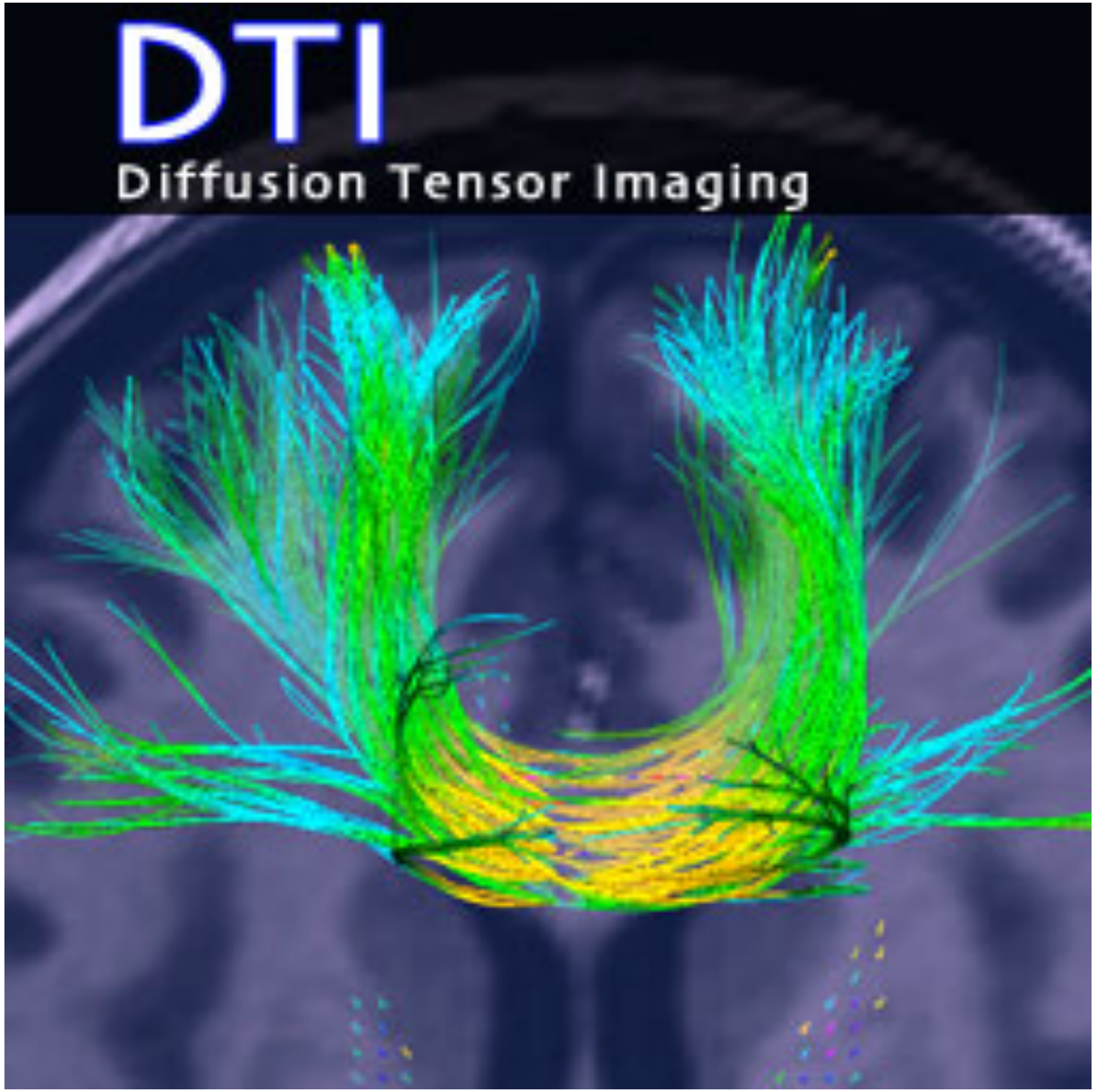

Diffusion tensor imaging (Part 2)

Valentina Giunchiglia

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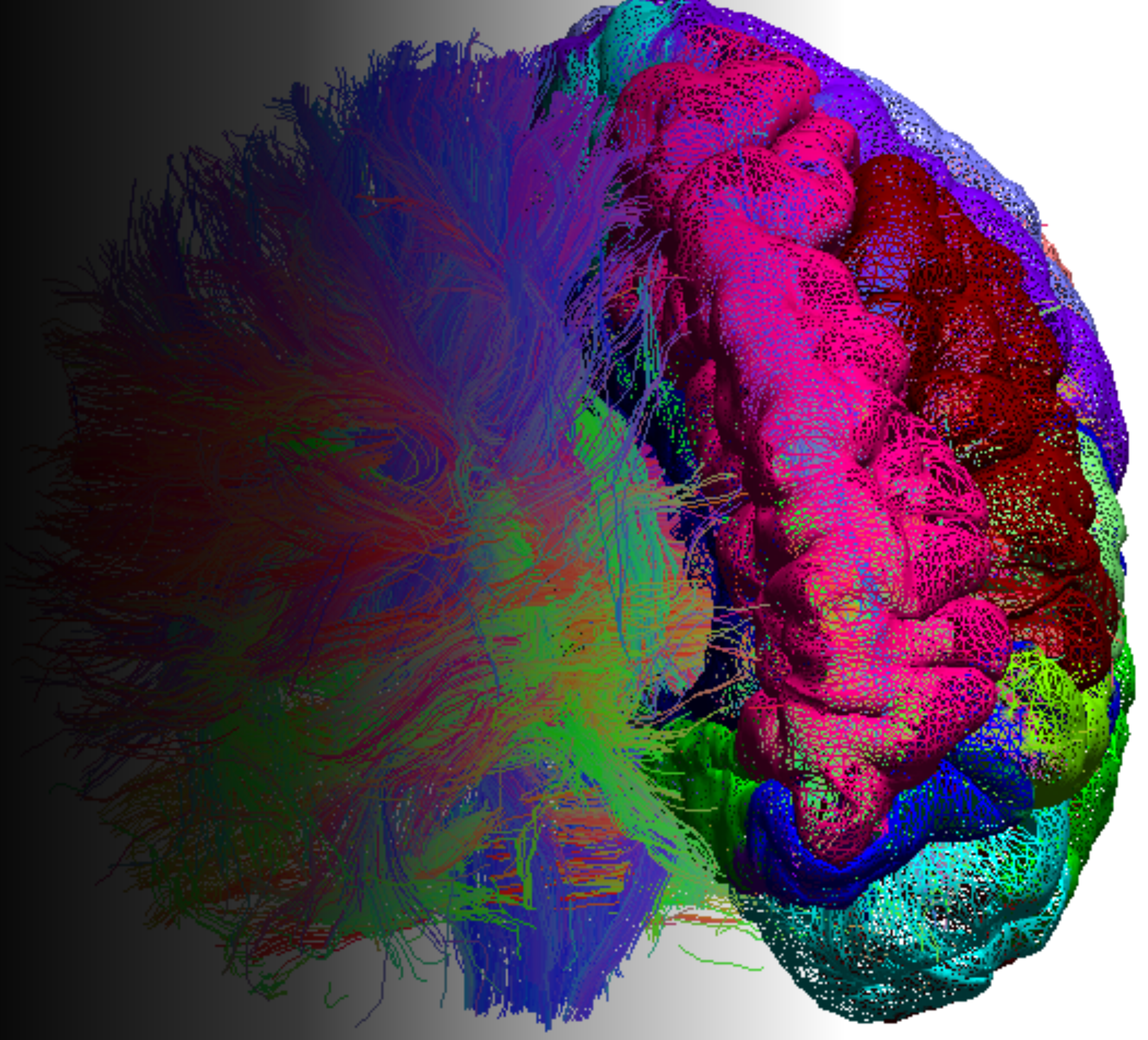
@valegiunca

What you will learn from this talk

- What diffusion is
- How we acquire brain images sensitive to diffusion

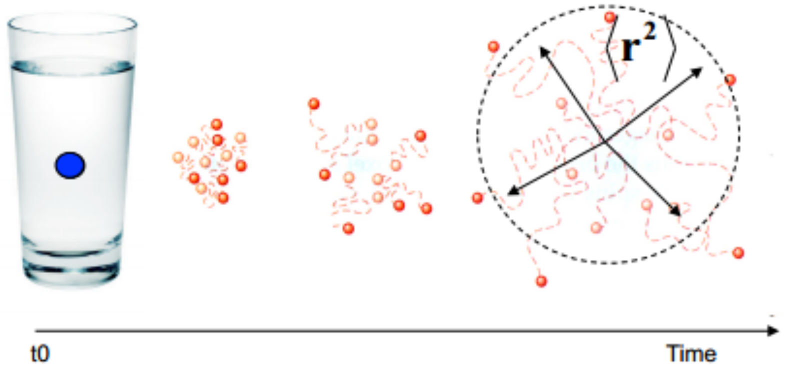
- Diffusion tensor imaging
- Imaging metrics

- Tractography
- Limitations
- Spherical deconvolution



Diffusion

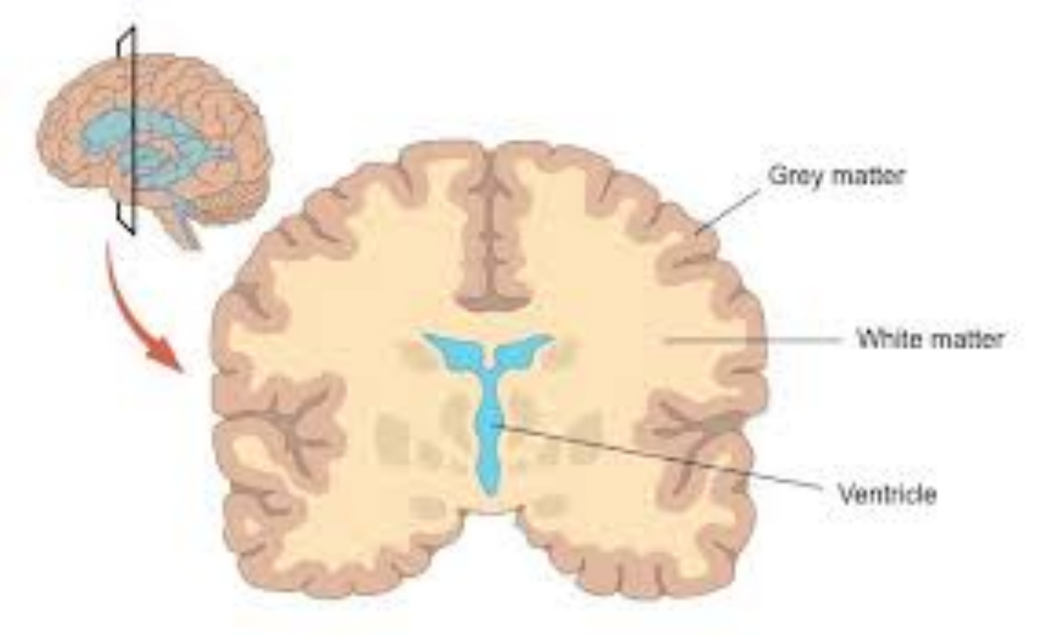
Diffusion is a <u>random walk process</u>
(e.g. Random motion of water molecules)



$$\boxed{\langle r^2 \rangle = 6Dt}$$

Mean Square Displacement
Diffusion Coefficient
Time

Displacement is proportional to the Diffusion Coefficient and the Time.

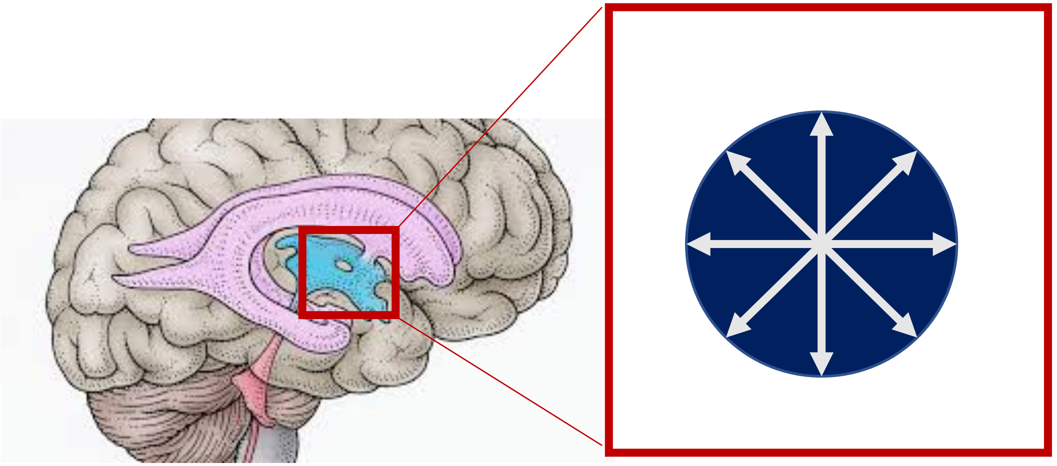


Different parts of the brain will have different diffusion properties due to their structure

