Defining the human connectome

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Emi Takahashi	*Boston Children's*
T Ellen Grant	*Boston Children's*
H Gene Stanley	*BU*
Doug Rosene	*BU*

Wendell Krieg 1963 - human white matter by dissection

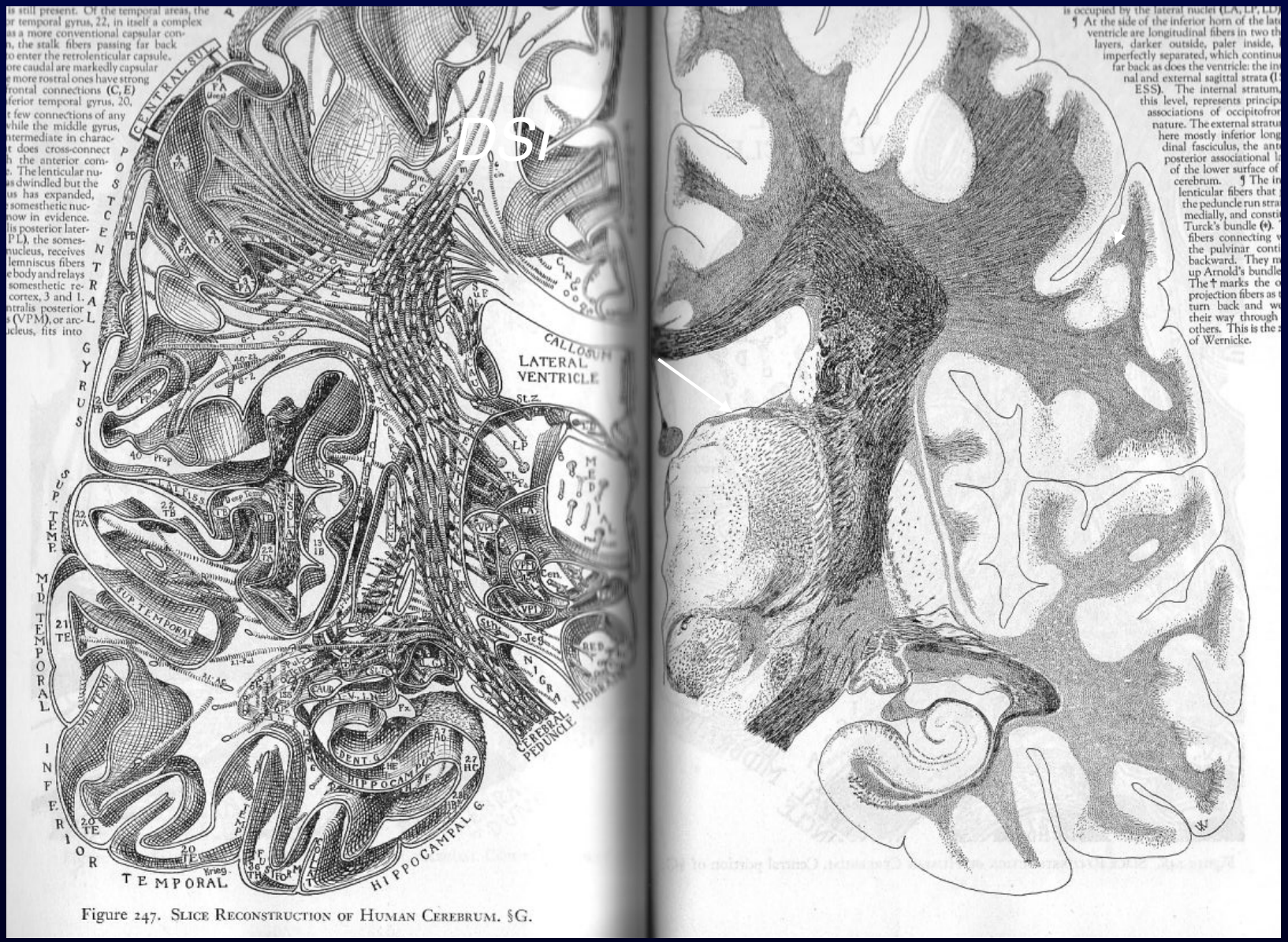

Figure 247. Slice Reconstruction of Human Cerebrum. §G.

DTI tractography - HBM Paris 1995

WHITE MATTER CONNECTIVITY EXPLORED BY MRI

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Massachusetts General Hospital and Harvard Medical School, Boston, MA, USA

Introduction

Water diffusion assessed by MRI accurately portrays the local material anisotropy of living tissue. In the CNS, MRI of diffusion anisotropy can provide dramatic images of the orientation fields of cerebral white matter. In order to map neuroanatomic connectivity, we have investigated the feasibility of deducing from these orientation fields the large scale trajectories of cerebral white matter tracts.

Putative white matter tracts were defined by numerical integration of the diffusion anisotropy tensor field. Two approaches were investigated. The first approach postulates fiber tracts parallel with the principal orientation of diffusivity at each location. Then fiber position $x^\alpha(\tau)$, $\alpha \in \{1,2,3\}$, will satisfy the first order differential equation:

$$dx^\alpha/d\tau \pm e_1(x)\, v_1^\alpha(x) = 0 \qquad [1]$$

where e_1 denotes the maximal eigenvalue of the diffusion tensor and v_1^α is its respective eigenvector. The sign ambiguity of Eq. [1] is resolved by an arbitrary, but locally consistent, choice. The second approach considers the distance in tissue defined by the mean diffusion times between points. This distance defines a (non-Euclidean) geometry in which the role of a metric tensor is played by the negative of the diffusion tensor, and it is natural to postulate that fiber tracts are the minimal paths between points. Such paths satisfy the second order geodesic equation:

$$d^2x^\alpha/d\tau^2 + \Gamma^\alpha_{\mu\gamma}(dx^\mu/d\tau)(dx^\gamma/d\tau) = 0 \qquad [2a]$$

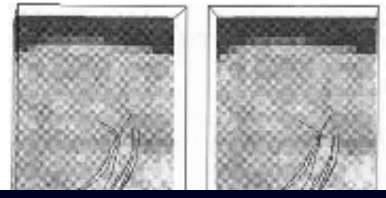
with repeated indices summed, where Γ represents the connection coefficients of $\mathbf{D} = D_{\alpha\beta}$:

$$\Gamma^\alpha_{\mu\gamma} = 1/2\,(\mathbf{D}^{-1})^{\alpha\varepsilon}(\partial D_{\mu\beta}/\partial x^\gamma + \partial D_{\mu\gamma}/\partial x^\beta + \partial D_{\mu\beta}/\partial x^\gamma) \qquad [2b].$$

Eq. [2] may be solved given an initial point x^α and an initial slope $dx^\alpha/d\tau$.

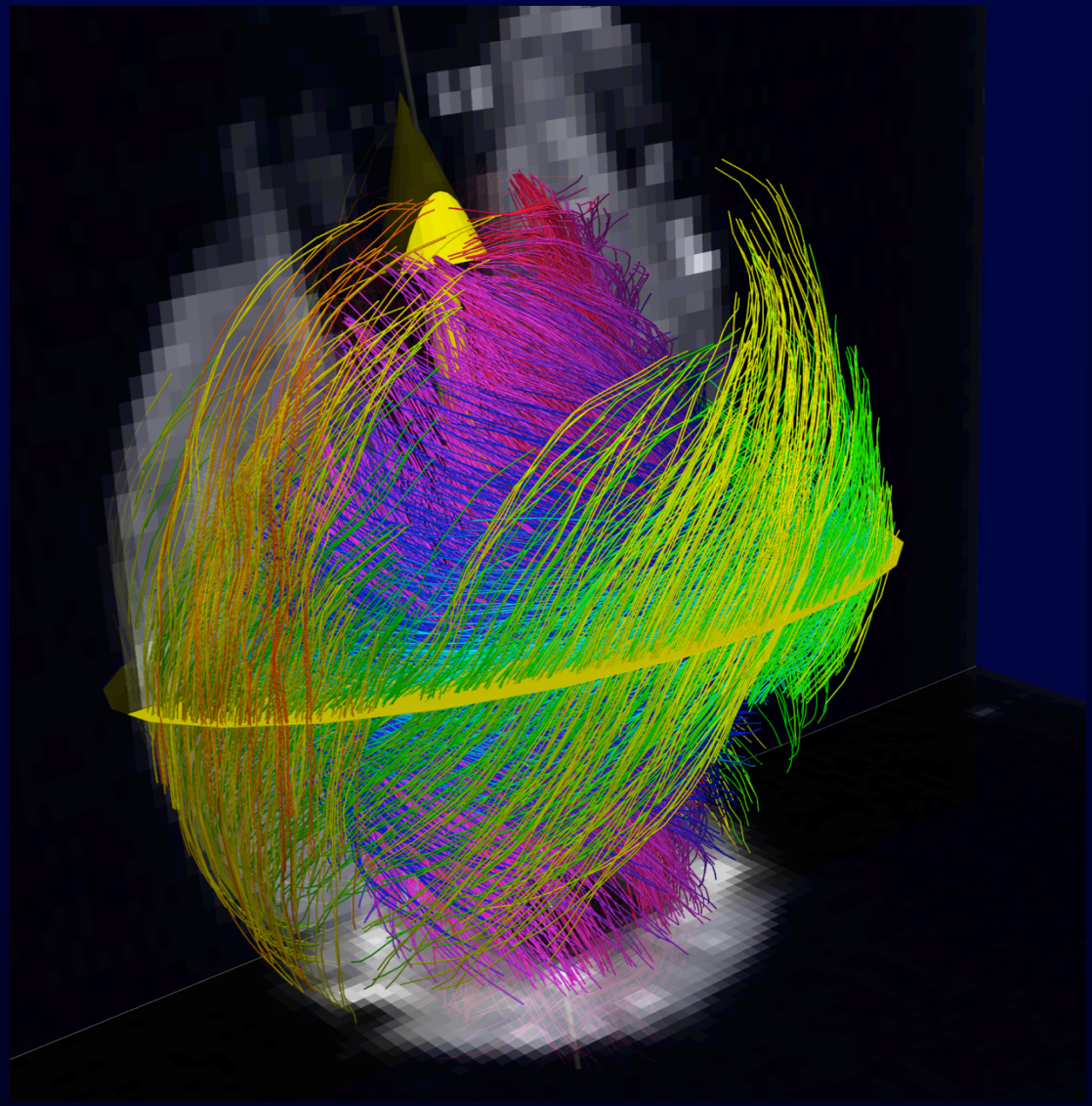
Results

Fiber tracts reconstructed via Eq. [1] were in good agreement with known anatomy. Fig 1 shows fibers of the left *corona radiata* tracked from diencephalon to cortical mantle; fiber data are superposed upon parasagittal magnitude MRI; right is rostral.



