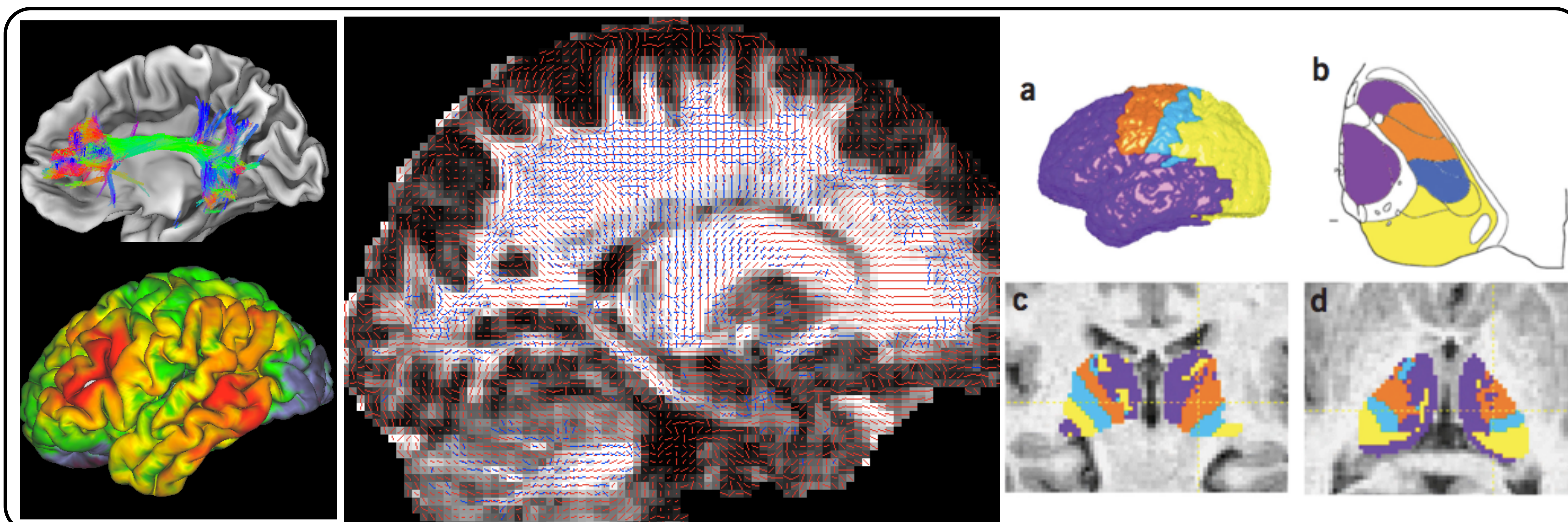
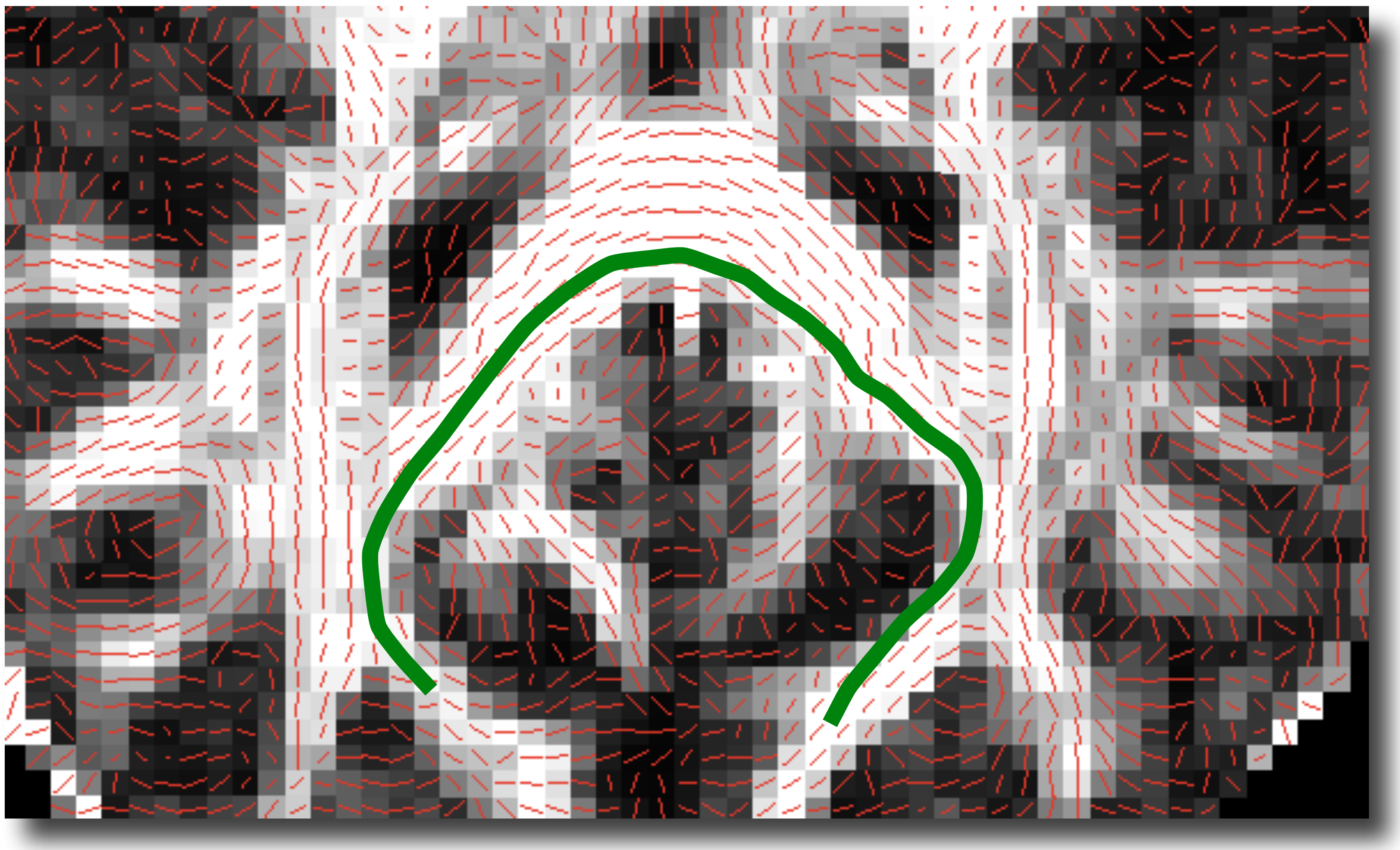
Diffusion Tractography

- Goal of tractography
- Estimating Fibre Orientations - BEDPOSTX
- Probabilistic Tractography - PROBTRACKX
- ProbtrackX outputs
- Tractography limitations

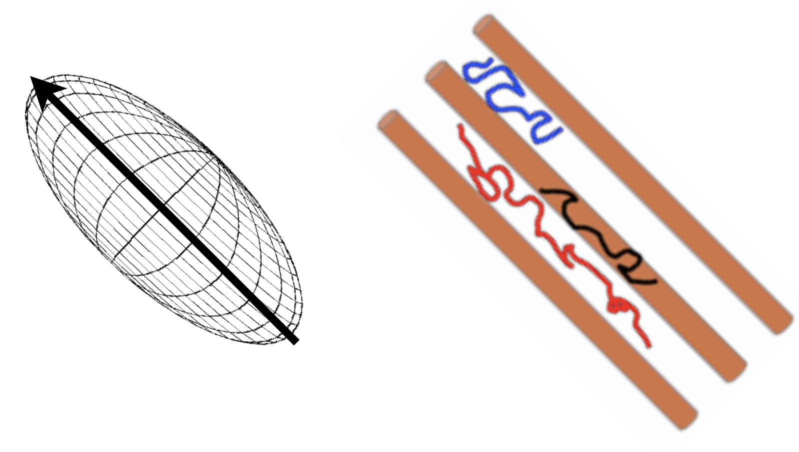


DTI tractography

$\mathbf{v}_1$ map
Principal Diffusion Direction



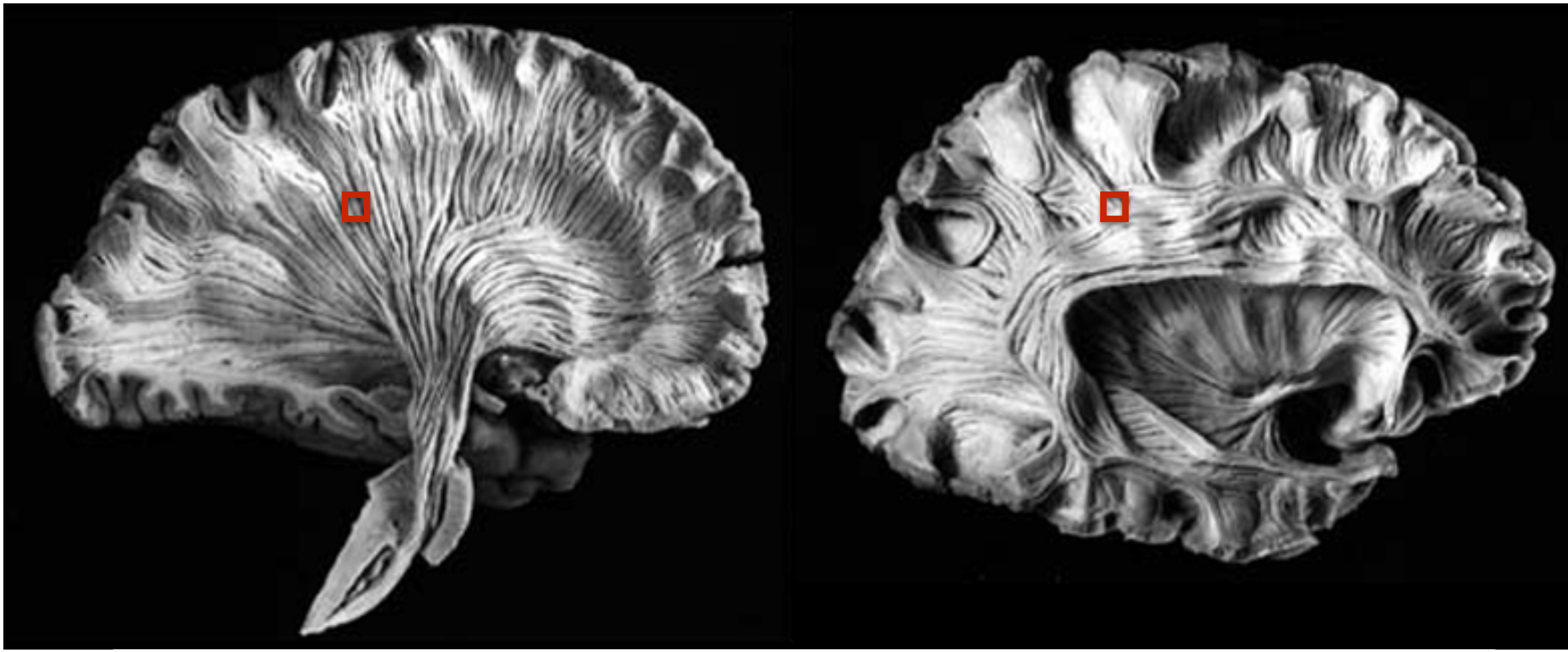
Principal Diffusion Direction



<u>Assumption</u>:

Direction of maximum diffusivity
(in anisotropic voxels)
is an **<u>estimate</u> of the major fibre orientation**.

