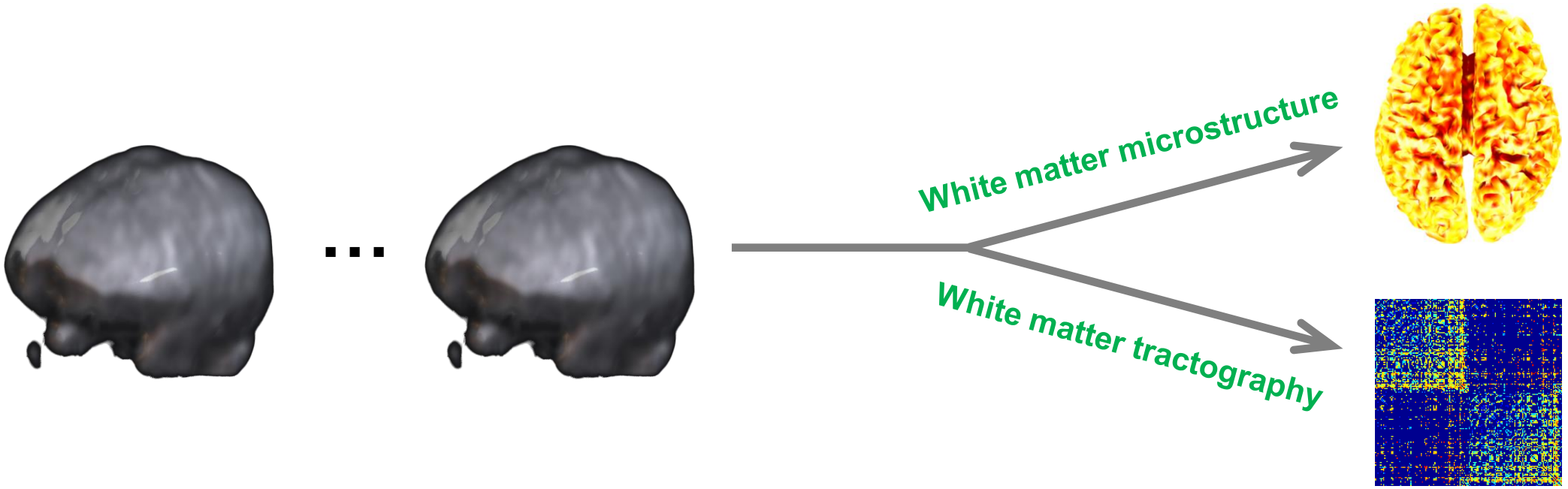
Medical/Bio Research Topics Ⅰ: Week 08 (25.04.2024)

Diffusion-weighted MRI (2): Data Processing

확산가중 자기공명영상 (2): 데이터 처리 방법

Brain Mapping with Diffusion-weighted MRI (dMRI)

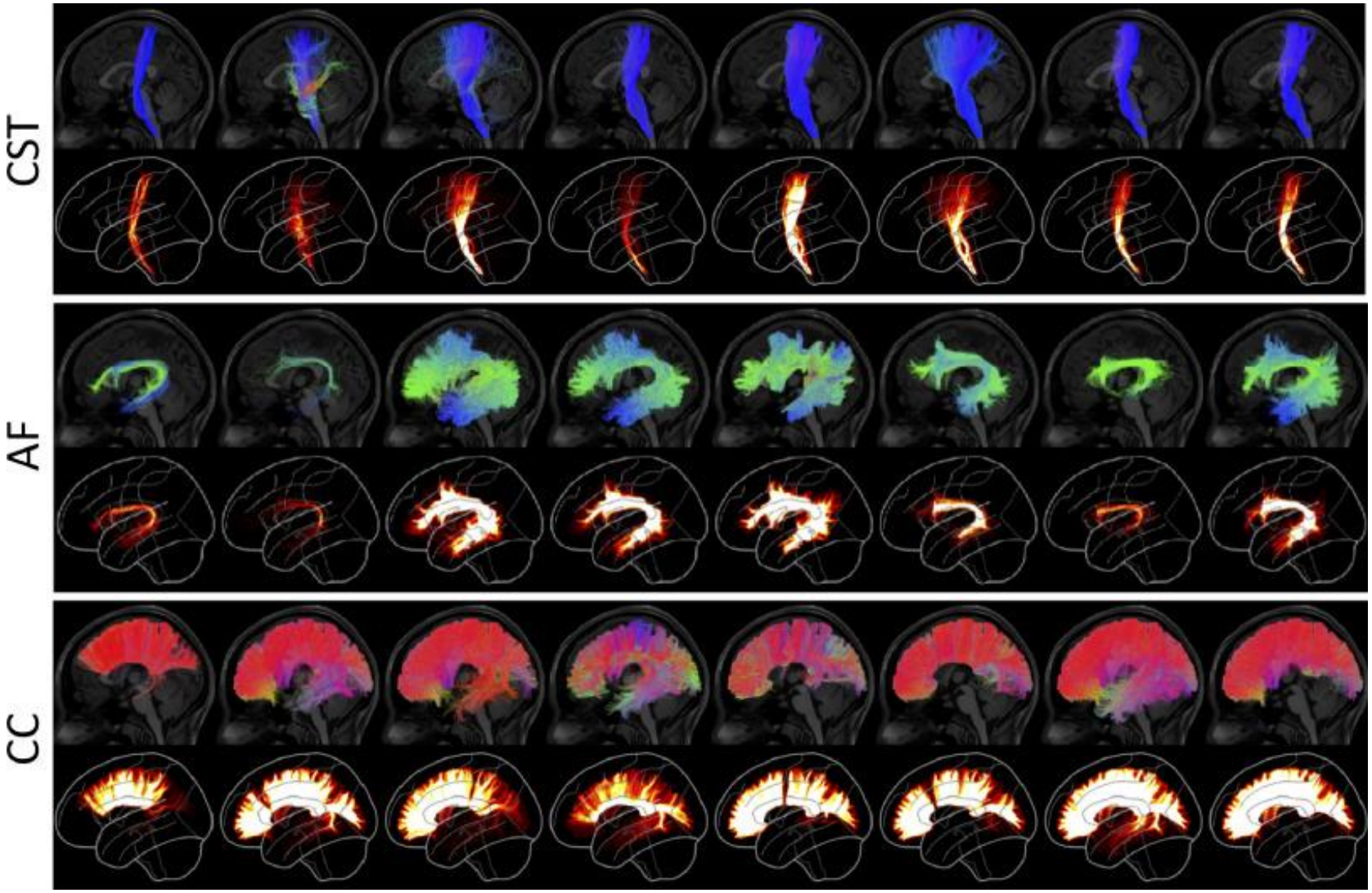
- Diffusion-weighted MRI



Analytical Variability in dMRI

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

[Schilling et al., 2021]



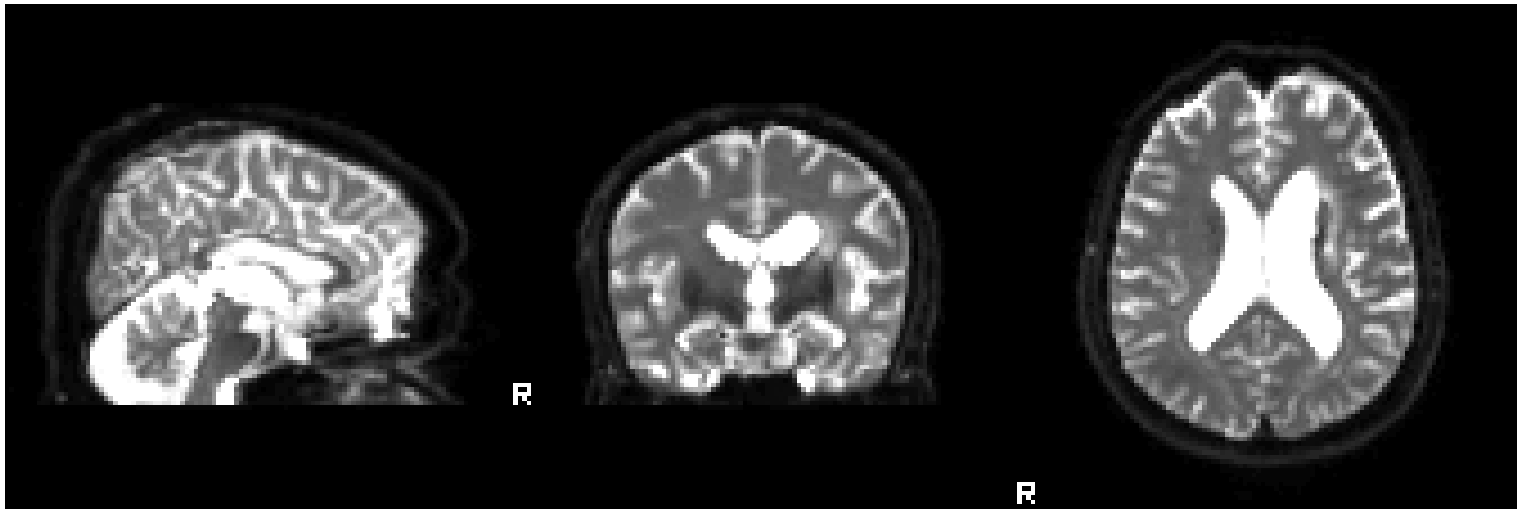
[Schilling et al., 2021]

Variation in protocols for white matter fibre bundle segmentation

Preprocessing

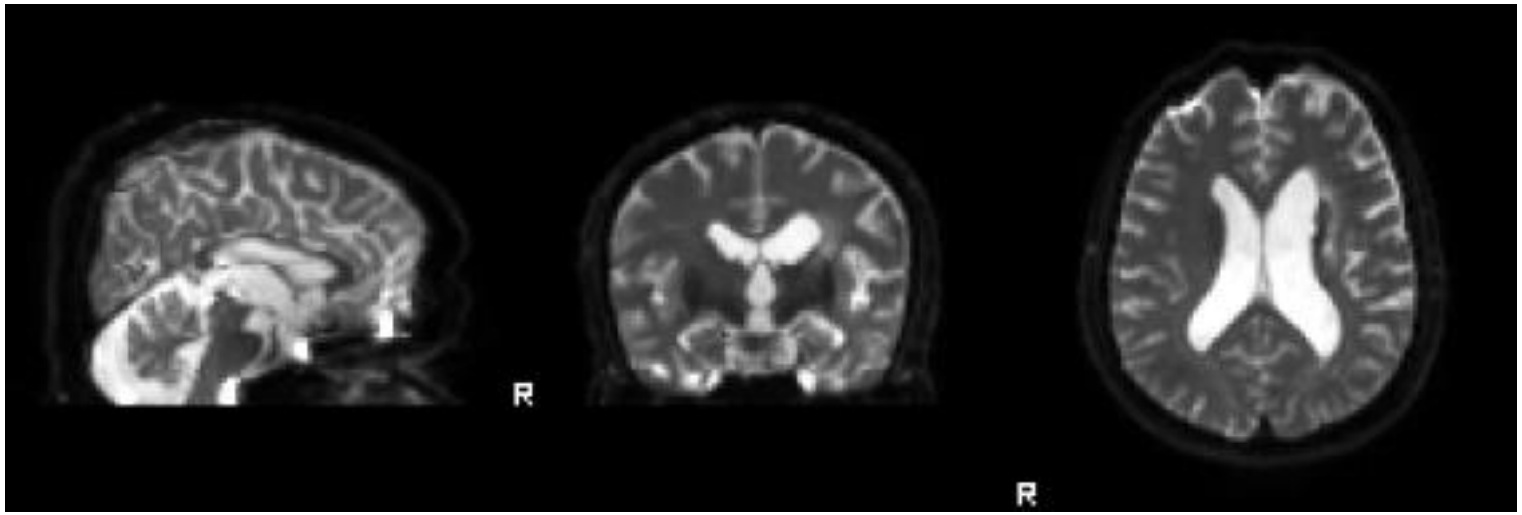
- Numerous steps to clean dMRI data before diffusion modelling
  - Correction for unwanted variation
    - Head motion
    - Eddy current-induced distortion
    - Inhomogeneity-induced distortion

[dMRI: Preprocessing]

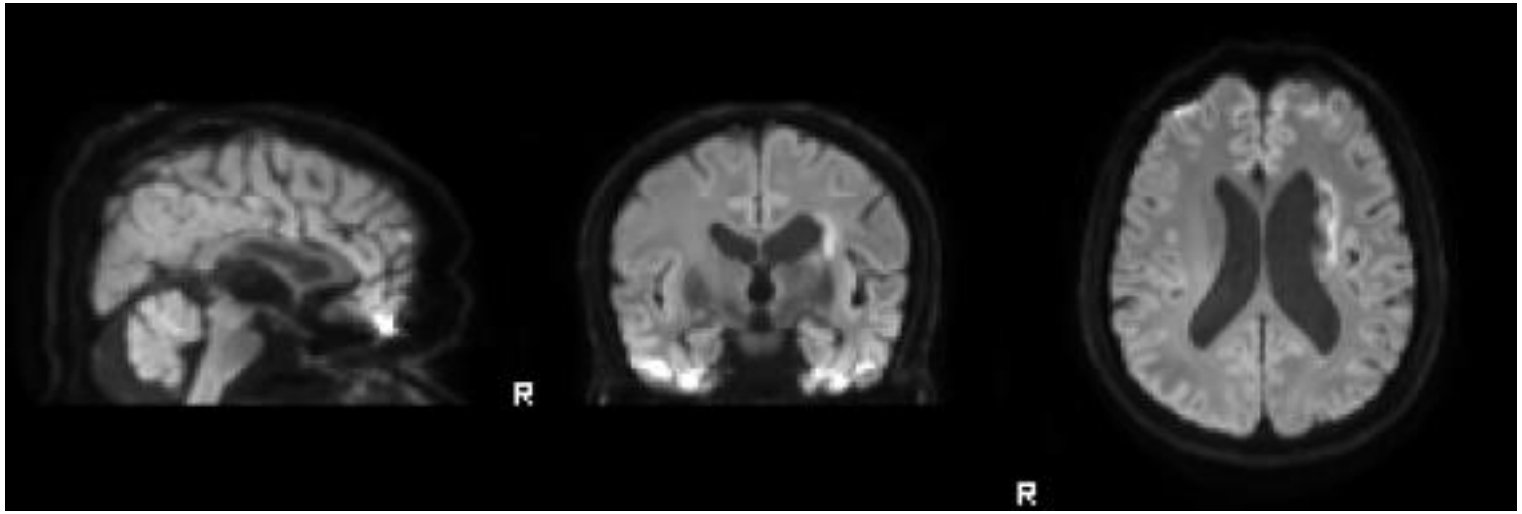


- 46 scans
  - 1 scan without diffusion weighting
  - 45 scans with diffusion weighting at $b = 1000$ s/mm^2

