“Diffuse”

A toolbox for diffusion data processing in BrainVISA

Alexandre PRON & Lucile BRUN (INT, SCALP & MeCA Teams)
Starring Julien SEIN (Centre IRM-INT@CERIMED)

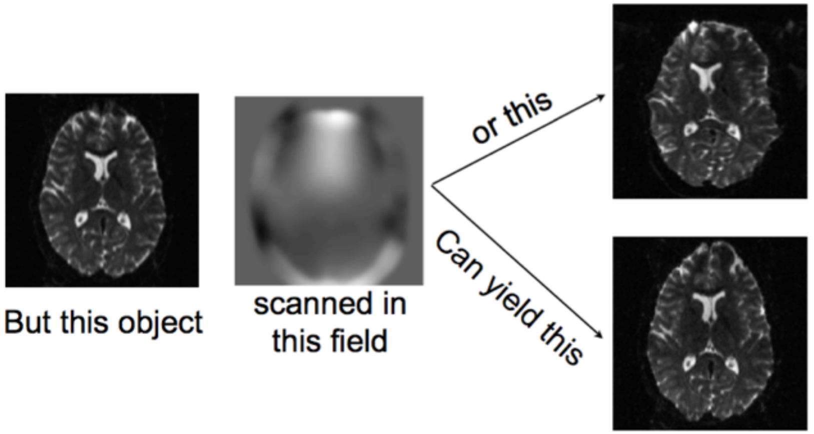
BrainVISA - Diffuse

- Introduction: dMRI data processing
  - Pre-processing
  - Post-processing: local models and tractography
- *Diffuse* toolbox
  - BrainVISA environment
  - Workflow
- Influence of pre-processing on post-processing analyses
  - Acquisition/Correction quality
  - Impact on co-registration
  - Impact on signal (diffusivity metrics)
- Outcome
  - Acquisition strategy
  - Centre IRM

BrainVISA - *Diffuse*

- Introduction: dMRI data processing
  - Pre-processing
  - Post-processing: local models and tractography
- *Diffuse* toolbox
  - BrainVISA environment
  - Workflow
  - Demo
- Influence of pre-processing on post-processing analyses
  - Acquisition/Correction quality
  - Impact on co-registration
  - Impact on signal (diffusivity metrics)
- Outcome
  - Acquisition strategy
  - CentreIRM

Geometric distortions



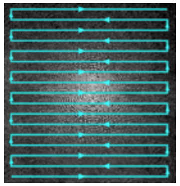
Andersson, HCP course, Boston 2016

"off-resonance field"

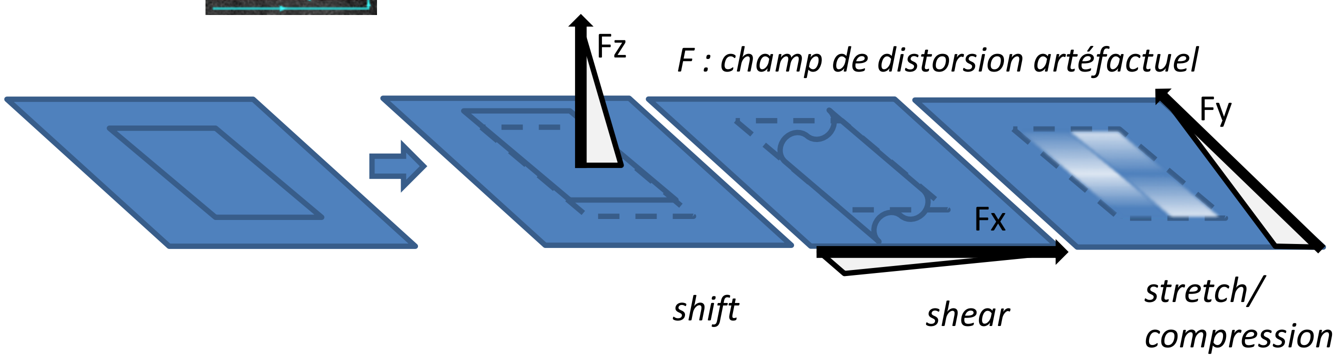
Two origins

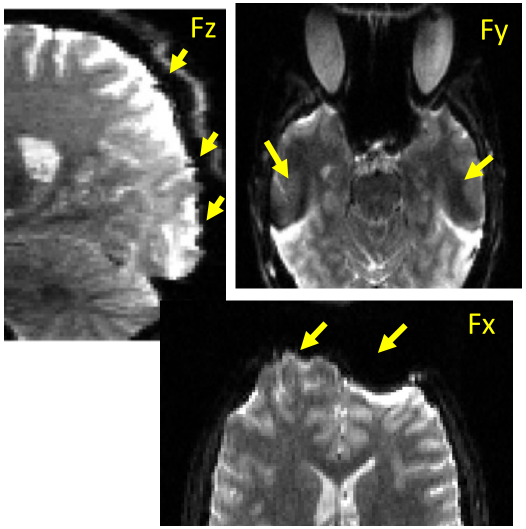
- **Susceptibility** differences between tissus
- Diffusion gradients: **Eddy currents** induced in gradient coils

+ EPI



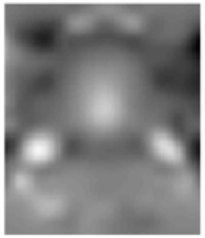
= **Distorsions in the pase encoding direction** (low Bdw)





Geometric distortions

Susceptibility



Stationary
(Linked to one head)

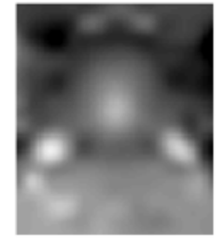
+

Eddy currents

+ motions
Change for every volume

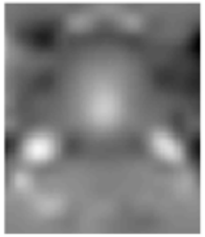
=

Total



Geometric distortions

Susceptibility



Stationary
(Linked to one head)

+

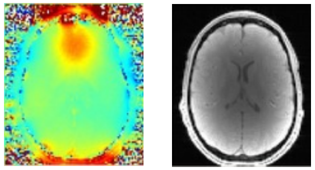
Eddy currents

+ motions
Change for every volume

=

Total

- **Mesure : fieldmap**

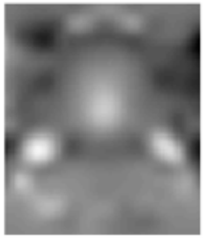


- Estimation : *FSL-topup*

- Linear estimation: affine registration of volumes
- Non-Linear estimation: *FSL-eddy*

Geometric distortions

Susceptibility



Stationary
(Linked to one head)

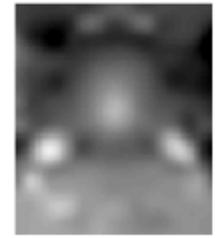
+

Eddy currents

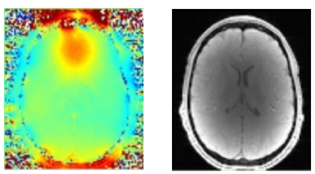
+ mouvements
Change for every volume

=

Total

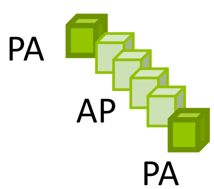


- Mesure : fieldmap



- **Estimation : *FSL-topup***

b=0
volumes



- Linear estimation: affine registration of volumes
- Non-Linear estimation: *FSL-eddy*

Geometric distortions

Susceptibility

Stationary
(Linked to one head)

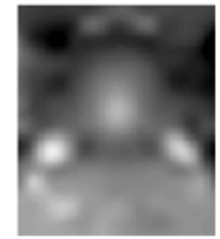
\+

Eddy currents

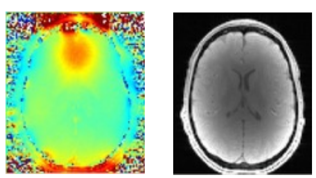
+ mouvements
Change for every volume

=

Total

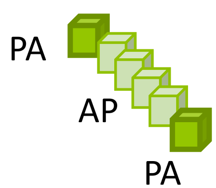


- Mesure : fieldmap

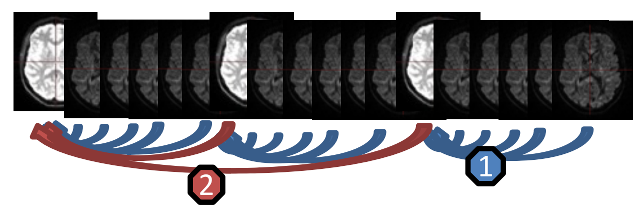


- Estimation : *FSL-topup*

b=0
volumes



- Linear estimation: affine registration of volumes



- Non-Linear estimation: *FSL-eddy*

Geometric distortions

Susceptibility

Constant
(propre au patient)

+

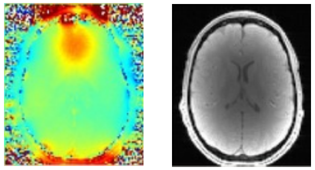
Eddy currents

+ mouvements
Volume - dépendant

=

Total

- Mesure : fieldmap

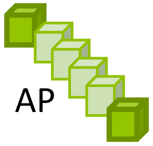


- Estimation : *FSL-topup*

Reversed
b=0 volumes

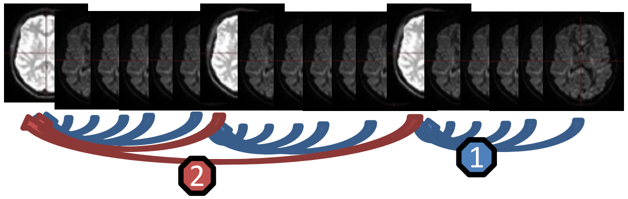
PA

AP



PA

- Linear estimation: affine registration of volumes

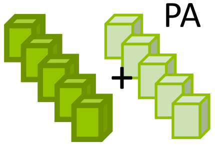


- Non-Linear estimation: *FSL-eddy*

++ high gradients
N > 60 & sampling
on the sphere

or

AP



PA

BrainVISA - *Diffuse*

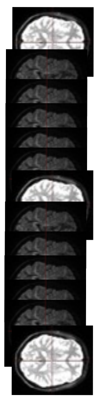
- Introduction: dMRI data processing
  - Pre-processing
  - Post-processing : local models and tractography
- *Diffuse* toolbox
  - BrainVISA environment
  - Workflow
  - Demo
- Influence of pre-processing on post-processing analyses
  - Acquisition/Correction quality
  - Impact on co-registration
  - Impact on signal (diffusivity metrics)
- Outcome
  - Acquisition strategy
  - CentreIRM

Modeling dMRI signal at voxel level

dMRI acquisition

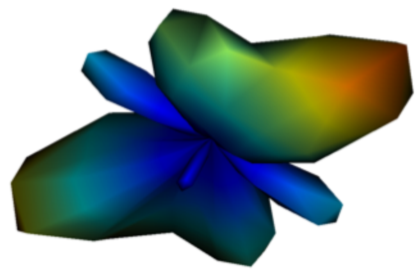
diffusion in complex media

dMRI signal

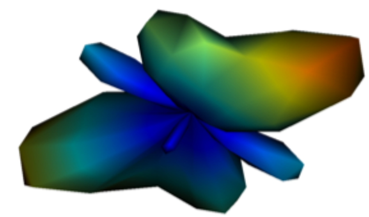


Diffusion Process

d**ODF**



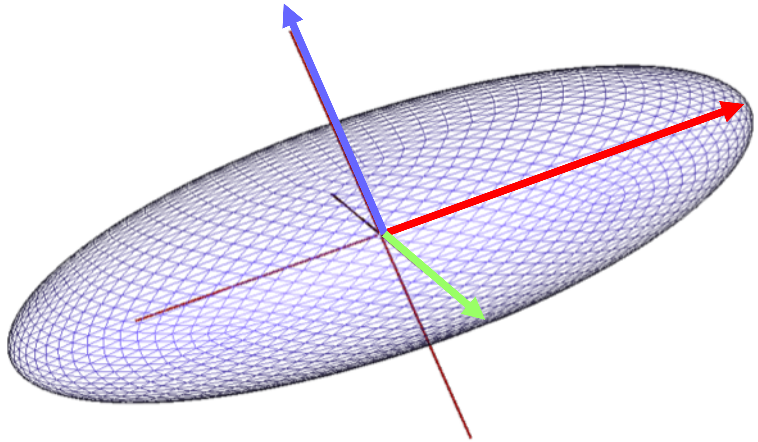
White matter FOD/fODF

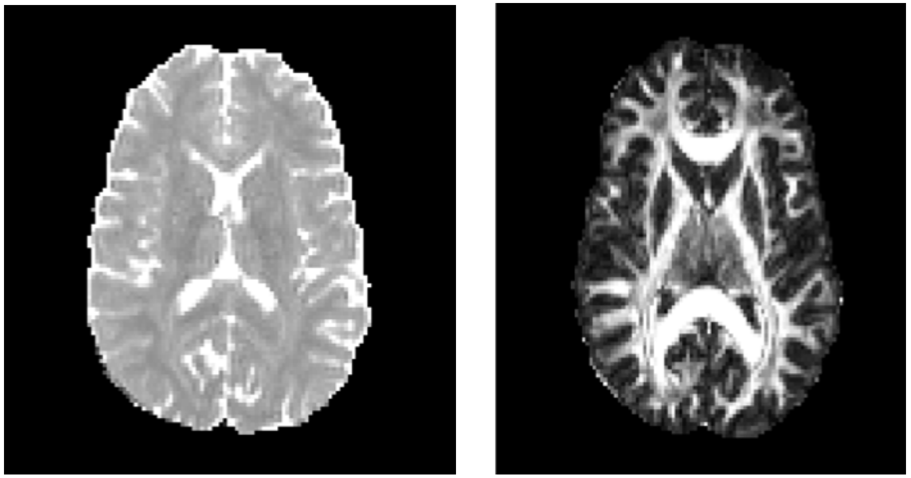


ODF: Orientation Distribution Function. Angular distribution of quantity of interest (on a sphere for diffusion).
dODF: diffusion ODF
FOD: Fiber Orientation Distribution = fiber ODF

Diffusion Tensor model

- **Signal in the voxel is assumed to derive from 3D non degenerated gaussian**



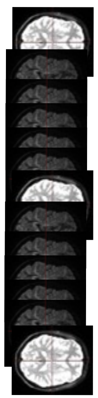


Modeling dMRI signal at voxel level

dMRI acquisition

diffusion in complex media

dMRI signal



Fourier Transform

Diffusion Process

→ d**ODF**

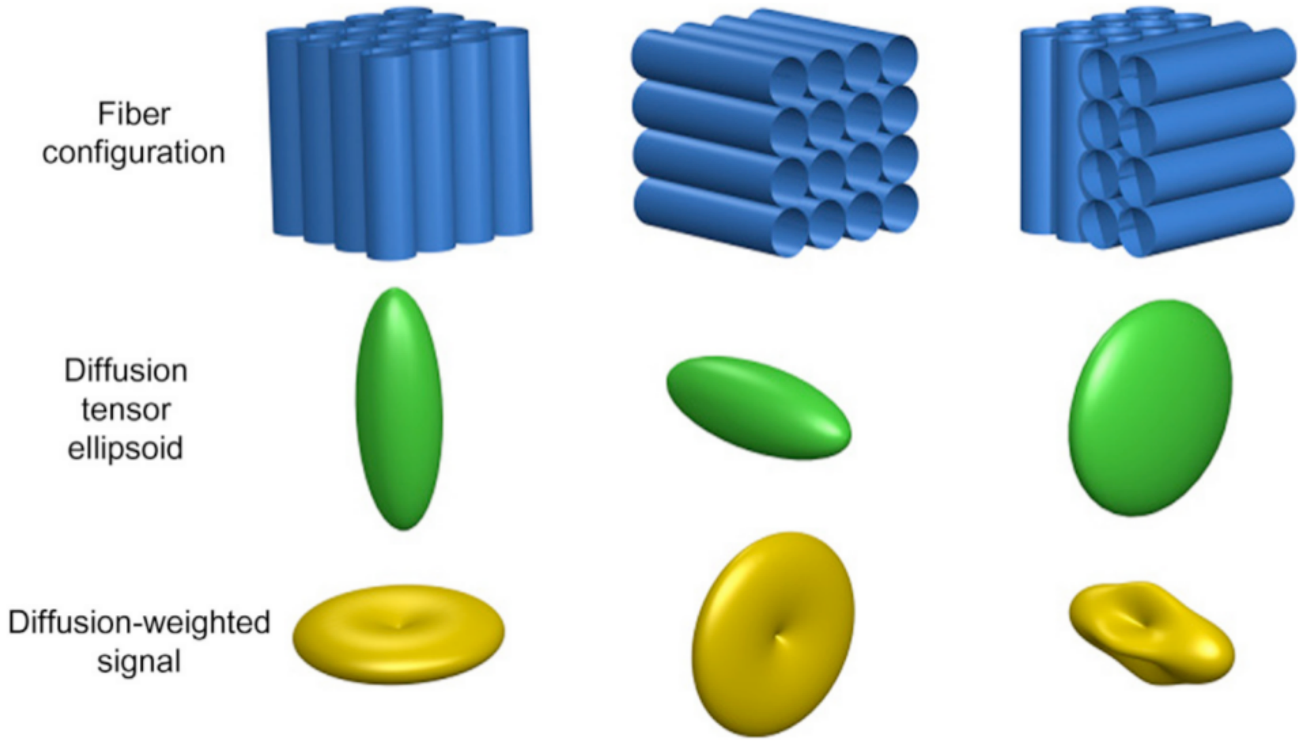
White matter

* macroscopical geometry (fibers)
* microstructure

→ **FOD/fODF**

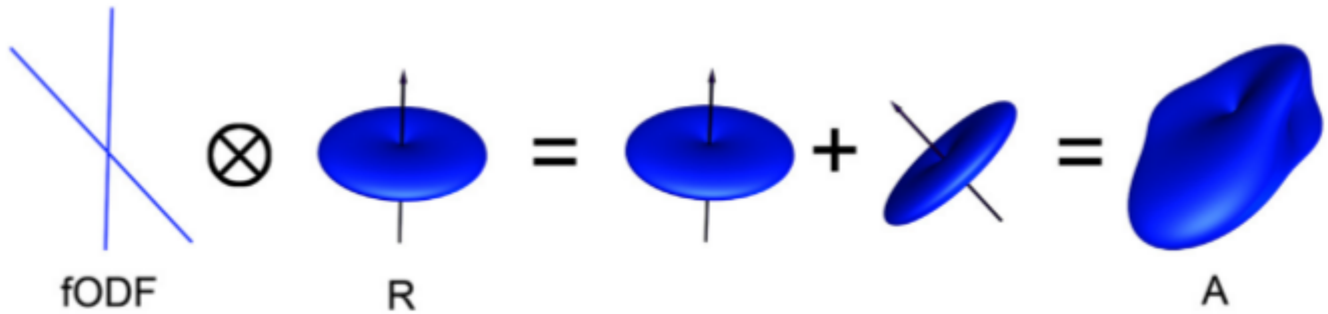
Modeling dMRI signal at voxel level

- **Signal in the voxel is a mixture of fiber with identical signal (impulsionnal response)**