But is WM always coherently organised within a voxel?



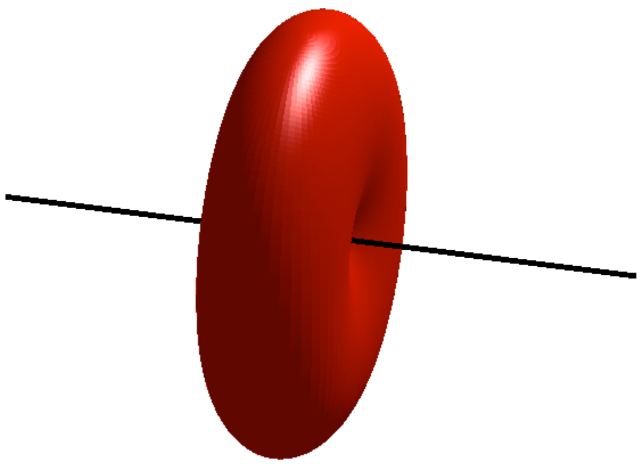
Unfortunately not, complex fibre patterns (e.g. crossings) are very common at the voxel scale.

Williams, Gluhbegovic, and Jew, "The Human Brain: Dissections of the Real Brain", Virtual Hospital, University of Iowa, 1997

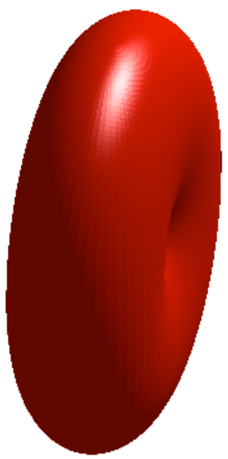
Predictions from the tensor model
no crossing fibres

One orientation

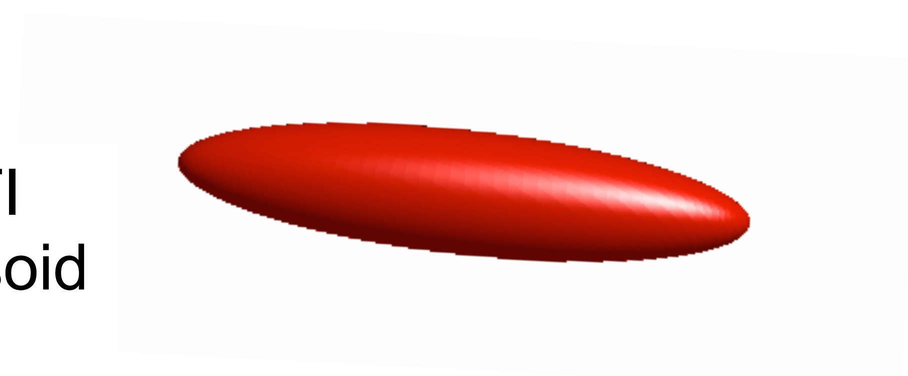
Measured
Signal
Shape



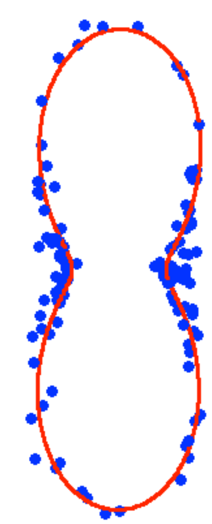
Predicted
Signal
Shape



DTI
Ellipsoid



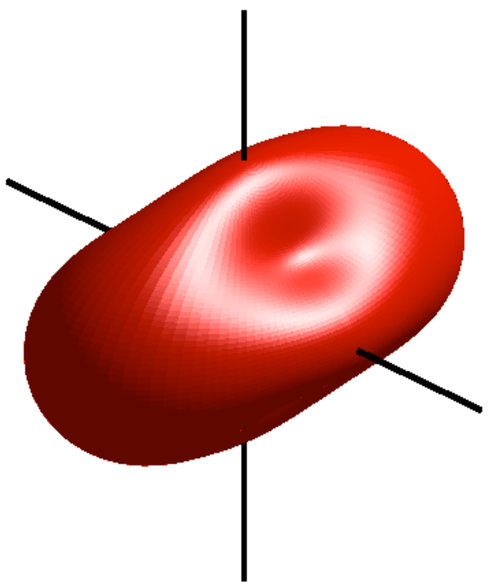
Prediction &
Measurements
in 2D



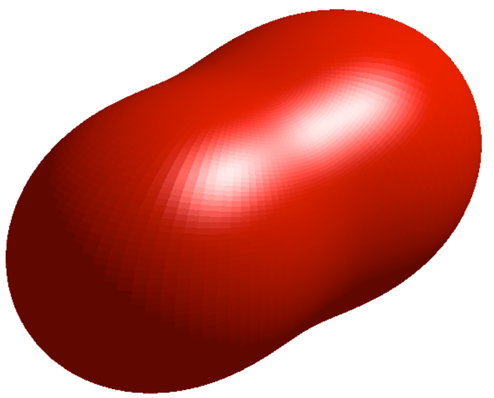
Predictions from the tensor model crossing fibres

Two orientations

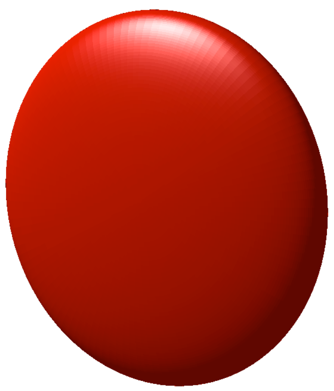
Measured
Signal
Shape



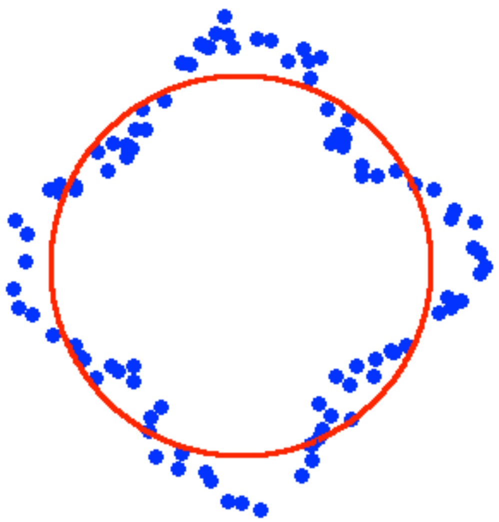
Predicted
Signal
Shape



DTI
Ellipsoid



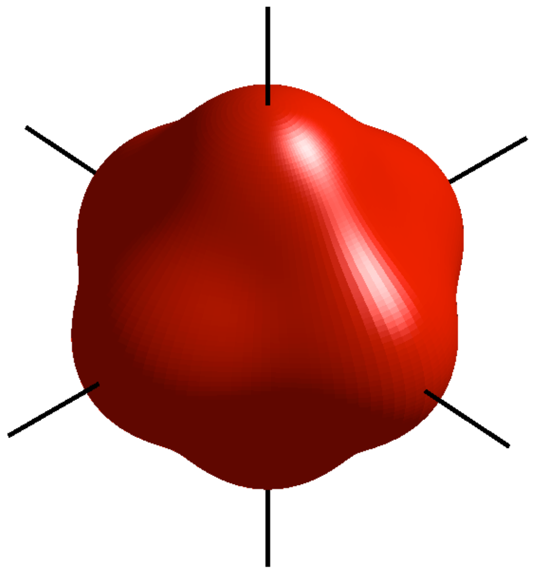
Prediction &
Measurements
in 2D



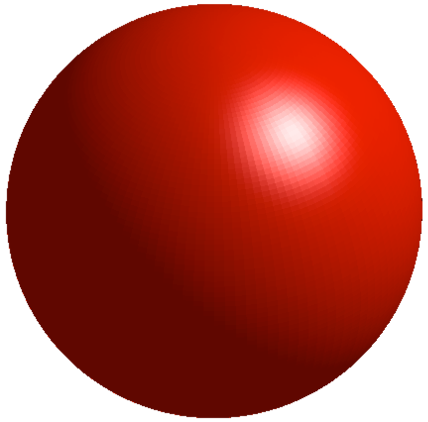
Predictions from the tensor model crossing fibres

