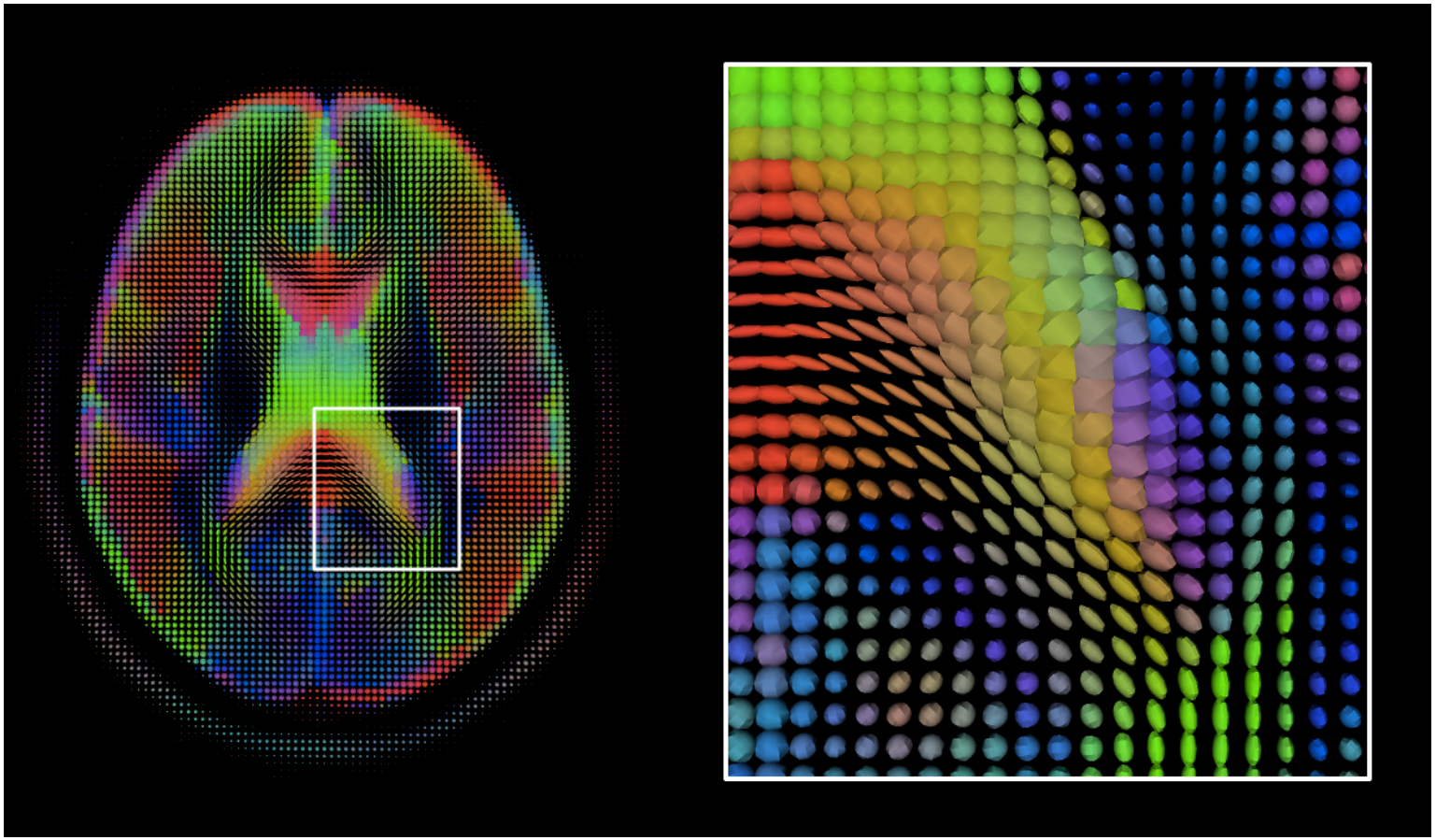
From K-space to Q-space to Brain Space



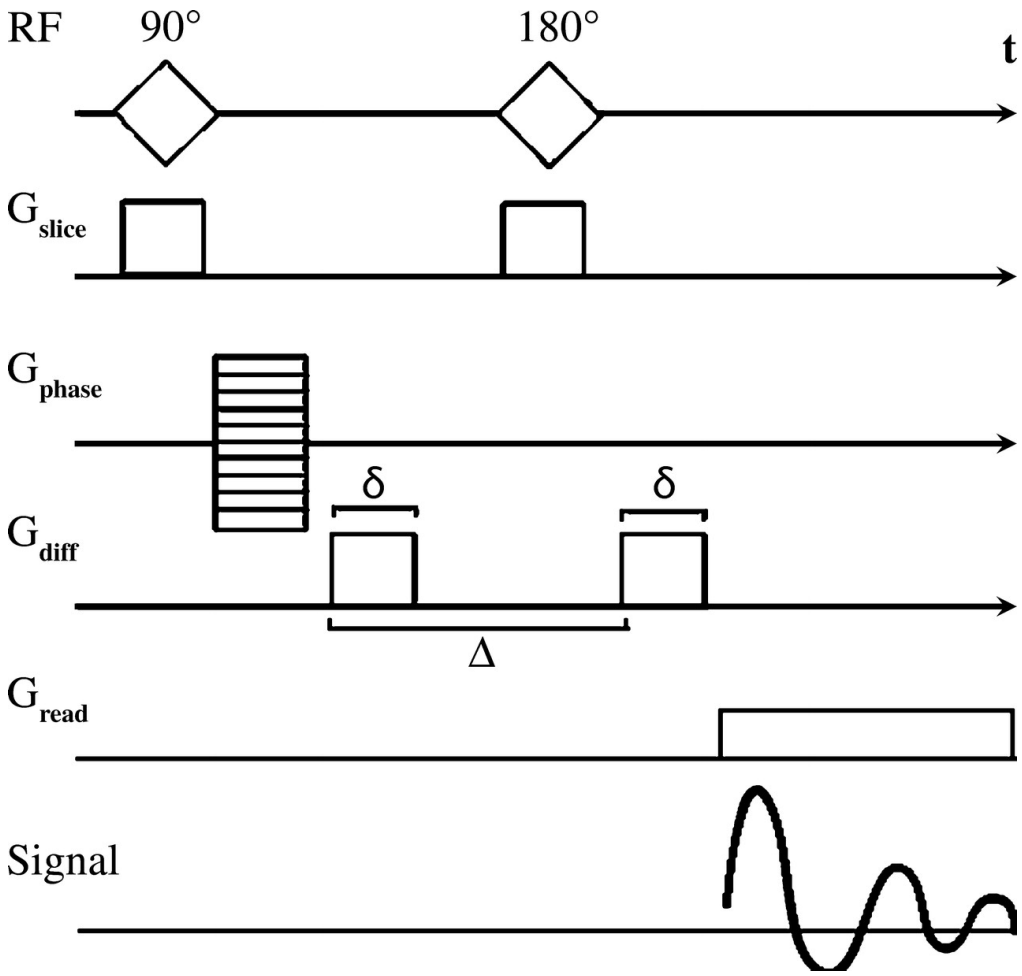
Virtual Neuroanatomy

Lecture Date: 09/02/2014

Learning Goals

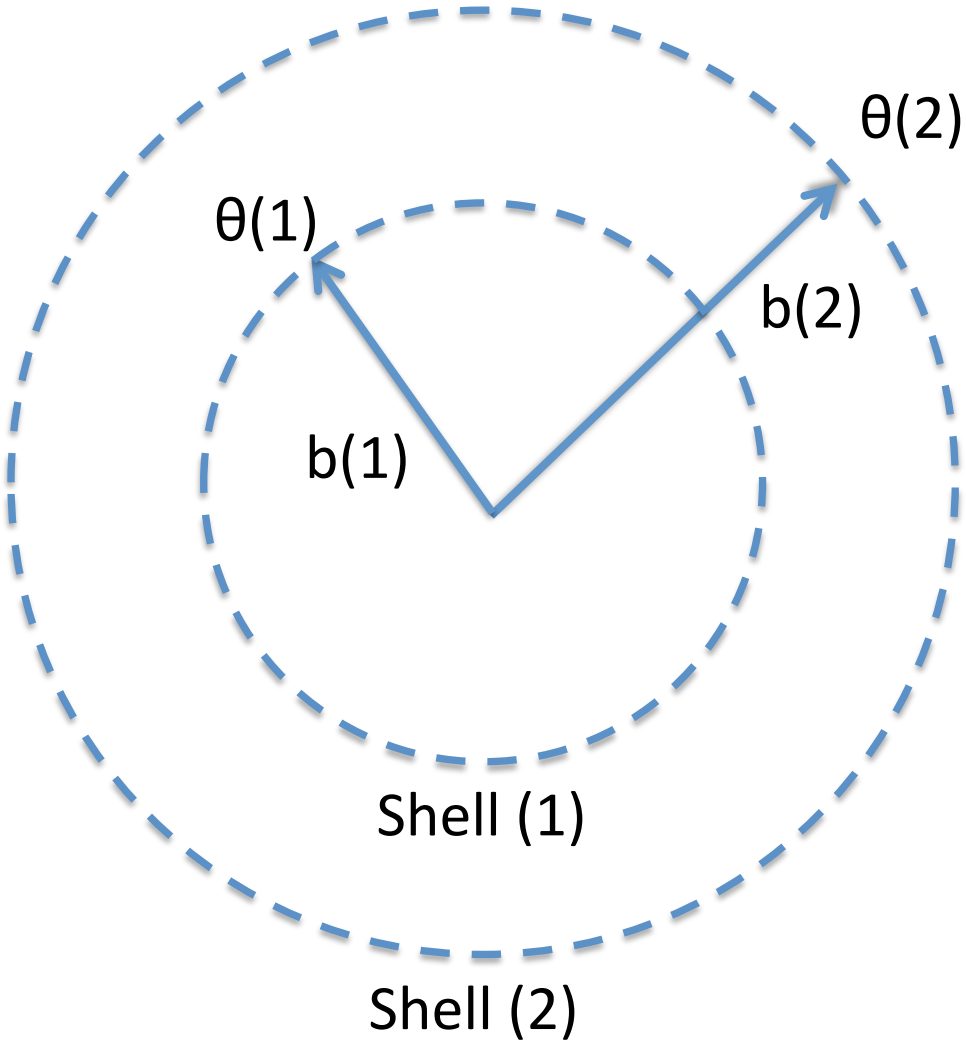
- What is “Q-Space” and how is it useful for mapping anatomical connections?
- What is the difference between a tensor model and model free approaches?
- What is fractional anisotropy and what does it reflect?
- What is an ODF?

