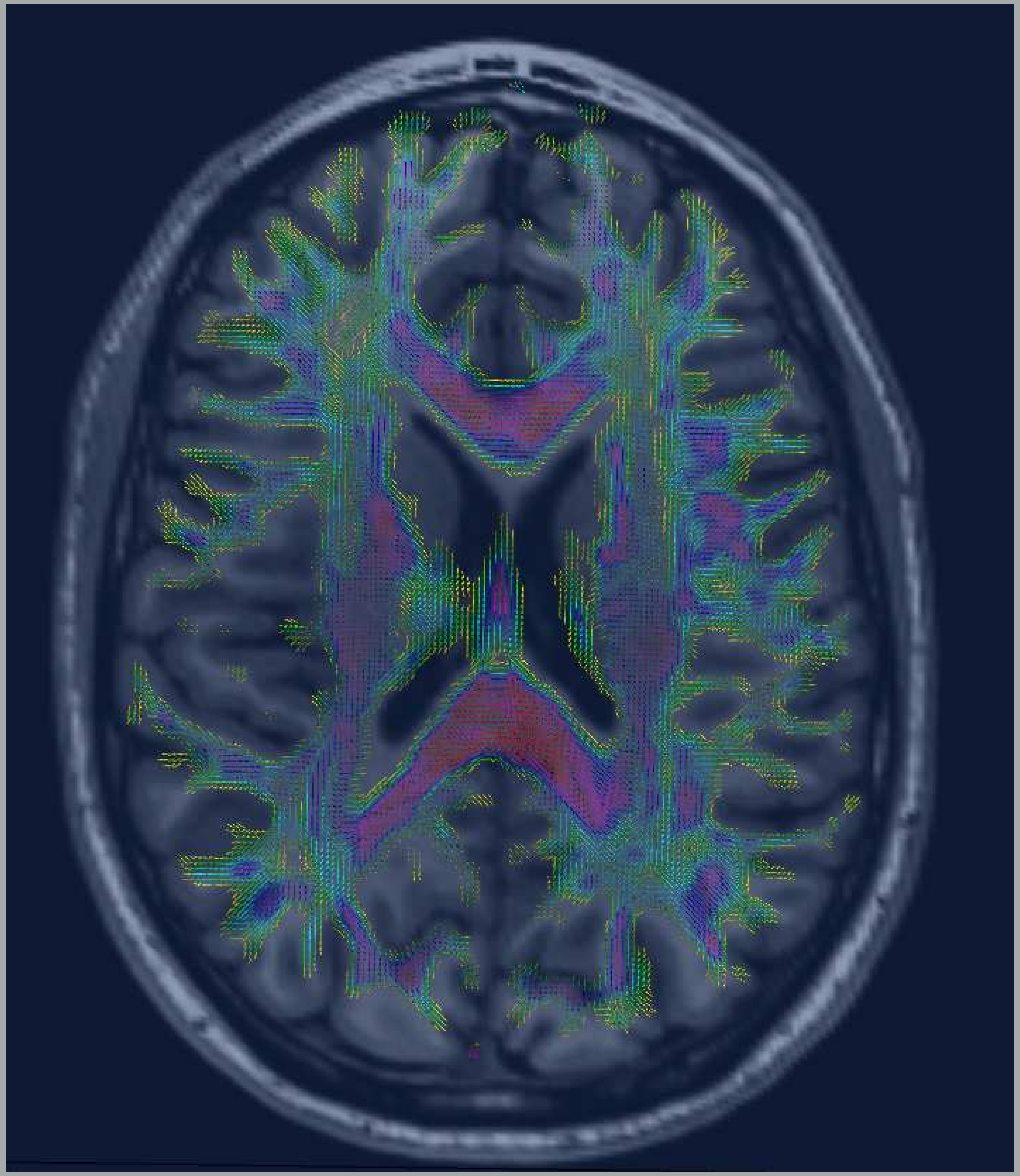
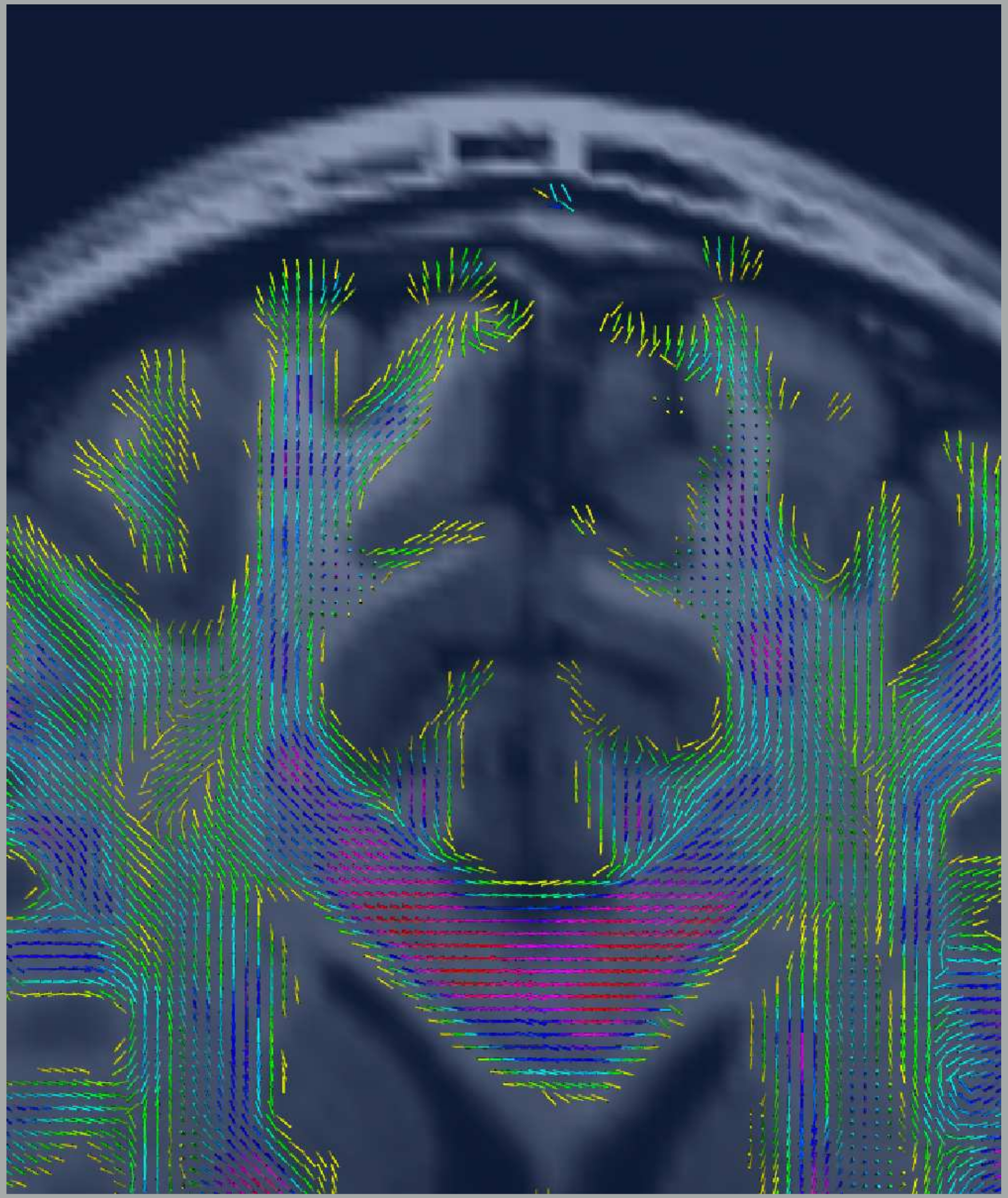
Lecture 15
Fiber Tract Mapping

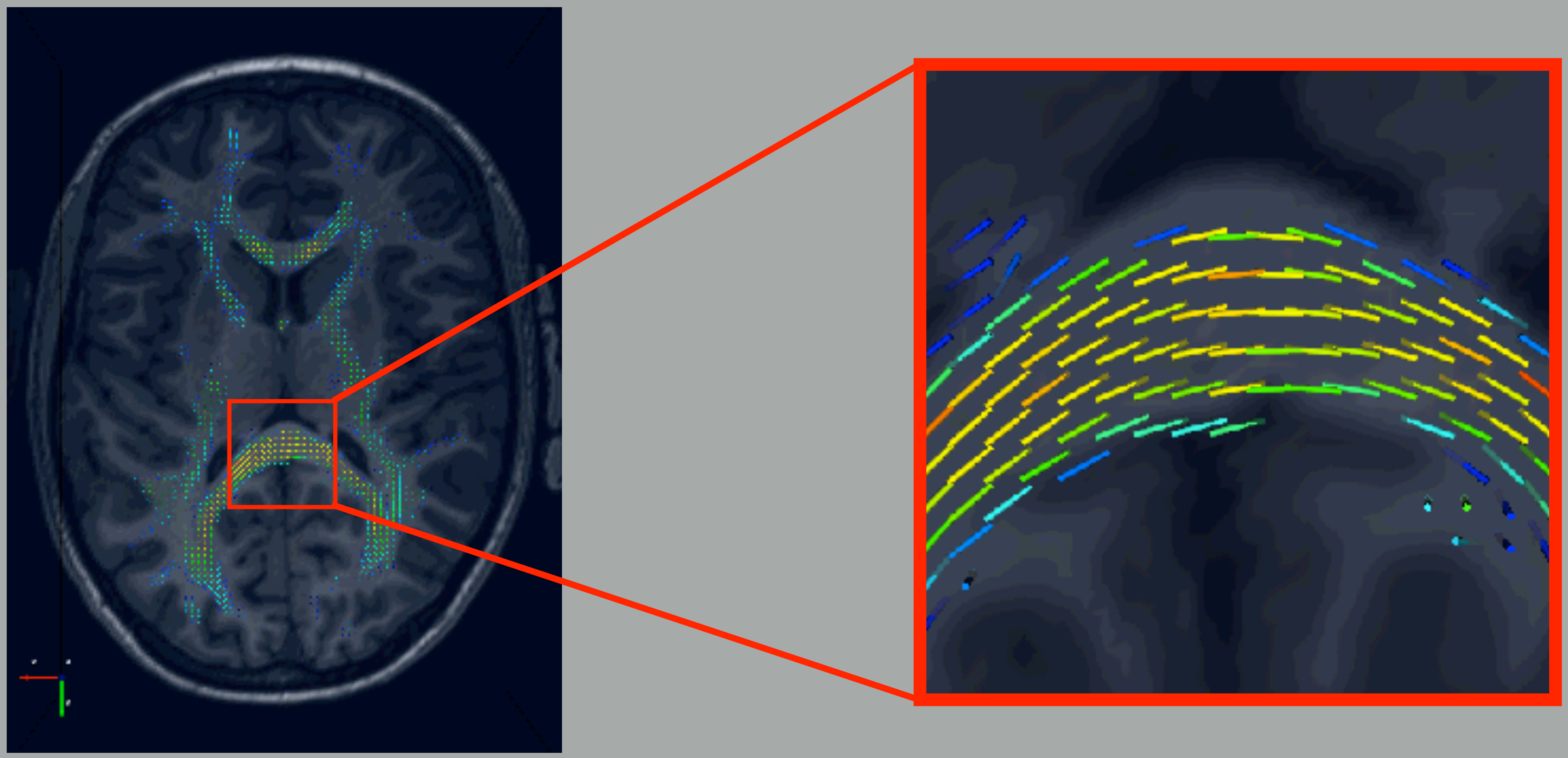
Principal Eigenvectors





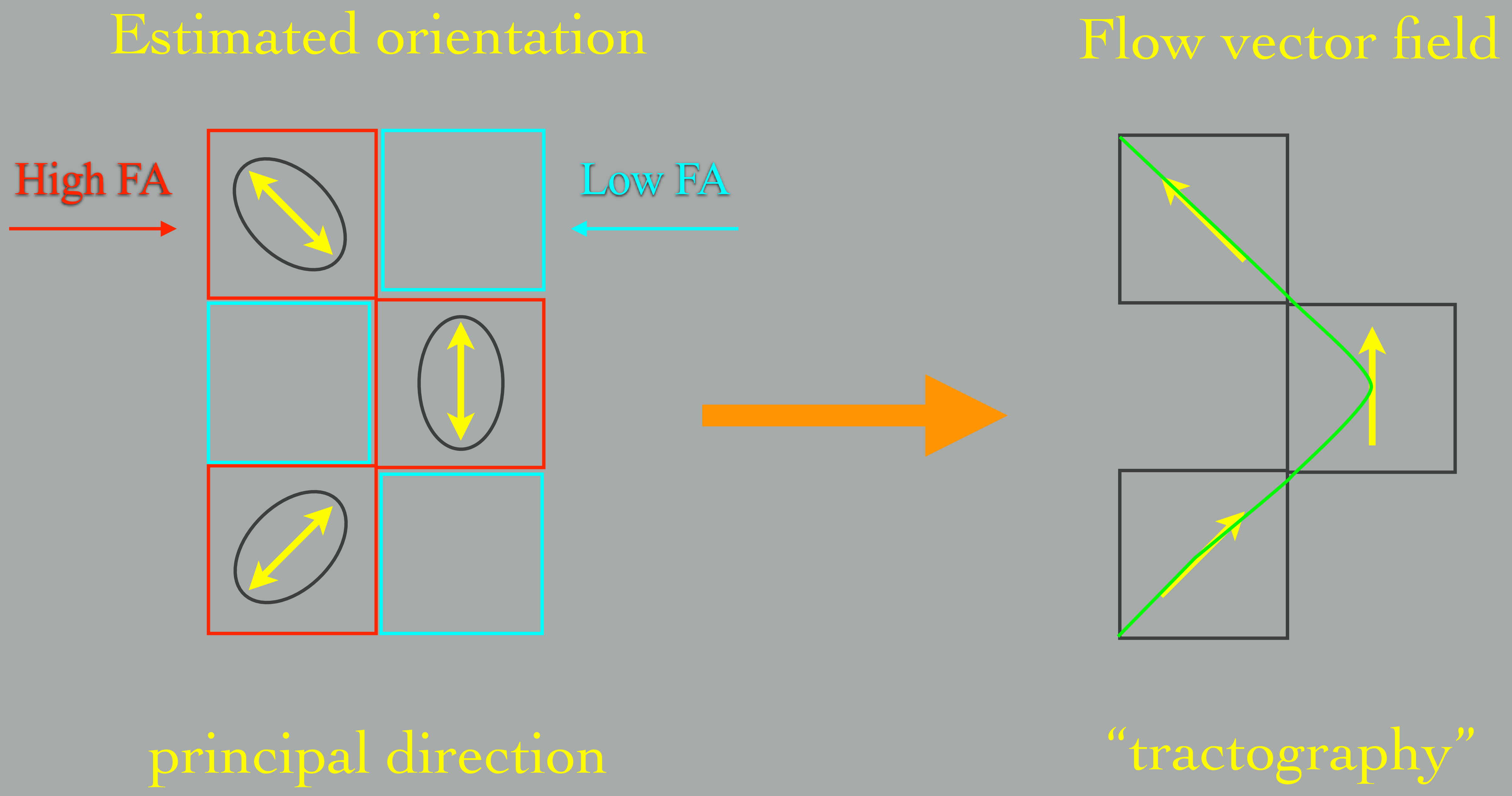
Fiber Orientation

The Gateway to Connectivity!



Aligned fibers in the corpus callosum

Streamline based tractography



Deterministic methods

1. Connect voxels (Conturo)
2. FACT (Mori,DTI Studio)
3. Path integral (Basser, Tuch)

Deterministic methods

1. Connect voxels (Conturo)
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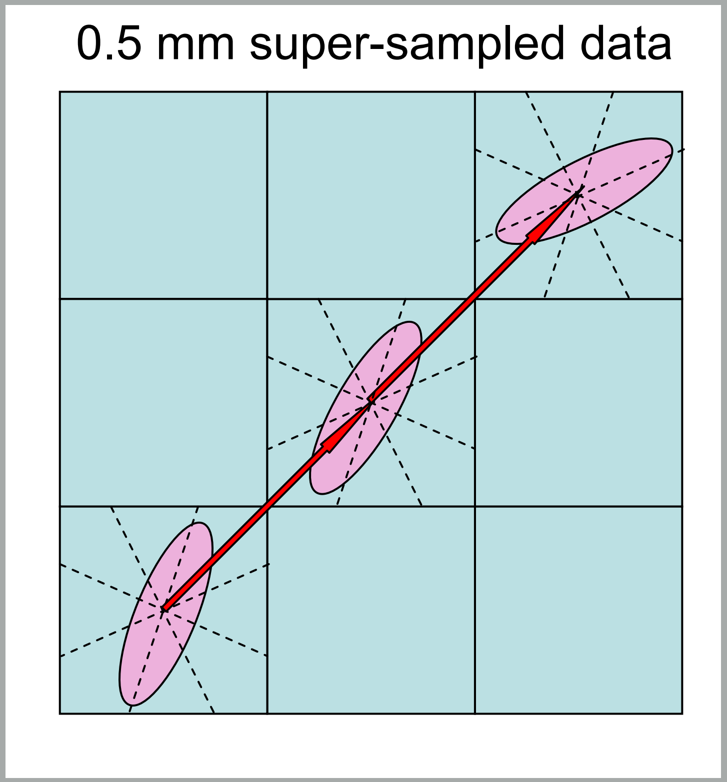
3. Path integral (Basser, Tuch)

Connect voxels
(Conturo, 1999 PNAS)

Resample tensor
(eg from 2.5mm to .5mm)

Follow voxel in direction
of PEV (both directions)

Stop when FA low



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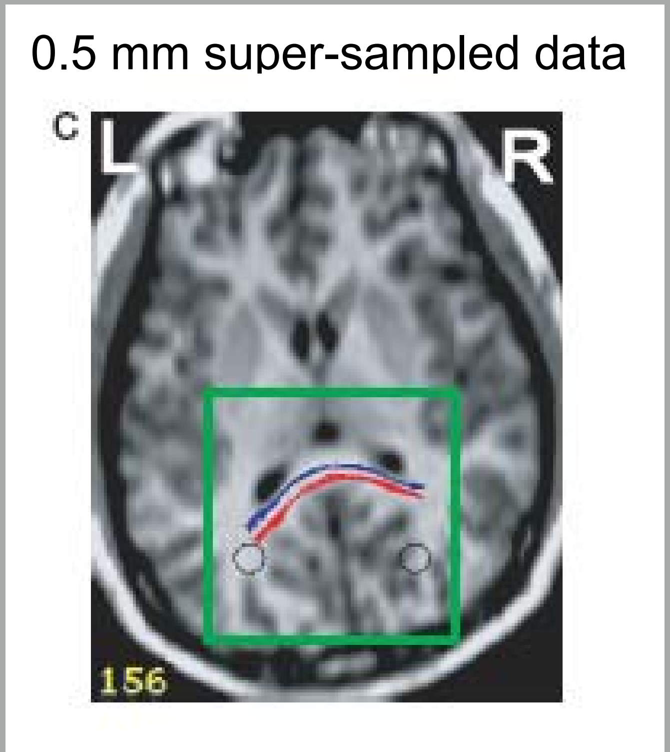
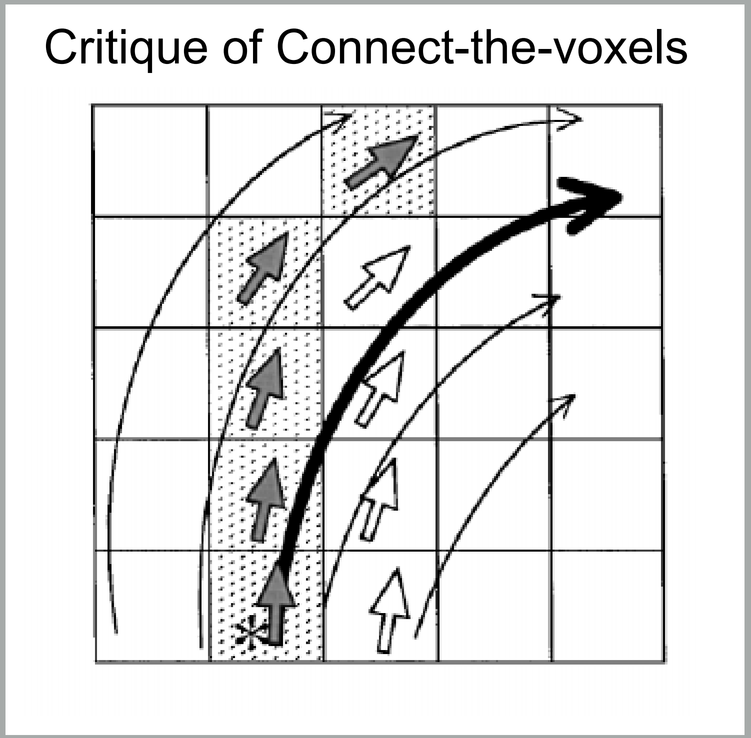


Fiber Assignment by Continuous Tracking (FACT) (Mori 1999)

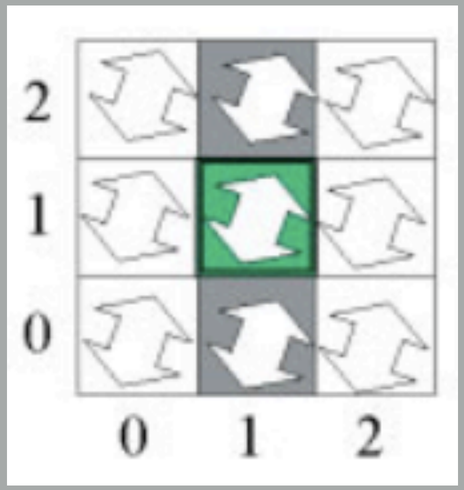


Start at seed and follow PEV until hit edge of voxel

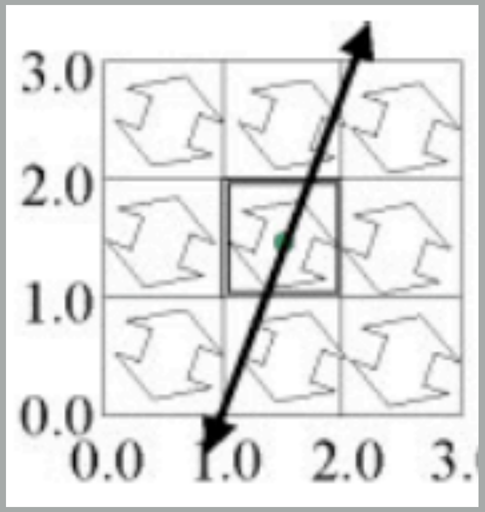
Move to next voxel tensor, repeat

Interpolate between data points

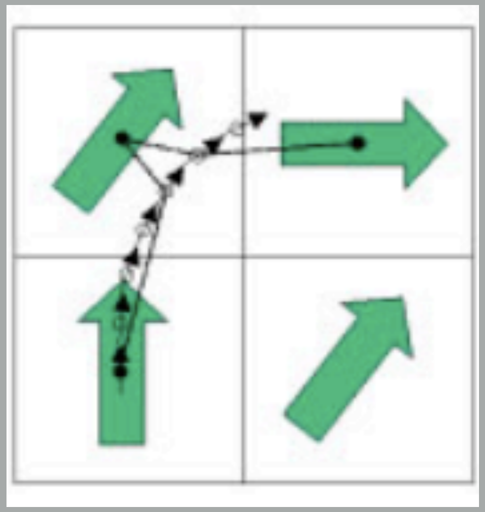
Fiber Assignment by Continuous Tracking (FACT)



