



UNIVERSITÉ  
**PARIS-SUD 11**

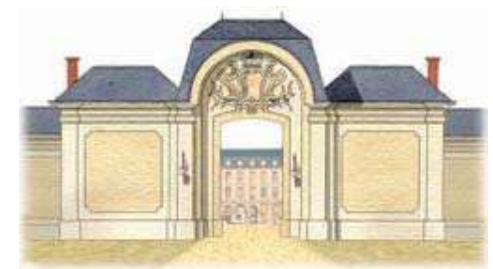
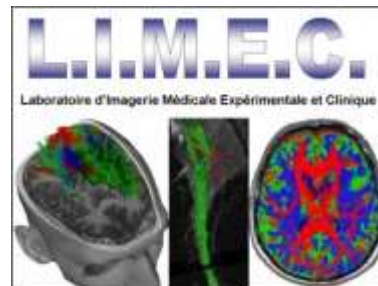
# Tractographie Par IRM de Diffusion

Pr Denis Ducreux

Neuroradiologie, CHU Bicetre

CNRS IR4M (UMR 8081), Université Paris 11

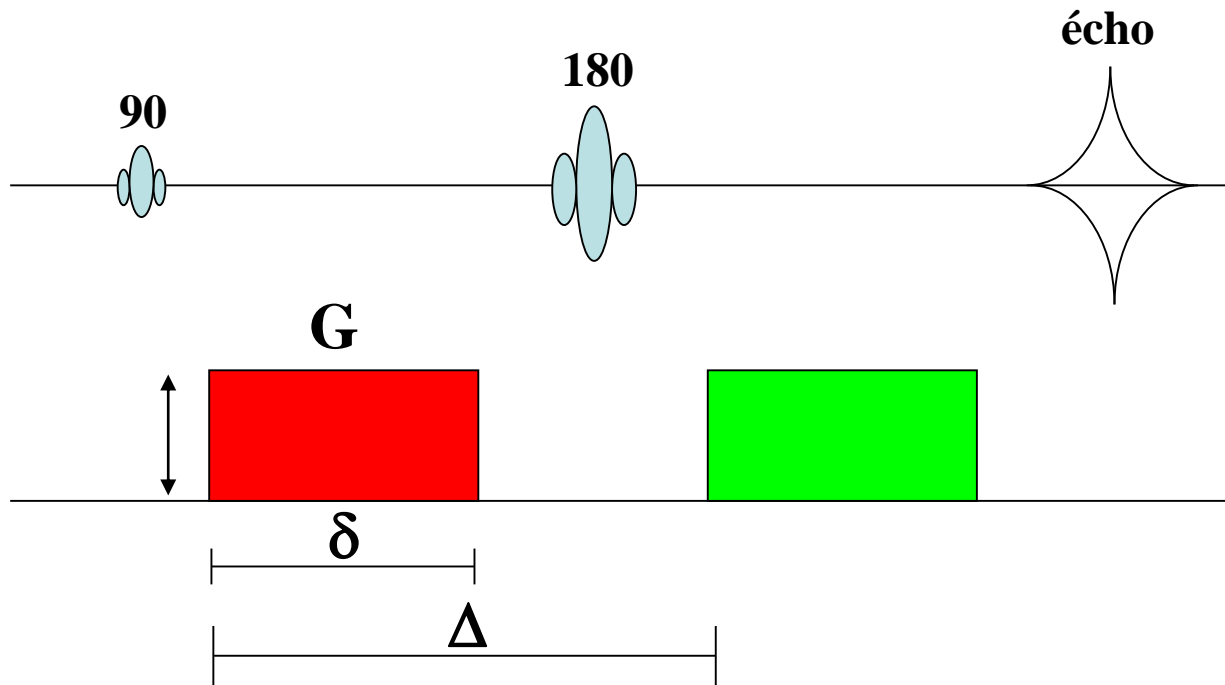
Hôpitaux  
universitaires  
**Paris-Sud**  
Antoine-Béclère Bicêtre Paul-Brousse



# Tenseur de Diffusion

# Méthodologie et Mise en Oeuvre

## IRM de Diffusion – Bases Physiques

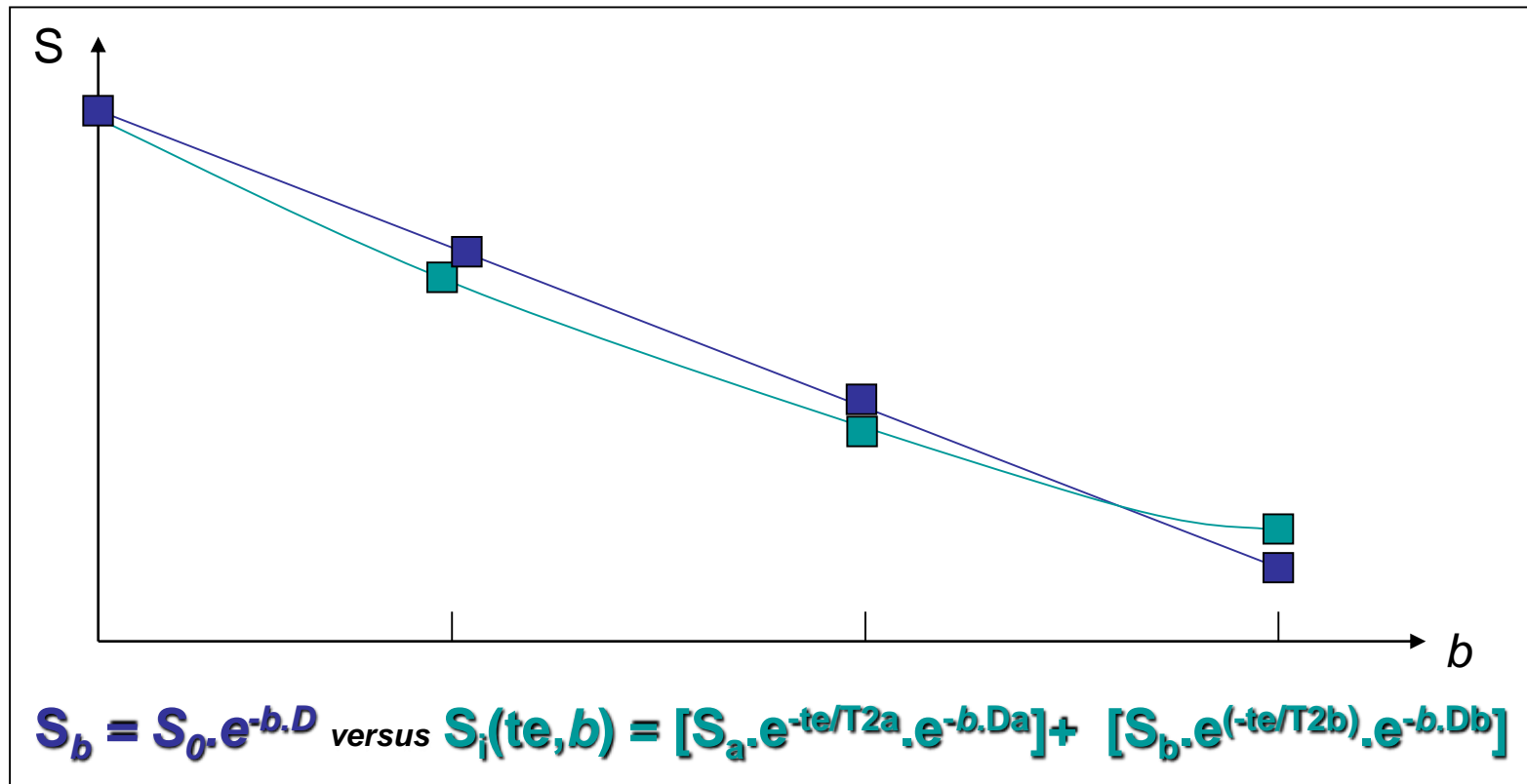


$$S = S_0 e^{-\gamma^2 \delta^2 G^2 (\Delta - \delta/3)}$$

# Méthodologie et Mise en Oeuvre

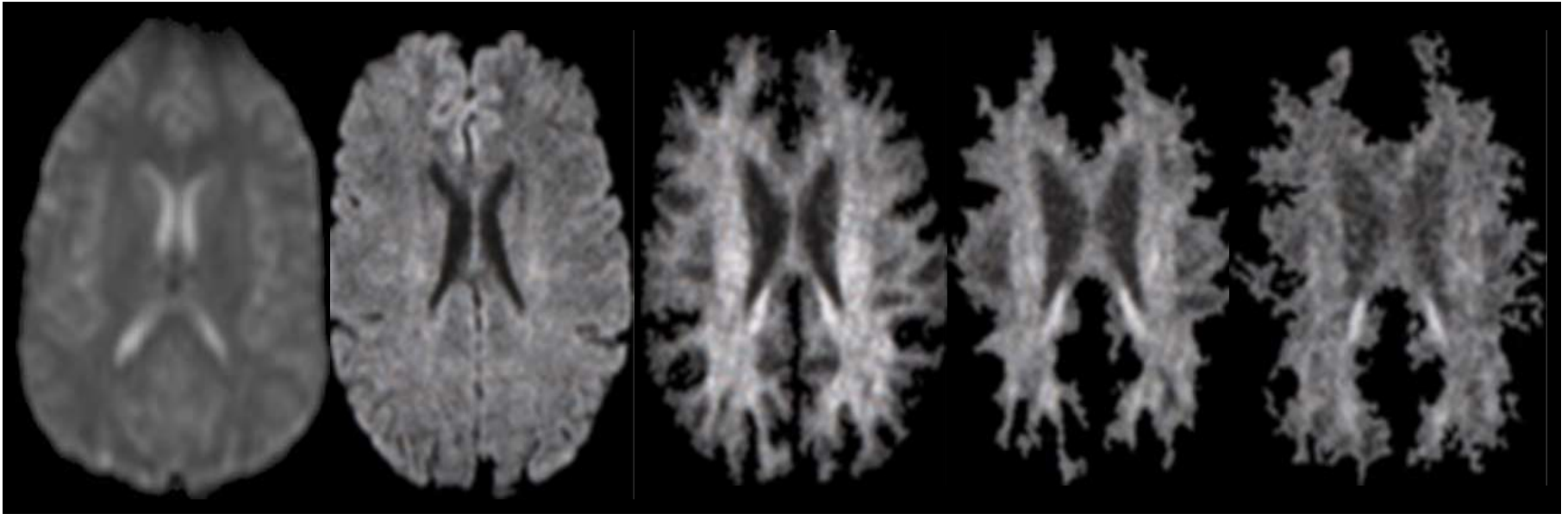
## IRM de Diffusion – Bases Physiques

Modèles mono et bi-compartmentaux



# DIFFUSION

## Séquence de Diffusion

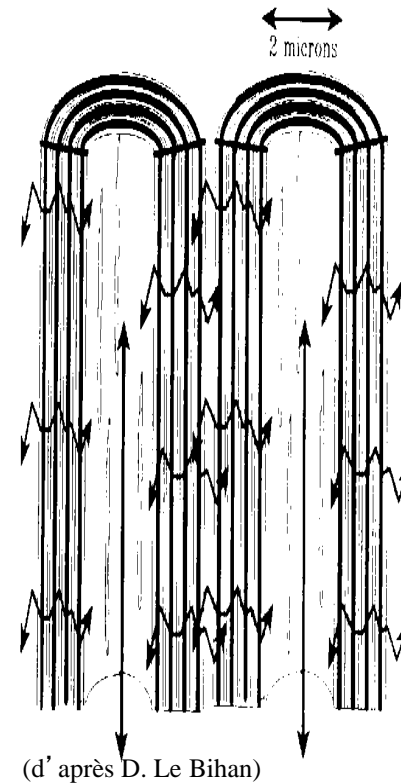
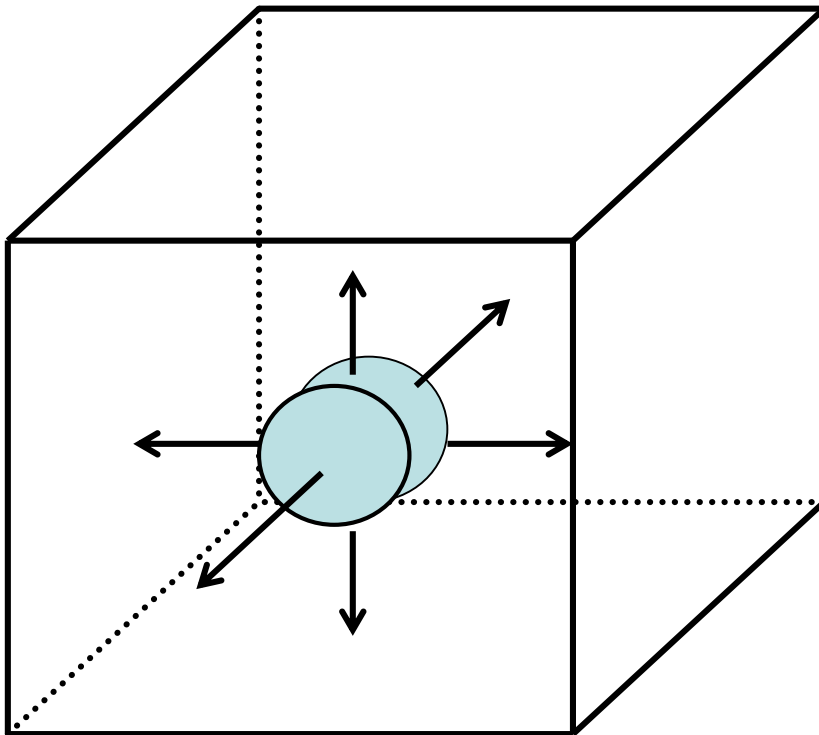


**T2 :  $b=0$  s/mm<sup>2</sup>    DWI :  $b=1000$  s/mm<sup>2</sup>    DWI :  $b=2000$  s/mm<sup>2</sup>    DWI :  $b=3000$  s/mm<sup>2</sup>    DWI :  $b=4000$  s/mm<sup>2</sup>**

# Méthodologie et Mise en Oeuvre

## IRM de Tenseur de Diffusion

- Description complète des propriétés de diffusion d'un voxel
- Tenseur de diffusion (gradients dans  $\geq 6$  dir. de l'espace)

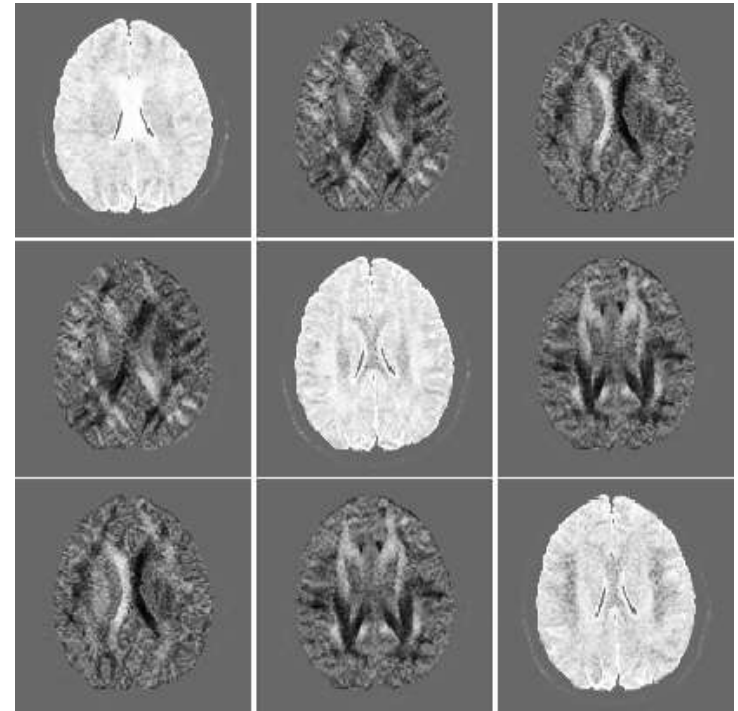


# Méthodologie et Mise en Oeuvre

## IRM de Tenseur de Diffusion

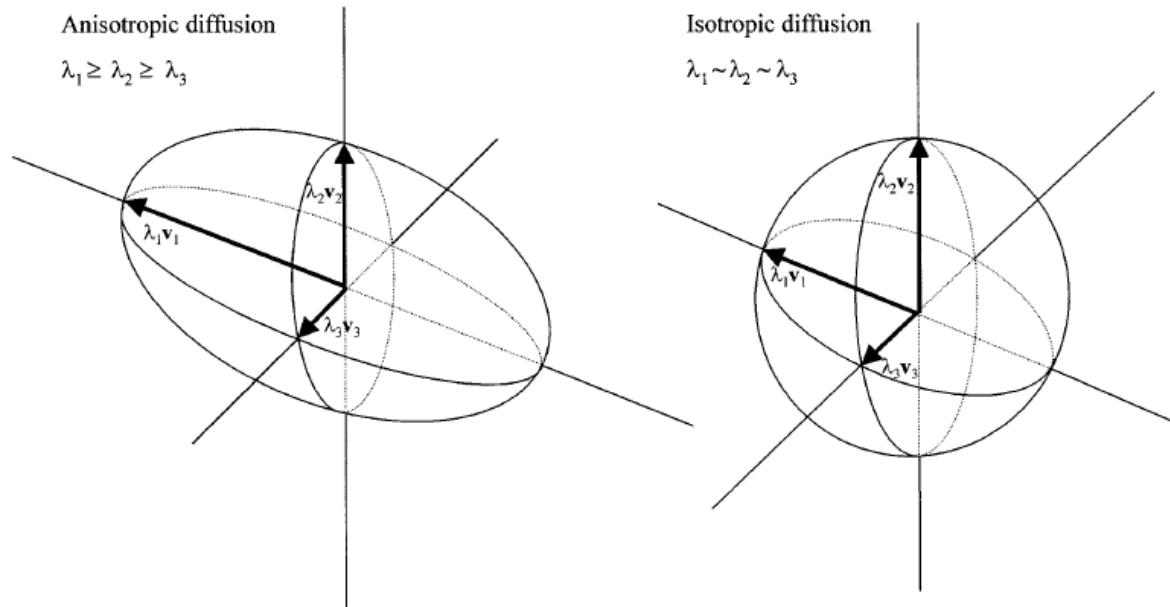
- DTI mesure l' ADC dans 6 directions de l' espace;
- le modèle: tenseur de diffusion  $D$  = matrice symétrique 3x3;
- le tenseur est calculé pour chaque voxel

$$D = \begin{pmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{zx} & D_{zy} & D_{zz} \end{pmatrix}$$



# Méthodologie et Mise en Oeuvre

## IRM de Tenseur de Diffusion



*$v_1, v_2$  et  $v_3$   
directions*

*$\lambda_1, \lambda_2$  et  $\lambda_3$   
valeurs propres  
(longueurs)*

- Tenseurs utilisés pour décrire la diffusion peuvent être conceptualisés et visualisés comme des ellipsoïdes
- Si les trois valeurs propres sont égales, la diffusion est isotrope et le tenseur de diffusion peut être visualisé comme une sphère



# Méthodologie et Mise en Oeuvre

## IRM de Tenseur de Diffusion

*Paramètres de la diffusion anisotrope :*

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

$$RA = \frac{1}{\sqrt{3}} \frac{\sqrt{(\lambda_1 - \lambda)^2 + (\lambda_2 - \lambda)^2 + (\lambda_3 - \lambda)^2}}{(\lambda_1 + \lambda_2 + \lambda_3)} \quad AI = \frac{ADC_{\max} - ADC_{\min}}{ADC_{\text{mean}}}$$

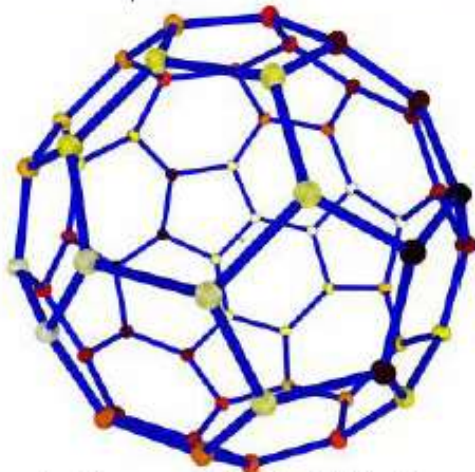
$$VR = \frac{V_{\text{ellipsoïde}}}{V_{\text{sphère}}} = \frac{\lambda_1 \lambda_2 \lambda_3}{(\lambda)^3} = \frac{\lambda_1 \lambda_2 \lambda_3}{\left(\frac{\lambda_1 + \lambda_2 + \lambda_3}{3}\right)^3} = 27 \frac{\text{Det}(D)}{\text{Trace}(D)^3}$$

# Méthodologie et Mise en Oeuvre

## IRM de Tenseur de Diffusion



*Vector representation for 30 directions*



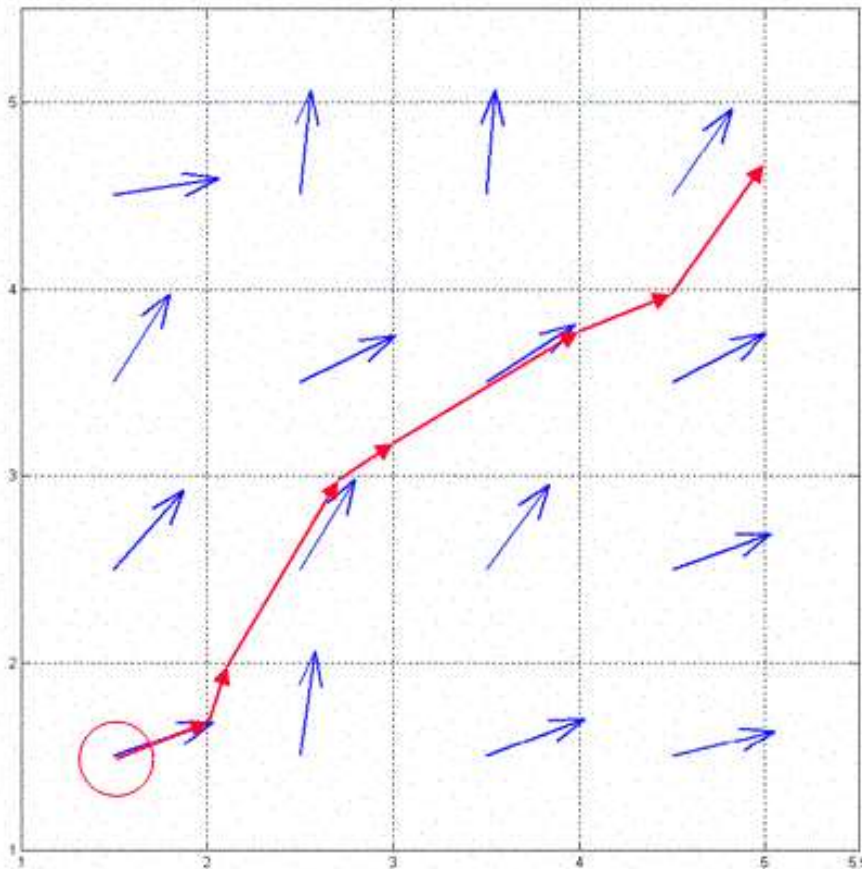
*Point representation for 30 directions*

Choix du nombre de directions :

- Compromis entre qualité (SNR) et durée de l'acquisition
- Utilisation du modèle mono-compartmental (1 valeur de  $b$ ) et du tenseur de diffusion (pas de DSI : nb directions < 30)
- Corrections des macro-mouvements liée au nb de directions

# Méthodologie et Mise en Oeuvre

## Tracking de Fibres – Modèle FACT (1)



A partir du point  $S(0)$ , on a l'équation en 3D suivante :

$$\delta S(t)/\delta t = R(t)$$

Avec :

- $S(t)$  : position de la fibre curviligne au temps  $t$
- $R(t)$  : tangente à la direction du faisceau

# Méthodologie et Mise en Oeuvre

## Tracking de Fibres – Modèle Advection – Diffusion <sup>(1)</sup>

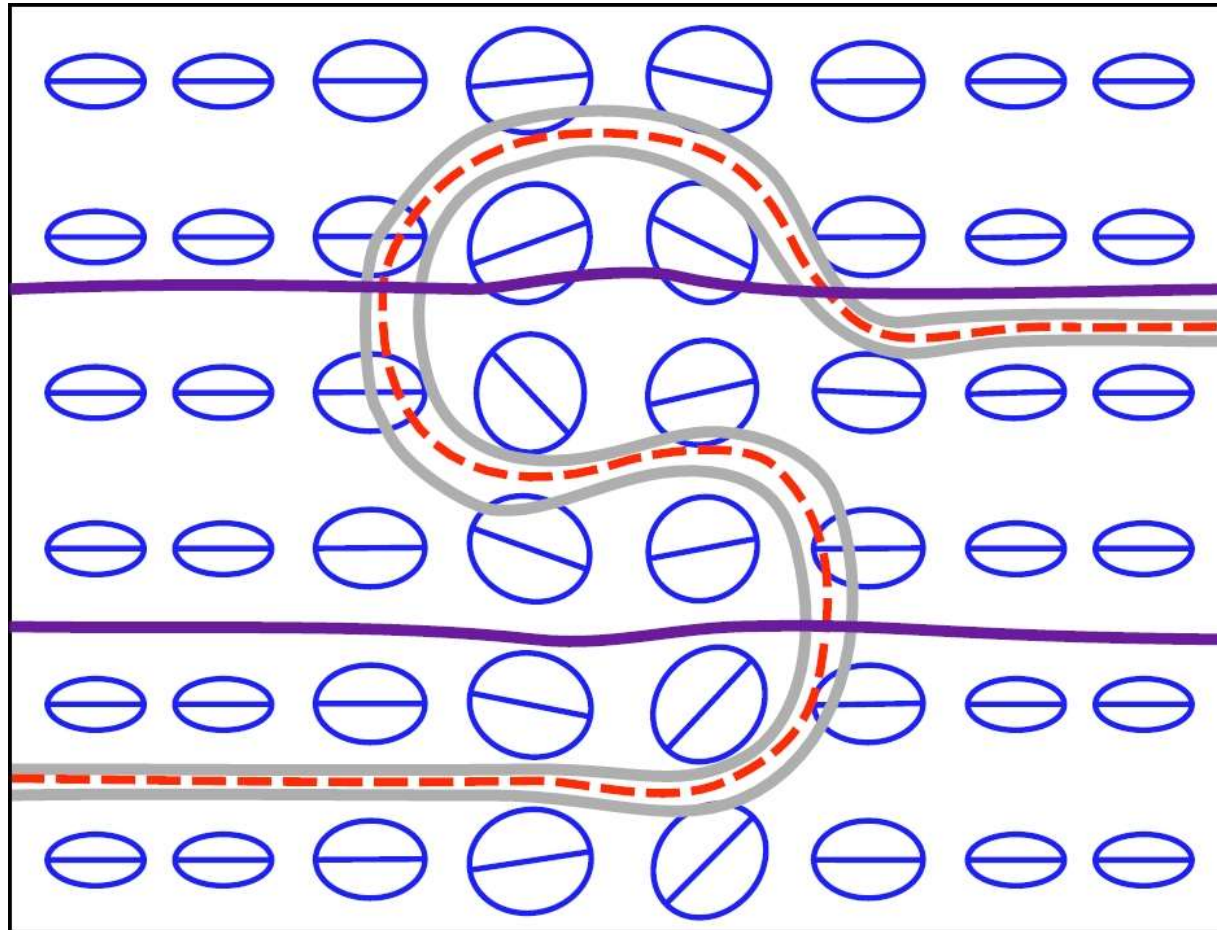
- Mélange d'un terme de diffusion et d'advection.
- Diffusion : suit la direction principale du tenseur  $v_1$ .
- Advection : combinaison linéaire entre la direction précédente  $v_{in}$  et  $v_{out} = Dv_{in}$ :

$$v_{out} = \underbrace{c_l v_1}_{\text{diffusion}} + \underbrace{(1 - c_l) \left( (1 - W) v_{in} + W v_{out} \right)}_{\text{advection}}$$

- Amélioration: interpolation tri-linéaire du champ de tenseurs avec les métriques Log-Euclidiennes <sup>(2)</sup>.