A modified T2* sequence



Hagmann P et al. Radiographics 2006;26:S205-S223

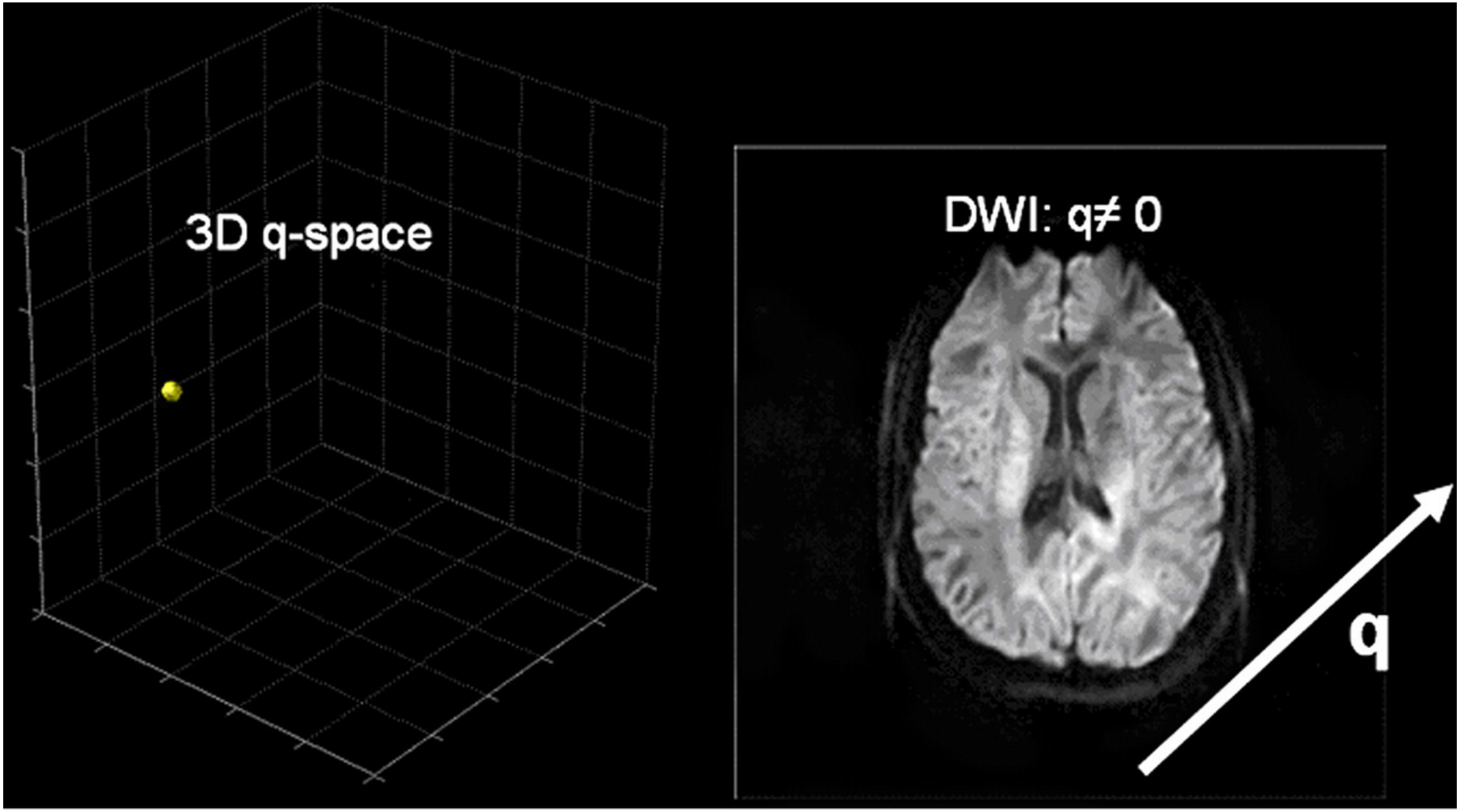
Q-Space



b-value: Strength of the diffusion gradient. Higher values = more energy & smaller compartments.

Shell: Sample of water "energy" that corresponds roughly to distance traveled.

Q-Space



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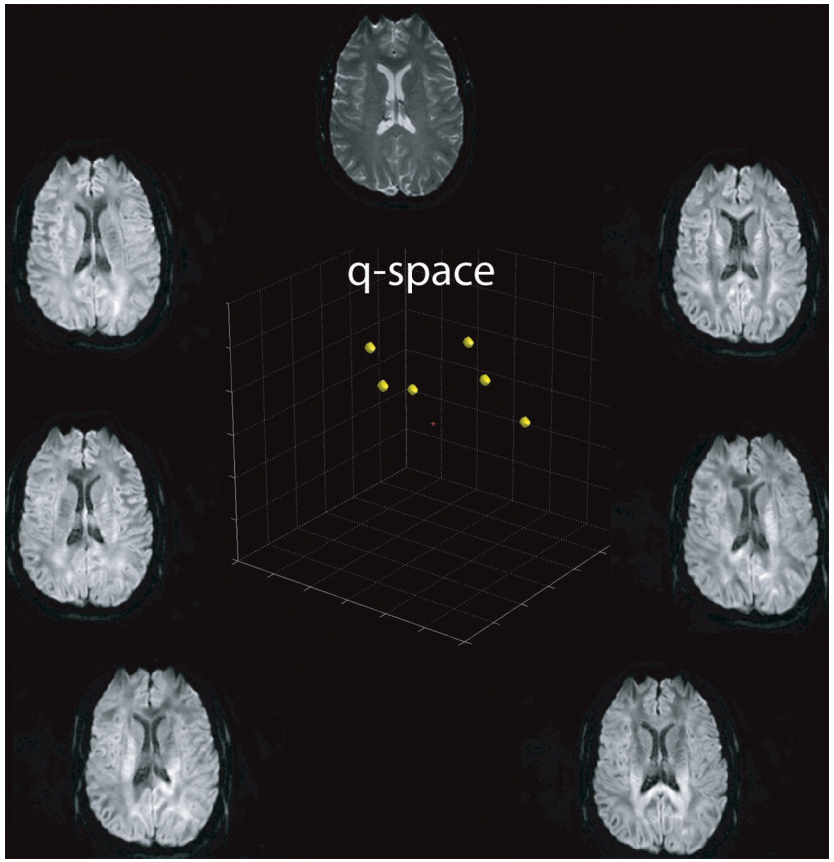
Methods of sampling q-space