Average image for b = 0 s/mm^2



Average image for b = 1,000 s/mm^2



– *b*-values

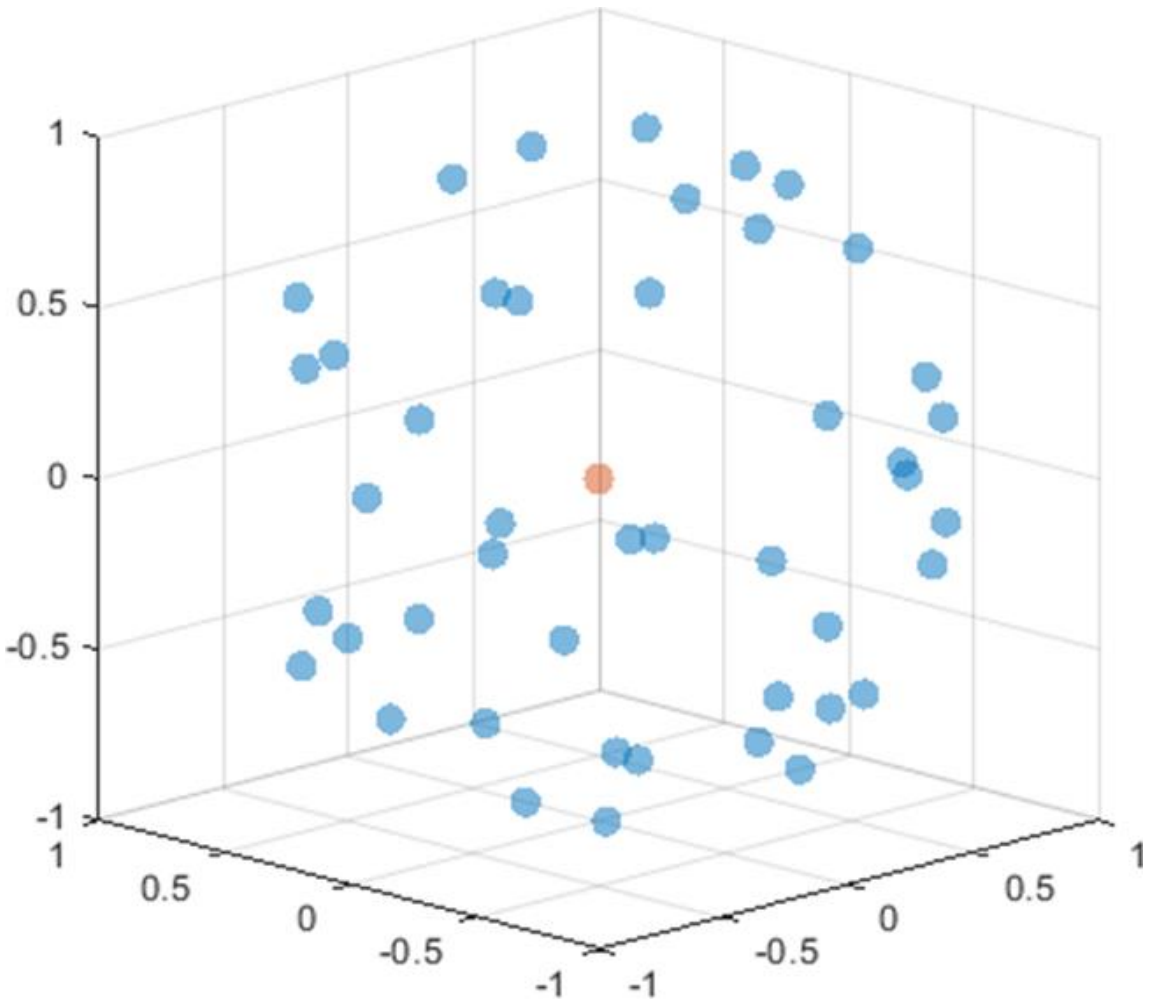
0	1000	1000	1000	1000	1000	1000	⋯ 1000

46 values

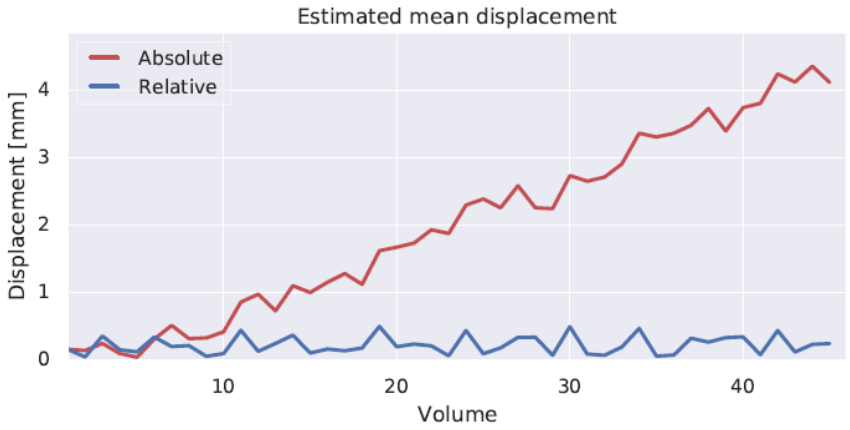
– *b*-vectors

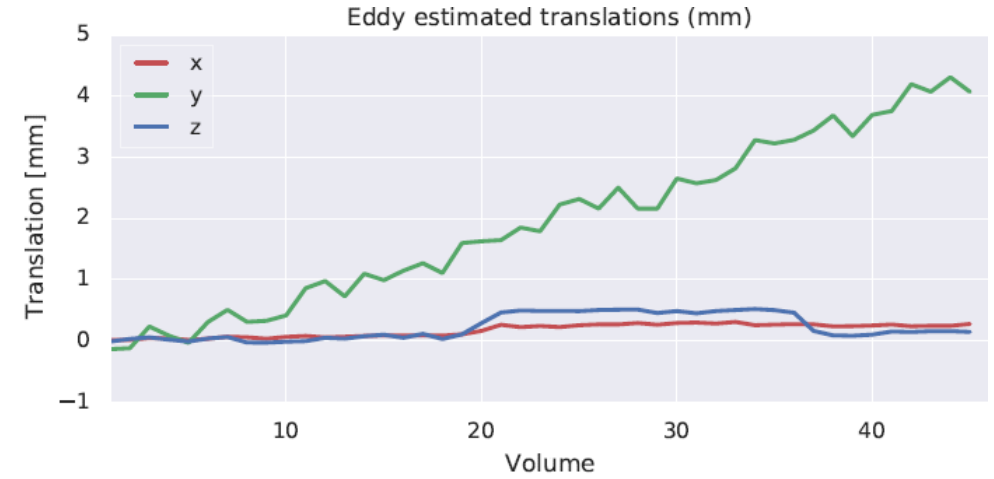
0	0.2488	-0.4396	0.6565	-0.3743	0.2818	⋯	0.4357
0	0.9672	0.7676	-0.0606	-0.5783	0.0936	⋯	0.8473
0	-0.0588	0.4671	-0.7513	0.7245	0.9545	⋯	0.3021

