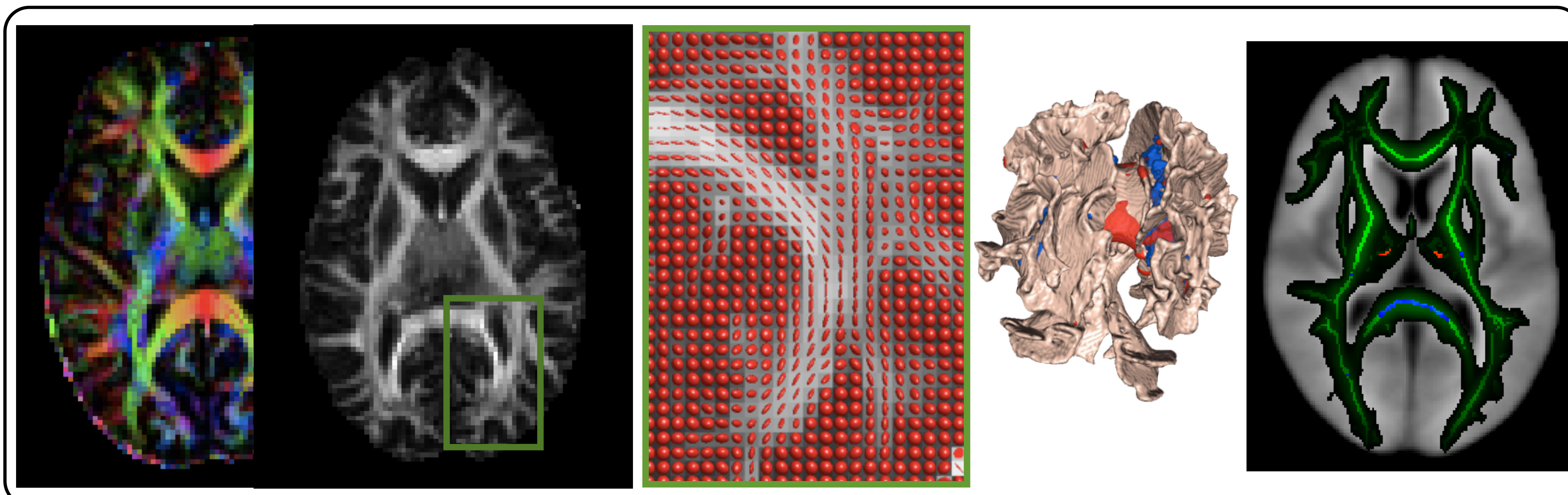
Diffusion MRI Processing and Analysis

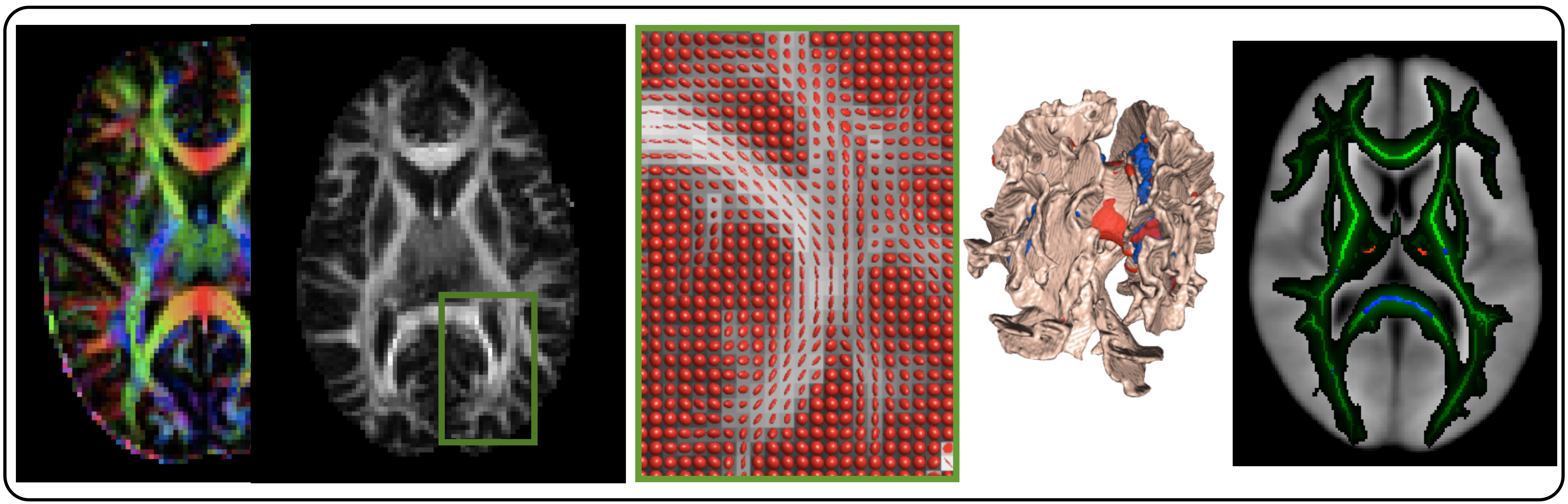
弥散MRI的处理与分析

中文翻译：李宏 孔亚卓



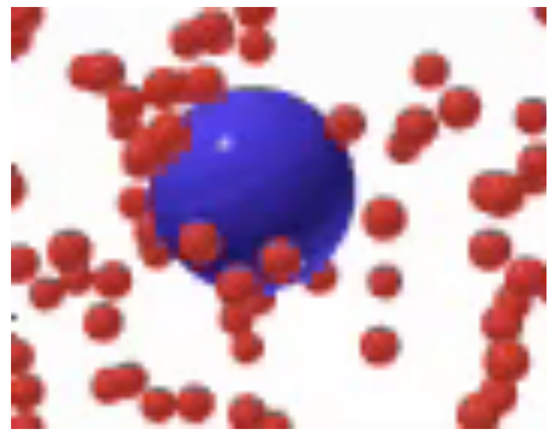
Overview
概述

- What is Diffusion? Diffusion-weighting in MRI 什么是弥散？MRI中的扩散加权
- Diffusion Tensor Model and DTI 扩散张量模型和DTI
- Tract-Based Diffusion analysis (TBSS) 纤维素追踪分析（TBSS）
- Distortion Correction for Diffusion MRI 扩散MRI的畸变校正



Diffusion - Brownian Motion
扩散-布朗运动

Robert Brown (1773-1858)



Molecules are in constant motion at non-zero absolute temperatures (> -273^{o} C)
分子在非零绝对温度下持续运动

Diffusion = thermally-driven random motion
弥散=热驱动随机运动

Diffusion - Brownian Motion
扩散-布朗运动

Albert Einstein (1879-1955)

How can we describe this motion?
我们应该怎么形容这种运动呢?
For an ensemble of molecules, in *n*-dimensional space: 对于n维空间中的分子集合:

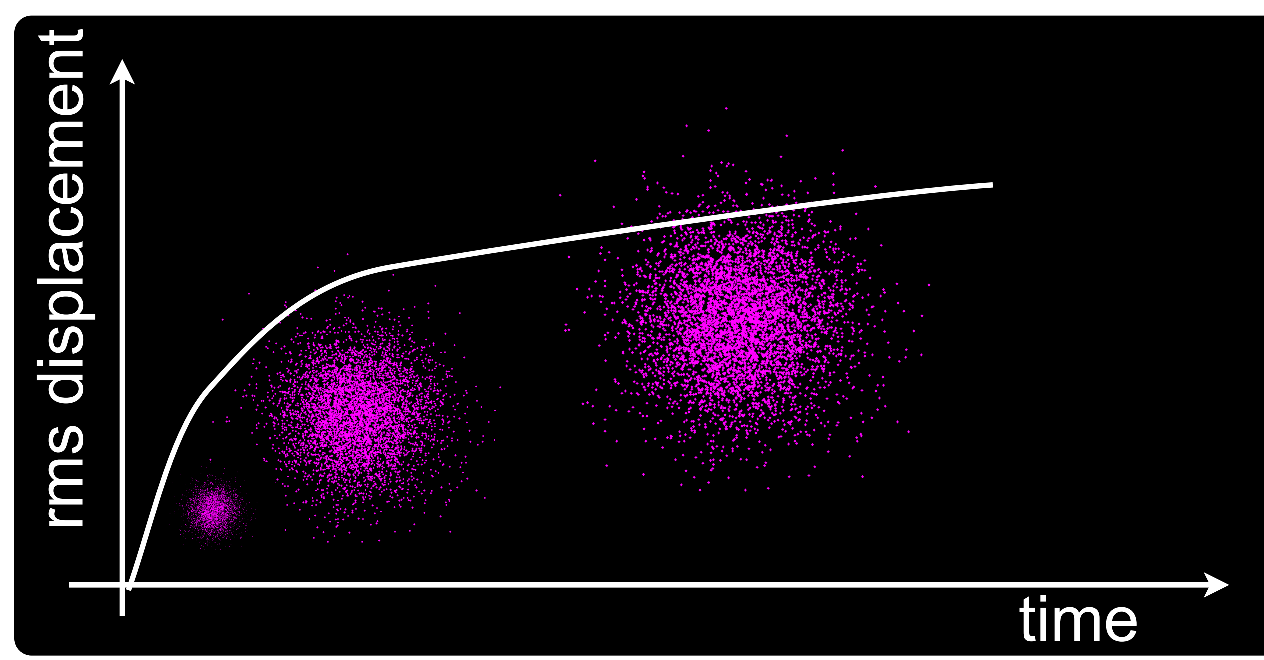
$$< x^2 >= 2nDt$$

mean squared displacement ($< x^2 >$)

Diffusion coefficient (D)

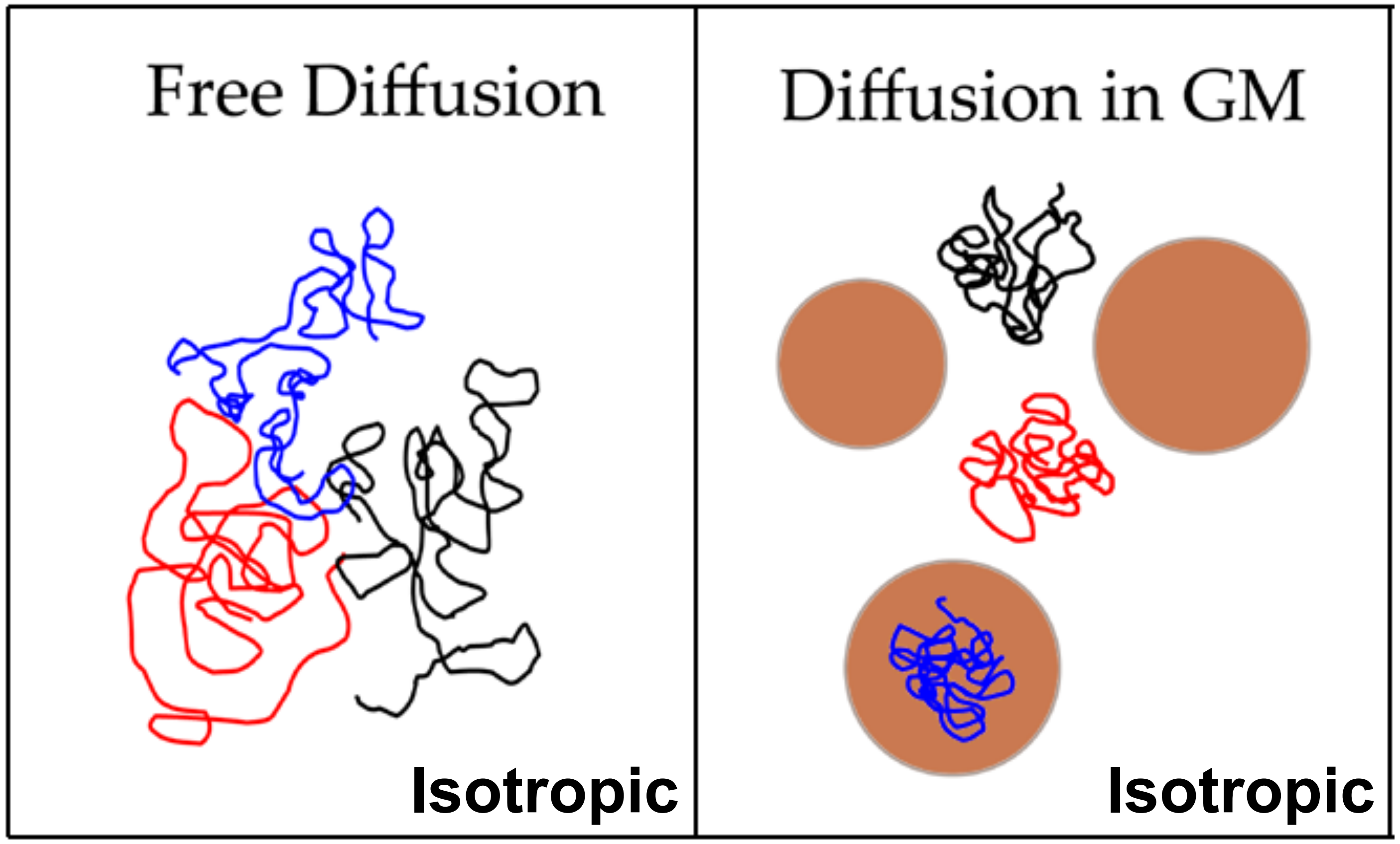
time (t)

Valid for a homogeneous, barrier-free medium.
适用于同质,
无障碍媒介。

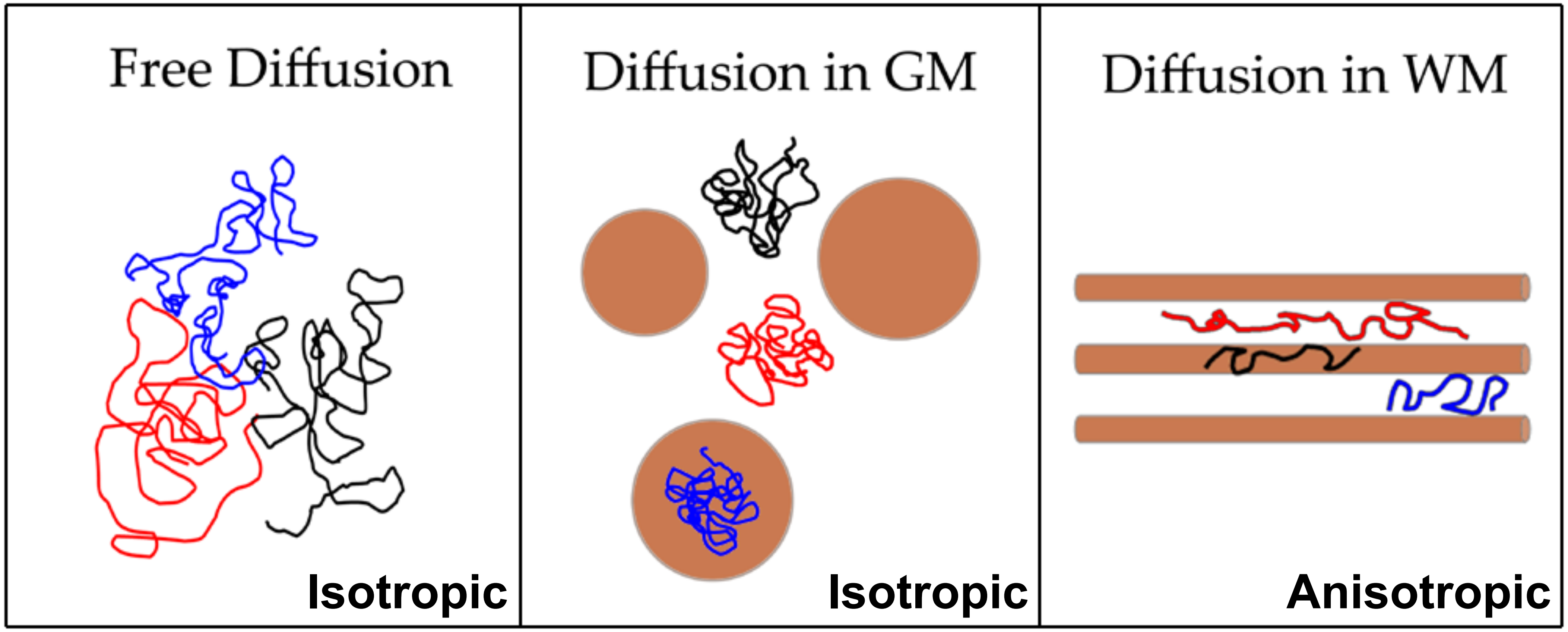


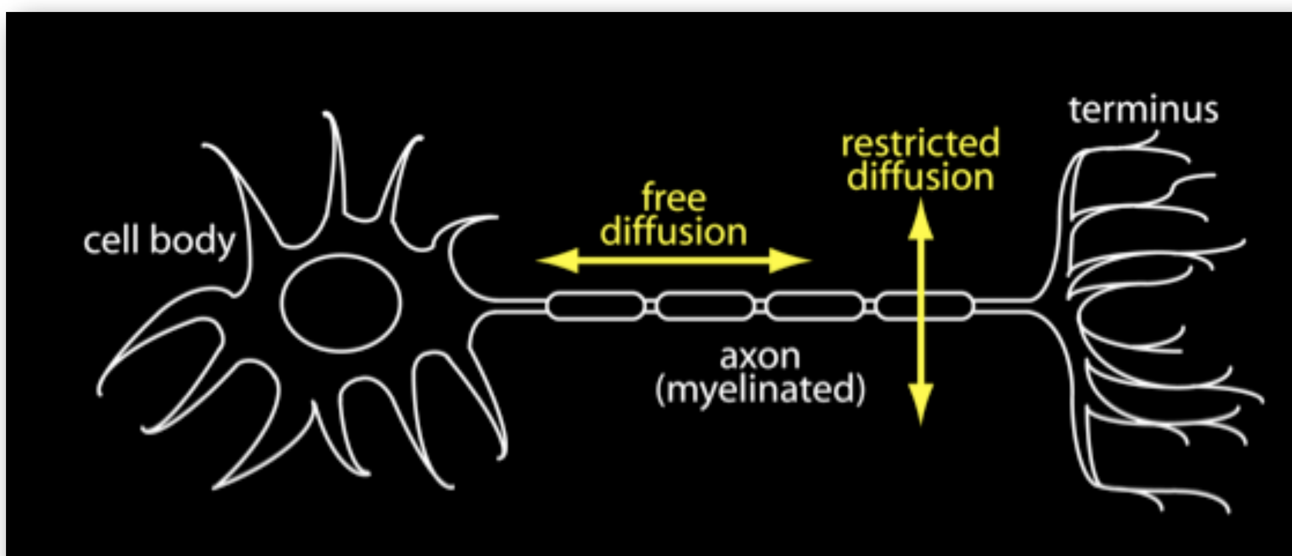
Water Diffusion in the Brain. Why is it Interesting?

Water Diffusion in the Brain. Why is it Interesting?



Water Diffusion in the Brain. Why is it Interesting?

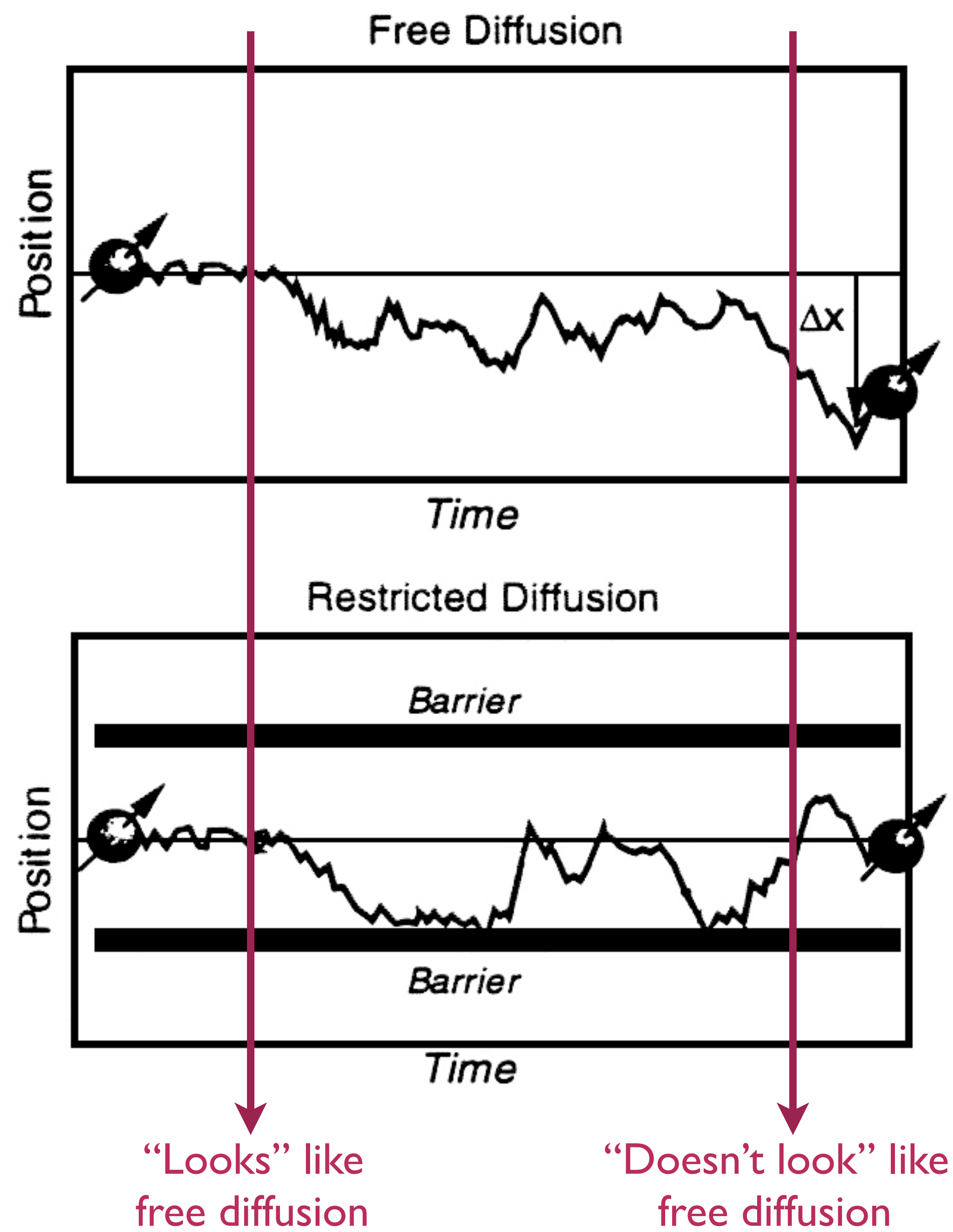




Diffusion is restricted by tissue boundaries, membranes, etc.
Marker for tissue microstructure (healthy and pathology)
Diffusion is **anisotropic** in white matter

[Beaulieu, NMR Biomed, 2002]

Apparent Diffusion 表观扩散

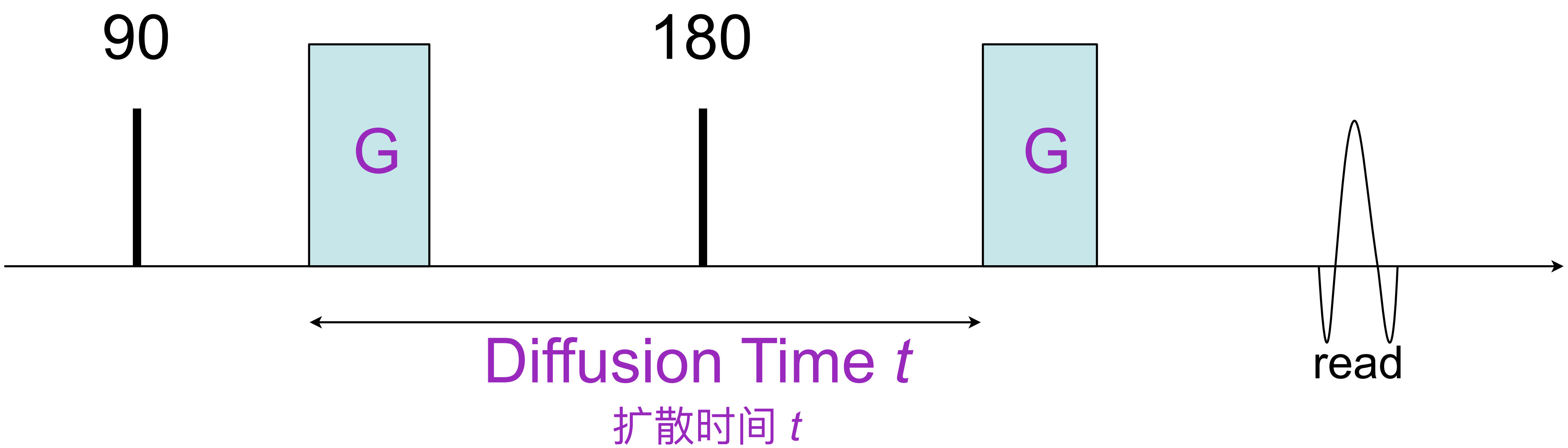


Observed diffusion in tissues depends on the experiment = "Apparent diffusion" & "Apparent diffusion coefficient" (ADC)

组织中观察到的扩散取决于实验="表观扩散"和"表观扩散系数"（ADC）

Measuring Diffusion with MRI:
用MRI测量扩散：Diffusion MRI (dMRI)

Pulsed-Gradient Spin-Echo Sequence: 脉冲梯度自旋回波序列：
To achieve diffusion-weighting along a direction **x**, apply strong magnetic field gradients along **x**. 为了沿x方向实现扩散加权，沿x施加强磁场梯度。

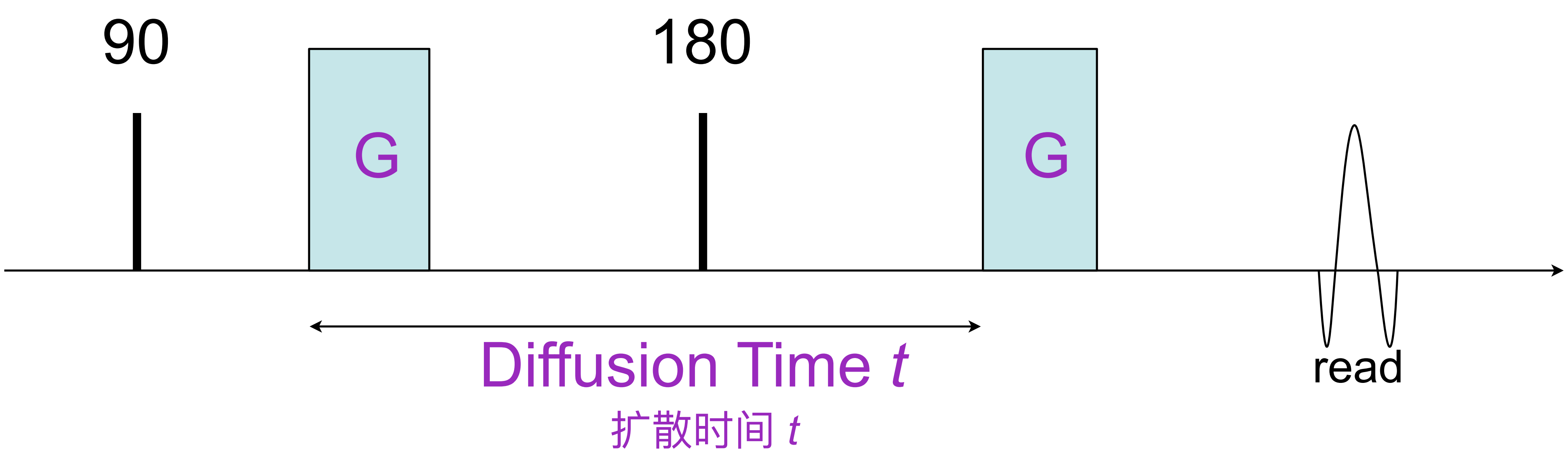


If particles diffuse along **x** during the allowed time (DiffTime), a signal attenuation is observed, compared to the signal with G=0.
如果粒子在允许时间（DiffTime）期间沿x扩散，则与G = 0的信号相比，观察到信号衰减。

[Stejskal & Tanner, 1965]

Measuring Diffusion with MRI:
用MRI测量扩散：Diffusion MRI (dMRI)

Pulsed-Gradient Spin-Echo Sequence: 脉冲梯度自旋回波序列：
To achieve diffusion-weighting along a direction **x**, apply strong magnetic field gradients along **x**. 为了沿x方向实现扩散加权，沿x施加强磁场梯度。



D ~ 2.4 μm²/ms
t~50ms

$\Rightarrow x=\sqrt{6Dt} \sim 27\mu m$

st. deviation of displacements
位移偏差

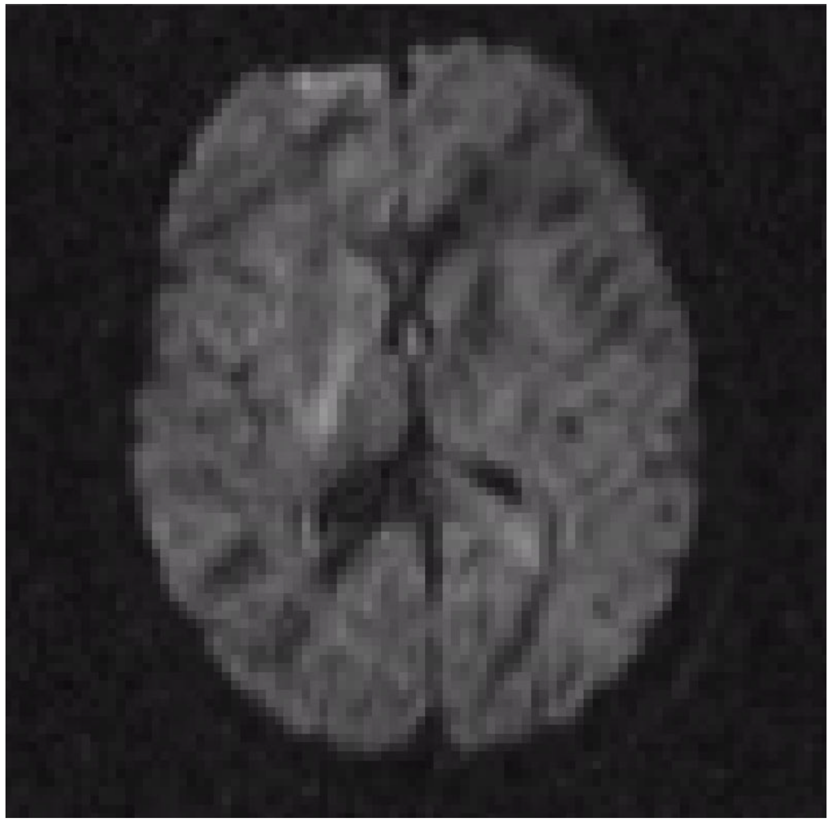
[Stejskal & Tanner, 1965]

Measuring Diffusion with MRI: Diffusion-Weighted Imaging (DWI)

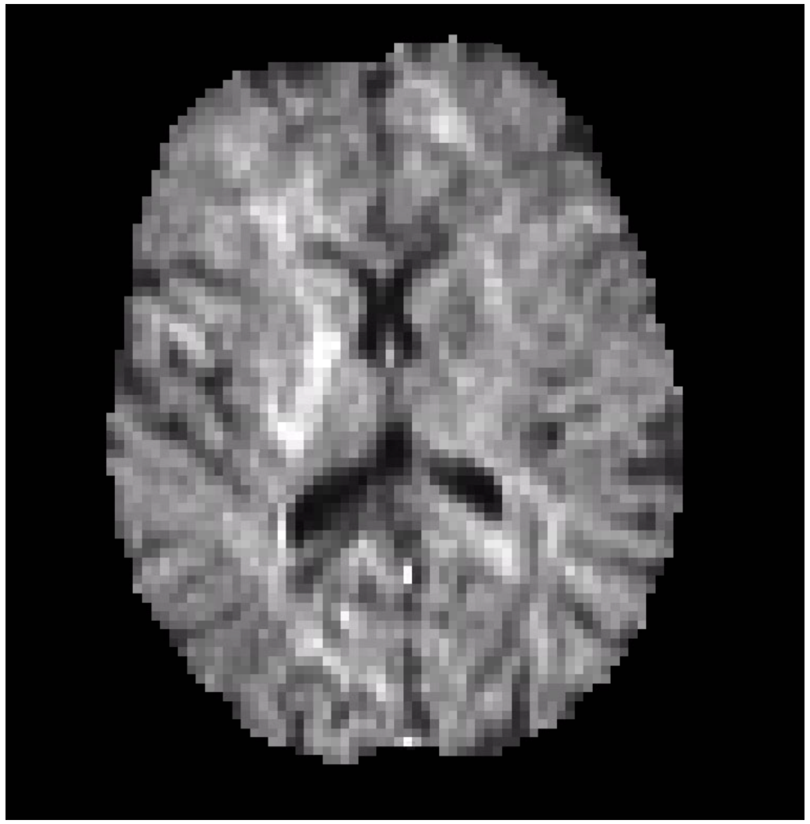
使用MRI测量扩散：扩散加权成像（DWI）

T2w Image
No Diffusion-weighting
T2加权图像
没有扩散加权
(G=0)
S_0

Diffusion-weighted Image
弥散加权图像
S



Ratio
比值
S/S_0



Removes T2w contrast

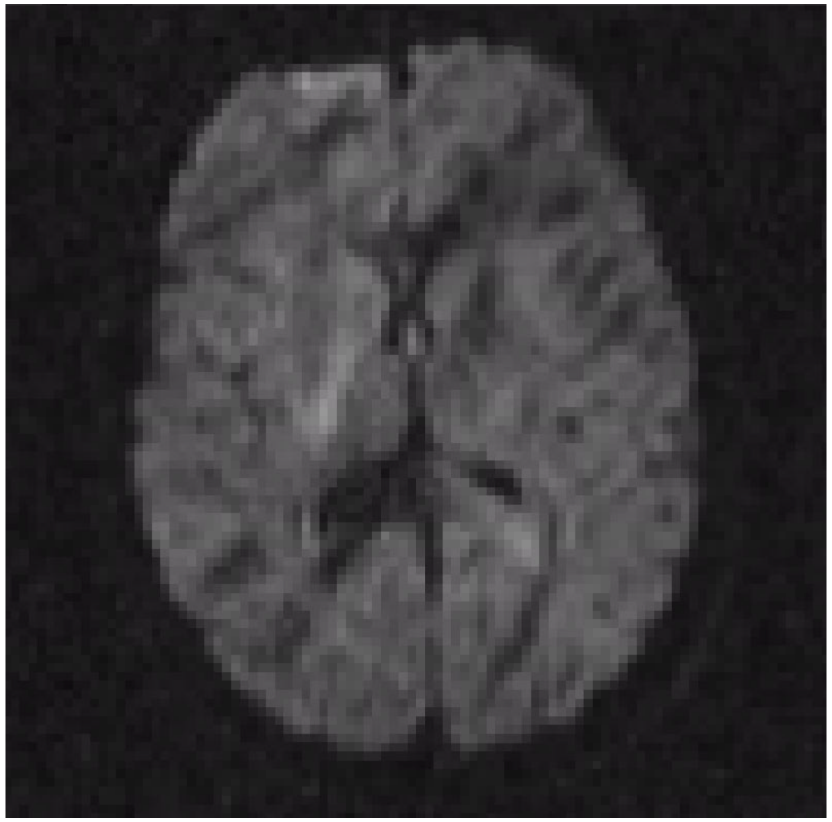
去除T2加权对比度

Measuring Diffusion with MRI: Diffusion-Weighted Imaging (DWI)

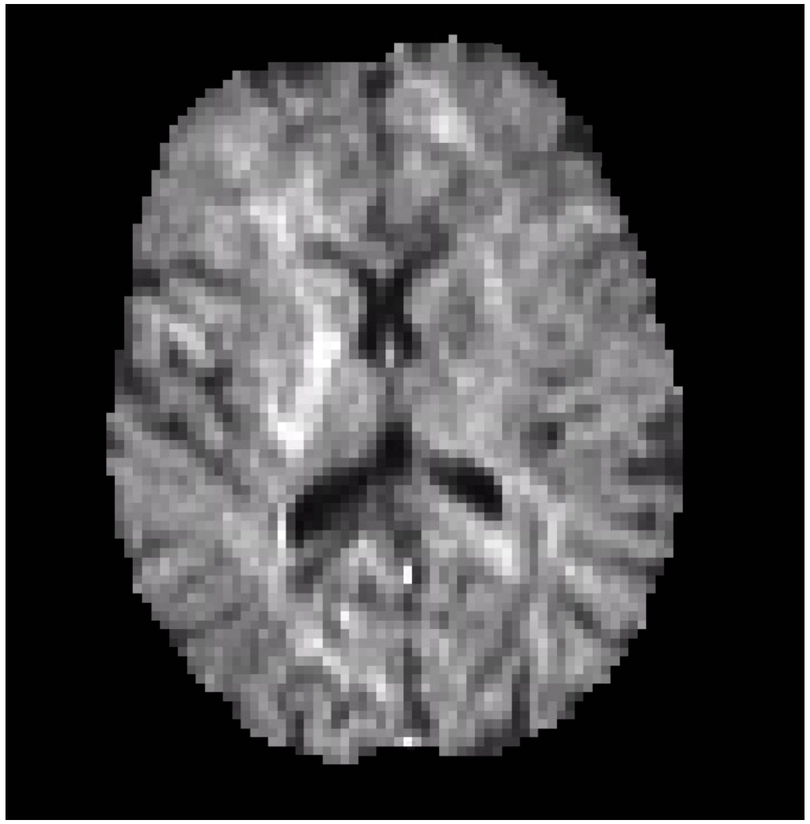
使用MRI测量扩散：扩散加权成像（DWI）

T2w Image
No Diffusion-weighting
T2加权图像
没有扩散加权
(G=0)
S_0

Diffusion-weighted Image
弥散加权图像
S



Ratio
比值
S/S_0



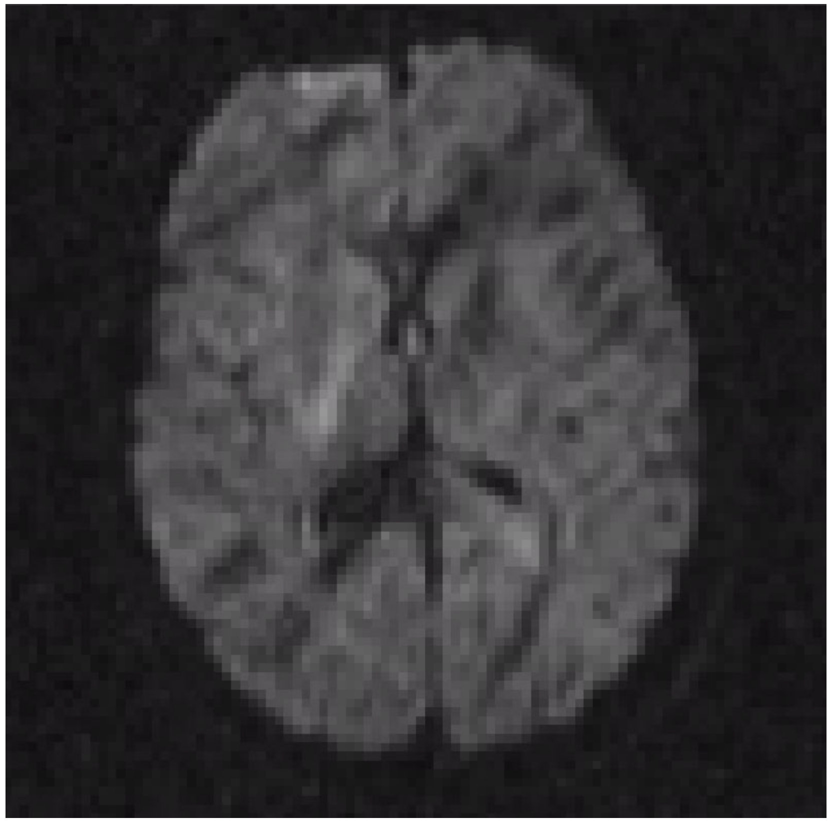
Removes T2w contrast

去除T2加权对比度

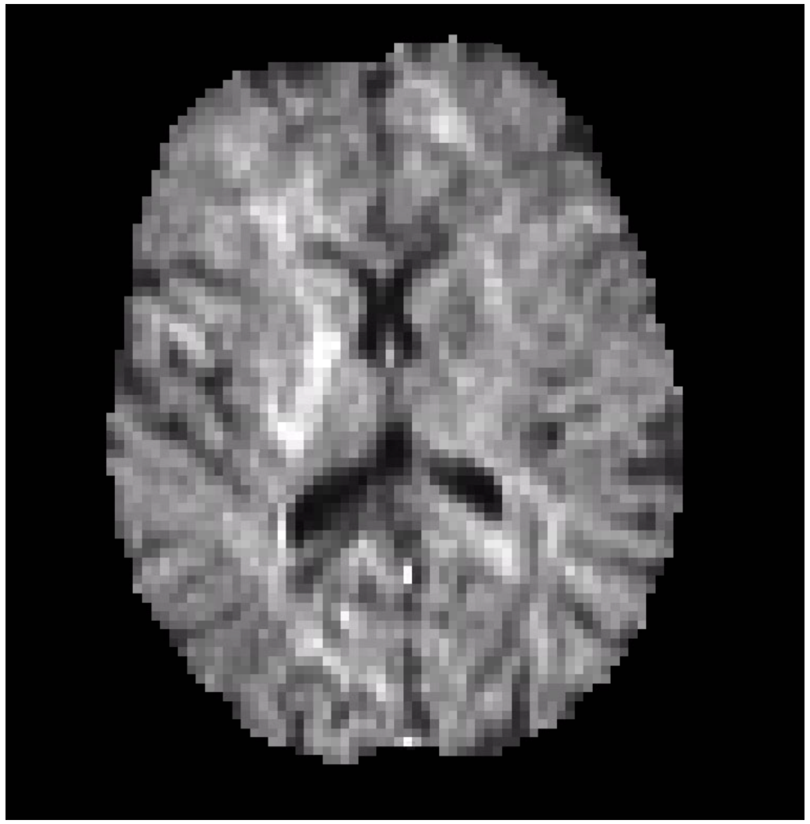
Measuring Diffusion with MRI: Diffusion-Weighted Imaging (DWI)
使用MRI测量扩散：扩散加权成像（DWI）

T2w Image
No Diffusion-weighting
T2加权图像
没有扩散加权
(G=0)
S_0

Diffusion-weighted Image
弥散加权图像
S



Ratio
比值
S/S_0



Removes T2w contrast

去除T2加权对比度

Measuring Diffusion with MRI: Diffusion-Weighted Imaging (DWI)
使用MRI测量扩散：扩散加权成像（DWI）

Diffusion contrast can be modulated by:扩散对比可以通过以下方式调节

A) **Diffusion weighting:** Gradient **strength,** Diffusion **time**
扩散加权：梯度强度，扩散时间

b value ~ G^2 . DiffTime (units in s/mm^2)

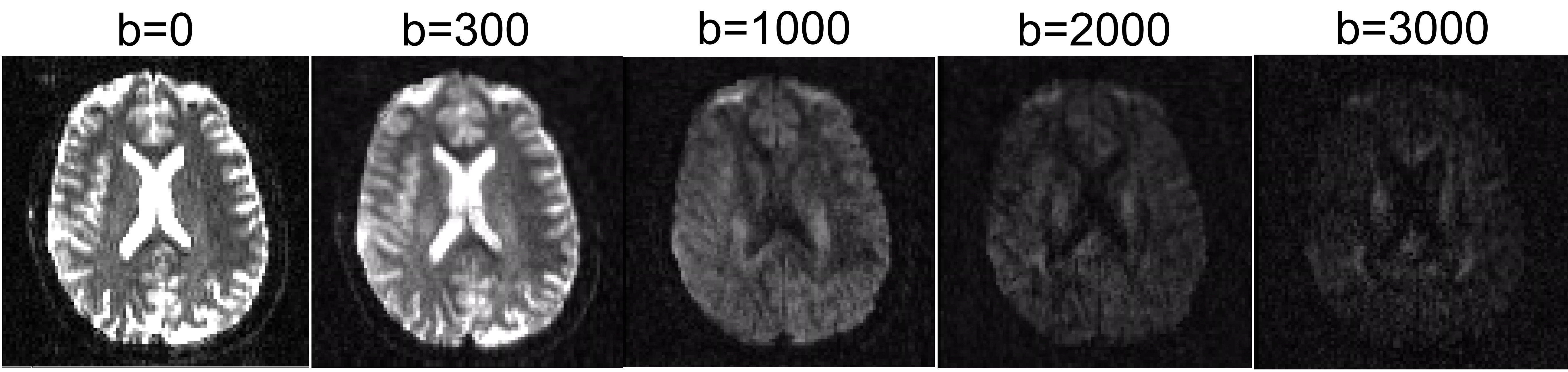
Measuring Diffusion with MRI: Diffusion-Weighted Imaging (DWI)
使用MRI测量扩散：扩散加权成像（DWI）