Q-Space: DTI



Diffusion Tensor Imaging (DTI): Sample water movement (q-space) in *orthogonal, independent directions* and *that travels at only a single distance.*

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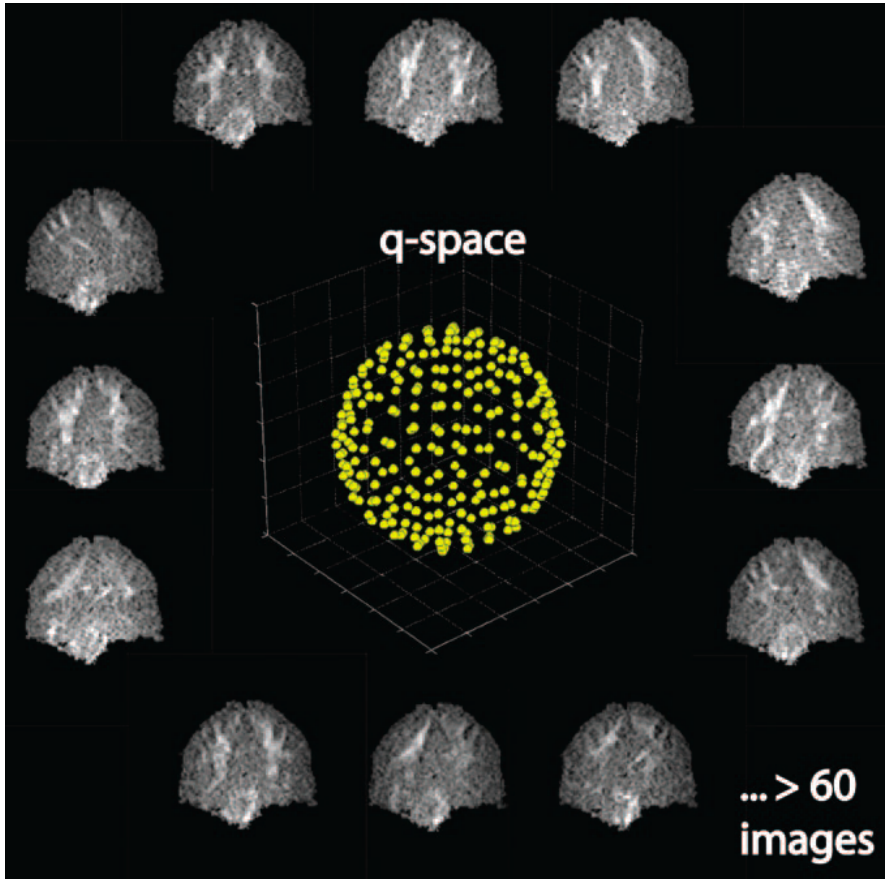
Q-Space: QBI (HARDI)



Q-ball Imaging (QBI):
Sample water movement (q-space) in *orthogonal, independent directions* and *sampled at a single high b-value.*

This is a form of **High Angular Resolution Diffusion Imaging (HARDI)** acquisition

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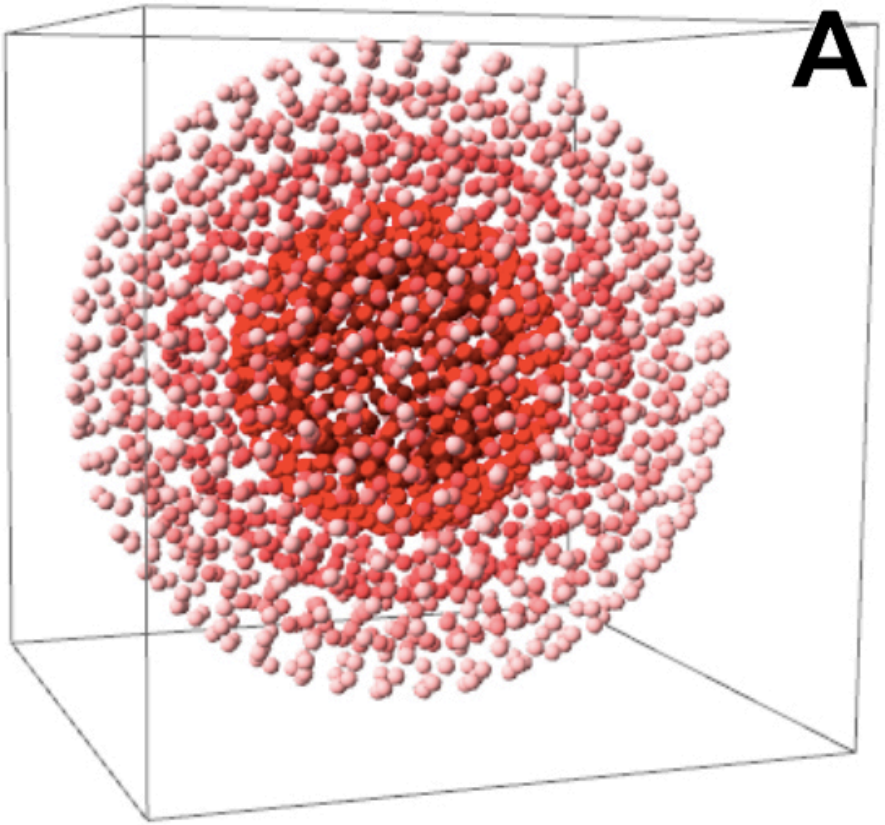
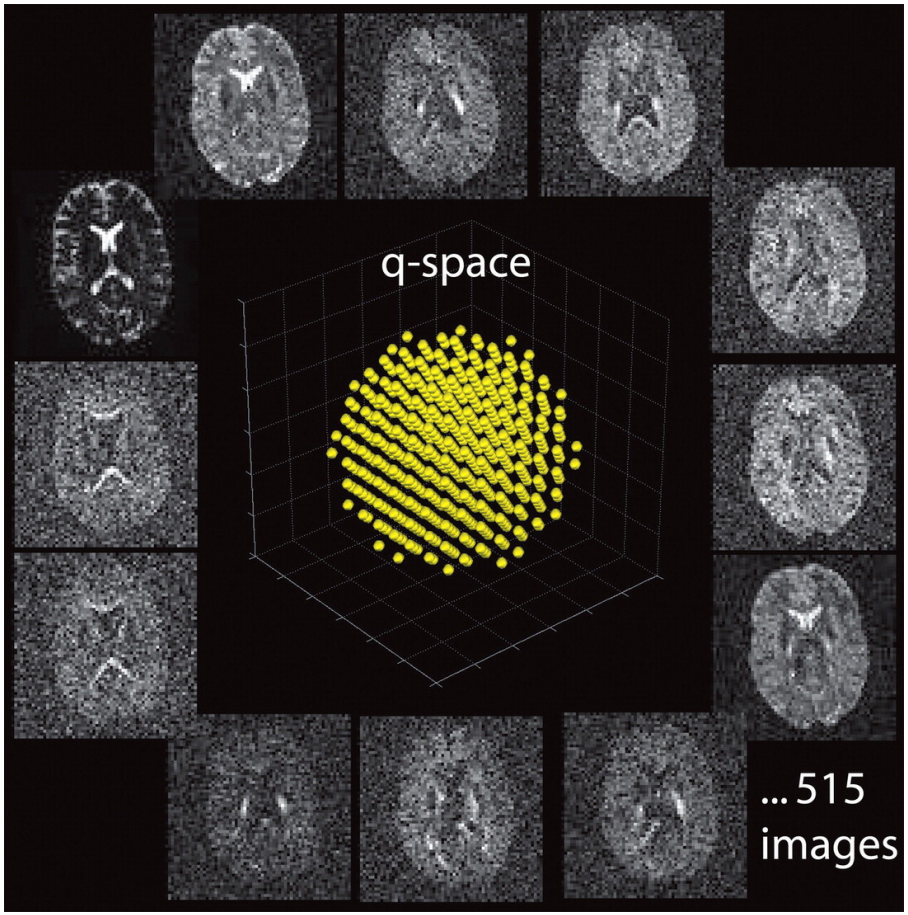
Q-Space: Multishell



Multishell:
Sample water movement (q-space) in *many directions* and *sampled at varied, but consistent single high b-value.*

This is not consistent with a **HARDI** acquisition.

Q-Space: Grid sampling



Diffusion Spectrum Imaging (DSI): Sample water movement (q-space) in *a grid fashion* and *that travels at multiple distances.*

DSI is <u>not</u> the same as multi-shell imaging.

