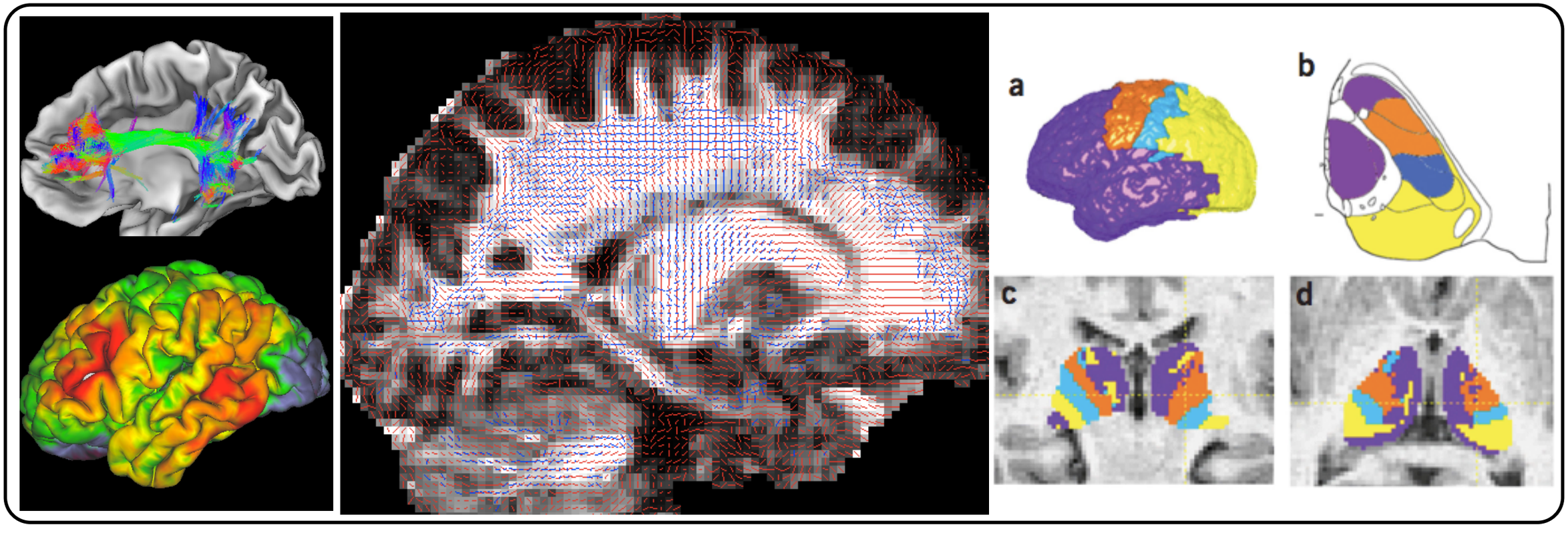
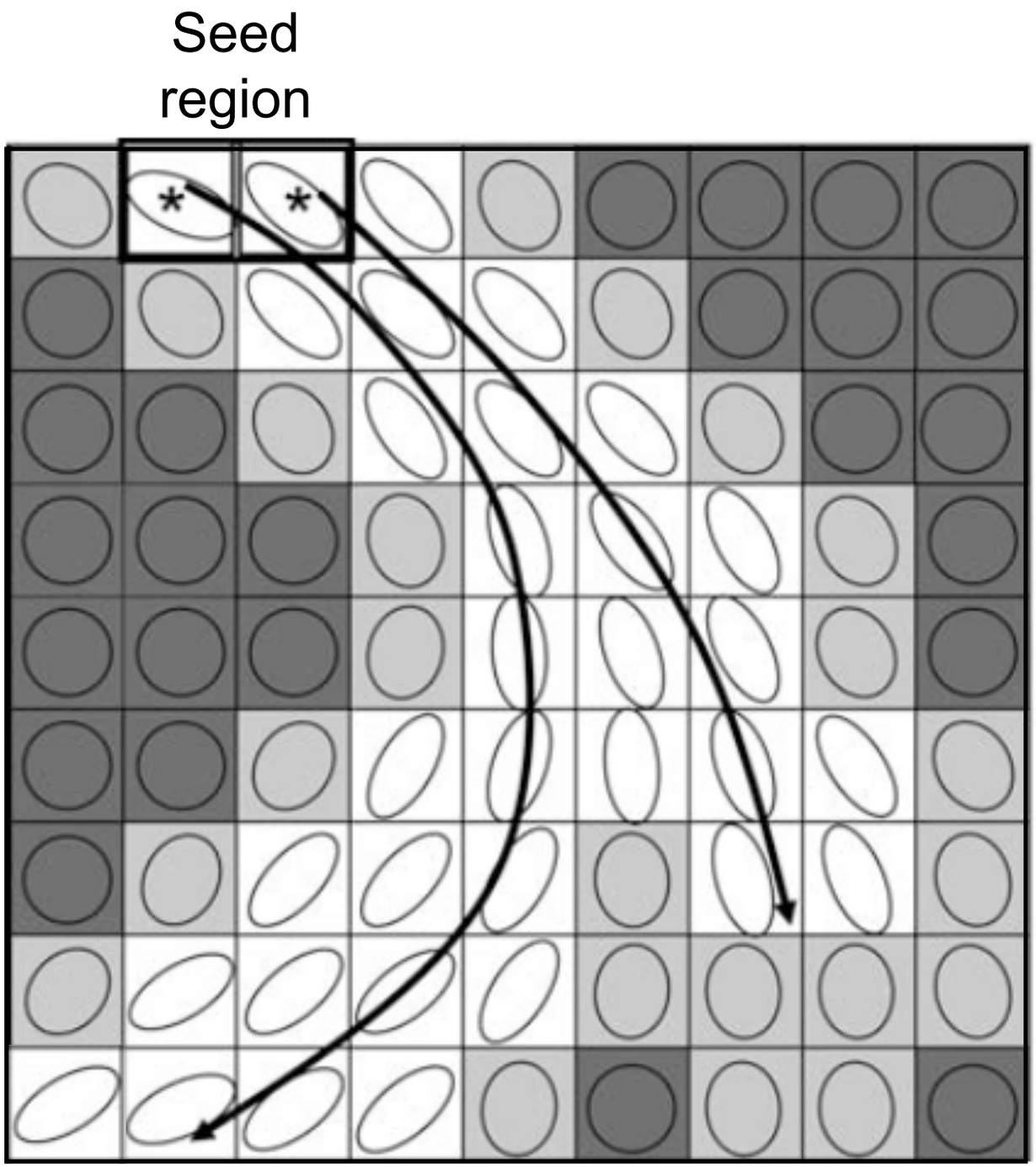
Diffusion Tractography

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



DTI Streamline Tractography



Mori S, Neuron 2006

Formally, we solve numerically the differential equation:

$$\frac{d\mathbf{r}(s)}{ds} = \mathbf{v_1}(\mathbf{r}(s)), \quad \mathbf{r}(0) = \mathbf{r}_0$$

