Diffusion MRI Analysis

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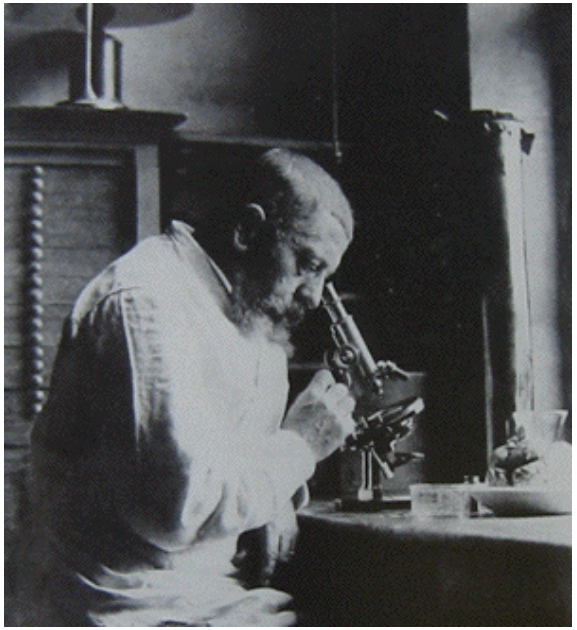
Brain Anatomy

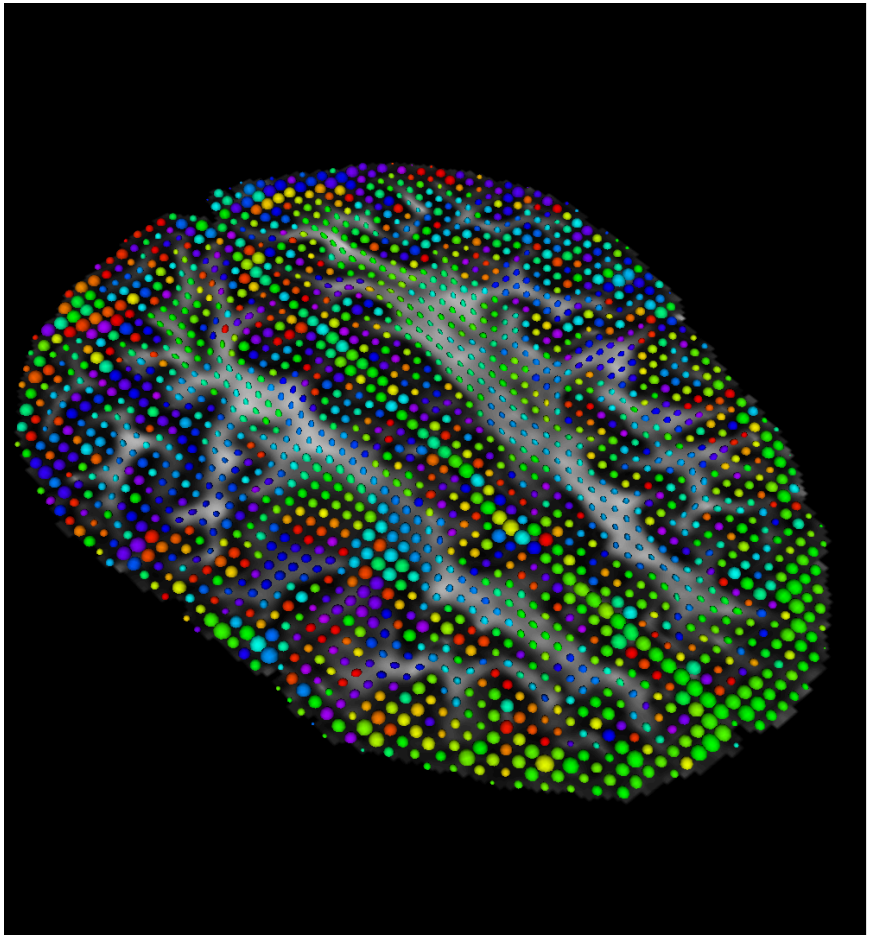
- White matter ~45% of the brain
- Myelinated nerve fibers (~ 10 μm axon diameter)

White Matter Exploration



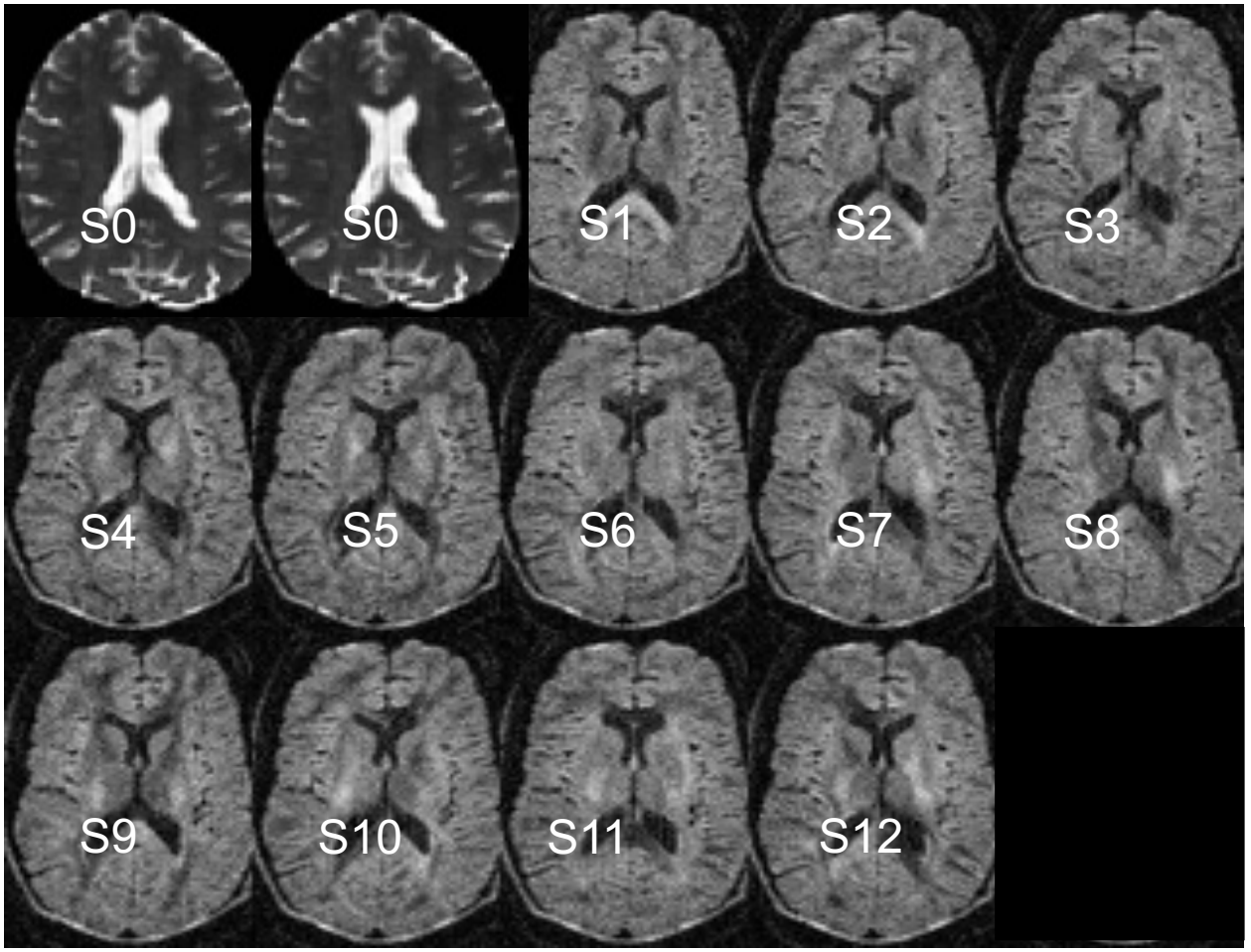
Jules Joseph Dejerine (*Anatomie des centres nerveux* (Paris, 1890-1901): Atlas of Neuroanatomy based on myelin stained preparation

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

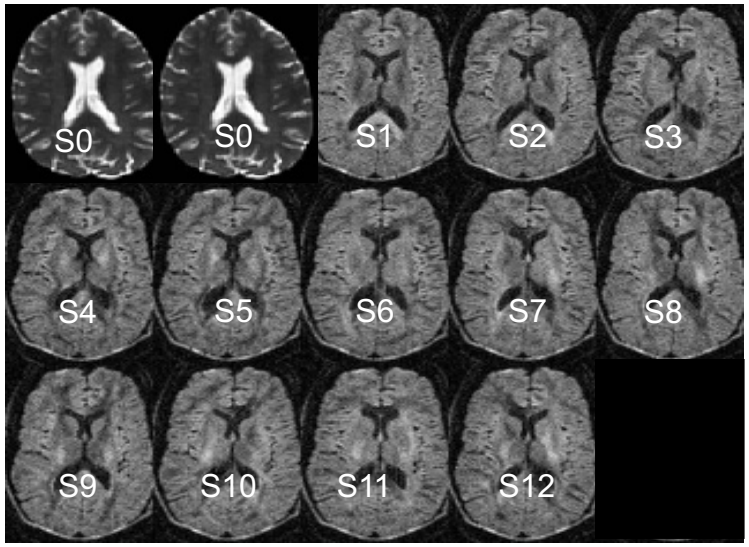
Diffusion Weighted Imaging (DWI)



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

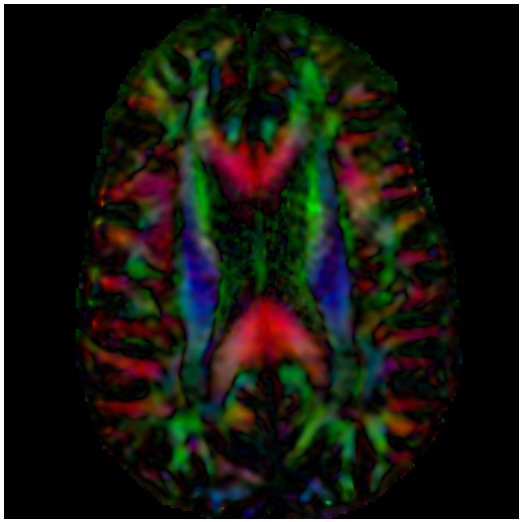
From DWI to DTI

DWI



DWI dataset acquired with
12 gradient and 2 baseline

DTI



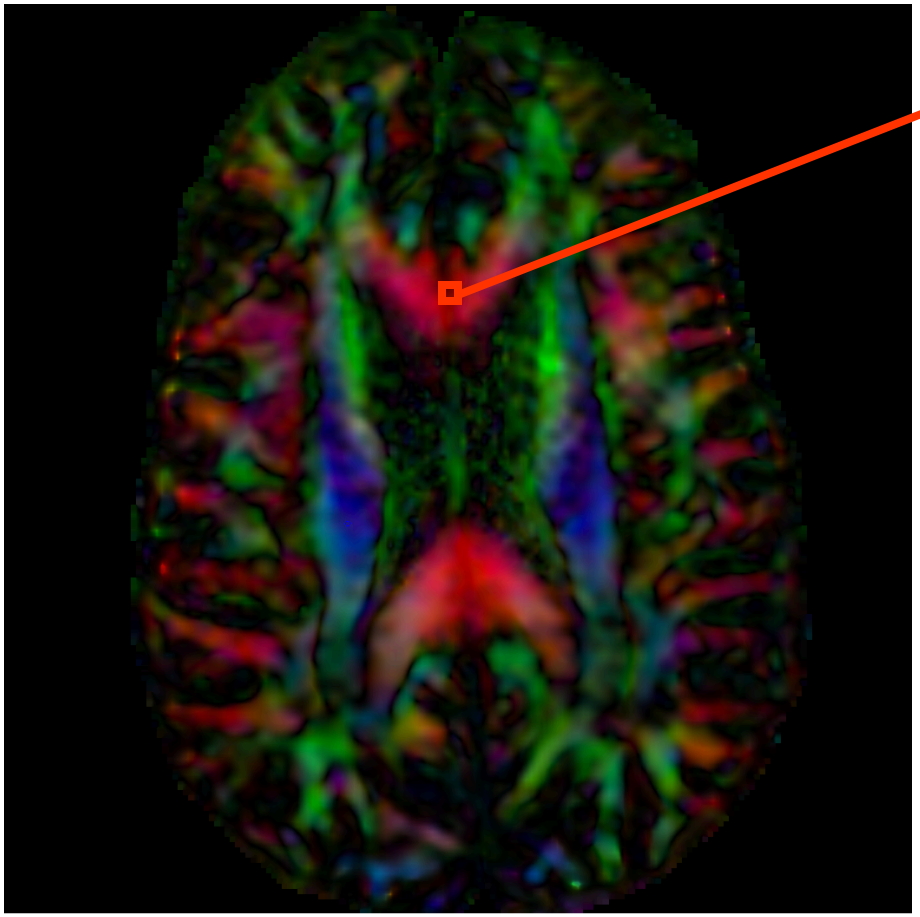
DTI dataset

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

Stejskal-Tanner (1965)

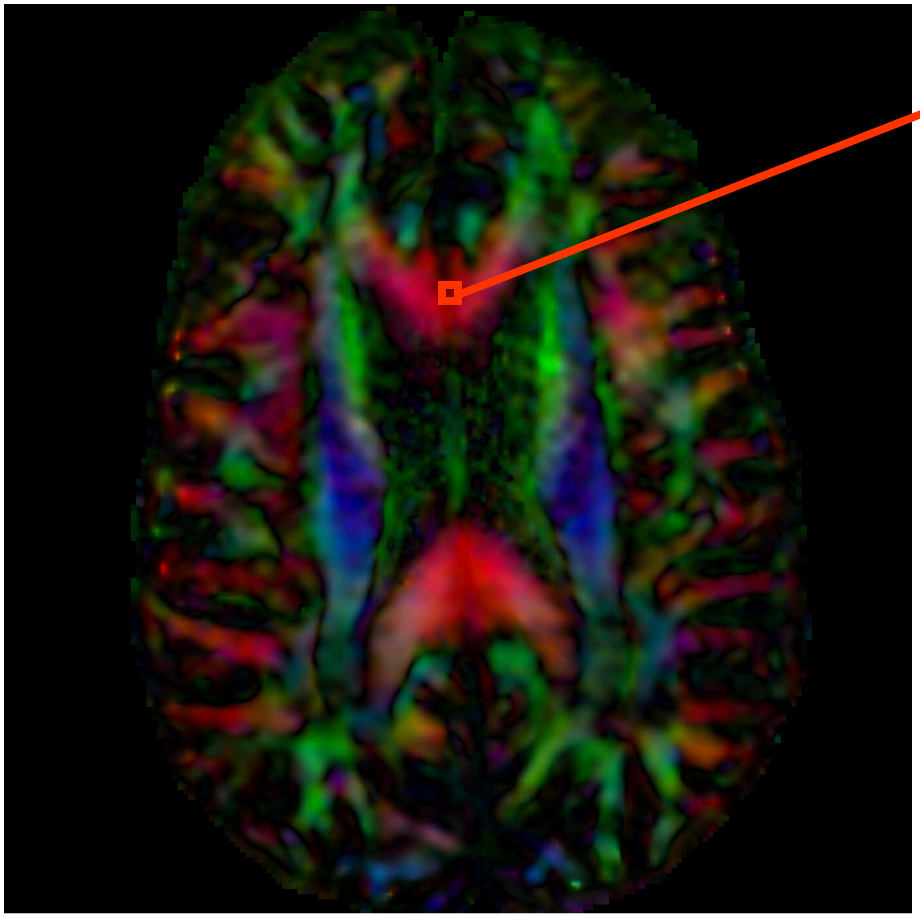
Si: DWI volume acquired with ith gradient
So: Baseline volume

Diffusion Tensor Imaging



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

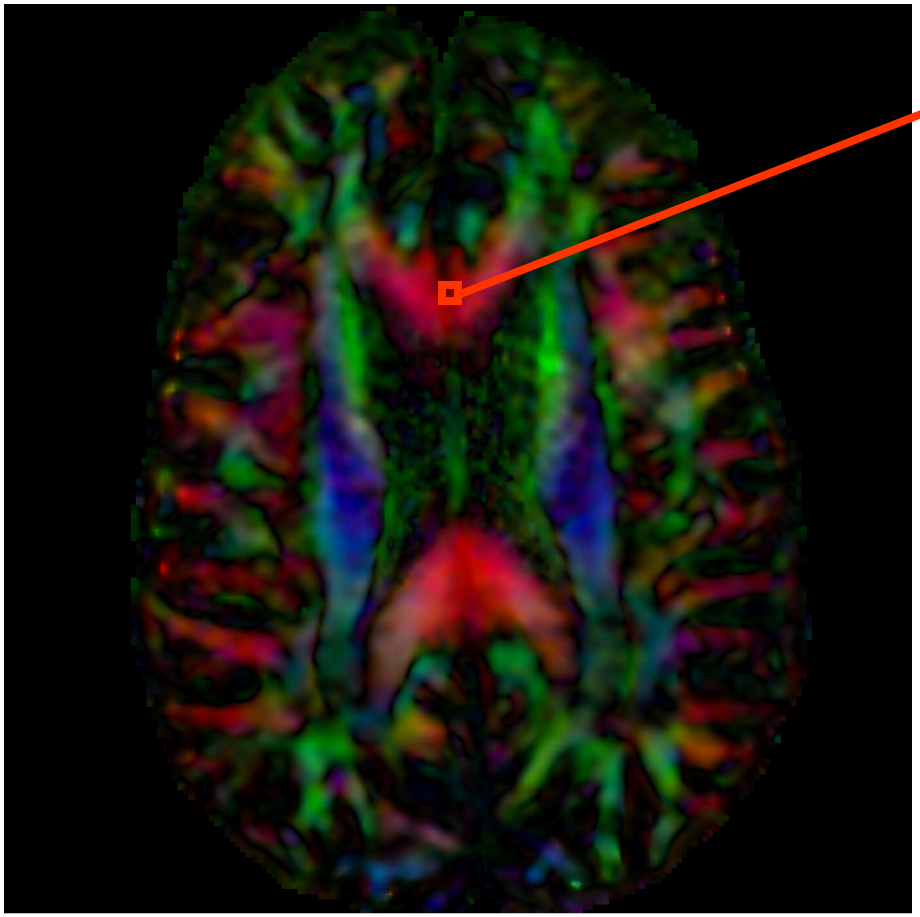
Diffusion Tensor Imaging



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

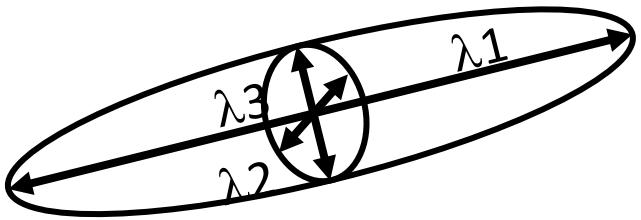
$$\underline{\mathbf{D}} = \begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{zx} & D_{zy} & D_{zz} \end{bmatrix}$$

Diffusion Tensor Imaging

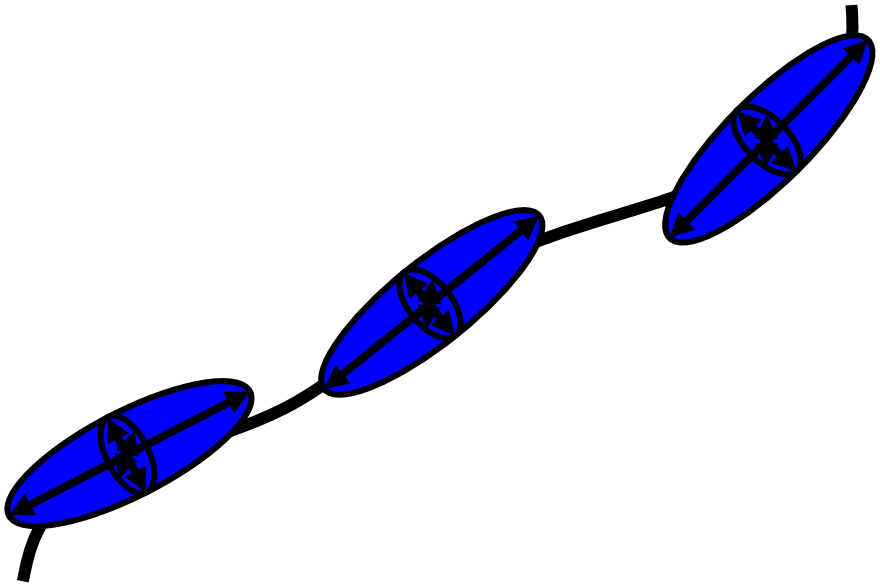


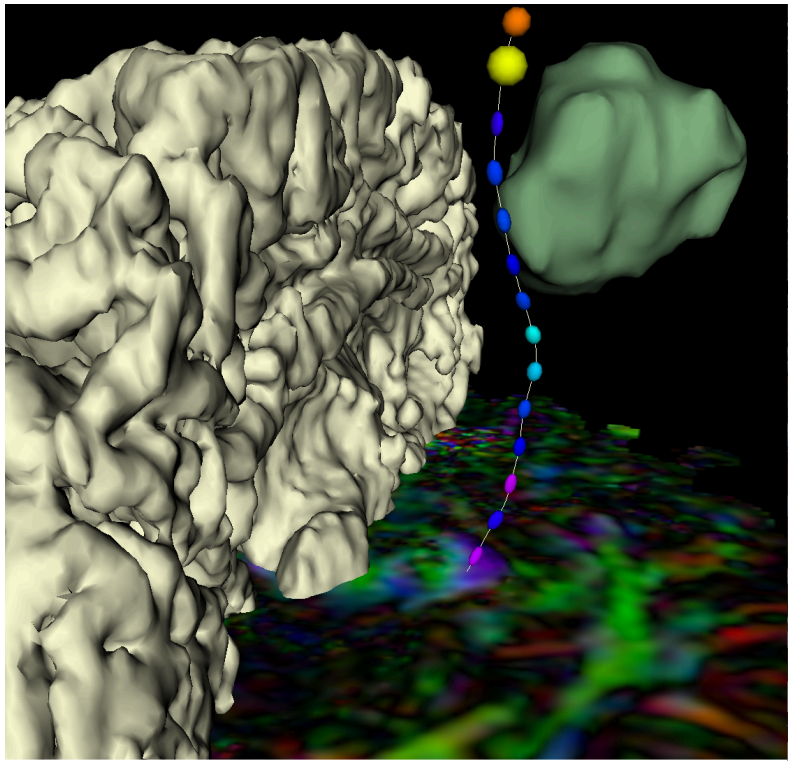
$$S_i = S_0 e^{-b\hat{g}i^T \underline{D} \hat{g}_i}$$

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



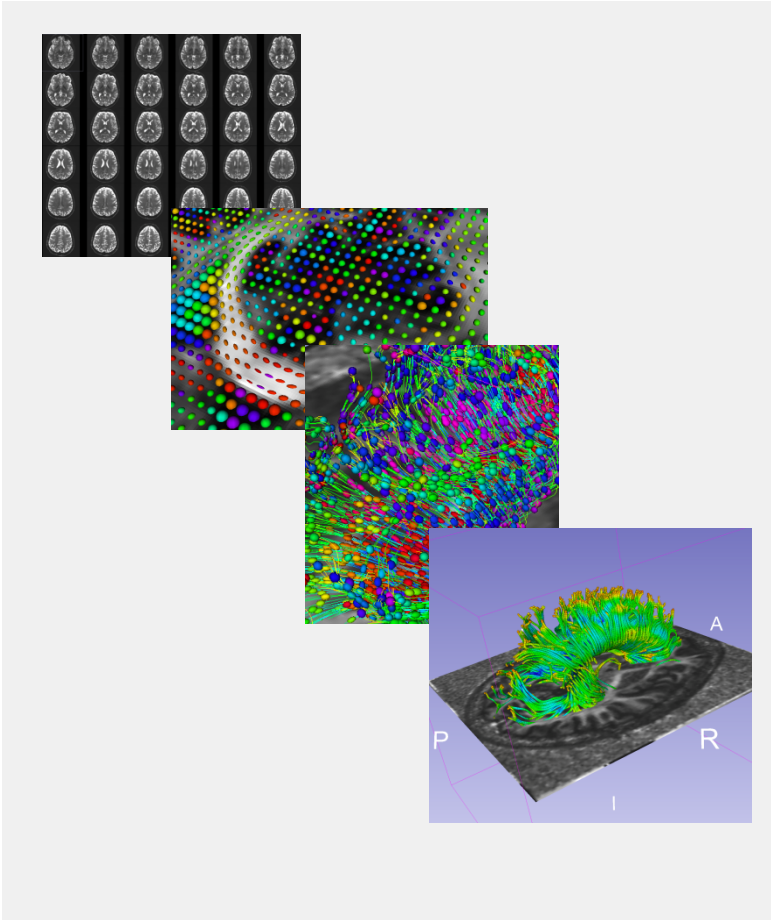
Tractography





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

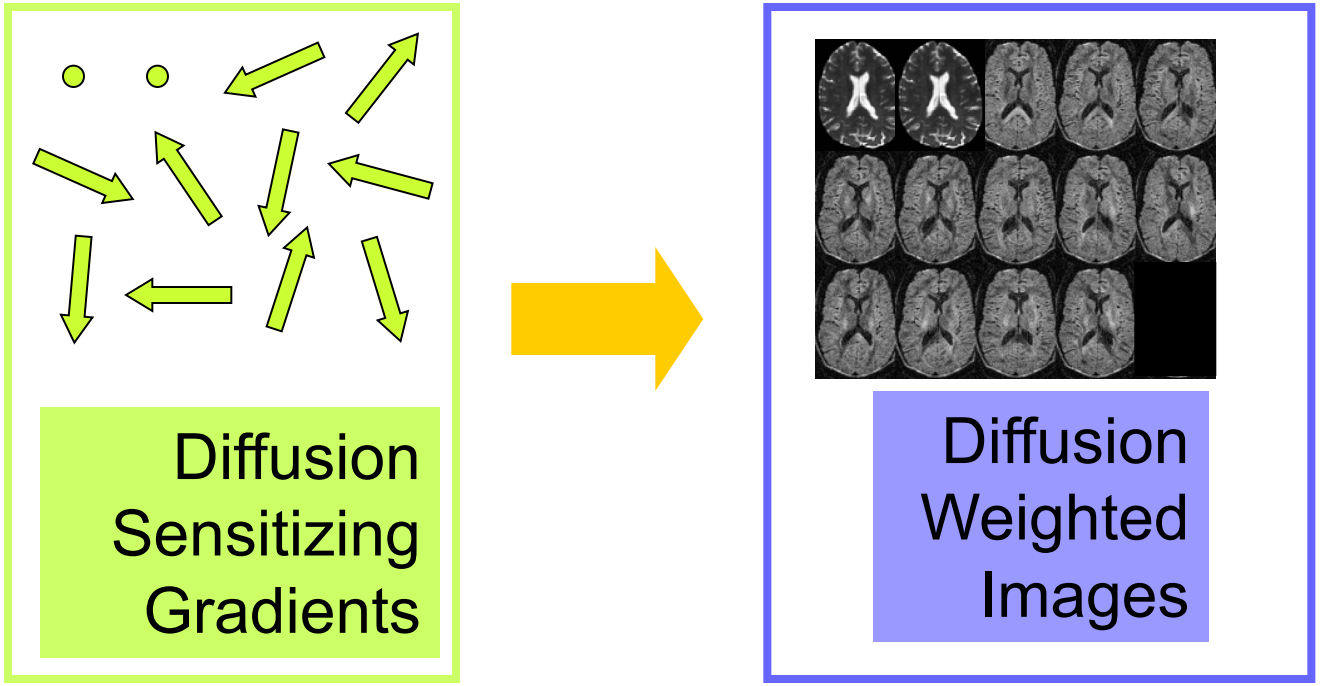
Tutorial Outline



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

Tutorial Dataset

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



Download the dataset at:
https://www.slicer.org/w/images/e/e6/Dti_tutorial_data.zip

3D Slicer

The tutorial uses the 3D Slicer (Version 4.8.1, revision 26813, Stable Release) software available at:

http://download.slicer.org

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.

SlicerDMRI

An open-source project to improve and extend diffusion magnetic resonance imaging software in 3D Slicer:

http://dmri.slicer.org

Disclaimer

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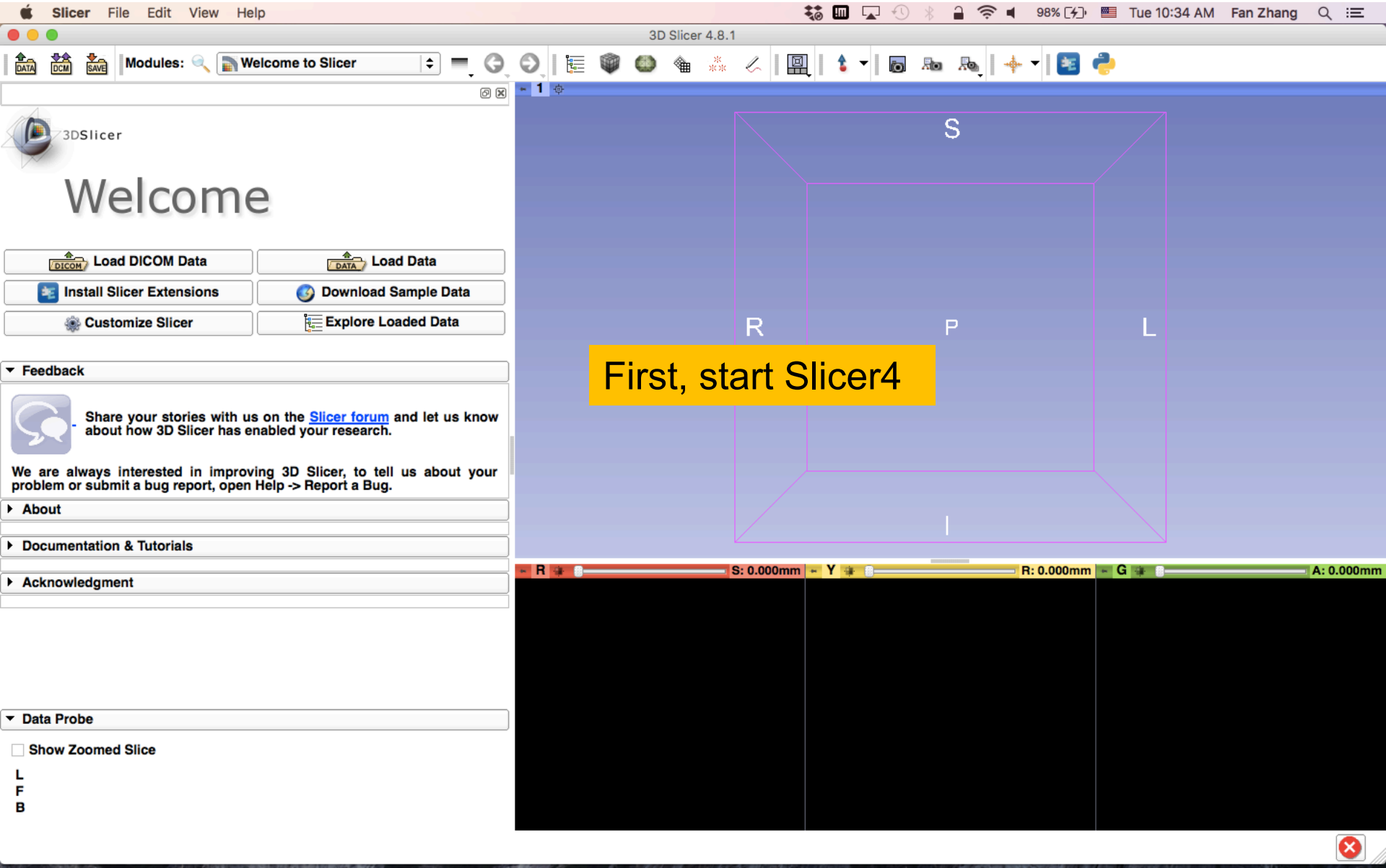
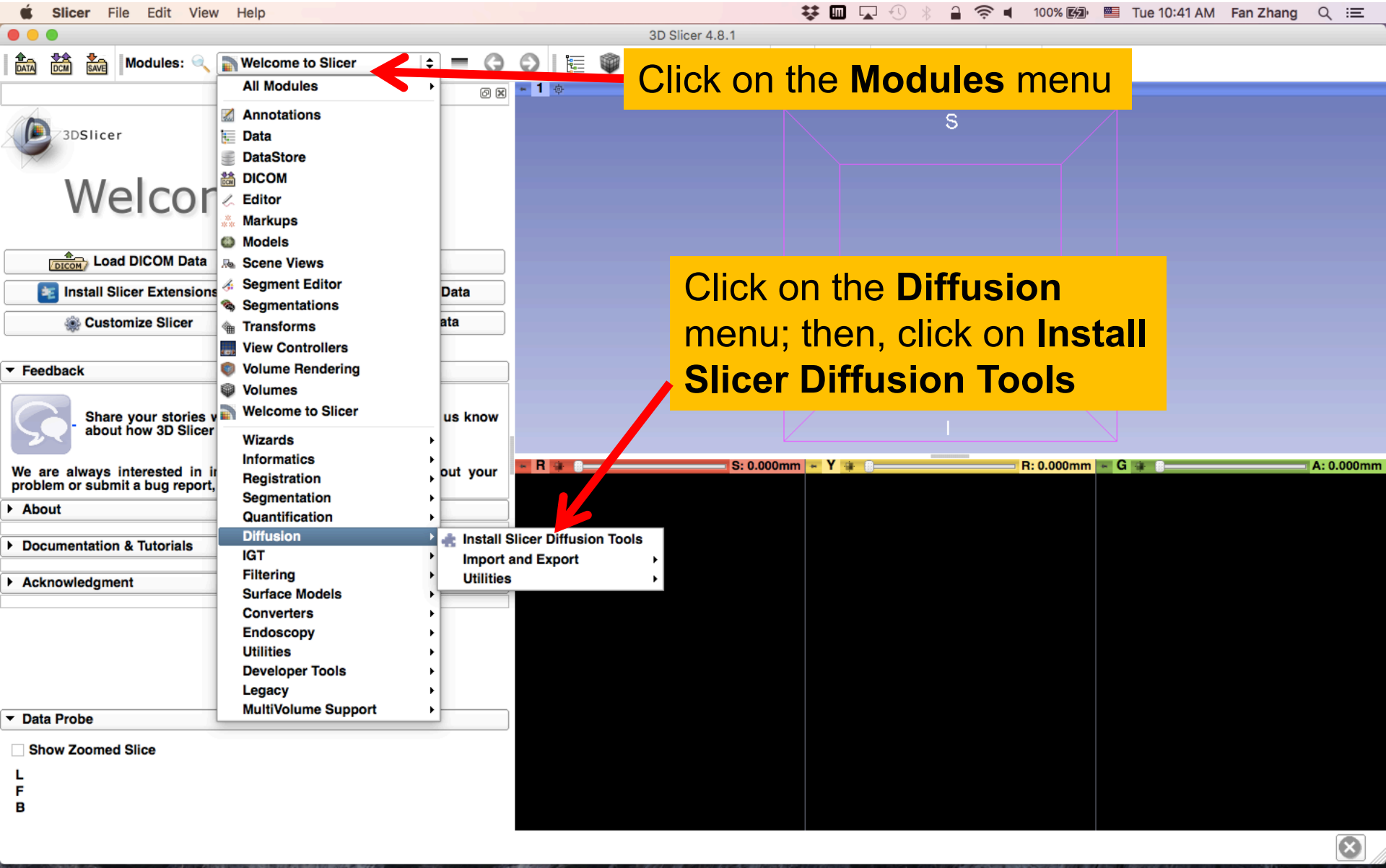
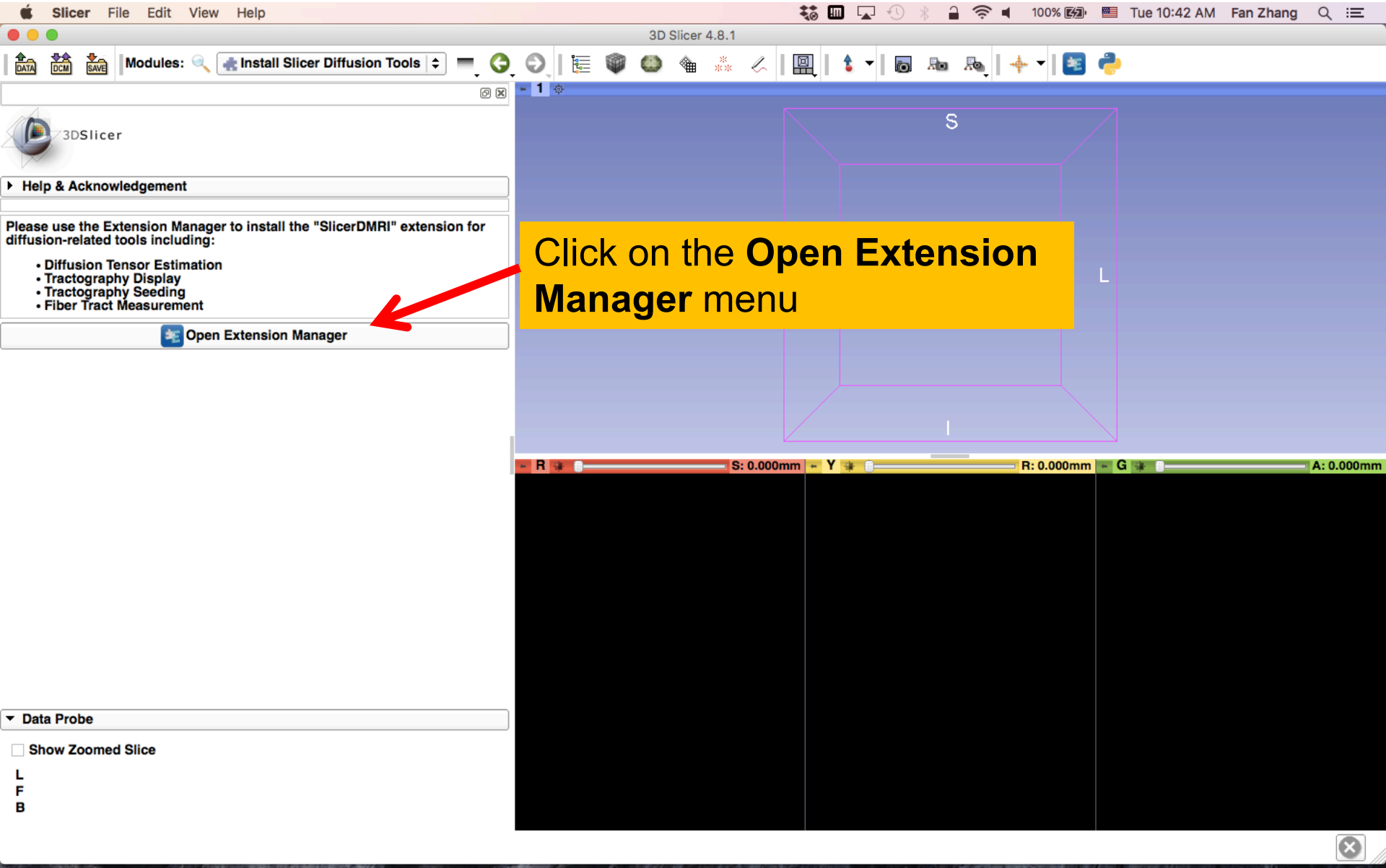
Install SlicerDMRI



