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

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- What is diffusion?
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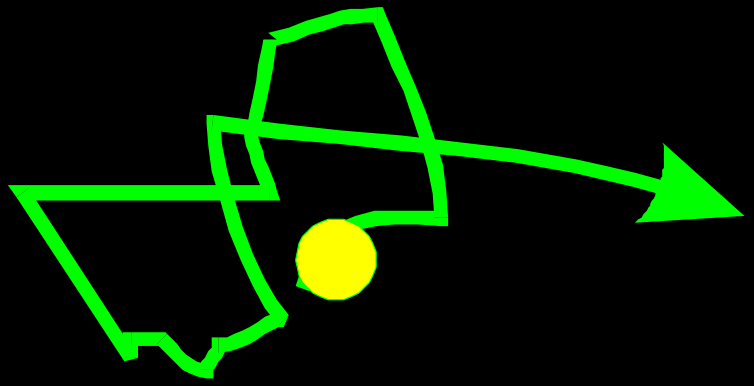
Diffusion

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

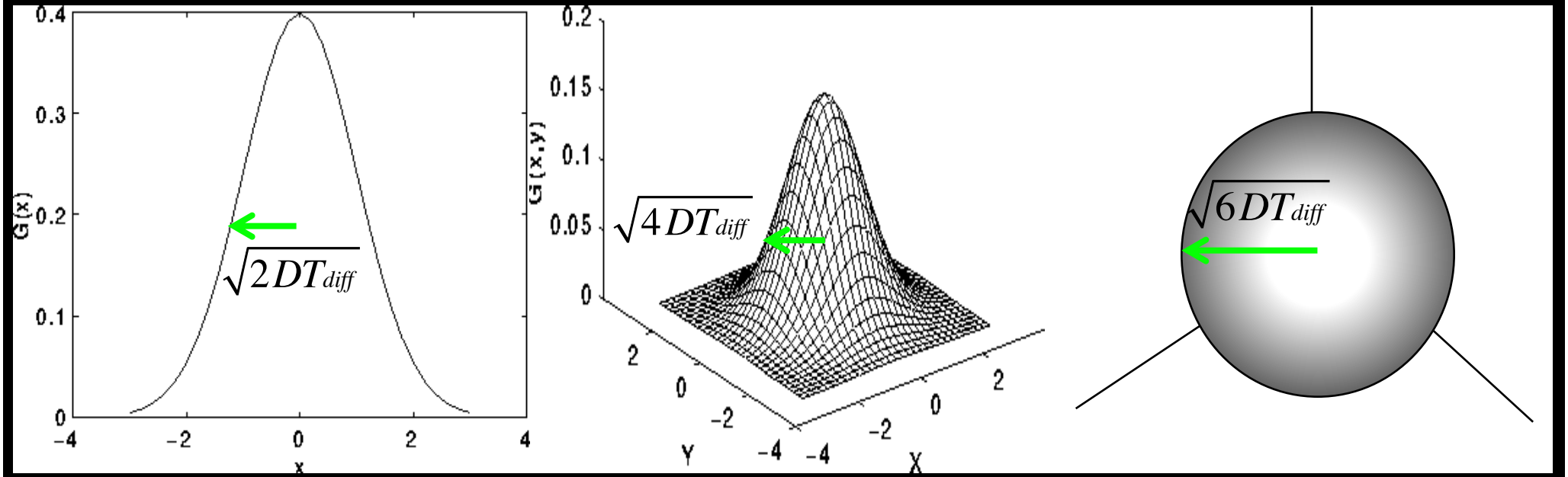


$$D = \frac{kT}{6\pi\eta R_H} \quad \text{(for sphere)}$$

Stokes-Einstein

Gaussian Distribution

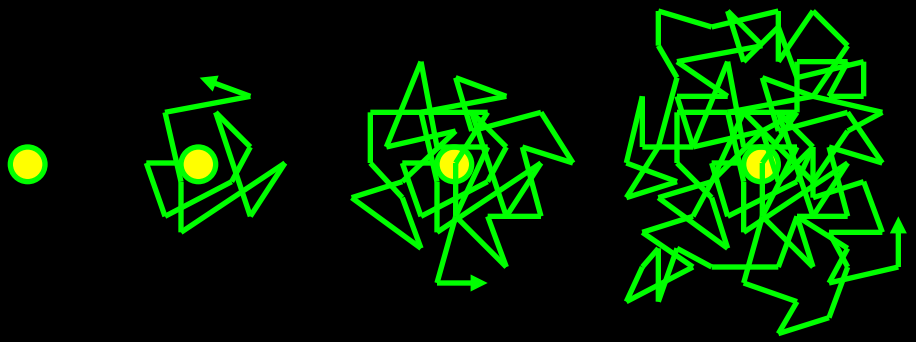
- A large number of particles that are free to diffuse have a squared displacement of a Gaussian form



1D 2D 3D

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

Diffusion



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

For H_2O at 37° C

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

$T_{dif} \approx 30\ ms$

$r \approx 25\ \mu m$

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

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Image Intensity in MRI

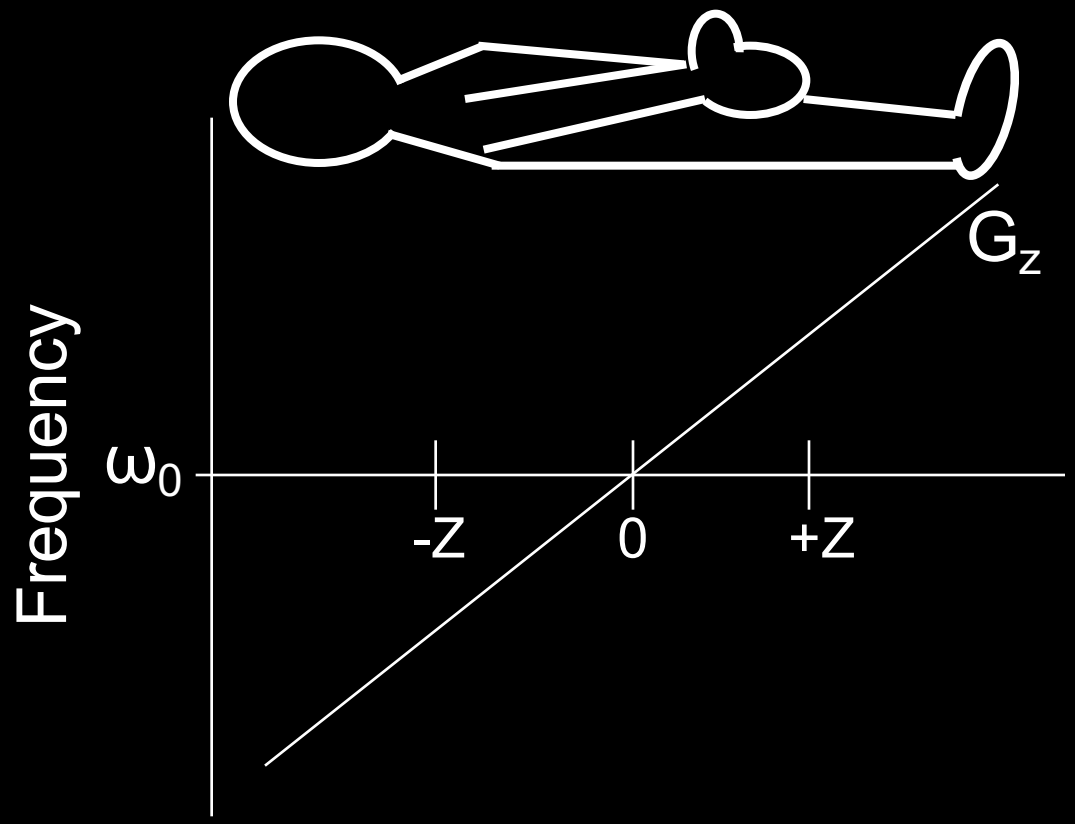
- Physical property of tissue water

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

- Experimentally controlled parameters

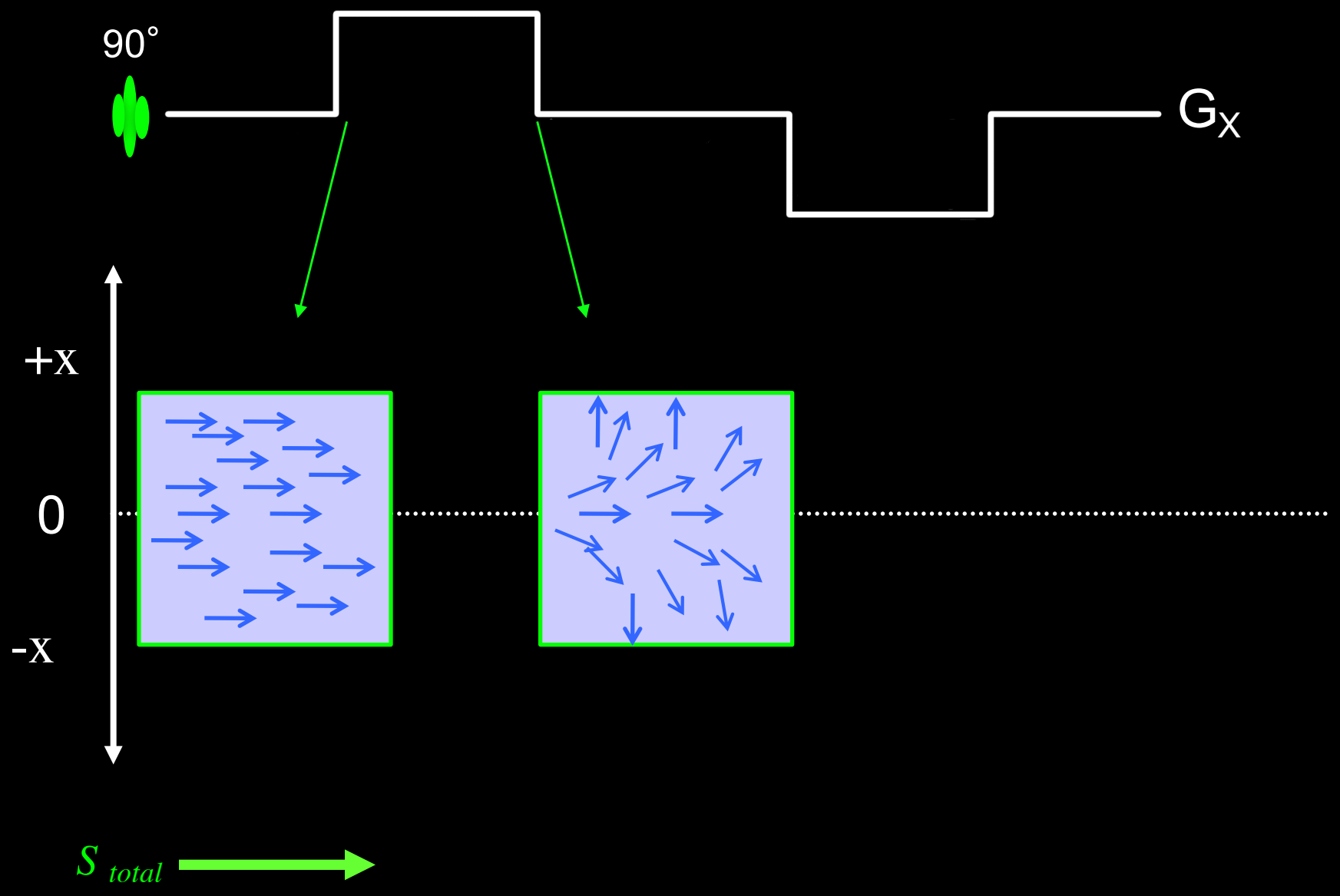
– Sequence	Spin-echo/gradient echo
– TR	Time of Repetition
– TE	Time to echo
– b-value	diffusion-weighting factor

Gradients make the resonance frequency a function of spatial position



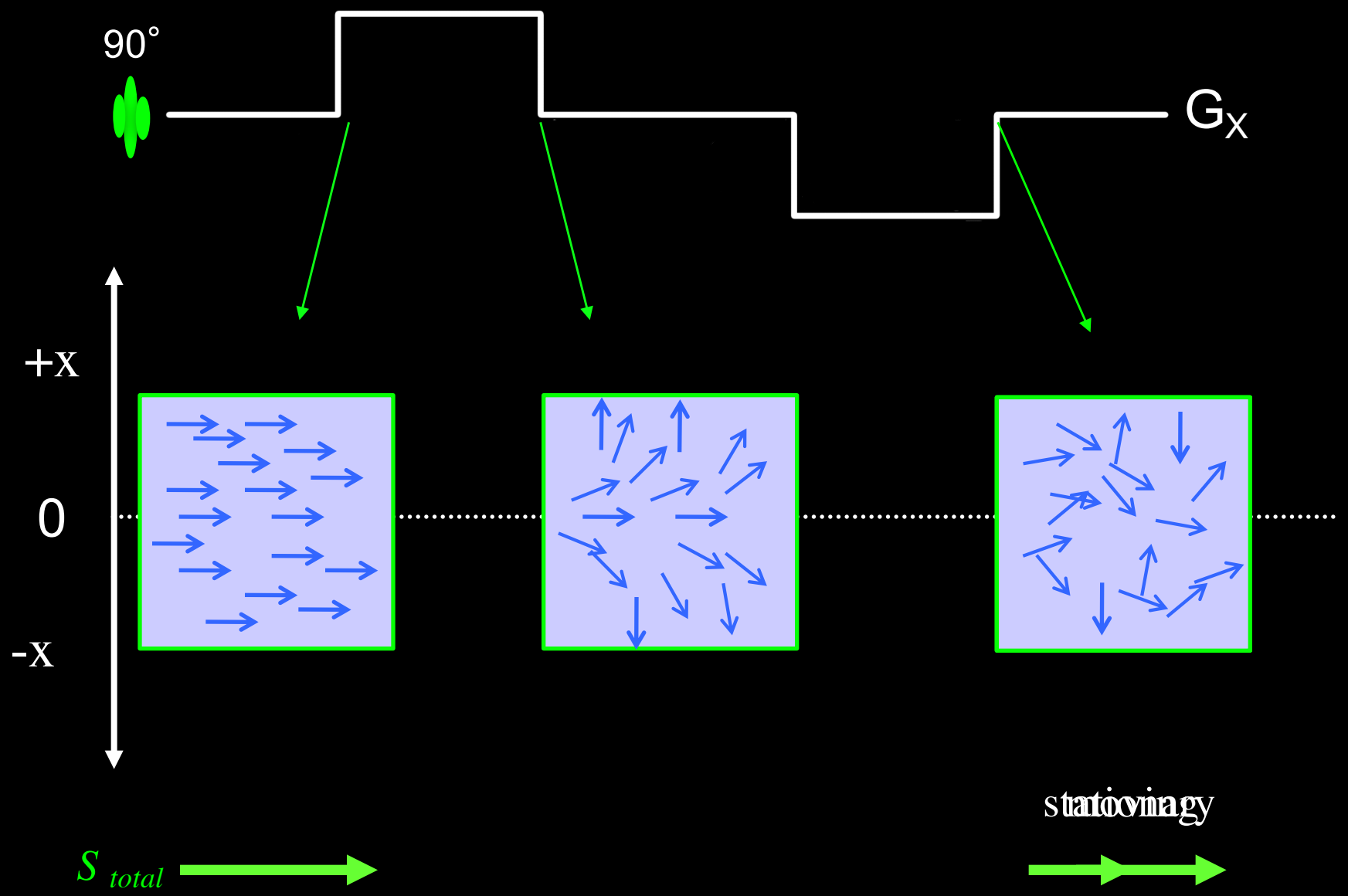
$$\omega = \gamma B = \gamma B_0 + \gamma z G_z$$