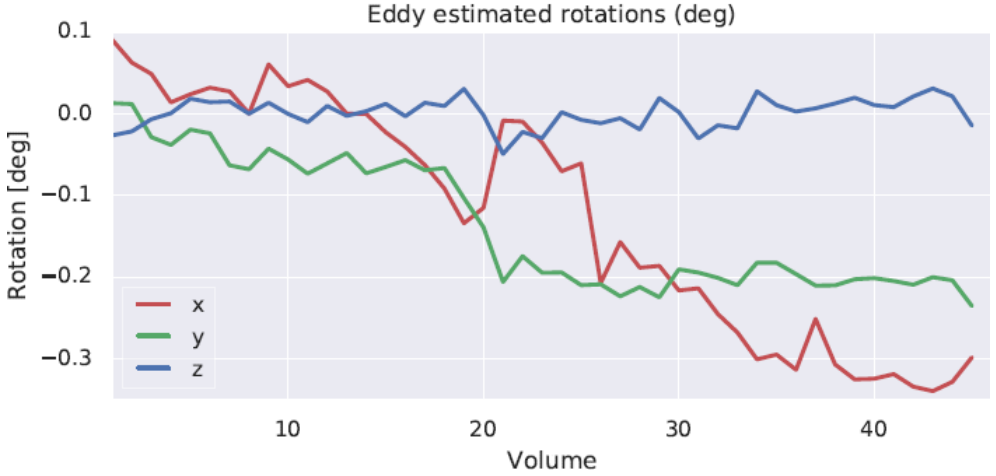
46 vectors

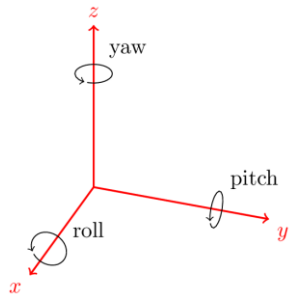


Diffusion-sensitizing gradient directions

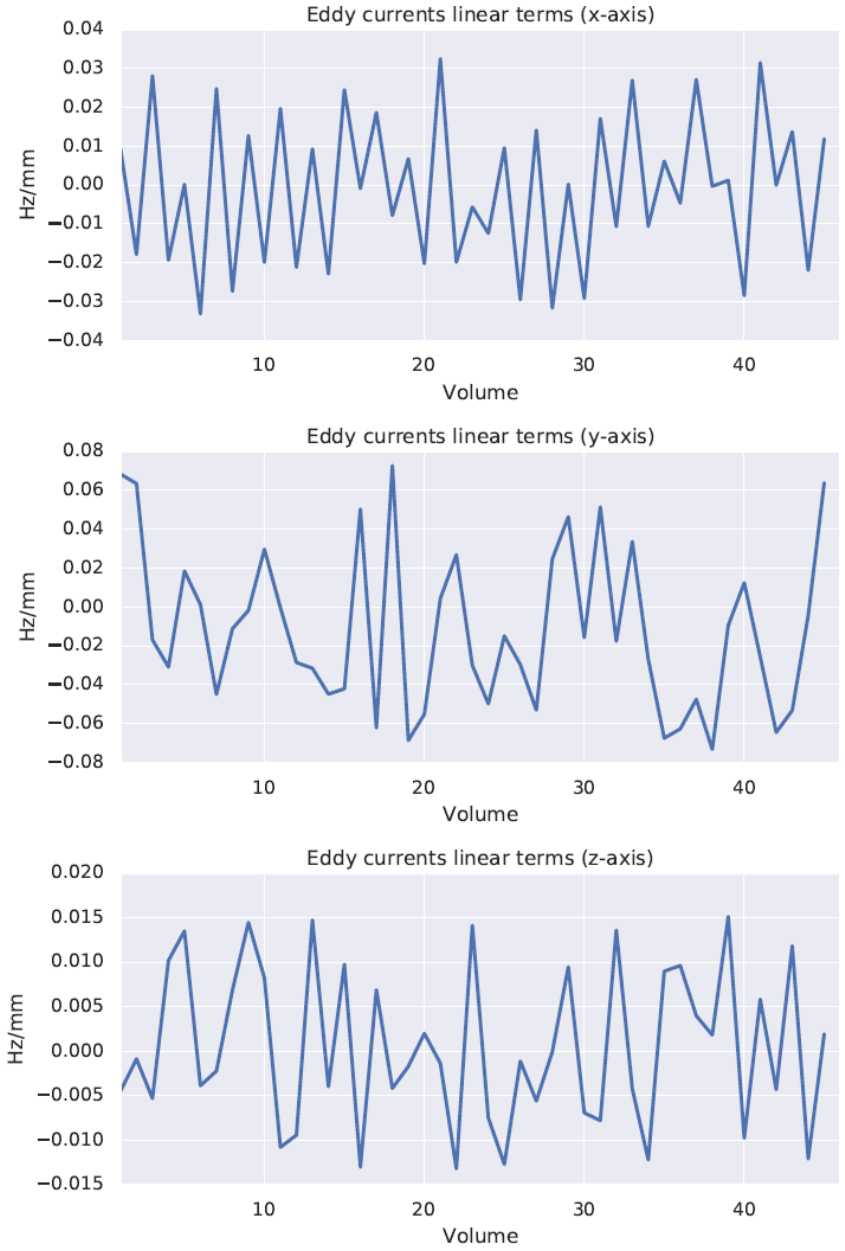








Estimated head motion

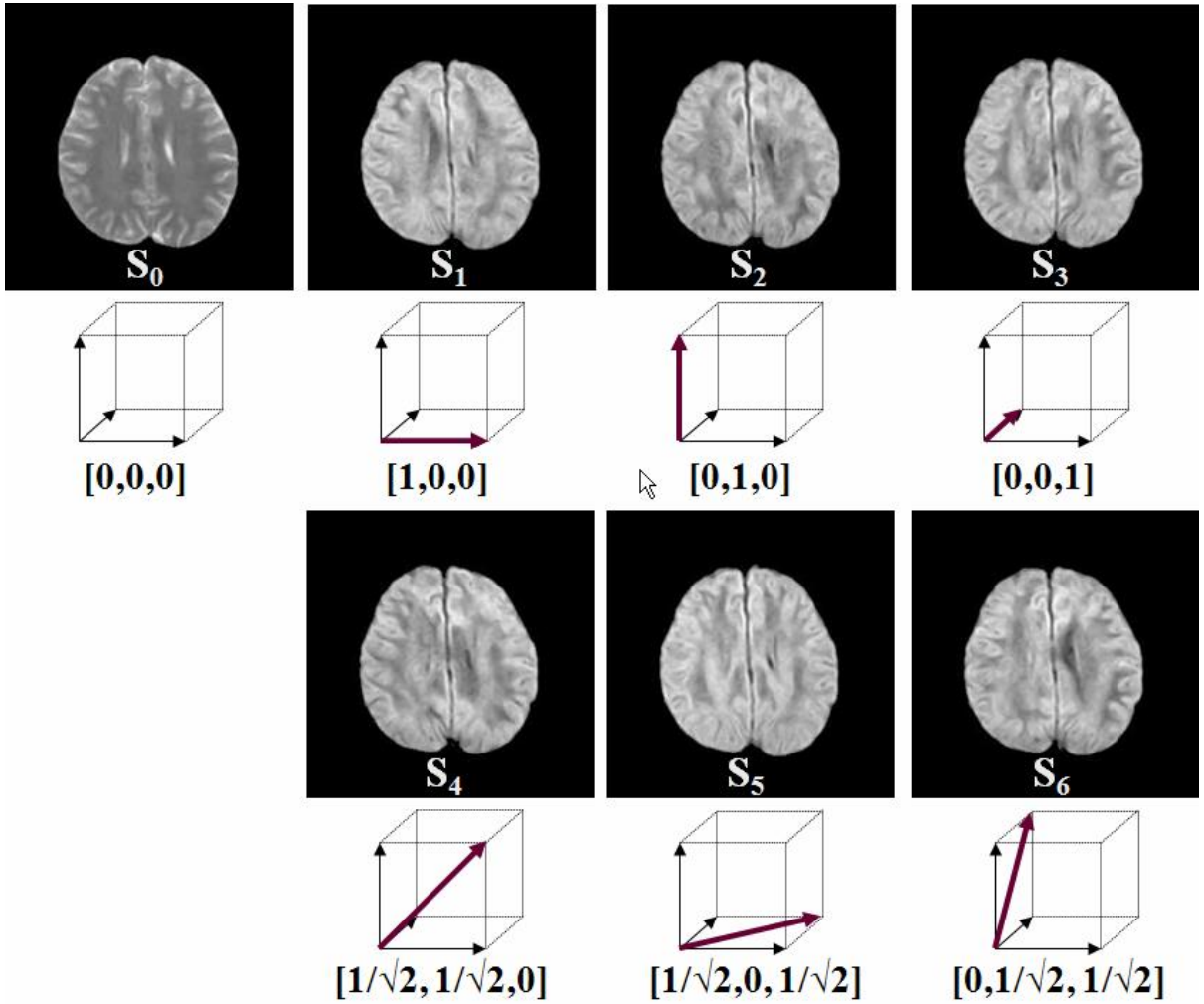


Estimated eddy currents

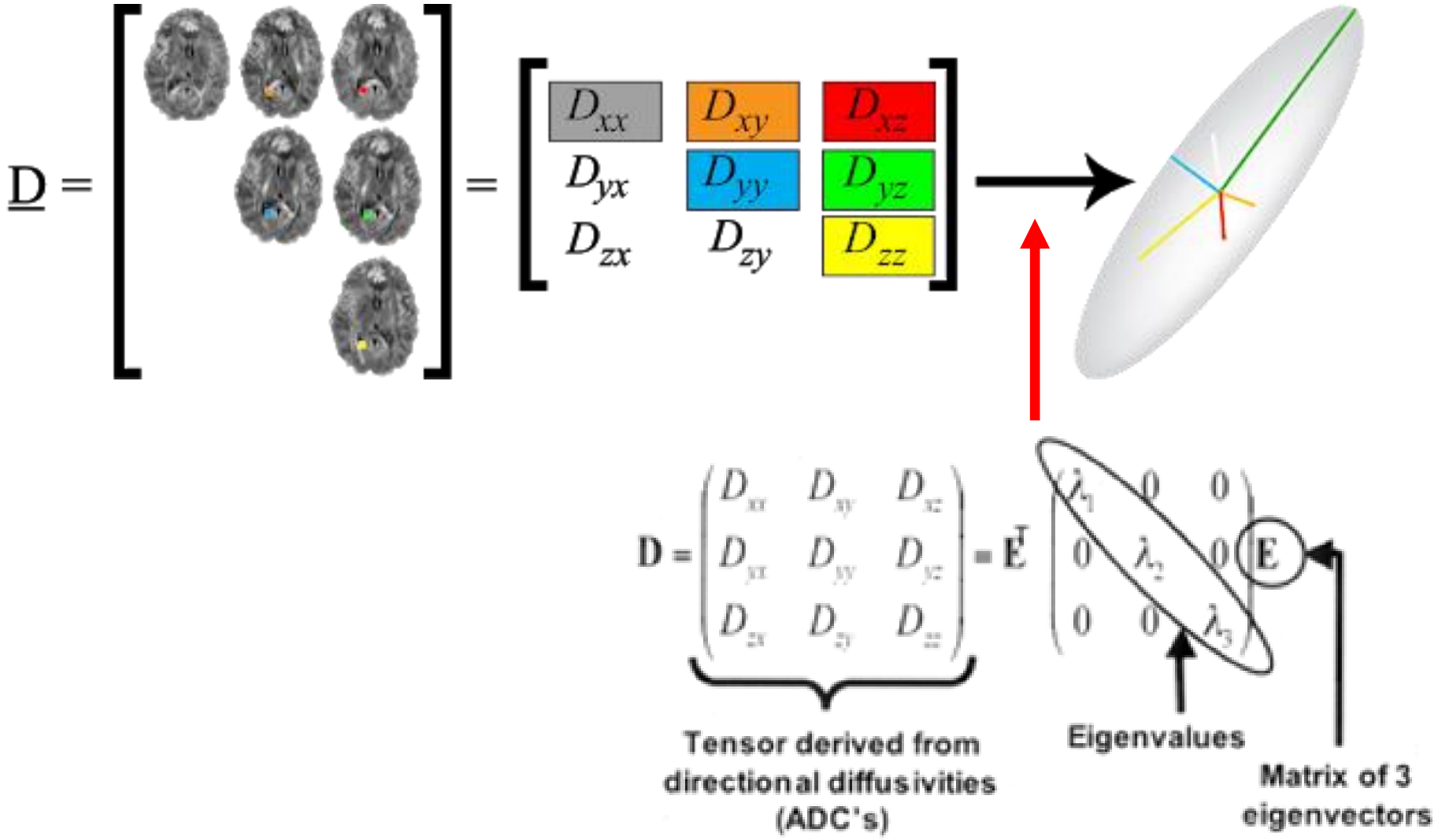
White Matter Microstructure

- 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: $\langle r^2 \rangle = 2Dt = \sim$ μm
- 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

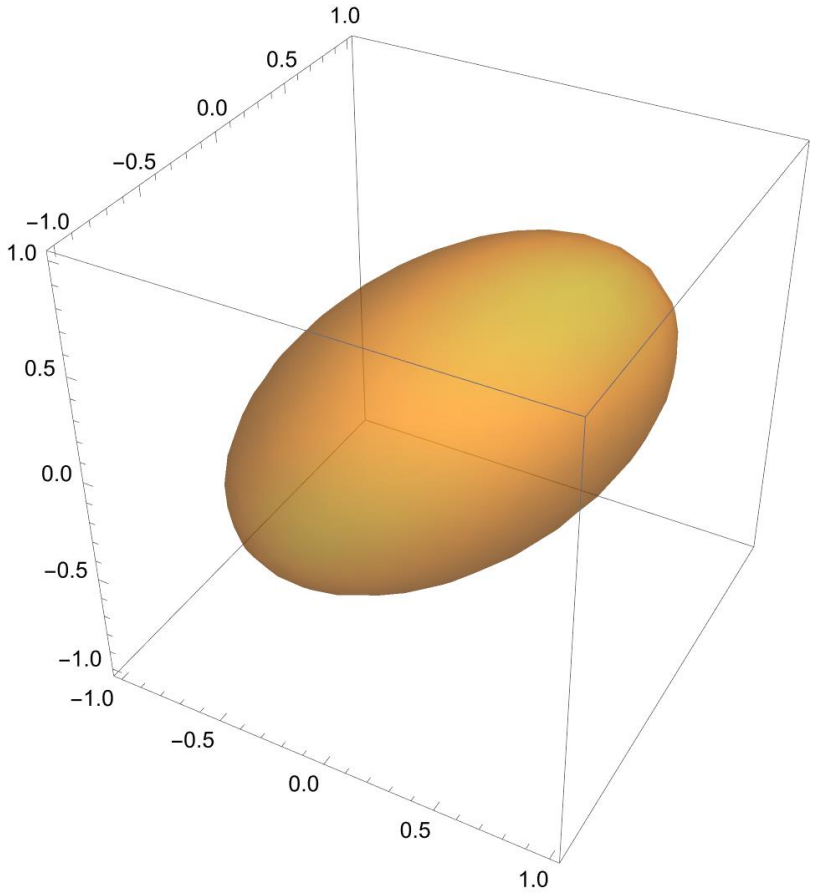


MRI signals measured without and with diffusion weighting

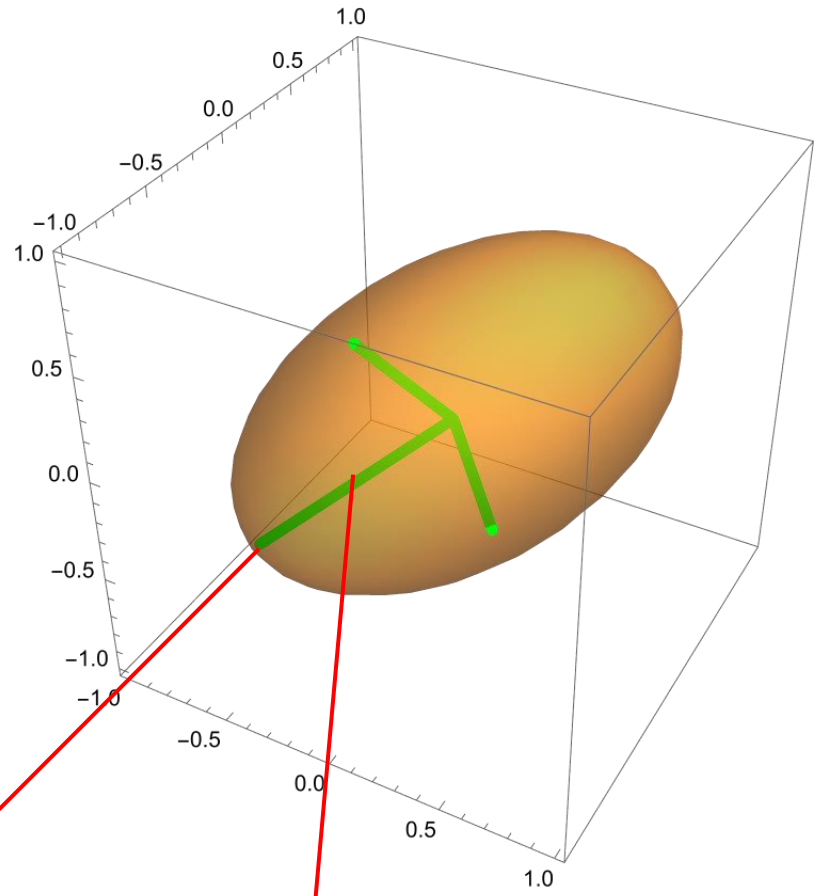


https://www.blog.brainsightai.com/post/from-dti-to-hardi]]

Diffusion tensor and its ellipsoid representation

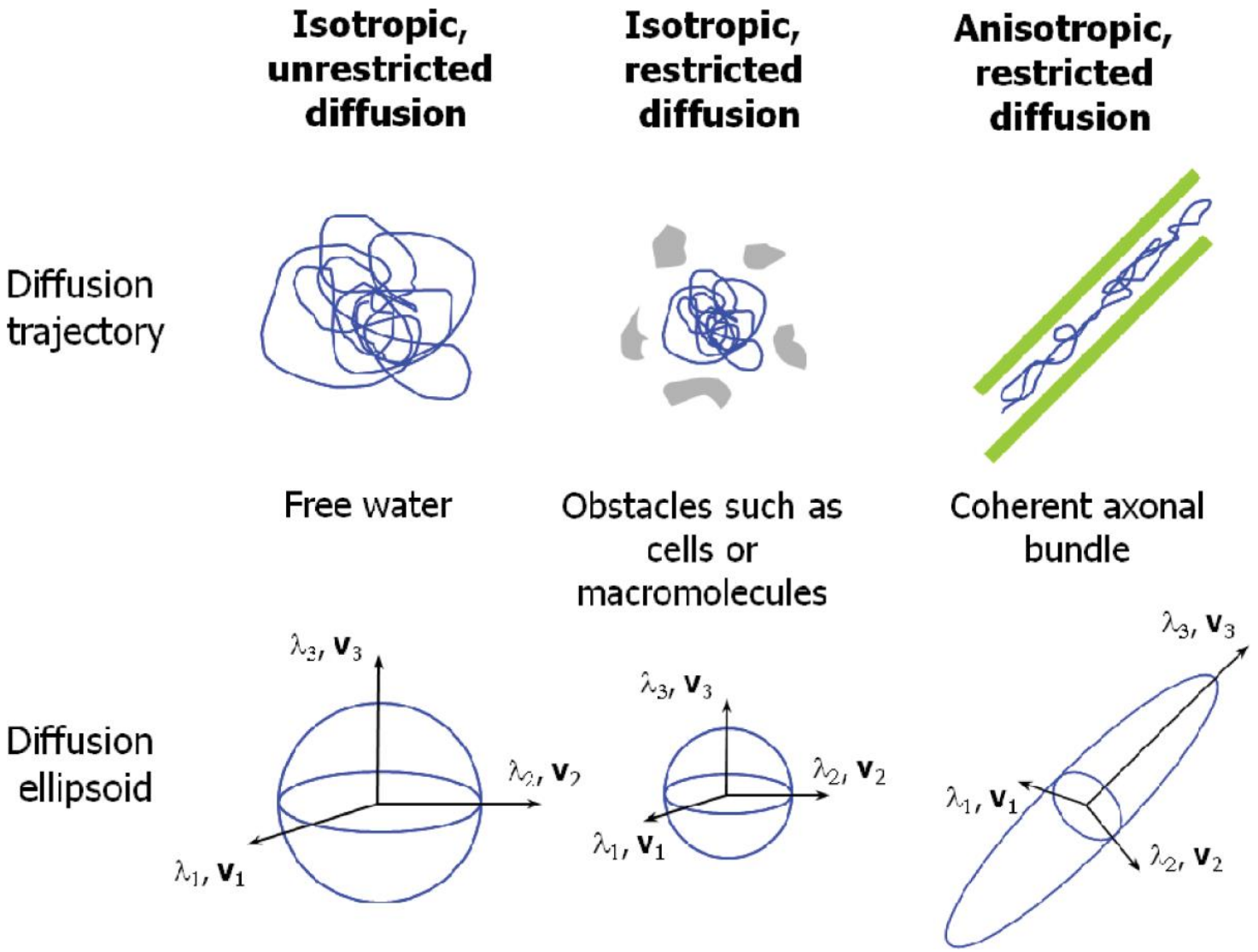


Eigendecomposition



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

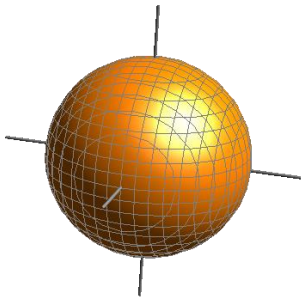
$$\begin{pmatrix} 0.68 & -0.69 & -0.25 \\ -0.30 & -0.57 & 0.76 \\ -0.67 & -0.44 & -0.59 \end{pmatrix}^{T} \begin{pmatrix} 30.4 & 0 & 0 \\ 0 & 20.1 & 0 \\ 0 & 0 & 9,5 \end{pmatrix} \begin{pmatrix} 0.68 & -0.69 & -0.25 \\ -0.30 & -0.57 & 0.76 \\ -0.67 & -0.44 & -0.59 \end{pmatrix}$$



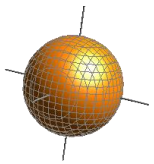
[Geva et al., 2011]

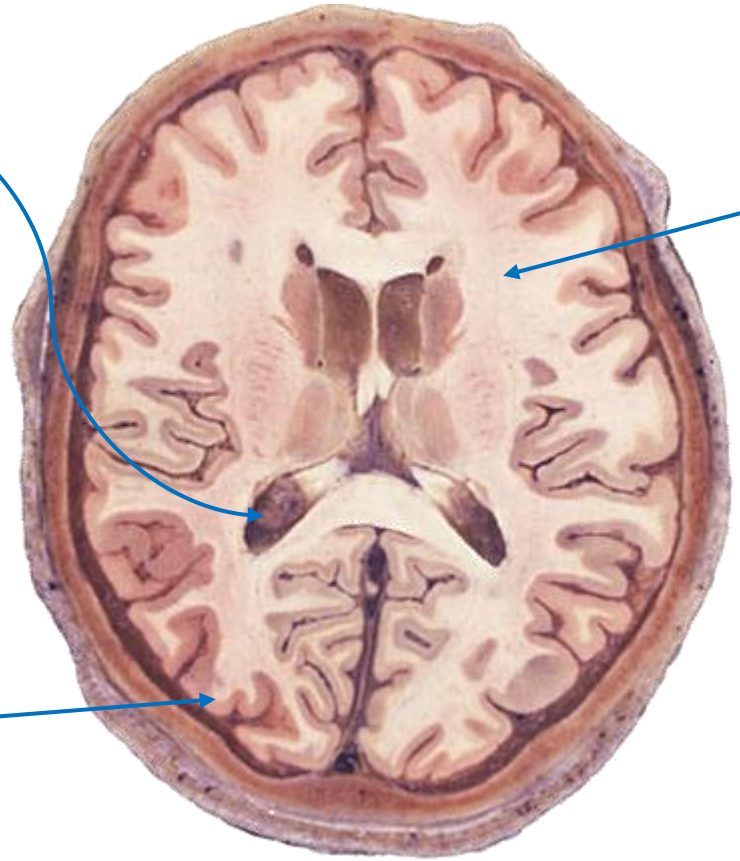
Isotropic and anisotropic diffusion represented by ellipsoids

CSF
Isotropic, unrestricted diffusion

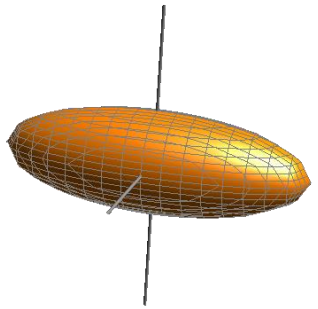


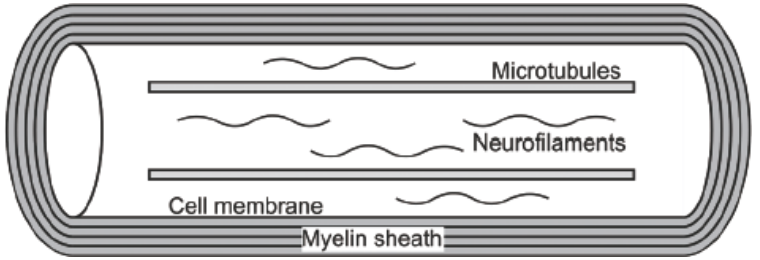
Grey matter
Isotropic, restricted diffusion





