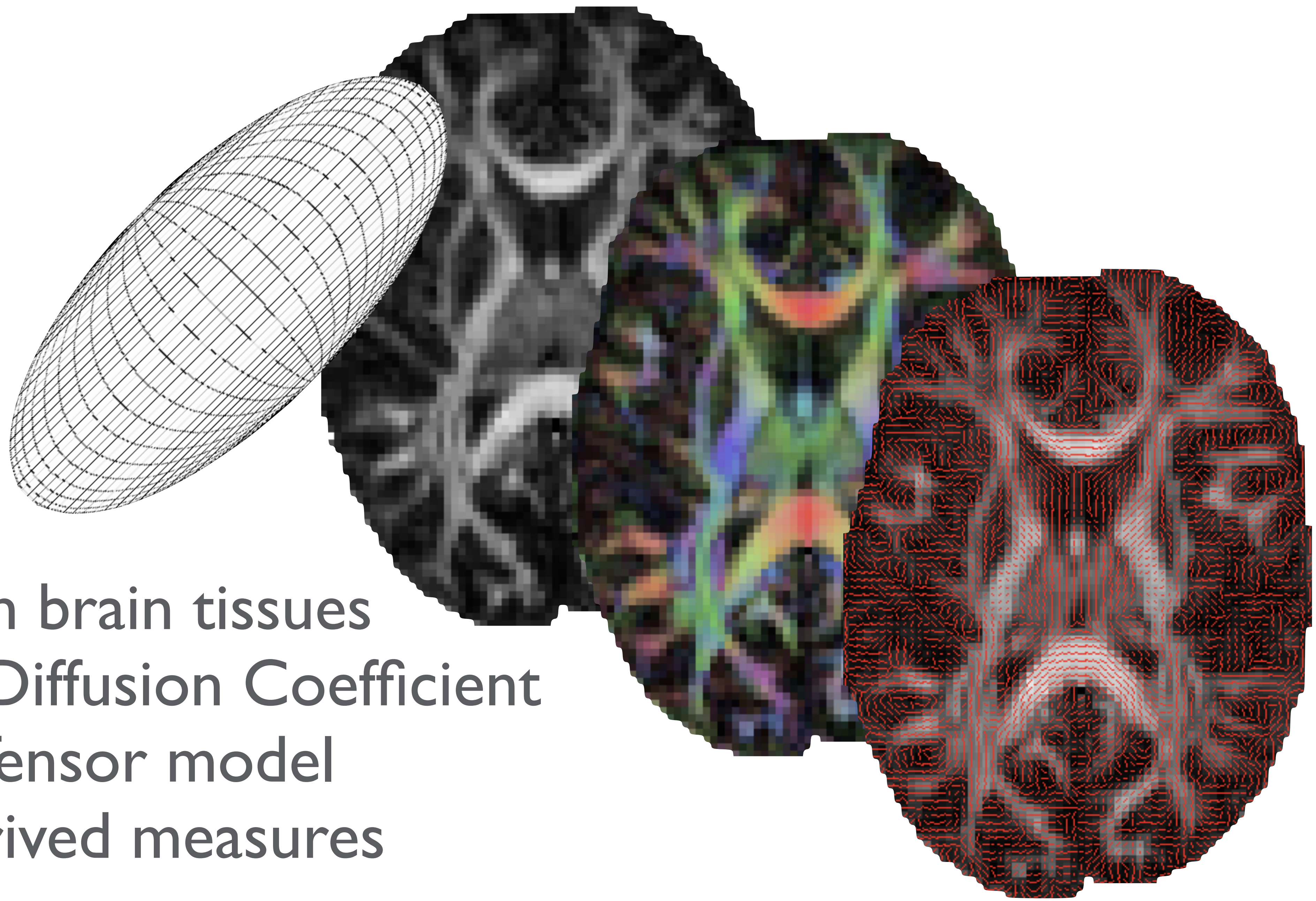
Diffusion Tensor Imaging - basic principles



- Diffusion in brain tissues
- Apparent Diffusion Coefficient
- Diffusion Tensor model
- Tensor-derived measures

Diffusion Tensor Imaging (DTI)

Diffusion Tensor Model. In each voxel:

b-value for gradient *j* (known)

Unit vector representing the direction of gradient *j* (known)

$$S_j = S_0 \exp(-b_j \boldsymbol{x}_j^T \boldsymbol{D} \boldsymbol{x}_j)$$

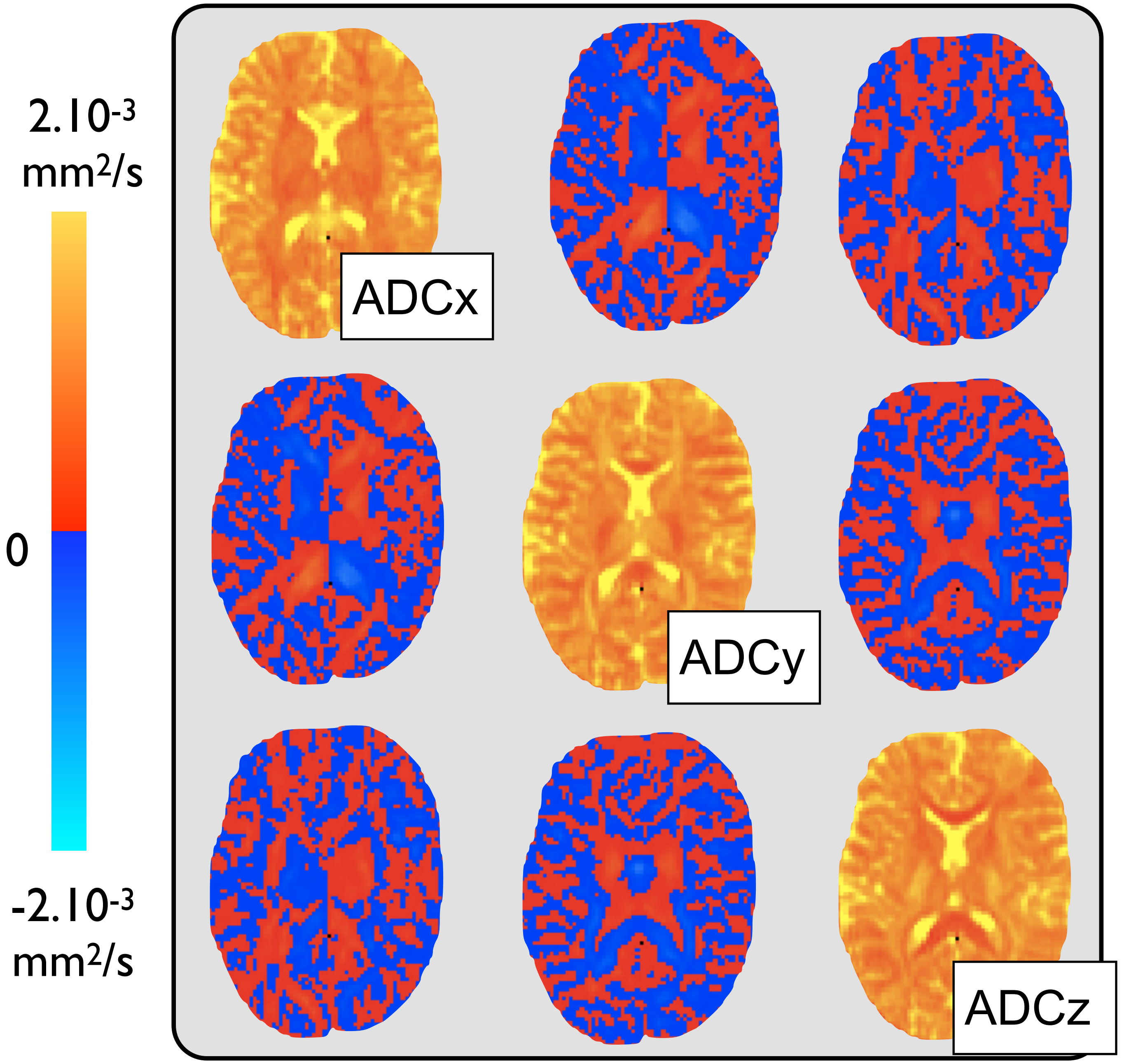
Signal measured after applying a Gradient *j* with direction $\boldsymbol{x}_j$ and b-value b_j (measured)

Signal measured with no diffusion gradient applied

3x3 Diffusion Tensor (unknown)

[Basser, Biophys J,1994], [Basser et al , J Magn Res, 1994]

The Elements of the Diffusion Tensor



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

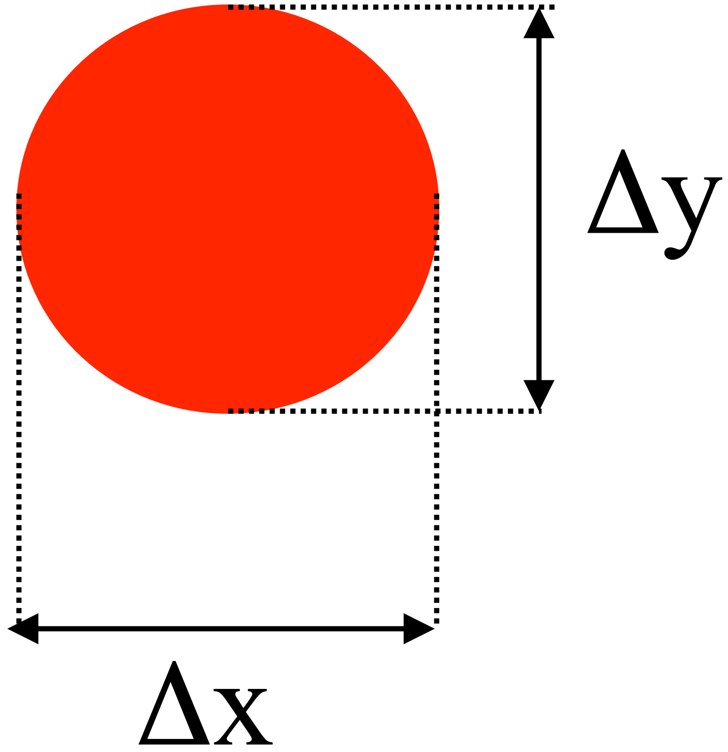
- Tensor is **symmetric** (6 unknowns)

- **Diagonal Elements** are proportional to the diffusion displacement variances (**ADCs**) along the three directions of the experiment coordinate system

-**Off-diagonal Elements** are proportional to the **correlations** (covariances) of displacements along these directions

$N_3(0, 2t\mathbf{D})$

Why do we need a tensor?



