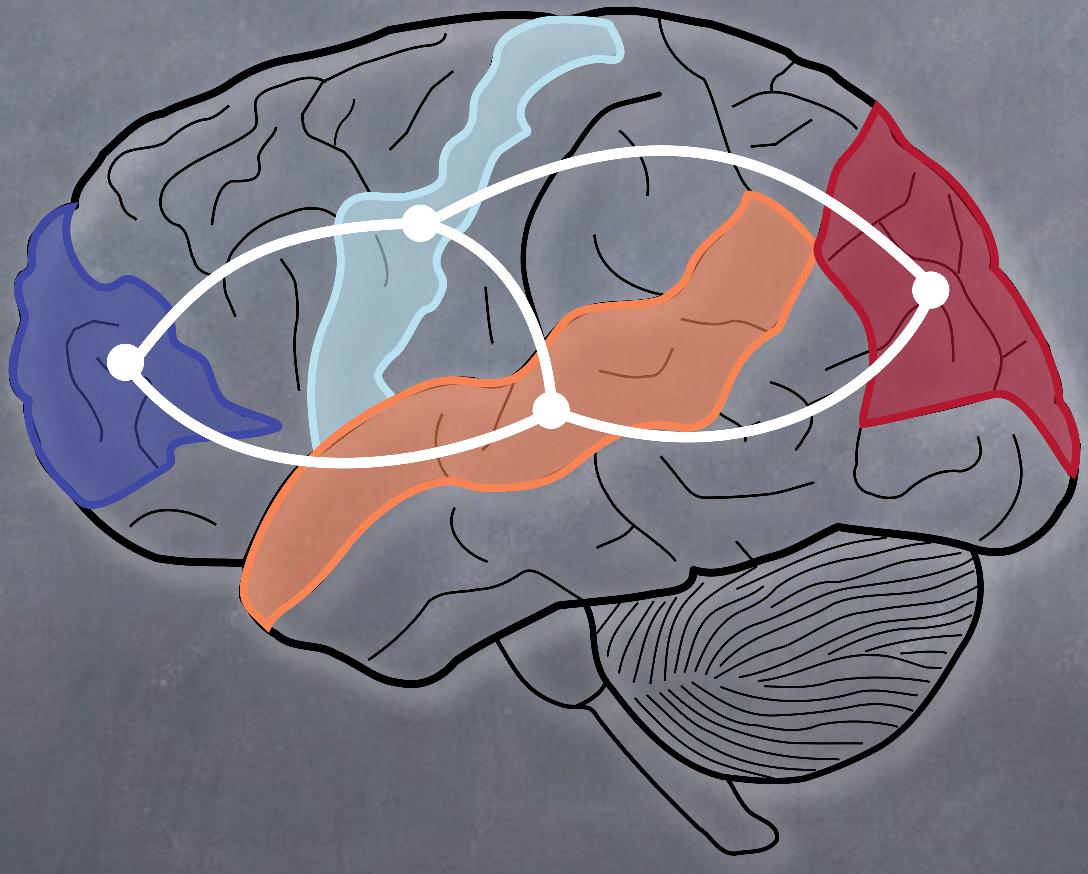
Multi-Fascicle Models for Population Studies of the Brain Microstructure

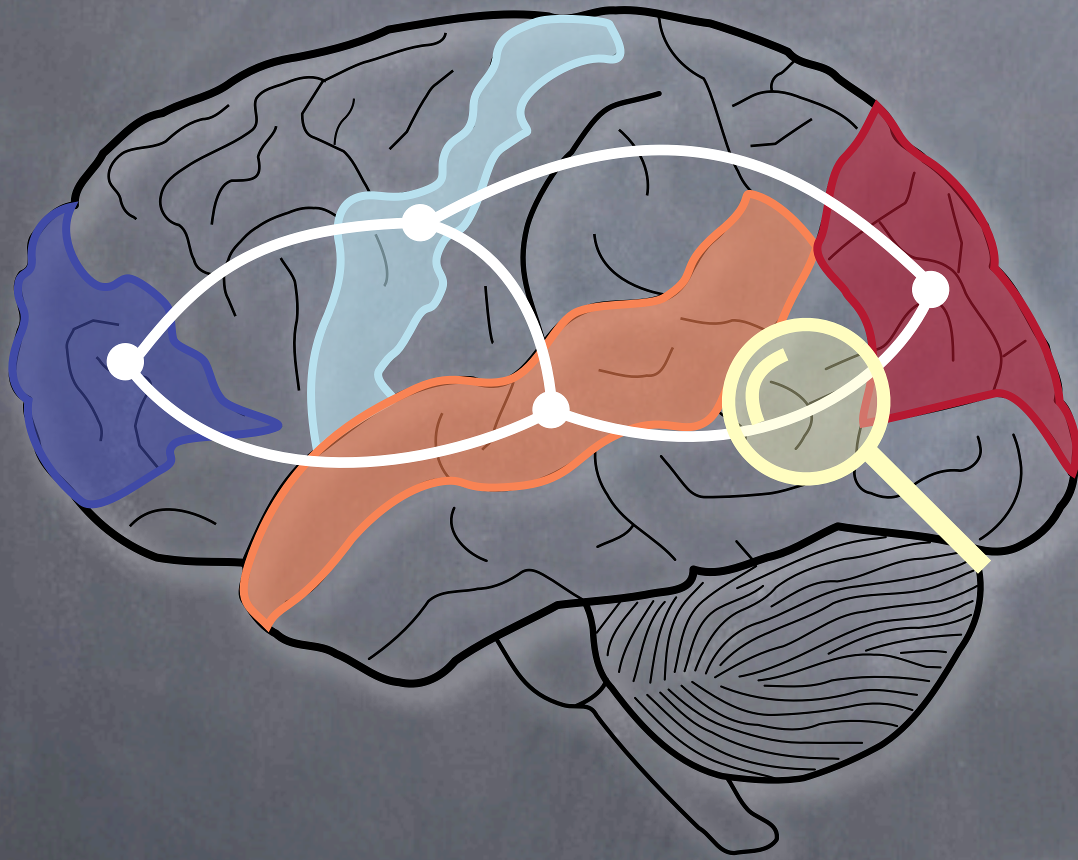
Soutenance de thèse
Louvain-la-Neuve, October 2013

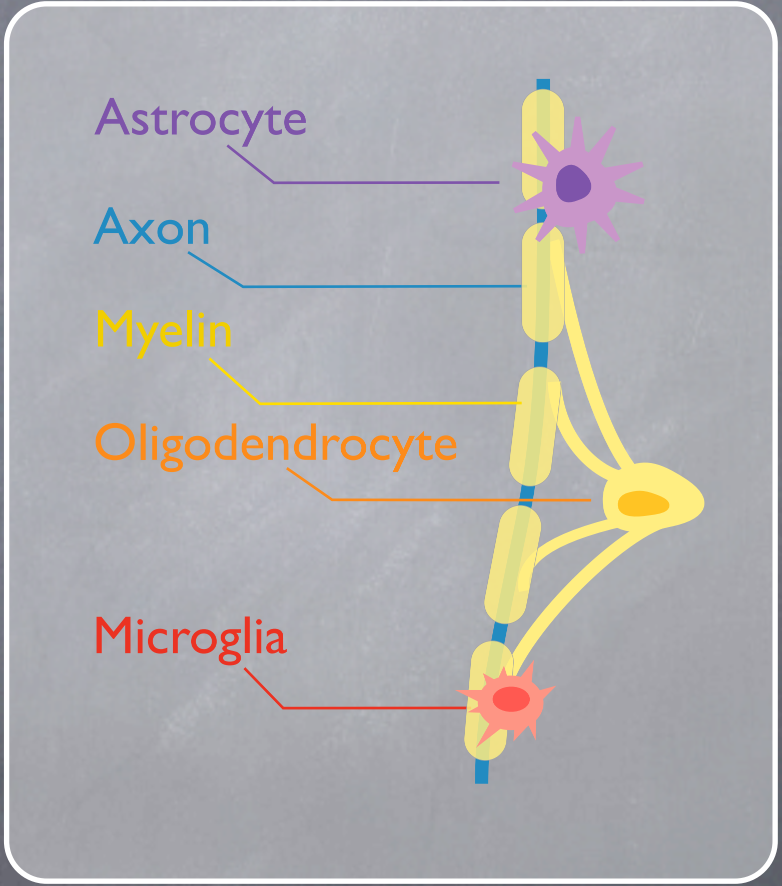
Maxime Taquet

Disconnection syndromes and other disorders are thought to affect the connections in the brain

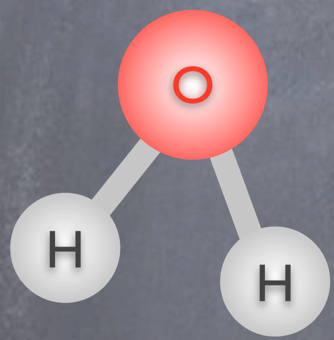


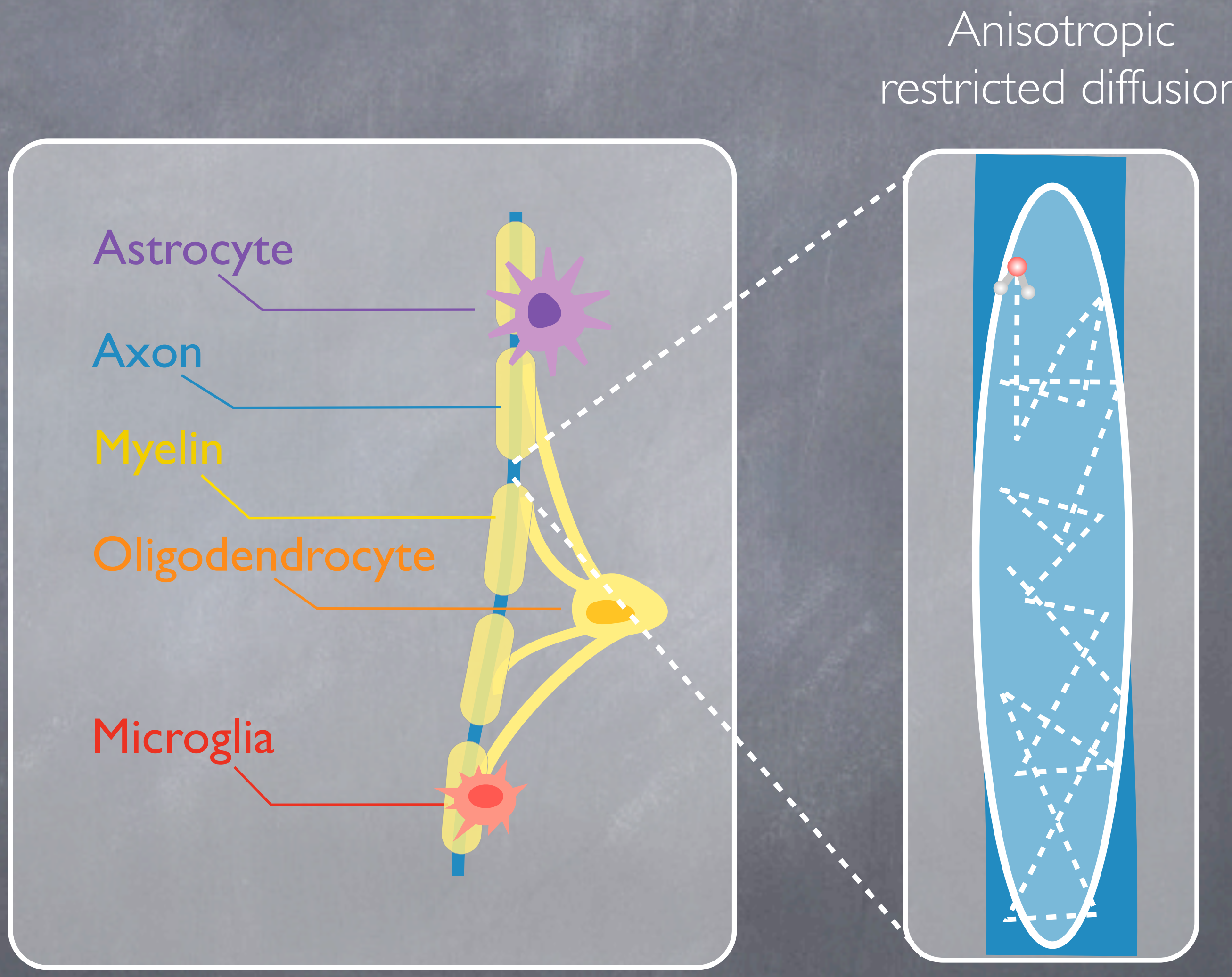
The microstructure underpins connectivity





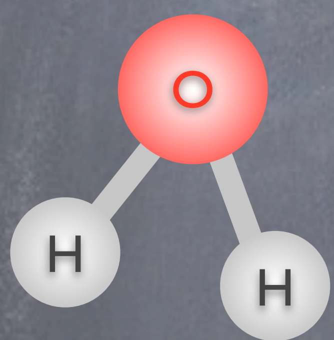
Diffusion imaging can probe the microstructure

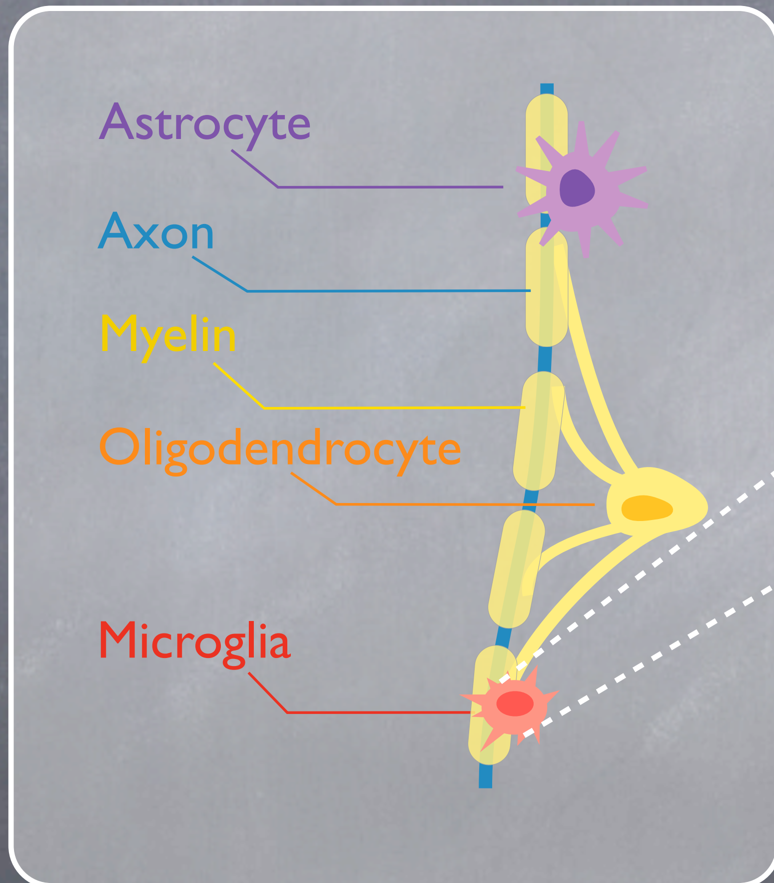


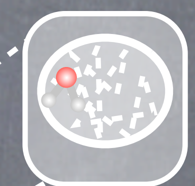


Diffusion imaging can probe the microstructure

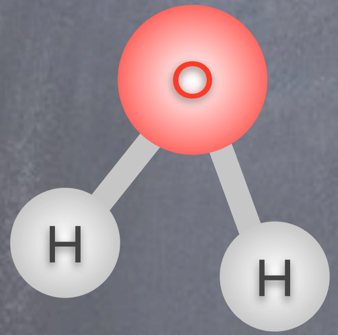
Isotropic
restricted diffusion

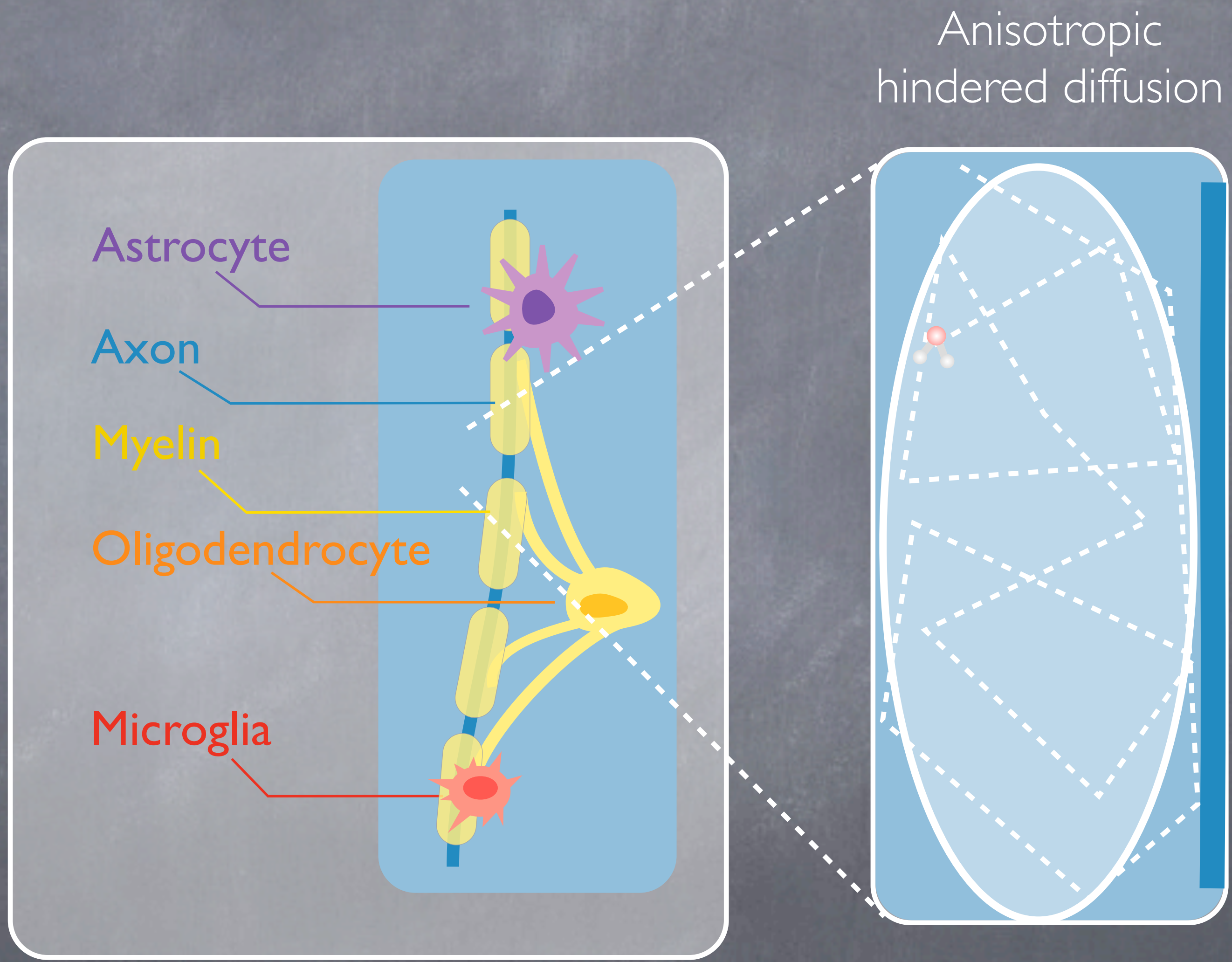




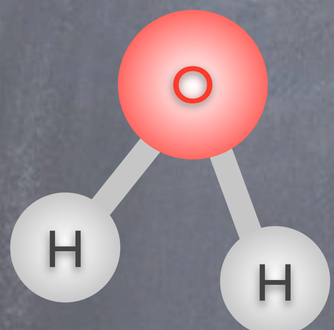


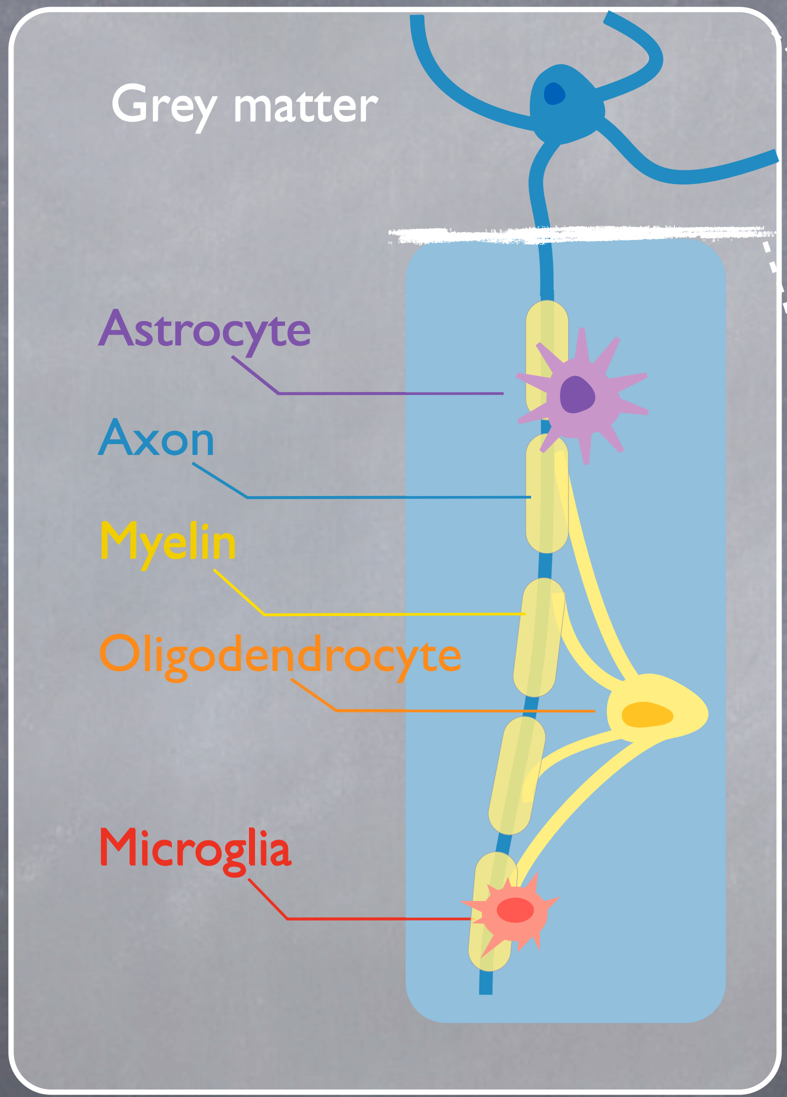
Diffusion imaging can probe the microstructure



