

Introduction to Diffusion-weighted Imaging

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Motivation

- Magnetic resonance imaging provides information about the spatial distribution of water.
- Diffusion-weighted MRI (DWI) provides information about the motion of water.
- DWIs are sensitive to cellular architecture and tissue integrity.
- DWI can provide quantitative measures that are directly comparable.
- Diffusion imaging can be used to identify specific white matter tracts

Outline

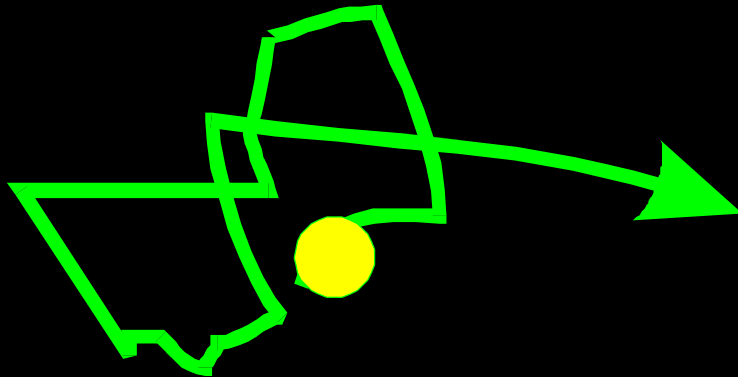
- What is diffusion?
- How do we measure diffusion in MRI?
- How do we extract directional information?
- What are the practical problems and limitations?
- Beyond the diffusion tensor

Outline

- What is diffusion?
- How do we measure diffusion in MRI?
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Diffusion

- Diffusion refers to the random translational (Brownian) motion of molecules that results from the thermal energy of these molecules

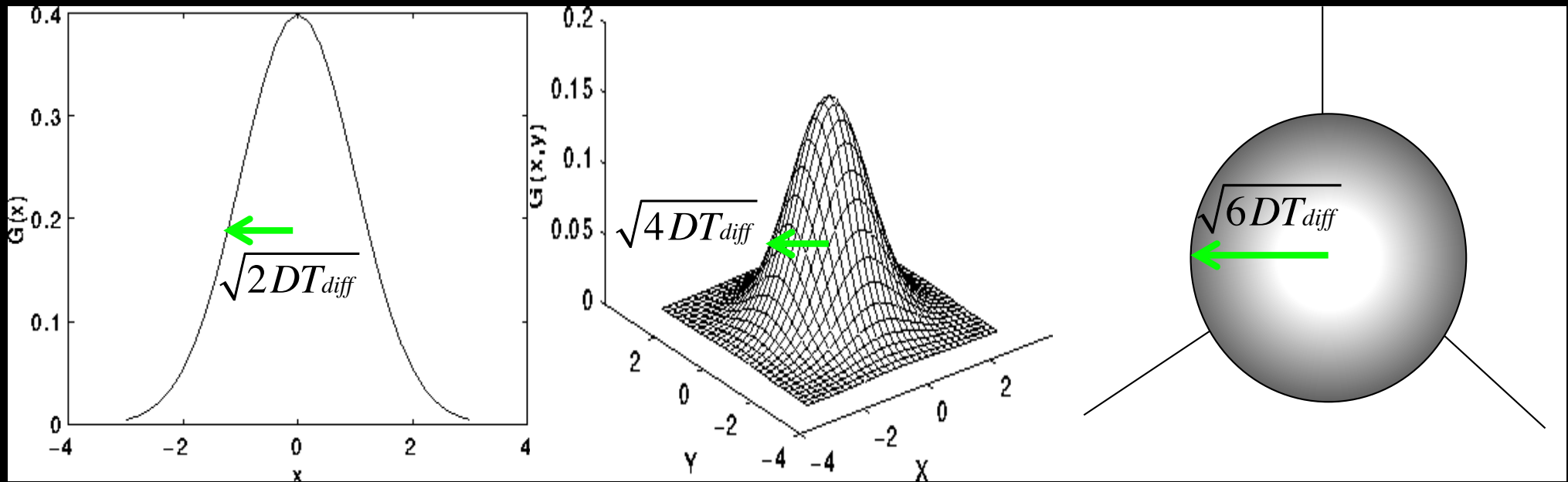


$$D = \frac{kT}{6\pi\eta R_H} \quad (\text{for sphere})$$

Stokes-Einstein

Gaussian Distribution

- A large number of particles that are free to diffuse have a squared displacement of a Gaussian form



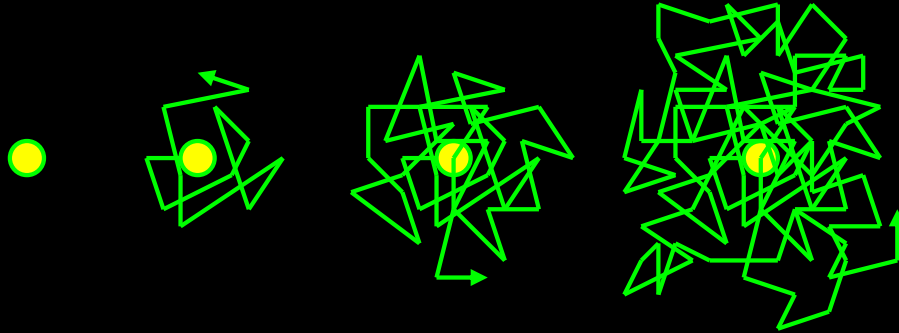
1D

2D

3D

Einstein, A. Ann Physik (1905) 4: 549-590

Diffusion



$$\langle r^2 \rangle \approx 6DT_{dif}$$

For H₂O at 37° C

$$D \approx 3.0 \times 10^{-3} \text{ mm}^2/\text{s}$$

$$T_{dif} \approx 30 \text{ ms}$$

$$r \approx 25 \text{ } \mu\text{m}$$

- If the motion of water is hindered by cell membranes, macromolecules, etc. the displacement will be less and D will appear lower.

Outline

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Image Intensity in MRI

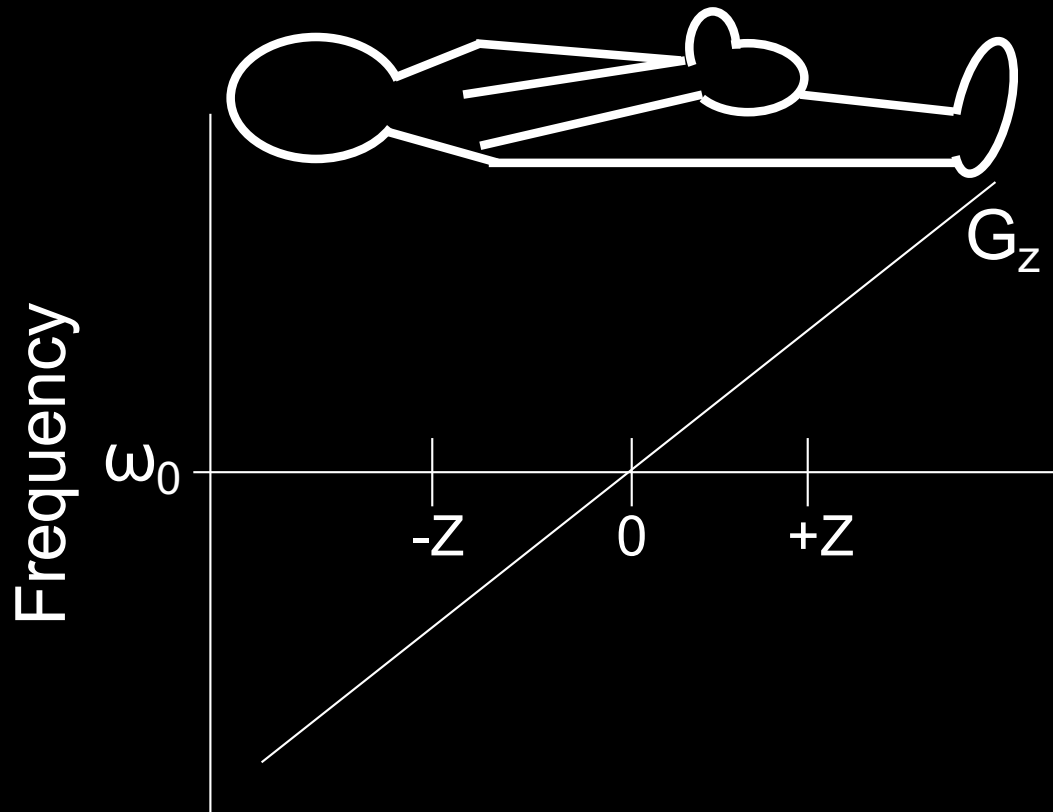
- Physical property of tissue water

– ρ	proton density	}	Concentration of water
– T1	relaxation time		Rotational motion,
– T2	relaxation time		Magnetic field strength
– T2*	relaxation time		
– D	diffusion coefficient		Translational motion

- Experimentally controlled parameters

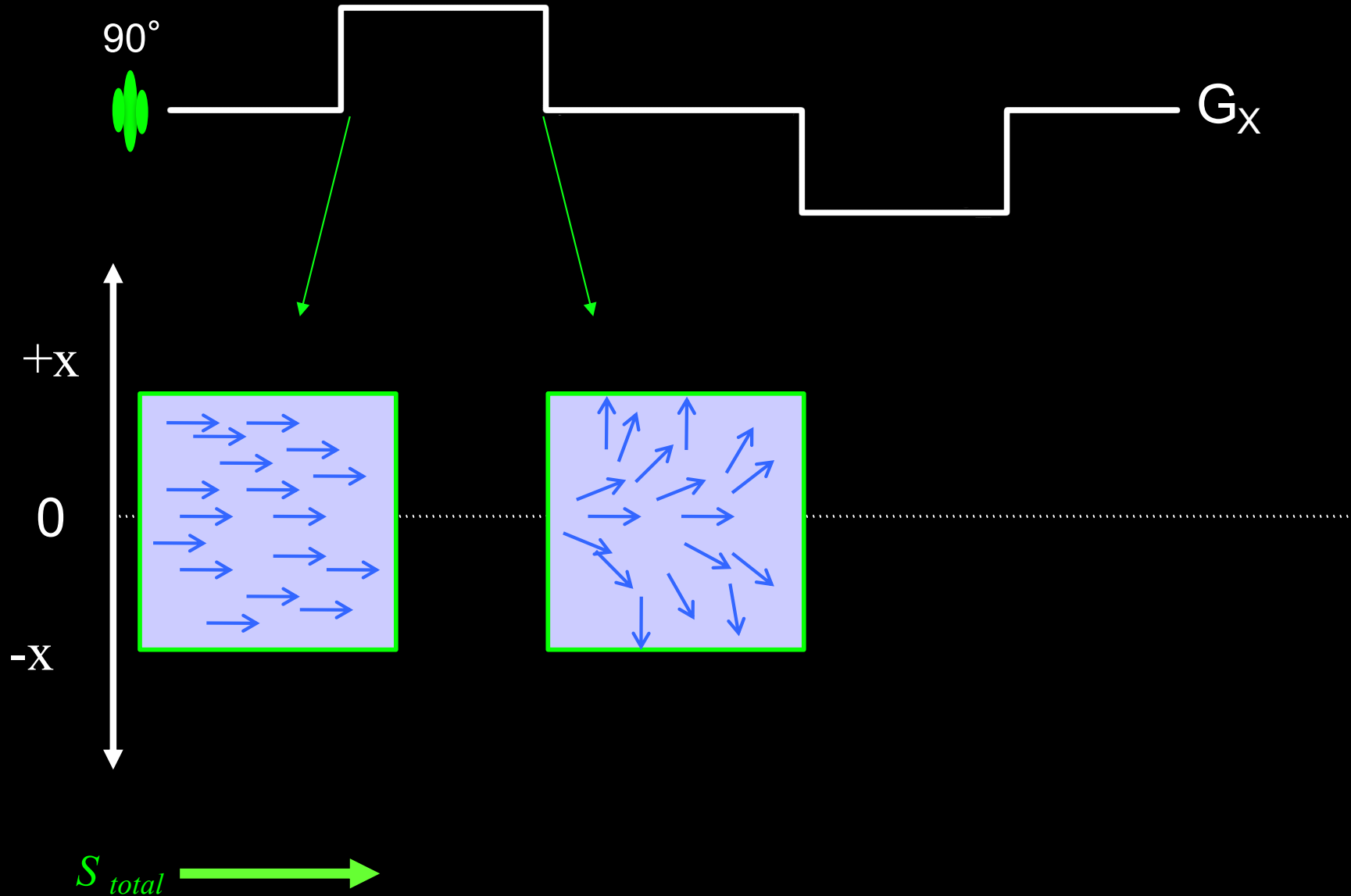
– Sequence	Spin-echo/gradient echo
– TR	Time of Repetition
– TE	Time to echo
– b-value	diffusion-weighting factor