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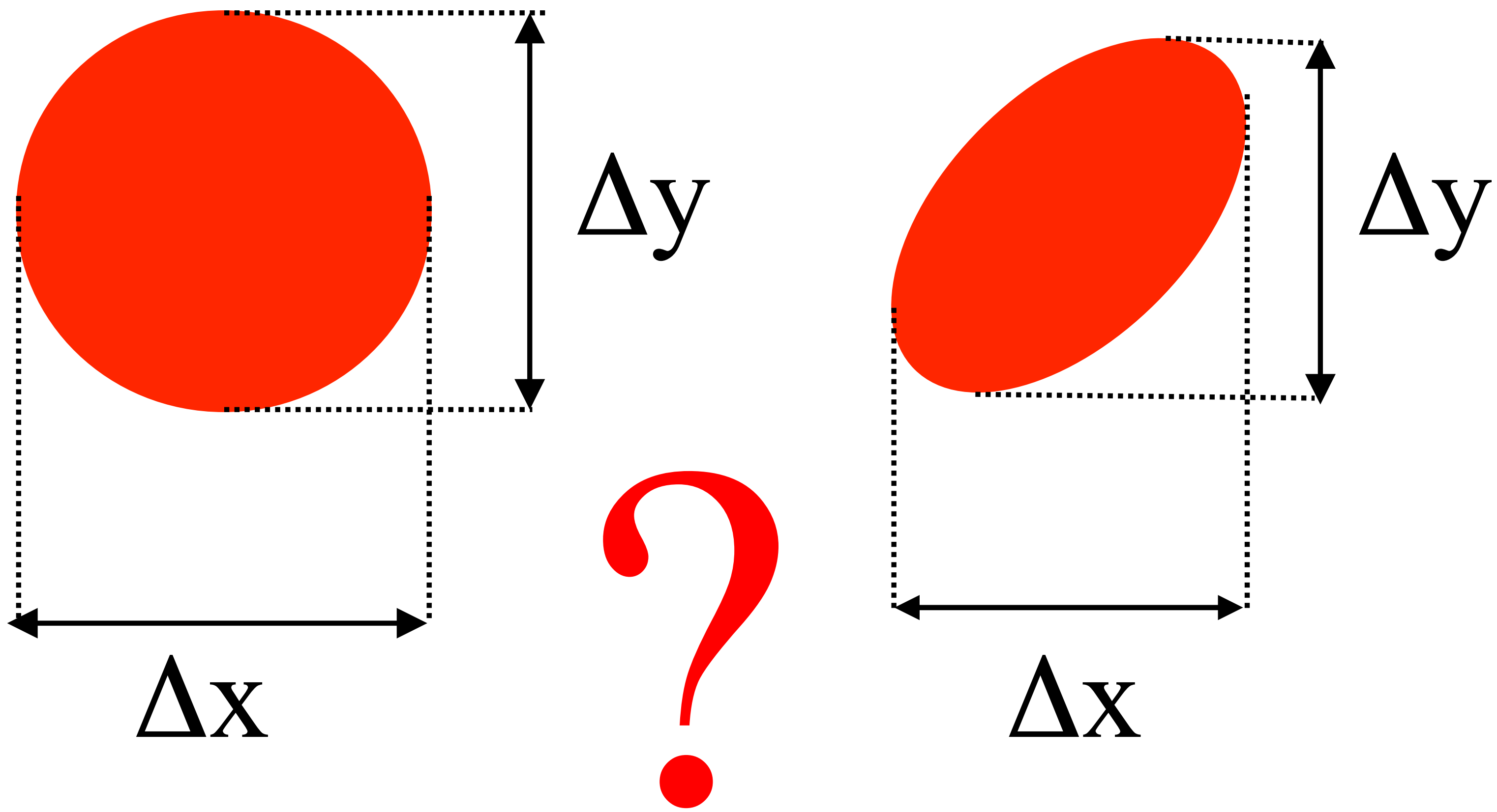

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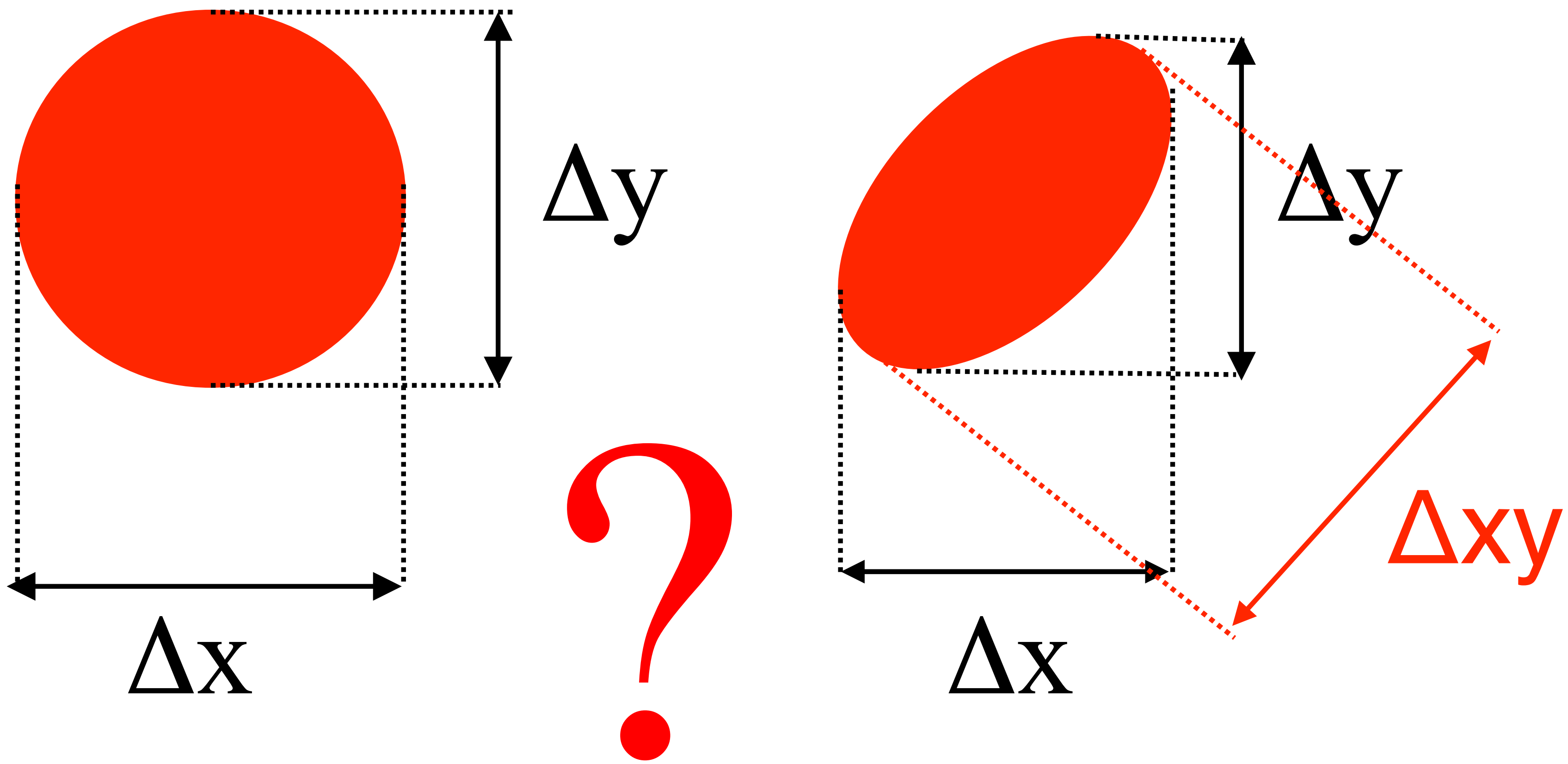

$$\begin{bmatrix} D_x & D_{xy} \\ D_{xy} & D_y \end{bmatrix}$$

The Diffusion Tensor Eigenspectrum

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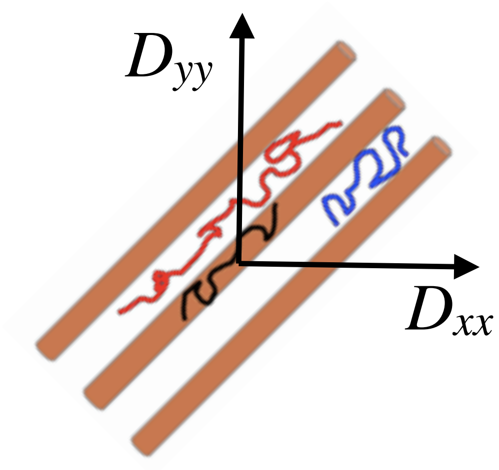

Once D is estimated, we get ADCs along the scanner's coordinate system. But we want ADCs along a local coordinate system in each voxel, determined by the anatomy.

The Diffusion Tensor Eigenspectrum

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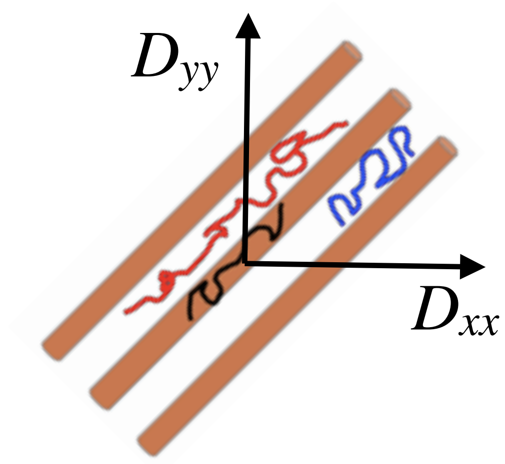
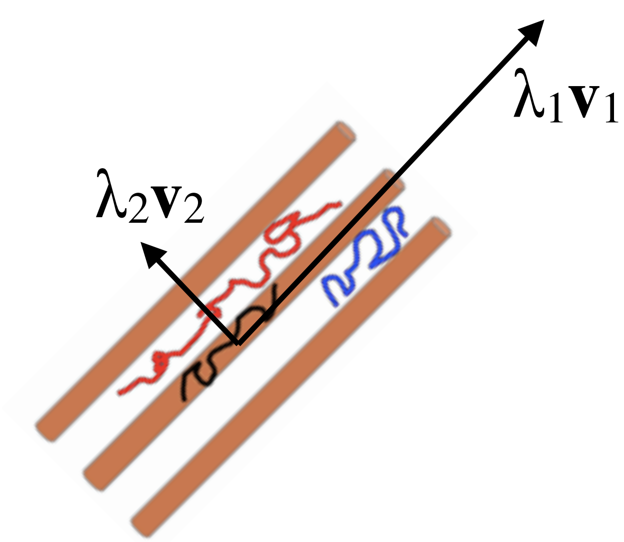


Once D is estimated, we get ADCs along the scanner's coordinate system. But we want ADCs along a local coordinate system in each voxel, determined by the anatomy.

