Diffusion MRI Analysis

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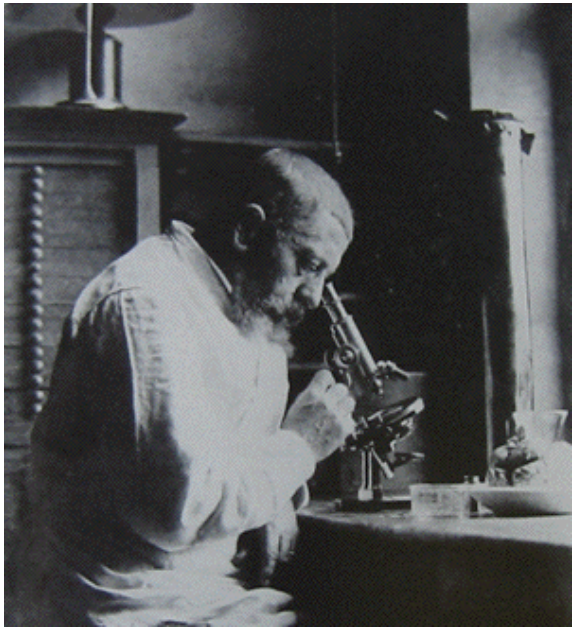
Brain Anatomy

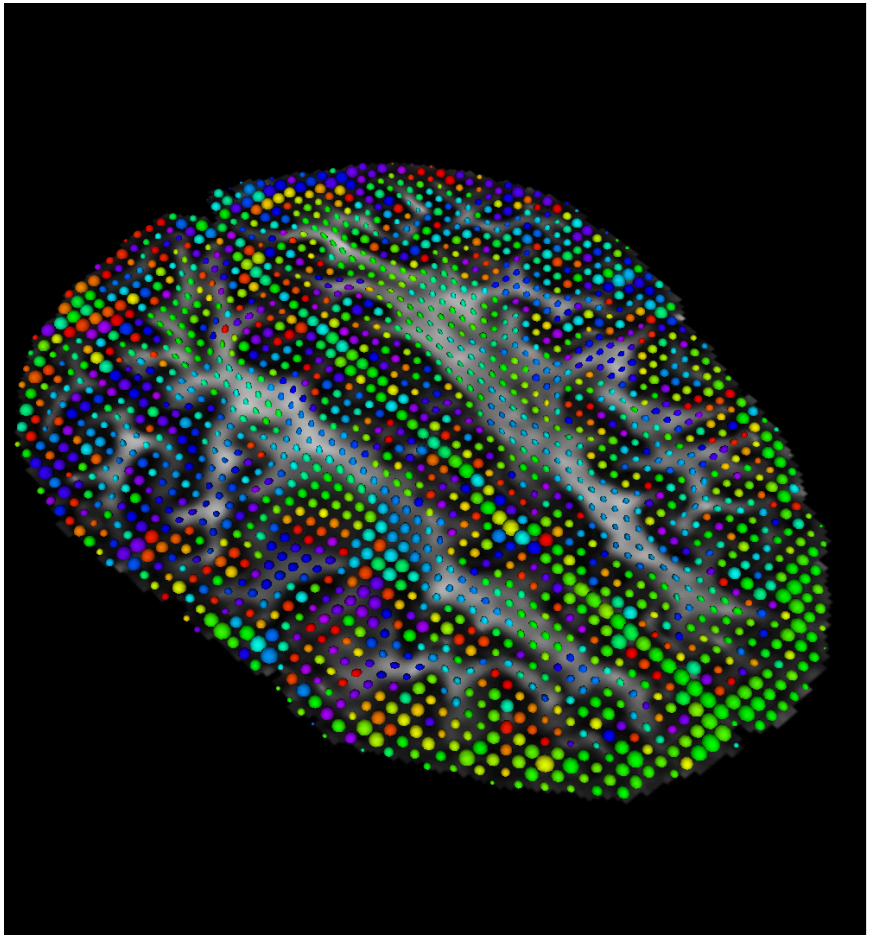
- White matter ~45% of the brain
- Myelinated nerve fibers (~ 10 μm axon diameter)

White Matter Exploration



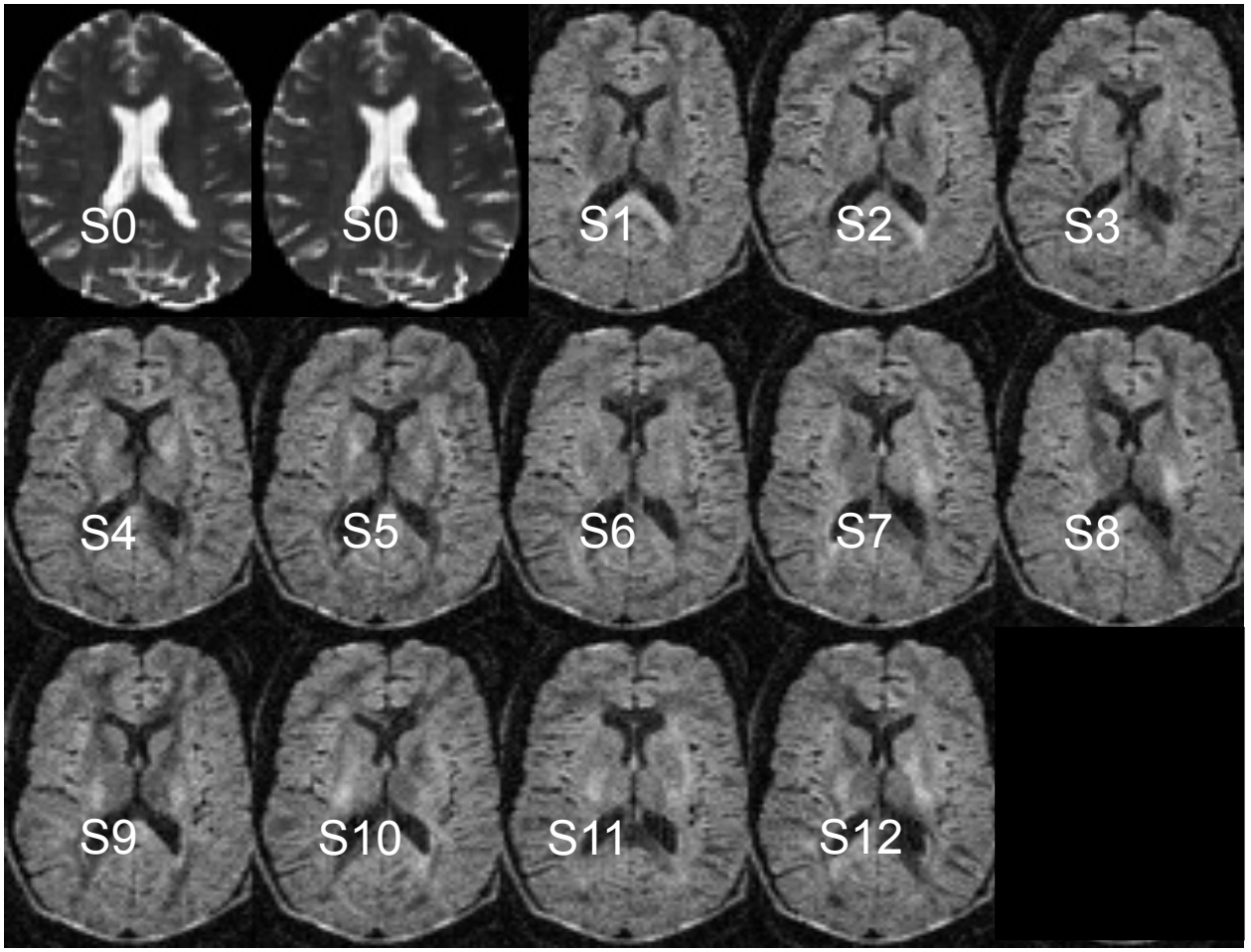
Jules Joseph and Augusta Dejerine (*Anatomie des centres nerveux* (Paris, 1890-1901)): Neuroanatomy atlas based on myelin stained preparation

Diffusion Tensor Imaging (DTI)



- First non-invasive window on white matter anatomy
- Measurement of the motion of water molecules using MRI techniques.
- Three-dimensional reconstruction of the trajectory of white matter bundles

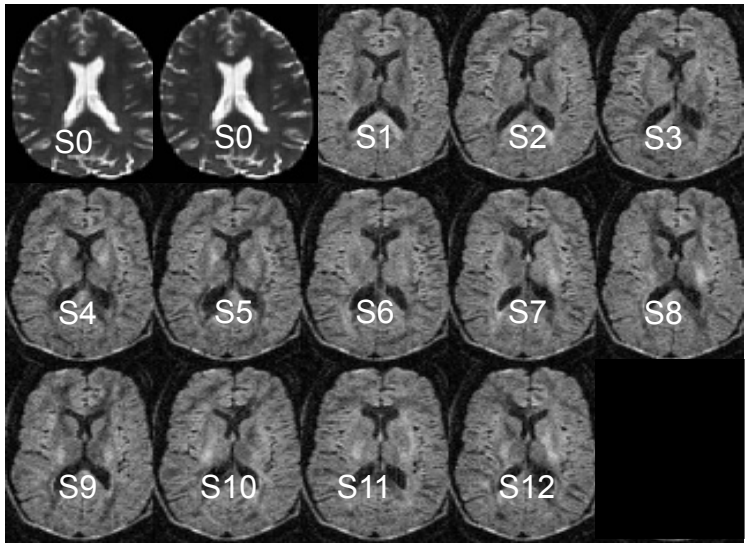
Diffusion Weighted Imaging (DWI)



In this example, the DWI scan was acquired with 12 diffusion sensitizing gradient directions (S1-S12) and 2 non-diffusion sensitizing gradients (S0)

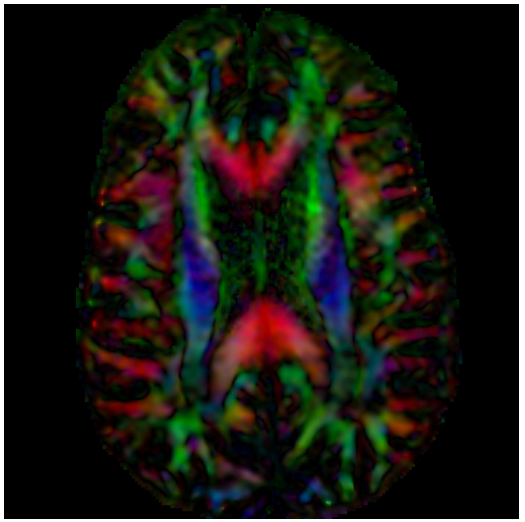
From DWI to DTI

DWI



DWI dataset

DTI



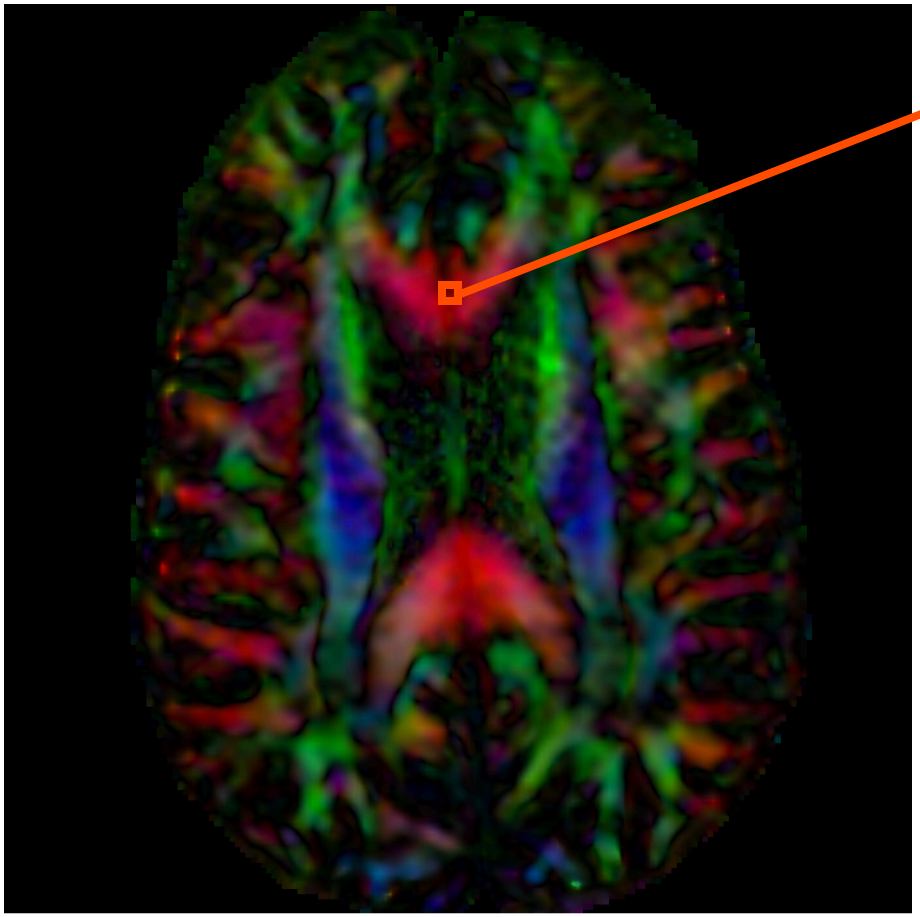
DTI dataset

$$S_i = S_0 e^{-b\hat{g}i^T \underline{D} \hat{g}_i}$$

Stejskal-Tanner (1965)

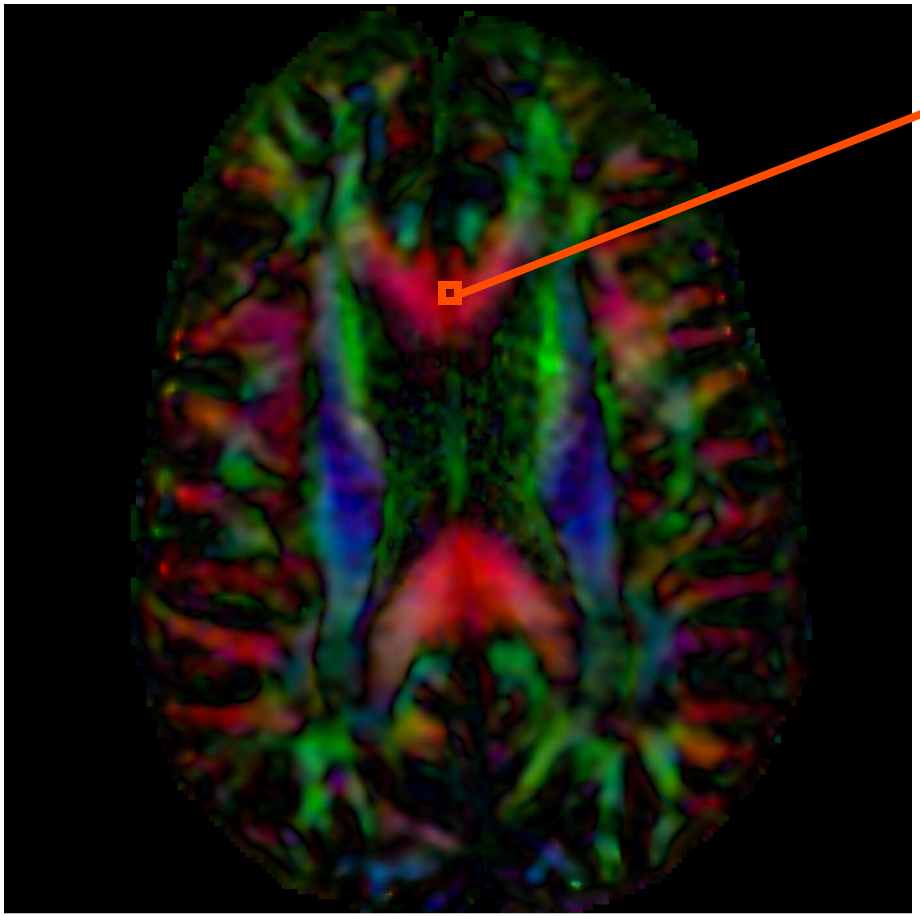
Si: DWI volume acquired with ith gradient
So: Baseline volume

Diffusion Tensor Imaging



$$S_i = S_0 e^{-b\hat{g}i^T \underline{D} \hat{g}_i}$$

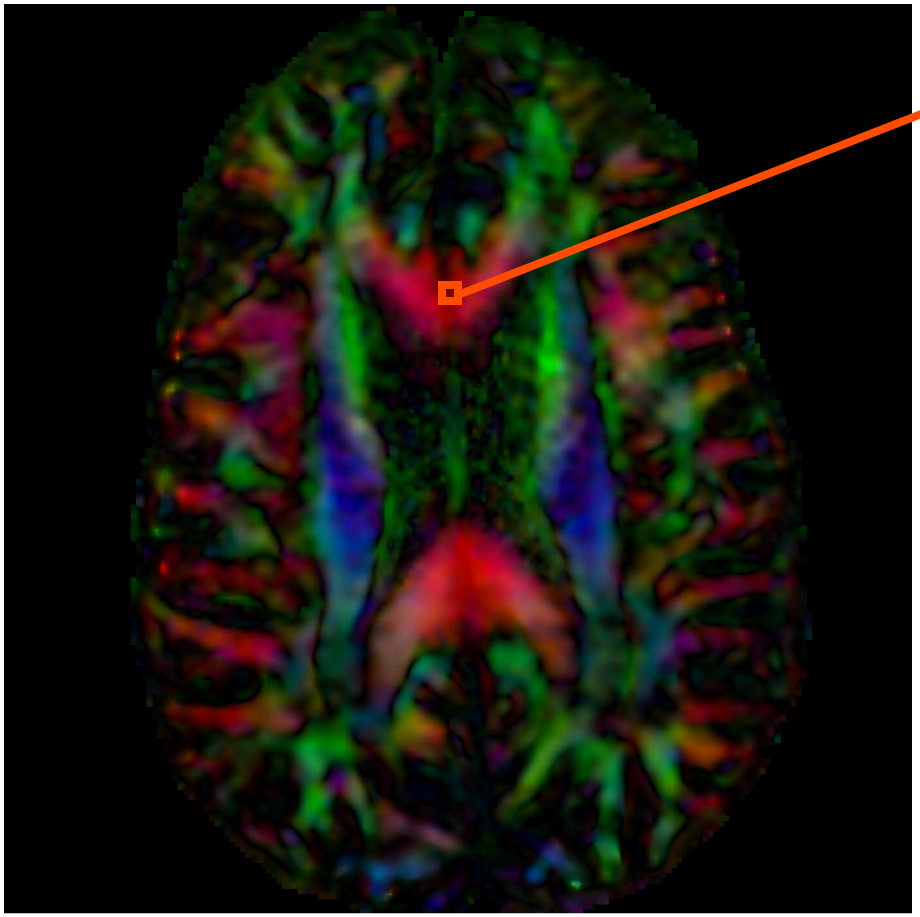
Diffusion Tensor Imaging



$$S_i = S_0 e^{-b\hat{g}i^T \underline{D} \hat{g}_i}$$

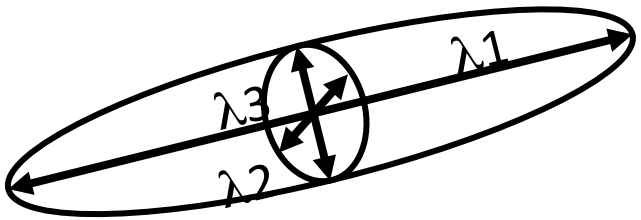
$$\underline{\mathbf{D}} = \begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{zx} & D_{zy} & D_{zz} \end{bmatrix}$$

Diffusion Tensor Imaging

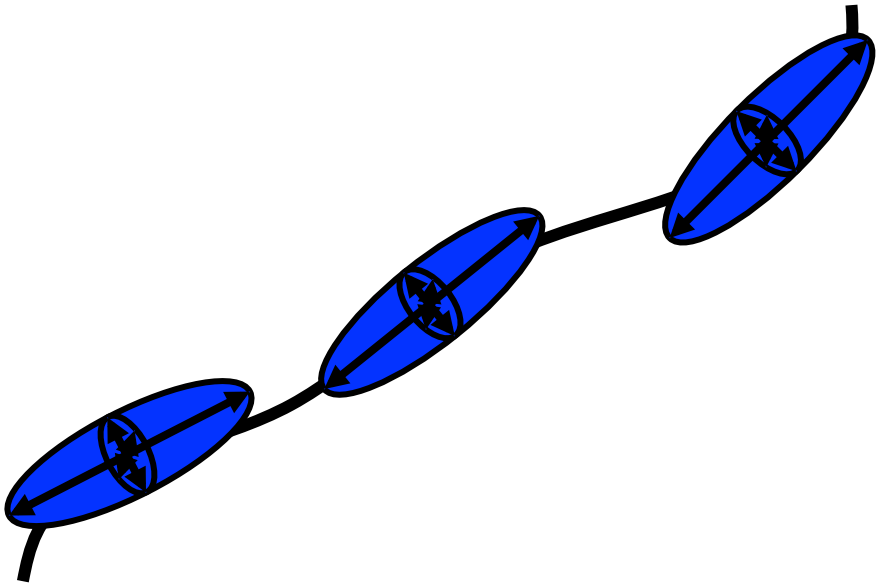


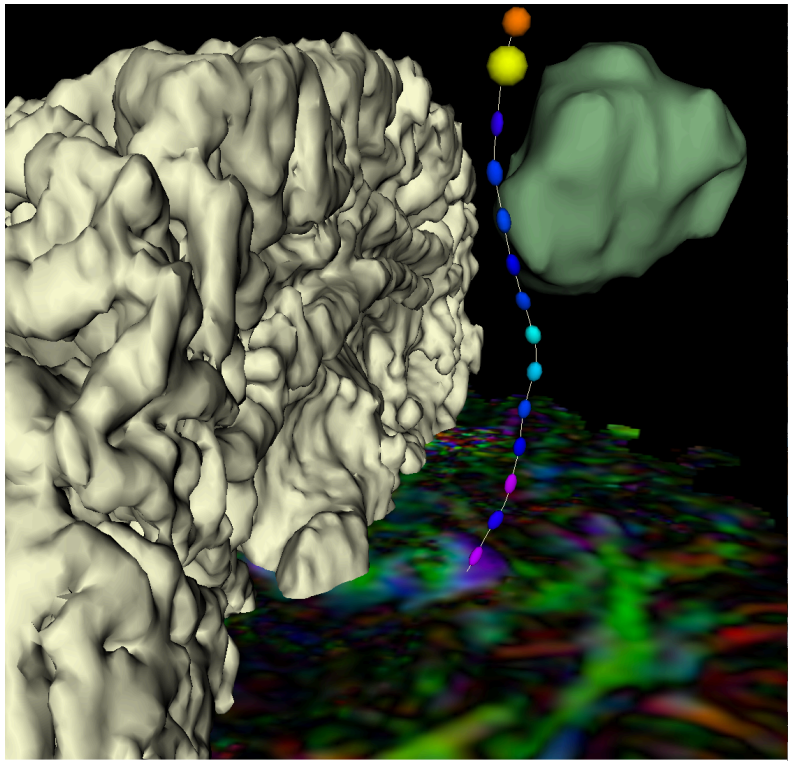
$$S_i = S_0 e^{-b\hat{g}i^T \underline{D} \hat{g}_i}$$

$$\underline{\mathbf{D}} = \begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{zx} & D_{zy} & D_{zz} \end{bmatrix}$$



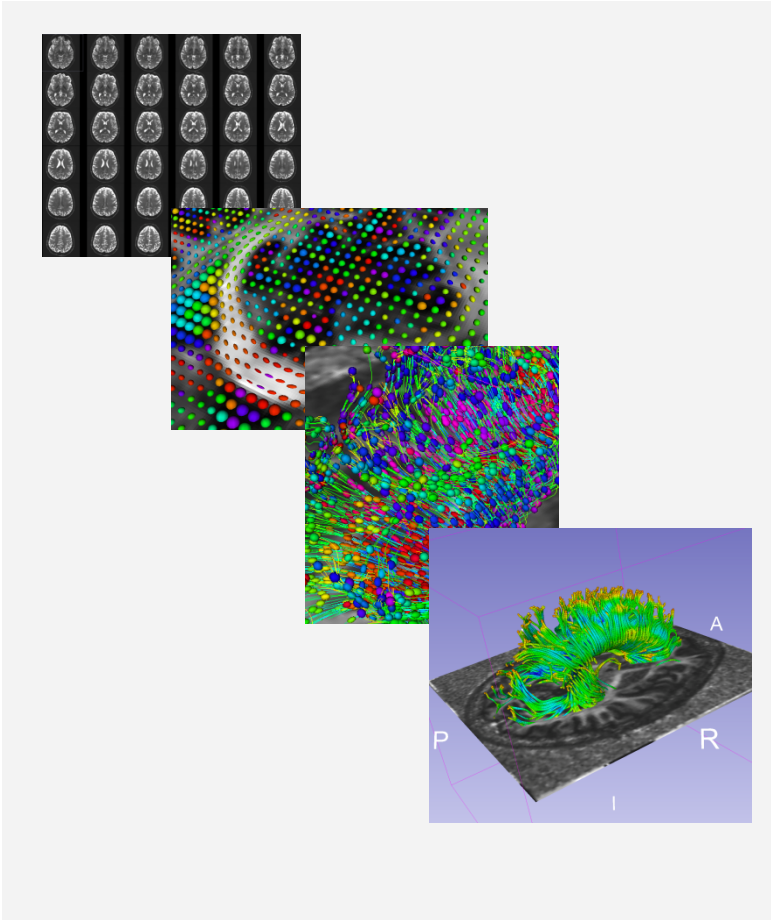
Tractography





DTI tractography provides 3D reconstruction of the trajectory of white matter pathways

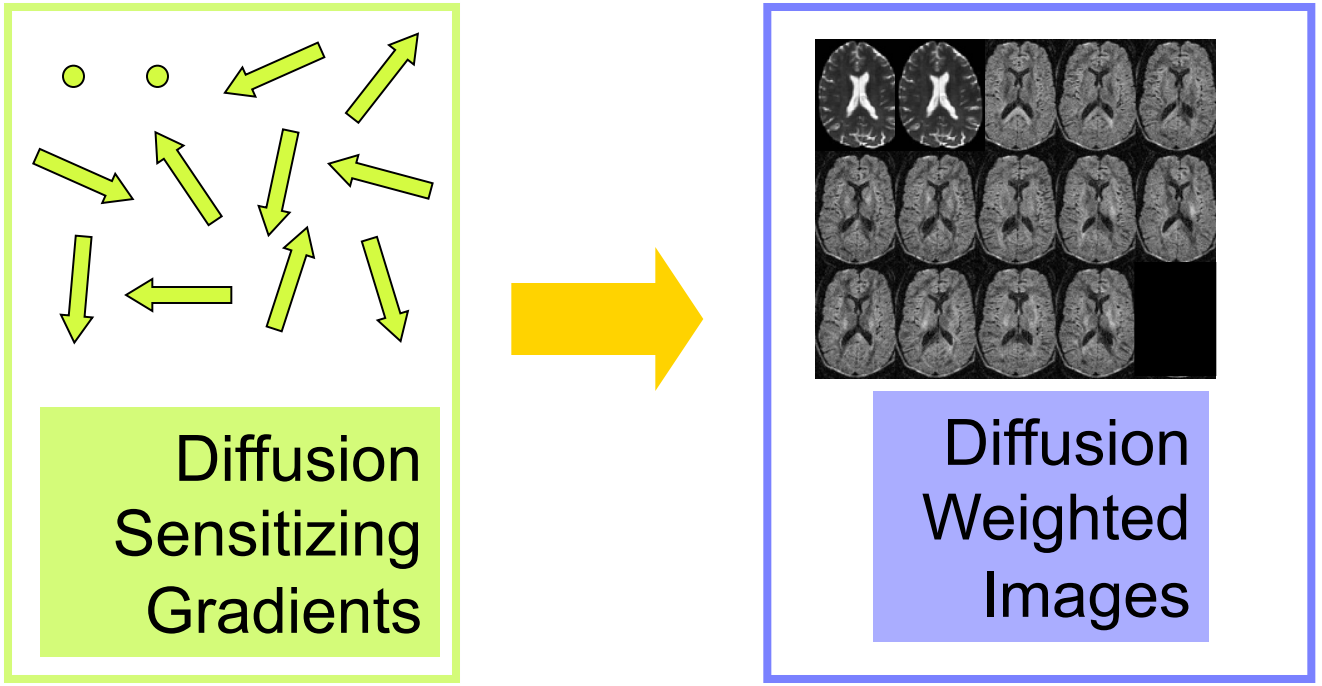
Tutorial Outline



This tutorial is an introduction to the fundamentals of Diffusion MRI analysis, from the estimation of diffusion tensors to the interactive 3D visualization of tracts.

Tutorial Dataset

The tutorial dataset is a Diffusion Weighted MR scan of the brain acquired with 41 diffusion sensitizing gradient directions and 7 baseline.



Tutorial Software

The tutorial was created using the 3D Slicer (Version 4.5) available at:

http://download.slicer.org

Please note that the **Diffusion Weighted Volume Masking** module has been updated in 2016. In this tutorial, we use a Slicer nightly build (Slicer4.5.0-2016-02-23). If you plan to use the Diffusion Weighted Volume Mask module, we recommend you download a Slicer nightly build version posterior to 02-23-2016.

Disclaimer

It is the responsibility of the user of 3DSlicer to comply with both the terms of the license and with the applicable laws, regulations and rules. Slicer is a tool for research, and is not FDA approved.

Learning Objectives

Following this tutorial, you'll be able to

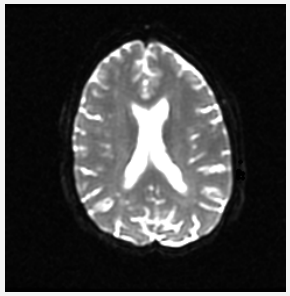
1) Estimate a tensor volume from a set of Diffusion Weighted Images

2) Understand the shape and size of the diffusion ellipsoid

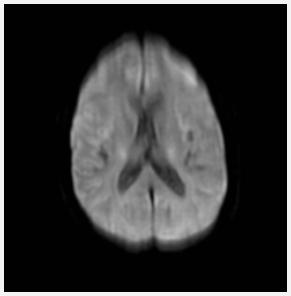
3) Reconstruct DTI tracts from a pre-defined region of interest

4) Interactively visualize DTI tracts seeded from a fiducial

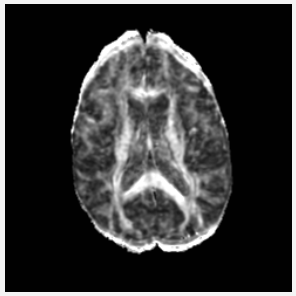
MR Diffusion Analysis Pipeline



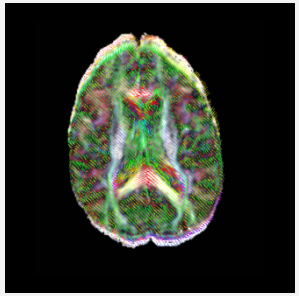
DWI
Acquisition



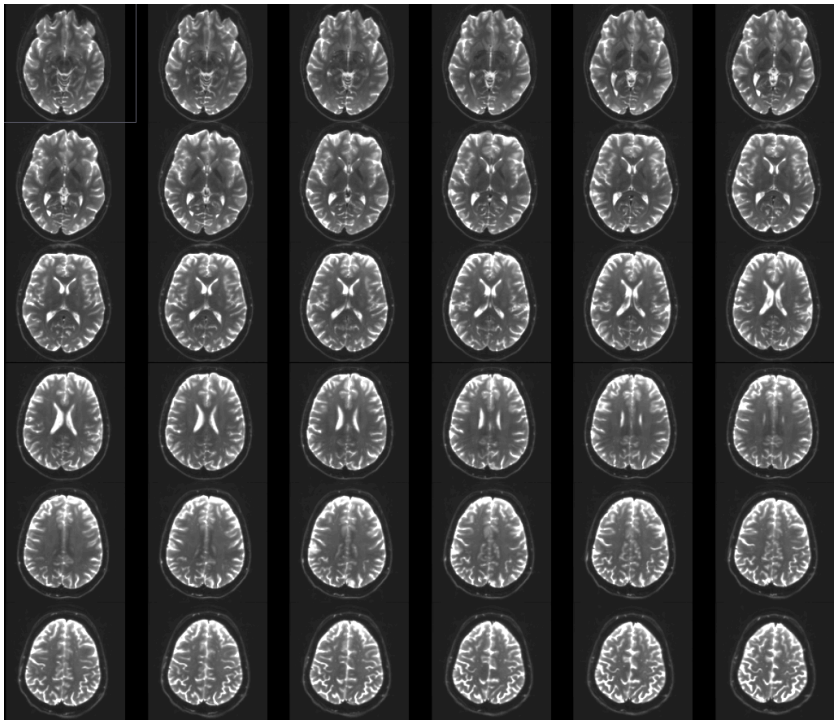
Tensor
Calculation



Scalar
Maps

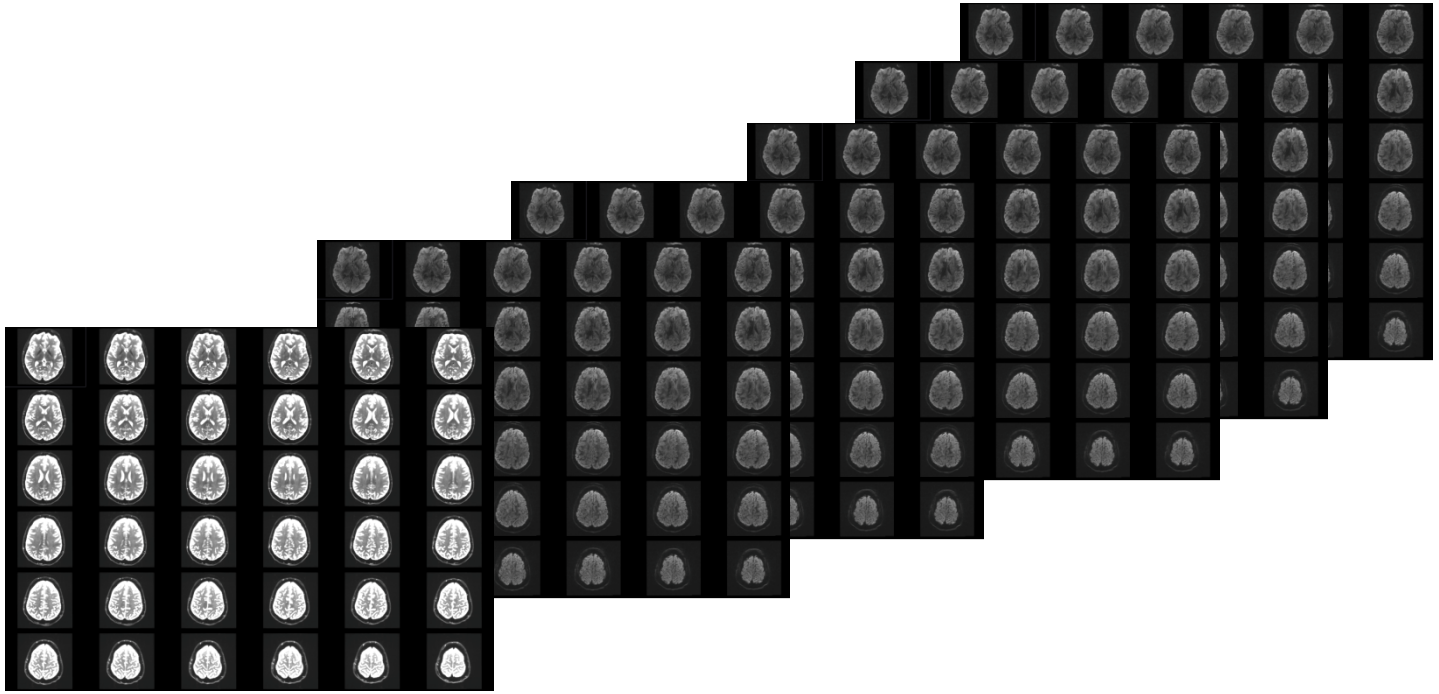


3D
Visualization



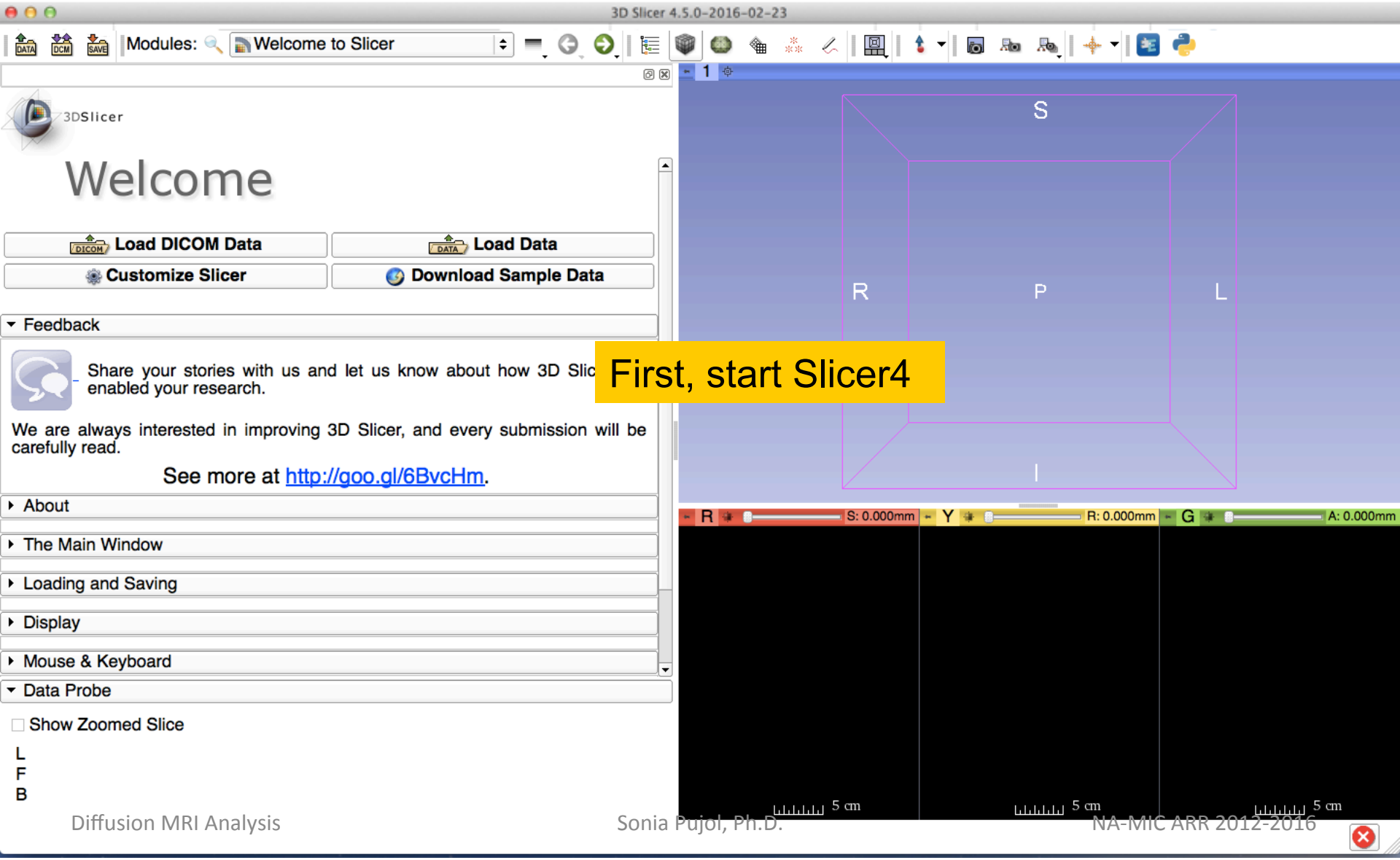
Part 1: From DWI images to Tensors

Understanding the DWI Dataset

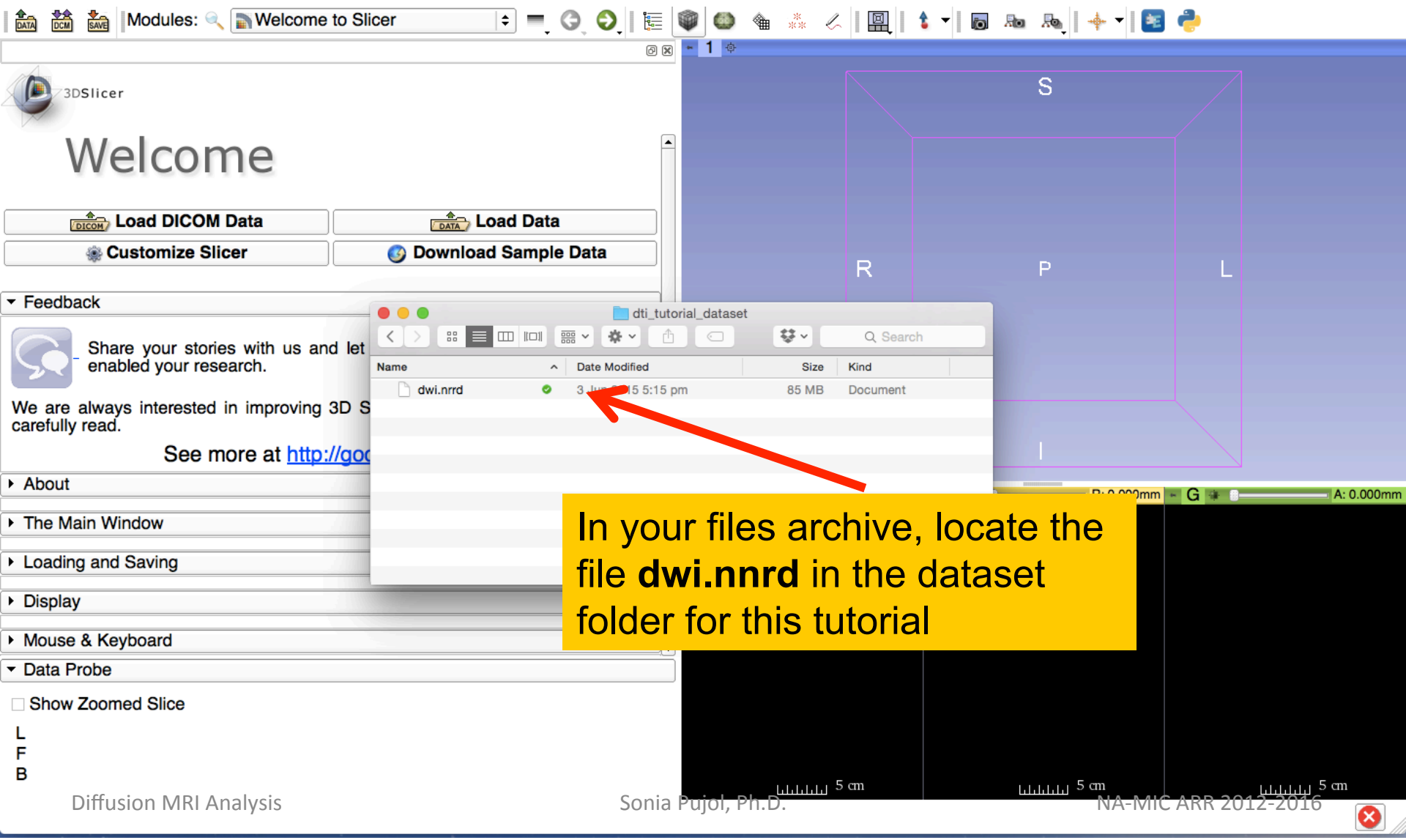


The Diffusion Weighted Imaging (DWI) dataset is composed of 48 volumes acquired with 41 different diffusion-sensitizing gradient directions, and 7 baseline image acquired without diffusion weighting.

