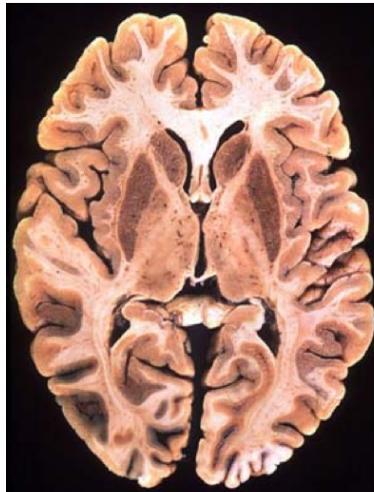




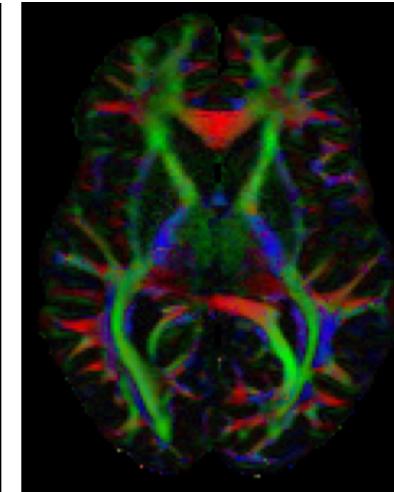
# Diffusion Tensor Imaging in SPM - complementary information to VBM



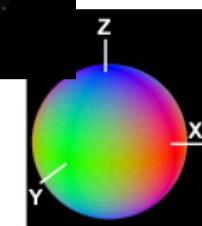
Histology



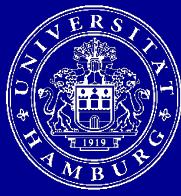
Volumetry



DTI

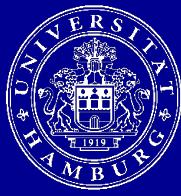


Siawoosh Mohammadi  
[s.mohammadi@uke.de](mailto:s.mohammadi@uke.de)



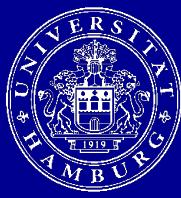
## Outline of this talk

- Motivation: remember VBM?
- What does DTI reveal about microstructure?
- Technical differences compared to VBM
- The orientation information in DTI
- Limitations & outlook
- Implementation in SPM



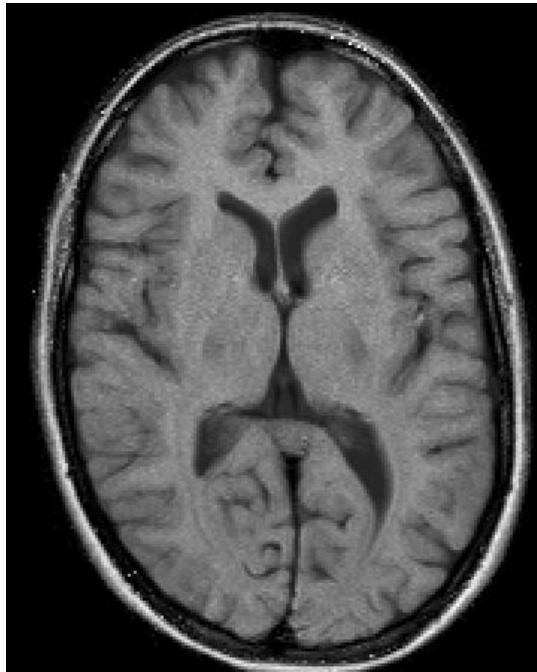
## Outline of this talk

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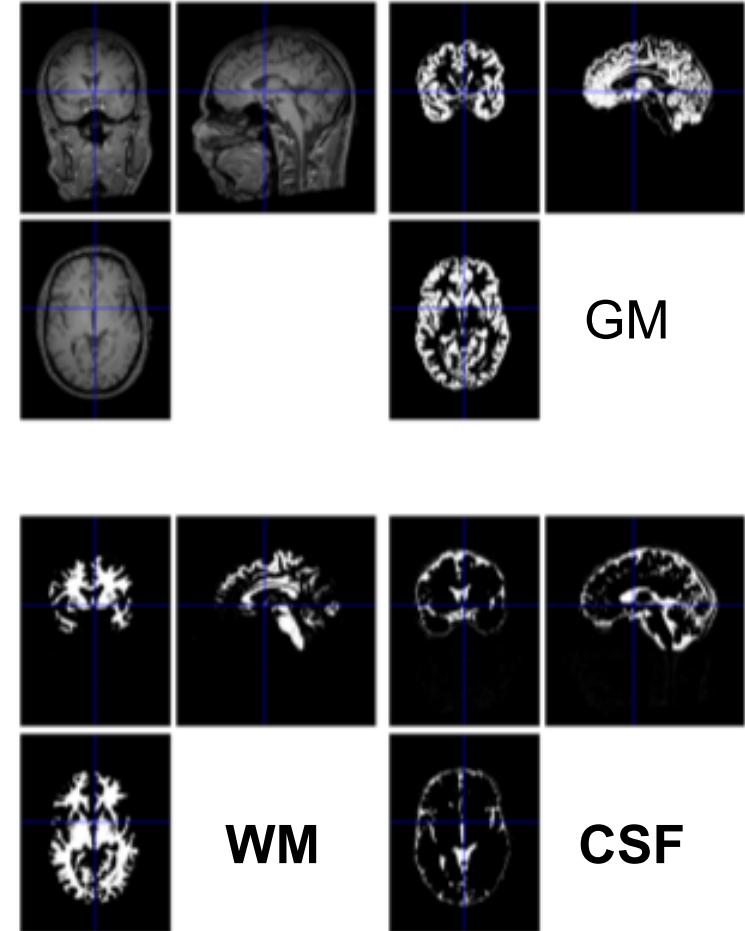


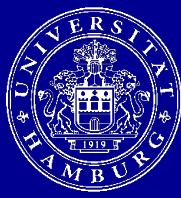
# Remember VBM

## Segmentation



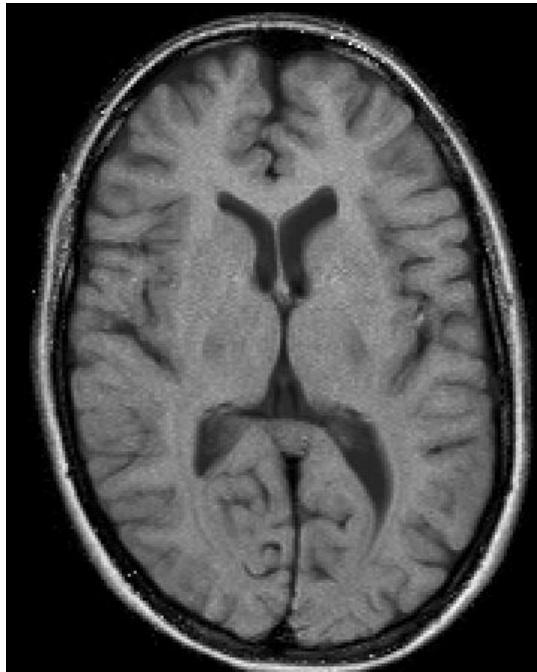
T1w image



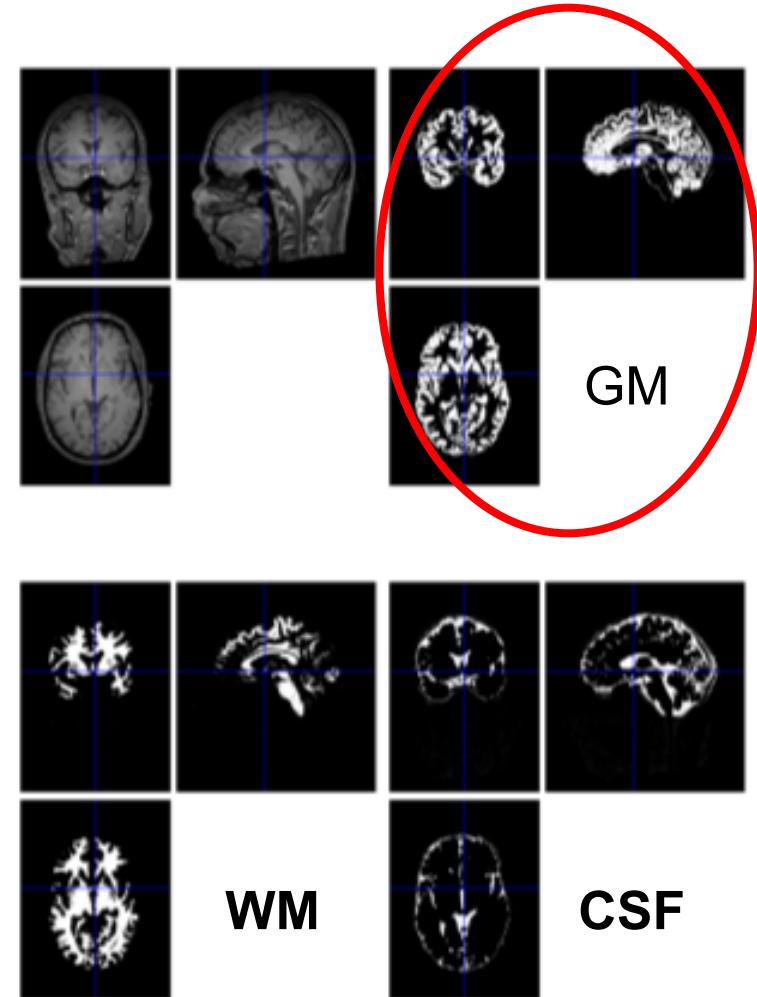


# Remember VBM

## Segmentation



T1w image

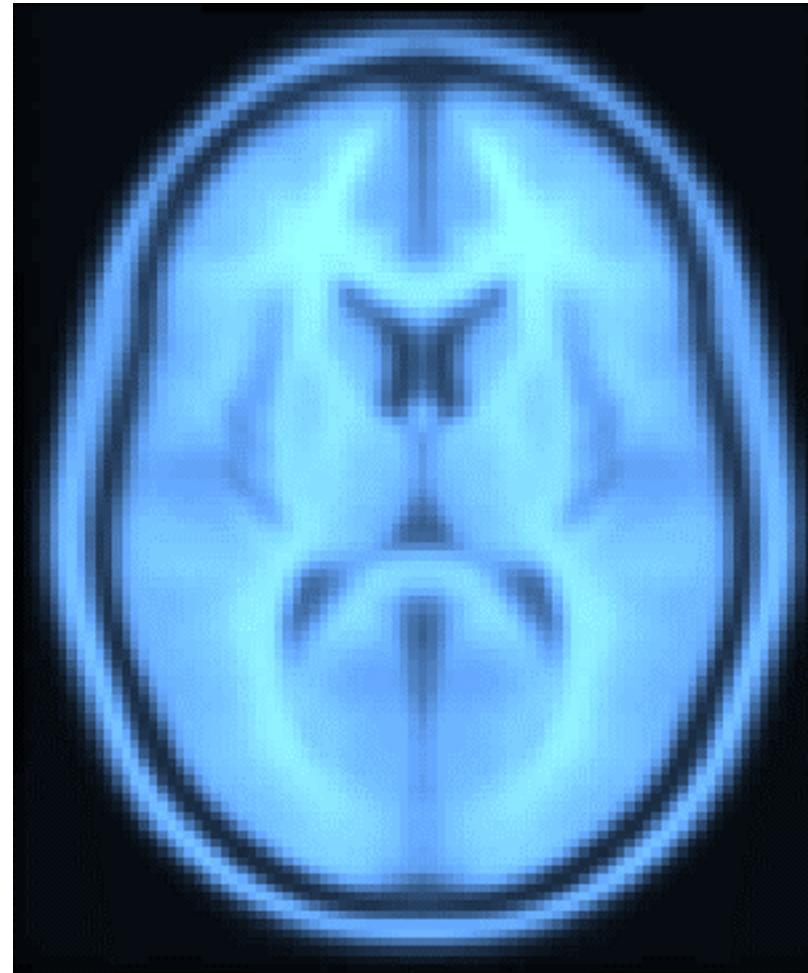




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# Remember VBM

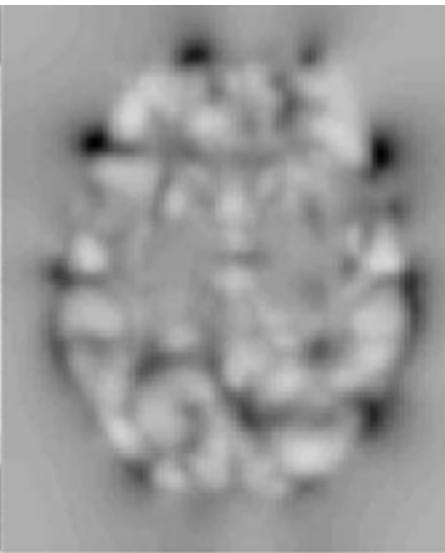
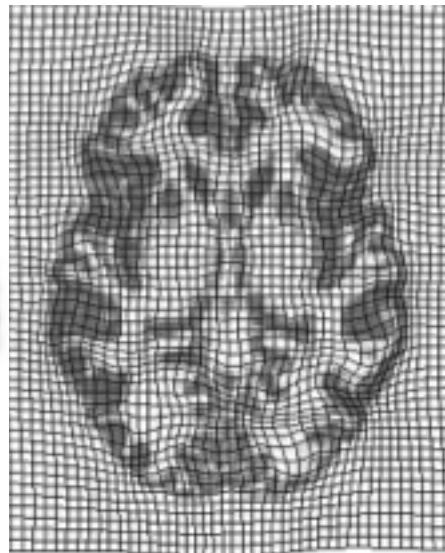
## Spatial Registration



[www.fil.ion.ucl.ac.uk/~john/](http://www.fil.ion.ucl.ac.uk/~john/)



