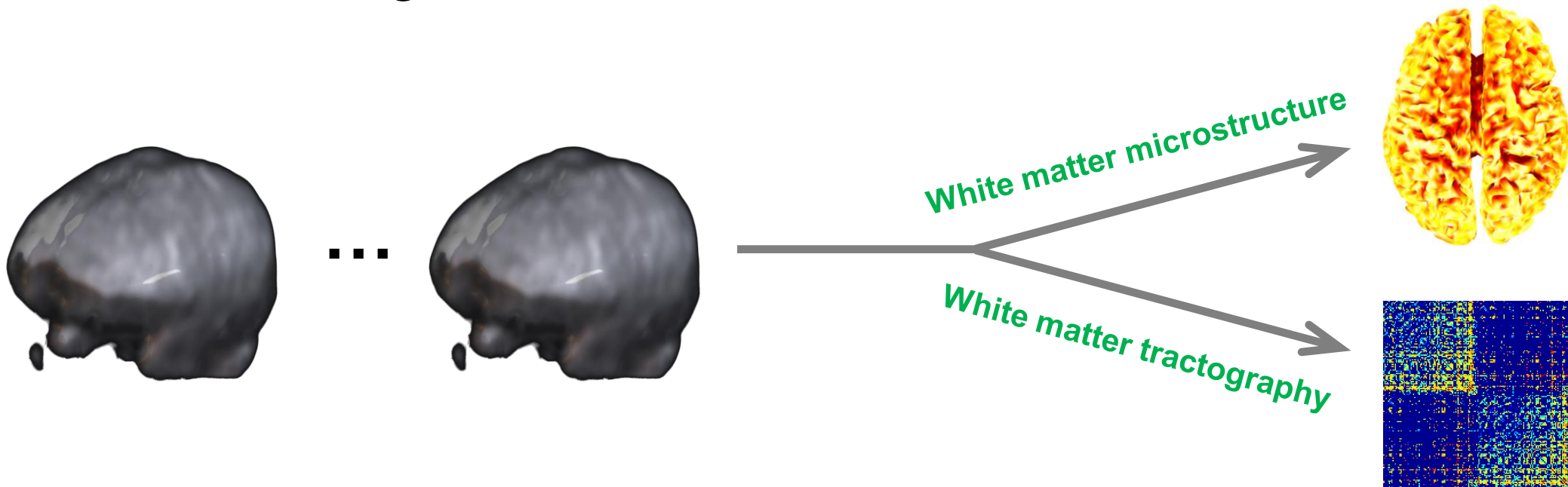


## Diffusion-weighted MRI (2): Data Processing

확산가중 자기공명영상 (2):  
데이터 처리 방법

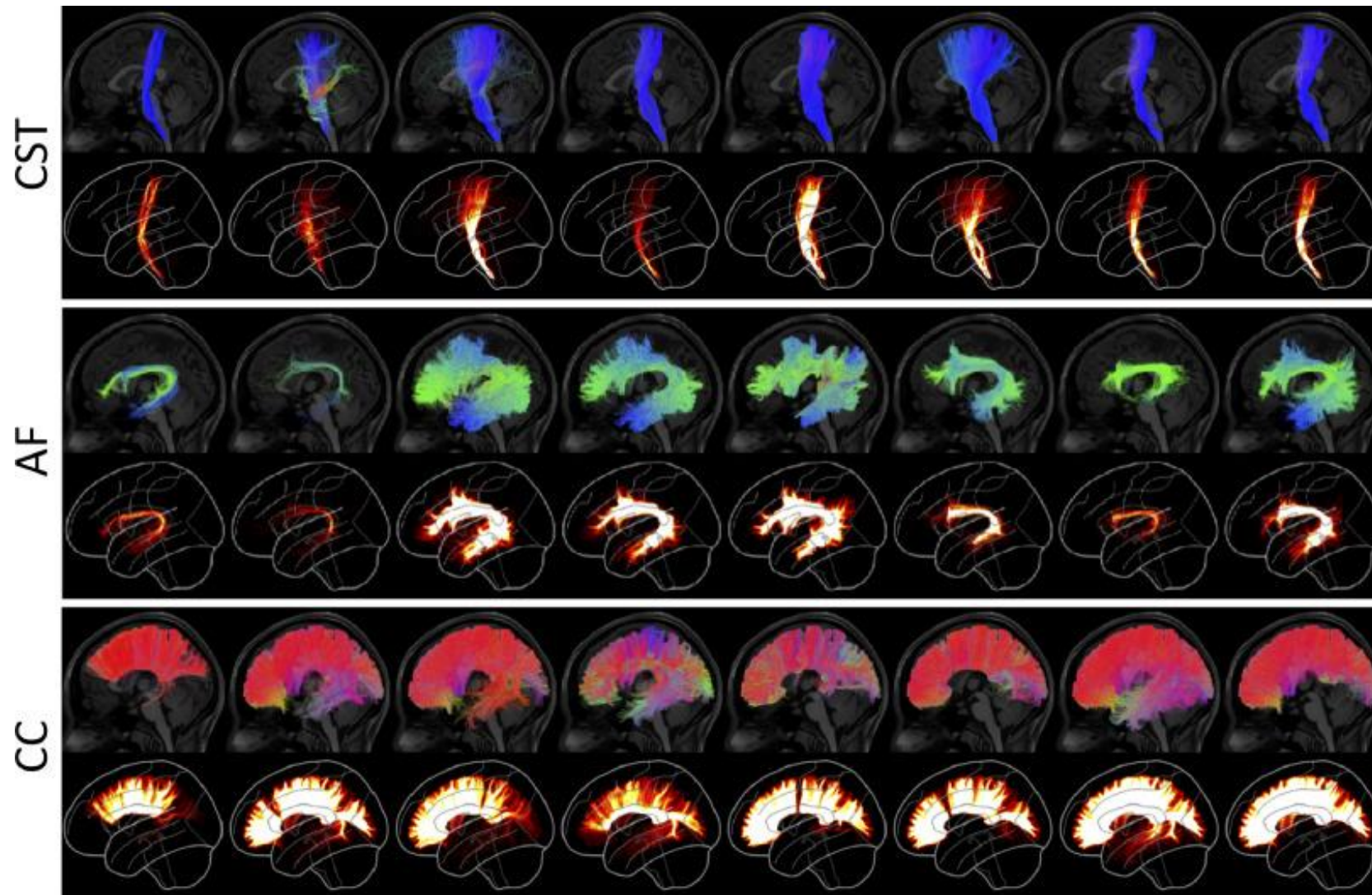
# Brain Mapping with Diffusion-weighted MRI (dMRI)

- Diffusion-weighted MRI



# Analytical Variability in dMRI

- Variability of white matter tractography [\[Schilling et al., 2021\]](#)
  - Resulted from different protocols for white matter fibre bundle segmentation

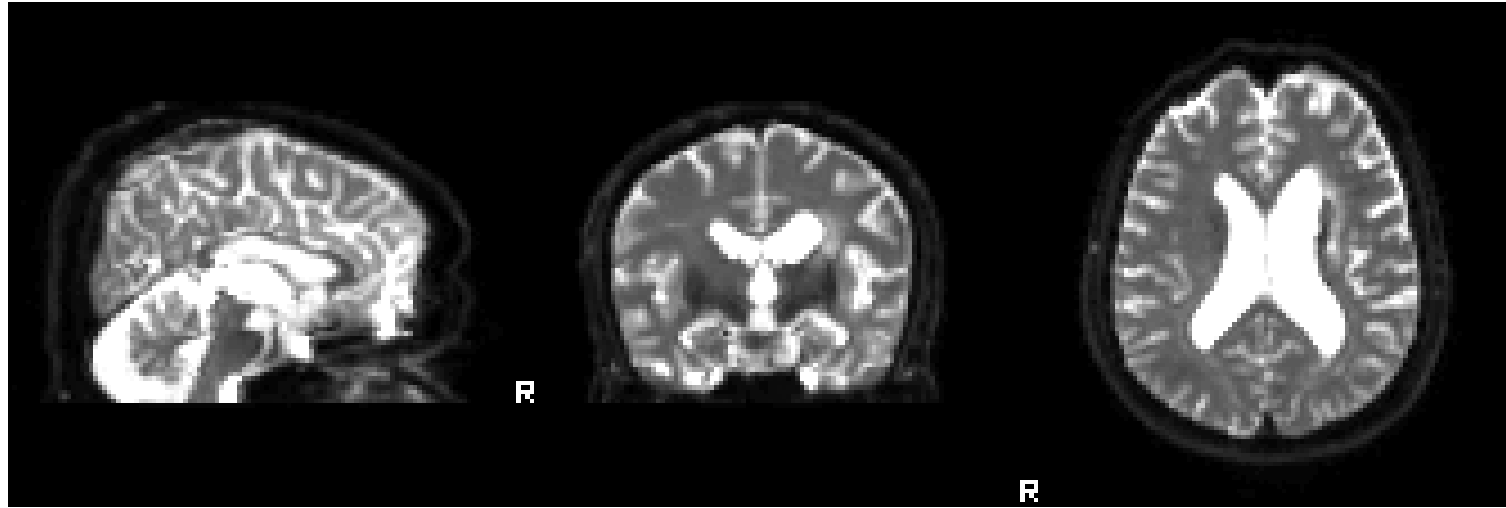


**Variation in protocols for white matter fibre bundle segmentation**

# Preprocessing

- Numerous steps to clean dMRI data before diffusion modelling
  - Correction for unwanted variation
    - Head motion
    - Eddy current-induced distortion
    - Inhomogeneity-induced distortion

# [dMRI: Preprocessing]

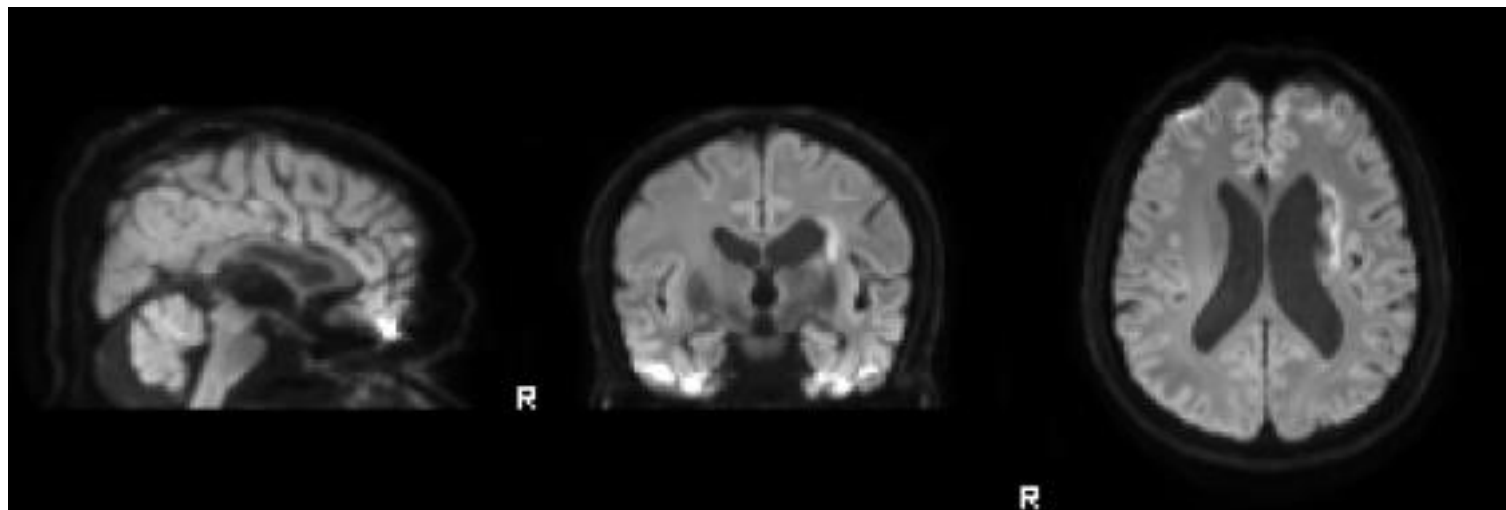


- 46 scans
  - 1 scan without diffusion weighting
  - 45 scans with diffusion weighting at  $b = 1000 \text{ s/mm}^2$