Basic Diffusion-weighting

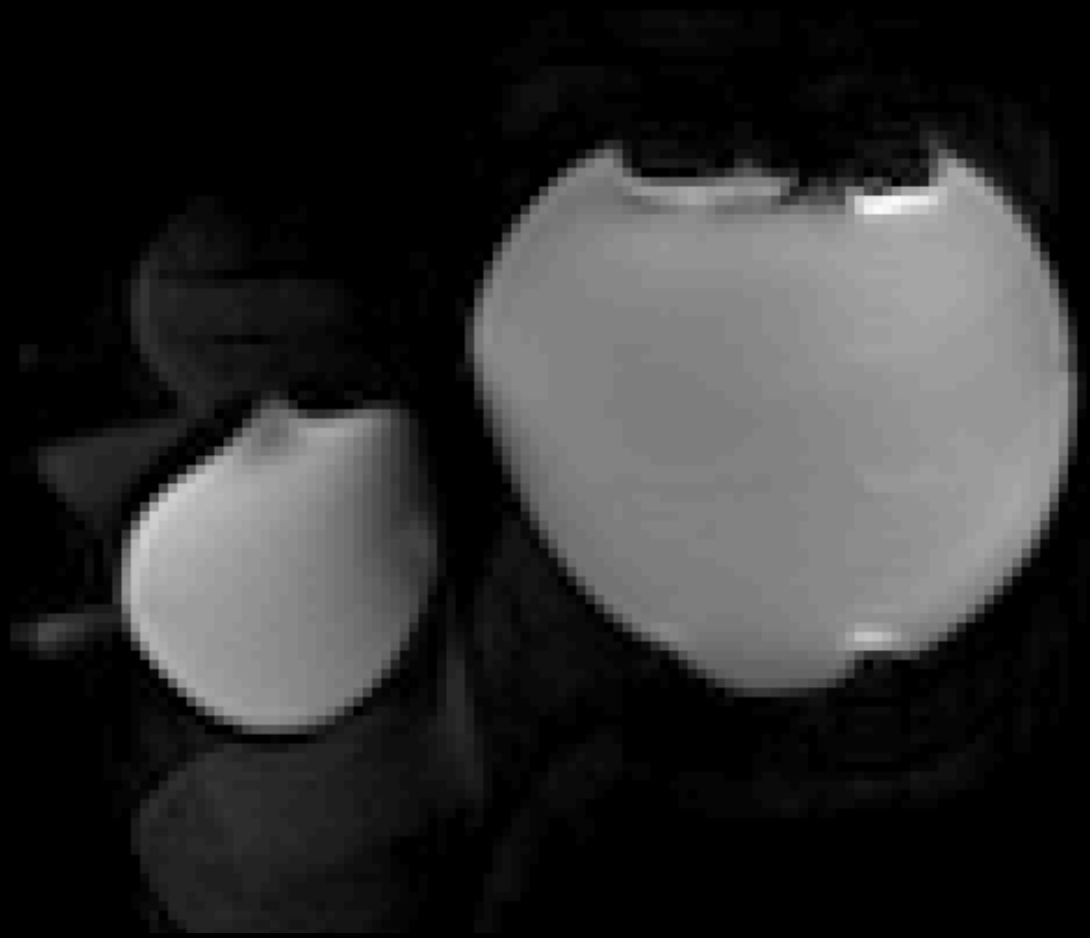


Phase Twist

Basic Diffusion-weighting



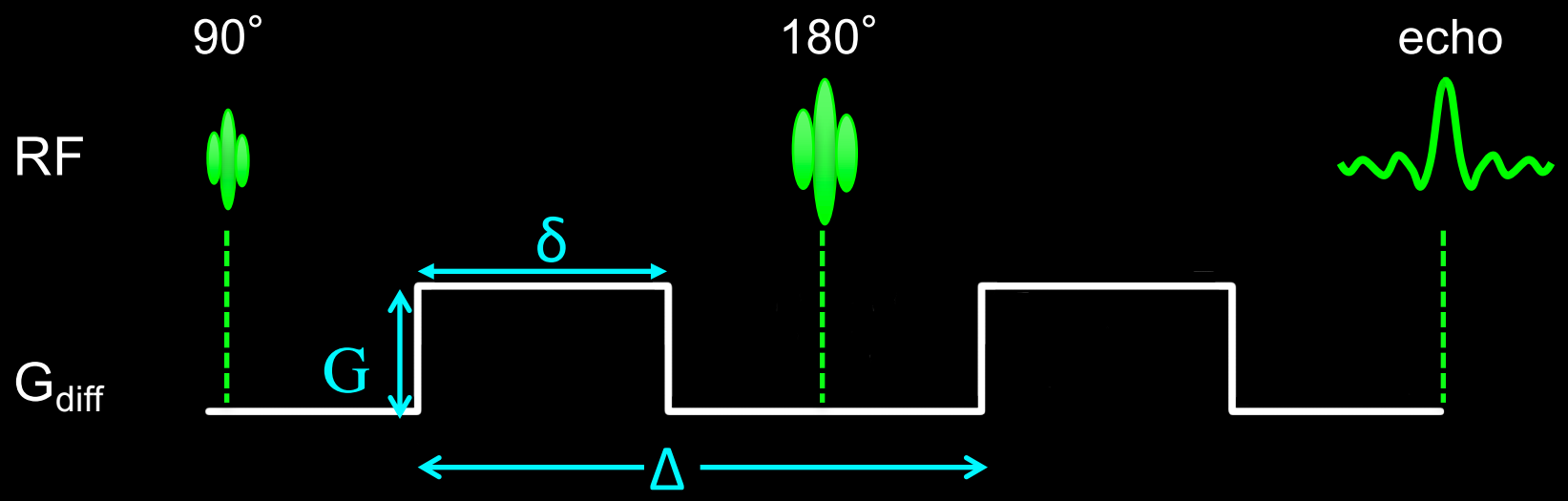
Guess the intensity



No Diffusion weighting

Diffusion-weighted

Spin-echo Diffusion Preparation



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

Stejskal, EO and Tanner, JE. J Chem Phys (1965) 42 : 288-292

DWI

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

Non-diffusion-weighted signal intensity

B-value
sec/mm^2

Diffusion Coefficient
mm^2/sec

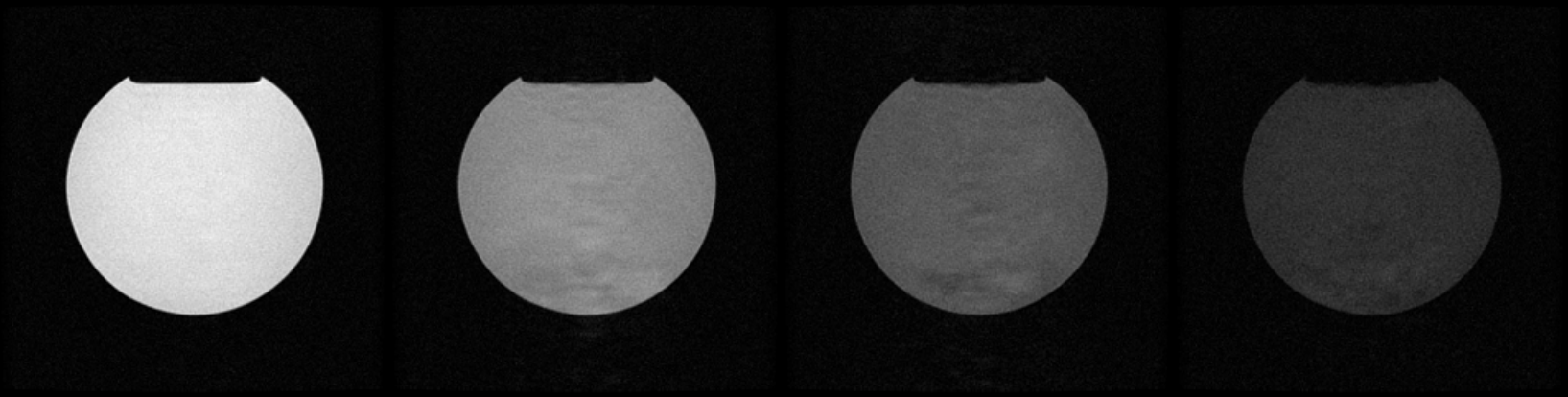
Typical DWI

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

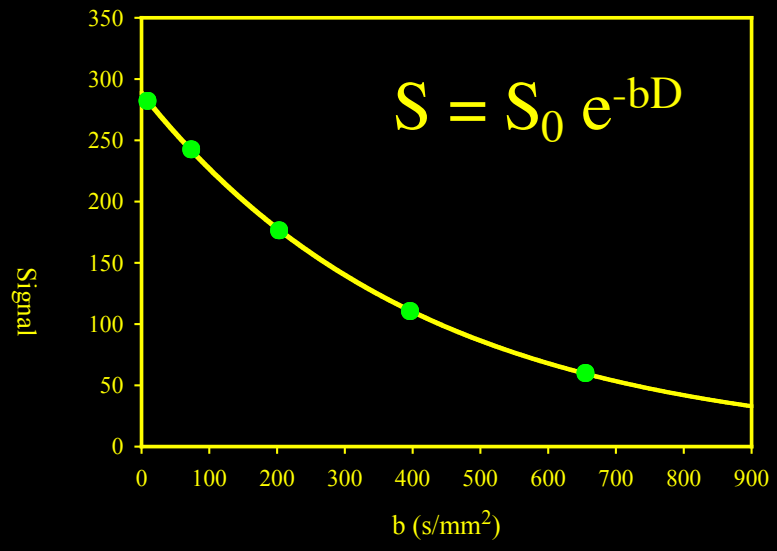
Parameter	Value	Comment
TE	50-100ms	Limited by b-value
TR	>5s	Fully relaxed
Matrix	96 x 96	2.5 x 2.5 mm
Slice Thickness	2.5 mm	Equal dimensions
B-value	~1000 s/mm^2	For brain*

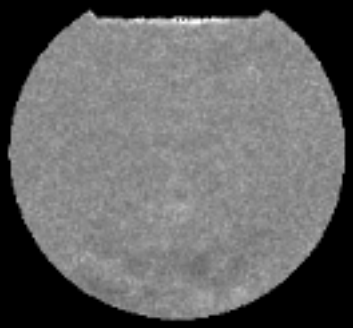
*Jones D., *et al*. Mag Res Med (1999) 42 : 515

Calculate Diffusion Parameters

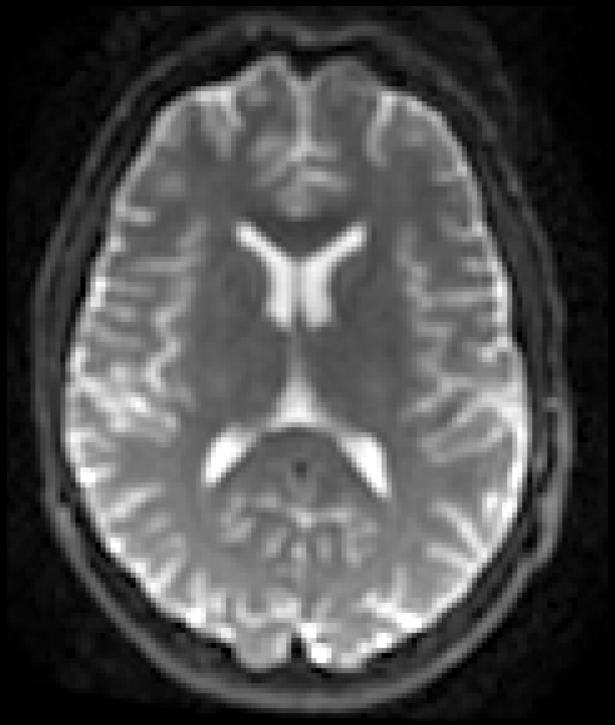


b (s/mm^2) 8 200 400 650



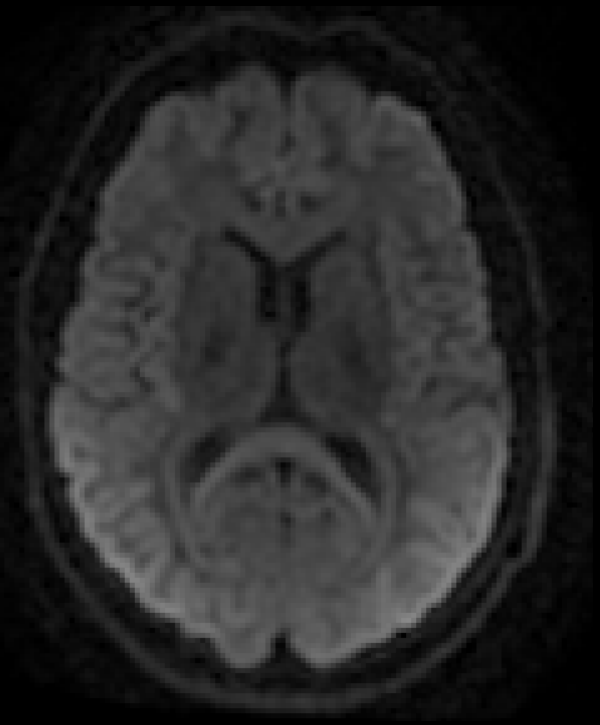


Diffusion map



b = 0 s/mm^2

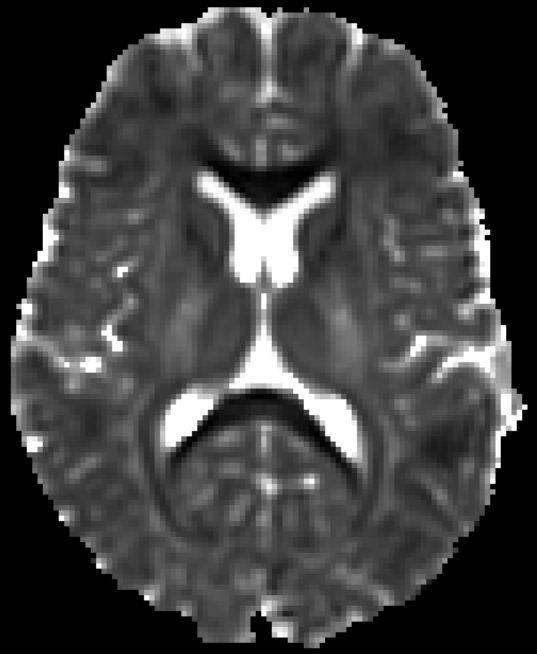
I_0



b = 1100 s/mm^2

Gz

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



Dz

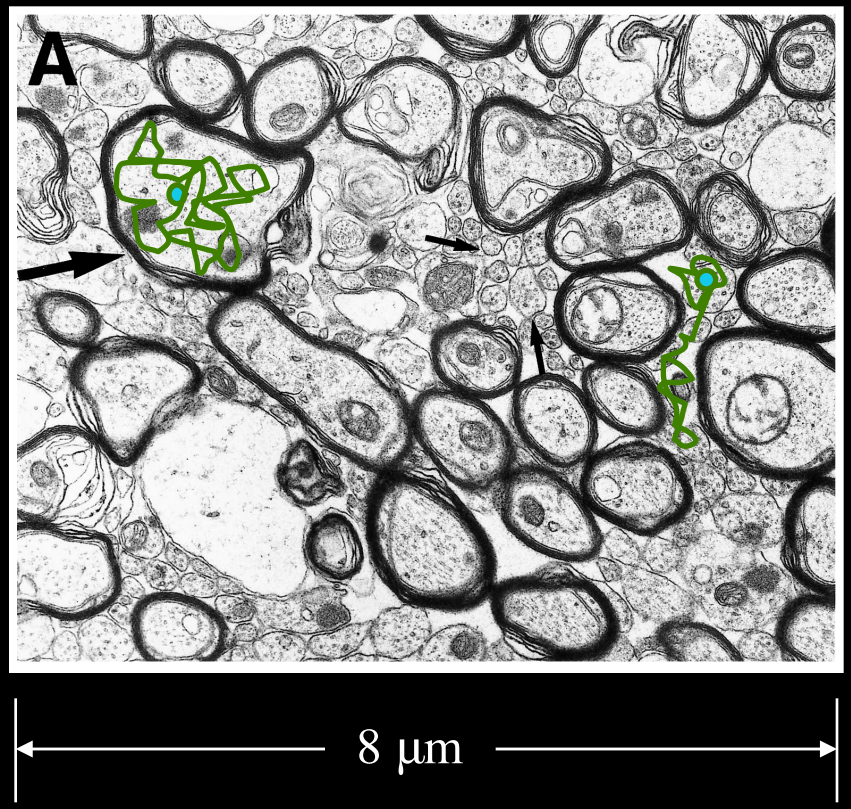
$$D_z = \frac{1}{-b} \ln\left(\frac{I_z}{I_0}\right)$$