Diffusion in the brain

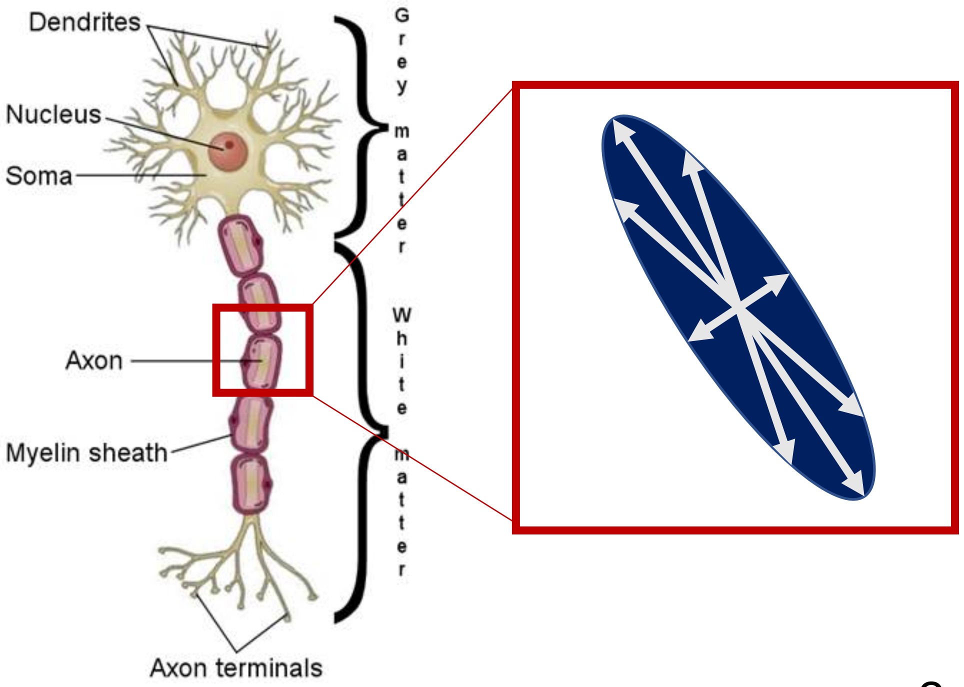
Isotropy

Unconstrained diffusion



Anisotropy

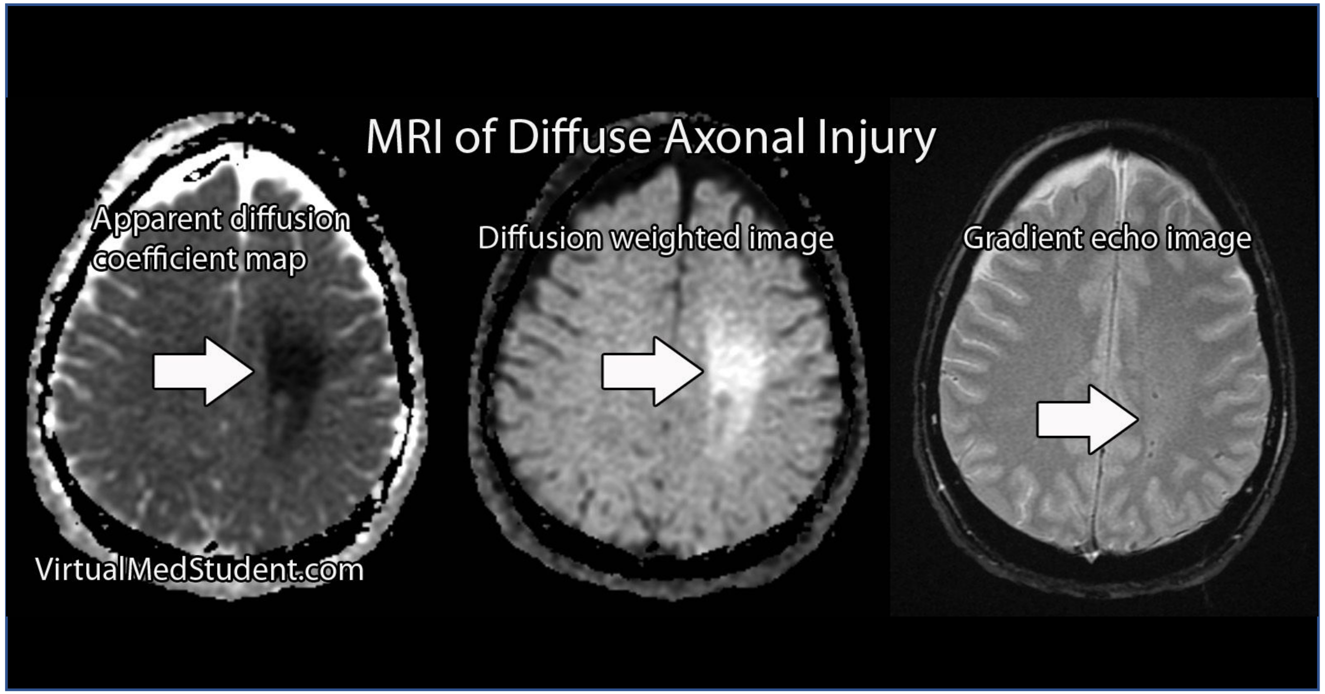
Restricted diffusion

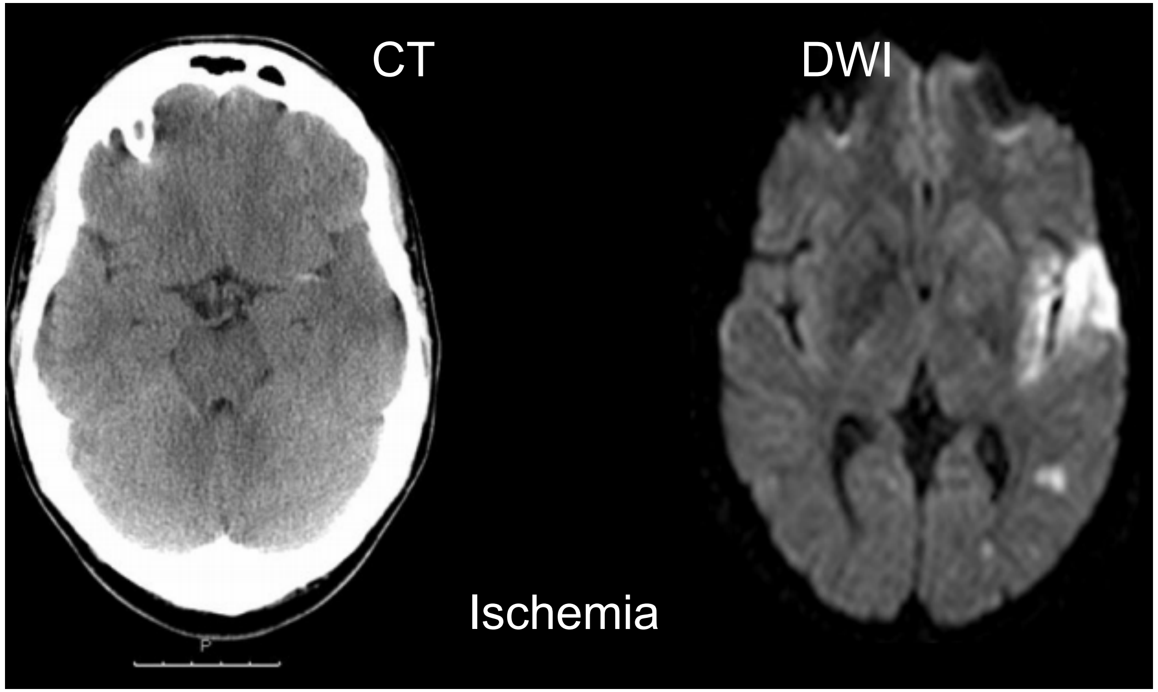


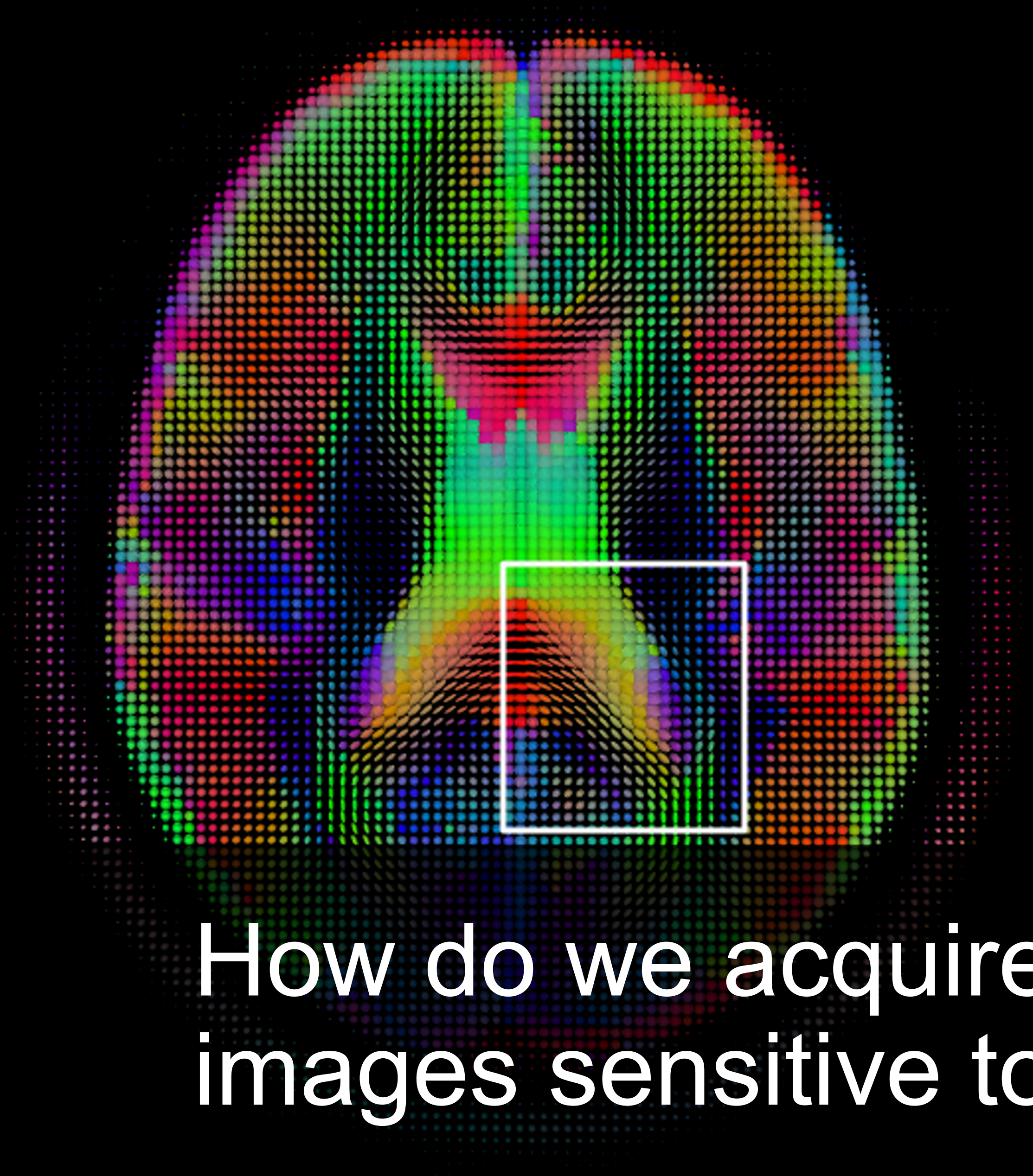
Clinical benefits of diffusion weighted imaging

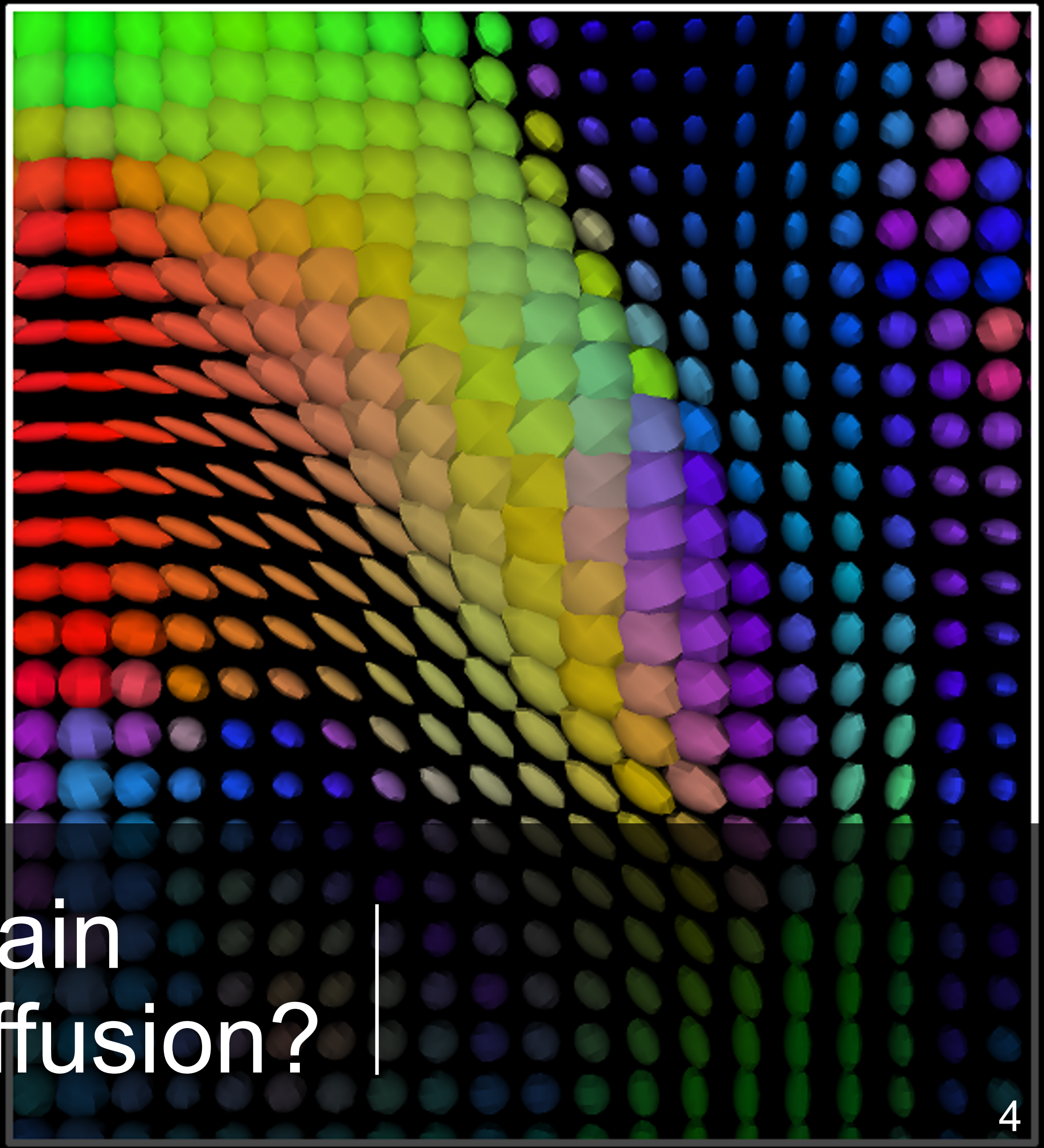
NOW ➡ CT scans are used to examine white matter damage and ischemia.