Position along a curve

Principal eigenvector $\mathbf{v_1}$ at position $\mathbf{r}(s)$

Starting Position

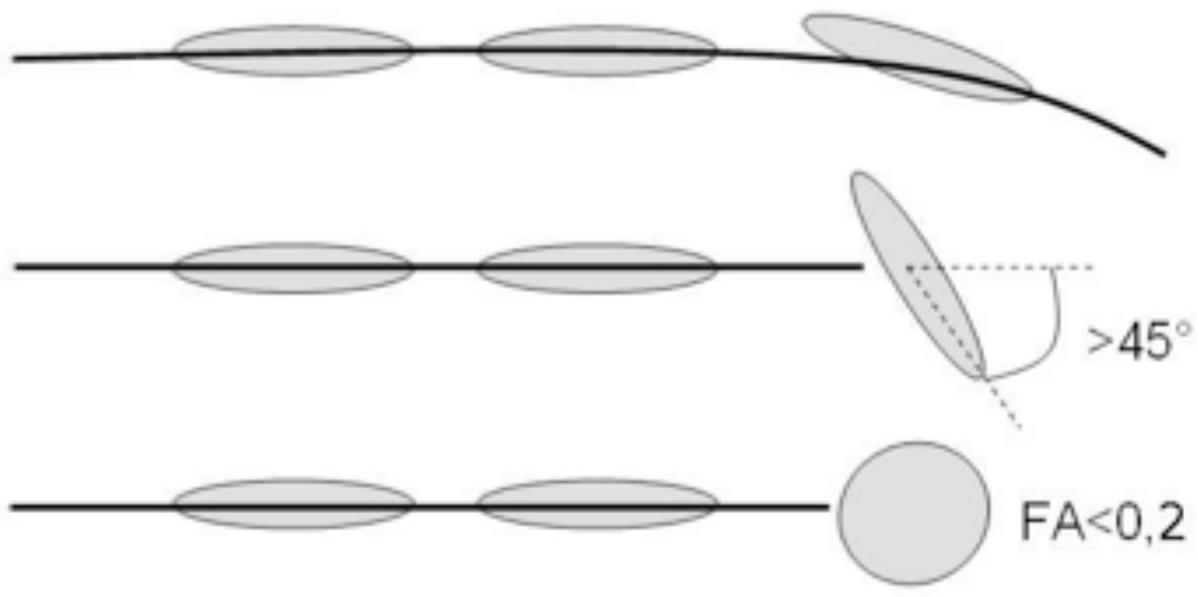
DTI Streamline Tractography

But When to Stop?
Heuristics to avoid error propagation.
+ Knowledge of the anatomy

Curvature Change Threshold: To avoid crossings of boundaries and very bended trajectories, impose a smoothness criterion.

Anisotropy Threshold: To avoid propagating in regions where $\mathbf{v}_1$ is meaningless.

Anatomical criteria (e.g. reach grey matter)



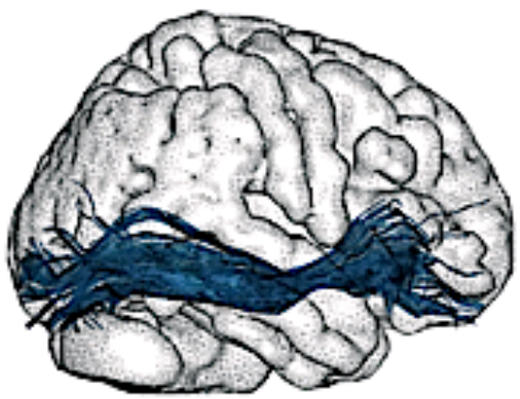
Streamline tractography can dissect major bundles