Discrete:
voxel connected to adjacent
one to which it "points"



Continuous Linear:
Line is propagated



Continuous Non-linear:
Line is weighted by distanced weighted
average of the surrounding vectors

Mori & Van Zijl, NMR Biomed 2002

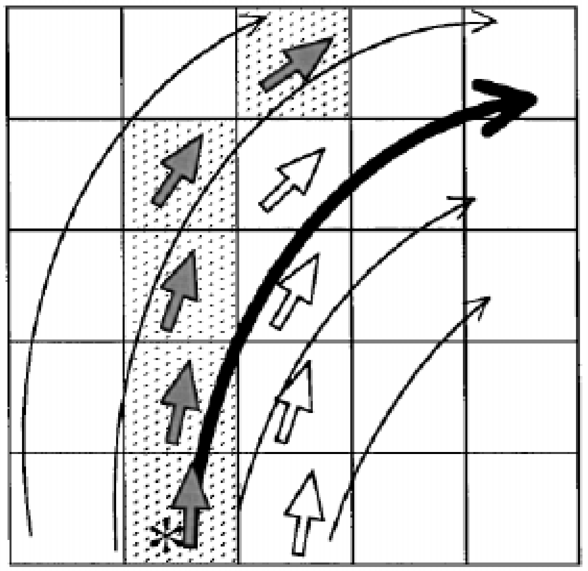
Fiber Assignment by Continuous Tracking (FACT) (Mori 1999)

Start at seed and follow PEV until hit edge of voxel

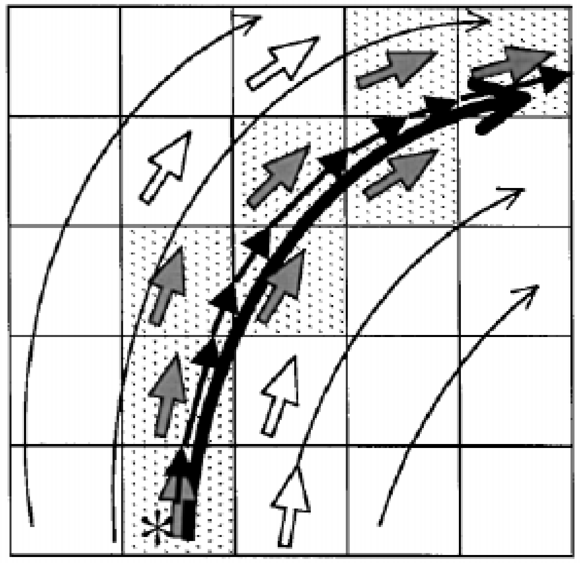
Move to next voxel tensor, repeat

Interpolate between data points

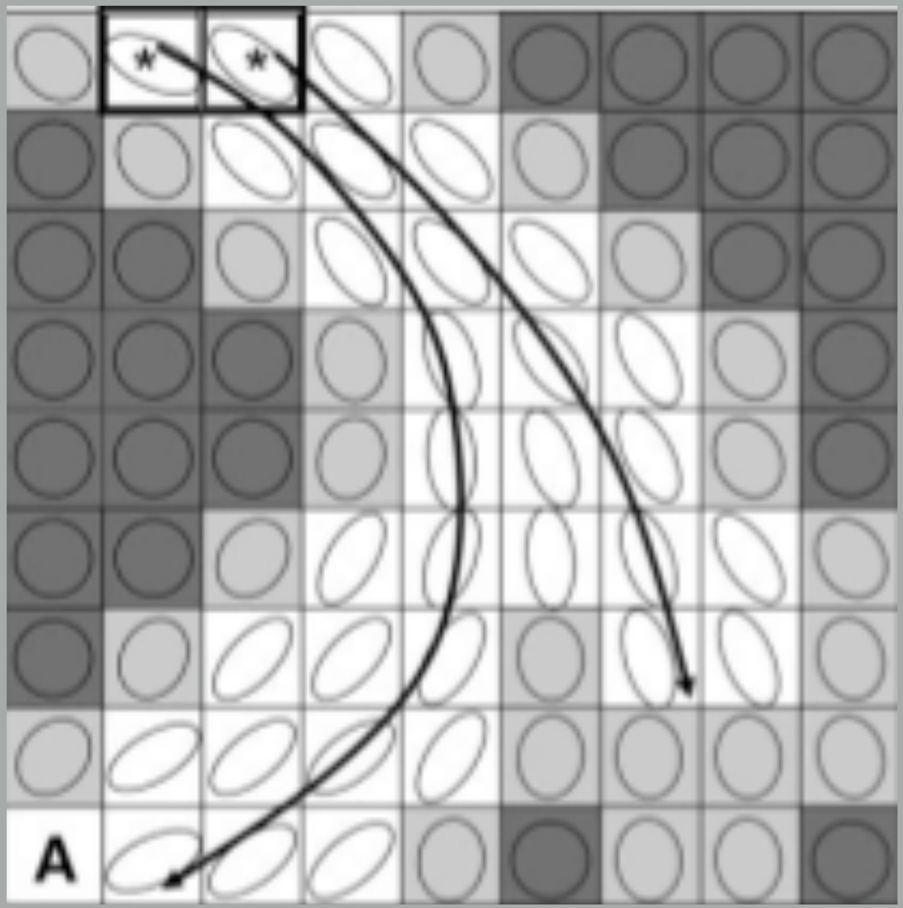
Critique of Connect-the-voxels

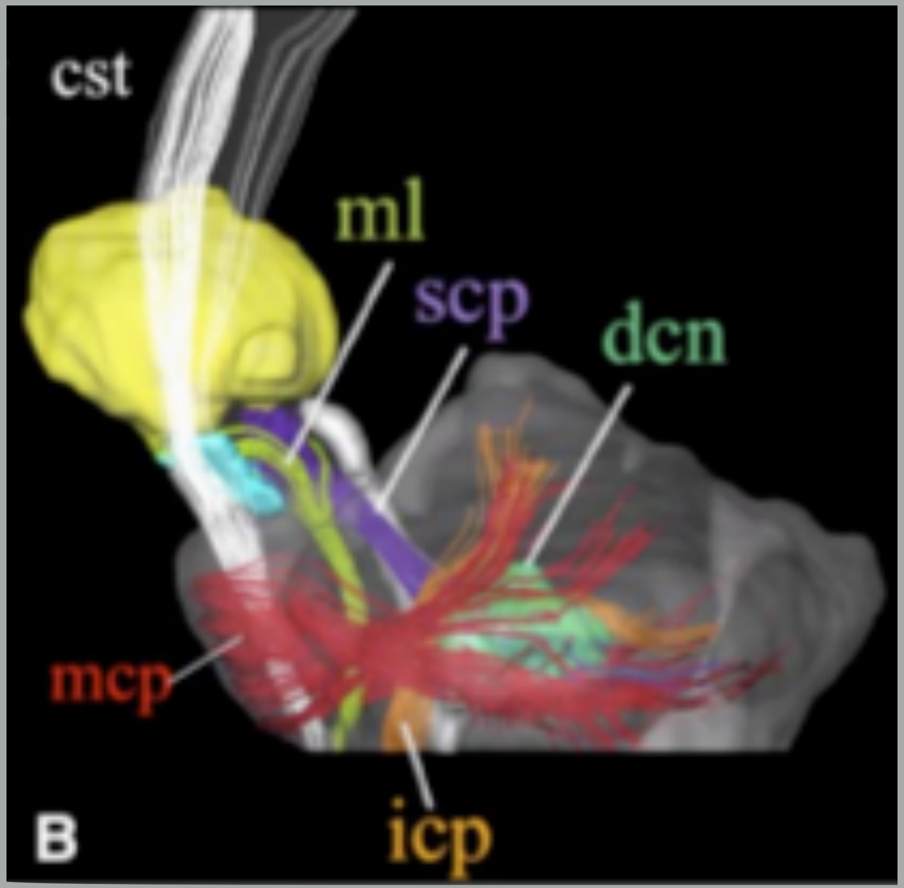


Modified algorithm



FACT



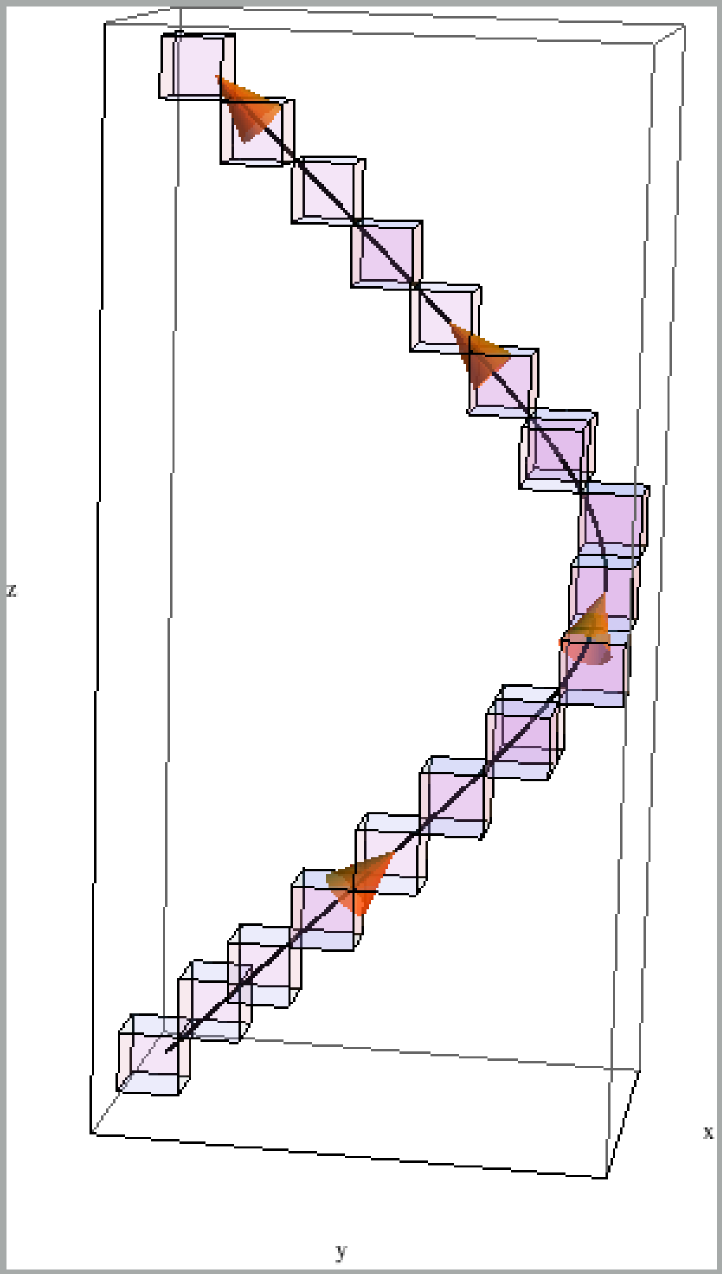


Mori & Zhang, Neuron 2006

Path Integral method
(Basser 2000)

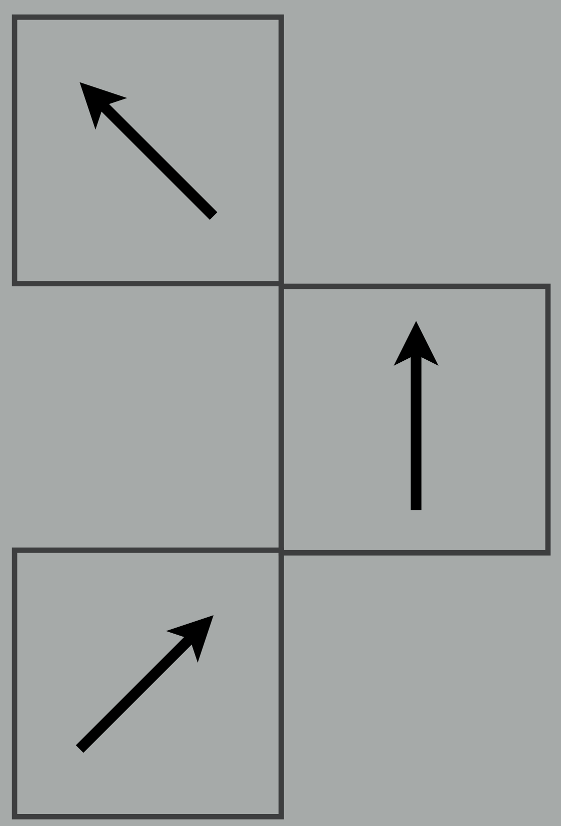
PEV direction is considered
to be path tangent

Tracing the Principal Eigenvectors

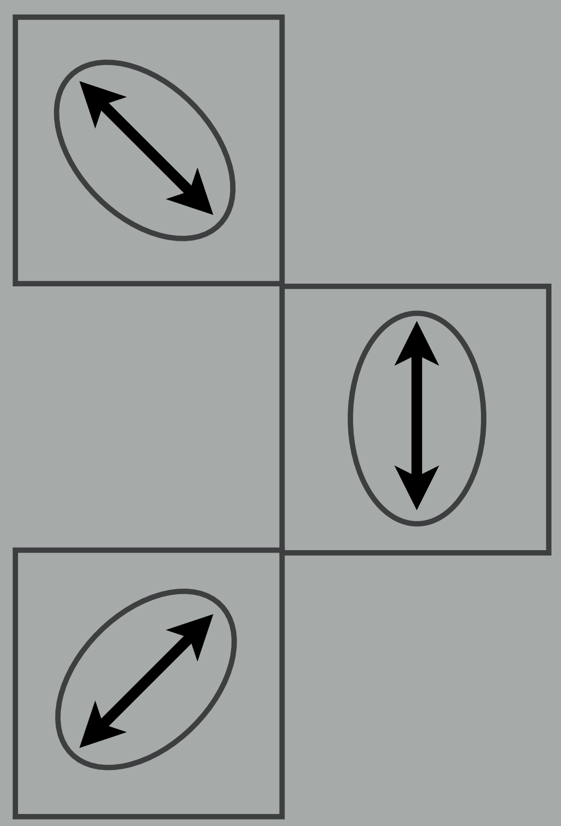


Streamlines

Flow vector field

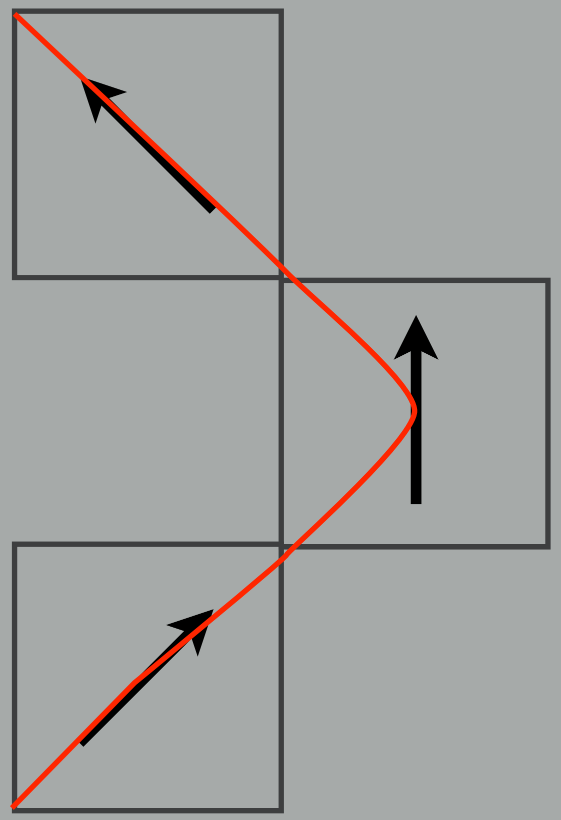


Principal eigenvector field

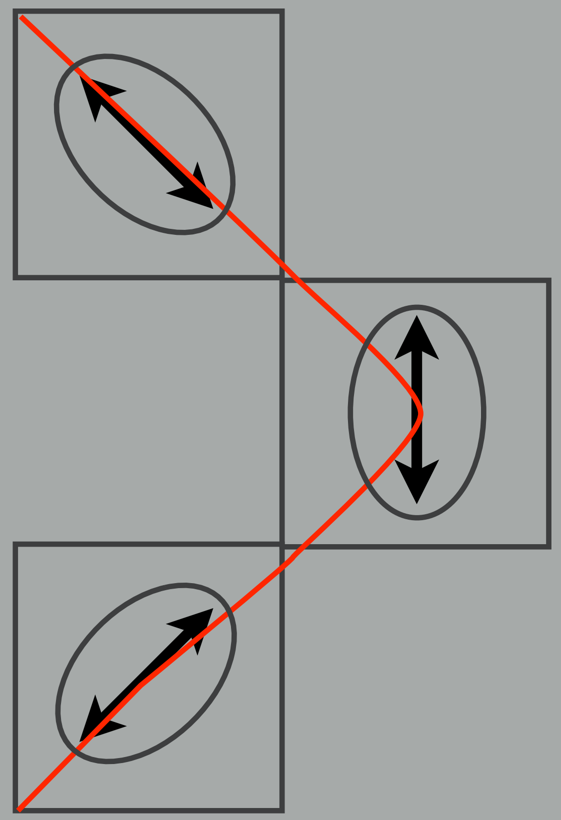


Streamlines

Flow vector field

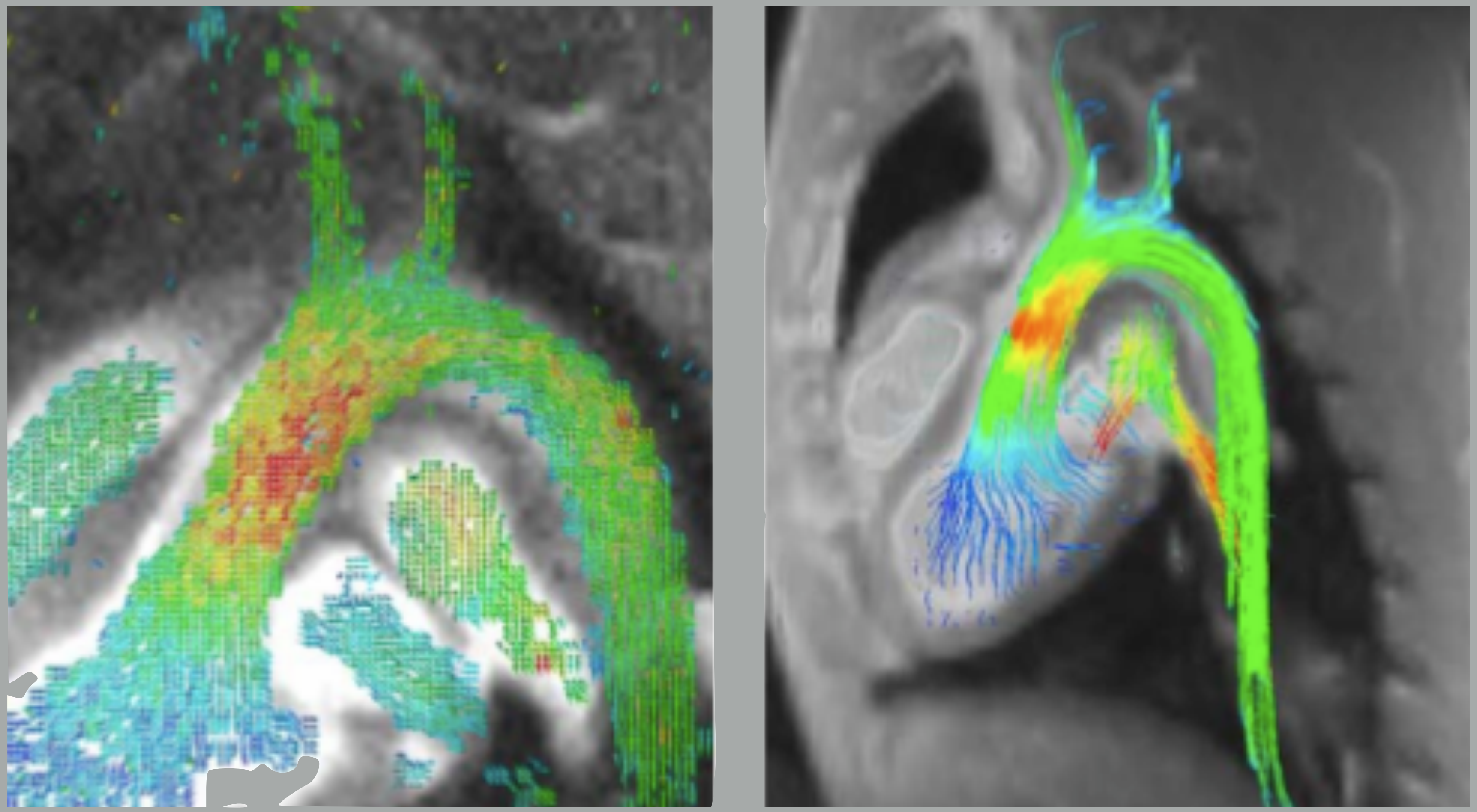


Principal eigenvector field



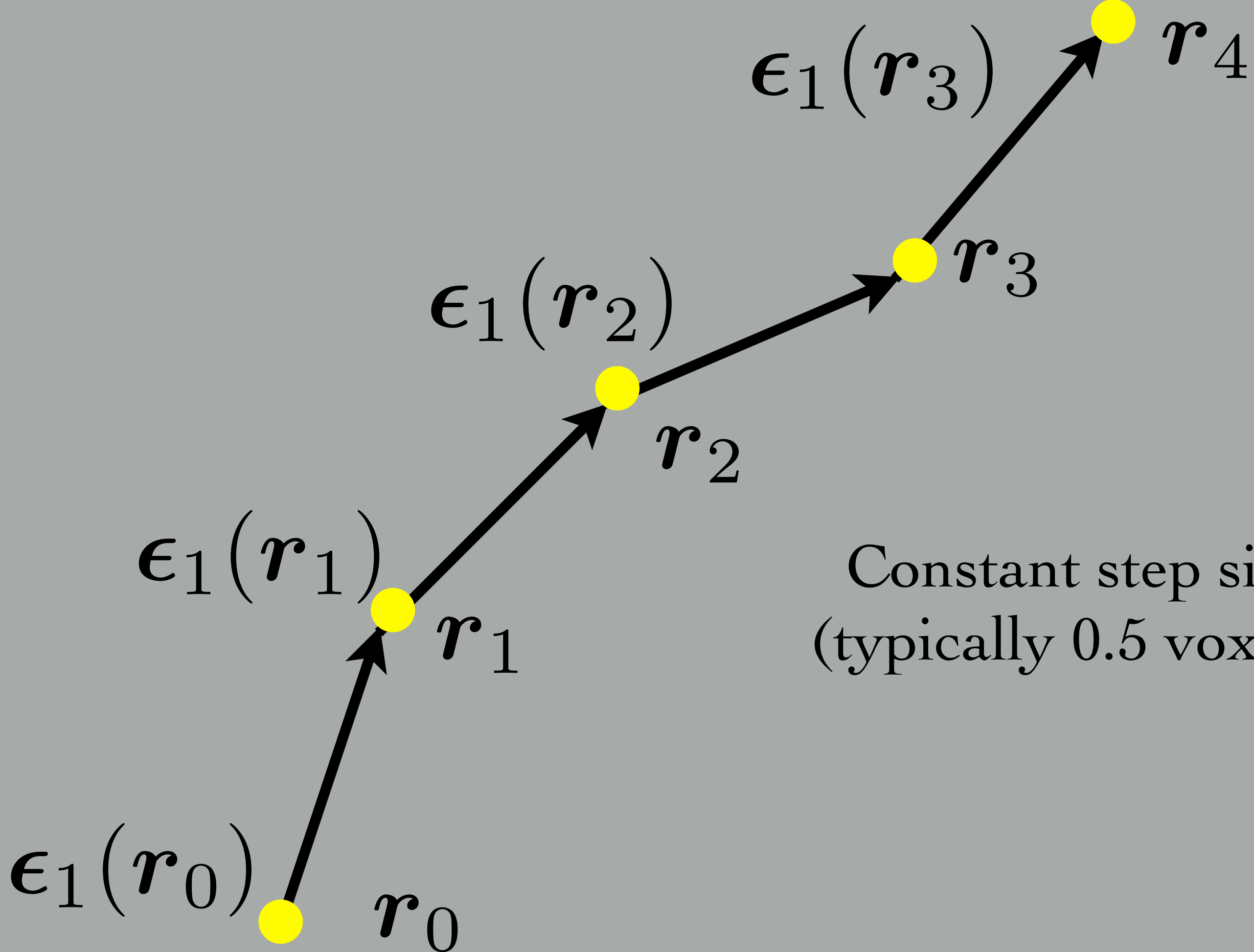
Streamlines

Path traced by a massless particle in a velocity vector field



R. Unterhinninghofen, et. al.

Streamlines



Constant step size
(typically 0.5 voxels)