Solution of the geodesic Eq. [2a-2b] is less robust. In the

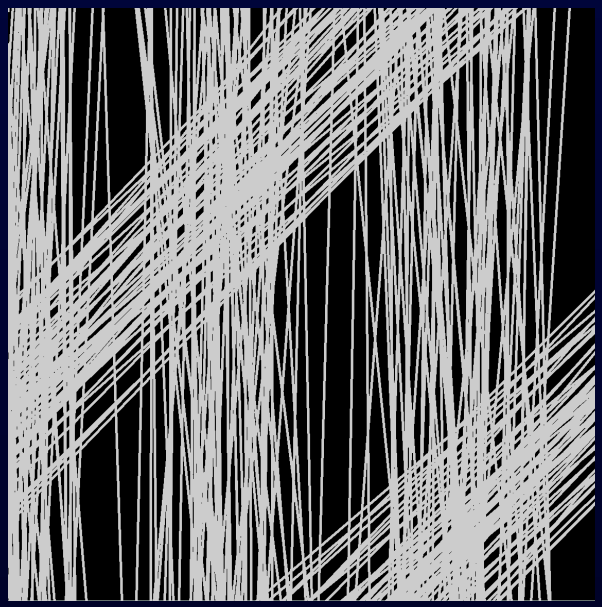
DTI tracography of the myocardium



Diffusion MRI - tissue structure is traced by 3D patterns of water diffusion

1994: diffusion tensors show average fiber directions

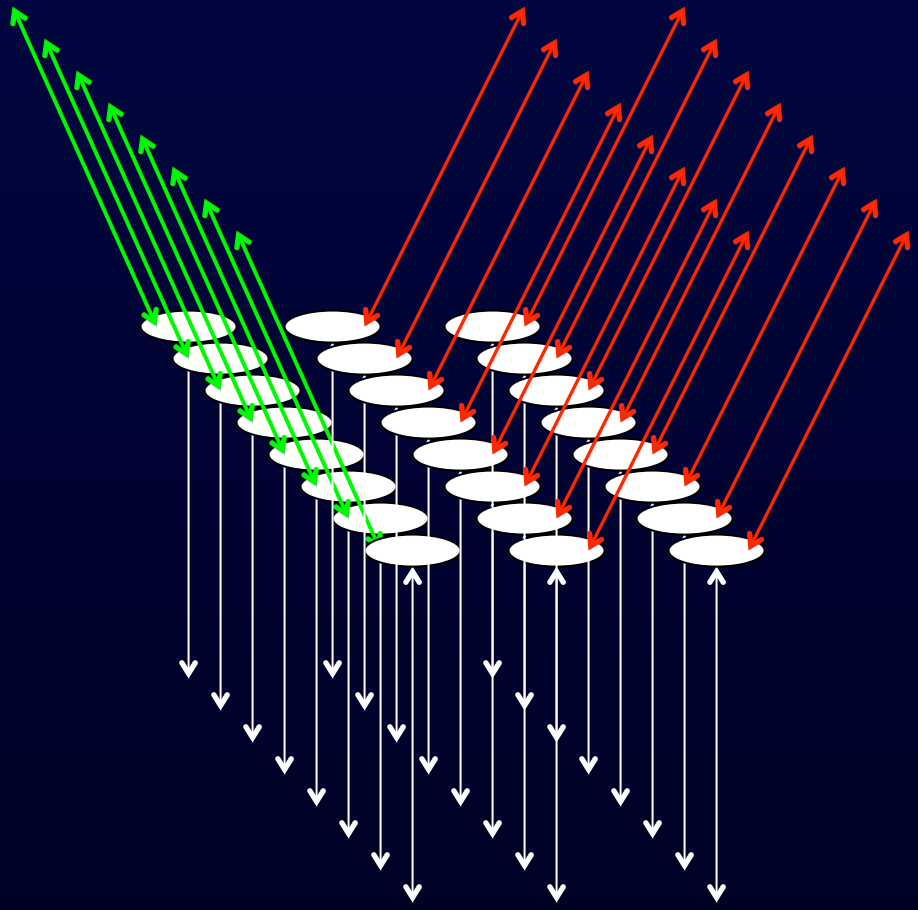
tissue



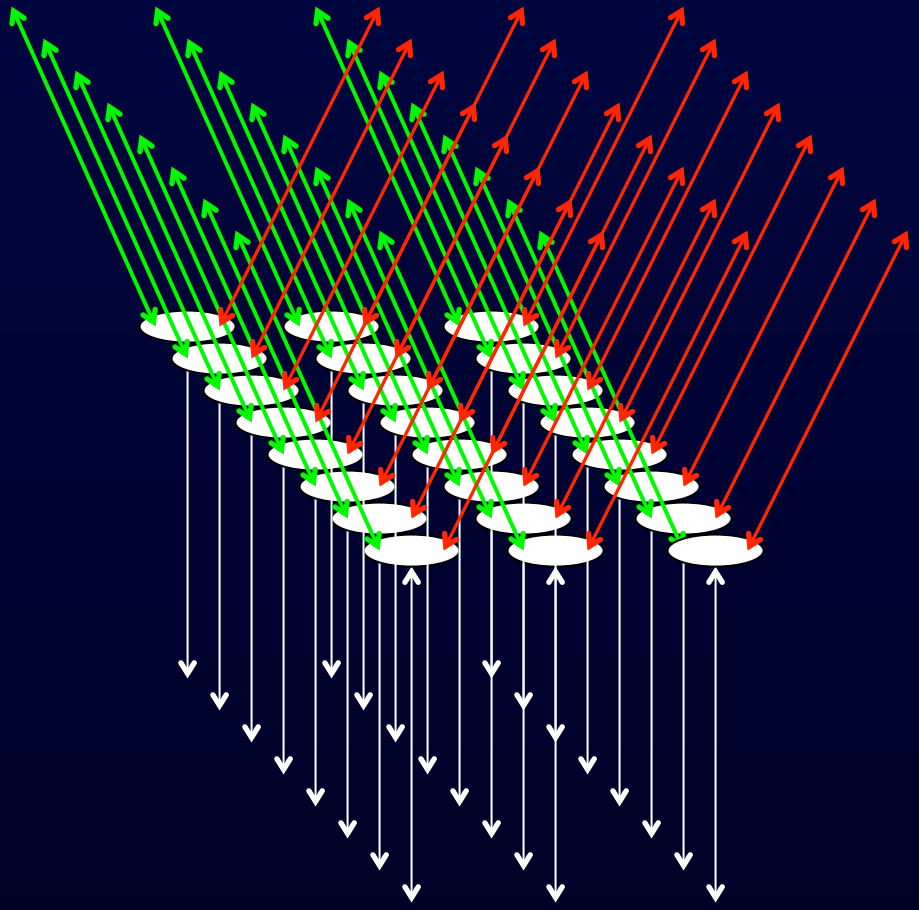
diffusion tensor

Pathway overlap is a defining characteristic of the brain

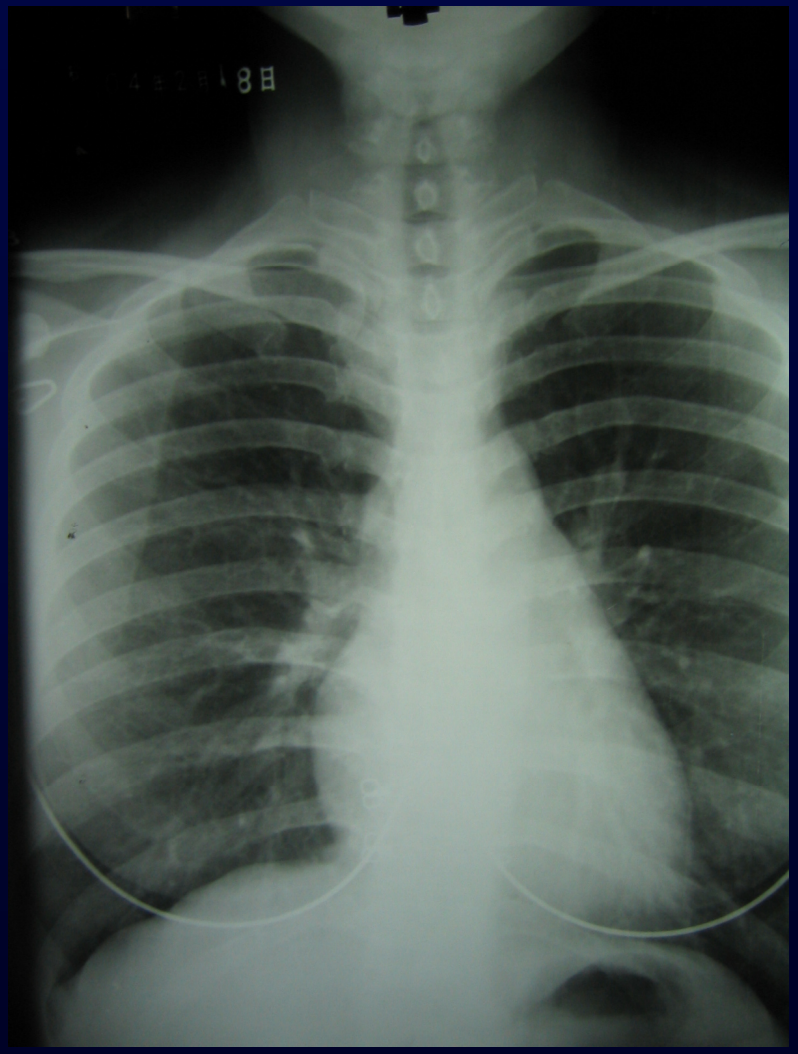
not brainy



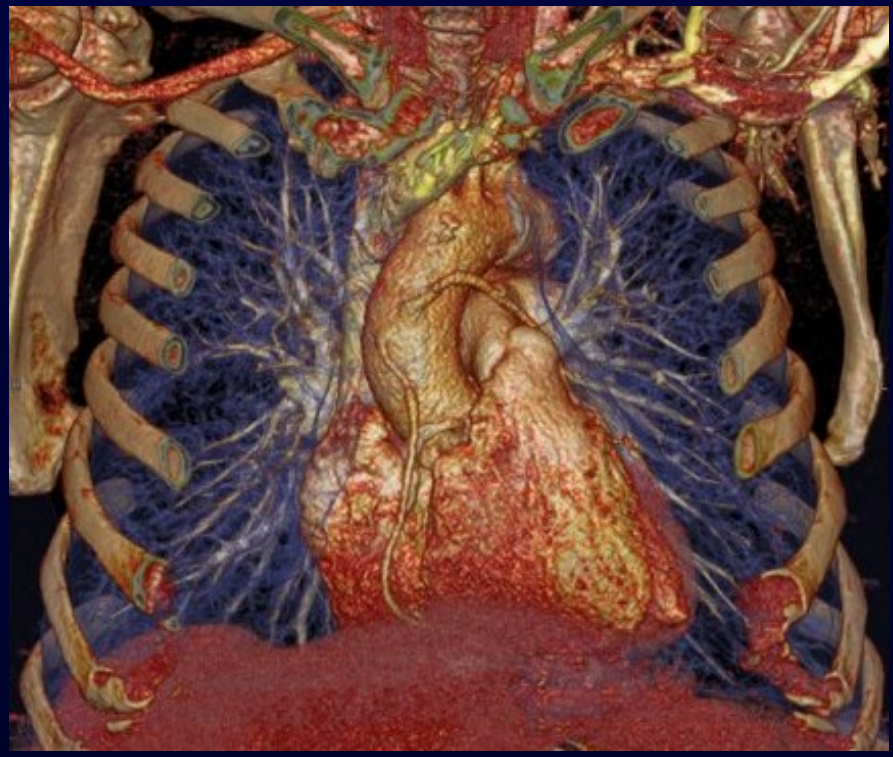
brainy