BUT ➡ Huge applications for diffusion weighted imaging in clinical practice.









How do we acquire brain images sensitive to diffusion?

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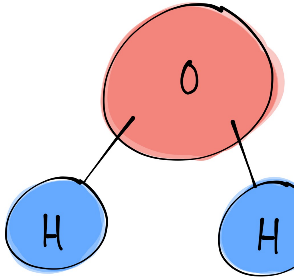
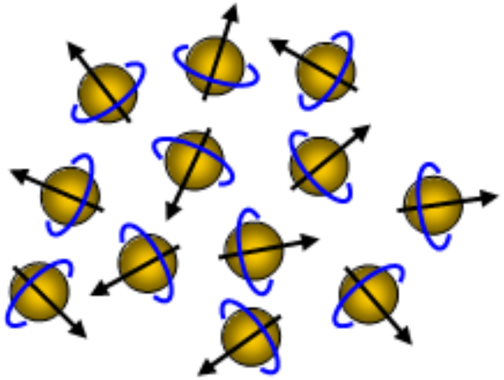
MRI summary

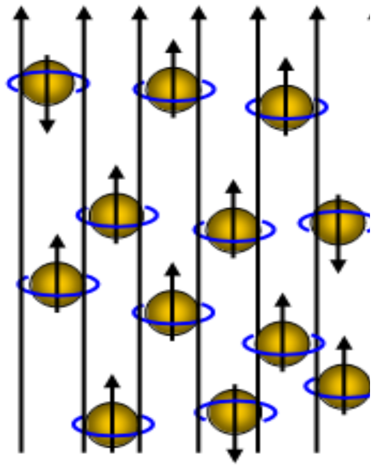
a. The body is 60% H_2O



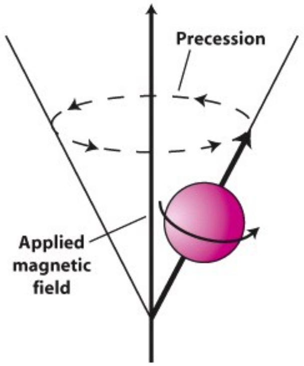
bi. Protons normally dance around



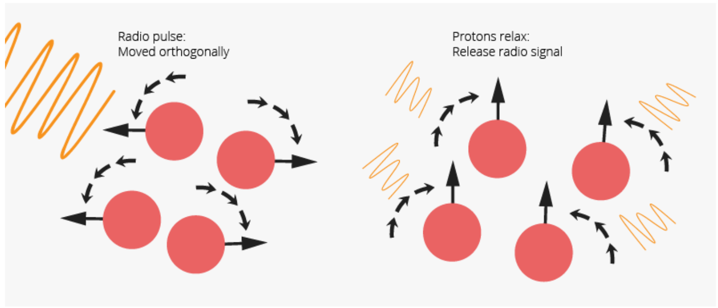
bii. Protons align inside a magnetic field



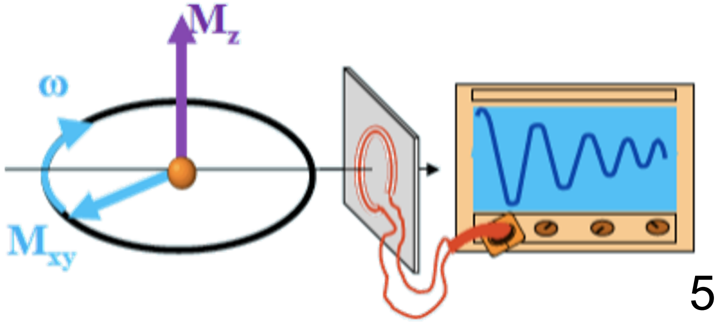
c. Precession



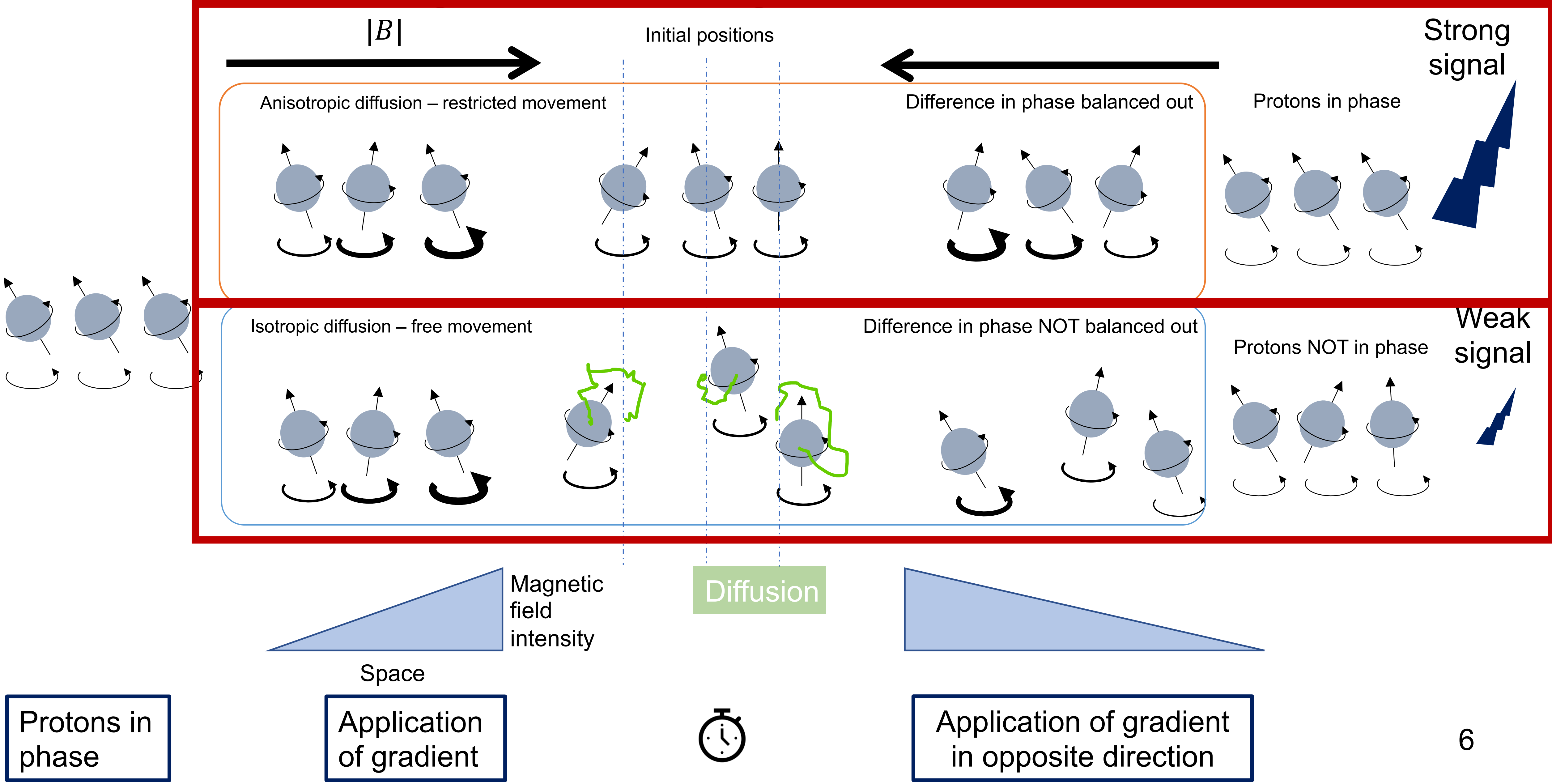
d. RF pulses give energy to the protons.



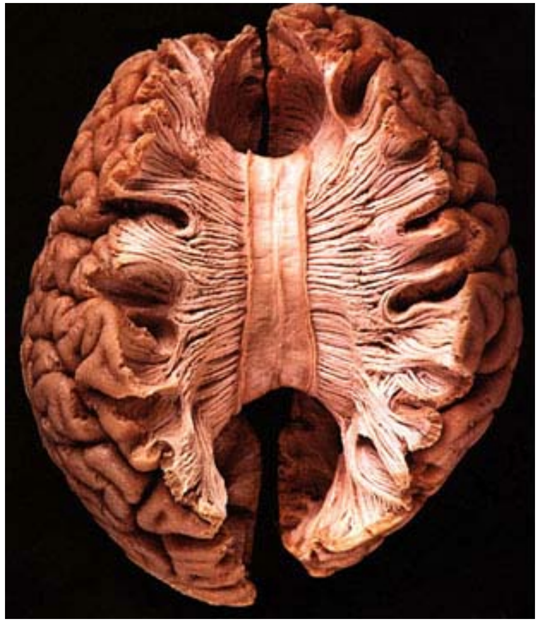
e. MRI measures the energy released

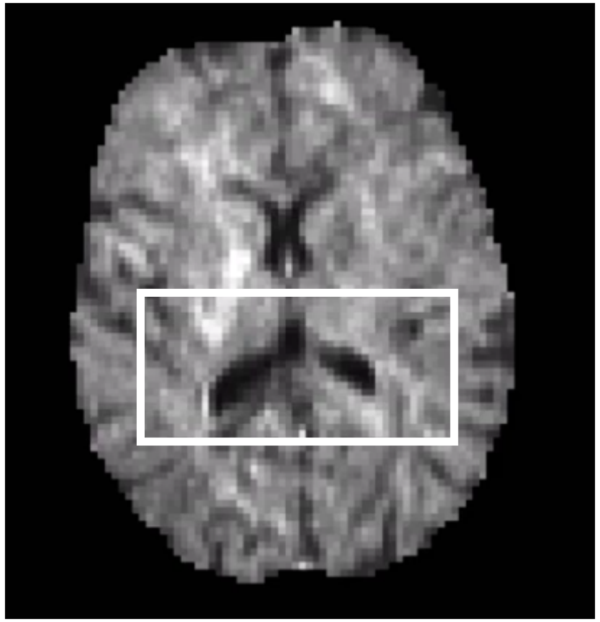


Diffusion weighted images

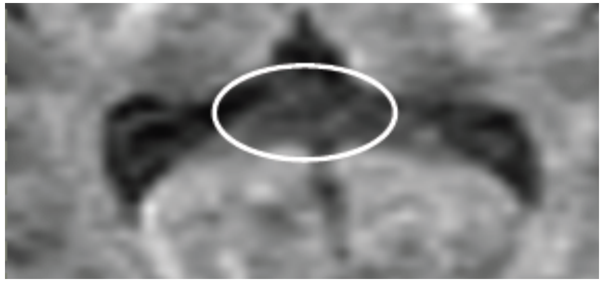


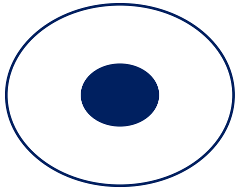
Diffusion is along the direction of the gradient…

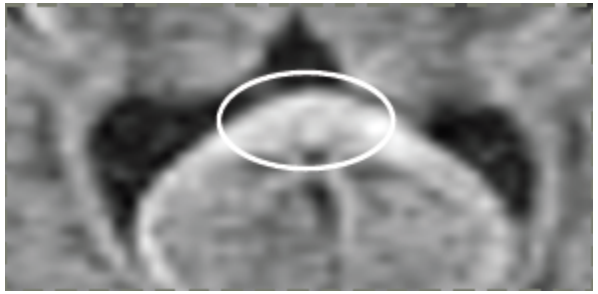




Corpus Callosum



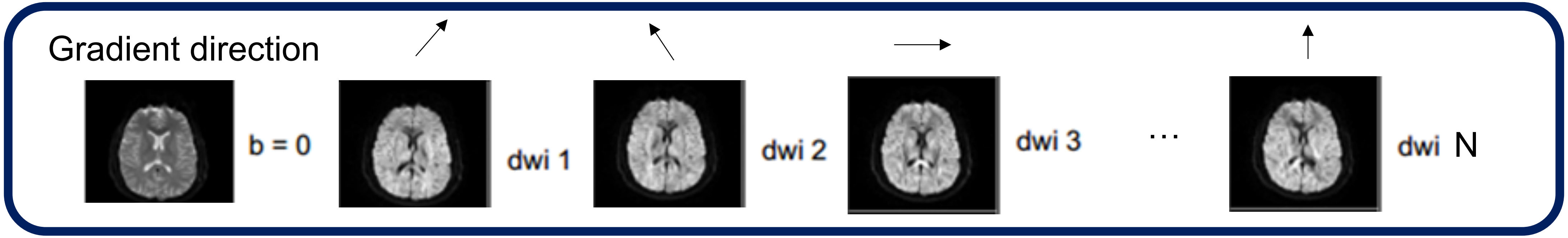




Diffusion MRI encoding

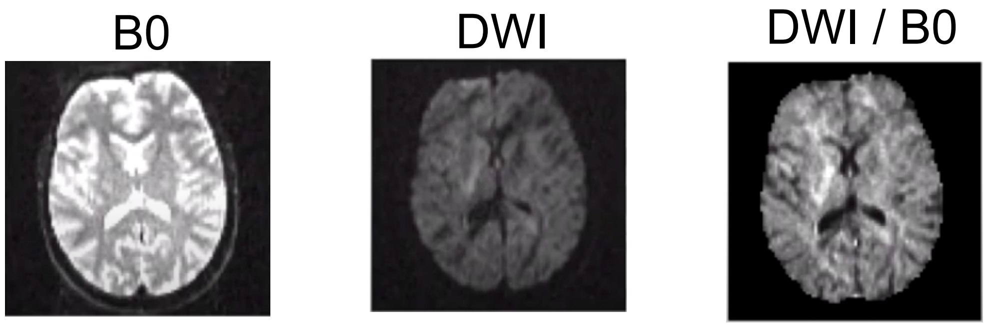
1

- Acquisition of multiple DWI with different gradient directions
  - Directions must be uniform through space
  - Minimum: 6, Quality data > 30
  - We normally use 64 directions