# Remember VBM Modulation



**GM**

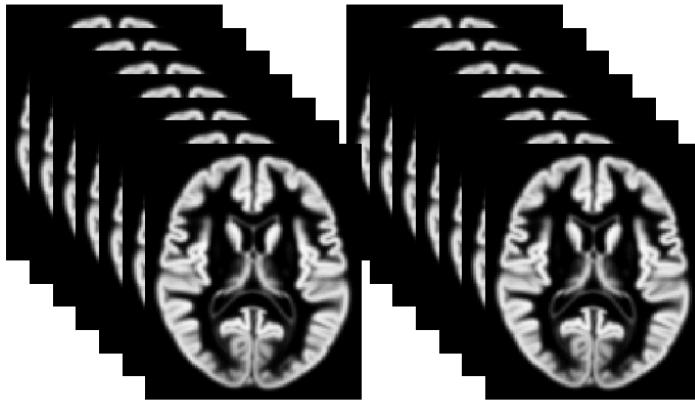
**Deformation field**

**Jacobian**

**Modulated GM**

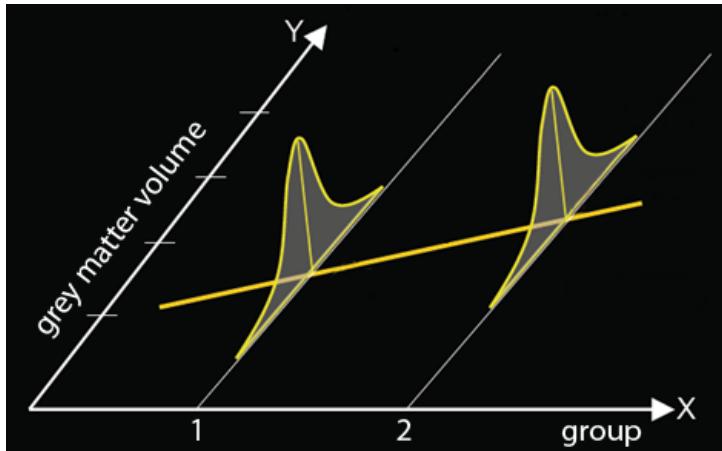


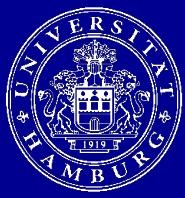
## General Linear Model



Compare Volume differences between 2 groups

$$Y = X\beta + \epsilon$$





## Juggler Experiment

Example: learning to juggle changed gray matter volume





## Juggler Experiment

Example: learning to juggle changed gray matter volume



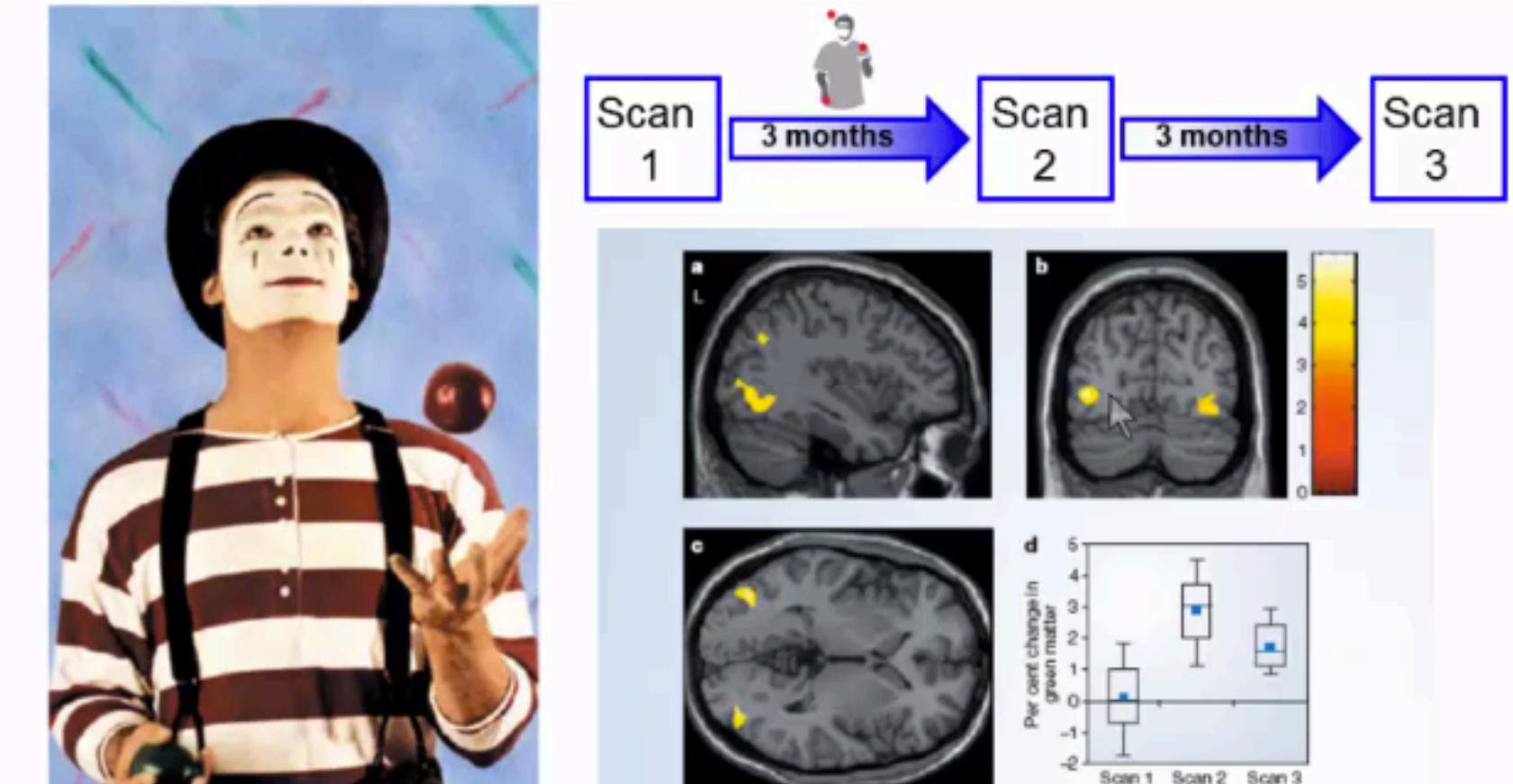
*Arne May*



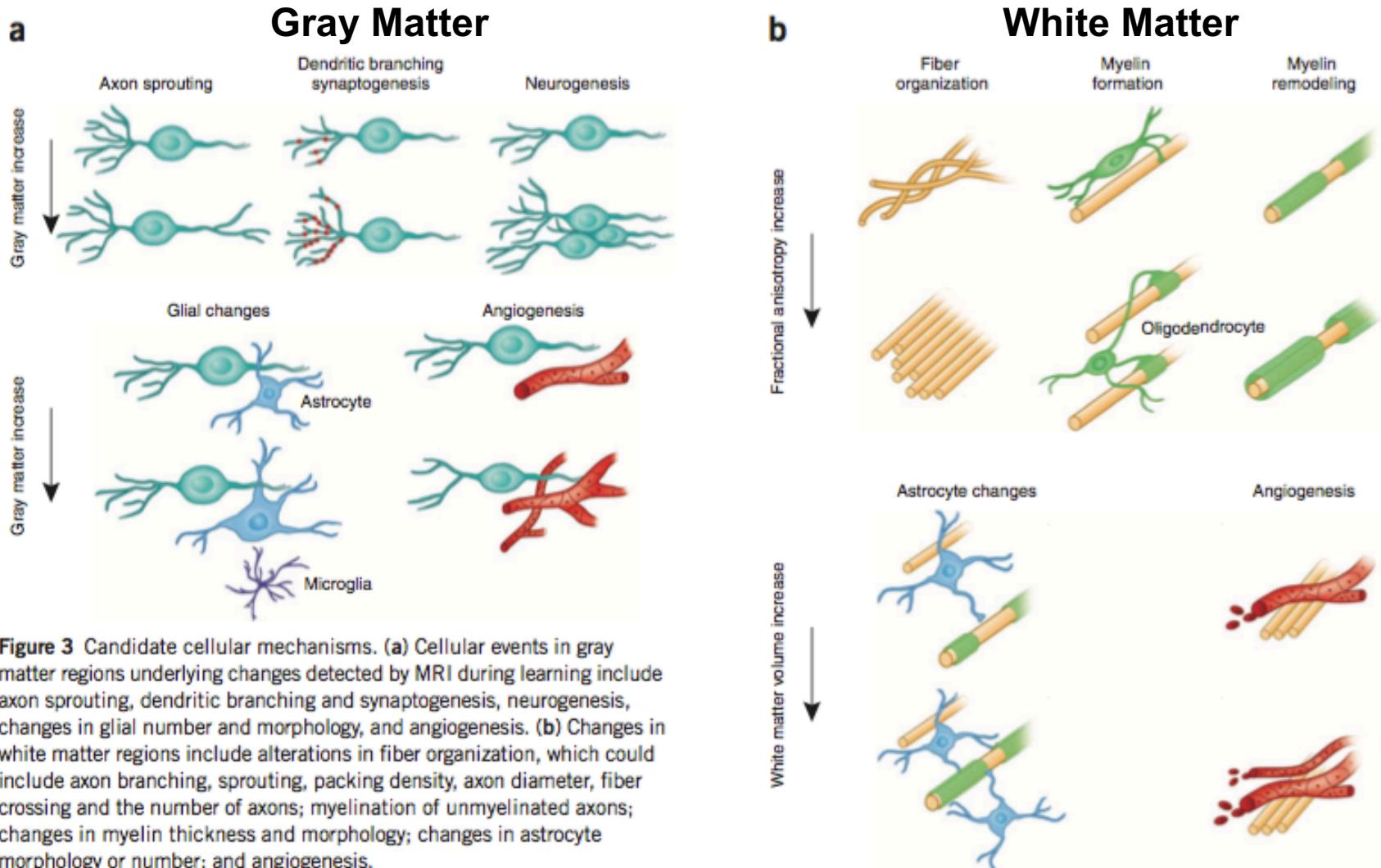
*Christian Gaser*

## Juggler Experiment

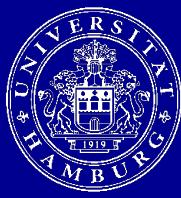
Example: learning to juggle changed gray matter volume



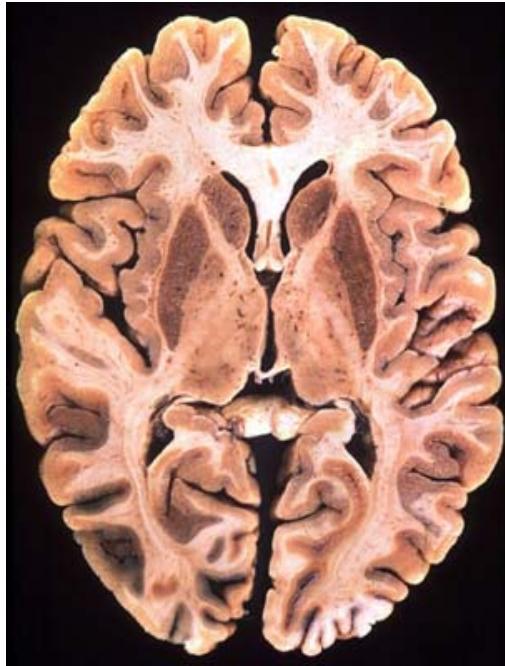
## What is the mechanism?



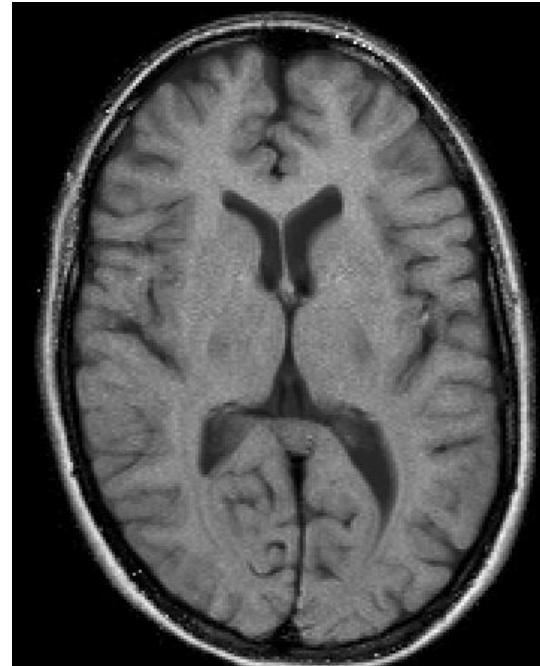
**Figure 3** Candidate cellular mechanisms. (a) Cellular events in gray matter regions underlying changes detected by MRI during learning include axon sprouting, dendritic branching and synaptogenesis, neurogenesis, changes in glial number and morphology, and angiogenesis. (b) Changes in white matter regions include alterations in fiber organization, which could include axon branching, sprouting, packing density, axon diameter, fiber crossing and the number of axons; myelination of unmyelinated axons; changes in myelin thickness and morphology; changes in astrocyte morphology or number; and angiogenesis.



# Do we have a method to map microstructure?



**Histology**

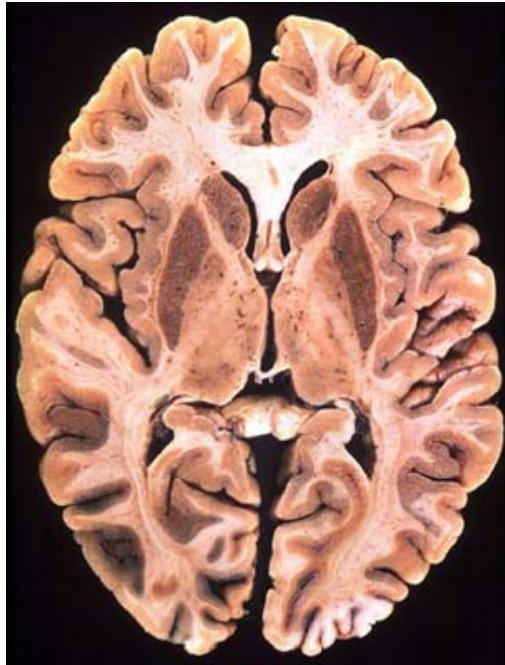


**T1w image**



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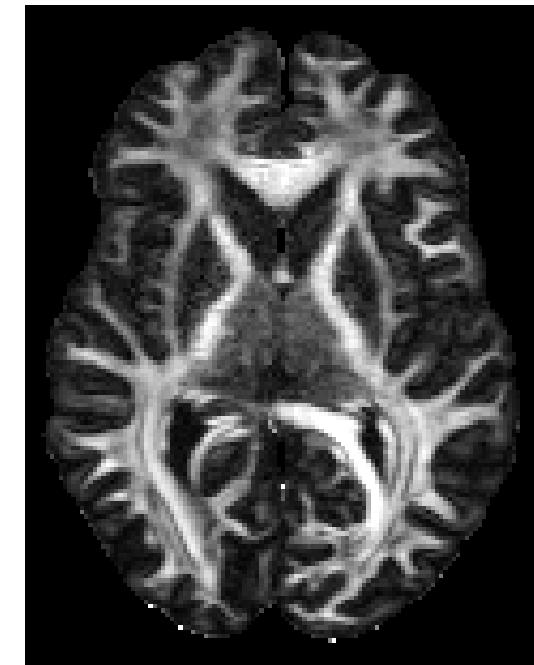
# Diffusion MRI reveals microstructural information



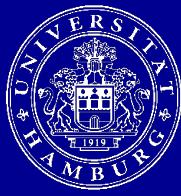
**Histology**



**T1w image**



**DTI index map**



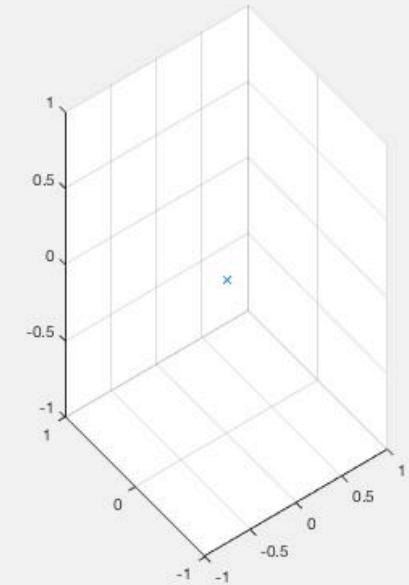
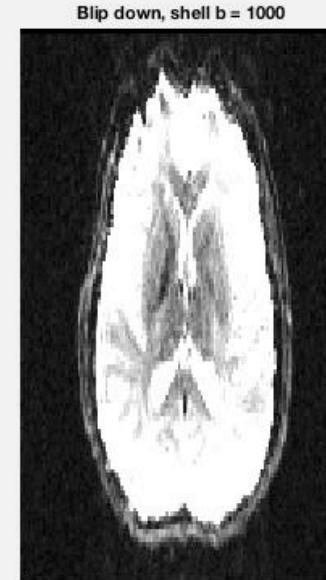
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# How does a typical DTI dataset look like?

