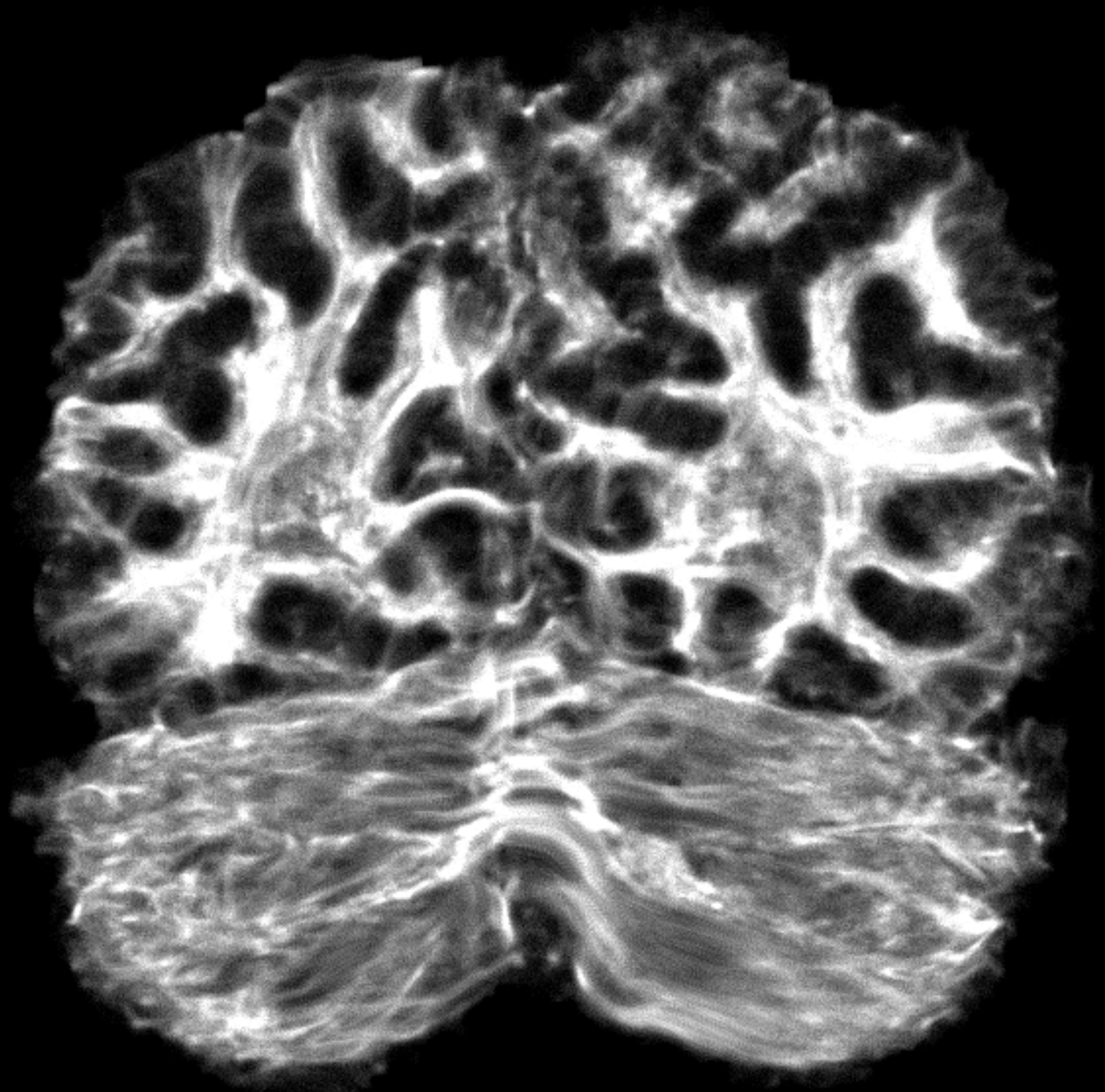
Tract-Density Imaging 纤维束密度图像

[Calamante NeuroImage 2010]

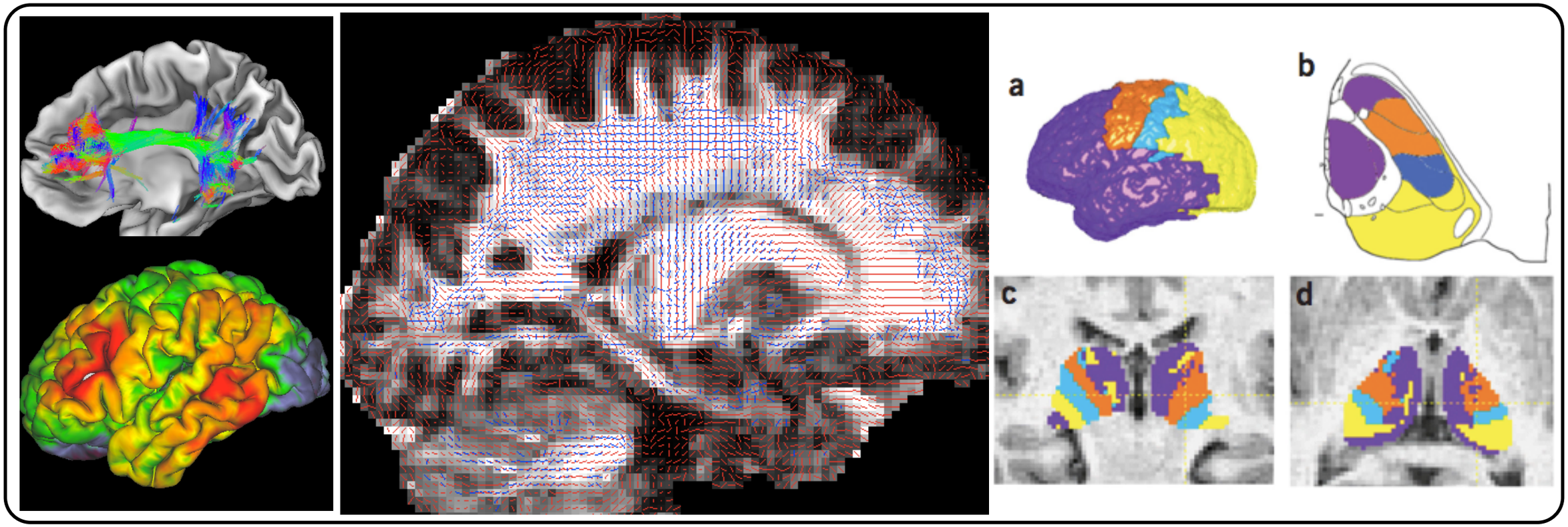
Single HCP subject 单个HCP被试

TDI @ 0.2mm



Overview
概况

- Estimating Fibre Orientations - BEDPOSTX 估计纤维束方向
- Probabilistic Tractography - PROBTRACKX 纤维束概率追踪
- ProbtrackX outputs ProbtrackX的输出
- Tractography limitations 概率追踪的局限性



Overview

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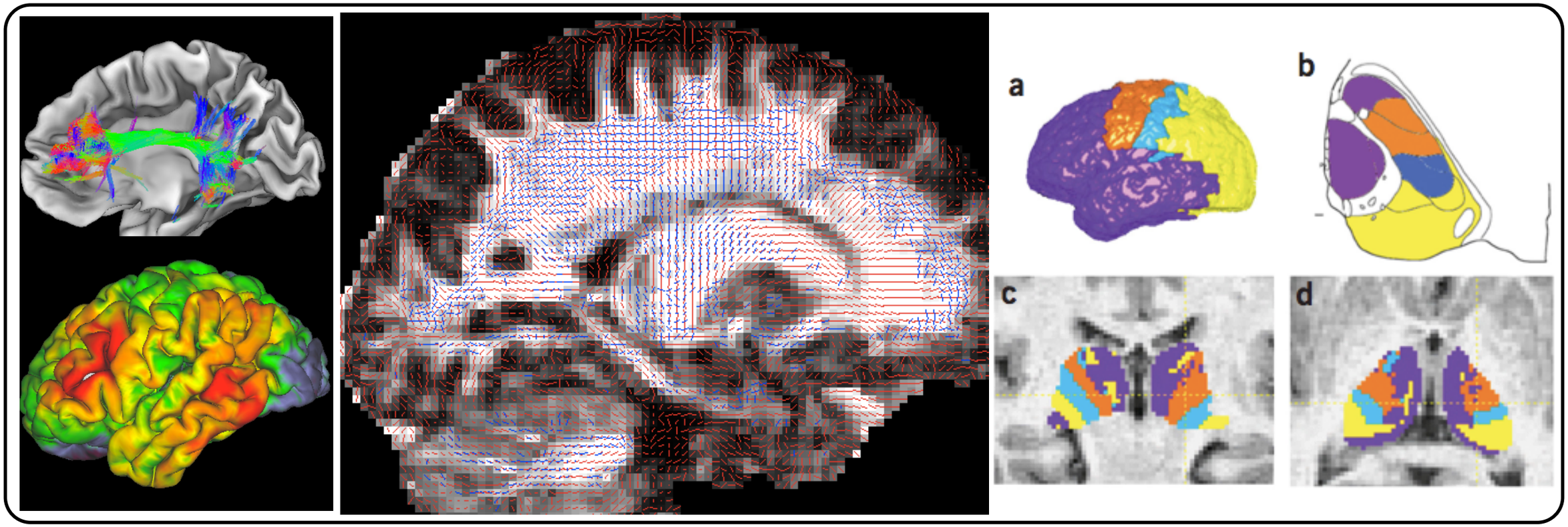
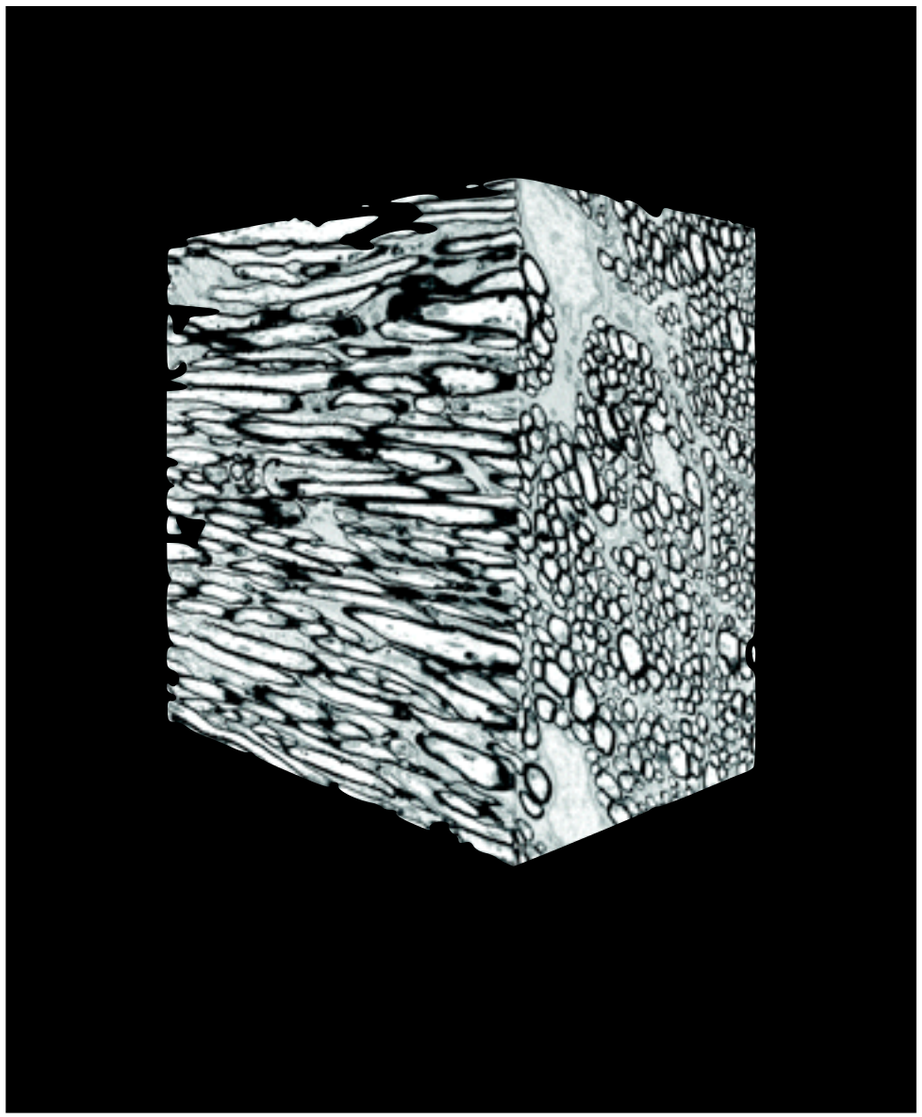


Why do we need modelling?

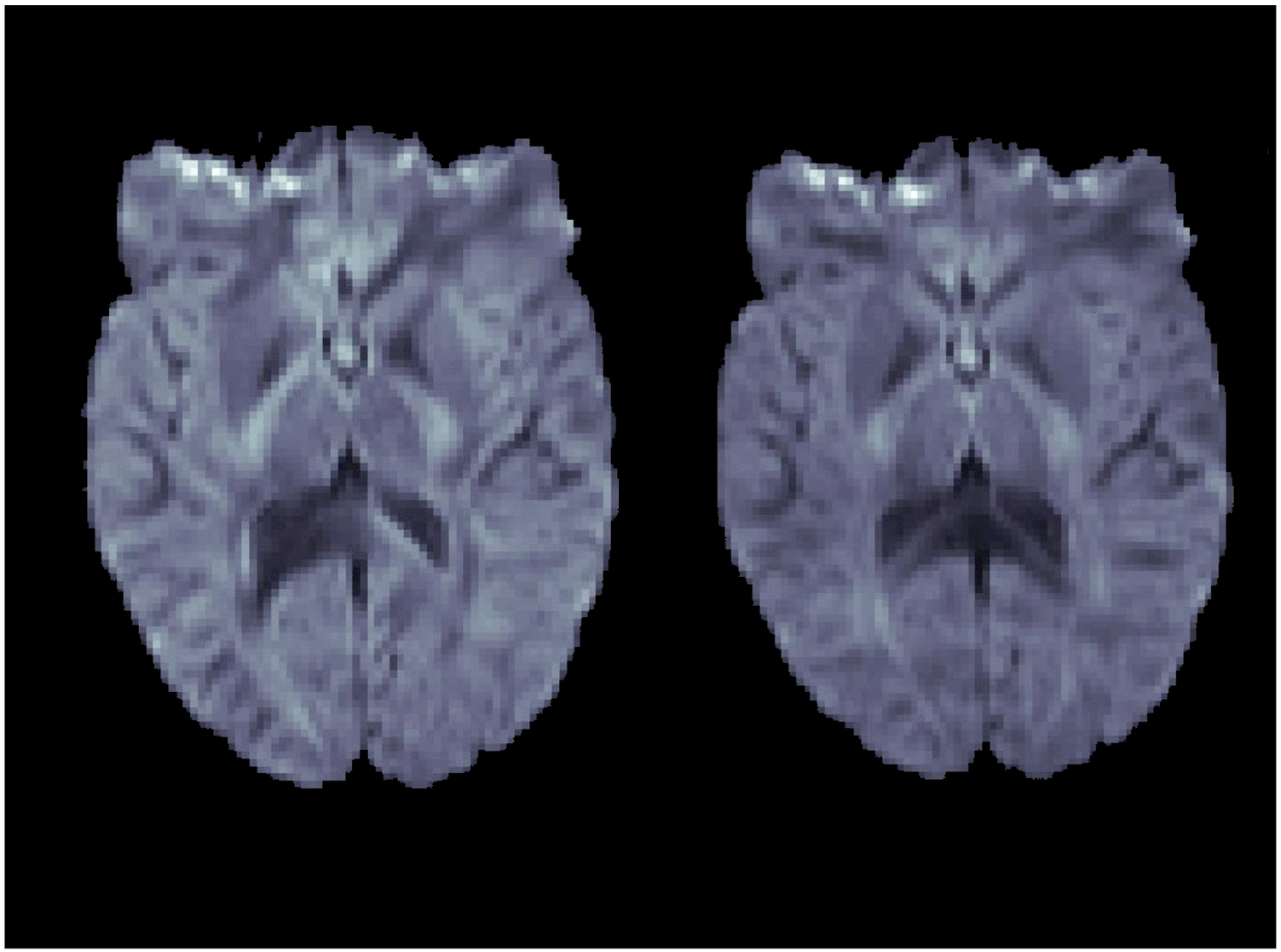
为什么我们需要建模?

Micro-connectme
微连接组



Ohno et al. 2013

Micro-connectome
微连接组



Iowa Virtual hospital

What is Tractography?

什么是追踪?

Post-mortem dissection of some white matter fibre bundles (tracts)

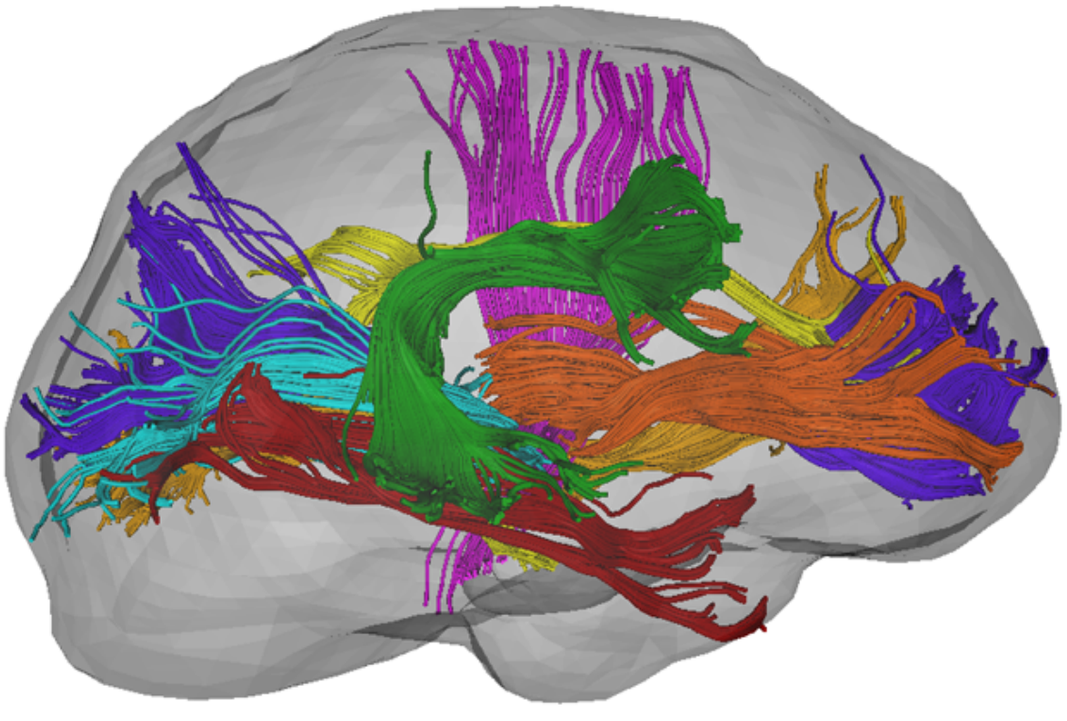
一些白质纤维束（大片）的尸检解剖

Tractography

The post-imaging reconstruction of fibre bundles/ anatomical connections in the brain using a set of DW images. (in-vivo virtual dissection)

追踪技术

使用一组DW图像对大脑中的纤维束/解剖连接进行成像后重建(体内虚拟解剖)

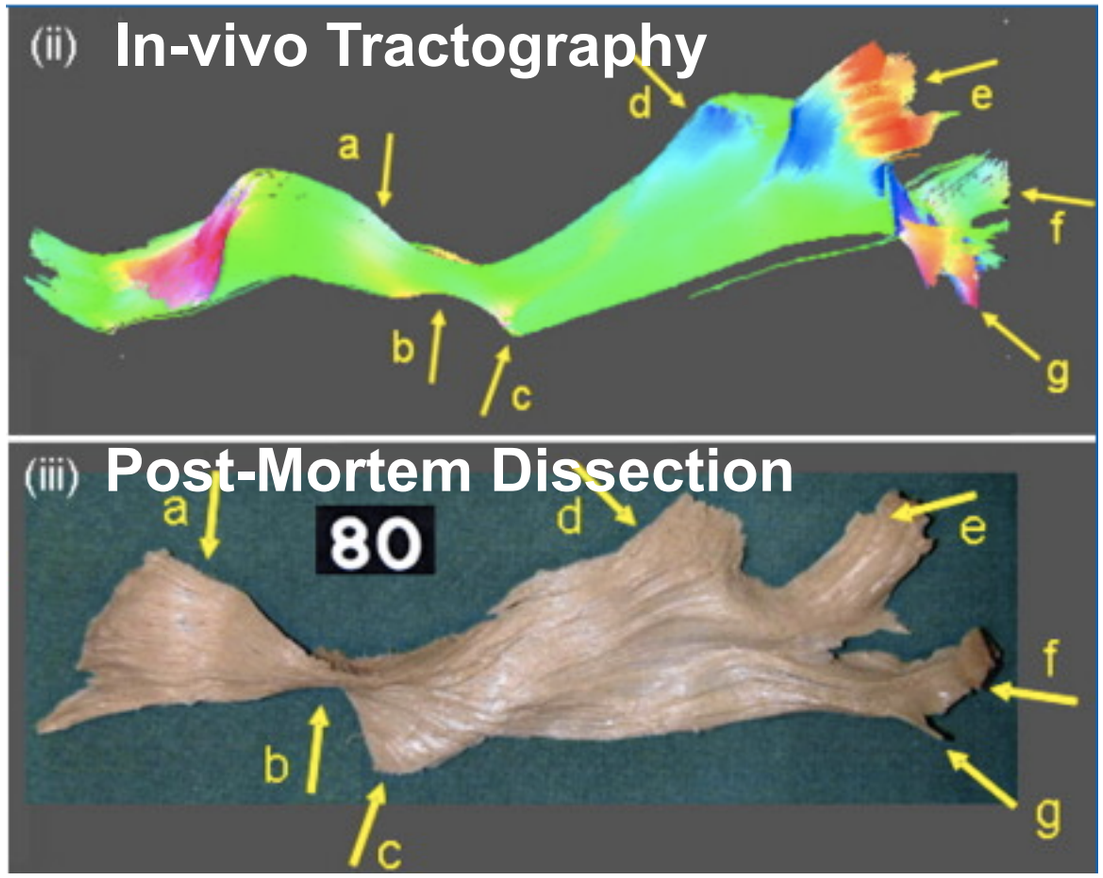


What does tractography offer?

纤维束成像可以提供什么?

+ non-invasive 无创
+ in-vivo 被检体内
+ whole brain 全脑
+ can address new questions

  可以解决新问题



Lawes et al. 2008

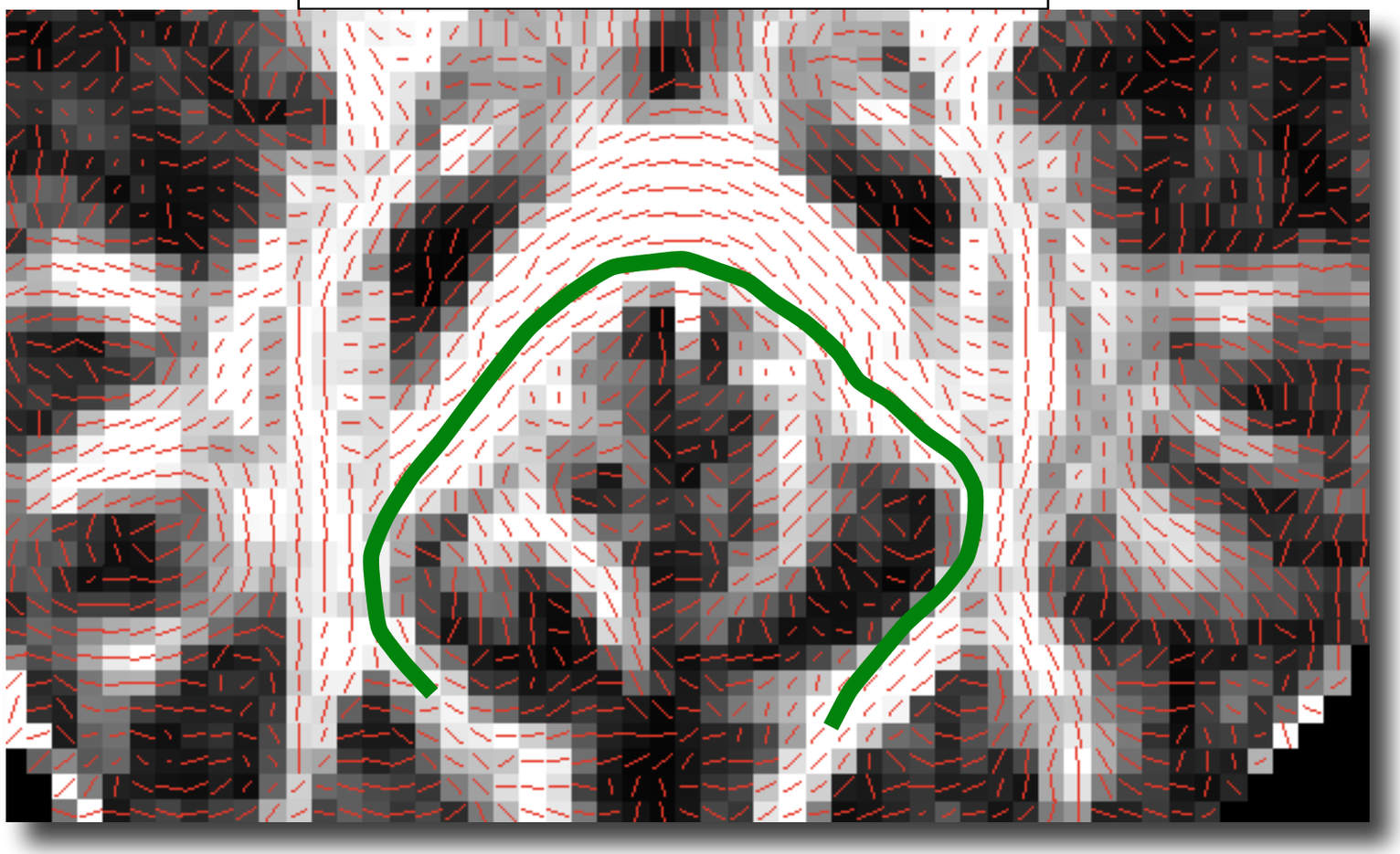
…But 但是

- low resolution (large bundles) 低分辨率（大束）
- indirect (diffusion paths) 间接（扩散路径）
- error prone (MRI is noisy) 容易出错（MRI噪声大）
- difficult to interpret quantitatively 难以定量解释

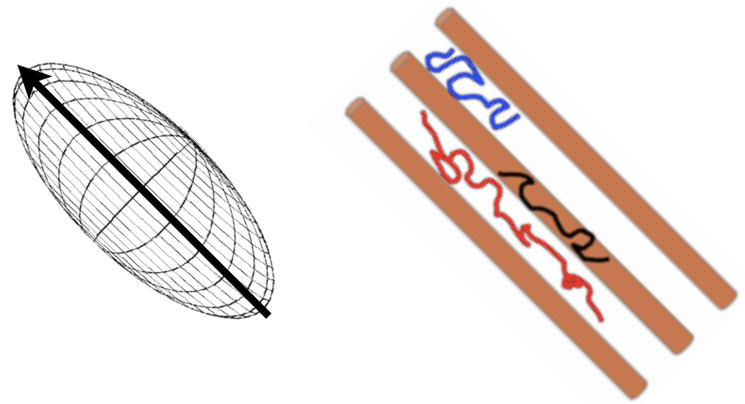
DTI tractography DTI追踪

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

$\mathbf{v}_1$ 图像
主扩散方向



Principal Diffusion Direction
主扩散方向



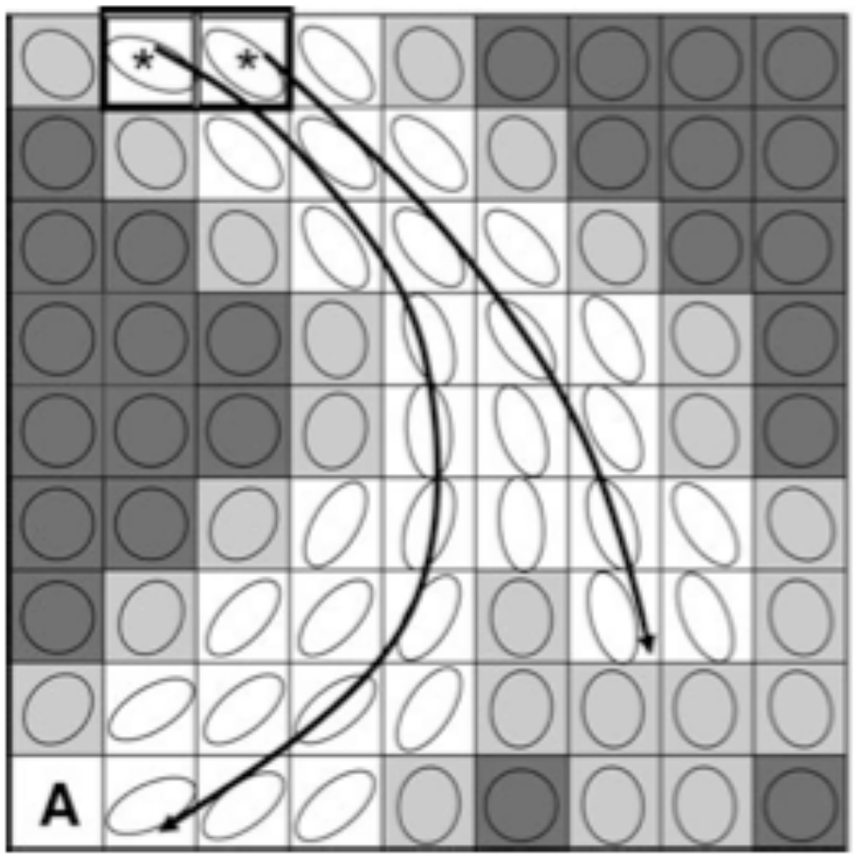
Assumption:

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

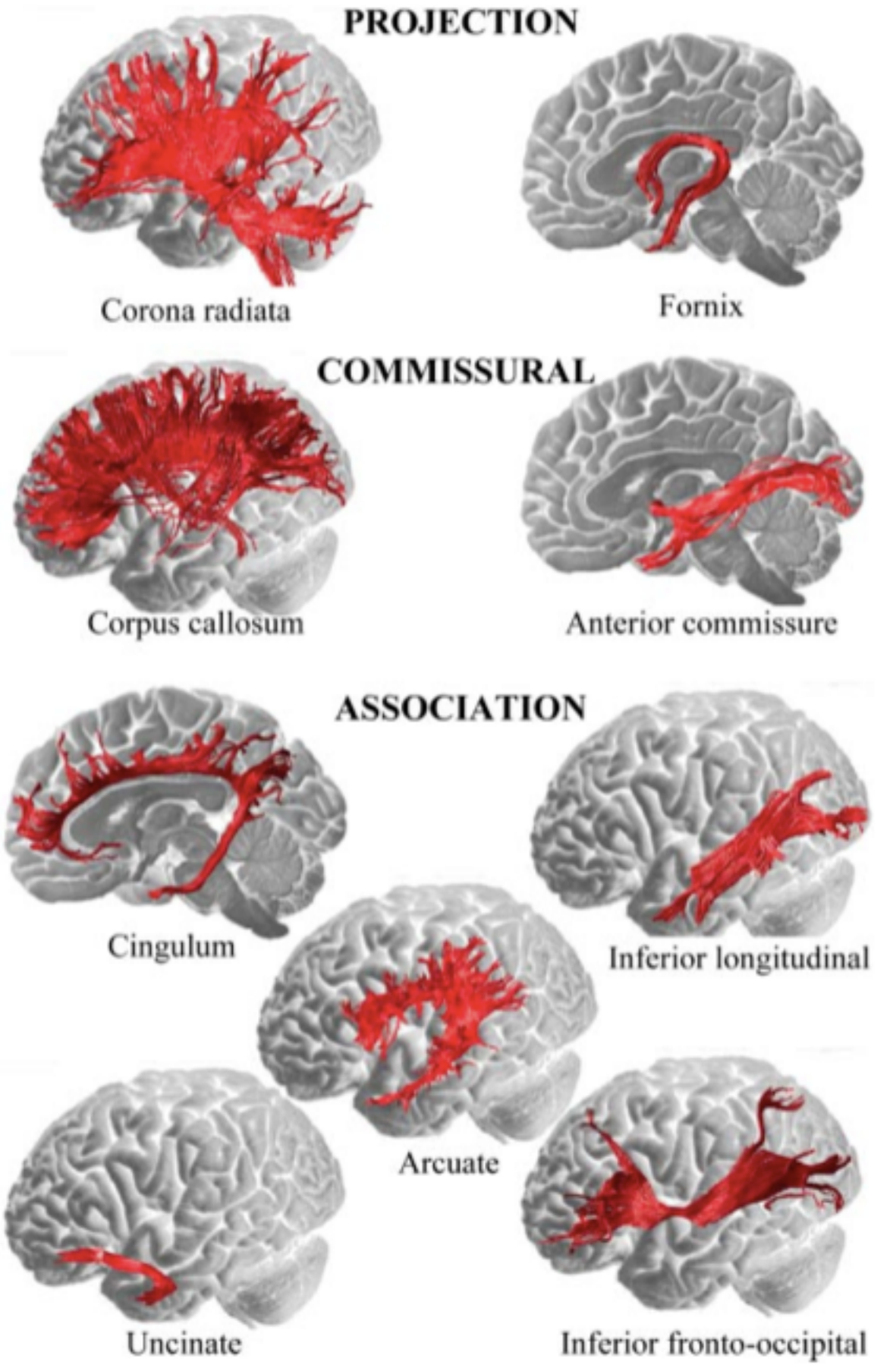
假设：
最大扩散率的方向
（各向异性体素内）
是主要纤维取向的估计

DTI tractography

DTI追踪



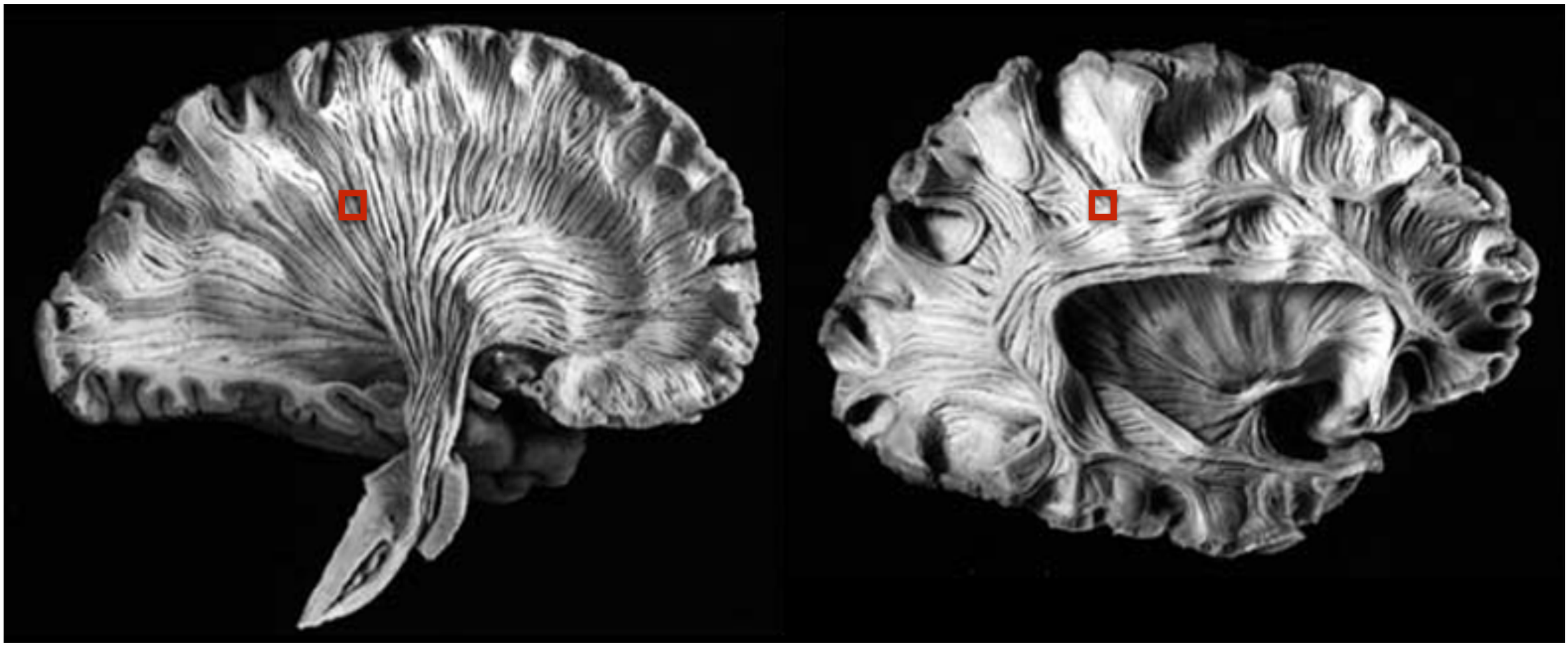
[Basser et al, Magn Reson Med, 2000]



[Catani et al, NeuroImage, 2003]

But is WM always coherently organised within a voxel?

但是WM是否总是在体素内连贯地组织起来?