2

- Diffusivity calculated relative to the b=0 image



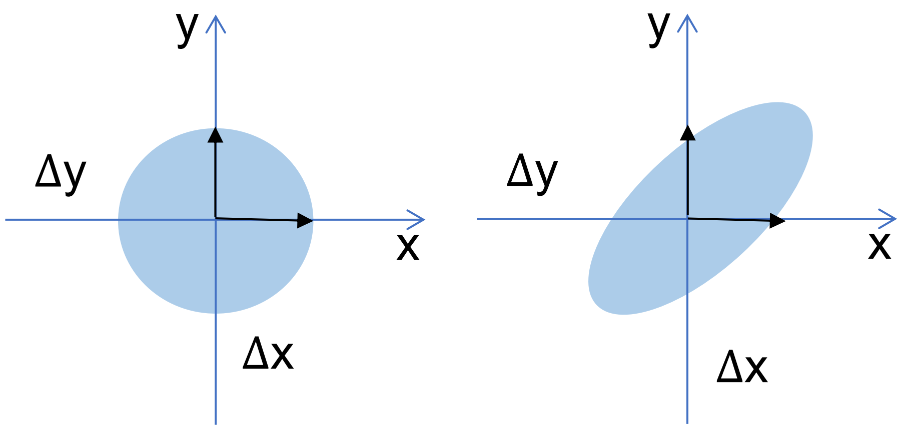
The diffusion tensor and array

$$\begin{bmatrix} D\color{green}{xx} & Dxy & Dxz \\ Dxy & D\color{green}{yy} & Dyz \\ Dxz & Dyz & D\color{green}{zz} \end{bmatrix}$$

DIFFUSION TENSOR: 3x3 symmetric matrix that represents the diffusion rates in each combination of directions.

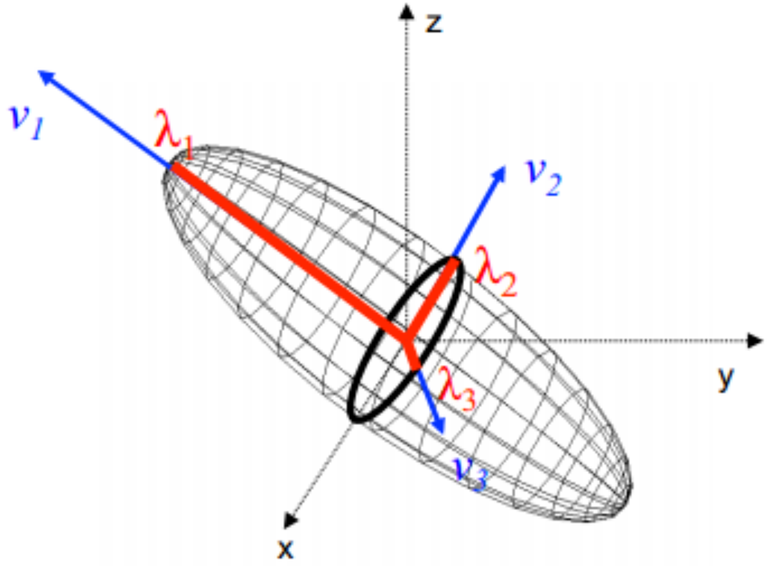
Diagonal elements (Dxx, Dyy and Dzz) diffusion coefficients along x,y and z axis.

Off-diagonal elements correlation of motions between each pair of directions.



According to Δx and Δy, they look the same

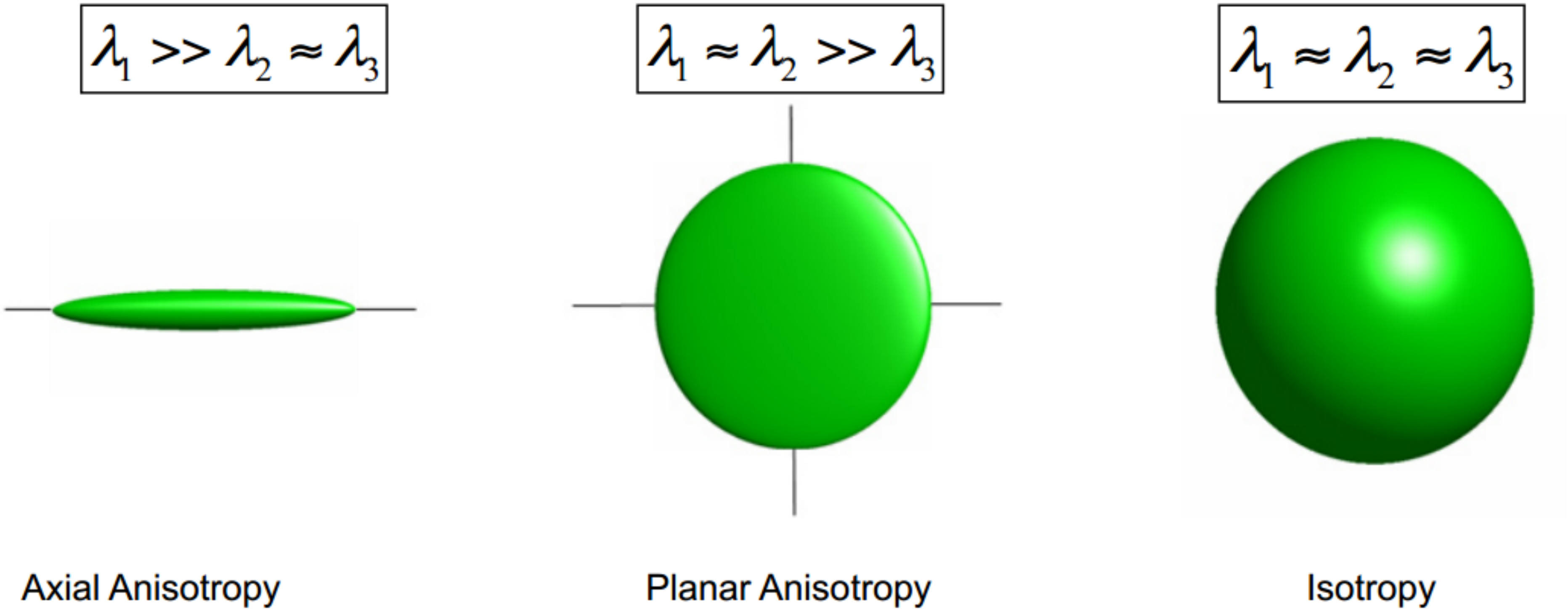
How to get a more interpretable coordinate system?



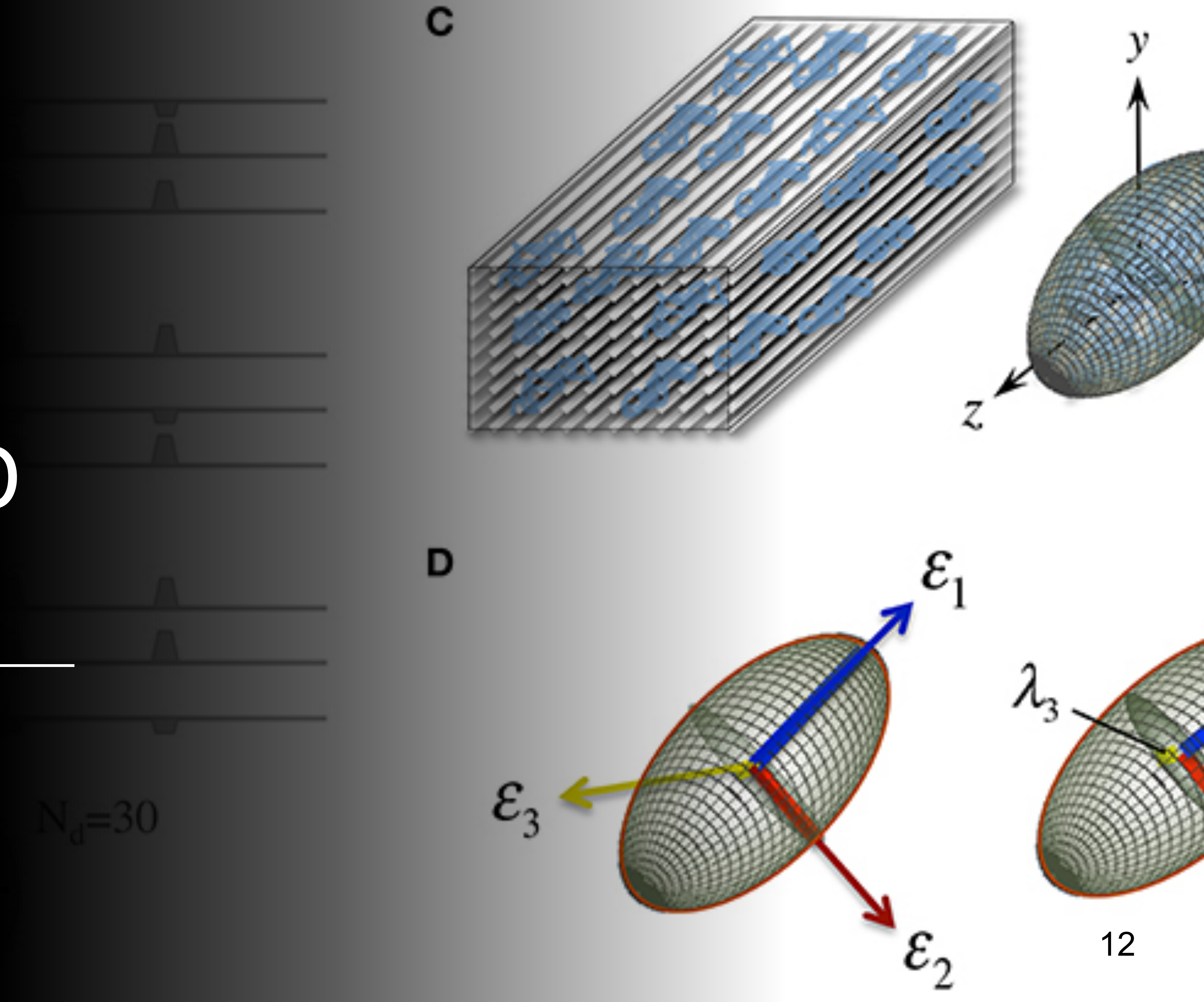
Eigenvalue decomposition

- 3 Eigenvectors –
  - Represent the **direction** of diffusion
  - First eigenvector = preferred direction
- 3 Eigenvalues -
  - Represent the **magnitude** of diffusion.

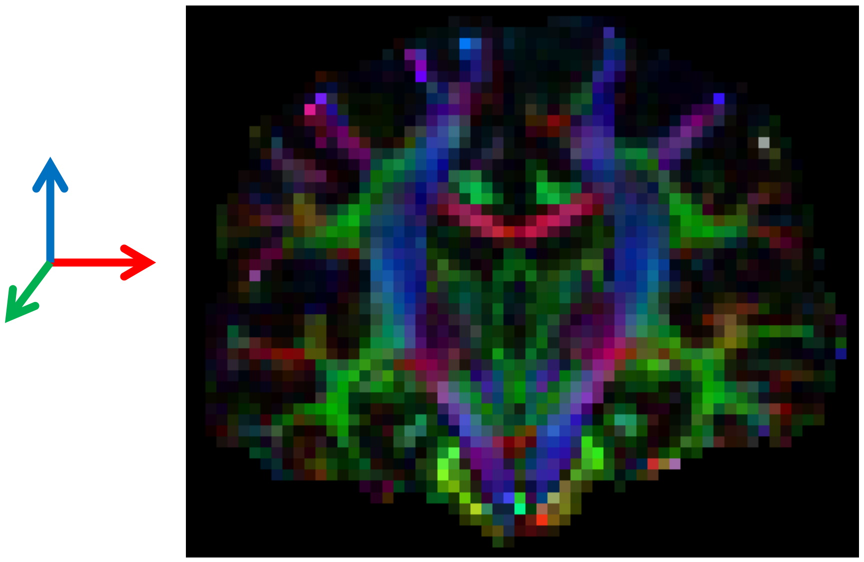
Ellipsoid tensors provide 3D characterisations of water diffusivity

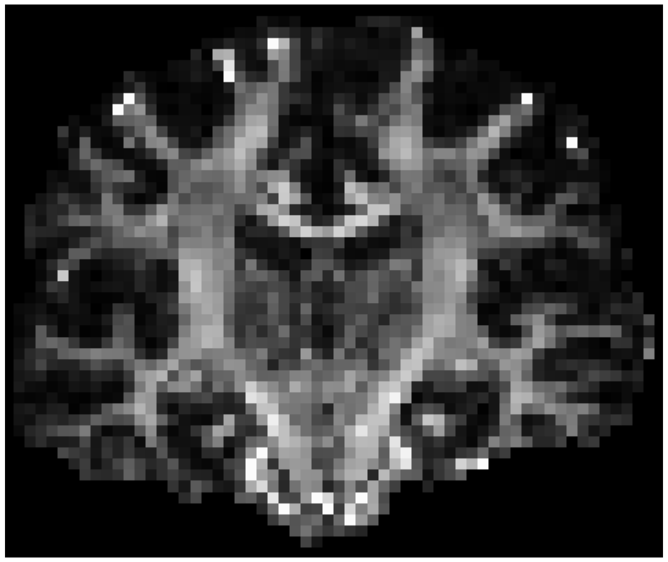


How do we represent 3D diffusion?