Two-shell diffusion dataset ( $b=1000$  and  $b=2500$ )



Reference

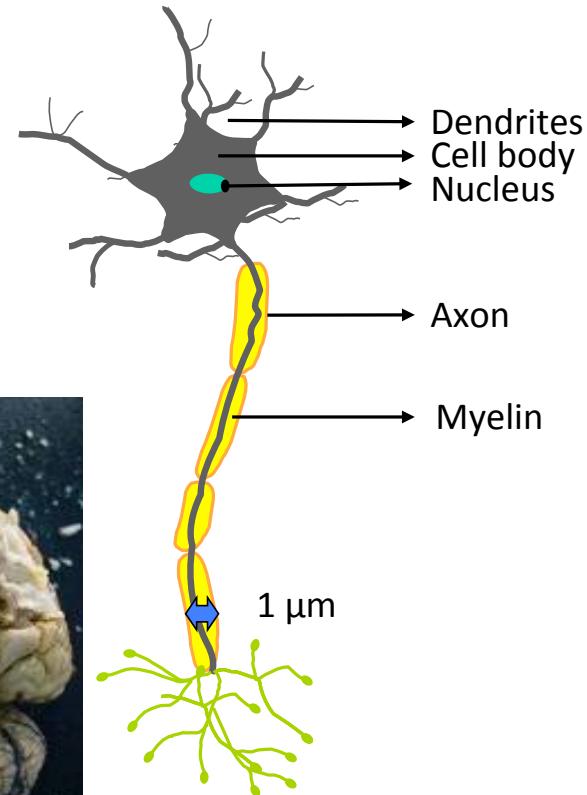
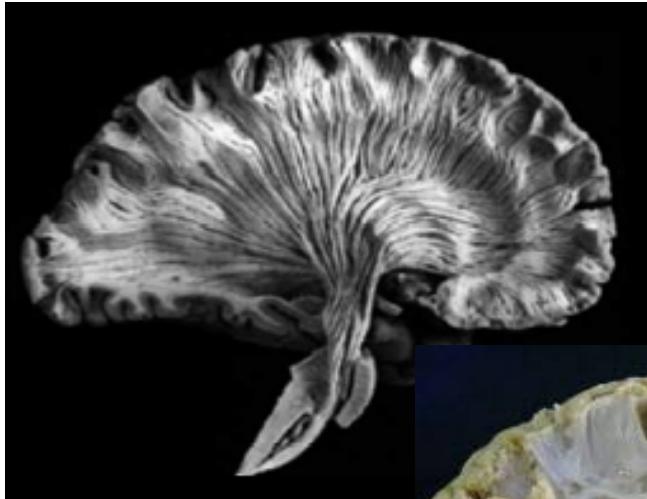
Blip-up dataset

Blip-up dataset

b-vector

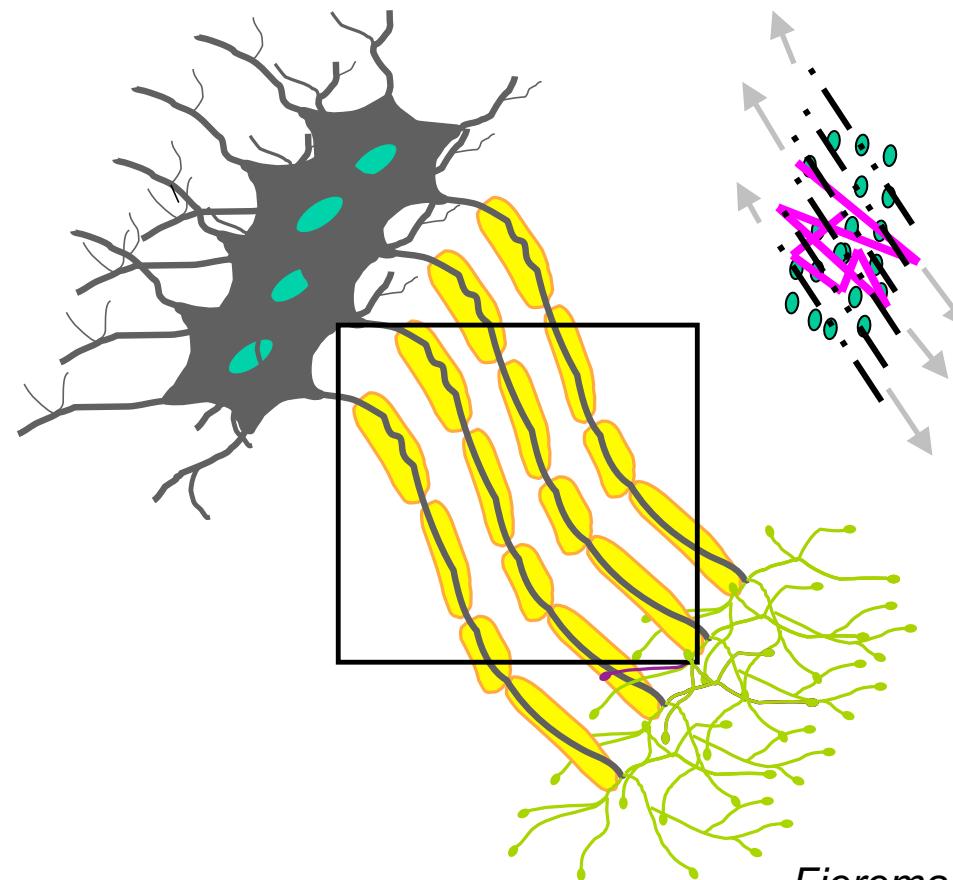


# Main features of fibers in the white matter

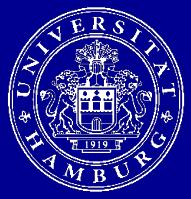


*Fieremans, ESMRMB, 2015*

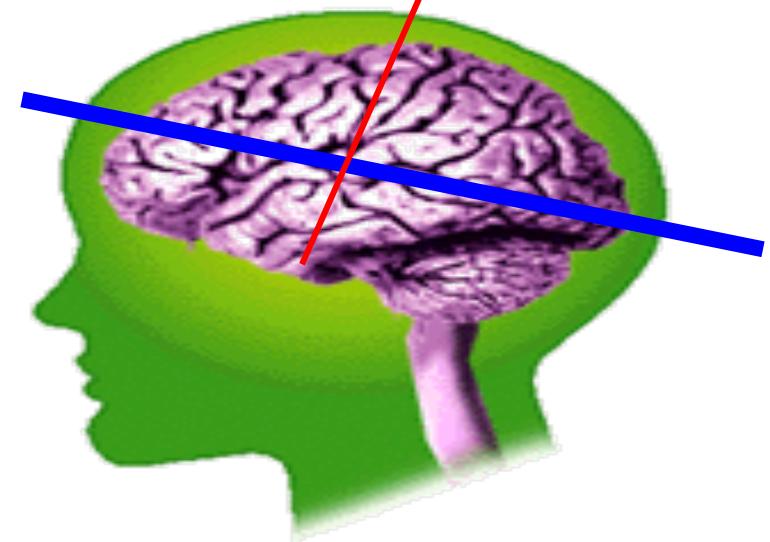
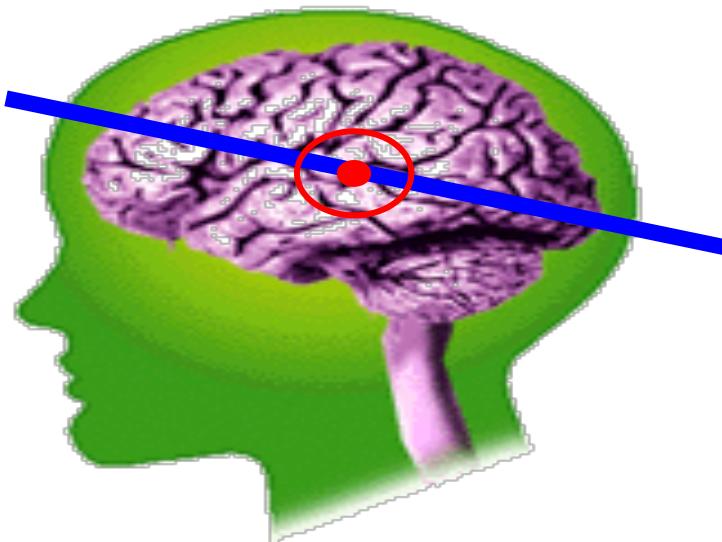
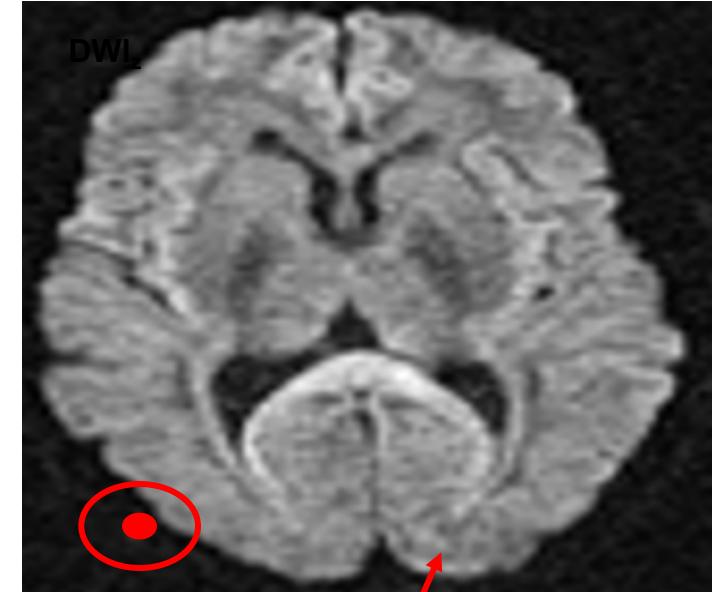
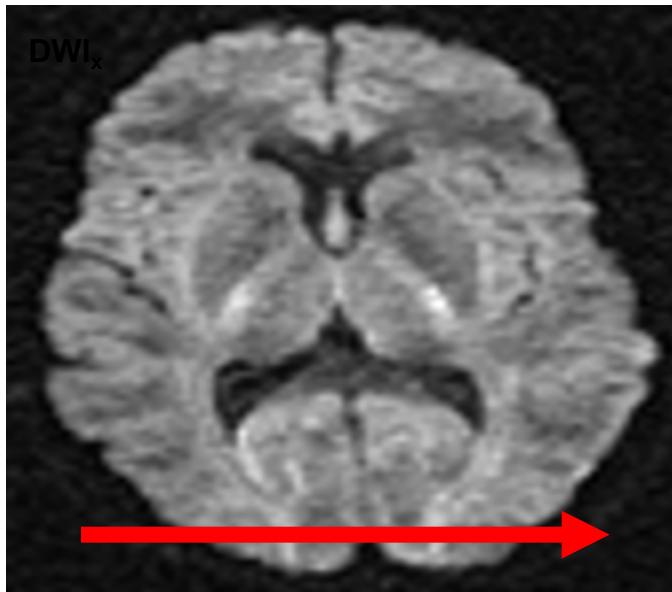
## Aligned axons in fiber pathways

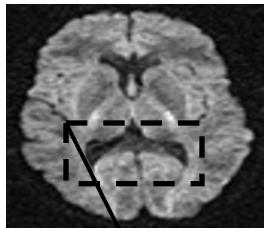
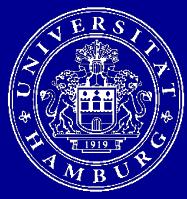


Fieremans, ESMRMB, 2015

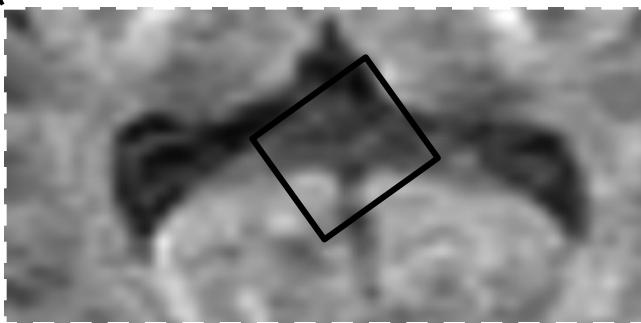


# Diffusion weighted images

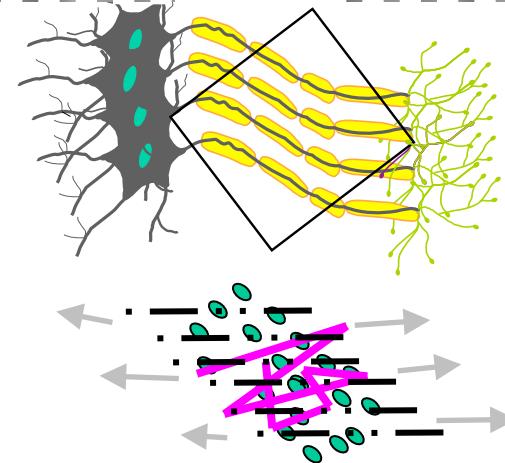
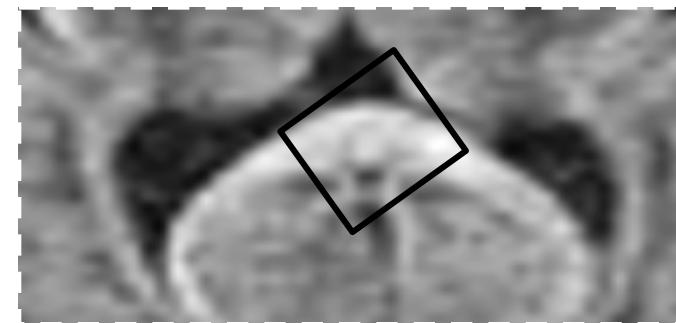