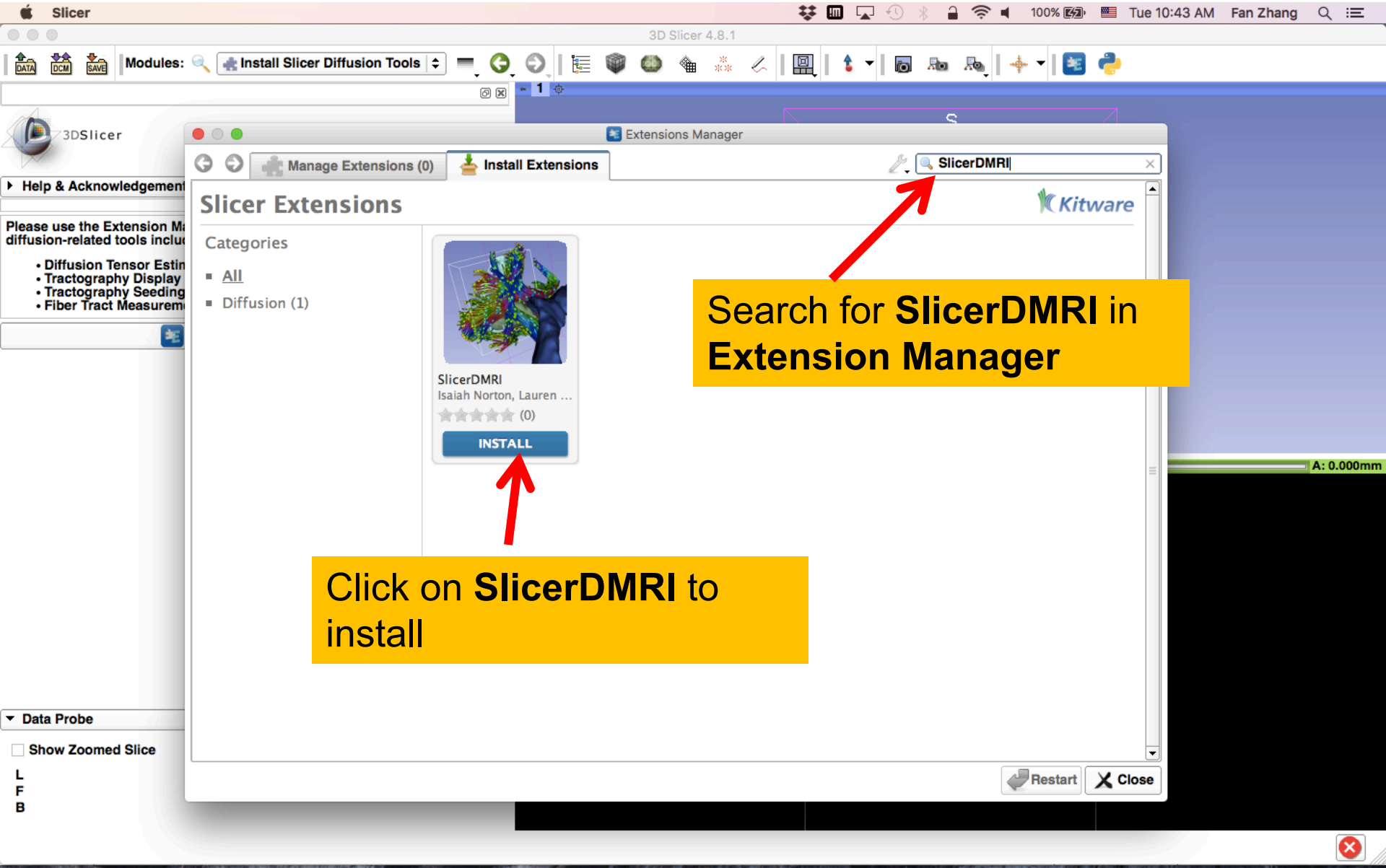
Install SlicerDMRI



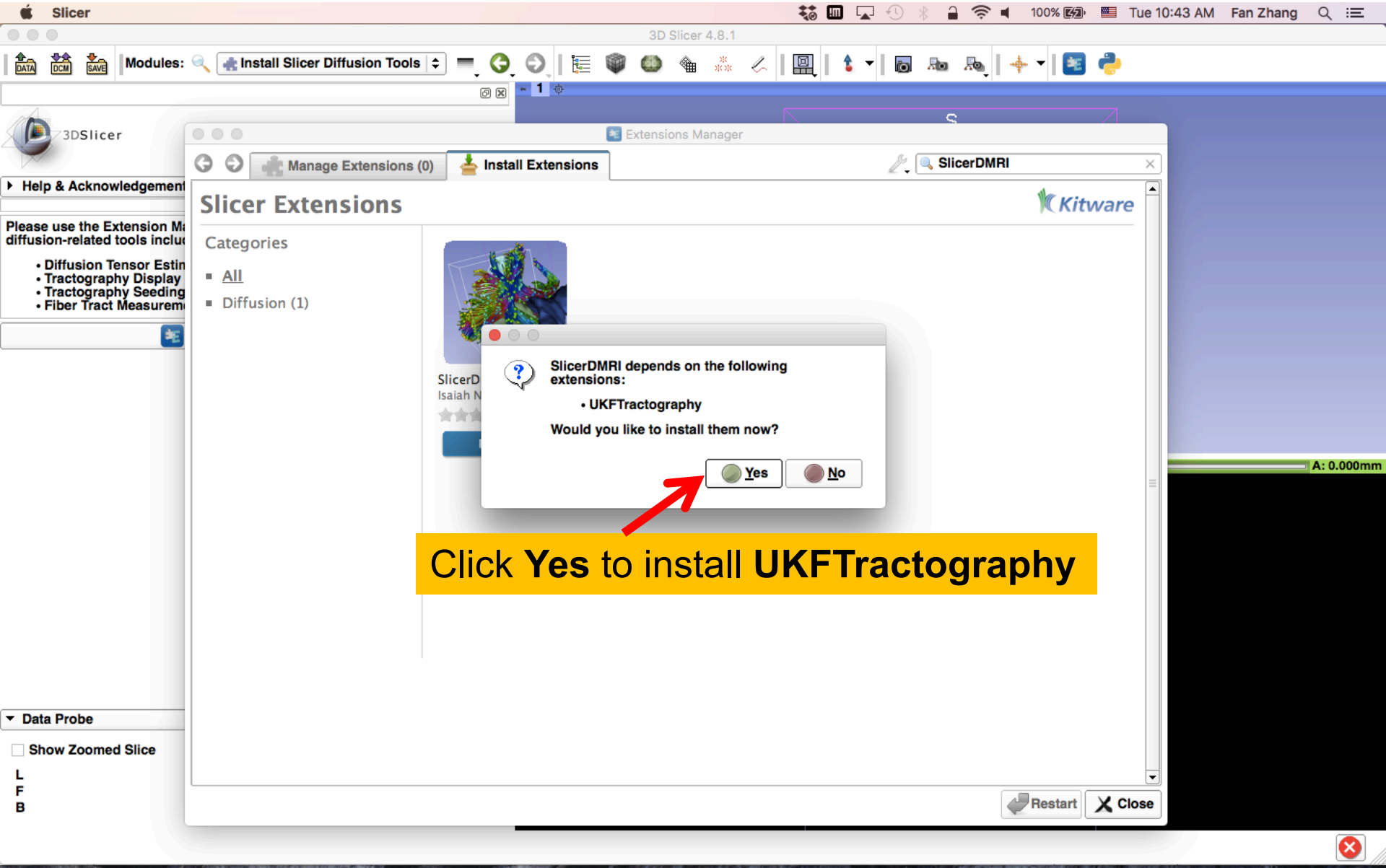
Install SlicerDMRI



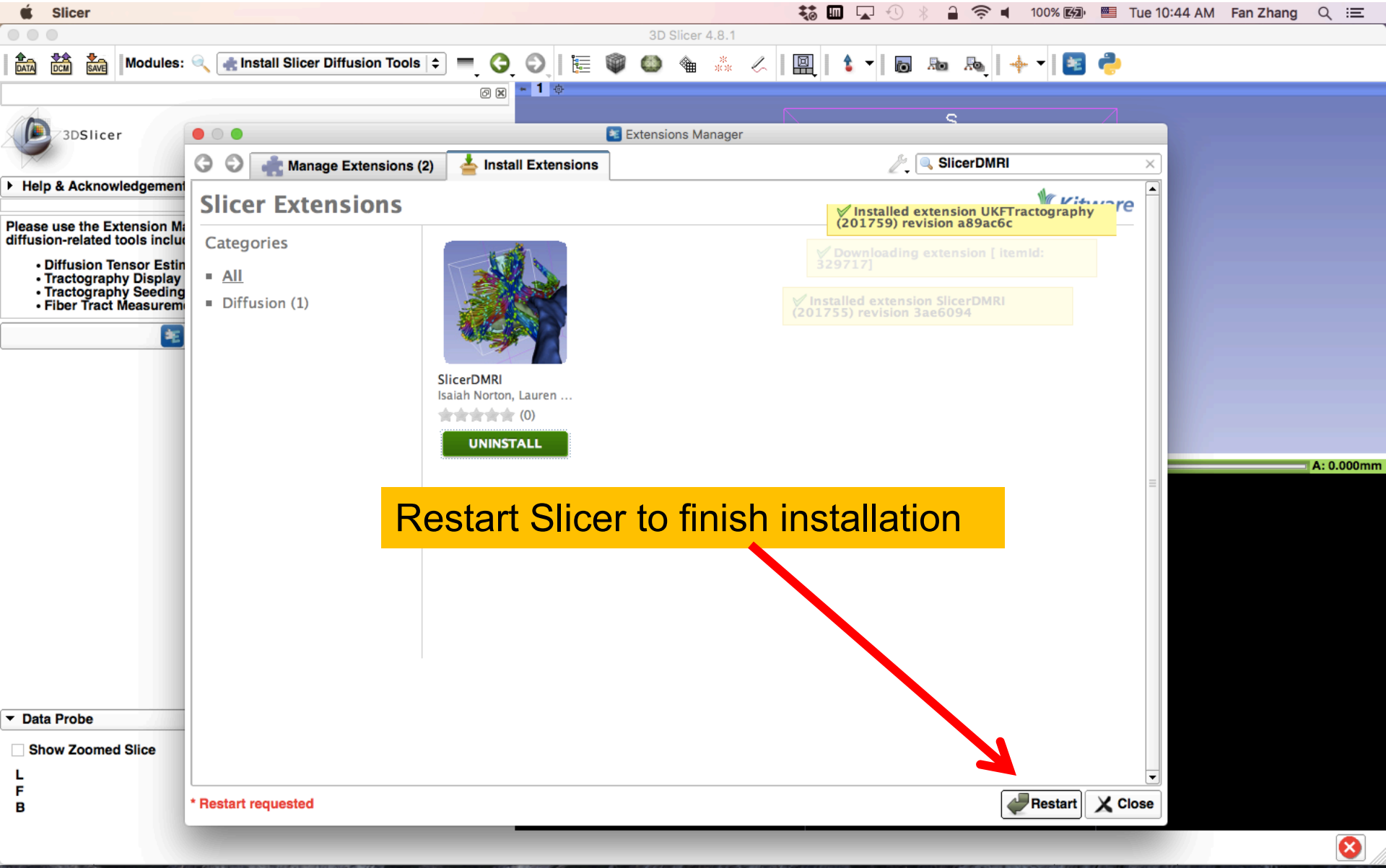
Install SlicerDMRI



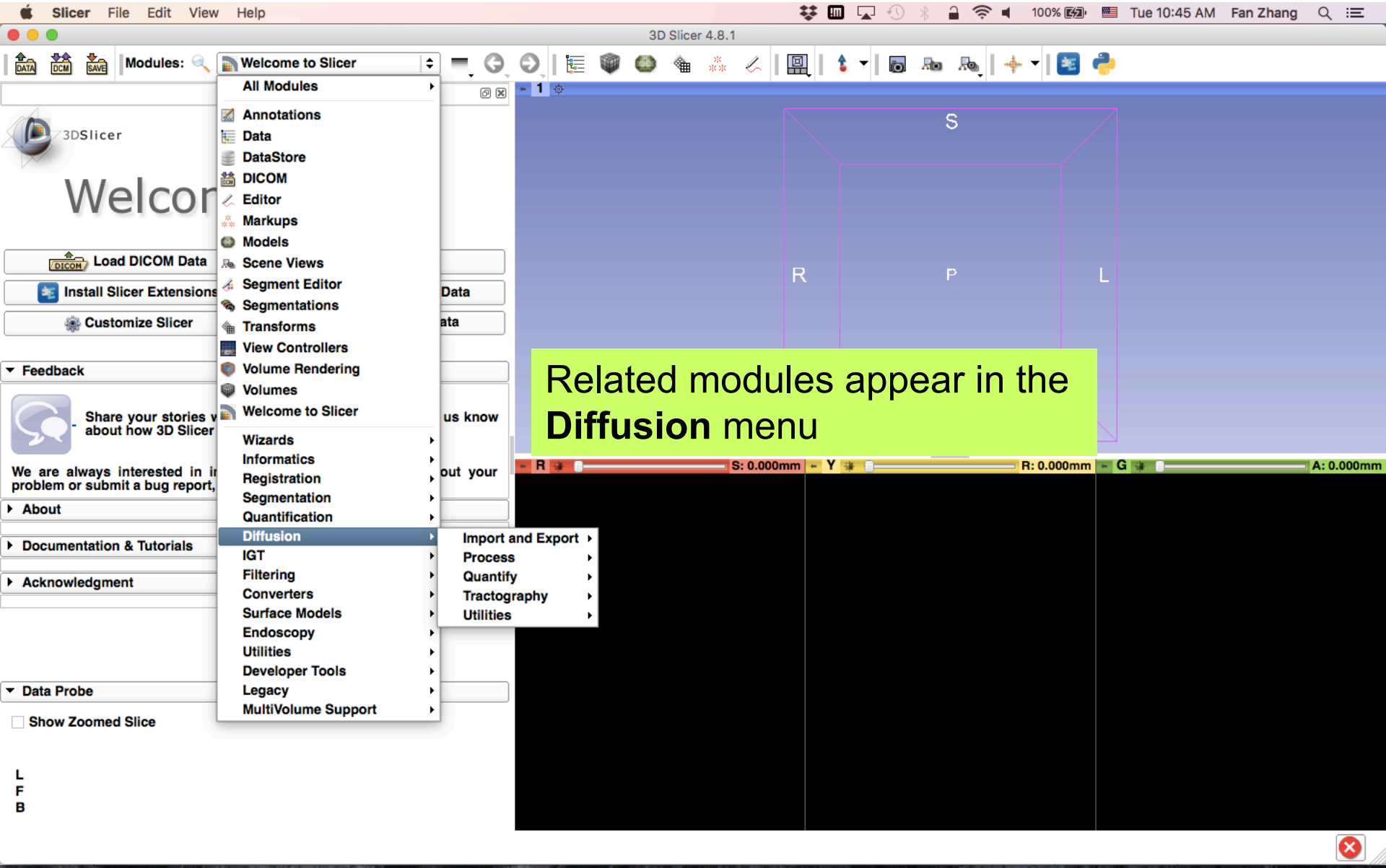
Install SlicerDMRI



Install SlicerDMRI



Install SlicerDMRI



Learning Objectives

Following this tutorial, you'll be able to

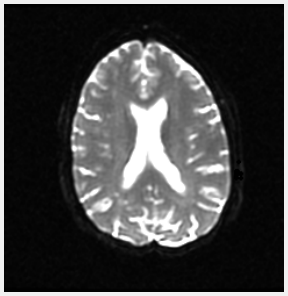
1) Estimate a tensor volume from a set of Diffusion Weighted Images

2) Understand the shape and size of the diffusion ellipsoid

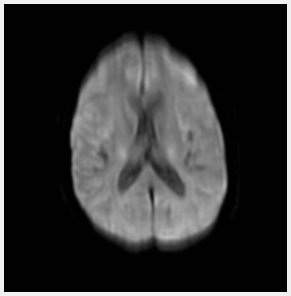
3) Reconstruct DTI tracts from a pre-defined region of interest

4) Interactively visualize DTI tracts seeded from a fiducial

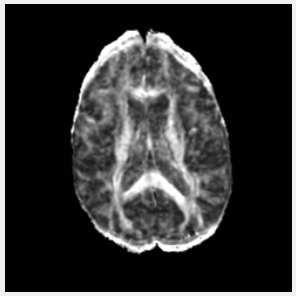
MR Diffusion Analysis Pipeline



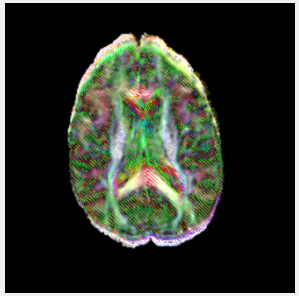
DWI
Acquisition



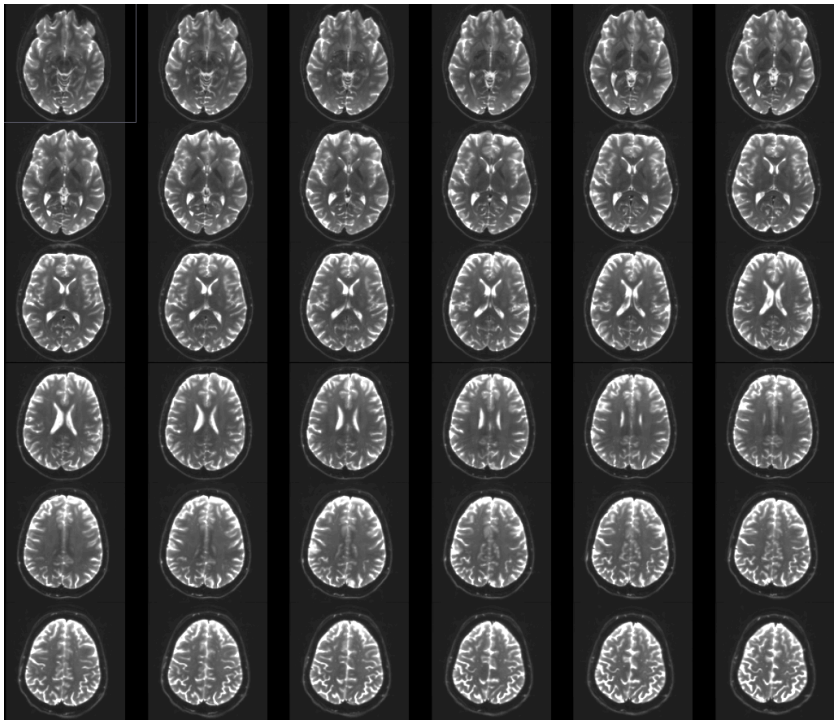
Tensor
Calculation



Scalar
Maps

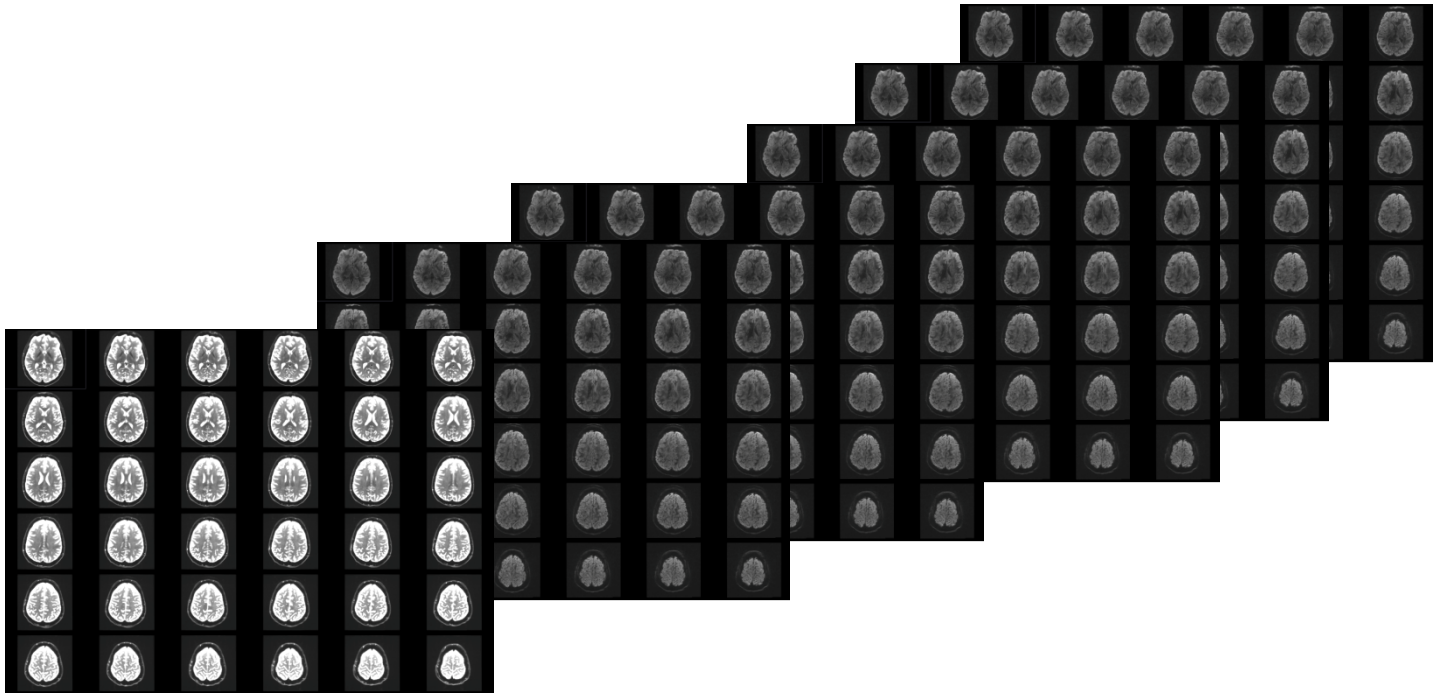


3D
Visualization



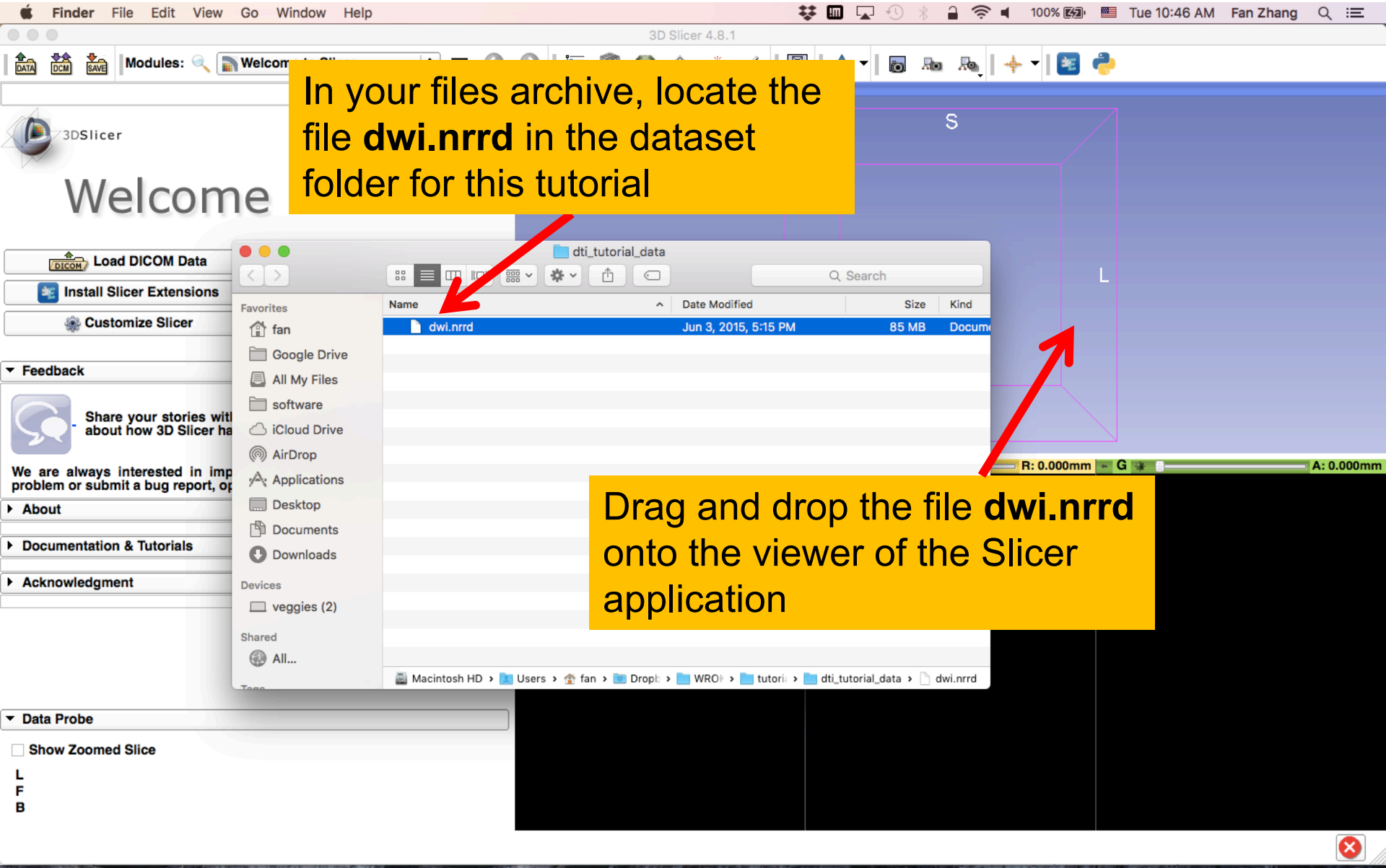
Part 1:
From DWI images to Tensors

Understanding the DWI Dataset

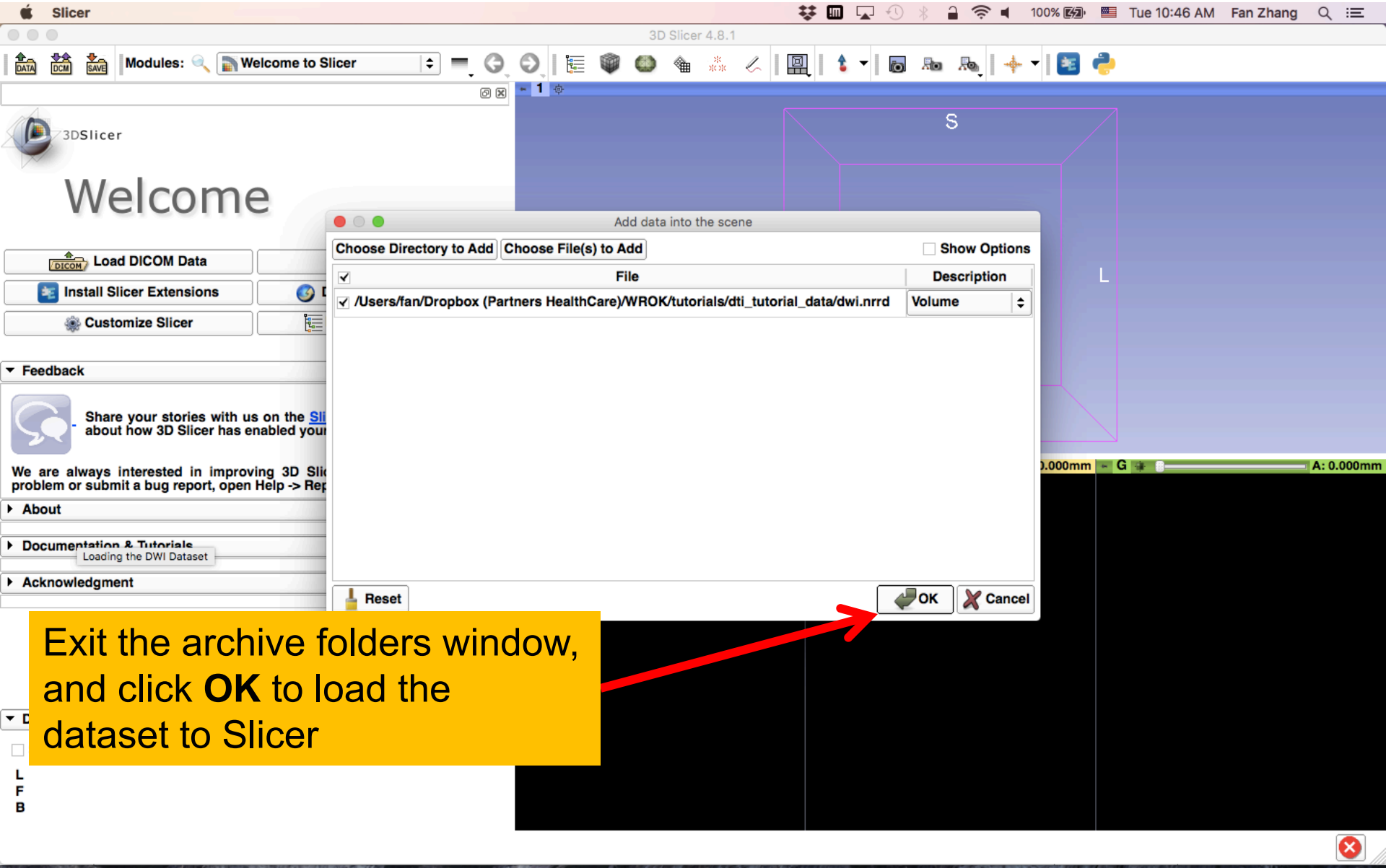


The Diffusion Weighted Imaging (DWI) dataset is composed of 41 volumes acquired with 41 different diffusion-sensitizing gradient directions, and one baseline image acquired without diffusion weighting.