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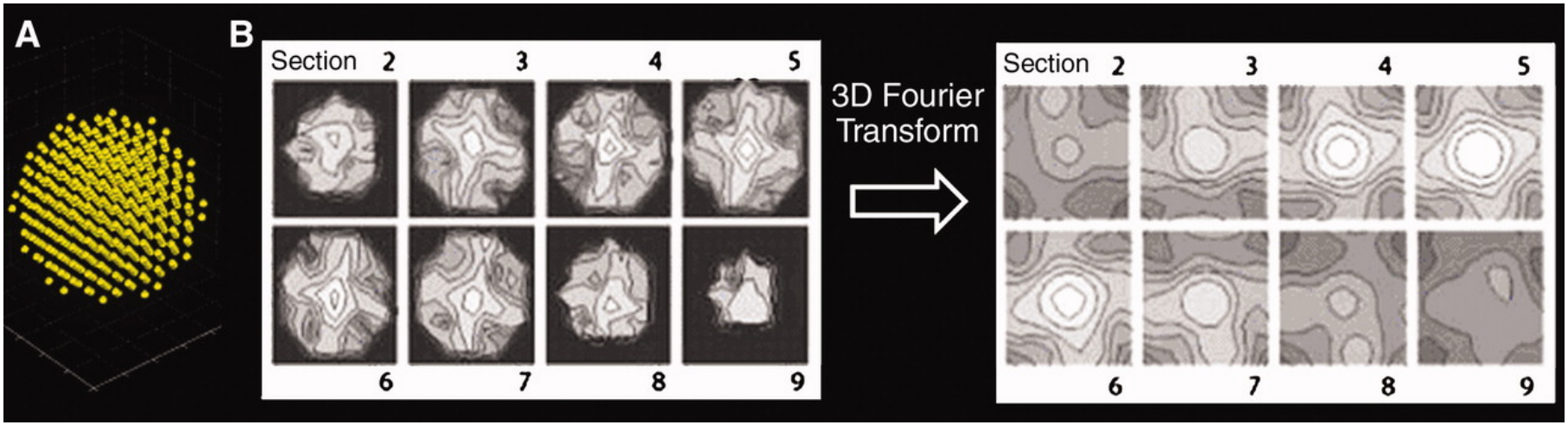
Estimating the PDF



Based on the change in signal you can estimate the directional probability distribution of underlying water.

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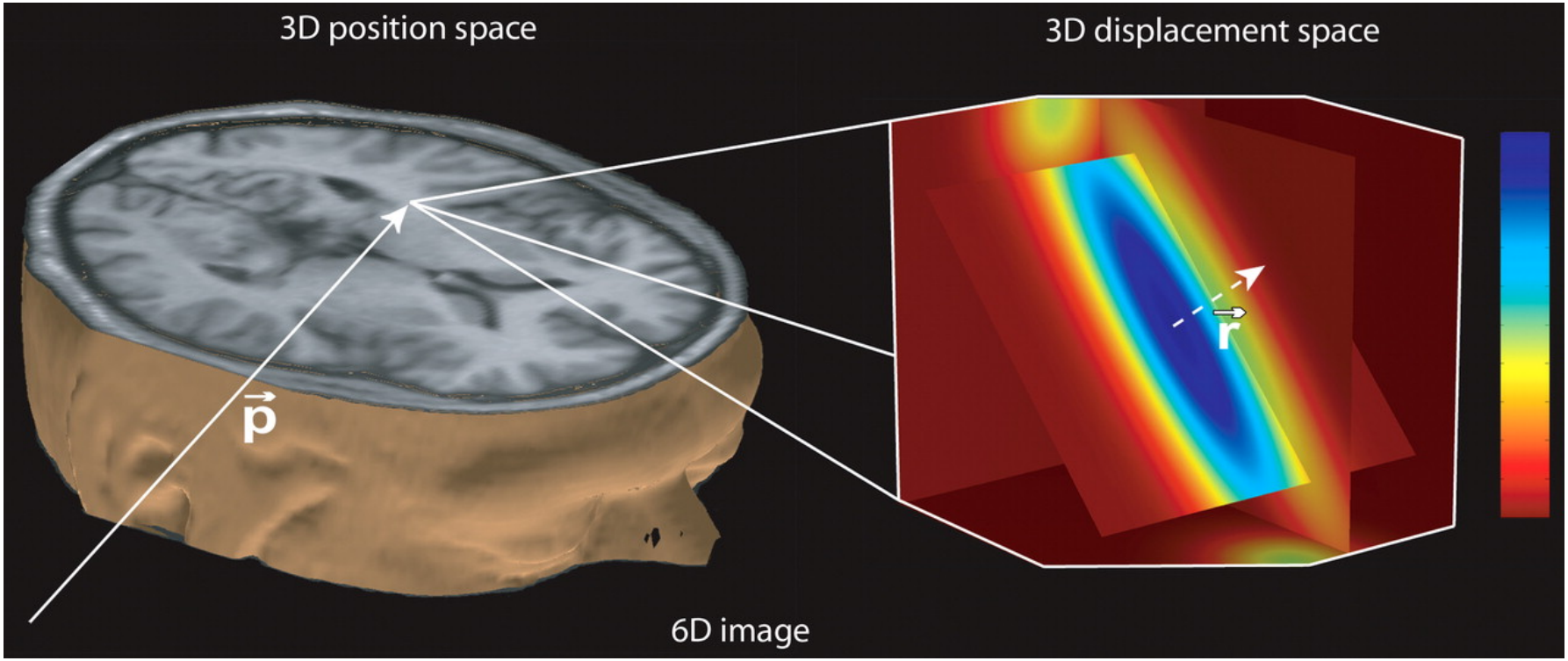
Reconstruction of water diffusion within voxels

6 Dimensional Data

a) Voxel location: X, Y, Z
b) Diffusion within voxels: X, Y, Z



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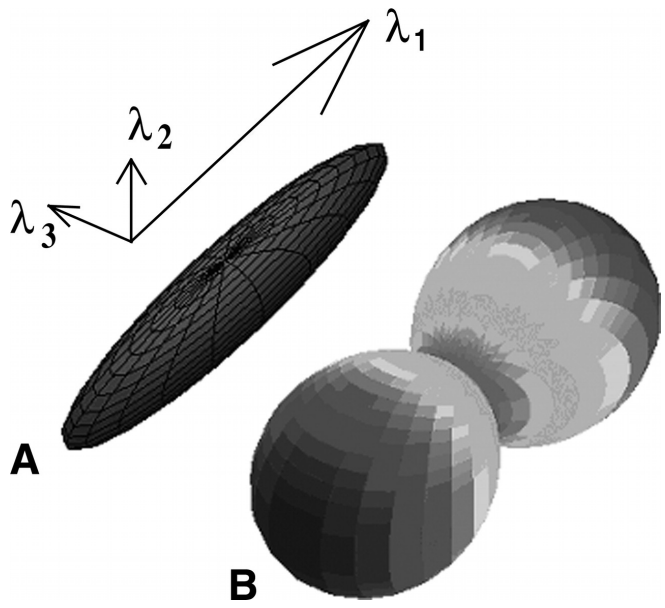
Two general classes of reconstruction algorithms for dMRI data

1. **Tensor-based approaches**: Assume a particular shape to the diffusion pattern and fit that shape given dMRI data.
   - DTI
   - Ball & Stick (FSL)
2. **Model-free approaches**: Infer the shape of water diffusion by looking at the probability distribution function based off of the dMRI data.
   - QBI
   - DSI
   - GQI

Tensor-based approaches

The Diffusion Tensor Model



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

A model the diffusion of water as eigenvalues (λ) in 3D space that reflect the principle *tensor lengths* (i.e., all orthogonal) of directional diffusion.