$$\vec{G}^D = \begin{pmatrix} G_x & 0 & 0 \end{pmatrix}$$



$$\vec{G}^D = \begin{pmatrix} 0 & 0 & G_z \end{pmatrix}$$

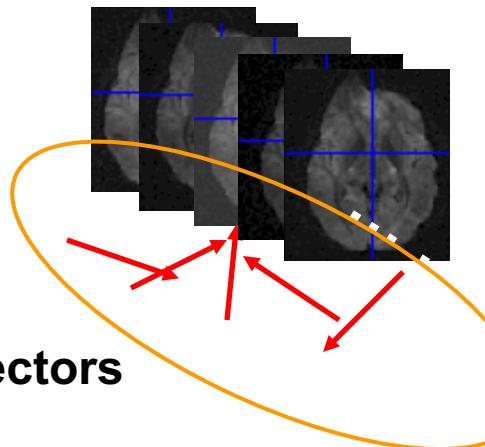




# What do we need for diffusion MRI?

**Shell 1**  
(b-value e.g  $1000 \text{ s/mm}^2$ )

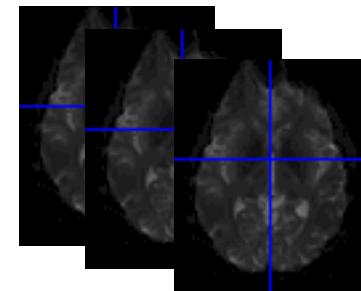
$n$  DW images



+

**Shell 0**  
(b-value e.g 0 or  $100 \text{ s/mm}^2$ )

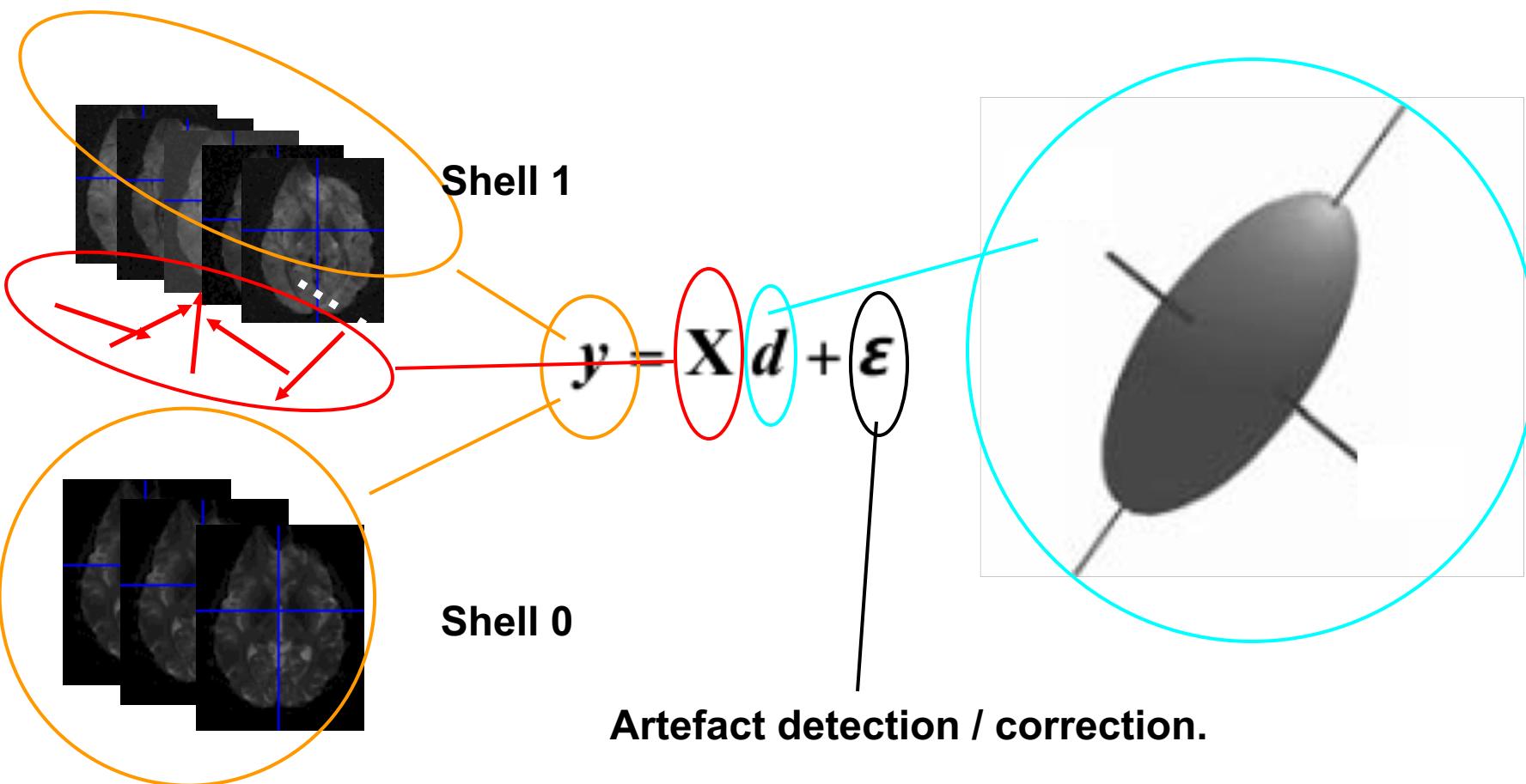
$m$  reference images

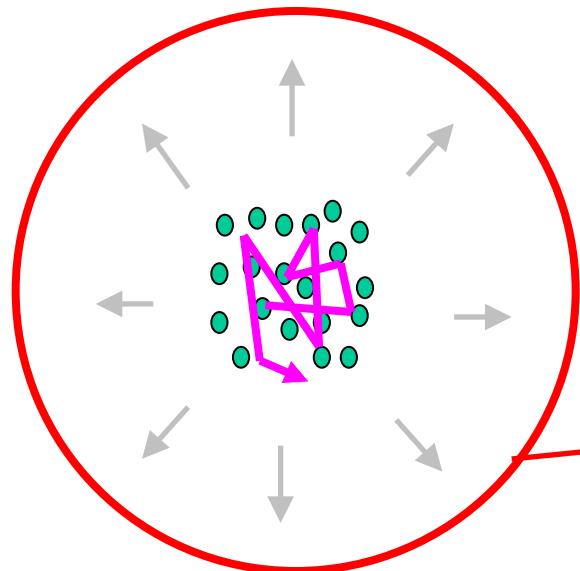


+

**Model**

# The general linear model framework for diffusion MRI





CSF: Isotropic diffusion

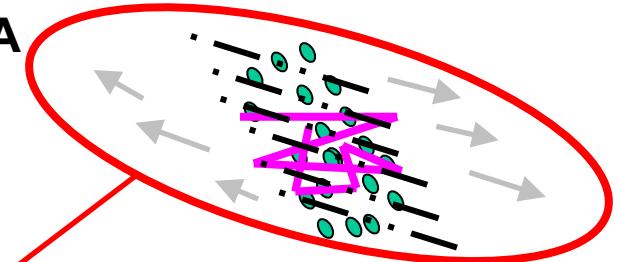
## Fractional anisotropy - FA





# Diffusion MRI : interpreting fractional anisotropy

Fractional anisotropy - FA

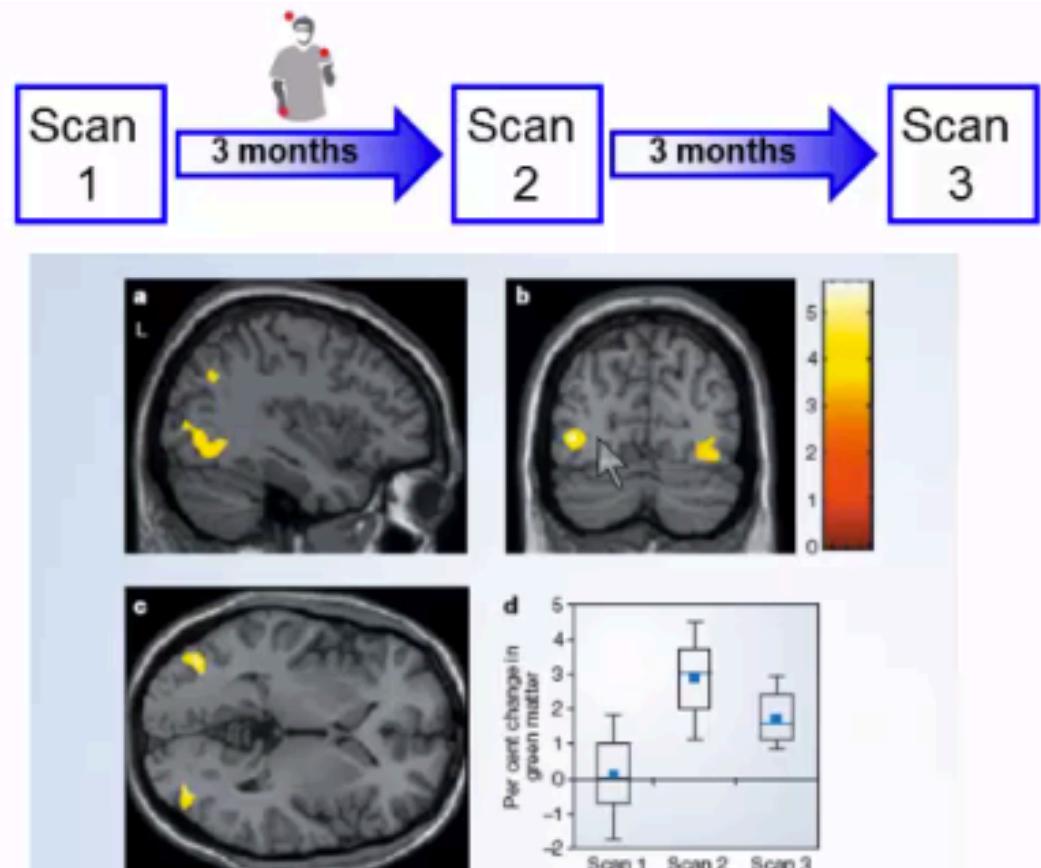


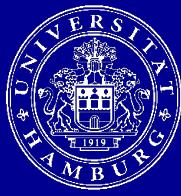
**WM: Anisotropic diffusion**





# Diffusion MRI : interpreting fractional anisotropy





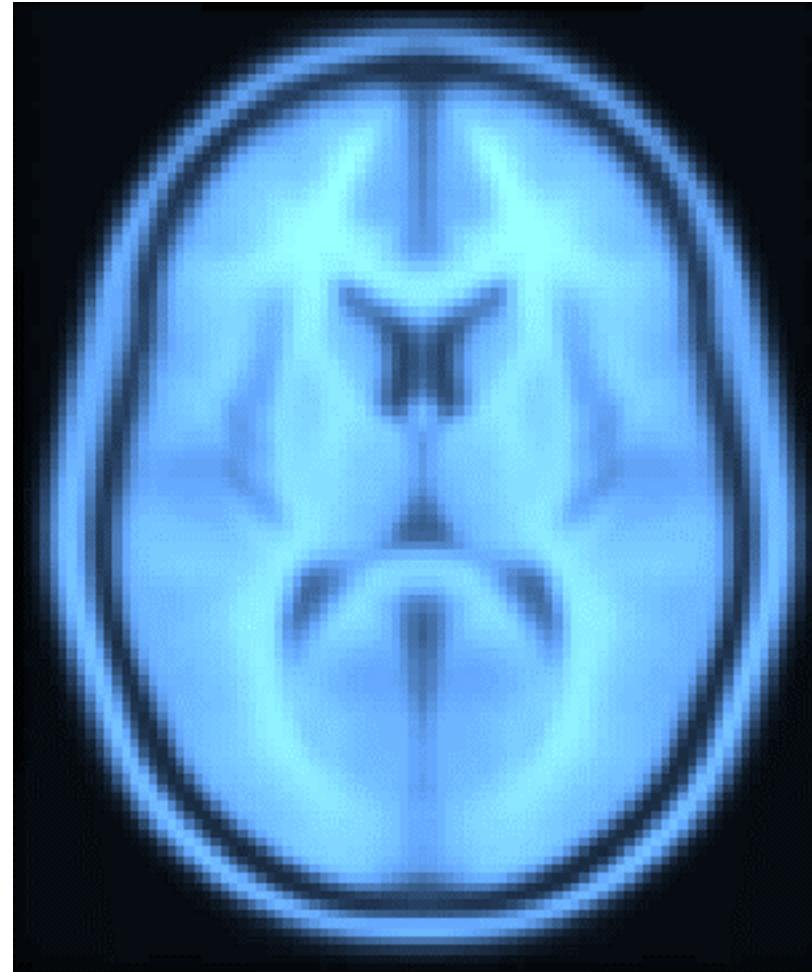
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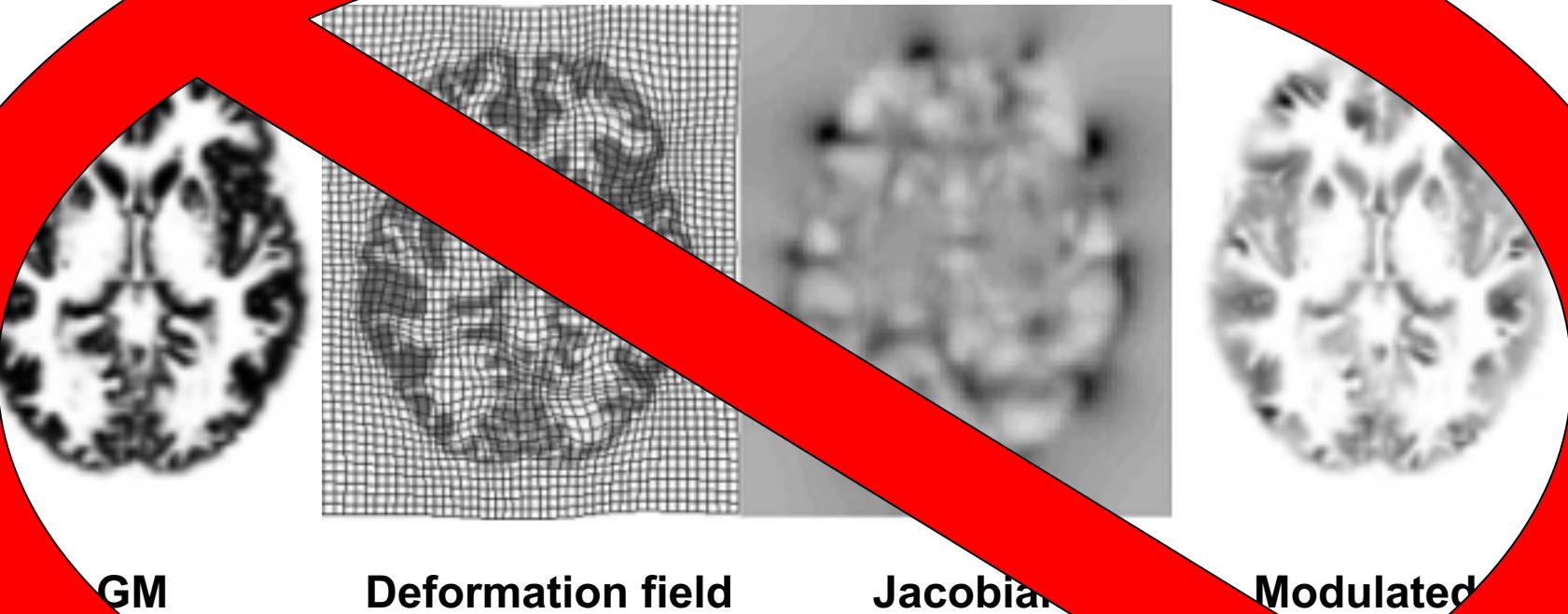
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# Using SPM Spatial Registration



[www.fil.ion.ucl.ac.uk/~john/](http://www.fil.ion.ucl.ac.uk/~john/)

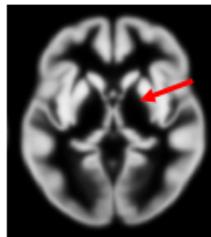
# Remember VBM Modulation



# Removing residual misregistration by dedicated smoothing (VBQ)

## Step 1:

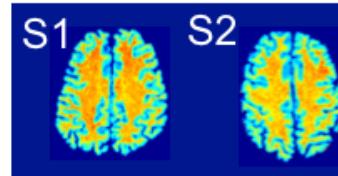
Segment  
Into Tissue  
Classes



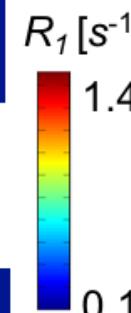
Old TPM (GM)

## Step 2:

Nonlinear Spatial  
Registration

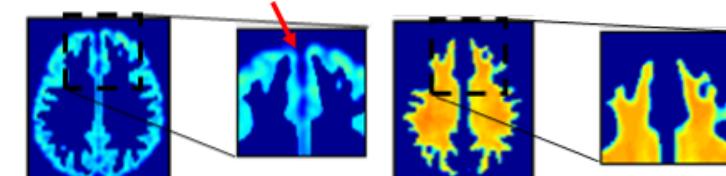


Individual Space

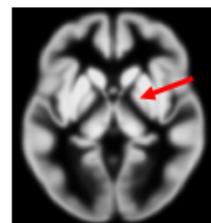


## Step 3:

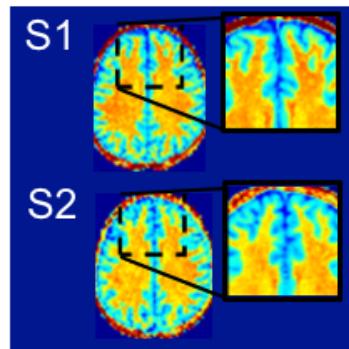
Tissue Weighted (VBQ)  
Smoothing



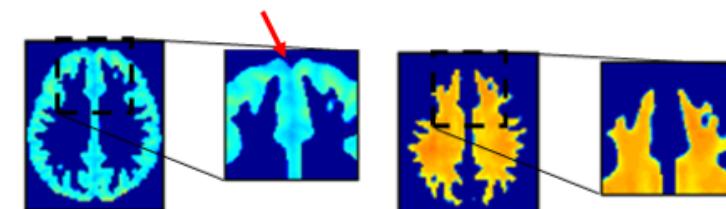
Gaussian Smoothing (4mm FWHM)



New TPM (GM)



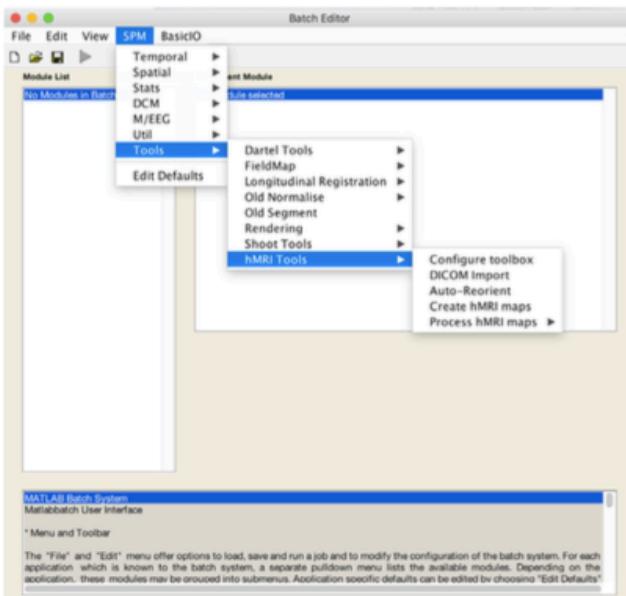
Common Space



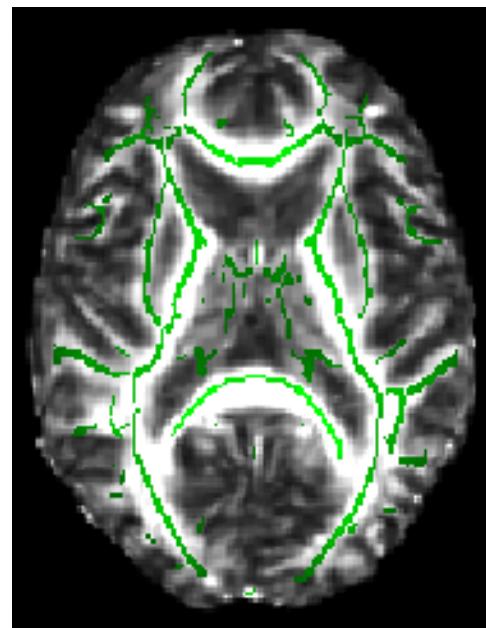
VBQ Smoothing (4mm FWHM)