Loading the DWI Dataset

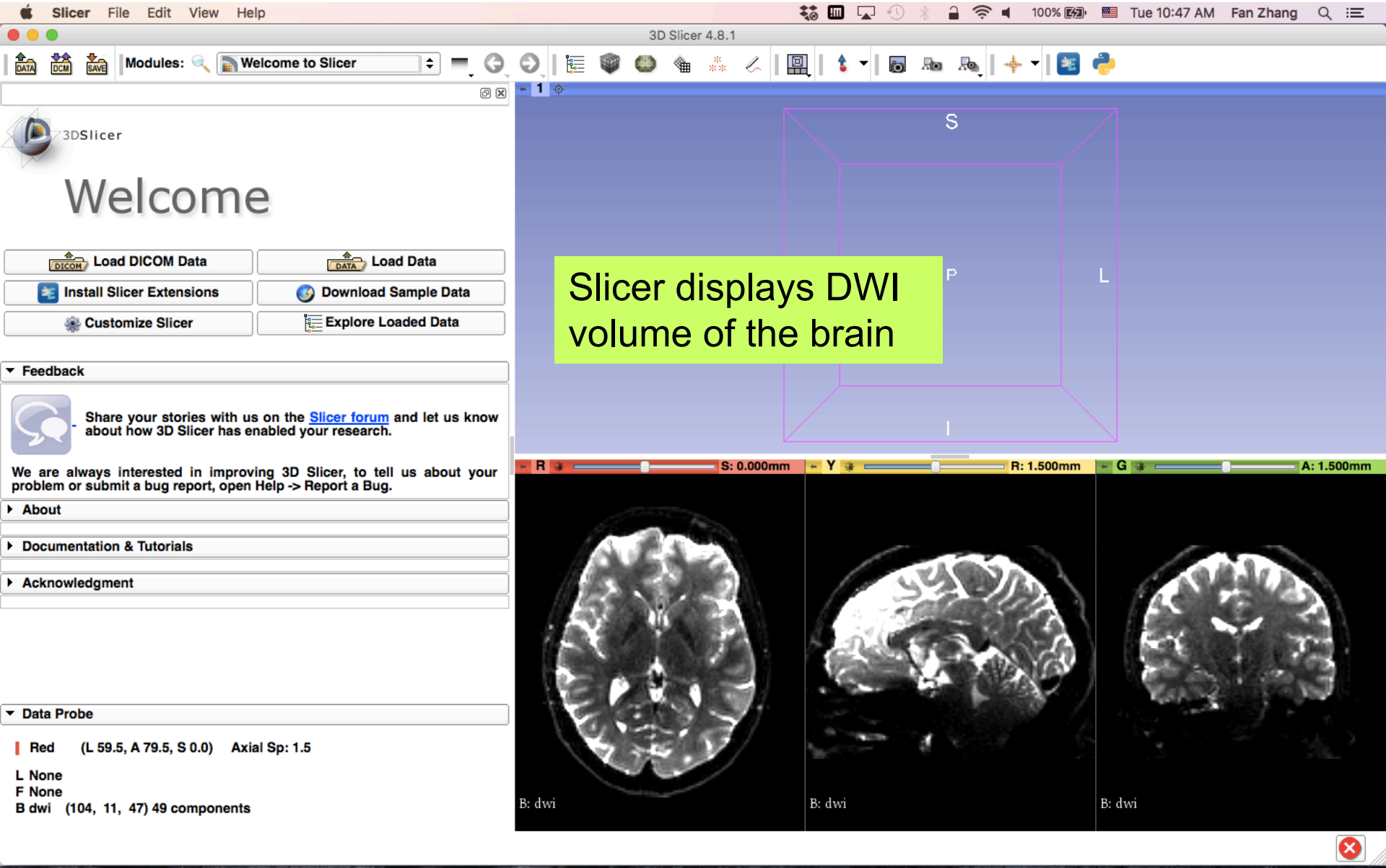


Loading the DWI Dataset

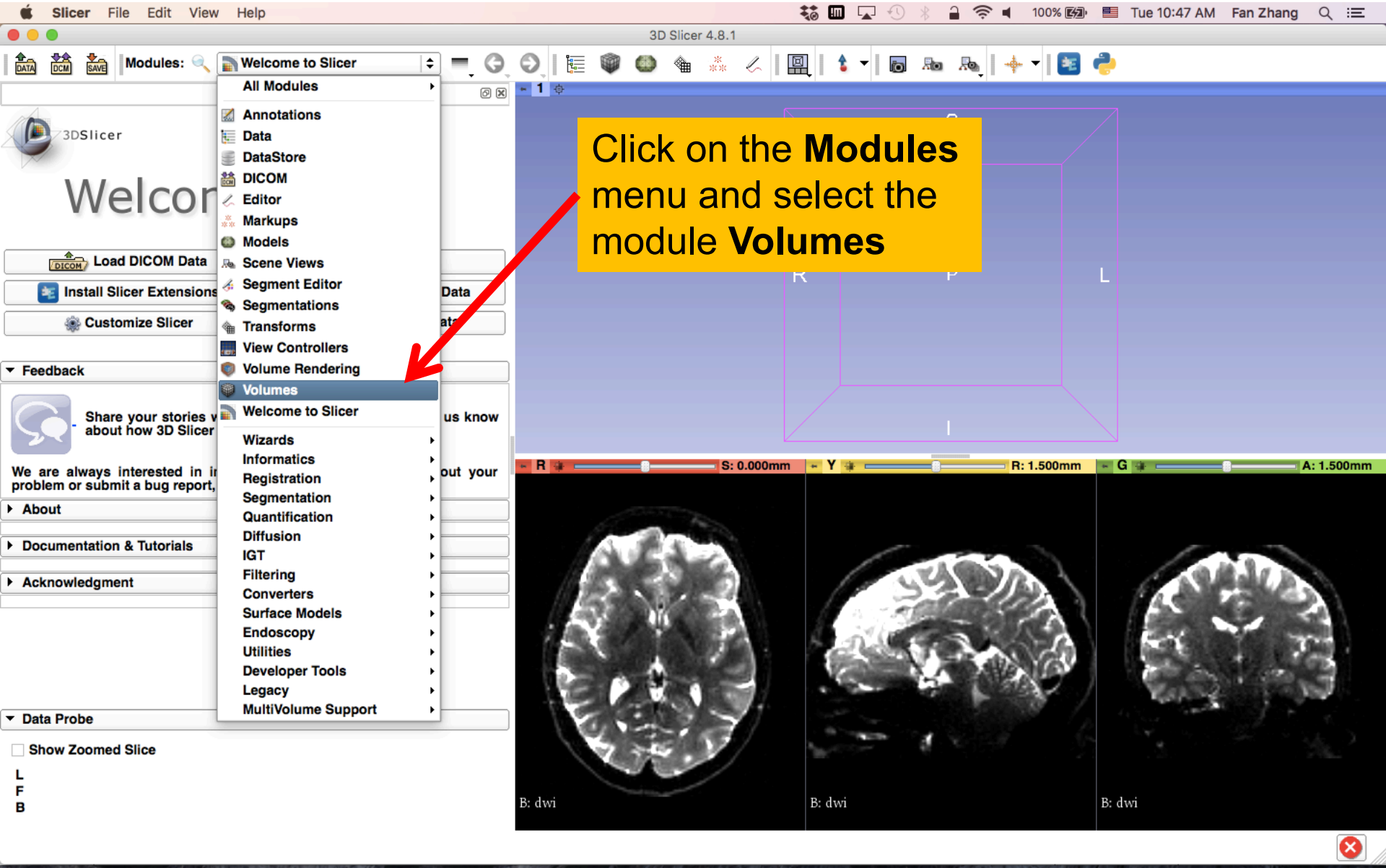


Exit the archive folders window, and click **OK** to load the dataset to Slicer

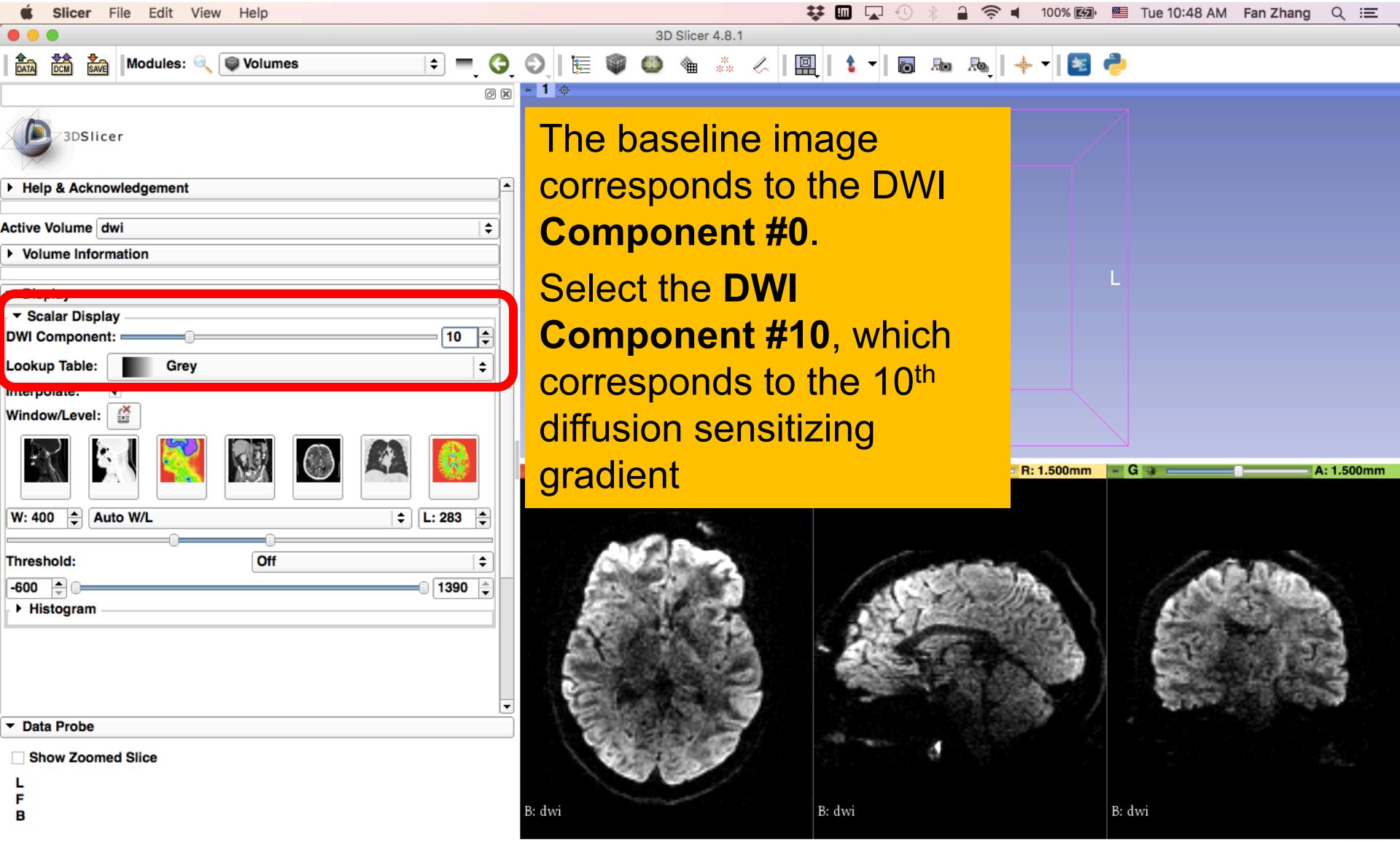
Loading the DWI Dataset



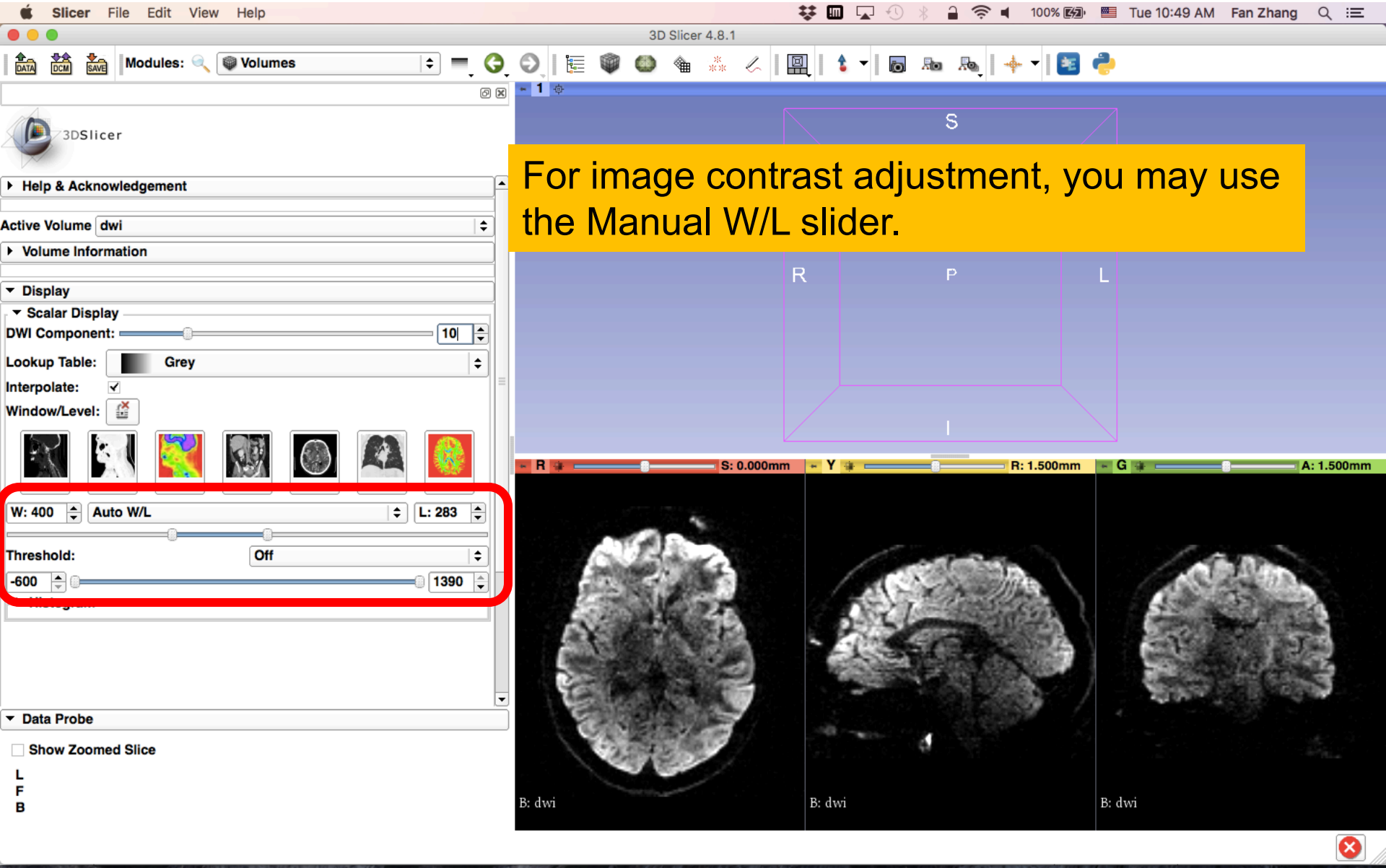
Loading the DWI Dataset



Loading the DWI Dataset



Loading the DWI Dataset



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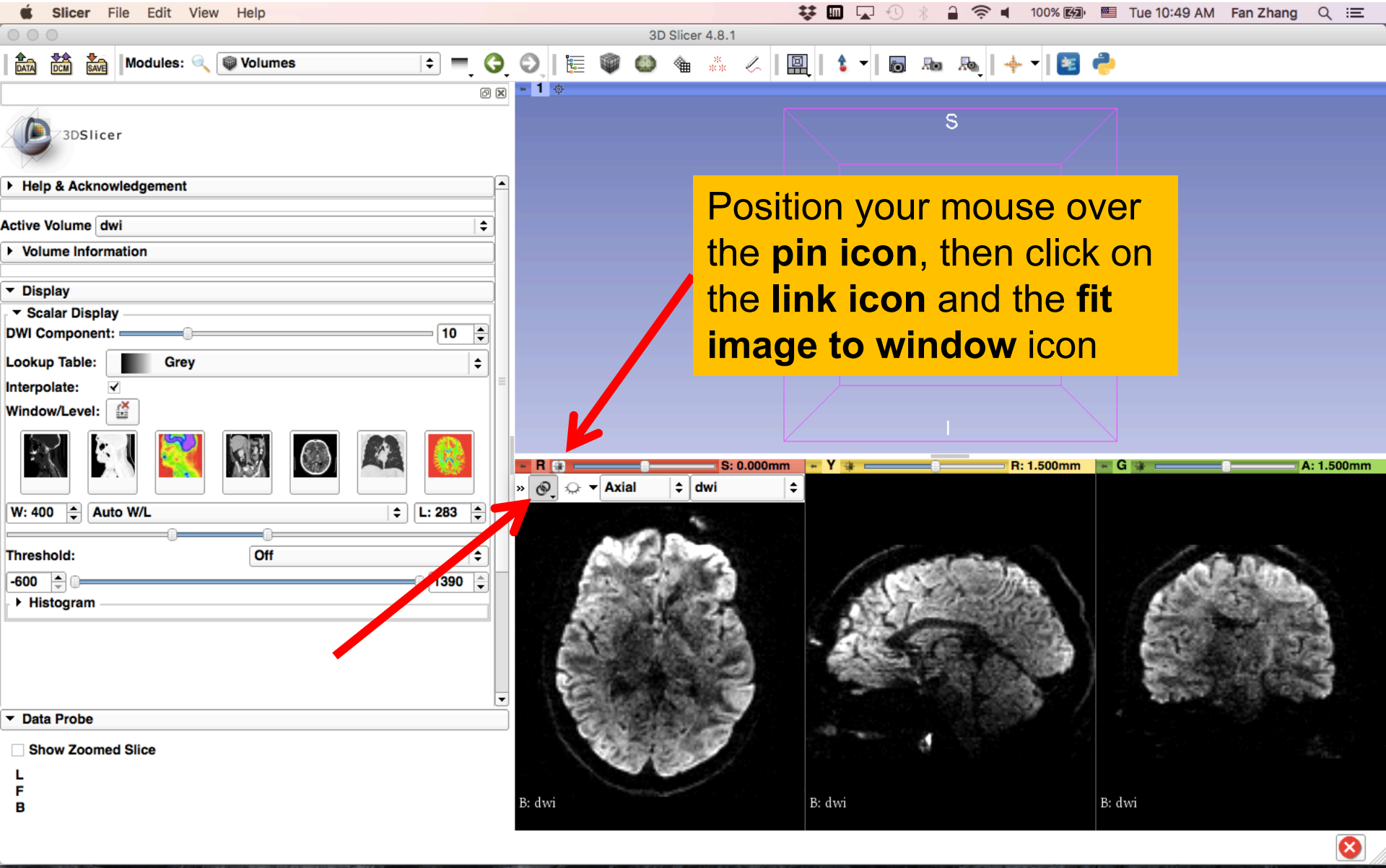
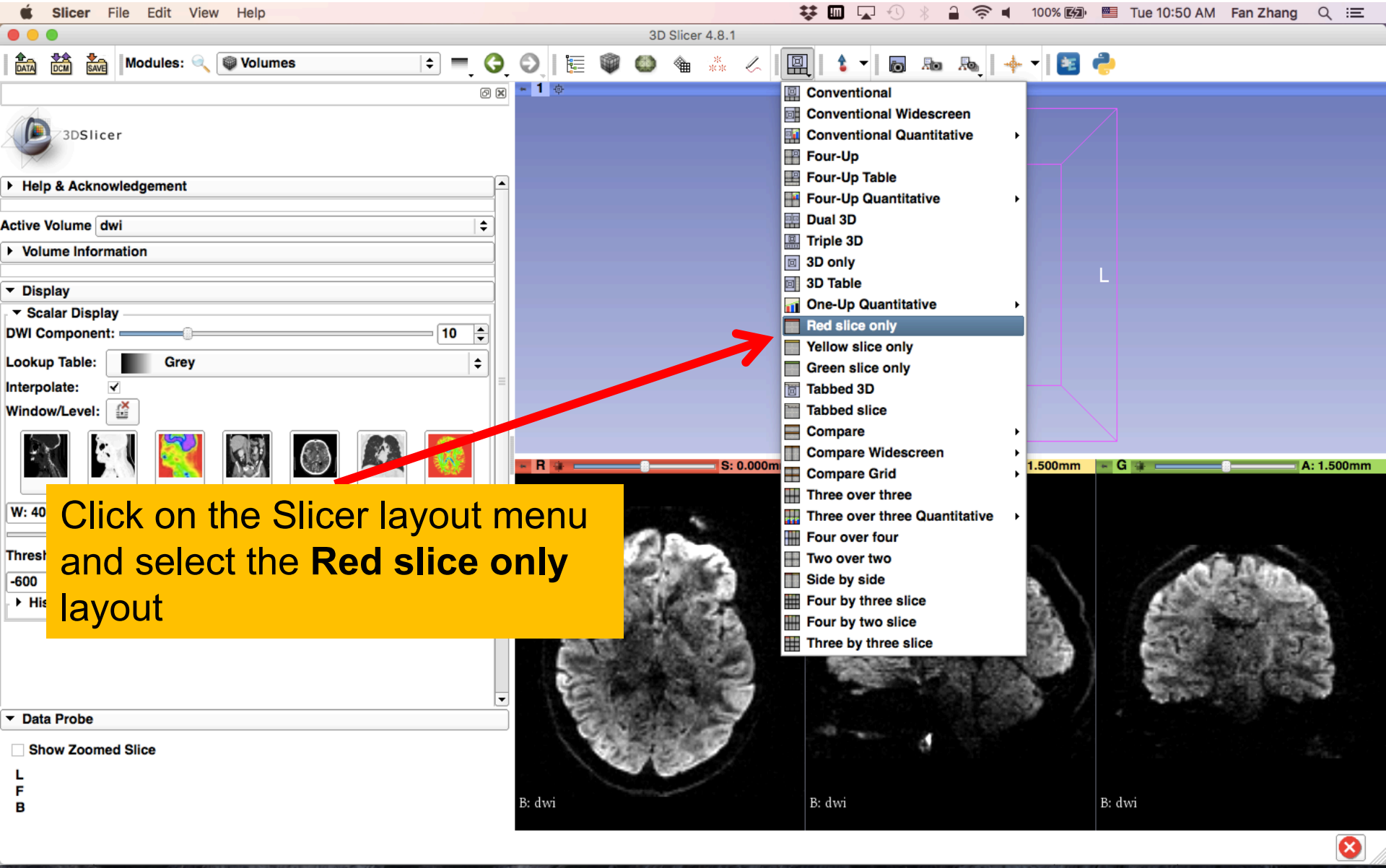
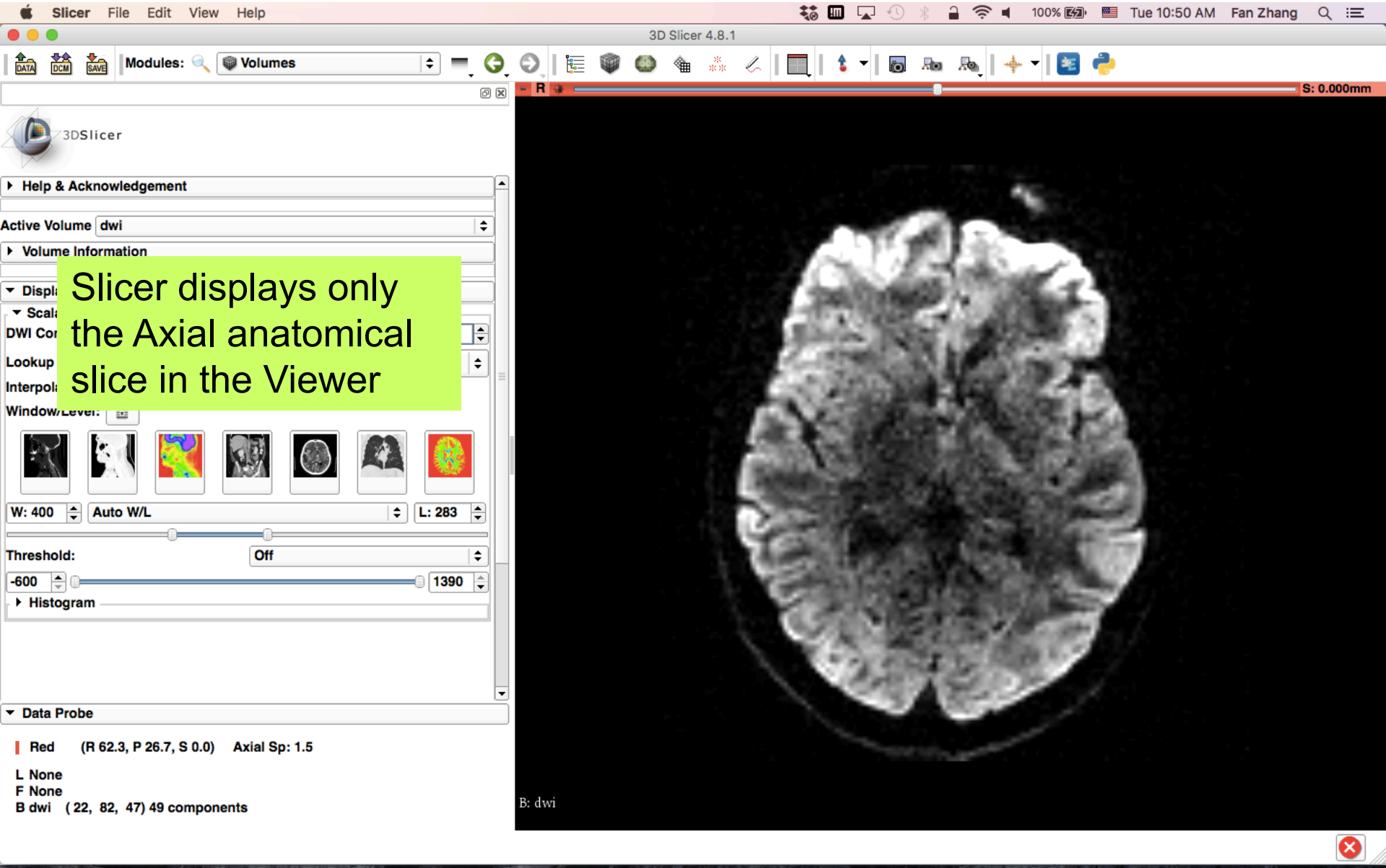


Loading the DWI Dataset

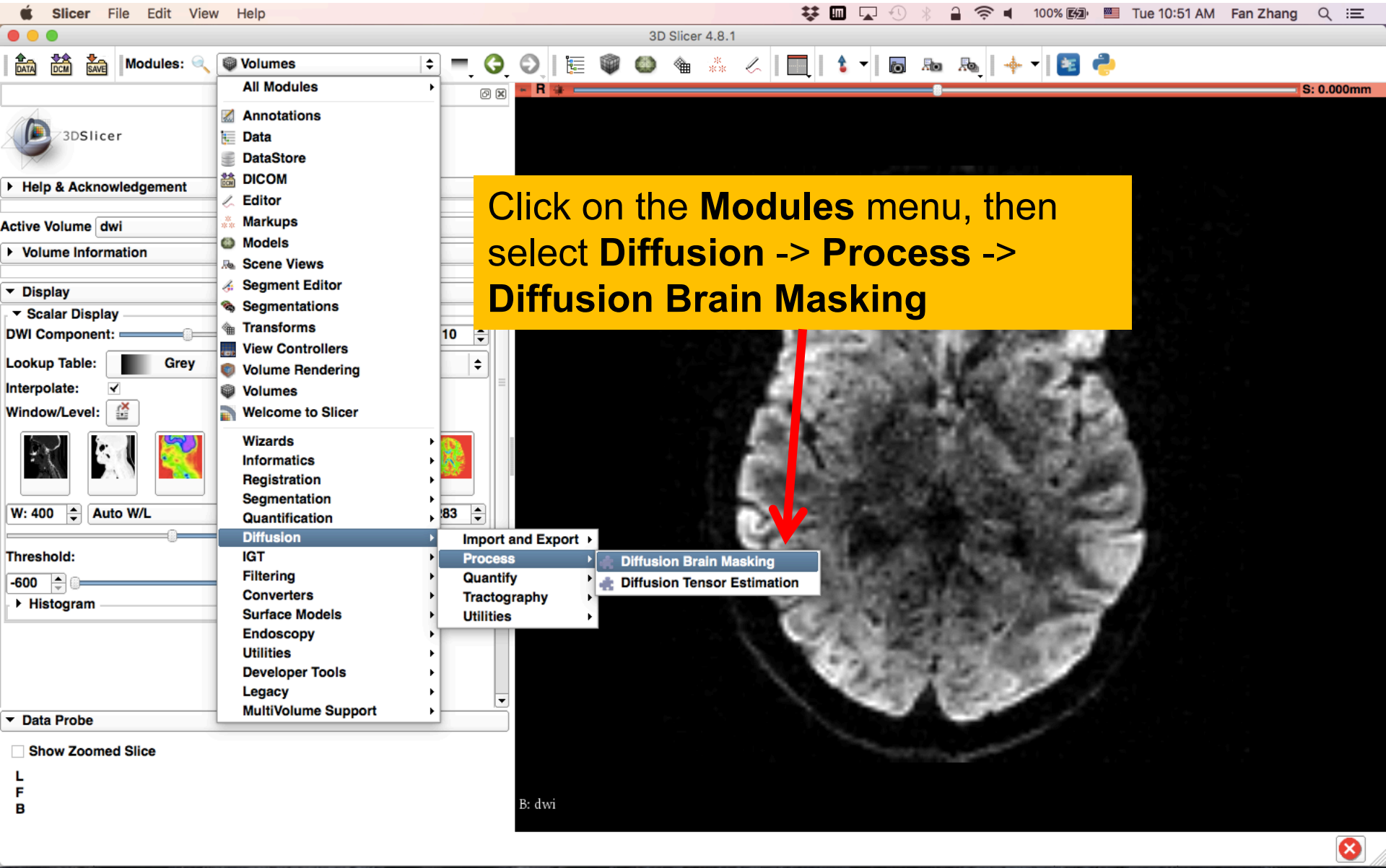


Click on the Slicer layout menu and select the **Red slice only** layout

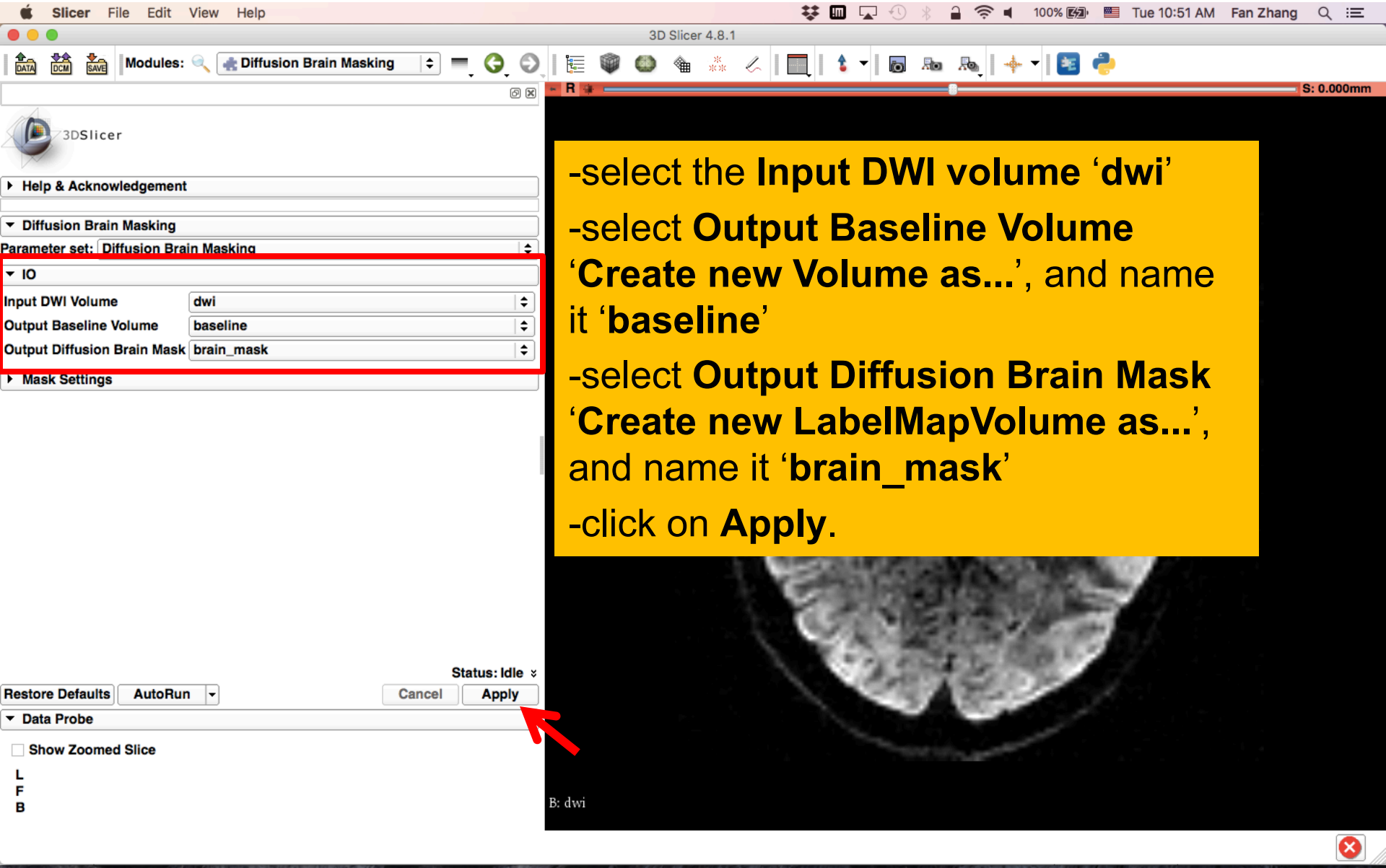
Loading the DWI Dataset



Creating a brain mask



Creating a brain mask



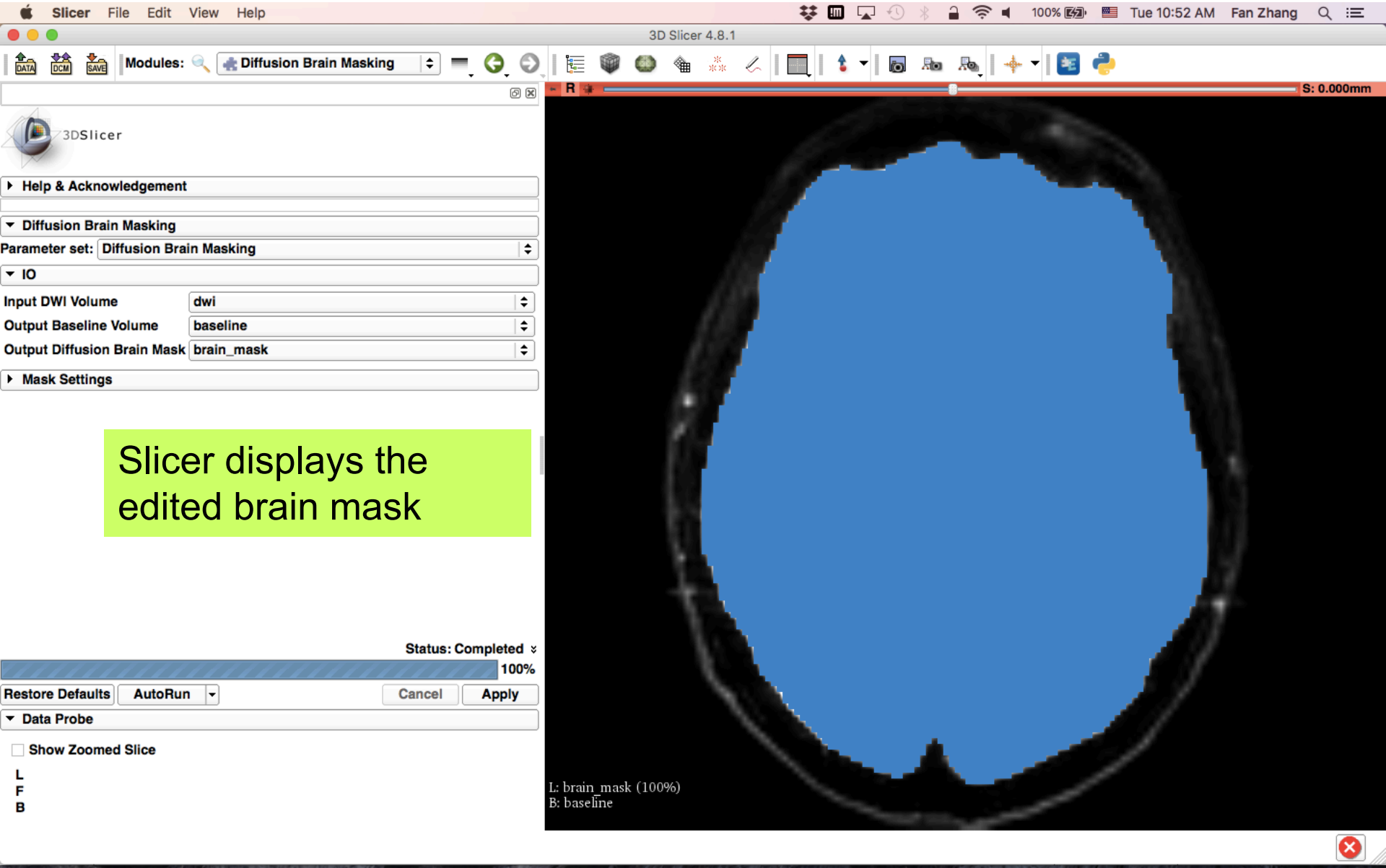
-select the **Input DWI volume 'dwi'**

-select **Output Baseline Volume 'Create new Volume as...'**, and name it '**baseline**'

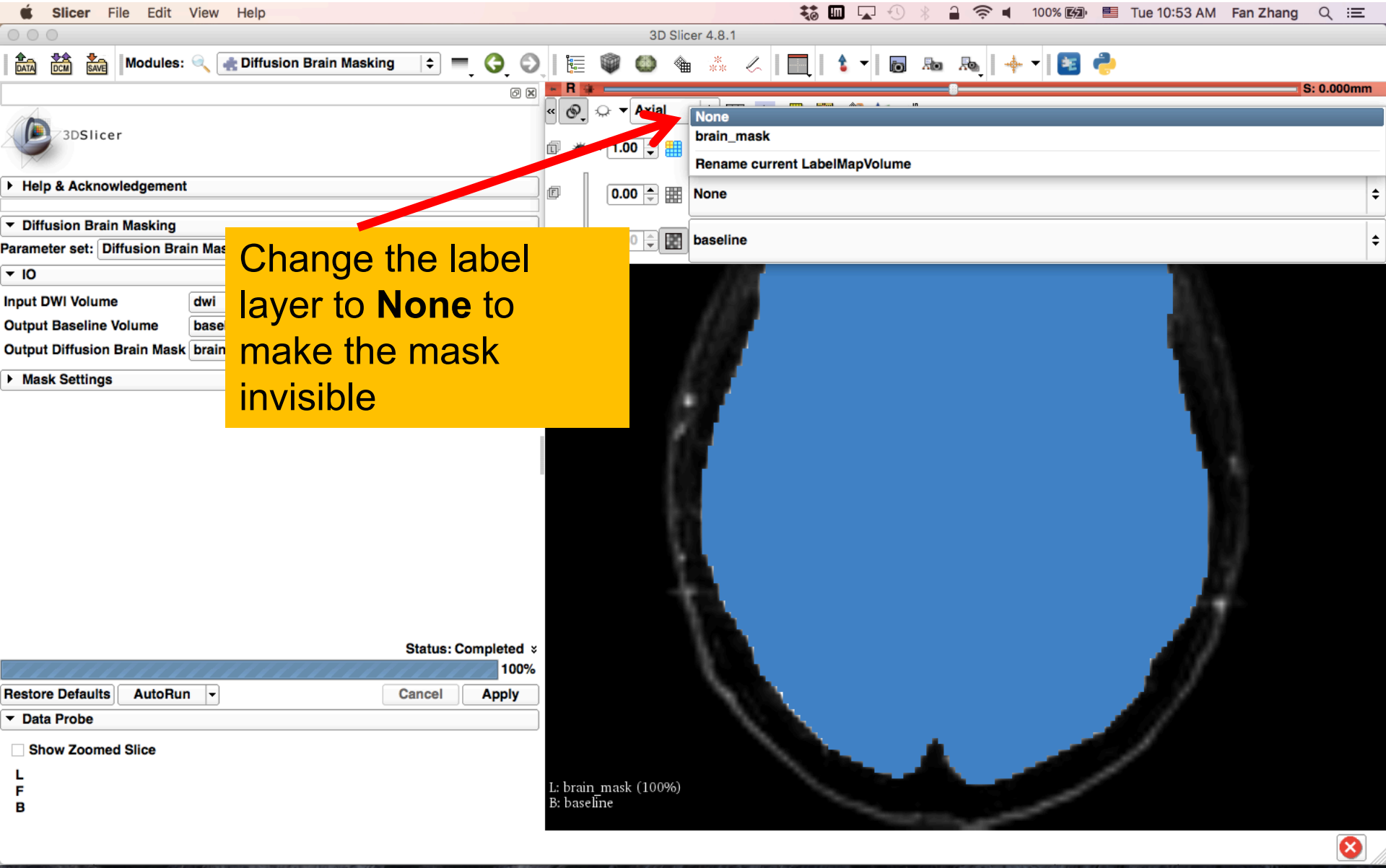
-select **Output Diffusion Brain Mask 'Create new LabelMapVolume as...'**, and name it '**brain_mask**'

-click on **Apply**.

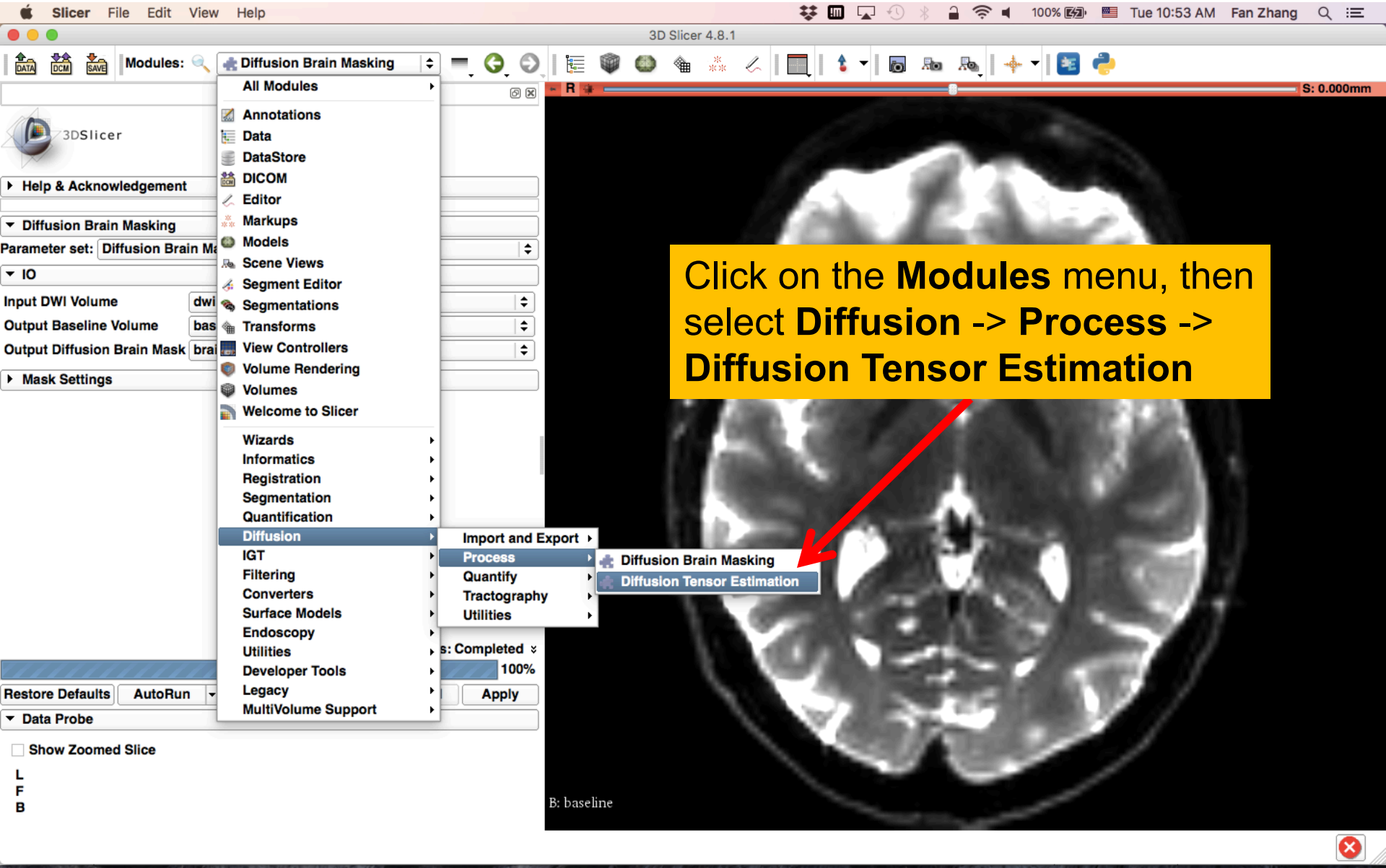
Creating a brain mask



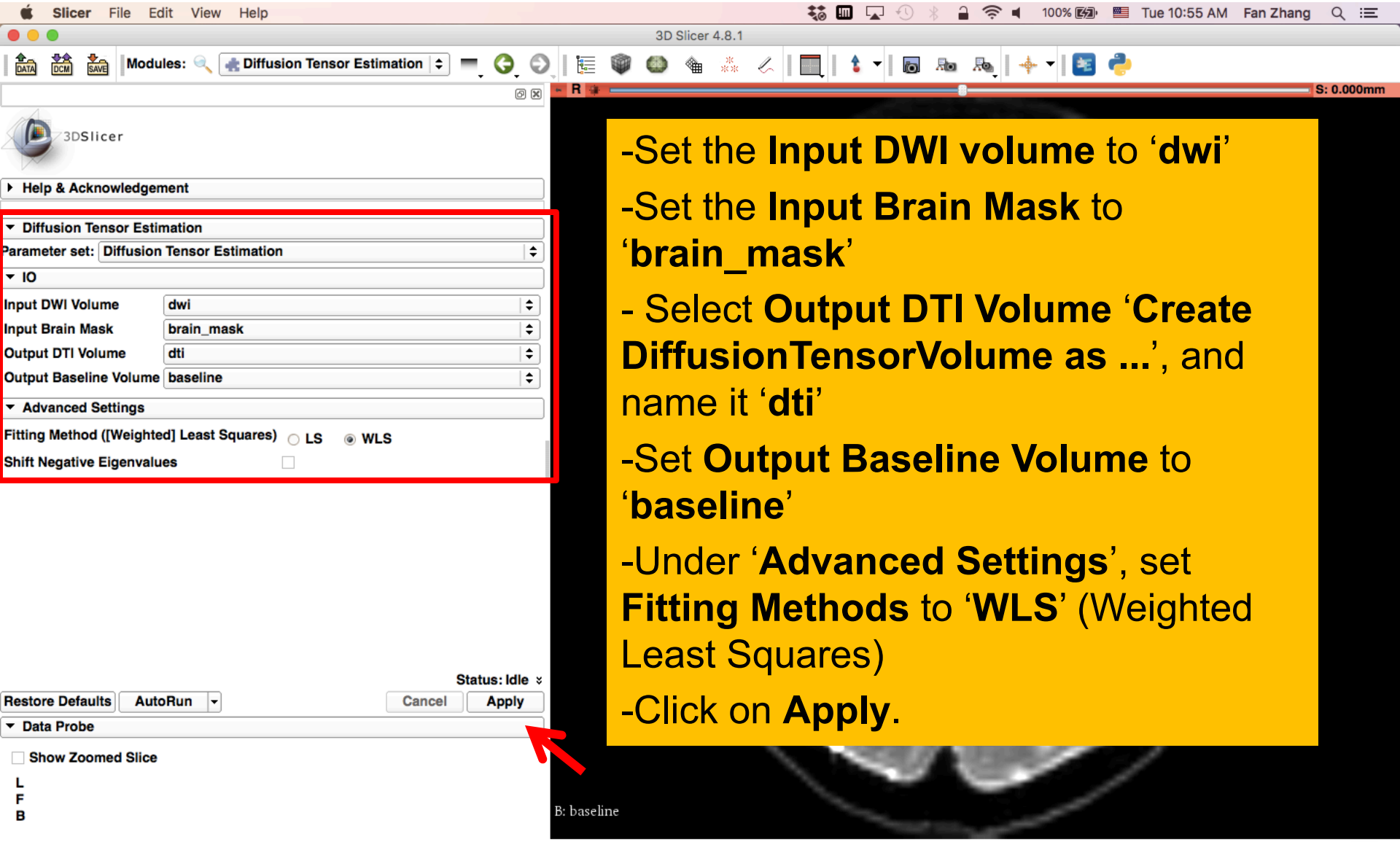
Creating a brain mask



Estimating the tensor



Estimating the tensor



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

-Set the **Input Brain Mask** to '**brain_mask**'

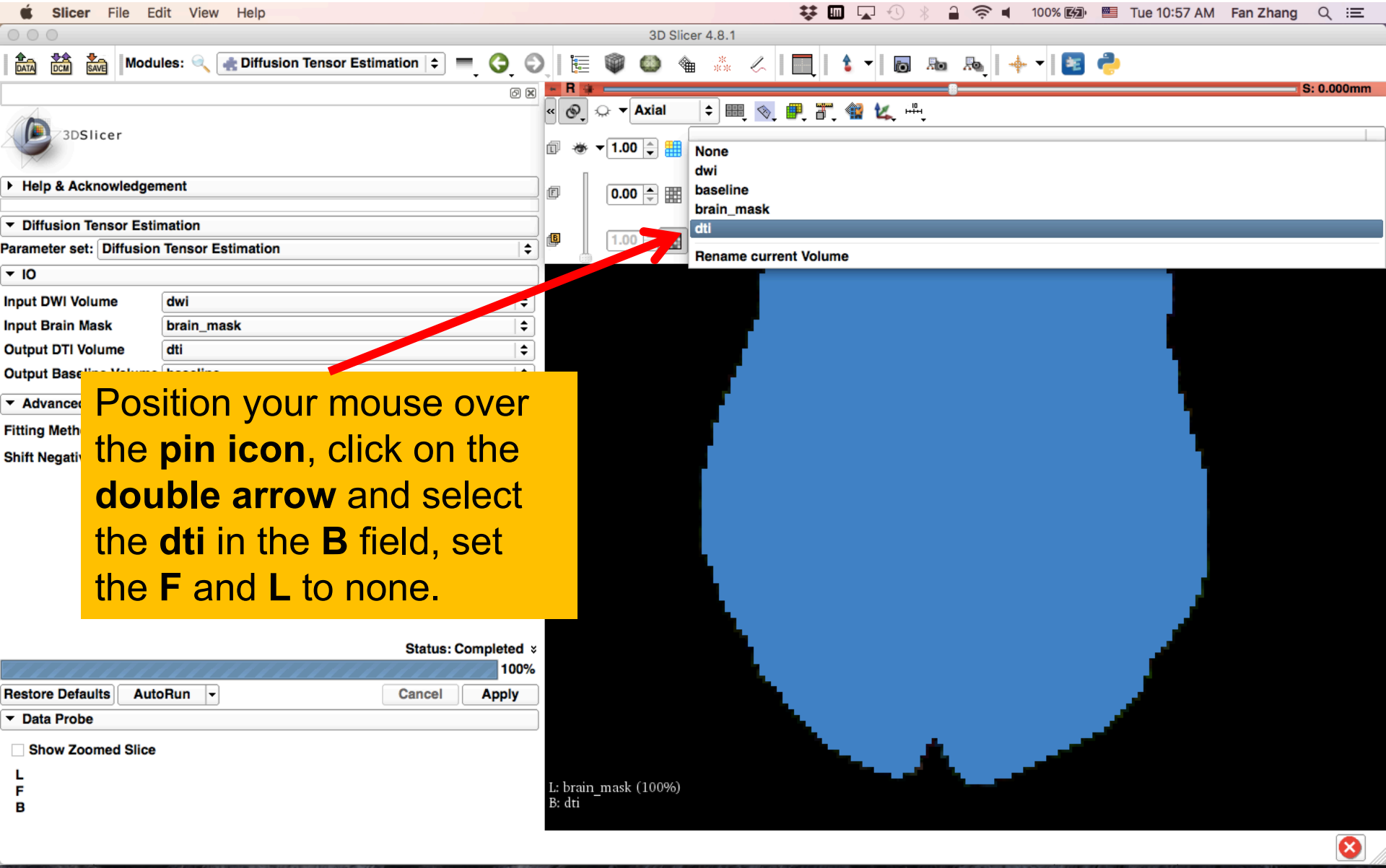
- Select **Output DTI Volume** '**Create DiffusionTensorVolume as ...**', and name it '**dti**'

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

-Under '**Advanced Settings**', set **Fitting Methods** to '**WLS**' (Weighted Least Squares)

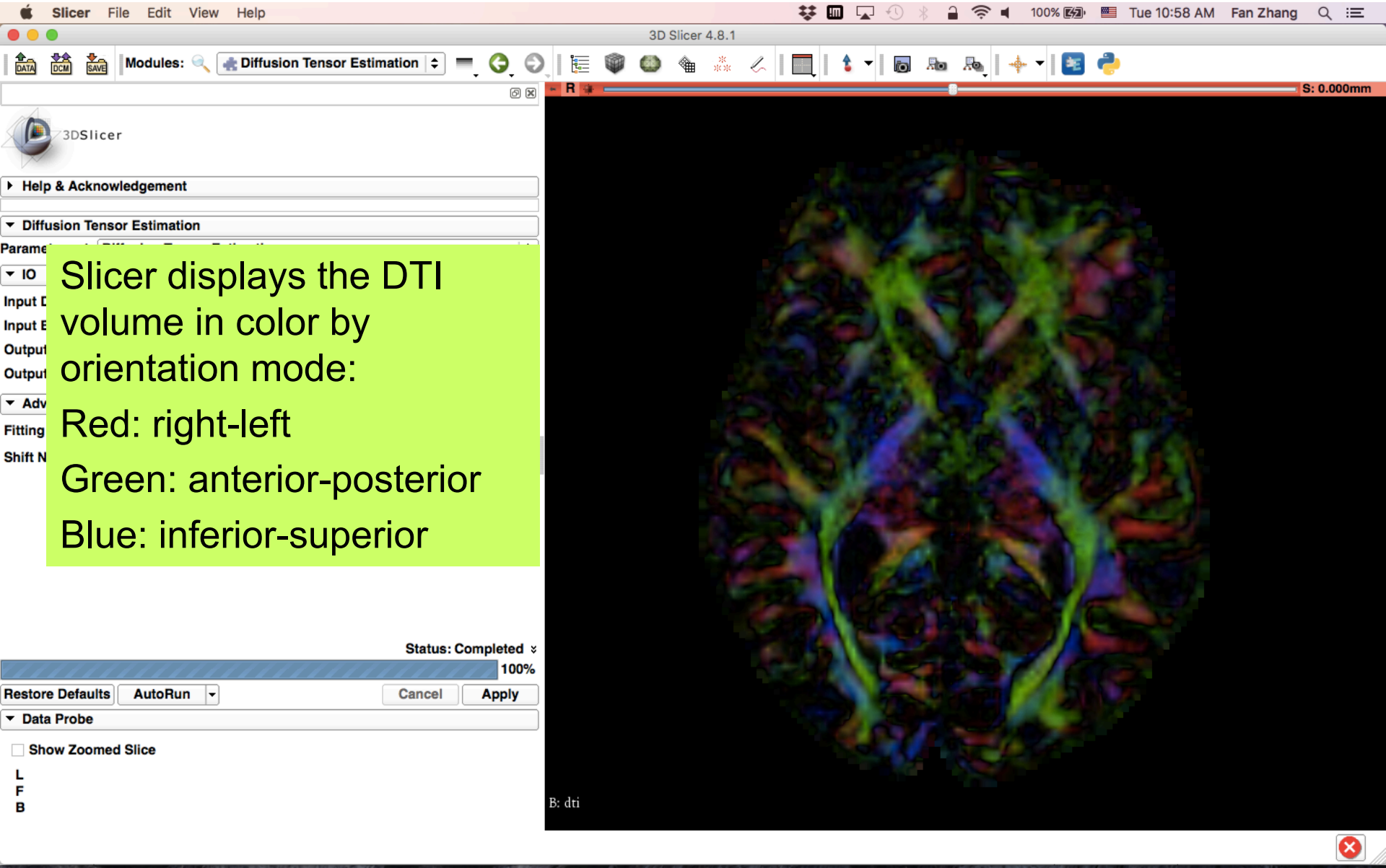
-Click on **Apply**.

Estimating the tensor

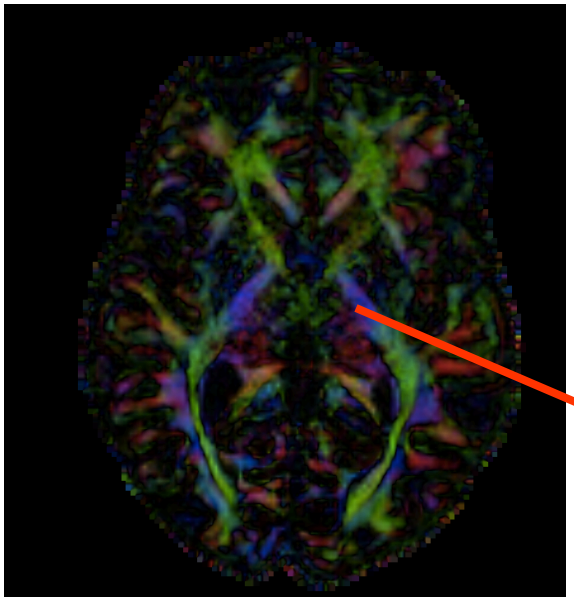


Position your mouse over the **pin icon**, click on the **double arrow** and select the **dti** in the **B** field, set the **F** and **L** to none.

Exploring the DWI Dataset



Diffusion Tensor Data



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

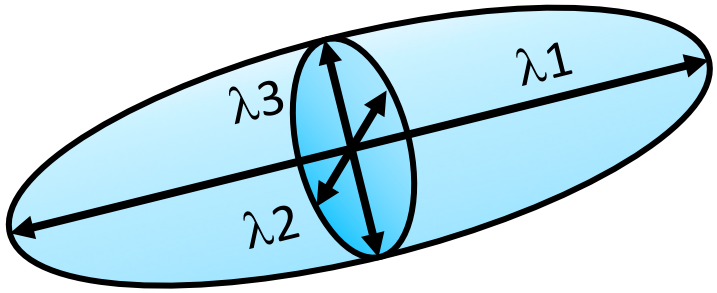
Stejskal-Tanner equation (1965)

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

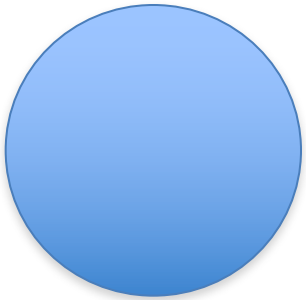
The diffusion tensor $\underline{D}$ in the voxel (I,J,K) is a 3x3 symmetric matrix.

Diffusion Tensor

- The diffusion tensor 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.

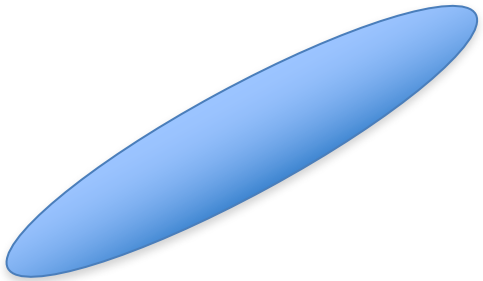


Diffusion Tensor Shape

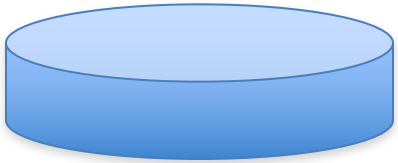


$\lambda 1 = \lambda 2 = \lambda 3$

Isotropic media
(Cerebrospinal
Fluid, gray matter)



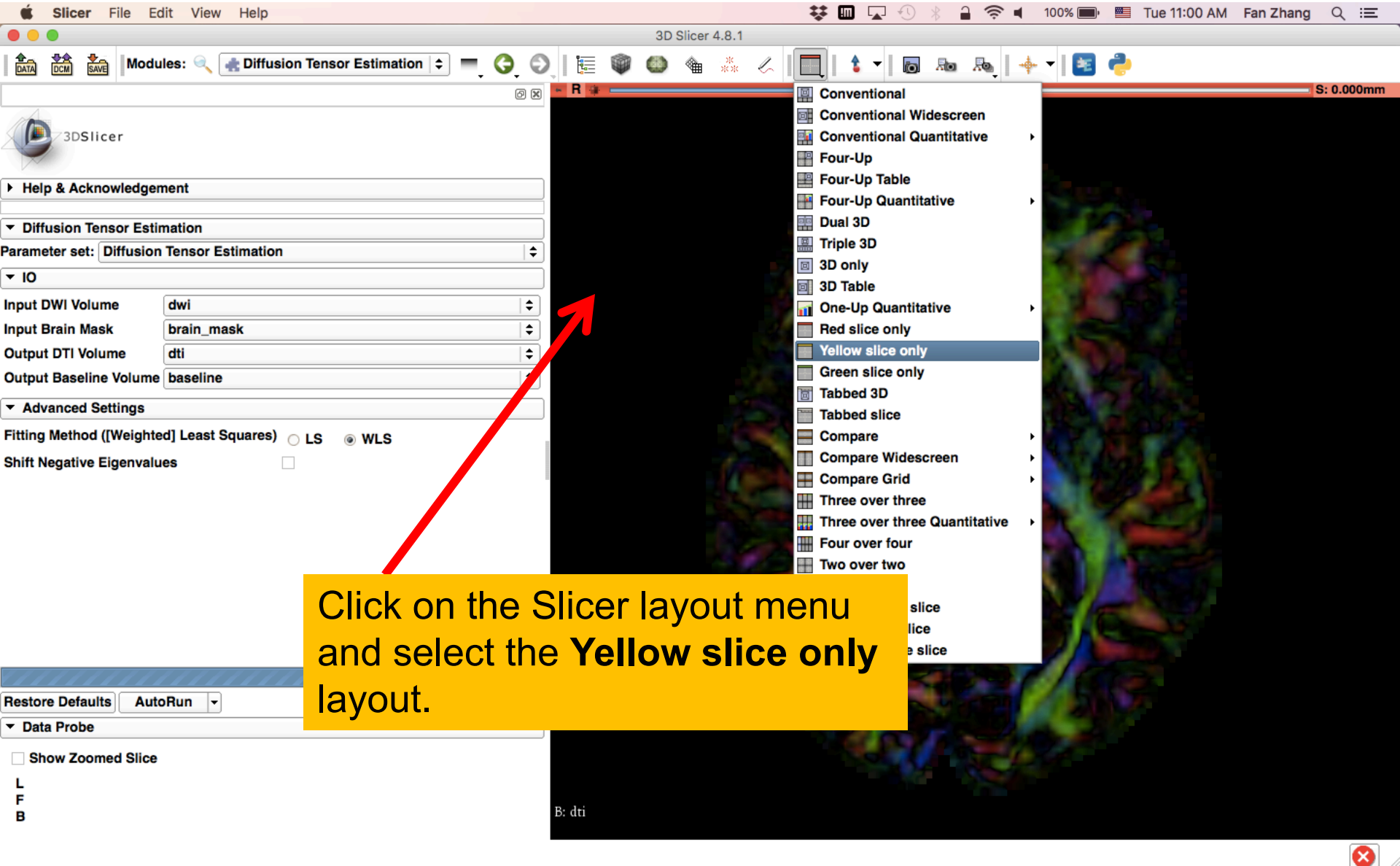
$\lambda 1 >> \lambda 2, \lambda 3$



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

Anisotropic media
(white matter)

Exploring the DWI Dataset



Click on the Slicer layout menu and select the **Yellow slice only** layout.