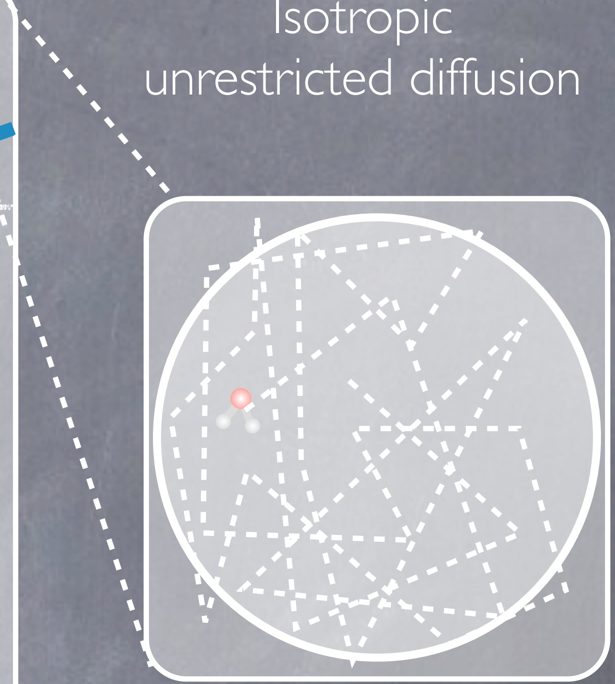


Diffusion imaging can probe the microstructure



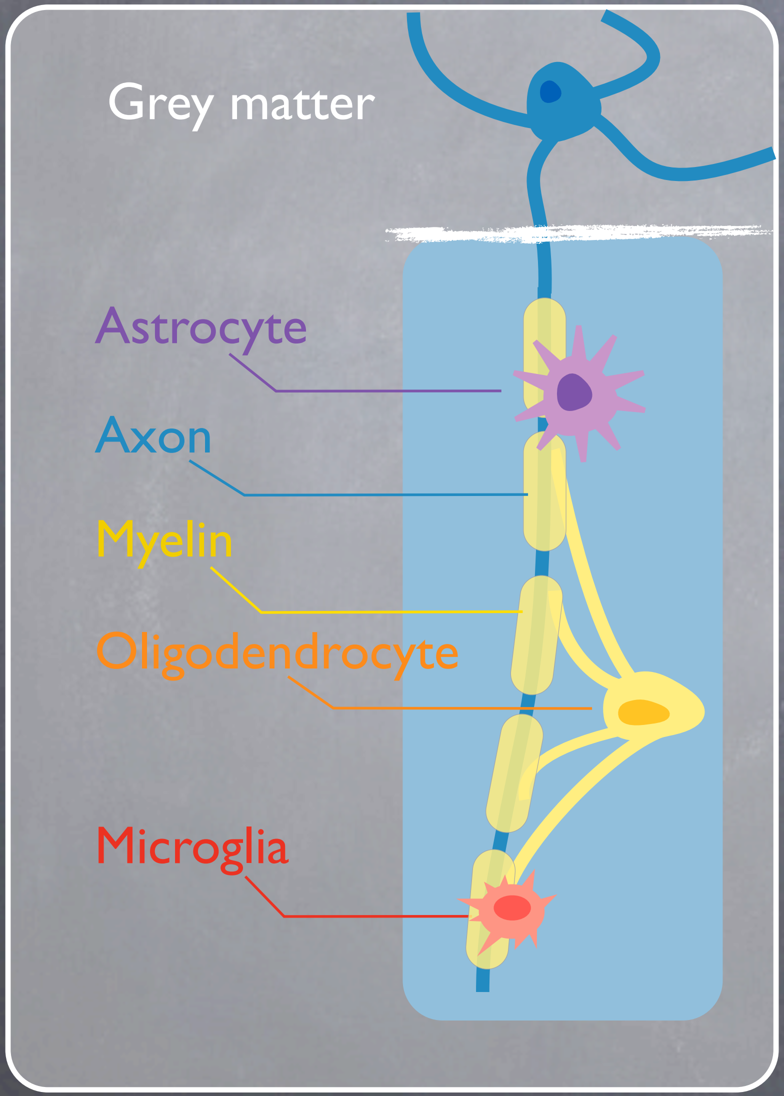


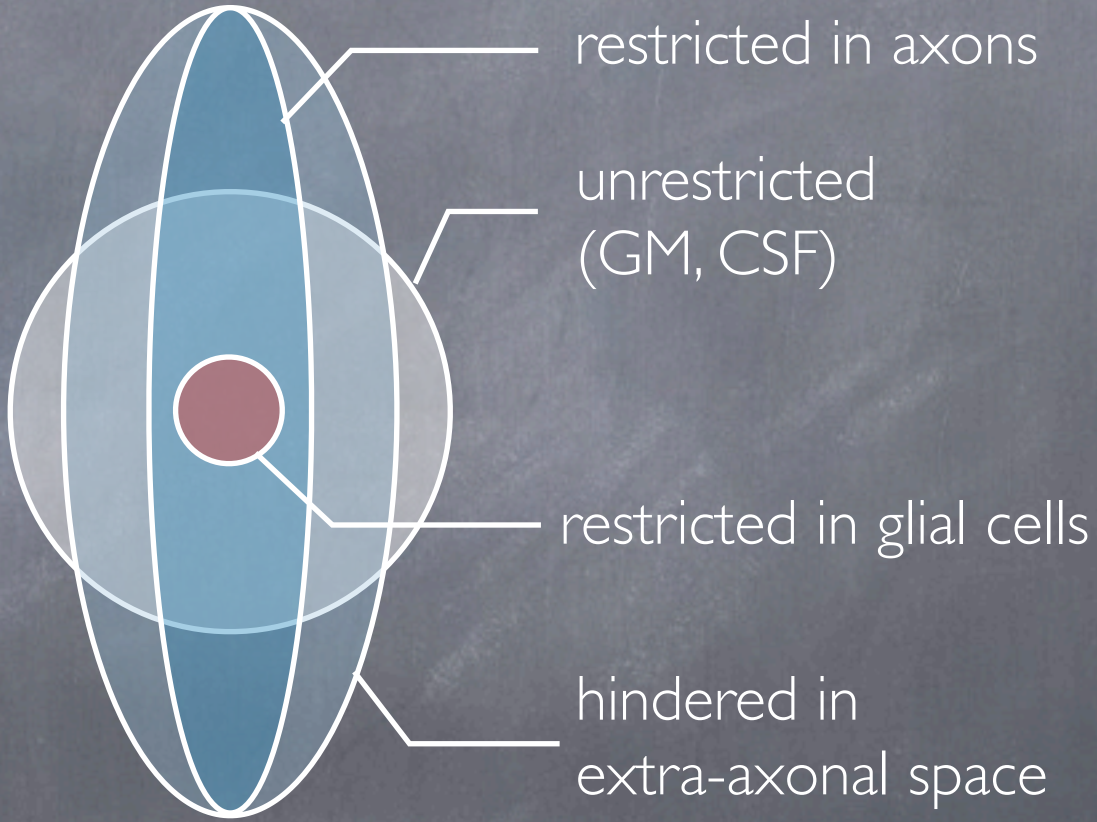
Isotropic
unrestricted diffusion



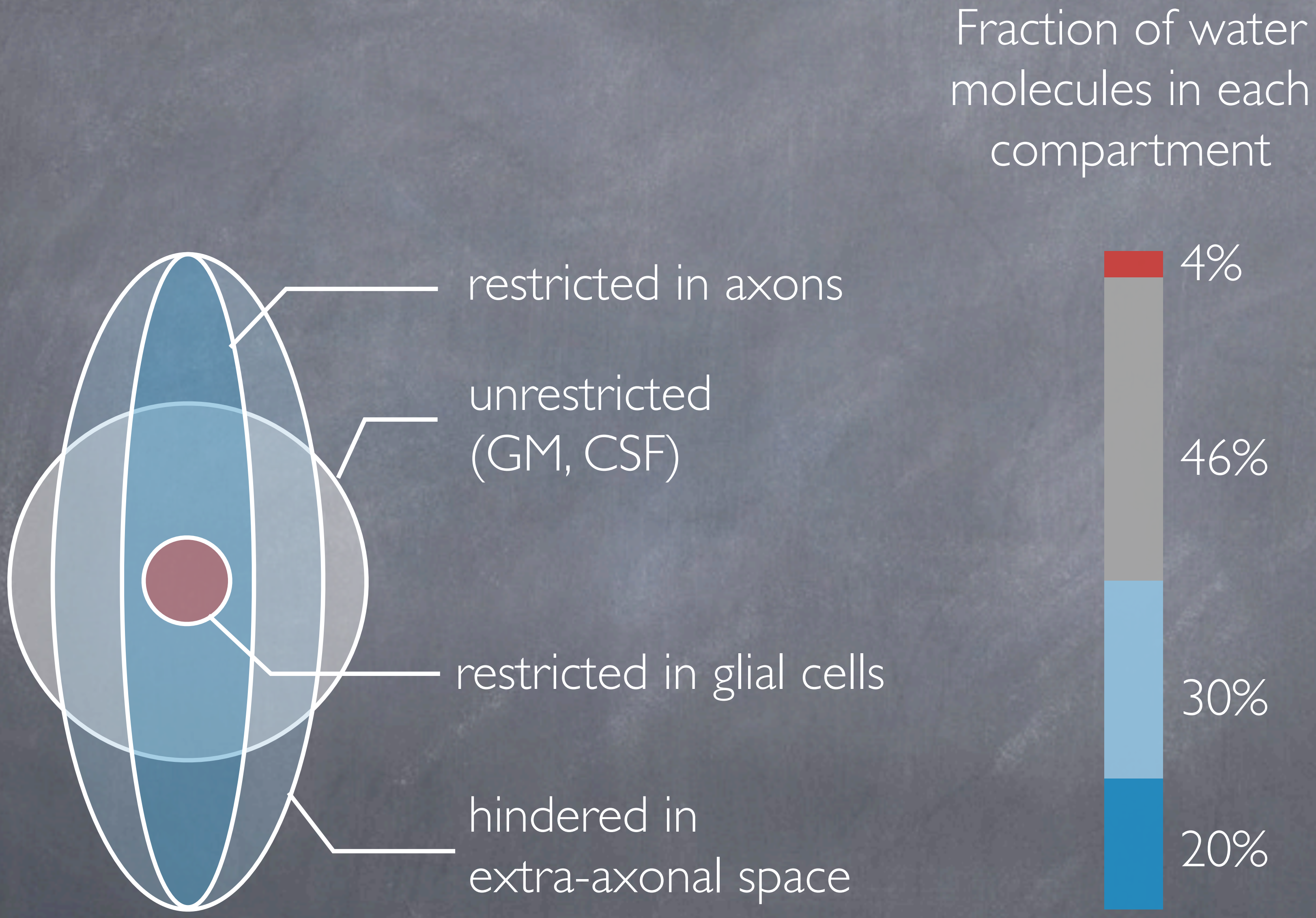
Diffusion imaging can probe the microstructure

If there is no exchange of water molecules between the different compartments



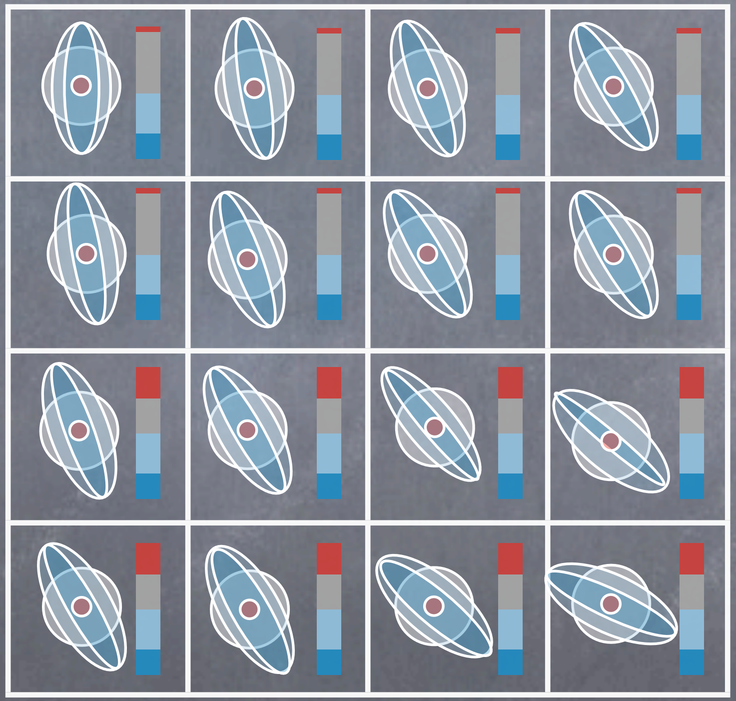


Diffusion imaging can probe the microstructure

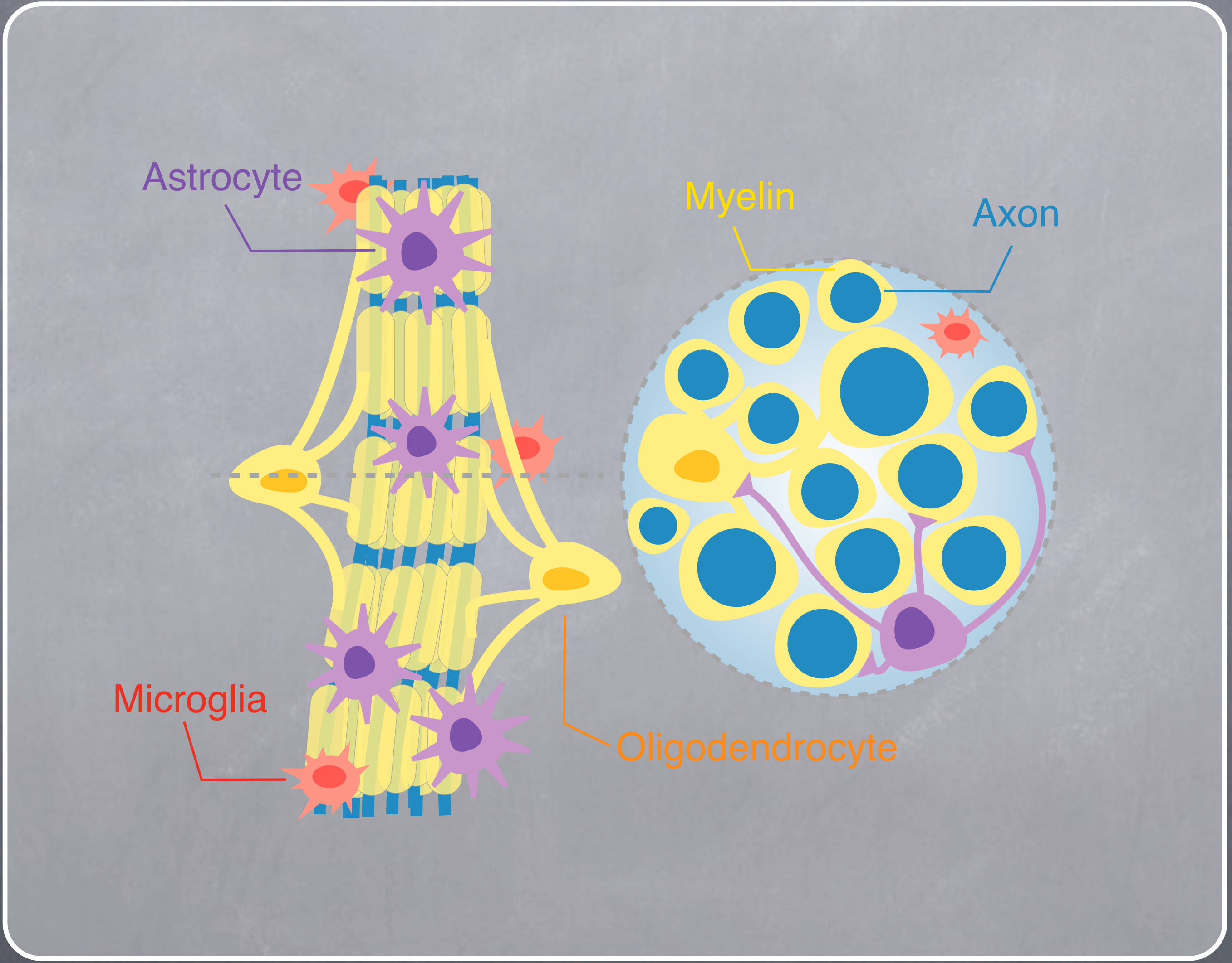


Images of the brain microstructure contain a model in each voxel

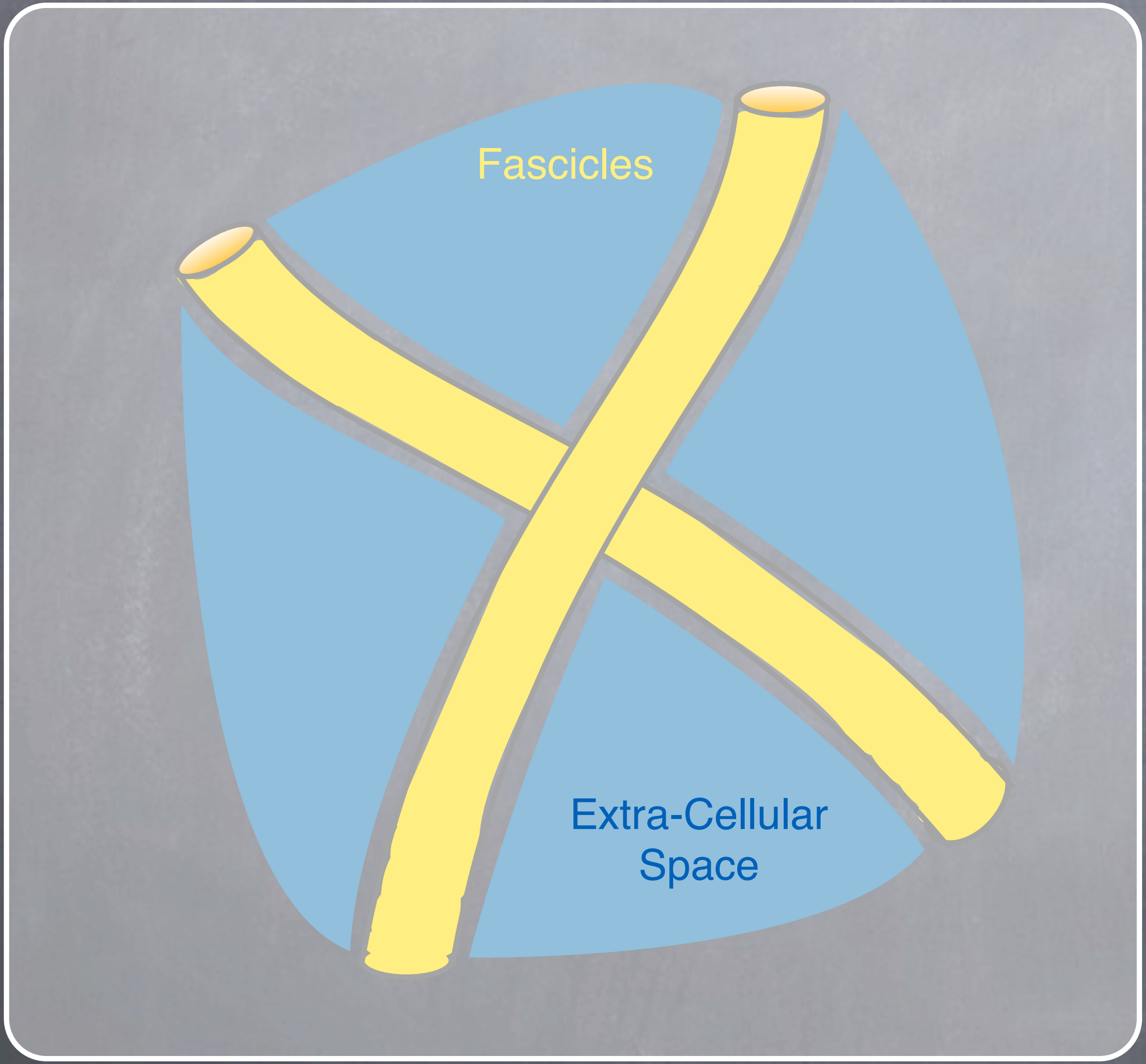
The models in different voxels have different parameters