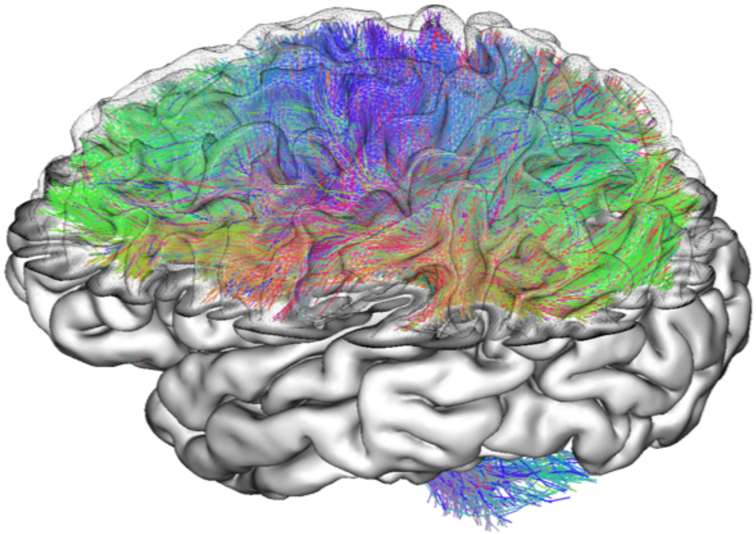
Constrained Spherical Deconvolution

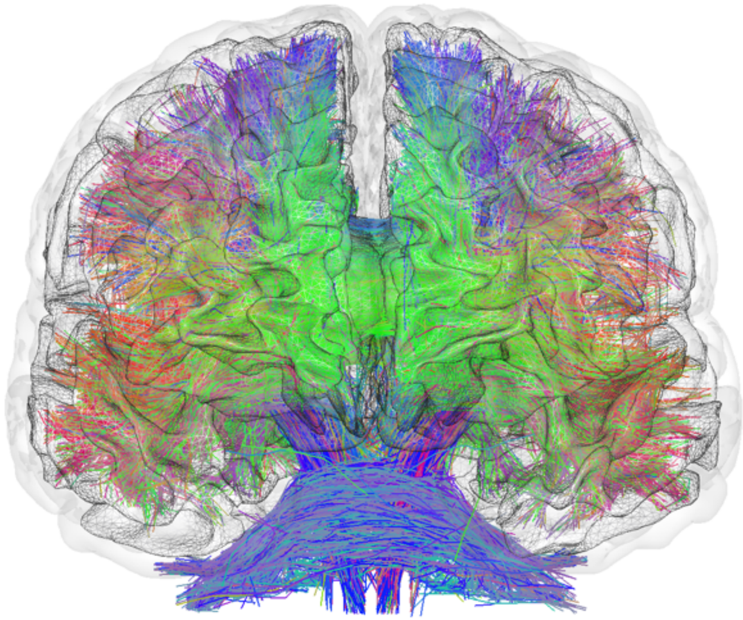
- **Signal in the voxel is a mixture of fiber with identical signal (impulsionnal response)**



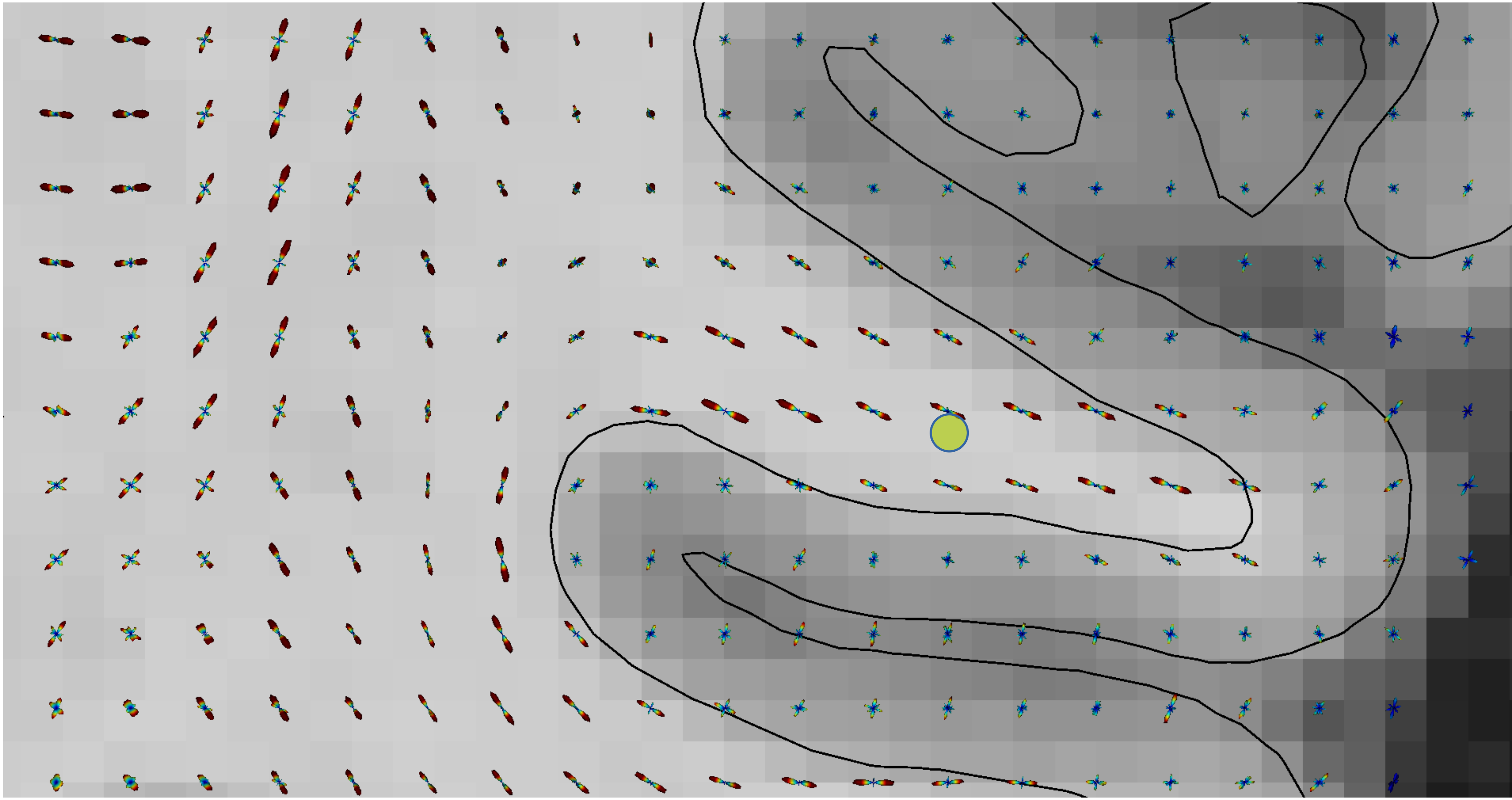
- Impulsionnal response is estimated from « single fiber voxels » [Tax, Tournier]
- Spherical deconvolution in the Fourier domain is an ill posed problem and must be regularized [Tournier, Cheng] to avoid negative signal values, e.g. regularization sphere