Average image for  $b = 0 \text{ s/mm}^2$



Average image for  $b = 1,000 \text{ s/mm}^2$



–  $b$ -values

0    1000    1000    1000    1000    1000    1000    ...    1000

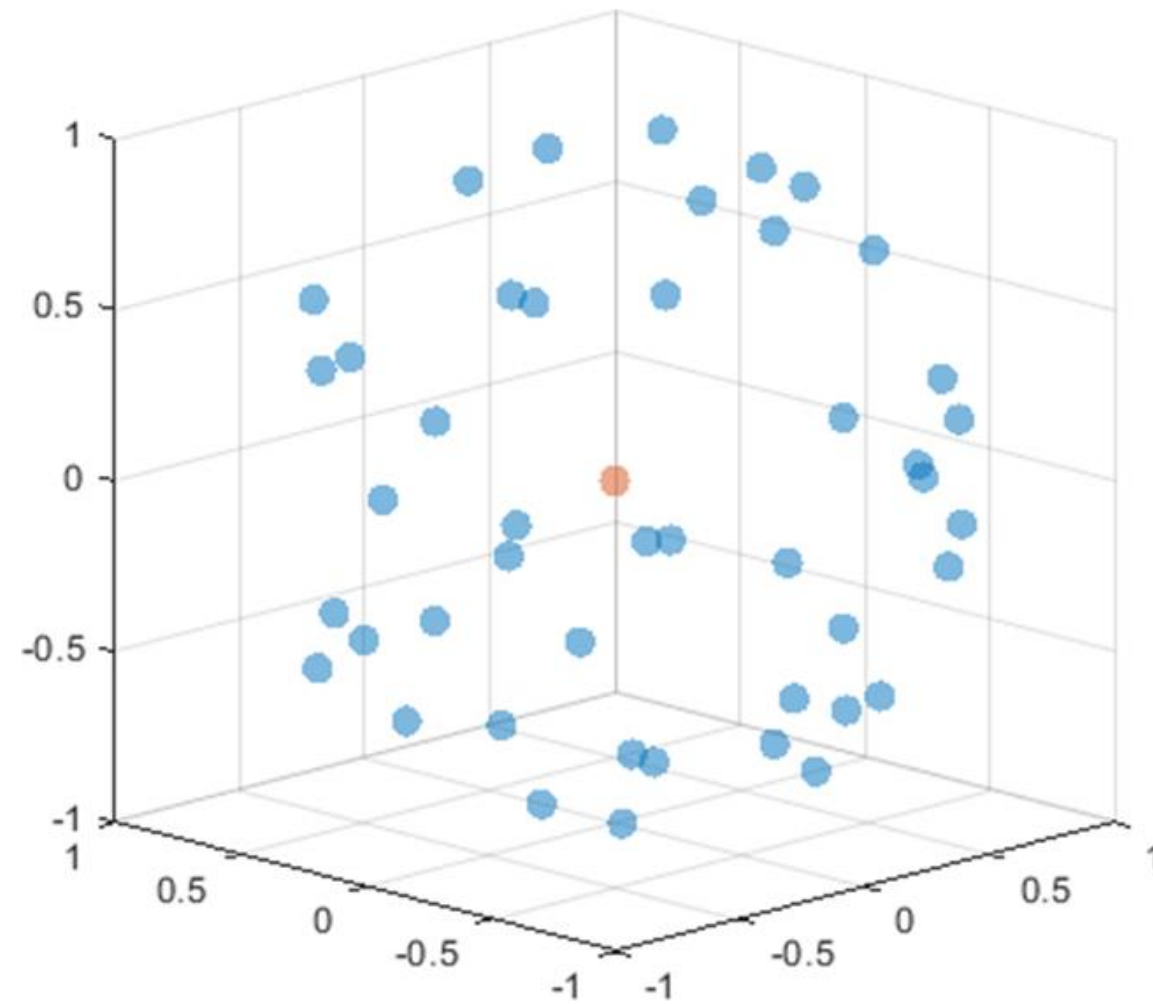
46 values

–  $b$ -vectors

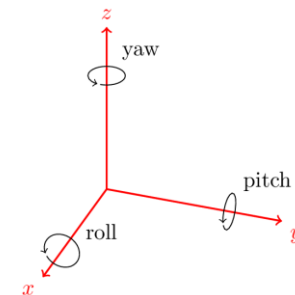
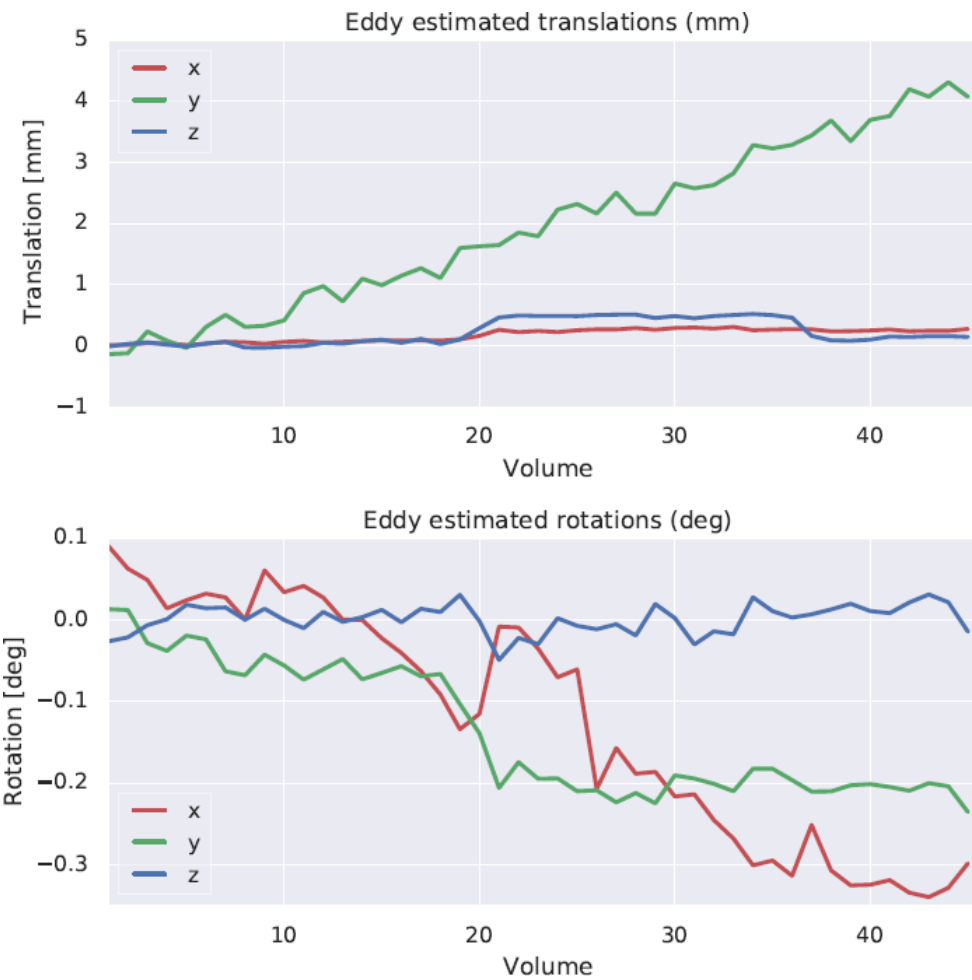
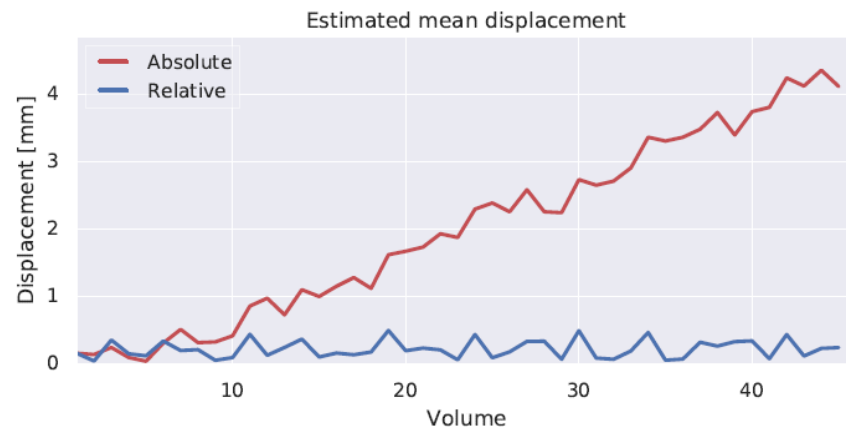
0	0.2488	-0.4396	0.6565	-0.3743	0.2818	...	0.4357
0	0.9672	0.7676	-0.0606	-0.5783	0.0936	...	0.8473
0	-0.0588	0.4671	-0.7513	0.7245	0.9545	...	0.3021

46 vectors

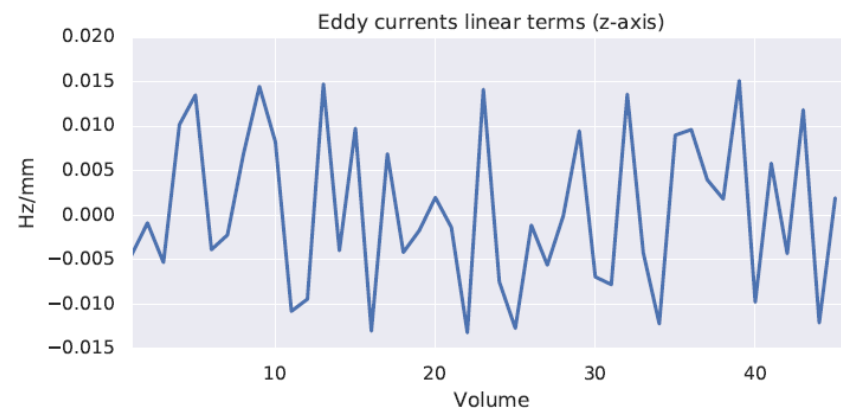
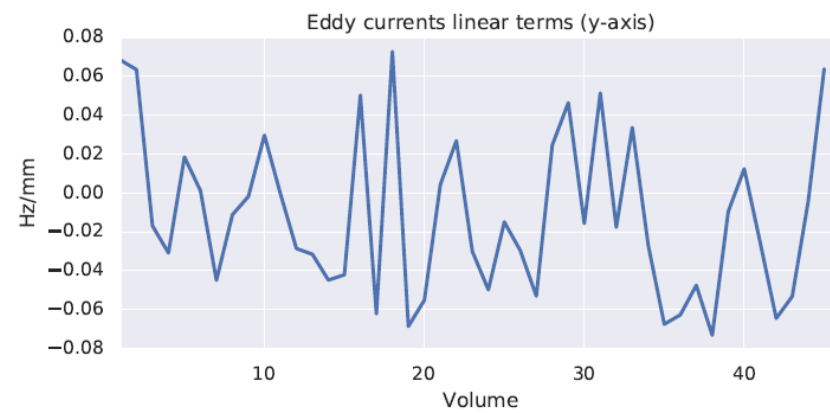
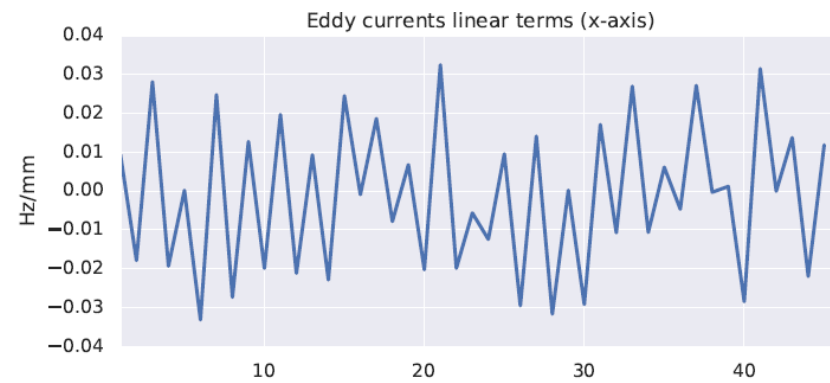




**Diffusion-sensitizing gradient directions**



## Estimated head motion

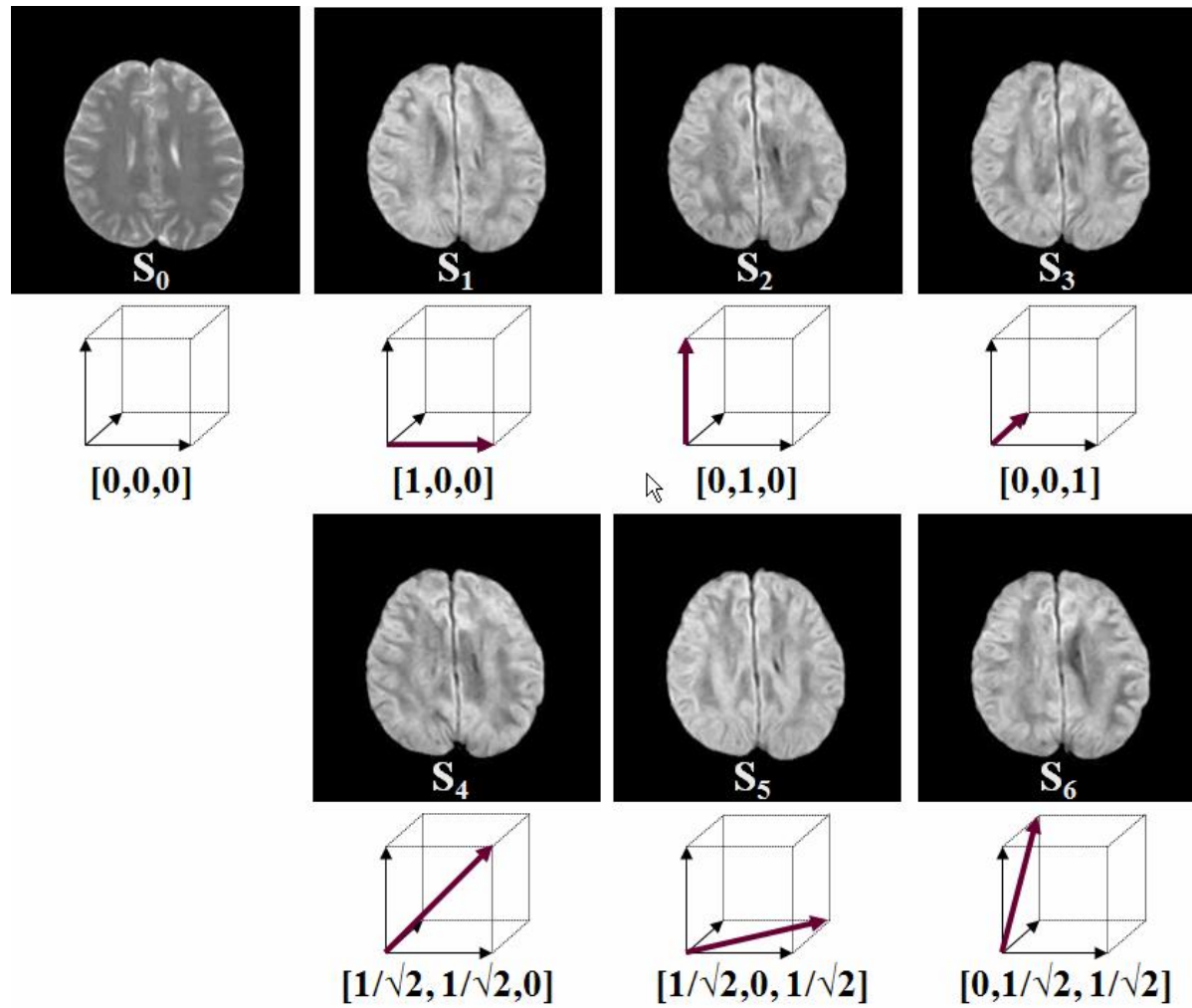


**Estimated eddy currents**

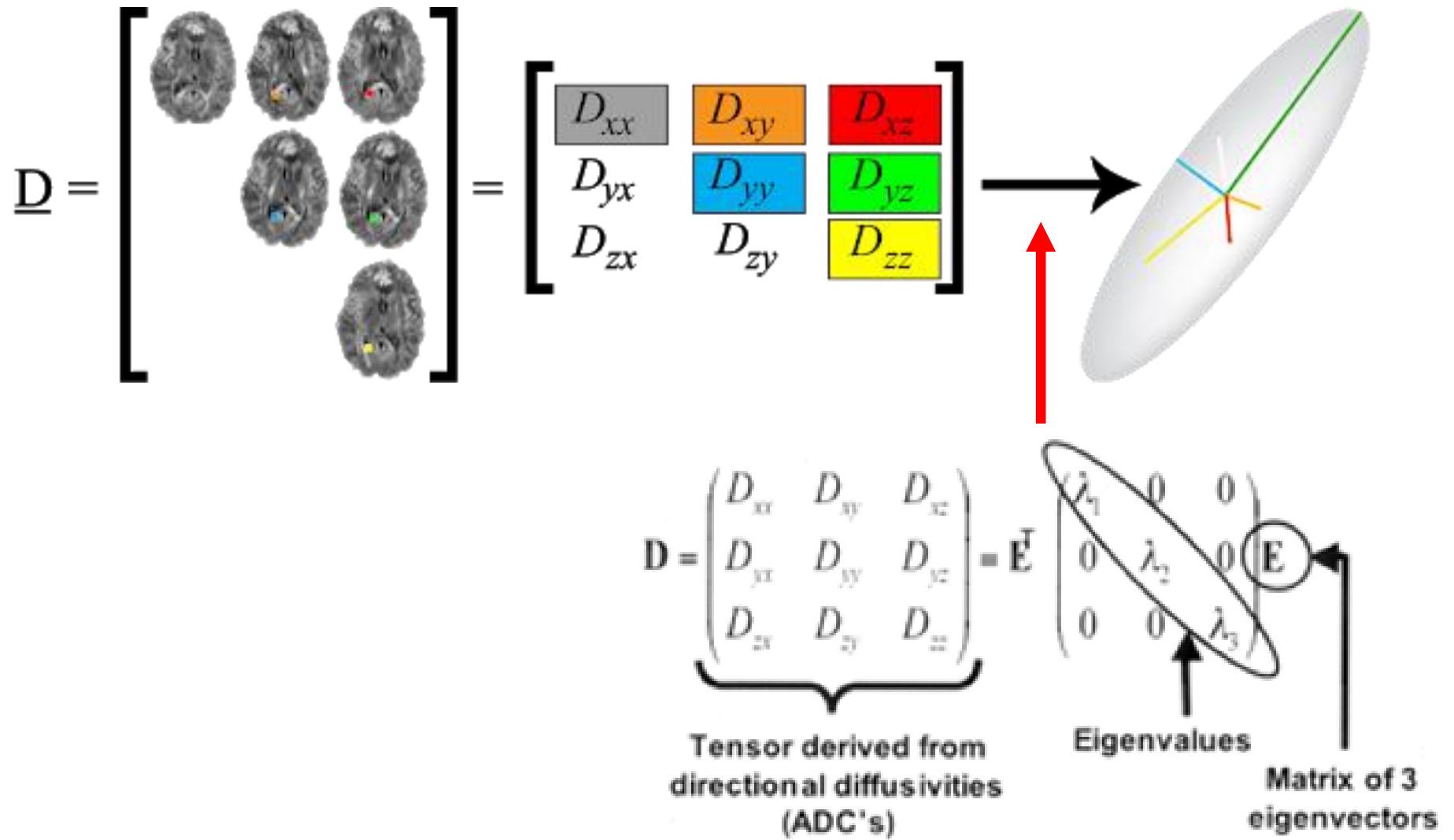
# White Matter Microstructure

- Given the notion that diffusion measurement is sensitive to water molecular diffusion on a "microscopic scale"
  - Mean squared displacement in terms of time elapsed and diffusivity:  $\langle r^2 \rangle = 2Dt = \sim \mu\text{m}$
  - Through measurement of the average Brownian diffusion behaviour of water molecules by averaging diffusion properties over a great many cells and axons within a voxel

- Diffusion tensor model
  - Represents the directional dependence of diffusion by a diagonalized matrix or an ellipsoid
  - Depicts only a single fibre population at each voxel based on the assumption that the probability density function describing the random displacement of water molecules due to diffusion is Gaussian
    - Not proper to voxels that have multiple fibre populations crossing or highly curving fibre bundles