Axons travel in fascicles



In most voxels, several fascicles cross each other



At typical resolution,

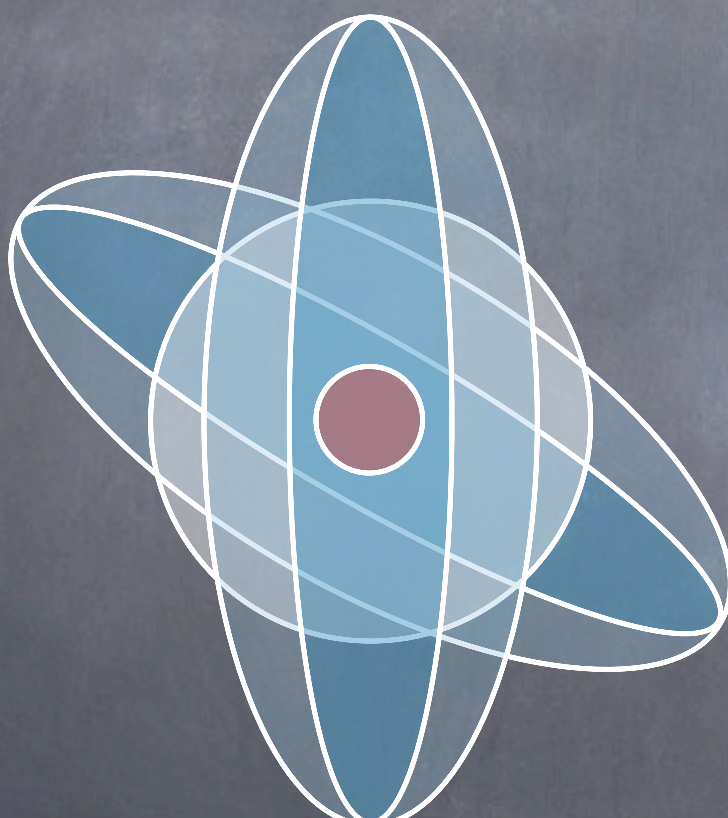
60-90% of the brain voxels

contain crossing fascicles

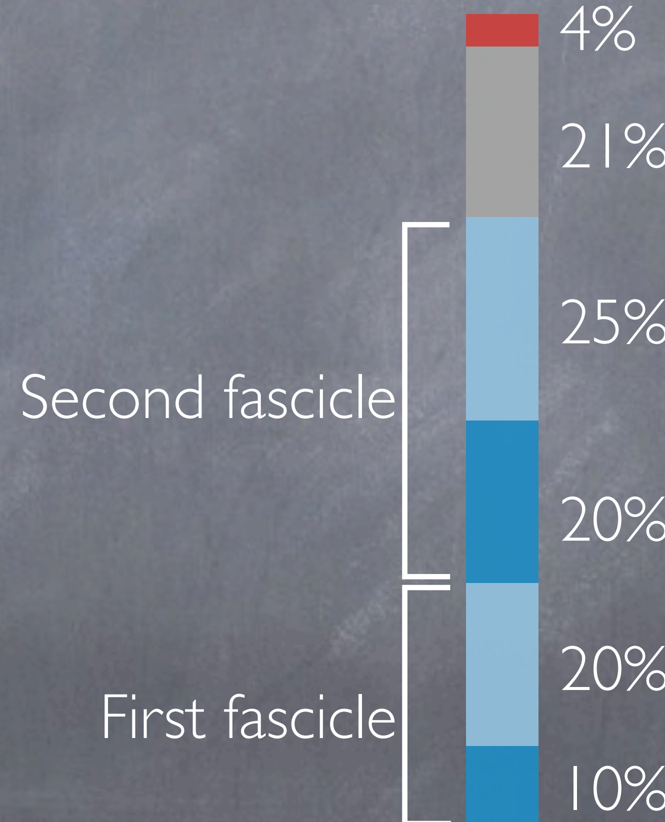
Jeurissen et al., 2012

In most voxels, several fascicles cross each other

Multi-Fascicle models of the brain microstructure

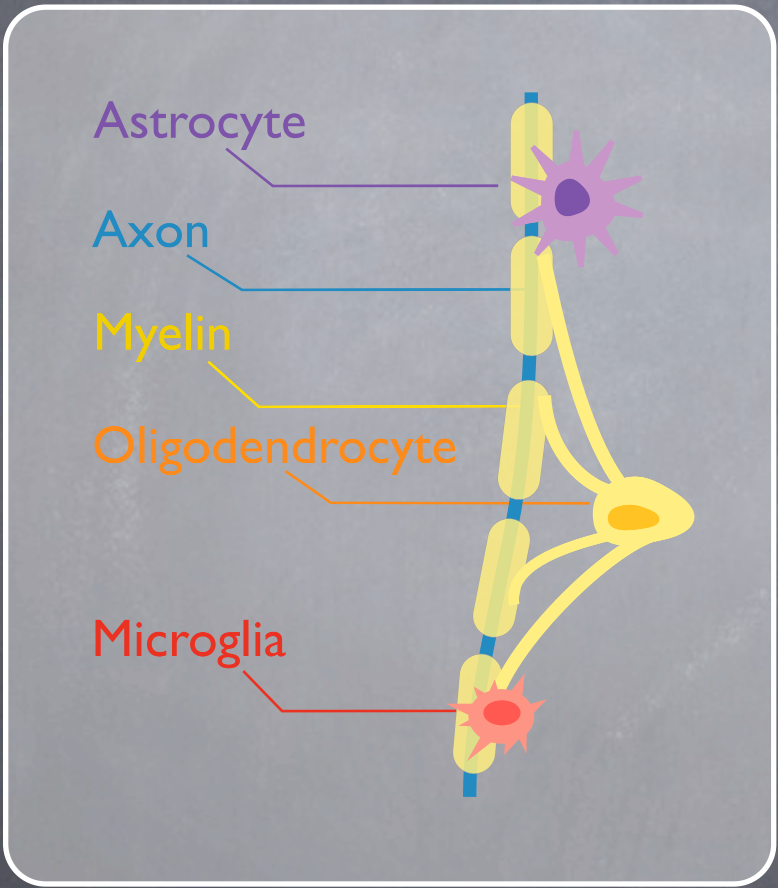


Fraction of water molecules in each compartment

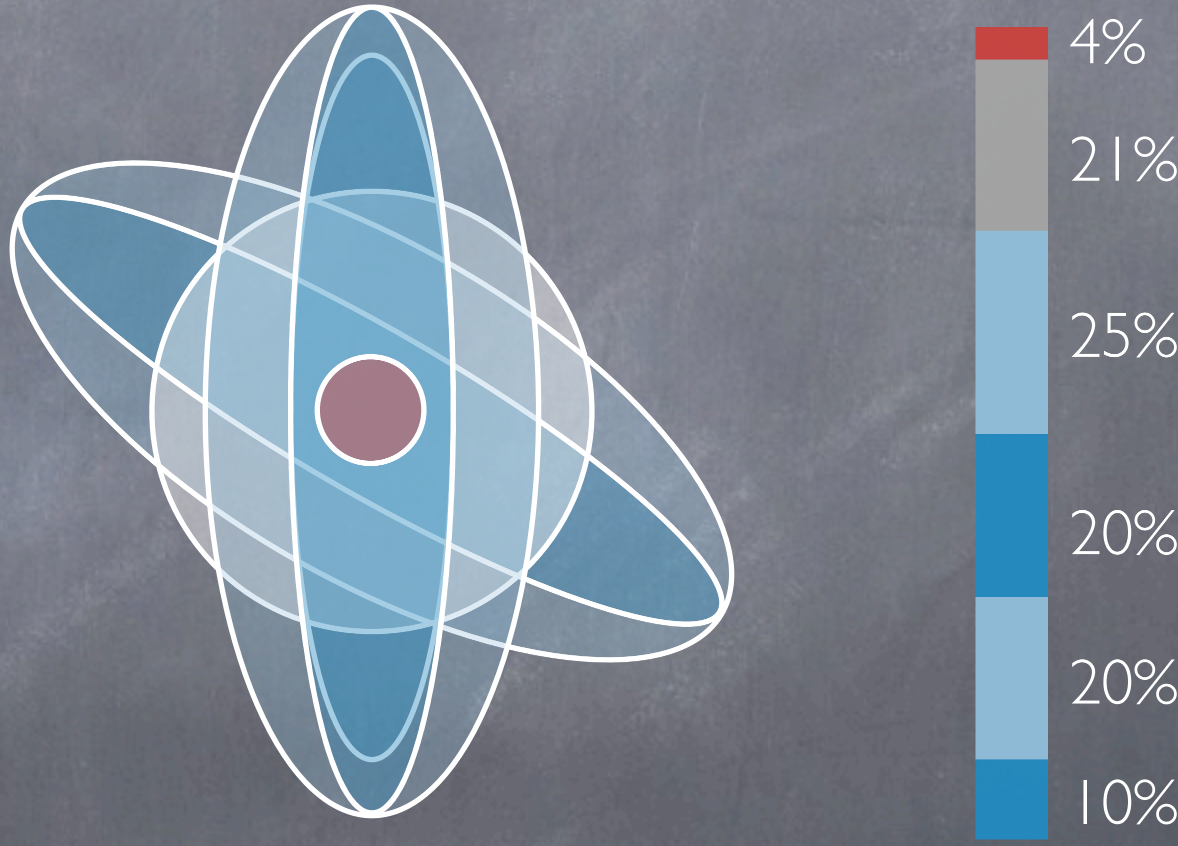


Myelin injury is translated in a decreased axial diffusivity

Axon injury

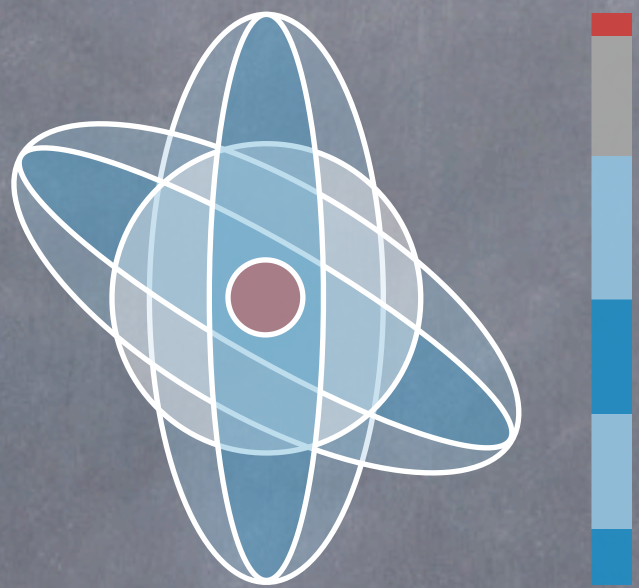


Multi-Fascicle models of the brain microstructure



Song et al., Neuroimage 2003

Population studies of the brain microstructure from diffusion imaging



Acquire Diffusion-Weighted MRI → **Estimate** Microstructural Models → **Register** Microstructural Models → Perform **Statistical Analysis**

New assets and capabilities to conduct population studies of the brain microstructure

1. Selection of the appropriate model
2. Registration and atlas construction
3. Statistical analysis of microstructure
4. Estimation from single b-value data

New assets and capabilities to conduct population studies of the brain microstructure

1. **Selection of the appropriate model**

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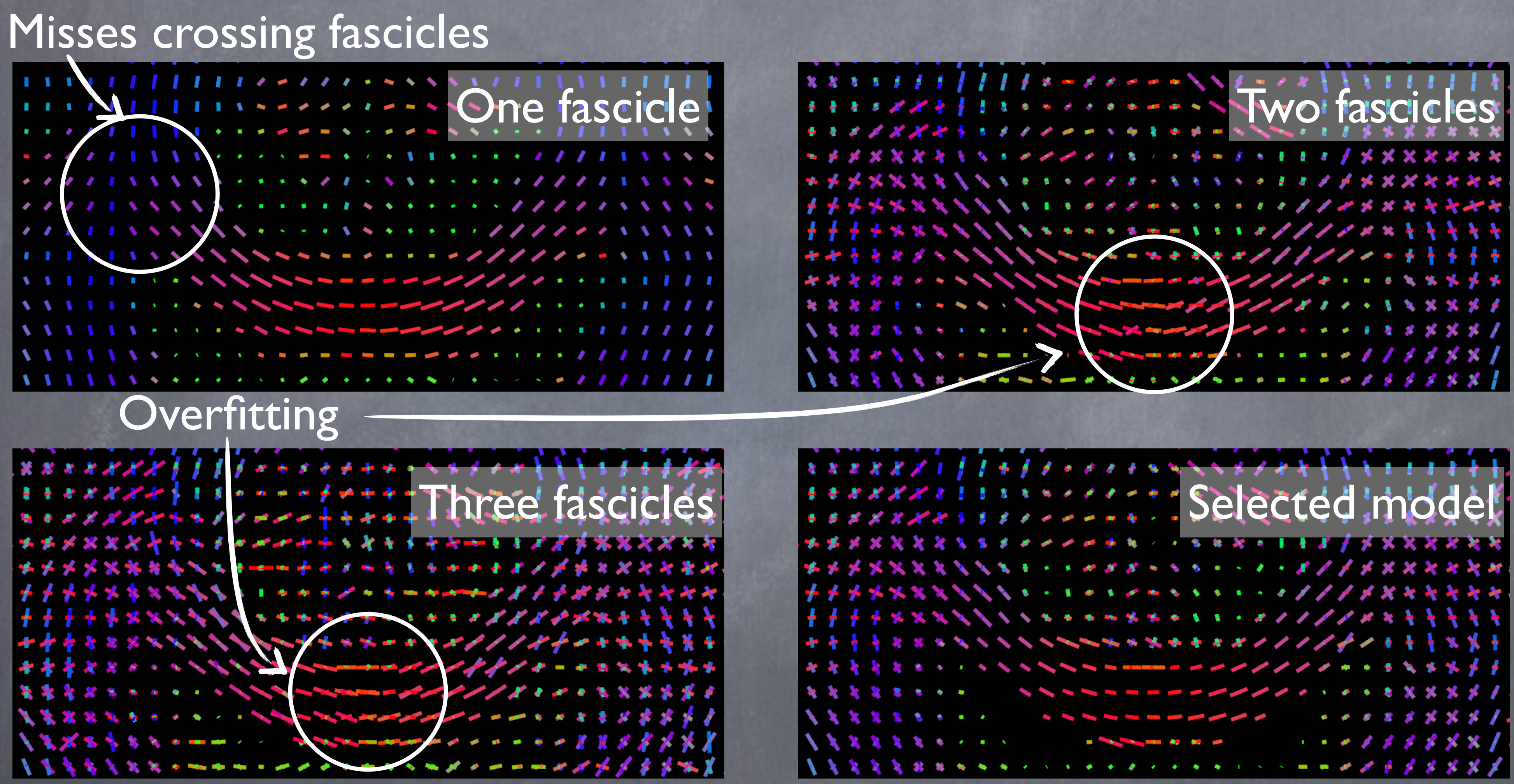
Given a set of data, we ought to know what model can be reliably estimated



Scherrer, Taquet and Warfield, IPMI, 2013

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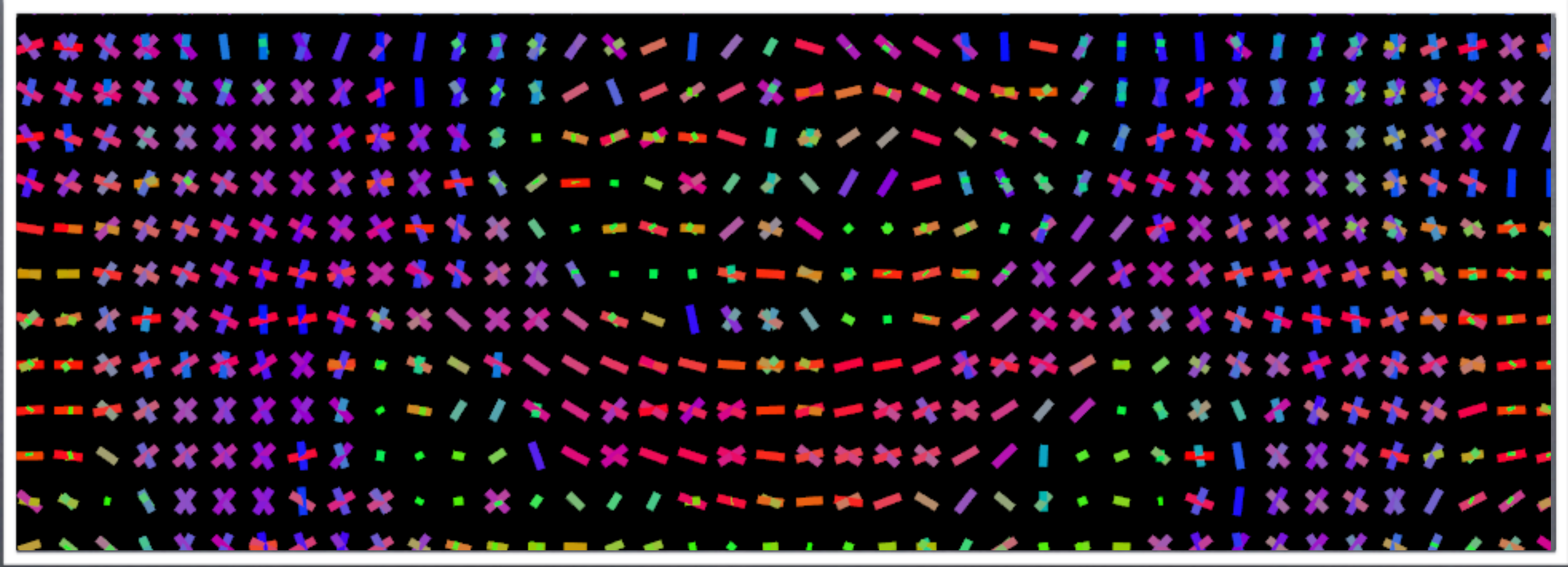
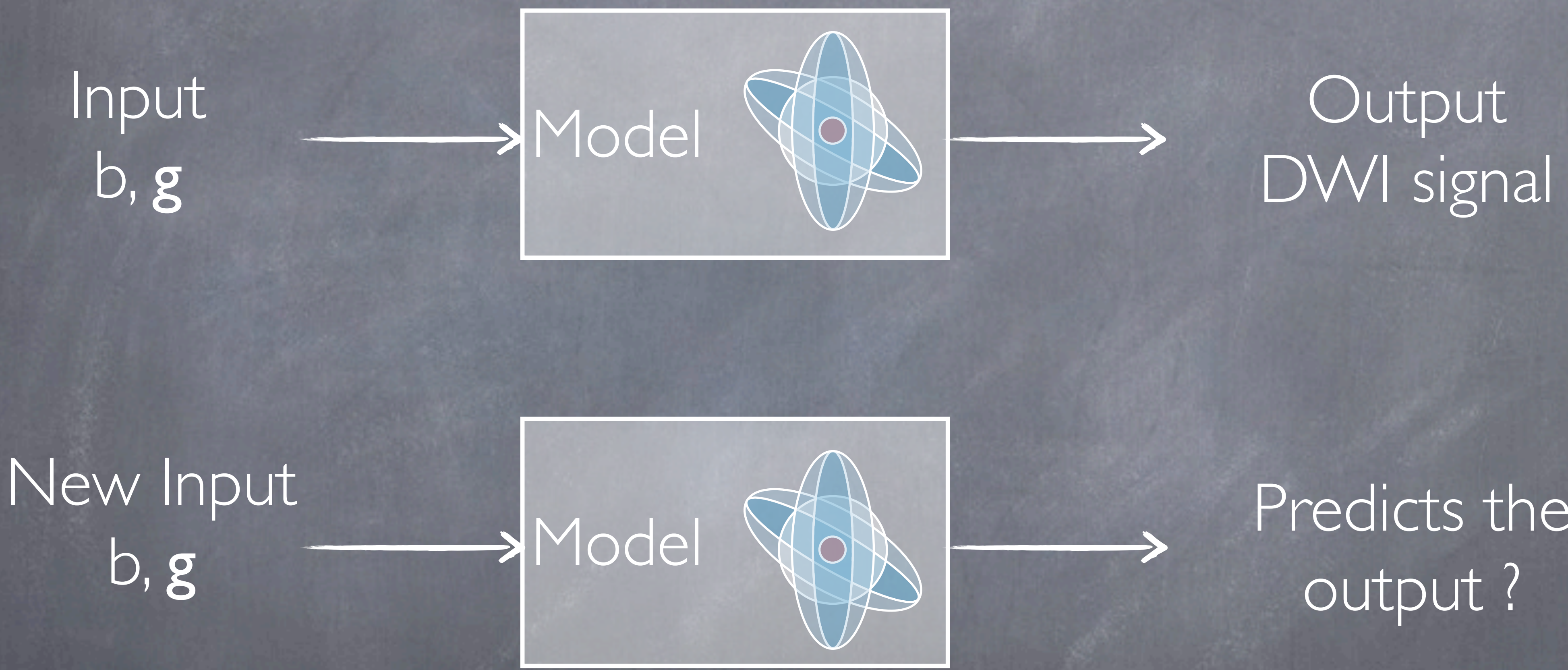


Scherrer, Taquet and Warfield, IPMI, 2013

We proposed that the appropriate model best generalizes to new data not included in the estimation

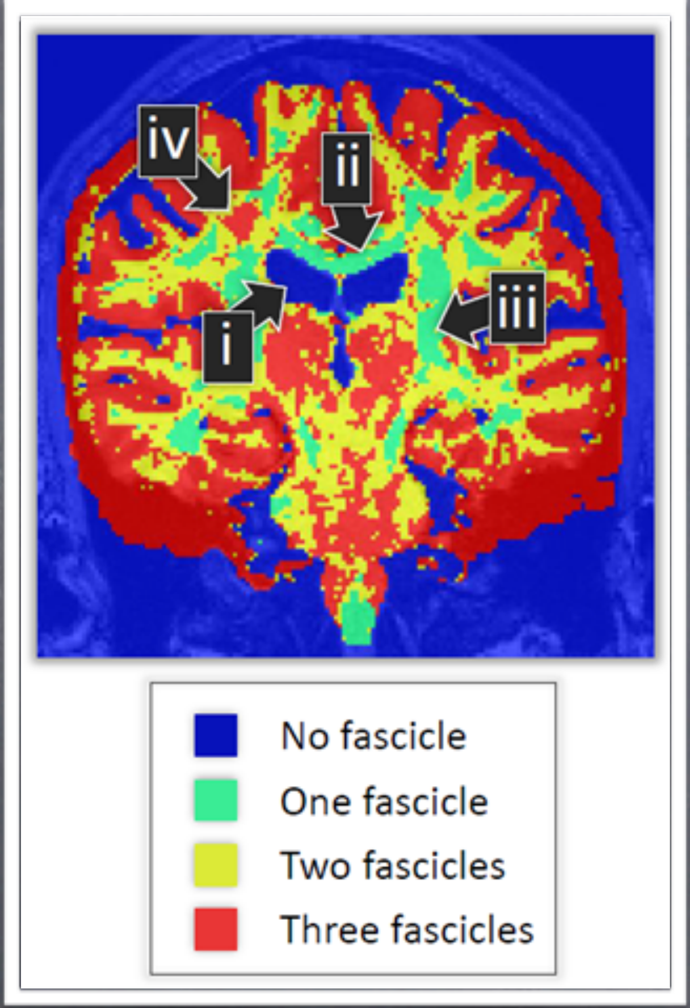


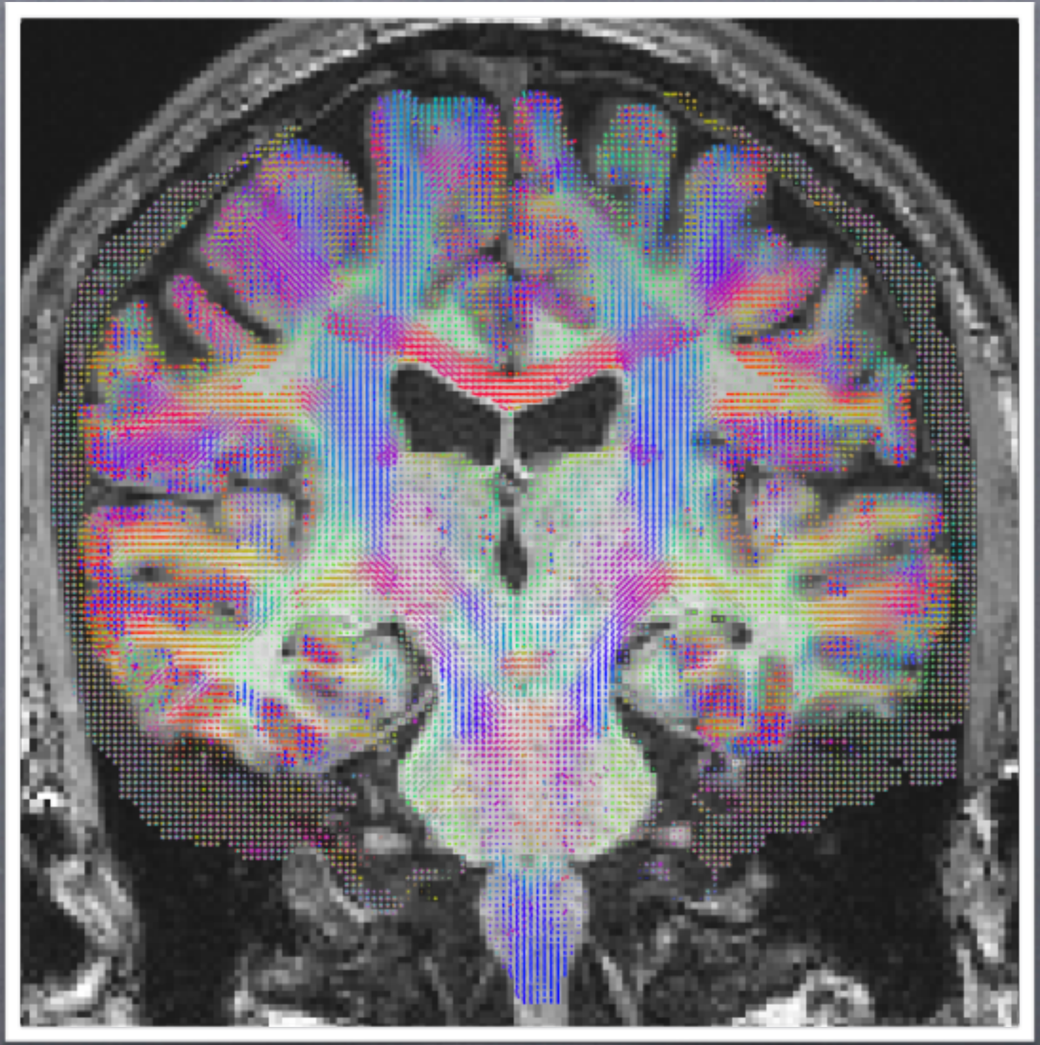
→ Compute the generalization error

632 Bootstrap estimator

Scherrer, Taquet and Warfield, IPMI, 2013

As a result, we obtain a reliable and robust selection of the microstructure model





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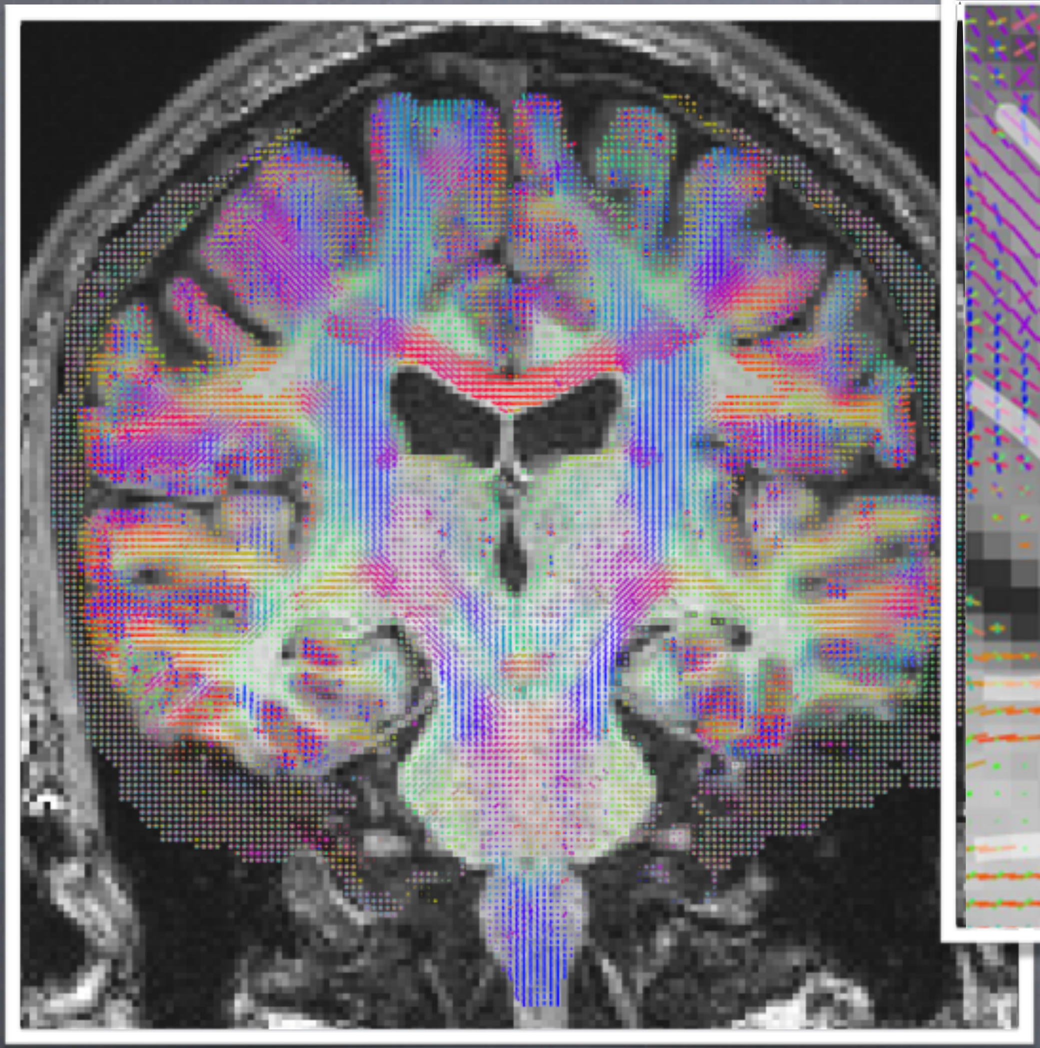

