

# 3-D electron temperature and X-ray emission tomography of the ICF hotspot at the National Ignition Facility

APS DPP annual meeting 2020 poster session

November 13th, 2020

Ka Wai (Karry) Wong  
Benjamin Bachmann

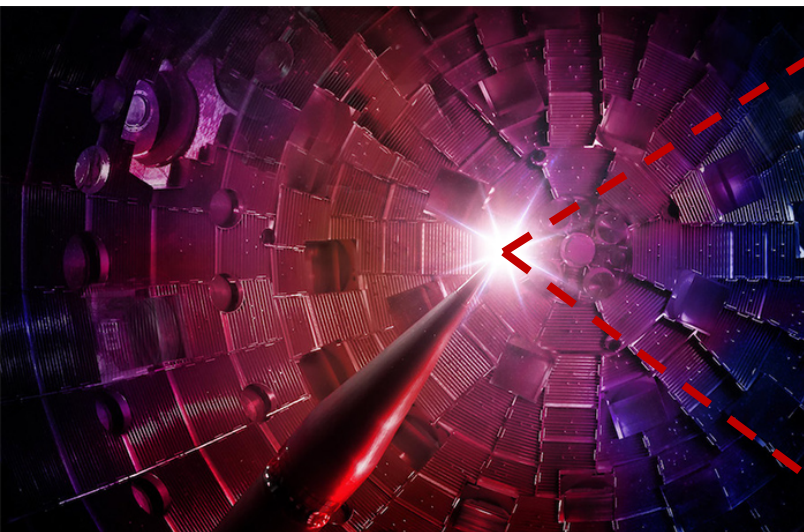


# Measuring 3D electron temperature of the ICF hotspot is feasible

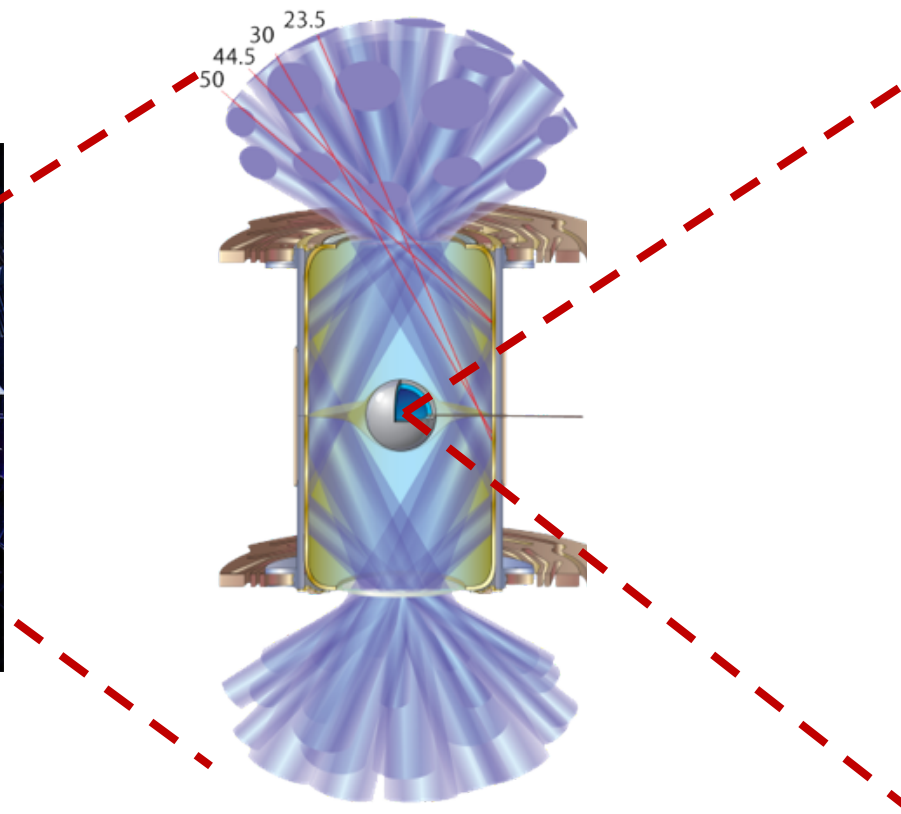
We have

- tested iterative algebraic method ART to reconstruct 3D X-ray emission distributions of the ICF hotspot.
- obtained 3D X-ray reconstructions with two or three LOS and made 3D electron temperature  $T_e$  measurement in the ICF hotspot using synthetic and experimental data
- laid out a future path on how to perform 3D  $T_e$  measurement on the NIF.

# 3D hotspot electron temperature $T_e$ measurements can help to further our understanding of the ICF stagnation physics

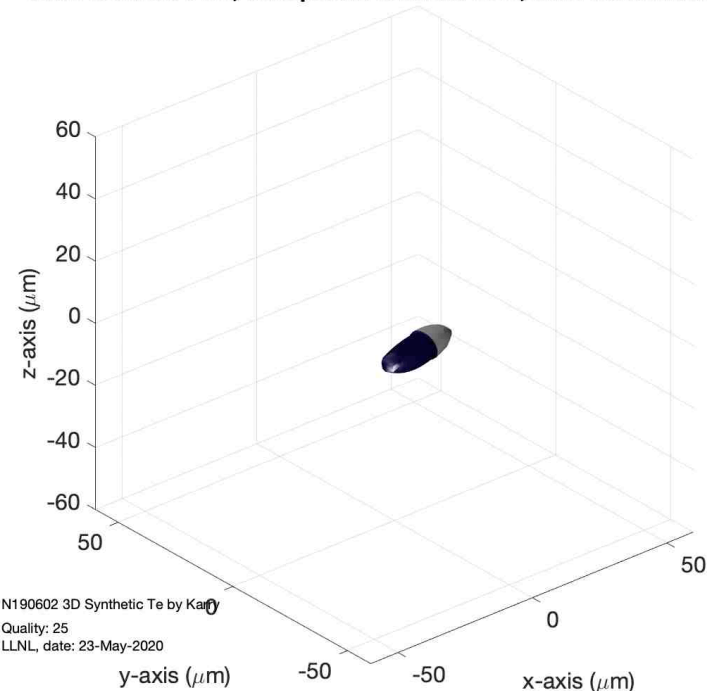


NIF target chamber



Hohlraum

3D Te model, 2  $\mu\text{m}$  resolution,  
outer contour: 94%, transparent contour: 50%, inner contour: 95%

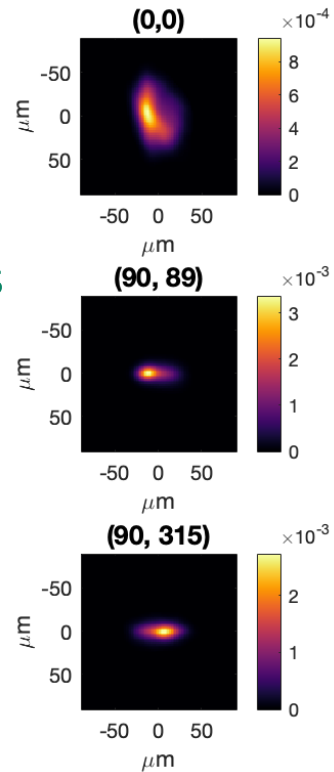


N190602 3D Synthetic Te by Karly  
Quality: 25  
LLNL, date: 23-May-2020

Hotspot  $T_e$  distribution

# We reconstruct 3D X-ray emission distributions from 2D projections and infer $T_e$ using different X-ray energy channels

Input:  
X-ray images



Our goal is to reconstruct a 3D  $T_e$  distribution of the hotspot plasma using very few 2D X-ray images from different directions.

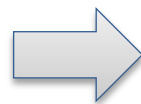
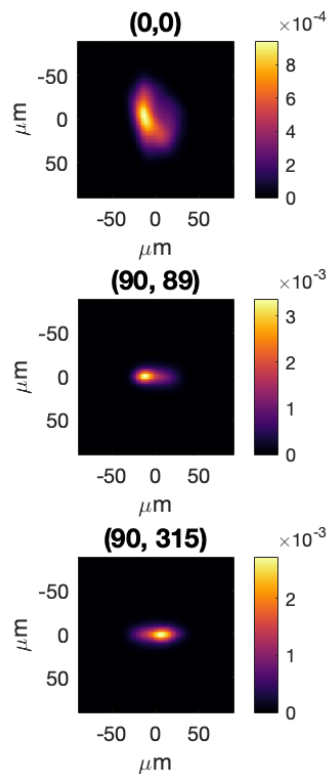
Previous work done on 3-D reconstructions of neutron/x-ray source from 2-D projections. Ref:

1. Volegov et al., Neutron source reconstruction from pinhole imaging at national ignition facility. *Rev. Sci. Instrum.* 2014
2. Volegov et al., On three-dimensional reconstruction of a neutron/x-ray source from very few two-dimensional projections. *J. Appl. Phys.* 2015



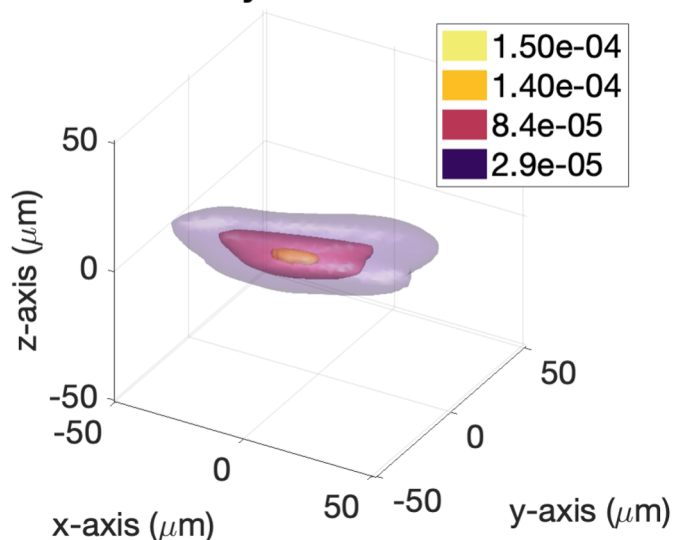
# We reconstruct 3D X-ray emission distributions from 2D projections and infer $T_e$ using different X-ray energy channels

Input:  
X-ray images



## 3D X-ray reconstruction

Max X-ray emission:  $1.5\text{e-}04$ ,  
min X-ray emission:  $1.5\text{e-}07$



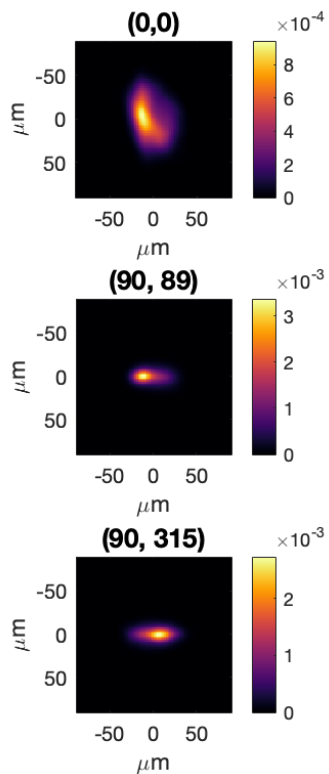
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Previous work done on 3-D reconstructions of neutron/x-ray source from 2-D projections. Ref:

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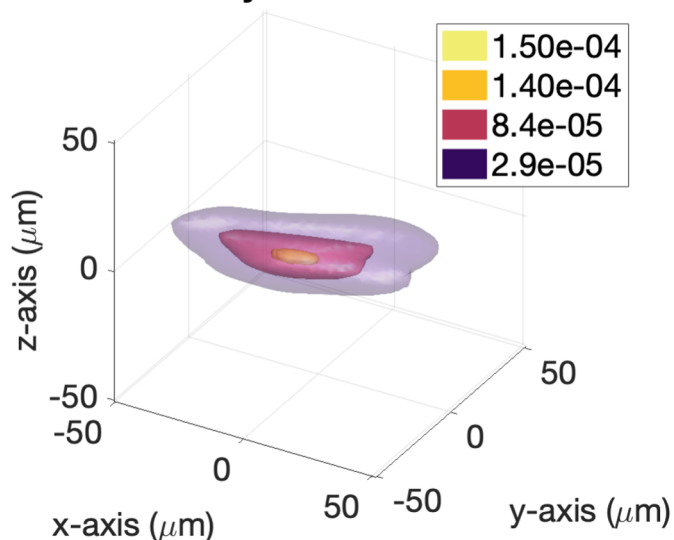
# We reconstruct 3D X-ray emission distributions from 2D projections and infer $T_e$ using different X-ray energy channels