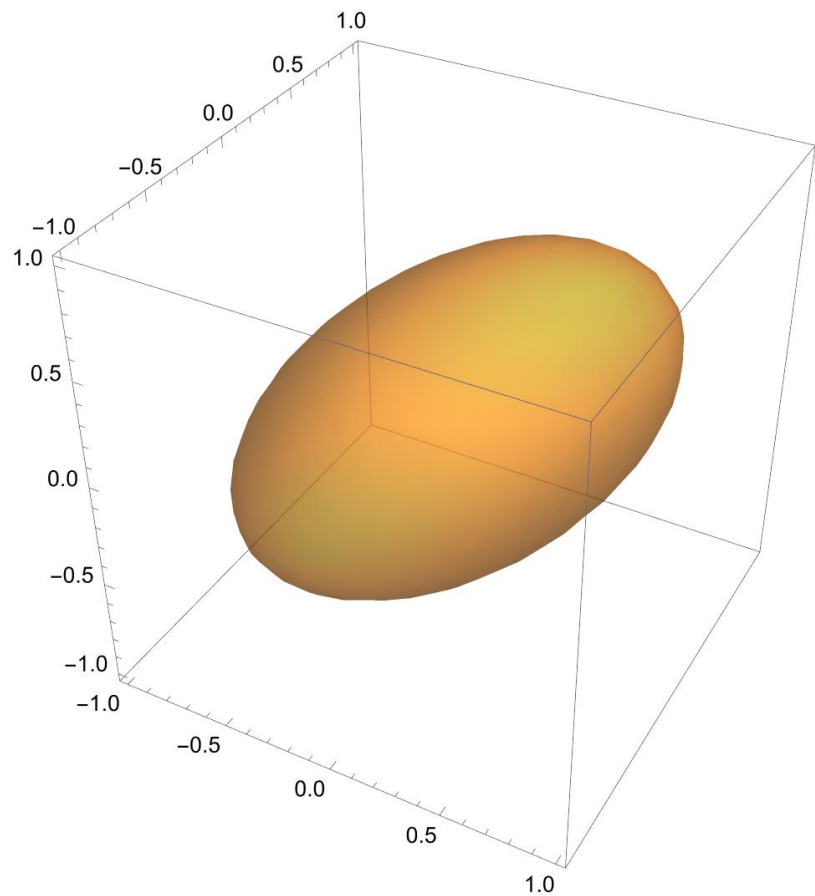


**MRI signals measured without and with diffusion weighting**

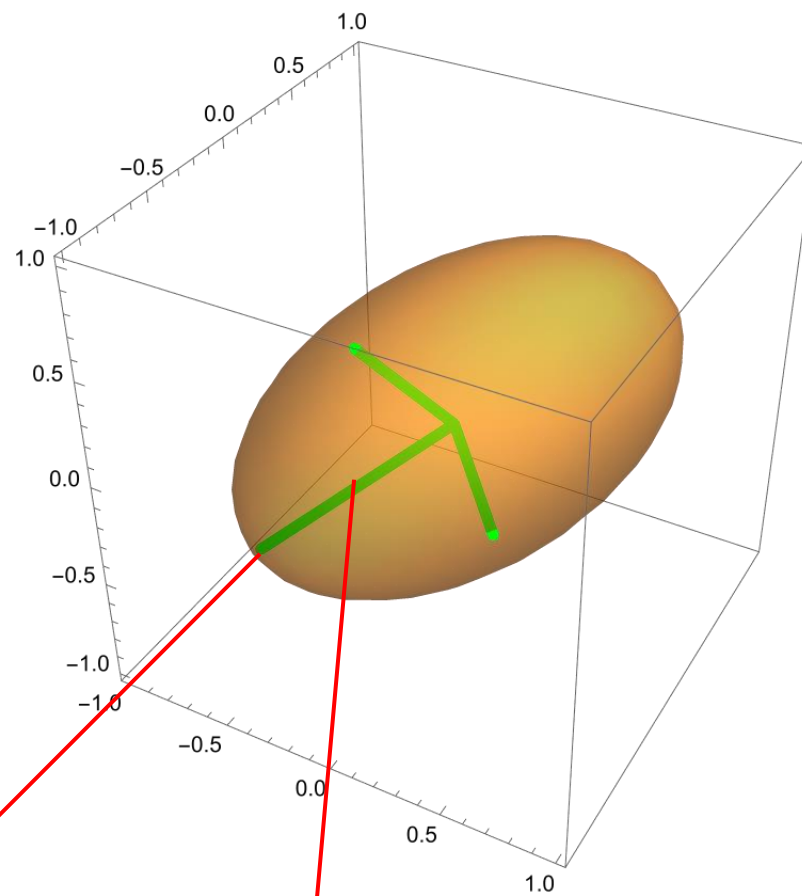


<https://www.blog.brainsightai.com/post/from-dti-to-hardi>

## Diffusion tensor and its ellipsoid representation



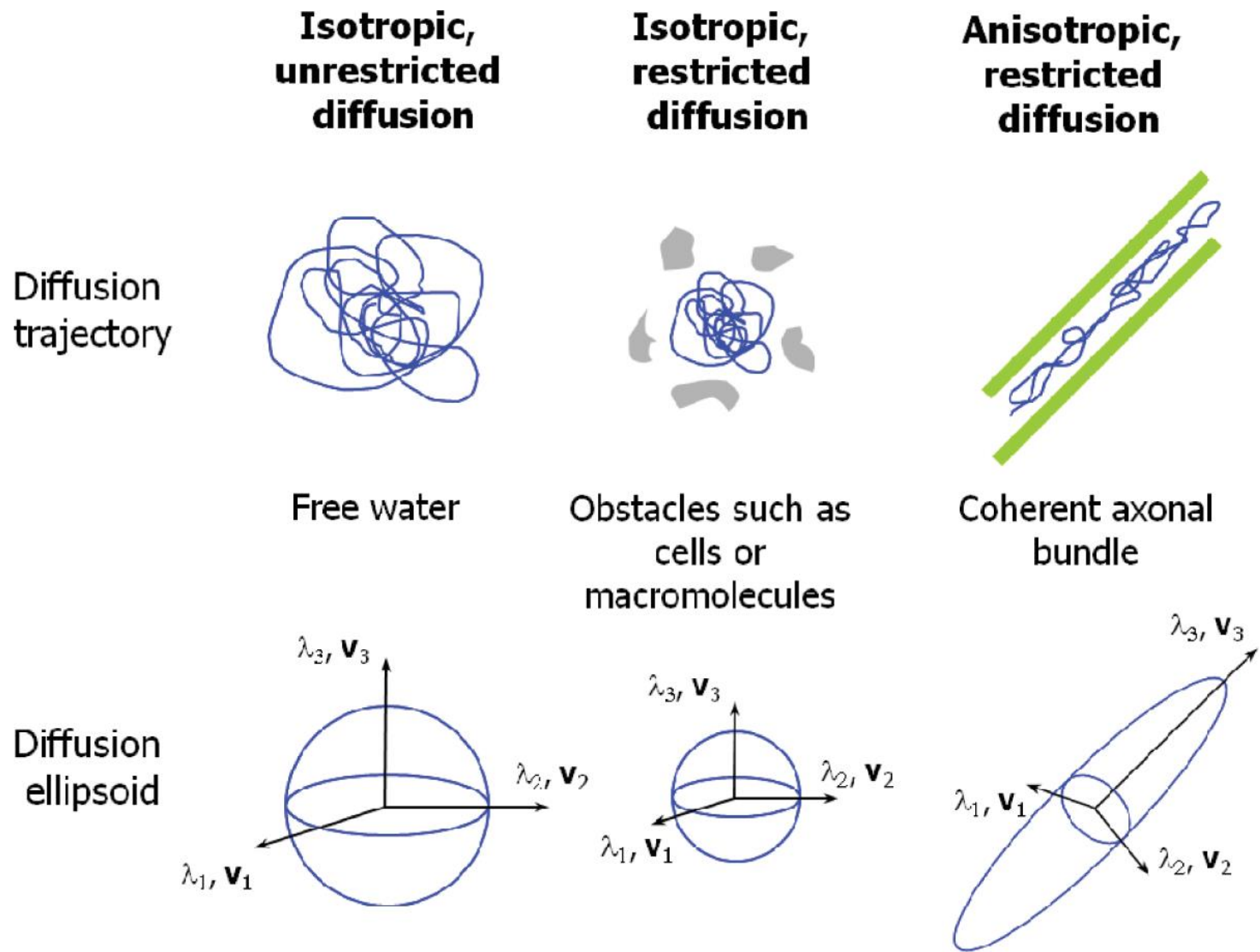
→  
Eigendecomposition



$$\begin{pmatrix} 20 & -8 & -6 \\ -8 & 23 & -1 \\ -6 & -1 & 17 \end{pmatrix}$$

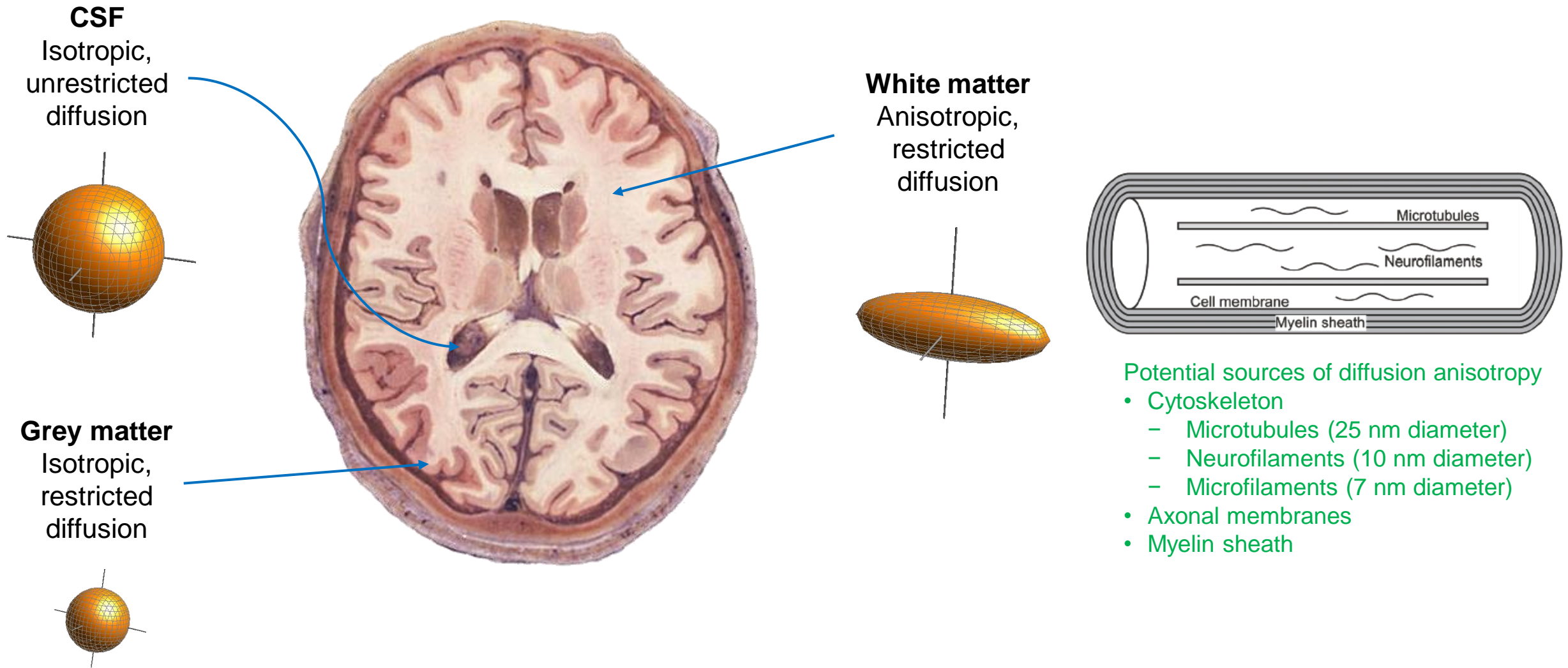
$$\begin{pmatrix} 0.68 & -0.69 & -0.25 \\ -0.30 & -0.57 & 0.76 \\ -0.67 & -0.44 & -0.59 \end{pmatrix}^T \begin{pmatrix} 30.4 & 0 & 0 \\ 0 & 20.1 & 0 \\ 0 & 0 & 9.5 \end{pmatrix} \begin{pmatrix} 0.68 & -0.69 & -0.25 \\ -0.30 & -0.57 & 0.76 \\ -0.67 & -0.44 & -0.59 \end{pmatrix}$$





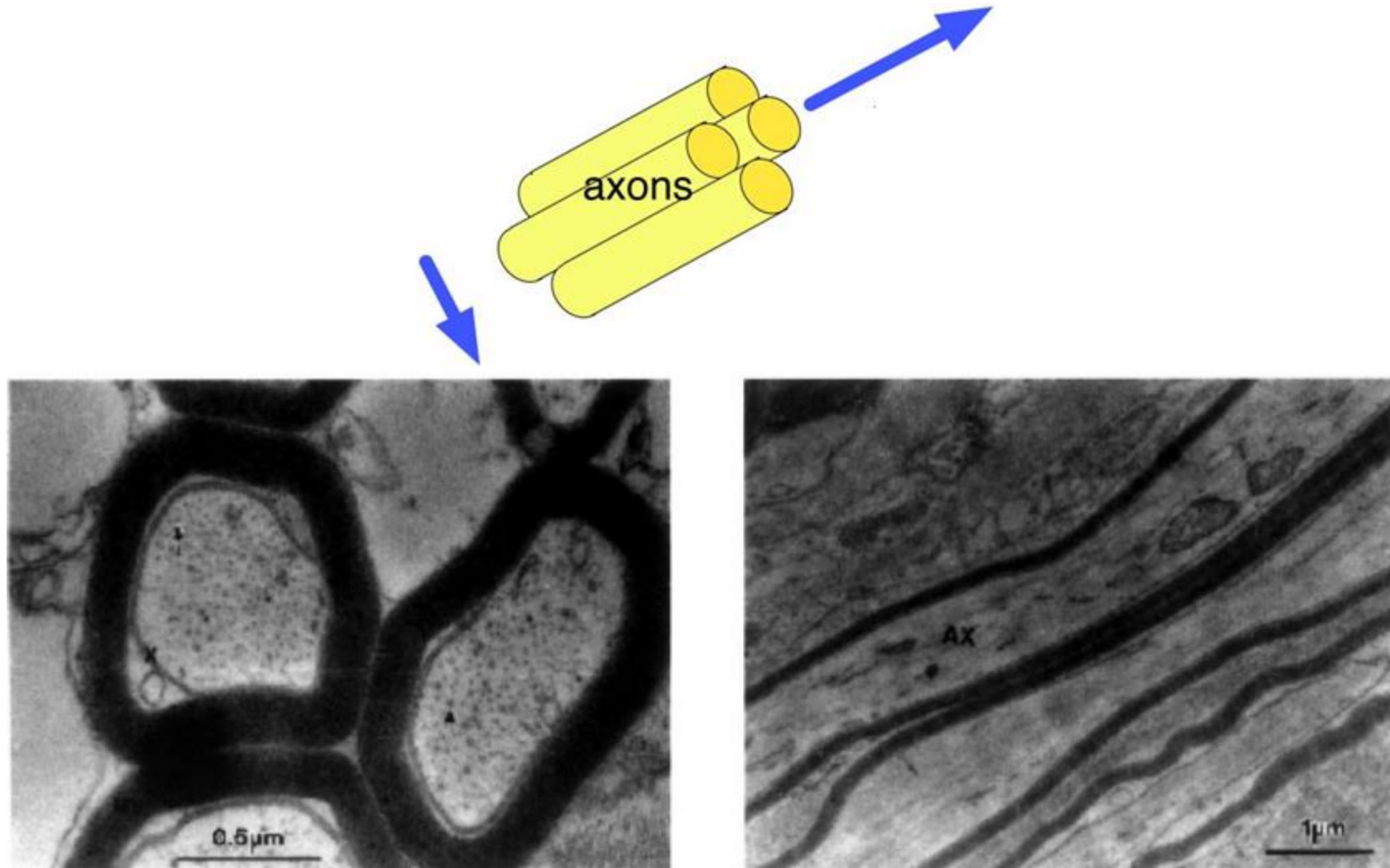
[Geva et al., 2011]

**Isotropic and anisotropic diffusion represented by ellipsoids**



[Noguerol et al., 2017]]