Water Diffusion in Tissue

Not Free

Cell membranes
Myelin
Organelles
Extracellular matrix

EM of mouse corpus callosum

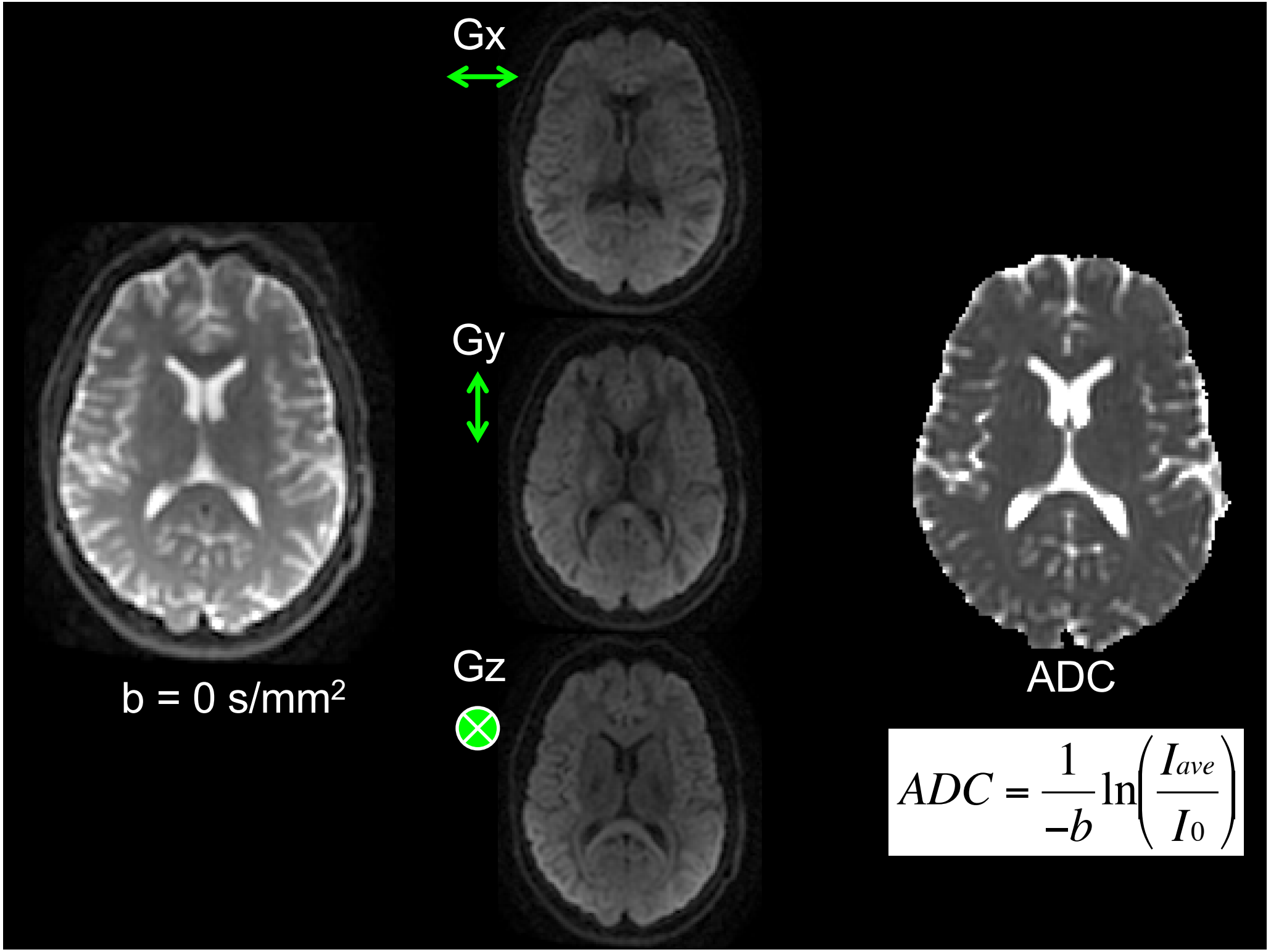


Anisotropy

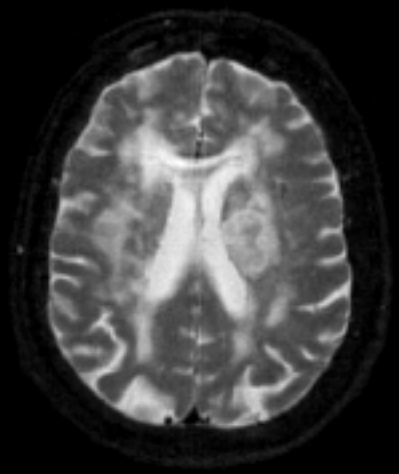
$D_{perpendicular}$ ⟷

$D_{parallel}$ ⊗

$D_{perp} << D_{par}$

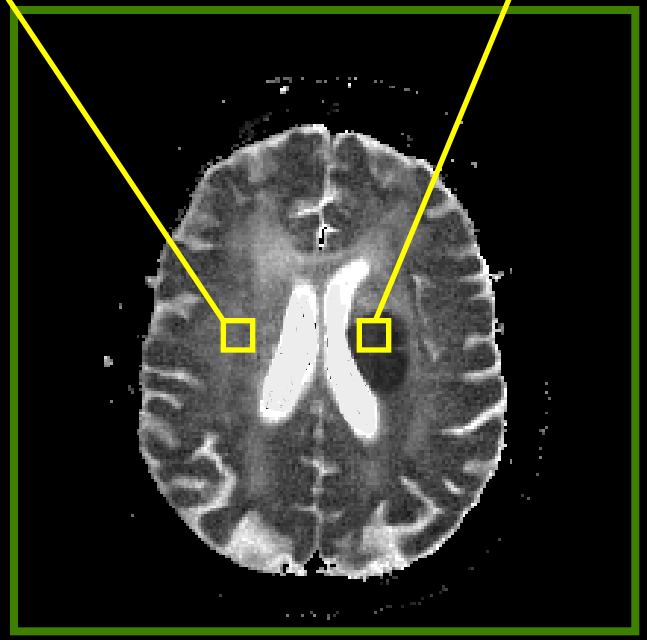

Gx
Gy
Gz
b = 0 s/mm²
ADC
$ADC = \frac{1}{-b} \ln\left(\frac{I_{ave}}{I_0}\right)$

Acute Stroke



b = 0 s/mm^2

720 s/mm^2



Diffusion Map

Warach S., *et al*. Ann Neurol (1995) 37:231-241

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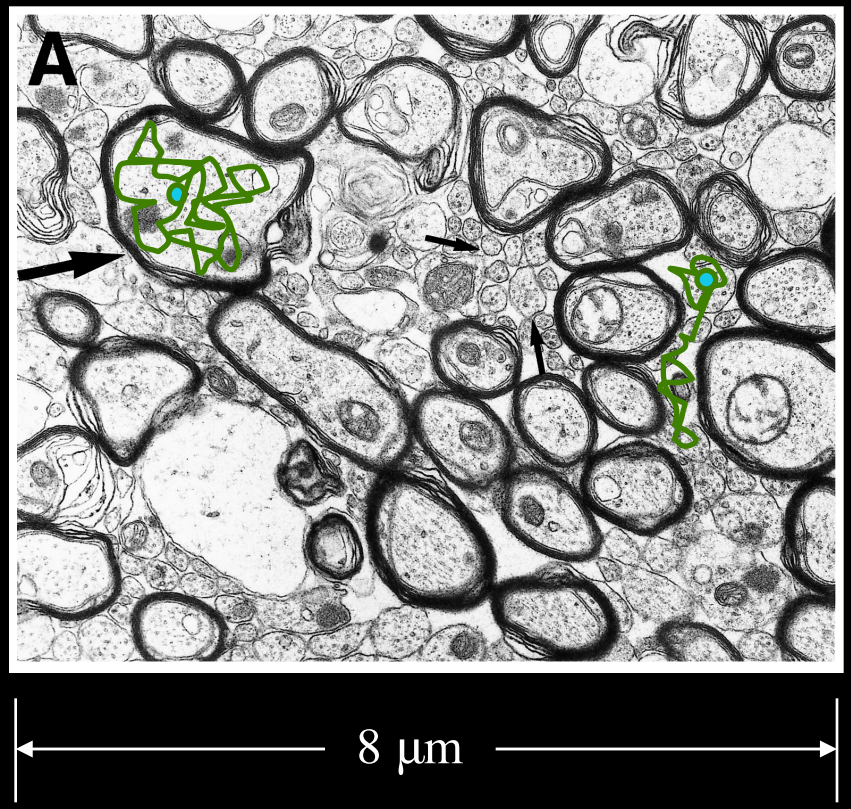


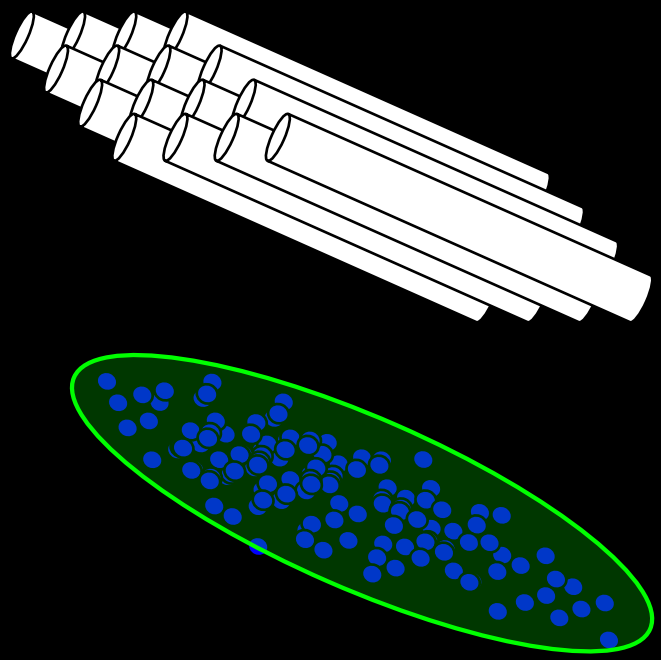
Anisotropy

$D_{perpendicular}$ ⟷

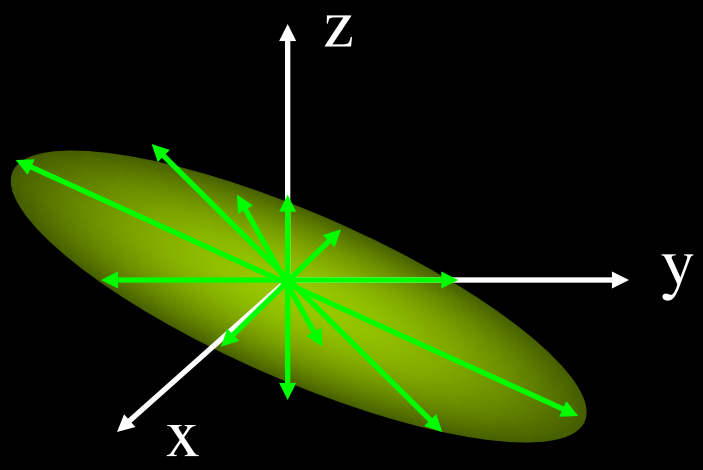
$D_{parallel}$ ⊗

$D_{perp} << D_{par}$

Anisotropic Diffusion



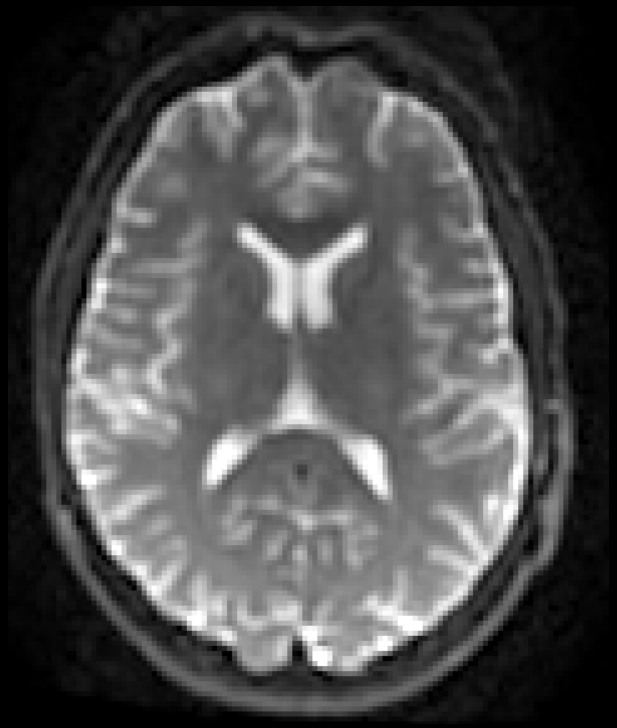
The Diffusion Tensor



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

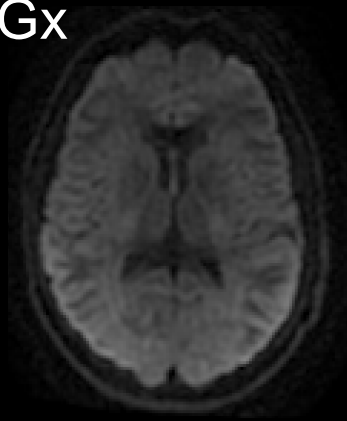
Basser, P, *et. al*. J Magn Reson B (1994) 3 : 247-254