Input:  
X-ray images



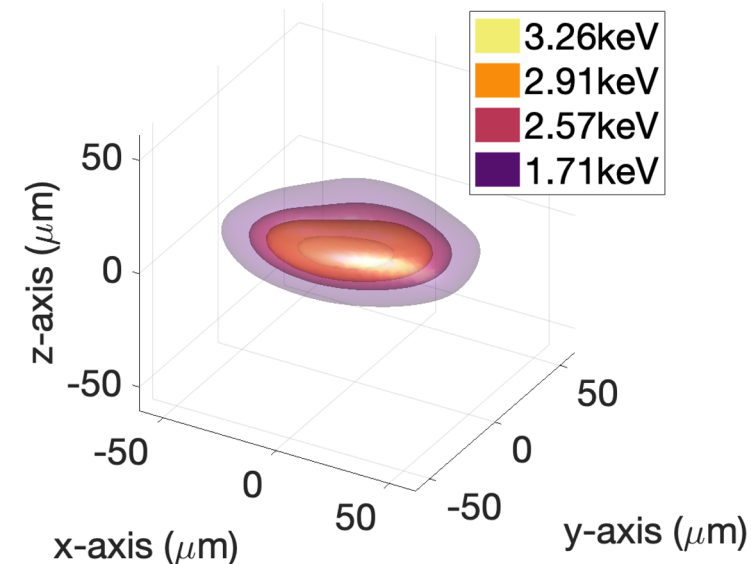
3D X-ray reconstruction

Max X-ray emission:  $1.5\text{e-}04$ ,  
min X-ray emission:  $1.5\text{e-}07$



3D  $T_e$  measurement

Max temperature:  $3.43\text{keV}$ ,

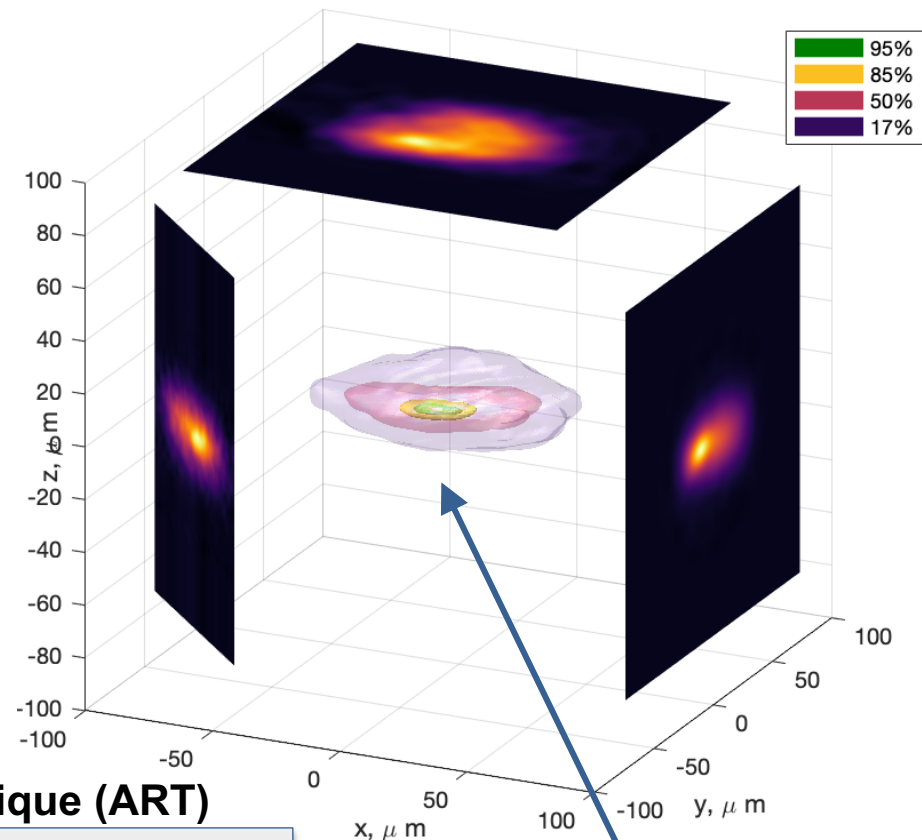
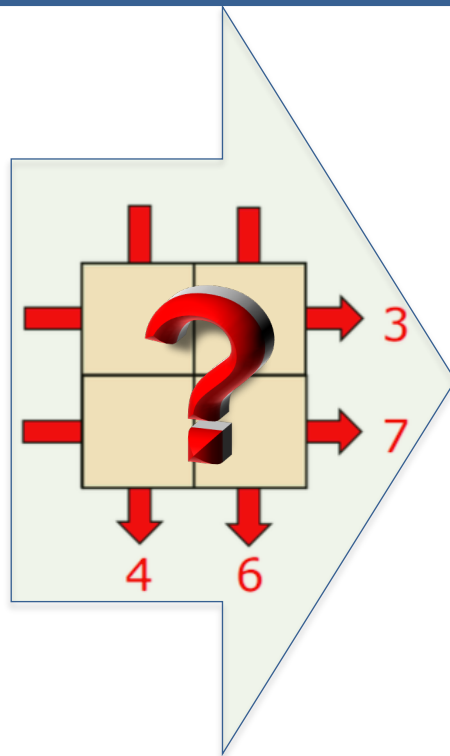
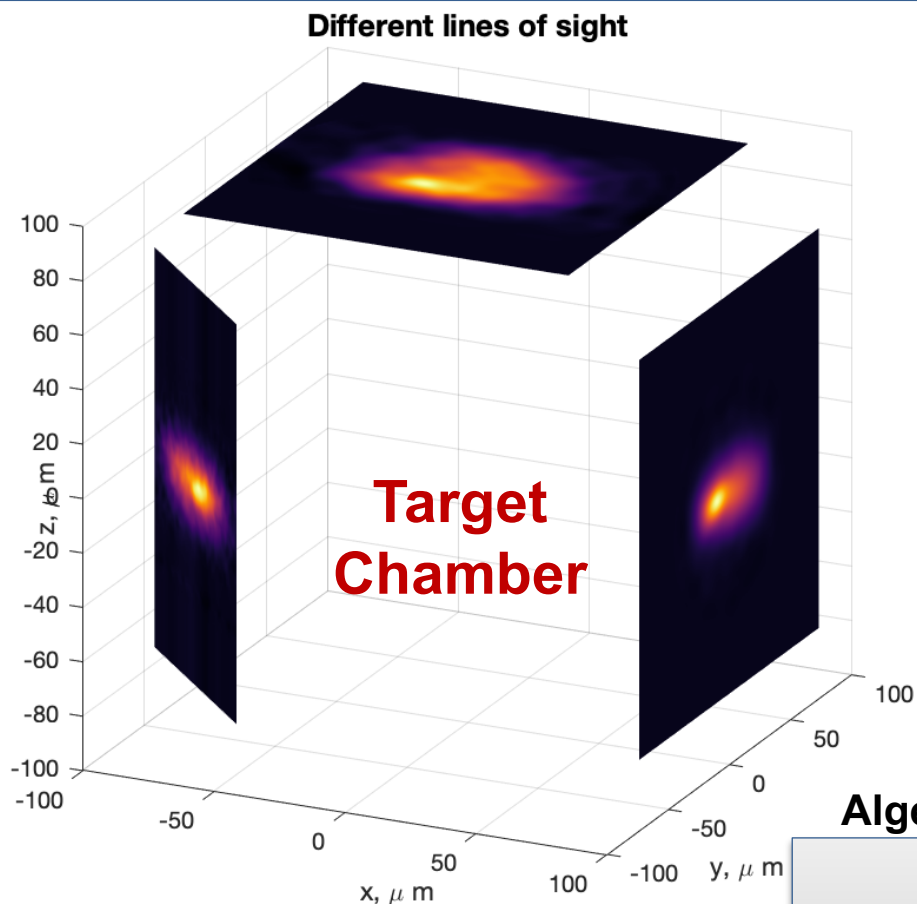


Our goal is to reconstruct a 3D  $T_e$  distribution of the hotspot plasma using very few 2D X-ray images from different directions.

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2. Volegov et al., On three-dimensional reconstruction of a neutron/x-ray source from very few two-dimensional projections. *J. Appl. Phys.* 2015

# Step 1: We reconstruct 3D X-ray emission distribution using very few 2D X-ray projections via ART – like solving a “3D Sudoku” puzzle



## Algebraic Reconstruction Technique (ART)

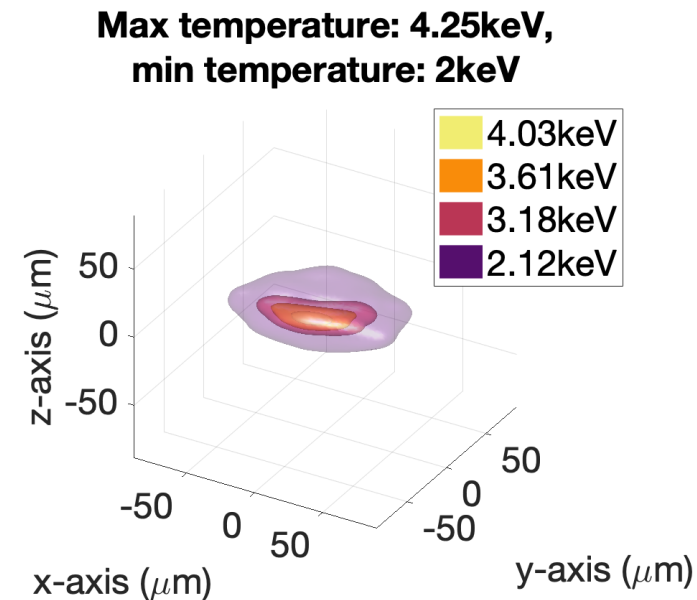
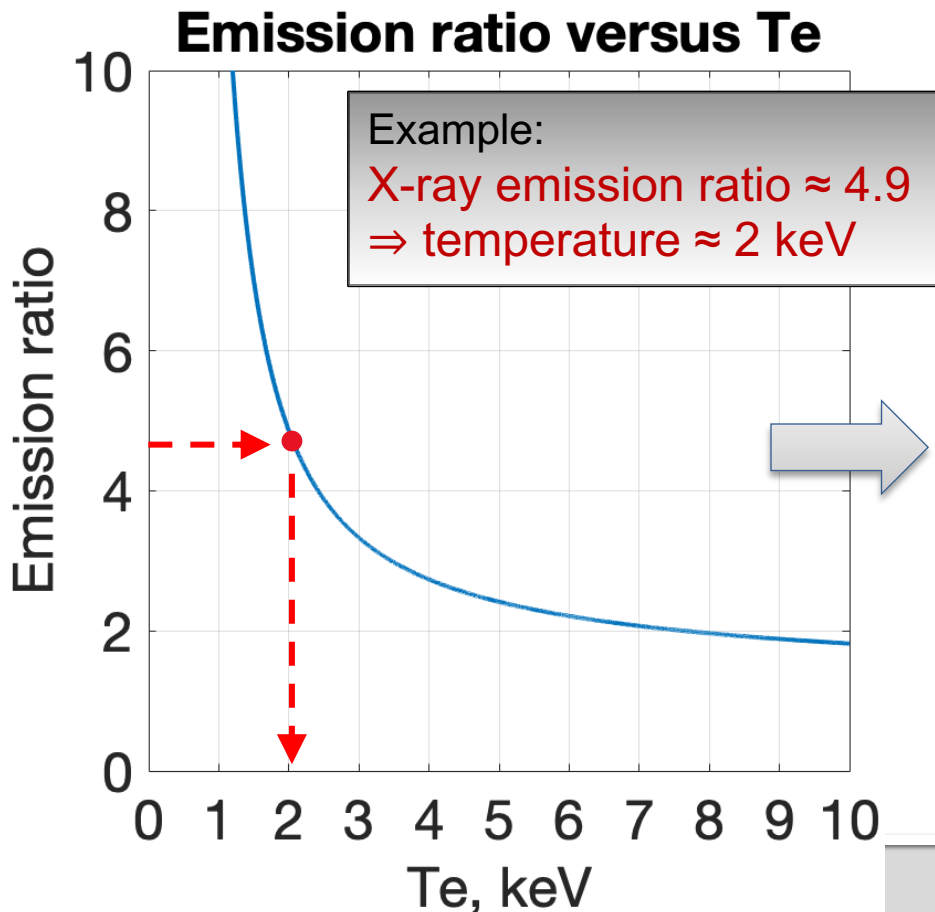
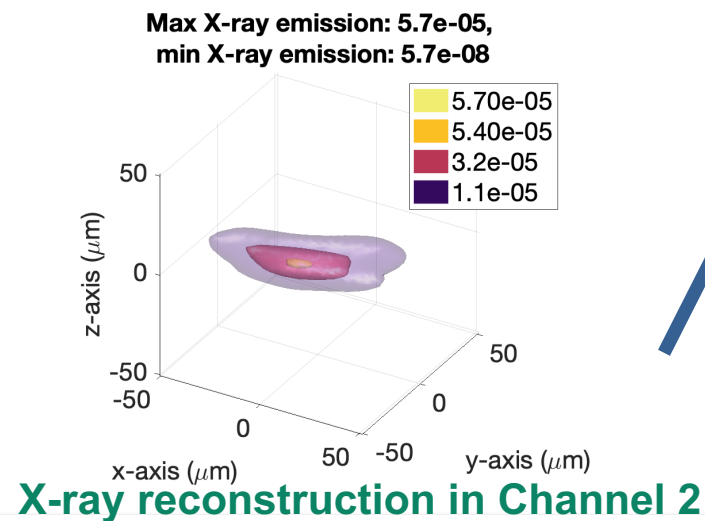
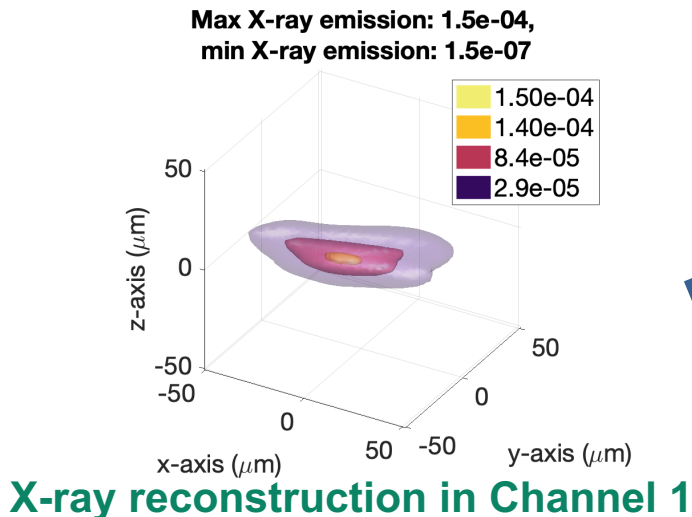
Solve  
 $Ax = b$

$$\begin{pmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix} = \begin{pmatrix} 3 \\ 7 \\ 4 \\ 6 \end{pmatrix}$$

# Step 2: We compute $T_e$ measurement from the ratio of detected X-ray emission values in channels 1 and 2

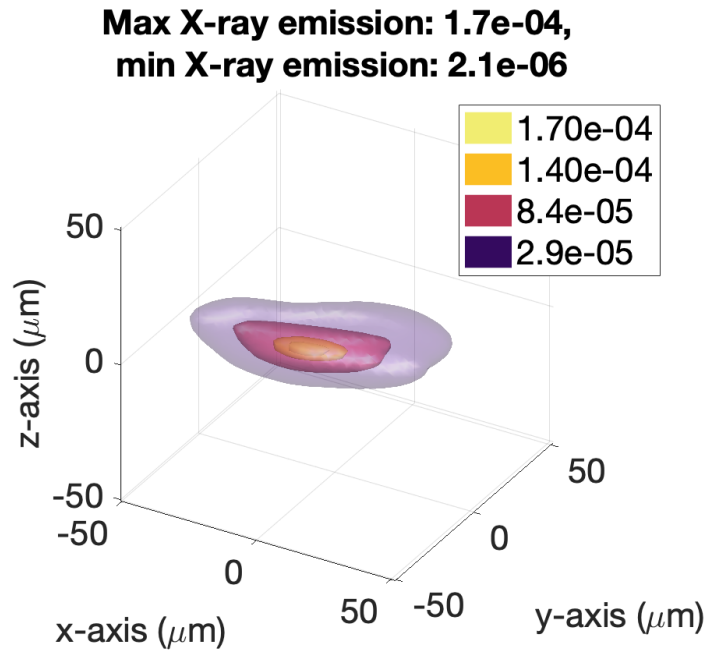
$$f(T_e) = \frac{\tilde{\varepsilon}_1(T_e)}{\tilde{\varepsilon}_2(T_e)} = \frac{\int \varepsilon(h\nu, T_e) \cdot s_1(h\nu) d(h\nu)}{\int \varepsilon(h\nu, T_e) \cdot s_2(h\nu) d(h\nu)},$$