arcuate fasciculus

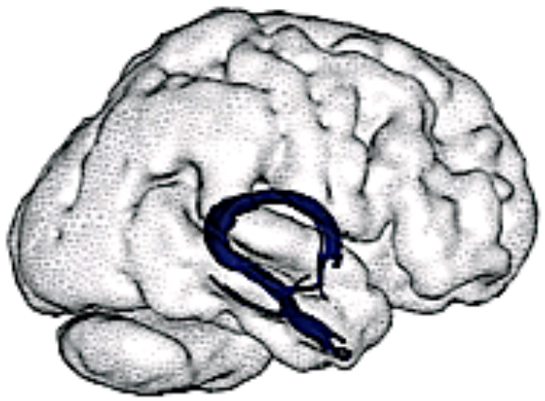
cingulum bundle

inferior longitudinal fasciculus

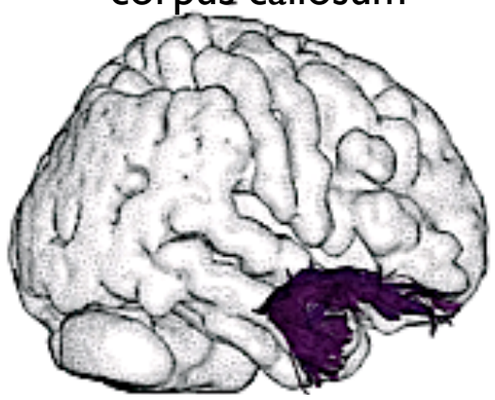
corpus callosum



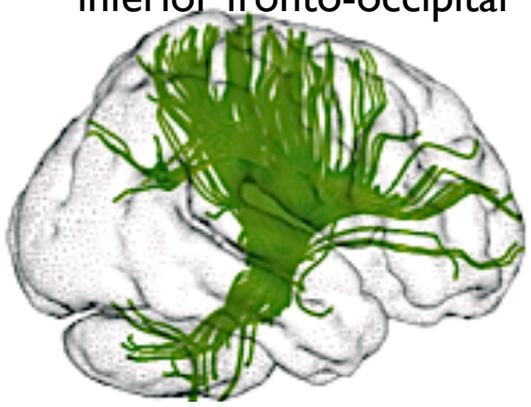
inferior fronto-occipital



fornix



uncinate fasciculus



corona radiata

cerebellar tracts

Catani and Thiebaut de Schotten 2008

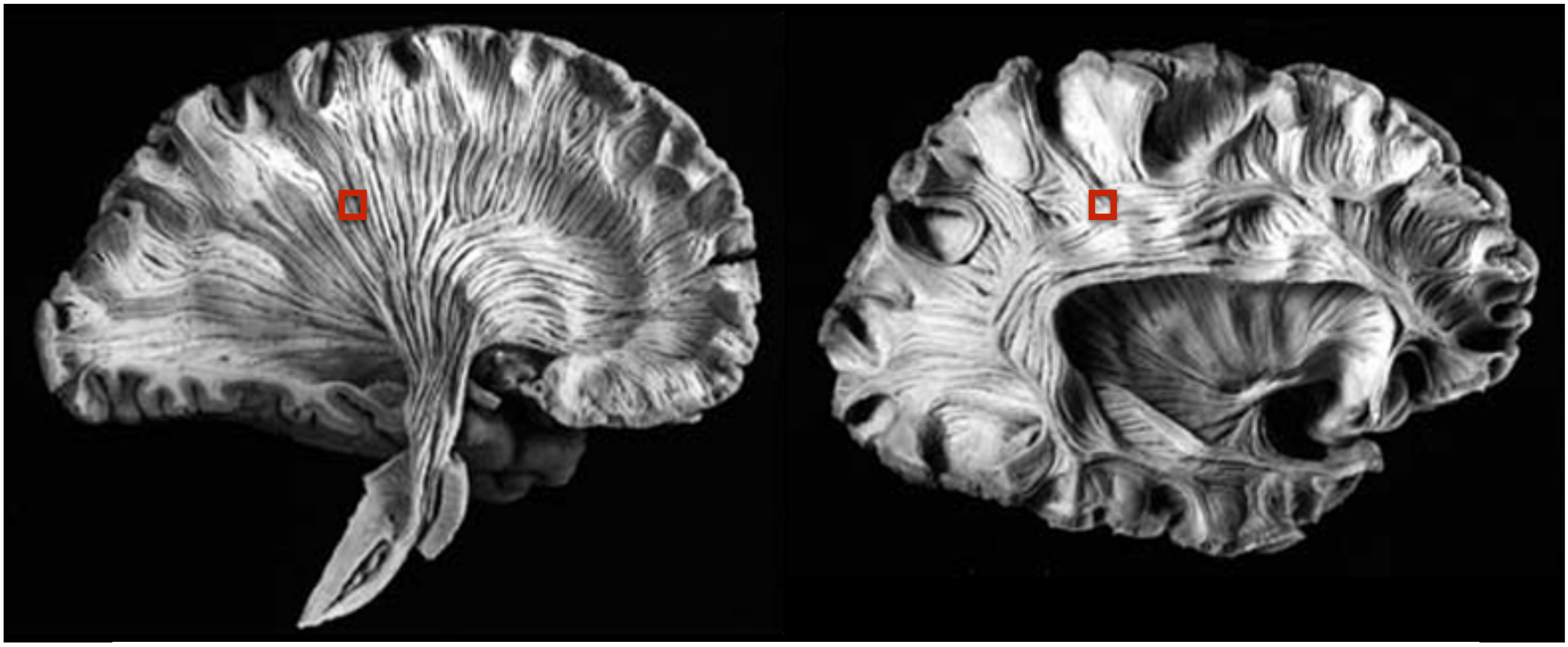
DTI Streamline Tractography Summary

- Use the major axis of the DTI ellipsoid as a fibre orientation estimate.

- Propagate curves within this vector field until empirical thresholds are exceeded.

- Major fibre bundles can be reconstructed.

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

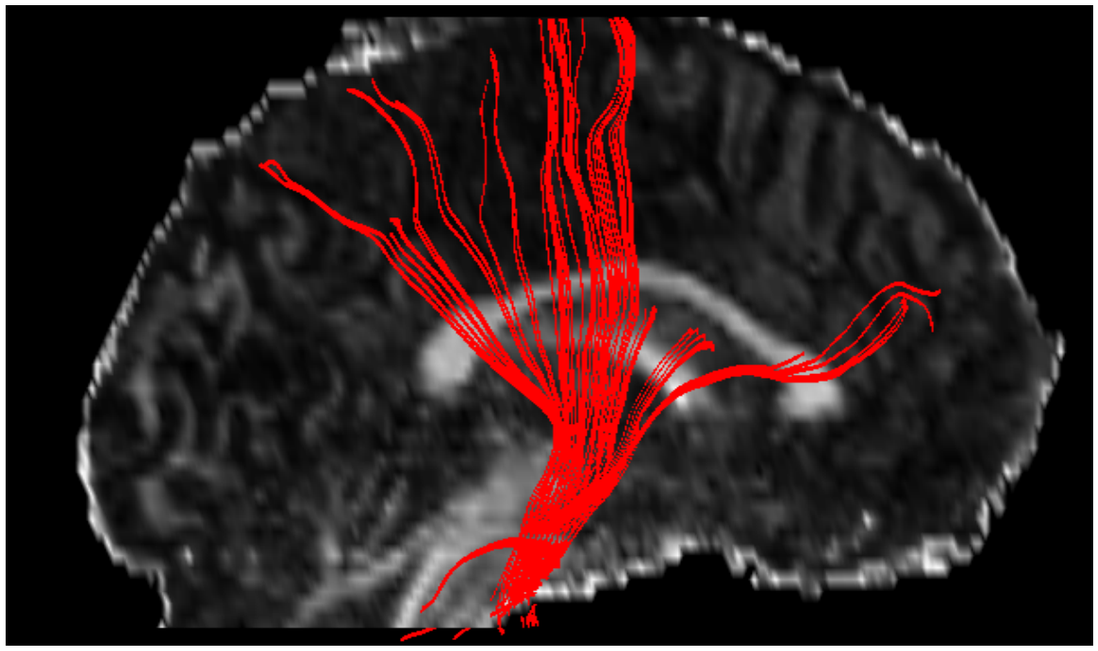
Streamlining reproducibility

Repeat an acquisition many times and repeat streamline tracking.

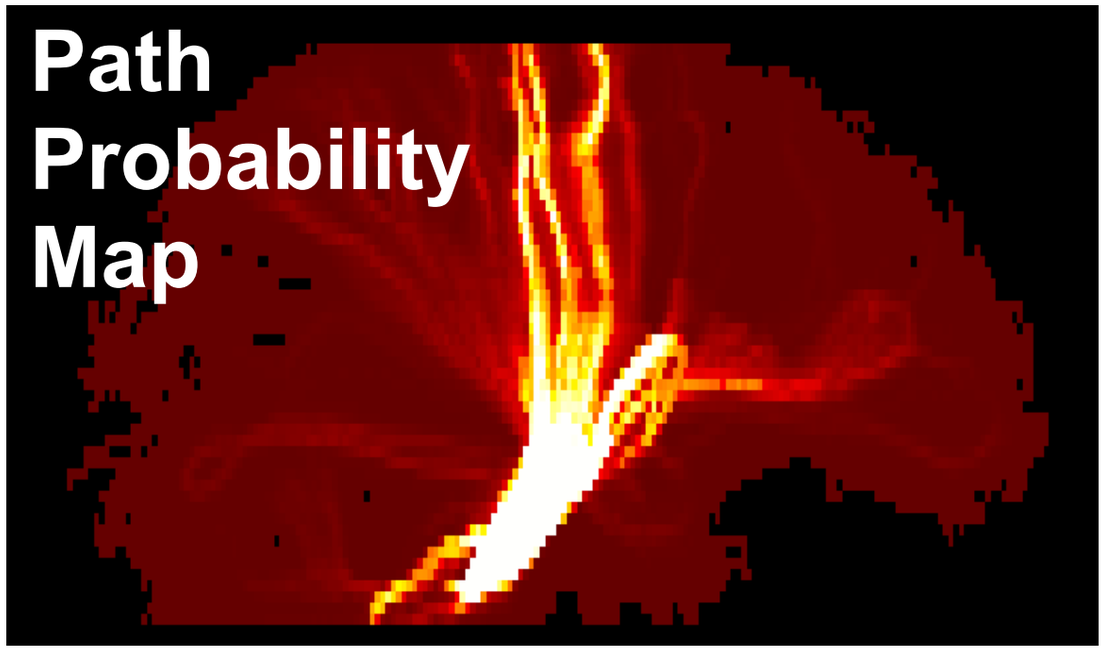
Due to uncertainty in $\mathbf{v}_1$, curves will not perfectly overlap

Create a map that shows the degree of overlap across the trials.

Streamlines from a single dataset



Map that shows where results across datasets overlap



Low Reproducibility — High Reproducibility

Probabilistic Tractography

- We normally have one dataset per subject, not many.