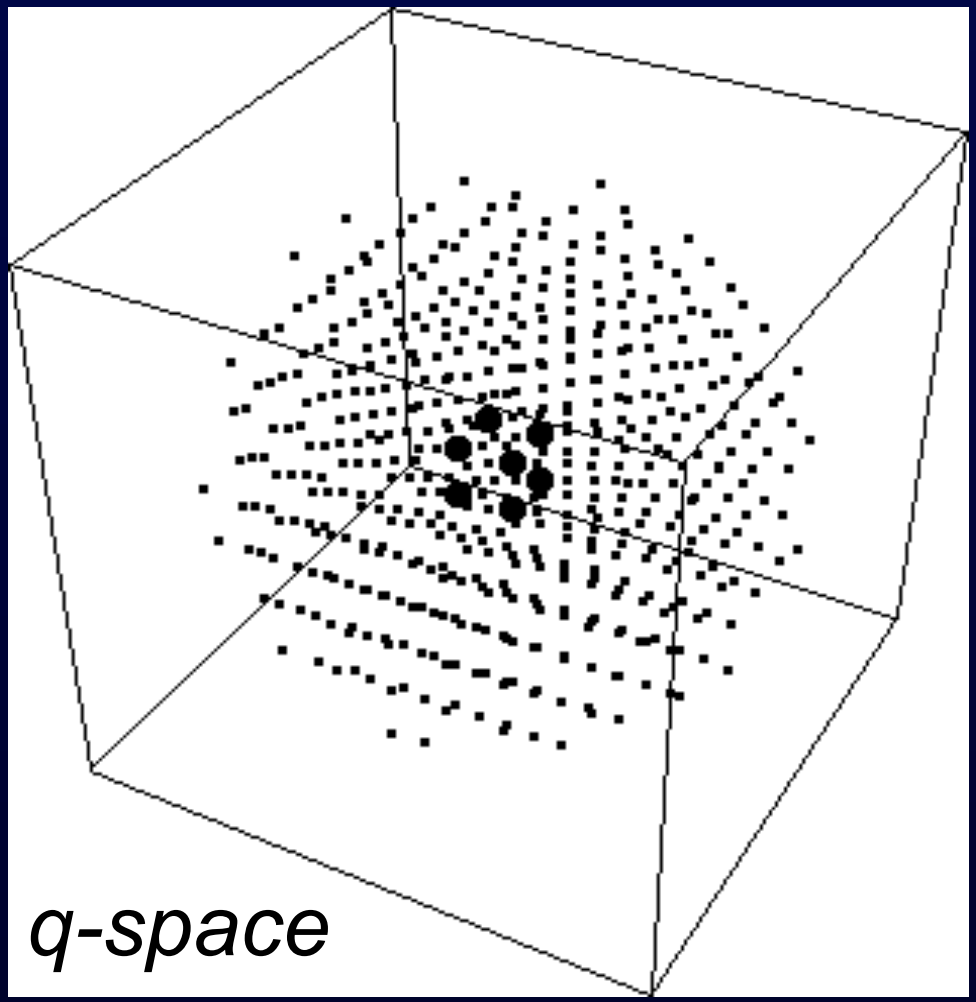


x-ray, overlap



CT, overlap resolved



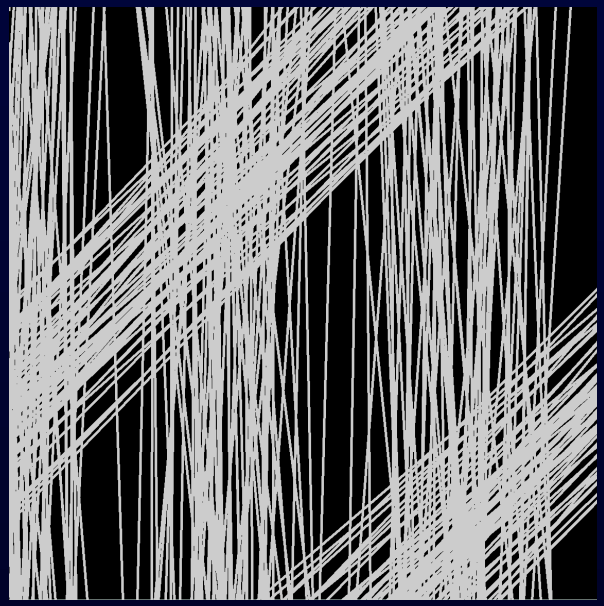


DTI: 7 q-samples, recon with tensor fit
DSI: 500 q-samles, recon with 3DFT

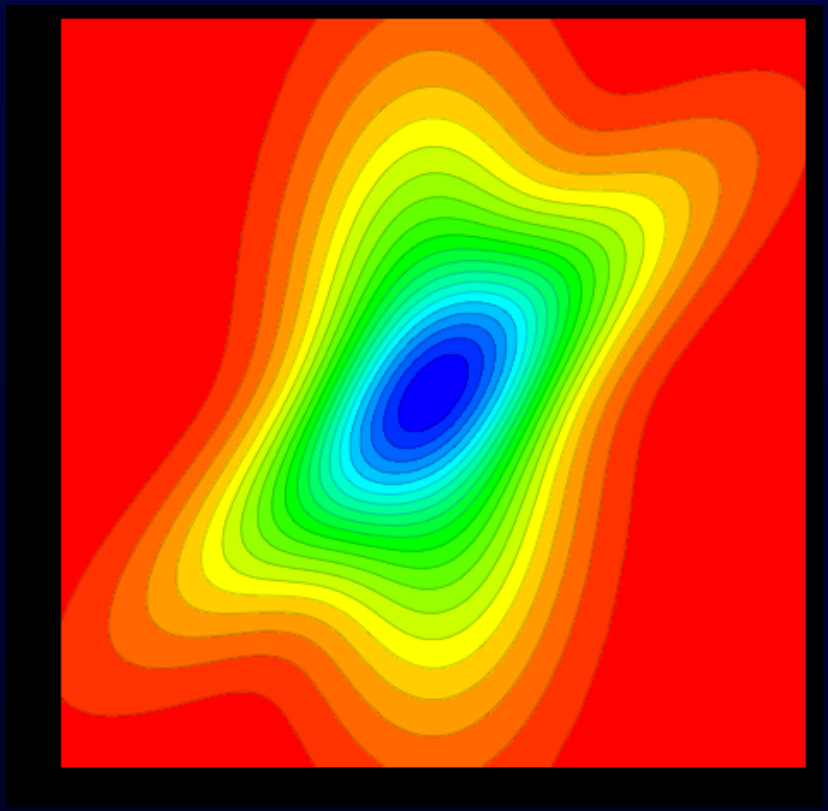
Water diffusion traces tissue fiber structure

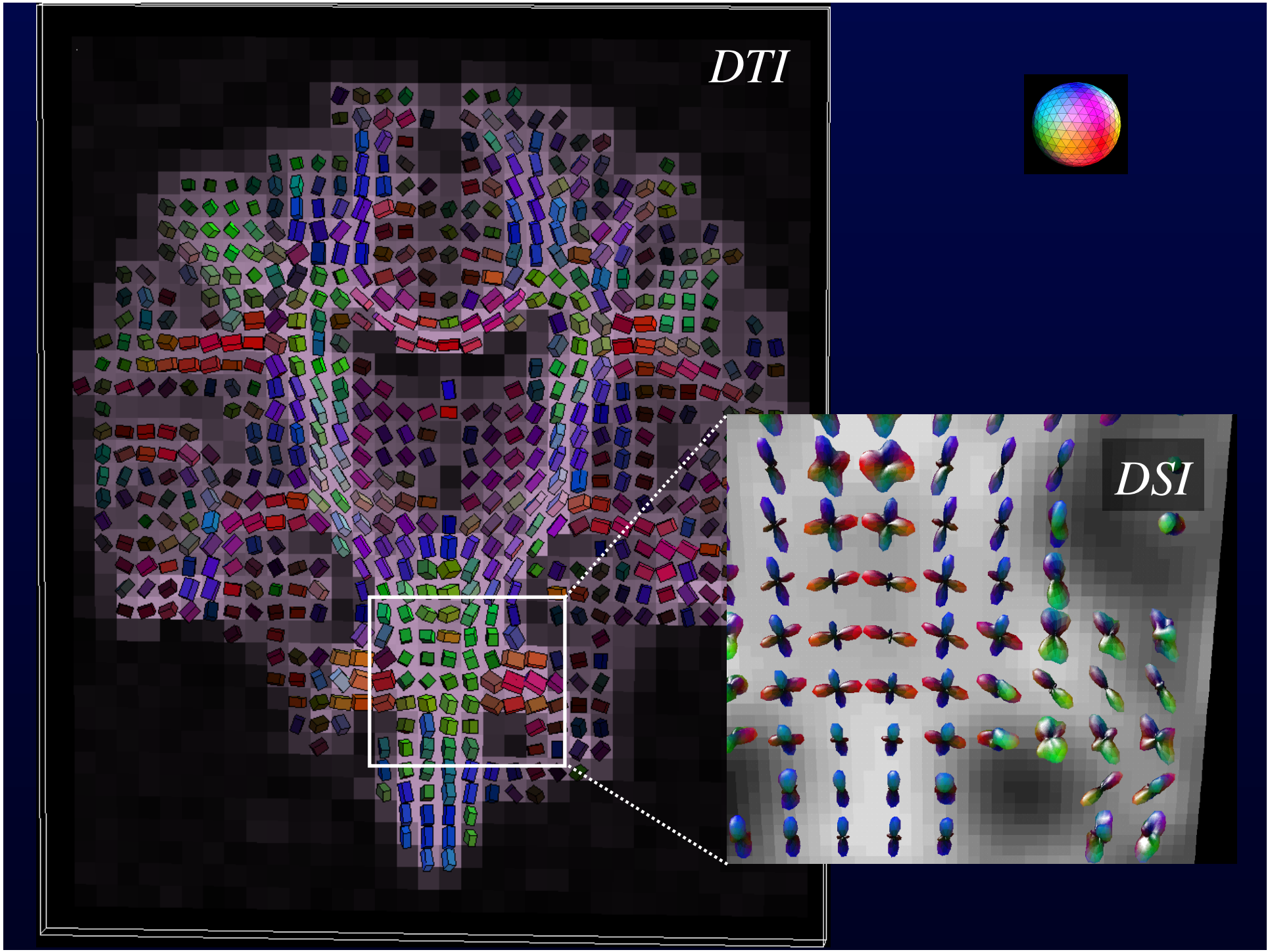
2000: diffusion spectrum MRI (DSI) resolves the crossings

brain tissue

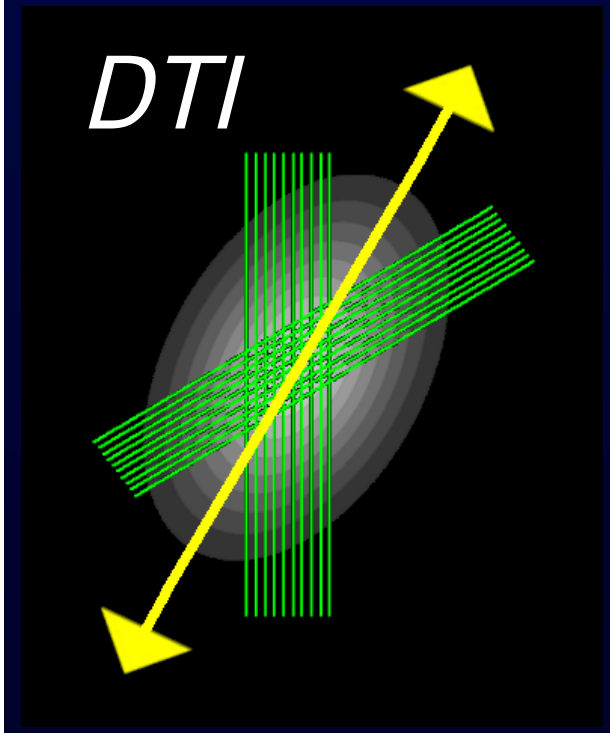


diffusion spectrum

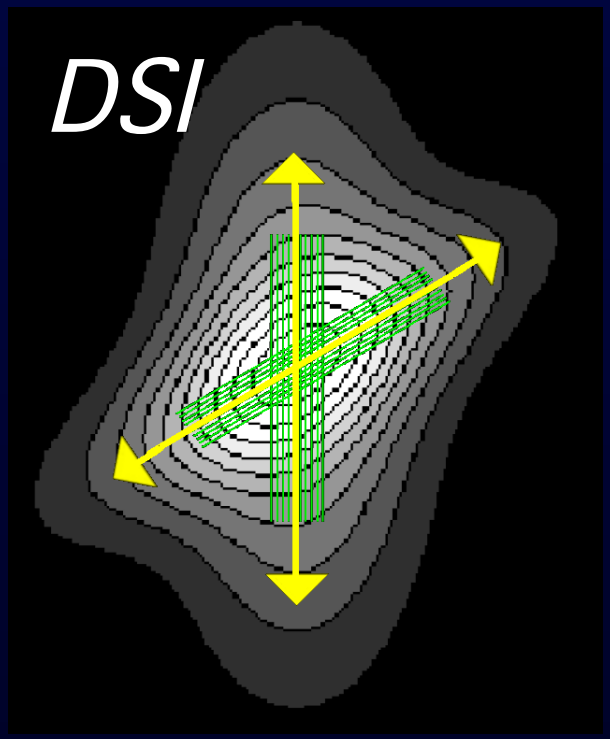



DTI
DSI

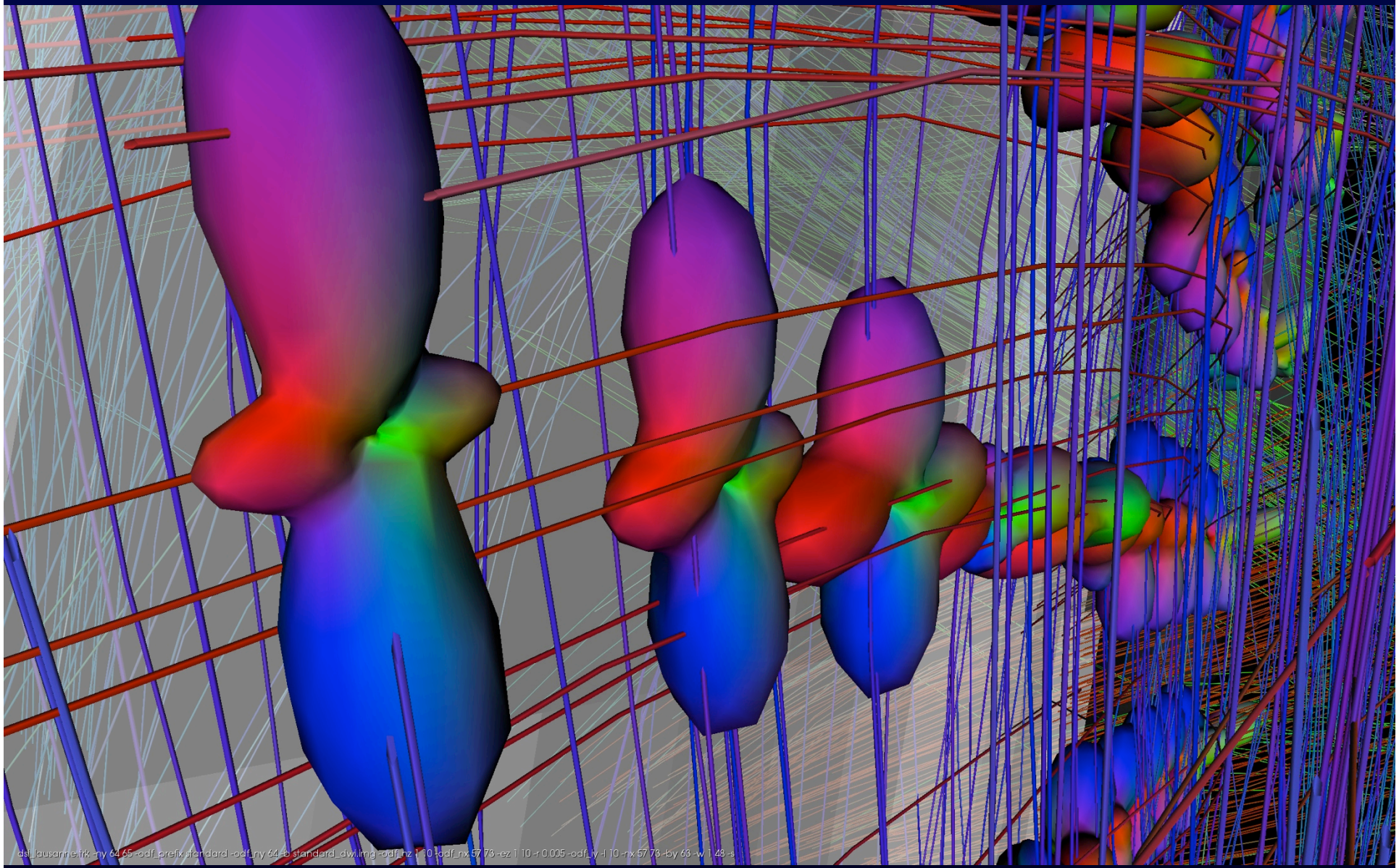
Why DSI not DTI?