$\tilde{\varepsilon}$  detected x-ray emission  
 $\varepsilon$  x-ray emission  
 $s_i$  system response

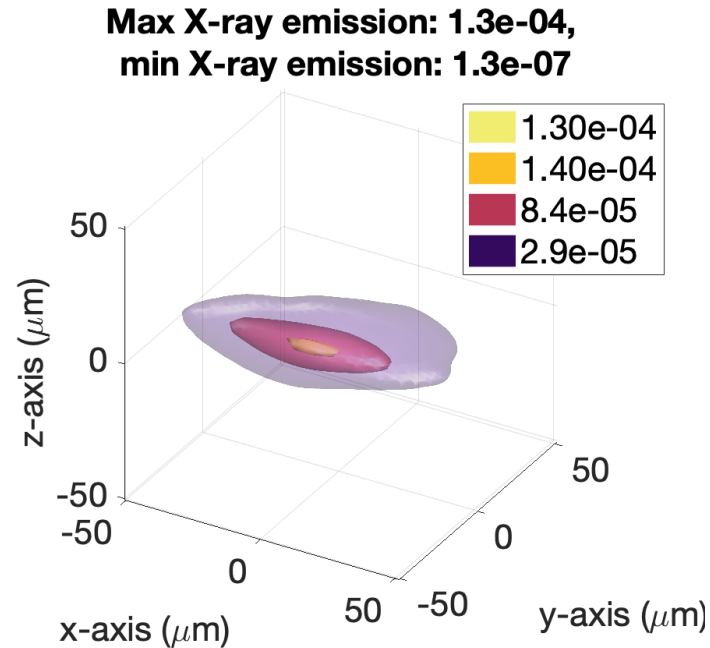




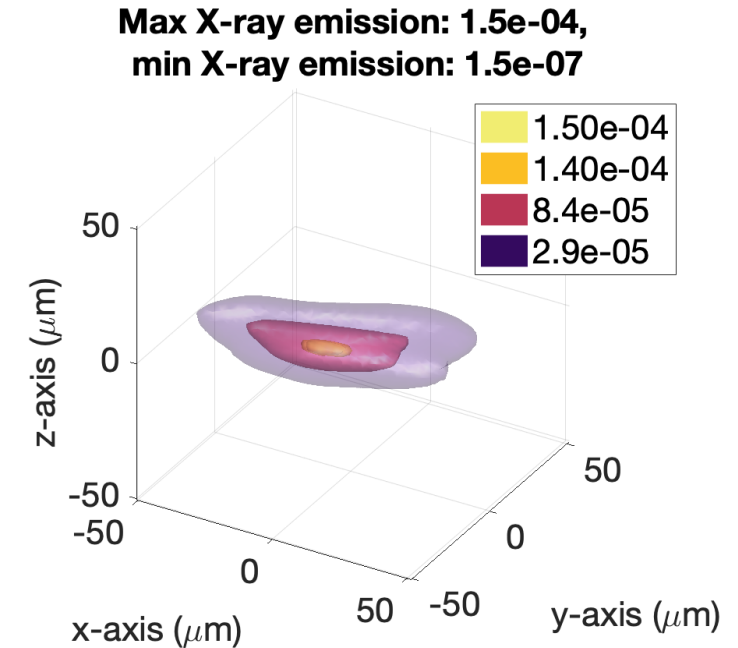
# Synthetic data study: 3D X-ray reconstructions with two versus three LOS



Synthetic data



Reconstruction using 2 LOS

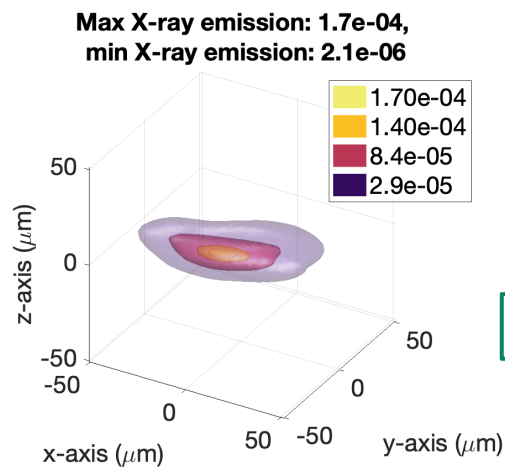


Reconstruction using 3 LOS

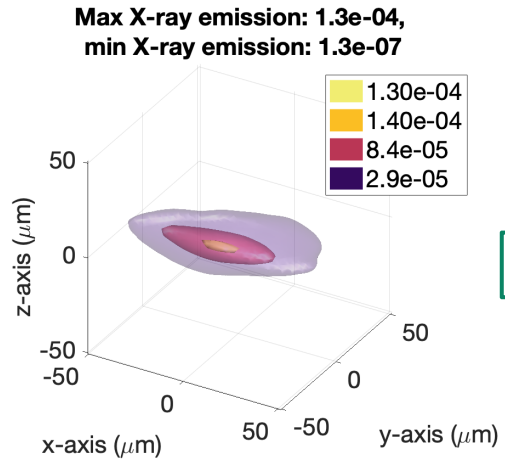
Contour percentages from innermost to outermost: **95%, 85%, 50%, 17%**

**Reconstruction using three LOS has a more similar shape to the original model**

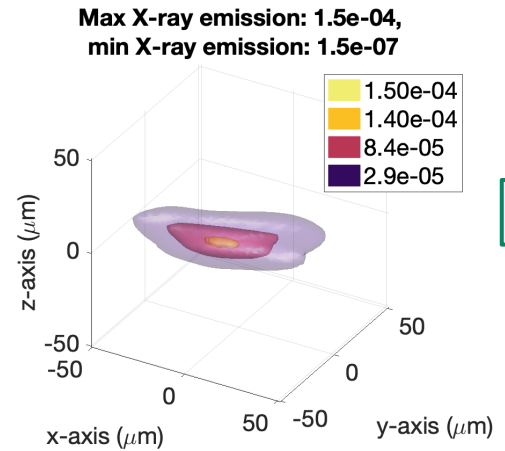
# X-ray reconstructions using 3 LOS agree better with synthetic models than using 2 LOS



model



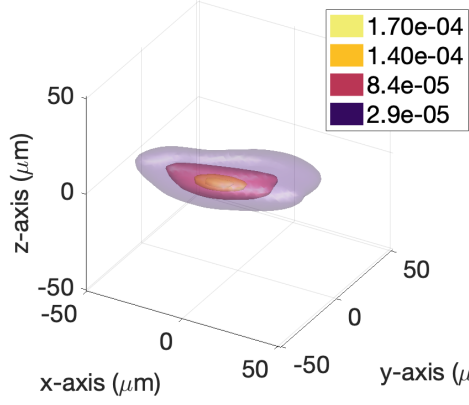
2LOS



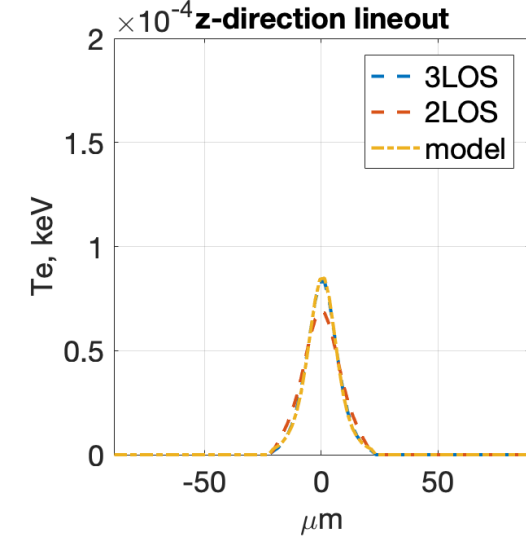
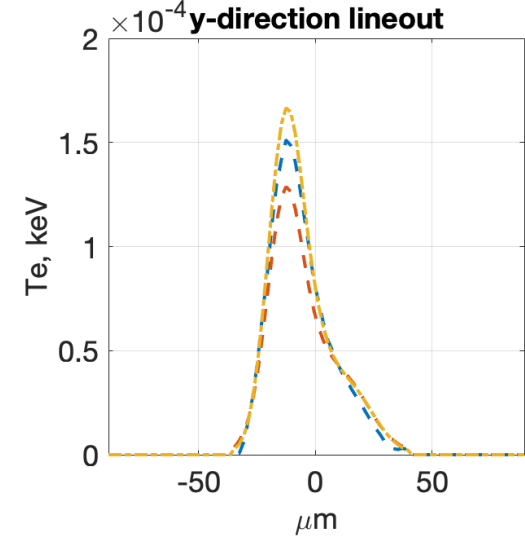
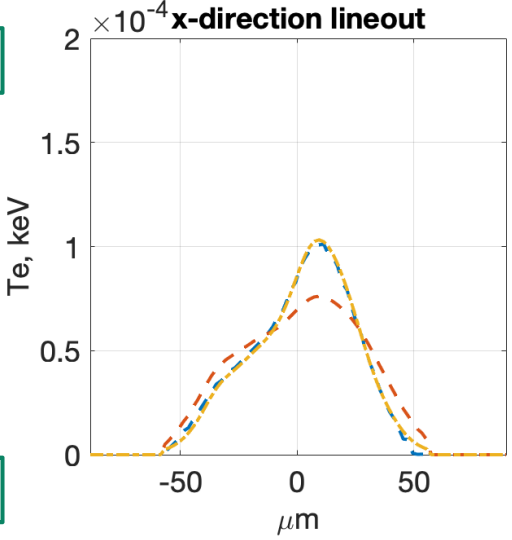
3LOS

# X-ray reconstructions using 3 LOS agree better with synthetic models than using 2 LOS

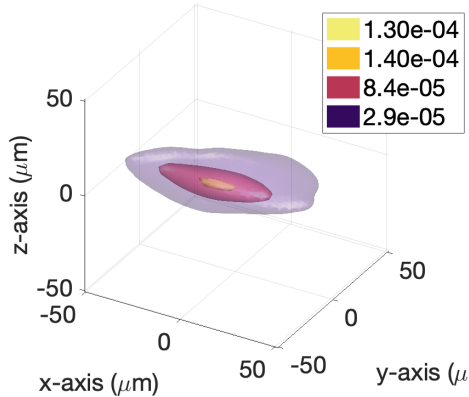
Max X-ray emission:  $1.70 \times 10^{-4}$ ,  
min X-ray emission:  $2.1 \times 10^{-6}$



model

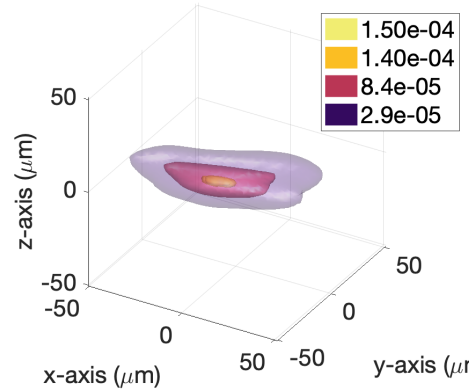


Max X-ray emission:  $1.3 \times 10^{-4}$ ,  
min X-ray emission:  $1.3 \times 10^{-7}$



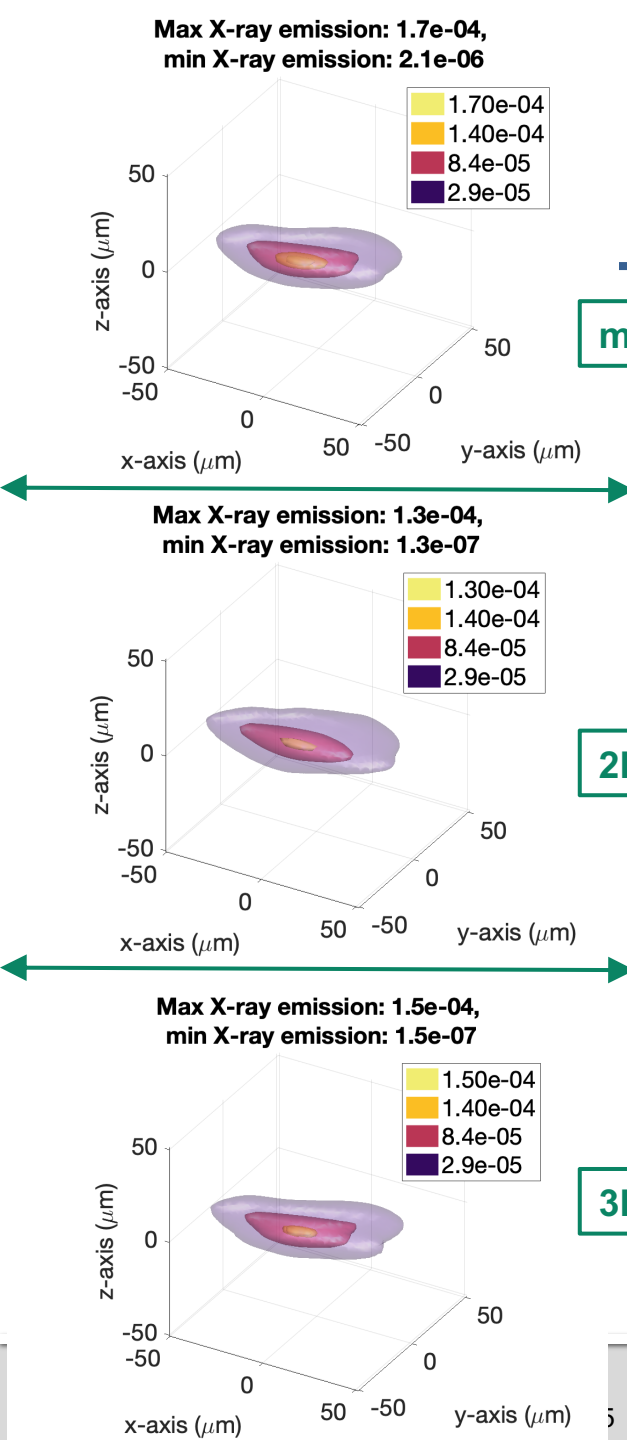
2LOS

Max X-ray emission:  $1.5 \times 10^{-4}$ ,  
min X-ray emission:  $1.5 \times 10^{-7}$



