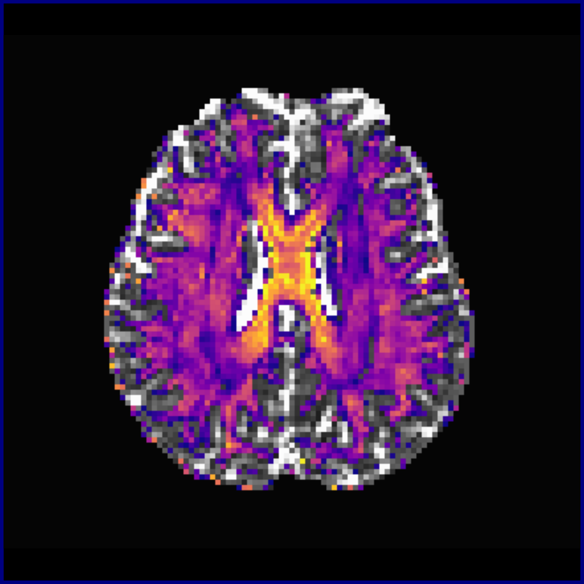
Introduction to: DWI + DTI

AFNI Bootcamp (SSCC, NIMH, NIH)



Outline

+ DWI and DTI
  - Concepts behind diffusion imaging
  - Diffusion imaging basics in brief
  - Connecting DTI parameters and geometry
  - Role of noise+distortion →DTI parameter uncertainty

What is diffusion tensor imaging?

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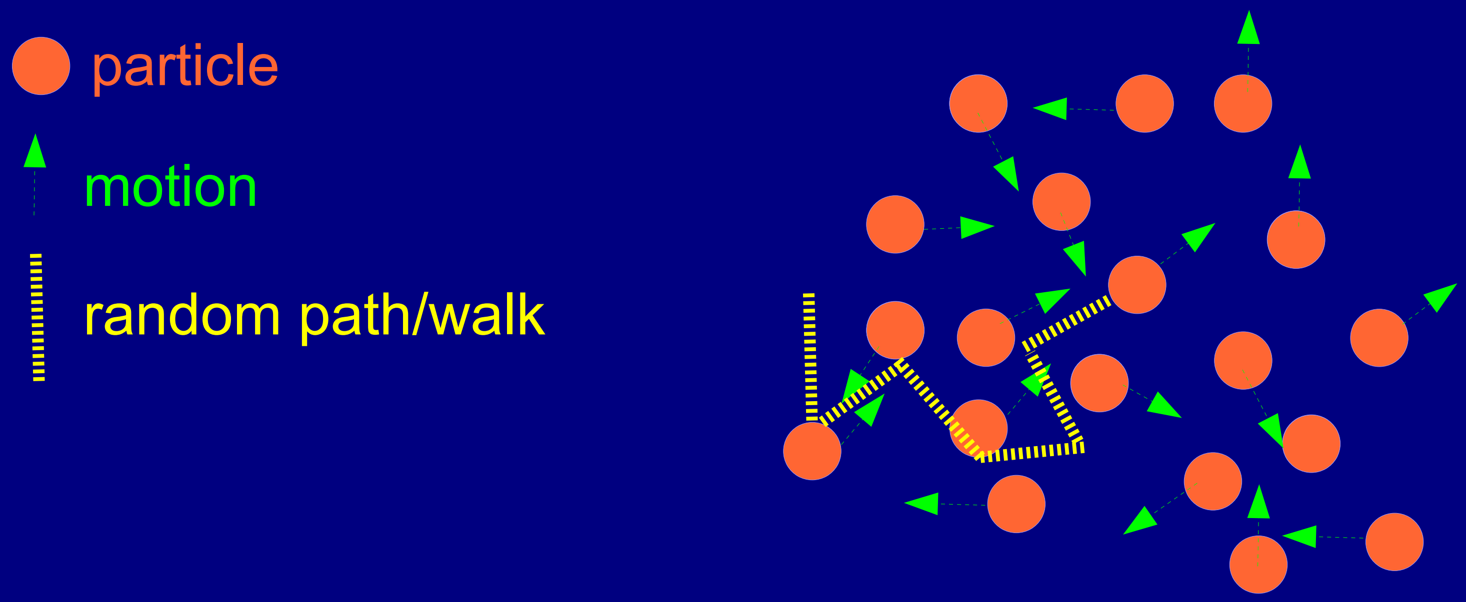
*D*iffusion: random motion of particles, tending to spread out

→ here, hydrogen atoms in aqueous brain tissue



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*T*ensor: a mathematical object (a matrix) to store information

→ here, quantifying particle spread in all directions

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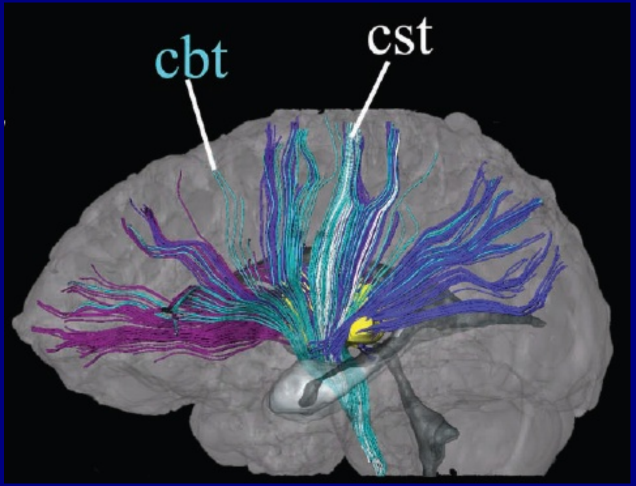
*I*maging: quantifying brain properties

→ here, esp. for white matter



The DTI model:

Assumptions and relation to WM properties

Diffusion as environmental marker

Diffusion: random (Brownian) motion of particles → mixing or spreading

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Atoms have equal probability of movement any direction
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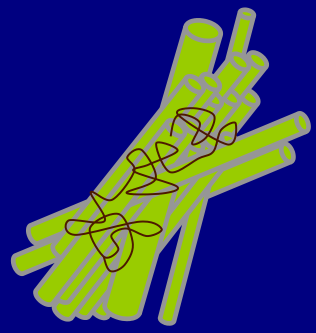
→ ***Diffusion shape tells of* structure presence *and* spatial orientation**

Local Structure via Diffusion MRI



(In brief)

1) Random motion of molecules affected by local structures

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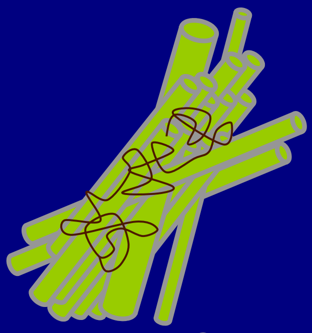
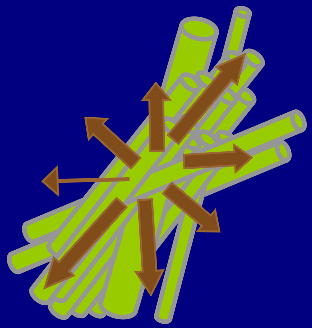


2) Statistical motion measured using diffusion weighted MRI



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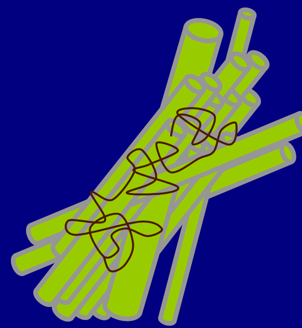

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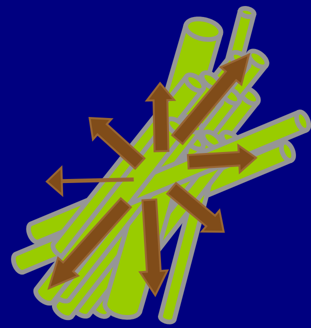
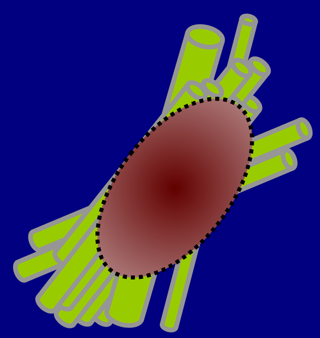


3) Bulk features of local structure approximated with various reconstruction models, mainly grouped by number of major structure directions/voxel:

+ one direction:
  DTI (Diffusion Tensor Imaging)



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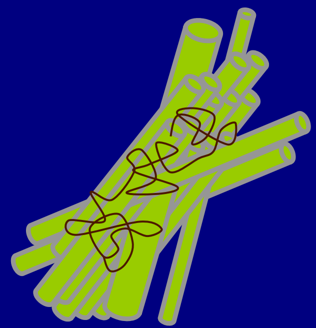

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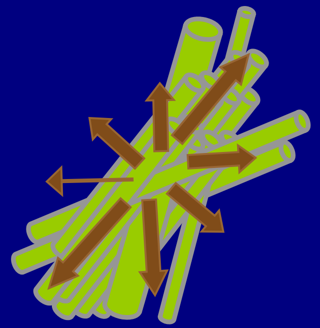

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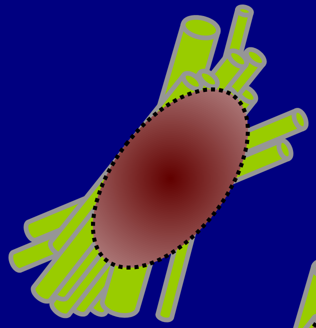

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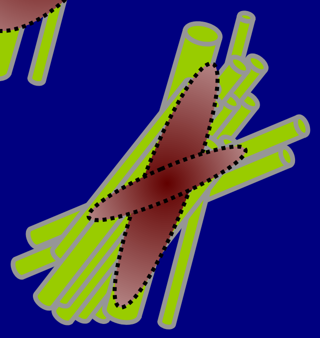

- >=1 direction:
  HARDI (High Angular Resolution Diffusion Imaging)
  Qball, DSI, ODFs, ball-and-stick, multi-tensor, CSD, ...