# Removing residual misregistration by dedicated smoothing

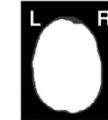
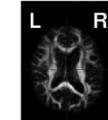
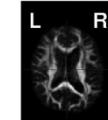
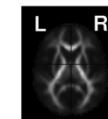
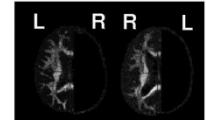
## hMRI toolbox



## TBSS



## DTI based

registration approach	(i)	(ii)	(iii)
contrast	b0 (T2)	FA	FA
selection mask	no	whole brain	separated hemisphere
source			
template			

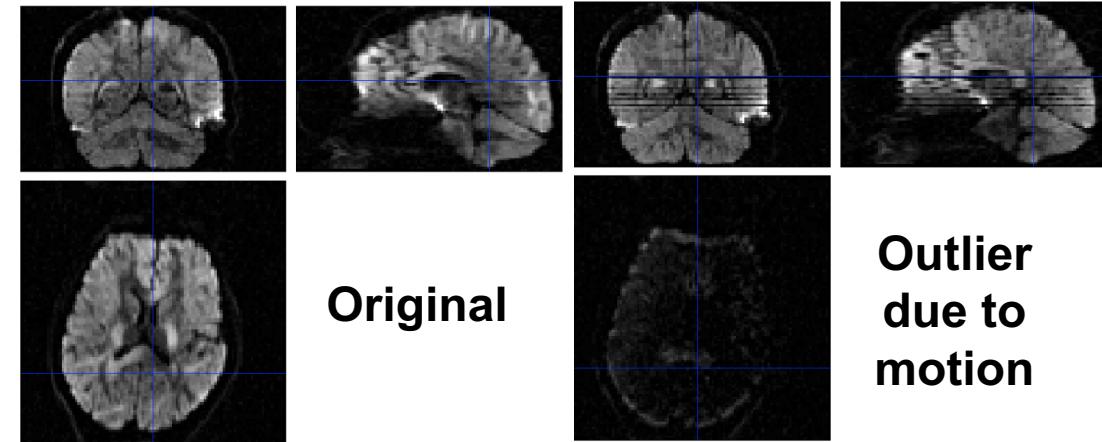
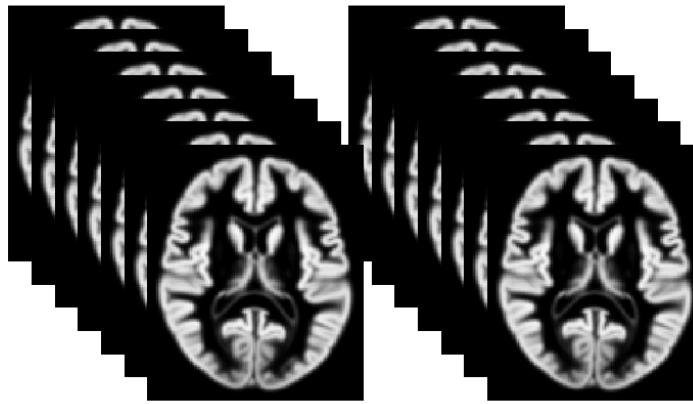
[www.hmri.info](http://www.hmri.info)

[www.fsl.fmrib.ox.ac.uk](http://www.fsl.fmrib.ox.ac.uk)

Mohammadi et al., PLoS one, 2012



Mind the outliers!

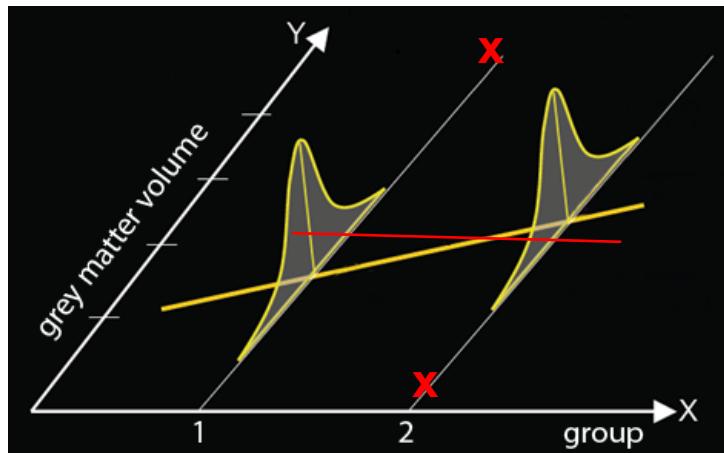
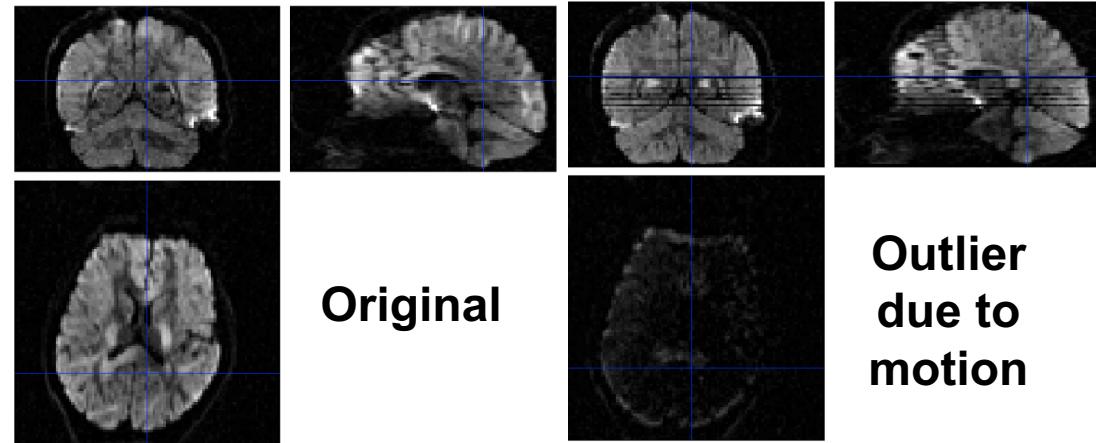
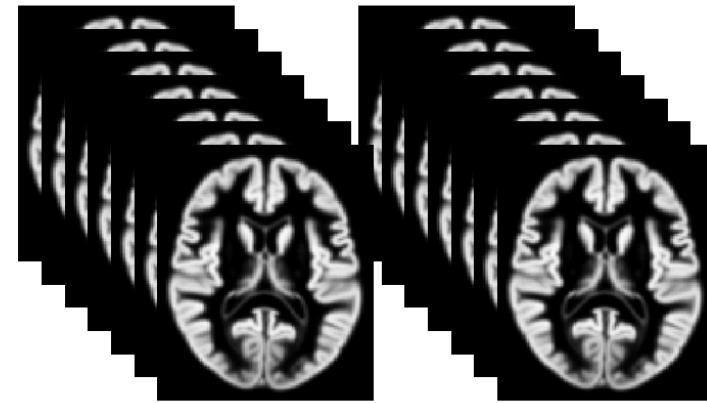


Original

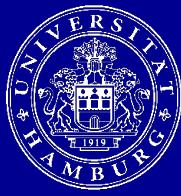
Outlier  
due to  
motion

# VBQ Analysis

## Mind the outliers!



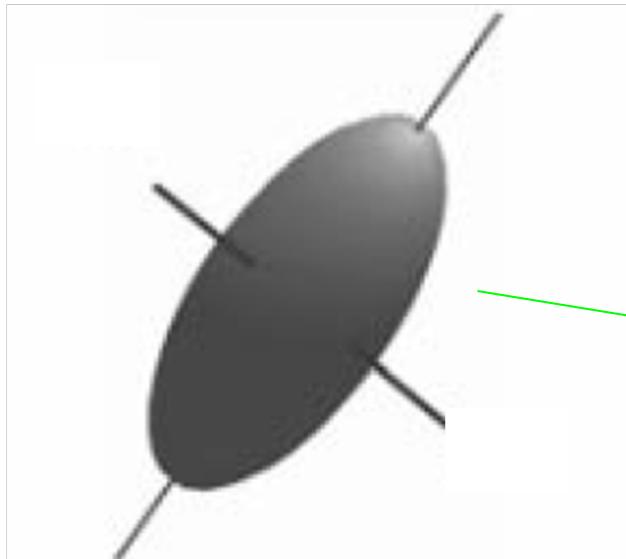
- No statistical difference because of outliers
- Include knowledge about outliers, e.g., by using SwE Toolbox in SPM (<http://www.nisox.org/Software/SwE>)



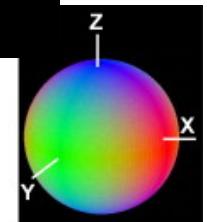
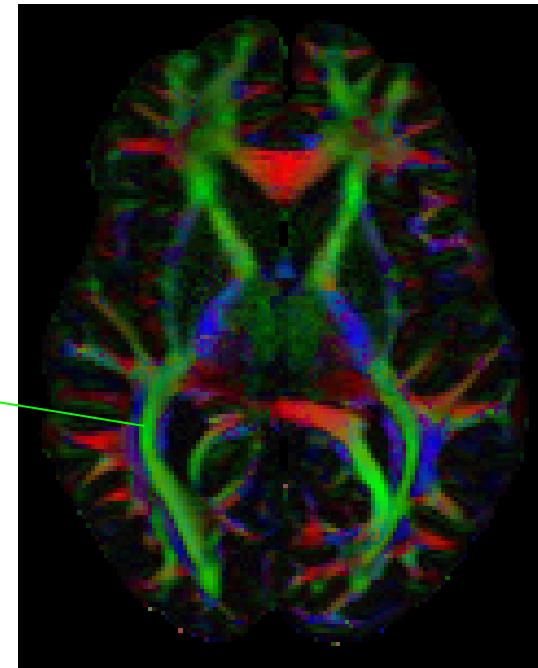
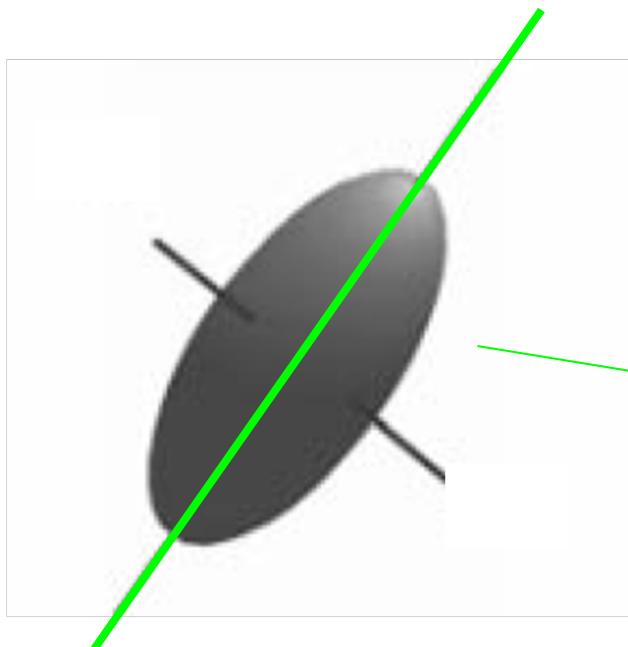
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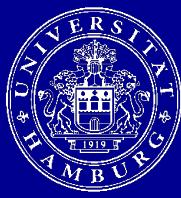
# What else does the diffusion tensor reveal?



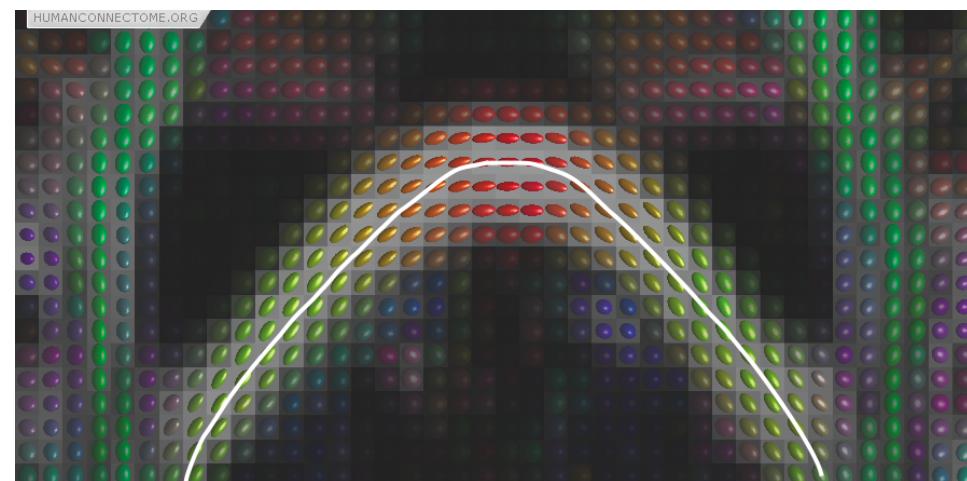
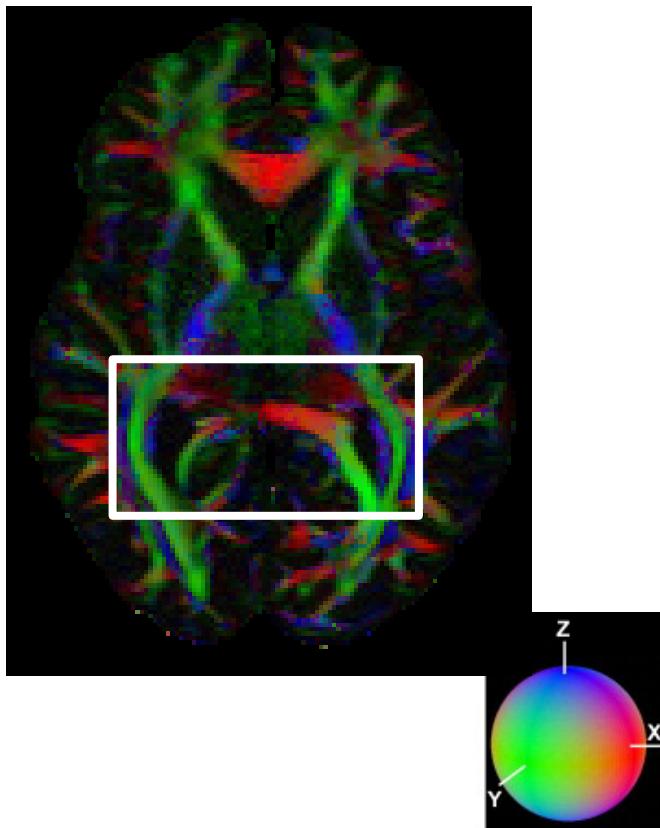
- Diffusion tensor = ellipsoid
- Long axis= *principal diffusion direction*



- Diffusion tensor = ellipsoid
- Long axis= *principal diffusion direction*



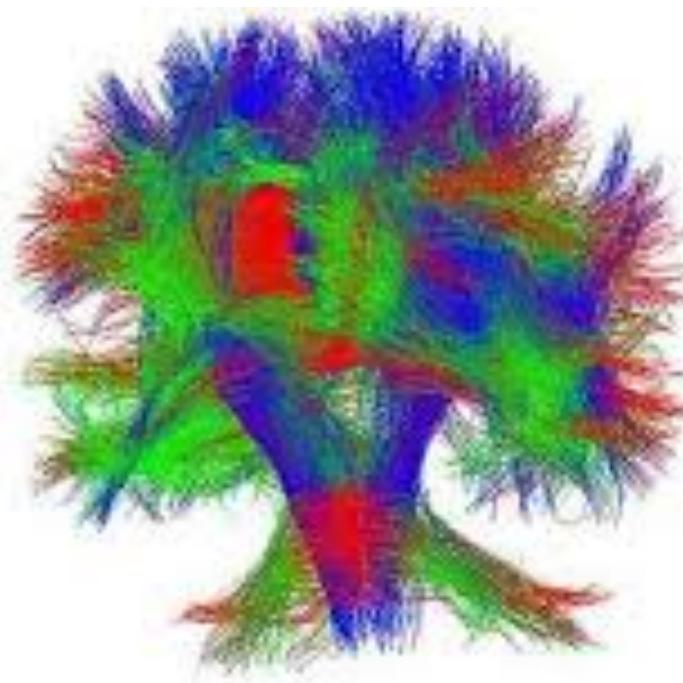
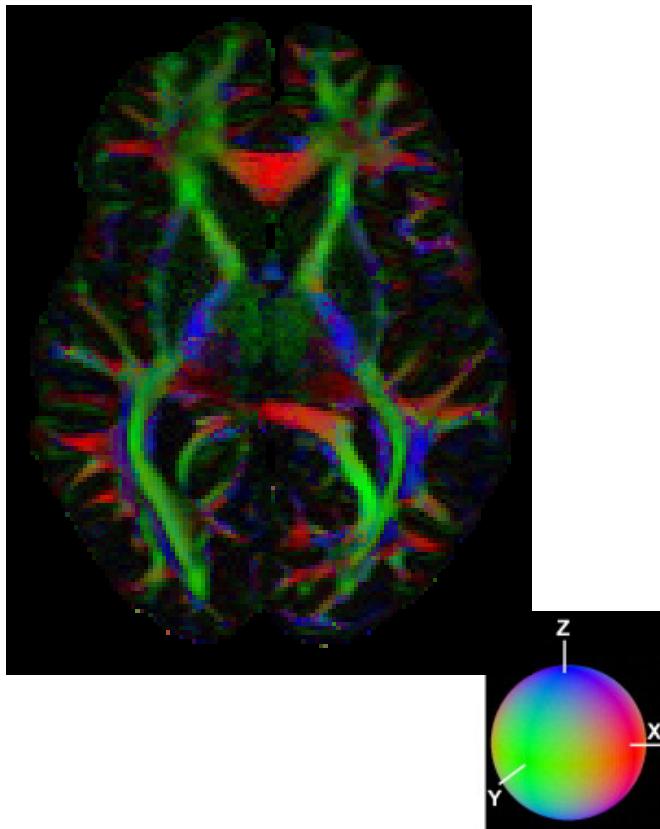
# DTI reveals orientation information