Gradients make the resonance frequency a function of spatial position



$$\omega = \gamma B = \gamma B_0 + \gamma Z G_z$$

Basic Diffusion-weighting

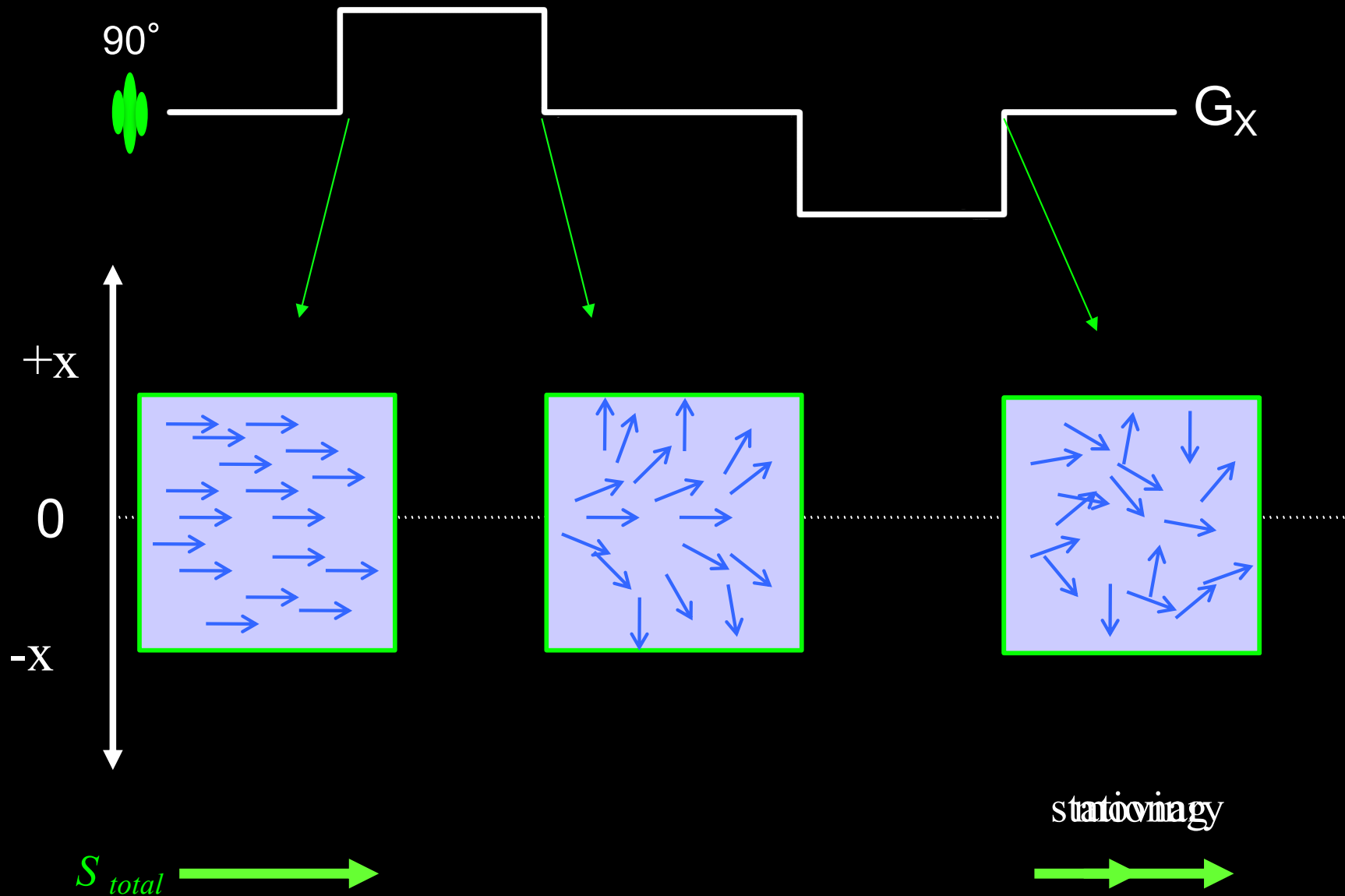


Phase Twist

+Z
0
-Z



Basic Diffusion-weighting

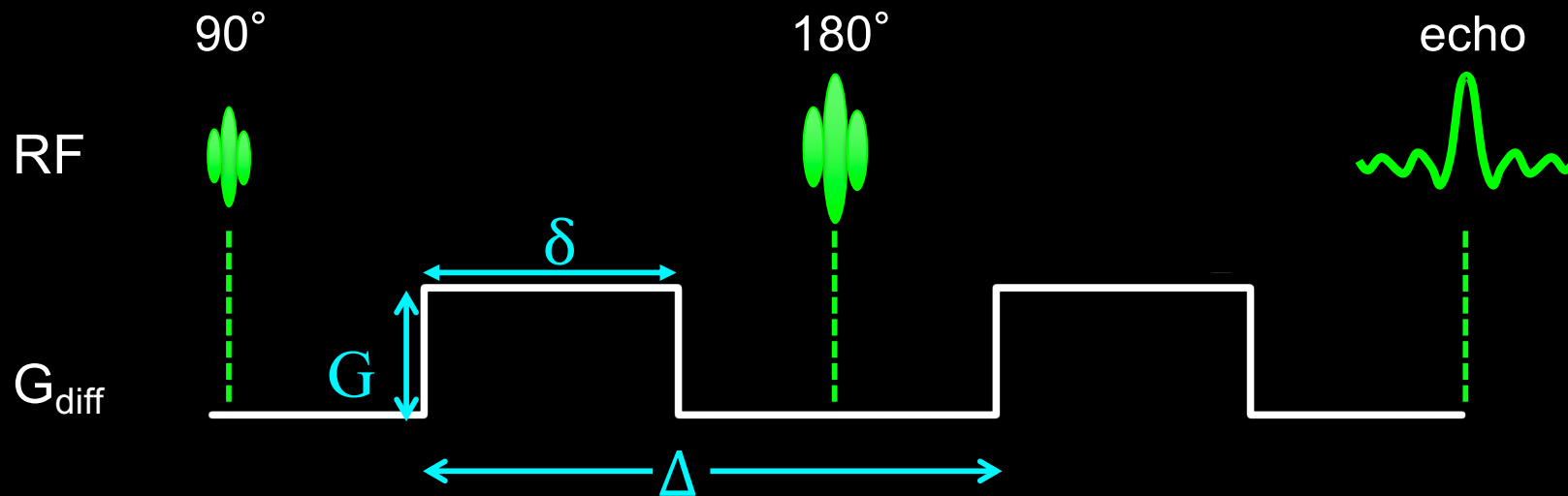


Guess the intensity



No Diffusion weighting

Spin-echo Diffusion Preparation



$$b = (\gamma G \delta)^2 \left(\Delta - \frac{\delta}{3} \right)$$

DWI

$$S = S_0 e^{-bD}$$

Non-diffusion-weighted
signal intensity

B-value
sec/mm²

Diffusion
Coefficient
mm²/sec

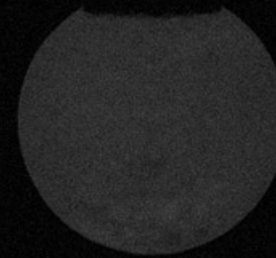
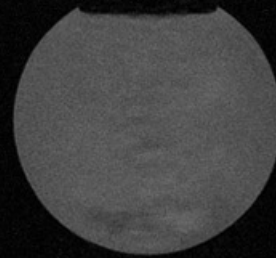
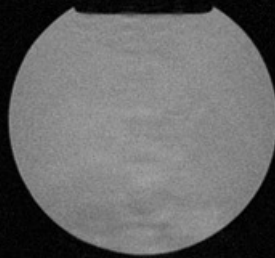
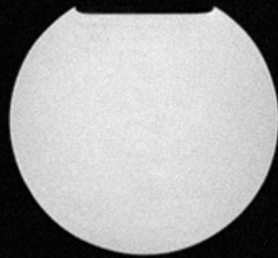
Typical DWI

- Single-shot “spin-echo” Echo Planar Imaging

Parameter	Value	Comment
TE	50-100ms	Limited by b-value
TR	>5s	Fully relaxed
Matrix	96 x 96	2.5 x 2.5 mm
Slice Thickness	2.5 mm	Equal dimensions
B-value	~1000 s/mm ²	For brain*

*Jones D., *et al.* Mag Res Med (1999) 42 : 515

Calculate Diffusion Parameters



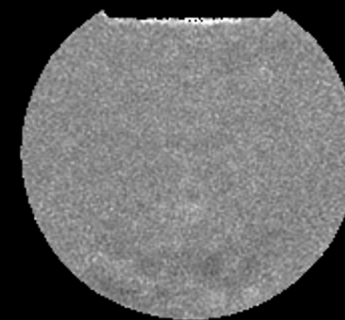
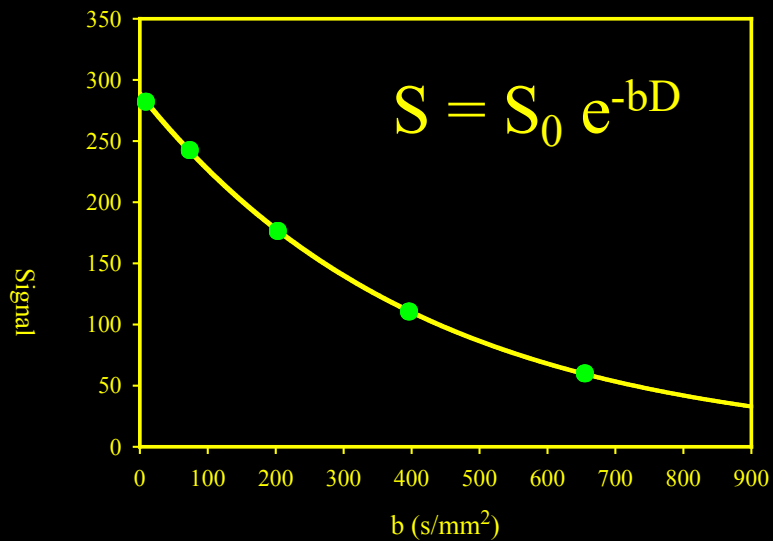
b (s/mm²)

8

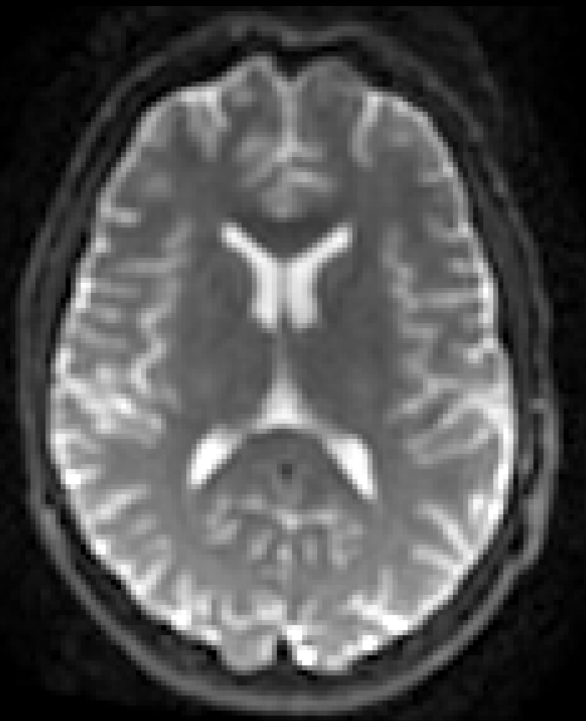
200

400

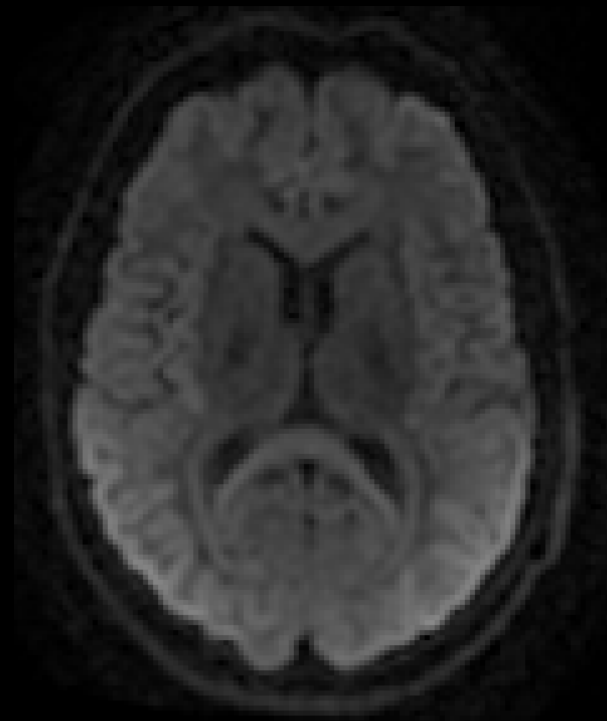
650



Diffusion map

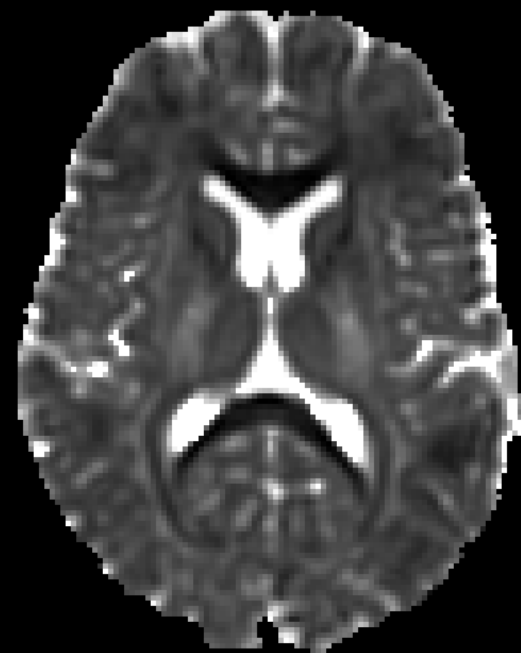


$b = 0 \text{ s/mm}^2$
 I_0



$b = 1100 \text{ s/mm}^2$
 I_z

$$I_z = I_0 e^{-bD_z}$$



D_z

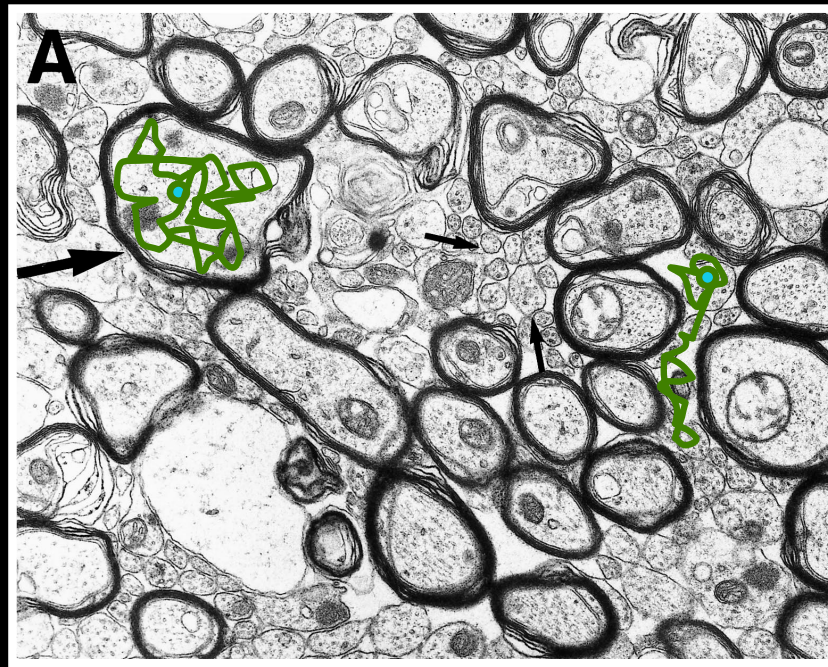
$$D_z = \frac{1}{-b} \ln \left(\frac{I_z}{I_0} \right)$$