White matter
Anisotropic, restricted diffusion

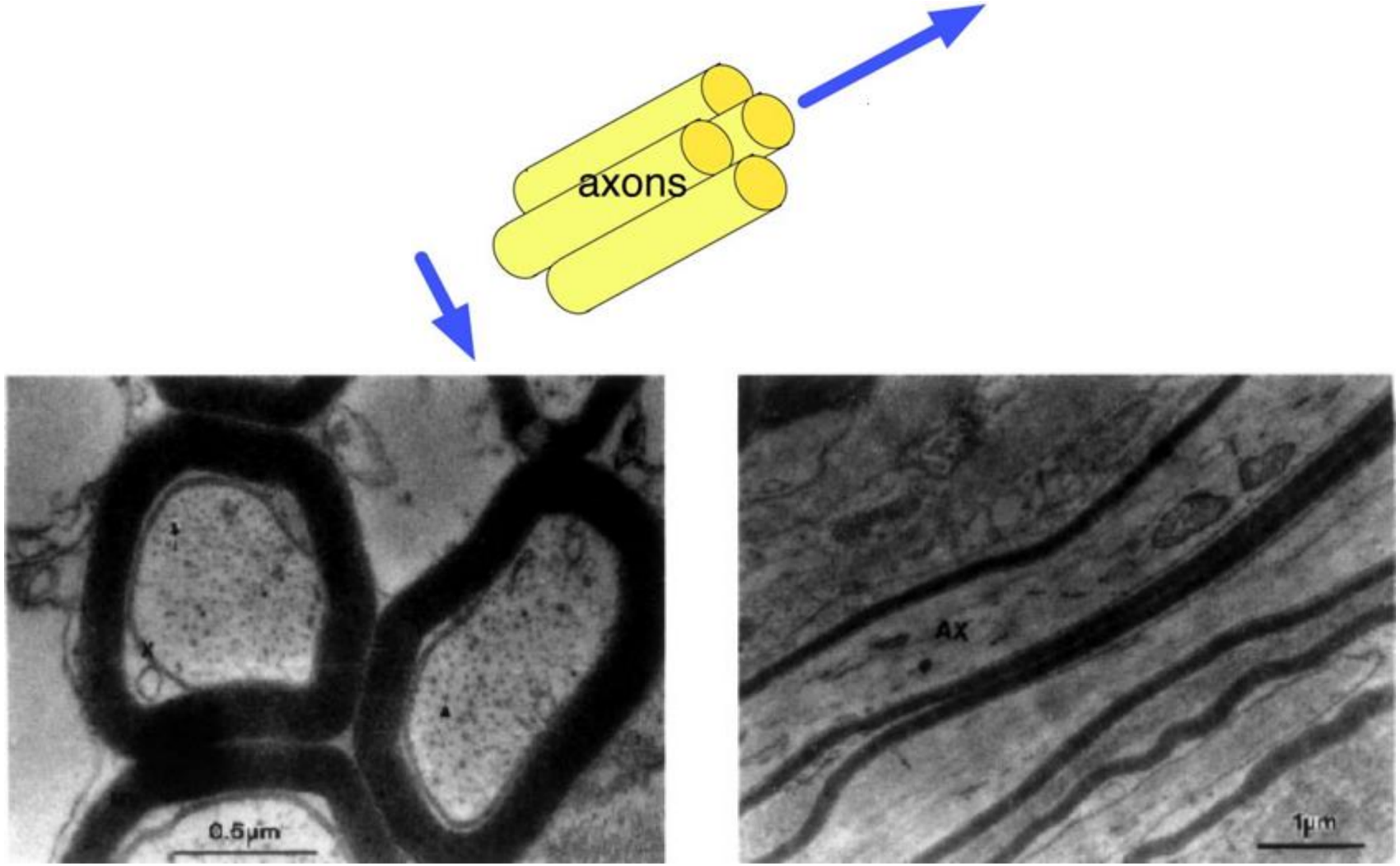




Potential sources of diffusion anisotropy
- Cytoskeleton
  - Microtubules (25 nm diameter)
  - Neurofilaments (10 nm diameter)
  - Microfilaments (7 nm diameter)
- Axonal membranes
- Myelin sheath

[Noguerol et al., 2017]]

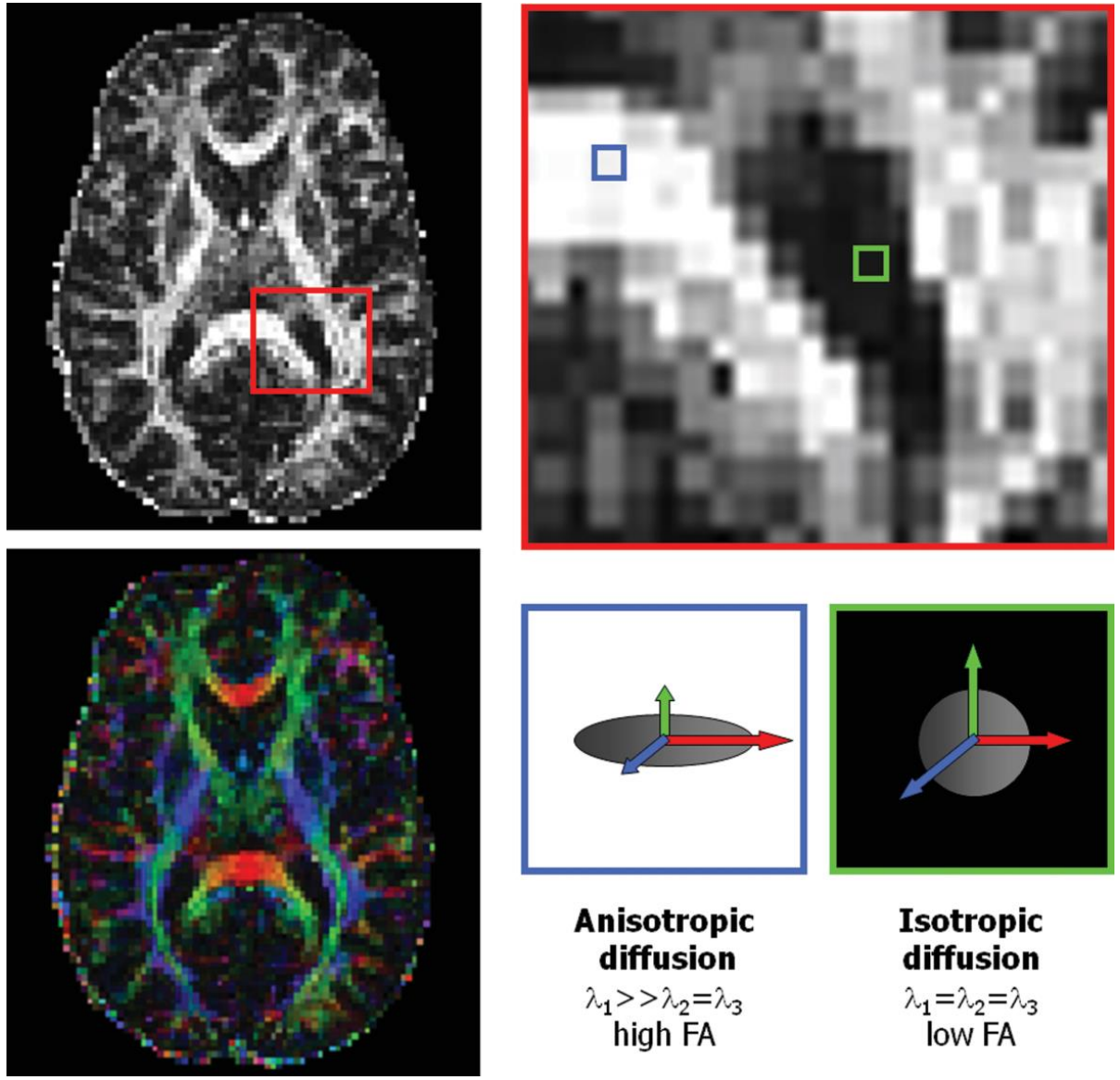
Isotropic and anisotropic diffusion in brain tissues



[Beaulieu, 2002]]

Transverse and longitudinal sections of myelinated optic nerves of the garfish

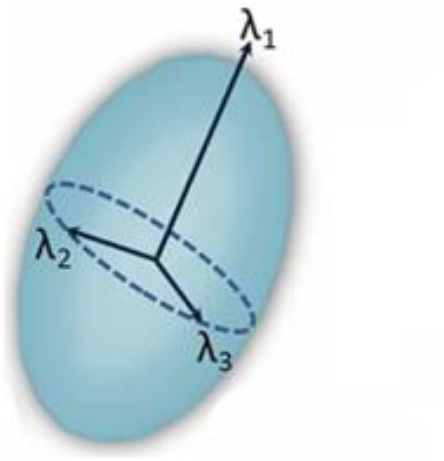
- Scalar invariants that are quantities independent of the coordinate system in which the diffusion tensor is expressed
  - Characterize aspects of water molecular diffusion, such as the magnitude and anisotropy (directional dependence), offering insights into tissue structure and organization
  - Fractional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



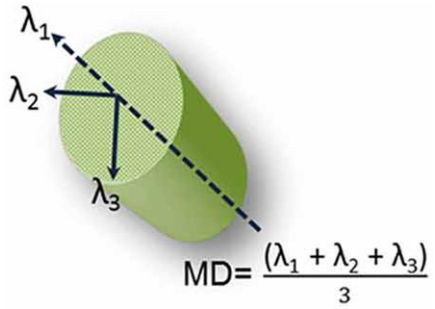
[Geva et al., 2011]

Directional information added to an FA map

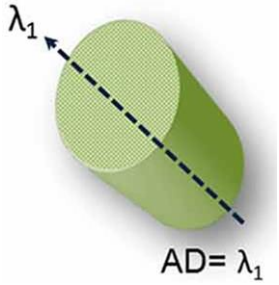
[dMRI: Diffusion Modelling]



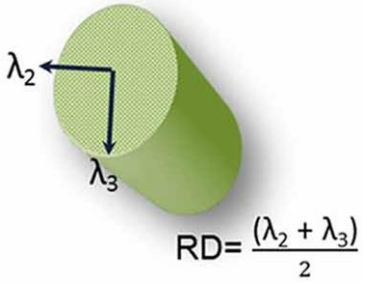
$$FA = \sqrt{\frac{1}{2}} \cdot \frac{\sqrt{(\lambda_1 - \lambda_2)^2 + (\lambda_2 - \lambda_3)^2 + (\lambda_3 - \lambda_1)^2}}{\sqrt{(\lambda_1)^2 + (\lambda_2)^2 + (\lambda_3)^2}}$$



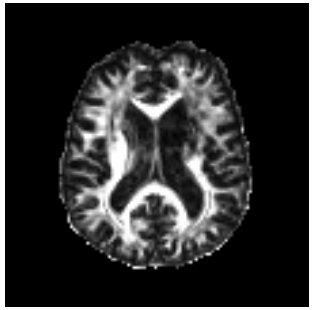
$$MD = \frac{(\lambda_1 + \lambda_2 + \lambda_3)}{3}$$



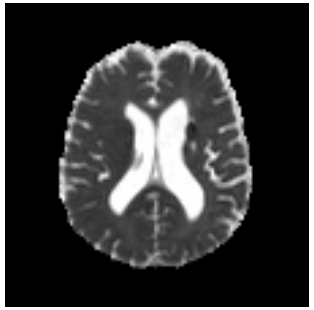
$$AD = \lambda_1$$



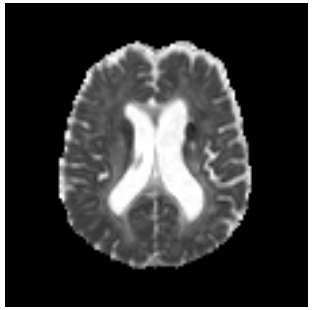
$$RD = \frac{(\lambda_2 + \lambda_3)}{2}$$