3D diffusion





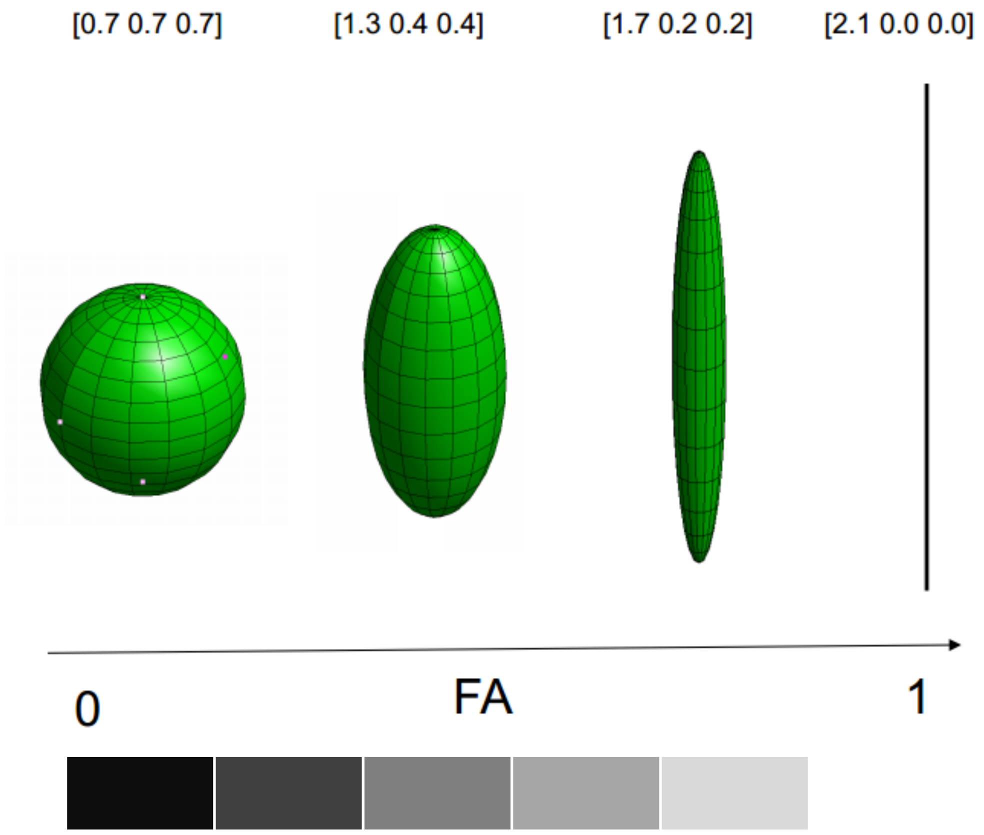
RGB maps represent the orientation of each voxels tensor

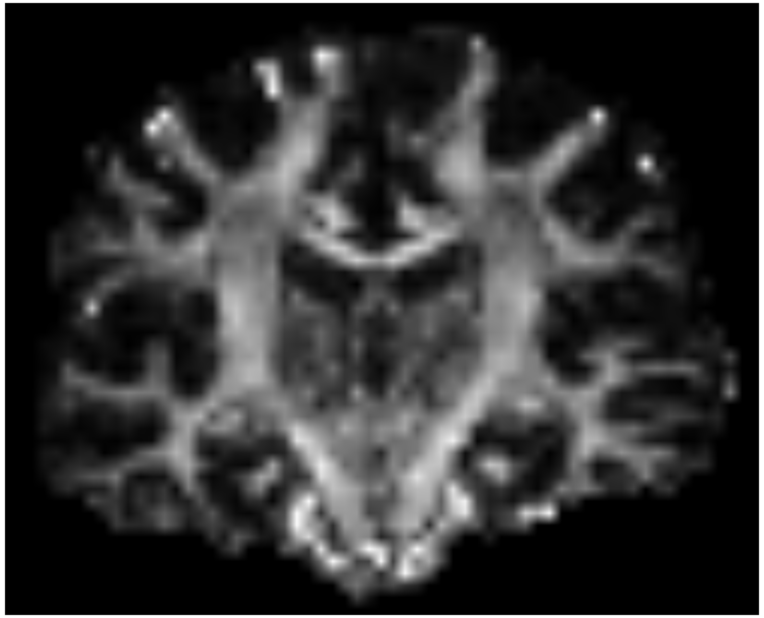
Maps based on different measures of diffusivity:

- Fractional Anisotropy
- Mean Diffusivity

Fractional Anisotropy

Eigenvalues’ variance

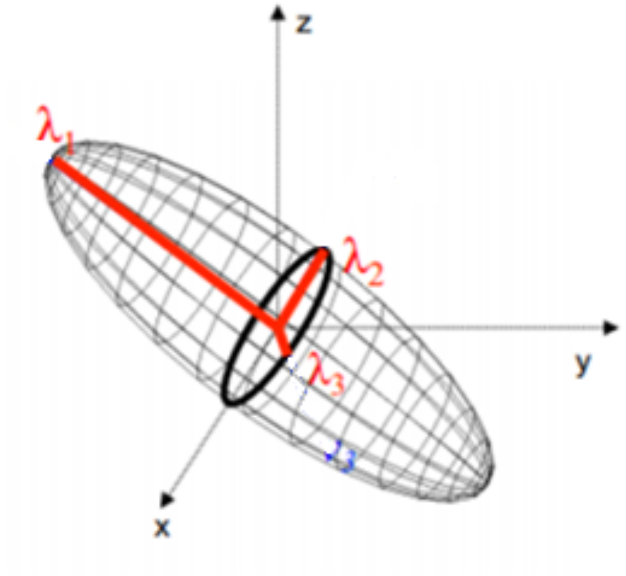


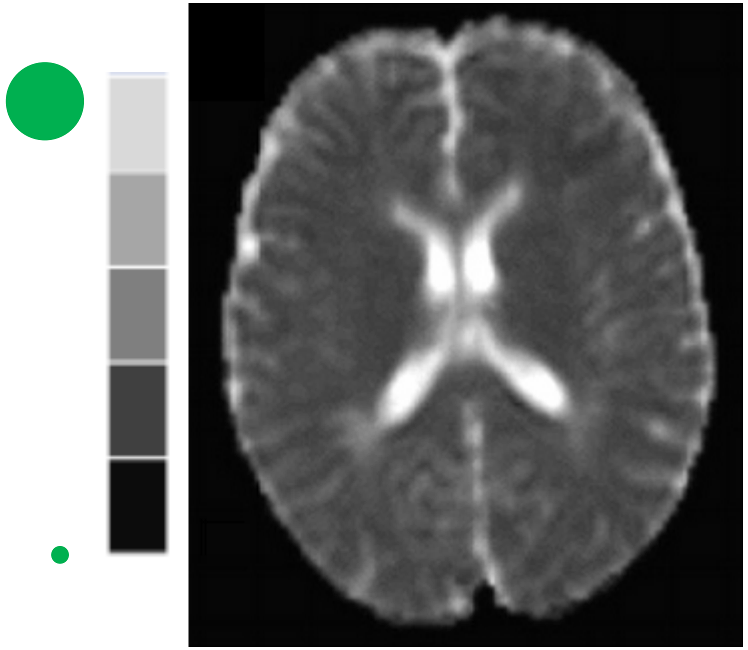


$$FA = \sqrt{\frac{3\sum_{i=1}^{3}(\lambda_i - \overline{\lambda})^2}{2\sum_{i=1}^{3}\lambda_i^2}}, \qquad FA \text{ in } [0,1]$$

Mean Diffusivity

Eigenvalues' mean





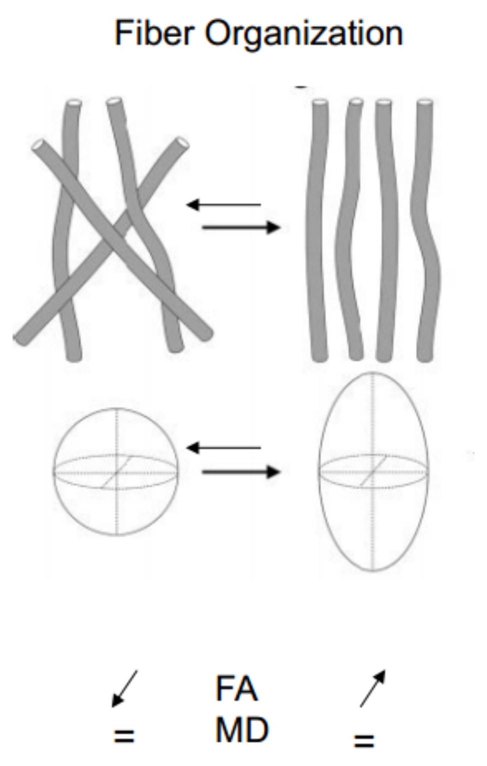
- Average mobility of the tissue.

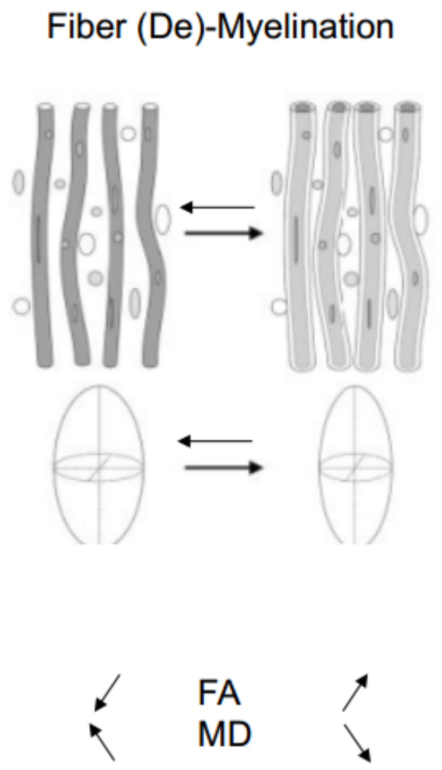
- The bigger the sphere, the greater the overall diffusion.

$$MD = (\lambda_1 + \lambda_2 + \lambda_3)/3$$

Different measures provide different information about white matter microstructure

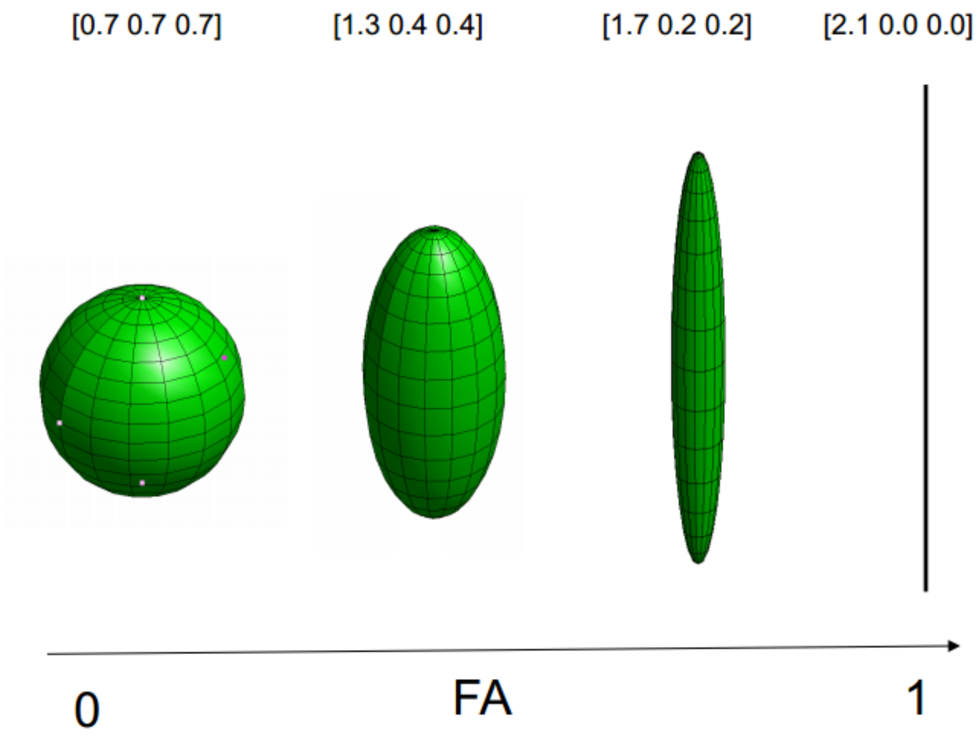
	FA	MD	AD	RD
		$(\lambda_1+\lambda_2+\lambda_3)/3$	λ_1	$(\lambda_2+\lambda_3)/2$
	FA is a summary measure of microstructural integrity. While FA is highly sensitive to microstructural changes, it is less specific to the type of change.	MD is an inverse measure of the membrane density, is very similar for both GM and WM and higher for CSF. MD is sensitive to cellularity, edema, and necrosis.	AD tends to be variable in WM changes and pathology. In axonal injury AD decreases. The ADs of WM tracts have been reported to increase with brain maturation.	RD increases in WM with de- or dys-myelination. Changes in the axonal diameters or density may also influence RD.
Gray Matter	↓	–	↓	↑
White Matter	↑	–	↑	↓
CSF	↓	↑	↑	↑
High myelination	↑	↓	–	↓
Dense axonal packing	↑	↓	–	↓
WM Maturation	↑	↓	↑	↓
Axonal degeneration	↓	↑	↓	↑
Demyelination	↓	↑	–	↑
Low SNR	↓	↑	↓	–





J.Dubois et al Human Brain Mapping 29:14–27 (2008)

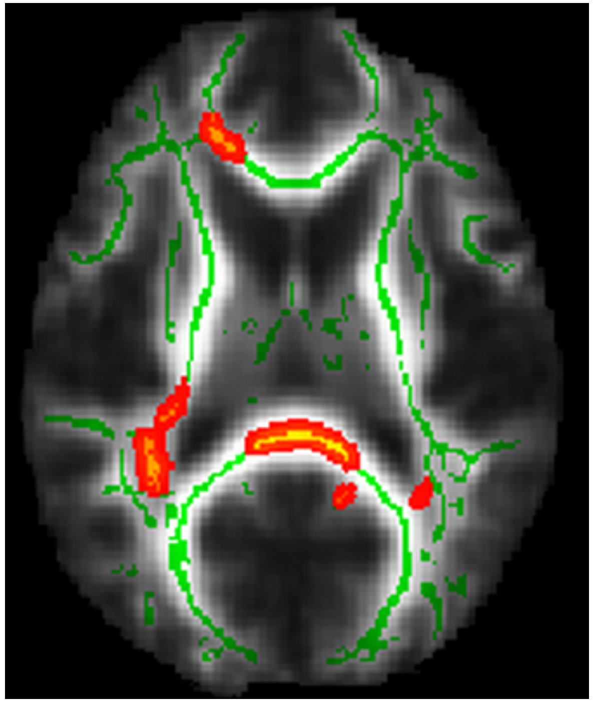
Which ellipsoid has the greatest MD?