Water Diffusion in Tissue

Not Free

Cell membranes
Myelin
Organelles
Extracellular matrix

EM of mouse corpus callosum



Anisotropy

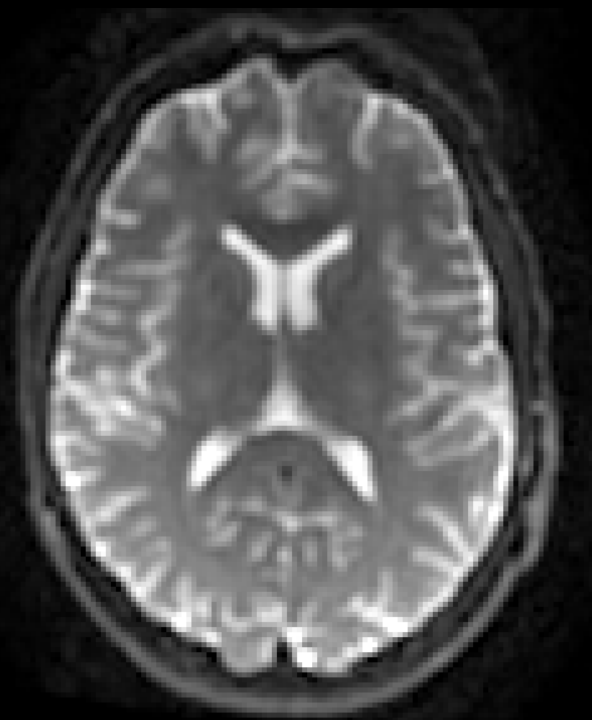
$D_{\text{perpendicular}}$



D_{parallel}

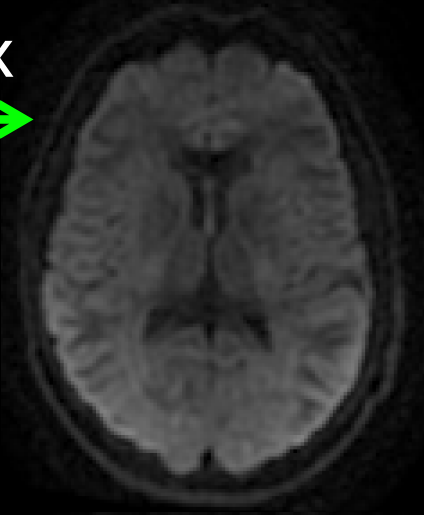


$D_{\text{perp}} \ll D_{\text{par}}$

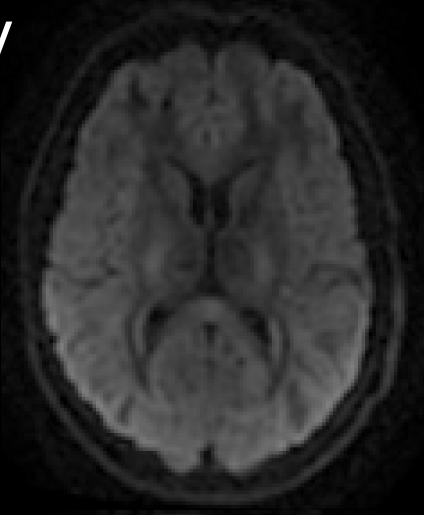


$b = 0 \text{ s/mm}^2$

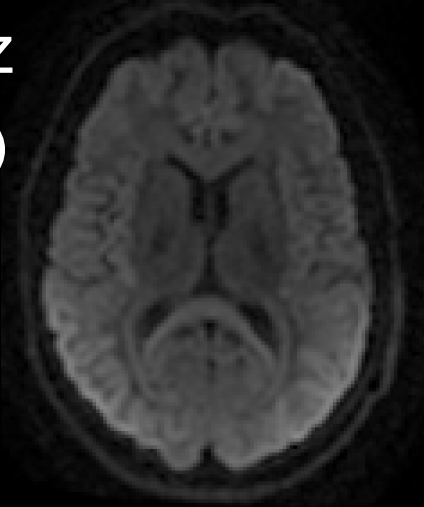
Gx

Gy

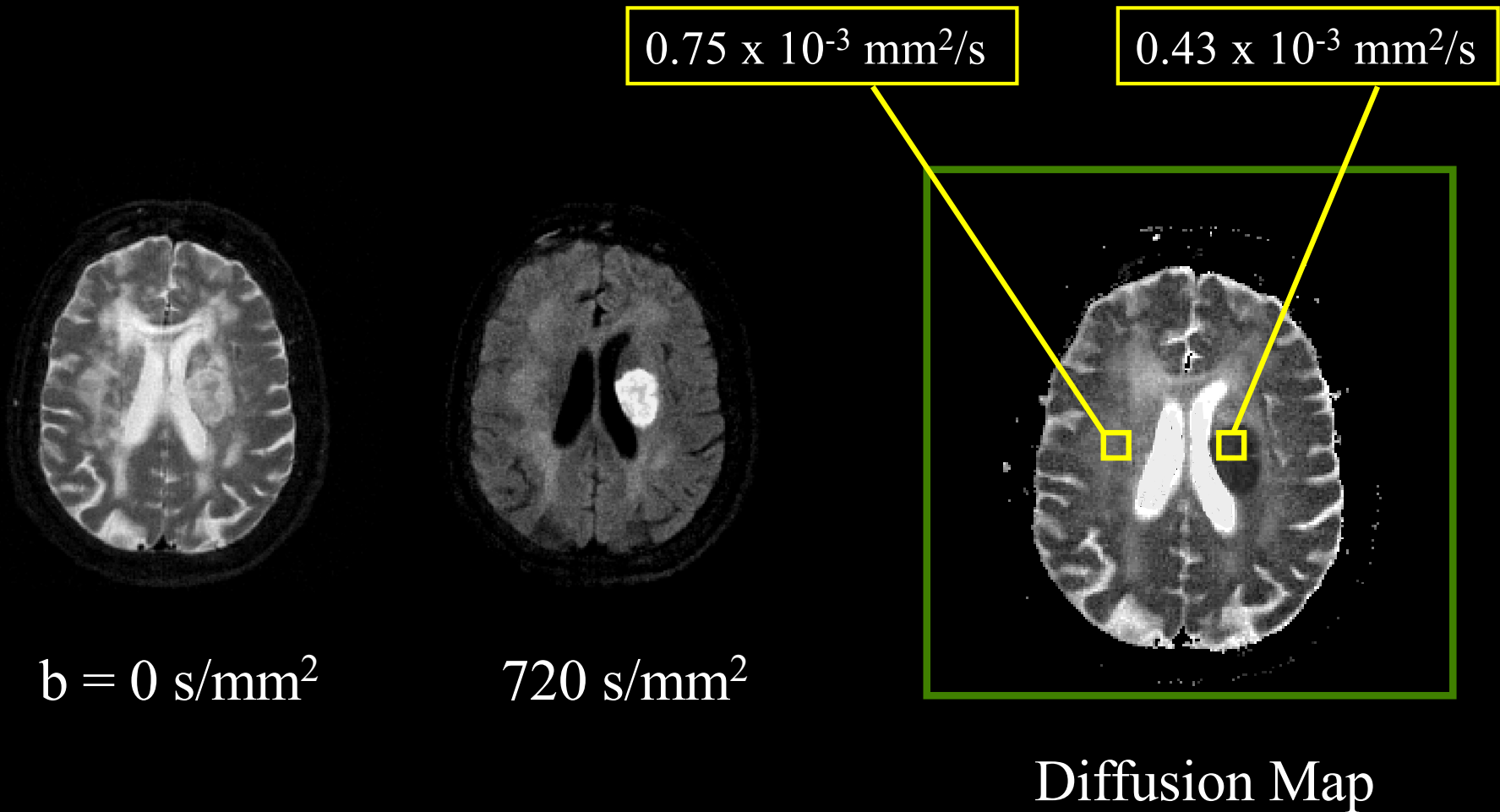
Gz

ADC

$$ADC = \frac{1}{-b} \ln \left(\frac{I_{ave}}{I_0} \right)$$

Acute Stroke



Outline

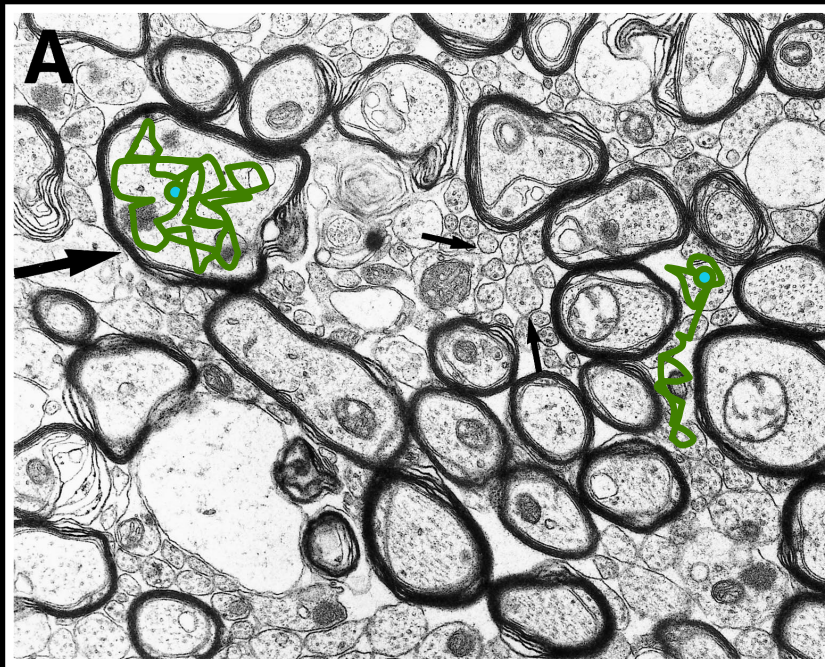
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Water Diffusion in Tissue

Not Free

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EM of mouse corpus callosum



Anisotropy

$D_{\text{perpendicular}}$

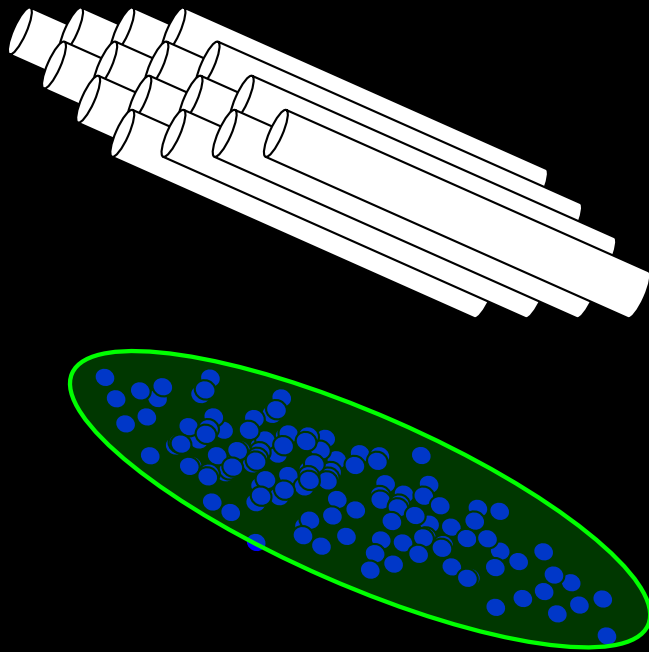


D_{parallel}

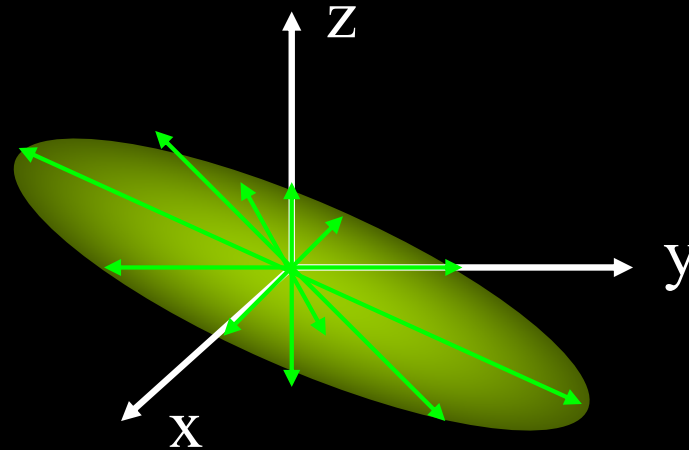


$D_{\text{perp}} \ll D_{\text{par}}$

Anisotropic Diffusion



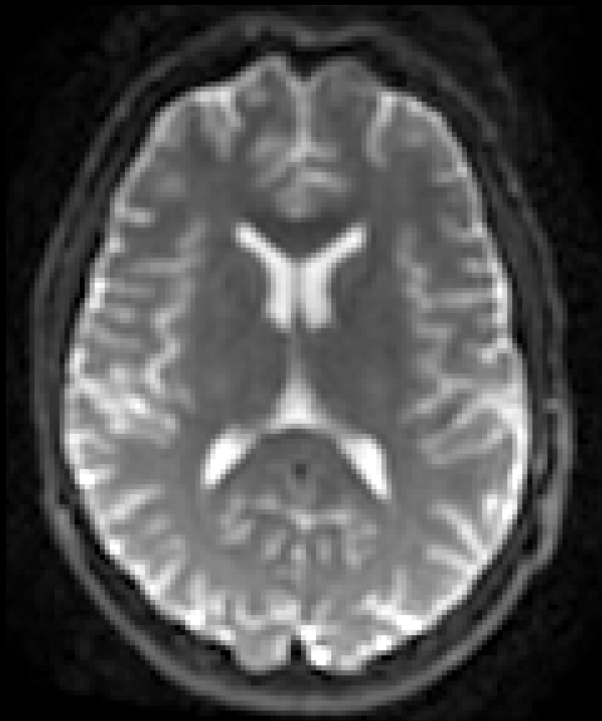
The Diffusion Tensor



$$\underline{\underline{D}} = \begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{zx} & D_{zy} & D_{zz} \end{bmatrix}$$

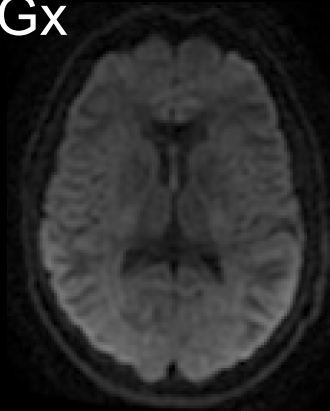
Basser, P, *et. al.* J Magn Reson B (1994) 3 : 247-254