DTI

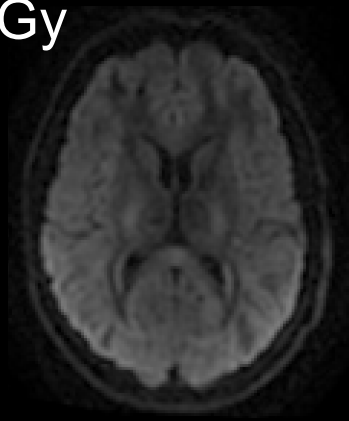


b = 0 s/mm^2

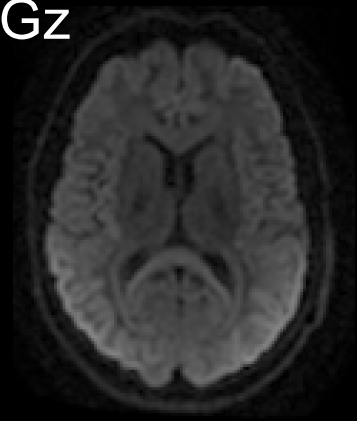
Gx



Gy

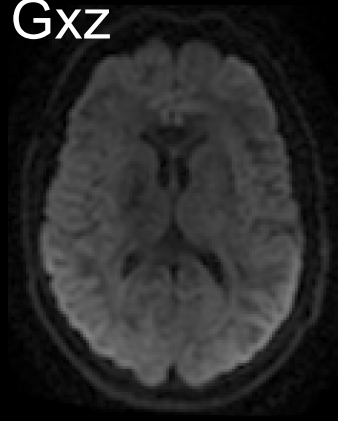


Gz

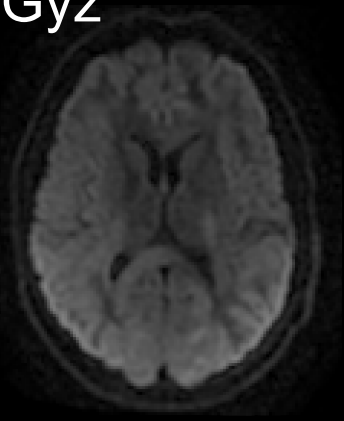


Gxy

Gxz

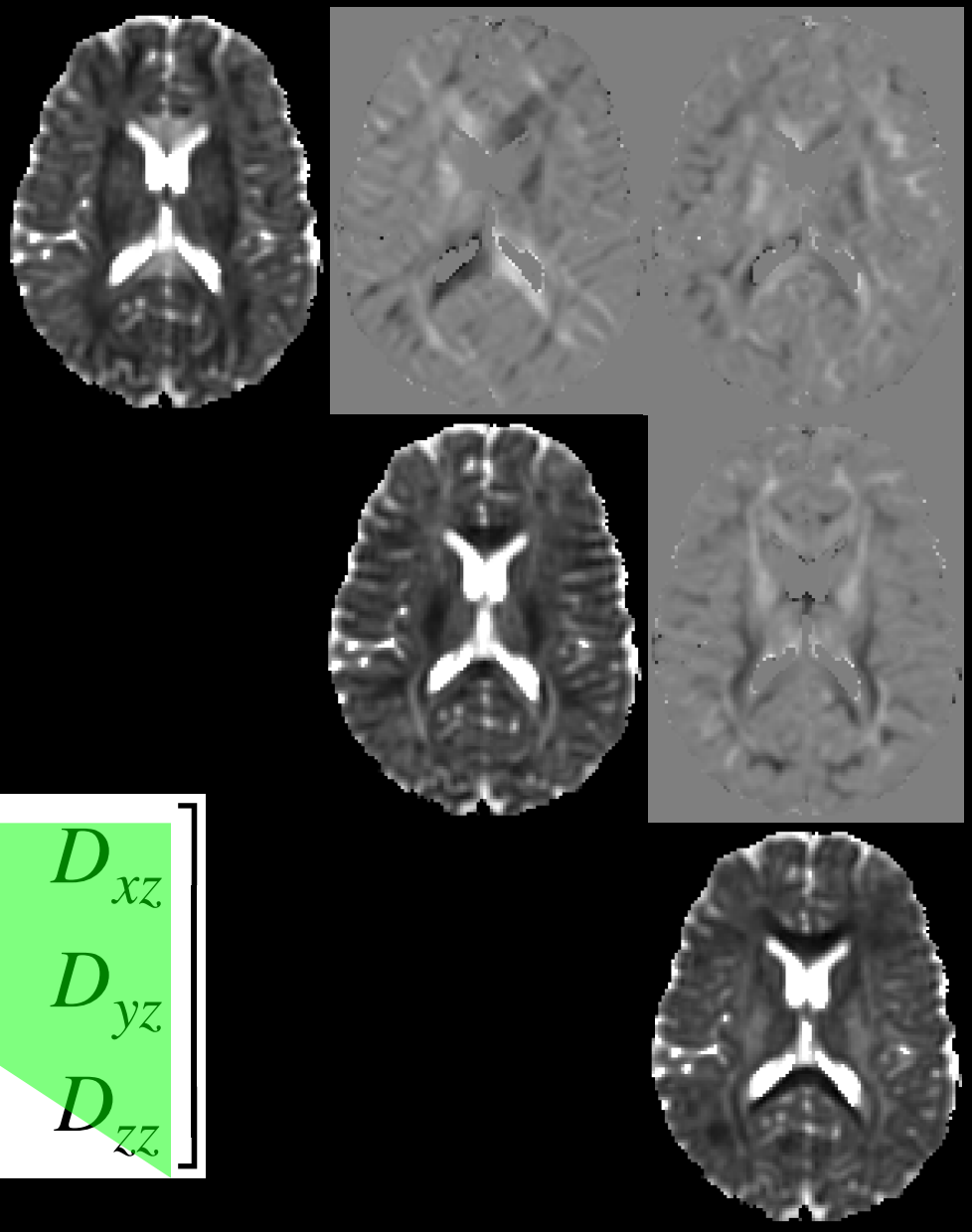


Gyz



b = 1100 s/mm^2

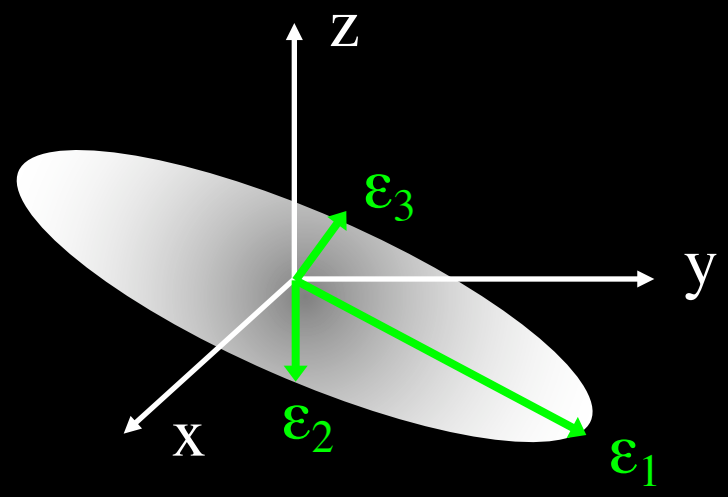
Calculate Diffusion Tensor



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

Diagonalize DT

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

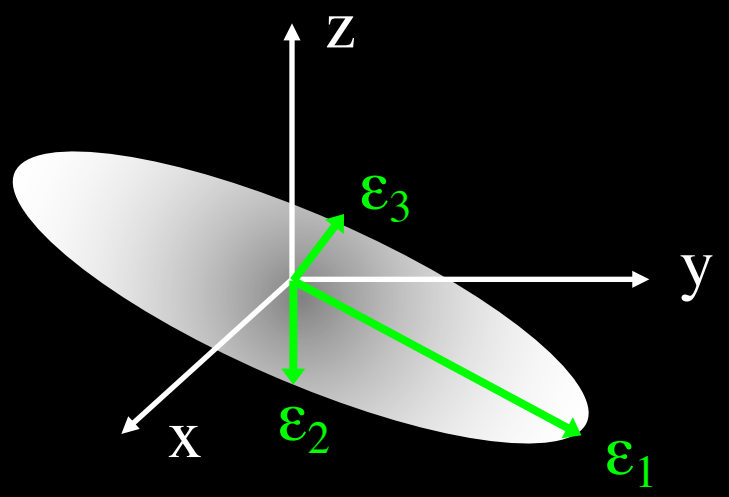


Eigenvalues

Eigenvectors

Quantitative Parameters

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



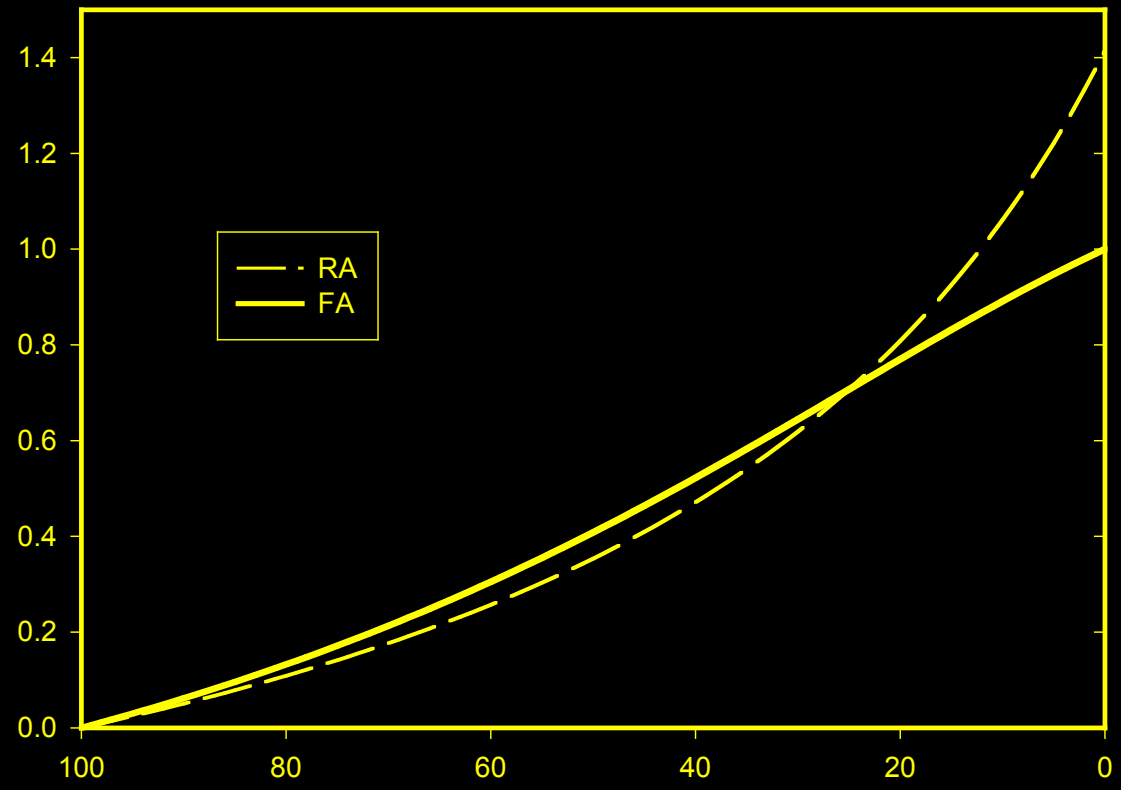
Average Diffusivity

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

Fractional Anisotropy

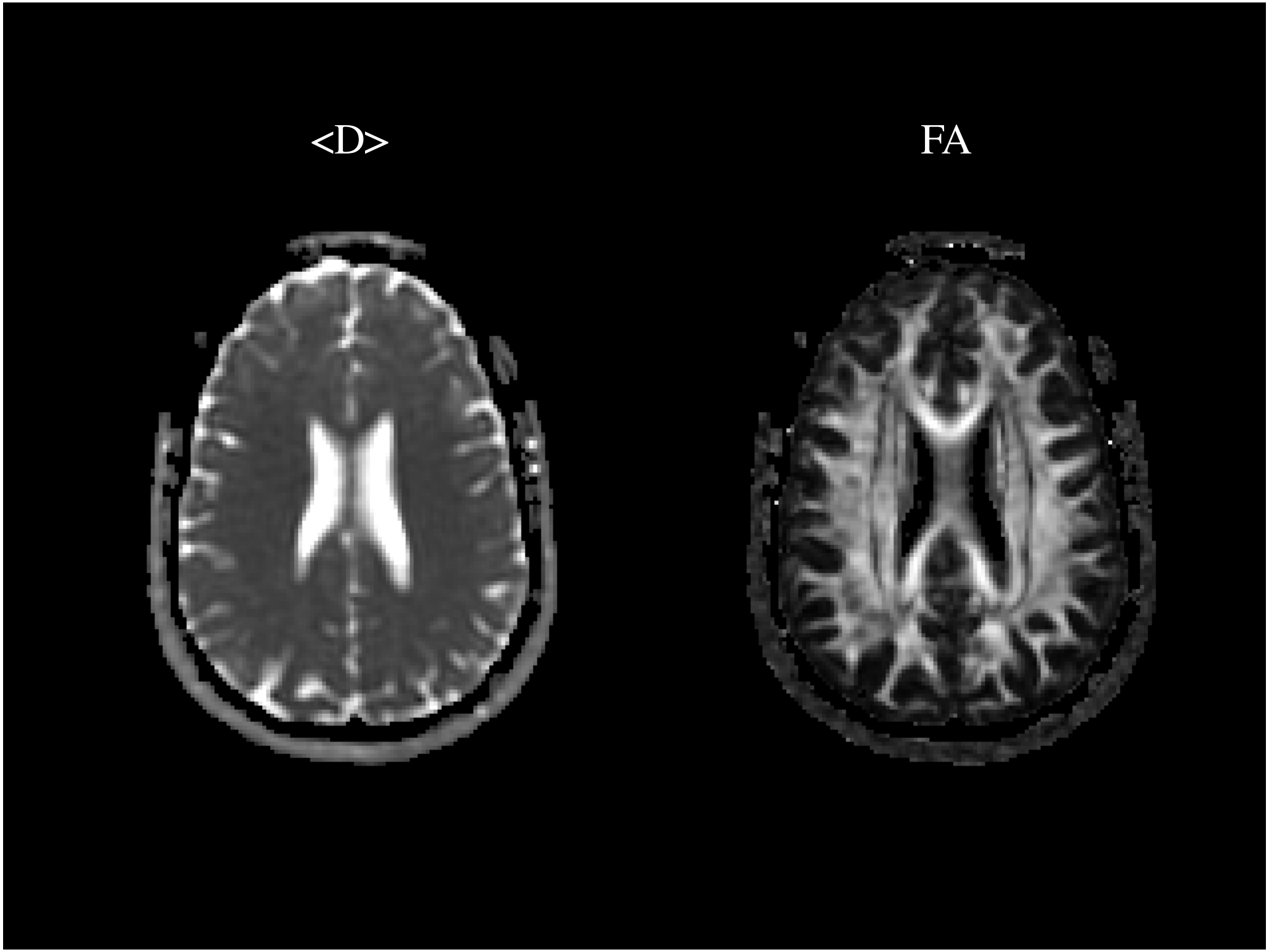
$$FA = \frac{\sqrt{3\left(\lambda_1 - \langle\lambda\rangle\right)^2 + \left(\lambda_2 - \langle\lambda\rangle\right)^2 + \left(\lambda_3 - \langle\lambda\rangle\right)^2}}{\sqrt{2\left(\lambda_1^{\,2} + \lambda_2^{\,2} + \lambda_3^{\,2}\right)}}$$