Diffusion contrast can be modulated by:扩散对比可以通过以下方式调节

A) **Diffusion weighting:** Gradient **strength,** Diffusion **time**

扩散加权：梯度强度，扩散时间

b value ~ G^2 . DiffTime (units in s/mm^2)



More diffusion contrast with higher b :)

…But less signal left - exponential decay :(

b更高的扩散对比度

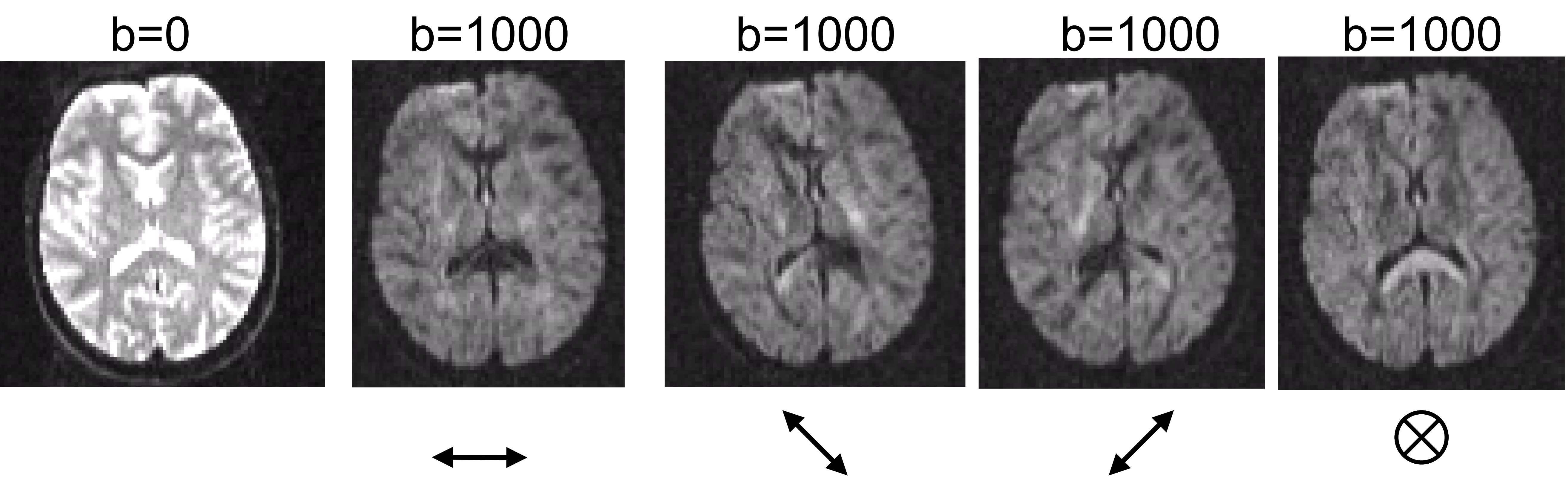
但剩下的信号减少 - 指数衰减

Measuring Diffusion with MRI: Diffusion-Weighted Imaging (DWI)

使用MRI测量扩散：扩散加权成像（DWI）

Diffusion contrast can be modulated by　扩散对比可以通过以下方式调节

B) Gradient Direction　x的梯度方向

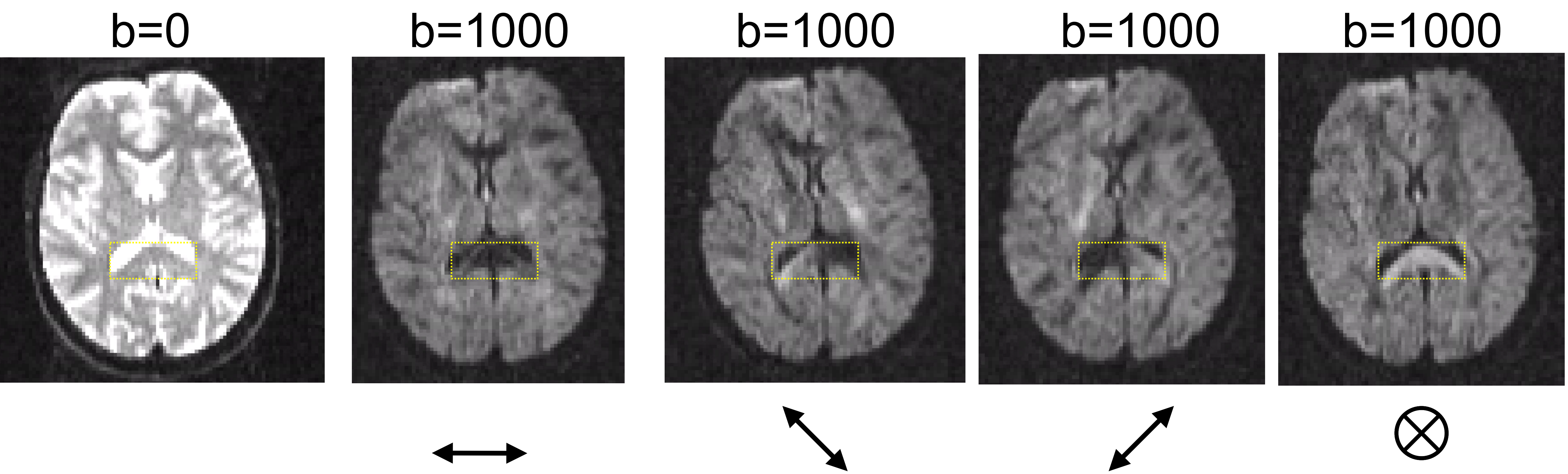


Measuring Diffusion with MRI: Diffusion-Weighted Imaging (DWI)

使用MRI测量扩散：扩散加权成像（DWI）

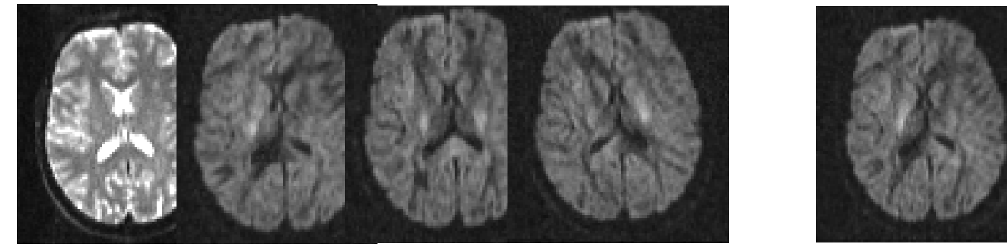
Diffusion contrast can be modulated by 扩散对比可以通过以下方式调节

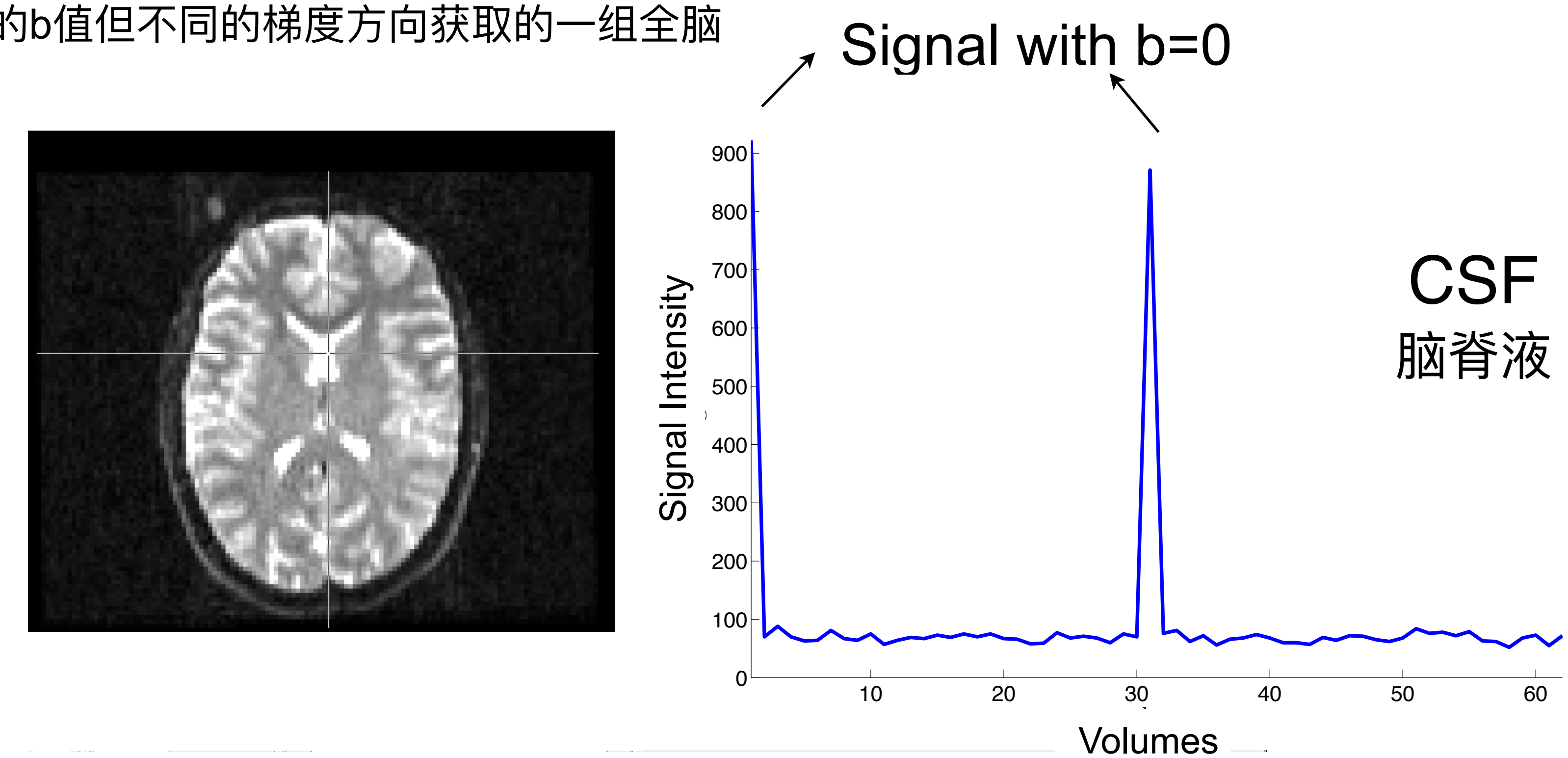
B) Gradient Direction x的梯度方向



A Typical dMRI Protocol 典型的dMRI流程

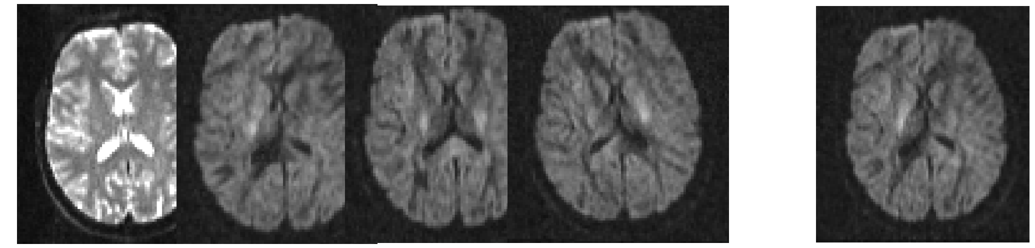
- Normally a few (at least one) b=0 volumes acquired, along with shells at higher b (~1000 s/mm^2).
  通常获得一些（至少一个）b = 0全脑，以及更高b（~1000s /mm^2）的壳
- A shell is a set of volumes acquired with the same b-value, but different gradient orientation
  壳是使用相同的b值但不同的梯度方向获取的一组全脑

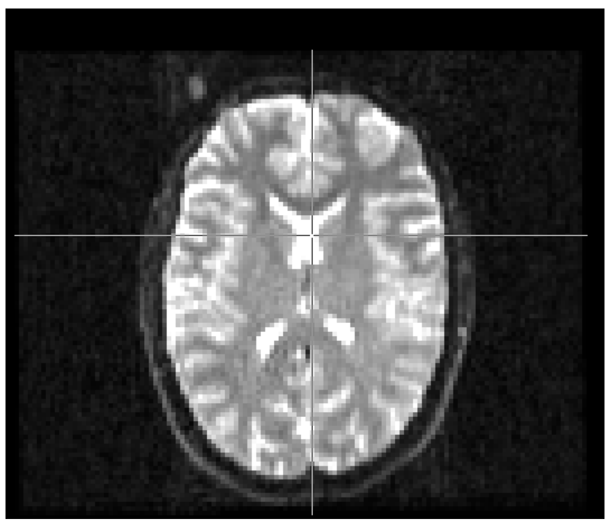


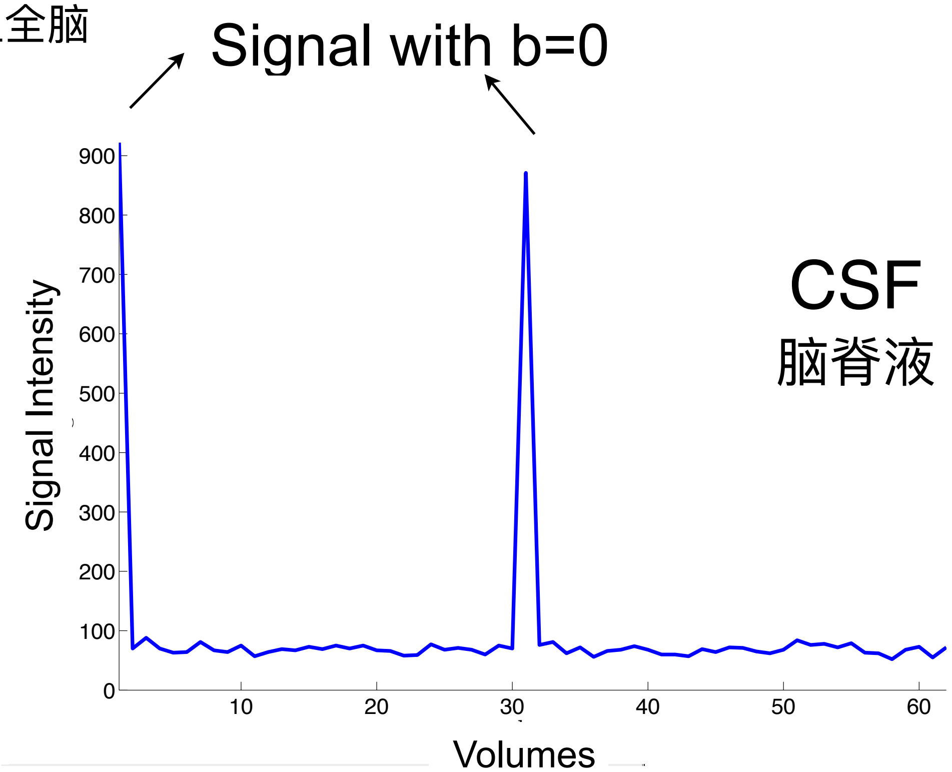


A Typical dMRI Protocol 典型的dMRI流程

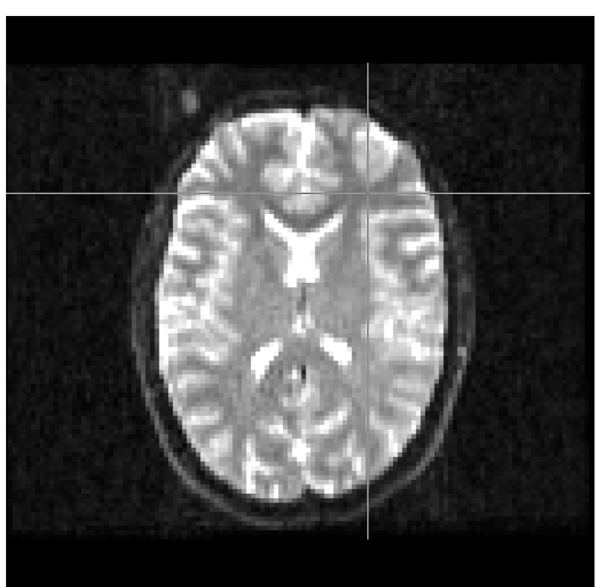
- Normally a few (at least one) b=0 volumes acquired, along with shells at higher b (~1000 s/mm²).
  通常获得一些（至少一个）b = 0全脑，以及更高b（~1000s /mm²）的壳
- A shell is a set of volumes acquired with the same b-value, but different gradient orientation
  壳是使用相同的b值但不同的梯度方向获取的一组全脑

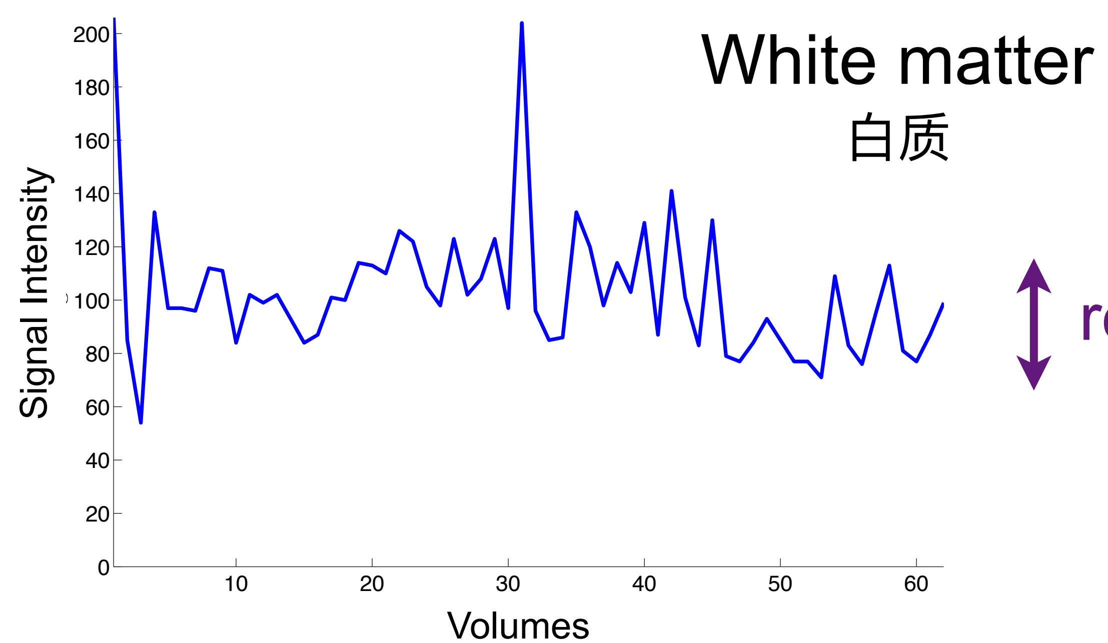






relates to ADC
与ADC有关





relates to anisotropy
与各向异性有关

dMRI Summary 总结

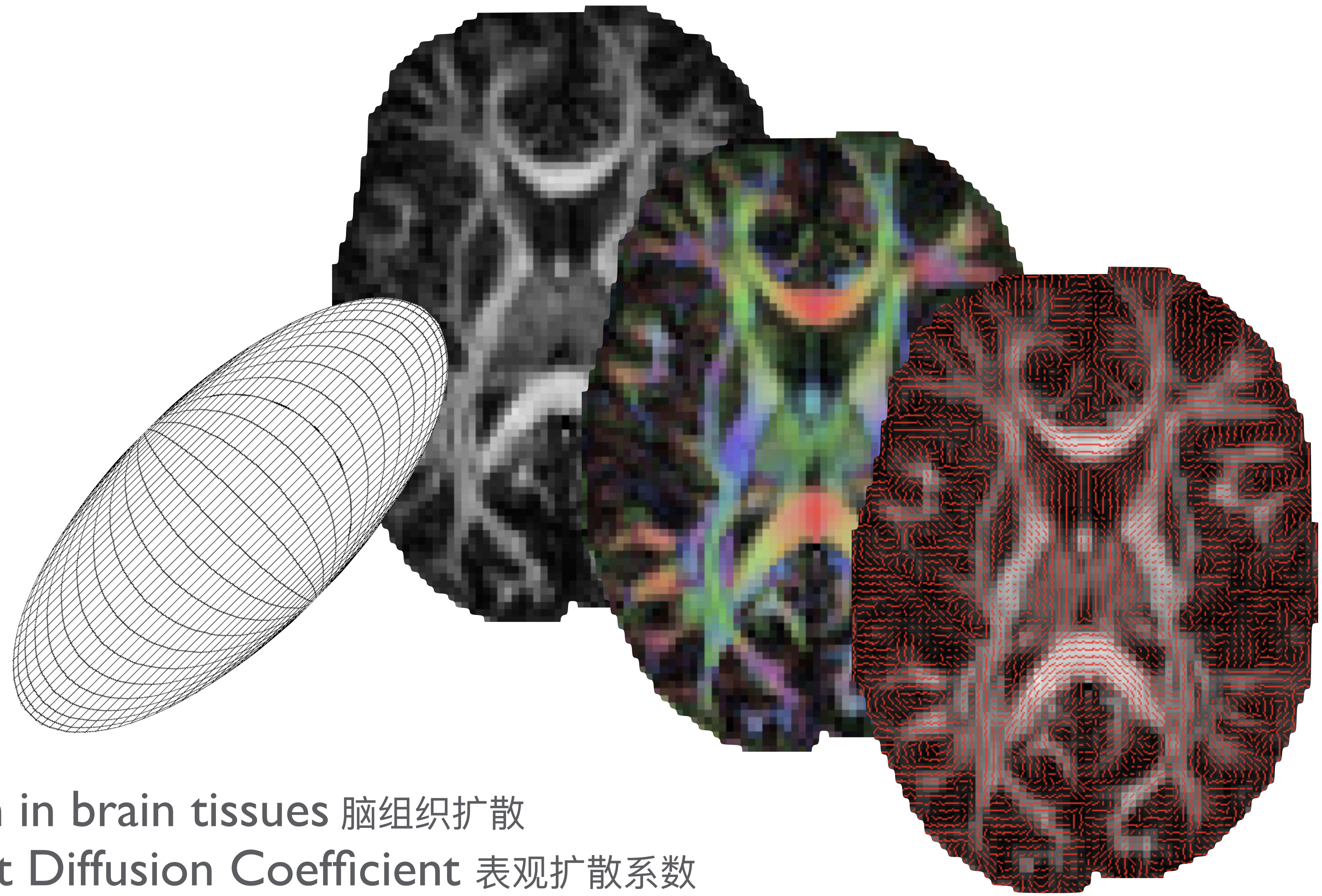
- Images acquired with a Gradient along **x**, have contrast that is sensitive to diffusion of water molecules along **x**.
  沿着x的梯度获得的图像具有对水分子沿x的扩散敏感的对比度。

- When diffusion occurs, signal is attenuated compared to the one with no diffusion-weighting.
  当发生扩散时，与没有扩散加权的信号相比，信号衰减。

- In WM, measurements are anisotropic.
  在白质中，测量是各向异性的。

- In GM and CSF, measurements are roughly isotropic.
  在灰质和脑脊液中，测量大致是各向同性的。

Diffusion Tensor Imaging - basic principles
扩散张量成像 - 基本原理



- Diffusion in brain tissues 脑组织扩散
- Apparent Diffusion Coefficient 表观扩散系数
- Diffusion Tensor model 扩散张量模型
- Tensor-derived measures 张量导出的度量

Diffusion Tensor Imaging (DTI)
弥散张量成像

Diffusion Tensor Model. In each voxel:
扩散张量模型。在每个体素中：

梯度j的b值（已知的）

b-value for gradient *j* (known)

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

表示梯度j方向的单位向量（已知）

$$S_j = S_0 \exp(-b_j \, \boldsymbol{x}_j^T \, \boldsymbol{D} \, \boldsymbol{x}_j)$$

Signal measured after applying a Gradient *j* with direction $\boldsymbol{x}_j$ and b-value b_j (measured)

应用具有方向xj和b值bj（测量）的梯度j后测量的信号

Signal measured with no diffusion gradient applied

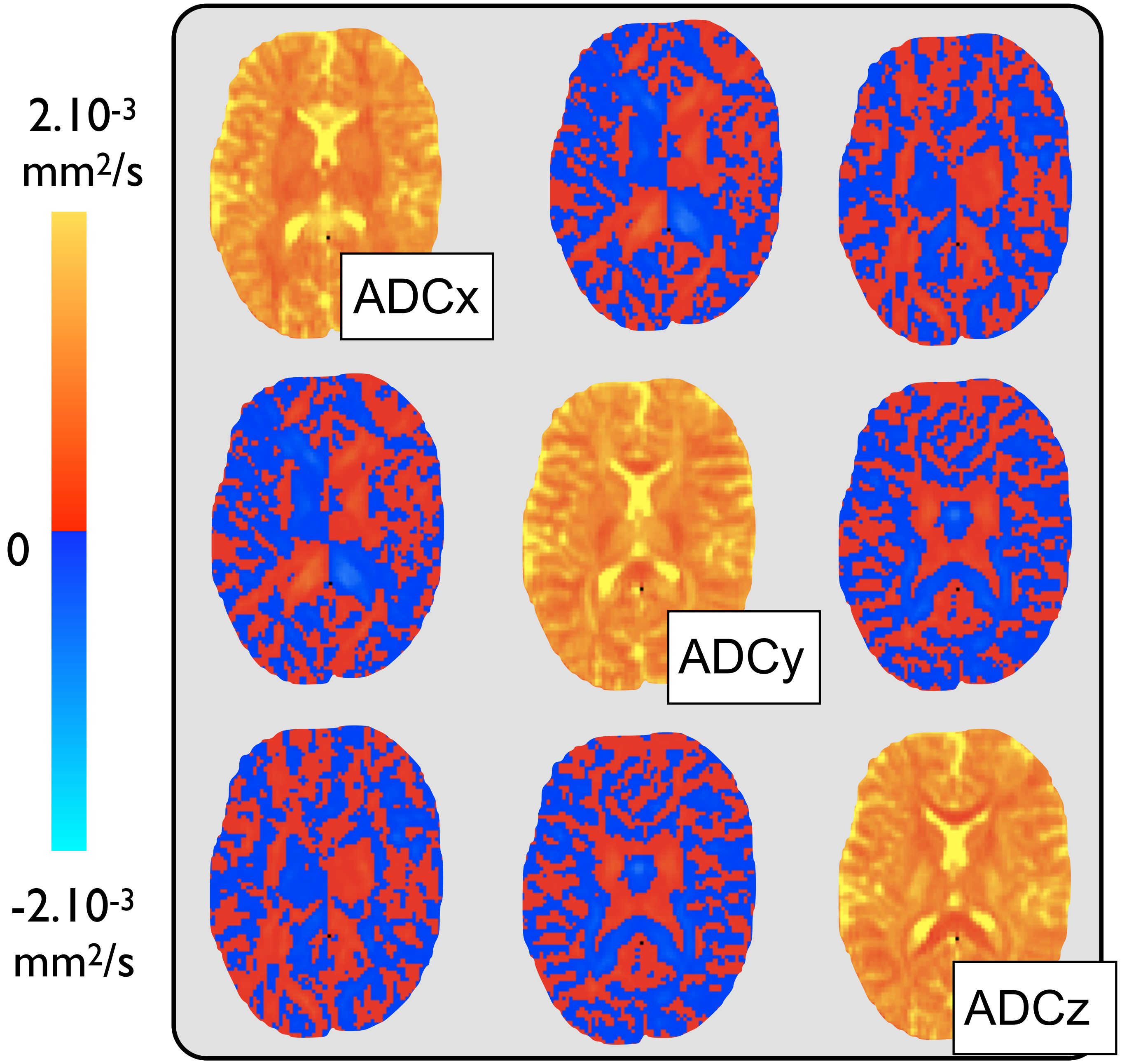
测量信号，未施加扩散梯度

3x3 Diffusion Tensor (unknown)

3x3扩散张量（未知）

[Basser, Biophys J,1994], [Basser et al , J Magn Res, 1994]

The Elements of the Diffusion Tensor
扩散张量的要素



$$\mathbf{D} = \begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{xy} & D_{yy} & D_{yz} \\ D_{xz} & D_{yz} & D_{zz} \end{bmatrix}$$

- Tensor is **symmetric** (6 unknowns)
  张量是对称的（6个未知数）

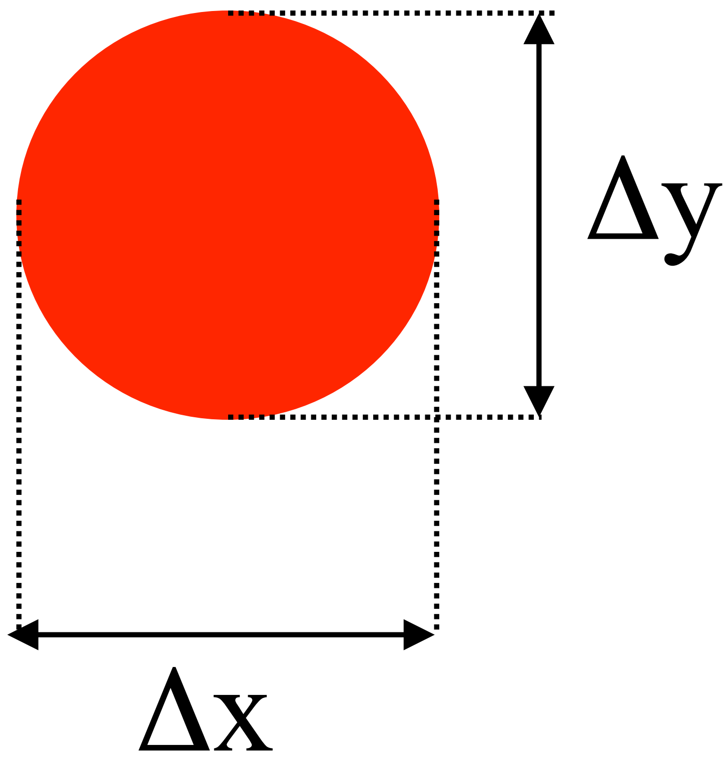
- **Diagonal Elements** are proportional to the diffusion displacement variances (**ADCs**) along the three directions of the experiment coordinate system
对角线元素与沿实验坐标系的三个方向的扩散位移方差（ADC）成比例

-**Off-diagonal Elements** are proportional to the **correlations** (covariances) of displacements along these directions
非对角线元素与沿这些方向的位移的相关性（协方差）成比例

$N_3(0, 2t\mathbf{D})$

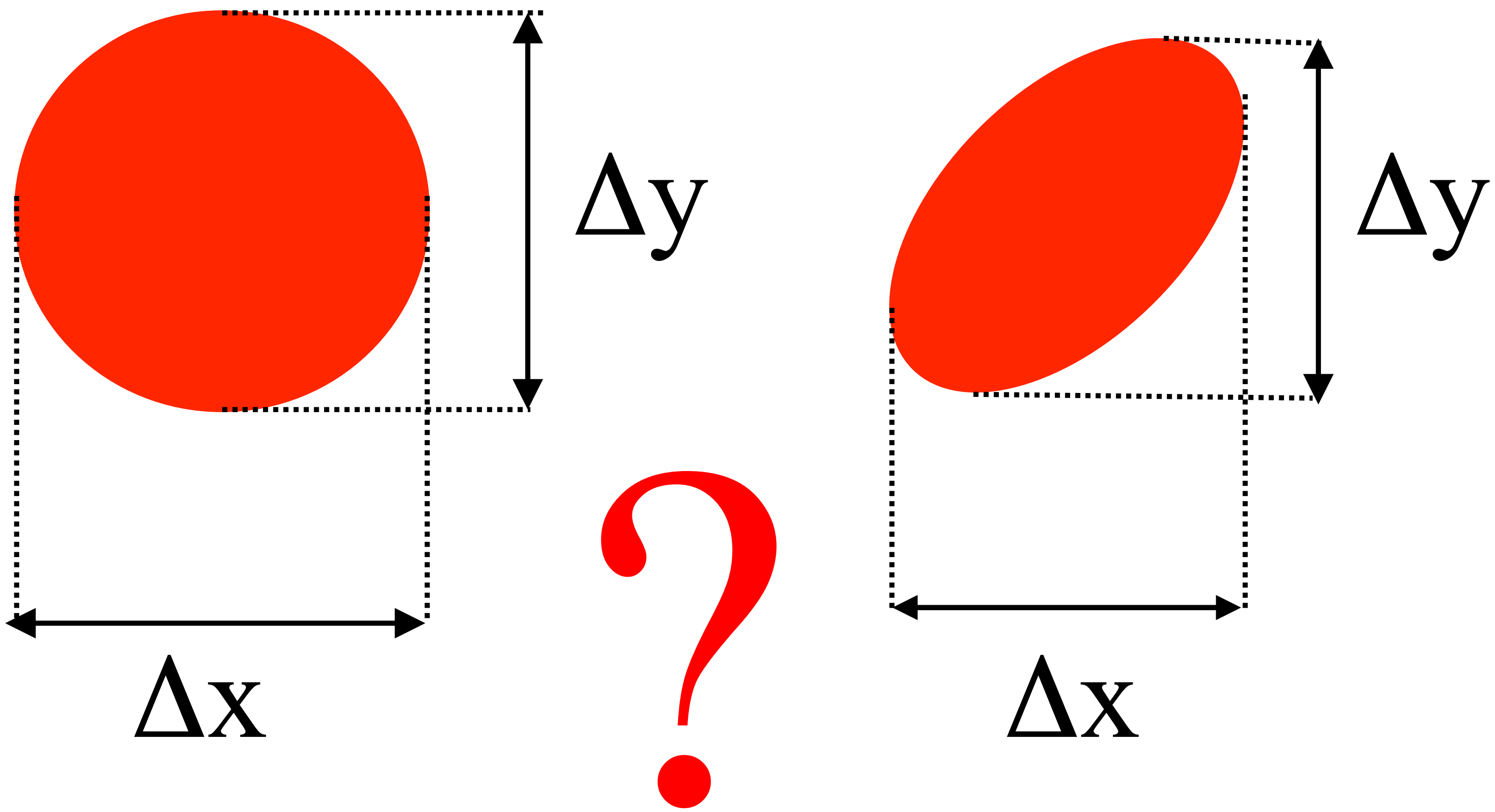
Why do we need a tensor?

为什么我们需要张量?

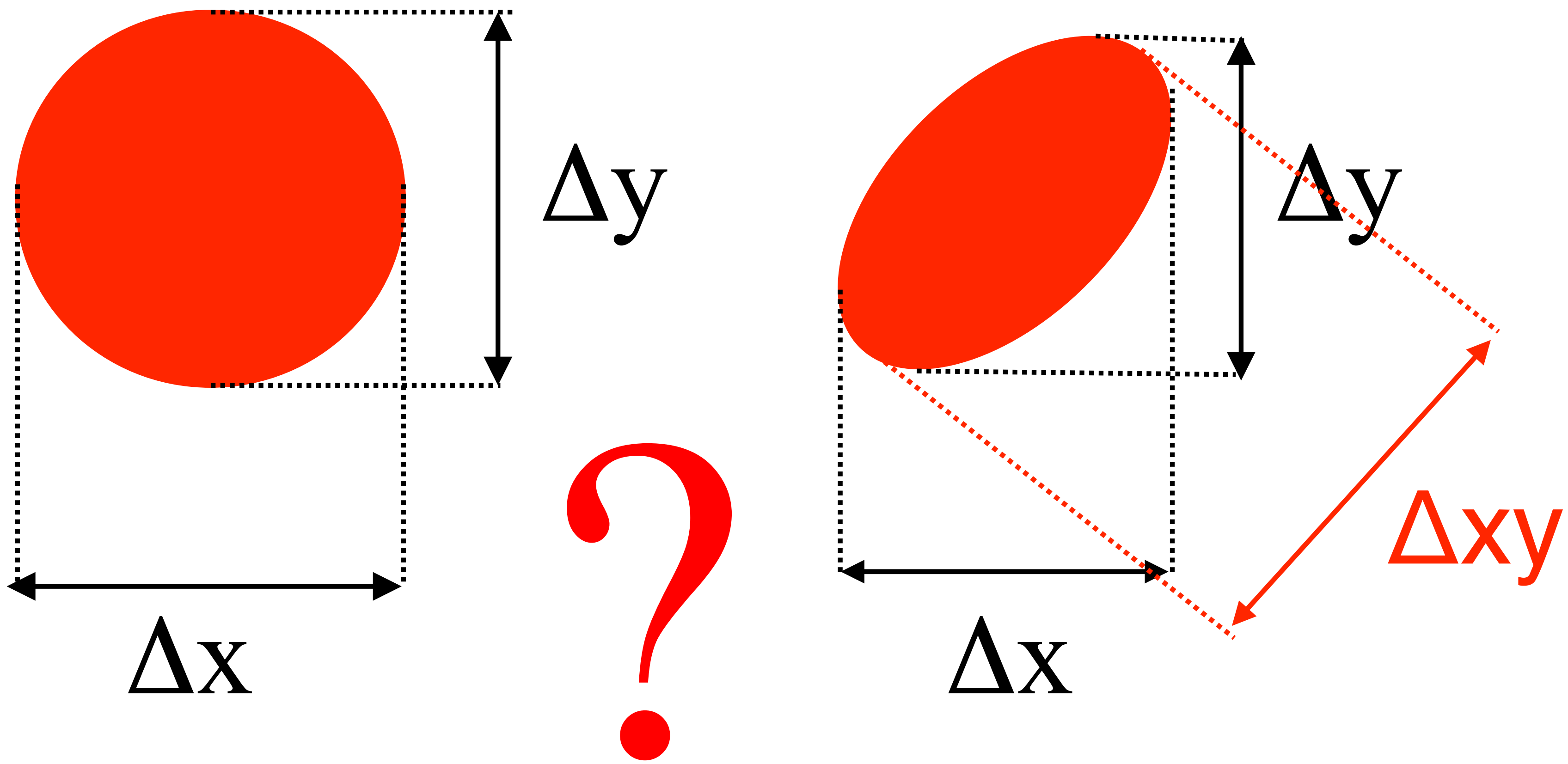


Why do we need a tensor?

为什么我们需要张量?



Why do we need a tensor?
为什么我们需要张量?