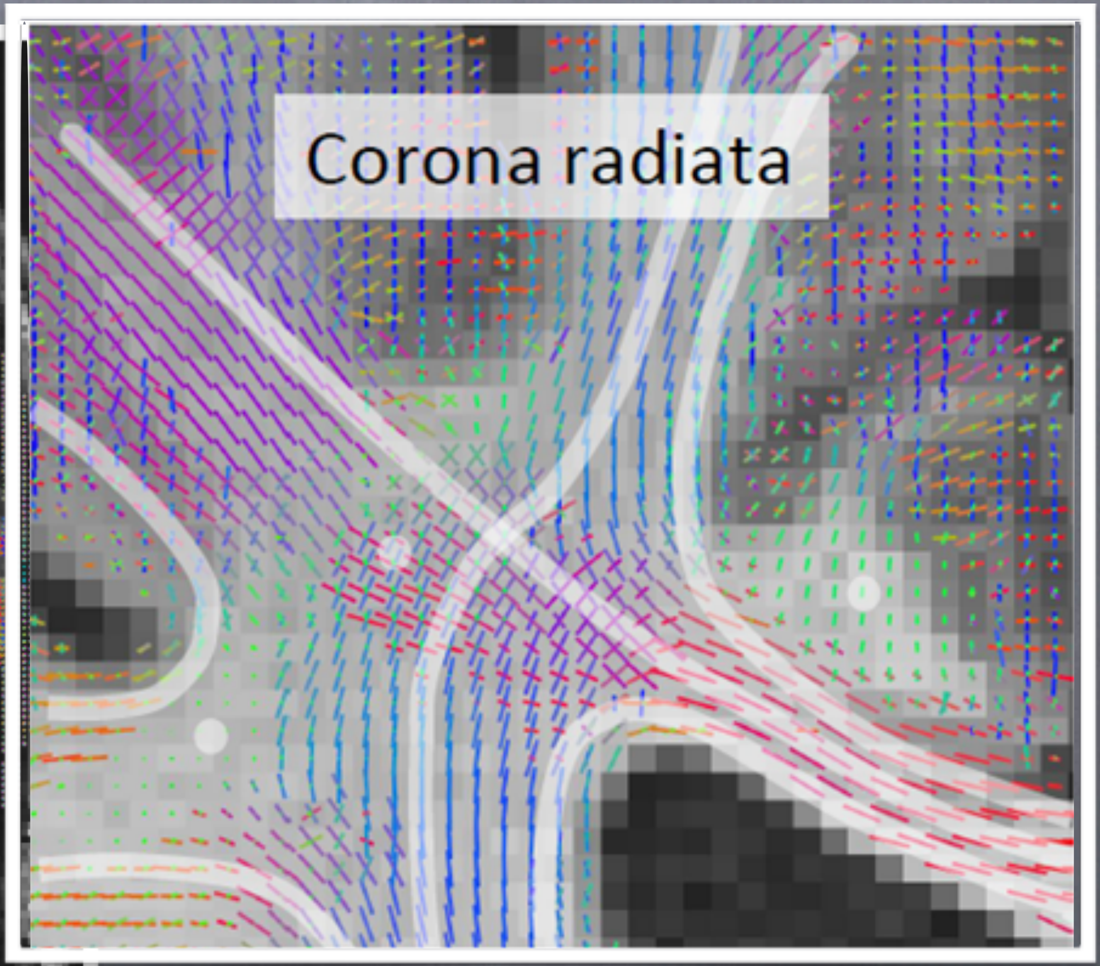

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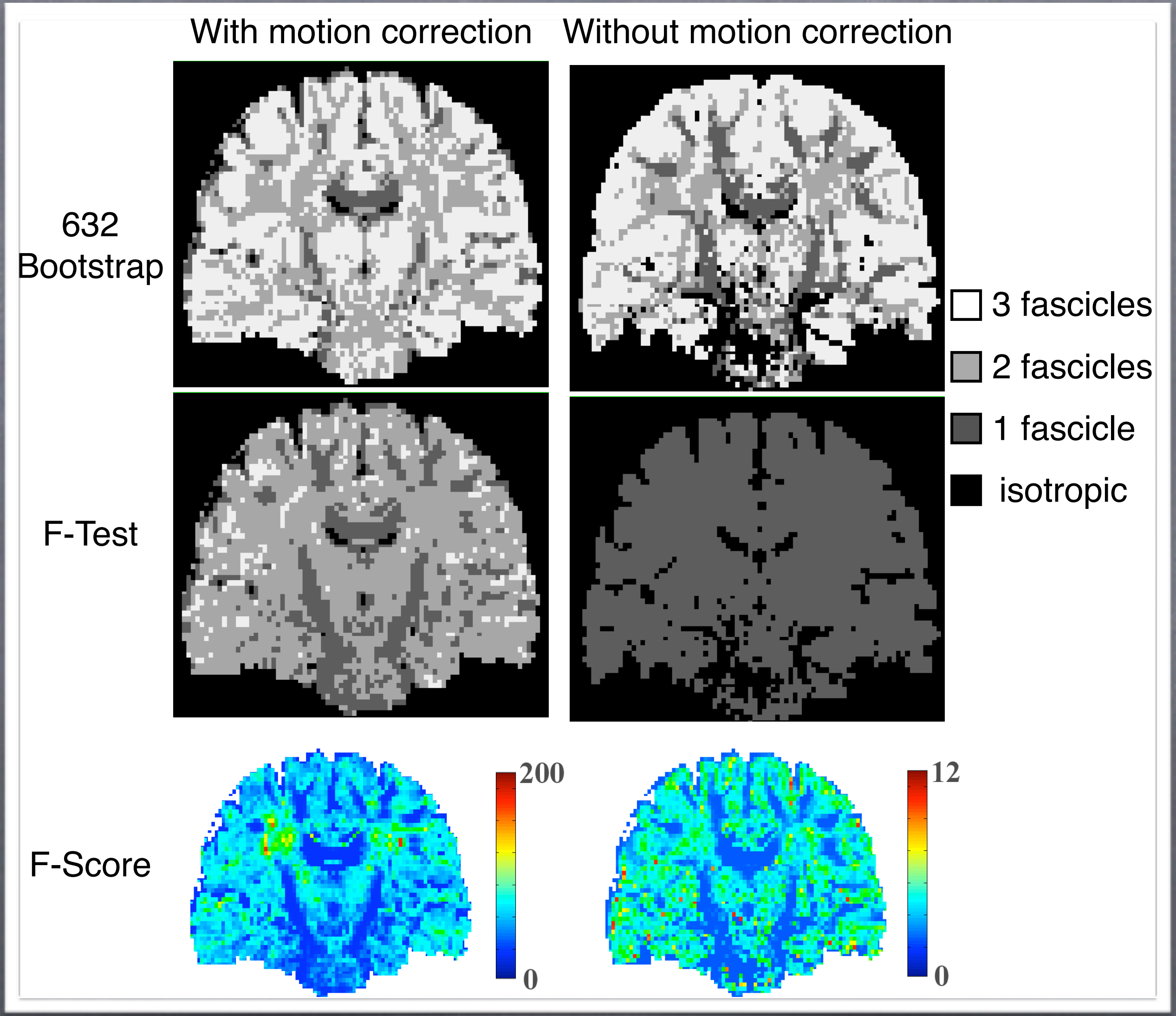

Scherrer, Taquet and Warfield, IPMI, 2013

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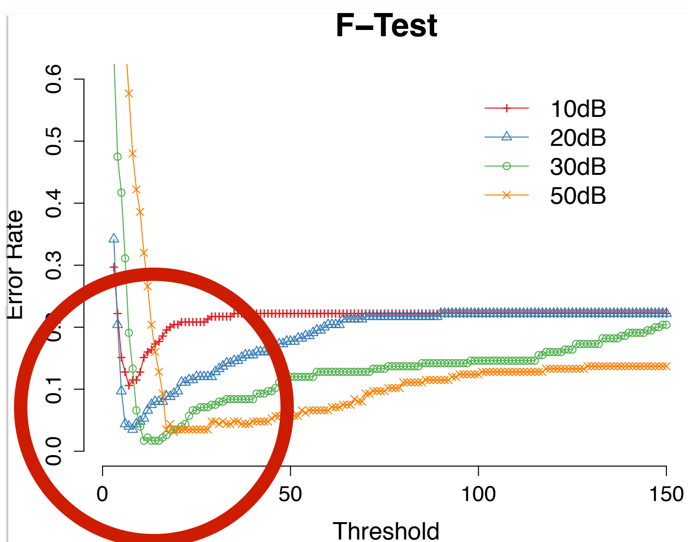
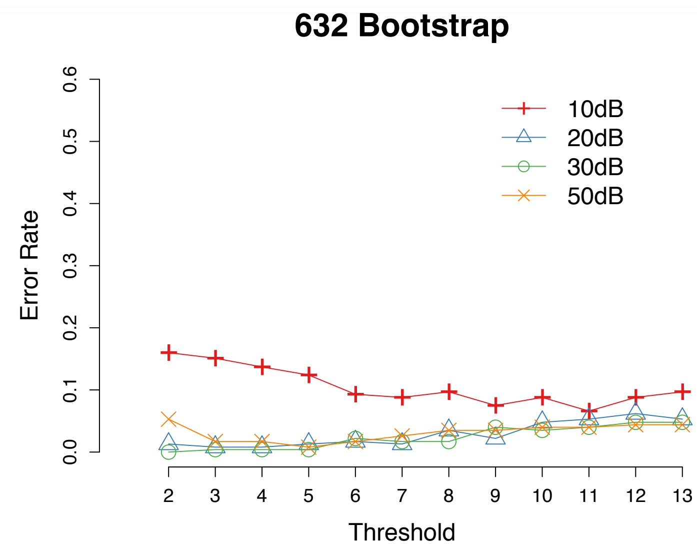


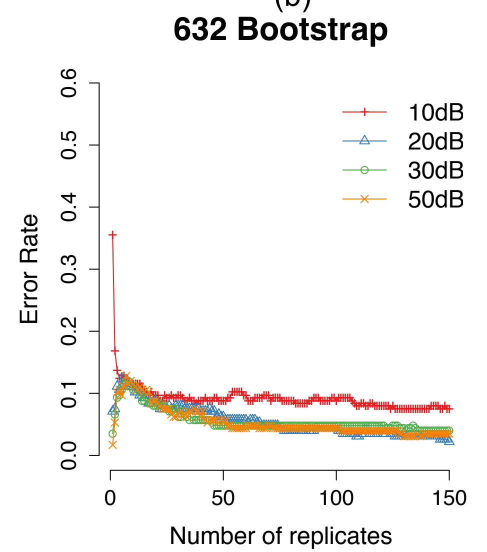
(a)



(b)

		10dB	20dB	30dB	50dB
overall minimum	F-Test	24 (10%)	8 (3%)	4 (2%)	7 (3%)
overall minimum	632 Bootstrap	**15 (7%)**	**2 (0.9%)**	**0 (0%)**	**2 (0.9%)**
single threshold	F-Test	44 (19%)	20 (9%)	6 (3%)	8 (4%)
single threshold	632 Bootstrap	**20 (9%)**	**3 (1%)**	**4 (2%)**	**6 (3%)**

(c)



(d)

Scherrer, Taquet and Warfield, IPMI, 2013

New assets and capabilities to conduct population studies of the brain microstructure

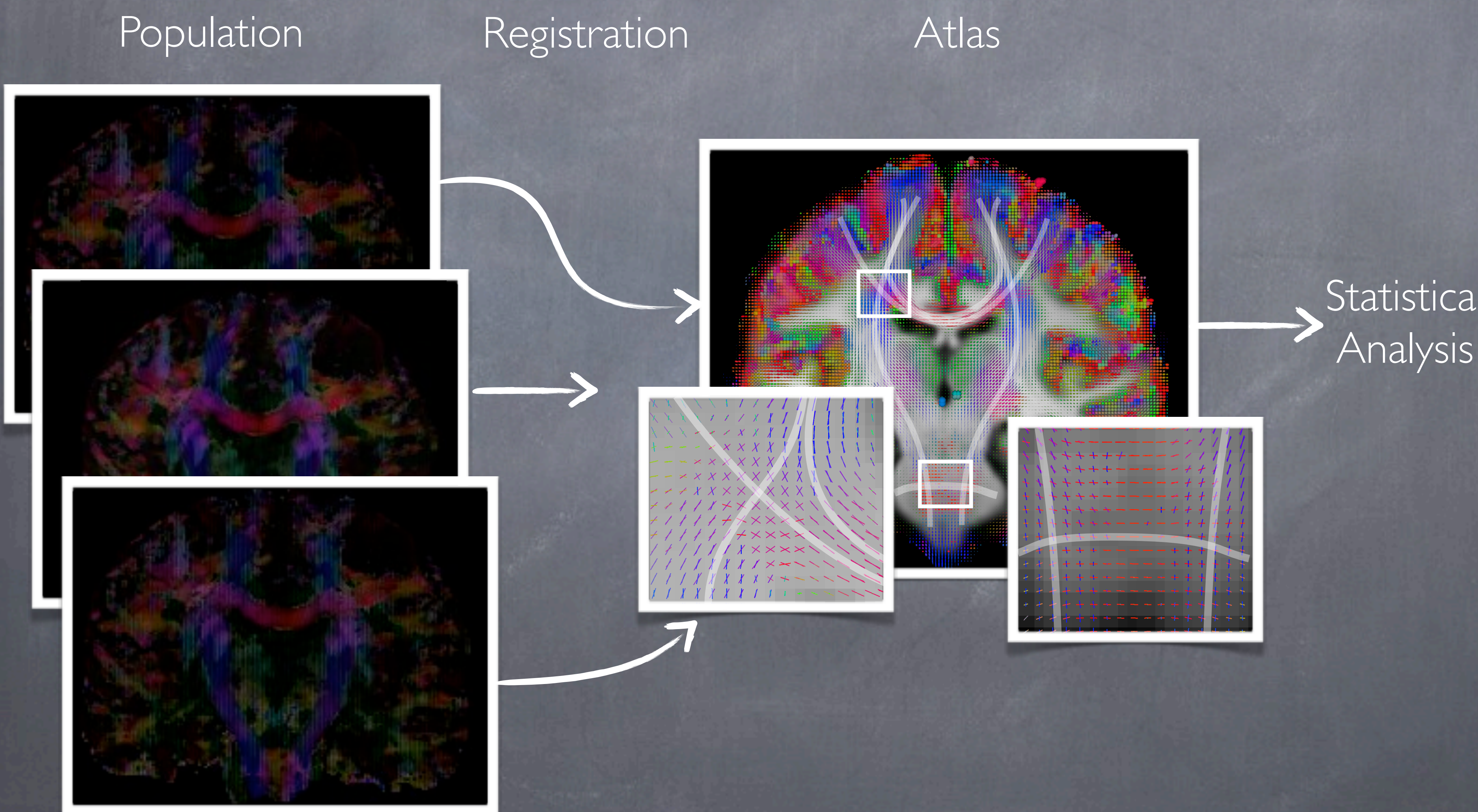
1. Selection of the appropriate model

2. **Registration and atlas construction**

3. Statistical analysis of microstructure

4. Estimation from single b-value data

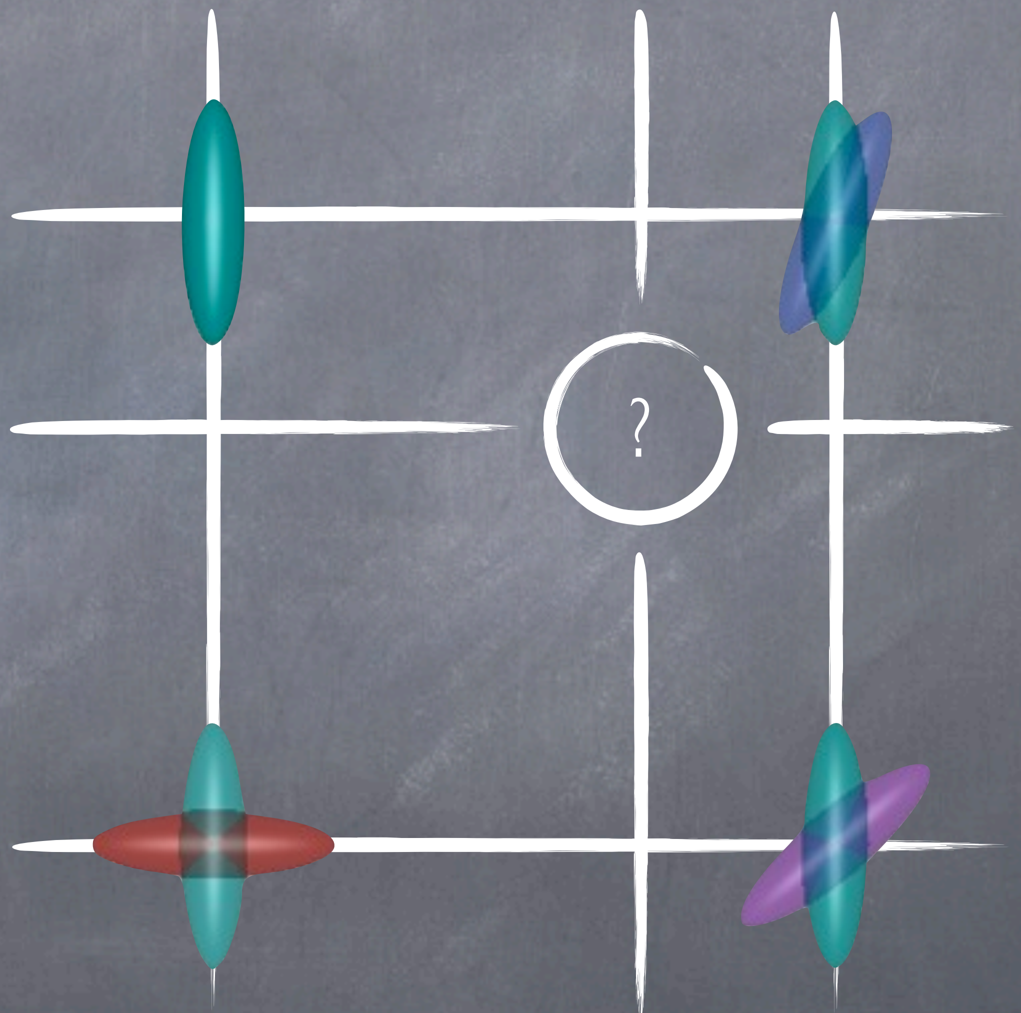
Registration and atlas construction are at the heart of population studies



Taquet et al., IEEE TMI, in press, 2013

Registration and atlasing require specific operations

Interpolation

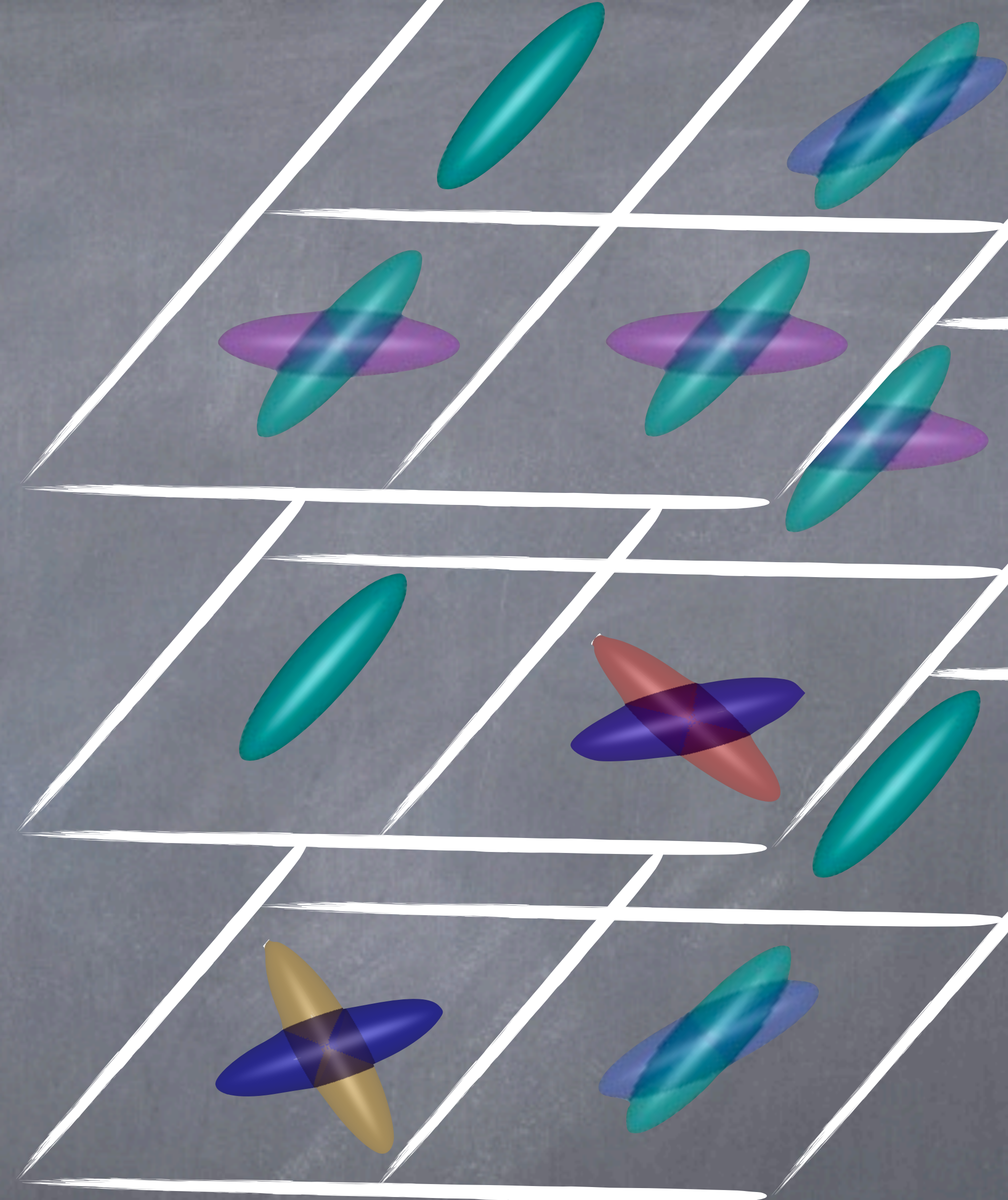


Taquet et al., IEEE TMI, in press, 2013

Registration and atlasing require specific operations

Interpolation

Averaging



Taquet et al., IEEE TMI, in press, 2013

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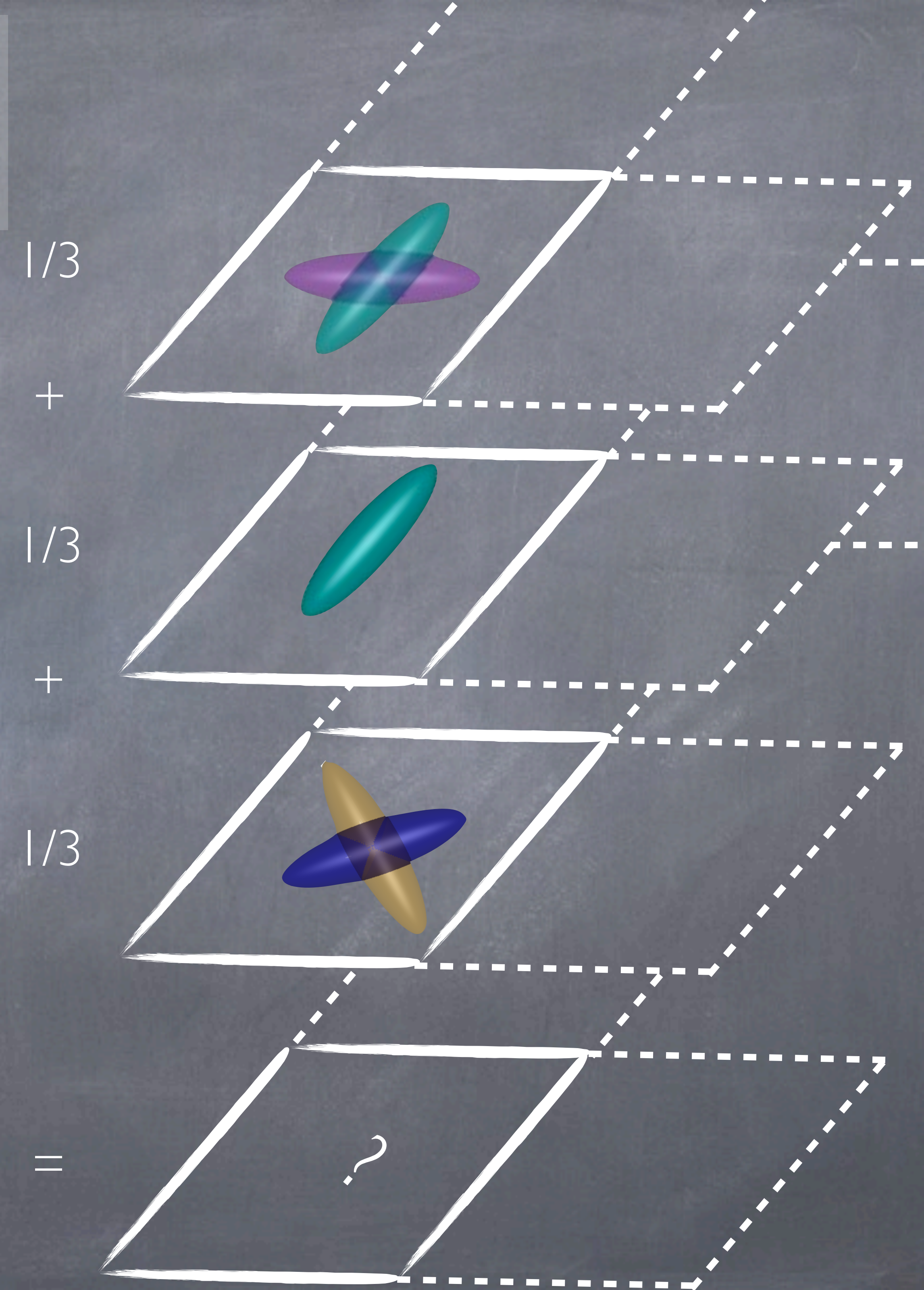