Three Orientations

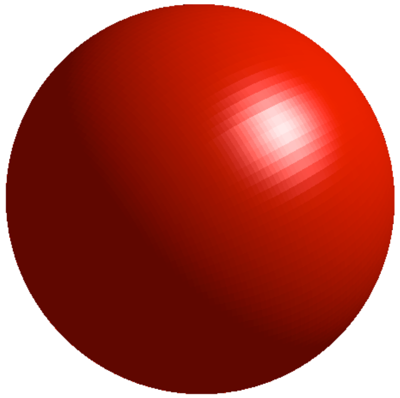
Measured Signal Shape



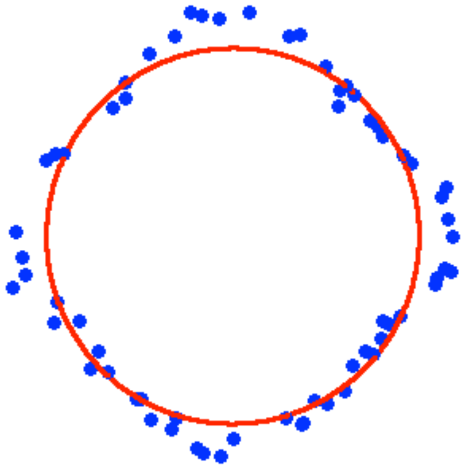
Predicted Signal Shape



DTI Ellipsoid



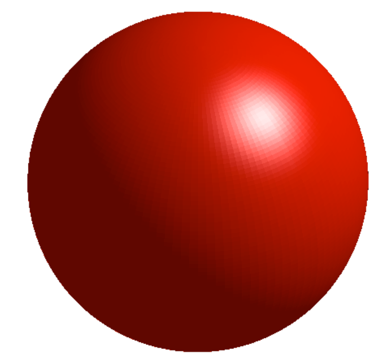
Prediction & Measurements in 2D

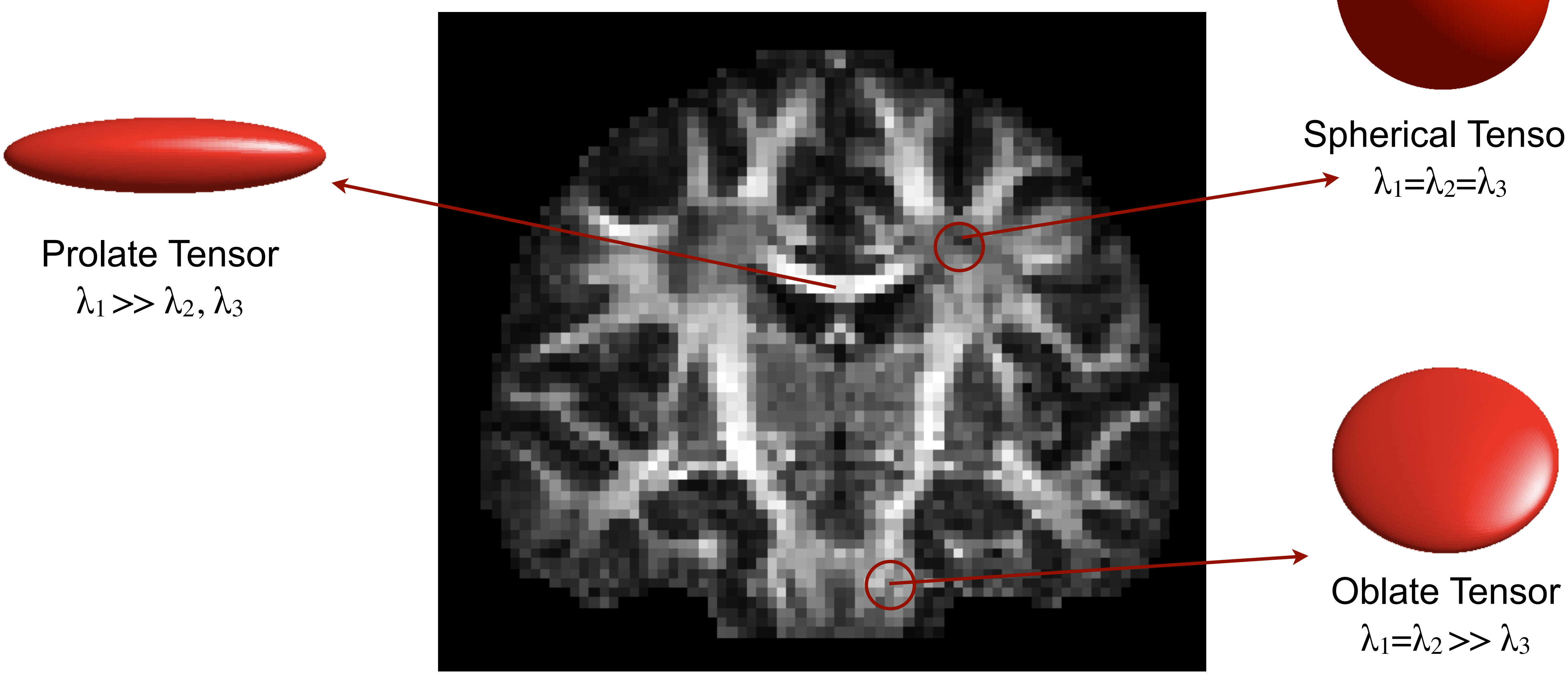


How good is the DTI Model in regions with crossing fibres?

- In voxels containing two crossing bundles, the tensor ellipsoid is pancake-shaped (oblate, planar tensor).
- In voxels containing three crossing bundles, the tensor ellipsoid is spherical.

- In these areas, DTI $\mathbf{v_1}$ is meaningless.



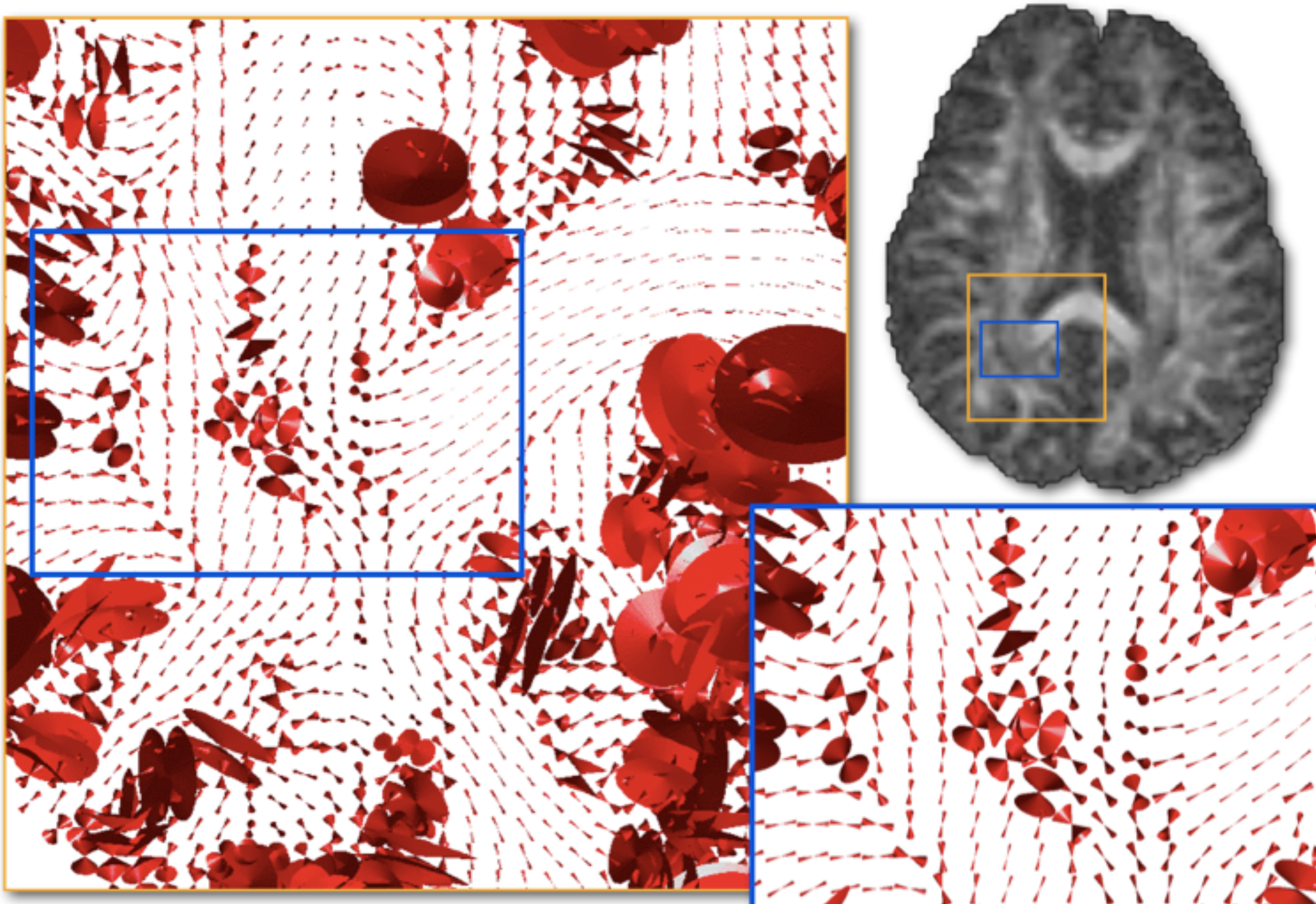


Uncertainty on DTI Fibre Orientation Estimates

Repeat an acquisition many times and obtain the variability in $\mathbf{v_1}$ from the different datasets.

Uncertainty Sources

- Modelling errors
- Noise

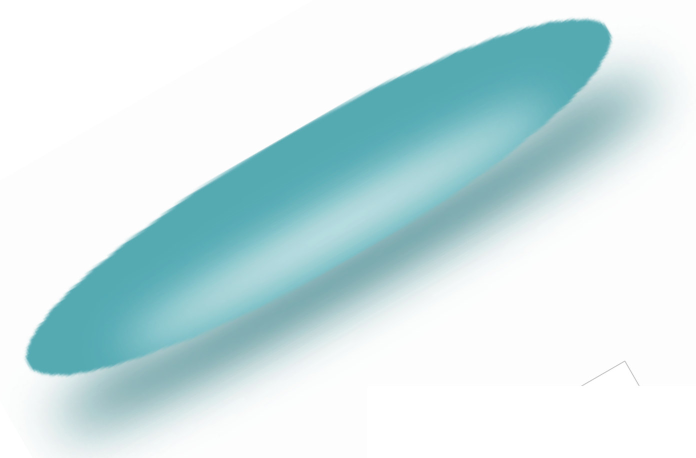


Cones of uncertainty on DTI $\mathbf{v_1}$

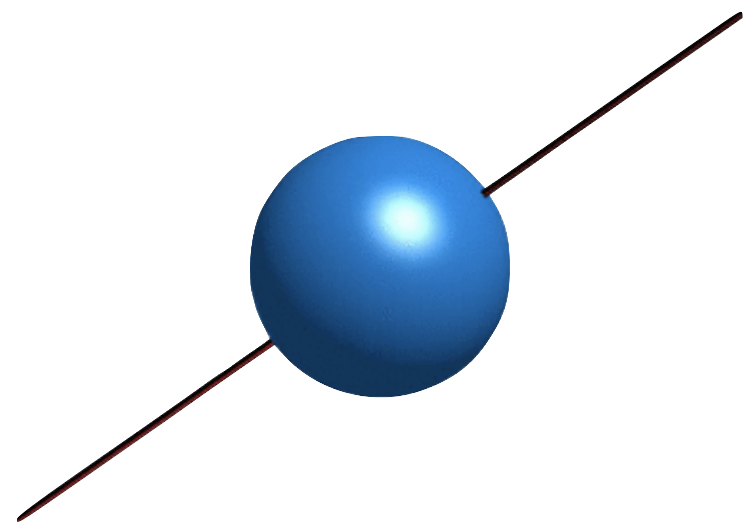
Jones, 2002

Do we have to use the DTI model to estimate orientations? Not really, many models exist

DTI model (dtifit)



Ball & sticks model (bedpostx)



Anisotropic Volume Fraction (unknown)

Diffusivity (unknown)

Fibre Orientation (unknown)

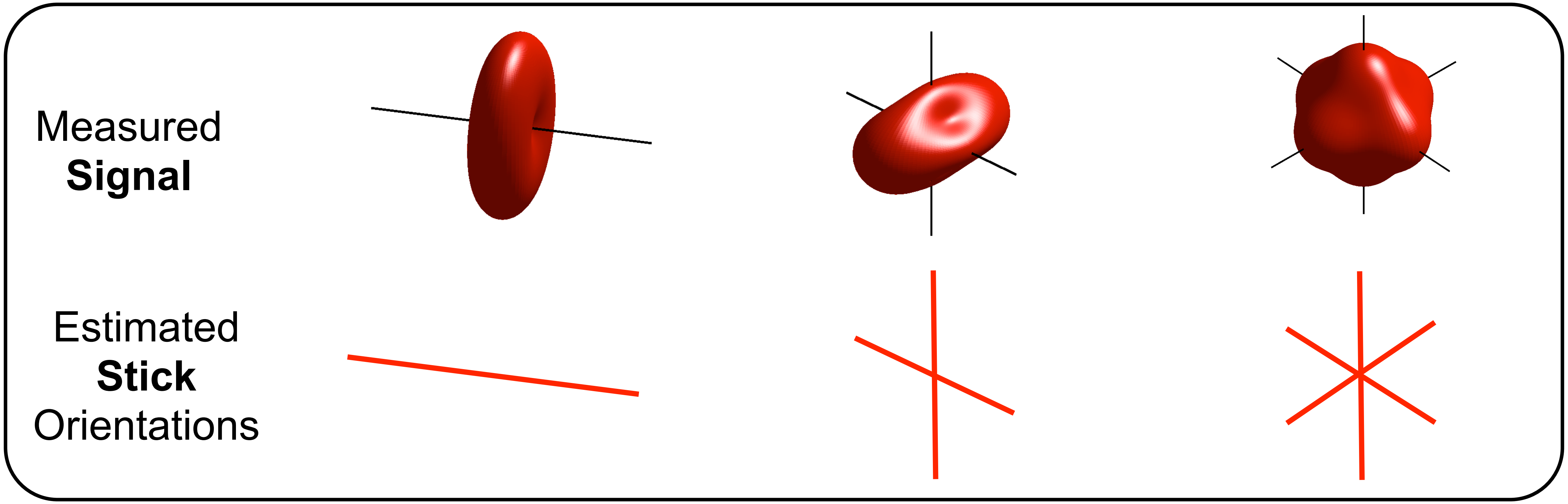
$$\boxed{s_j = s_0\,[(1-f)\exp(-b_j\, d)+f\,\exp(-b_j\, d(\boldsymbol{x}_j^{\mathrm{T}}\boldsymbol{v})^2)]}$$