Tractography : from local to global

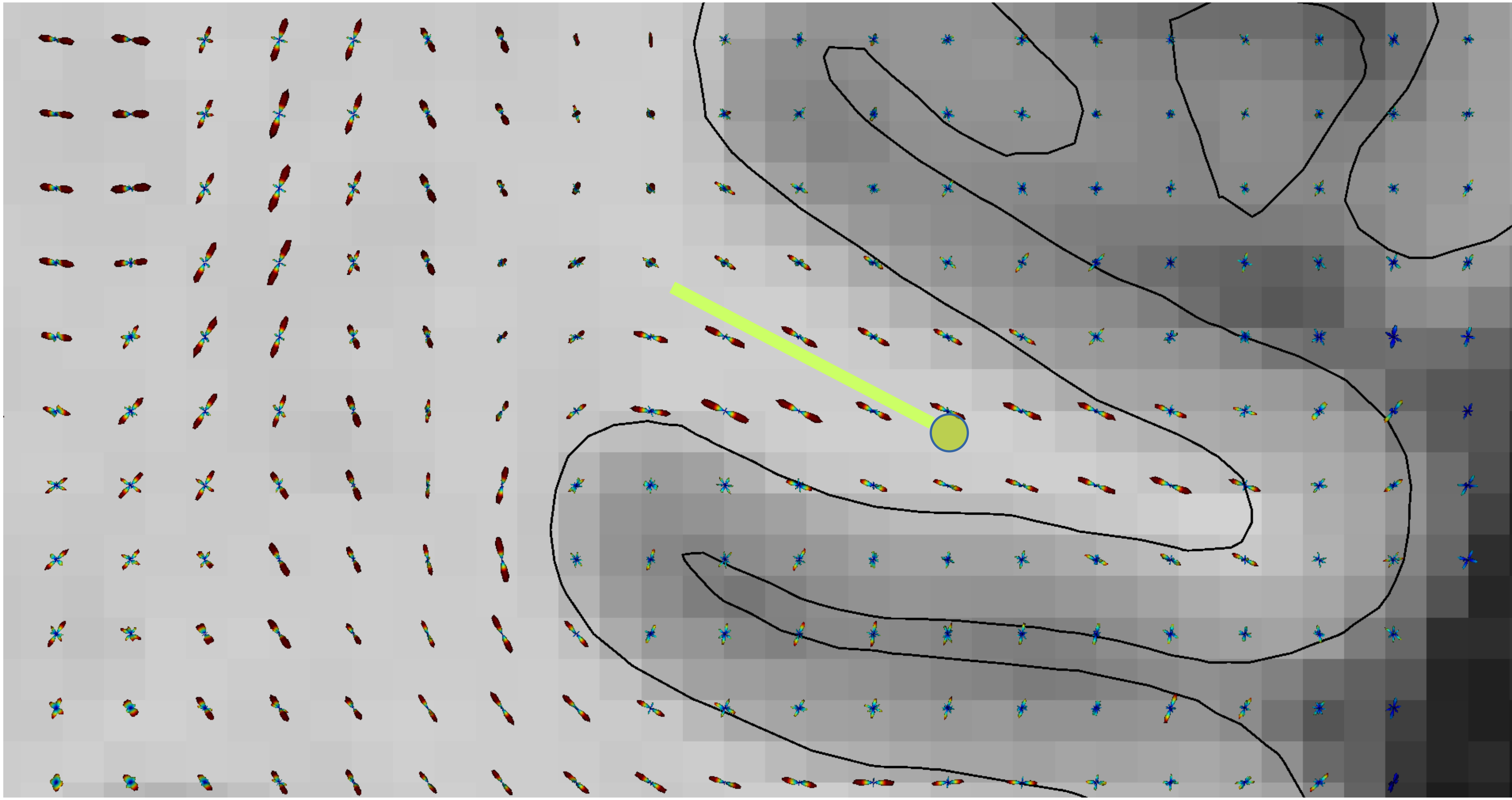




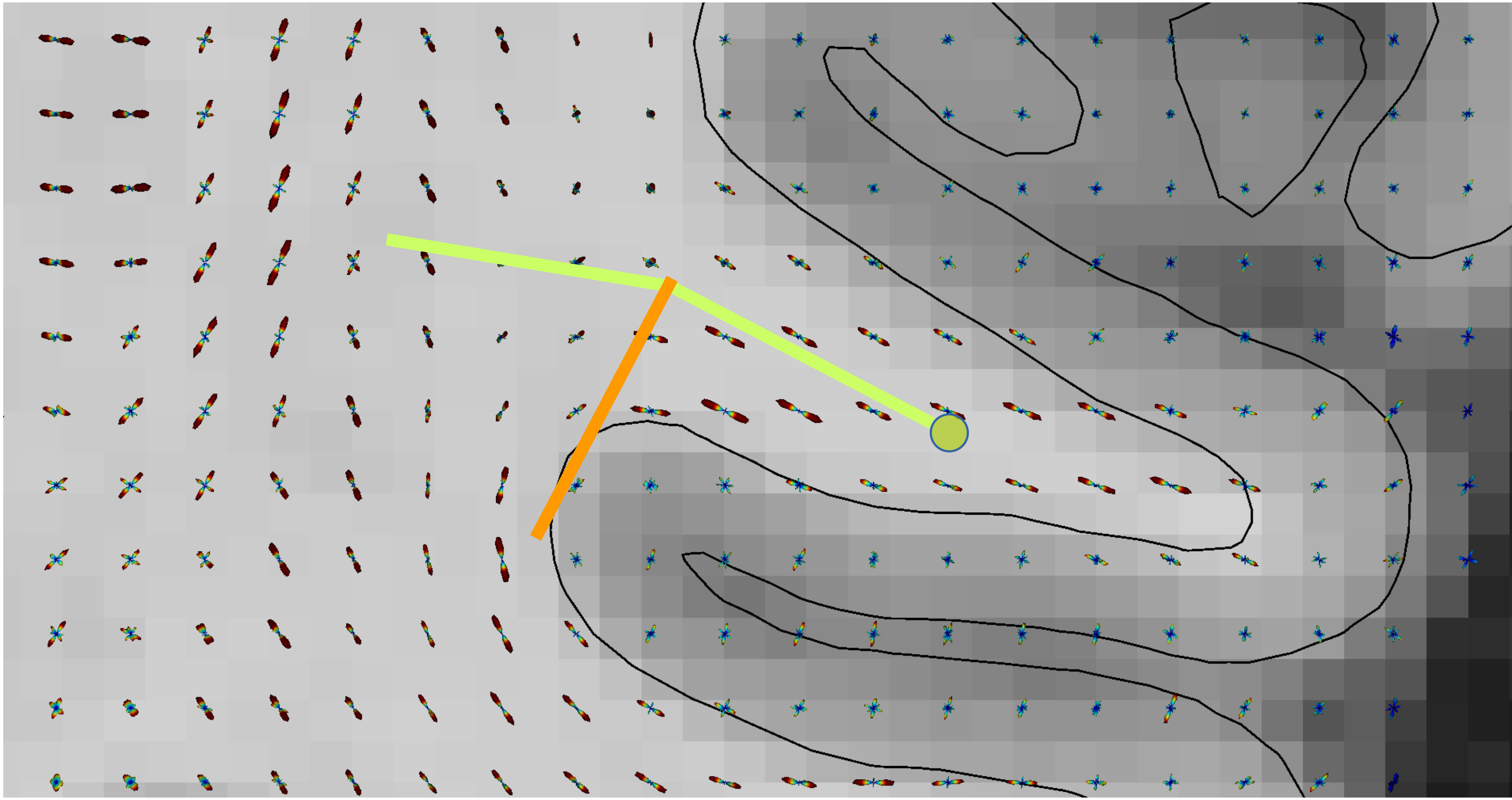
Tractography : principle



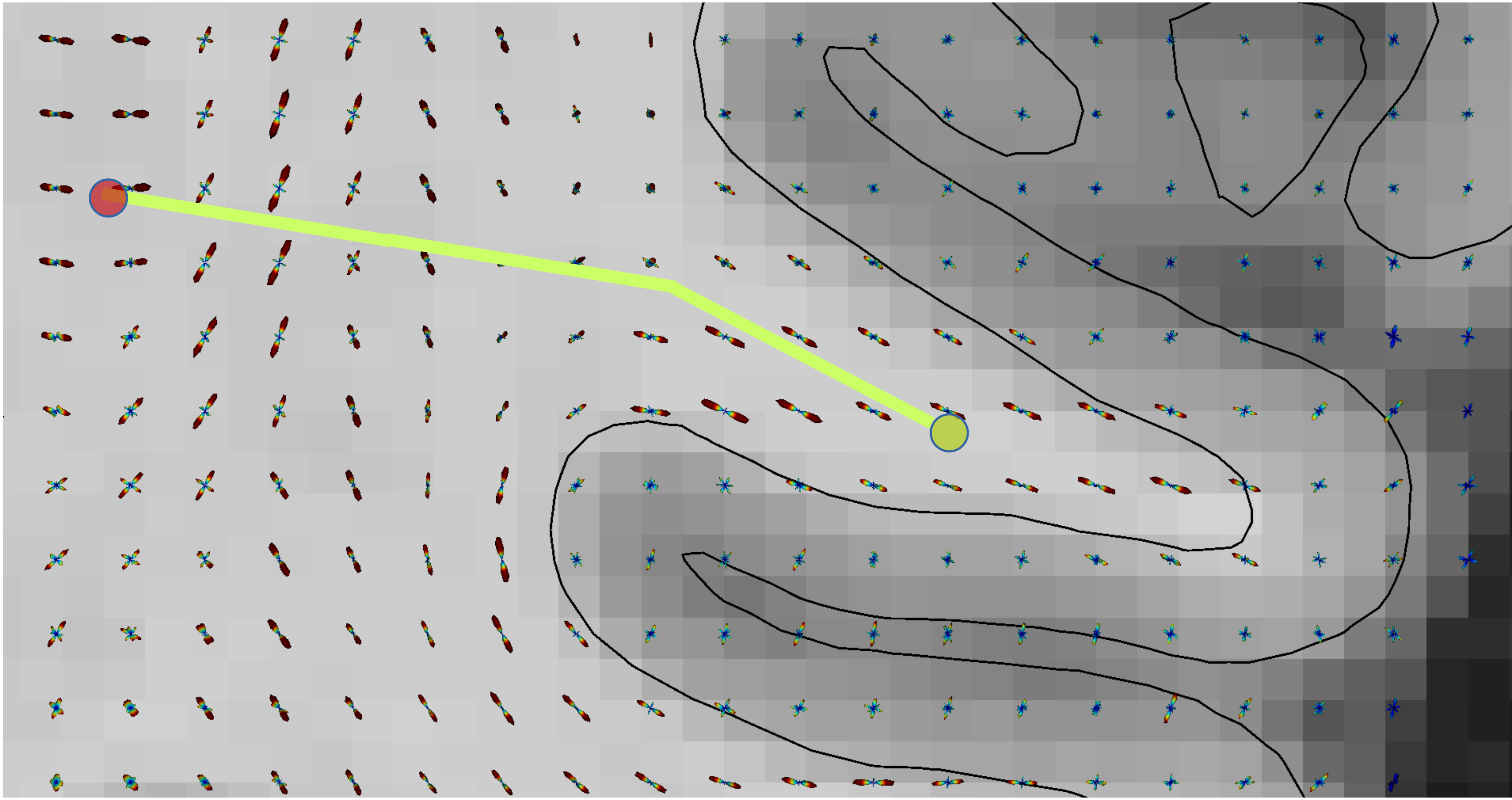
Tractography : principle



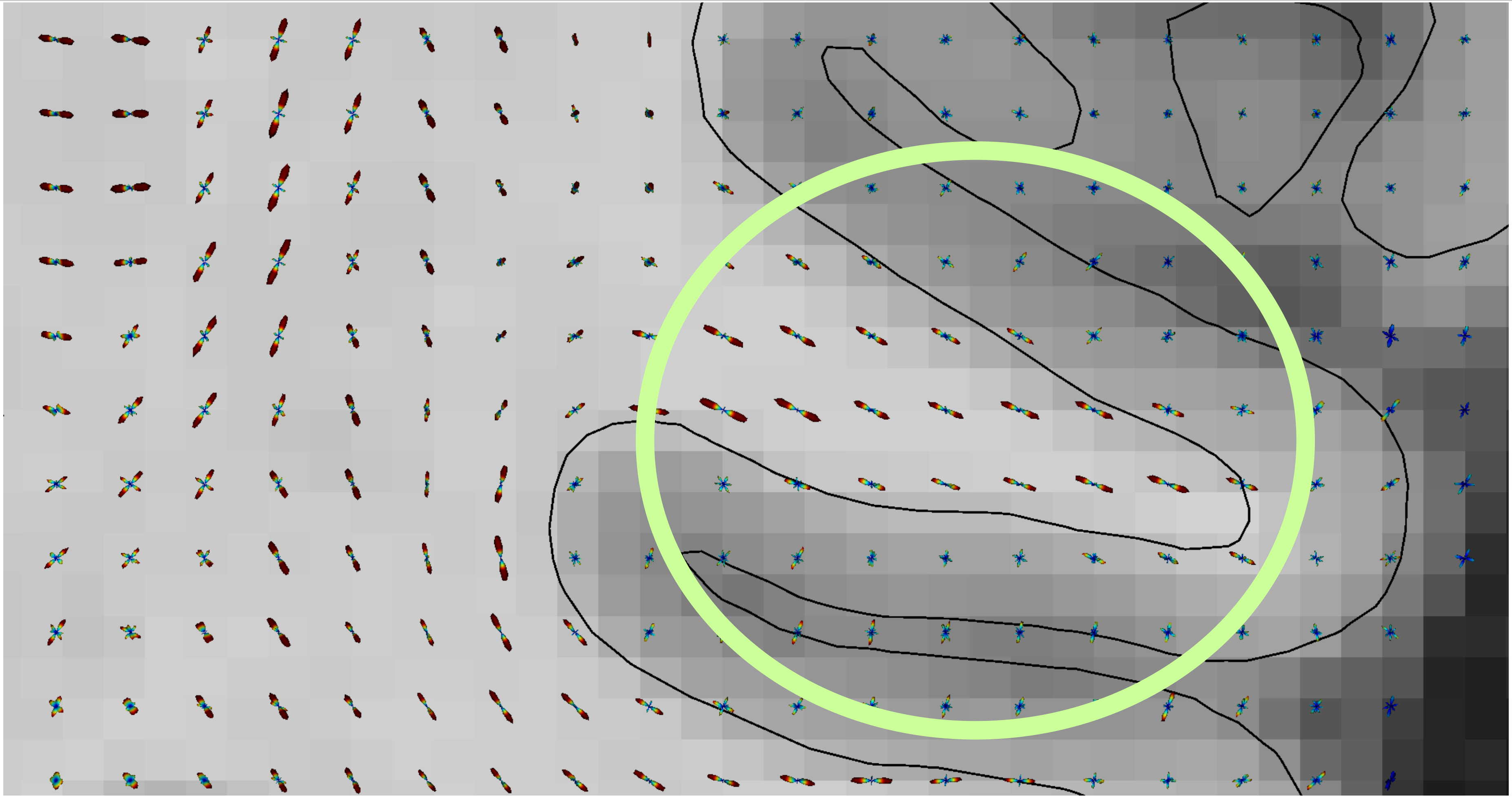
Tractography : principle



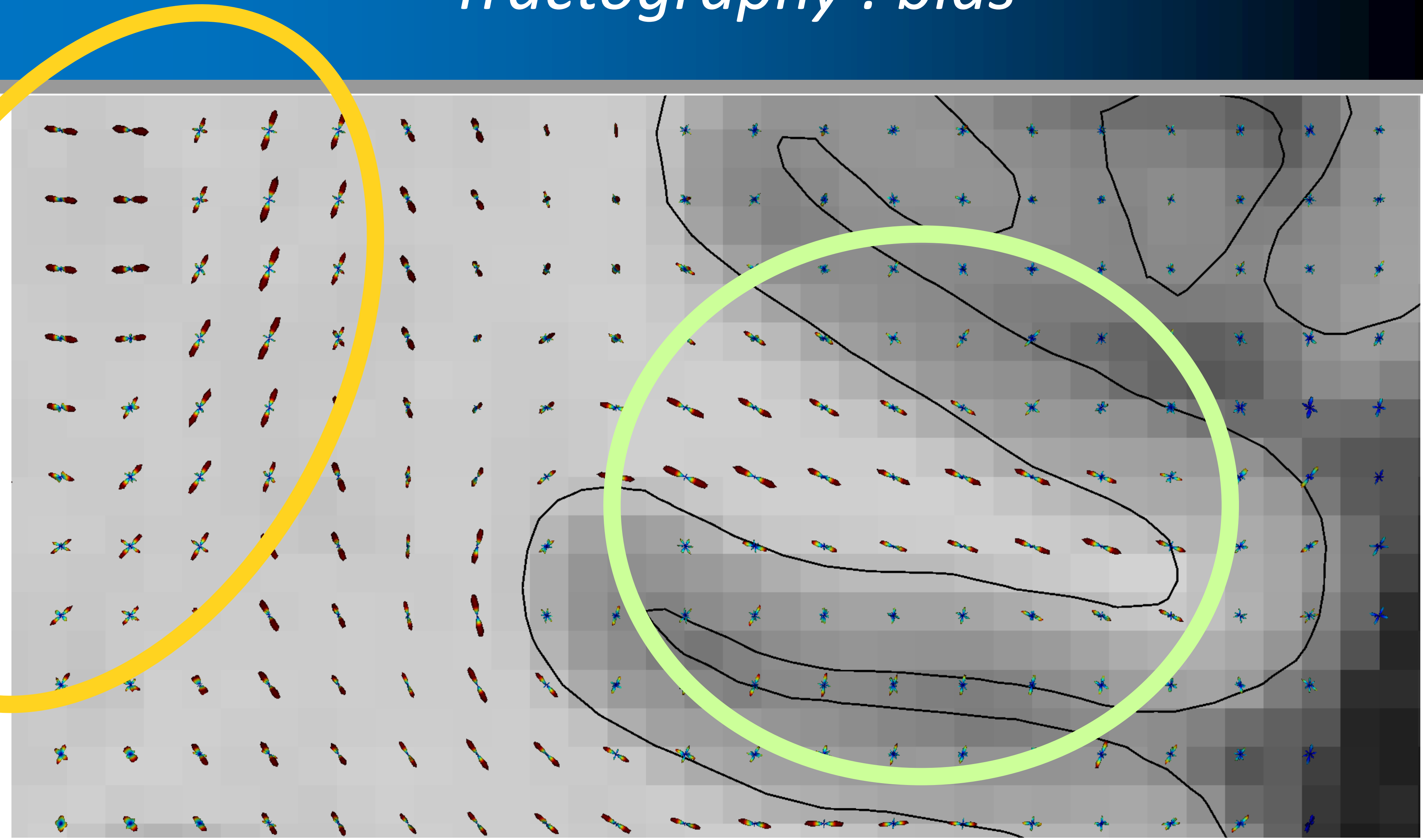
Tractography : principle



Tractography : principle



Tractography : bias



Tractography : from local to global

- **Aim : Estimate macroscropic fiber bundle geometry by integrating local diffusion information**

- **What is needed ?**
- start point i.e. **seed** (surfacic / volumic strategy ; random /deterministic position)
- end point (ending criteria)
- integration method (probabilistic, deterministic, first order, second order and beyond)
- integration step
- interpolation method (for ODF) (trilinear in the spherical harmonics basis)
- a priori:
  - geometrical constraints e.g on curvature [ref Descoteaux , Jones]
  - anatomical constraints e.g no streamline ending into cerebro-spinal fluid [ref ACT]
  - microstructural constraints ? e.g. axonal radius. [ref MIT]

Tractography : from local to global

- **Known bias: a short list. See [Ref Jones, Descoteaux]**
- **Gyral bias:** Due to sharp angle and partial volume effect, streamlines end easily near gyral crests.
- **Seeding bias :** 1 seed = 1 streamline thus longer streamlines are over- represented.
- **Growing litterature on the topic, solutions are set up by methodologists :**
- **Gyral bias →** priors on local fiber orientation **[Achille Teillac, SET]**
- **Seeding bias →** Seeding from grey/white interface, post-tractography filtering (SIFT, SIFT2, COMMIT)
- **Complex configuration → global tractography with dynamic priors [Mangin]**

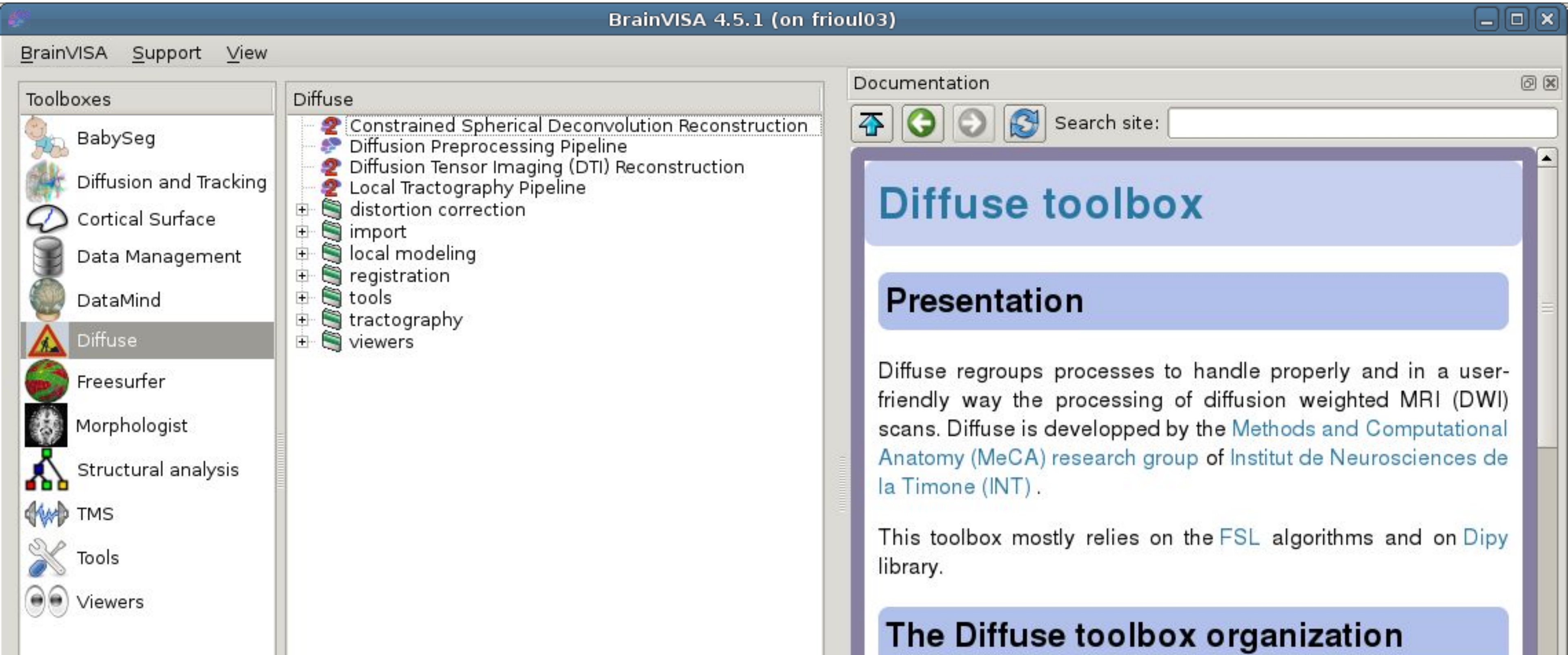
BrainVISA - *Diffuse*

- Introduction: dMRI data processing
  - Pre-processing
  - Post-processing: local models and tractography
- *Diffuse* toolbox
  - BrainVISA environment
  - Workflow
  - Demo
- Influence of pre-processing on post-processing analyses
  - Acquisition/Correction quality
  - Impact on co-registration
  - Impact on signal (diffusivity metrics)
- Outcome
  - Acquisition strategy
  - CentreIRM

Diffuse Toolbox

- Toolbox for processing Diffusion MRI
  - Guided and adapted for each acquisition type
  - Automated
  - Allowing interface with anatomical data

http://brainvisa.fr/web/index.html



Diffuse Toolbox

- Toolbox for processing Diffusion MRI
  - Guided and adapted for each acquisition type
  - Automated
  - Allowing interface with anatomical data
- Pre-processing : assembly of FSL tools in pipelines
- Post-processing : integration of Dipy functions