DTI

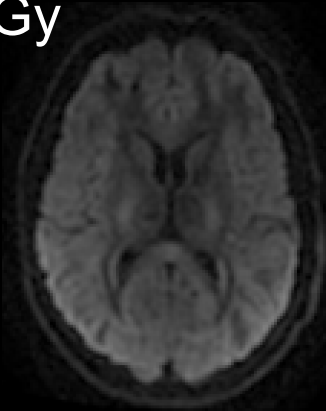


$b = 0 \text{ s/mm}^2$

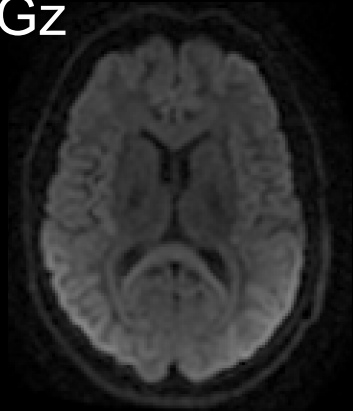
Gx



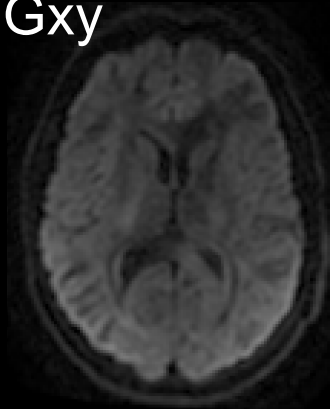
Gy



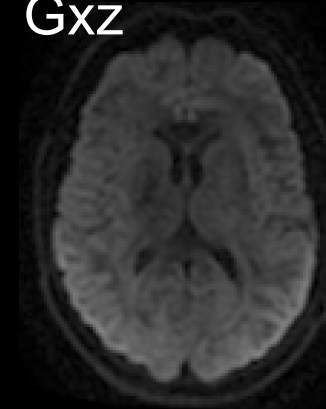
Gz



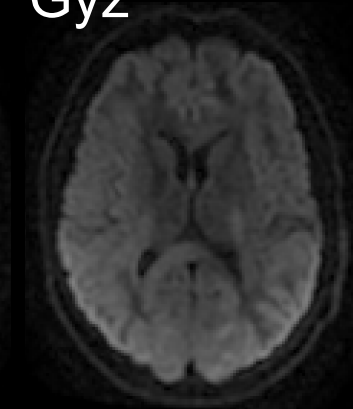
Gxy



Gxz

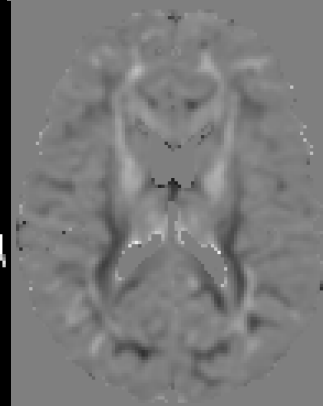
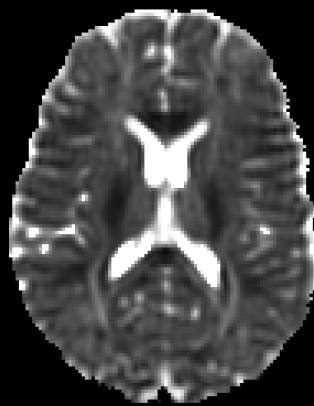
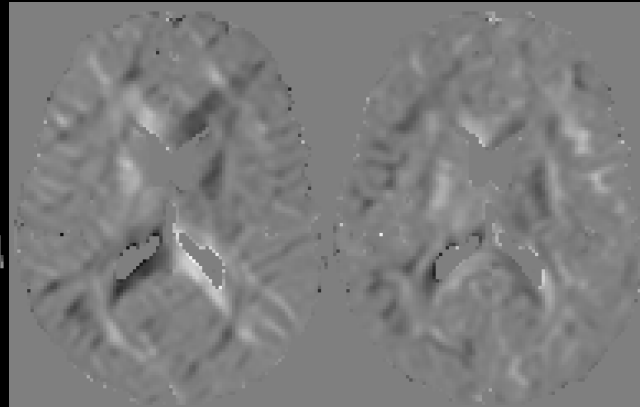
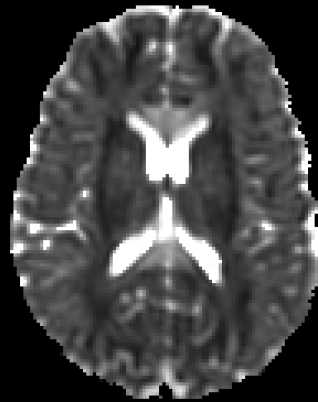


Gyz

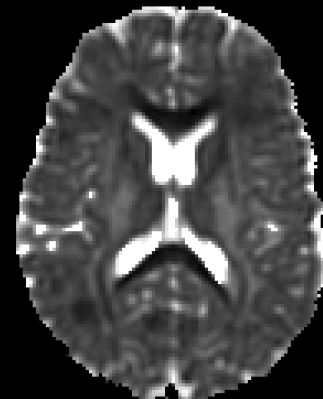


$b = 1100 \text{ s/mm}^2$

Calculate Diffusion Tensor



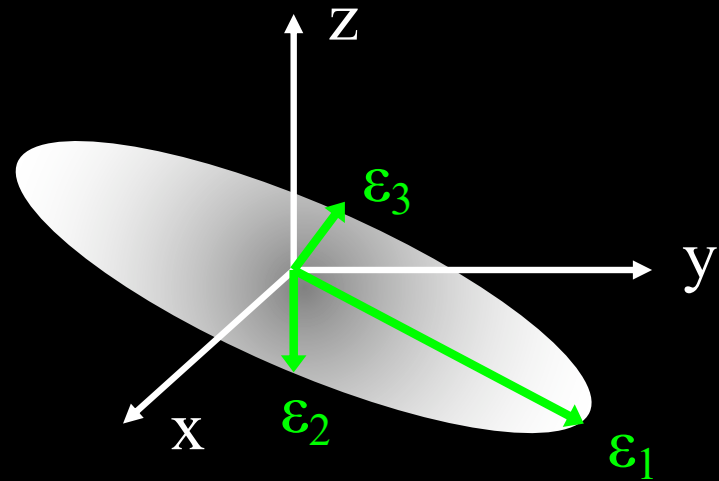
$$\underline{D} = \begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{zx} & D_{zy} & D_{zz} \end{bmatrix}$$



Diagonalize DT

$$\underline{D} = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix}$$

Eigenvalues



Eigenvectors

Quantitative Parameters

$$\underline{D} = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix}$$

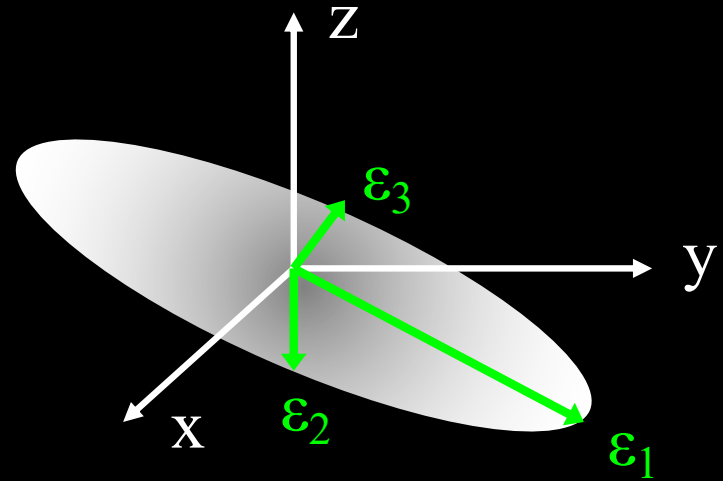
Average Diffusivity

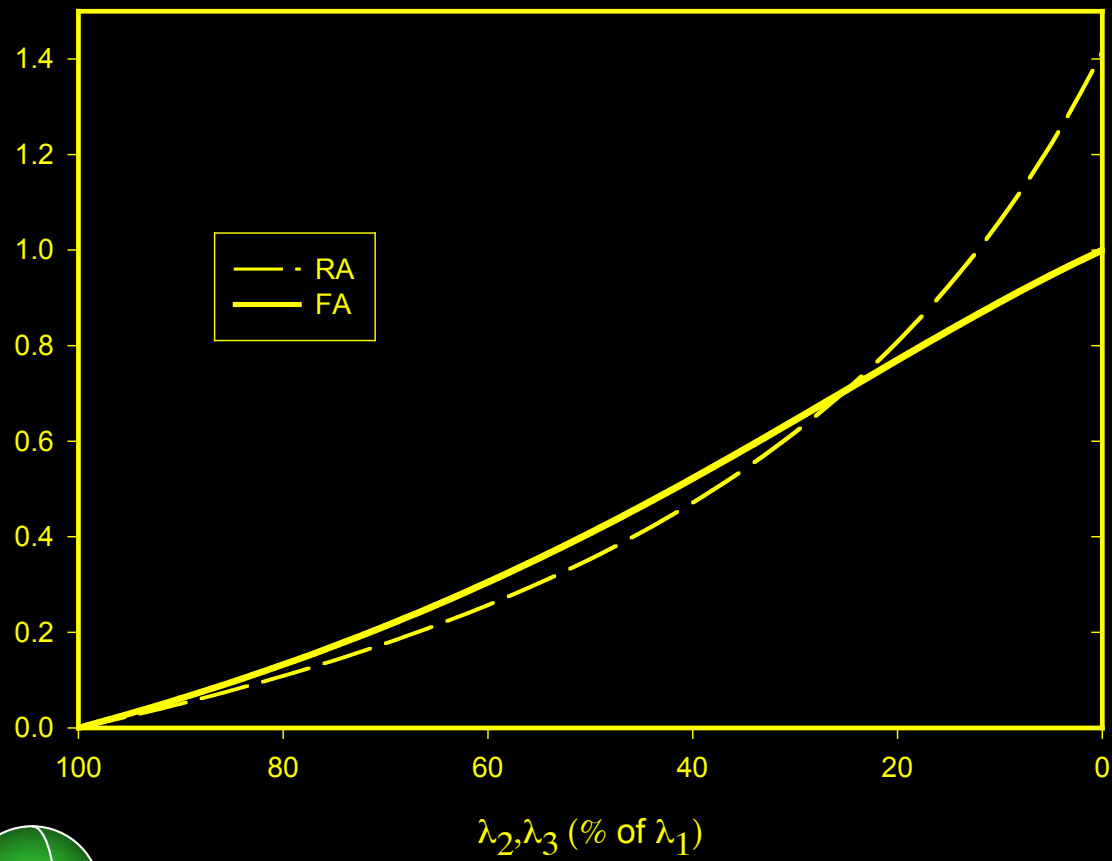
$$\langle D \rangle = \frac{\lambda_1 + \lambda_2 + \lambda_3}{3}$$

Fractional Anisotropy

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

$$0 \leq FA \leq 1$$





isotropic



anisotropic

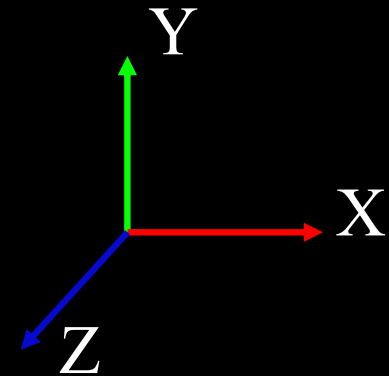
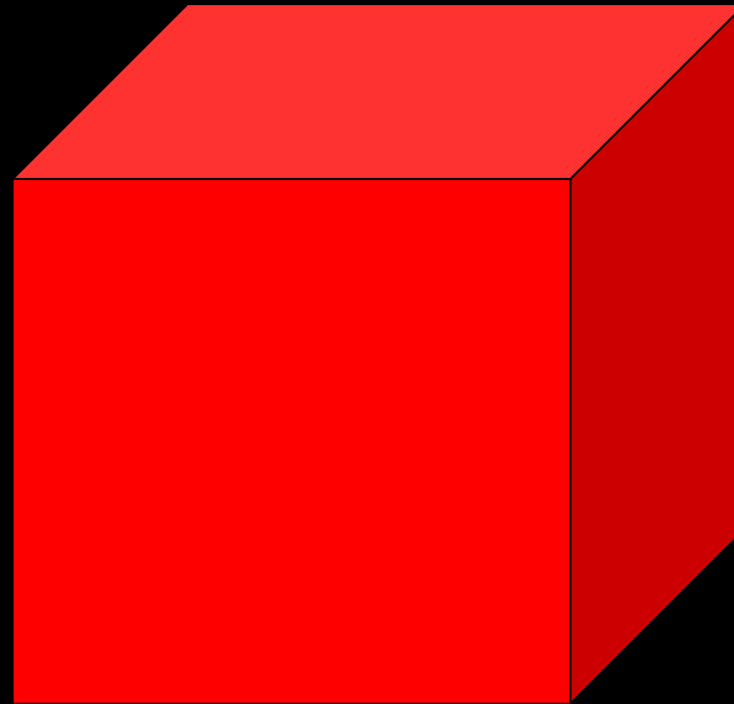
<D>



FA



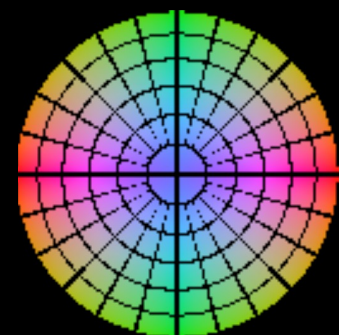
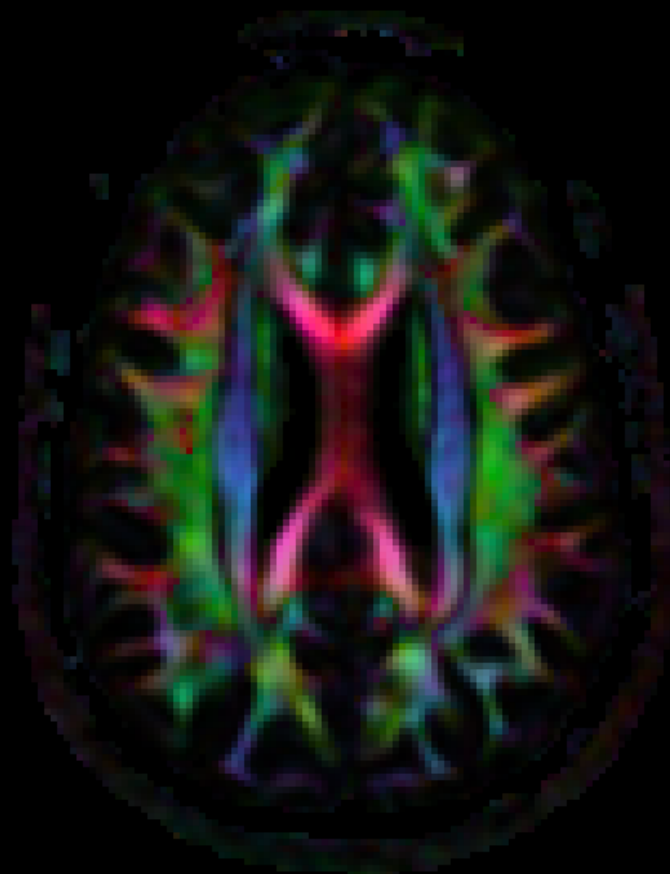
Directional Encoding for DTI