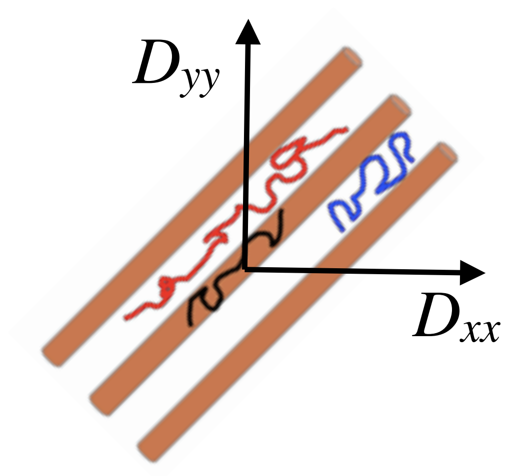


$$\begin{bmatrix} D_x & D_{xy} \\ D_{xy} & D_y \end{bmatrix}$$

The Diffusion Tensor Eigenspectrum

弥散张量特征谱

$$\mathbf{D} = \begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{xy} & D_{yy} & D_{yz} \\ D_{xz} & D_{yz} & D_{zz} \end{bmatrix}$$

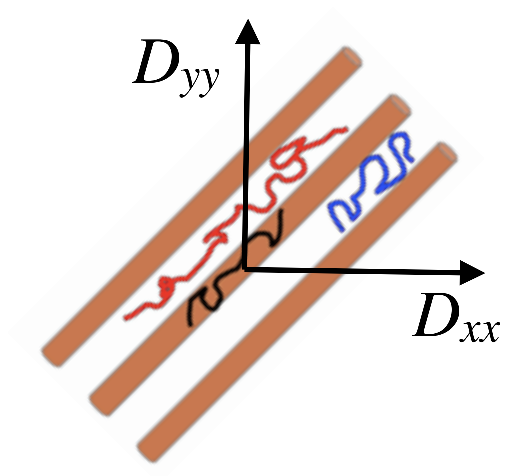


Once D is estimated, we get ADCs along the scanner's coordinate system. But we want ADCs along a local coordinate system in each voxel, determined by the anatomy. 一旦D被估计，我们就可以沿着扫描仪的坐标系得到ADC。但我们希望ADC沿着每个体素的局部坐标系，由解剖学决定

The Diffusion Tensor Eigenspectrum

弥散张量特征谱

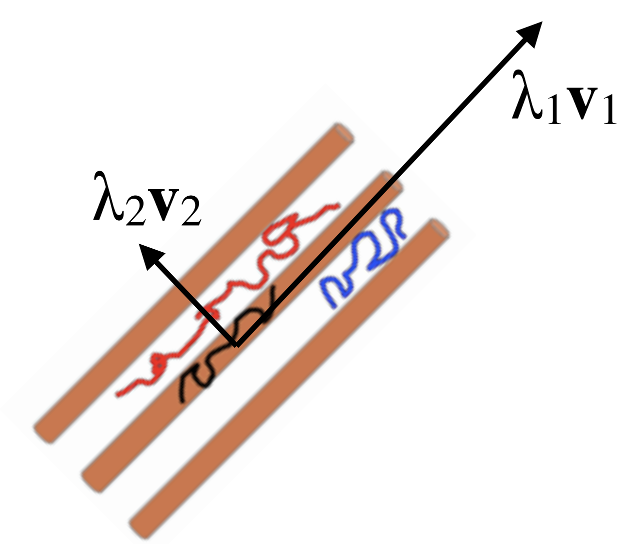
$$\mathbf{D} = \begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{xy} & D_{yy} & D_{yz} \\ D_{xz} & D_{yz} & D_{zz} \end{bmatrix}$$



Once D is estimated, we get ADCs along the scanner's coordinate system. But we want ADCs along a local coordinate system in each voxel, determined by the anatomy. 一旦D被估计，我们就可以沿着扫描仪的坐标系得到ADC。但我们希望ADC沿着每个体素的局部坐标系，由解剖学决定

Diagonalize the estimated tensor in each voxel

对角化每个体素中的估计张量



$$\mathbf{D} = [\mathbf{v_1}|\mathbf{v_2}|\mathbf{v_3}]^{\mathrm{T}} \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix} [\mathbf{v_1}|\mathbf{v_2}|\mathbf{v_3}]$$

eigenvalues: ADCs along $\mathbf{v}_1$,$\mathbf{v}_2$,$\mathbf{v}_3$

特征值：沿 v1、v2、v3 的 ADC

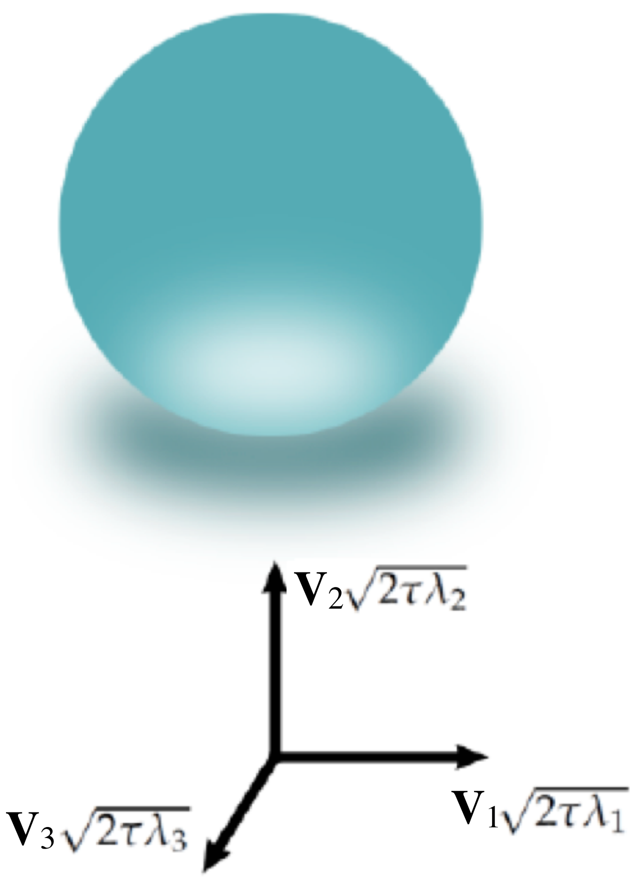
eigenvectors - $\mathbf{v}_1$=direction of max diffusivity

特征向量 值- v1=最大扩散方向

The Diffusion Tensor Ellipsoid
扩散张量椭球

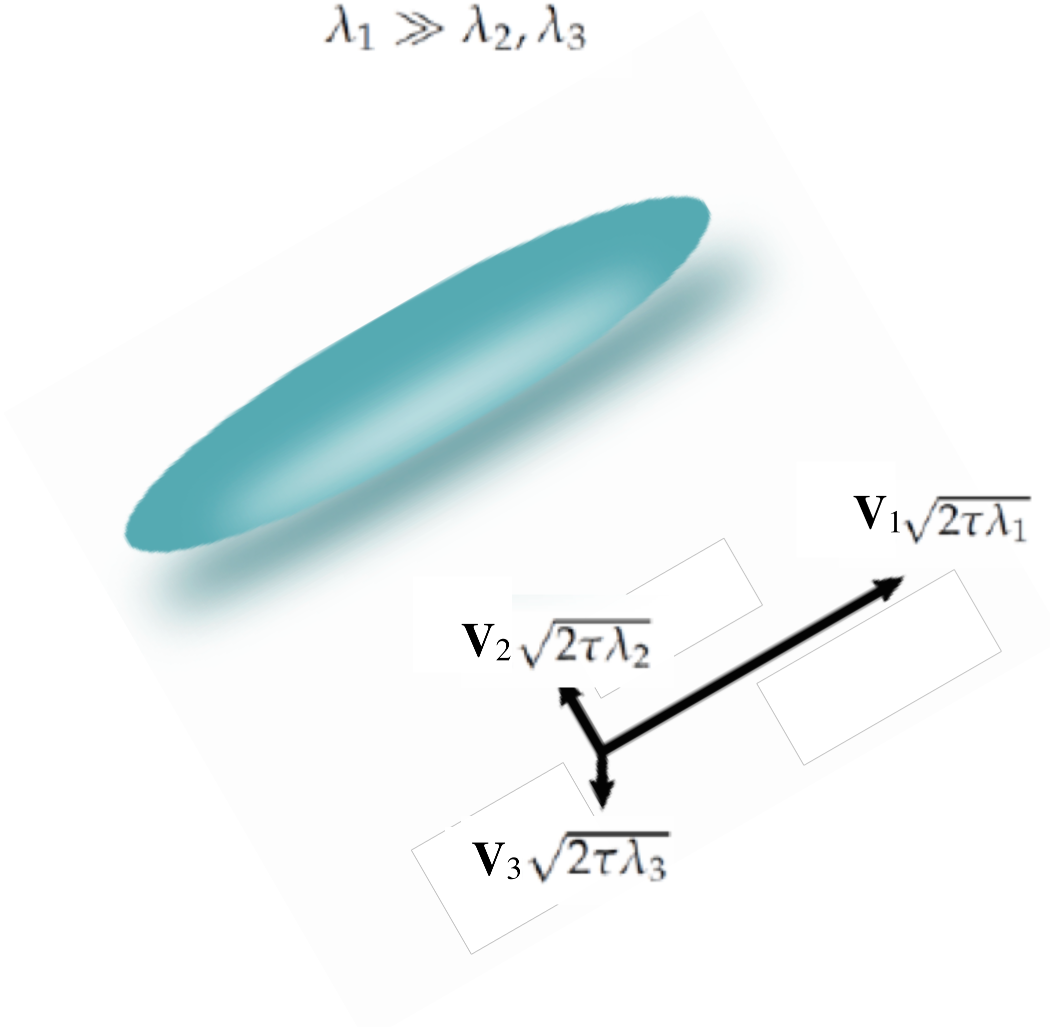
Isotropic voxel
各向同性体素

$\lambda_1 \approx \lambda_2 \approx \lambda_3$

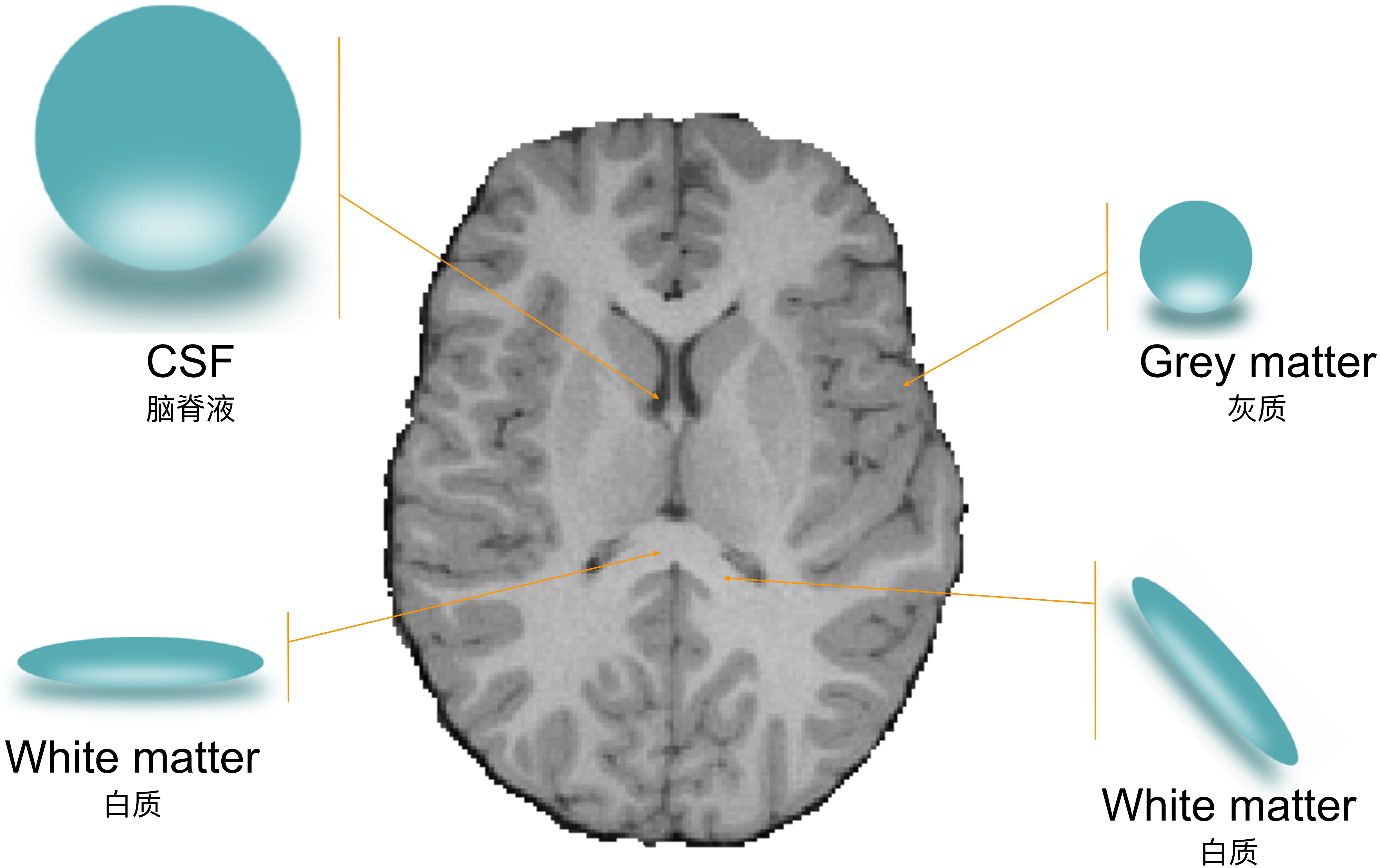


Anisotropic voxel
各向异性体素

$\lambda_1 \gg \lambda_2, \lambda_3$



The Diffusion Tensor Ellipsoid
扩散张量椭球



Quantitative Diffusion Maps 定量扩散图

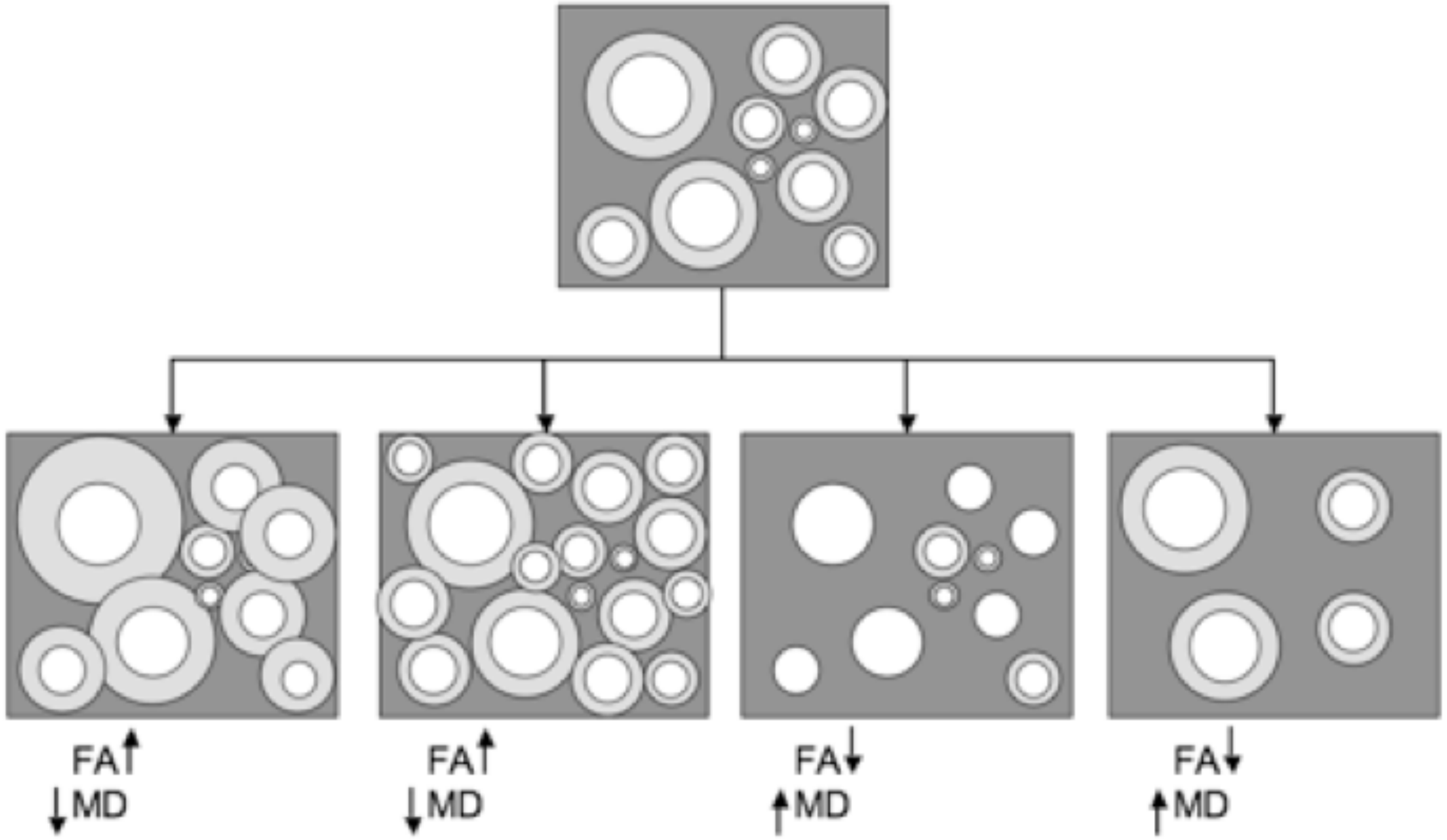
Fractional Anisotropy (FA) ~ Eigenvalues Variance (normalised)
Mean Diffusivity (MD) = Eigenvalues Mean
分数各向异性（FA）～特征值方差（归一化）
平均扩散率（MD）=特征值均值

$$FA = \sqrt{\frac{3\sum_{i=1}^{3}(\lambda_i - \overline{\lambda})^2}{2\sum_{i=1}^{3}\lambda_i^2}}, \qquad FA \text{ in } [0,1]$$

$$MD = \frac{D_{xx} + D_{yy} + D_{zz}}{3} = \frac{\lambda_1 + \lambda_2 + \lambda_3}{3}$$

Quantitative Diffusion Maps 定量扩散图

Different scenarios can have same effect on FA, MD
不同的场可以对FA，MD产生相同的影响



Swelling

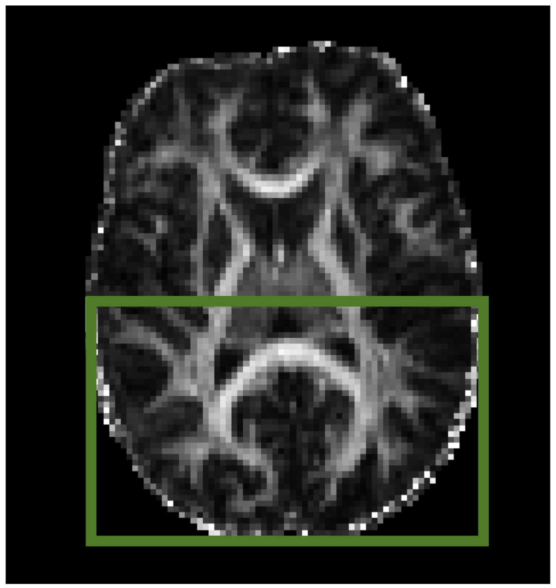
Higher Density

Myelin Loss

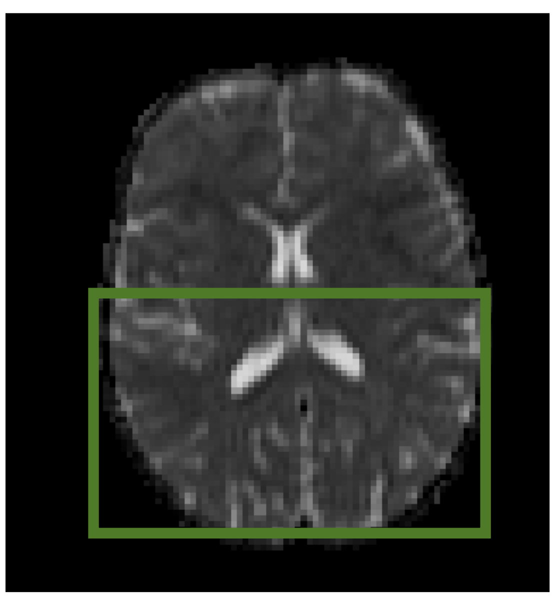
Cell Death

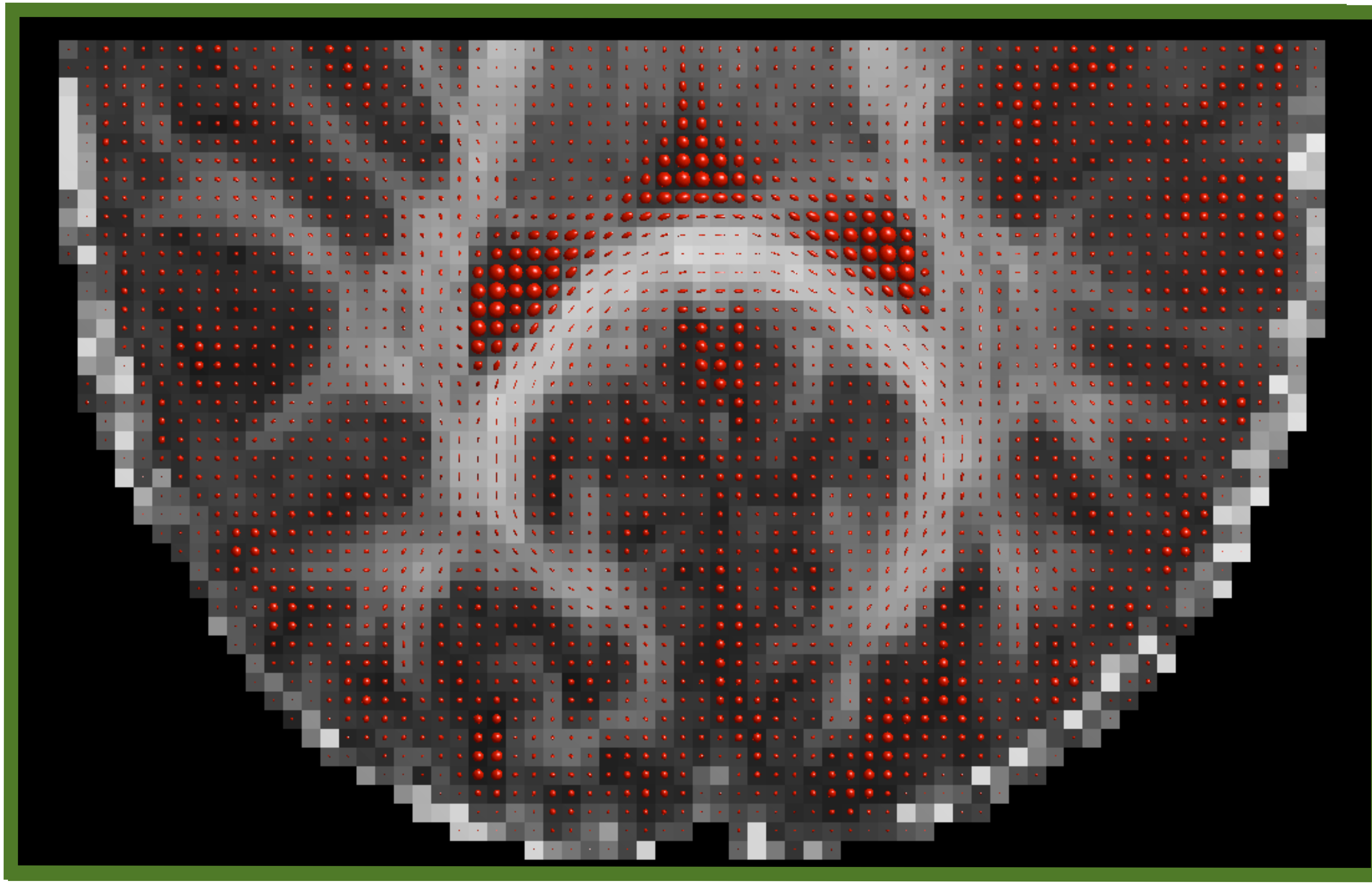
Diffusion Tensor Ellipsoids
扩散张量椭圆体

分数各向异性
Fractional anisotropy



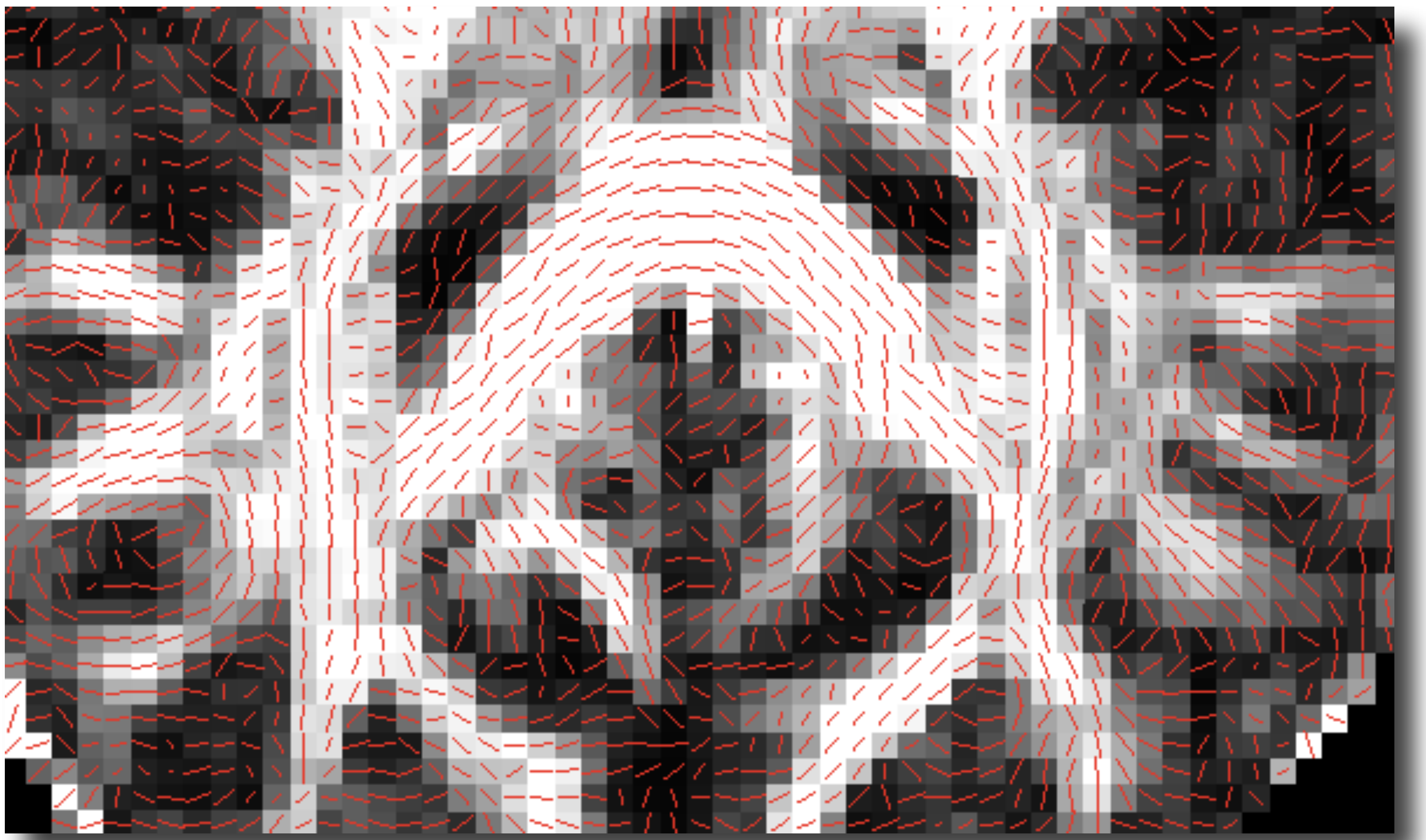
Mean diffusion 平均弥散



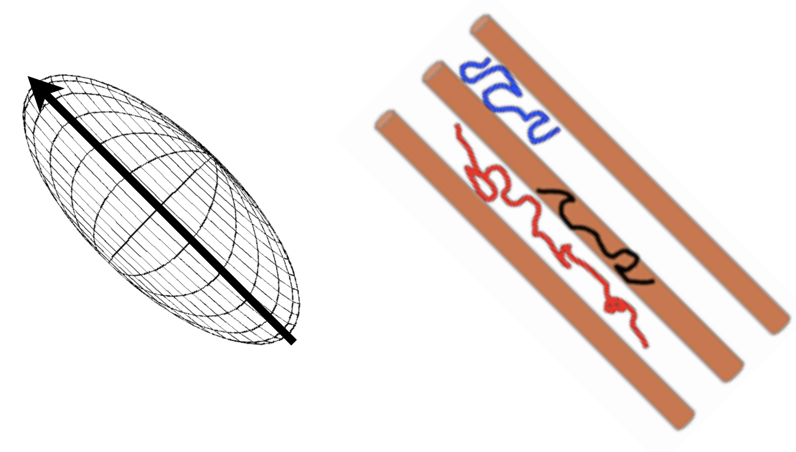


Estimates of Principal Fibre Orientation in WM
WM中主要纤维取向的估算

$\mathbf{v}_1$ map
Principal Diffusion Direction
主扩散方向



Principal Diffusion Direction
主扩散方向



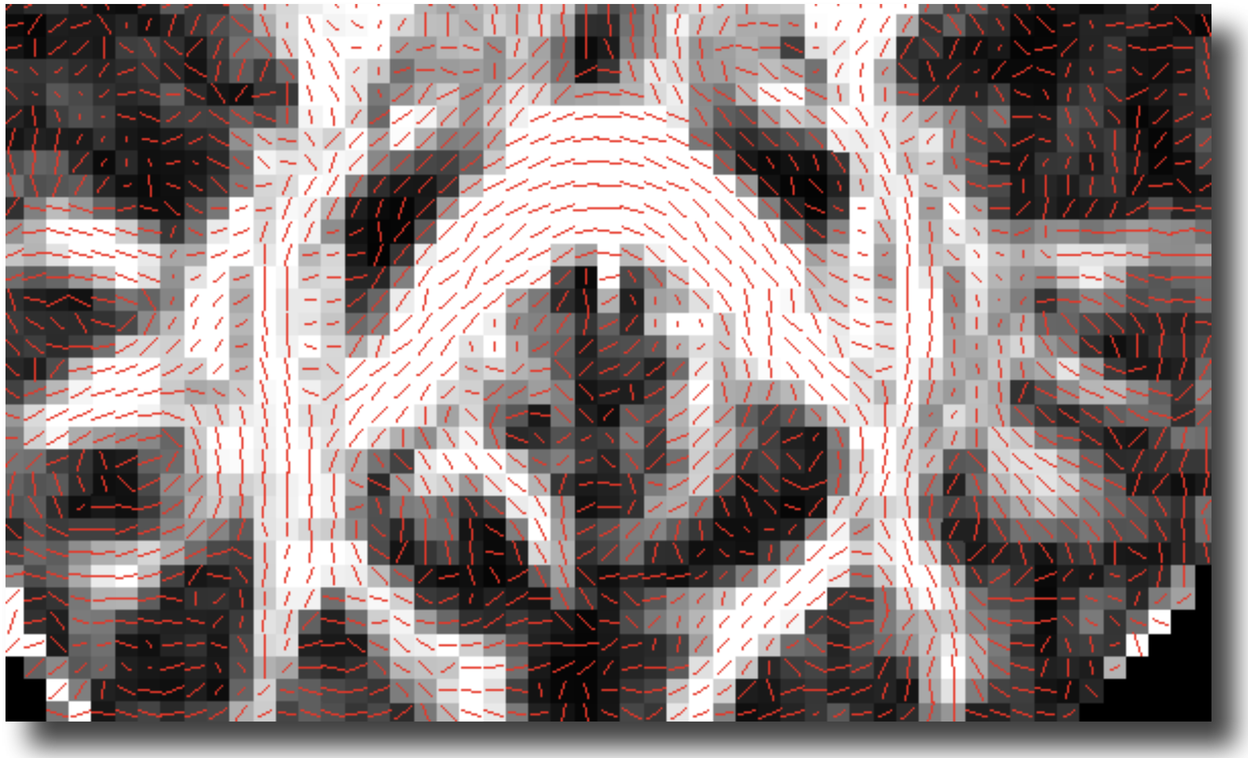
Assumption!! 假设!

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

具有各向异性轮廓的体素中的最大扩散率的方向是主要纤维取向的估计。

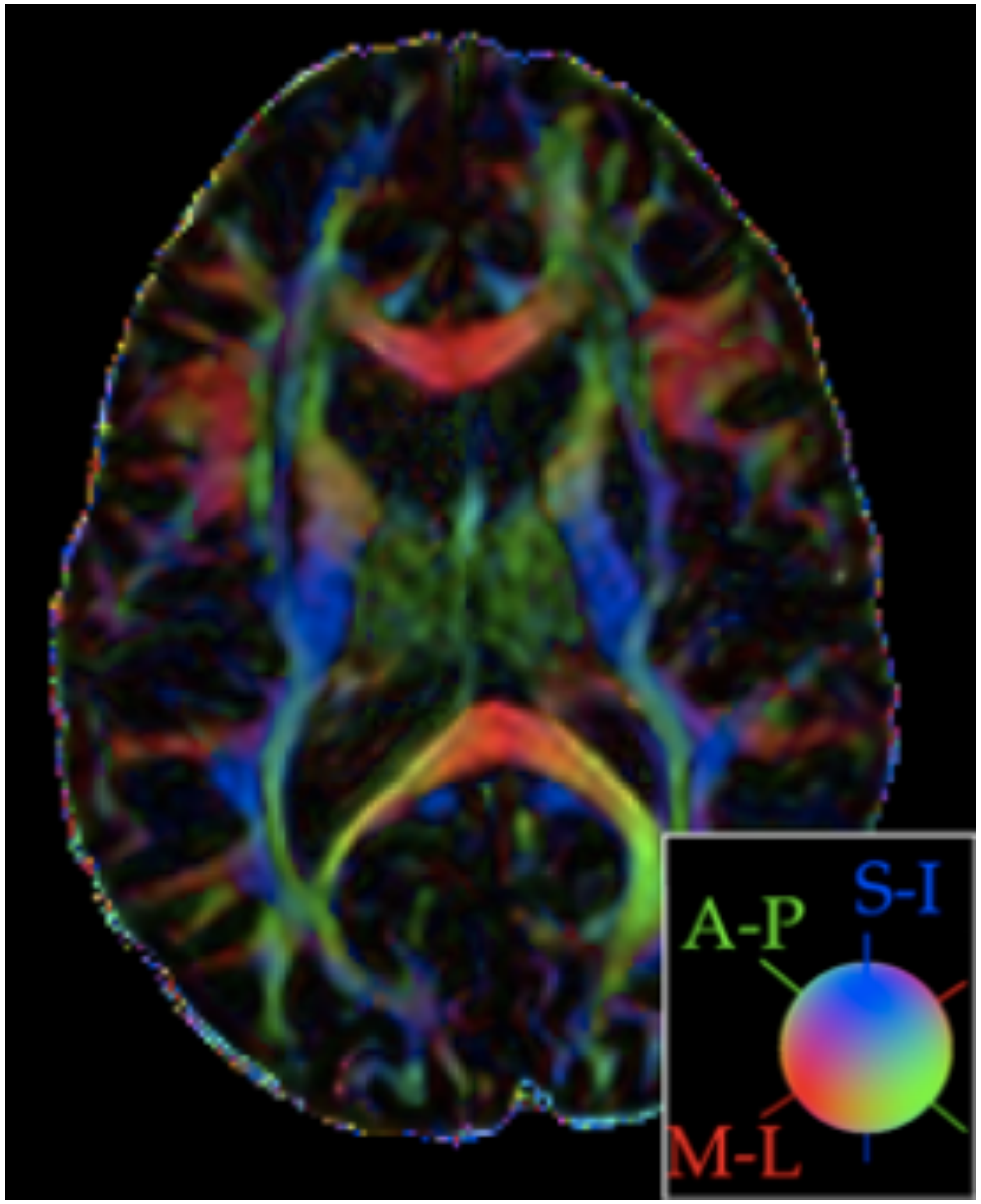
Estimates of Principal Fibre Orientation in WM

WM中主要纤维取向的估算



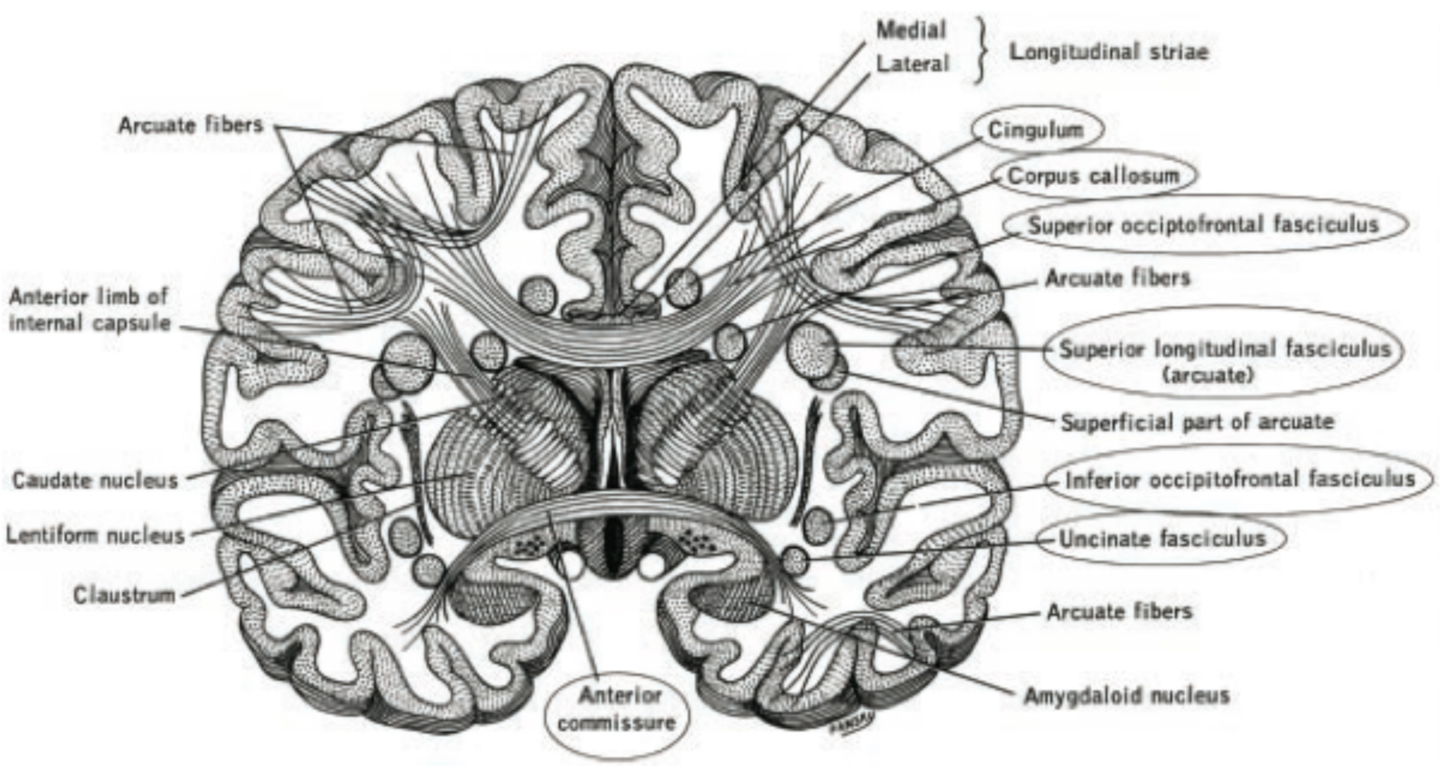
彩色编码的v1地图

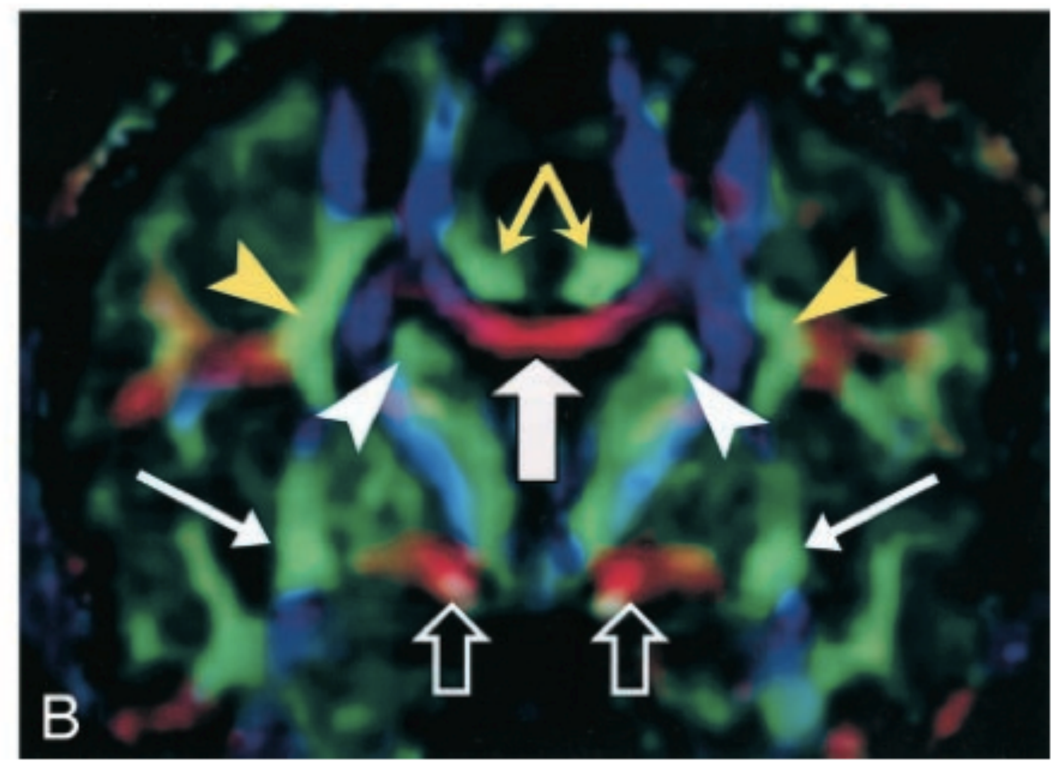
Colour-coded $\mathbf{v_1}$ map



Estimates of Principle Fibre Orientation in WM

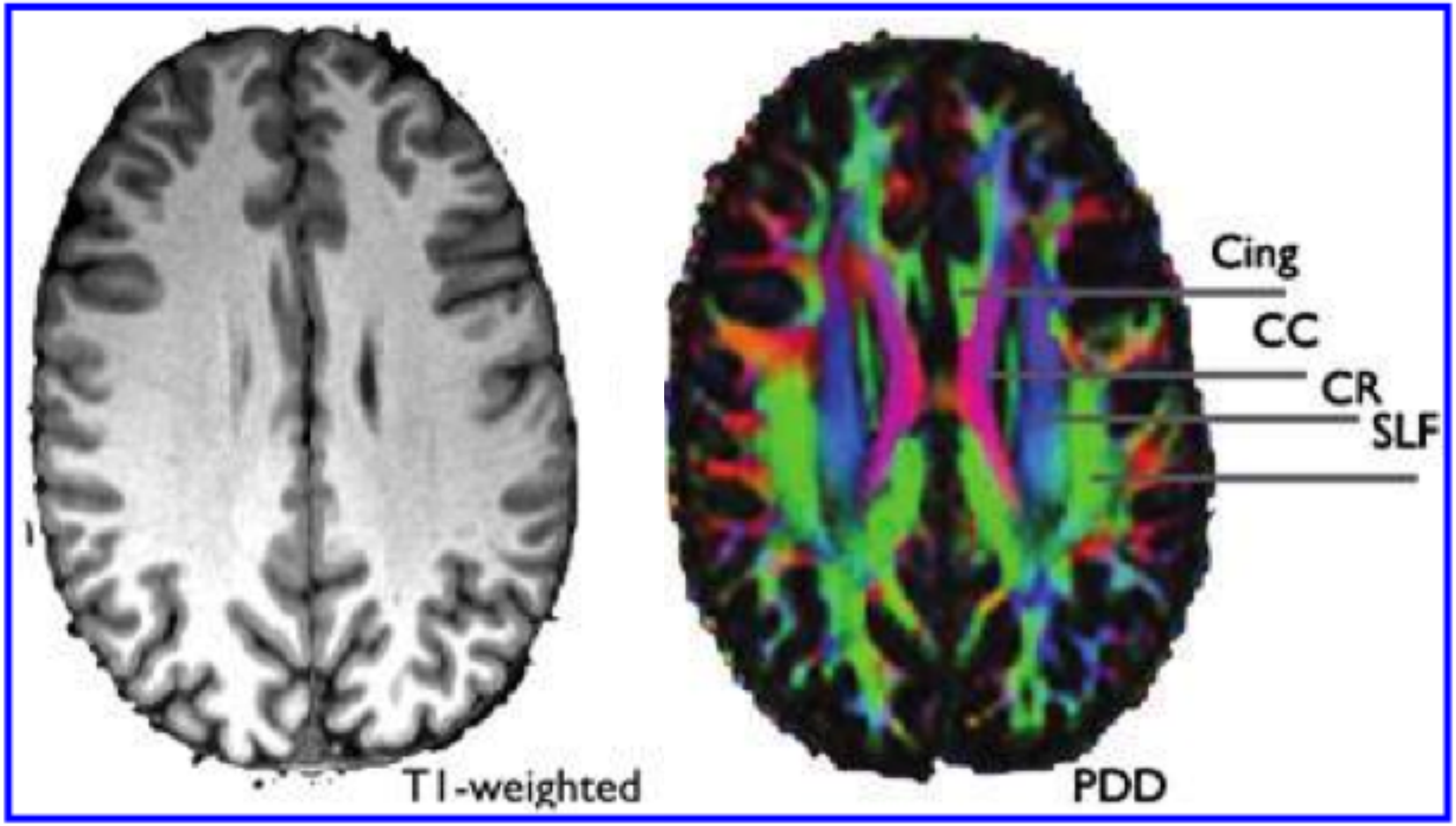
WM中原理纤维取向的估算





Directional contrast in DTI

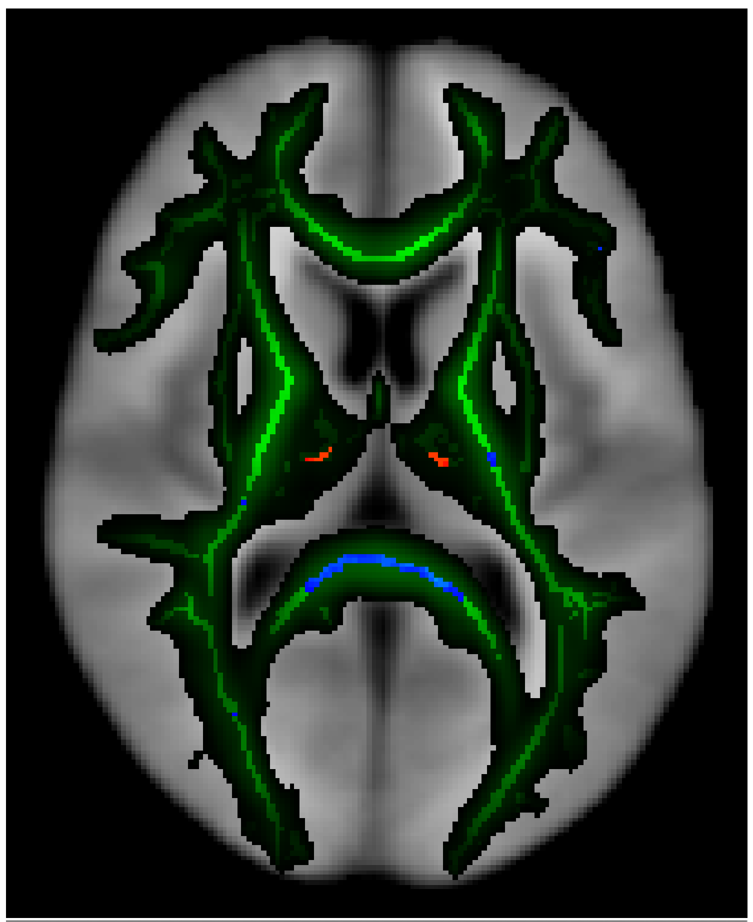
DTI中的方向对比

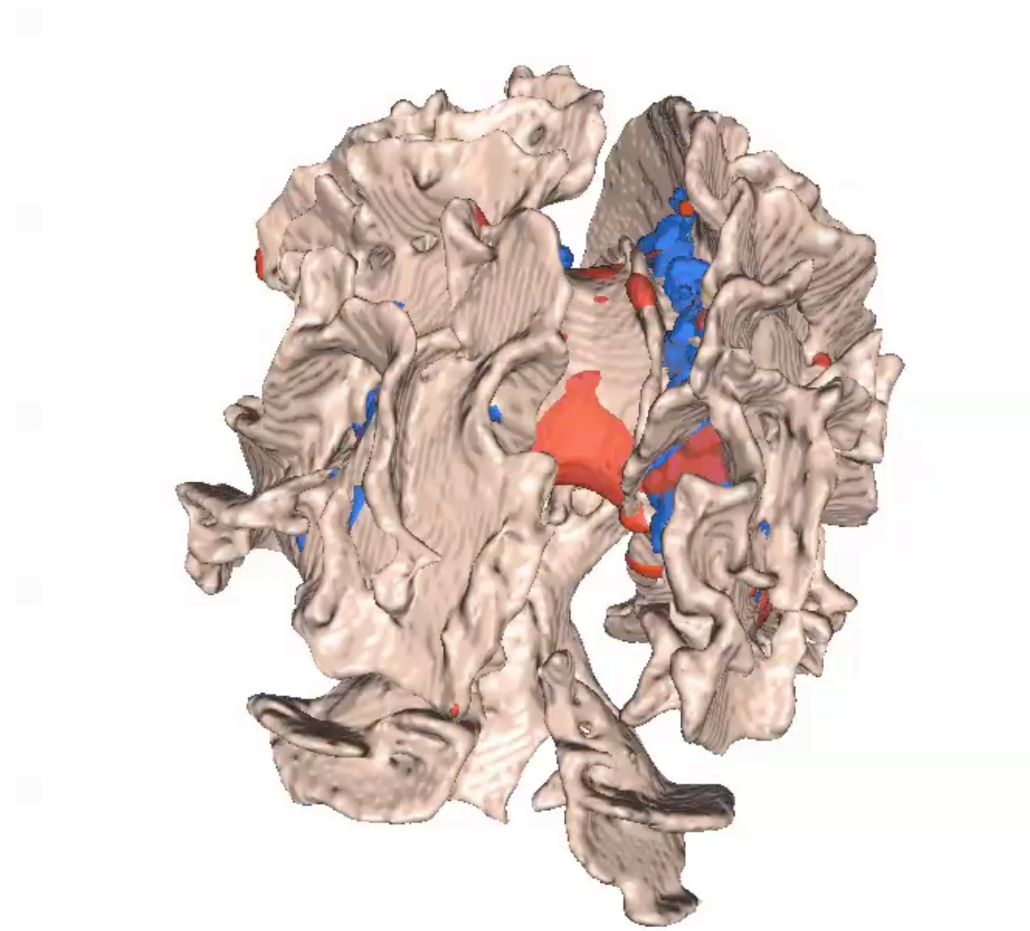


TBSS : Tract-Based Spatial Statistics

TBSS：基于白质纤维束骨架的空间统计分析

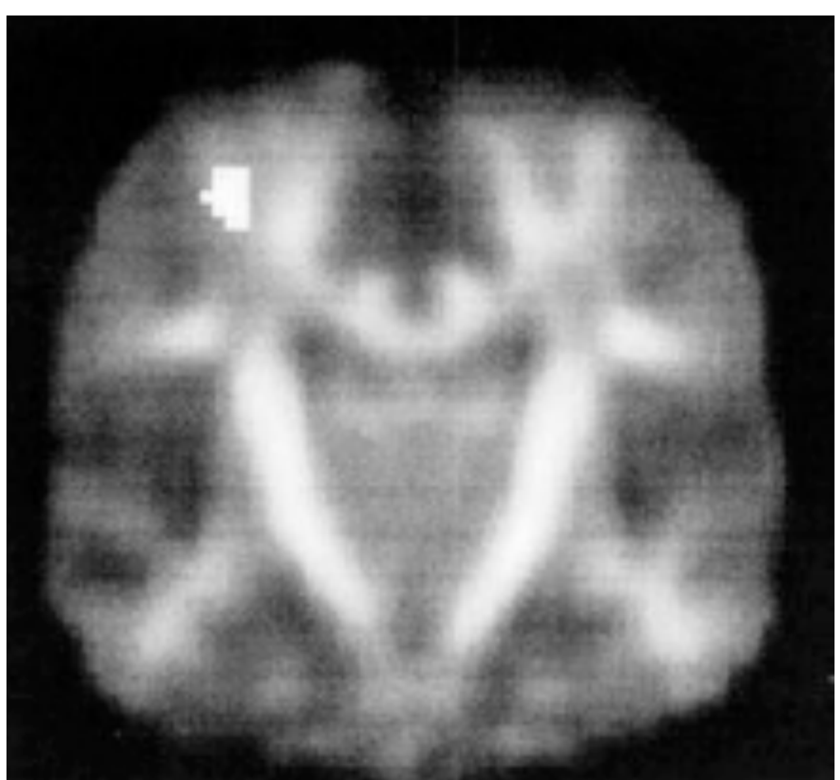
Robust "voxelwise" cross-subject stats
on diffusion-derived measures
被试间基于体素的稳健的扩散统计方法



