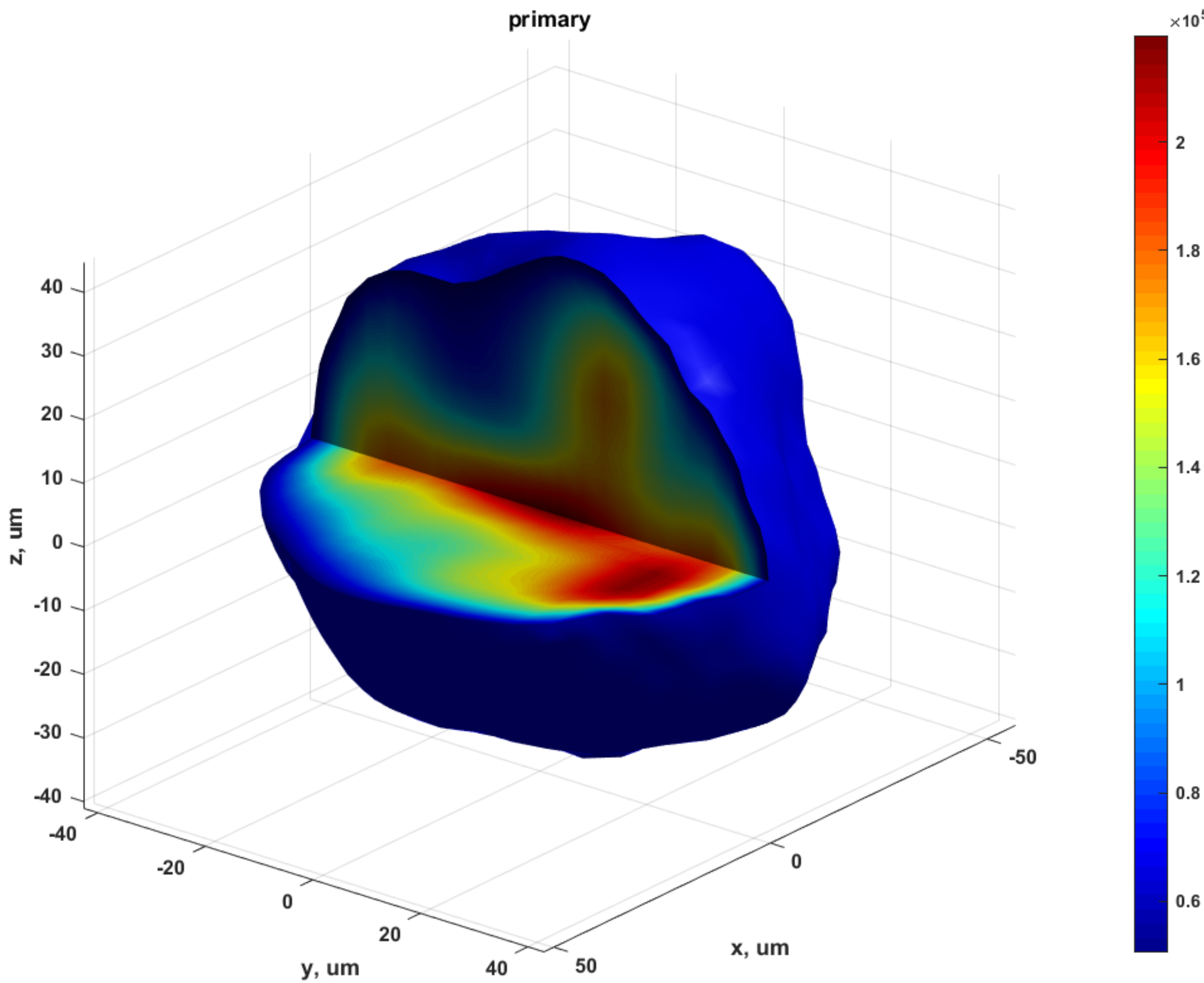


Down-scattered

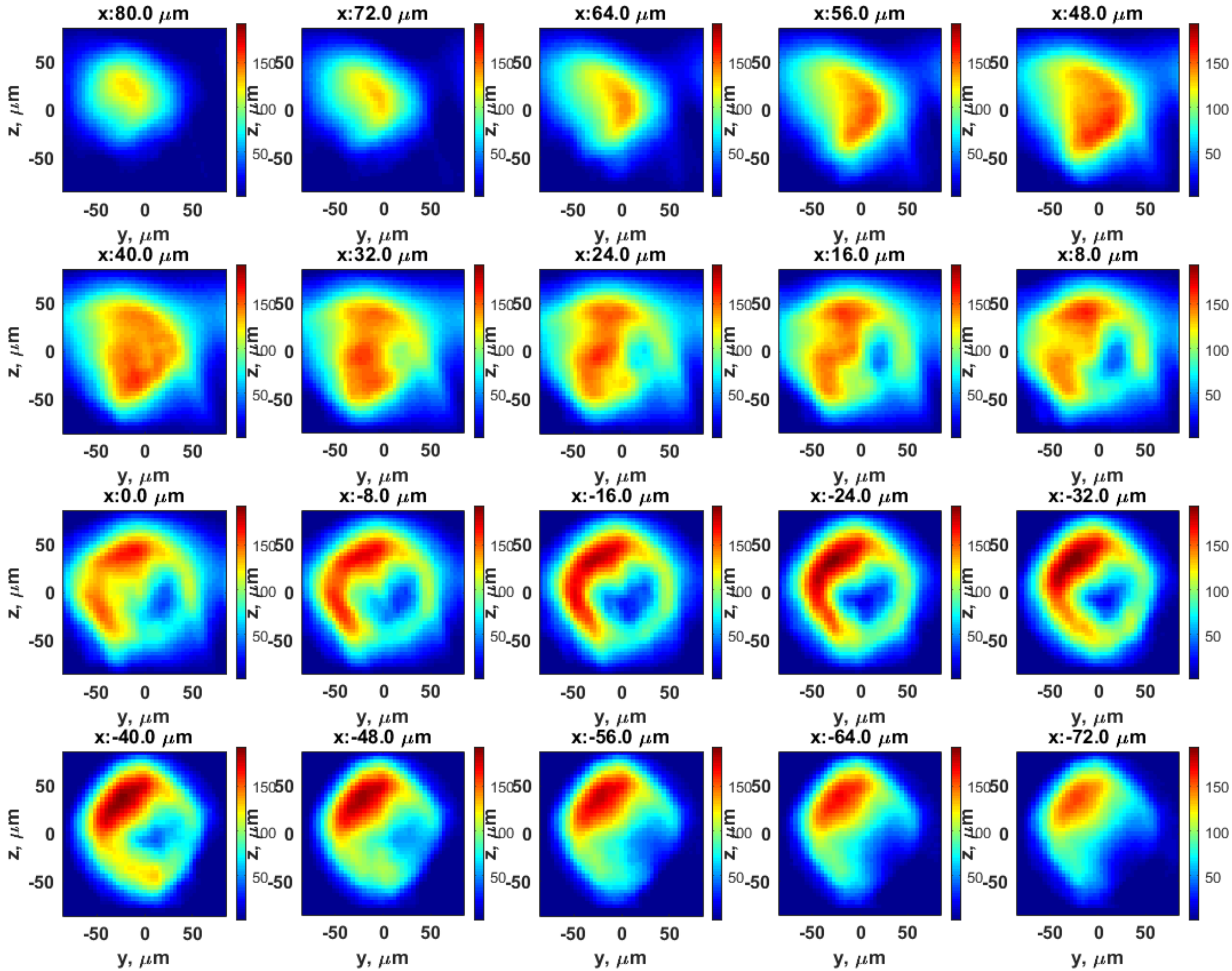
Reconstructed primary source: YZ-slices (i.e. almost orthogonal to SPECE LOS)



Reconstructed primary source

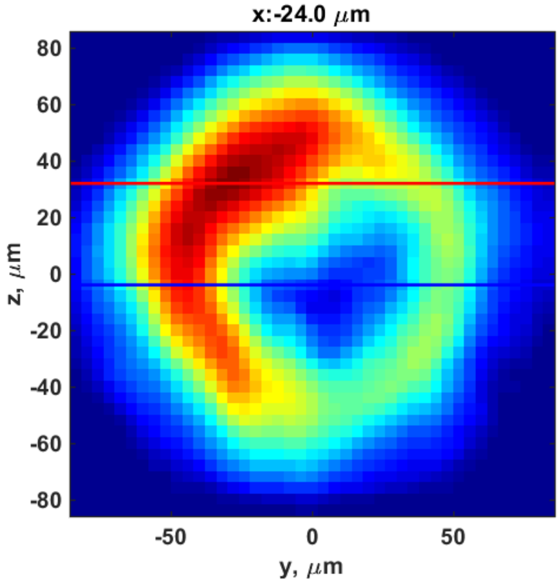


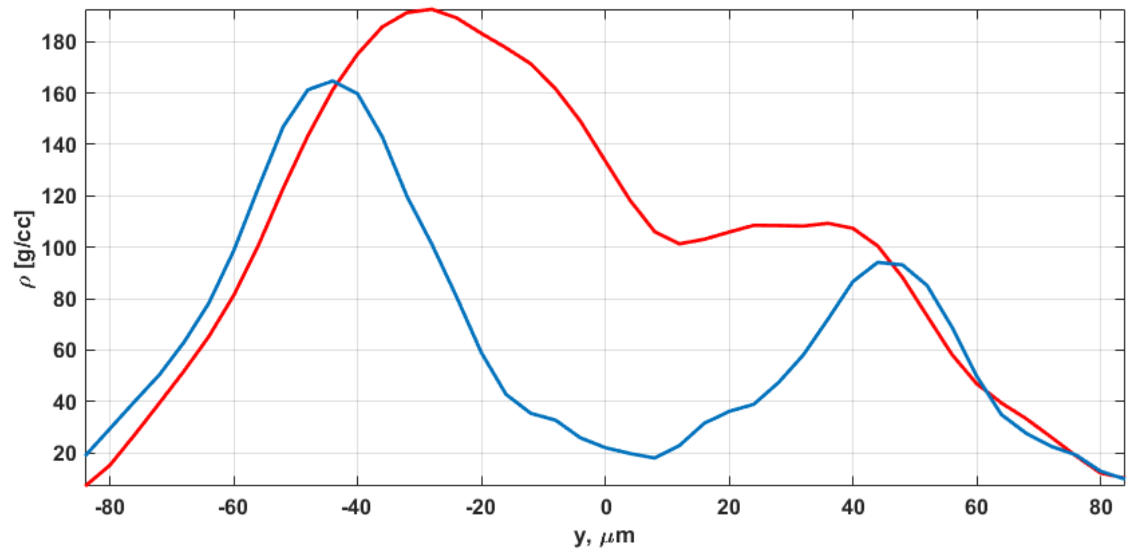
Reconstructed density: YZ-slices (i.e. almost orthogonal to SPECE LOS), color map is

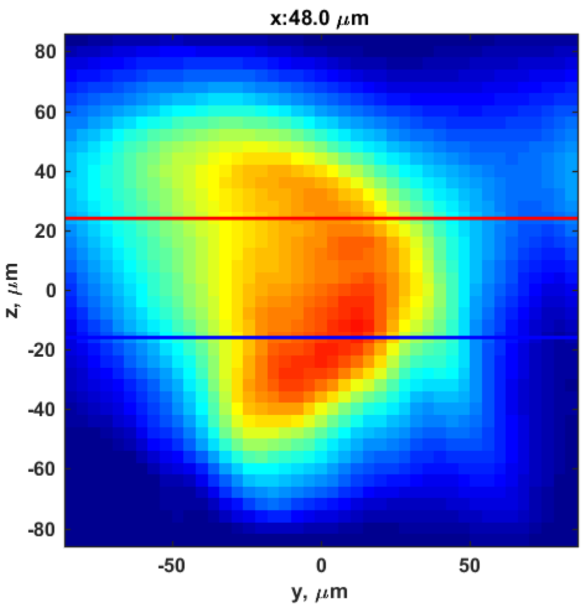


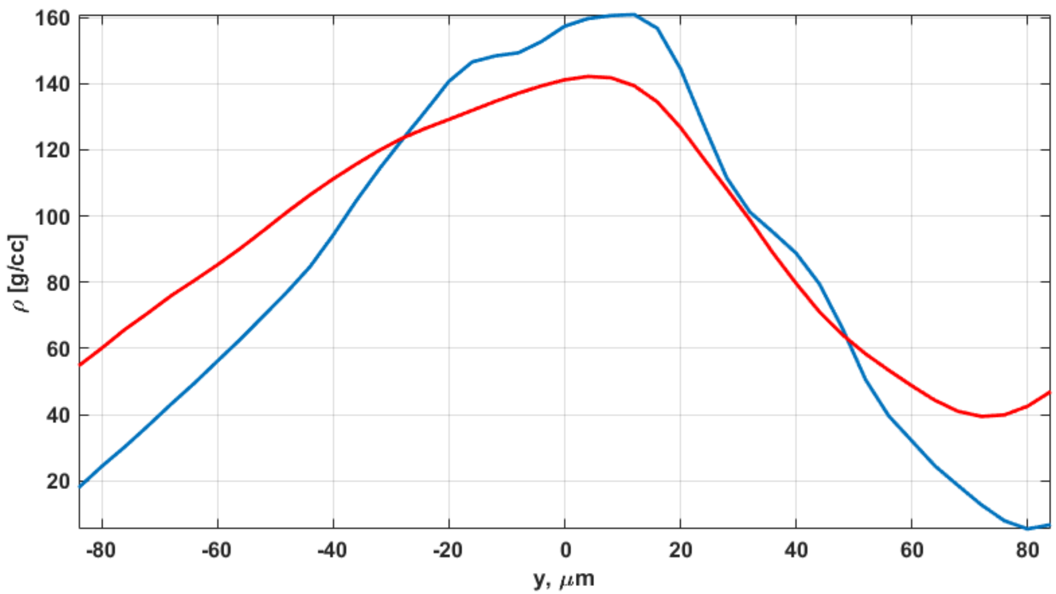
Mass: 258 μg (total), 187 μg (inside 30% level)