Measured Signal for Gradient *j*

b-value for gradient *j* (known)

Unit vector representing the direction of gradient *j* (known)

Ball & Sticks Model
Unlike the DT model, it can represent many orientations



- Anisotropic tensors (sticks) with isotropic background (ball)
- Fibre Orientations modelled explicitly and separated from isotropic partial volumes

Anisotropic Volume Fractions (unknown)

Diffusivity (unknown)

Max number of sticks (user-defined)

Fibre Orientation (unknown)

$$s_j = s_0\,[(1-\Sigma f_n)\exp(-b_j\, d) + \Sigma f_n\, \exp(-b_j\, d(\mathbf{x}_j^{\mathrm{T}}\mathbf{v}_n)^2)]$$

Measured Signal for Gradient *j*

b-value for gradient *j* (known)

Unit vector representing the direction of gradient *j* (known)

Predictions from the ball and sticks model crossing fibres

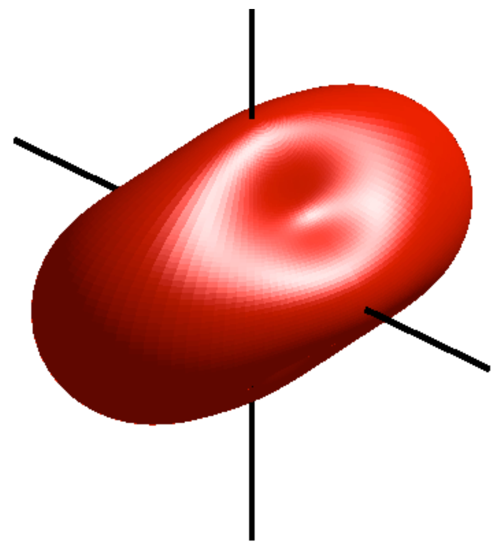
Measured
Signal Shape

Prediction &
Measurement in 2D

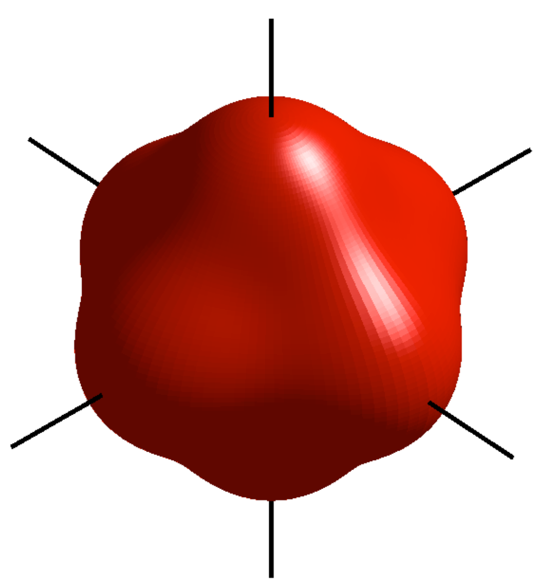
DTI

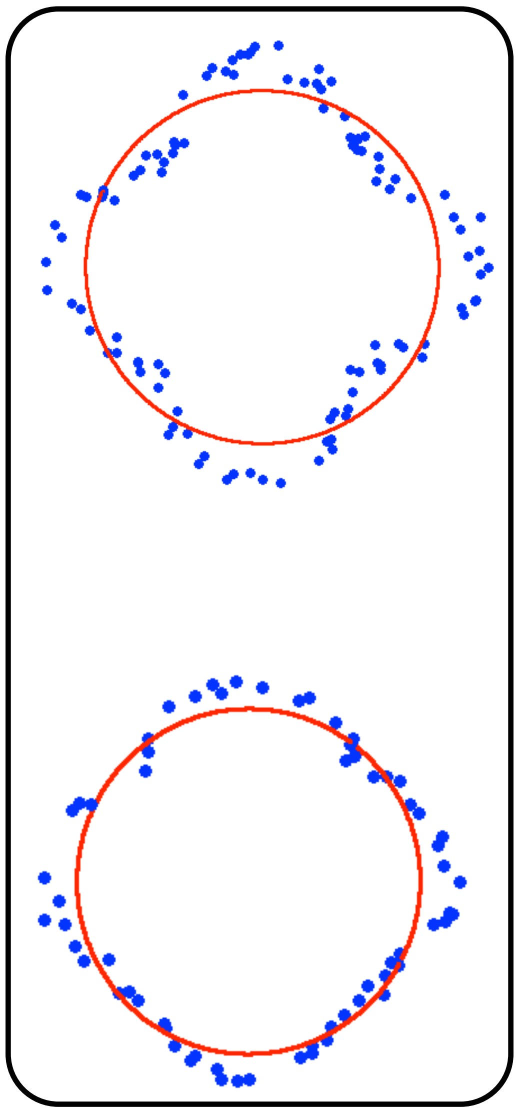
Ball & sticks

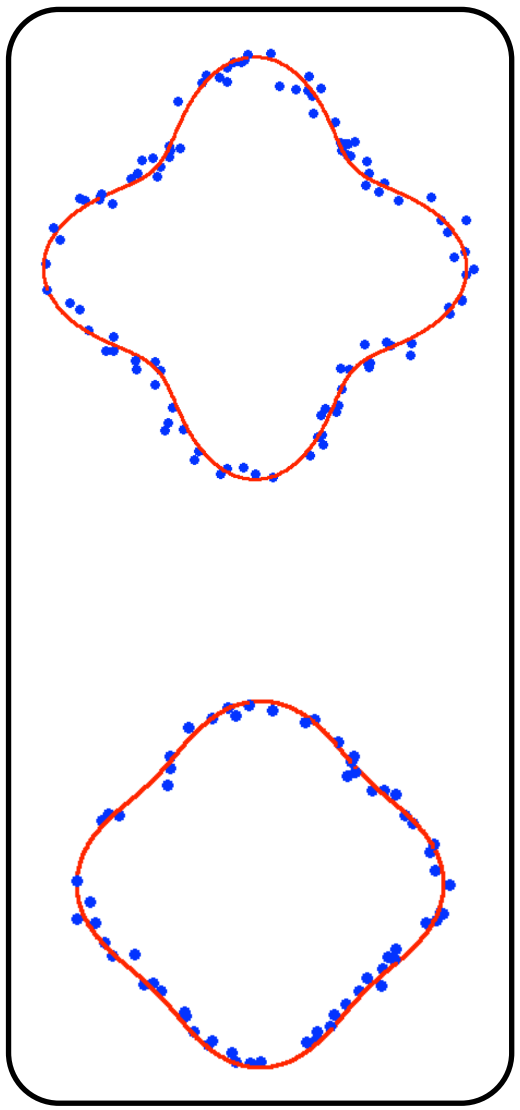
Two orientations



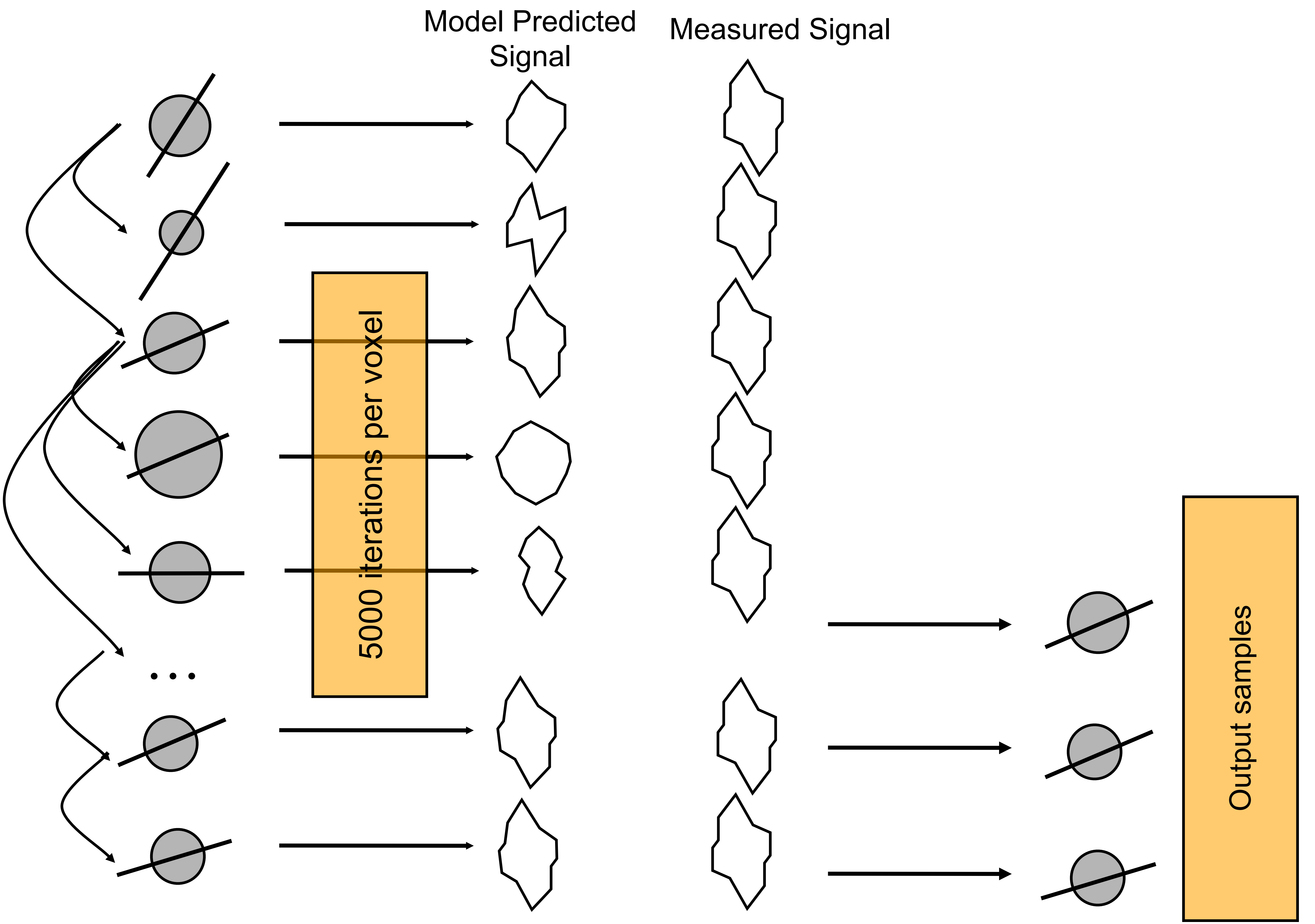
Three orientations



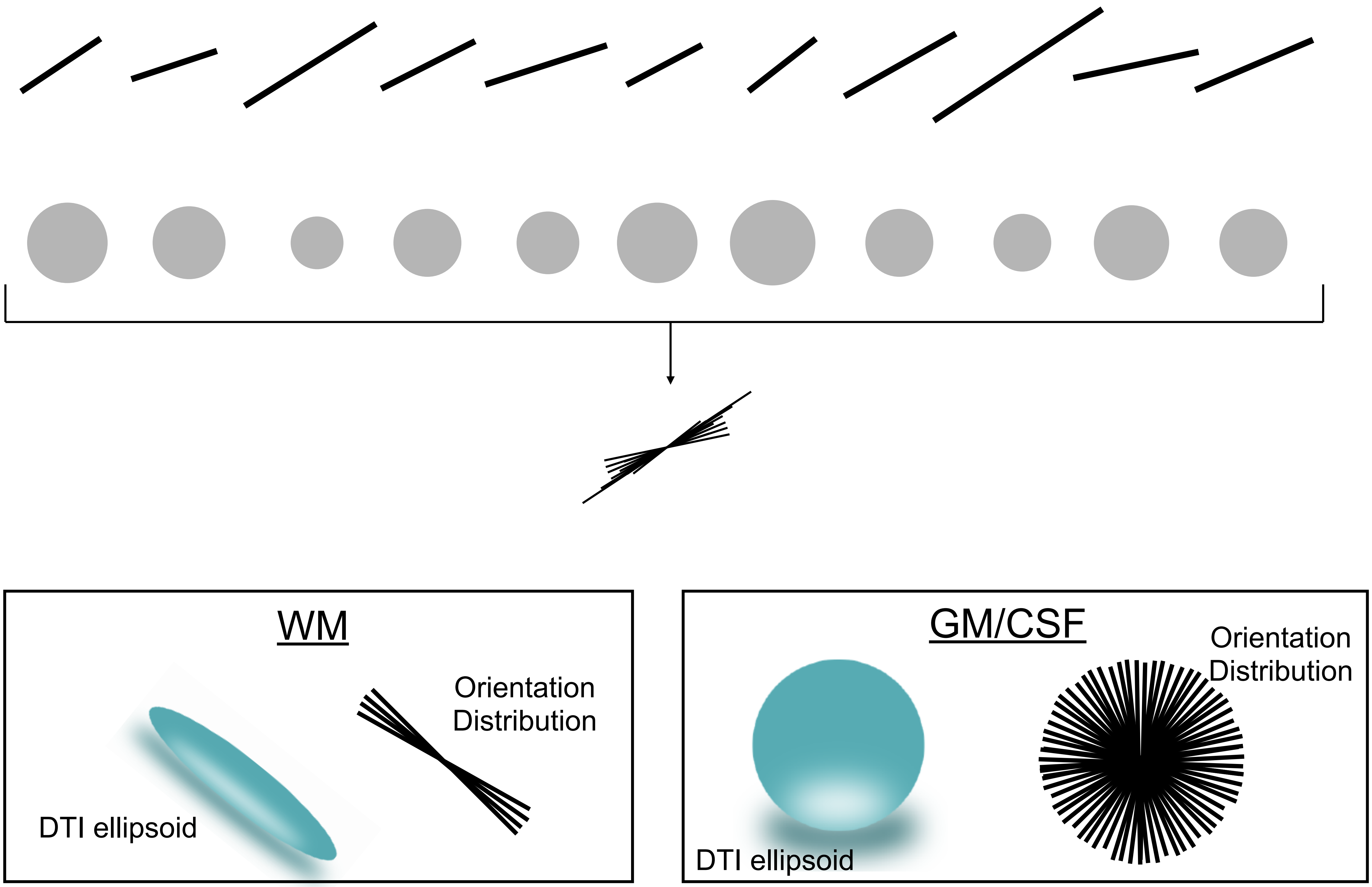




Markov Chain - Monte Carlo (MCMC) Sampling

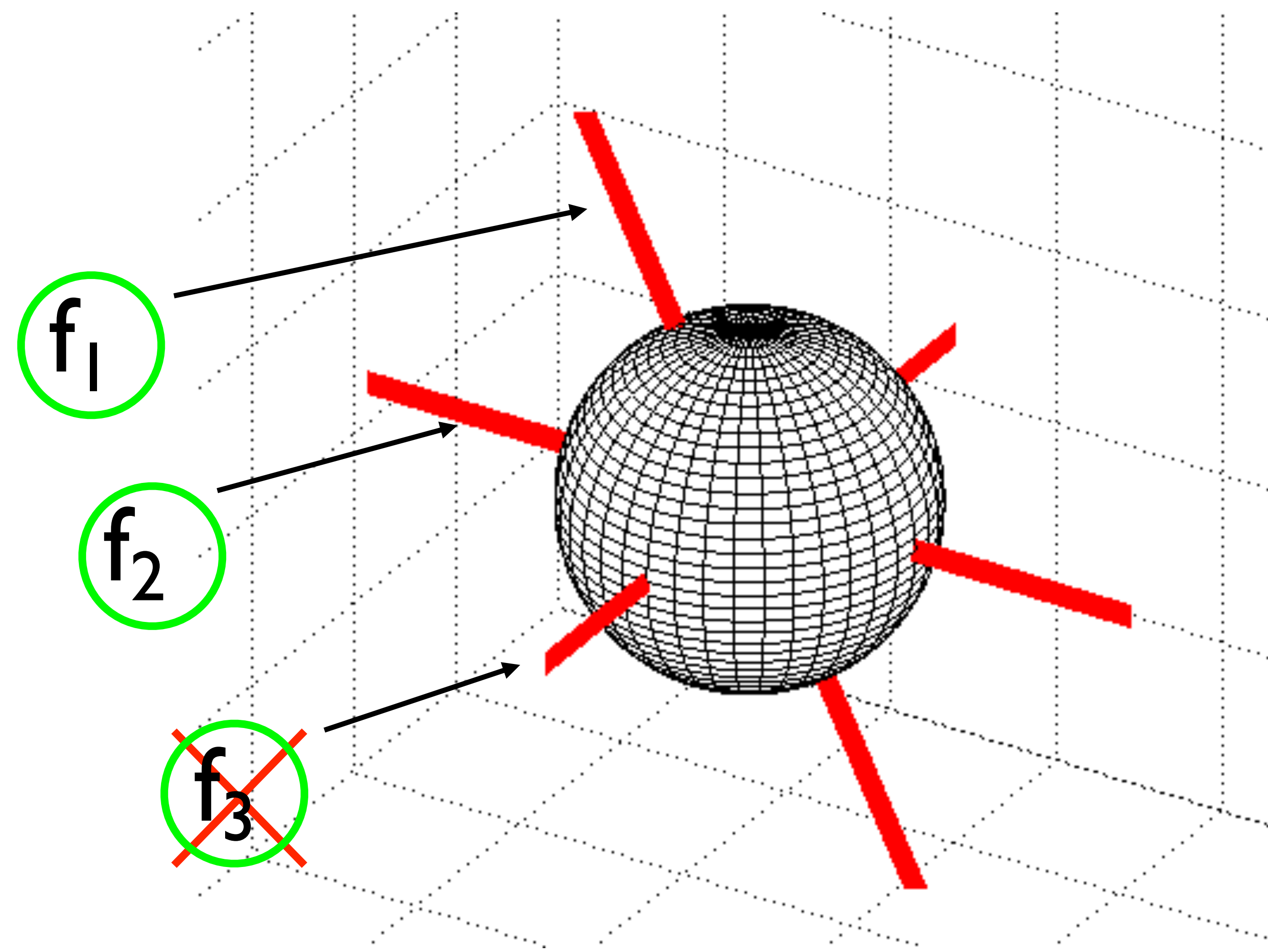


Output in Each voxel = Distributions of Parameters



Ball & Sticks Model Selection

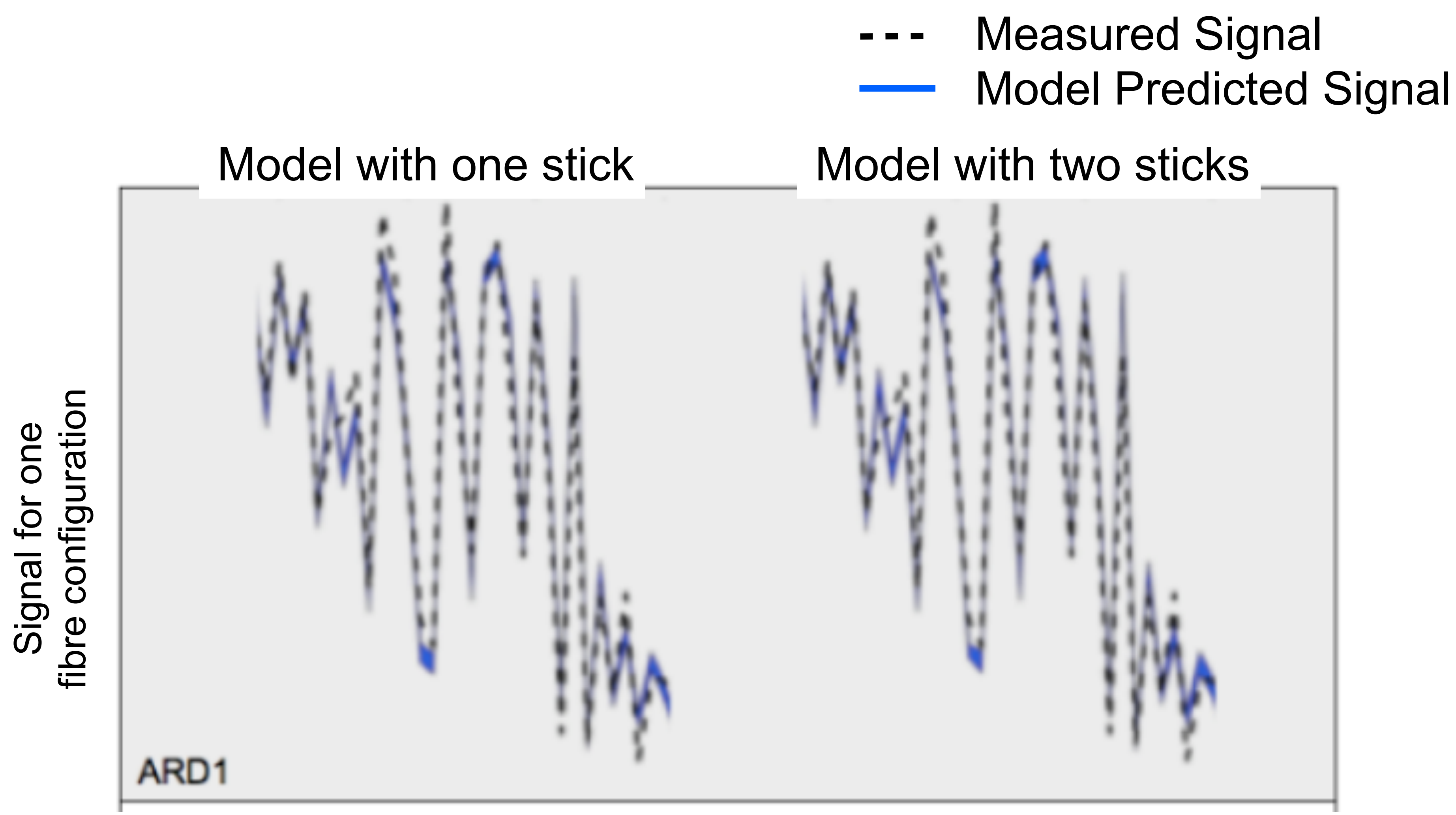
- Model selection problem: One, two or more fibres within a voxel?
- Automatic Relevance Determination: Only estimate complexity that is supported by the data



Modelling Complex Fibre Architectures

Automatic Relevance Determination (A.R.D.)