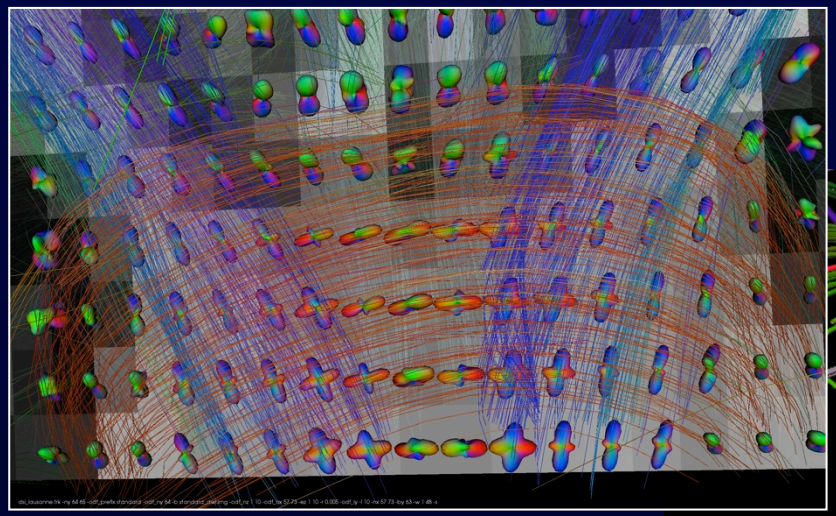
fibers
diffusion observed
tractography

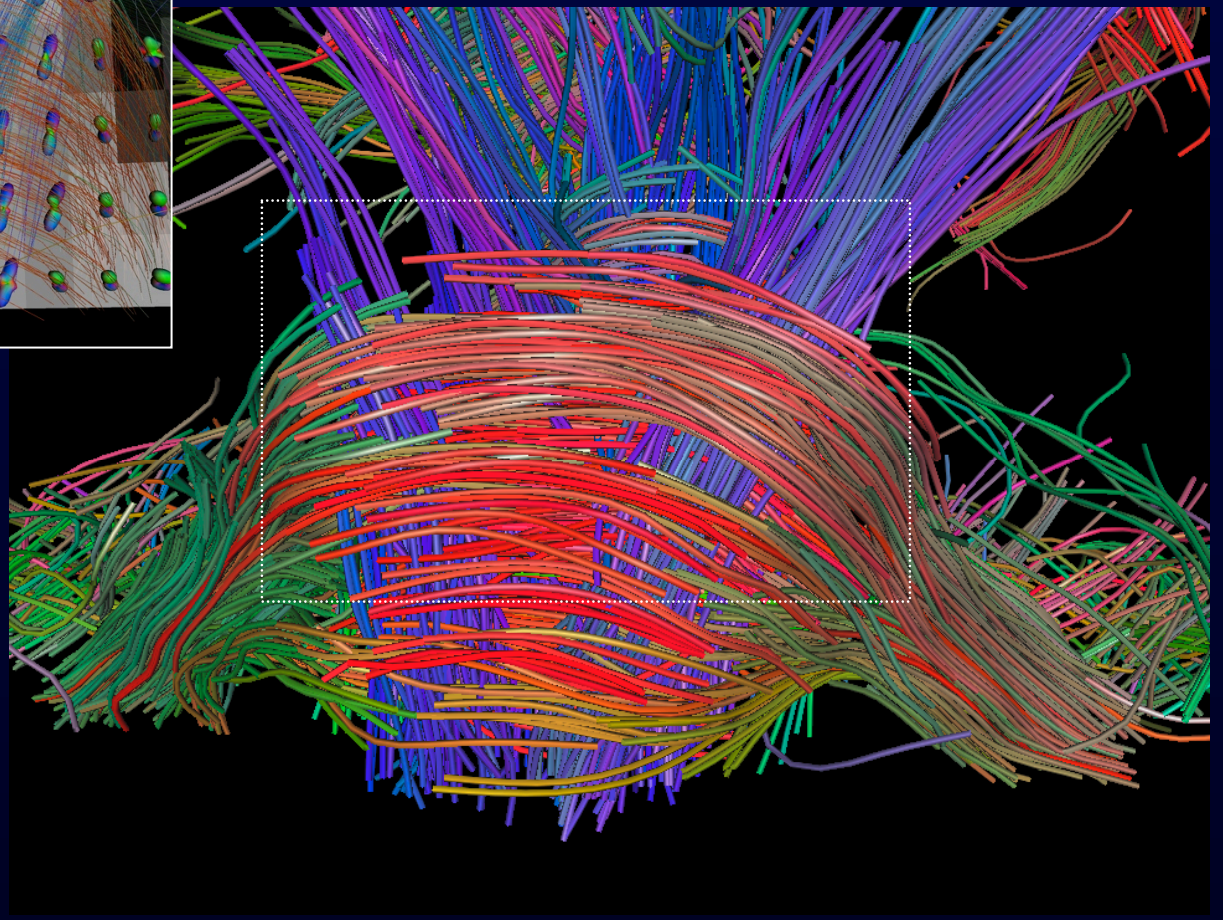


ODFs and tracks, human pons in vivo 3T



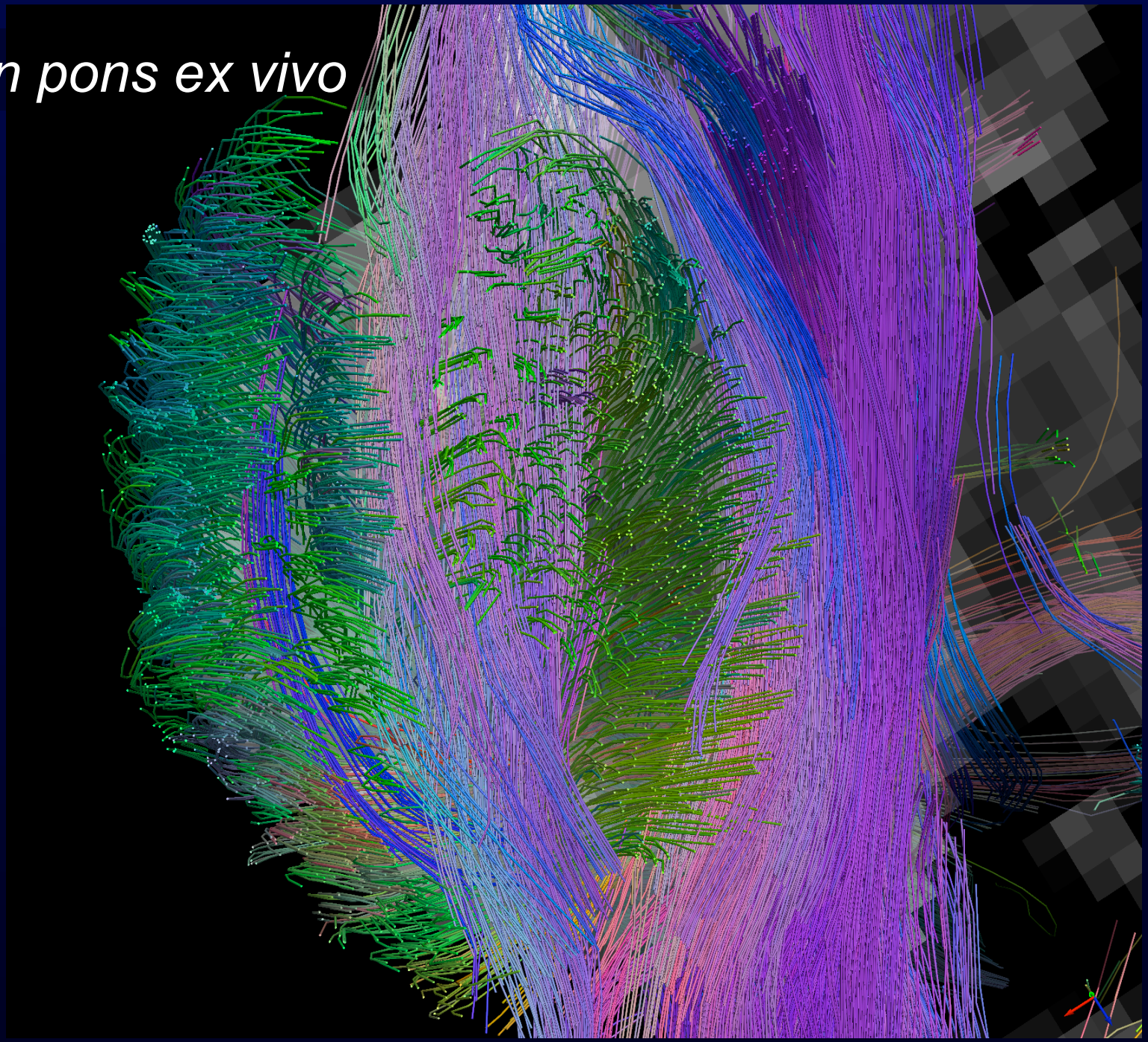
DSI tractography - Pons normal human subject in vivo
middle cerebellar peduncle - red
corticospinal tract - blue