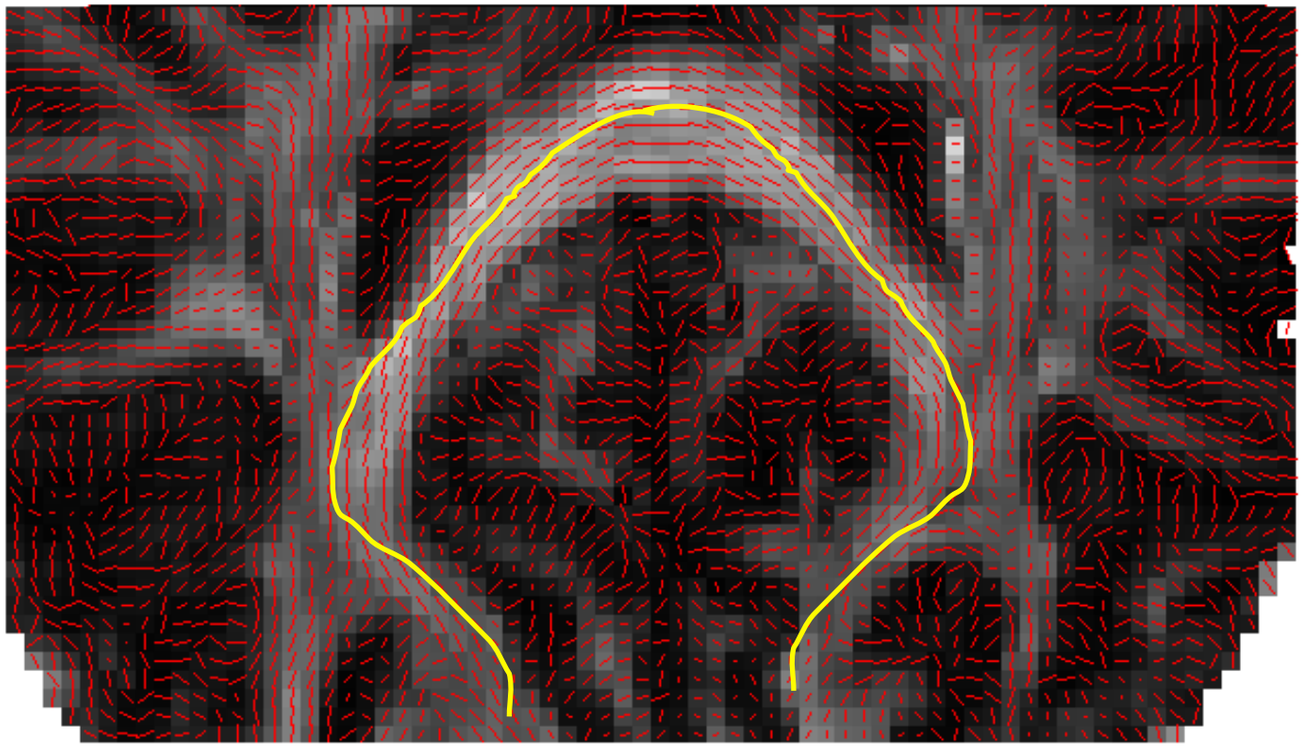
- Probabilistic Tractography as a two-step process:

a) Use DWI data and a model to infer a fibre orientation **and its uncertainty** in each voxel.

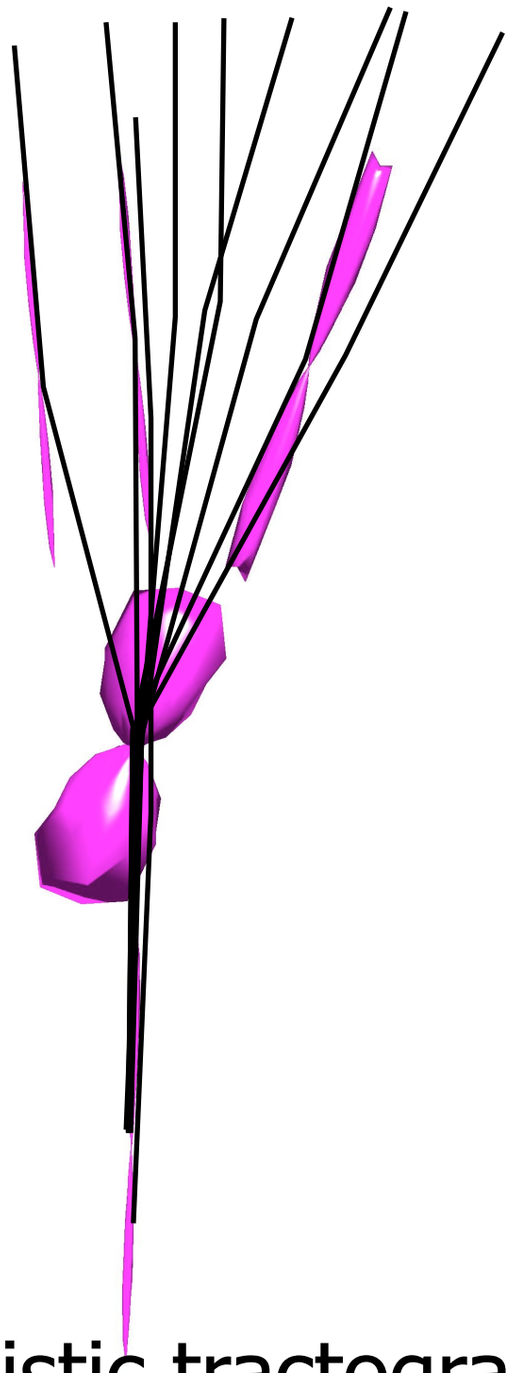
b) Use the estimates **and the uncertainty to build a path probability map** to a seed.

Probabilistic tractography

- But now, we no longer have a single direction at each voxel. How can we do tractography?



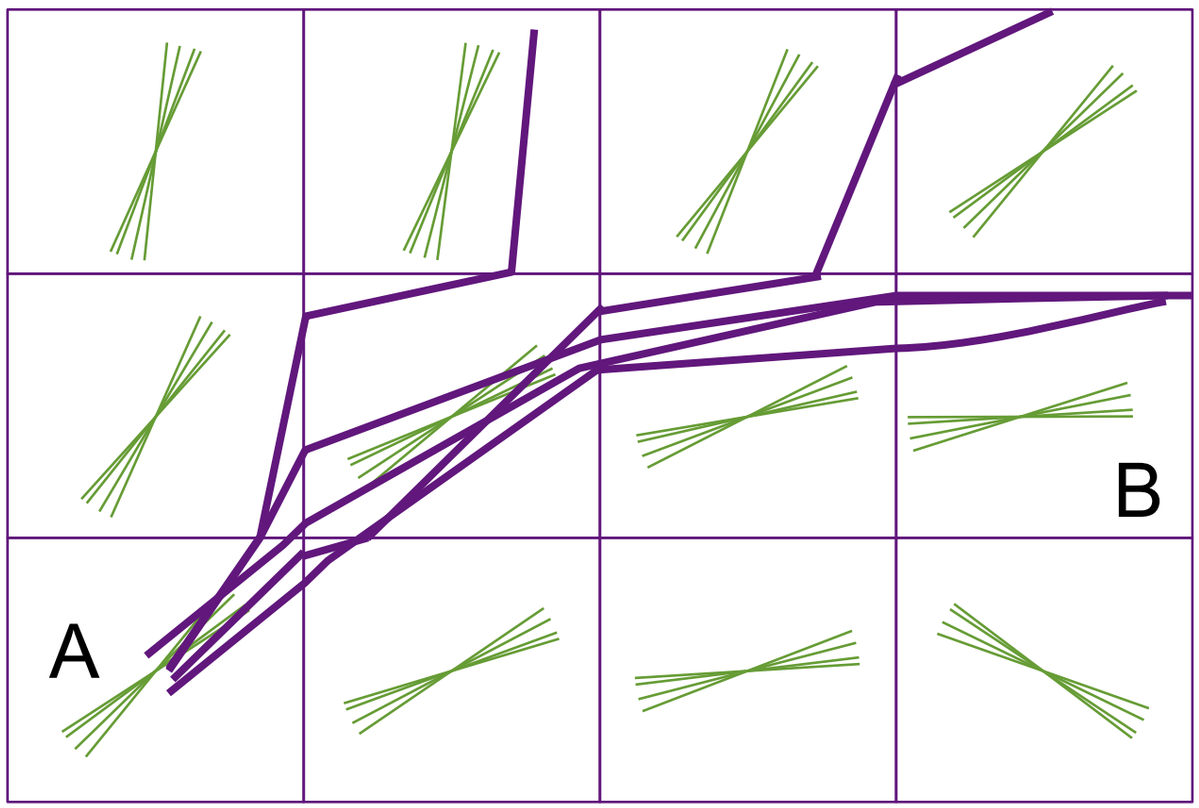
'Streamlining'