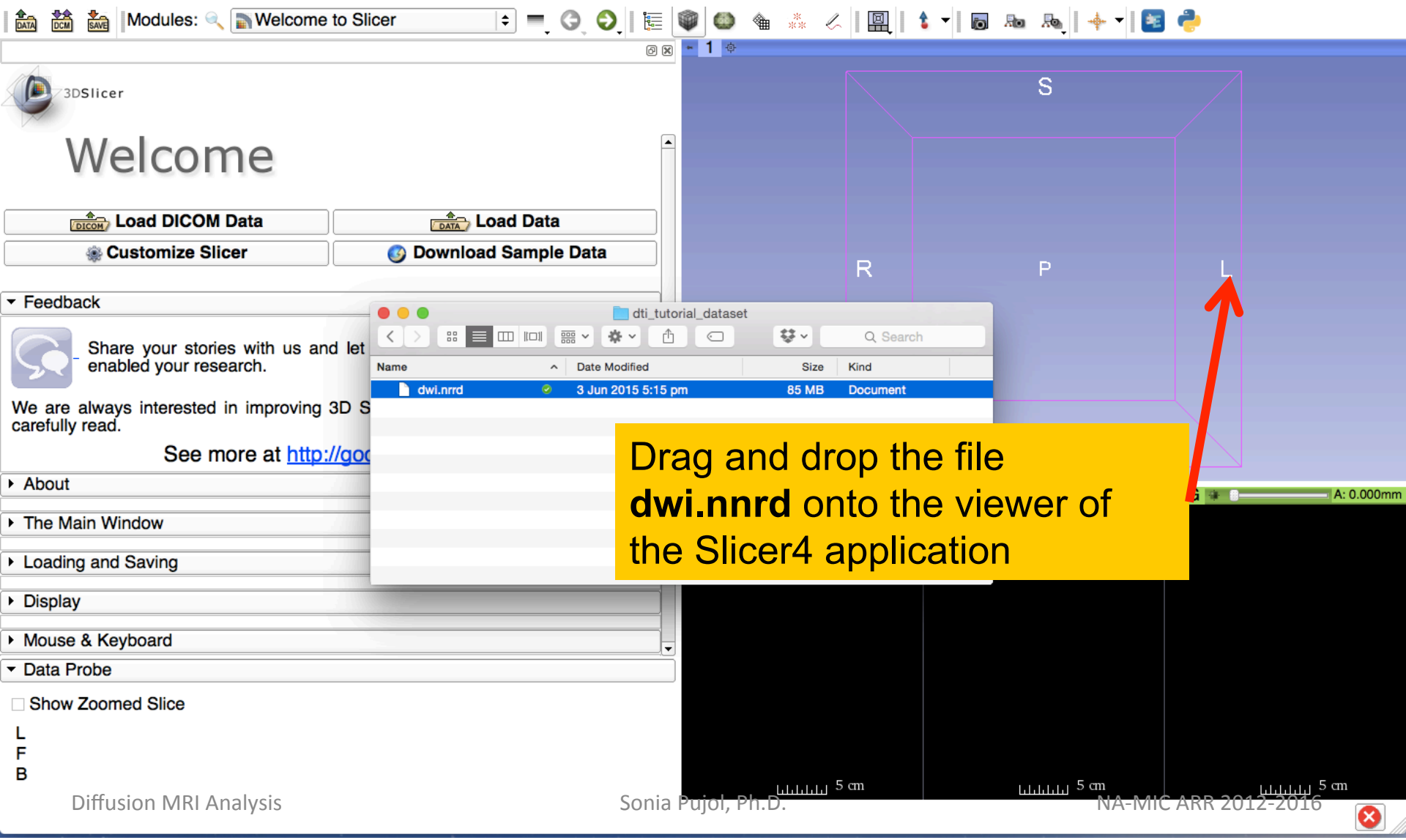
Loading the DWI Dataset



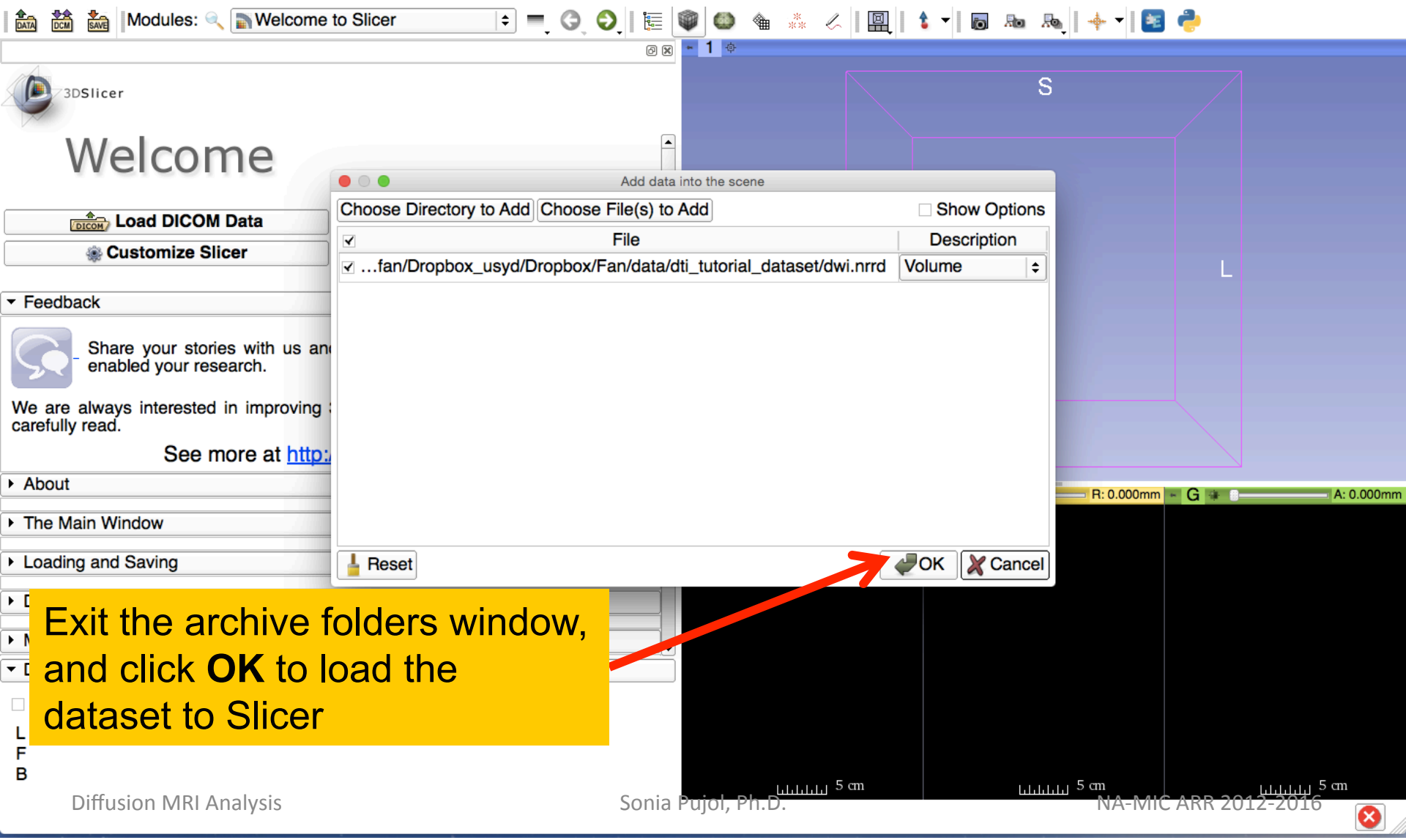
Loading the DWI Dataset



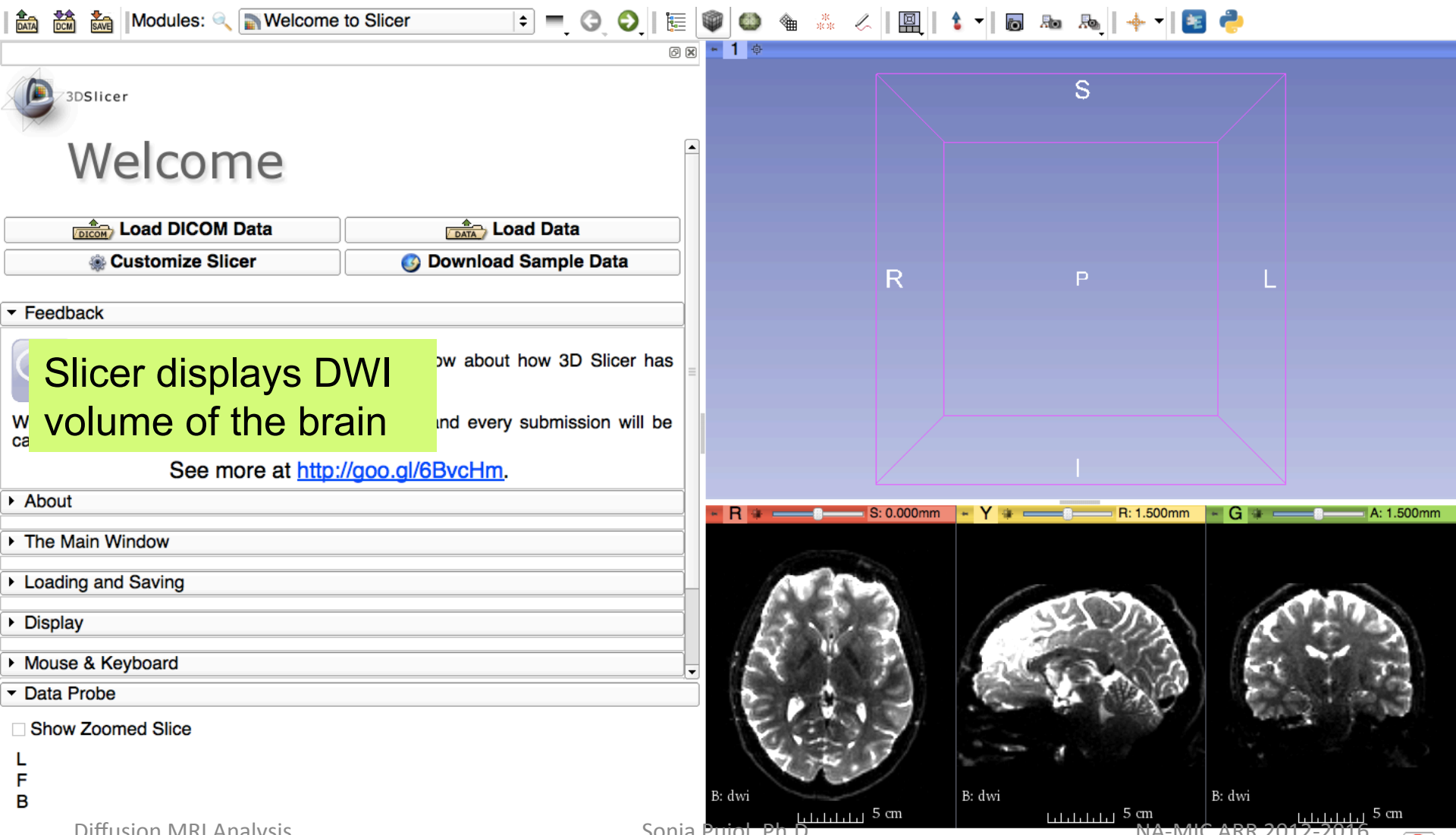
Loading the DWI Dataset



Loading the DWI Dataset

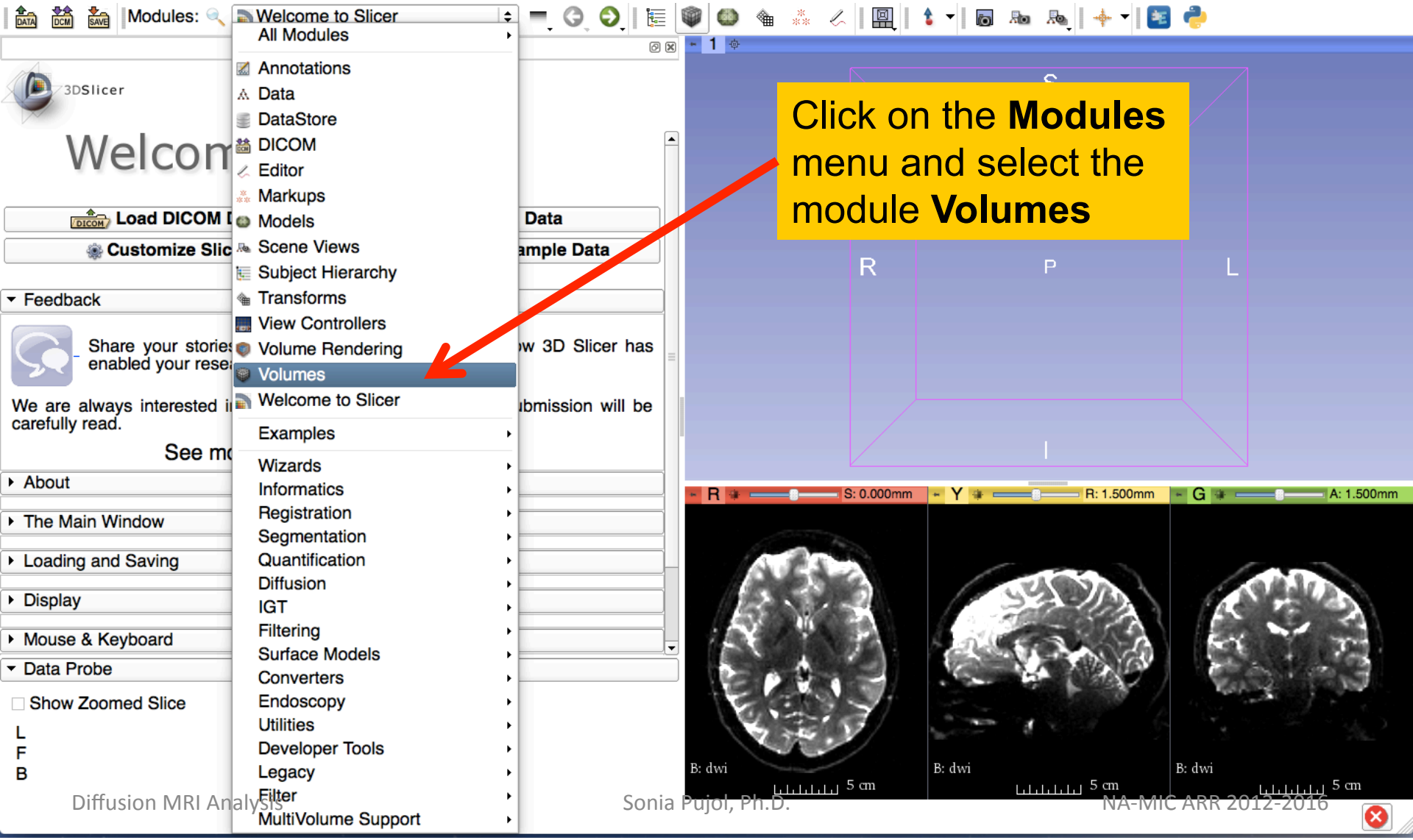


Loading the DWI Dataset

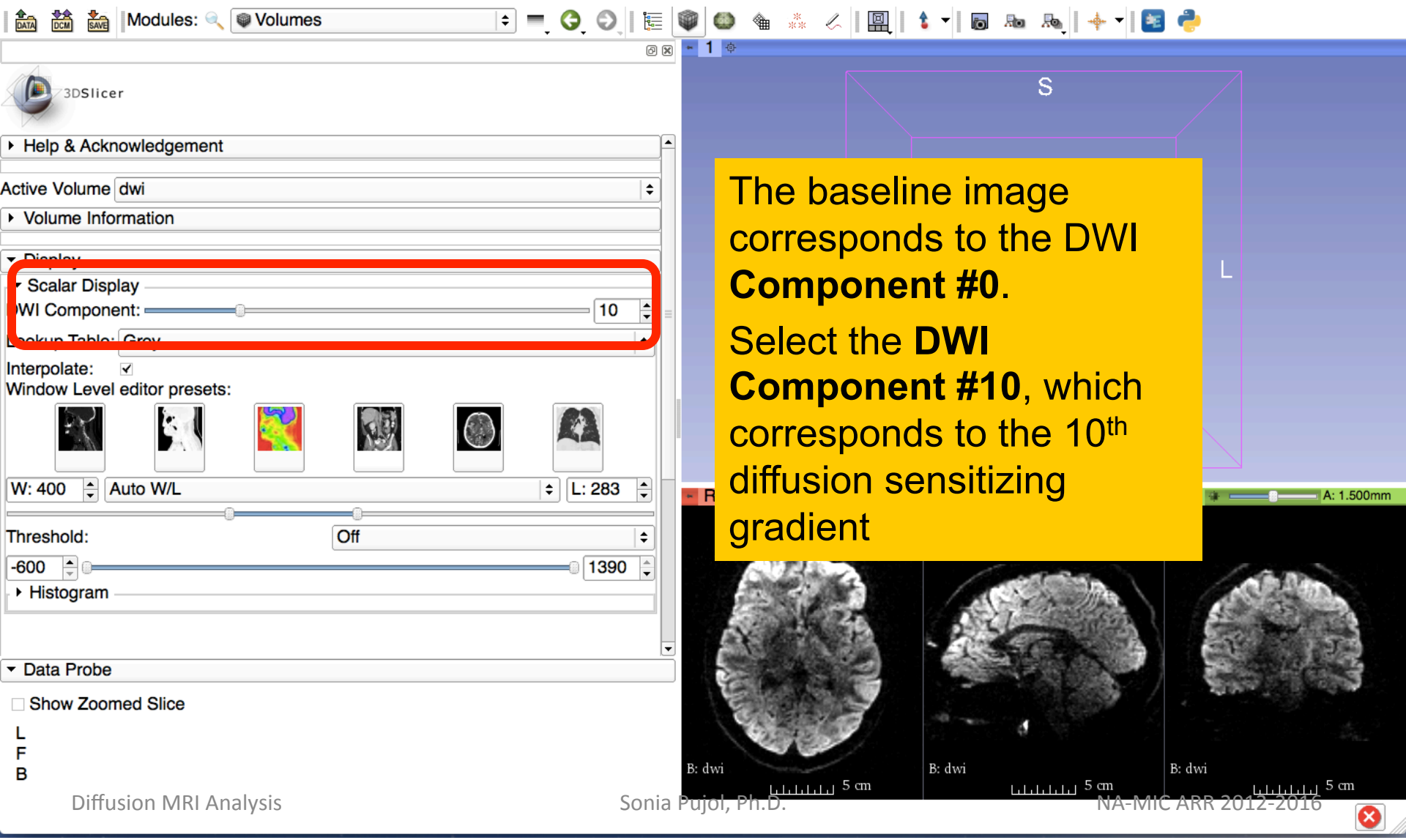


Slicer displays DWI volume of the brain

Loading the DWI Dataset



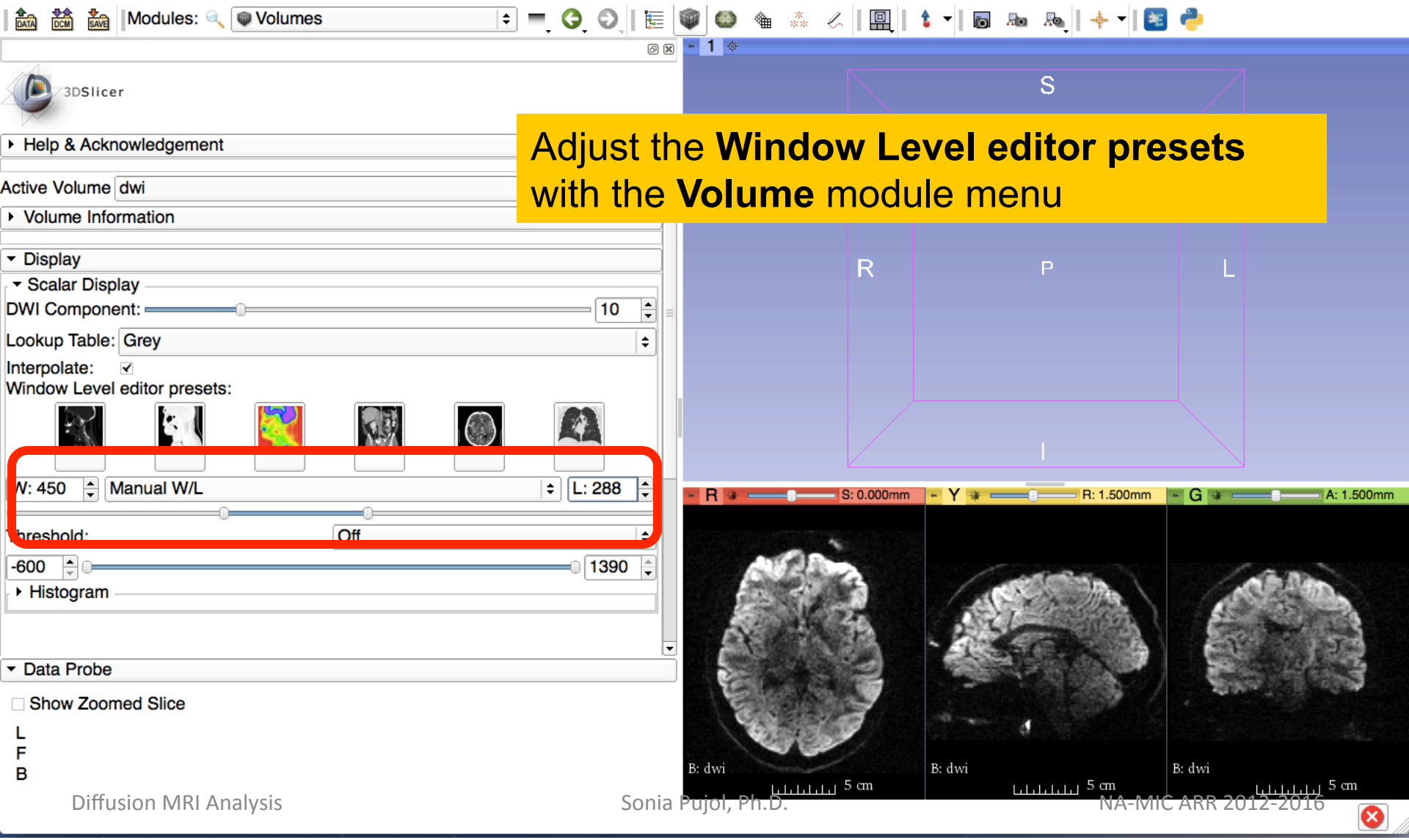
Loading the DWI Dataset



The baseline image corresponds to the DWI **Component #0**.

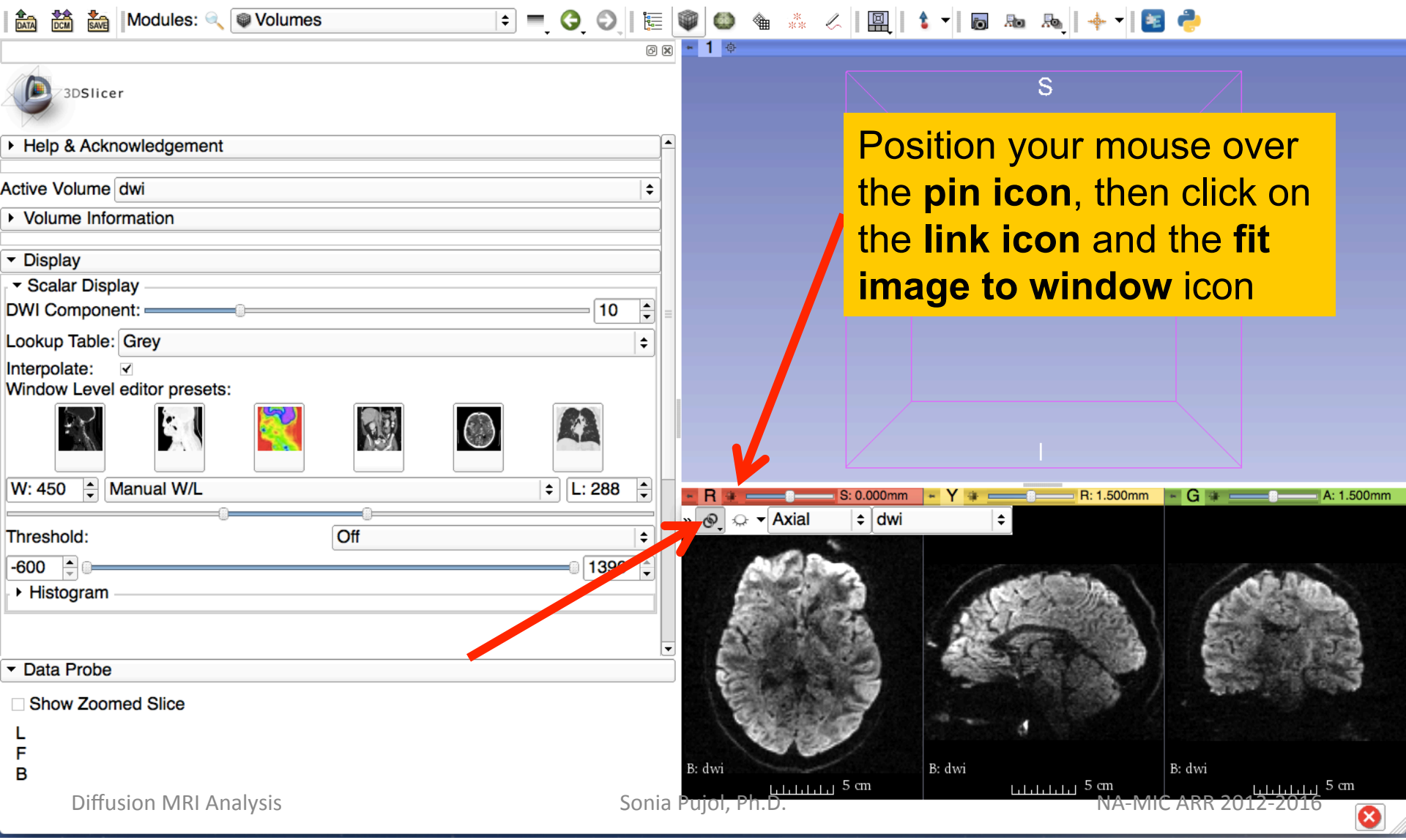
Select the **DWI Component #10**, which corresponds to the 10th diffusion sensitizing gradient

Loading the DWI Dataset

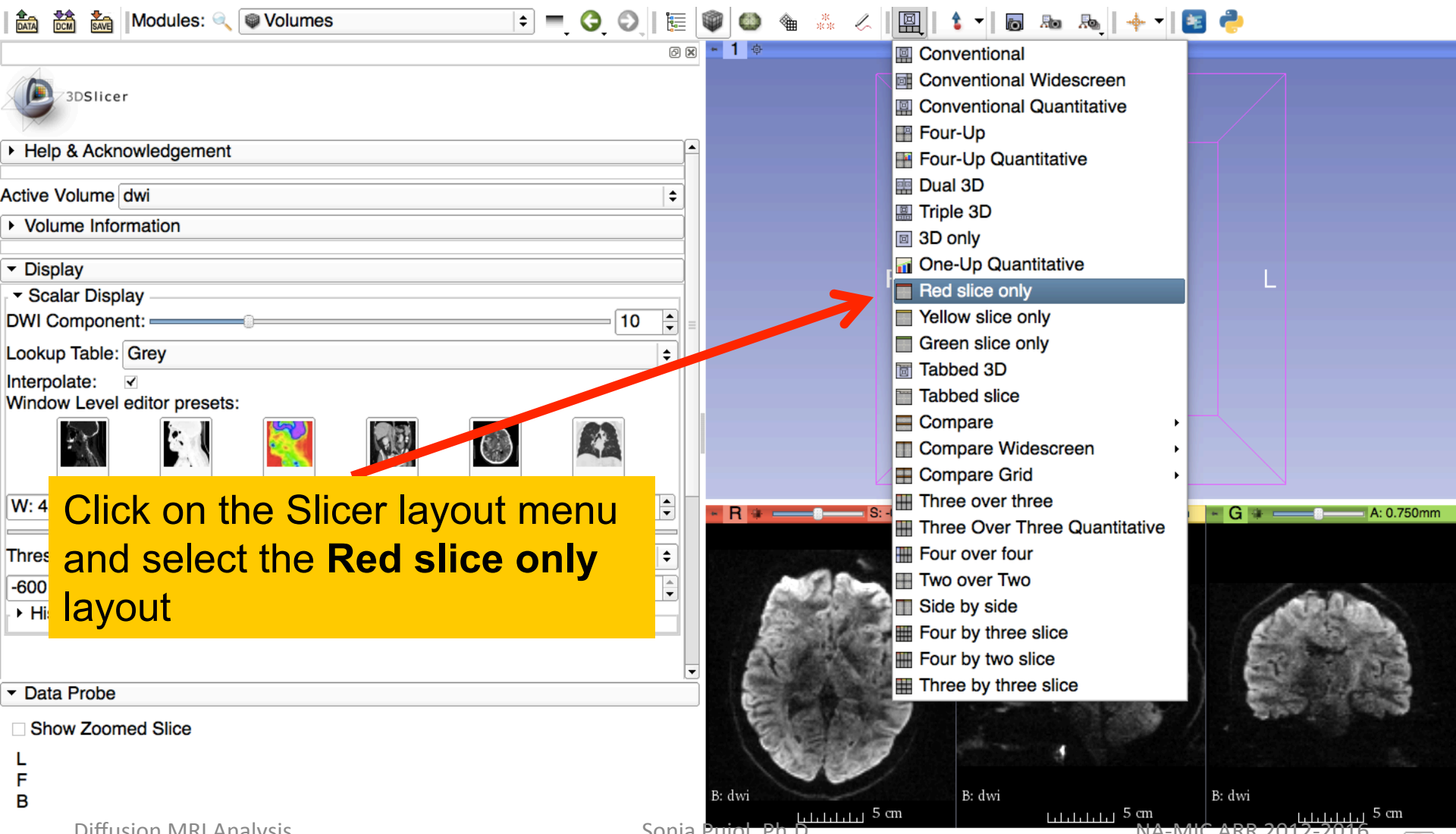


Adjust the **Window Level editor presets** with the **Volume** module menu

Loading the DWI Dataset

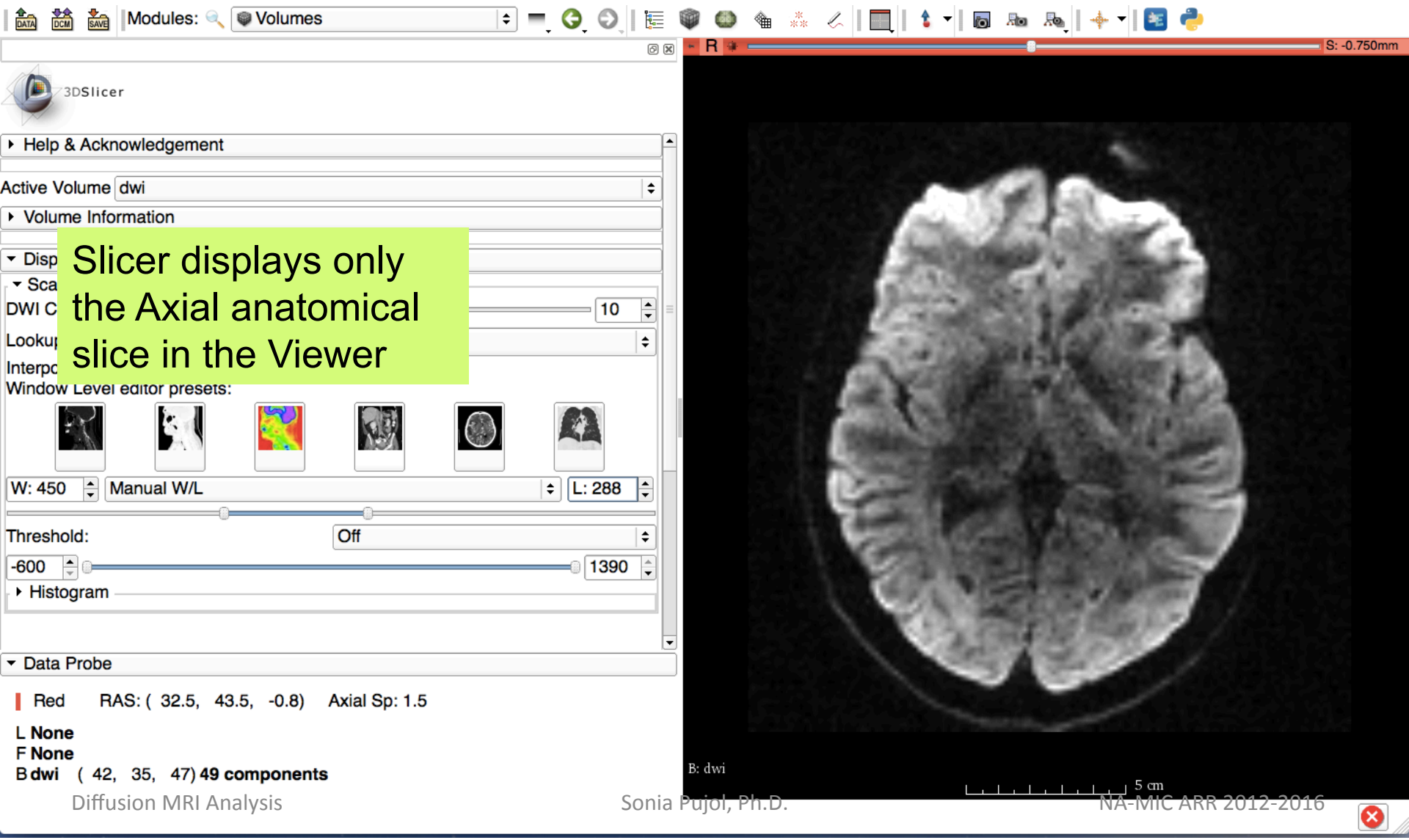


Loading the DWI Dataset

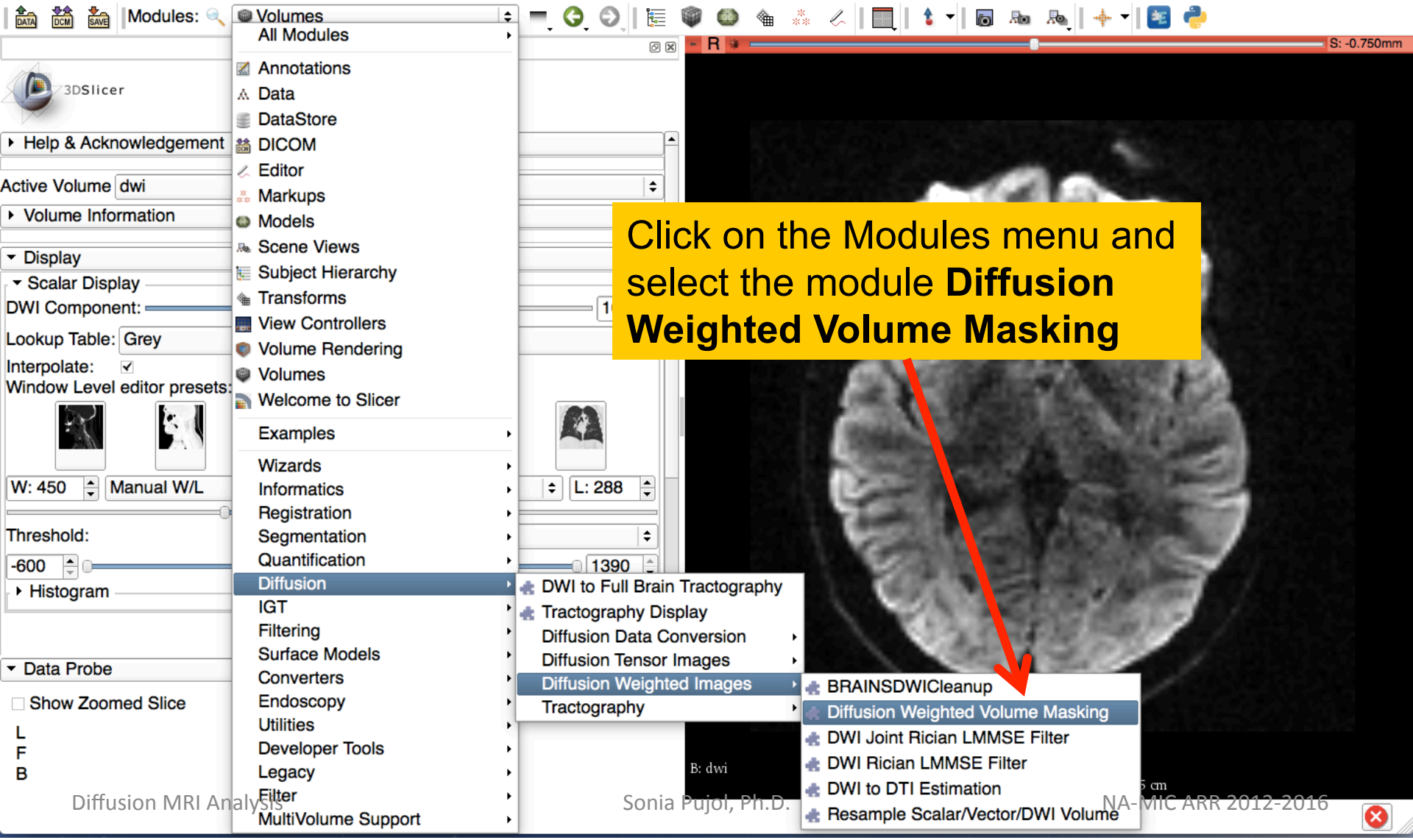


Click on the Slicer layout menu and select the **Red slice only** layout

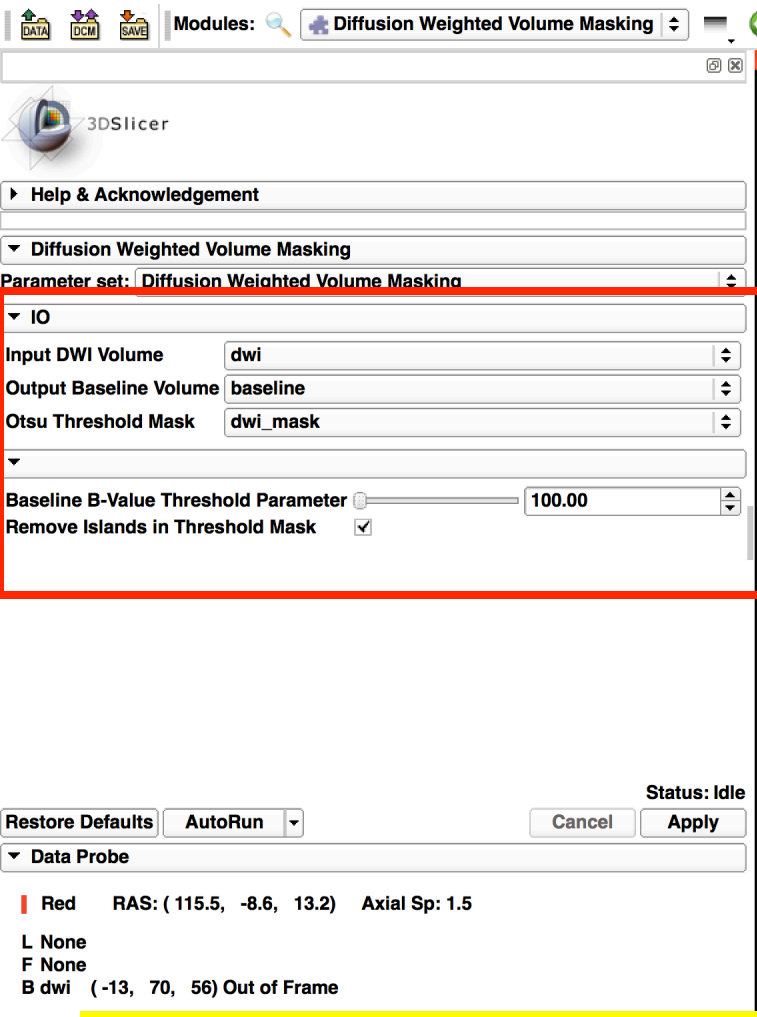
Loading the DWI Dataset



Creating a brain mask



Creating a brain mask



-Select the **Input DWI volume 'dwi'**

-Select **Output Baseline Volume 'Create and Rename New Volume'**, and rename it '**baseline**'

-Select **Output Threshold Volume 'Create and Rename new Volume'**, and rename it '**dwi_mask**'