Diagonalize the estimated tensor in each voxel



$$\mathbf{D} = [\mathbf{v_1}|\mathbf{v_2}|\mathbf{v_3}]^{\mathrm{T}} \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix} [\mathbf{v_1}|\mathbf{v_2}|\mathbf{v_3}]$$

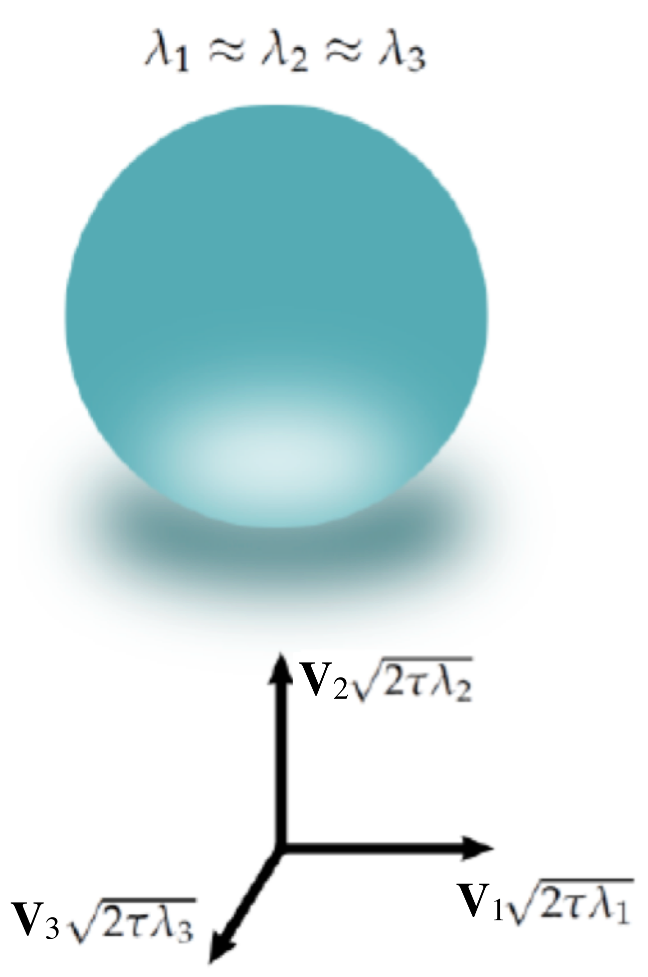
eigenvectors - $\mathbf{v}_1$=direction of max diffusivity

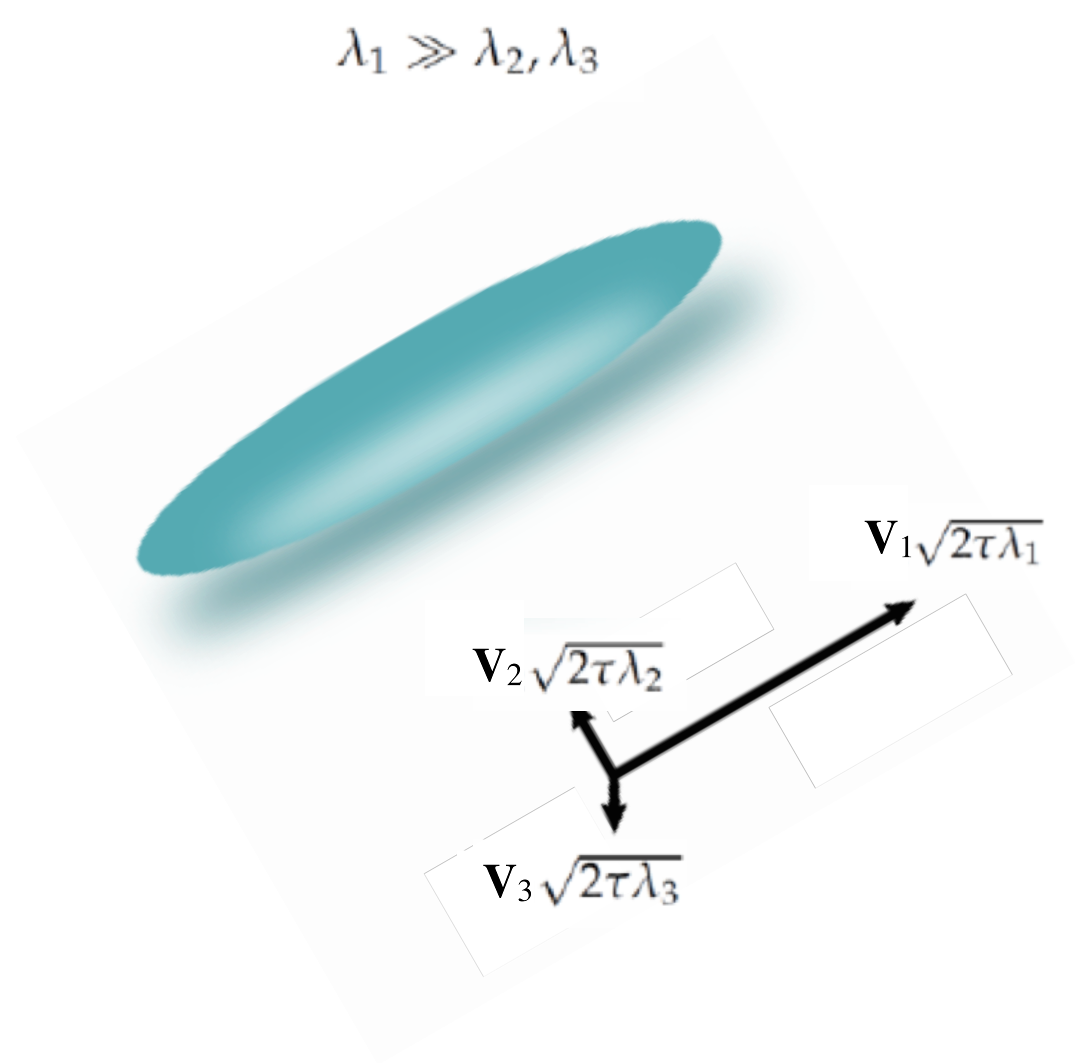
eigenvalues: ADCs along $\mathbf{v}_1$,$\mathbf{v}_2$,$\mathbf{v}_3$