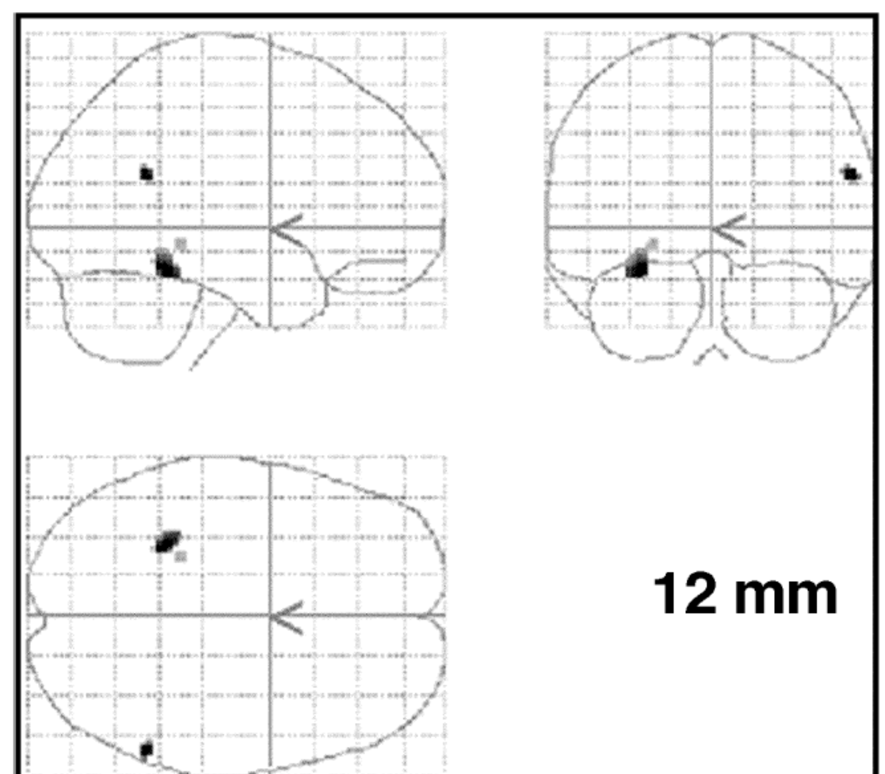


VBM-style Analysis of FA 基于VBM的FA分析

- VBM [Ashburner 2000, Good 2001]
- Align all subjects' data to standard space 所有被试配到标准空间
- Segment -> grey matter segmentation 分割-灰质分割
- Smooth GM 灰质平滑
- Do voxelwise stats (e.g. controls-patients) 体素统计
- VBM on FA [Rugg-Gunn 2001, Büchel 2004, Simon 2005]
- Like VBM but no segmentation needed 像VBM一样但不需要分割



Büchel 2004

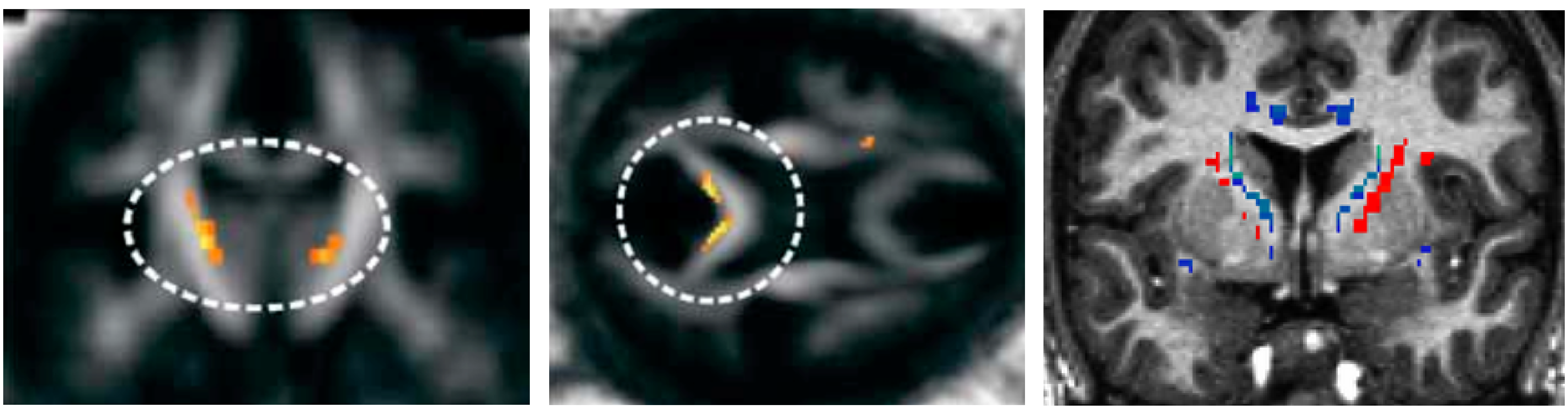


Jones 2005

VBM-style Analysis of FA 基于VBM的FA分析

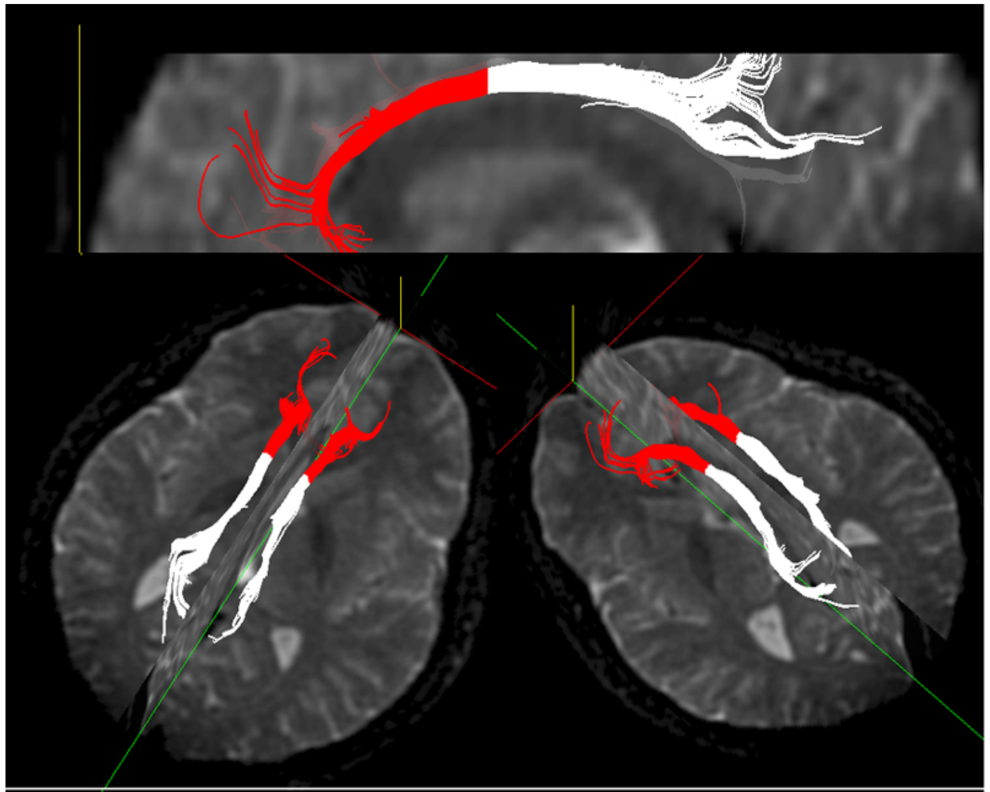
- Strengths 优点
  - Fully automated & quick 完全自动化和快速
  - Investigates whole brain 全脑分析

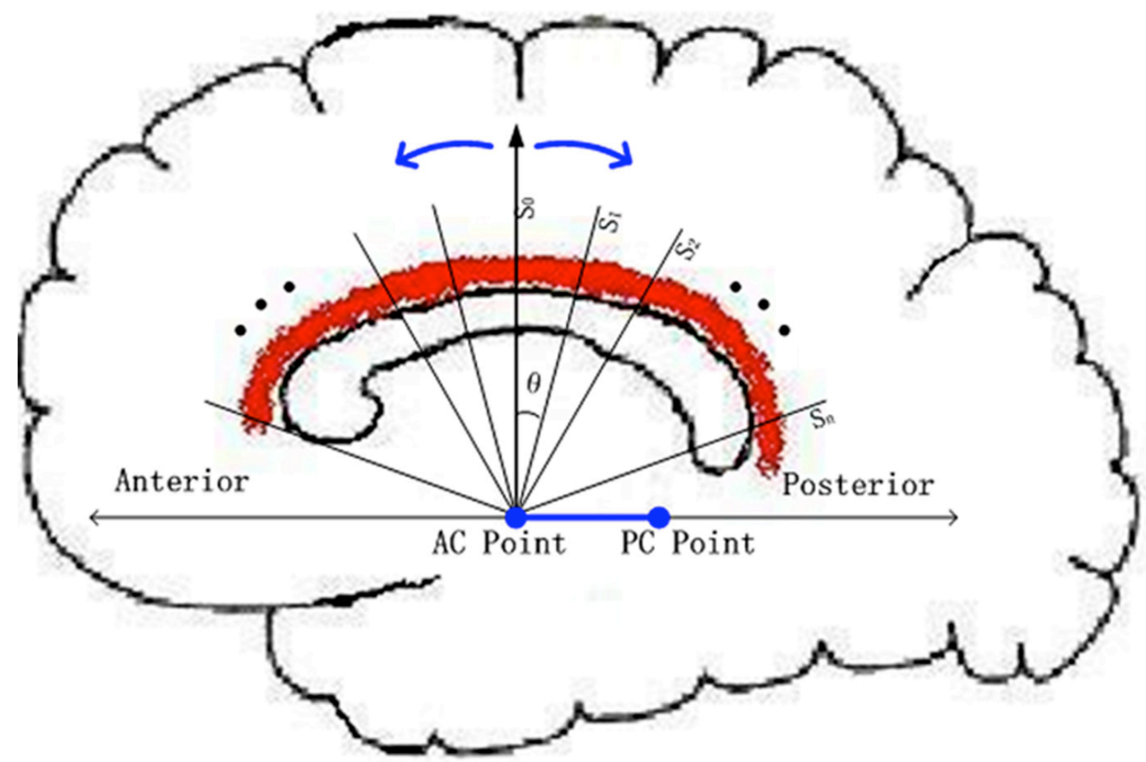
- Problems [Bookstein 2001, Davatzikos 2004, Jones 2005] 缺陷
  - Alignment difficult; smallest systematic shifts between groups can be incorrectly interpreted as FA change
    对齐困难;组间最小的系统偏移可能被错误地解释为FA变化
  - Needs smoothing to help with registration problems 需要平滑来解决配准问题
  - No objective way to choose smoothing extent 没有客观的方法来选择平滑程度



Hand-placed voxel/ROI-based FA Comparison
基于手动绘制的体素/ROI FA 比较

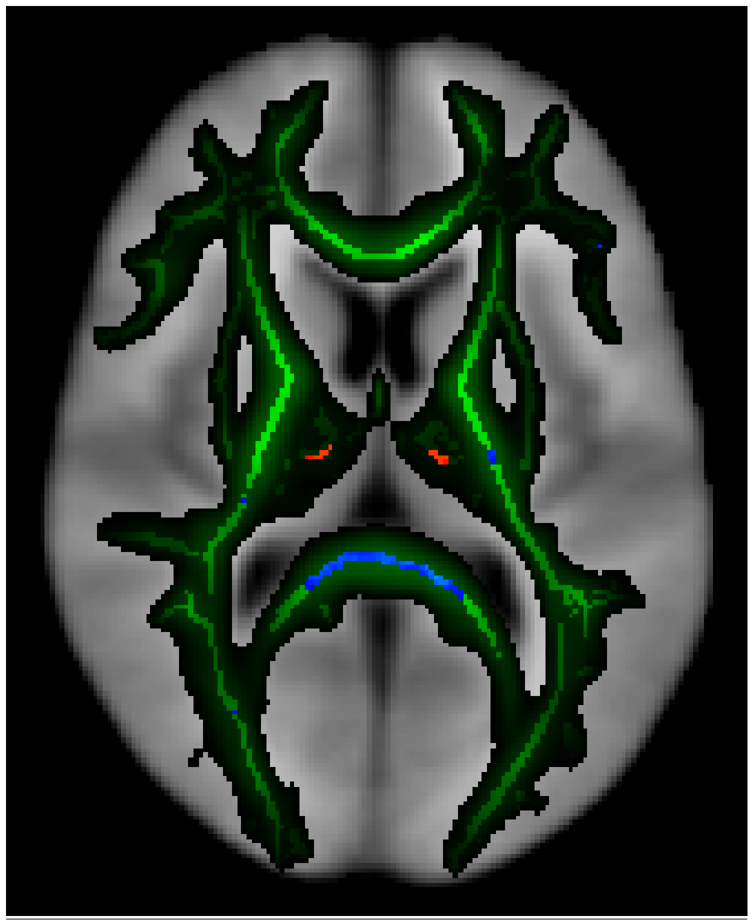
Tractography-Based FA Comparison 基于追踪的FA比较

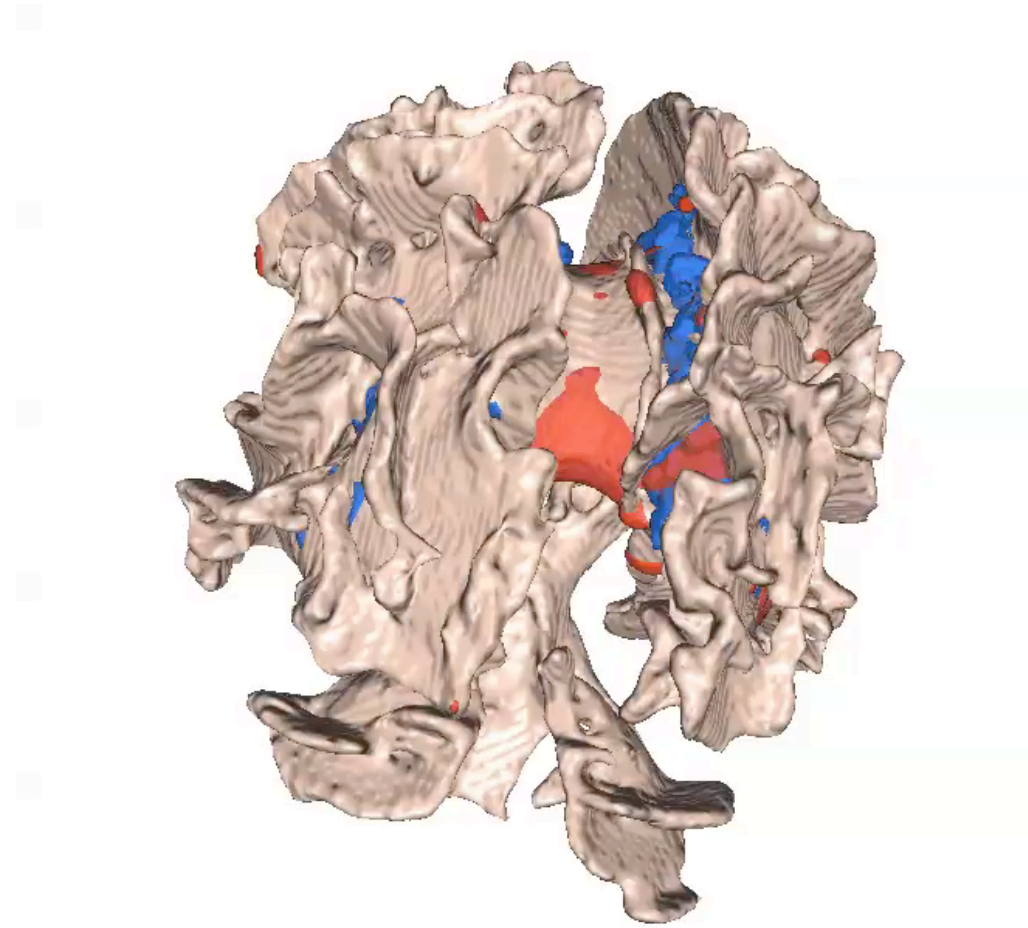




- Method [Gong 2005, Corouge 2006] 方法
  - Define a given tract in all subjects 根据所有被试定义一个纤维束
  - Parameterise FA along tract 沿着纤维束参数化FA
  - Compare between subjects 被试间比较
- Strength: correspondence issue hopefully resolved 优点：通路问题有希望解决
- Problems 问题
  - Currently requires manual intervention to specify tract 目前需要人工干预来指定纤维束
  - Hence doesn't investigate whole brain 因此不考查整个大脑
  - Projection of FA onto tract needs careful thought FA在纤维束上的投射需要仔细考虑

TBSS : Tract-Based Spatial Statistics
基于白质纤维束骨架的空间统计分析

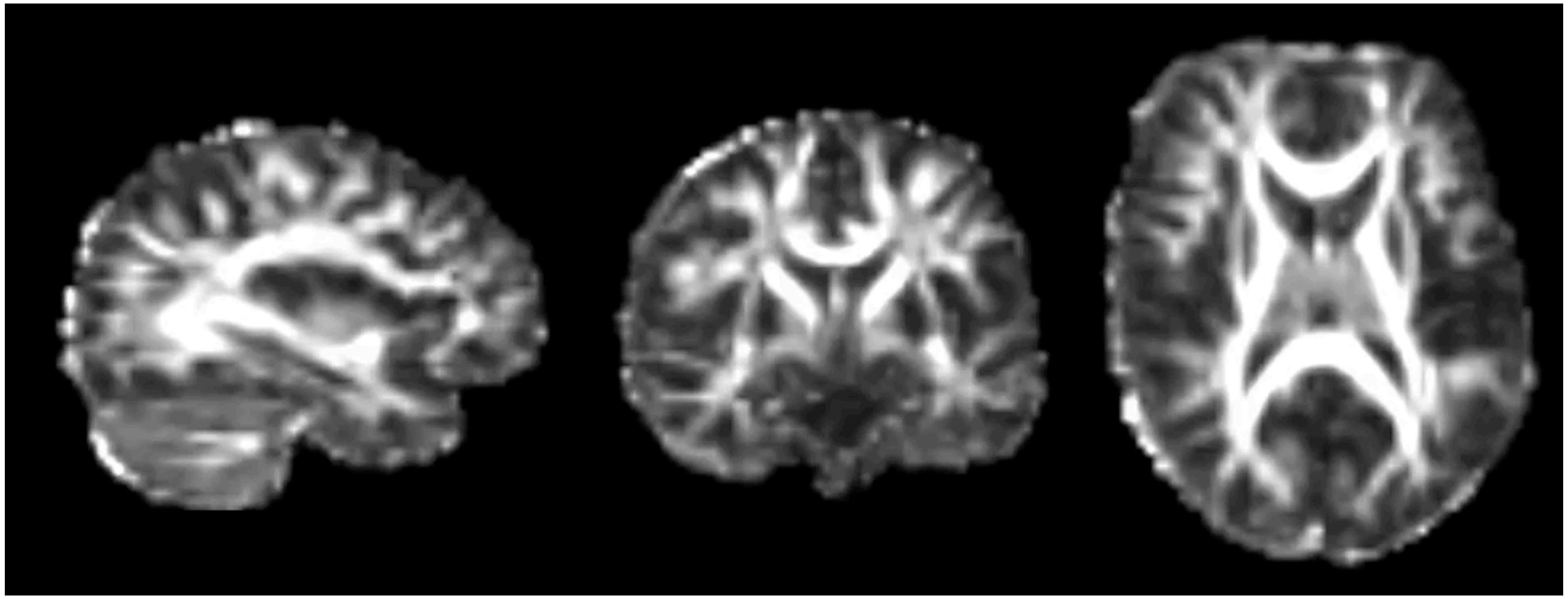




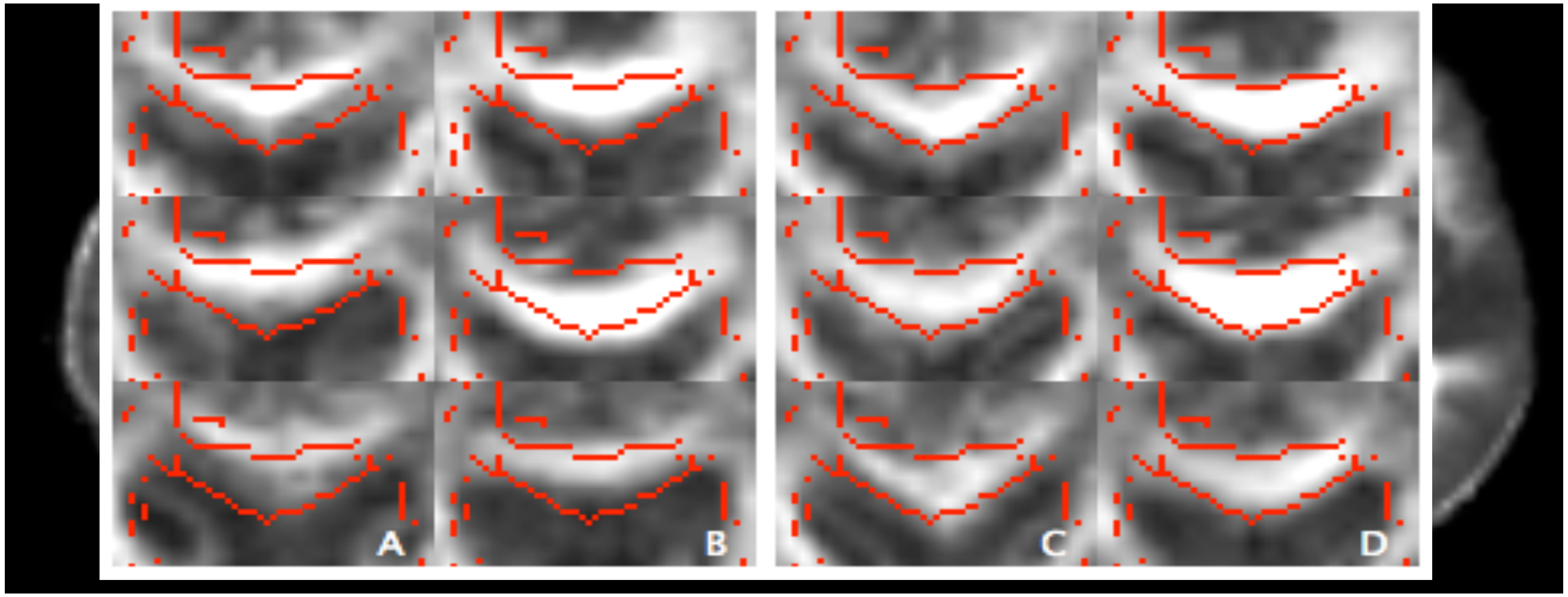
- Need: robust “voxelwise” cross-subject stats on DTI
  需要：DTI的强大基于“体素”的被试间统计数据
- Problem: alignment issues confound valid local stats
  问题：对齐问题会混淆有效的统计数据
- TBSS: solve alignment using alignment-invariant features:
  TBSS：使用对齐不变特征解决对齐：
- Compare FA taken from tract centres (via skeletonisation)
  比较从纤维束中取得的FA（通过骨架化）

1. Use medium-DoF nonlinear reg to pre-align all subjects' FA (nonlinear reg: FNIRT)

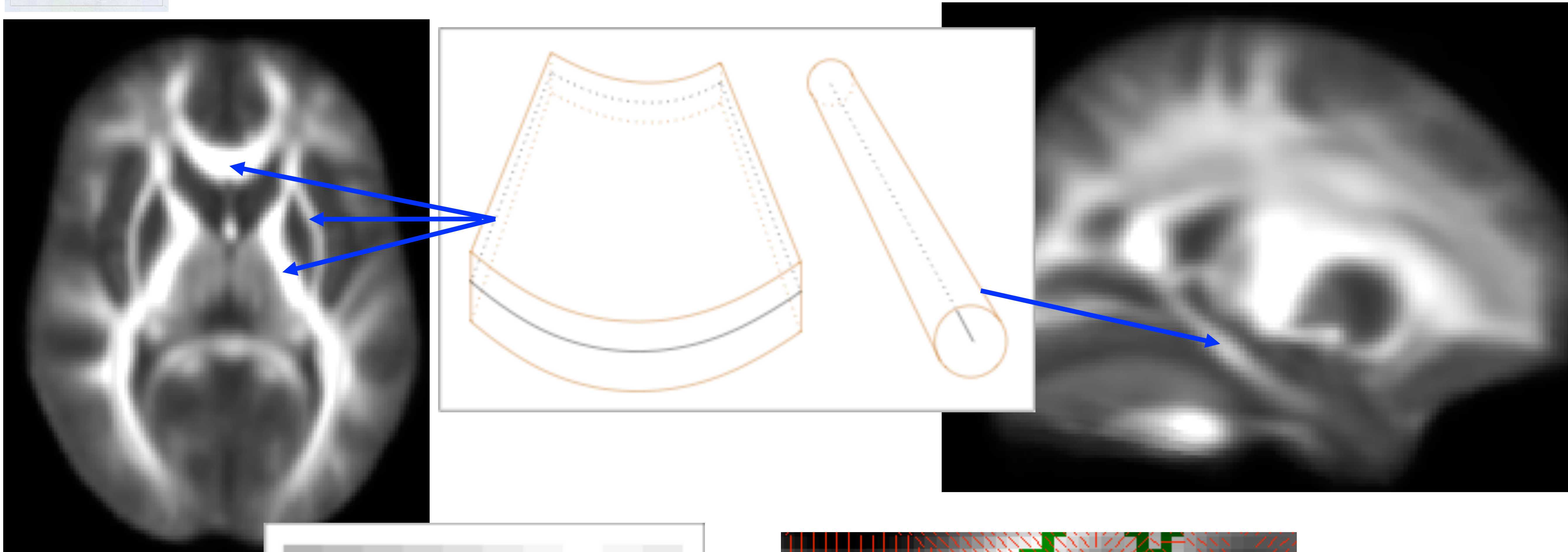
使用中心-自由度非线性配准预先对准所有受试者的FA
（非线性配准：FNIRT）

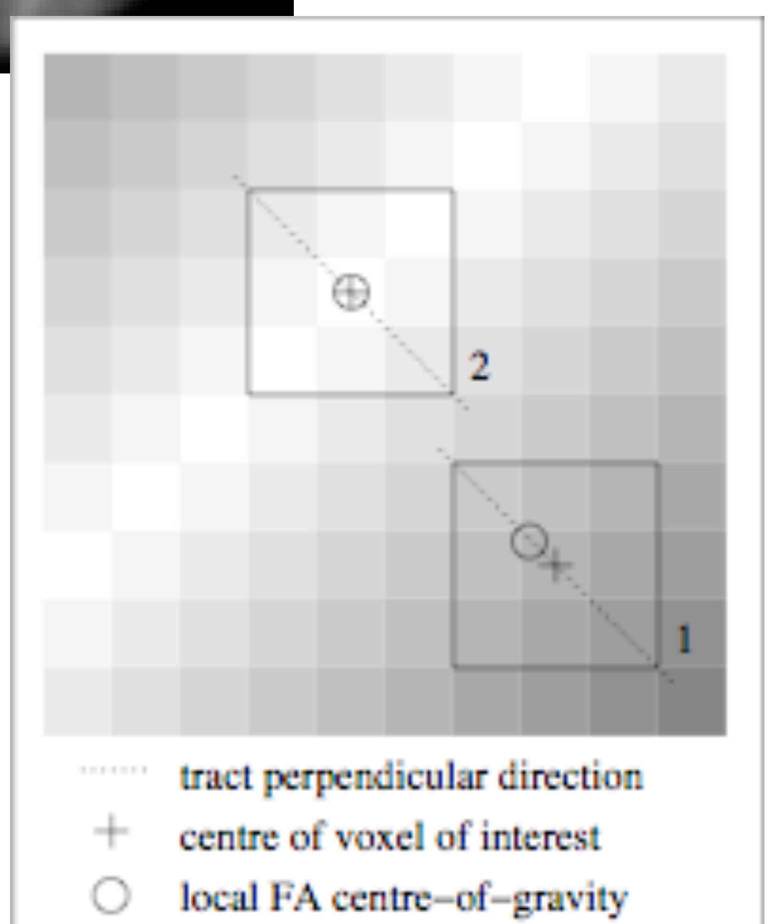


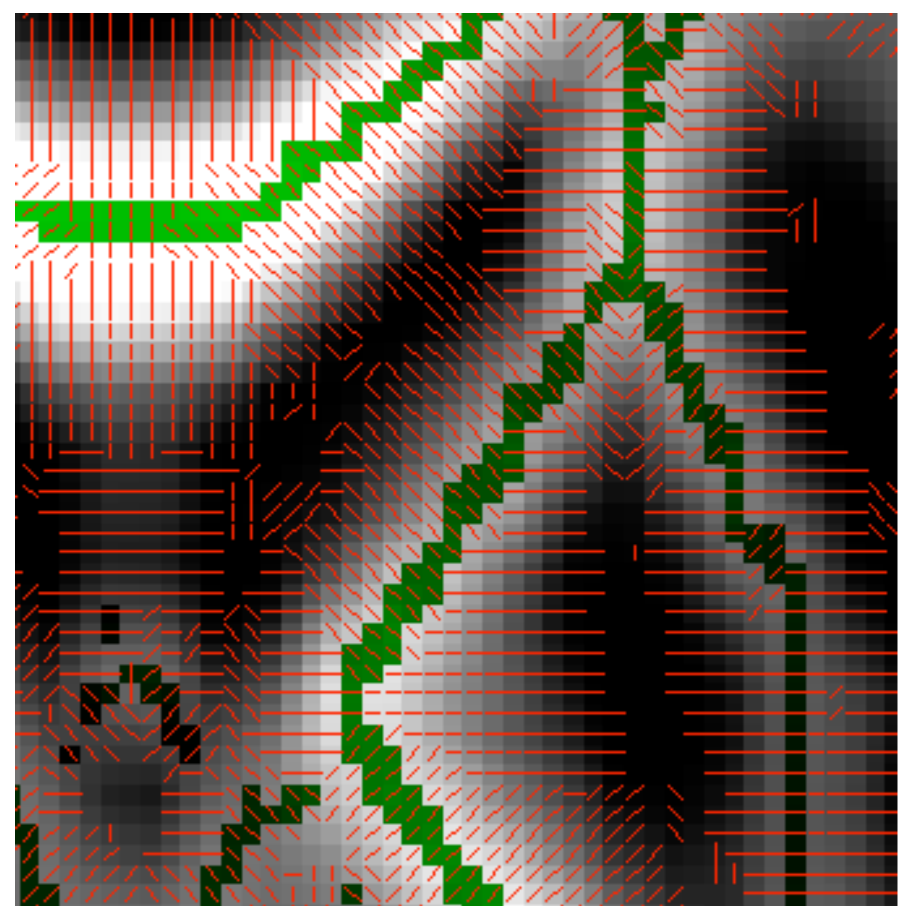
2. Create mean FA image (no smoothing) 生成FA平均图像（无平滑）



2. "Skeletonise" Mean FA 骨架平均FA

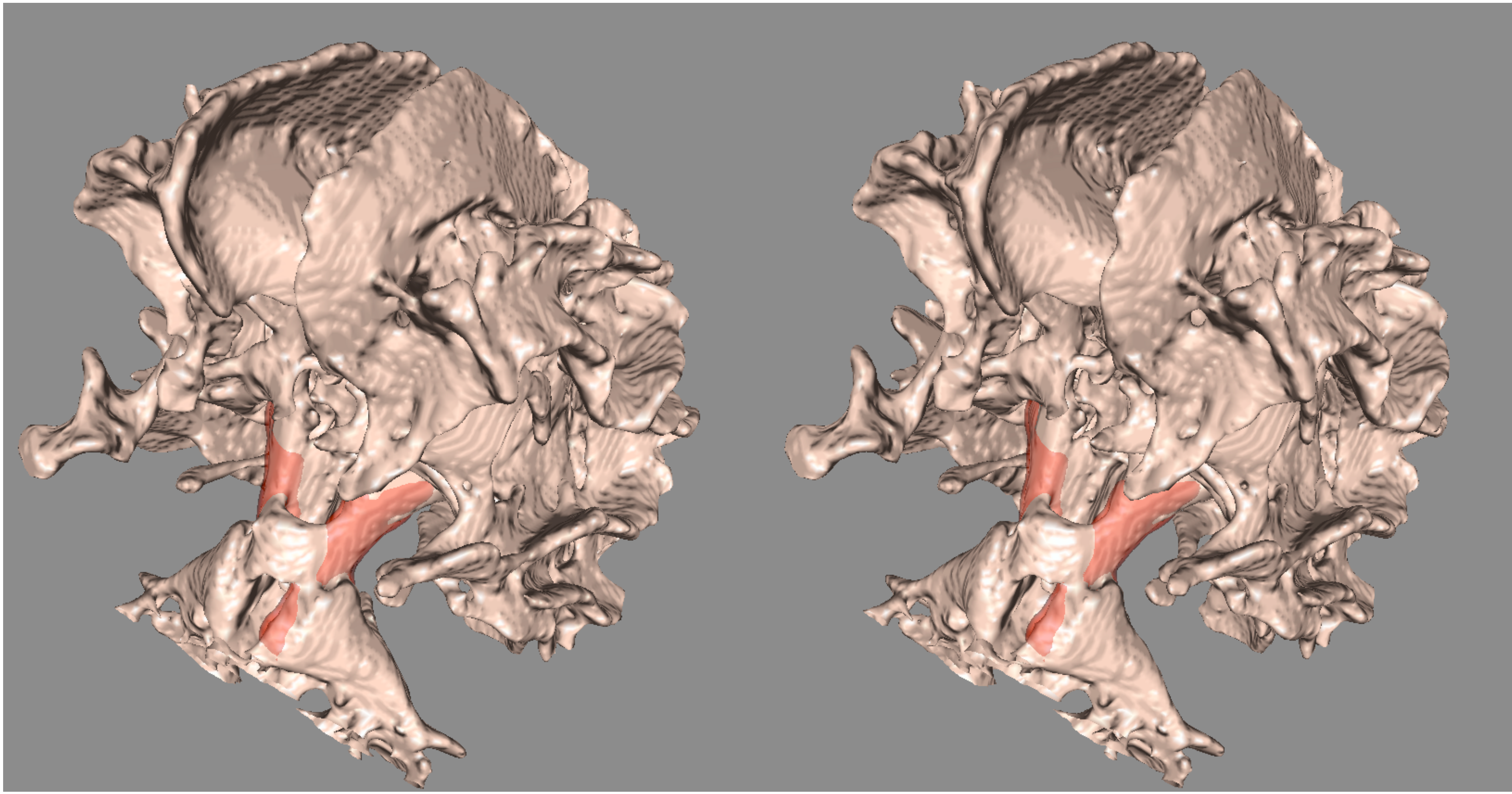






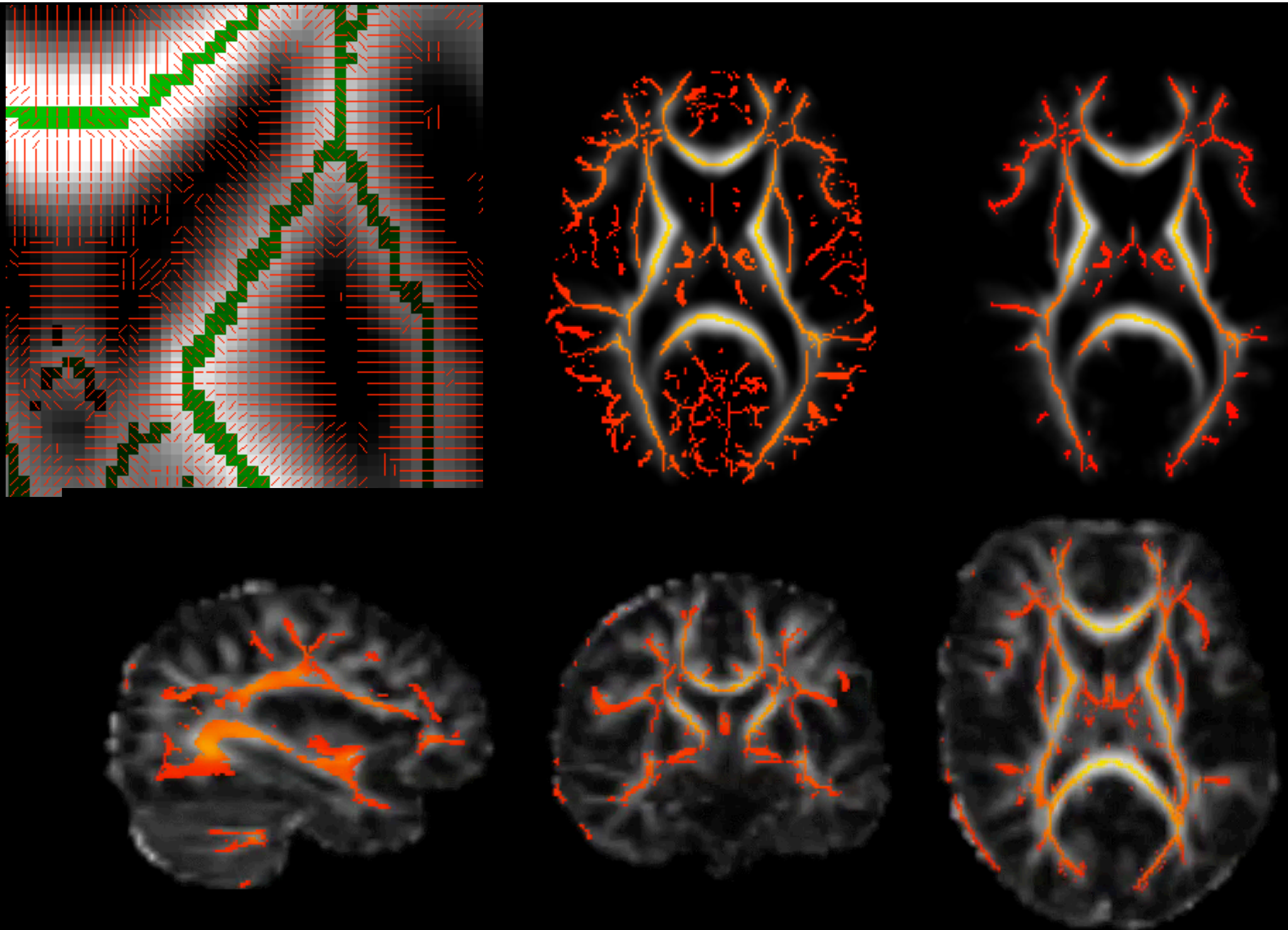
3. Threshold Mean FA Skeleton 阈值均值FA骨架

giving “objective” tract map 给出“客观”的纤维束图



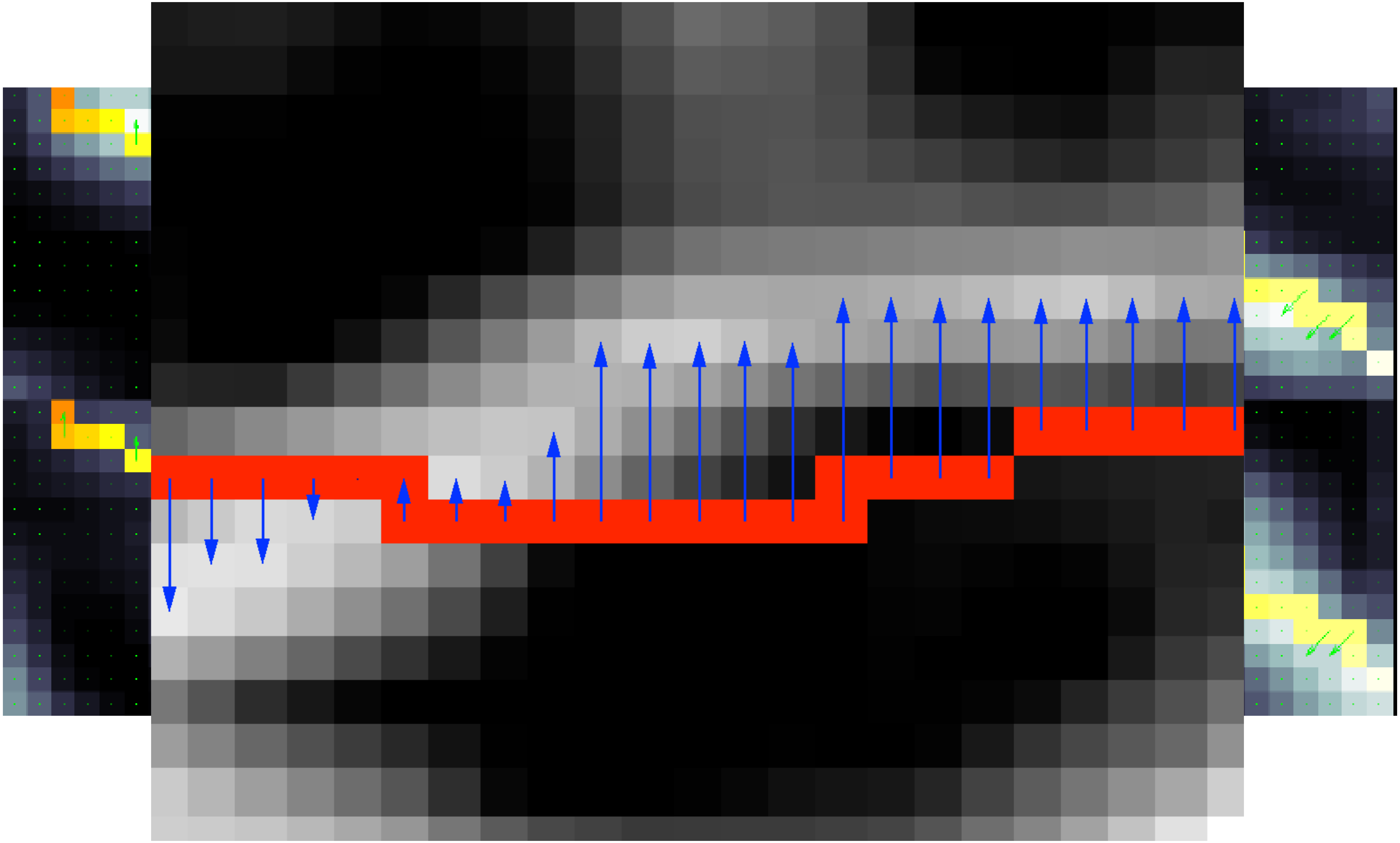
3. Threshold Mean FA Skeleton 阈值均值FA骨架

giving “objective” tract map 给出“客观”的纤维束图



4. For each subject's warped FA, fill each point on the mean-space skeleton with nearest maximum FA value (i.e., from the centre of the subject's nearby tract)