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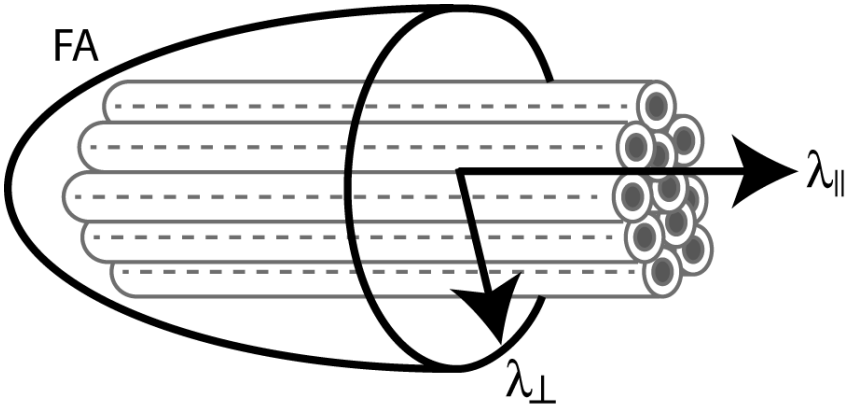
The Diffusion Tensor Model



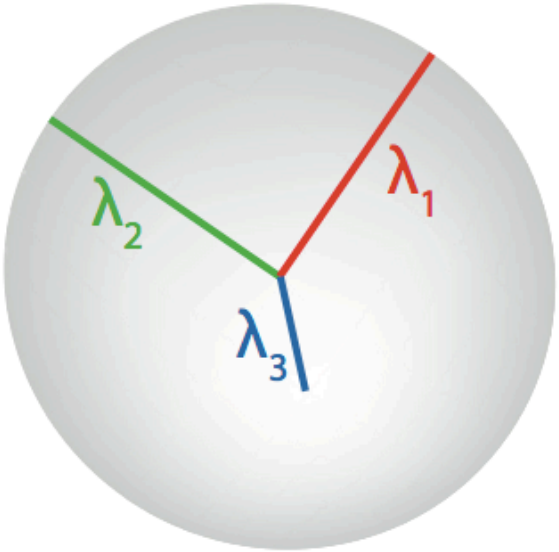
Fractional Anisotropy (FA):
Degree of anisotropy of the underlying water diffusion. A standard measure of white matter integrity.

$$\mathrm{FA} = \sqrt{\frac{3}{2}} \frac{\sqrt{(\lambda_1 - \hat{\lambda})^2 + (\lambda_2 - \hat{\lambda})^2 + (\lambda_3 - \hat{\lambda})^2}}{\sqrt{\lambda_1^2 + \lambda_2^2 + \lambda_3^2}}$$

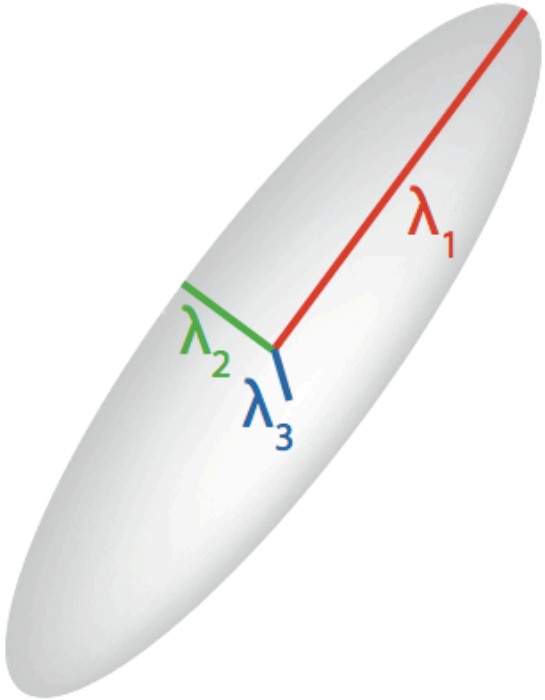
σ

μ

The Tensor Model



Isotropic

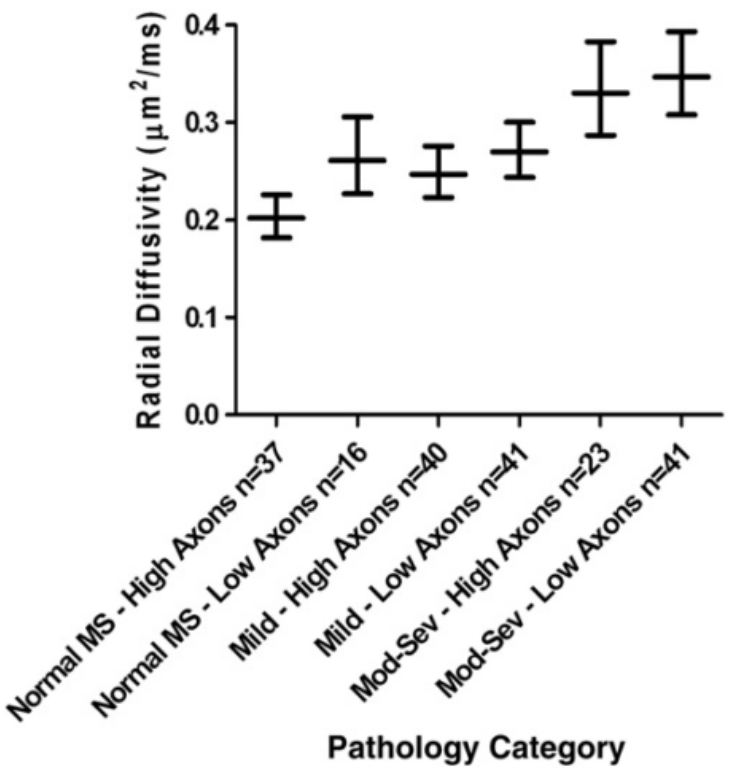


Anisotropic

λ_1 = longitudinal (axial) diffusivity(AD)
$(\lambda_2 + \lambda_3)/2$ = radial diffusivity (RD)
$(\lambda_1 + \lambda_2 + \lambda_3)/3$ = mean diffusivity (MD)

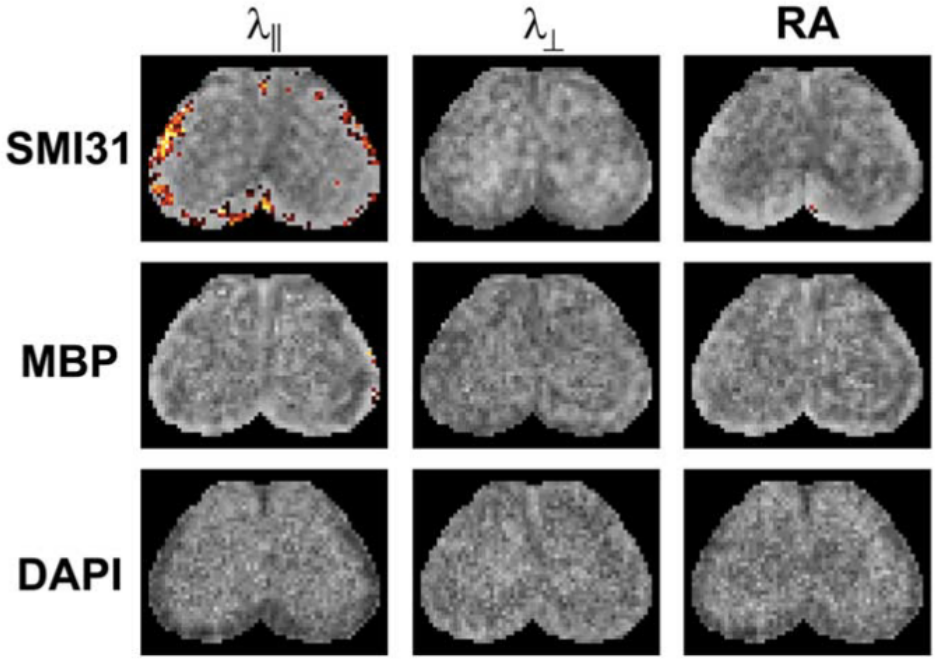
What do AD & RD reflect?