3LOS

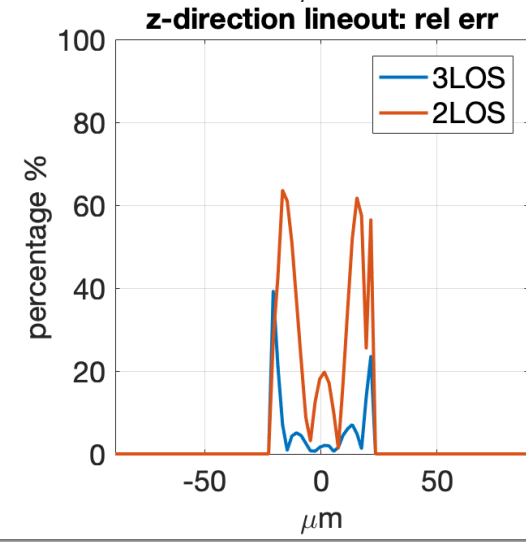
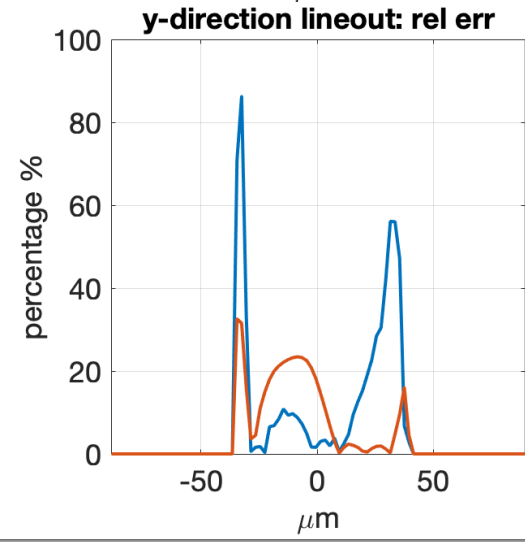
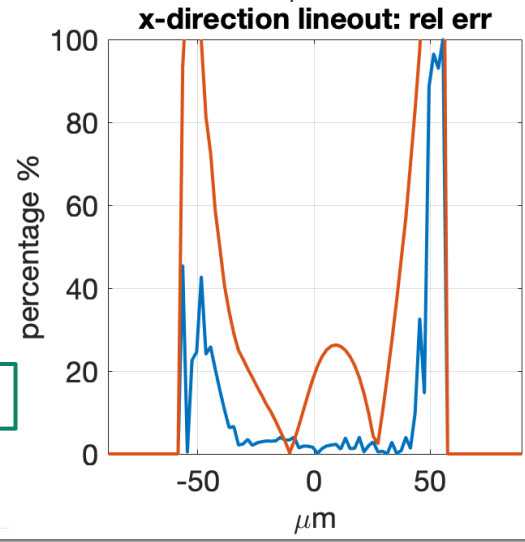
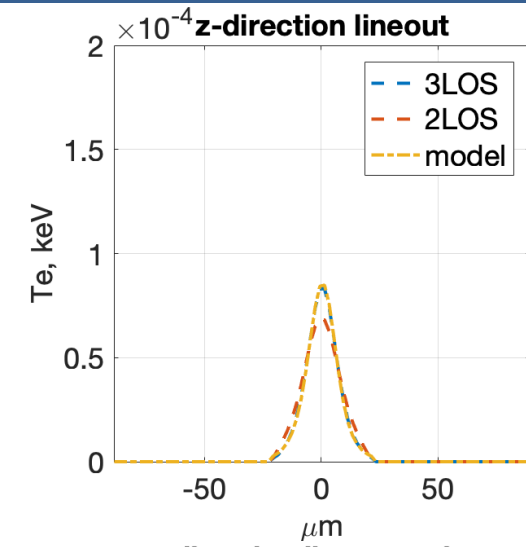
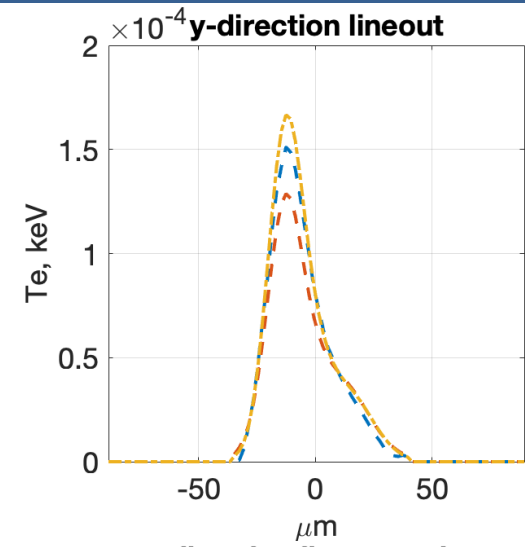
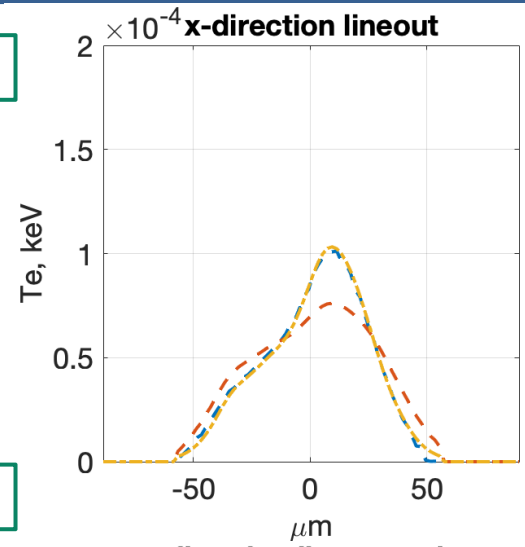
# X-ray reconstructions using 3 LOS agree better with synthetic models than using 2 LOS



**model**

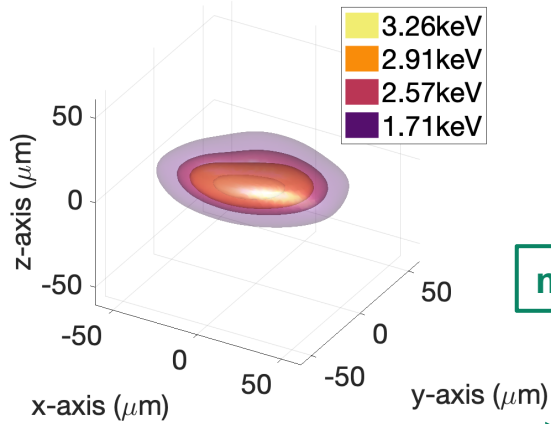
**2LOS**

**3LOS**



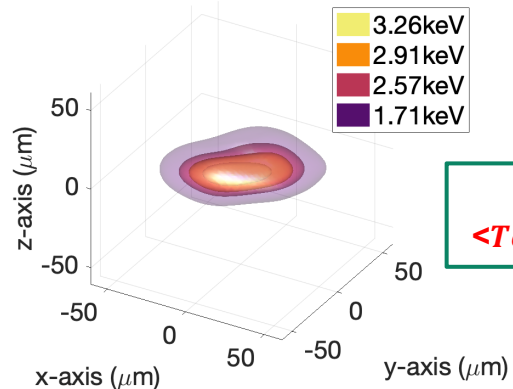
# Relative $T_e$ errors improve to below $\sim 10\%$ by fielding a third LOS

Max temperature: 3.43keV,



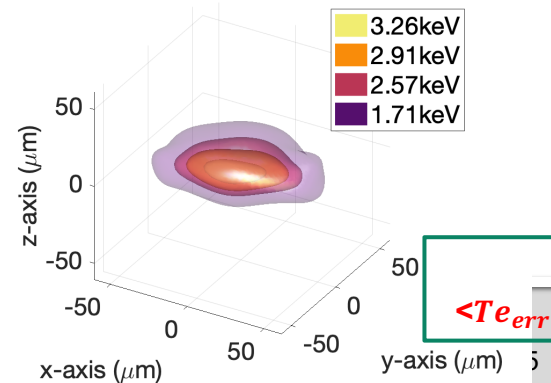
model

Reconstructed model -  $\langle T_e \text{ error} \rangle = 0.26\text{keV}$ ,  
max temperature: 3.52keV



2LOS  
 $\langle T_e \text{ err} \rangle = 0.26\text{keV}$

Reconstructed model -  $\langle T_e \text{ error} \rangle = 0.094\text{keV}$ ,  
max temperature: 3.46keV



3LOS  
 $\langle T_e \text{ err} \rangle = 0.094\text{keV}$

Max temperature: 3.43keV,

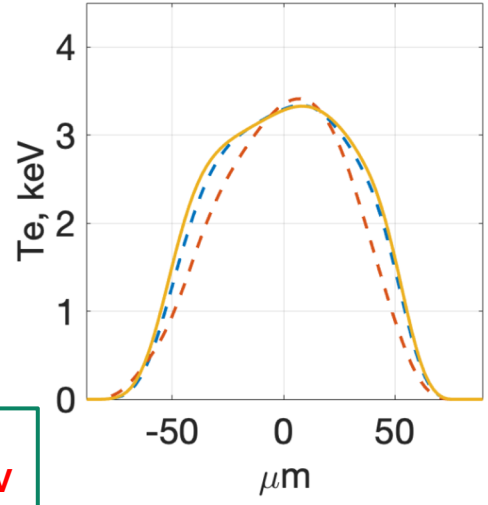
# Relative $T_e$ errors improve to below $\sim 10\%$ by fielding a third LOS



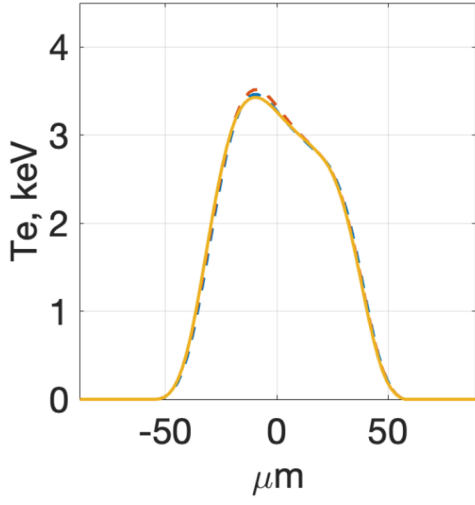
**model**

Reconstructed model -  $\langle T_e \text{ error} \rangle = 0.26\text{keV}$ ,  
max temperature: 3.52keV

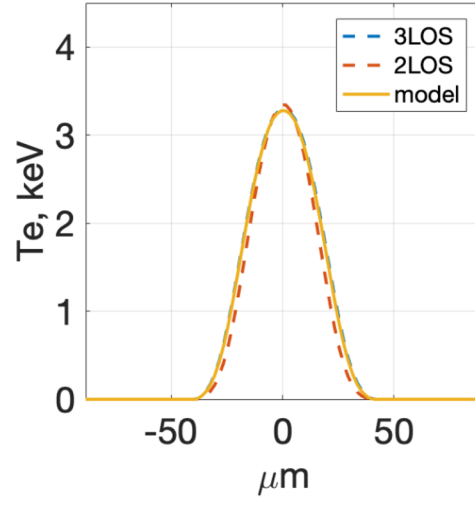
**x-direction lineout**



**y-direction lineout**

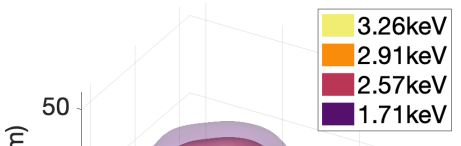


**z-direction lineout**



**2LOS**  
 $\langle T_e \text{ error} \rangle = 0.26\text{keV}$

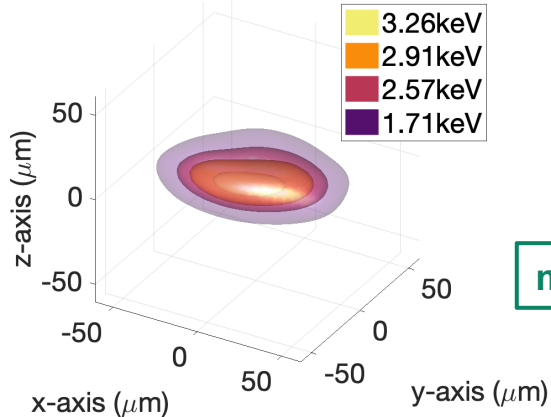
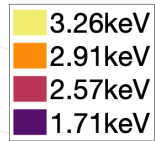
Reconstructed model -  $\langle T_e \text{ error} \rangle = 0.094\text{keV}$ ,  
max temperature: 3.46keV



**3LOS**  
 $\langle T_e \text{ error} \rangle = 0.094\text{keV}$

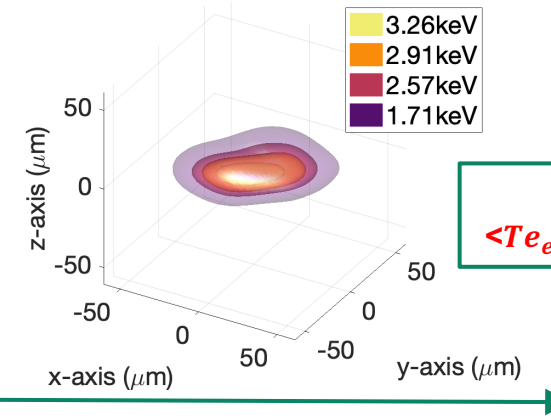
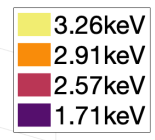
Max temperature: 3.43keV,

# Relative $T_e$ errors improve to below $\sim 10\%$ by fielding a third LOS



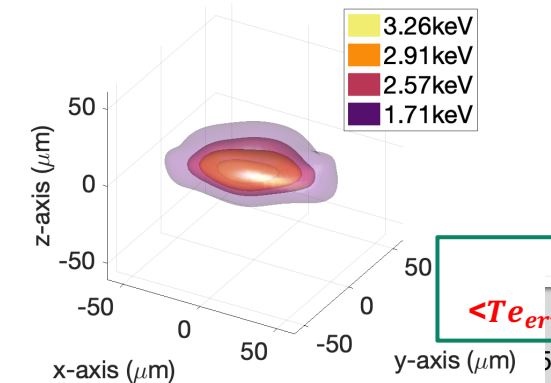
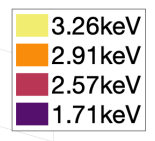
**model**

Reconstructed model -  $\langle T_e \text{ error} \rangle = 0.26\text{keV}$ ,  
max temperature: 3.52keV