$0 \leq FA \leq 1$

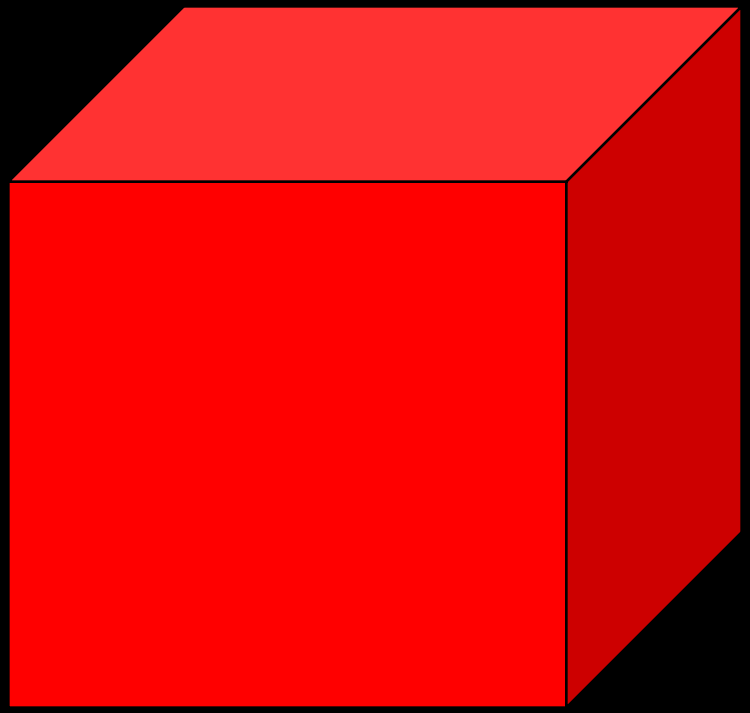


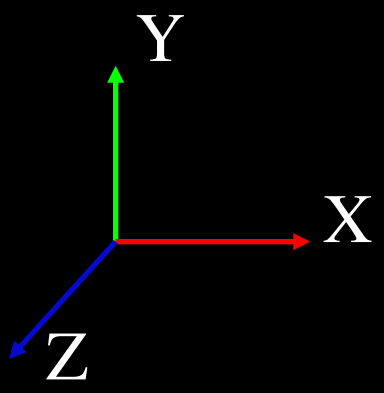
isotropic

anisotropic


<D>
FA

Directional Encoding for DTI



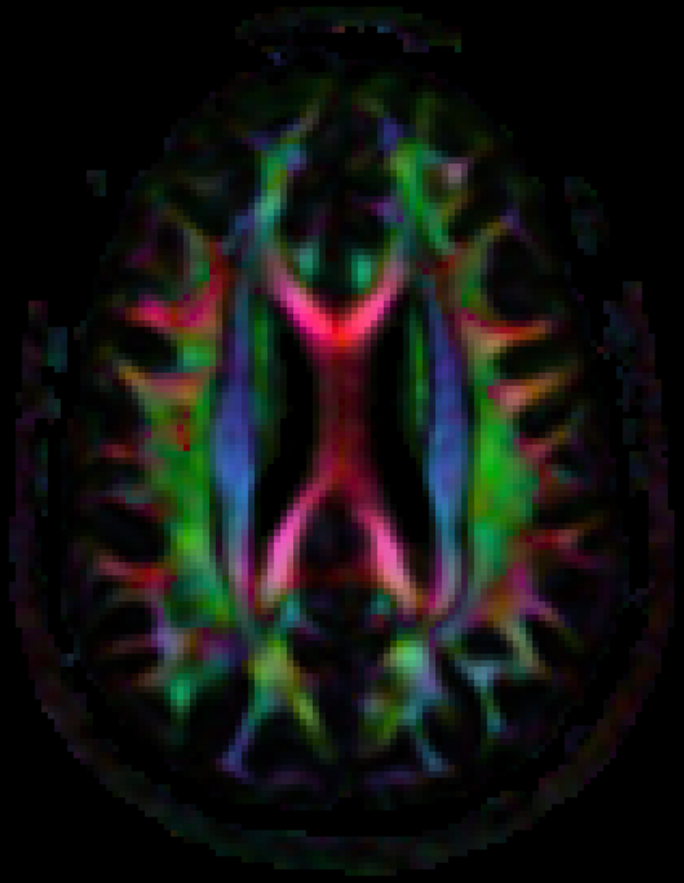


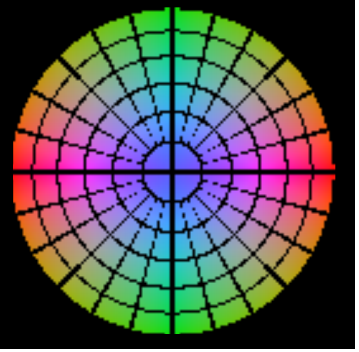
$$\underline{D} = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix}$$

Pajevic S. and Pierpaoli C., Magn Reson Med (1999) 43 : 526-540

<D>

Directional Encoded Color Map





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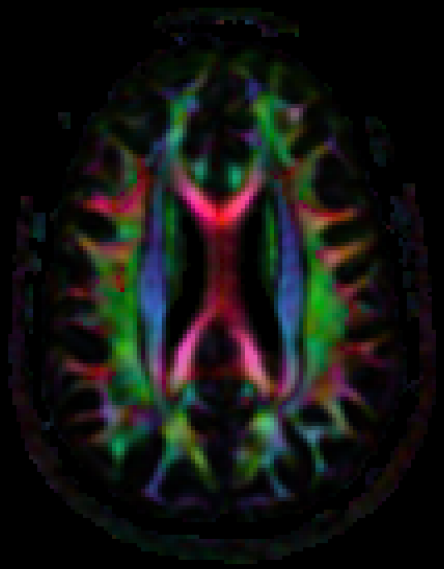
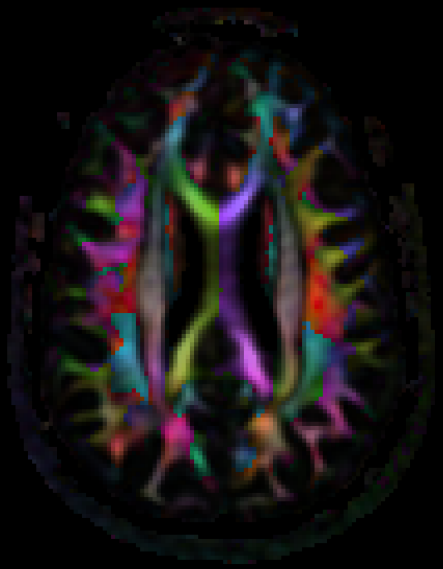
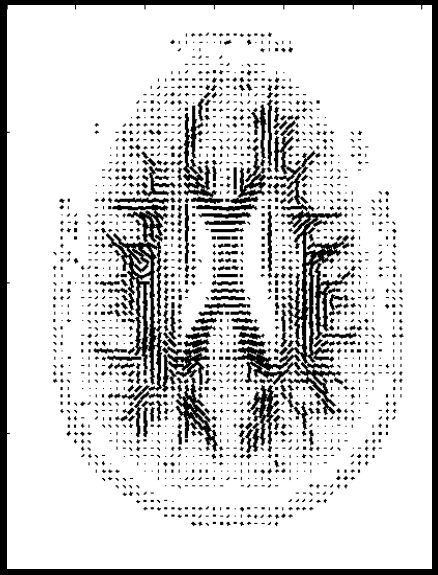
FA



DEC



No sym DEC



Line Field

Linear

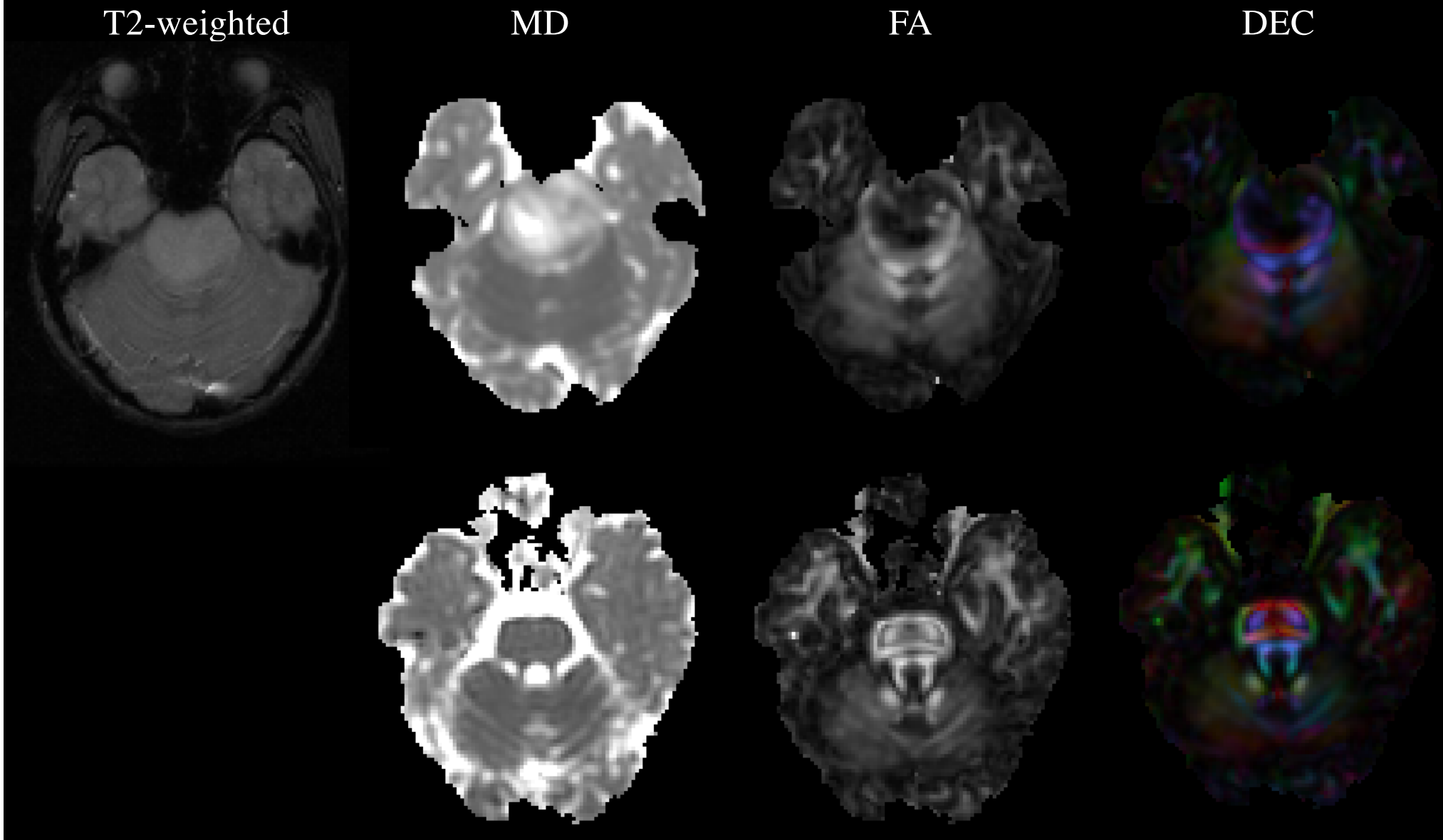
Planar

Spherical

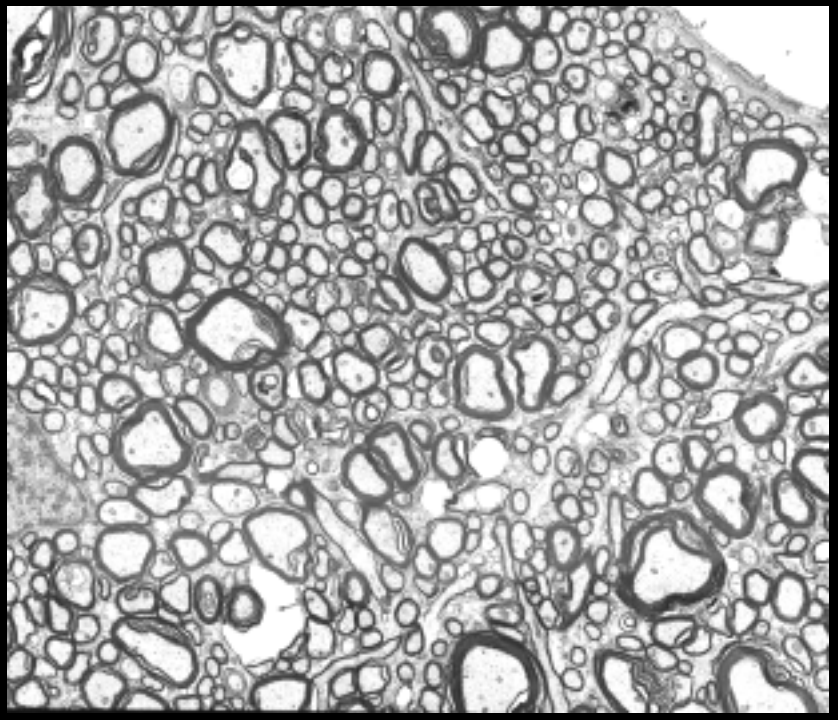
Applications of DTI

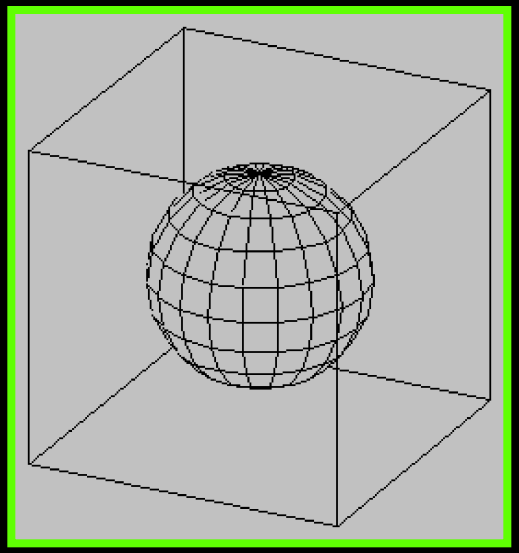
- Cerebral Ischemia (Stroke)
- Brain Cancer and Effects of Radiotherapy
- Multiple Sclerosis
- Epilepsy
- Metabolic Disorders
- Normal Brain Maturation and Aging
- Traumatic Brain Injury
- Alzheimer's Disease
- Amyotrophic Lateral Sclerosis
- Niemann-Pick type C Disease
- Dementias
- Connectivity