$$\underline{D} = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix}$$

<D>

Directional Encoded Color Map

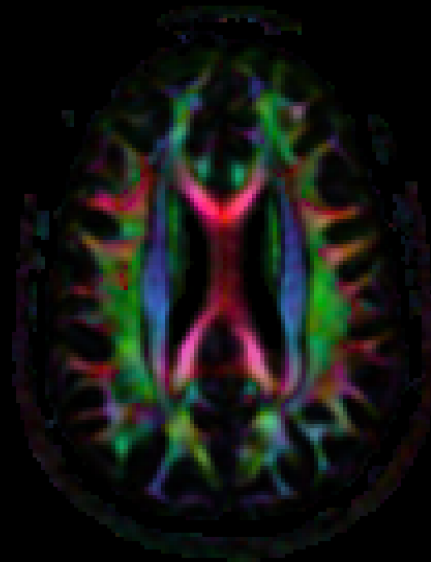




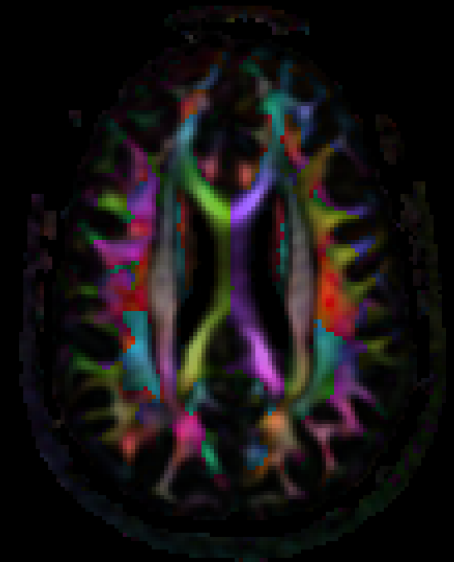
$\langle D \rangle$



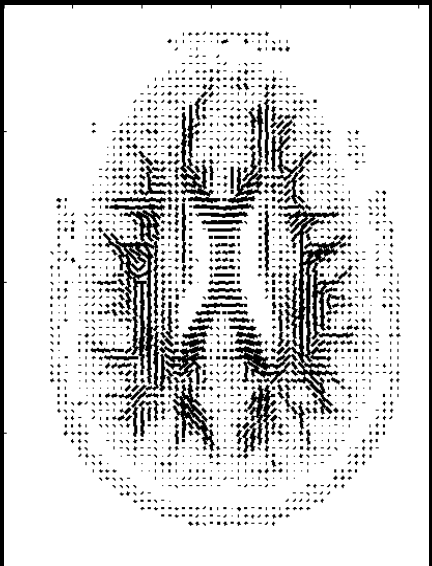
FA



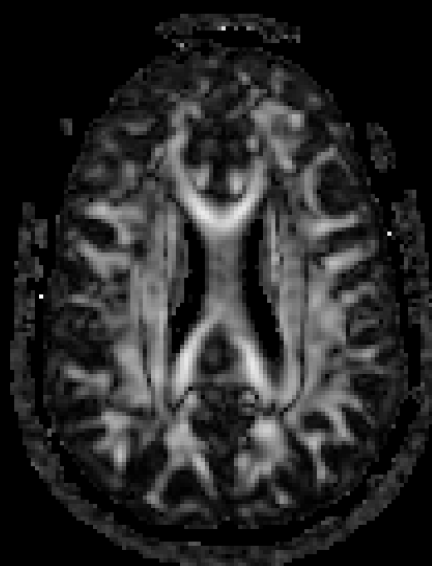
DEC



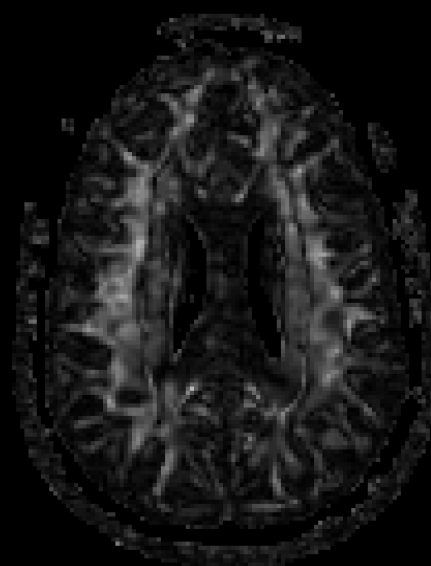
No sym DEC



Line Field



Linear



Planar



Spherical

Applications of DTI

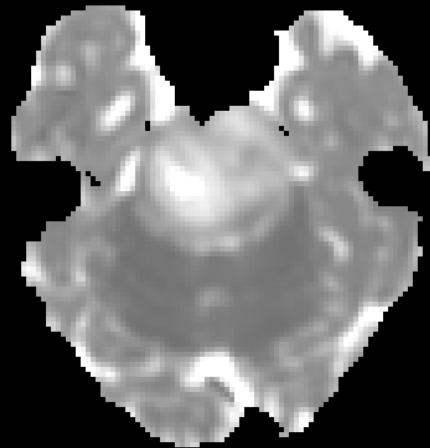
- Cerebral Ischemia (Stroke)
- Brain Cancer and Effects of Radiotherapy
- Multiple Sclerosis
- Epilepsy
- Metabolic Disorders
- Normal Brain Maturation and Aging
- Traumatic Brain Injury
- Alzheimer's Disease
- Amyotrophic Lateral Sclerosis
- Niemann-Pick type C Disease
- Dementias
- Connectivity

Pediatric DIPG

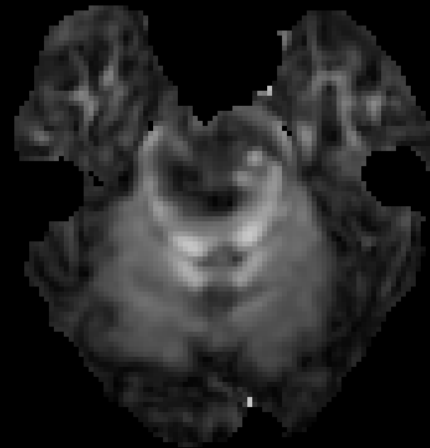
T2-weighted



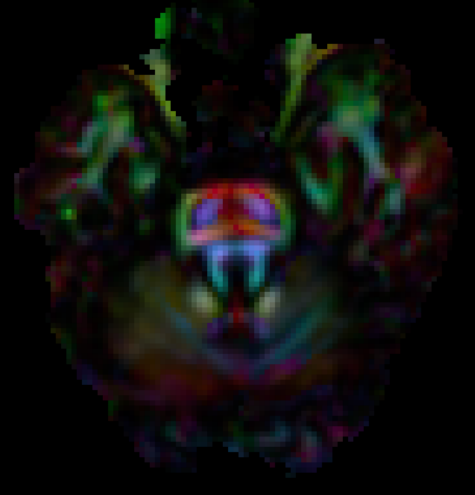
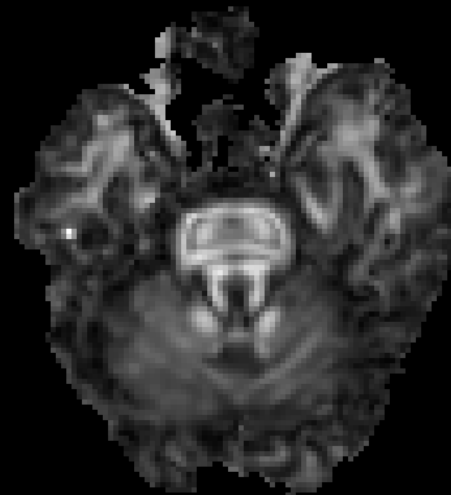
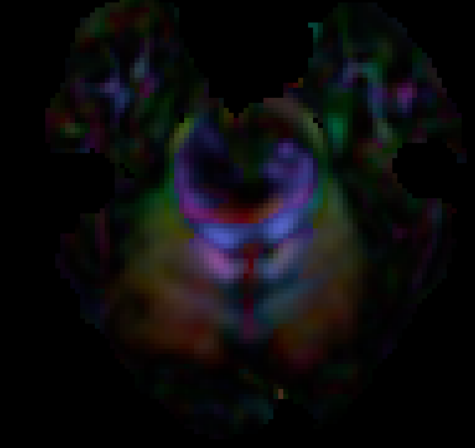
MD



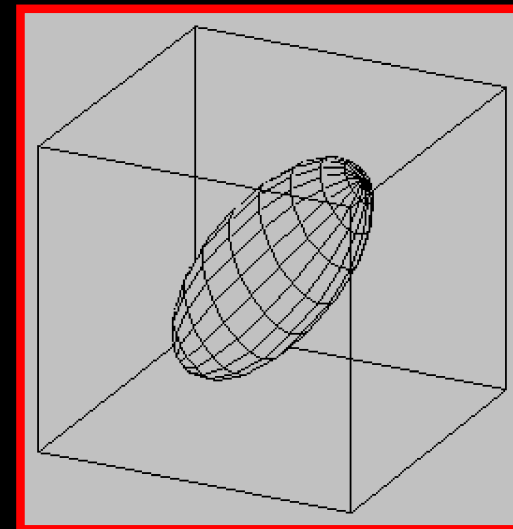
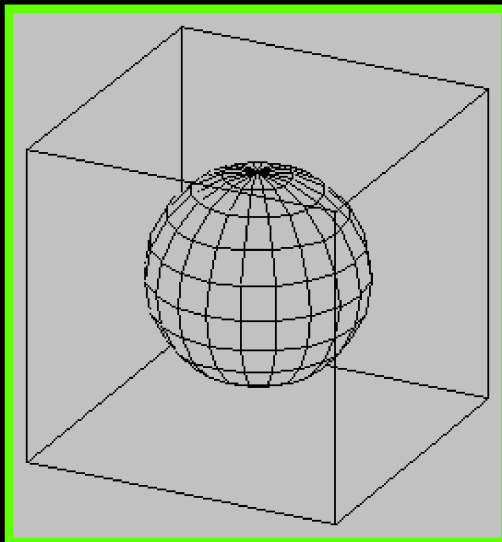
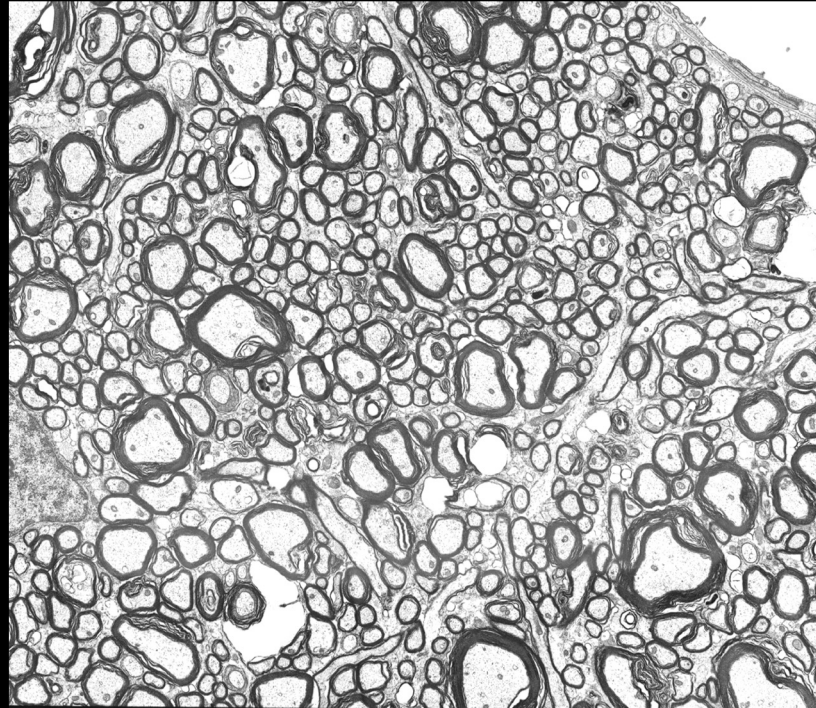
FA



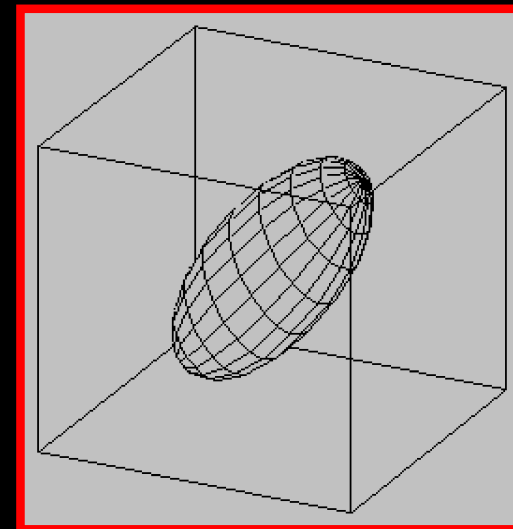
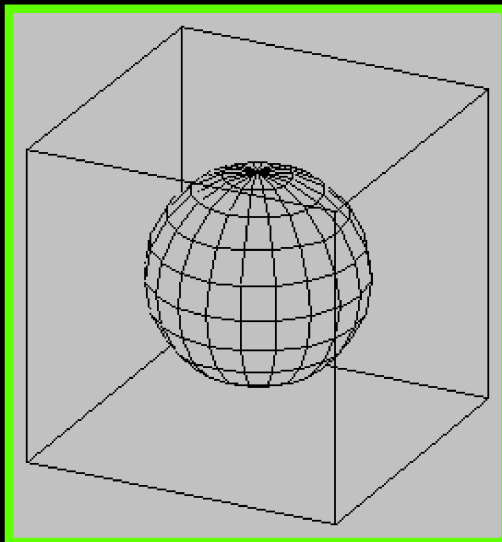
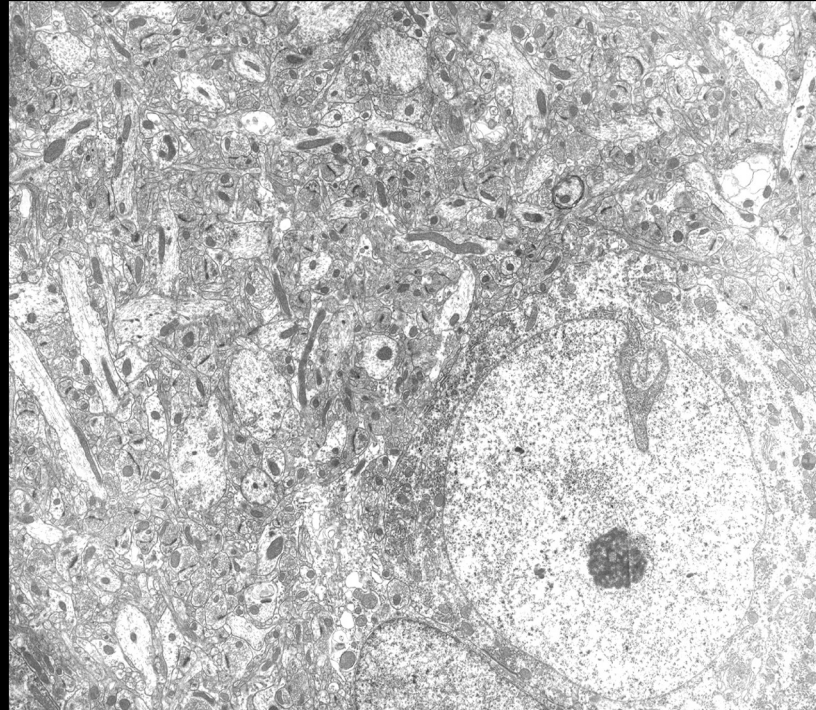
DEC