Density profiles for representative YZ slices

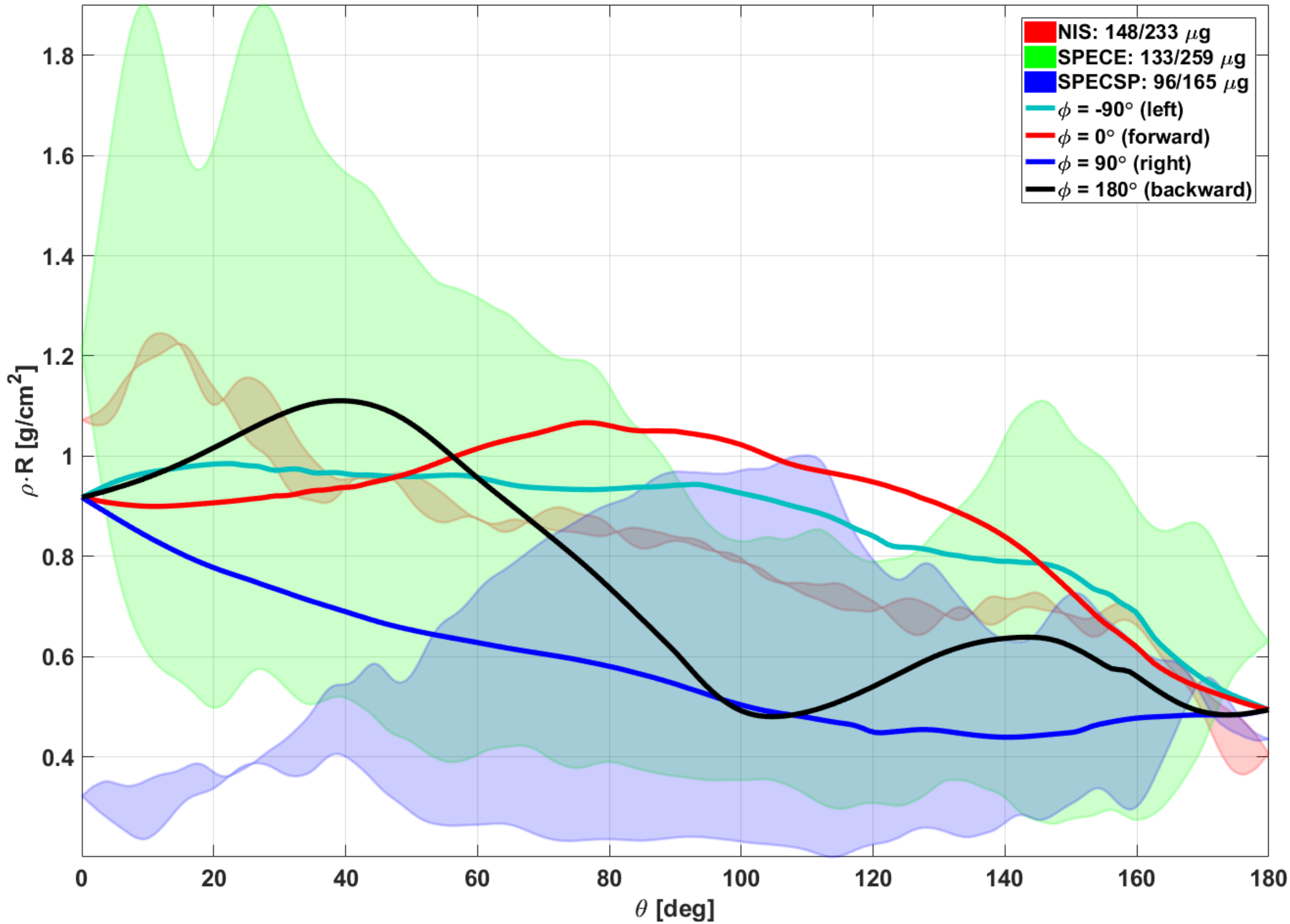




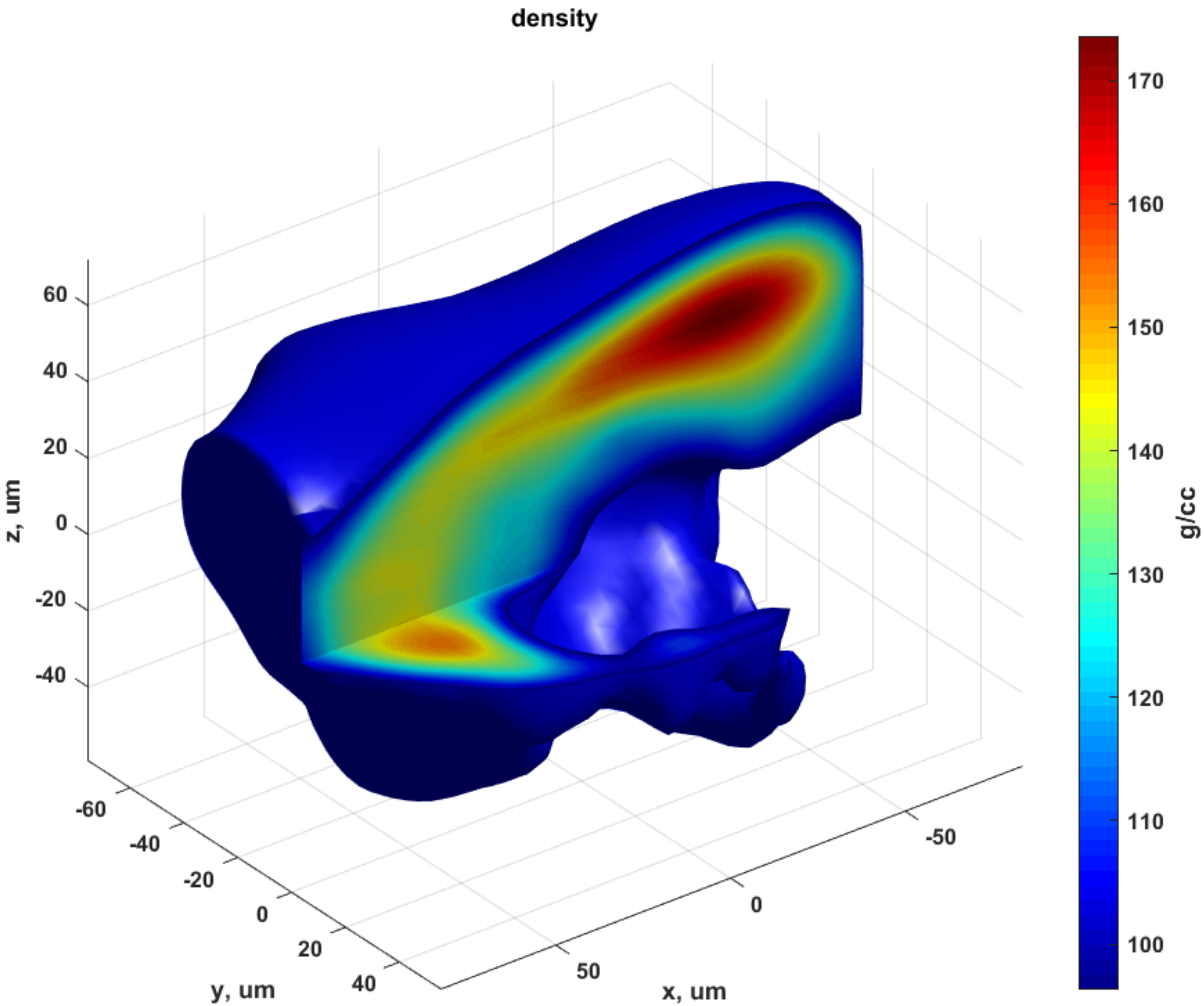




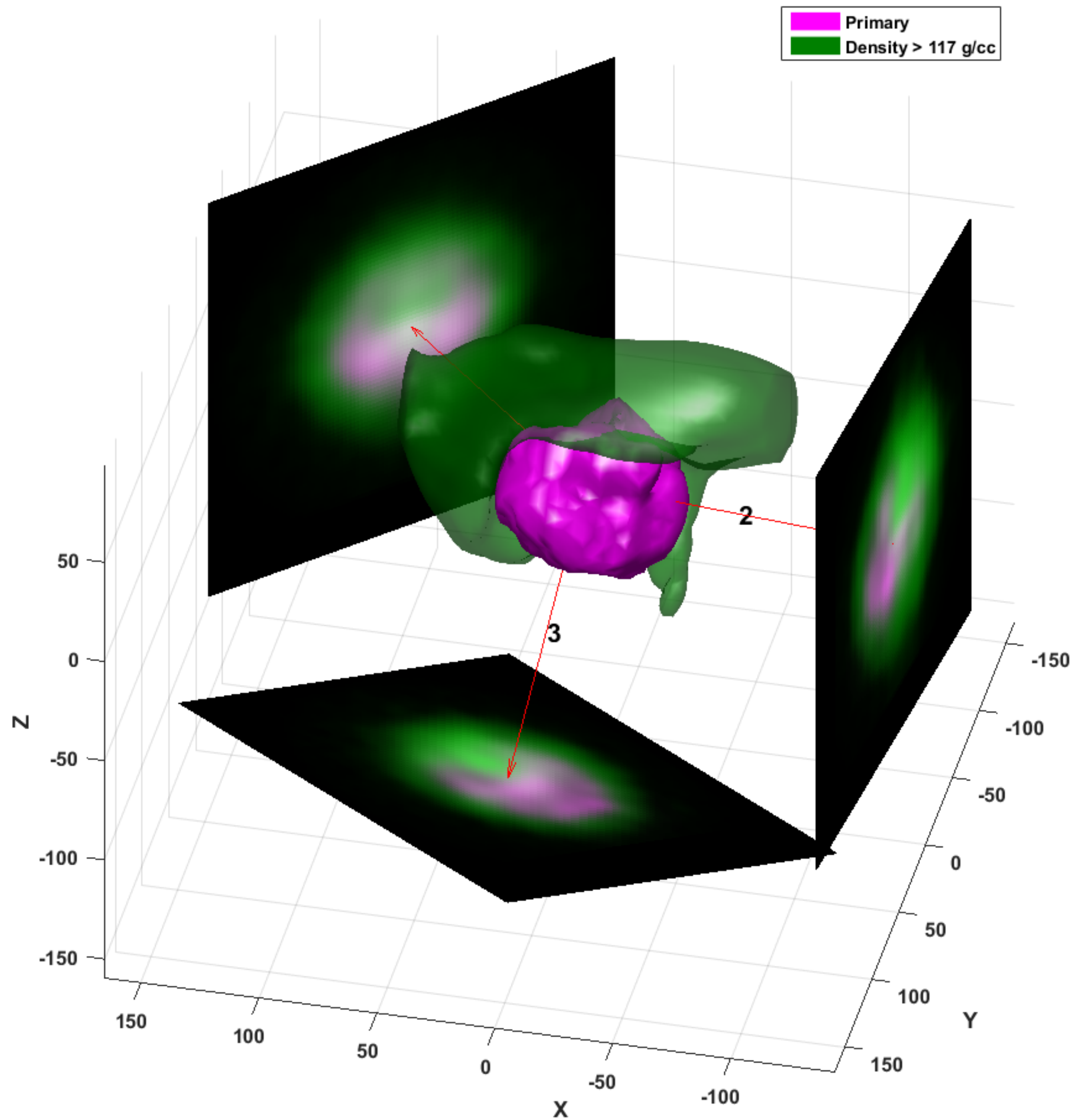
Rho-R as a function of polar angle



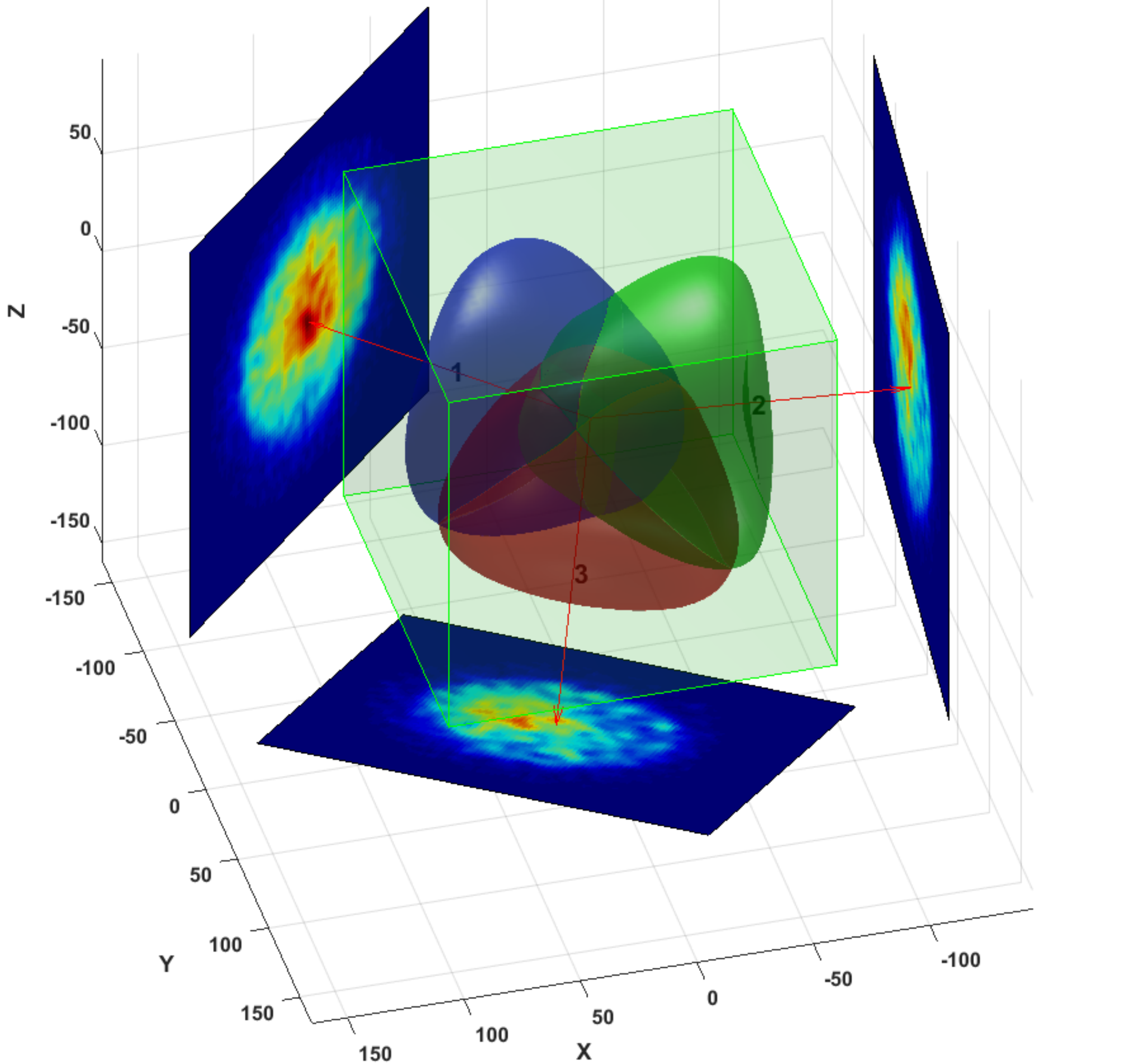
Mass: 258 μg (total), 187 μg (inside 30% level)



density
60
40
20
0
-20
-40
z, um
-60
-40
-20
0
20
40
y, um
50
0
-50
x, um
170
160
150
140
130
120
110
100
g/cc


Primary
Density > 117 g/cc
2
3
50
0
-50
-100
-150
Z
150
100
50
0
-50
-100
X
-150
-100
-50
0
50
100
150
Y

Down-scattered image projection kernels $\Phi(\mathbf{r}, \mathbf{p})$ for the reconstructed primary sou



Conclusion & Future Plans

1. A method to reconstruct cold fuel density using a single scattering model has been developed and validated against MCNP model
2. The method provides density in ***physical units***, i.e. g/cc
3. The method applied to the experimental data provided physically plausible and interesting results
4. The method requires inferring 3D distribution of the primary source. Given one projection direction this results in assuming axial symmetry of the reconstructed objects. This could be deceiving for reconstruction of a fuel assembly with this large 3D structure. Multiple views will alleviate this restriction and improve the density reconstruction
5. Source localization, i.e. array characterization, is of paramount importance

Nearest goals:

1. Extensively validate the technique using both simulation and experimental data
2. Develop an iterative procedure to account for the attenuation terms
3. Combine with polar x-ray images in attempt to account for low order asymmetry

Thank you!
and…
Questions?

Preliminary analysis of N160602 Gamma Ray Imaging

neutron imaging

P-23 Advanced Imaging Team, LANL

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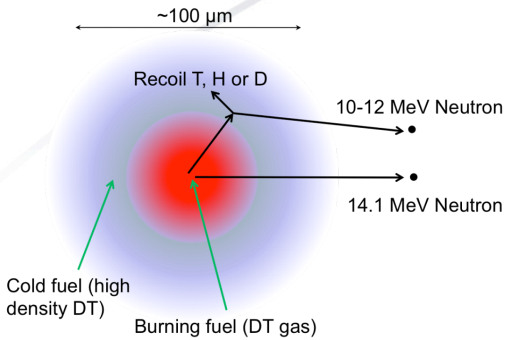
Doug Wilson, Frank Merrill
Gary Grim, David Fittinghoff

June 21, 2016

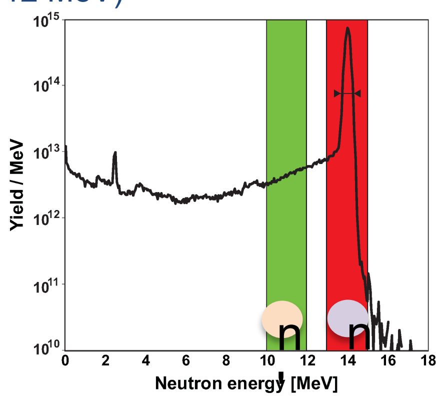
Los Alamos NATIONAL LABORATORY EST. 1943

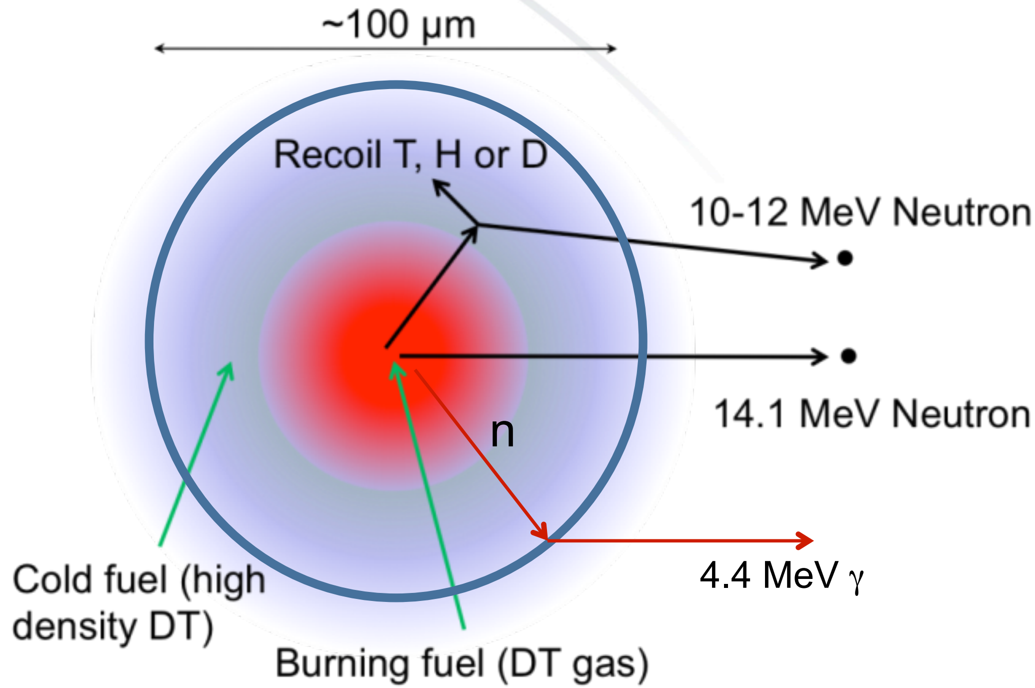
NNSA National Nuclear Security Administration

Neutron images provide the shape and size of the imploded fuel at stagnation. Gamma imaging can measure the ablator location.