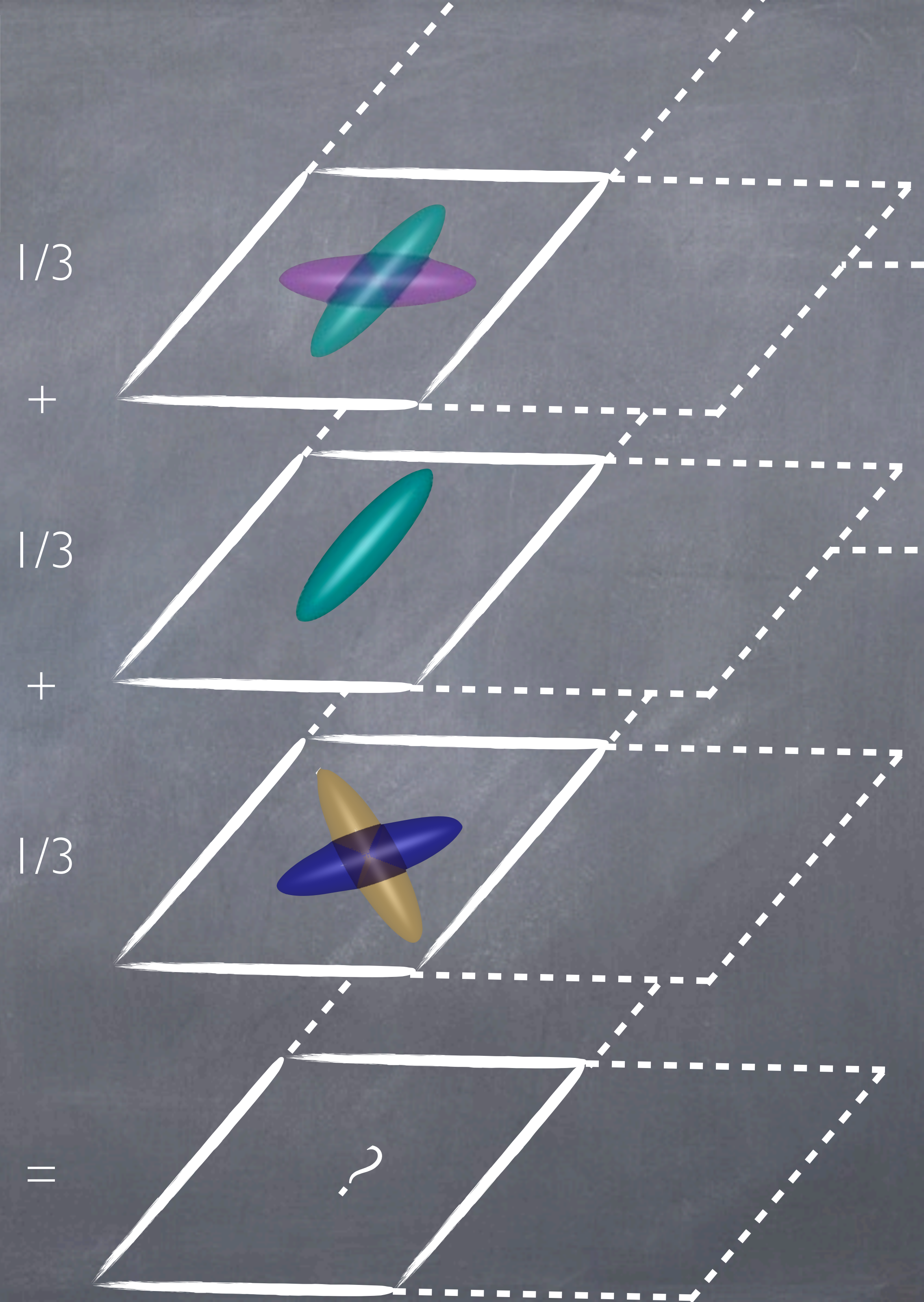
Taquet et al., IEEE TMI, in press, 2013

Registration and atlasing require specific operations

Interpolation

Averaging

Smoothing



Taquet et al., IEEE TMI, in press, 2013

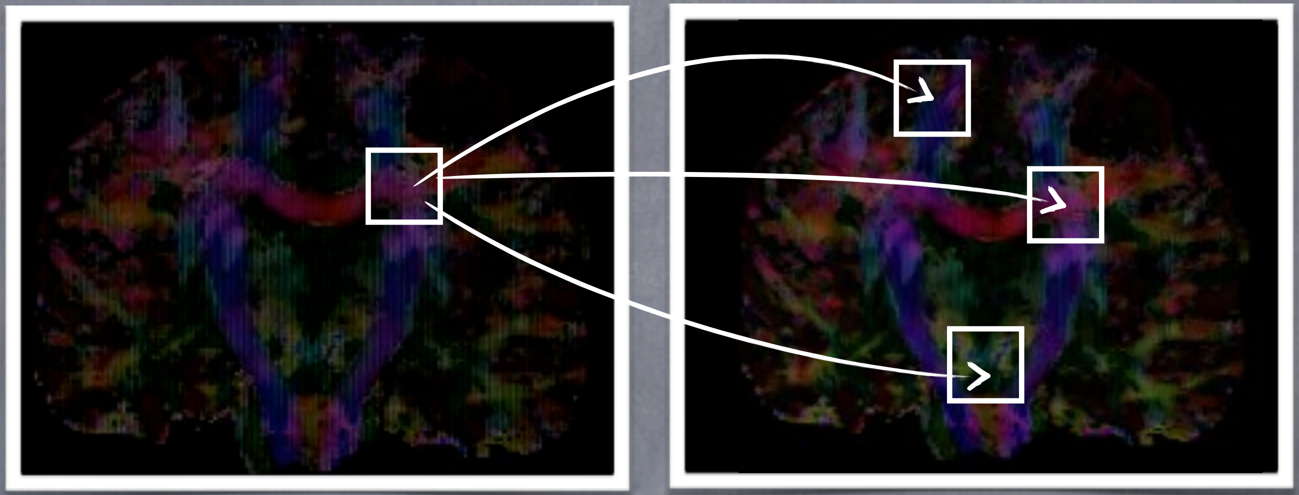
Registration and atlasing require specific operations

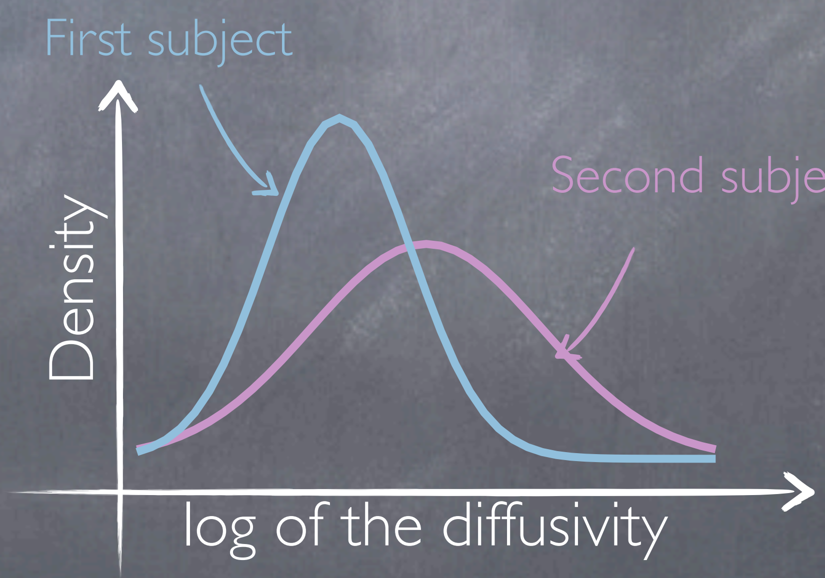
Interpolation

Averaging

Smoothing

Similarity metric

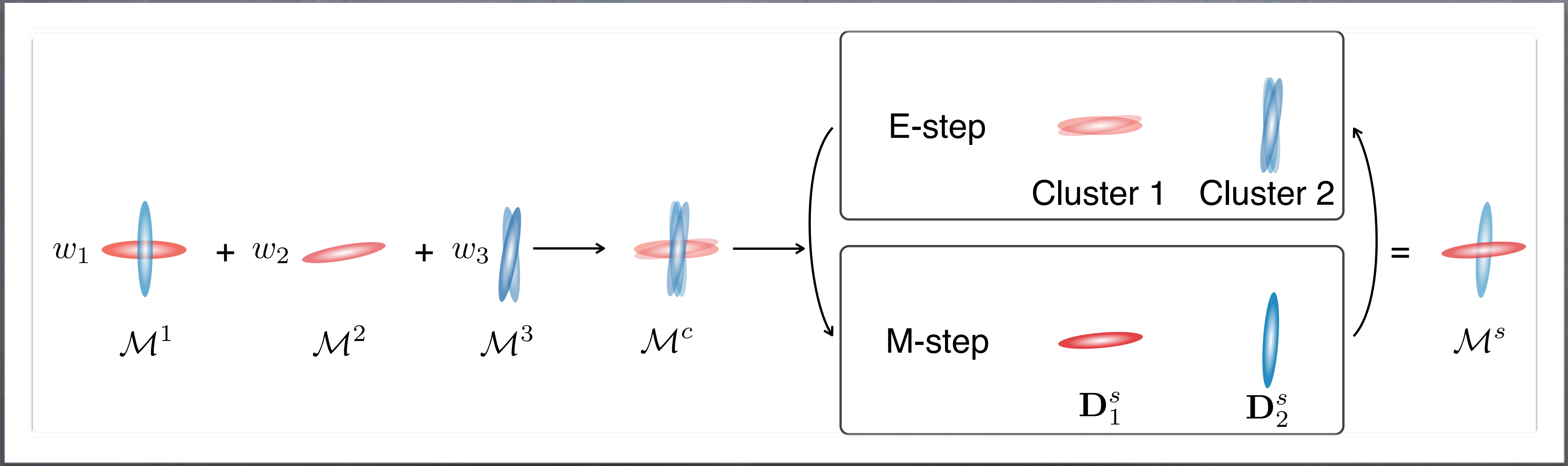




Diffusivities differ between subjects

Taquet et al., IEEE TMI, in press, 2013

We proposed a mathematical framework that includes image analysis operators for multi-fascicle models



Minimization of the
cumulative differential relative entropy

Taquet et al., IEEE TMI, in press, 2013

We proposed a mathematical framework that includes image analysis operators for multi-fascicle models

Generalized correlation coefficient

$$\rho(R,S) = \left\langle \frac{R-\mu_R}{||R-\mu_R||}, \frac{S-\mu_S}{||S-\mu_R||} \right\rangle$$

$$\rho(R,S) = m\left(\frac{R-m(R,T)T}{n_m(R-m(R,T)T)}, \frac{S-m(S,T)T}{n_m(S-m(S,T)T)} \right)$$

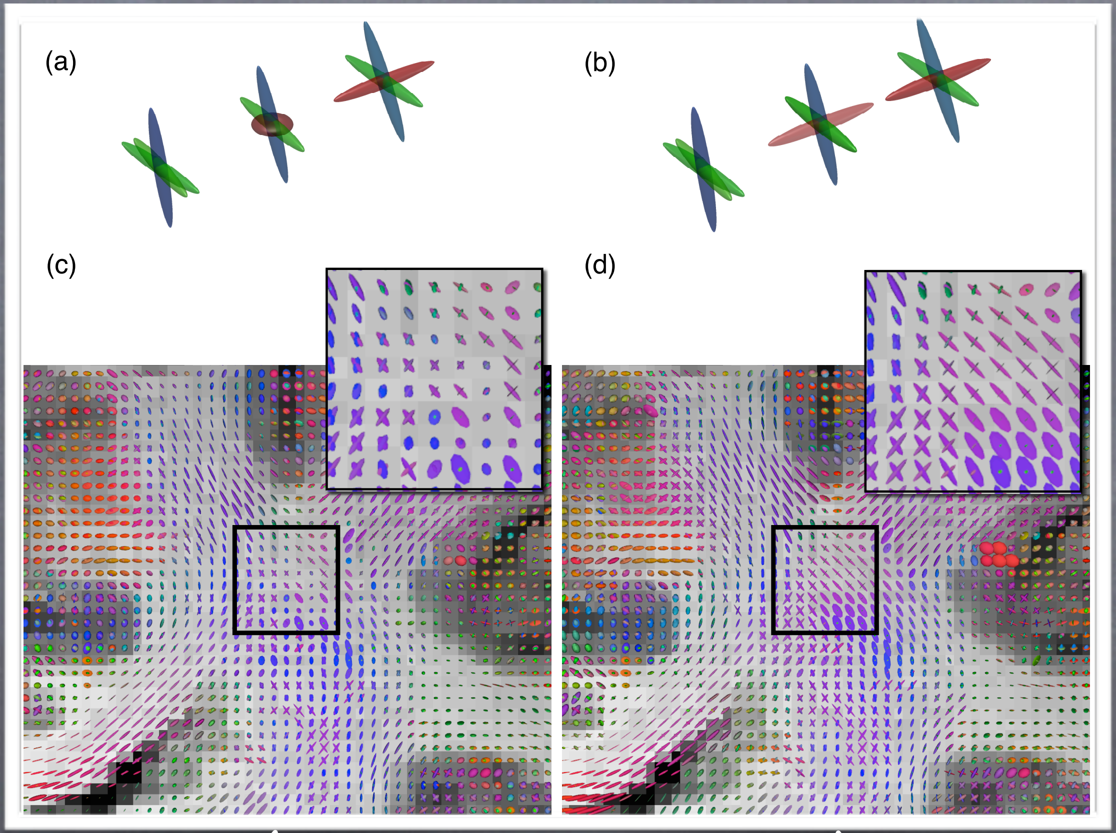
$$m(R,S) = \sum_{x\in\Omega} \max_{\pi} \sum_{i=1}^{N} f_i g_{\pi(i)} \left\langle \log \mathbf{D}_i^R, \log \mathbf{D}_{\pi(i)}^S \right\rangle$$

invariant under linear transformations of the log-eigenvalues

Taquet et al., IEEE TMI, in press, 2013

Our framework enables accurate registration and atlas construction from multi-fascicle models

Experiment 1: Interpolation Error



Multi-channel

Our approach

Taquet et al., IEEE TMI, in press, 2013

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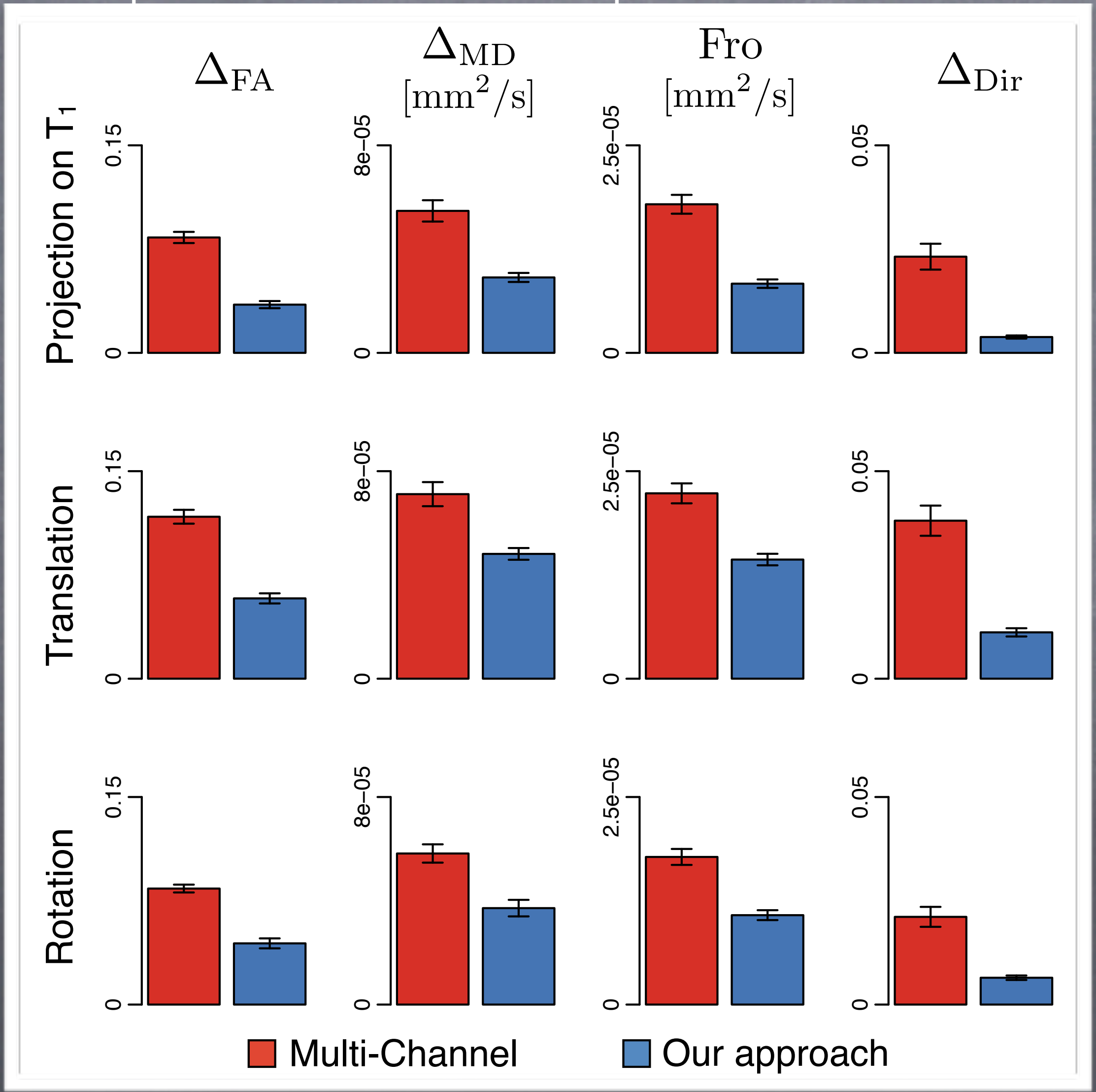

Taquet et al., IEEE TMI, in press, 2013

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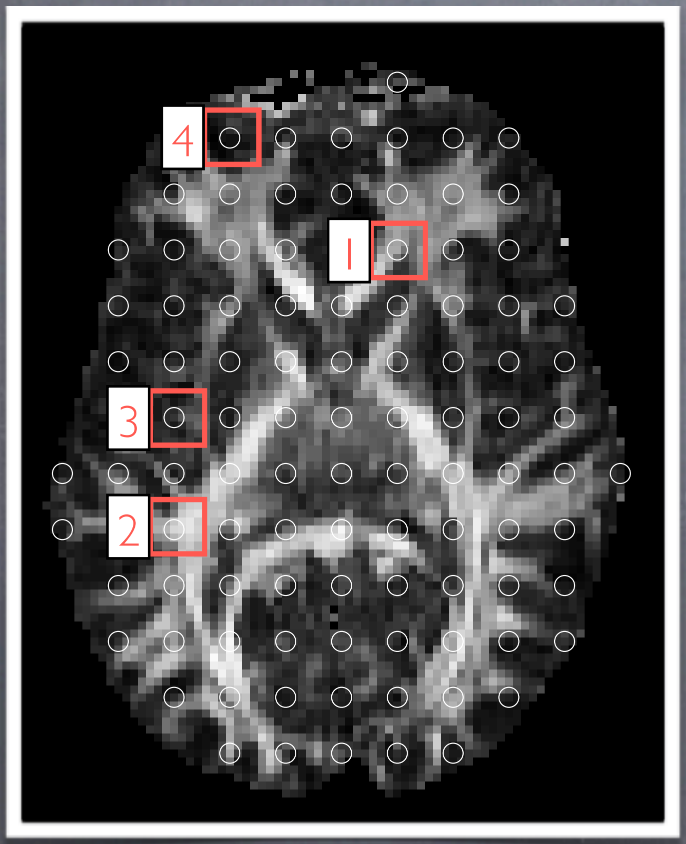
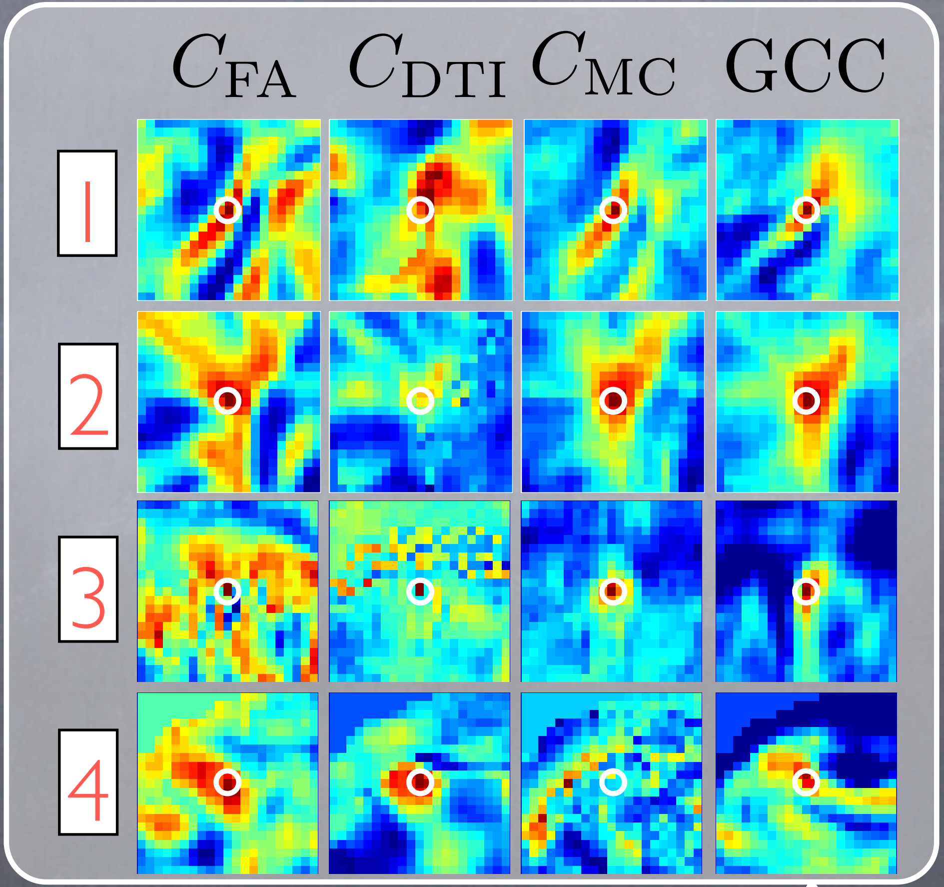
Experiment 2: Scan-Rescan to test the similarity metric