Guess the ellipsoid



Guess the ellipsoid



Outline

- What is diffusion?
- How do we measure diffusion in MRI?
- How do we extract directional information?
- **What are the practical problems and limitations?**
- Beyond the diffusion tensor

Typical DW SSEPI

PRO

Time Efficient

Insensitive to
Bulk motion



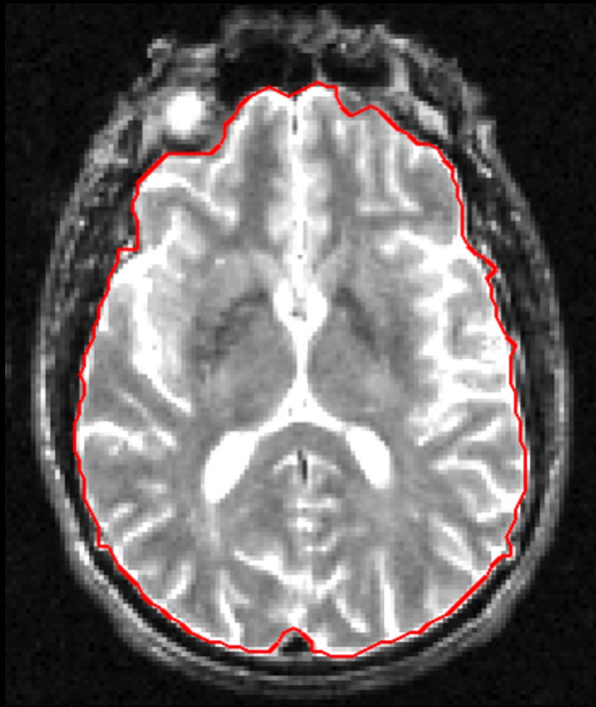
CON

Low Resolution

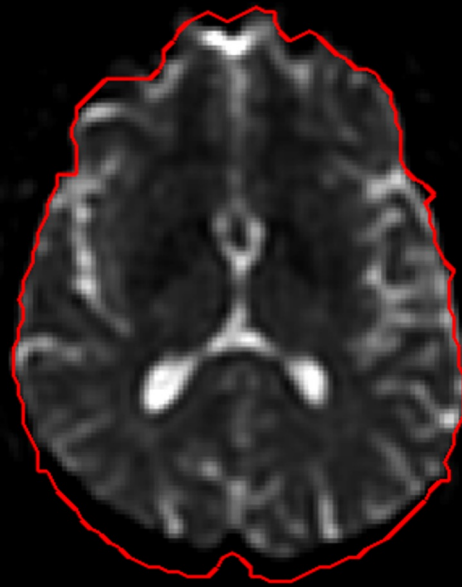
Distortions - Field
inhomogeneities

Distortions -
Diffusion weighting

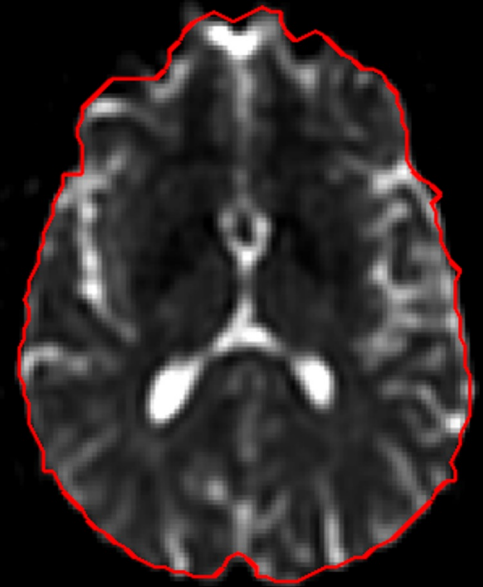
CON: Distortions from field inhomogeneities



T2-weighted
FSE

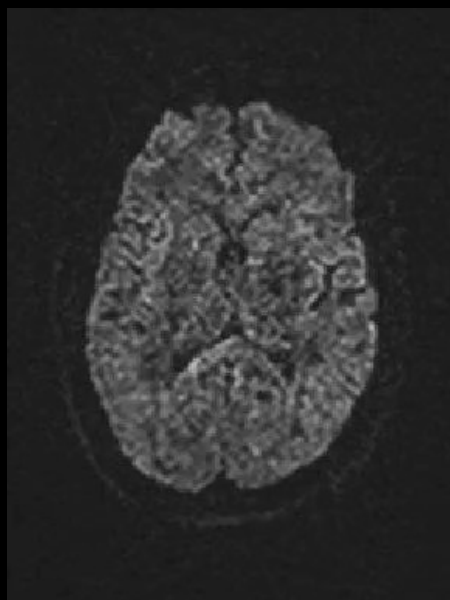


Non-diffusion-weighted
SSEPI

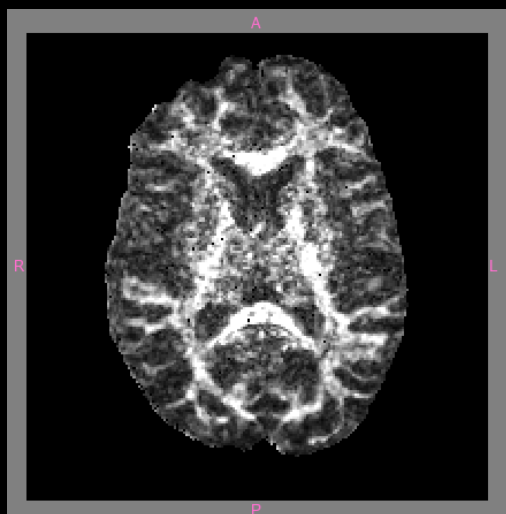
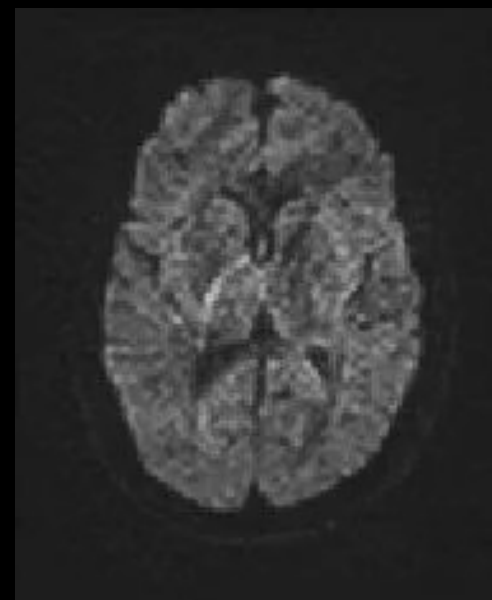