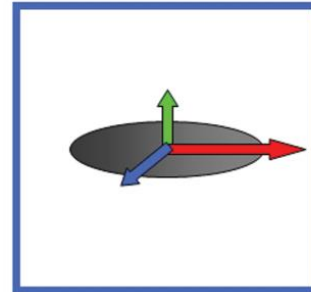
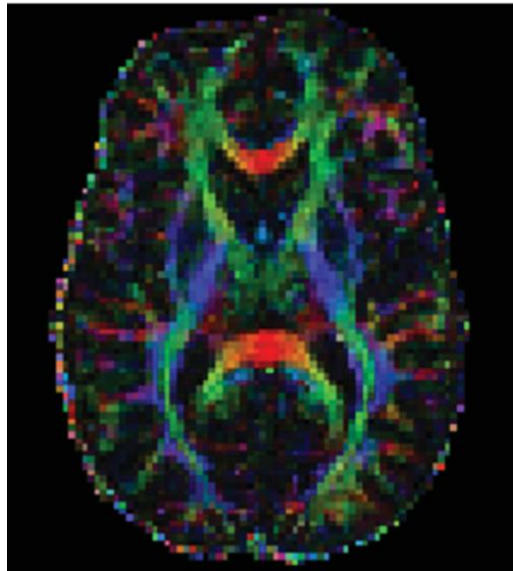
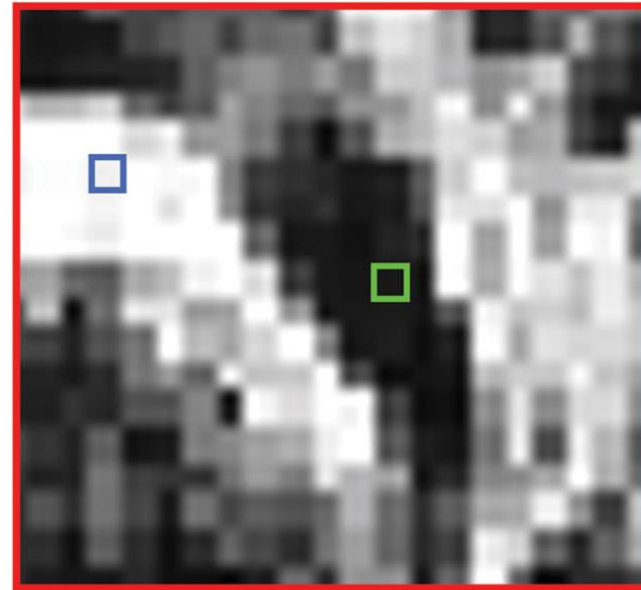
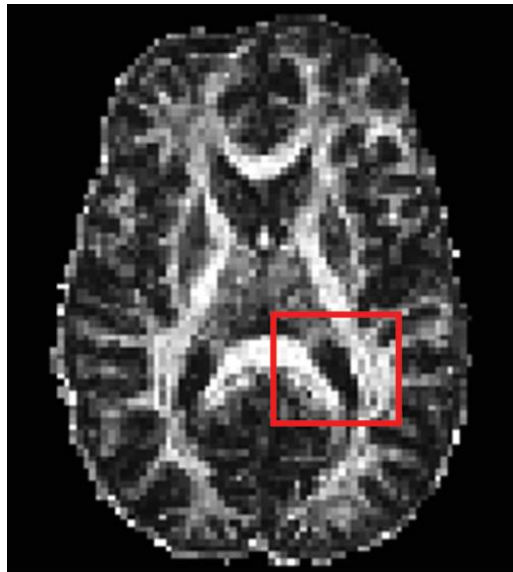
## Isotropic and anisotropic diffusion in brain tissues



[Beaulieu, 2002]]

**Transverse and longitudinal sections of myelinated optic nerves of the garfish**

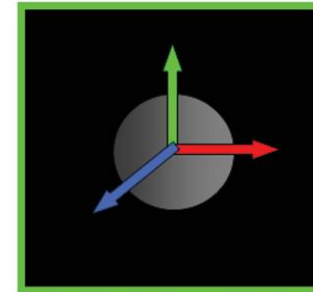
- Scalar invariants that are quantities independent of the coordinate system in which the diffusion tensor is expressed
  - Characterize aspects of water molecular diffusion, such as the magnitude and anisotropy (directional dependence), offering insights into tissue structure and organization
  - Fractional anisotropy (FA)
  - Mean diffusivity (MD)
  - Axial diffusivity (AD)
  - Radial diffusivity (RD)



**Anisotropic  
diffusion**

$$\lambda_1 \gg \lambda_2 = \lambda_3$$

high FA



**Isotropic  
diffusion**

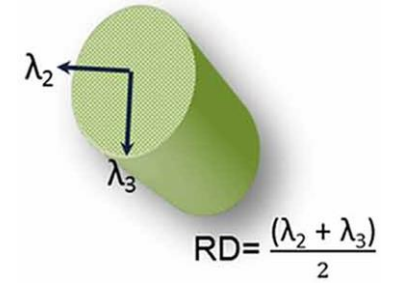
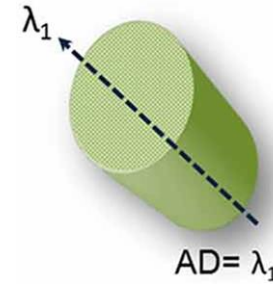
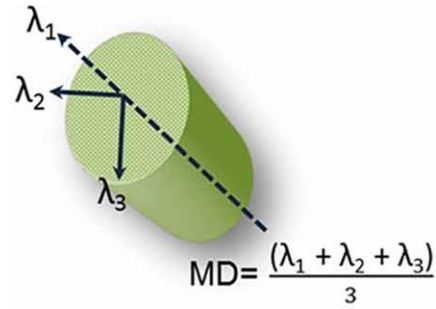
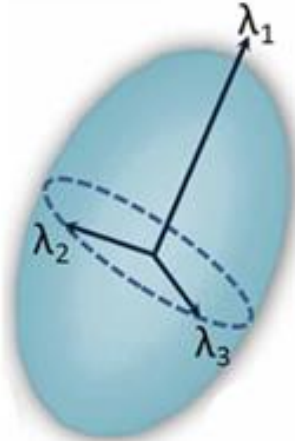
$$\lambda_1 = \lambda_2 = \lambda_3$$

low FA

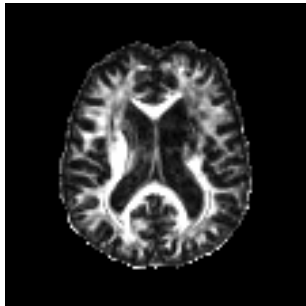
[Geva et al., 2011]

**Directional information added to an FA map**

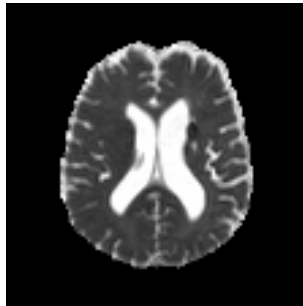
# [dMRI: Diffusion Modelling]



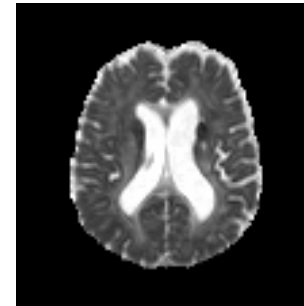
$$FA = \sqrt{\frac{1}{2}} \cdot \frac{\sqrt{(\lambda_1 - \lambda_2)^2 + (\lambda_2 - \lambda_3)^2 + (\lambda_3 - \lambda_1)^2}}{\sqrt{(\lambda_1)^2 + (\lambda_2)^2 + (\lambda_3)^2}}$$



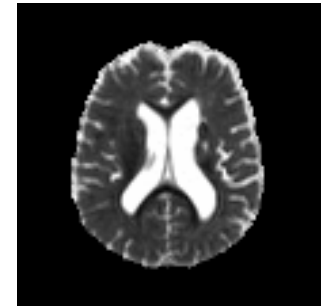
FA



MD

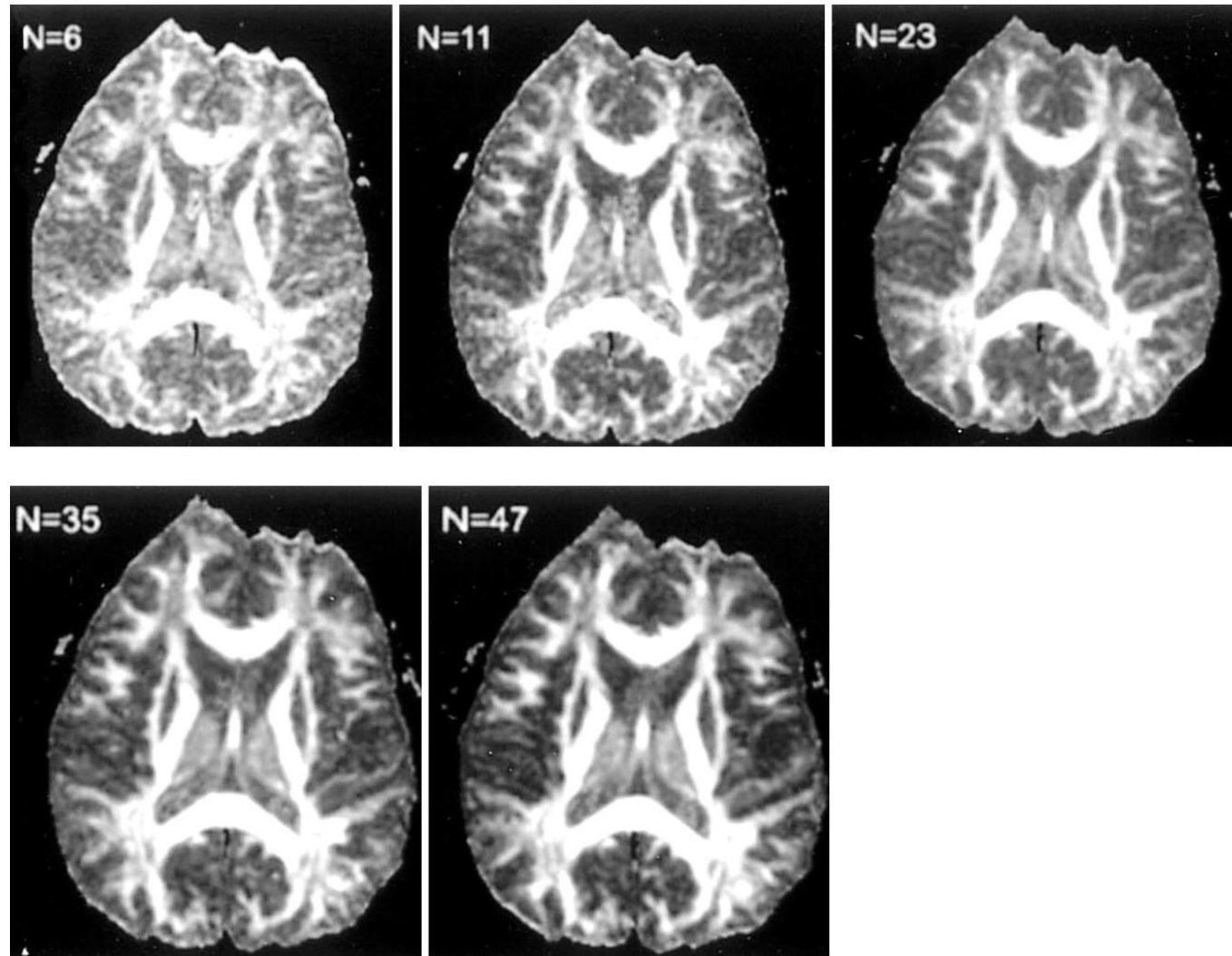


AD



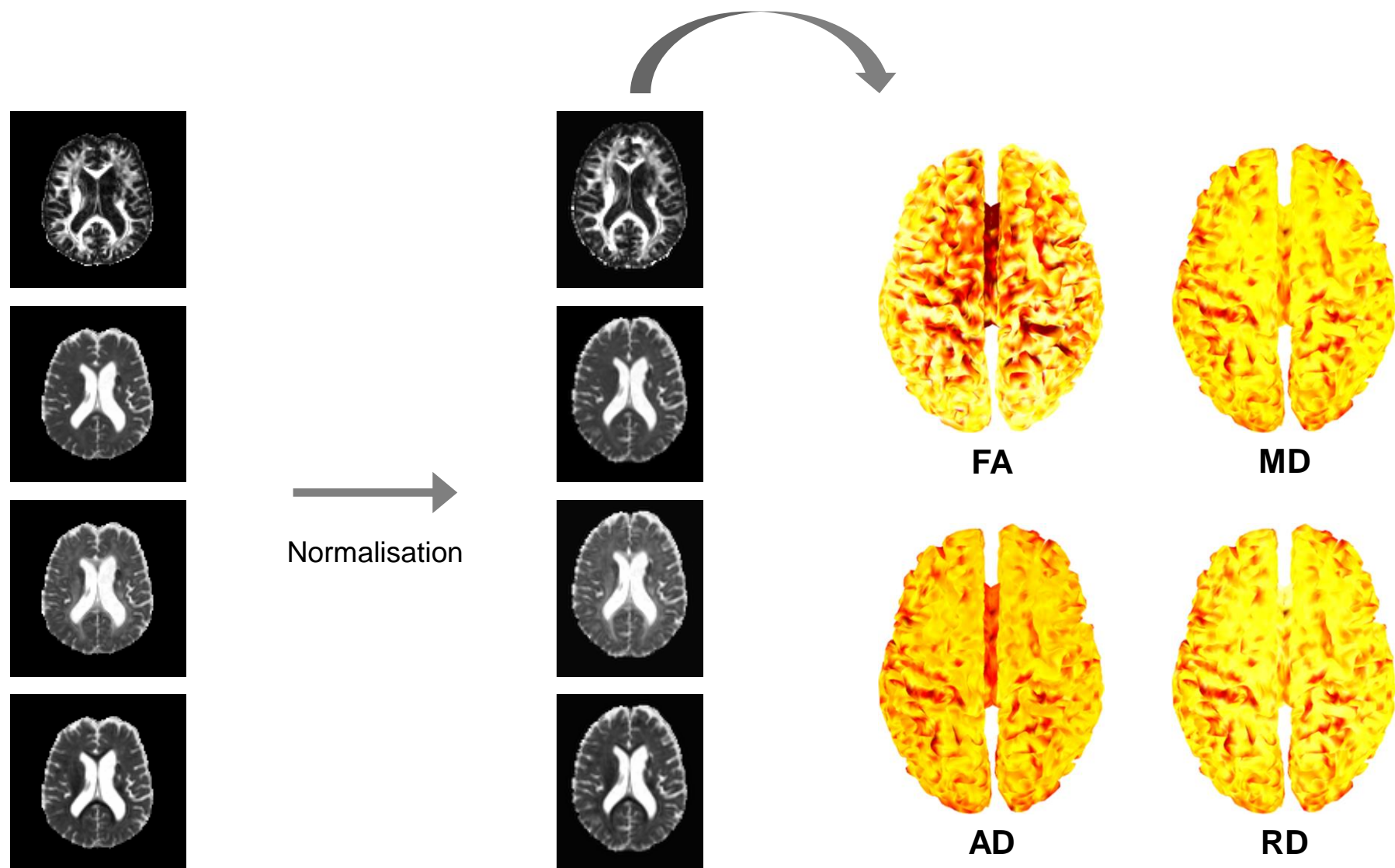
RD





[Chang et al., 2005]