# Méthodologie et Mise en Oeuvre

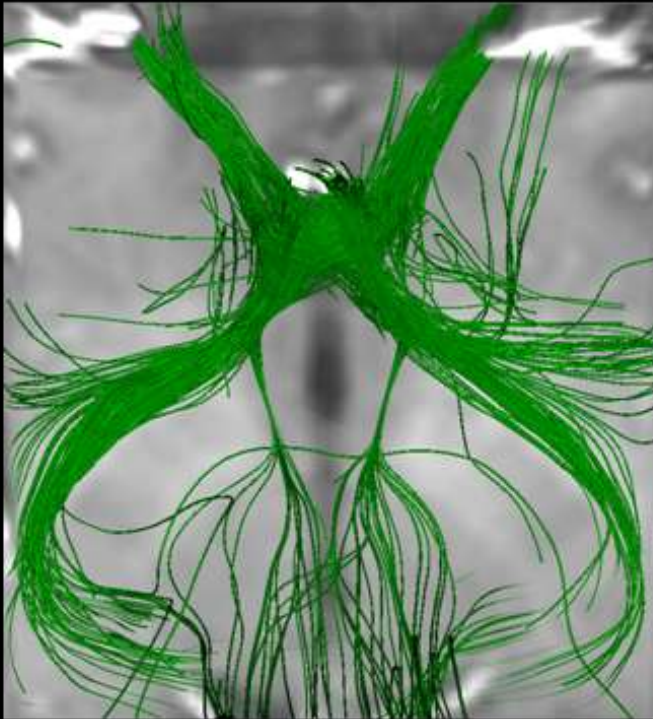
## Tracking de Fibres – Comparaison FACT et A.D.



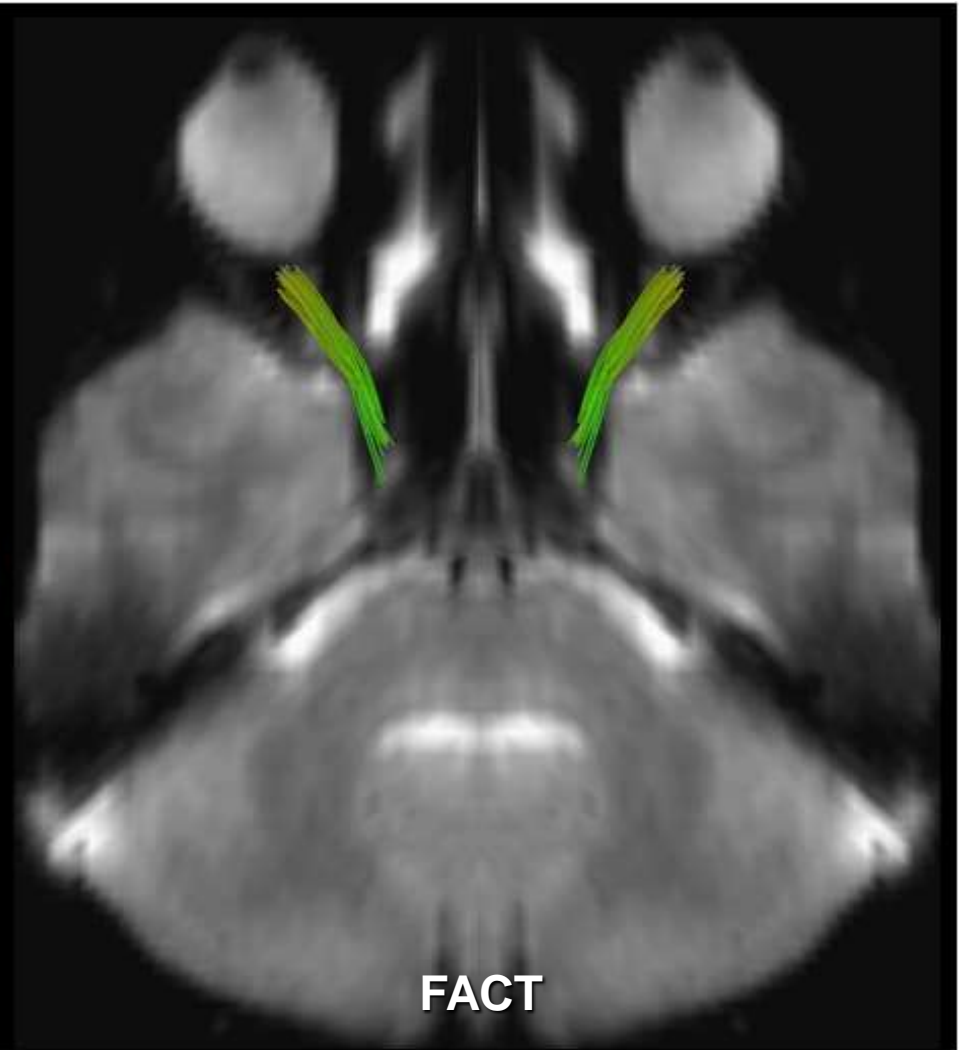
**Streamline** vs **Advection - Diffusion**

# Méthodologie et Mise en Oeuvre

## Tracking de Fibres



AD + Log-Euclidiens



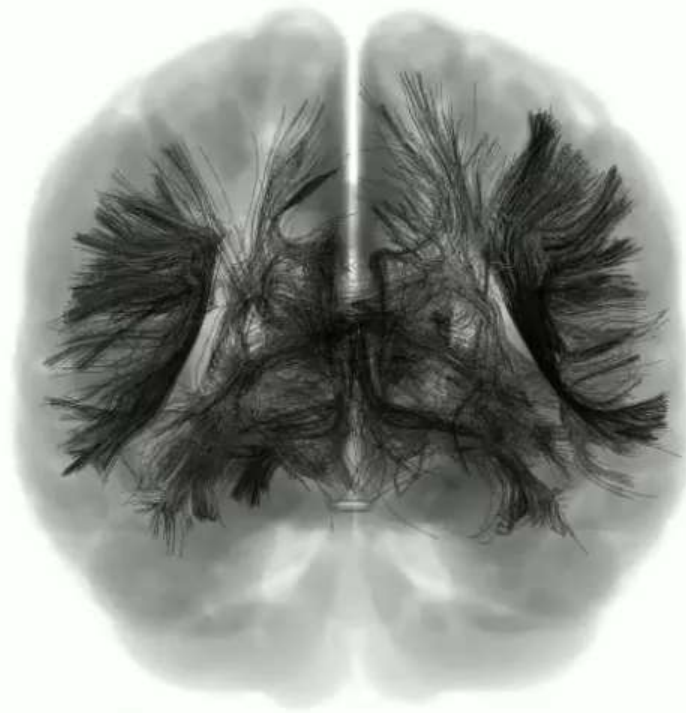
FACT

**Anatomie Normale**

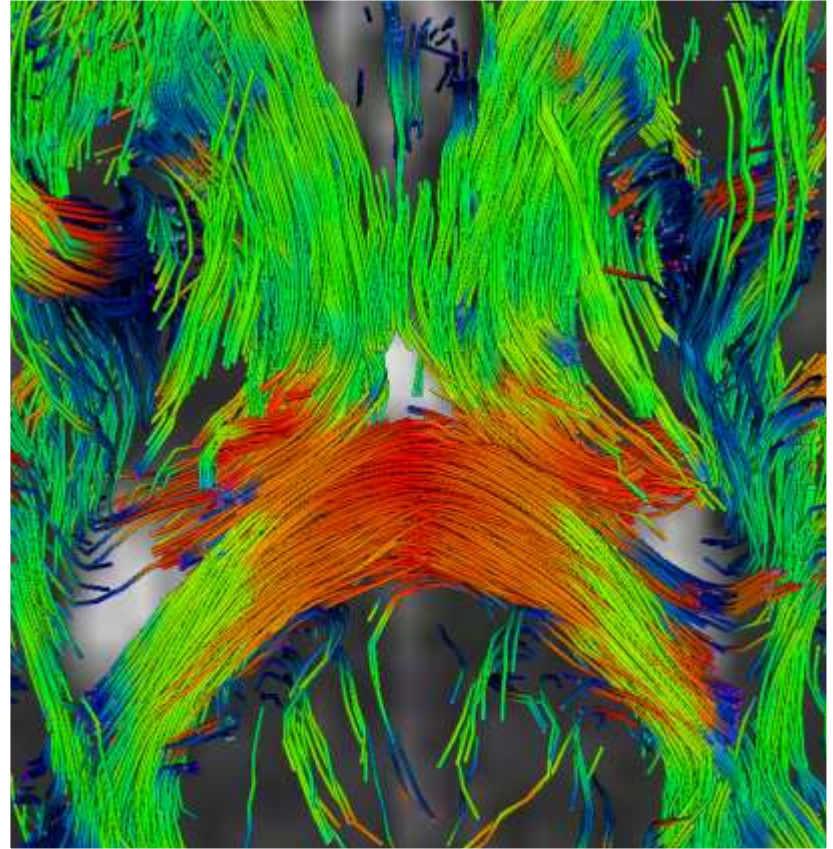
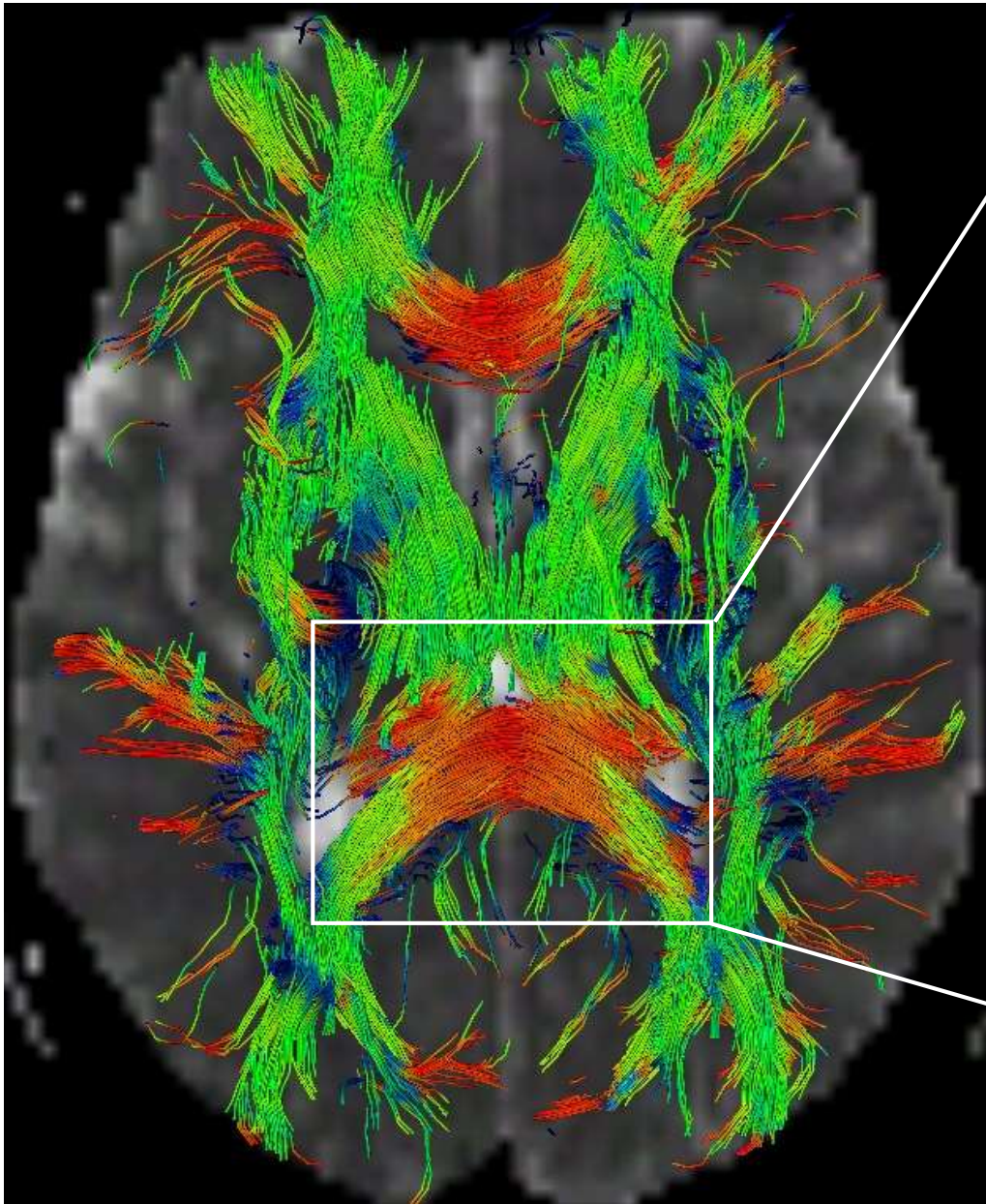
**Cerveau**



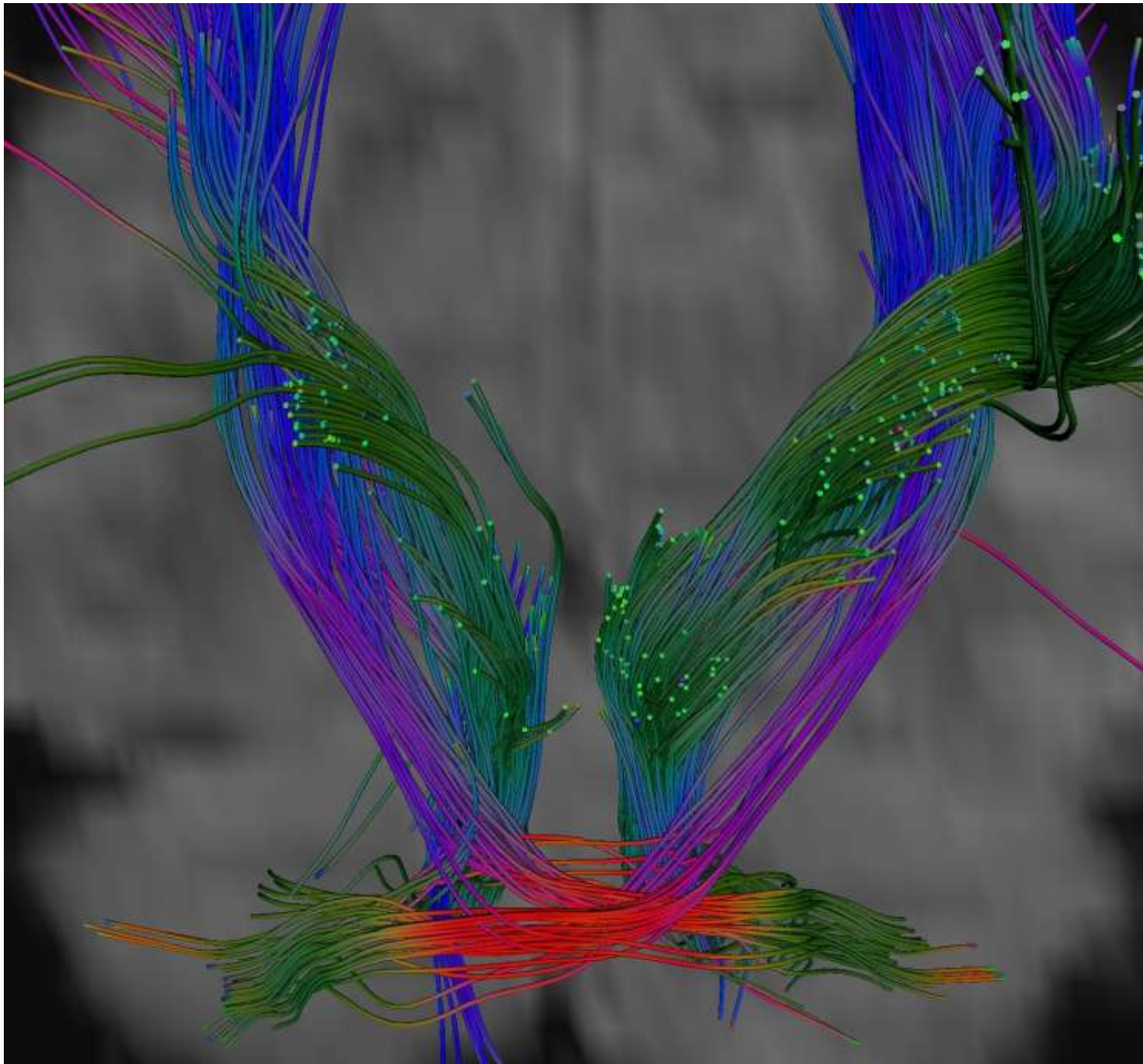
Made with fMRICRoTools

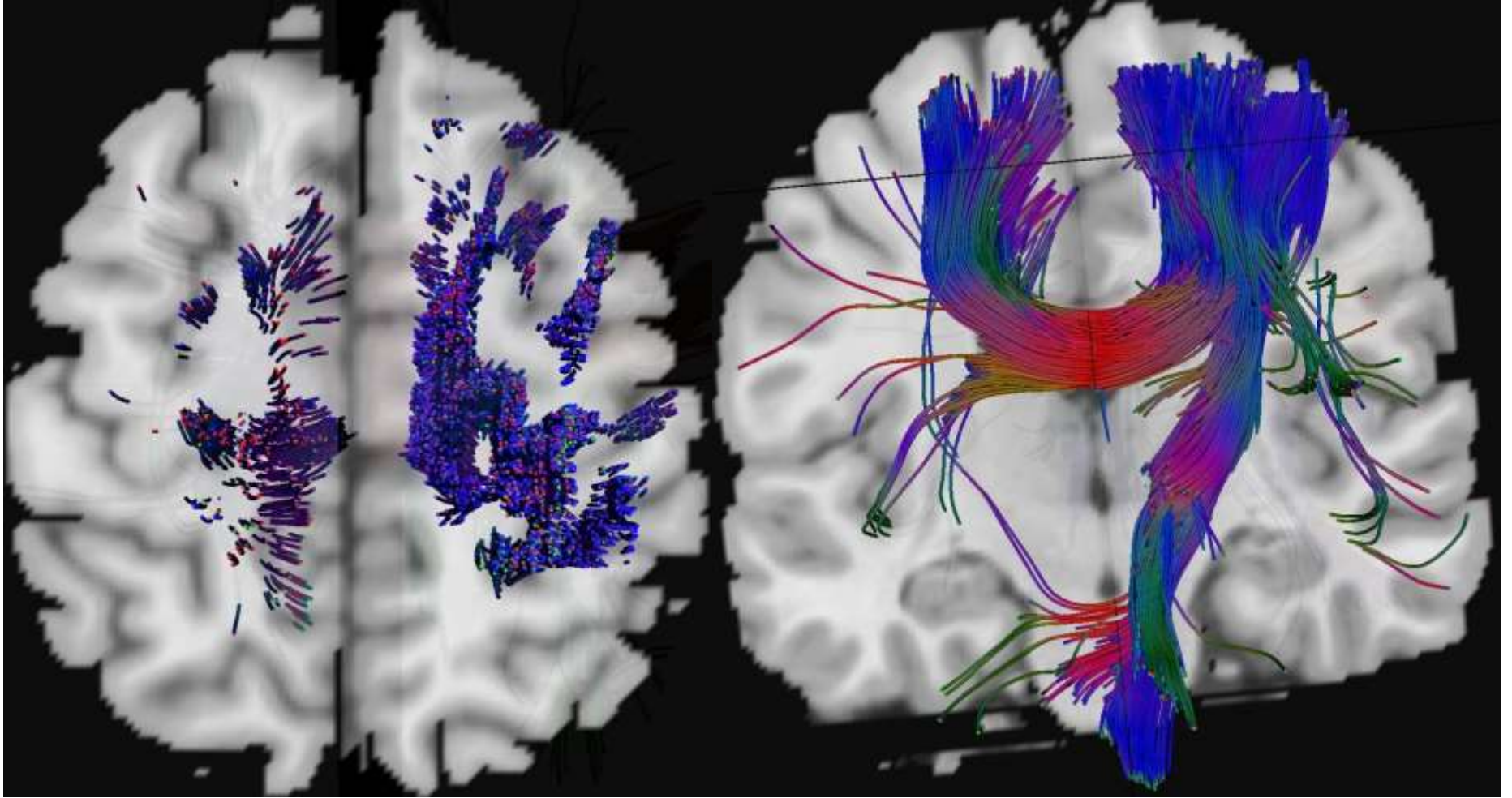




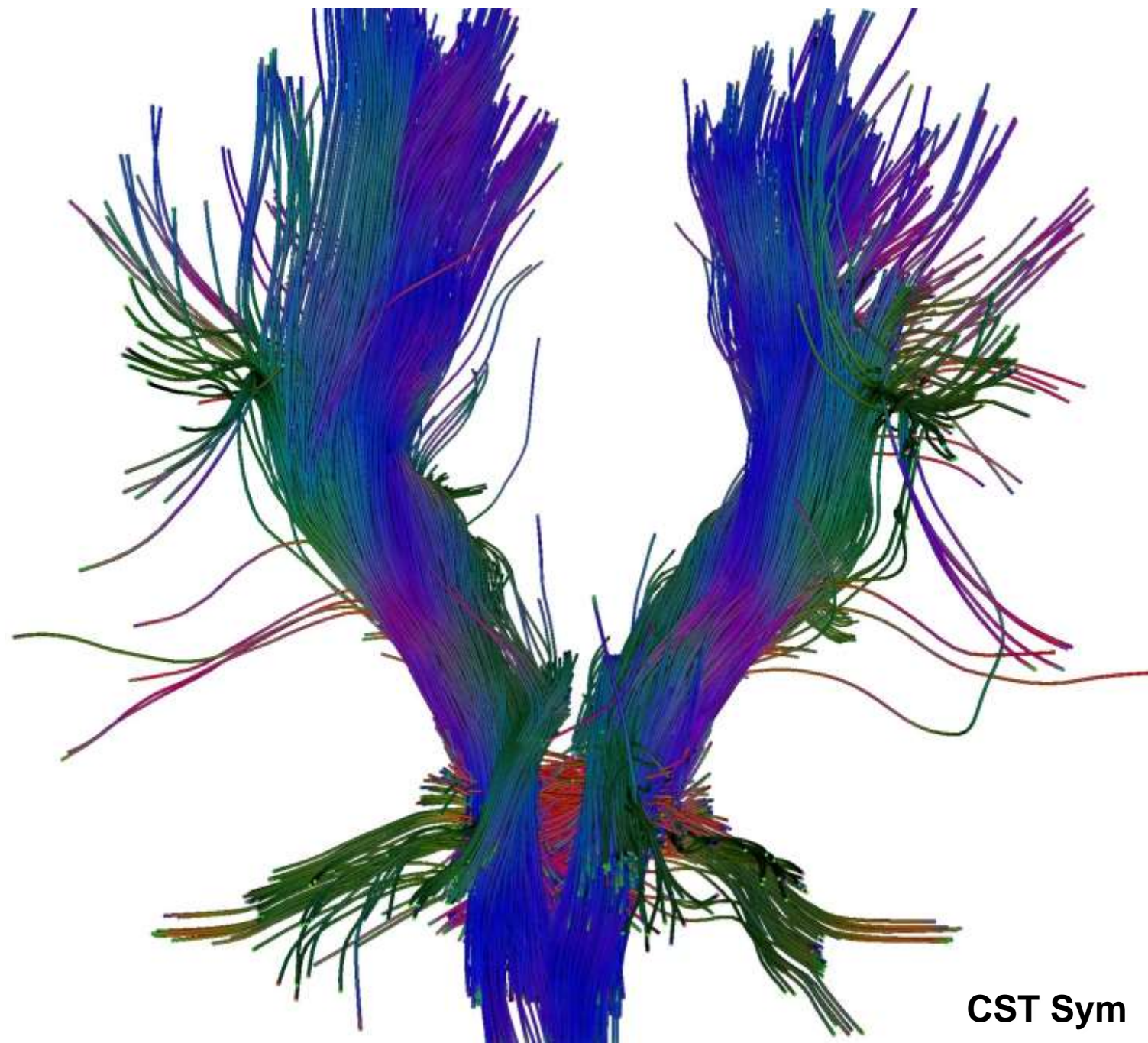




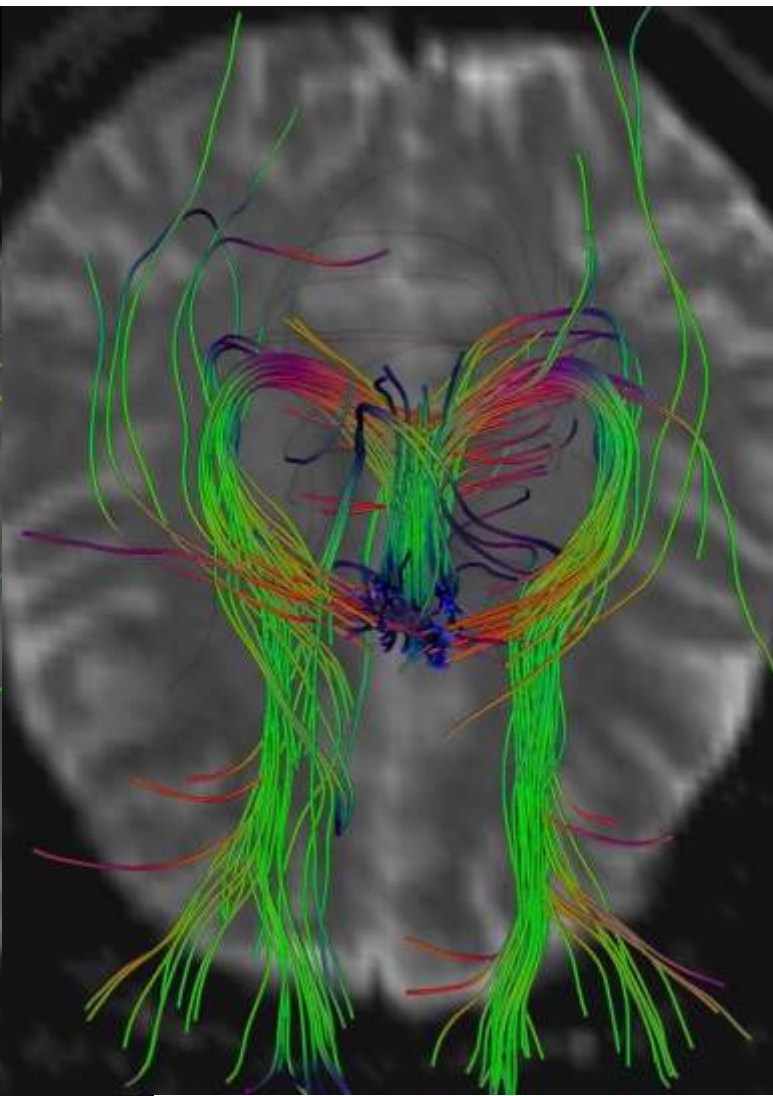
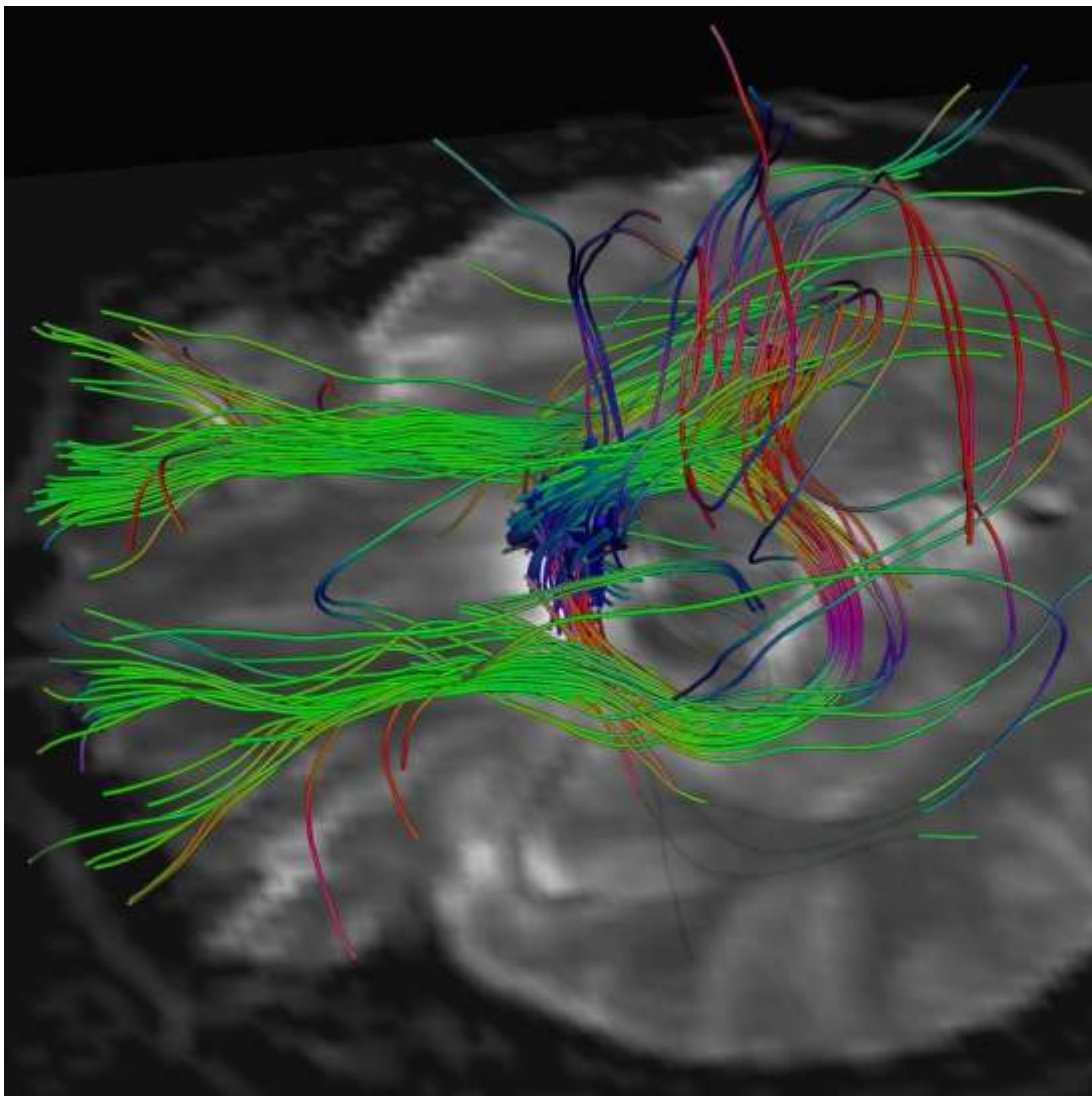