Radial Diffusivity ~ Myelin Damage



Klawiter et al. Neuroimage 2011

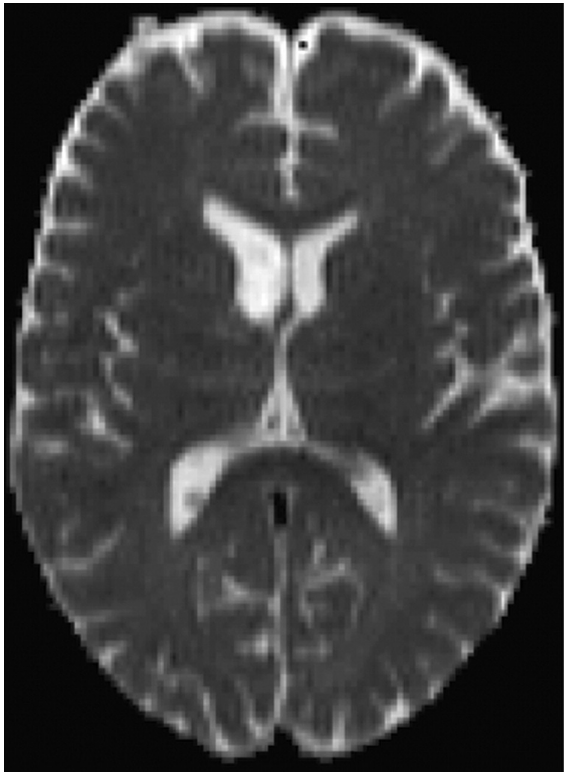
Axial Diffusivity ~ Axon Damage



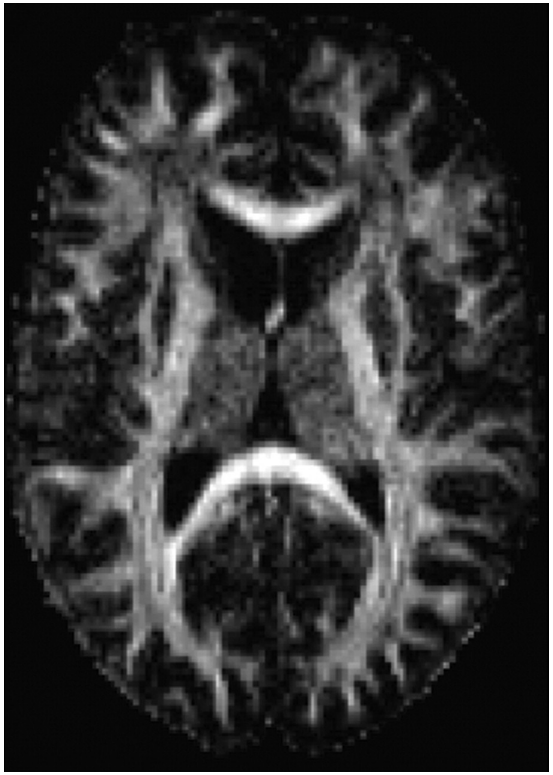
Budde et al. J. Neuroscience 2009

The Tensor Model

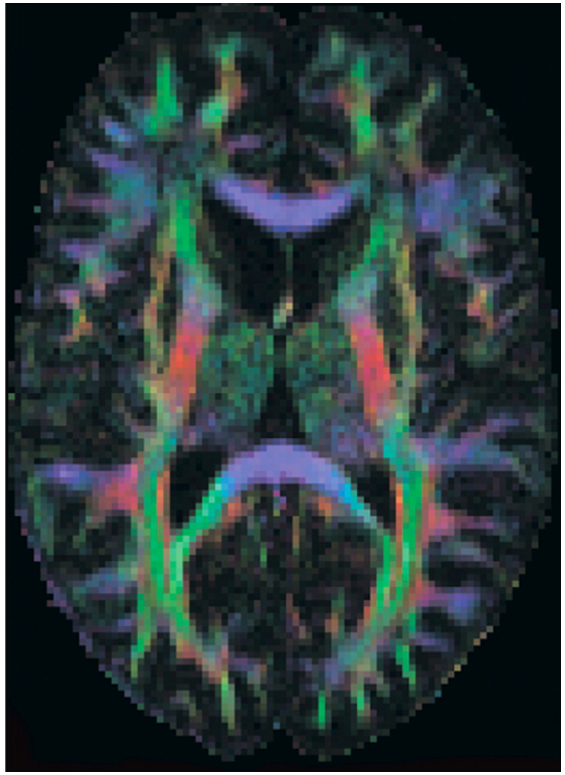
Diffusion Image (b0)



FA Image



3 Principle Tensors



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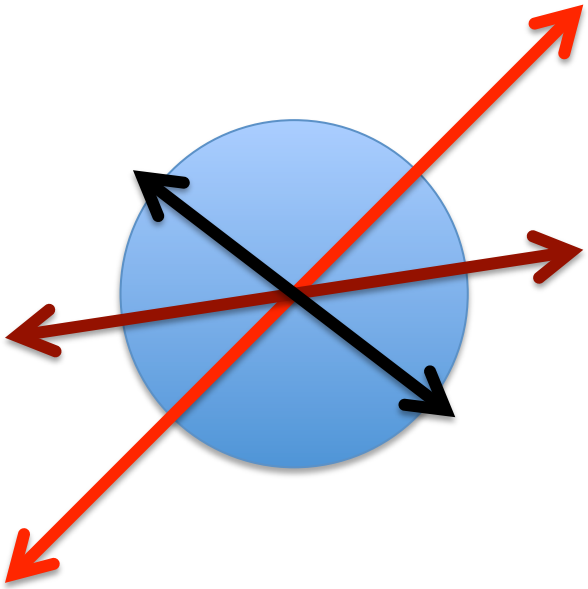
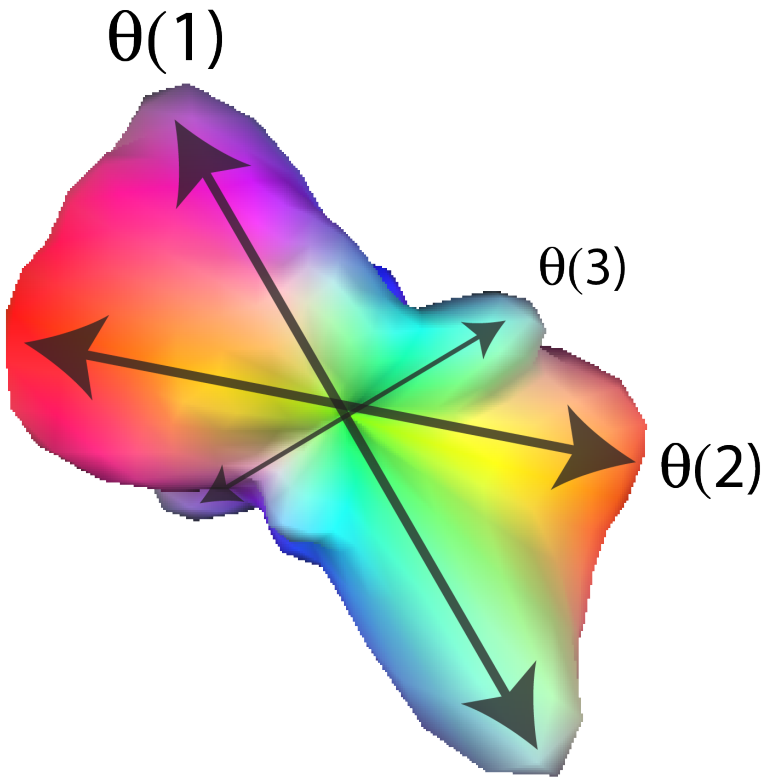
Ball-and-Stick Model



- Variant of the tensor model.
- Orientation and magnitude of up to N anisotropic compartments.
- Reconstruction approach used in FSL.

Model-free approaches

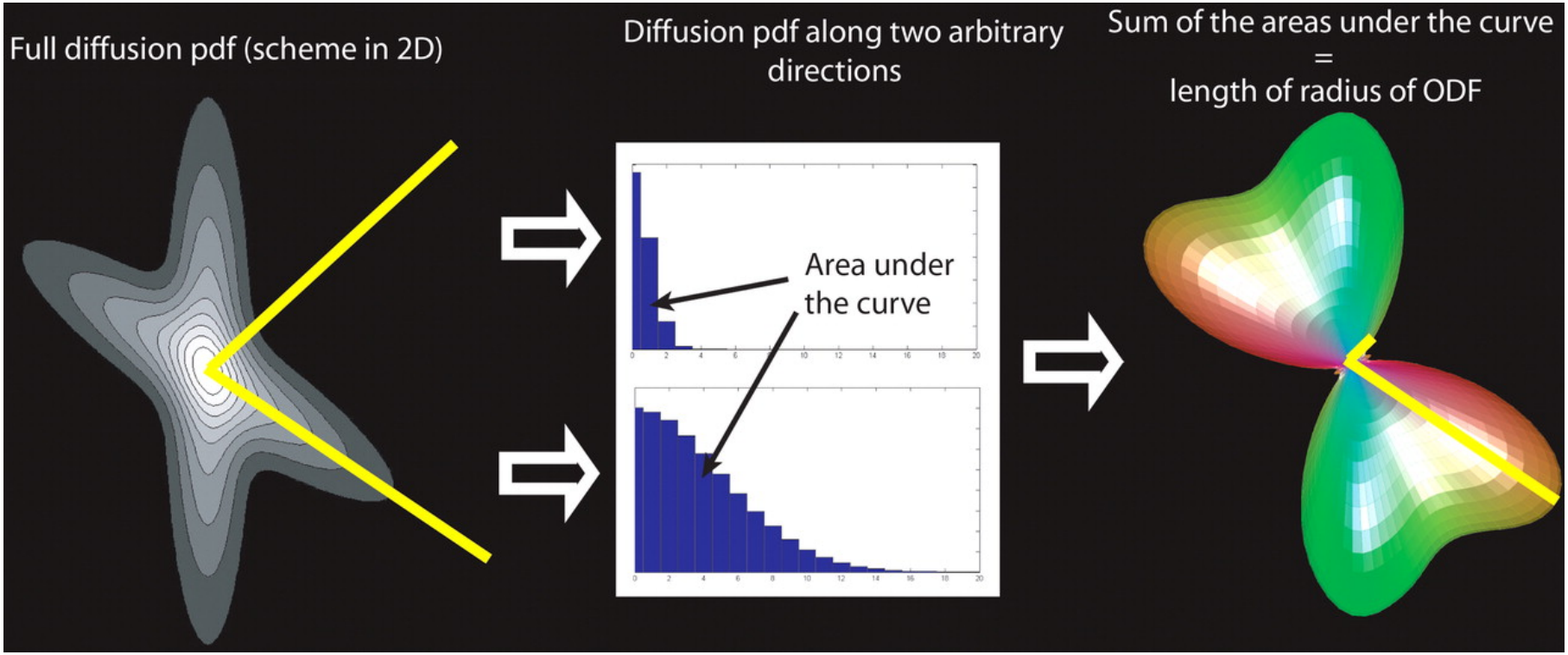
The Orientation Distribution Function (ODF)