Neutron images are used to diagnose NIF implosions. Temporal separation of neutrons after 28 m drift results in ability to collect two neutron images: Primary (13-17 MeV), Down-Scattered (10-12 MeV)





<u>Gamma Ray Imaging</u>

At yields $>10^{16}$ neutrons and sufficient remaining ablator mass there should be enough C(n,γ) reactions to form images of the ablator location.

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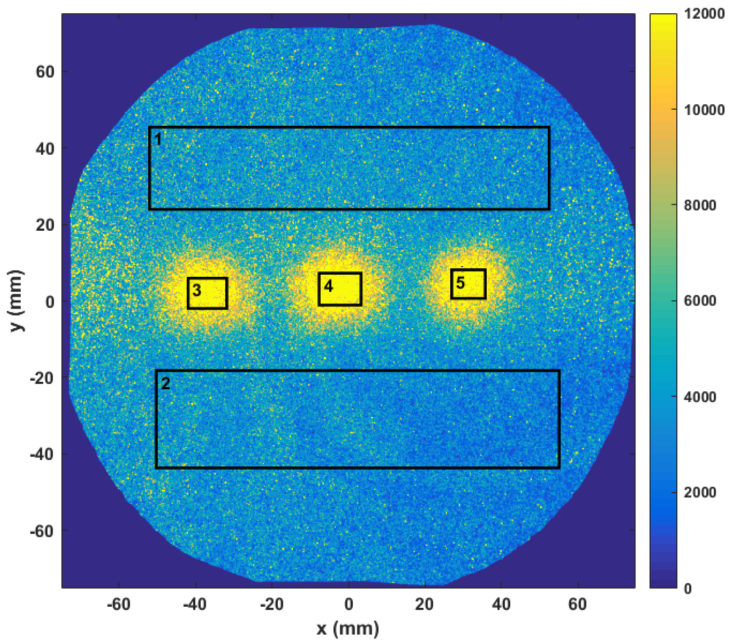
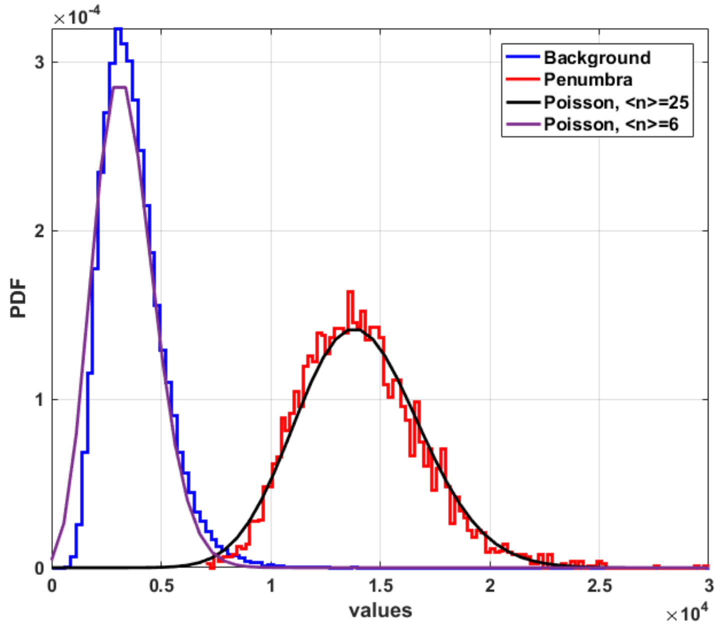
Noise analysis of N160602 data (260 micron pixel) indicates higher signal level than expected





No	Background (1,2)	Penumbra (3,4,5)
Mean	3730	14100
STD	1550	2840
SNR	2.4	5.0
$\langle N_\gamma/\text{pixel}\rangle$	~6	~25

Poisson distribution: $P(n|\bar{n}) = \frac{(\alpha\bar{n})^n e^{-\alpha\bar{n}}}{n!}$

Back of the envelope:

$$N_\gamma \Delta S = \frac{Y_\gamma \Delta S}{4\pi R^2}$$

$$Y_n \approx 1.6\times10^{15} \Rightarrow Y_\gamma \approx 8\times10^{12}\ into\ 4\pi$$

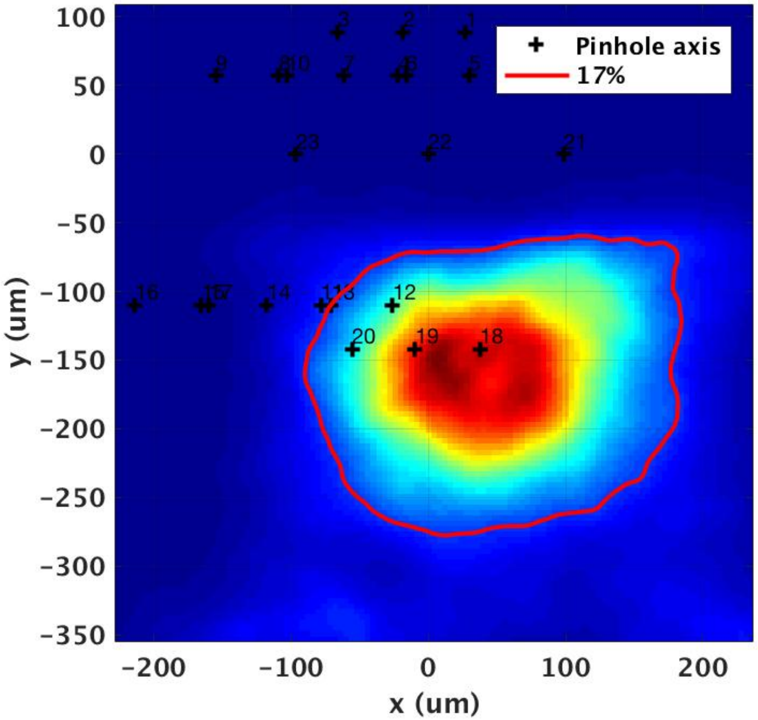
$$0.26\ mm\ pixel\ @\ 28\ m \Rightarrow \sim55\ gammas\ per\ pixel$$

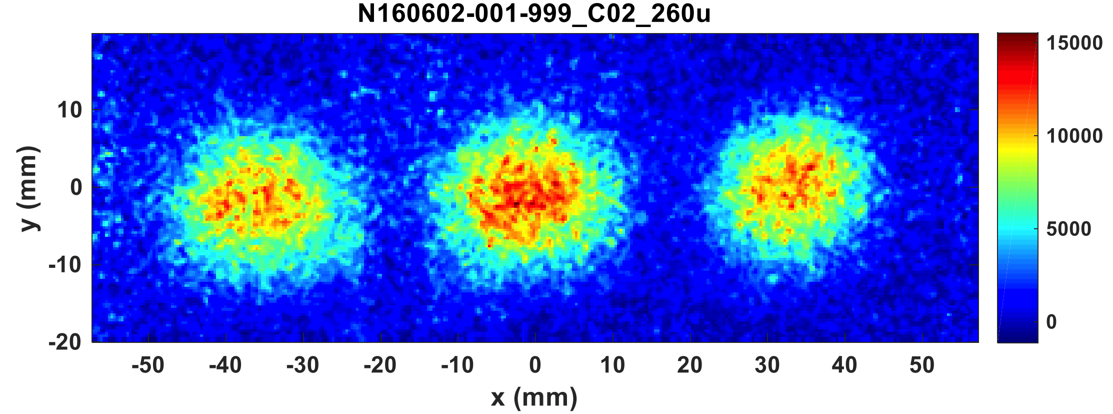
$$\sim15\%\ DQE\ (plastic\ scintillator)$$

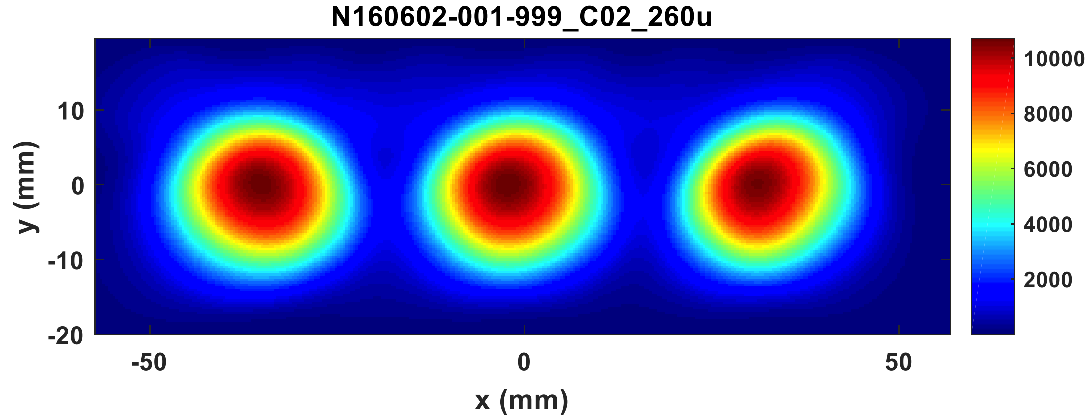
$$\Rightarrow \sim8\ gamma\ per\ pixel\ (\times2+???)$$

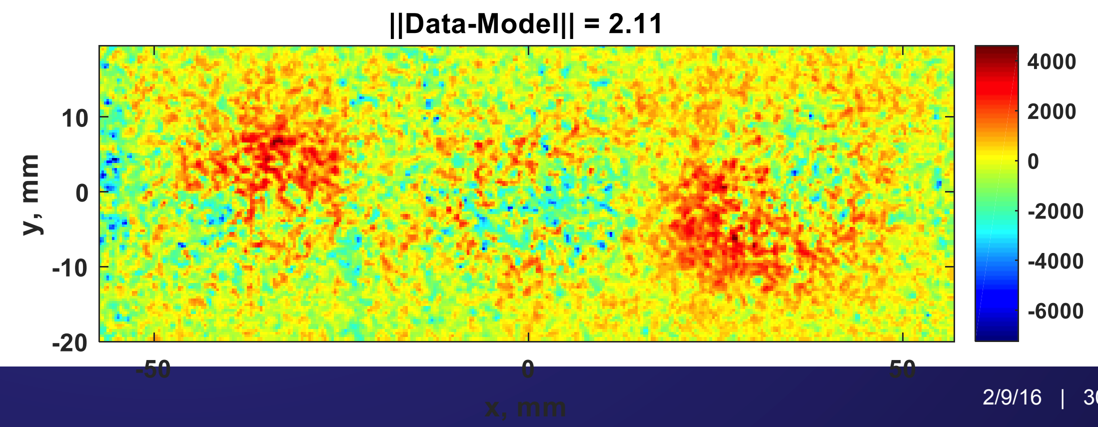
GRH measurement of C-12 gamma would help interpret this data

N160602: Expectation Maximization





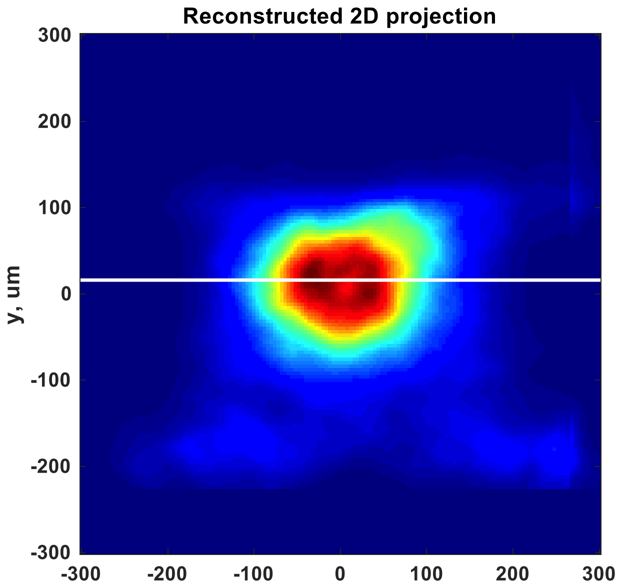


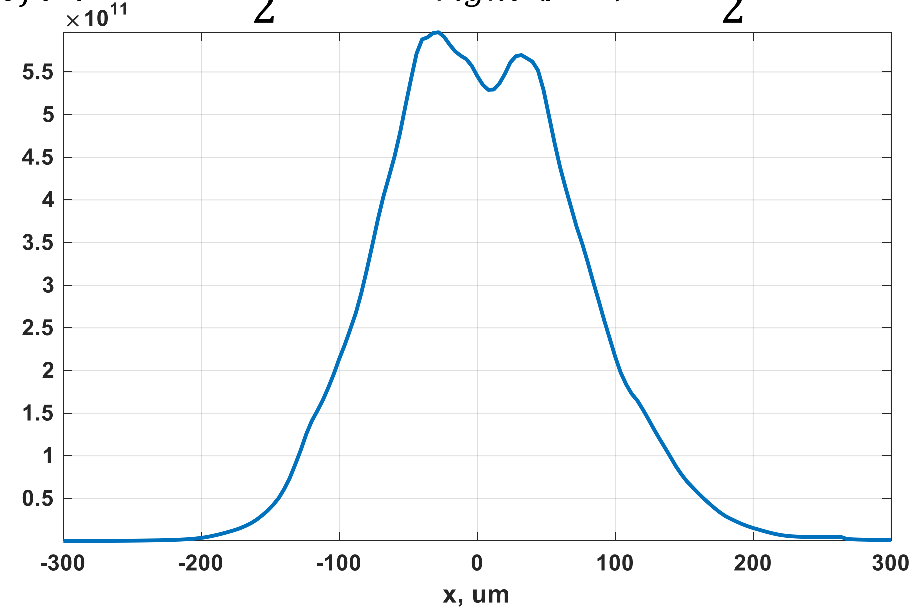


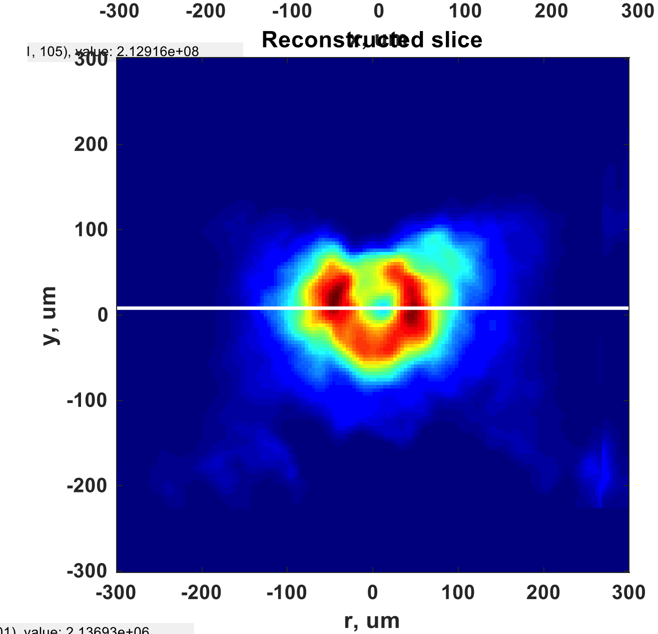
Position: (52, -163)
Size @17%: (278,217)
P0 = 129
P2/P0 = -16%