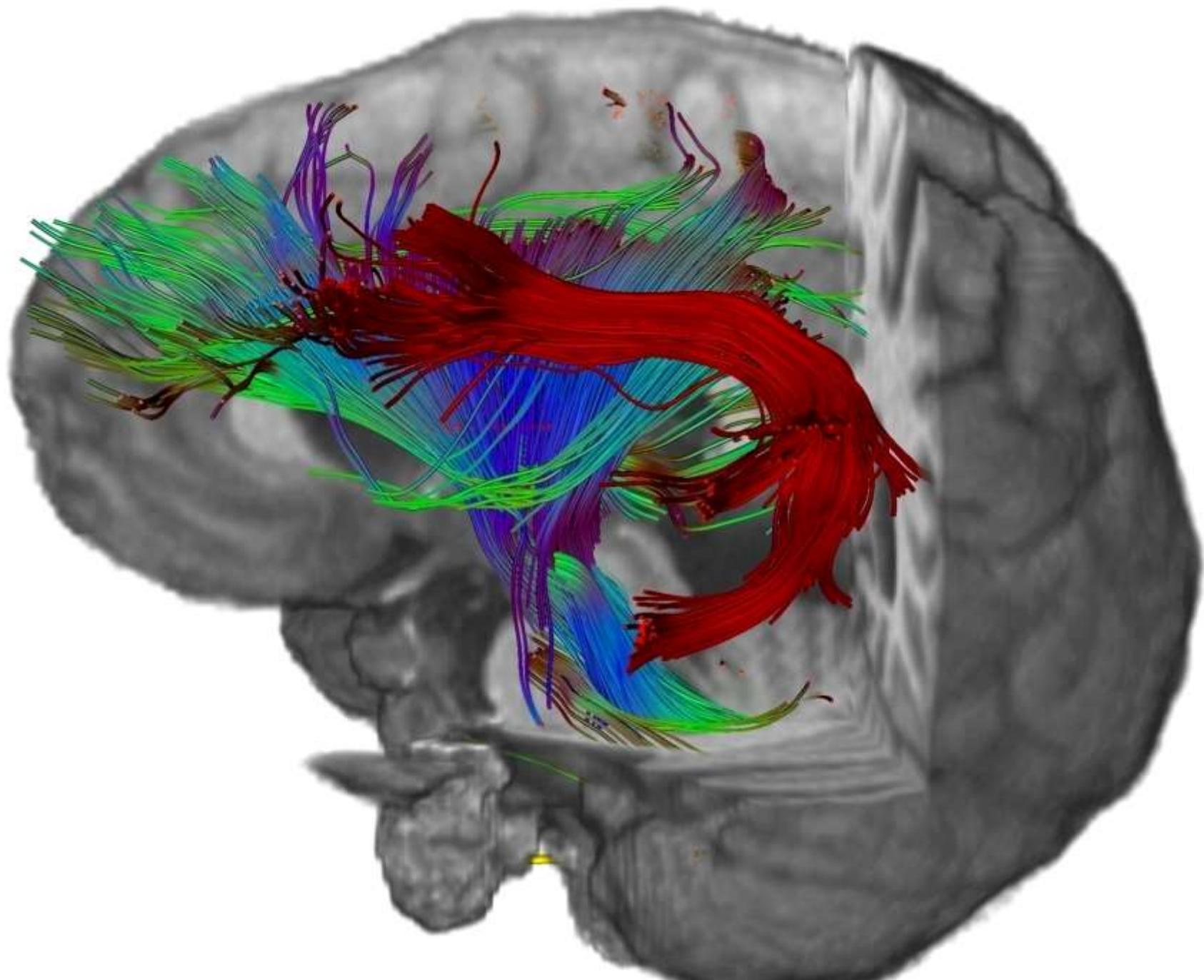


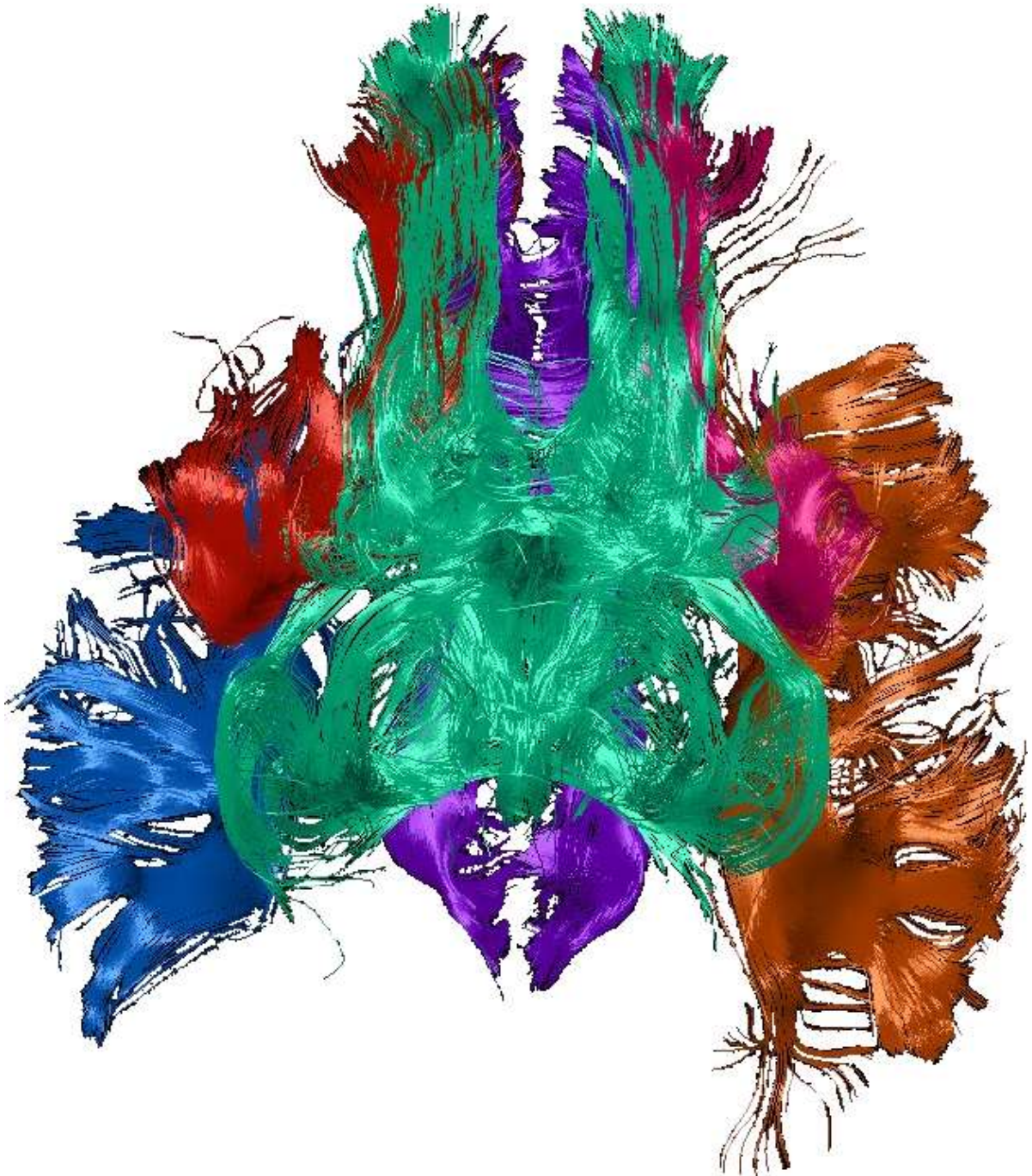


**CST Sym**





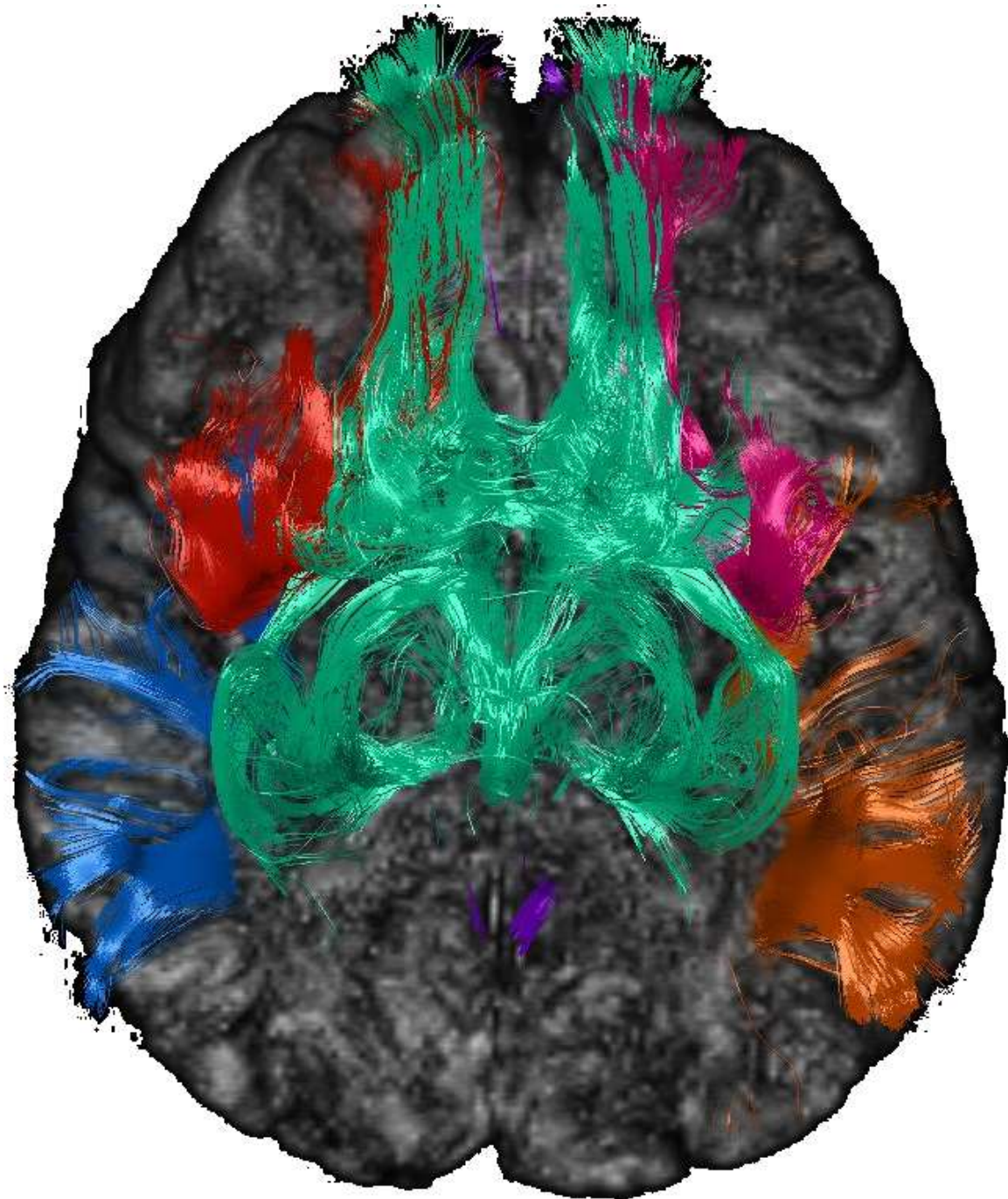


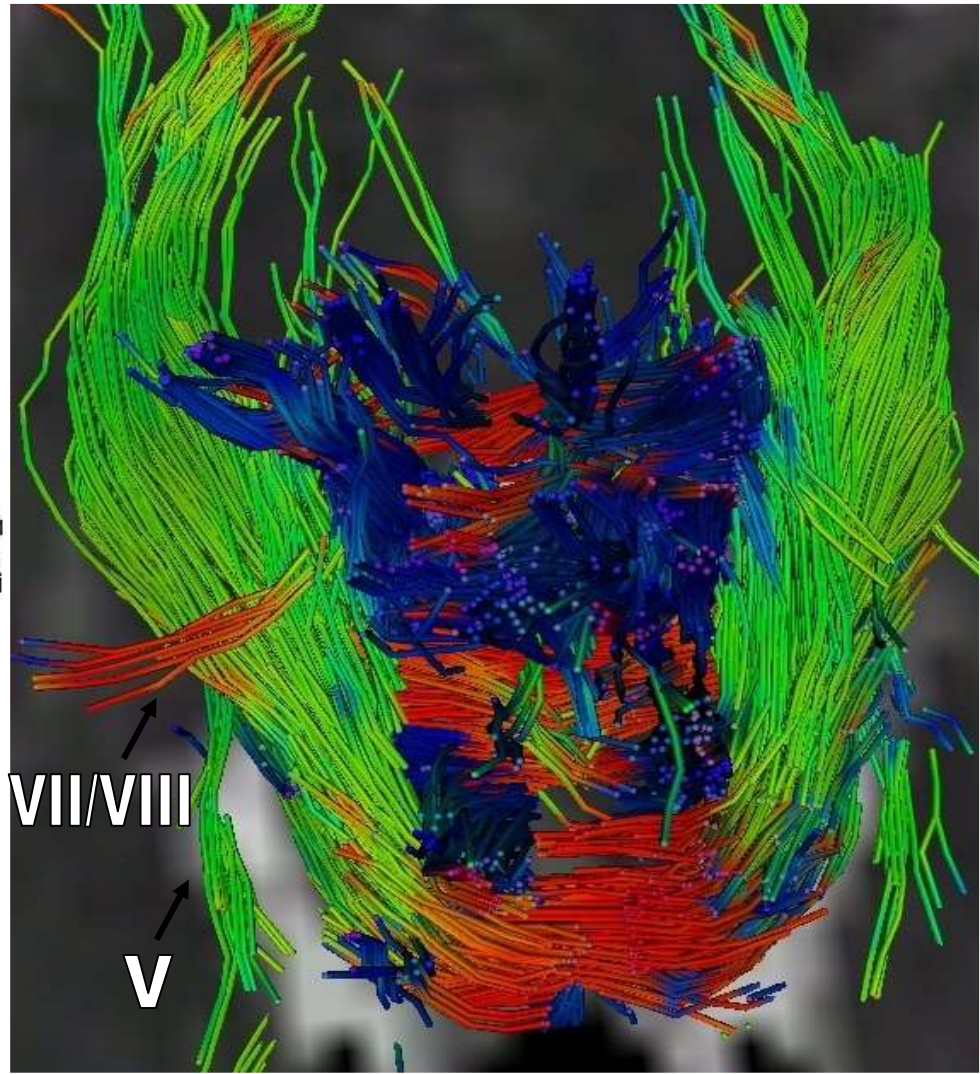
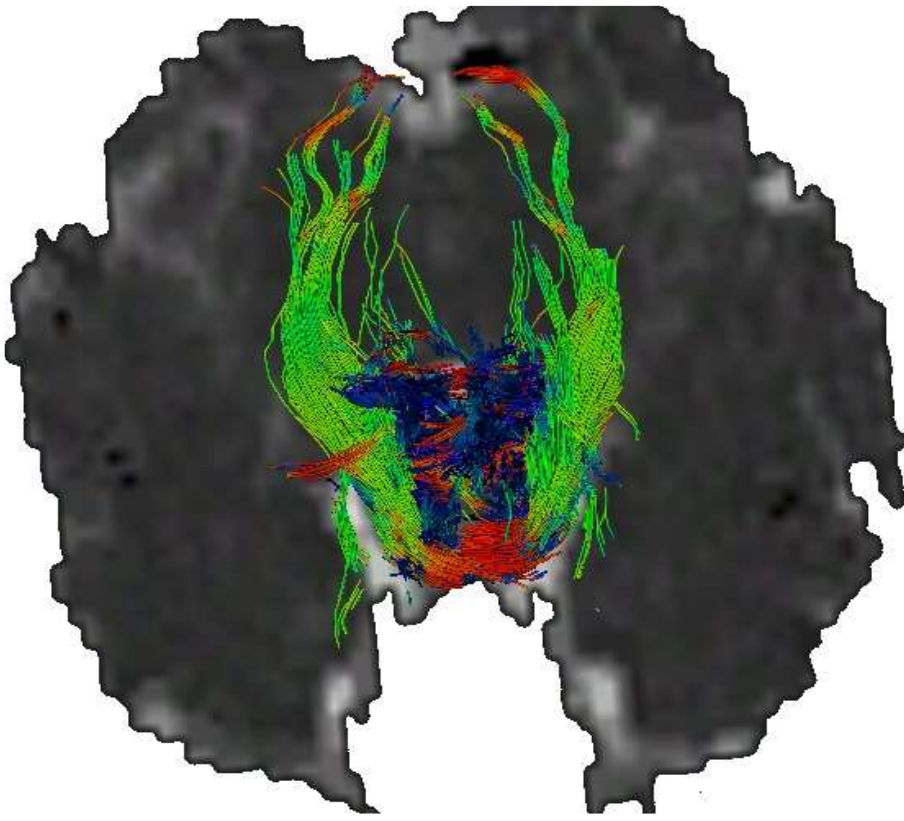








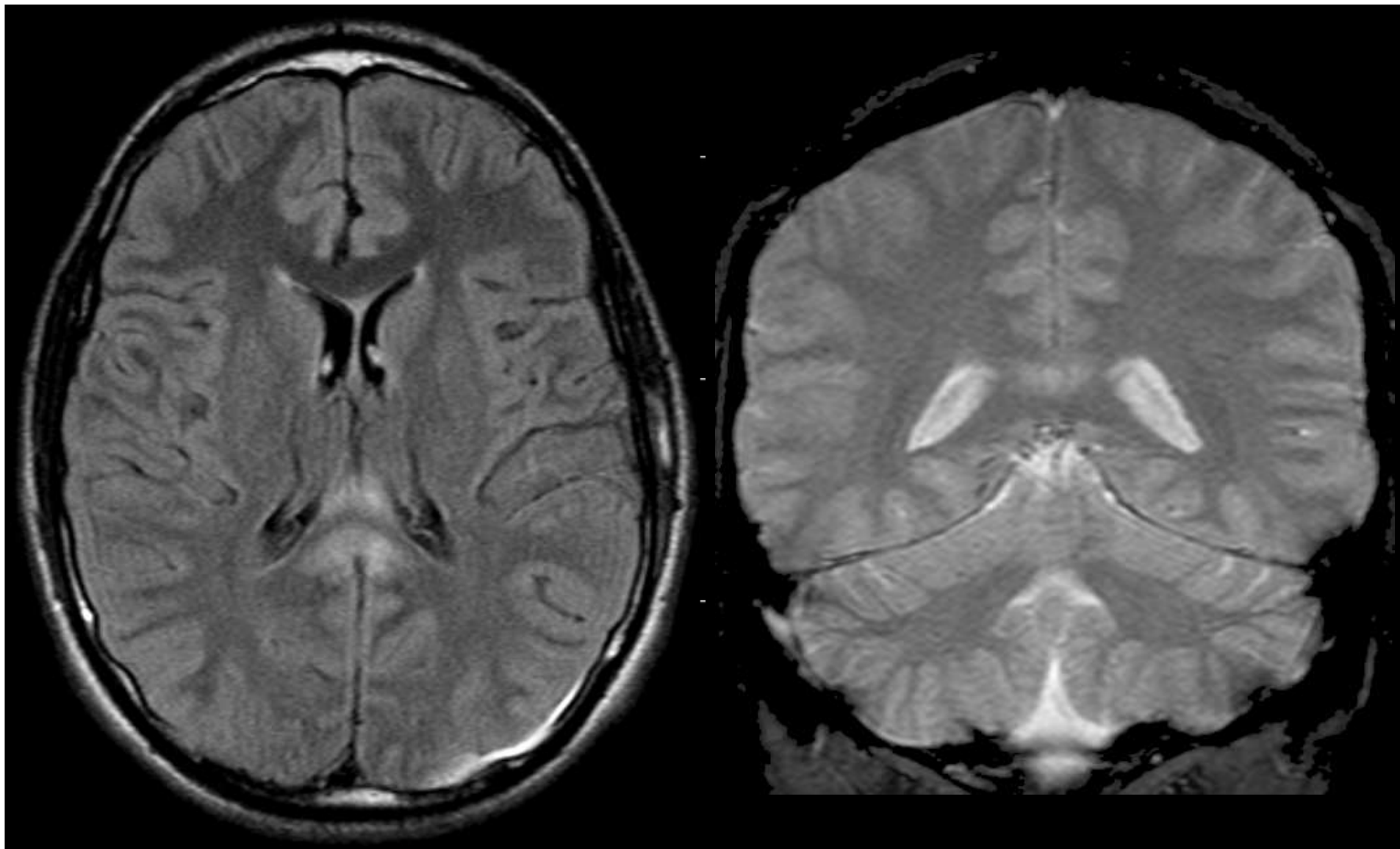


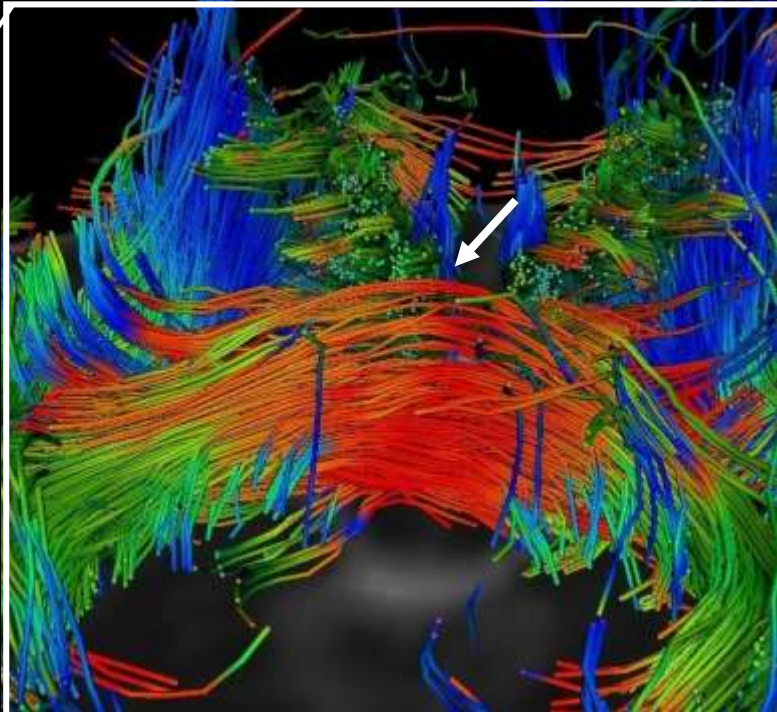
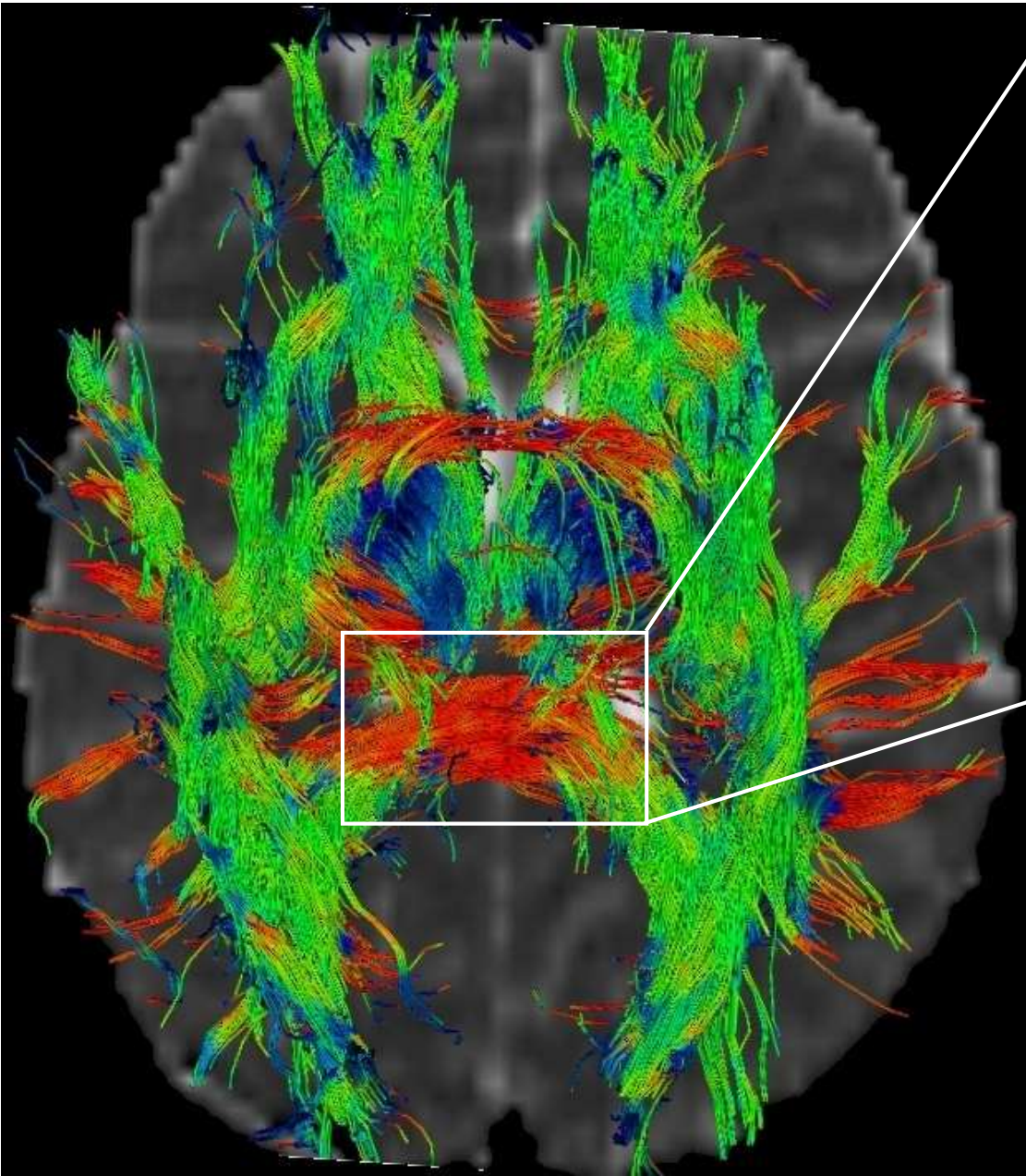