......they all have the same MD!

Whole brain vs ROI measures

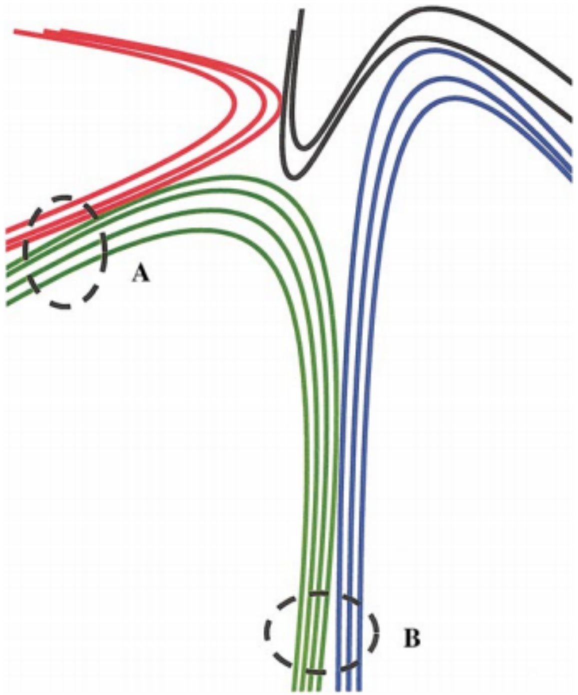
- Whole brain TBSS



(Smith et al., 2006)

http://fsl.fmrib.ox.ac.uk/fsl/fsl4.0/tbss/index

- ROI tractography

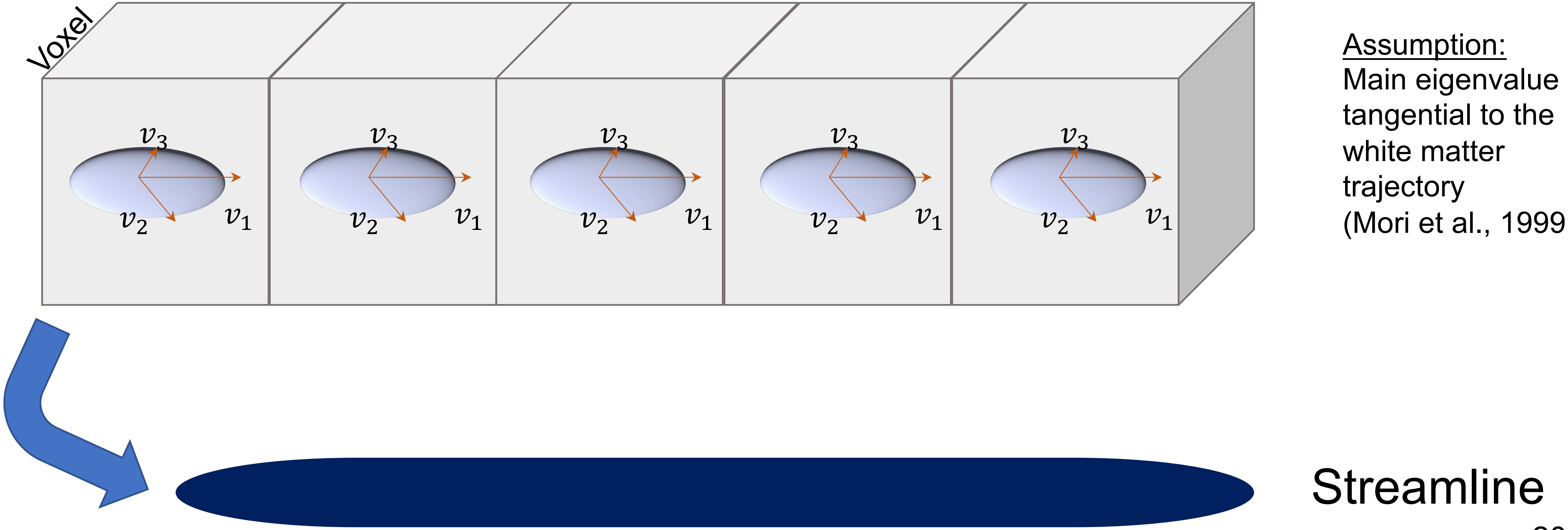


(Catani et al., 2002)

Tractography

Tractography

Indirect reconstruction of the white matter anatomy based on the diffusion of water molecules



Assumption:
Main eigenvalue tangential to the white matter trajectory
(Mori et al., 1999)

There are limitations!

1

Stopping rules	
FA thresholds	Curvature
< 0.2 FA	>45 degrees

2

Data quality	
SNR	Spatial resolution

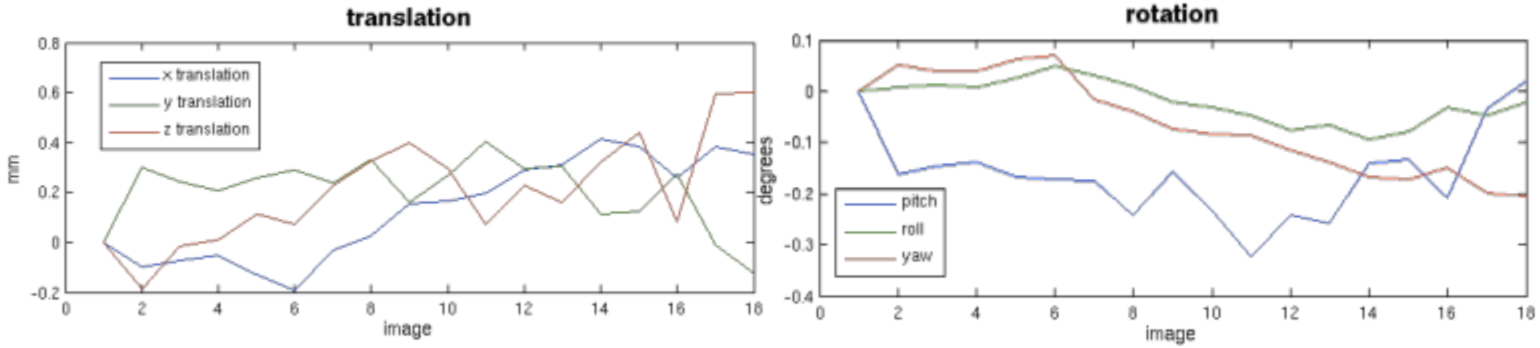
3

Model limitations	
Partial Volume	Crossing
bending	kissing

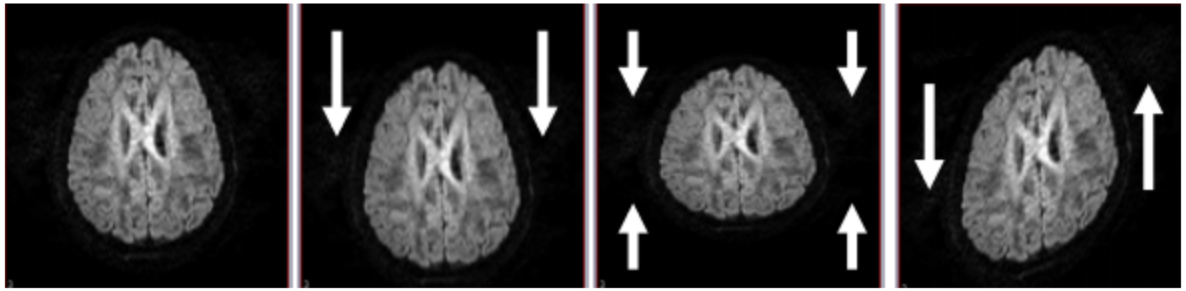
Thanks to Flavio Dell'Acqua

Data quality is essential!

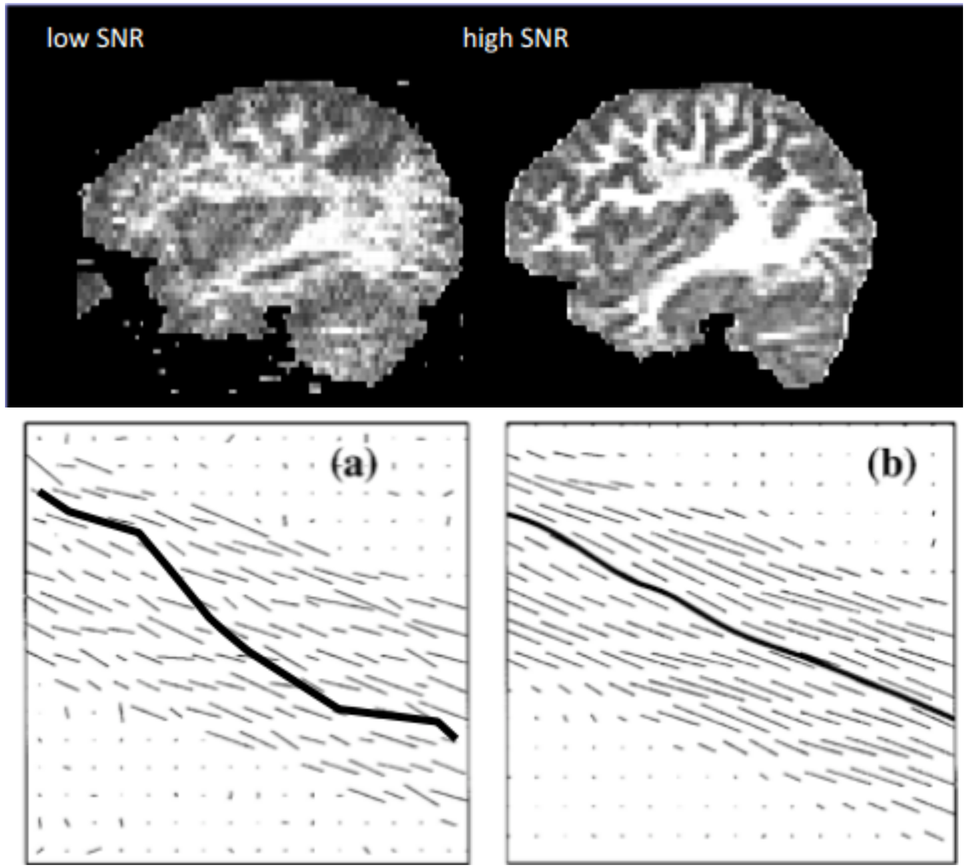
- Head motion

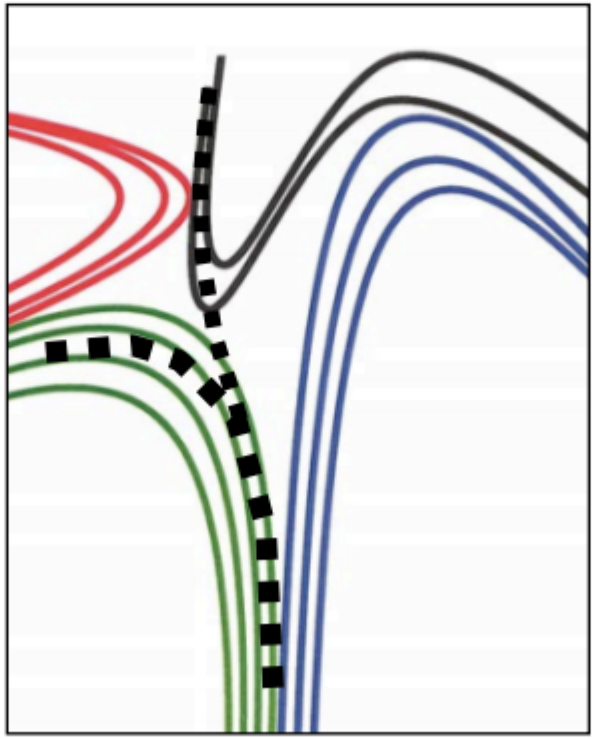


- Eddy current distortion



2 Data quality



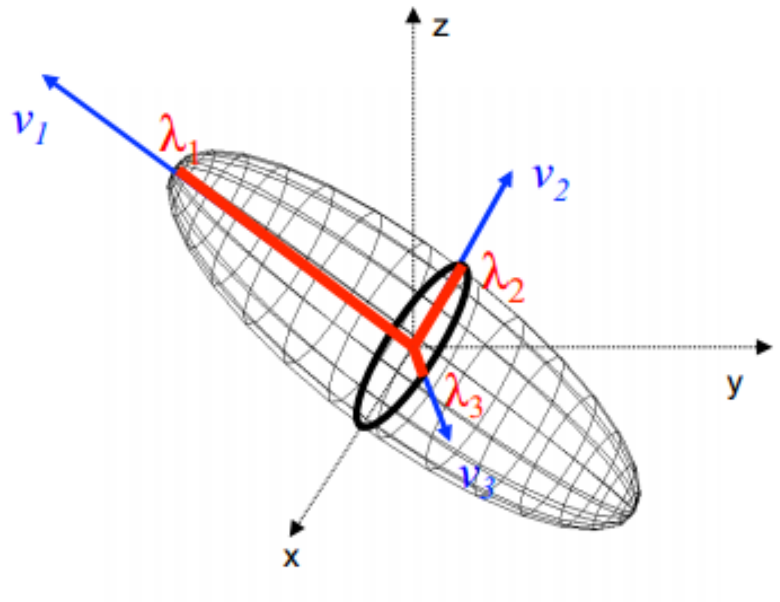


SNR

Trajectory estimation accuracy

(Catani et al., 2002)