Termination criterion:

1. Minimum FA
2. Maximum curvature
3. Maximum fiber length
4. Specified final point

Streamlines

1. Deterministic
2. Integration of principal eigenvector
3. Requires only diffusion tensor D but does not depend on underlying model for diffusion (i.e., can be any type of fiber)

Streamline Tractography

Space curves (Basser, et. al.)

$$\frac{d\boldsymbol{r}(s)}{ds} = \boldsymbol{t}(s)$$

$$\boldsymbol{r}(s) = \text{trajectory}$$

$$\boldsymbol{t}(s) = \text{tangent to } \boldsymbol{r}(s) \text{ at } s$$

$$s = \text{arc length}$$

Assert: Principal eigenvector lies in direction of tangent

Streamline Tractography

Assertion: Principal eigenvector $\boldsymbol{e}_1$ lies in the direction of the tangent $\boldsymbol{t}(s)$

$$\boldsymbol{t}(s) = \boldsymbol{e}_1(\boldsymbol{r}(s))$$

Streamline Tractography

$$\frac{d\boldsymbol{r}(s)}{ds} = \boldsymbol{t}(s)$$

can then be written

$$\frac{d\boldsymbol{r}(s)}{ds} = \boldsymbol{e}_1(\boldsymbol{r}(s))$$

Streamline Tractography

$$\frac{d\boldsymbol{r}(s)}{ds} = \boldsymbol{e}_1(\boldsymbol{r}(s))$$

$$\boldsymbol{t}(s) = \boldsymbol{e}_1(\boldsymbol{r}(s))$$

Solve for $\boldsymbol{r}(s)$ with initial condition

$$\boldsymbol{r}(0) = \boldsymbol{r}_o$$

Euler's Method

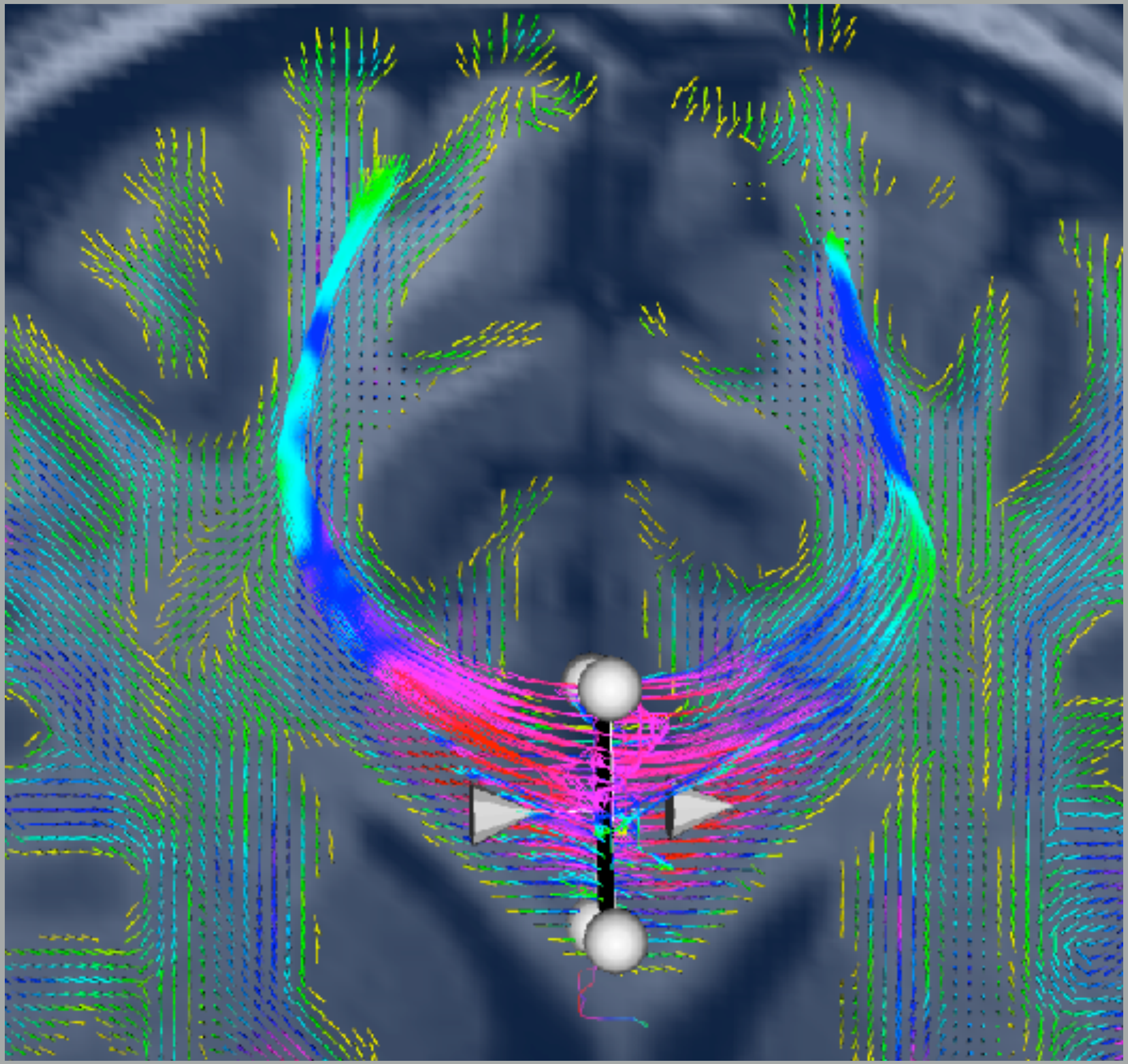
$$\frac{d\boldsymbol{r}(s)}{ds} = \boldsymbol{e}_1(\boldsymbol{r}(s))$$

$$\boldsymbol{t}(s) = \boldsymbol{e}_1(\boldsymbol{r}(s))$$

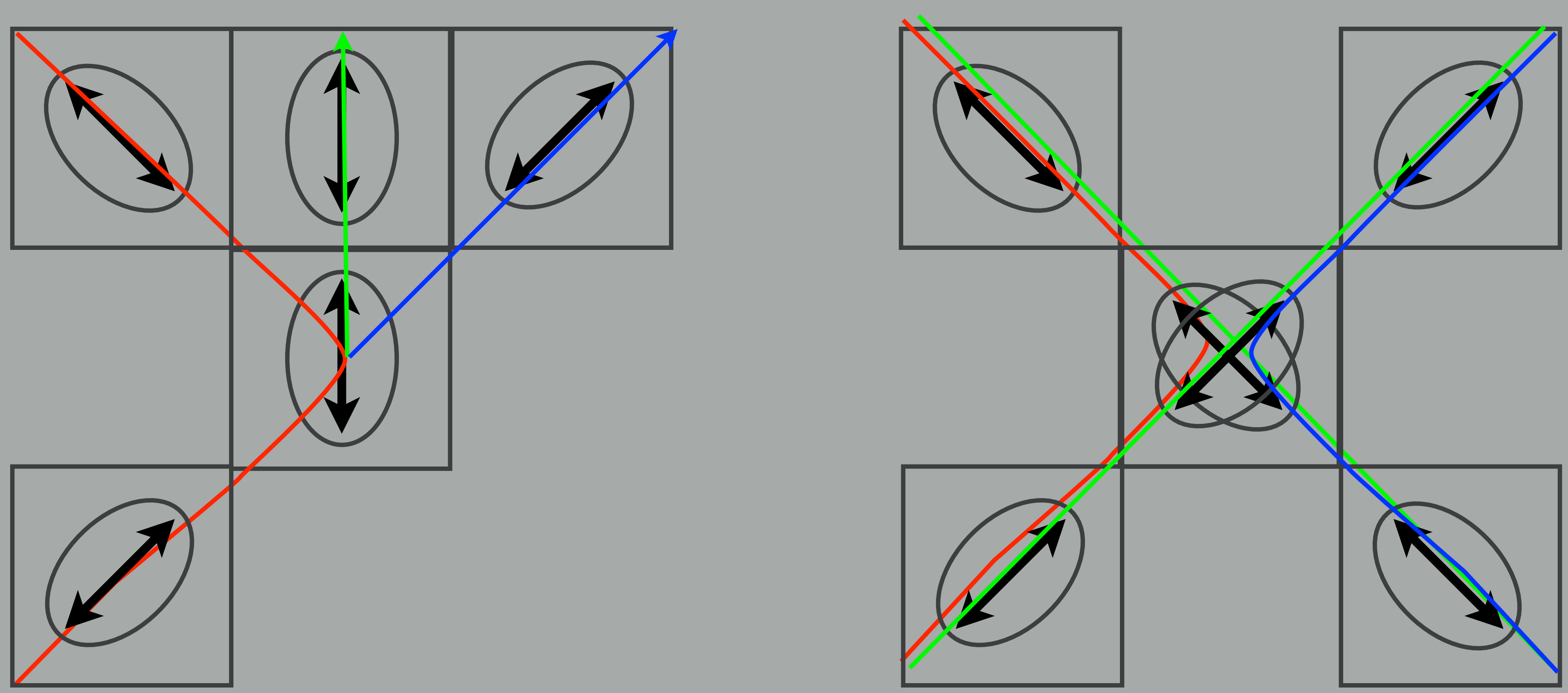
Solve for initial conditions

$$\boldsymbol{r}(0) = \boldsymbol{r}_o$$

Streamlines



Streamlines: Trouble Ahead?



path ambiguity

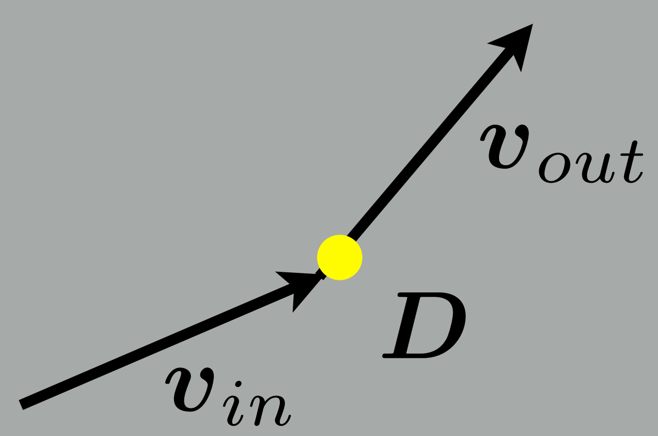
crossing fibers

Tensorlines

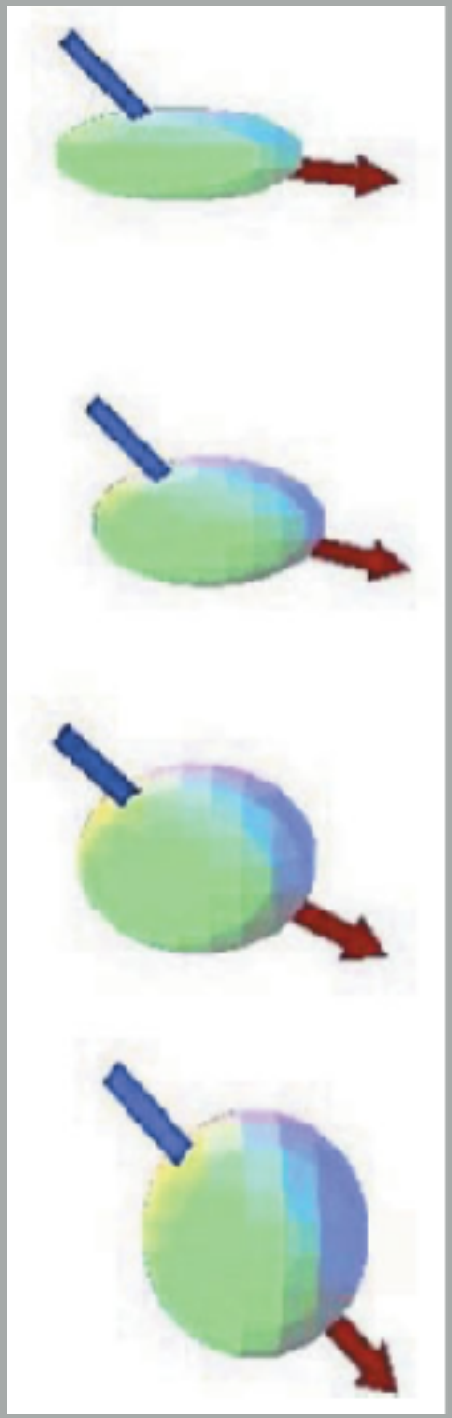
Taking into account regions of low FA

$$\boldsymbol{v}_{out} = \boldsymbol{D}\,\boldsymbol{v}_{in}$$

Fiber direction is deflected by tensor
in direction of principal eigenvector



Tensorlines

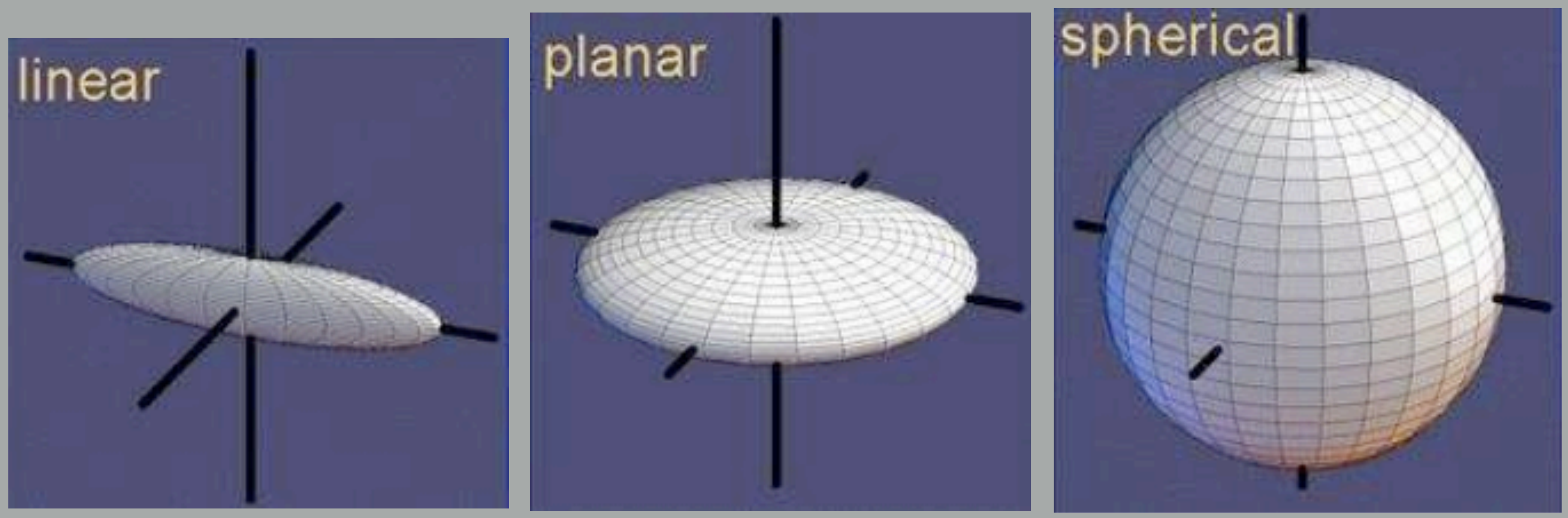


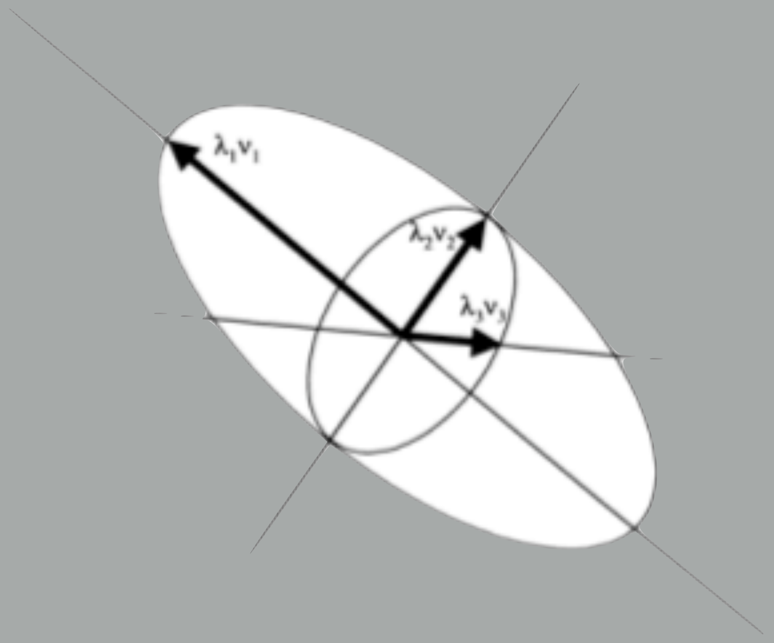
highly anisotropic - large deflection

spherical - no deflection

from Mori & Zhang

Anisotropy Indices





Let $\lambda_1 \geq \lambda_2 \geq \lambda_3 \geq 0$.

- Linear: $\lambda_1 \gg \lambda_2 \simeq \lambda_3$
- Planar: $\lambda_1 \simeq \lambda_2 \gg \lambda_3$
- Spherical: $\lambda_1 \simeq \lambda_2 \simeq \lambda_3$

Anisotropy Indices

$$c_l = \frac{\lambda_1 - \lambda_2}{\lambda_1 + \lambda_2 + \lambda_3} \quad \text{linear}$$

$$c_p = \frac{2(\lambda_2 - \lambda_3)}{\lambda_1 + \lambda_2 + \lambda_3} \quad \text{planar}$$

$$c_s = \frac{3\lambda_3}{\lambda_1 + \lambda_2 + \lambda_3} \quad \text{spherical}$$

Westin, et. al.