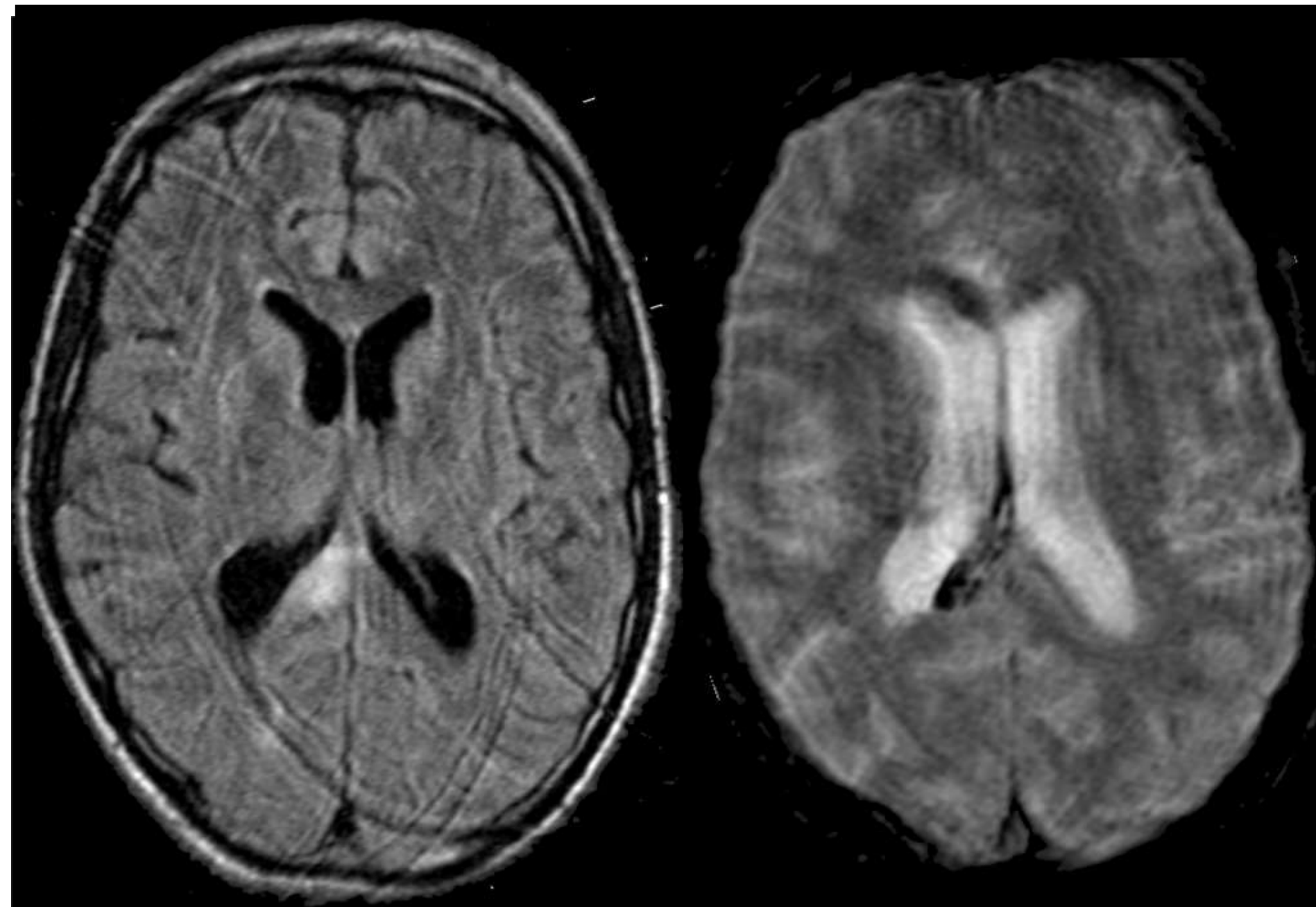
# Applications Cliniques

# Lésions de Cisaillement Axonal

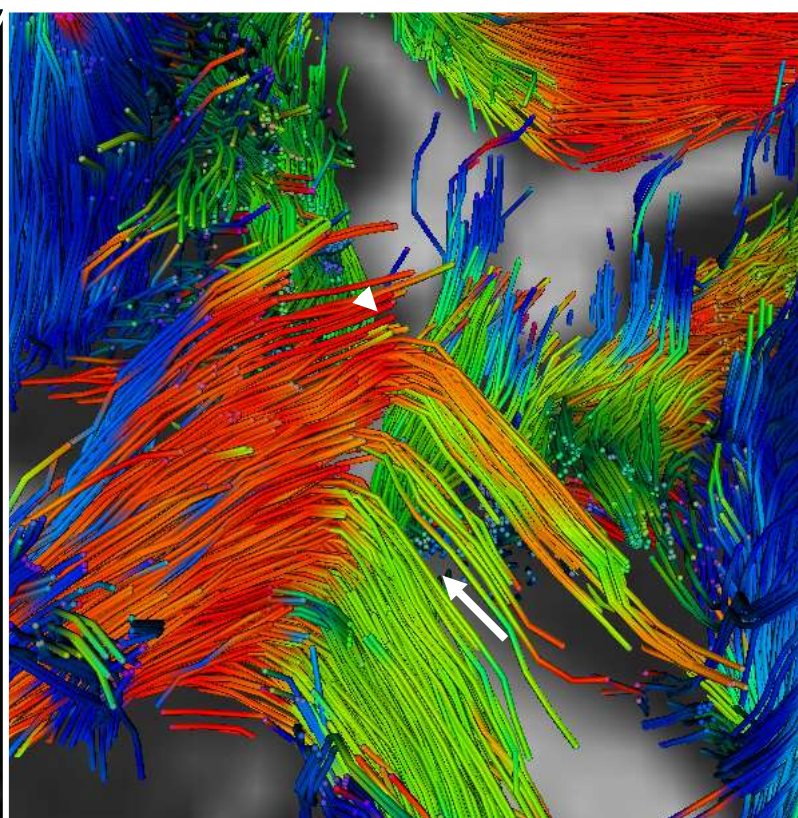
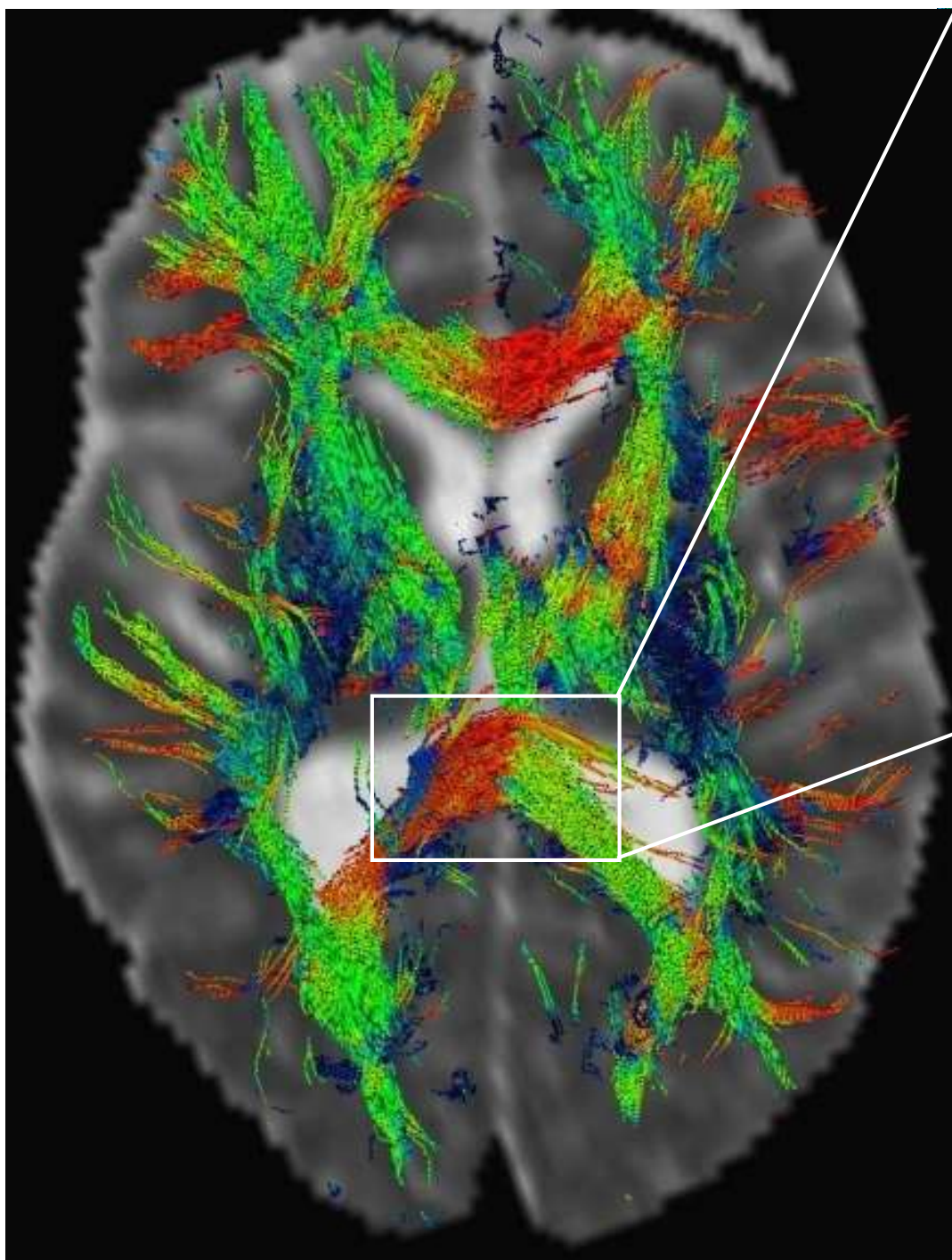














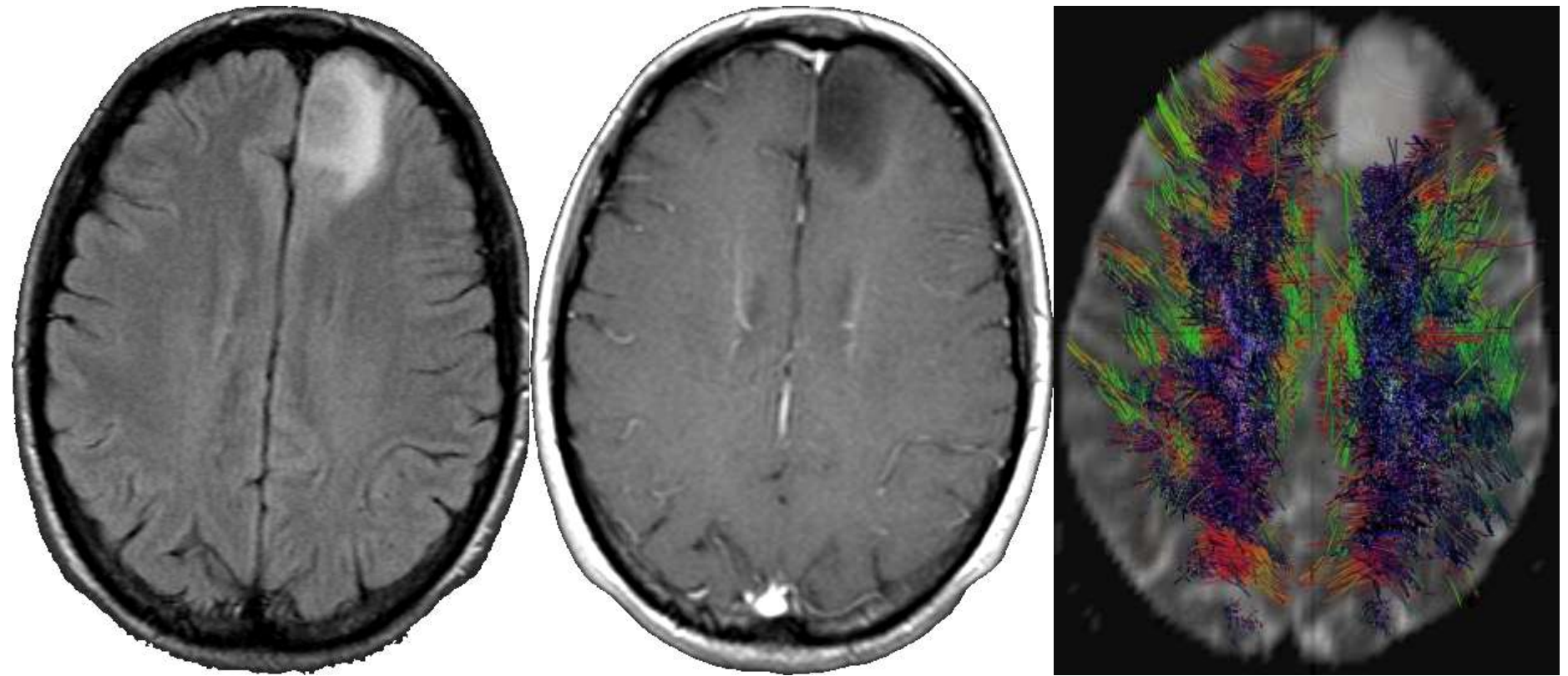
# Névrites Optiques Rétro-Bulbaires



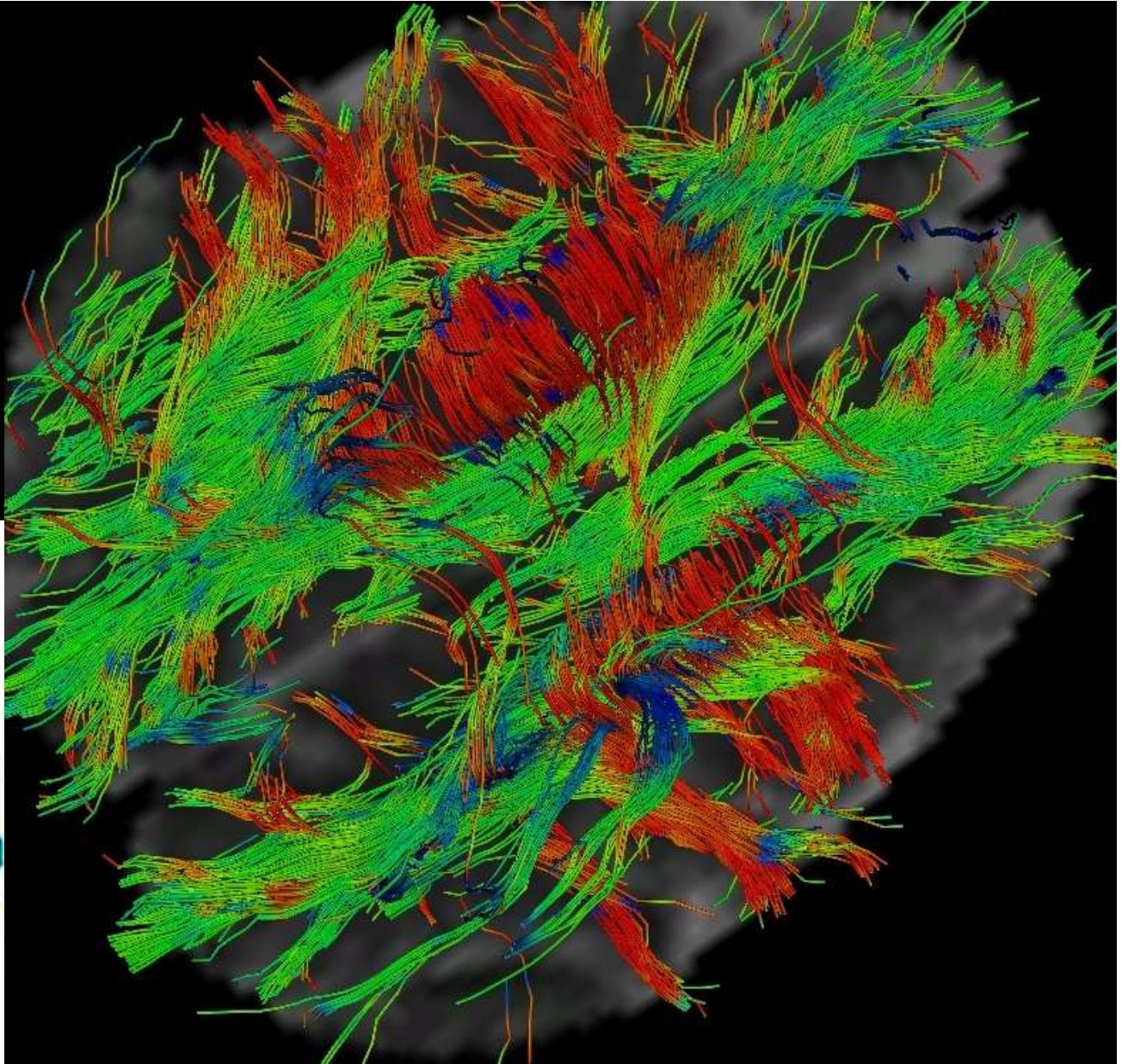
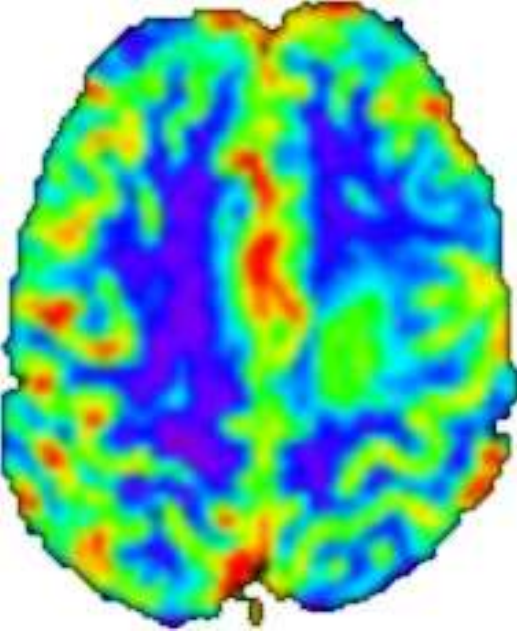
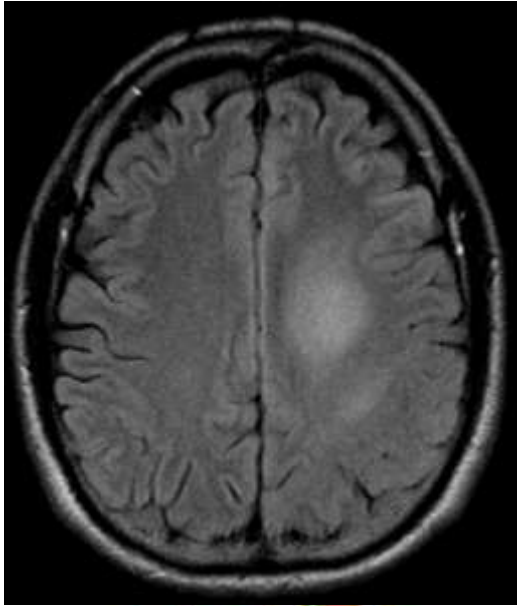
# Tumeurs Cérébrales et Syndromes Inflammatoires

# Tracking de Fibres

## Tumeurs Infiltrantes







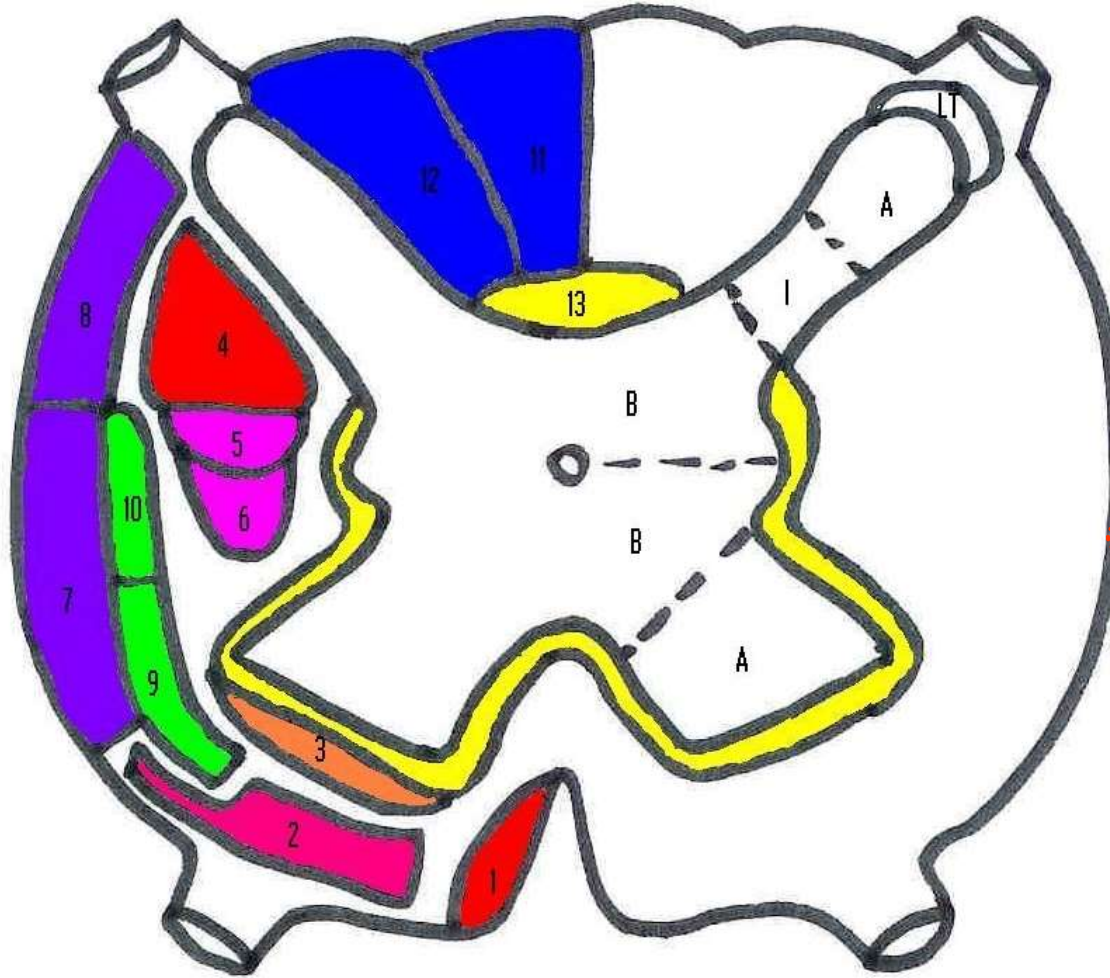
Anatomie Normale

Moelle

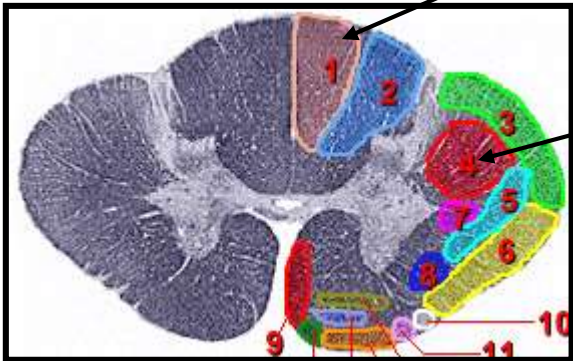
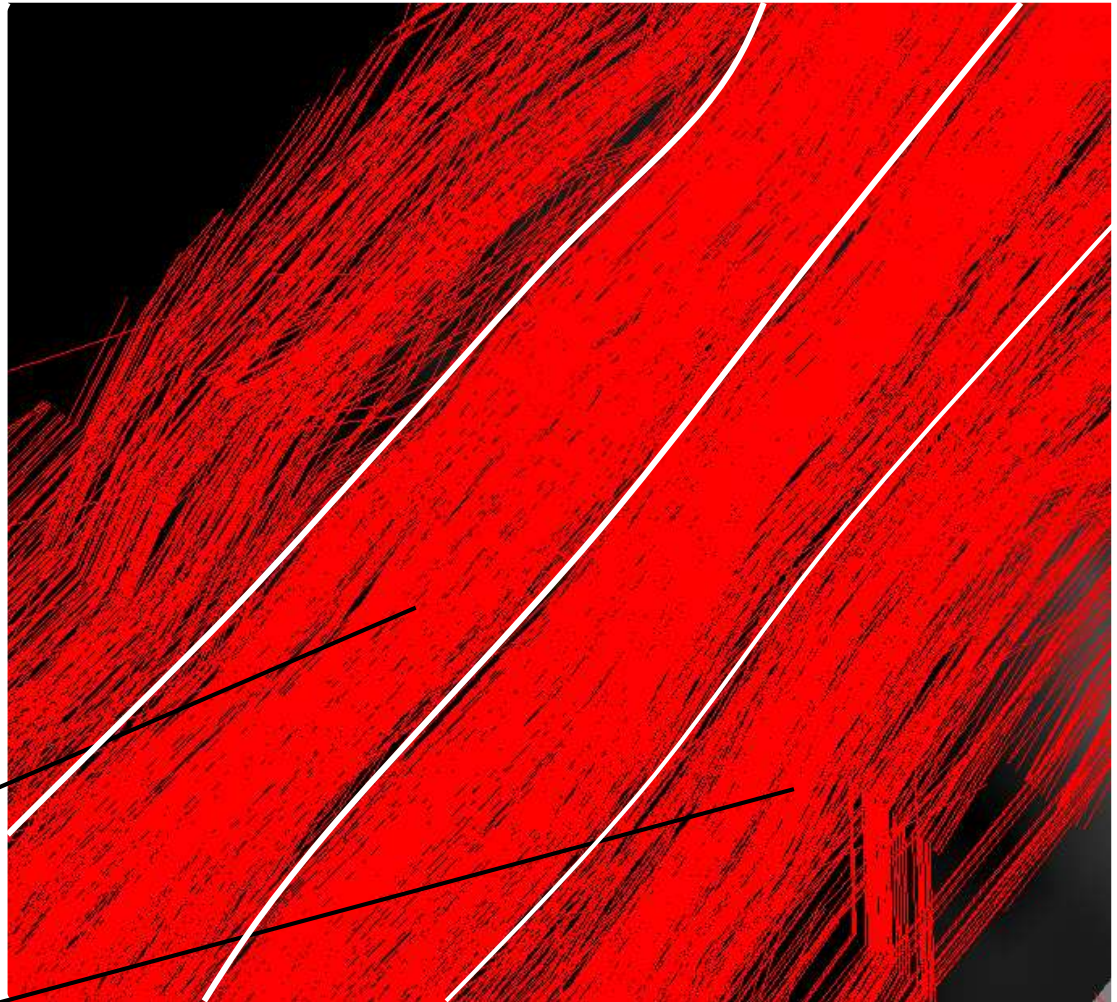
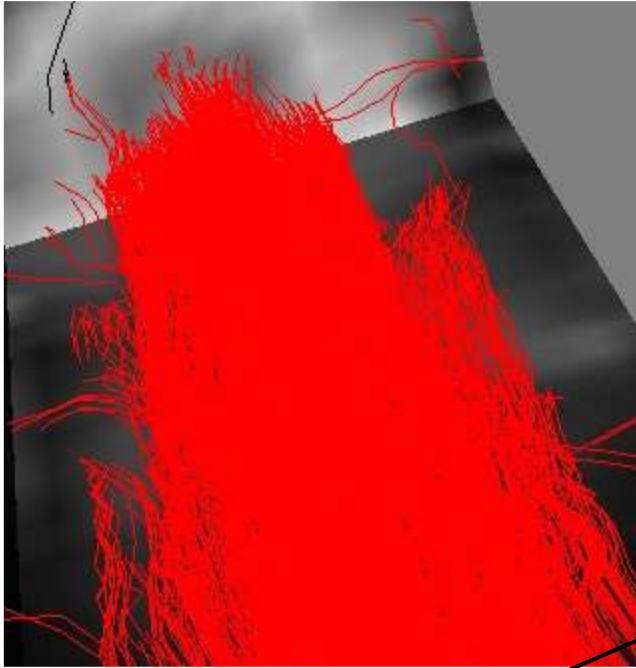