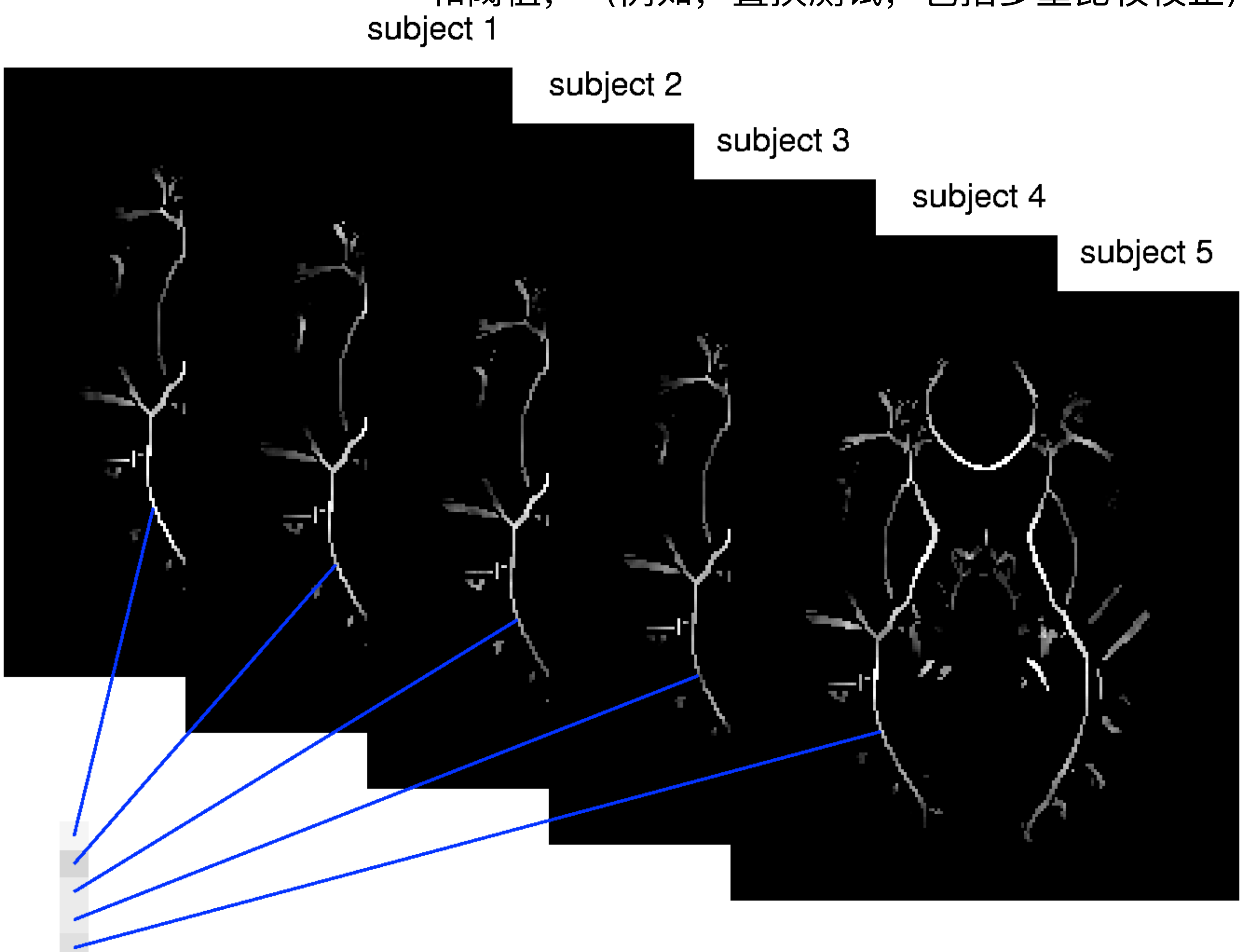
对于每个受试者的扭曲FA，用最接近的最大FA值（即，从受试者的附近区域的中心）填充平均空间骨架上的每个点。



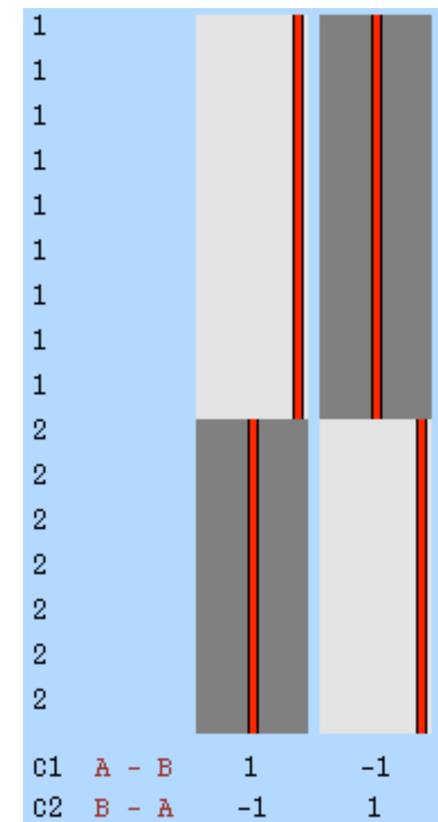
5. Do cross-subject voxelwise stats on skeleton-projected FA and Threshold, (e.g., permutation testing, including multiple comparison correction)

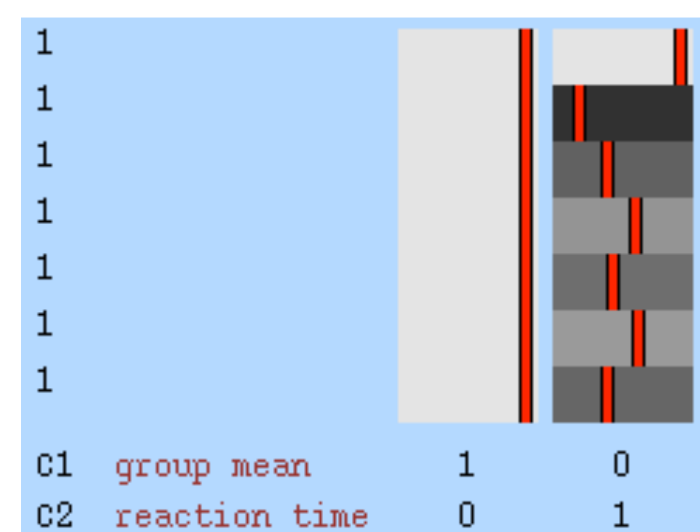
在骨架投射的FA上进行被试间体素统计

和阈值，（例如，置换测试，包括多重比较校正）



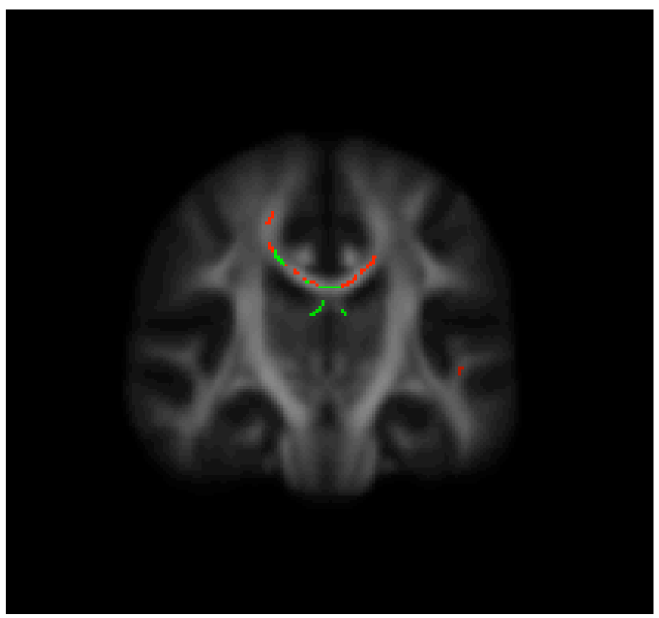
one skeleton voxel's data vector (to be fed into GLM)

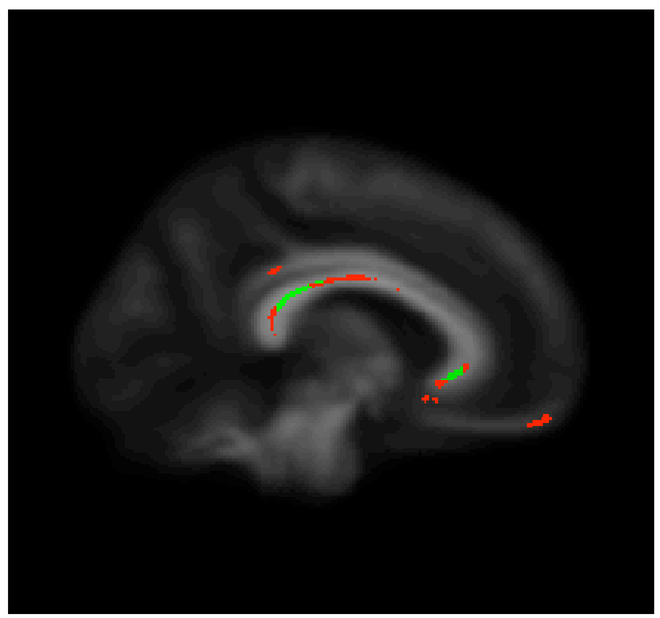


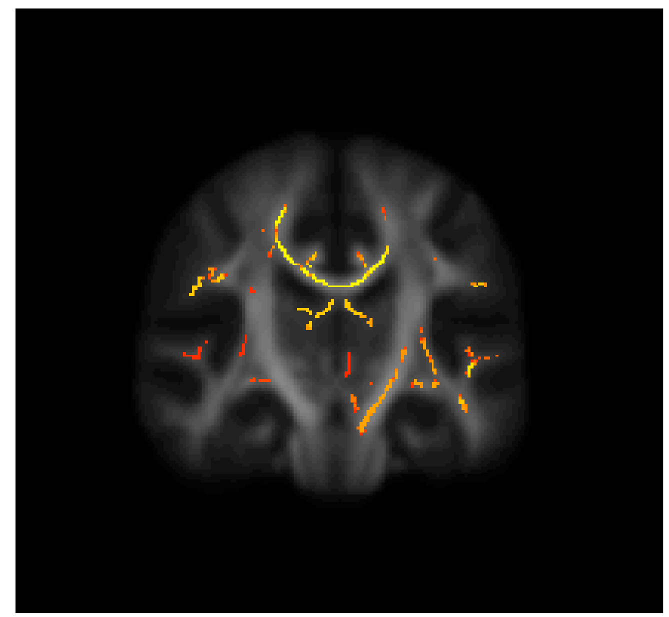


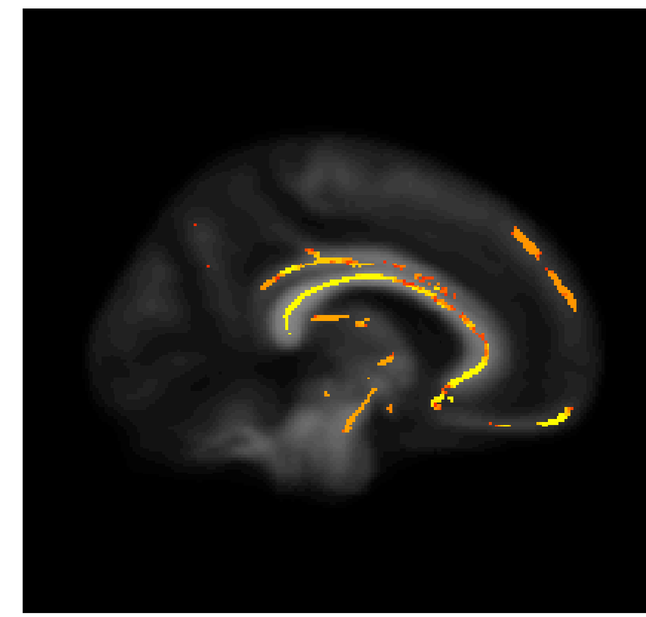
TFCE for TBSS

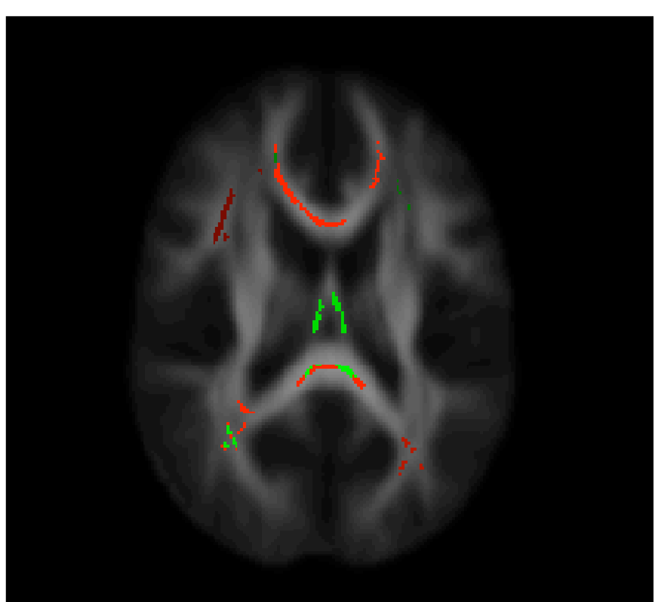
controls > schizophrenics
$p<0.05$ corrected for multiple comparisons across space, using randomise



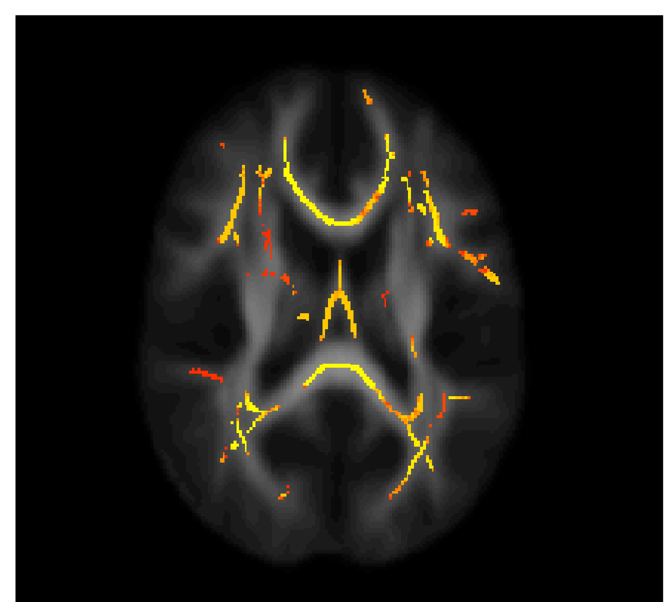








cluster-based:
cluster-forming
threshold =
2 or 3



TFCE

Schizophrenia (Mackay) 精神分裂症

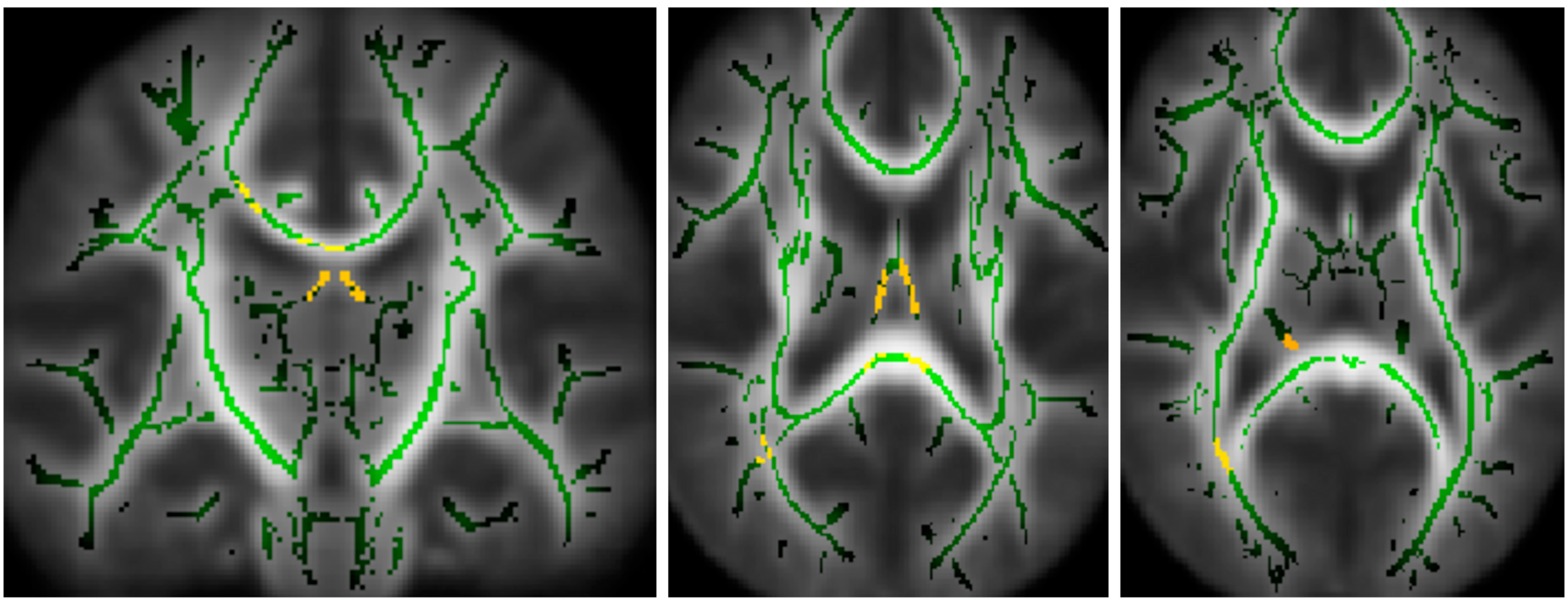
TBSS & VBM show reduced FA in corpus callosum & fornix

TBSS和VBM显示胼胝体和穹窿中的FA降低

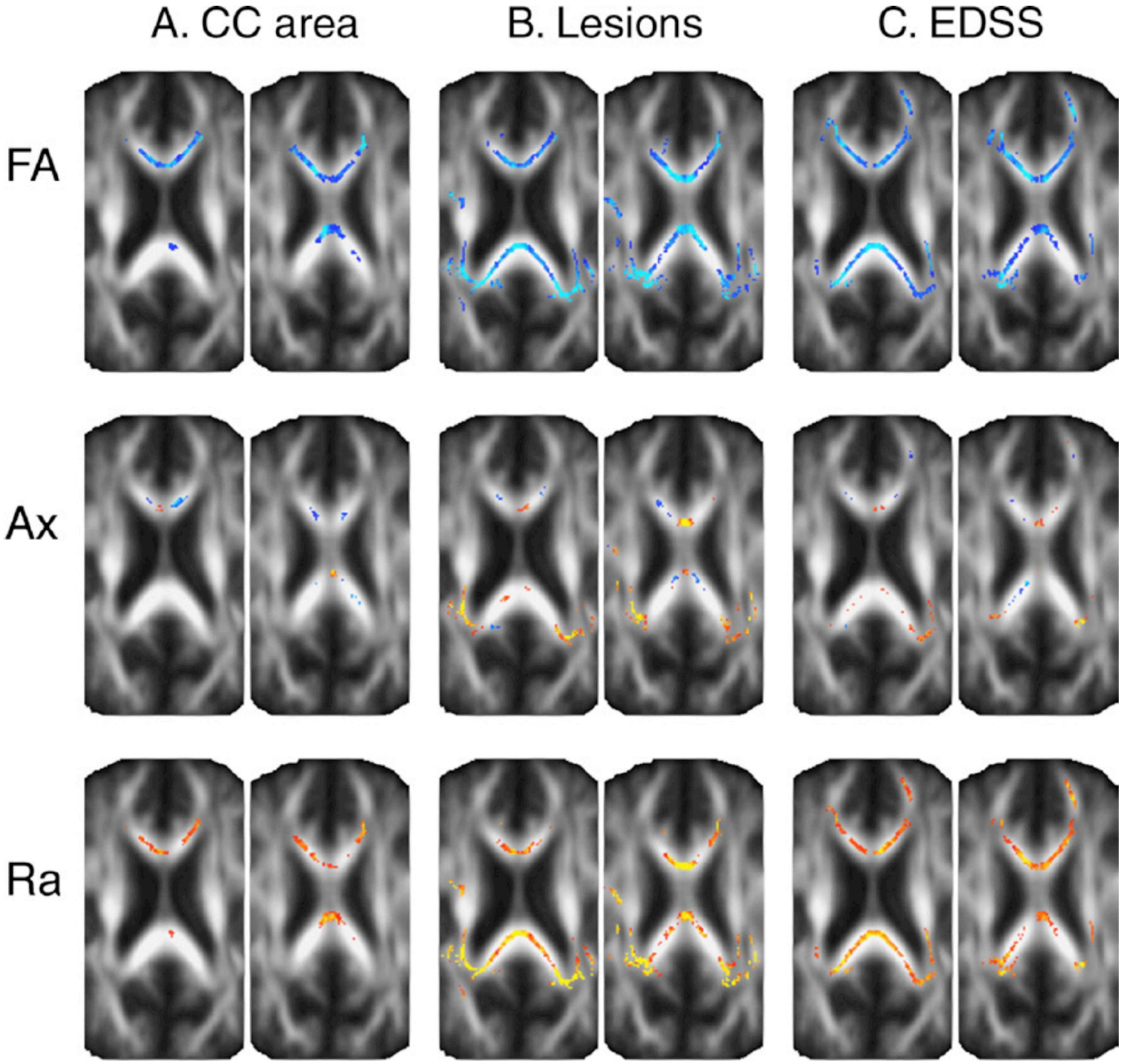
VBM shows spurious result in thalamus due to increased ventricles in schiz.

VBM在丘脑中显示虚假结果，原因是schiz的心室增加

TBSS VBM mean FA (controls) mean FA (schiz.)



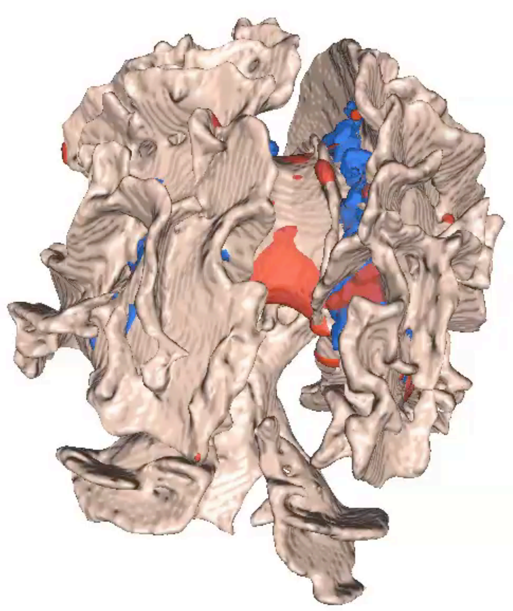
Multiple Sclerosis (Cader, Johansen-Berg & Matthews)
多发性硬化症



TBSS - Conclusions 结论

- Attempting to solve correspondence/smoothing problems
  试图解决对应/平滑问题
- Less ambiguity of interpretation / spurious results than VBM
  与VBM相比，解释/虚假结果的含糊性较小
- Easier to test whole brain than ROI / tractography
  比种子点/概率纤维束追踪法更容易测试整个大脑
- Limitations & Dangers 局限性和坑
  - Interpretation of partial volume tracts still an issue 部分体素的解释仍然是一个问题
  - Crossing tracts? 纤维束之间?

- Future work 未来工作
  - Use full tensor (for registration and test statistic)
    使用完整张量（用于配准和统计测试）
  - Use other test statistics (MD, PDD, width) 使用其他统计方法
  - Multivariate stats (across voxels and/or different diffusion measures) & discriminant (ICA, SVM)
    多元统计信息（跨体素和/或不同
    扩散方法）和分类法（ICA，SVM）

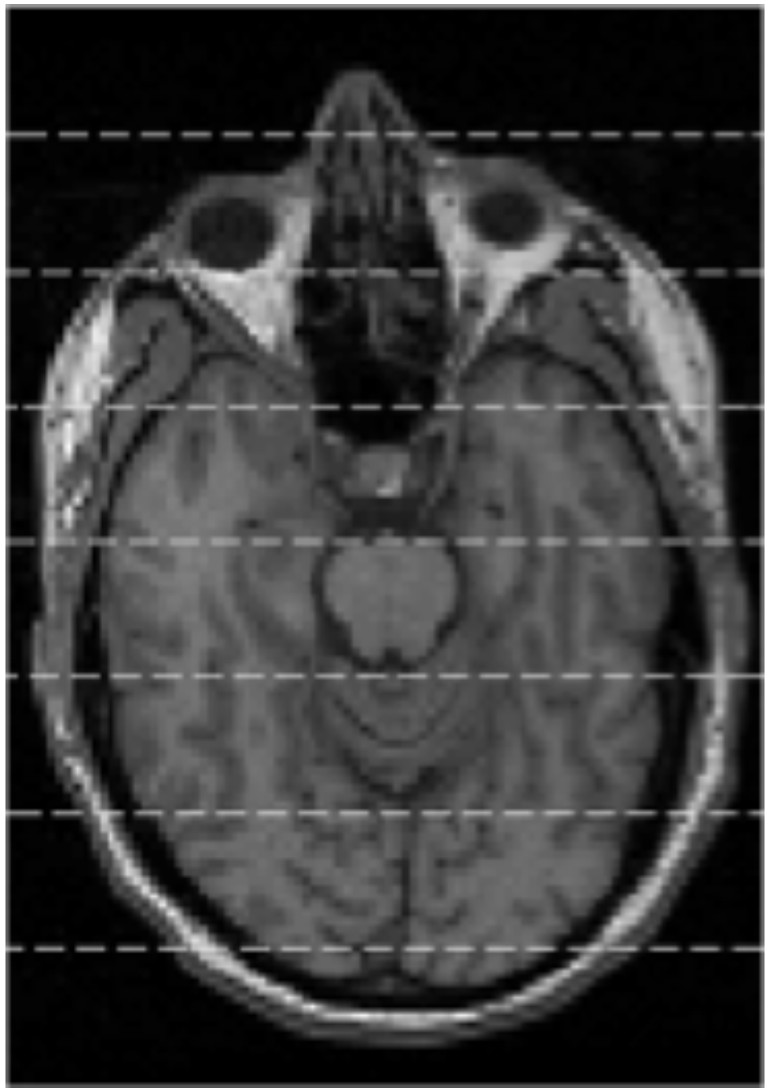


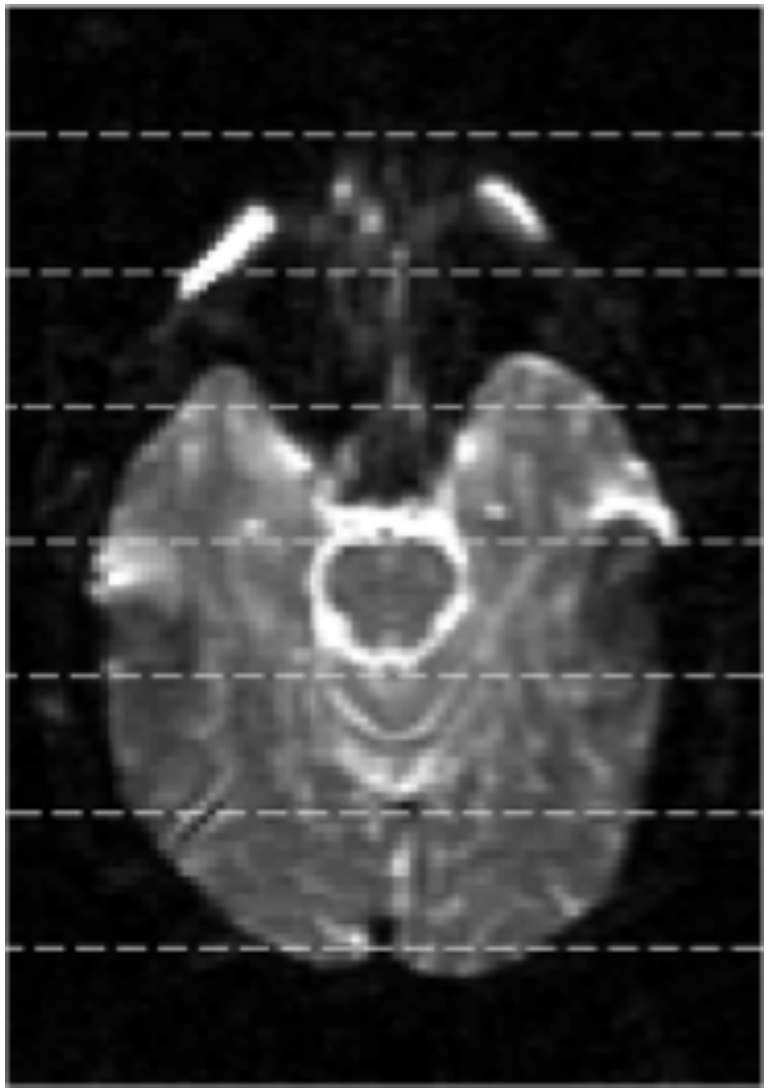
Outline of the talk 大纲

• What is the problem with diffusion data?	扩散数据有什么问题?
• Off-resonance field	非共振场
• How does it cause distortions?	它如何引起失真?
• Where does it come from?	它从何而来?
• Registering diffusion data	弥散数据的配准
• How topup works topup	topup如何起作用补满的?
• How eddy works eddy	eddy实现涡流矫正?
• Practicalities	实用性
• Some results	一些结果
• Quality control	质控
• New eddy features	新的涡流功能

What is the problem with diffusion data?

扩散数据有什么问题?



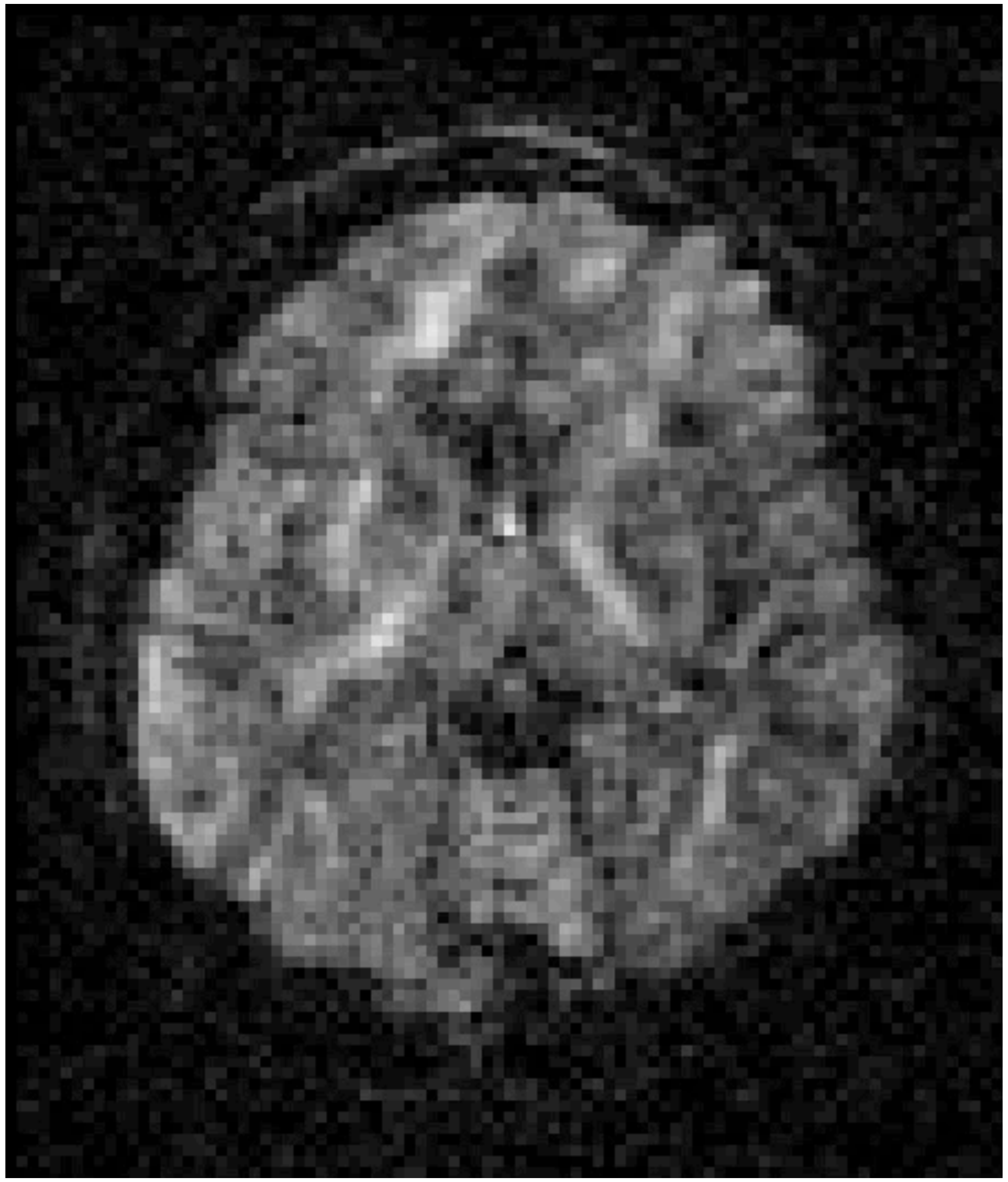


Well, it isn't very anatomically faithful

嗯，这在解剖学上不是很准确可靠

What is the problem with diffusion data?

扩散数据有什么问题?



In fact, it isn’t even internally consistent

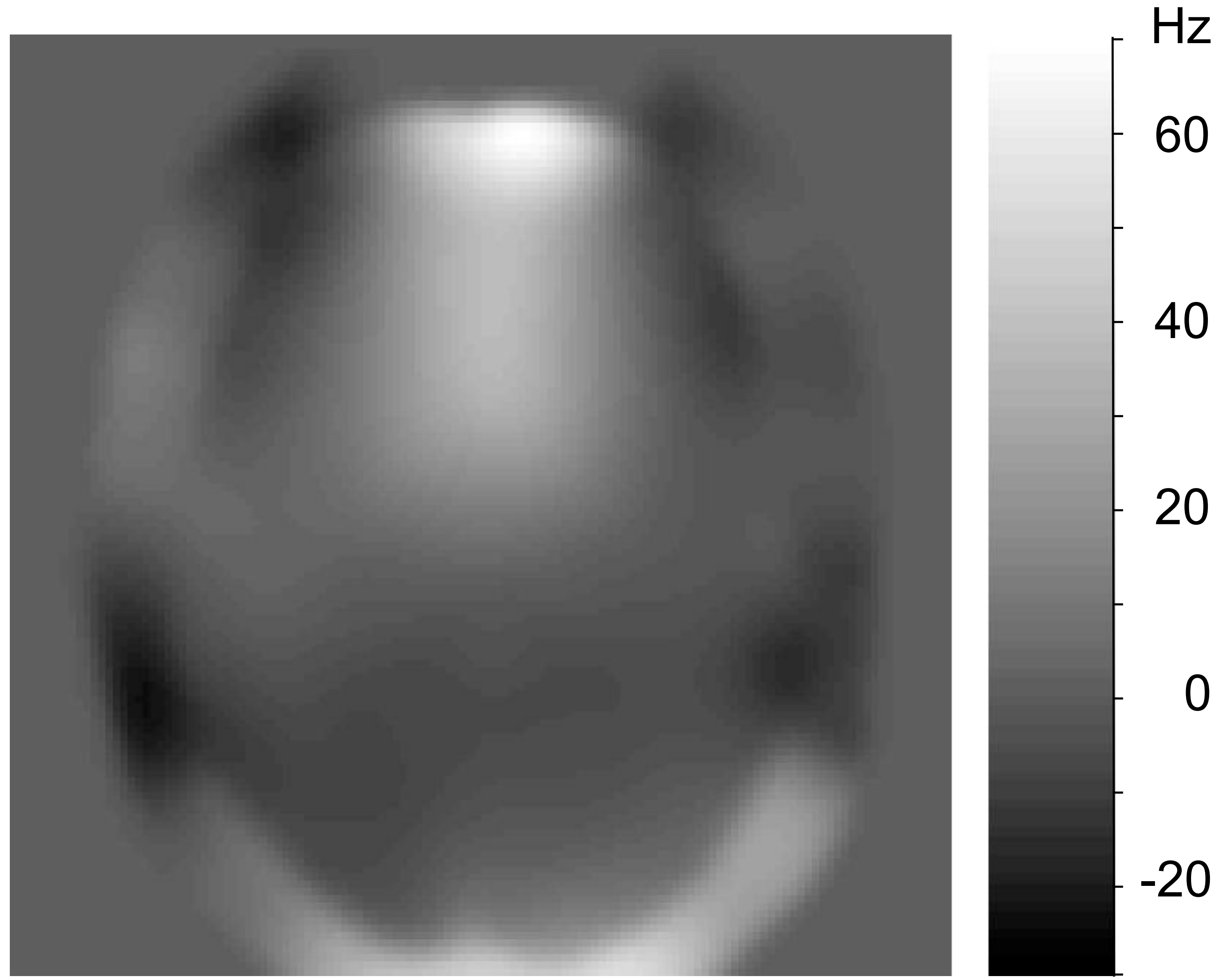
实际上，它甚至在内部都不是一致的

Outline of the talk 大纲

- What is the problem with diffusion data? 扩散数据有什么问题?
- Off-resonance field 非共振场
  - How does it cause distortions? 它如何引起失真?
  - Where does it come from? 它从何而来?
- Registering diffusion data 弥散数据的配准
  - How topup works topup topup如何起作用补满的?
  - How eddy works eddy eddy实现涡流矫正?
- Practicalities 实用性
- Some results 一些结果
- Quality control 质控
- New eddy features 新的涡流功能

Off-resonance field ⇒ Distortions

非共振场⇒失真



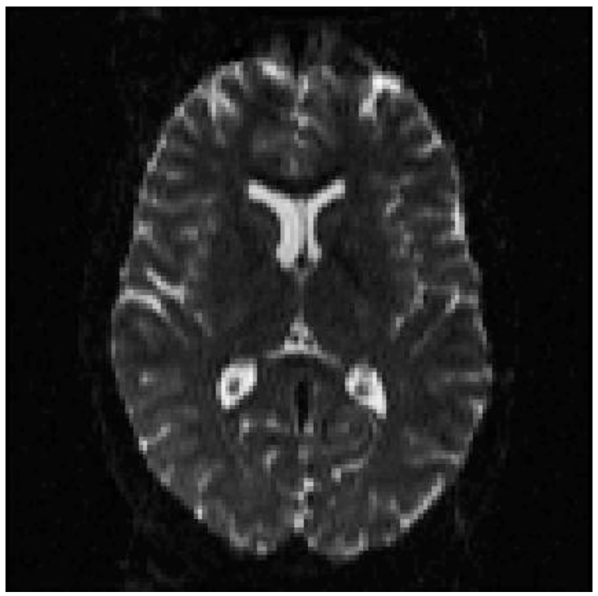
An “off-resonance” field is a map of the difference between what we think the field is and what it really is.
“非共振”场是我们认为该场与实际场之间的差异的映射。

It is all caused by an “off-resonance” field

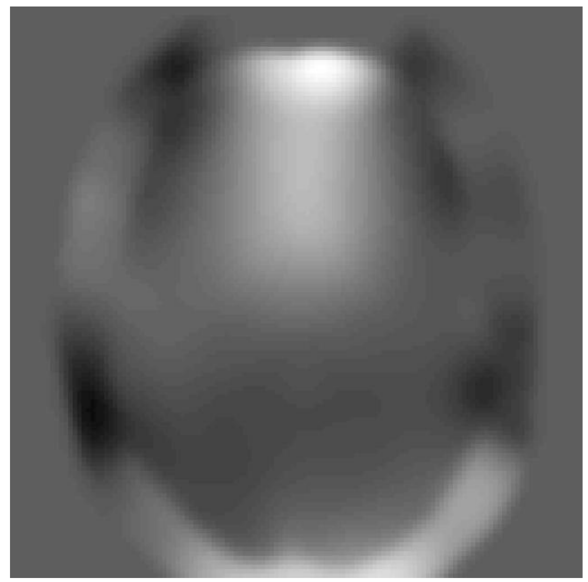
这都是由“共振”场引起的

Off-resonance field ⇒ Distortions

非共振场⇒失真

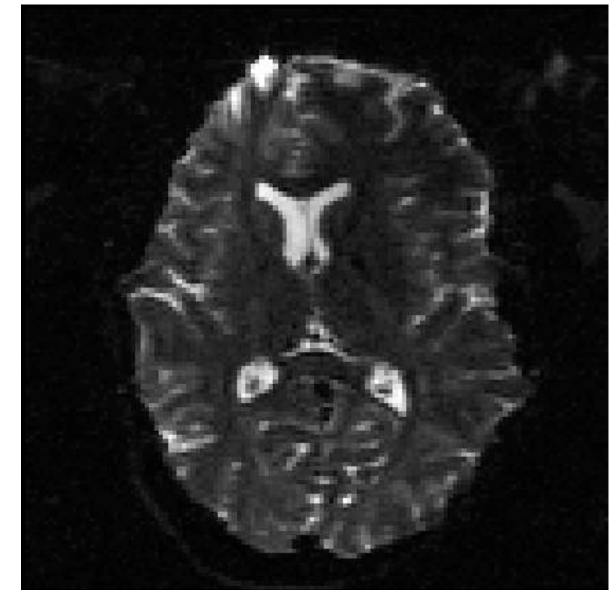


But this object
这个对象

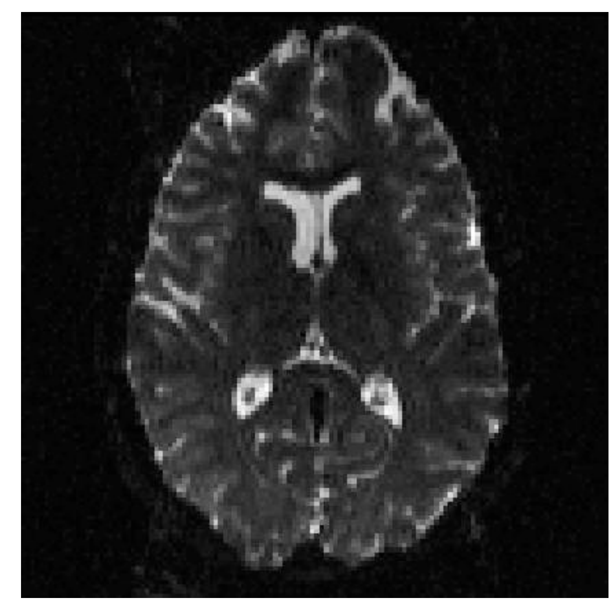


scanned in this field
在此场中扫描

or this
可能是这样



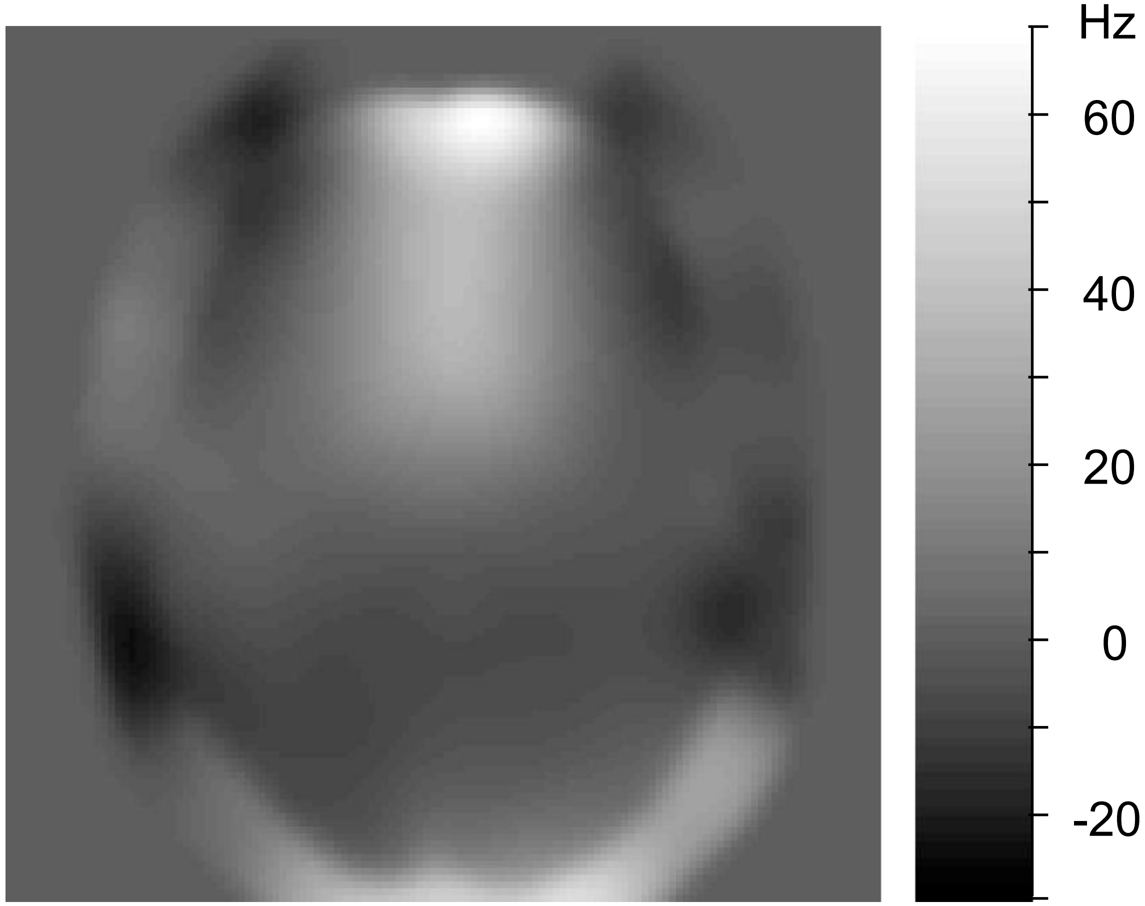
Can yield this
也可能生成这个



So there is clearly more to this story…
因此，这个故事显然还有更多……

Off-resonance field ⇒ Distortions

非共振场⇒失真



An off-resonance field is effectively a scaled voxel-displacement map.