Probabilistic tractography

Behrens et al, 2003, Parker et al. 2003, Hagmann et al 2003, Jones et al. 2004

Probabilistic Tractography - Propagating the Uncertainty

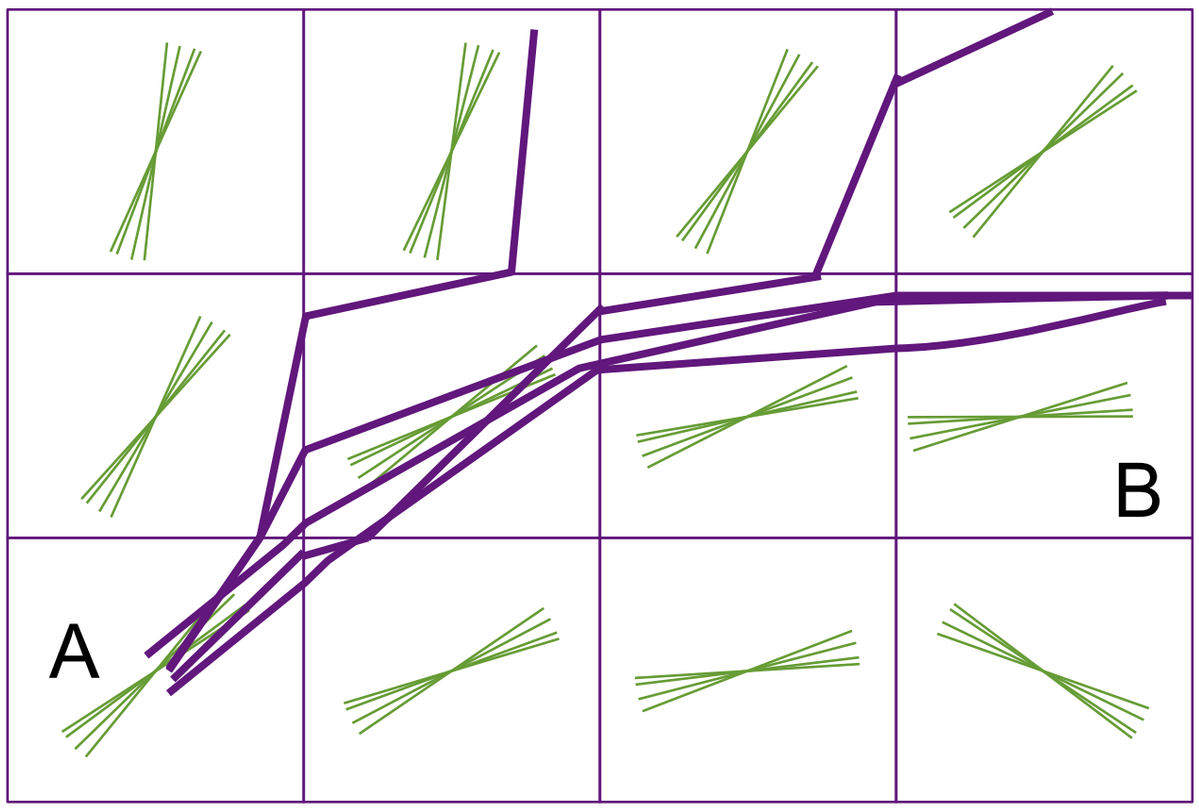


Behrens et al, 2003
Parker et al, 2003

- Propagate N streamlines from a seed, but for each propagation step choose randomly an orientation from the underlying distribution.

- Build a spatial distribution of curves that mimics the overlapped results from multiple deterministic tracking on multiple scans

Probabilistic Tractography - Propagating the Uncertainty



Behrens et al, 2003
Parker et al, 2003

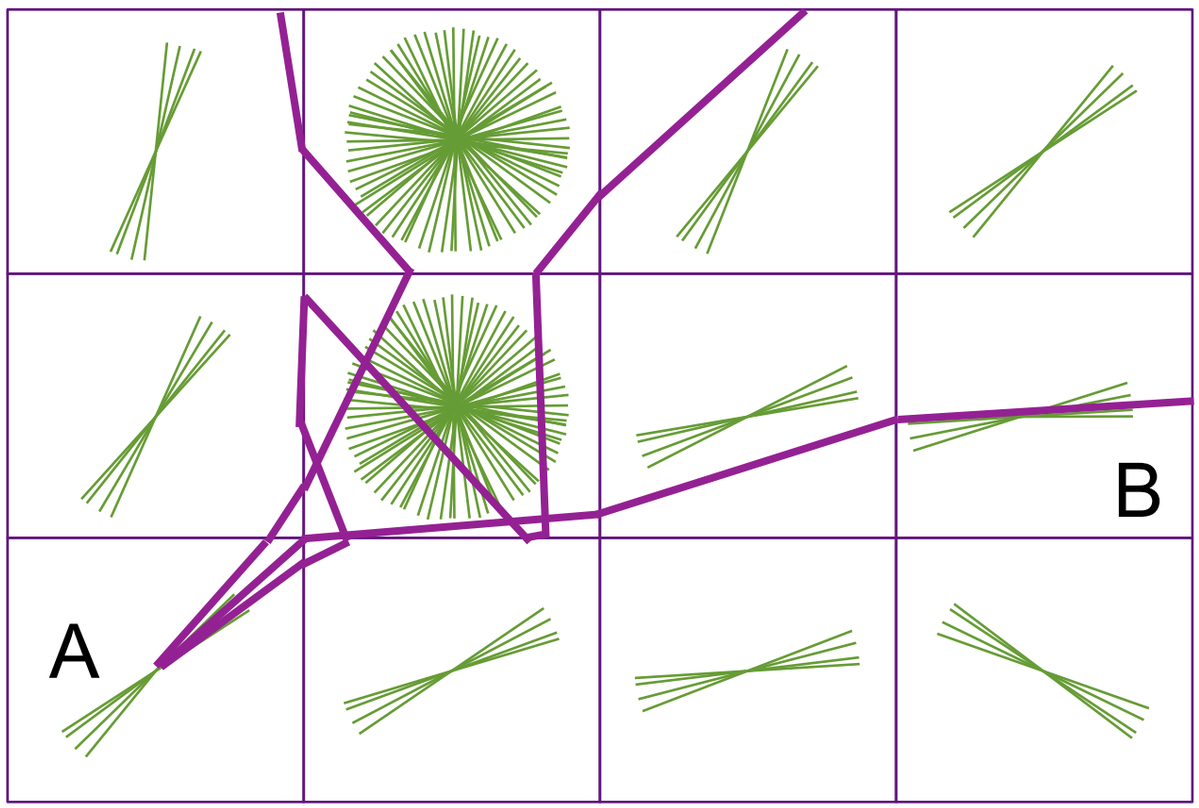
Define the degree of overlap at each location B, as:

$$P_{AB} = M/N$$

M:number of streamlines that go through B
N: total streamlines generated from A

This is the probability of a curve starting at A and going through B.