Corpus Callosum

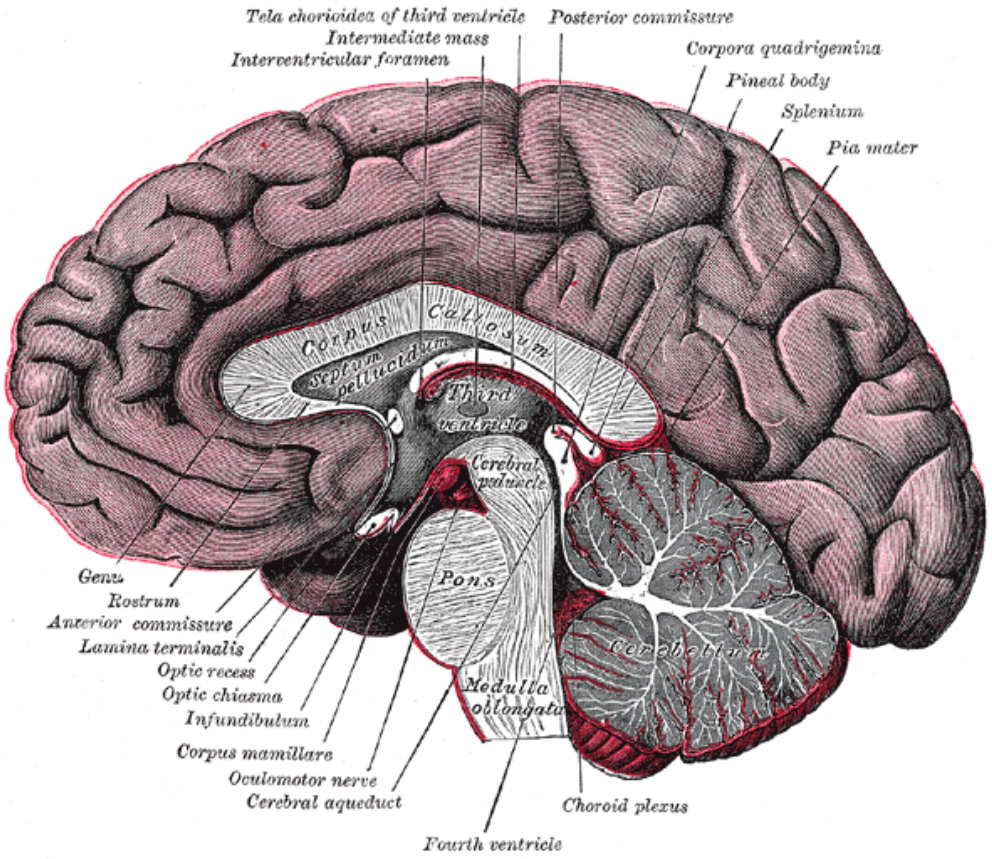
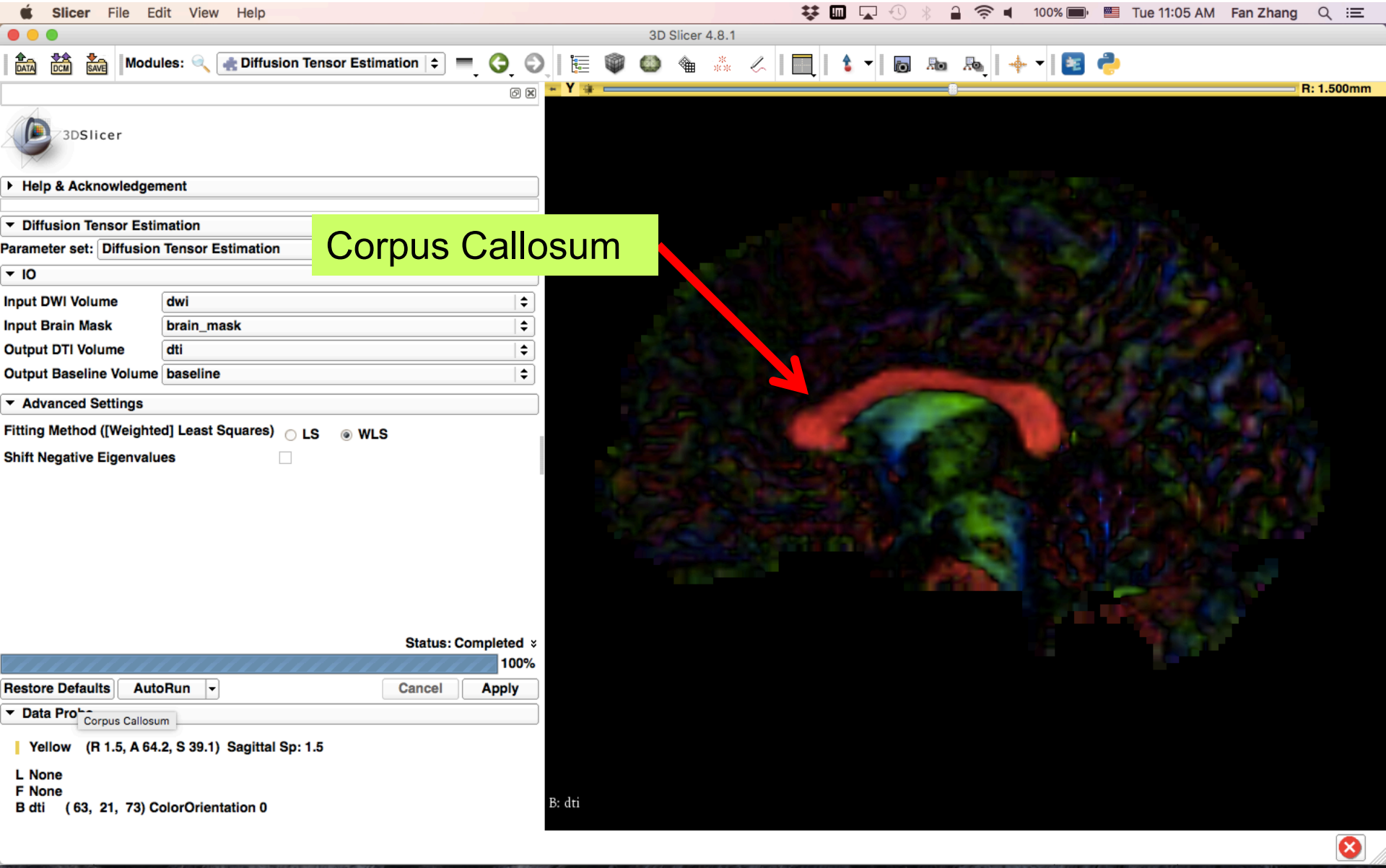


Image from Gray's Anatomy

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

Corpus Callosum

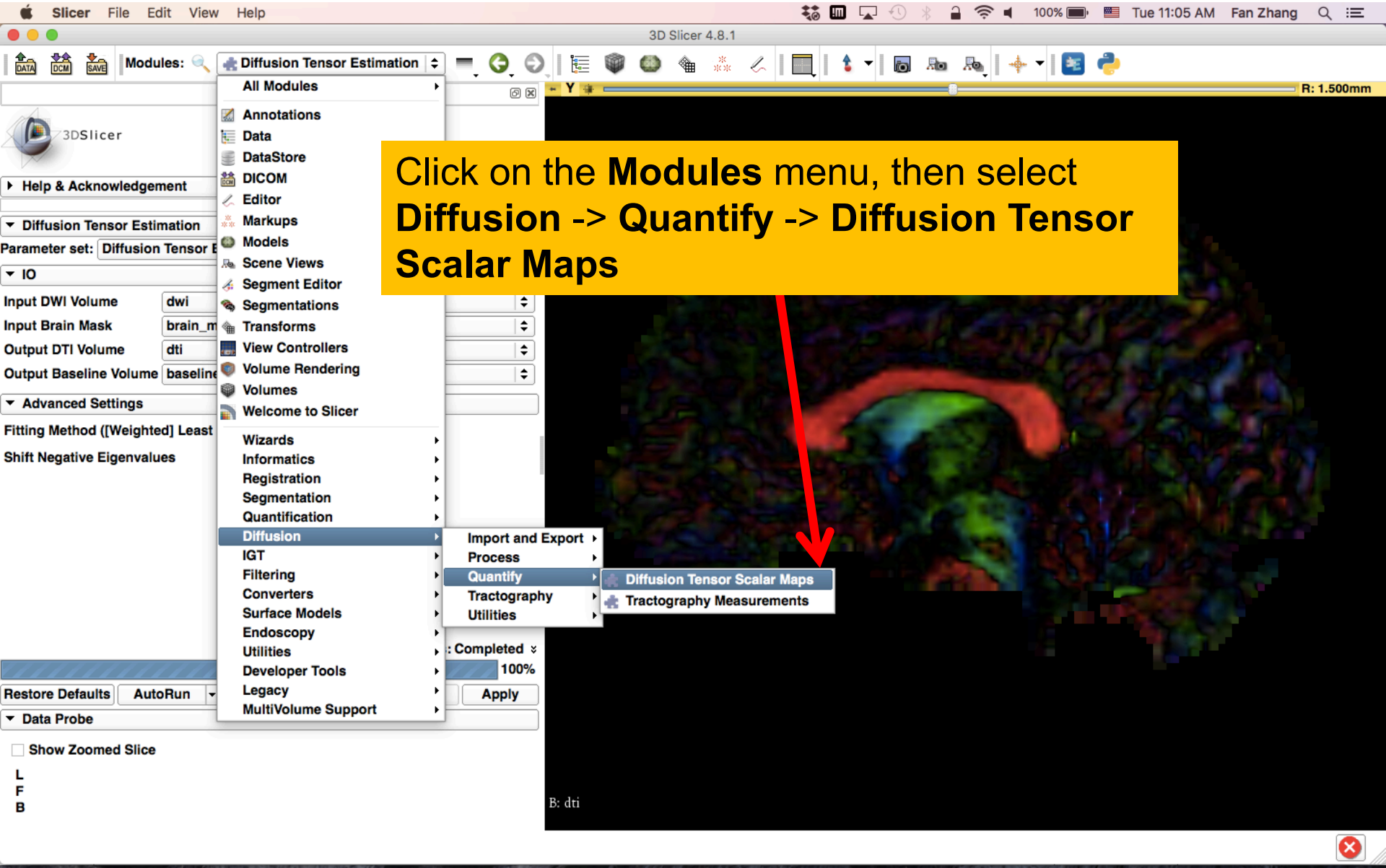


Characterizing the Size of the tensor: Trace

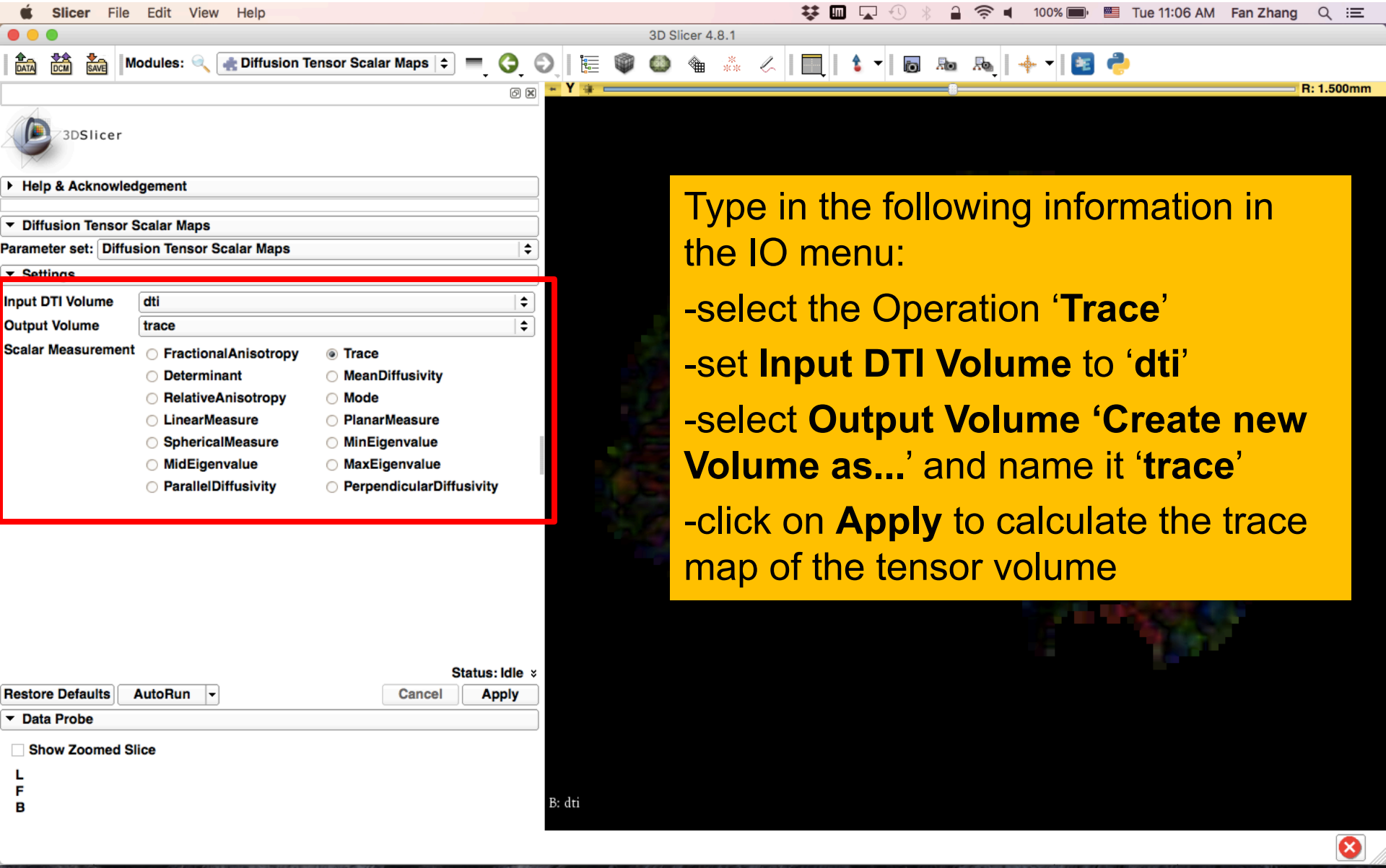
$$\text{Trace}(D) = \lambda 1 + \lambda 2 + \lambda 3$$

- 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


Slicer File Edit View Help
100% Tue 11:05 AM Fan Zhang
3D Slicer 4.8.1
Modules:
Diffusion Tensor Estimation
All Modules
Annotations
Data
DataStore
DICOM
Editor
Markups
Models
Scene Views
Segment Editor
Segmentations
Transforms
View Controllers
Volume Rendering
Volumes
Welcome to Slicer
Wizards
Informatics
Registration
Segmentation
Quantification
Diffusion
IGT
Filtering
Converters
Surface Models
Endoscopy
Utilities
Developer Tools
Legacy
MultiVolume Support
Import and Export
Process
Quantify
Tractography
Utilities
Diffusion Tensor Scalar Maps
Tractography Measurements
3DSlicer
Help & Acknowledgement
Diffusion Tensor Estimation
Parameter set: Diffusion Tensor E
IO
Input DWI Volume dwi
Input Brain Mask brain_m
Output DTI Volume dti
Output Baseline Volume baseline
Advanced Settings
Fitting Method ([Weighted] Least
Shift Negative Eigenvalues
: Completed
100%
Restore Defaults
AutoRun
Apply
Data Probe
Show Zoomed Slice
L
F
B
Y
R: 1.500mm
B: dti
Click on the Modules menu, then select Diffusion -> Quantify -> Diffusion Tensor Scalar Maps

Trace



Type in the following information in the IO menu:

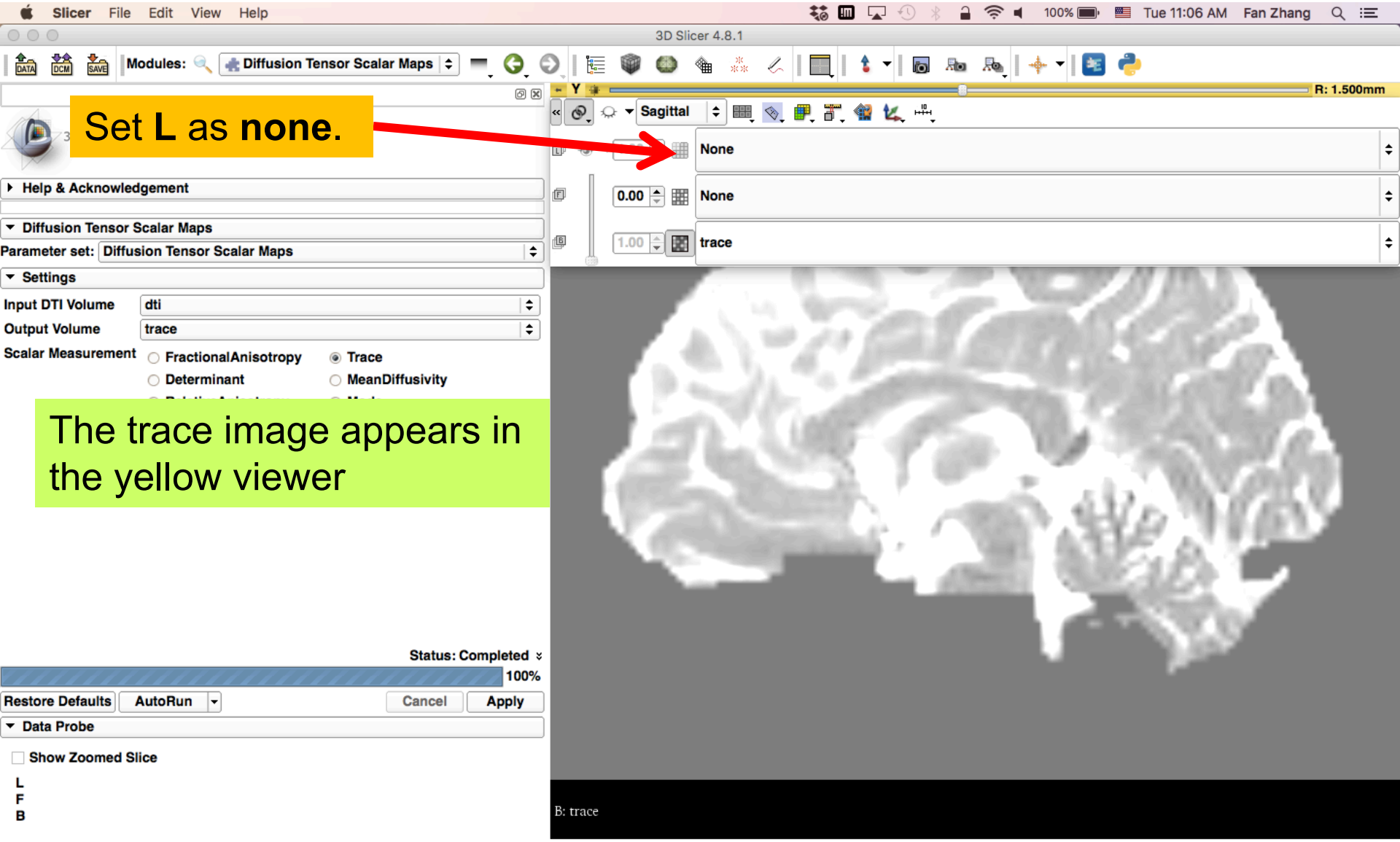
-select the Operation '**Trace**'

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

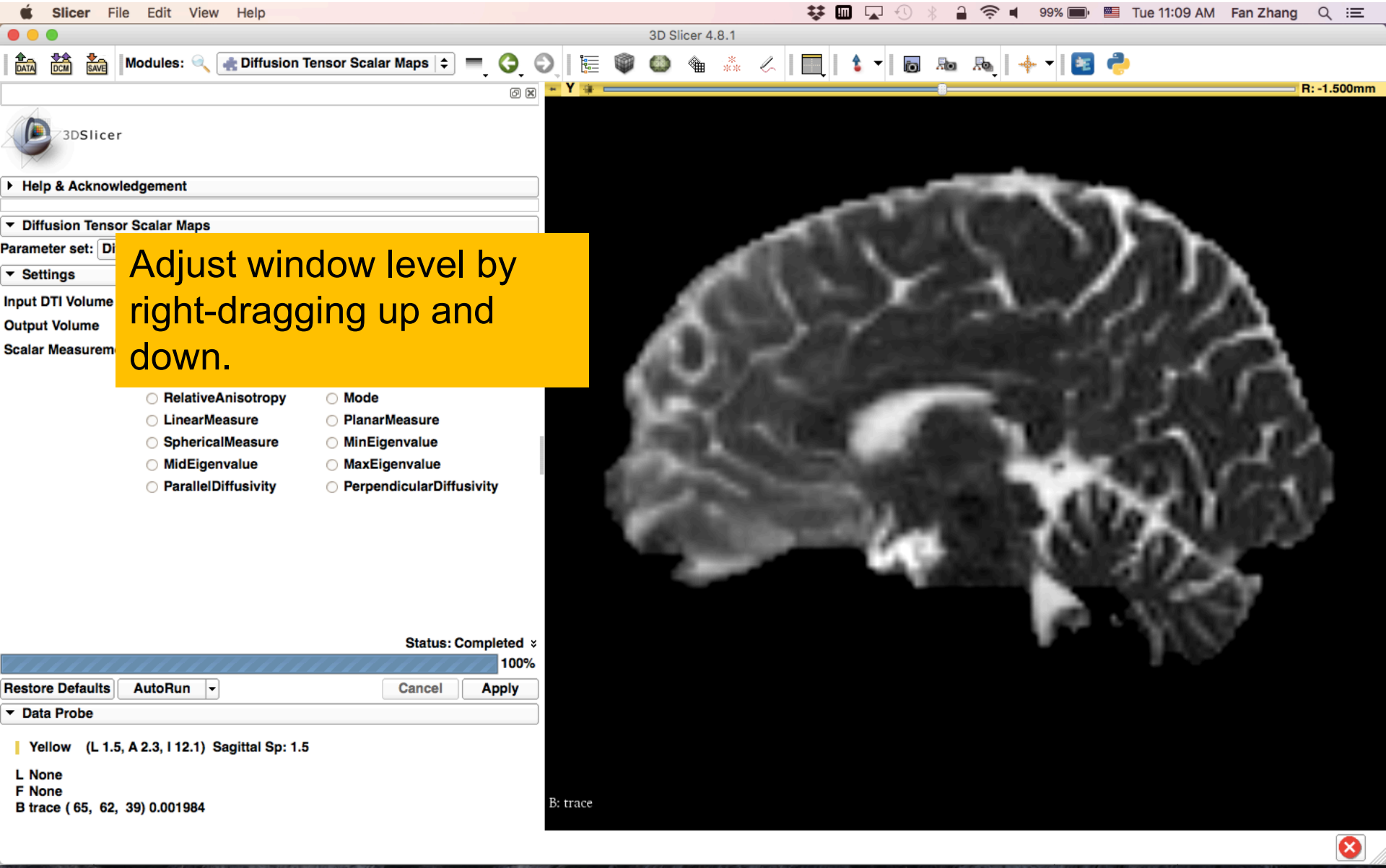
-select **Output Volume 'Create new Volume as...**' and name it '**trace**'

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

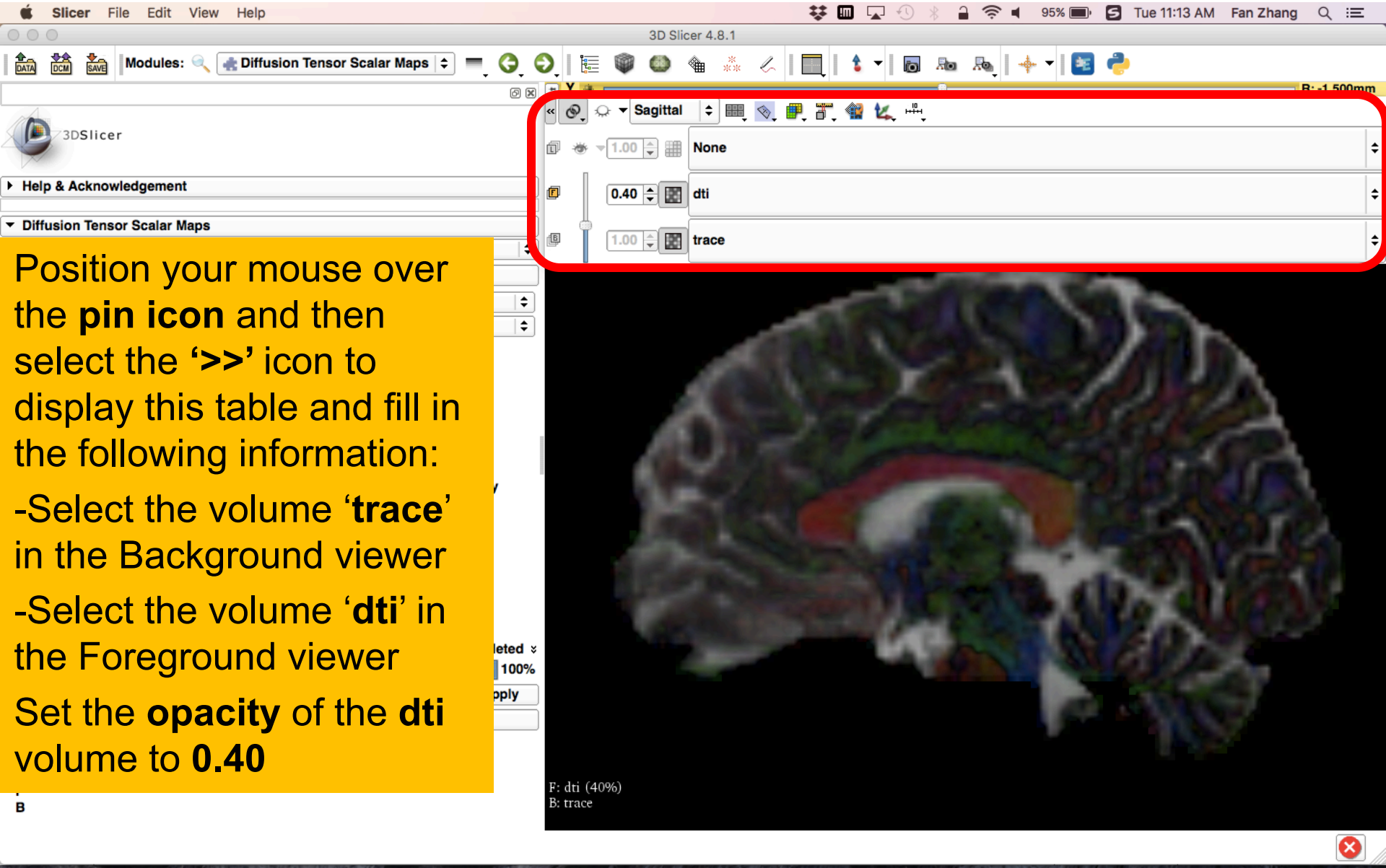
Trace


Slicer File Edit View Help
100% Tue 11:06 AM Fan Zhang
3D Slicer 4.8.1
Modules: Diffusion Tensor Scalar Maps
Set L as none.
Help & Acknowledgement
Diffusion Tensor Scalar Maps
Parameter set: Diffusion Tensor Scalar Maps
Settings
Input DTI Volume dti
Output Volume trace
Scalar Measurement
FractionalAnisotropy
Trace
Determinant
MeanDiffusivity
The trace image appears in the yellow viewer
Status: Completed
100%
Restore Defaults
AutoRun
Cancel
Apply
Data Probe
Show Zoomed Slice
L
F
B
Sagittal
R: 1.500mm
None
0.00
None
1.00
trace
B: trace

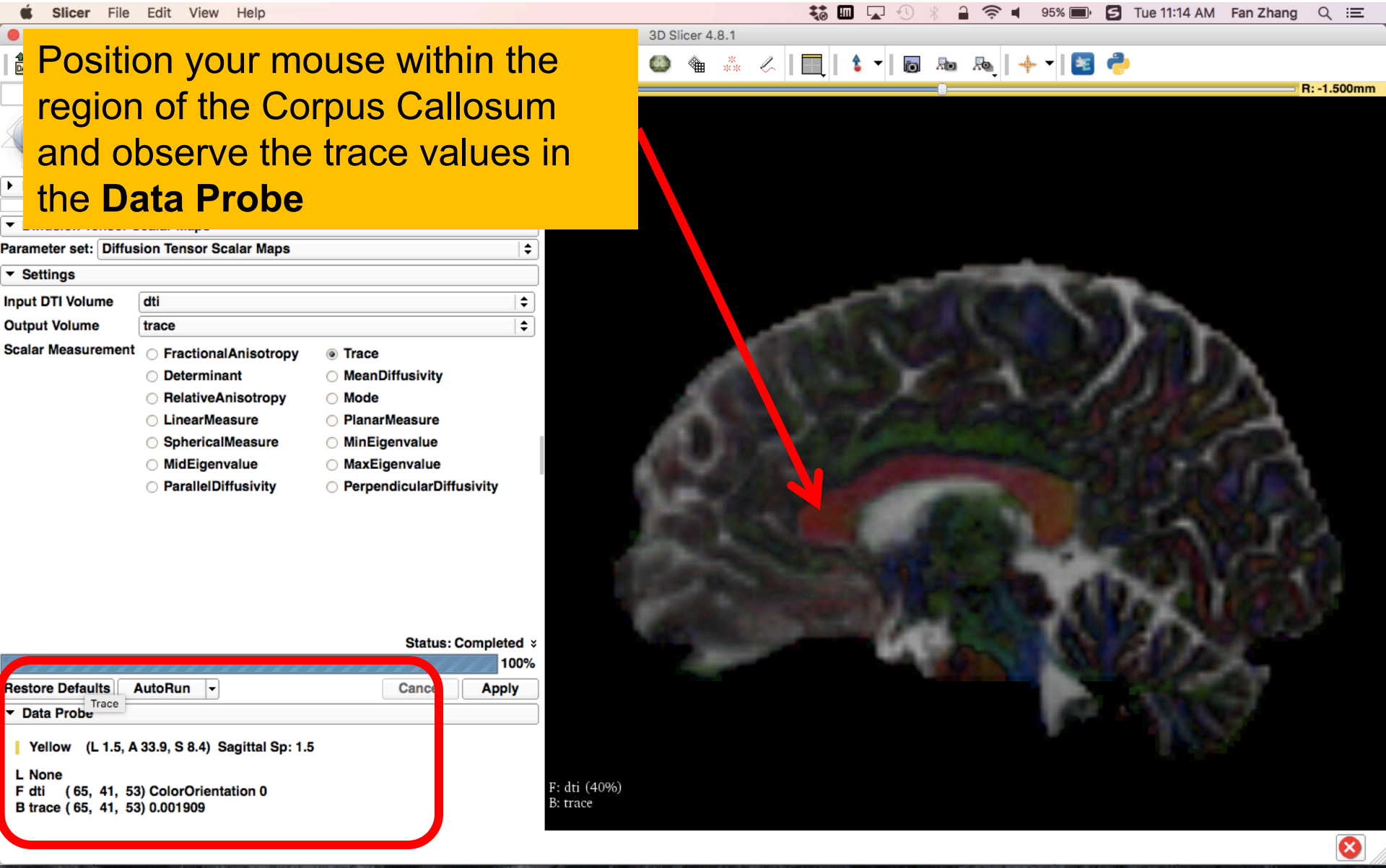
Trace


Slicer File Edit View Help
99% Tue 11:09 AM Fan Zhang
3D Slicer 4.8.1
Modules: Diffusion Tensor Scalar Maps
3DSlicer
Help & Acknowledgement
Diffusion Tensor Scalar Maps
Parameter set:
Settings
Input DTI Volume
Output Volume
Scalar Measurem
Adjust window level by right-dragging up and down.
RelativeAnisotropy
Mode
LinearMeasure
PlanarMeasure
SphericalMeasure
MinEigenvalue
MidEigenvalue
MaxEigenvalue
ParallelDiffusivity
PerpendicularDiffusivity
Status: Completed
100%
Restore Defaults
AutoRun
Cancel
Apply
Data Probe
Yellow (L 1.5, A 2.3, I 12.1) Sagittal Sp: 1.5
L None
F None
B trace (65, 62, 39) 0.001984
Y
R: -1.500mm
B: trace

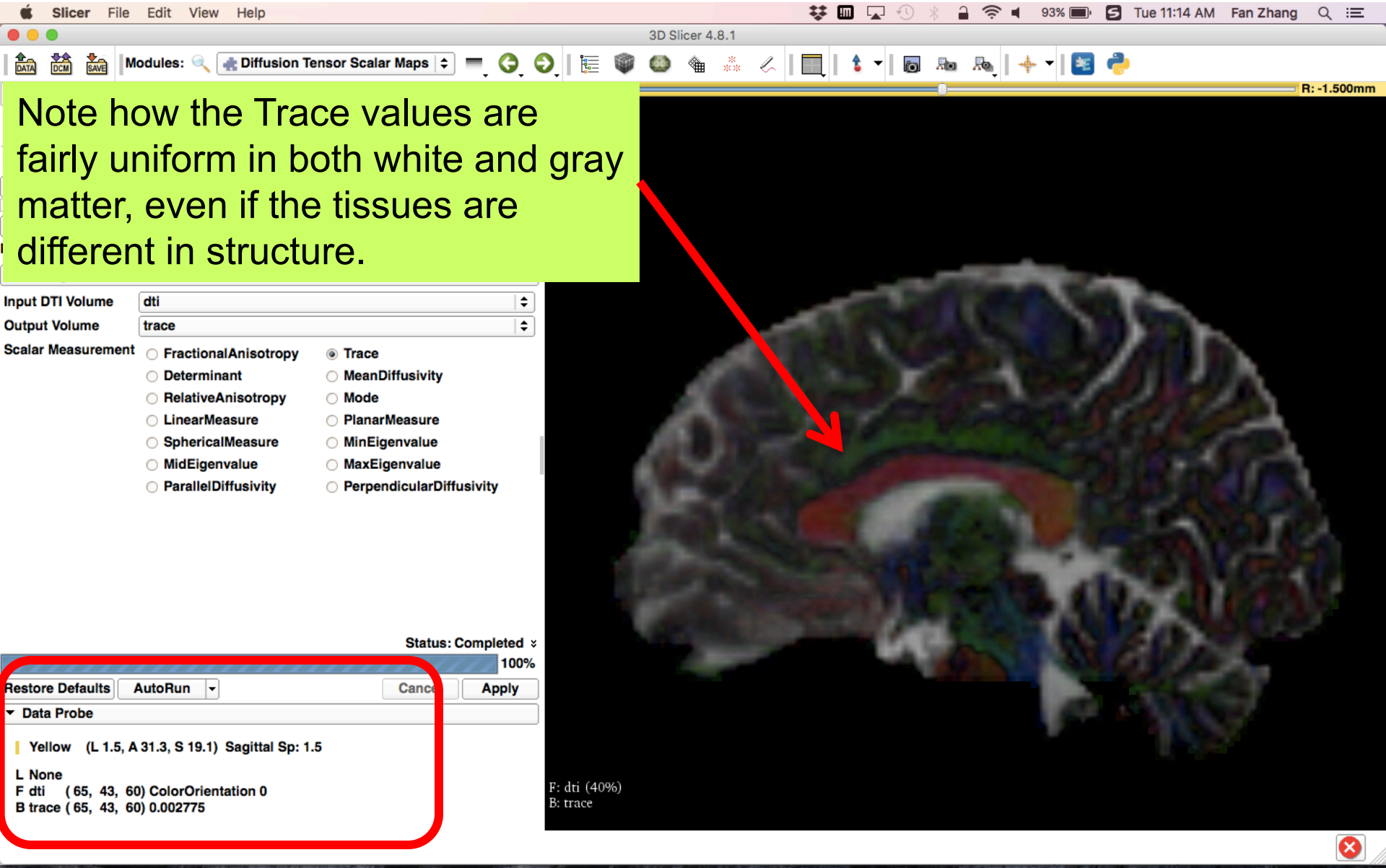
Trace


Slicer File Edit View Help
95% Tue 11:13 AM Fan Zhang
3D Slicer 4.8.1
Modules: Diffusion Tensor Scalar Maps
3DSlicer
Help & Acknowledgement
Diffusion Tensor Scalar Maps
Sagittal
1.00
None
0.40
dti
1.00
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**
F: dti (40%)
B: trace

Trace


Slicer File Edit View Help
95% Tue 11:14 AM Fan Zhang
3D Slicer 4.8.1
R: -1.500mm
Position your mouse within the region of the Corpus Callosum and observe the trace values in the **Data Probe**
Parameter set: Diffusion Tensor Scalar Maps
Settings
Input DTI Volume dti
Output Volume trace
Scalar Measurement
FractionalAnisotropy
Trace
Determinant
MeanDiffusivity
RelativeAnisotropy
Mode
LinearMeasure
PlanarMeasure
SphericalMeasure
MinEigenvalue
MidEigenvalue
MaxEigenvalue
ParallelDiffusivity
PerpendicularDiffusivity
Status: Completed
100%
Restore Defaults
AutoRun
Cancel
Apply
Trace
Data Probe
Yellow (L 1.5, A 33.9, S 8.4) Sagittal Sp: 1.5
L None
F dti (65, 41, 53) ColorOrientation 0
B trace (65, 41, 53) 0.001909
F: dti (40%)
B: trace

Trace

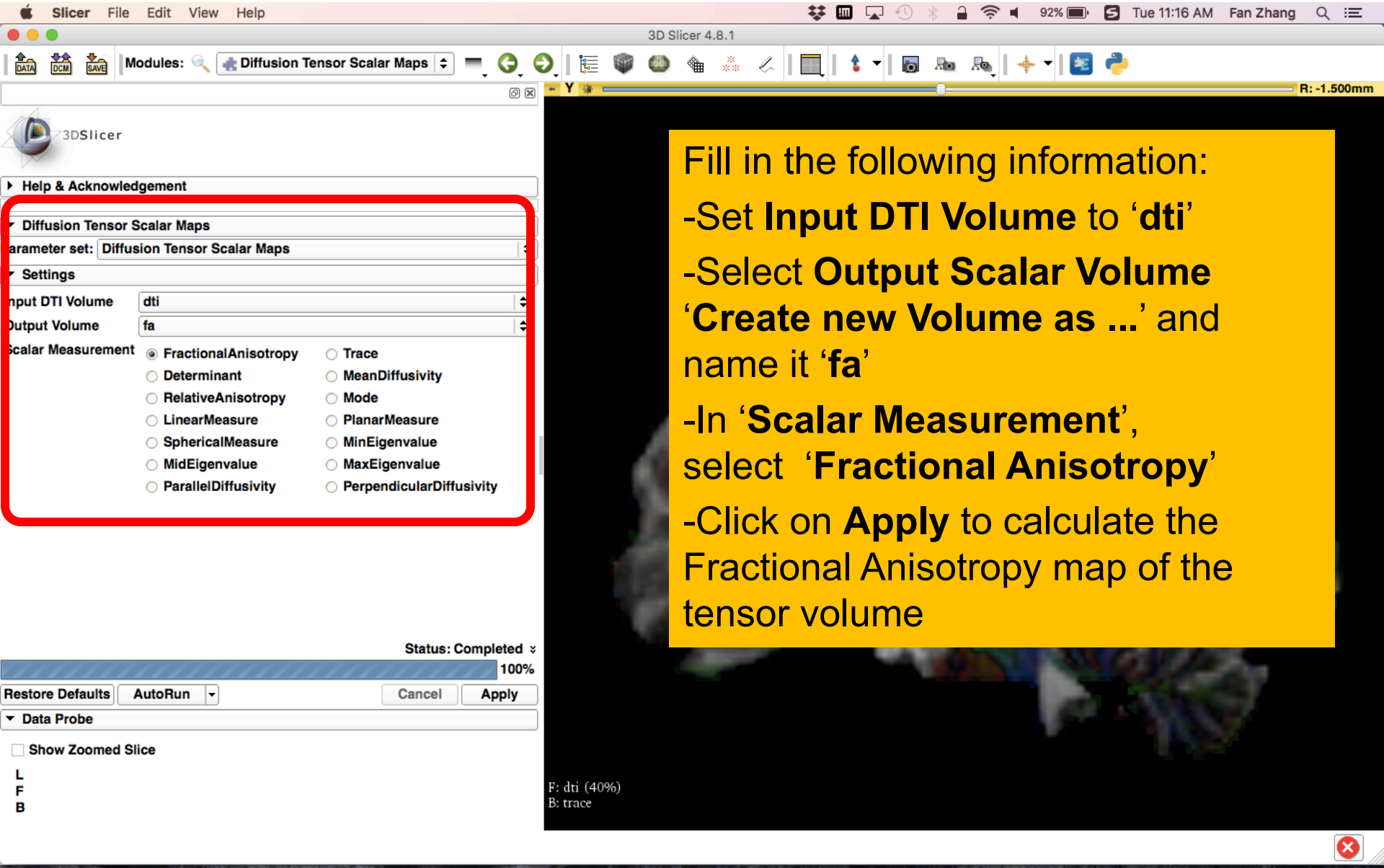

Slicer File Edit View Help
93% Tue 11:14 AM Fan Zhang
3D Slicer 4.8.1
Modules: Diffusion Tensor Scalar Maps
R: -1.500mm
Note how the Trace values are fairly uniform in both white and gray matter, even if the tissues are different in structure.
Input DTI Volume dti
Output Volume trace
Scalar Measurement
FractionalAnisotropy
Trace
Determinant
MeanDiffusivity
RelativeAnisotropy
Mode
LinearMeasure
PlanarMeasure
SphericalMeasure
MinEigenvalue
MidEigenvalue
MaxEigenvalue
ParallelDiffusivity
PerpendicularDiffusivity
Status: Completed
100%
Restore Defaults
AutoRun
Cancel
Apply
Data Probe
Yellow (L 1.5, A 31.3, S 19.1) Sagittal Sp: 1.5
L None
F dti (65, 43, 60) ColorOrientation 0
B trace (65, 43, 60) 0.002775
F: dti (40%)
B: trace