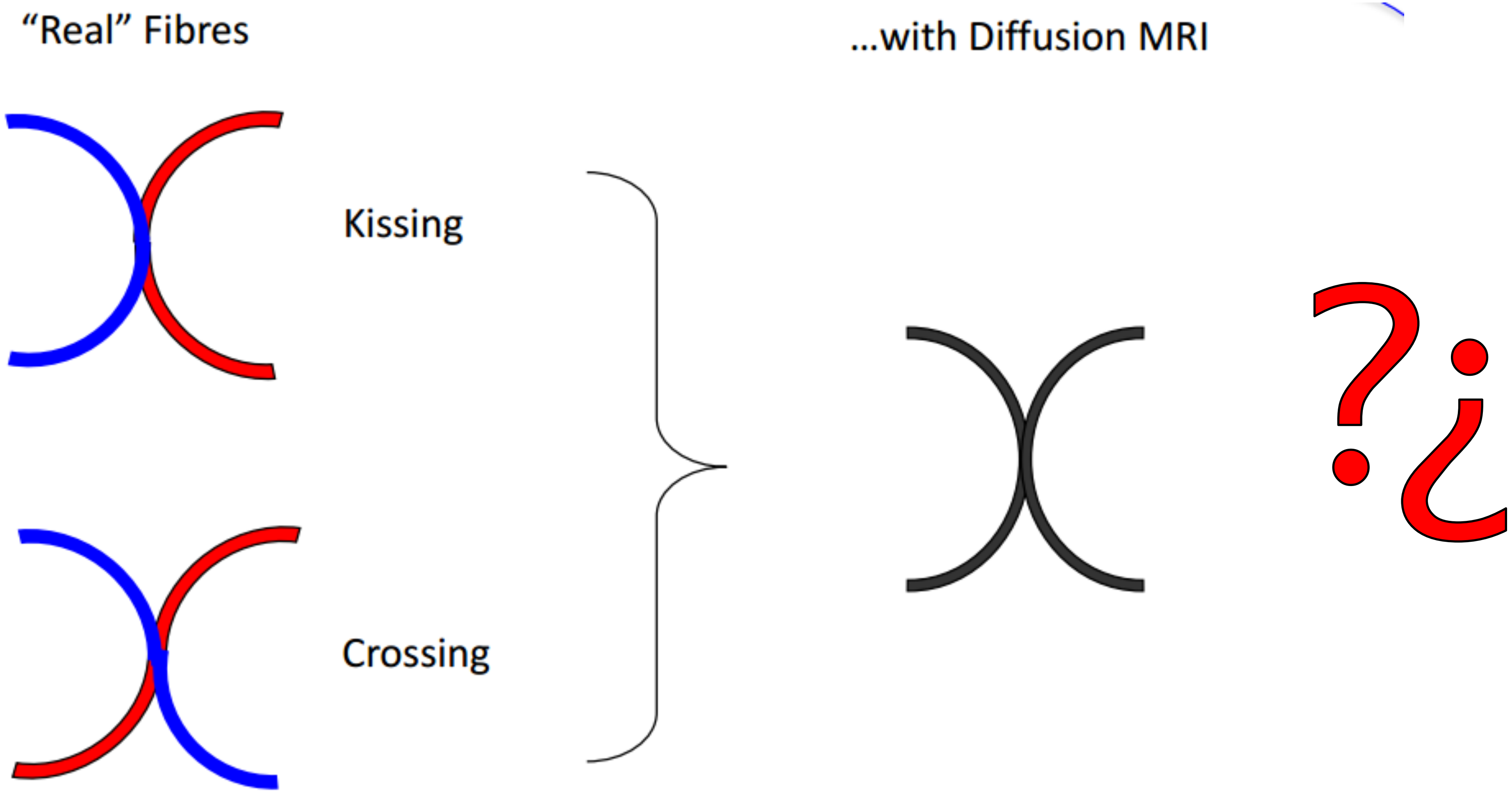
3 Model limitations



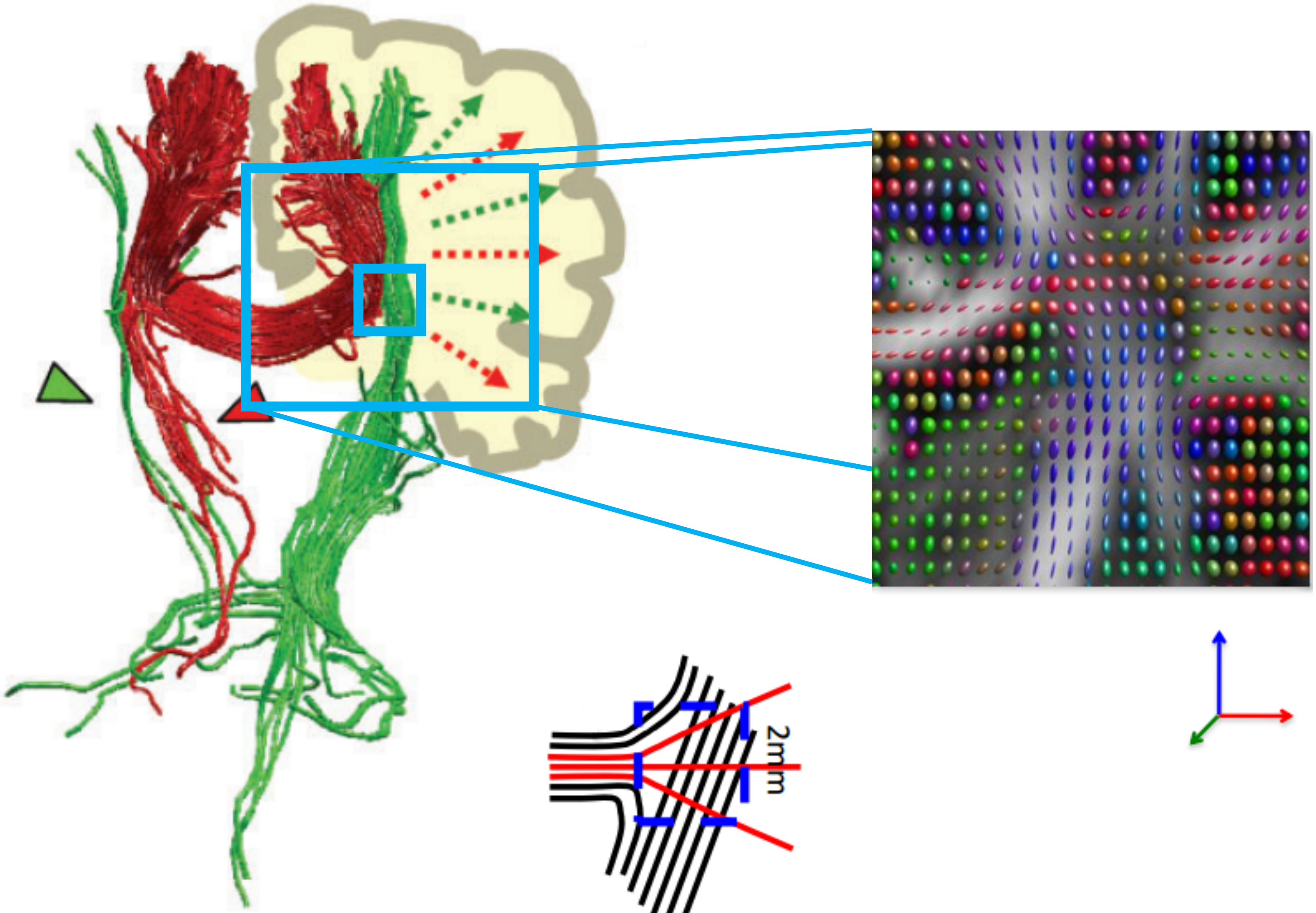
Diffusivity based on 3 Eigenvalues (λ1, λ2, λ3)