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

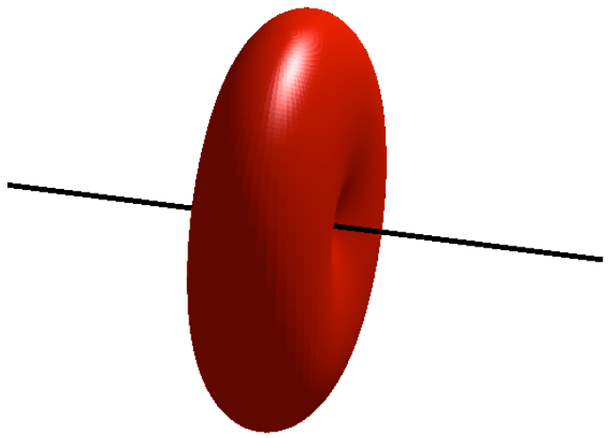
不幸的是，复杂的纤维图案（例如交叉）在体素尺度上非常常见。

Predictions from the tensor model
no crossing fibres
张量模型的预测
没有交叉纤维

One orientation
一个方向

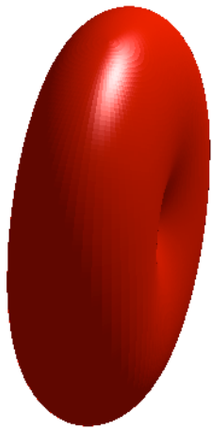
Measured Signal Shape

测量信号形状



Predicted Signal Shape

预测信号形状

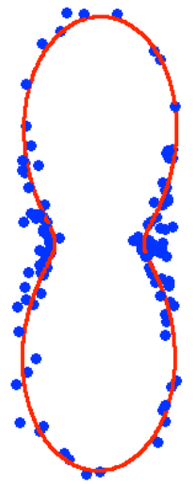


DTI Ellipsoid

DTI椭球

Prediction & Measurements in 2D

在2D图像中的预测和测量

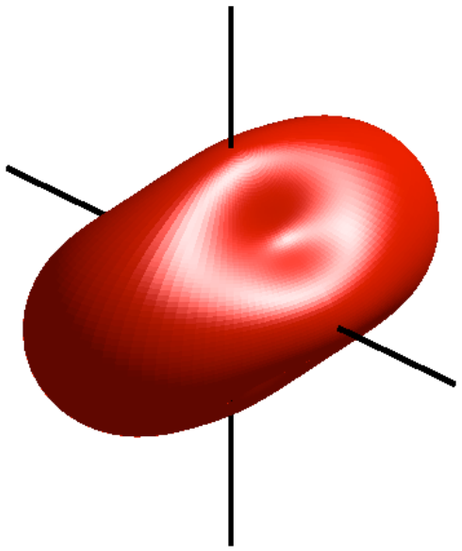


Predictions from the tensor model
no crossing fibres
张量模型的预测
没有交叉纤维

Two orientations
两个方向

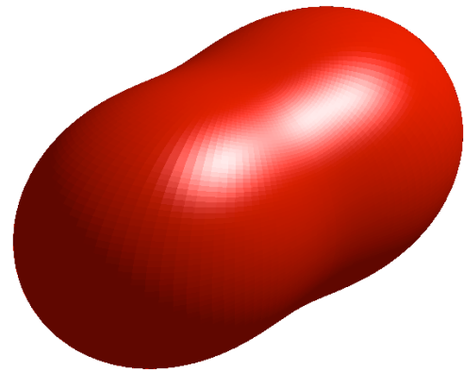
Measured Signal Shape

测量信号形状



Predicted Signal Shape

预测信号形状



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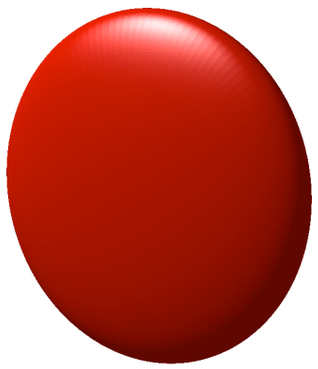
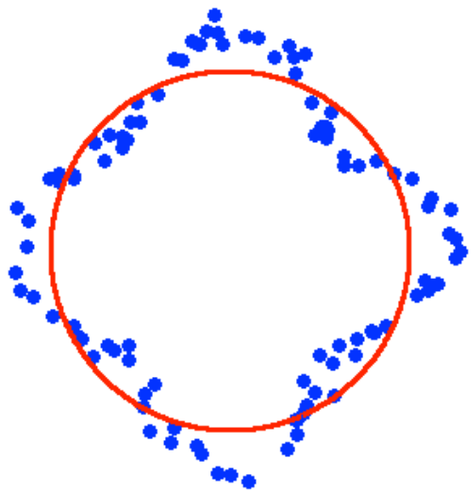


Prediction & Measurements in 2D

在2D图像中的预测和测量



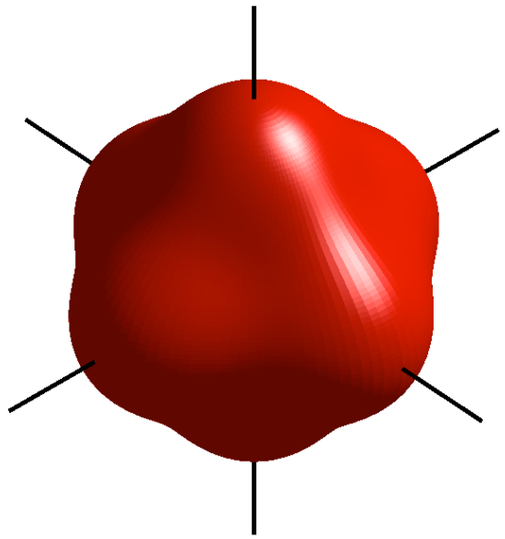
Predictions from the tensor model
no crossing fibres
张量模型的预测
没有交叉纤维

Three Orientations

三个方向

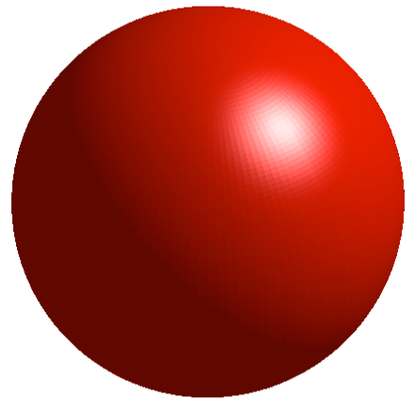
Measured Signal Shape

测量信号形状



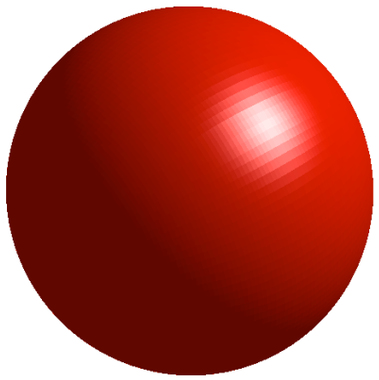
Predicted Signal Shape

预测信号形状



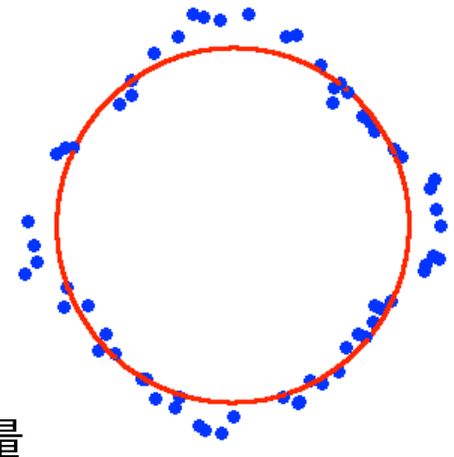
DTI Ellipsoid

DTI椭球



Prediction & Measurements in 2D

在2D图像中的预测和测量

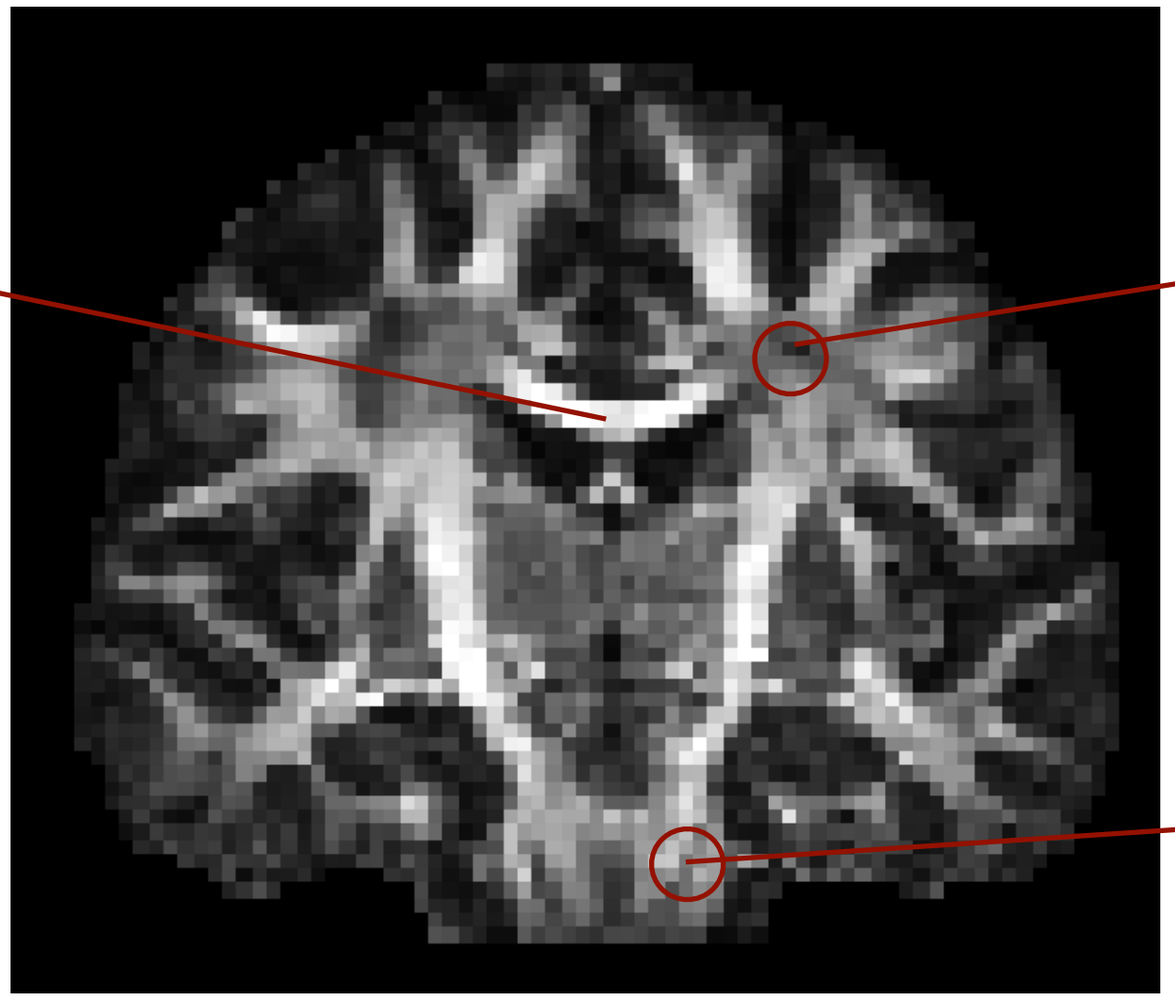


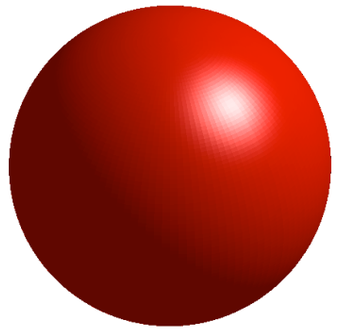
How good is the DTI Model in regions with crossing fibres?

在具有纤维交叉的区域中DTI的模型如何?

- In voxels containing two crossing bundles, the tensor ellipsoid is pancake-shaped (oblate, planar tensor). 在包含两个交叉束的体素中，张量椭球是扁平形状（扁圆形，平面张量）。
- In voxels containing three crossing bundles, the tensor ellipsoid is spherical.在包含三个交叉束的体素中，张量椭球是球形的。
- In these areas, DTI $\mathbf{v}_1$ is meaningless. 在这些领域，DTI v1毫无意义。

Prolate Tensor
扁长的纤维束
$\lambda_1 >> \lambda_2, \lambda_3$





Spherical Tensor
球面的纤维束
$\lambda_1=\lambda_2=\lambda_3$

Oblate Tensor
扁圆的纤维束
$\lambda_1=\lambda_2 >> \lambda_3$

Uncertainty on DTI Fibre Orientation Estimates

DTI纤维方向估算的不确定性

Repeat an acquisition many times and obtain the variability in $\mathbf{v}_1$ from the different datasets.

多次重复采集并从不同的数据集中获得v1的可变性

Uncertainty Sources

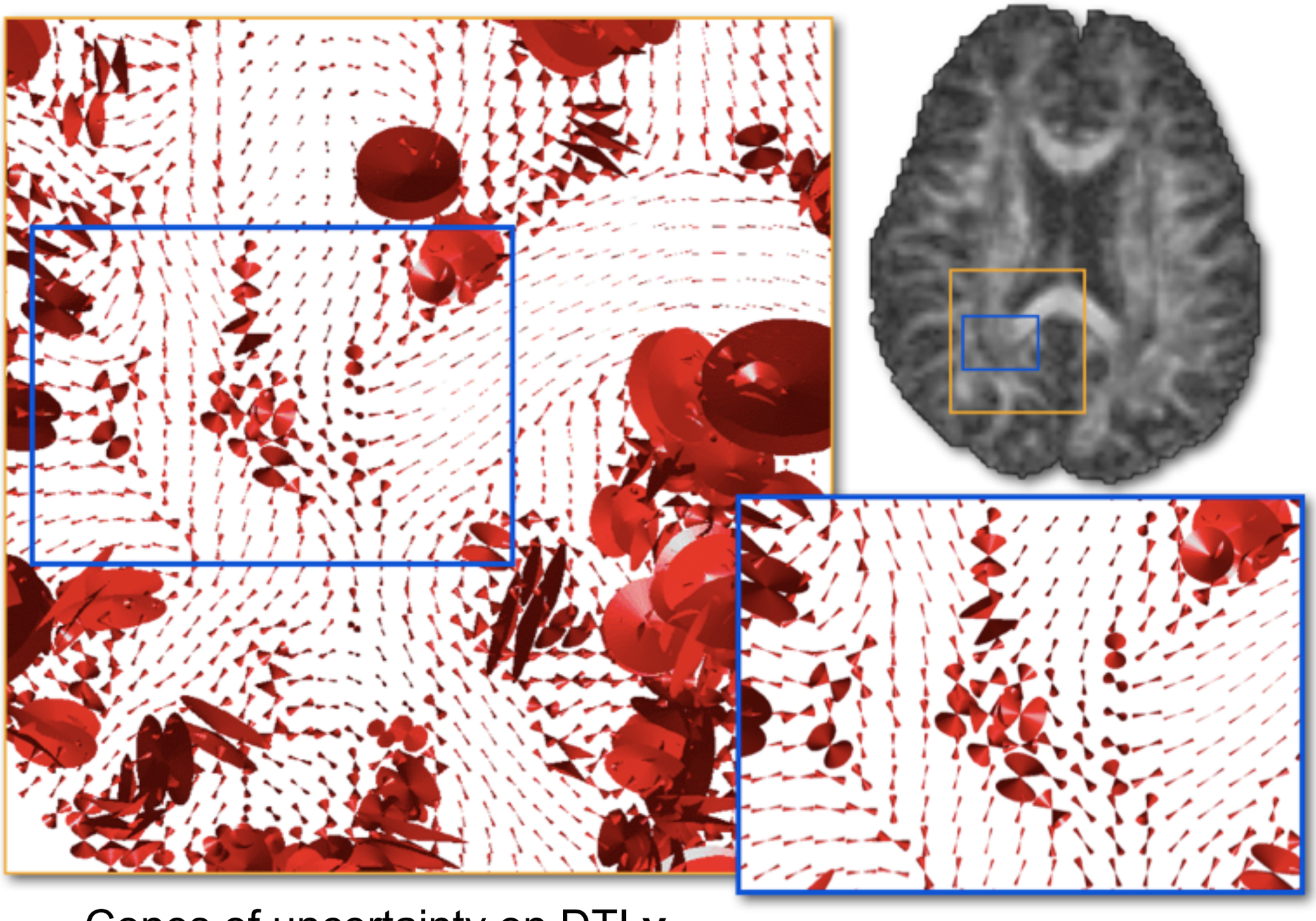
不确定来源

- Modelling errors

模型误差

- Noise

噪声



Cones of uncertainty on DTI $\mathbf{v}_1$

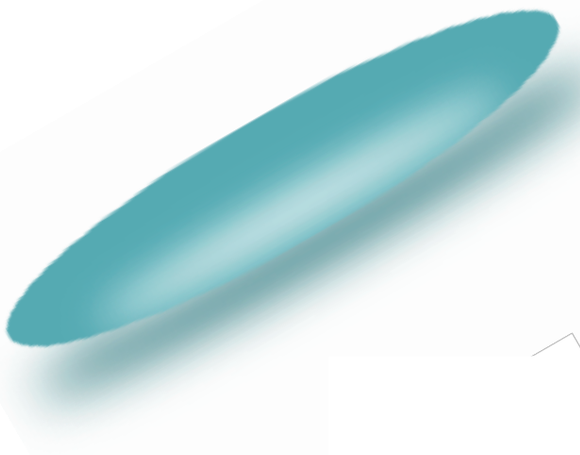
DTI v1的不确定因素

Jones, 2002

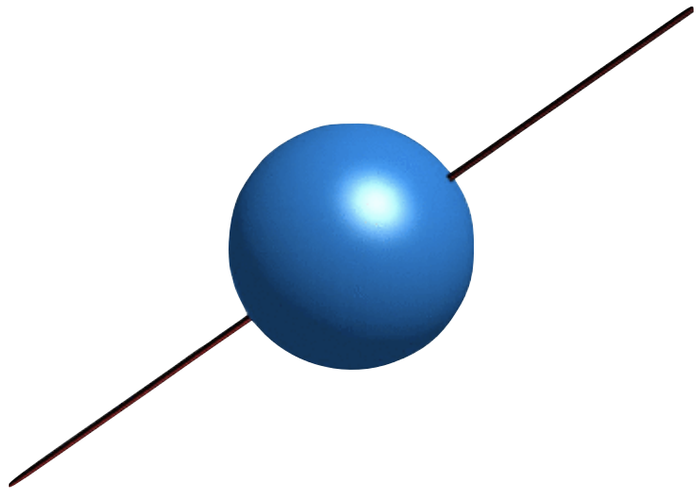
Do we have to use the DTI model to estimate orientations? Not really, many models exist

我们是否必须使用DTI模型来估计方向？不是，许多模型都可以

DTI model (dtifit)
DTI模型



Ball & sticks model (bedpostx)
球和棒模型



Anisotropic Volume Fraction (unknown)
各向异性体积分数（未知）

Diffusivity (unknown)
扩散（未知）

Fibre Orientation (unknown)
纤维方向（未知）

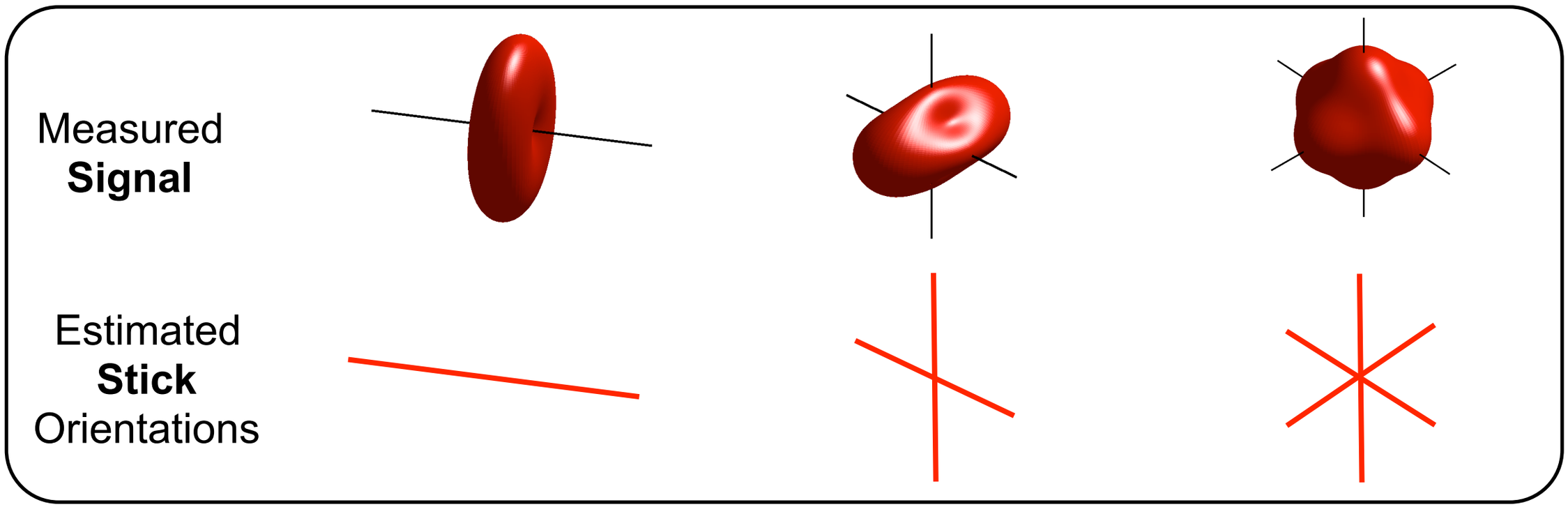
$$s_j = s_0 [(1-f)\exp(-b_j\, d) + f \exp(-b_j\, d(\boldsymbol{x}_j^{\mathrm{T}} \boldsymbol{v})^2)]$$

Measured Signal for Gradient *j*
梯度*j*的测量信号

b-value for gradient *j* (known)
梯度j的b值（已知的）

Unit vector representing the direction of gradient *j* (known)
表示梯度j方向的单位向量（已知）

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)

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

Measured Signal for Gradient *j*

b-value for gradient *j* (known)

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

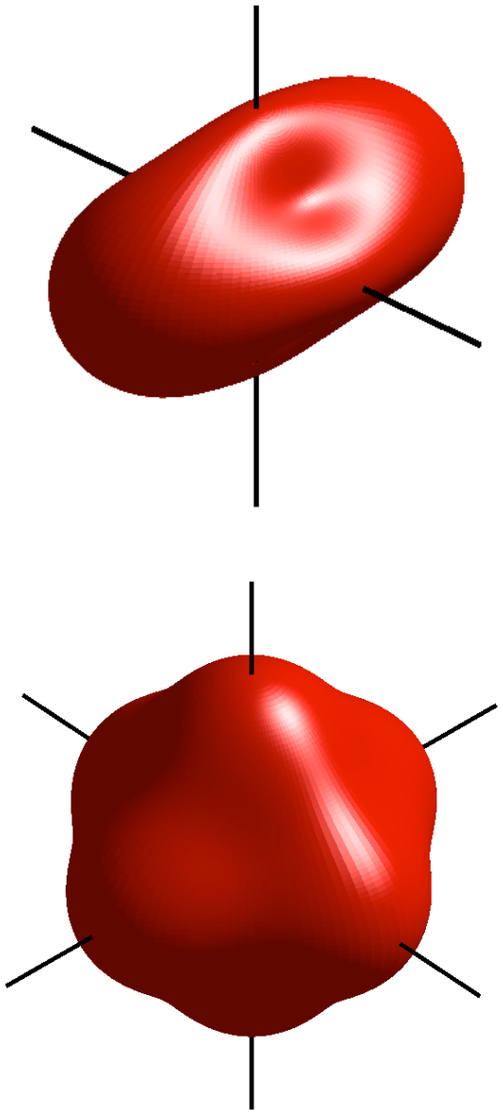
Predictions from the ball and sticks model crossing fibres

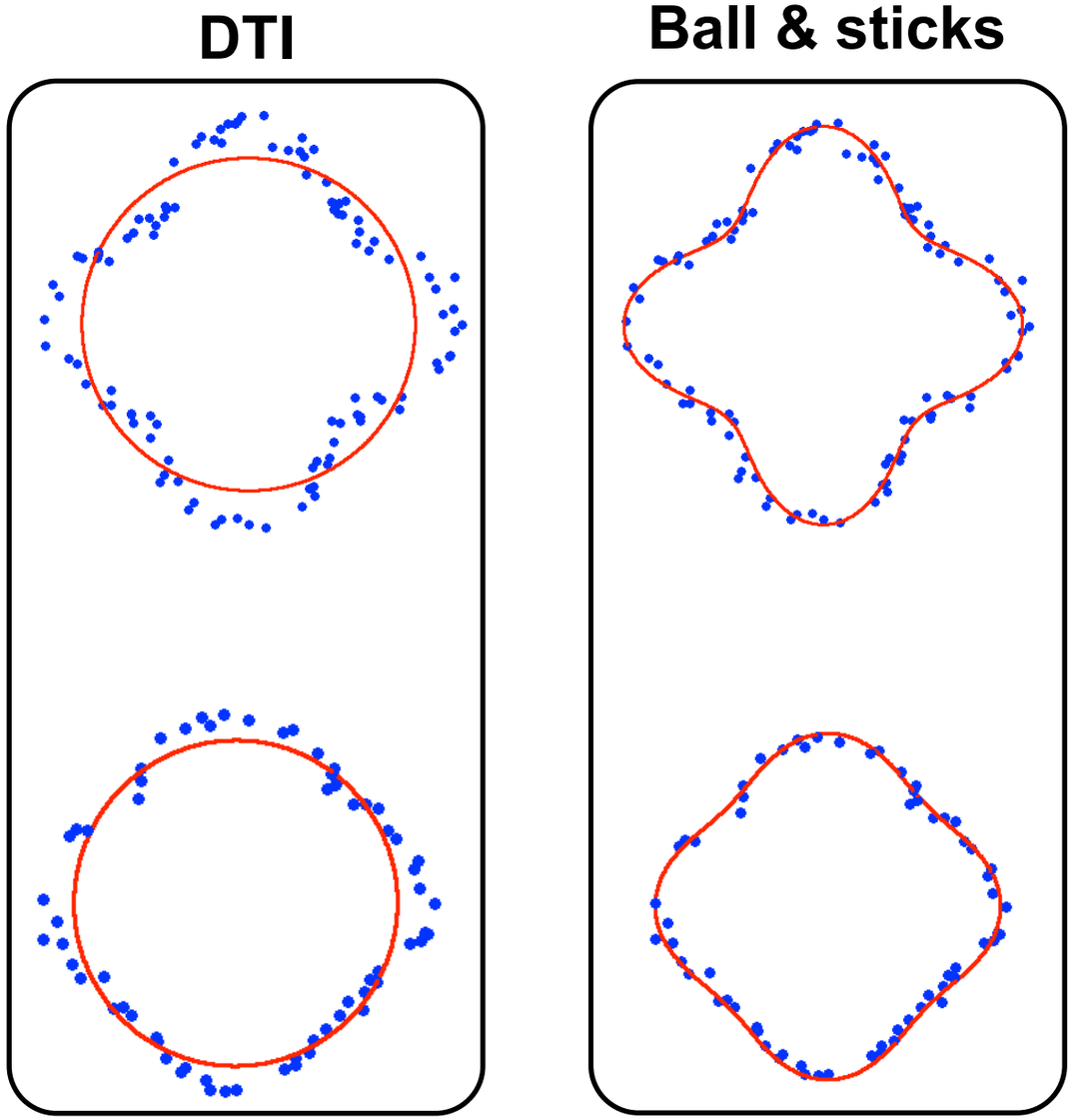
Measured
Signal Shape

Prediction &
Measurement in 2D

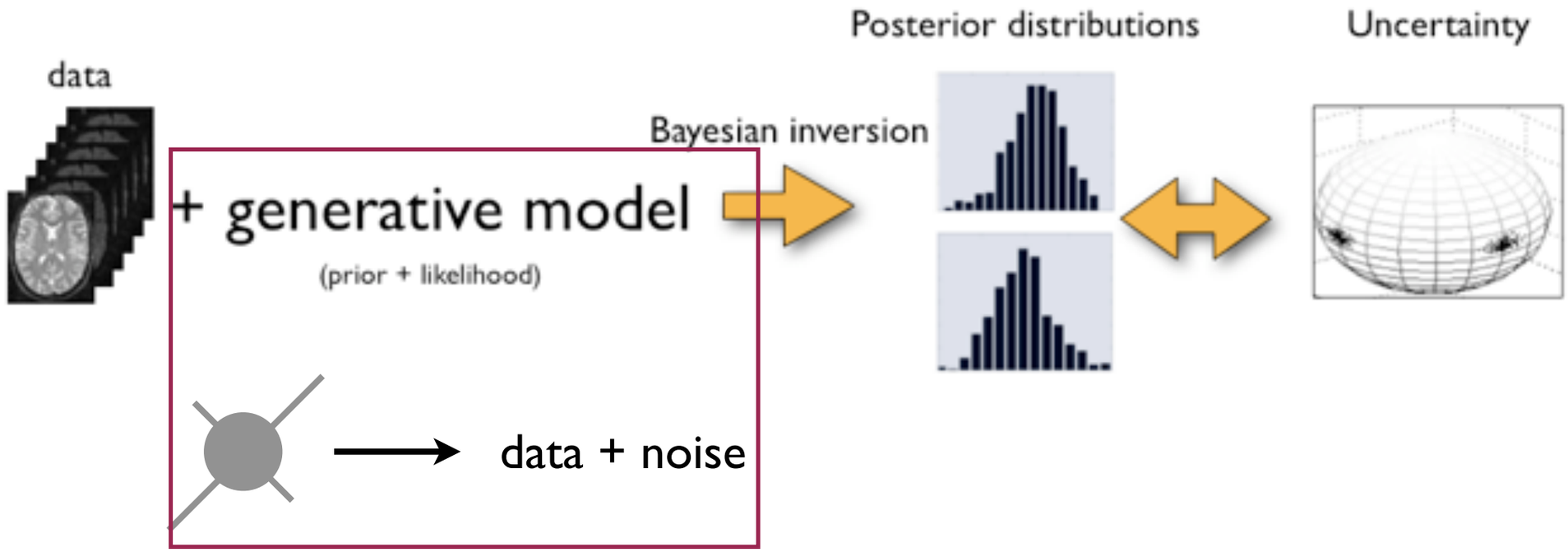
Two orientations

Three orientations

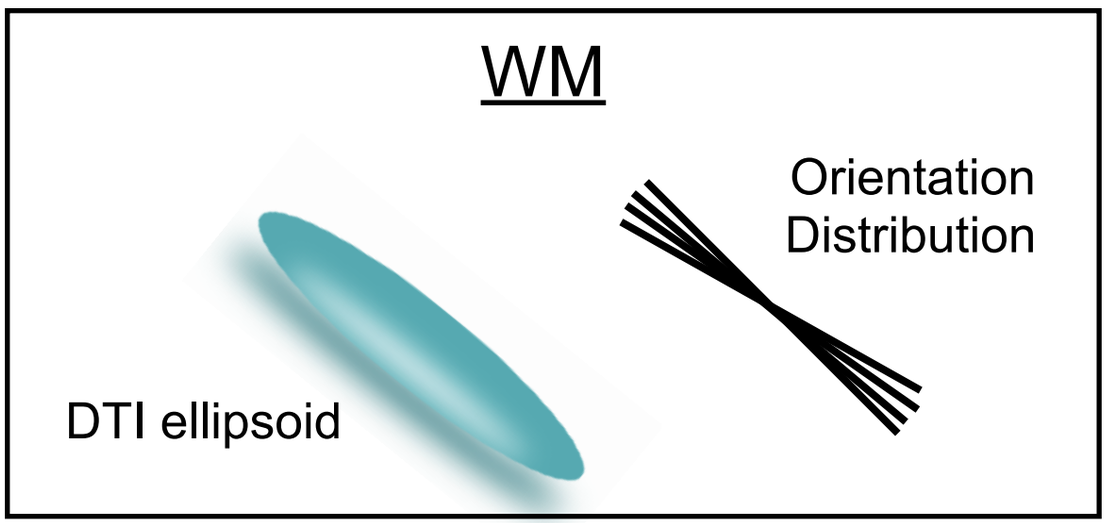


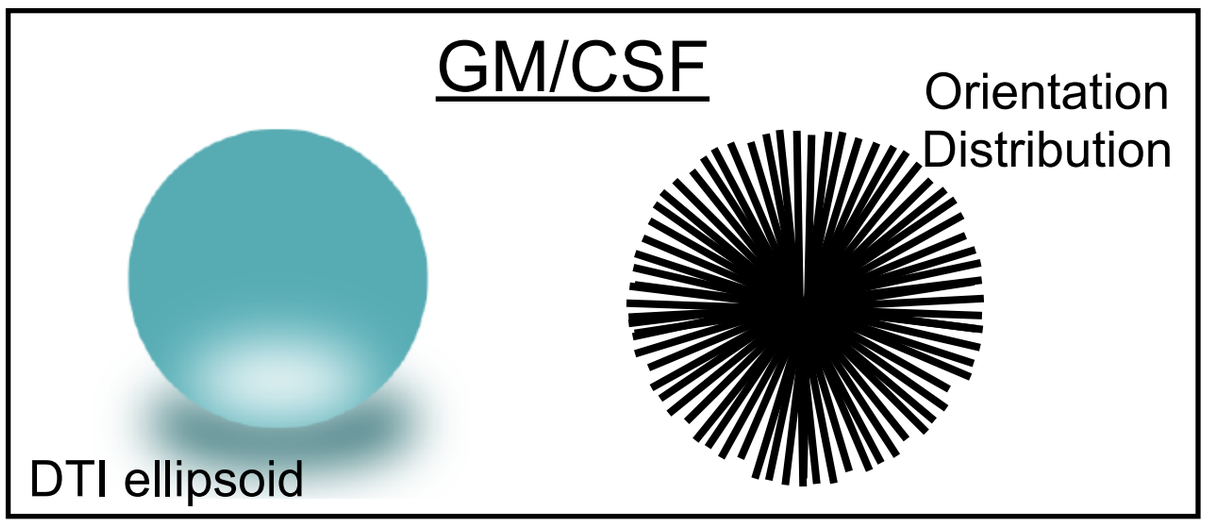


Quantifying Uncertainty
Bayesian Modelling (FDT BedpostX)
量化不确定性
贝叶斯建模（FDT BedpostX）



- Uncertainty can be quantified from a single data set
  不确定性可以从单个数据集量化
- Instead of a single orientation estimate, infer a distribution of orientations in each voxel.
  而不是单个方向估计，推断每个体素中的方向分布

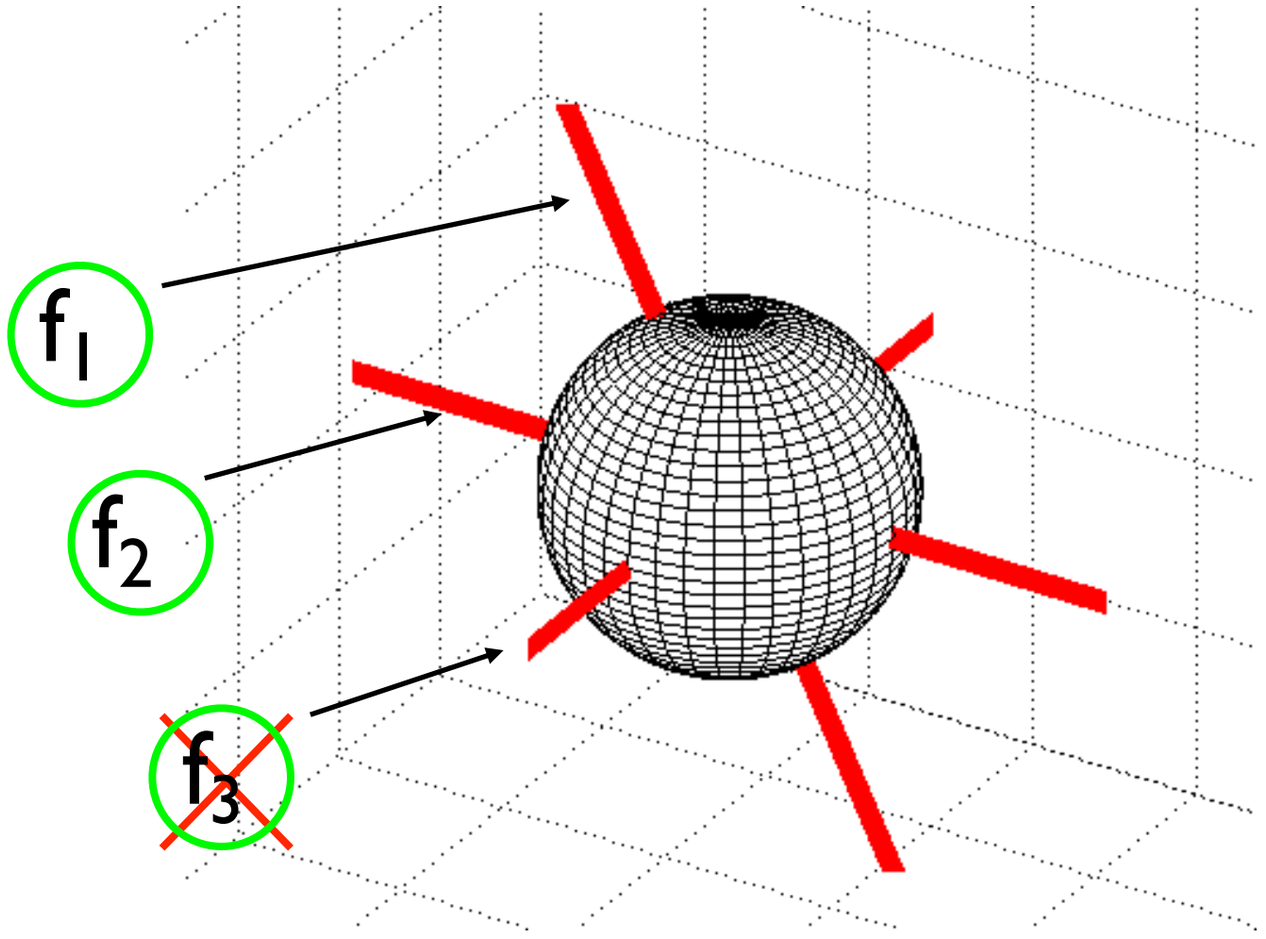




Ball & Sticks Model Selection
球形和棒形模型选择

- Model selection problem: One, two or more fibres within a voxel?
  模型选择问题：体素内有一根，两根或更多根纤维?