Brain Visa

http://brainvisa.fr/web/index.html

FSL

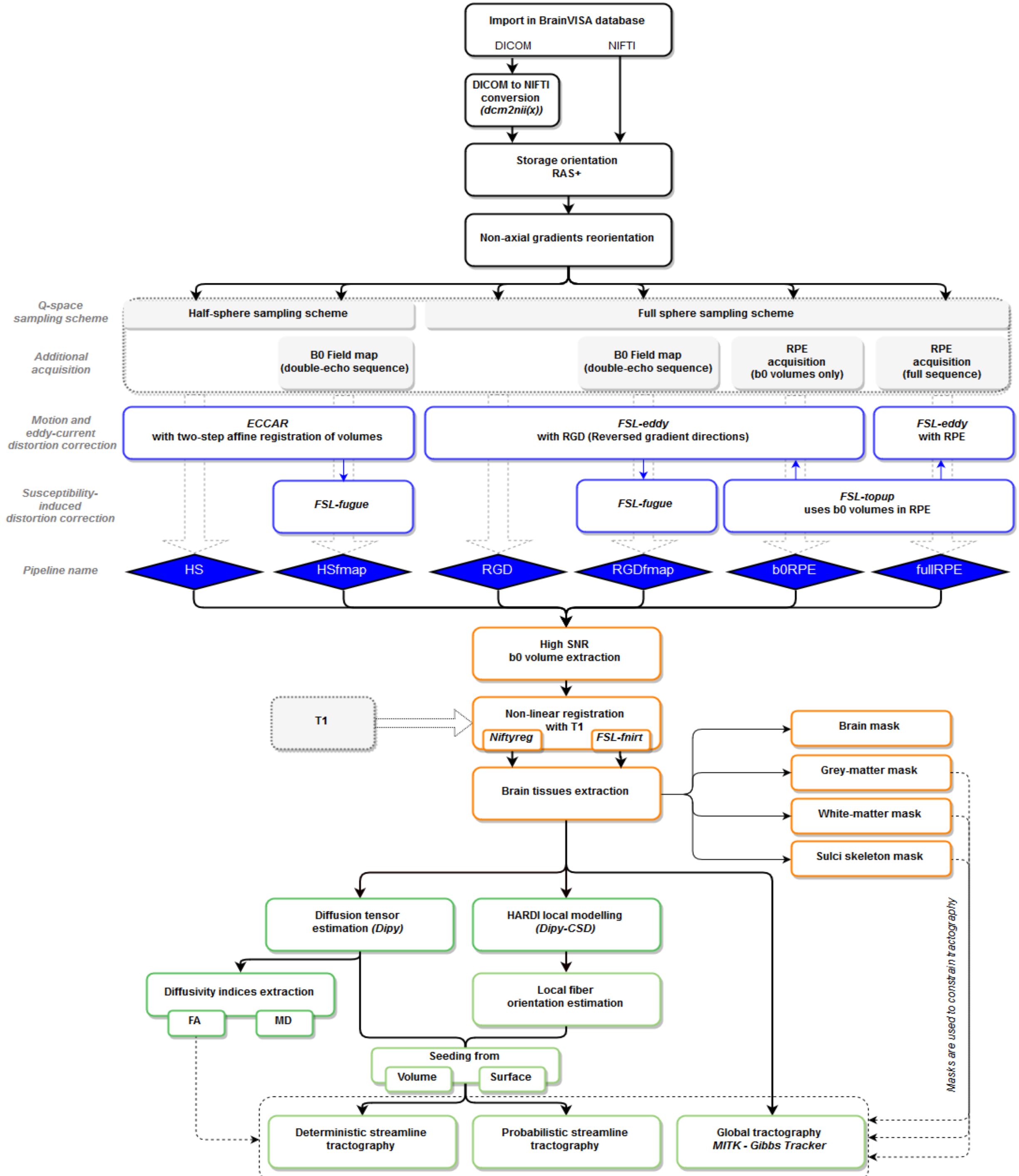
http://fsl.fmrib.ox.ac.uk/fsl/fslwiki/

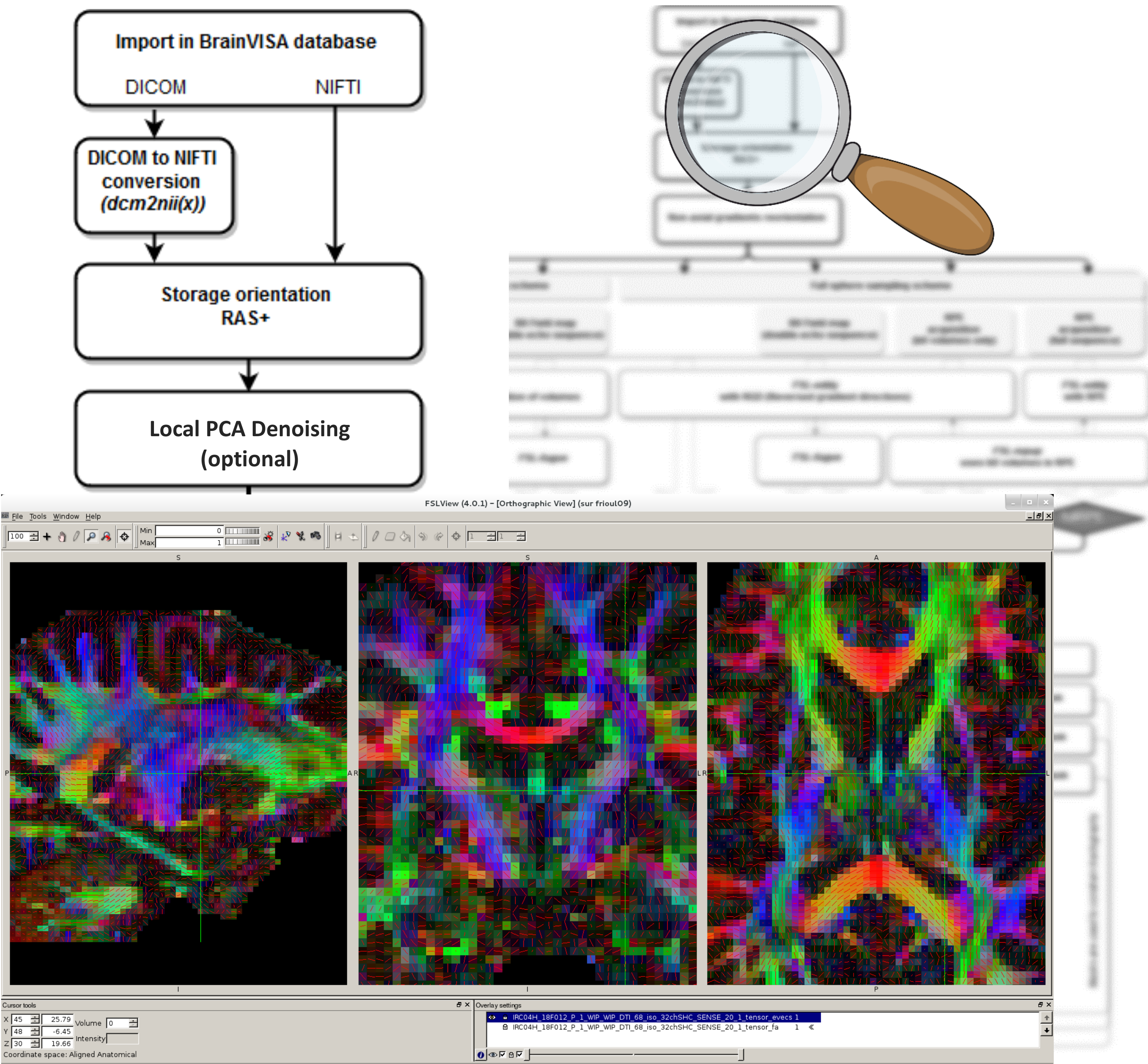
DIPY

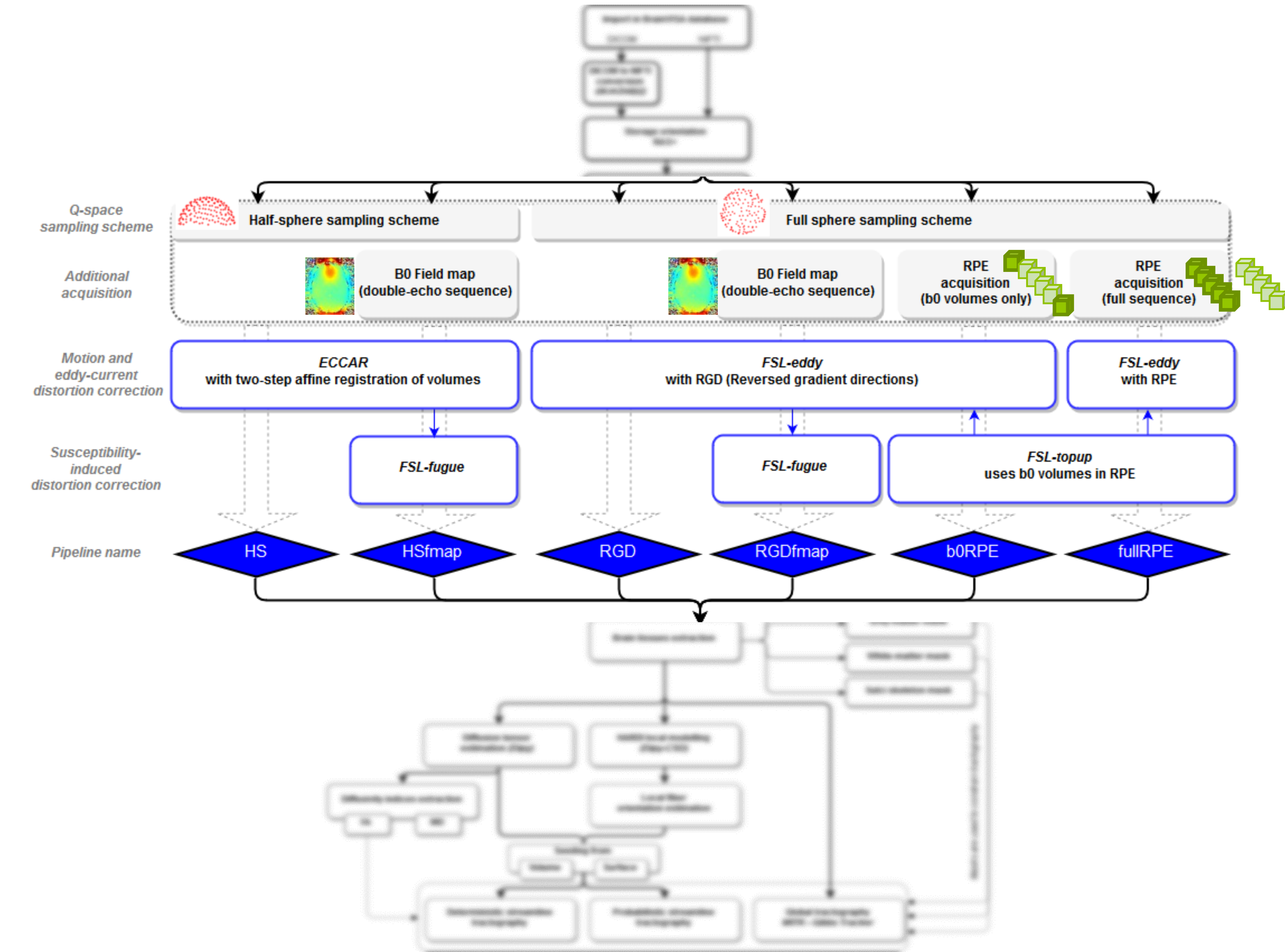
http://nipy.org/dipy/

BrainVISA - Diffuse

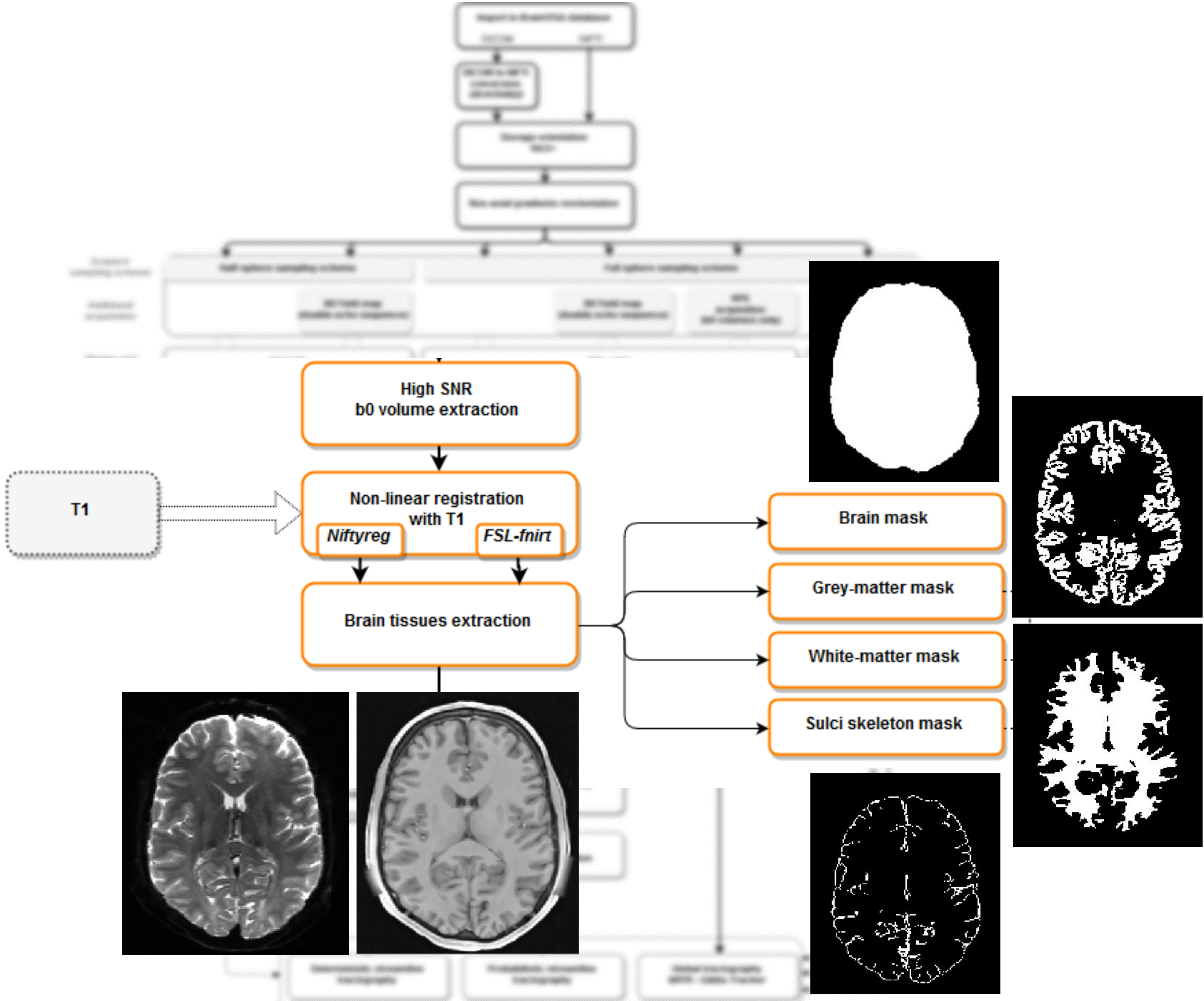
- Introduction: dMRI data processing
  - Pre-processing
  - Post-processing: local models and tractography
- *Diffuse* toolbox
  - BrainVISA environment
  - Workflow
  - Demo
- Influence of pre-processing on post-processing analyses
  - Acquisition/Correction quality
  - Impact on co-registration
  - Impact on signal (diffusivity metrics)
- Outcome
  - Acquisition strategy
  - CentreIRM

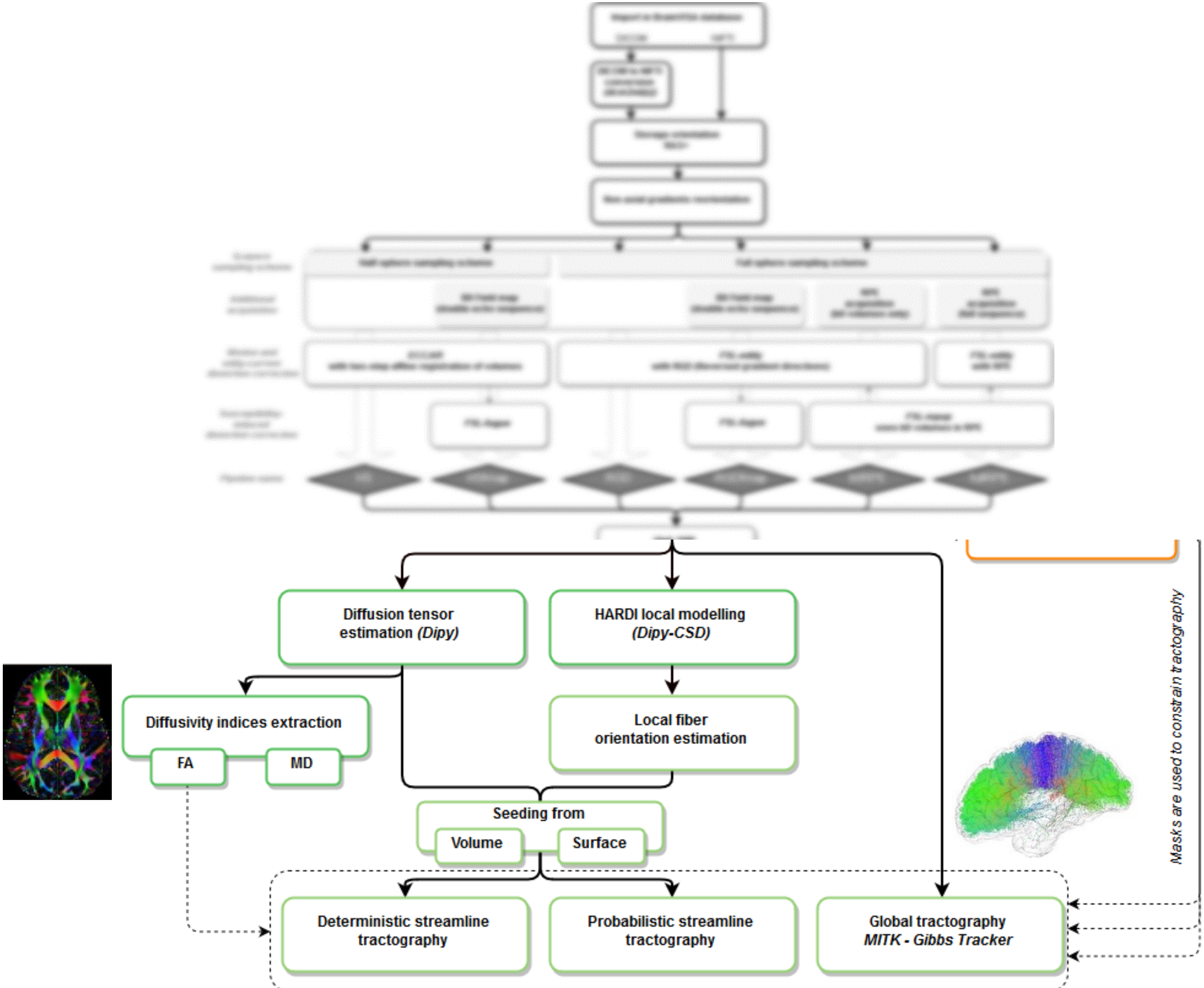

Import in BrainVISA database
DICOM
NIFTI
DICOM to NIFTI conversion (dcm2nii(x))
Storage orientation RAS+
Non-axial gradients reorientation
Q-space sampling scheme
Half-sphere sampling scheme
Full sphere sampling scheme
Additional acquisition
B0 Field map (double-echo sequence)
B0 Field map (double-echo sequence)
RPE acquisition (b0 volumes only)
RPE acquisition (full sequence)
Motion and eddy-current distortion correction
ECCAR with two-step affine registration of volumes
FSL-eddy with RGD (Reversed gradient directions)
FSL-eddy with RPE
Susceptibility-induced distortion correction
FSL-fugue
FSL-fugue
FSL-topup uses b0 volumes in RPE
Pipeline name
HS
HSfmap
RGD
RGDfmap
b0RPE
fullRPE
High SNR b0 volume extraction
T1
Non-linear registration with T1
Niftyreg
FSL-fnirt
Brain tissues extraction
Brain mask
Grey-matter mask
White-matter mask
Sulci skeleton mask
Masks are used to constrain tractography
Diffusion tensor estimation (Dipy)
HARDI local modelling (Dipy-CSD)
Diffusivity indices extraction
FA
MD
Local fiber orientation estimation
Seeding from
Volume
Surface
Deterministic streamline tractography
Probabilistic streamline tractography
Global tractography MITK - Gibbs Tracker


Import in BrainVISA database
DICOM
NIFTI
DICOM to NIFTI conversion (dcm2nii(x))
Storage orientation RAS+
Local PCA Denoising (optional)
FSLView (4.0.1) - [Orthographic View] (sur frioul09)
File Tools Window Help
Cursor tools
Overlay settings
Coordinate space: Aligned Anatomical
IRC04H_18F012_P_1_WIP_WIP_DTI_68_iso_32chSHC_SENSE_20_1_tensor_evecs 1
IRC04H_18F012_P_1_WIP_WIP_DTI_68_iso_32chSHC_SENSE_20_1_tensor_fa



Q-space sampling scheme
Half-sphere sampling scheme
Full sphere sampling scheme
Additional acquisition
B0 Field map (double-echo sequence)
B0 Field map (double-echo sequence)
RPE acquisition (b0 volumes only)
RPE acquisition (full sequence)
Motion and eddy-current distortion correction
ECCAR with two-step affine registration of volumes
FSL-eddy with RGD (Reversed gradient directions)
FSL-eddy with RPE
Susceptibility-induced distortion correction
FSL-fugue
FSL-fugue
FSL-topup uses b0 volumes in RPE
Pipeline name
HS
HSfmap
RGD
RGDfmap
b0RPE
fullRPE

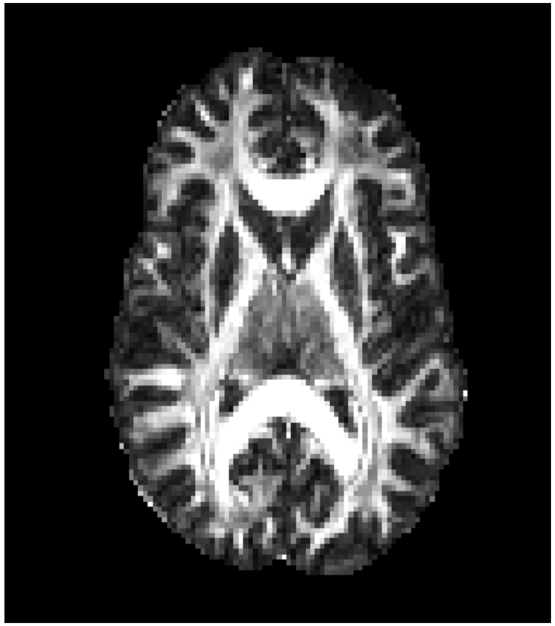

High SNR
b0 volume extraction
T1
Non-linear registration
with T1
Niftyreg
FSL-fnirt
Brain tissues extraction
Brain mask
Grey-matter mask
White-matter mask
Sulci skeleton mask


Diffusion tensor estimation (Dipy)
HARDI local modelling (Dipy-CSD)
Diffusivity indices extraction
FA
MD
Local fiber orientation estimation
Seeding from
Volume
Surface
Masks are used to constrain tractography
Deterministic streamline tractography
Probabilistic streamline tractography
Global tractography MITK - Gibbs Tracker

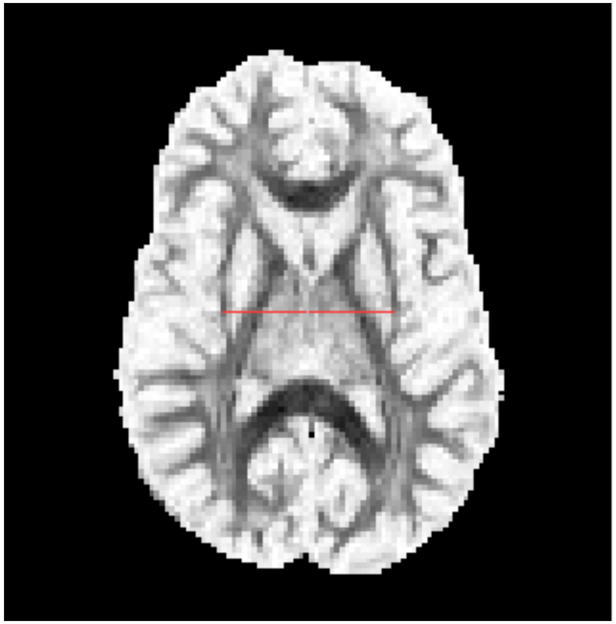
Diffuse Toolbox : DTI model

- Several estimation methods are available (Least Square, Weighted Least Square, Non Linear Least Square)