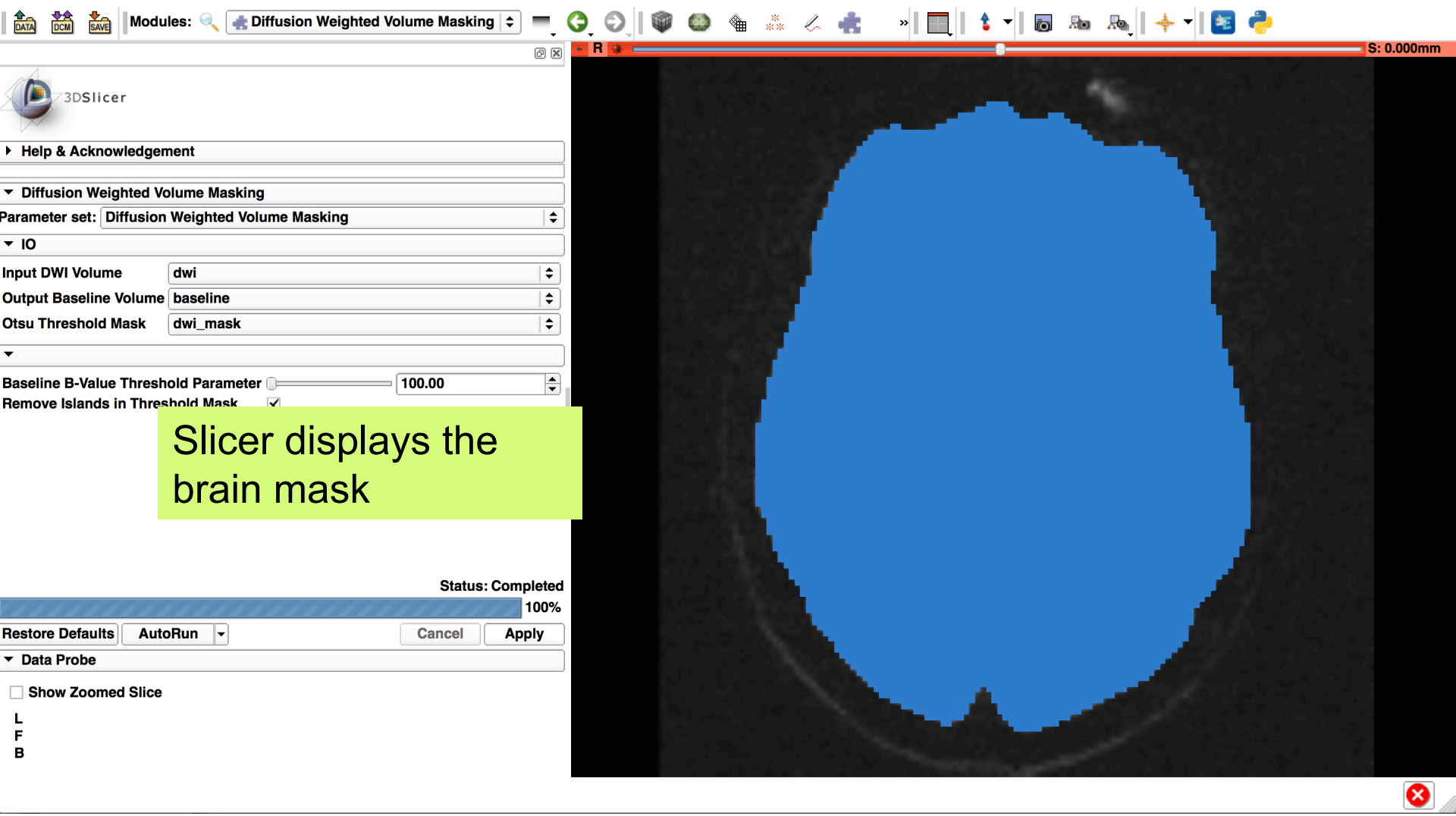
-set **Baseline B-Value Threshold Parameter to 100**

-Check **Remove Islands in Threshold Mask**

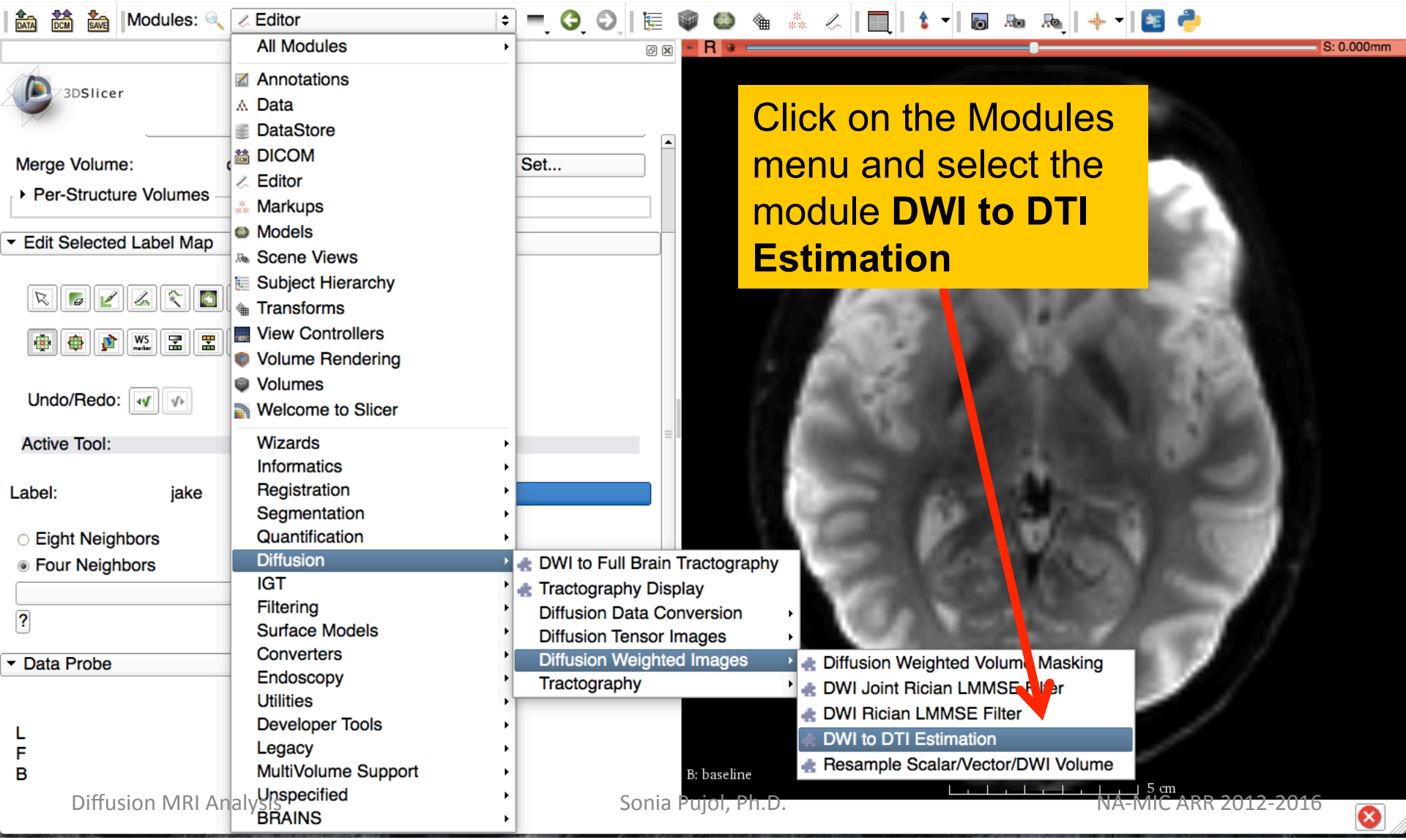
-Click on **Apply**.

Note: This version of the Diffusion Weighted Volume Masking module is available in the Slicer4.5 nighlty build posterior to Feb.23, 2016

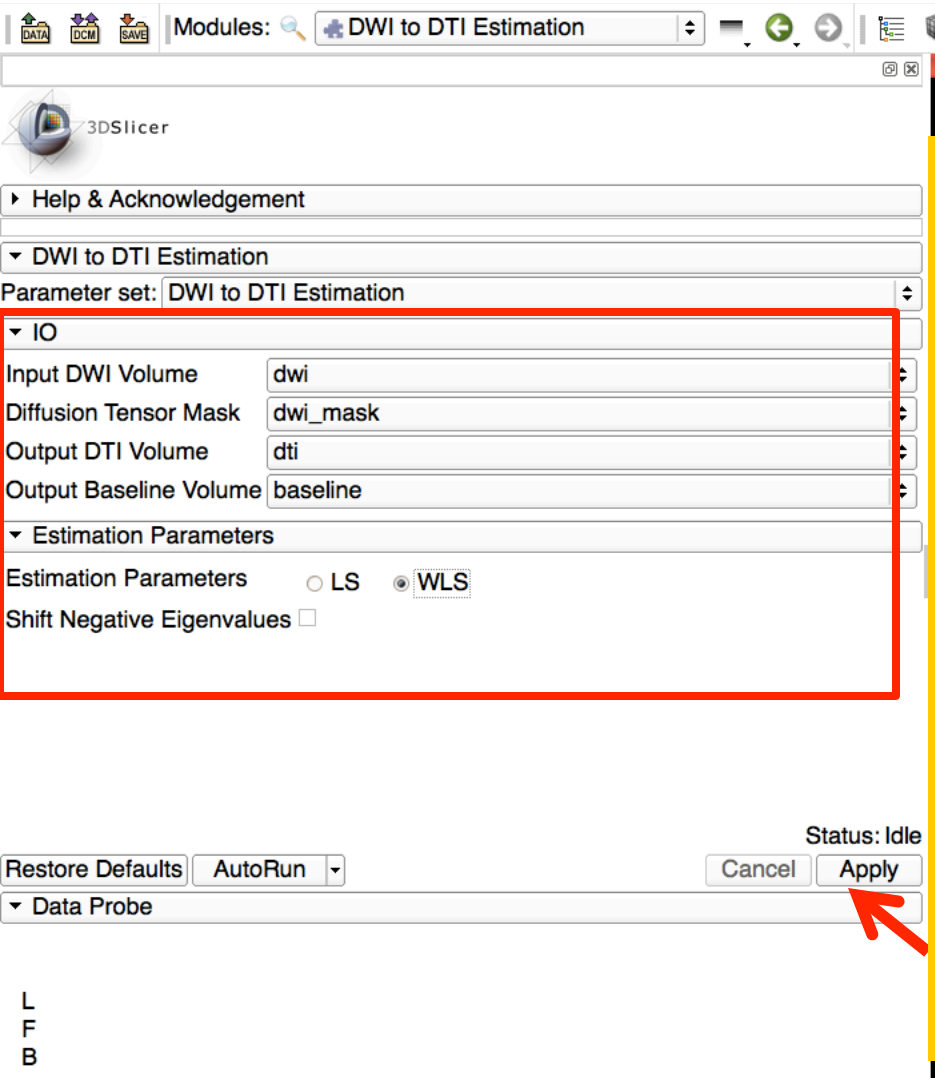
Creating a brain mask



Estimating the tensor



Estimating the tensor



Select the module **DWI to DTI Estimation** in the modules menu:

-Set the **Input DWI volume** to '**dwi**'

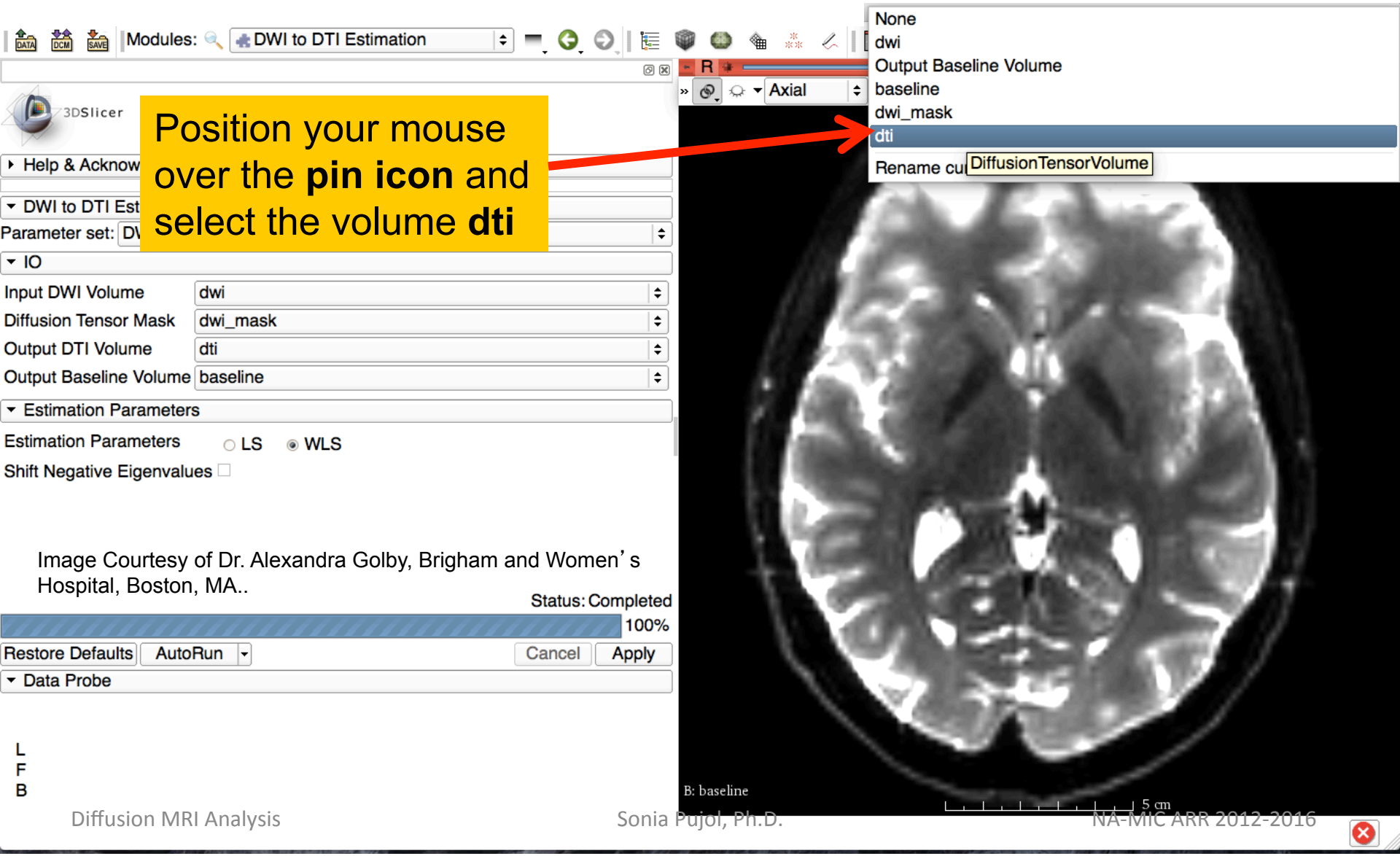
-Set the **Diffusion Tensor Mask** to '**dwi_mask**'

- Select **Output DTI Volume** '**Create and Rename New Volume**', and rename it '**dti**'

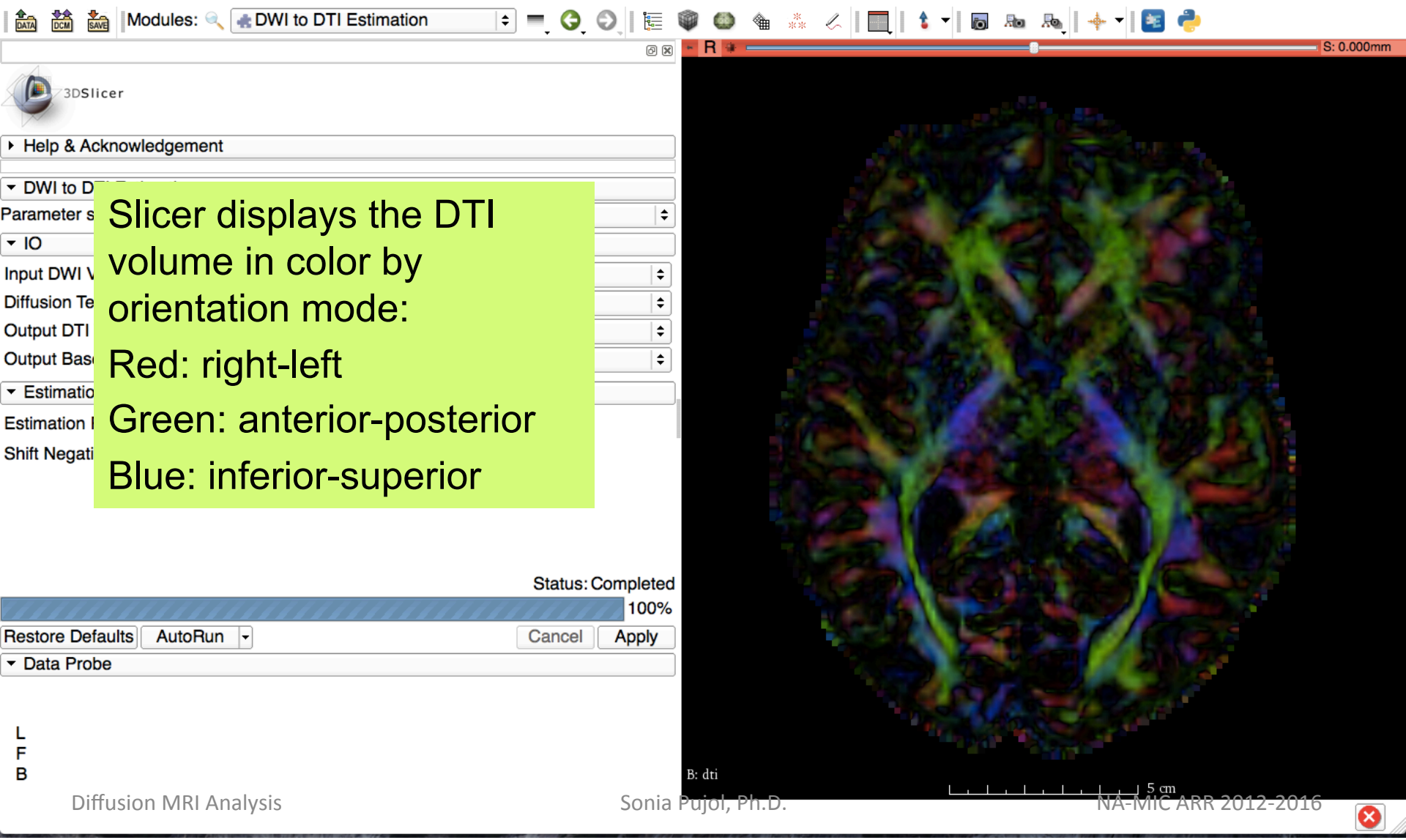
-Set **Output Baseline Volume** to '**baseline**'

-Select the **Estimation Parameters** '**WLS**' (Weighted Least Squares) and click on **Apply**.

Estimating the tensor



Exploring the DWI Dataset



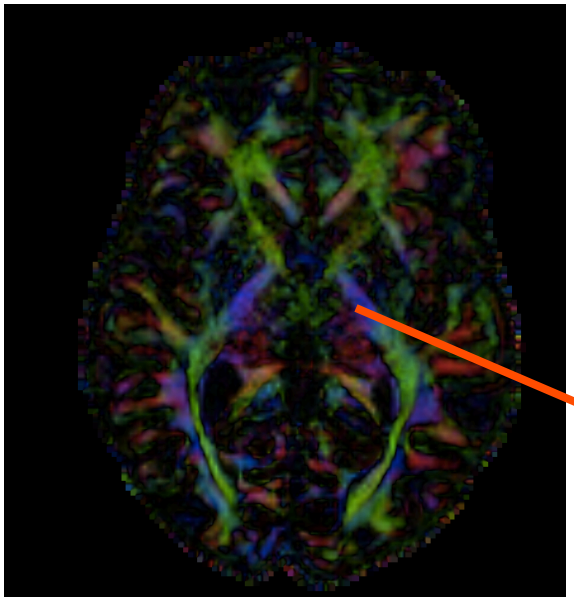
Slicer displays the DTI volume in color by orientation mode:

Red: right-left

Green: anterior-posterior

Blue: inferior-superior

Diffusion Tensor Data



$$S_i = S_0 e^{-b\hat{g}i^T \underline{D} \hat{g}_i}$$

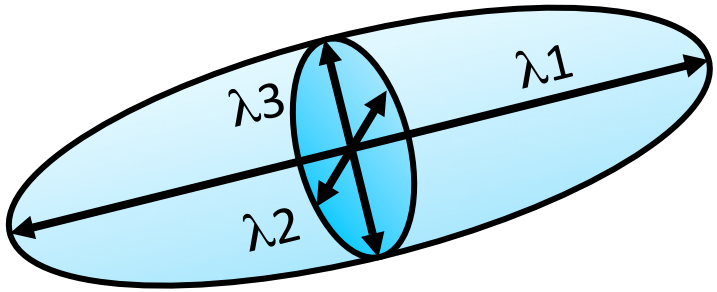
Stejskal-Tanner equation (1965)

$$\underline{\mathbf{D}} = \begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{zx} & D_{zy} & D_{zz} \end{bmatrix}$$

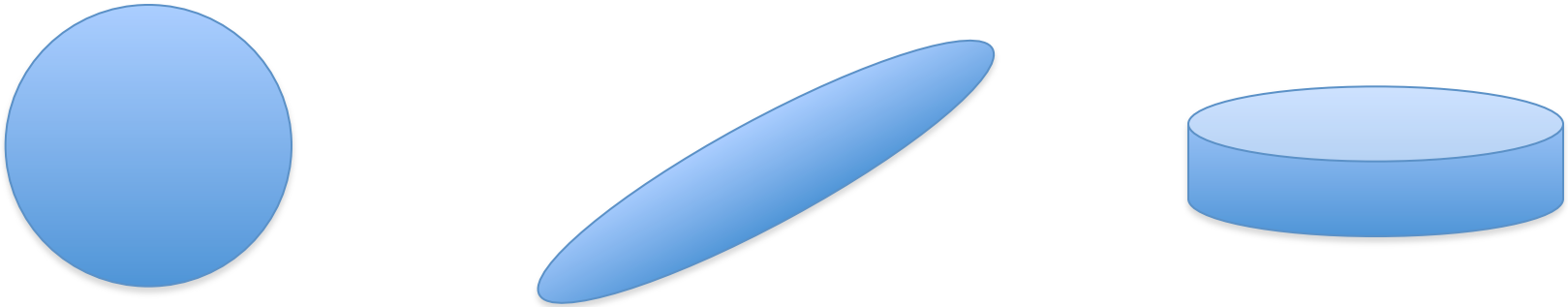
The diffusion tensor D in the voxel (I,J,K) is a 3x3 symmetric matrix.

Diffusion Tensor

- The diffusion tensor $\underline{D}$ in each voxel can be visualized as a diffusion ellipsoid, with the eigenvectors indicating the directions of the principal axes, and the ellipsoidal proportional to the square root of the eigenvalues defining the
- Scalar maps can be derived from the rotationally invariant eigenvalues λ1, λ2, λ3 to characterize the size and shape of the diffusion tensor.



Diffusion Tensor Shape



$\lambda 1 = \lambda 2 = \lambda 3$

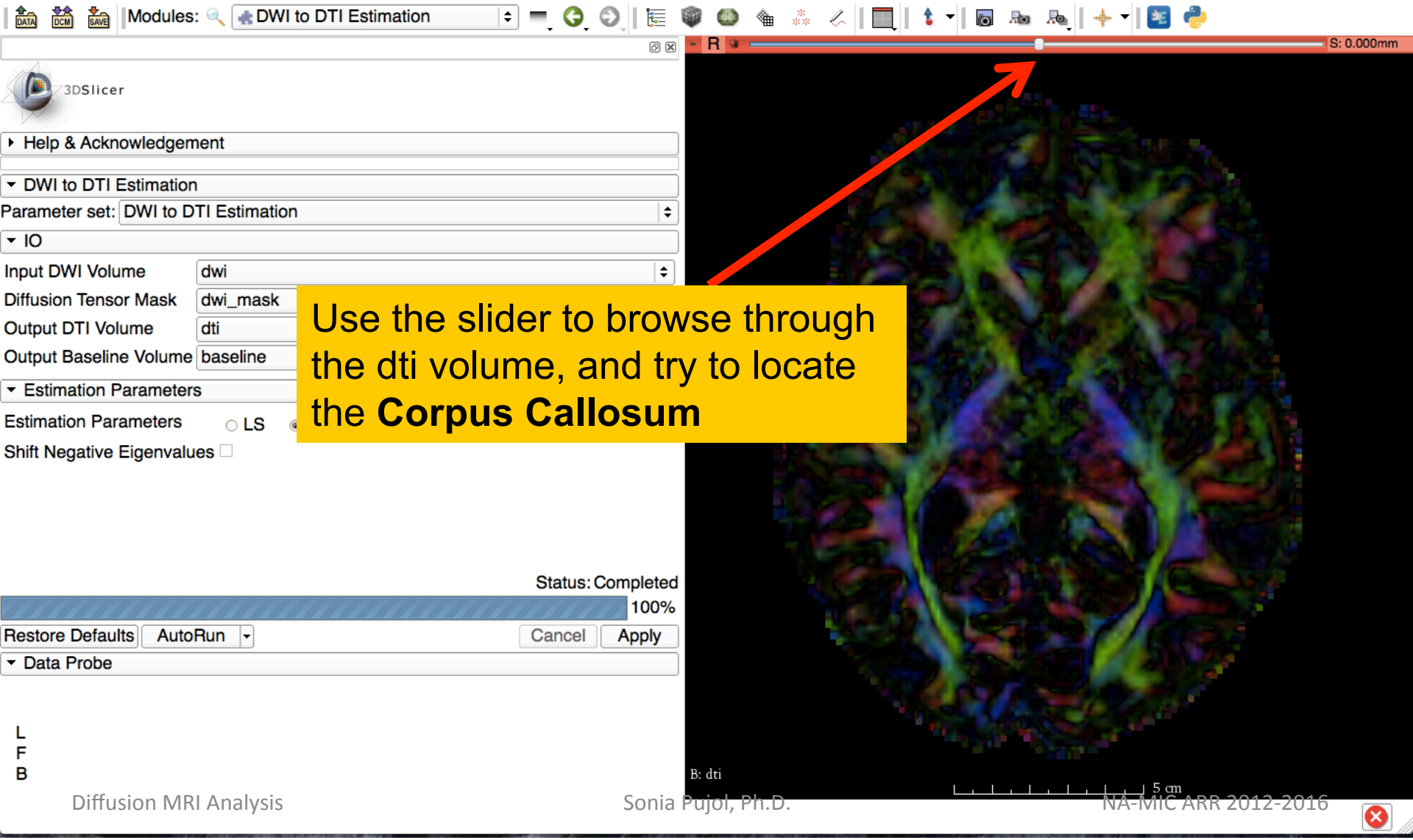
$\lambda 1 >> \lambda 2, \lambda 3$

$\lambda 1 \sim \lambda 2 >> \lambda 3$

Isotropic media (Cerebrospinal Fluid, gray matter)

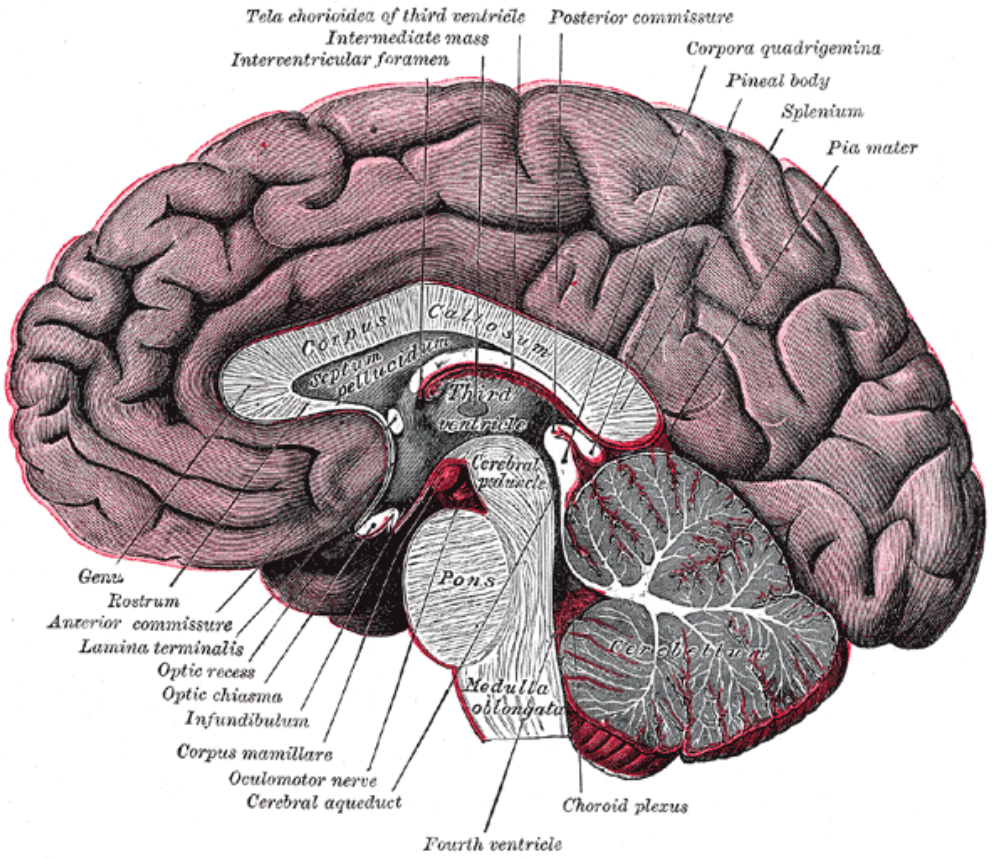
Anisotropic media (white matter)

Exploring the DWI Dataset



Use the slider to browse through the dti volume, and try to locate the **Corpus Callosum**

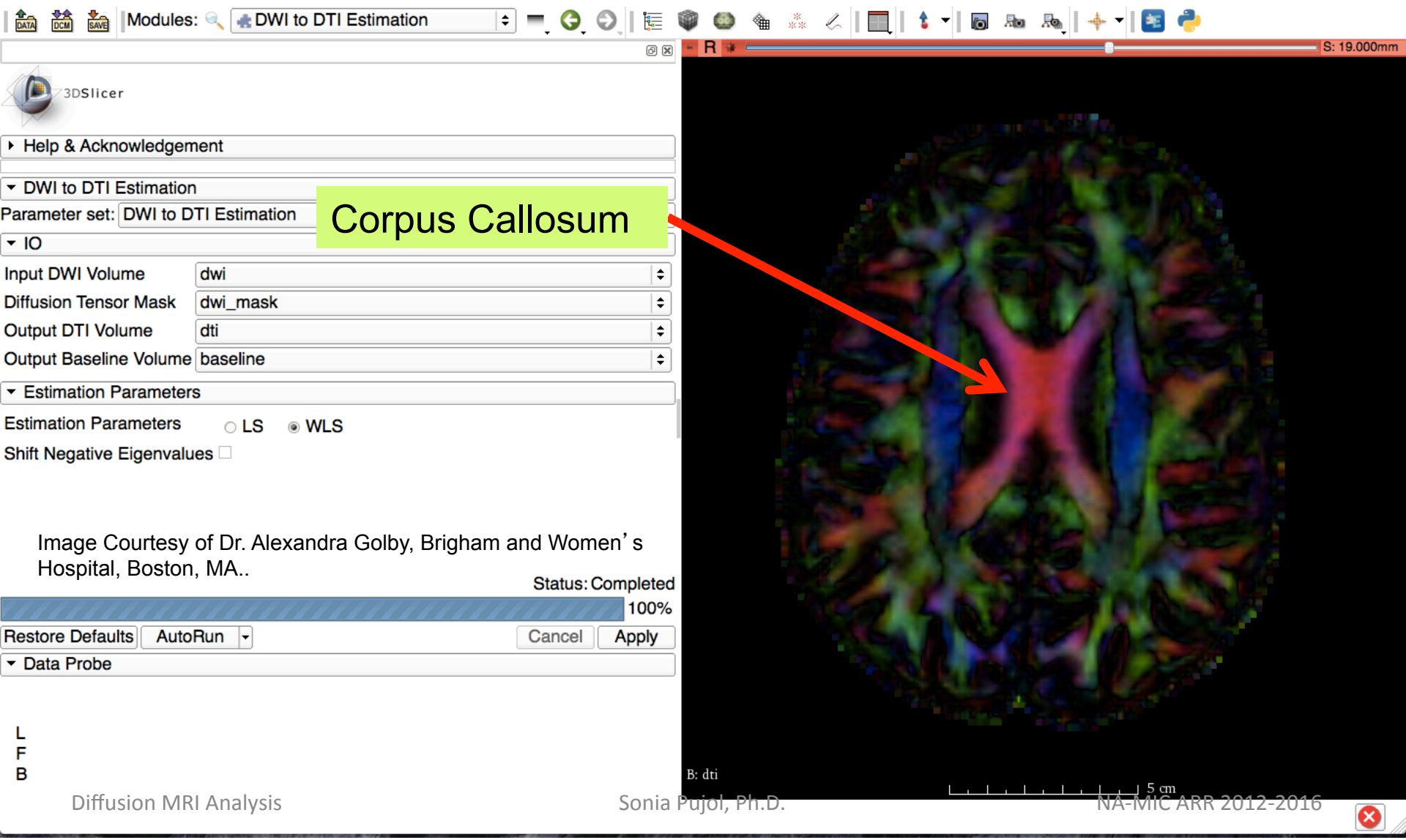
Corpus Callosum



The corpus callosum is a broad thick bundle of dense myelinated fibers that connect the left and right hemisphere. It is the largest white matter structure in the brain

Image from Gray's Anatomy

Corpus Callosum

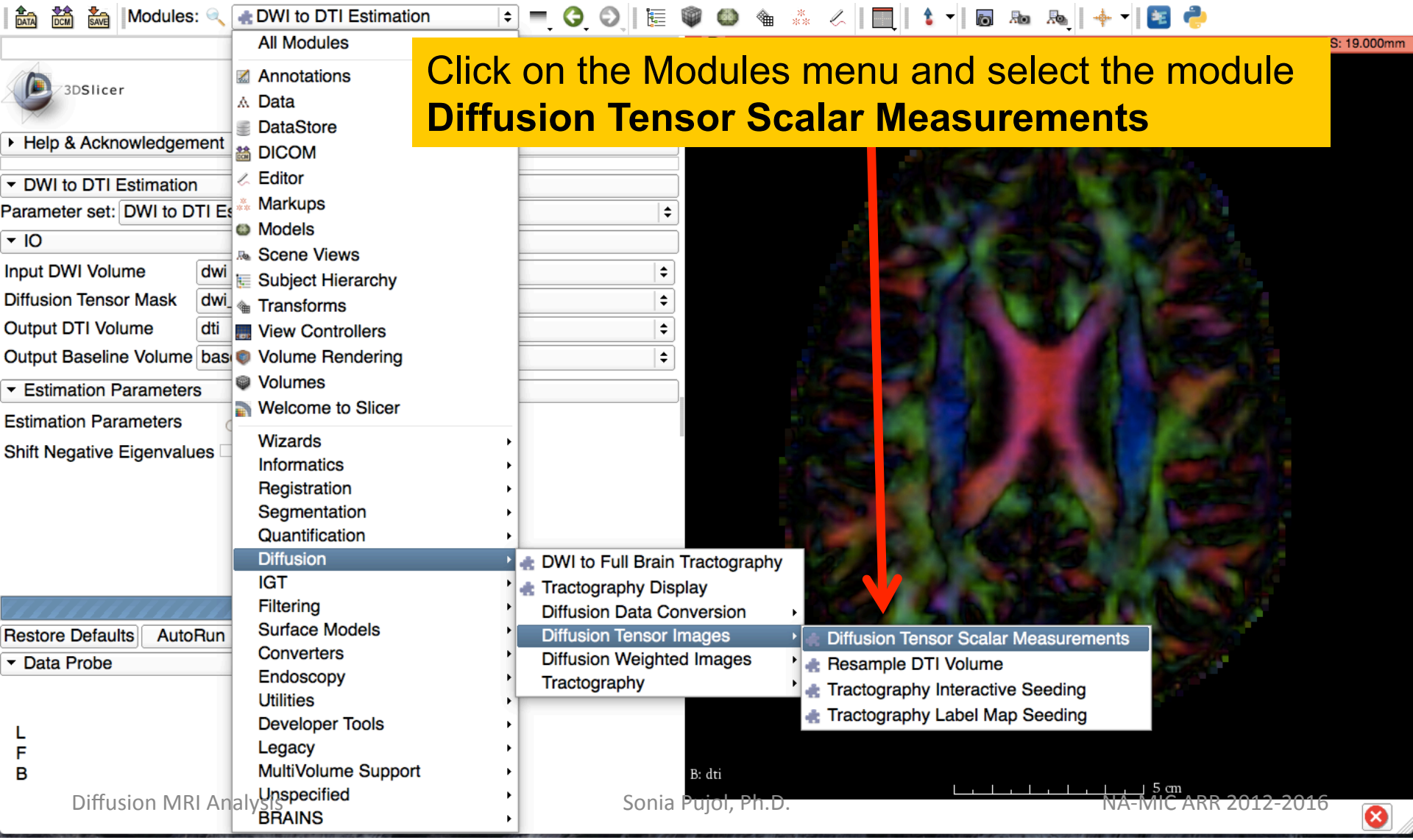


Characterizing the Size of the tensor: Trace

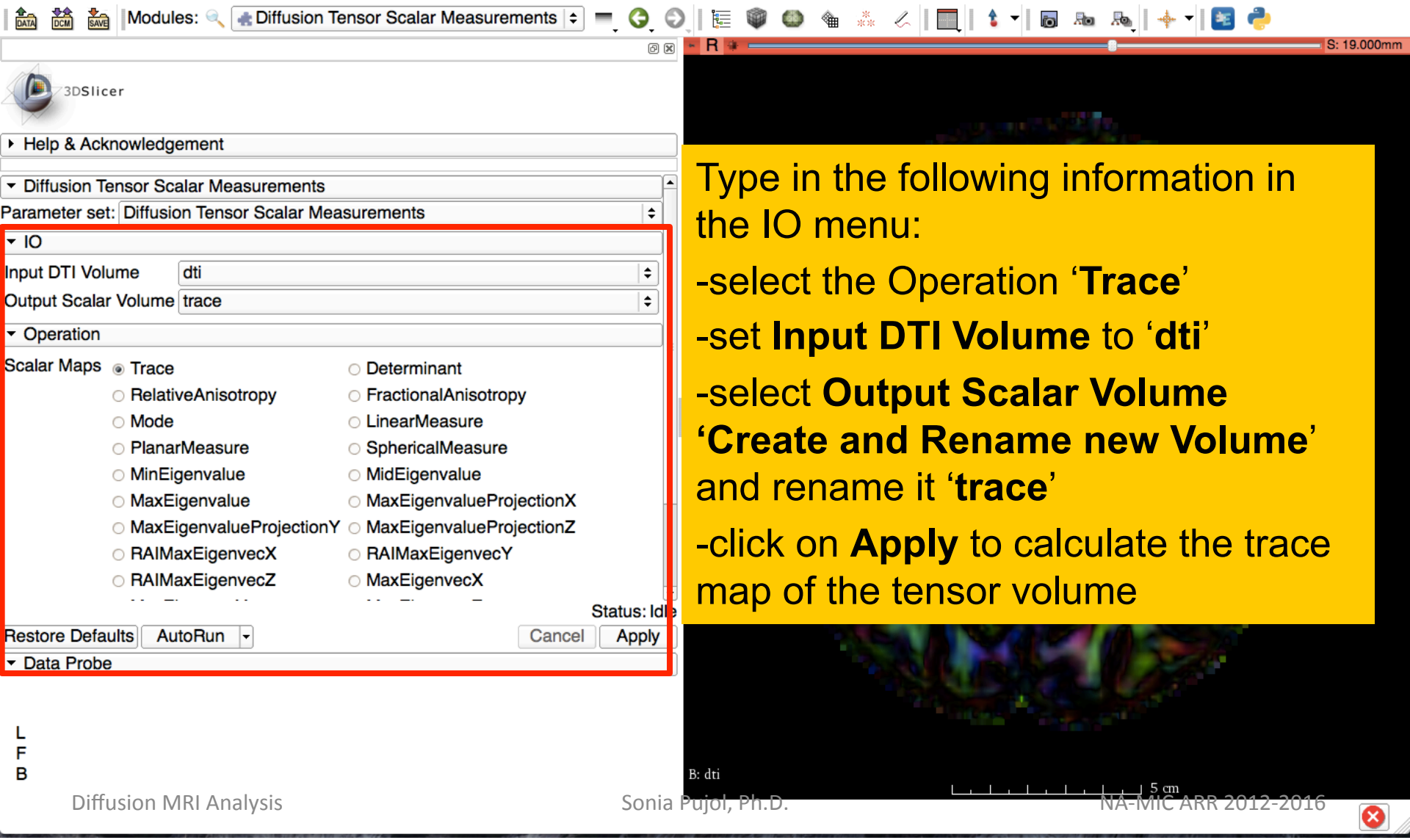
$$\text{Trace}(D) = \lambda 1 + \lambda 2 + \lambda 3$$

- Trace(D) is intrinsic to the tissue and is independent of fiber orientation, and diffusion sensitizing gradient directions
- Trace(D) is a clinically relevant parameter for monitoring stroke and neurological condition (degree of structural coherence in tissue)
- Trace(D) is useful to characterize the size of the diffusion ellipsoid

Trace


Modules:
DWI to DTI Estimation
All Modules
Annotations
Data
DataStore
DICOM
Editor
Markups
Models
Scene Views
Subject Hierarchy
Transforms
View Controllers
Volume Rendering
Volumes
Welcome to Slicer
Wizards
Informatics
Registration
Segmentation
Quantification
Diffusion
IGT
Filtering
Surface Models
Converters
Endoscopy
Utilities
Developer Tools
Legacy
MultiVolume Support
Unspecified
BRAINS
DWI to Full Brain Tractography
Tractography Display
Diffusion Data Conversion
Diffusion Tensor Images
Diffusion Weighted Images
Tractography
Diffusion Tensor Scalar Measurements
Resample DTI Volume
Tractography Interactive Seeding
Tractography Label Map Seeding
Click on the Modules menu and select the module
Diffusion Tensor Scalar Measurements
3DSlicer
Help & Acknowledgement
DWI to DTI Estimation
Parameter set:
IO
Input DWI Volume
Diffusion Tensor Mask
Output DTI Volume
Output Baseline Volume
Estimation Parameters
Estimation Parameters
Shift Negative Eigenvalues
Restore Defaults
AutoRun
Data Probe
L
F
B
B: dti
5 cm