Tensorlines

Weighted average of tensor deflected vectors

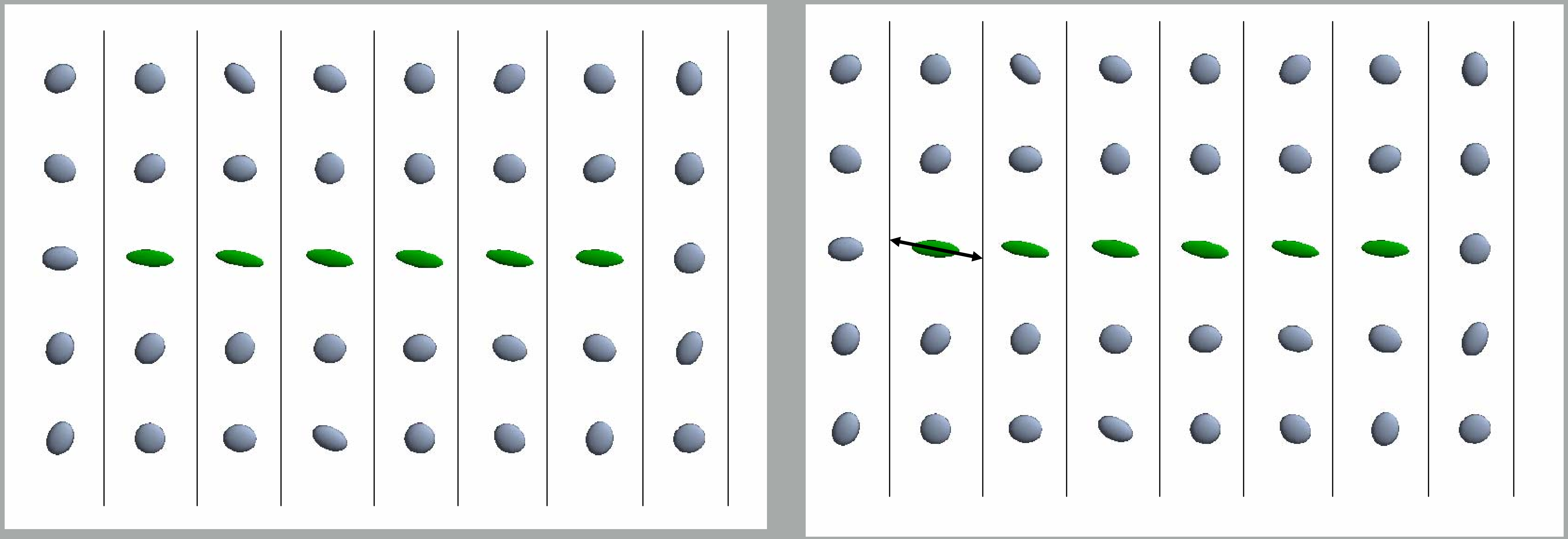
$$\boldsymbol{v}_{new} = c_l \boldsymbol{v}_1 + (1 - c_l)\tilde{\boldsymbol{v}}$$

$$\tilde{\boldsymbol{v}} = f \boldsymbol{v}_{in} + (1 - f)\boldsymbol{v}_{out} \quad , \quad 0 \leq f \leq 1$$

$$\boldsymbol{v}_{out} = \boldsymbol{D}\, \boldsymbol{v}_{in}$$

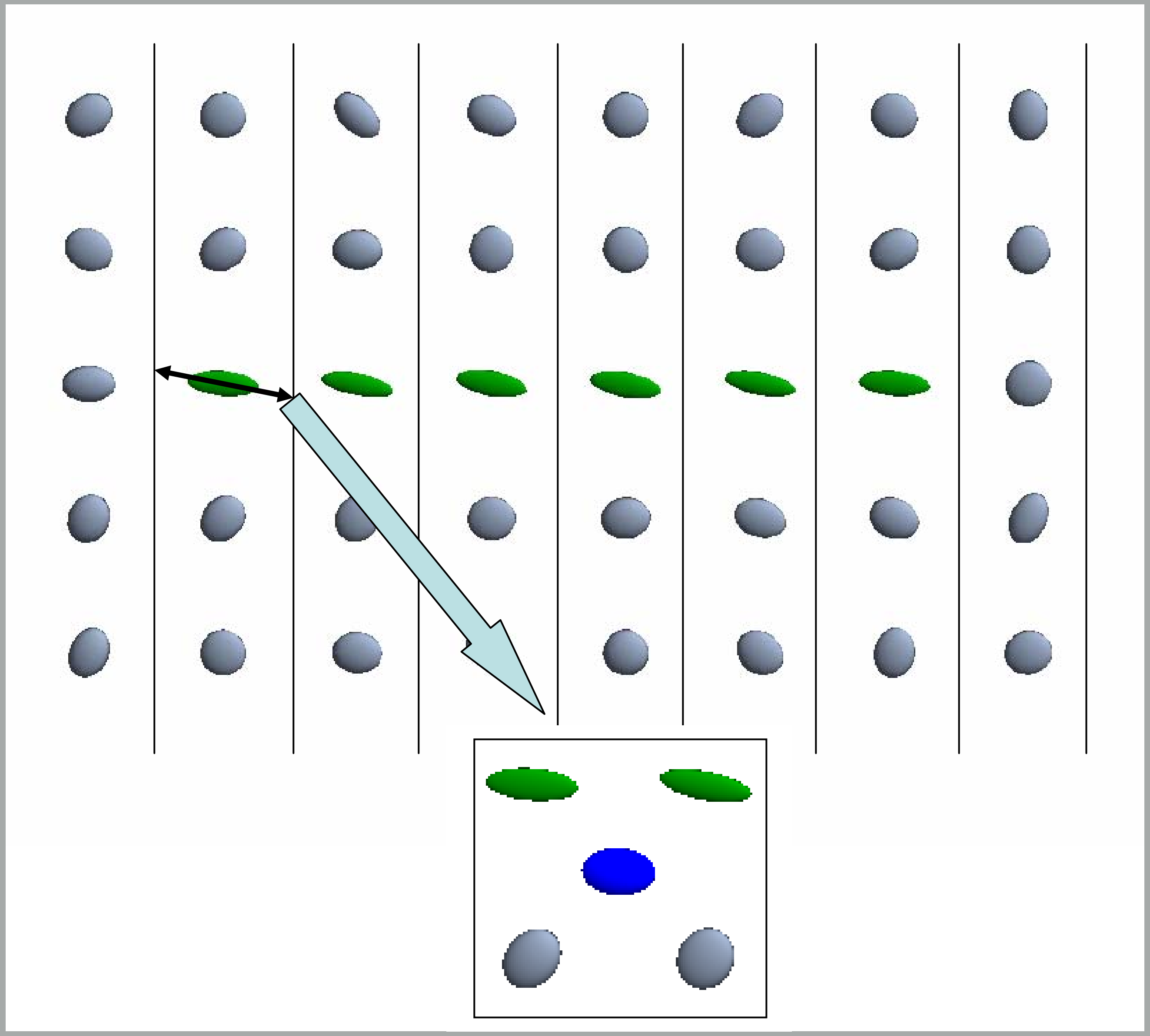
Weinstein, et. al.

Tensor interpolation



from Wandell

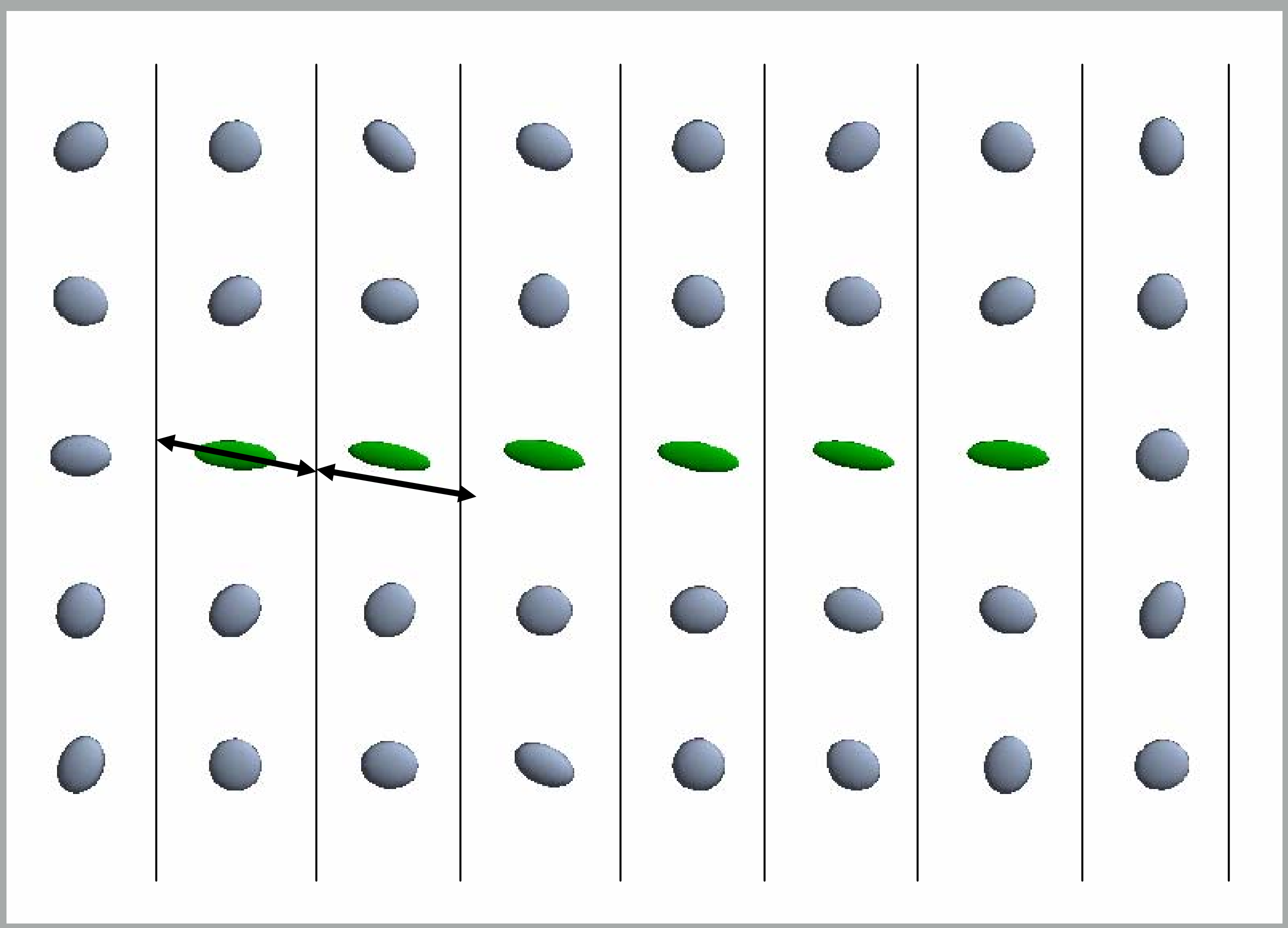
Tensor interpolation



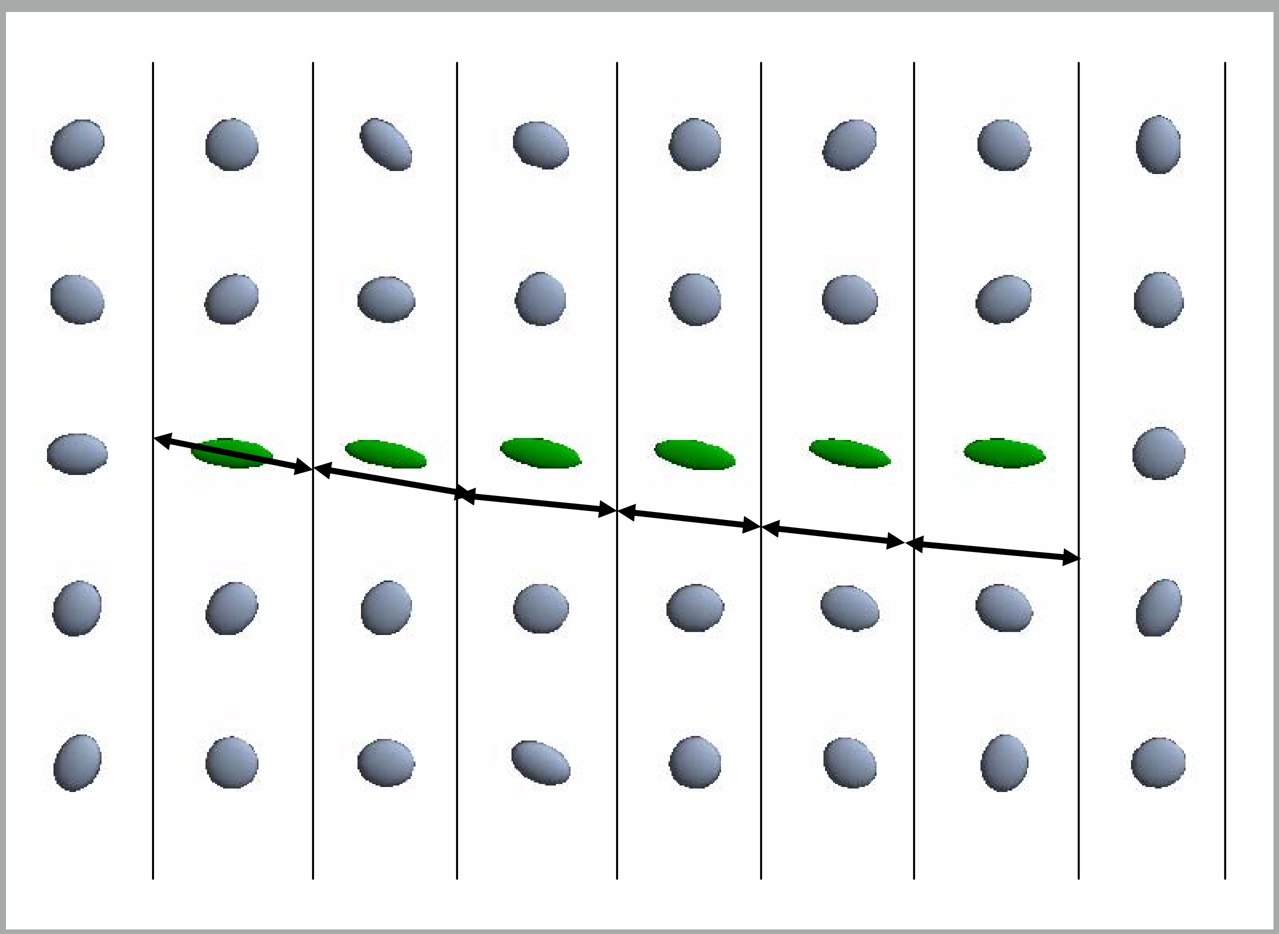
interpolate new tensor at endpoint ...

from Wandell

Tensor interpolation



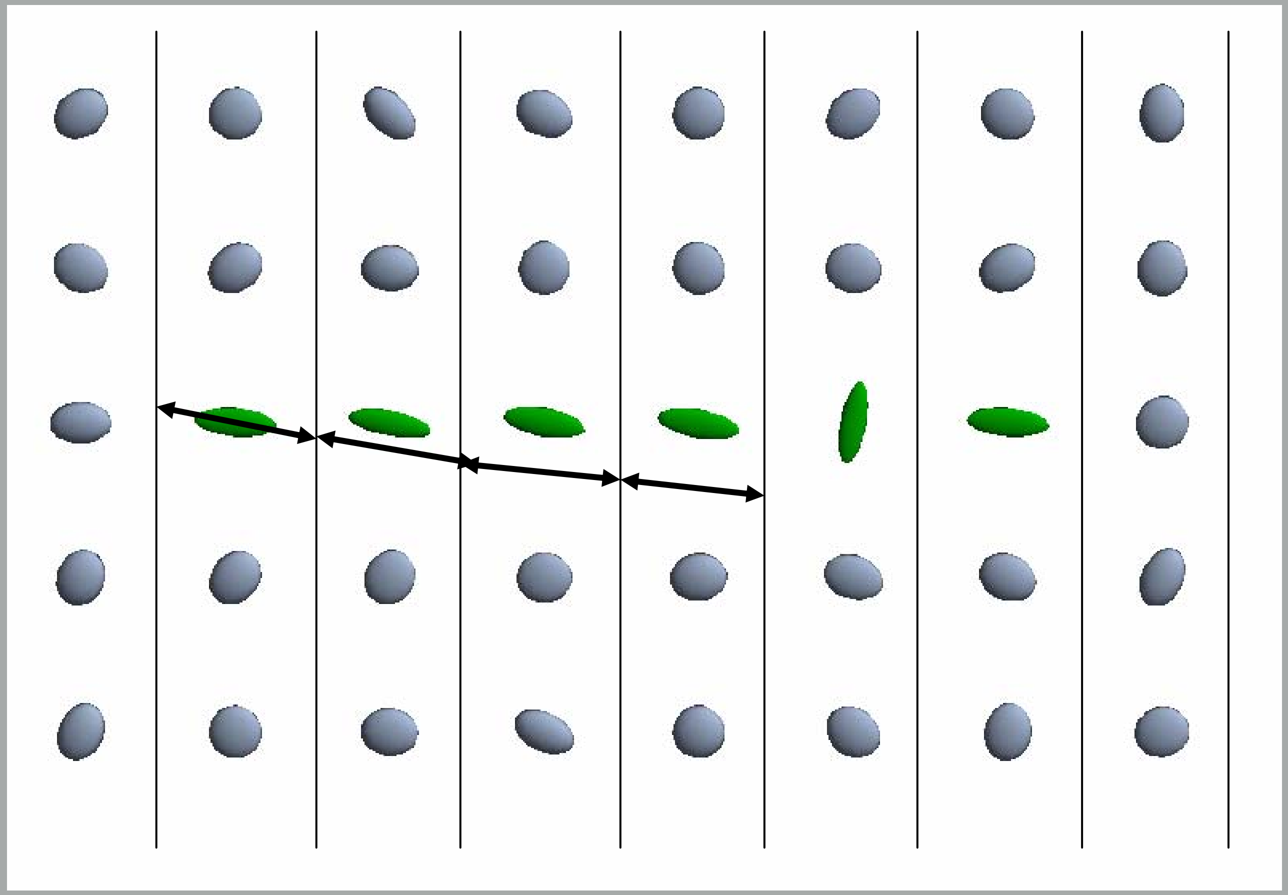
interpolation ...



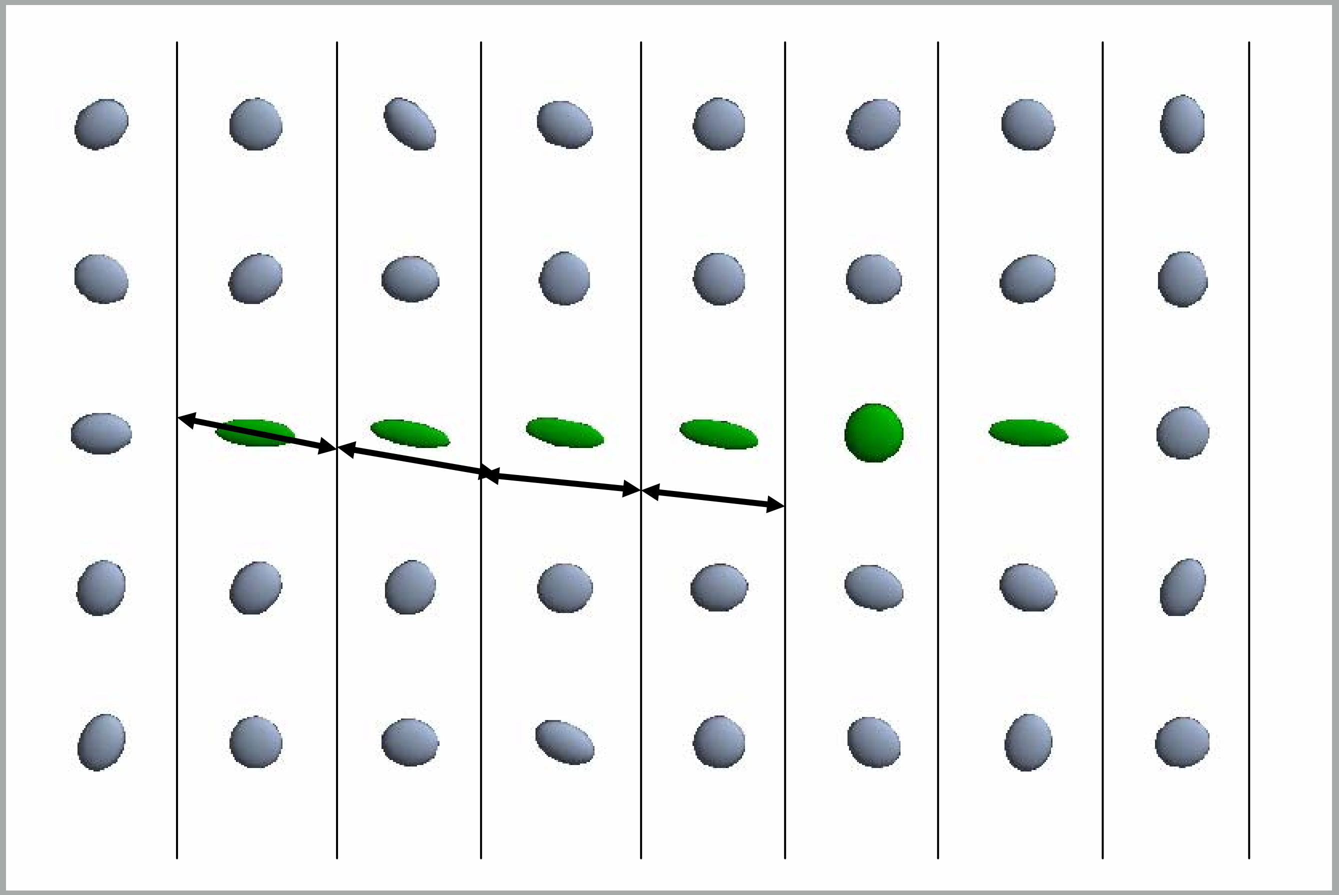
repeat...

from Wandell

Termination



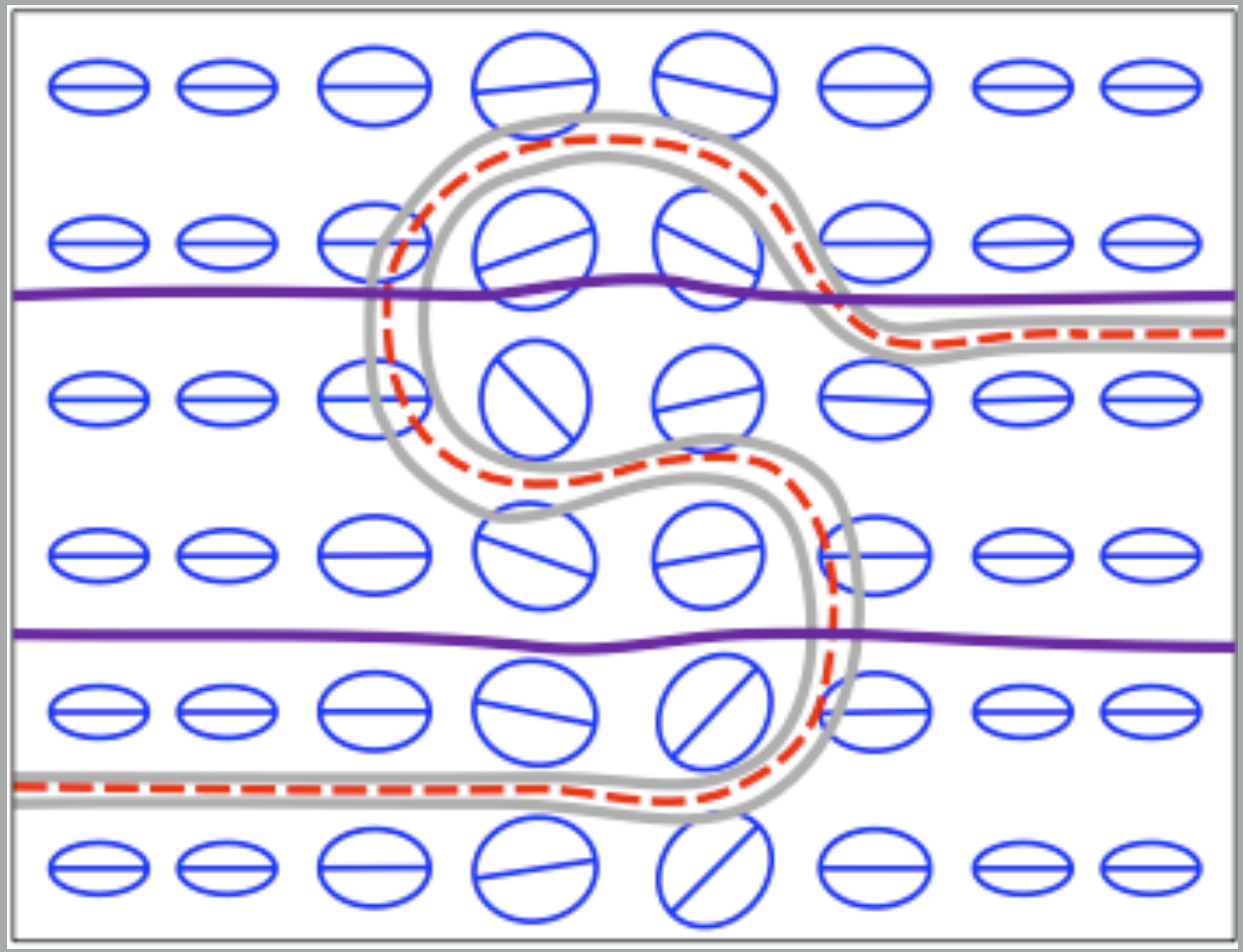
angle



anisotropy

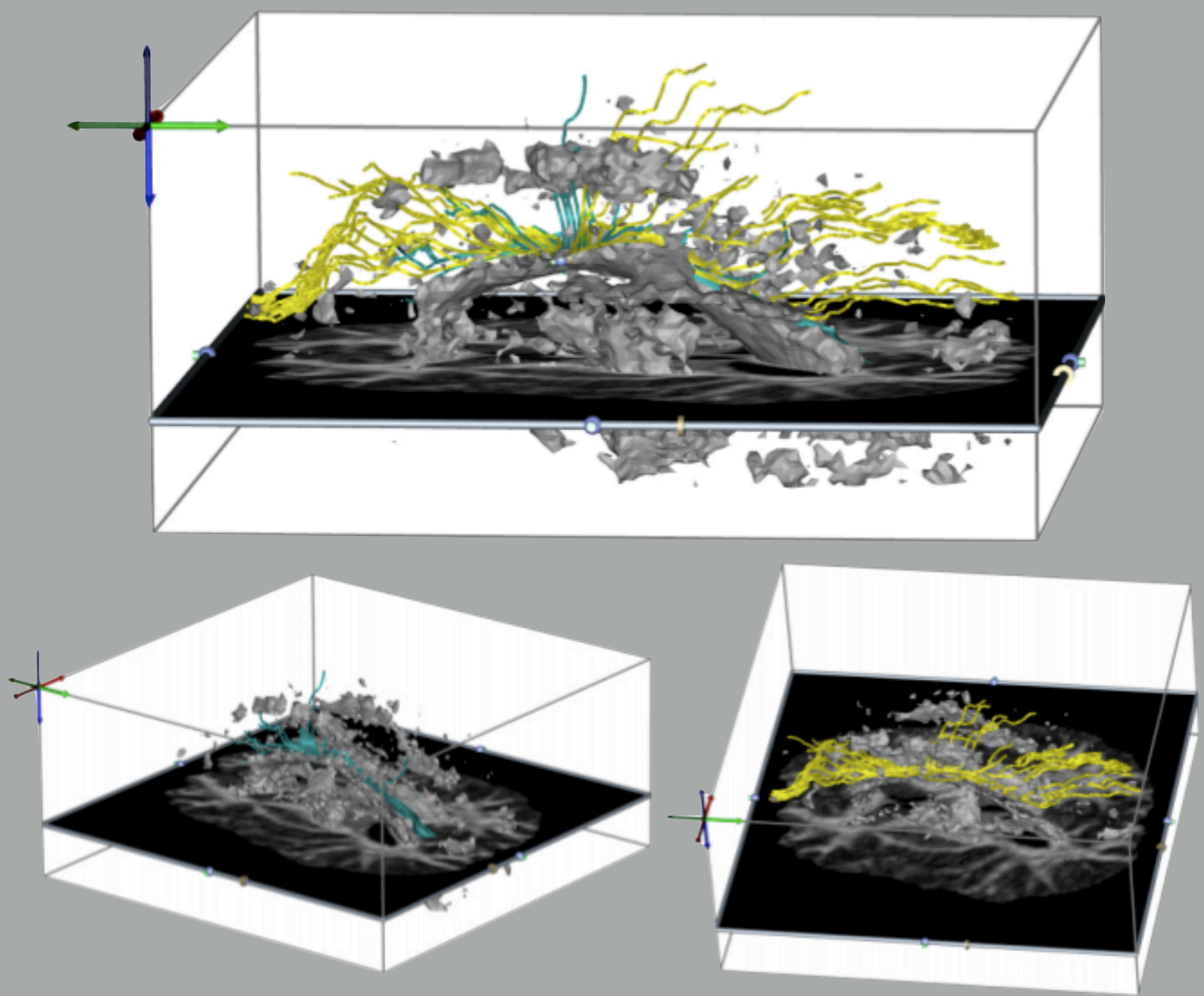
from Wandell

Tensorlines



Weinstein, et. al.