<https://www.humanconnectome.org/study/hcp-young-adult/project-protocol/diffusion-tractography>

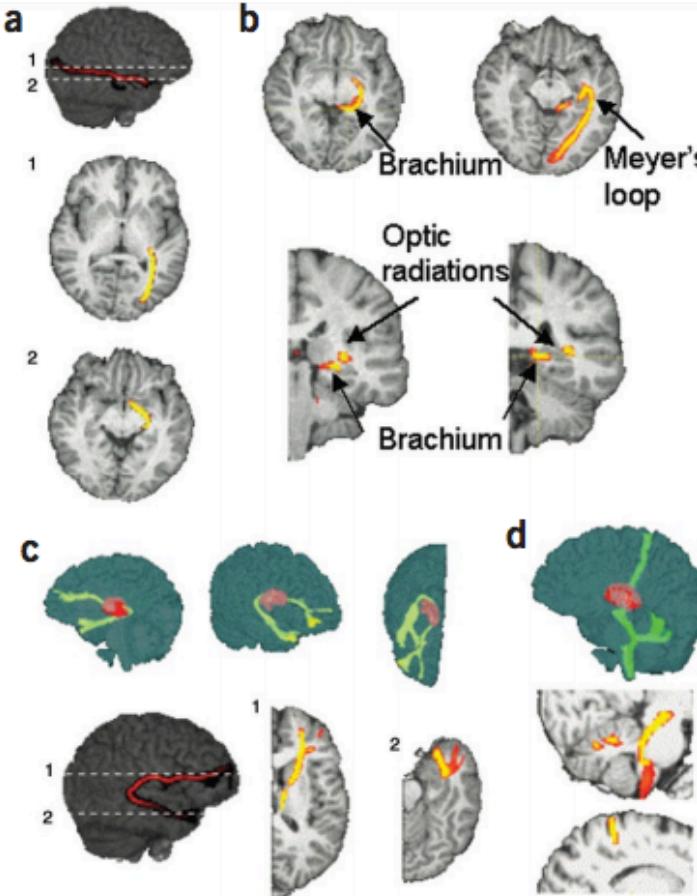


# DTI reveals orientation information

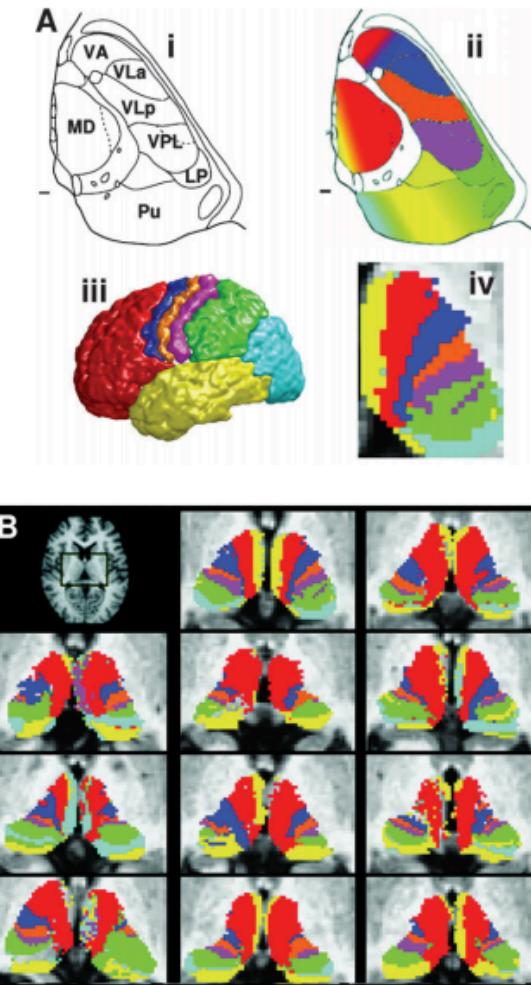


<https://www.uniklinik-freiburg.de/mren/members/current/reisert/>

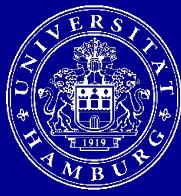
## Application – Thalamus parcellation



Johansen-Berg et al., 2003

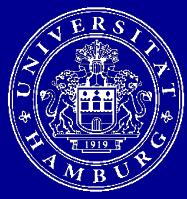


Johansen-Berg et al., 2005

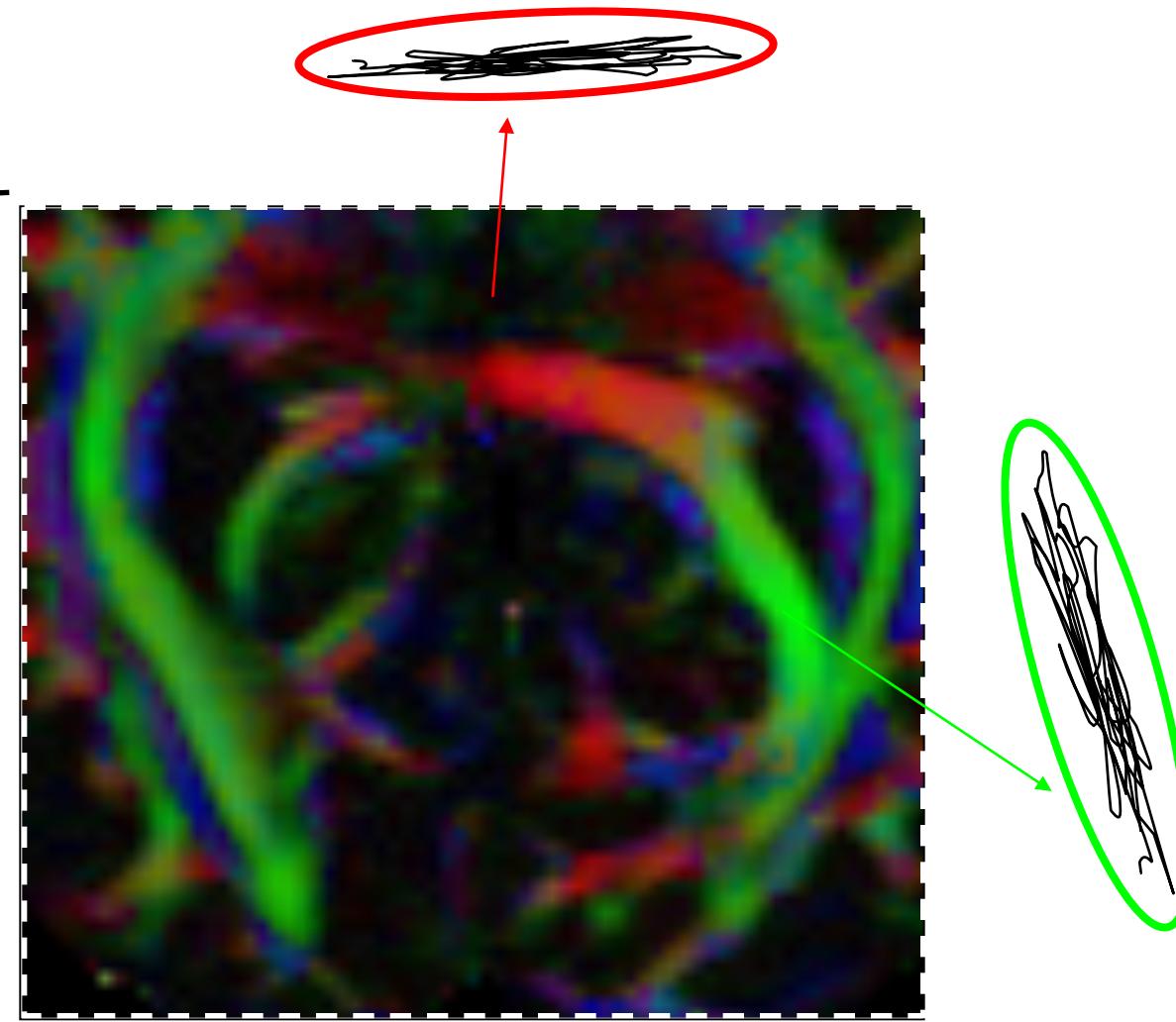
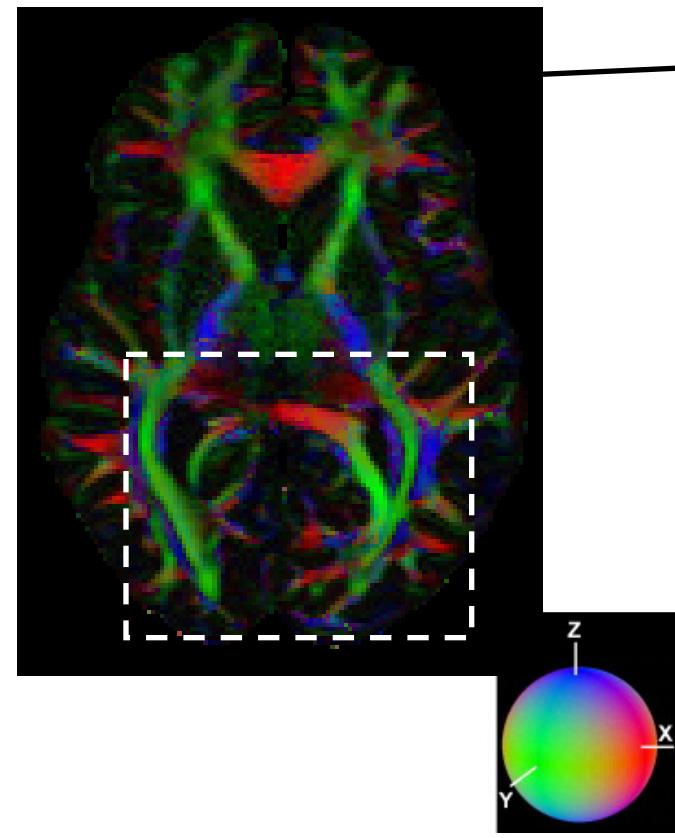


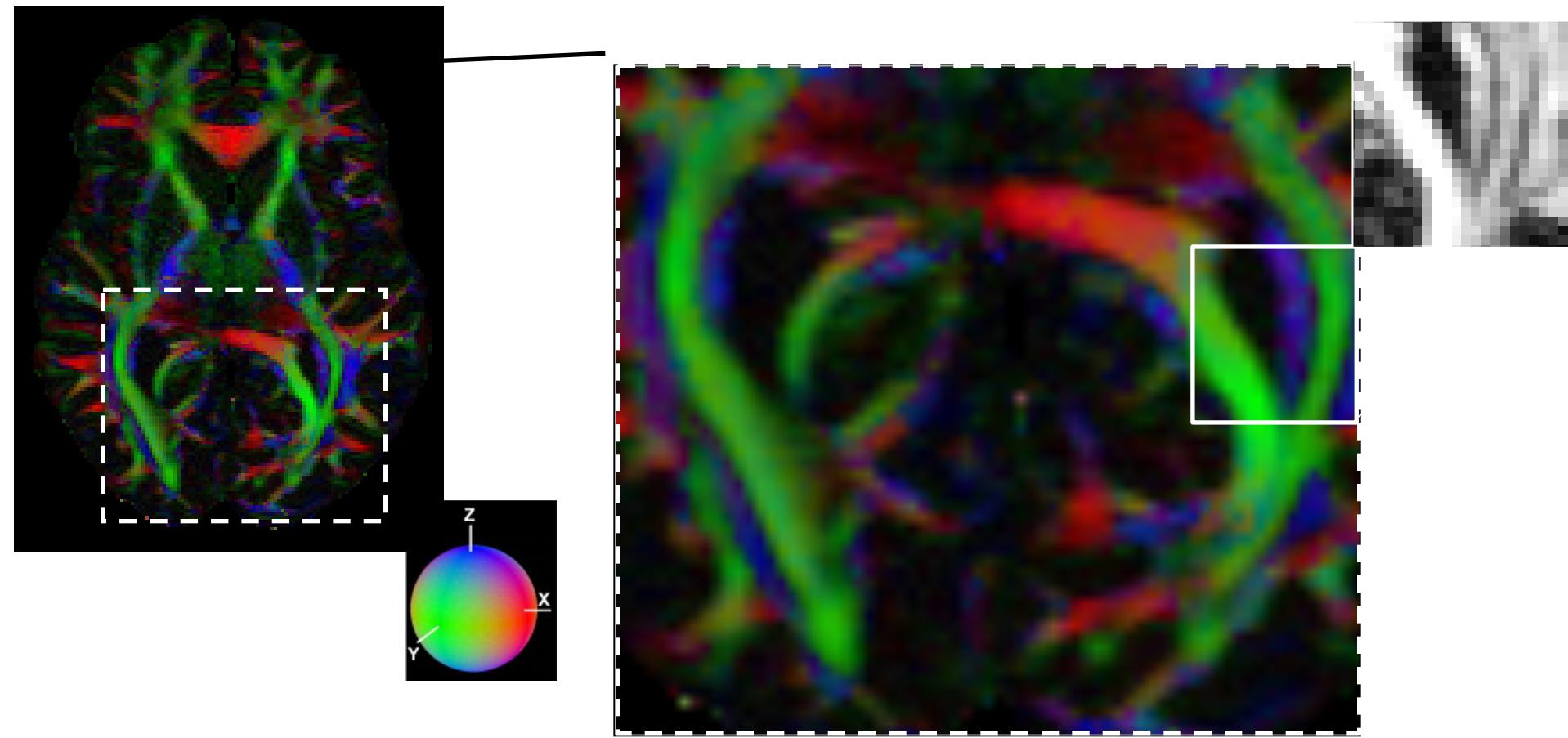
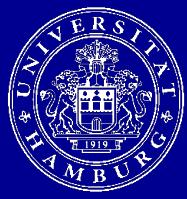
## Outline of this talk

- Motivation: remember VBM?
- What does DTI reveal about microstructure?
- Technical differences compared to VBM
- The orientation information in DTI
- Limitations & outlook
- Implementation in SPM