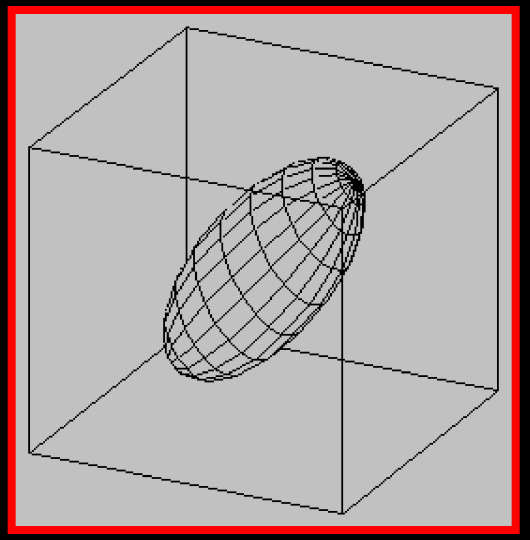
Pediatric DIPG



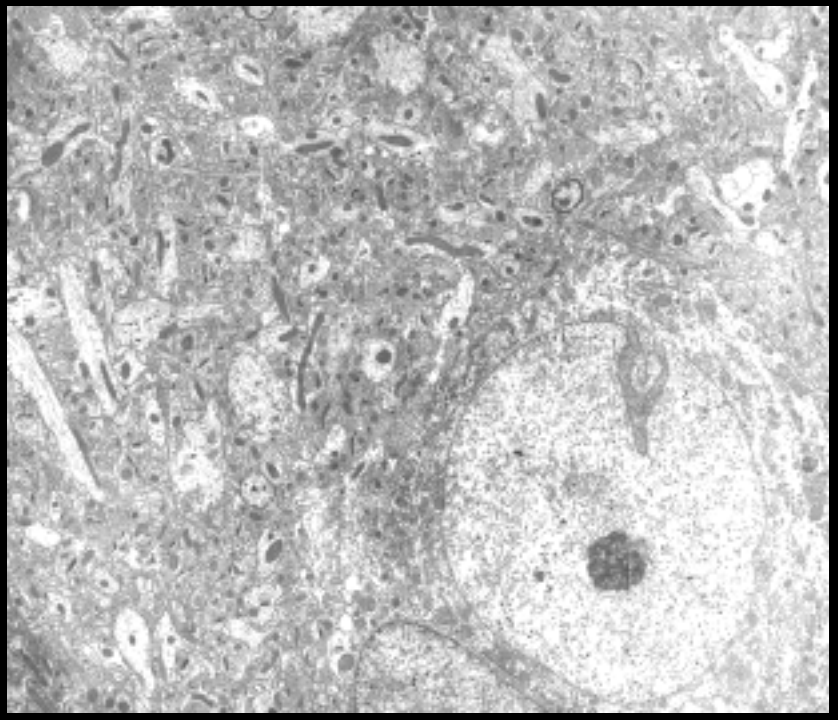
Guess the ellipsoid

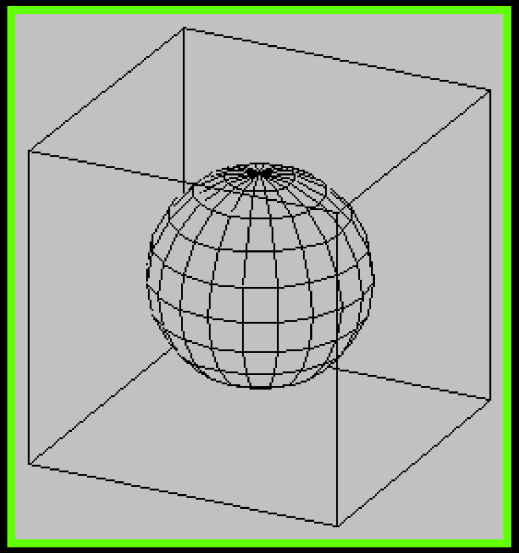


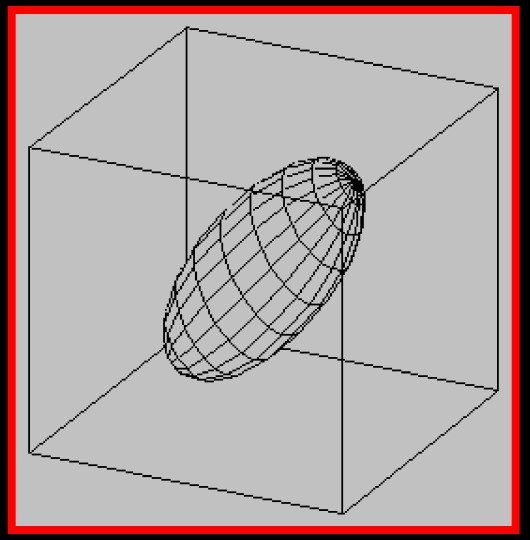




Guess the ellipsoid







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

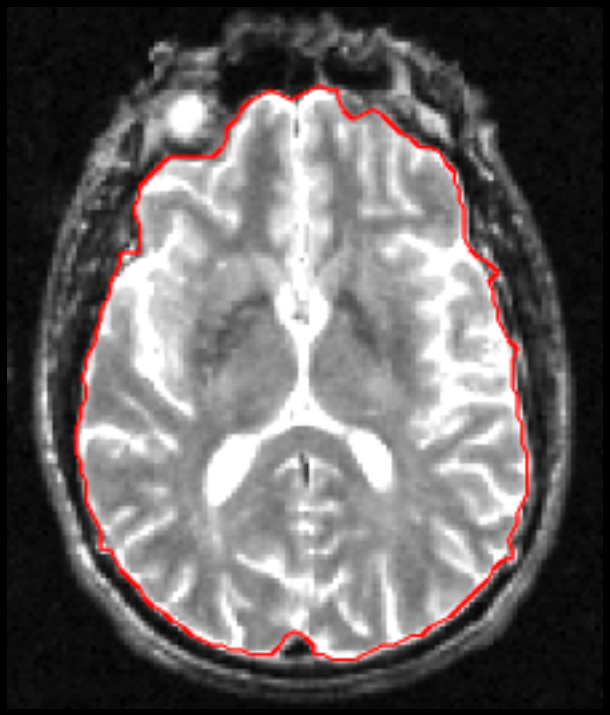
CON

Low Resolution

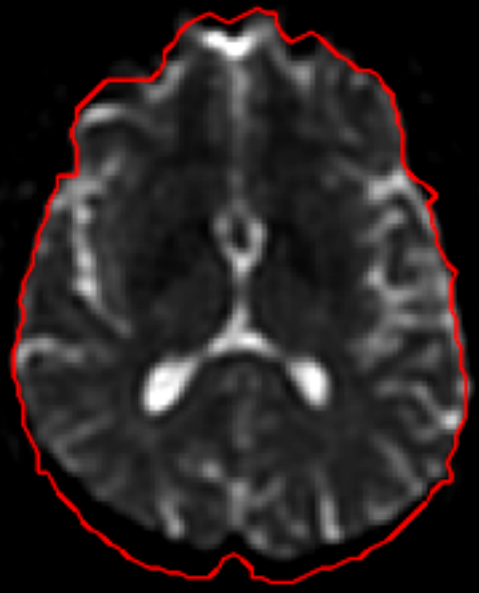
Distortions - Field inhomogeneities

Distortions - Diffusion weighting

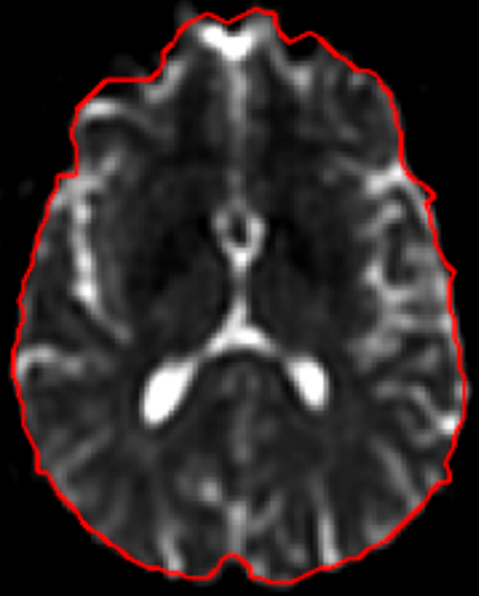
CON: Distortions from field inhomogeneities