Probabilistic Tractography - Propagating the Uncertainty



Behrens et al, 2003
Parker et al, 2003

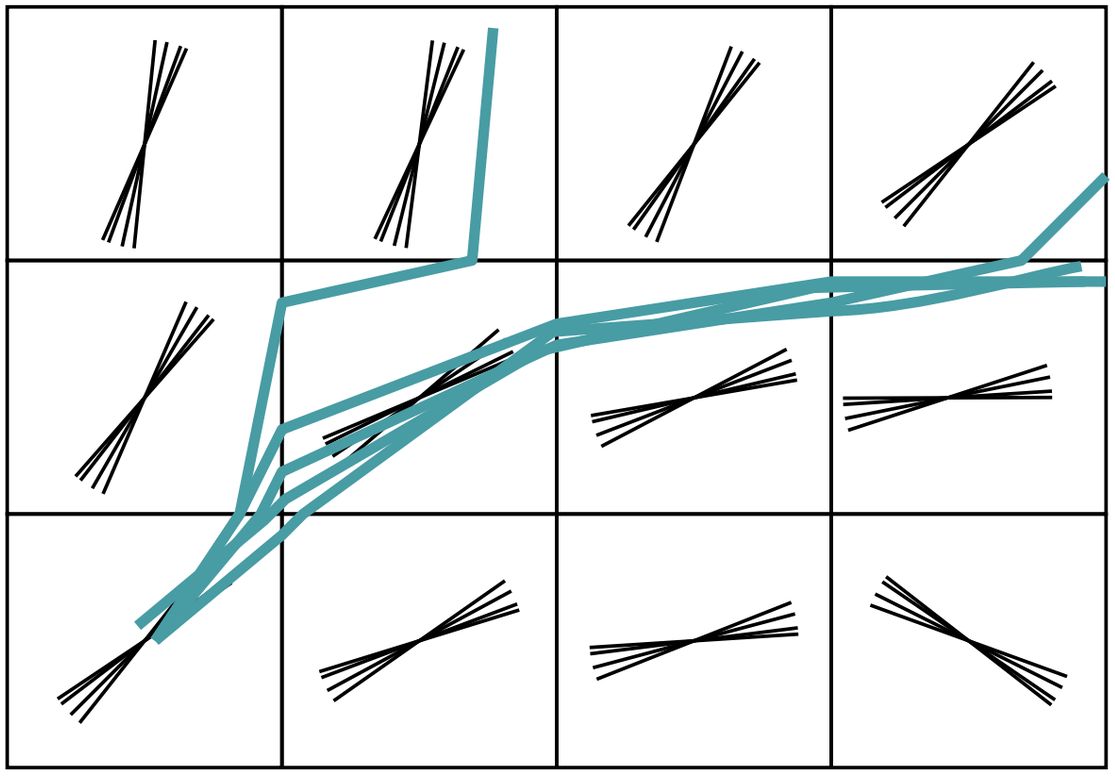
- Can now propagate through isotropic regions (e.g. GM).

- Do not need to stop when anisotropy is low, as in deterministic tracking.

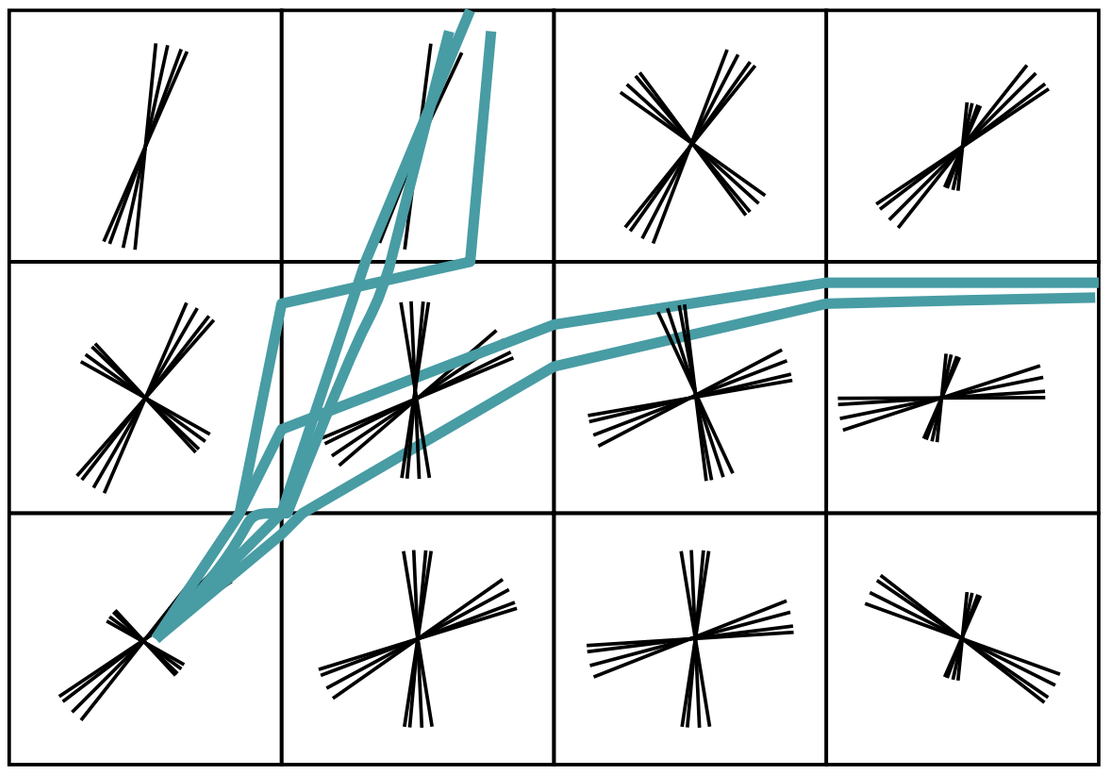
- The high uncertainty will be reflected in the probability map.

-Still impose a curvature threshold to avoid swirled trajectories.

Probabilistic Tractography in Multi-Fibre Fields



Behrens et al, 2003, Parker et al. 2003,
Hagmann et al 2003, Jones et al. 2004



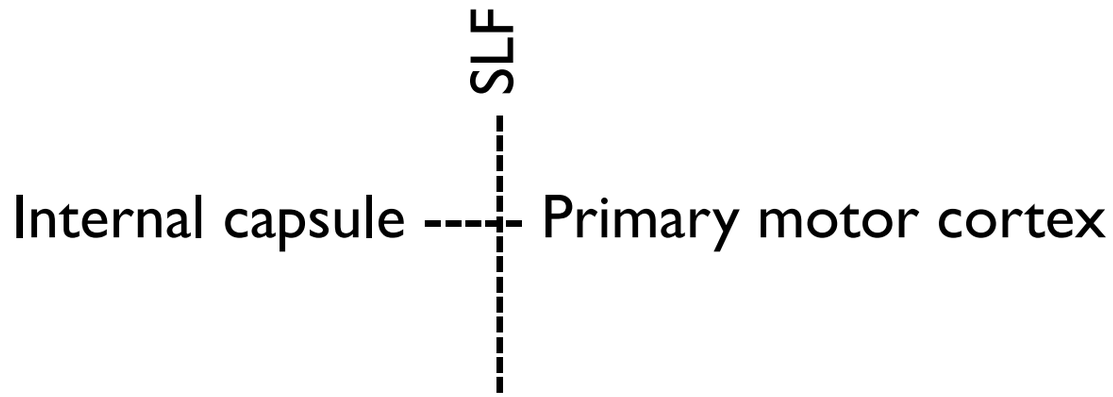
Parker & Alexander 2003,
Behrens et al, 2007