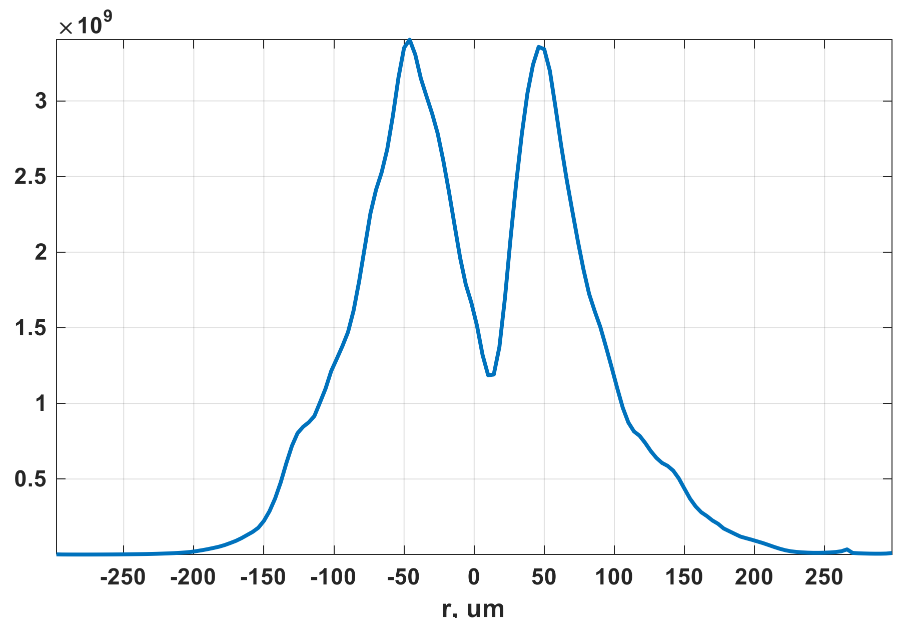
EMML, stop @ $\Delta\chi2/\chi2 < 10^{-4}$

Abel inversion: $S(\rho,\phi,z) = S_{left}(\rho,z)\dfrac{1-sin\phi}{2} + S_{right}(\rho,z)\dfrac{1+sin\phi}{2}$

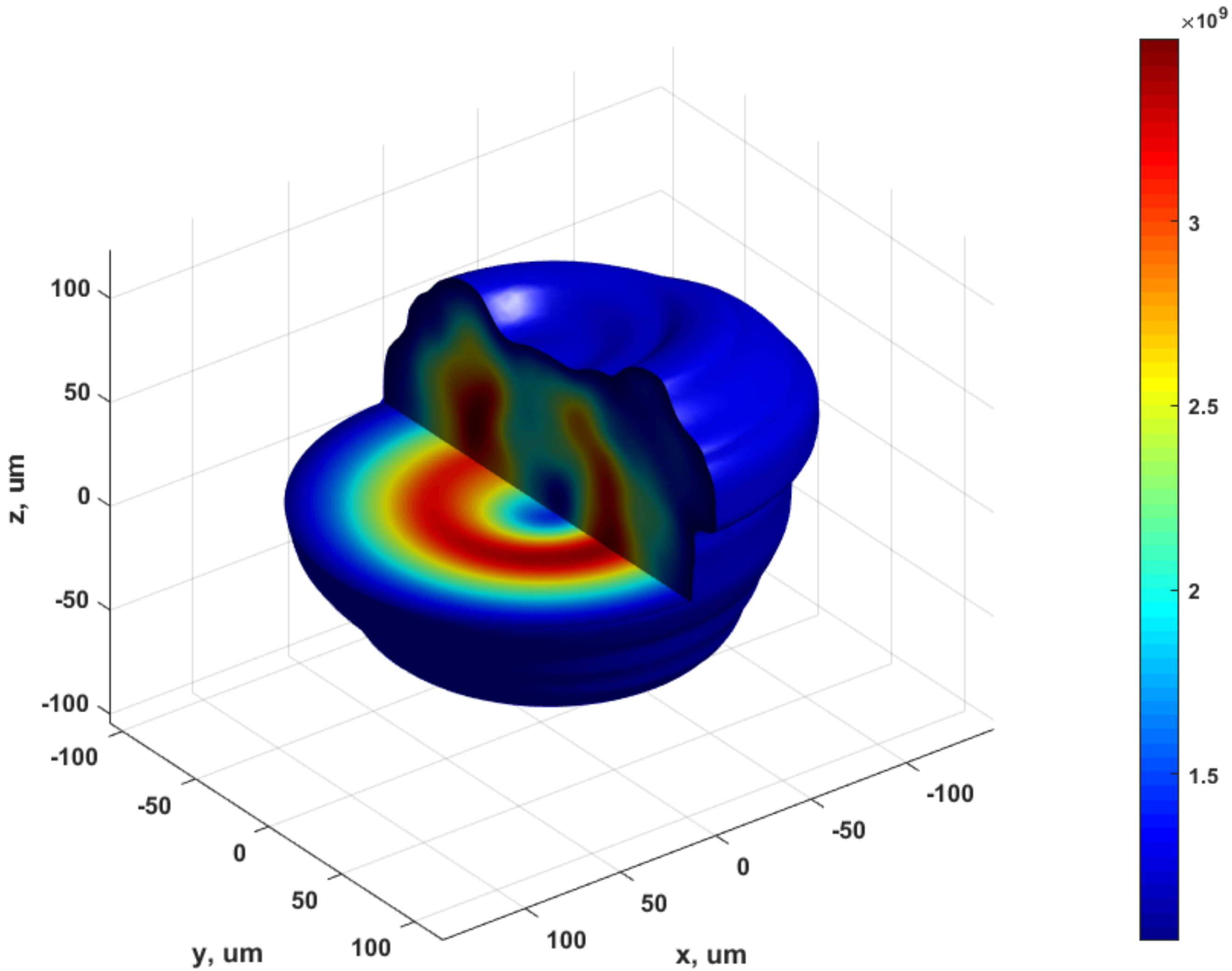




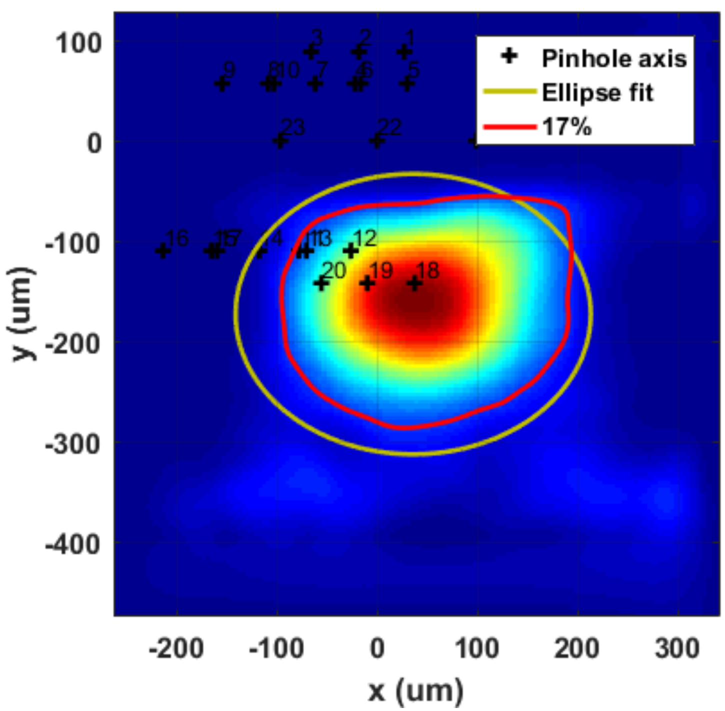


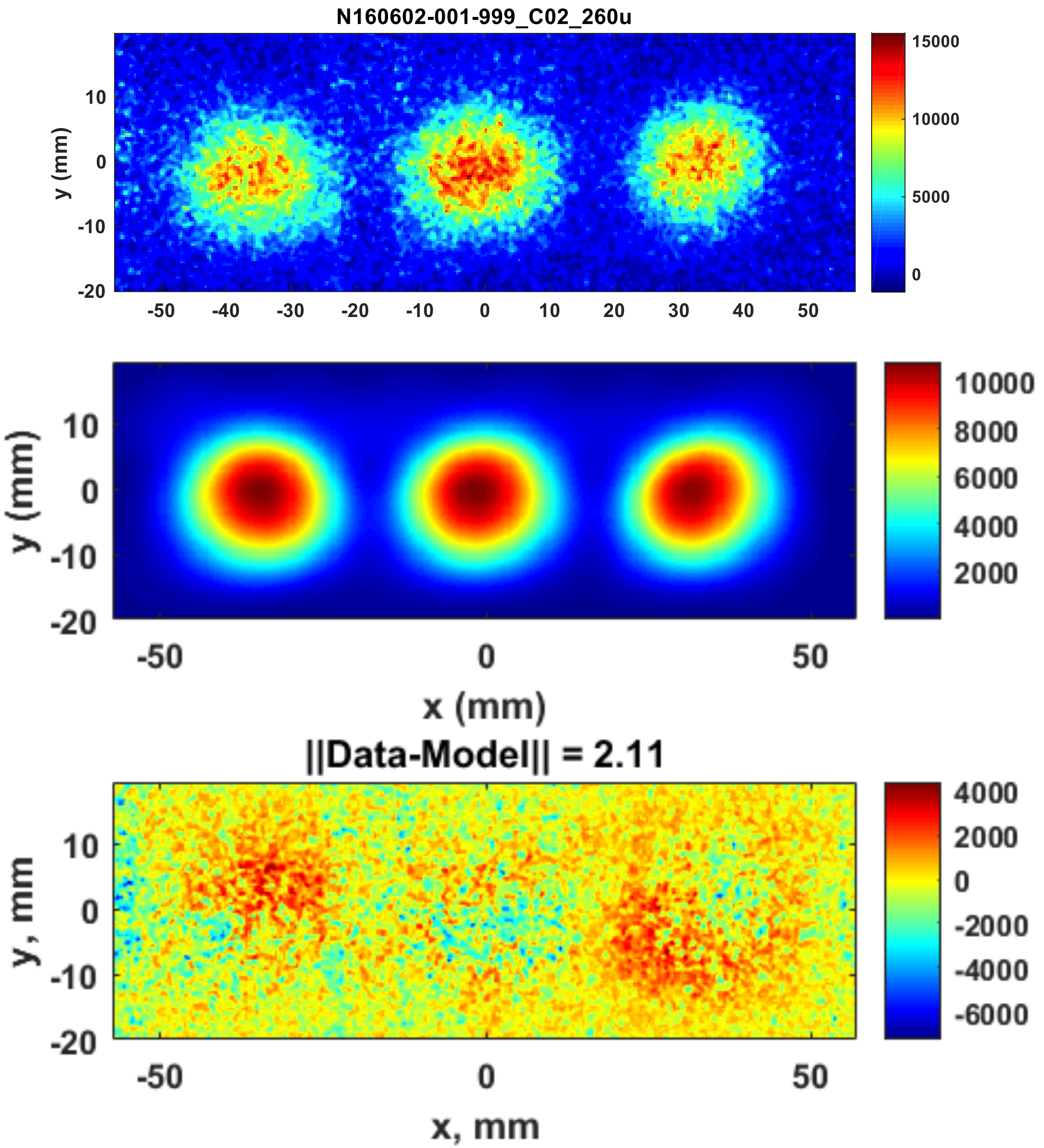


N160602: 3D rendering of reconstructed gamma source



N160602: Generalized Expectation Maximization with Gibbs prior

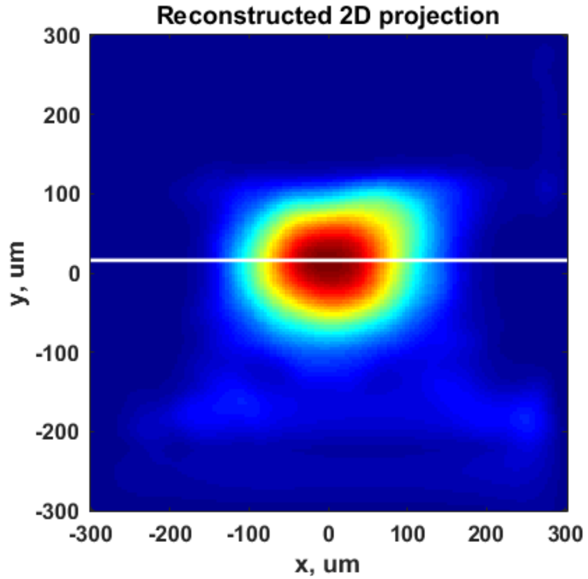


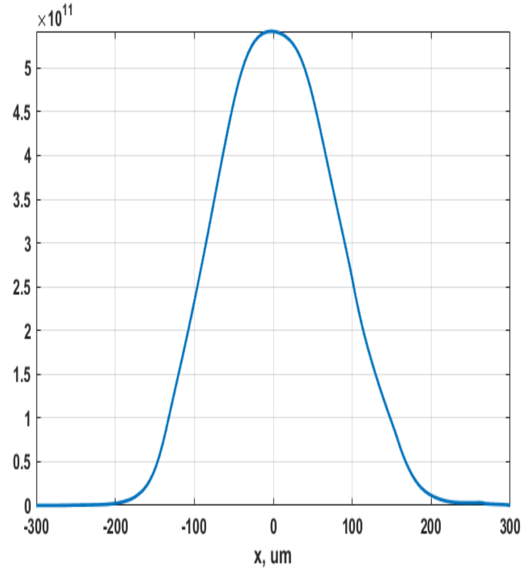


Position: (51, -164)
Size @17%: (299,229)
P0 = 138
P2/P0 = -17%

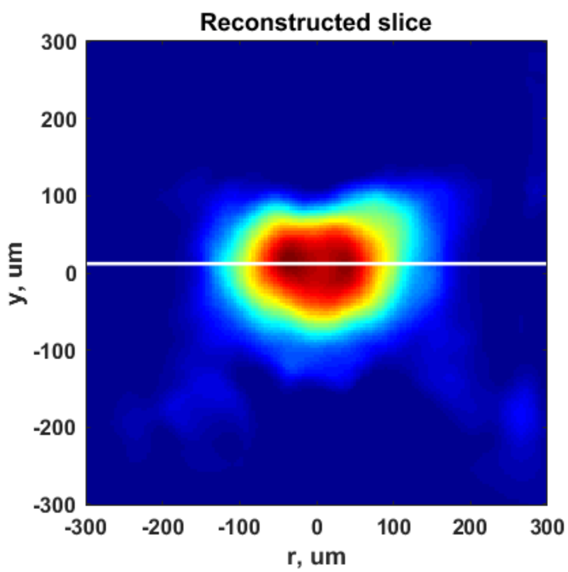
GEMMAP:
$\lambda=10^{-3}$, stop @ $\Delta\chi2/\chi2 < 10^{-4}$