**FA maps according to different numbers of diffusion-sensitizing gradient directions**



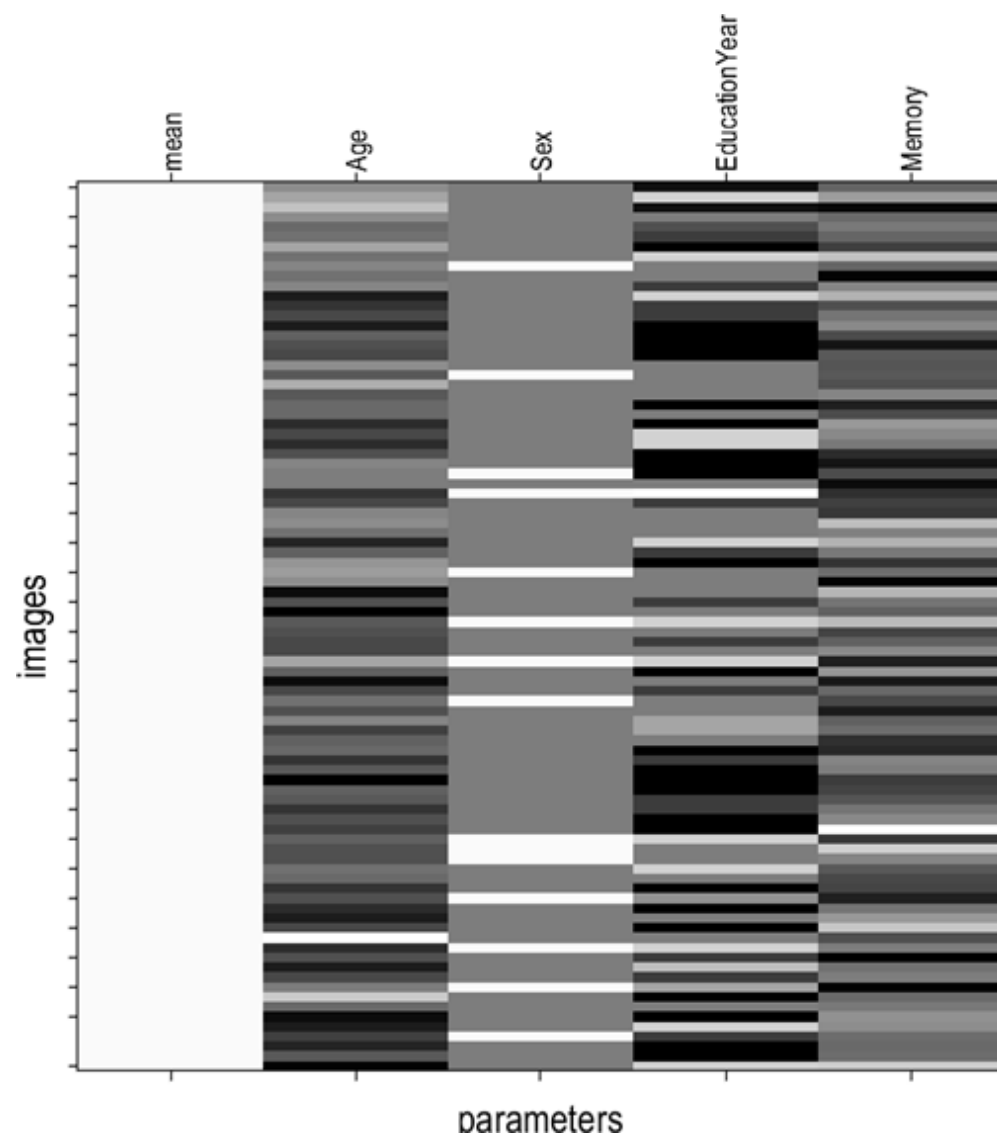
**Information of white matter microstructure**



# [Statistical Analysis of dMRI]

- $FA \sim$   
Age +  
Sex +  
Education year +  
Memory performance

# Design matrix



# Output

## Regression



Positive correlaton



Negative correlation

- MD  $\sim$

Age +

Sex +

Education year +

Memory performance

# Output

Regression

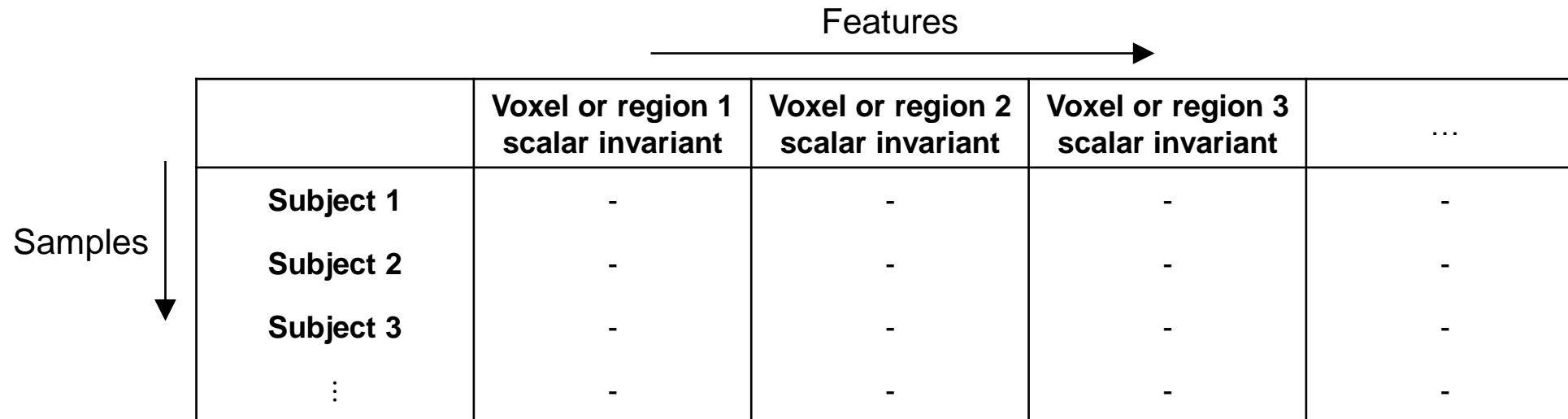


Positive correlaton



Negative correlation

- Input to machine learning models
  - Table of voxel-wise or region-wise scalar values for diffusion tensors

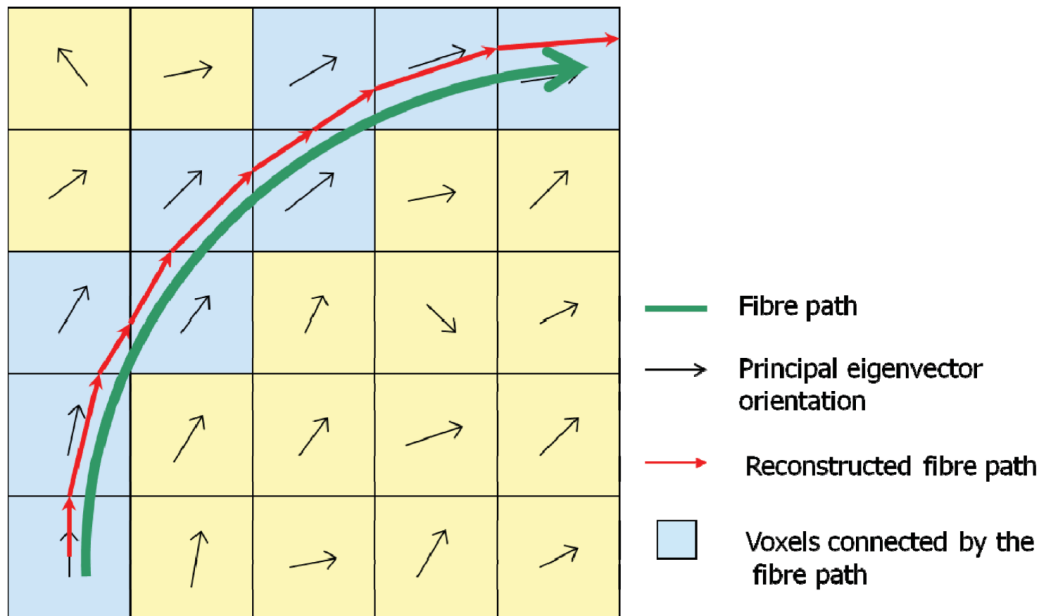


	Features →			
	Voxel or region 1 scalar invariant	Voxel or region 2 scalar invariant	Voxel or region 3 scalar invariant	...
Subject 1	-	-	-	-
Subject 2	-	-	-	-
Subject 3	-	-	-	-
⋮	-	-	-	-

- Diffusion tensor-derived scalar invariant map

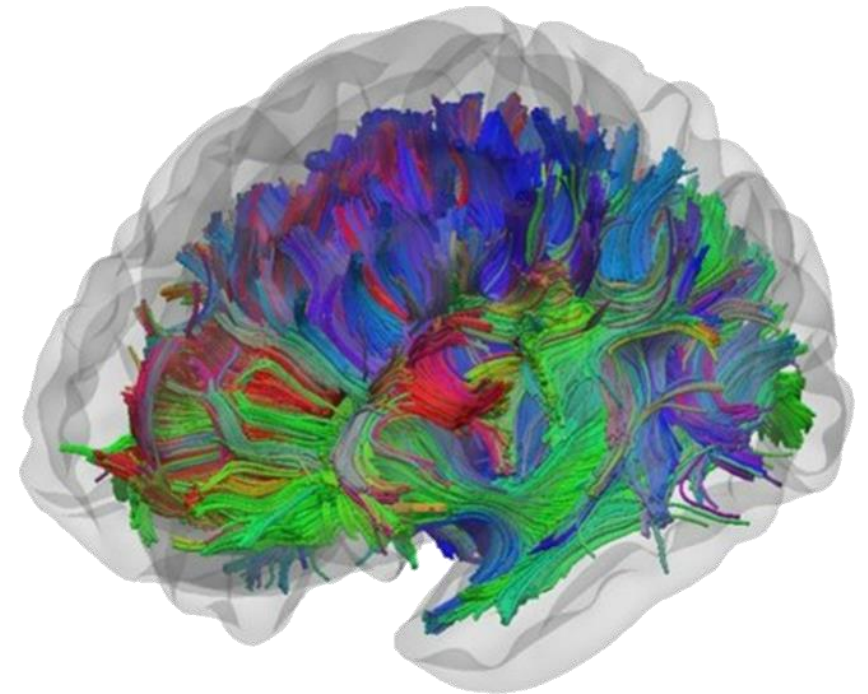
# White Matter Tractography

- Map of connectional anatomy of the white matter
  - Bundled streamlines that reflect where organized white matter fibre tracts are likely to be
  - Based on how strongly and in what directions water molecules diffuse given physical constraints in the brain



Streamlines based on common directions of water molecular diffusion

Many times across the brain

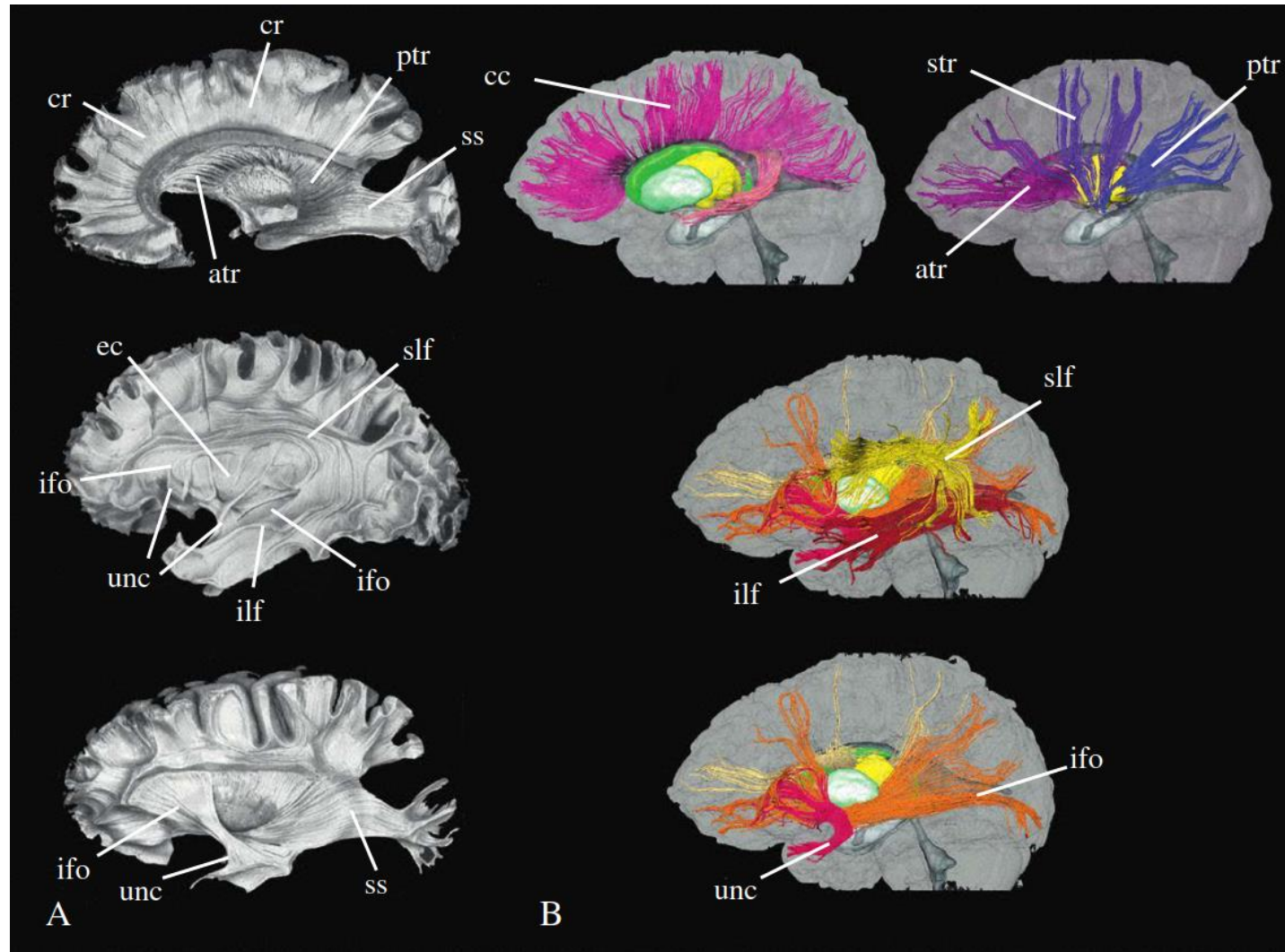


White matter fibre tracts

[Geva et al.,2011]

## White matter tractography

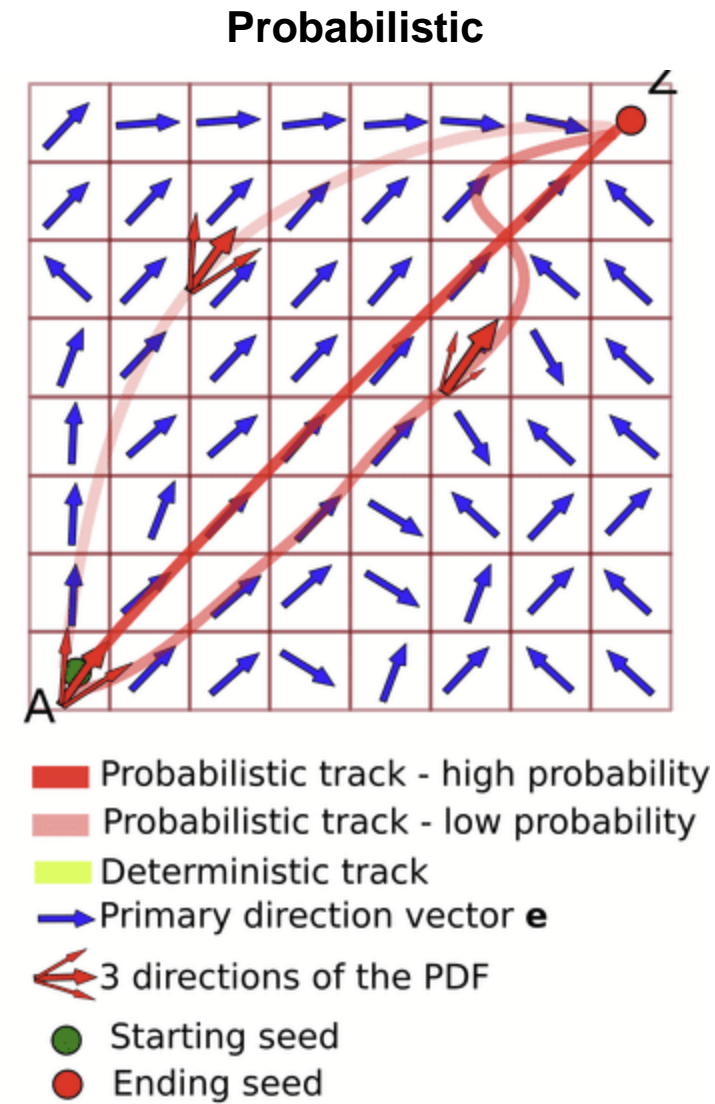
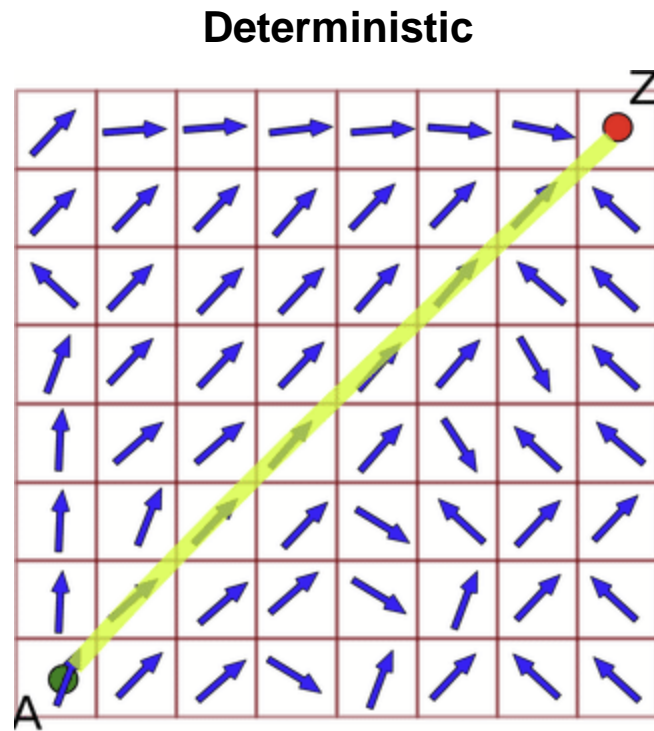