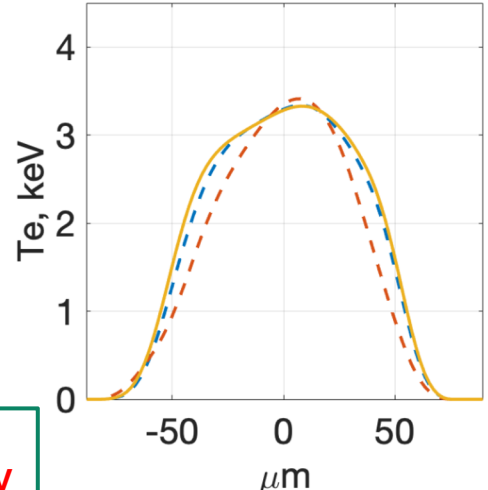
**2LOS**  
 $\langle T_{e \text{ err}} \rangle = 0.26\text{keV}$

Reconstructed model -  $\langle T_e \text{ error} \rangle = 0.094\text{keV}$ ,  
max temperature: 3.46keV

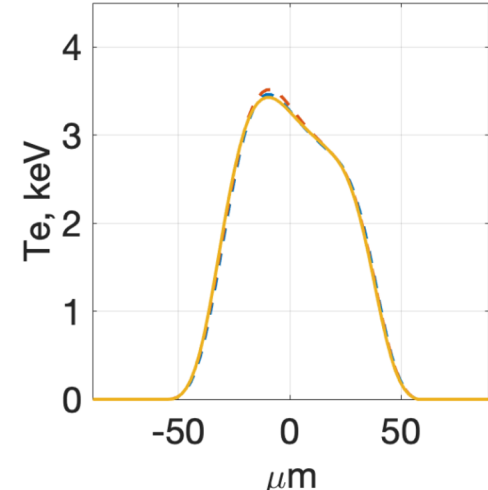


**3LOS**  
 $\langle T_{e \text{ err}} \rangle = 0.094\text{keV}$

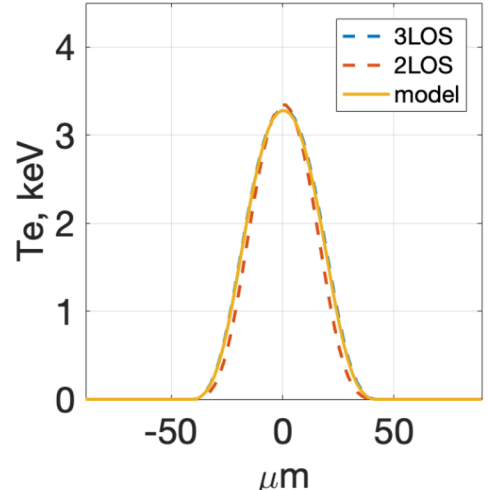
**x-direction lineout**



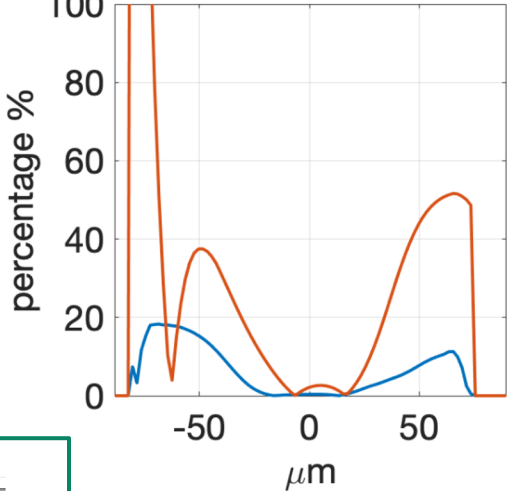
**y-direction lineout**



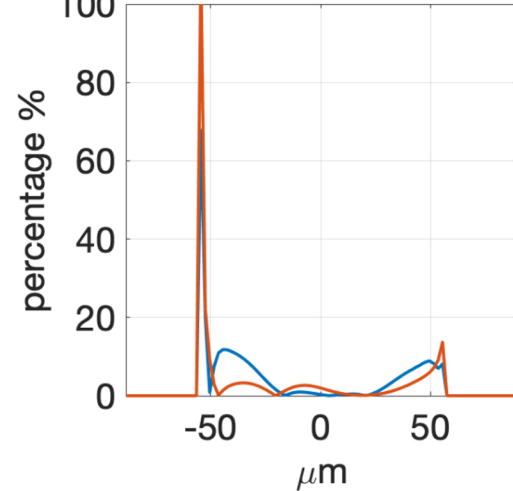
**z-direction lineout**



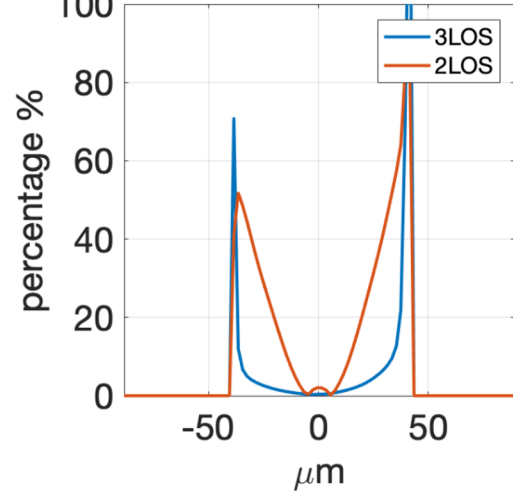
**x-direction lineout: rel err**



**y-direction lineout: rel err**

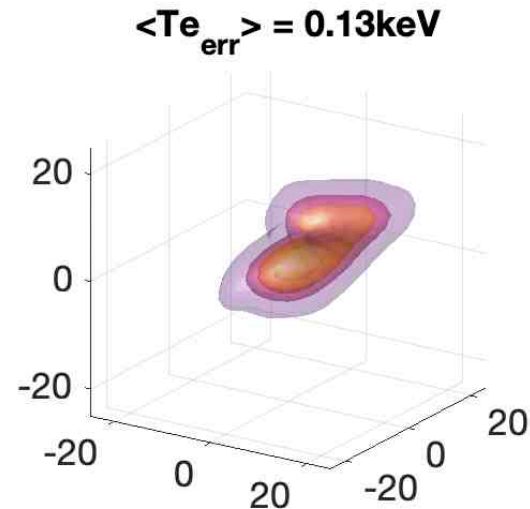
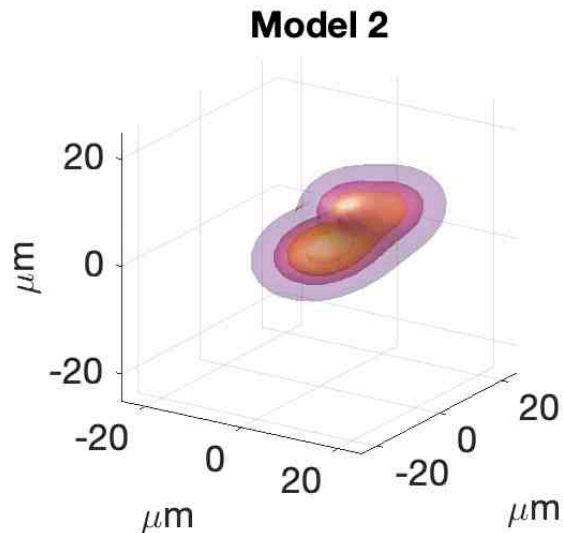
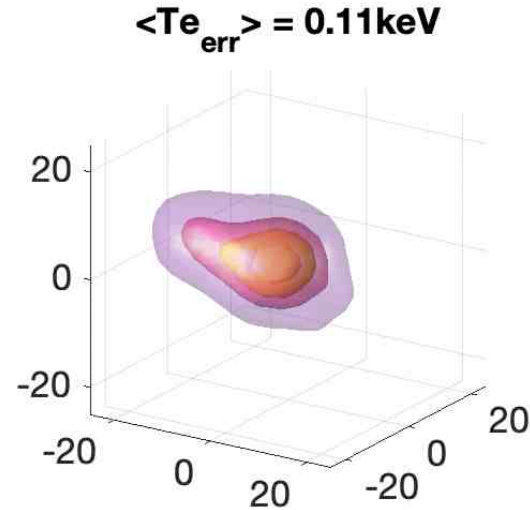
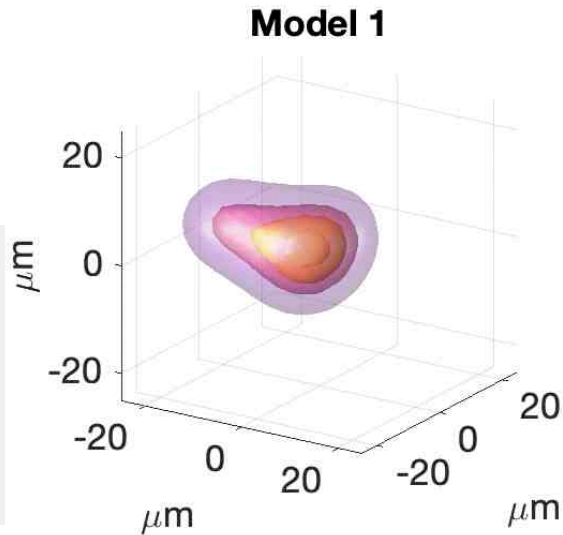


**z-direction lineout: rel err**



# We tested a collection of synthetic $T_e$ models with various shapes

Synthetic model



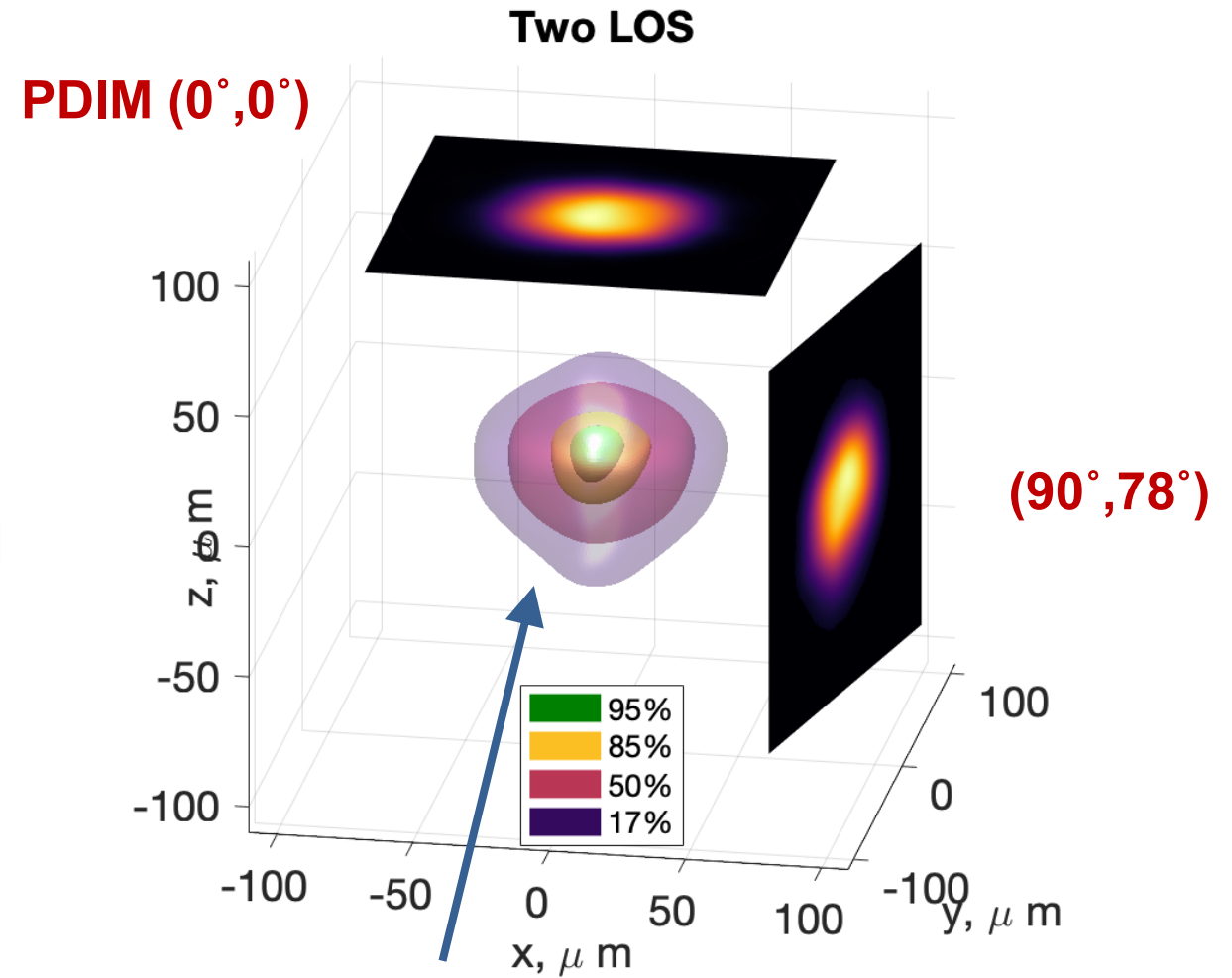
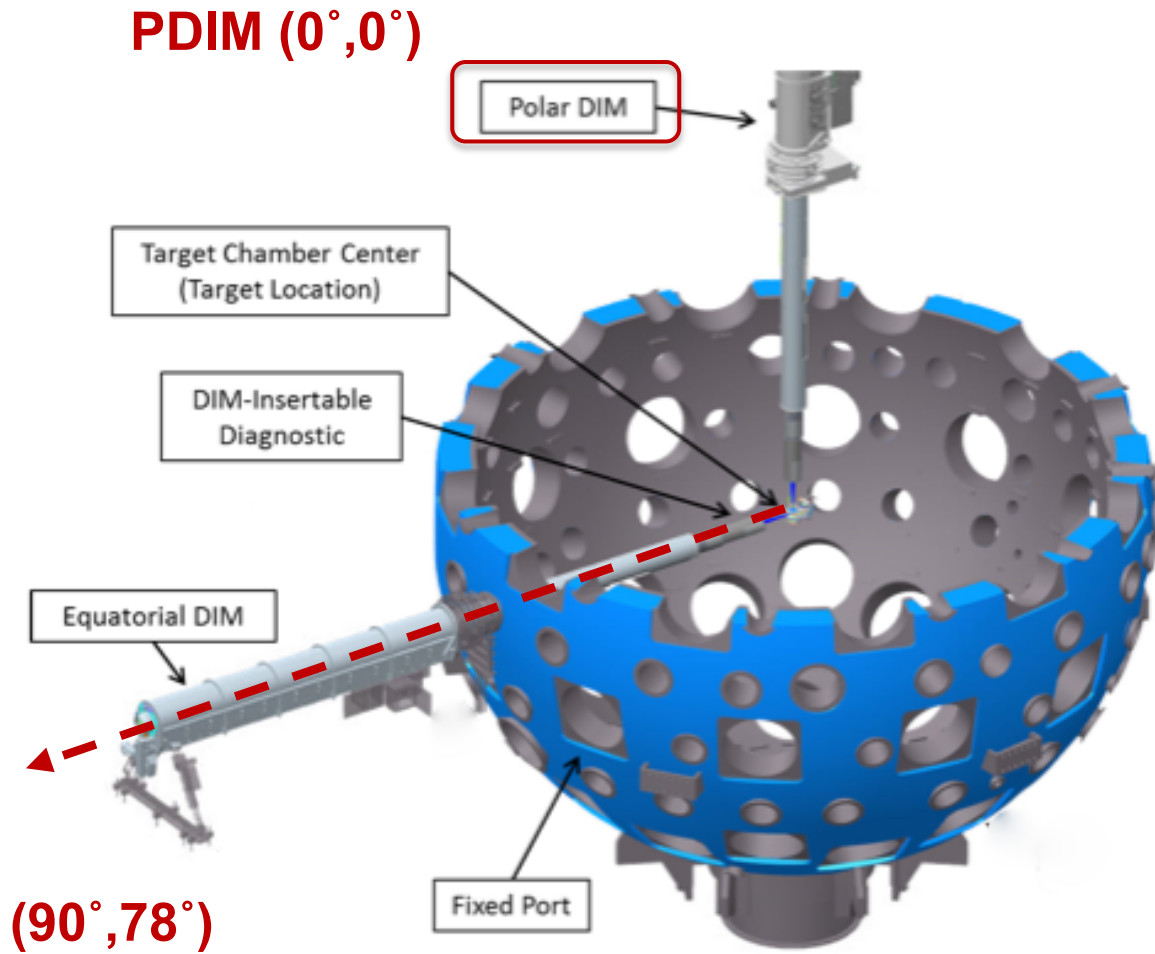
$T_e$  measurements