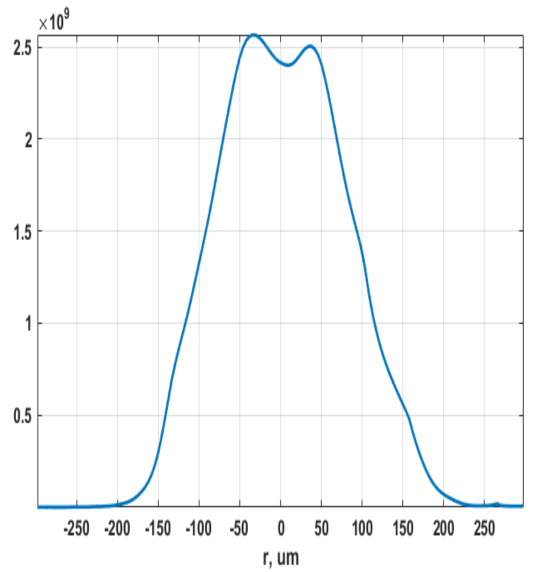
N160602: Abel inversion

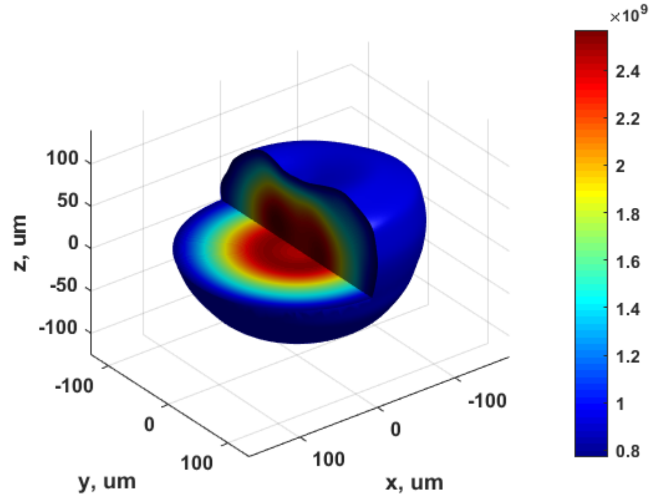




With a different prior, the void is not as obvious

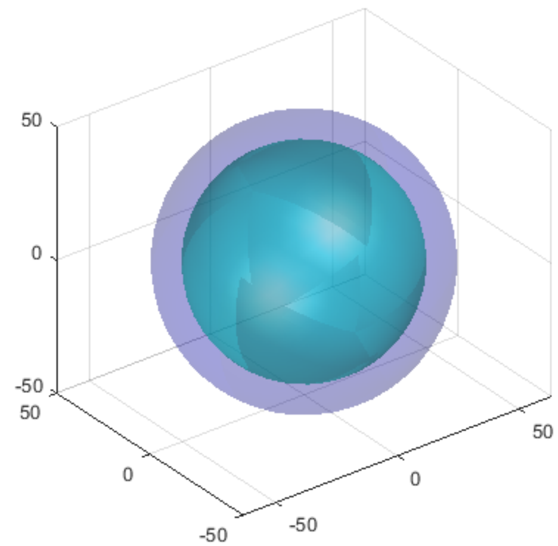






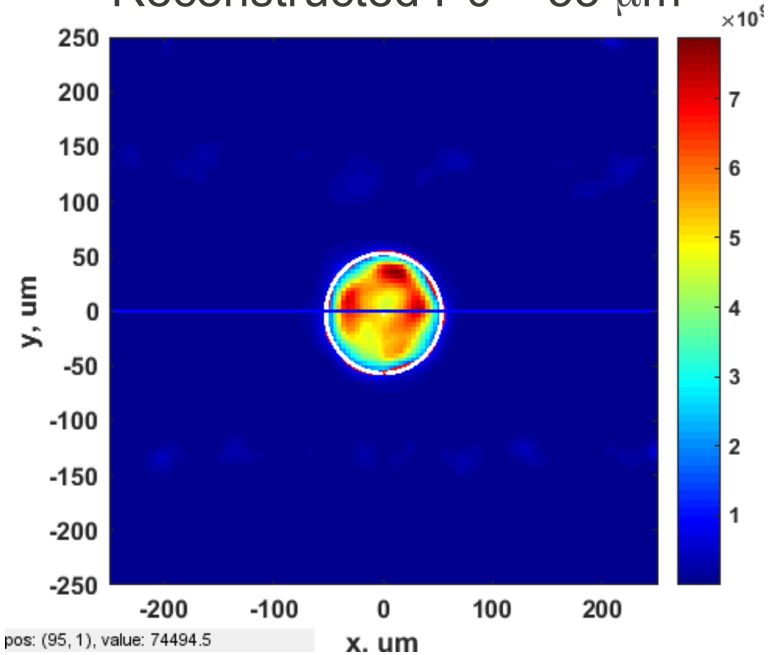
Use a simple shell model to simulate the gamma emission

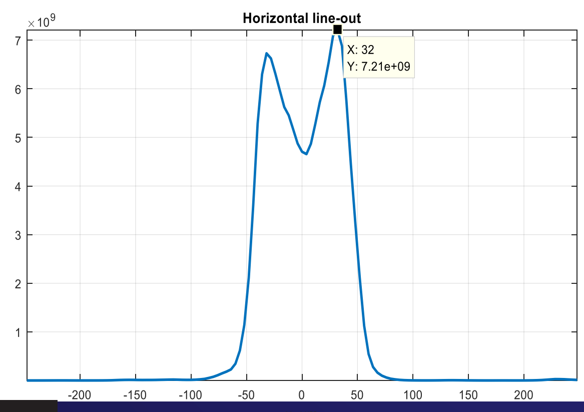
- 80 μm inner diameter, 100 μm outer diameter shell source of gammas
- Signal levels are adjusted to show scaling of N160602

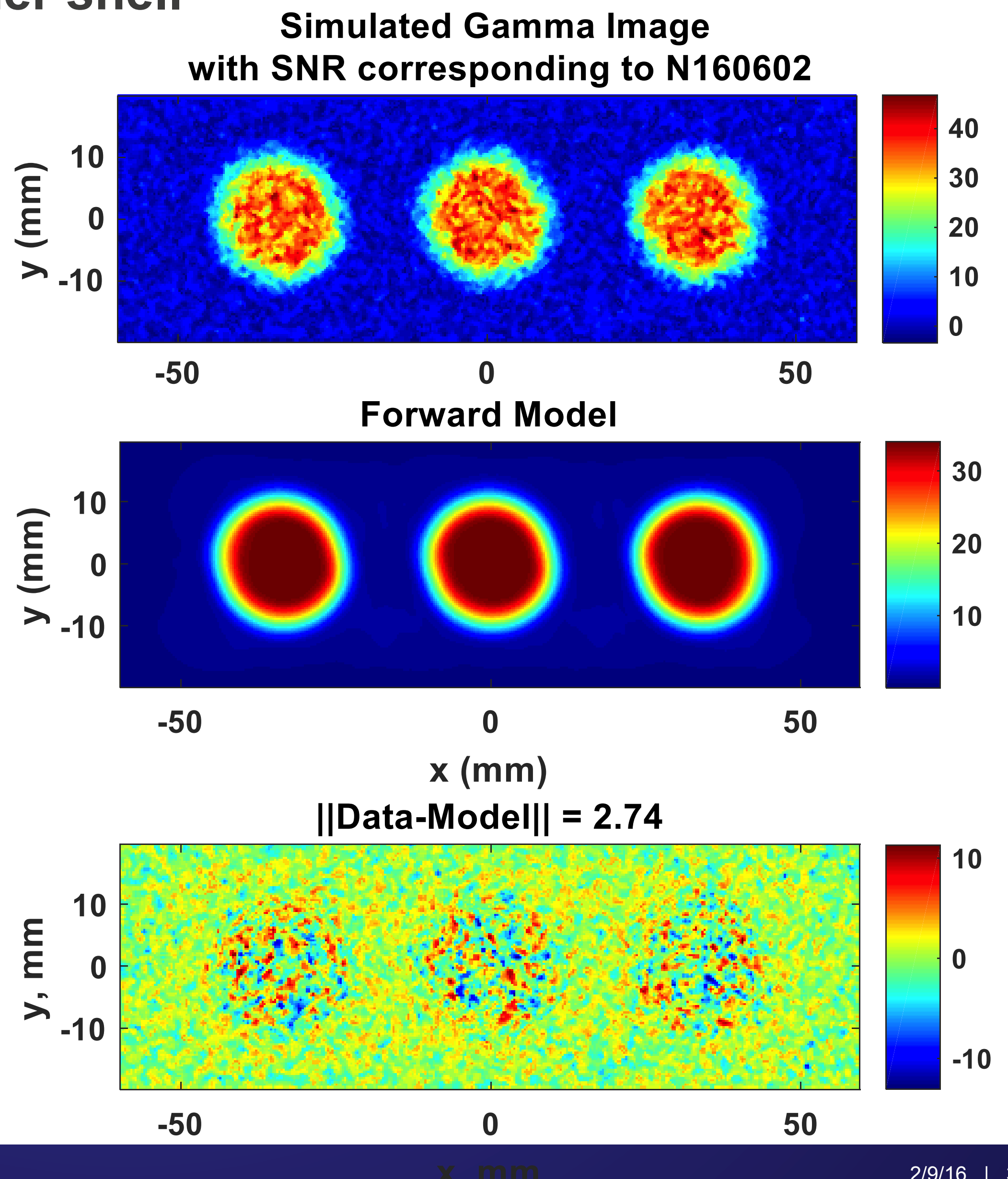


Simulated images using SNR similar to observed data (N160602) shows indications of the inner shell

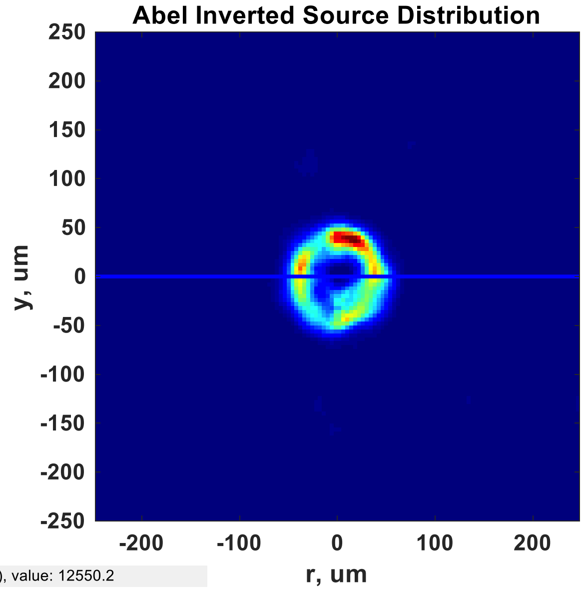
Reconstructed P0 = 53 μm

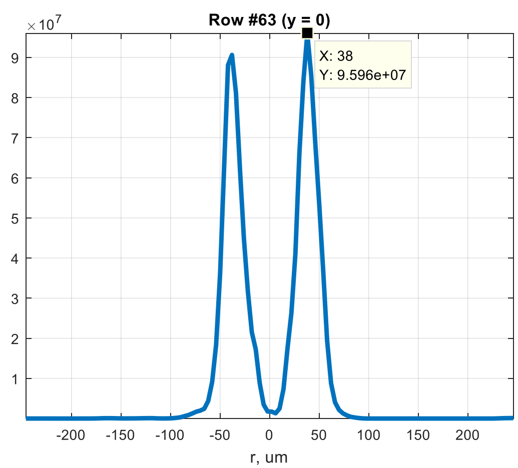


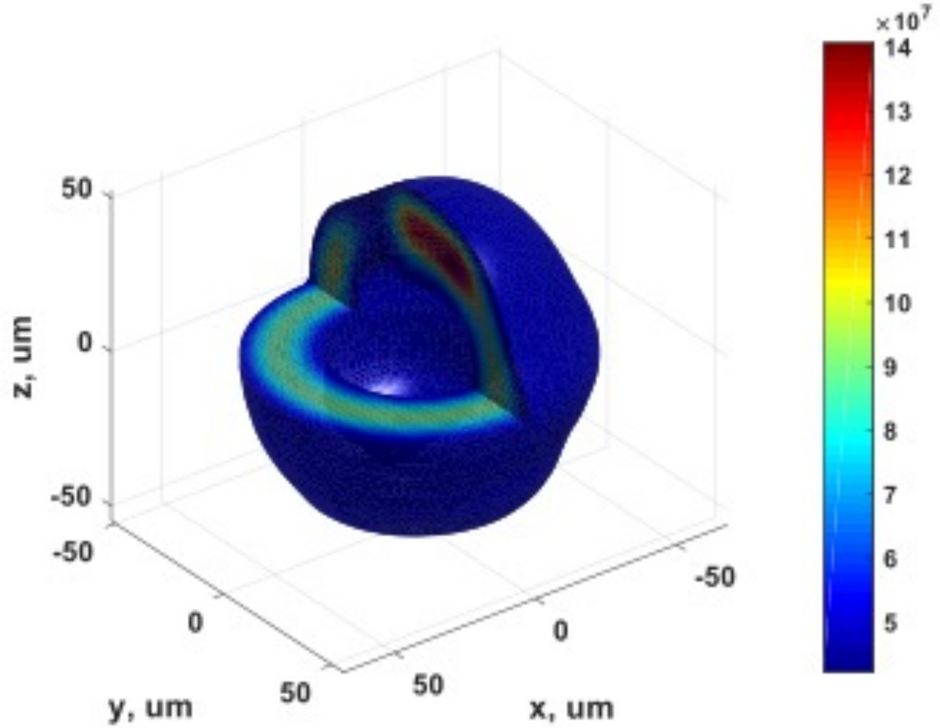




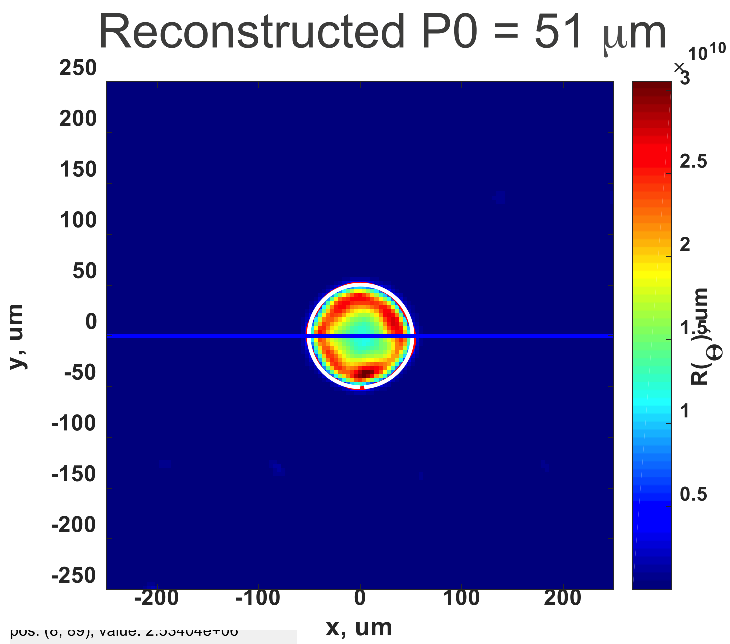
Abel inversion

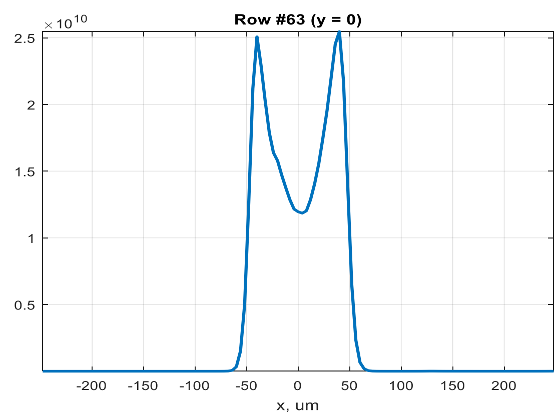


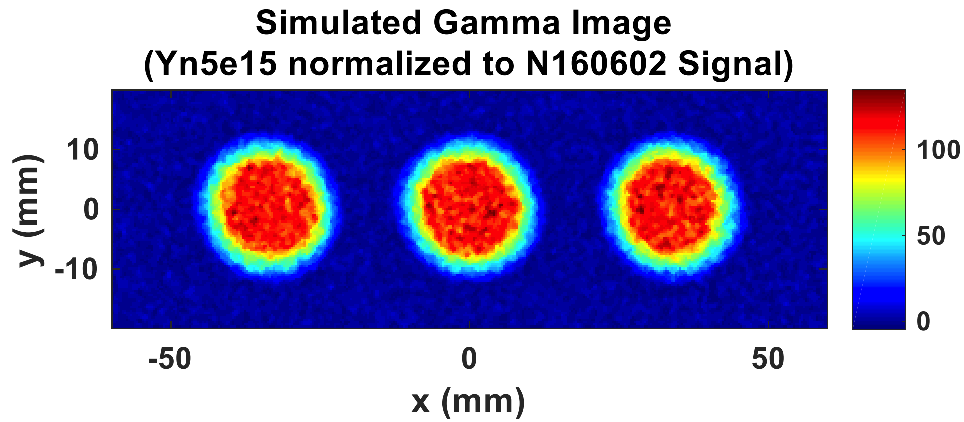


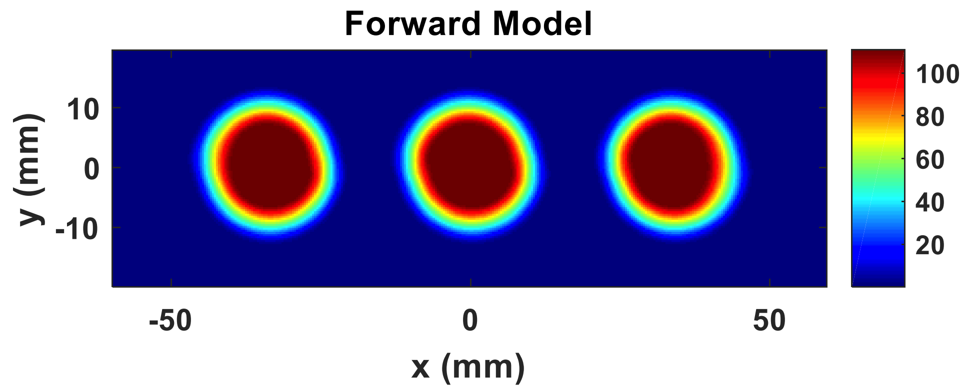


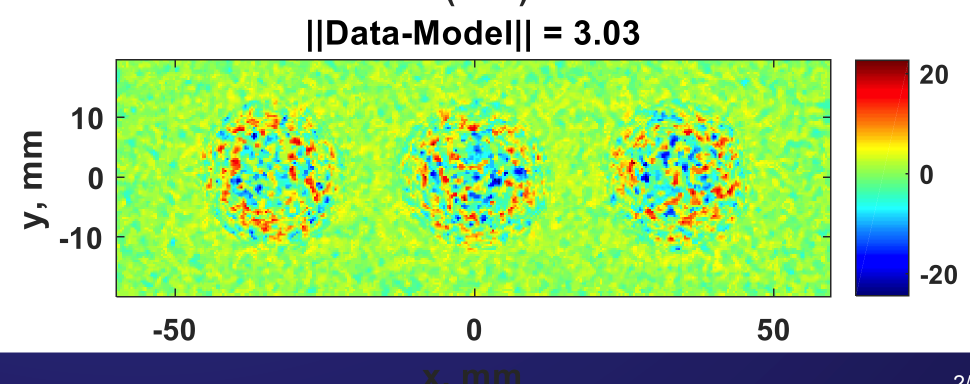
Simulated images ~3 times the signal of N160602