[Oishi et al., 2011]

**Comparison between postmortem preparation and dMRI-based white matter reconstructions**

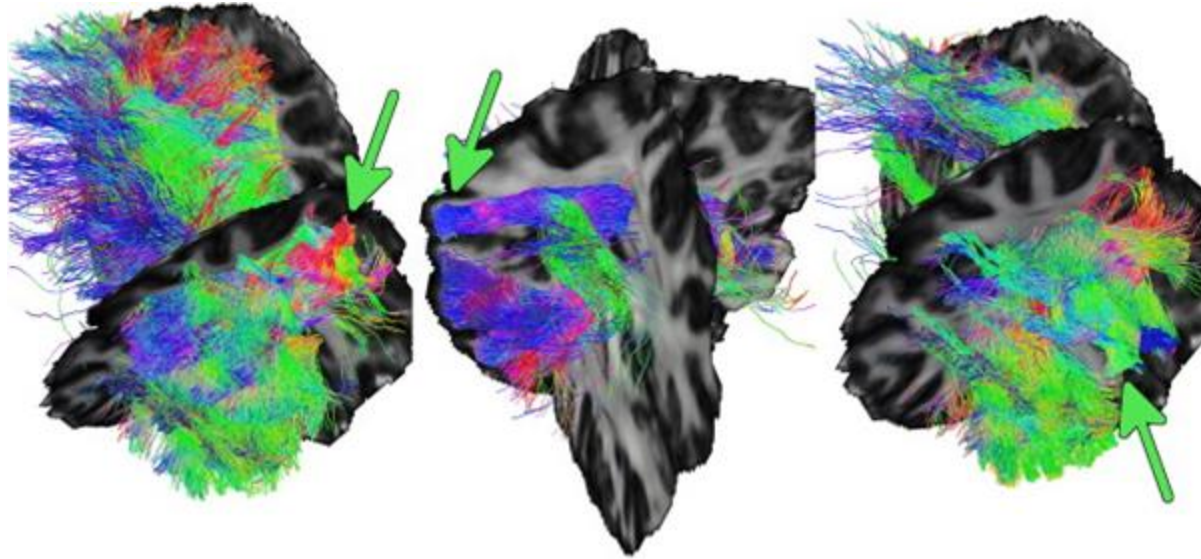
- Deterministic vs. probabilistic ways
  - Deterministic by strictly following the directions of water molecular diffusion
  - Probabilistic by inferring a probability of different directions of water molecular diffusion at any given location



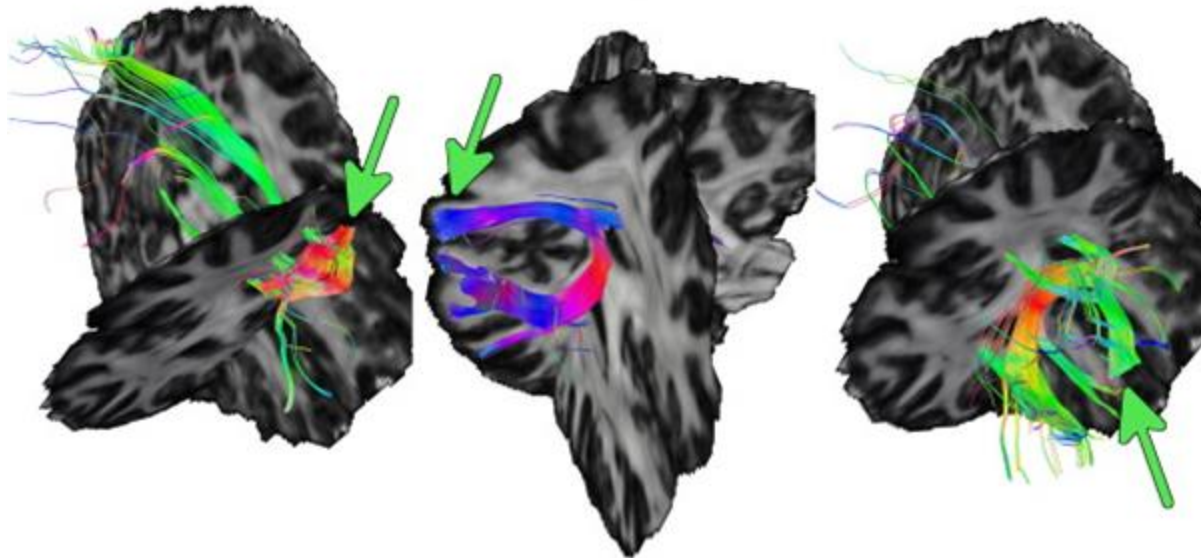
[Garyfallidis, 2012]

**Deterministic and probabilistic ways for white matter tractography**

**Probabilistic**



**Deterministic**



[Schreiber et al., 2014]

**Comparison between probabilistic and deterministic tractography**

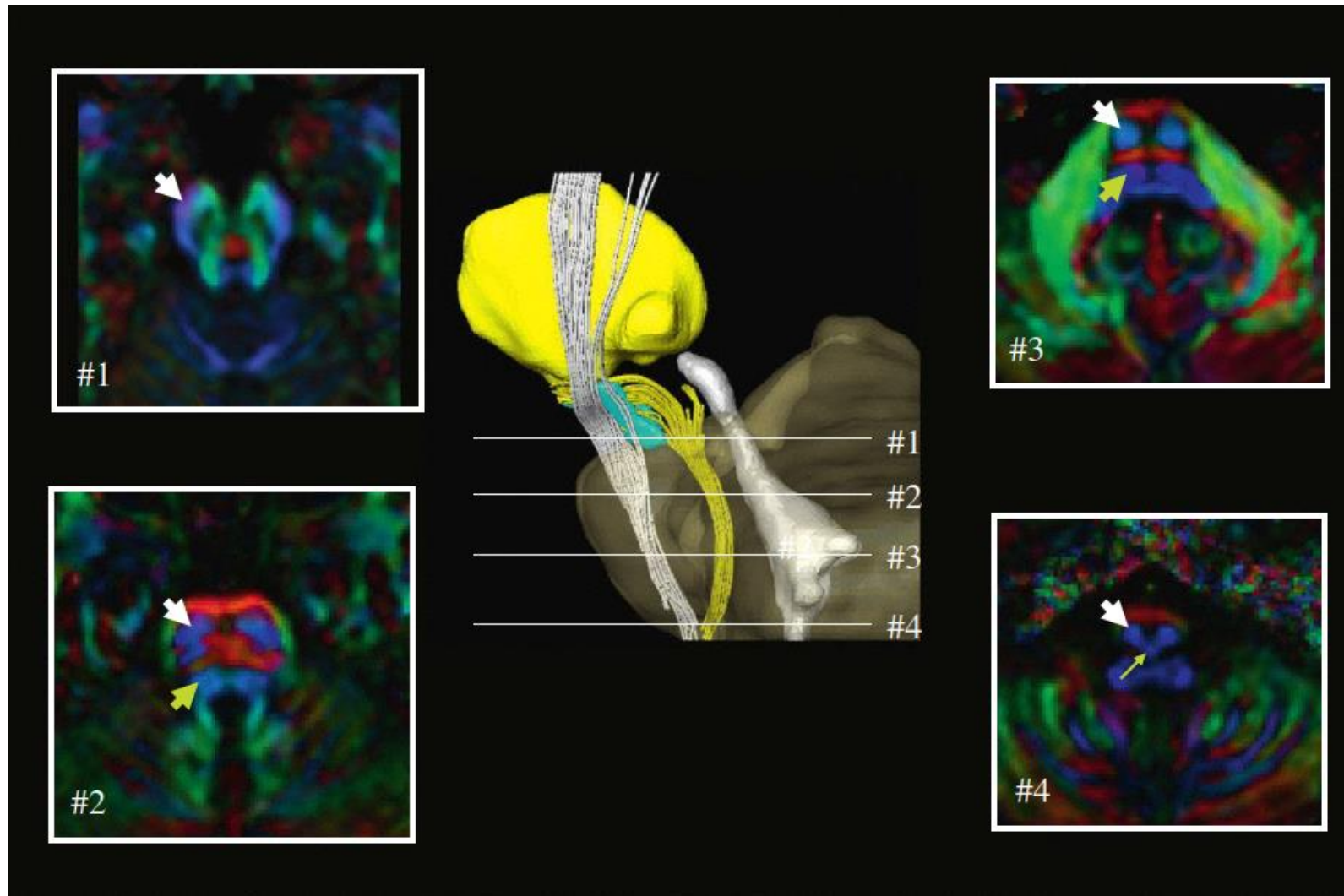
- White matter fibre tract
  - Segmented white matter
  - Based on information about:
    - Terminations of each white matter fibre tract into the cortex
    - Histologically-derived definitions for each white matter fibre tract





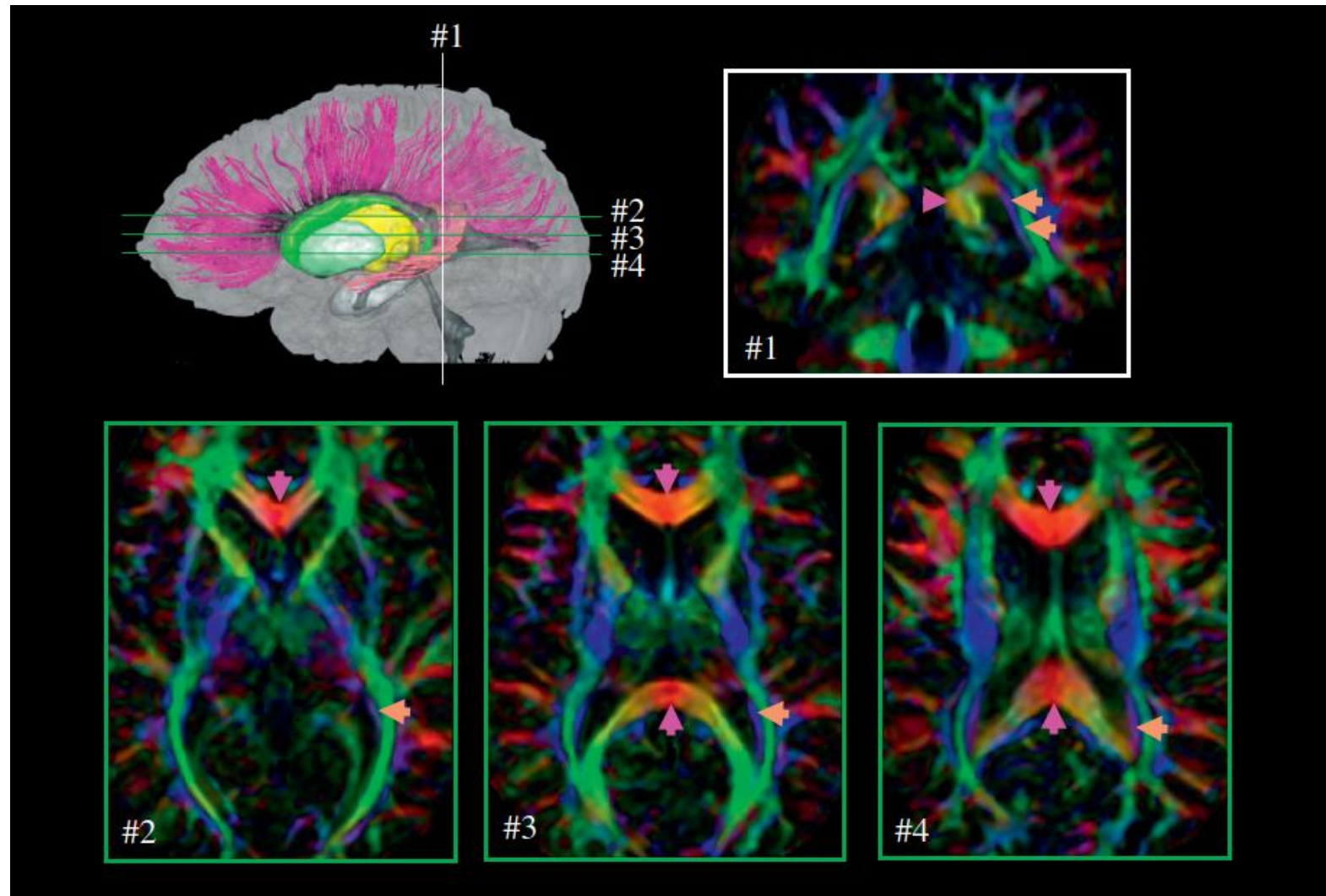
[\[https://www.mrtrix.org/\]](https://www.mrtrix.org/)

**Determination of white matter fibre tracts**



[Oishi et al., 2011]

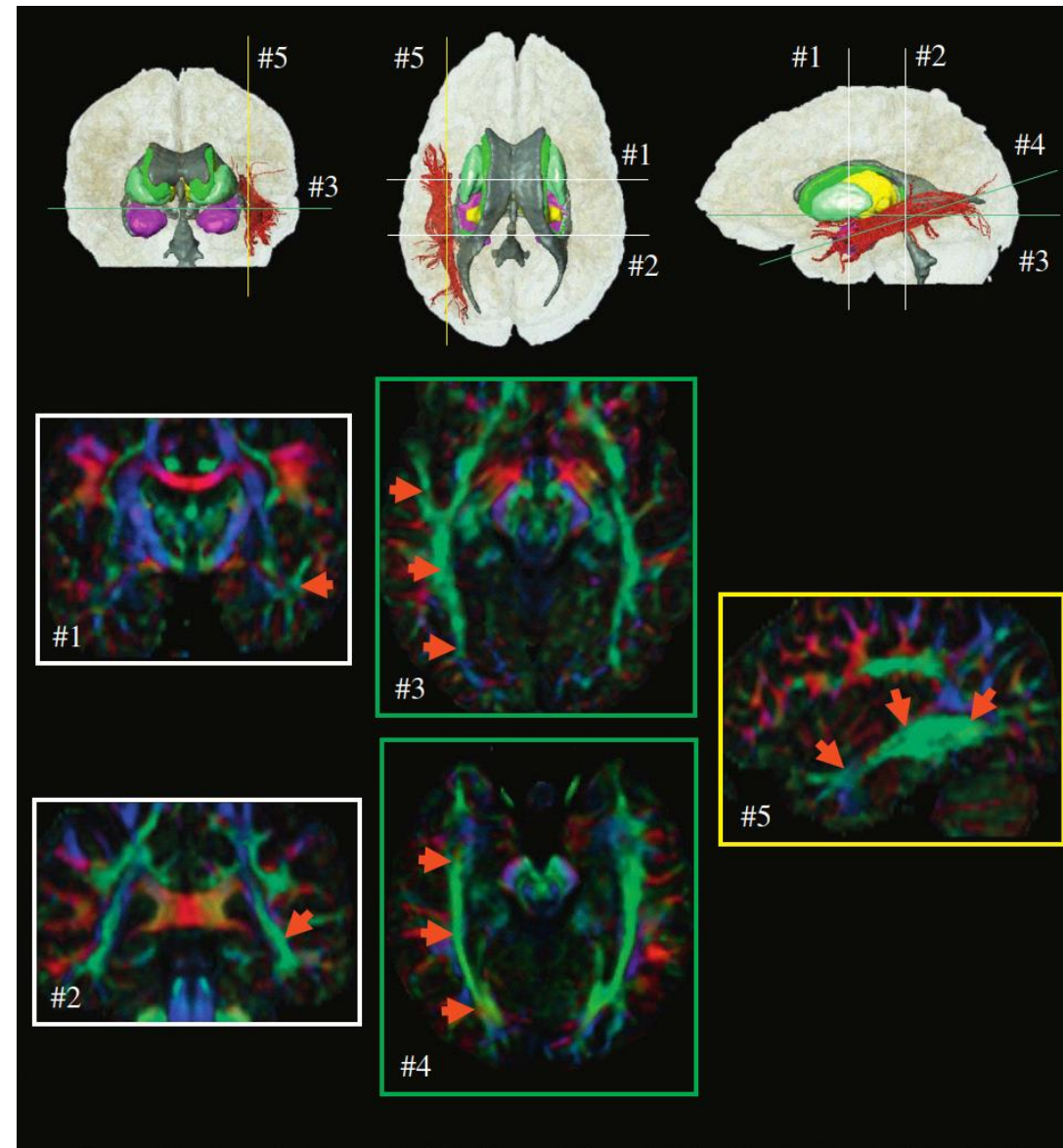
**Trajectory of the corticospinal tract**