- Automatic Relevance Determination: Only estimate complexity that is supported by the data
  自动相关性确定：仅估计数据支持的复杂性



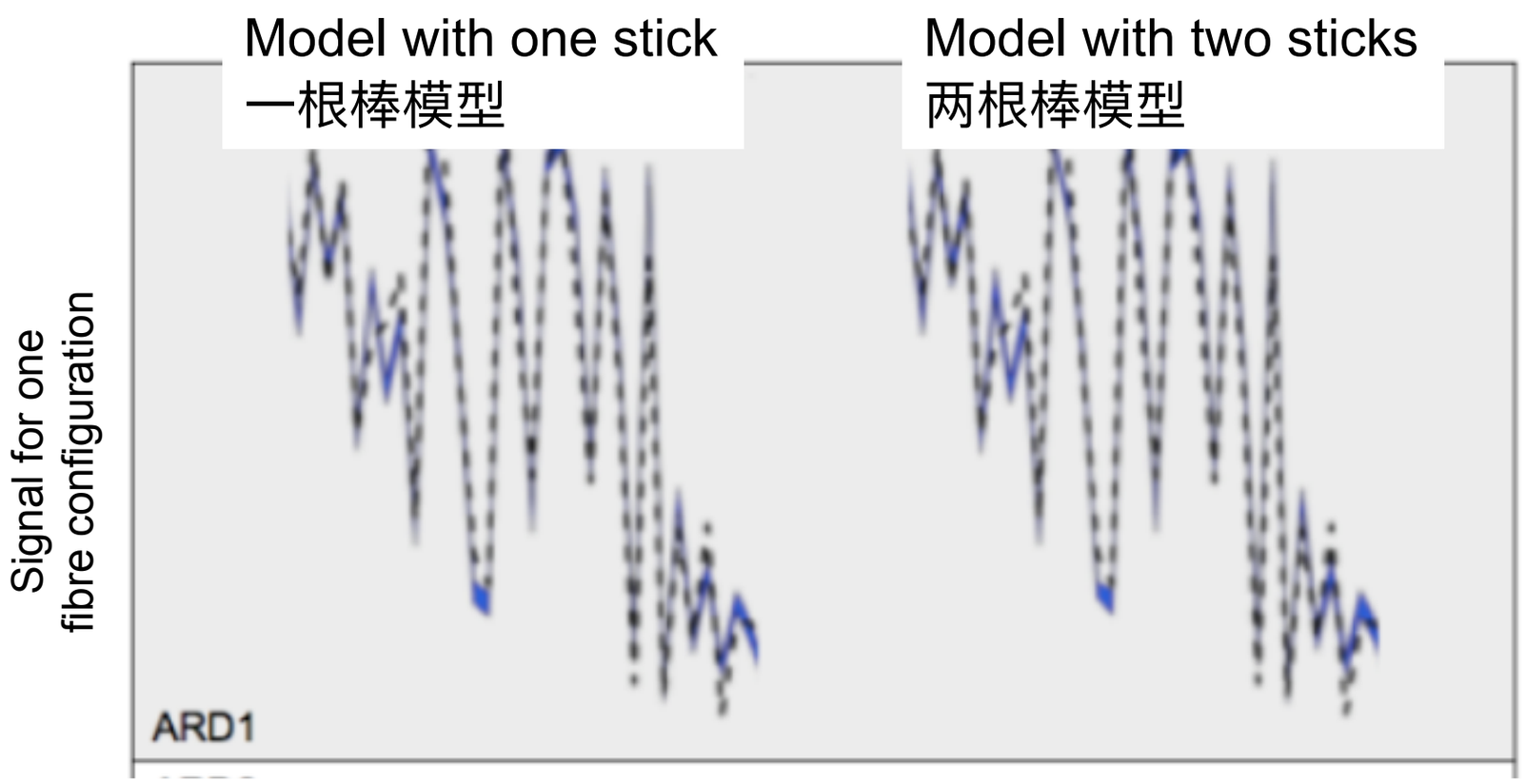
Modelling Complex Fibre Architectures
复杂纤维架构建模

Automatic Relevance Determination (A.R.D.)
自动相关性确定（A.R.D.）

--- Measured Signal
— Model Predicted Signal

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

- 包括第二根纤维=>第二体积分数变为零没有益处



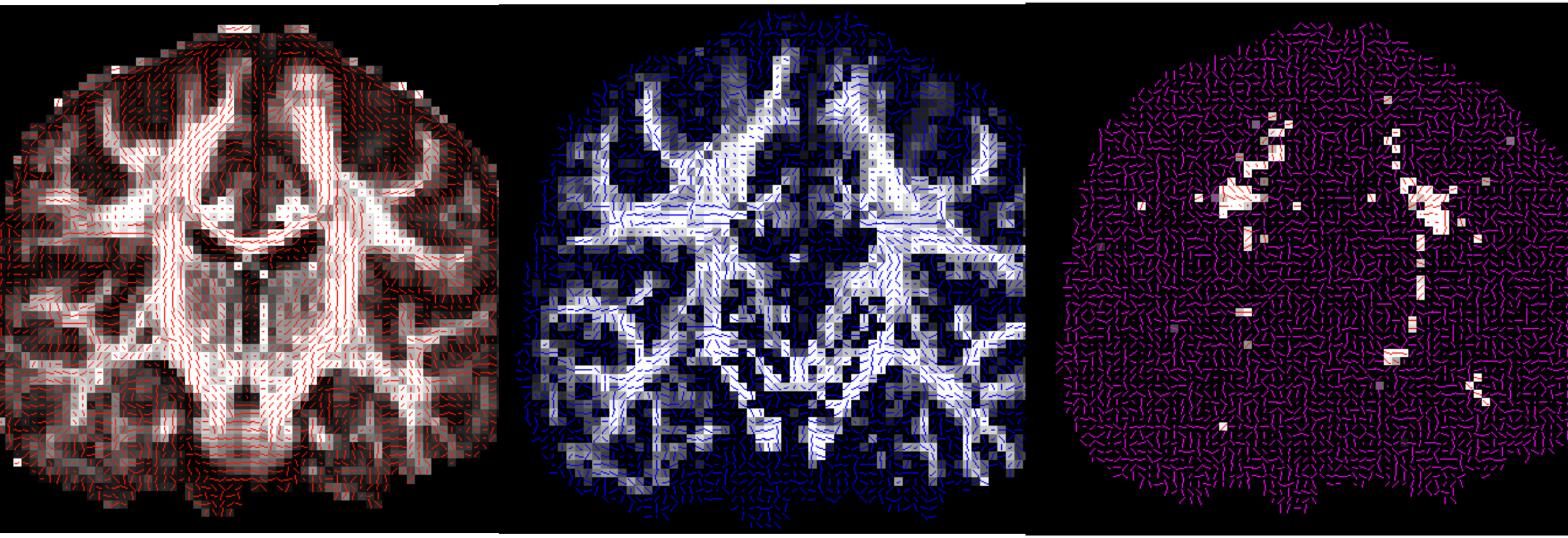
Modelling Complex Fibre Architectures
复杂纤维架构建模
Automatic Relevance Determination (A.R.D.)
自动相关性确定（A.R.D.）

- After running BedpostX all voxels will have estimated parameters for the maximum number of sticks requested. 在运行BedpostX之后，所有体素将具有所要求的最大棒数的估计参数。

- But due to ARD, the sticks that are not supported in a voxel will have an almost zero volume fraction. 但是由于ARD，体素中不支持的棒将具有几乎为零的体积分数。

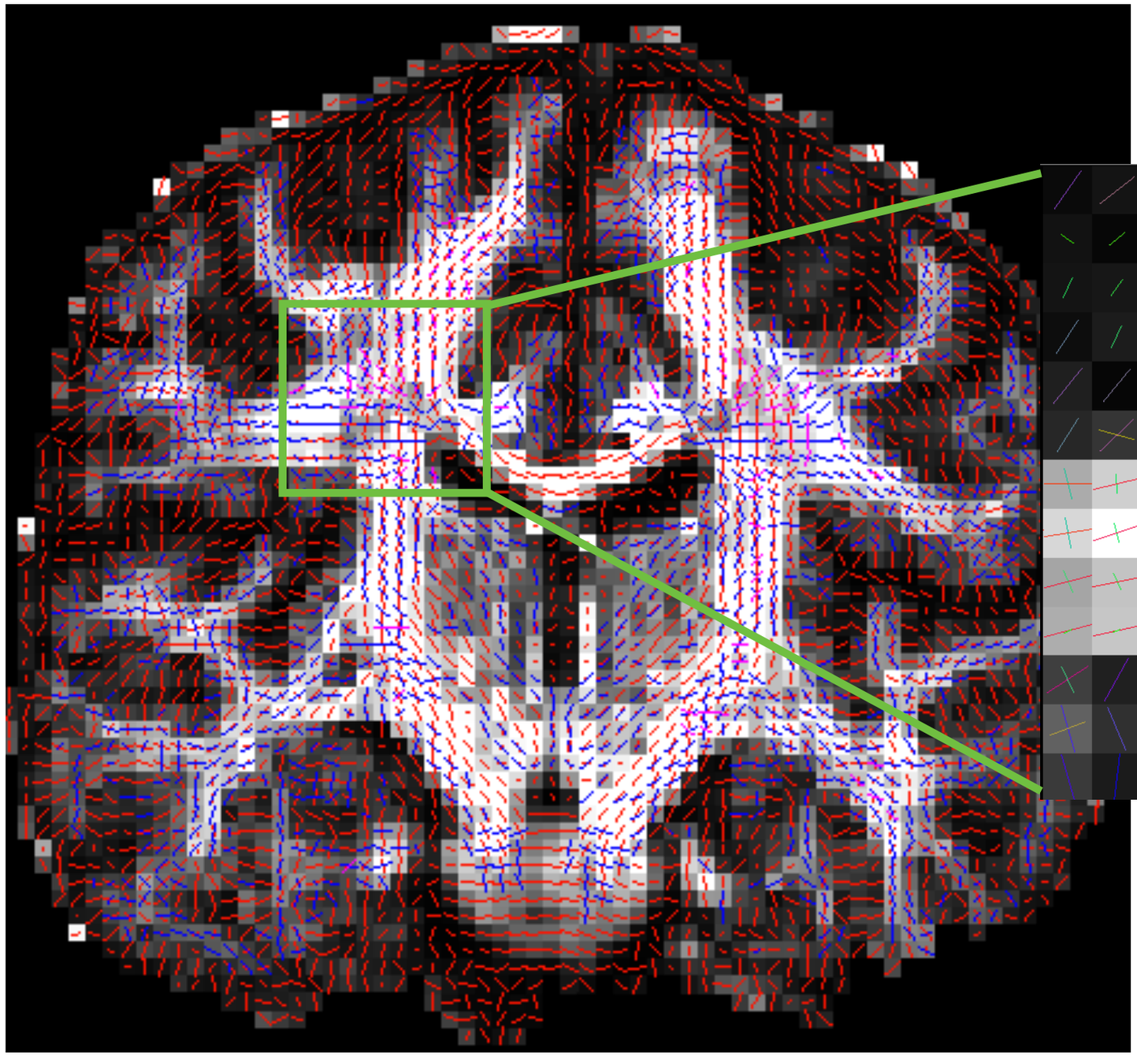
- We use a threshold (e.g. >5%) to **exclude sticks with tiny volume fraction**.
我们使用阈值（例如> 5%）来排除具有微小体积分数的棒。

Stick1 Stick2 Stick3

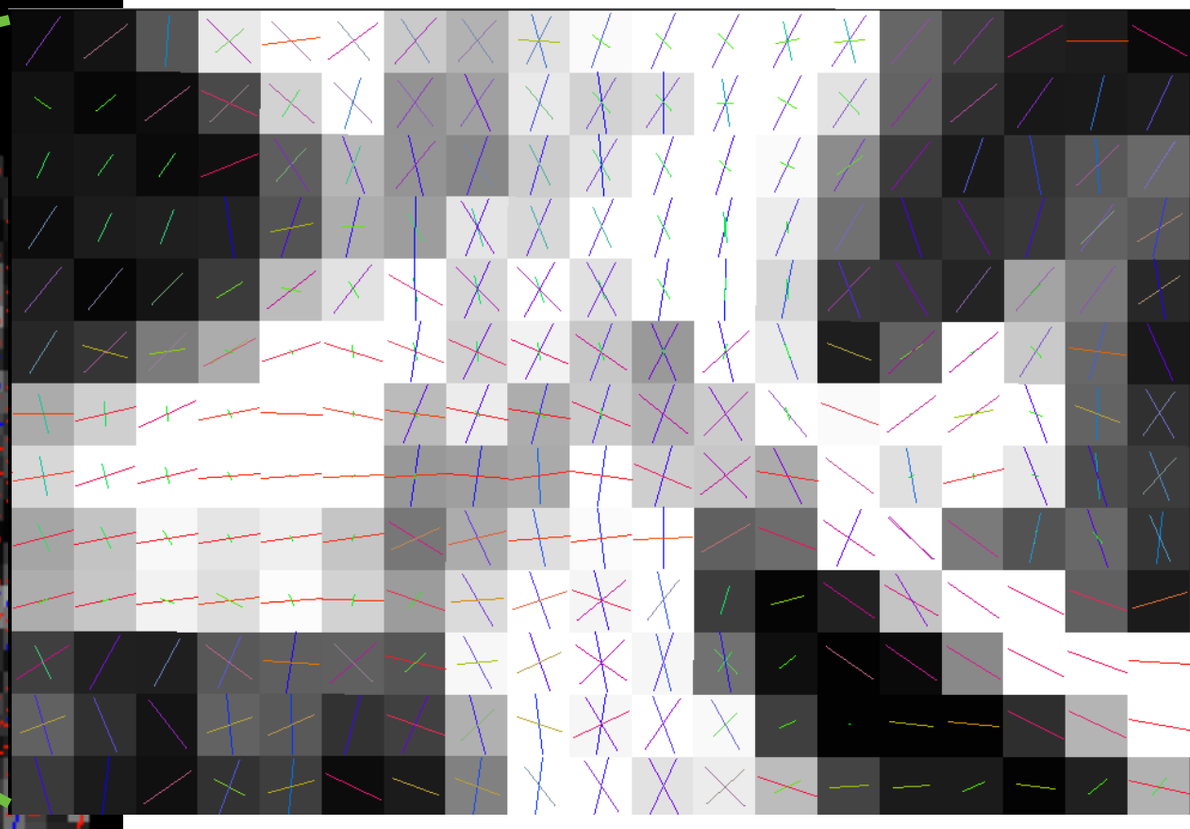


Ball & Sticks Orientations
球形和棒形的方向

All sticks, with secondary ones thresholded (f_n>5%)
所有棒，第二根棒的阈值（fn> 5%）

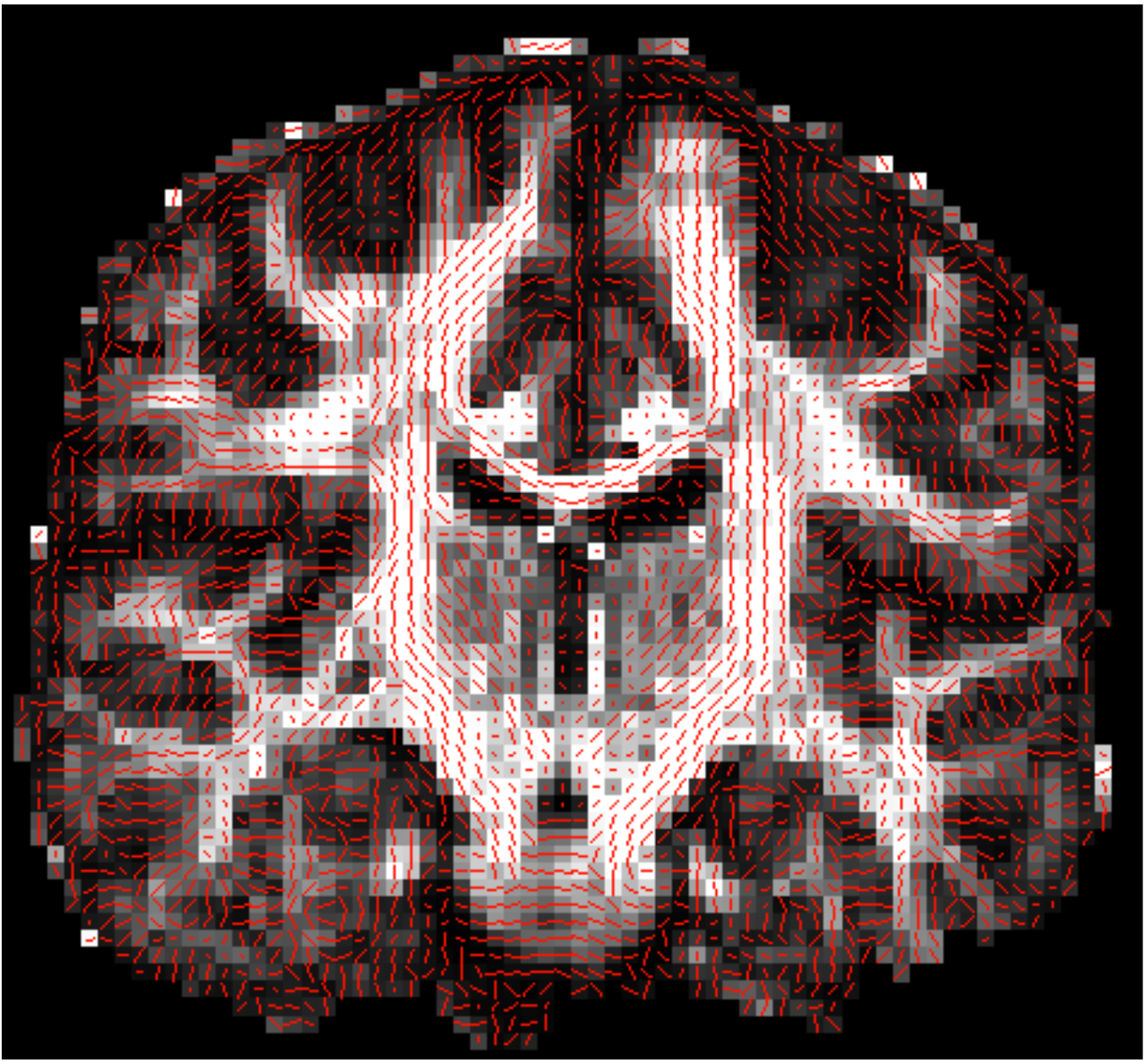


Orientations RGB-colour coded
方向RGB颜色编码

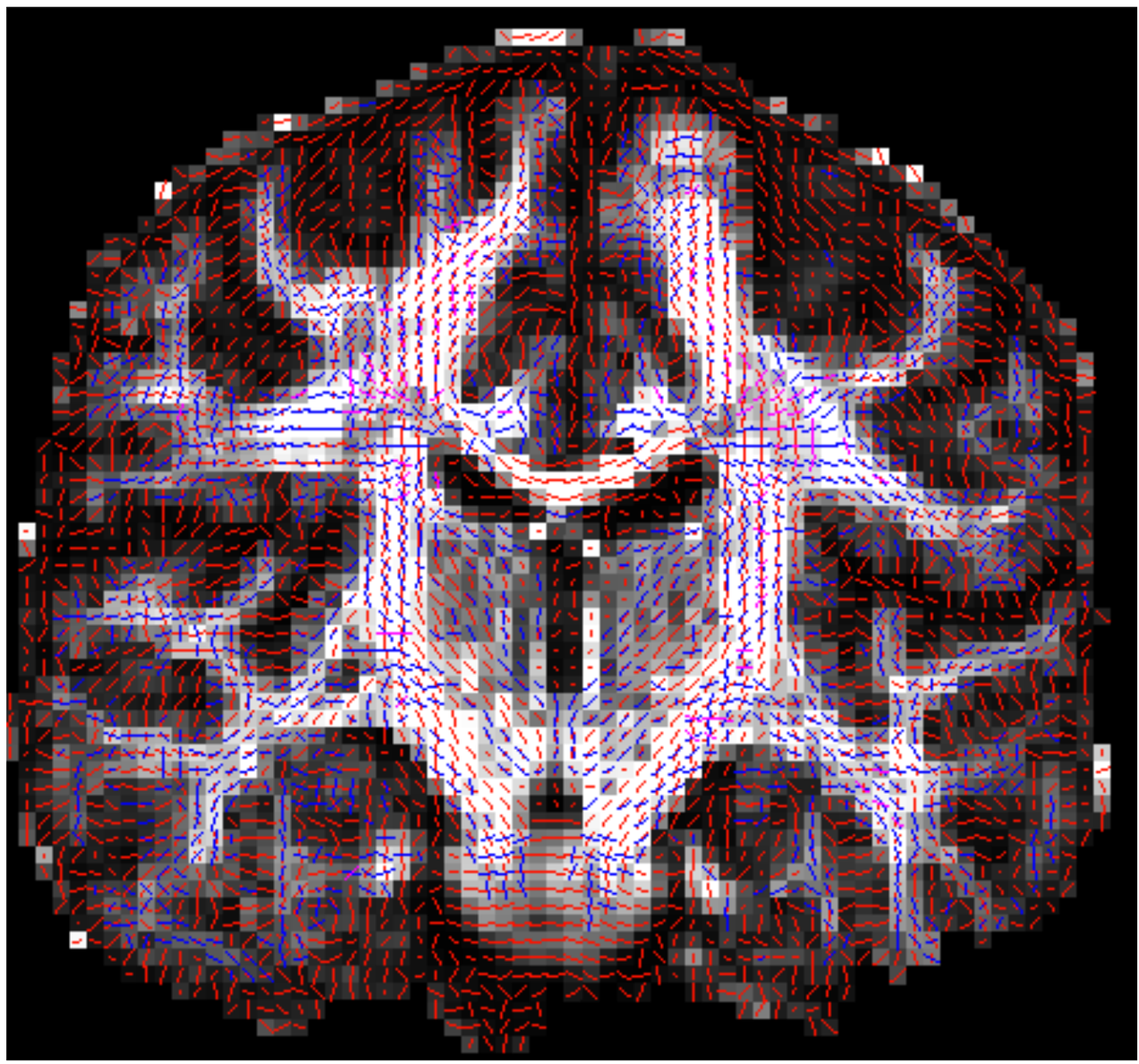


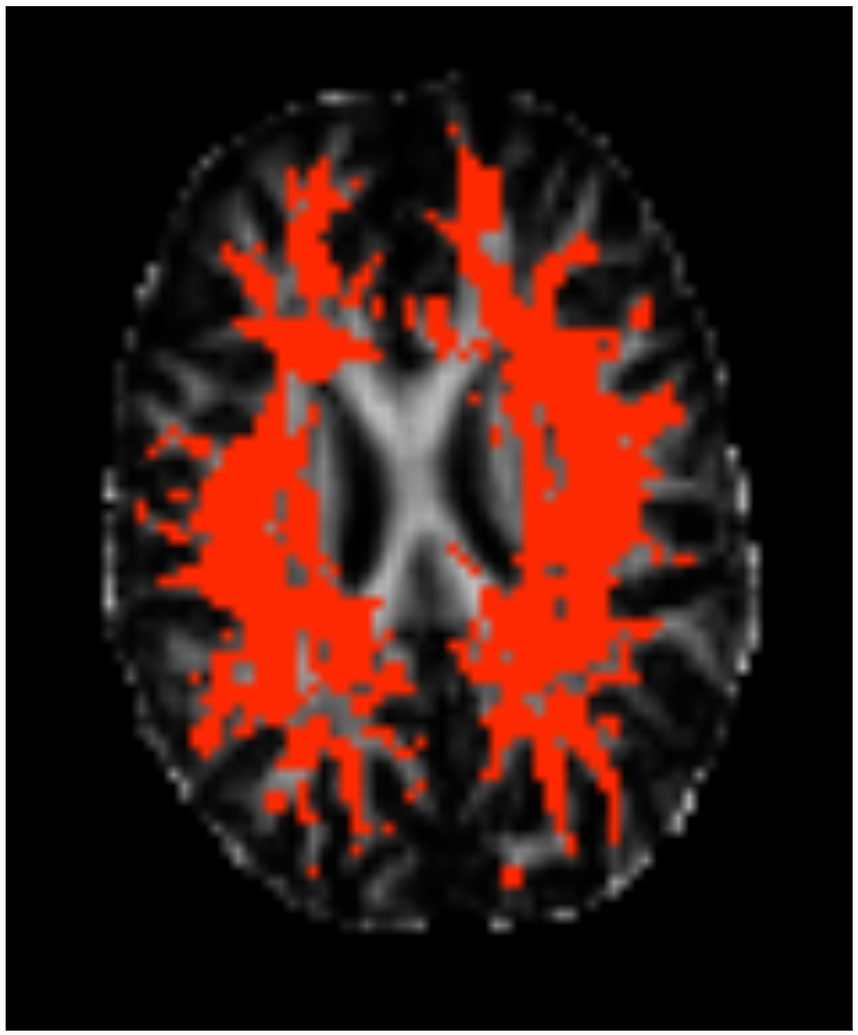
DTI vs Ball & Sticks Orientations
DTI与球形和棒形的方向

DTI



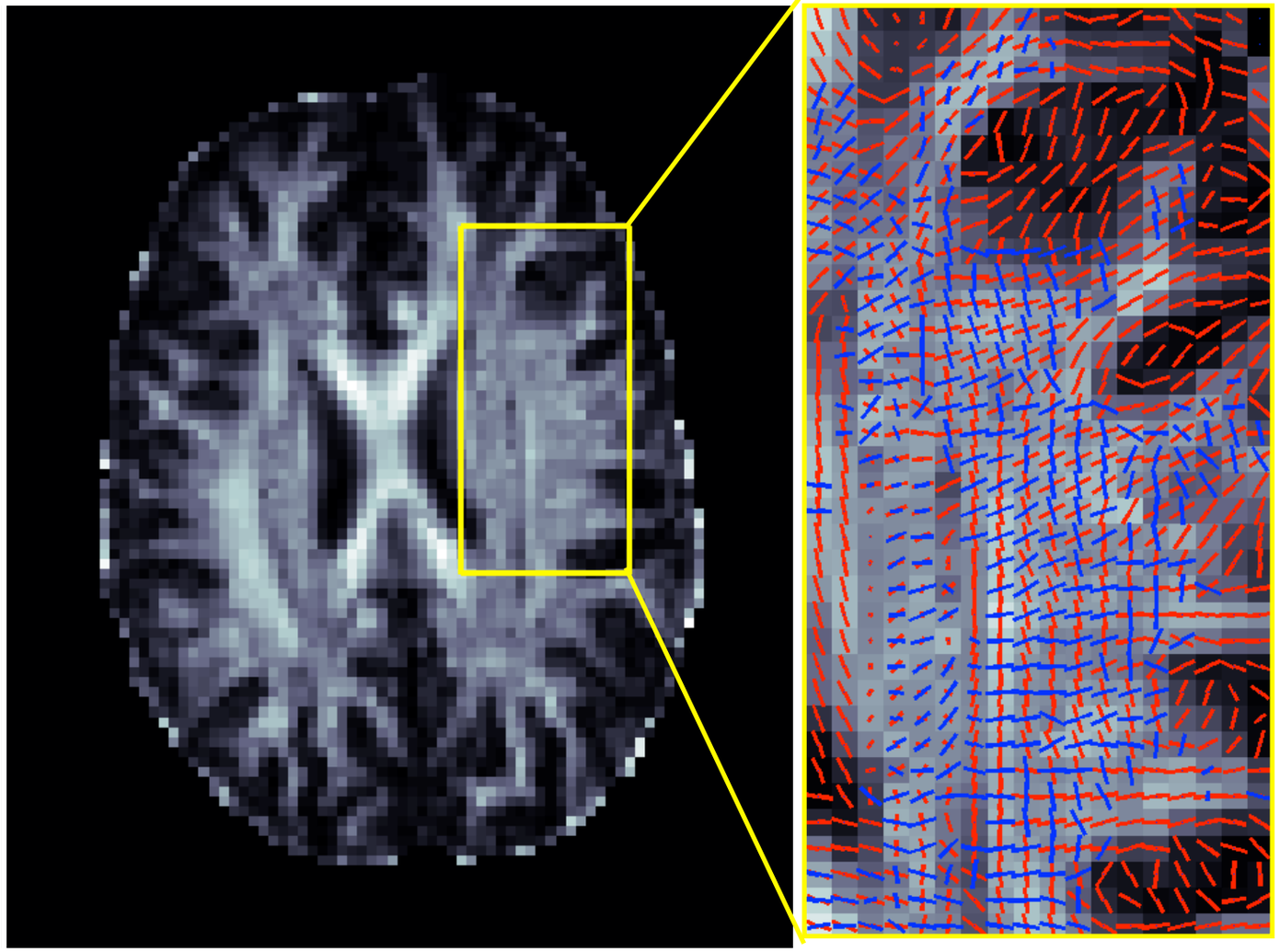
Ball & Sticks





A large portion of the WM supports crossing fibres

WM的很大一部分支持交叉纤维



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

方向的连贯性表明我们并不过度拟合（ARD工作）

Multi-Shell Diffusion Acquisitions 多核扩散采集

Why bother? 为什么呢?

One Orientation
一个方向

Two Orientations
两个方向

Three Orientations
三个方向

Signal at different b values (s/mm^2)

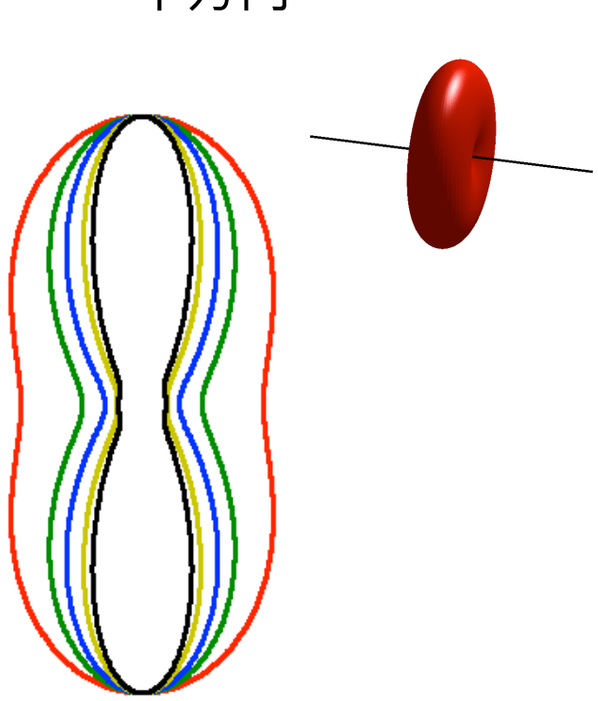
b=1000

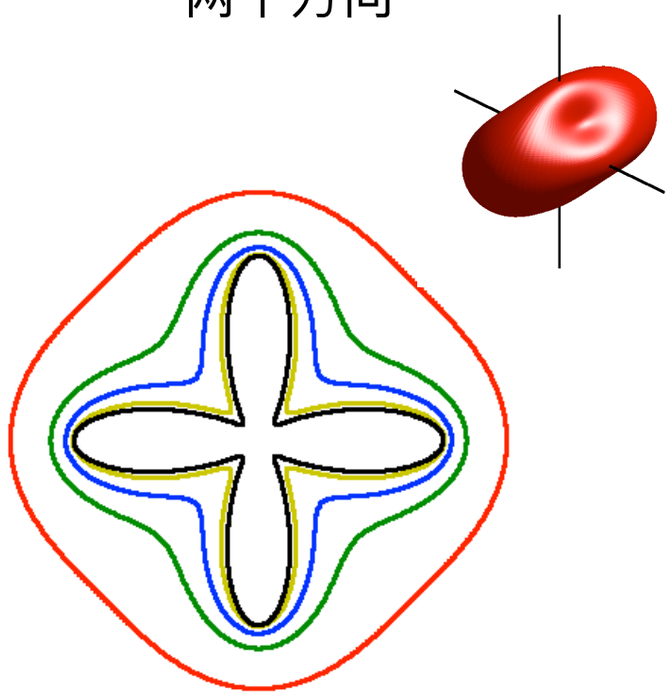
b=2000

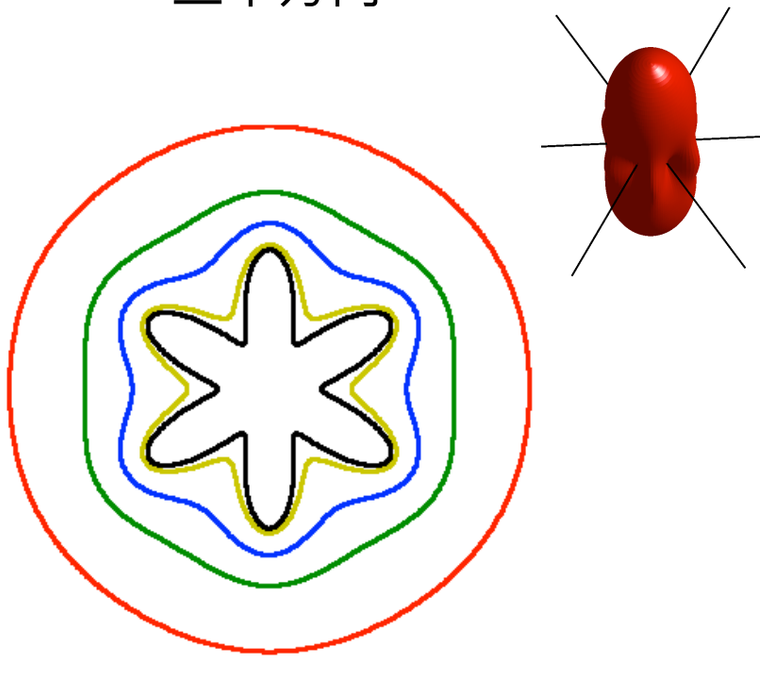
b=3000

b=4000

b=5000







Higher b value gives us more angular contrast!!!

b值越高，角度对比越大!

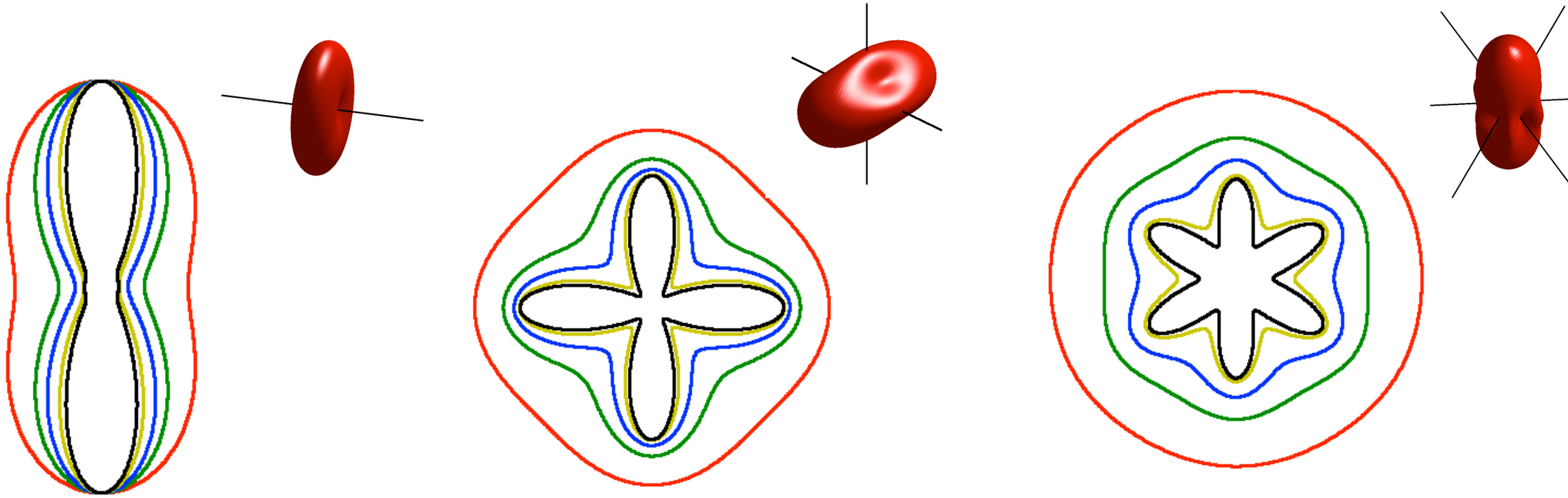
Multi-Shell Diffusion Acquisitions 多核扩散采集

Why bother? 为什么呢?