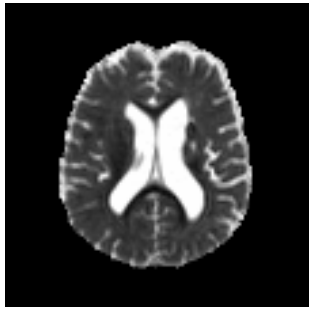
FA



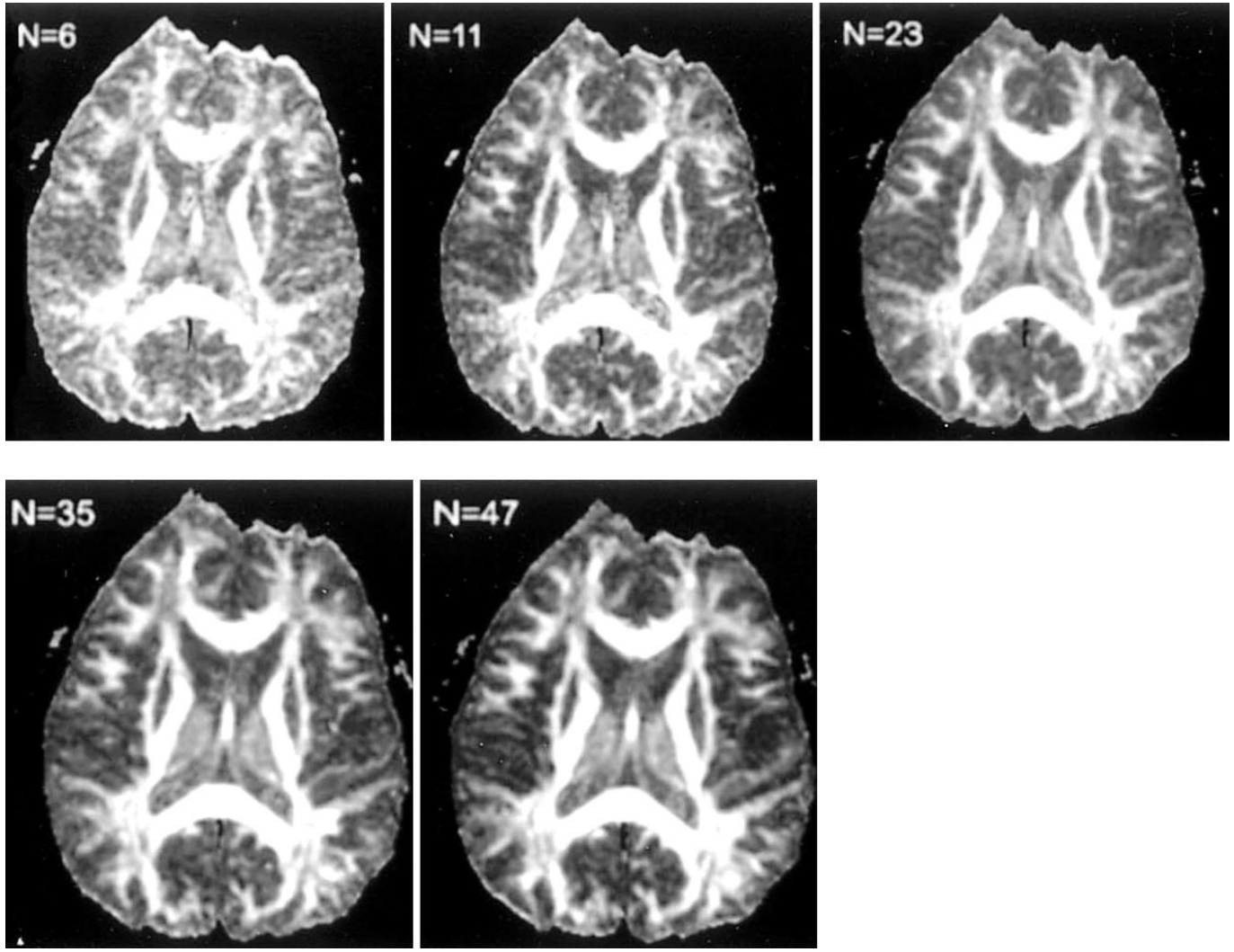
MD



AD

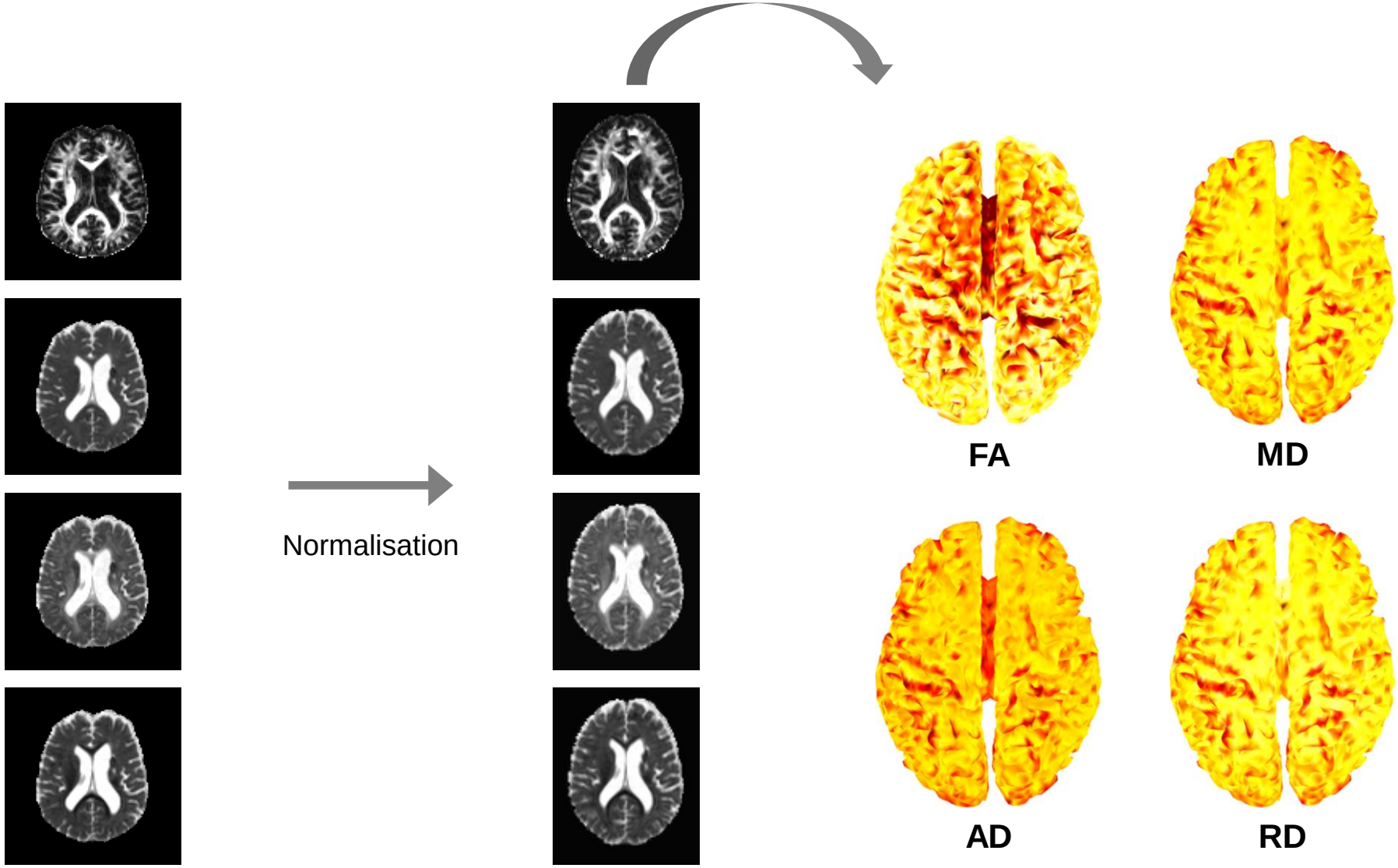


RD



[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 ~

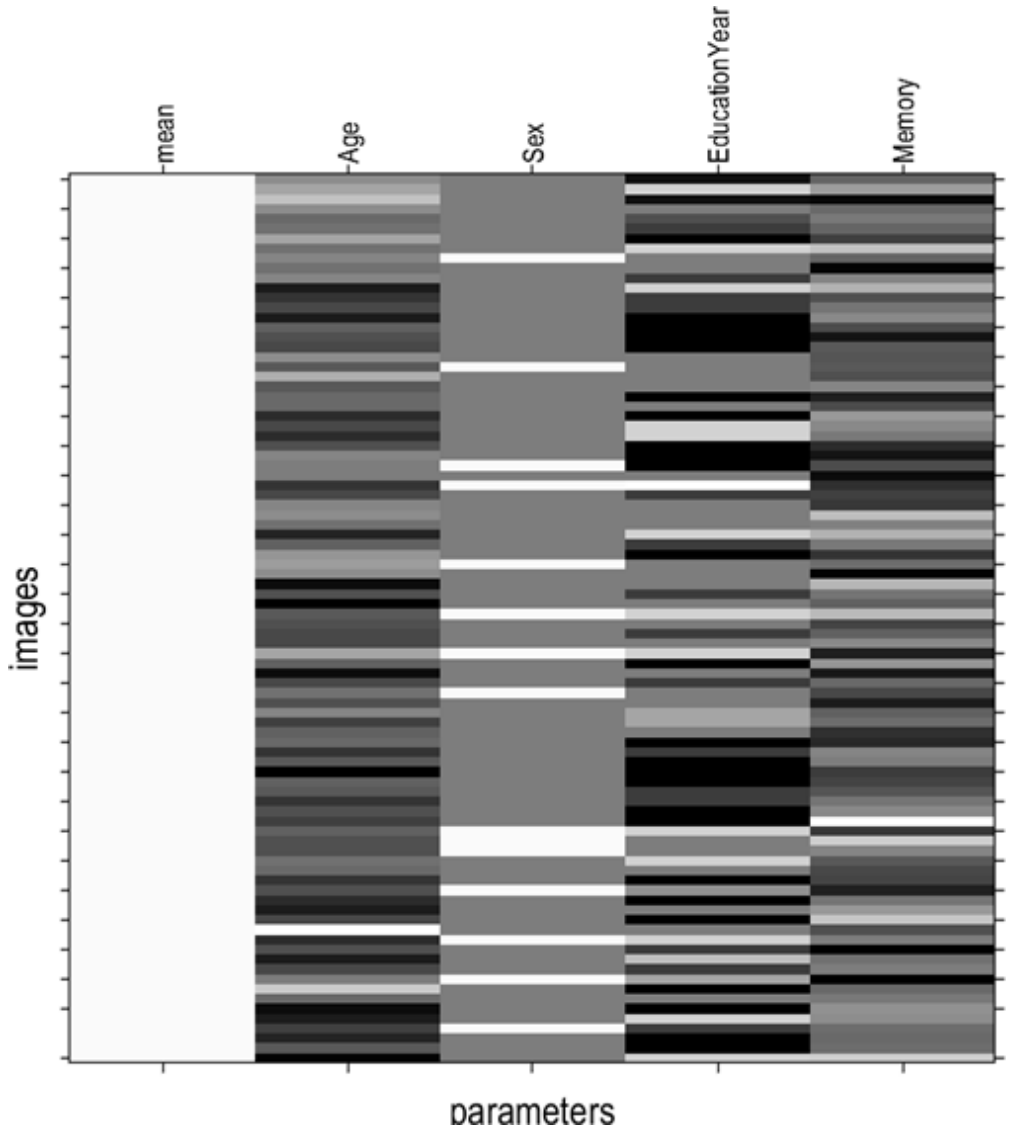
  Age +

  Sex +

  Education year +

  Memory performance

Design matrix



Output

Regression

Positive correlaton

Negative correlation

- MD ~
  - 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 →

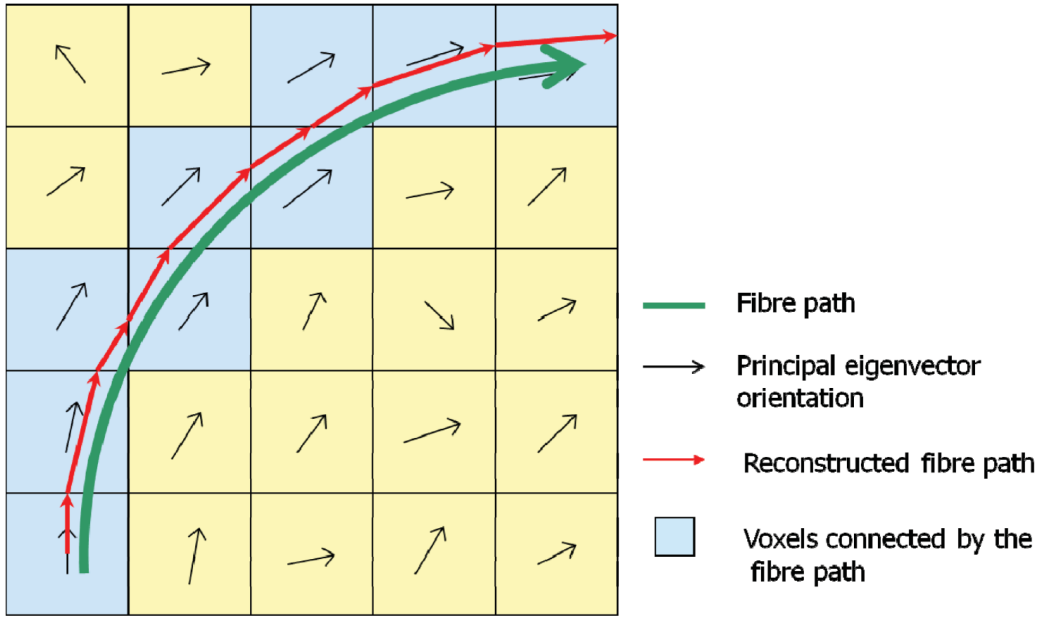
Samples ↓

	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

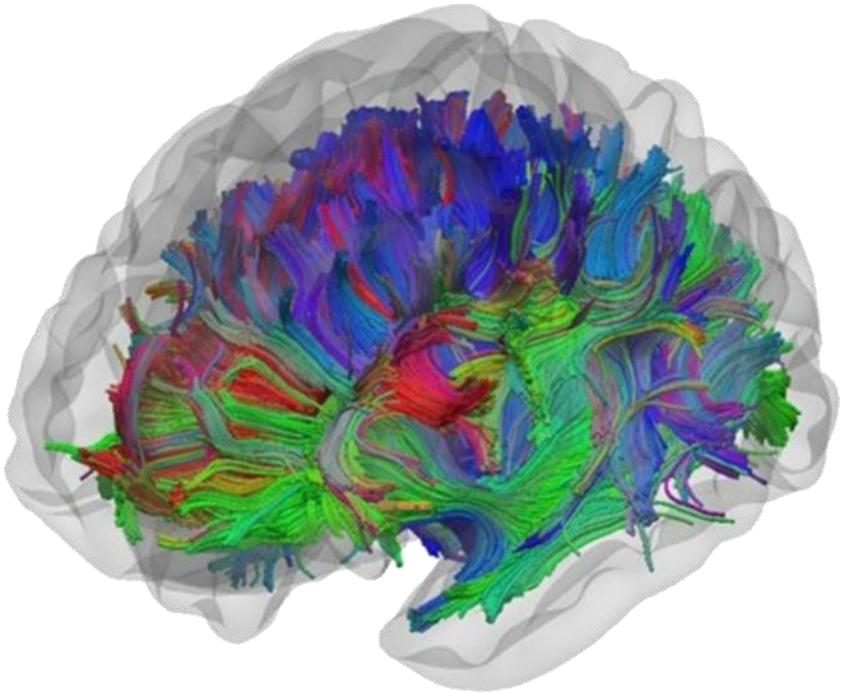
White Matter Tractography

- 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

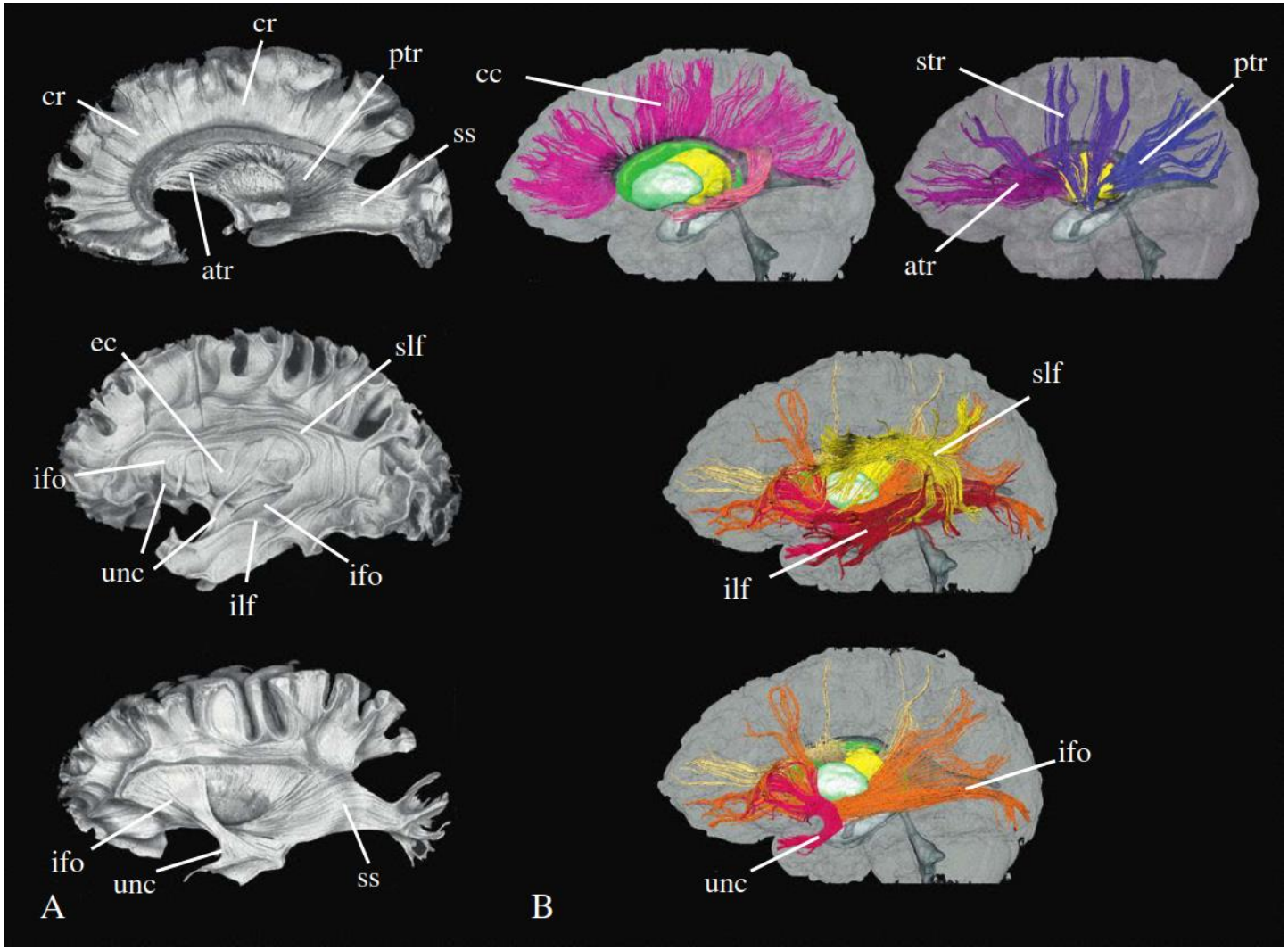
Many times across the brain



White matter fibre tracts

[Geva et al.,2011]