- No benefit from including a 2nd fibre => 2nd volume fraction goes to zero

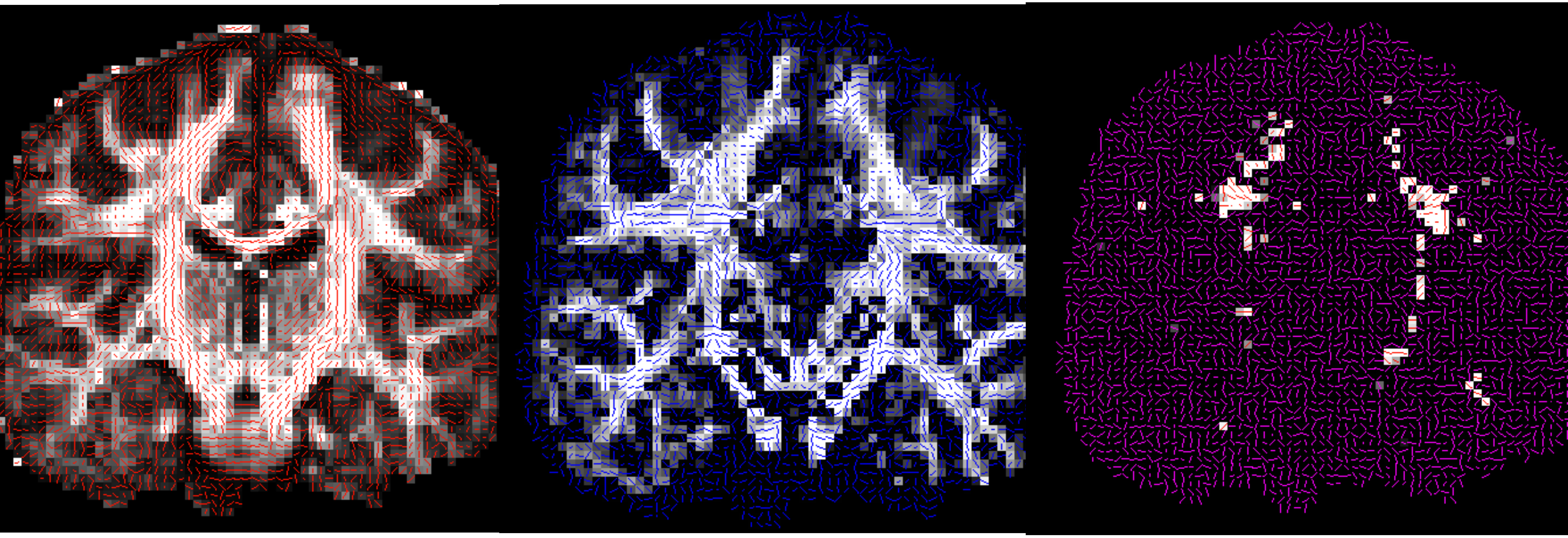


Modelling Complex Fibre Architectures

Automatic Relevance Determination (A.R.D.)

- After running BedpostX all voxels will have estimated parameters for the maximum number of sticks requested.
- But due to ARD, the sticks that are not supported in a voxel will have an almost zero volume fraction.
- We use a threshold (e.g. >5%) to **exclude sticks with tiny volume fraction**.

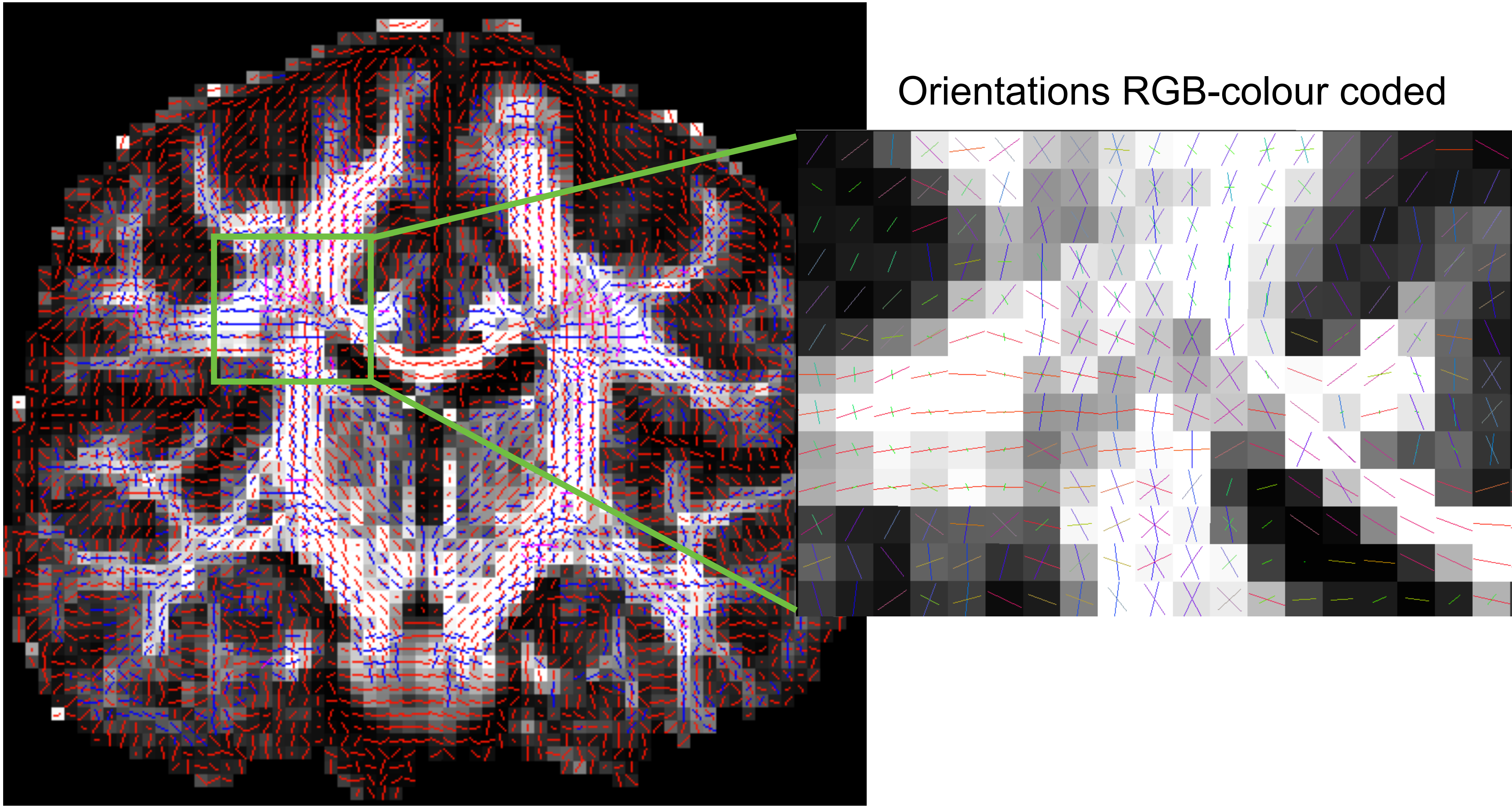
Stick1 Stick2 Stick3



Ball & Sticks Orientations

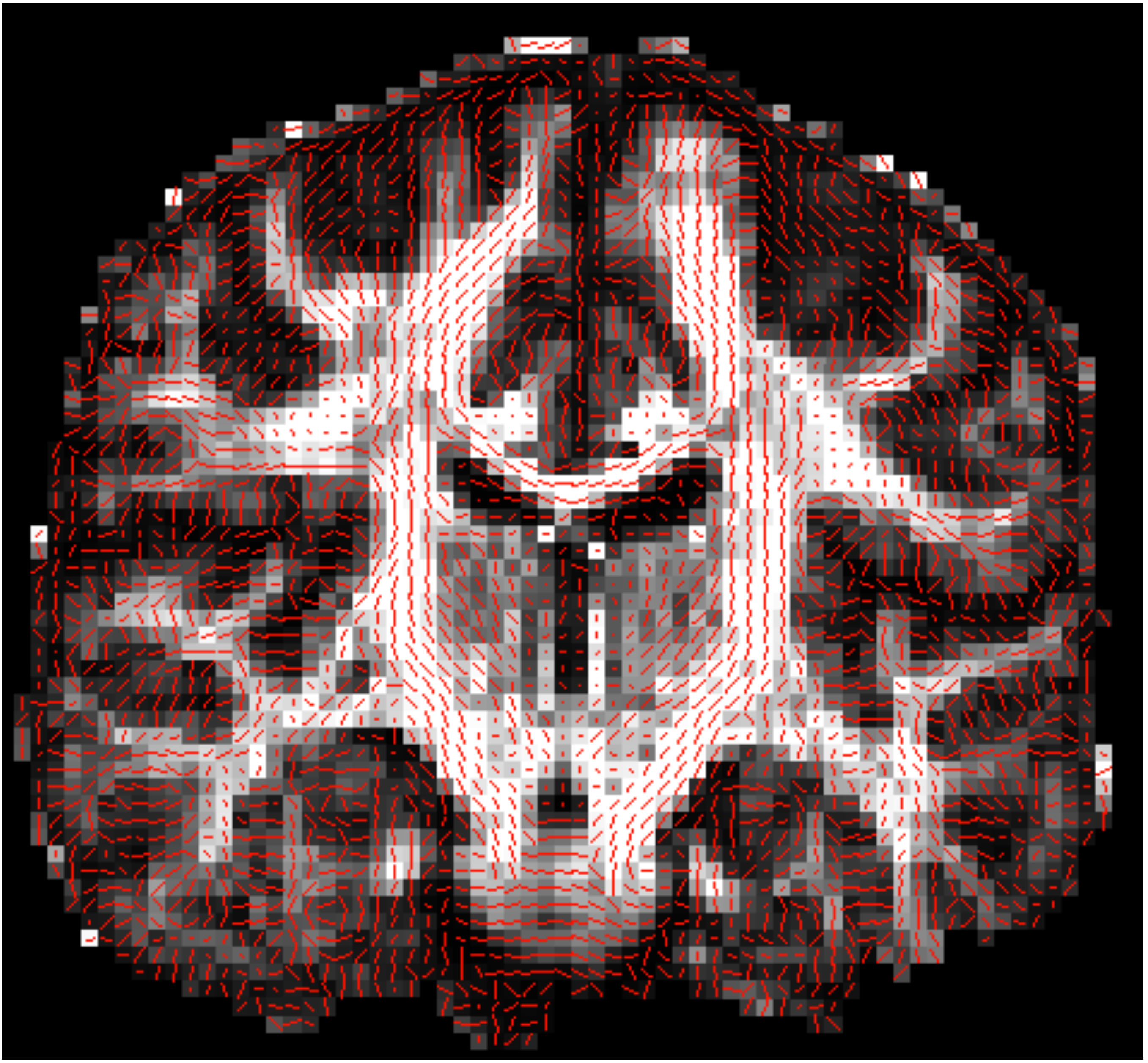
All sticks, with secondary ones thresholded (f_n>5%)