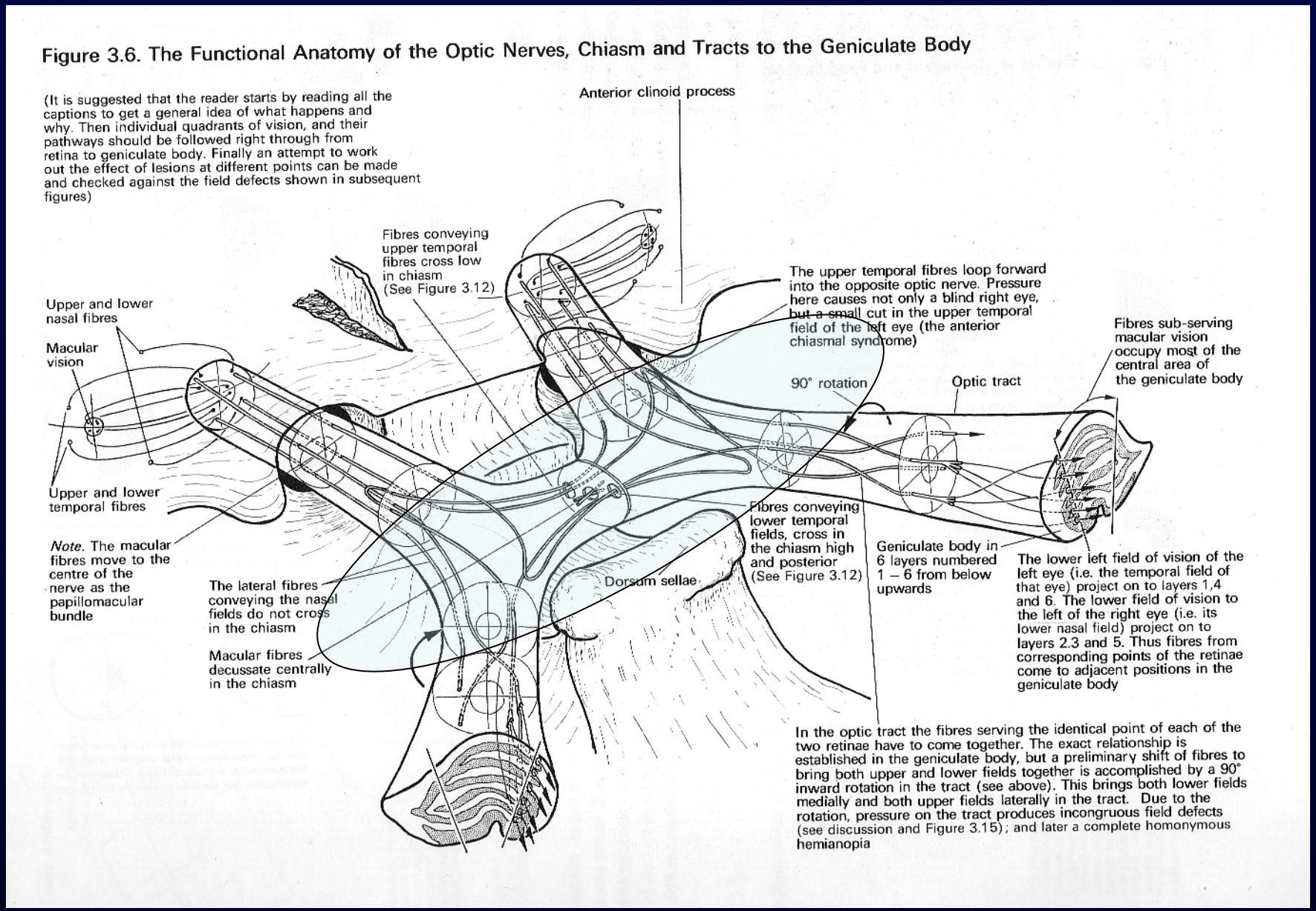


3T DSI SE 3500/96
2.6mm b_{max}8500 53min

Human pons ex vivo

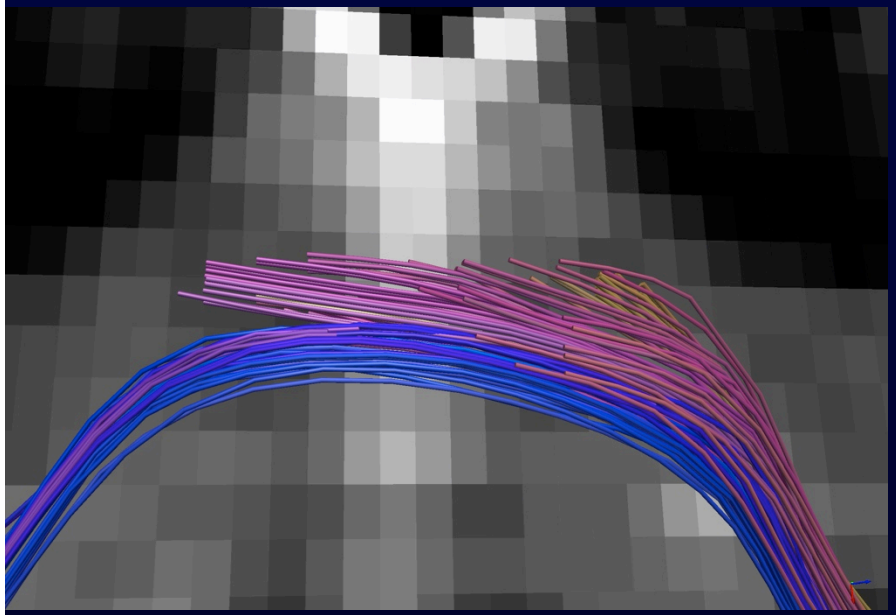


Optic chiasm

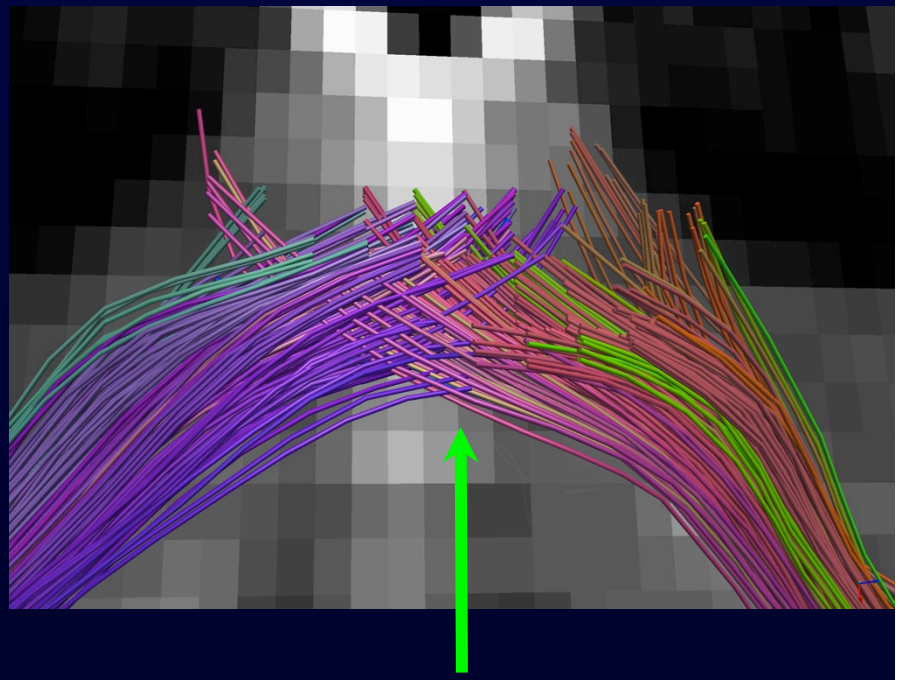


Optic chiasm

DTI



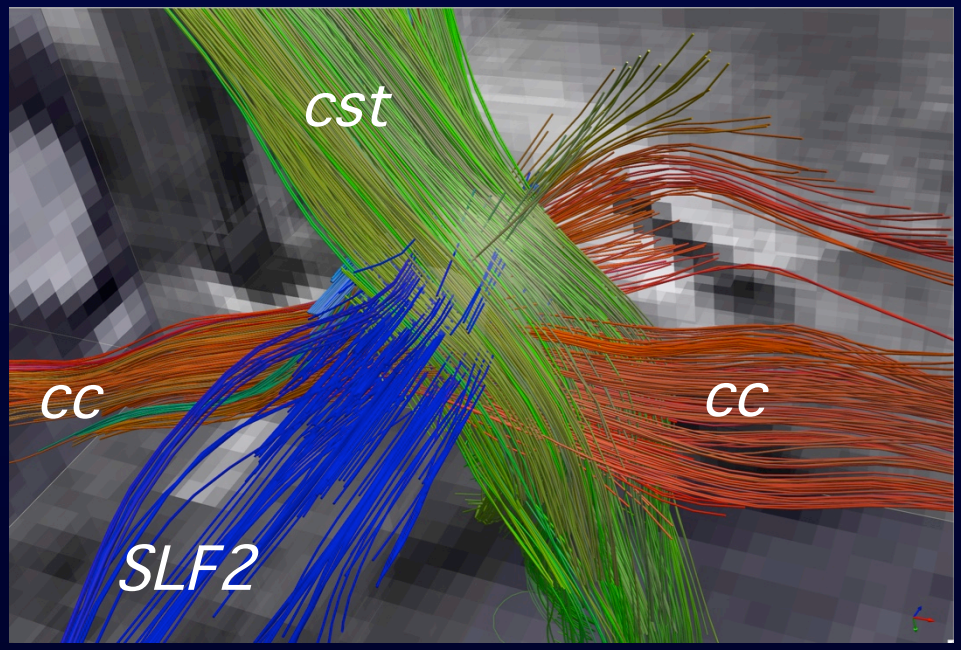
DSI



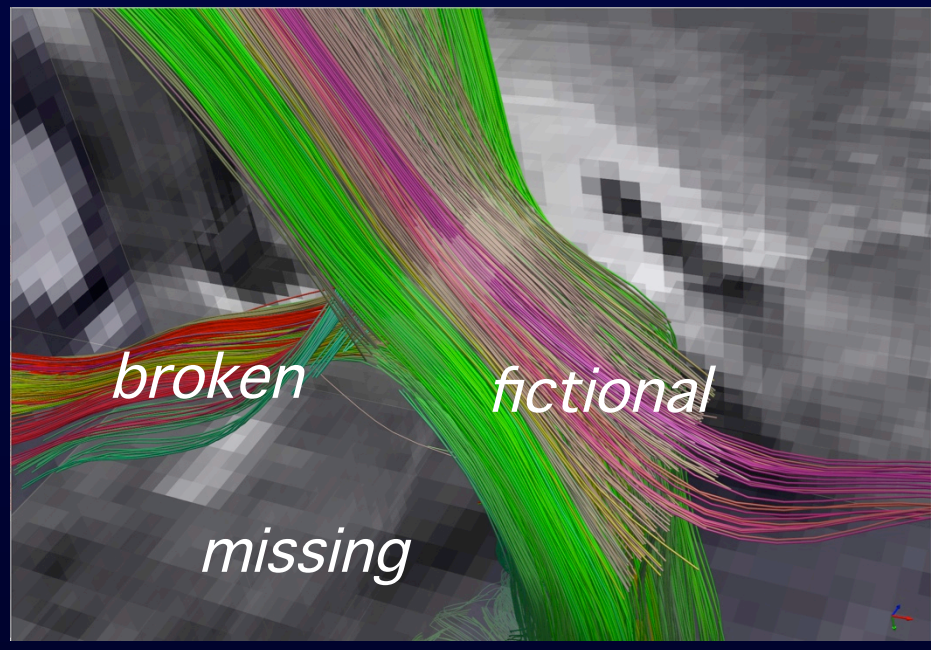
crossing

DSI vs DTI - centrum semiovale of macaque

DSI



DTI



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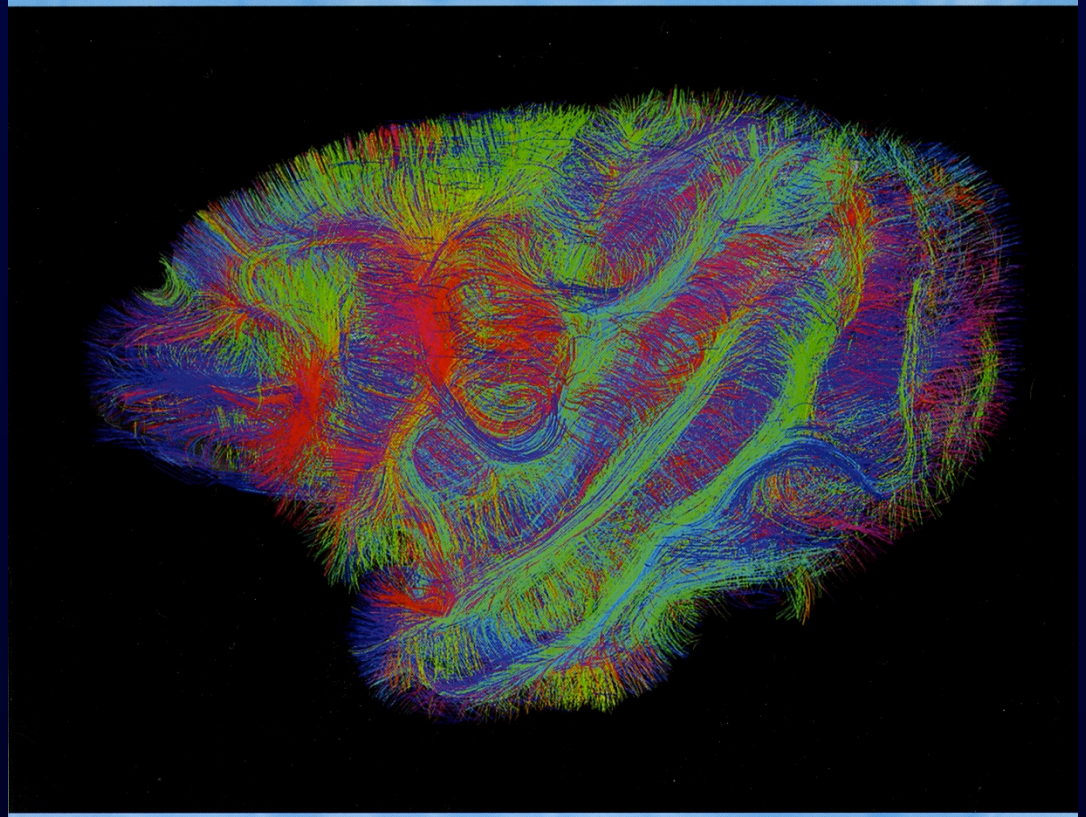