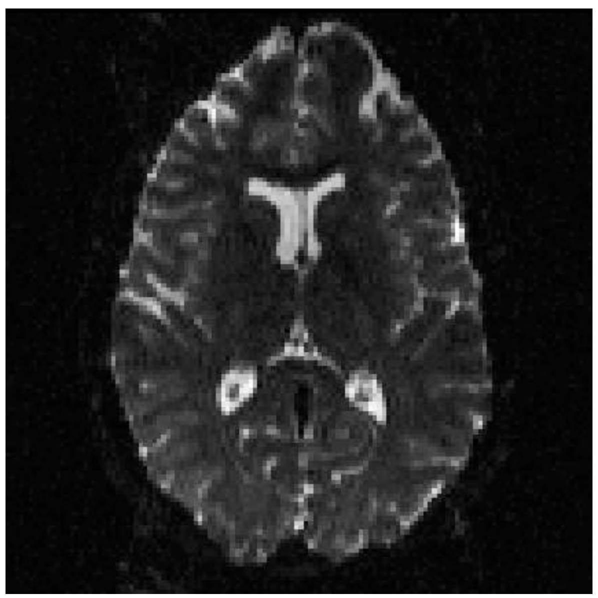
非共振场实际上是缩放的体素位移图。

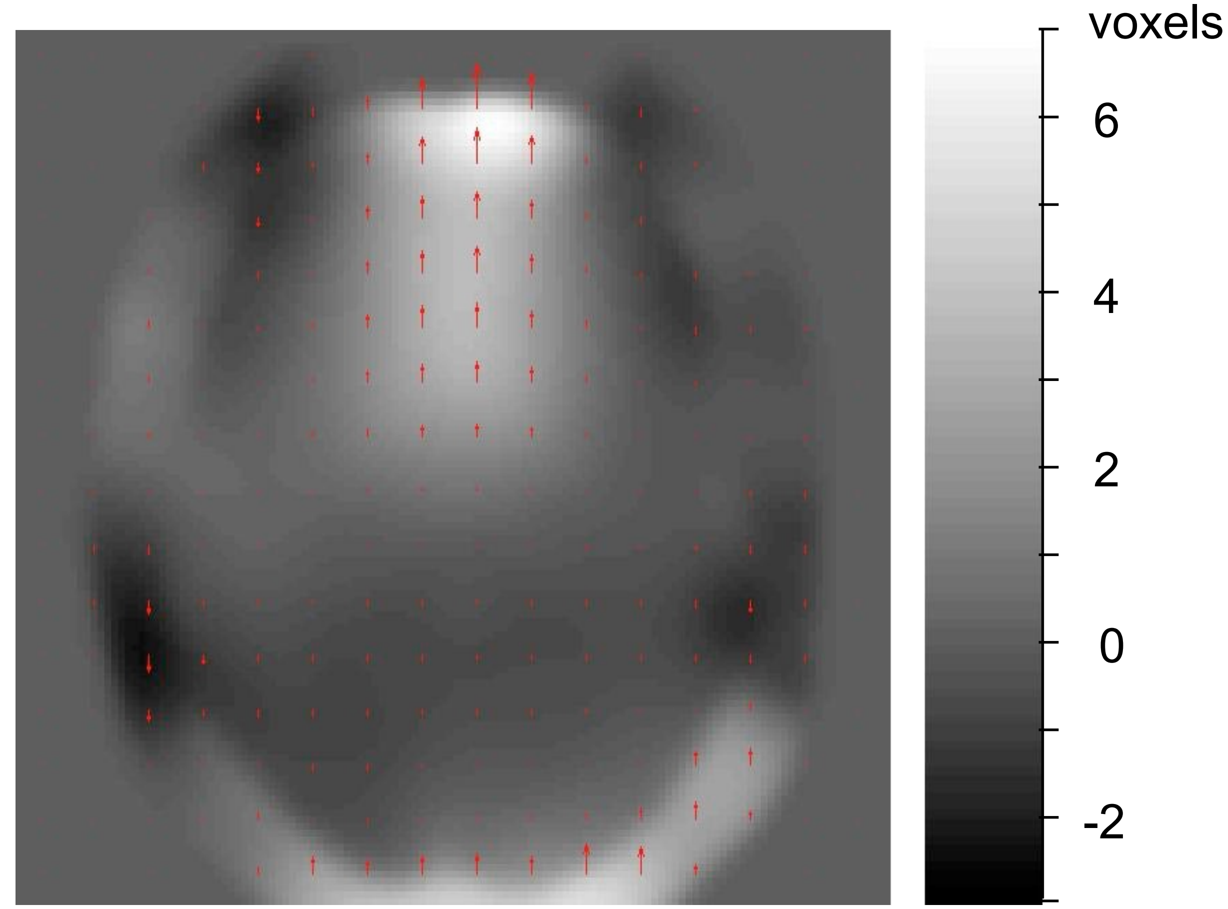
If we know the imaging parameters we can do the translation.

如果我们知道成像参数，就可以进行位移变换

Off-resonance field ⇒ Distortions

非共振场⇒失真





And know what to expect

并且知道会发生什么

An off-resonance field is effectively a scaled voxel-displacement map.

非共振场实际上是缩放的体素位移图。

If we know the imaging parameters we can do the translation.

如果我们知道成像参数，就可以进行位移变换

BW/voxel = 10Hz, **p** = [0 1 0]

Outline of the talk 大纲

- What is the problem with diffusion data? 扩散数据有什么问题?
- Off-resonance field 非共振场
  - How does it cause distortions? 它如何引起失真?
  - Where does it come from? 它从何而来?
- Registering diffusion data 弥散数据的配准
  - How topup works topup topup如何起作用补满的?
  - How eddy works eddy eddy实现涡流矫正?
- Practicalities 实用性
- Some results 一些结果
- Quality control 质控
- New eddy features 新的涡流功能

Where does the off-resonance field come from?

非共振场来自哪里?

- There are two sources 有两个来源
- The first is the object (head) itself. 第一个是对象（头部）本身。

(CT of) Human head CT脑图

$B_0 \odot$

Resulting field 结果场

PPMs

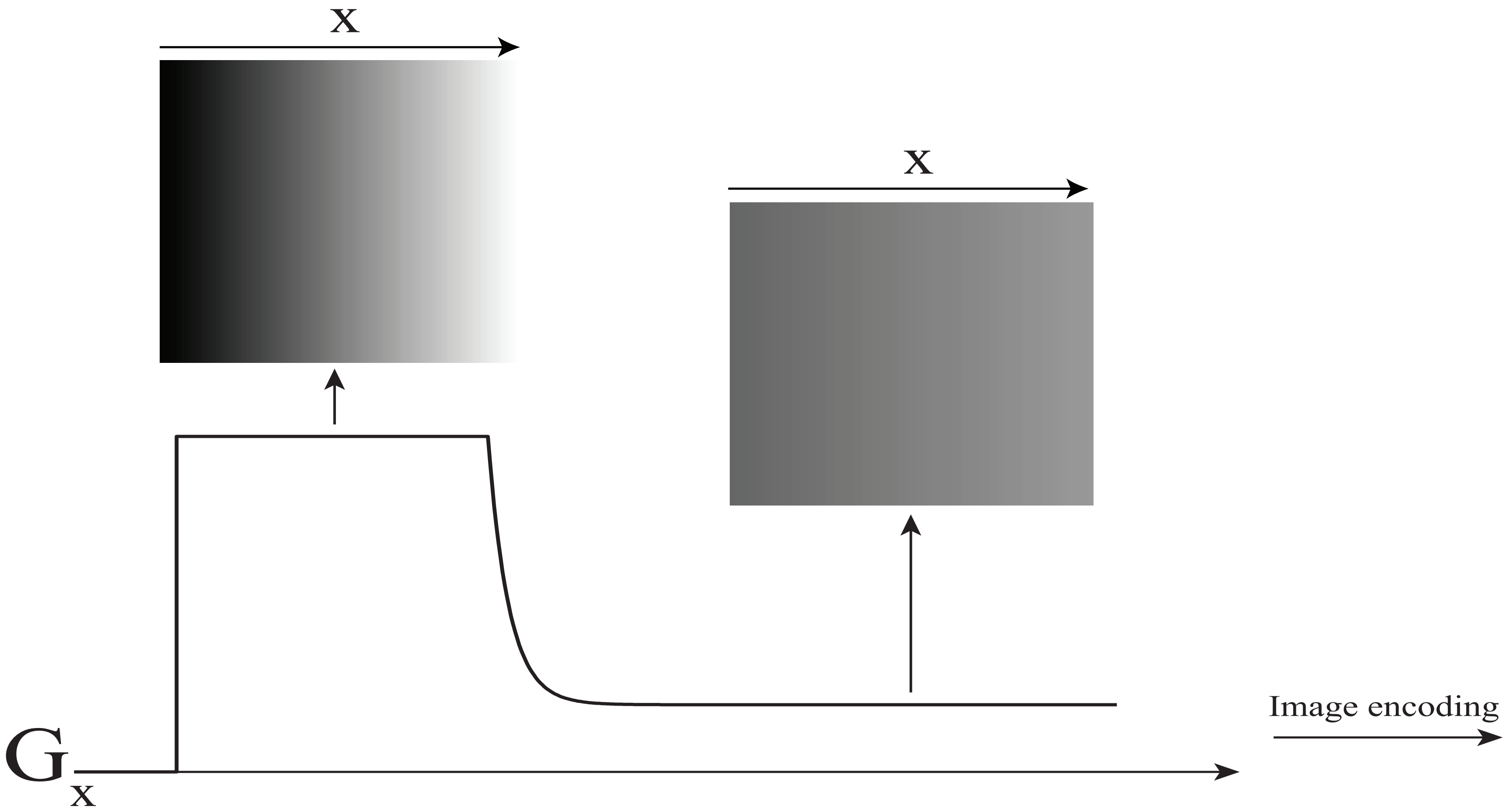
$$\text{Must fulfil} \begin{cases} \nabla \times \mathbf{H} = 0 \\ \nabla \bullet \mathbf{B} = 0 \end{cases} \quad \text{(still)}$$

Where does the off-resonance field come from?

非共振场来自哪里?

- There are two sources 有两个来源
- The first is the object (head) itself. 第一个是对象（头部）本身

- The second is caused by the diffusion gradient 第二是由扩散梯度引起的



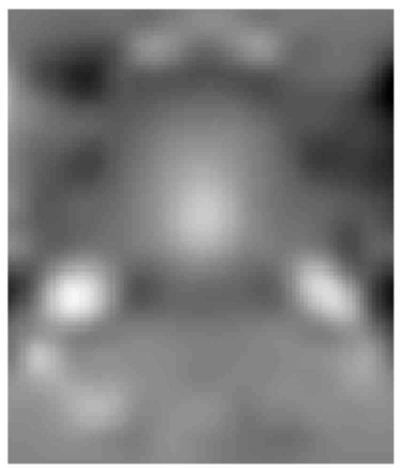
Where does the off-resonance field come from?

非共振场来自哪里?

So for any diffusion weighted volume the off-resonance field is the sum of these two contributions

因此，对于任何扩散加权图像，非共振场都是这两个贡献的总和

受磁率 Susceptibility

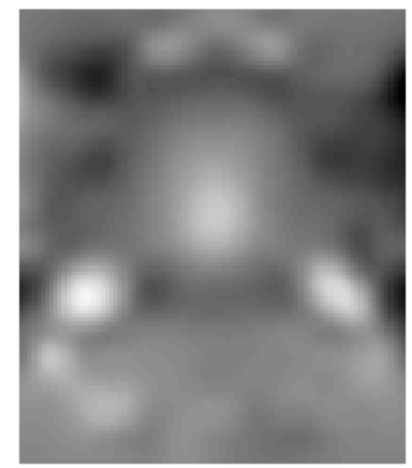


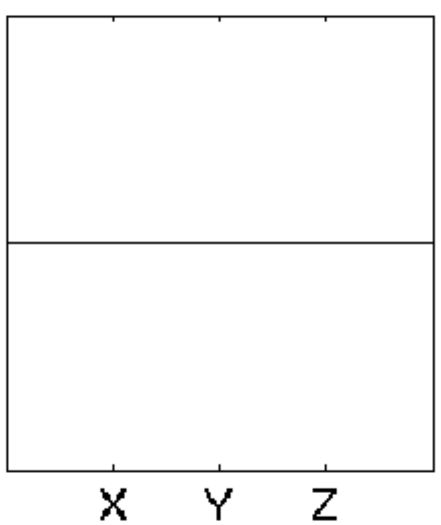
+

Eddy currents 涡流

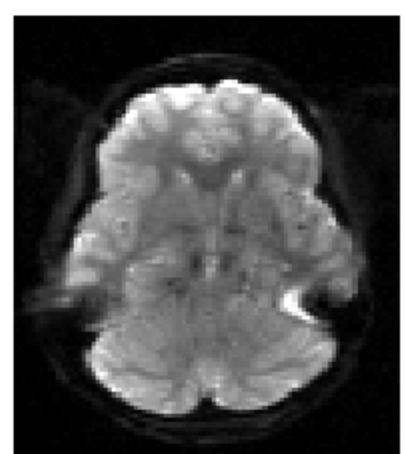
=

Total 总和



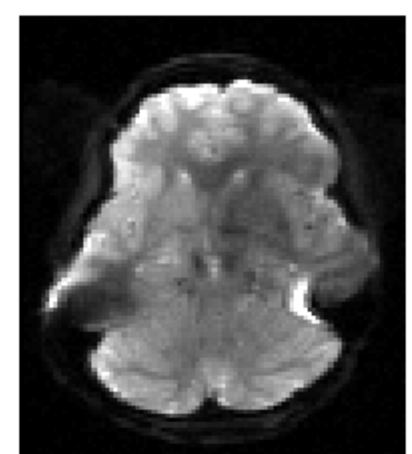


梯度场 Diffusion gradient



“True” object

真实图像



Observed image

观察到的图像

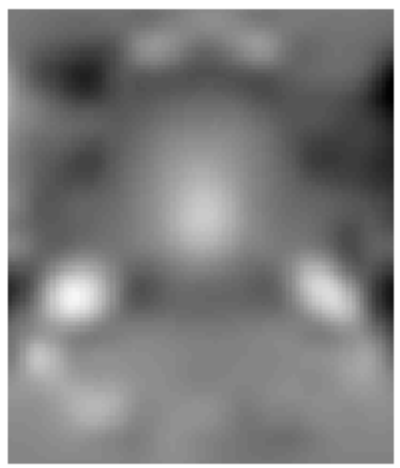
Where does the off-resonance field come from?

非共振场来自哪里?

So for any diffusion weighted volume the off-resonance field is the sum of these two contributions

因此，对于任何扩散加权图像，非共振场都是这两个贡献的总和

受磁率 Susceptibility

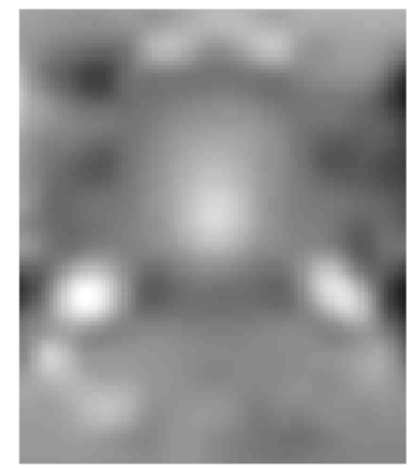


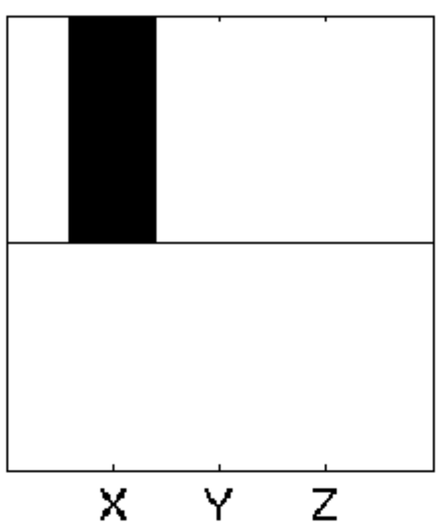
\+

Eddy currents 涡流

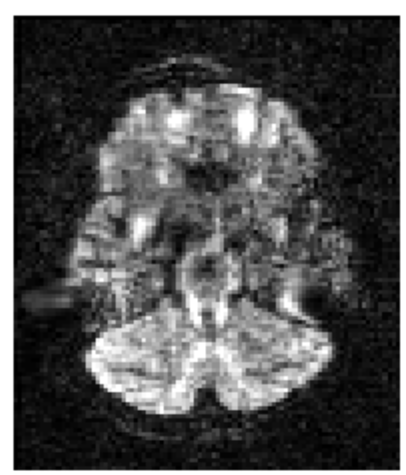
=

Total 总和





梯度场 Diffusion gradient



“True” object

真实图像

Observed image

观察到的图像

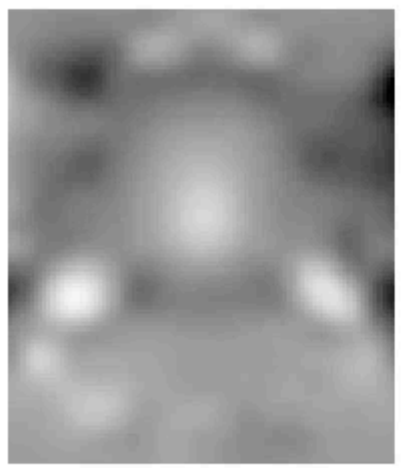
Where does the off-resonance field come from?

非共振场来自哪里?

So for any diffusion weighted volume the off-resonance field is the sum of these two contributions

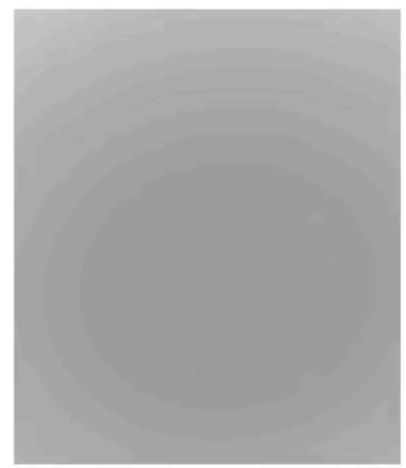
因此，对于任何扩散加权图像，非共振场都是这两个贡献的总和

受磁率 Susceptibility



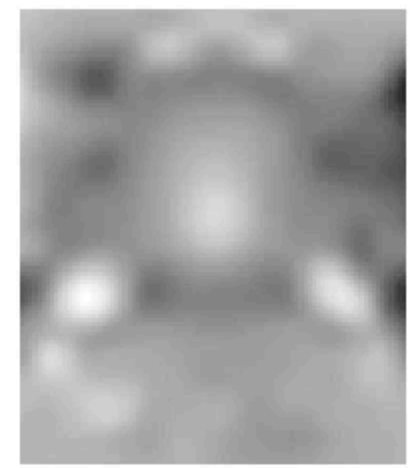
+

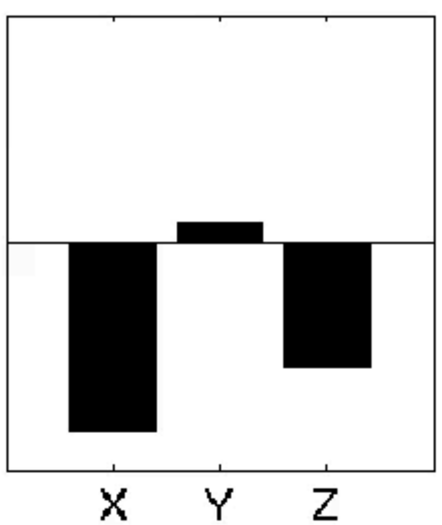
Eddy currents 涡流



=

Total 总和





梯度场 Diffusion gradient

“True” object

真实图像

Observed image

观察到的图像

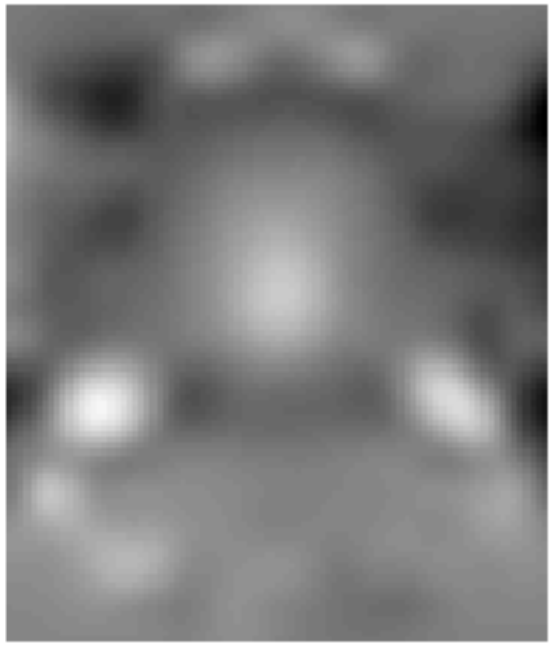
Separate estimation of susceptibility- and eddy current-fields

磁化场和涡流场的单独估算

So, what we need to estimate is

因此，我们需要估算的是

One of these per subject
其中一个被试



One of these per volume
其中一个体素

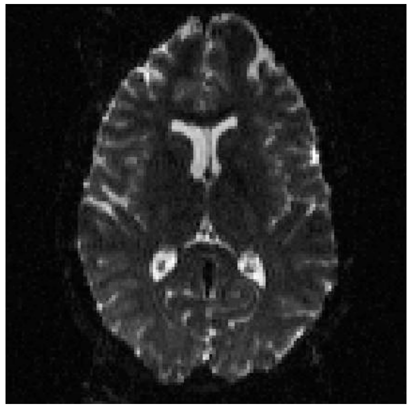
FSL-tools: topup eddy

Outline of the talk 大纲

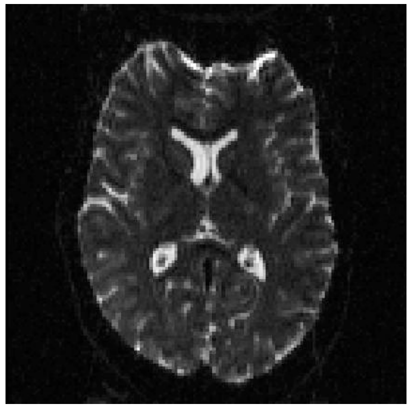
- What is the problem with diffusion data? 扩散数据有什么问题?
- Off-resonance field 非共振场
  - How does it cause distortions? 它如何引起失真?
  - Where does it come from? 它从何而来?
- Registering diffusion data 弥散数据的配准
  - How topup works topup topup如何起作用补满的?
  - How eddy works eddy eddy实现涡流矫正?
- Practicalities 实用性
- Some results 一些结果
- Quality control 质控
- New eddy features 新的涡流功能

How topup works (very briefly)

topup的工作原理（非常简短）



p=[0 1 0]



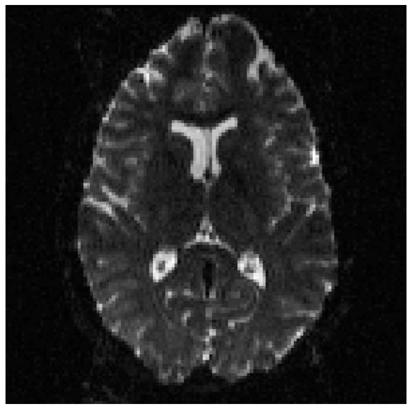
p=[0 -1 0]

Given two images acquired with different phase-encoding

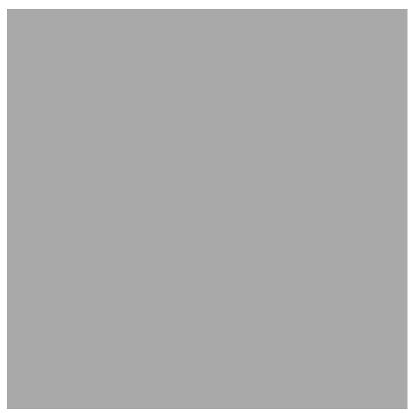
给定两个使用不同相位编码获取的图像

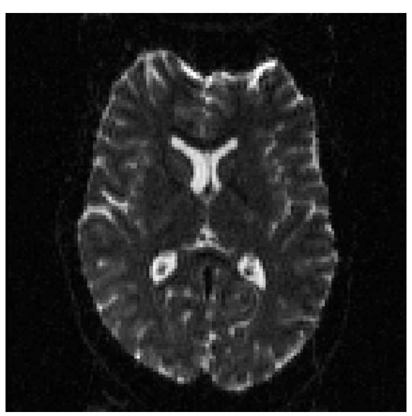
How topup works (very briefly)

topup的工作原理（非常简短）



p=[0 1 0]





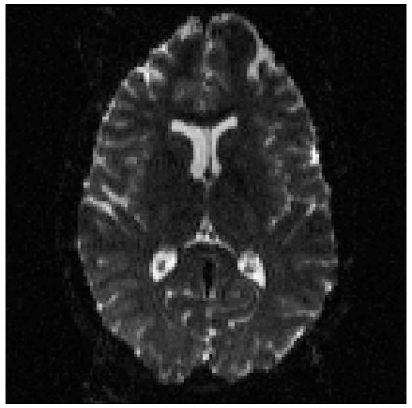
p=[0 -1 0]

topup “guesses” a field…

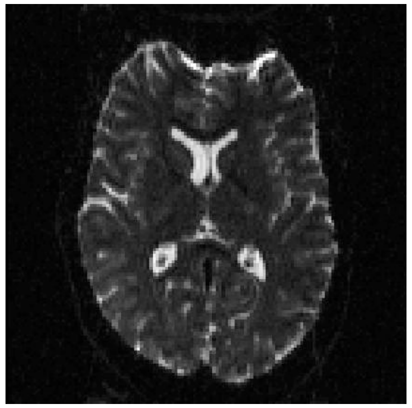
topup 猜测一个场

How topup works (very briefly)

topup的工作原理（非常简短）



p=[0 1 0]



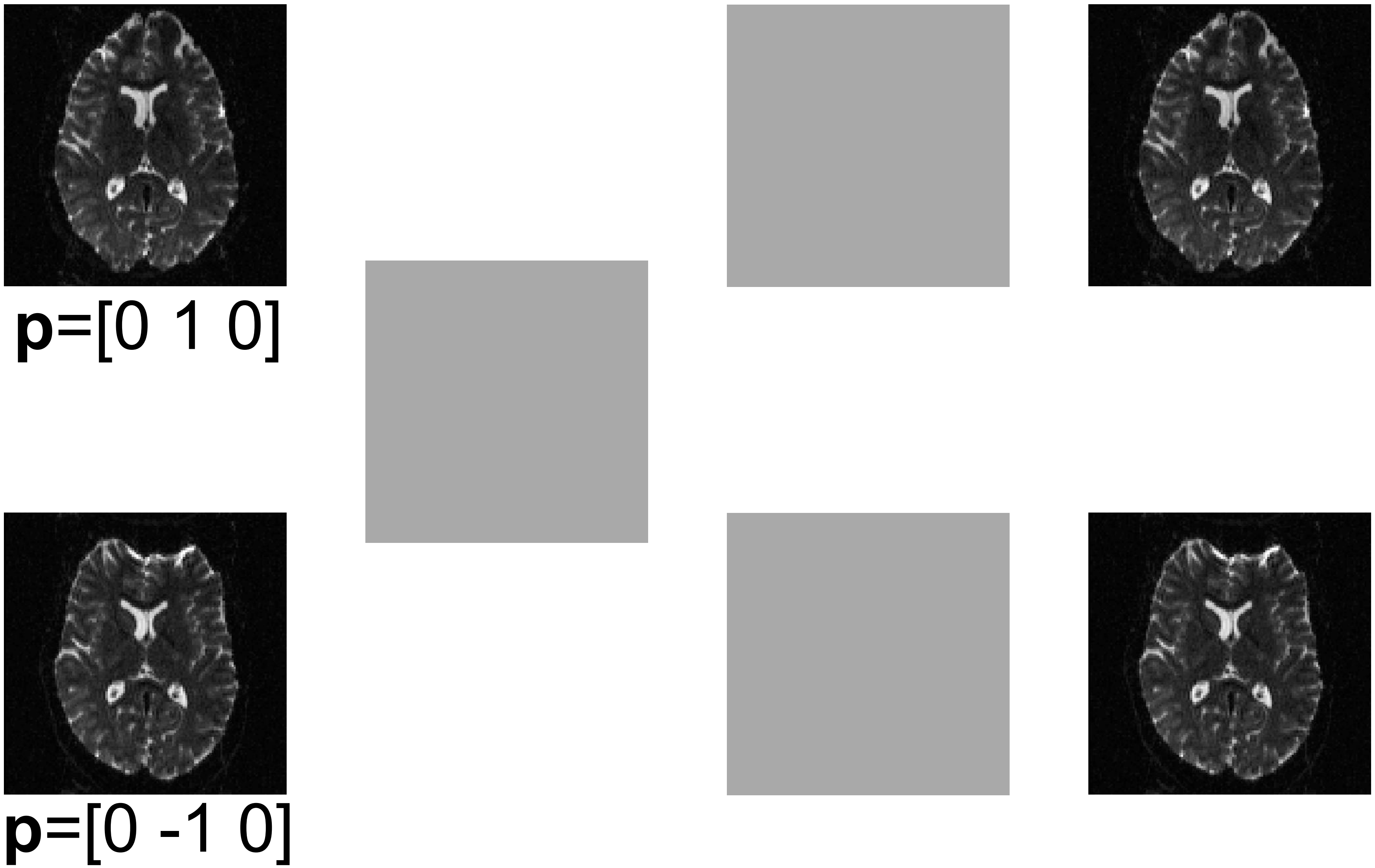
p=[0 -1 0]

...calculates the displacement maps…

...计算位移图...

How topup works (very briefly)

topup的工作原理（非常简短）

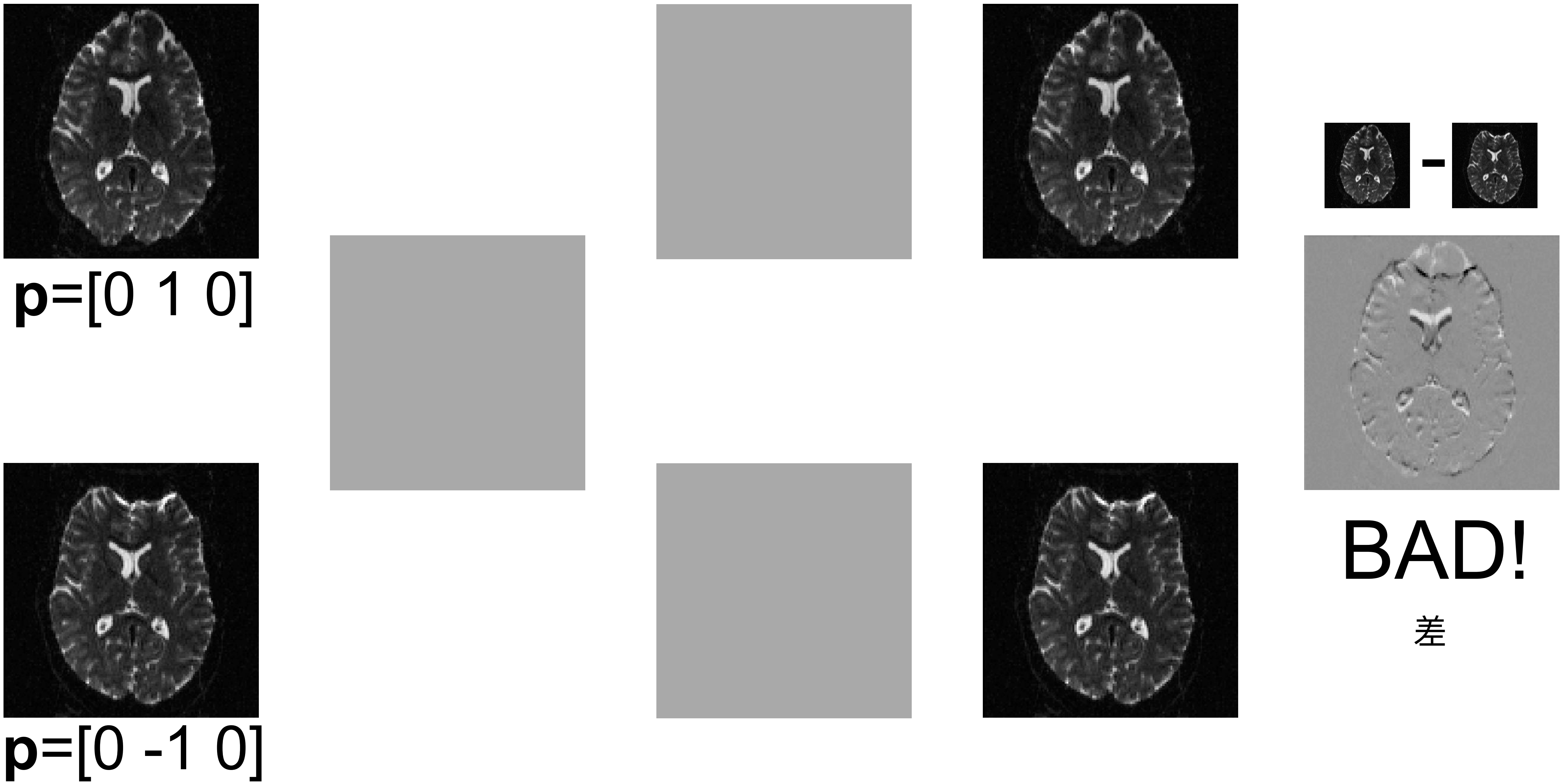


...”corrects” the images…

校正图像

How topup works (very briefly)

topup的工作原理（非常简短）

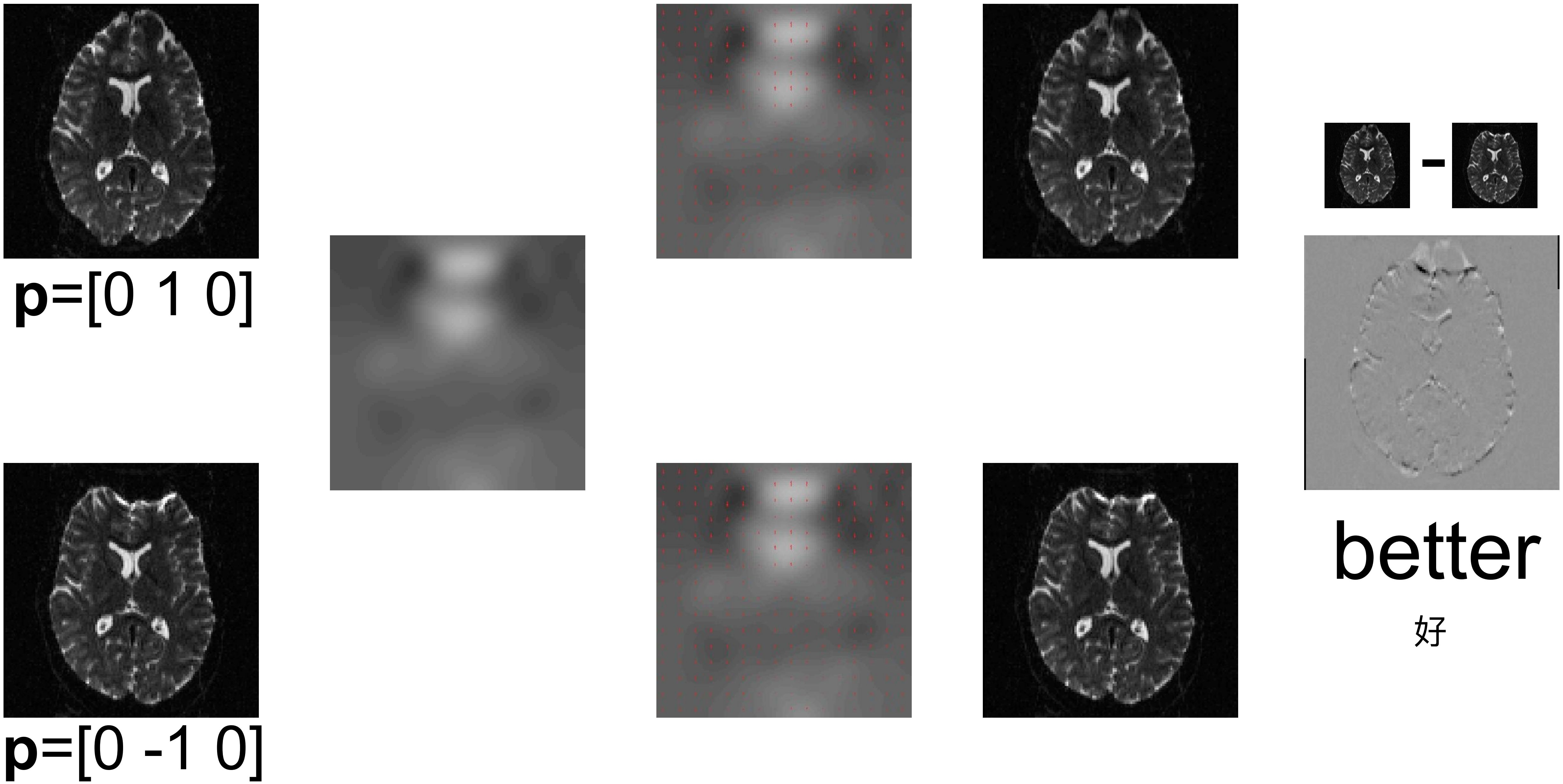


...and evaluates the results...
And **this** is the crucial bit.