ODF: A 3D representation of underlying water diffusion whose radius in any direction is proportional to the summed diffusion probability distribution in that direction

Jarbo et al. NeuroImage 2012

The Orientation Distribution Function (ODF)



Hagmann P et al. Radiographics 2006;26:S205-S223

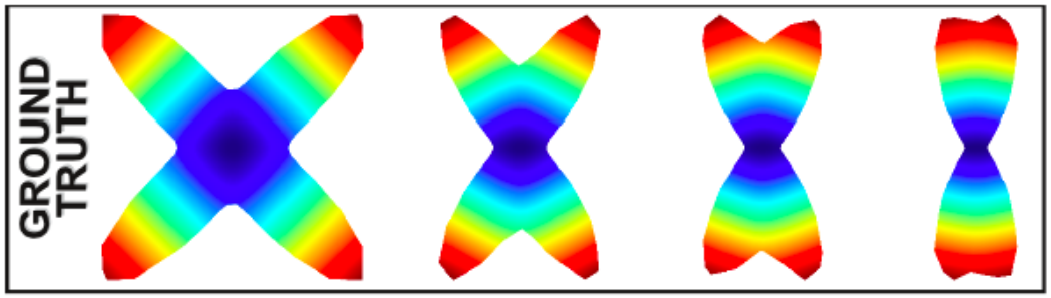
ODF estimation algorithms

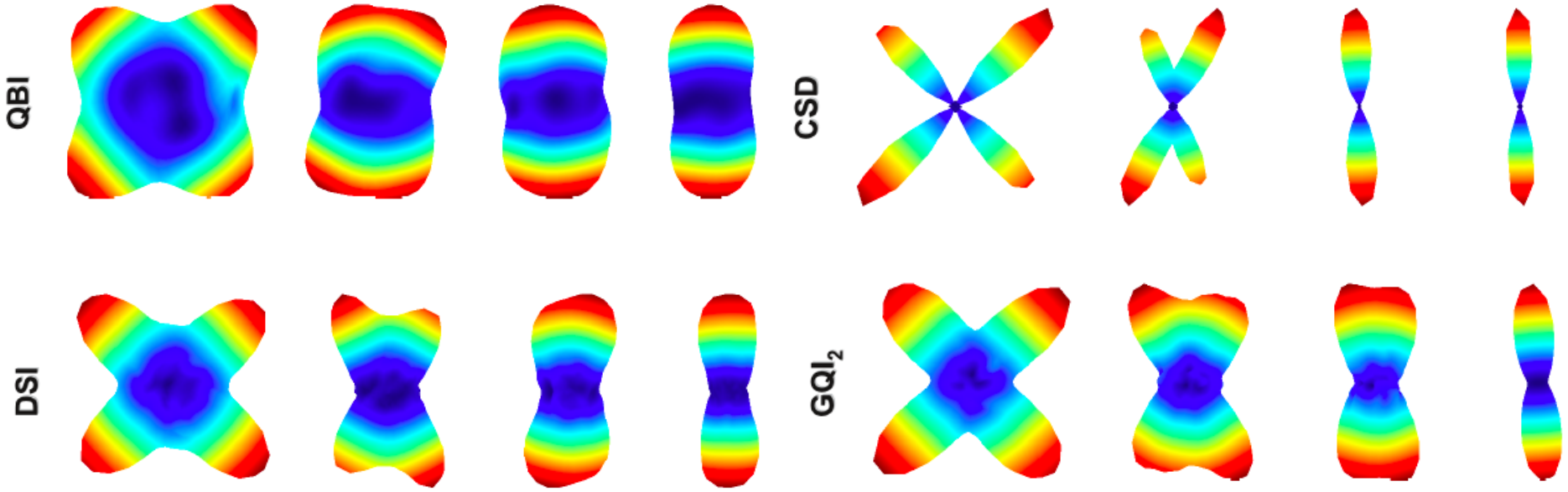
1. **HARDI-based Reconstruction Schemes**
   - Q-Ball Imaging (QBI)
   - Constrained Spherical Deconvolution (CSD)

2. **DSI-based Reconstruction Schemes**
   - Diffusion Spectrum Imaging (DSI)
   - Generalized Q-space Imaging (GQI)

Note: Model-free approaches are heavily dependent on the way Q-space is sampled.

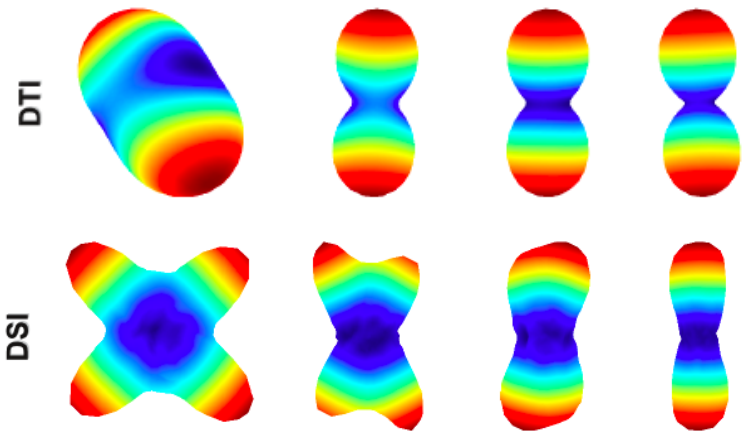
The Orientation Distribution Function (ODF)

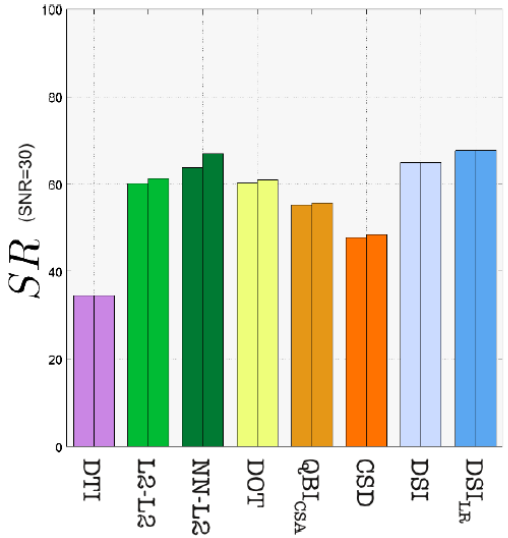


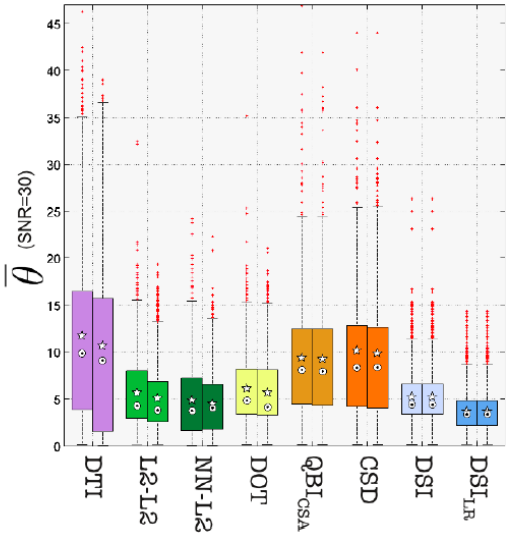


Daducci et al. IEEE Trans Med Imaging. 2014

The Orientation Distribution Function (ODF)