Mean diffusivity



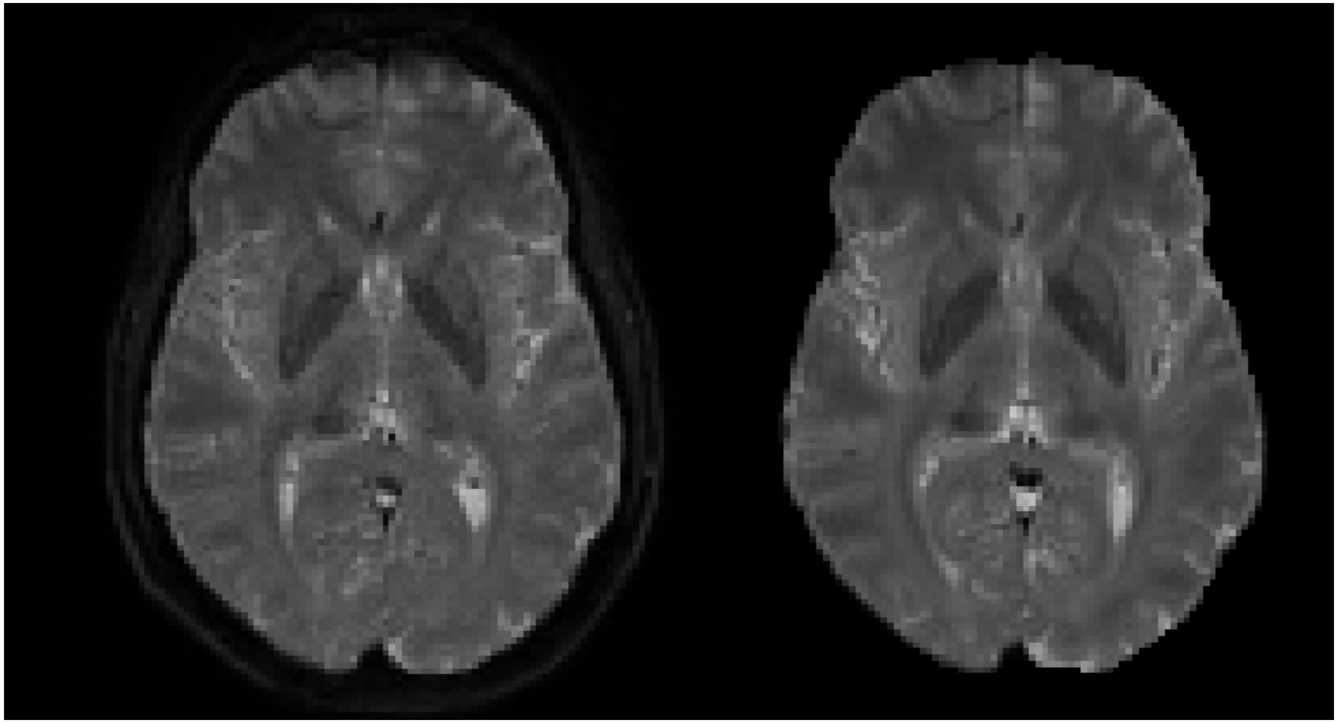
Fractionnal Anisotropy



Sphericity

Diffuse Toolbox : DTI model

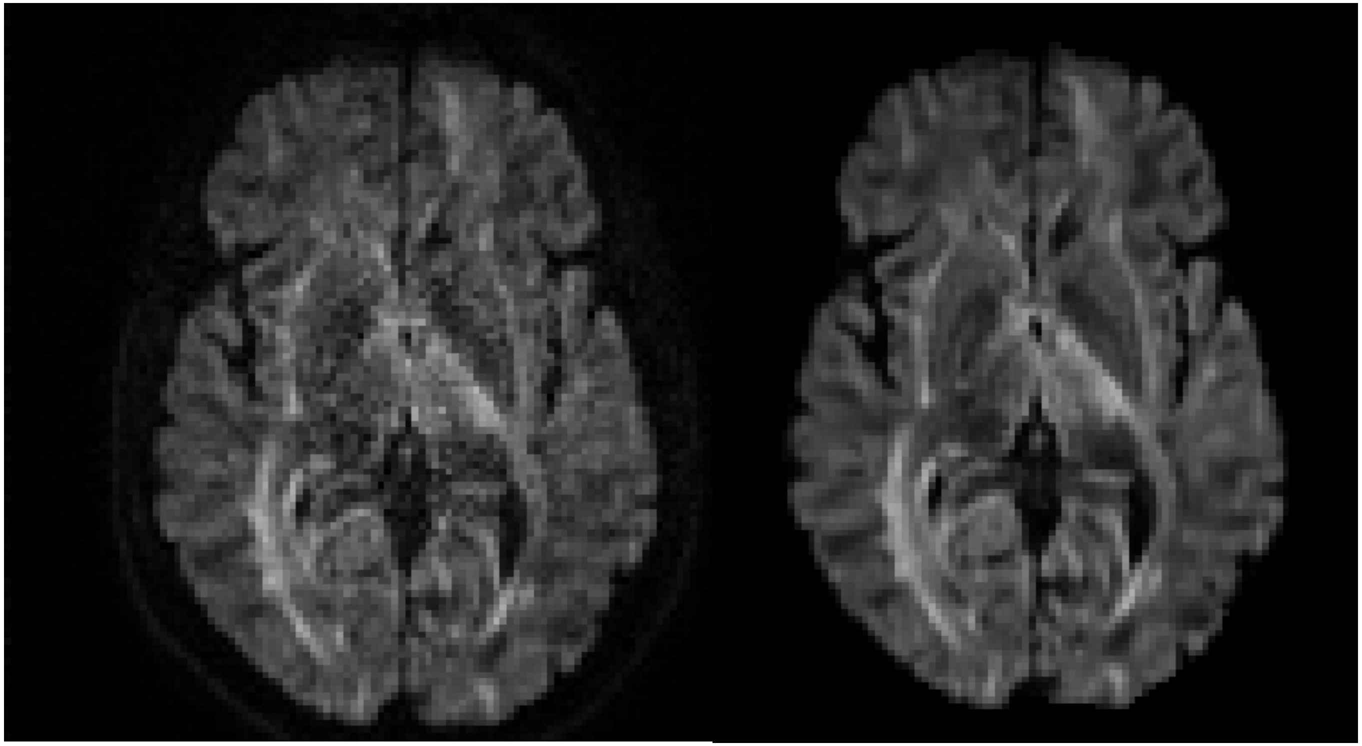
From tensor coefficients back to signal : dMRI signal prediction

- 

b=0 : left (original), right (predicted)

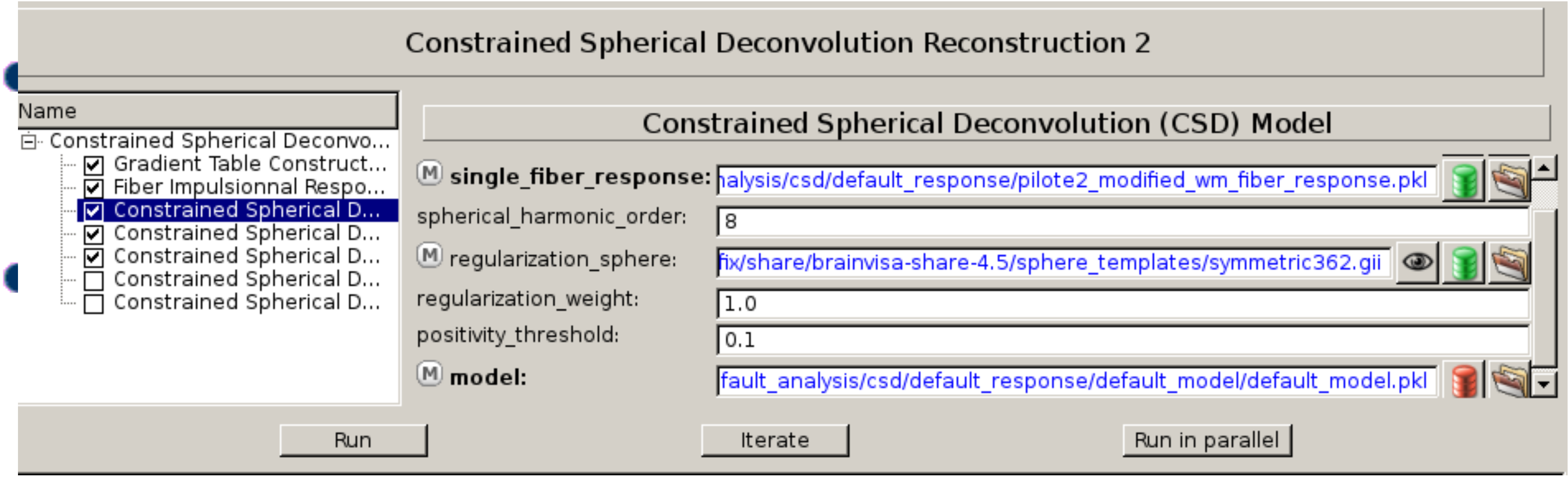
Diffuse Toolbox : DTI model

From tensor coefficients back to signal : dMRI signal prediction

- 

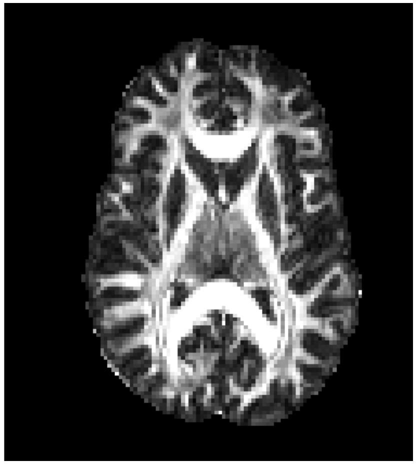
b=2000 : left (original), right (predicted)

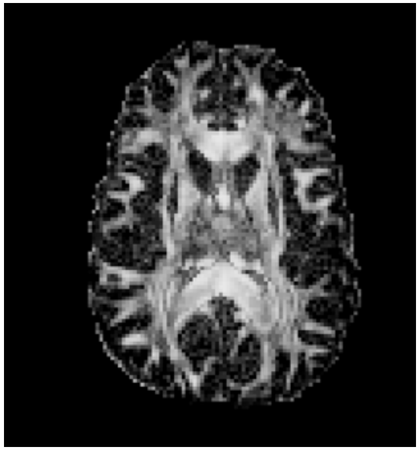
Diffuse Toolbox : CSD model



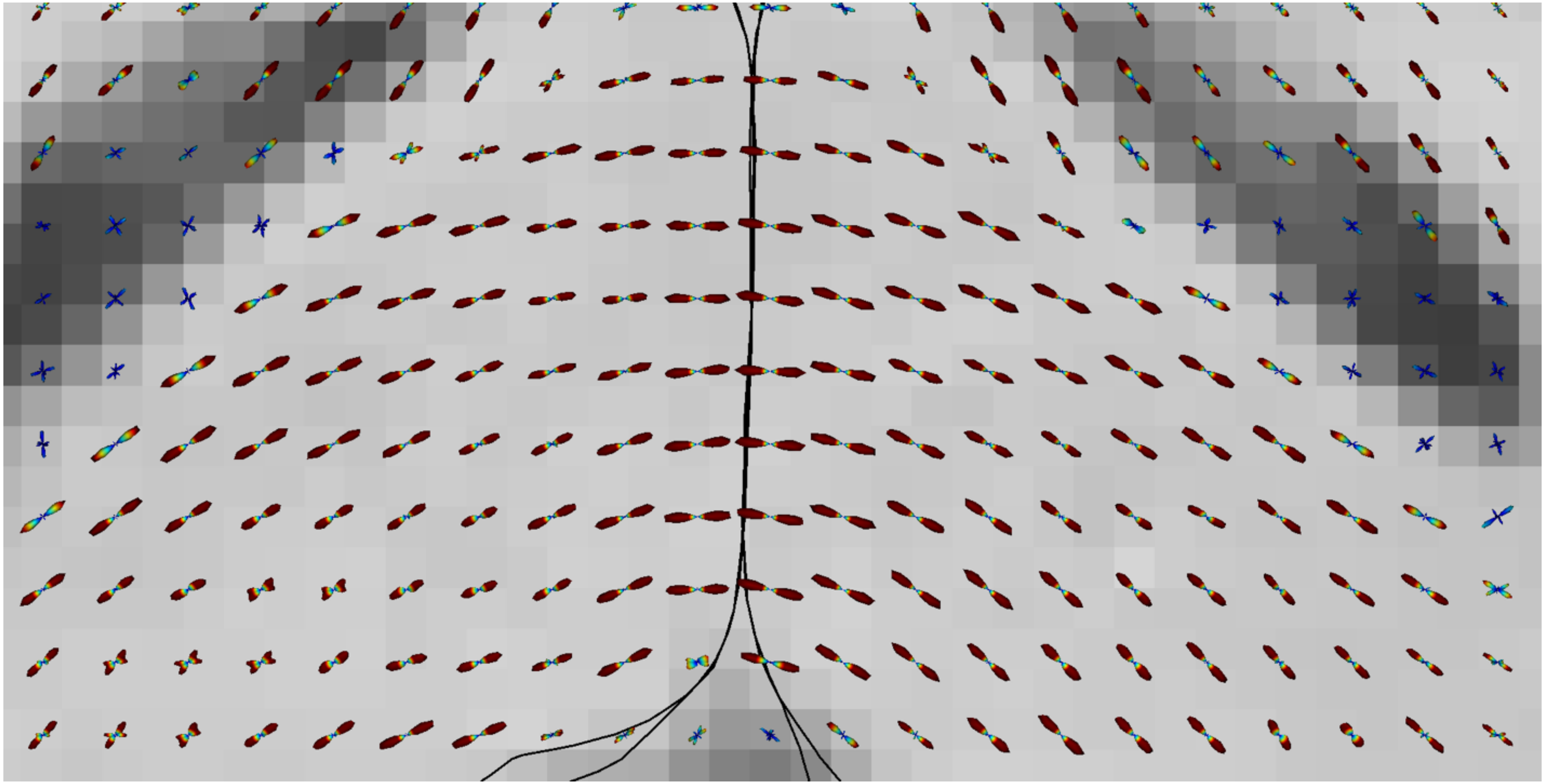
Estimation parameters such as spherical harmonic order and regularization sphere are setup automatically according to diffusion data sequence but can also be tuned using graphical user interface.