...并评估结果...这是至关重要的一点。

How topup works (very briefly)

topup的工作原理（非常简短）

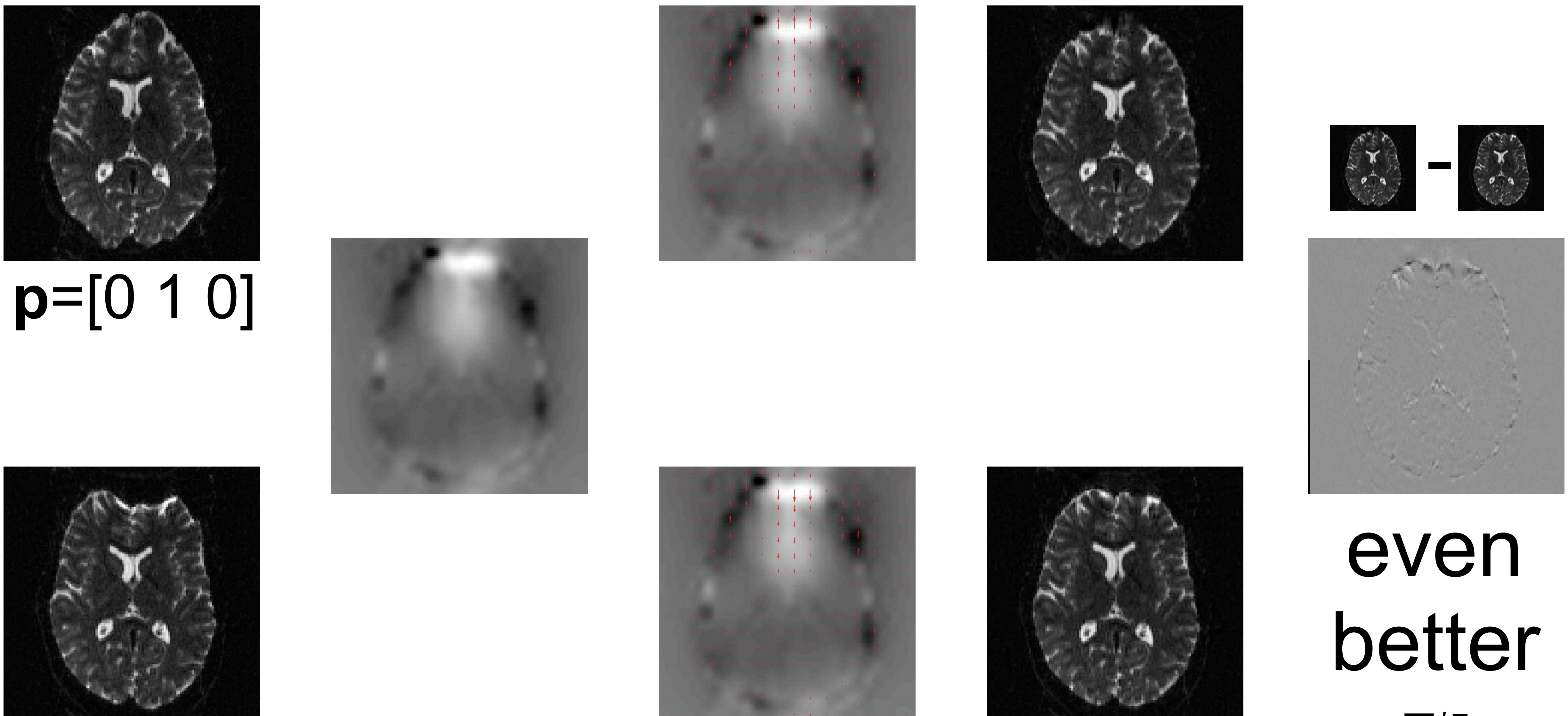


Because topup can then “guess” another field

因为topup然后可以“猜测”另一个场

How topup works (very briefly)

topup的工作原理（非常简短）



p=[0 -1 0]

even better

更好

...and another...until it is happy, and then it “knows” the field

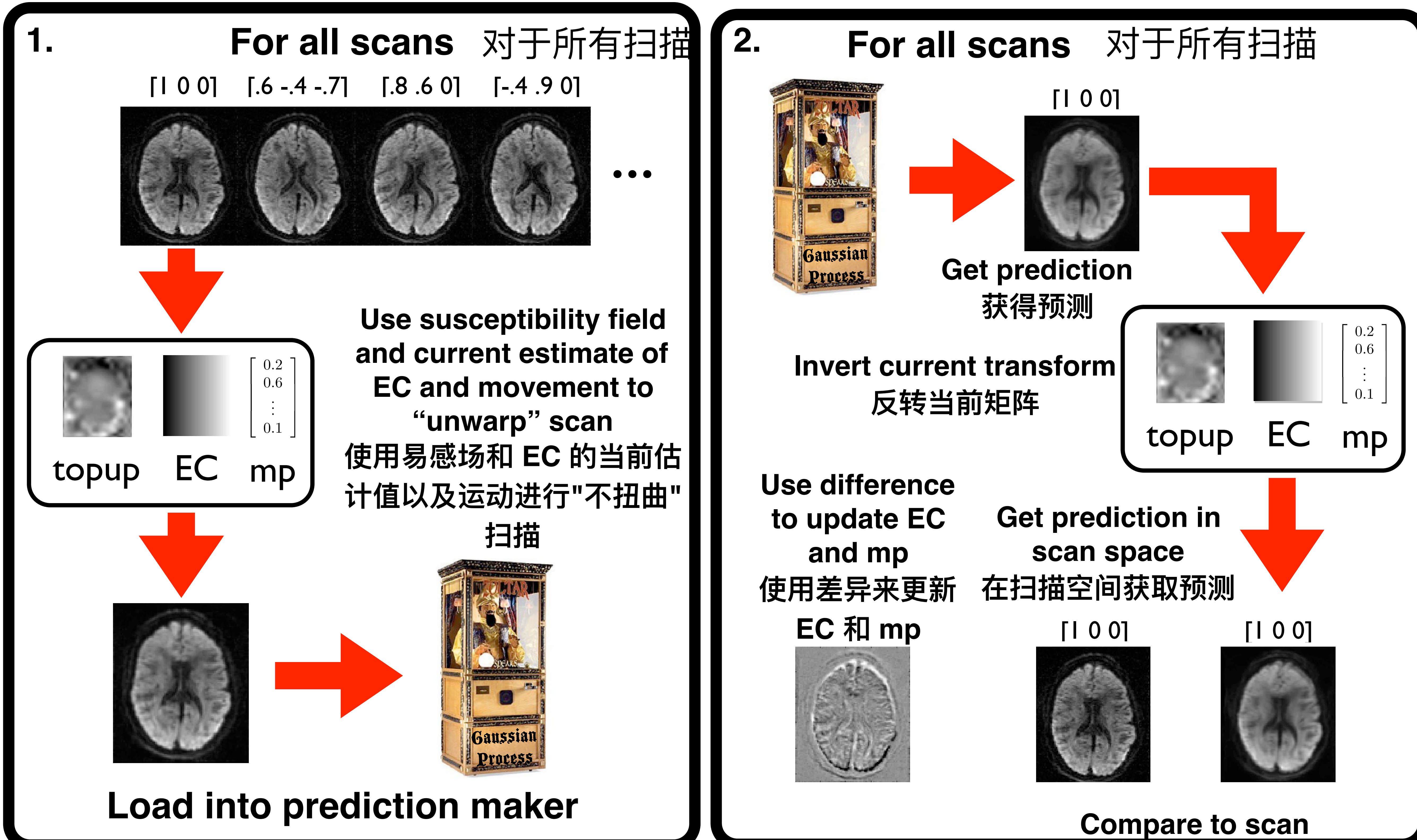
还有一个...直到高兴，然后才“知道”这个场

Outline of the talk 大纲

- What is the problem with diffusion data? 扩散数据有什么问题?
- Off-resonance field 非共振场
  - How does it cause distortions? 它如何引起失真?
  - Where does it come from? 它从何而来?
- Registering diffusion data 弥散数据的配准
  - How topup works topup topup如何起作用补满的?
  - How eddy works eddy eddy实现涡流矫正?
- Practicalities 实用性
- Some results 一些结果
- Quality control 质控
- New eddy features 新的涡流功能

How eddy works

涡流的工作原理

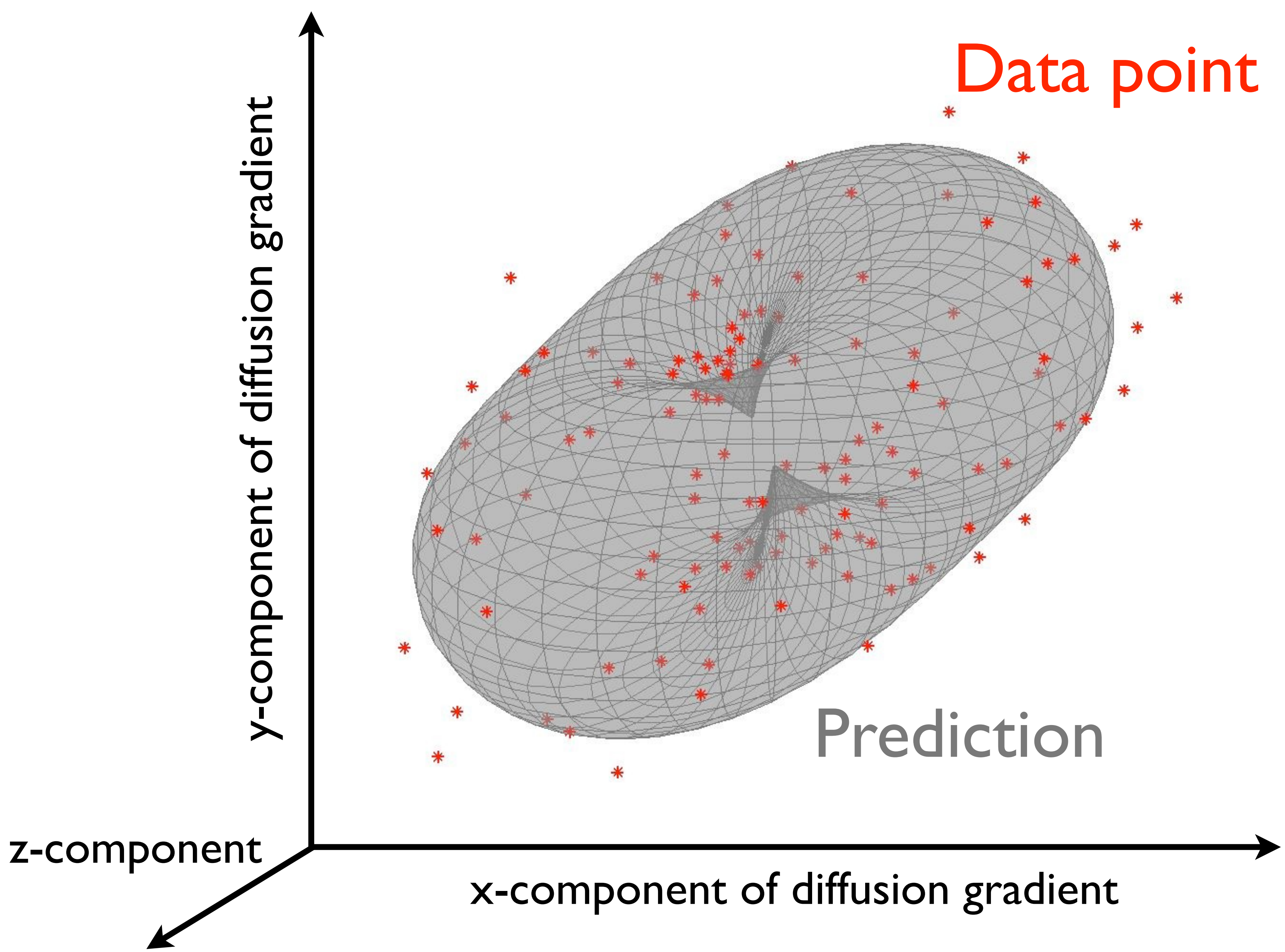


加载到预测创建器

与扫描进行比较

Under the hood of Zoltar

现在让我们掀起Zoltar的盖头来



The signal is “modelled” in a data-driven fashion assuming that points close together on the unit sphere have similar signal.

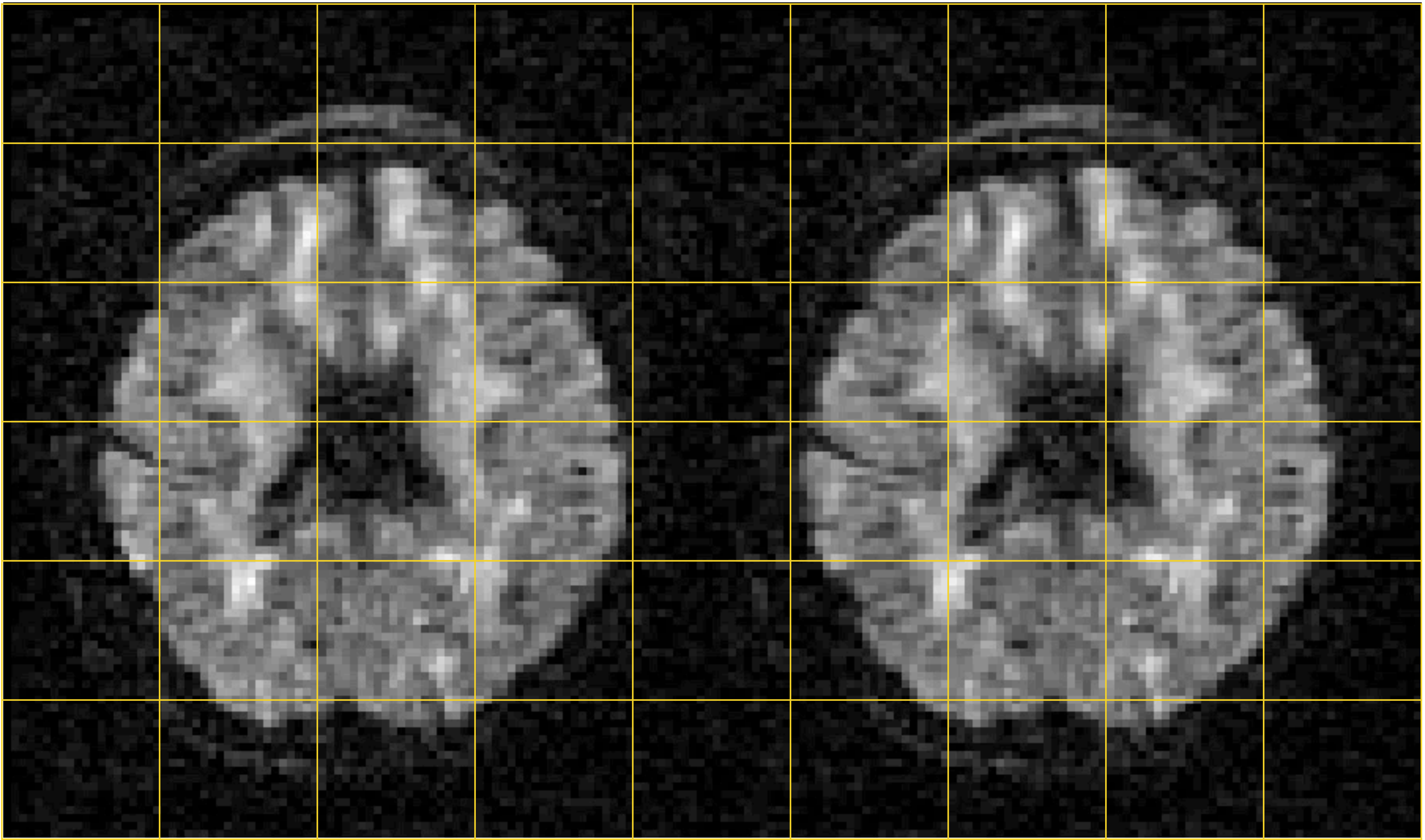
假设在单位球体上靠近的点具有相似的信号，则以数据驱动的方式对信号进行“建模”

Outline of the talk 大纲

- What is the problem with diffusion data? 扩散数据有什么问题?
- Off-resonance field 非共振场
  - How does it cause distortions? 它如何引起失真?
  - Where does it come from? 它从何而来?
- Registering diffusion data 弥散数据的配准
  - How topup works topup topup如何起作用补满的?
  - How eddy works eddy eddy实现涡流矫正?
- Practicalities 实用性
- Some results 一些结果
- Quality control 质控
- New eddy features 新的涡流功能

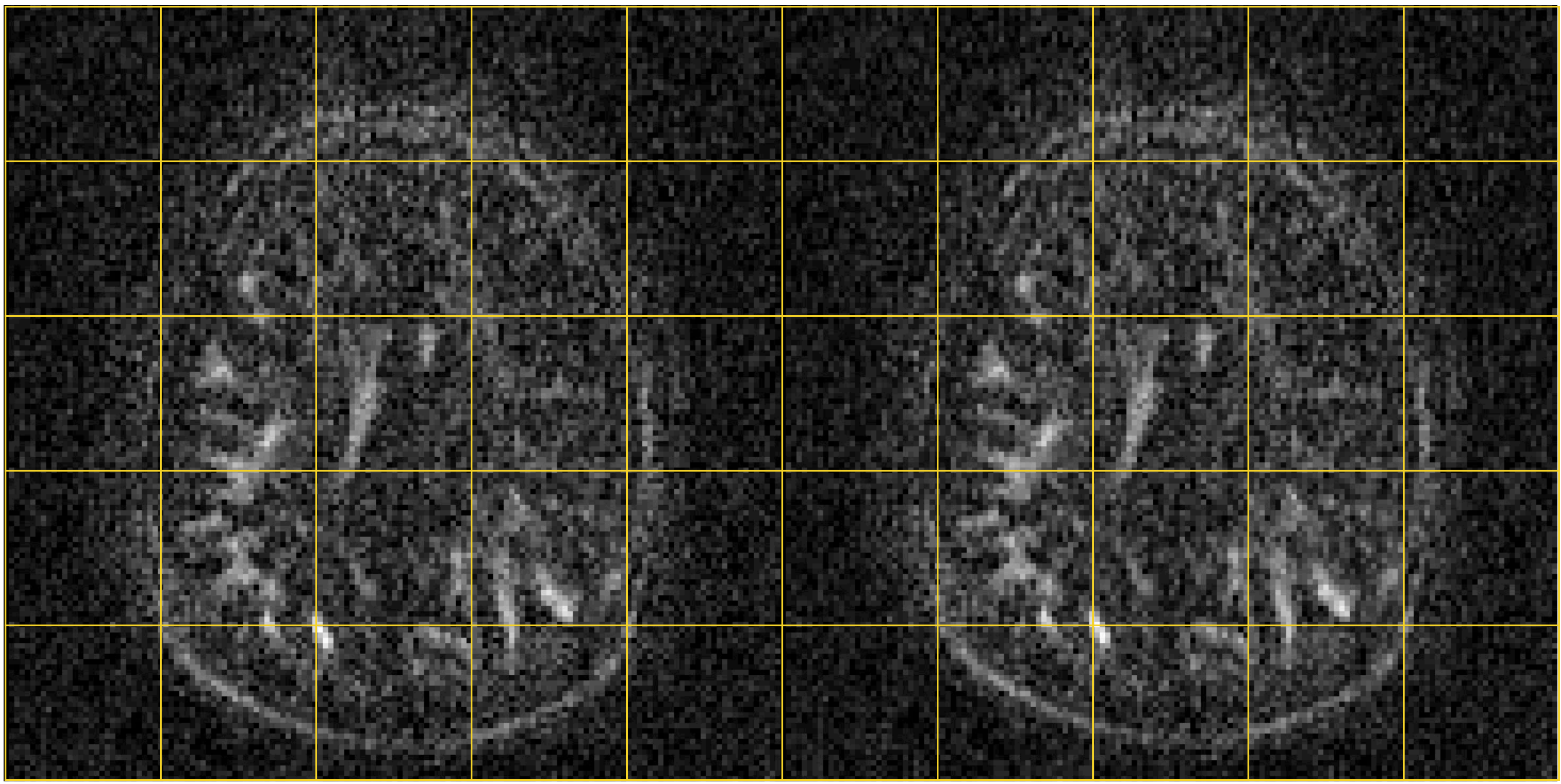
HCP-data, 150 directions, b=3000, blip-up-blip-down

HCP 数据，150 个方向，b=3000，向上—向下



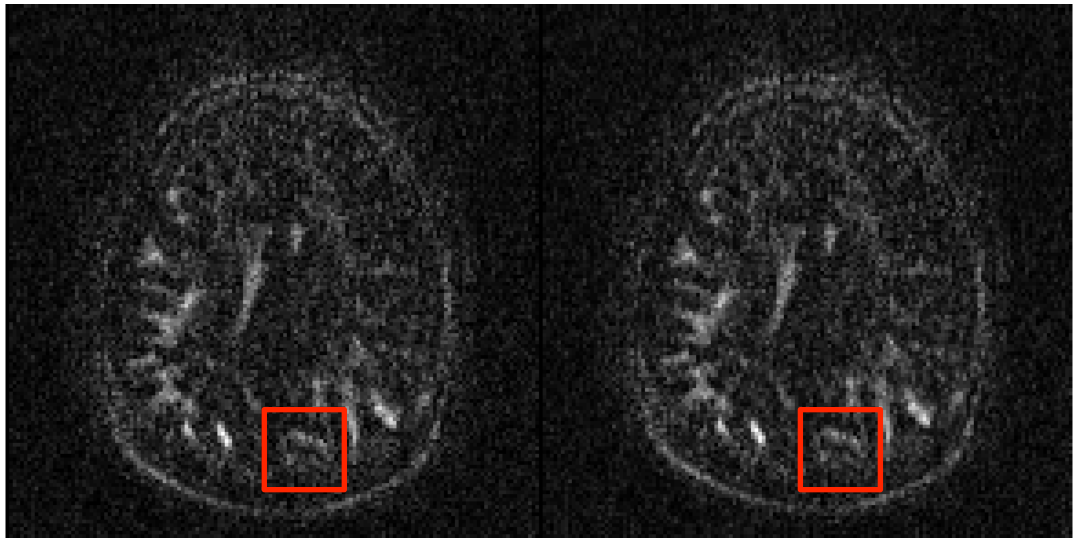
MGH-data, 198 directions, b=10000!

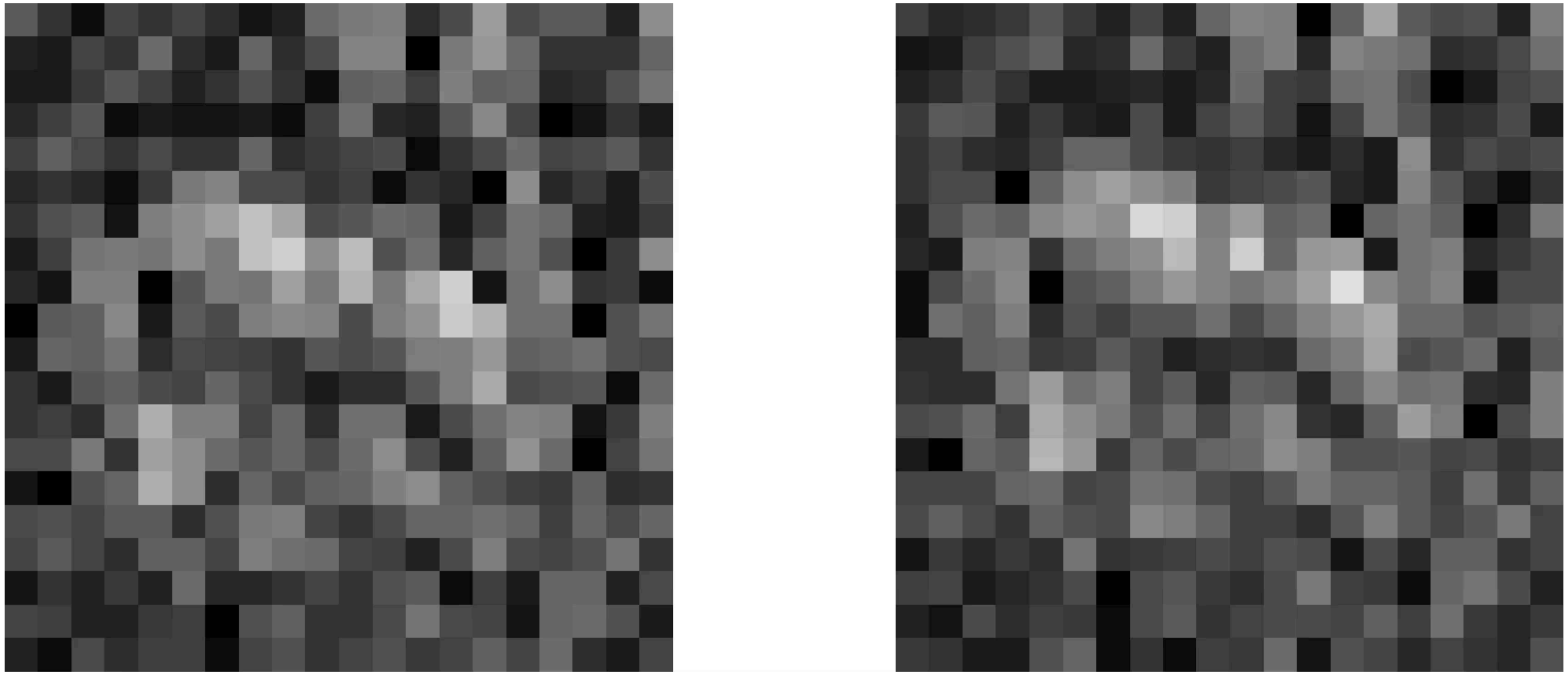
MGH 数据，198 方向，b=10000！



MGH-data, 198 directions, b=10000!

MGH 数据，198 方向，b=10000!



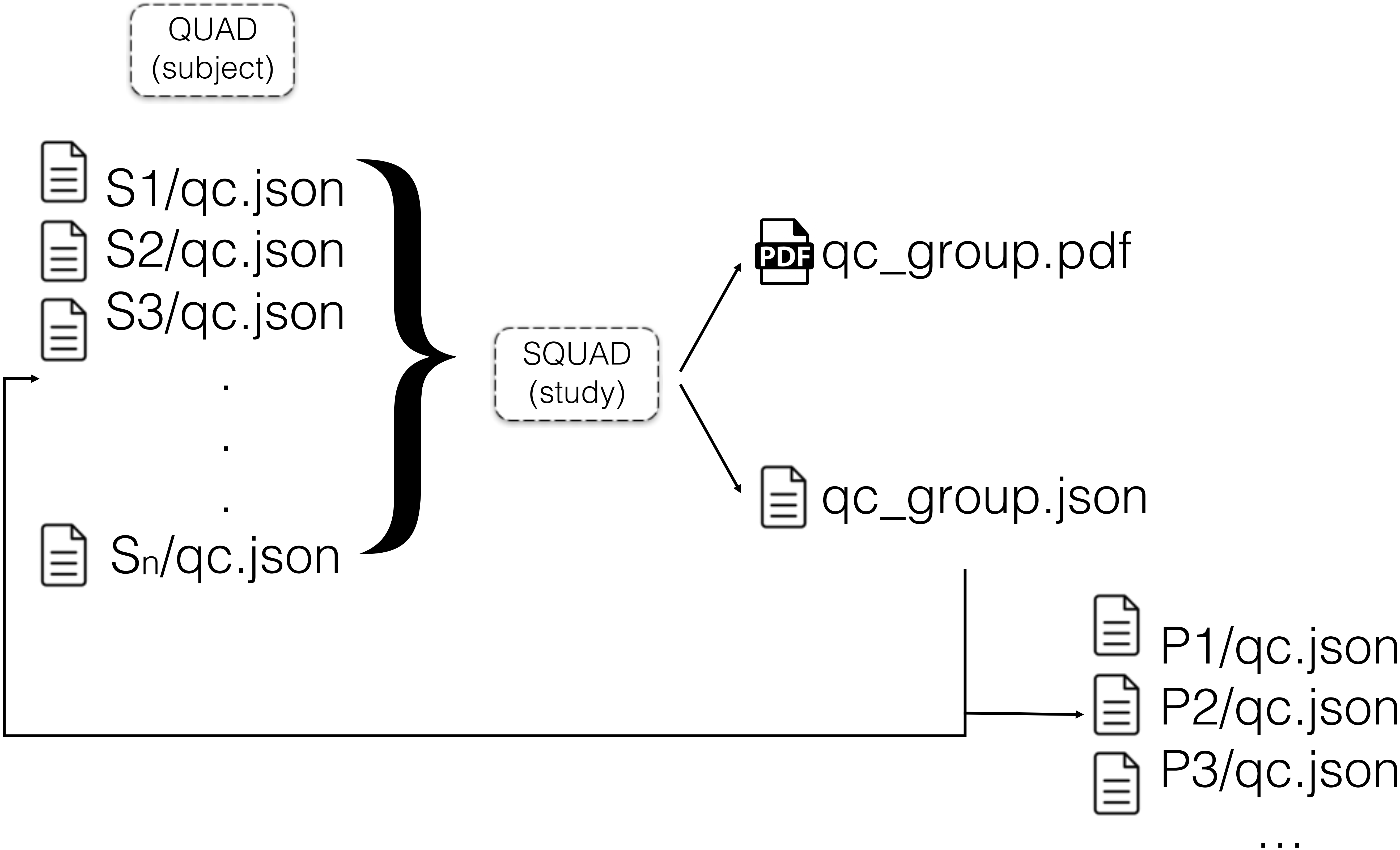


Outline of the talk 大纲

• What is the problem with diffusion data?	扩散数据有什么问题?
• Off-resonance field	非共振场
• How does it cause distortions?	它如何引起失真?
• Where does it come from?	它从何而来?
• Registering diffusion data	弥散数据的配准
• How topup works topup	topup如何起作用补满的?
• How eddy works eddy	eddy实现涡流矫正?
• Practicalities	实用性
• Some results	一些结果
• Quality control	质控
• New eddy features	新的涡流功能

EDDY QC: data quality summary

涡流质控：数据质量总结



EDDY QC: single-subject reports

涡流质控：单个被试报告

Biobank subject A

Volume-to-volume motion

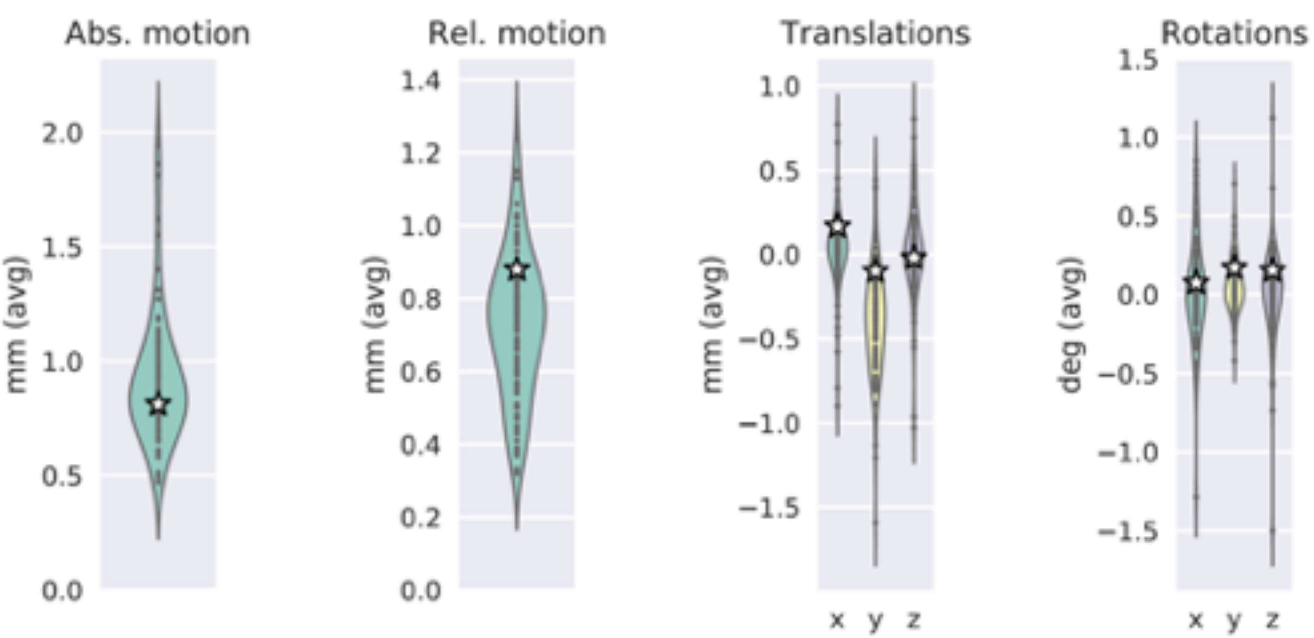
Average abs. motion (mm)	0.81
Average rel. motion (mm)	0.88
Average x translation (mm)	0.17
Average y translation (mm)	-0.10
Average z translation (mm)	-0.02
Average x rotation (deg)	0.07
Average y rotation (deg)	0.17
Average z rotation (deg)	0.15

Within-volume motion

Avg std x translation (mm)	0.02
Avg std y translation (mm)	0.11
Avg std z translation (mm)	0.04
Avg std x rotation (deg)	0.05
Avg std y rotation (deg)	0.05
Avg std z rotation (deg)	0.06

Outliers

Total outliers (%)	0.11
Outliers (b=1000 s/mm^2)	0.22
Outliers (b=2000 s/mm^2)	0.00
Outliers (PE dir=[0. 1. 0.])	0.00
Outliers (PE dir=[0. -1. 0.])	0.11



Biobank subject B

Volume-to-volume motion

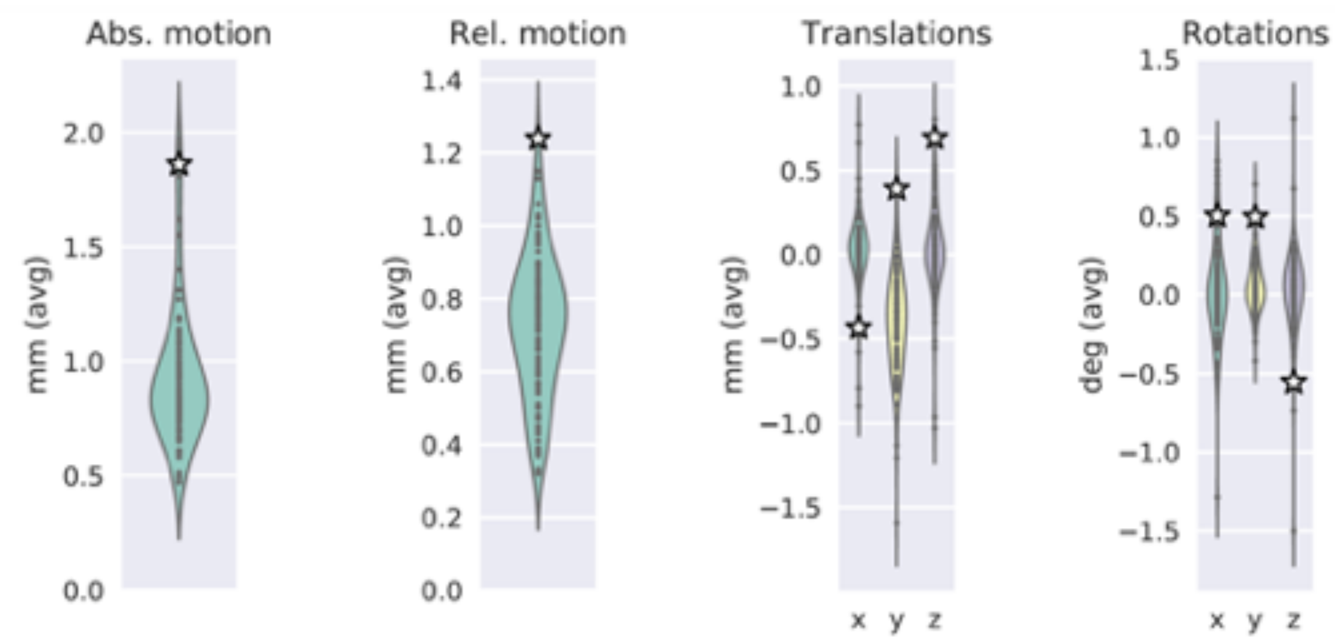
Average abs. motion (mm)	1.86
Average rel. motion (mm)	1.24
Average x translation (mm)	-0.43
Average y translation (mm)	0.39
Average z translation (mm)	0.69
Average x rotation (deg)	0.50
Average y rotation (deg)	0.49
Average z rotation (deg)	-0.55

Within-volume motion

Avg std x translation (mm)	0.08
Avg std y translation (mm)	0.22
Avg std z translation (mm)	0.13
Avg std x rotation (deg)	0.15
Avg std y rotation (deg)	0.09
Avg std z rotation (deg)	0.11

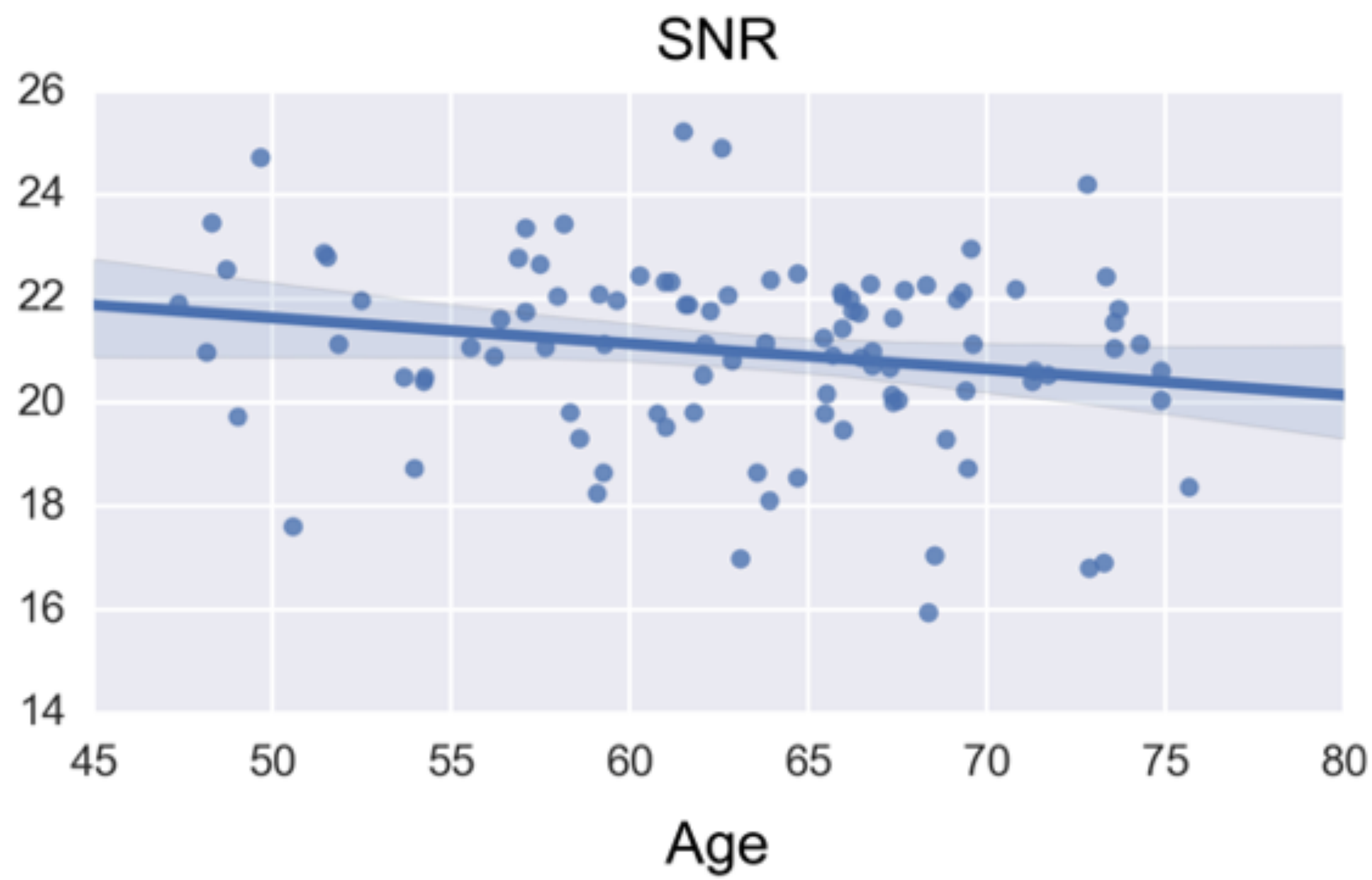
Outliers

Total outliers (%)	2.86
Outliers (b=1000 s/mm^2)	4.69
Outliers (b=2000 s/mm^2)	1.13
Outliers (PE dir=[0. 1. 0.])	2.55
Outliers (PE dir=[0. -1. 0.])	2.66

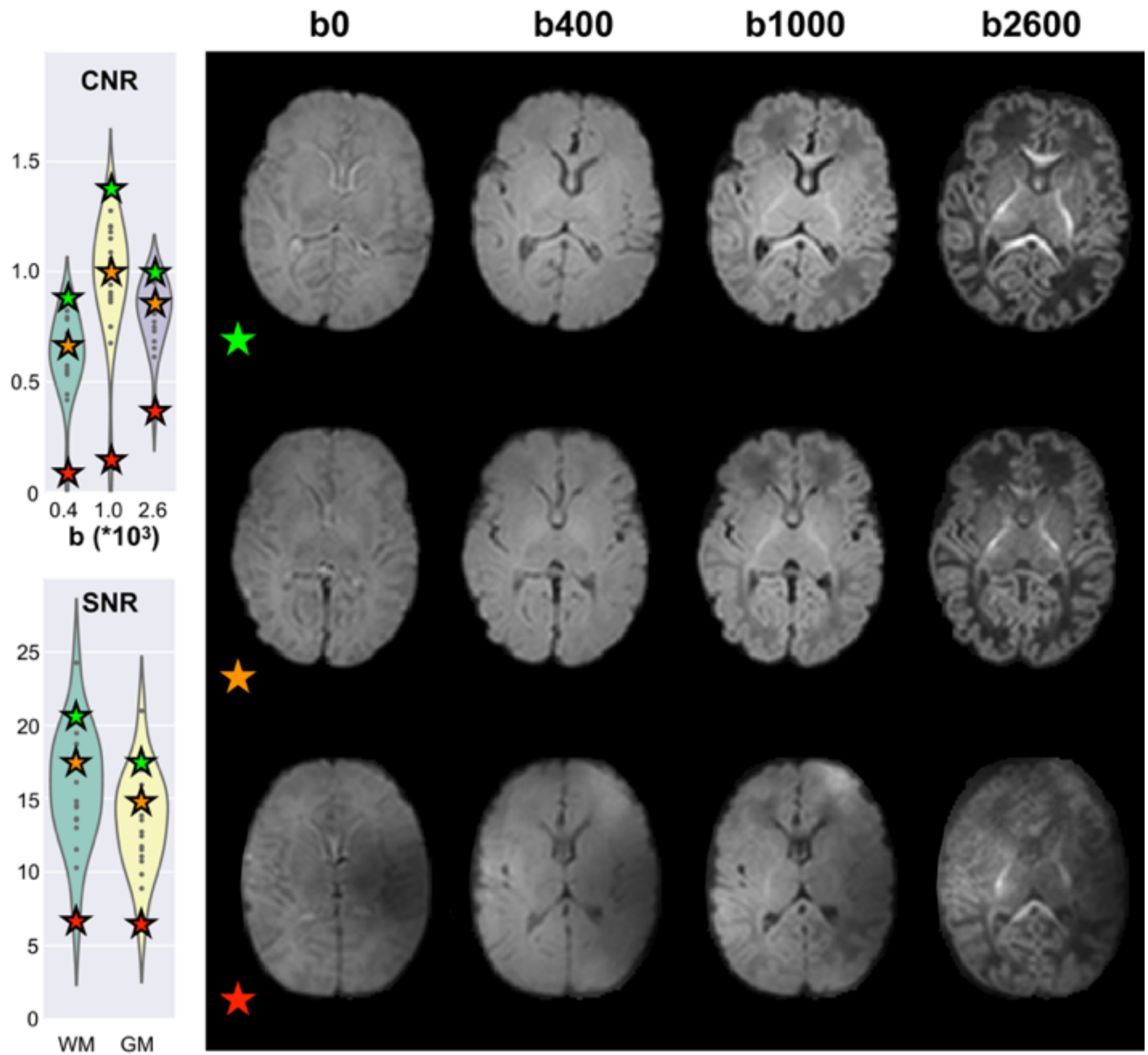


EDDY QC: group report

涡流质控：组报告



Data quality illustration 数据质量说明

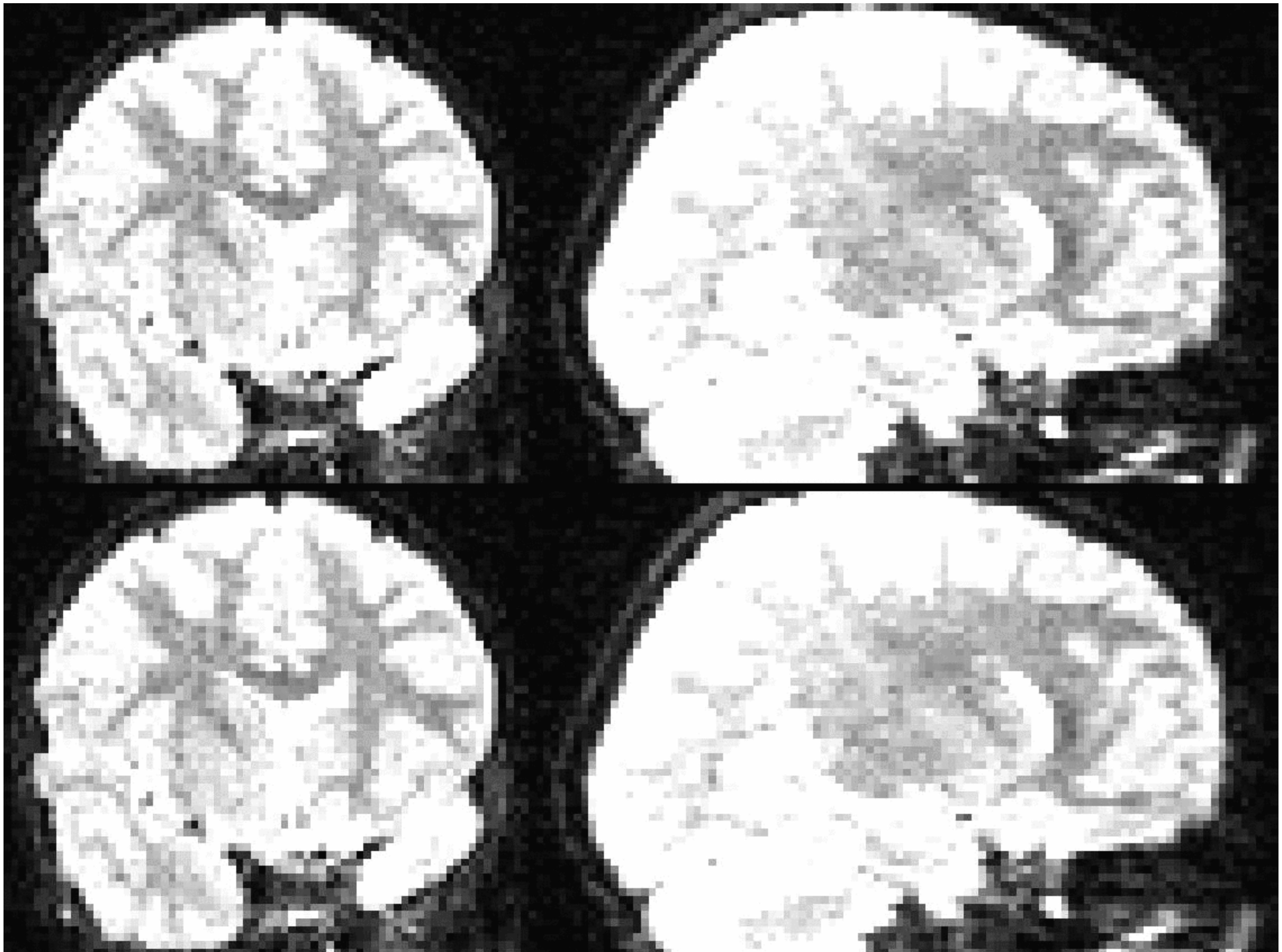


Outline of the talk

概况

- What is the problem with diffusion data?
- Off-resonance field
- Registering diffusion data
- Practicalities
- Some results
- New eddy features
  - Movement-induced dropout 运动引起的异常
  - Intra-volume motion

Norwegian data. 32 directions.
Hundreds of children. 挪威数据 32个方向 数百名儿童



Eight year old who gets tired towards the end of scanning
八岁的孩子在扫描结束时感到疲倦

After outlier detection and replacement by eddy
经过异常检测并由边缘值替换

Outline of the talk

概况

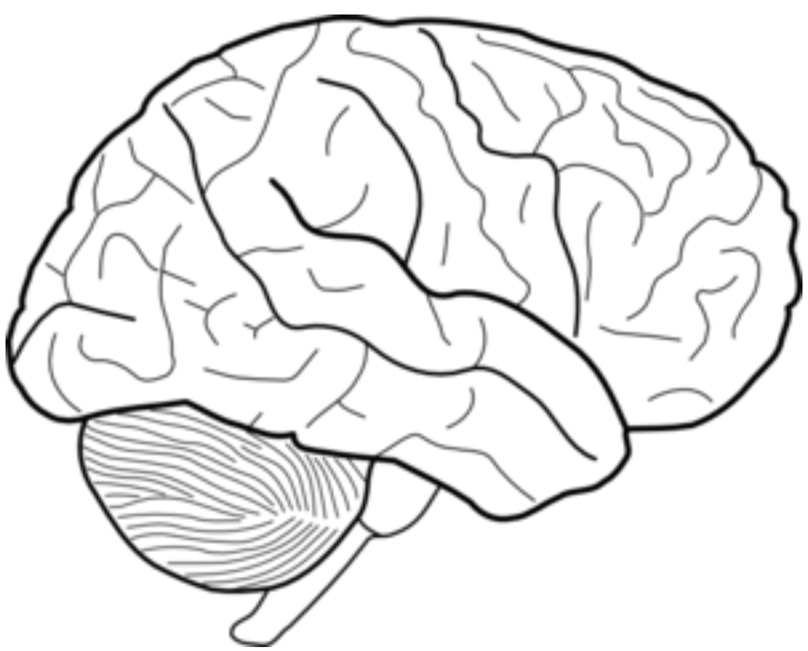
- What is the problem with diffusion data?
- Off-resonance field
- Registering diffusion data
- Practicalities
- Some results
- New eddy features
    - Movement-induced dropout
    - Intra-volume motion 图像间运动

Intra-volume movement

图像间运动

One of the (possibly naive) assumptions of most movement correction is that any movement is instantaneous and occurs between the acquisition of consecutive volumes.