Saliency maps





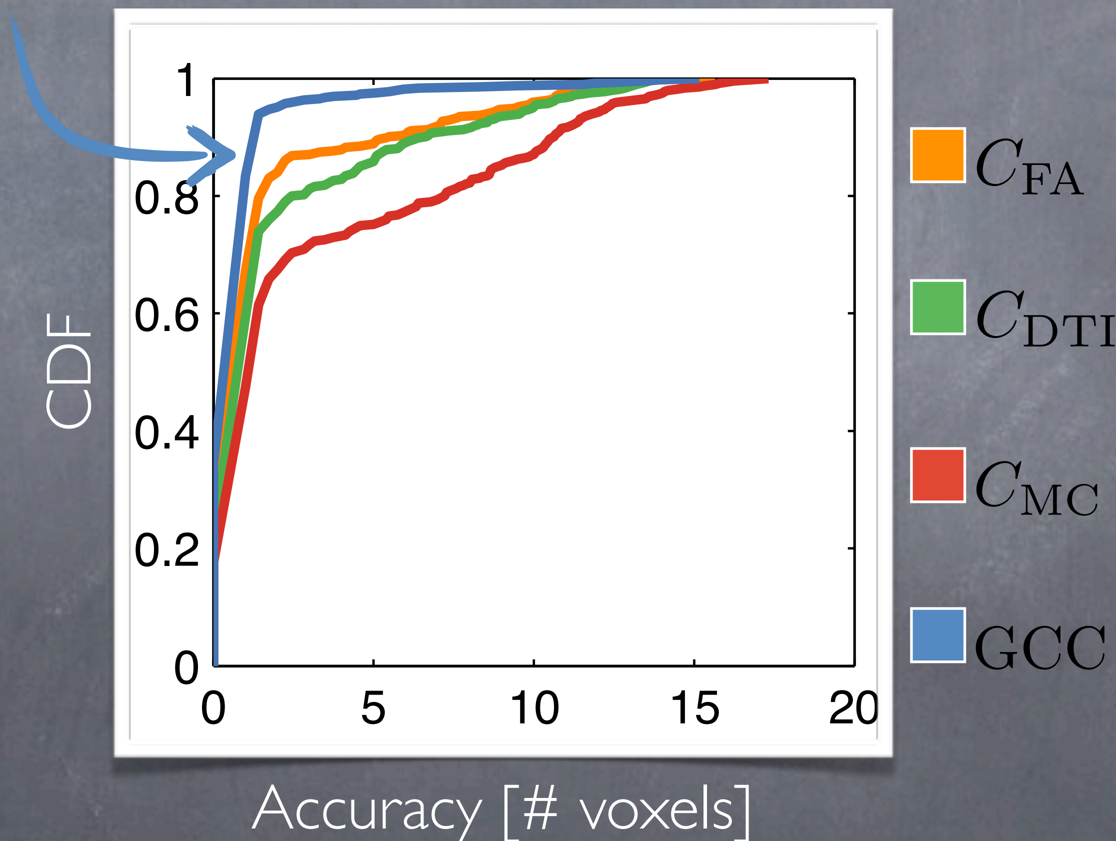
Our metric

Taquet et al., IEEE TMI, in press, 2013

Our framework enables accurate registration and atlas construction from multi-fascicle models

Experiment 2: Scan-Rescan to test the similarity metric

Our metric leads to significantly smaller registration errors

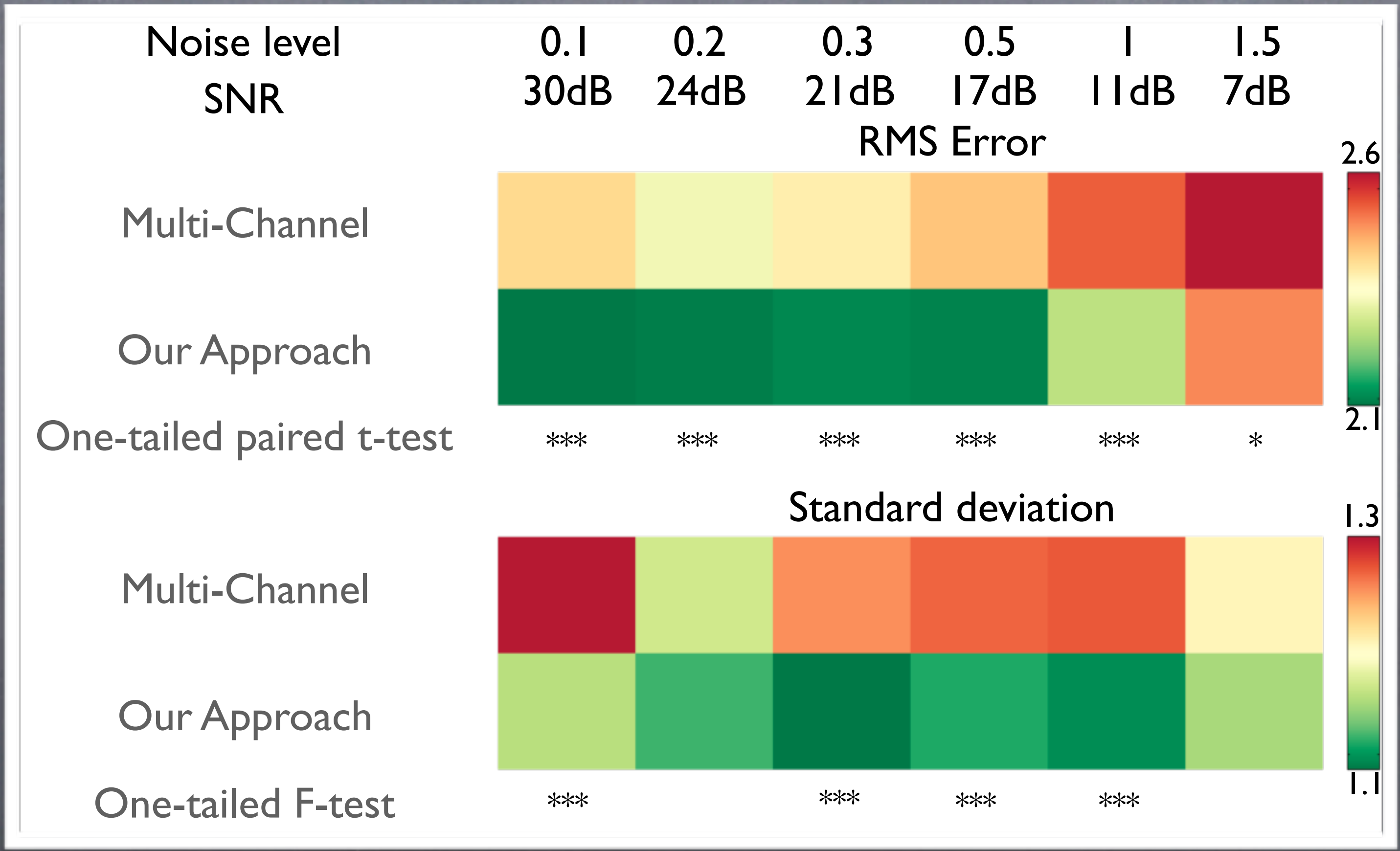


Taquet et al., IEEE TMI, in press, 2013

Our framework enables accurate registration and atlas construction from multi-fascicle models

Experiment 3: 1,440 synthetic field registrations

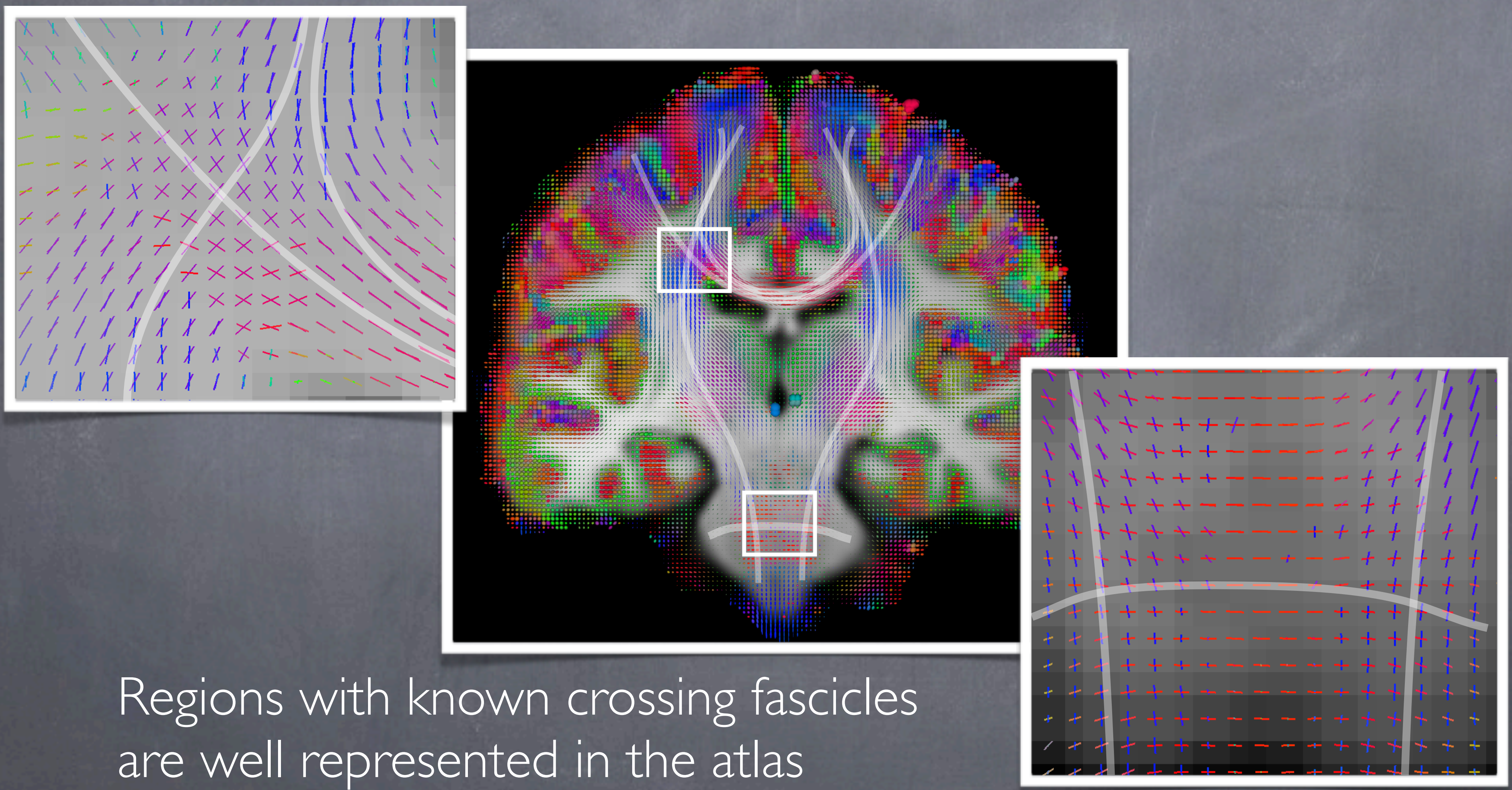
Our method performs significantly better



Taquet et al., IEEE TMI, in press, 2013

Our framework enables accurate registration and atlas construction from multi-fascicle models

Our framework enables the construction of a multi-fascicle atlas



Regions with known crossing fascicles
are well represented in the atlas

Taquet et al., IEEE TMI, in press, 2013

New assets and capabilities to conduct population studies of the brain microstructure

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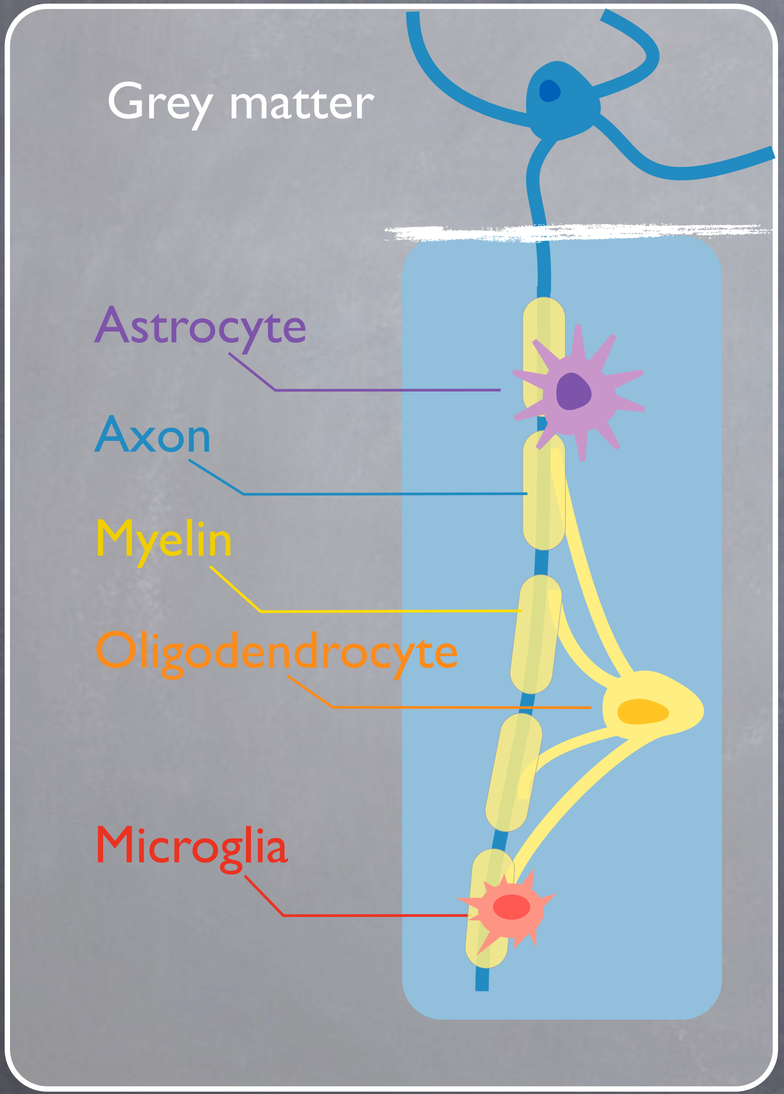
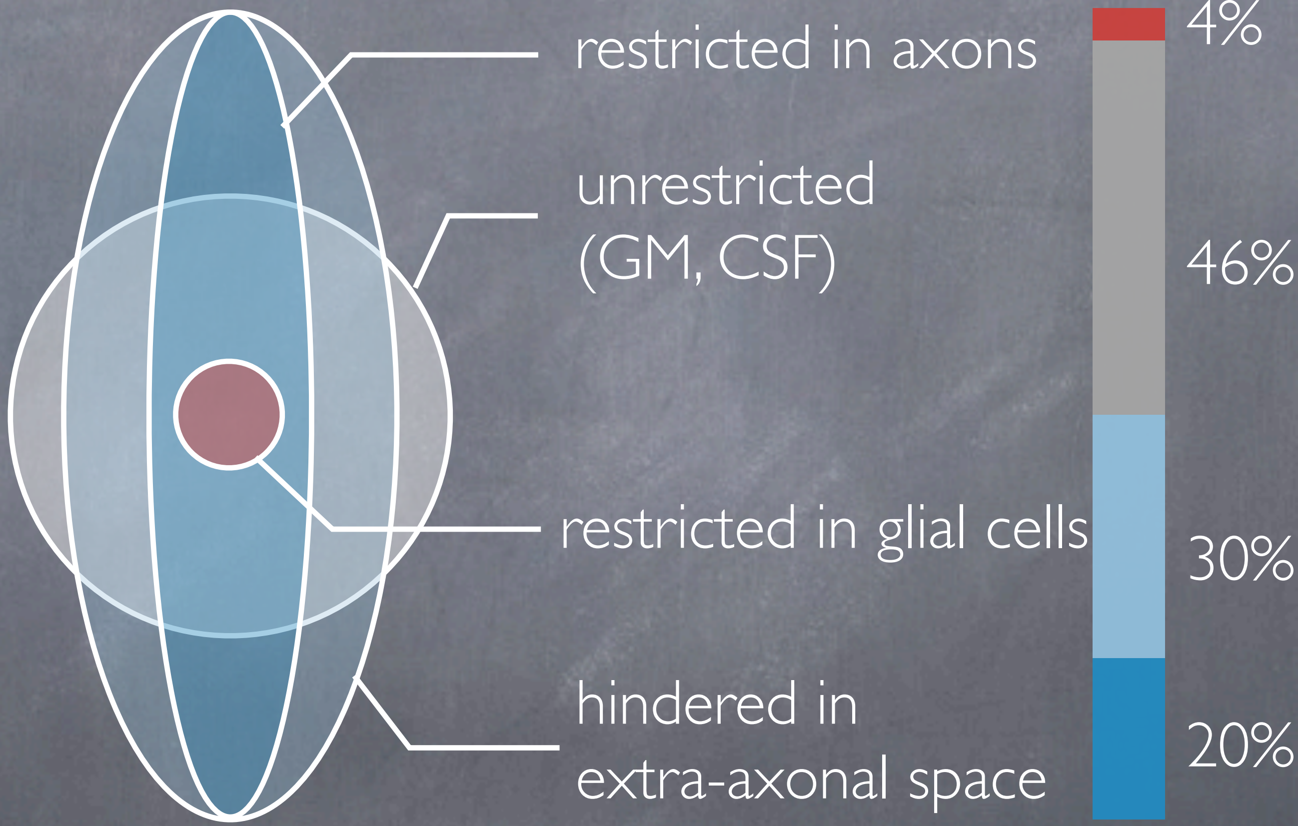
3. **Statistical analysis of microstructure**
4. Estimation from single b-value data

Features of the brain microstructure may relate to a particular fascicle or to the surrounding volume





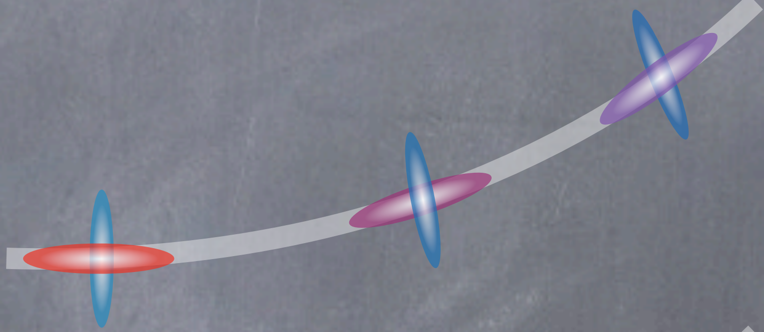
We proposed a system of two methods for the statistical analysis of microstructural features

Fascicle-based spatial statistics

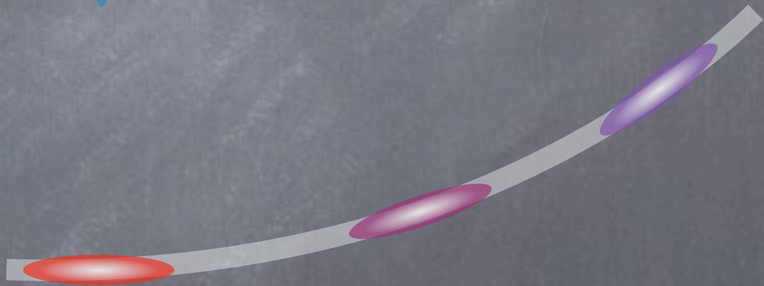
for properties related to fascicles

1. tractography

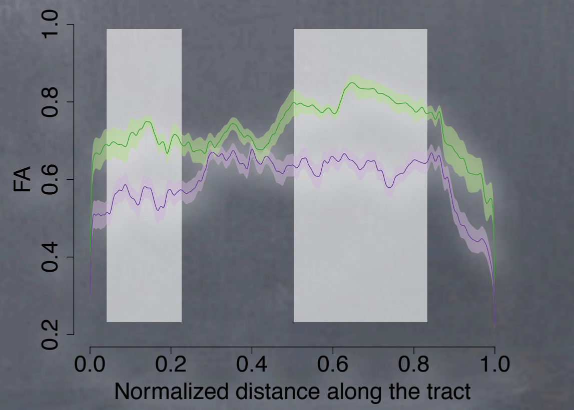
2. interpolation



3. selection



4. cluster-based statistics

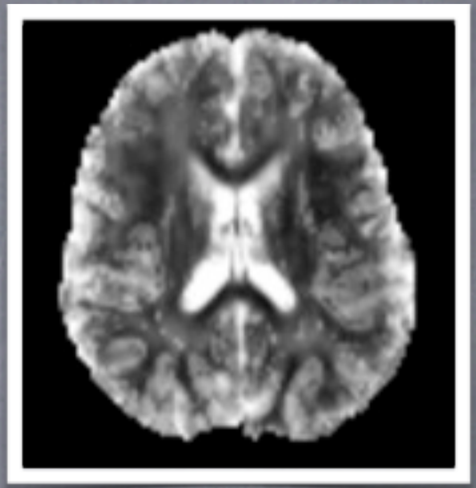


We proposed a system of two methods for the statistical analysis of microstructural features