Scalar Maps: Fractional Anisotropy

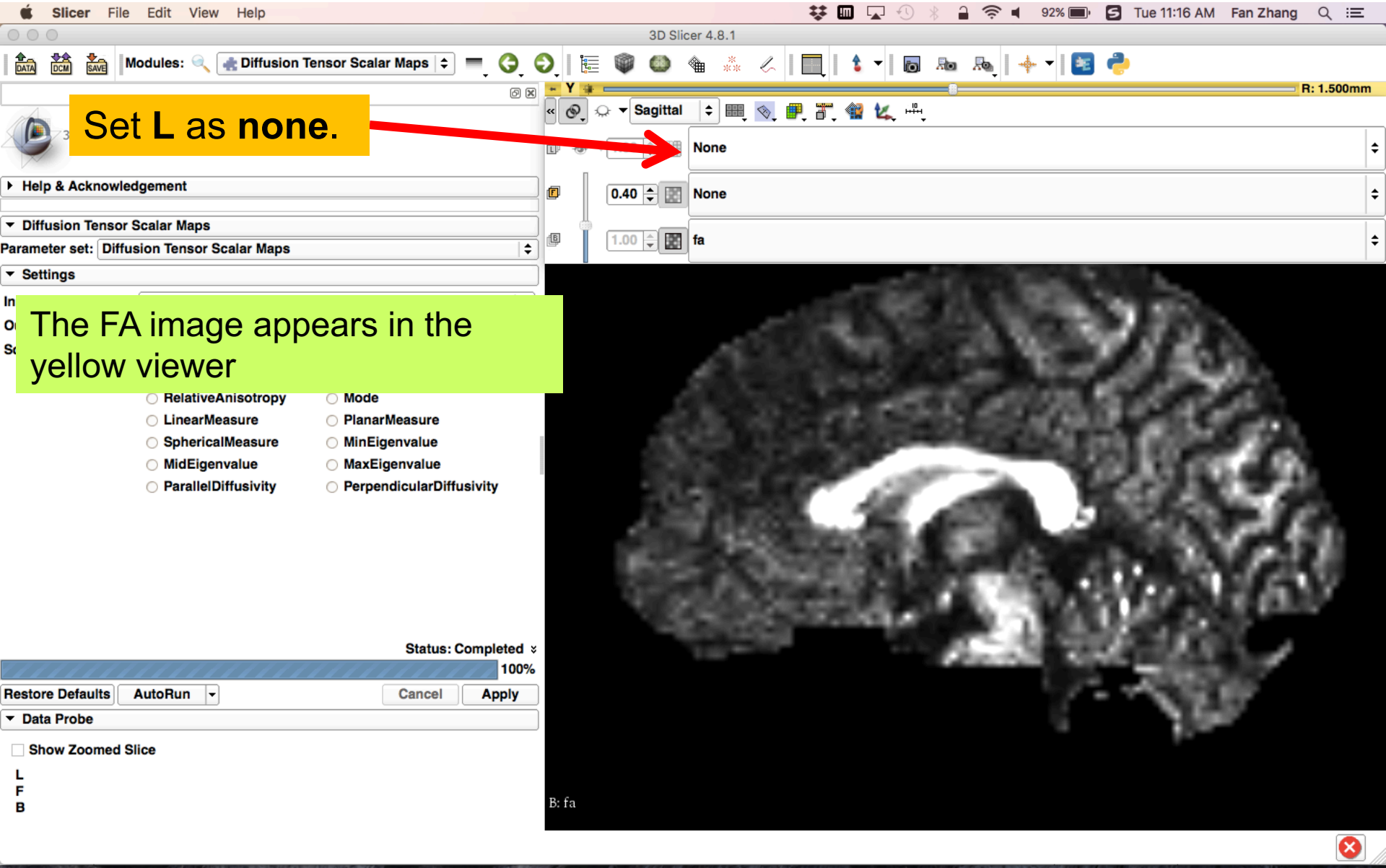
$$FA(D) = \frac{\sqrt{(\lambda_1 - \lambda_2)^2 + (\lambda_1 - \lambda_3)^2 + (\lambda_2 - \lambda_3)^2}}{\sqrt{2}\sqrt{\lambda_1^2 + \lambda_2^2 + \lambda_3^2}}$$

- 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: 

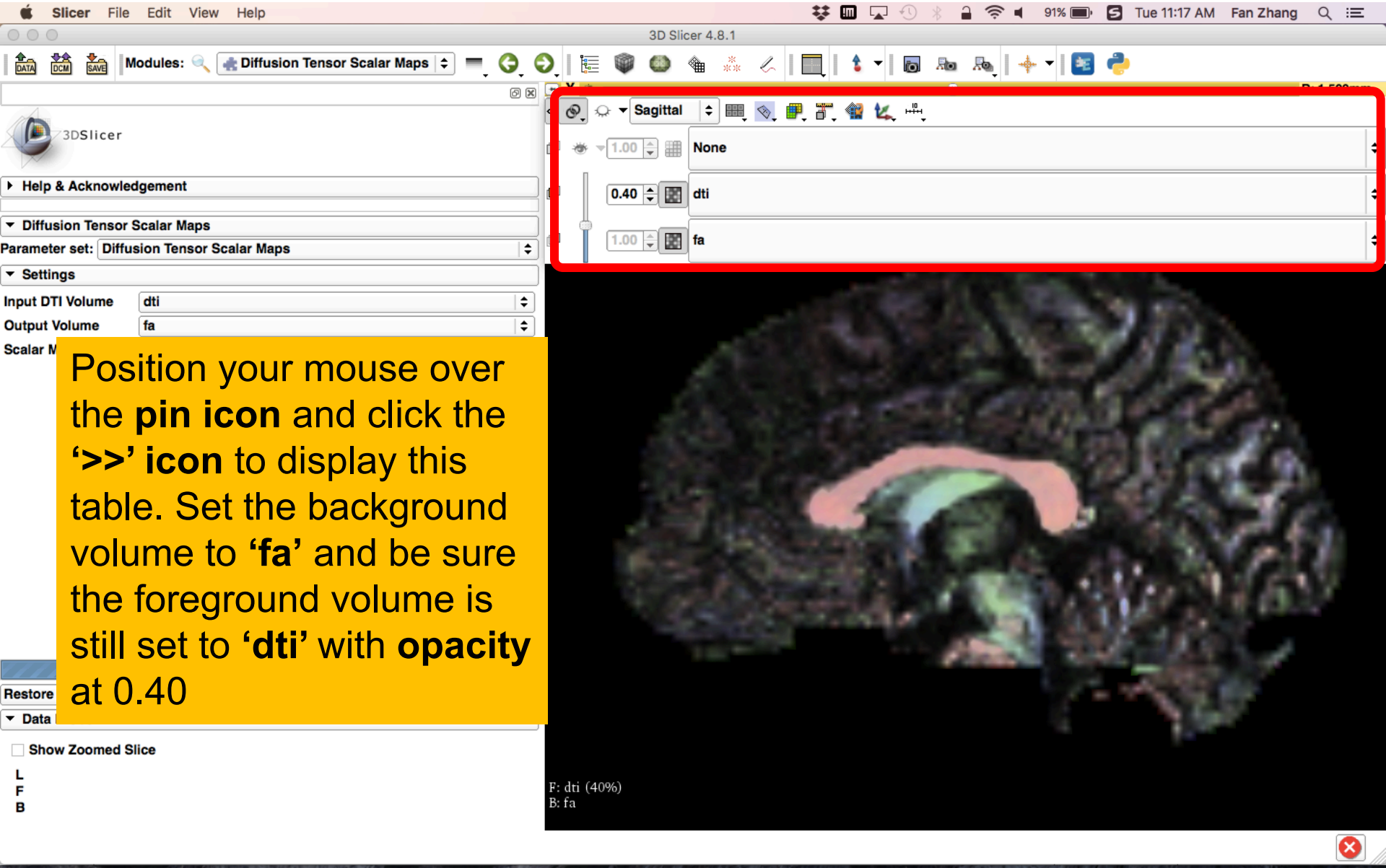
Fractional Anisotropy



Fractional Anisotropy

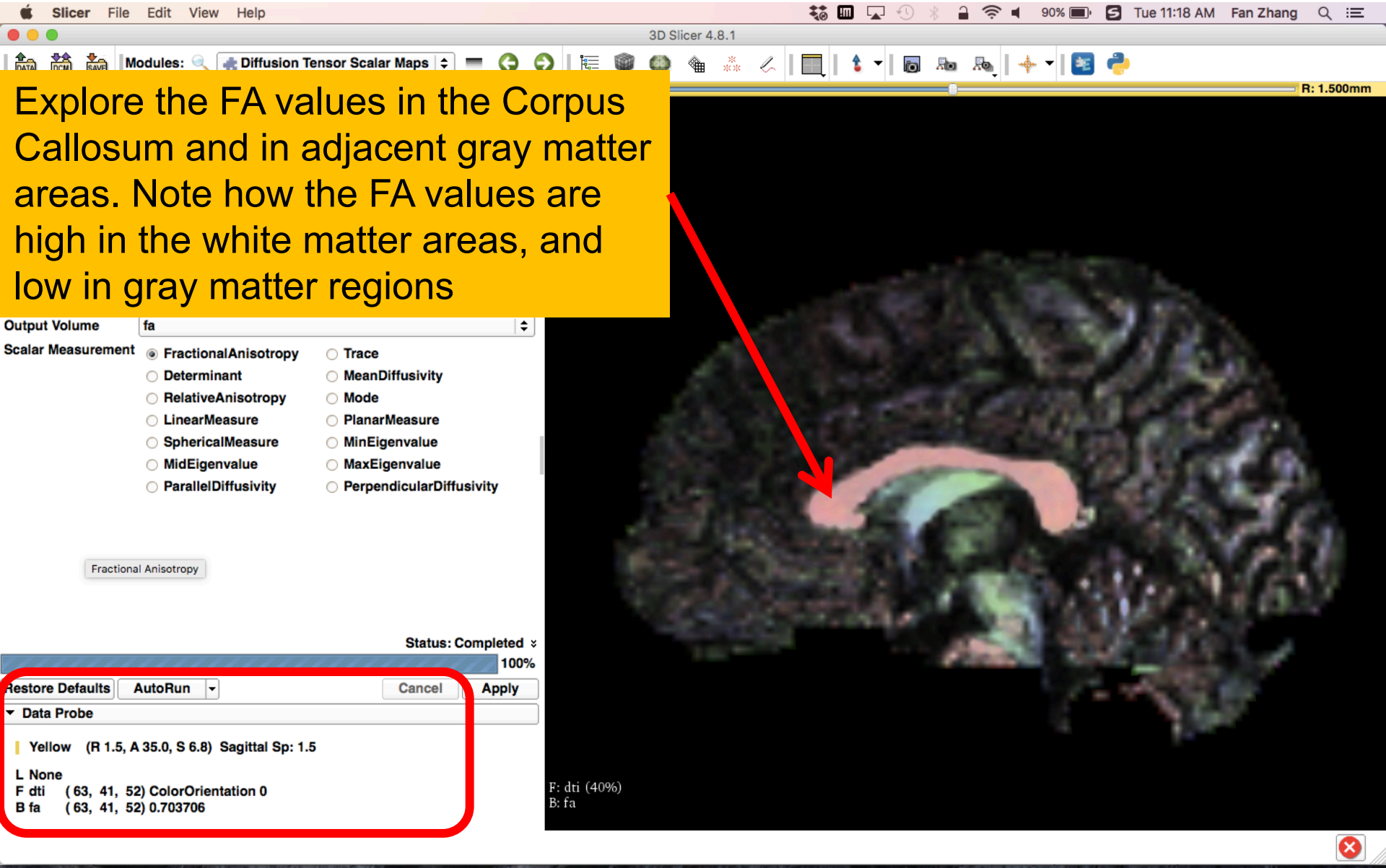


Fractional Anisotropy

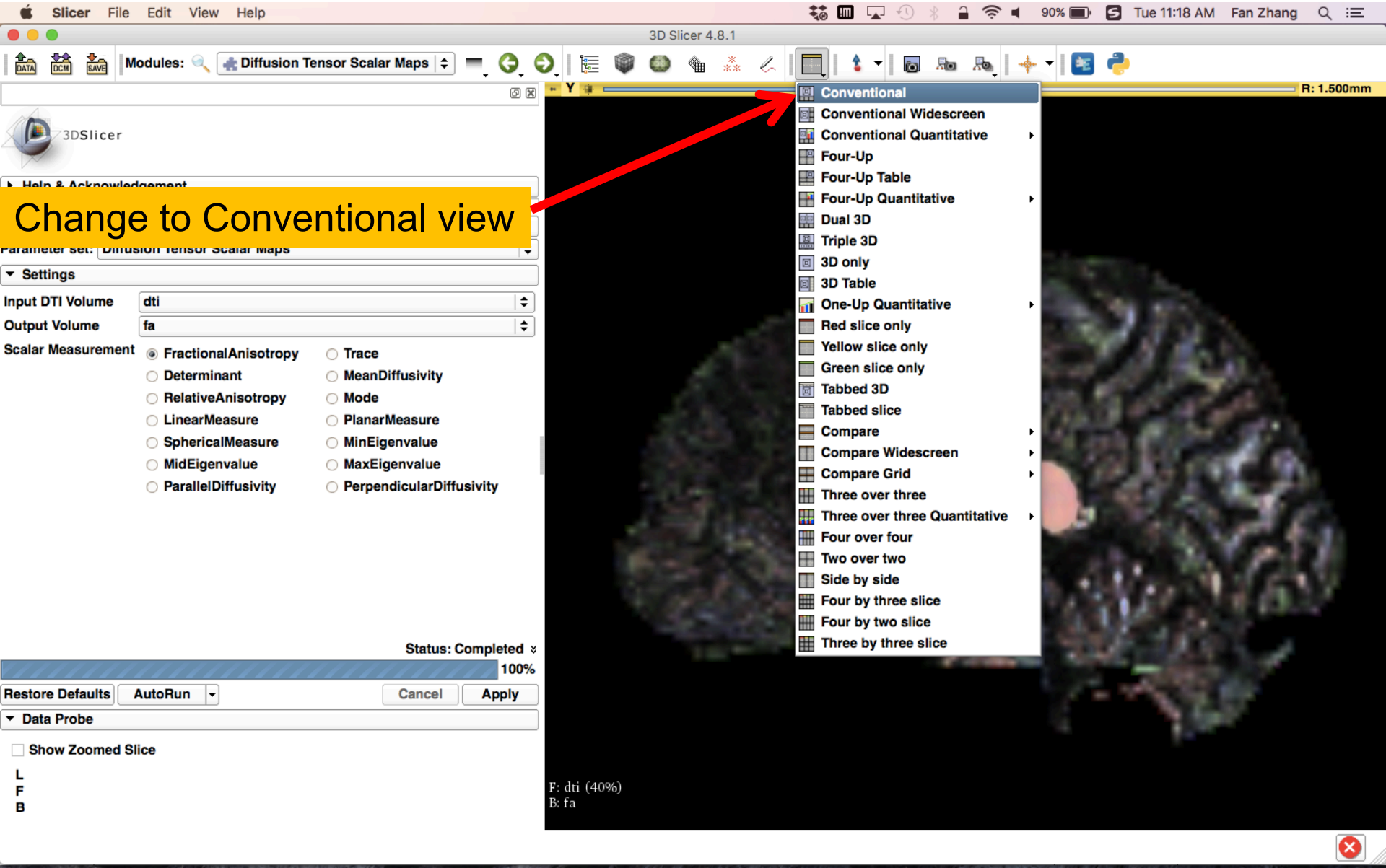


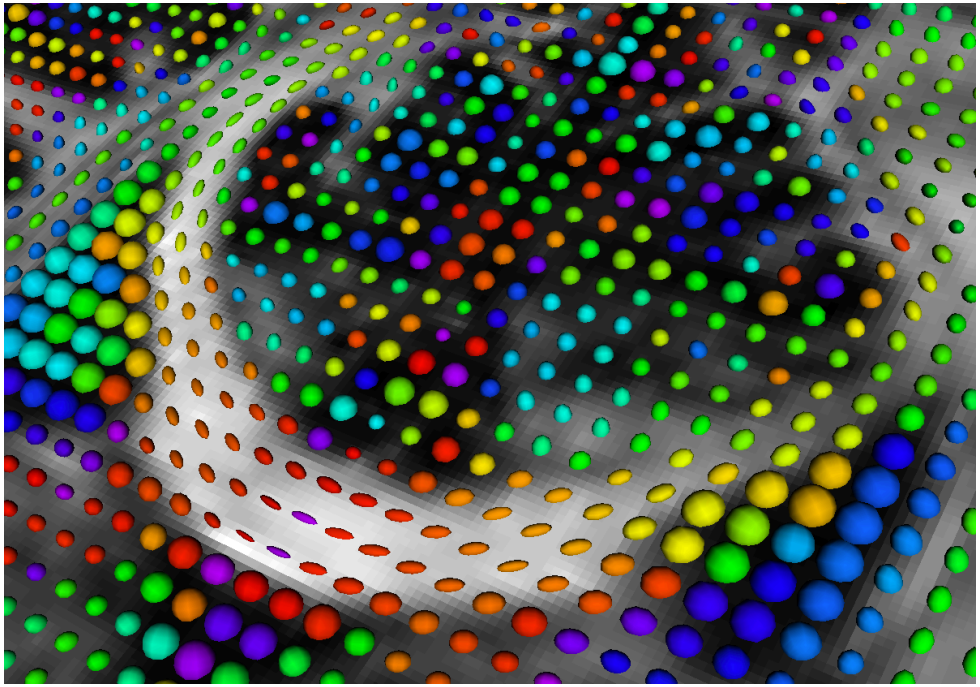
Position your mouse over the **pin icon** and click the **'>>' icon** to display this table. Set the background volume to **'fa'** and be sure the foreground volume is still set to '**dti**' with **opacity** at 0.40

Fractional Anisotropy



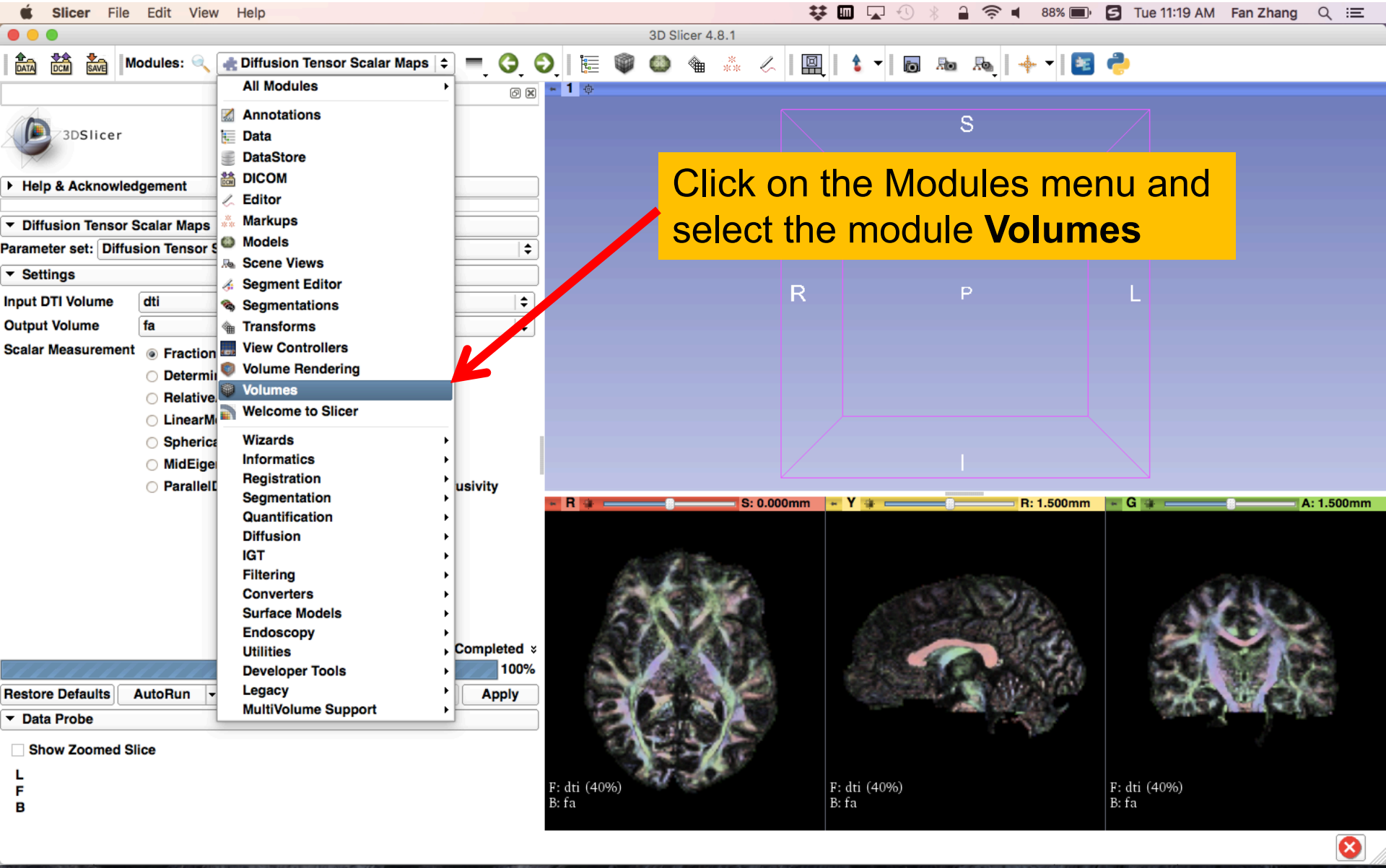
Fractional Anisotropy



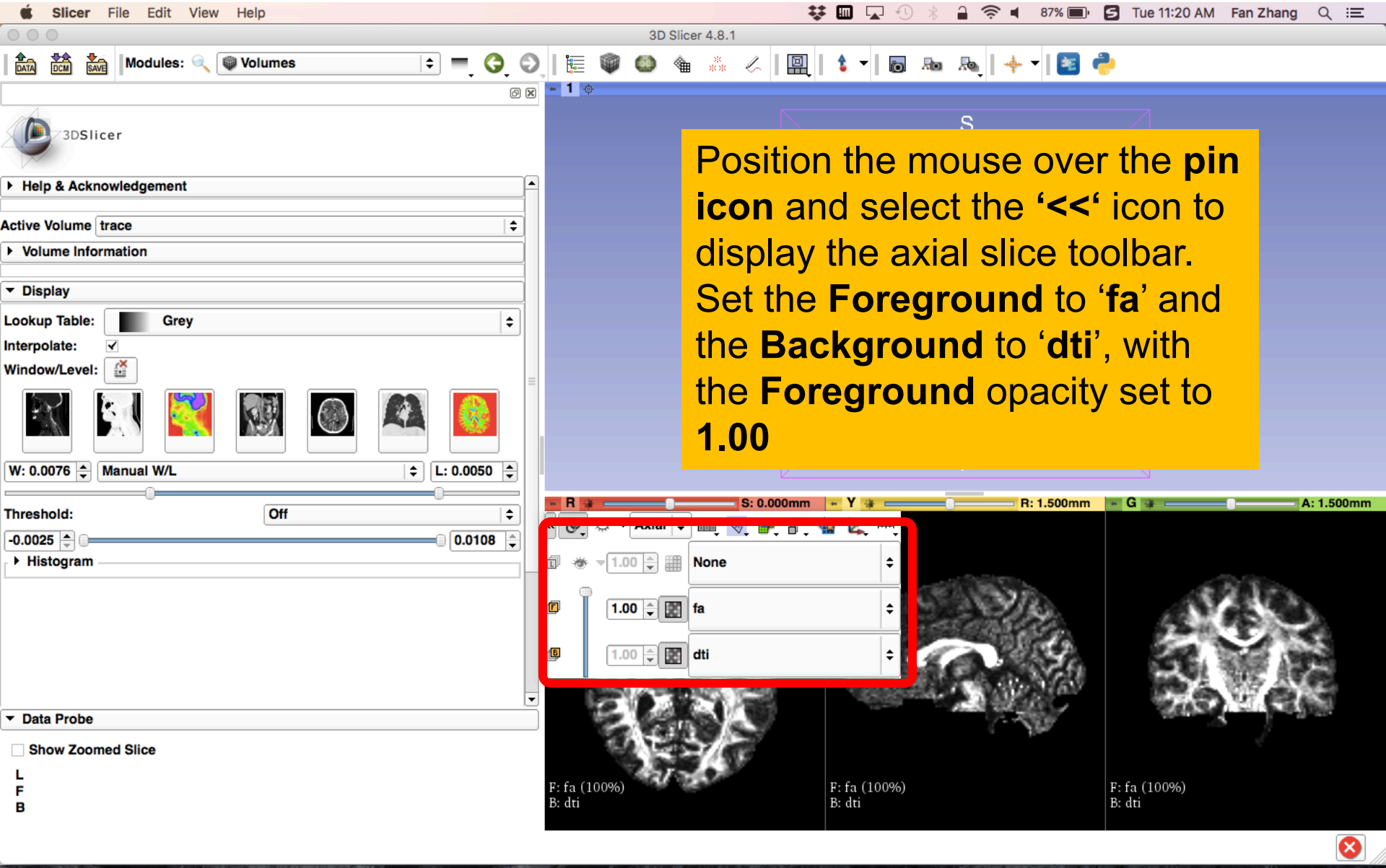


Part 2: Visualizing the tensor data

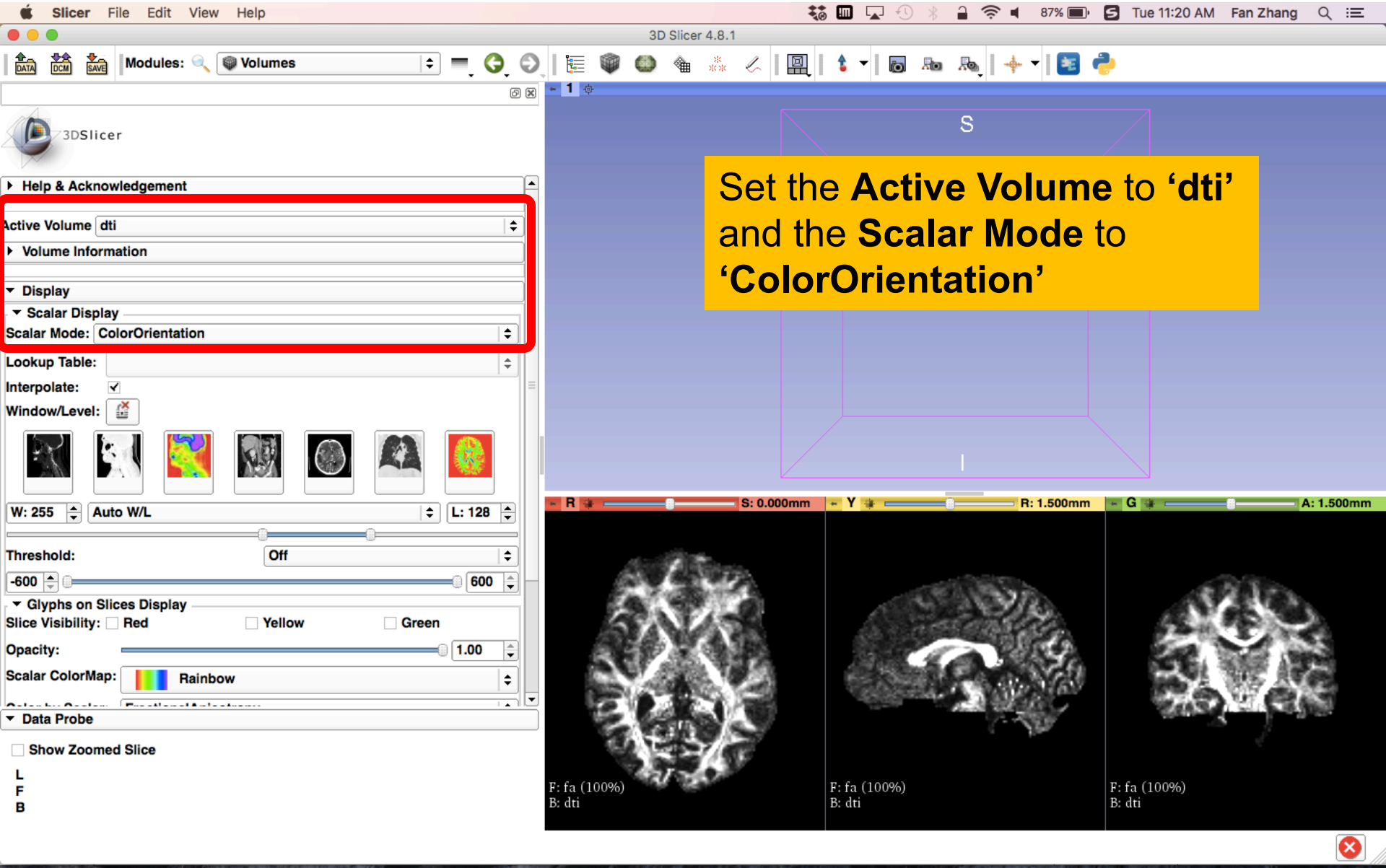
3D Visualization: Glyphs



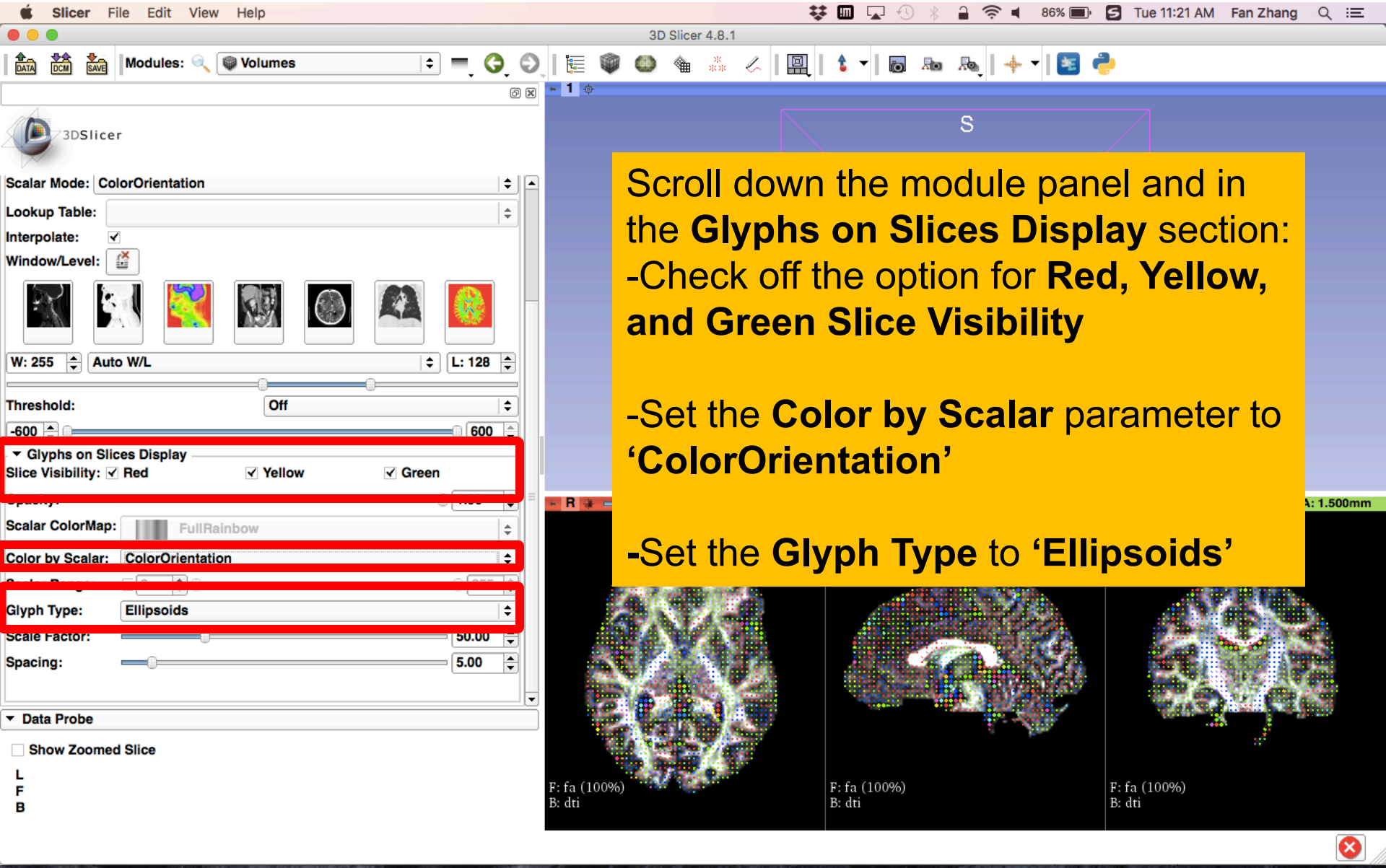
3D Visualization: Glyphs



3D Visualization: Glyphs



3D Visualization: Glyphs

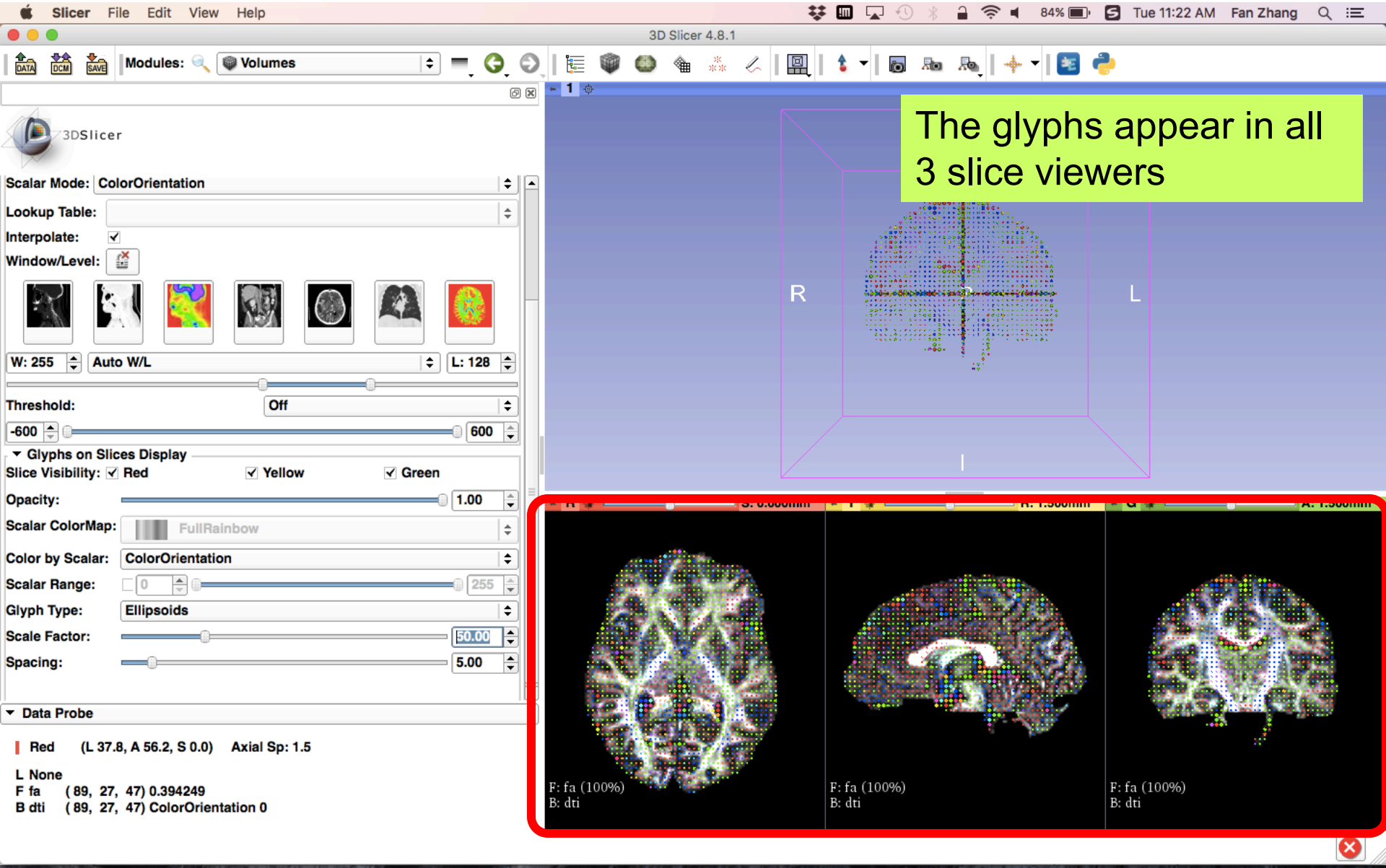


Scroll down the module panel and in the **Glyphs on Slices Display** section:
-Check off the option for **Red, Yellow, and Green Slice Visibility**

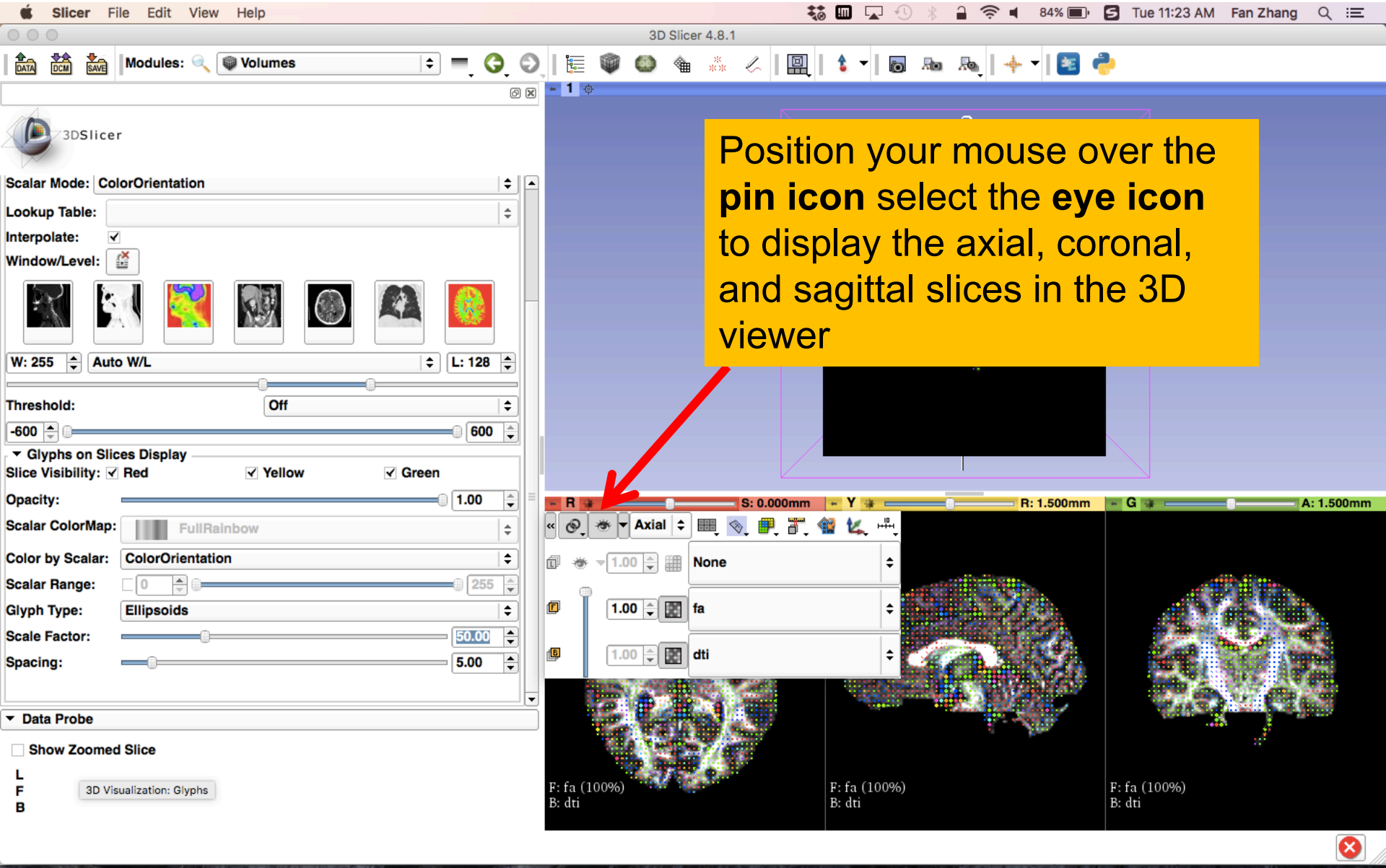
-Set the **Color by Scalar** parameter to **'ColorOrientation'**