大多数运动校正的（可能是天真的）假设之一是任何运动都是瞬时的并且发生在连续每帧图像的获取之间。



This is the brain we set out to image

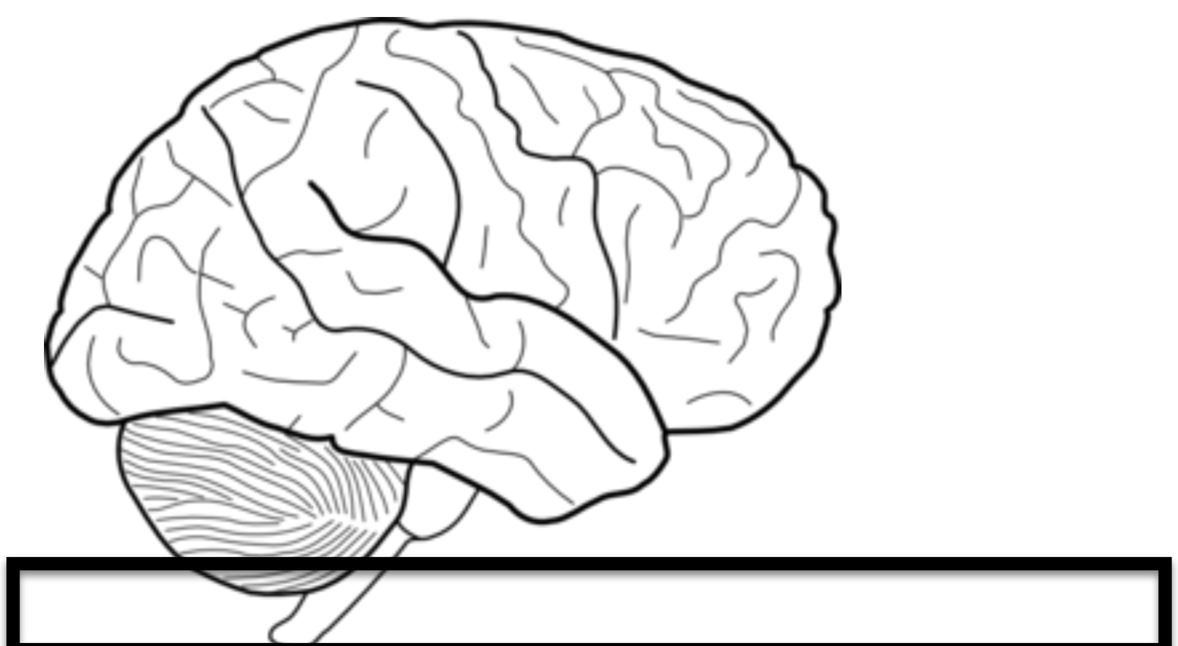
这是我们即将开始扫描的大脑

Intra-volume movement

图像间运动

One of the (possibly naive) assumptions of most movement correction is that any movement is instantaneous and occurs between the acquisition of consecutive volumes.

大多数运动校正的（可能是天真的）假设之一是任何运动都是瞬时的并且发生在连续每帧图像的获取之间。



This is the brain we set out to image

这是我们即将开始扫描的大脑

这是我们获得的第一层

And here we have acquired the first slice

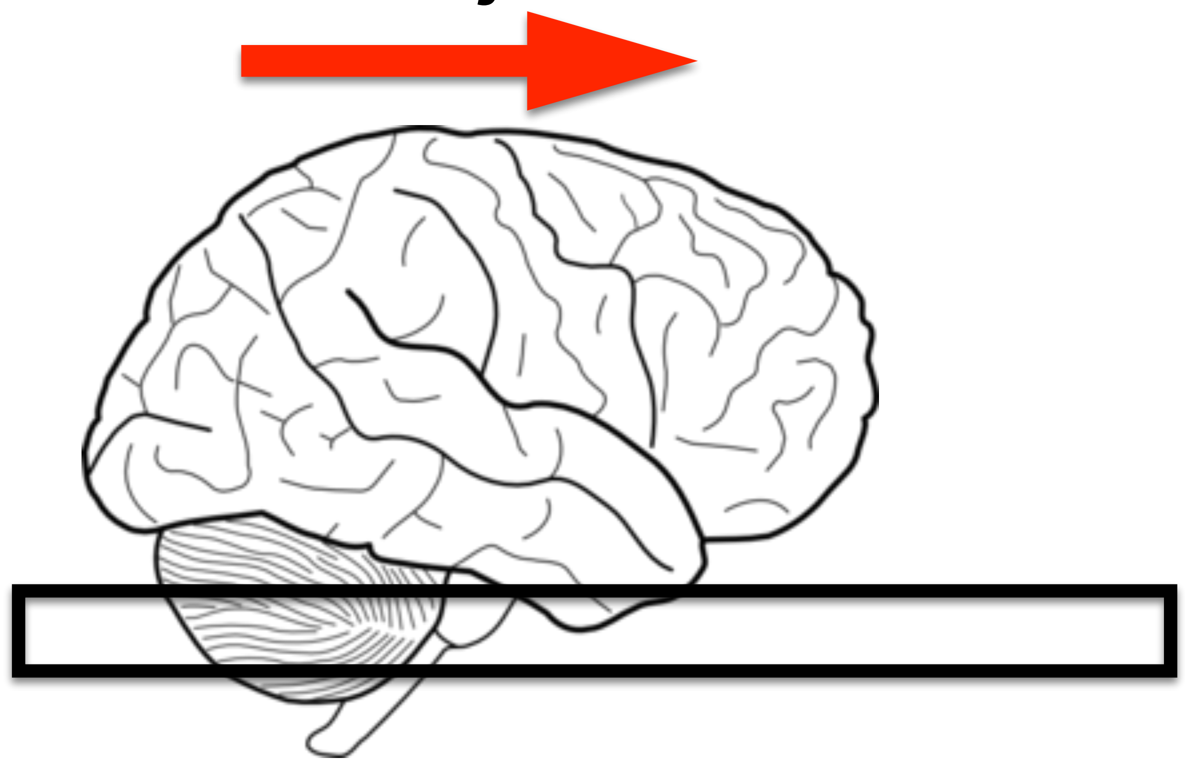
Intra-volume movement

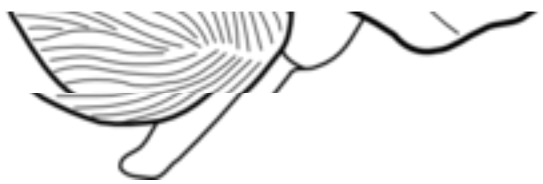
图像间运动

One of the (possibly naive) assumptions of most movement correction is that any movement is instantaneous and occurs between the acquisition of consecutive volumes.

大多数运动校正的（可能是天真的）假设之一是任何运动都是瞬时的并且发生在连续每帧图像的获取之间。

But the subject moves 但是被试在移动





所以大脑在第二层中被抵消了

This is the brain we set out to image

这是我们即将开始扫描的大脑

So the brain is offset in the second slice

Intra-volume movement

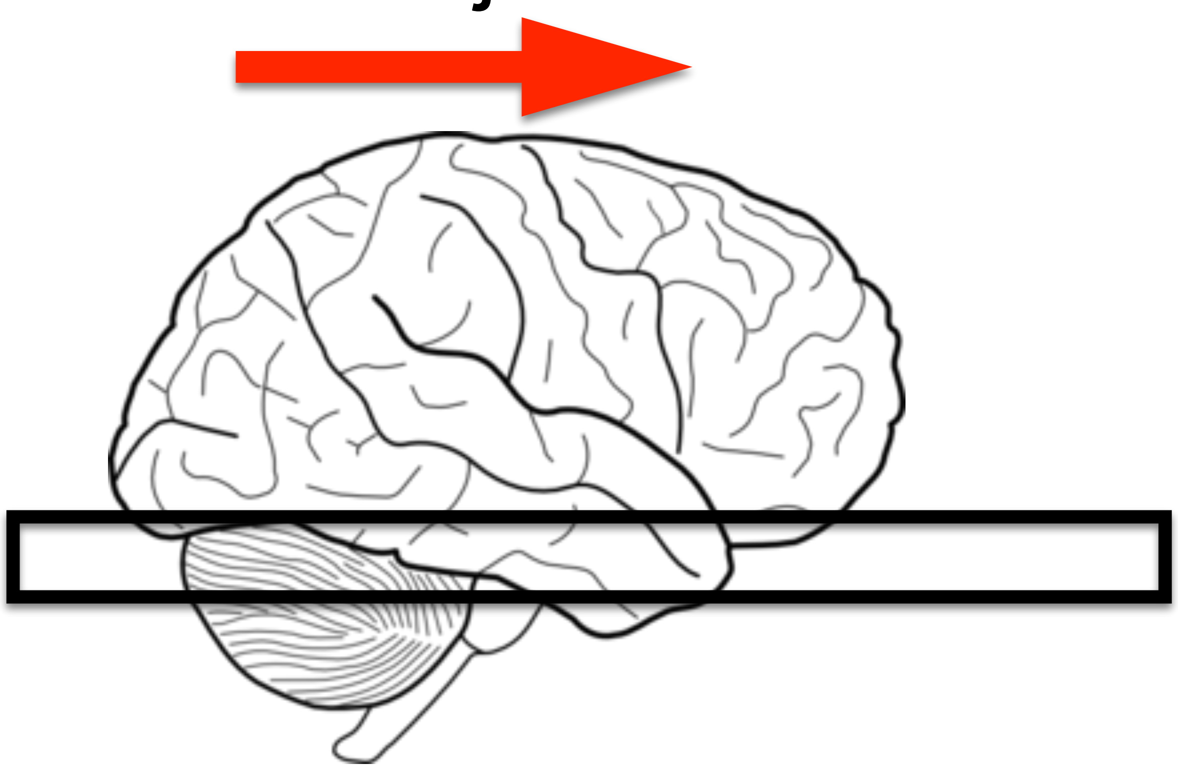
图像间运动

One of the (possibly naive) assumptions of most movement correction is that any movement is instantaneous and occurs between the acquisition of consecutive volumes.

大多数运动校正的（可能是天真的）假设之一是任何运动都是瞬时的并且发生在连续每帧图像的获取之间。

But the subject moves

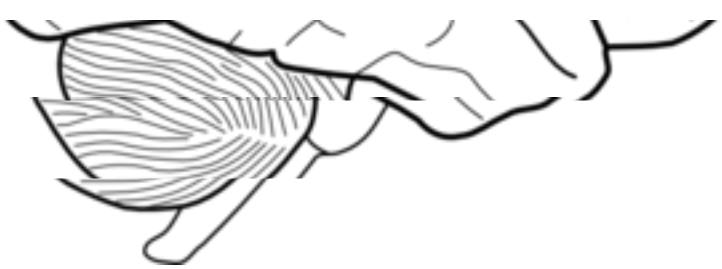
但是被试在移动



This is the brain we set out to image

这是我们即将开始扫描的大脑

在第三层中更加明显



And even more so in the third slice

Intra-volume movement

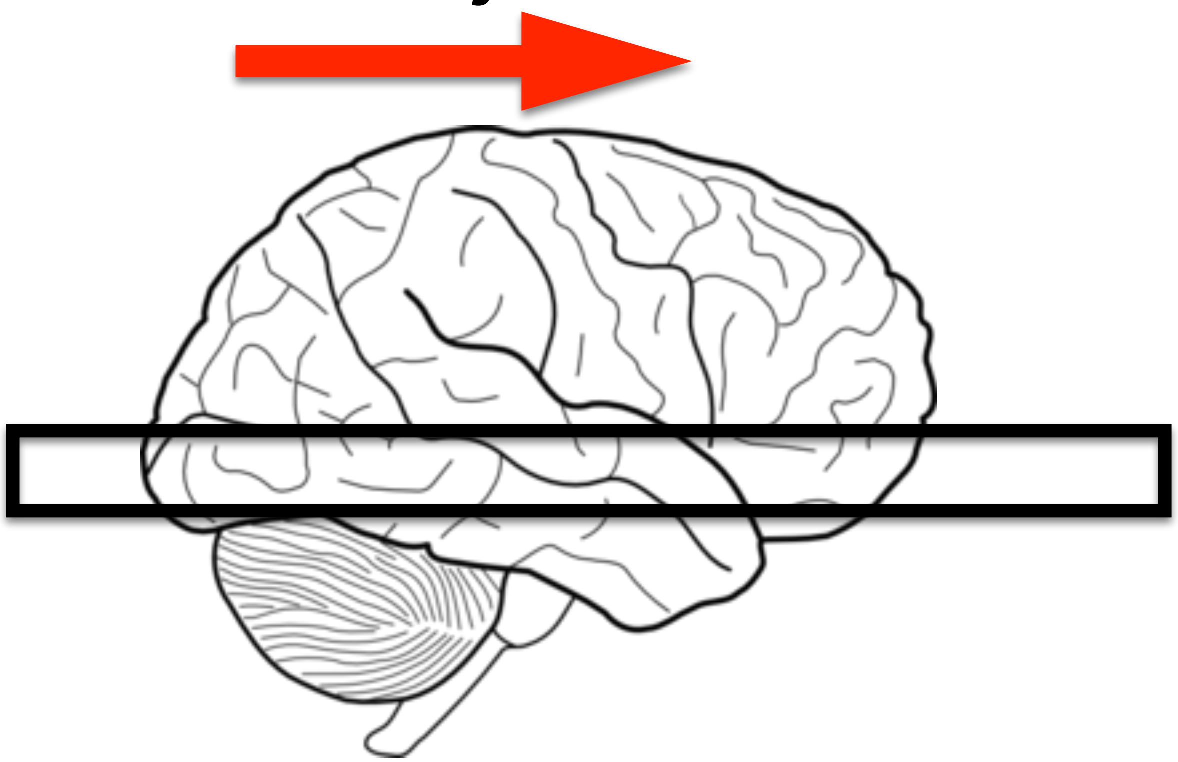
图像间运动

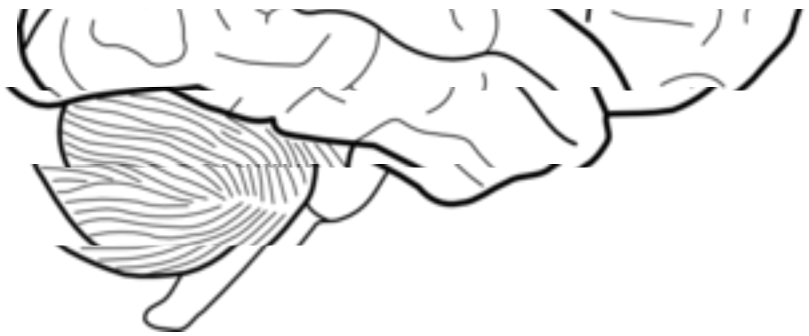
One of the (possibly naive) assumptions of most movement correction is that any movement is instantaneous and occurs between the acquisition of consecutive volumes.

大多数运动校正的（可能是天真的）假设之一是任何运动都是瞬时的并且发生在连续每帧图像的获取之间。

But the subject moves

但是被试在移动





This is the brain we set out to image

这是我们即将开始扫描的大脑

And more …

更多

Intra-volume movement

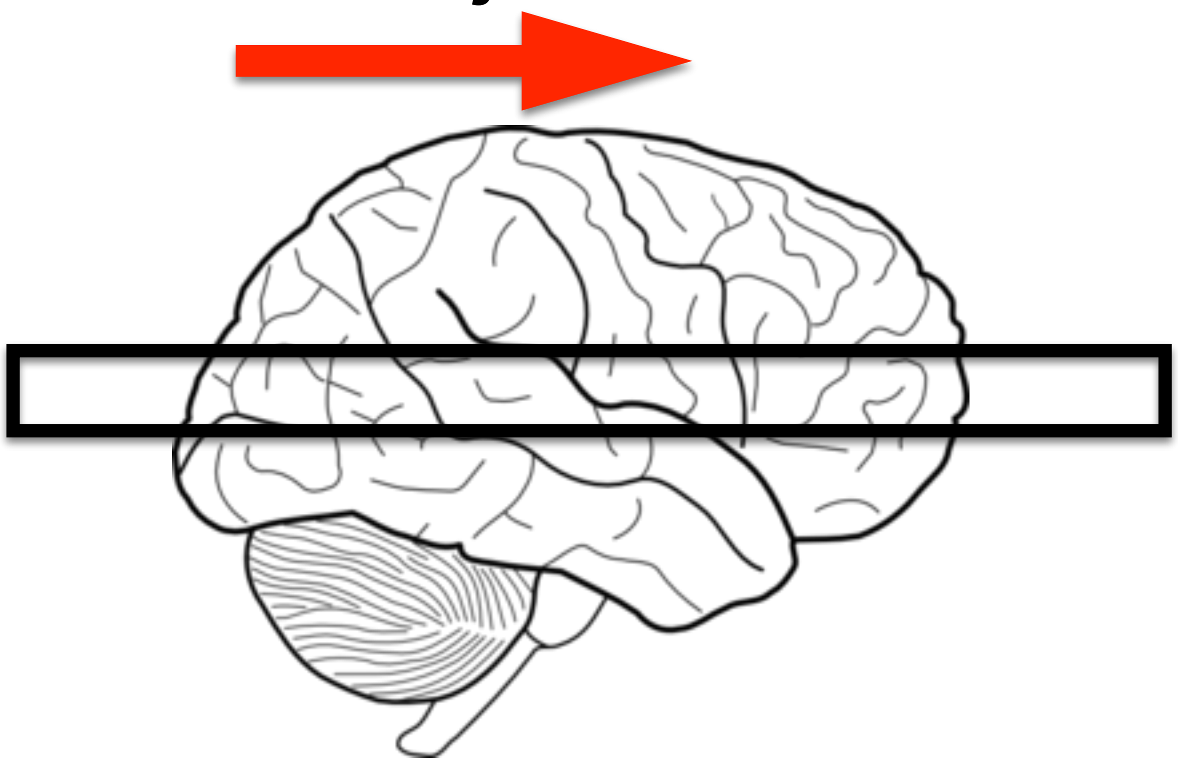
图像间运动

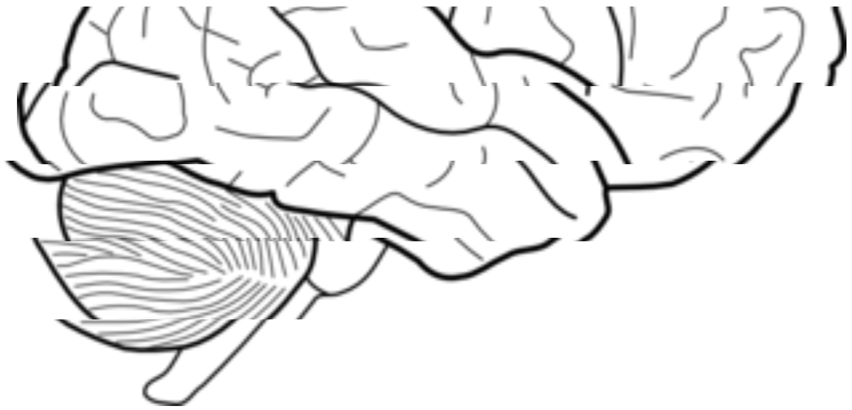
One of the (possibly naive) assumptions of most movement correction is that any movement is instantaneous and occurs between the acquisition of consecutive volumes.

大多数运动校正的（可能是天真的）假设之一是任何运动都是瞬时的并且发生在连续每帧图像的获取之间。

But the subject moves

但是被试在移动





This is the brain we set out to image

这是我们即将开始扫描的大脑

… and more …

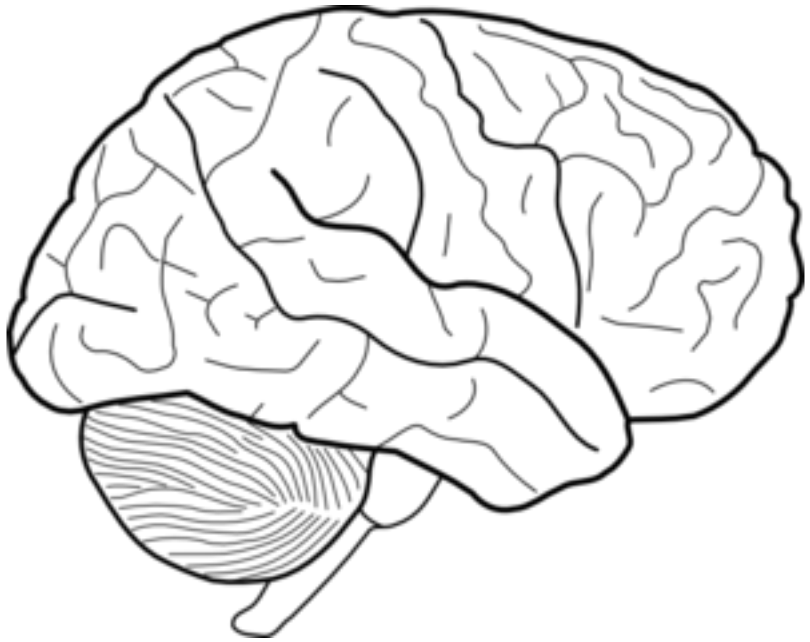
更多

Intra-volume movement

图像间运动

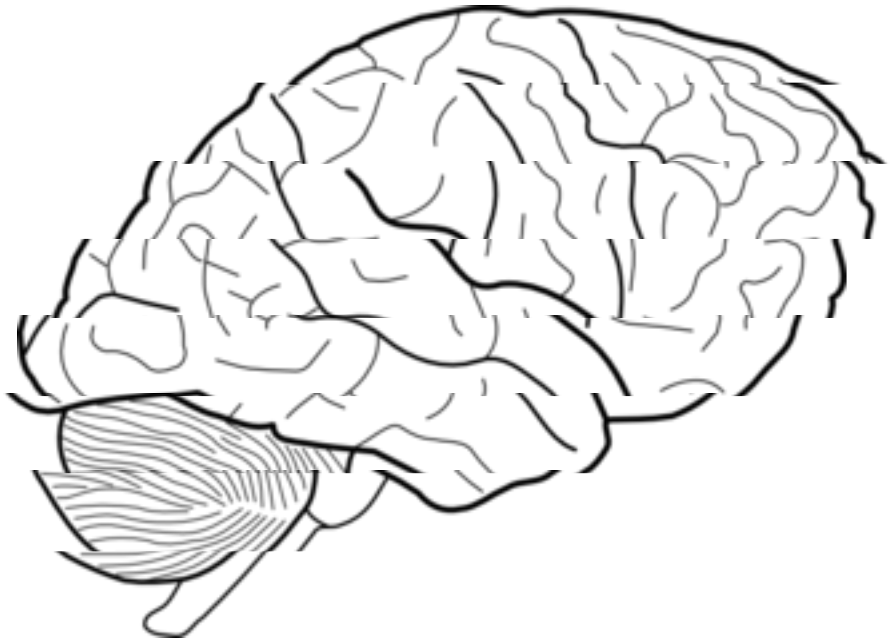
One of the (possibly naive) assumptions of most movement correction is that any movement is instantaneous and occurs between the acquisition of consecutive volumes.

大多数运动校正的（可能是天真的）假设之一是任何运动都是瞬时的并且发生在连续每帧图像的获取之间。



This is the brain we set out to image

这是我们即将开始扫描的大脑

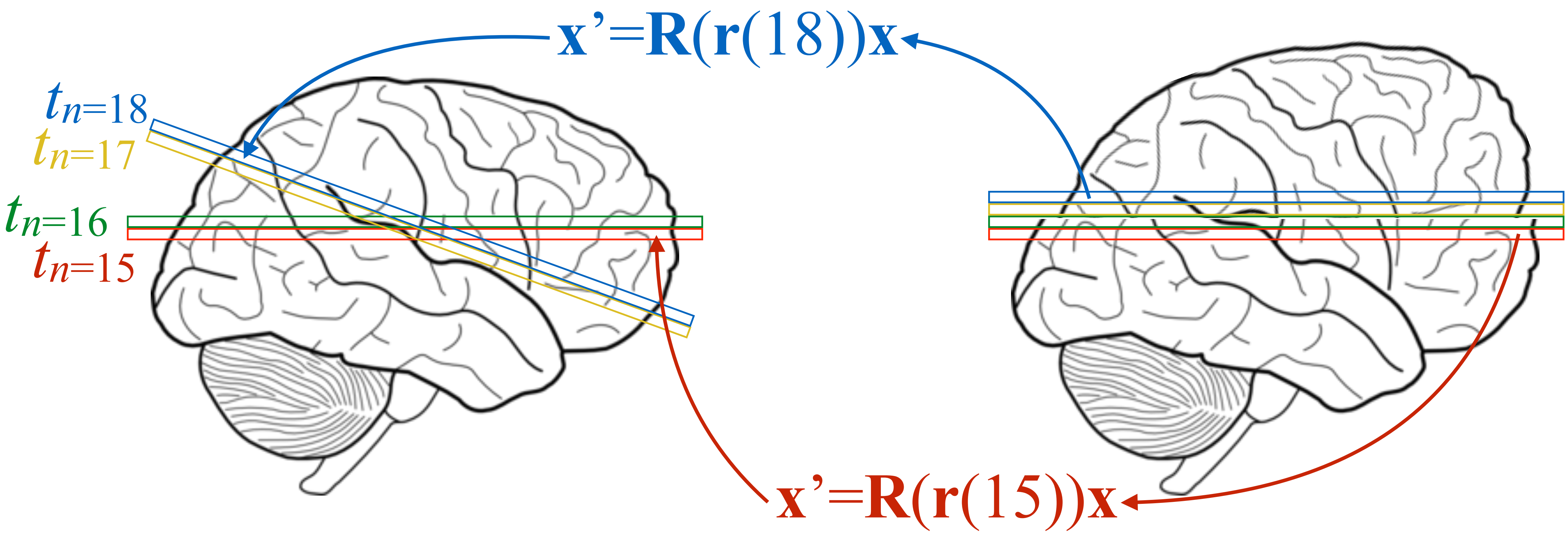


etc.

Intra-volume movement

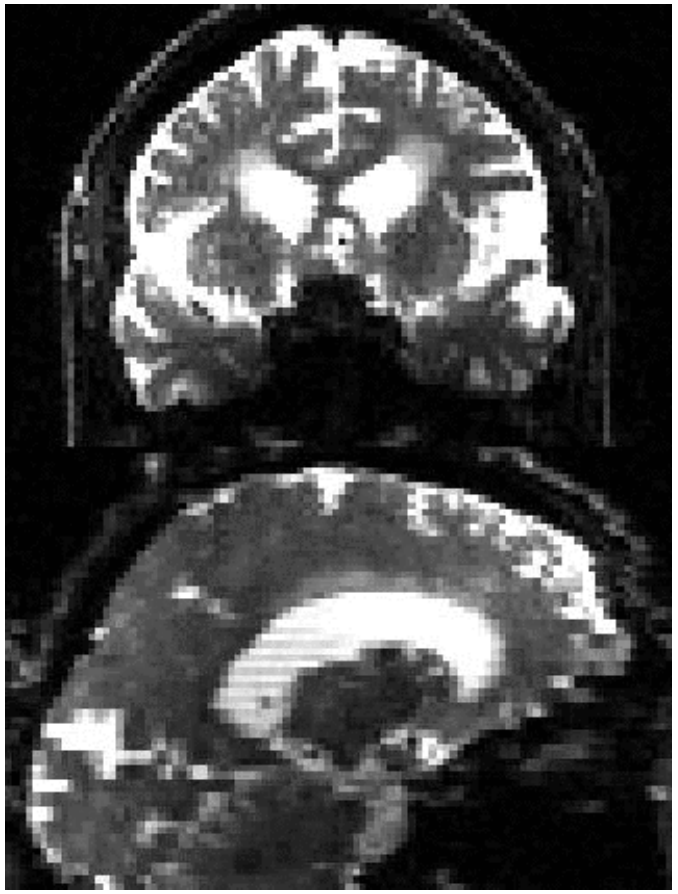
图像间运动

- This is known as the “slice-to-vol” problem or the “intra-volume movement” problem.
  这被称为“层到”问题或“体积内运动”问题
- The new version of `eddy` addresses this problem. 新版本的eddy解决了这个问题
- It estimates the slice wise movement through the same Gaussian Process based forward model.
- 它通过相同的基于高斯过程的正演模型估计切片运动



Intra-volume movement

图像间运动



Original data

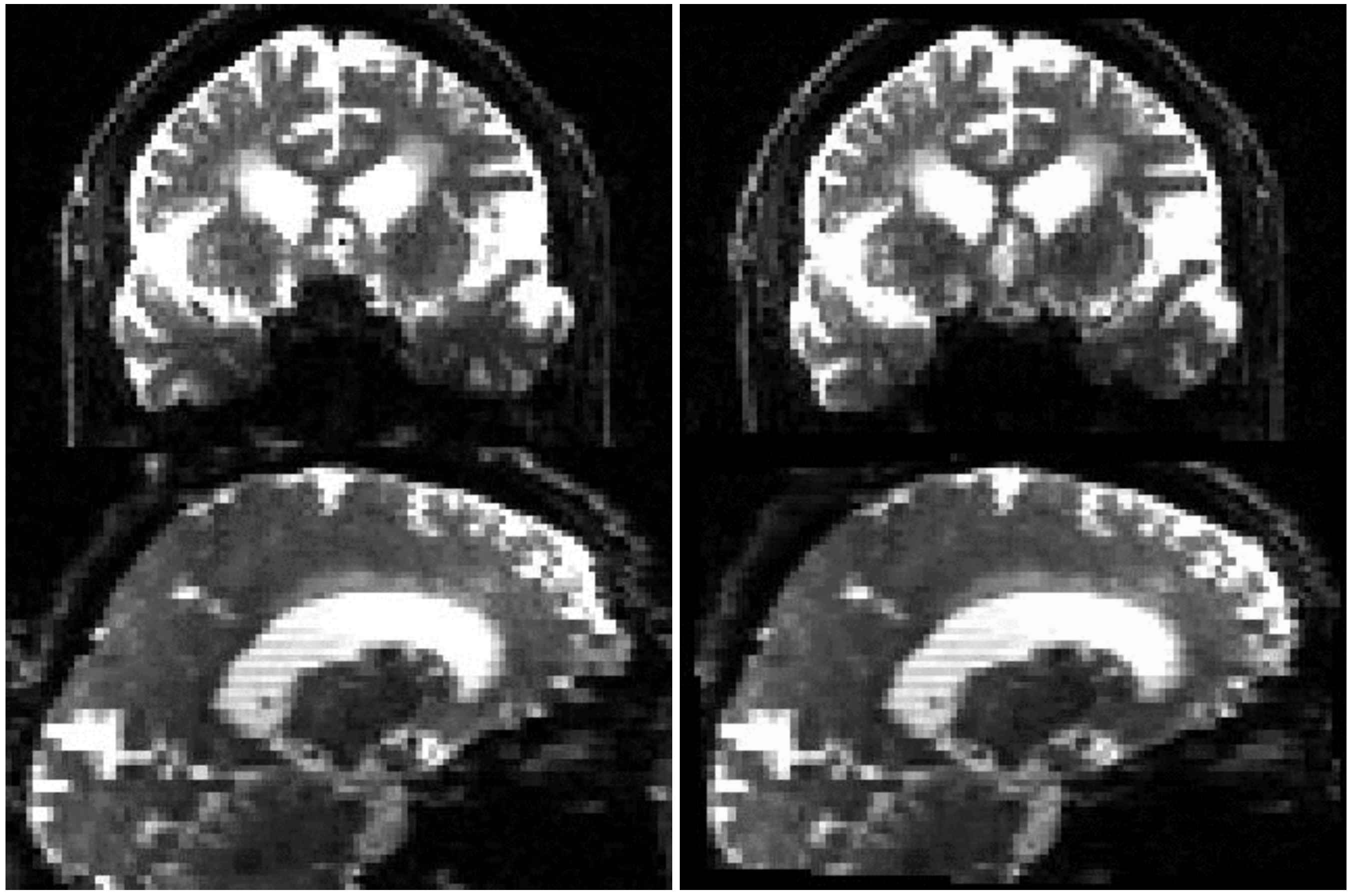
原始数据

Problematic elderly subject. Lots of movement induced signal loss and intravolume movement

有问题的老年人。 大量运动引起信号丢失和图像间运动

Intra-volume movement

图像间运动



Original data

After correction without outlier correction

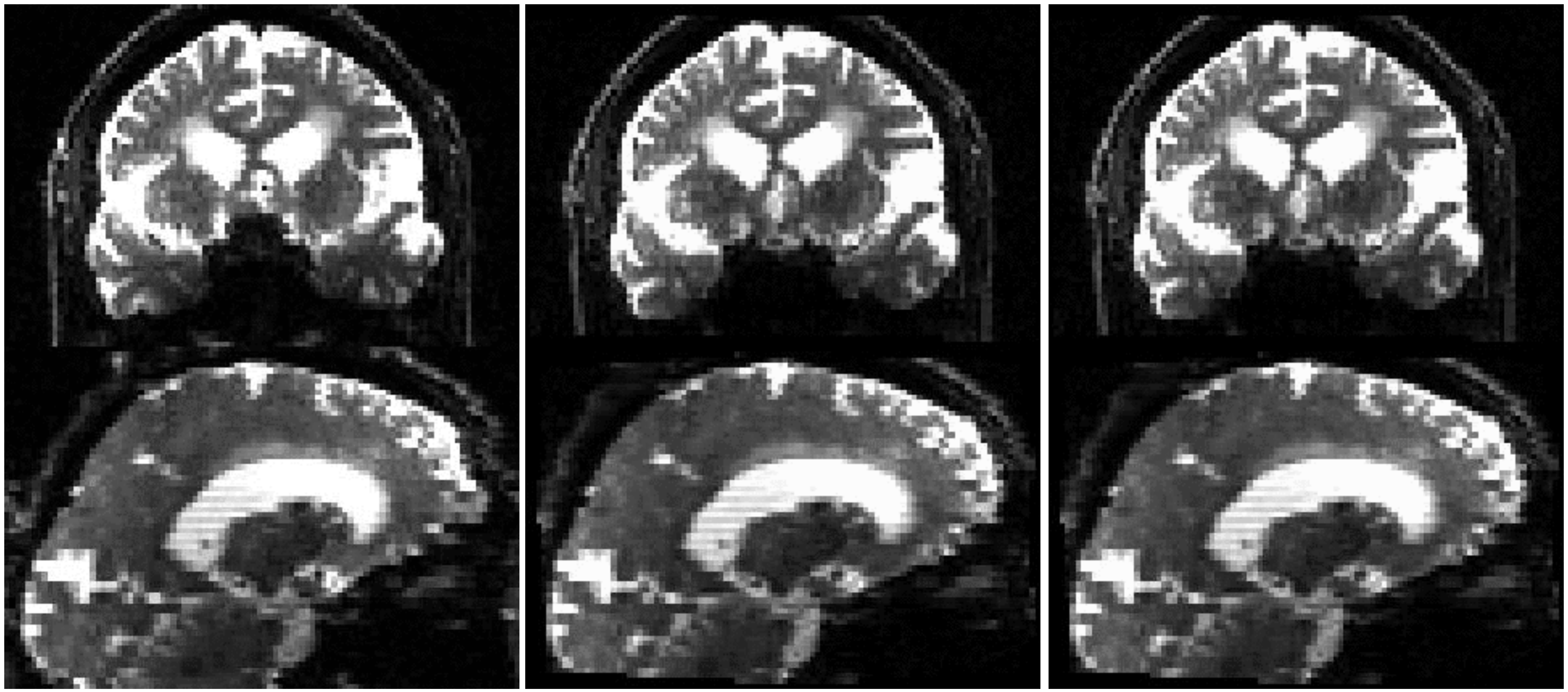
异常值校正后

Problematic elderly subject. Lots of movement induced signal loss and intravolume movement

有问题的老年人。 大量运动引起信号丢失和图像间运动

Intra-volume movement

图像间运动



Original data

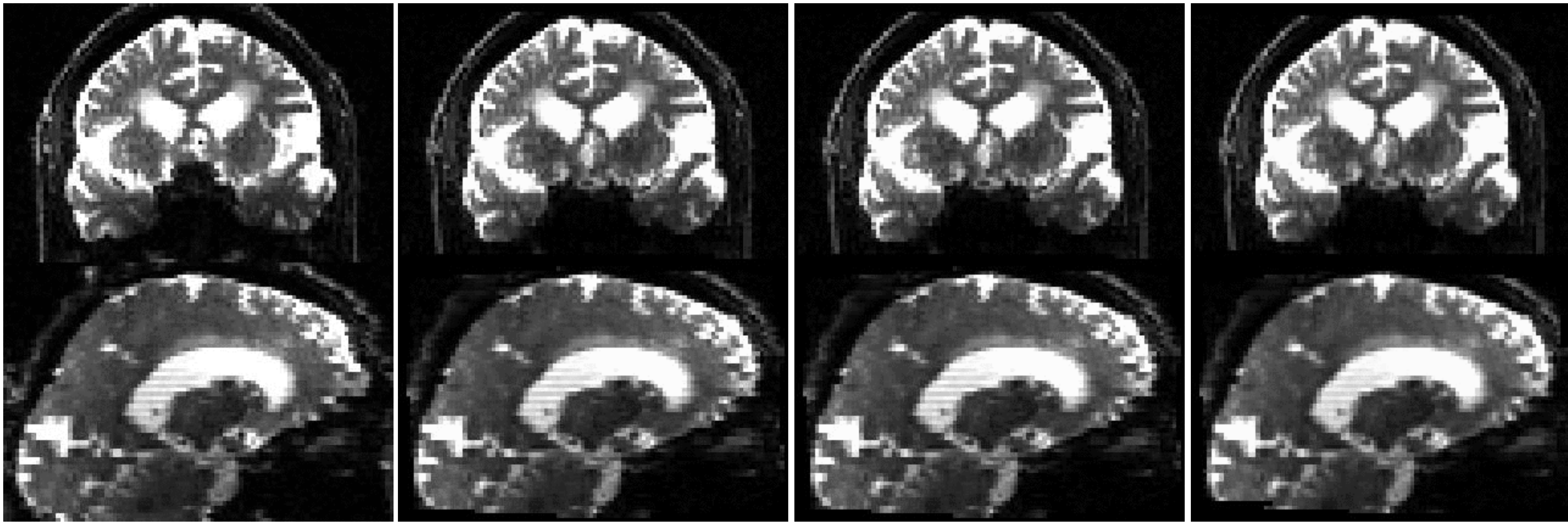
After correction without outlier correction

After correction with outlier replacement
用异常值替换校正后

Problematic elderly subject. Lots of movement induced signal loss and intravolume movement
有问题的老年人。 大量运动引起信号丢失和图像间运动

Intra-volume movement

图像间运动



Original data
原始数据

After correction without outlier correction

After correction with outlier replacement

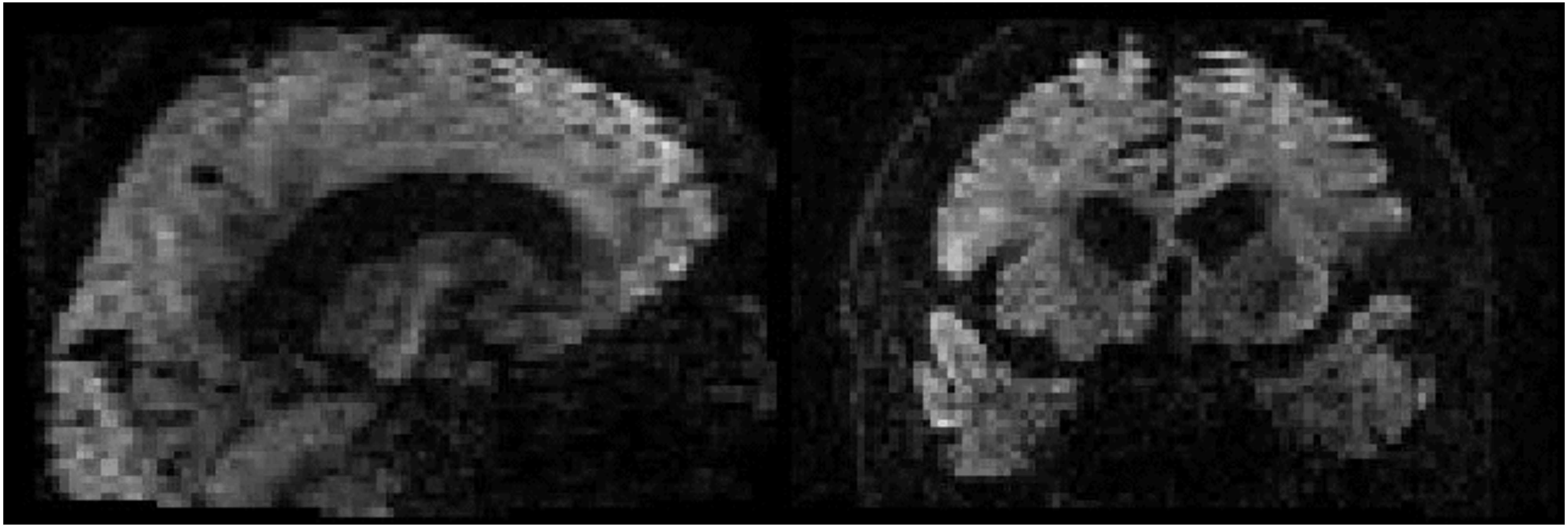
After intravolume movement correction.
经过图像间运动校正

Problematic elderly subject. Lots of movement induced signal loss and intravolume movement

有问题的老年人。 大量运动引起信号丢失和图像间运动

Intra-volume movement

图像间运动



Highlighting the difference between just OLR and OLR combined with S2V correction

突出OLR和OLR之间的差异以及S2V校正

Problematic elderly subject. Lots of movement induced signal loss and intravolume movement

有问题的老年人。 大量运动引起信号丢失和图像间运动