One Orientation

Two Orientations

Three Orientations



Signal at different b values (s/mm^2)

b=1000

b=2000

b=3000

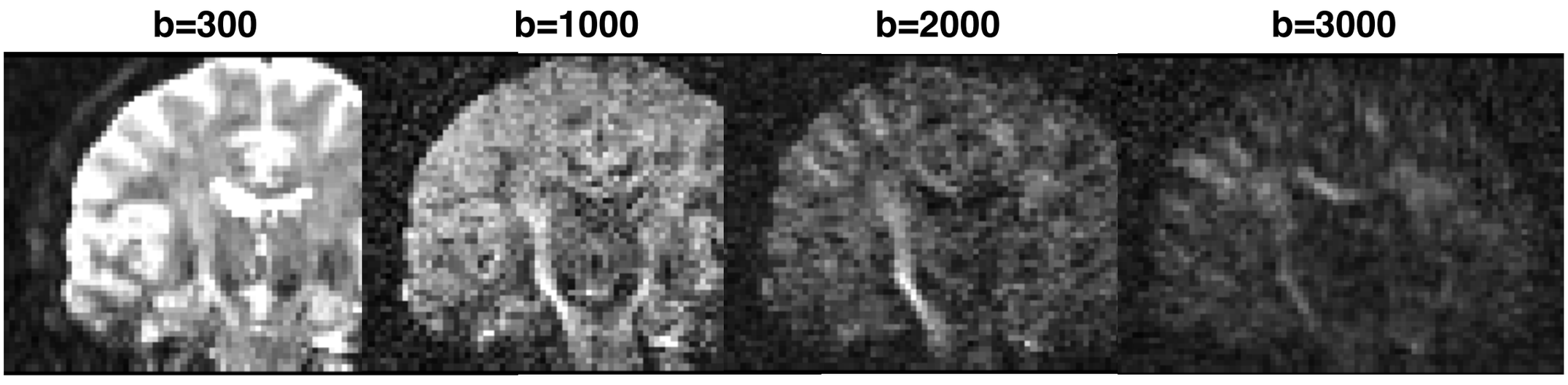
b=4000

b=5000

不同b值的信号

但是，随着b的改变SNR很快就会下降

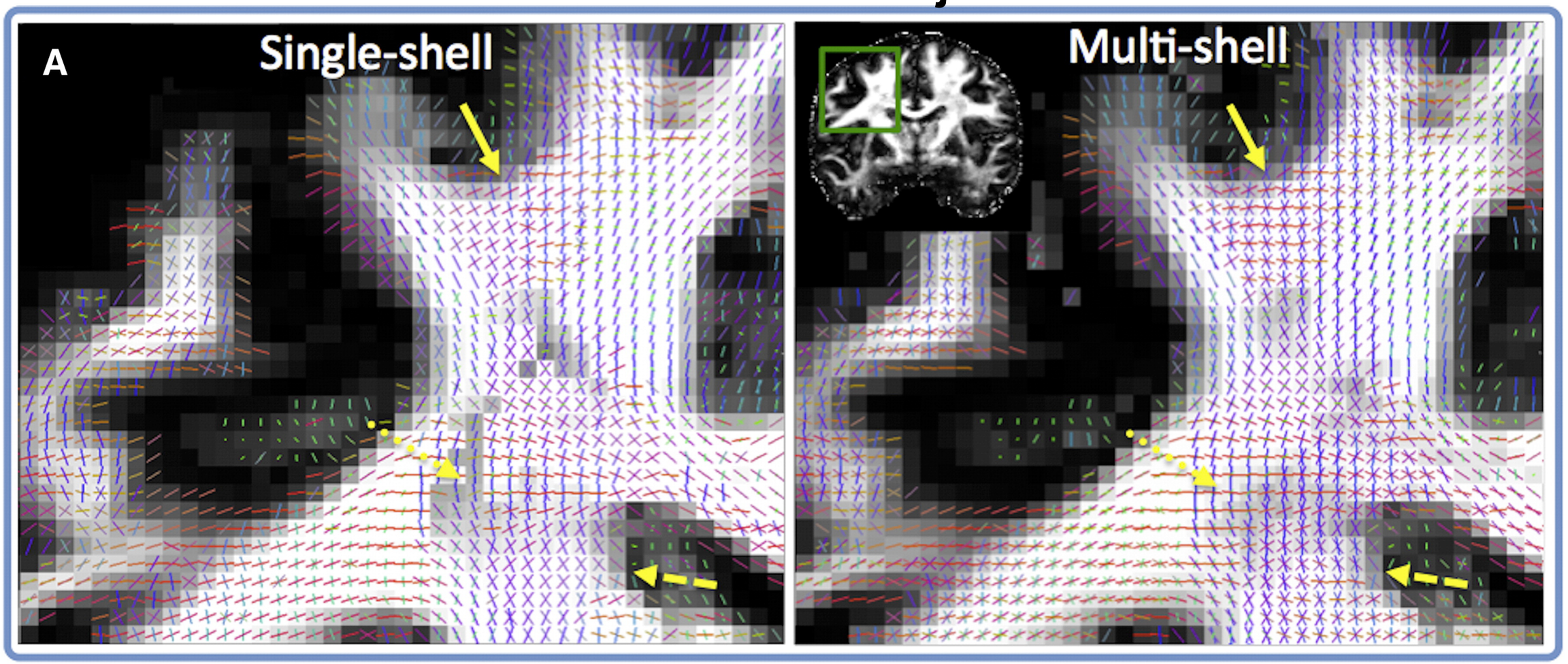
But SNR goes down very quickly with b…



Generalised Ball & sticks Model 球形 & 棒形模型
Gets best of both worlds 对他们最佳的理解

- Multi-shell model (or model=2) in Bedpostx options.Bedpostx
  选项中的多种模型（或模型= 2）
- Allows representation of multiple diffusivities within a voxel (rather than just one).
  允许在体素内表示多个扩散（而不是仅仅一个）
- More accurate model for multi-shell data & partial volume effects.
  更准确的多核数据模型和部分体素效果

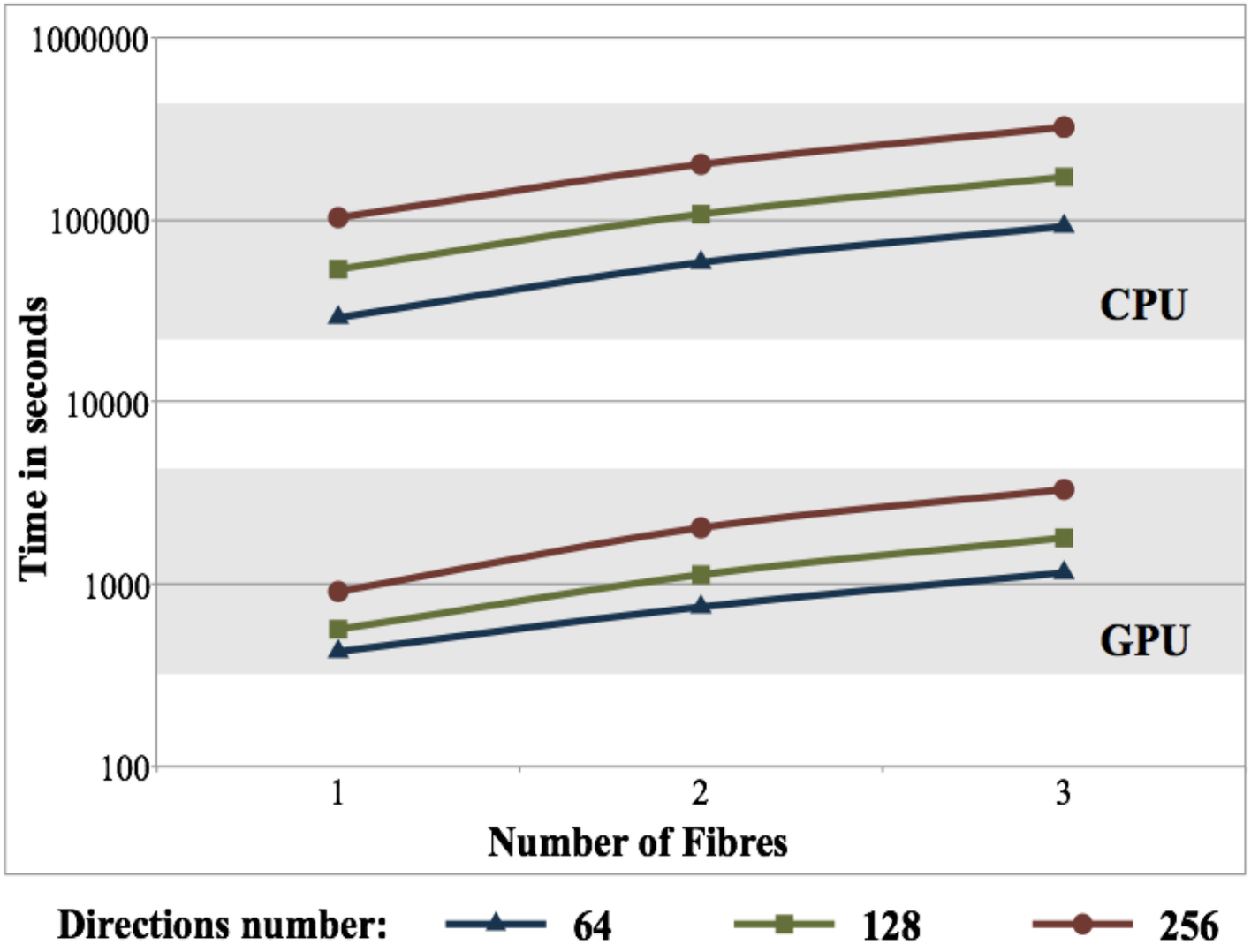
Human Connectome Project Data



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

Faster bedpostx on GPUs

GPU上运行Bedpostxg更快

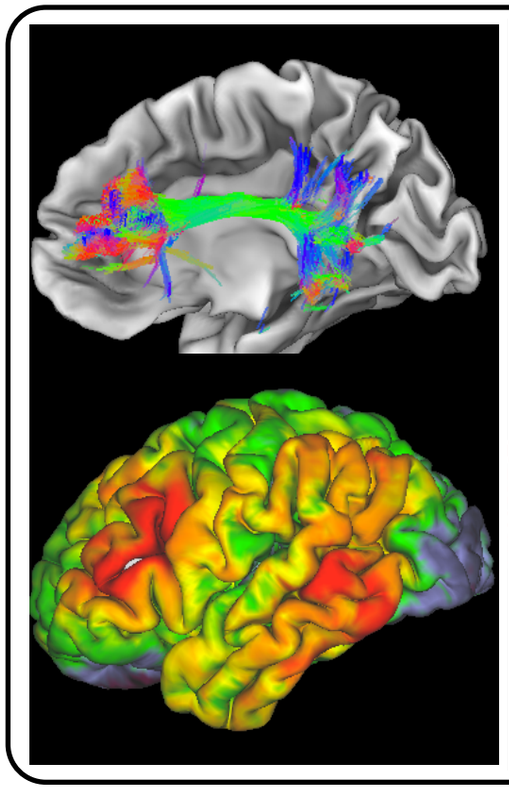
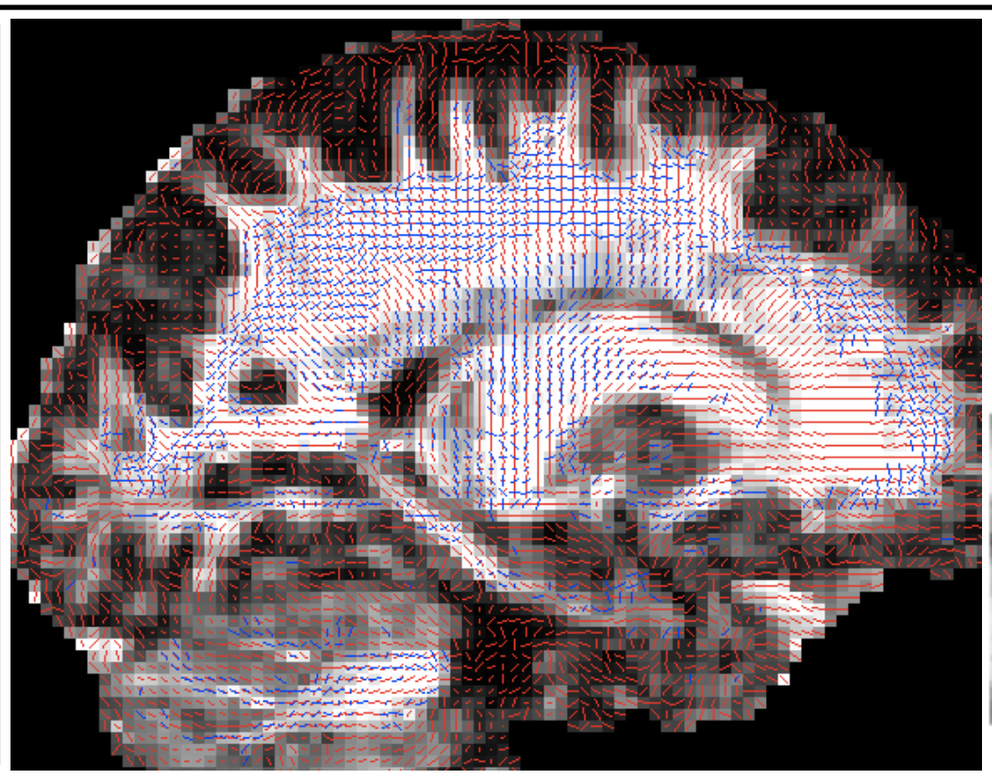
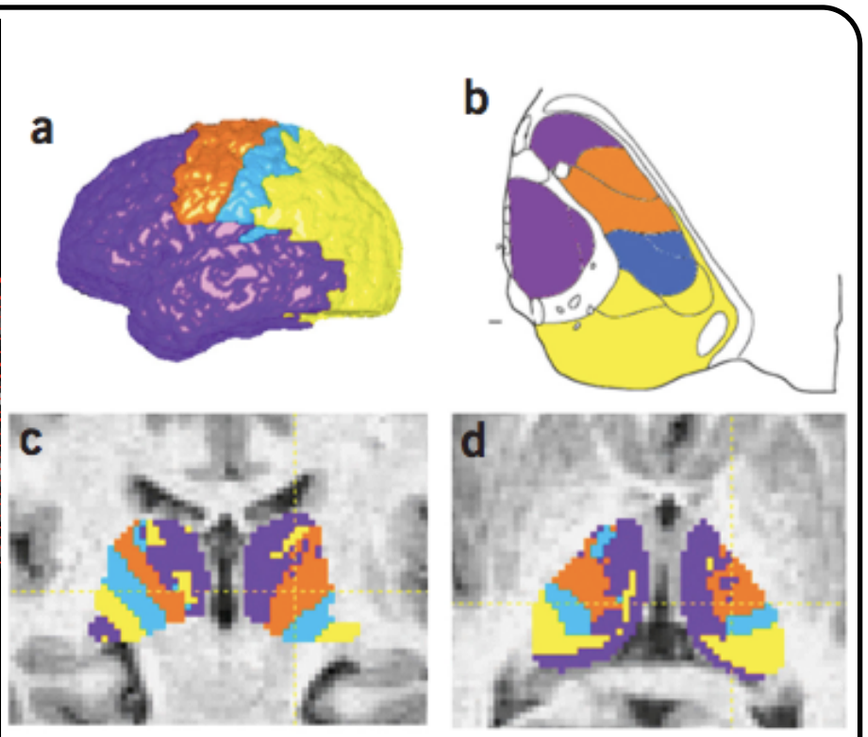


50x-150x Speedup using GPUs

Hernandez et al, Plos One 2013

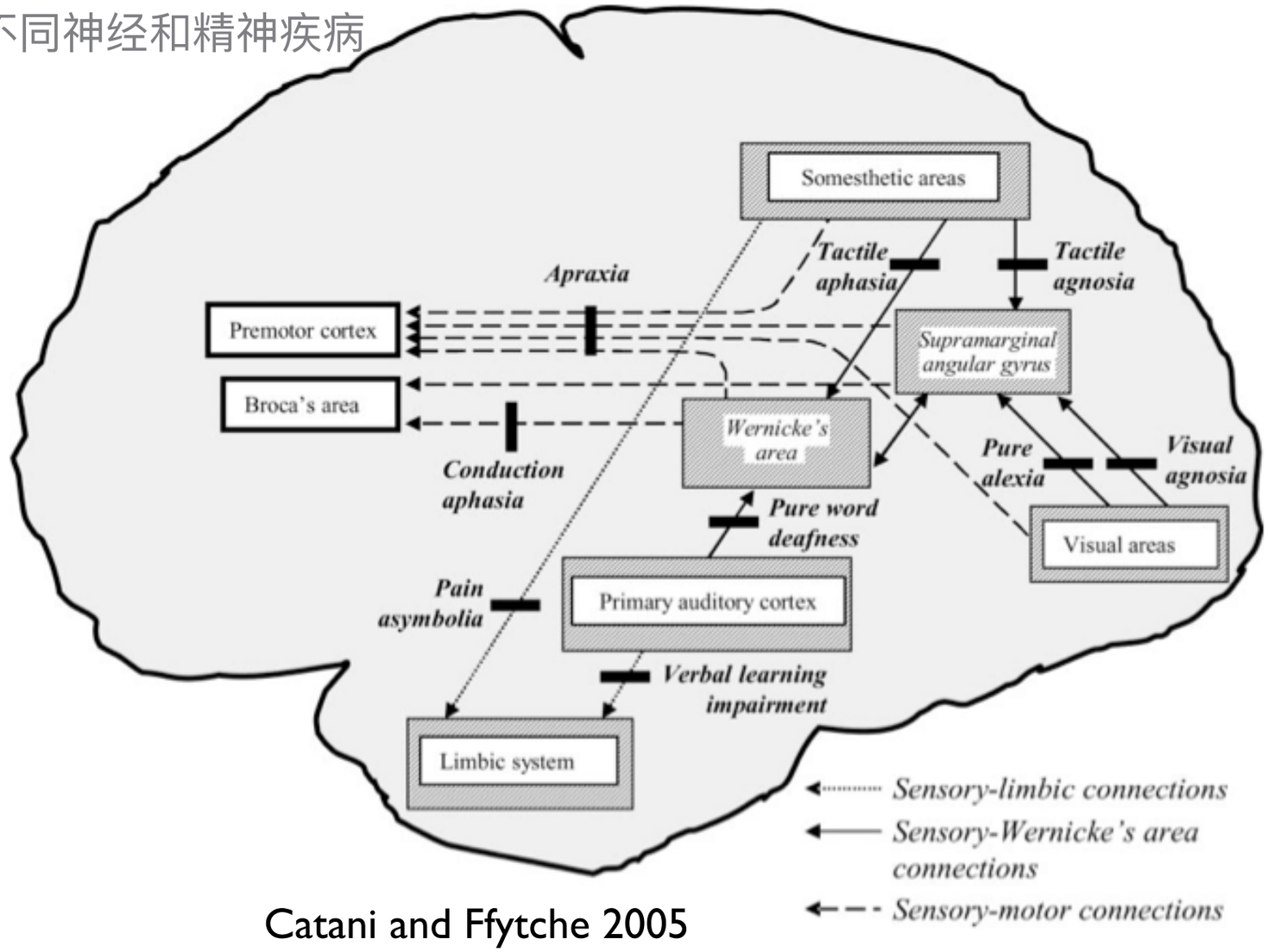
Overview
概況

- Estimating Fibre Orientations - BEDPOSTX
- Probabilistic Tractography - PROBTRACKX 概率追踪
- ProbtrackX outputs
- Tractography limitations

Connectivity - Why do we care?
连通性 - 我们为什么关心?

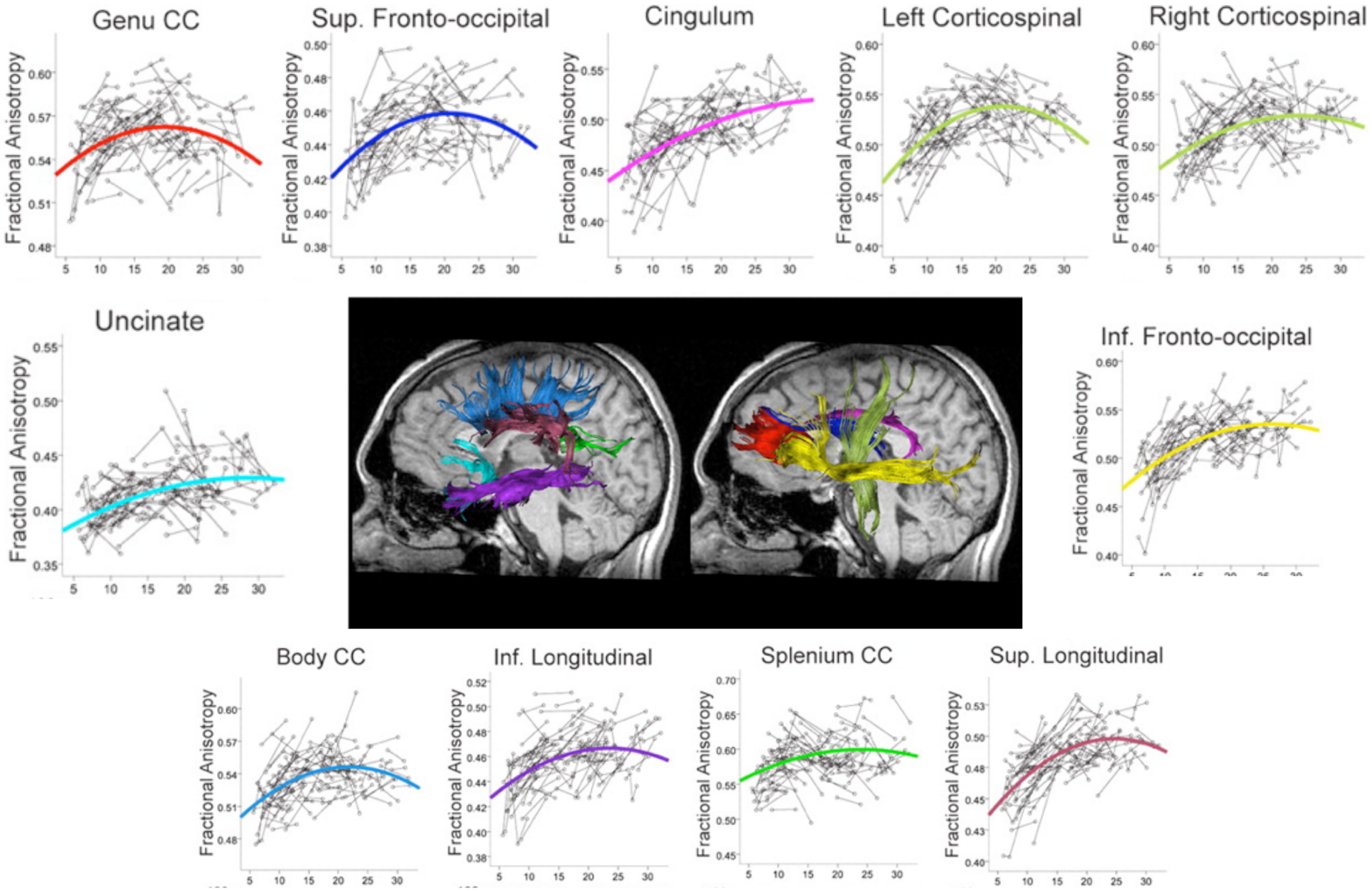
- White matter (dys)connectivity is thought to form the substrate for many different neurological and psychiatric disorders.
- 白质（异常）连通性被认为是许多不同神经和精神疾病的基础。



Catani and Ffytche 2005

Connectivity - Why do we care? 连通性 - 我们为什么关心?

- Tractography provides non-invasive localisation and semi-quantitative biomarkers Tractography
- 提供非侵入性定位和半定量生物标记

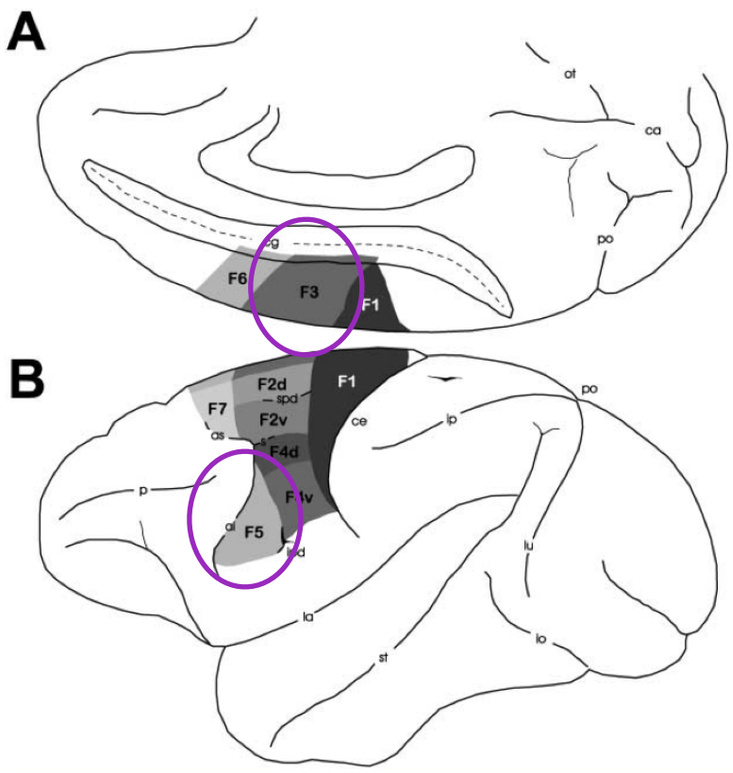


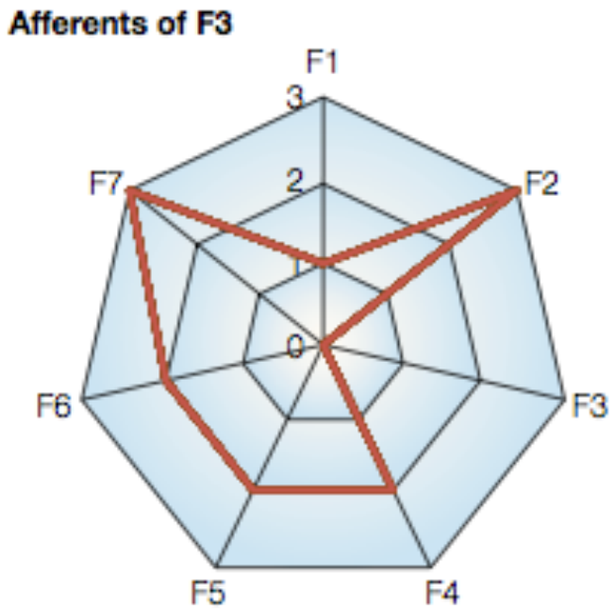
Lebel, Beaulieu J Neuroscience 2011

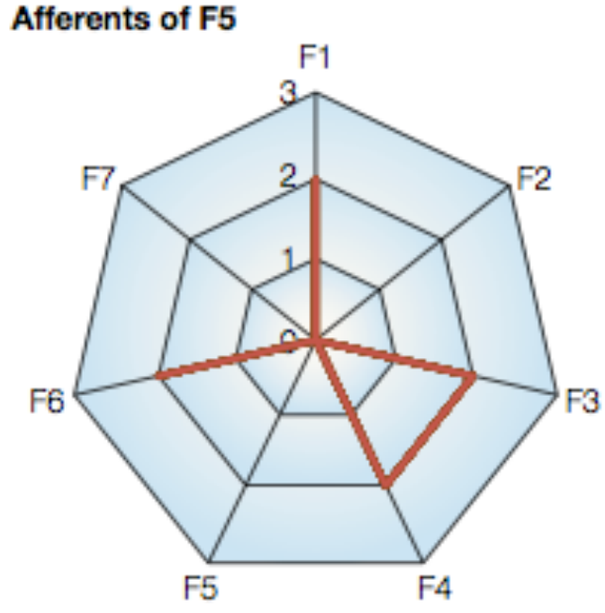
Connectivity - Why do we care? 连通性 - 我们为什么关心?

- Connections constrain function
- 连接约束功能

- Different regions have distinct connectivity fingerprints
- 不同区域具有不同的连接模式





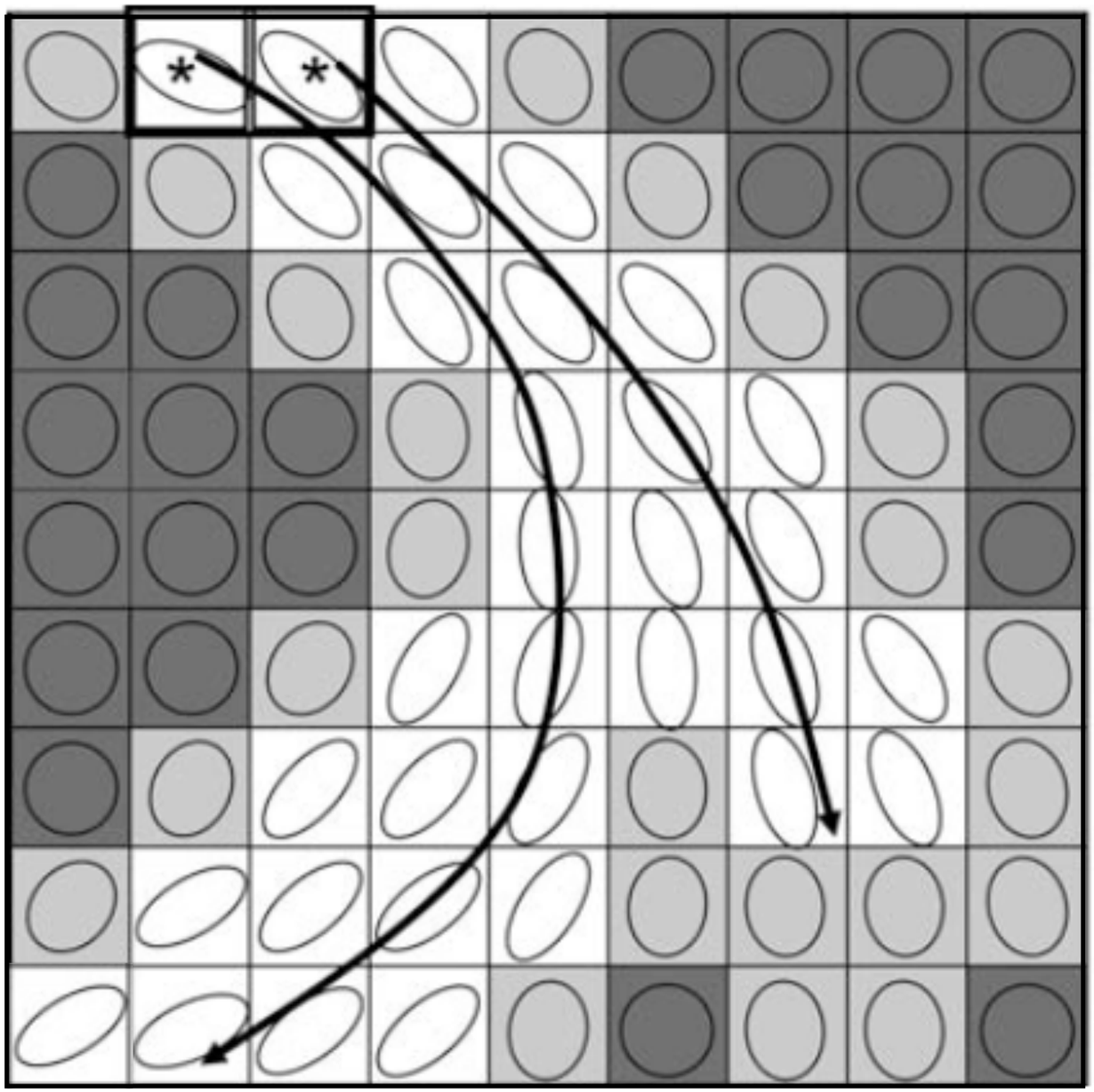


Passingham et al. 2002

DTI Streamline Tractography

DTI流线型的纤维束追踪

Seed region 种子区域



Mori S, Neuron 2006

Formally, we solve numerically the differential equation:

形式上，我们用数值求解微分方程

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

- $\frac{d\mathbf{r}(s)}{ds}$: Position along a curve — 沿曲线定位
- $\mathbf{v_1}(\mathbf{r}(s))$: Principal eigenvector $\mathbf{v_1}$ at position $\mathbf{r}(s)$ — 位置r（s）的主特征向量v1
- $\mathbf{r}_0$: Starting Position — 起始位置

DTI Streamline Tractography

DTI简化的纤维束追踪

But When to Stop? 但什么时候停止?