[Oishi et al., 2011]

**Trajectory of the corpus callosum**

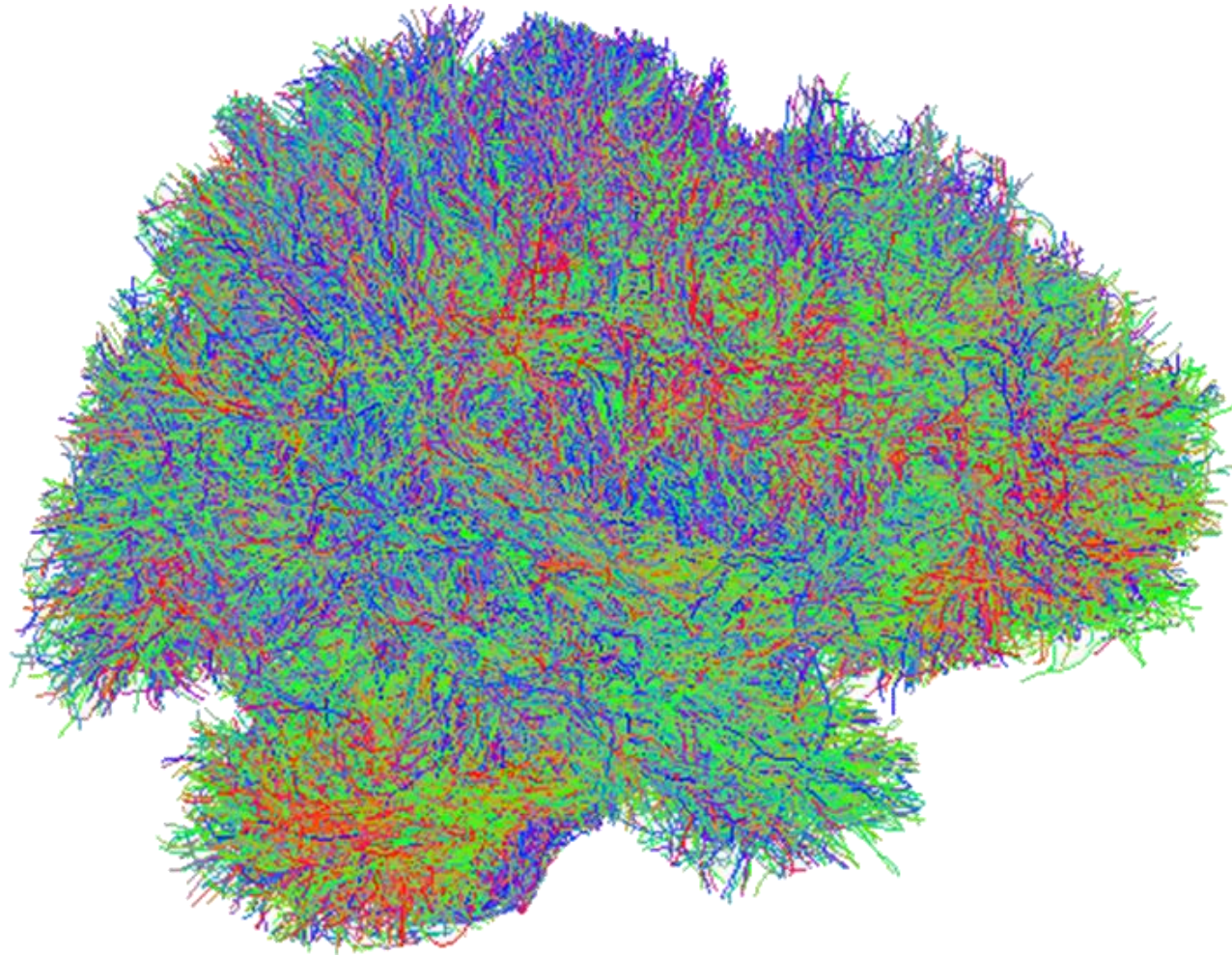




[Oishi et al., 2011]

**Trajectory of the inferior longitudinal fasciculus**

# [dMRI: White Matter Tractography]

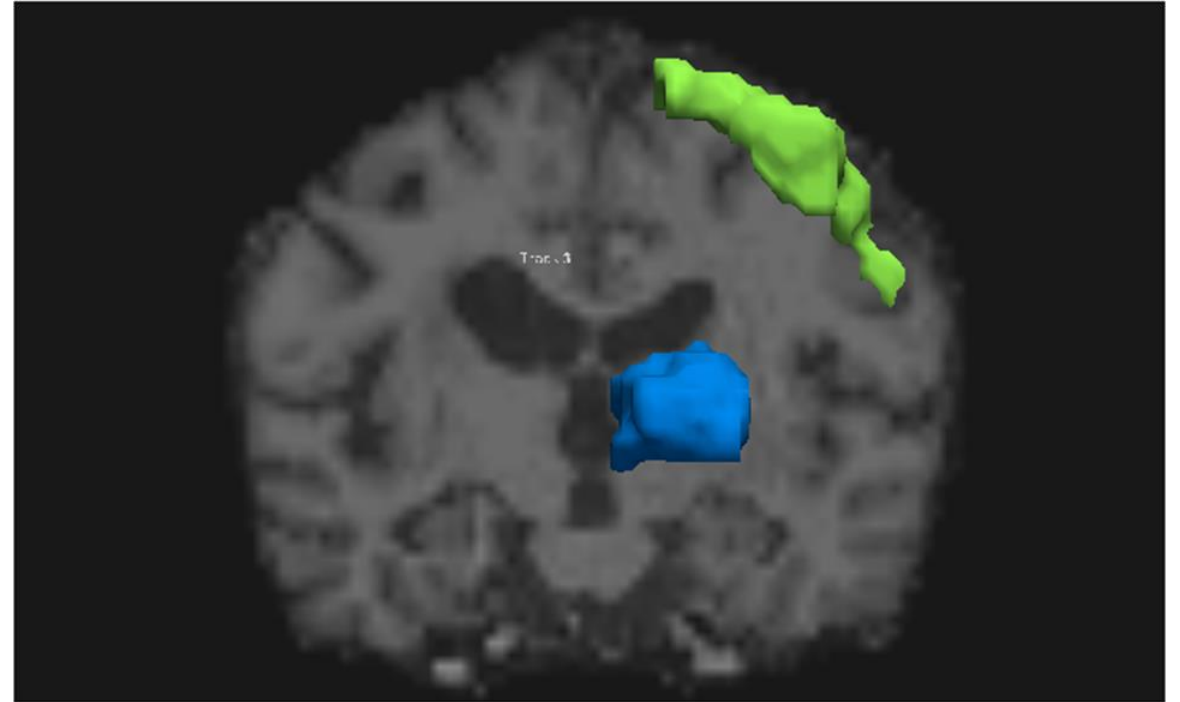
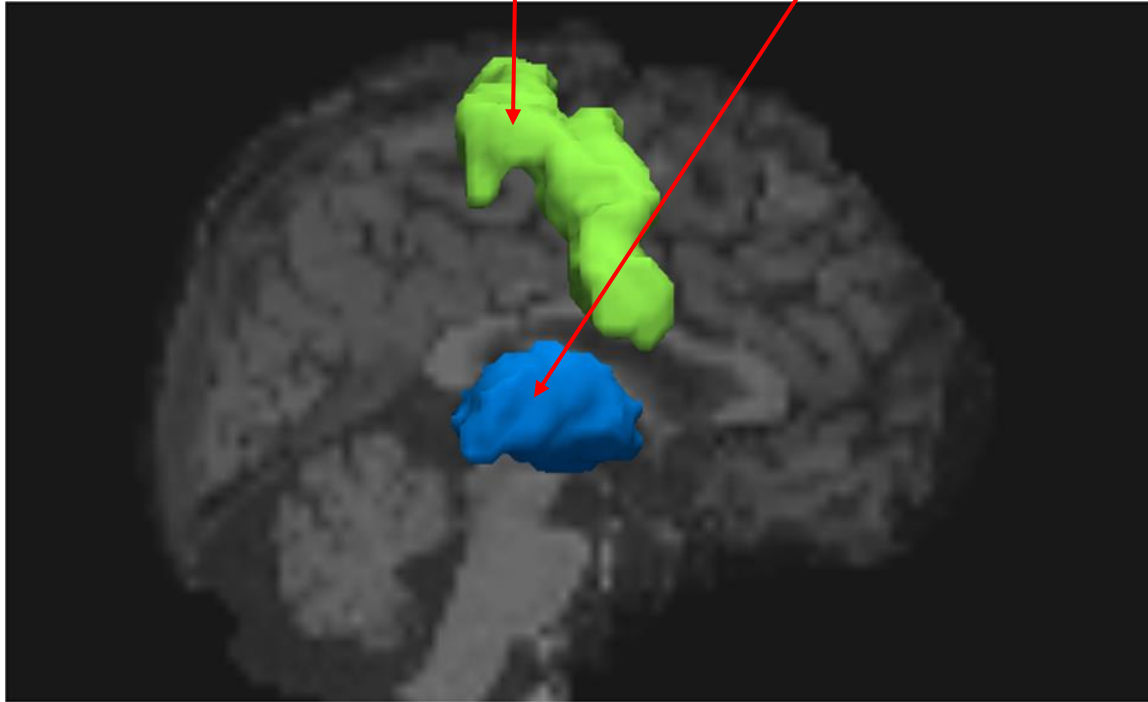


1,500,000 streamlines

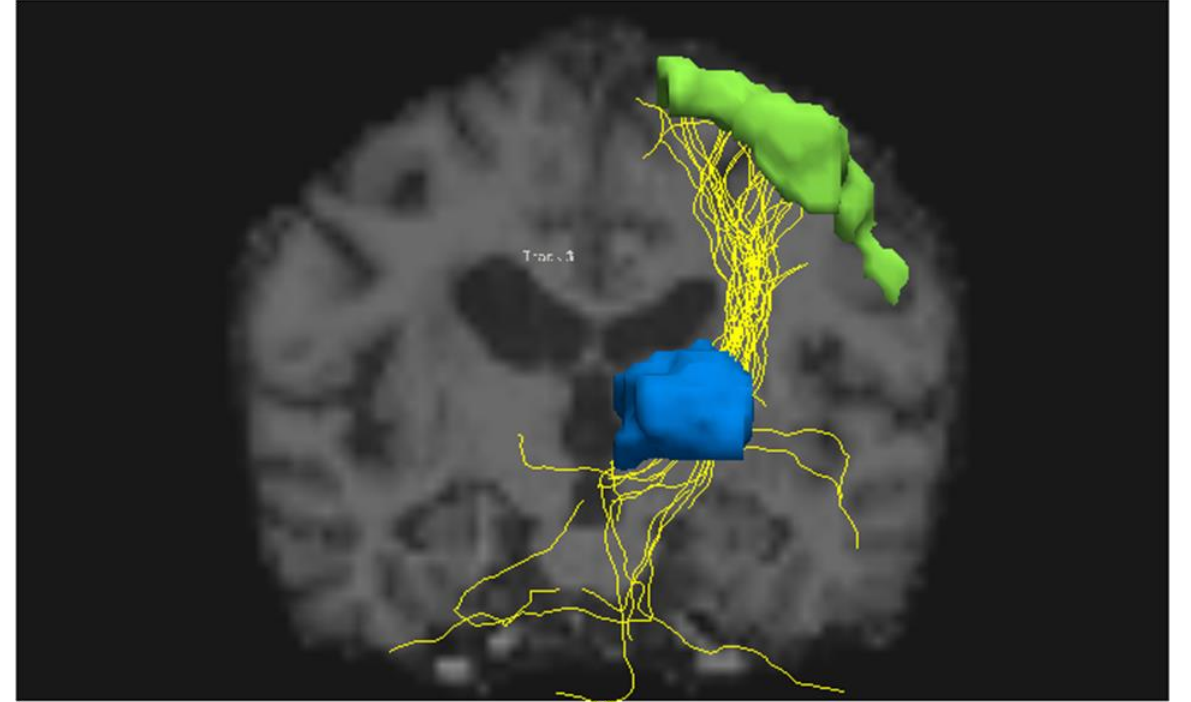
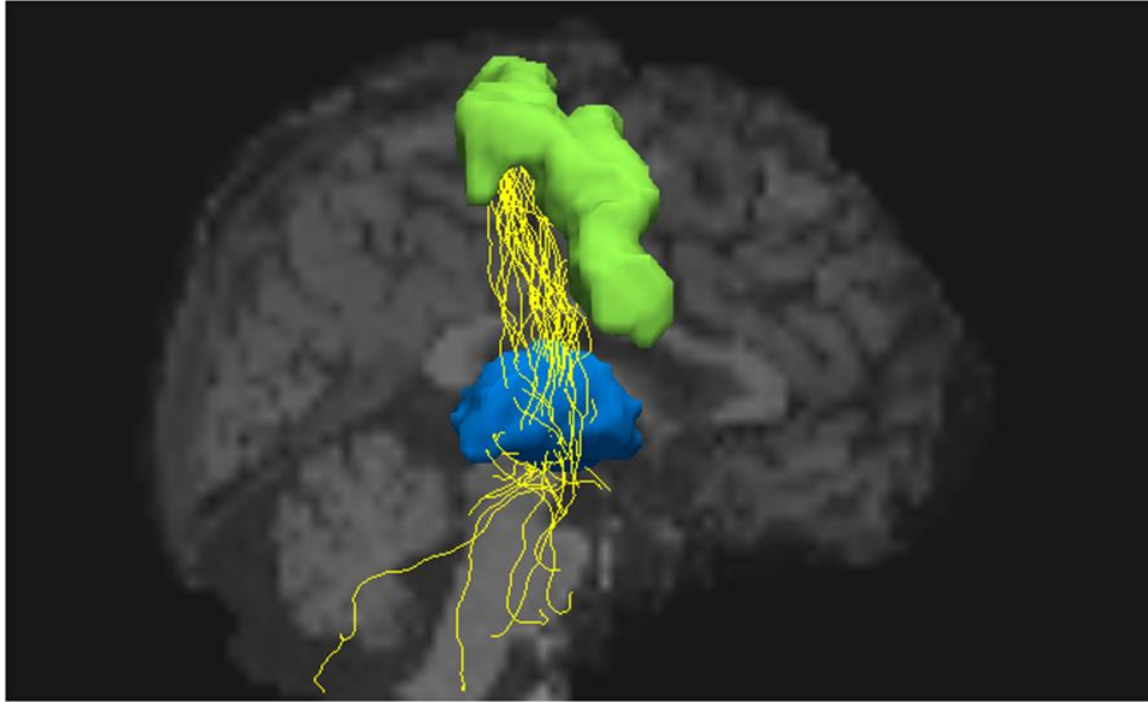
**Whole brain white matter tractography**