Trace



Type in the following information in the IO menu:

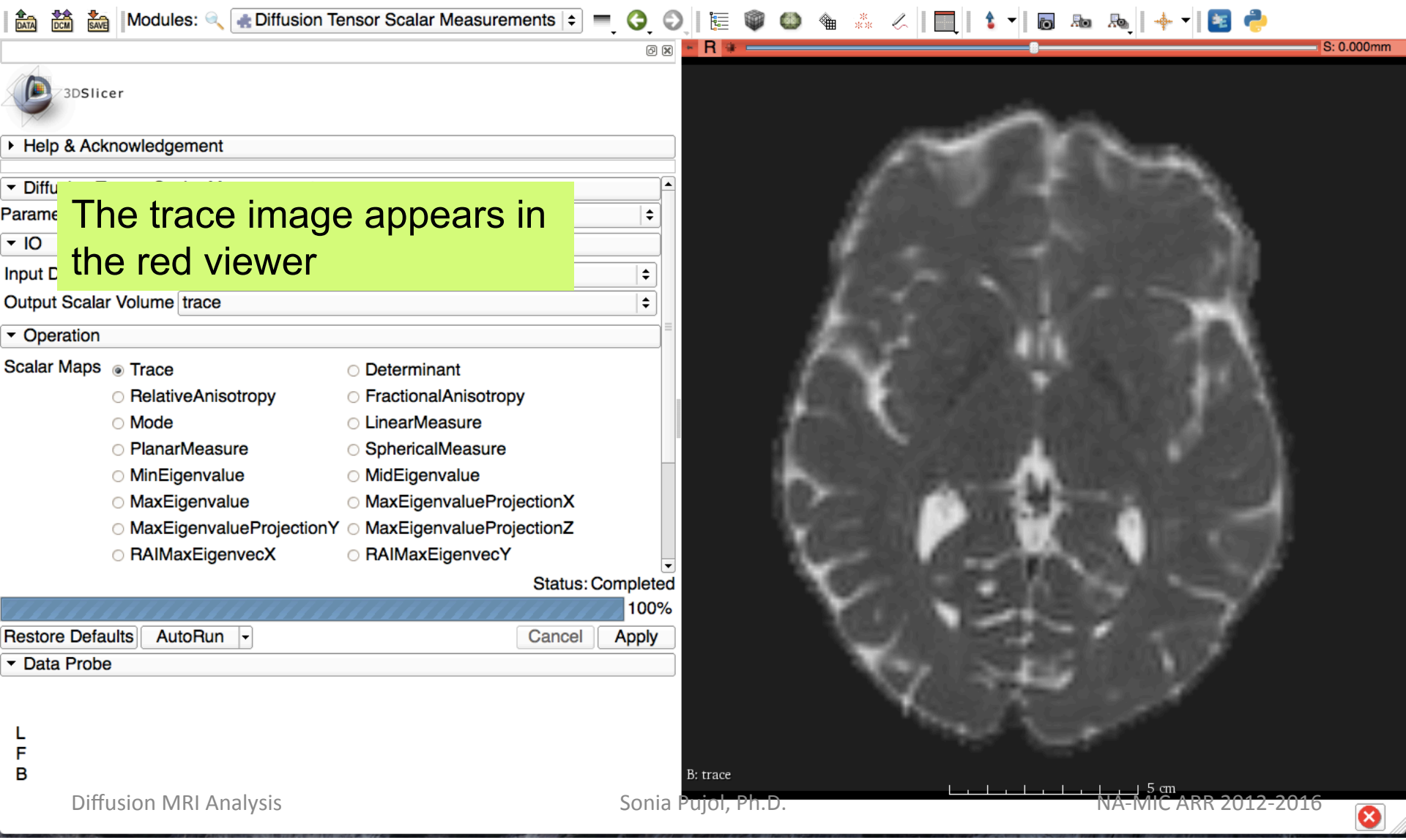
-select the Operation '**Trace**'

-set **Input DTI Volume** to '**dti**'

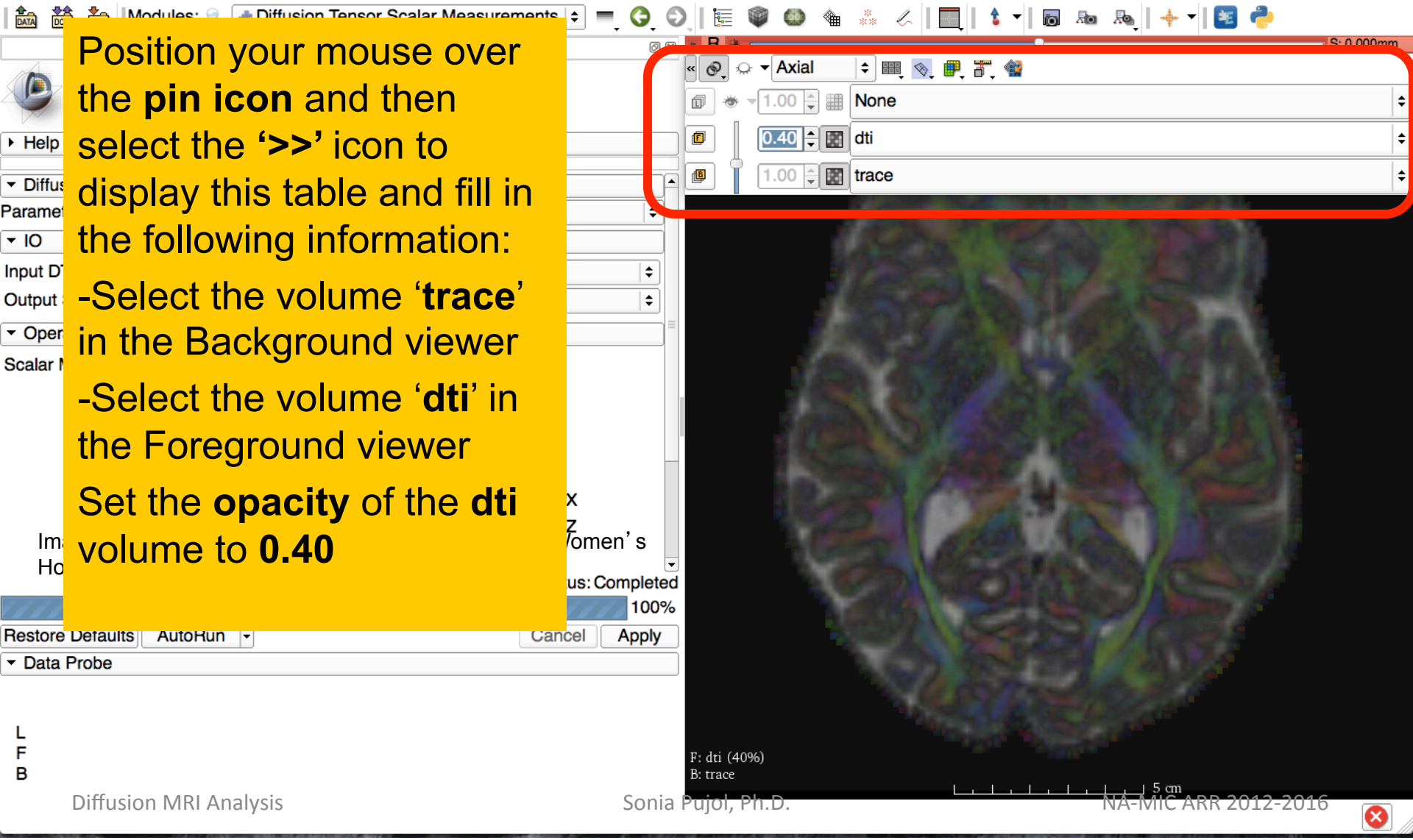
-select **Output Scalar Volume** '**Create and Rename new Volume**' and rename it '**trace**'

-click on **Apply** to calculate the trace map of the tensor volume

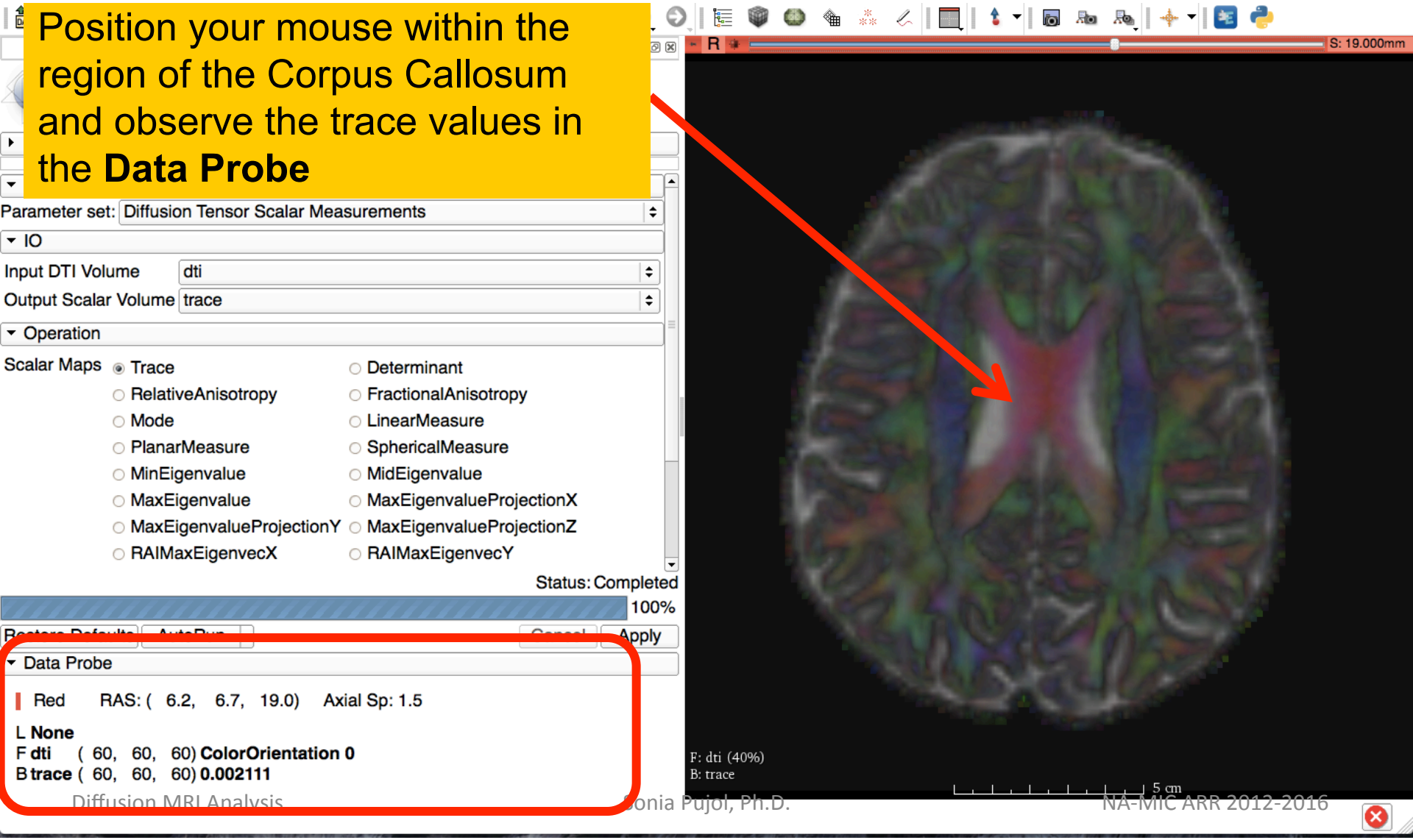
Trace


Modules:
Diffusion Tensor Scalar Measurements
3DSlicer
Help & Acknowledgement
The trace image appears in the red viewer
IO
Output Scalar Volume
trace
Operation
Scalar Maps
Trace
Determinant
RelativeAnisotropy
FractionalAnisotropy
Mode
LinearMeasure
PlanarMeasure
SphericalMeasure
MinEigenvalue
MidEigenvalue
MaxEigenvalue
MaxEigenvalueProjectionX
MaxEigenvalueProjectionY
MaxEigenvalueProjectionZ
RAIMaxEigenvecX
RAIMaxEigenvecY
Status: Completed
100%
Restore Defaults
AutoRun
Cancel
Apply
Data Probe
L
F
B
R
S: 0.000mm
B: trace
5 cm

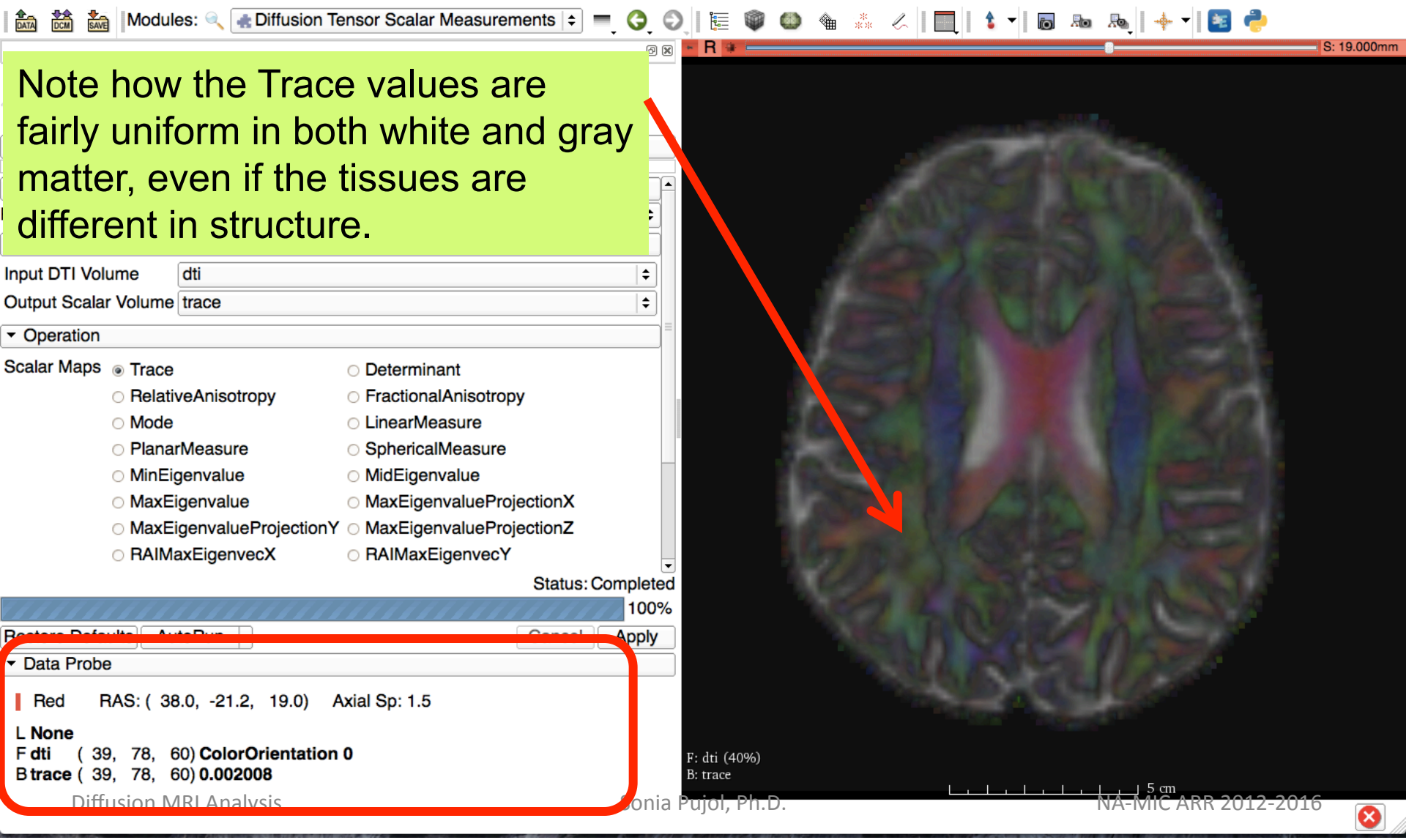
Trace


Position your mouse over the **pin icon** and then select the **'>>'** icon to display this table and fill in the following information:
-Select the volume '**trace**' in the Background viewer
-Select the volume '**dti**' in the Foreground viewer
Set the **opacity** of the **dti** volume to **0.40**
Axial
1.00
None
0.40
dti
1.00
trace
Help
IO
Data Probe
Restore Defaults
AutoRun
Cancel
Apply
100%
F: dti (40%)
B: trace
5 cm
L
F
B

Trace


Position your mouse within the region of the Corpus Callosum and observe the trace values in the **Data Probe**
Parameter set: Diffusion Tensor Scalar Measurements
IO
Input DTI Volume dti
Output Scalar Volume trace
Operation
Scalar Maps
Trace
Determinant
RelativeAnisotropy
FractionalAnisotropy
Mode
LinearMeasure
PlanarMeasure
SphericalMeasure
MinEigenvalue
MidEigenvalue
MaxEigenvalue
MaxEigenvalueProjectionX
MaxEigenvalueProjectionY
MaxEigenvalueProjectionZ
RAIMaxEigenvecX
RAIMaxEigenvecY
Status: Completed
100%
Apply
Data Probe
Red RAS: (6.2, 6.7, 19.0) Axial Sp: 1.5
L None
F dti (60, 60, 60) ColorOrientation 0
B trace (60, 60, 60) 0.002111
R
S: 19.000mm
F: dti (40%)
B: trace
5 cm

Trace

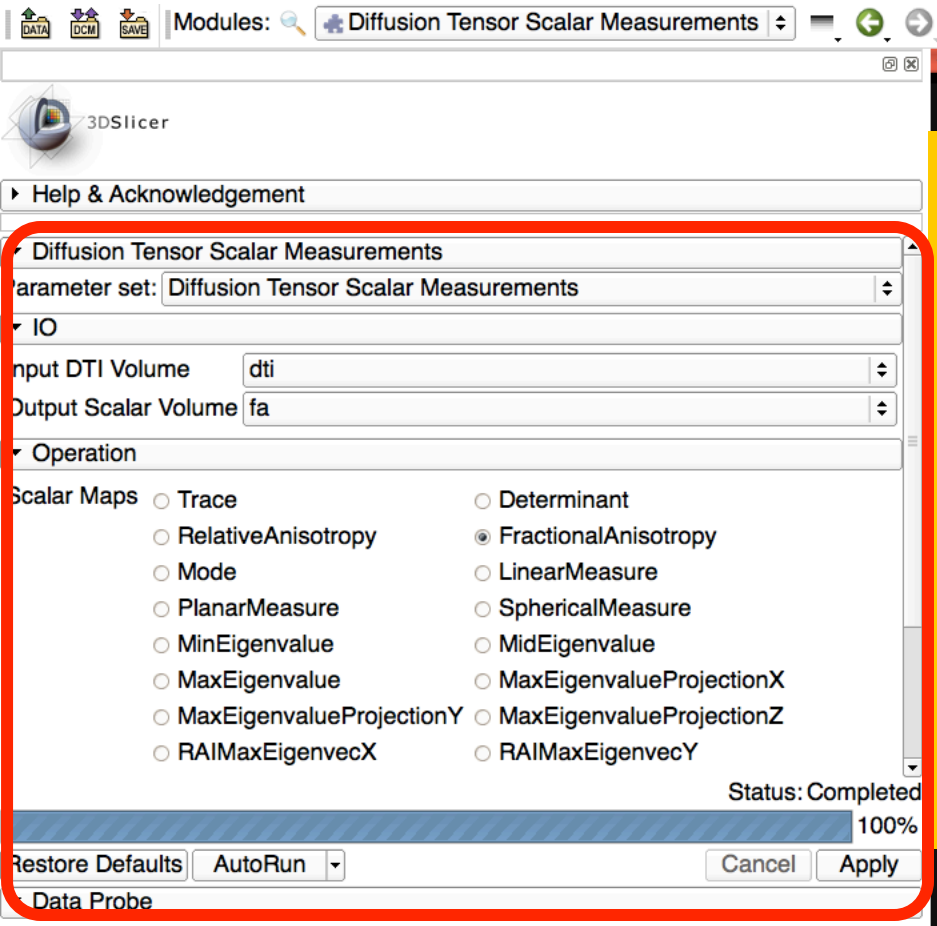

Modules:
Diffusion Tensor Scalar Measurements
Note how the Trace values are fairly uniform in both white and gray matter, even if the tissues are different in structure.
Input DTI Volume
dti
Output Scalar Volume
trace
Operation
Scalar Maps
Trace
Determinant
RelativeAnisotropy
FractionalAnisotropy
Mode
LinearMeasure
PlanarMeasure
SphericalMeasure
MinEigenvalue
MidEigenvalue
MaxEigenvalue
MaxEigenvalueProjectionX
MaxEigenvalueProjectionY
MaxEigenvalueProjectionZ
RAIMaxEigenvecX
RAIMaxEigenvecY
Status: Completed
100%
Apply
Data Probe
Red RAS: (38.0, -21.2, 19.0) Axial Sp: 1.5
L None
F dti (39, 78, 60) ColorOrientation 0
B trace (39, 78, 60) 0.002008
R
S: 19.000mm
F: dti (40%)
B: trace
5 cm

Scalar Maps: Fractional Anisotropy

$$FA(D) = \frac{\sqrt{(\lambda_1 - \lambda_2)^2 + (\lambda_1 - \lambda_3)^2 + (\lambda_2 - \lambda_3)^2}}{\sqrt{2}\sqrt{\lambda_1^2 + \lambda_2^2 + \lambda_3^2}}$$

- FA(D) is intrinsic to the tissue and is independent of fiber orientation, and diffusion sensitizing gradient directions
- FA(D) is useful to characterize the shape (degree of 'out-of-roundness') of the diffusion ellipsoid
- Low FA:  High FA: 

Fractional Anisotropy



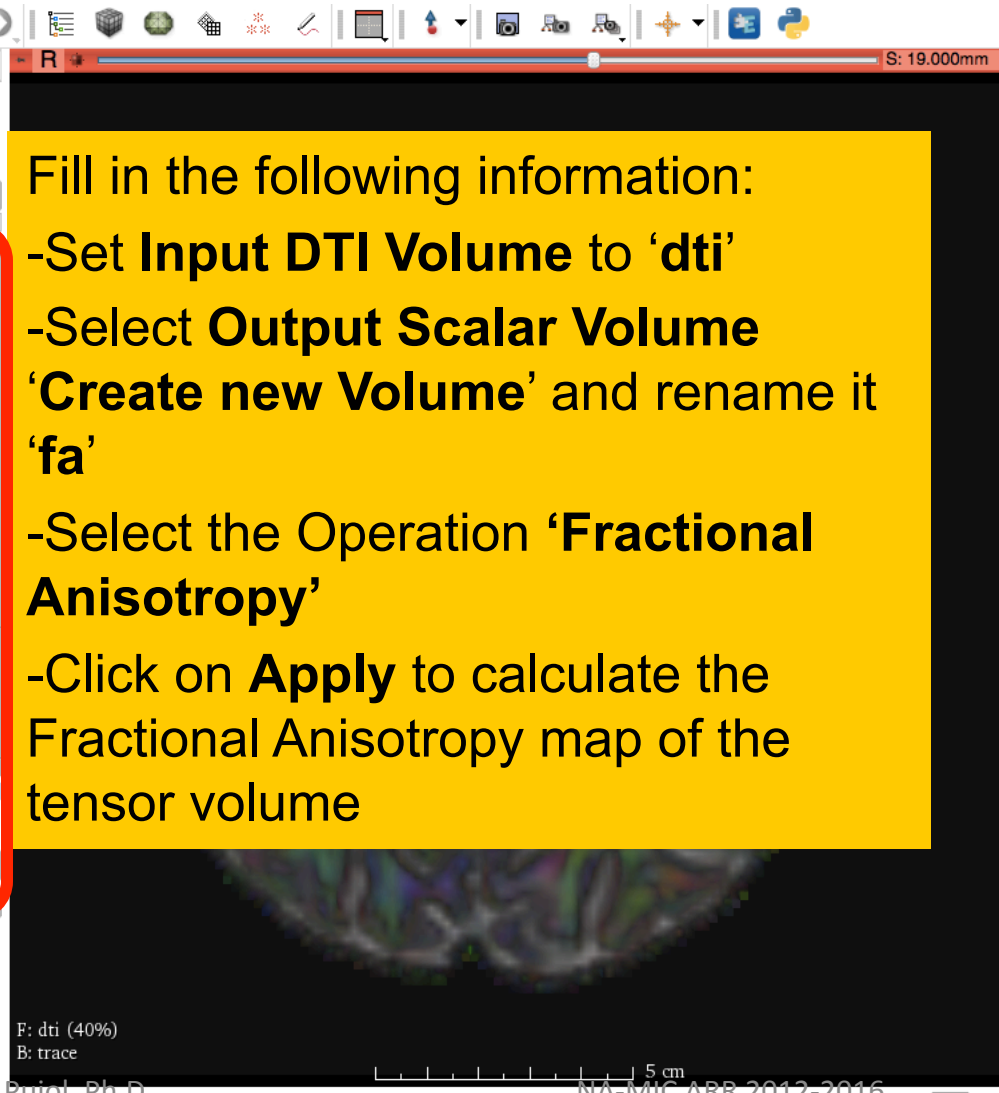
Fill in the following information:

-Set **Input DTI Volume** to '**dti**'

-Select **Output Scalar Volume** '**Create new Volume**' and rename it '**fa**'

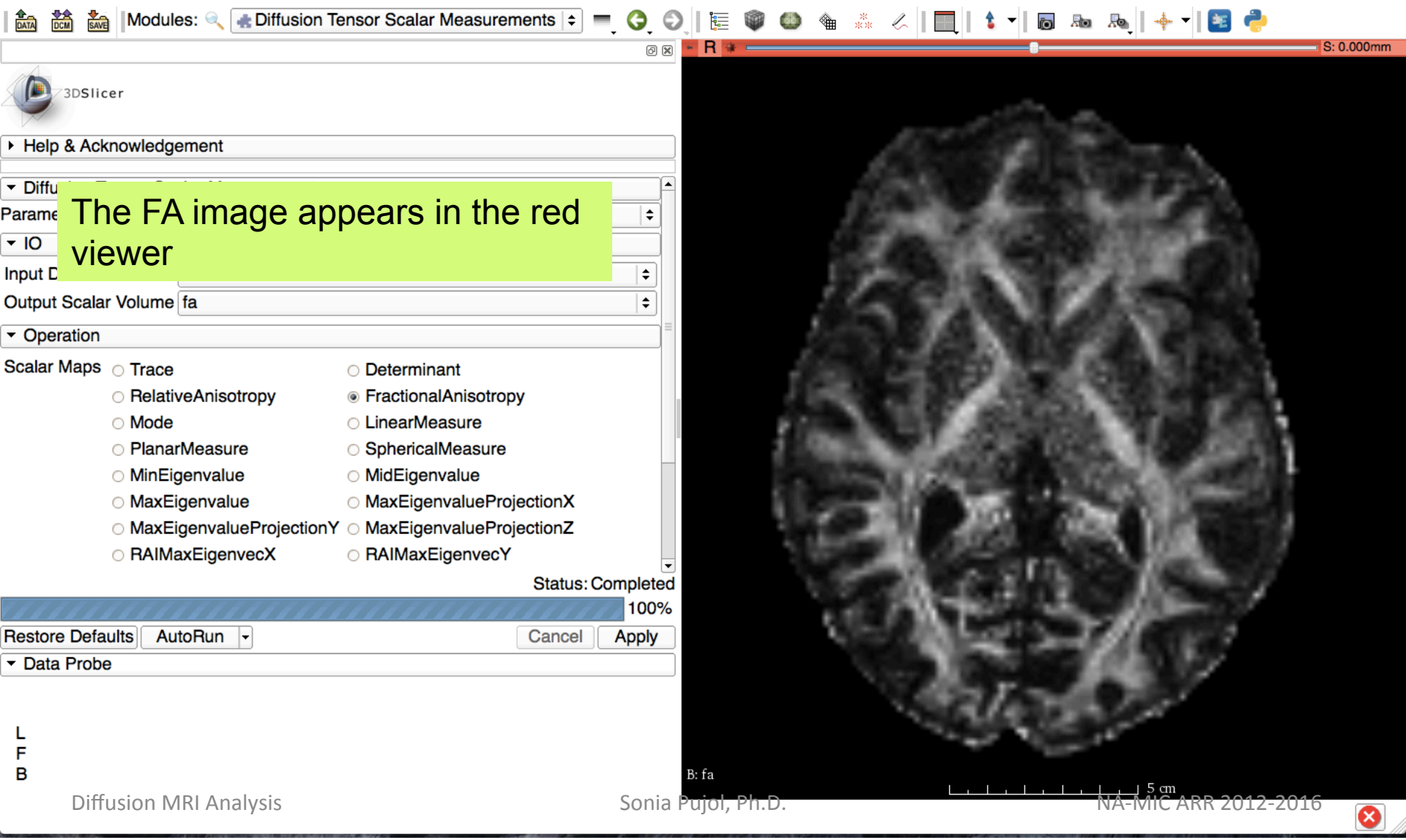
-Select the Operation **'Fractional Anisotropy'**

-Click on **Apply** to calculate the Fractional Anisotropy map of the tensor volume

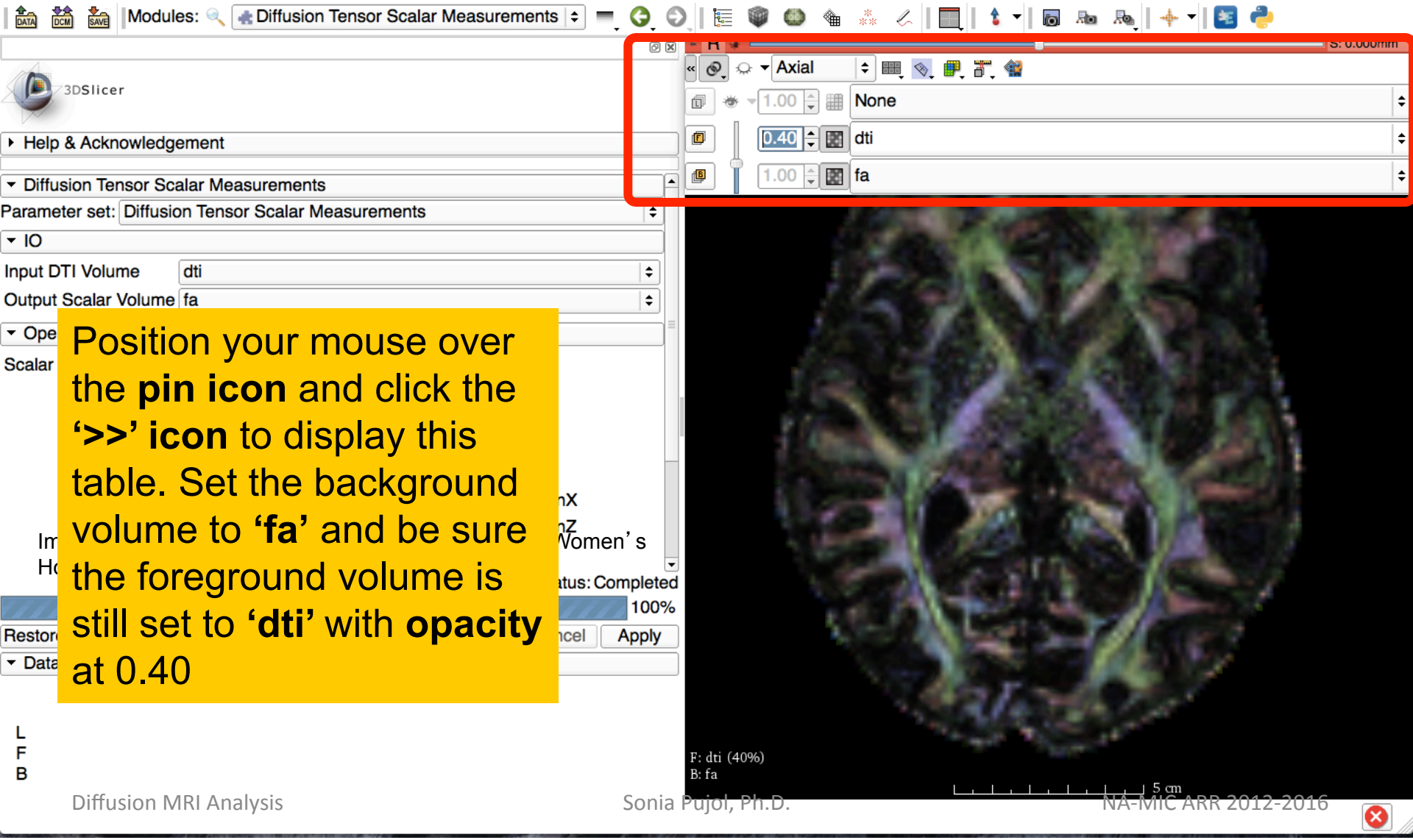


L
F
B

Fractional Anisotropy

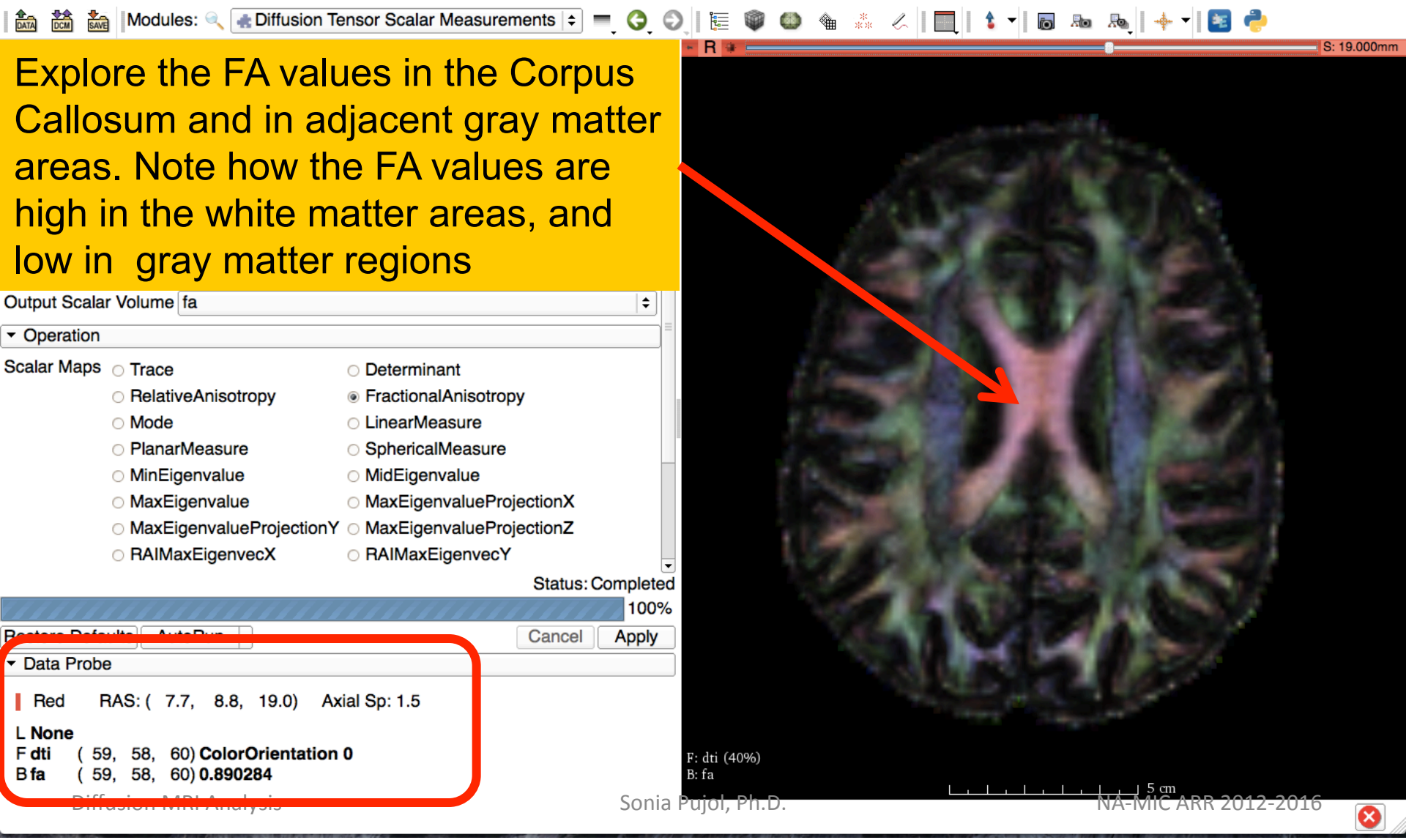


Fractional Anisotropy

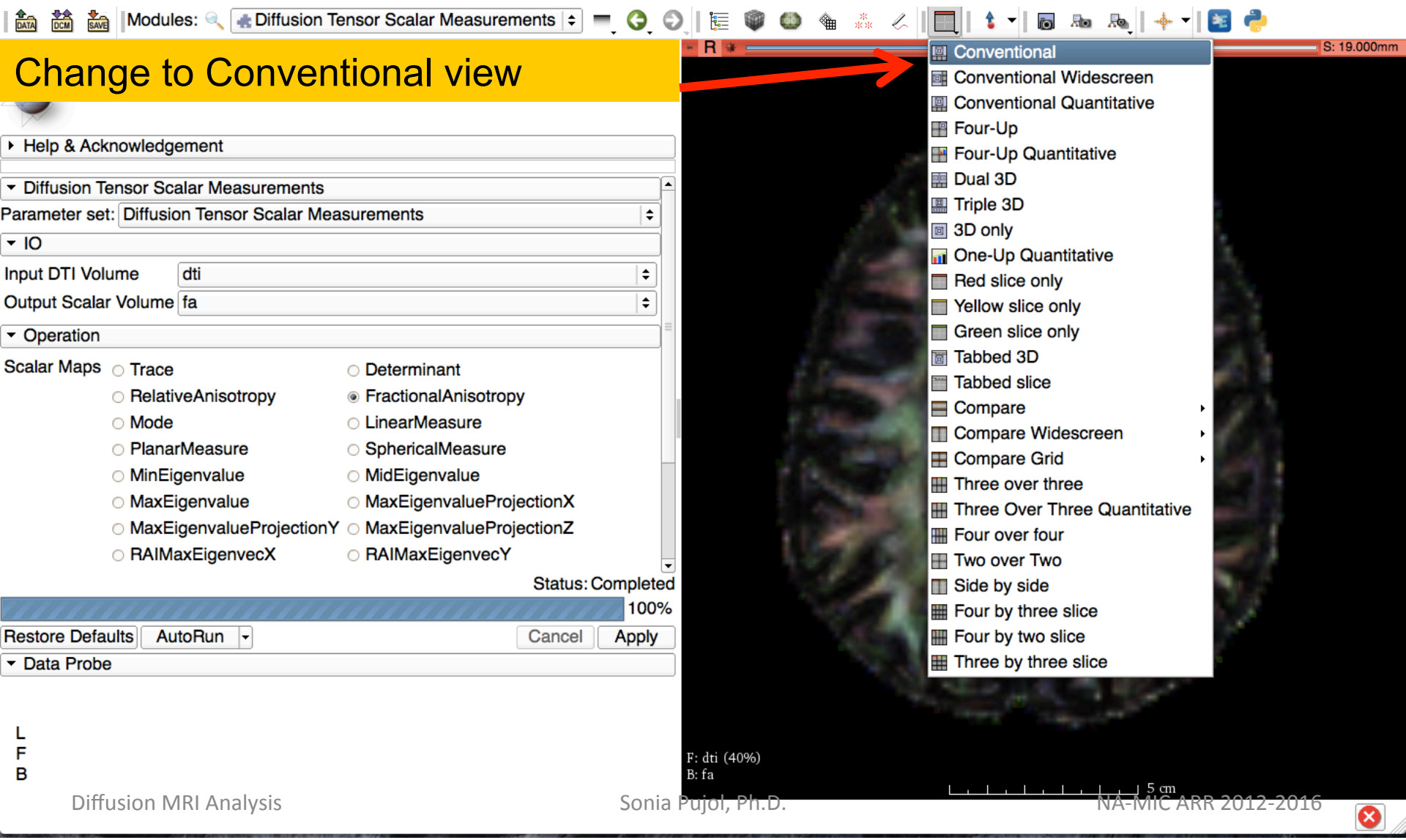


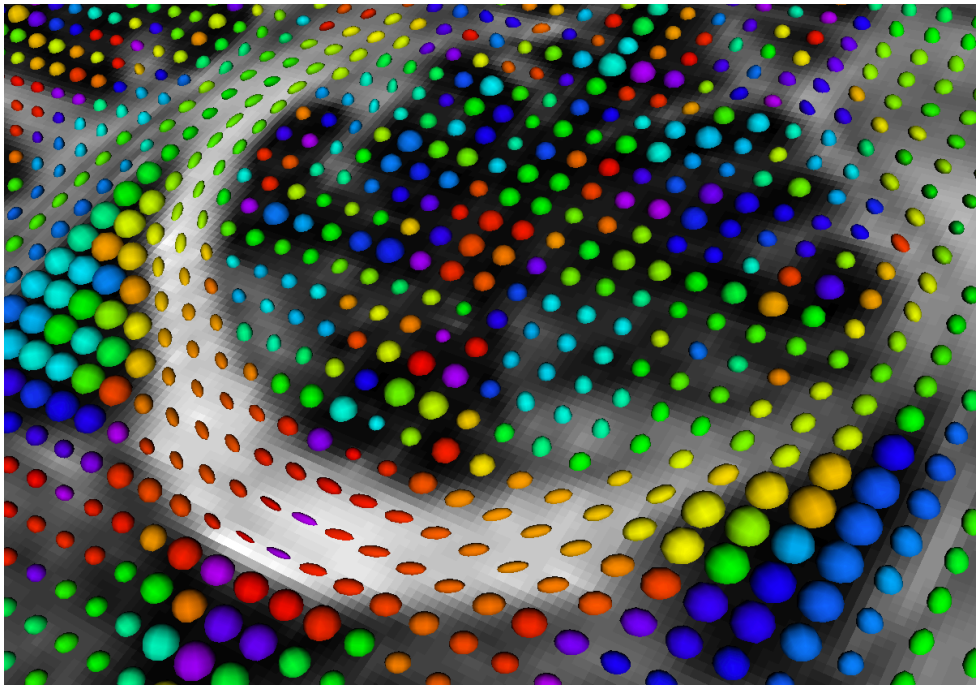
Position your mouse over the **pin icon** and click the **'>>' icon** to display this table. Set the background volume to **'fa'** and be sure the foreground volume is still set to **'dti'** with **opacity** at 0.40