Heuristics to avoid error propagation. 启发式算法以避免错误传播。

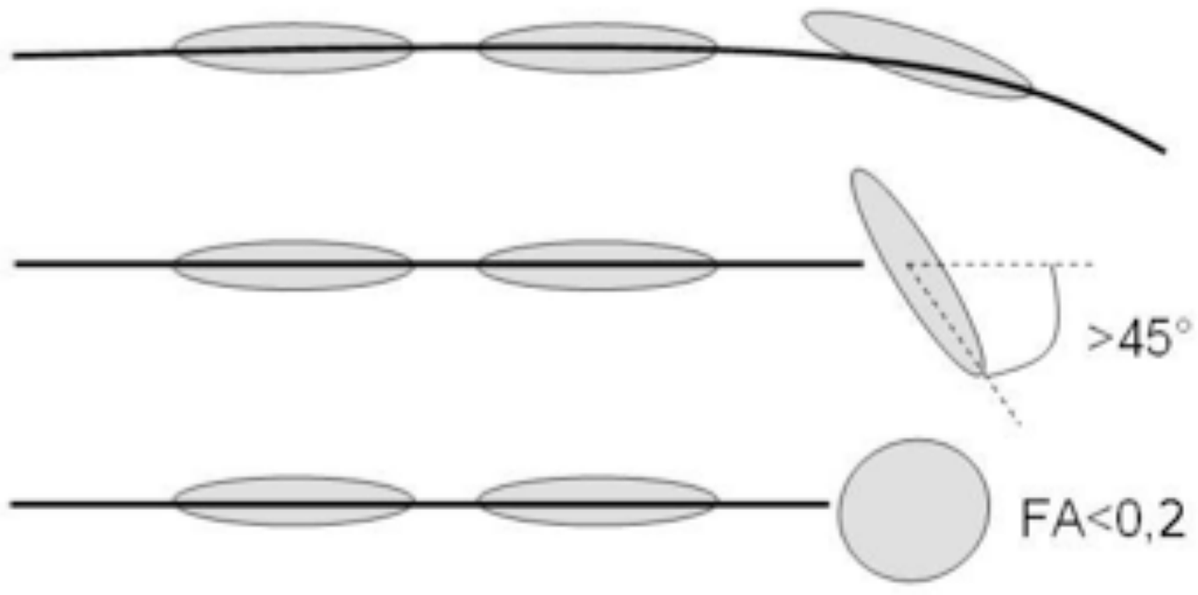
+ Knowledge of the anatomy 了解解剖学

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

曲率变化阈值：为避免边界和非常弯曲的轨迹的交叉，需限制平滑度标准。

Anisotropy Threshold: To avoid propagating in regions where $\mathbf{v}_1$ is meaningless. 各向异性阈值：避免在v1无意义的区域中传播。

Anatomical criteria (e.g. reach grey matter) 解剖标准（例如达到灰质）



Streamline tractography can dissect major bundles

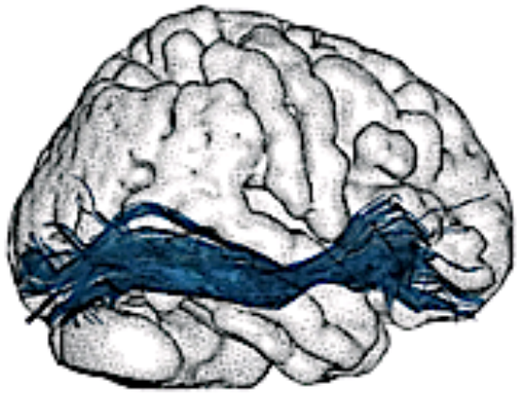
流线型细胞分析术可以剖析主要的束

arcuate fasciculus

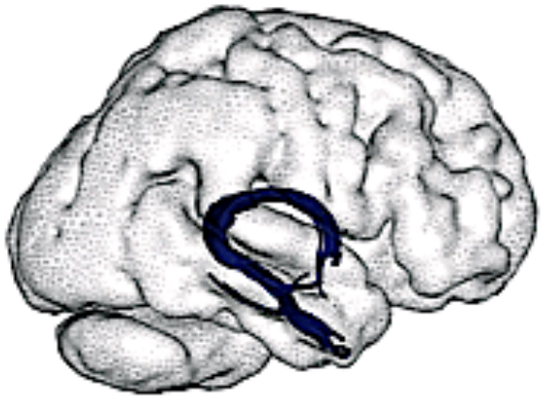
cingulum bundle

inferior longitudinal fasciculus

corpus callosum

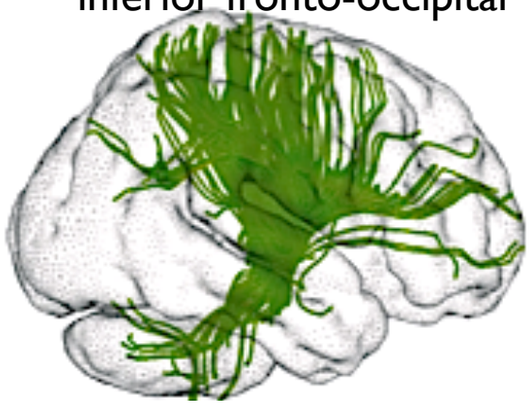


inferior fronto-occipital



fornix

uncinate fasciculus



corona radiata

cerebellar tracts

Catani and Thiebaut de Schotten 2008

DTI Streamline Tractography Summary

DTI流线型的纤维束追踪的总结

- Use the major axis of the DTI ellipsoid as a fibre orientation estimate. 使用DTI椭球的长轴作为纤维方向估计。

- Propagate curves within this vector field until empirical thresholds are exceeded. 在此向量字段内传播曲线，直到超过经验阈值。

- Major fibre bundles can be reconstructed. 主要纤维束可以重建。

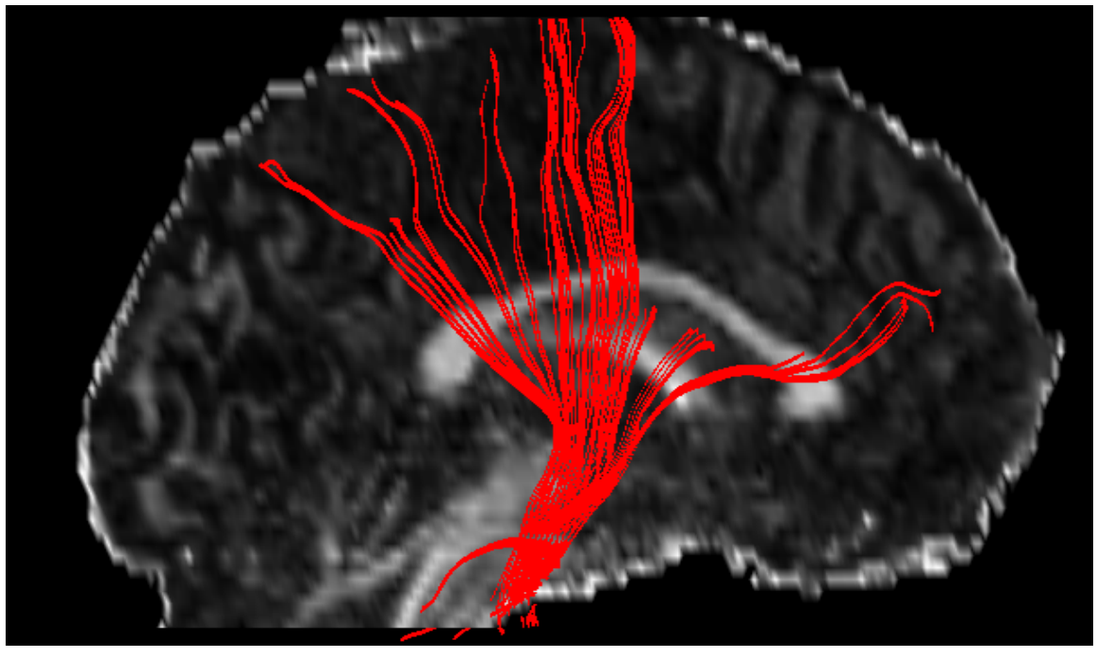
Streamlining reproducibility 纤维束重建

Repeat an acquisition many times and repeat streamline tracking.
多次重复采集并重复流线跟踪

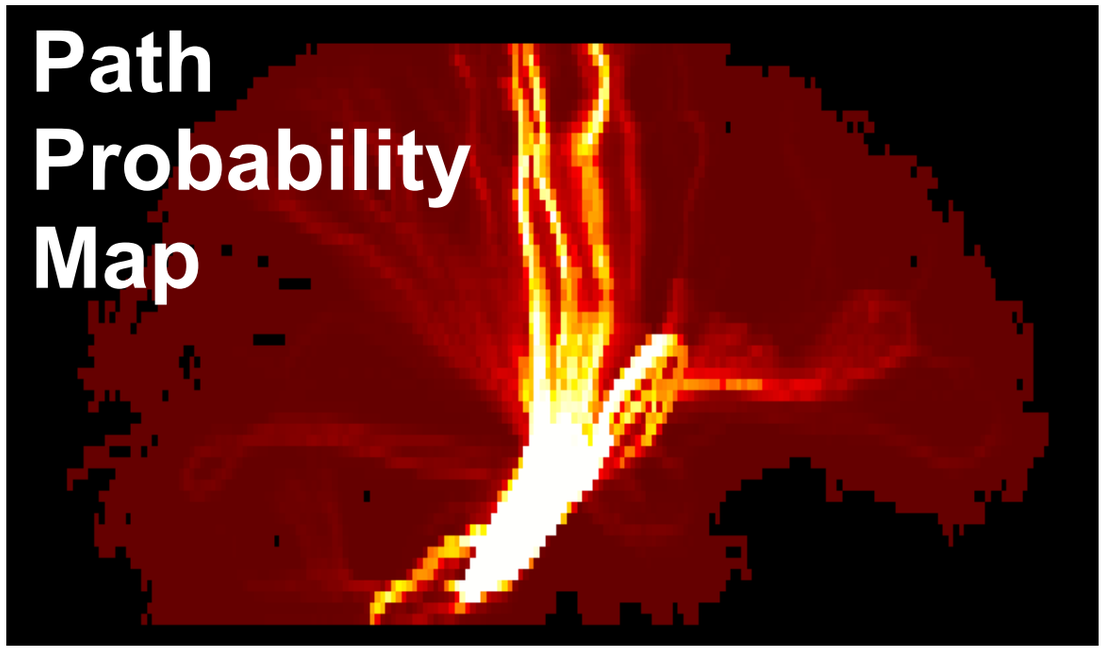
Due to uncertainty in $\mathbf{v_1}$, curves will not perfectly overlap
由于v1的不确定性，曲线不会完全重叠

Create a map that shows the degree of overlap across the trials.
创建一个显示试验中重叠程度的地图

Streamlines from a single dataset
单个数据集的纤维束



Map that shows where results across datasets overlap
数据集间结果的重叠图



Low Reproducibility — High Reproducibility

Probabilistic Tractography
概率追踪

- We normally have one dataset per subject, not many.
  我们通常每个被试有一个数据集，不是很多

- Probabilistic Tractography as a two-step process:
  概率性追踪分为两步：

a) Use DWI data and a model to infer a fibre orientation **and its uncertainty** in each voxel. 使用DWI数据和模型推断每个体素中的纤维方向及其不确定性

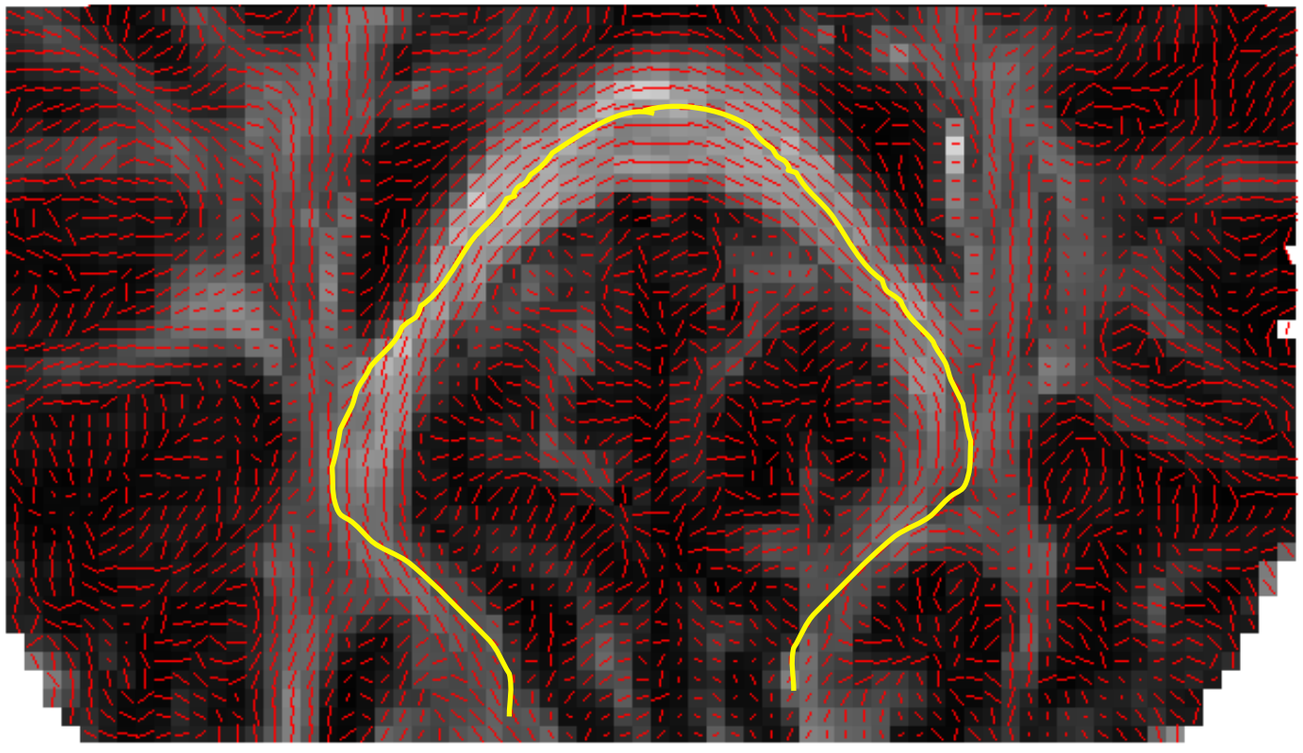
b) Use the estimates **and the uncertainty to build a path probability map** to a seed. 使用估计值和不确定性来构建种子的路径概率图

Probabilistic tractography

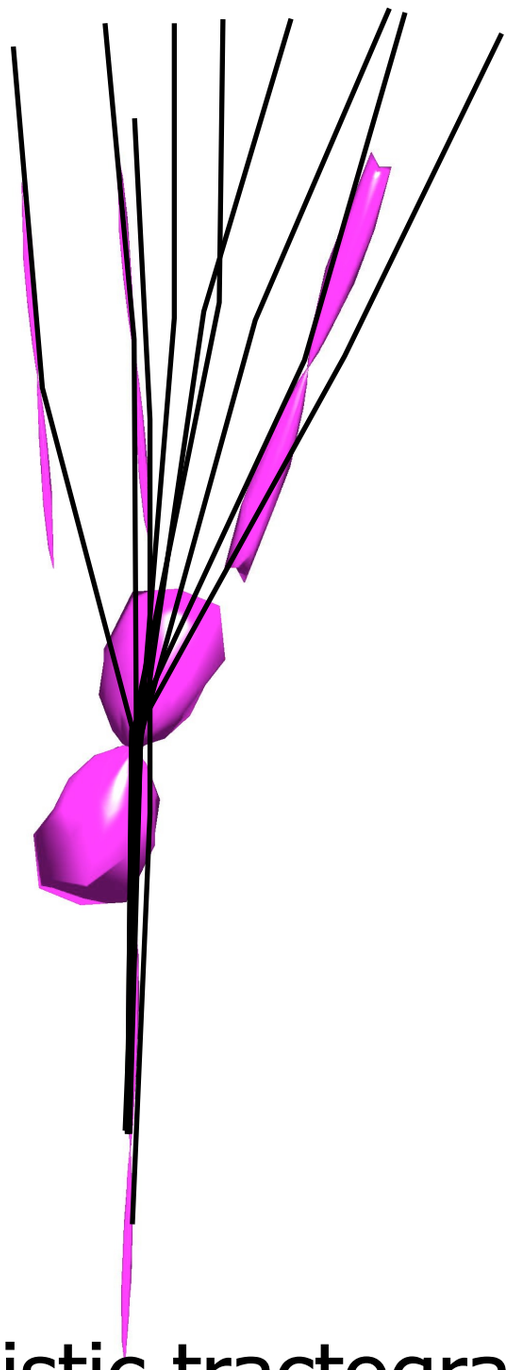
概率追踪

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

但是现在我们在每个体素并没有单一方向。那我们该怎样做追踪呢?



'Streamlining'

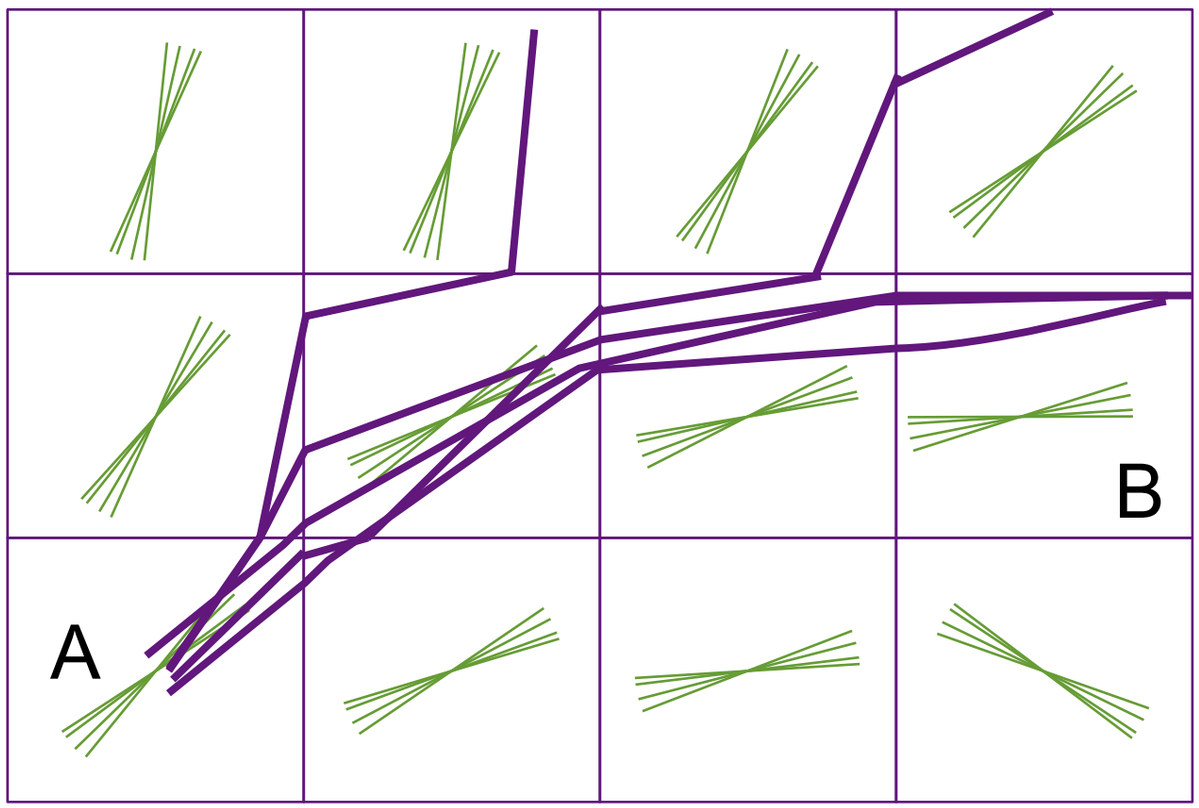


Probabilistic tractography

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

Probabilistic Tractography - Propagating the Uncertainty

概率追踪 - 传播的不确定性



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.

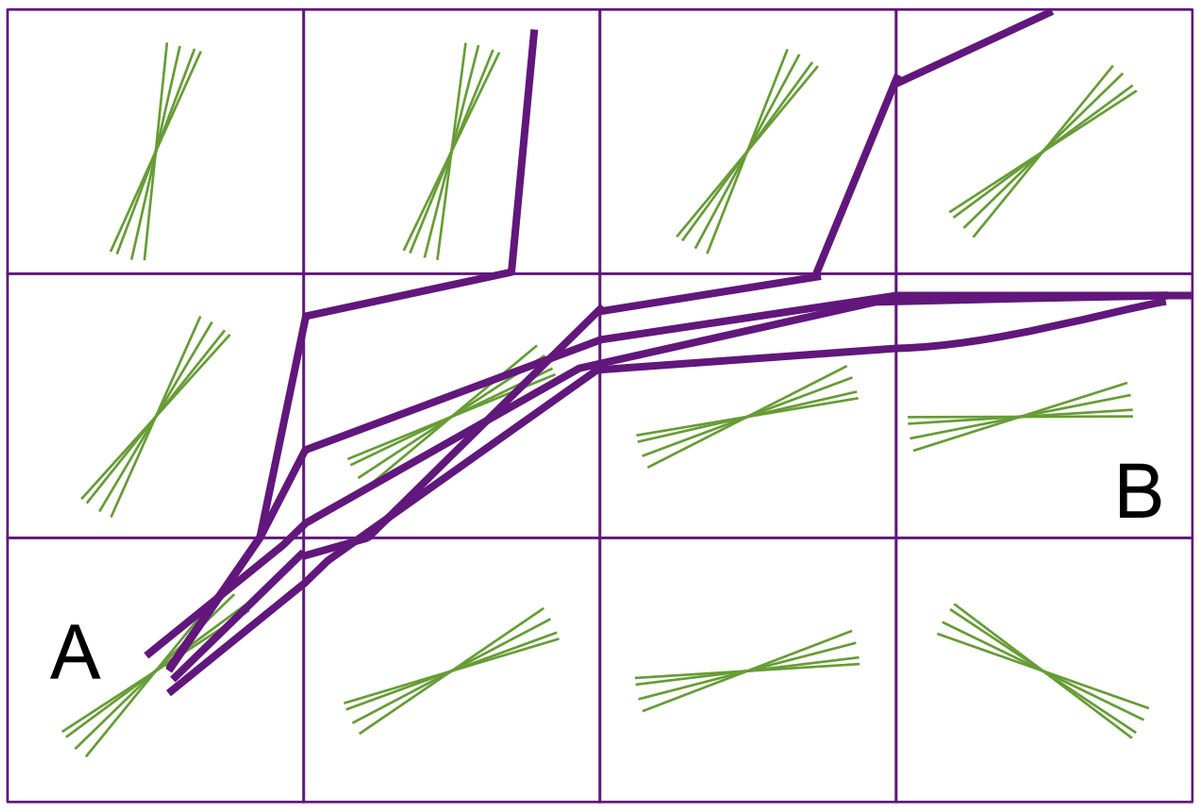
从种子区传播N条流线，但是对于每个传播步骤，从基础分布中随机选择一个方向

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

建立曲线的空间分布，以模仿多次扫描中多次确定性追踪产生的重叠结果

Probabilistic Tractography - Propagating the Uncertainty

概率追踪 - 传播的不确定性



Behrens et al, 2003
Parker et al, 2003

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

在每个B地点定义重叠度为

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

M:number of streamlines that go through B

N: total streamlines generated from A

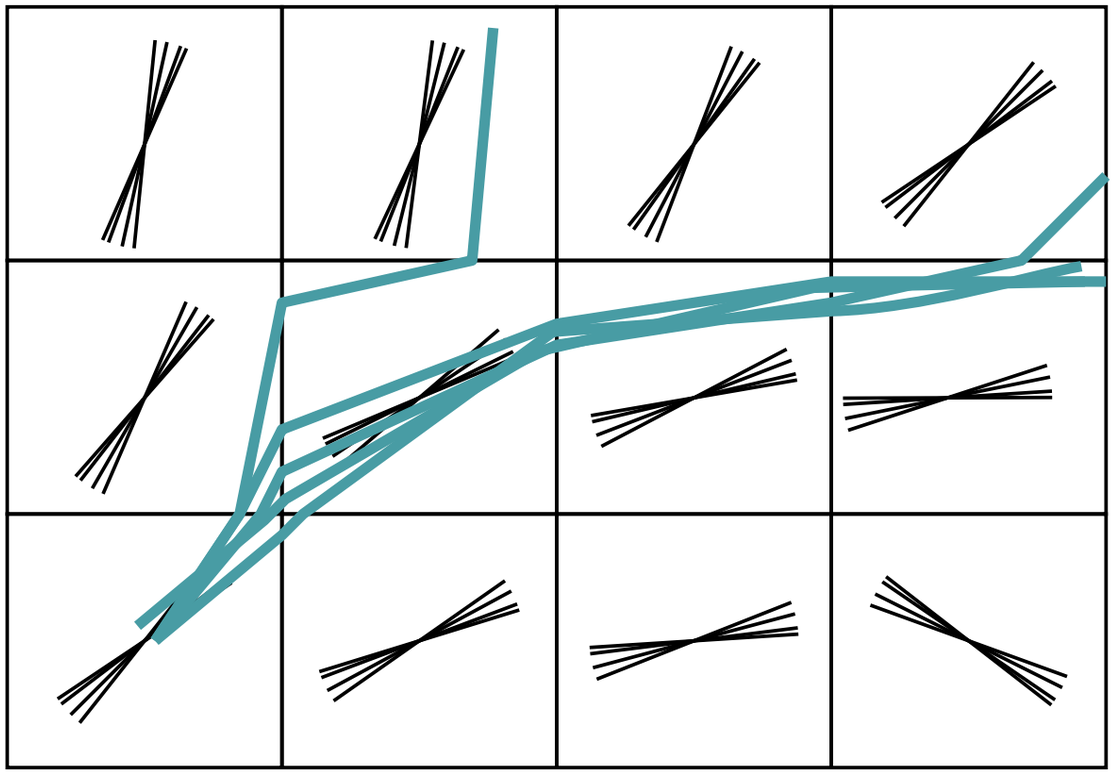
M： 穿过B区流线的数量　　N: 从A区产生的流线数目总和

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

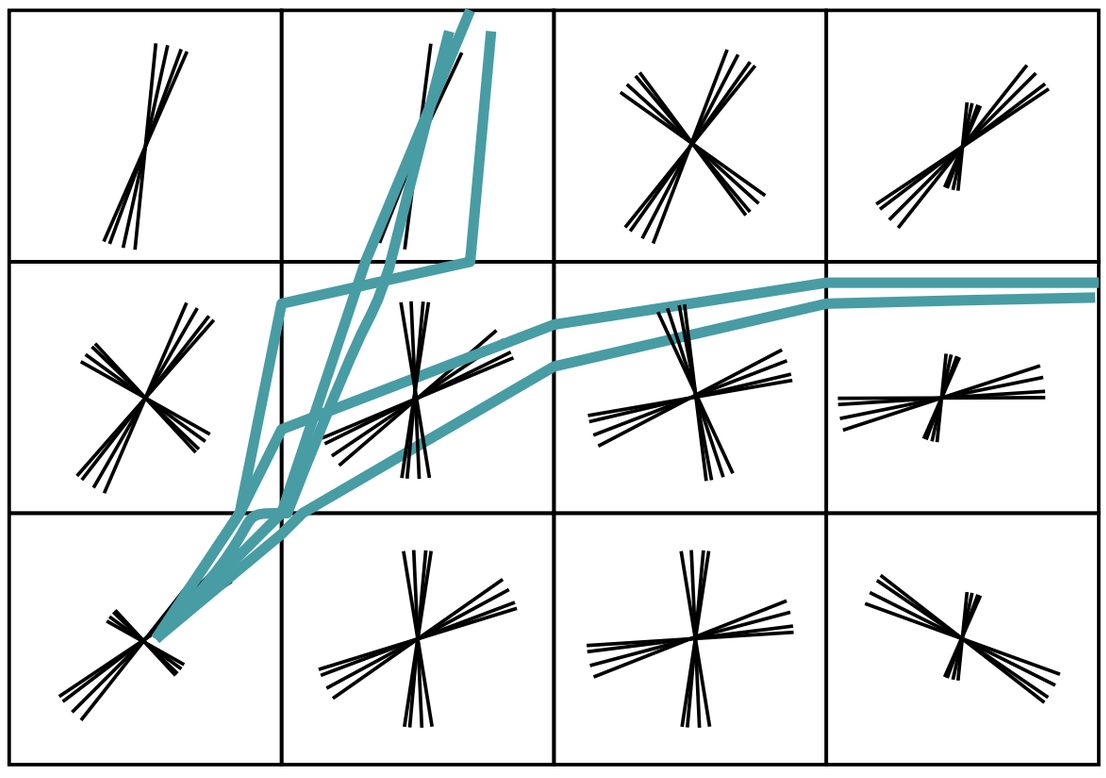
这就是一个始于A穿过B的追踪曲线的概率

Probabilistic Tractography in Multi-Fibre Fields

多纤维场概率追踪



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.

当在一个体素中存在多个纤维方向时，选择与传入轨迹最兼容的那一个

Probabilistic Tractography in Multi-Fibre Fields
Examples

多纤维场概率追踪

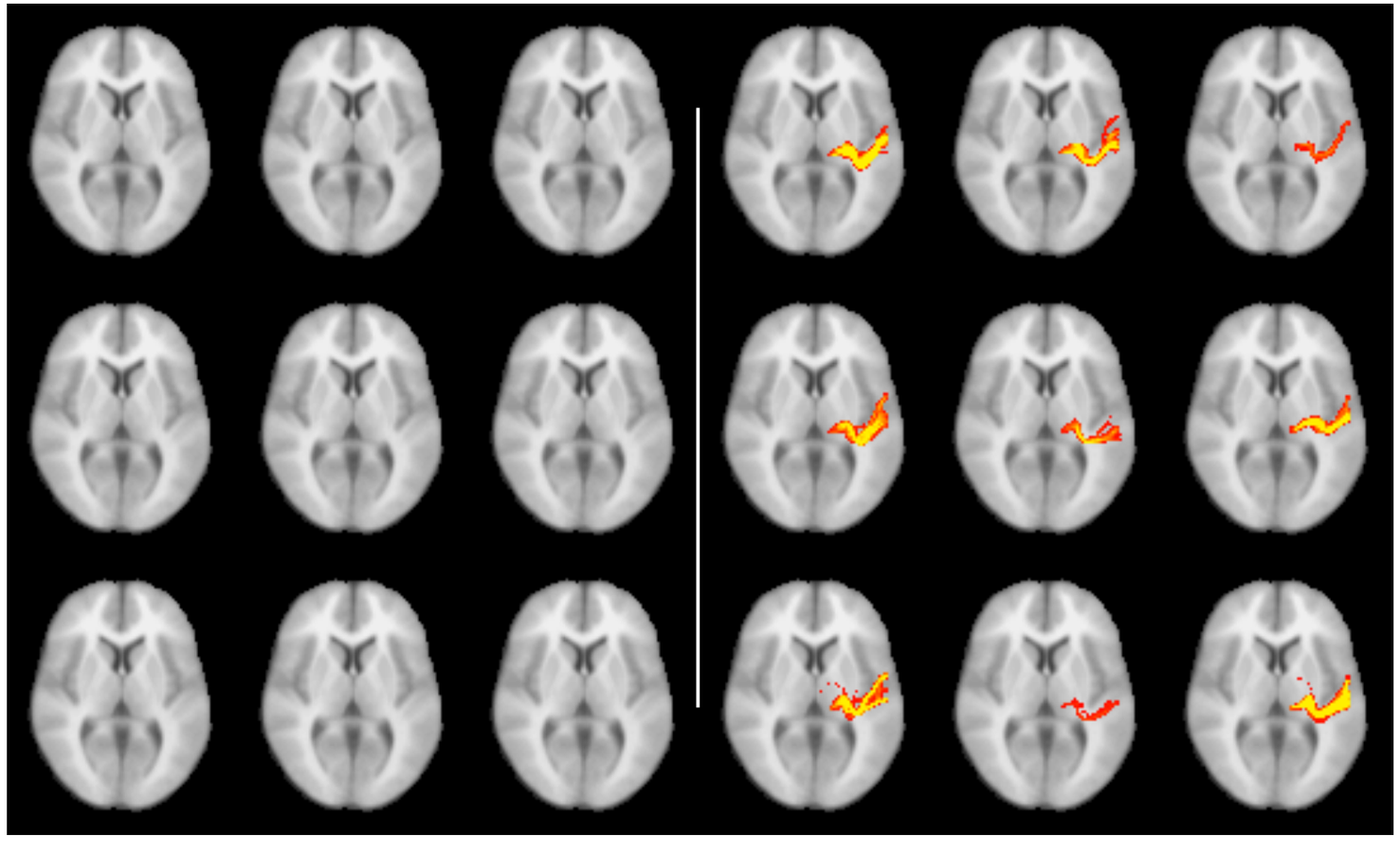
Acoustic radiations.

9 subjects

Behrens et al, 2007

Opt.R

MGN --- Primary Auditory cortex



one fibre

two fibres

Path Probability Map 路径概率图谱

- Recall that it assesses how reproducible results are

回想一下它评估结果的可重复性

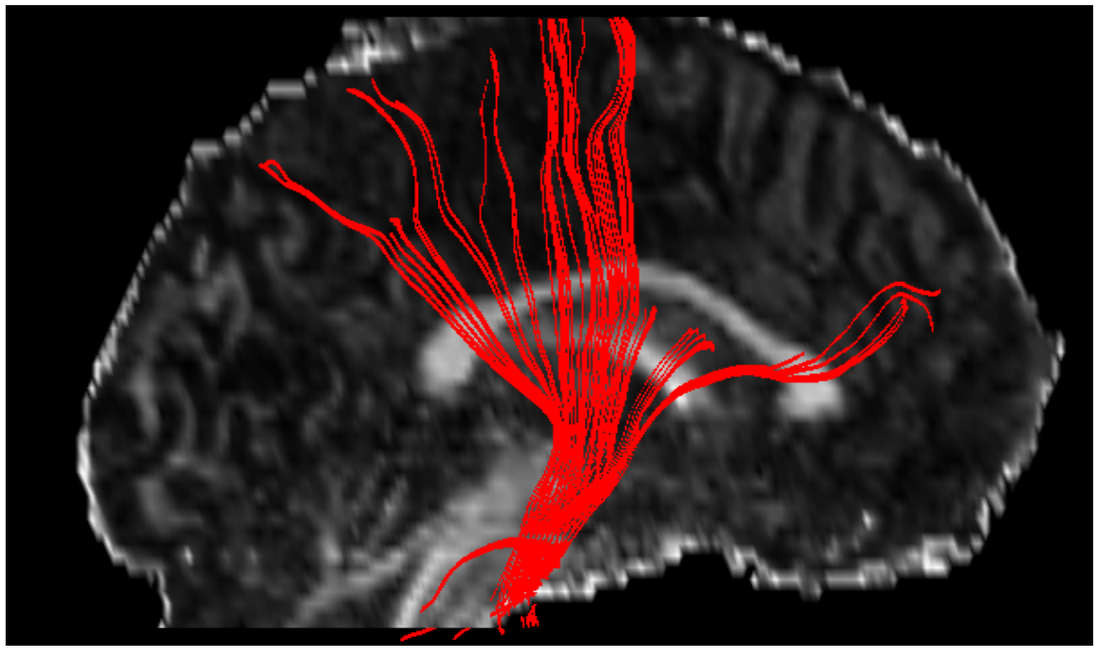
- Often called “connection probability”, “connectivity index”, “connectivity strength”. But it does not quantify how strong a connection is...

通常称为“连接概率”，“连接指数”，“连接强度”。 但这无法量化连接的强度...

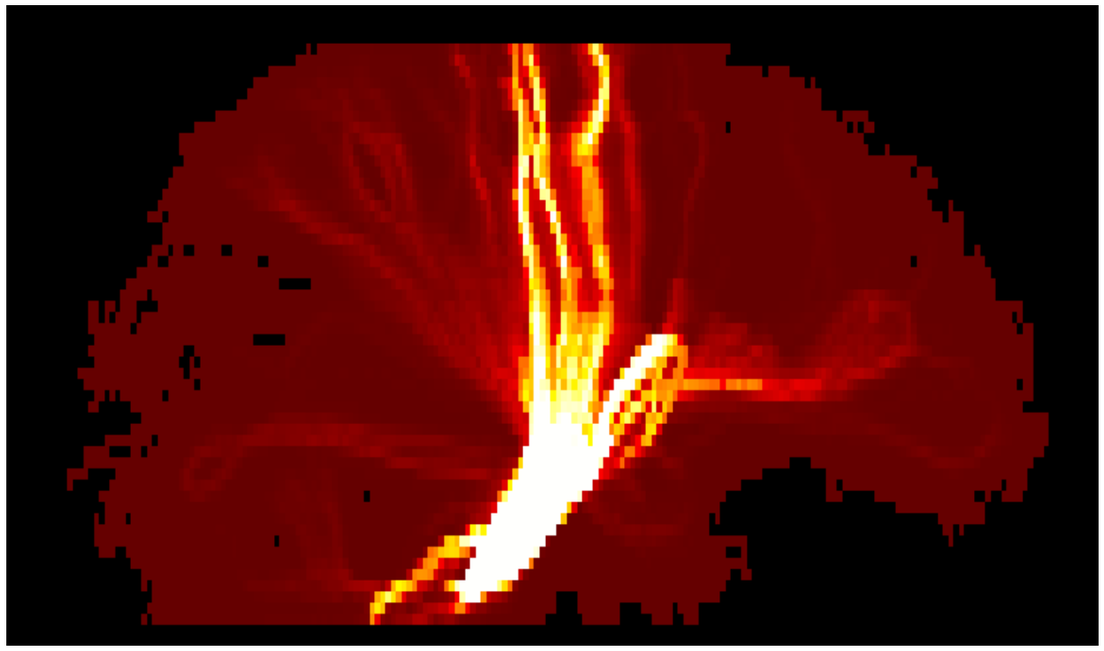
- Rather, how robust it is against noise/uncertainty

相反，它表示对噪声/不确定性的鲁棒性

Deterministic Tractography 确定性追踪



Probabilistic Tractography 概率性追踪

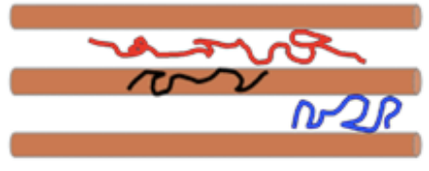


Probabilistic Streamline Tractography Summary
纤维束概率追踪总结

- 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!
  需要除方向估计之外的需求，估计其不确定性。不需要是球棒模型，可以使用DTI模型代替！

- 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.
  从种子区重复传播流线，但方向字段不再是确定性的。在每个传播步骤中，从基础分布中随机选择一个方向。

- 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.**
  可以从种子A到脑B中的任何体素获得连接概率值≥0。这评估了从A到B的路径的再现性，水分子优选地沿着该路径扩散。



Overview
概况

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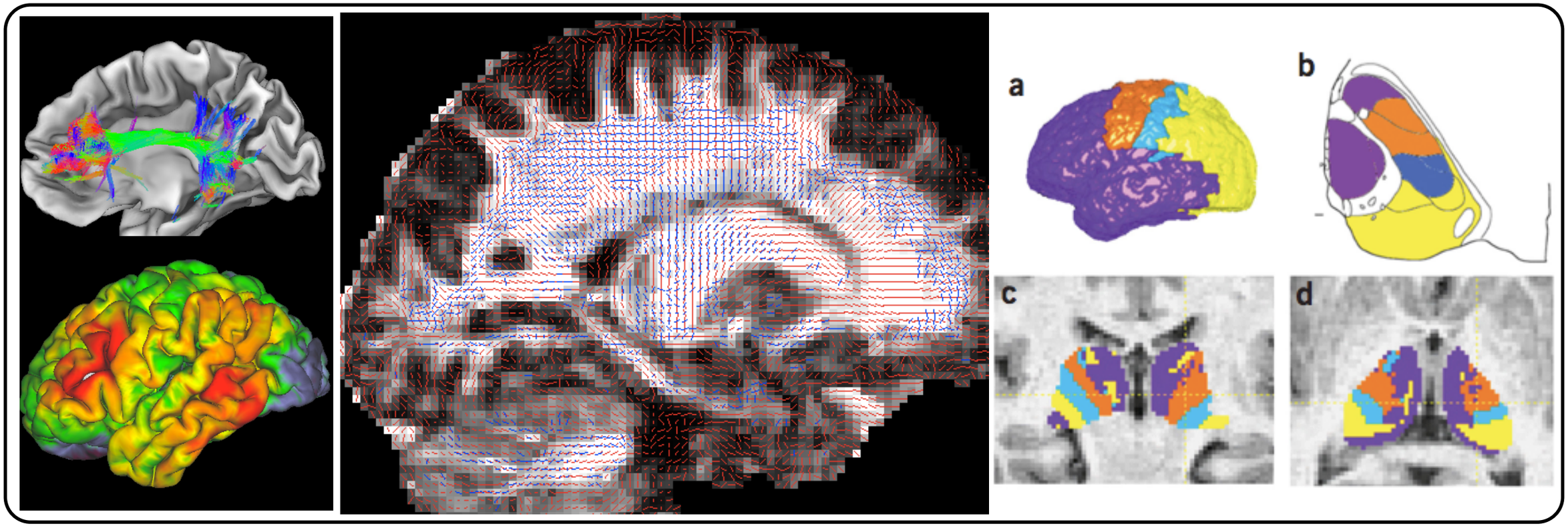
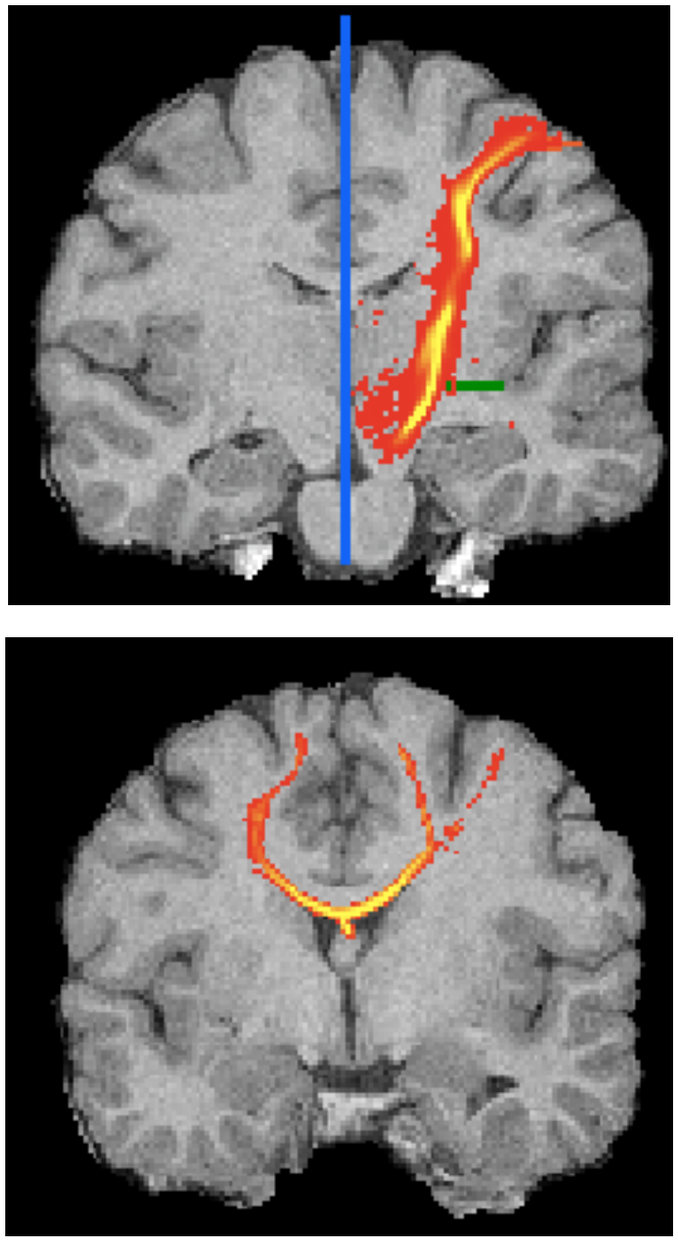
- Probabilistic Tractography - PROBTRACKX
- ProbtrackX outputs **ProbtrackX输出**
- Tractography limitations