White matter tractography

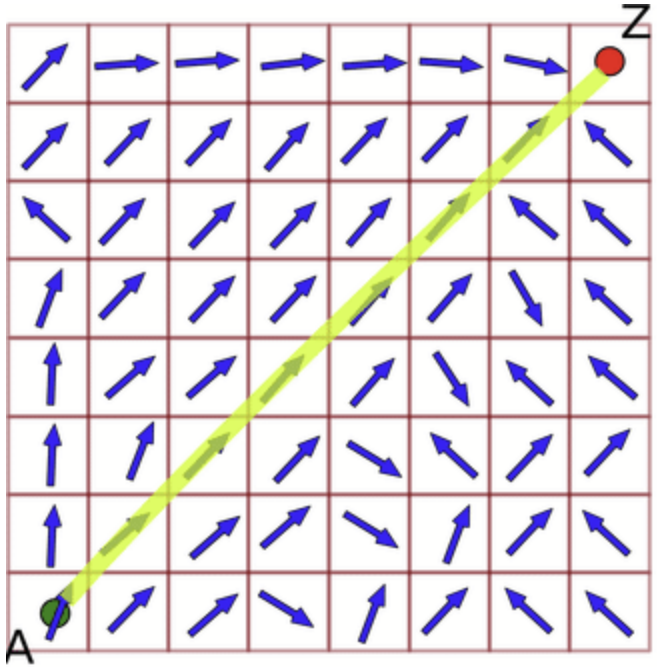


[Oishi et al., 2011]

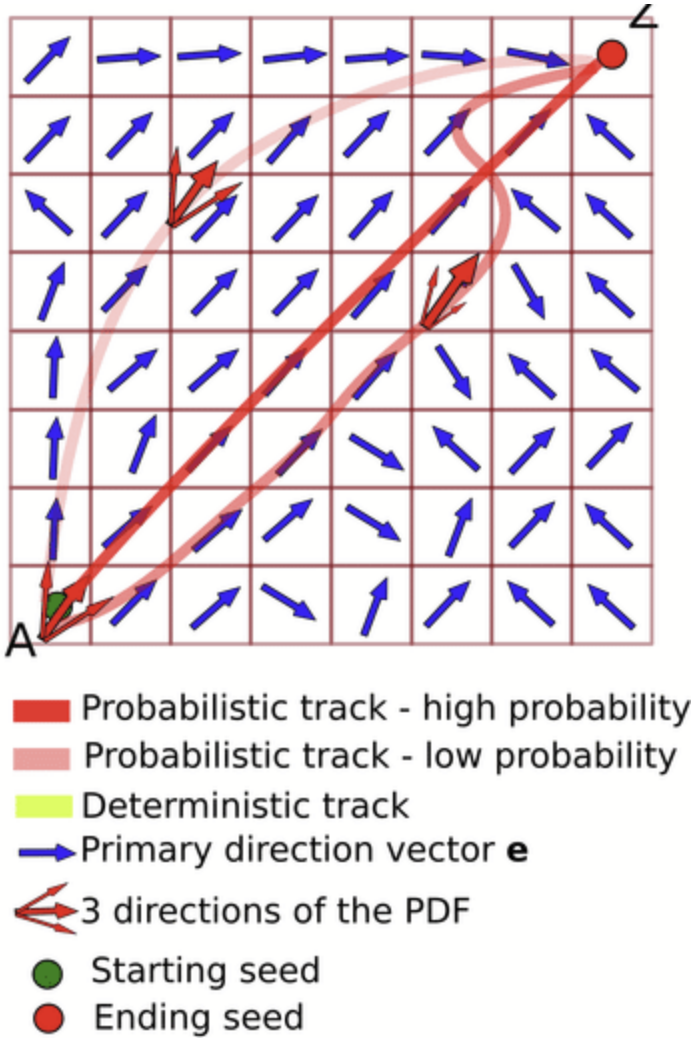
Comparison between postmortem preparation and dMRI-based white matter reconstructions

- 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

Deterministic



Probabilistic

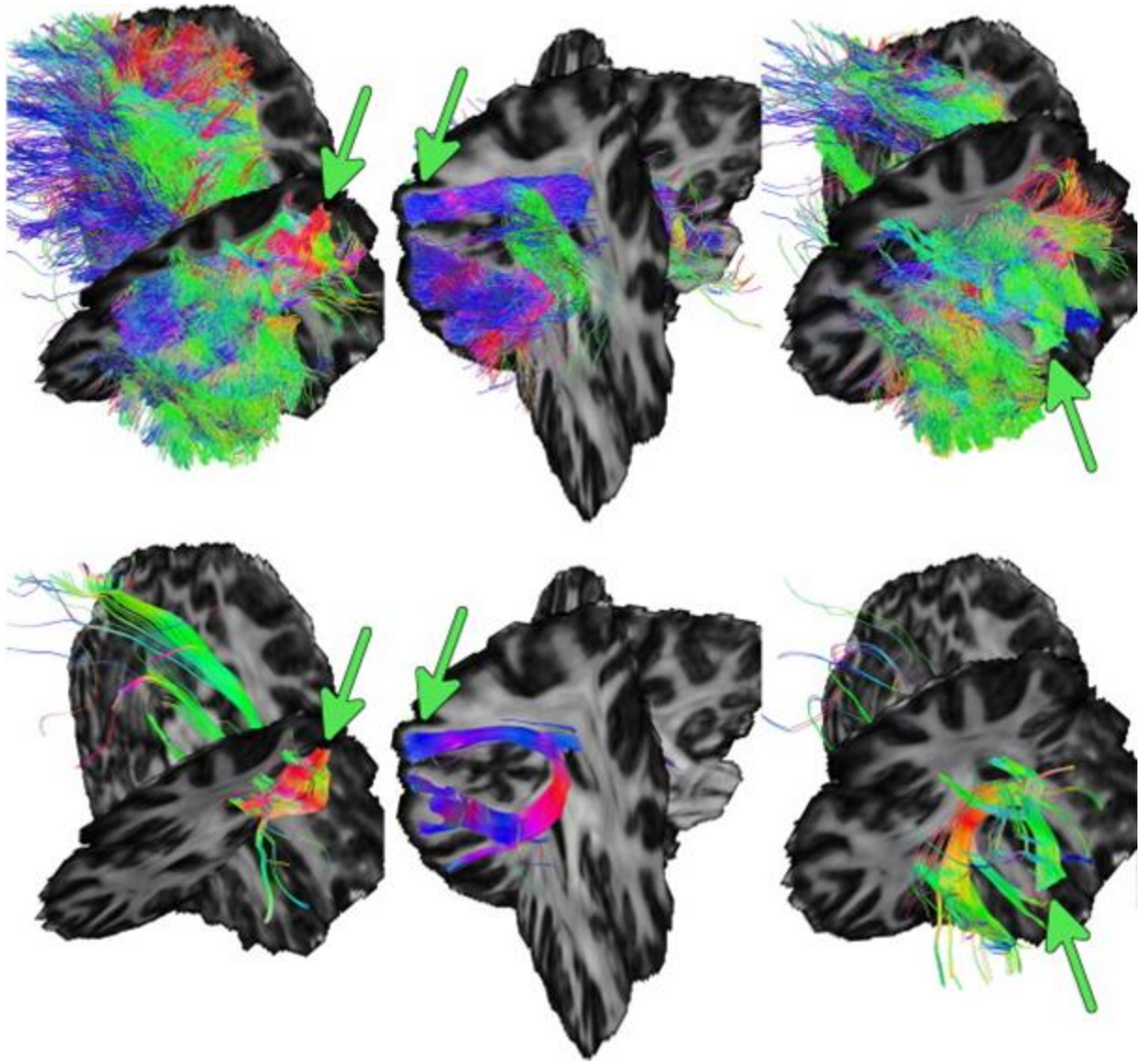


[Garyfallidis, 2012]

Deterministic and probabilistic ways for white matter tractography

Probabilistic

Deterministic



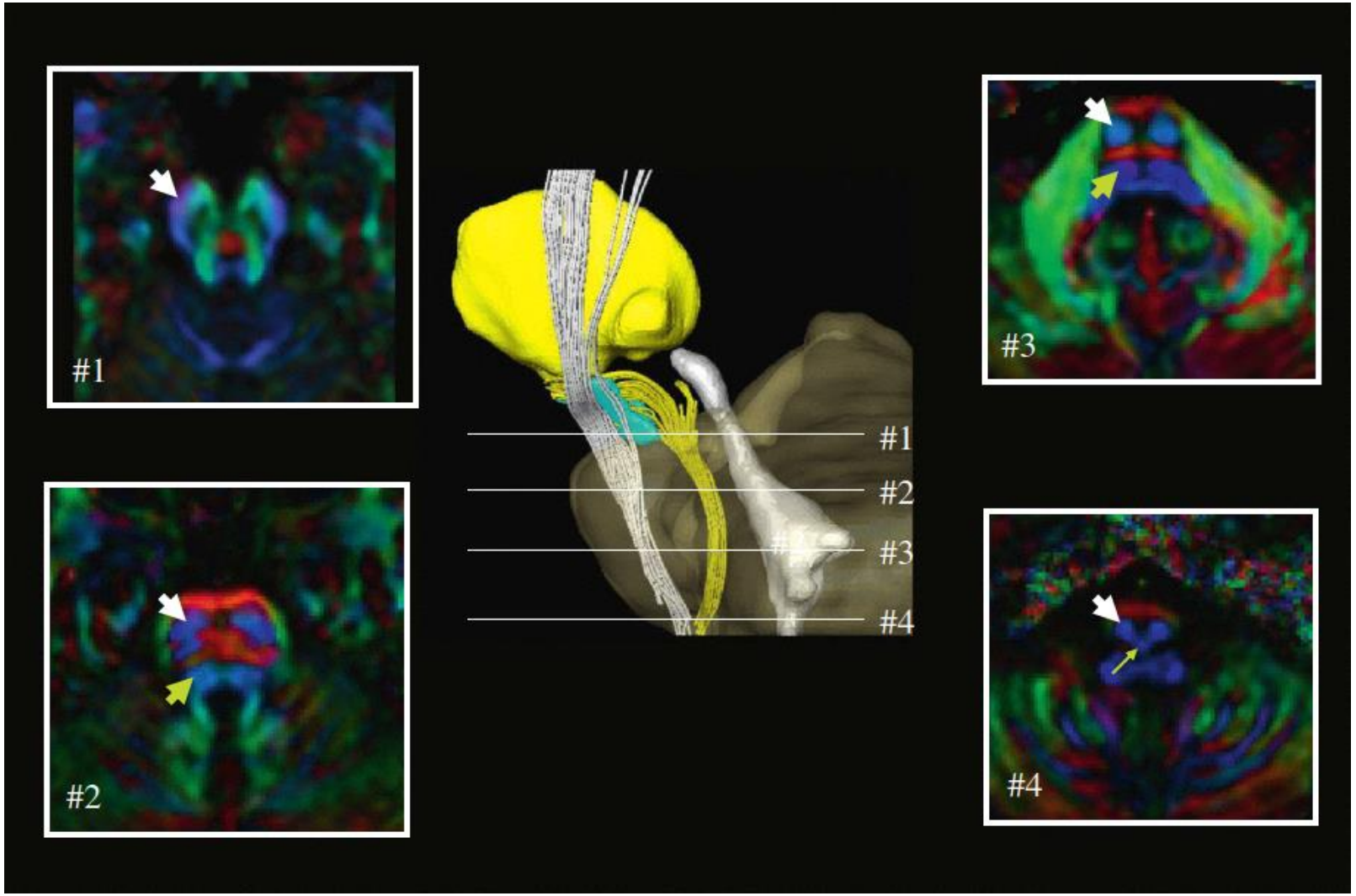
[Schreiber et al., 2014]

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

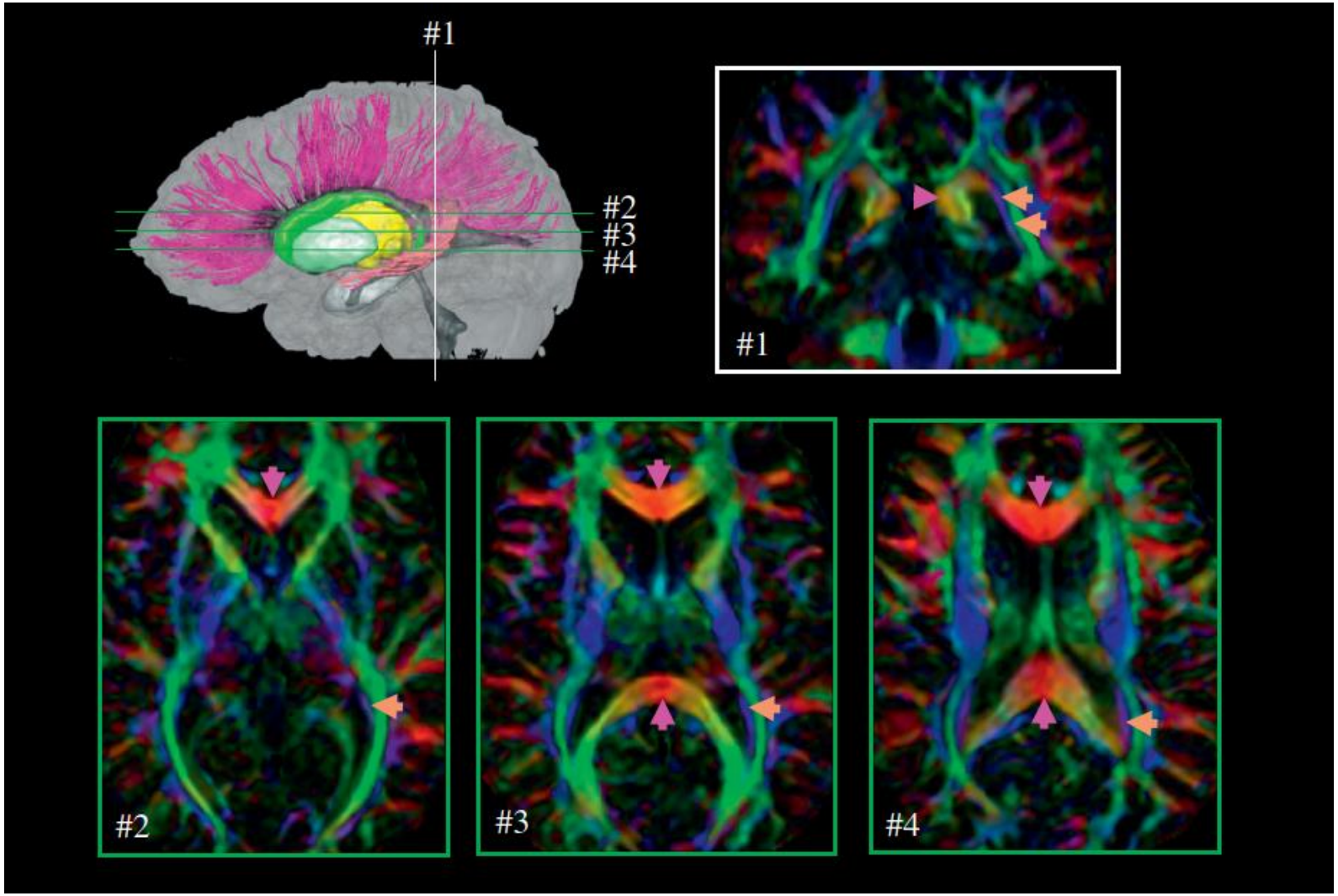
[https://www.mrtrix.org/]]