Fractional Anisotropy



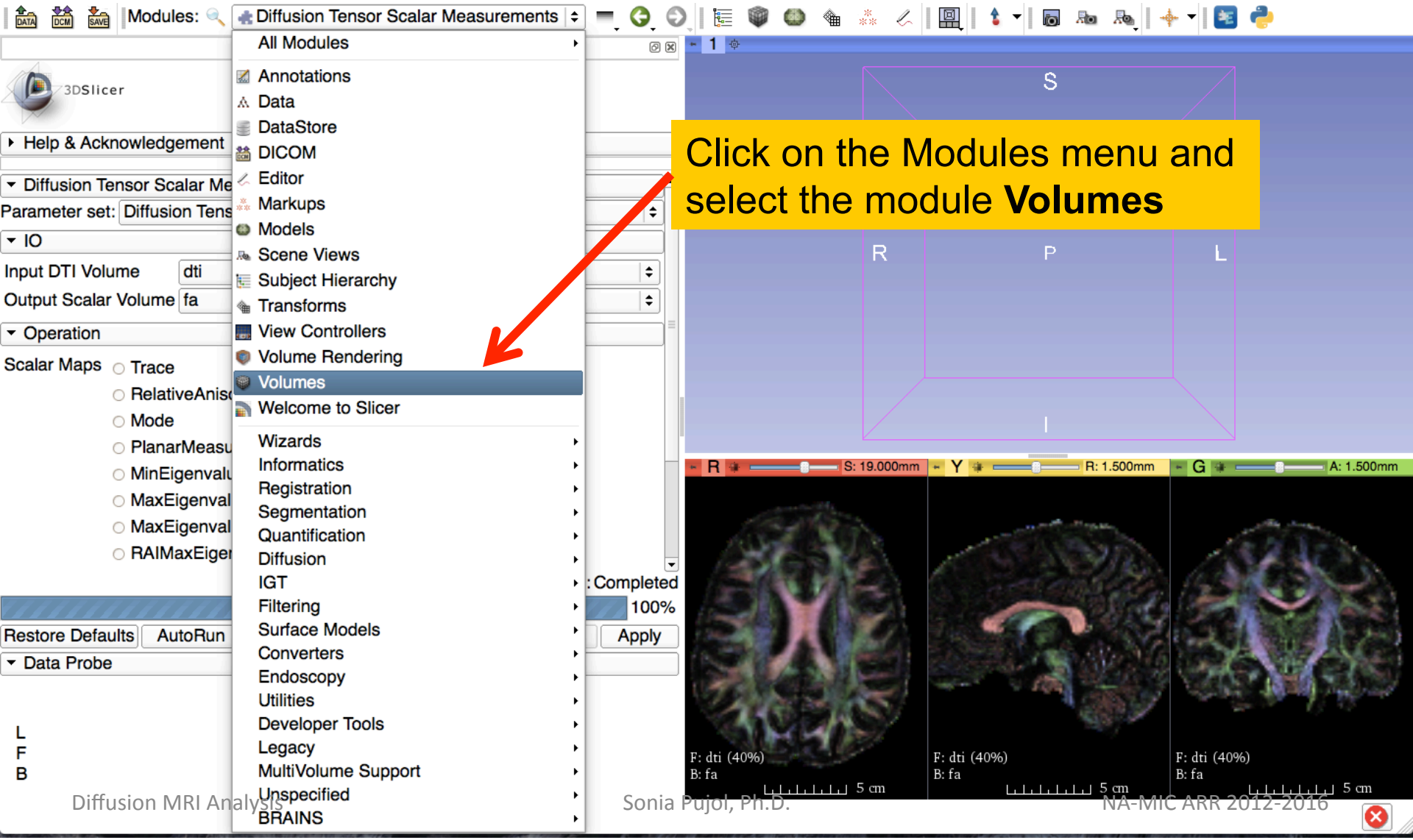
Fractional Anisotropy



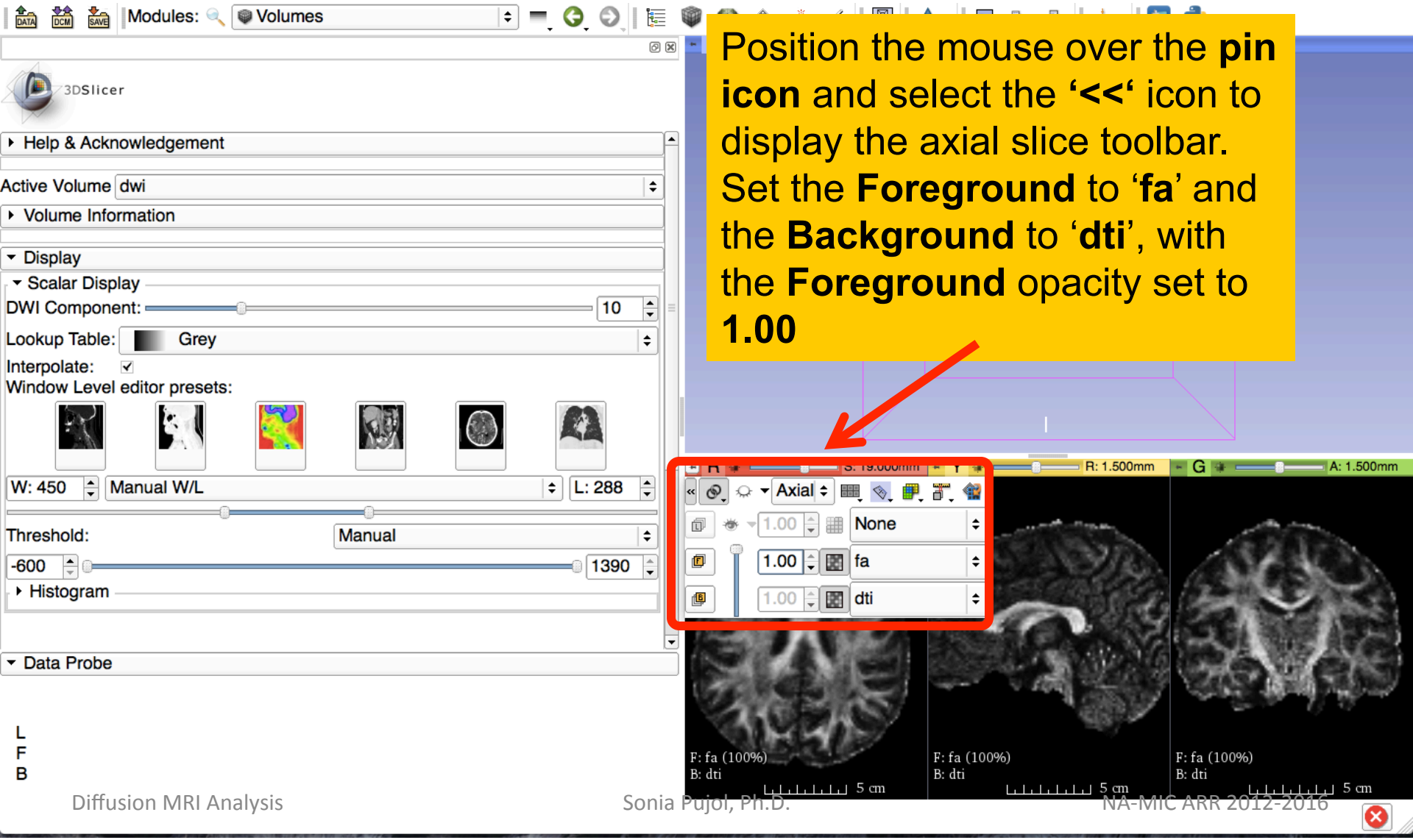


Part 2: Visualizing the tensor data

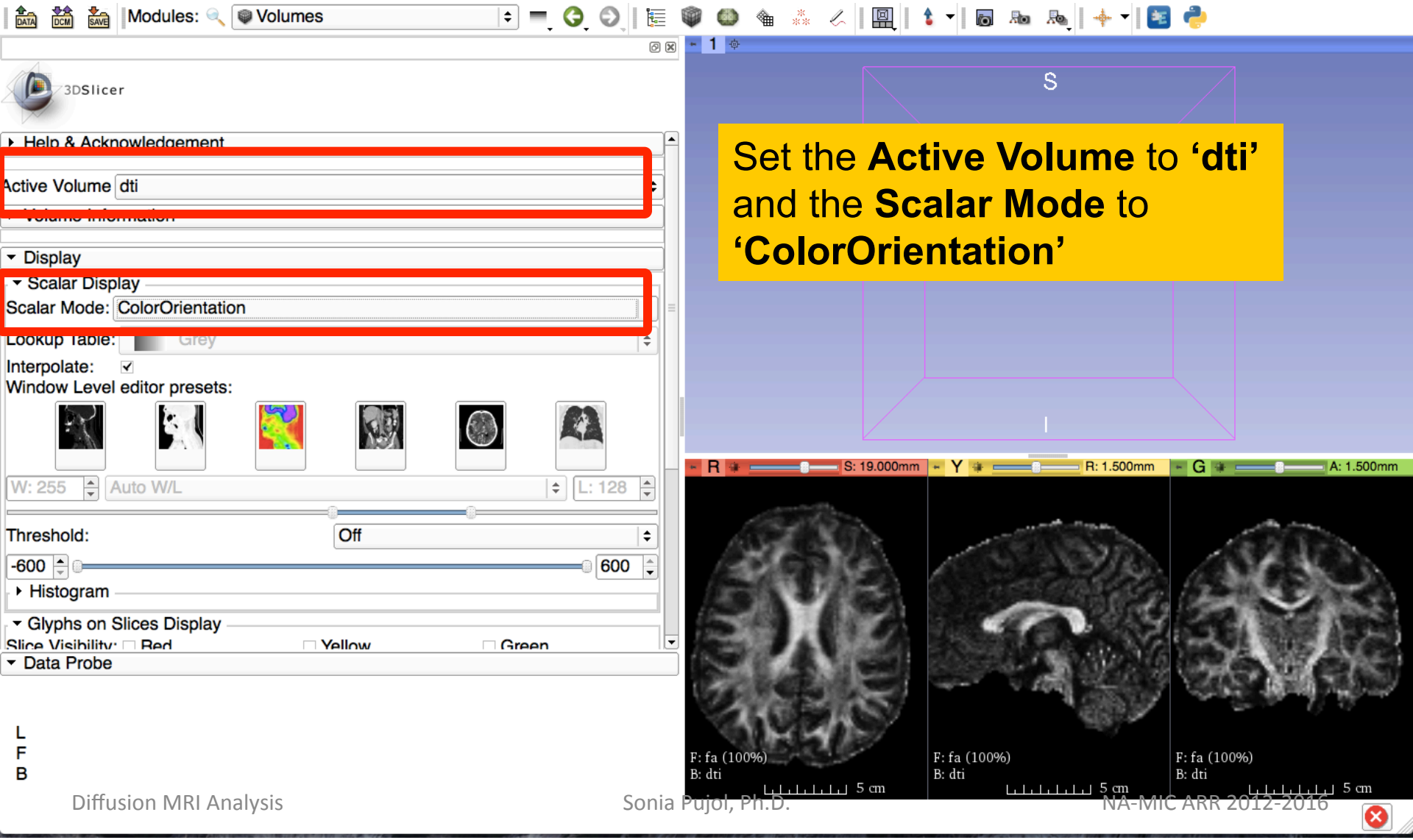
3D Visualization: Glyphs



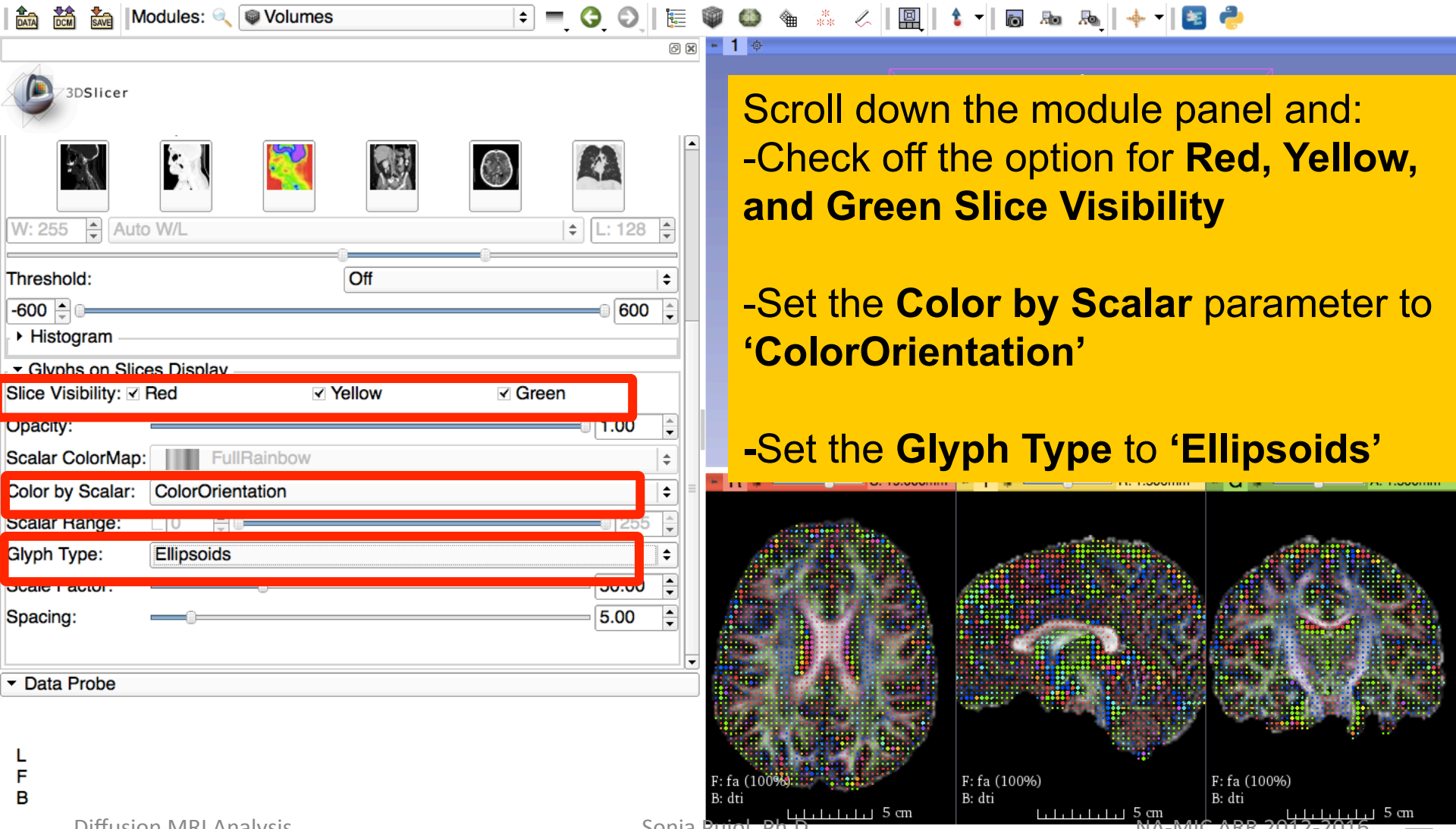
3D Visualization: Glyphs



3D Visualization: Glyphs



3D Visualization: Glyphs

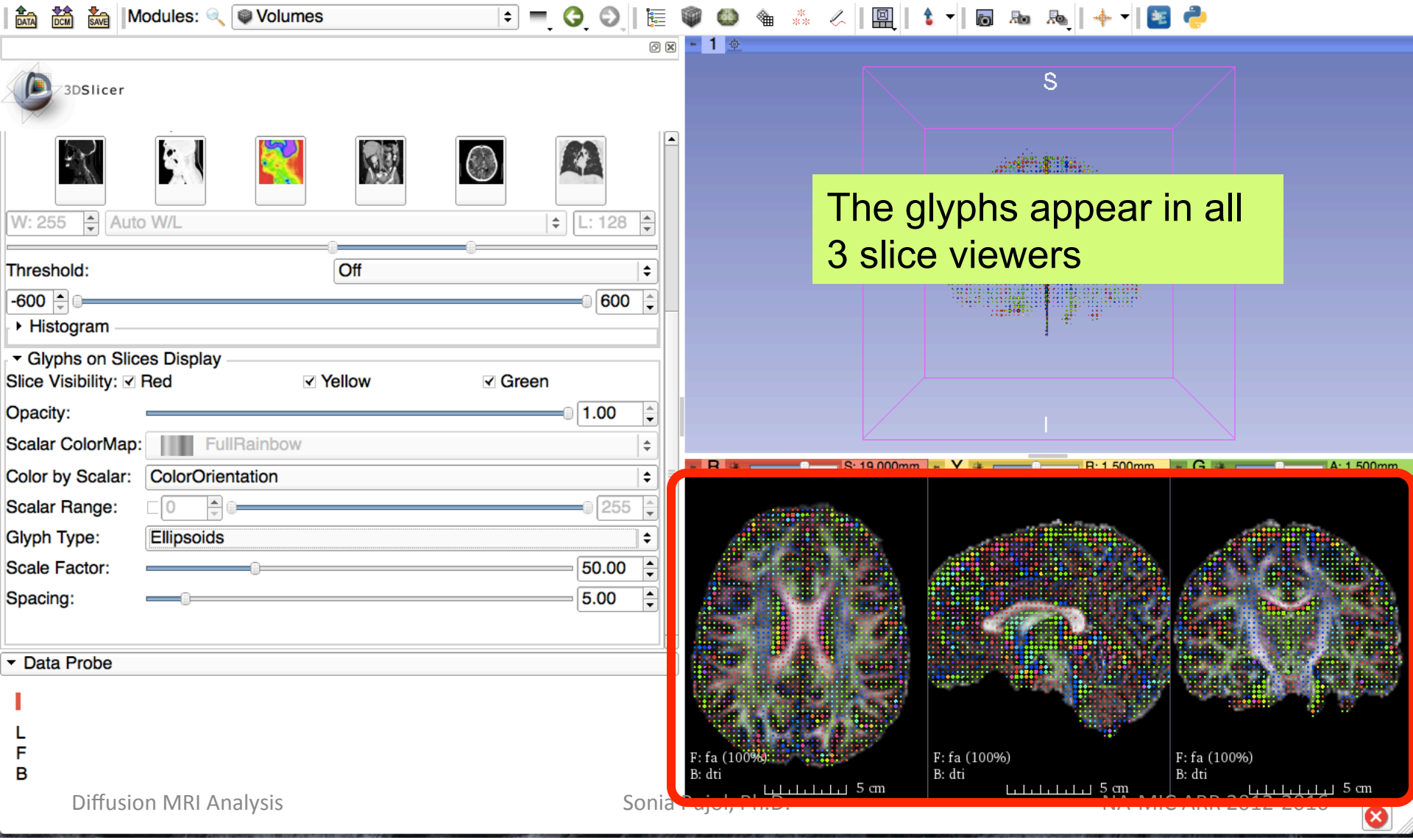


Scroll down the module panel and:
-Check off the option for **Red, Yellow, and Green Slice Visibility**

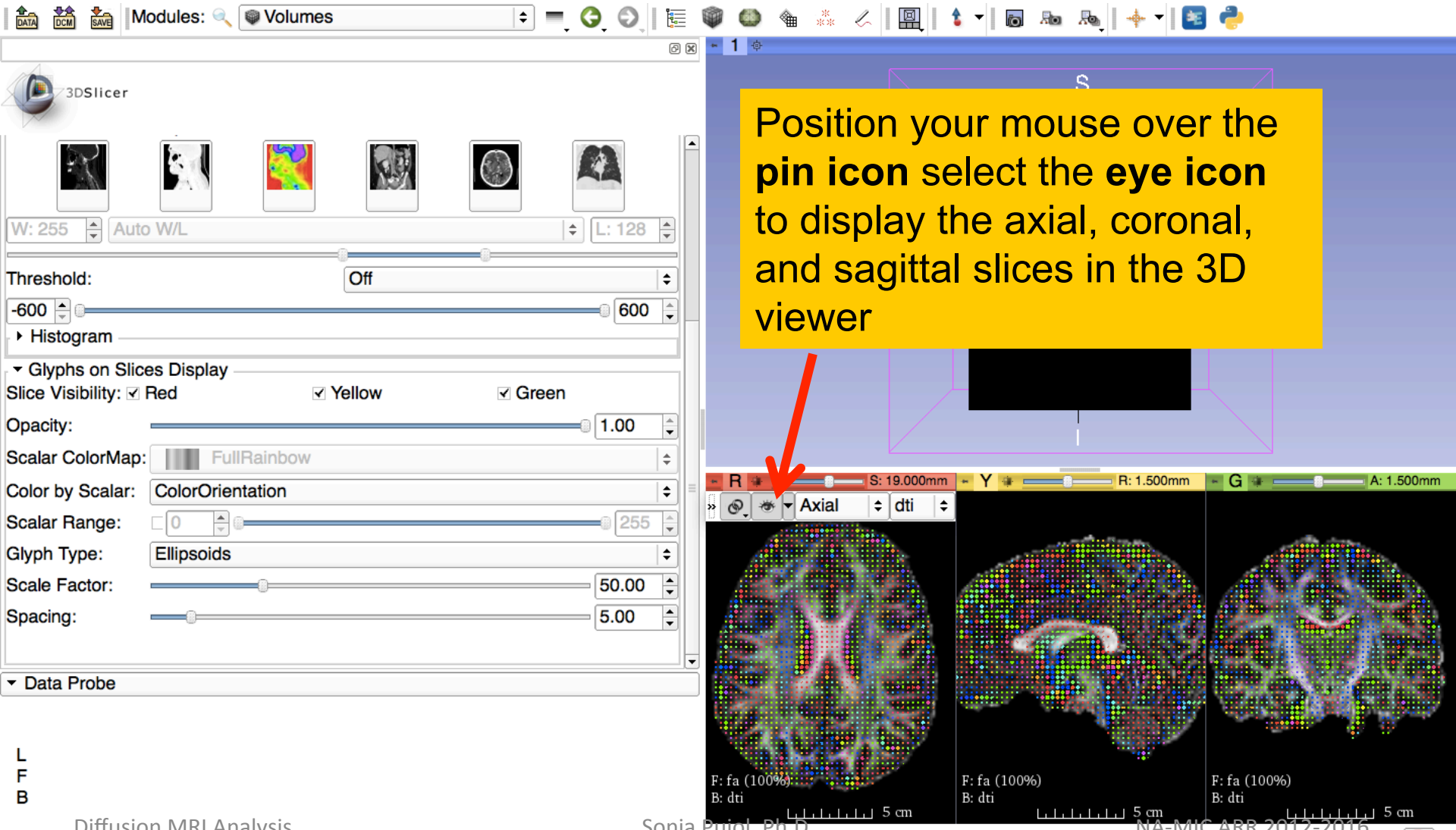
-Set the **Color by Scalar** parameter to **'ColorOrientation'**