ProbtrackX outputs

ProbtrackX的输出

Known white matter tracts
已知的白质纤维束

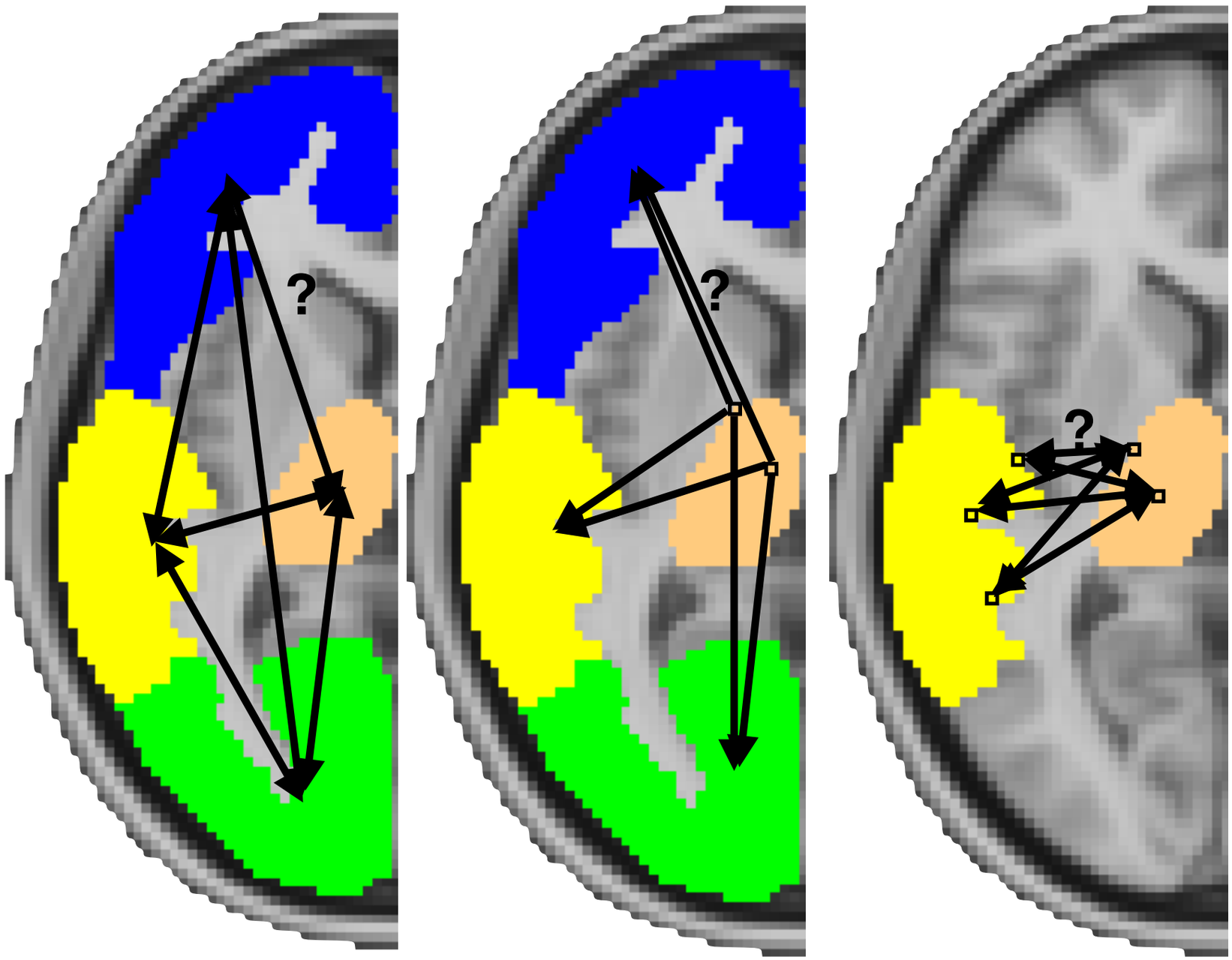


Connectivity matrices 连接矩阵

ROI by ROI

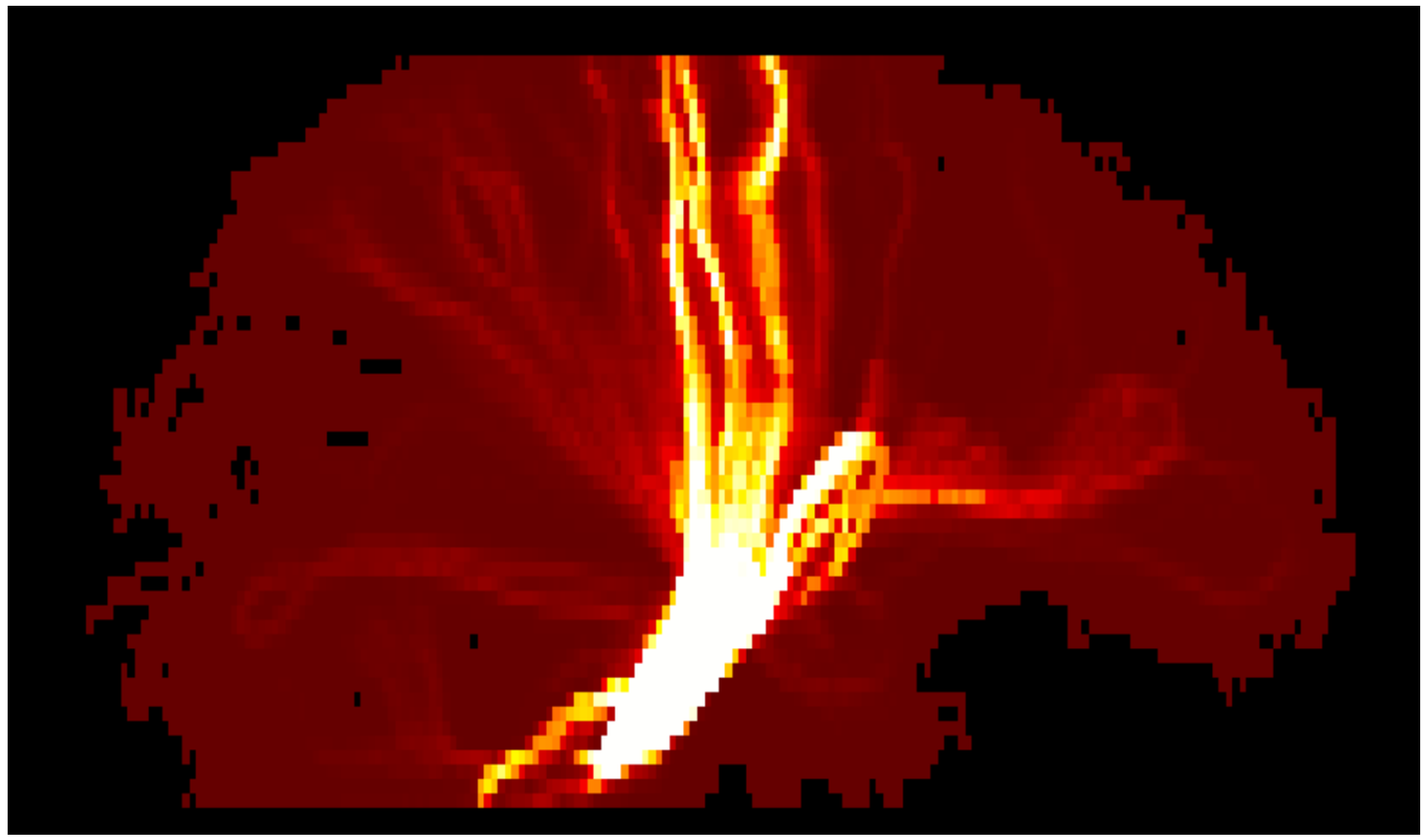
voxel by ROI

voxel by voxel



Adding Prior Knowledge to Tractography
概率追踪前需要了解的知识

- Because of the uncertainty propagation, the spatial distribution of paths is often very wide. 由于弥散的不确定性，路径的空间分布通常非常宽。

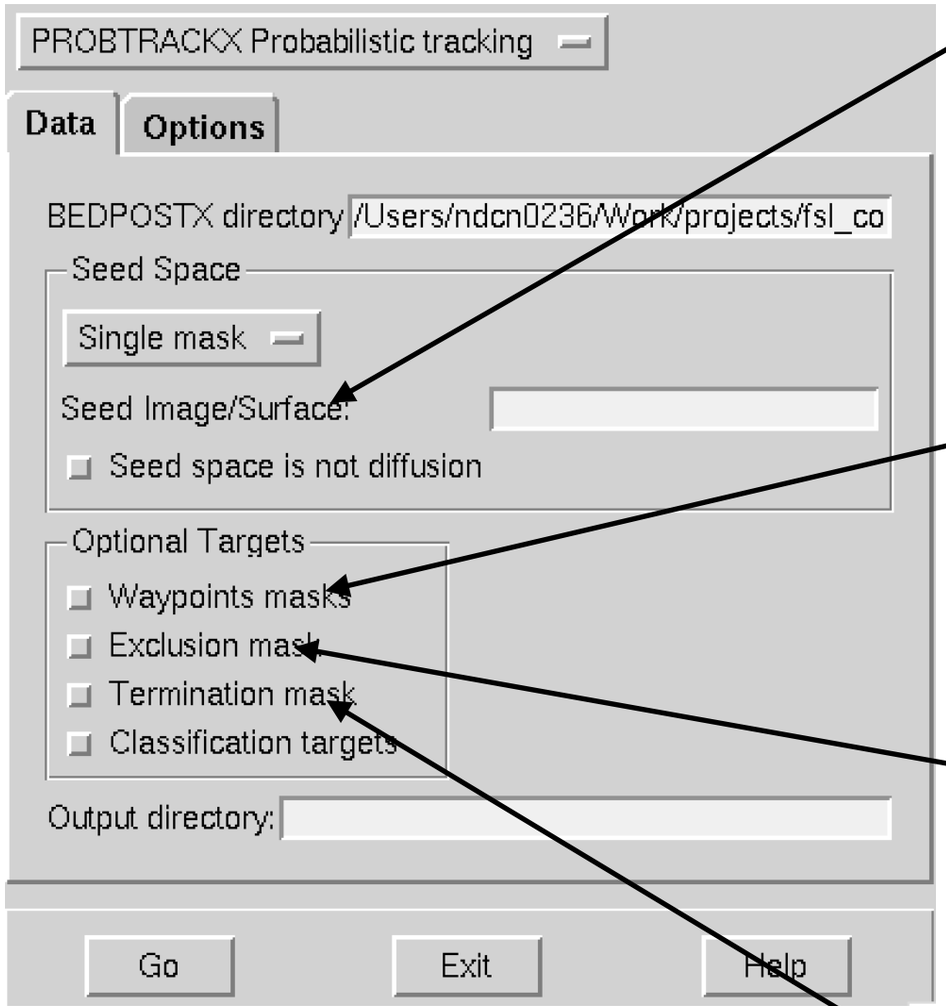


Low Probability

High Probability

Adding Prior Knowledge to Tractography
概率追踪前需要了解的知识

Fdt GUI FDT图形界面



- Once a seed is specified, prior anatomical knowledge can be imposed to assist the dissection of a specific tract.
  一旦指定了种子，就可以添加先前的解剖学知识以帮助解剖特定的纤维束。

- **Waypoint** ROIs 路径点兴趣区
  If a curve does not go through, it is discarded.
  如果曲线未通过，则将其丢弃。

- **Exclusion** ROI 排除兴趣区
  If a curve goes through, it is discarded.
  如果曲线经过，则将其丢弃。

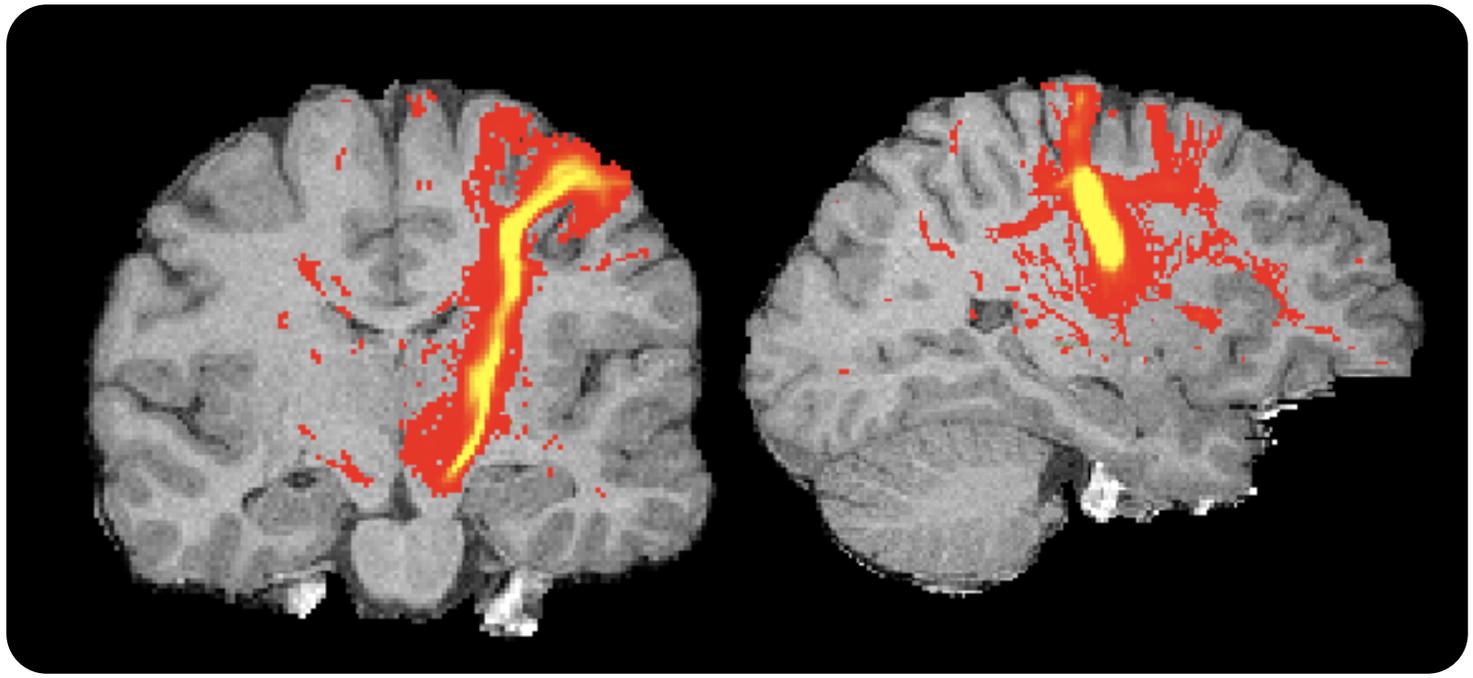
- **Termination** ROI 终止兴趣区
  If a curve goes through, it is terminated.
  如果曲线经过，则终止。

Adding Prior Knowledge to Tractography
概率追踪前需要了解的知识

Cortico-spinal tract 皮质脊髓束

Seed: M1, hand area

种子点：M1，手的区域



No ROIs

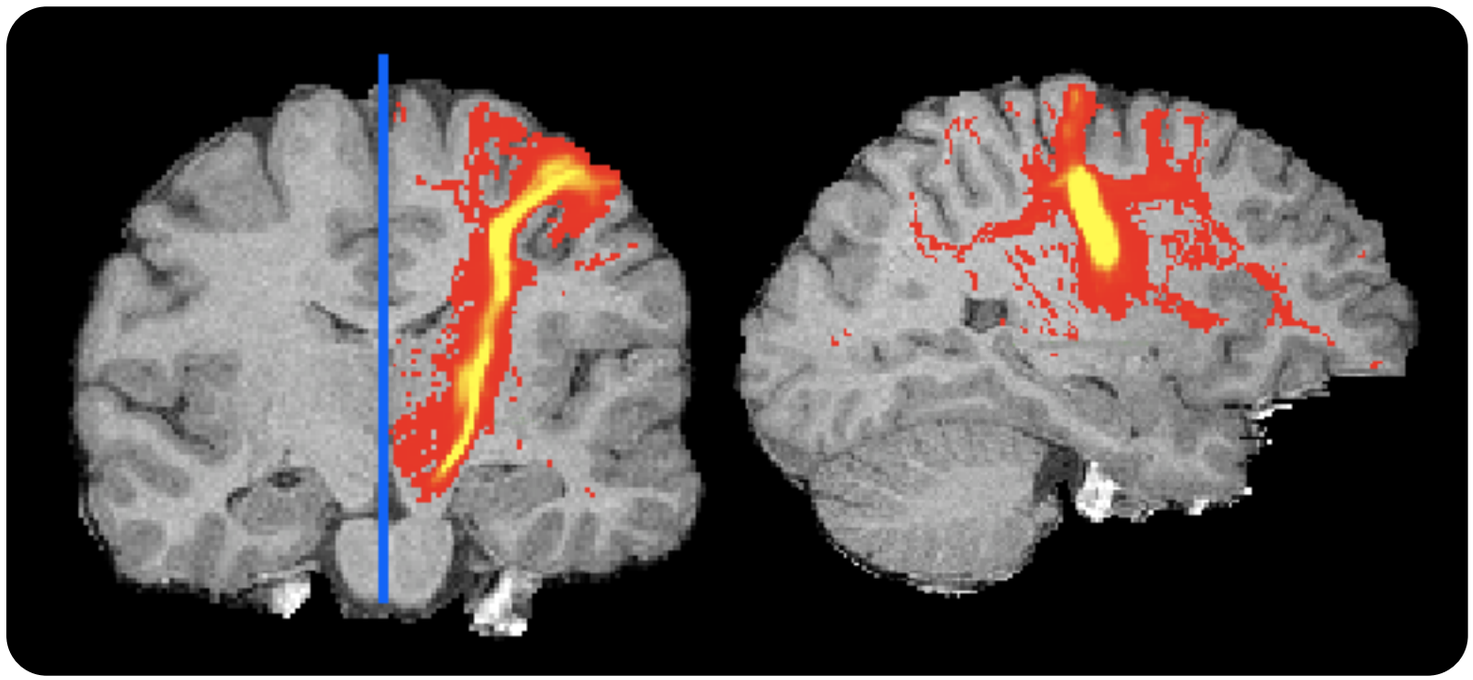
没有感兴趣区

Adding Prior Knowledge to Tractography
概率追踪前需要了解的知识

Cortico-spinal tract 皮质脊髓束

Seed: M1, hand area

种子点：M1，手的区域



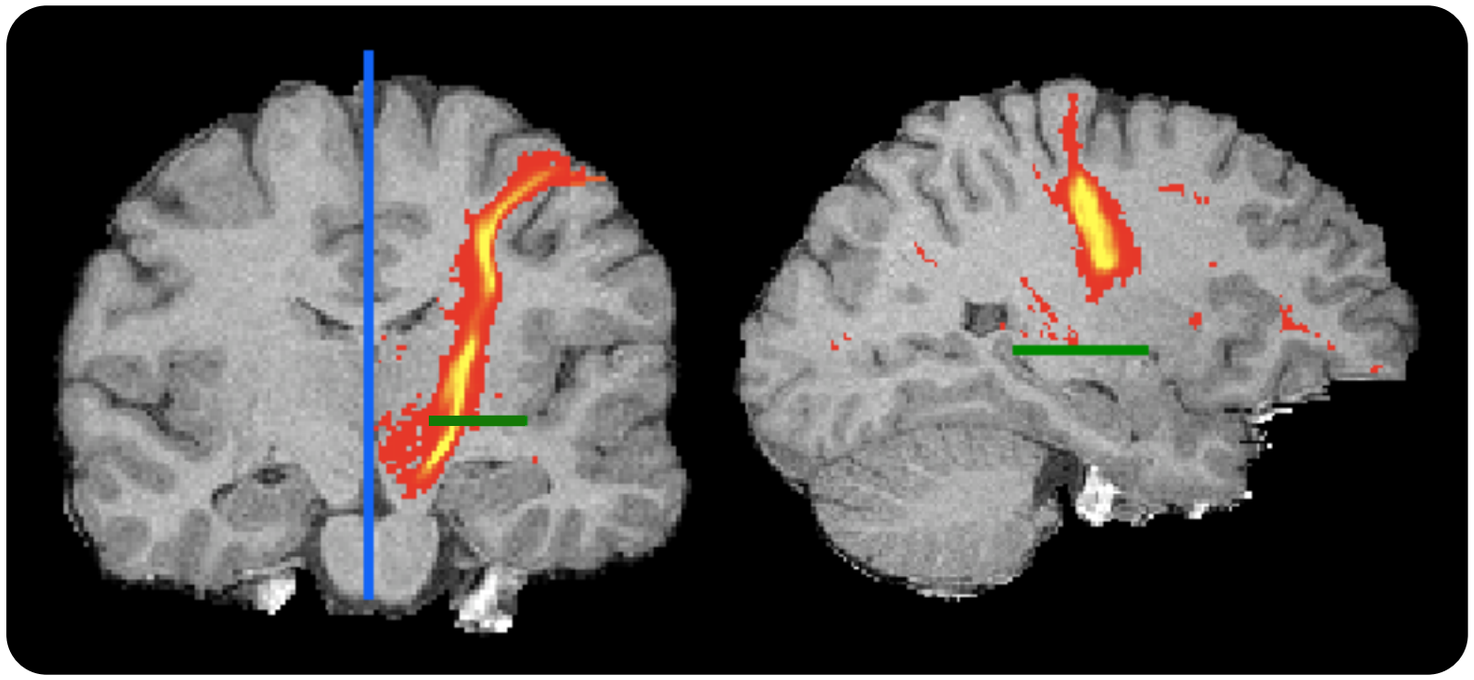
Exclusion: Mid-Sagittal plane

排除：中矢状平面

Adding Prior Knowledge to Tractography
概率追踪前需要了解的知识

Cortico-spinal tract 皮质脊髓束

Seed: M1, hand area



Waypoint: Internal Capsule

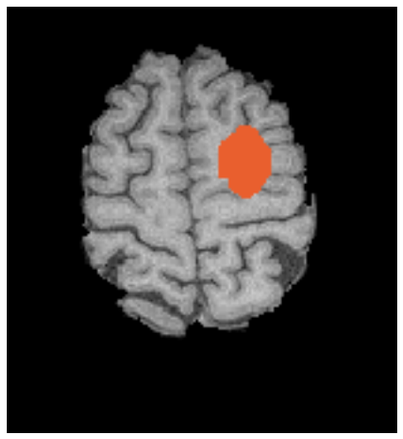
路径点：纹状体

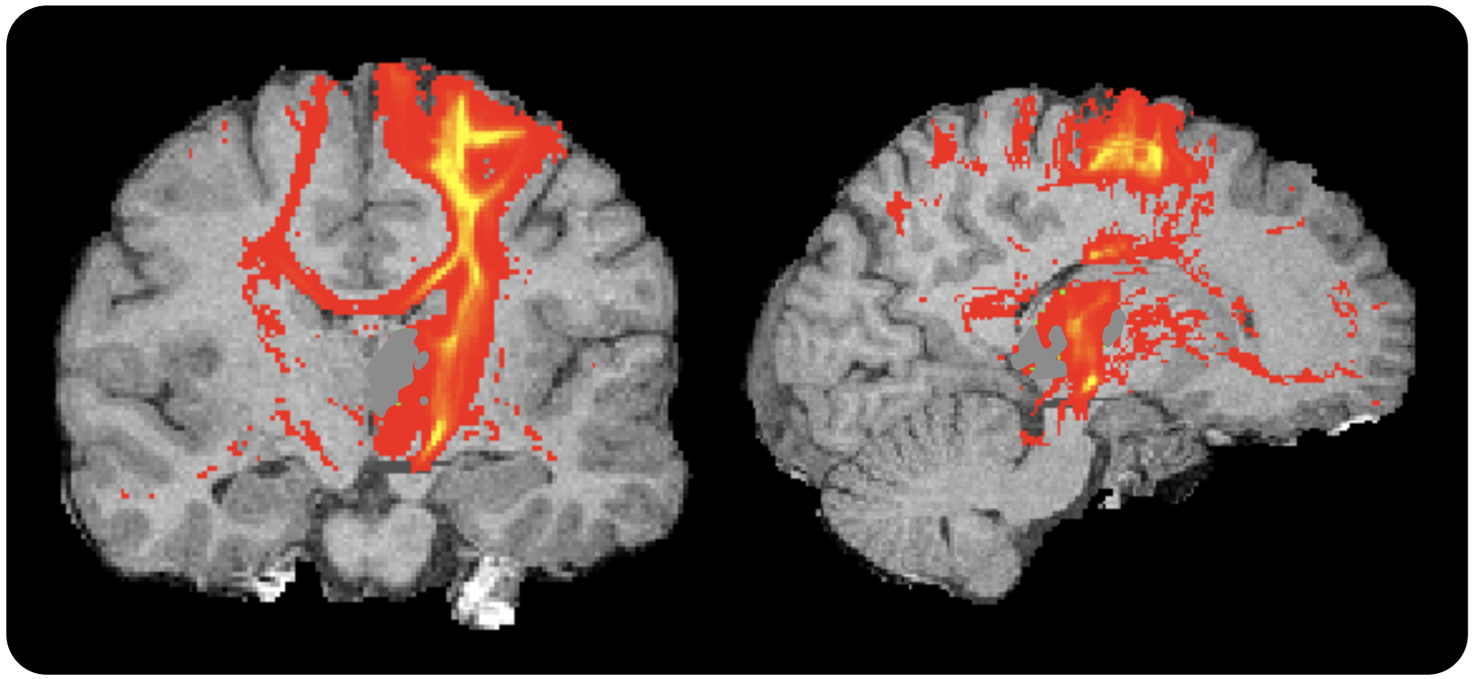
Adding Prior Knowledge to Tractography
概率追踪前需要了解的知识

Corpus Callosum 胼胝体

Seed: dorsal PMC

种子点：背侧PMC





No ROIs

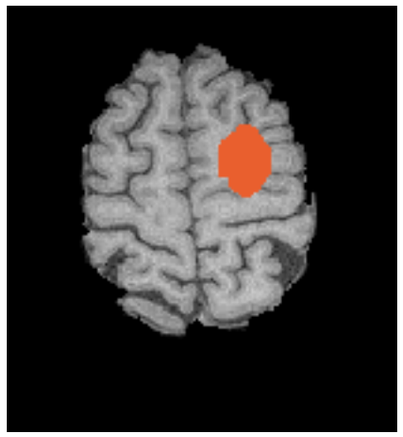
没有感兴趣区

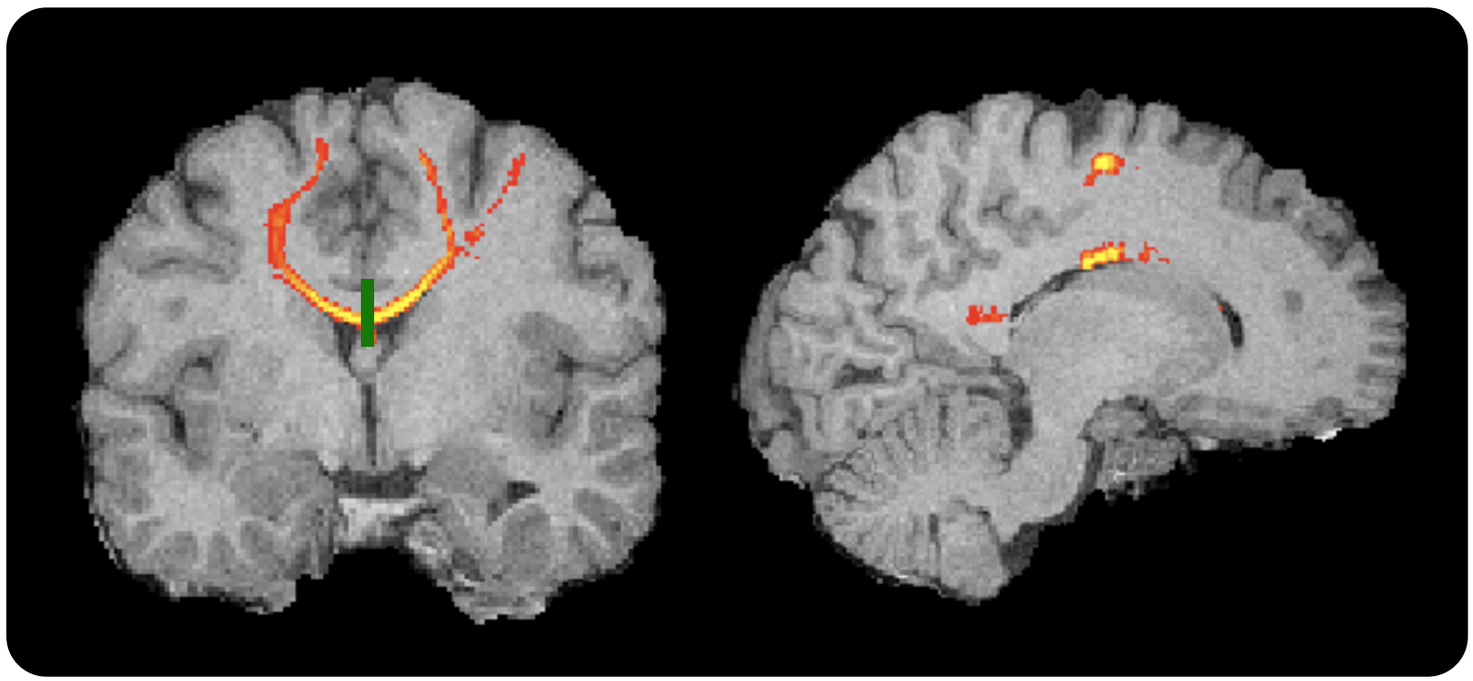
Adding Prior Knowledge to Tractography
概率追踪前需要了解的知识

Corpus Callosum 胼胝体

Seed: dorsal PMC

种子点：背侧PMC





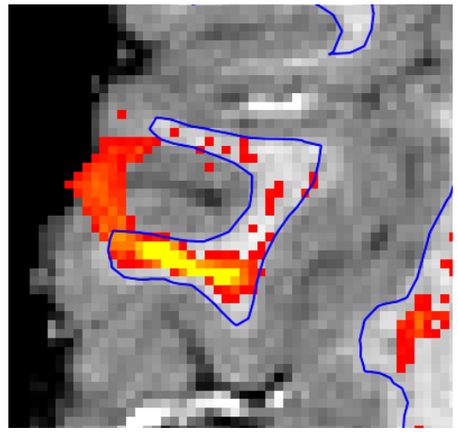
Waypoint: Corpus Callosum

路径点：胼胝体

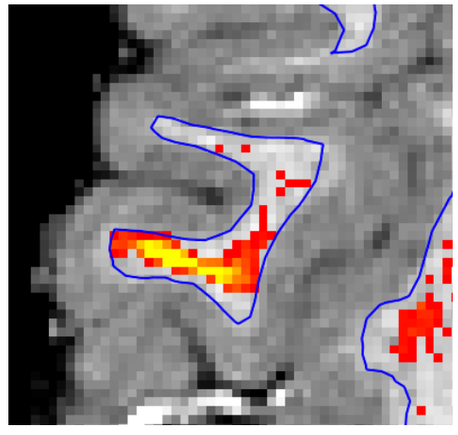
Surfaces as constraints

皮层作为约束

No surface constraint 没有表面约束



Surface as termination mask 皮层作为终止掩模



Autoptx: generating tracts for you

Autoptx：生成纤维束

Input: pre-processed diffusion MRI data
输入：预处理扩散MRI数据

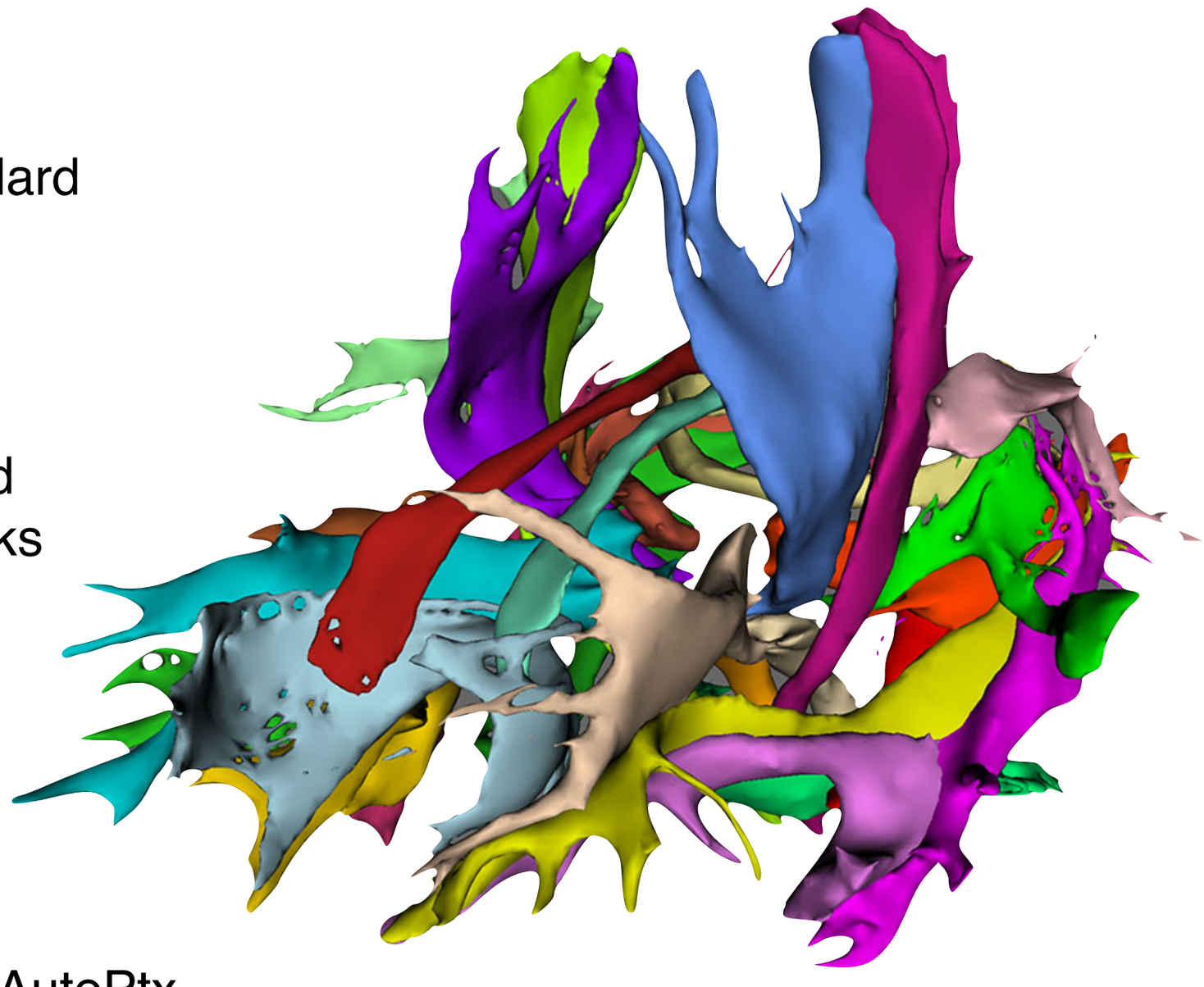
Autoptx does:

- Run *dtifit* and register FA to standard space

  运行dtifit并将FA配准到标准空间

- Run bedpostX 运行bedpostX
- Run probtrackX using pre-defined seed, waypoint, & exclusion masks for **27** tracts