Precentral gyrus

Thalamus

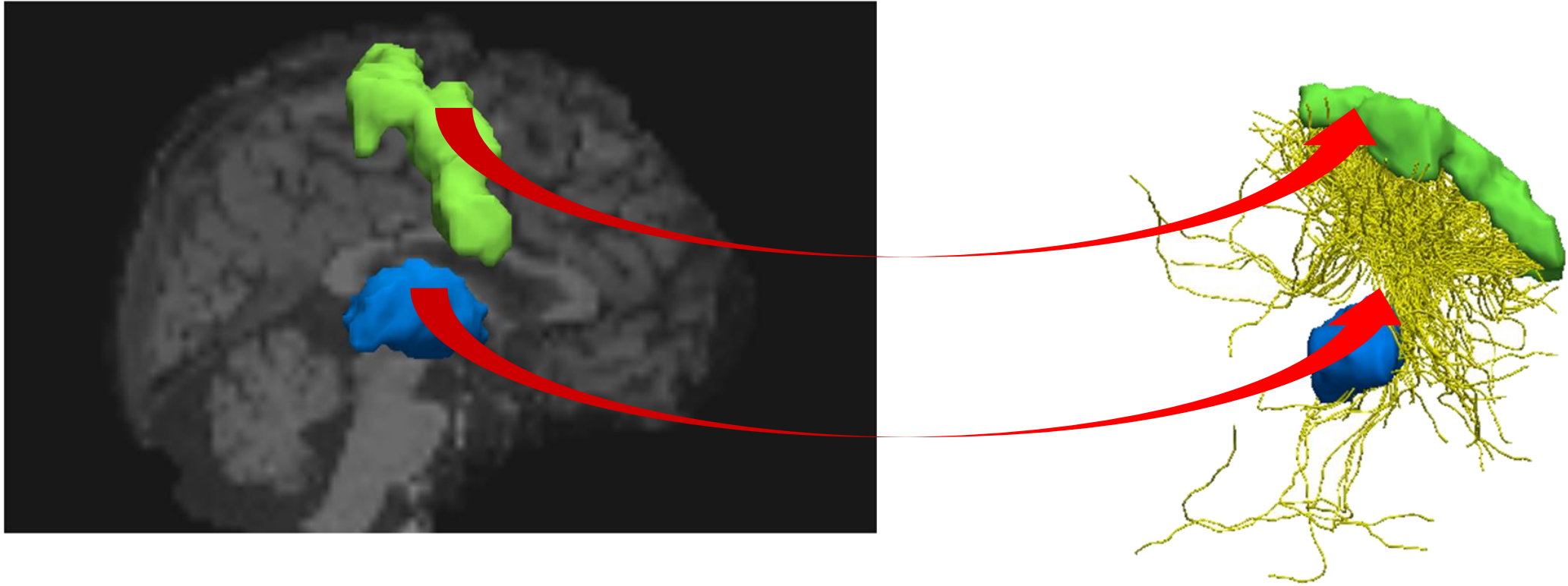


**Terminations of streamlines**



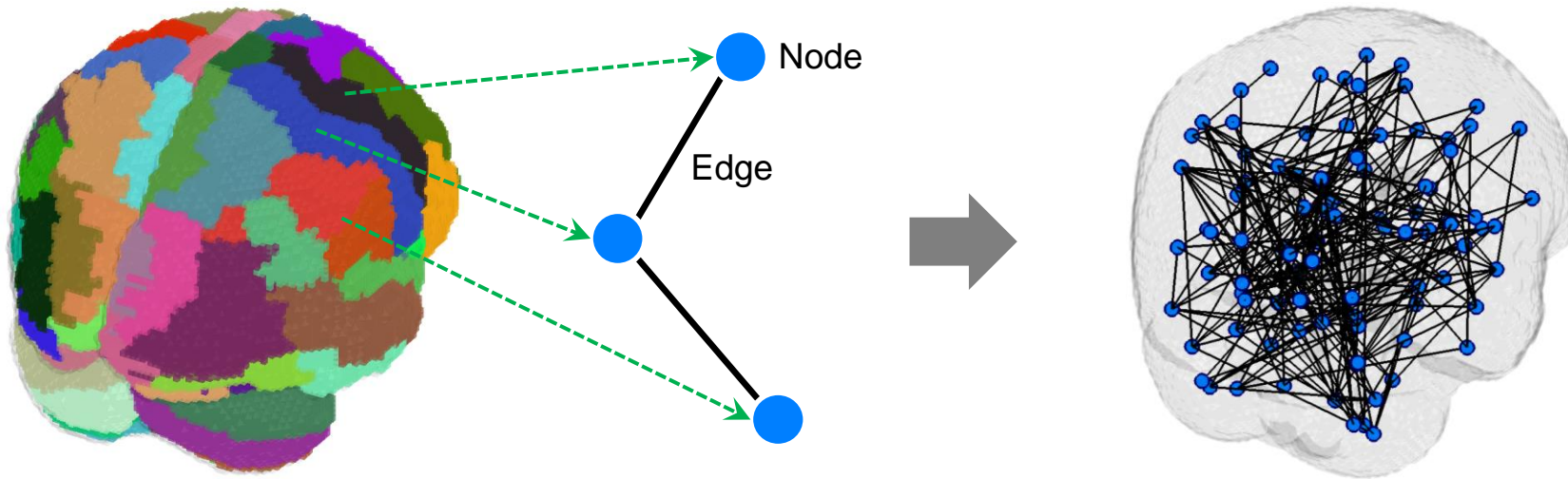
**Generated streamlines**

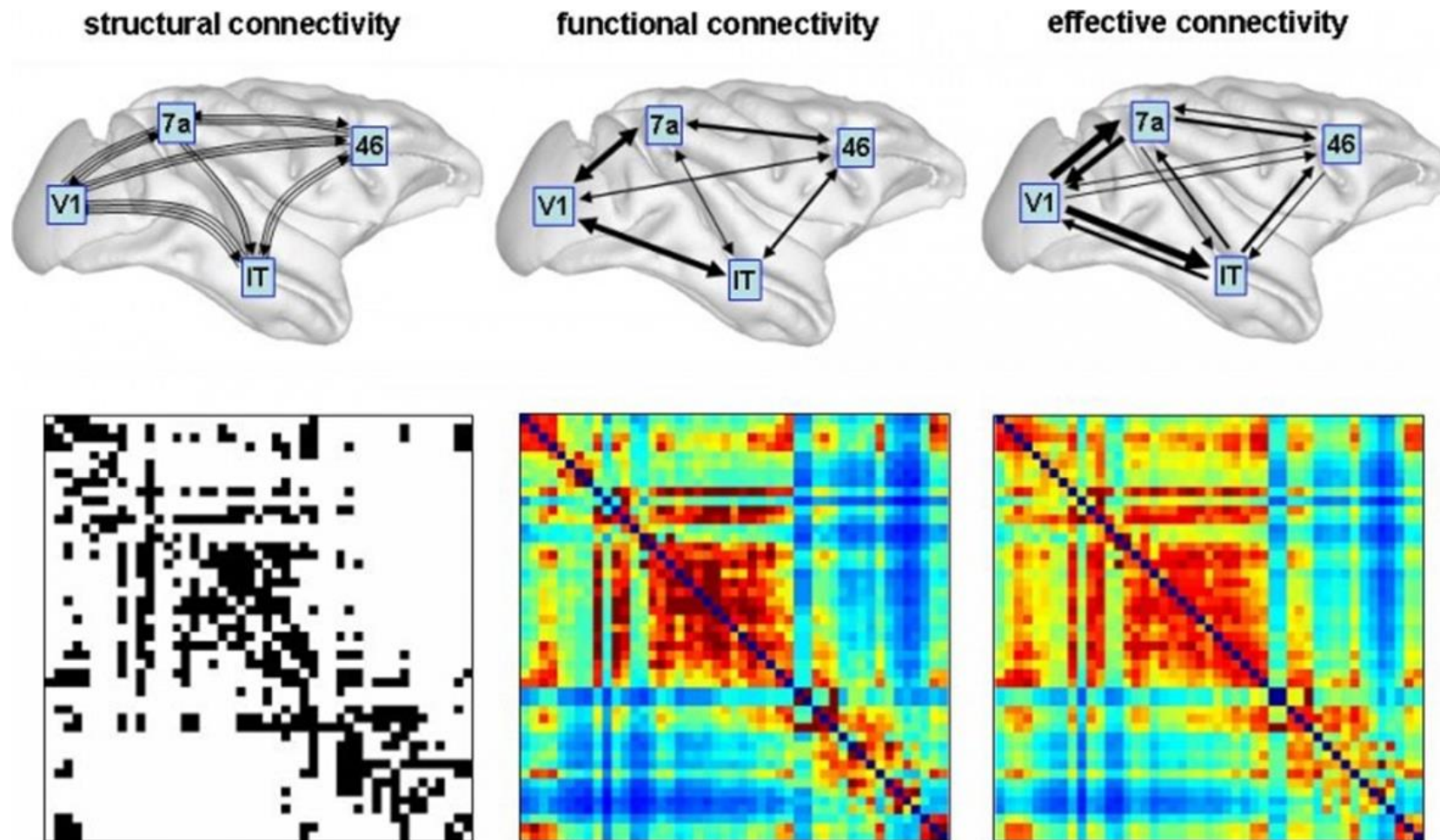




**Determination of white matter fibre tracts**

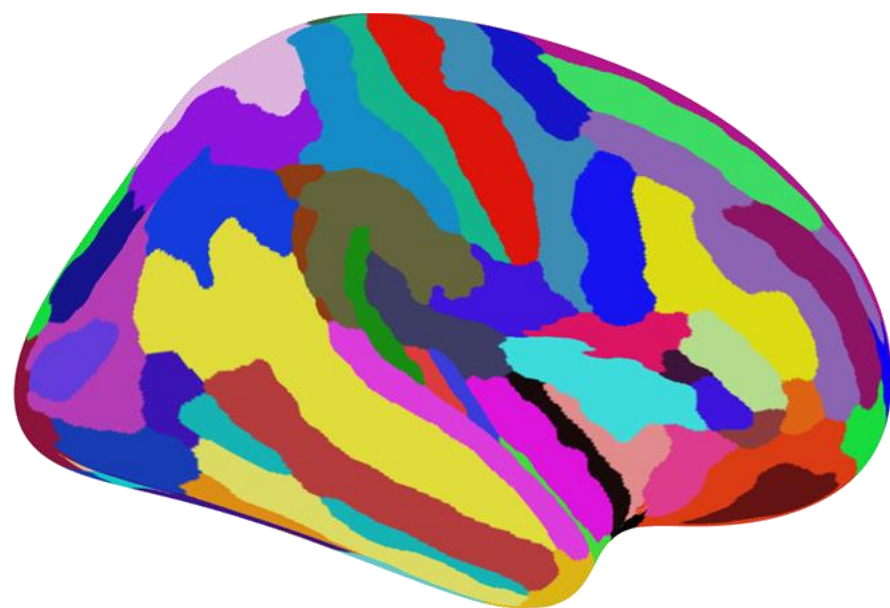
- Network
  - Set of nodes and edges
    - Nodes: pre-defined regions
    - Edges: connectivity (white matter fibre tracts) between regions



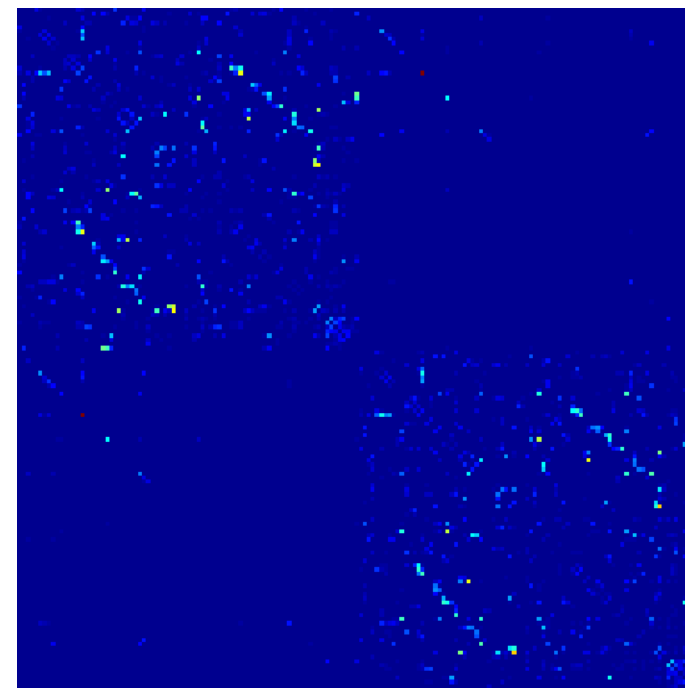


[Honey et al., 2007]

**Modes of brain connectivity**



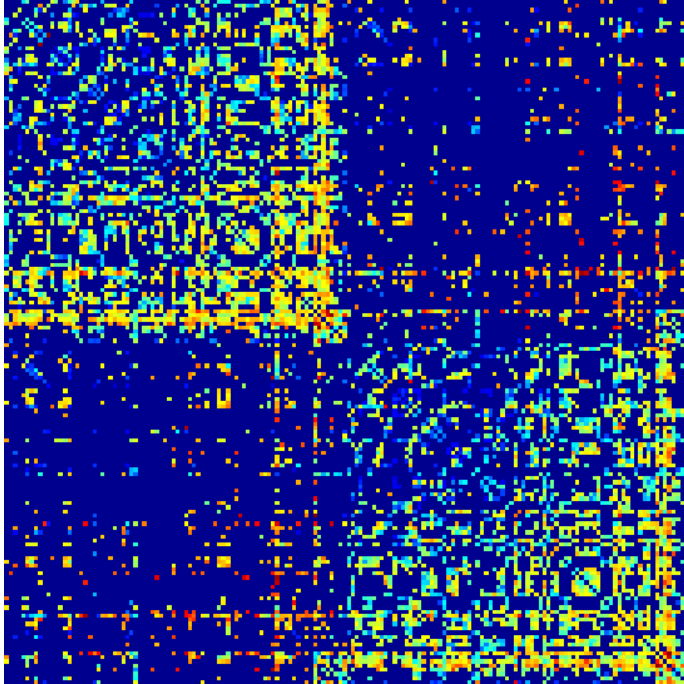
White matter tracts



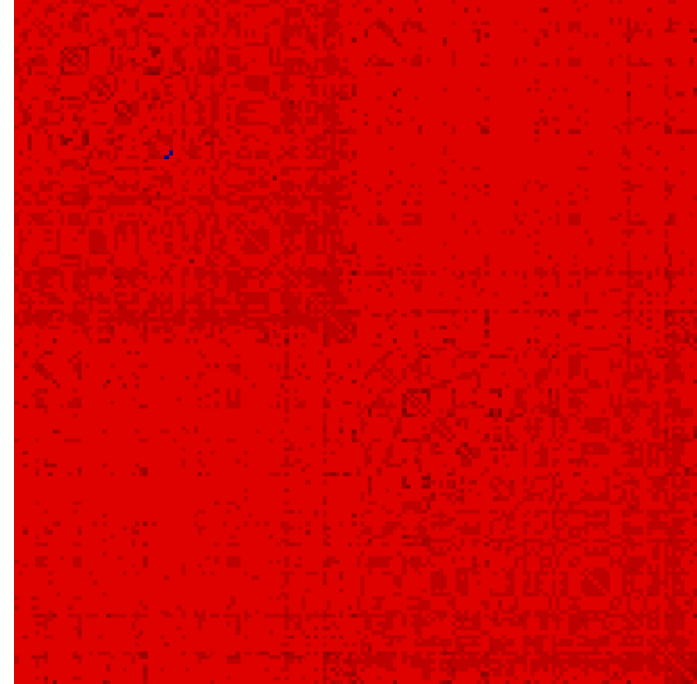
Tract count

**Structural network or connectome**





FA



MD

**Structural network based on diffusion tensor-derived scalar invariants**

- Input to machine learning models
  - Table of region-to-region connectivity (white matter fibre tracts) values

		Features			
		Brain regions 1 – 2 connectivity	Brain regions 1 – 3 connectivity	Brain regions 1 – 4 connectivity	...
Samples	Subject 1	-	-	-	-
	Subject 2	-	-	-	-
	Subject 3	-	-	-	-
	⋮	-	-	-	-

- Structural network map