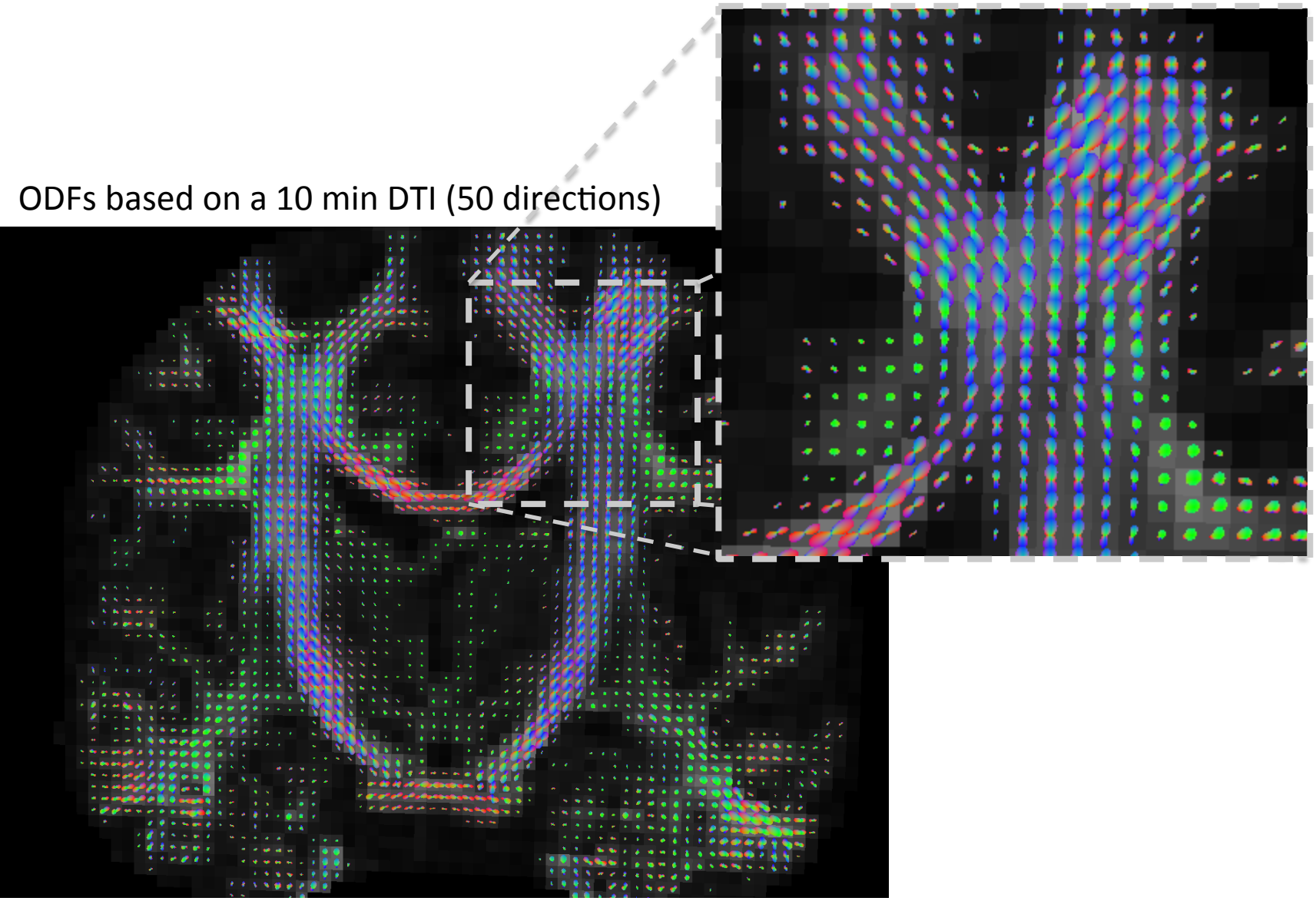


Model-free approaches tend to capture complexity in underlying pathways better than tensor-based reconstruction approaches.

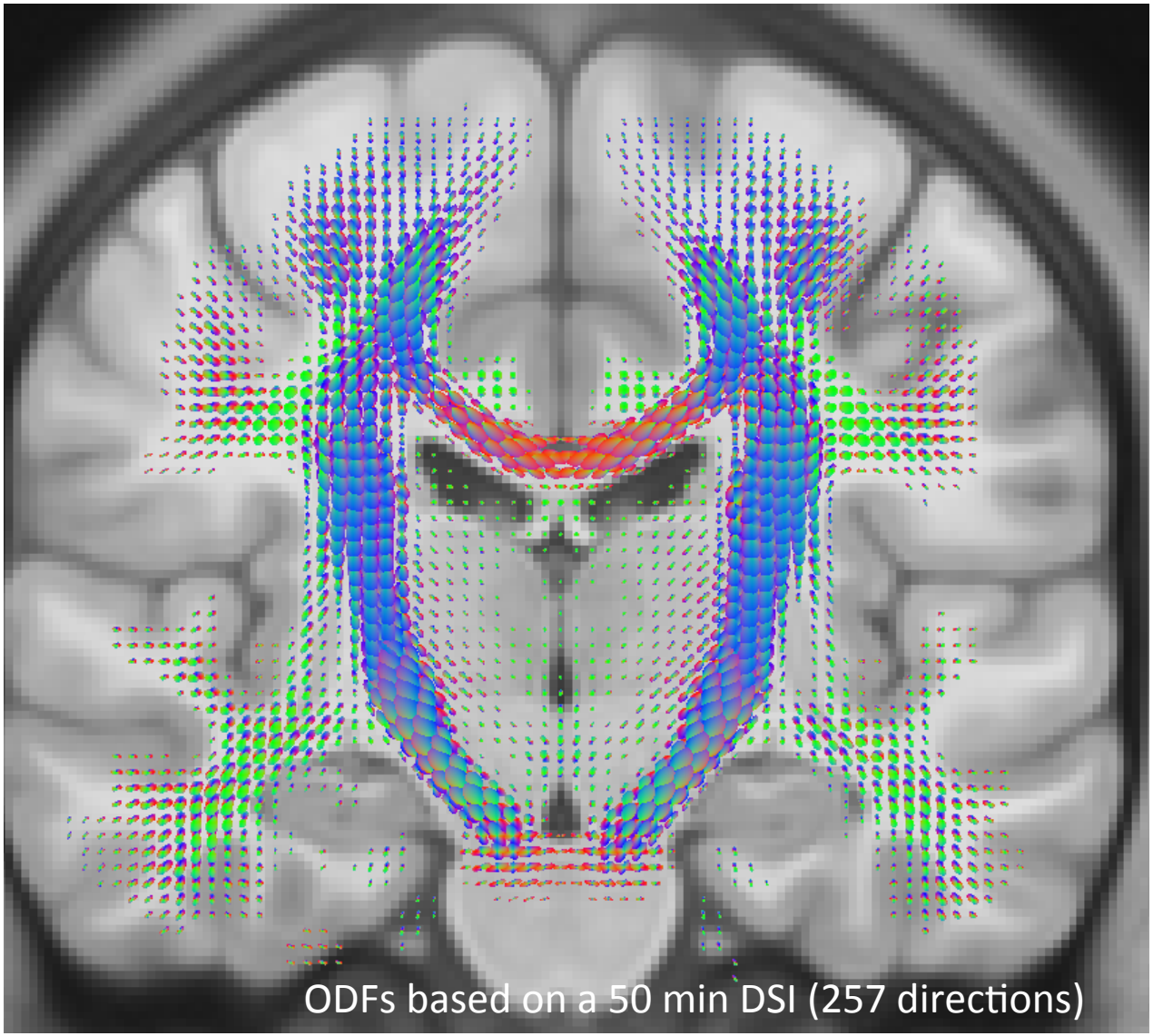
Daducci et al. IEEE Trans Med Imaging. 2014

The Orientation Distribution Function (ODF)

ODFs based on a 10 min DTI (50 directions)



The Orientation Distribution Function (ODF)



Pros & Cons

1. **Tensor-based approaches**:
   - *Pros*: Easy to calculate, conceptually simple, few assumptions of how q-space is sampled.
   - *Cons*: Difficulty capturing complex fiber crossings (even ball & stick).

2. **Model-free approaches**:
   - *Pros*: Captures complex patterns in underlying diffusion, more complete picture of voxelwise signals.
   - *Cons*: Highly dependent on q-space sampling approach, computationally expensive.

Learning Goals

- What is “Q-Space” and how is it useful for mapping anatomical connections?
- What is the difference between a tensor model and model free approaches?
- What is fractional anisotropy and what does it reflect?
- What is an ODF?