  使用预定义的种子，路径点和排除掩板运行probtrackX，用于27个区域



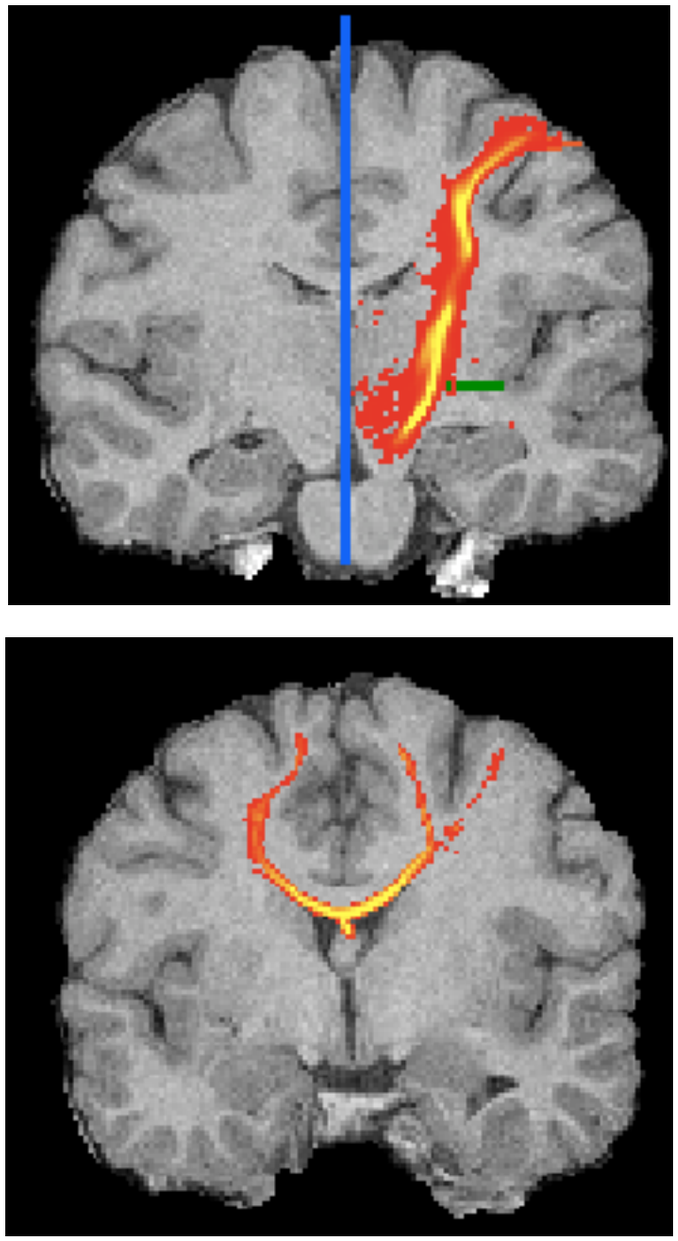
Download scripts from:
https://fsl.fmrib.ox.ac.uk/fsl/fslwiki/AutoPtx

ProbtrackX outputs

ProbtrackX 输出

Known white matter tracts

已知白质纤维束

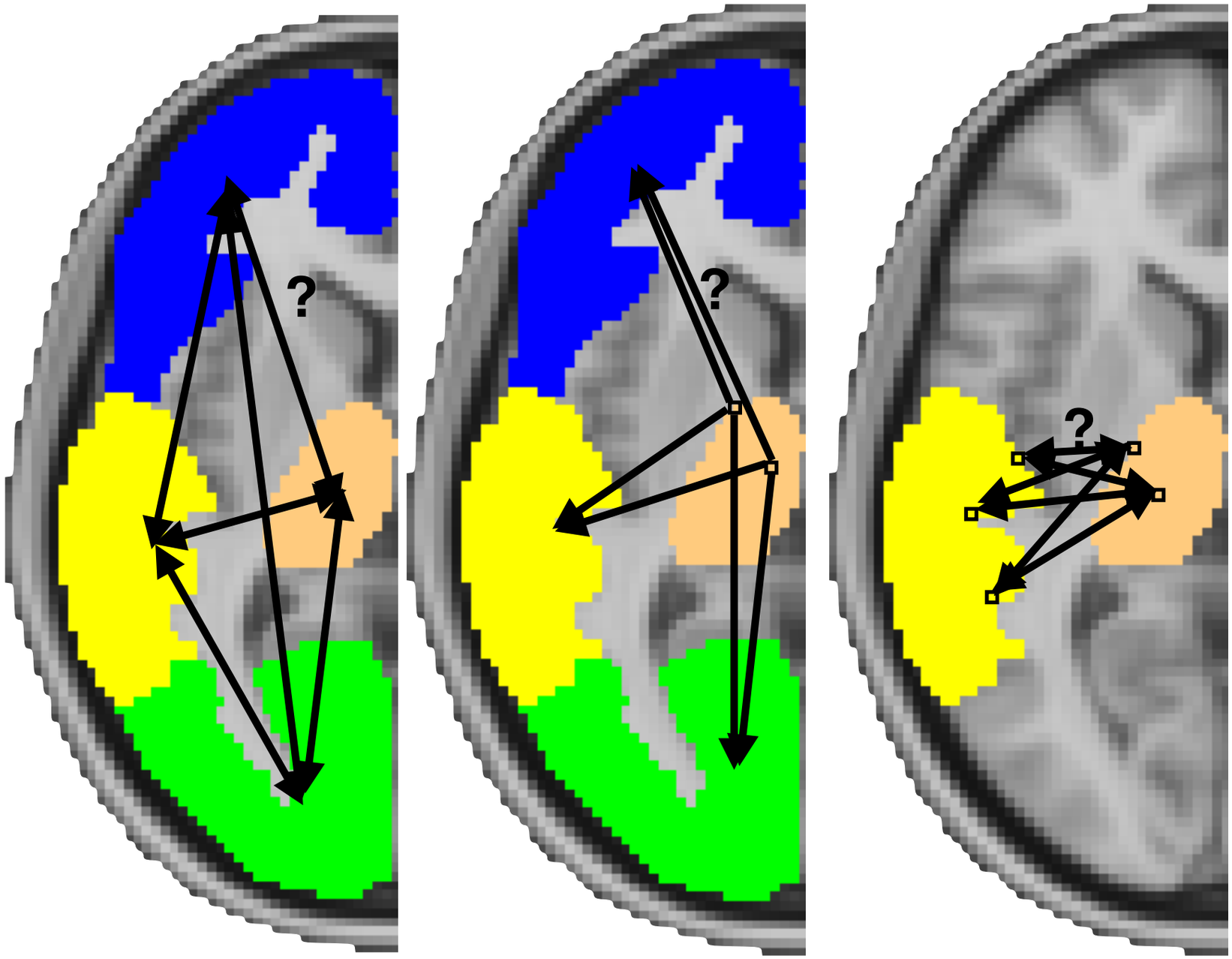


Connectivity matrices 连接矩阵

ROI by ROI

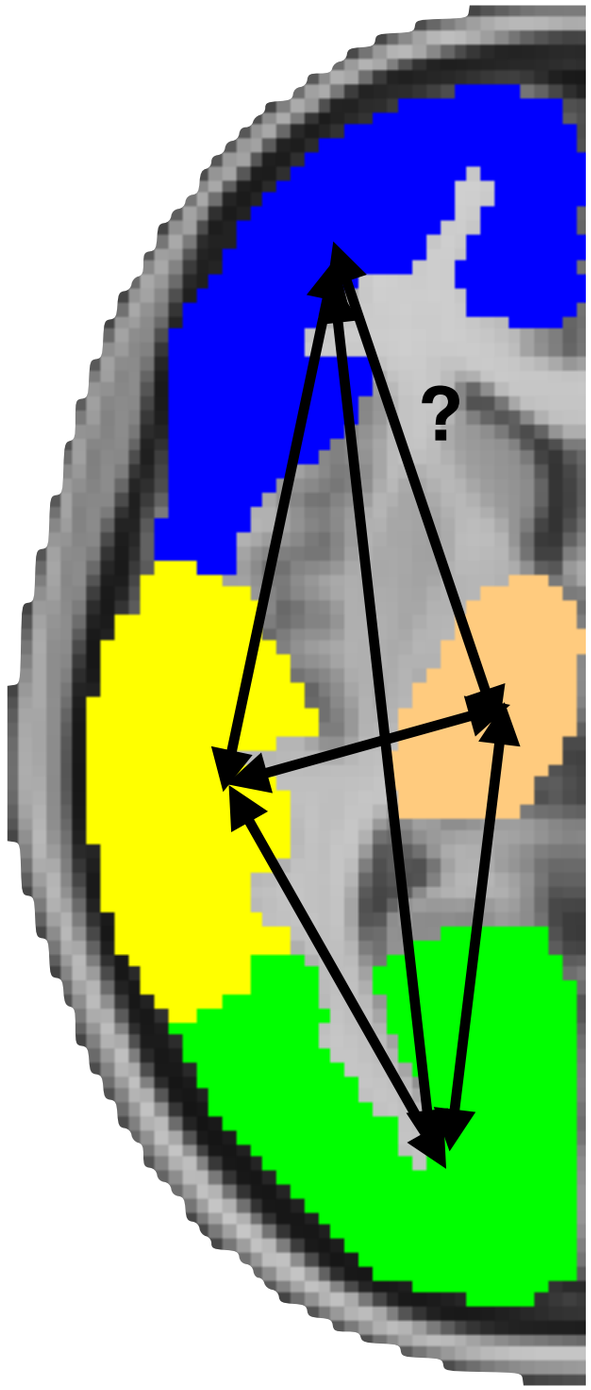
voxel by ROI

voxel by voxel



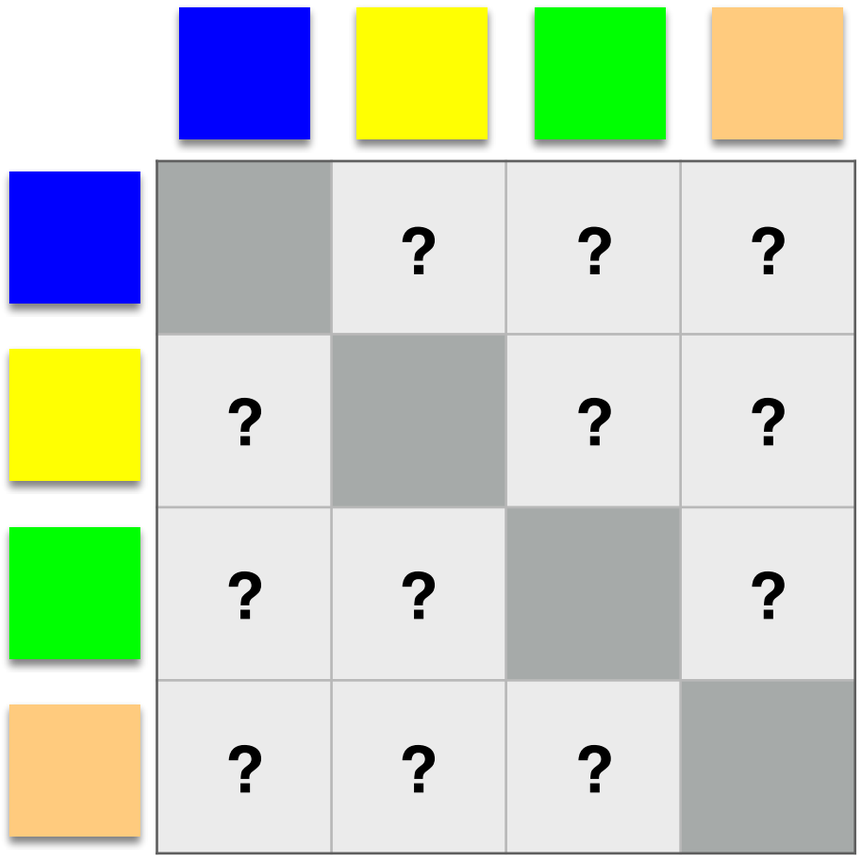
Connectivity between ROIs

ROI间的连接



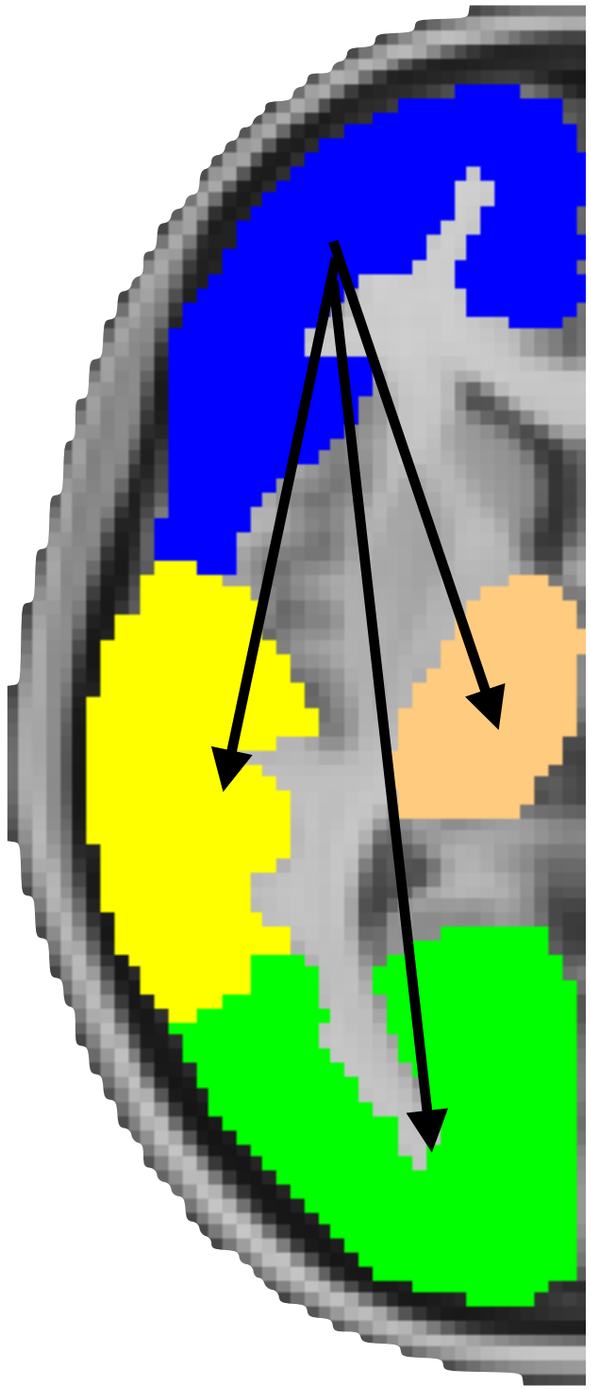
Resulting matrix:

结果矩阵



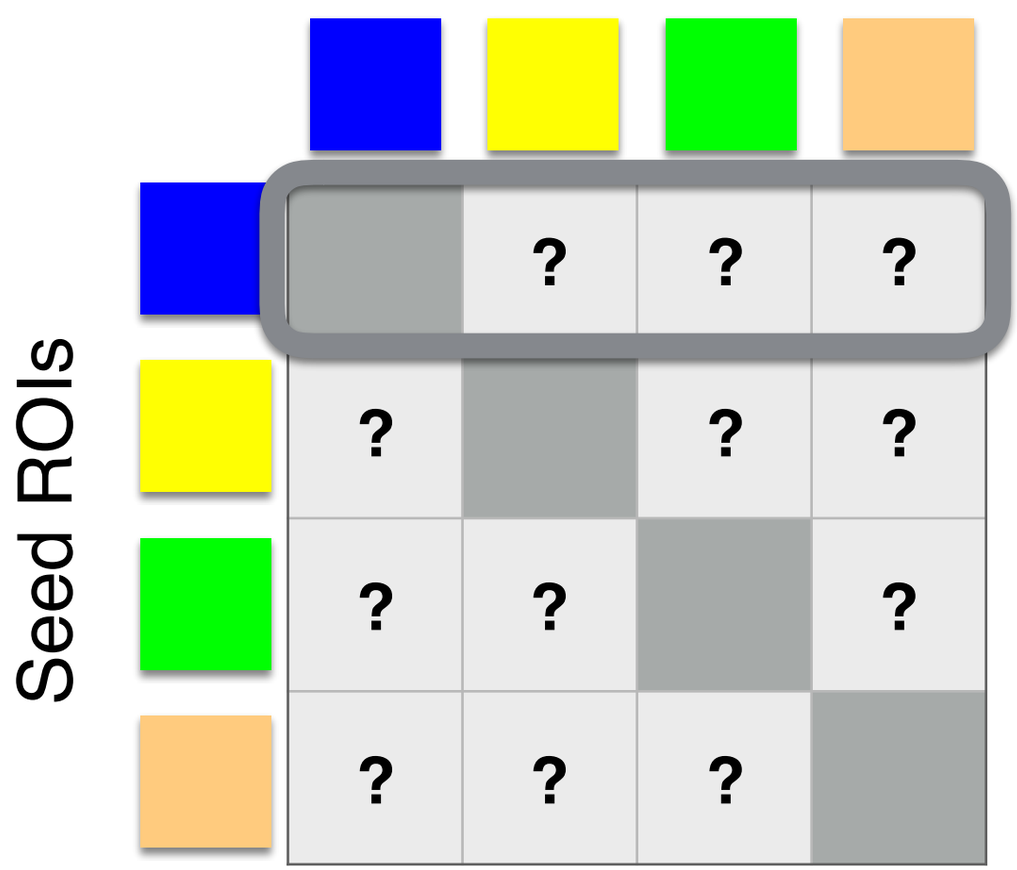
Connectivity between ROIs

ROI间的连接



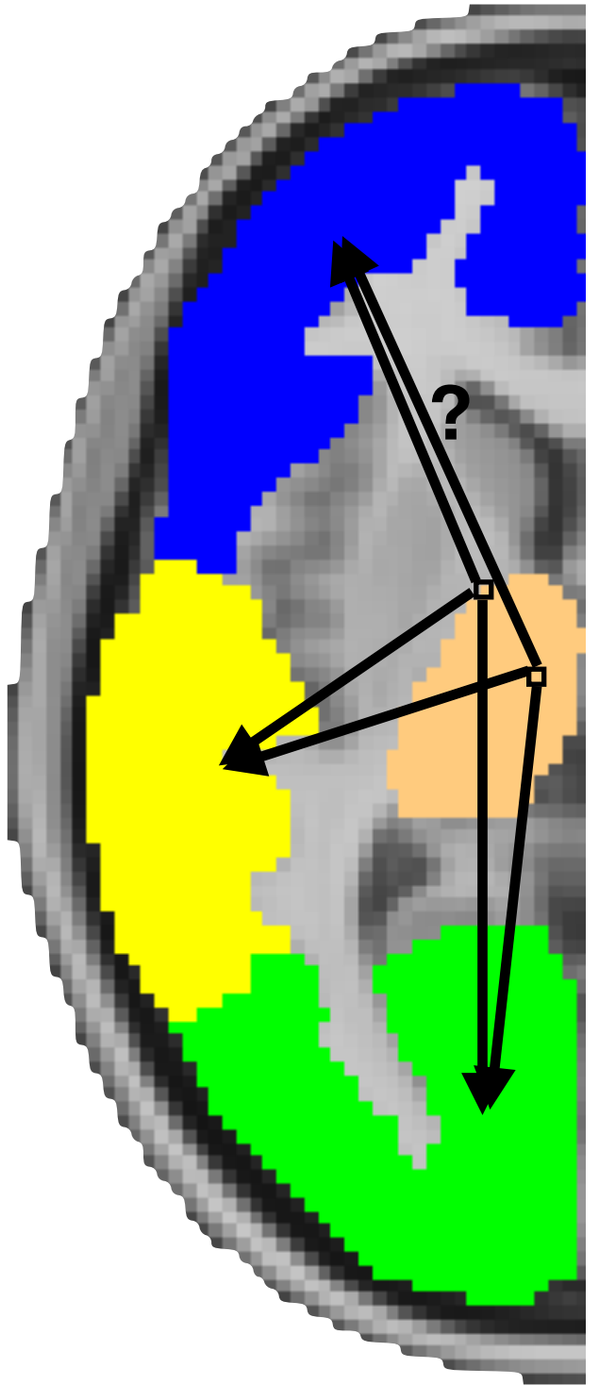
- Seed from blue 以蓝色区域为种子点
- Other ROIs are waypoints 其他ROI是路径点
- Fill first row of matrix 填充第一行矩阵

Resulting matrix: 结果矩阵



Connectivity between voxels and ROIs

体素和ROI之间的连接



Resulting matrix: 结果矩阵

Target ROIs

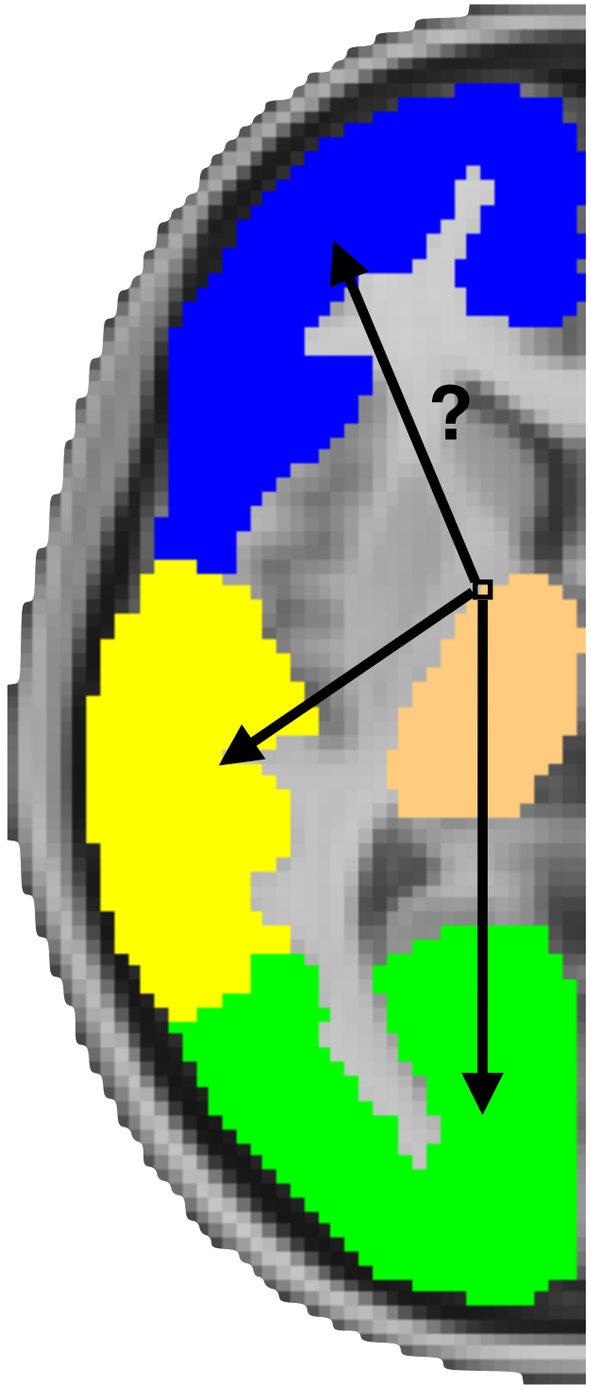
Seed voxels

?	?	?
?	?	?
?	?	?
?	?	?

• • •

Connectivity between voxels and ROIs

体素和ROI之间的连接



Resulting matrix: 结果矩阵

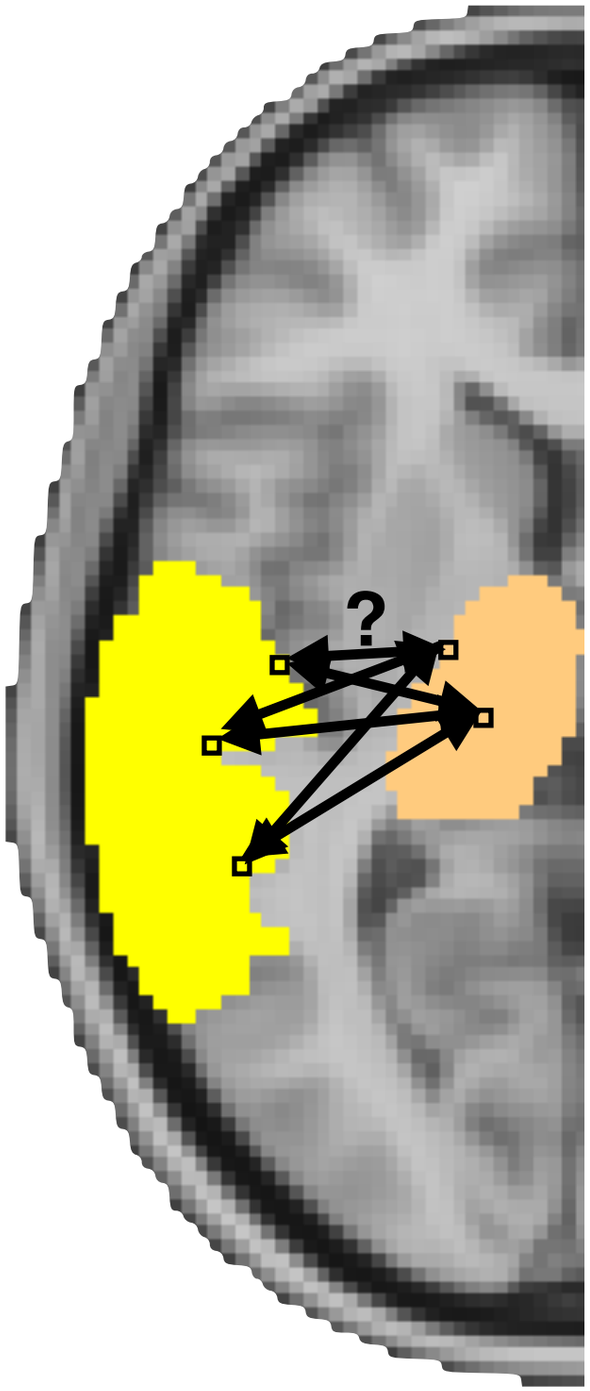
Target ROIs

Seed voxels

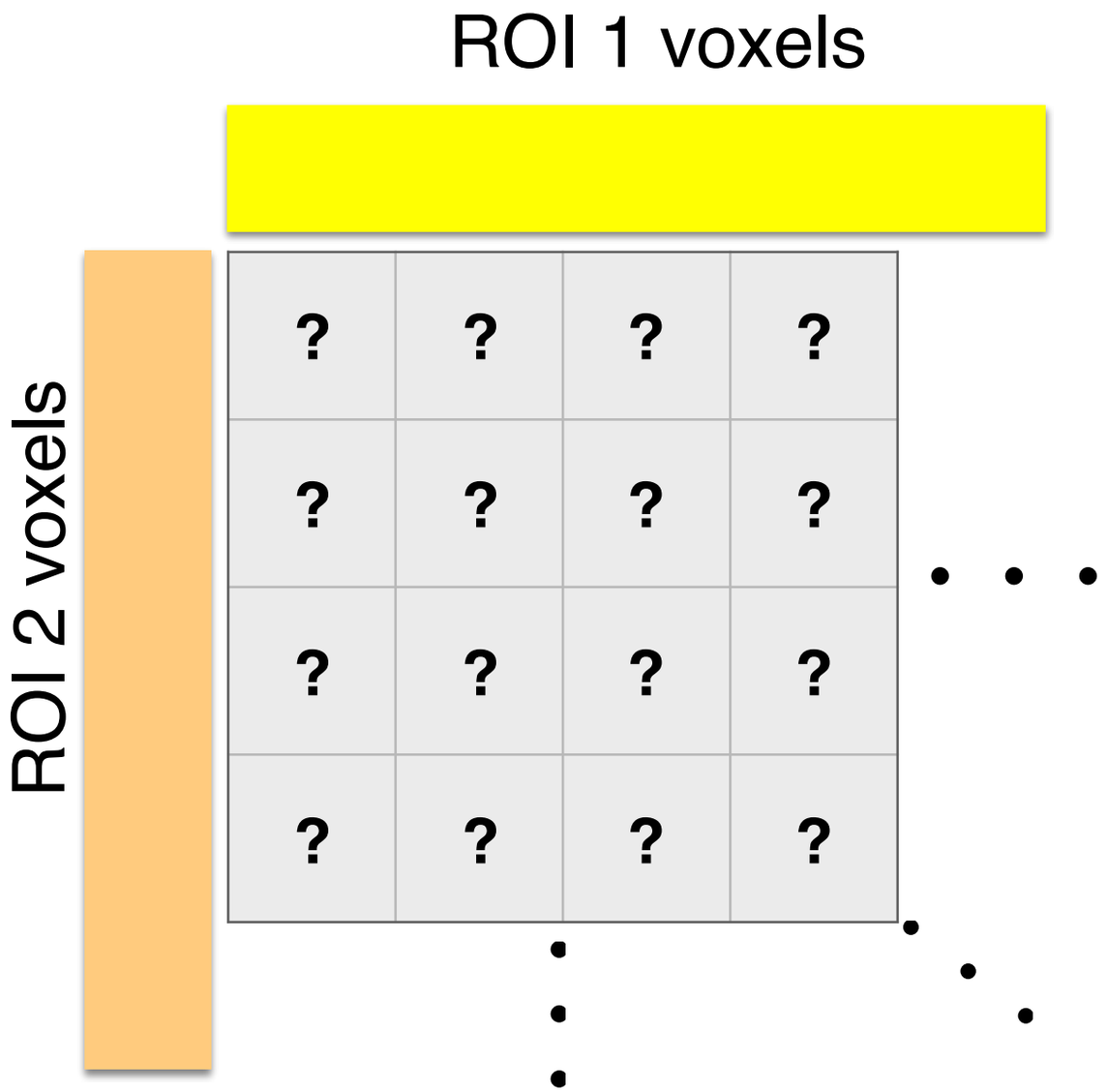
?	?	?
?	?	?
?	?	?
?	?	?
•	•	•
•	•	•
•	•	•

Connectivity between voxels

体素间的连接



Resulting matrix:

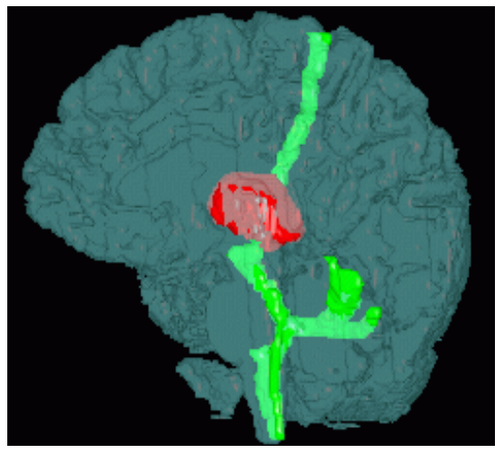


Segmenting the thalamus

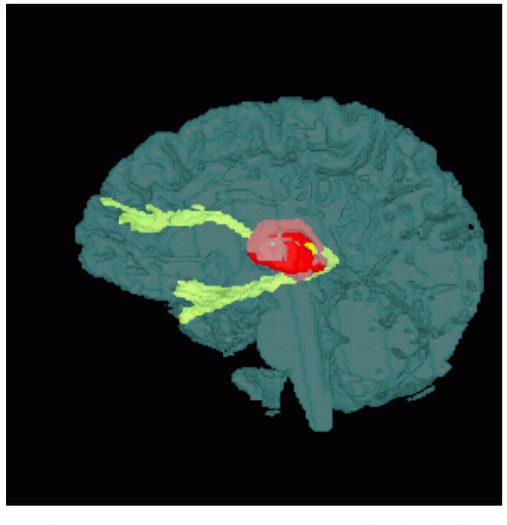
丘脑的分割

no contrast on conventional MRI

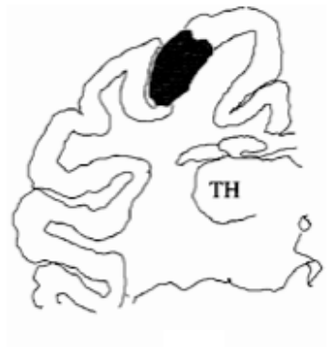
VL –> M1

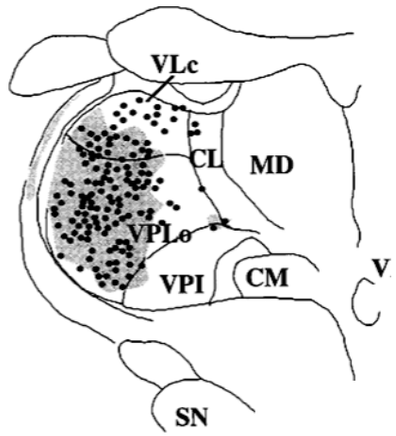


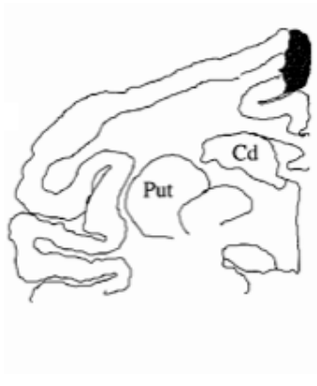
MD –> PFC

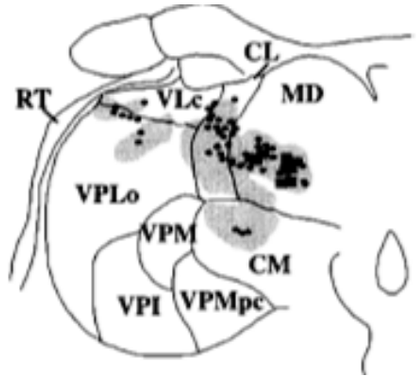


Behrens et al, 2003
(probabilistic tractography)







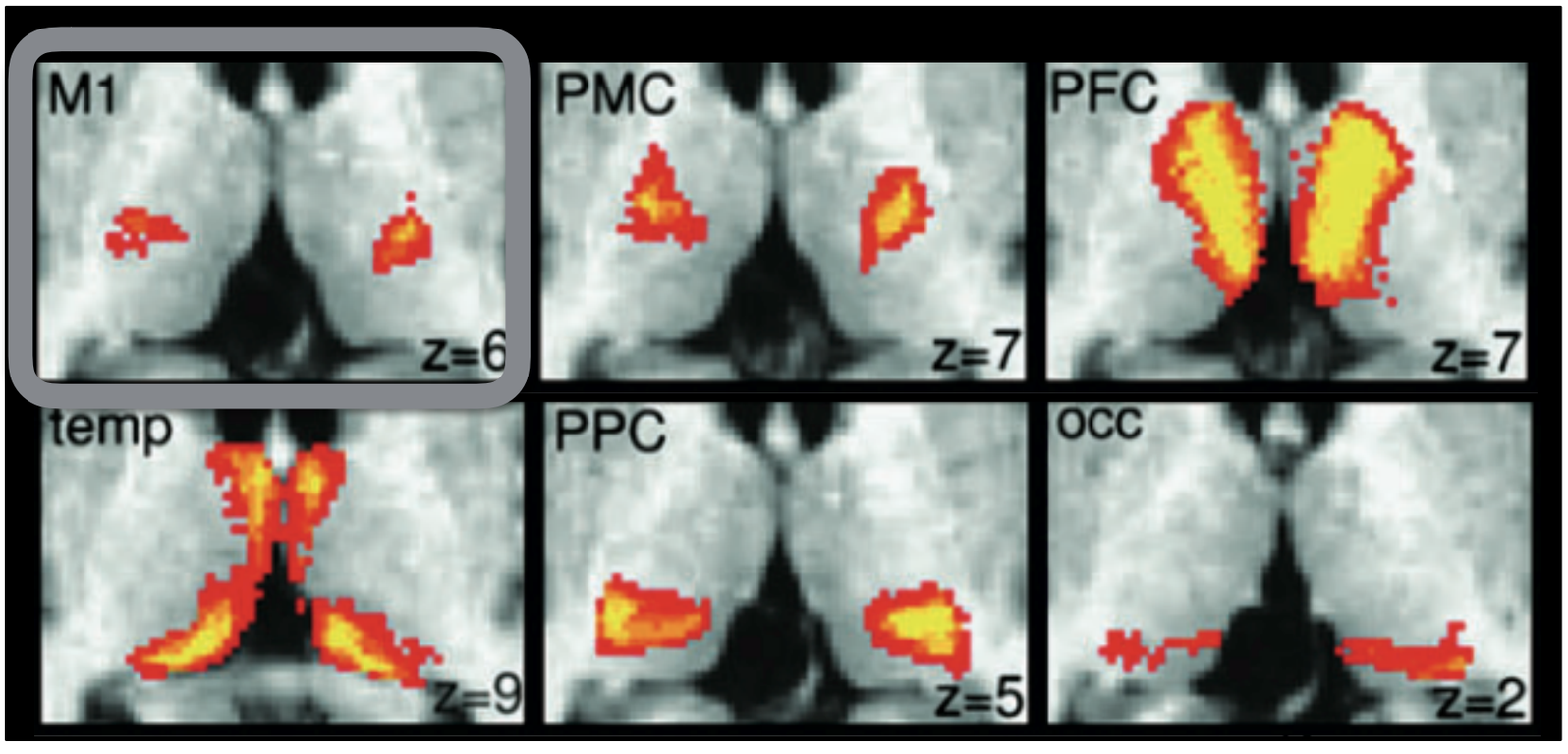


Rouiller et al, 1998
(BDA anterograde tracing)