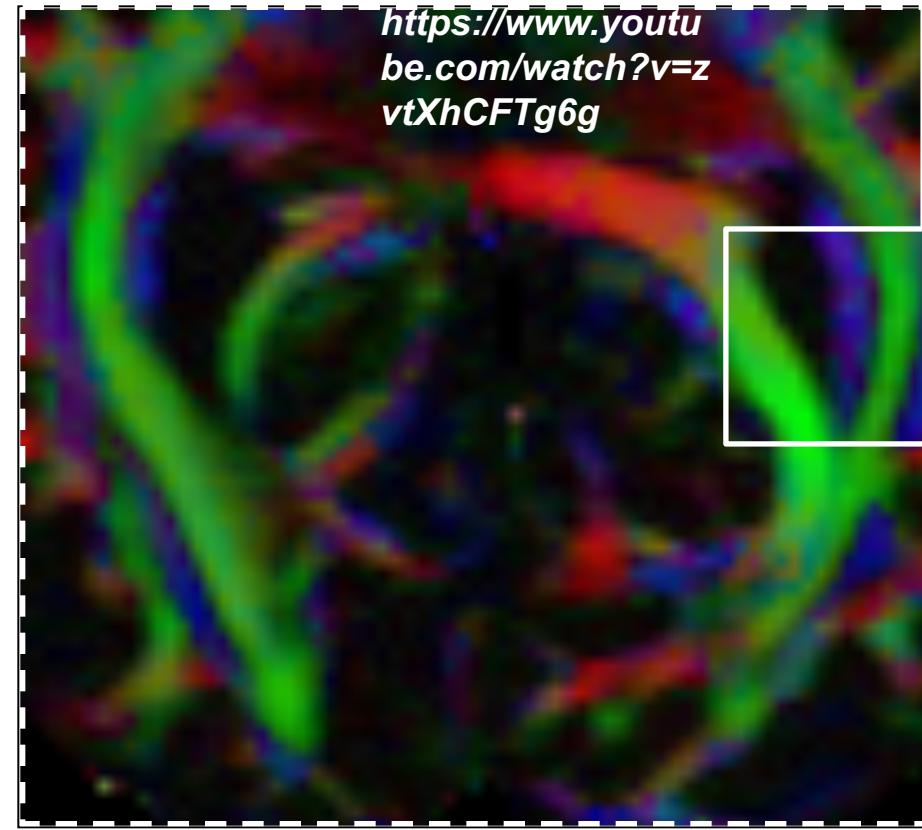
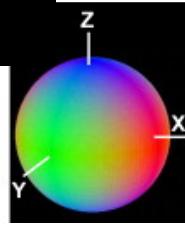
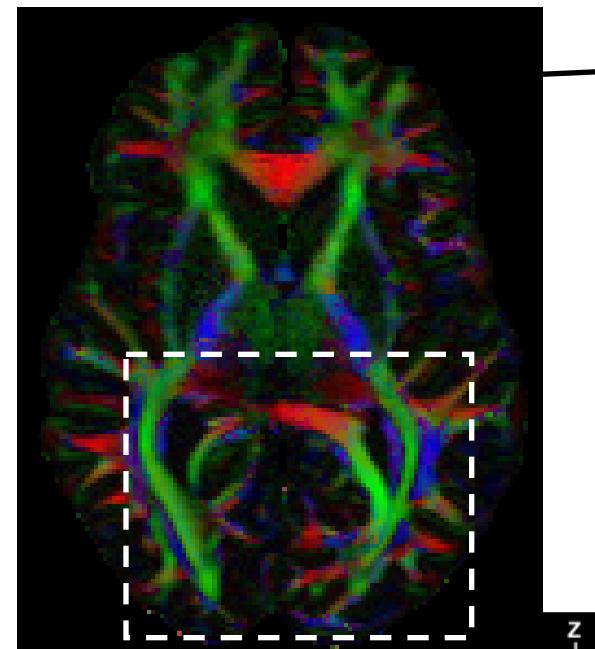
## Limitations & Outlook



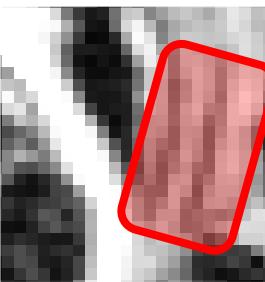
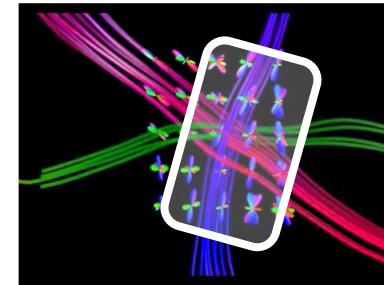




# Limitations & Outlook

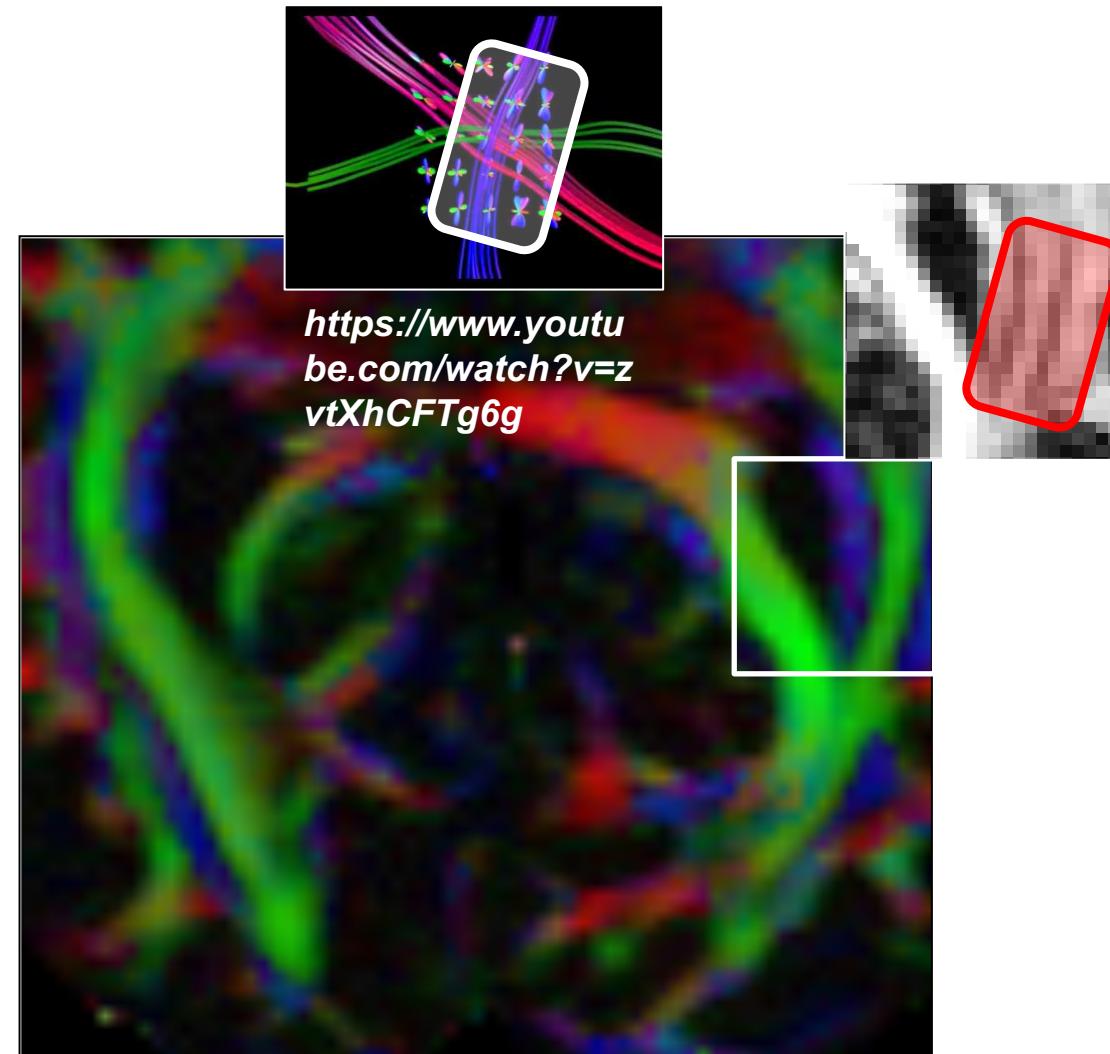


<https://www.youtube.com/watch?v=zvtXhCFTg6g>

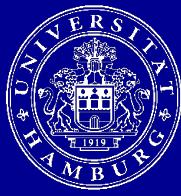


## Limitations

- Orientation information might be biased in DTI
- Fractional anisotropy (FA) is not necessarily sensitive to microstructure



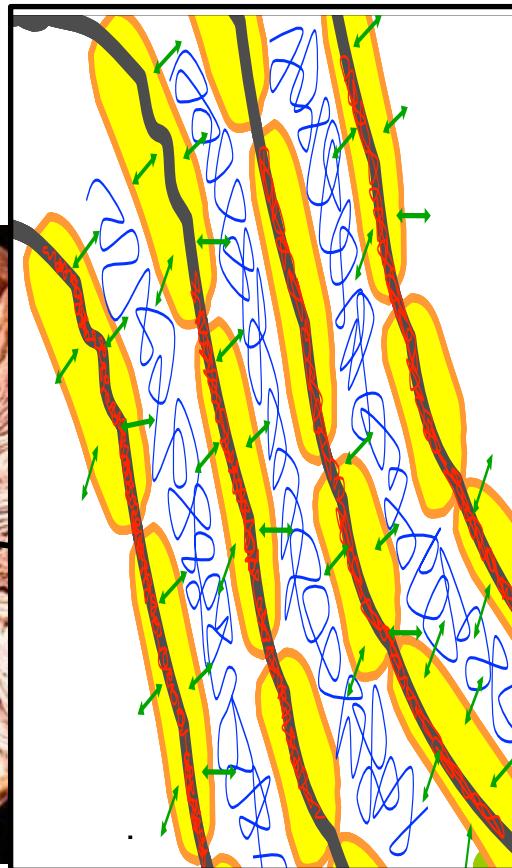
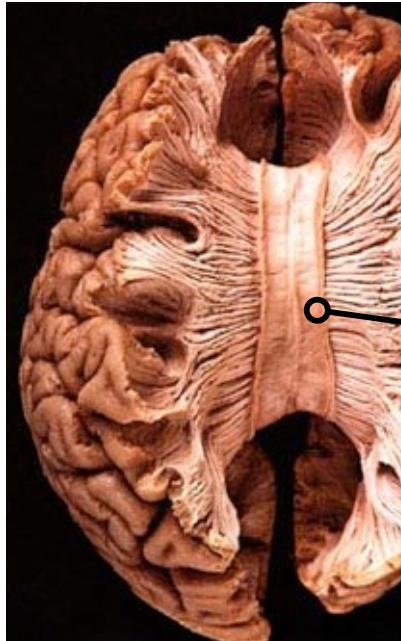
1) Edwards et al, 2017; 2) Mohammadi et al., 2014



## Outlook

- Biophysical models might improve interpretability of DTI parameter maps (e.g. NODDI-DTI<sup>1</sup>)
- More advanced models (DKI<sup>2</sup>) can resolve crossing fibers

1) Edwards et al, 2017; 2) Mohammadi et al., 2014

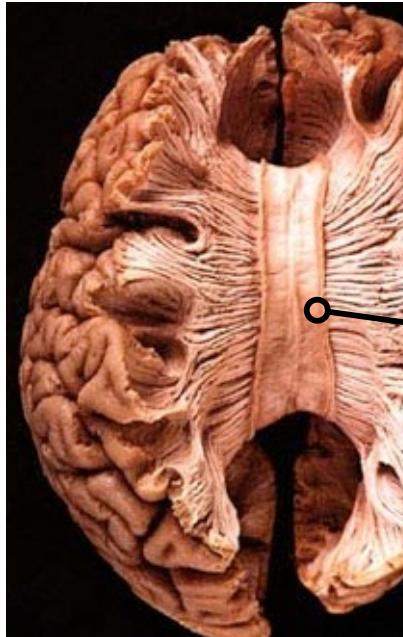


Zhang, OHBM, 2014

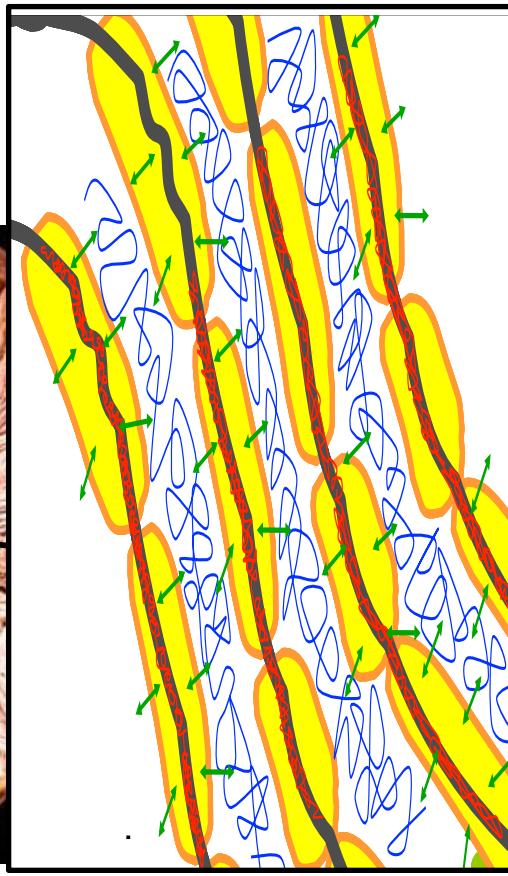
Fieremans, ESMRMB, 2015



# Biophysical model of the diffusion signal



Zhang, OHBM, 2014



Fieremans, ESMRMB, 2015

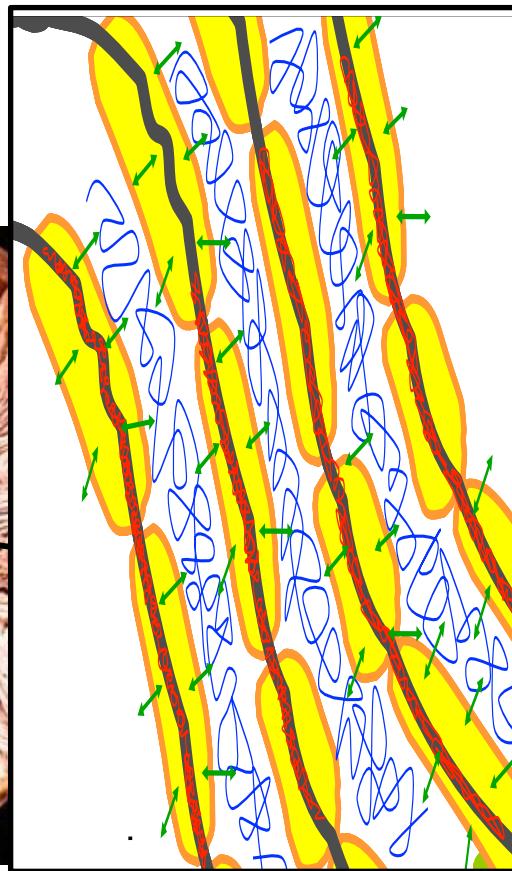
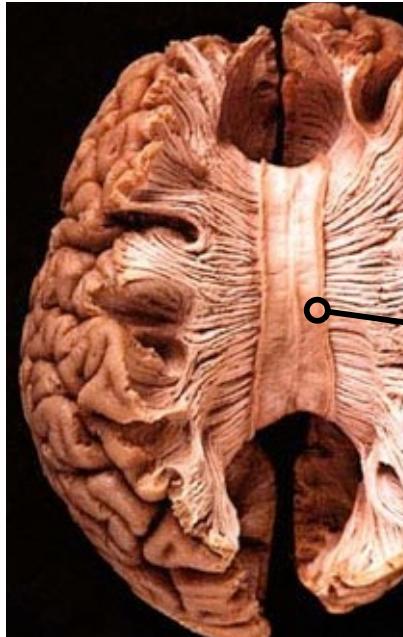
Intra-cellular diffusion  
=  
restricted diffusion