# Méthodologie et Mise en Oeuvre

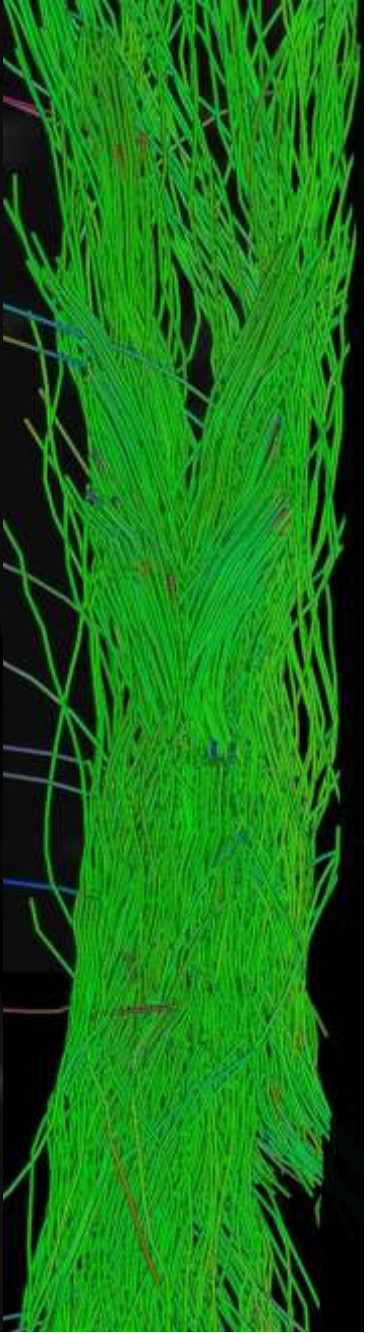
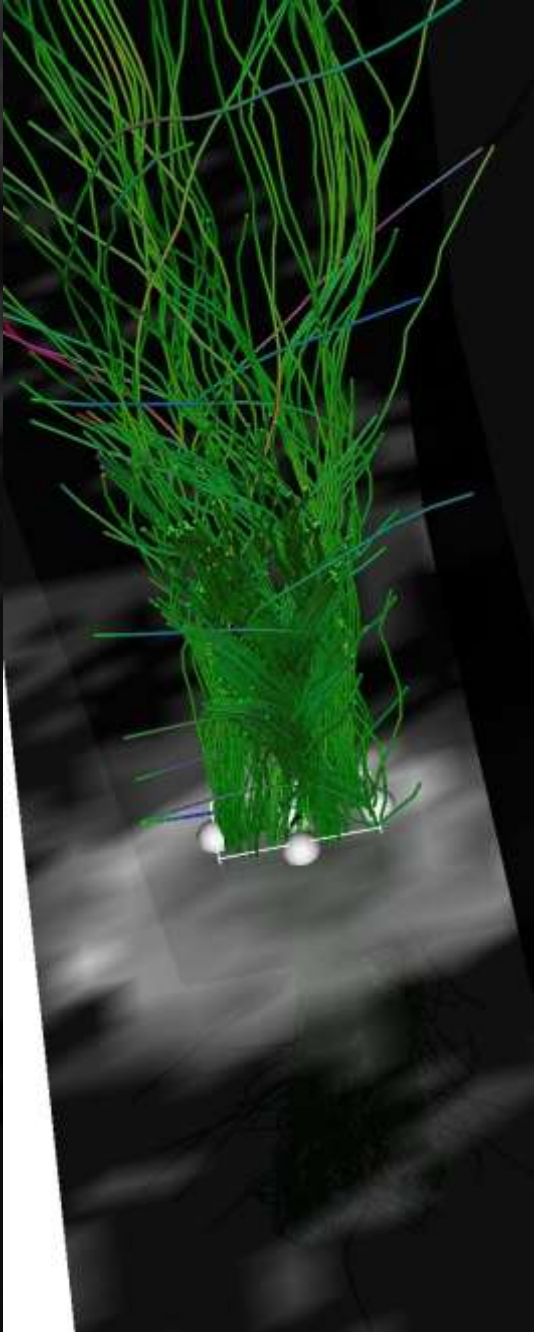
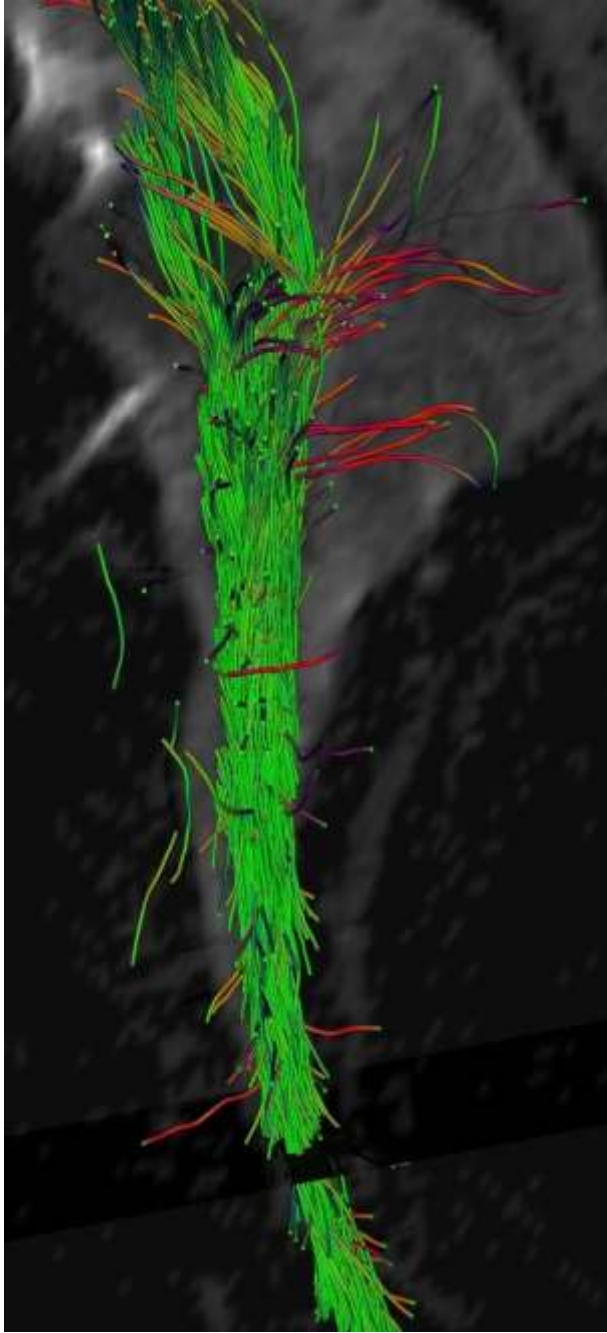
## Anatomie de la moelle épinière



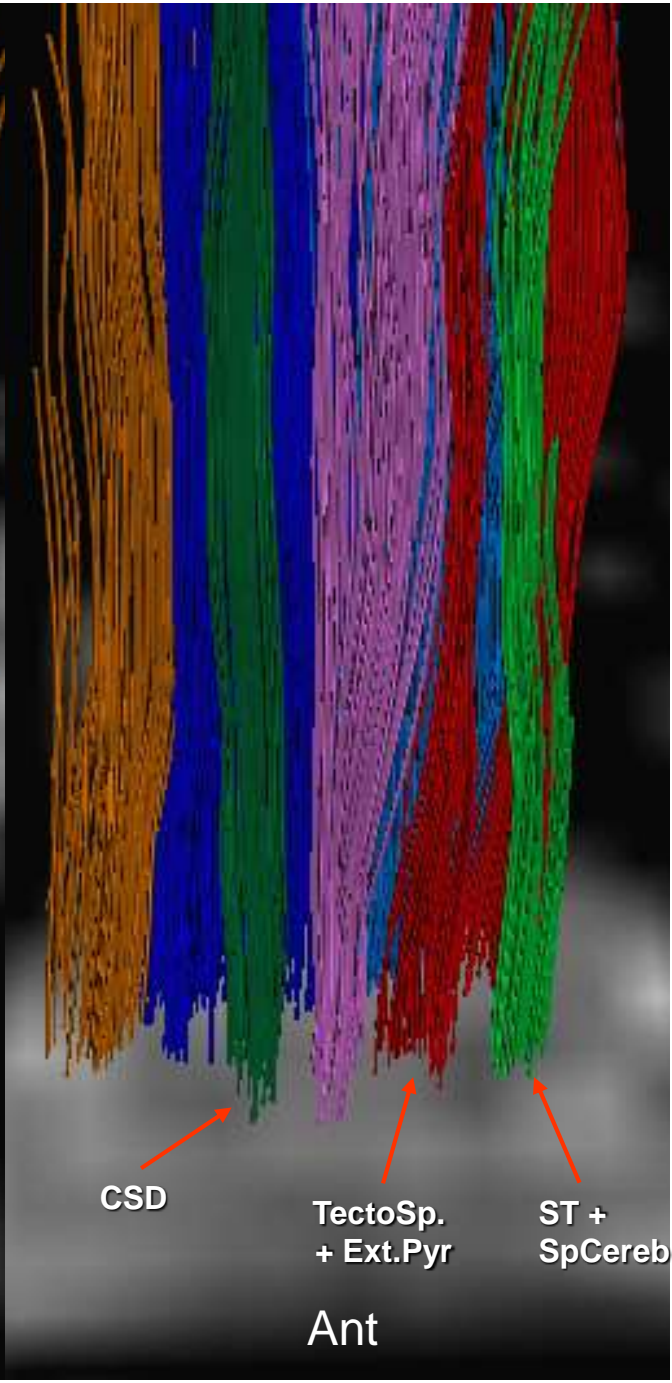
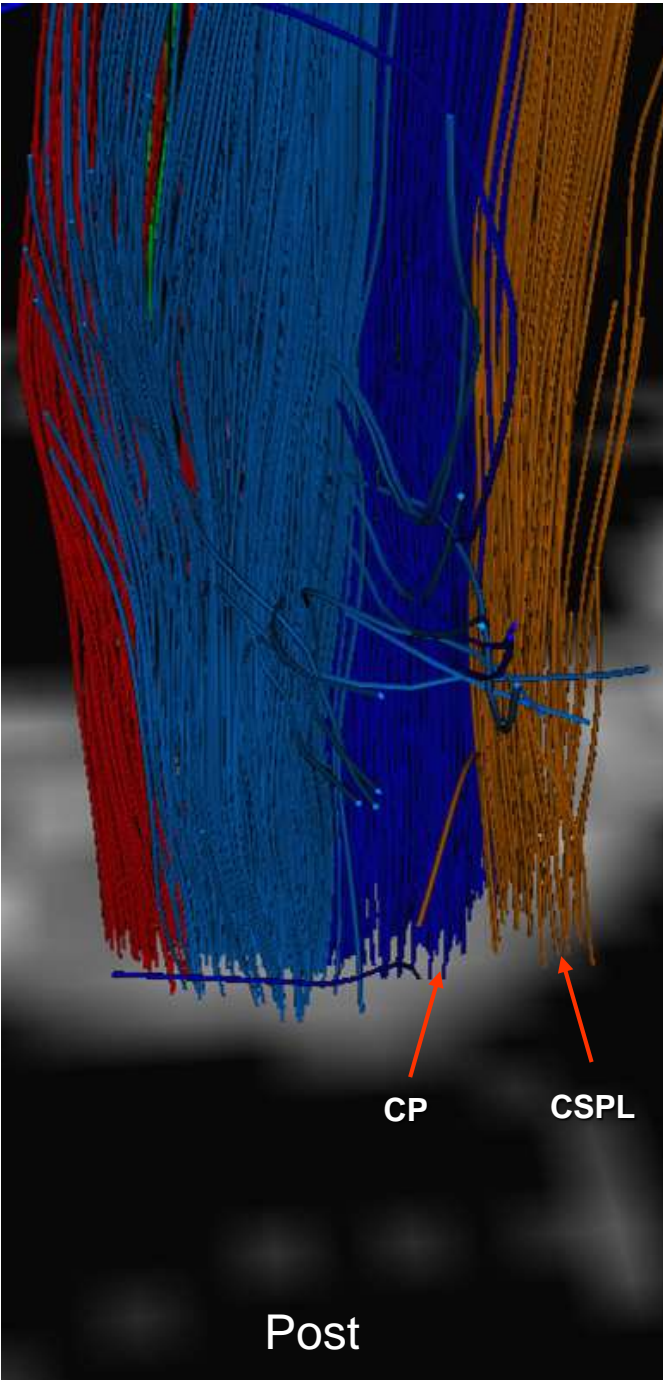
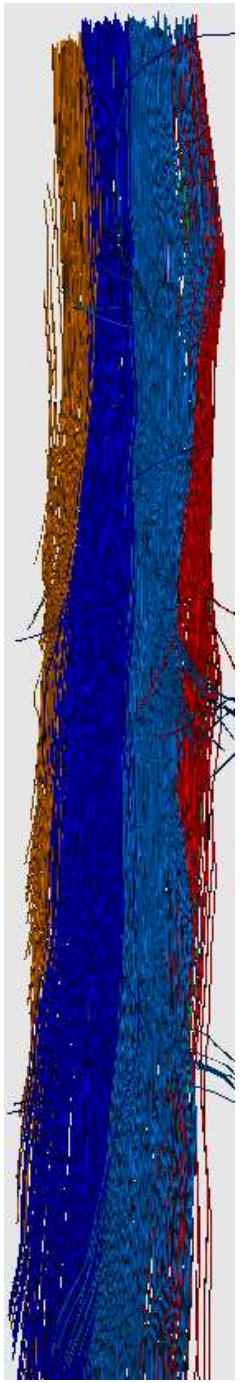
- 1-Faisceau cortico –spinal ventral
  - 2-Champ de faisceaux extrapyramidaux
  - 3-Faisceau tecto-spinal
  - 4-Faisceau cortico-spinal dorsal
  - 5-Faisceau rubro-spinal
  - 6-Faisceau réticulo spinal latéral
  - 7-Faisceau spino-cérébelleux ventral
  - 8-Faisceau spino-cérébelleux dorsal
  - 9-Faisceau spino-thalamique ventral
  - 10-Faisceau spino-thalamique dorsal
  - 11-Faisceau gracile
  - 12-Faisceau cunéiforme
  - 13-Faisceaux propres
- A- Apex  
B- Base  
I- Isthme  
LT- Lame Terminale





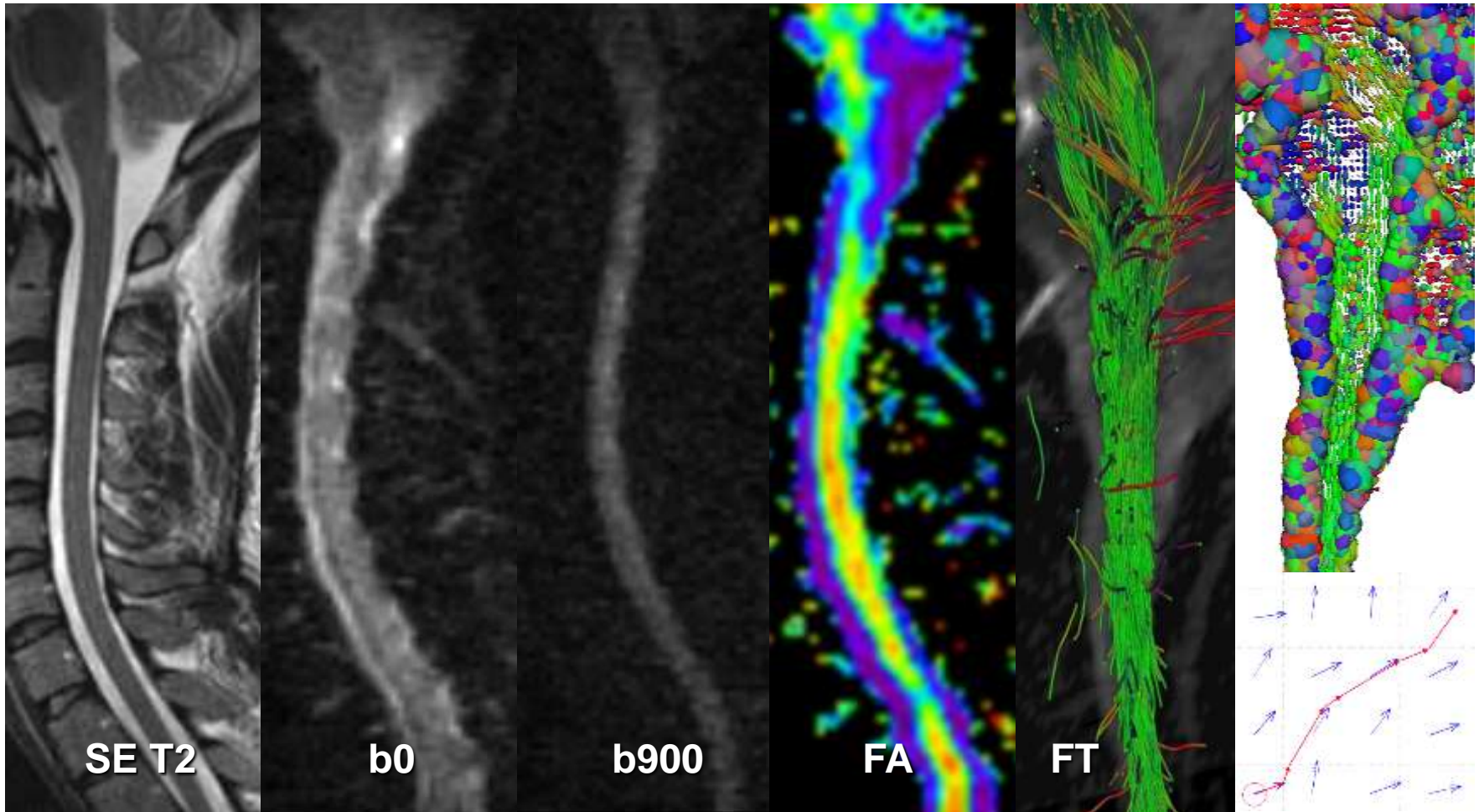






# Tractographie de la moelle

## Moelle Saine





# Tractographie de la moelle

## Moelle Saine

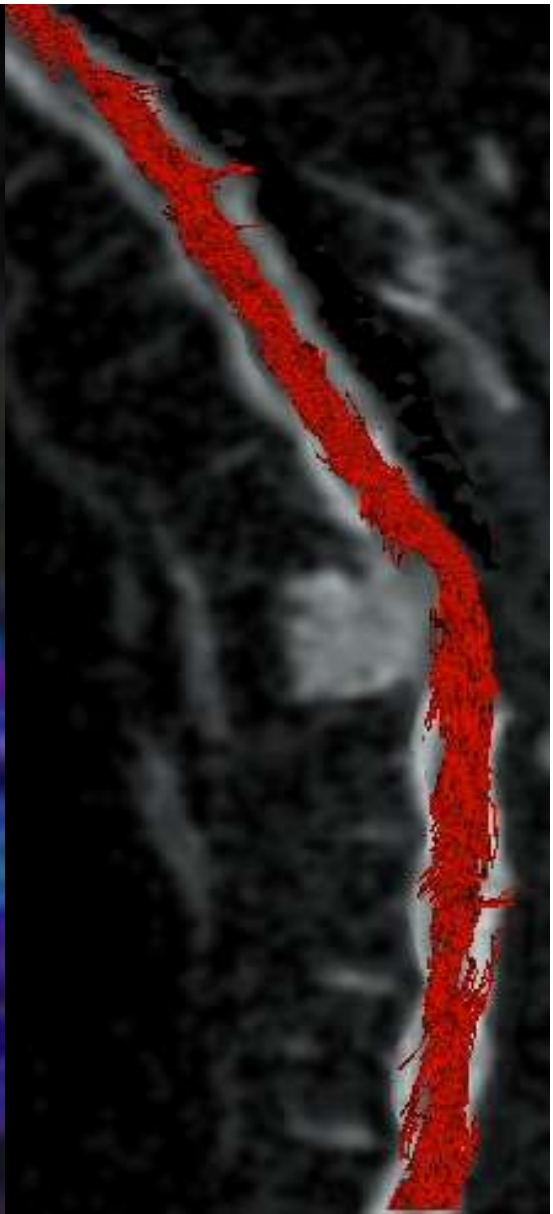
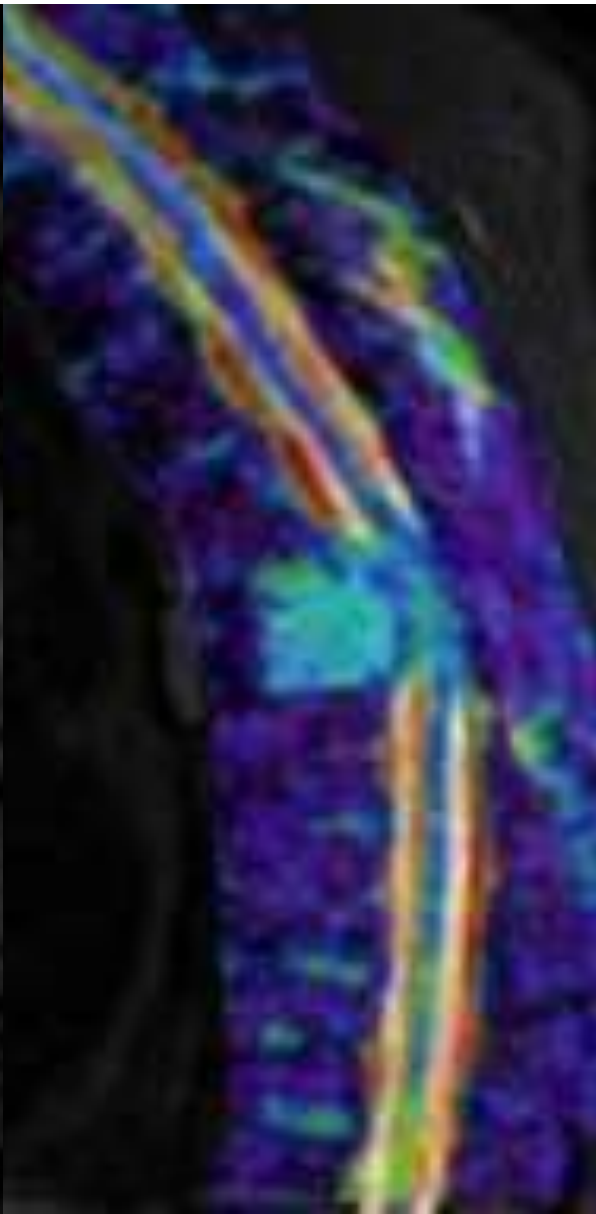
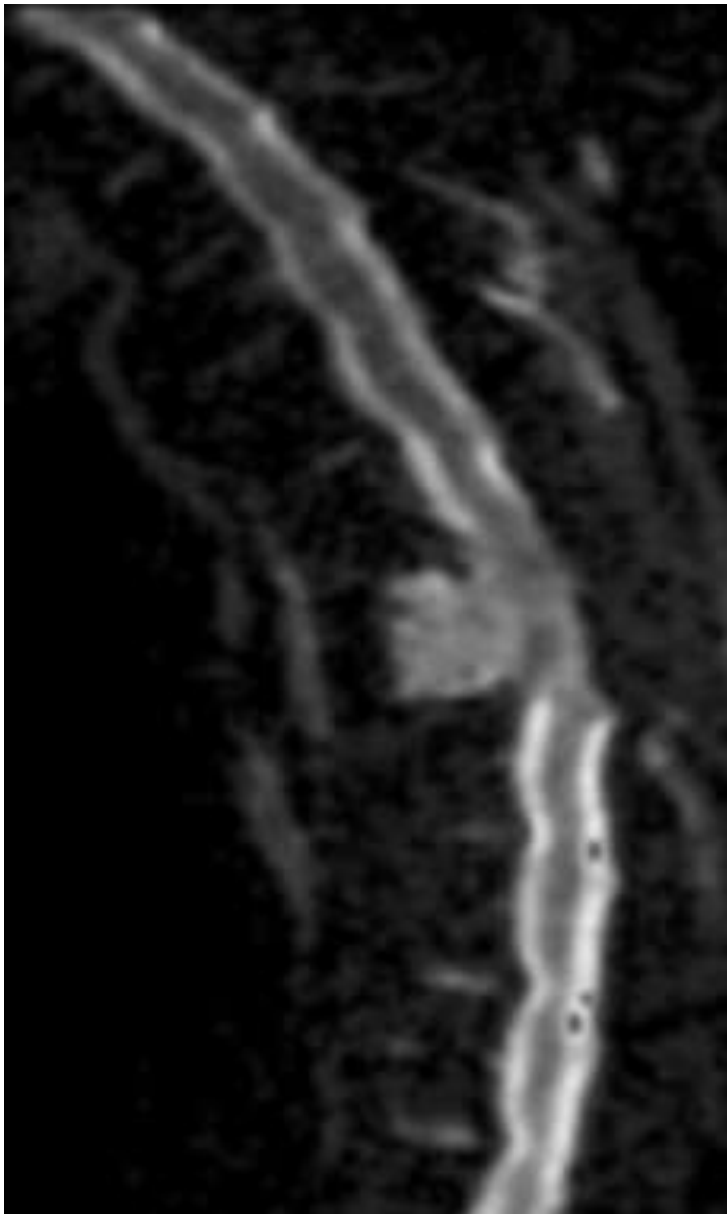
Faisceaux	ADC moyen	FA moyen	Nb « fibres »
CSLD	1.05	0,71 ± 0.02	22 (soit ~3 M)
CPD	0.96	0,79 ± 0.02	65 (soit ~9 M)
CPG	0.96	0,80 ± 0.02	63 (soit ~9 M)
CSLG	1.03	0,73 ± 0.02	19 (soit ~3 M)

**NB : Résultats obtenus en région cervicale moyenne (C4) avec un voxel de 6 mm<sup>3</sup>.  
Dix fibres sont arbitrairement affichées dans un voxel, avec une moyenne histologique connue de 20000 fibres / mm<sup>3</sup>, soit environ 12000 fibres réelles par « fibre » représentée.**