- Compact Description
- Oversimplified Description

3 Model limitations



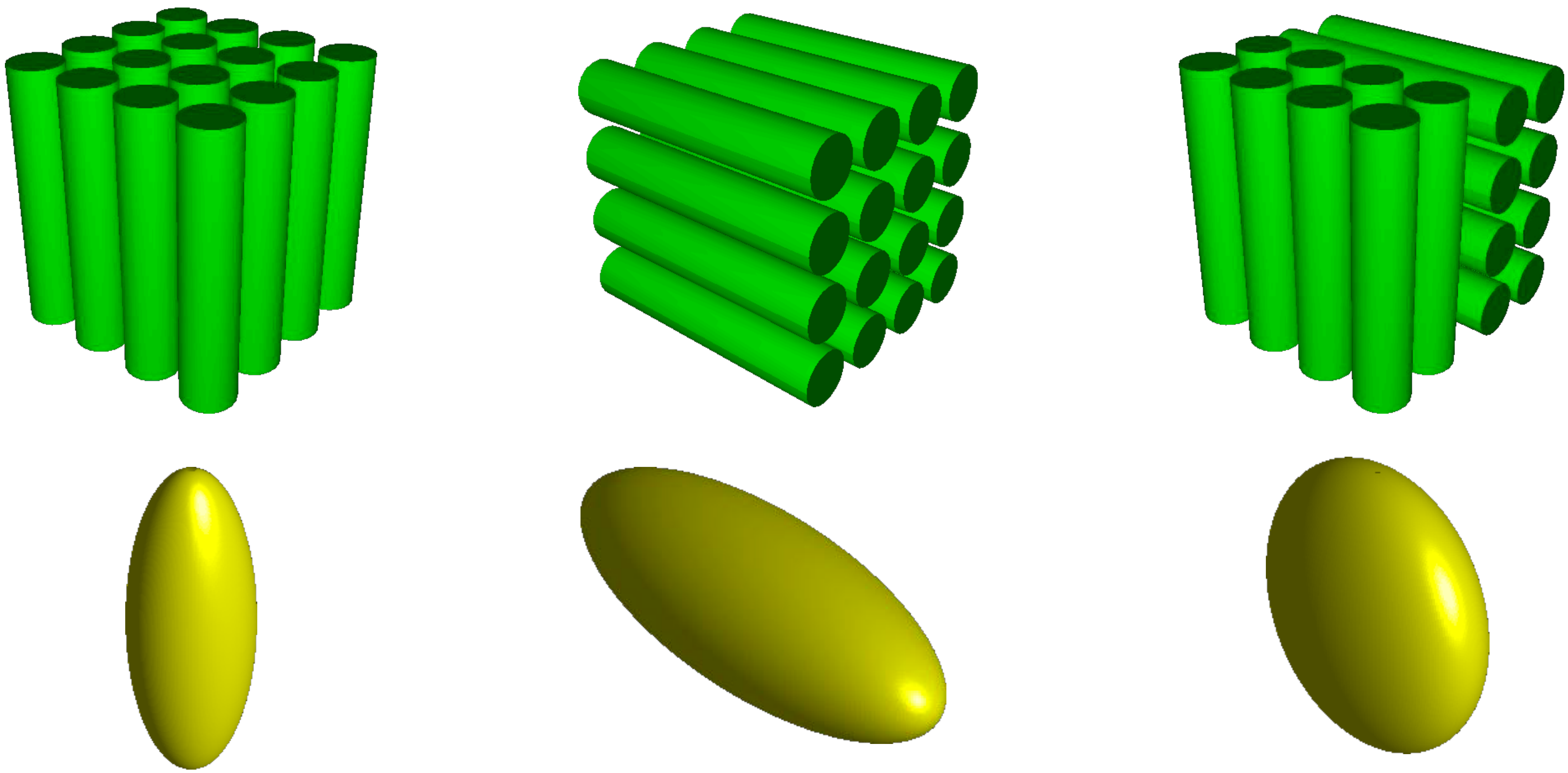
Model limitations



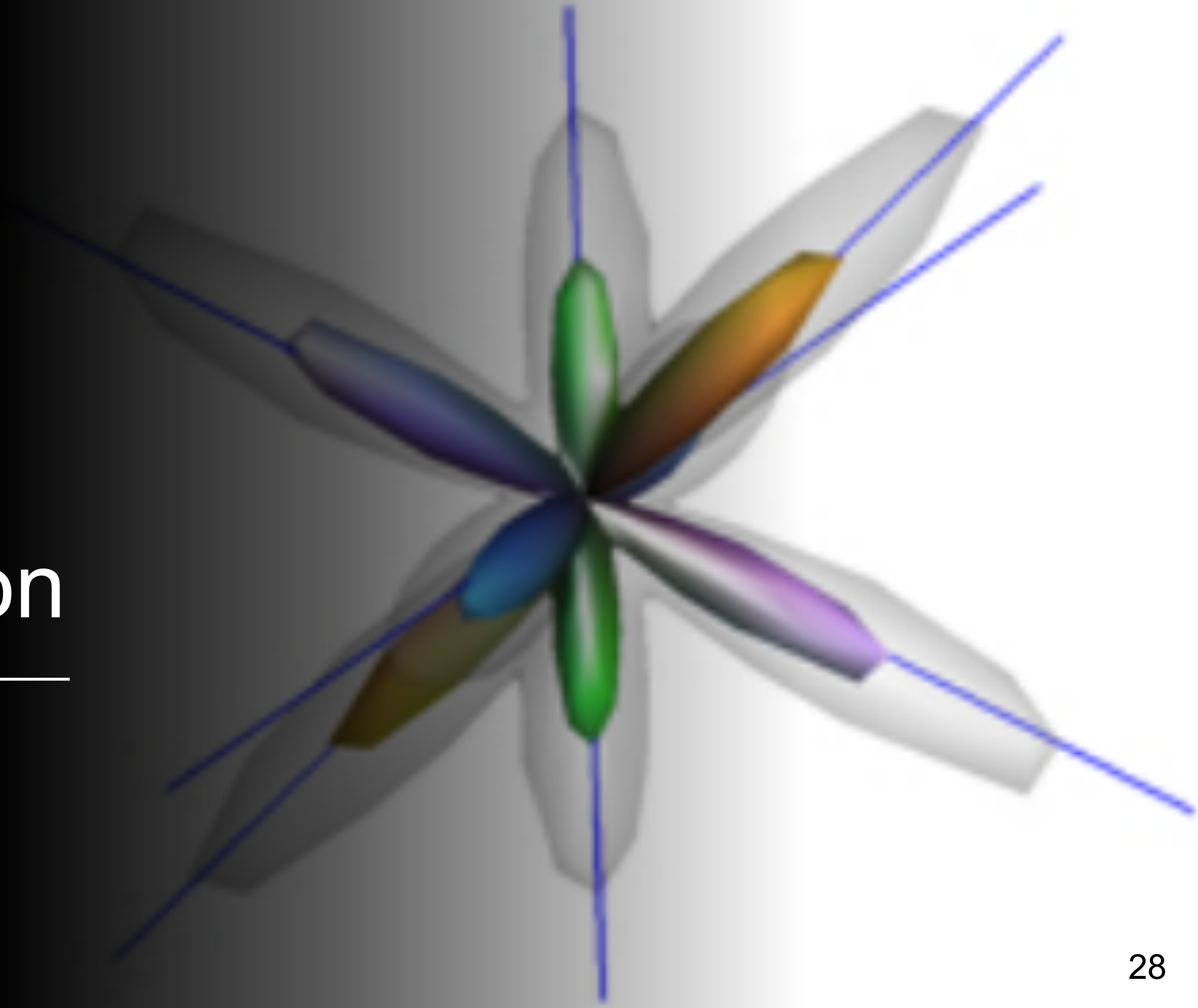
CROSSING FIBERS…

Crossing fibers

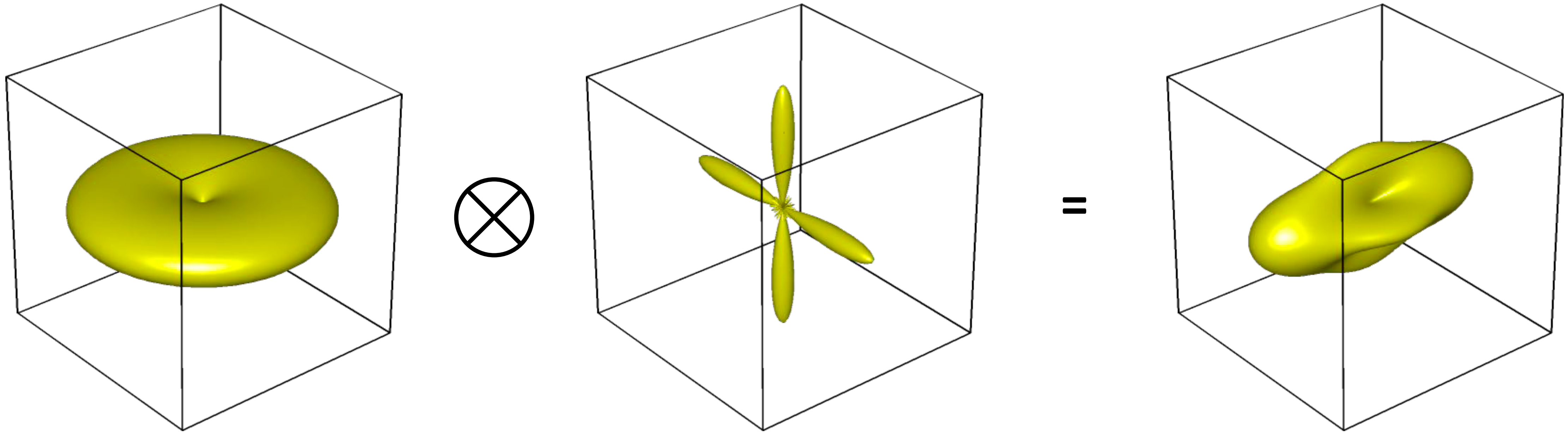
How to address the problem?



Spherical Deconvolution

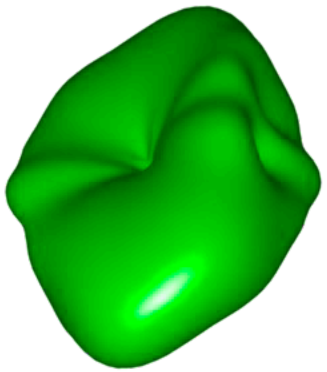


Convolution

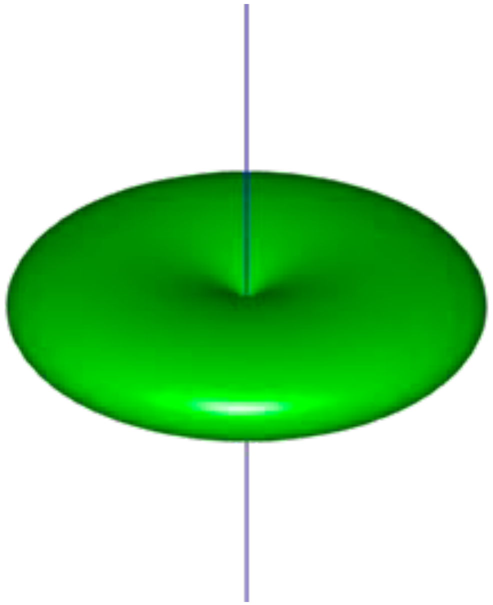


Response function. Fiber orientation distribution function DWI signal

Deconvolution



$\otimes^{-1}$



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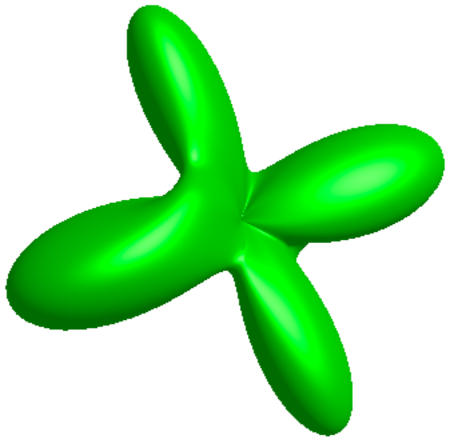
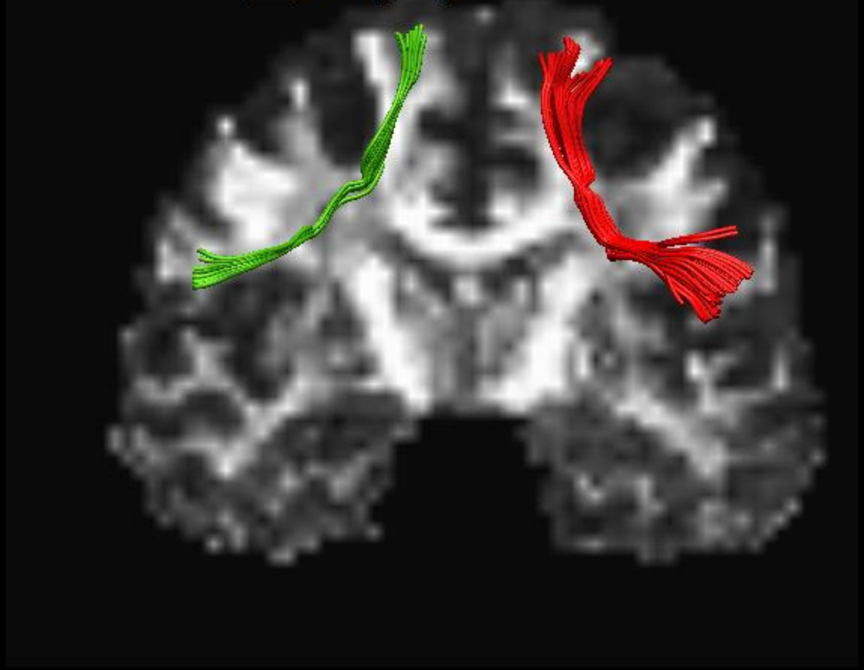


DWI signal

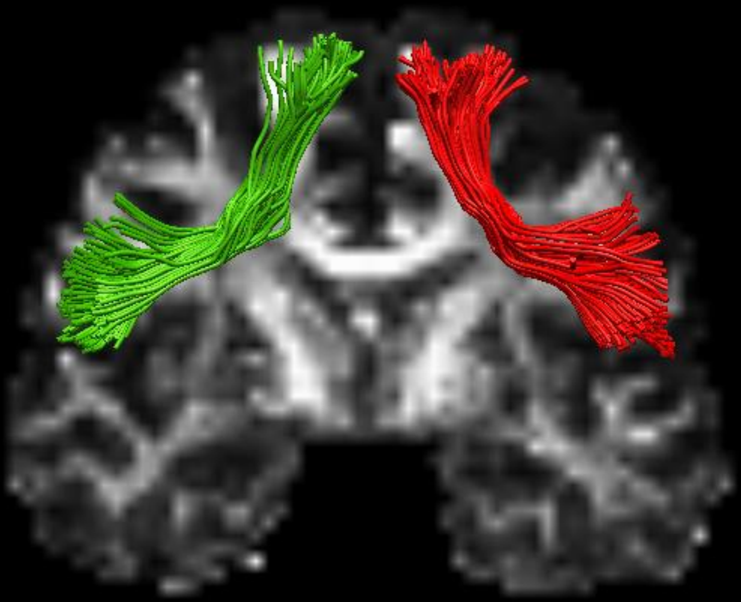
Response function.

Fiber orientation distribution function

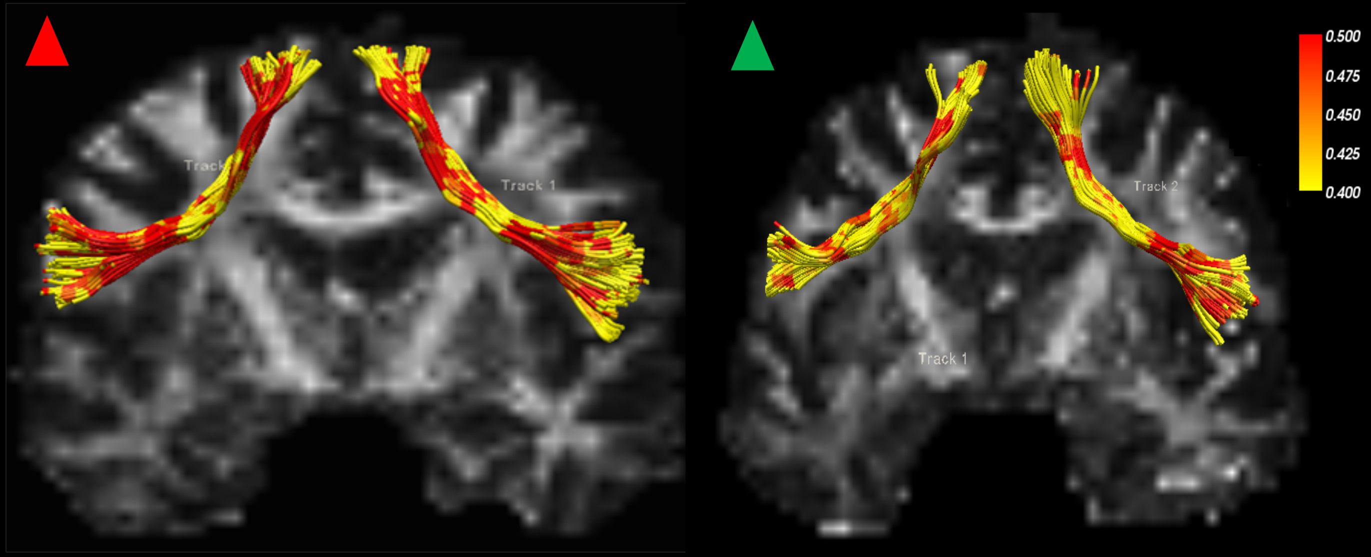
DTI

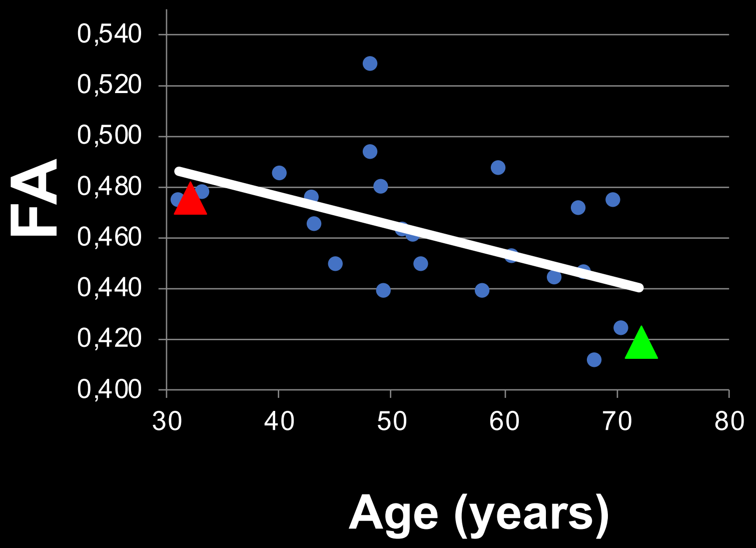


SD



Application?





(r=-.538, p = .007).

Questions?

With thanks to Richard Daws and Amy Jolly for help with slides