Diffusion in MRI

Mathematical properties
of the matrix/tensor:

$$\mathbf{D} = \begin{pmatrix} D_{11} & D_{12} & D_{13} \\ D_{21} & D_{22} & D_{23} \\ D_{31} & D_{32} & D_{33} \end{pmatrix}$$

Having: 3 eigenvectors: $\mathbf{e}_i$
3 eigenvalues: λ_i

- Real-valued
- Positive definite ($\mathbf{r}^T\mathbf{D}\mathbf{r} > 0$)

  $\mathbf{De}_i = \lambda\lambda_i\, \mathbf{e}_i$, $\lambda_i > 0$
- Symmetric ($D_{12} = D_{21}$, etc)

  6 independent values

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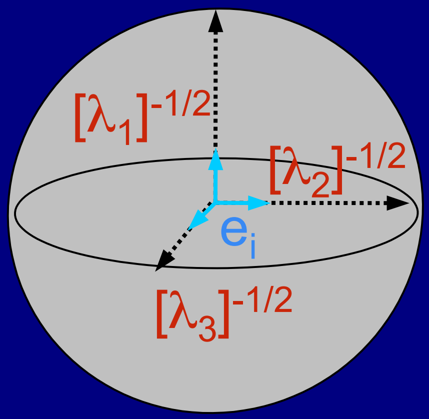
Geometrically, this describes an ellipsoid surface:

$$C = D_{11}x^2 + D_{22}y^2 + D_{33}z^2 + 2(D_{12}xy + D_{13}xz + D_{23}yz)$$

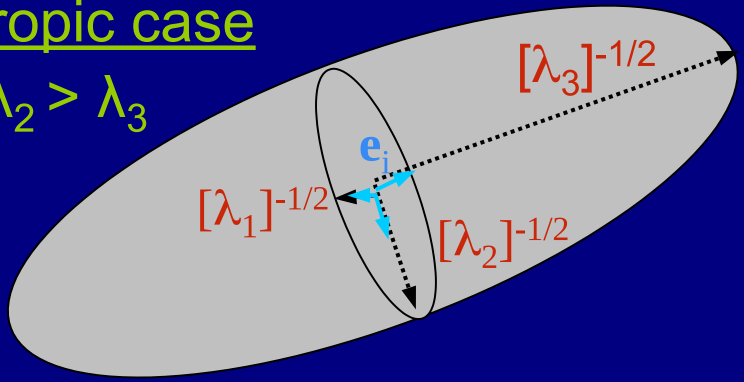
isotropic case

$\lambda_1 = \lambda_2 = \lambda_3$



anisotropic case

$\lambda\lambda_1 > \lambda_2 > \lambda_3$



DTI: ellipsoids

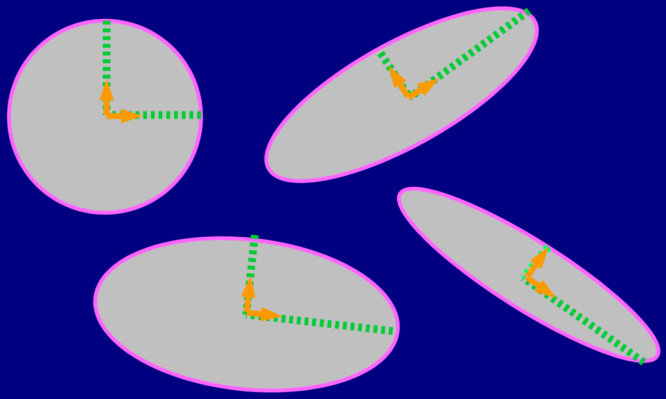
Important mathematical properties of the diffusion tensor:

+ Help to picture diffusion model:

  tensor **D** → **ellipsoid surface**

  eigenvectors $\mathbf{e}_i$ → orientation in space

  eigenvalues λ_i → 'pointiness' + 'size'



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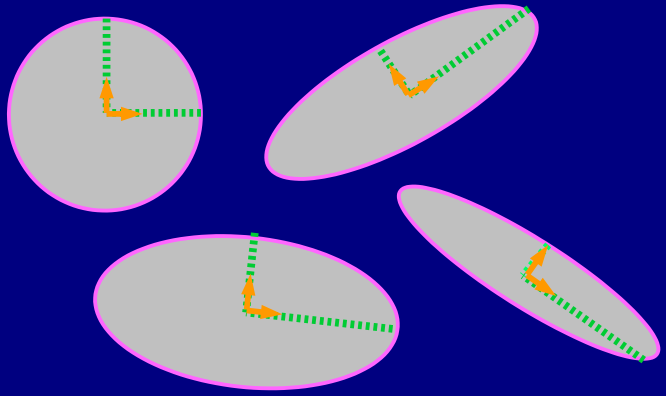

+ Determine the minimum number of
  DWIs measures needed (6 + baseline)

$$\begin{pmatrix} D_{11} & D_{12} & D_{13} \\ D_{21} & D_{22} & D_{23} \\ D_{31} & D_{32} & D_{33} \end{pmatrix}$$

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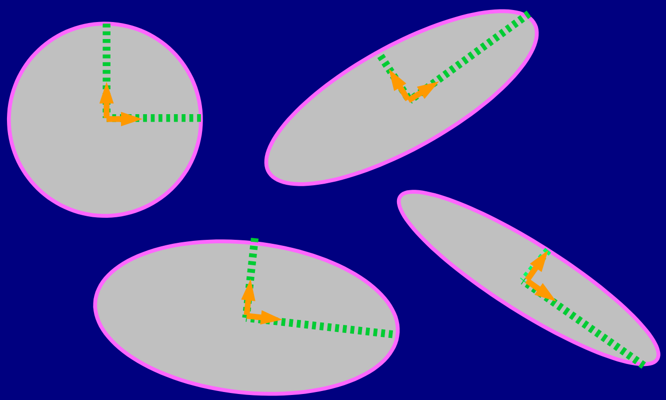

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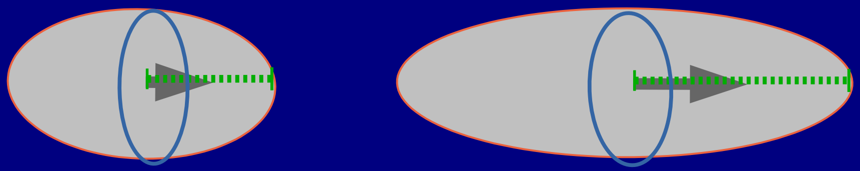
+ Determine much of the processing and noise minimization steps

“Big 5” DTI ellipsoid parameters

Main quantities of diffusion (motion) surface

first eigenvalue, L1
(= λ_1, parallel/axial diffusivity, AD)



$L1_1 < L1_2$

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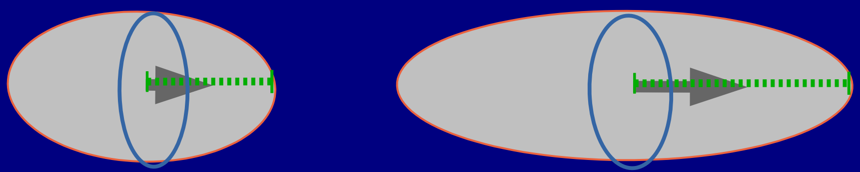
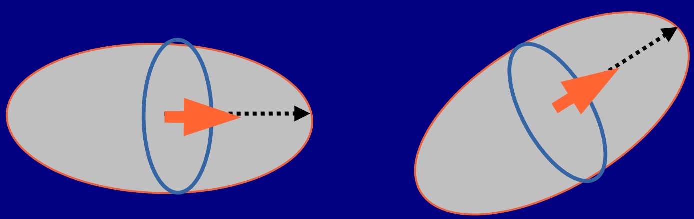


$L1_1$ < $L1_2$

first eigenvector, e_1
(DT orientation in space)



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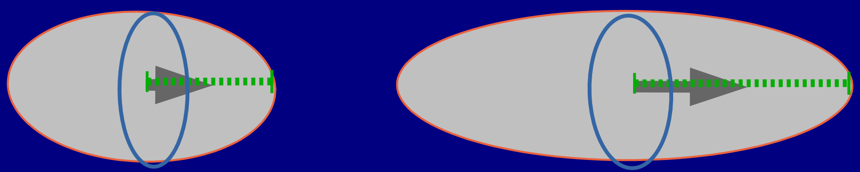

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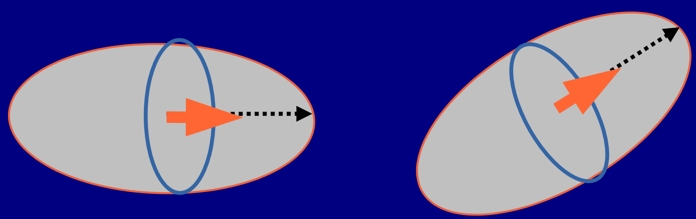
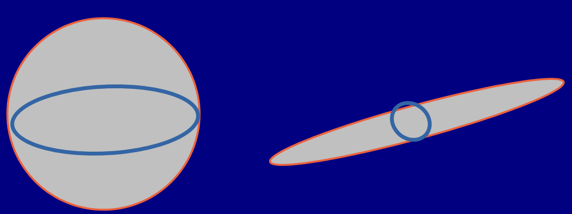


e_1 e_1

Fractional anisotropy, FA
(stdev of eigenvalues)