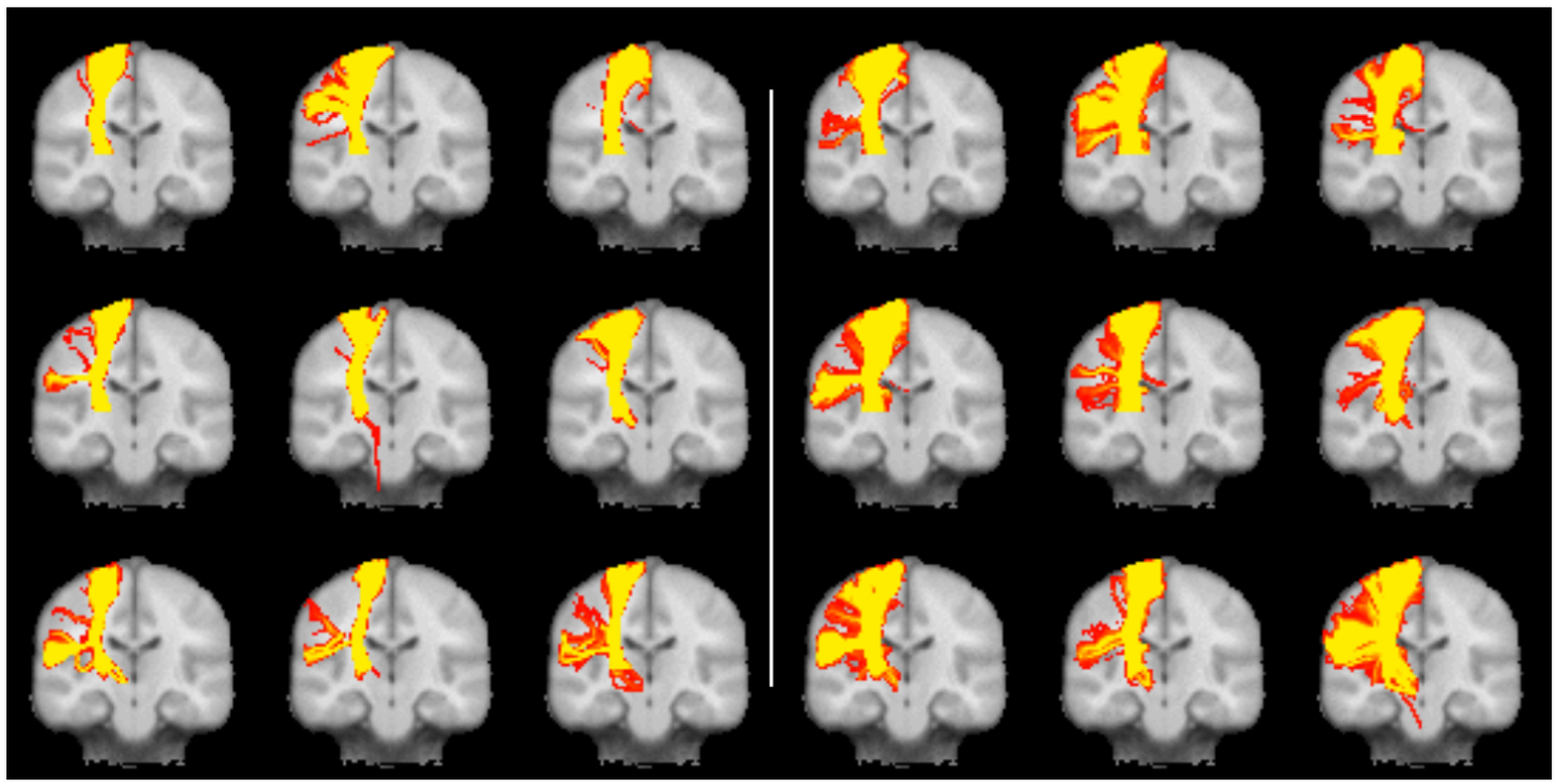
When multiple fibre orientations exist in a voxel, choose the one that is most compatible with the incoming trajectory.

Probabilistic Tractography in Multi-Fibre Fields
Examples

Cortico-spinal tracts.
9 subjects

Behrens et al, 2007





one fibre

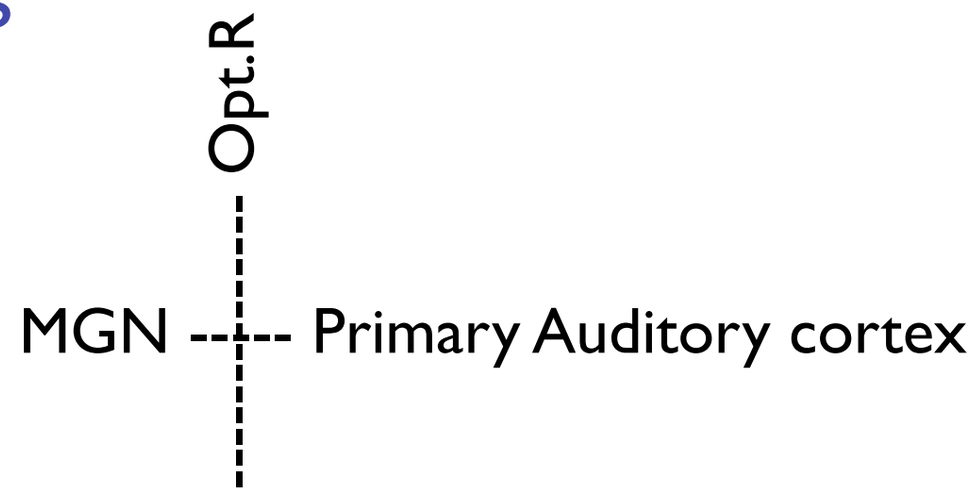
two fibres

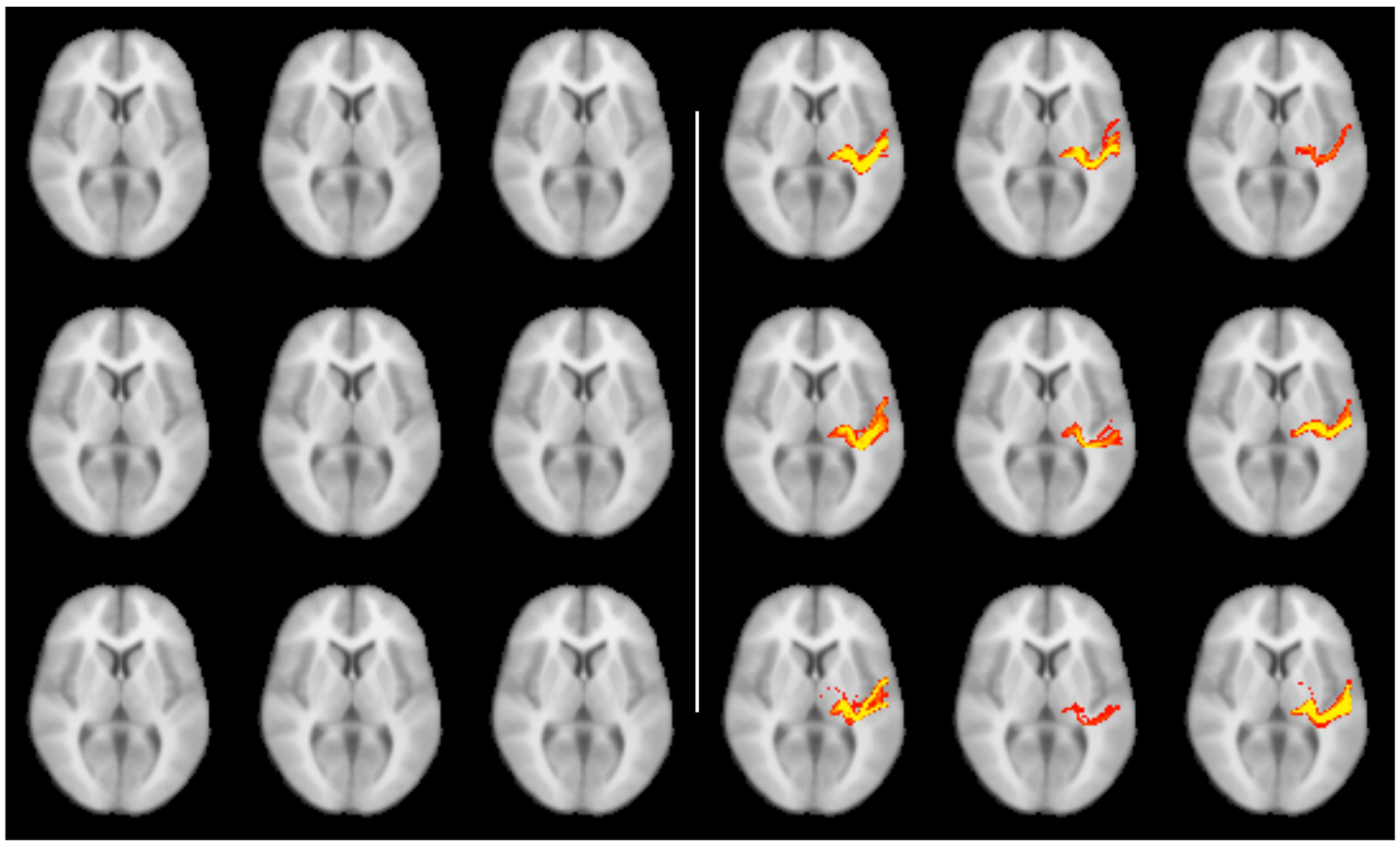
* If one fibre is modelled and we track through a crossing, a) we may not make it through the crossing, b) if we make it, the connectivity index will be relatively low.