Isotropic diffusion analysis

for properties related to volume

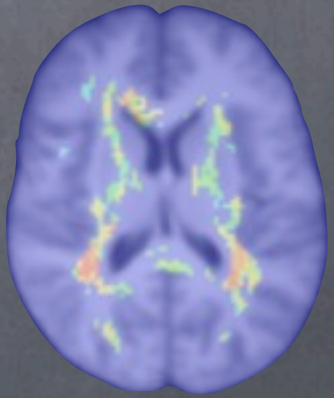
1. Feature extraction



2. Feature transformation

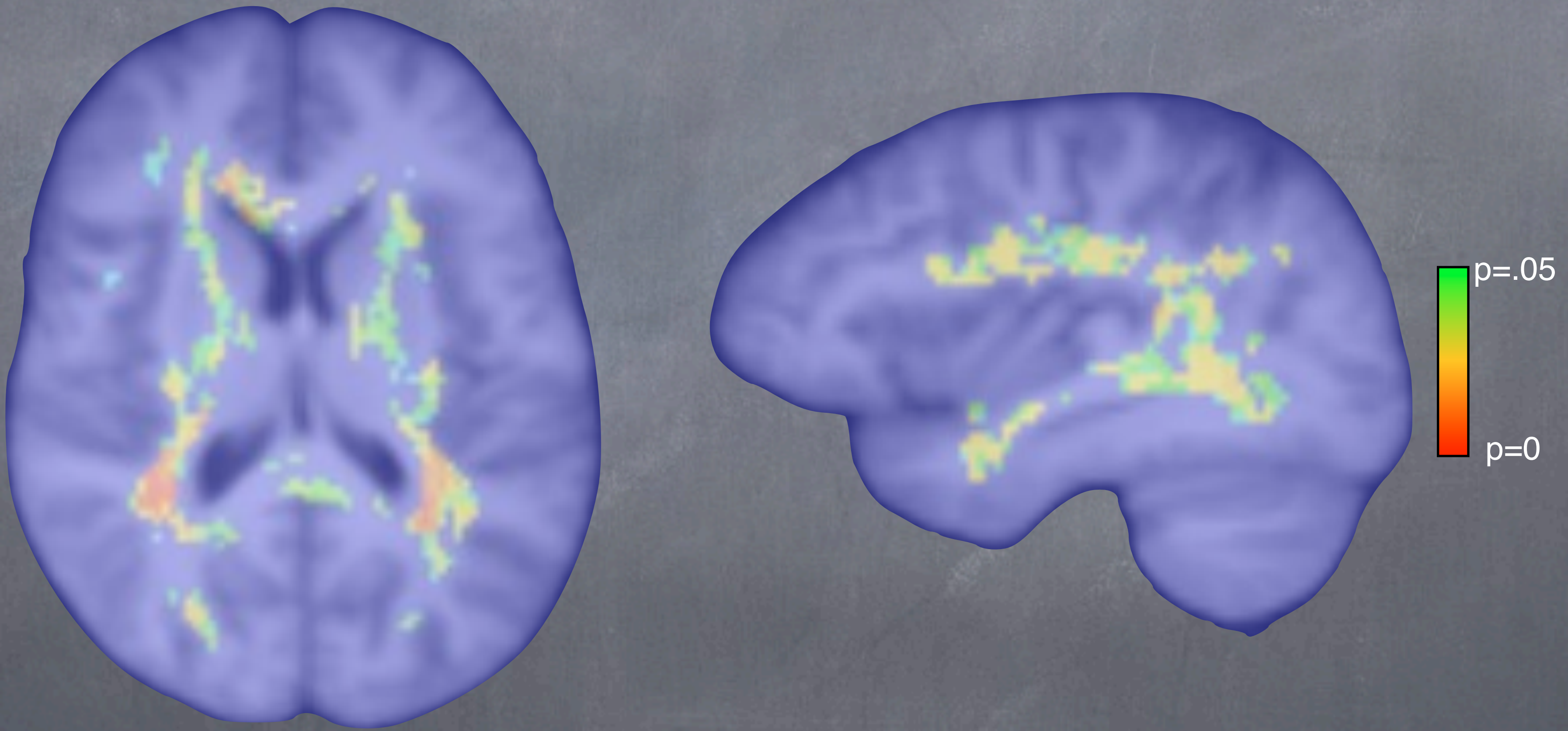
$$l_{\mathrm{iso}} = \operatorname{logit} f_{\mathrm{iso}}$$

3. cluster-based statistics



Our system detects differences between healthy controls and children with autism

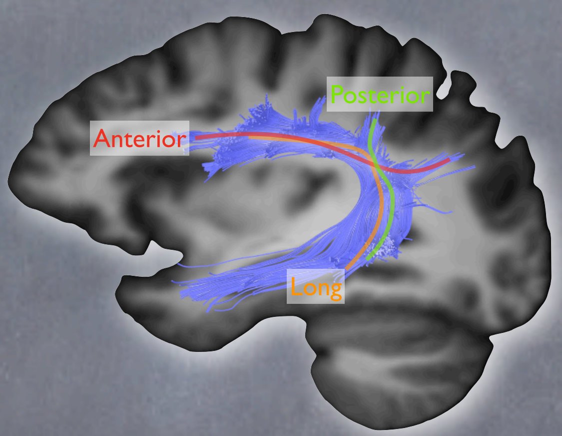
IDA reveals regions with abnormally high fraction of molecules diffusing freely, mostly in the dorsal language pathway.

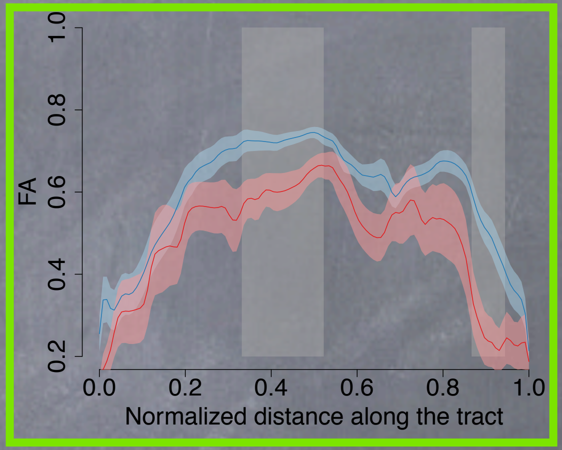


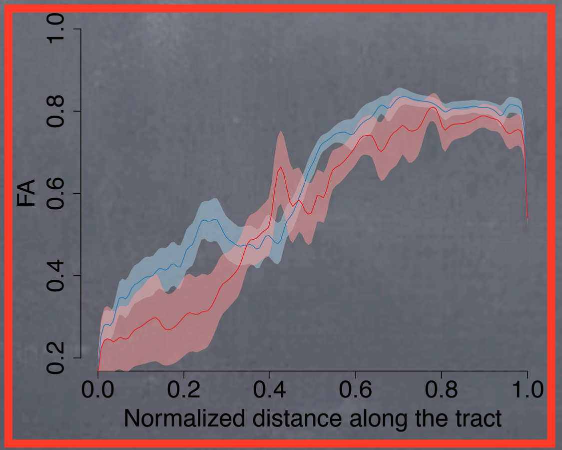
This finding may point to the hypothesis that autism results from an autoimmune response.

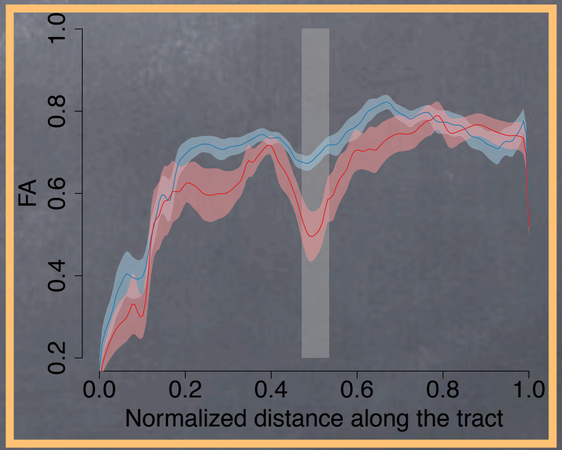
Our system detects differences between healthy controls and children with autism

FBSS reveals few clusters of significantly lower fractional anisotropy along the dorsal language pathway.





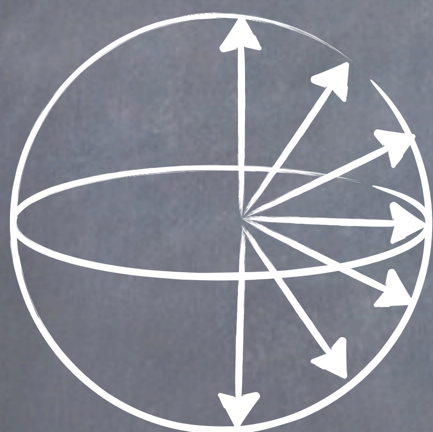




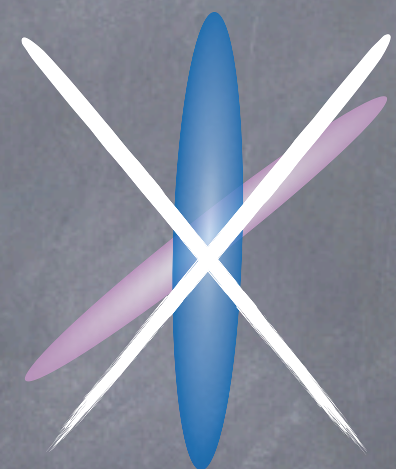
New assets and capabilities to conduct population studies of the brain microstructure

1. Selection of the appropriate model
2. Registration and atlas construction
3. Statistical analysis of microstructure
4. **Estimation from single b-value data**

Multi-fascicle models cannot be directly estimated from data at a single b-value

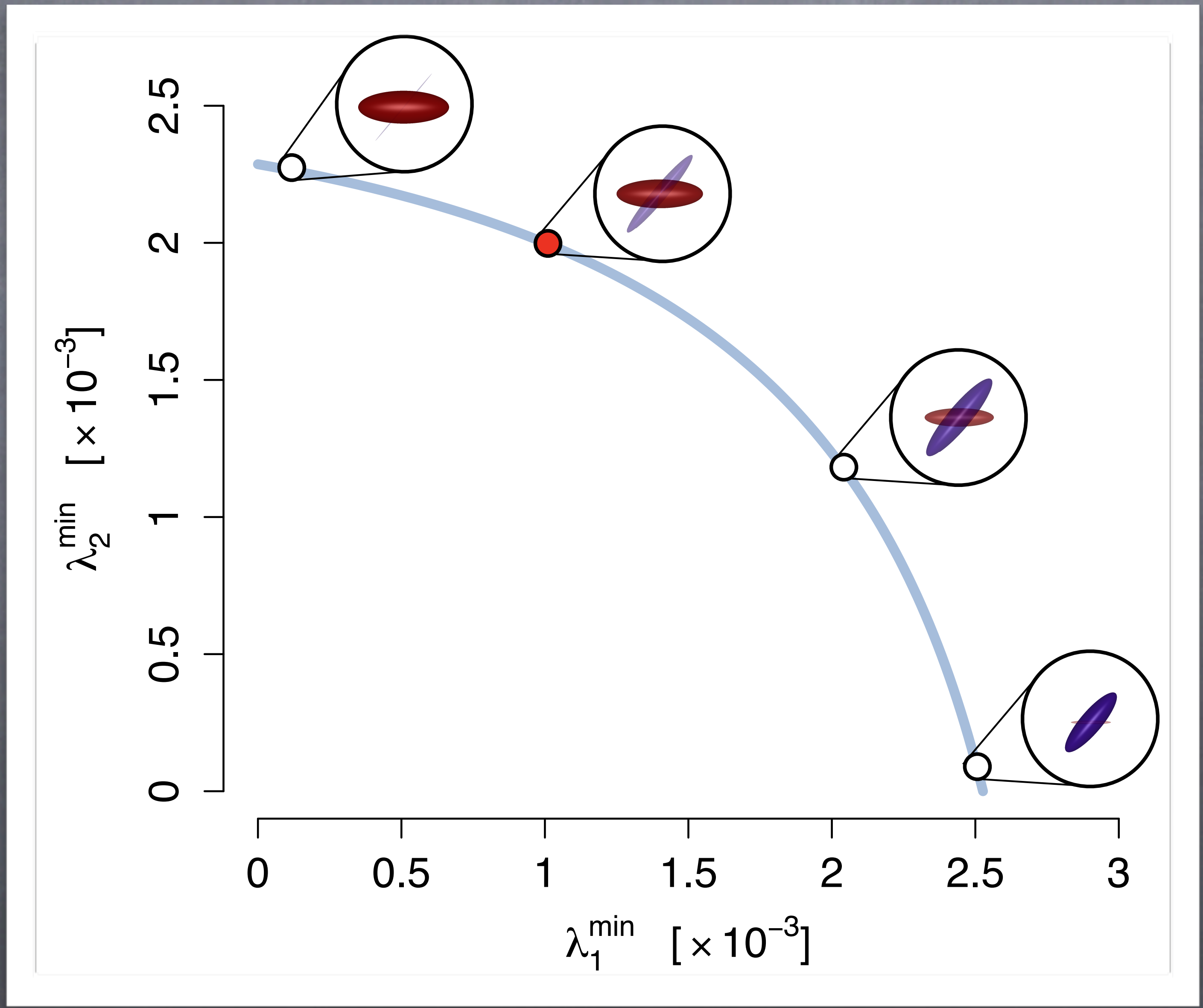


Single gradient shell



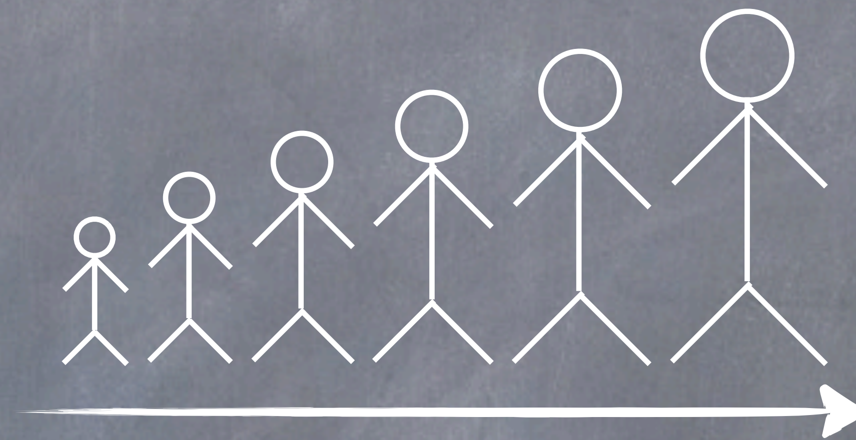
The problem is ill-posed

All those models produce the same signal



This may result in a waste of effort

PING



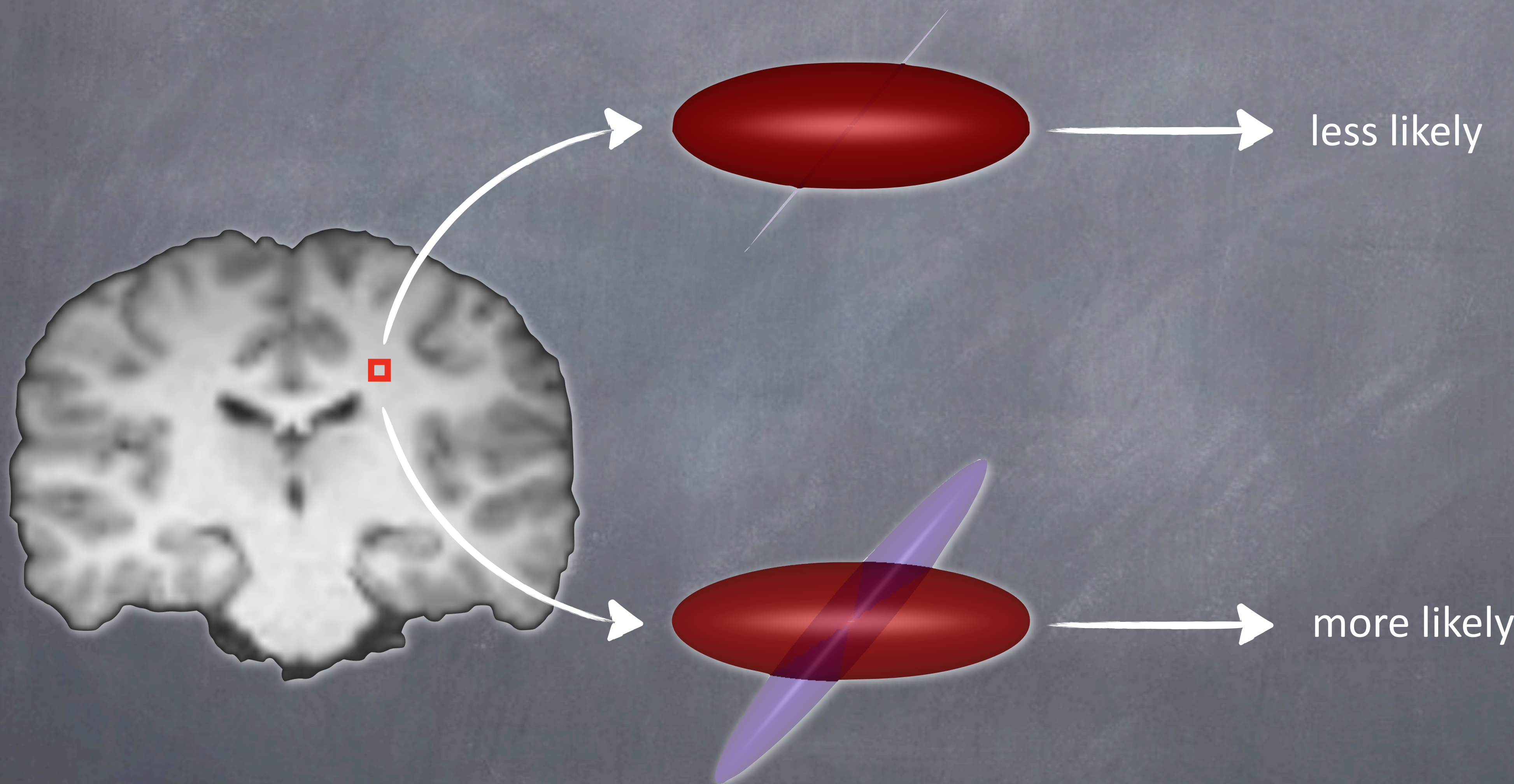
Age

Images and neuropsychological data from 1,400 children

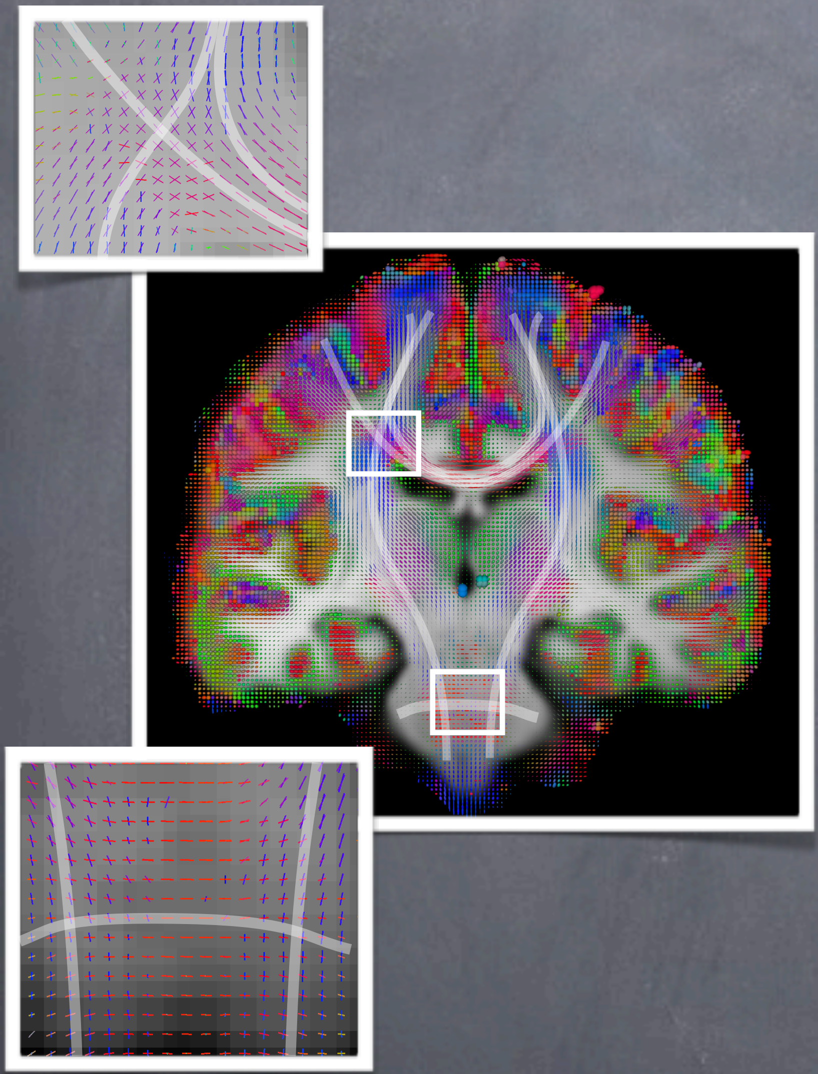
Acquisition Protocol

DWI
b-value: 1000 s/mm^2

Not all models are as likely given the known anatomy



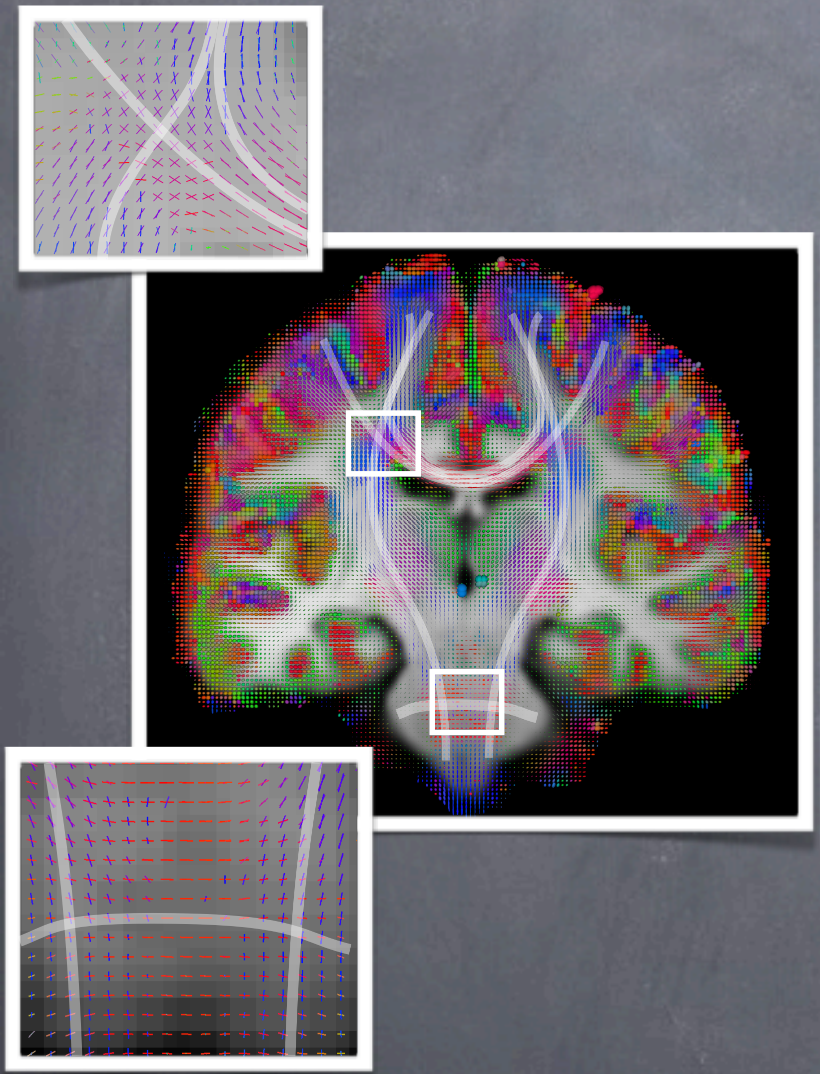
We proposed to incorporate prior information from other subjects scanned at multiple b-values



Each voxel of the atlas contains a parametric distribution of the parameters

Taquet et al., MICCAI, 2013

We proposed to incorporate prior information from other subjects scanned at multiple b-values



Each voxel of the atlas contains a parametric distribution of the parameters

$$p(\boldsymbol{f}, \boldsymbol{D}|\text{Data}) \propto \underbrace{p(\text{Data}|\boldsymbol{f}, \boldsymbol{D})}_{\text{Likelihood}}\underbrace{p(\boldsymbol{f}, \boldsymbol{D})}_{\text{Prior}}$$