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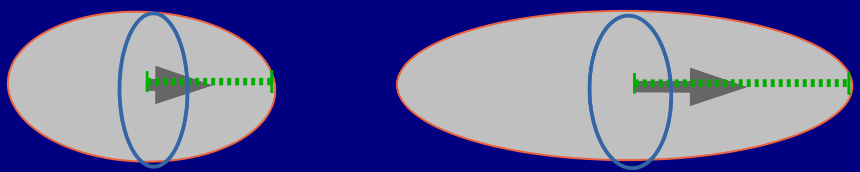

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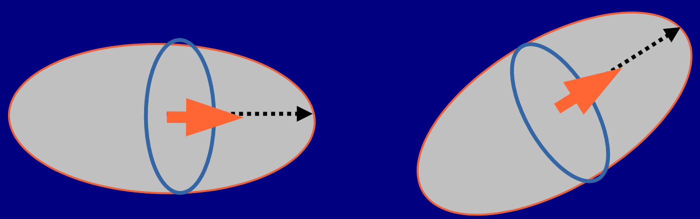

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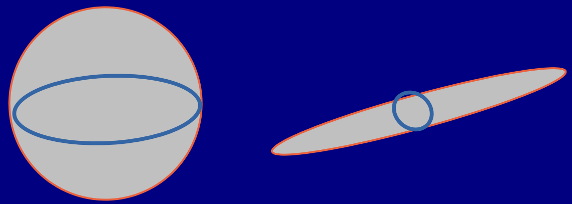
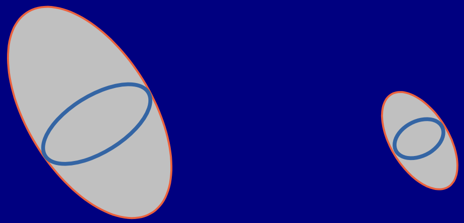


FA≈0 FA≈1

Mean diffusivity, MD
(mean of eigenvalues)



MD_1 > MD_2

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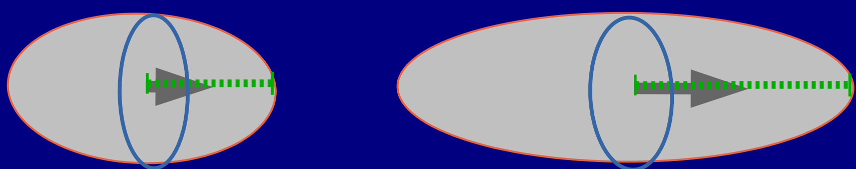

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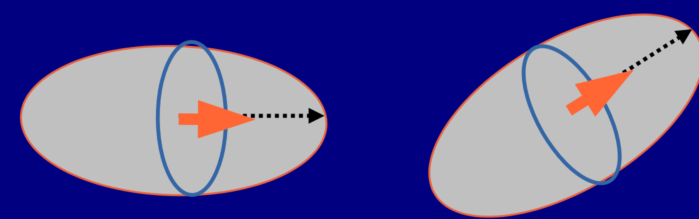

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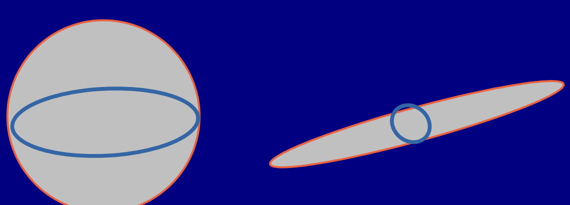

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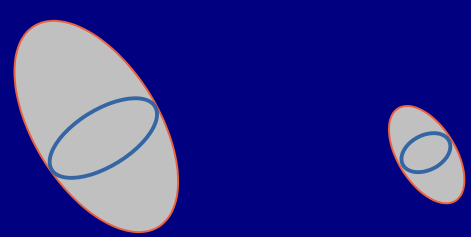
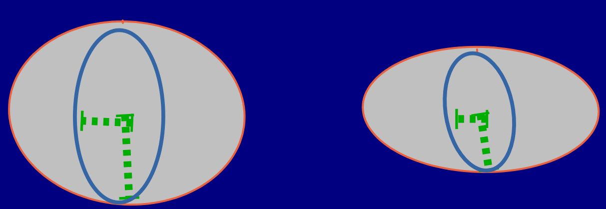


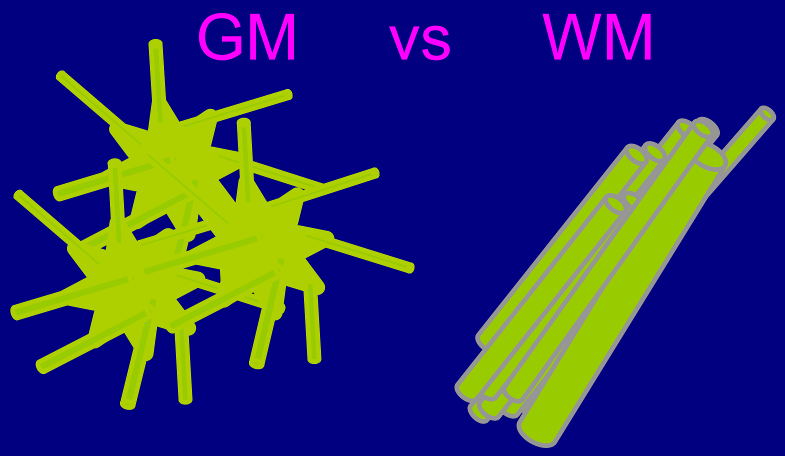
MD_1 > MD_2

Radial diffusivity, RD
(= $(\lambda_2+\lambda_3)/2$)



RD_1 > RD_2

Cartoon examples: white matter $\leftrightarrow$ FA



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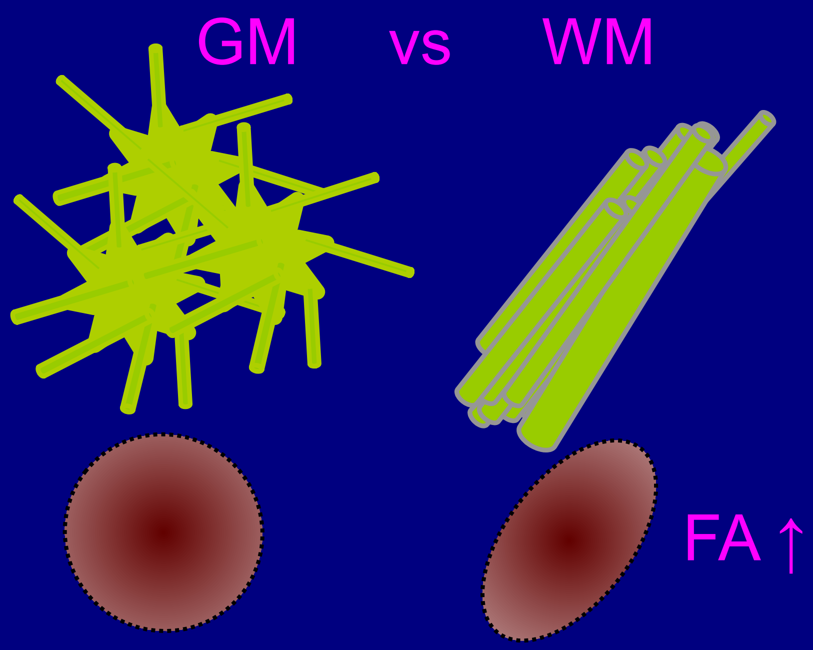

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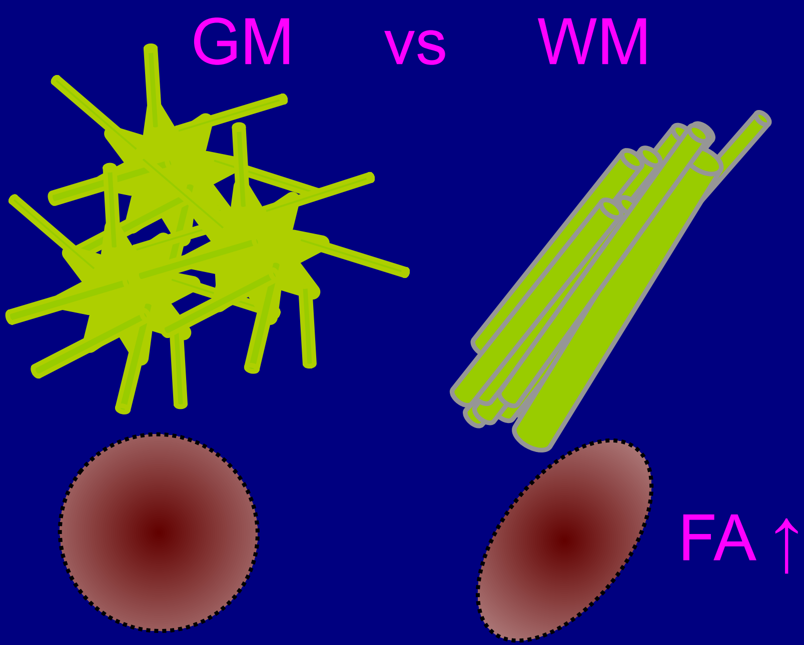