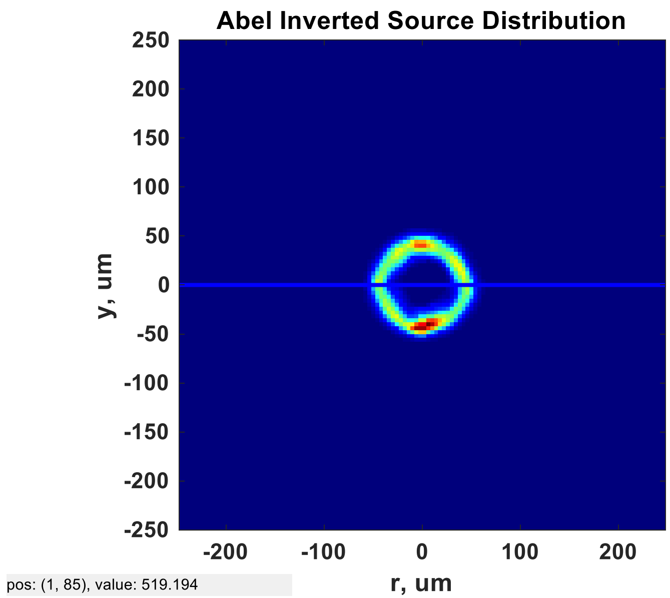


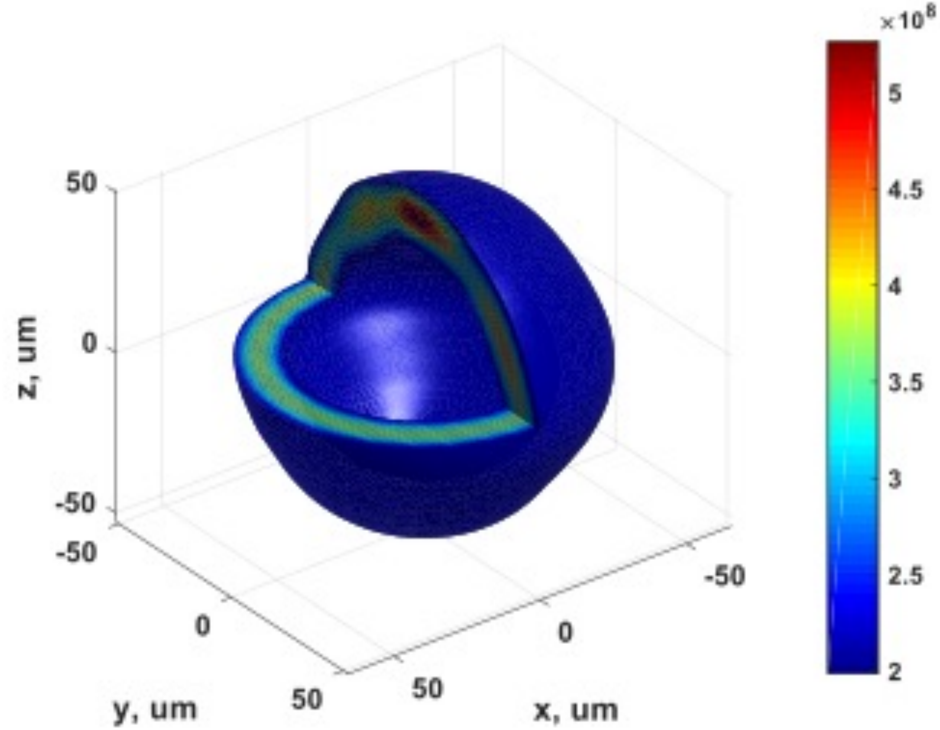


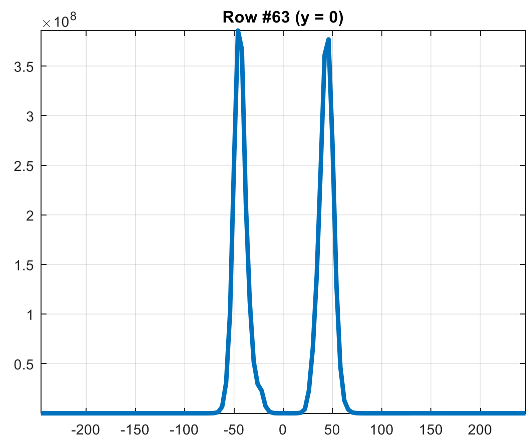


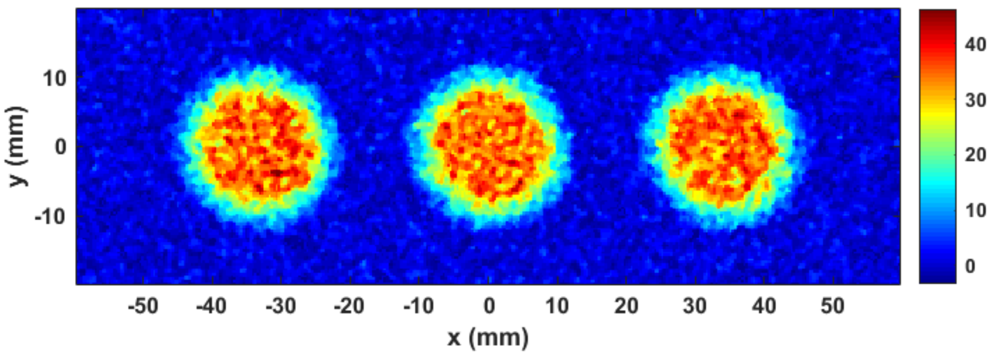


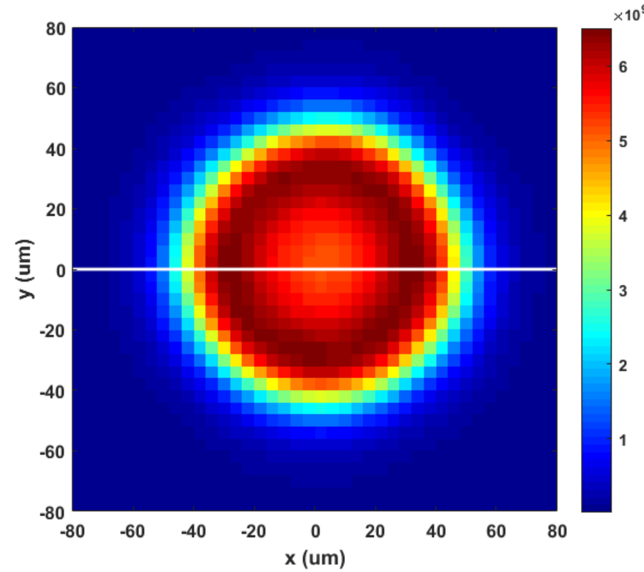
Abel inversion

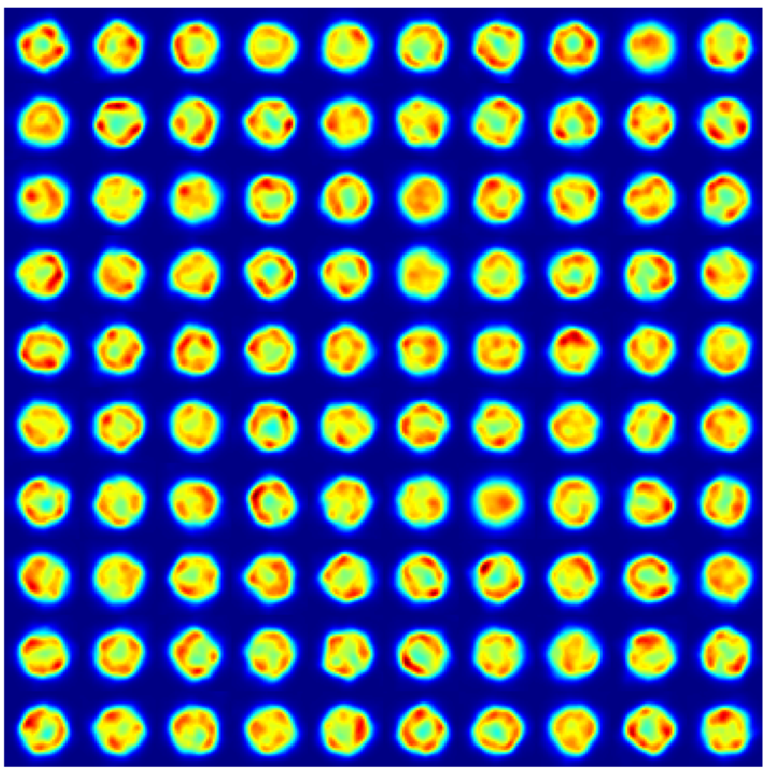


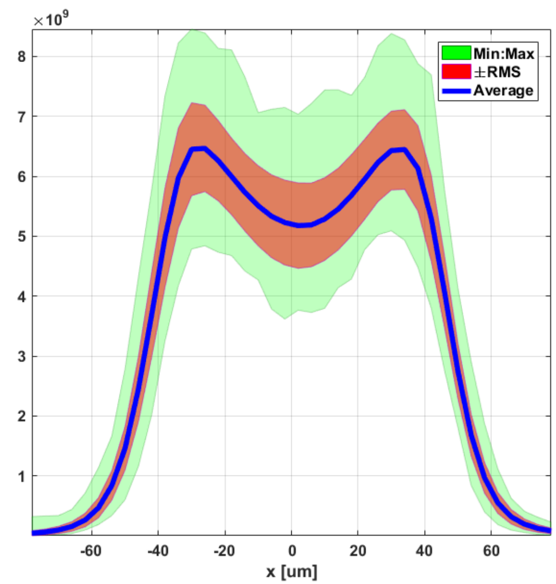




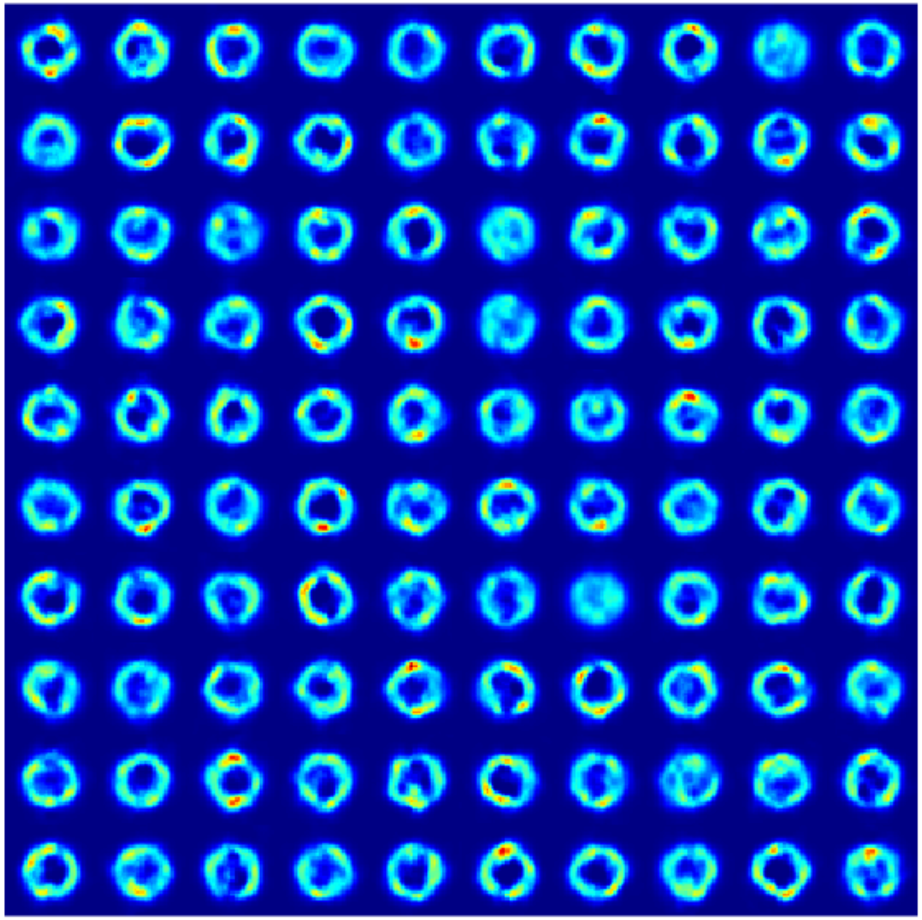

y (mm)
10
0
-10
-50
-40
-30
-20
-10
0
10
20
30
40
50
x (mm)
40
30
20
10
0

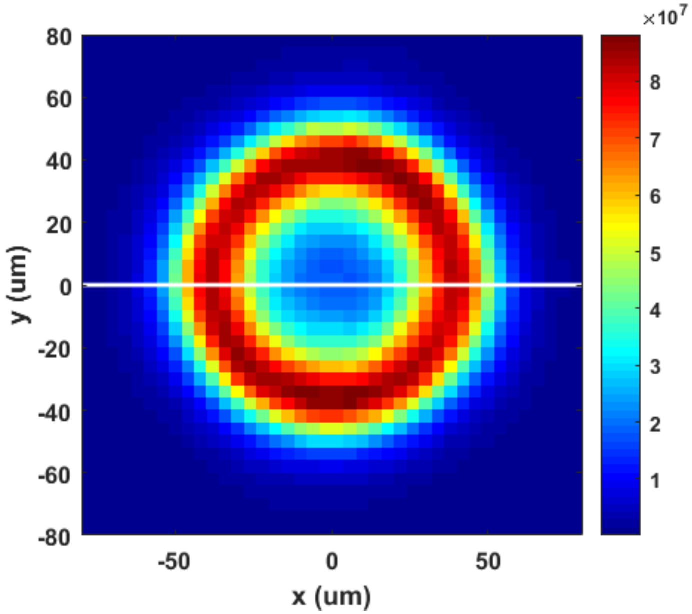

80
60
40
20
0
-20
-40
-60
-80
y (um)
x (um)
$\times 10^9$
6
5
4
3
2
1

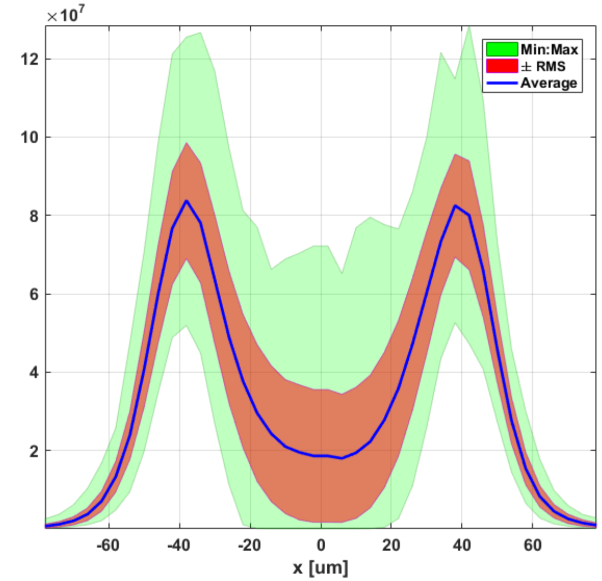



$\times 10^9$
8
7
6
5
4
3
2
1
-60
-40
-20
0
20
40
60
x [um]
Min:Max
±RMS
Average

Stat Tests: Abel inversion

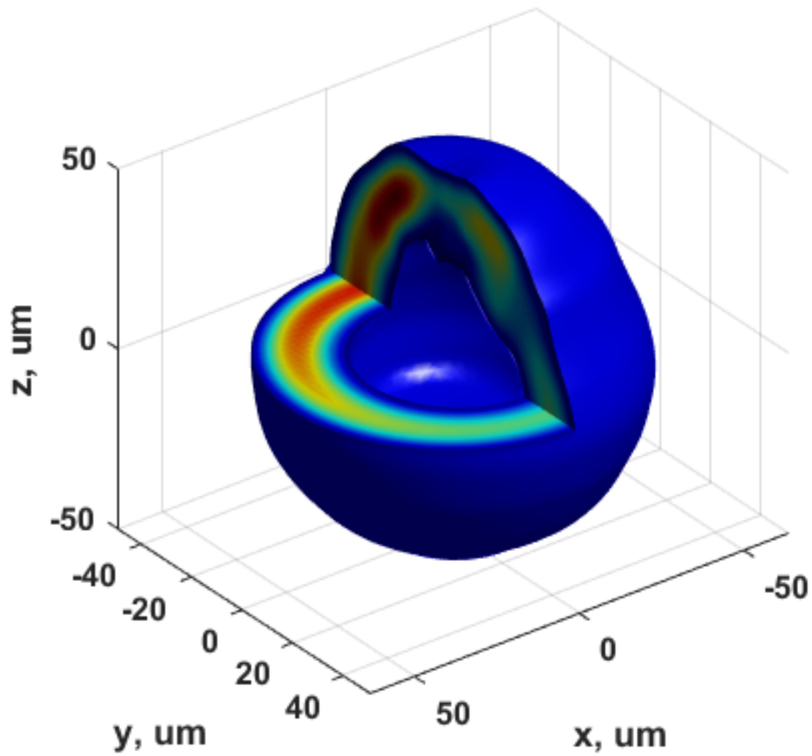




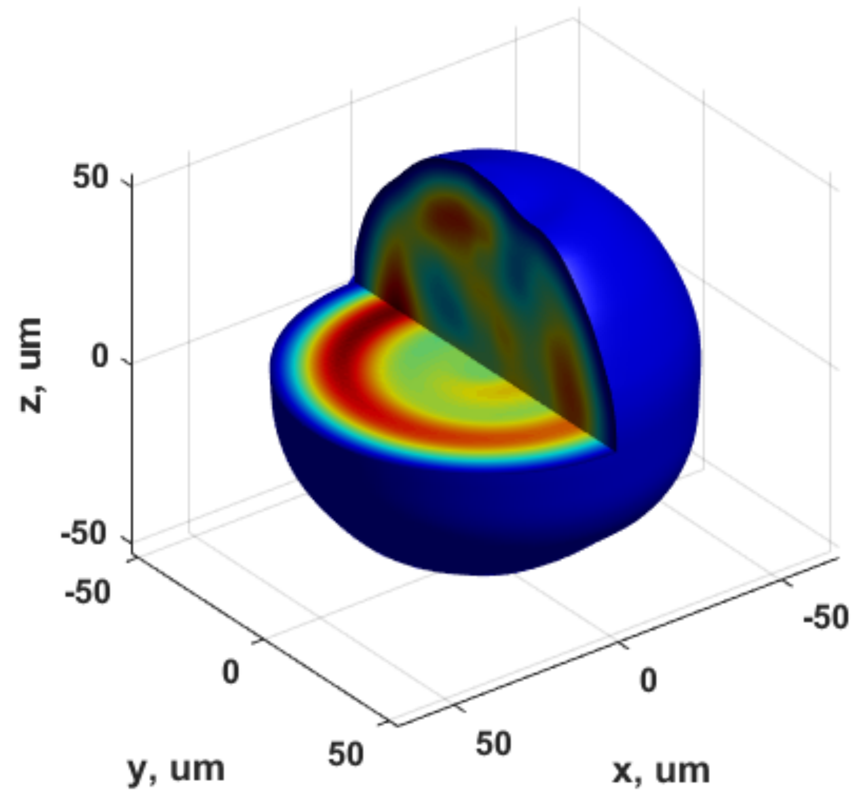


Stat Tests: “Best” and “worst” cases

~90%

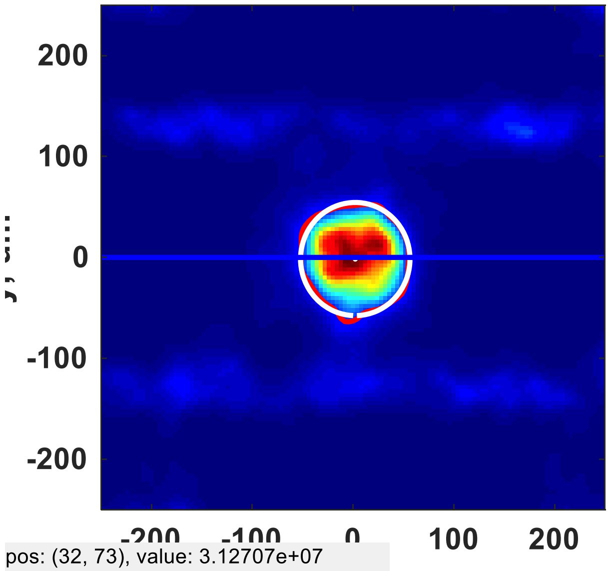


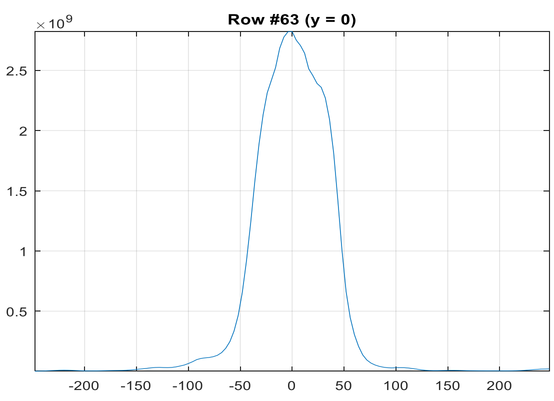
~10%

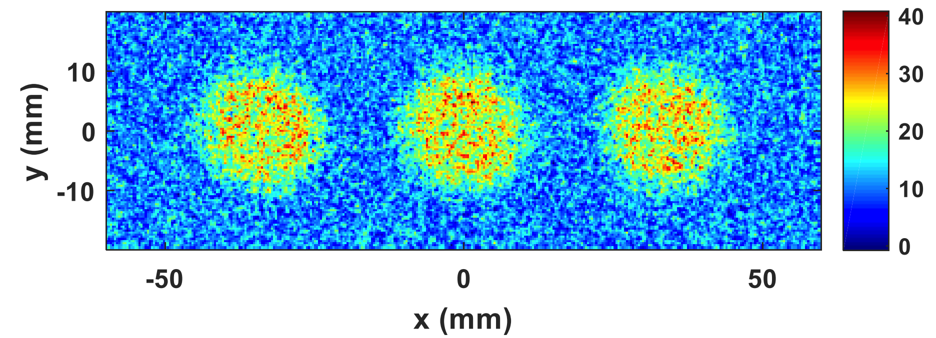


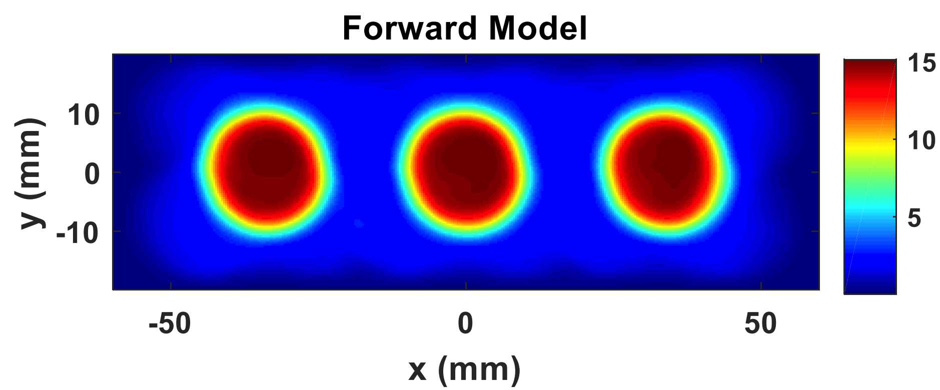
Simulated images with expected signal for N160602 (0.5% Yn)