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

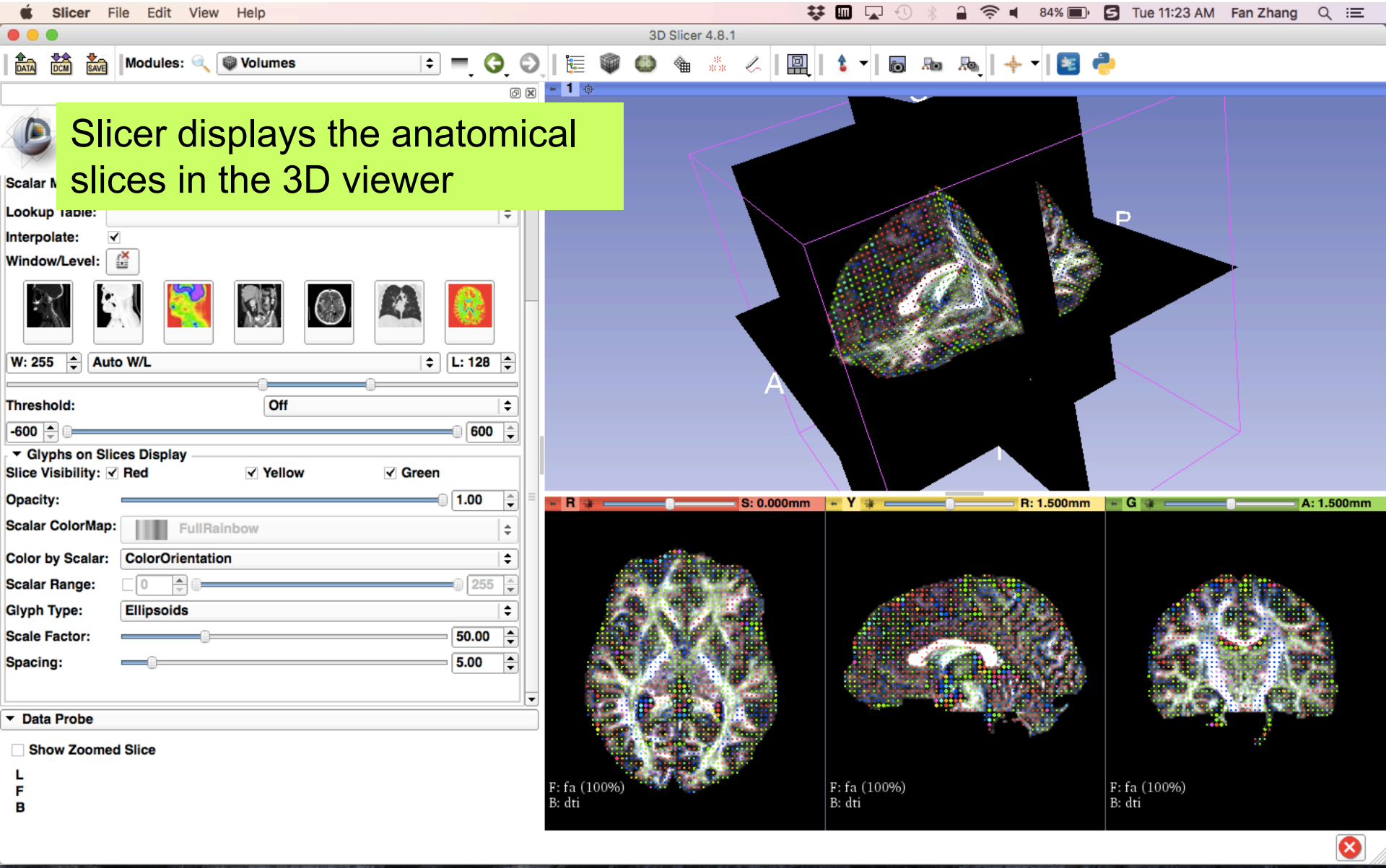
3D Visualization: Glyphs



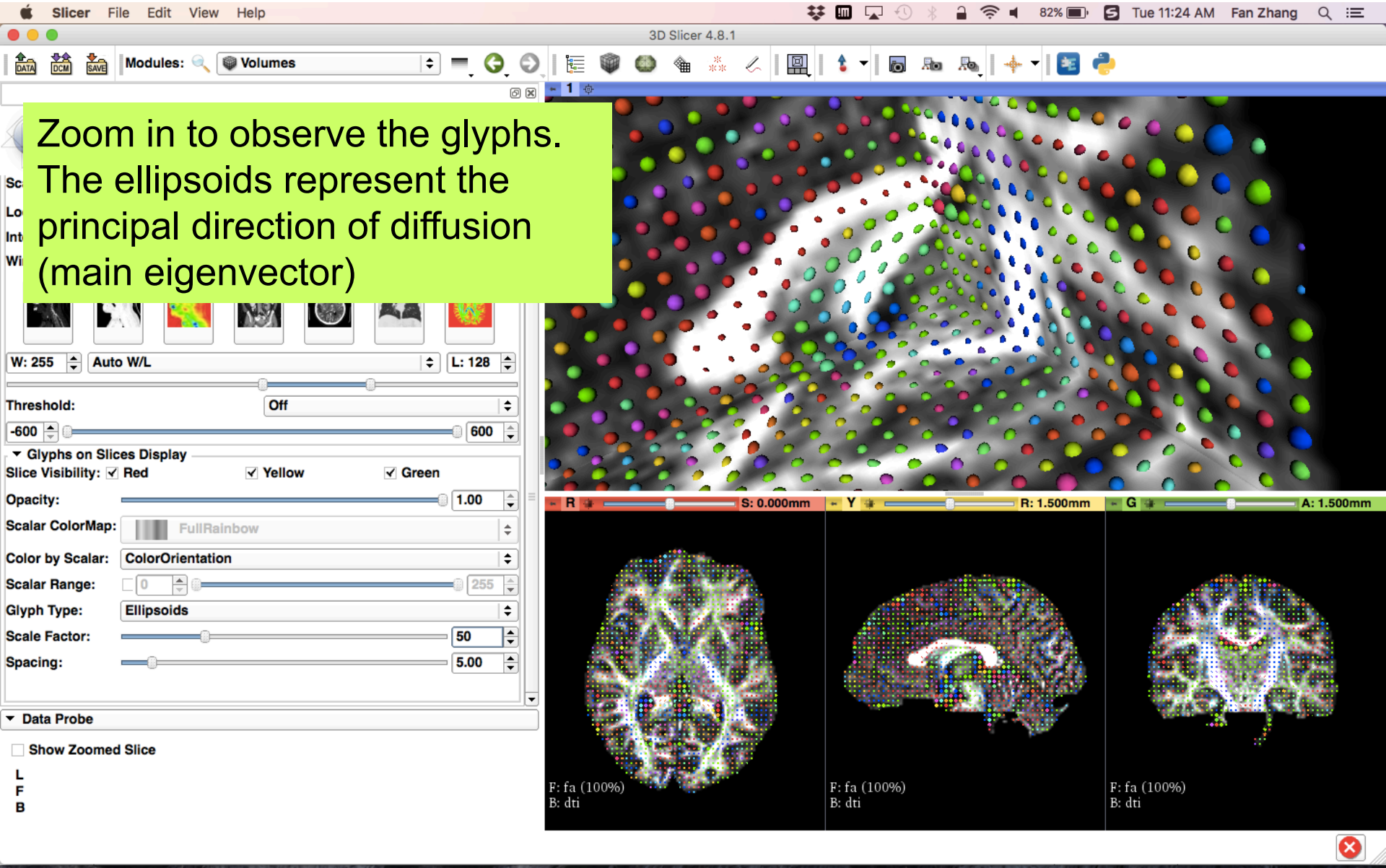
3D Visualization: Glyphs



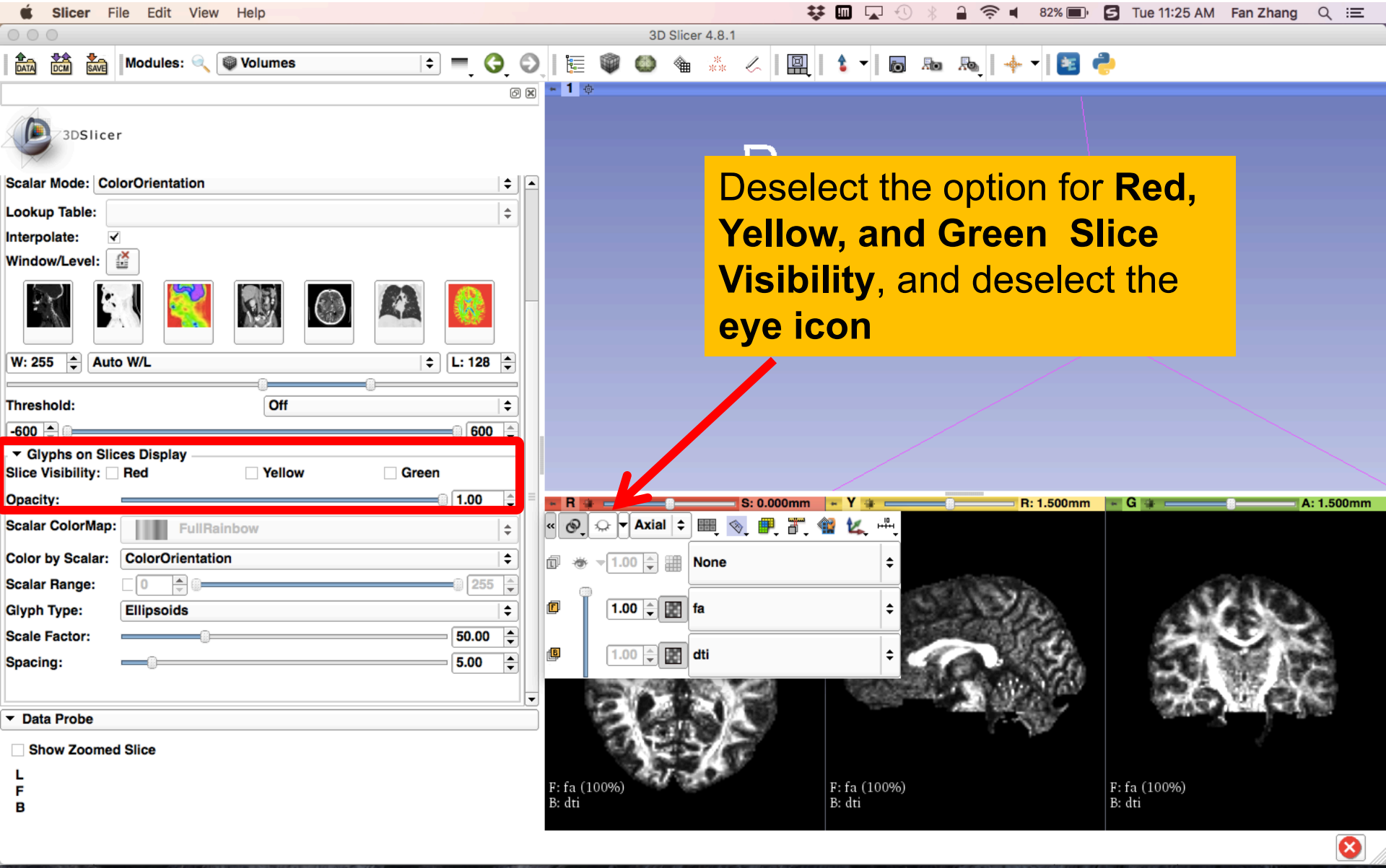
3D Visualization: Glyphs



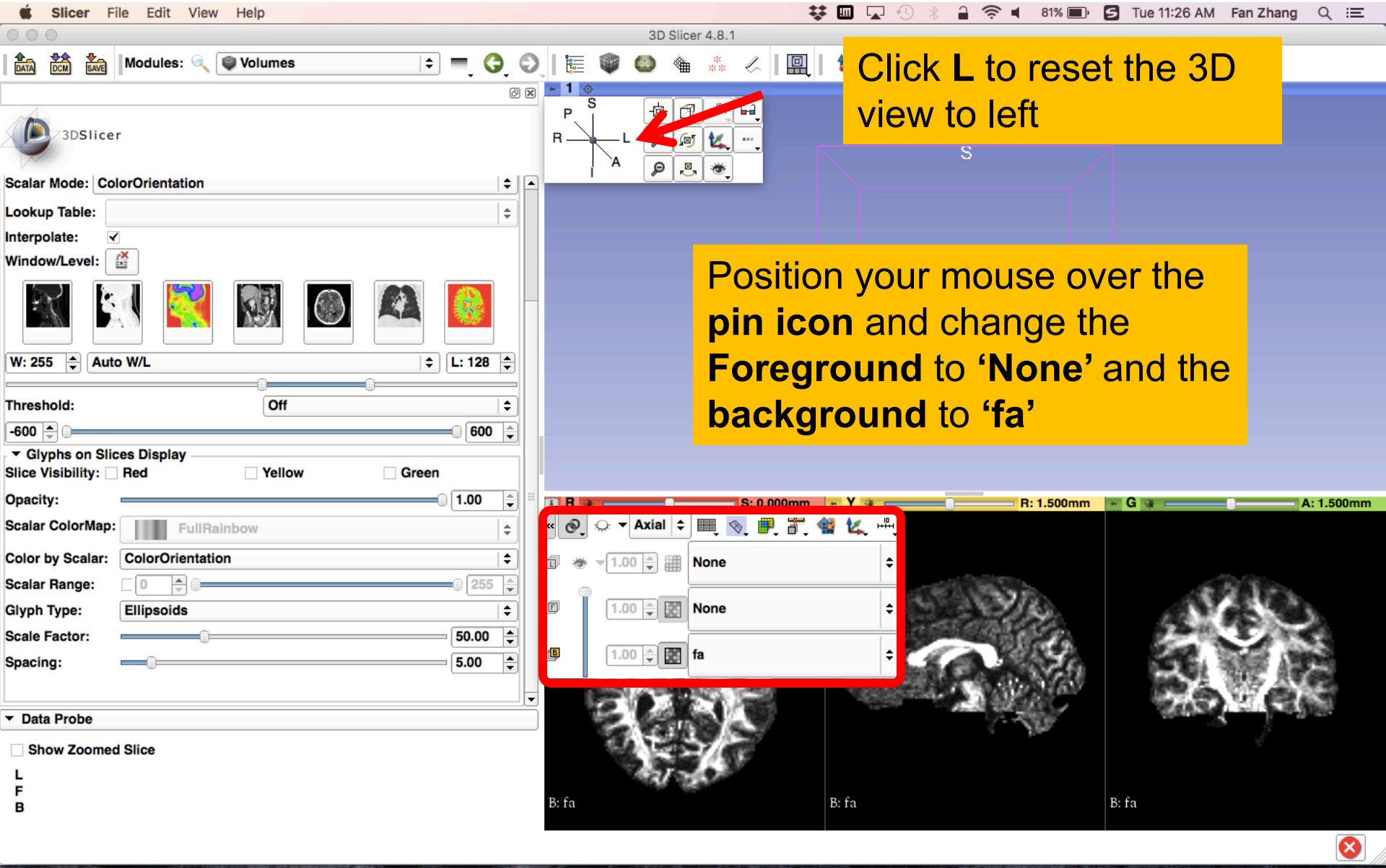
3D Visualization: Glyphs

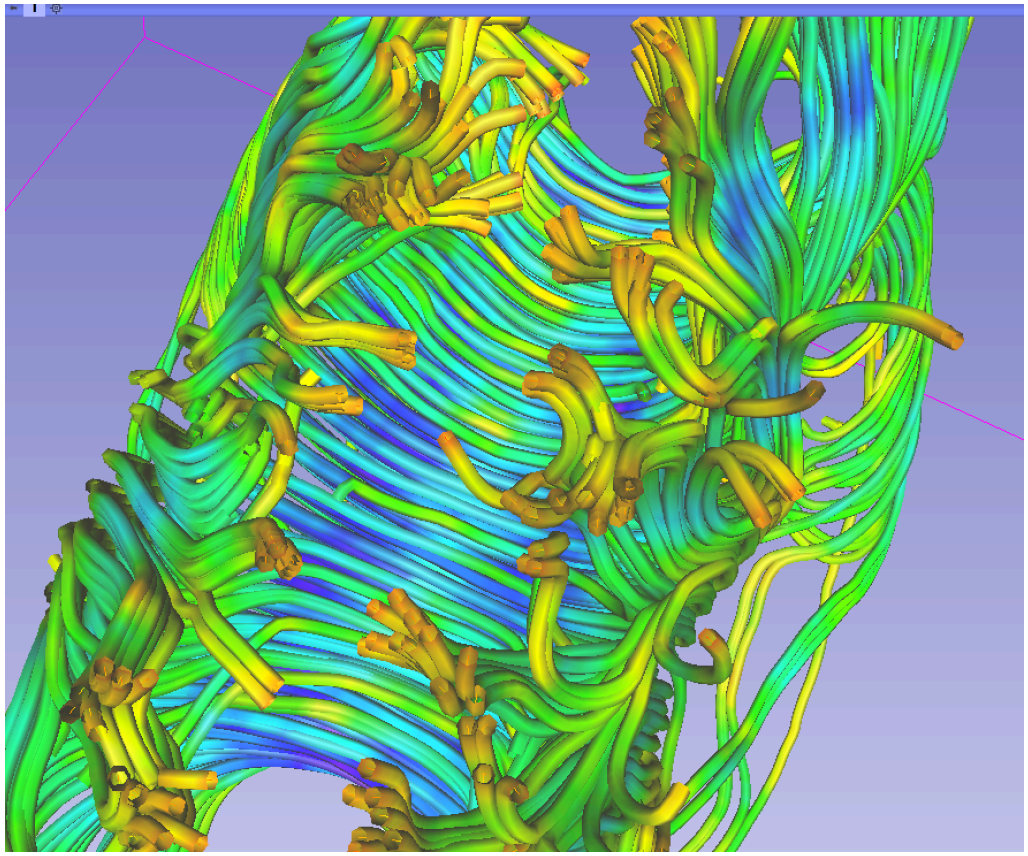


Diffusion MRI tractography



Diffusion MRI tractography



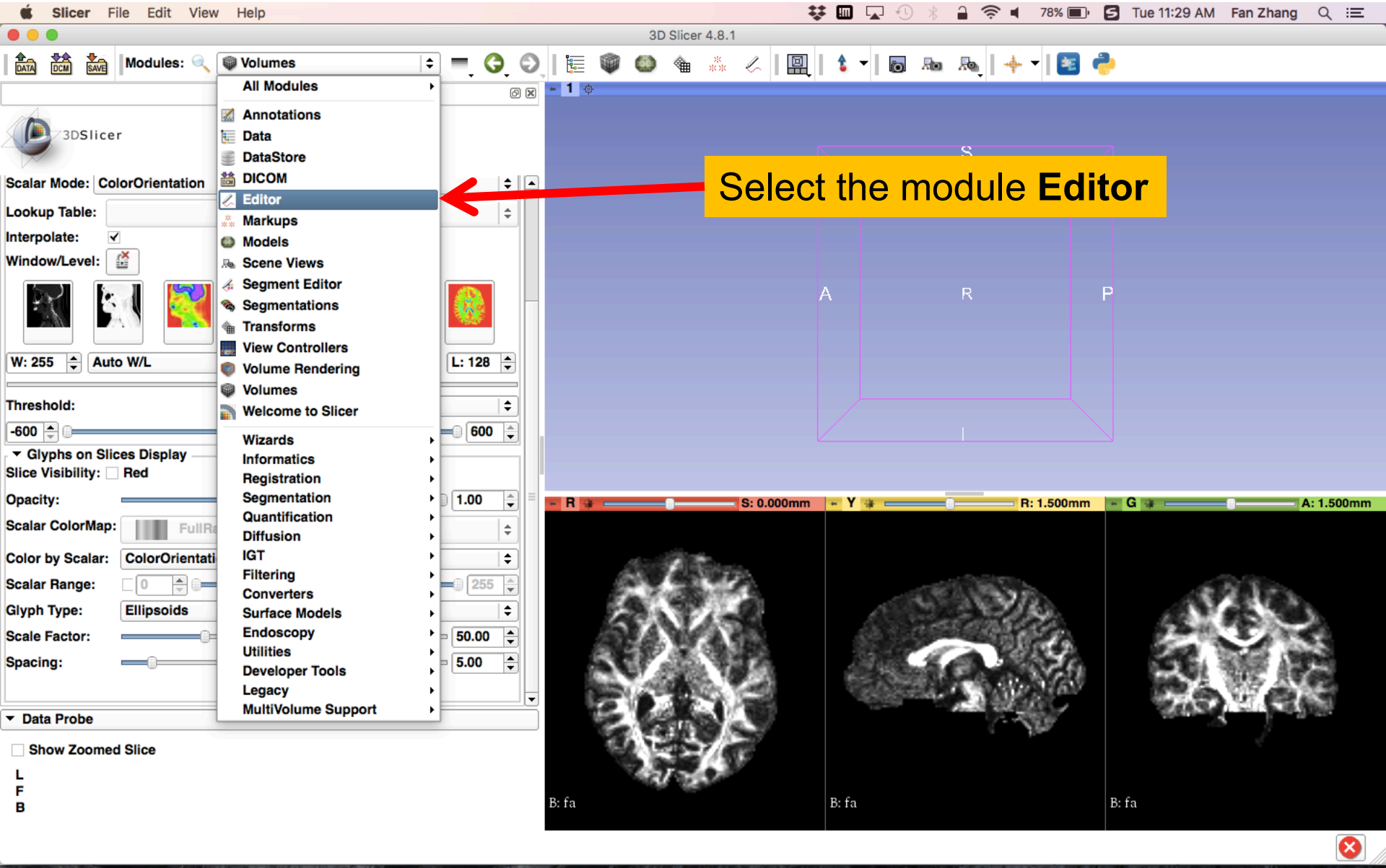


Part 3: From tensors to tracts

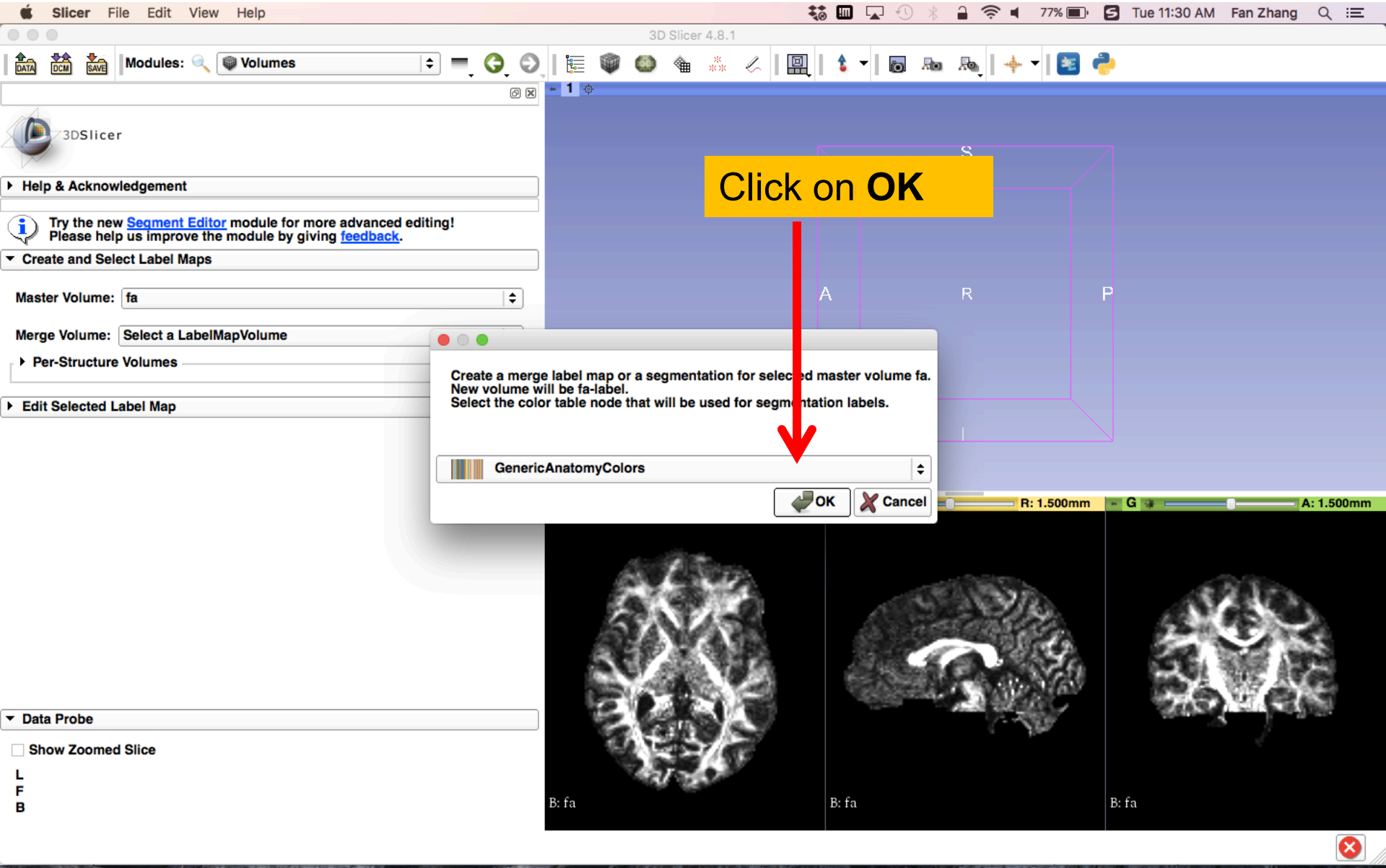
DTI tractography

- 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)

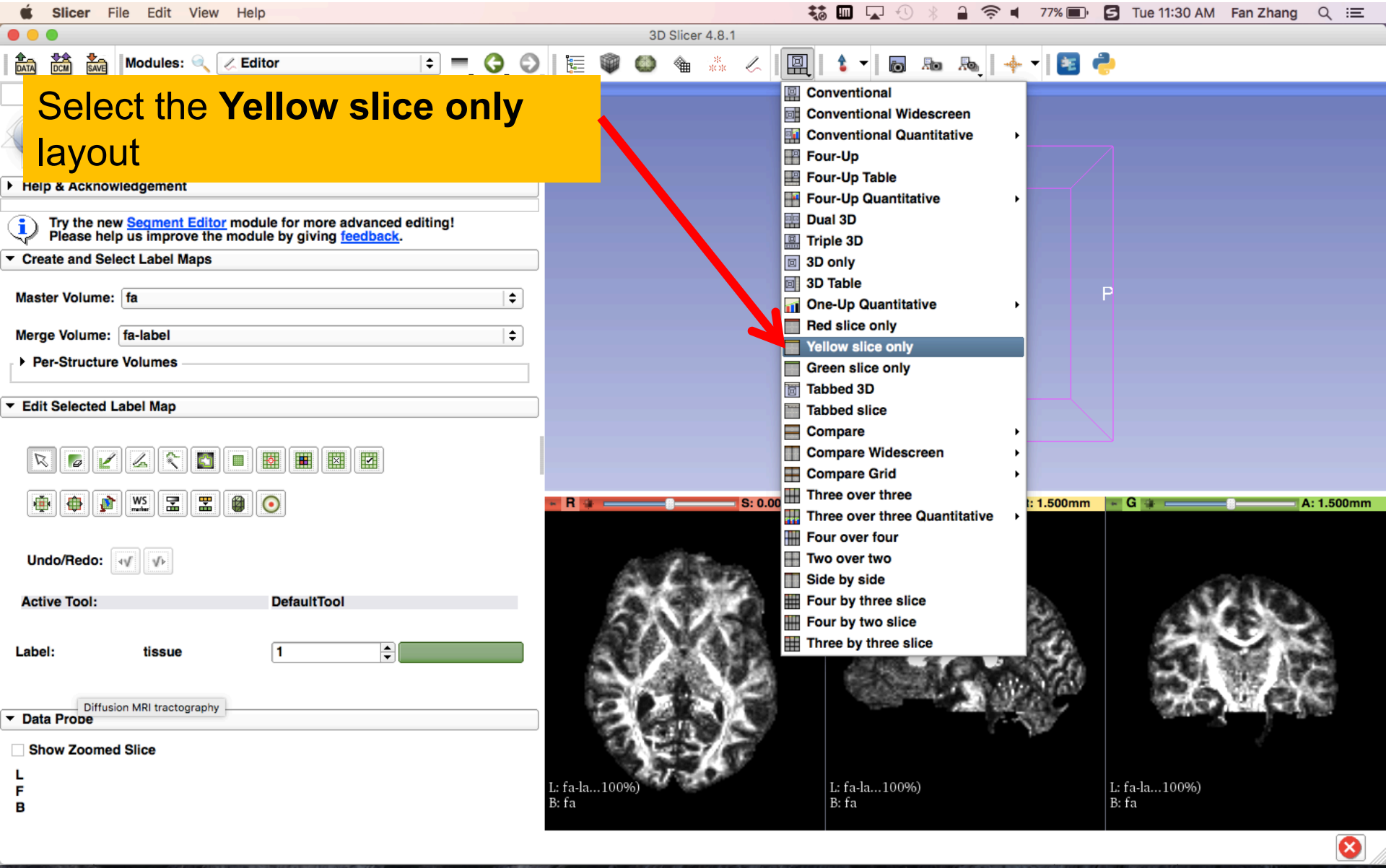
Diffusion MRI tractography



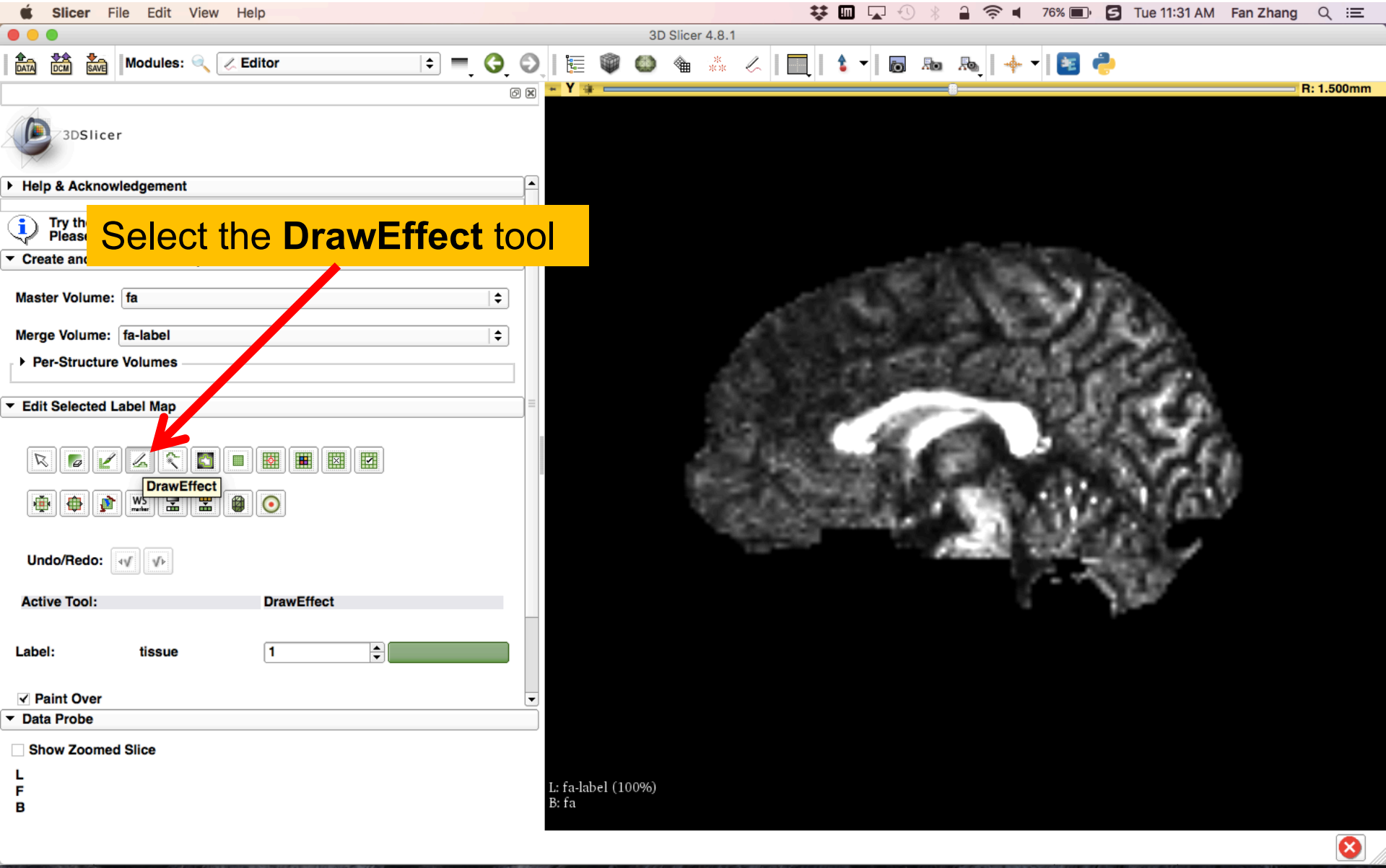
Diffusion MRI tractography



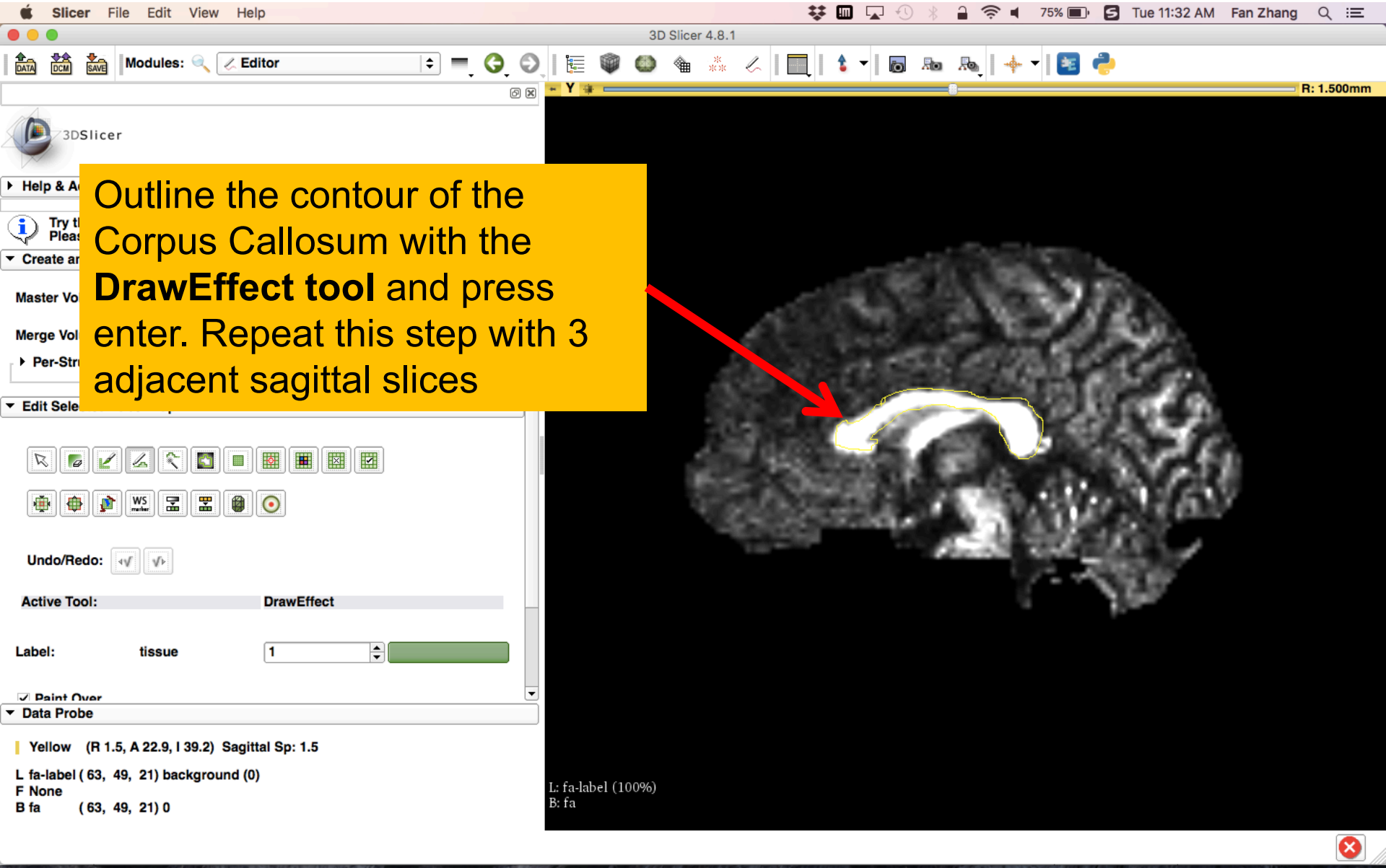
Diffusion MRI tractography



Diffusion MRI tractography

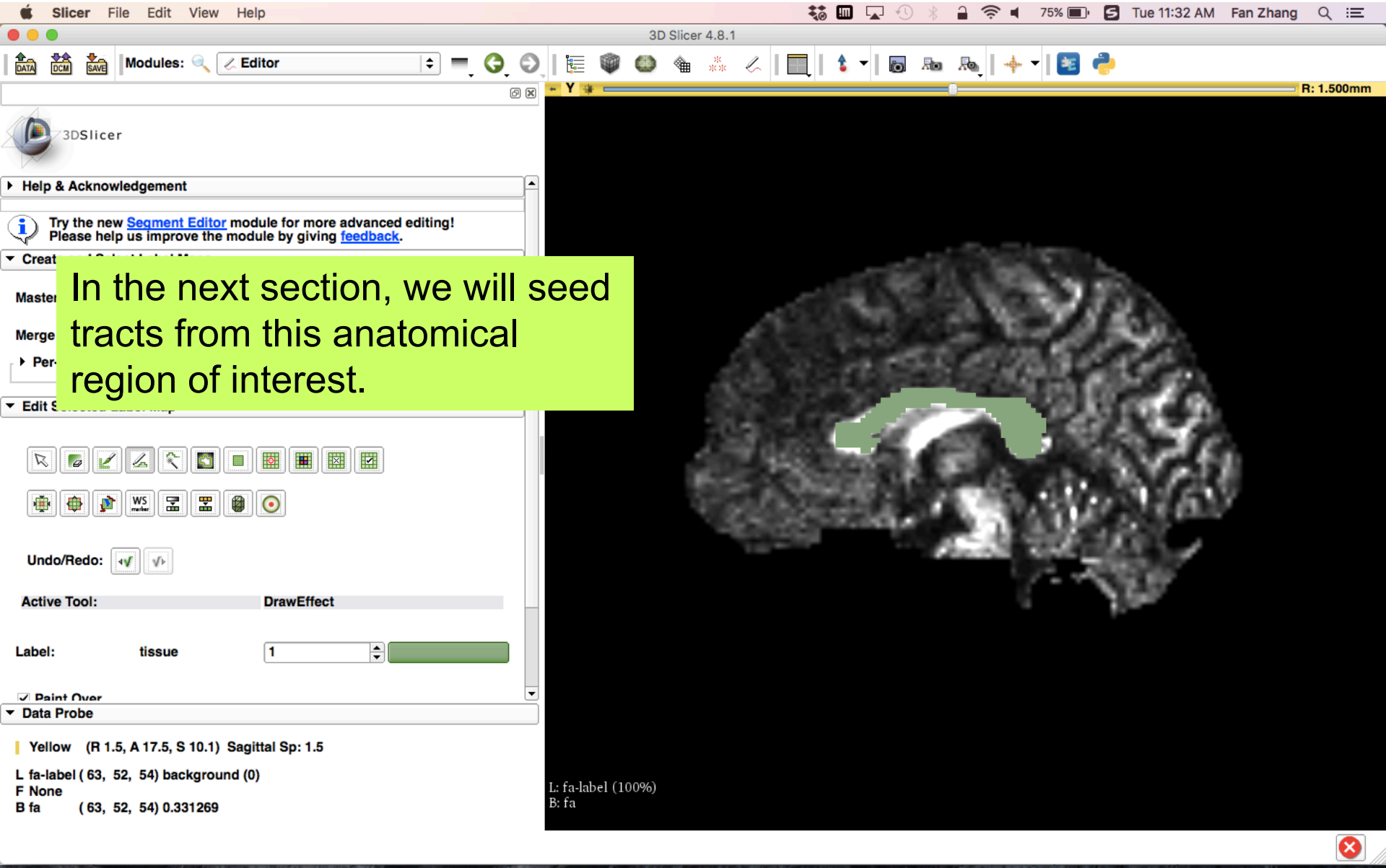


Diffusion MRI tractography

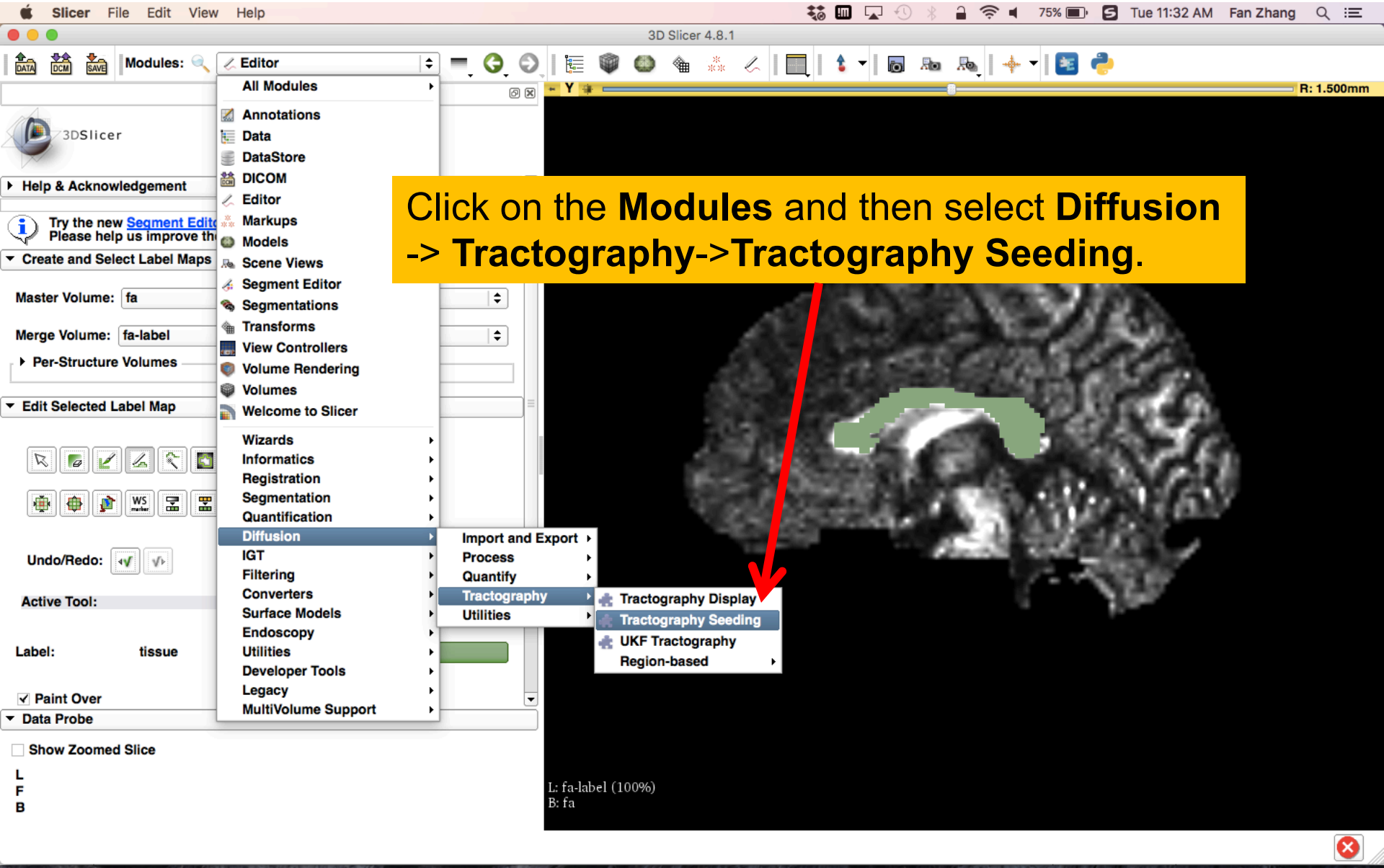


Outline the contour of the Corpus Callosum with the **DrawEffect tool** and press enter. Repeat this step with 3 adjacent sagittal slices