Diffuse Toolbox : CSD model

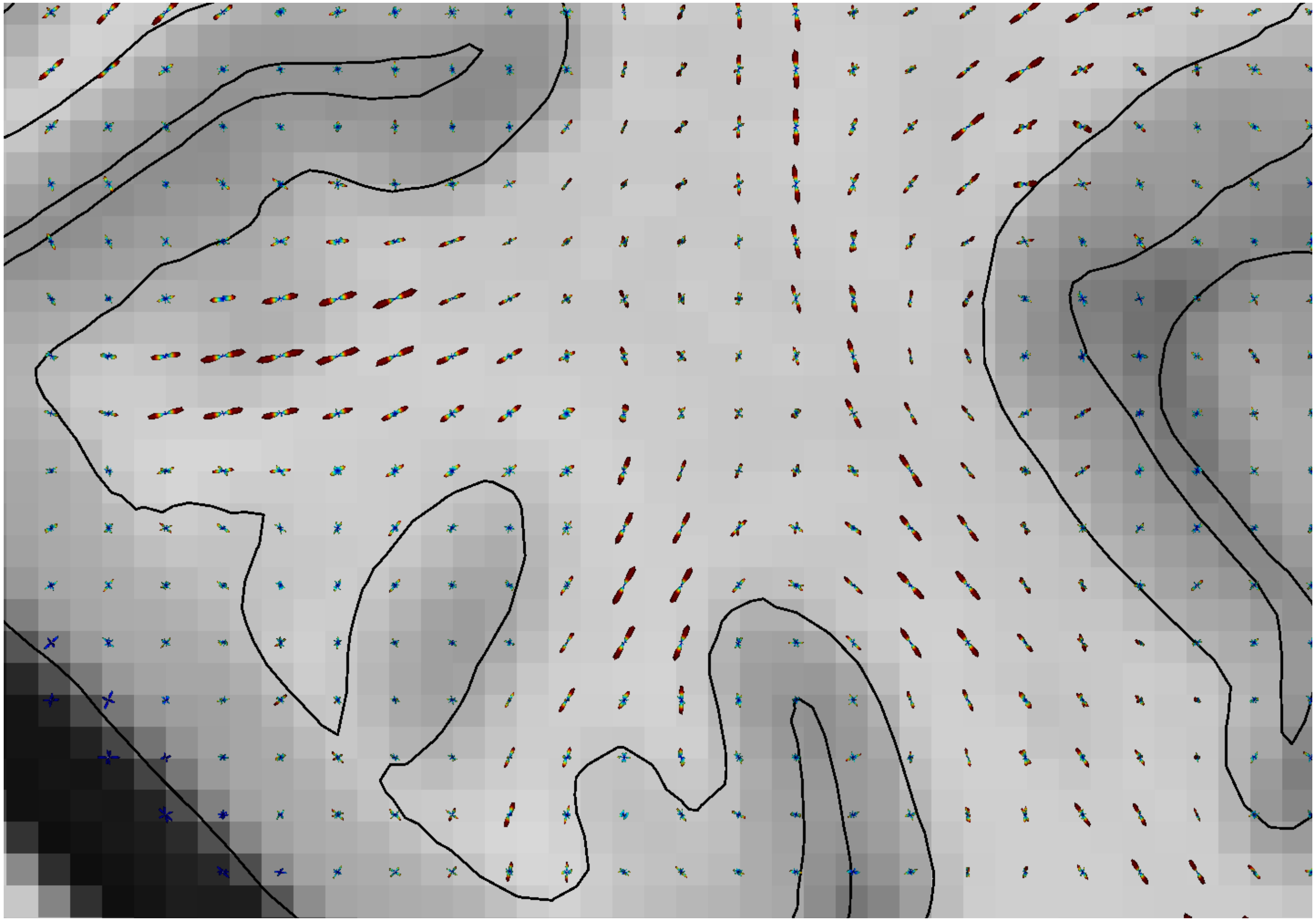




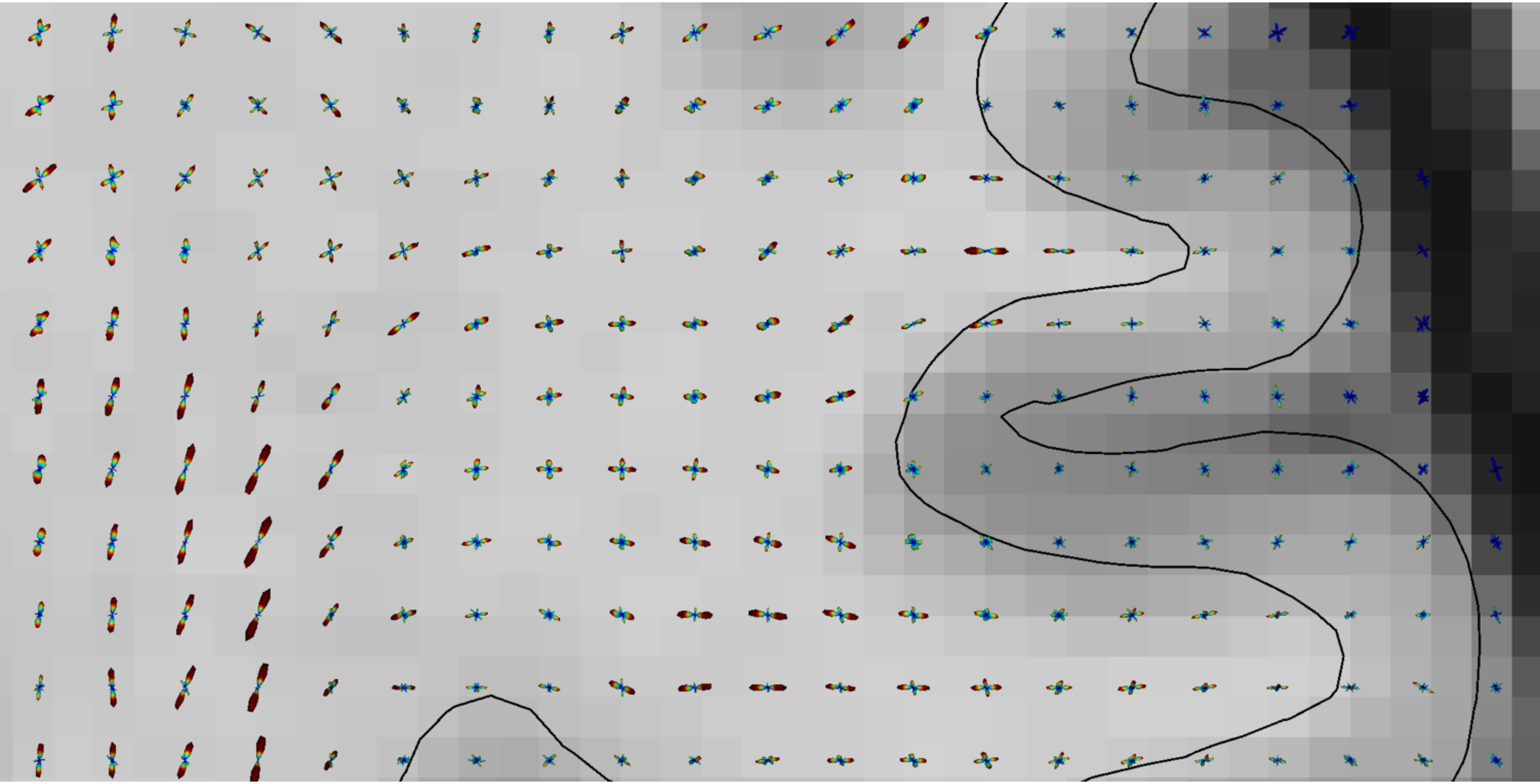
Diffuse Toolbox : CSD model



Diffuse Toolbox : CSD model



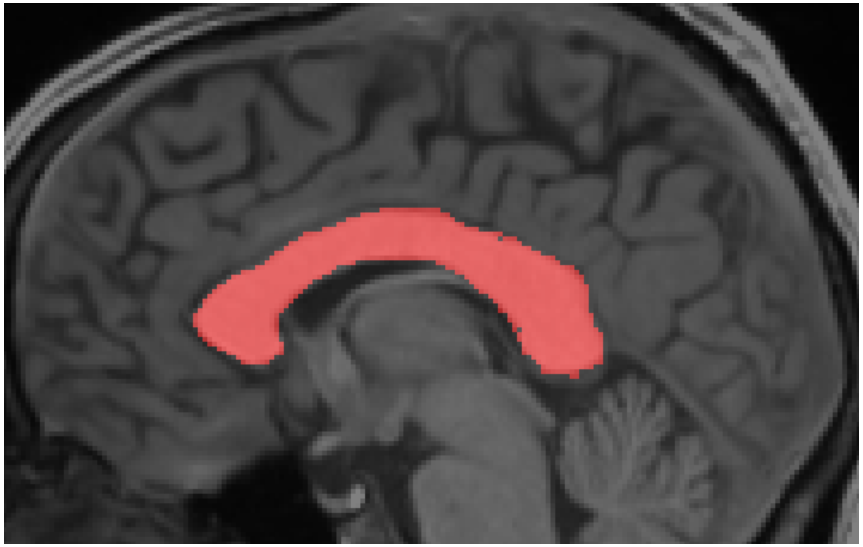
Diffuse Toolbox : CSD model



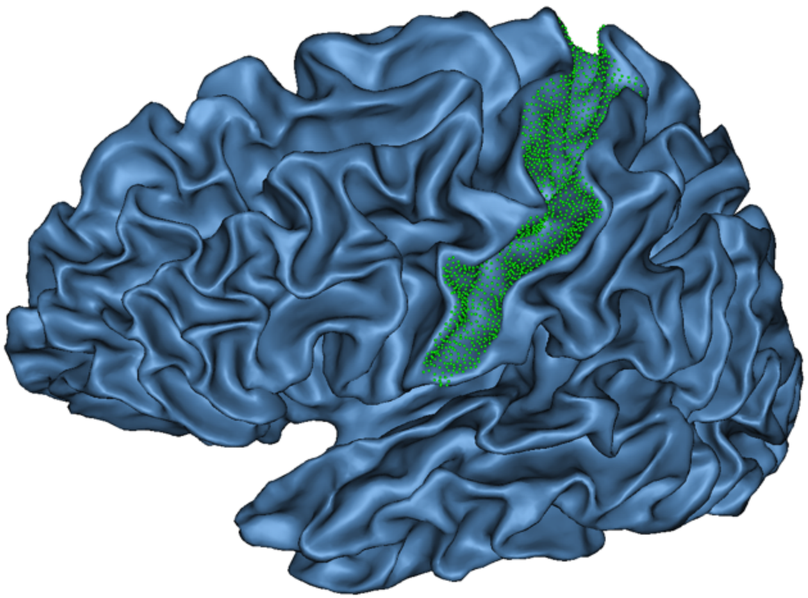
Diffuse Toolbox : Seeding strategy

- **Volumic Seeding**

Surfacic seeding



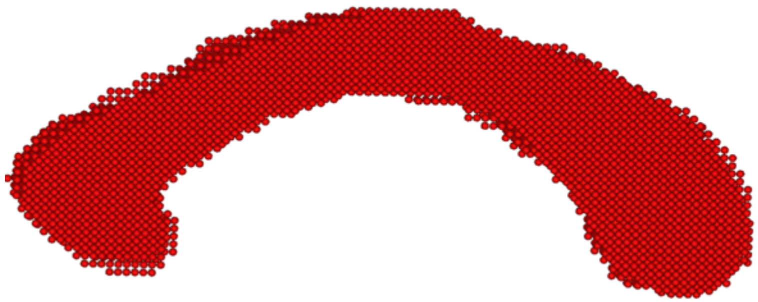
Manually extracted corpus callosum ROI from T1, diffusion space, subject pilote2 from IRM center.



Central sulcus area (green) manually drawn on left white mesh, diffusion space.

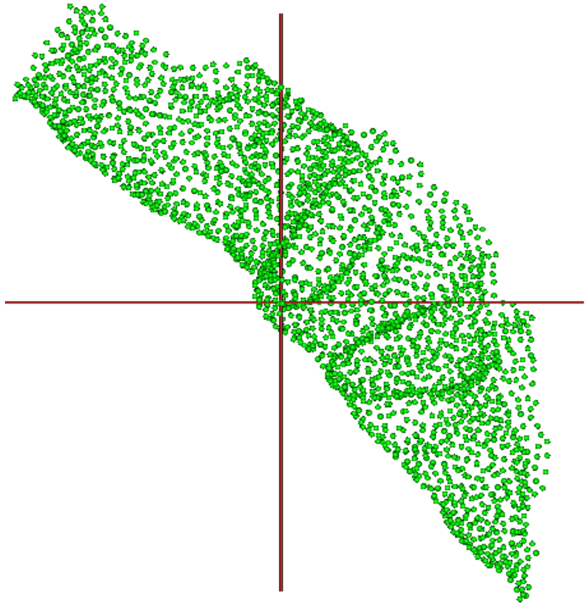
Diffuse Toolbox : Seeding strategies

- **Volumic Seeding**



Seeds from ROI mask, 1 seed/voxel
Deterministic placement.

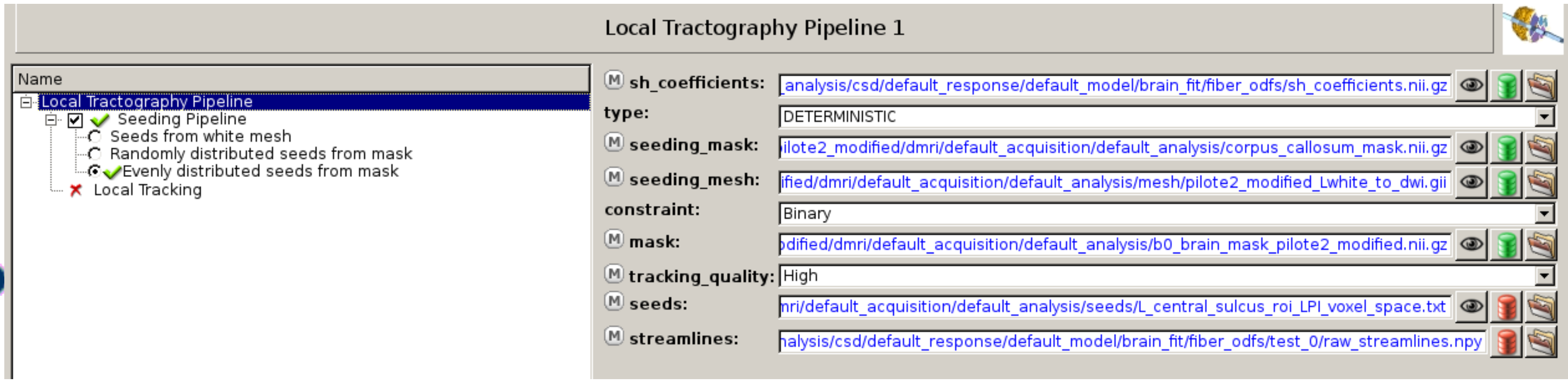
Surfacic seeding



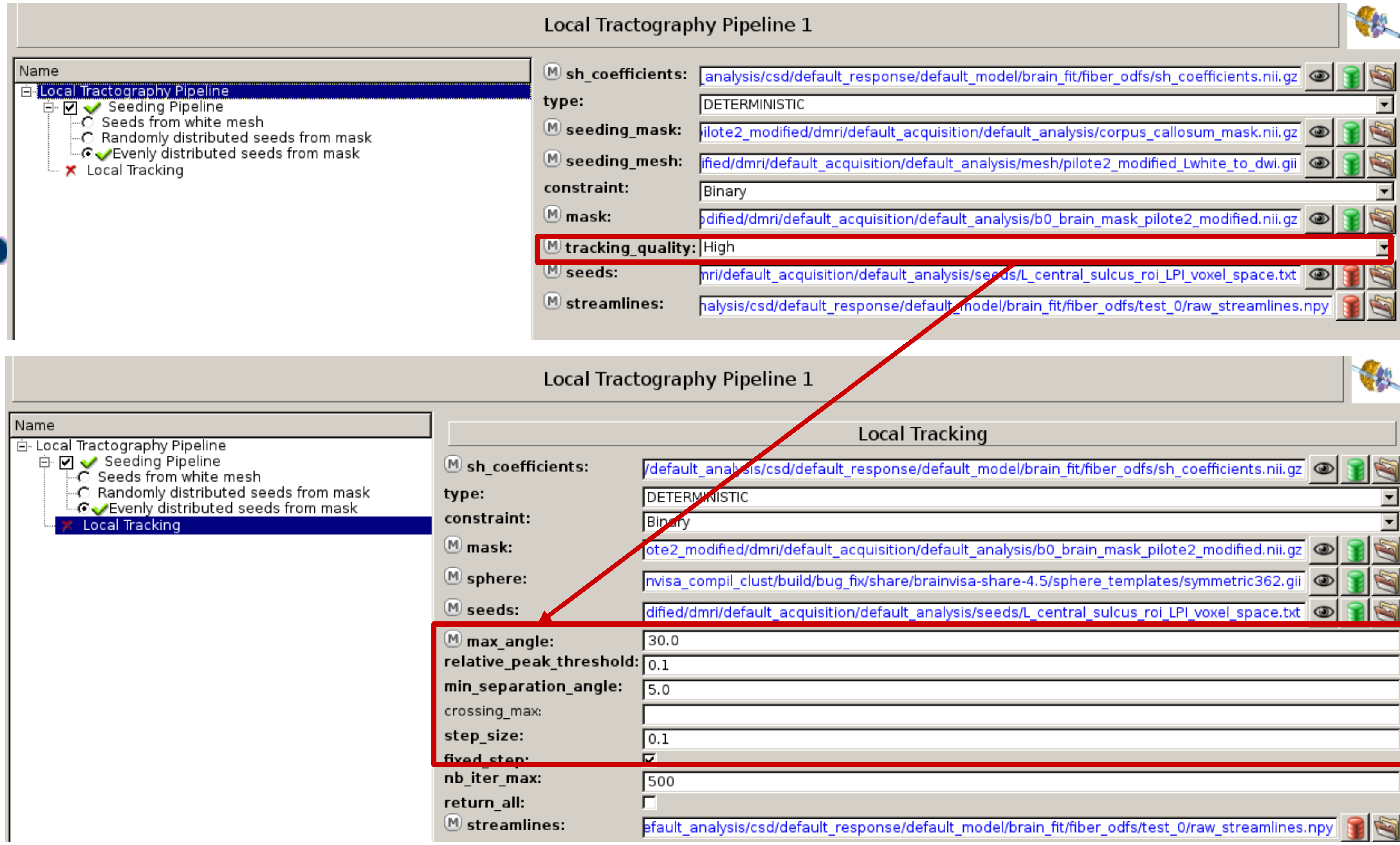
Seeds from surfacic ROI,
1seed/vertex. Refinement is possible

These two mecanism can easily be combined to generate hybrid seeds (e.g. volumic from subcortical grey volume and surfacic from white mesh)

Diffuse Toolbox : Tractography parameters



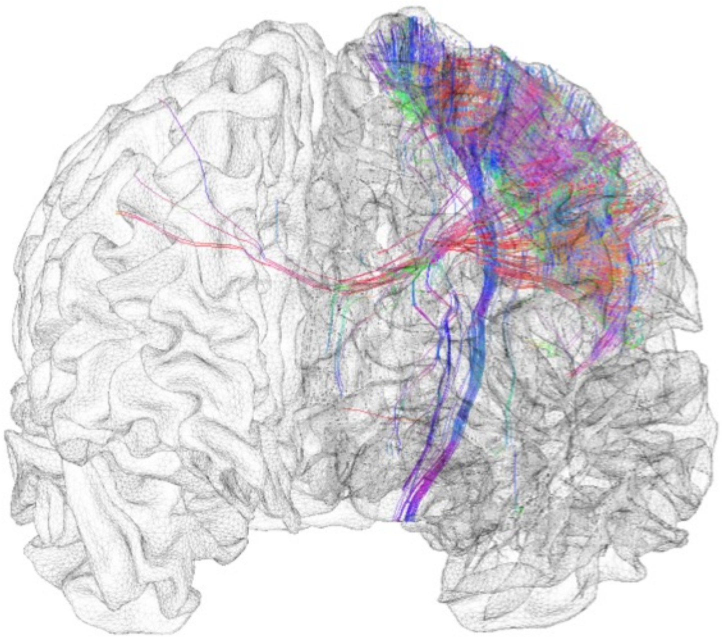
Diffuse Toolbox : Tractography parameters

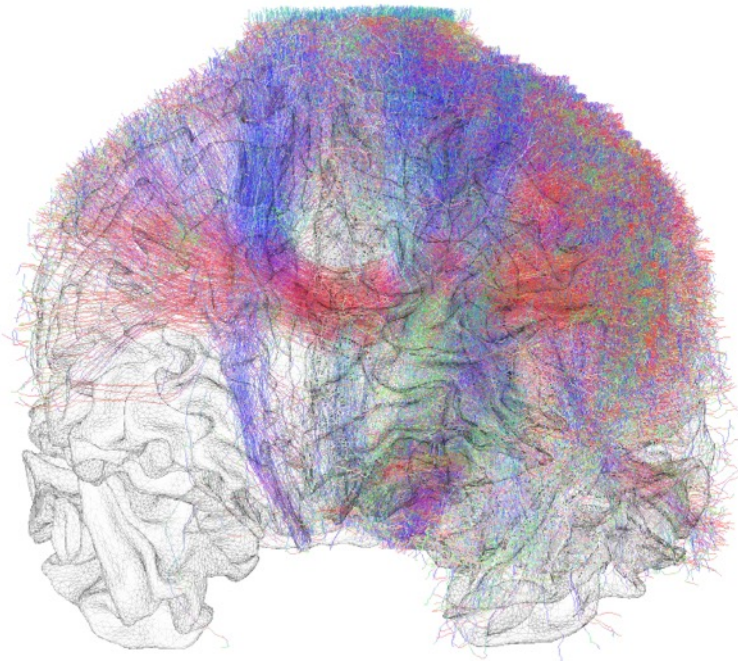


Diffuse Toolbox : Tractography examples

- **Deterministic tracking**

Probabilistic tracking





Surfacic seeds,left central sulcus, angle=45 degrees, step size=0.1

BrainVISA - Diffuse

- Introduction: dMRI data processing
  - Pre-processing
  - Post-processing: local models and tractography
- *Diffuse* toolbox
  - BrainVISA environment
  - Workflow
  - Demo
- Influence of pre-processing on post-processing analyses
  - Acquisition/Correction quality
  - Impact on co-registration
  - Impact on signal (diffusivity metrics)
- Outcome
  - Acquisition strategy
  - CentreIRM

BrainVISA - Diffuse

- Introduction: dMRI data processing
  - Pre-processing
  - Post-processing: local models and tractography
- *Diffuse* toolbox
  - BrainVISA environment
  - Workflow
  - Demo
- Influence of pre-processing on post-processing analyses
  - Acquisition/Correction quality
  - Impact on co-registration
  - Impact on signal (diffusivity metrics)
- Outcome
  - Acquisition strategy
  - CentreIRM

Données

HCP Data - 900 Subjects

- 20 sujets sains, 25-30 ans
- 1,25 x 1,25 x 1,25 mm
- b = 1000, 2000, 3000 s/mm²
- 3 x 95 directions (sphère entière, régulière)
- Double encodage de phase LR/RL
- Fieldmap

3T Prisma/Skyra

TR = 5520 ms
TE = 89.5 ms
MB = 3
FOV = 210 x 188

Centre IRM - INT

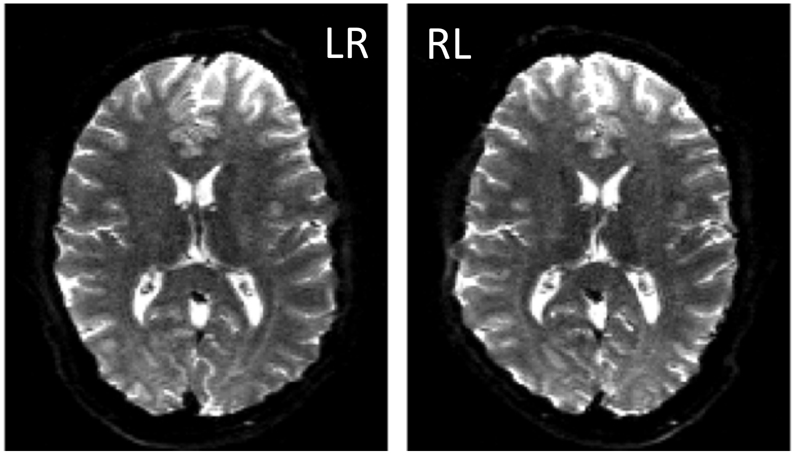
- 1 sujet sain, 25 ans
- 1,5 x 1,5 x 1,5 mm
- b = 2000 s/mm²
- 60 directions (sphère entière, régulière)
- Double encodage de phase AP/PA
- Fieldmap