Orientations RGB-colour coded

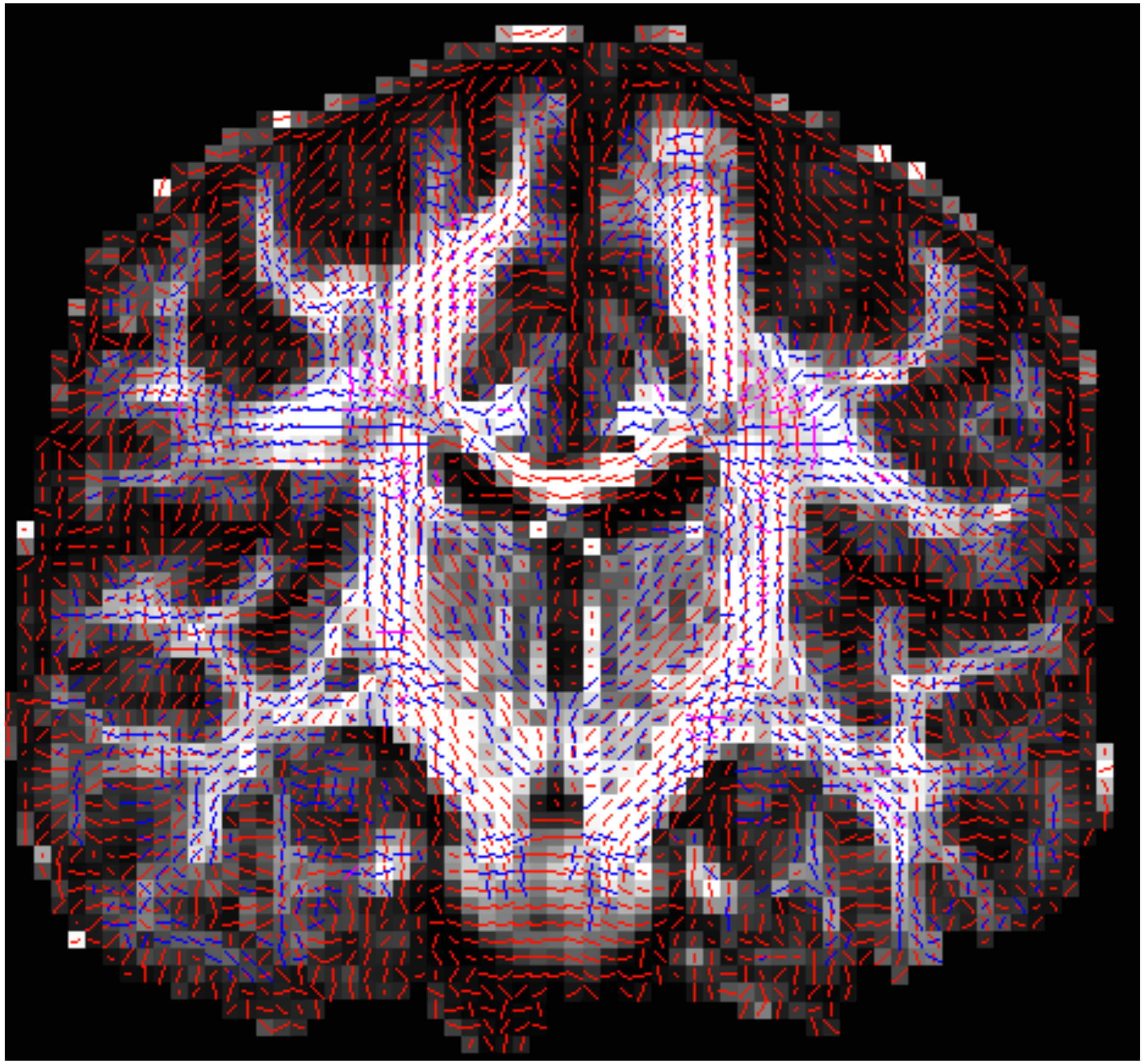


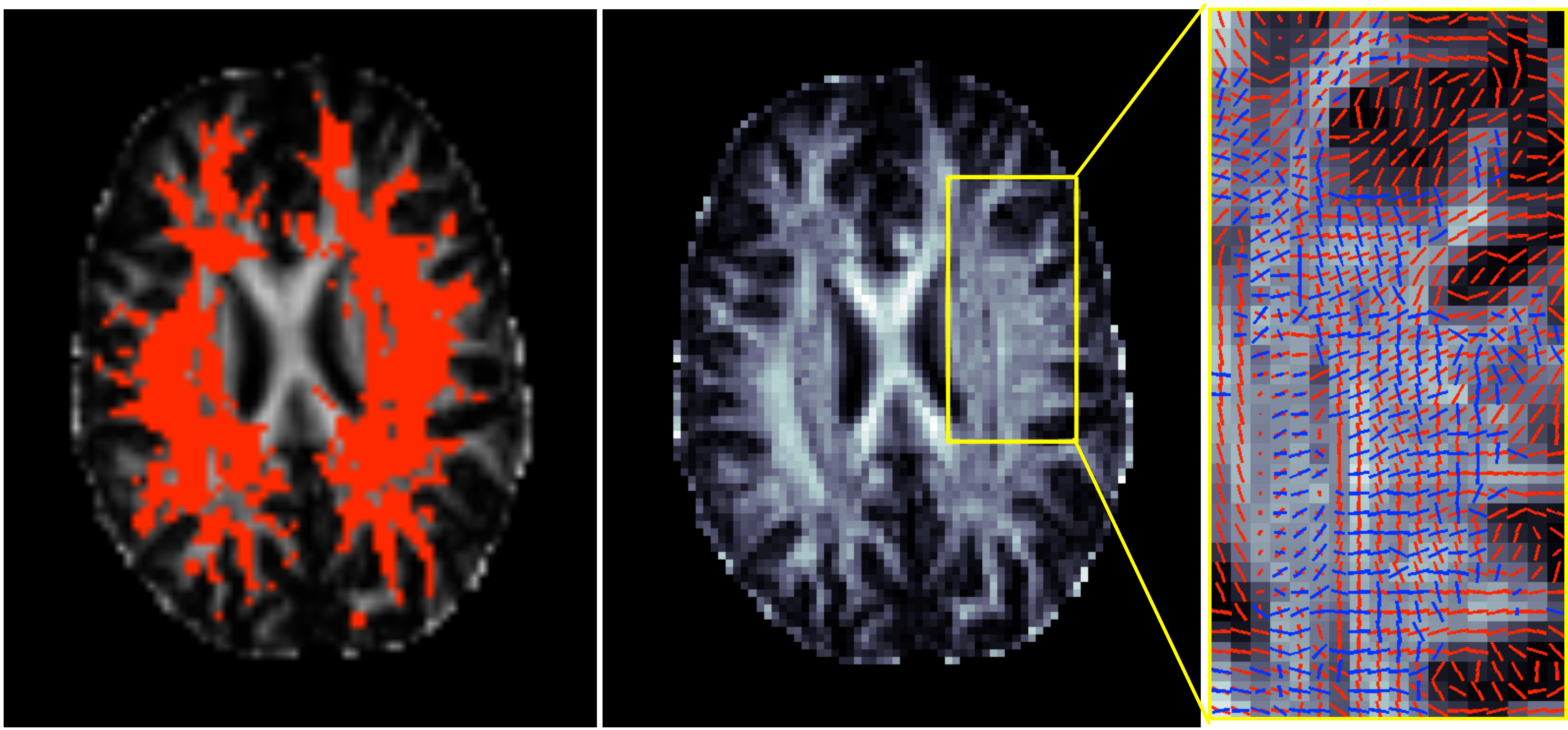
DTI vs Ball & Sticks Orientations

DTI



Ball & Sticks





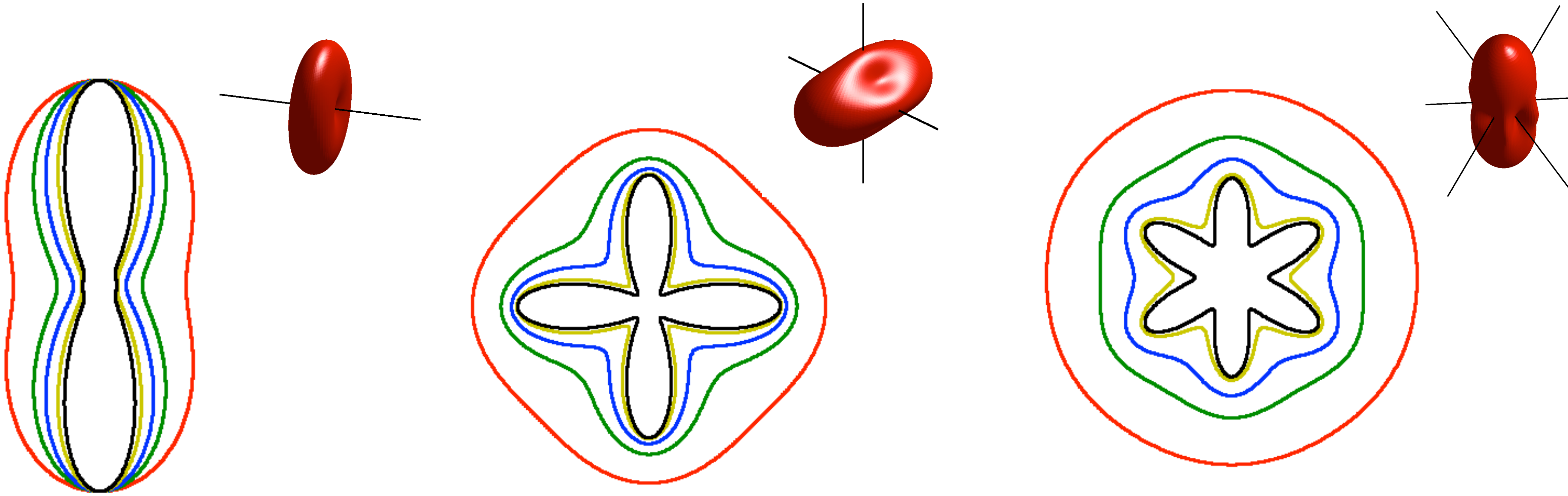
A large portion of the WM supports crossing fibres

Coherence in orientations shows that we are not over-fitting (the ARD works)

Multi-Shell Diffusion Acquisitions
Why bother?