Tensorlines



Weinstein, et. al.

Validation

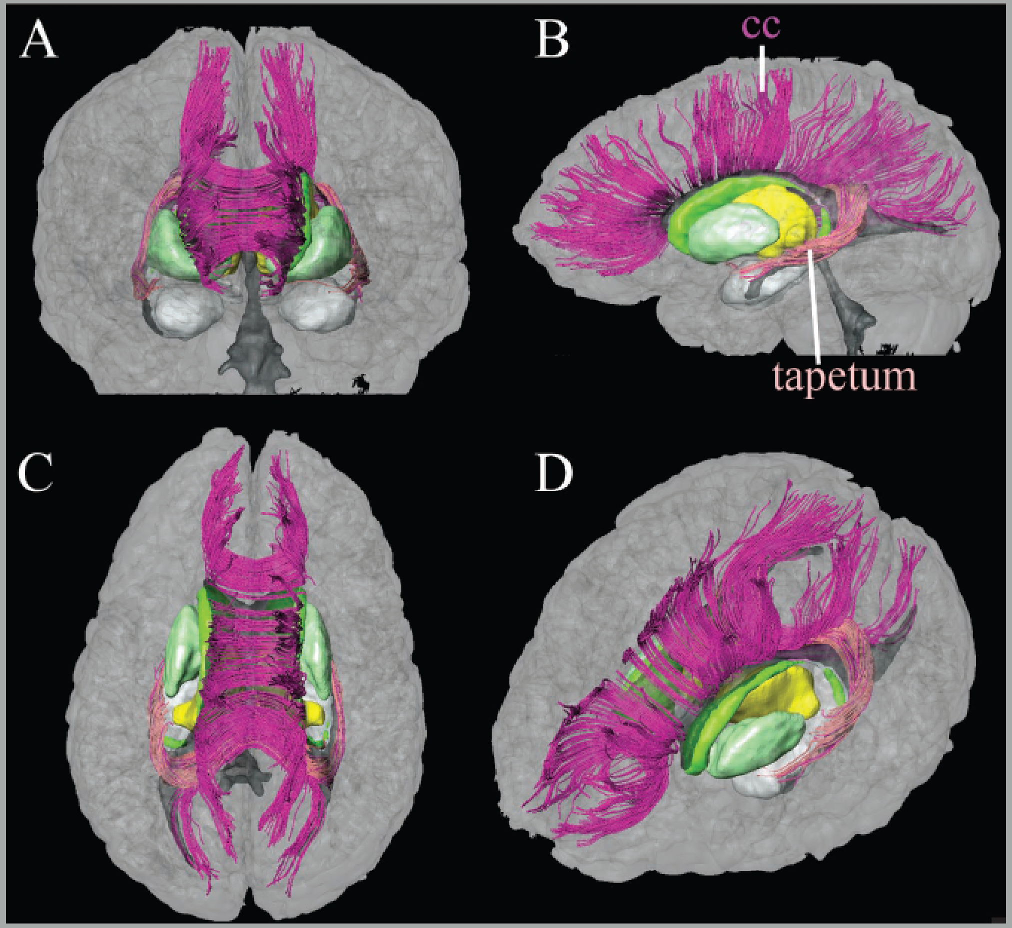
Radiology

Special Report

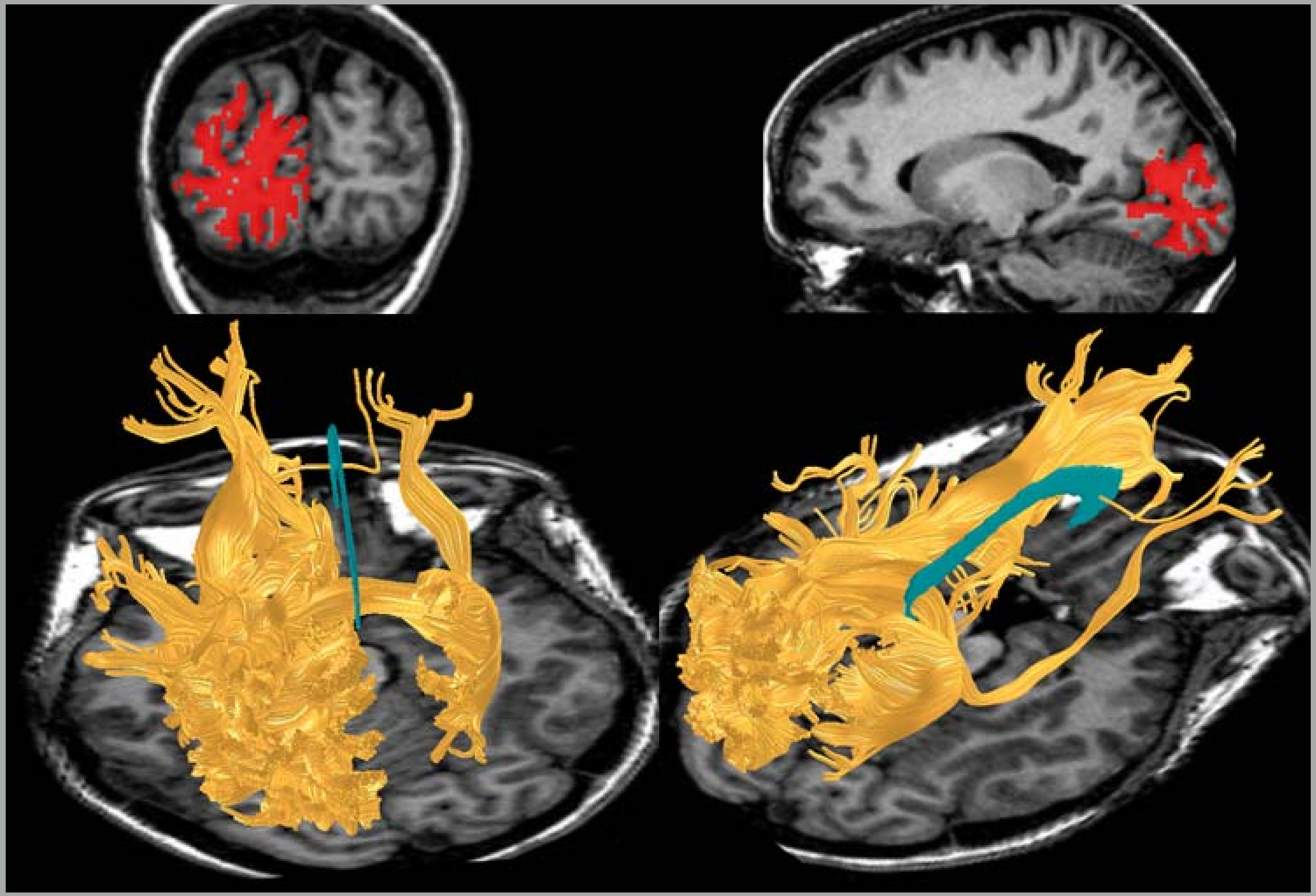
Setsu Wakana, MD
Hangyi Jiang, PhD
Lidia M. Nagae-Poetscher, MD
Peter C. M. van Zijl, PhD
Susumu Mori, PhD

Fiber Tract–based Atlas of Human White Matter Anatomy[1]

Two- and three-dimensional (3D) white matter atlases were created on the basis of



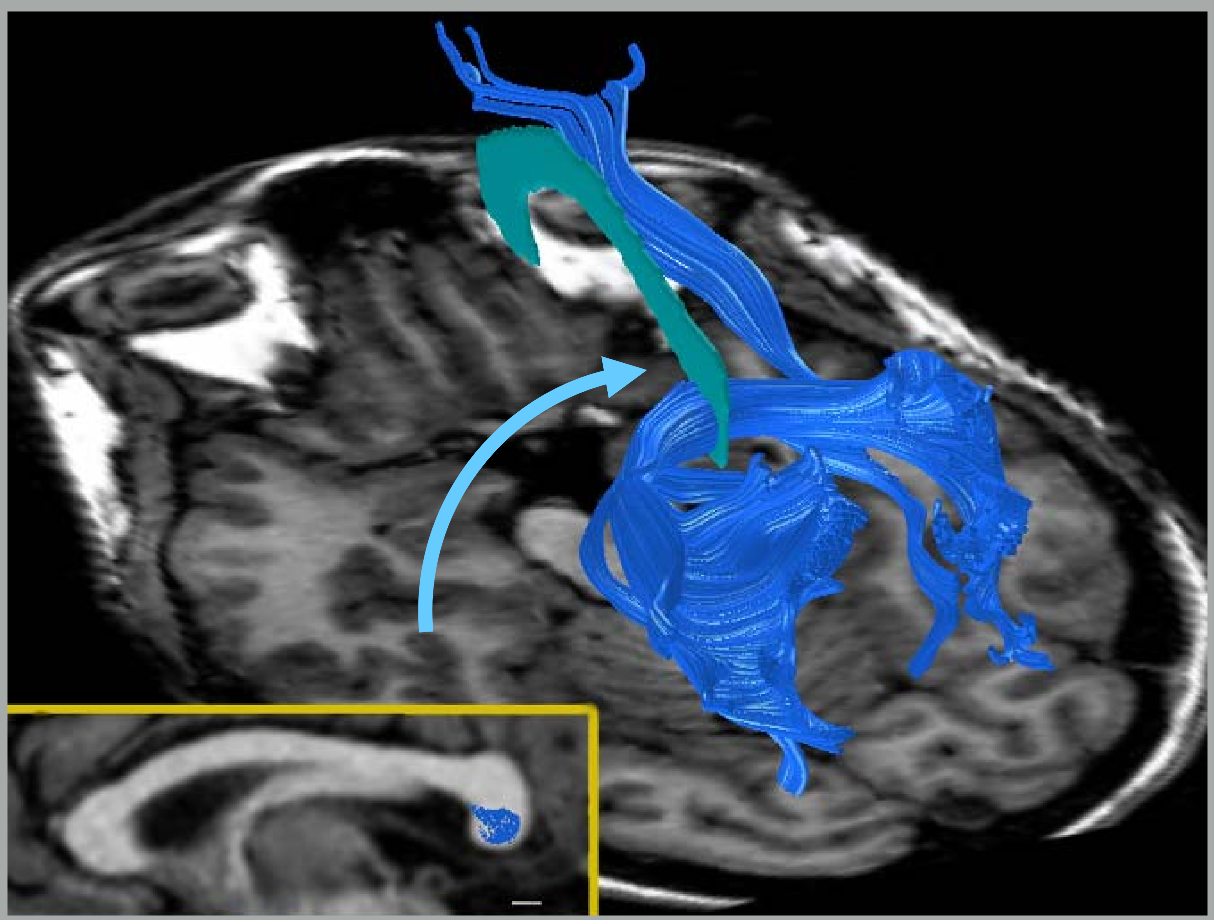
Occipital seeds



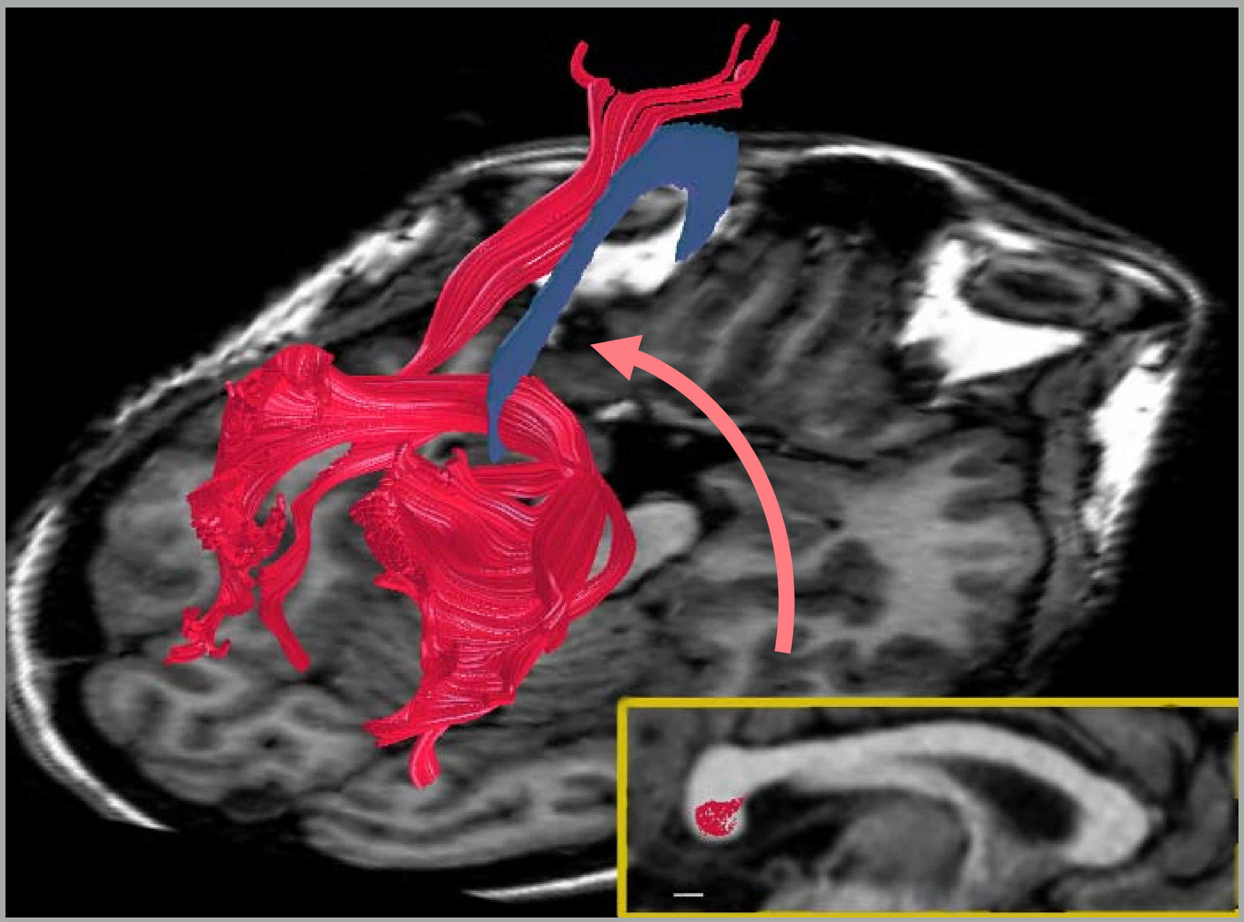
Dougherty PNAS 2005

Tracking through corpus callosum

Left occipital seeds



Right occipital seeds



Dougherty PNAS 2005

Probabilistic tractography

- Take into account the uncertainty of fiber orientation
- Allows multiple paths
- Schemes based on

- Regularized stochastic models
- Linear state space models
- Bending energy models
- Monte-Carlo methods

Probabilistic tractography

FSL's FDT (Behren's et. al.)

Assume partial volume model for voxels:
Some fraction *f* gray matter (isotropic) diffusion and the remaining fraction *(1-f)* is white matter (anisotropic) diffusion

$$\frac{s(b_i)}{s(0)} = f e^{-b_i d} + (1 - f) e^{-b_i \tilde{\boldsymbol{D}}}$$

where $\tilde{\boldsymbol{D}} = \boldsymbol{R}\boldsymbol{D}_\Lambda \boldsymbol{R}^t$

Probabilistic tractography

$$\frac{s(b_i)}{s(0)} = fe^{-b_i d} + (1-f)e^{-b_i \tilde{\boldsymbol{D}}}$$

$$\tilde{\boldsymbol{D}} = \boldsymbol{R}\boldsymbol{D}_\Lambda \boldsymbol{R}^t$$

$$\boldsymbol{D}_\Lambda = \begin{pmatrix} d & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

NOT the diffusion tensor model!

Only models diffusion along fiber direction

Probabilistic tractography

$$\frac{s(b_i)}{s(0)} = f e^{-b_i d} + (1-f) e^{-b_i \tilde{\boldsymbol{D}}}$$

$$\tilde{\boldsymbol{D}} = \boldsymbol{R}\boldsymbol{D}_\Lambda \boldsymbol{R}^t$$

assumes same d!

$$\boldsymbol{D}_\Lambda = \begin{pmatrix} d & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Behrens, et. al.

Probabilistic tractography

$$\frac{s(b_i)}{s(0)} = fe^{-b_i d} + (1-f)e^{-b_i d \tilde{\boldsymbol{A}}}$$

$$\tilde{\boldsymbol{A}} = \boldsymbol{R}\boldsymbol{A}\boldsymbol{R}^t$$

$$\boldsymbol{A} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Behrens, et. al.

Probabilistic tractography

signal model parameters: $\xi = \{\theta, \phi, d, \sigma, f, s_o\}$

$$P(\boldsymbol{y}|\xi, M) = \prod_{i=1}^{n} P(y_i|\xi, M)$$

$$\boldsymbol{y} = \{y_1, y_2, \ldots, y_n\}$$

$$P(y_i|\xi, M) \sim N(\mu_i, \sigma)$$

Behrens, et. al.