3T Siemens Prisma

TR/TE = 3270/87ms
MB = 4
FOV = 210^2

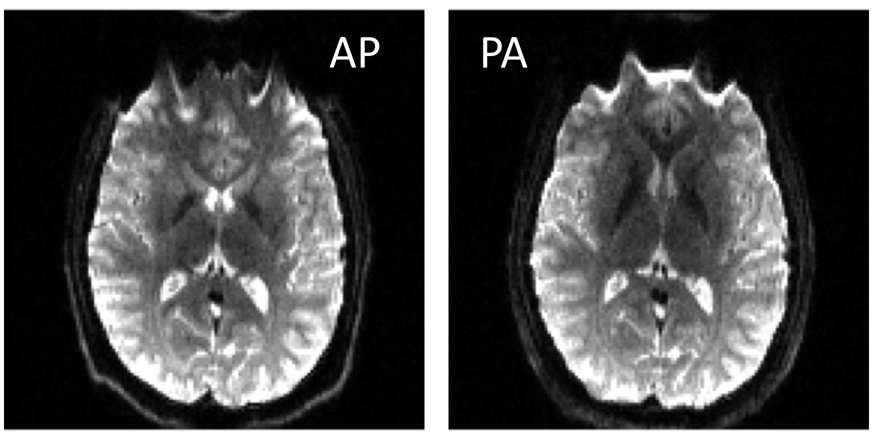
Données

HCP Data - 900 Subjects

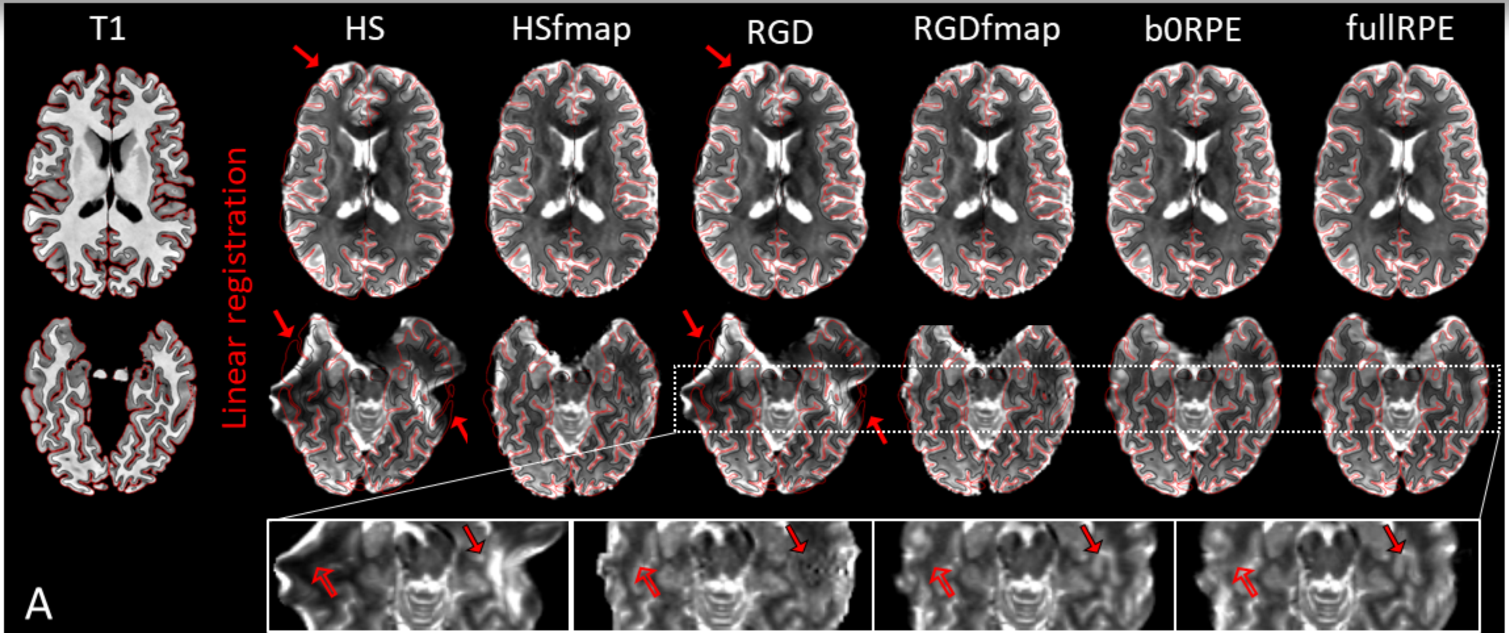


3T Siemens Prisma

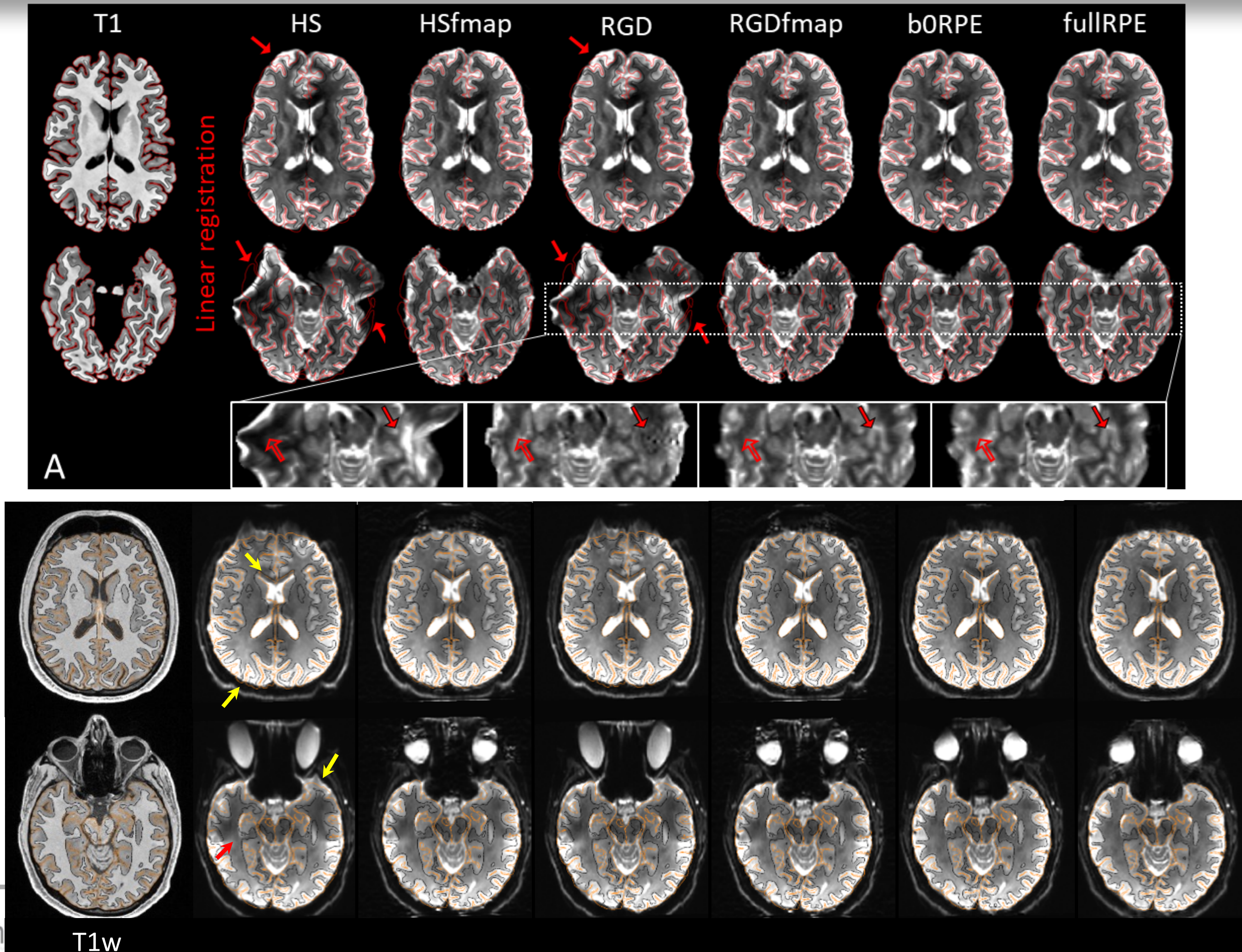
Centre IRM - INT



Comparison: distortion correction quality



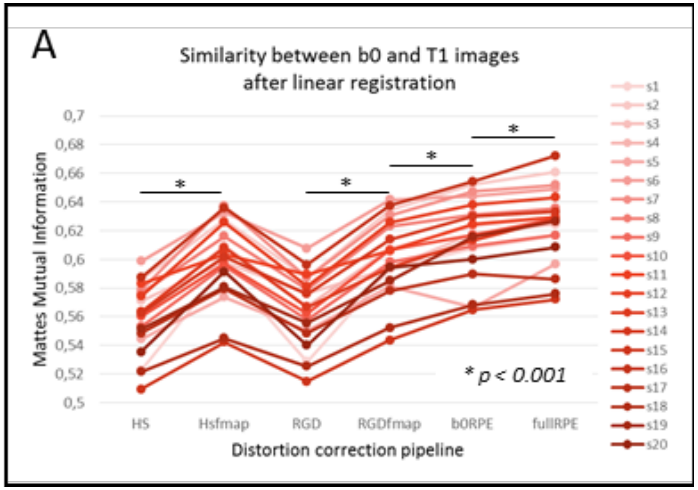
Comparison: distortion correction quality

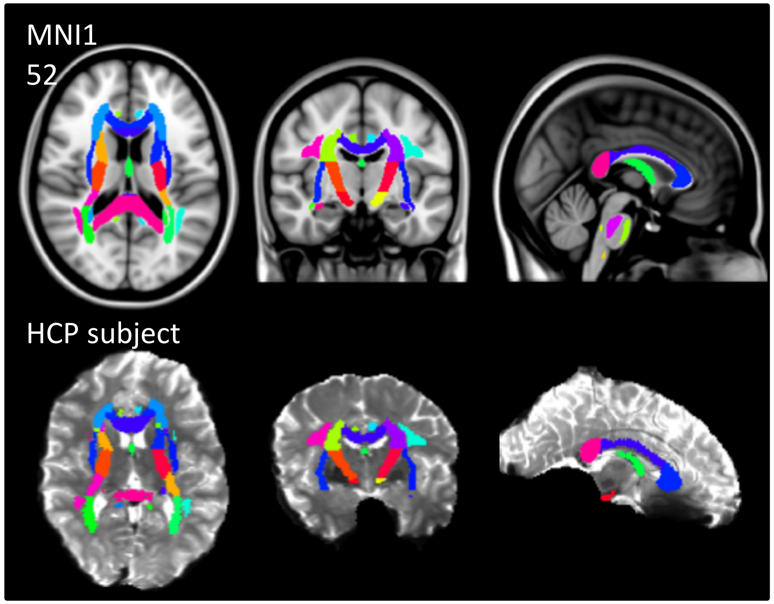


BrainVISA - *Diffuse*

- Introduction: dMRI data processing
  - Pre-processing
  - Post-processing: local models and tractography
- *Diffuse* toolbox
  - BrainVISA environment
  - Workflow
  - Demo
- Influence of pre-processing on post-processing analyses
  - Acquisition/Correction quality
  - Impact on co-registration
  - Impact on signal (diffusivity metrics)
- Outcome
  - Acquisition strategy
  - CentreIRM

Comparison: co-registration quality





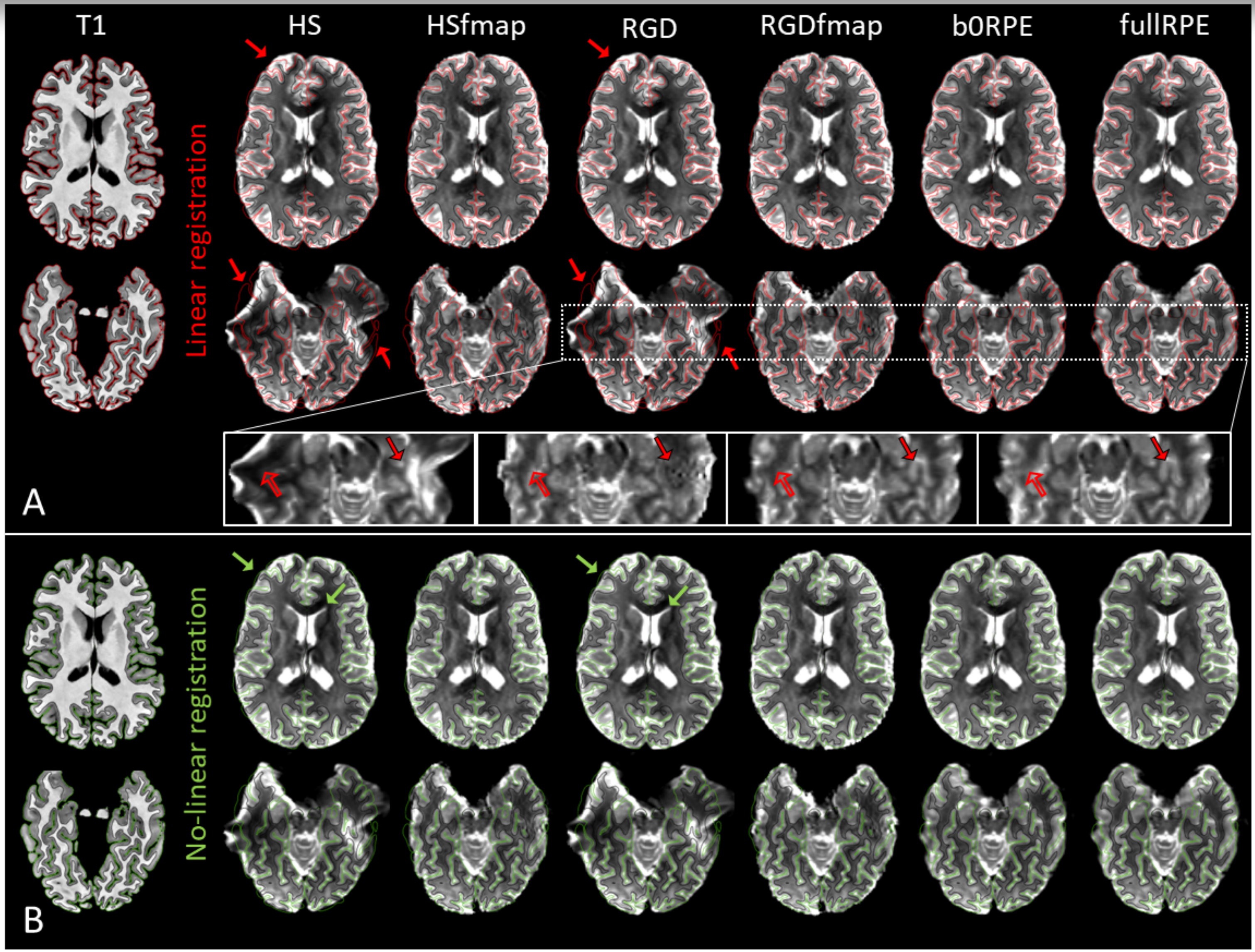
- Quality of distortion correction:

is the true brain geometry recovered ?

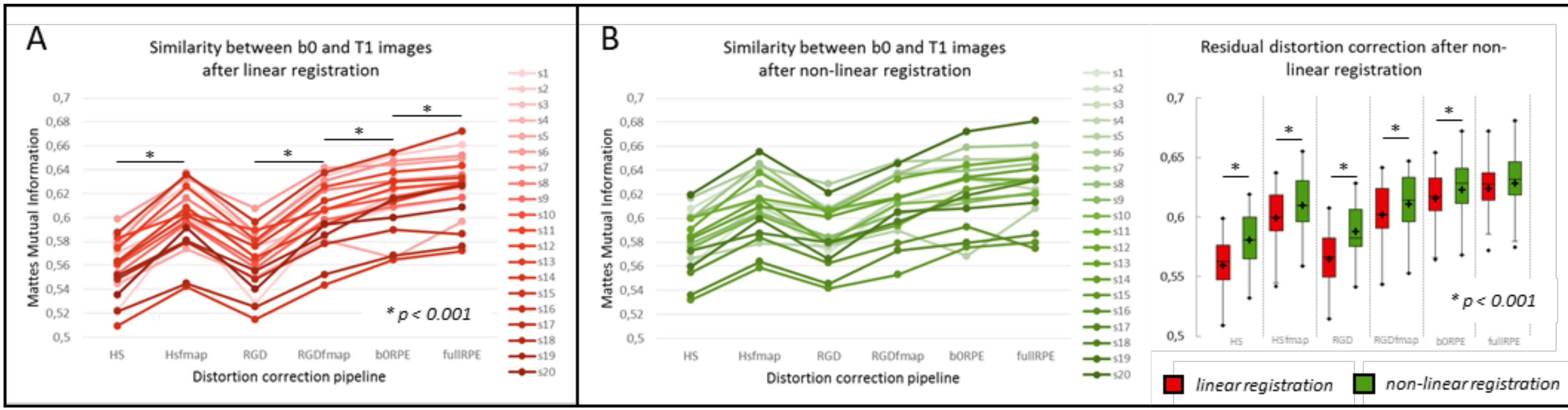
- Quality of co-registration with T1
    - Impact on brain masking/segmentation
    - Impact on **seeding strategy** !

$\Rightarrow$ **Use non-linear co-registration**

Comparison: non-linear registration



Comparison: non-linear registration

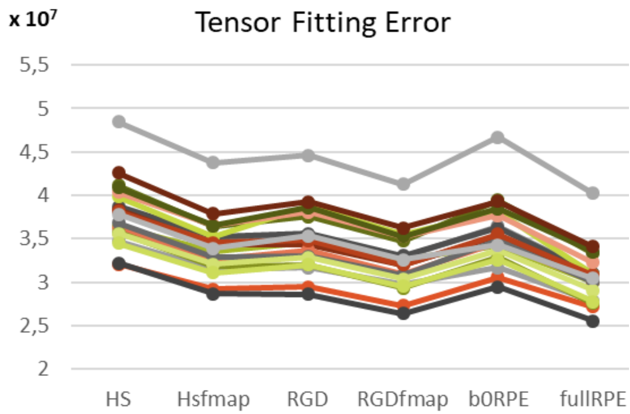


BrainVISA - *Diffuse*

- Introduction: dMRI data processing
  - Pre-processing
  - Post-processing: local models and tractography
- *Diffuse* toolbox
  - BrainVISA environment
  - Workflow
  - Demo
- Influence of pre-processing on post-processing analyses
  - Acquisition/Correction quality
  - Impact on co-registration
  - Impact on signal (diffusivity metrics)
- Outcome
  - Acquisition strategy
  - CentreIRM

Comparison: impact on diffusivity metrics

Quantitative metrics

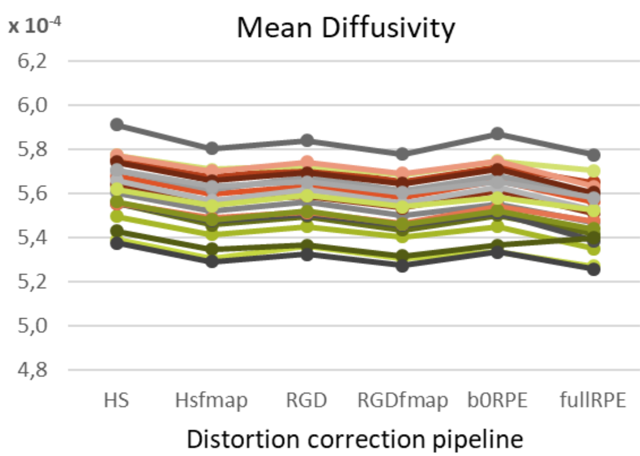


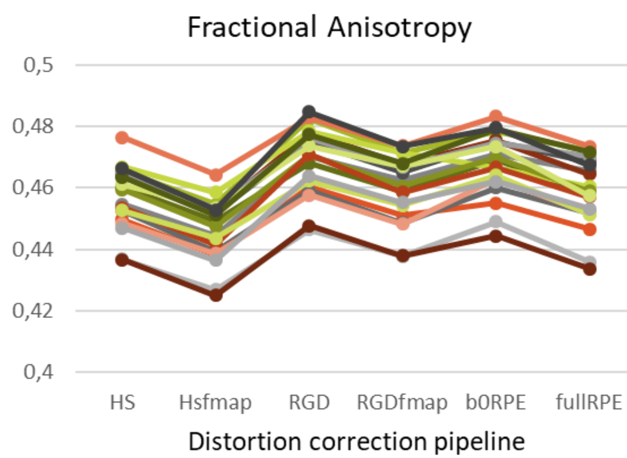
$$TFE = \sum_{i=1}^{N} \left(S_{mi} - S_{fi}\right)^2$$

$$MDI = \frac{1}{n(S)} \sum_{x \in S} \sqrt{\frac{\lambda_2 + \lambda_3}{2\lambda_1}}$$

$$\mathrm{FA} = \sqrt{\frac{3}{2}} \frac{\sqrt{(\lambda_1 - \hat{\lambda})^2 + (\lambda_2 - \hat{\lambda})^2 + (\lambda_3 - \hat{\lambda})^2}}{\sqrt{\lambda_1^2 + \lambda_2^2 + \lambda_3^2}}$$