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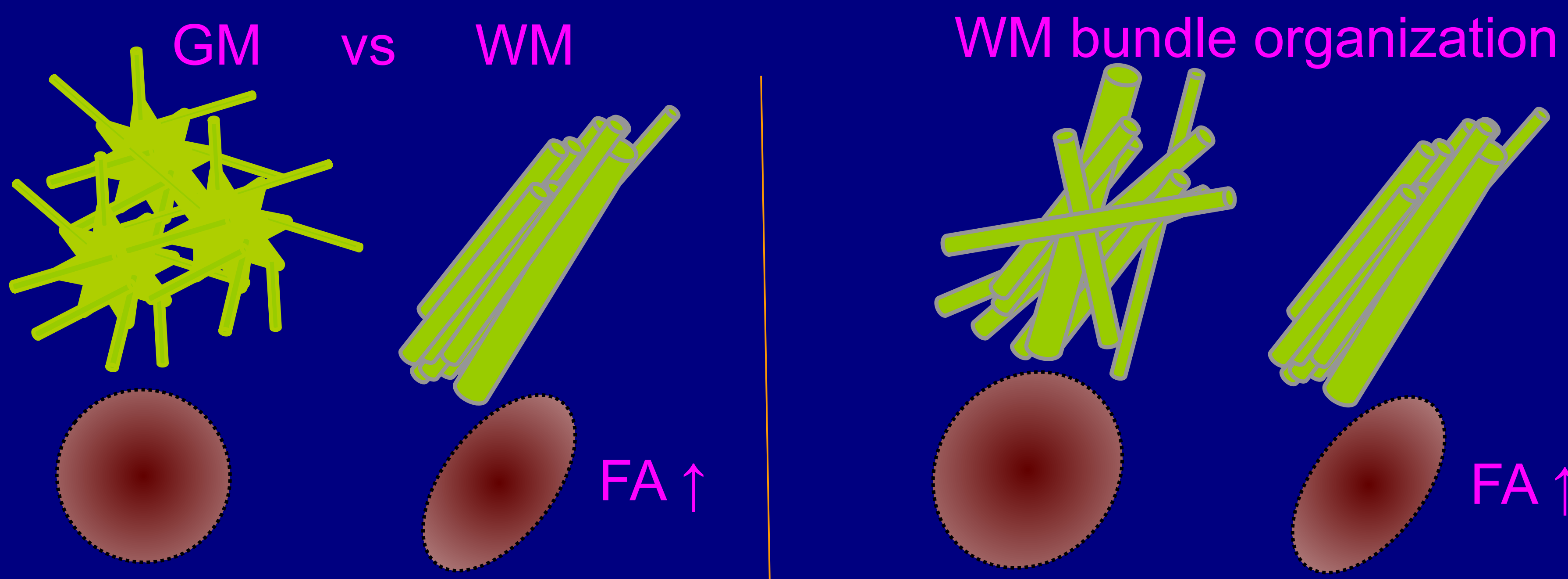

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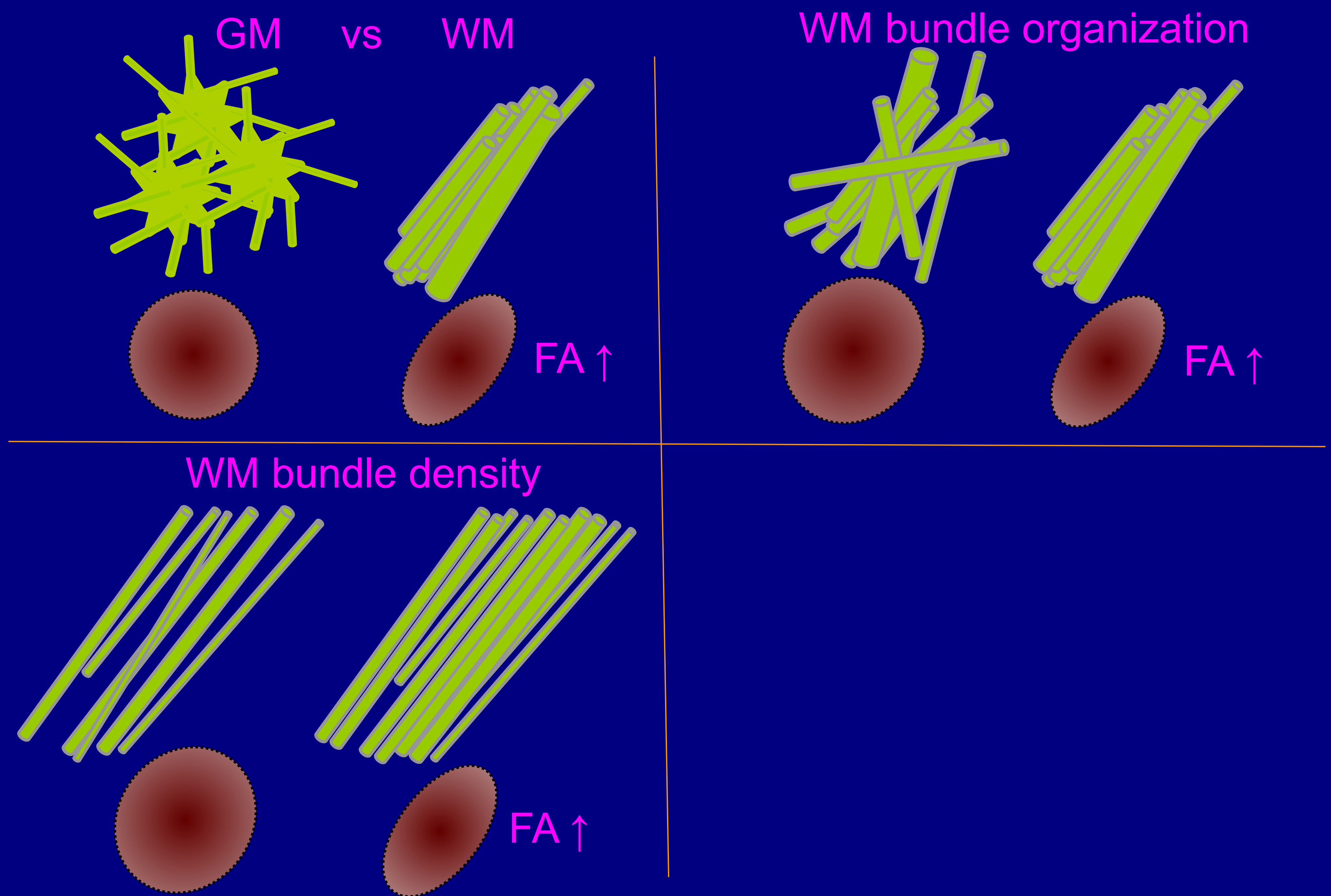

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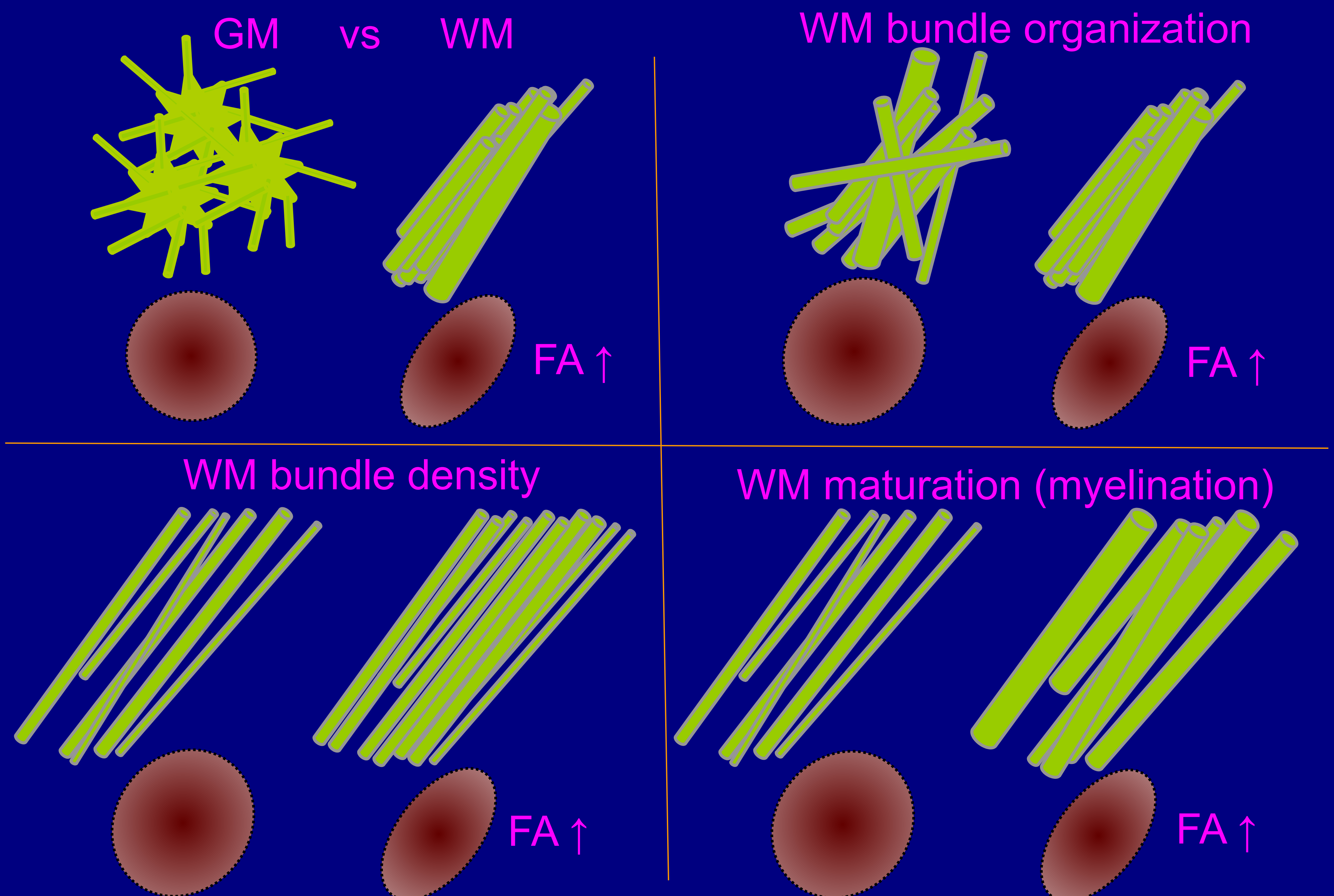