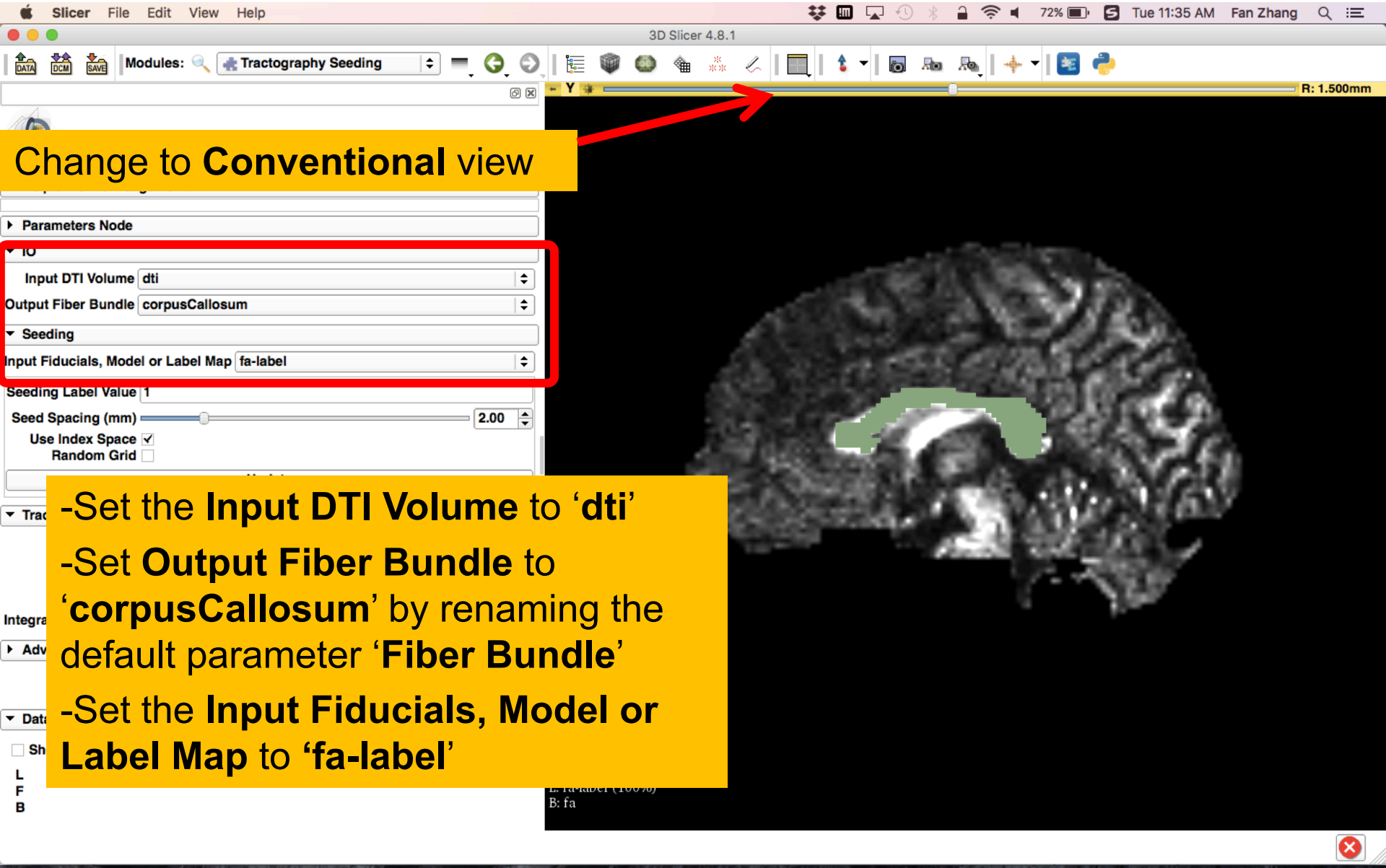
Diffusion MRI tractography



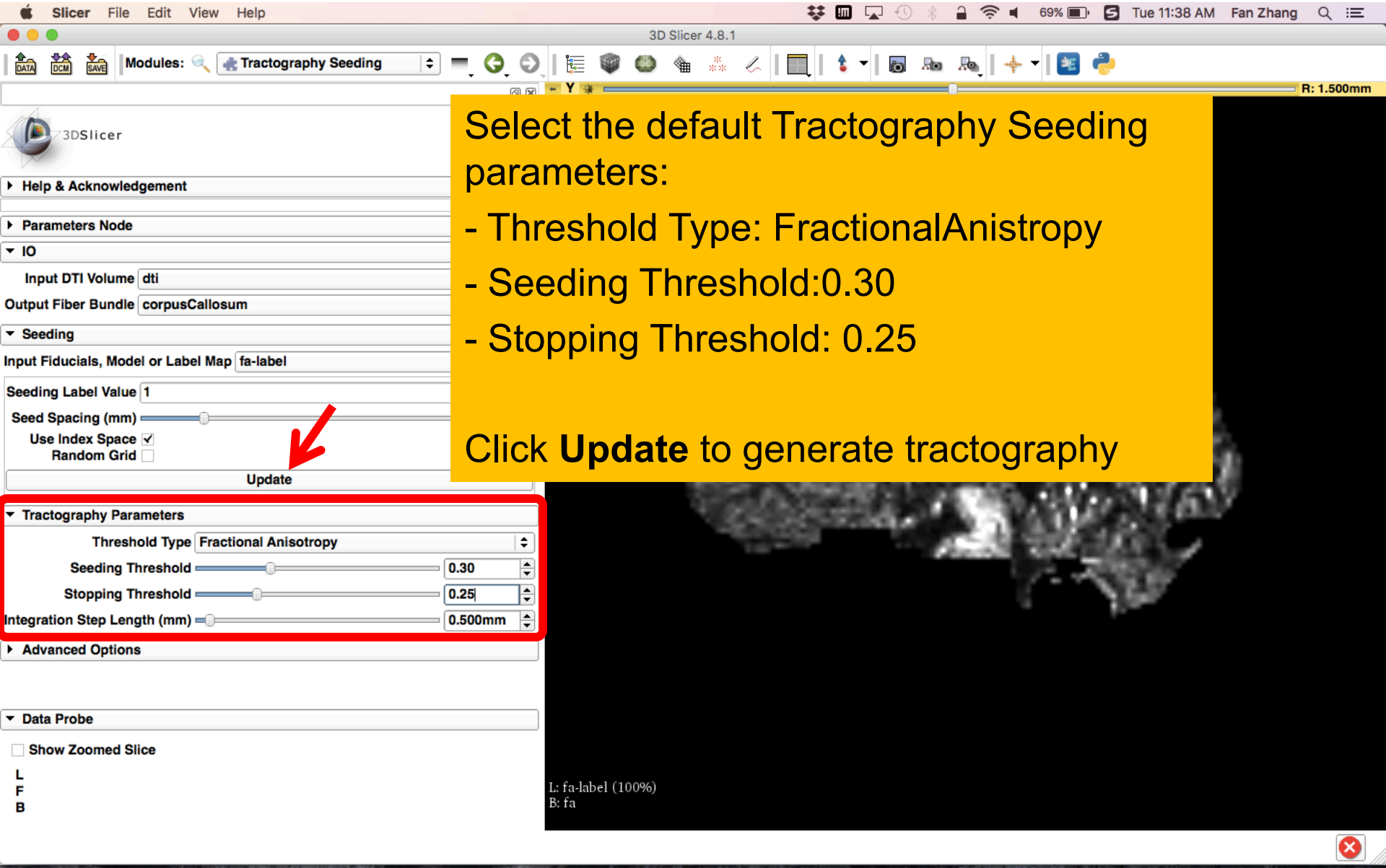
Diffusion MRI tractography



Step1: I/O


Slicer File Edit View Help
72% Tue 11:35 AM Fan Zhang
3D Slicer 4.8.1
Modules: Tractography Seeding
R: 1.500mm
Change to **Conventional** view
Parameters Node
IO
Input DTI Volume dti
Output Fiber Bundle corpusCallosum
Seeding
Input Fiducials, Model or Label Map fa-label
Seeding Label Value 1
Seed Spacing (mm) 2.00
Use Index Space
Random Grid
-Set the **Input DTI Volume** to '**dti**'
-Set **Output Fiber Bundle** to '**corpusCallosum**' by renaming the default parameter '**Fiber Bundle**'
-Set the **Input Fiducials, Model or Label Map** to '**fa-label**'
B: fa

Step 2: Seeding parameters

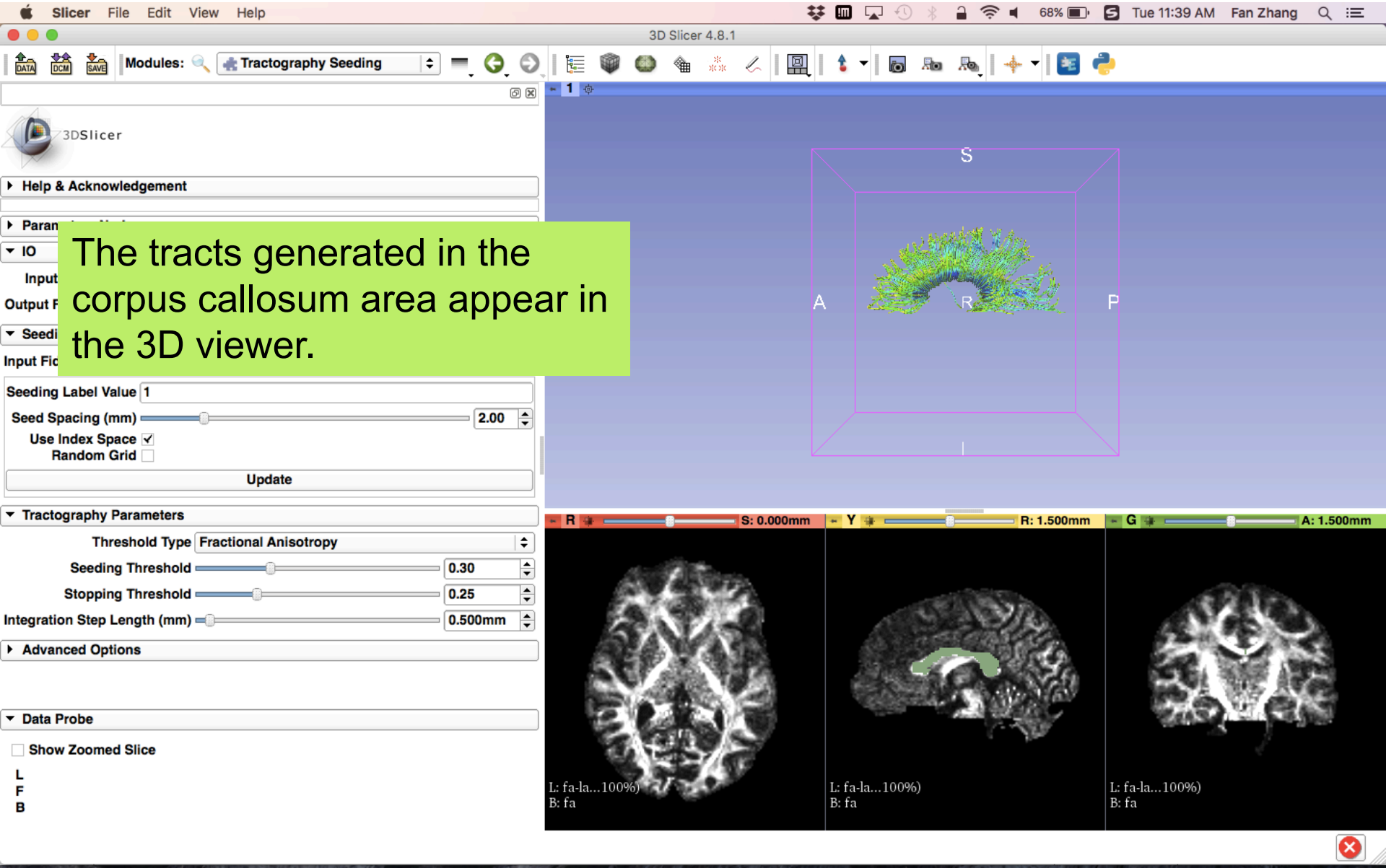


Select the default Tractography Seeding parameters:

- Threshold Type: FractionalAnistropy
- Seeding Threshold:0.30
- Stopping Threshold: 0.25

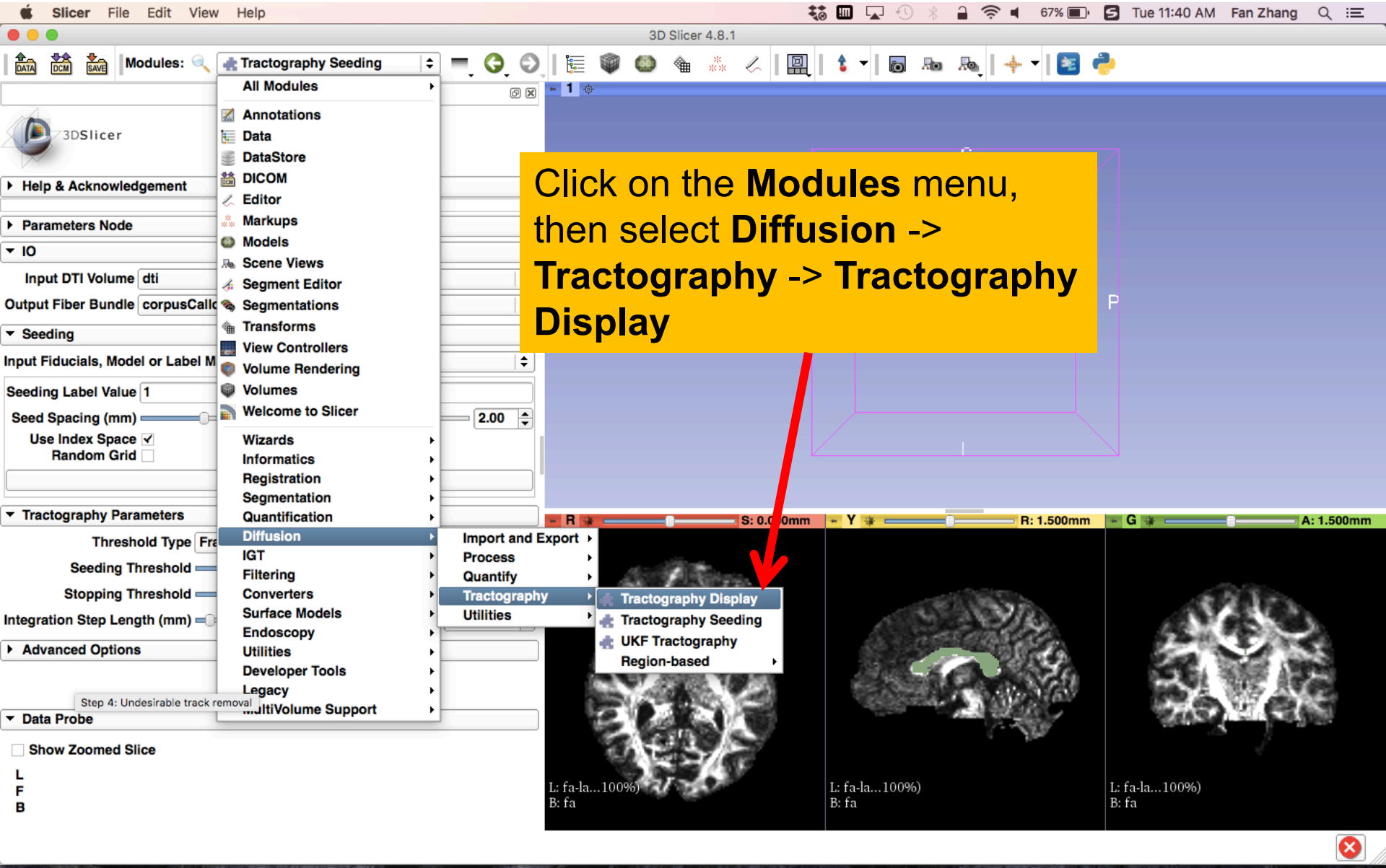
Click **Update** to generate tractography

Step 3: Generate Tracts

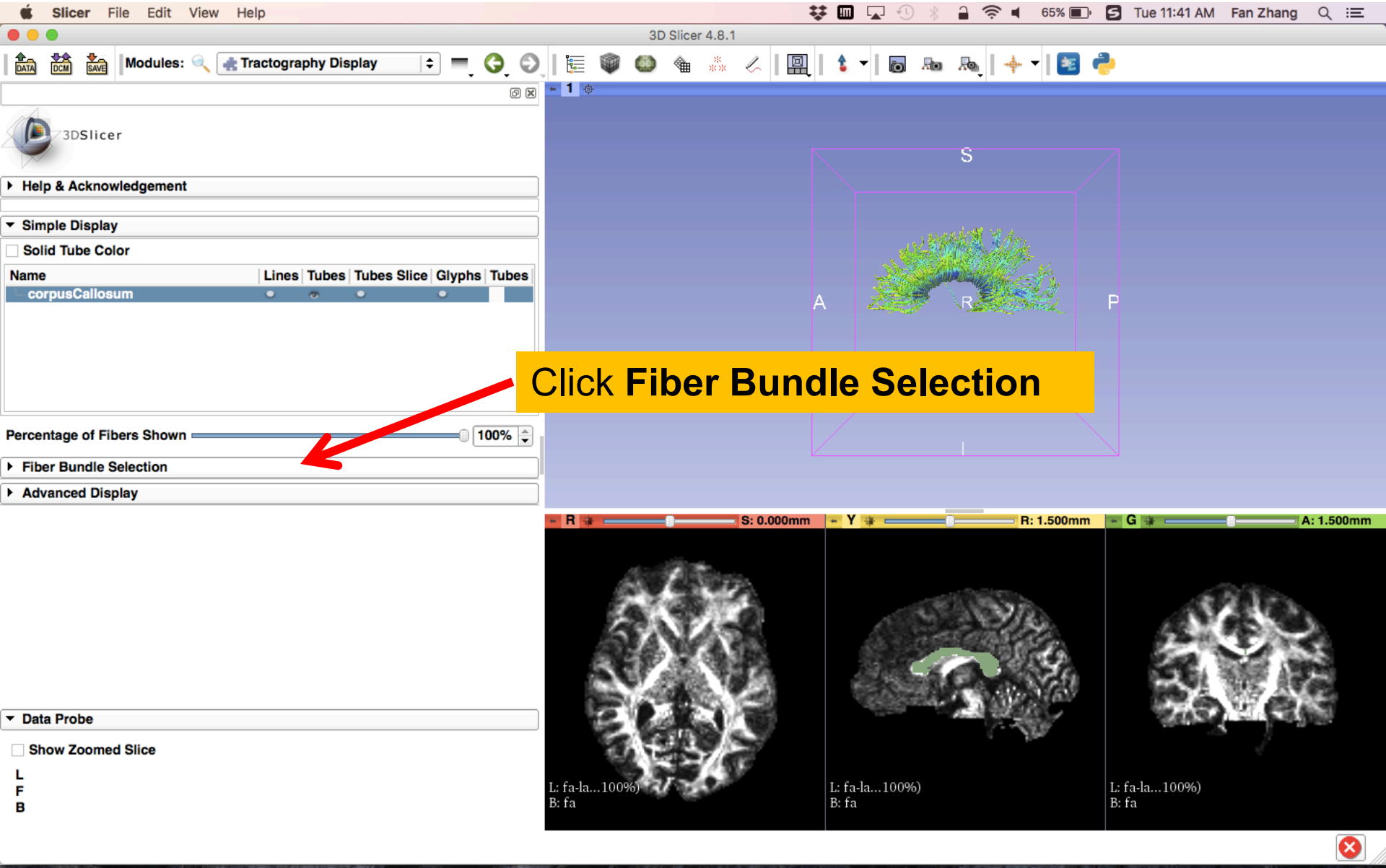


The tracts generated in the corpus callosum area appear in the 3D viewer.

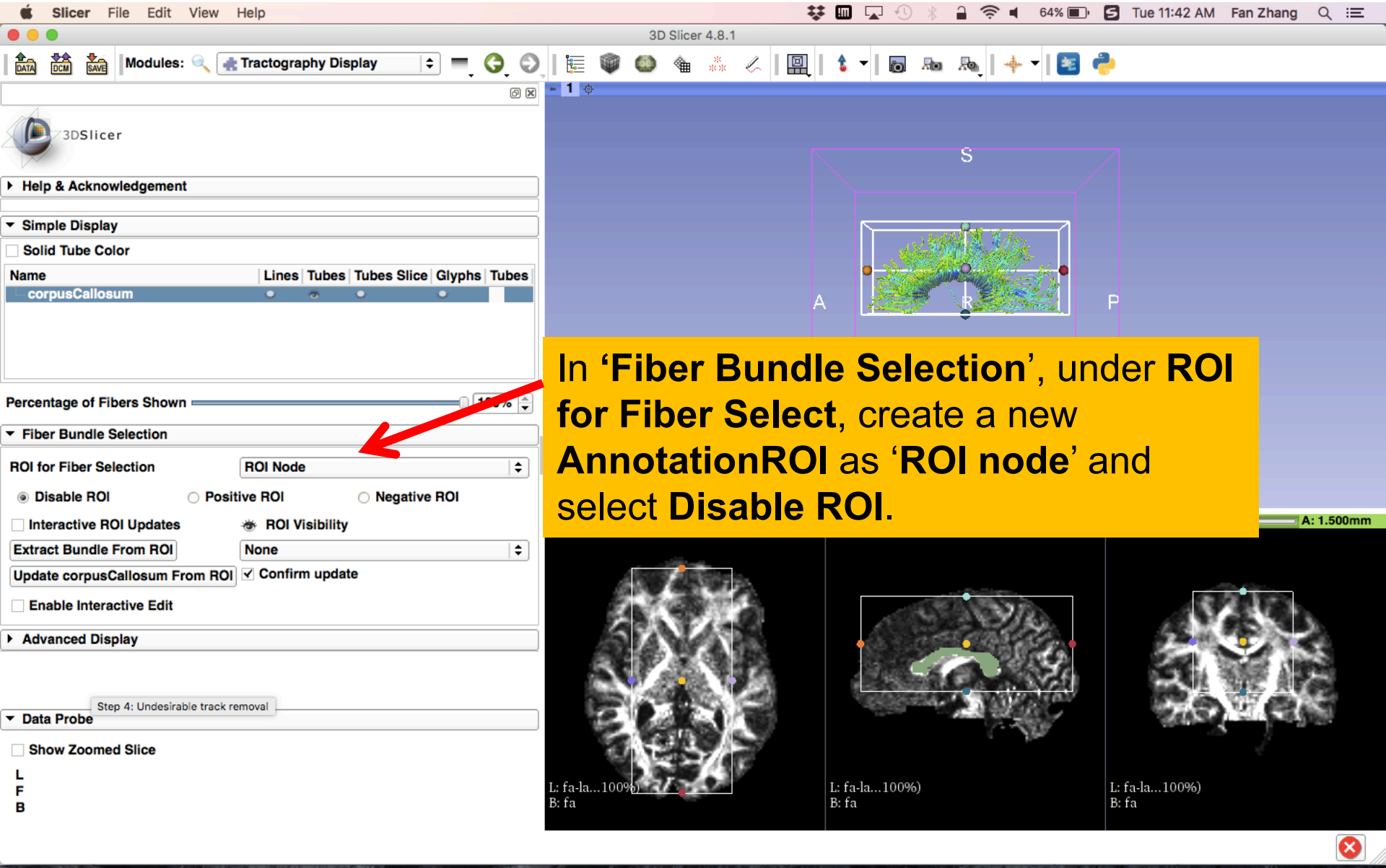
Step 4: Undesirable track removal



Step 4: Undesirable track removal

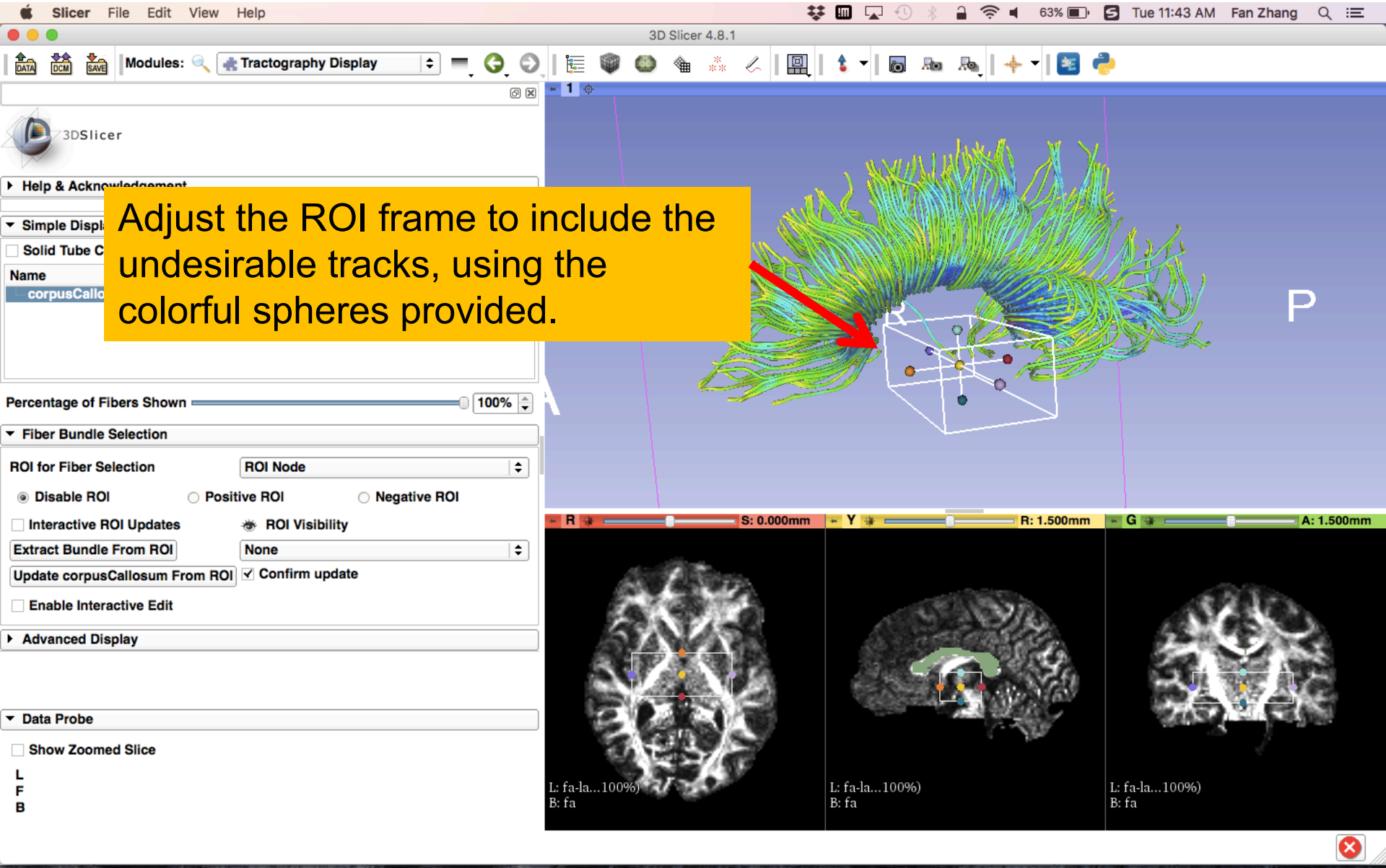


Step 4: Undesirable track removal

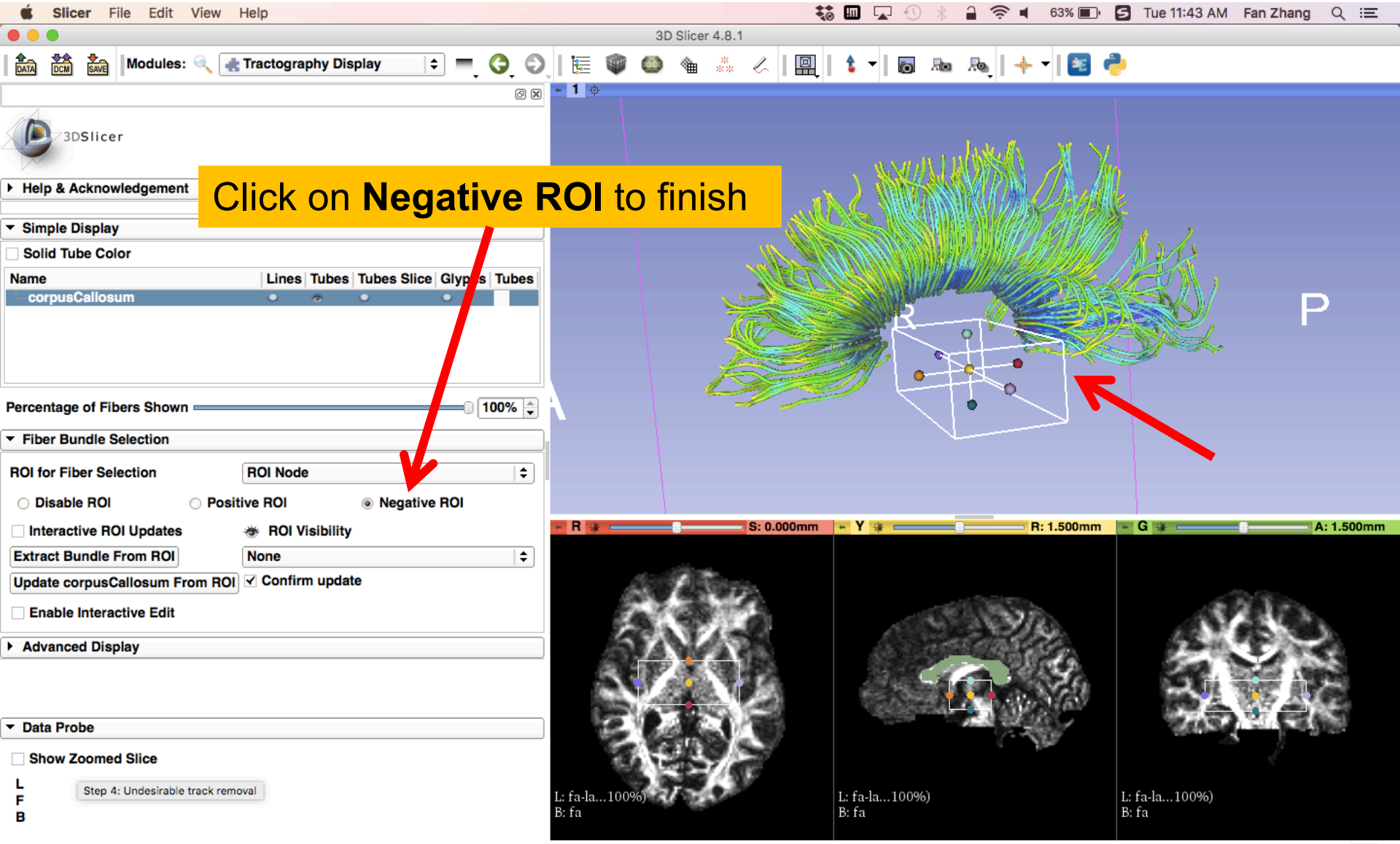


In **'Fiber Bundle Selection'**, under **ROI for Fiber Select**, create a new **AnnotationROI** as '**ROI node**' and select **Disable ROI**.