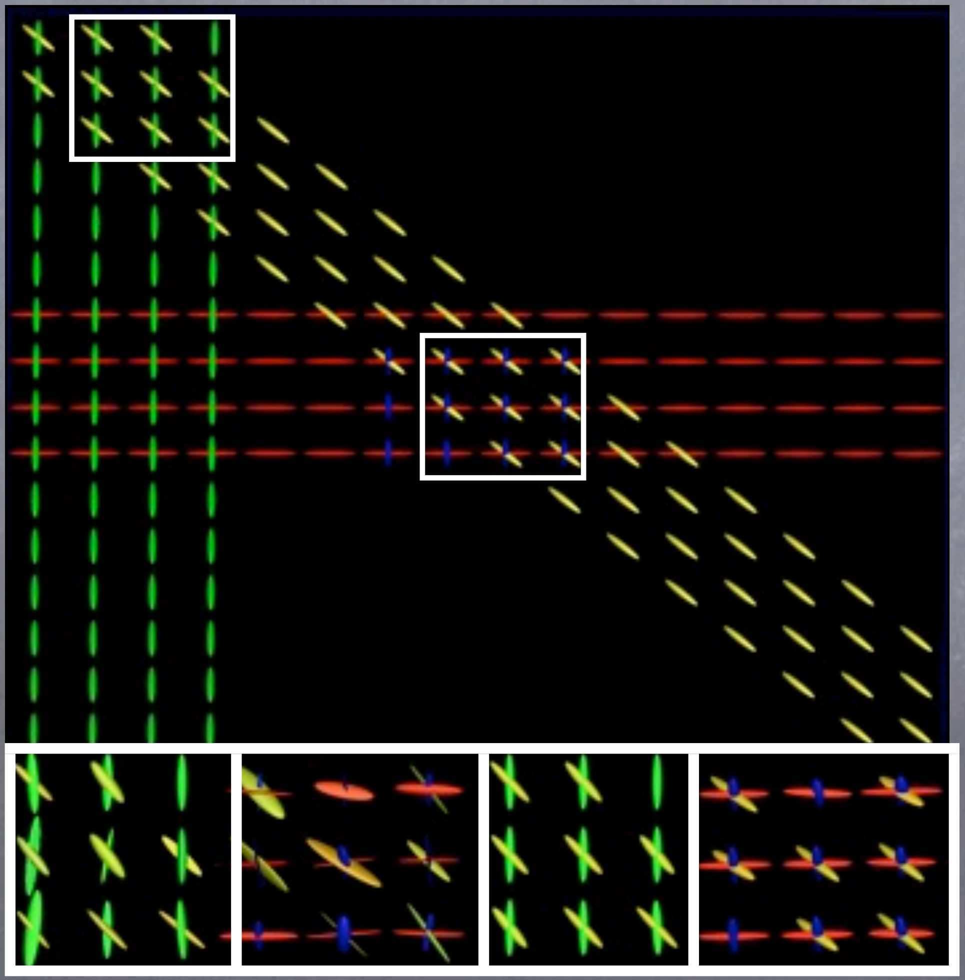
$p(\boldsymbol{f}, \boldsymbol{D})$ is informed by the atlas

$$p(\boldsymbol{f}, \boldsymbol{D}) = \underbrace{p(\boldsymbol{f})}_{\text{Dirichlet}}\underbrace{p(\boldsymbol{D})}_{\text{Matrix-variate Gaussian}}$$

Taquet et al., MICCAI, 2013

The population-informed prior significantly improves the accuracy of the estimation

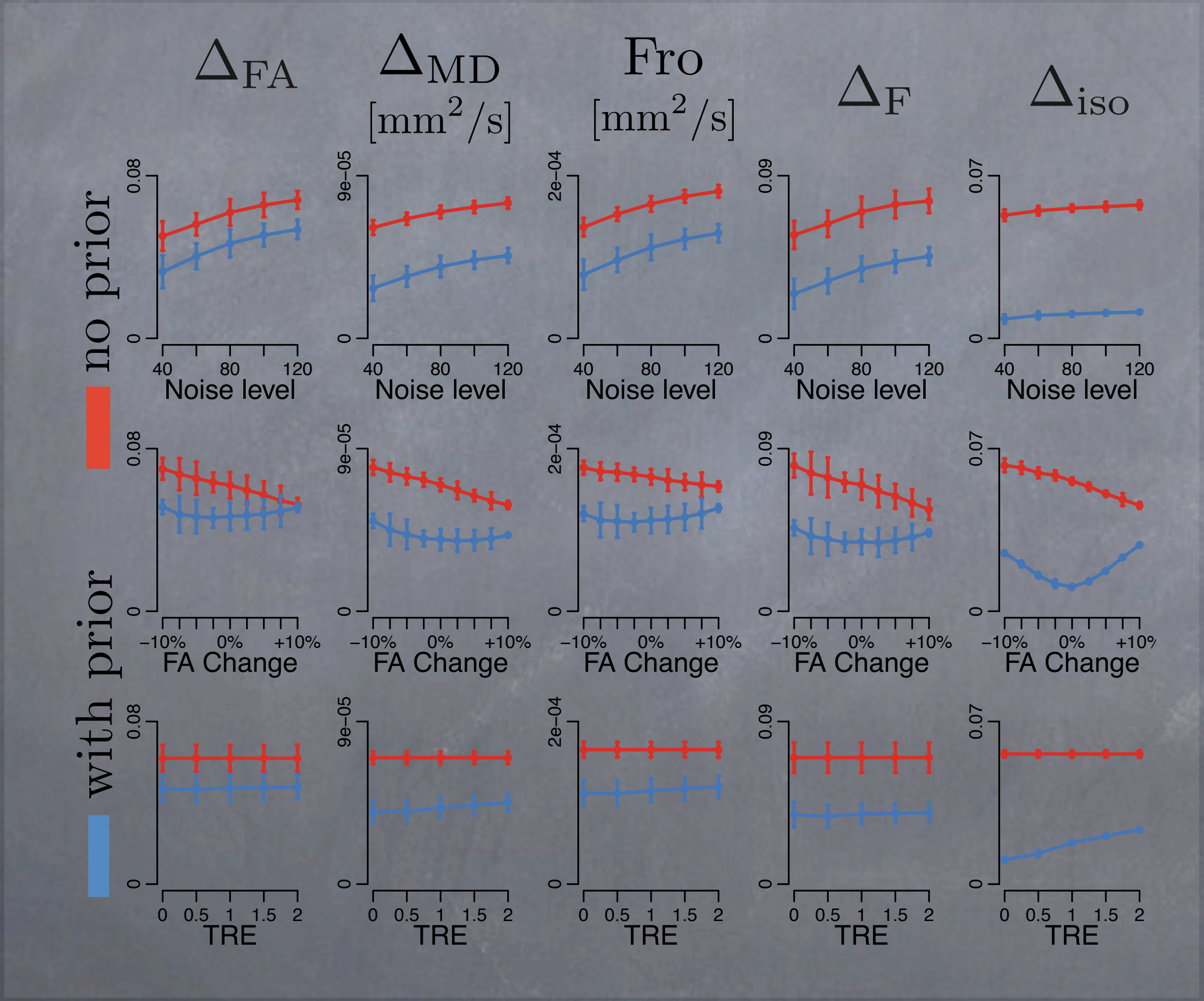
Experiment 1: Synthetic data



No prior With prior

The population-informed prior significantly improves the accuracy of the estimation

Experiment 1: Synthetic data



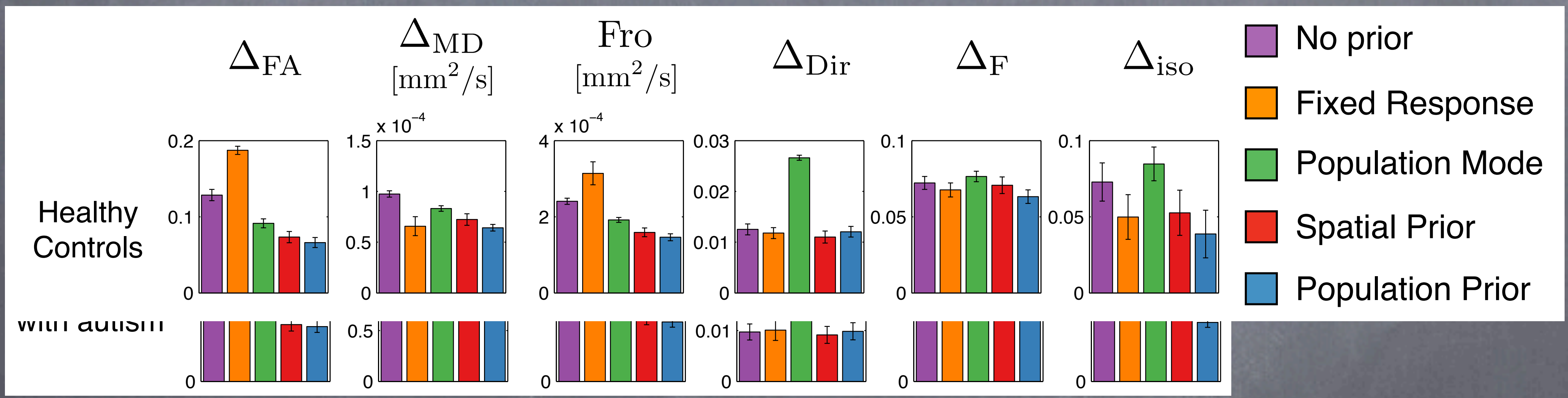
Under noise

Under group differences

Under registration error

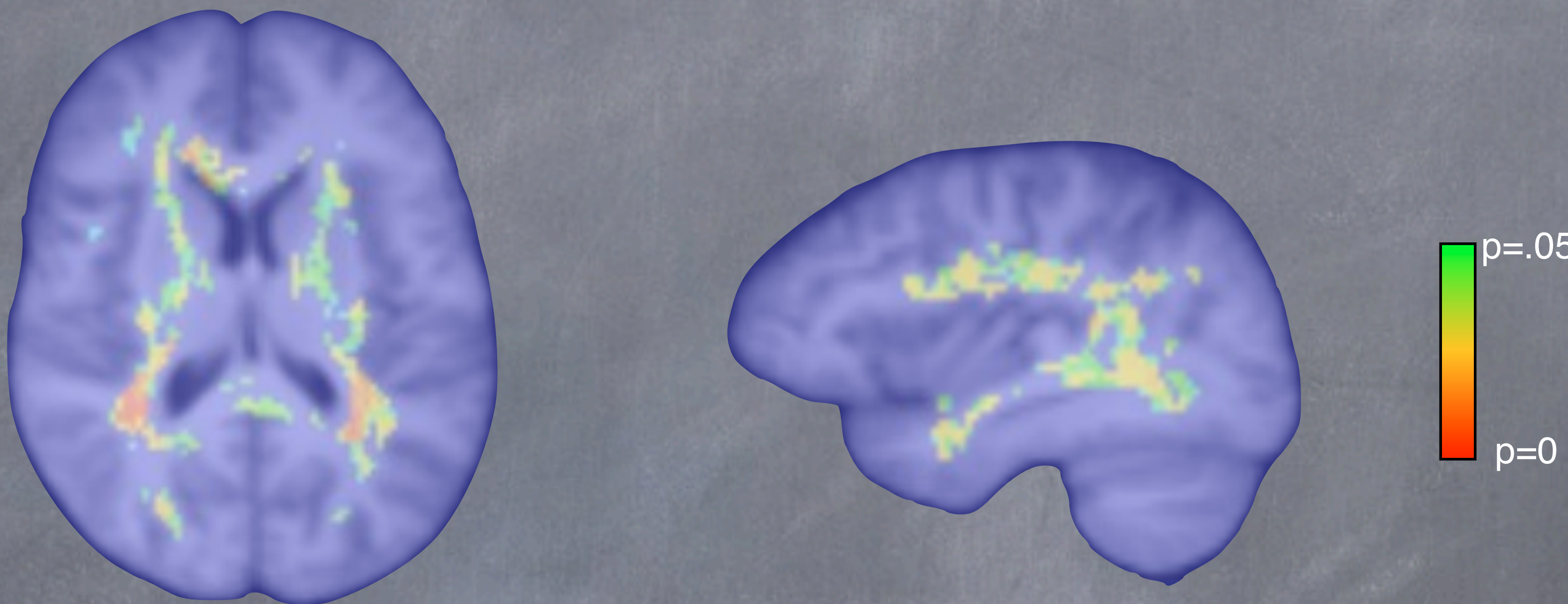
The population-informed prior significantly improves the accuracy of the estimation

Experiment 2: In-vivo data

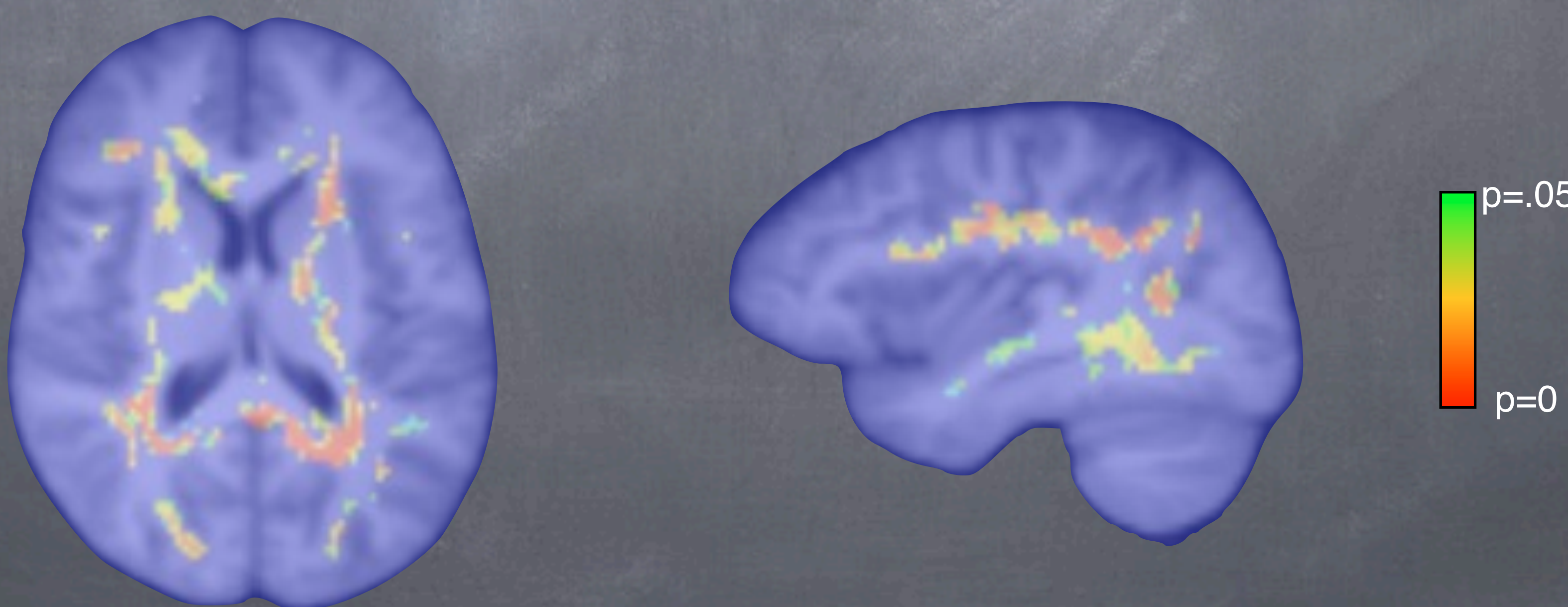


Detected group differences are remarkably close to those found with multiple b-values

With multiple b-values



With a single b-value



New assets and capabilities to conduct population studies of the brain microstructure

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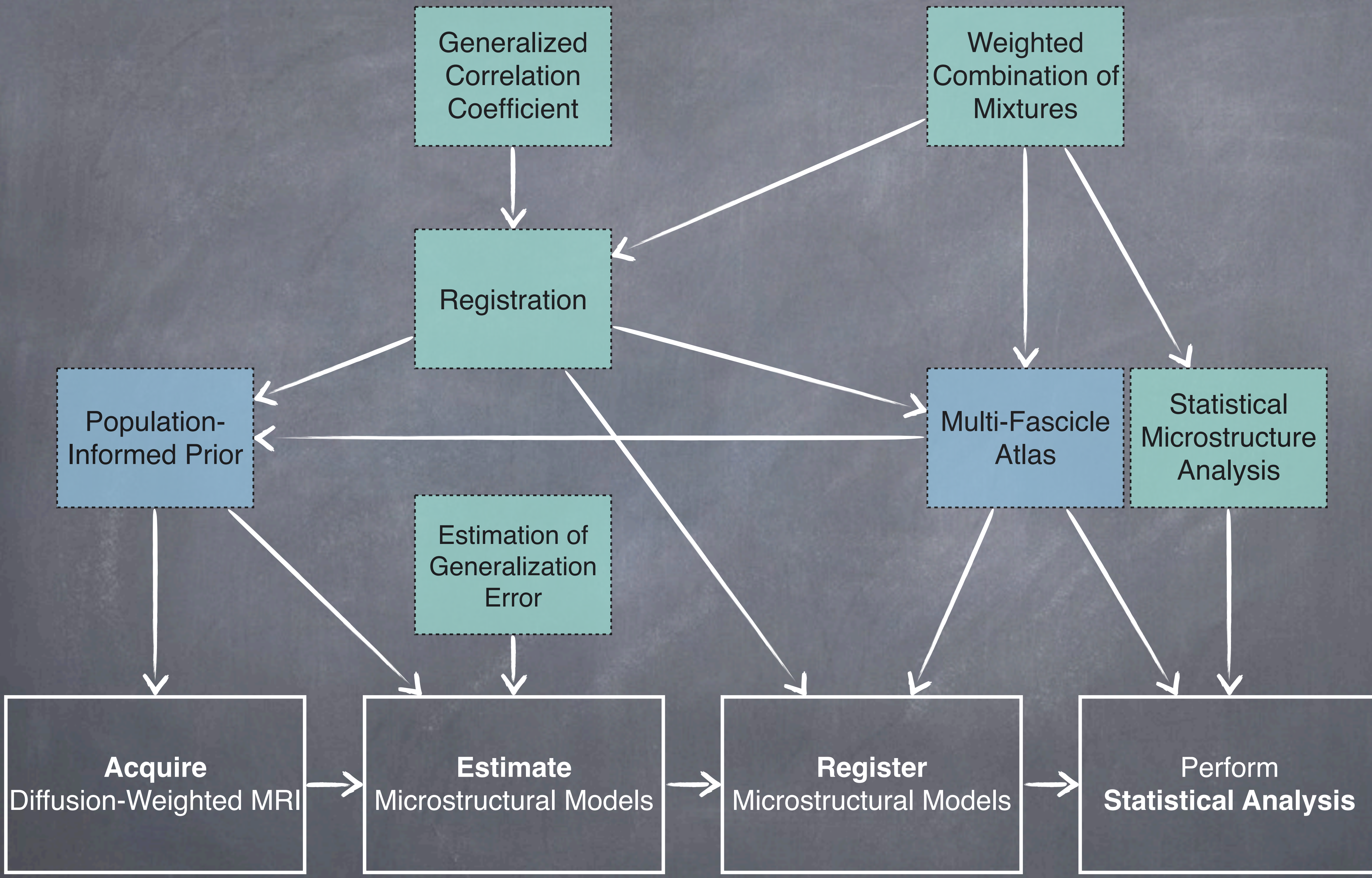
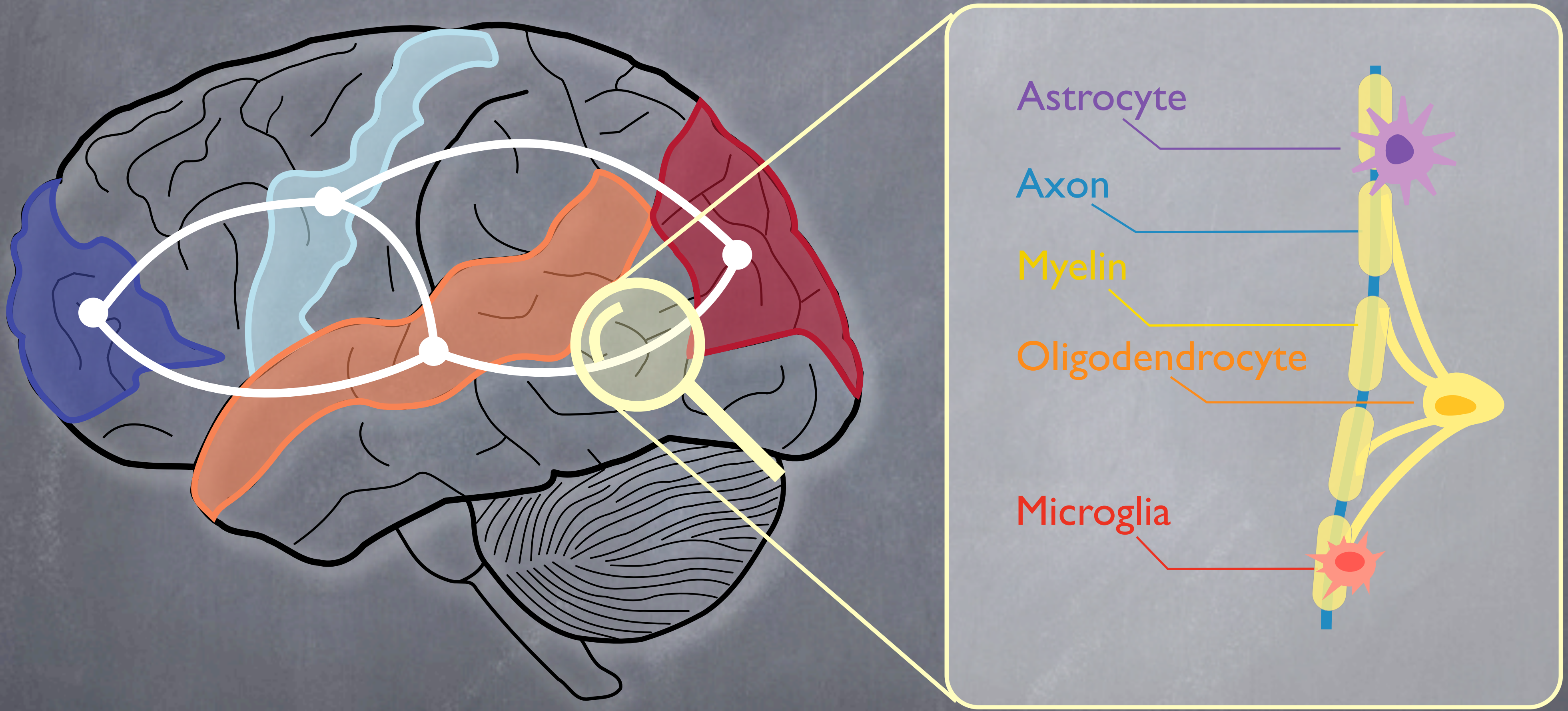

Generalized Correlation Coefficient
Weighted Combination of Mixtures
Registration
Population-Informed Prior
Multi-Fascicle Atlas
Statistical Microstructure Analysis
Estimation of Generalization Error
Acquire Diffusion-Weighted MRI
Estimate Microstructural Models
Register Microstructural Models
Perform Statistical Analysis


Astrocyte
Axon
Myelin
Oligodendrocyte
Microglia

Thank you

Journals

Taquet et al., Neuroimage (under review)

Taquet et al., IEEE TMI, 2013

Peters*, Taquet* et al., Future Neurology, 2013

Taquet and Peters, Médecine/Sciences, 2013

Peters*, Taquet*, et al., BMC Medicine, 2013

Peer-reviewed conference abstracts

Taquet et al., OHBM 2013

Taquet et al., ISMRM 2013

Scherrer et al., ISMRM 2013

Peters*, Taquet* et al., American Acad. of Neurology 2013

Peters*, Taquet* et al. Child Neurology Society, 2012

Taquet et al., CAOS 2010

Full-length peer-reviewed conference papers

Taquet et al., MICCAI 2013

Scherrer et al., MICCAI 2013

Scherrer*, Taquet* et al., IPMI 2013

Taquet et al., MICCAI 2012

Taquet et al., IEEE ISBI 2012

Taquet et al., IEEE MMBIA 2012

Taquet et al., MICCAI 2011

Taquet et al., IEEE ICIP 2011

Taquet et al., CTIC 2010

Taquet, IEEE Melecon 2010

* Equal contributions