T2-weighted FSE

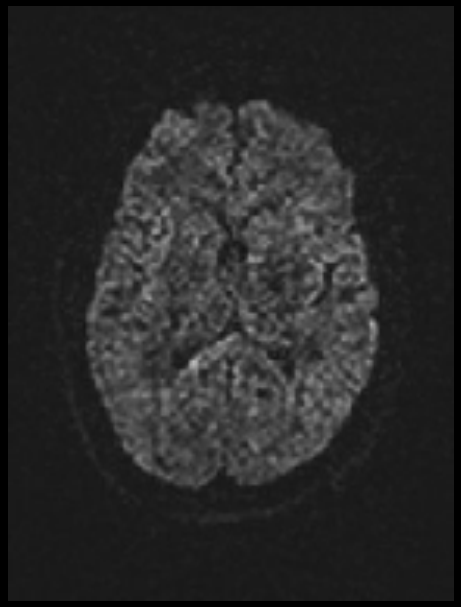


Non-diffusion-weighted SSEPI

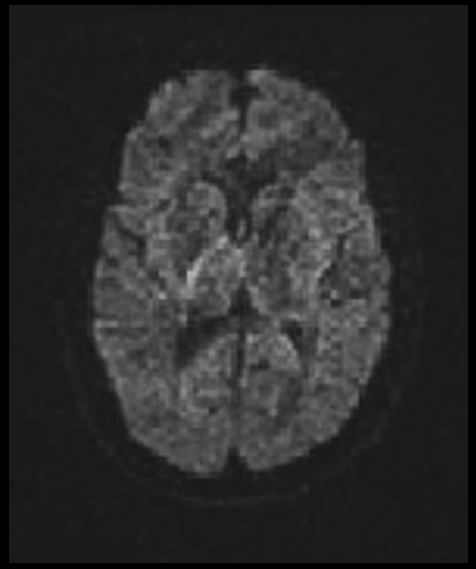


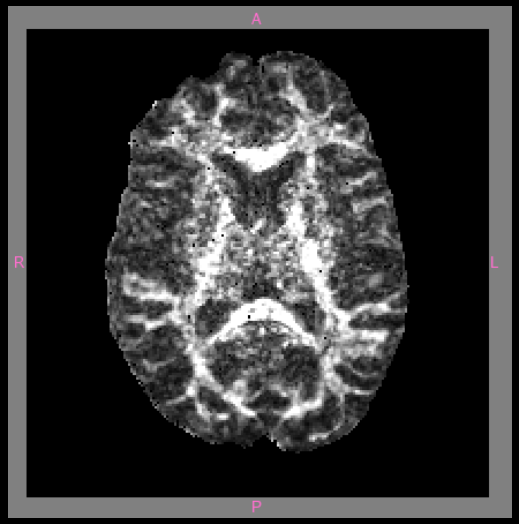
SSEPI corrected

CON: Distortions from DW

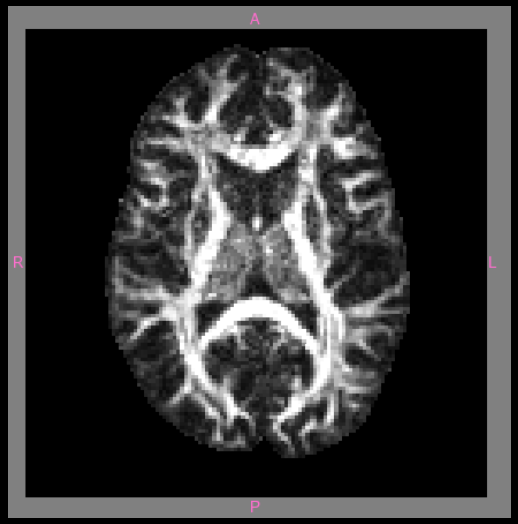


DW
SSEPI
volumes





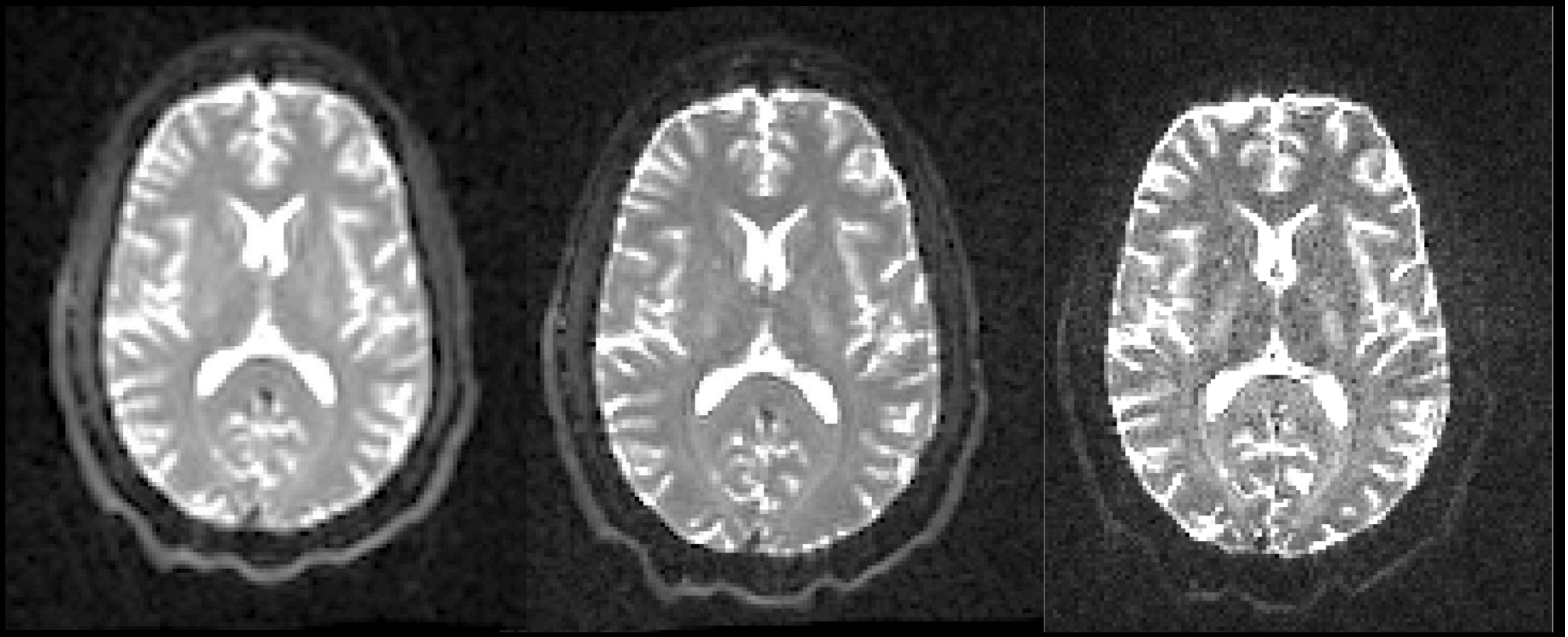
FA maps



Other Common Problems in DTI

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

Low SNR

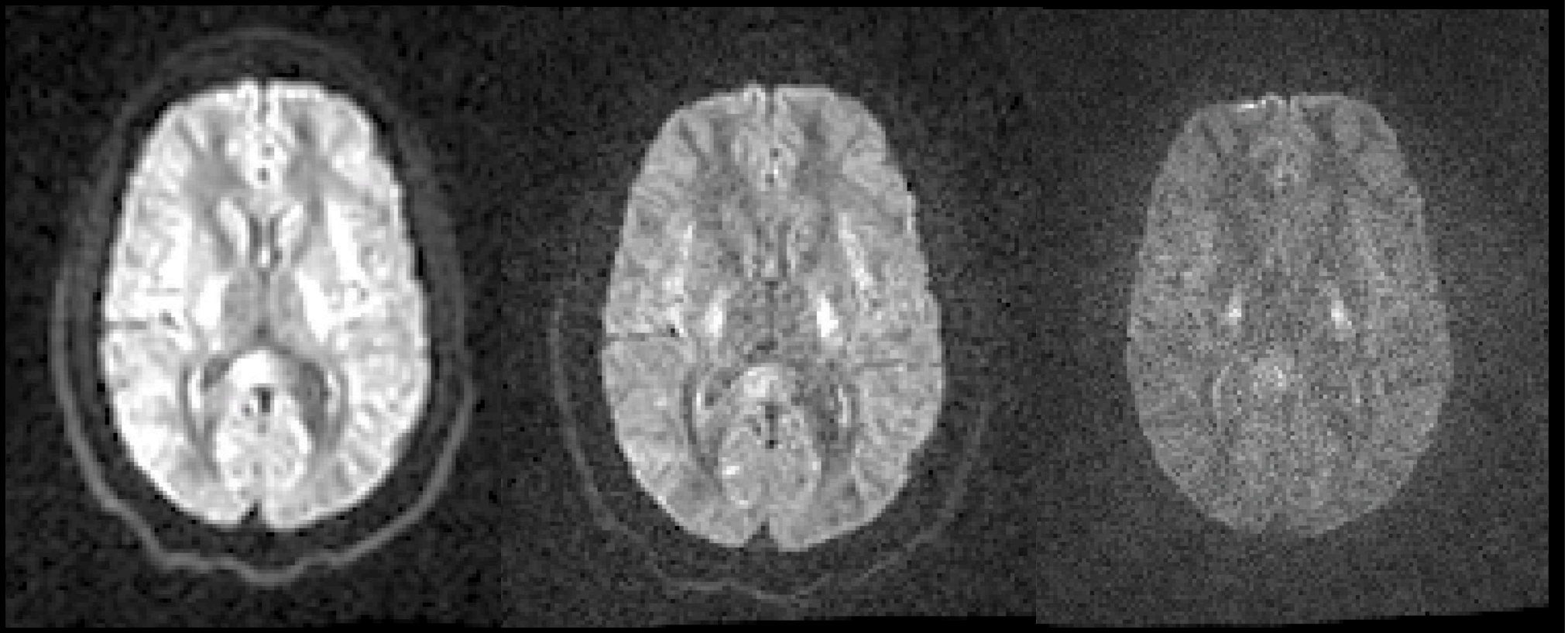


2.5 mm iso

1.7mm iso

1.3mm iso

Low SNR

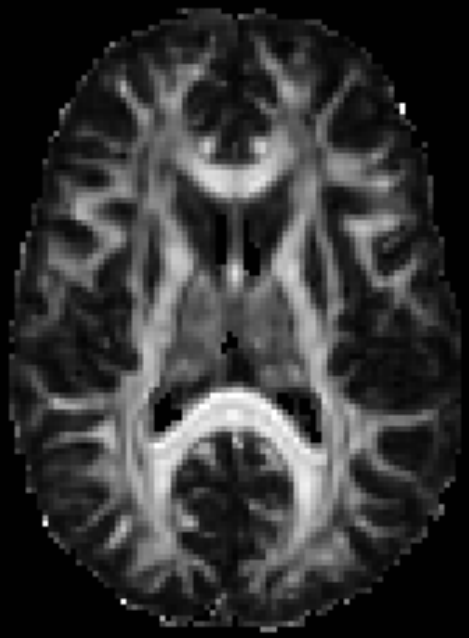


2.5 mm iso
15.625 mm^3

1.7mm iso
4.913 mm^3

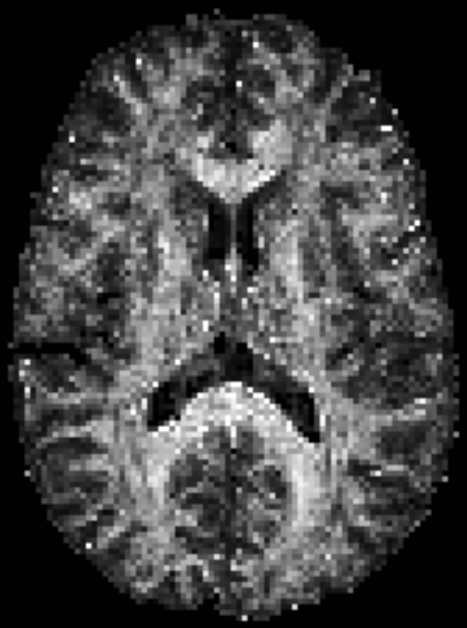
1.3mm iso
2.197 mm^3

Low SNR



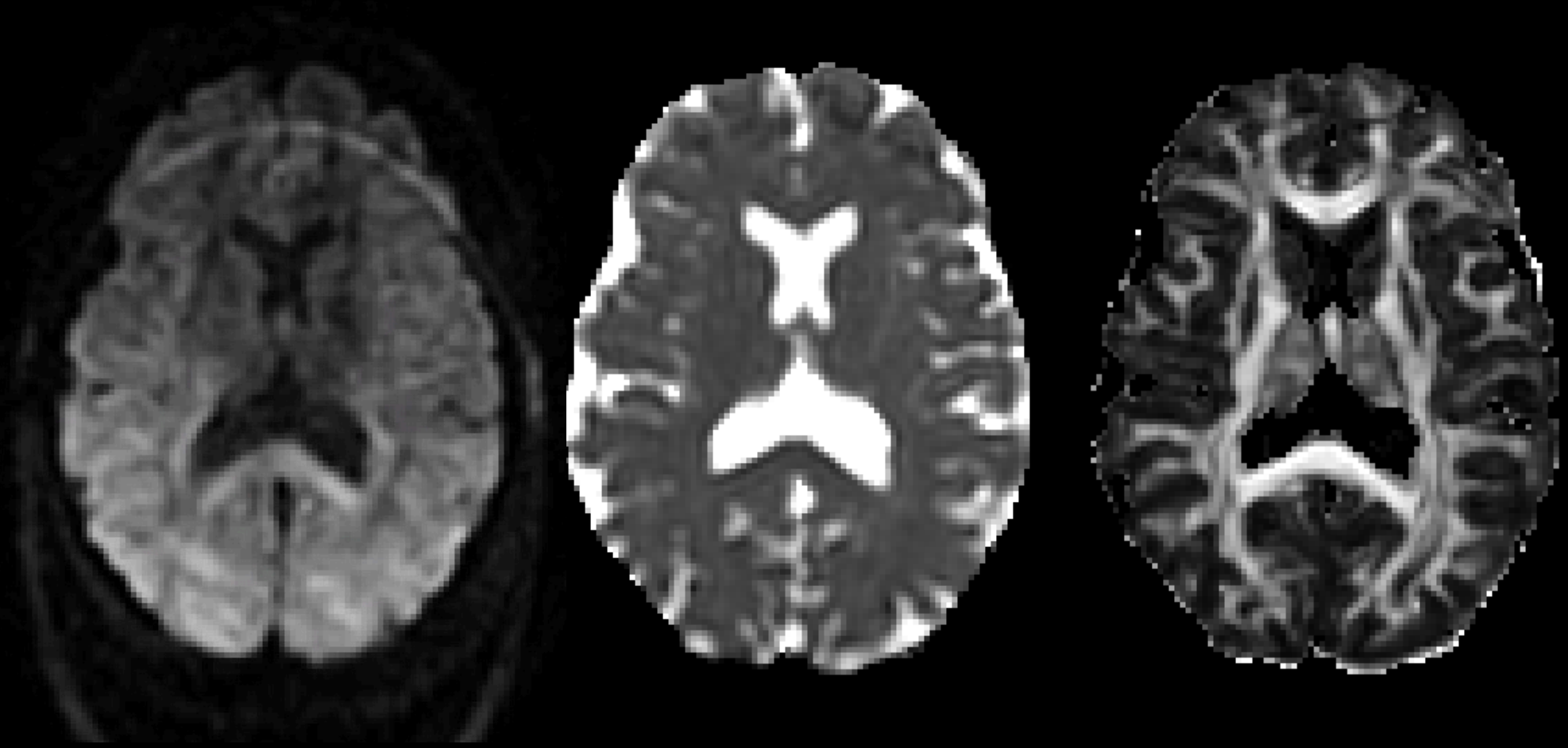
2.5 mm iso
15.625 mm^3

1.7mm iso
4.913 mm^3



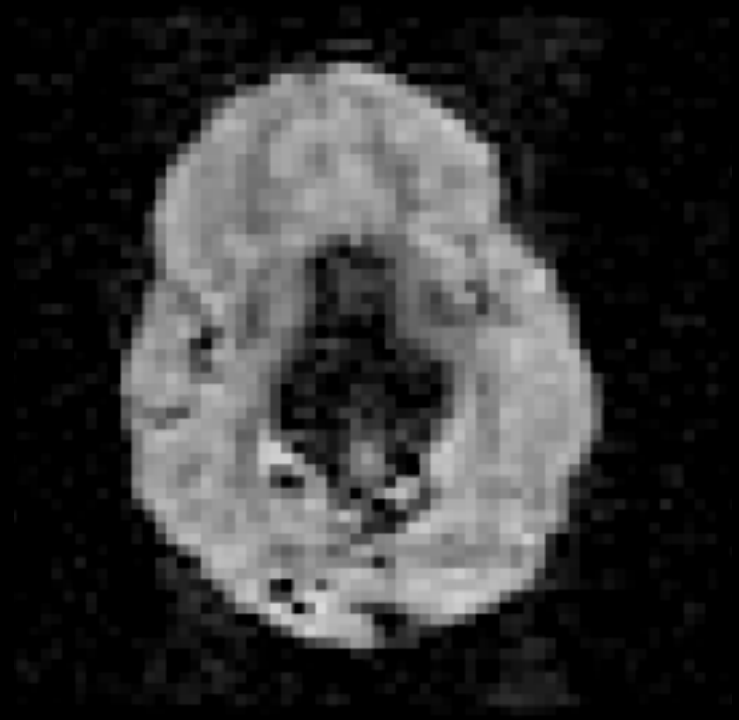
1.3mm iso
2.197 mm^3

Incomplete Fat Suppression



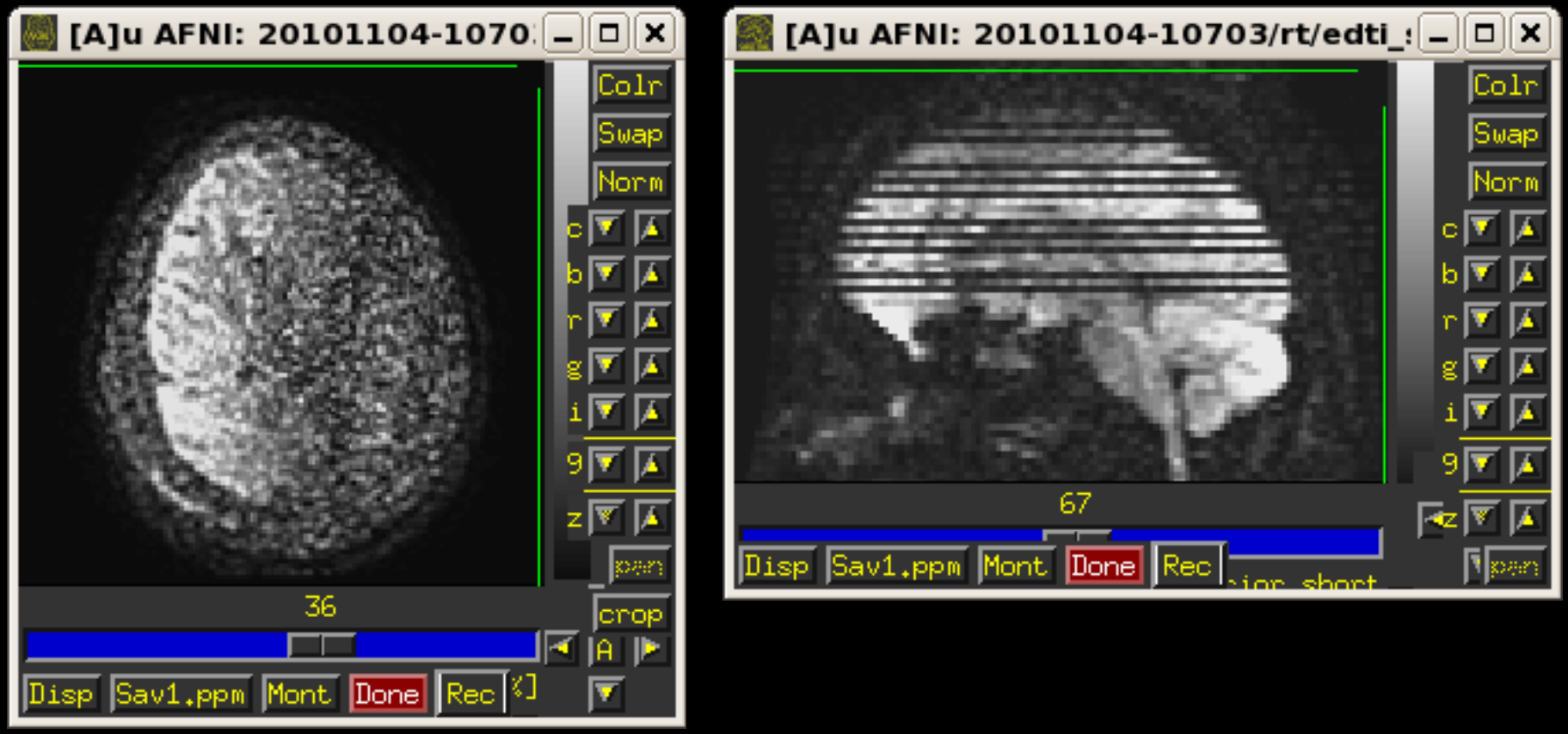
b=1100 s/mm^2 MD FA

Cardiac Pulsation



Diffusion weighting in Z

Bulk Movement



Outline

- What is diffusion?
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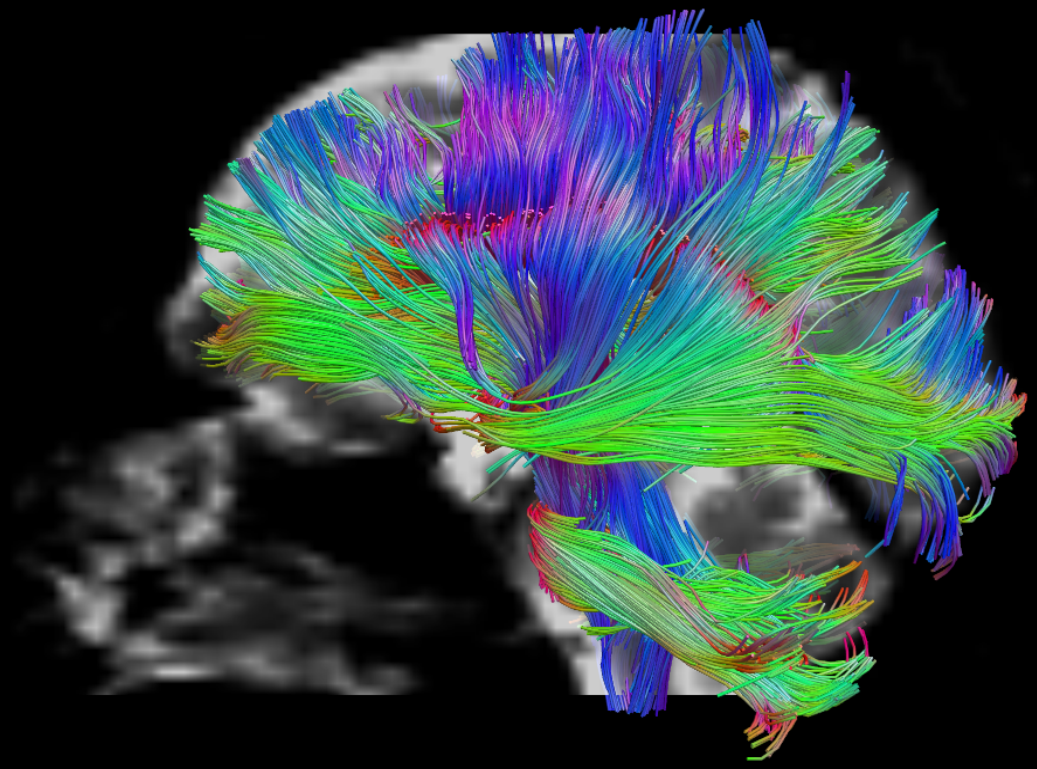
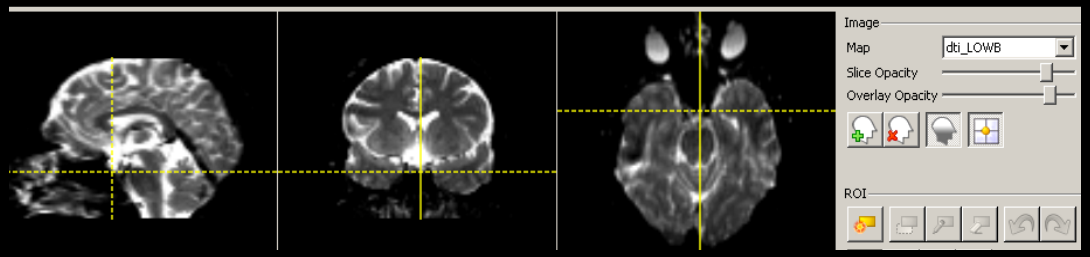
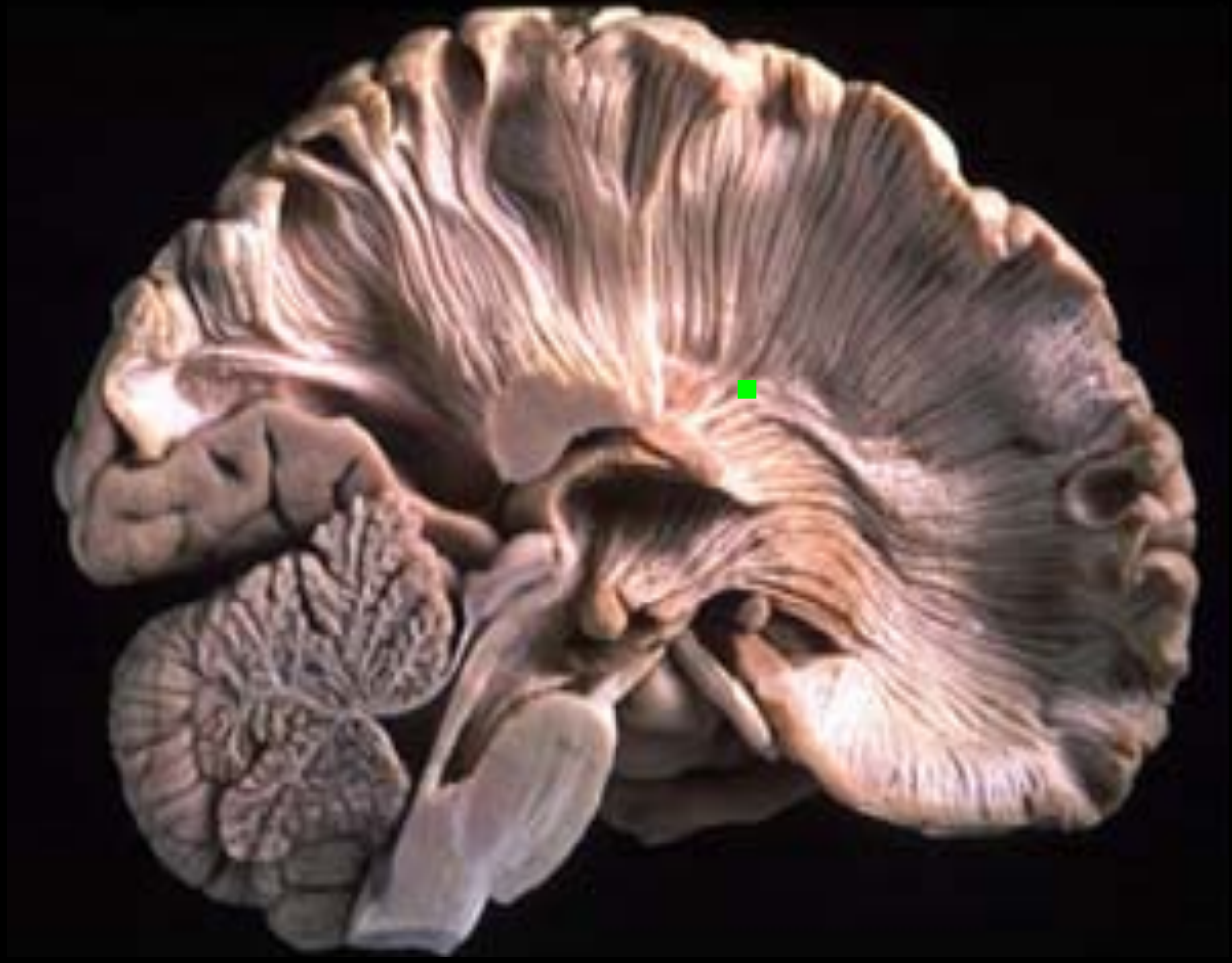
What isTractography?