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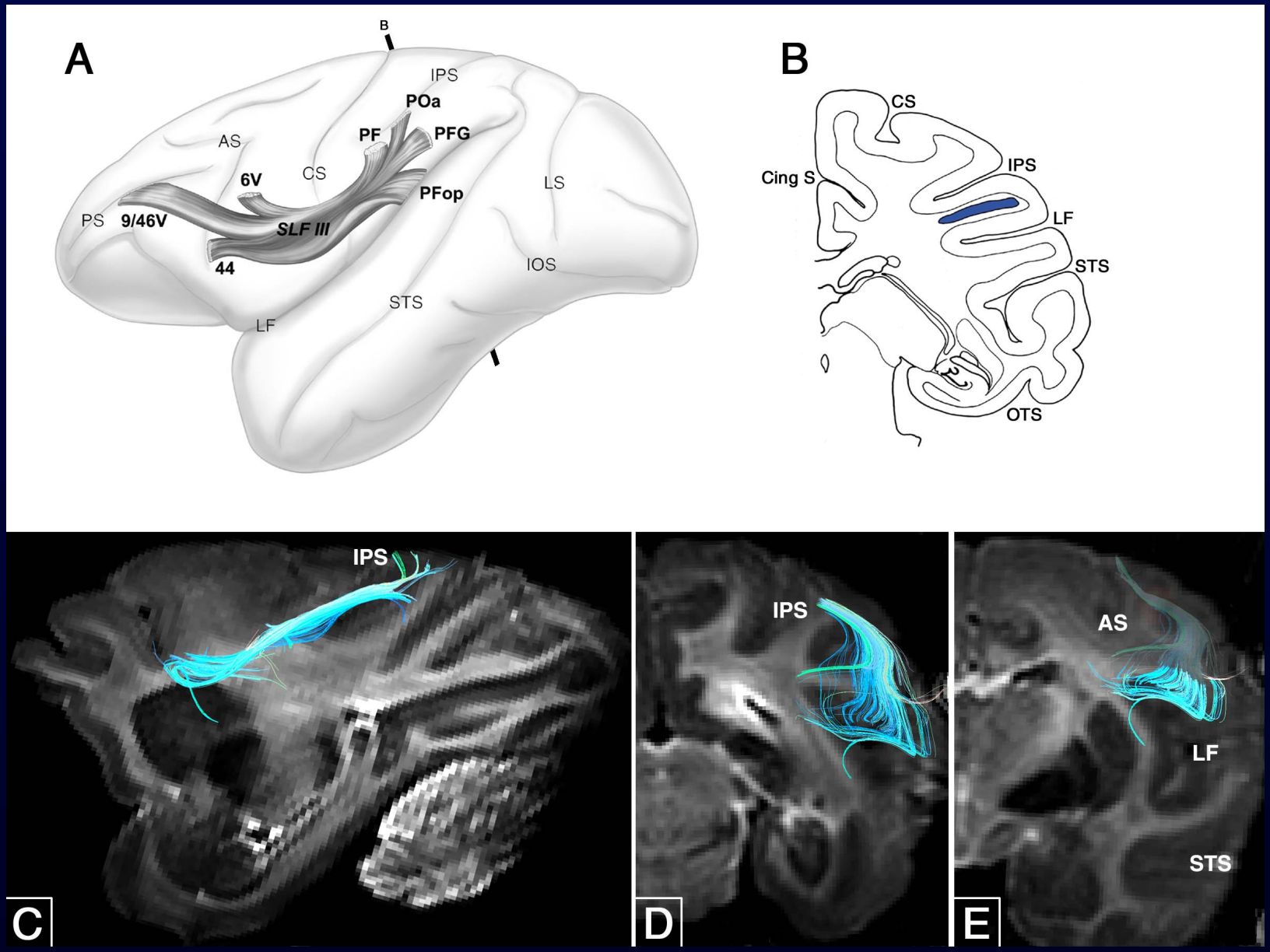
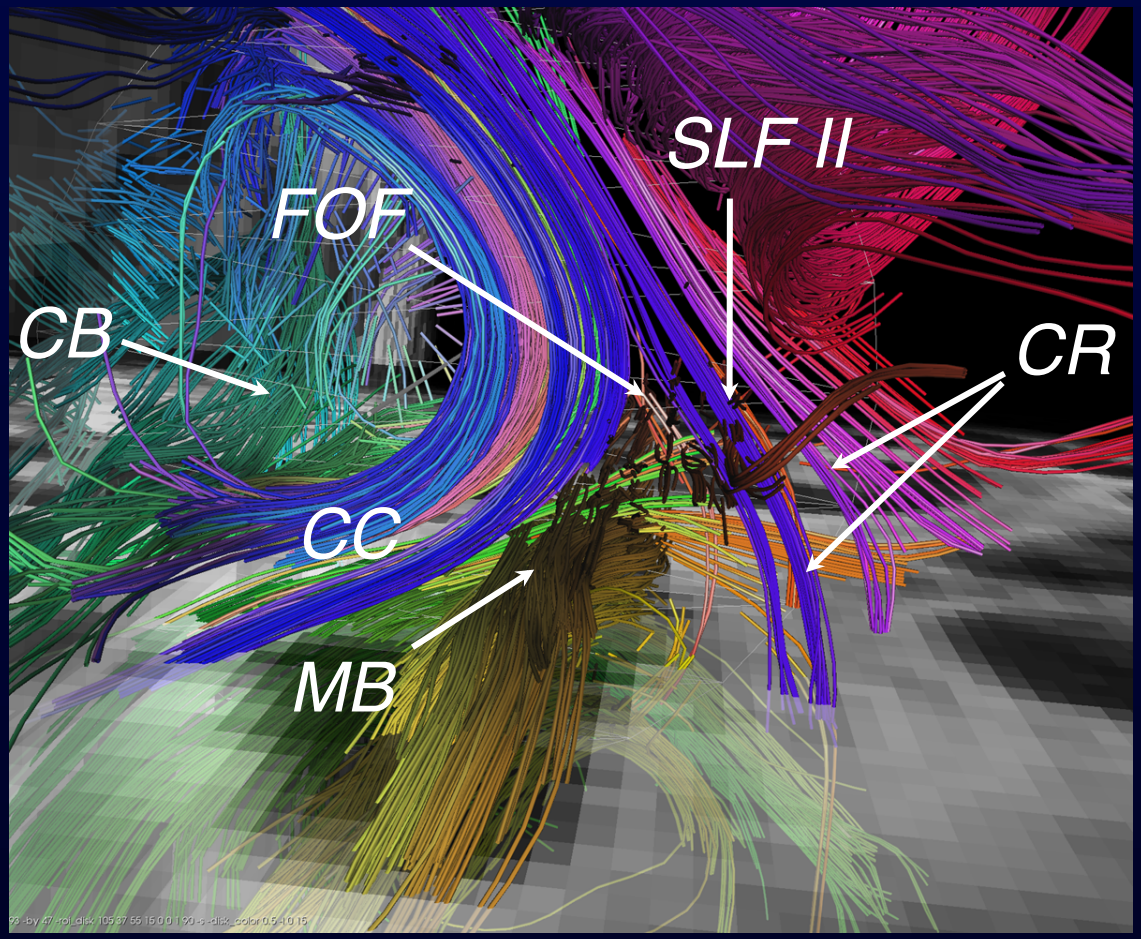
Tracer and DSI - SLFIII