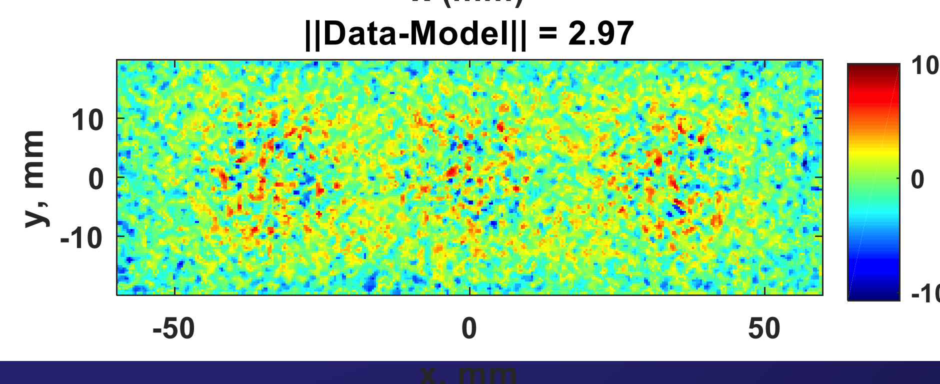
Reconstructed P0 = 55 μm



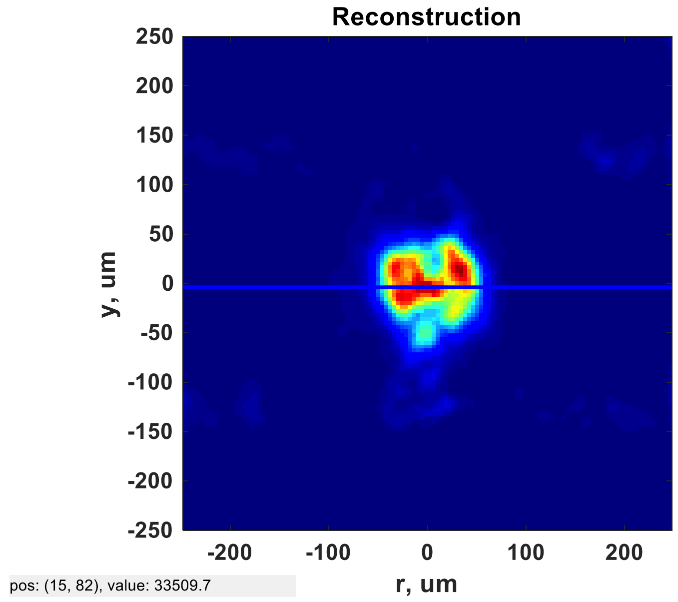


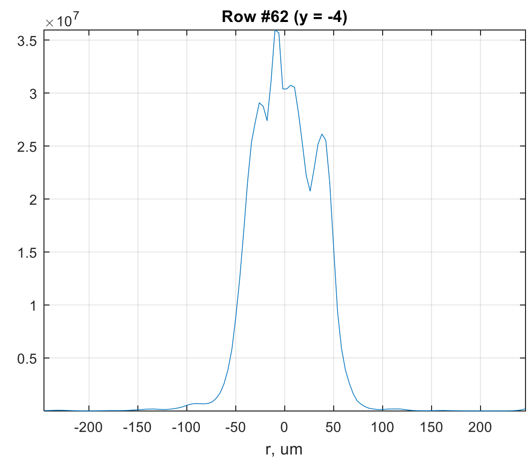


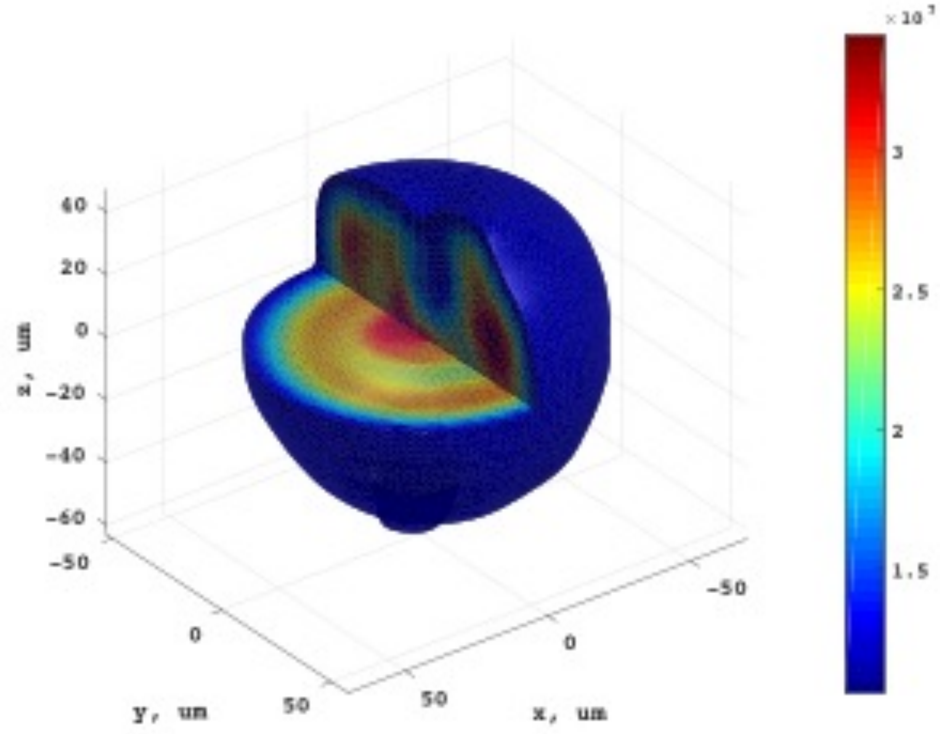




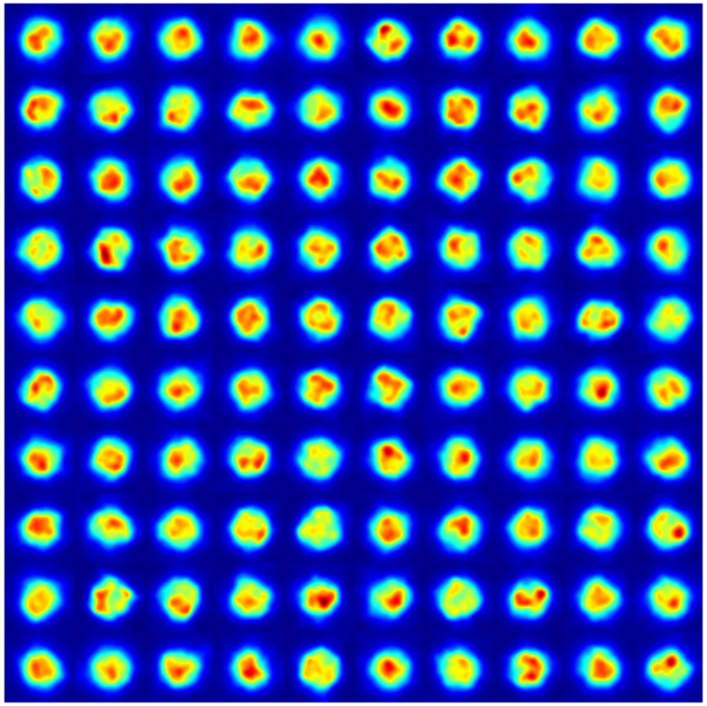
Abel inversion

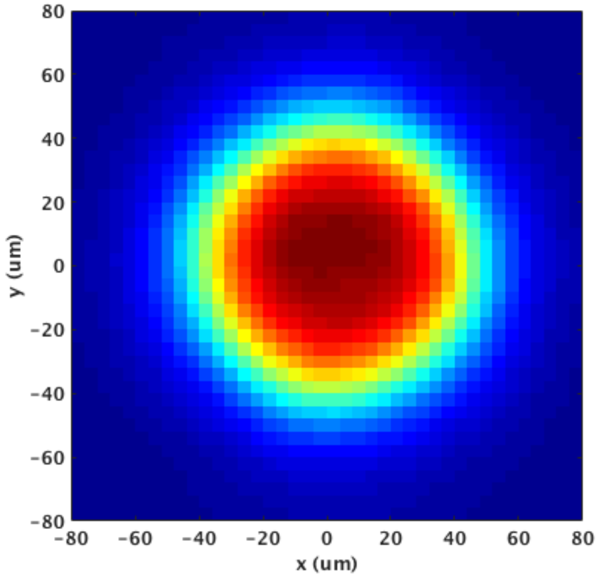


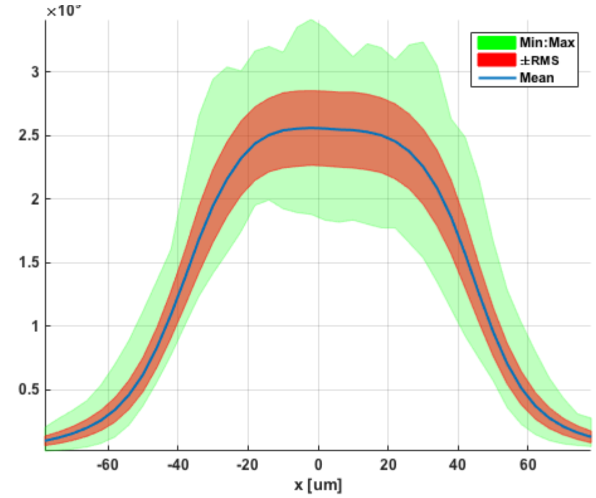




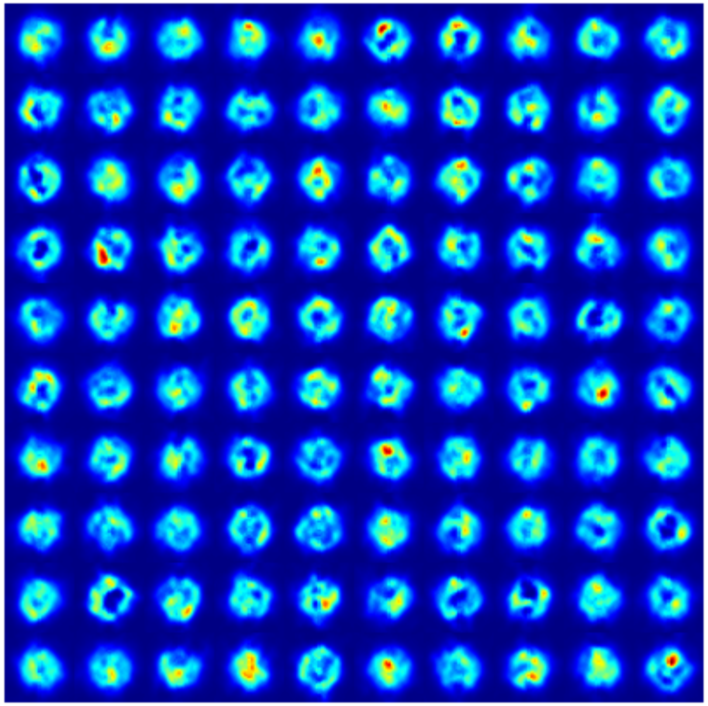
Stat test: Expected gamma statistics

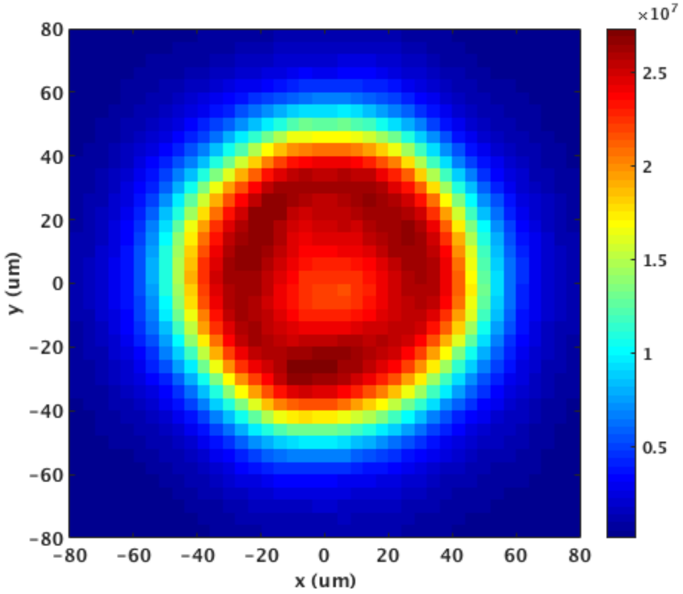


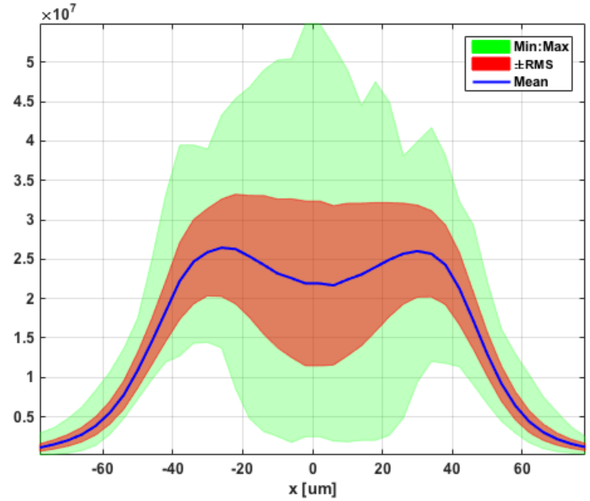




Stat test: Abel inversion

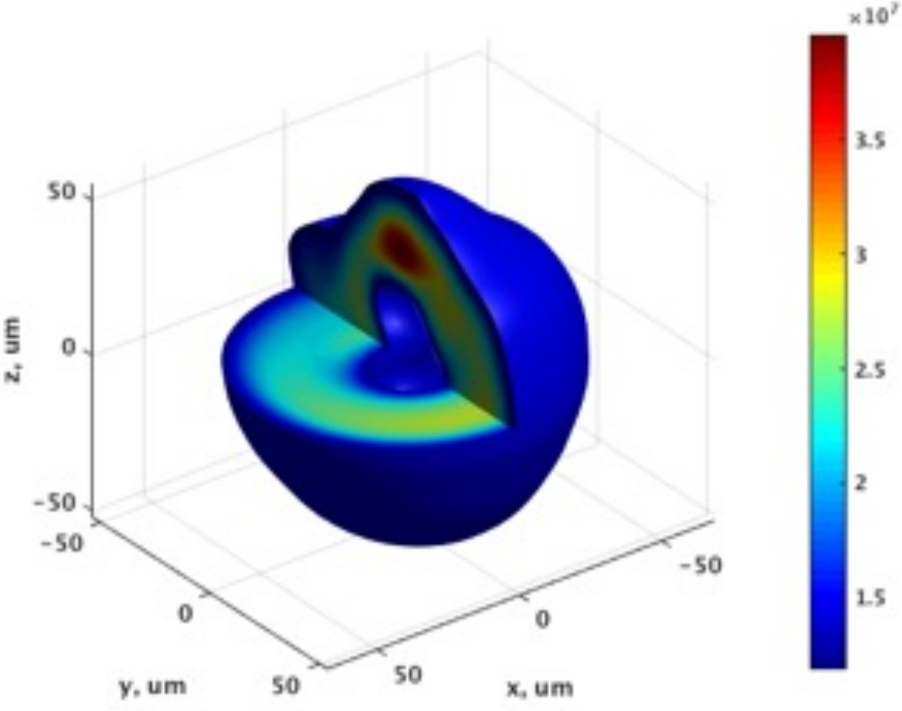




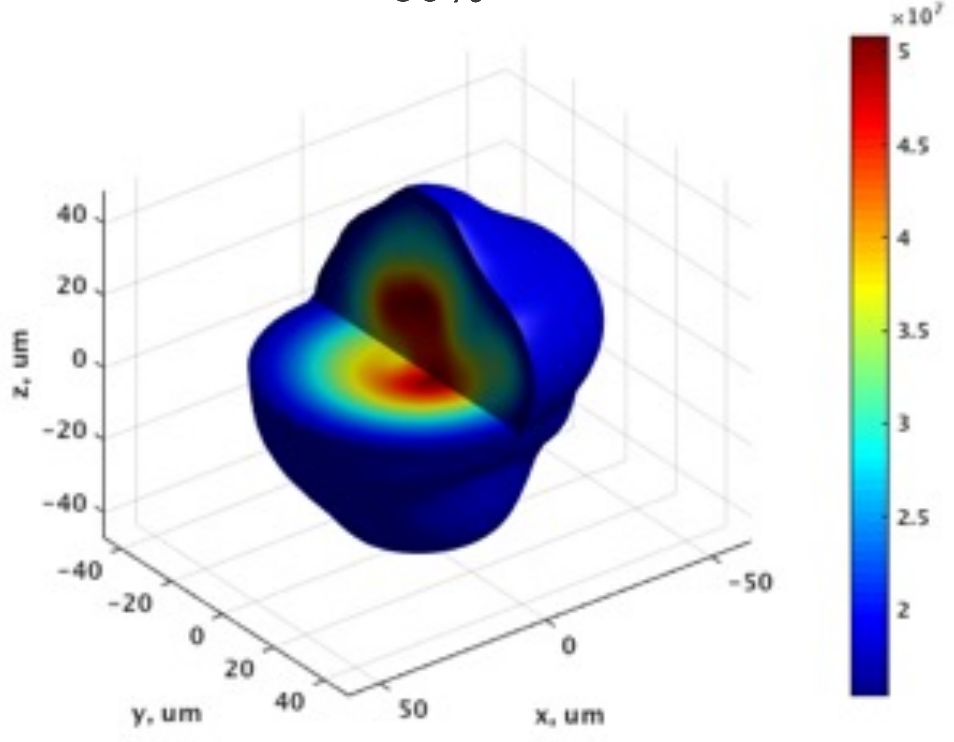


Best and worst case 3 D visualizations for expected gamma SNR

~50%



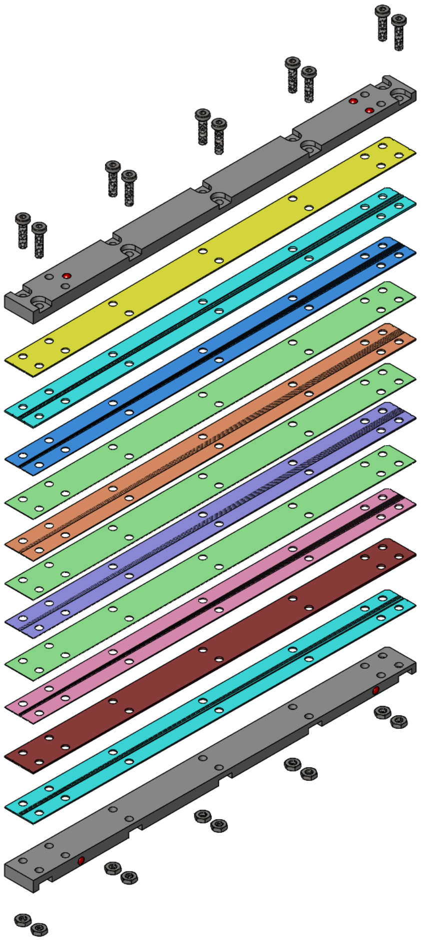
~50%

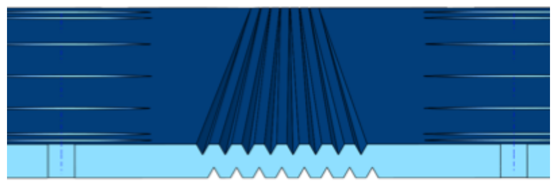


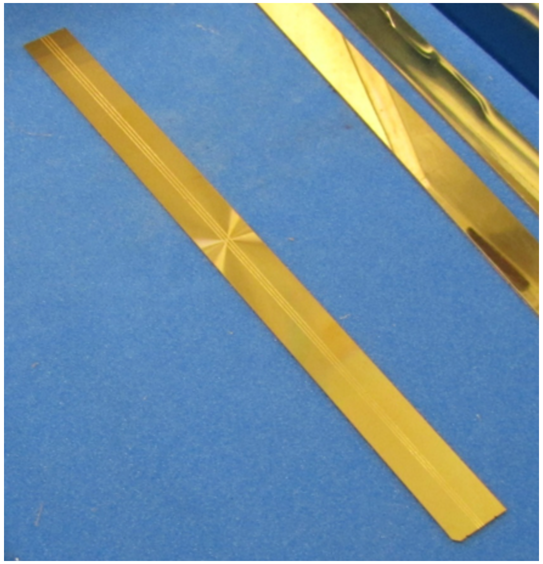
Going forward

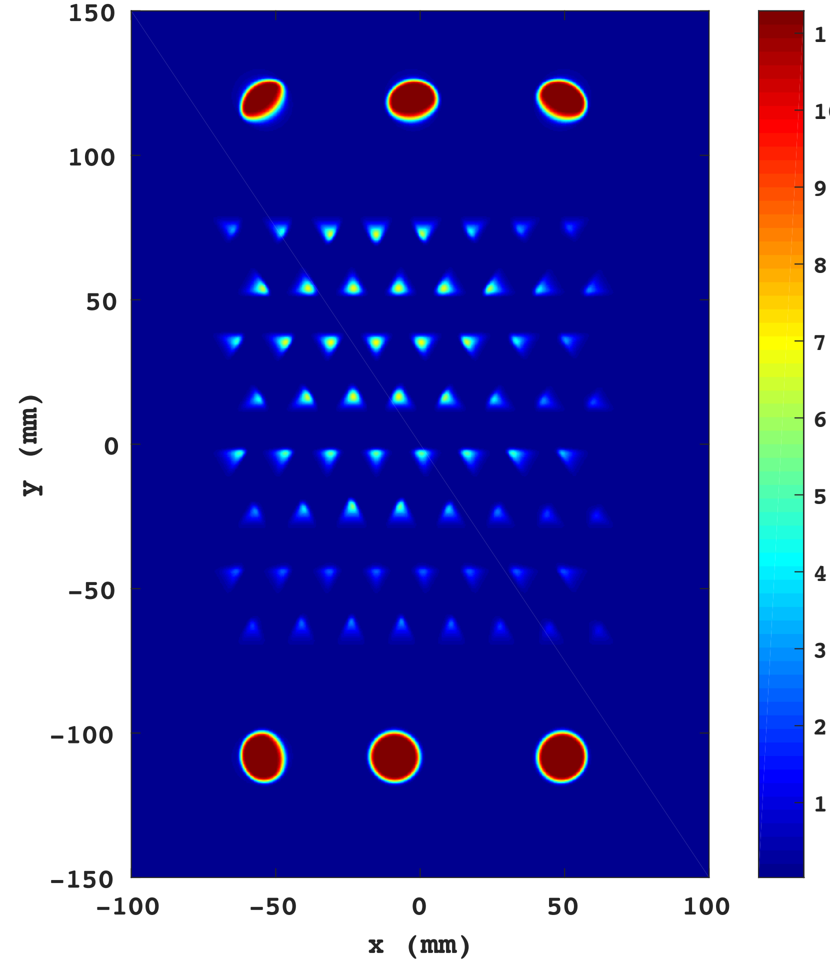
- **Need to identify where the elevated signal levels are coming from**
- **Need to characterize penumbral apertures for gammas**