Probabilistic tractography

Bayes' Theorem

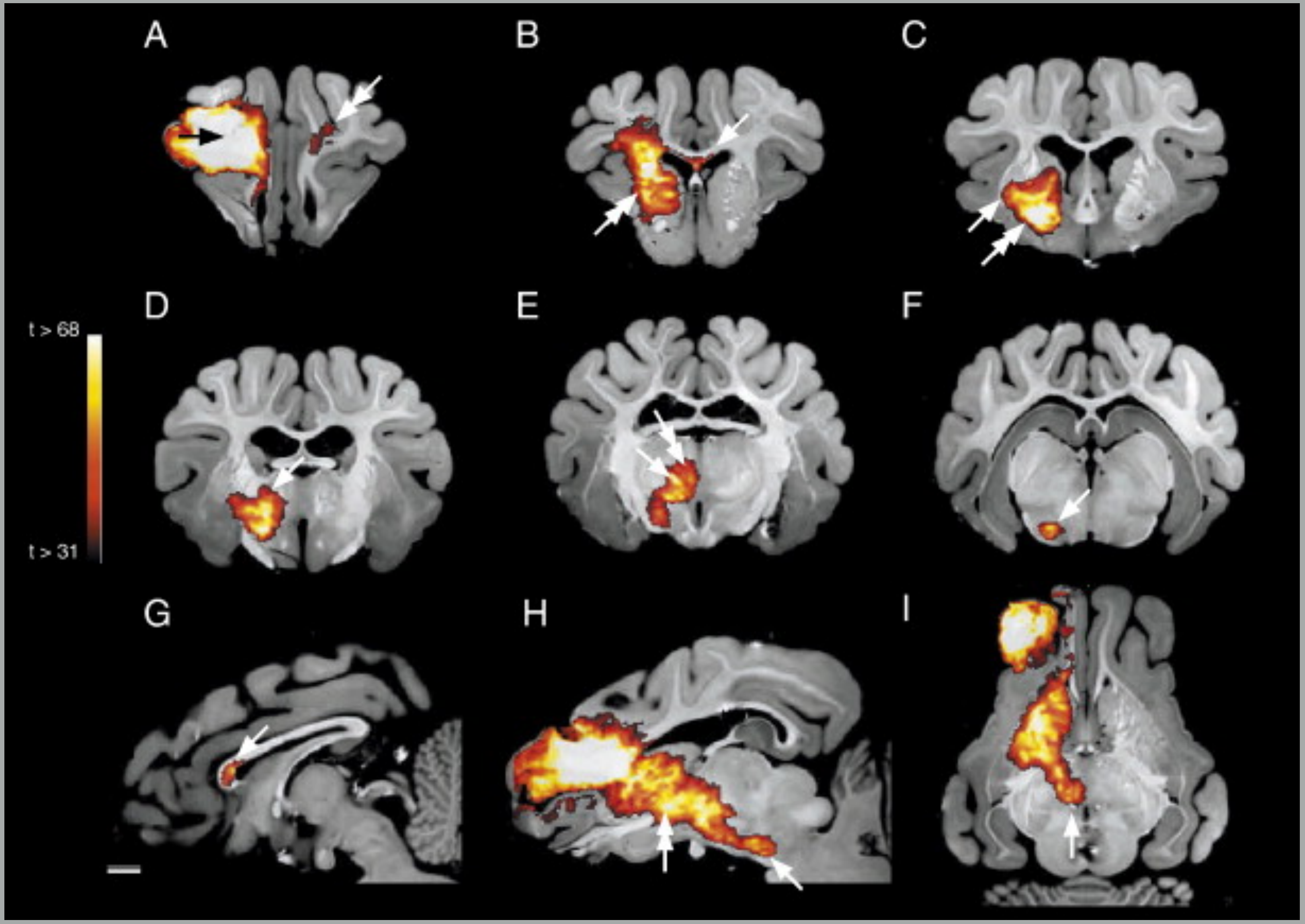
$$P(\xi|\boldsymbol{y}, M) = \frac{P(\boldsymbol{y}|\xi, M)P(\xi|M)}{\int_\xi P(\boldsymbol{y}|\xi, M)P(\xi|M)d\xi}$$

$P(\xi|\boldsymbol{y}, M) =$ joint distribution of the parameters ξ

$P(\xi|M) =$ prior distribution of the parameters ξ

Seek maximum posterior probability of parameters

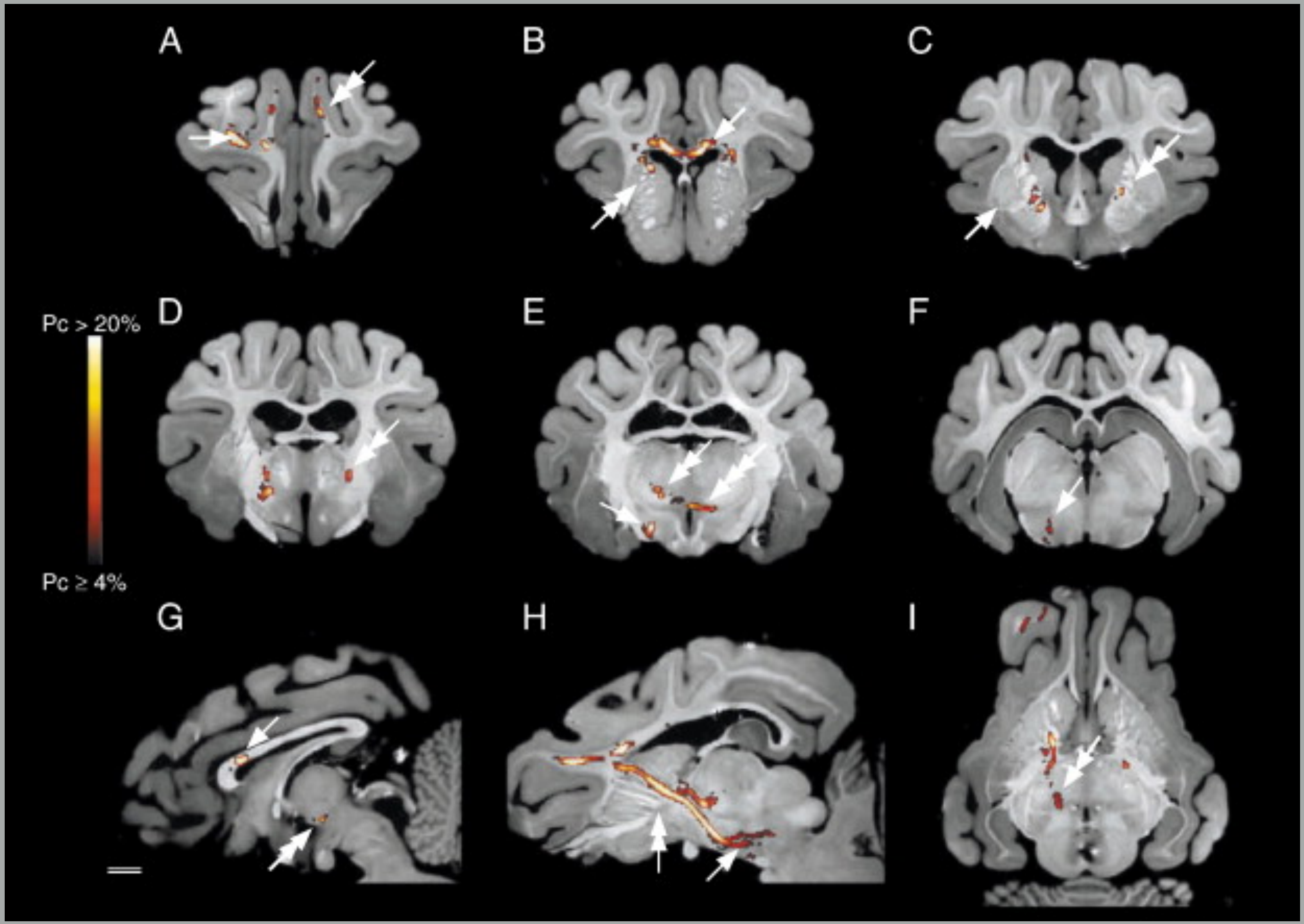
Probabilistic tractography



Generation of connected regions

Dyrby, NeuroImage 37 (4) 2007

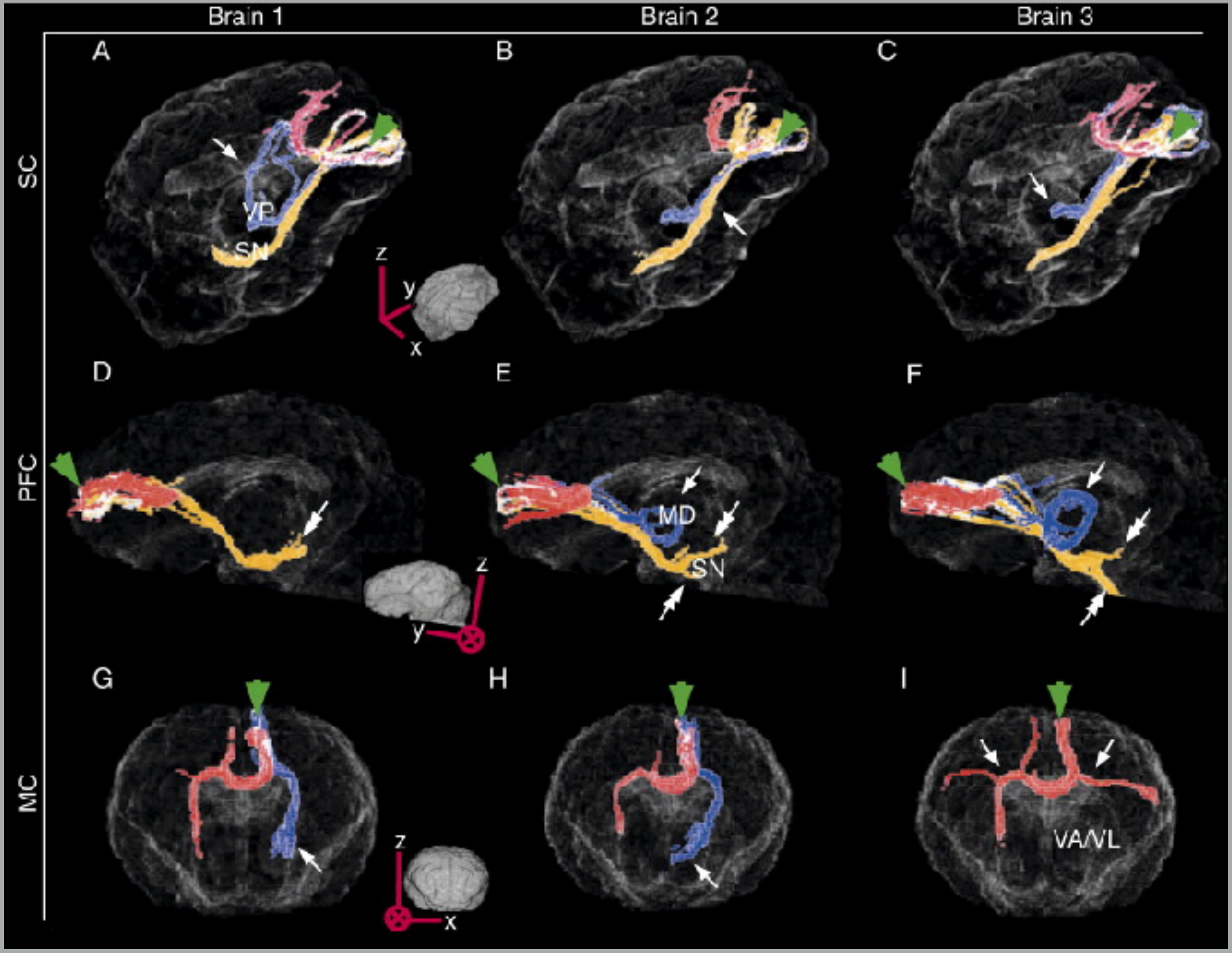
Probabilistic tractography



Seeding with constrains on path

Dyrby, NeuroImage 37 (4) 2007

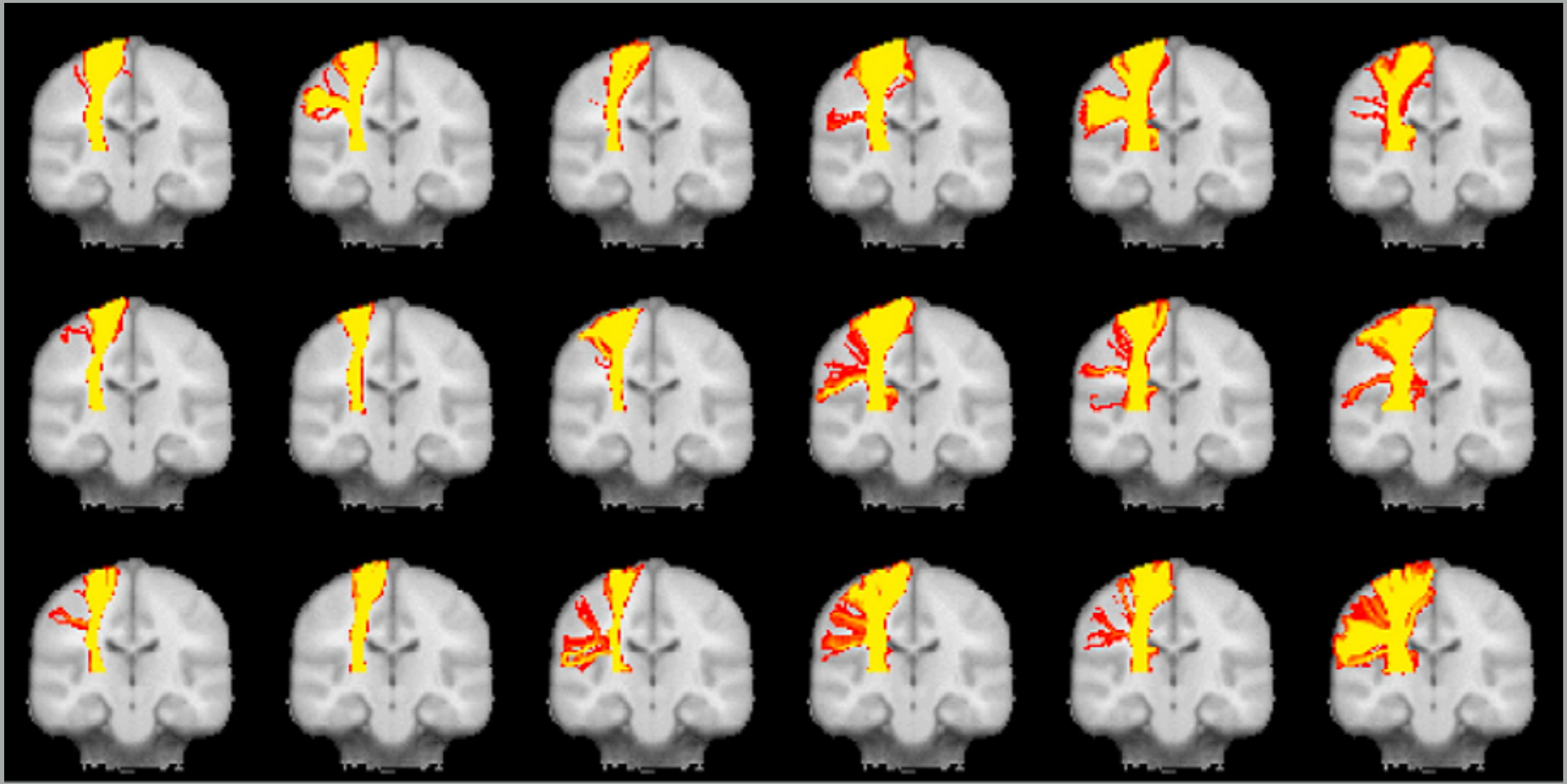
Probabilistic tractography



Reproducibility

Dyrby, NeuroImage 37 (4) 2007

Probabilistic tractography



Multifiber

Behrens, NeuroImage 37 (4) 2007

Probabilistic tractography

Advantages

1. Can represent uncertainty in fiber direction so can go in many directions
2. Robust to noise. Tracks along “noisy” paths tend to be of low probability and so disperse.

These have the effect of reducing the importance of curvature and anisotropy stopping criteria

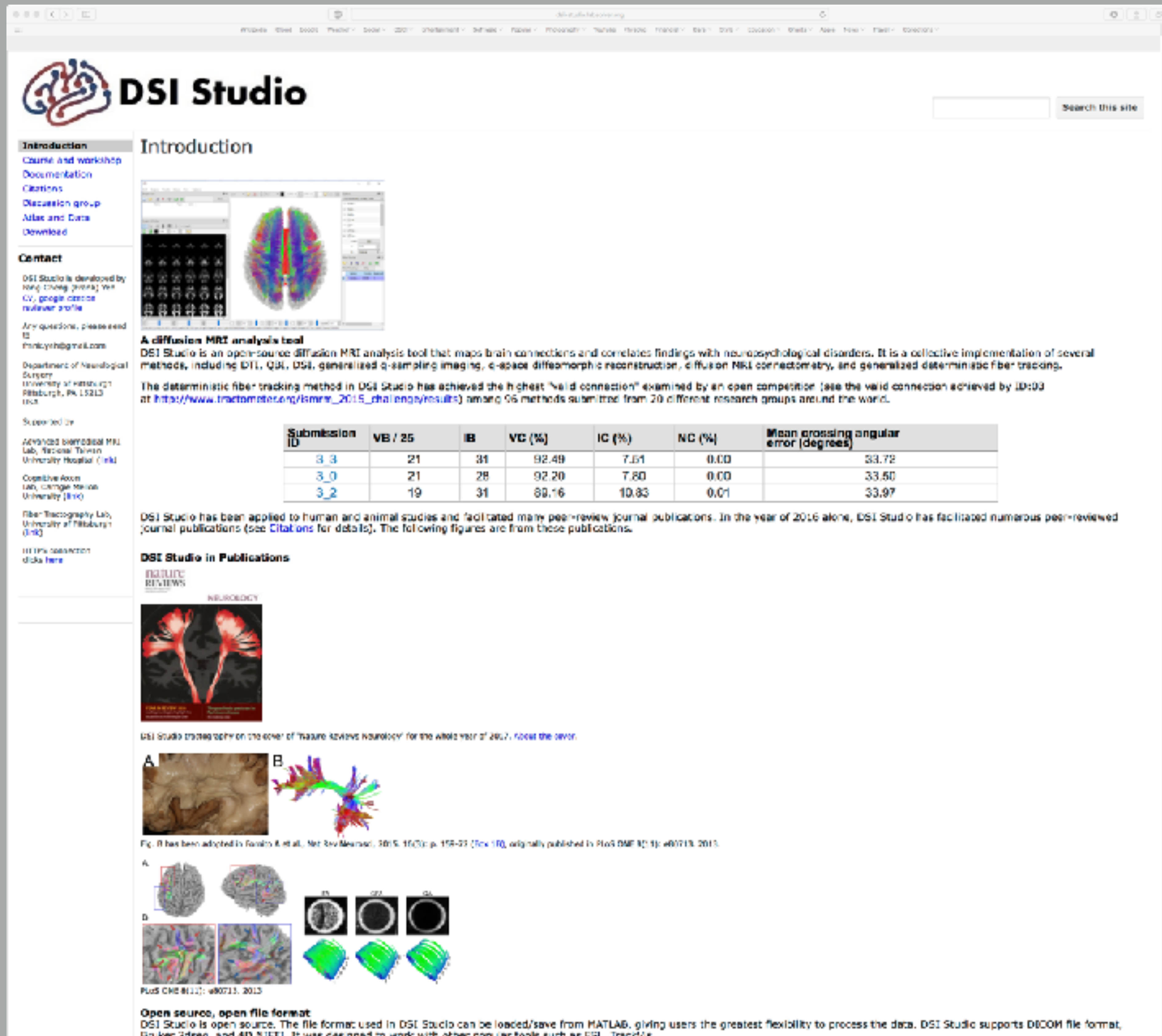
Probabilistic tractography

Interpretation:

Connectivity PDF is *not* distribution of connections from a seed point.

It is confidence bounds on location of most probable single connection

DSI Studio



DSI Studio

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DSI Studio is developed by

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reviewer profile

Any questions, please send to

Department of Neurological Surgery
University of Pittsburgh
Pittsburgh, PA 15213
USA

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Cognitive Axon Lab, Carnegie Mellon University (link)

Fiber Tractography Lab, University of Pittsburgh (link)

Introduction

A diffusion MRI analysis tool
DSI Studio is an open-source diffusion MRI analysis tool that maps brain connections and correlates findings with neuropsychological disorders. It is a collective implementation of several methods, including DTI, QBI, DSI, generalized q-sampling imaging, q-space diffeomorphic reconstruction, diffusion MRI connectometry, and generalized deterministic fiber tracking.

The deterministic fiber tracking method in DSI Studio has achieved the highest "valid connection" examined by an open competition (see the valid connection achieved by ID:03 at http://www.tractometer.org/ismrm_2015_challenge/results) among 96 methods submitted from 20 different research groups around the world.

Submission ID	VB / 25	IB	VC (%)	IC (%)	NC (%)	Mean crossing angular error (degrees)
3_3	21	31	92.49	7.51	0.00	33.72
3_0	21	28	92.20	7.80	0.00	33.50
3_2	19	31	89.16	10.83	0.01	33.97

DSI Studio has been applied to human and animal studies and facilitated many peer-review journal publications. In the year of 2016 alone, DSI Studio has facilitated numerous peer-reviewed journal publications (see Citations for details). The following figures are from these publications.

DSI Studio in Publications

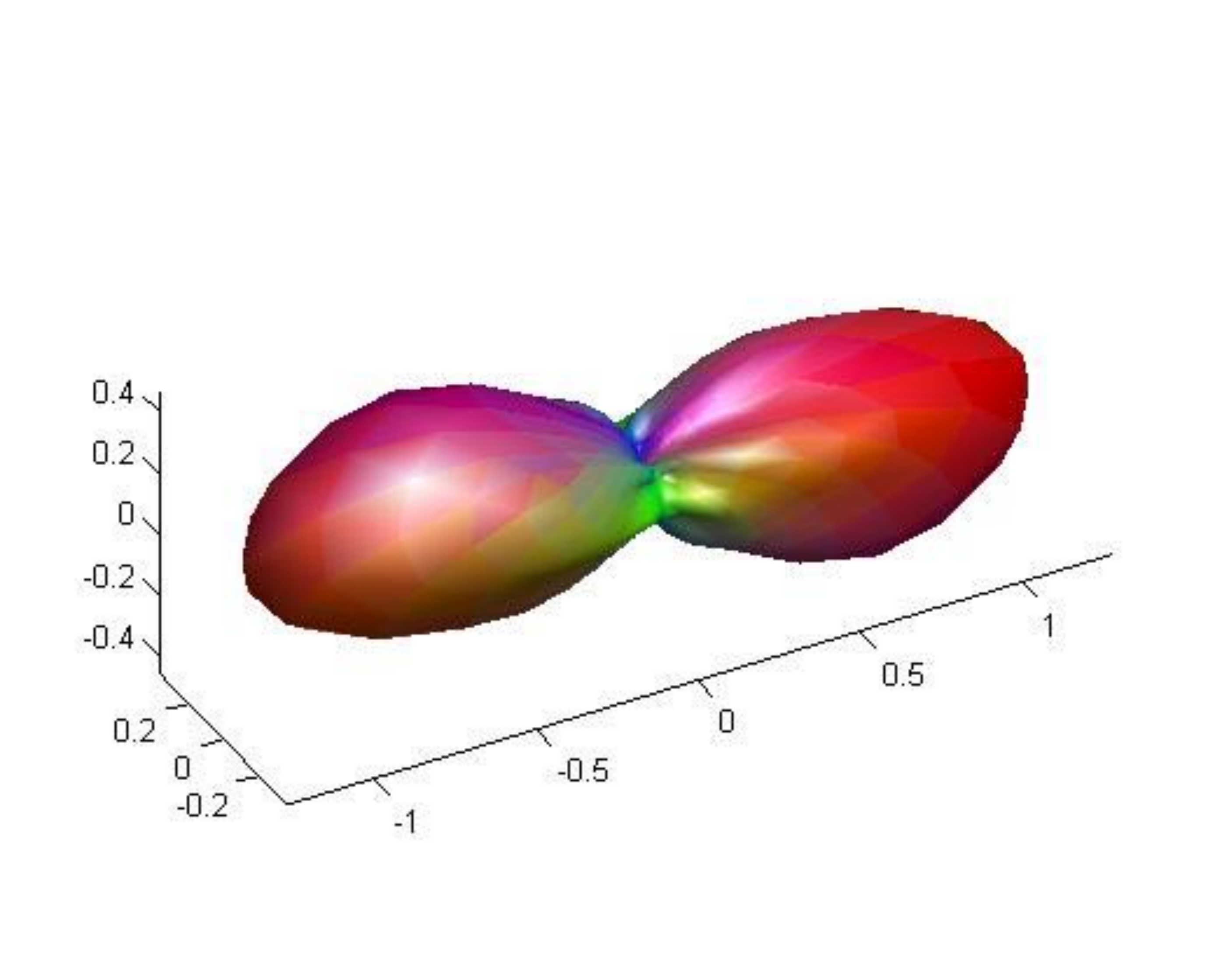
DSI Studio tractography on the cover of 'Nature Reviews Neurology' for the whole year of 2017. About the cover.

PLoS ONE 8(11): e80713, 2013

Open source, open file format
DSI Studio is open source. The file format used in DSI Studio can be loaded/save from MATLAB, giving users the greatest flexibility to process the data. DSI Studio supports DICOM file format, Bruker 2dseq, and 4D NIFTI. It was designed to work with other popular tools such as FSL, TrackVis.