One Orientation | Two Orientations | Three Orientations

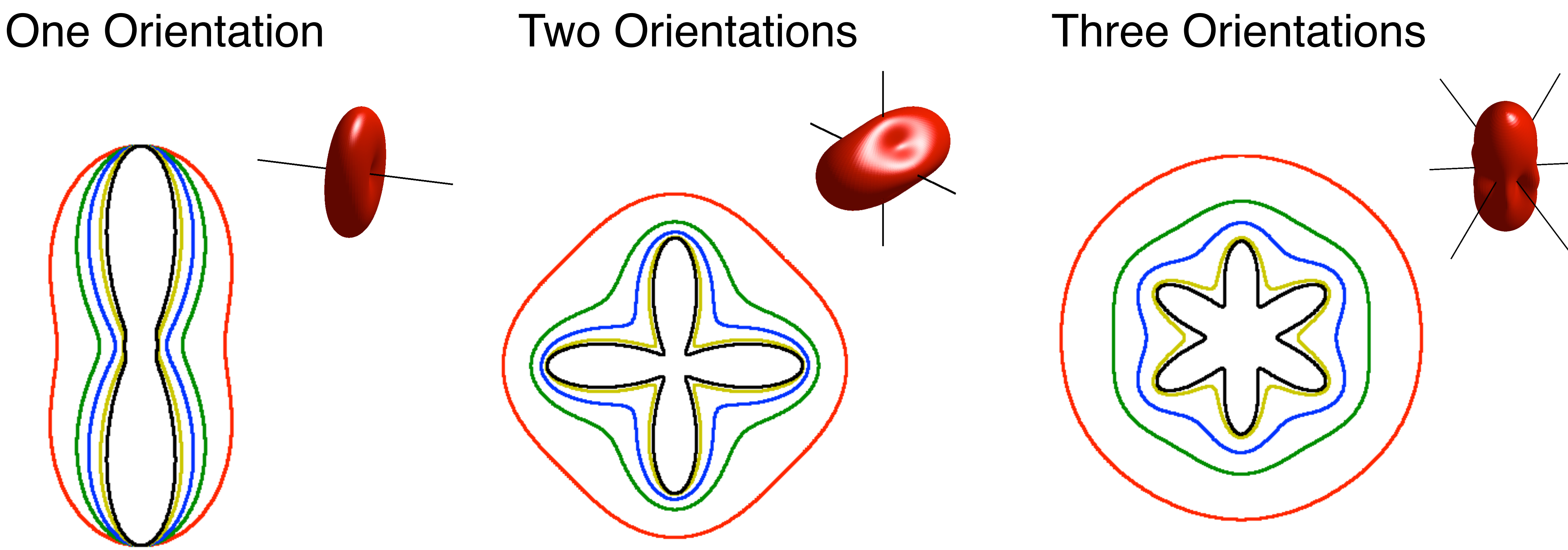
Signal at different b values (s/mm^2)
b=1000
b=2000
b=3000
b=4000
b=5000



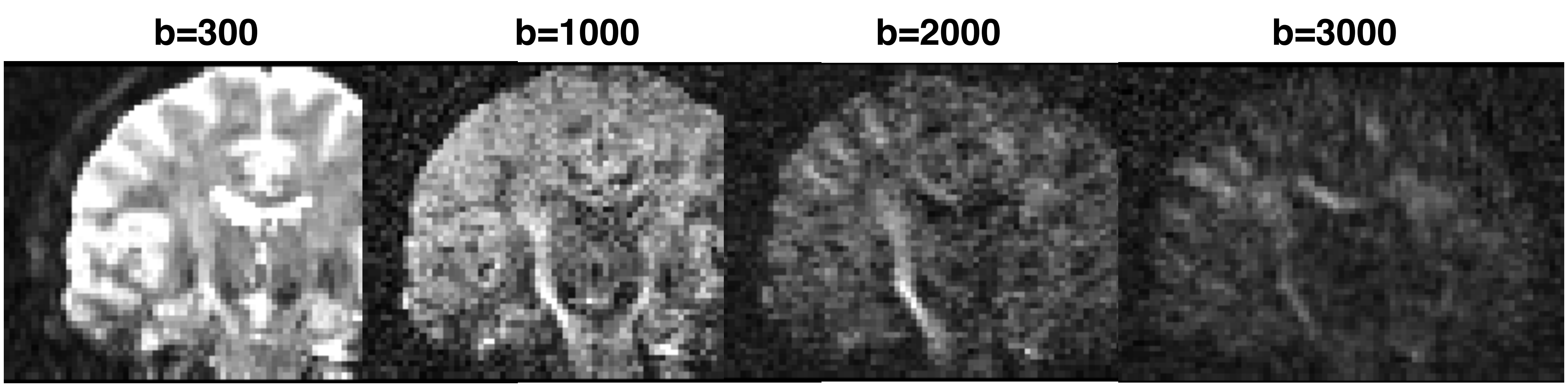
Higher b value gives us more angular contrast!!!

Multi-Shell Diffusion Acquisitions
Why bother?

Signal at different b values (s/mm^2)
b=1000
b=2000
b=3000
b=4000
b=5000



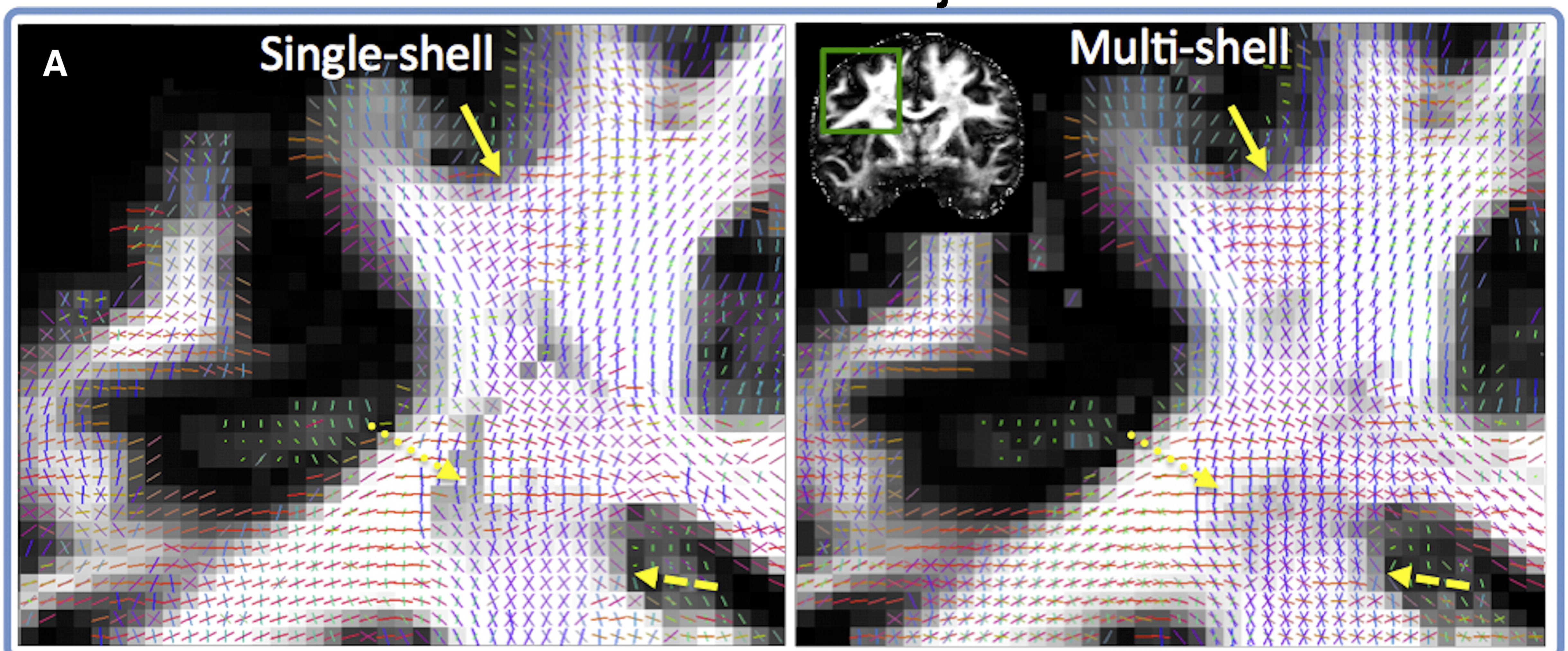
But SNR goes down very quickly with b…



Generalised Ball & sticks Model
Gets best of both worlds

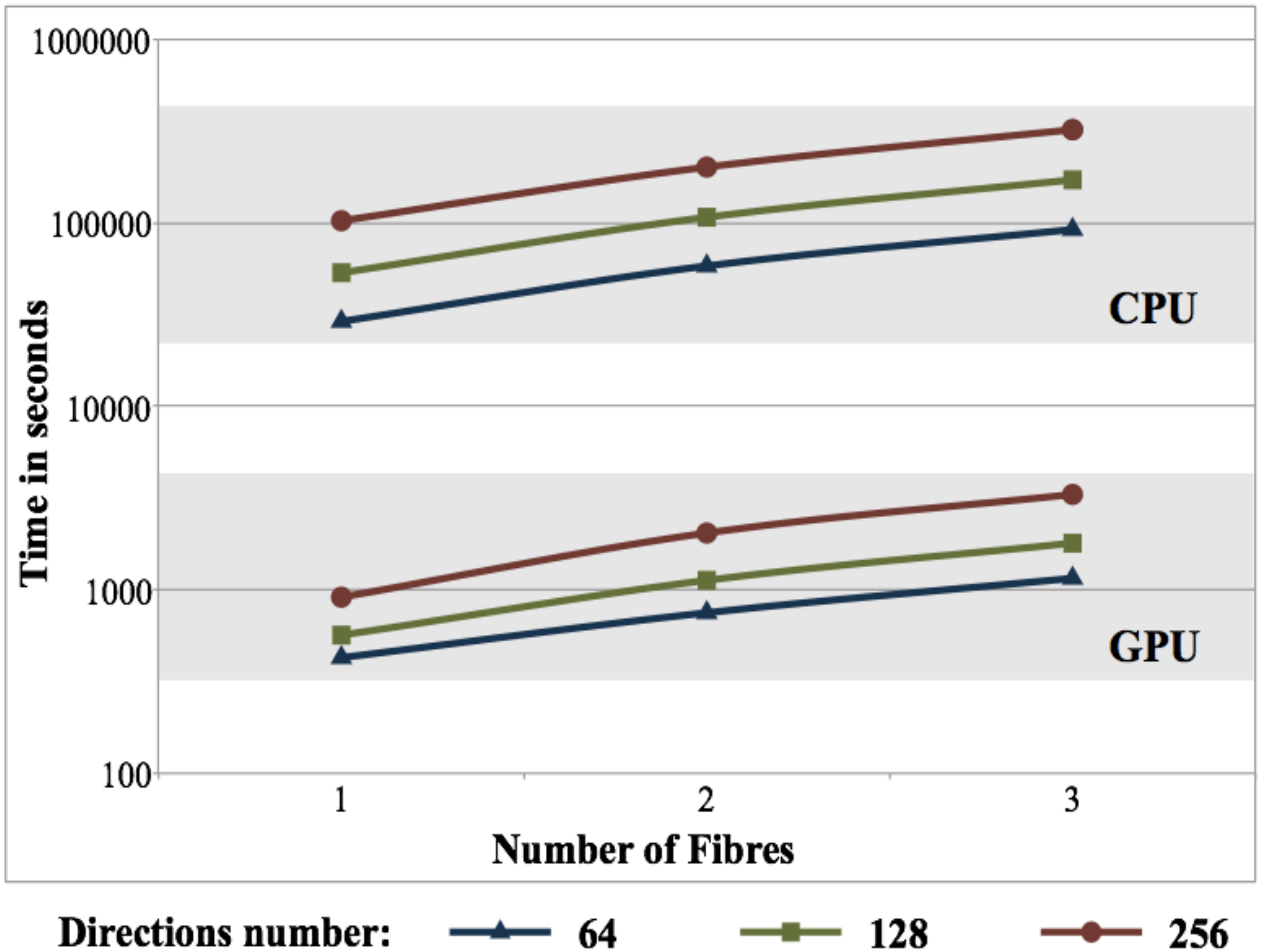
- Multi-shell model (or model=2) in Bedpostx options.
- Allows representation of multiple diffusivities within a voxel (rather than just one).
- More accurate model for multi-shell data & partial volume effects.

Human Connectome Project Data



*Jbabdi, Sotiropoulos et al, MRM 2012
* Sotiropoulos, Jbabdi et al, NeuroImage 2013

Faster bedpostx on GPUs



50x-150x Speedup using GPUs

Hernandez et al, Plos One 2013