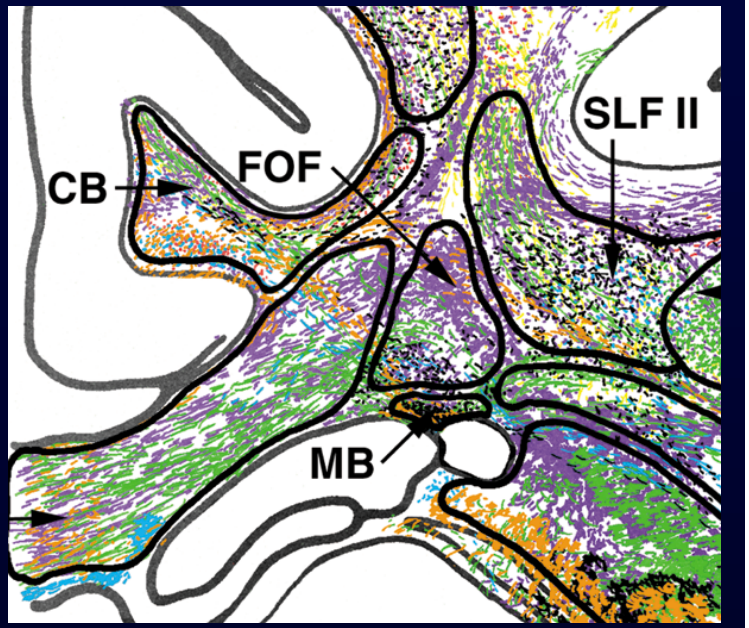


Macaque DSI and isotope gold standard

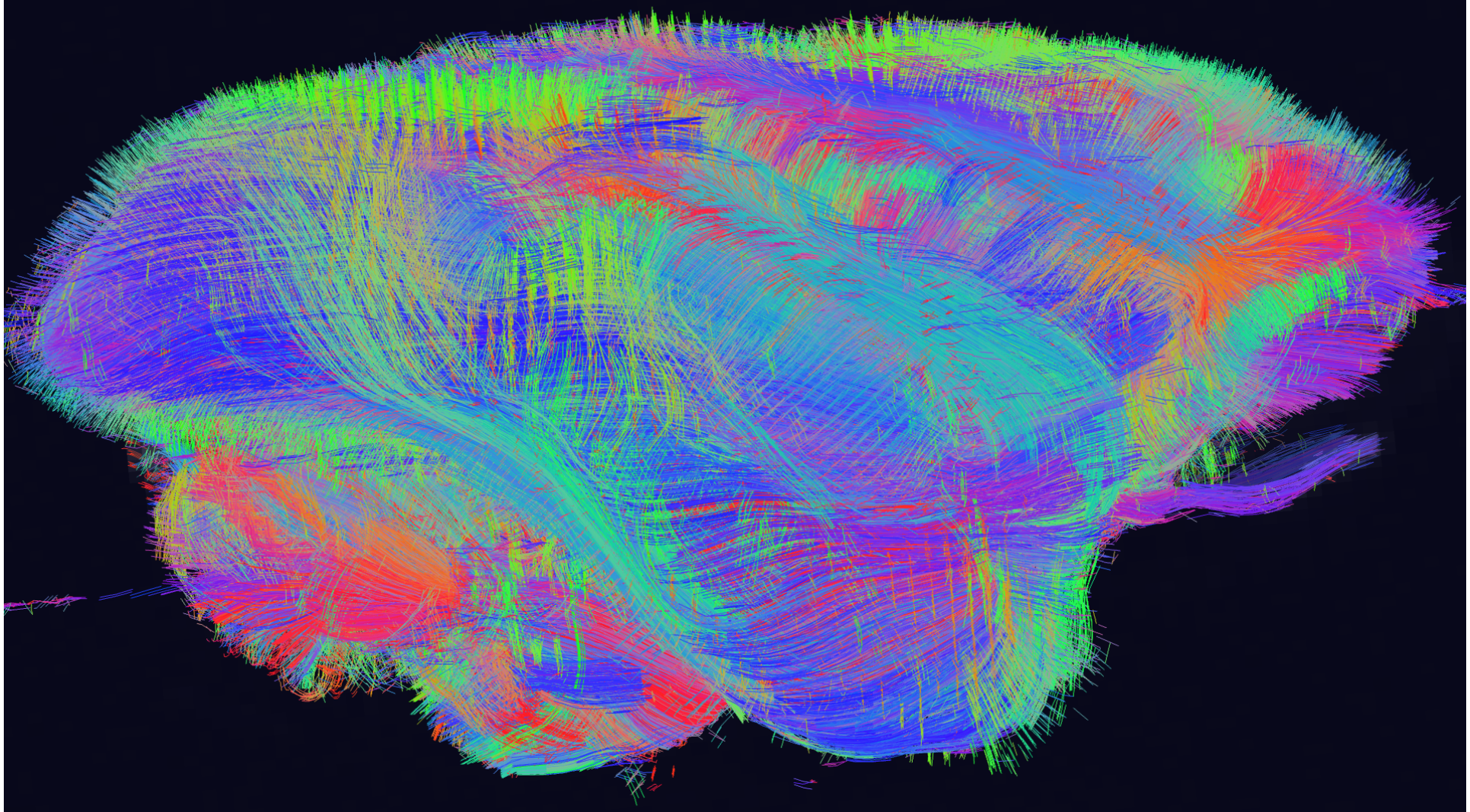
Muratoff bundle in context



Pandya & Schmahmann



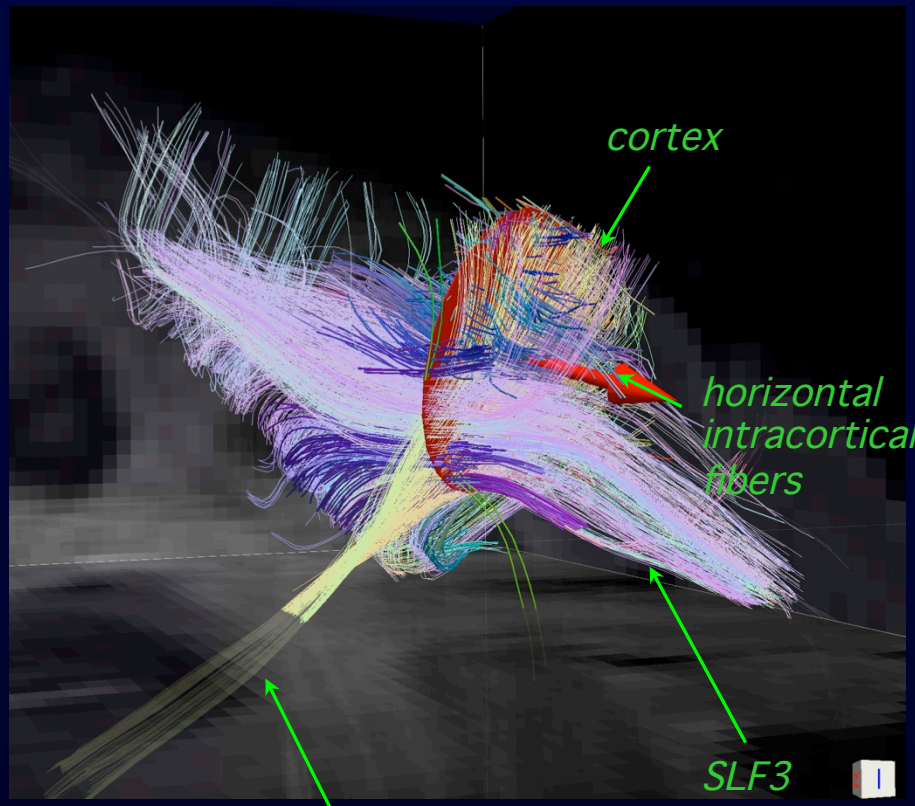
Intracortical connectivity

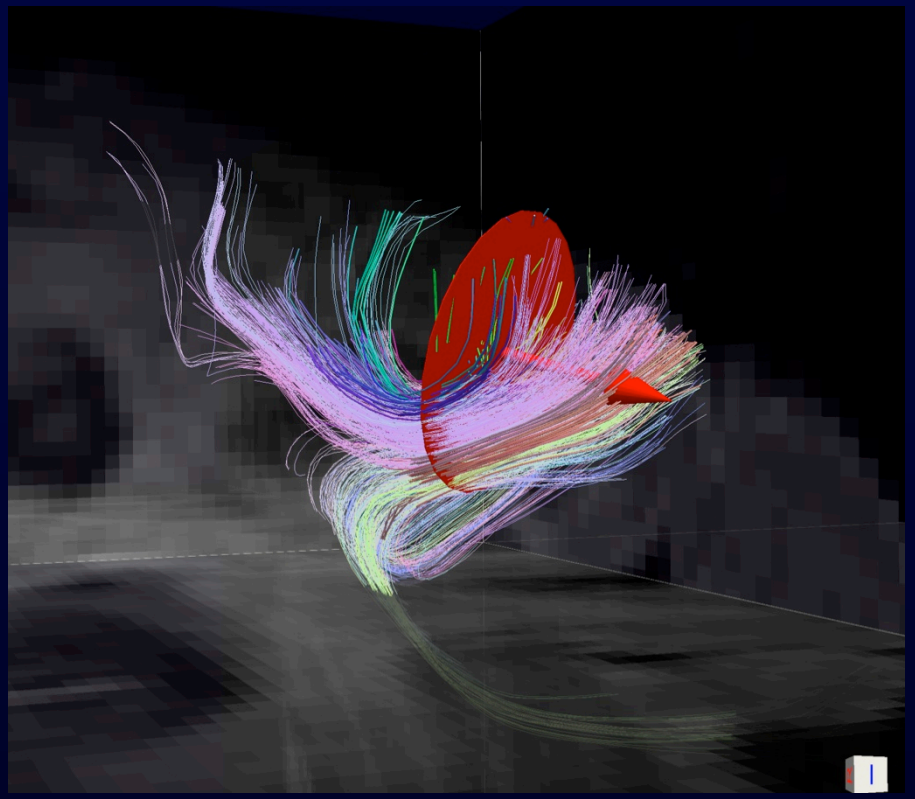


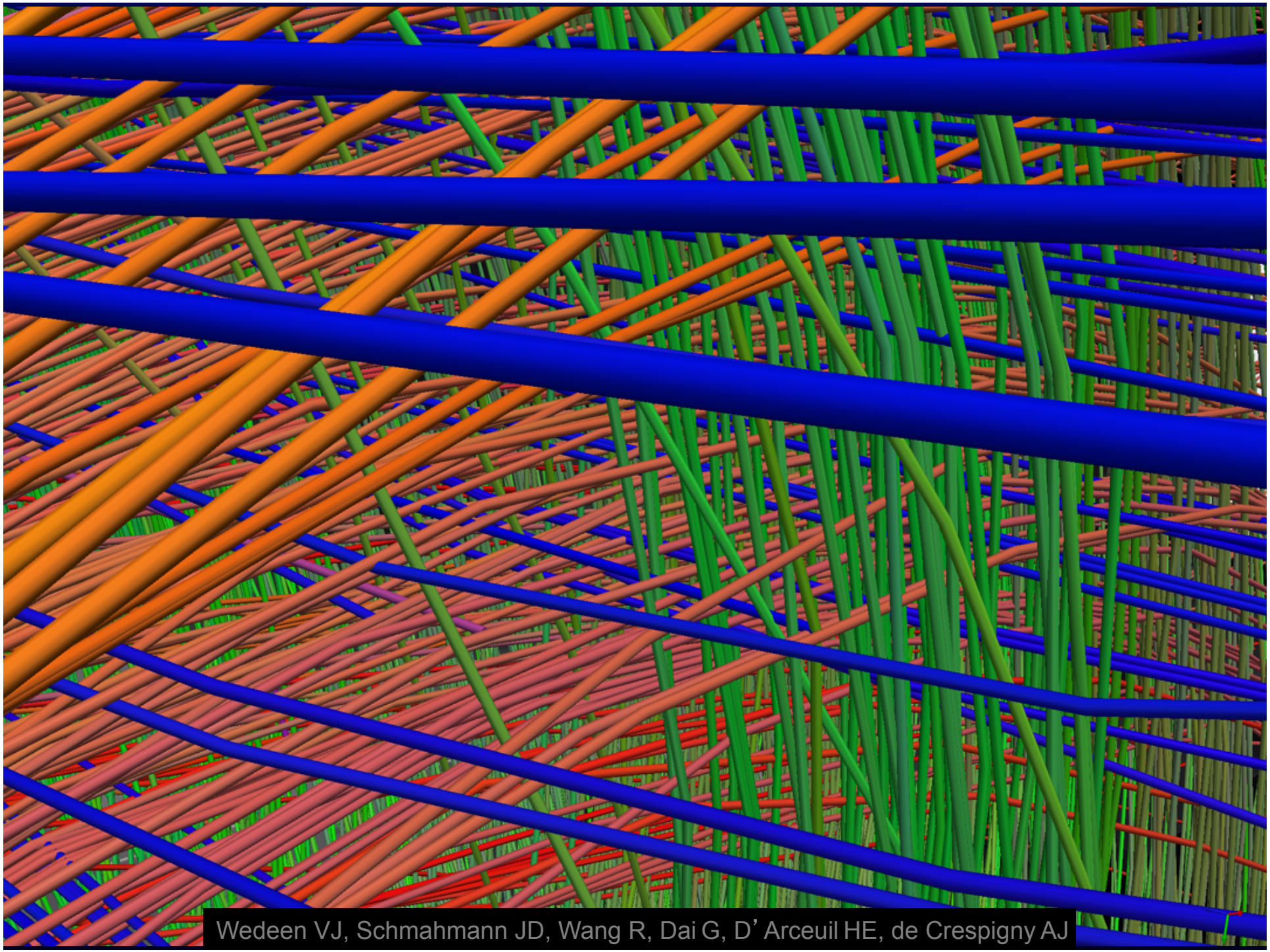
DSI vs DTI - connections of motor cortex
DTI is more or less all wrong

DSI

DTI



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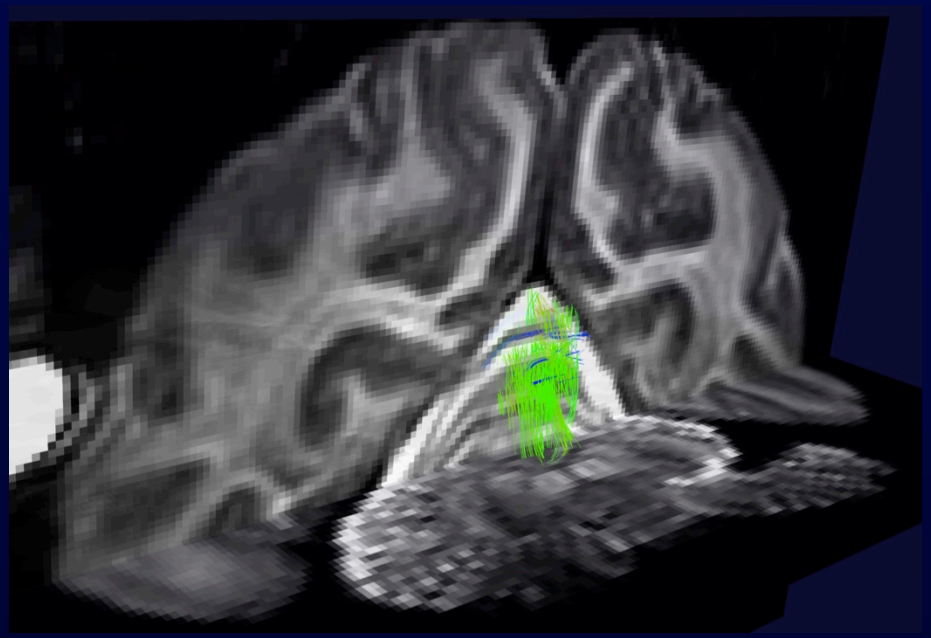
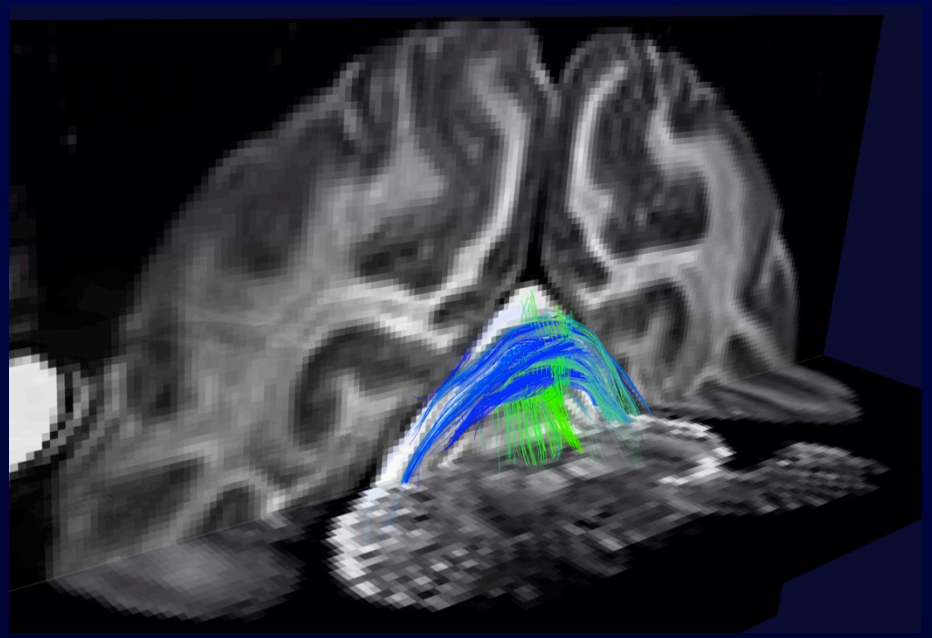
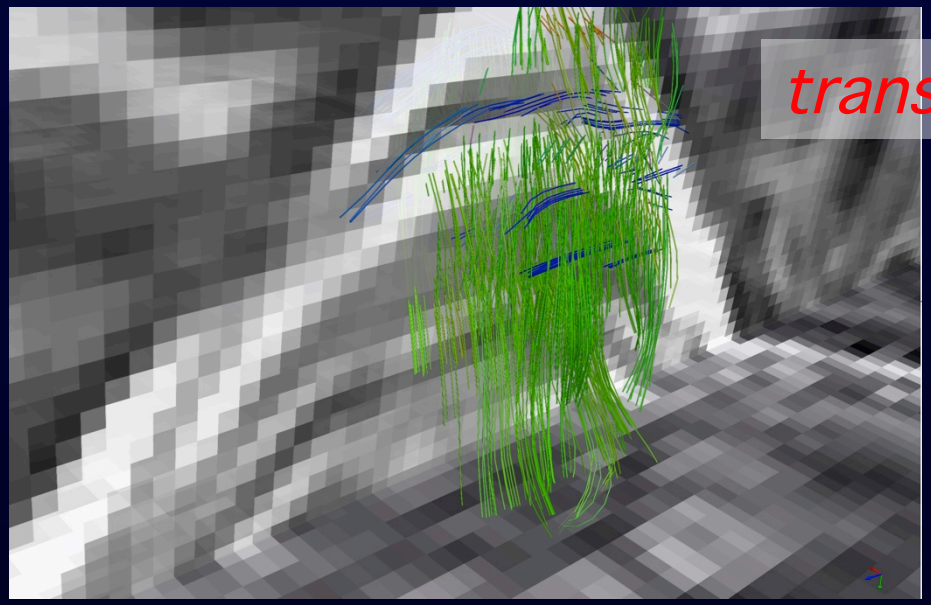
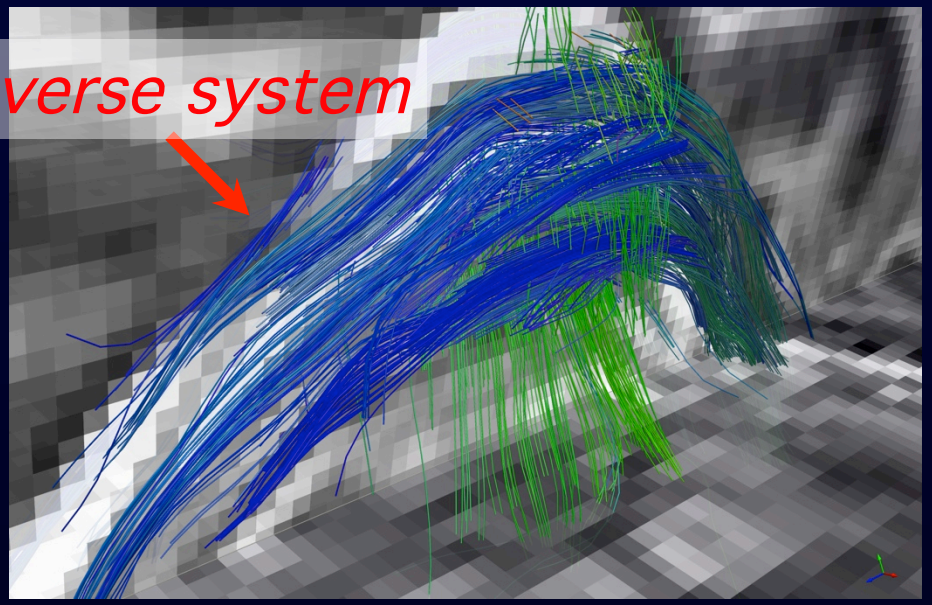
Cerebellum