  - Previous work (N. Guler) showed that reconstructions of the neutron images using the nominal design of the apertures do not agree with pinhole reconstructions
- **New aperture array with more penumbral apertures would increase signal strength and allow better reconstructions**
- **Fabricate a new detector (LYSO based) to increase quantum efficiency**

New aperture array









Thank you! Questions?

Our Latest Publications:

Neutron Imaging System:	Merrill, et al. Rev. Sci. Instrum. 83, 10D317 (2012)
Reconstruction Algorithm:	Volegov, et al. Rev. Sci. Instrum. 85, 023508 (2014)
Array Characterization:	Volegov, et al. Rev. Sci. Instrum. 85, 123506 (2014)
NXI at Omega:	Danly, et al. Rev. Sci. Instrum. 86, 043503 (2015)
NIF CNXI concept:	Merrill, et al. Rev. Sci. Instrum. 85, 11E614 (2014)
NIF CNXI detector pack:	Simpson, et al. Rev. Sci Instrum. 86, 125112 (2015)
Coregistration technique:	Danly, et al. Rev. Sci. Instrum 83, 10E522 (2012)
3D reconstruction:	Volegov, et al. J. Appl. Phys. 118, 205903 (2015)
Density reconstruction:	Forthcoming
3D Spherical Harmonics:	Forthcoming
Gamma images reconstruction:	Forthcoming