-Set the **Glyph Type** to **'Ellipsoids'**

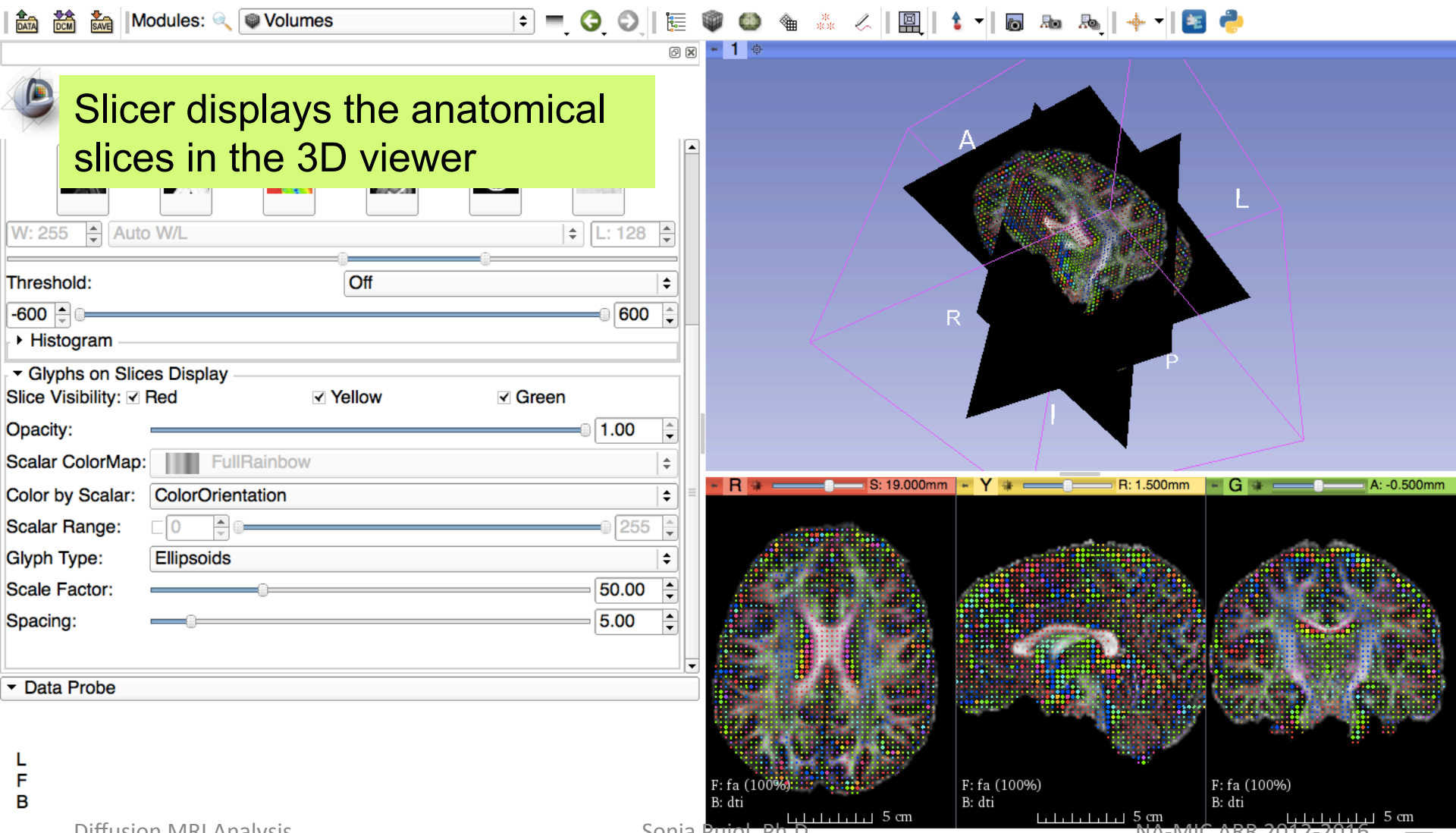
3D Visualization: Glyphs



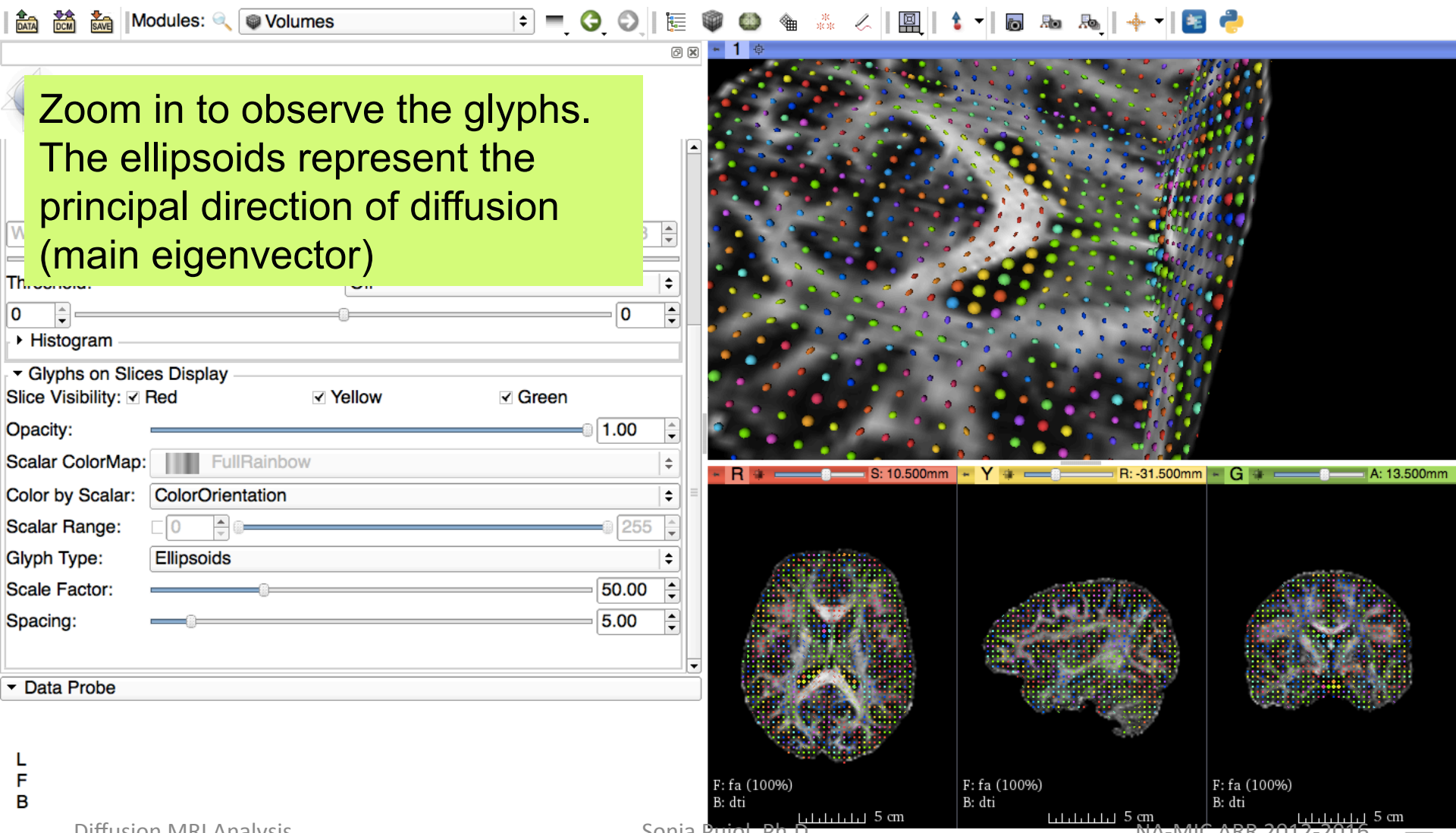
3D Visualization: Glyphs



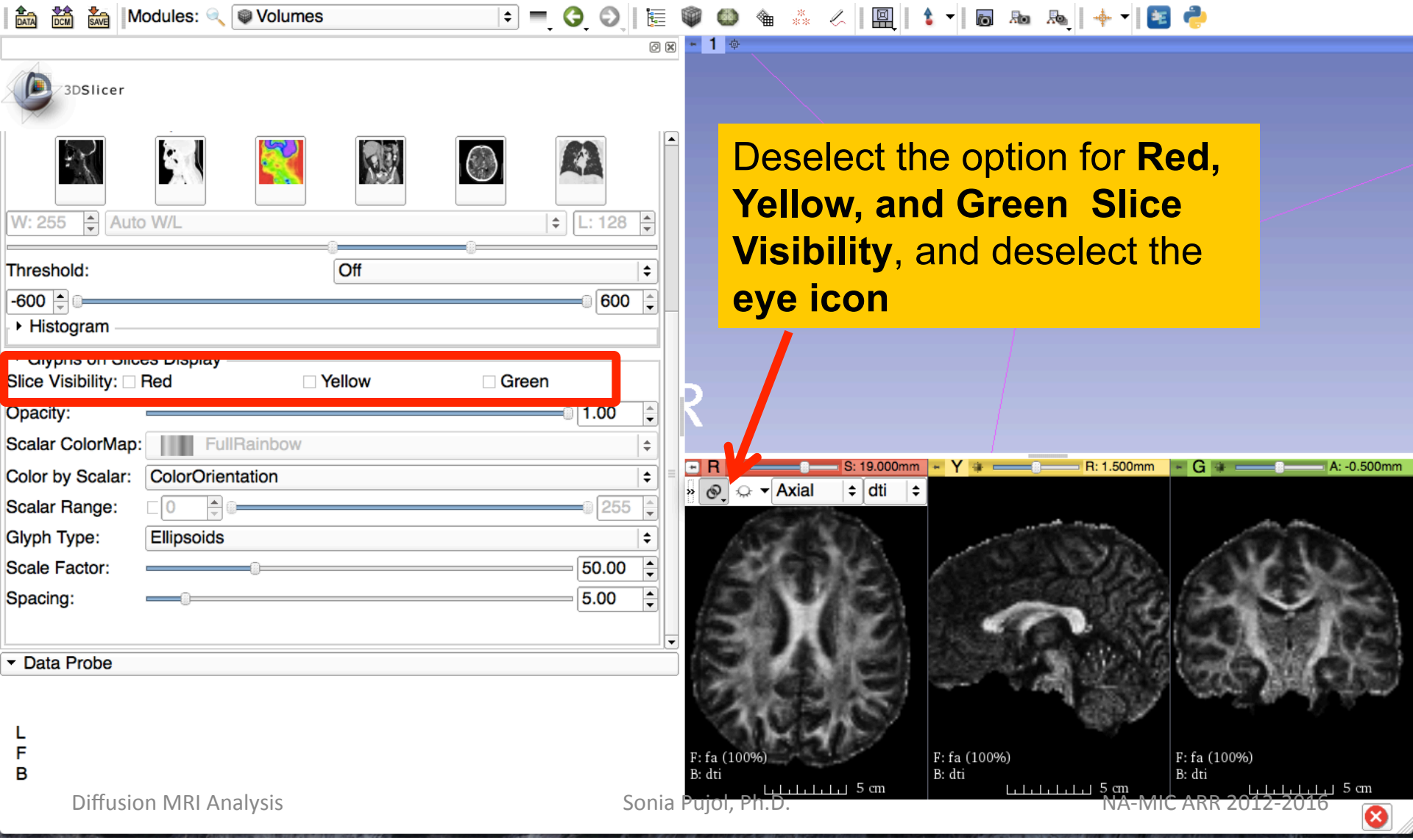
3D Visualization: Glyphs



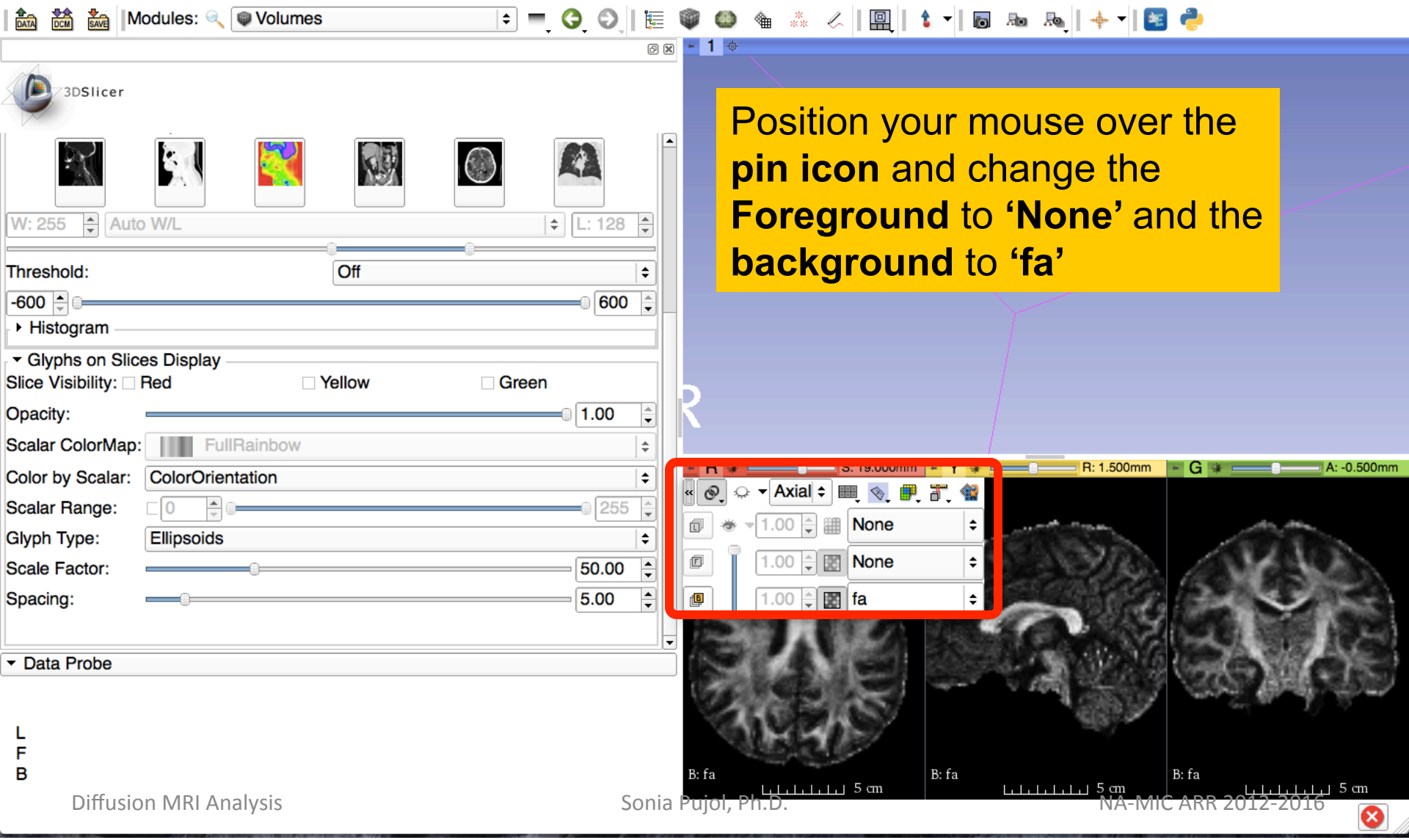
3D Visualization: Glyphs

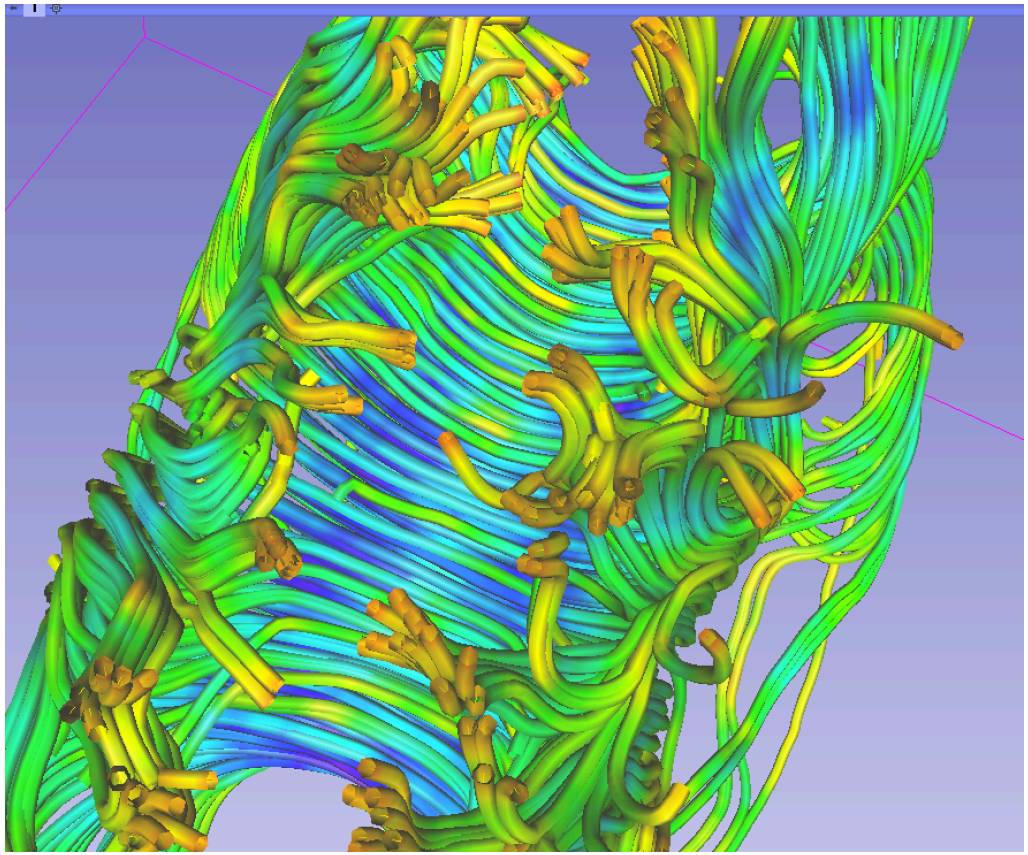


Diffusion MRI tractography



Diffusion MRI tractography



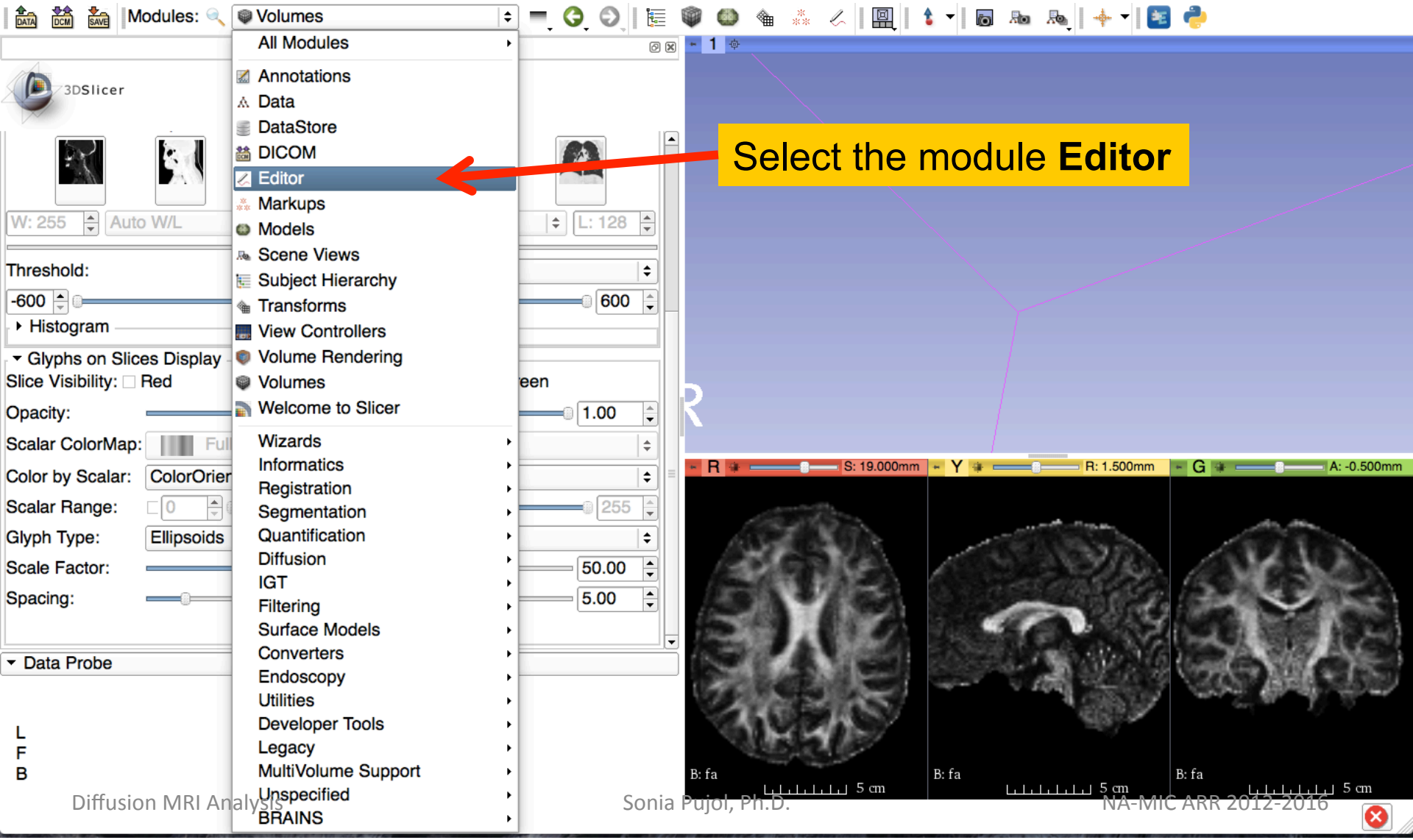


Part 3: From tensors to tracts

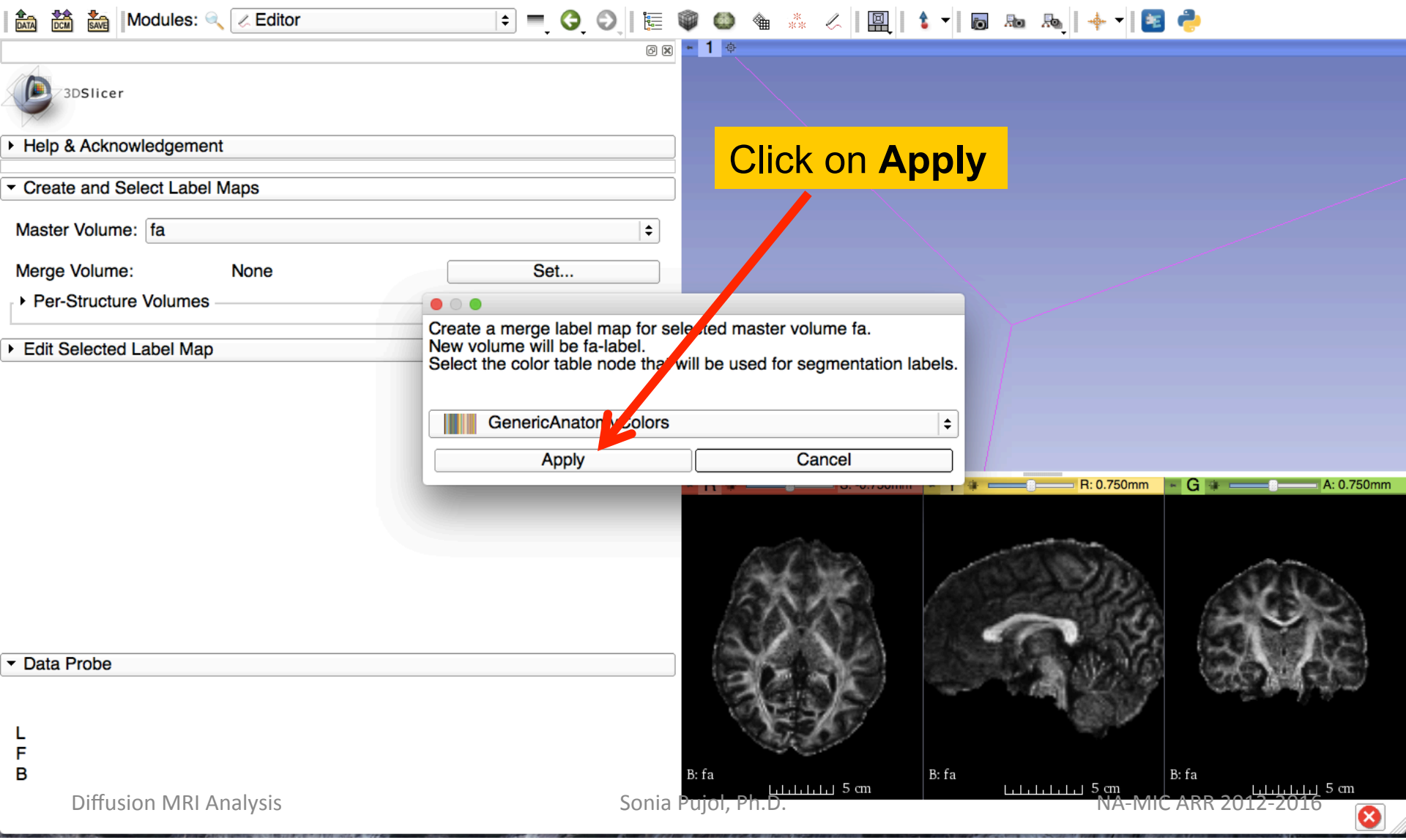
DTI tractography

- Definition of a region of interest (ROI) for seeding tract in an FA map (Editor module)
- Single-tensor tractography (Tractography Interactive Seeding module)
- Fiducial-seeding tractography (Tractography Interactive Seeding module)

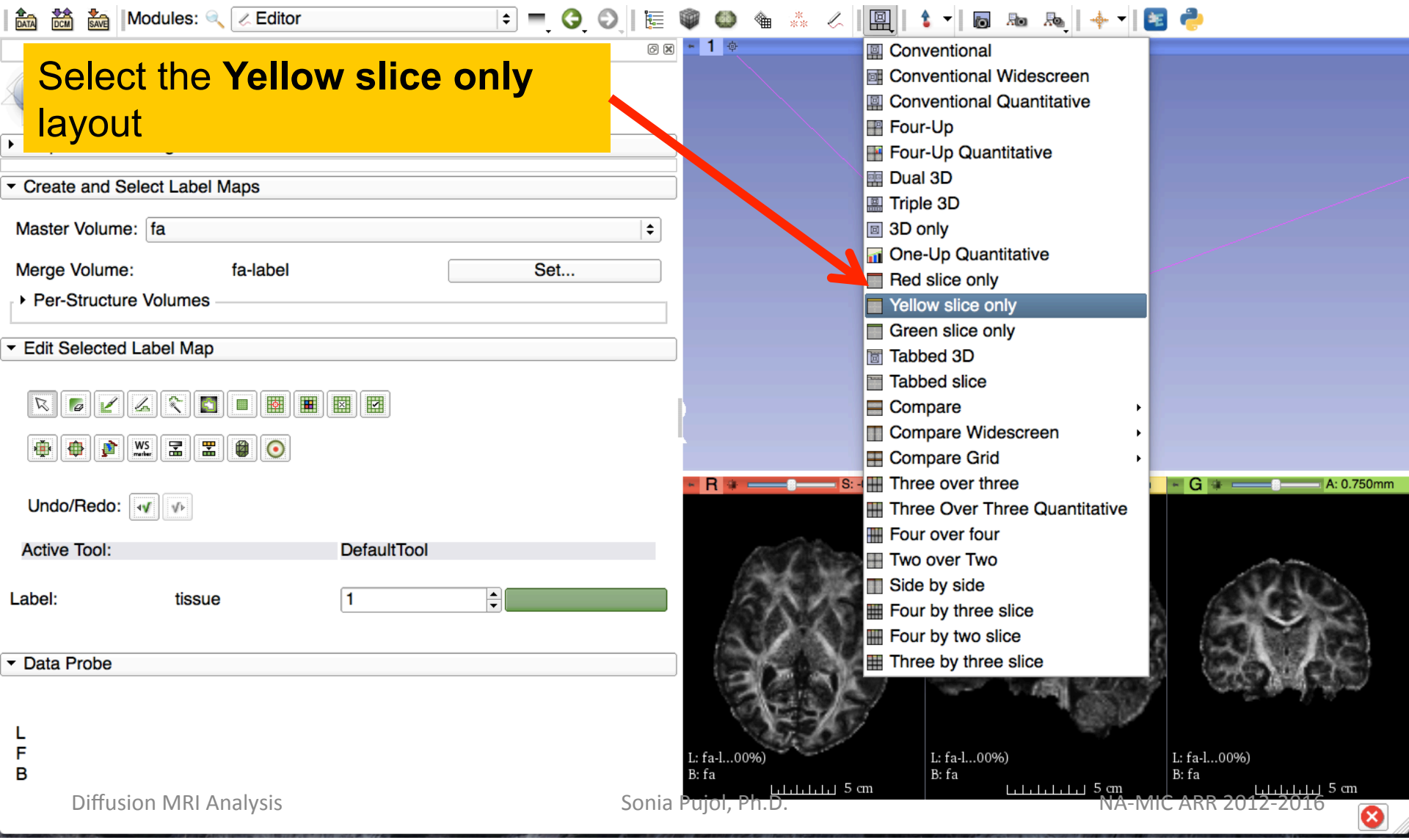
Diffusion MRI tractography



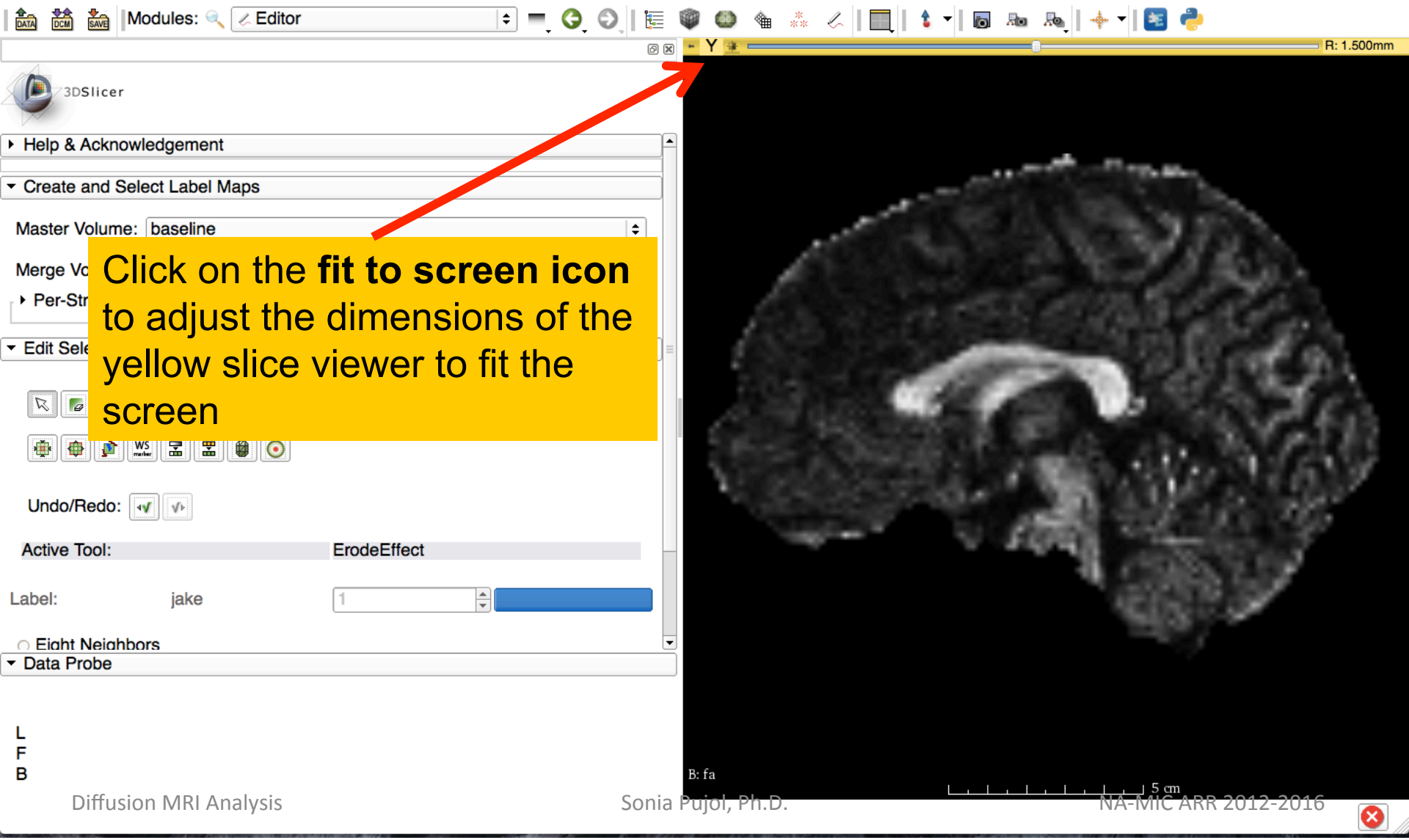
Diffusion MRI tractography



Diffusion MRI tractography

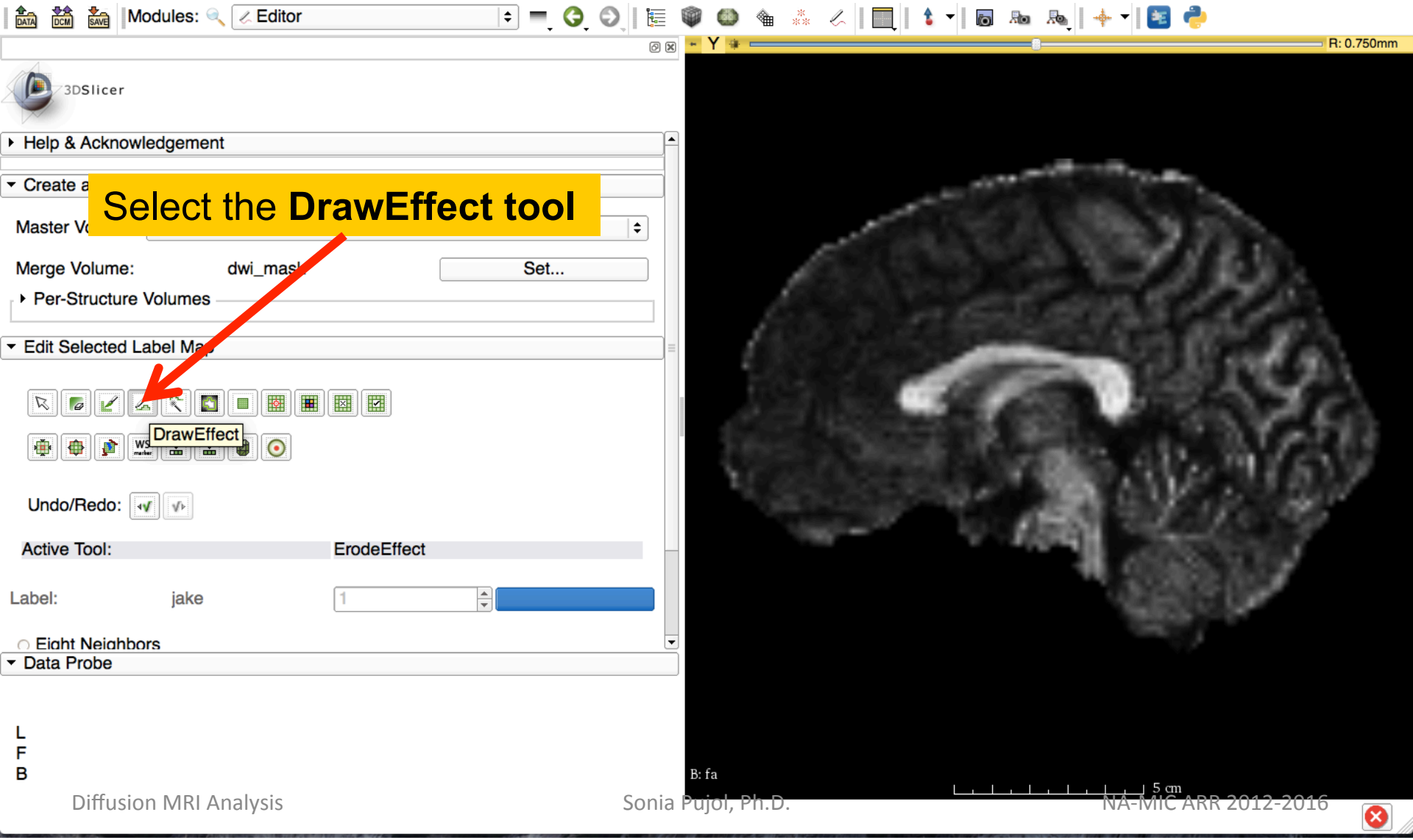


Diffusion MRI tractography

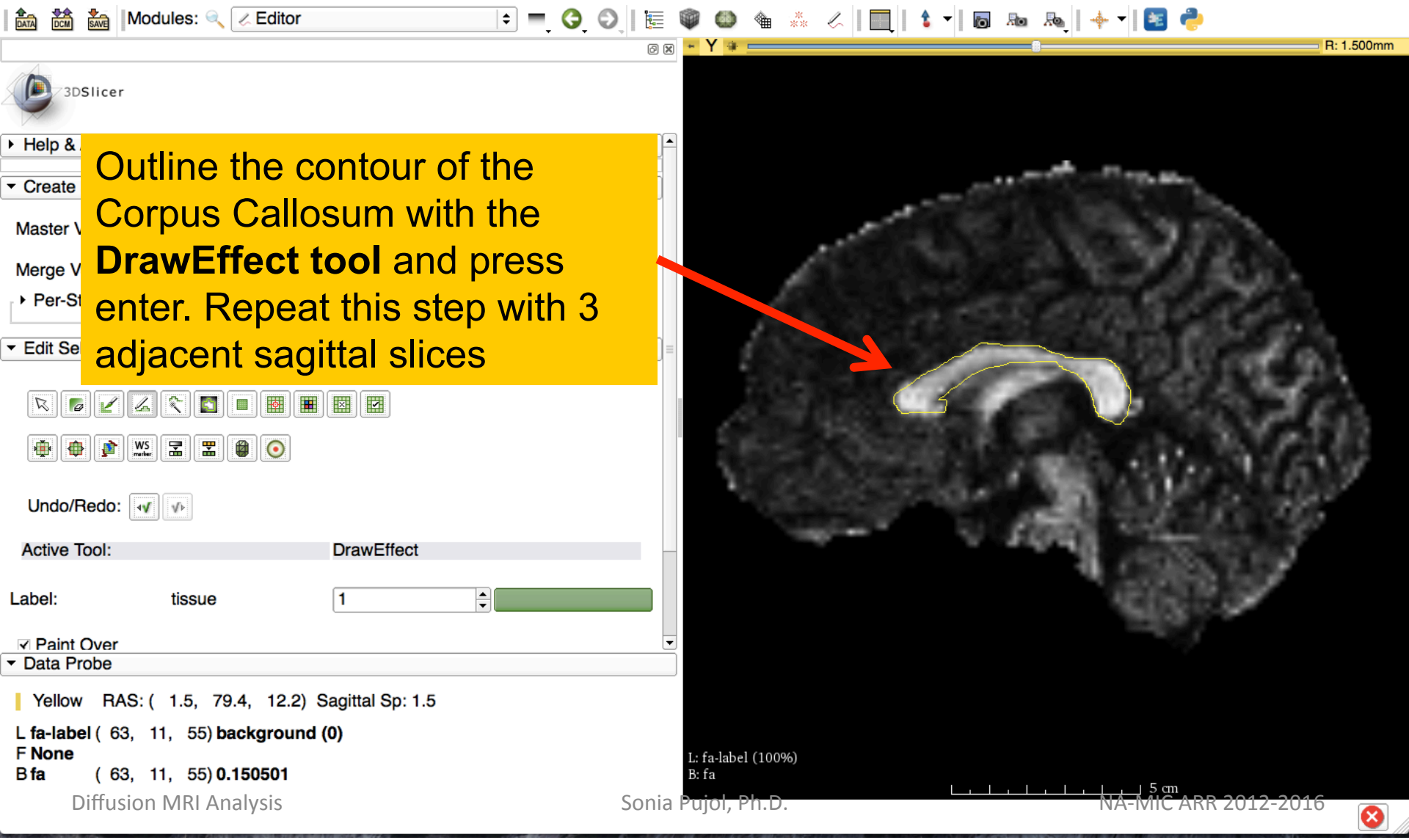


Click on the **fit to screen icon** to adjust the dimensions of the yellow slice viewer to fit the screen

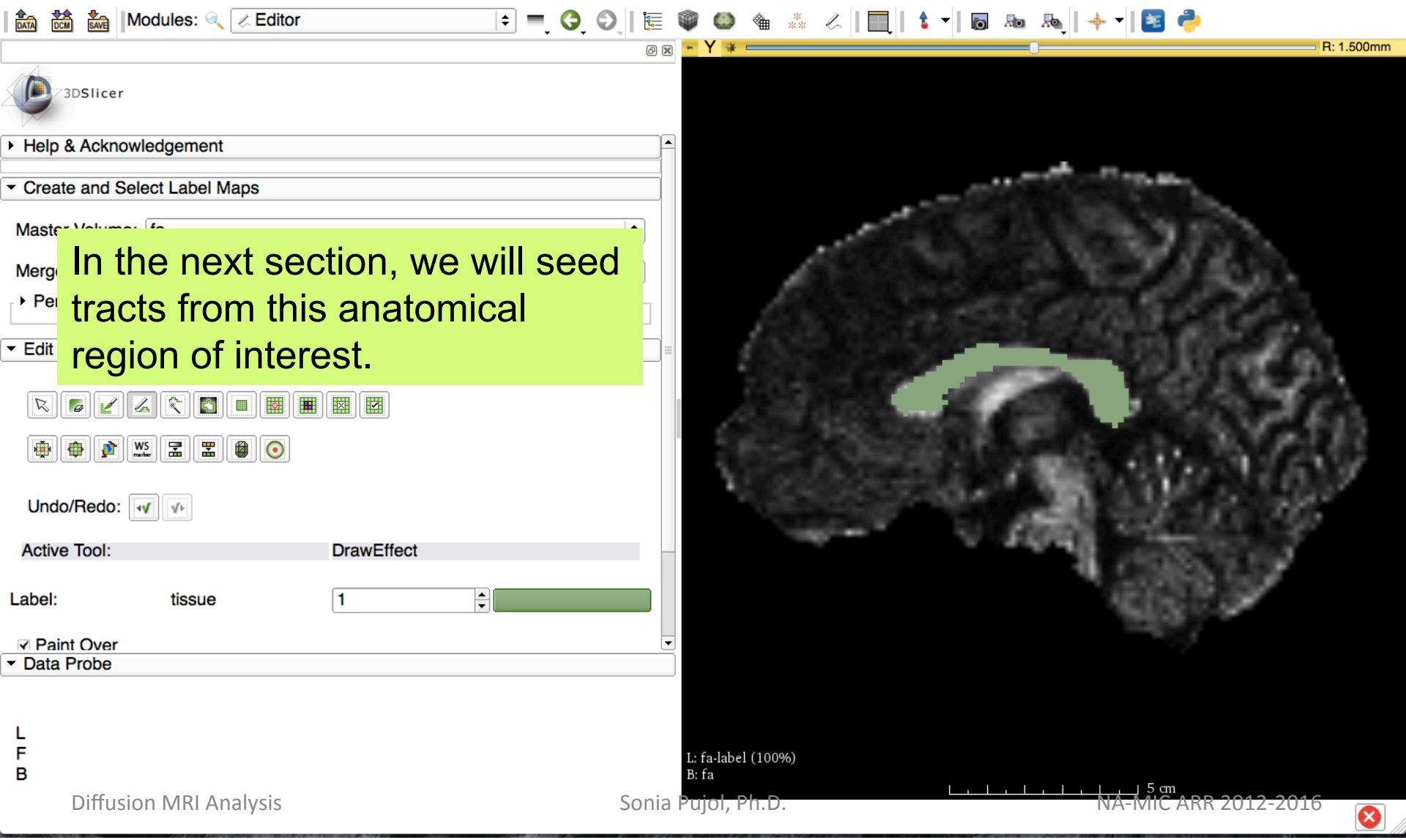
Diffusion MRI tractography



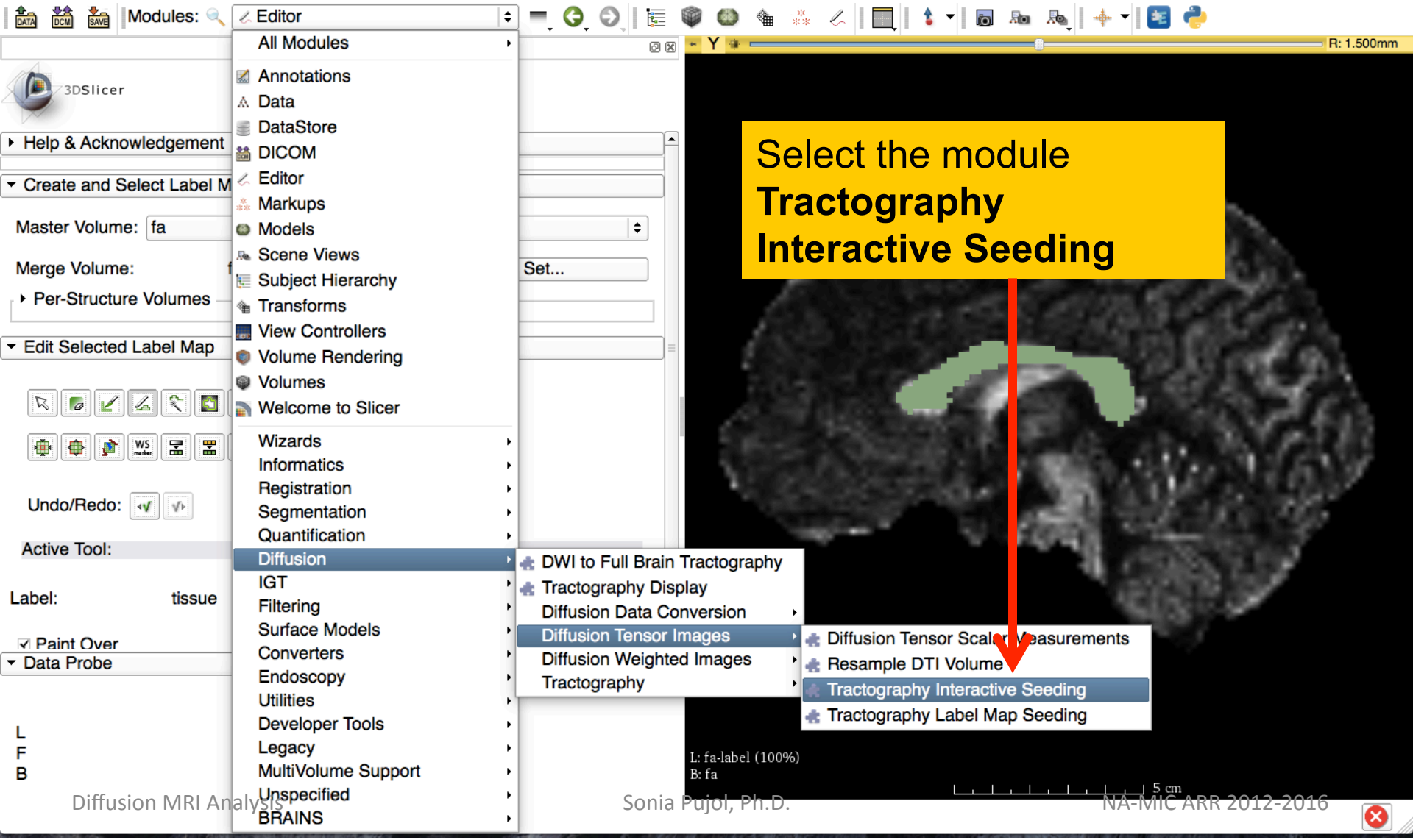
Diffusion MRI tractography



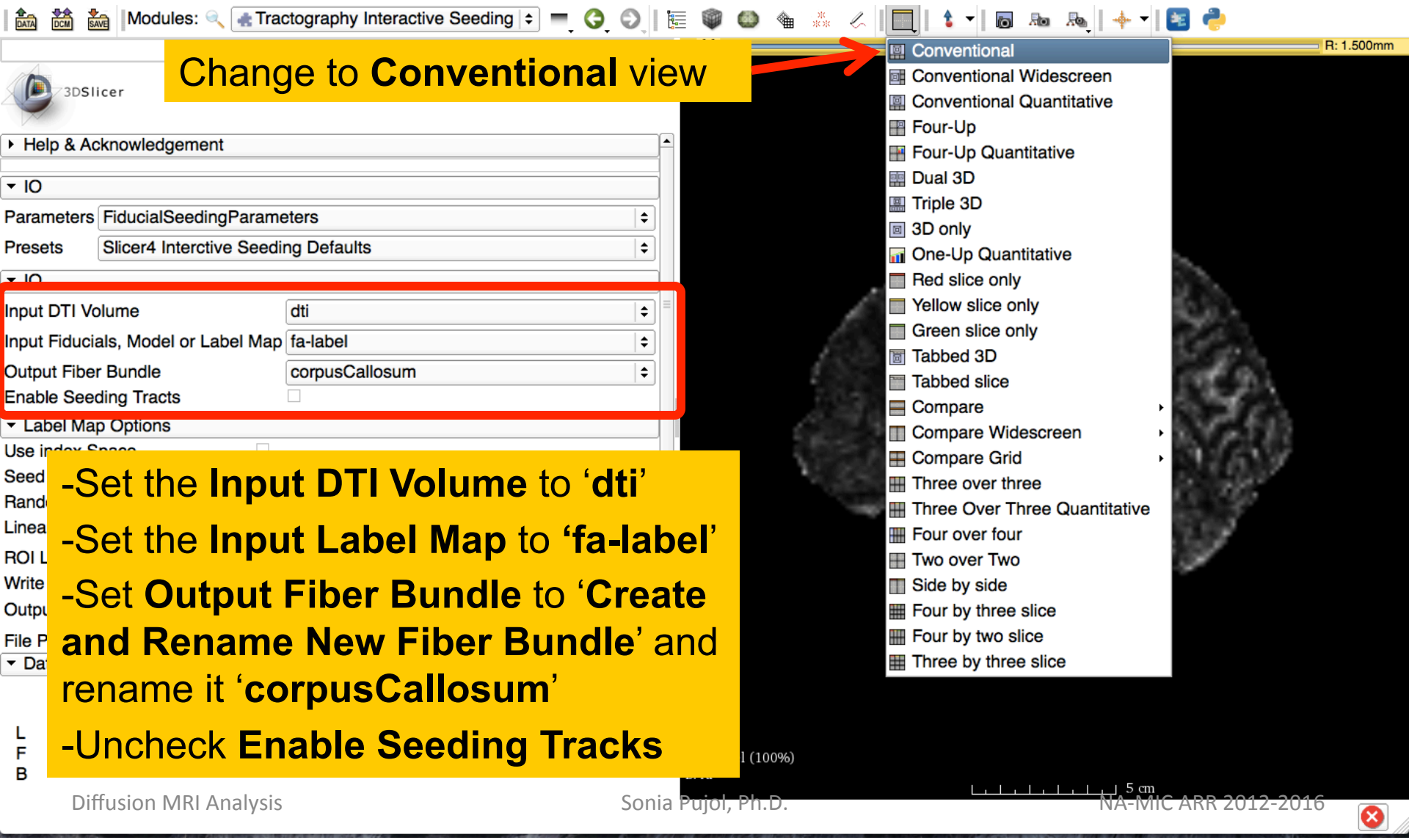
Diffusion MRI tractography



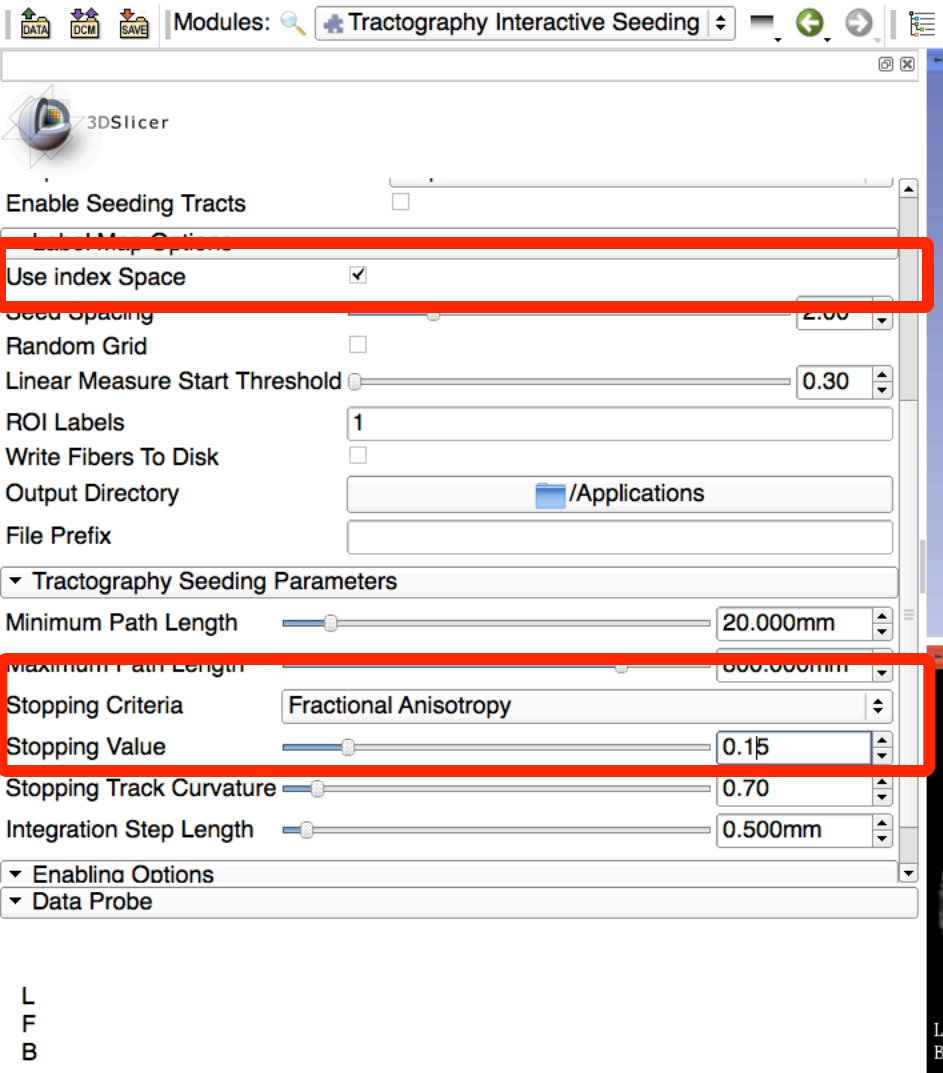
Diffusion MRI tractography

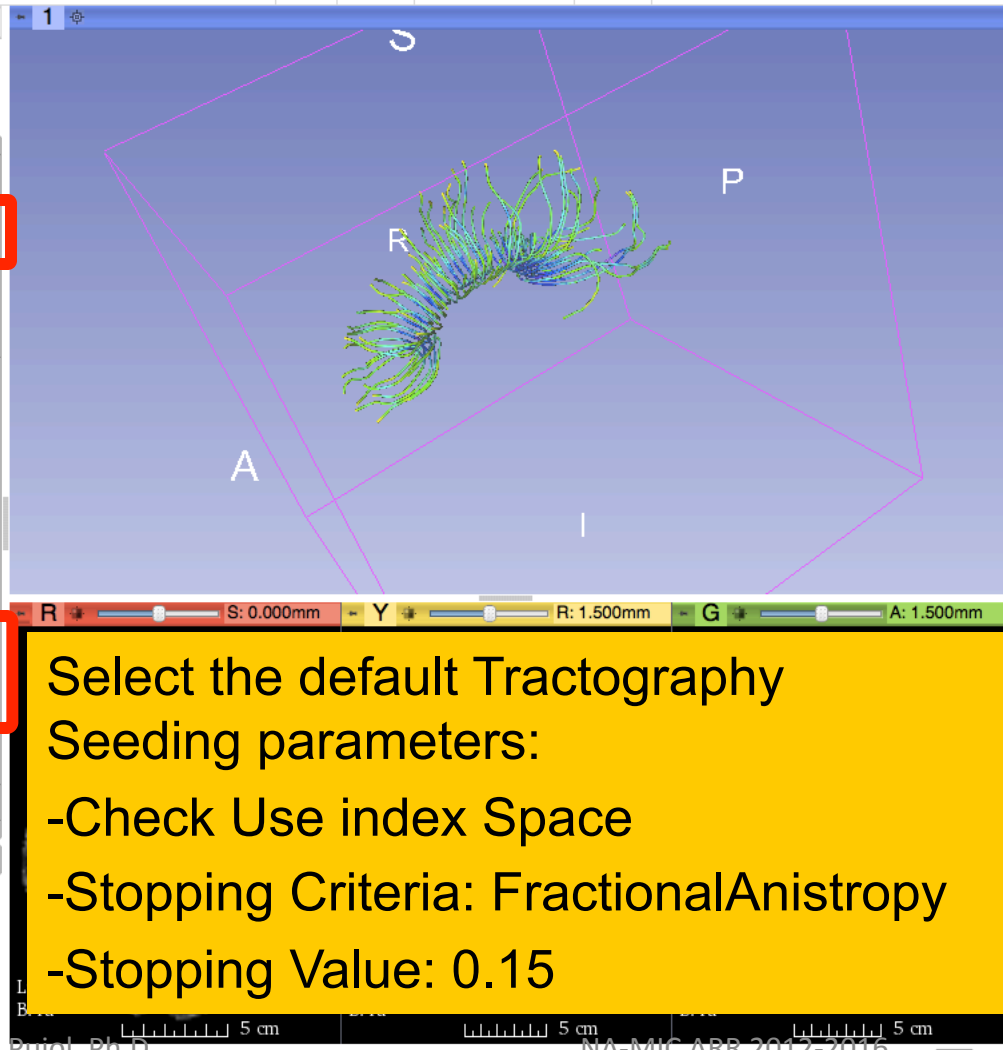


Labelmap Seeding: Step1: I/O



LabelMap Seeding: Step 2: Seeding parameters





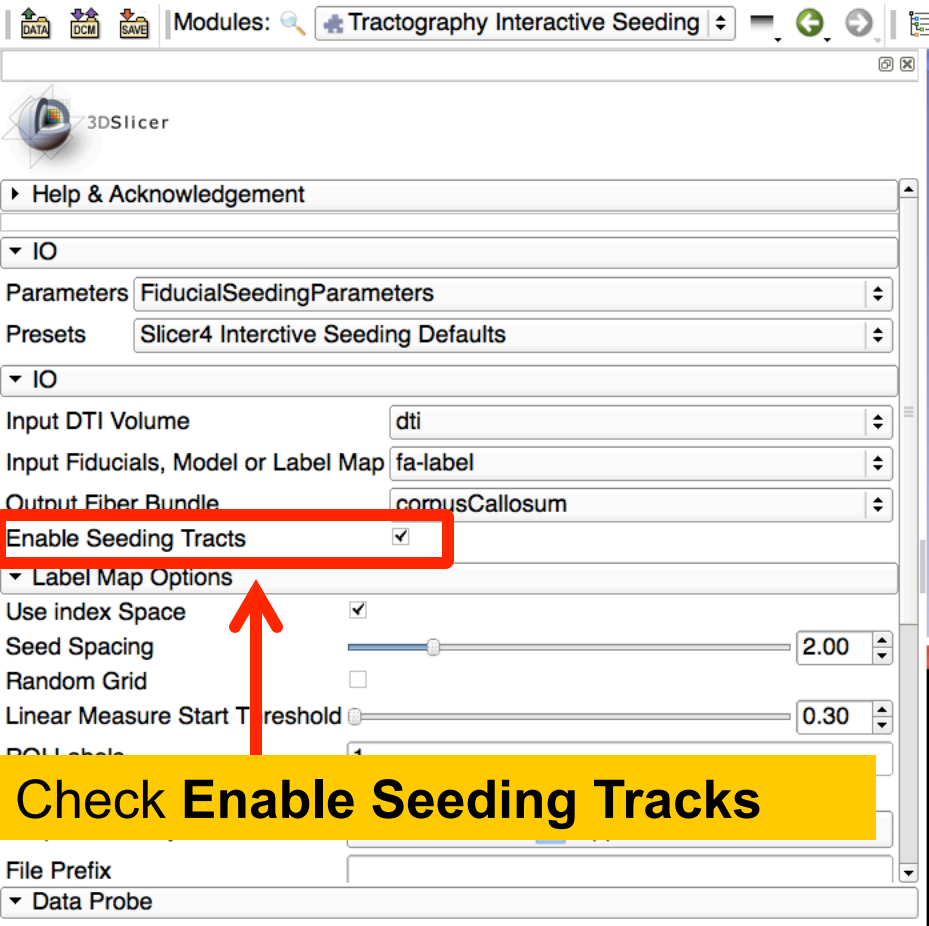
Select the default Tractography Seeding parameters:

-Check Use index Space

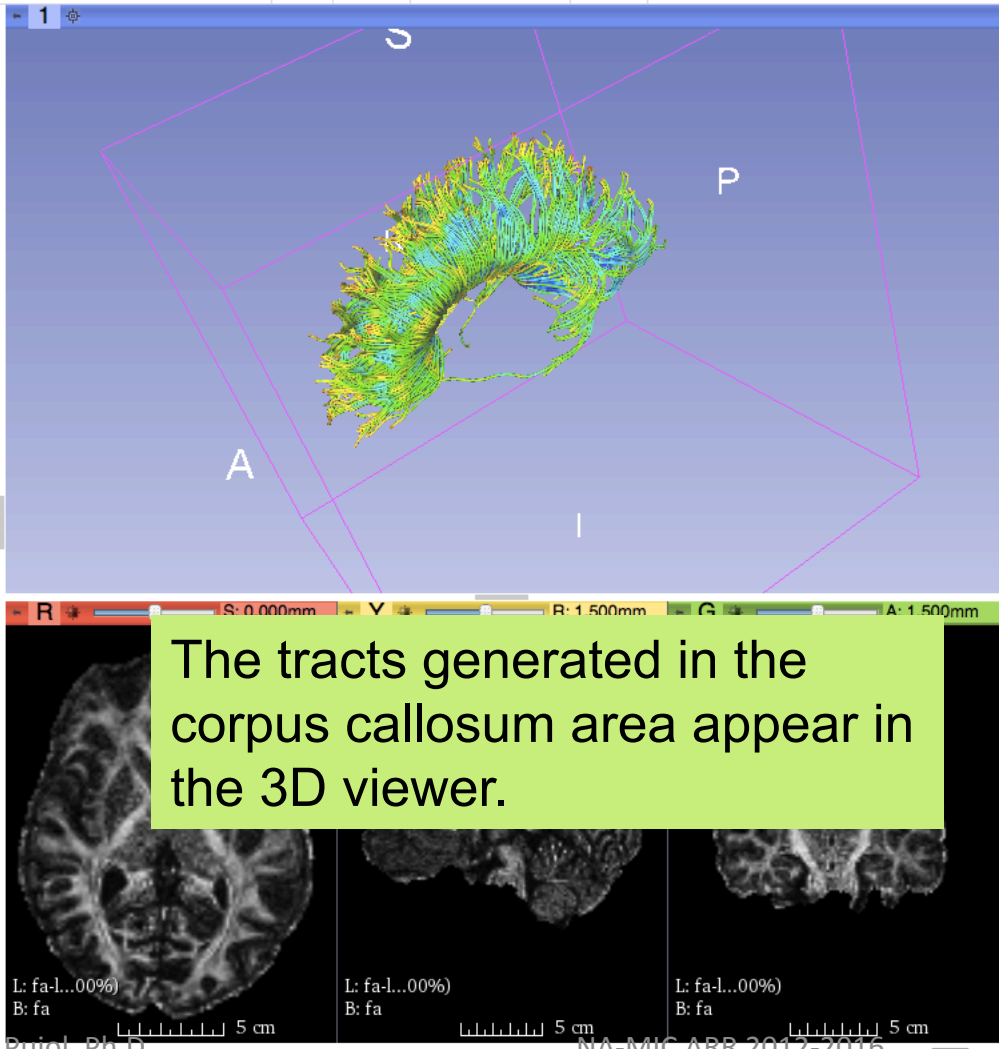
-Stopping Criteria: FractionalAnistropy

-Stopping Value: 0.15

LabelMap Seeding: Step 3: Generate Tracts

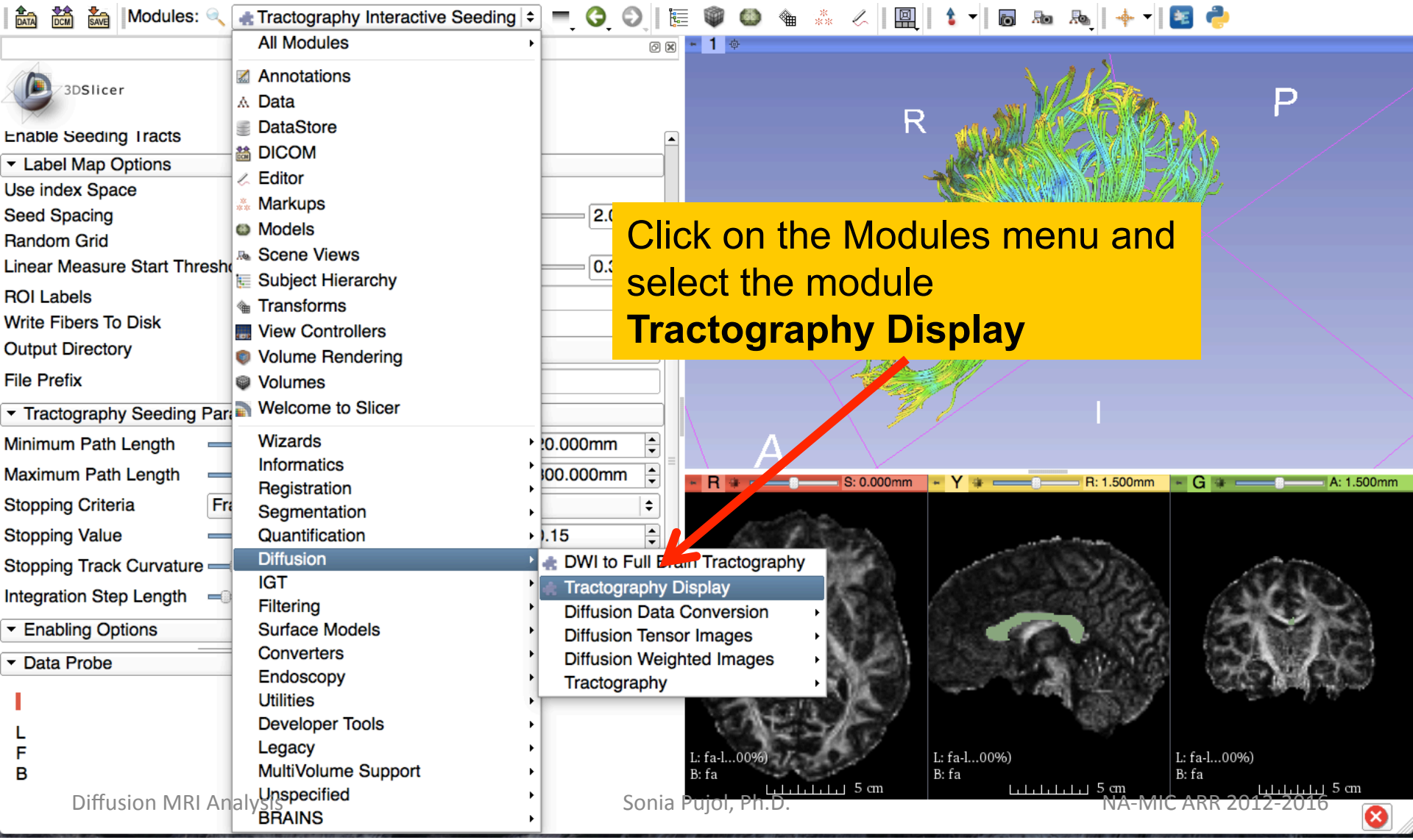


Check **Enable Seeding Tracks**

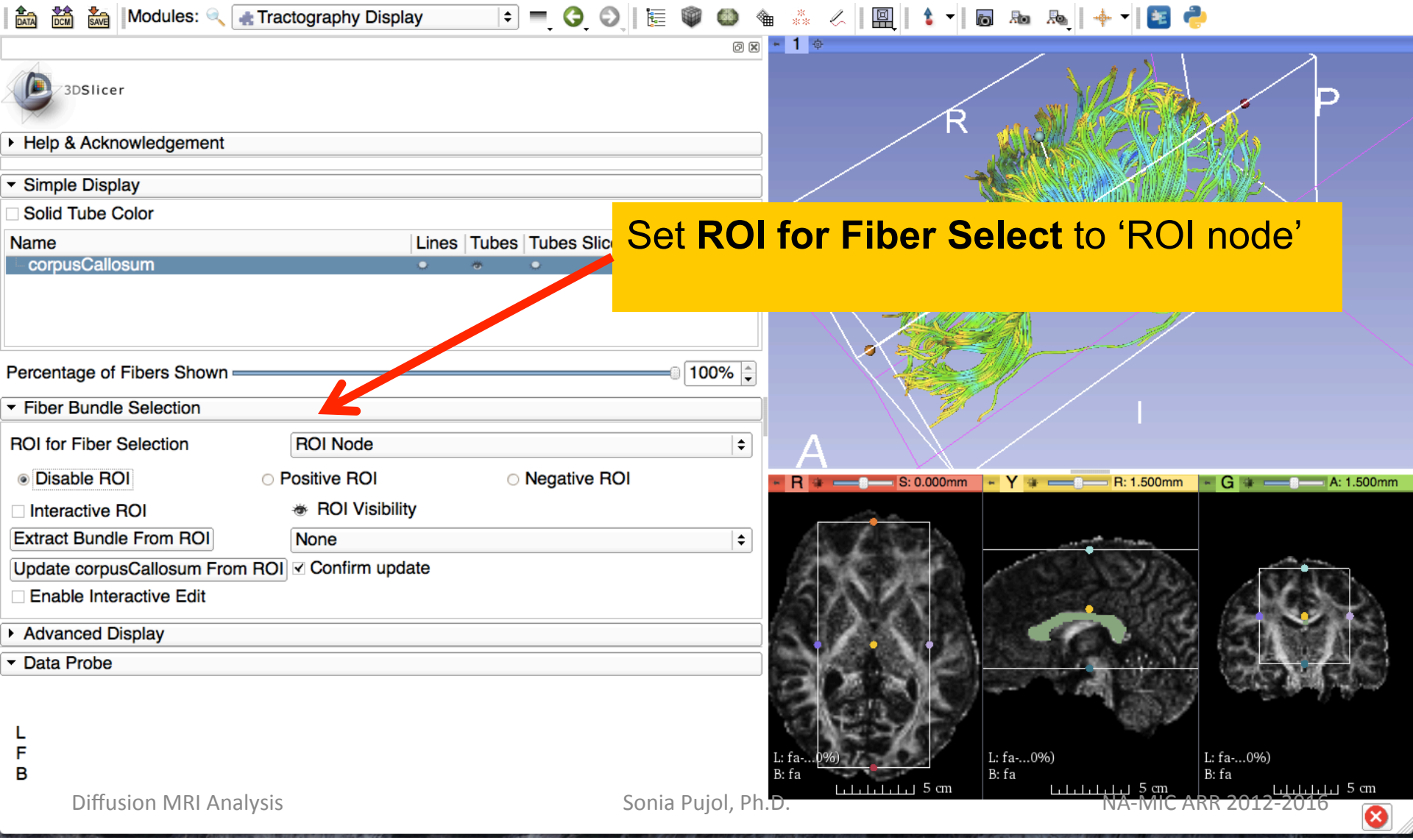


The tracts generated in the corpus callosum area appear in the 3D viewer.

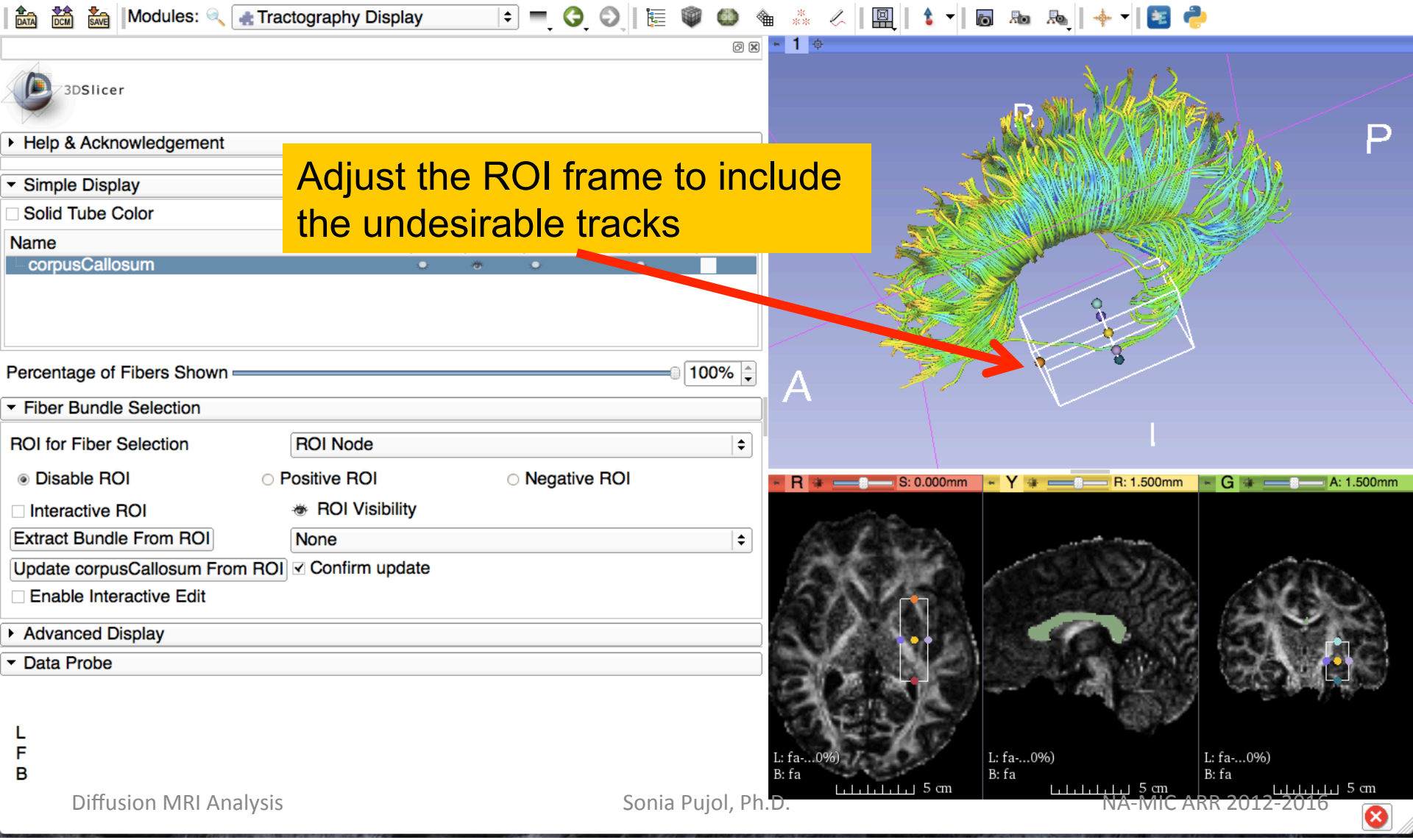
LabelMap Seeding: Step 4: Undesirable track removal



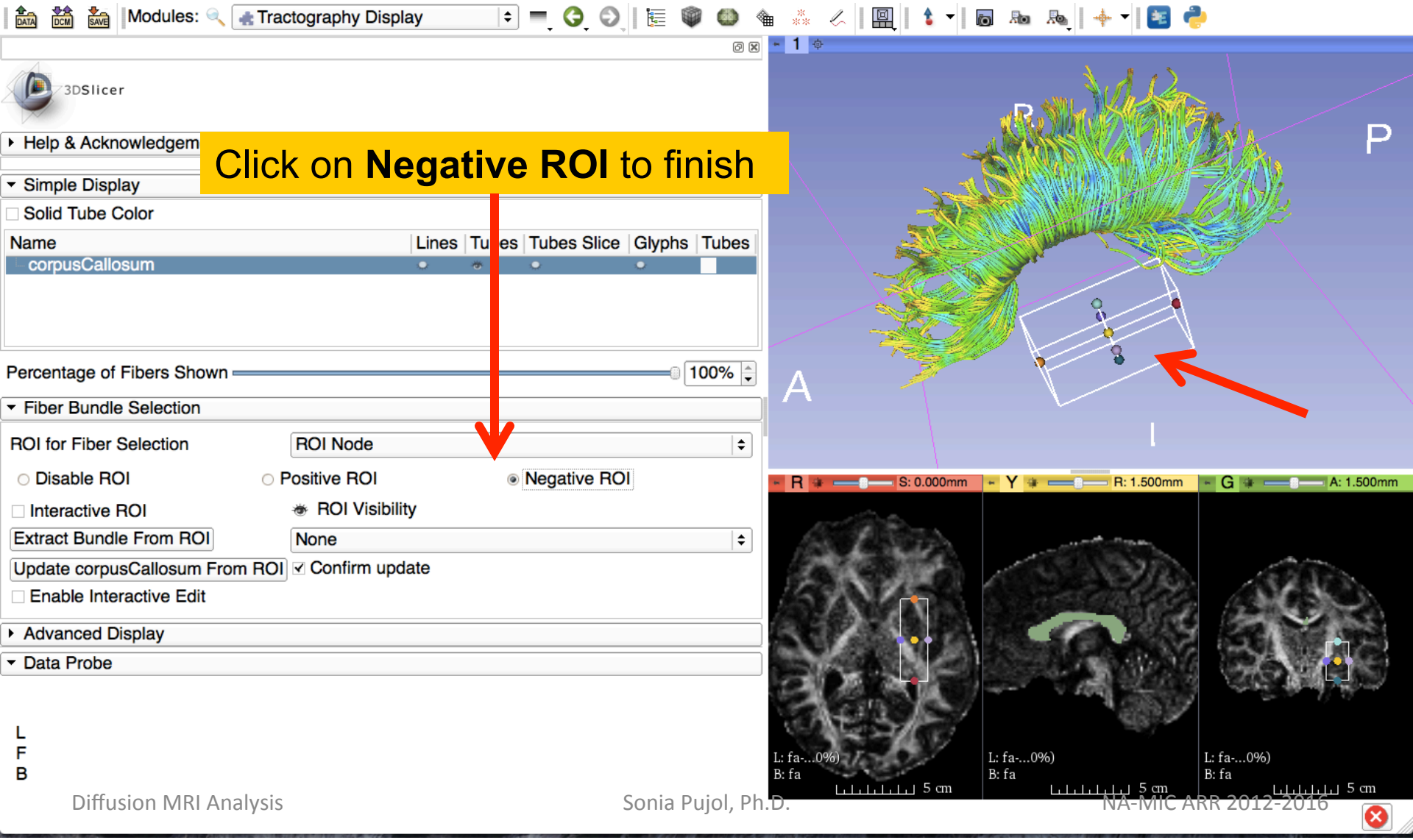
LabelMap Seeding: Step 4: Undesirable track removal



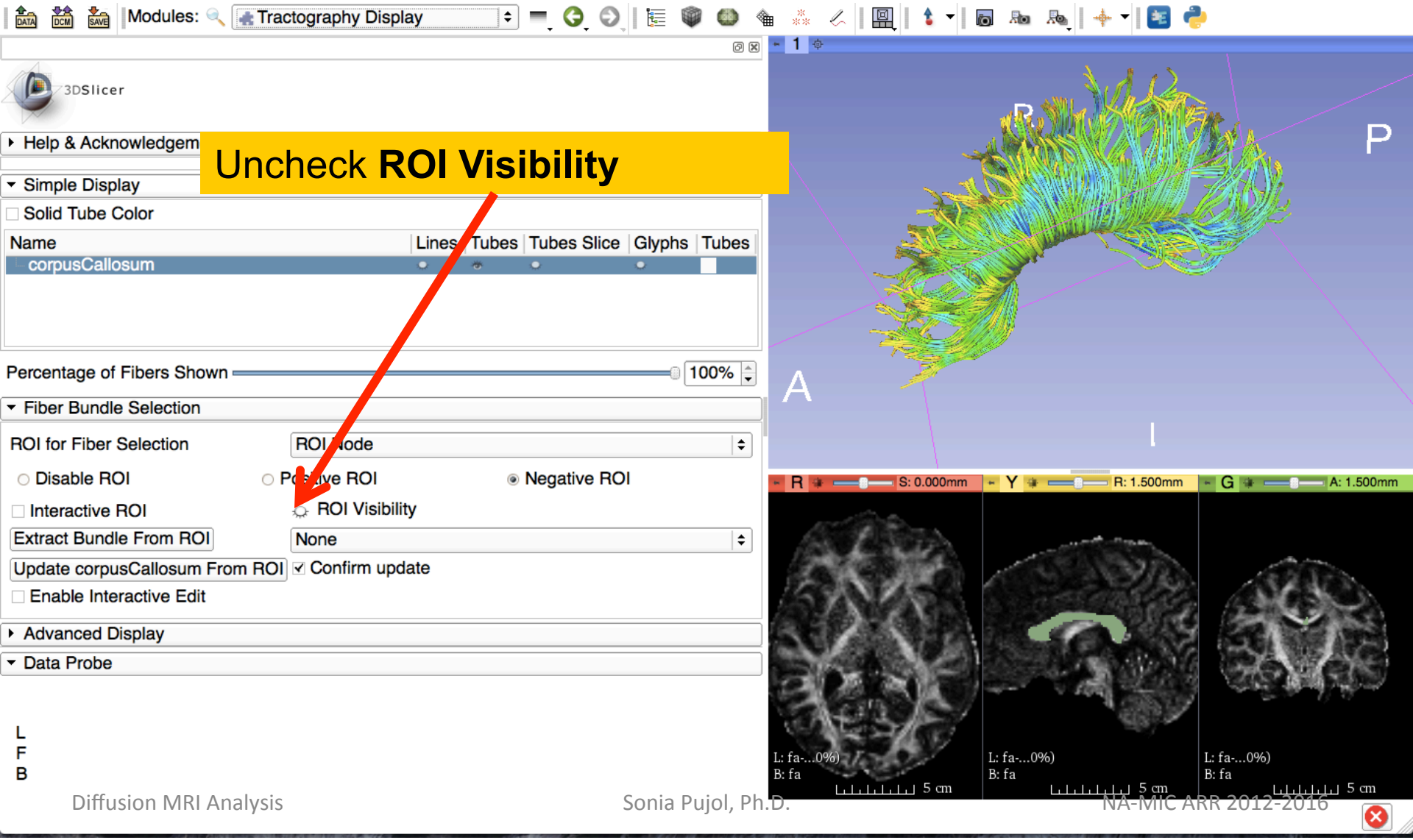
LabelMap Seeding: Step 4: Undesirable track removal



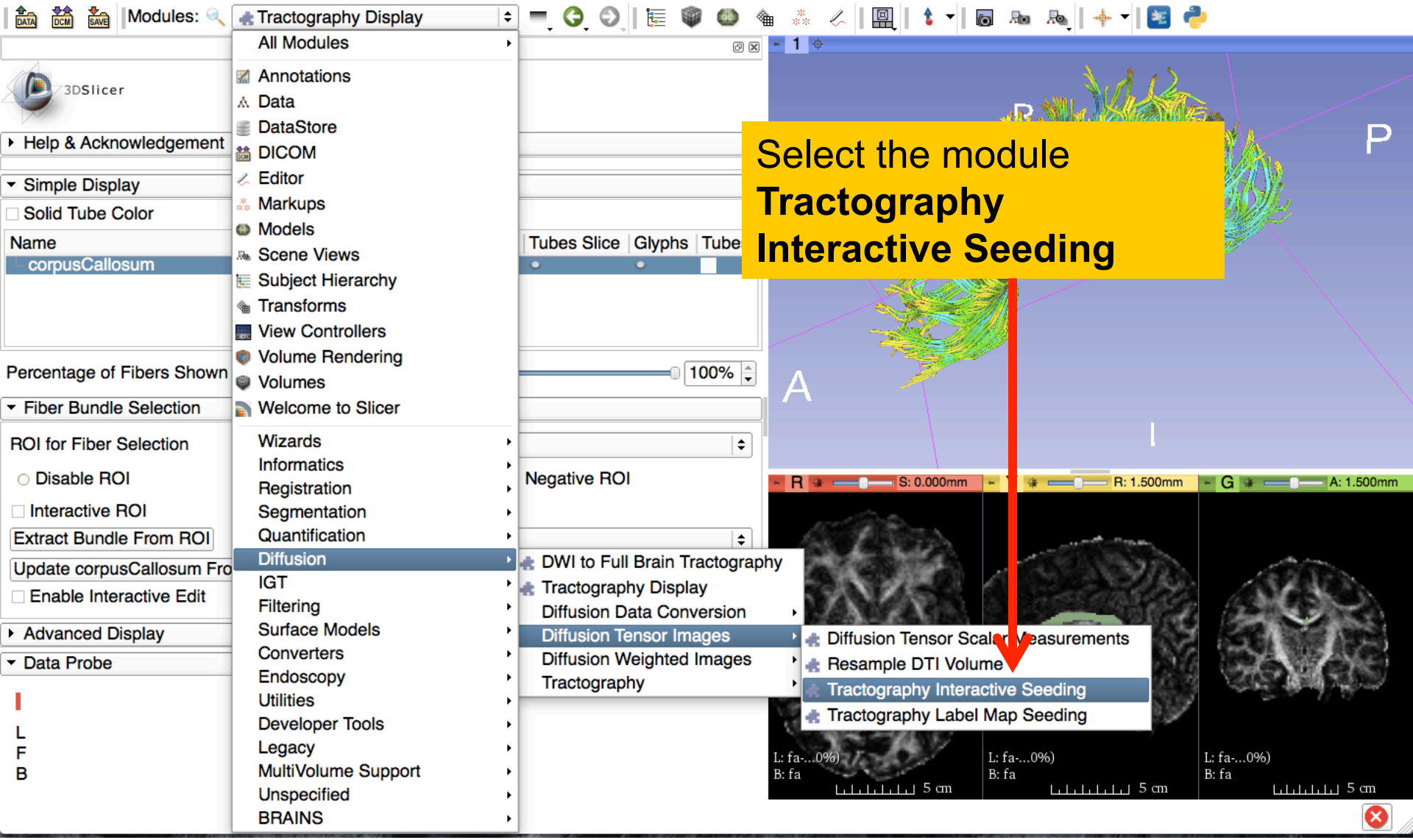
LabelMap Seeding: Step 4: Undesirable track removal



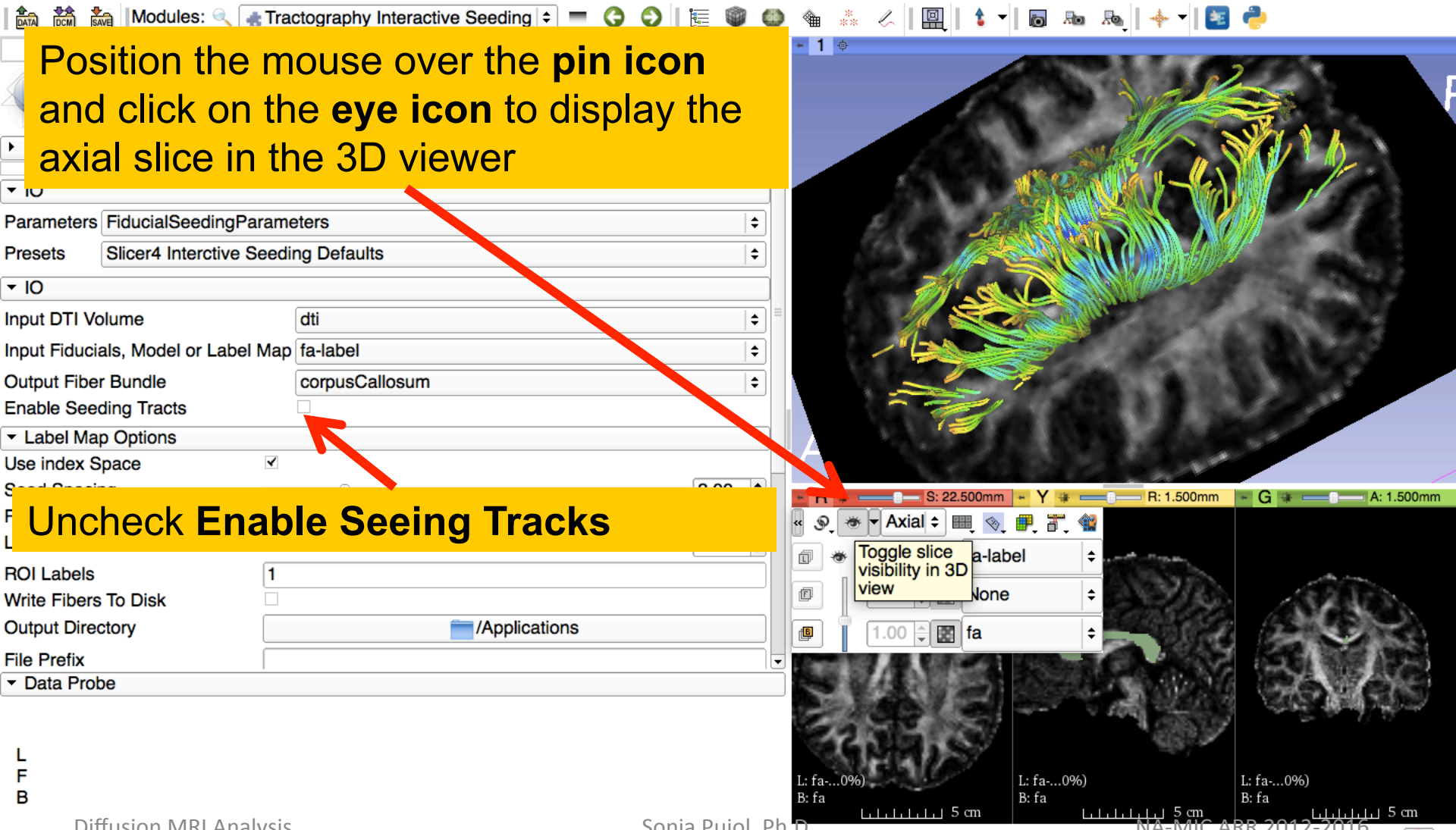
LabelMap Seeding: Step 4: Undesirable track removal