Interpreting DTI parameters

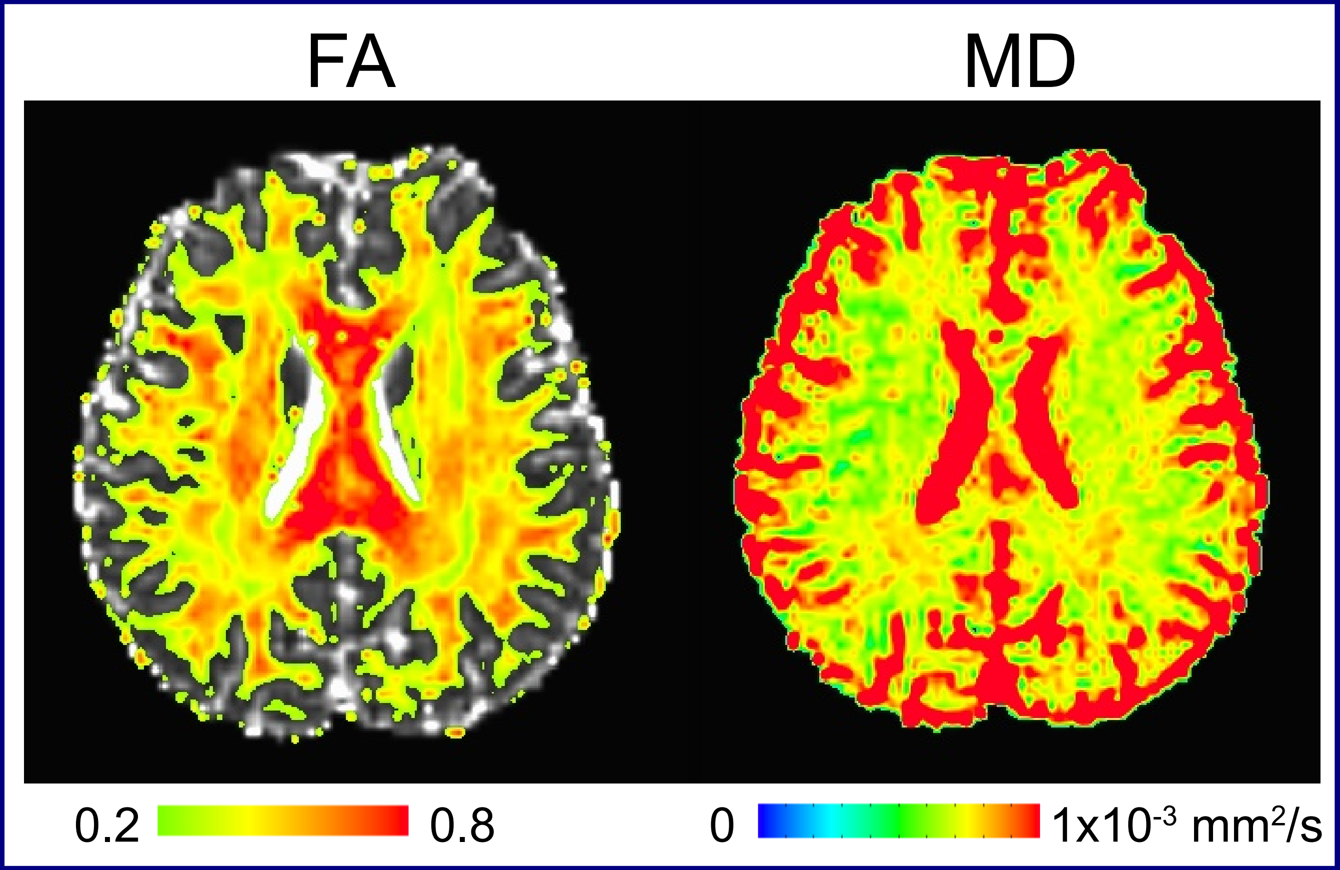
General literature:

FA: measure of fiber bundle coherence and myelination

- in adults, FA>0.2 is proxy for WM

MD, L1, RD: local density of structure

$\mathbf{e}_1$: orientation of major bundles



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Cautionary notes:

- Degeneracies of structural interpretations
- Changes in myelination may have small effects on FA
- WM bundle diameter << voxel size
  - don't know location/multiplicity of underlying structures
- More to diffusion than structure-- e.g., fluid properties
- Noise, distortions, etc. in measures

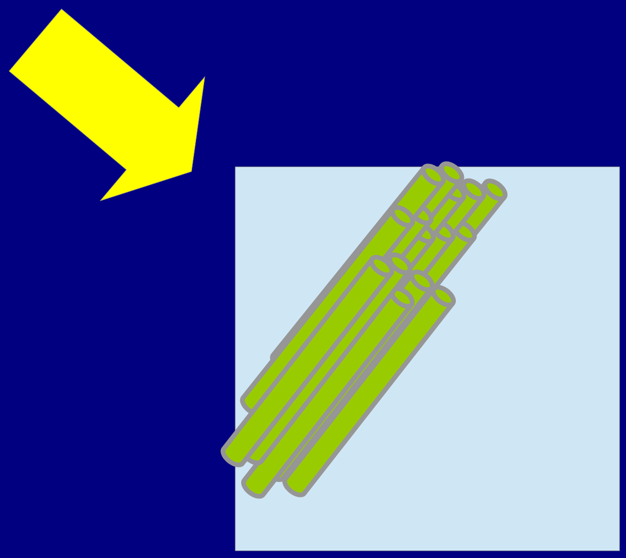
Acquiring DTI data:

diffusion weighted gradients in MRI

Diffusion weighted imaging

For a given voxel, observe relative diffusion along a given 3D spatial orientation (gradient)

DW gradient
$\mathbf{g_i} = (g_x, g_y, g_z)$



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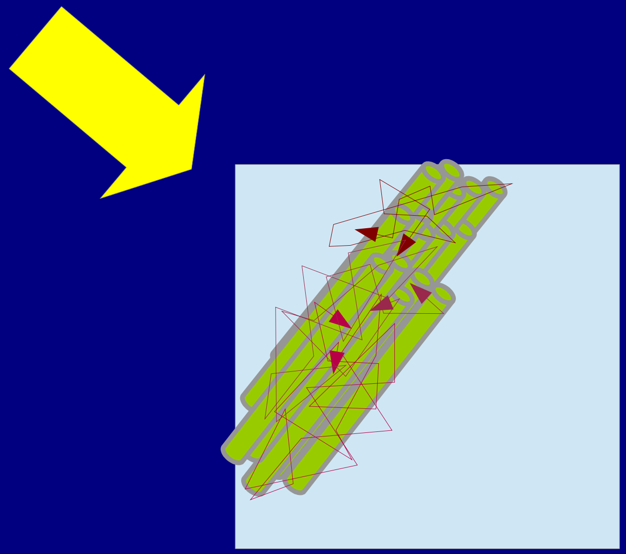

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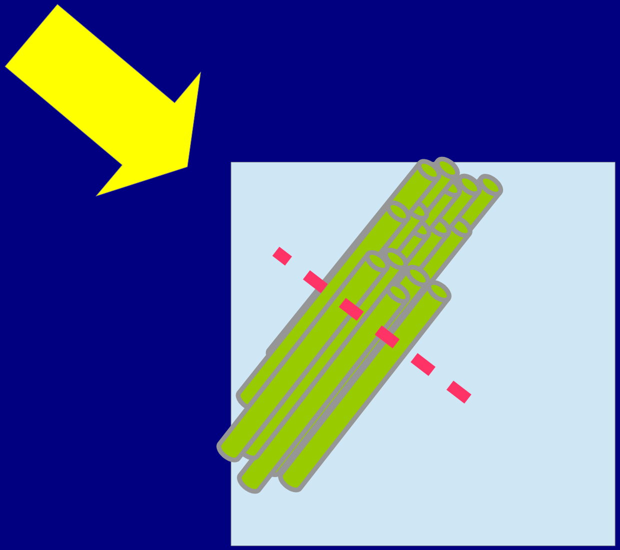

MR signal is attenuated by diffusion throughout the voxel in that direction:

$$S_i = S_0 \, e^{-b \, \mathbf{g}_\mathbf{i}^T \, \mathbf{D} \, \mathbf{g}_\mathbf{i}}$$

→ ellipsoid equation of diffusion surface:
$C = \mathbf{r}^T \, \mathbf{D}^{-1} \, \mathbf{r}.$

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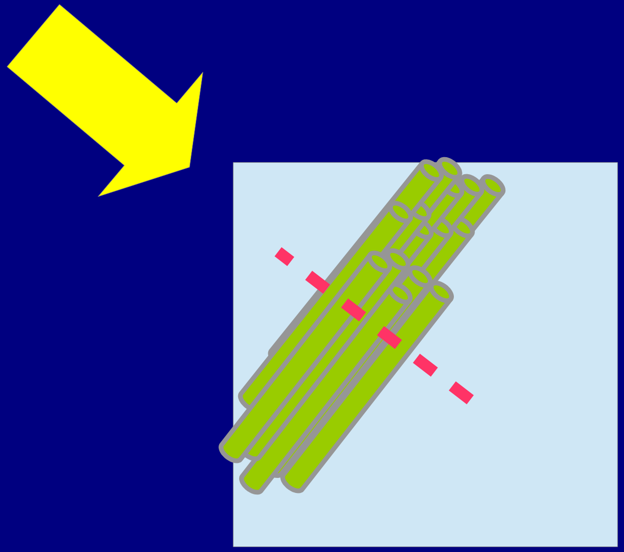
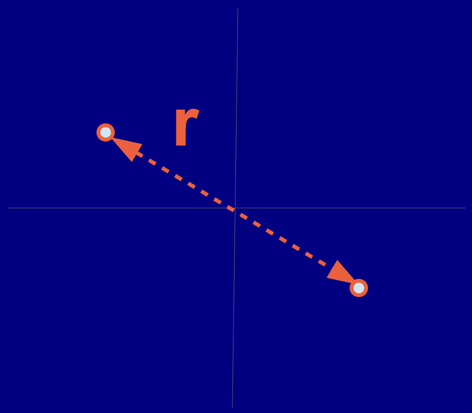


diffusion
motion
ellipsoid:

$C_2 = \mathbf{r}^T \mathbf{D}^{-1} \mathbf{r}.$



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diffusion motion ellipsoid:

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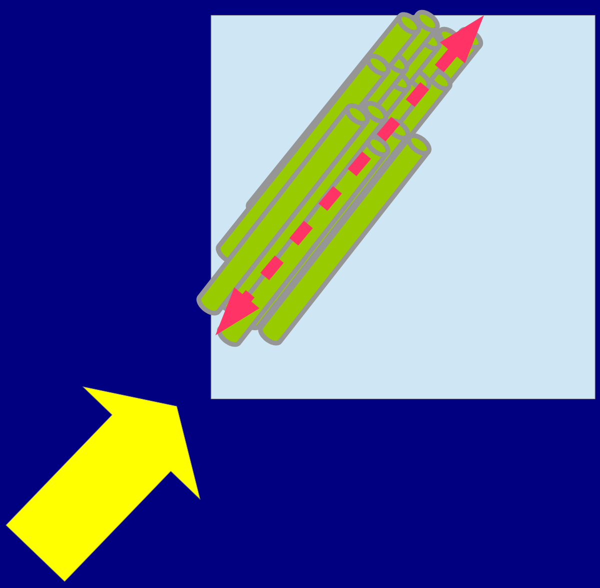

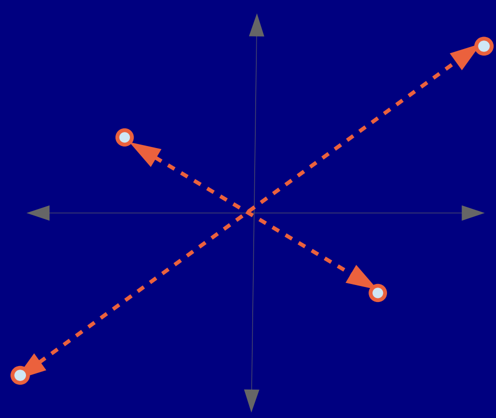

Diffusion weighted imaging

For a given voxel, observe relative diffusion along a given 3D spatial orientation (gradient)

DW gradient
$\mathbf{g_i} = (g_x, g_y, g_z)$

diffusion motion ellipsoid:
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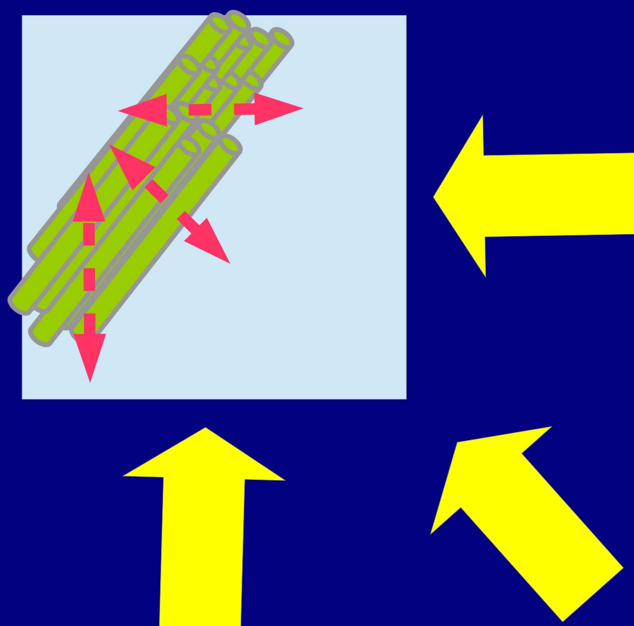

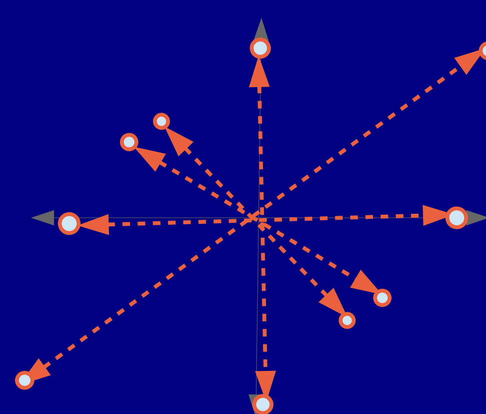

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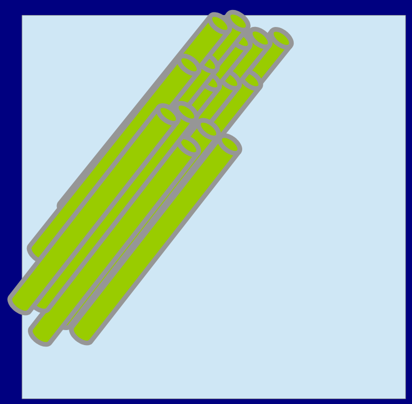
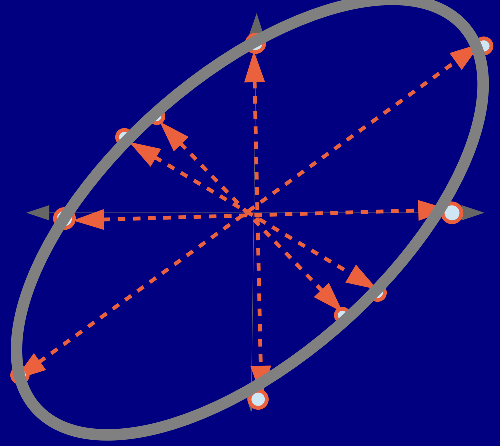


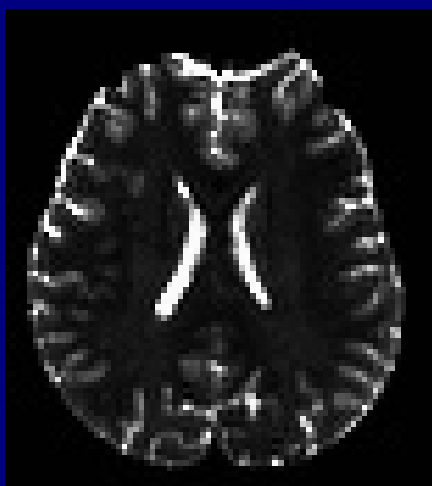


Individual points → Fit ellipsoid surface

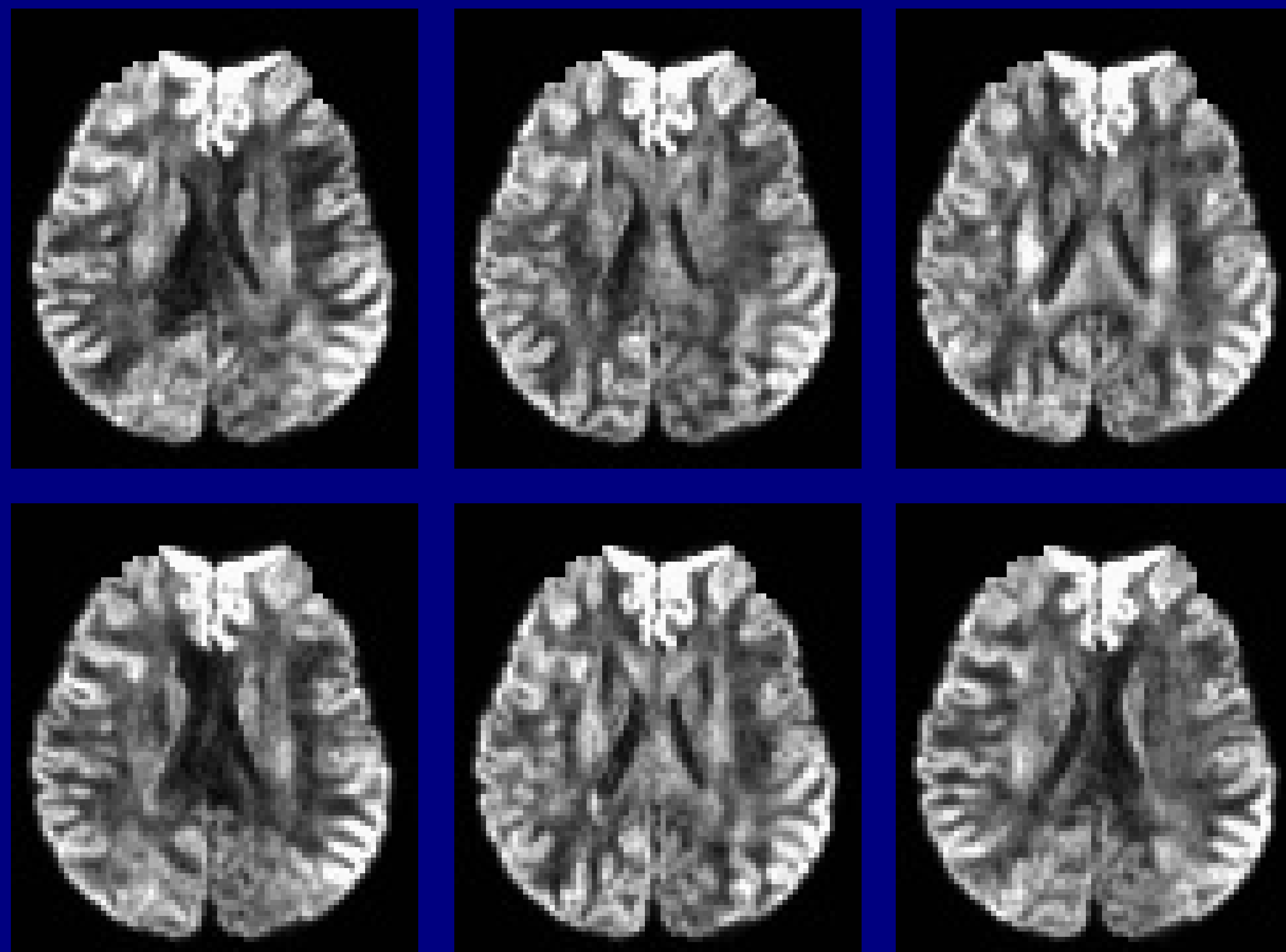
Individual signals → Solve for **D**

Sidenote: what DWIs look like

Unweighted
reference
b=0 s/mm^2



Diffusion weighted images
(example: b=1000 s/mm^2)