SSEPI
corrected

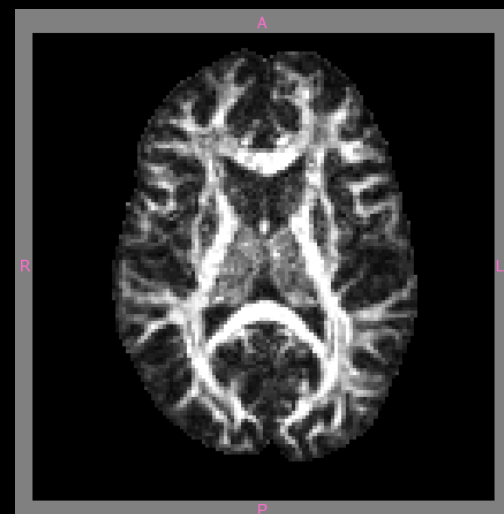
CON: Distortions from DW



DW
SSEPI
volumes



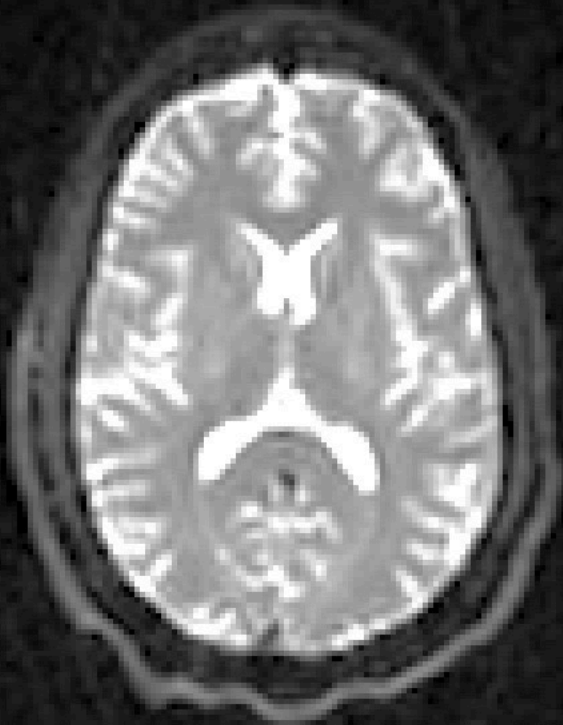
FA maps



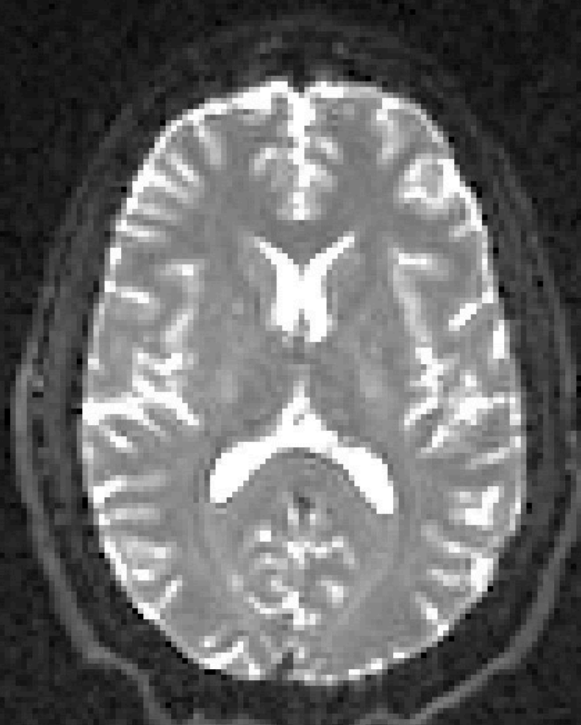
Other Common Problems in DTI

- Low SNR
- Incomplete Fat Suppression
- Bulk movement
- Cardiac pulsation

Low SNR



2.5 mm iso

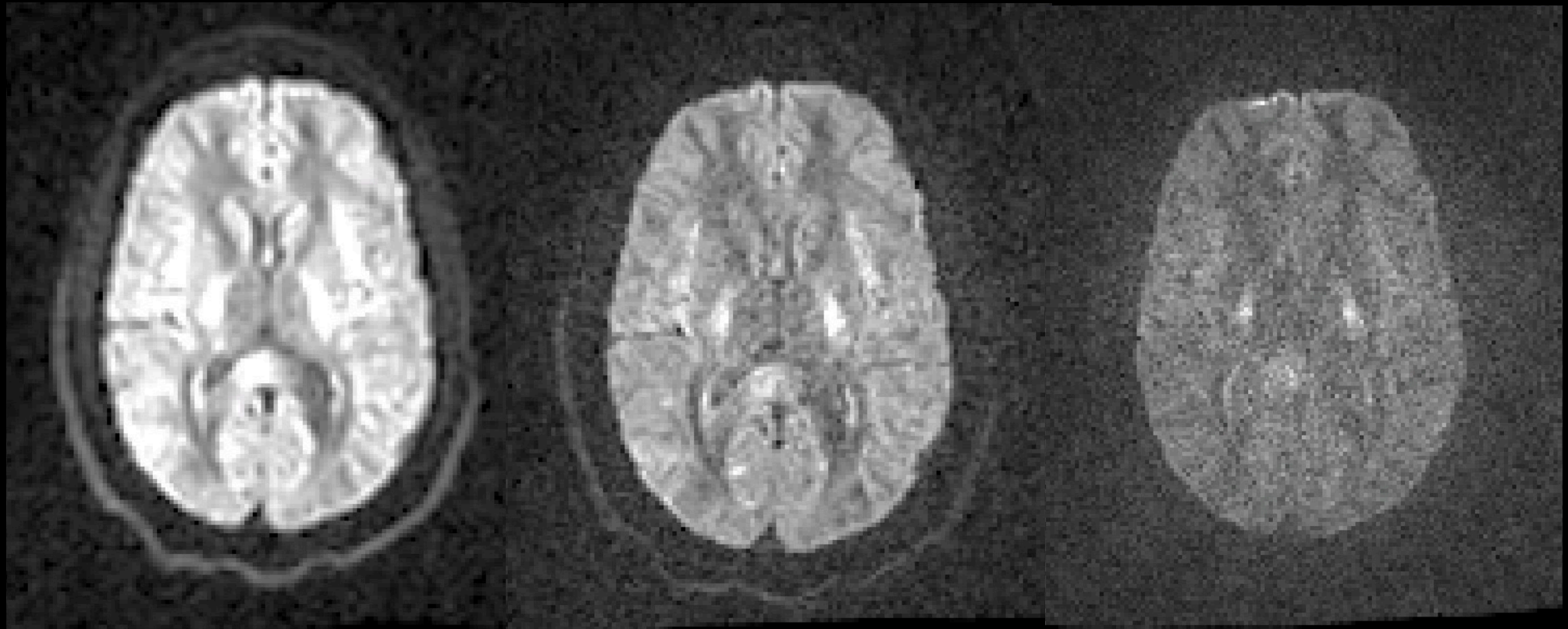


1.7mm iso



1.3mm iso

Low SNR

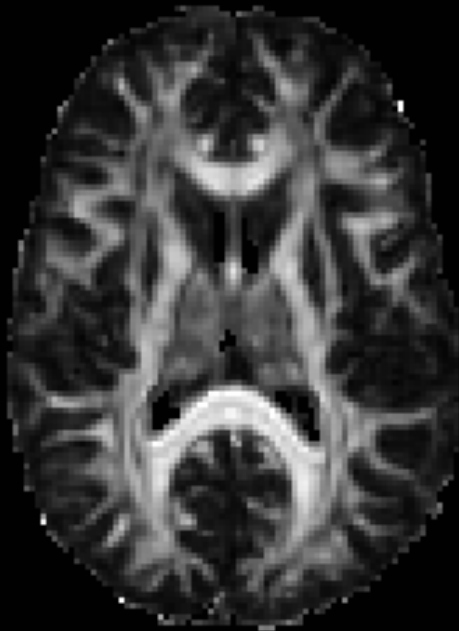


2.5 mm iso
15.625 mm³

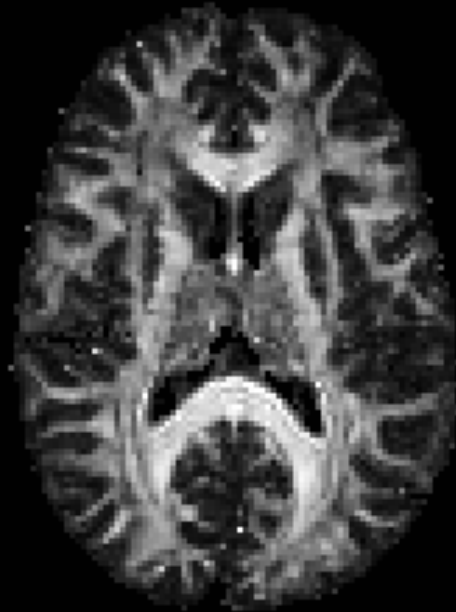
1.7mm iso
4.913 mm³

1.3mm iso
2.197 mm³

Low SNR



2.5 mm iso
15.625 mm³

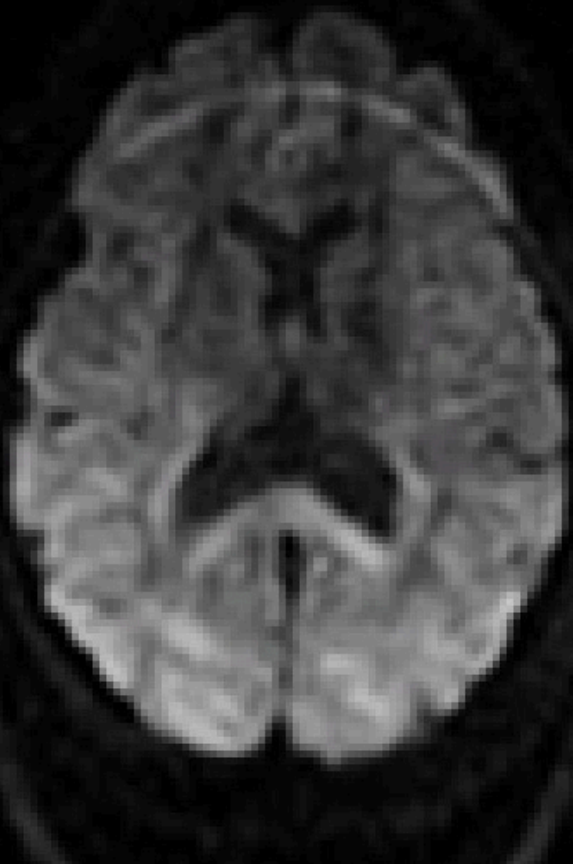


1.7mm iso
4.913 mm³

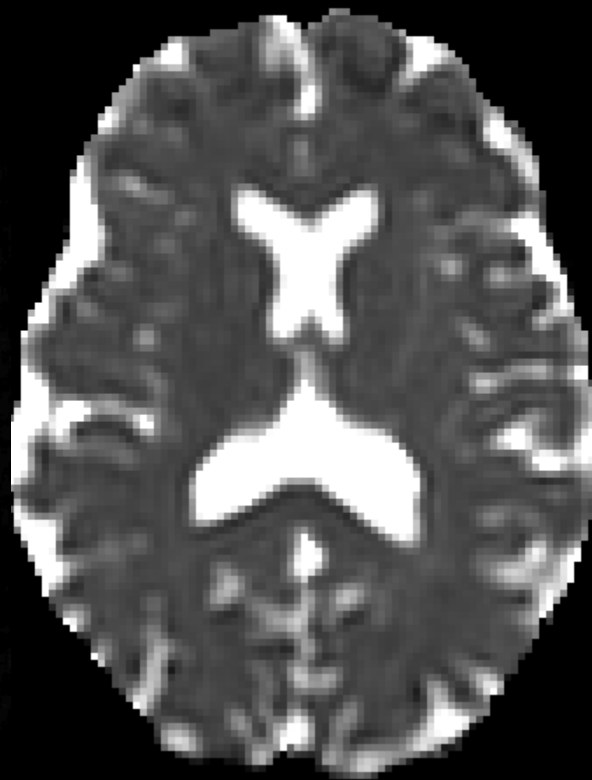


1.3mm iso
2.197 mm³

Incomplete Fat Suppression



$b=1100 \text{ s/mm}^2$

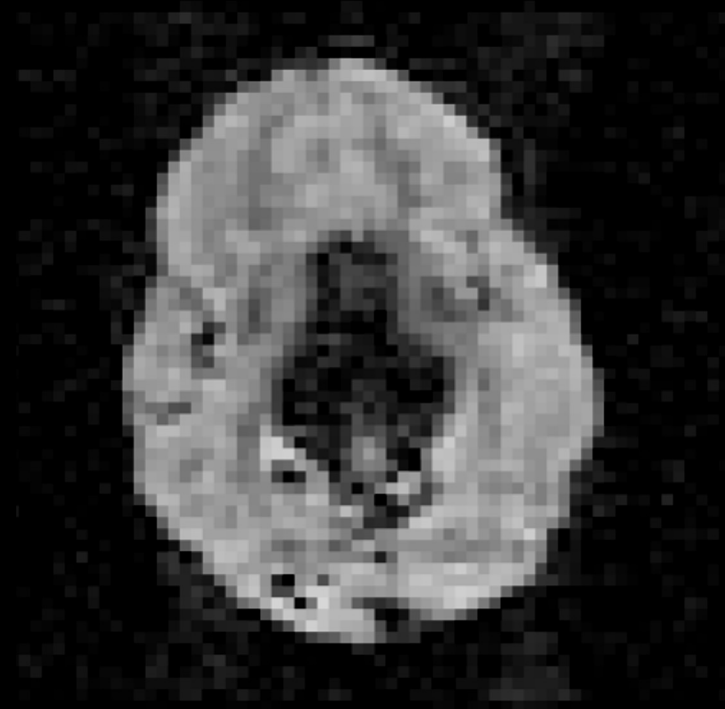


MD



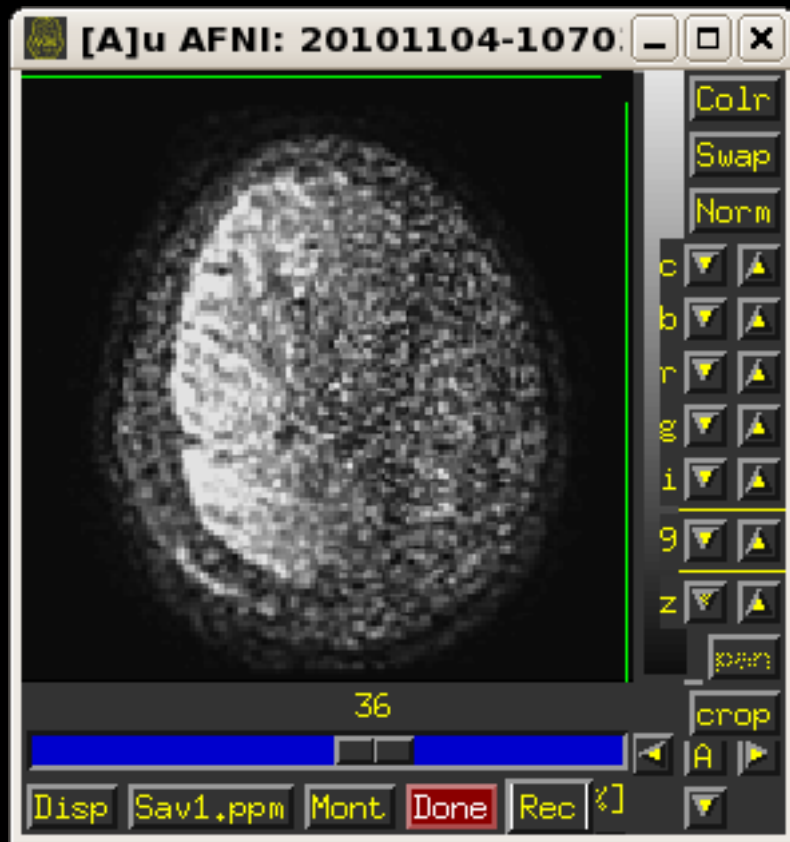
FA

Cardiac Pulsation



Diffusion weighting in Z

Bulk Movement

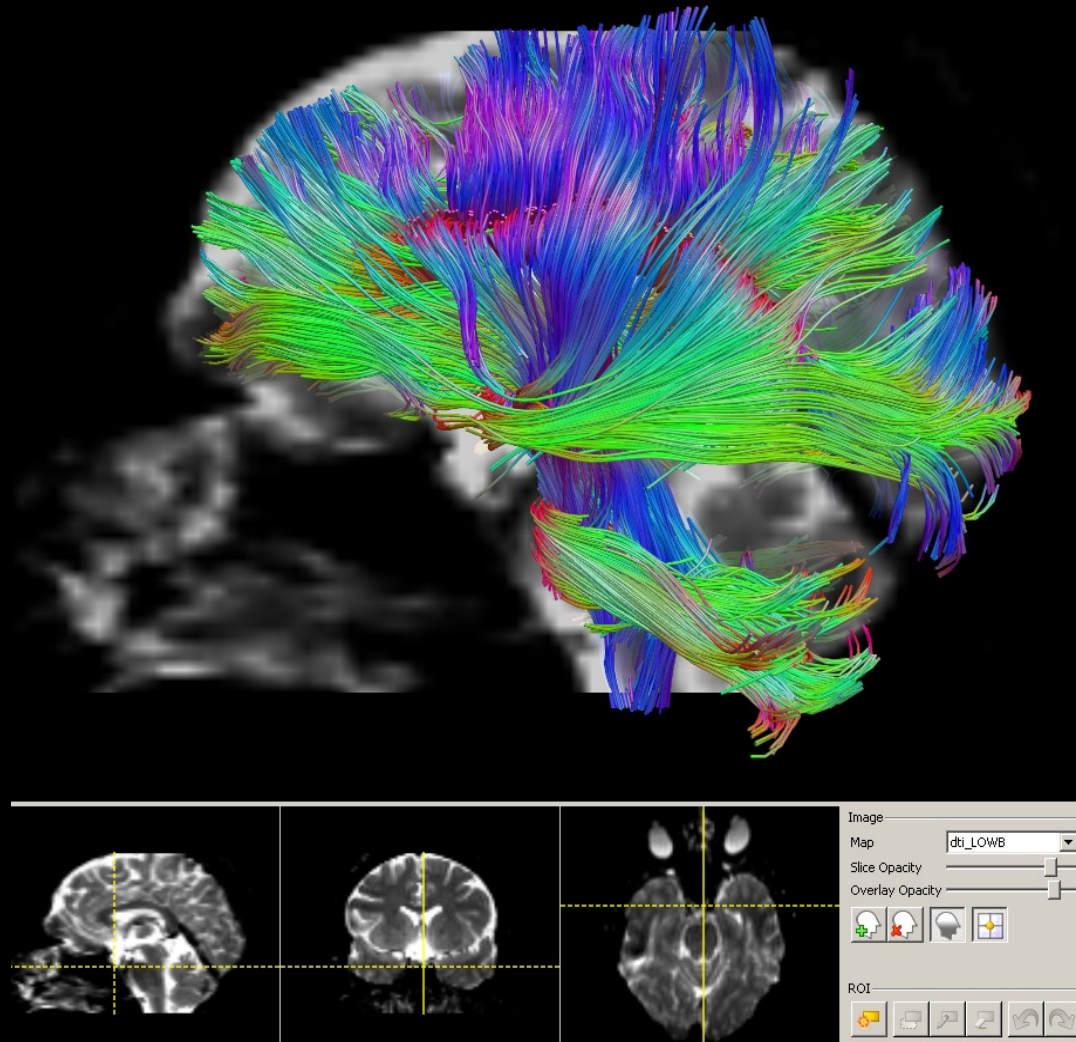


Outline

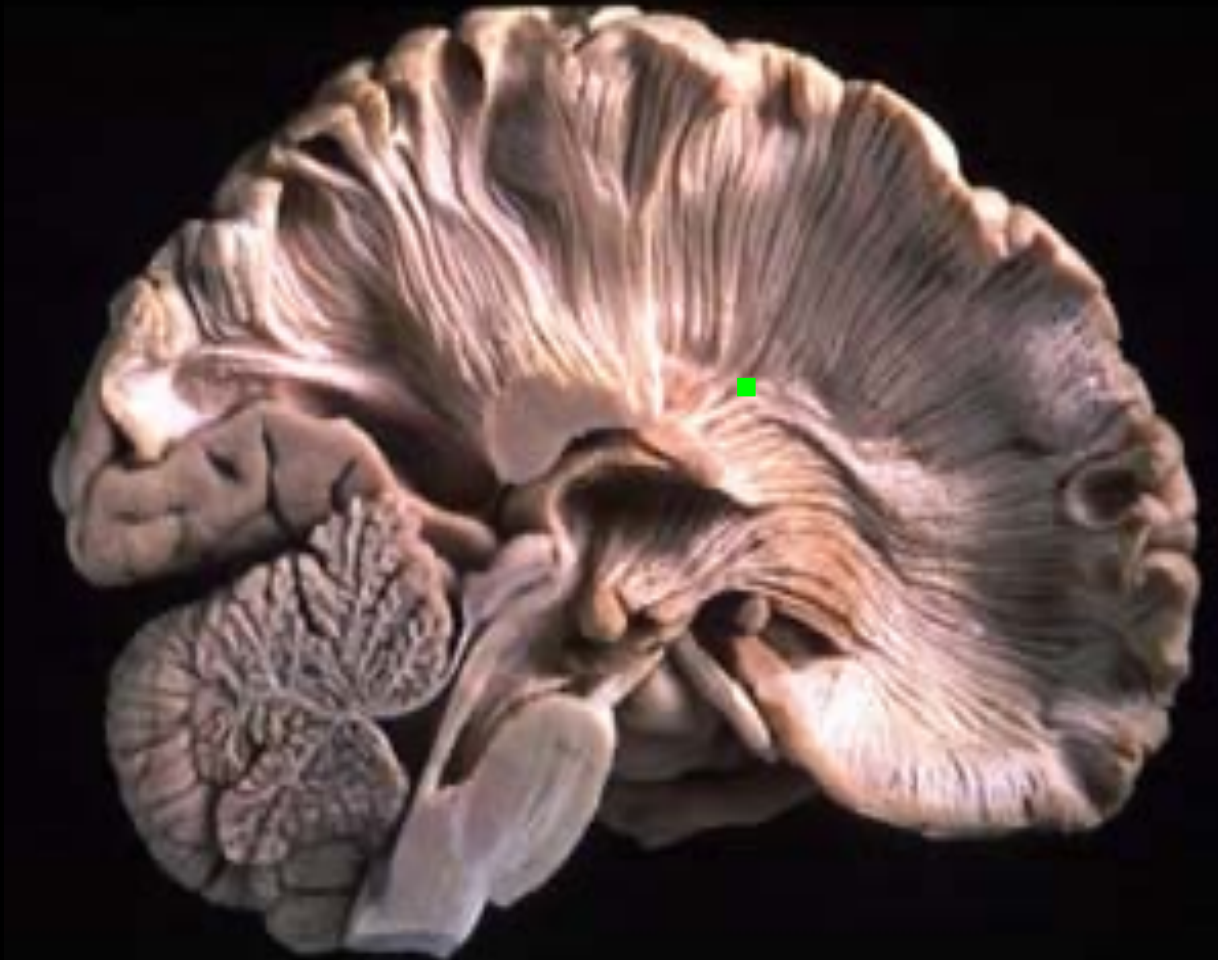
- What is diffusion?
- How do we measure diffusion in MRI?
- How do we extract directional information?
- What are the practical problems and limitations?
- **Beyond the diffusion tensor**

What is Tractography?