Determination of white matter fibre tracts



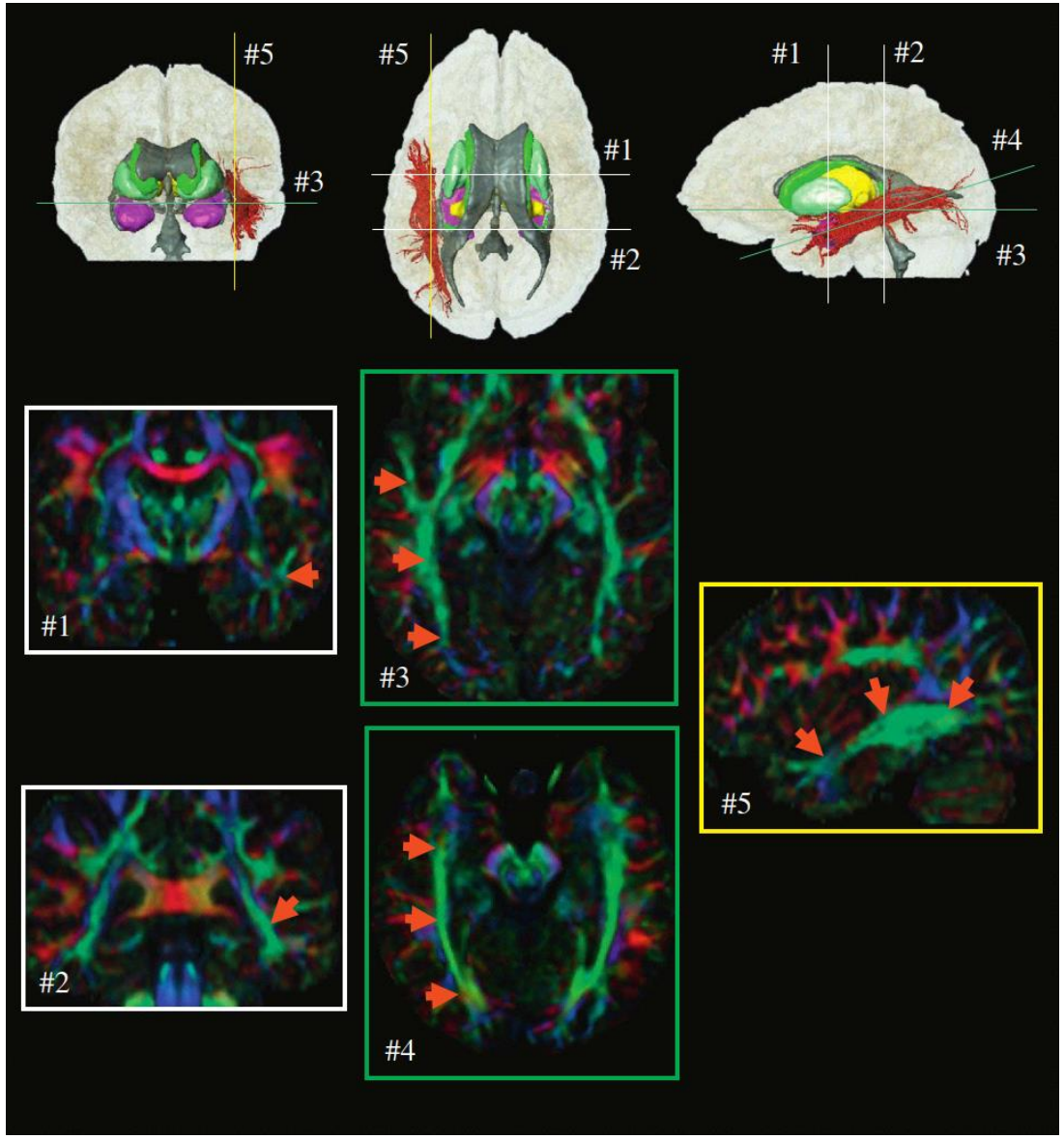
[Oishi et al., 2011]

Trajectory of the corticospinal tract



[Oishi et al., 2011]

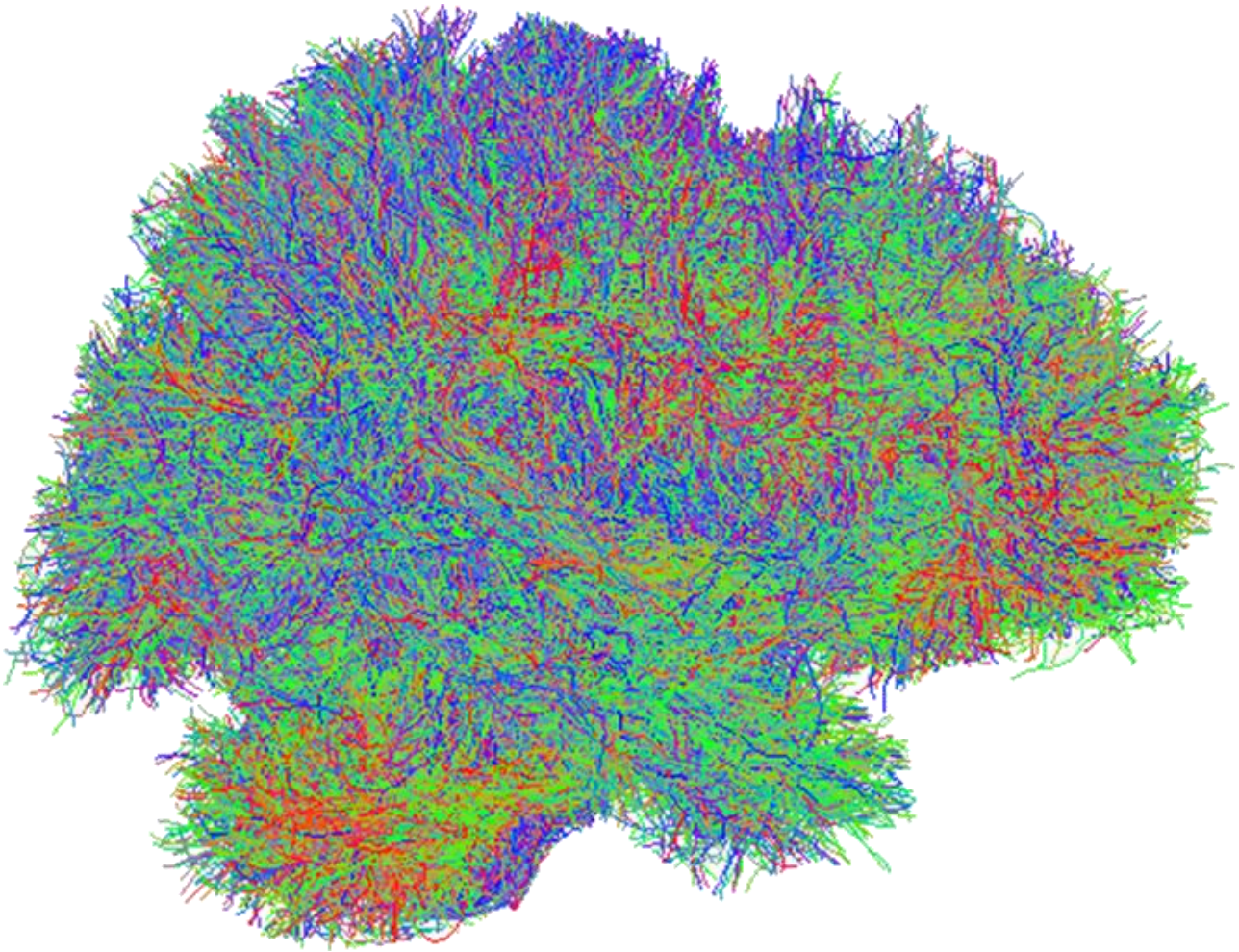
Trajectory of the corpus callosum



[Oishi et al., 2011]

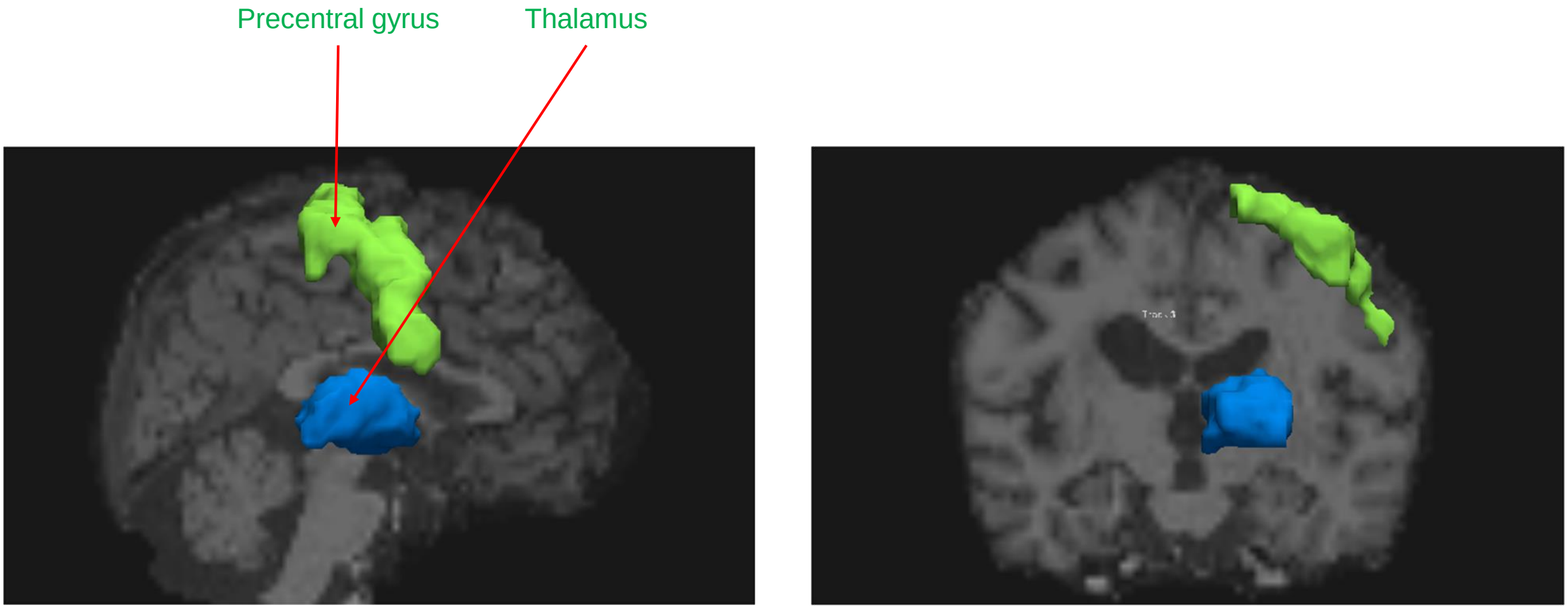
Trajectory of the inferior longitudinal fasciculus

[dMRI: White Matter Tractography]