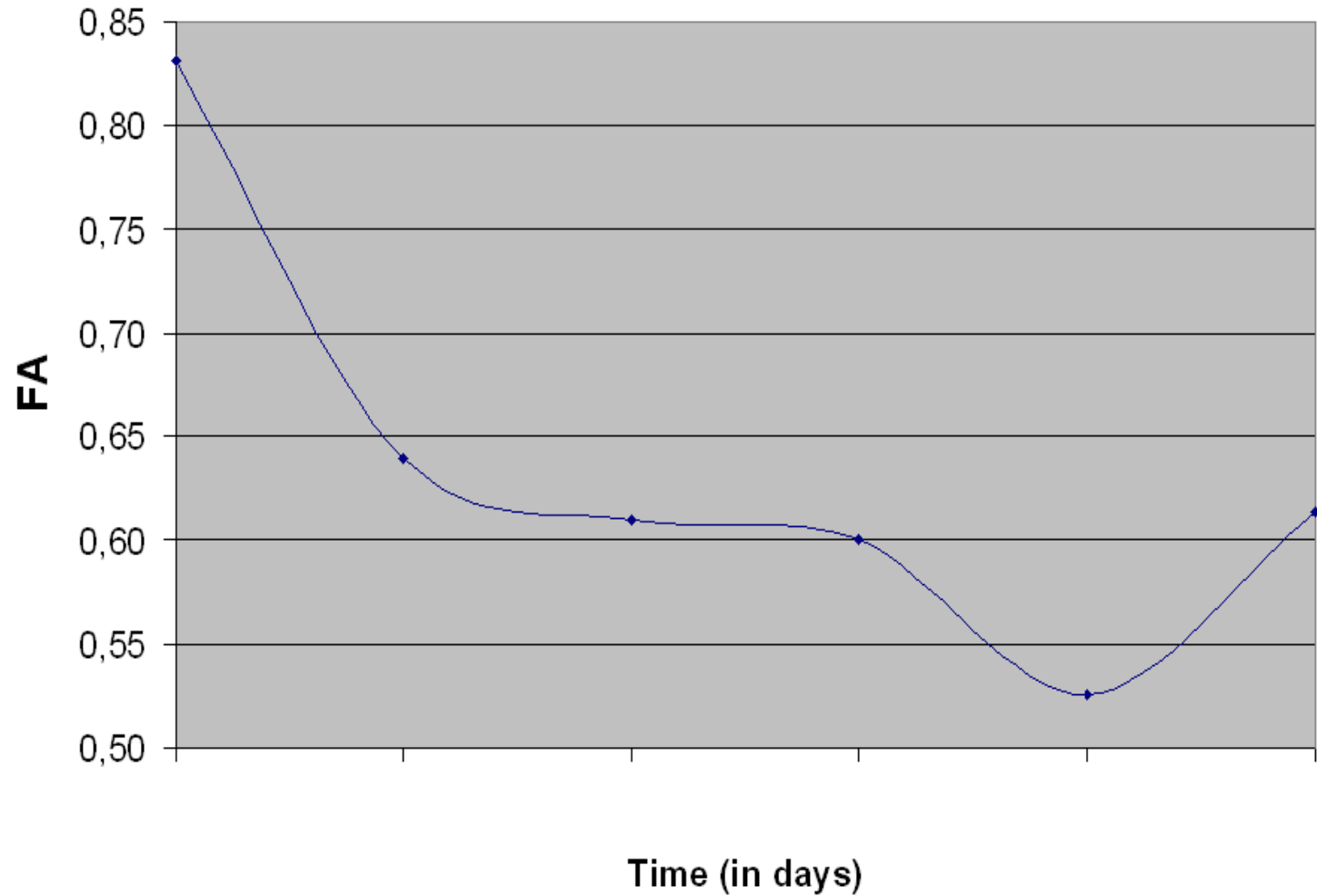


# Applications Cliniques

# Compressions Médullaires



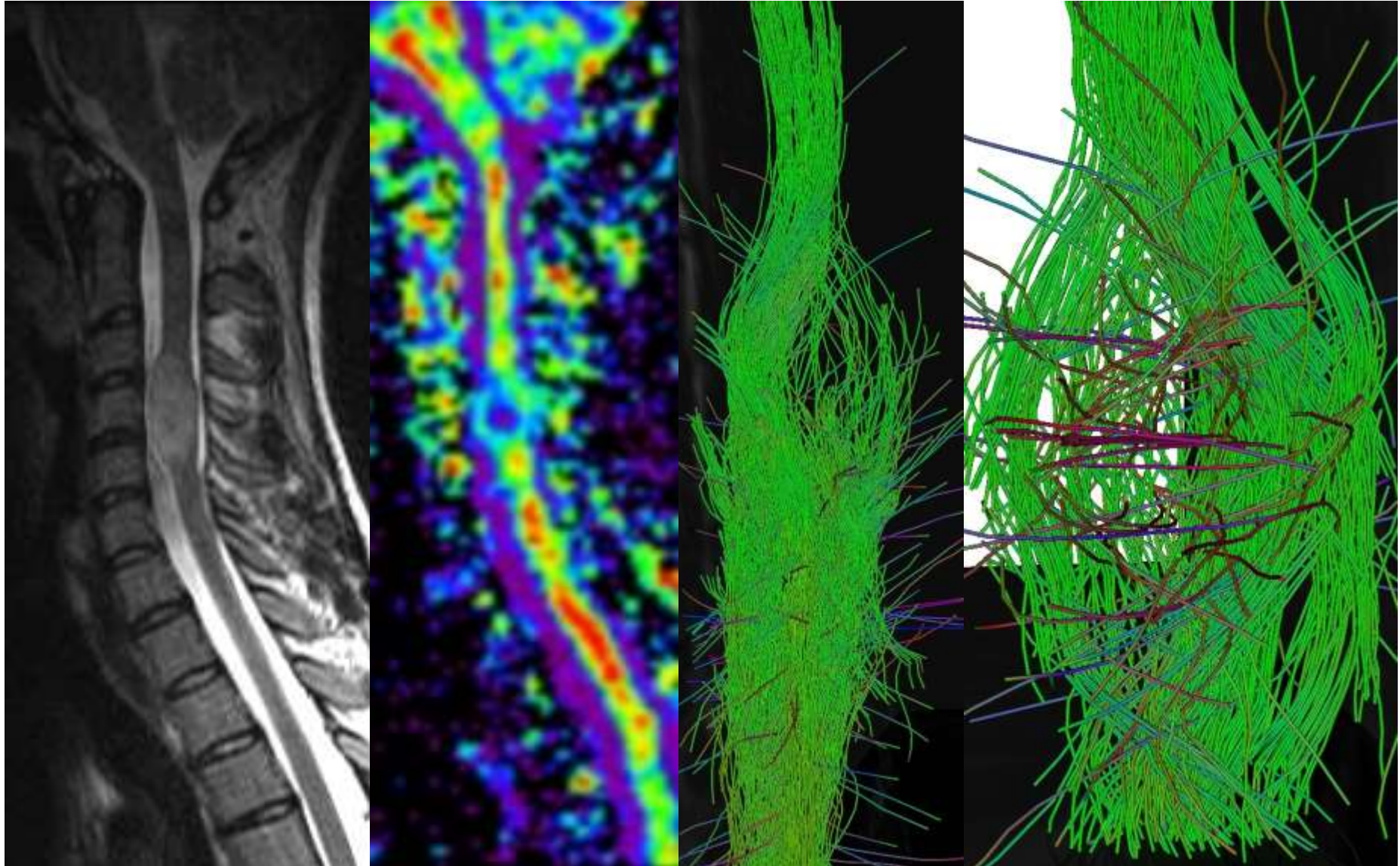
# FA versus Time





# Tumeurs Médullaires

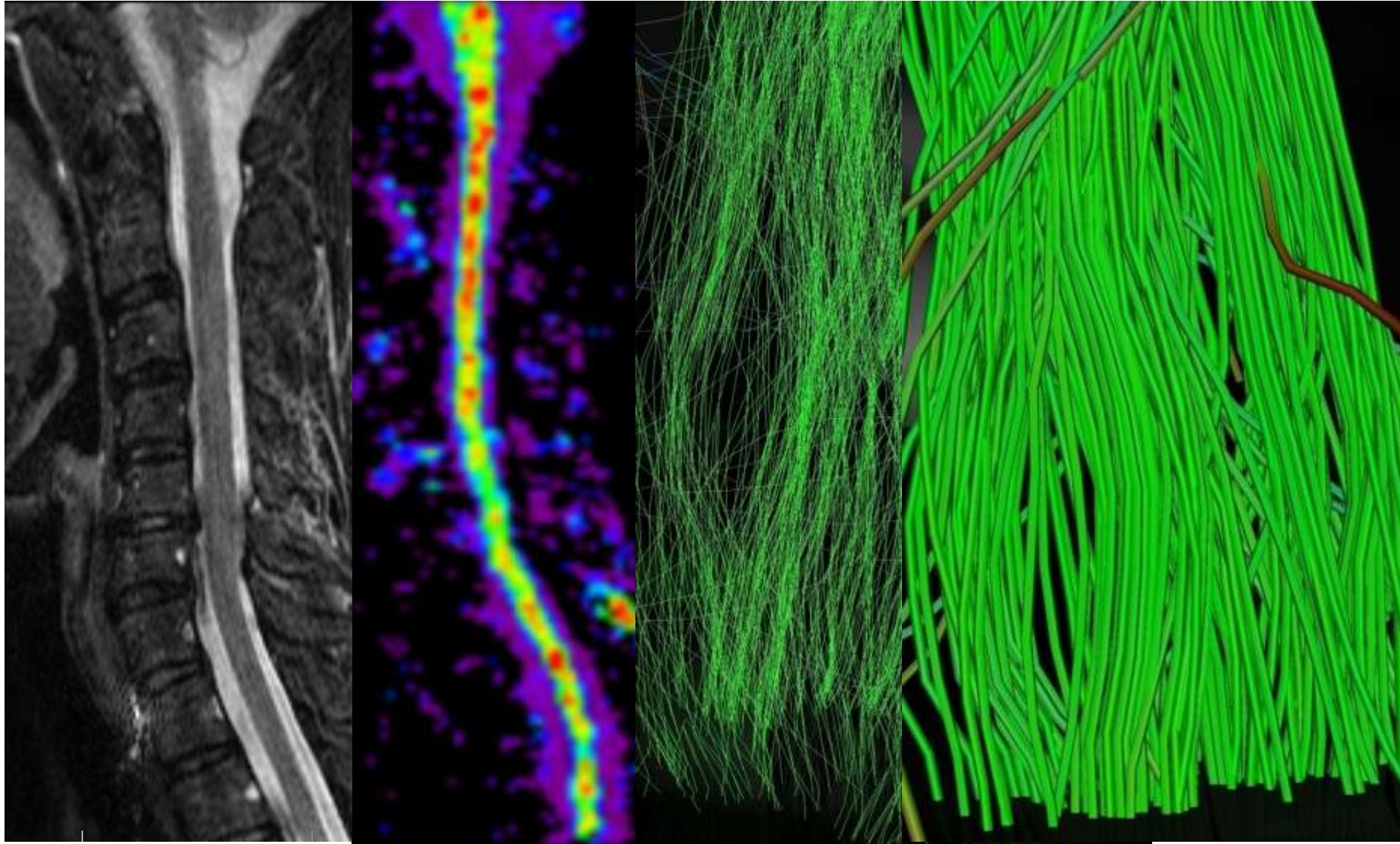
# Astrocytome



# Processus Inflammatoires Médullaires et Régénération Axonale

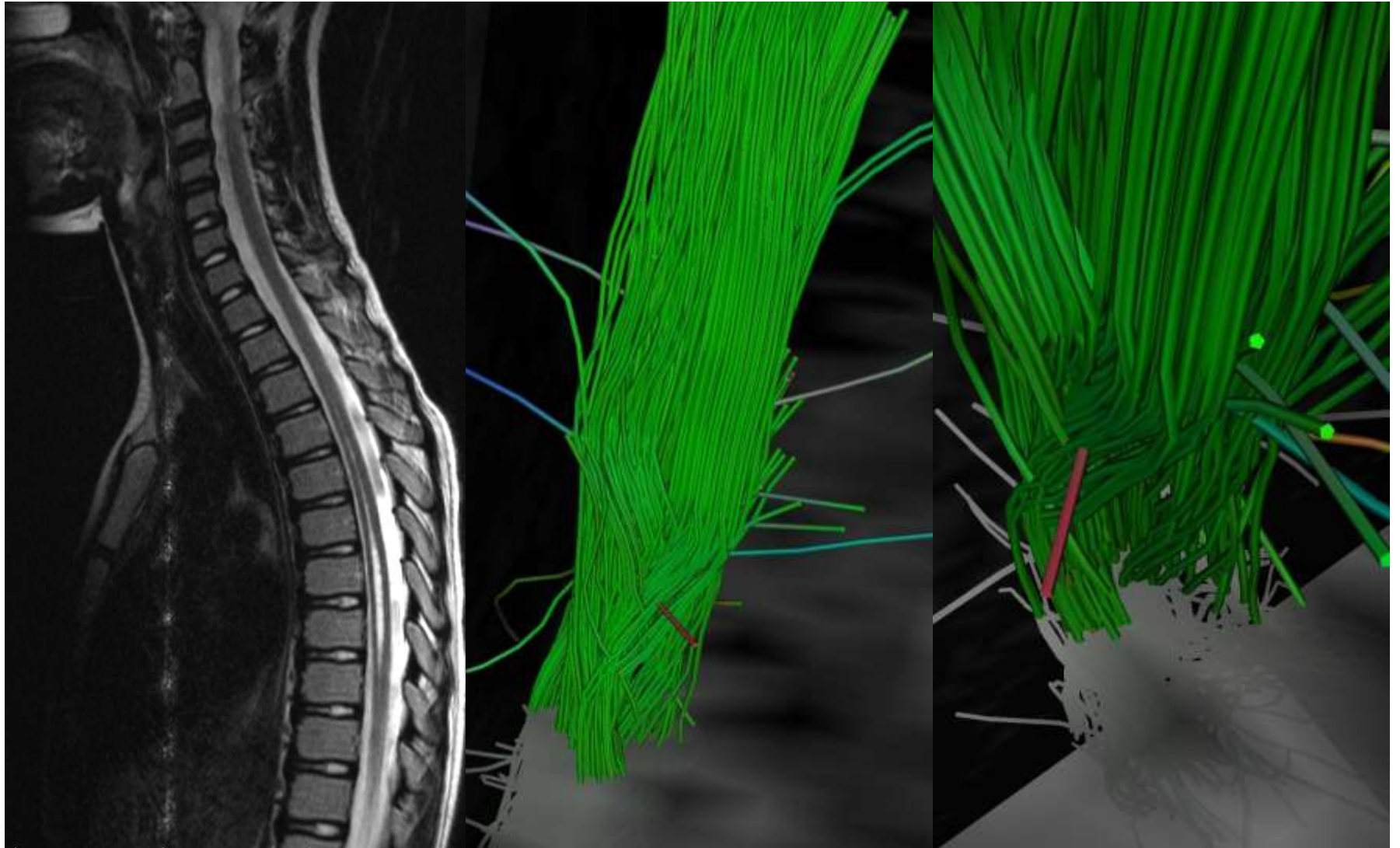


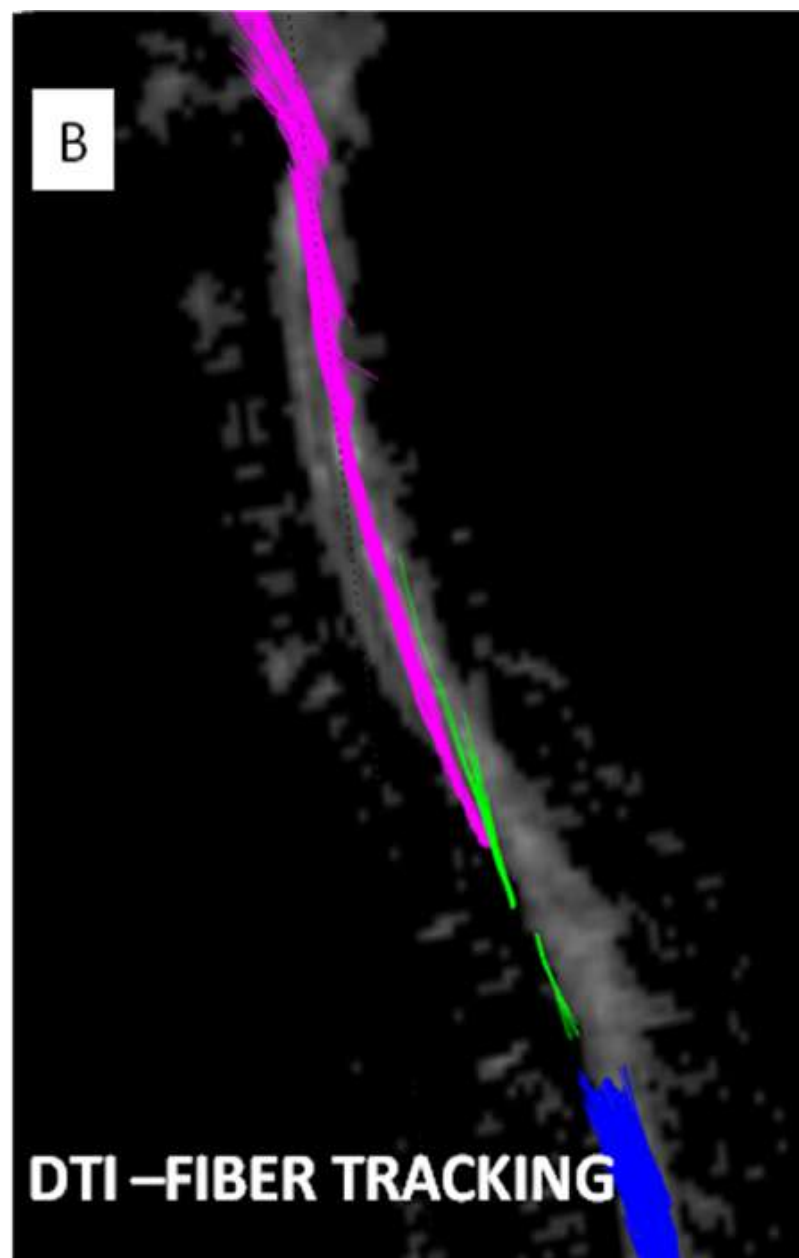
# Myelites





**Syringomyélie**

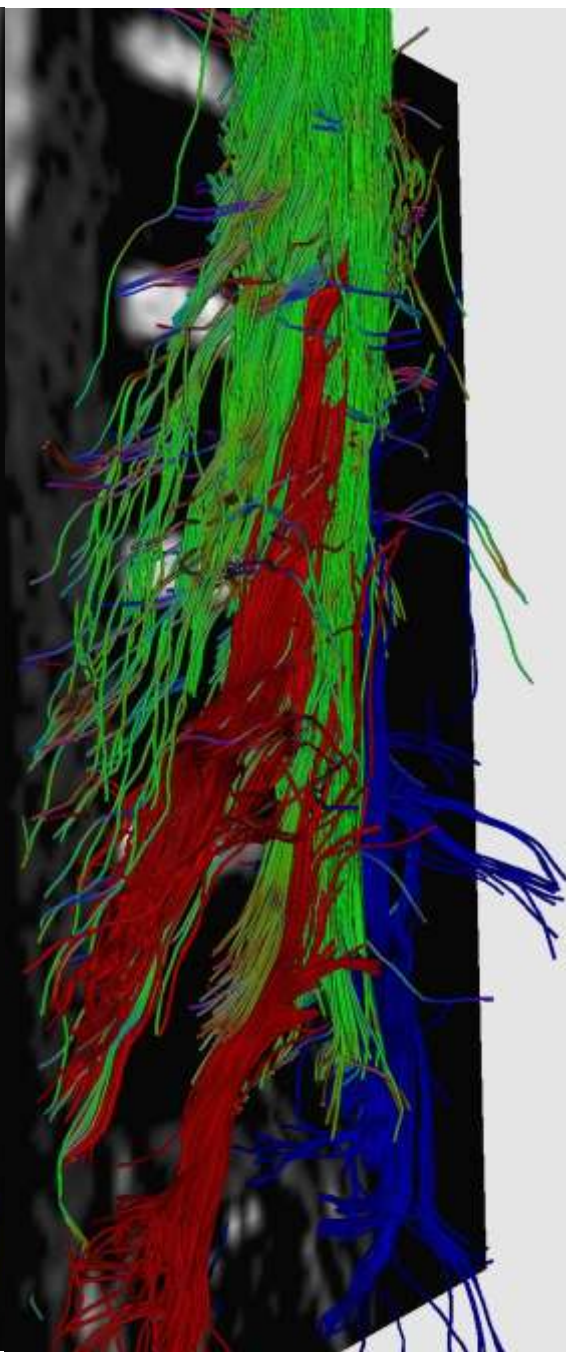
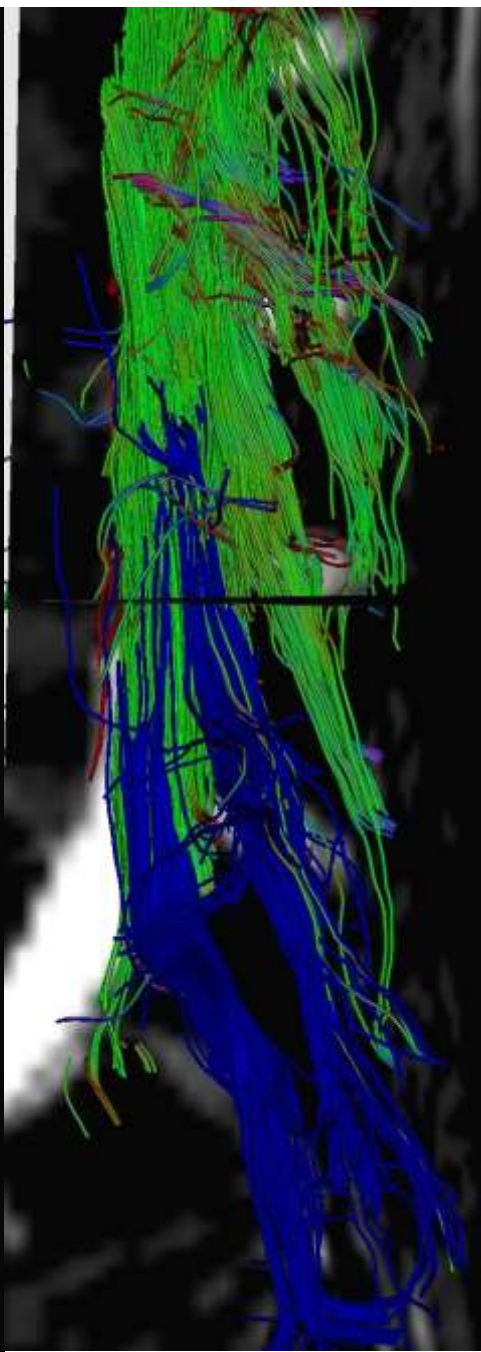
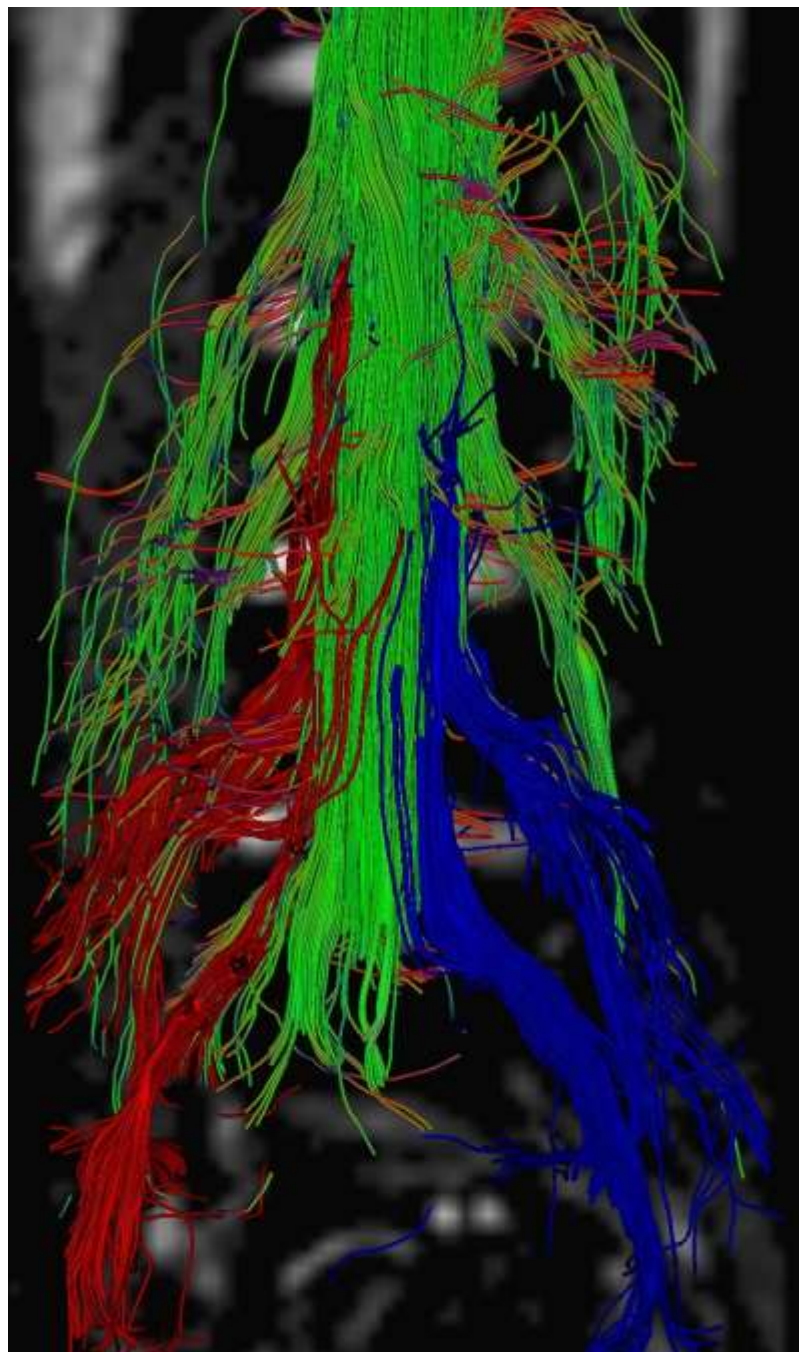