The use of orientation information from diffusion imaging to reconstruct estimates of white matter pathways in the brain.



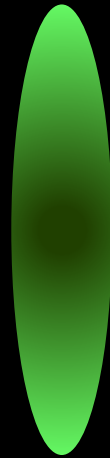
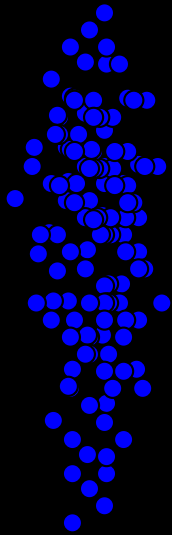
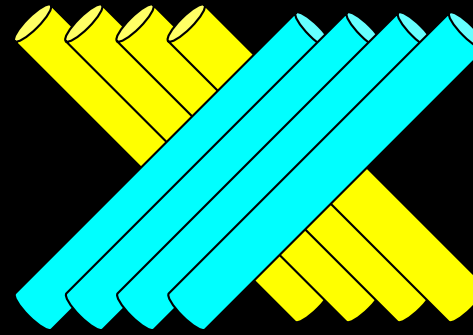
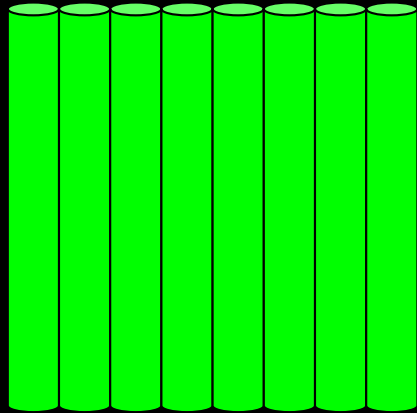
Limitation to DTI comes from partial volume effects



Typical resolution
for SSEPI DTI
2.5 x 2.5 x 2.5 mm

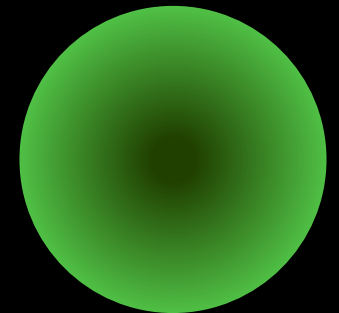
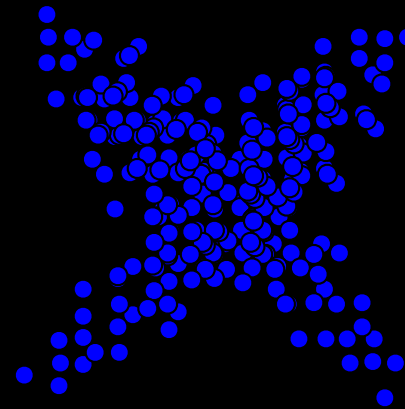
Cortical projection systems of left cerebral hemisphere

Partial Volume Effect



distribution

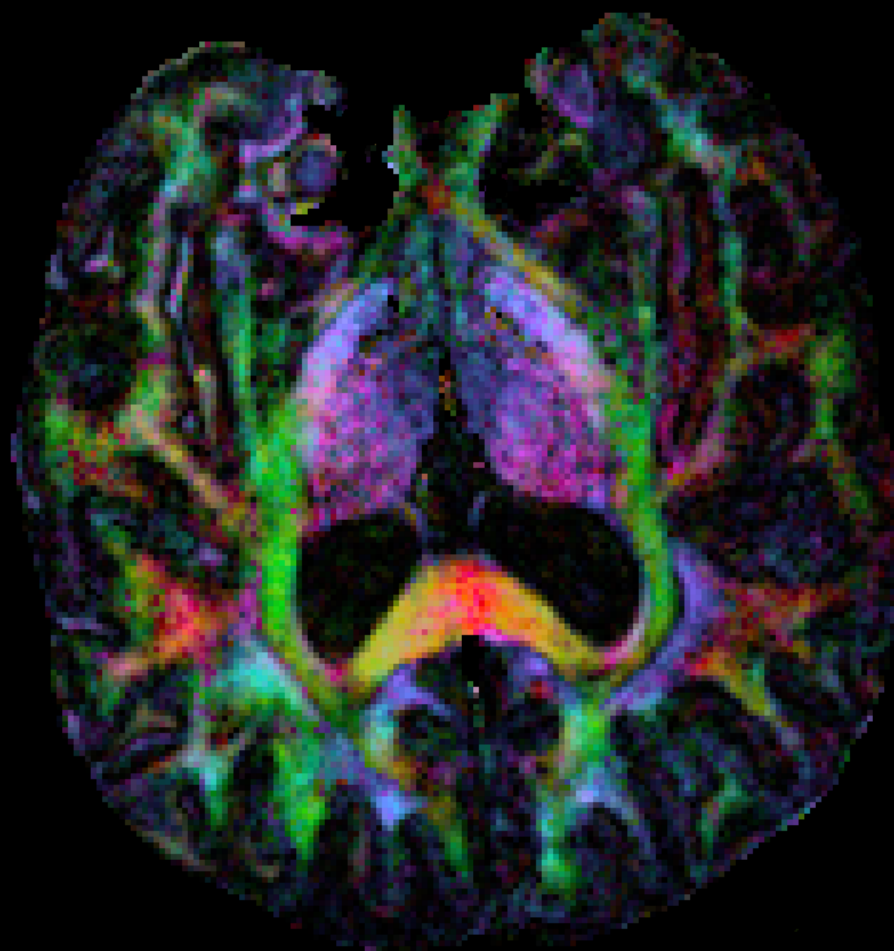
DT ellipsoid



distribution

DT ellipsoid

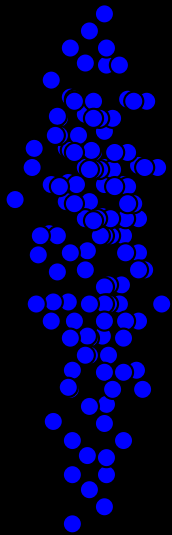
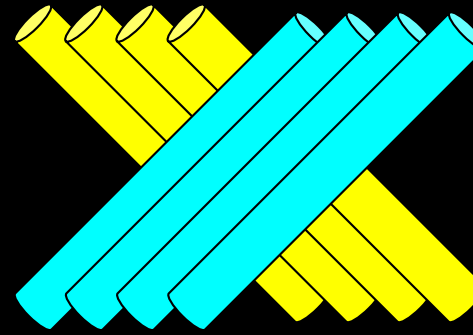
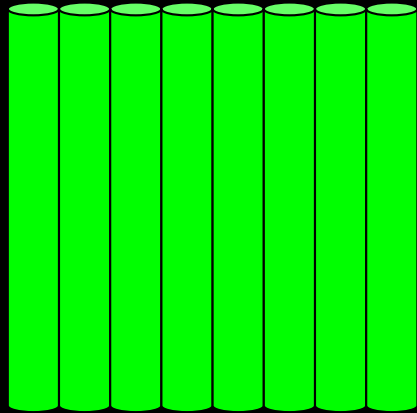
Sub-millimeter DTI



Beyond Standard DTI

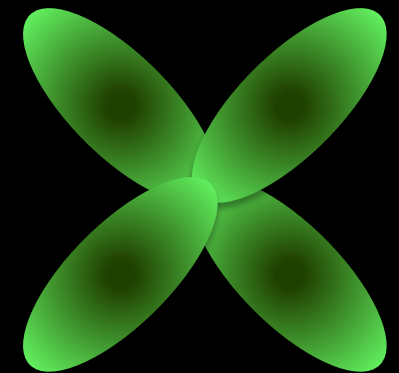
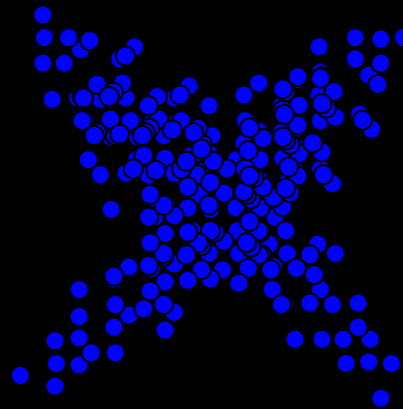
- High Angular Resolution Diffusion Imaging (HARDI)
 - Multi-tensor models
 - Non-parametric algorithms
 - DSI, Qball, SD, PAS

Non-parametric Algorithms



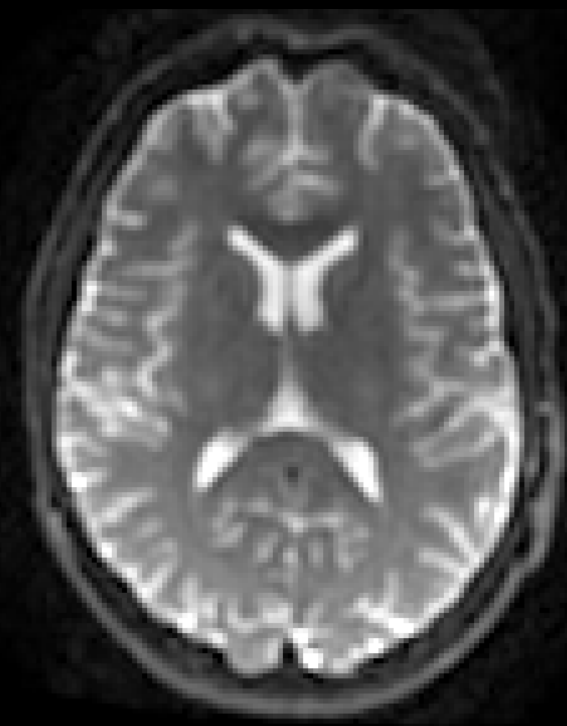
distribution

fODF

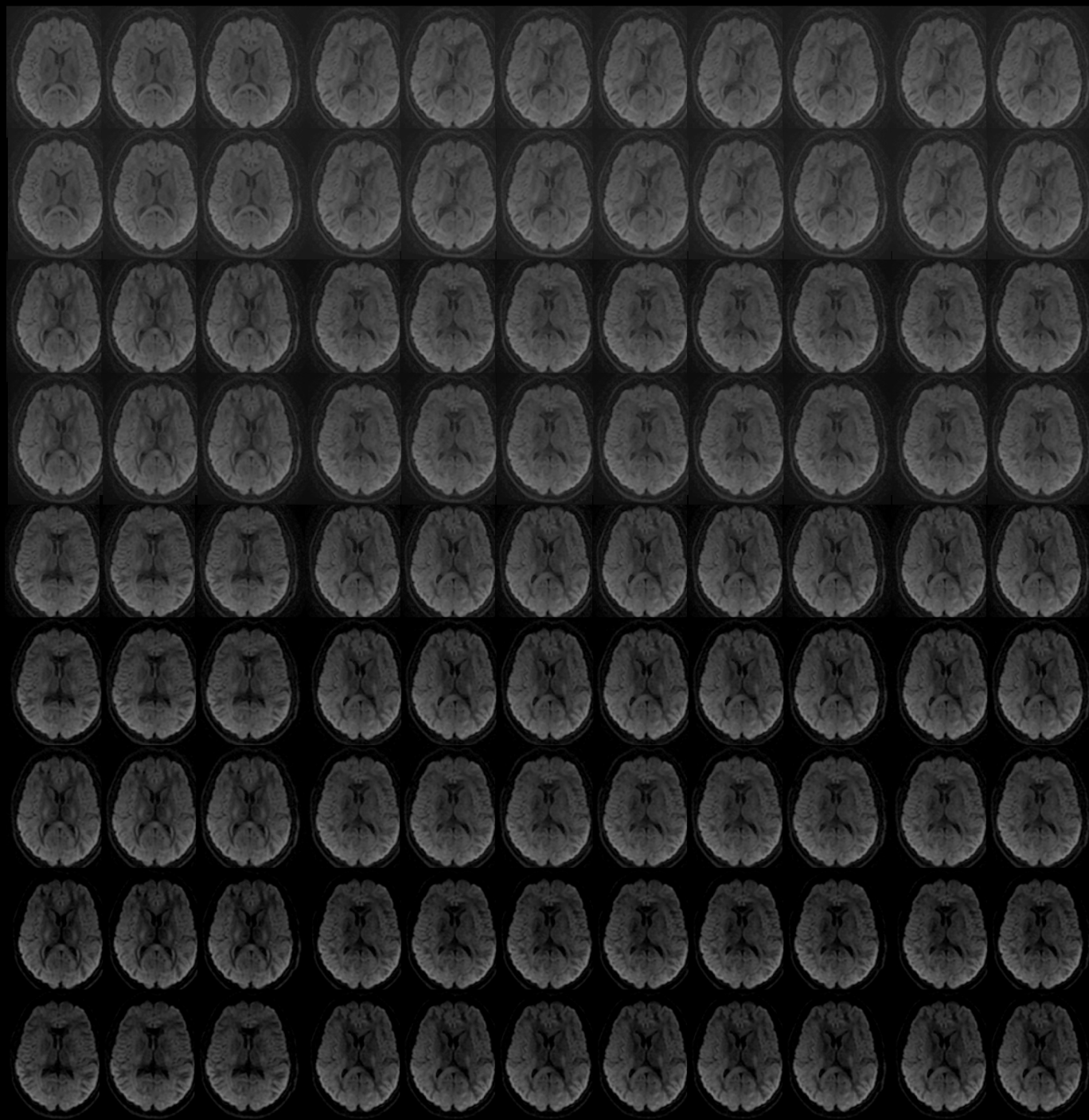


distribution

fODF



$b = 0 \text{ s/mm}^2$



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