Segmenting the thalamus

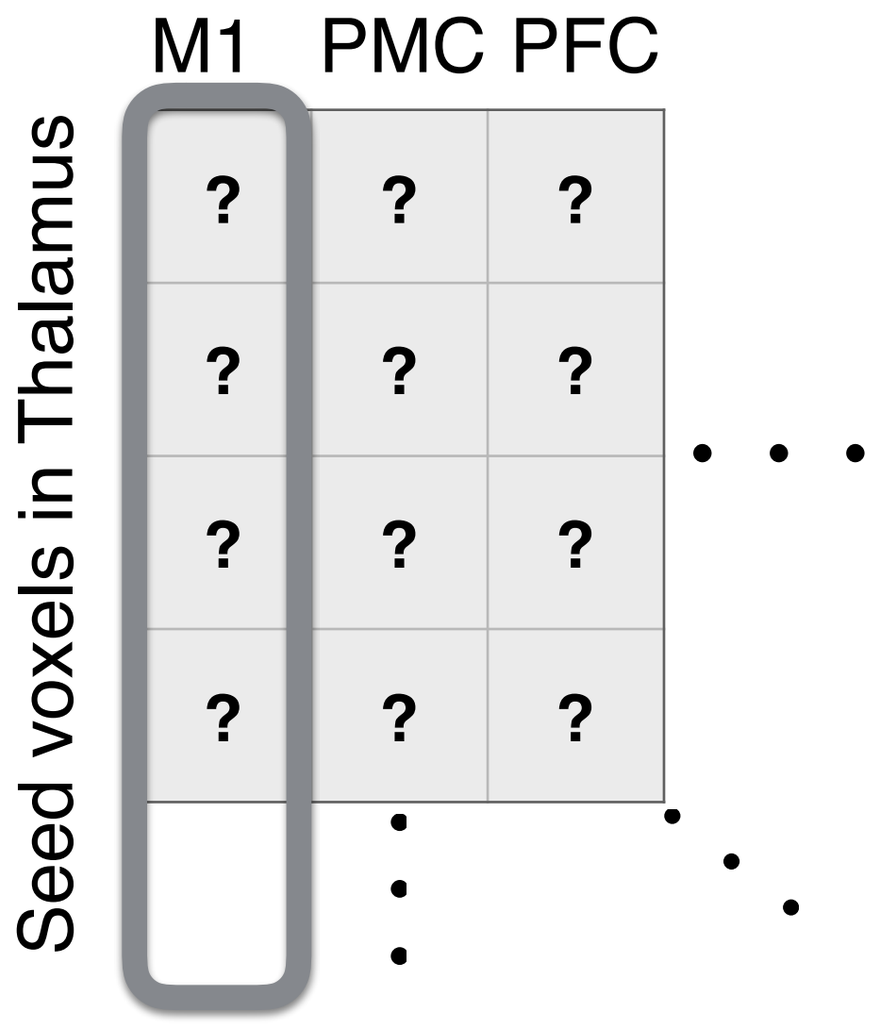
丘脑的分割

Prior cortical parcelaltion 先前的皮层分割



Resulting matrix: 结果矩阵

Target ROIs



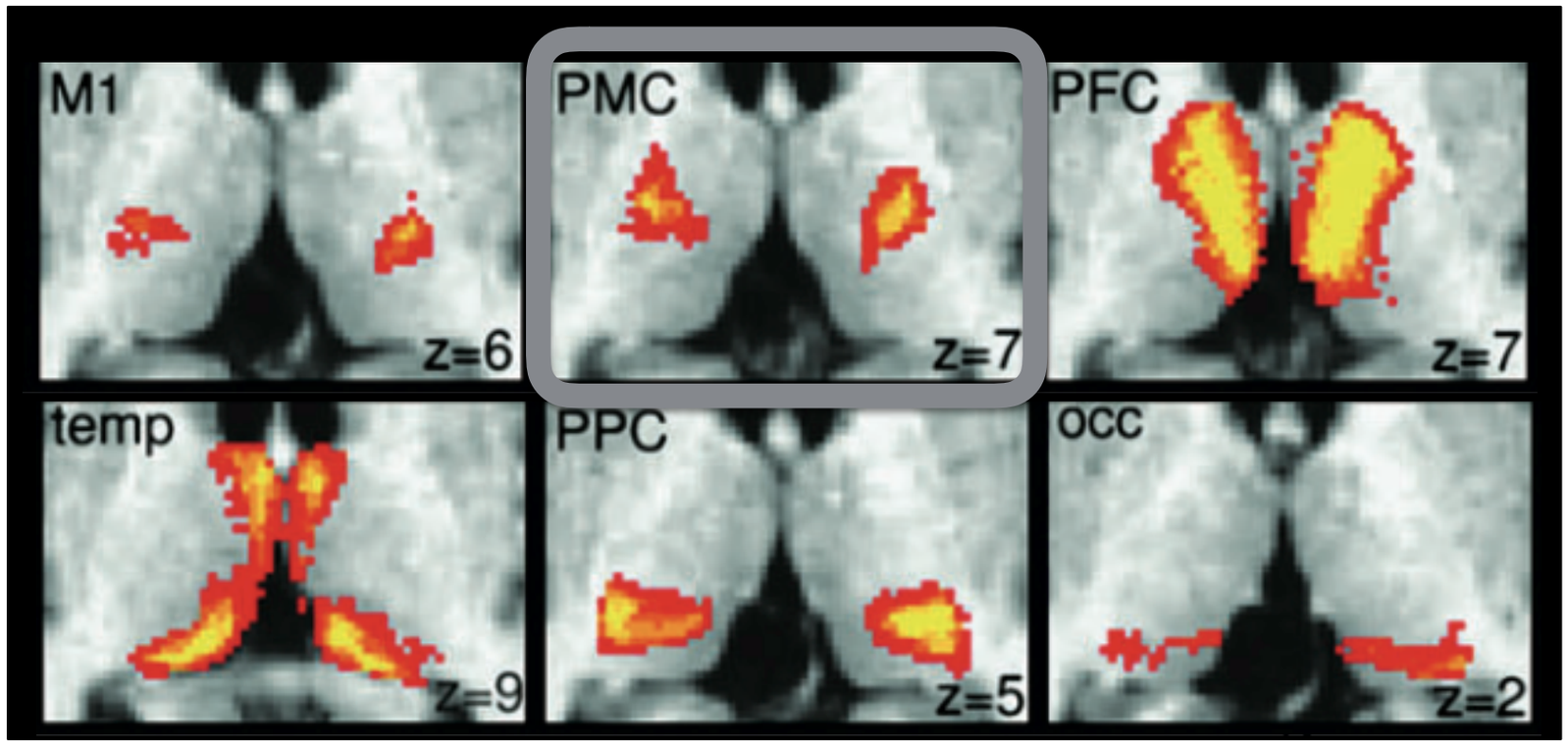
Behrens et al. Nat Neuro2003

Johansen-Berg et al. Cereb Ctx 2005

Segmenting the thalamus

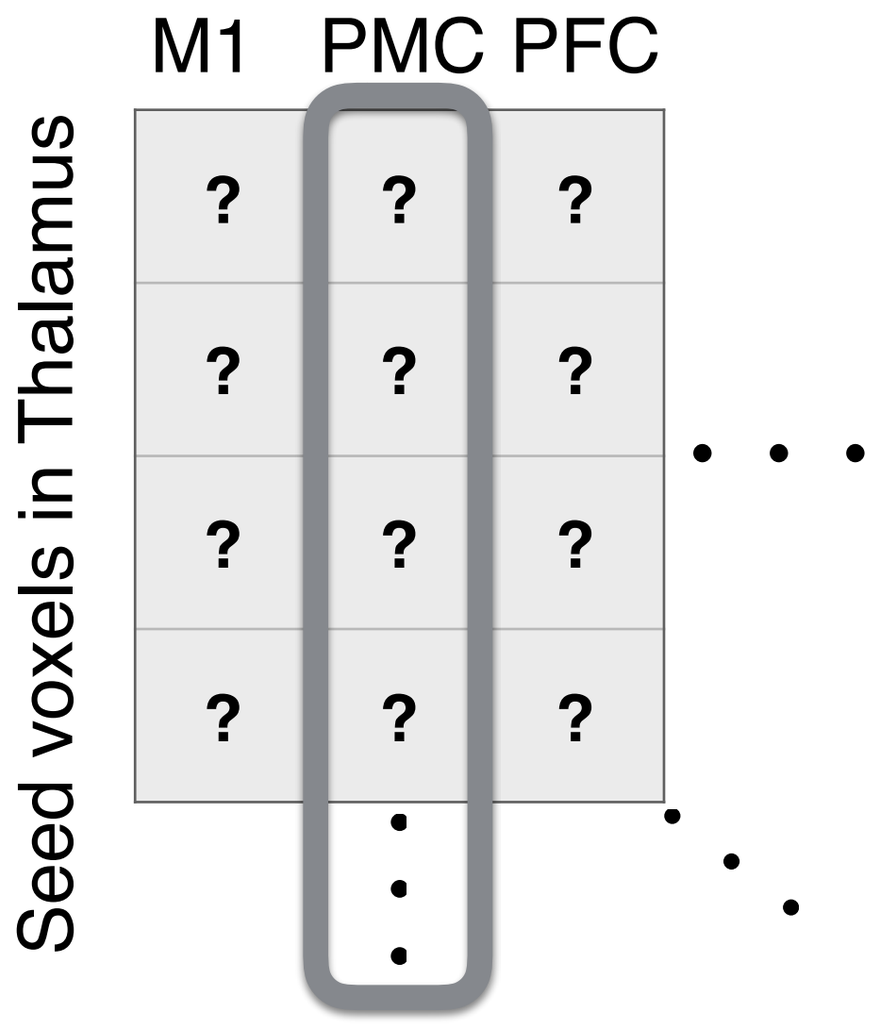
丘脑的分割

Prior cortical parcelaltion 先前的皮层分割



Resulting matrix: 结果矩阵

Target ROIs



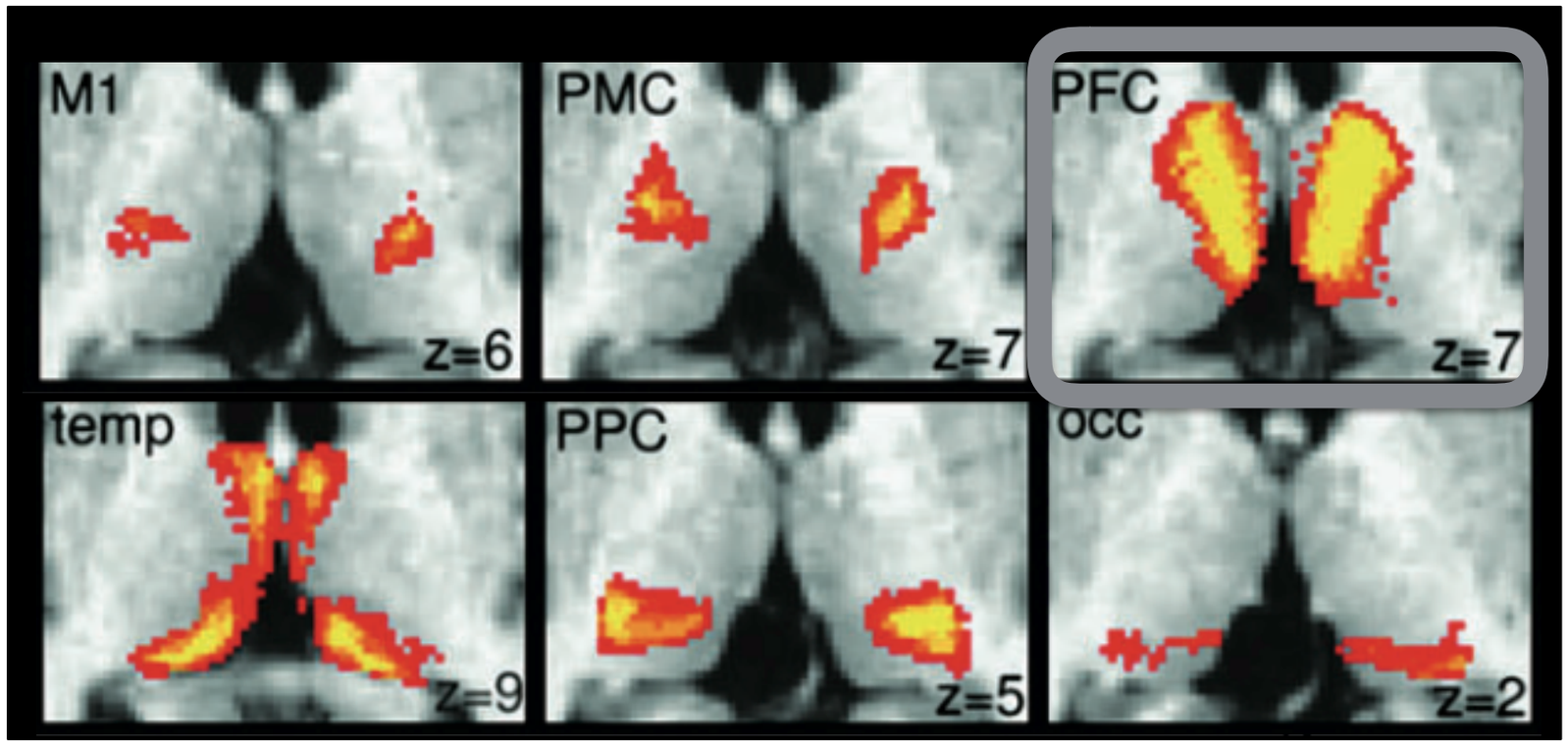
Behrens et al. Nat Neuro2003

Johansen-Berg et al. Cereb Ctx 2005

Segmenting the thalamus

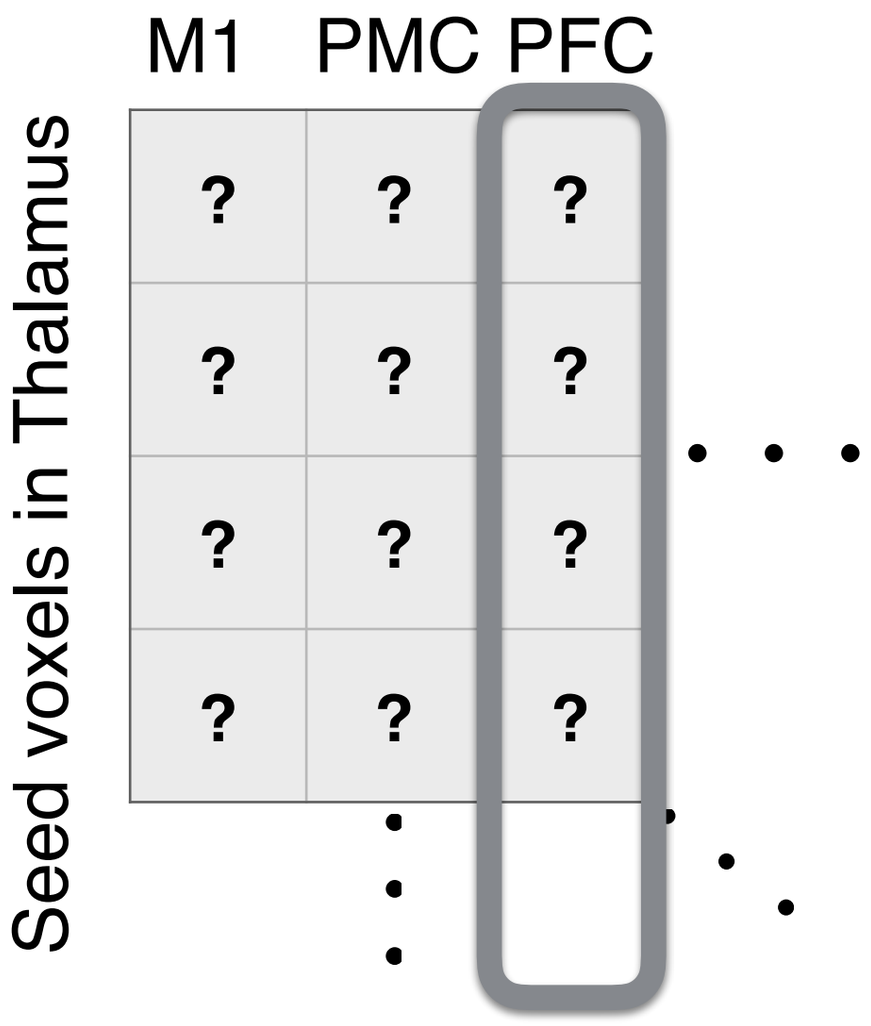
丘脑的分割

Prior cortical parcelaltion 先前的皮层分割



Resulting matrix: 结果矩阵

Target ROIs

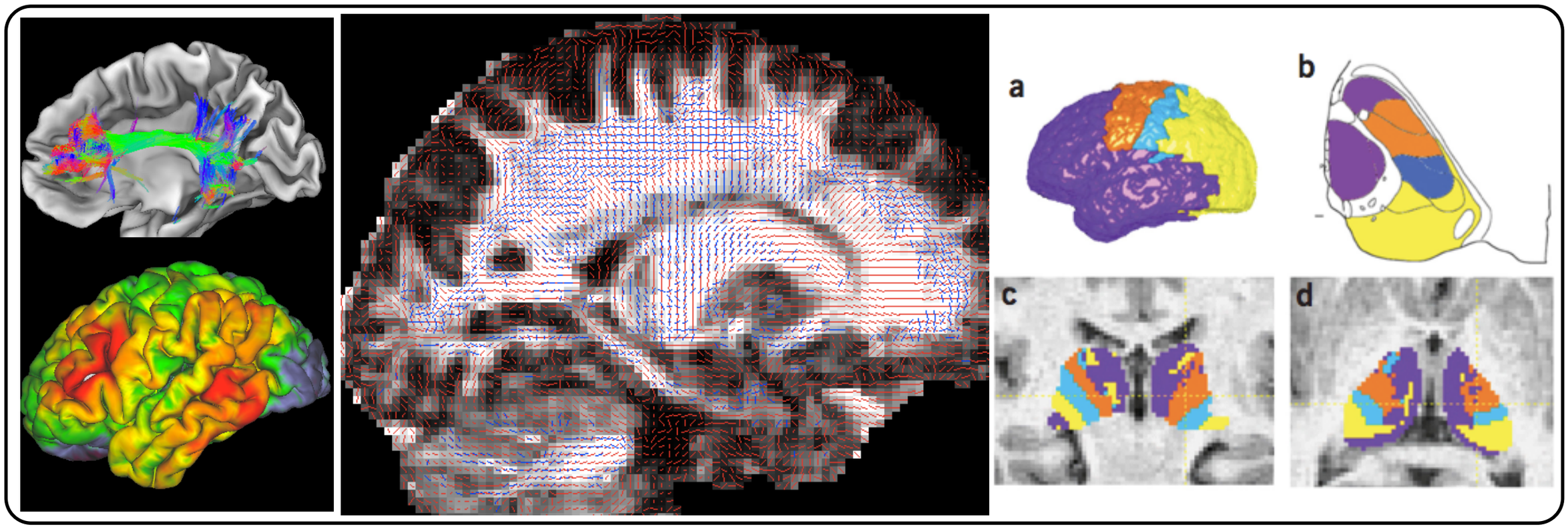


Behrens et al. Nat Neuro2003

Johansen-Berg et al. Cereb Ctx 2005

Overview
概况

- Estimating Fibre Orientations - BEDPOSTX
- Probabilistic Tractography - PROBTRACKX
- ProbtrackX outputs
- Tractography limitations 纤维追踪的局限



What is a quantitative measure of connectivity? 什么是连通性的量化指标?

- Number of axons connecting 2 areas?连接2个区域的轴突数量?
- Proportion of axons from a seed that reach a target? 种子到达目标的轴突比例?
- "Integrity" of the connecting white matter …连接白质的"完整性"……
  - Effective conductivity? 有效传导性?
  - Degree of myelination? 髓鞘化程度?
  - Packing density? 集群密度?
- What are we measuring? 我们在测量什么?
  - The probability that the **dominant** path through the diffusion field passes through this region.通过扩散场的主导路径通过该区域的概率。

Connection Probabilities 概率连接

- They may reflect "*Connection Strength*" 它们可能反映出"连接强度"

  - But they do also reflect other uninteresting factors, such as:
    但它们也反映了其他无趣的因素，例如：

Connection length: Longer connections have smaller probability than shorter ones 连接长度：较长的连接比较短的连接具有较小的概率

Geometric complexity: Probabilities of connections that go through regions of complex structure will be smaller than connections than go through more coherent regions

几何复杂性：通过复杂结构区域的连接概率将小于连接，而不是通过更连贯的区域

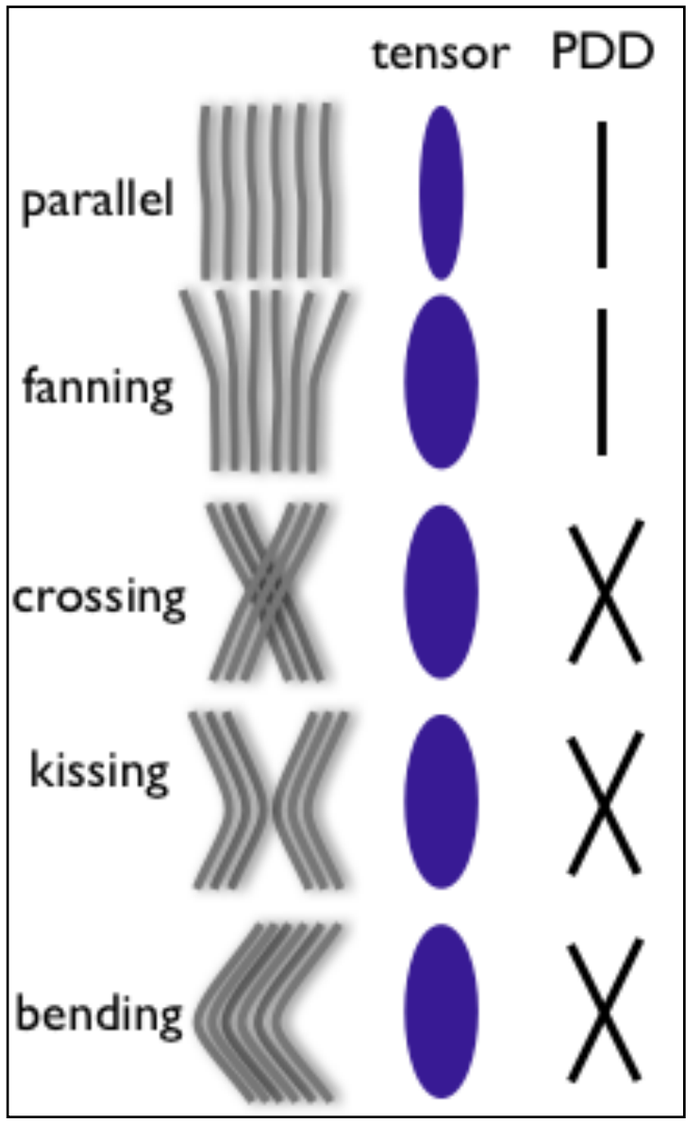
Resolution of the spatial grid: Probabilities change if we change the size of "bins" for displaying the spatial histogram

空间网格的分辨率：如果我们改变用于显示空间直方图的"区间"的大小，则概率会改变

Can we trust tractography? 概率追踪可信吗?

Is the direction of least hindrance to diffusion a good proxy for fibre orientation?

扩散阻碍最小的方向是纤维取向的良好代表吗?



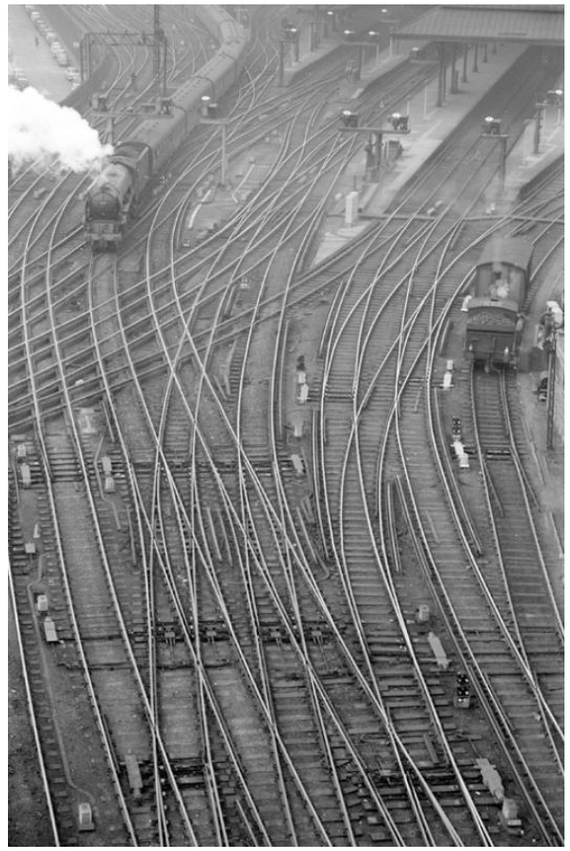
mapping between axon geometry and diffusion profile can be ambiguous

轴突几何与扩散剖面之间的映射可能是模糊的

What's in a voxel?
什么是体素?

bad

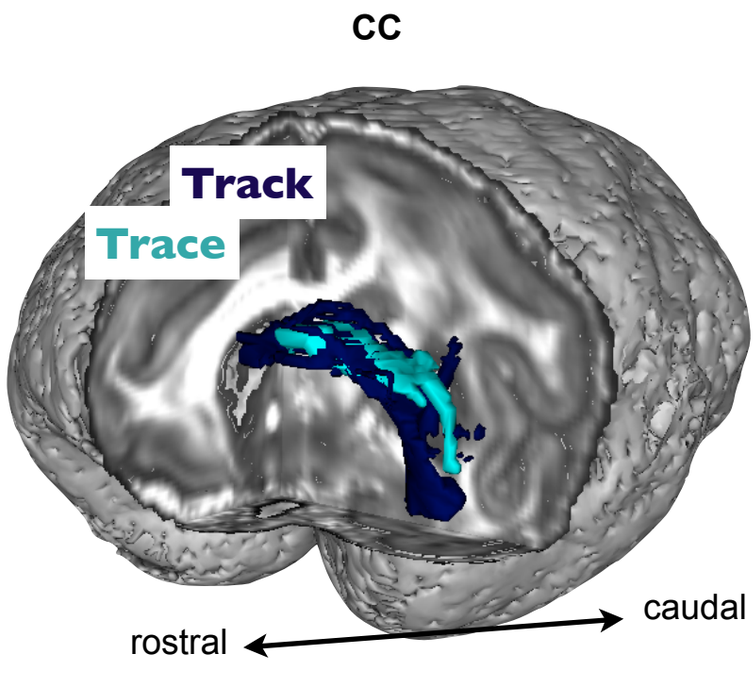
White matter?
白质?

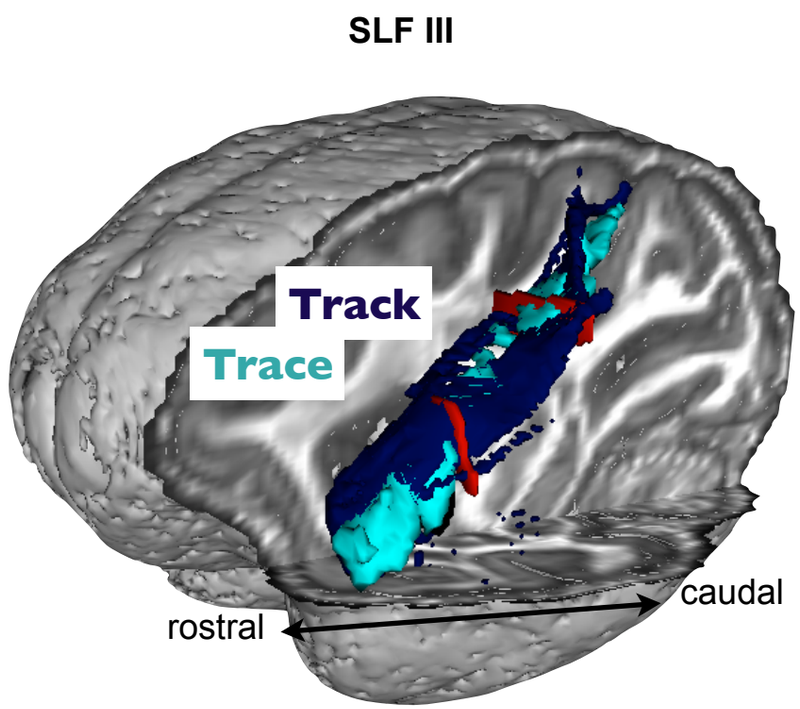


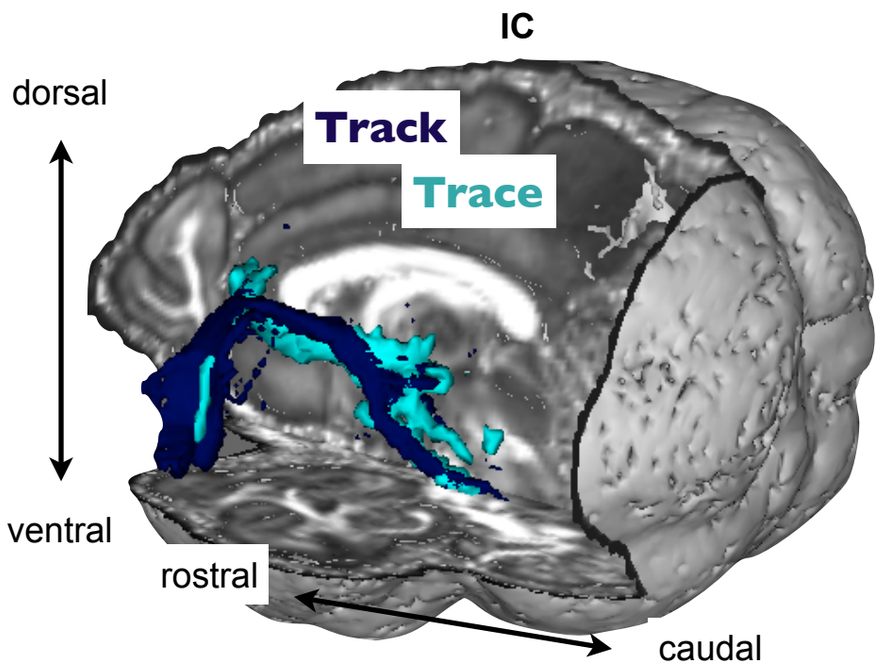
good

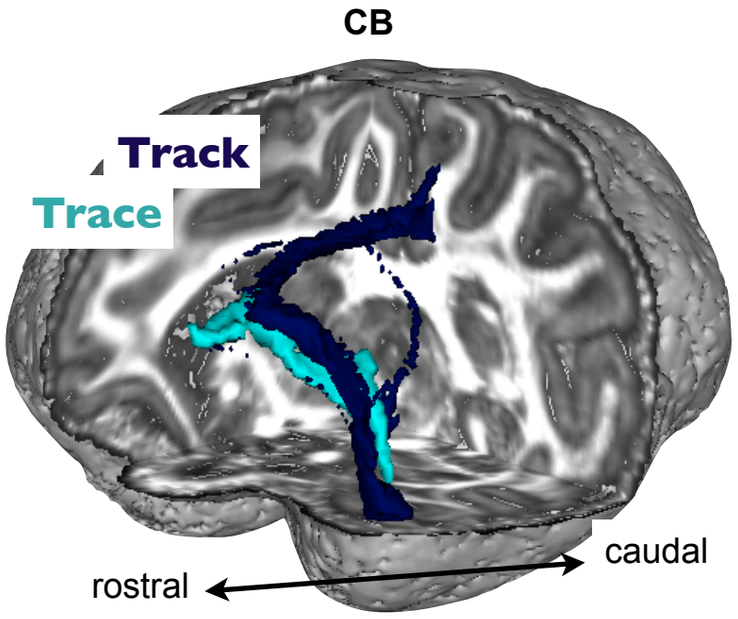
Validation: comparison with classical chemical tracing

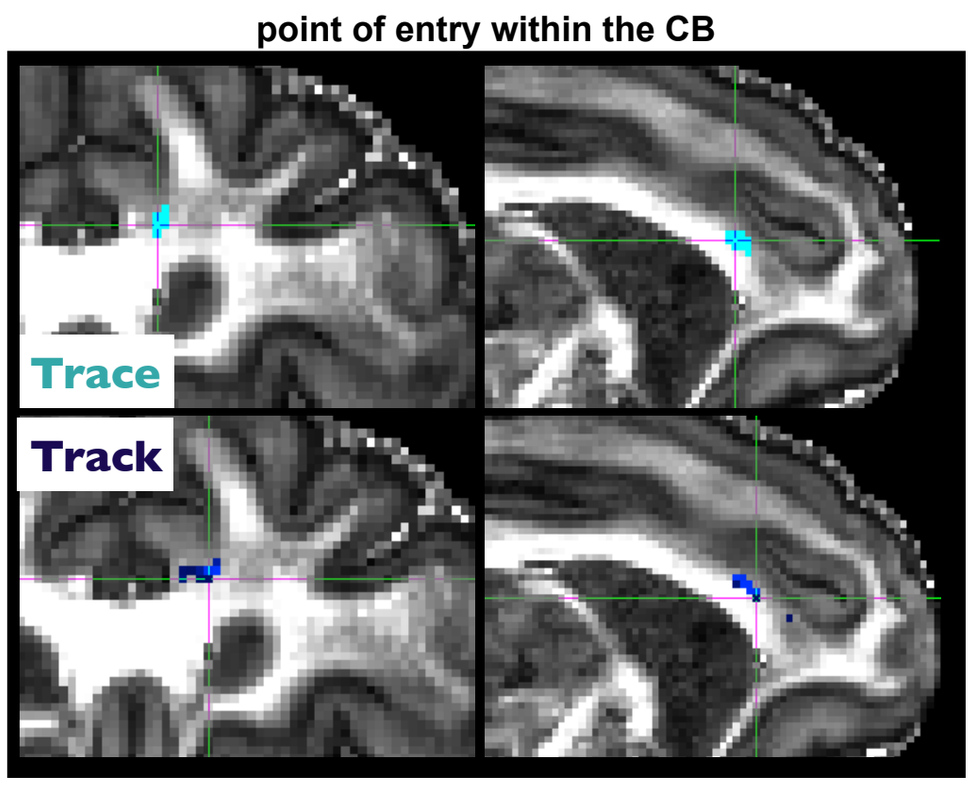
验证：与经典化学示踪比较











Jbabdi et al, Journal of Neuroscience, 2013

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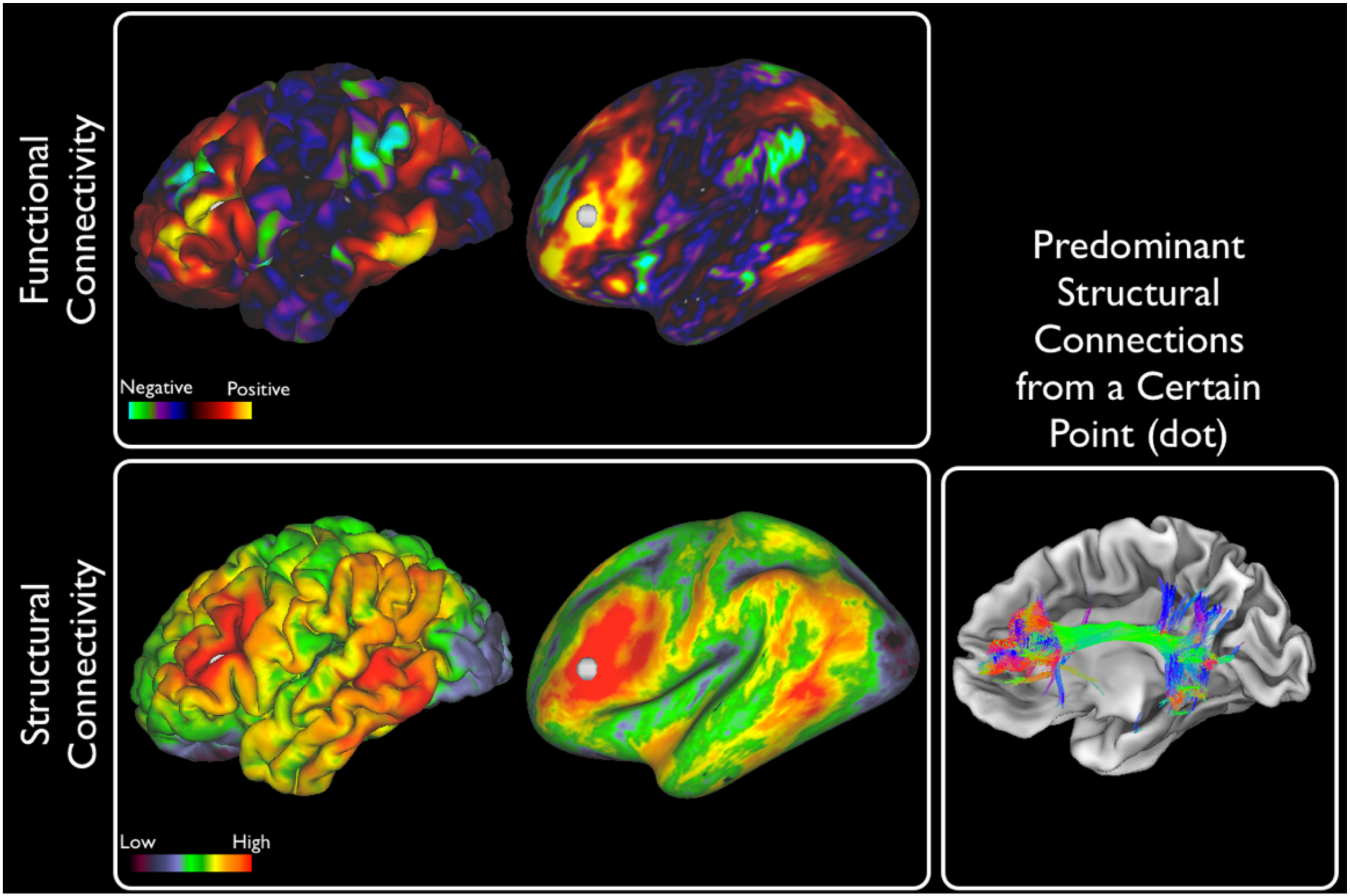

That's all folks