The Diffusion Tensor Ellipsoid

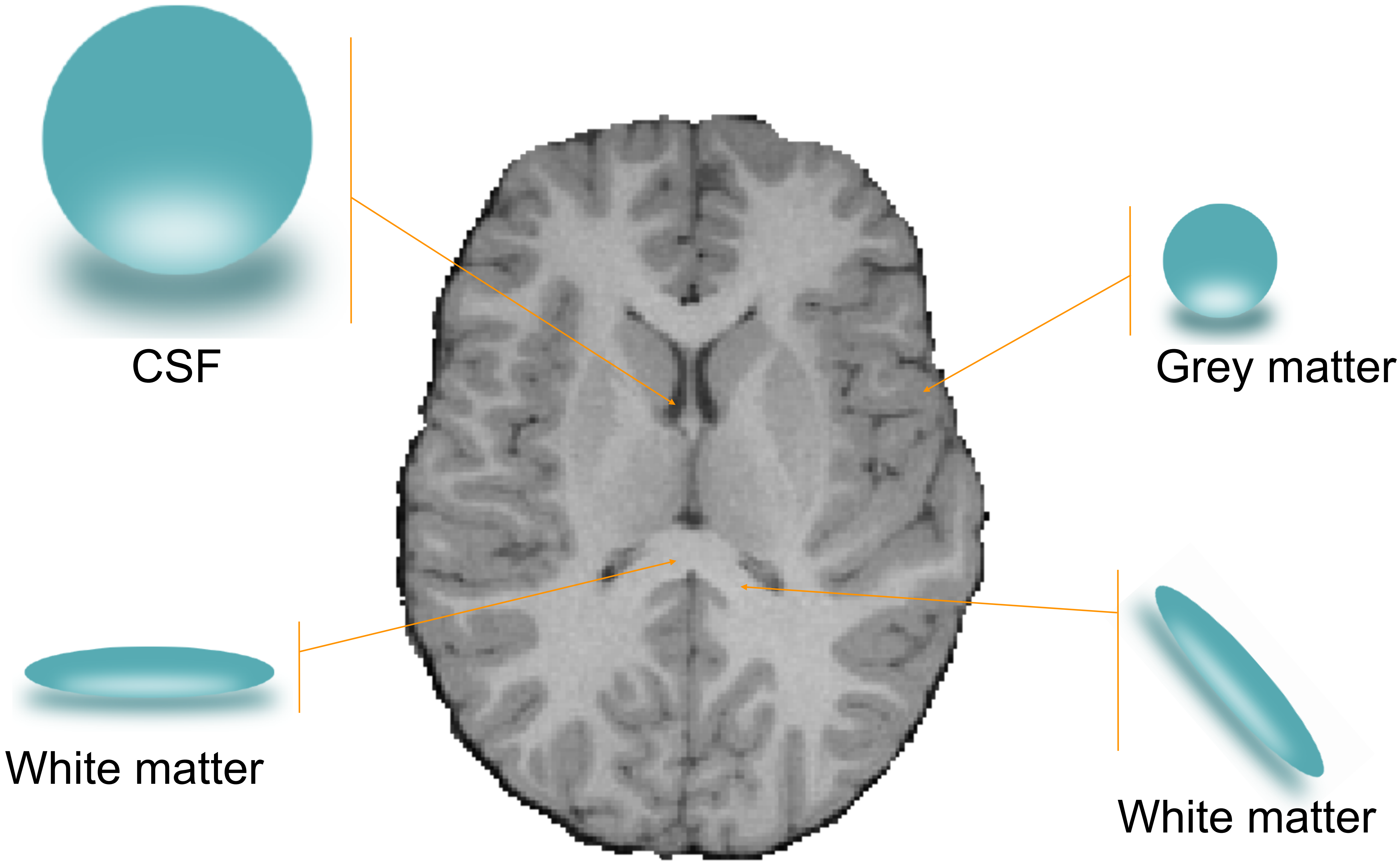
Isotropic voxel

Anisotropic voxel





The Diffusion Tensor Ellipsoid



Quantitative Diffusion Maps

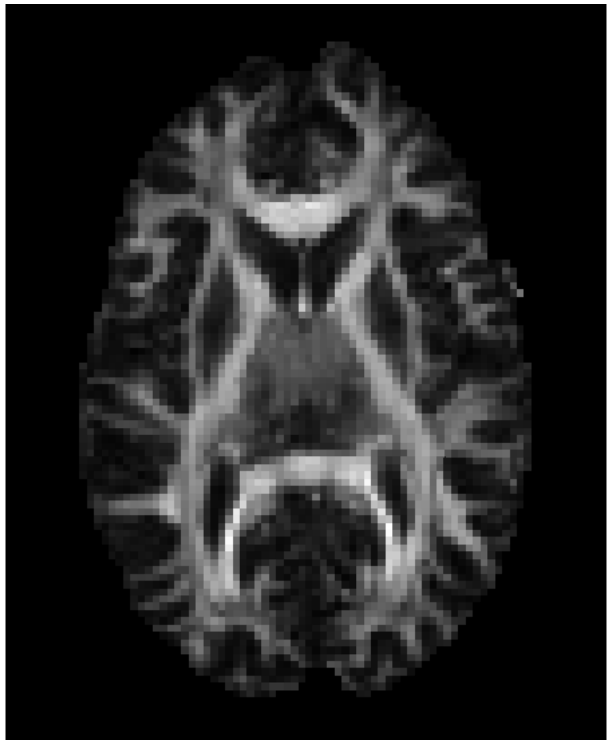
Fractional Anisotropy (FA) ~ Eigenvalues Variance (normalised)
Mean Diffusivity (MD) = Eigenvalues Mean

$$FA = \sqrt{\frac{3\sum_{i=1}^{3}(\lambda_i - \overline{\lambda})^2}{2\sum_{i=1}^{3}\lambda_i^2}}, \qquad FA \text{ in } [0,1]$$

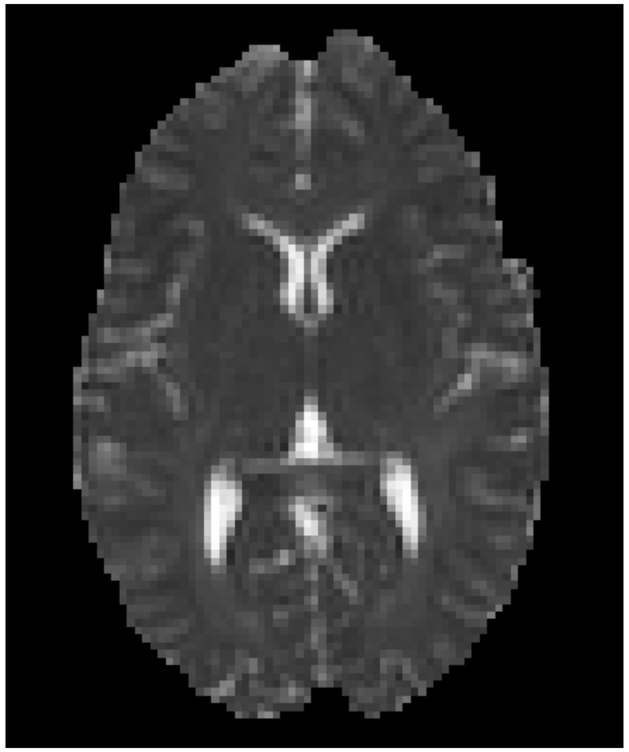
$$MD = \frac{D_{xx} + D_{yy} + D_{zz}}{3} = \frac{\lambda_1 + \lambda_2 + \lambda_3}{3}$$

Quantitative Diffusion Maps

FA

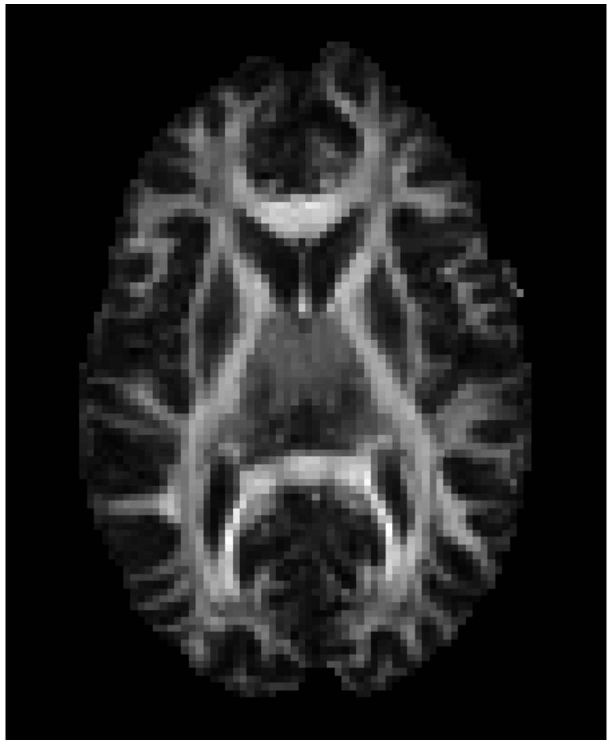


MD



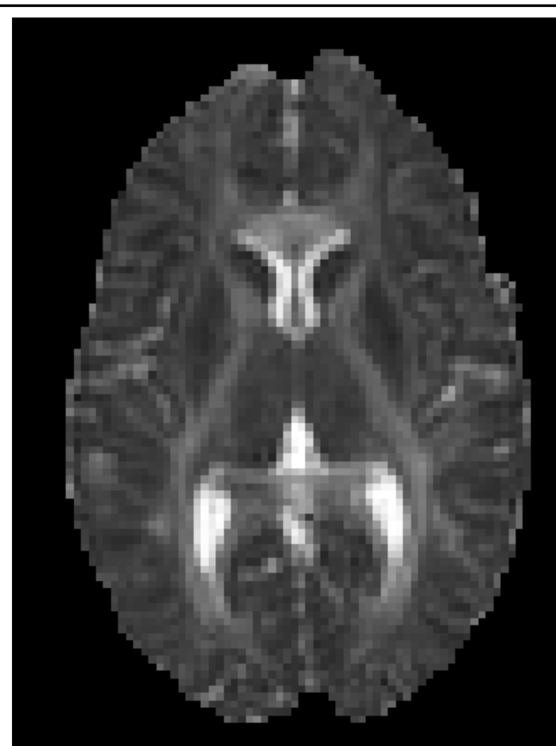
Quantitative Diffusion Maps

FA

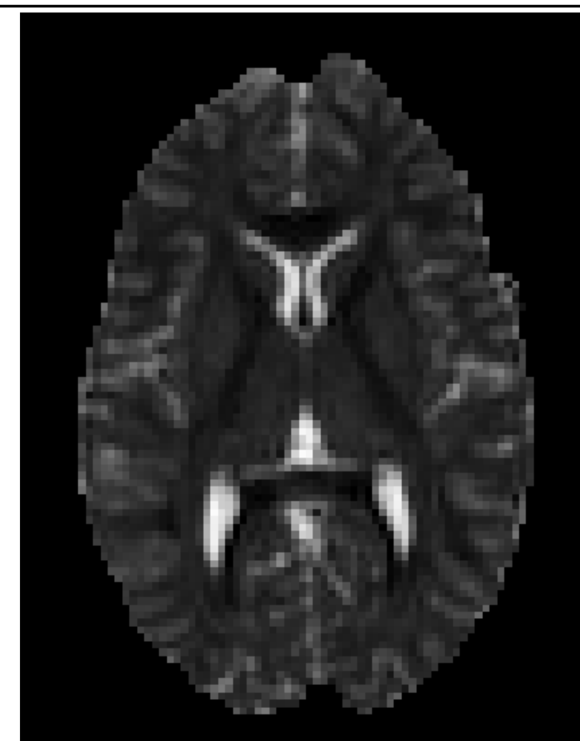


MD

Longitudinal/axial/parallel ADC
(λ_1)