Contour percentages from innermost to outermost:  
**95%, 85%, 75%, 50%**

$T_e$  measurements using 3 LOS have high accuracy despite complex geometries



# Experimental data study: experimentally fielded diagnostic at two LOS PDIM (0°, 0°) and (90°, 78°)



Reconstructed Hotspot X-ray emission

# N181007: Noise causes discrepancy in the common integrated profile (CIP) between PDIM and (90°, 78°)

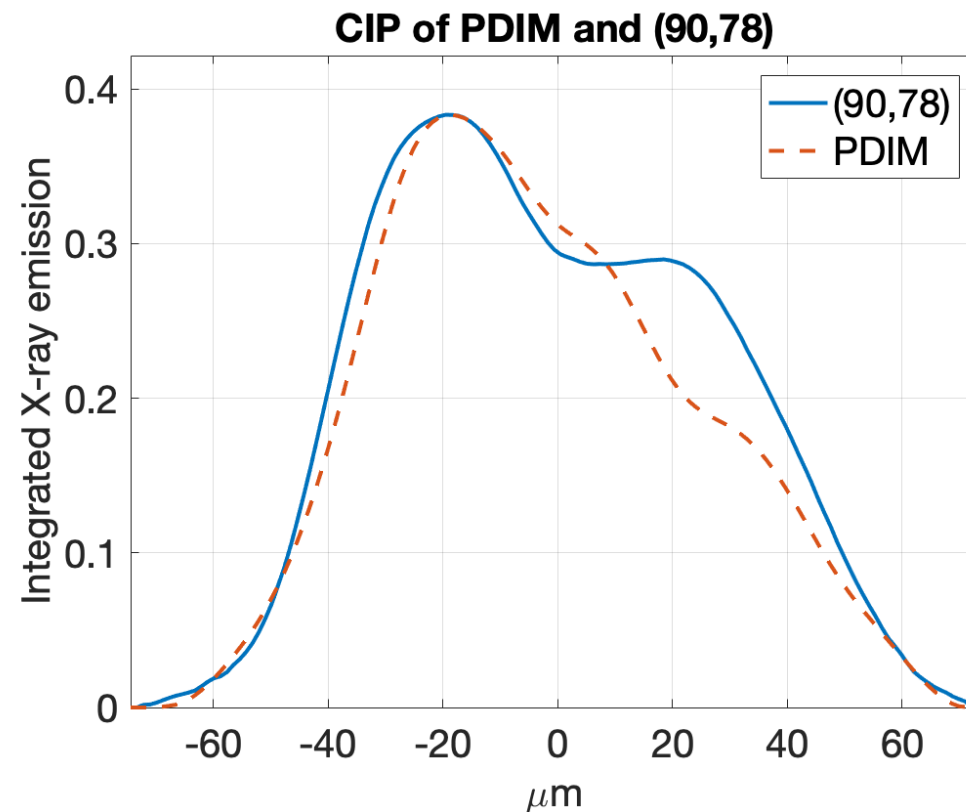
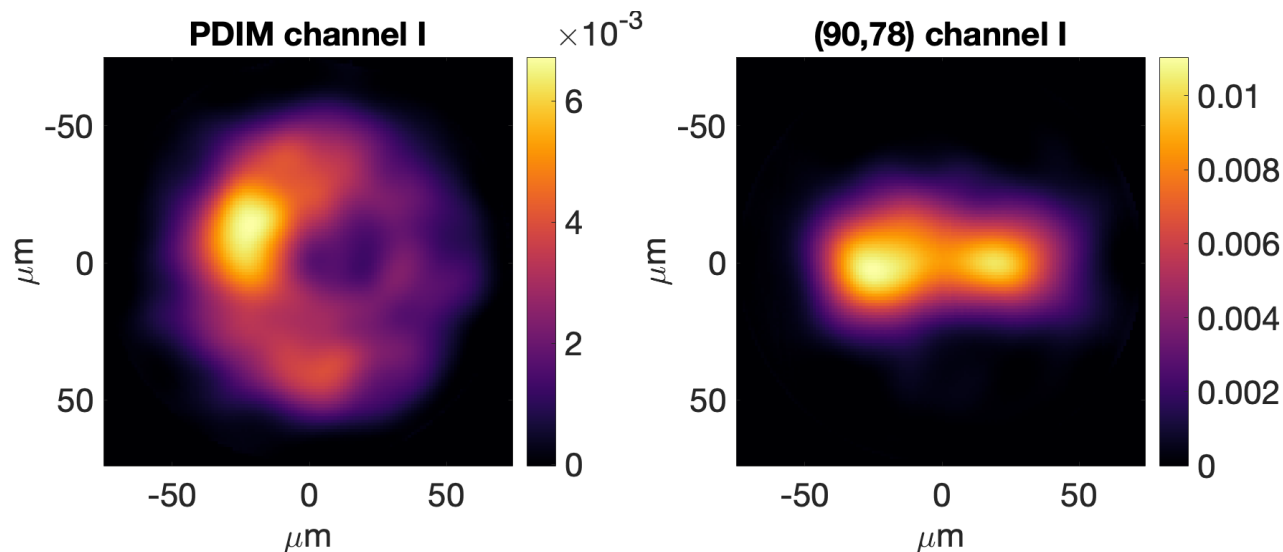
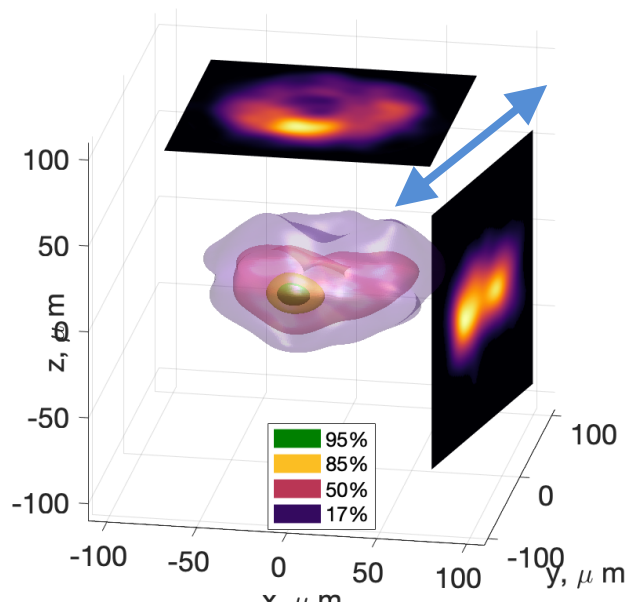
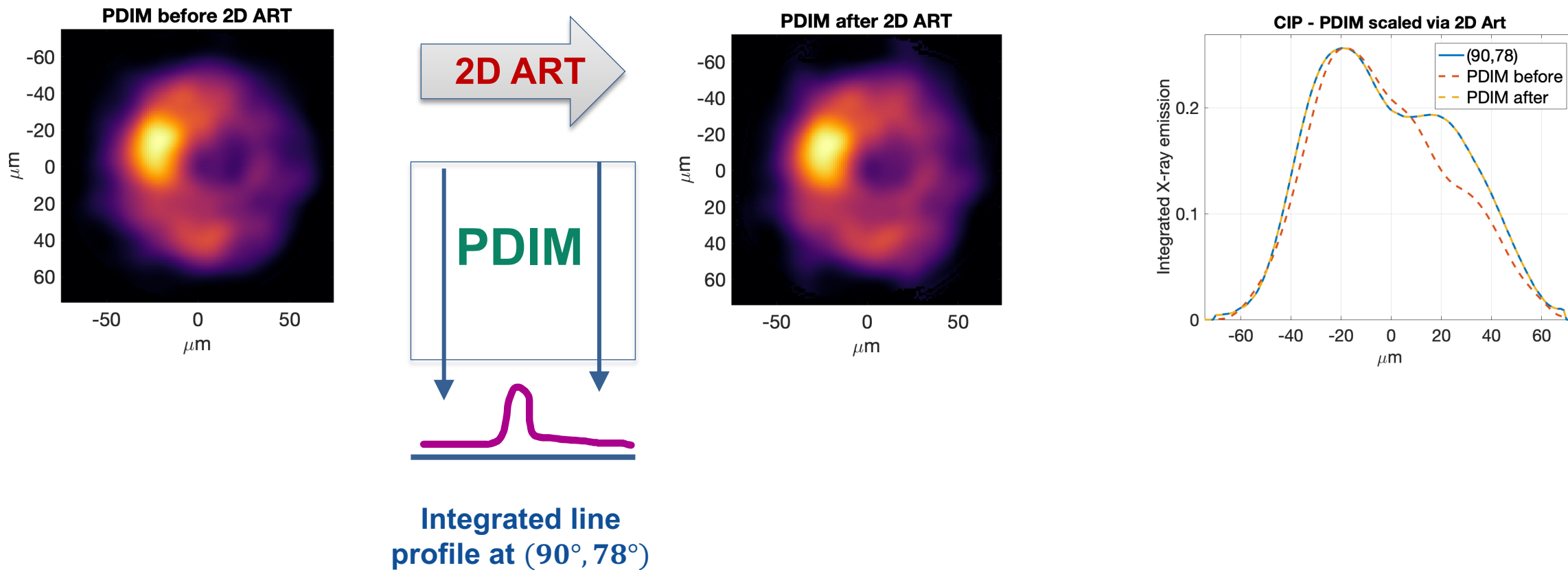


Image Resolution  $14\mu\text{m}$

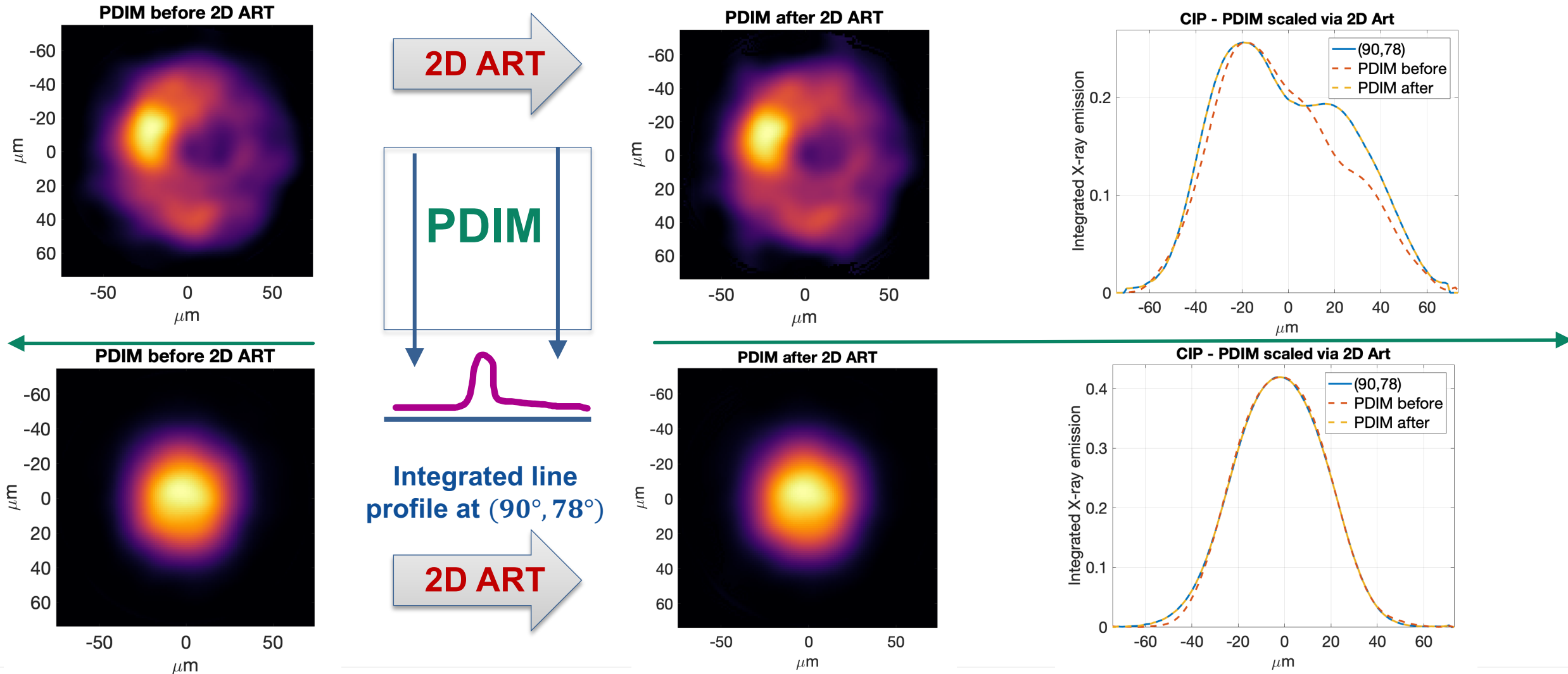


How to match PDIM and (90°, 78°) CIP without compromising the hotspot structure in input images?