Probabilistic Tractography in Multi-Fibre Fields
Examples

Acoustic radiations.
9 subjects

Behrens et al, 2007





one fibre

two fibres

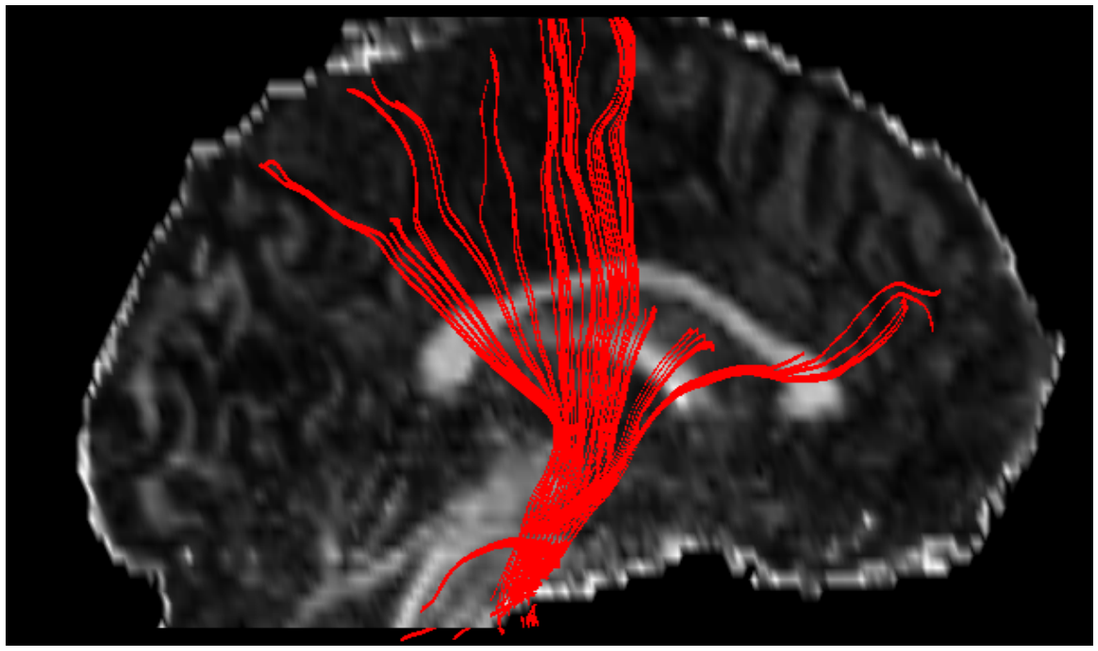
Path Probability Map

- Recall that it assesses how reproducible results are

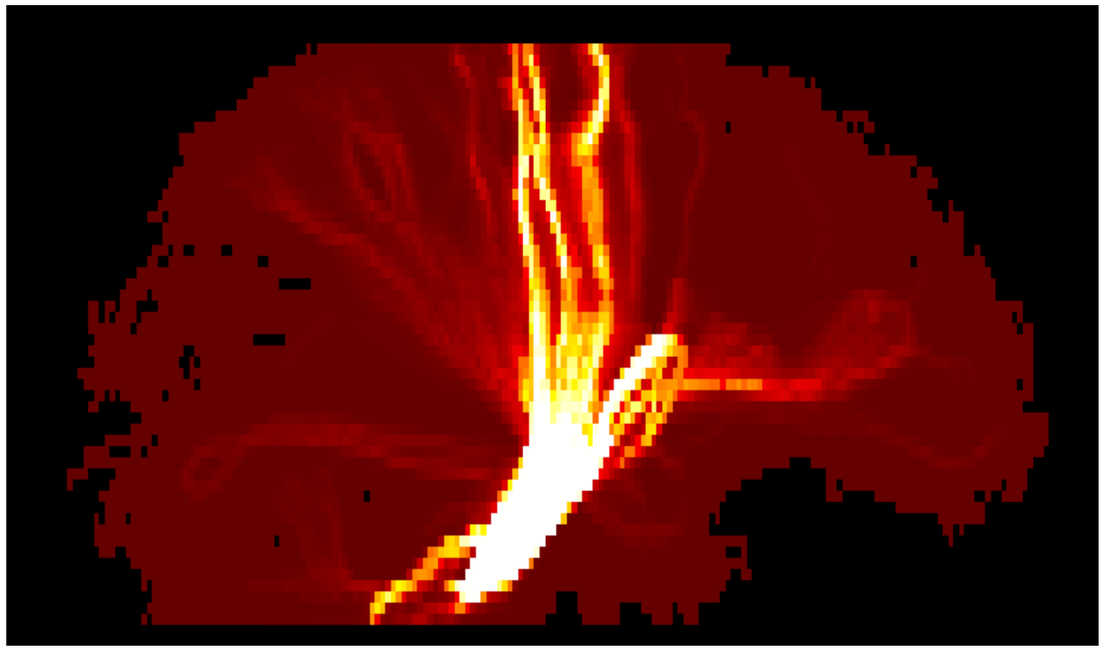
- Often called “connection probability”, “connectivity index”, “connectivity strength”. But it does not quantify how strong a connection is...

- Rather, how robust it is against noise/uncertainty

Deterministic Tractography



Probabilistic Tractography



Low Probability

High Probability

Probabilistic Streamline Tractography Summary

- Needs apart from orientation estimates, an estimate of their uncertainty. Does not need to be the ball and stick model, the DTI model can be used instead!

- Propagate streamlines repeatedly from a seed, but the orientation field is no longer deterministic. In each propagation step choose randomly an orientation from the underlying distribution.

- A connection probability value>=0 can be obtained from a seed A to any voxel in the brain B. This assesses **the reproducibility of the path from A to B, along which water molecules preferably diffuse.**