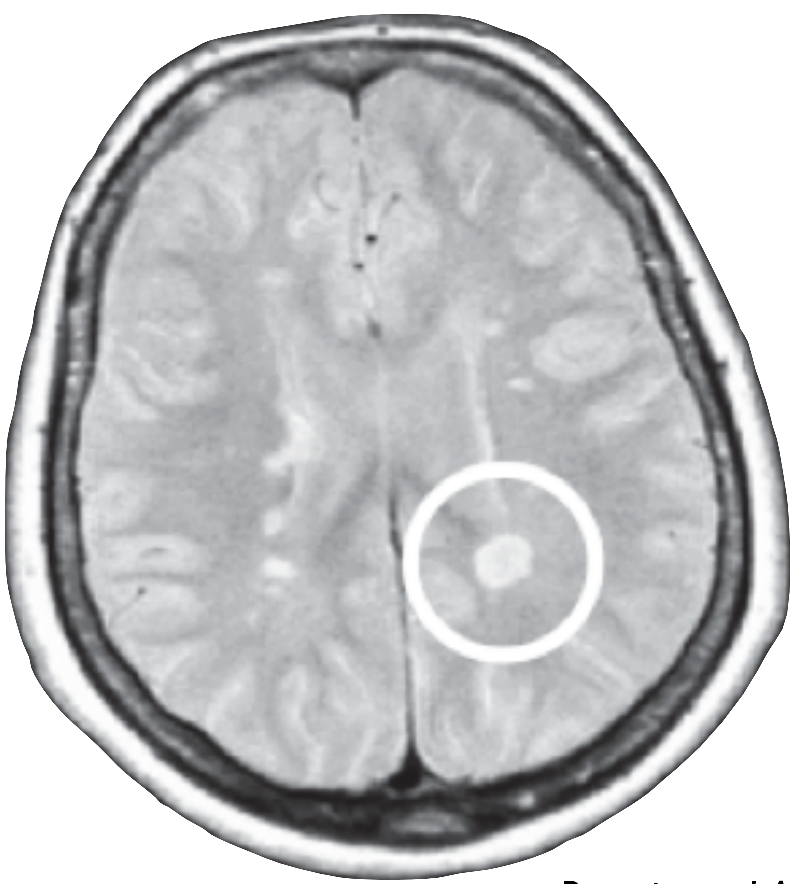


Transverse/radial/perpendicular ADC
$(\lambda_2+\lambda_3)/2$

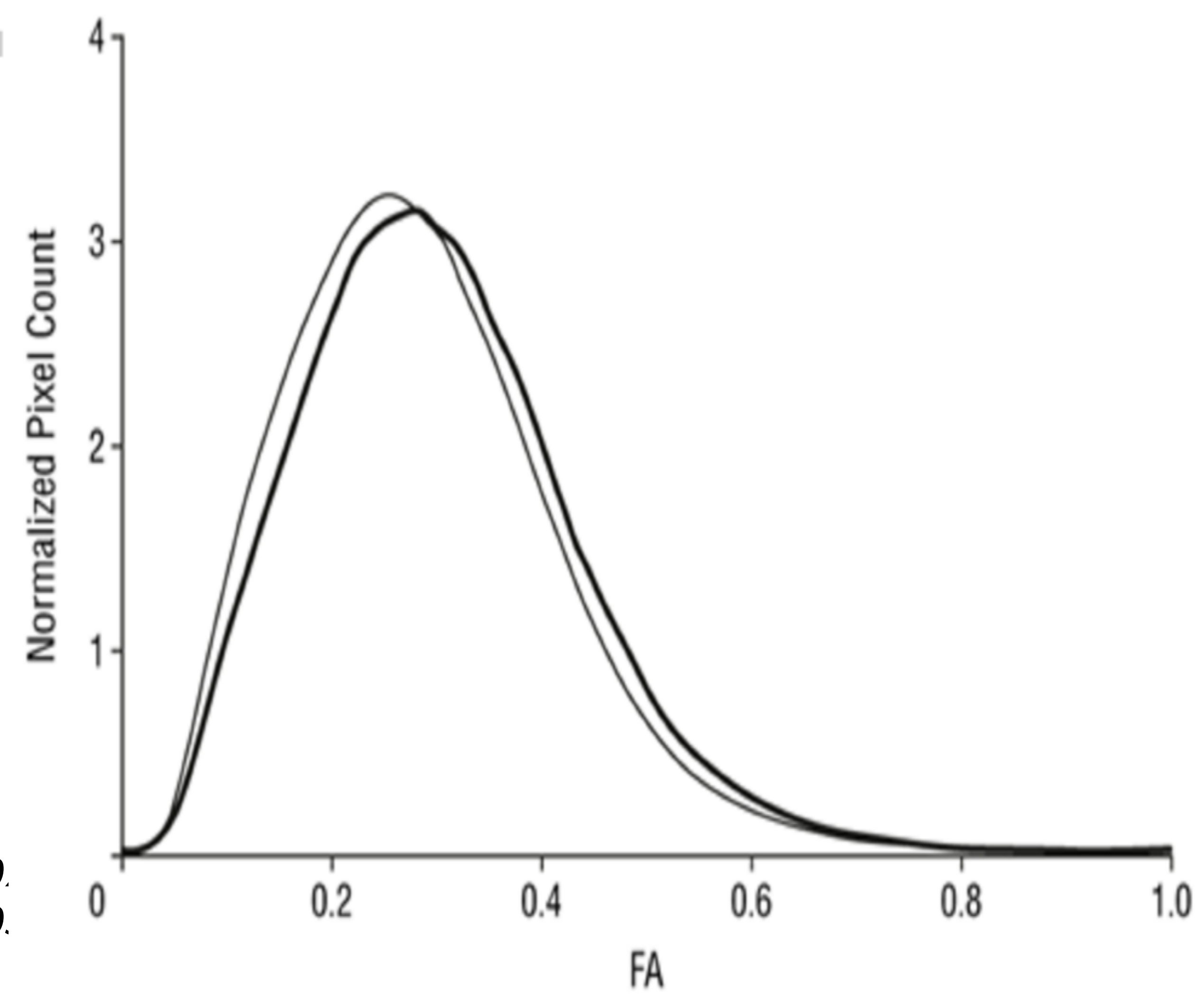


Quantitative Diffusion Maps

FA decrease/ MD increase has been associated in many studies with tissue breakdown (loss of structure).



Rovaris et al, Arch Neurol 200.
Gallo et al, Arch Neurol 200.



Fractional Anisotropy changes in MS normal appearing white matter

Quantitative Diffusion Maps

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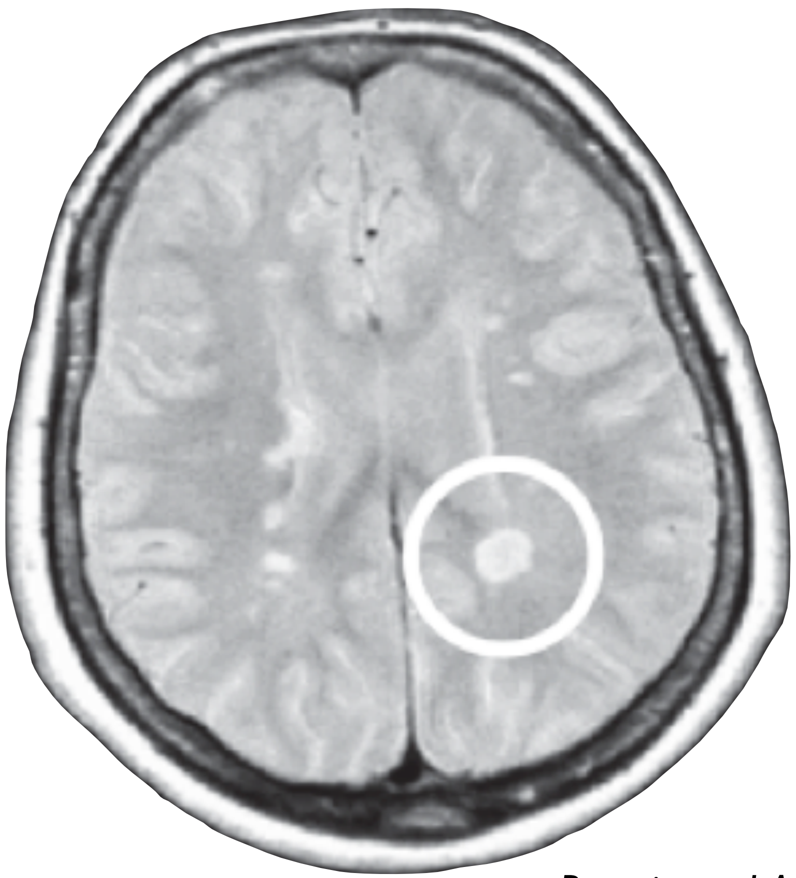