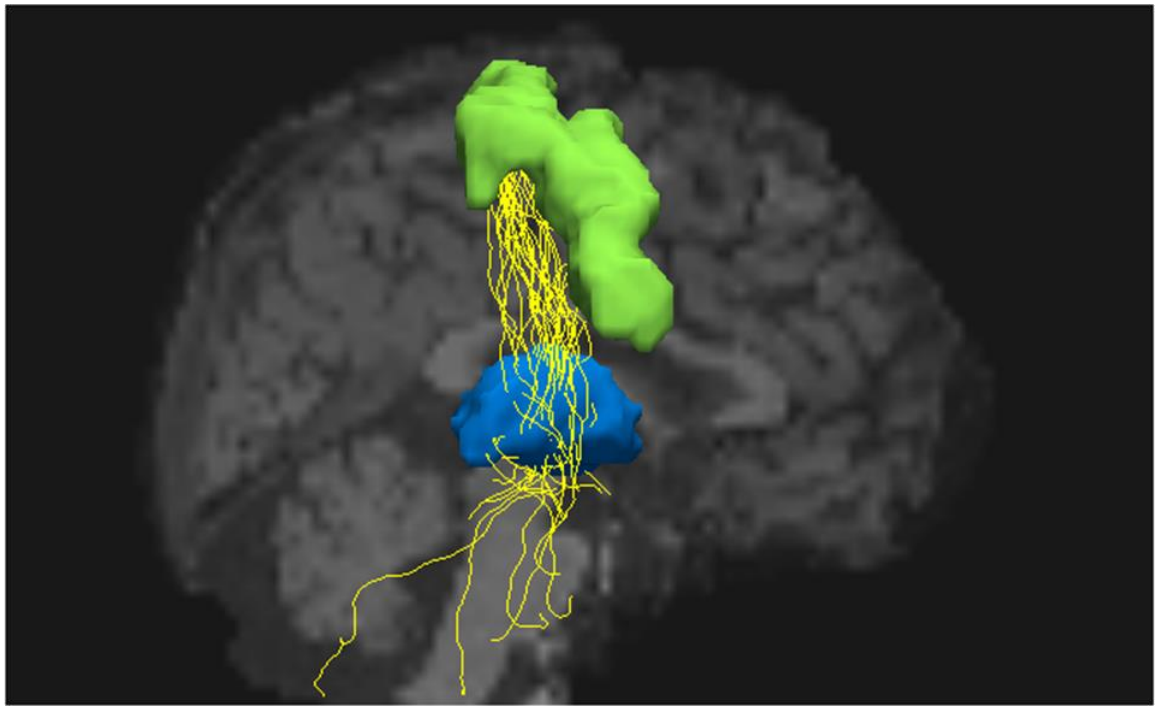


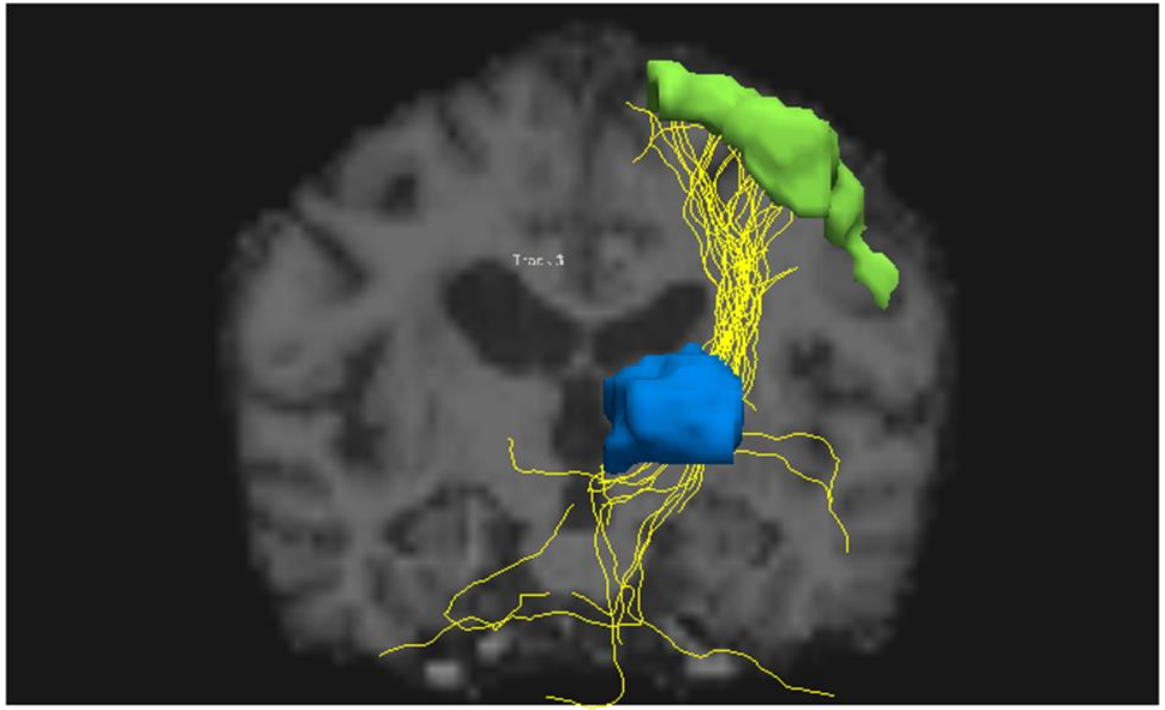
1,500,000 streamlines

Whole brain white matter tractography

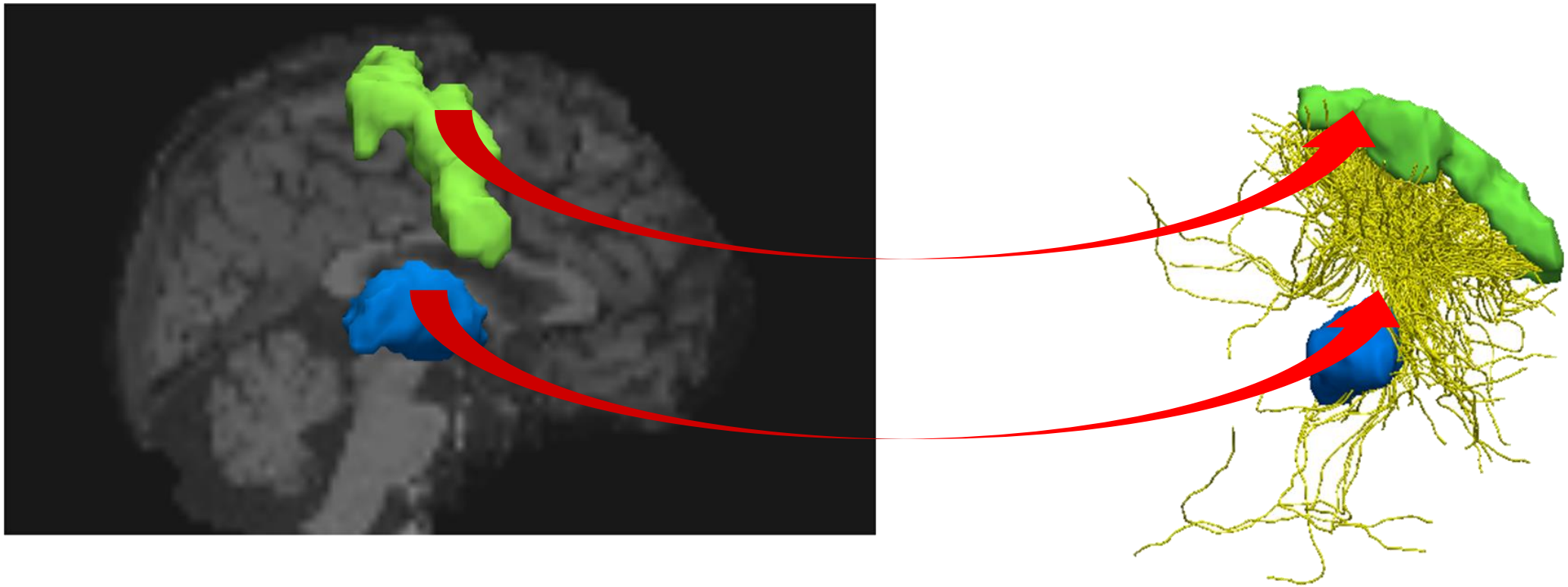


Terminations of streamlines



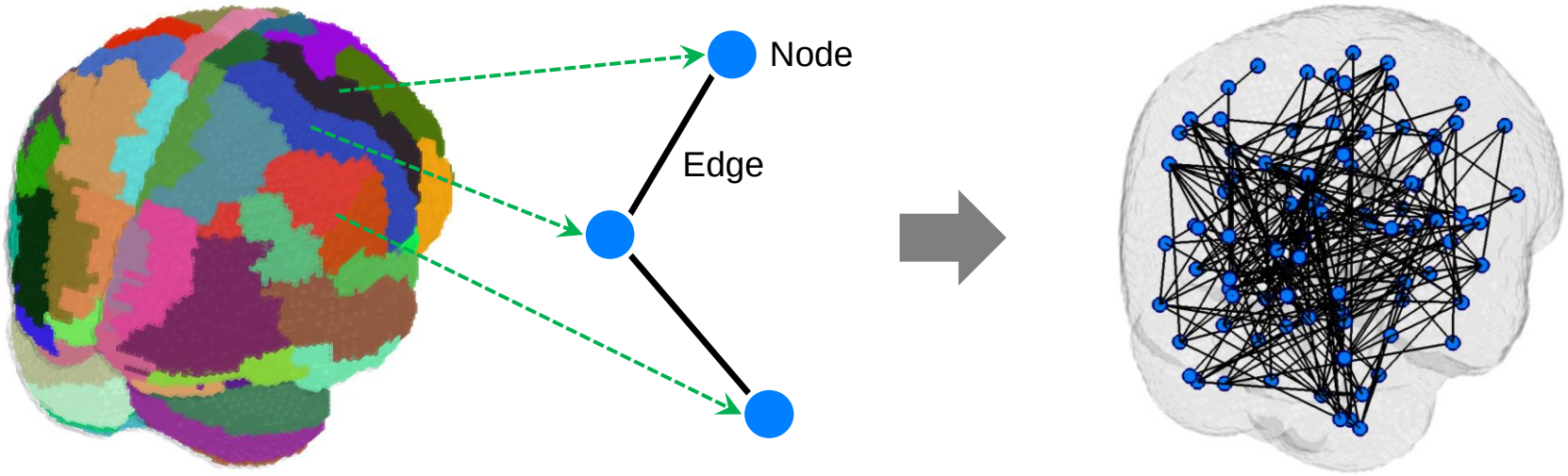


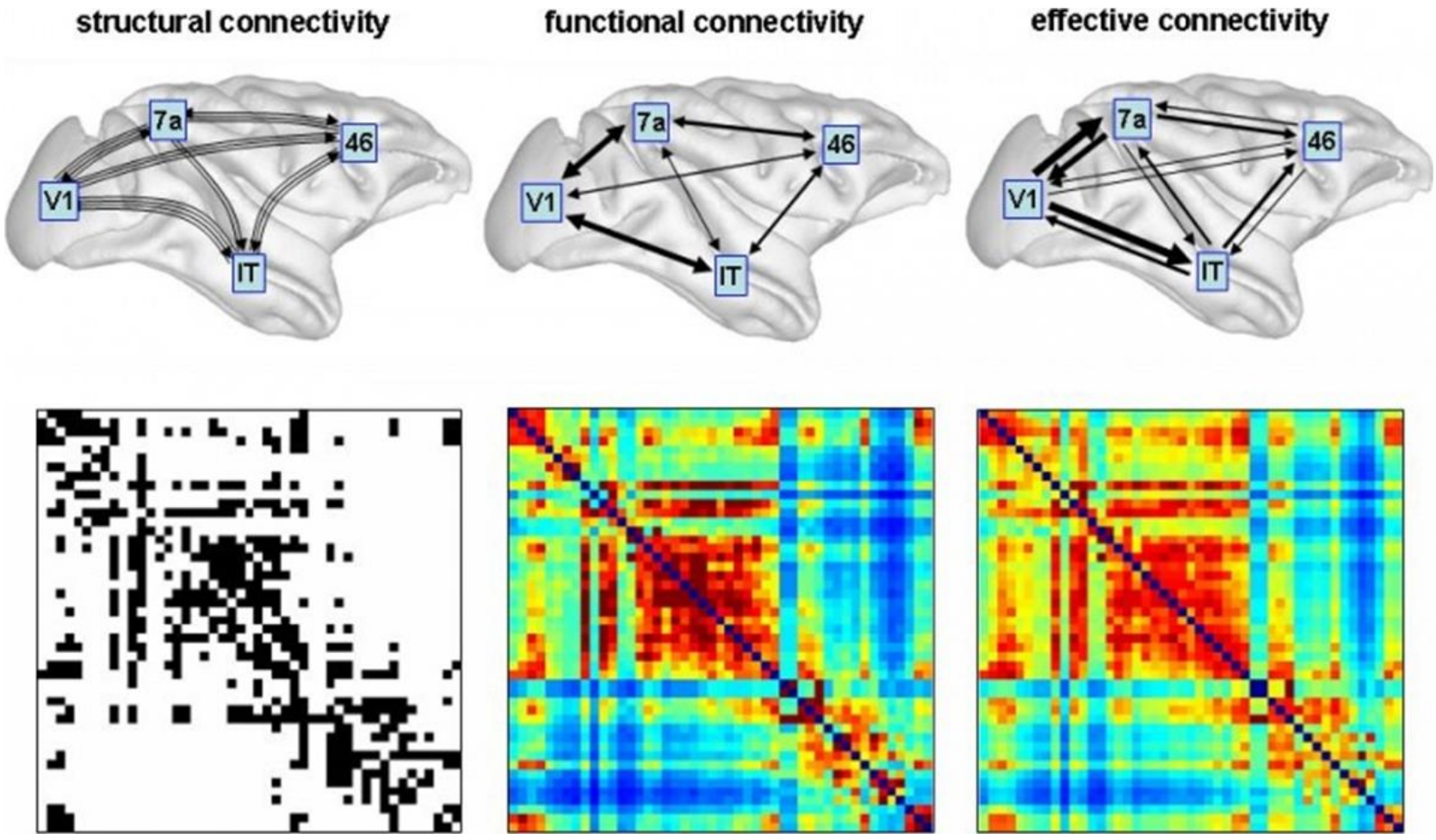
Generated streamlines



Determination of white matter fibre tracts

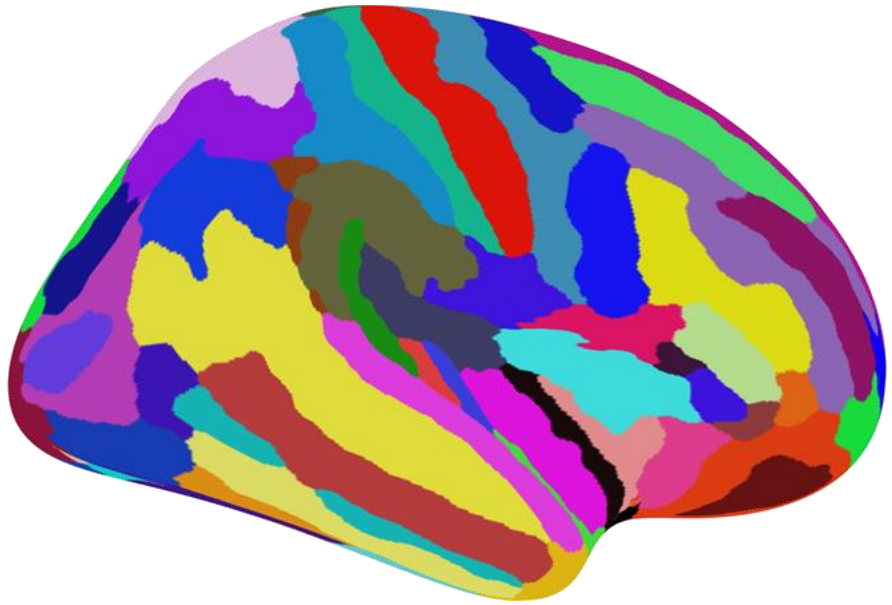
- Network
  - Set of nodes and edges
    - Nodes: pre-defined regions
    - Edges: connectivity (white matter fibre tracts) between regions



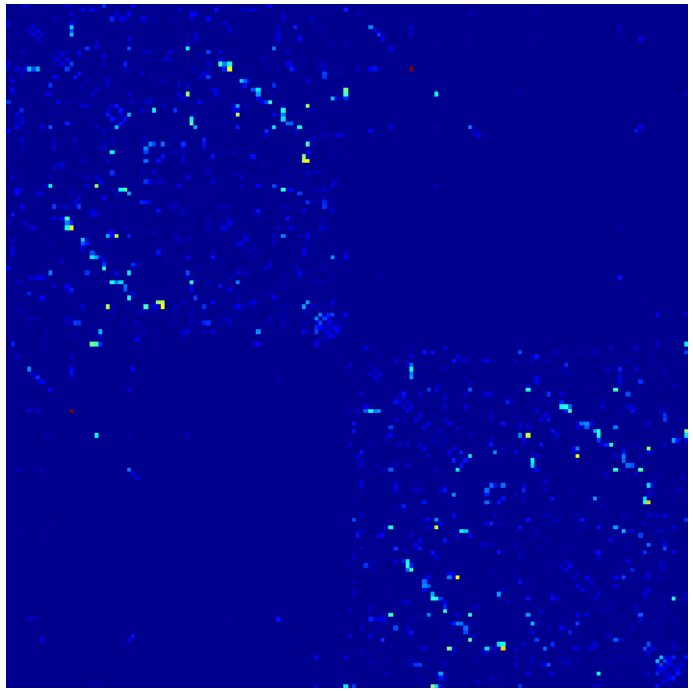


[Honey et al., 2007]

Modes of brain connectivity

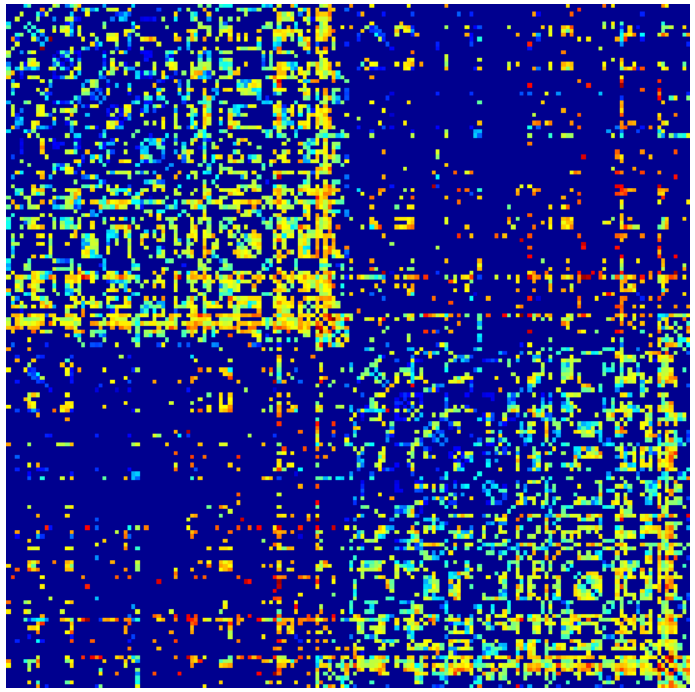


White matter tracts

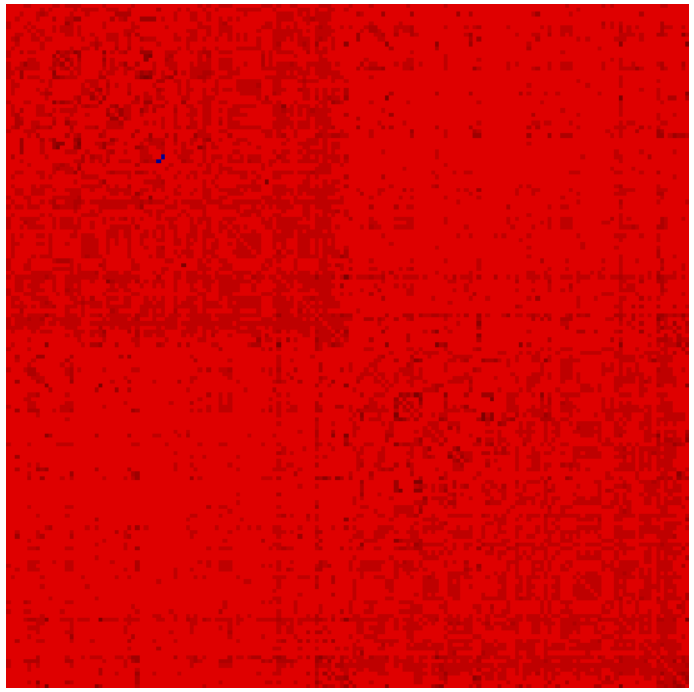


Tract count

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 →

Samples ↓

	Brain regions 1 – 2 connectivity	Brain regions 1 – 3 connectivity	Brain regions 1 – 4 connectivity	…
Subject 1	-	-	-	-
Subject 2	-	-	-	-
Subject 3	-	-	-	-
⋮	-	-	-	-

  - Structural network map