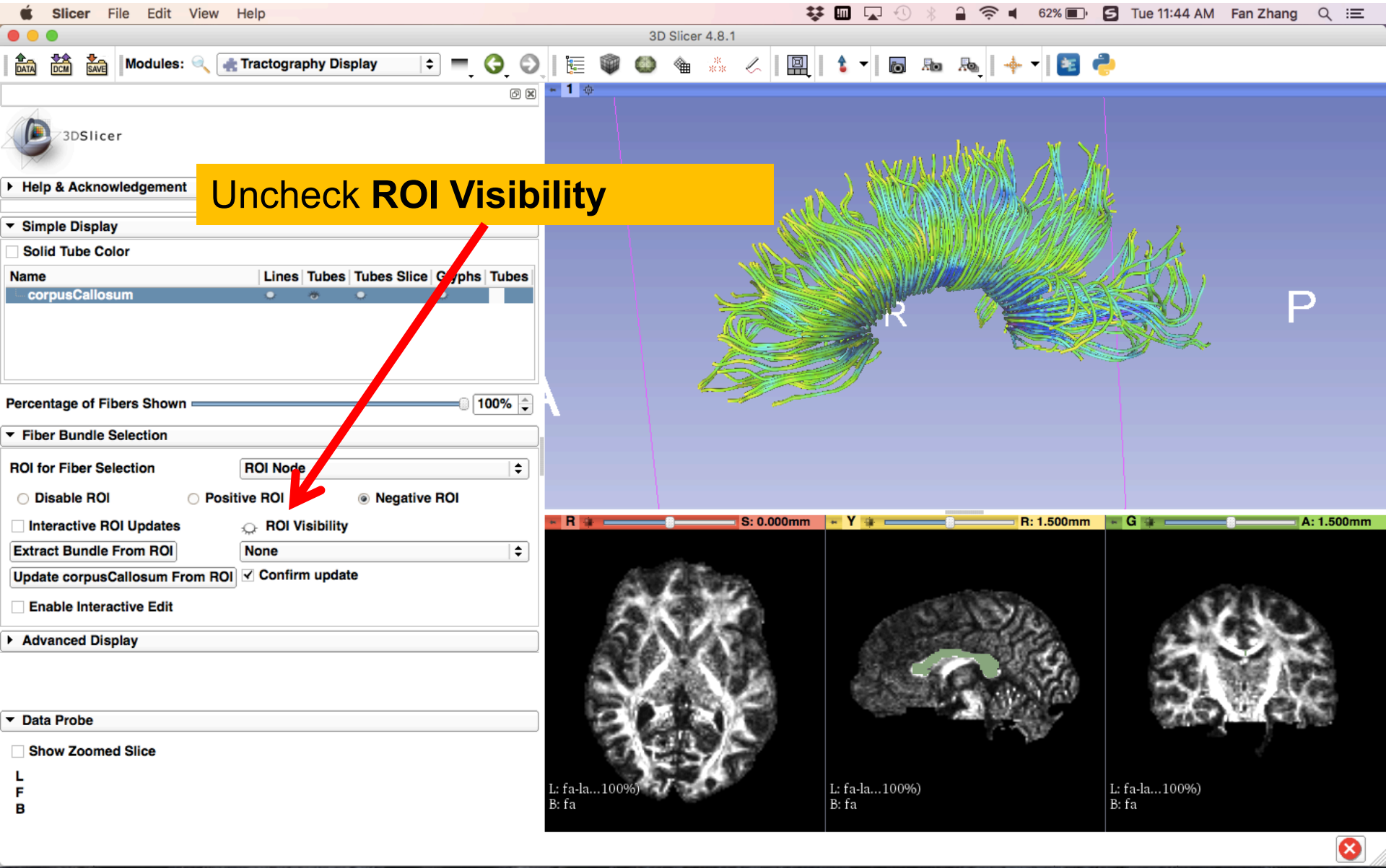
Step 4: Undesirable track removal



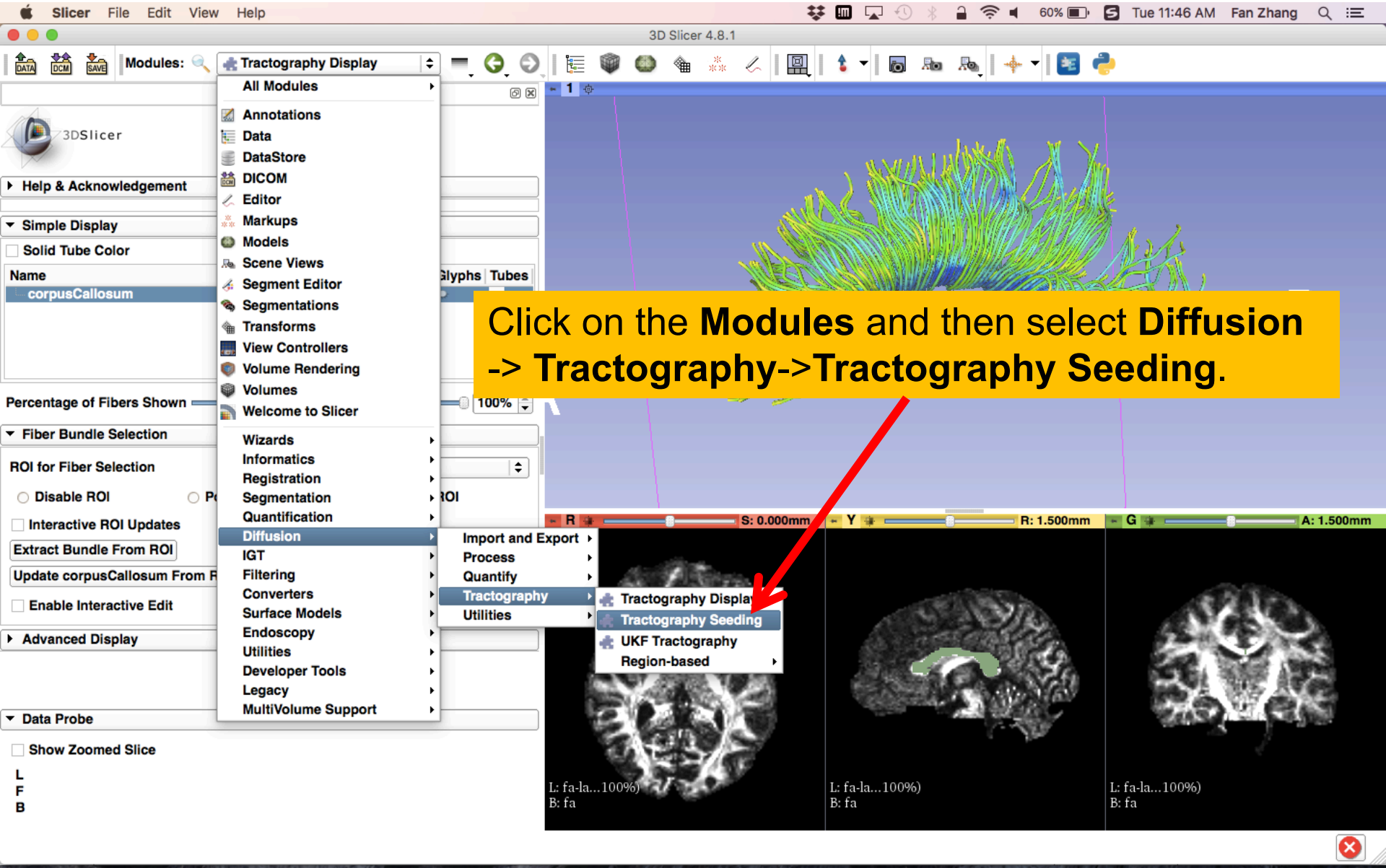
Step 4: Undesirable track removal



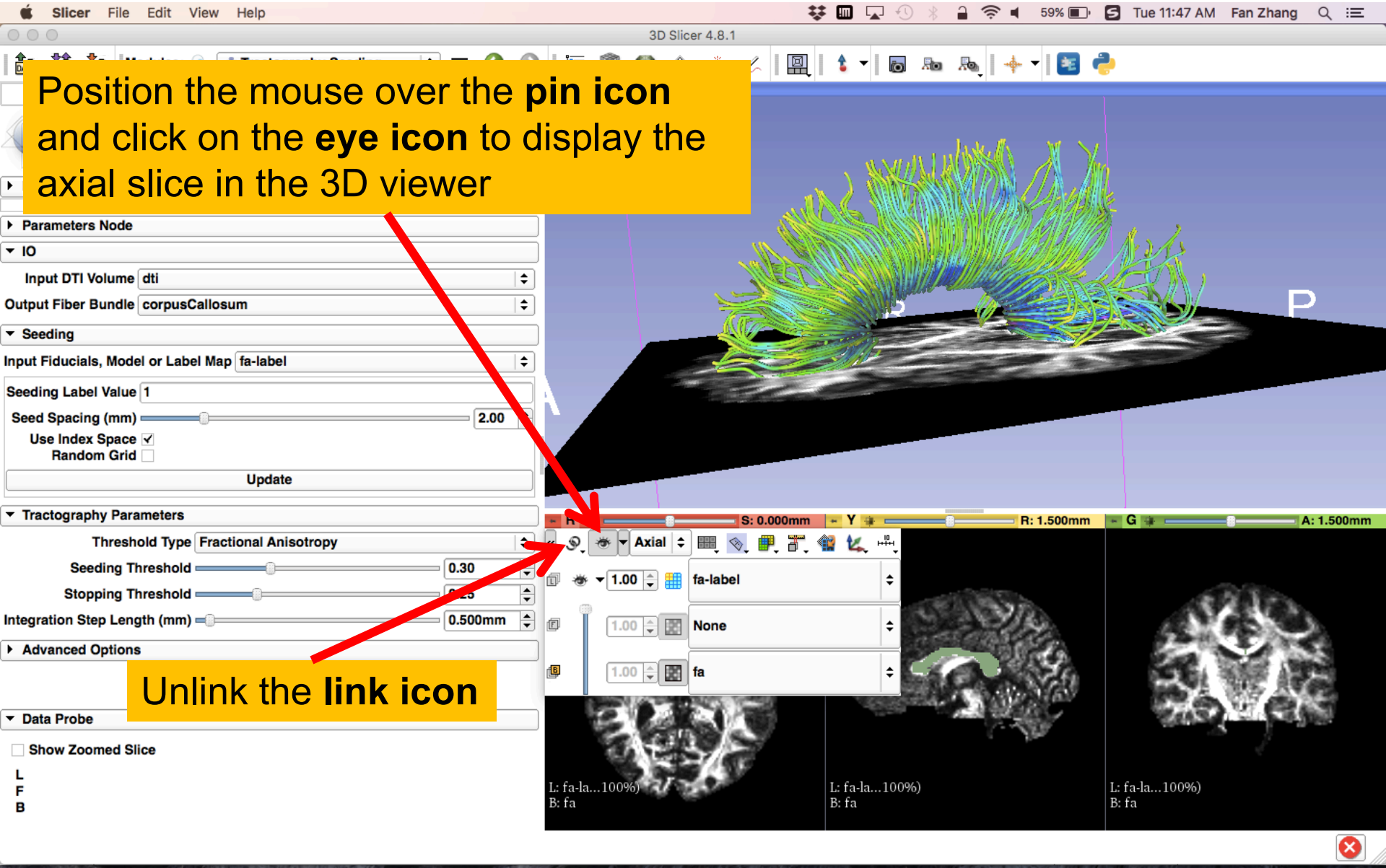
Step 4: Undesirable track removal



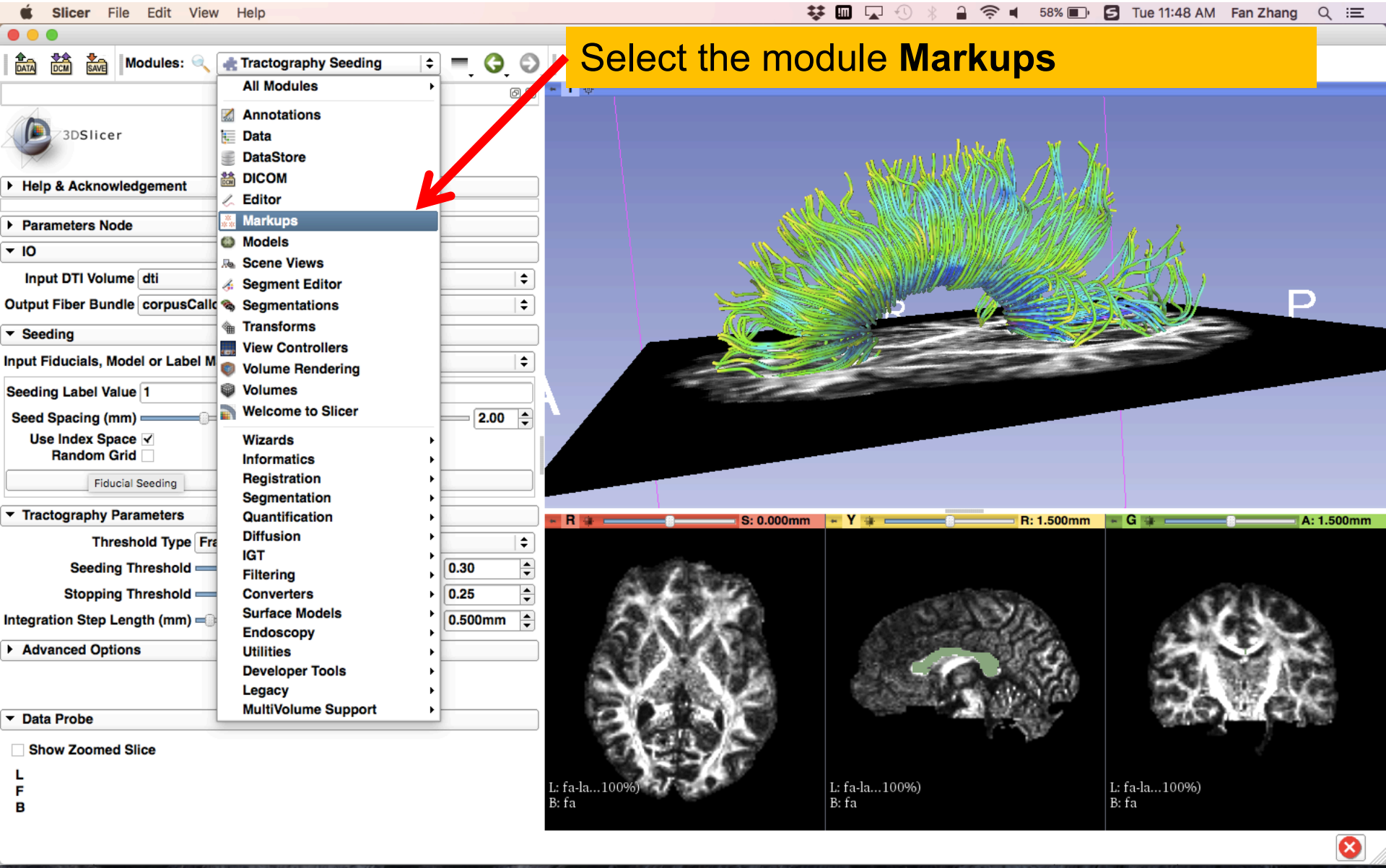
Fiducial Seeding



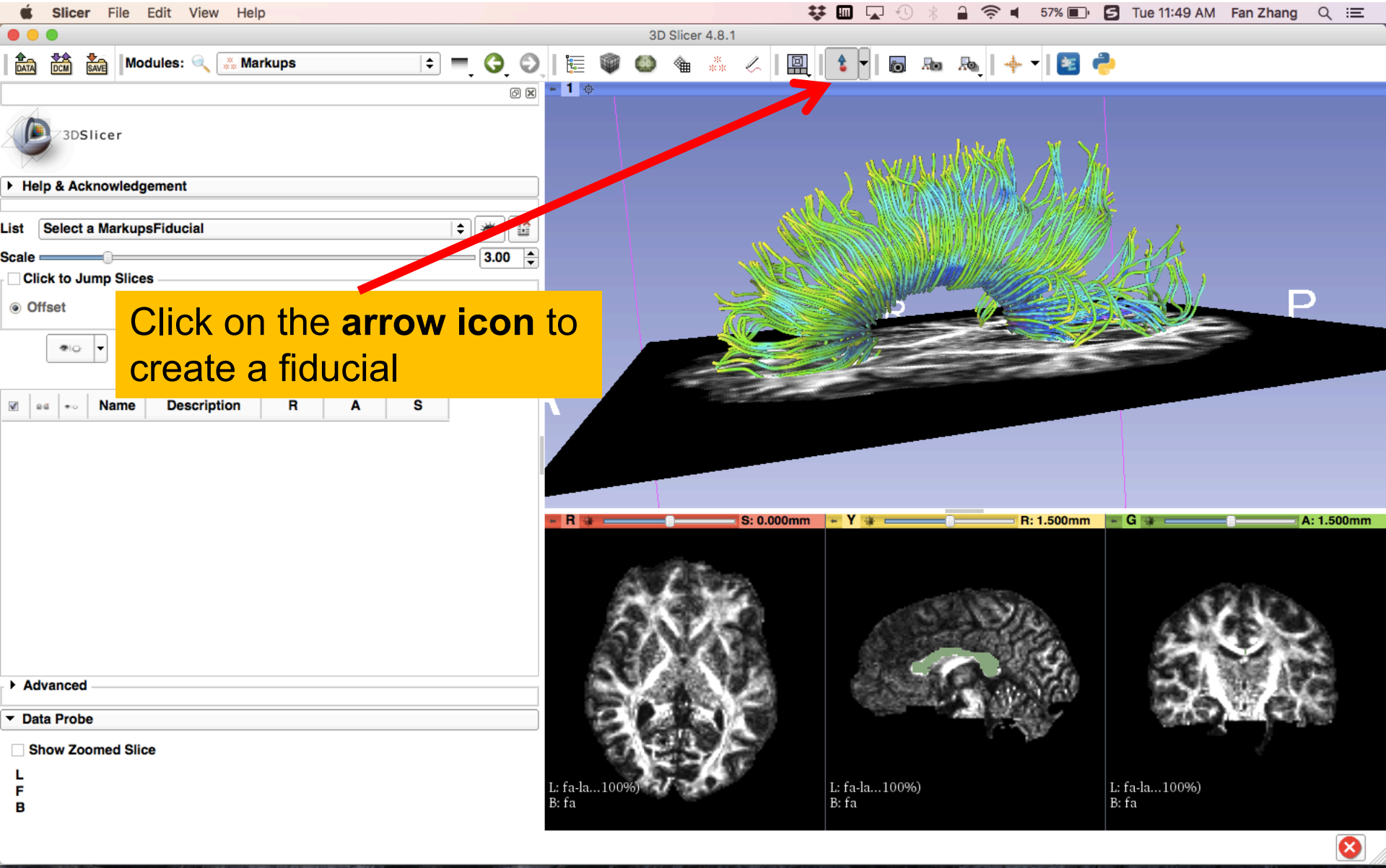
Fiducial Seeding



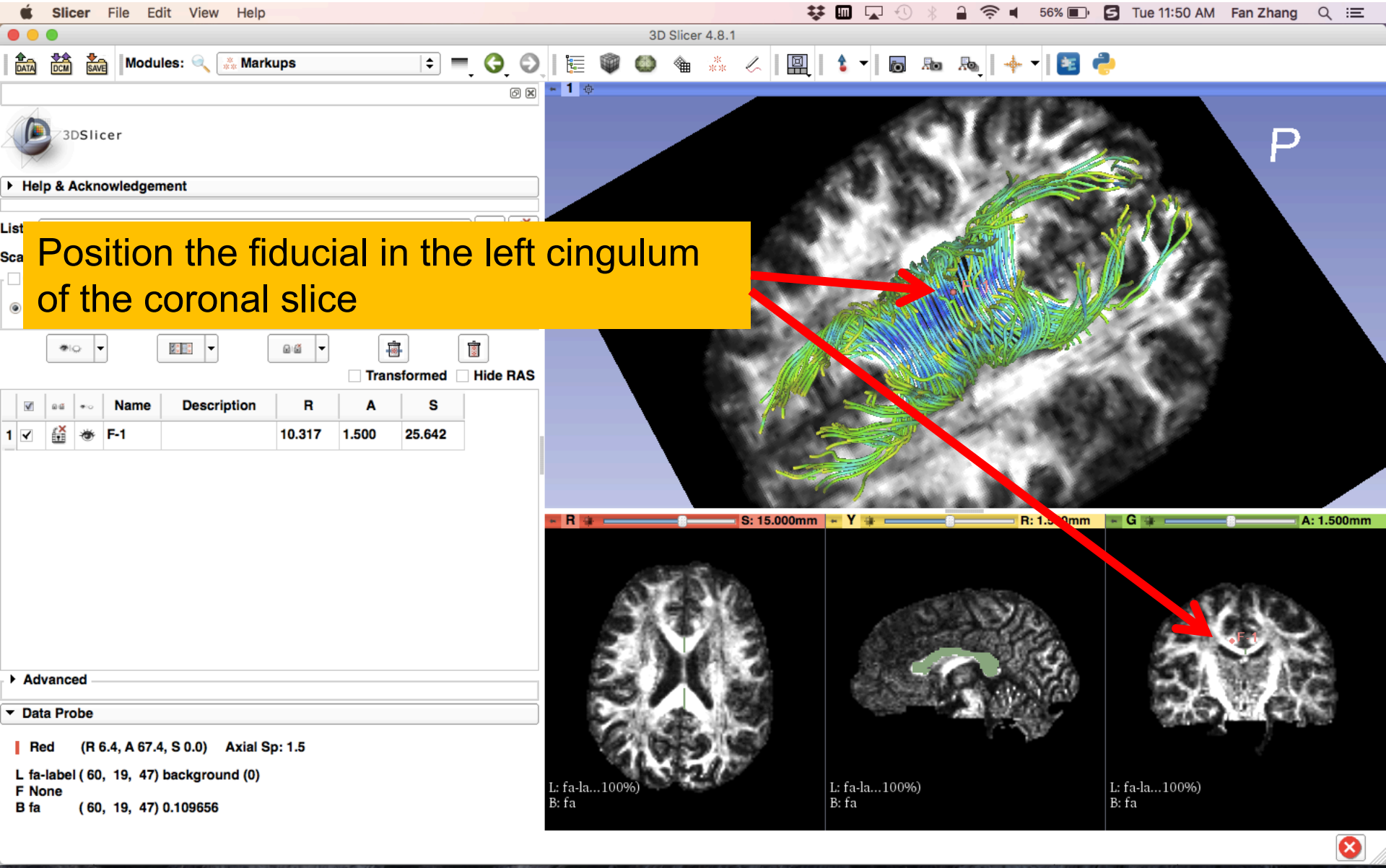
Fiducial Seeding



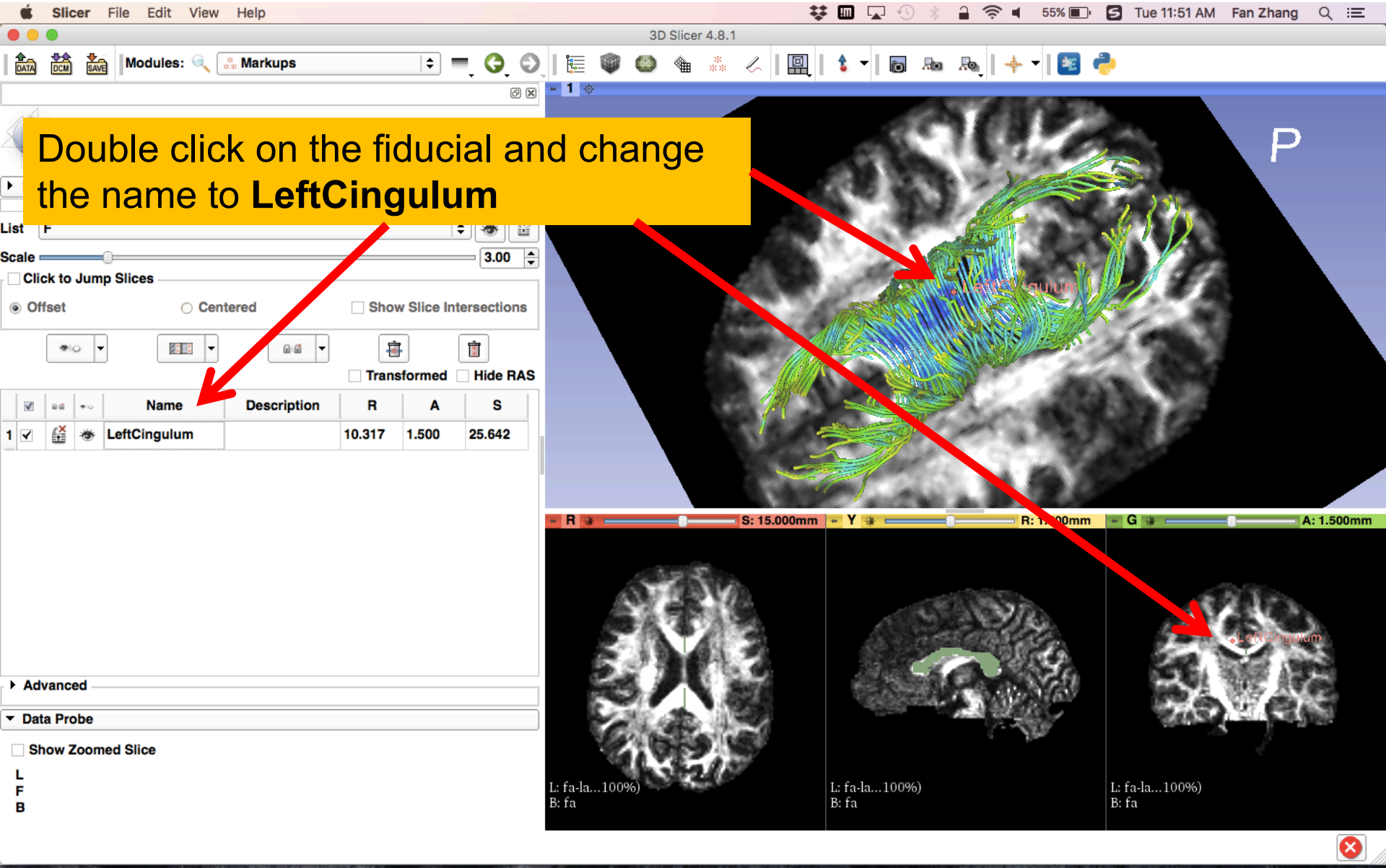
Fiducial Seeding



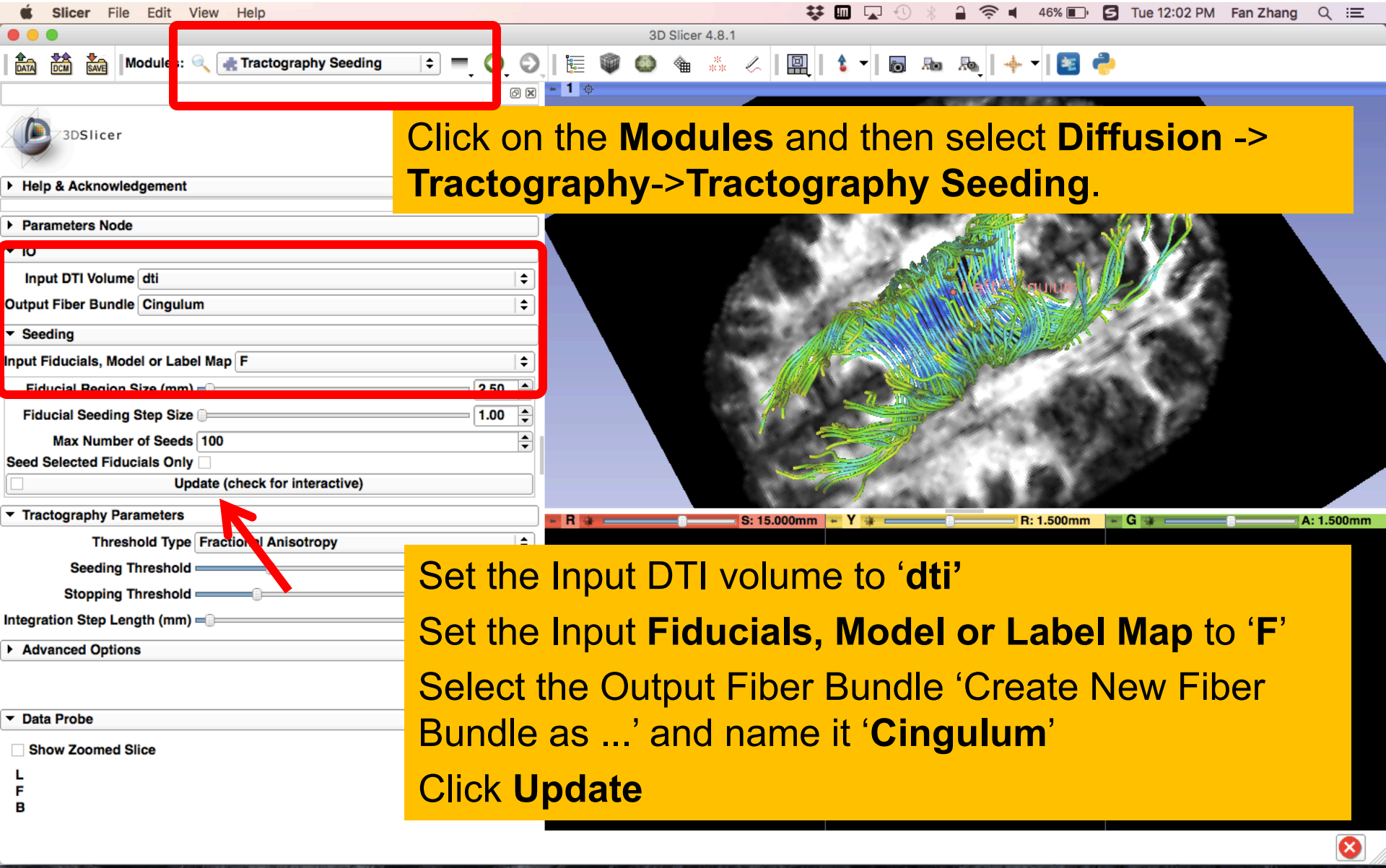
Fiducial Seeding



Fiducial Seeding



Fiducial Seeding



Click on the **Modules** and then select **Diffusion -> Tractography->Tractography Seeding**.

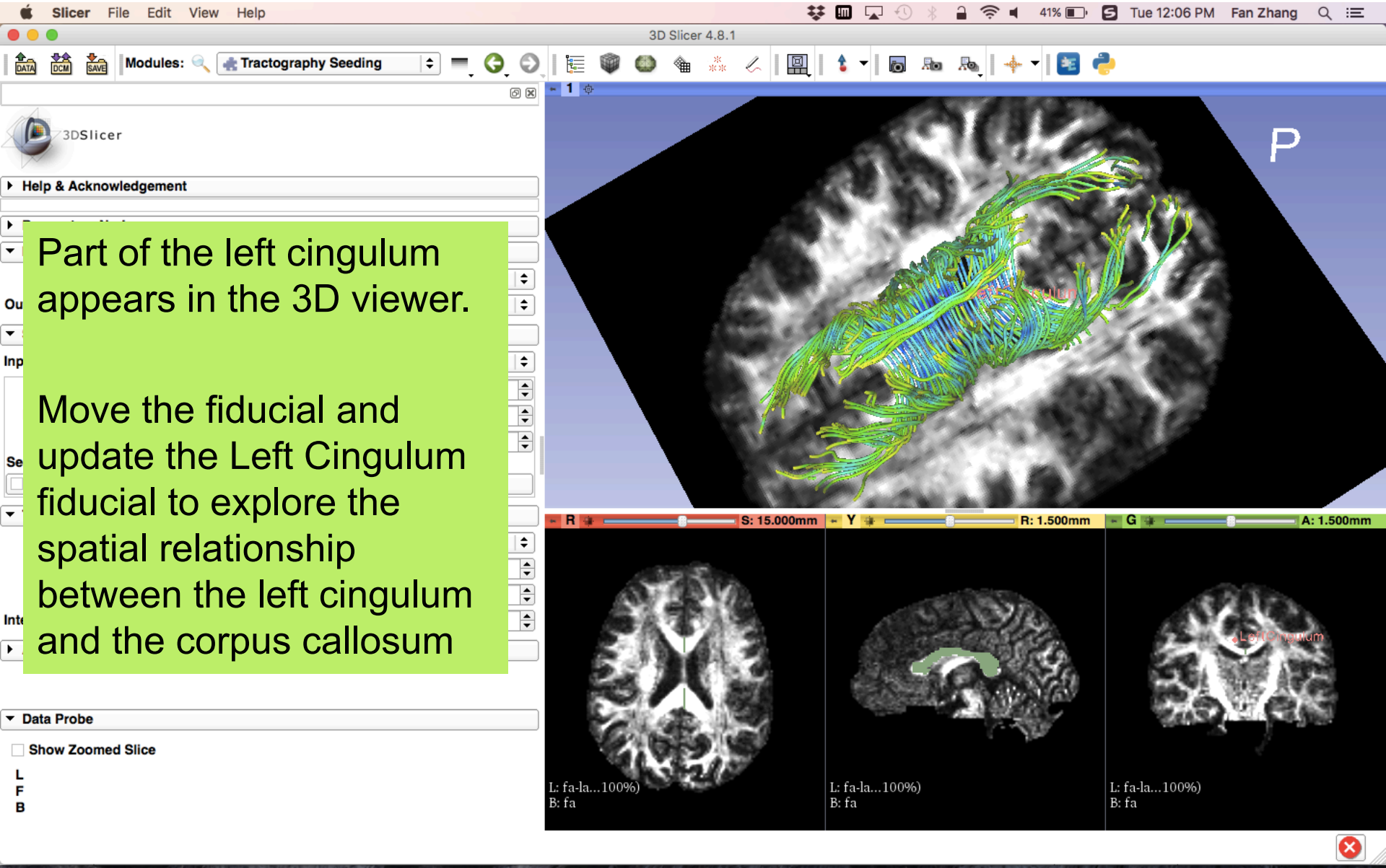
Set the Input DTI volume to '**dti**'

Set the Input **Fiducials, Model or Label Map** to '**F**'

Select the Output Fiber Bundle 'Create New Fiber Bundle as ...' and name it '**Cingulum**'

Click **Update**

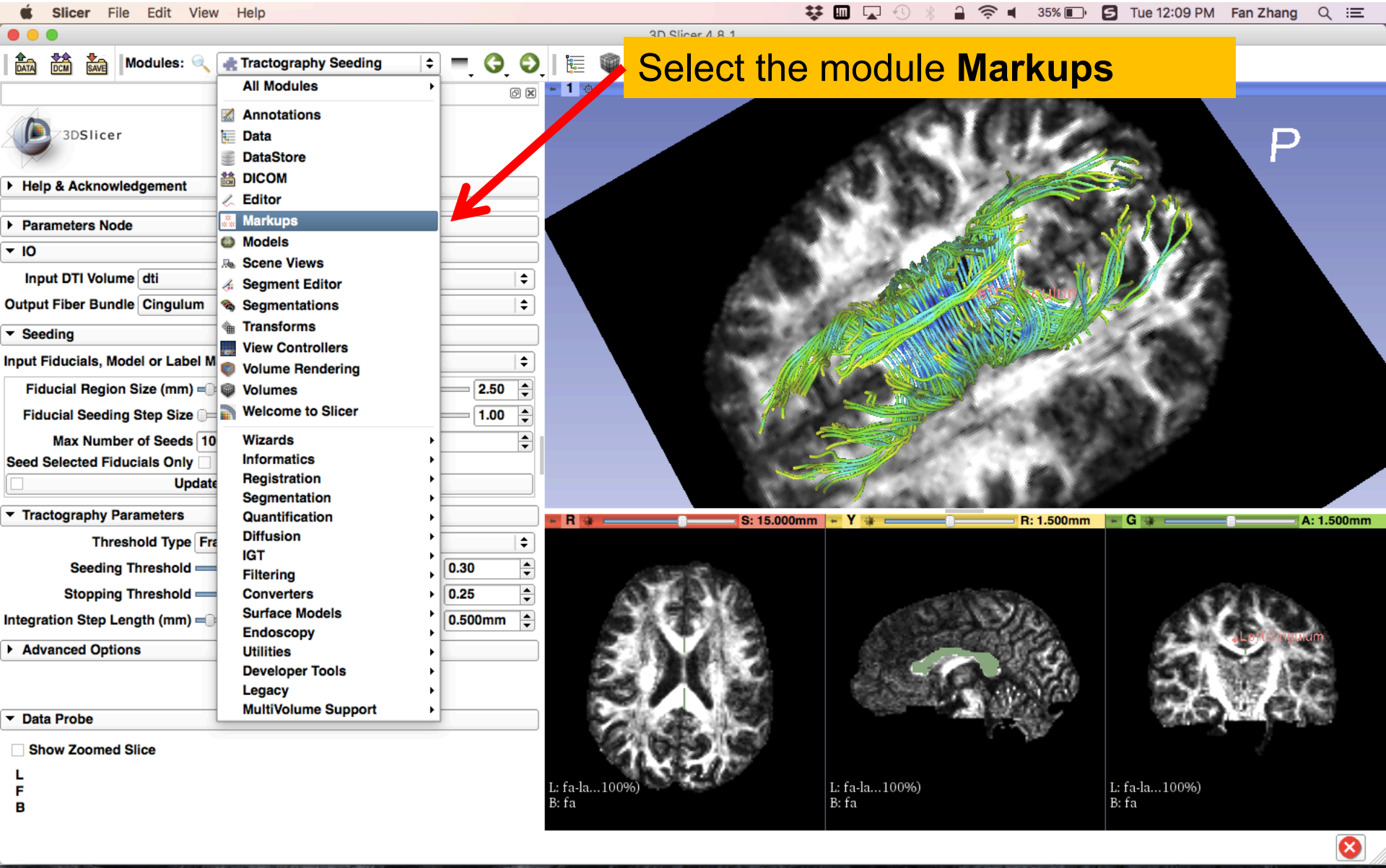
Fiducial Seeding



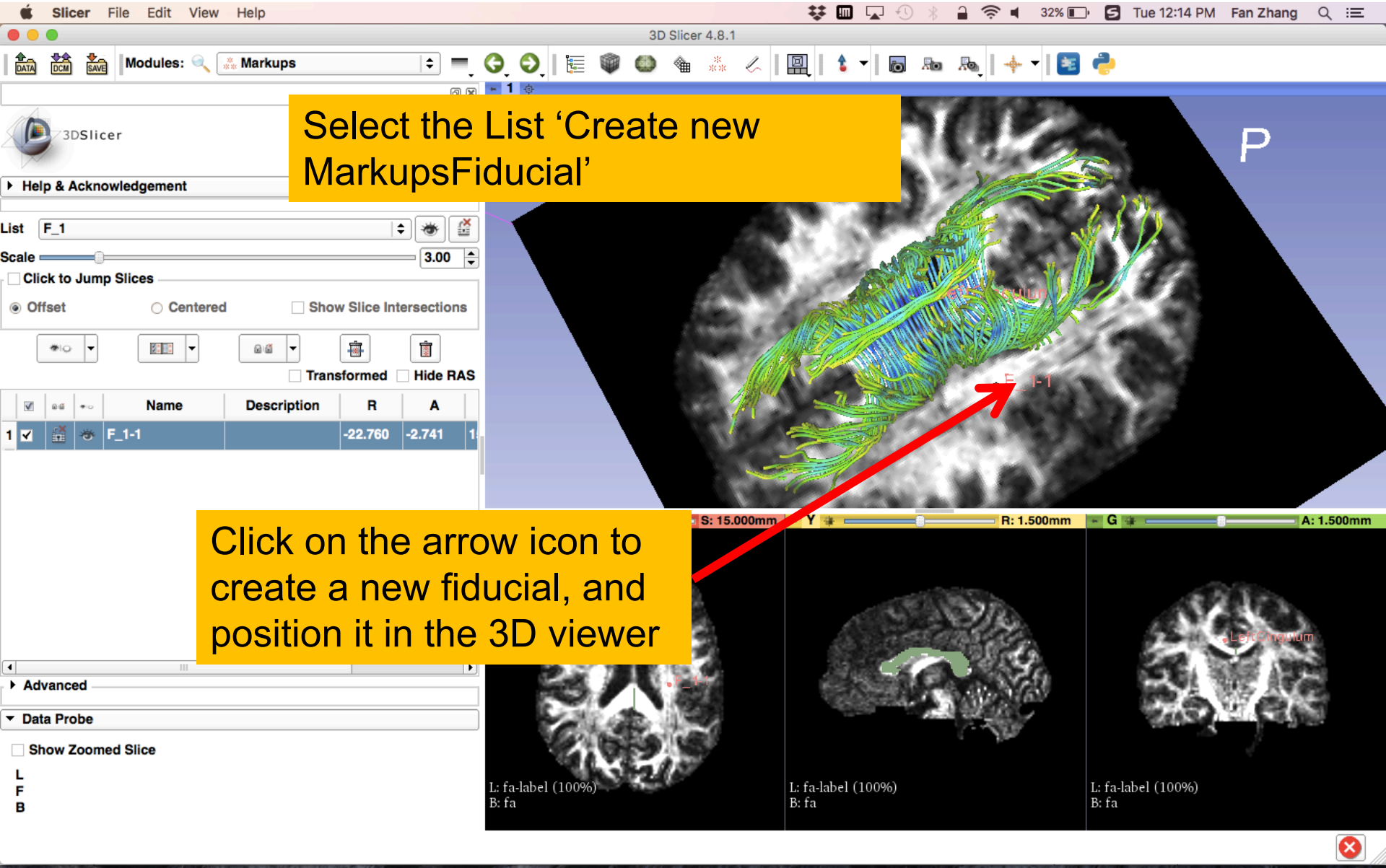
Part of the left cingulum appears in the 3D viewer.

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

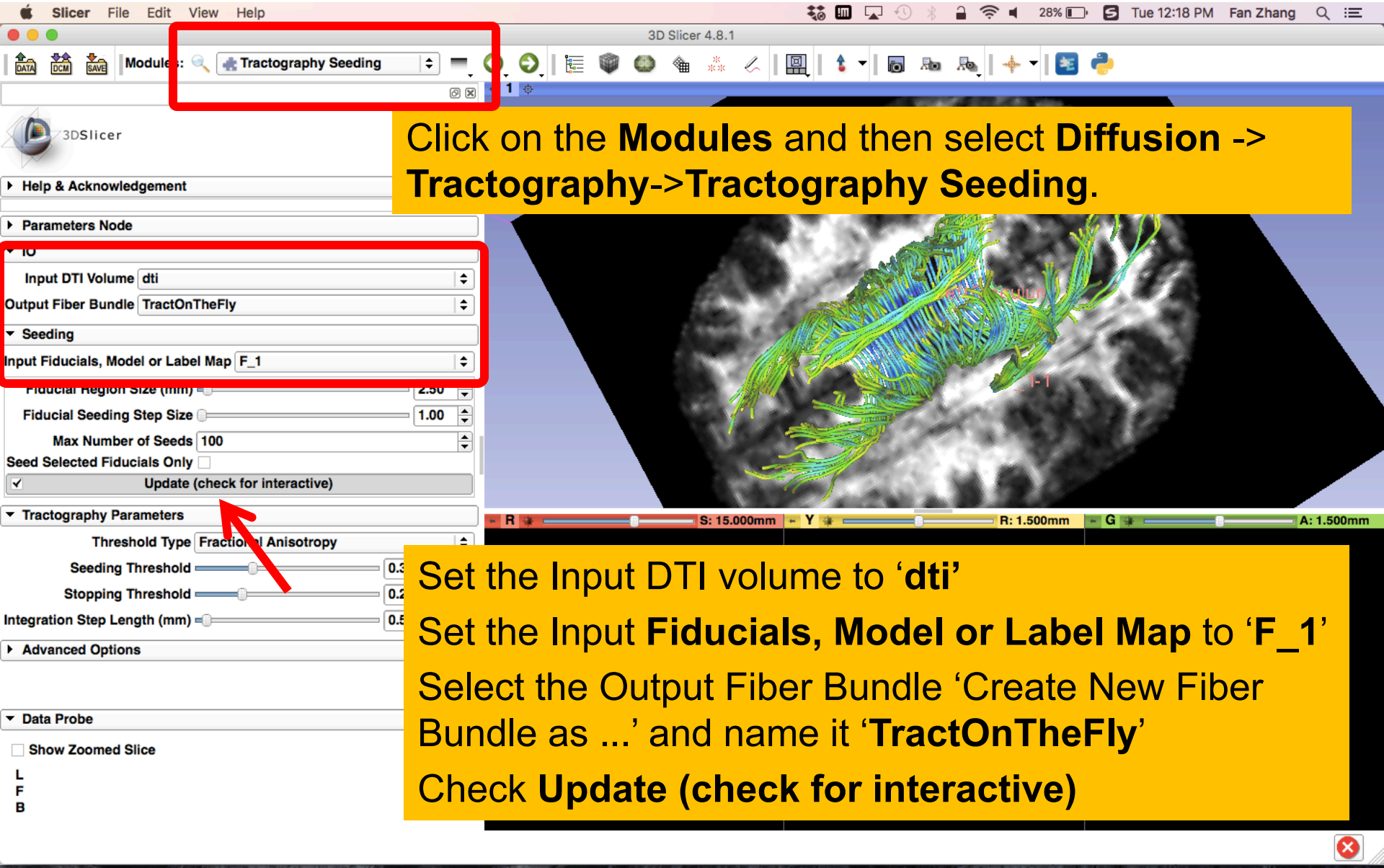
Tractography ‘on-the-fly’



Tractography ‘on-the-fly’



Tractography ‘on-the-fly’



Click on the **Modules** and then select **Diffusion -> Tractography->Tractography Seeding**.

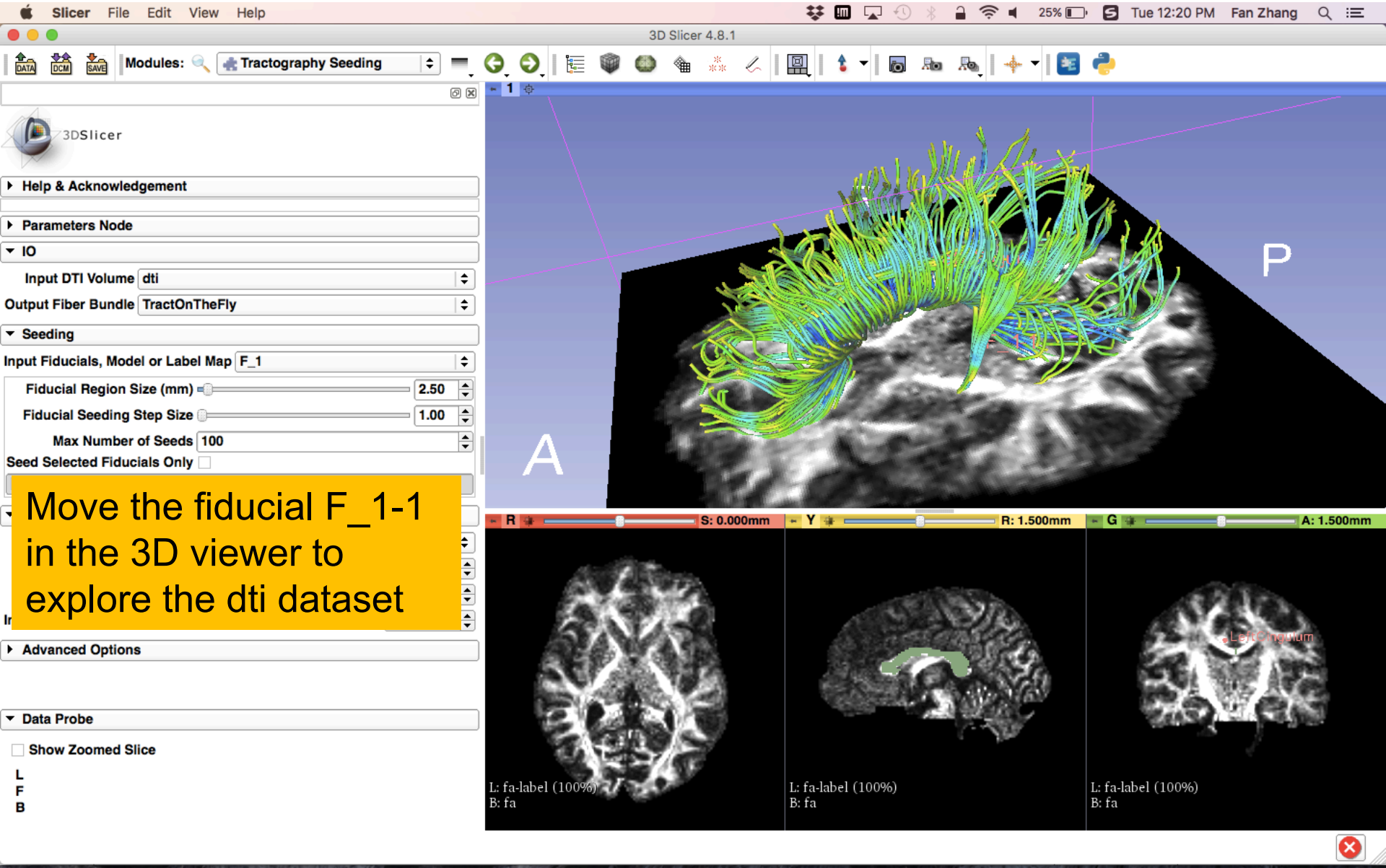
Set the Input DTI volume to ‘**dti**’

Set the Input **Fiducials, Model or Label Map** to ‘**F_1**’

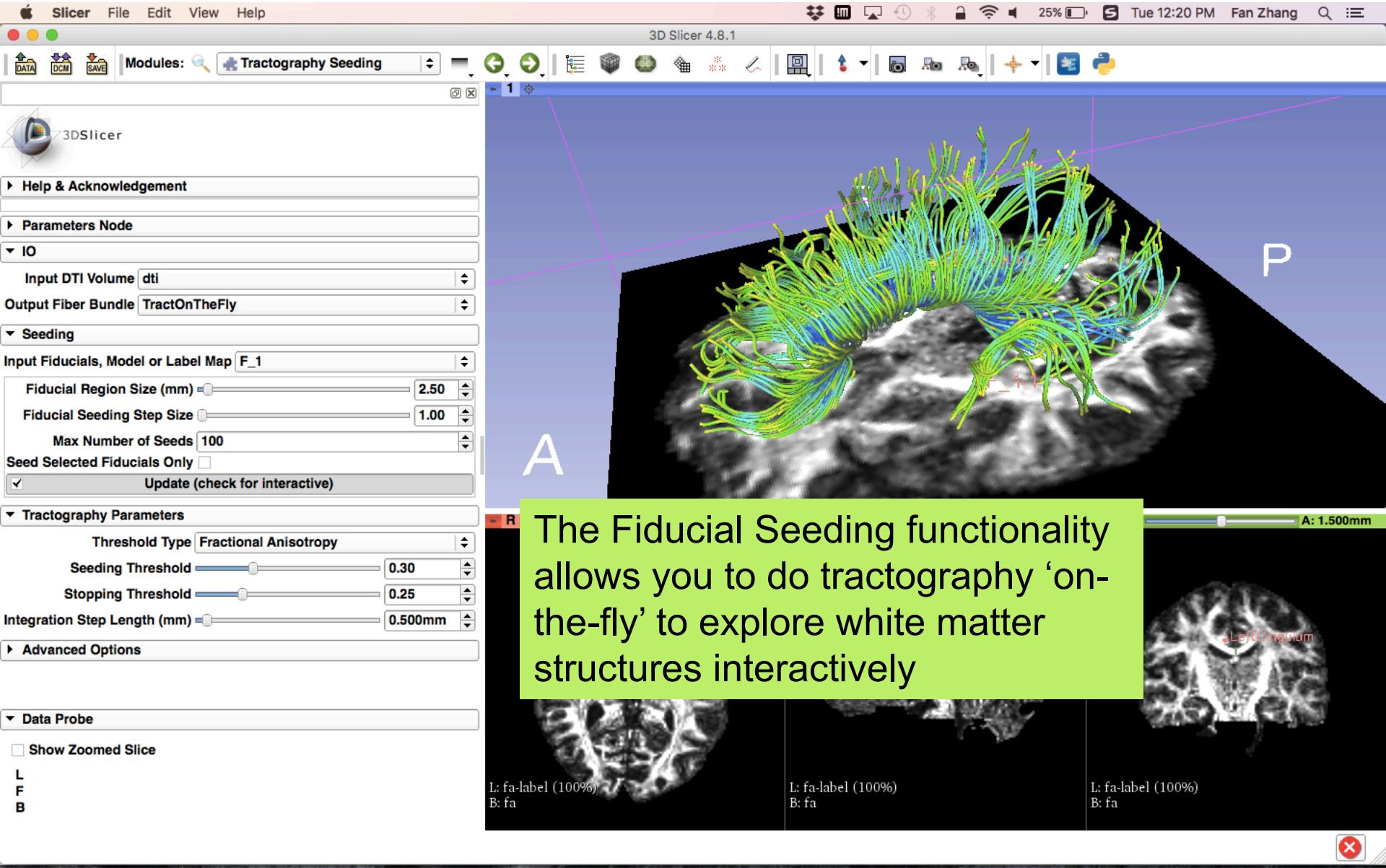
Select the Output Fiber Bundle ‘Create New Fiber Bundle as ...’ and name it ‘**TractOnTheFly**’

Check **Update (check for interactive)**

Tractography ‘on-the-fly’

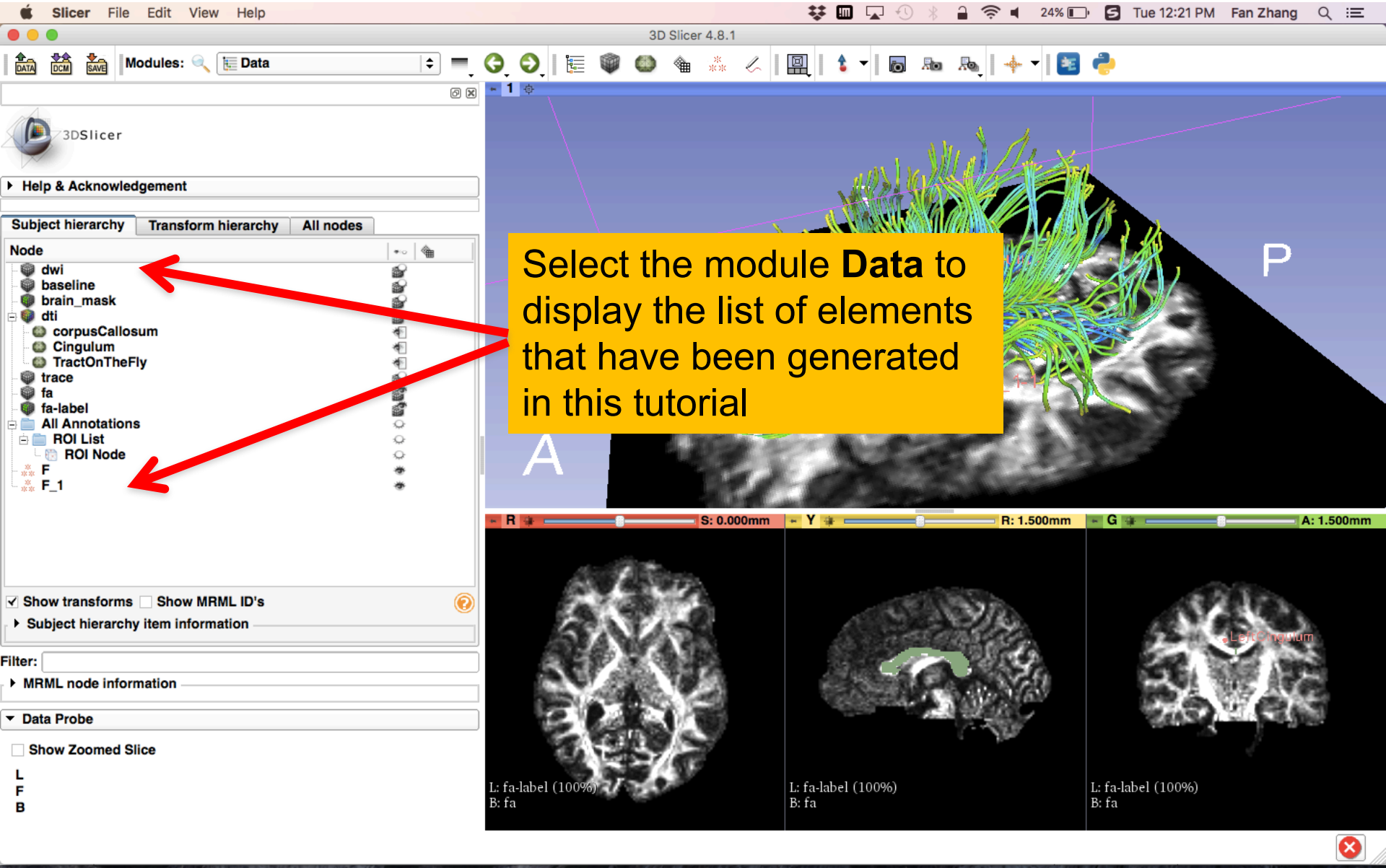


Tractography ‘on-the-fly’

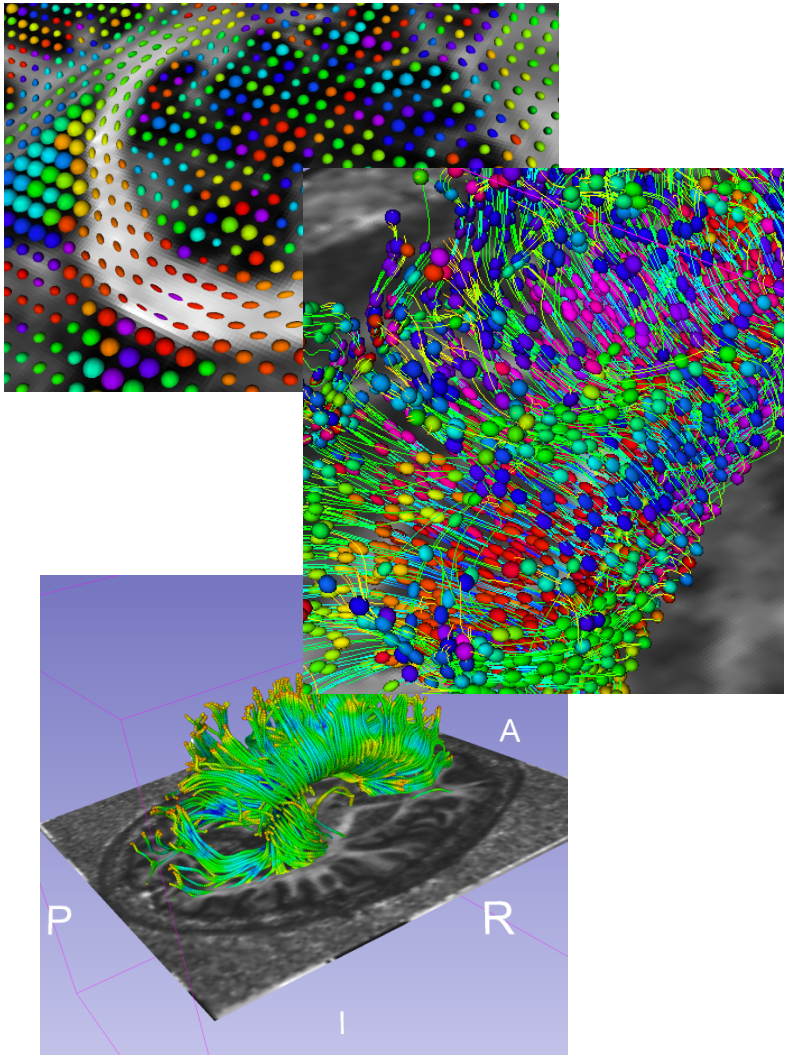


The Fiducial Seeding functionality allows you to do tractography ‘on-the-fly’ to explore white matter structures interactively

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.

Acknowledgments

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