Extra-cellular diffusion  
–  
restricted diffusion

Exchange



# Biophysical model of the diffusion signal

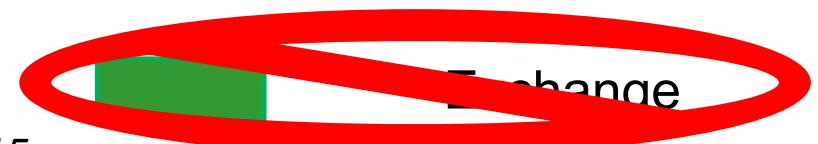


Zhang, OHBM, 2014

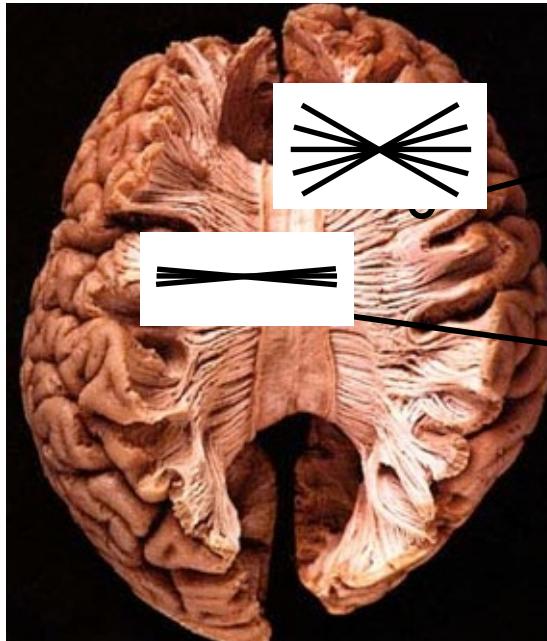
Fieremans, ESMRMB, 2015

Intra-cellular diffusion  
=  
restricted diffusion

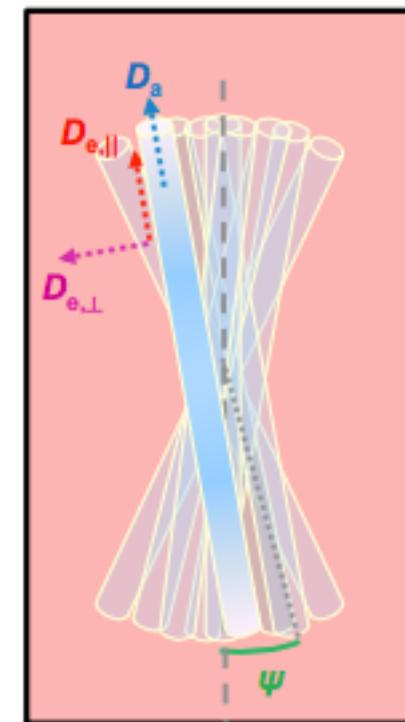
Extra-cellular diffusion  
—  
restricted diffusion



# Biophysical model of the diffusion signal



Zhang, OHBM, 2014



Axonal volume fraction

$$\frac{D_a}{D_a + D_{e,\parallel} + D_{e,\perp}} = f$$

Intra axonal space

$$D_a$$

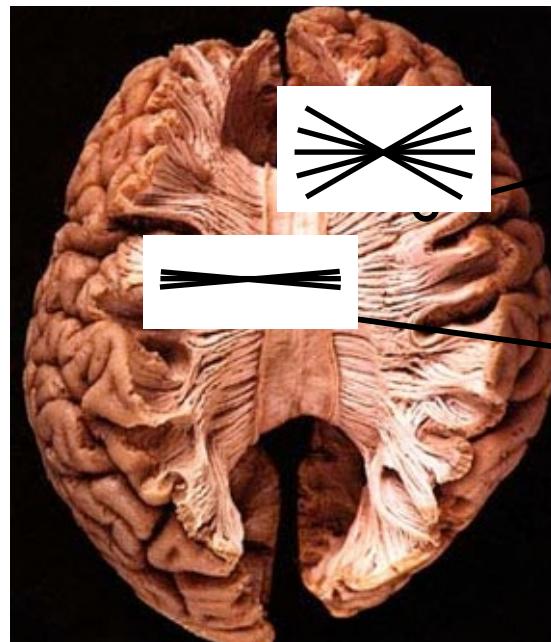
Extra axonal space

$$D_{e,\parallel}, D_{e,\perp}$$

Fieremans, ESMRMB, 2015

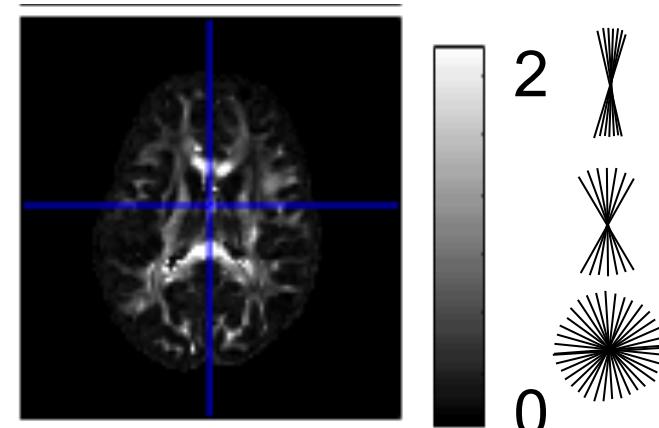


# Biophysical model of the diffusion signal

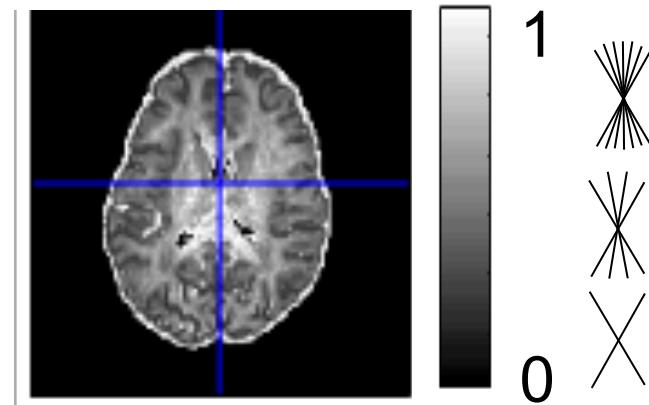


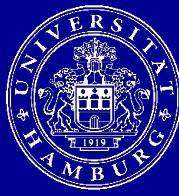
Zhang, OHBM, 2014

Fiber dispersion “” [a. u.]



Fiber density “ $\tau$ ” [a. u.]





NODDI-DTI:  
fiber density “ $\nu$ ”

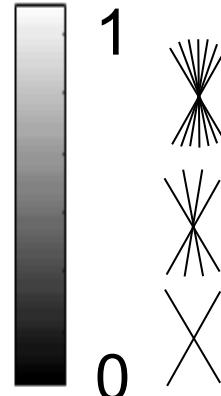
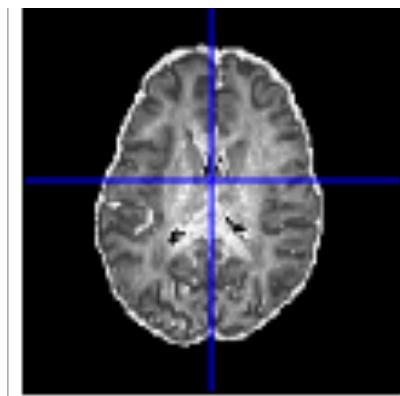
~

mean diffusivity “MD”

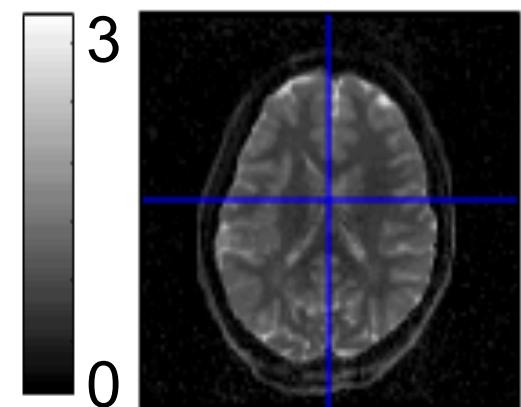
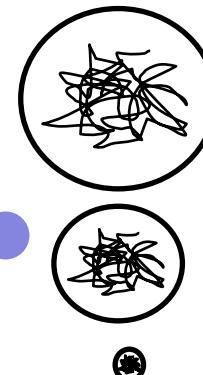
$$\nu = 1 - \sqrt{\frac{1}{2} \left( \frac{3\text{MD}}{d} - 1 \right)}$$

# Relation between MD and neurite density

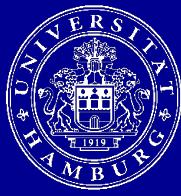
Fiber density [a. u.]



Mean diffusivity  $\left[ \frac{\text{mm}^2}{\text{s}} \times 10^{-3} \right]$



$$\nu = 1 - \sqrt{\frac{1}{2} \left( \frac{3MD}{d} - 1 \right)}$$



NODDI-DTI:

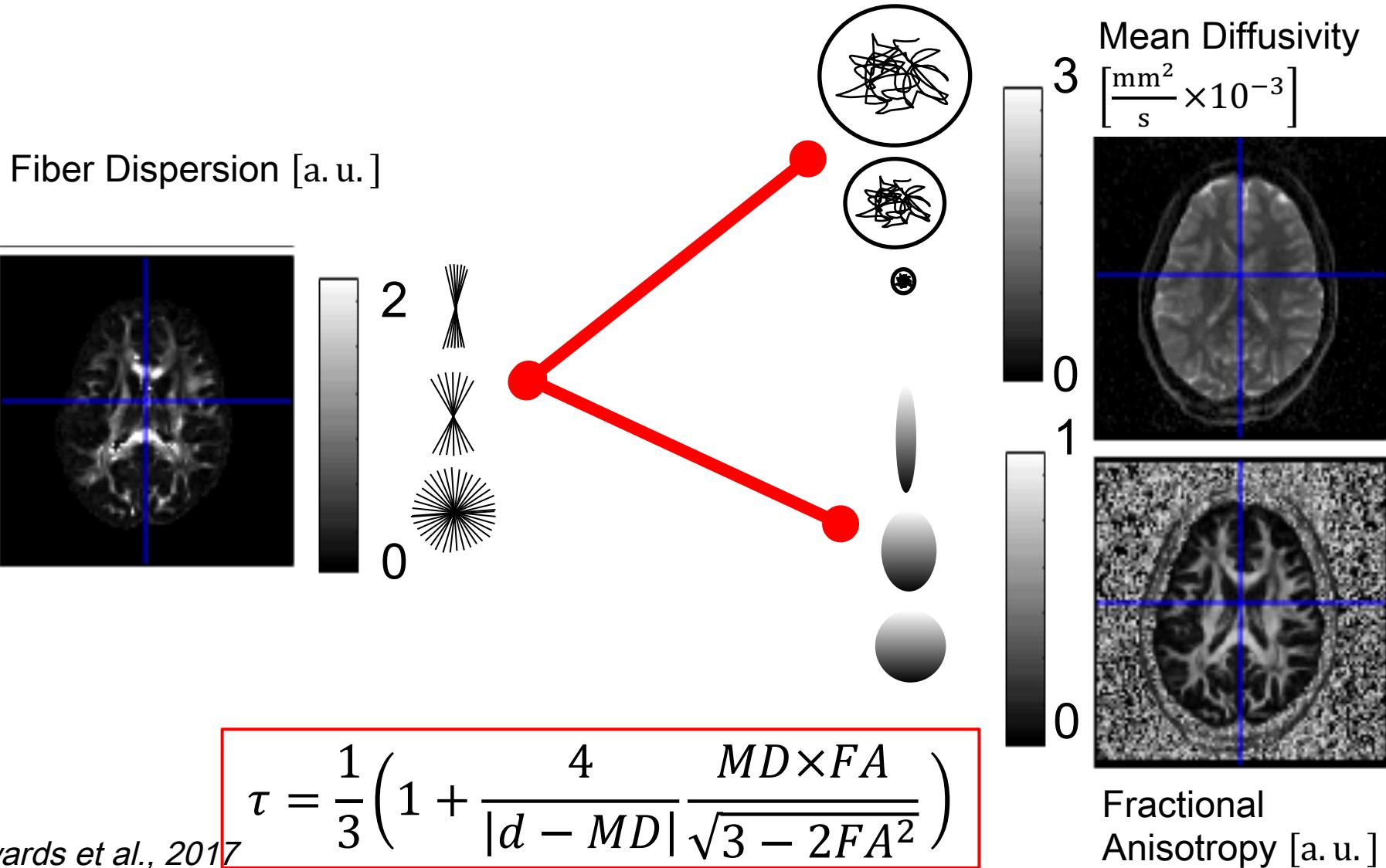
fiber dispersion “ $\tau$ ”

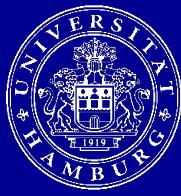
~

mean diffusivity “MD” & fractional anisotropy “FA”

$$\tau = \frac{1}{3} \left( 1 + \frac{4}{|d - MD|} \frac{MD \times FA}{\sqrt{3 - 2FA^2}} \right)$$

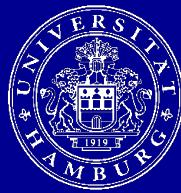
# Relation between FA and fiber dispersion





## Outline of this talk

- Motivation: remember VBM?
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[AAL](#) | [AAL2](#) | [ACID](#) | [AICHA](#) | [ALI](#) | [ALVIN](#) | [AMAT](#) | [AnalyzeMovie](#) | [Anatomy](#) | [AQuA](#) | [ArtRepair](#) | [asl](#) | [ASLtbx](#) | [at4fmri](#) | [aws4SPM](#) | [BAAD](#) | [BFAST3D](#) | [BrainNetViewer](#) | [Brainnetome](#) | [BRANT](#) | [BredeQuery](#) | [Bruker2nifti](#) | [bspmview](#) | [CAT](#) | [CCAfMRI](#) | [CLASS](#) | [Clinical](#) | [Complexity](#) | [conn](#) | [ConnExT](#) | [CPCA](#) | [DAiSS](#) | [DICOMCD Import](#) | [Diffusion II](#) | [DPABI](#) | [DPARSF](#) | [DRIFTER](#) | [EEGAnalyzer](#) | [EMS](#) | [ExtractVals](#) | [FASL](#) | [FAST](#) | [fECM](#) | [FDR](#) | [FieldMap](#) | [fieldmap undistort](#) | [FieldTrip](#) | [fMRIPower](#) | [fOSA](#) | [gPPI](#) | [GraphVar](#) | [GridCAT](#) | [Grocer](#) | [HV](#) | [hMRI](#) | [IBASPM](#) | [iBrainAT](#) | [iBrainLT](#) | [IBZM tool](#) | [ICN Atlas](#) | [ImaGIN](#) | [INRIAlign](#) | [ISAS](#) | [lead-dbs](#) | [lesion gnb](#) | [LI](#) | [LogTransform](#) | [MACS](#) | [Mantis](#) | [MARINA](#) | [MARS](#) | [MarsBar](#) | [MASCOI](#) | [mfBox](#) | [Masking](#) | [Masks](#) | [MEAW](#) | [MIP-C](#) | [MM](#) | [multifocal](#) | [MRTOOL](#) | [MRM](#) | [NIRS-SPM](#) | [NPBayes](#) | [NS](#) | [OCT](#) | [PETPVE12](#) | [pTFCE](#) | [Ortho](#) | [PSPM](#) | [QModeling](#) | [REST](#) | [rfxplot](#) | [RobustWLS](#) | [rsHRF](#) | [SAfE](#) | [SAMIT](#) | [SCRalyze](#) | [SDM](#) | [SGTT](#) | [SimpleROIBuilder](#) | [SnPM](#) | [SpikeDet](#) | [spm wavelet](#) | [SPMd](#) | [SPMMouse](#) | [SSM](#) | [STEM](#) | [SUIT](#) | [SurfRend](#) | [SwE](#) | [TDT](#) | [PhysIO](#) | [TOM](#) | [TFCE](#) | [UF2C](#) | [Unwarp2](#) | [VarTbx](#) | [VDB](#) | [Volumes](#) | [WBM](#) | [WSPM](#) | [WFU PickAtlas](#) | [xjView](#) | [XMLTools](#) | [ASLtbx](#) | [BENTbx](#) | [SVRLSMtbx](#) | [GIFT](#)

<https://www.fil.ion.ucl.ac.uk/spm/ext/>

## ACID - Artefact correction in diffusion MRI **SPM12 SPM8**

**Summary:** The Artefact correction in diffusion MRI (ACID) toolbox is an academic software toolkit for pre-processing of diffusion MRI data, estimation of DTI indices and normalisation of DTI index maps, which fully integrates into the batch system of SPM8.

**Author:** [Siawoosh Mohammadi](#)

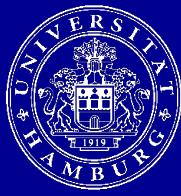
**URL:** <http://www.diffusiontools.com/>

## Diffusion II - Post-processing for diffusion weighted image series **SPM12 SPM8 SPM5 SPM2**

**Summary:** Post-processing for diffusion weighted image series. Functionality includes movement correction for image time series, estimation of the diffusion tensor, computation of anisotropy indices and tensor decomposition.

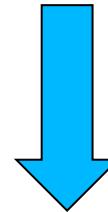
**Author:** [Volkmar Glauche](#)

**URL:** <http://sourceforge.net/projects/spmtools>



Where are the slides?

**www.diffusiontools.com**



**bitbucket**