# Radiculopathies

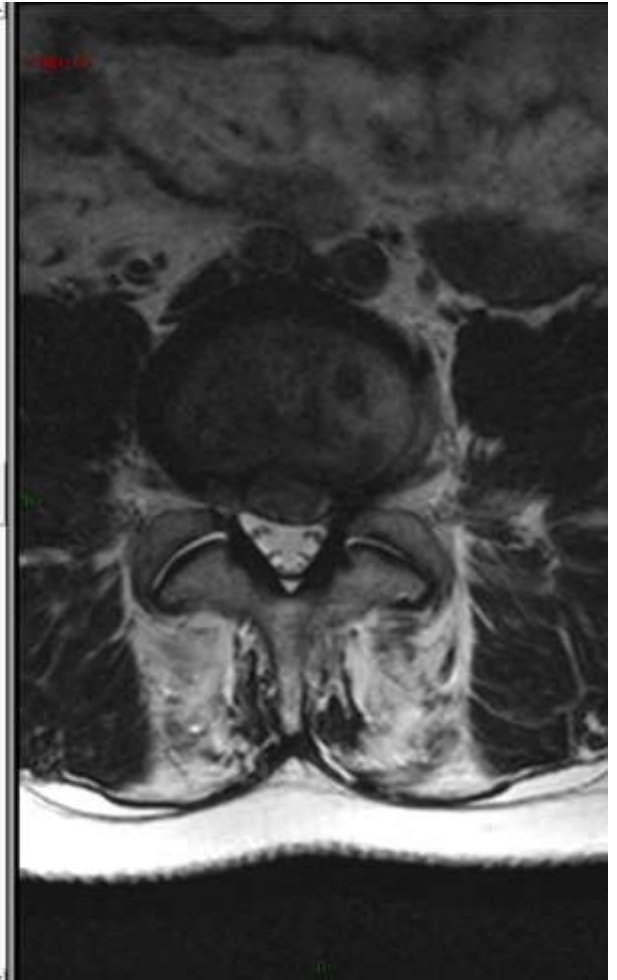




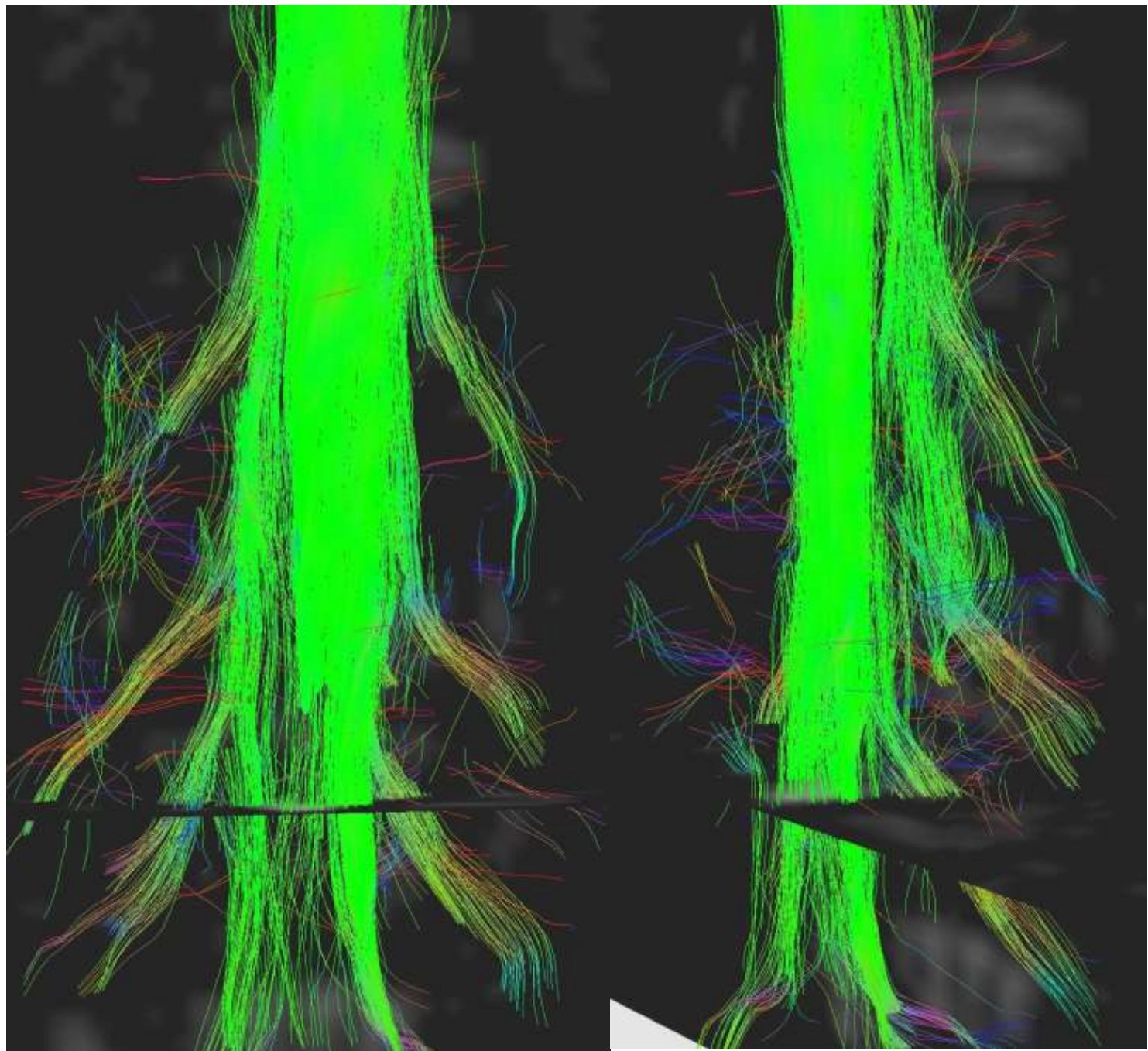


# Hernies Discales



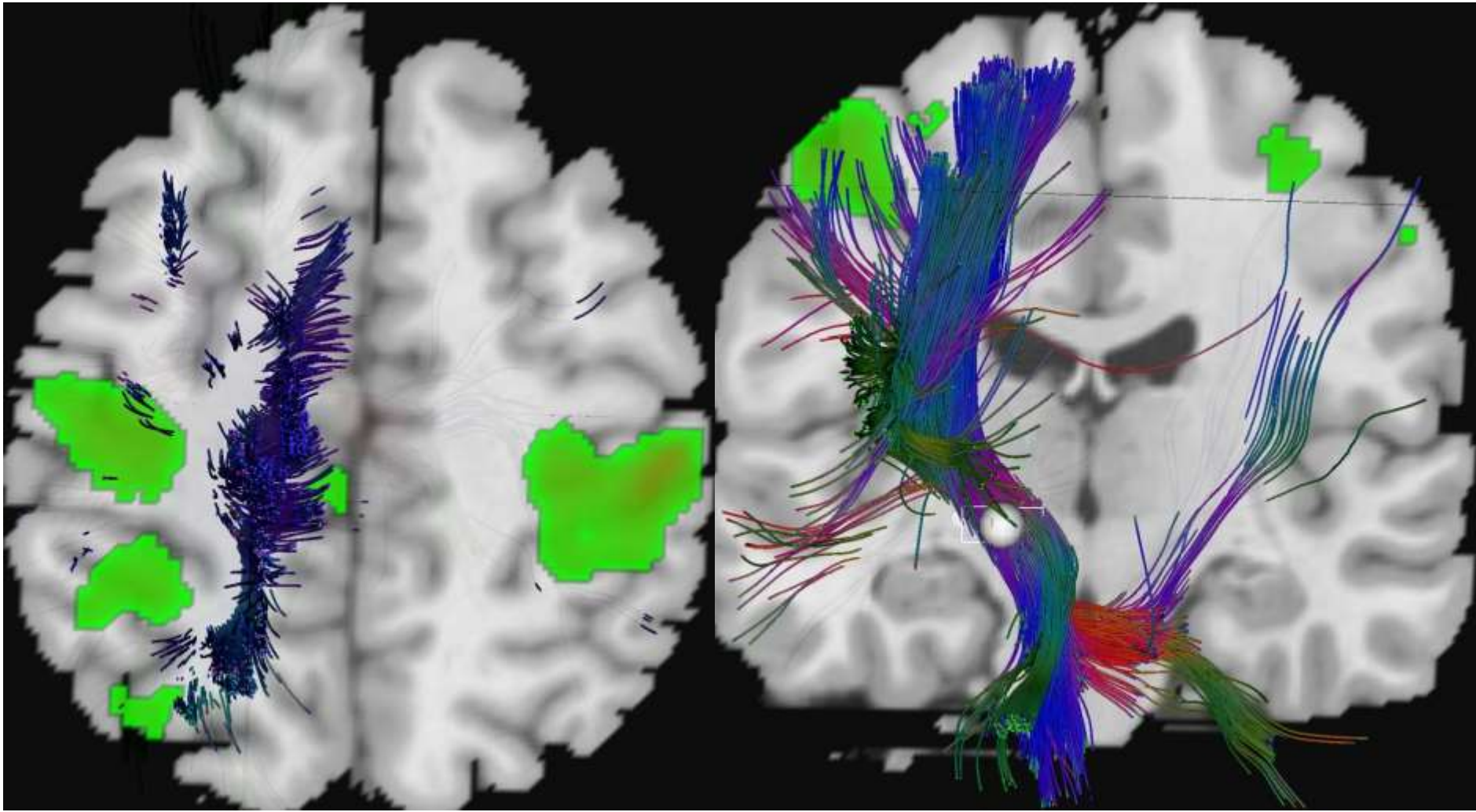






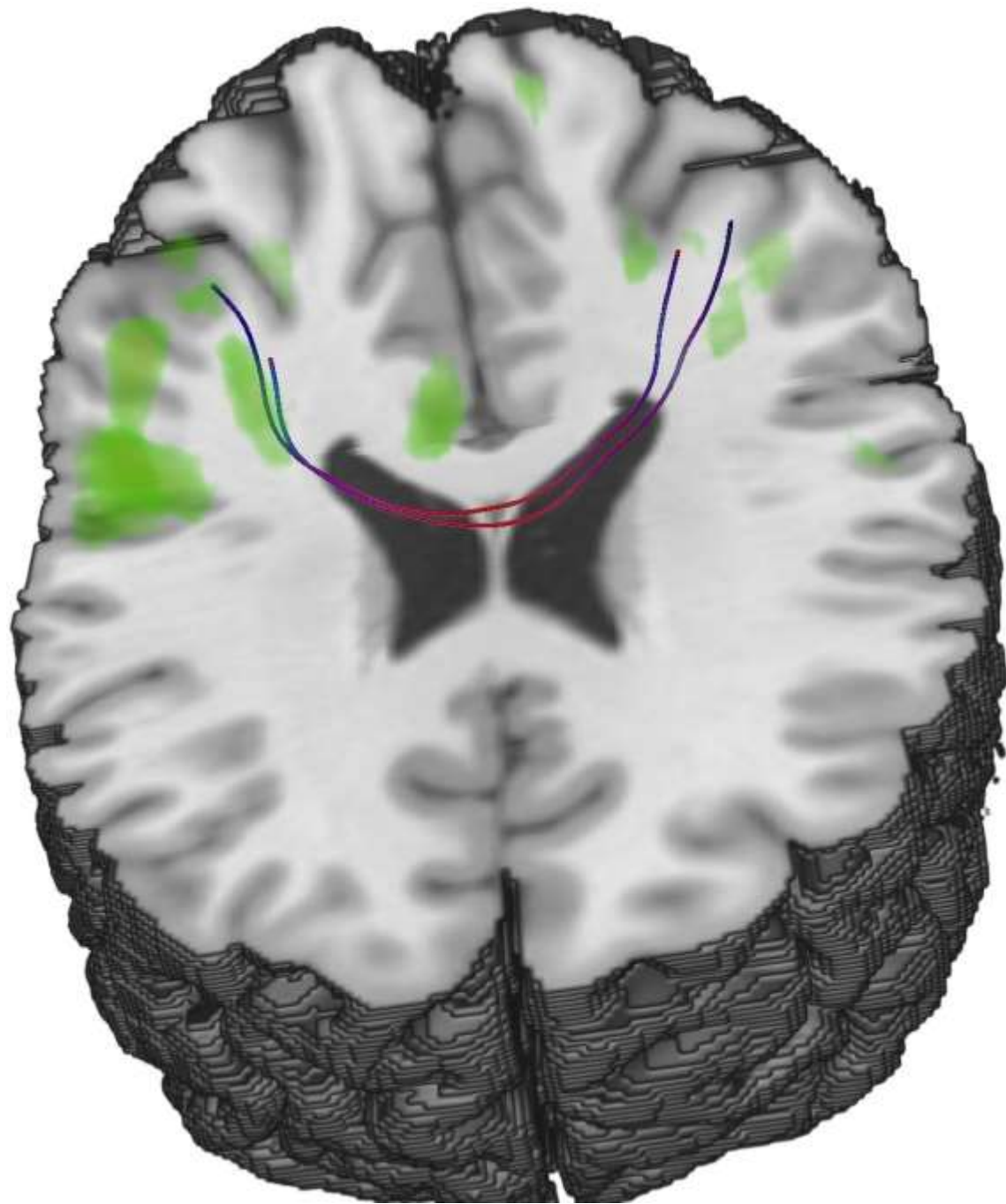
# Bilan Fonctionnel

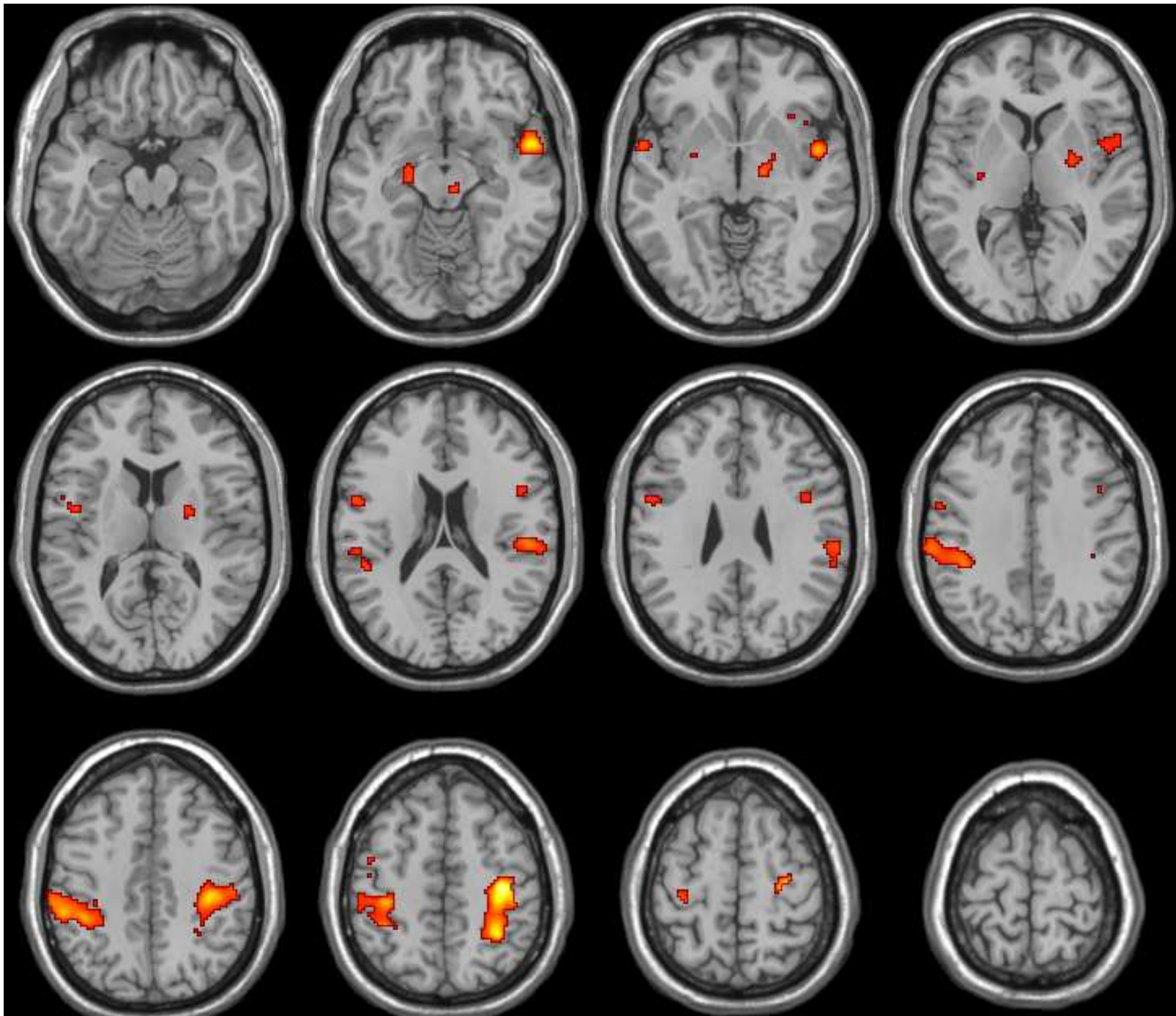
# Mouvements en Miroir sur Syndrome de Kallman

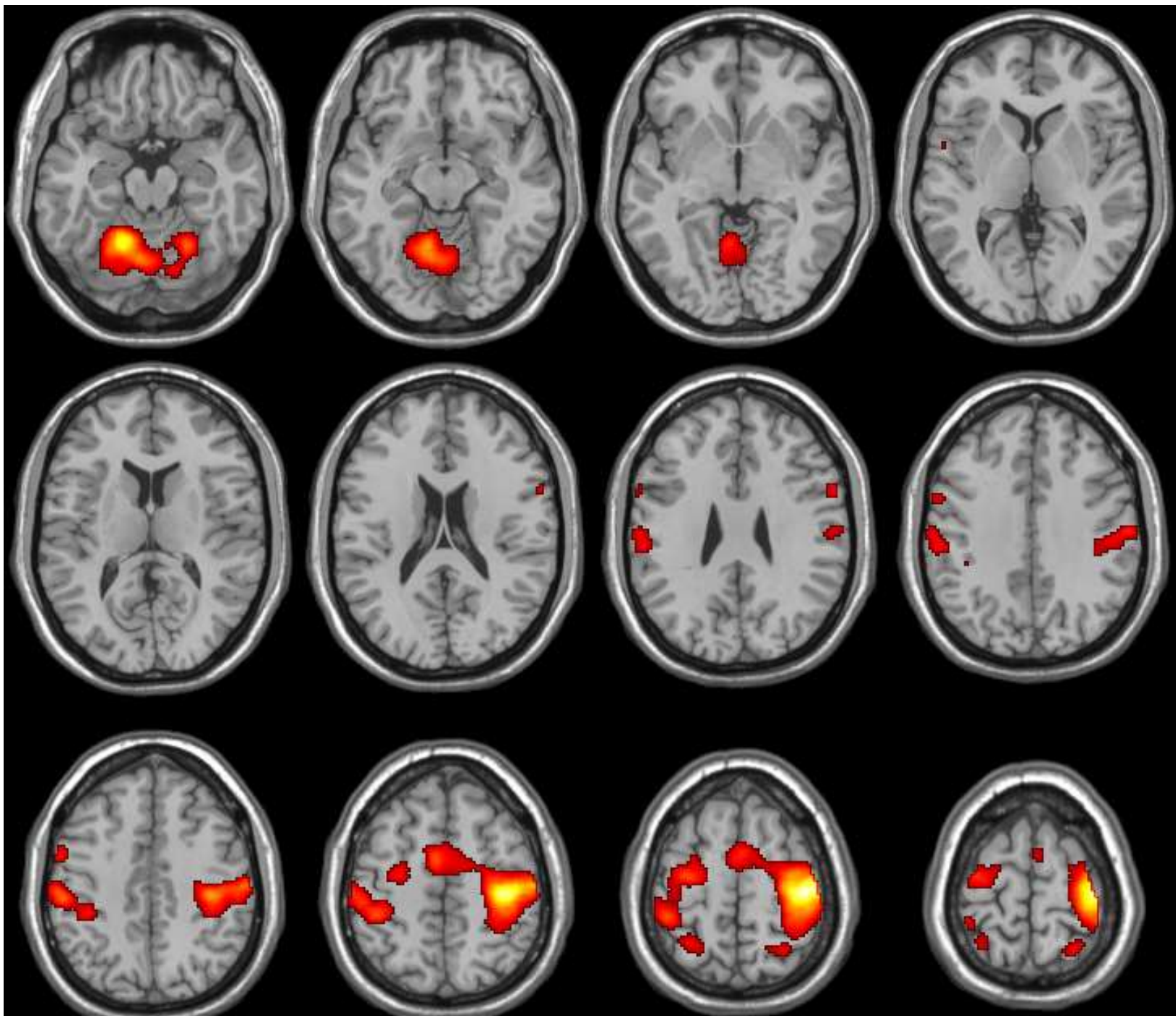


CST + Th







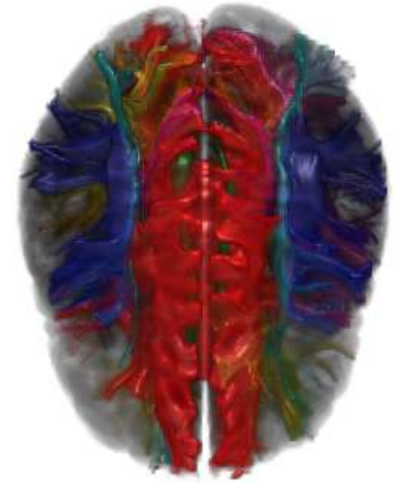
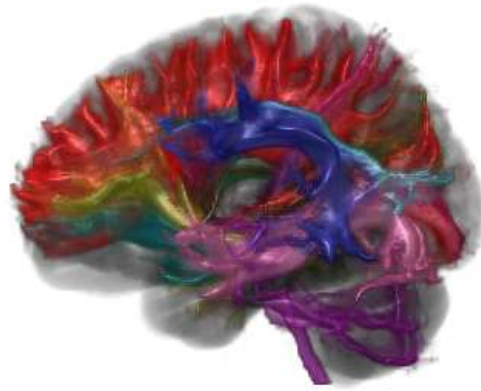
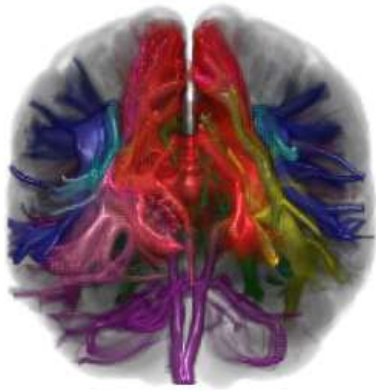


**Connectivité**

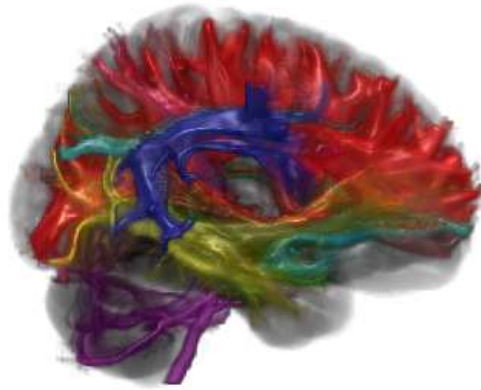
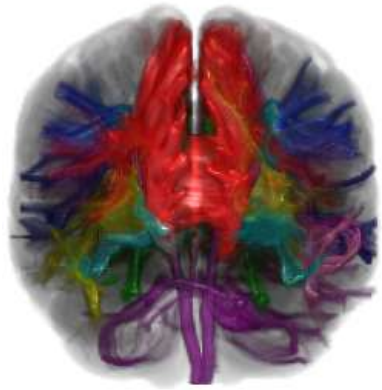
**Anatomo-fonctionnelle**



# Morphological Connectomic

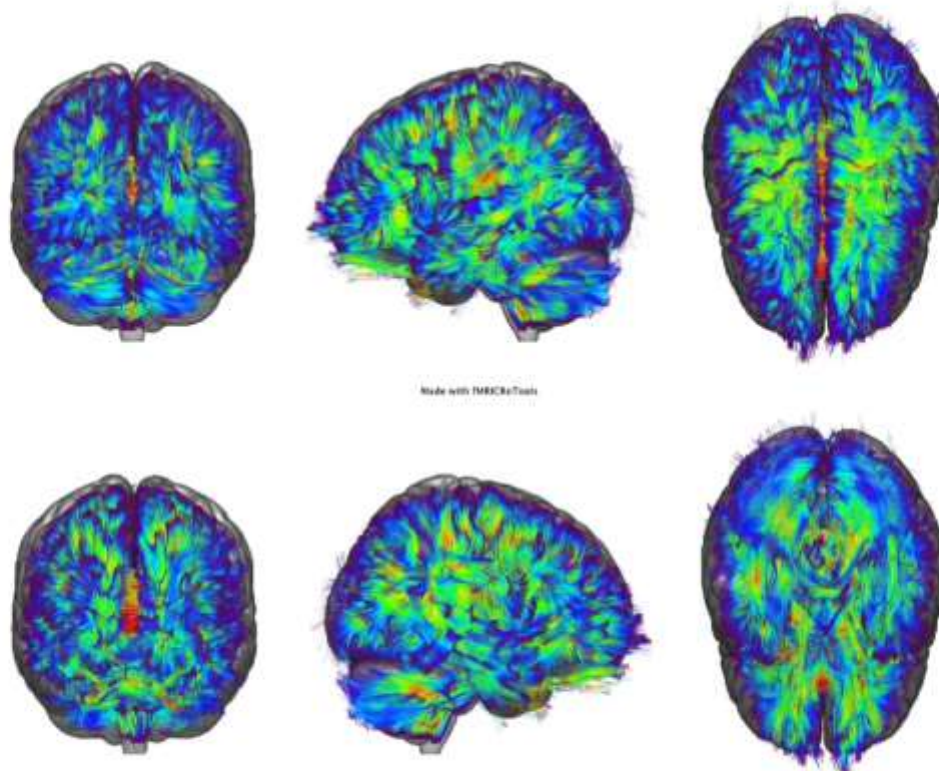


Made with Connectopedia

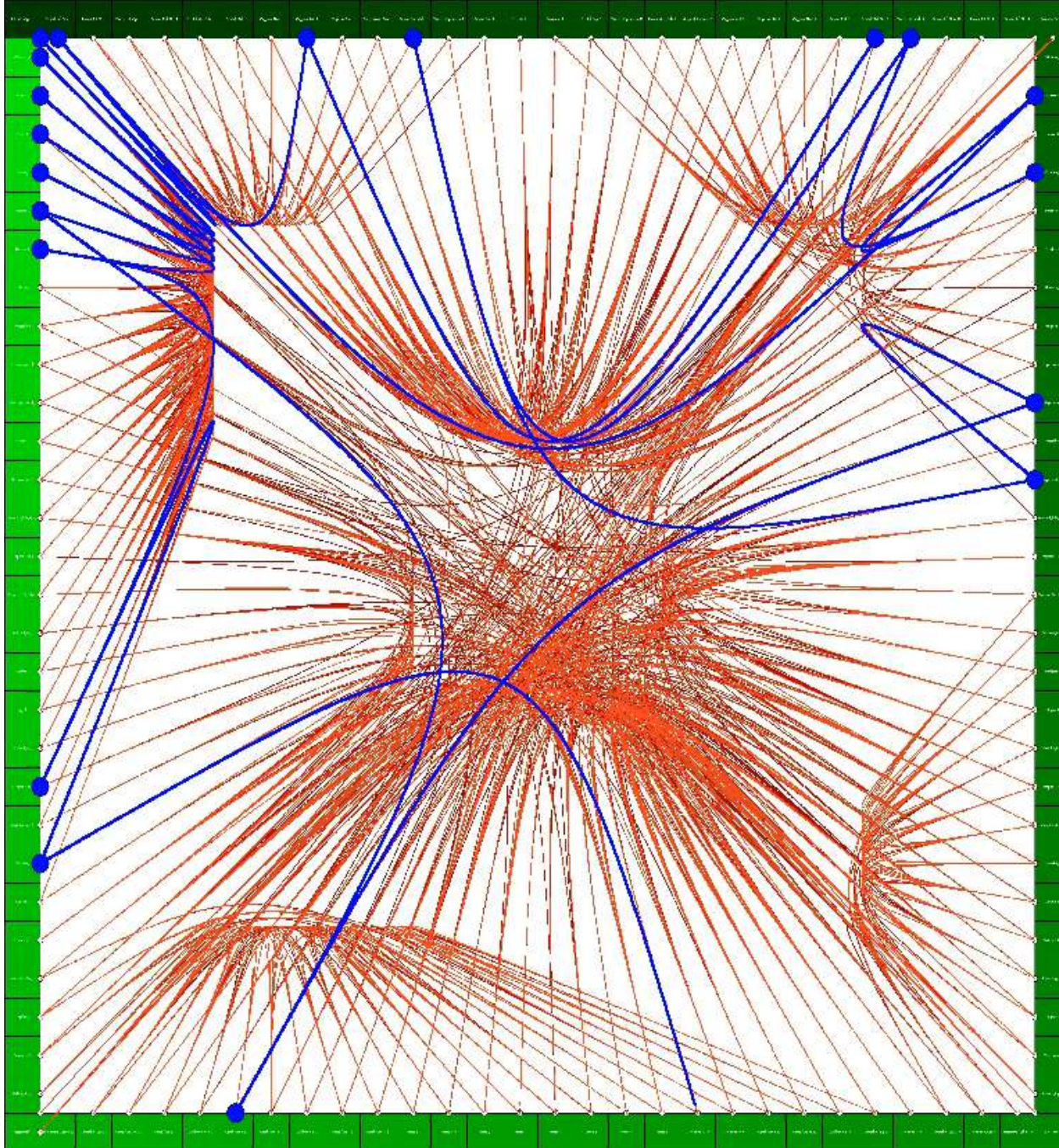


**Fibers Bundles Analysis:**

**Patient: DUCREUX\_DENIS / Date: 20151028**

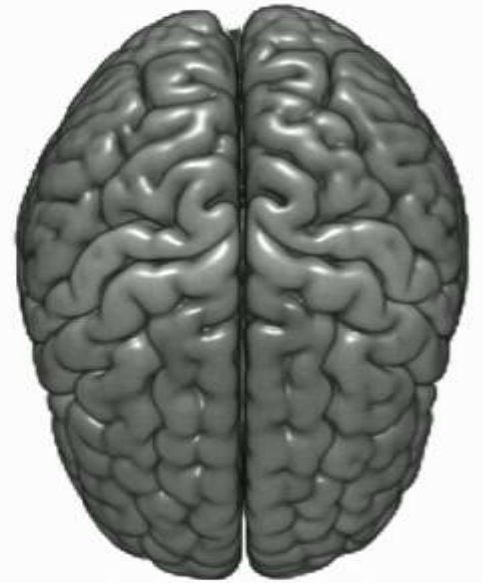
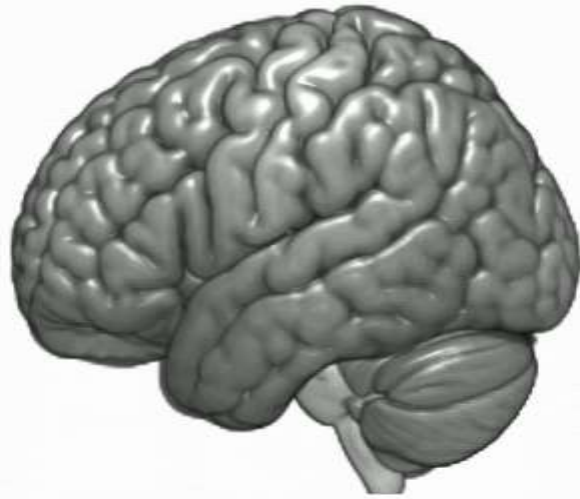




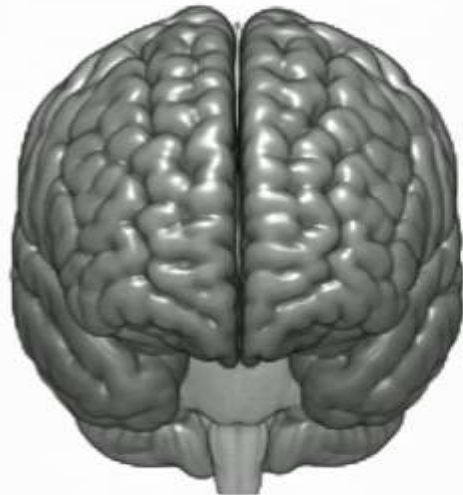


Anterior\_Commissure (Connections [Total/Min/Max/Mean/SD]: 114/0/17/0.982758620689655/3.11792226977515