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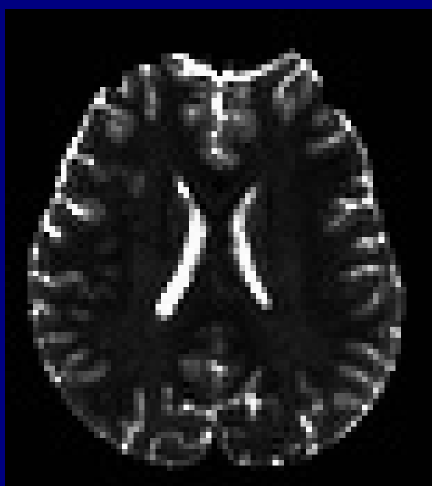

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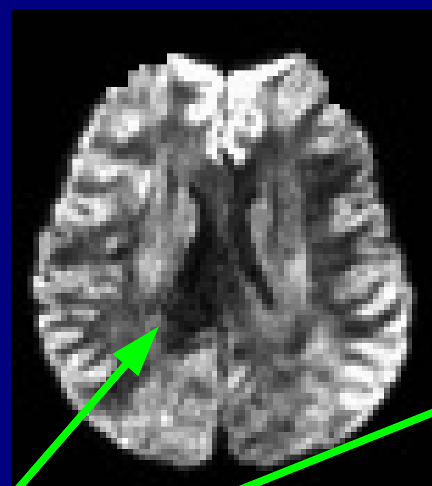

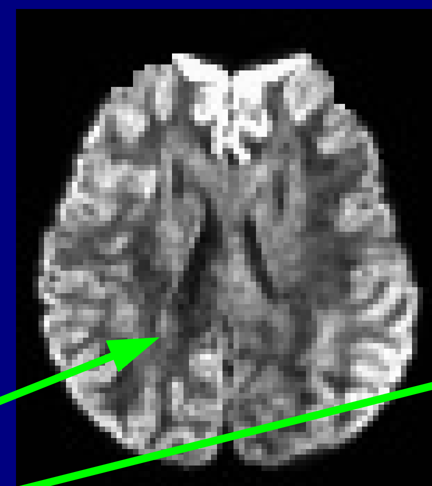

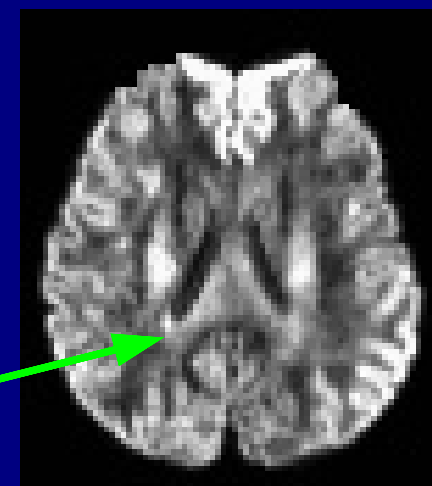

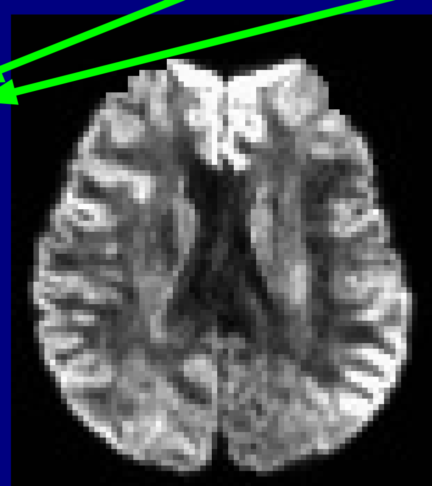

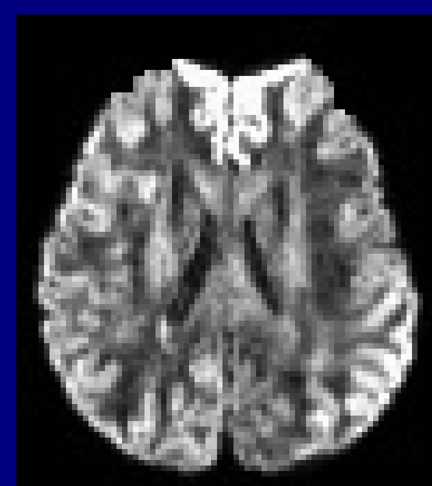

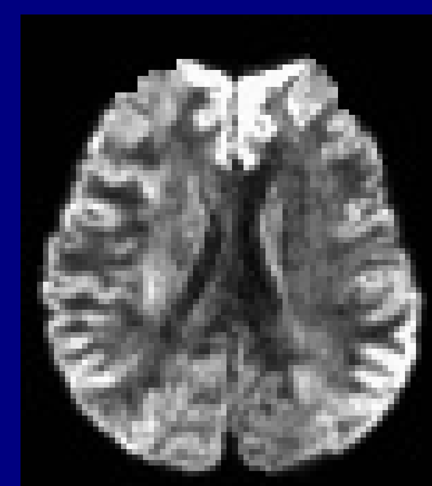

(Each DWI has a different brightness pattern: viewing structures from different angles.)

Noise in DW signals

MRI signals have additive noise

$$S_i = S_0 \, e^{-b \, \mathbf{g}_i^T \mathbf{D} \, \mathbf{g}_i} + \varepsilon,$$

where ε is (Rician) noise.

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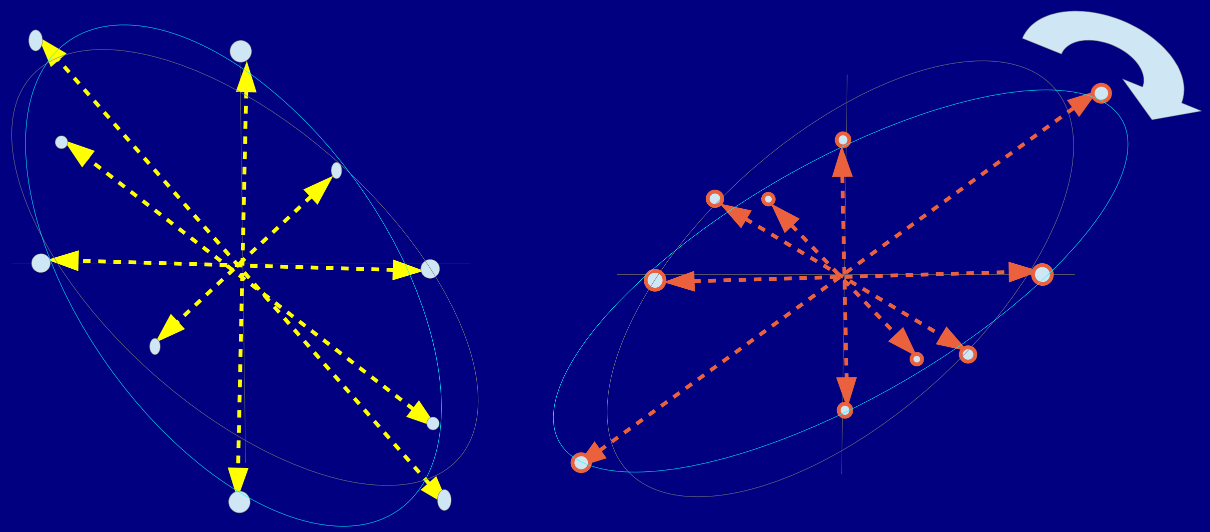

'Un-noisy' vs perturbed/noisy fit

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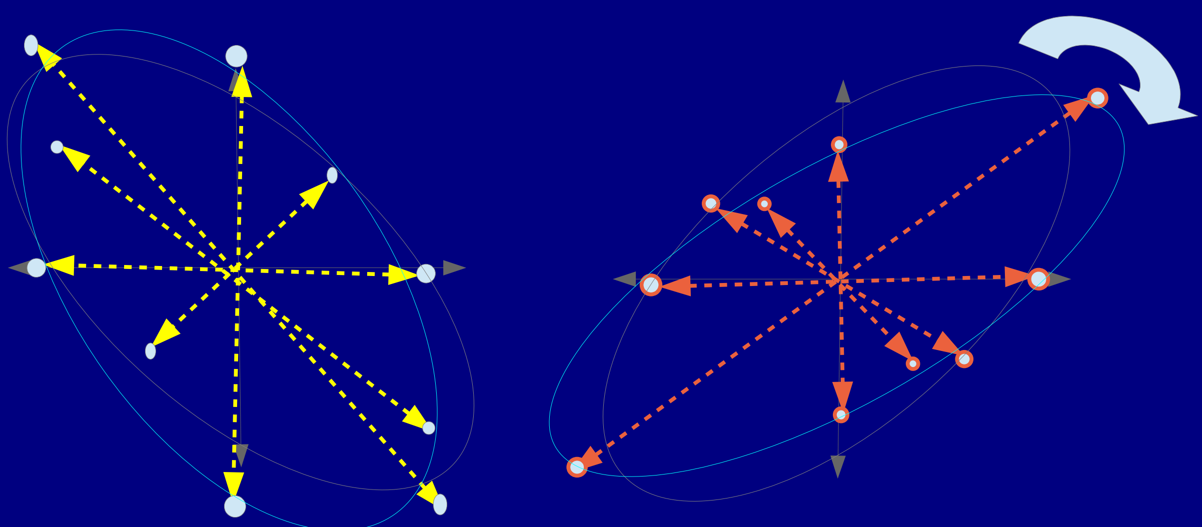