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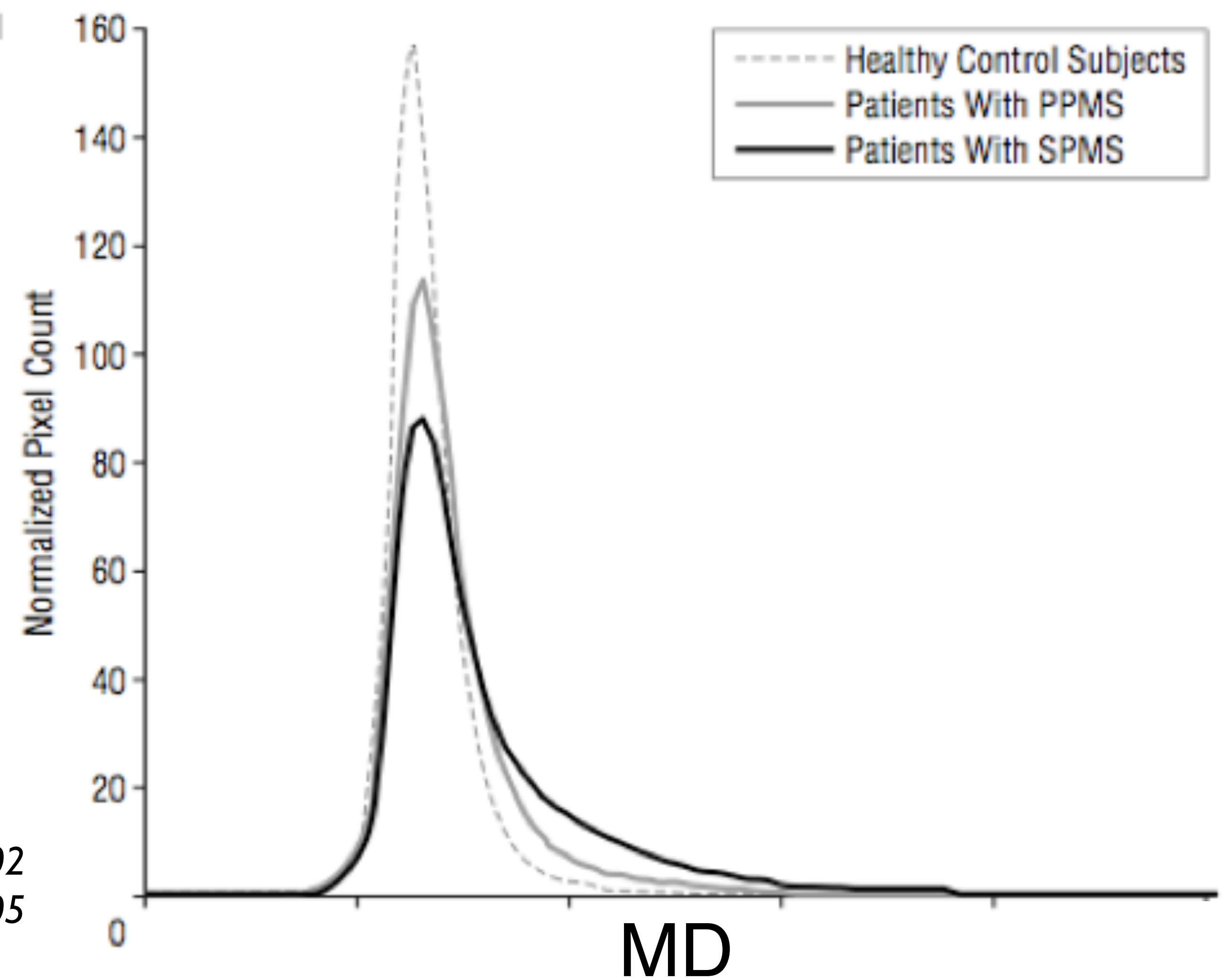
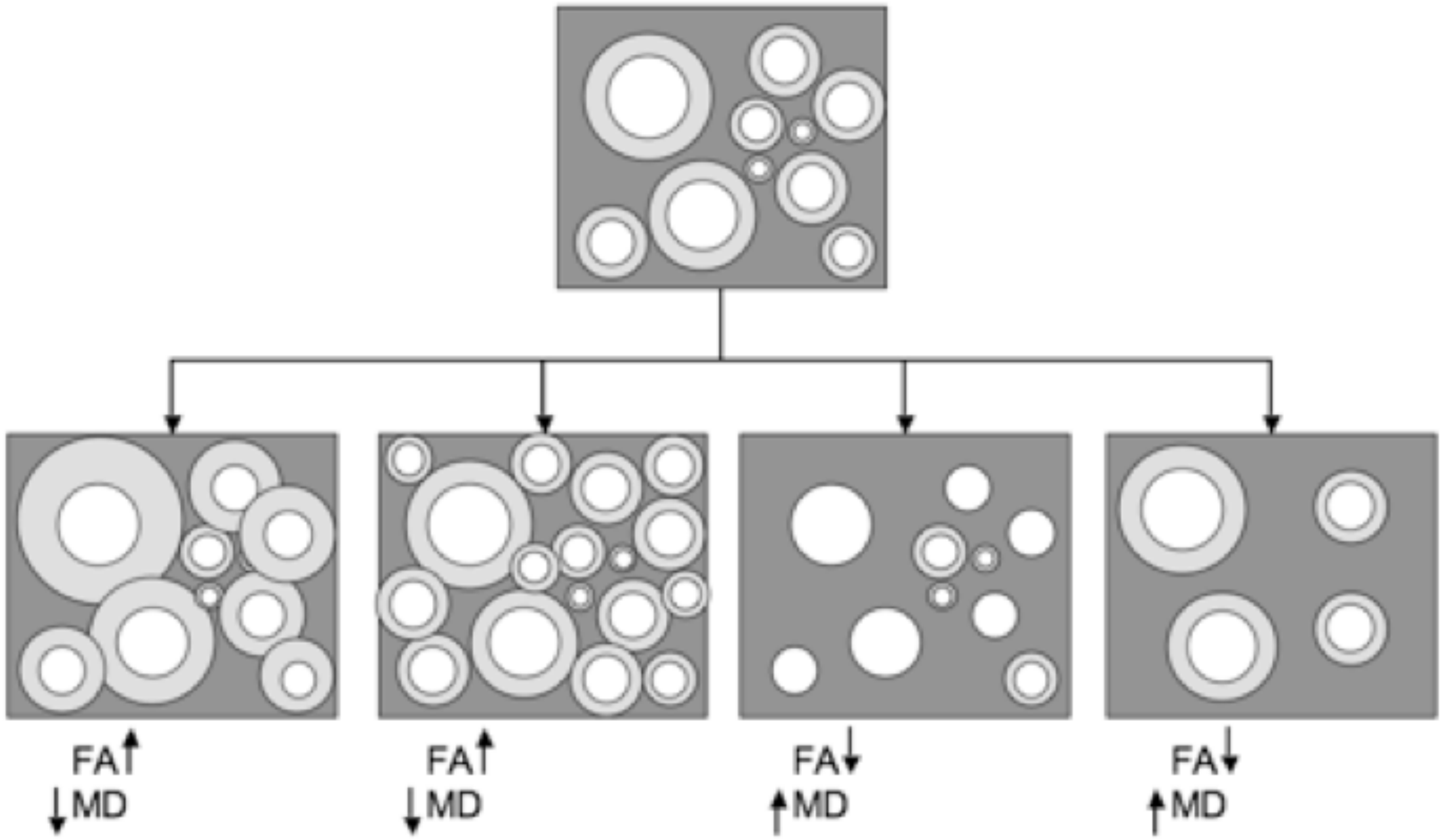


Fractional Anisotropy changes in MS normal appearing white matter

Quantitative Diffusion Maps

Different scenarios can have same effect on FA, MD



Swelling

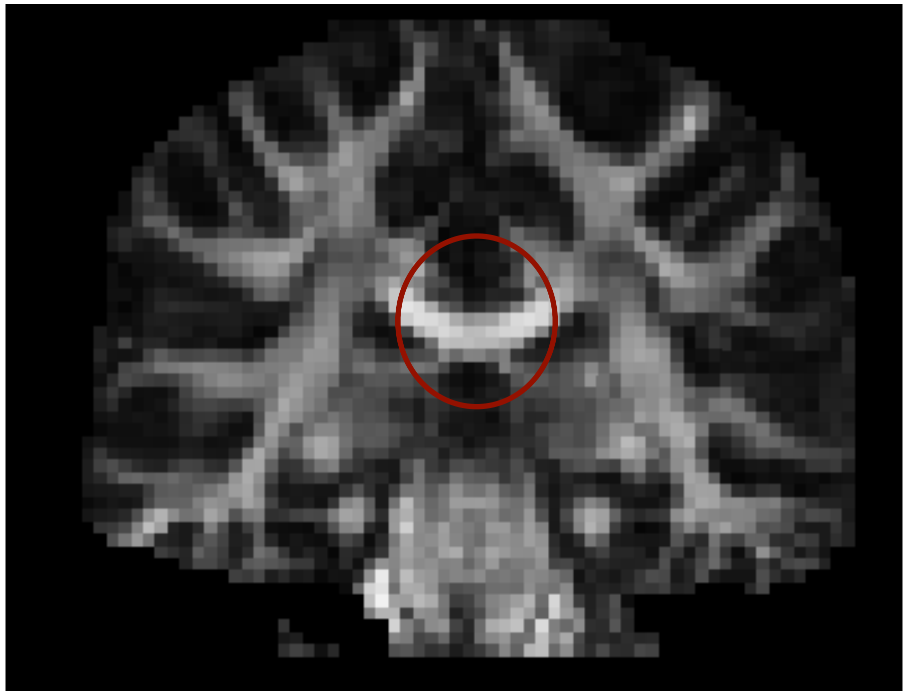
Higher Density

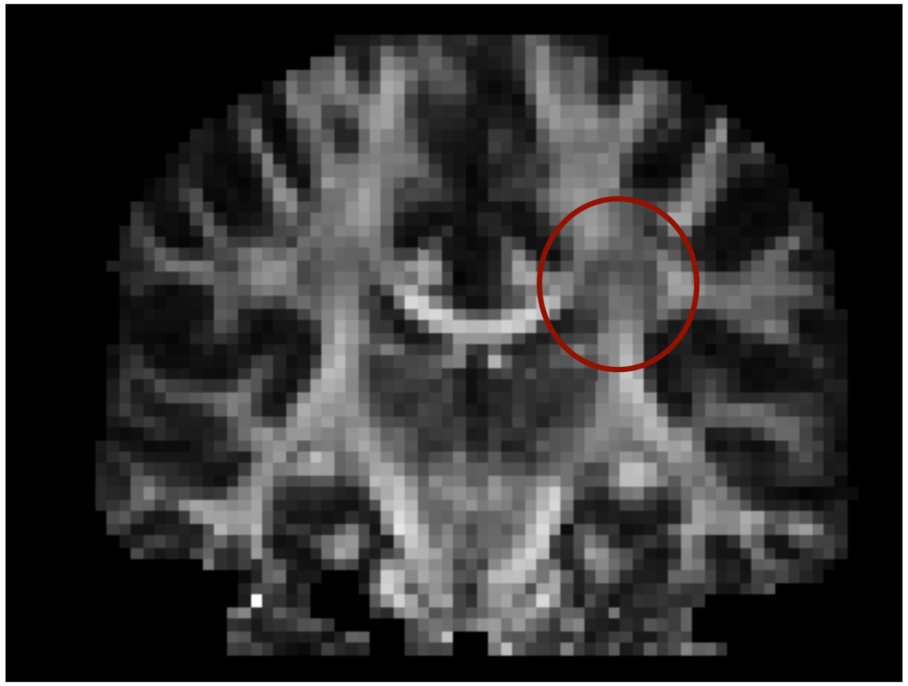
Myelin Loss

Cell Death

Tensor and FA in Crossing Regions

- In voxels containing two crossing bundles, FA is low and the tensor ellipsoid is pancake-shaped (oblate, planar tensor).