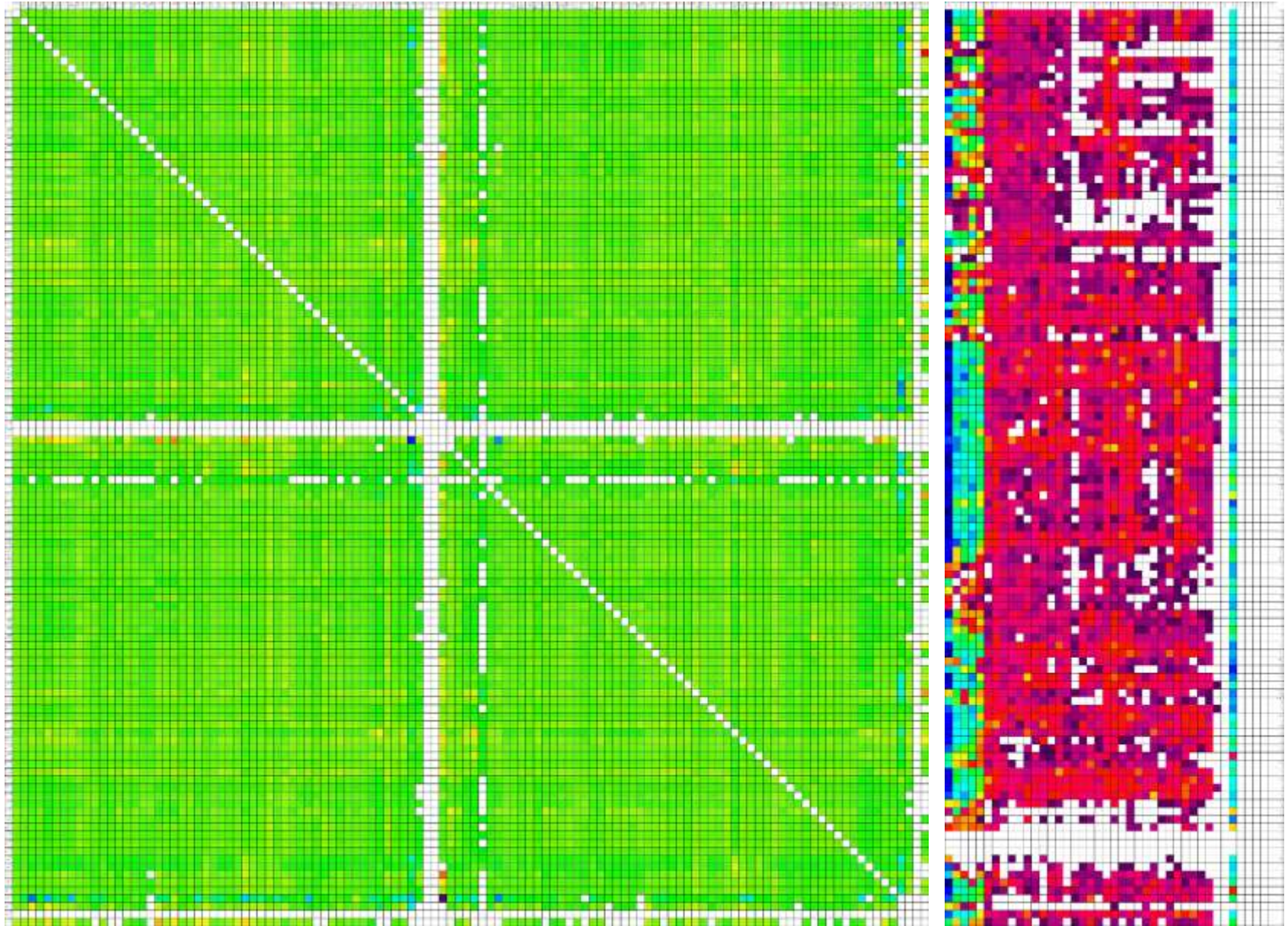


Made with fMRICRoTools

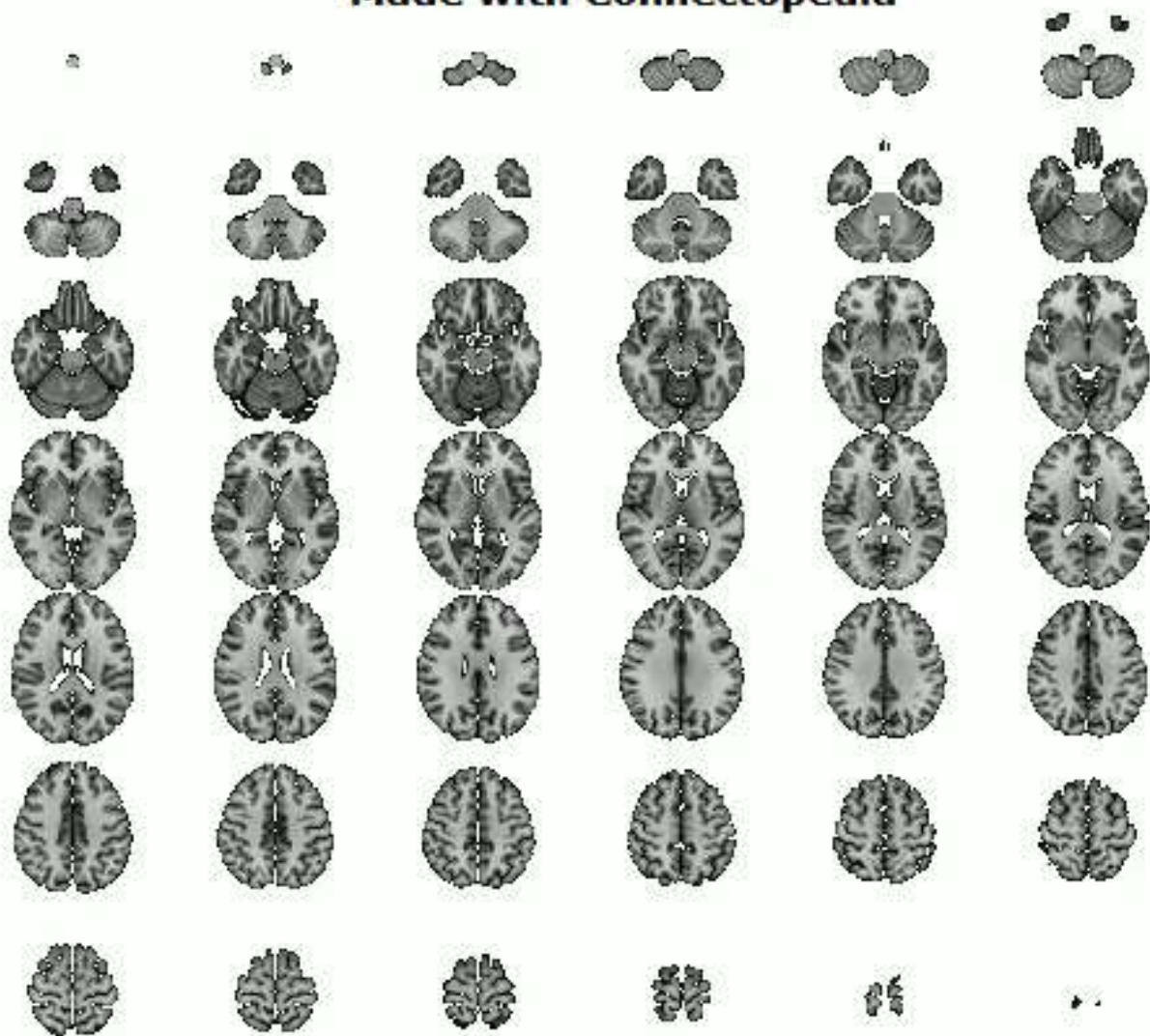




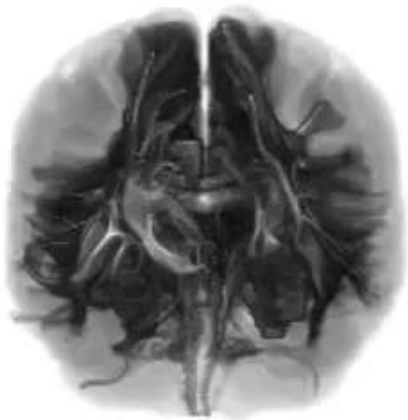
# Functional Connectomic



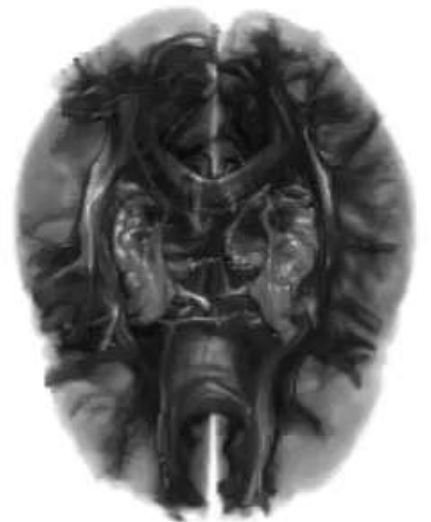
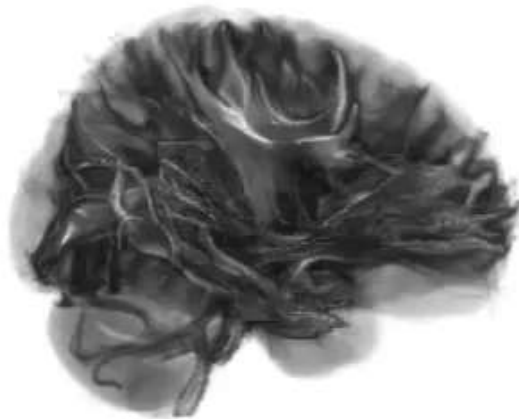
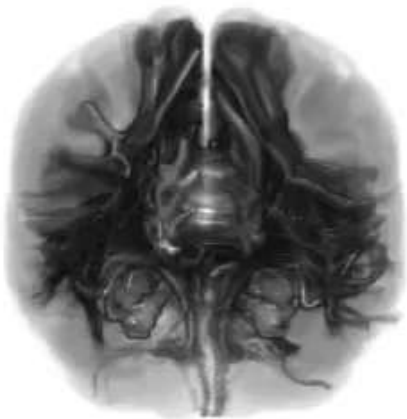
# Made with Connectopedia

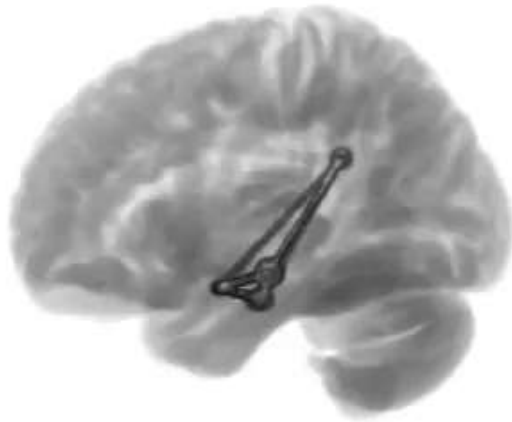
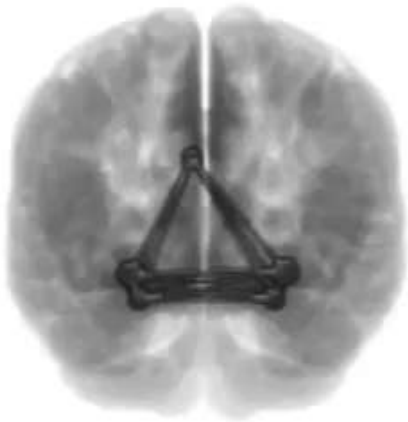




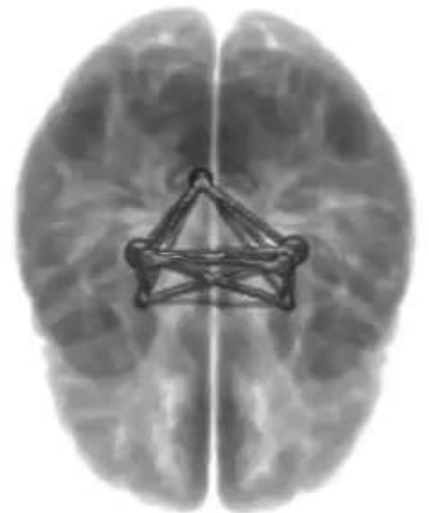
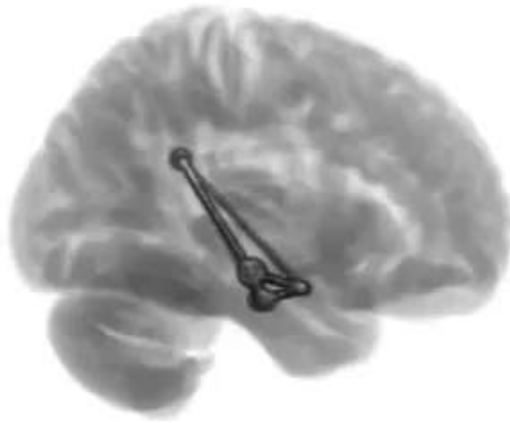
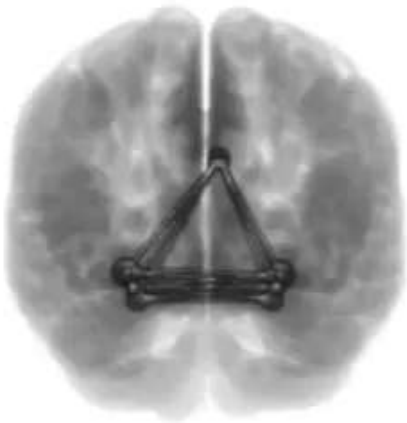


Made with Connectopedia



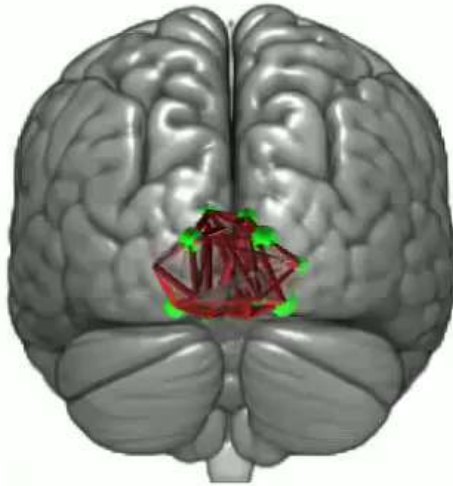


Made with [Connectopia](#)

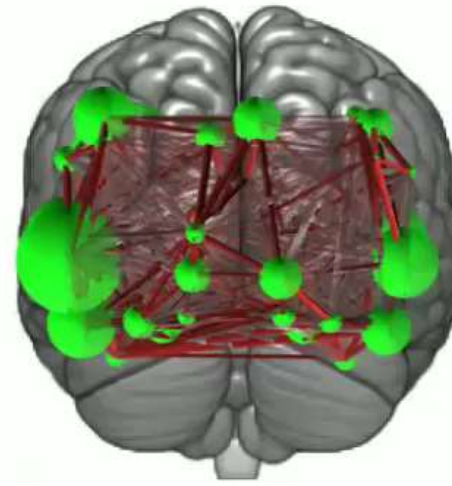




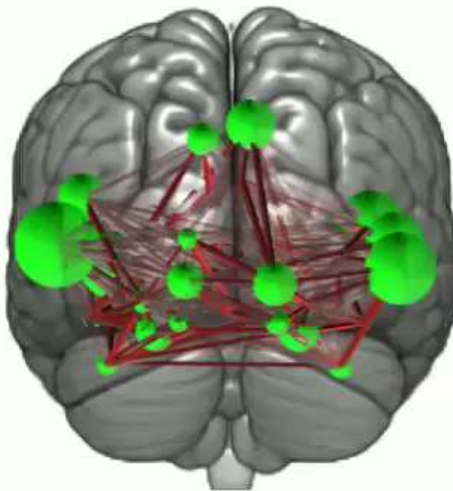
Made with fMRICRoTools



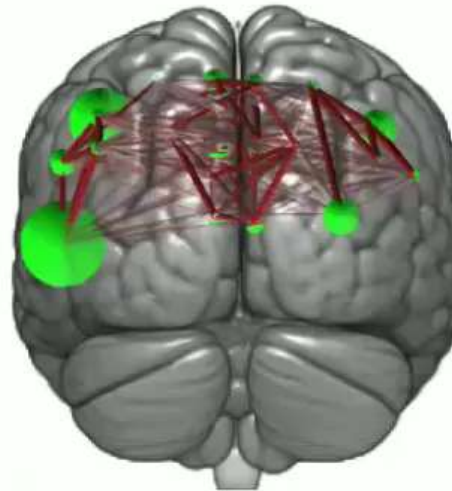
Made with fMRICRoTools



Made with fMRICRoTools



Made with fMRICRoTools





Emotion	Emotion processing	Emotion regulation	Emotional attachment	Emotional stimuli	Emotions self reflections decision making	Empathy	Empathy judgment	Erotica	Experiencing emotional states	Fear conditioning
Response aversive stimuli	Response aversive auditory stimulation	Religious feeling	Reappraise negative emotions	Processing emotions self reflections decision making	Processing emotions decision making	Processing emotional stimuli	Pleasure	Pleasant unpleasant emotions	Panic attack	Music enjoyment
Emotion language related	Evaluation emotional word	Expression emotional information	Generating melodic phrases	Generating sentences	Generation melodies	Idioms	Internally specified word generation	Language comprehension production	Language processing	Language switching
Selective attention speech	Response unintelligible speech	Receptive language	Prosodic integration	Processing phonological properties words	Phonological syntactic processing	Phonological processing	Phonemes	Perception prosodic information	Orthography phonology link	Nonspeech processing
Speech attention	Speech comprehension	Speech perception	Spoken language	Syntactic processing	Syntactical processing	Verb generation	Verbal creativity	Verbal encoding non semantic process	Verbal fluency	Verbal threat detection
Learning tone based second language	Learning	Learn complex procedure	Irony processing	Intentional forgetting	Identification familiar voices	Event time based prospective memory	Episodic memory retrieval	Episodic long term memory	Episodic encoding	Emotion memory
Memory retrieval	Mnemonic rehearsal	Multimodal memory retrieval	Naming items learned early life	Negative stimuli memory	Non verbal working memory	Processing metaphors	Prospective memory	Recall digit series	Recognition	Retrieval unpleasant experiences
Inhibition blinking	Horizontal saccadic eye movements	Executive control behavior	Discrimination finger gestures	Contralateral lower limb movement	Contralateral lip tongue face mouth movement	Contralateral finger hand wrist movement	Chewing	Bimanual manipulation	Working memory	Word retrieval specific entities



O ccurrence(s):



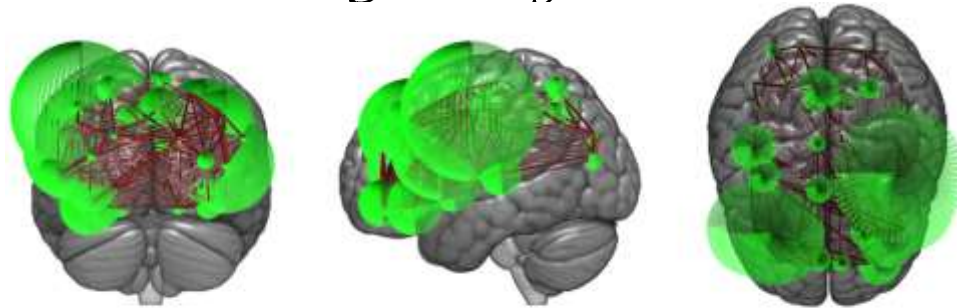




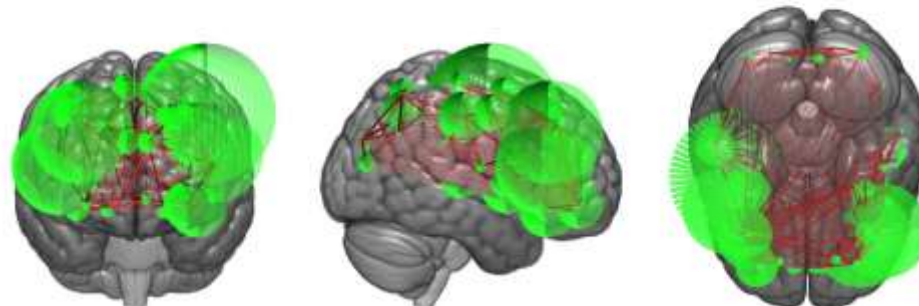
Made with Connectopedia



*Working Memory : 2,756 %*



Made with fMRICoTools

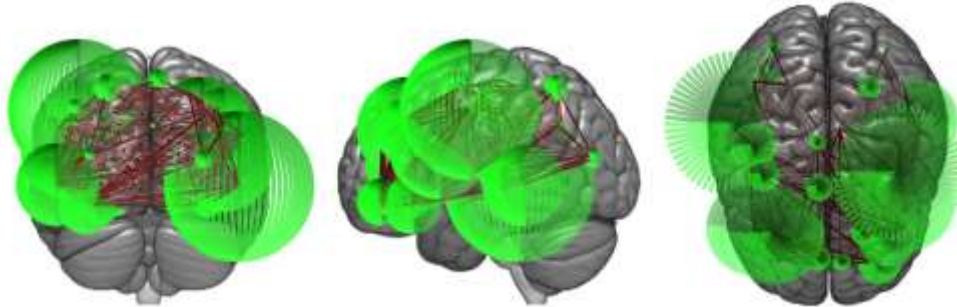




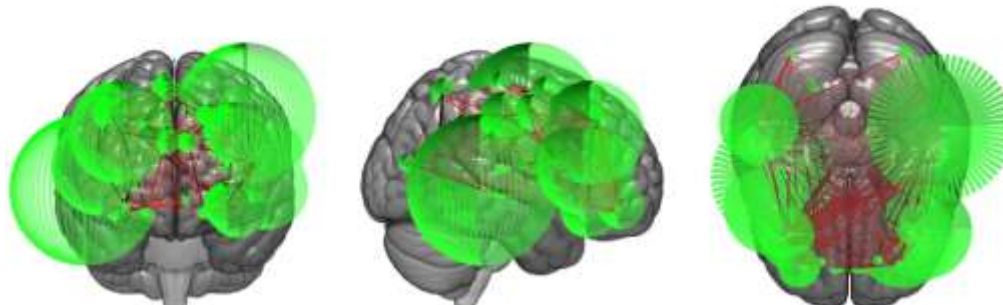
Made with Connectopedia

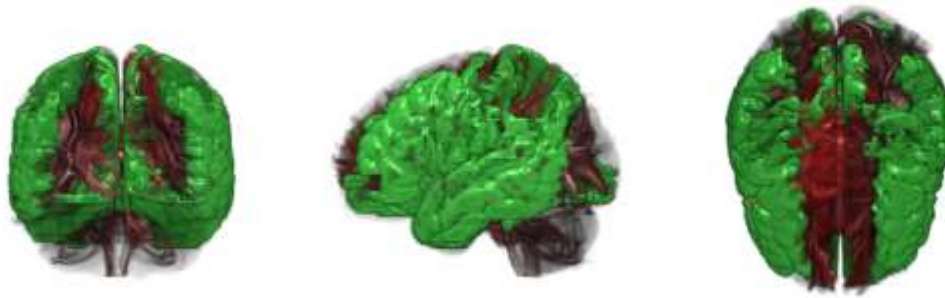


*Executive Control Behavior: 1,551 %*

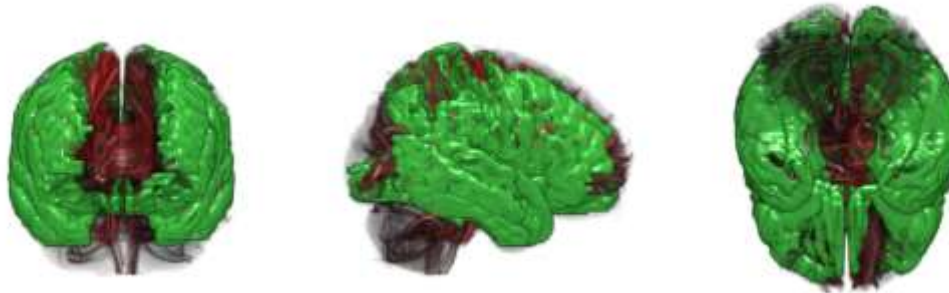


Made with fMRICRoTools

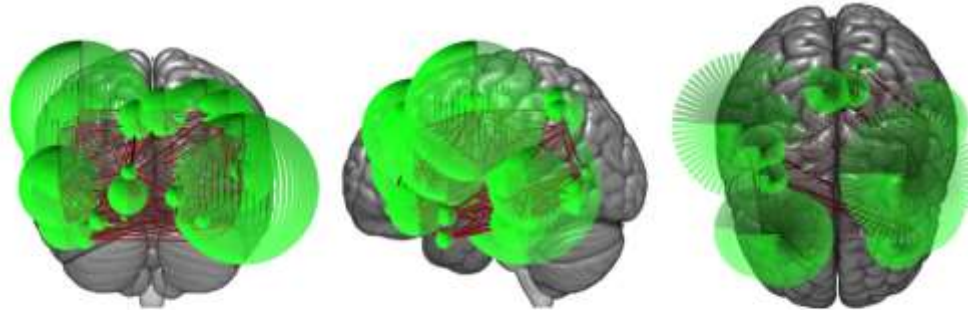




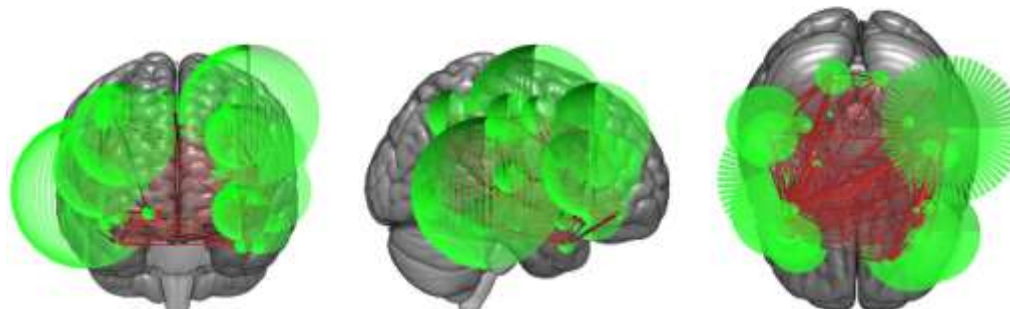
Made with Connectopedia



*Emotion Processing: 1,573 %*



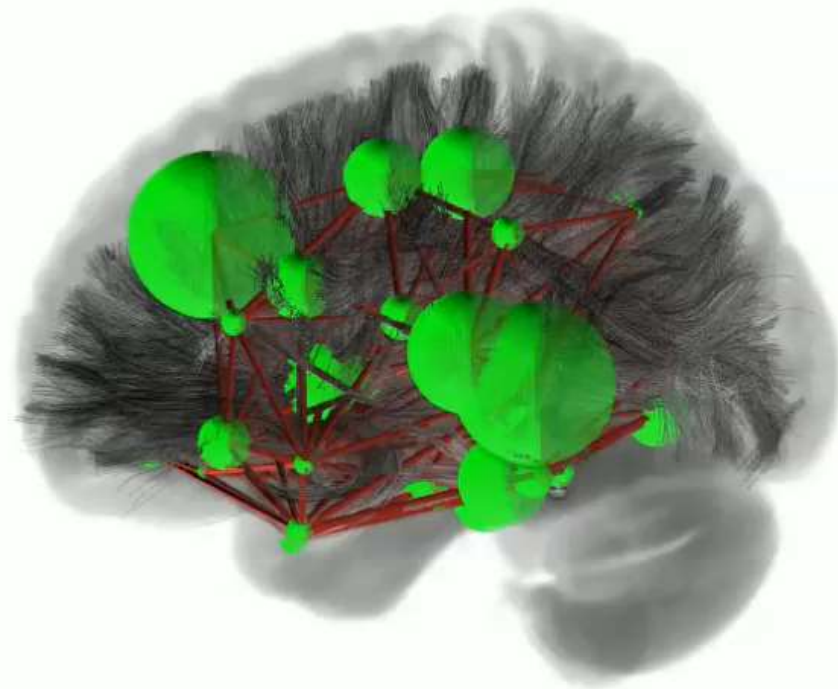
Made with fMRICROTools





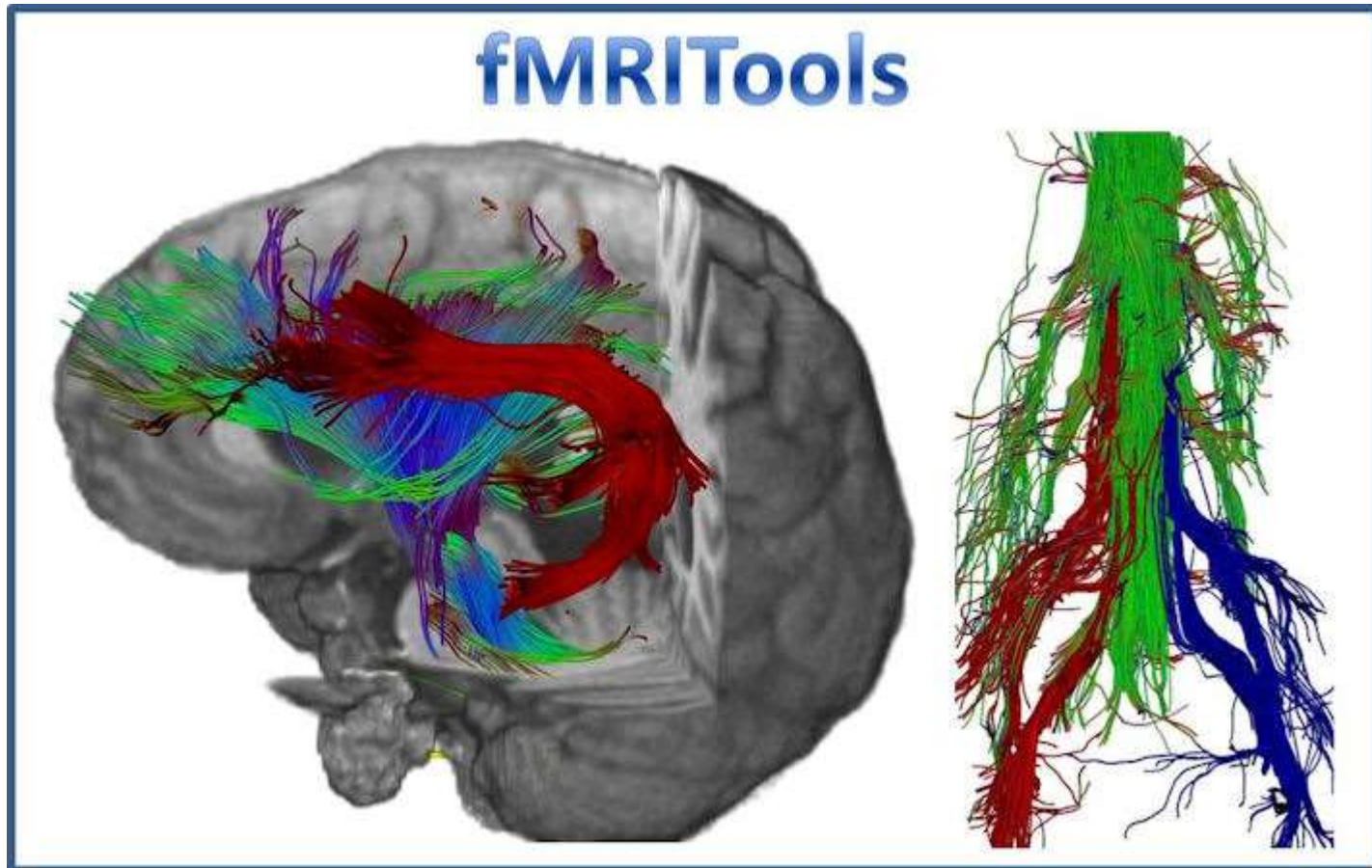
**Conclusions**

Made with fMRICRoTools



# L.I.M.E.C.

Laboratoire d'Imagerie Médicale Expérimentale et Clinique



<http://fmritools.com>