# We apply 2D ART to modify PDIM image such that it matches with the CIP of the equatorial image (top row - N181007, bottom row - N190730)

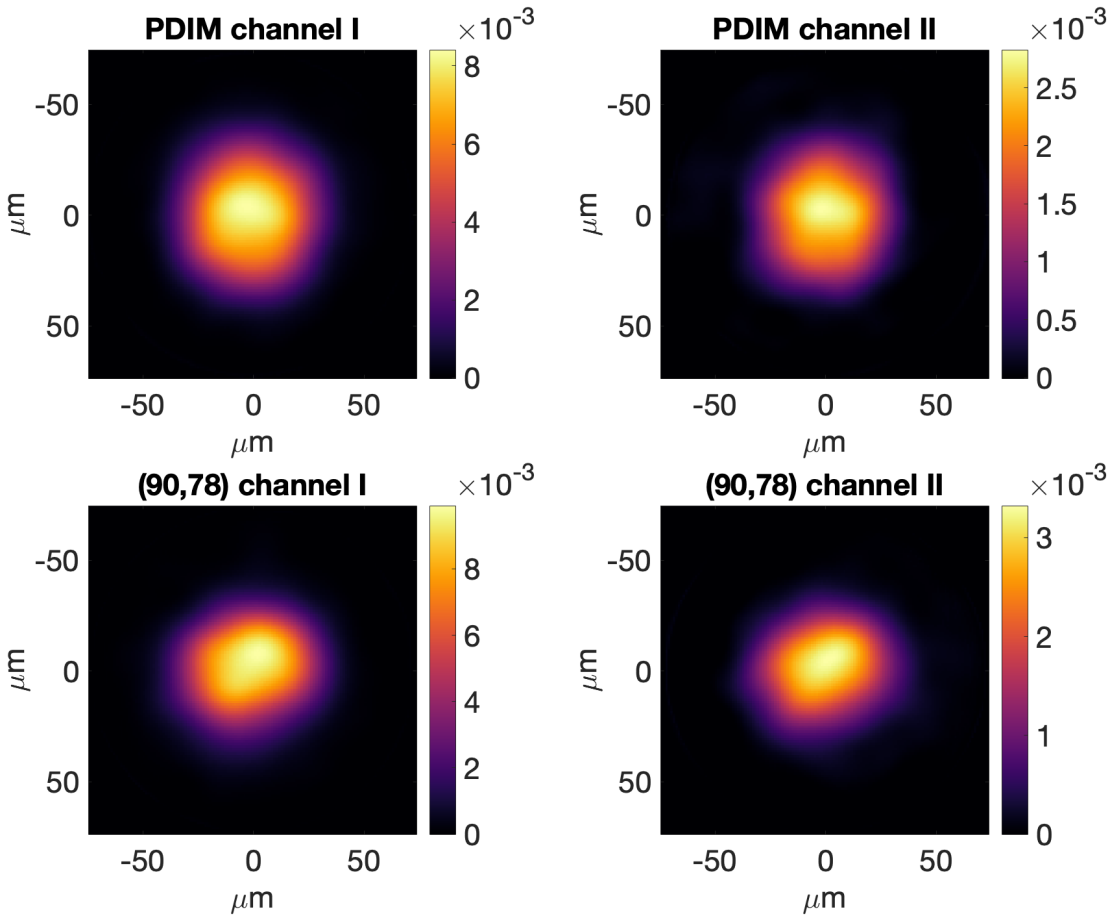


# We apply 2D ART to modify PDIM image such that it matches with the CIP of the equatorial image (top row - N181007, bottom row - N190730)



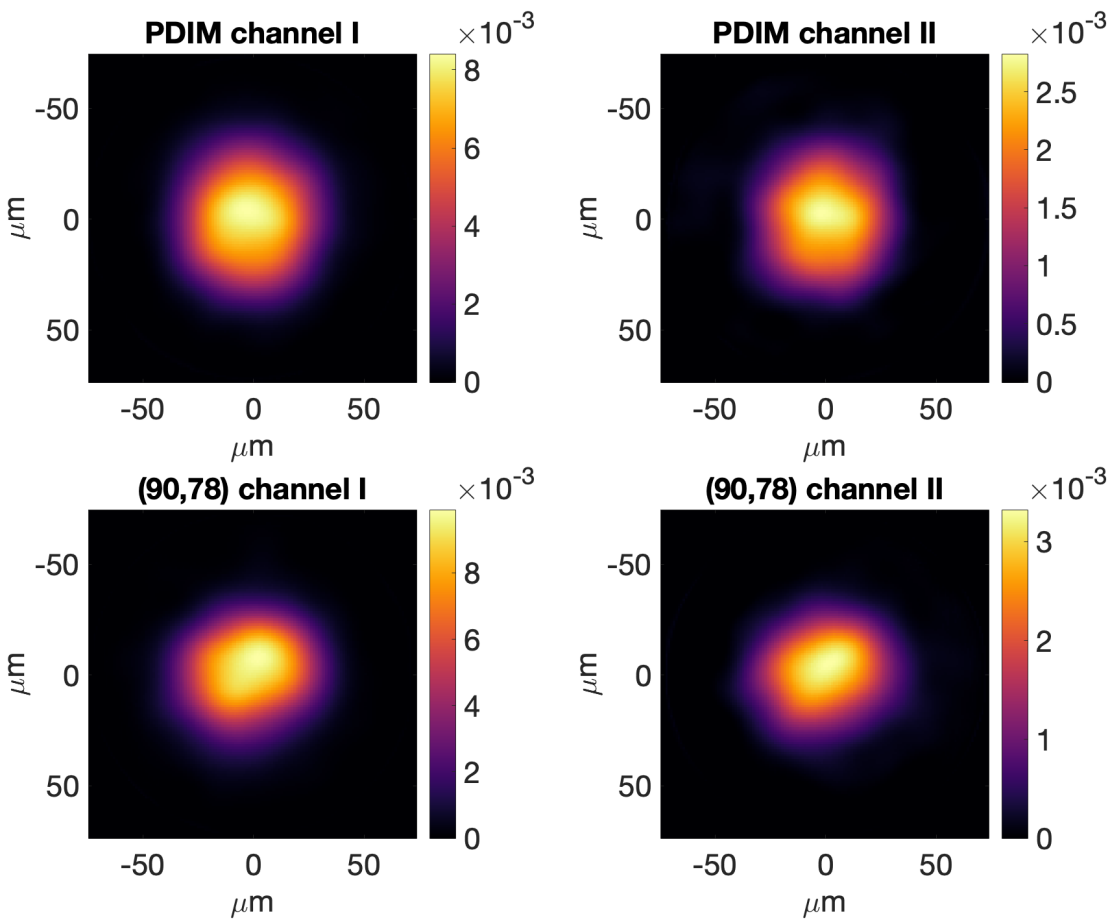
# N190730: X-ray images and 3D X-ray reconstructions show a round hotspot