Qualitative metrics

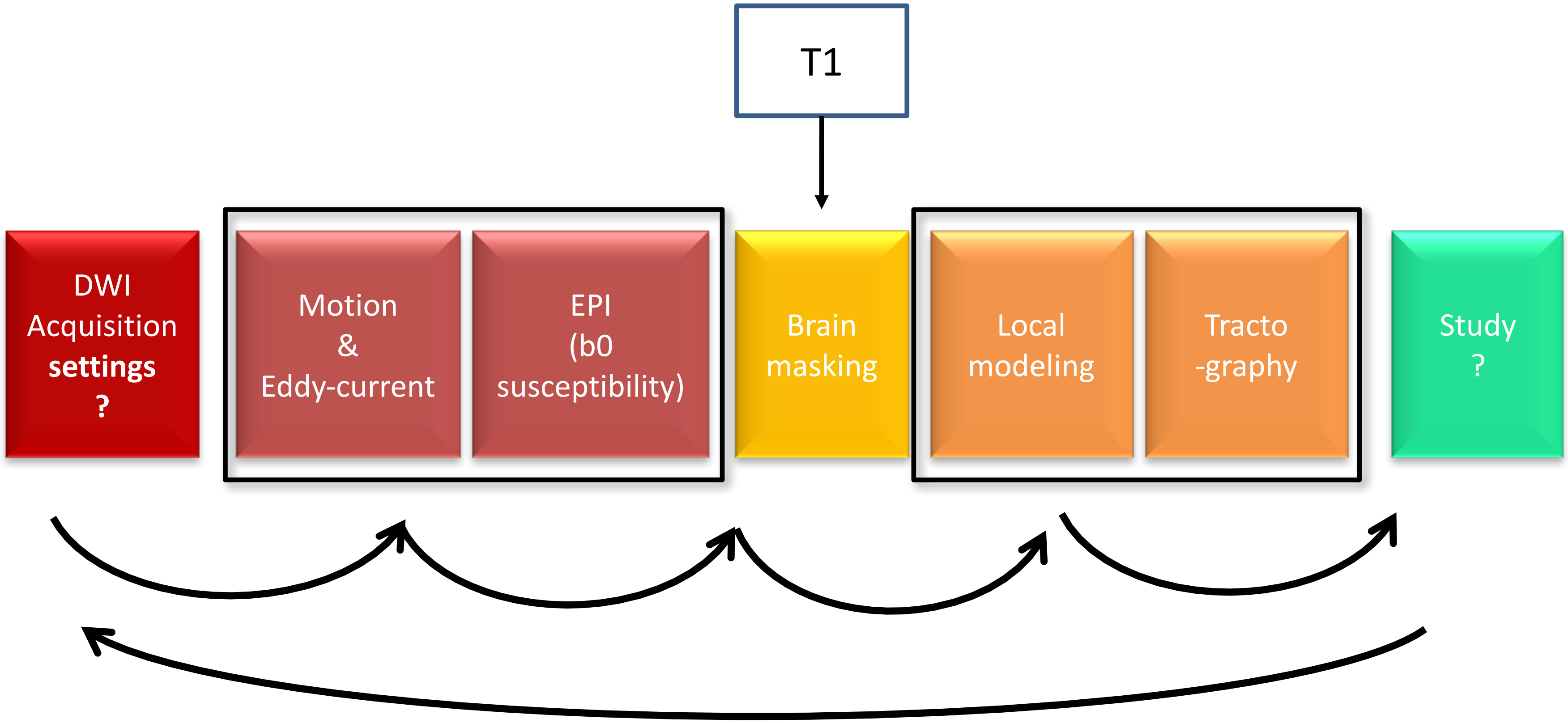




BrainVISA - Diffuse

- Introduction: dMRI data processing
  - Pre-processing
  - Post-processing: local models and tractography
- *Diffuse* toolbox
  - BrainVISA environment
  - Workflow
  - Demo
- Influence of pre-processing on post-processing analyses
  - Acquisition/Correction quality
  - Impact on co-registration
  - Impact on signal (diffusivity metrics)
- Outcome
  - Acquisition strategy
  - CentreIRM

Prétraitements et corrections des distorsions : quelle stratégie d'acquisition ?



Prétraitements et corrections des distorsions : quelle stratégie d'acquisition ?

On the menu of the MRI Center

Fast and less Furious

3min23s for AP acquisition : 76 volumes (32b100 + 32 b2000 + 6 b300 + 6 b0)

Resolution 1.8mm iso, MB4

Acquisition of only 6b0 in PA possible to gain time (acquisition time: 30s)

Less Fast and More Furious

5min39s for AP acquisition: 110 volumes (64b2000 + 32 b1000 + 6 b300 + 8b0)

Resolution 1.8mm iso, MB4

Acquisition of only 8b0 in PA possible to gain time (acquisition time: 40s)

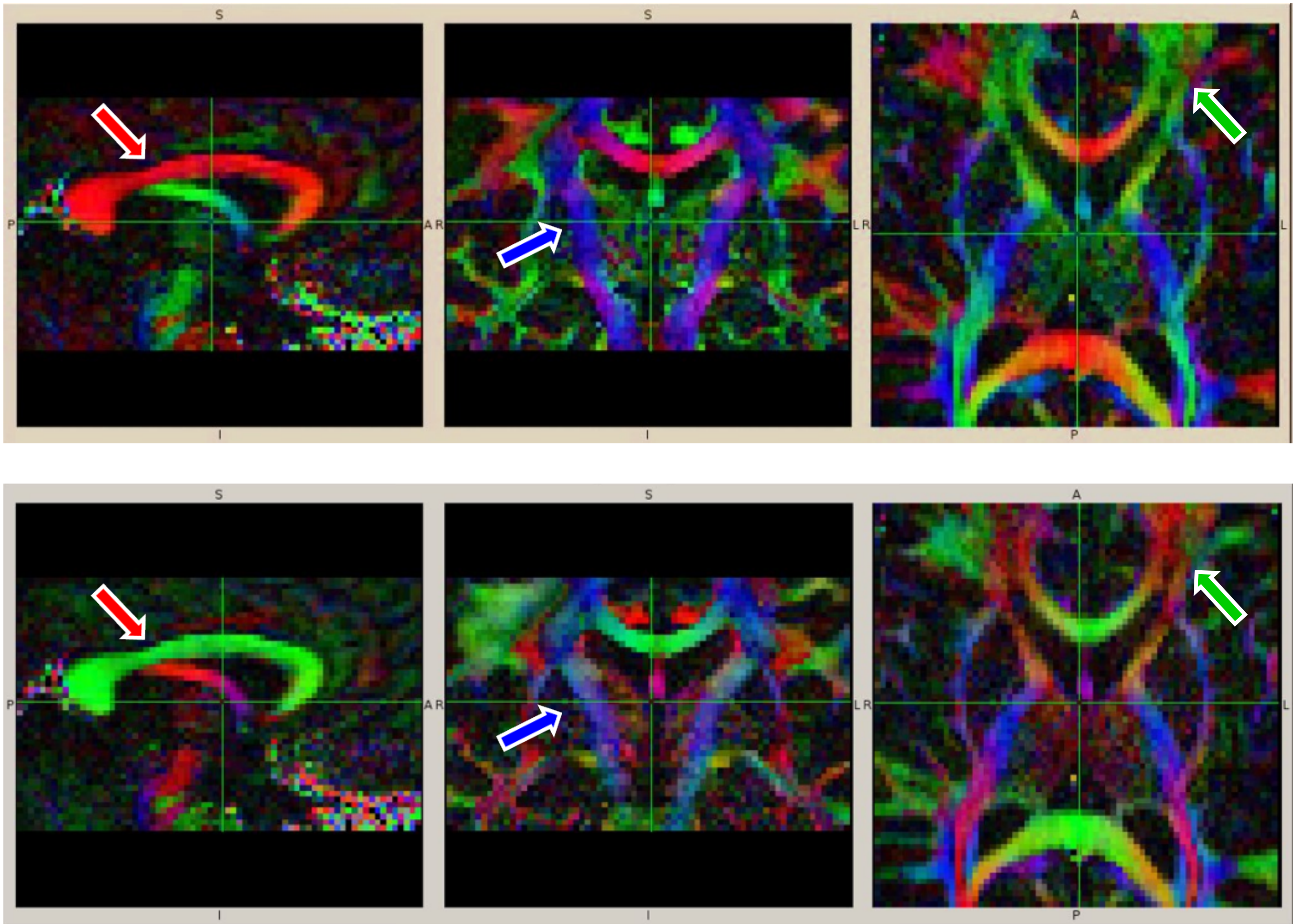
A la carte

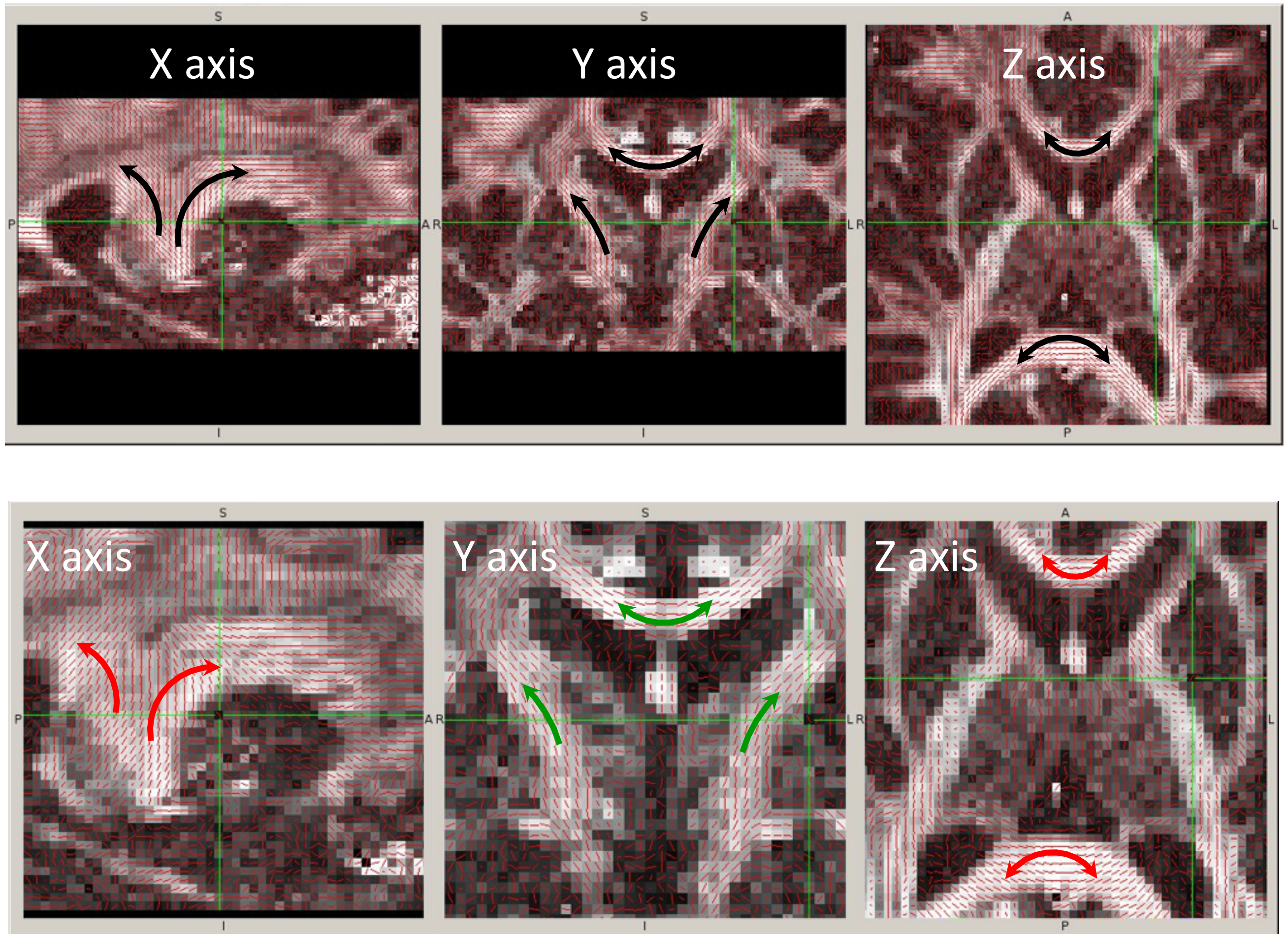
Possibility to chose any b-values , multishell , NODDI, DSI, HARDI…

INT - MeCA
Olivier COULON
Lucile Brun
Alexandre PRON

INT - SCALP
Christine DERUELLE

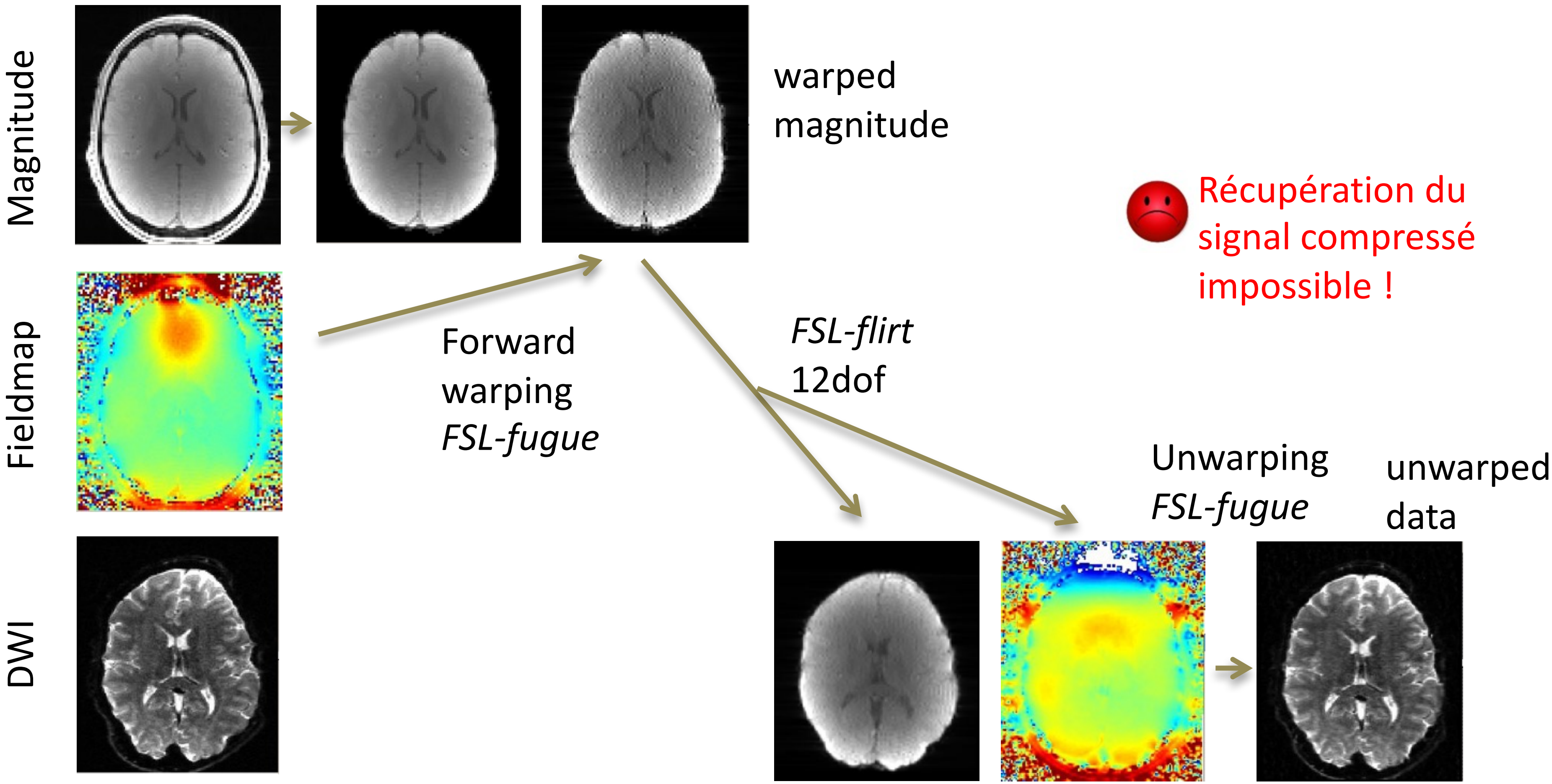
Centre IRM – INT @ CERIMED
Jean-Luc ANTON
Pascal BELIN
Bruno NAZARIAN
Julien SEIN


S
P
A
I
R
L


X axis
Y axis
Z axis
S
P
A
I
R
L
X axis
Y axis
Z axis

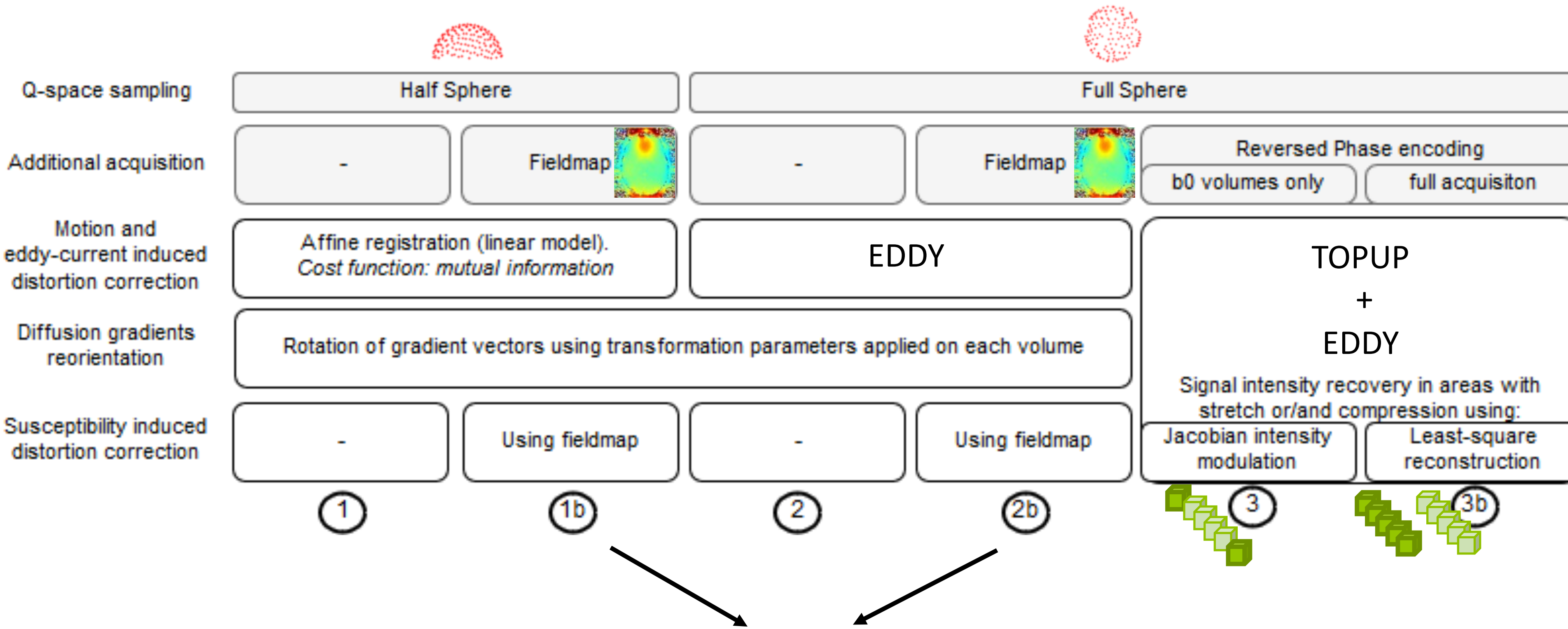
Magnetic susceptibility

Cusack et al, NeuroImage 2003



Récupération du signal compressé impossible !

Acquisition strategy



- Low computing time
- Two resampling steps

- Meilleure estimation du champ de distorsion des EC
- Un seul ré-échantillonnage de l'image finale