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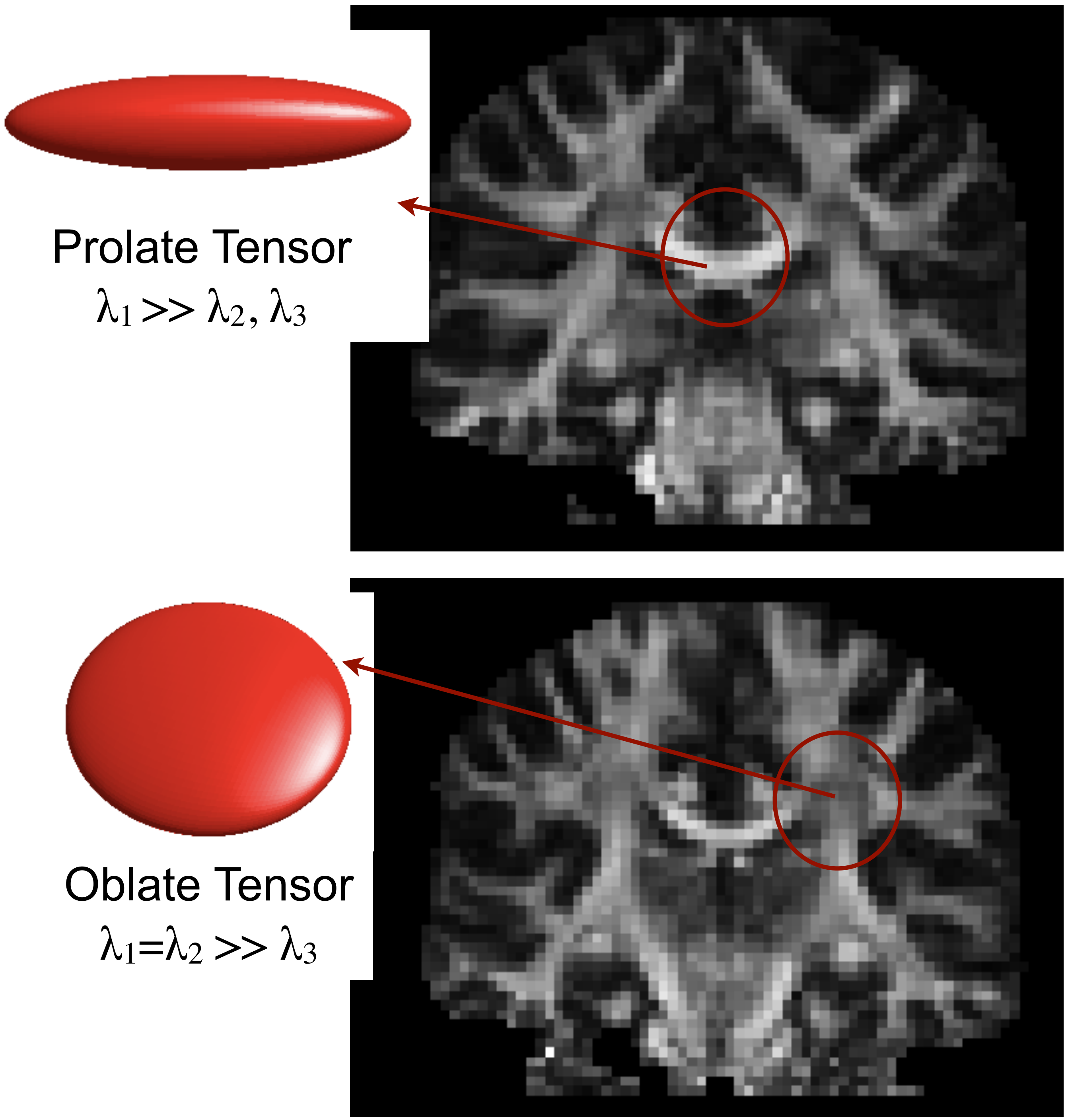
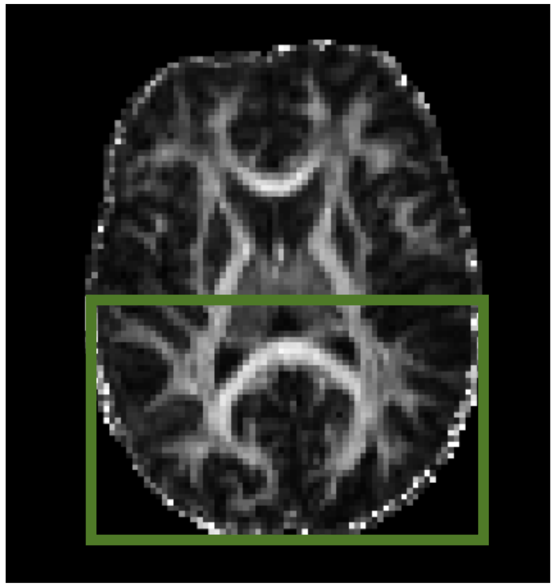
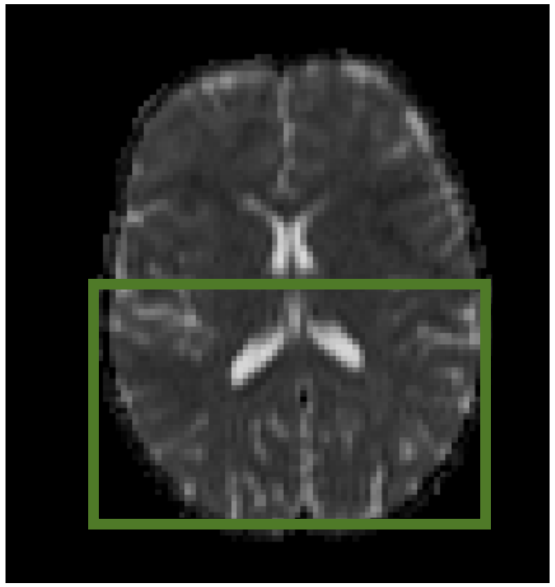
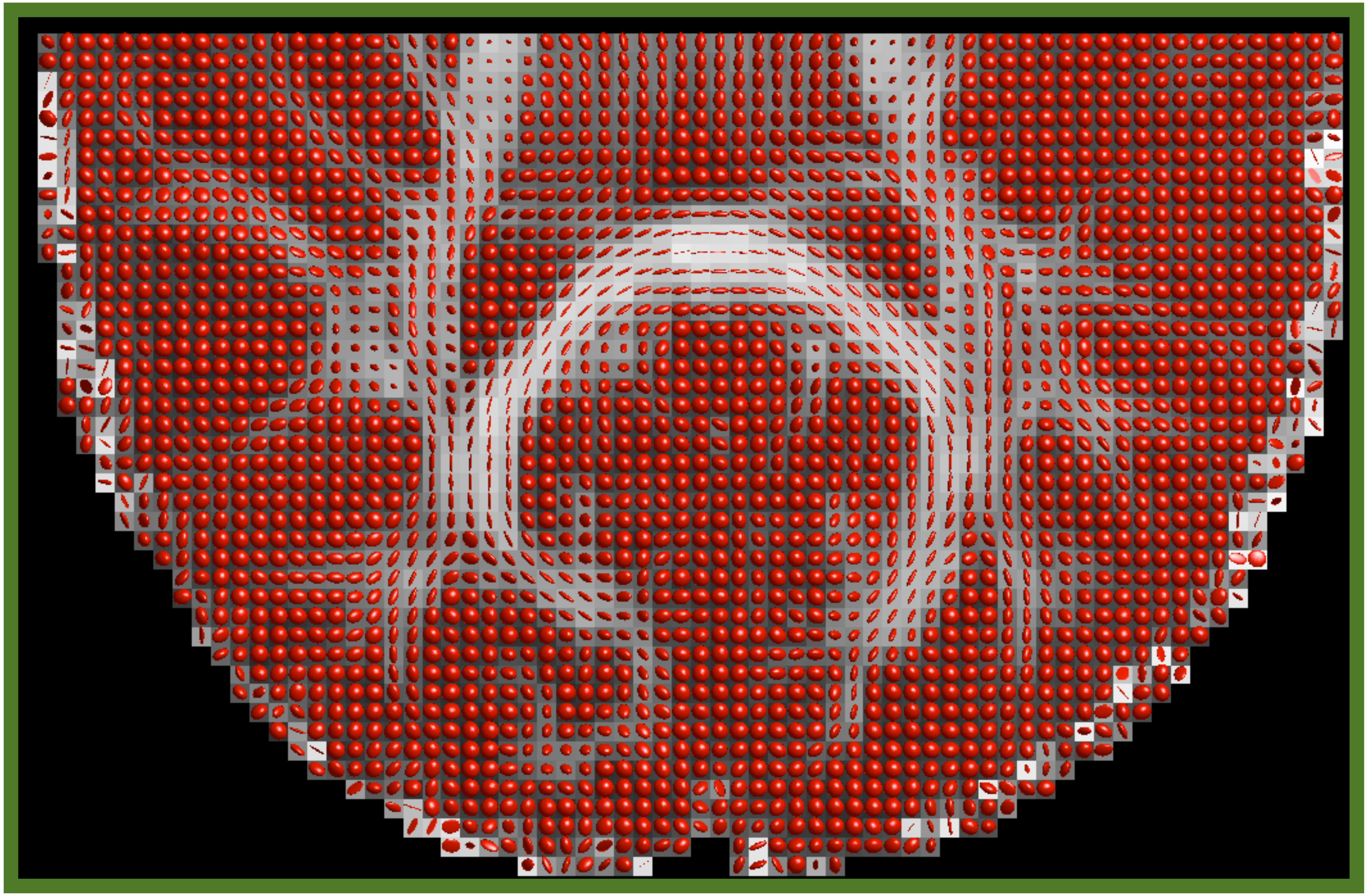