## Experimental X-ray images

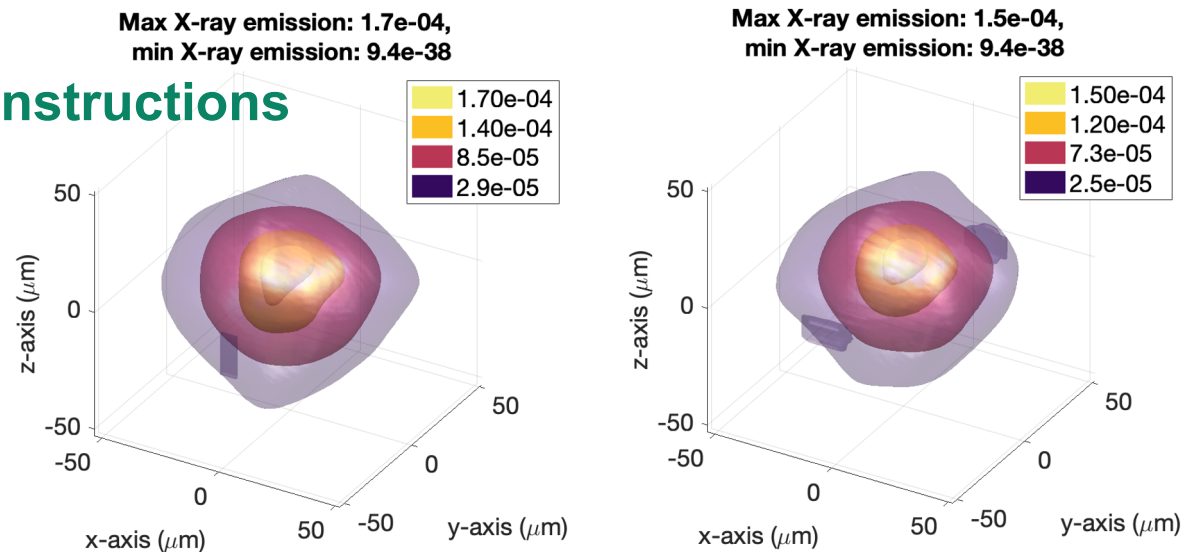


# N190730: X-ray images and 3D X-ray reconstructions show a round hotspot

## Experimental X-ray images

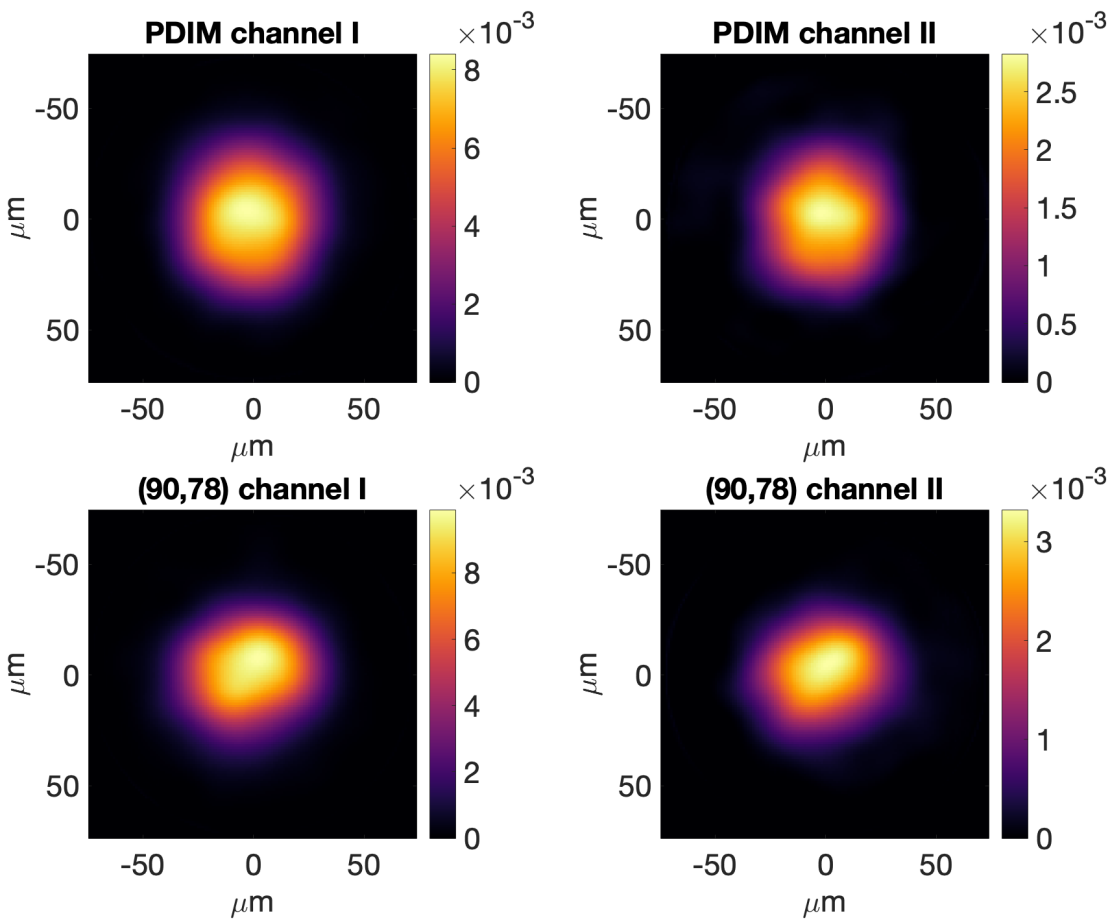


## Reconstructions

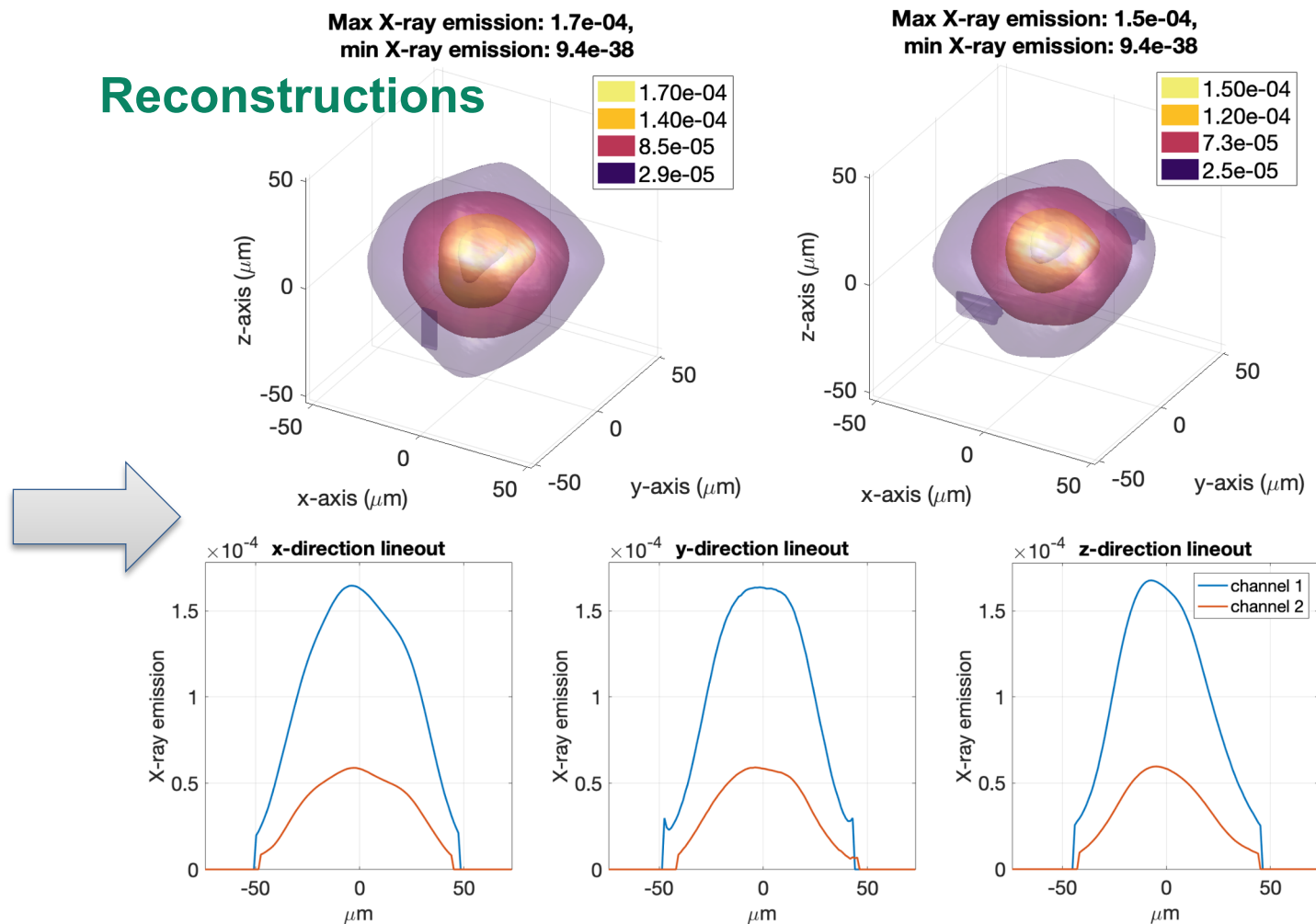


# N190730: X-ray images and 3D X-ray reconstructions show a round hotspot

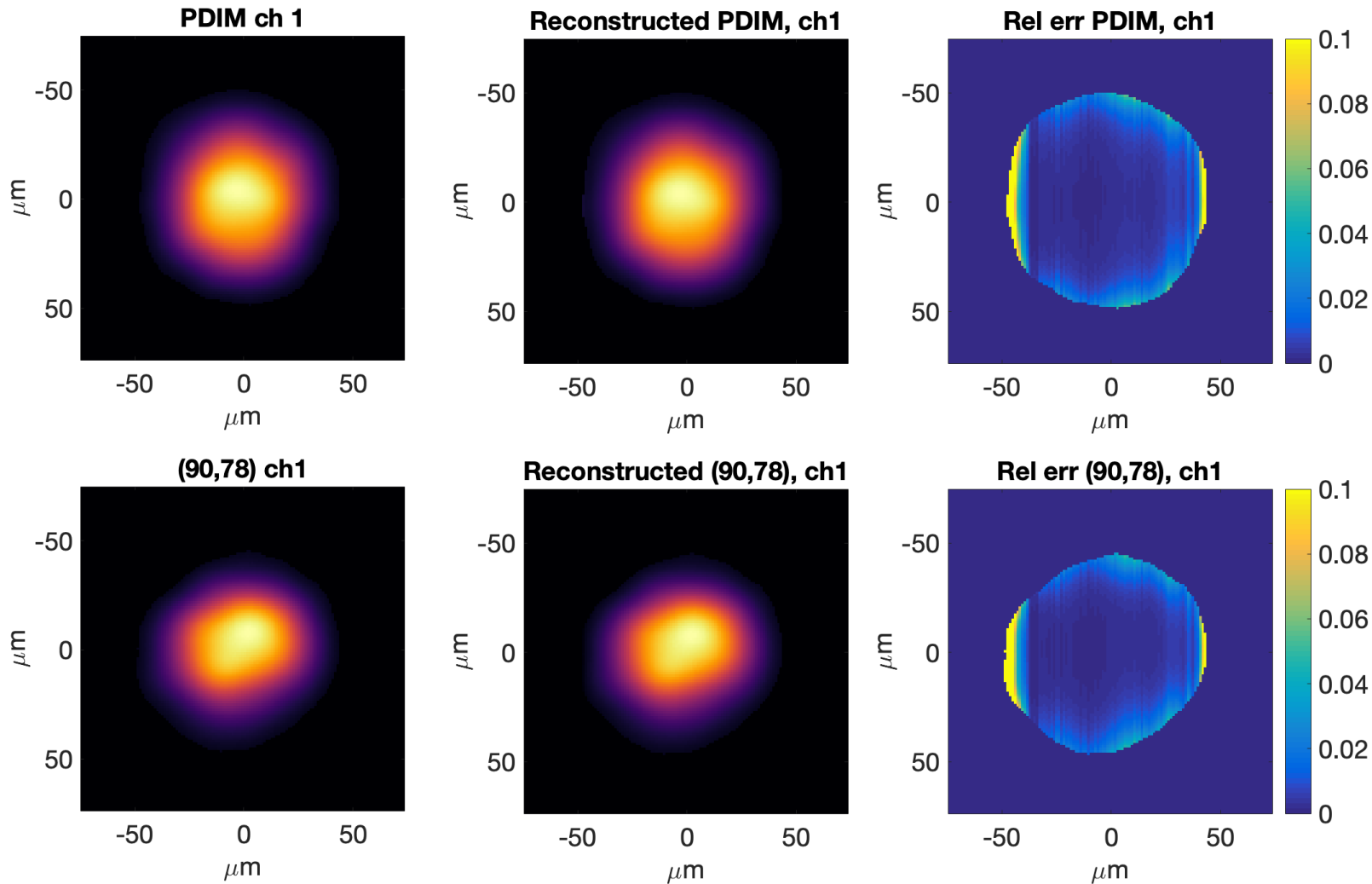
## Experimental X-ray images



## Reconstructions



# Our 3D X-ray reconstruction is consistent to input images

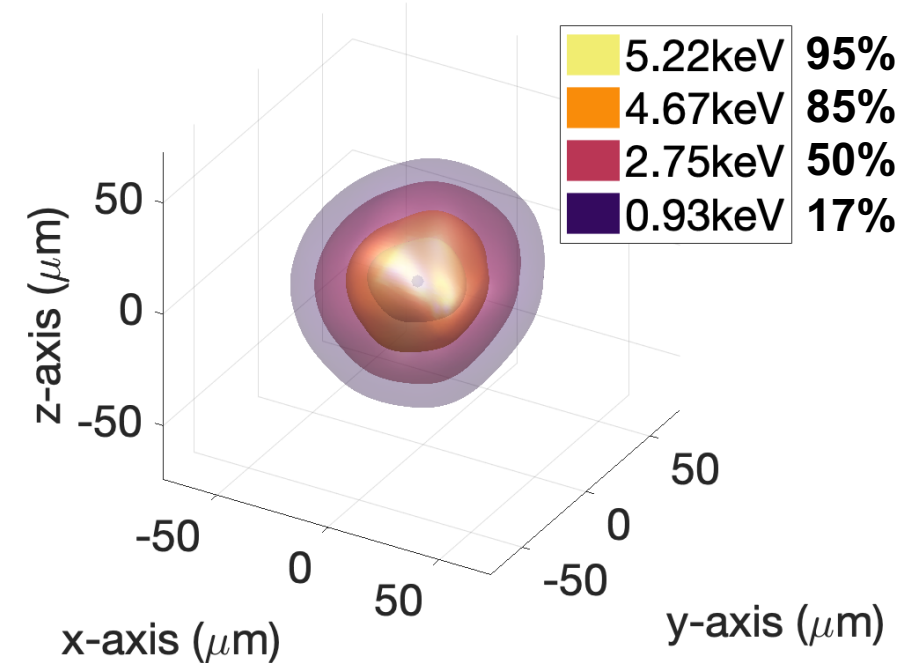
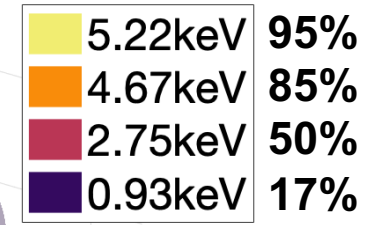


**The reconstructed projections agree well with the input experimental images.**

**The relative errors in the hotspot are largely zero.**

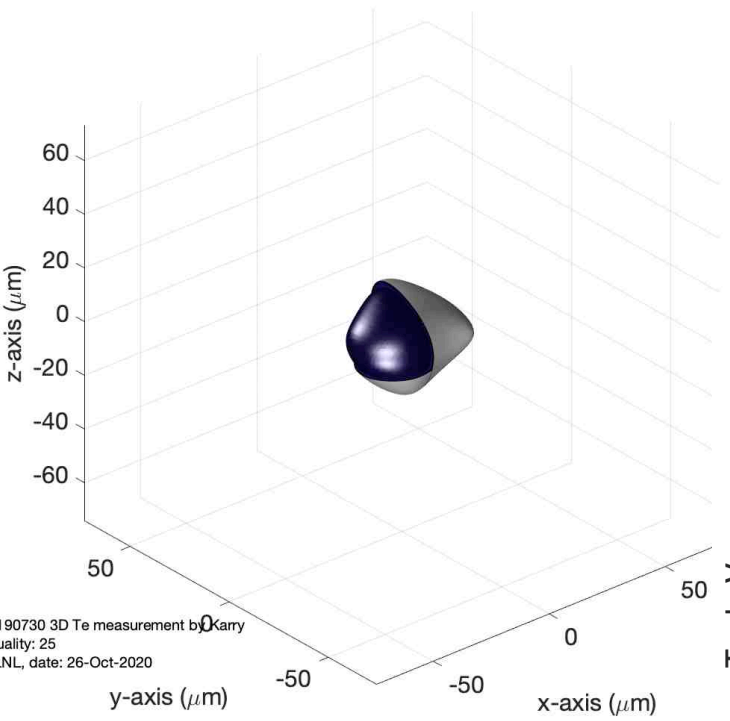


# 3D $T_e$ measurement of N190730

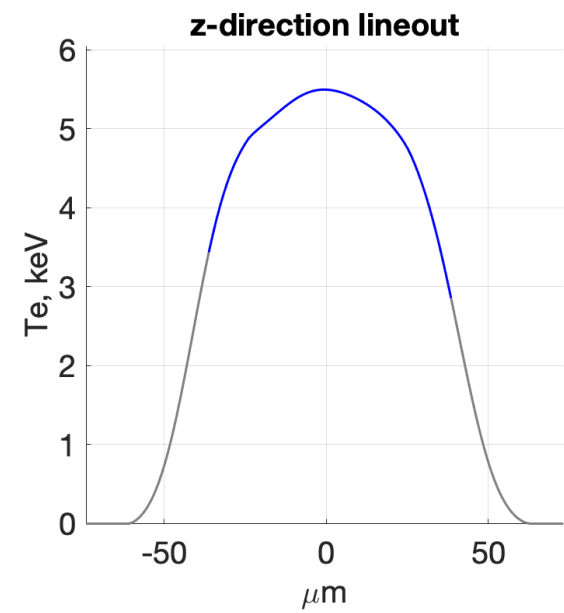
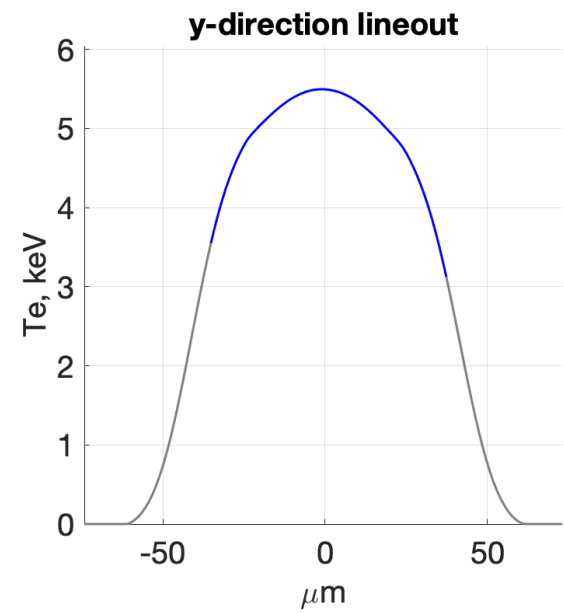
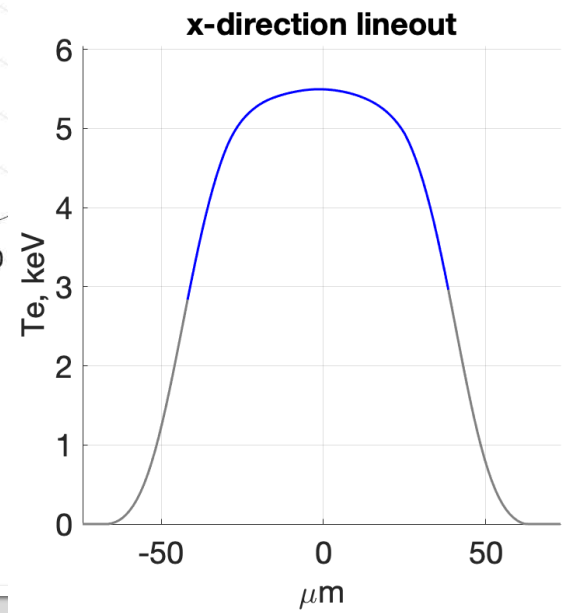


$\langle T_e \rangle_{(90^\circ, 78^\circ)} \approx 4.5 \text{ keV}$   
 $\langle T_e \rangle_{PDIM} \approx 4.2 \text{ keV}$   
 Ref. Jarrott et al., PRL 2018.

3D Te model, 16  $\mu\text{m}$  resolution, outer contour: 94%, transparent contour: 50%, inner contour: 95%



N190730 3D Te measurement by OKarry  
 Quality: 25  
 LLNL, date: 26-Oct-2020



# Measuring 3D electron temperature of the ICF hotspot is feasible

We have

- tested iterative algebraic method ART to reconstruct 3D X-ray emission distributions of the ICF hotspot.
- obtained 3D X-ray reconstructions with two or three LOS and made 3D electron temperature  $T_e$  measurement in the ICF hotspot using synthetic and experimental data
- laid out a future path on how to perform 3D  $T_e$  measurement on the NIF.

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