<u>Leads to standard:</u>
+ 30 DWs (~12 clinical)
+ repetitions of b=0
+ DW *b* chosen by:
  MD * *b* ≈ 0.84
+ nonlinear tensor fitting

'Un-noisy' vs perturbed/noisy fit

Distortions in DWI volumes

There are also **serious** sources of distortion when acquiring DWIs:

+ <u>Subject motion</u>

  due to movement during/between volume acq. -> signal loss/overlap

+ <u>Eddy current distortion</u>

  due to rapid switching of gradients -> nonlinear/geometric distortions

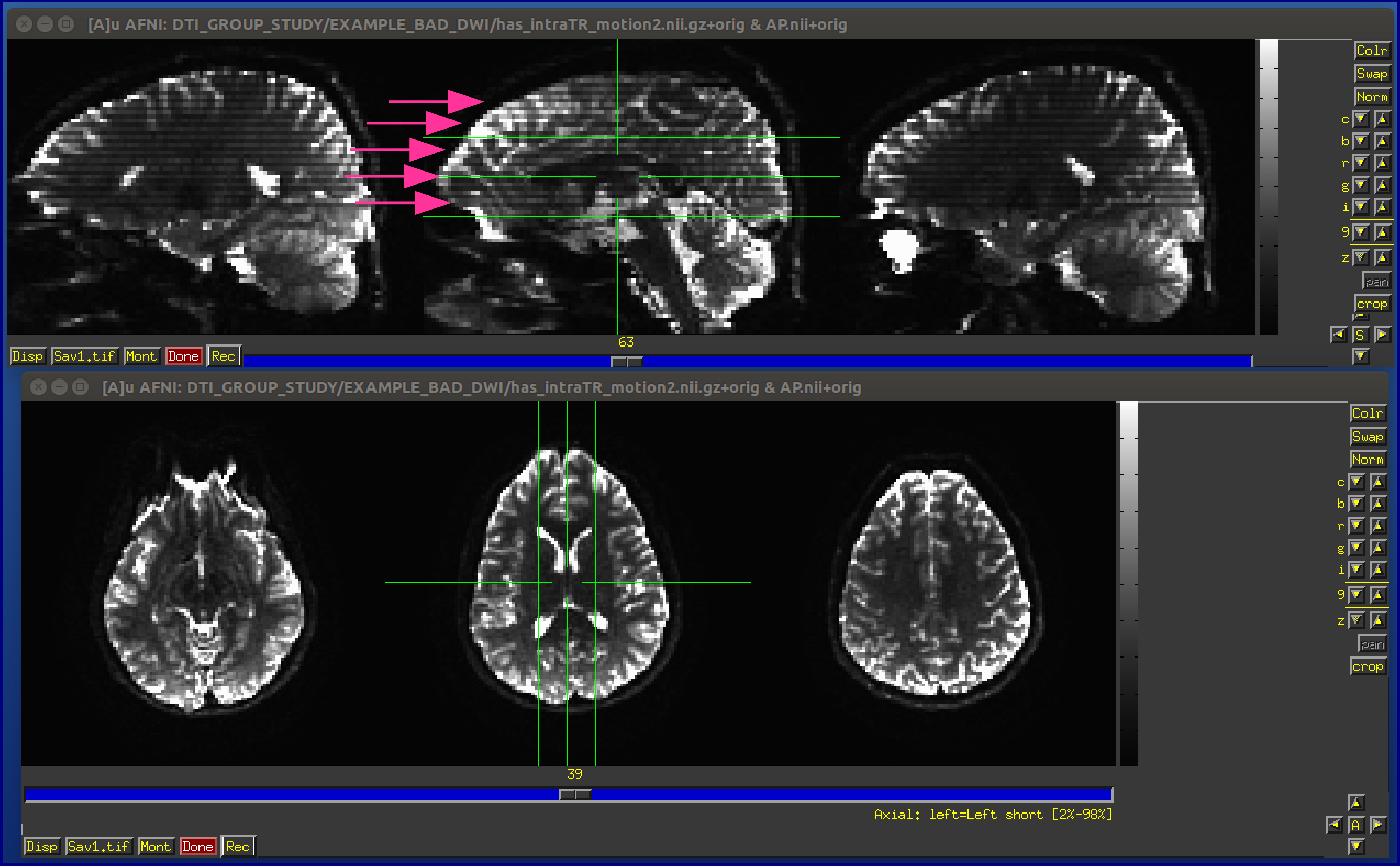
+ <u>EPI distortion</u>

  due to B0 inhomogeneity -> geometric distortions along phase encoding dir, signal pileup or attenuation

---> And effects combine! Need careful acquisition (sometimes perhaps even **re**acquisitions) and post-processing.

Distortions in DWI volumes

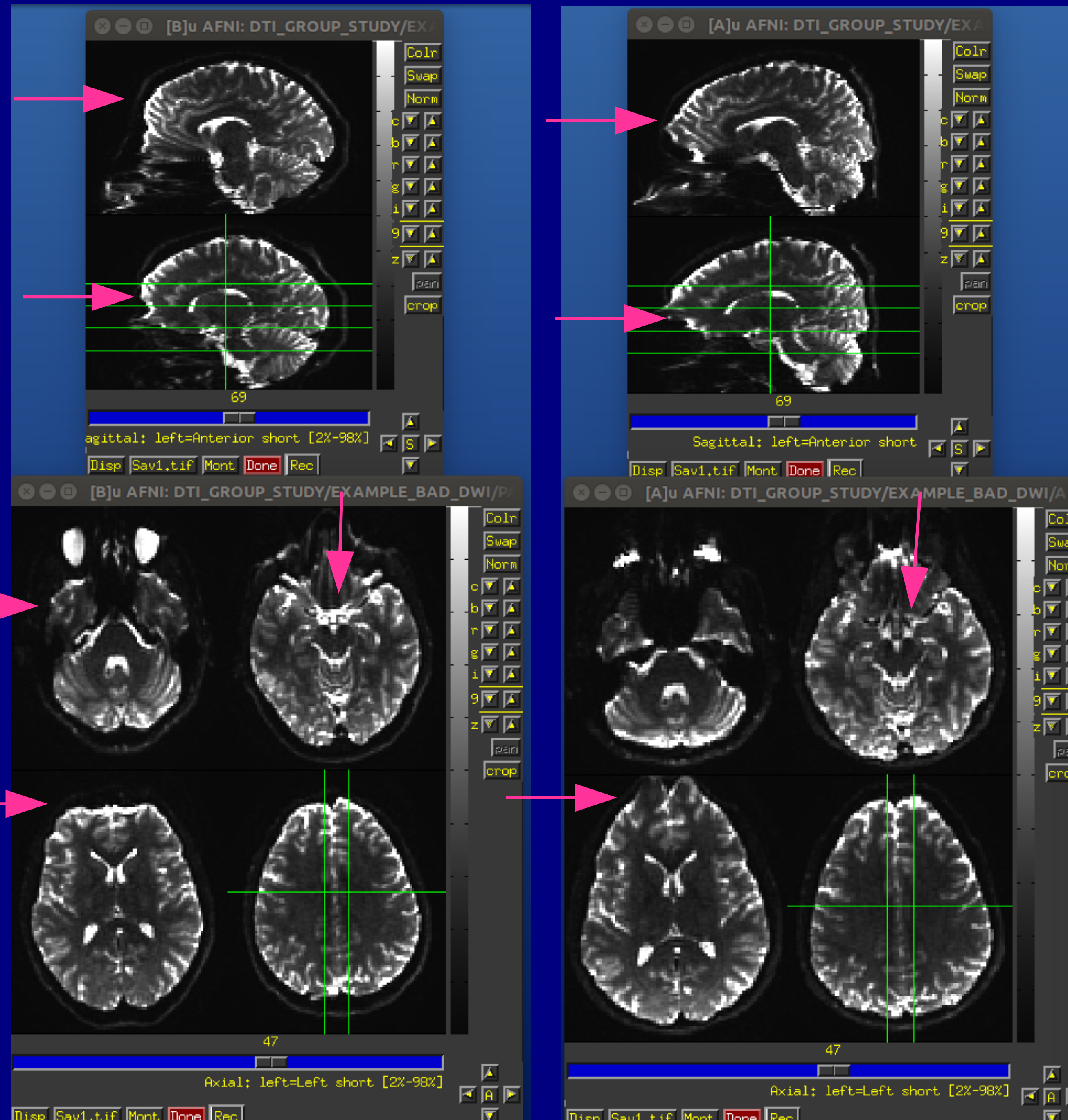
From subj motion: interleaved brightness distortions



Distortions in DWI volumes

From eddy and EPI distortions:

+ geometric/nonlinear warping
+ signal pileup and attenuation



SUMMARY

+ Diffusion-based MRI uses application of magnetic field gradients to probe the relative diffusivity of molecules along different directions.
+ DTI combines that information into a simple shape family, spheroids, to summarize the diffusivity.
+ From the DT, several useful properties are described in terms of scalar (e.g., FA, MD, L1) and vector (e.g., V1) parameters.
+ Many “standard” interpretations of DTI parameters exist (i.e., higher FA = “better” WM), but we must be cautious.
+ Distortions and noise affect all DTI estimates, and we must consider the consequences of these in all analyses.