Diffusion Tensor Ellipsoids

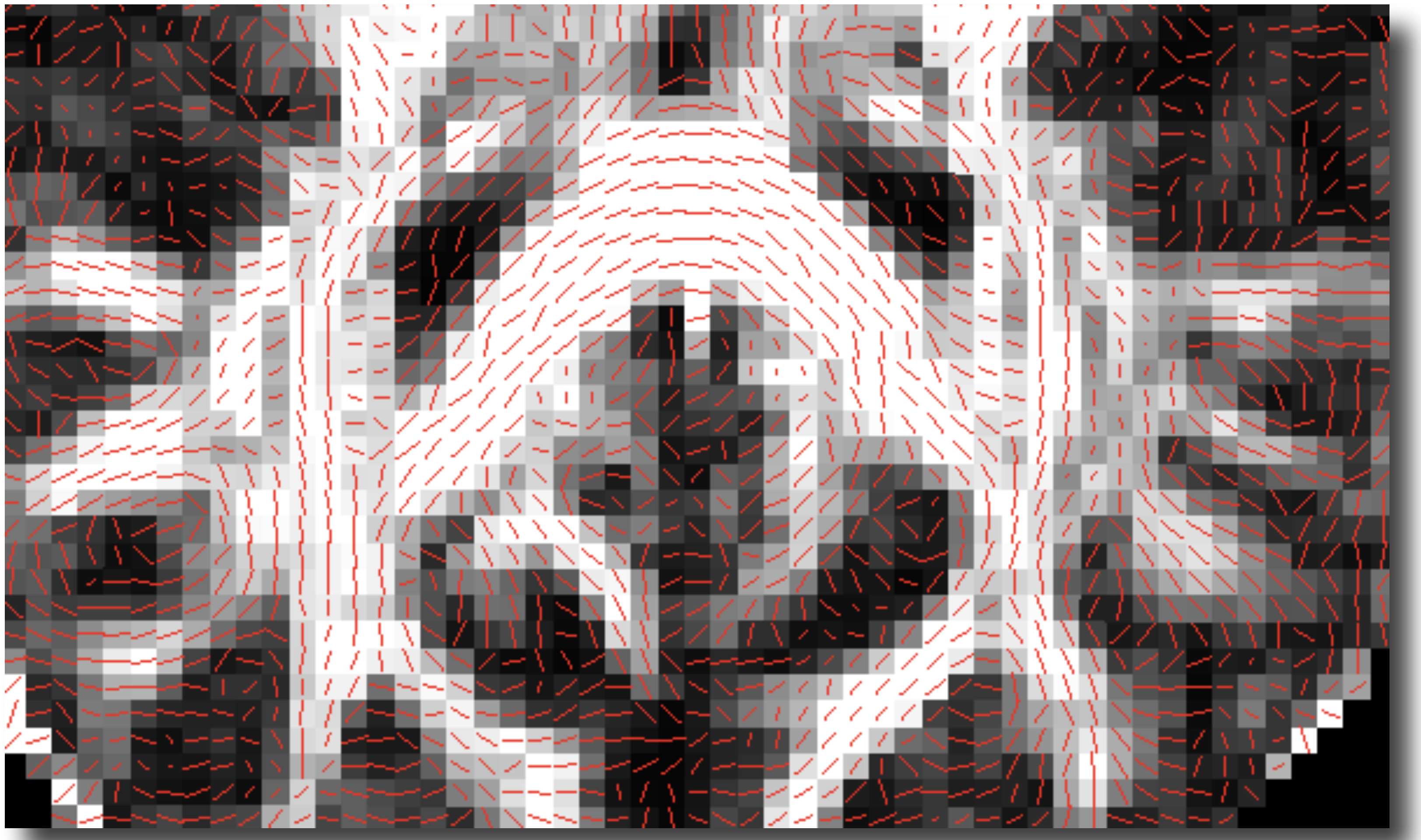






Estimates of Principal Fibre Orientation in WM

$\mathbf{v}_1$ map
Principal Diffusion Direction



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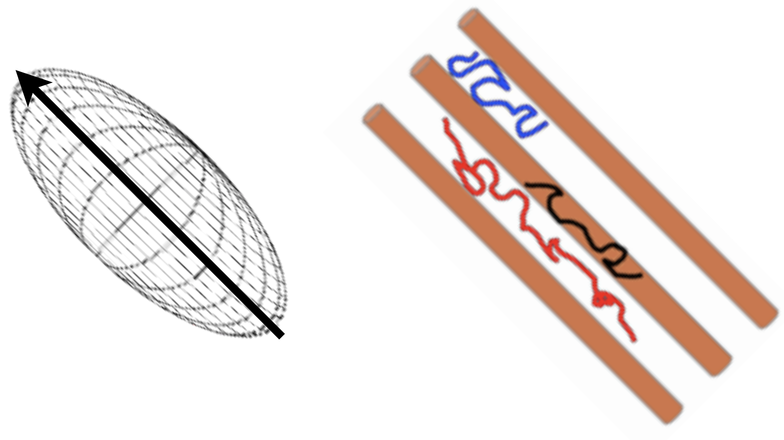
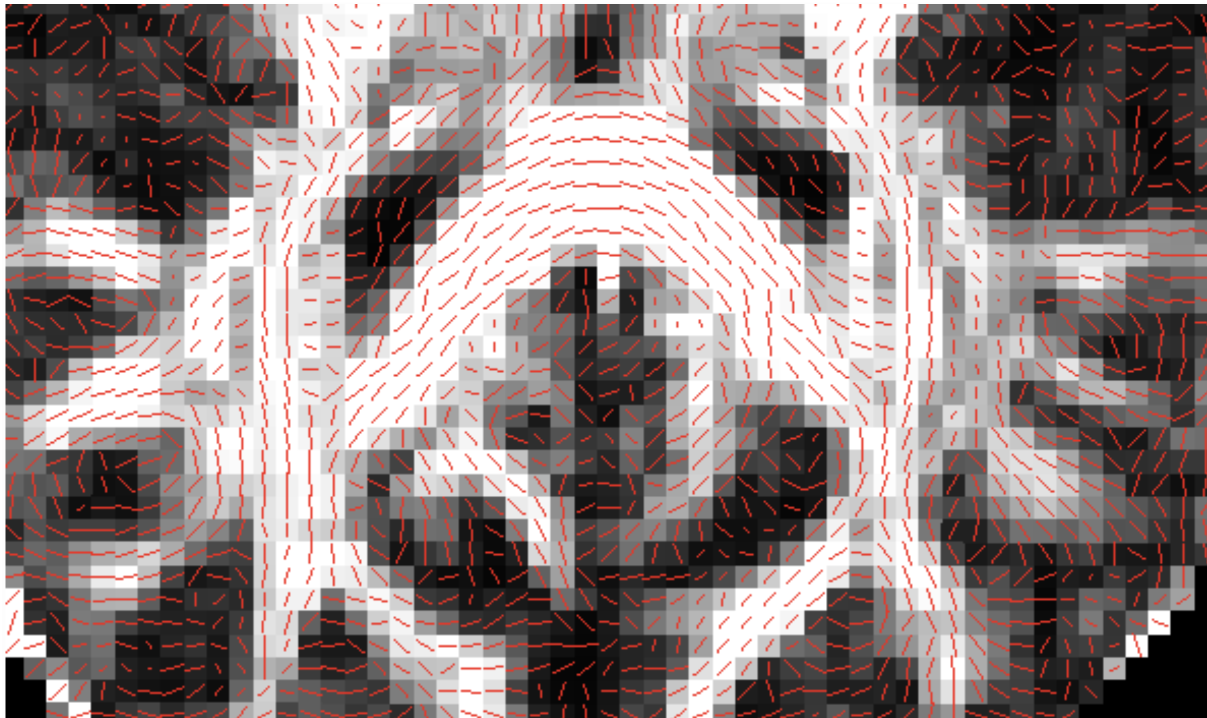


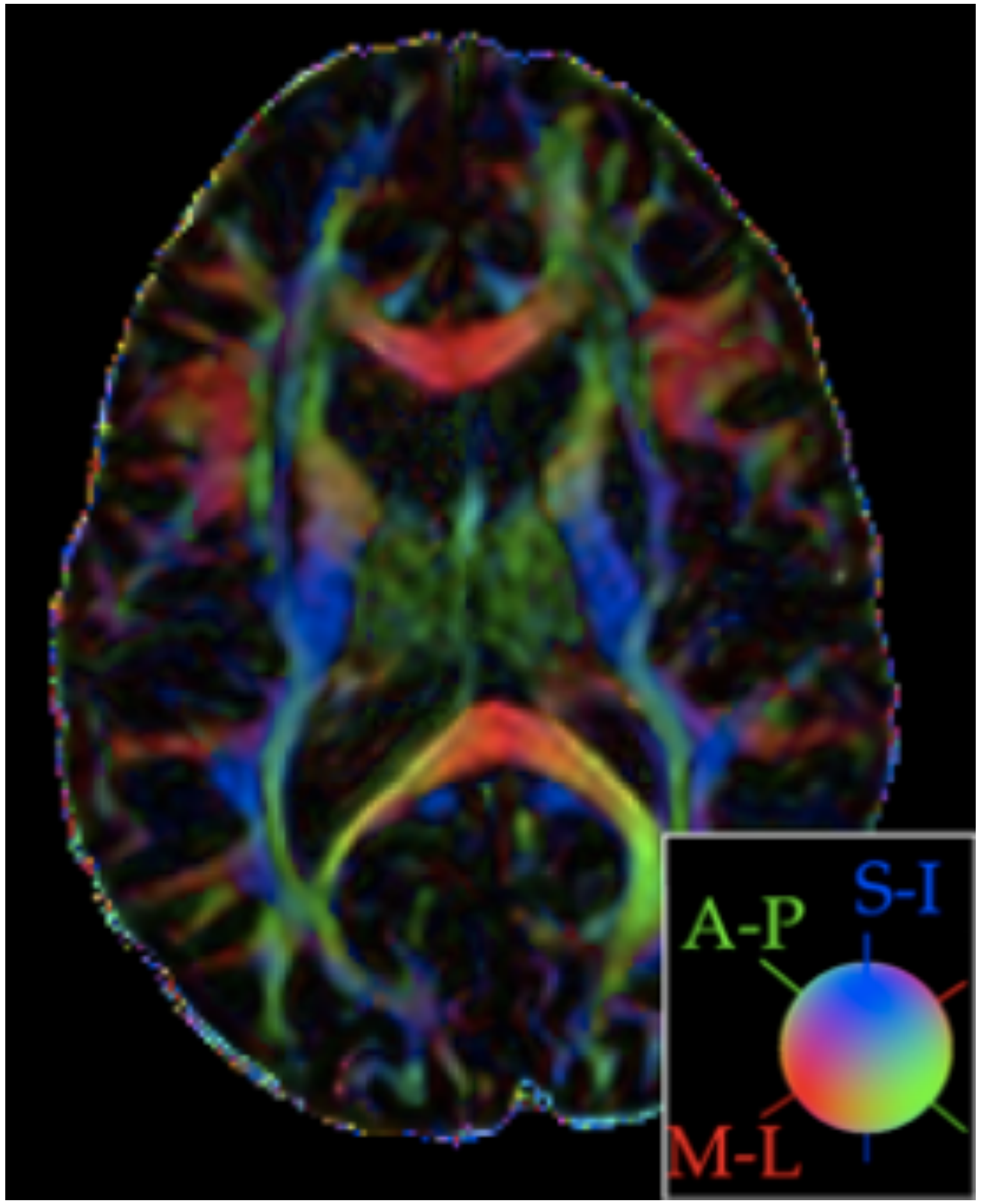
Assumption!!

Direction of maximum diffusivity in voxels with anisotropic profile is an **estimate of the major fibre orientation**.

Estimates of Principal Fibre Orientation in WM



Colour-coded $\mathbf{v_1}$ map



Directional contrast in DTI