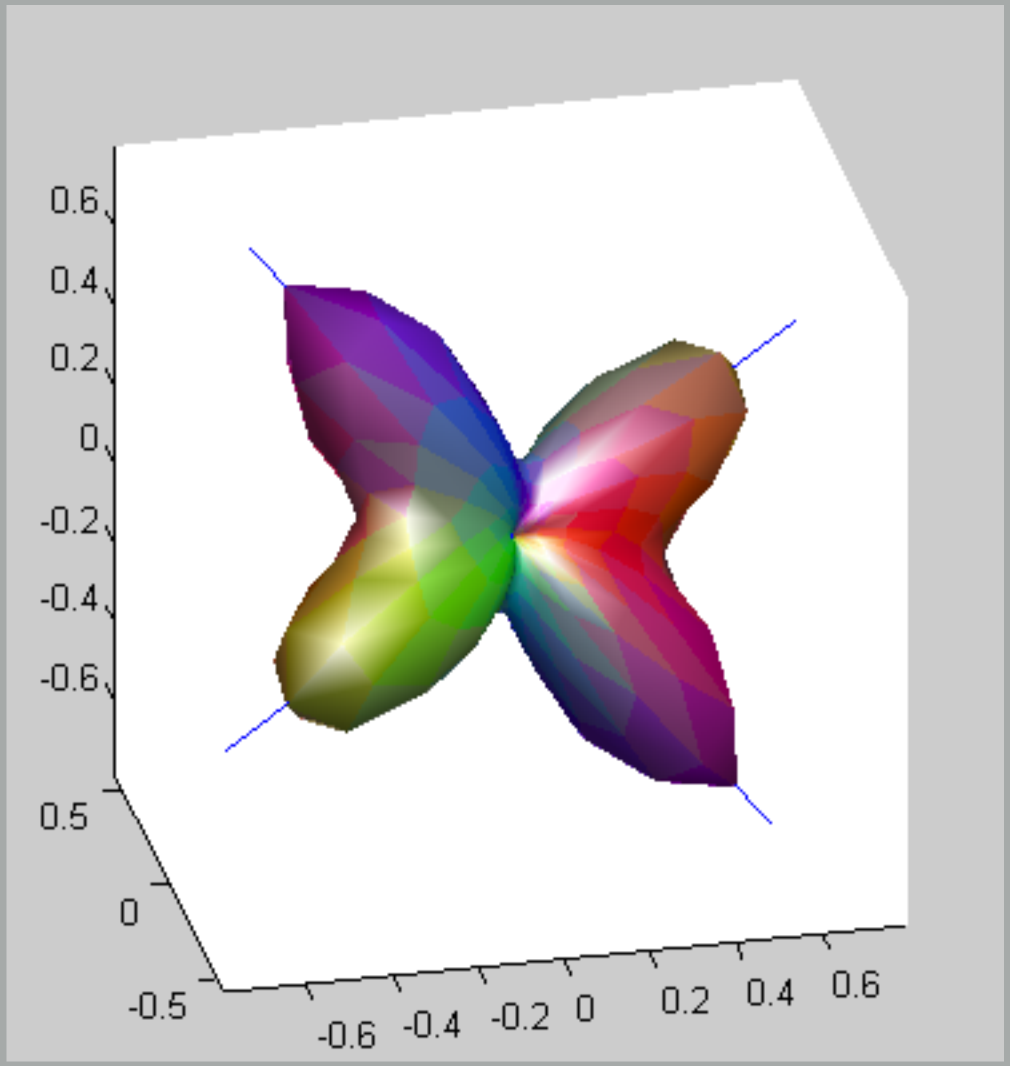
Track density imaging

3D presentation of the ODFs in Matlab

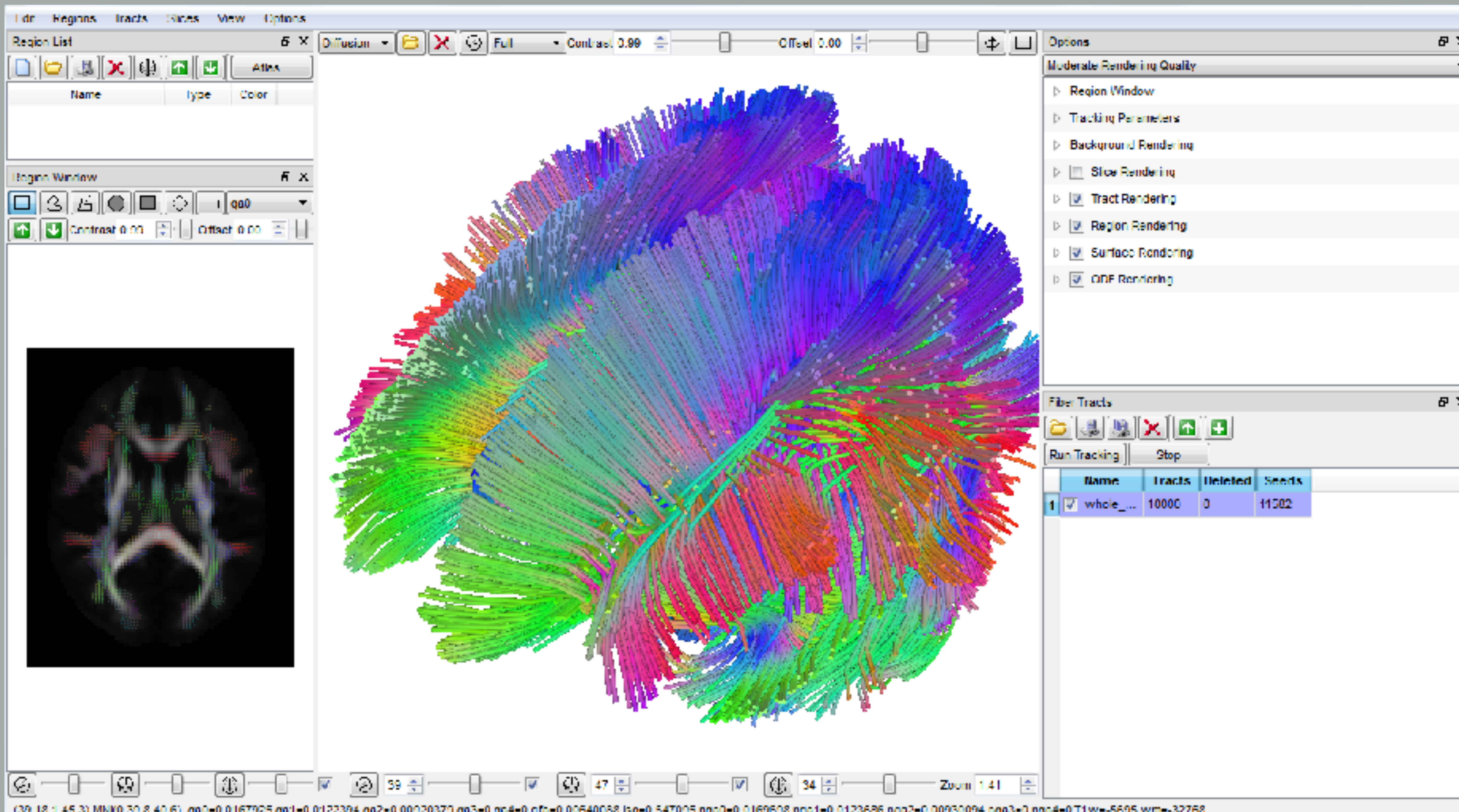


Track density imaging

3D presentation of the ODFs in Matlab

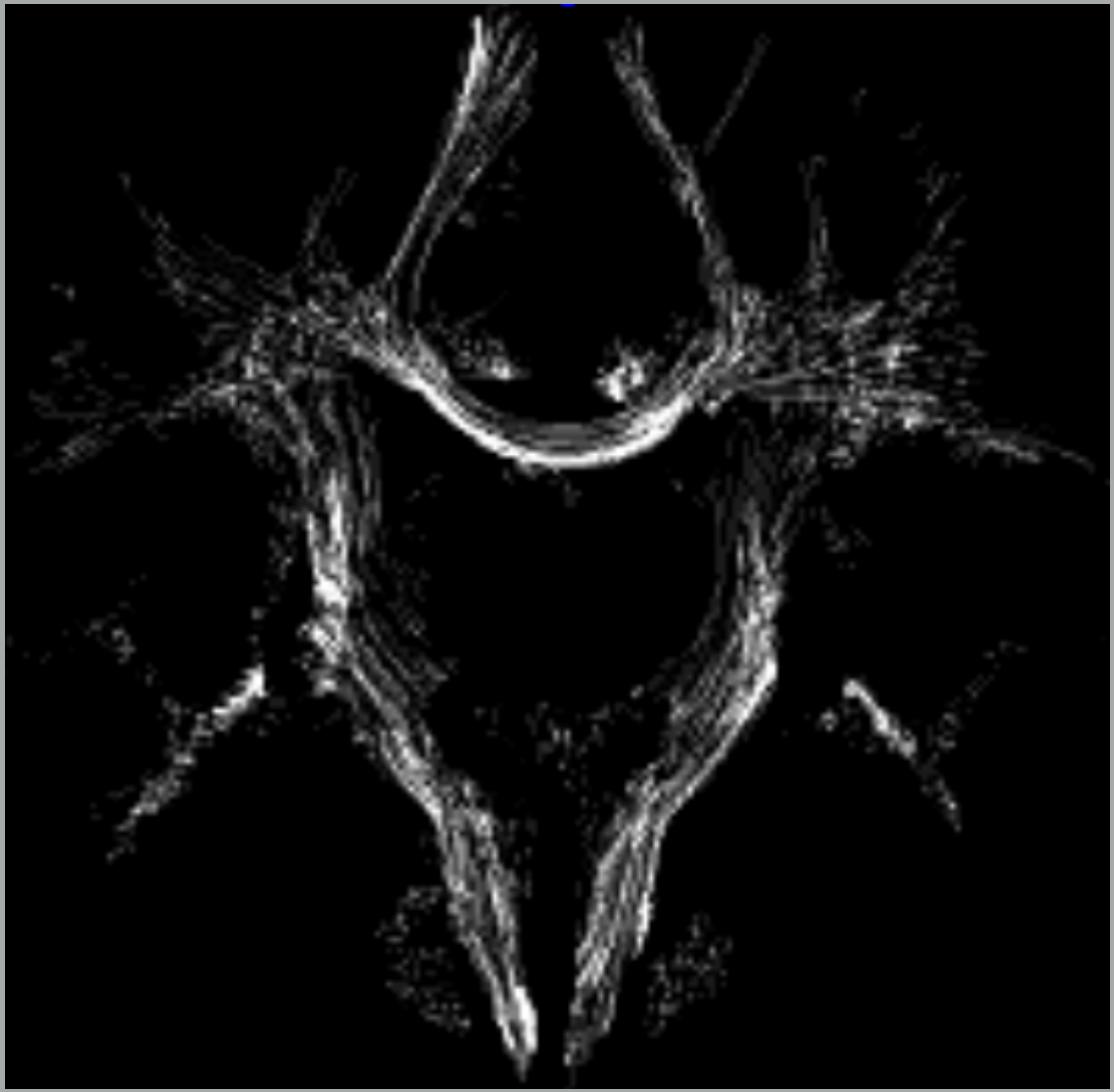


DSI Studio



Regions
Tracts
View
Region List
Name
Type
Color
Region Window
Diffusion
Full
Options
Region Window
Tracking Parameters
Background Rendering
Slice Rendering
Tract Rendering
Region Rendering
Surface Rendering
ODF Rendering
Fiber Tracts
Run Tracking
Stop
Name
Tracts
Deleted
Seeds
10000
0

Track density imaging



The challenge

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The challenge of mapping the human connectome based on diffusion tractography

Klaus H. Maier-Hein, Peter F. Neher, […] Maxime Descoteaux

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Computational biology and bioinformatics
Medical research
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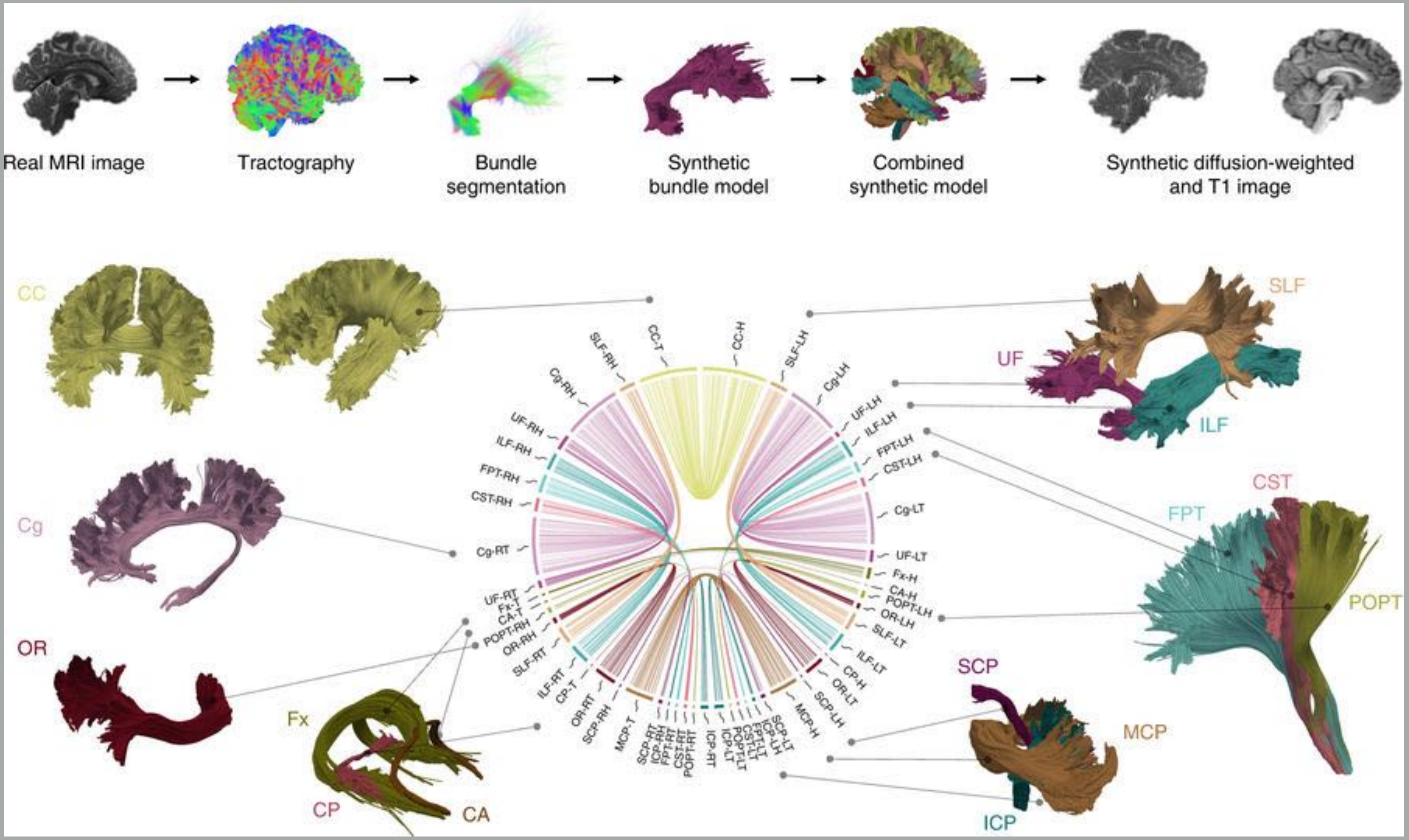
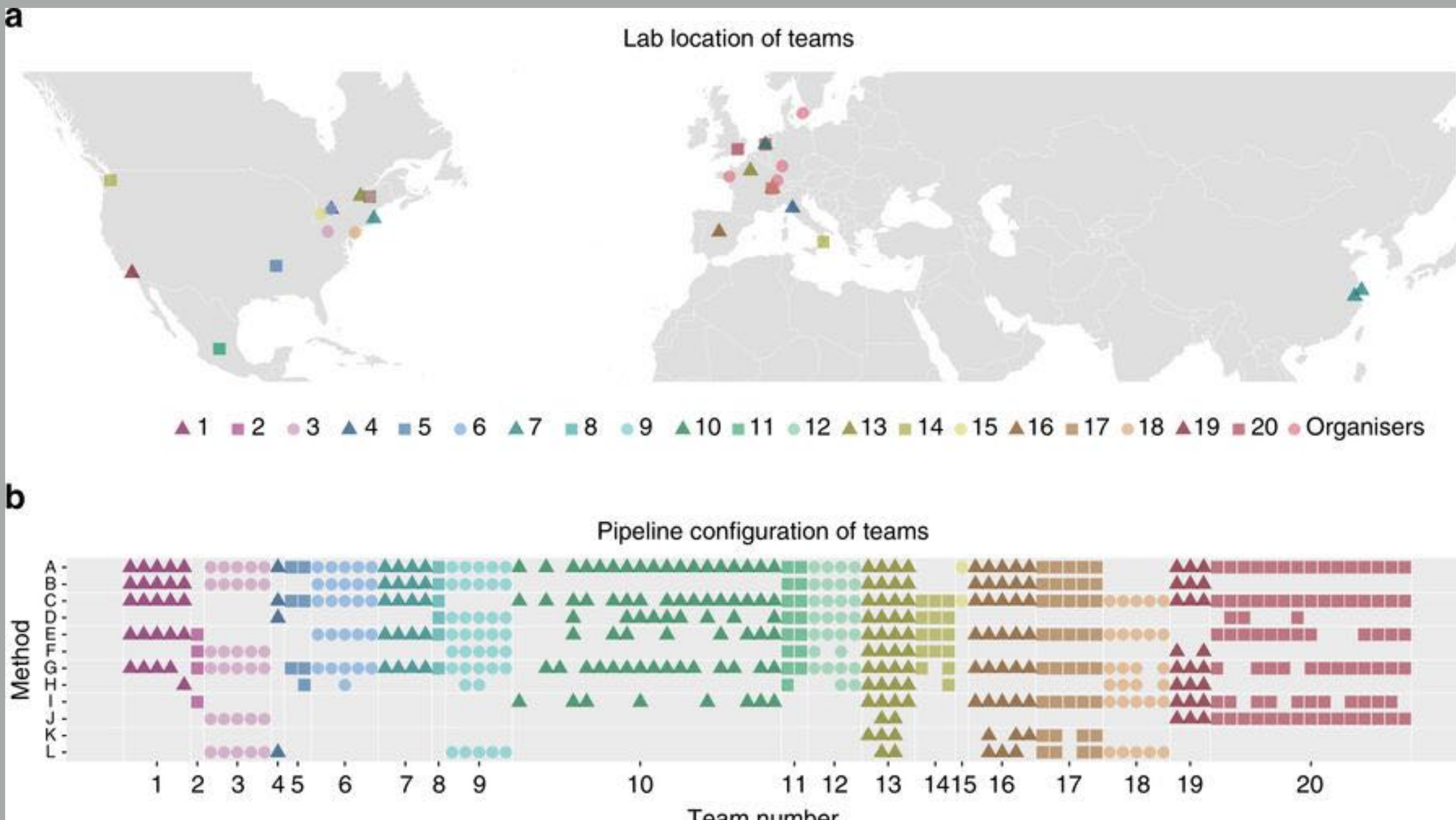
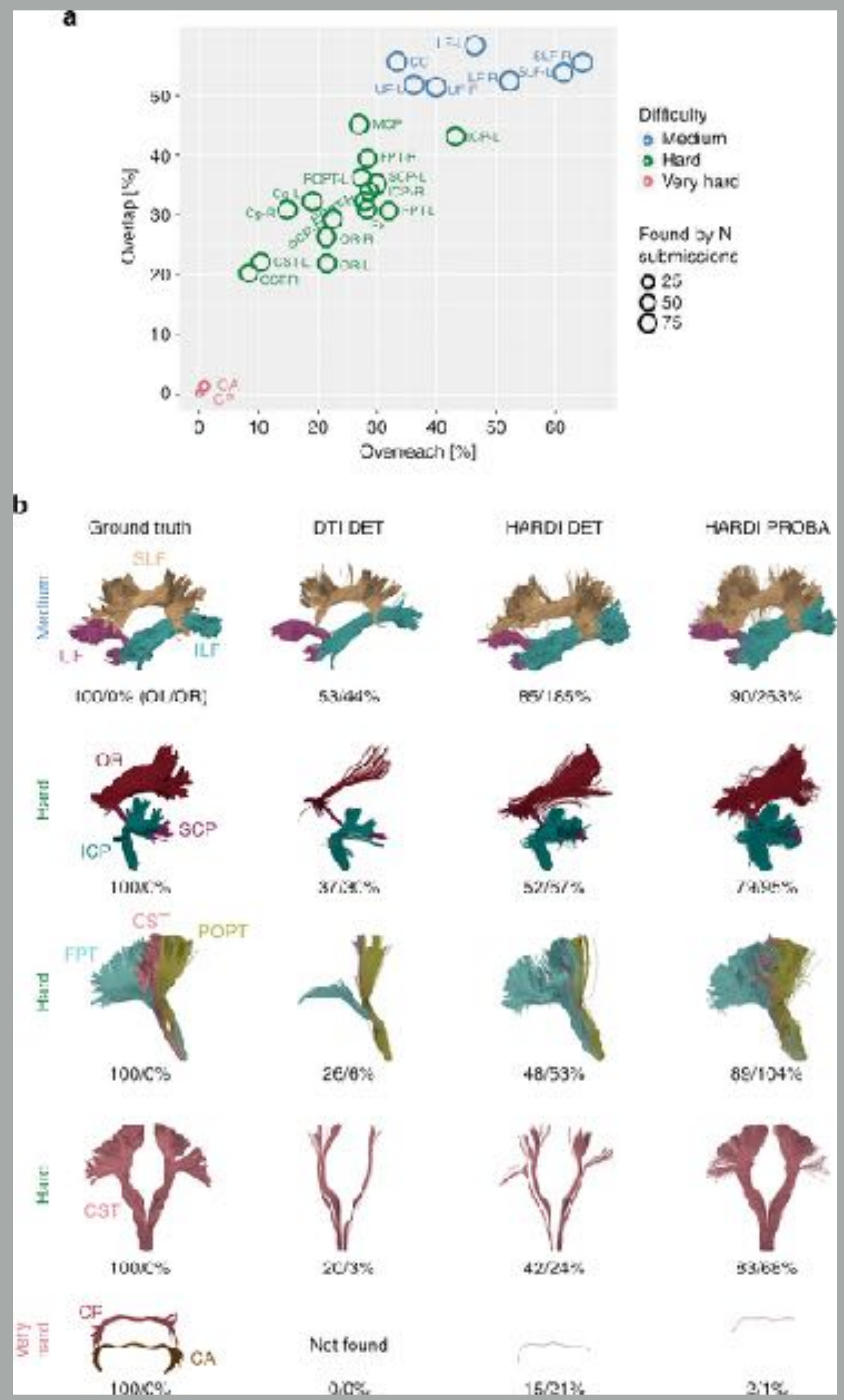
Overview of synthetic data set