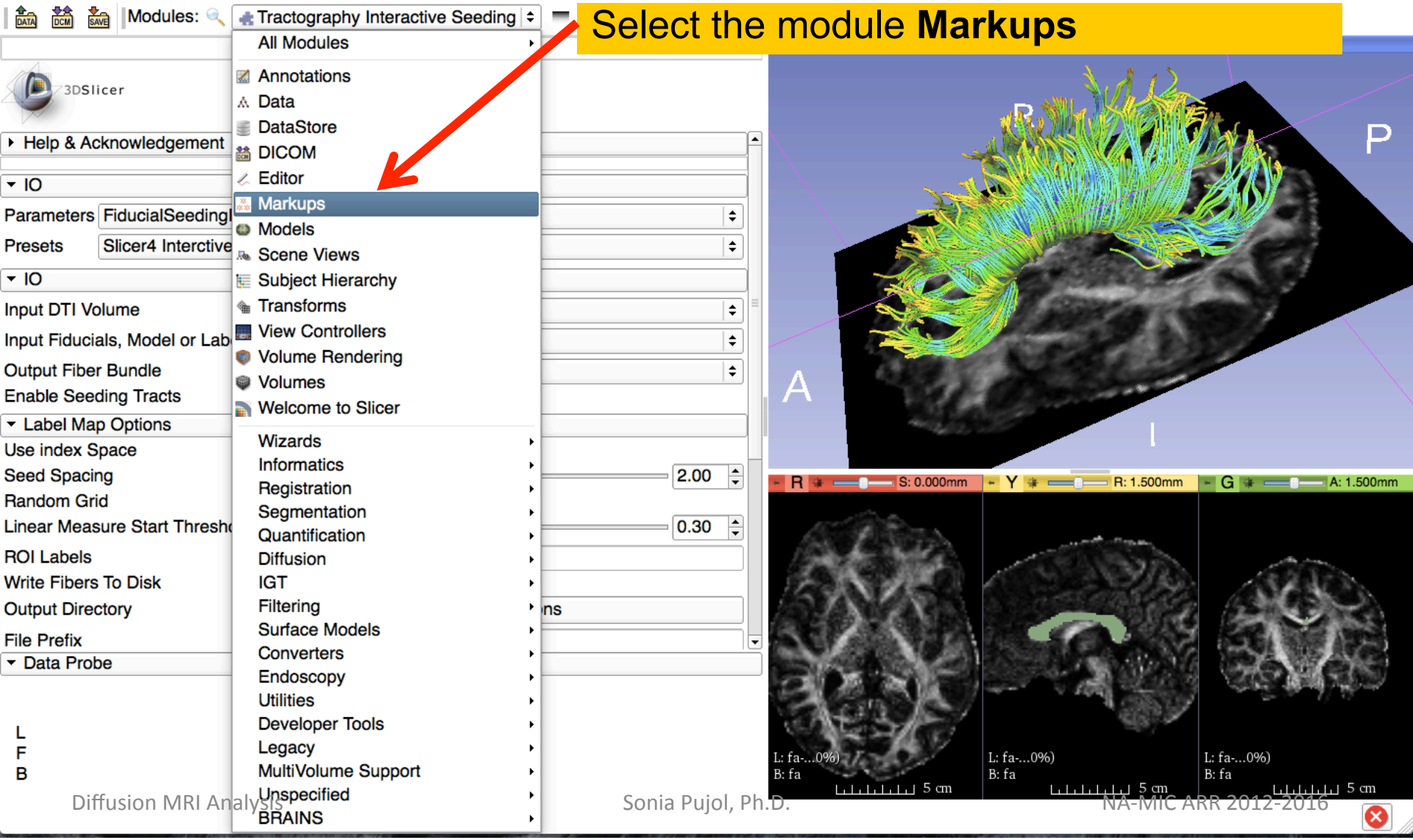
Labelmap Seeding: Tracts



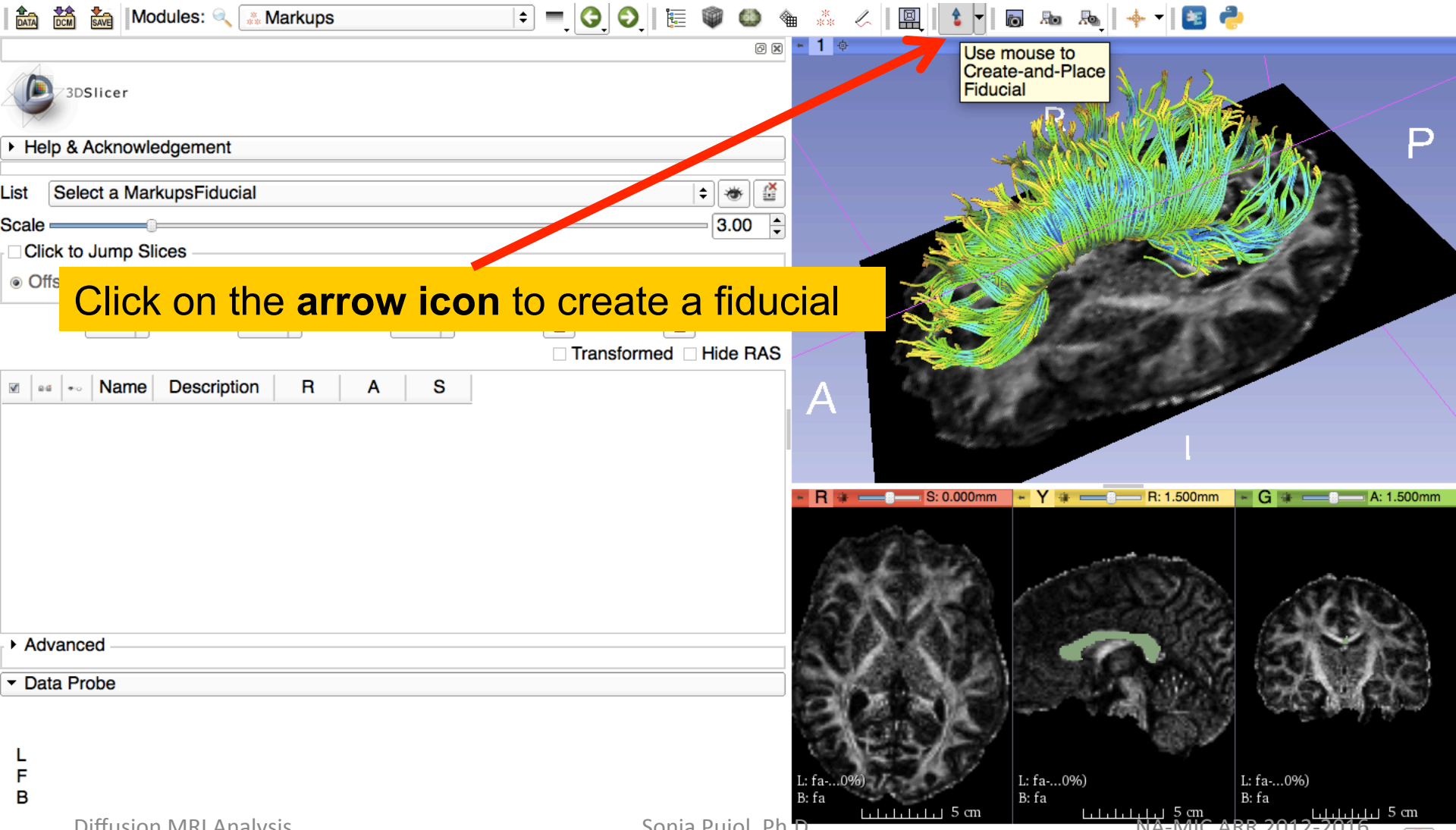
Tractography Results



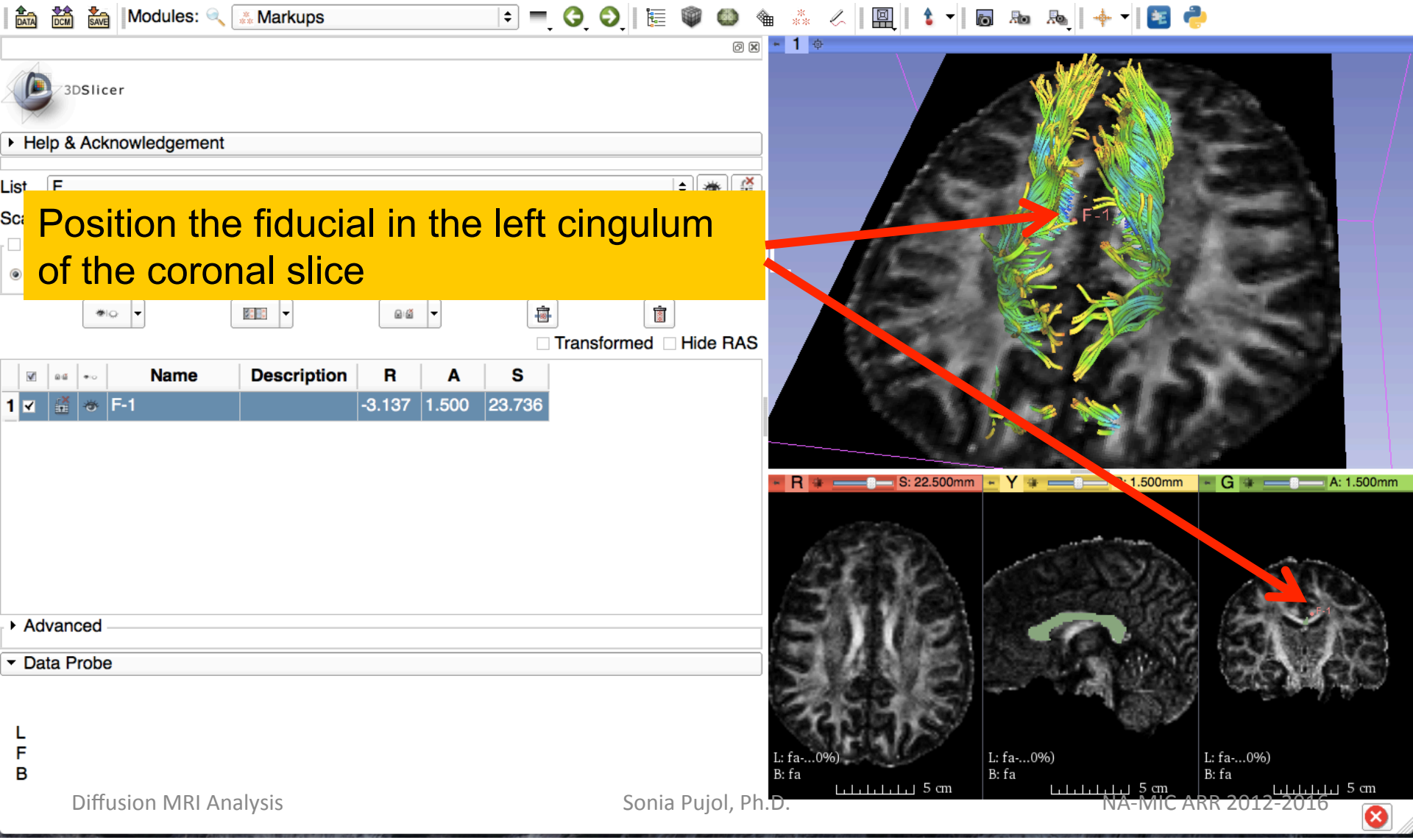
Fiducial Seeding



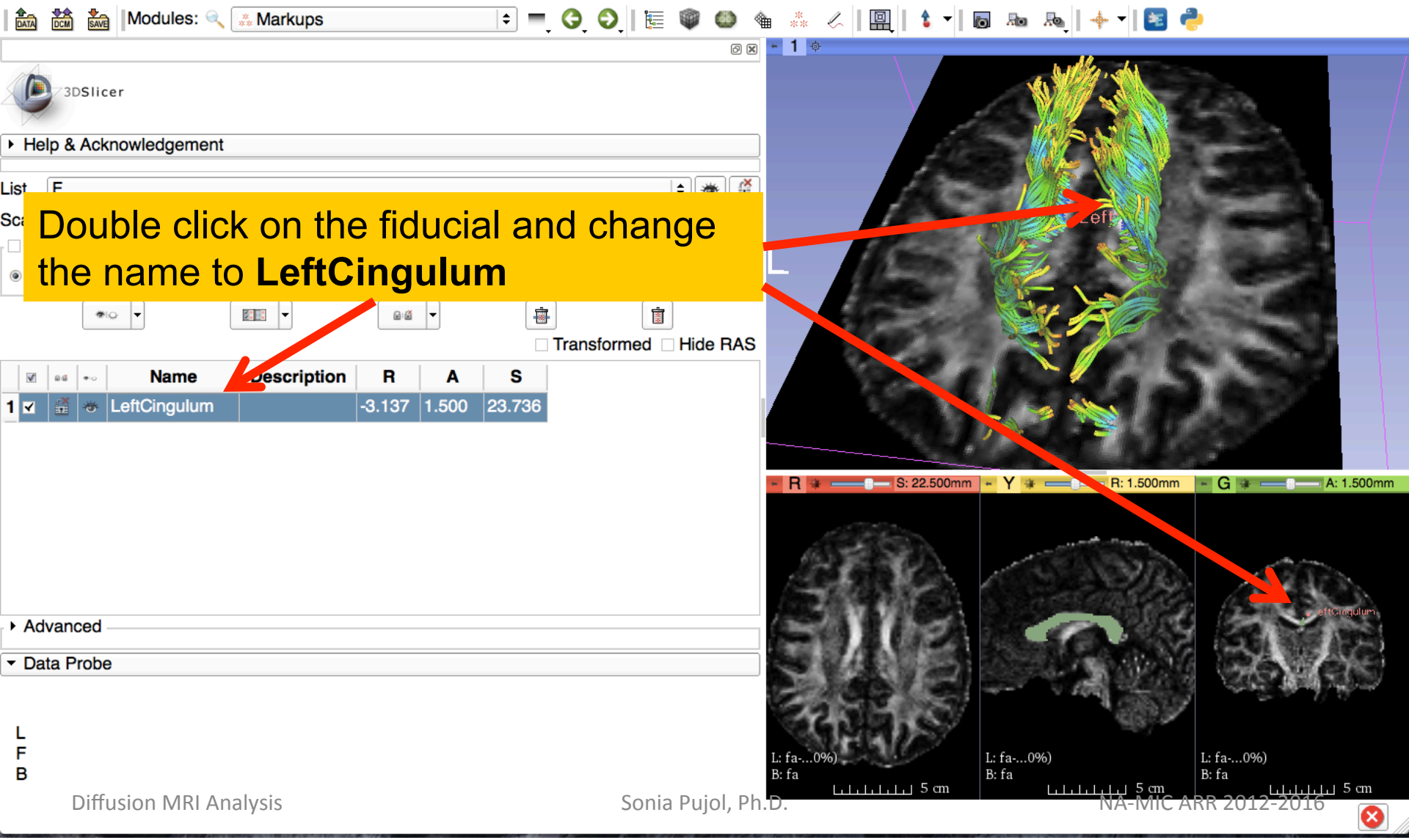
Fiducial Seeding



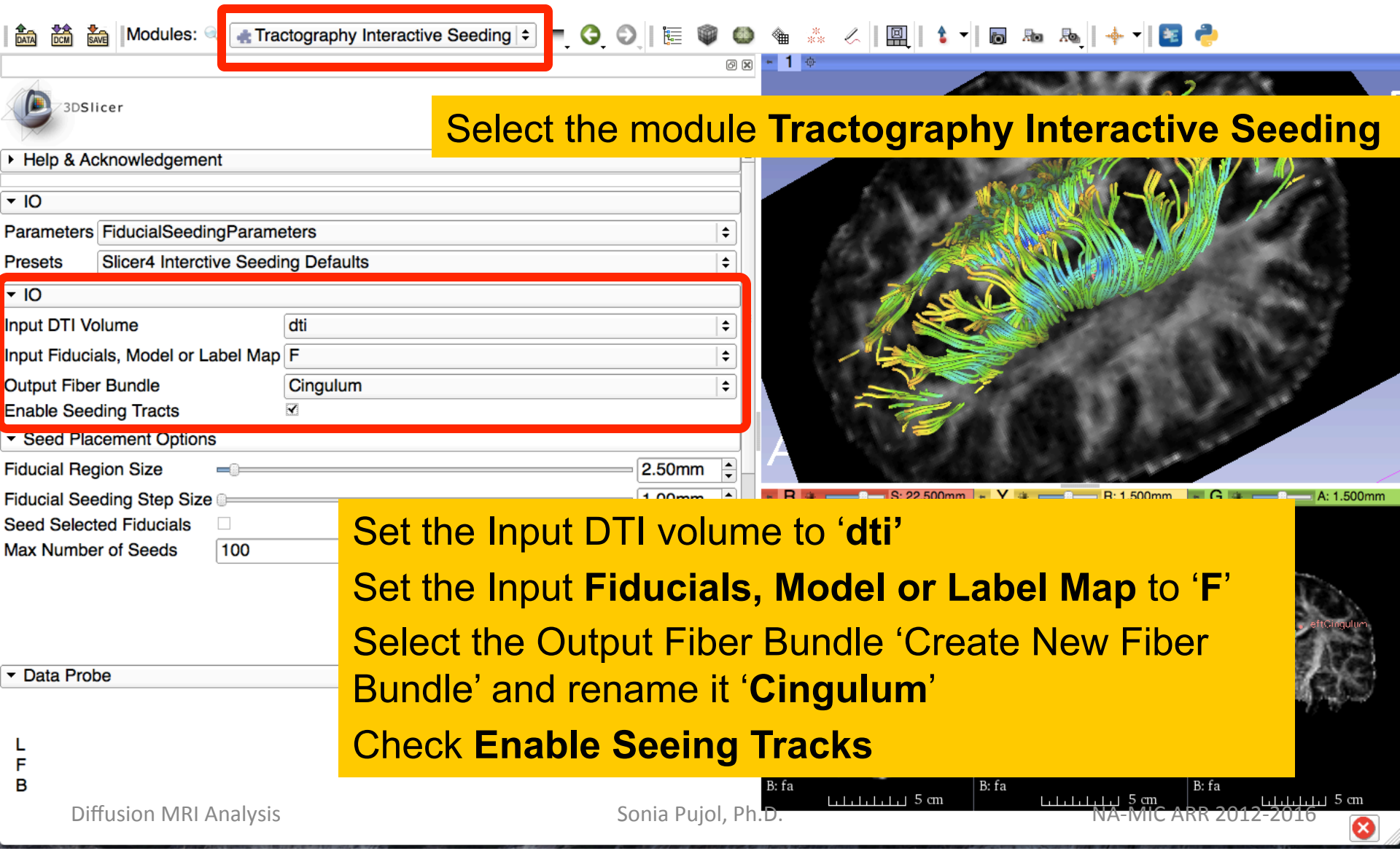
Fiducial Seeding



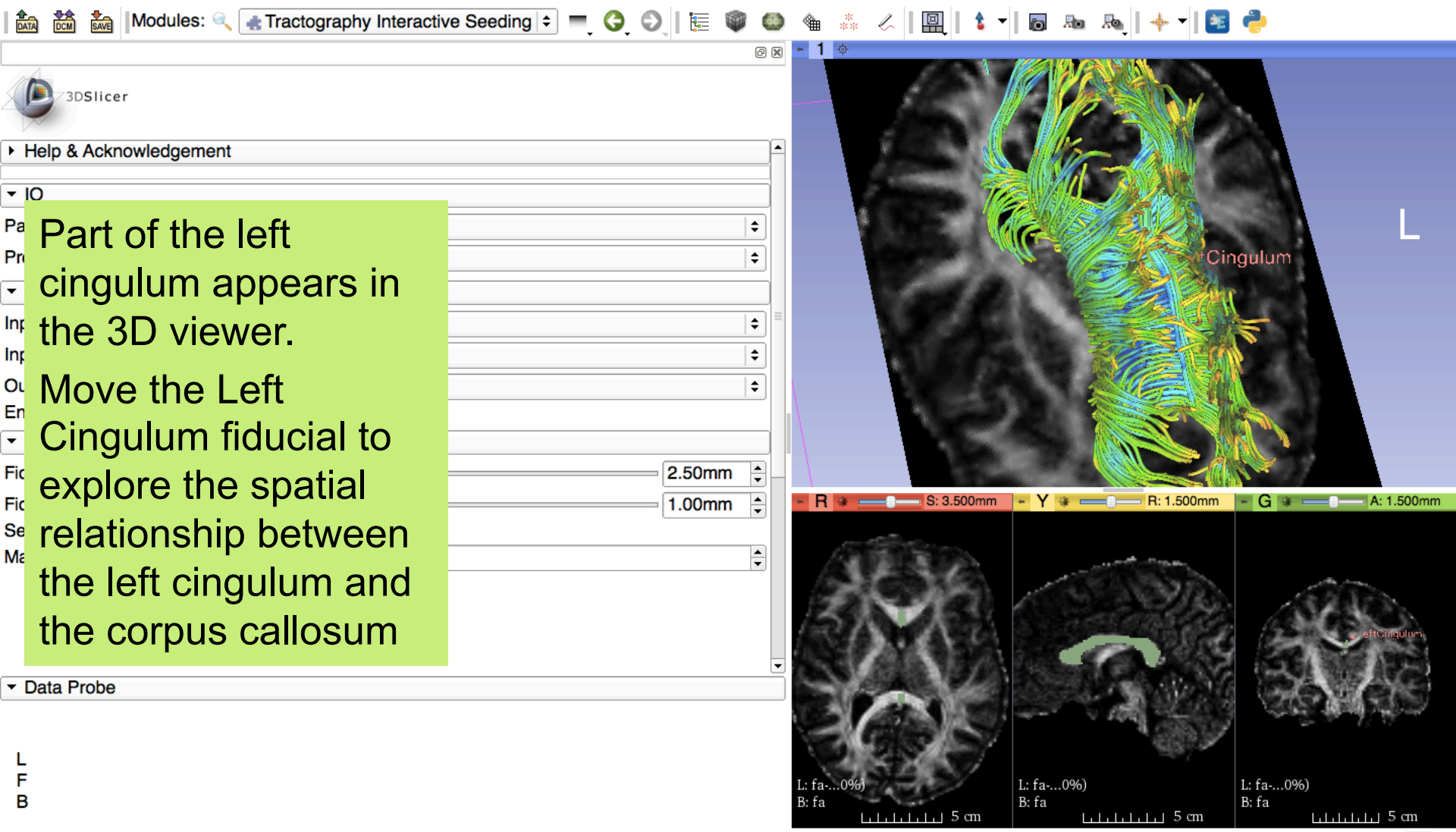
Fiducial Seeding



Fiducial Seeding



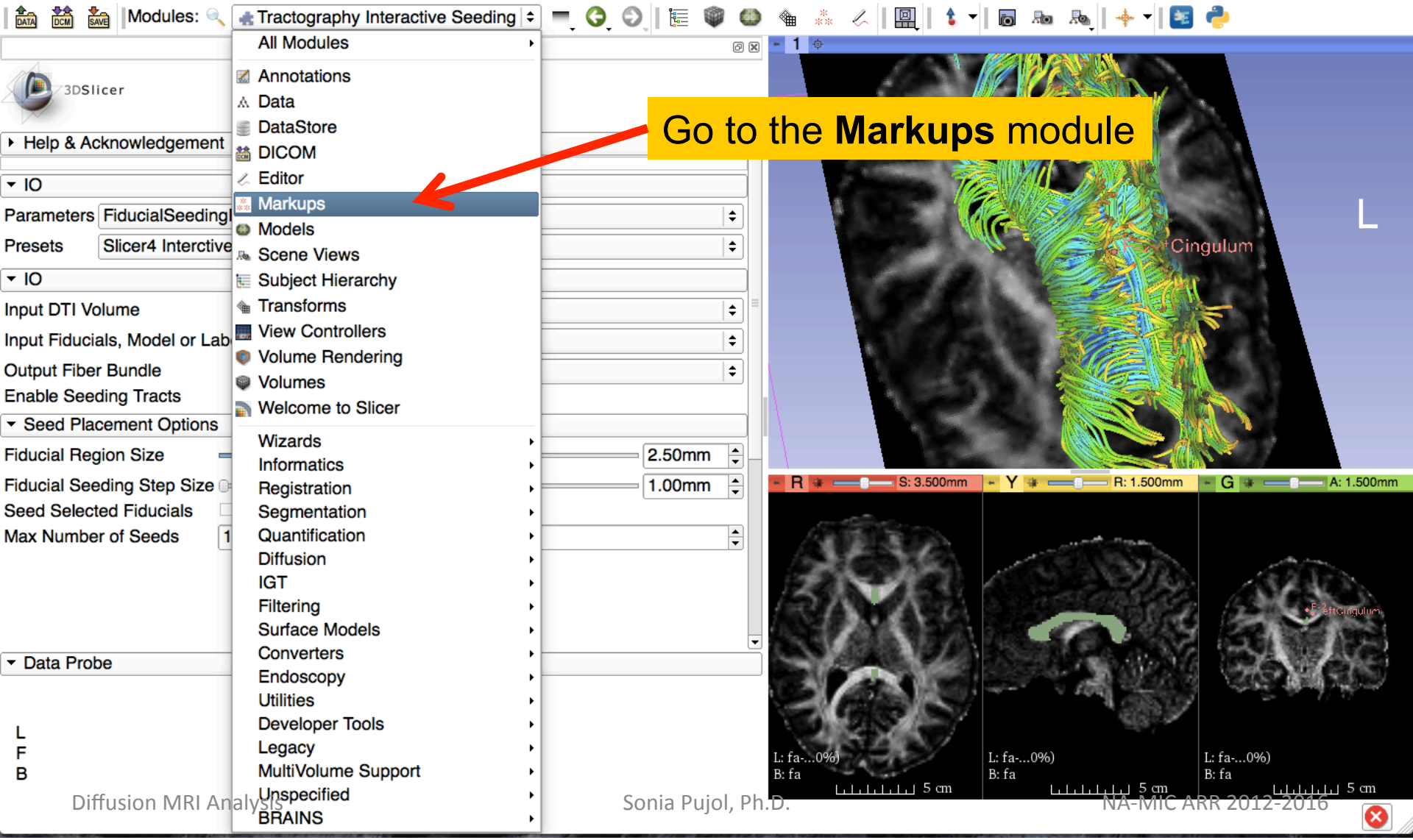
Fiducial Seeding



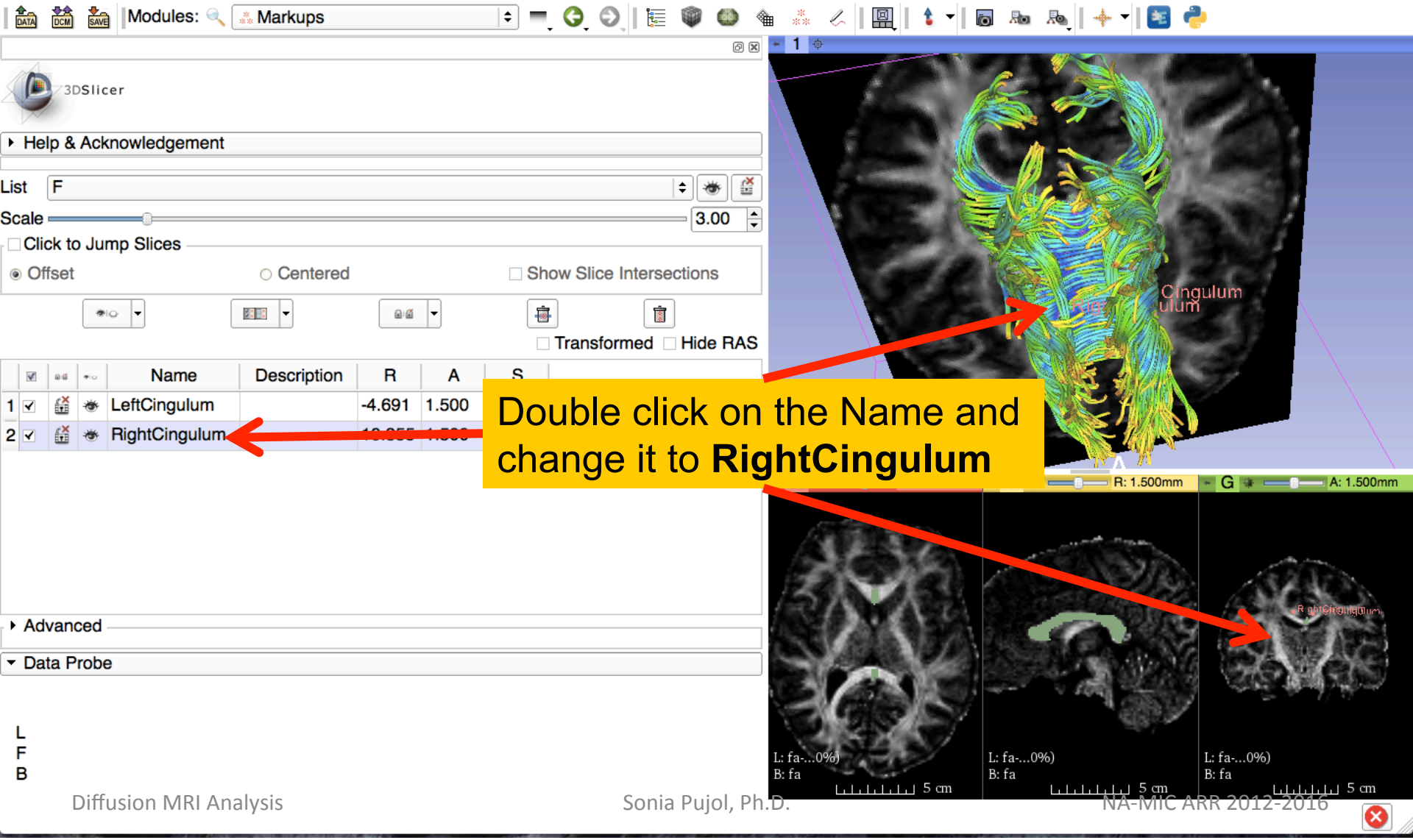
Part of the left cingulum appears in the 3D viewer.

Move the Left Cingulum fiducial to explore the spatial relationship between the left cingulum and the corpus callosum

Fiducial Seeding



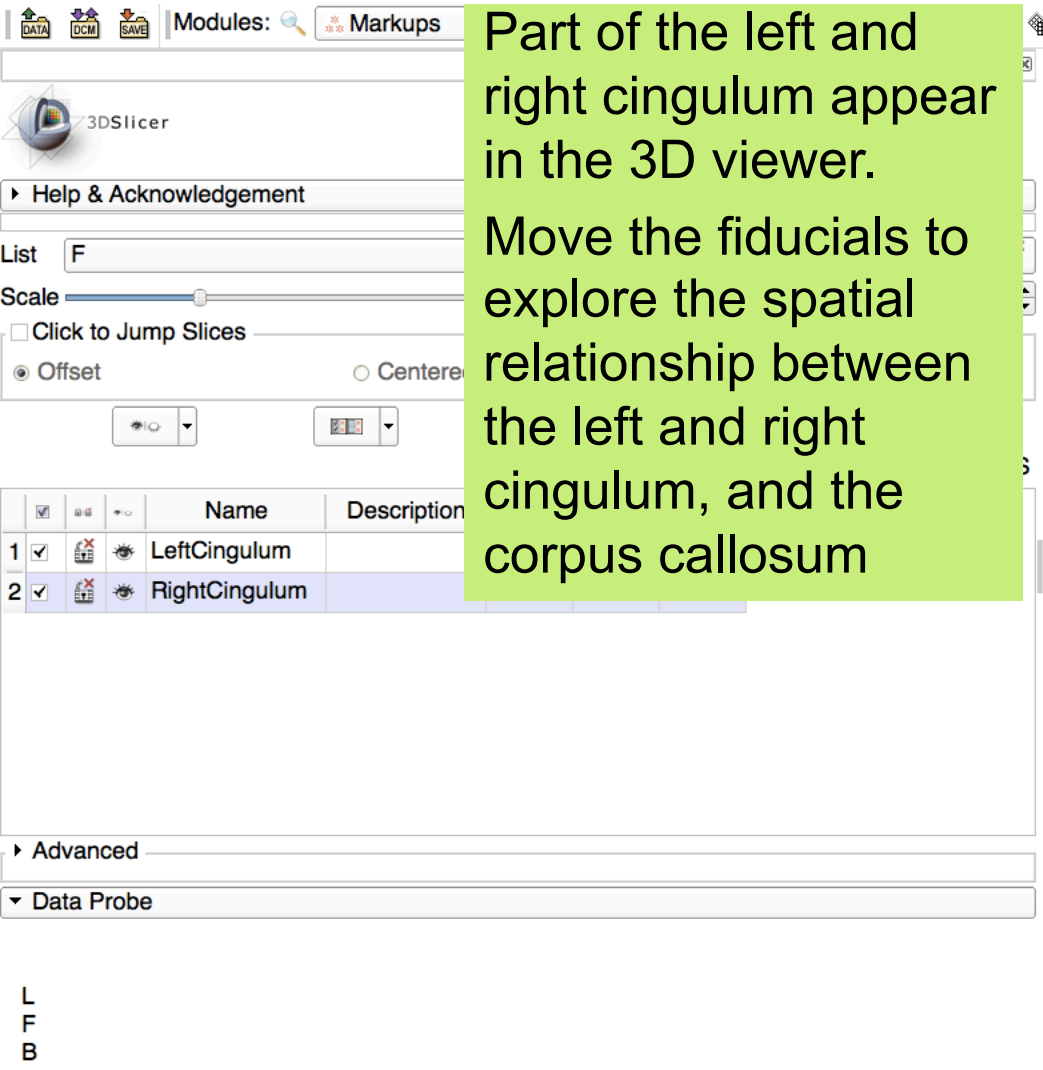
Fiducial Seeding

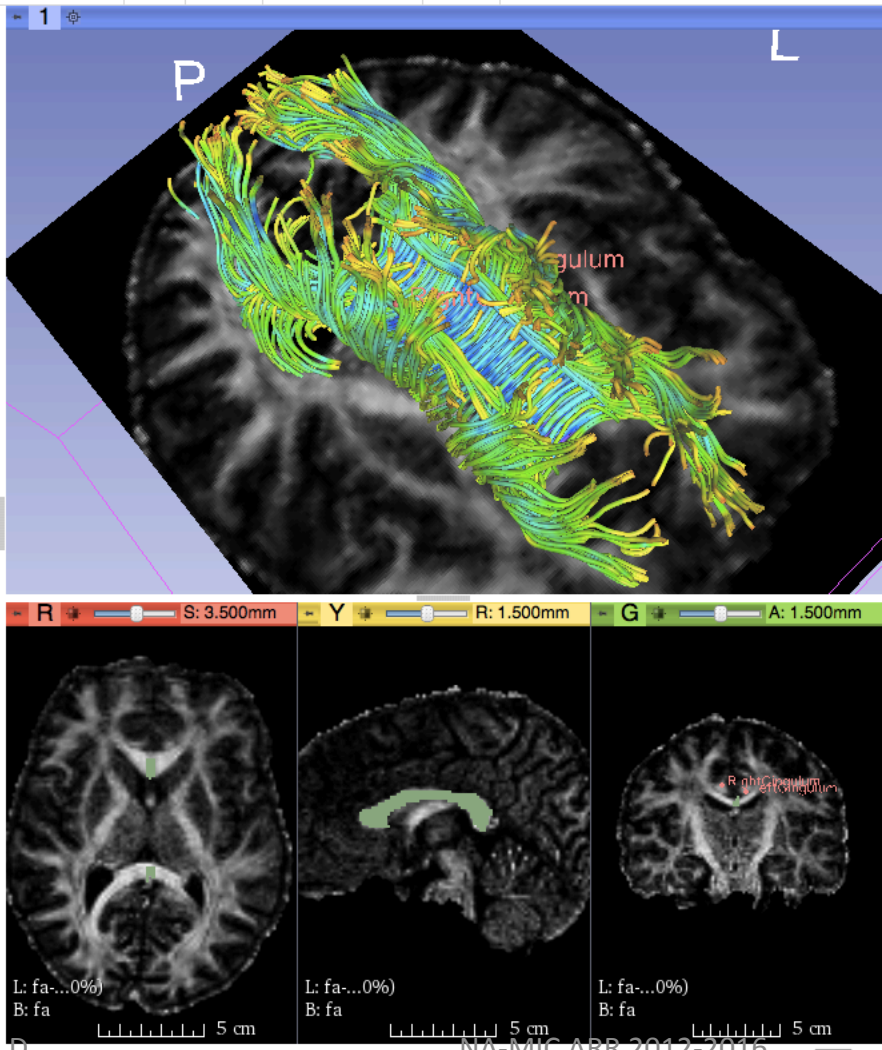


Fiducial Seeding

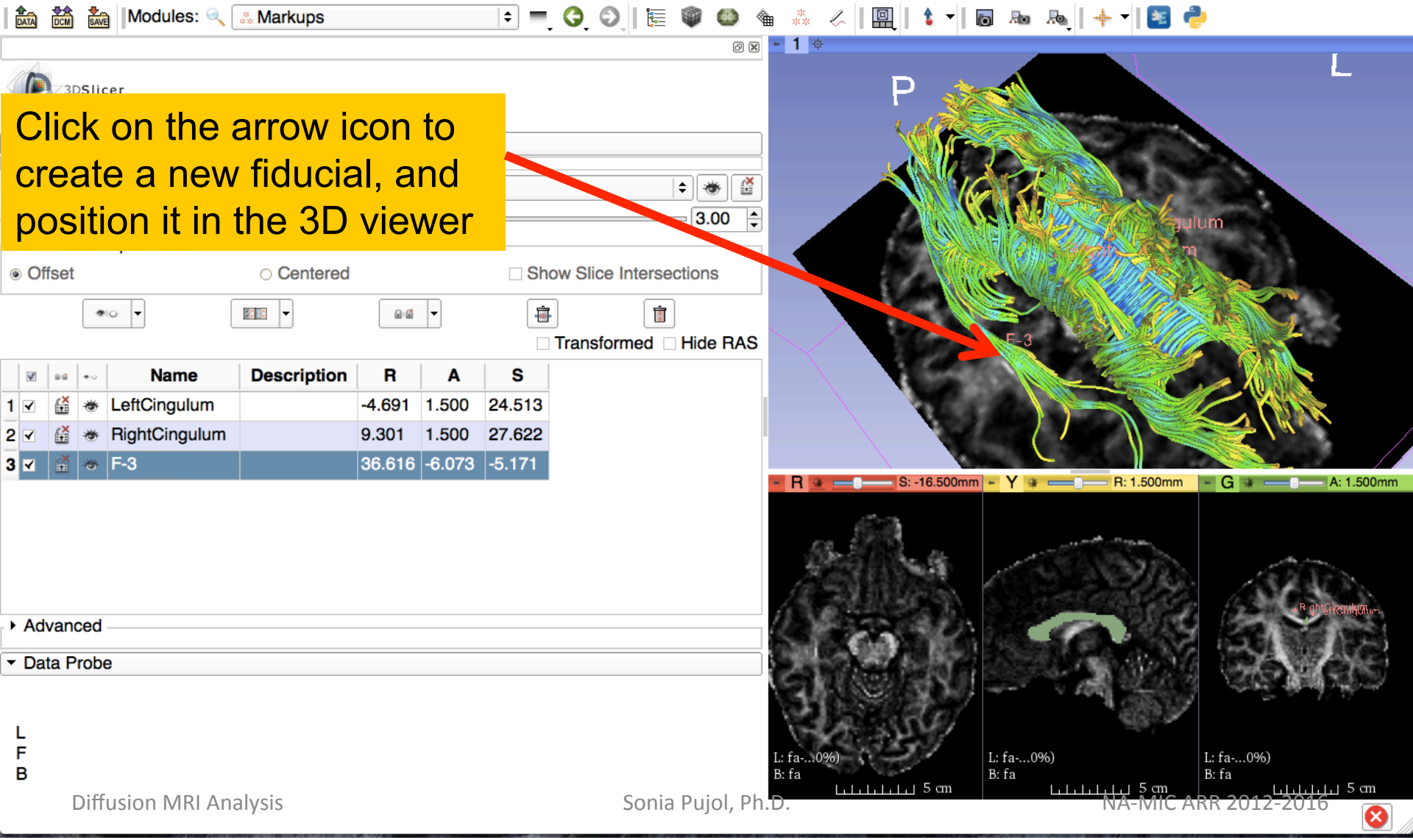
Part of the left and right cingulum appear in the 3D viewer.

Move the fiducials to explore the spatial relationship between the left and right cingulum, and the corpus callosum

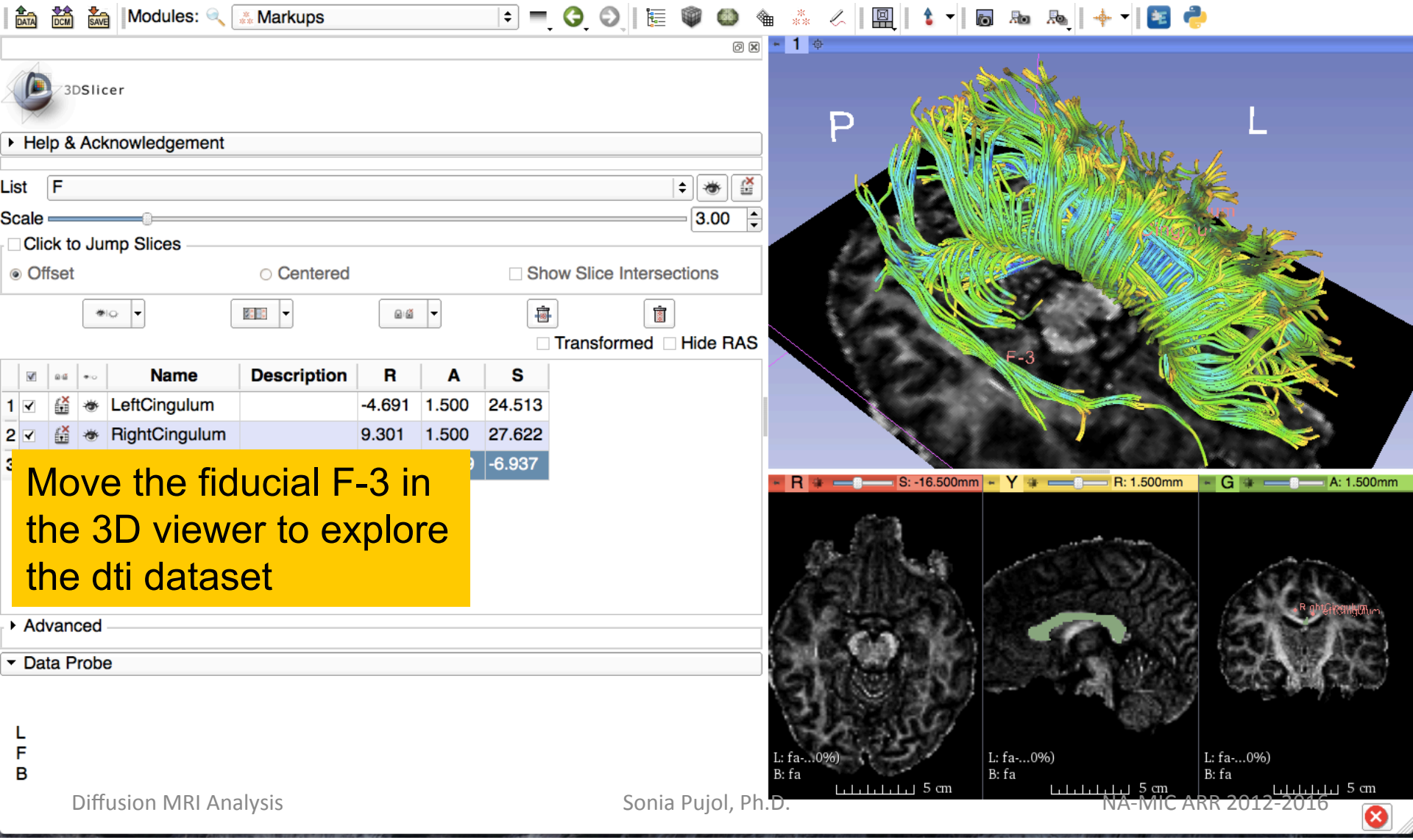




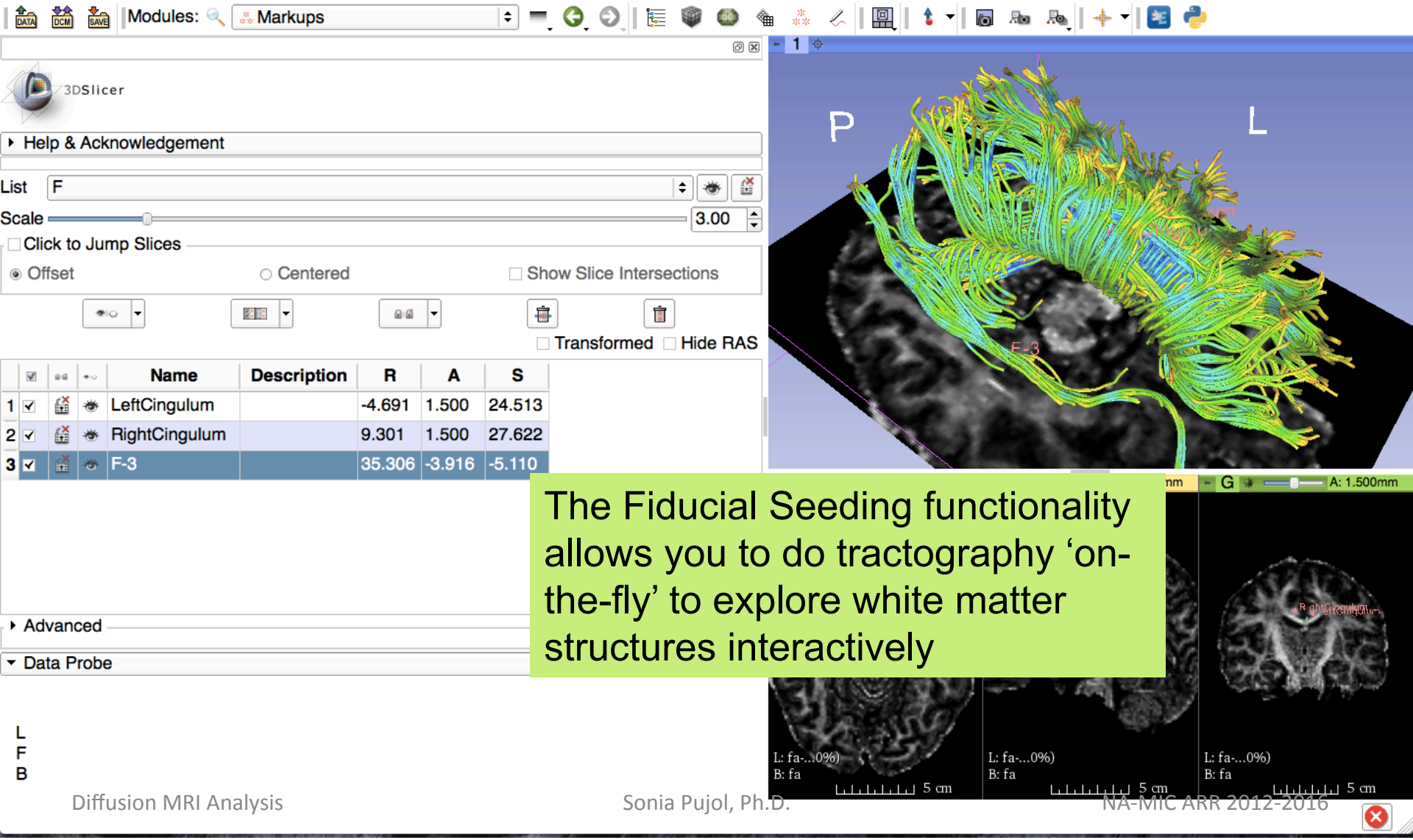
Fiducial Seeding



Fiducial Seeding

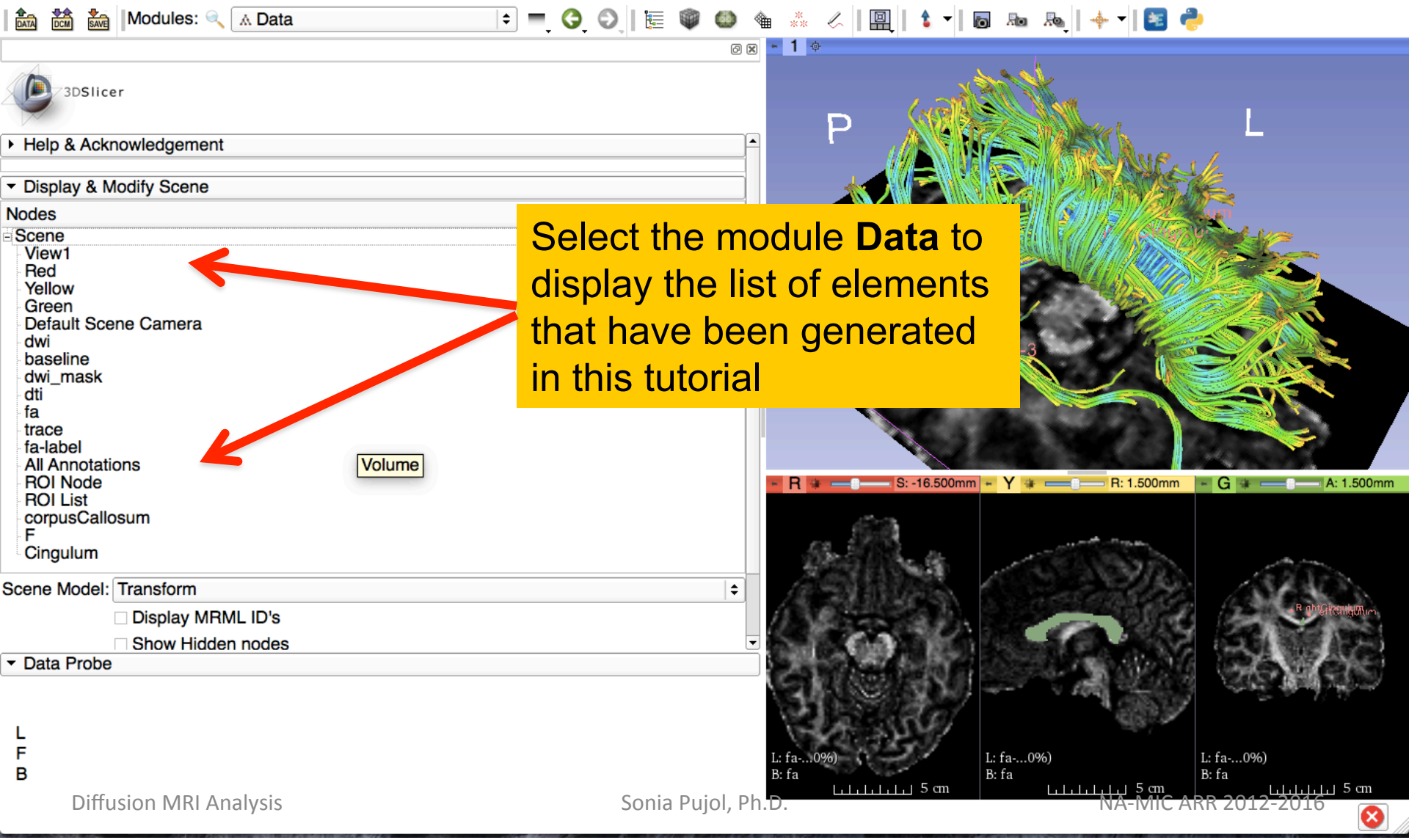


Tractography ‘on-the-fly’

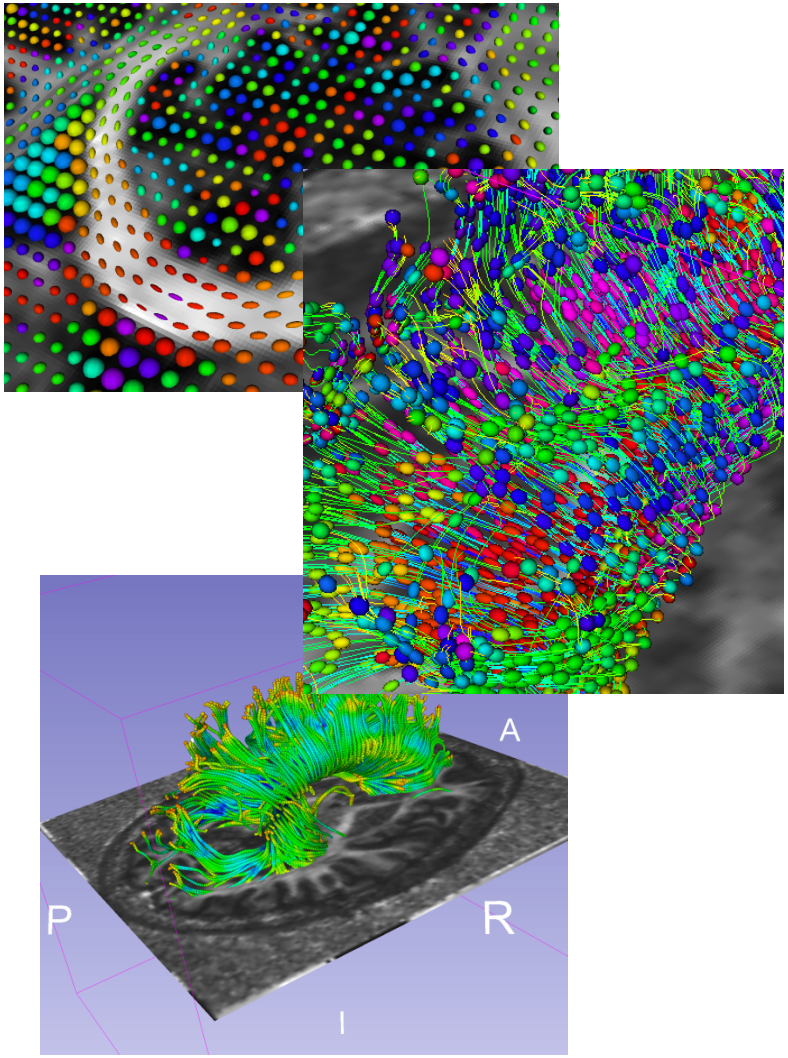


The Fiducial Seeding functionality allows you to do tractography ‘on-the-fly’ to explore white matter structures interactively

DTI Analysis



Conclusion



This tutorial guided you through the different steps of a Diffusion MR analysis pipeline, from tensor estimation to 3D tracts visualization, for exploring and studying the 3D architecture of the brain white matter.

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