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



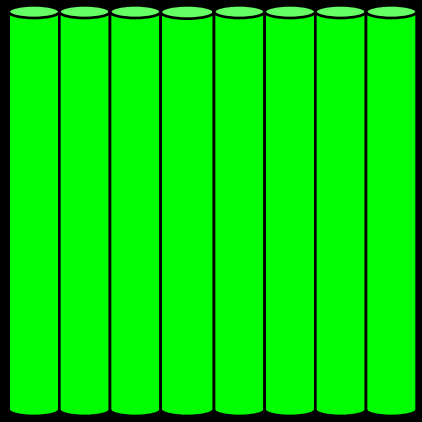
Typical resolution

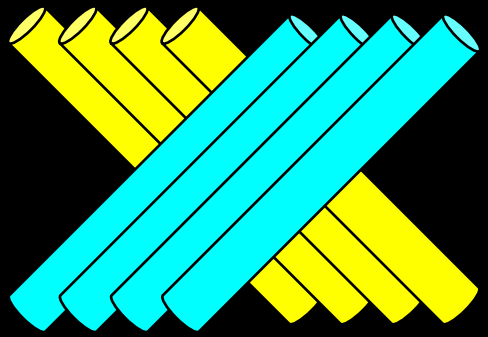
for SSEPI DTI

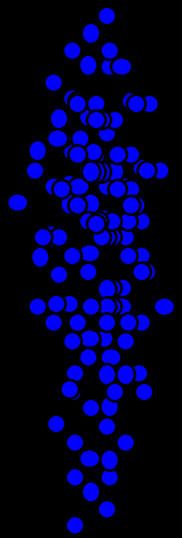
2.5 x 2.5 x 2.5 mm

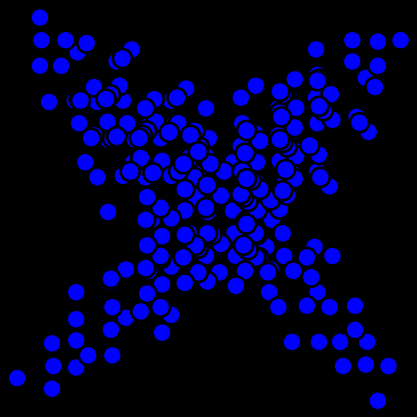
Cortical projection systems of left cerebral hemisphere

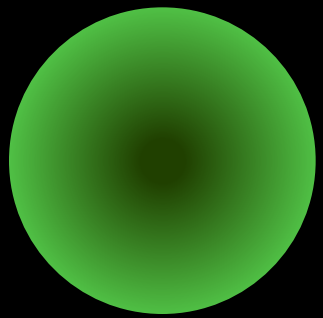
Partial Volume Effect





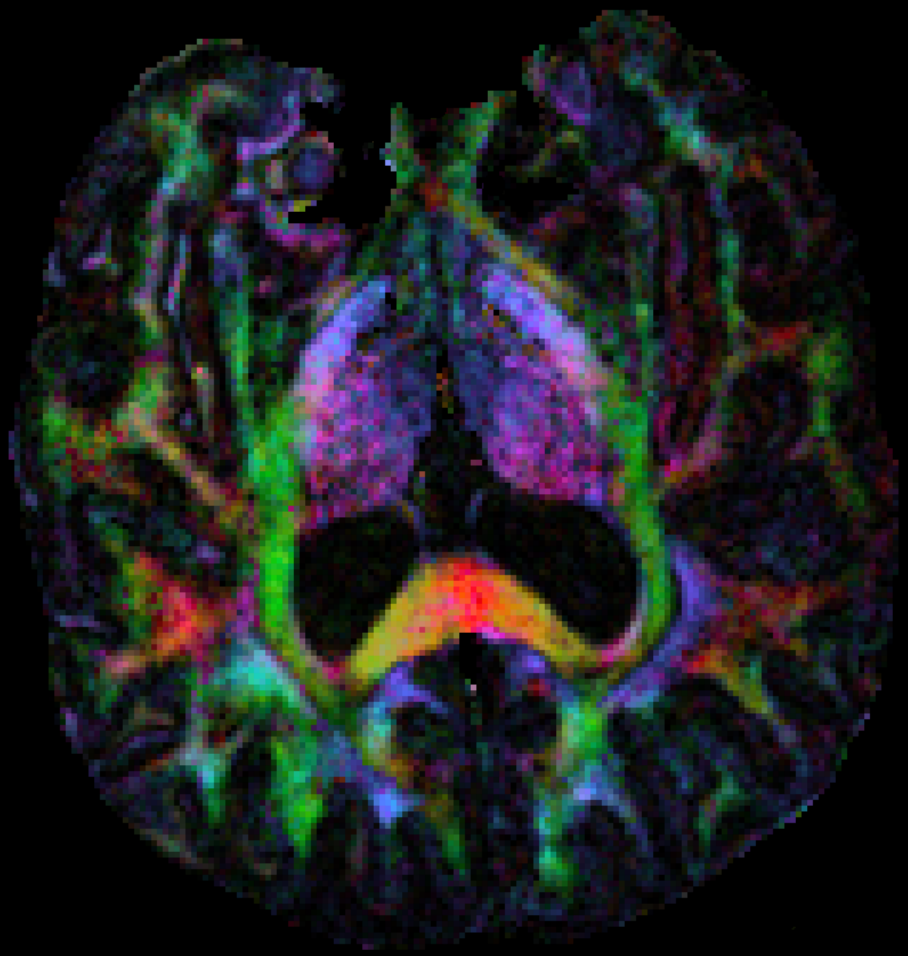






distribution DT ellipsoid distribution DT ellipsoid

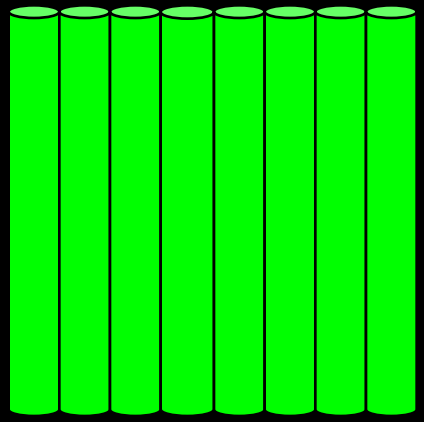
Sub-millimeter DTI

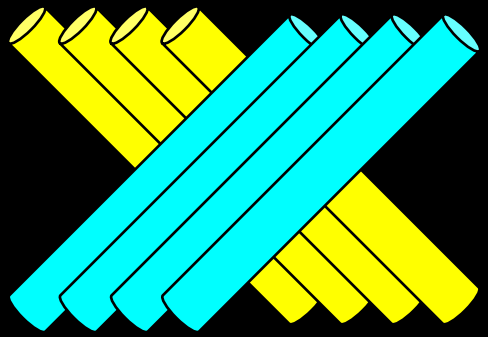


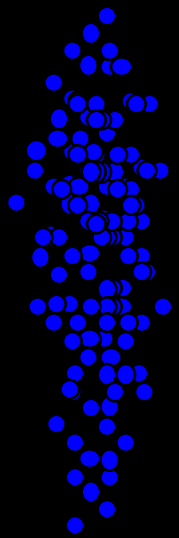
Beyond Standard DTI

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

Non-parametric Algorithms

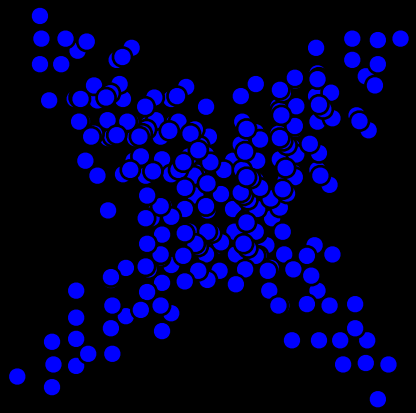


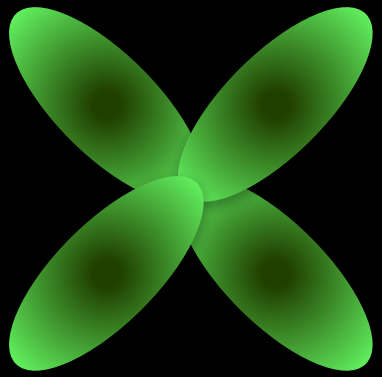




distribution

fODF





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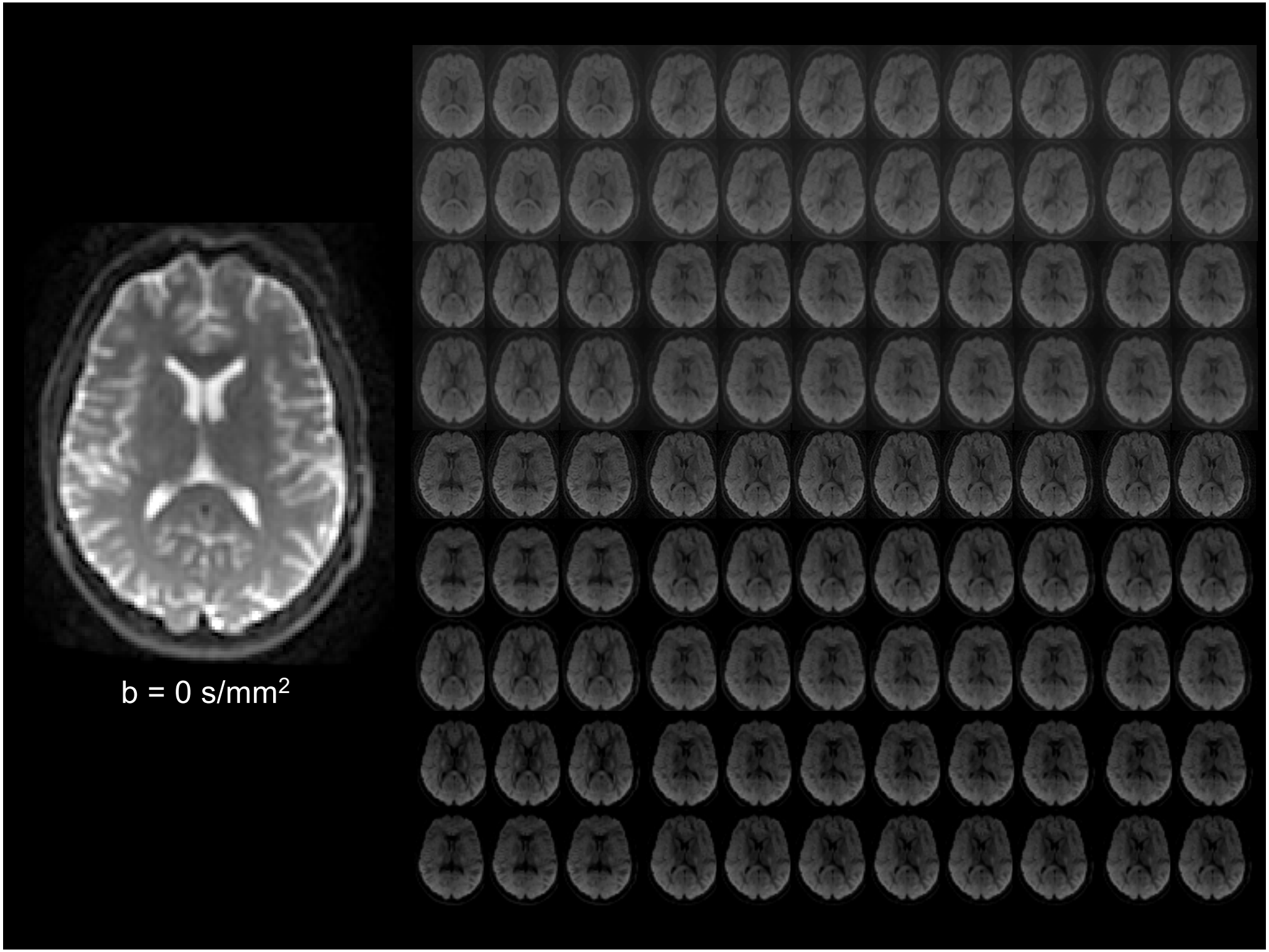
fODF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ACKNOWLEDGEMENTS

Peter Bandettini, PhD
Carlo Pierpaoli, MD,PhD
Ted Trouard, PhD
Lindsay Walker, MS
Kathy Warren, MD
Emilie Steffen
Dan Handwerker, PhD

THANK YOU