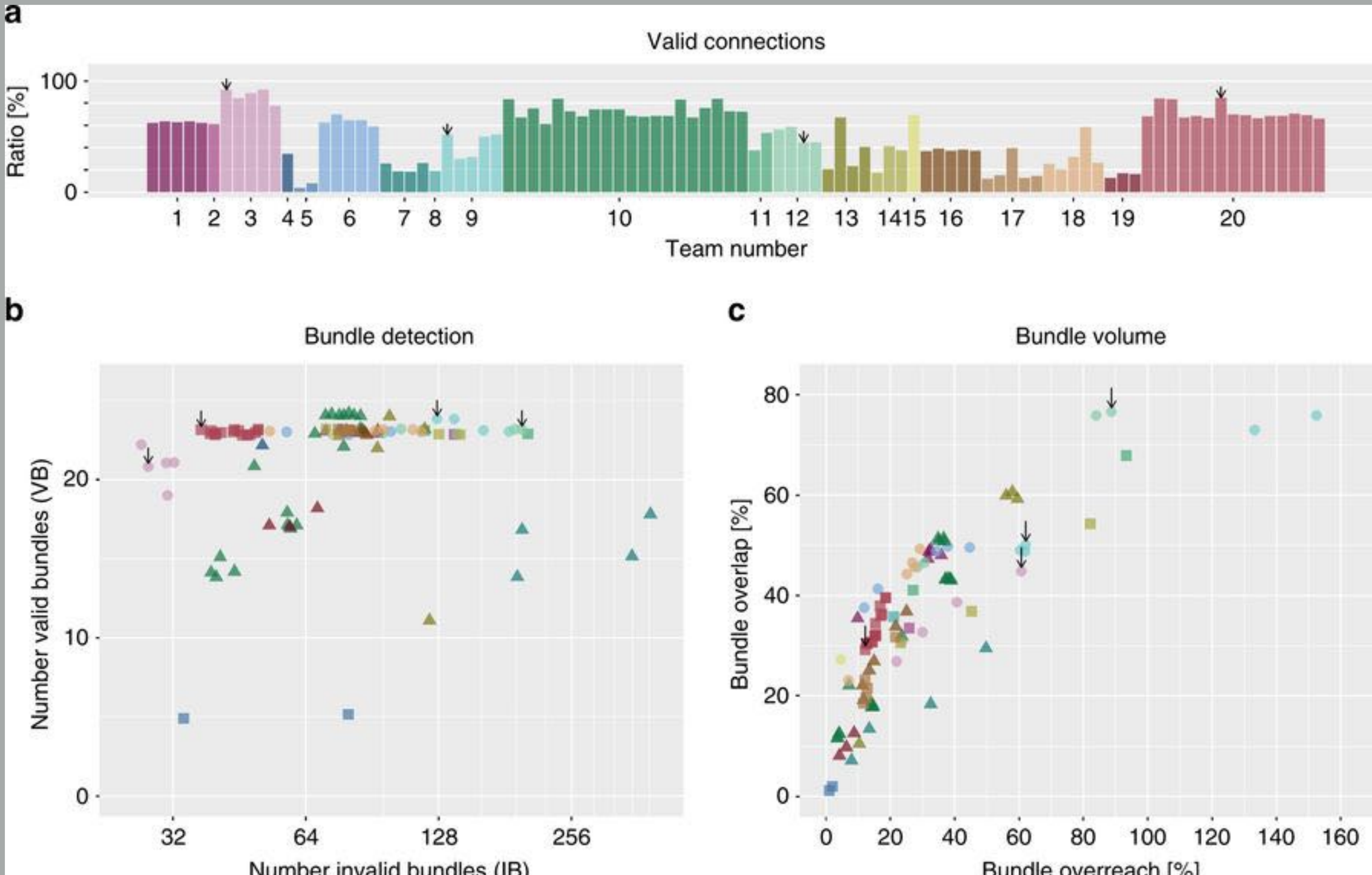
Summary of teams and tractography pipeline setups



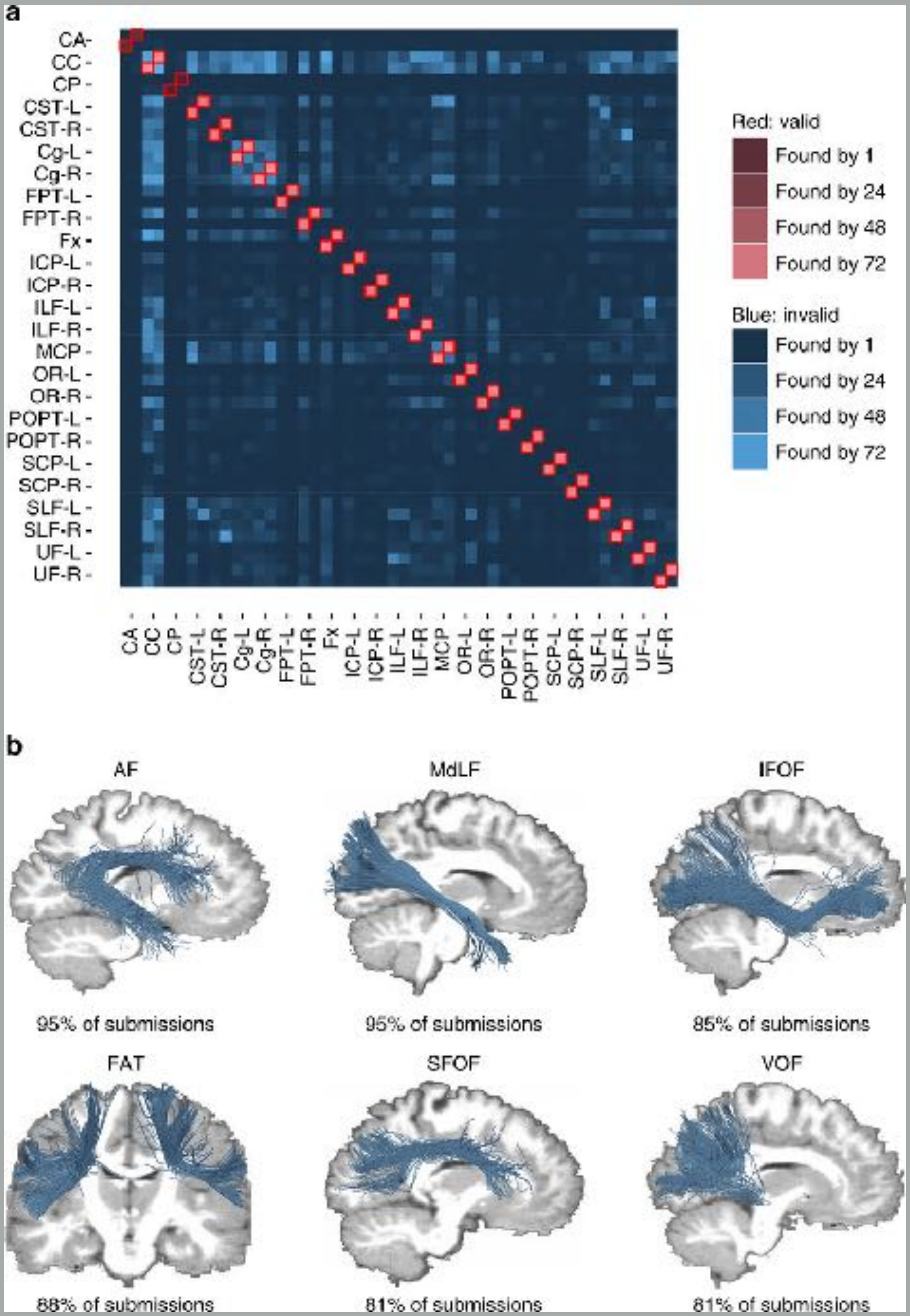
Tractography identifies most of the ground truth bundles, but not their full extent



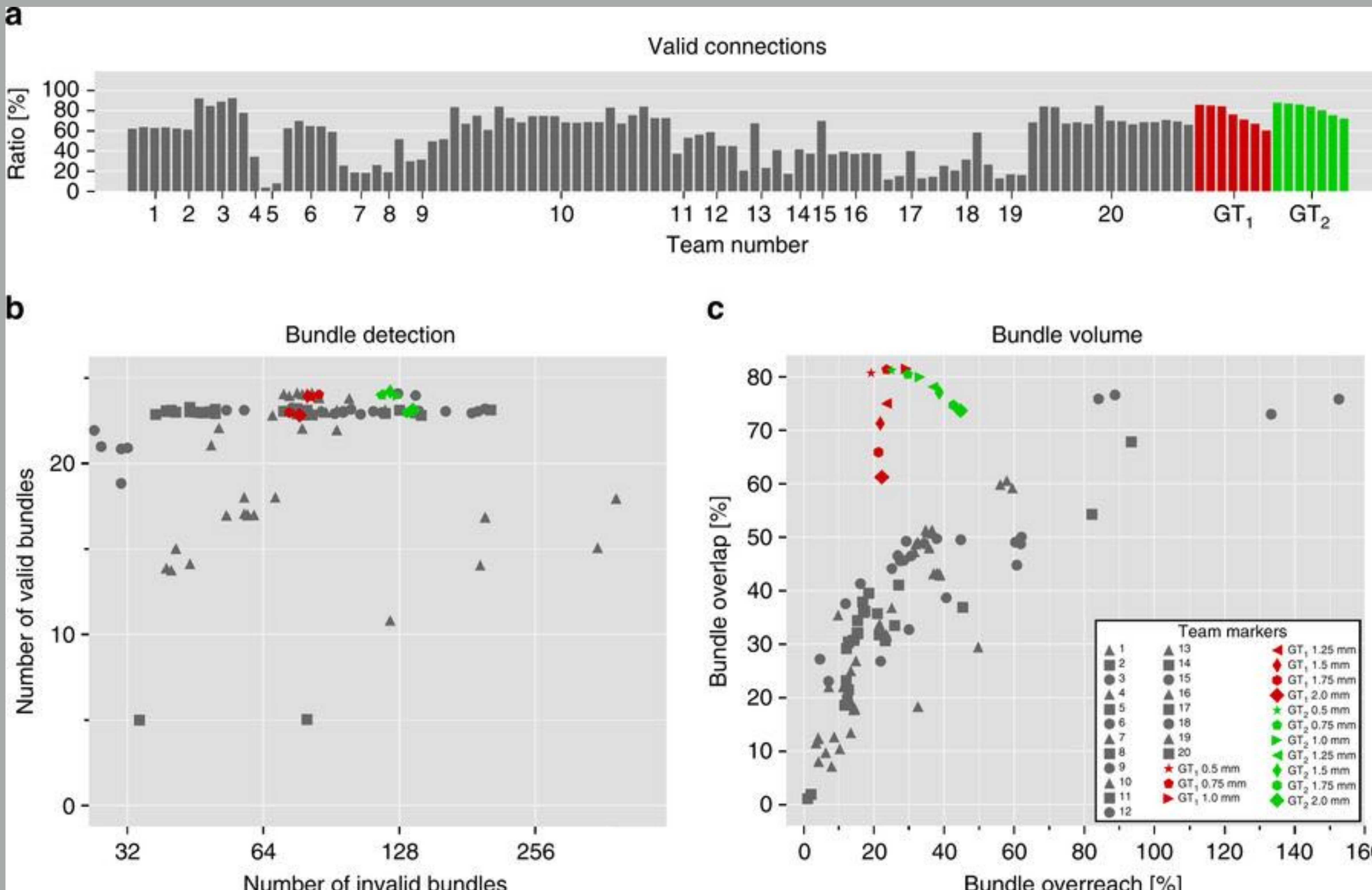
Between-group differences in tractography reconstructions of VBs and IBs



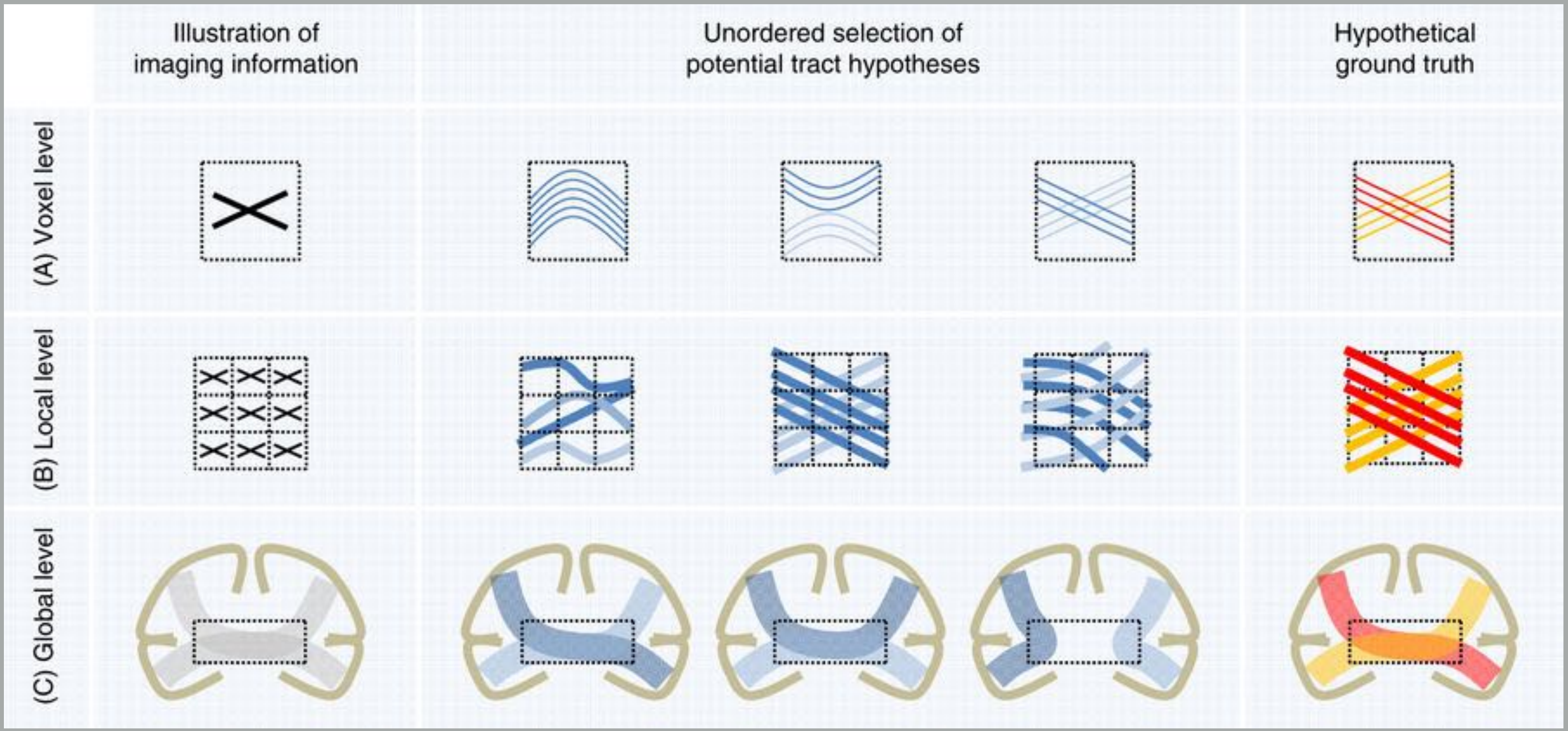
Overview of VBs and IBs and examples of invalid streamline clusters



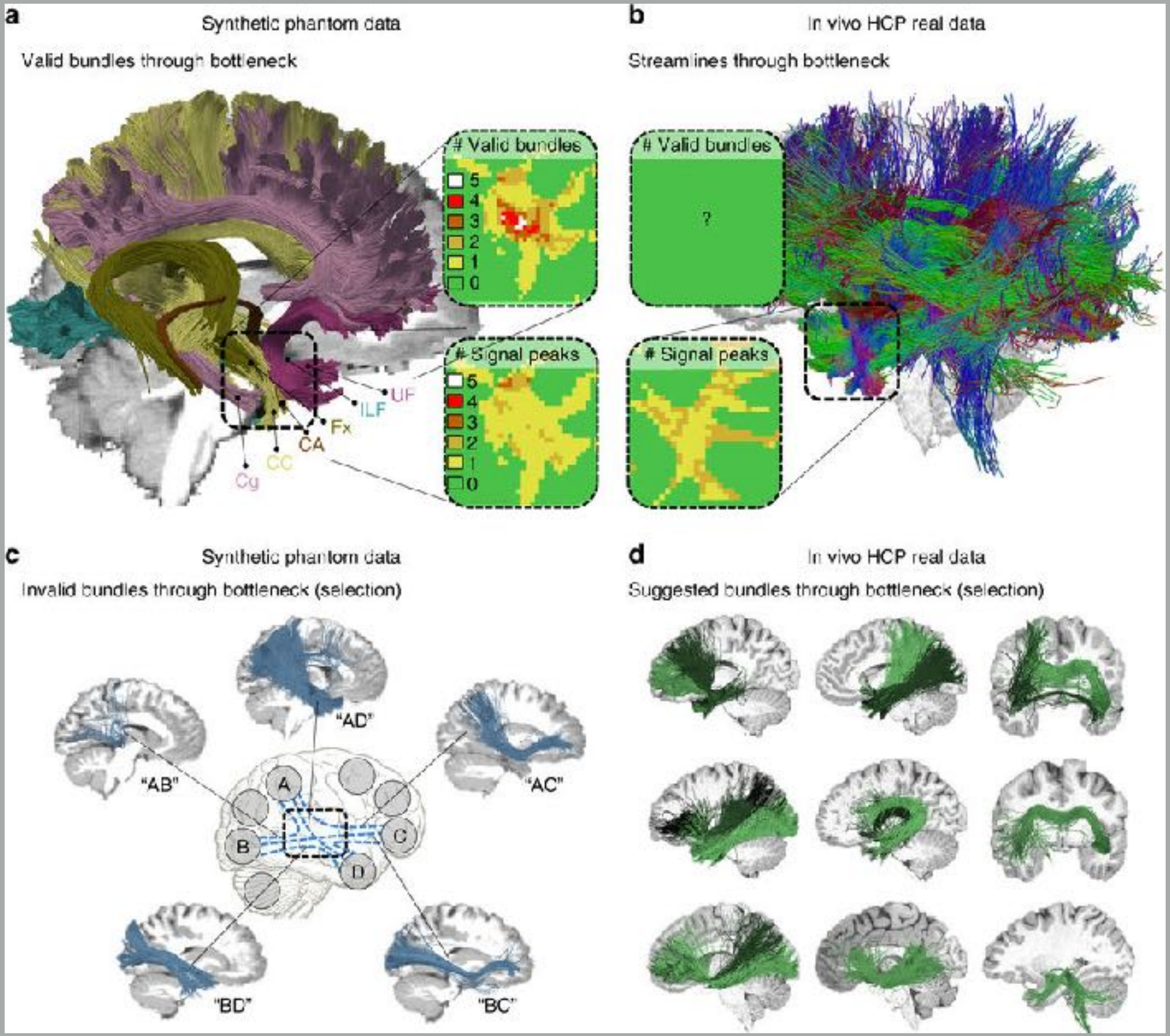
Tractography on ground truth directions with no noise still affected by IB problem



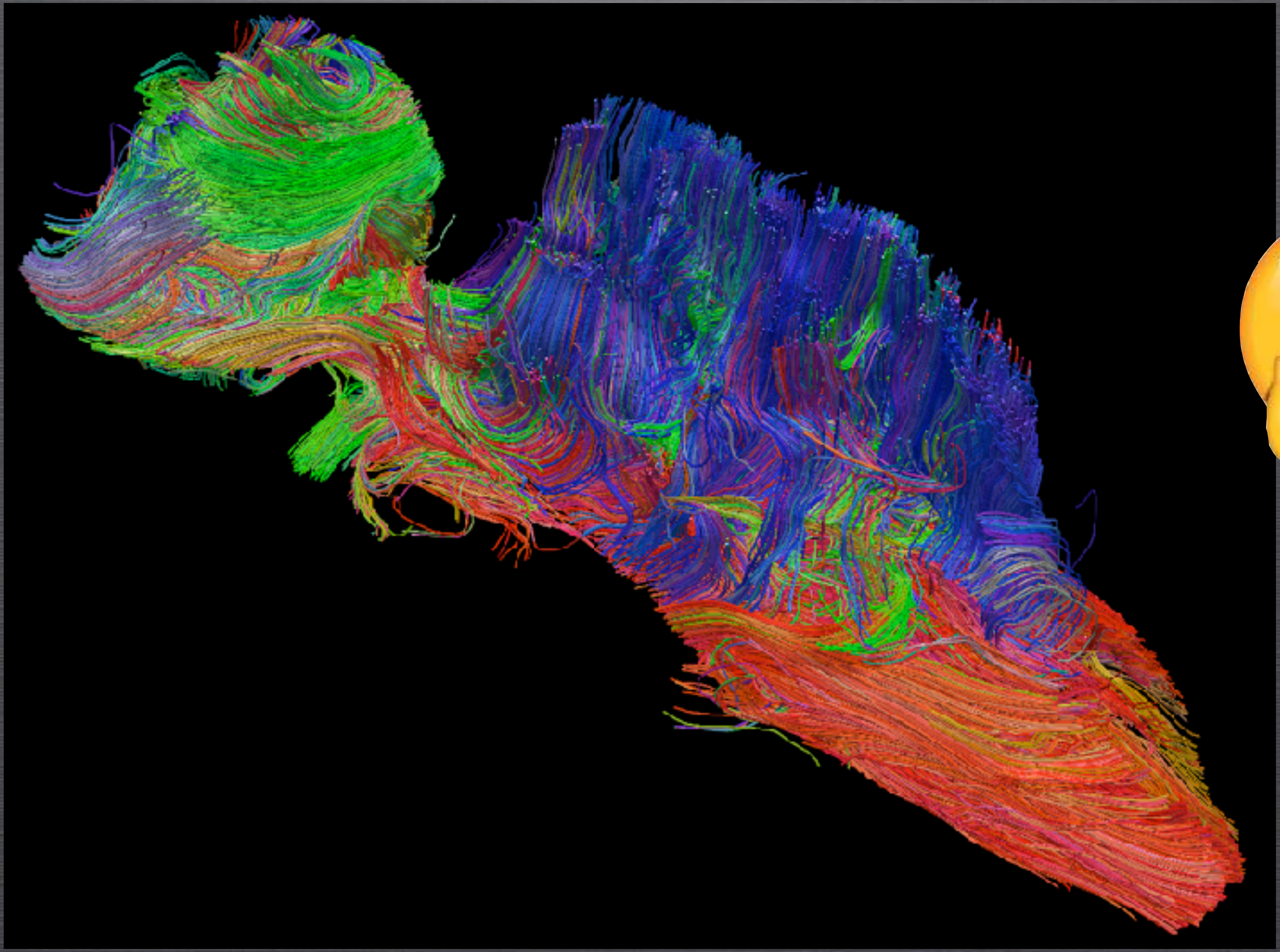
Ambiguous correspondences between diffusion directions and fiber geometry



Bottlenecks and the fundamental ill-posed nature of tractography



Is this correct??



DTI in *Mustelus henlei* @ 9.4T

Data: M. Tyszka, CalTech