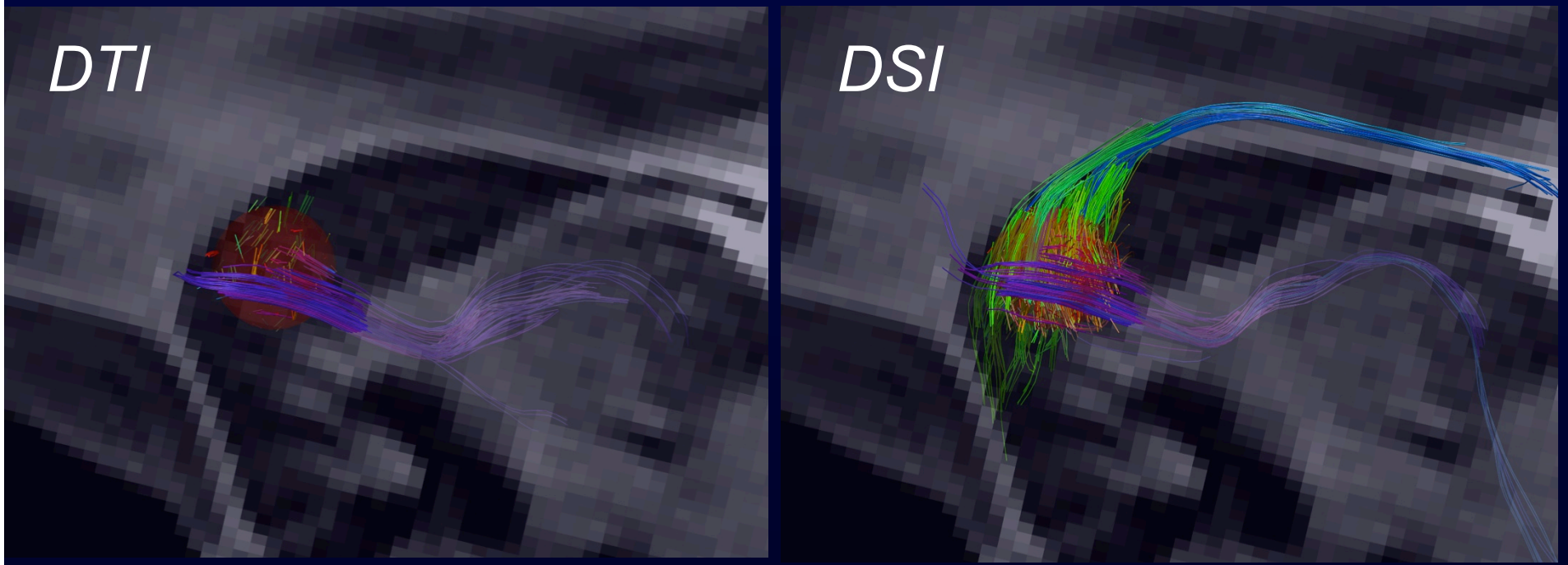






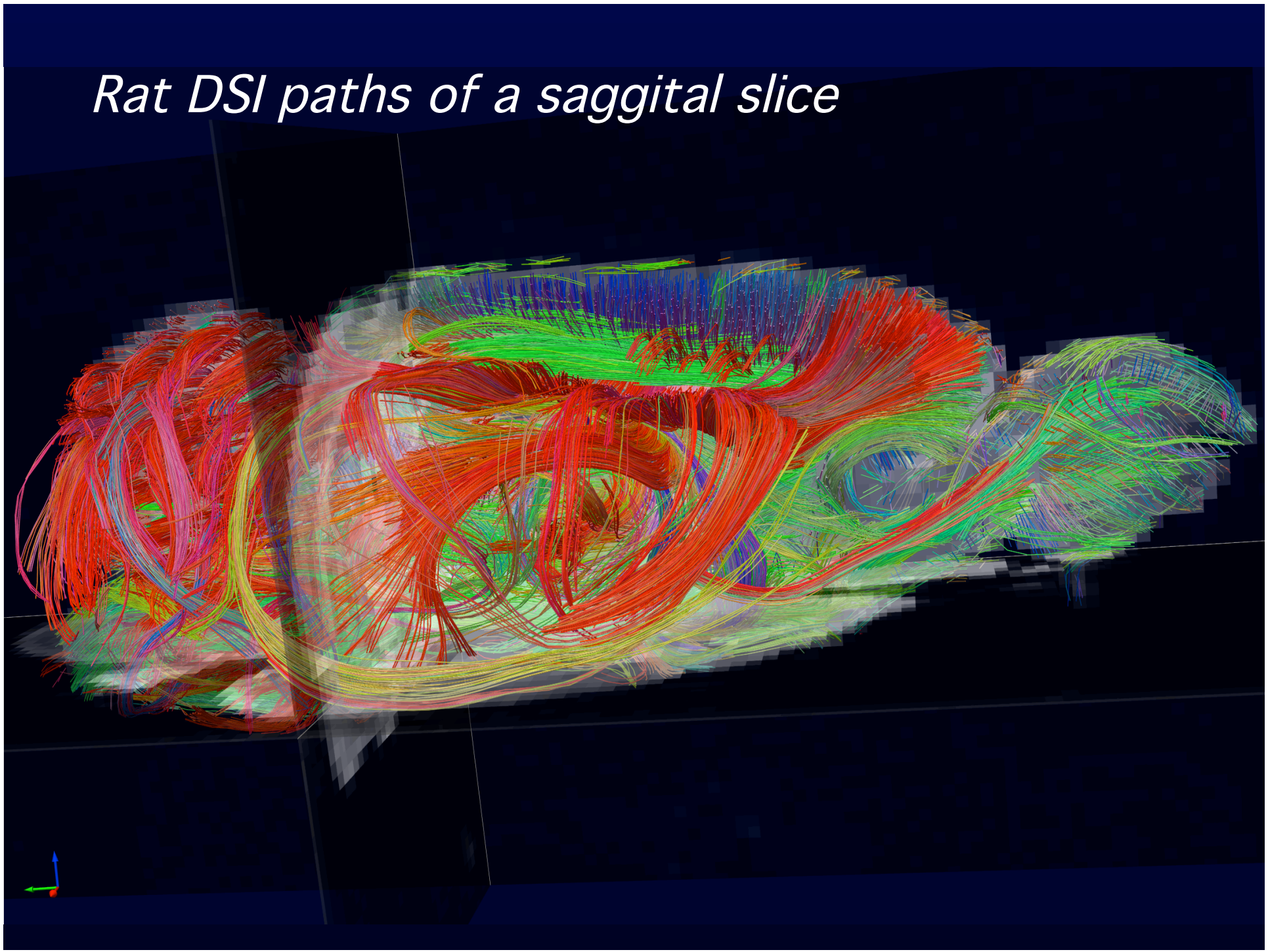


Tractography in caudate nucleus - Amygdalo-striate bundle of Muratoff

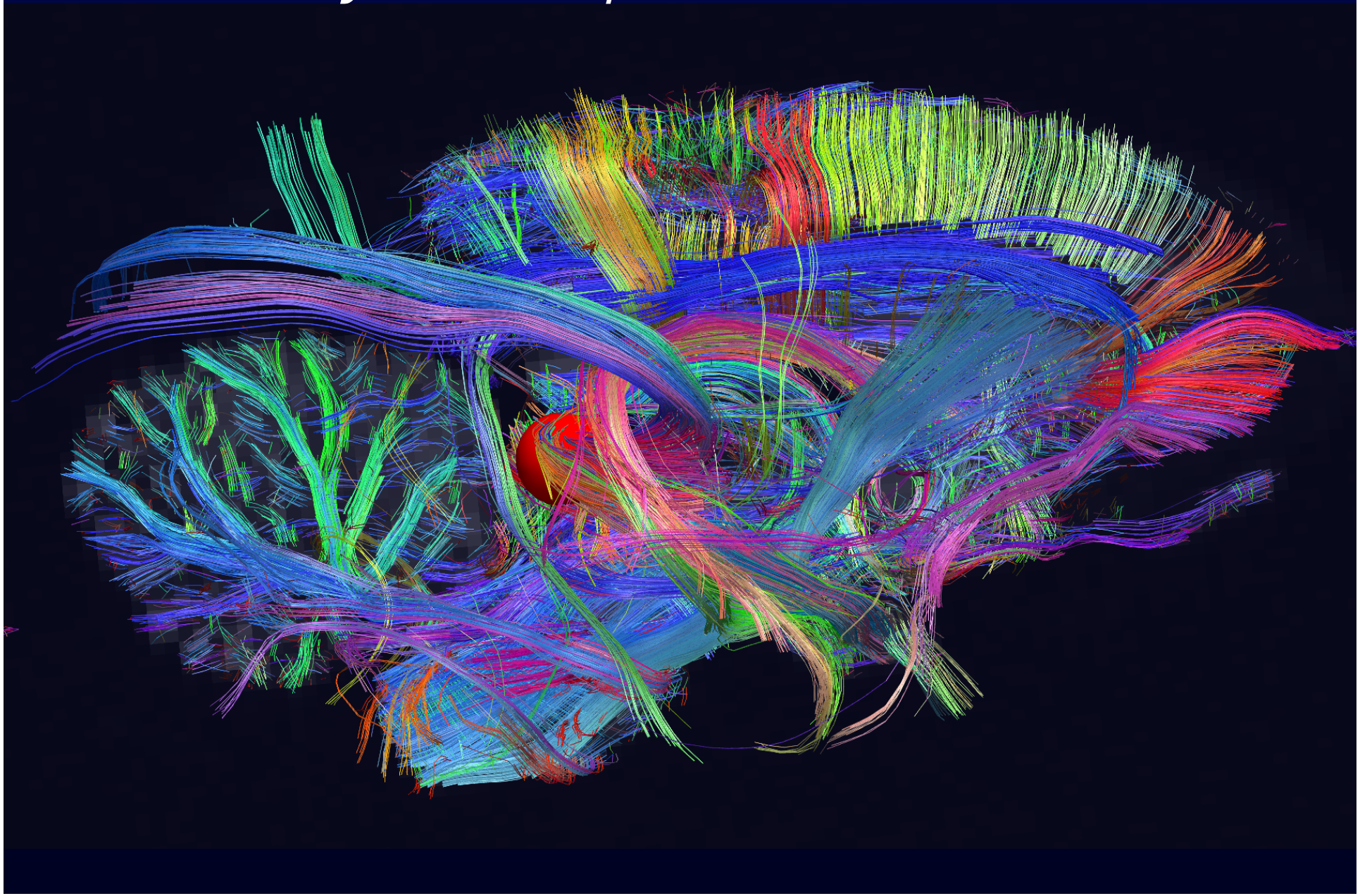


Wedeen et al Neruoimage 2008 in press

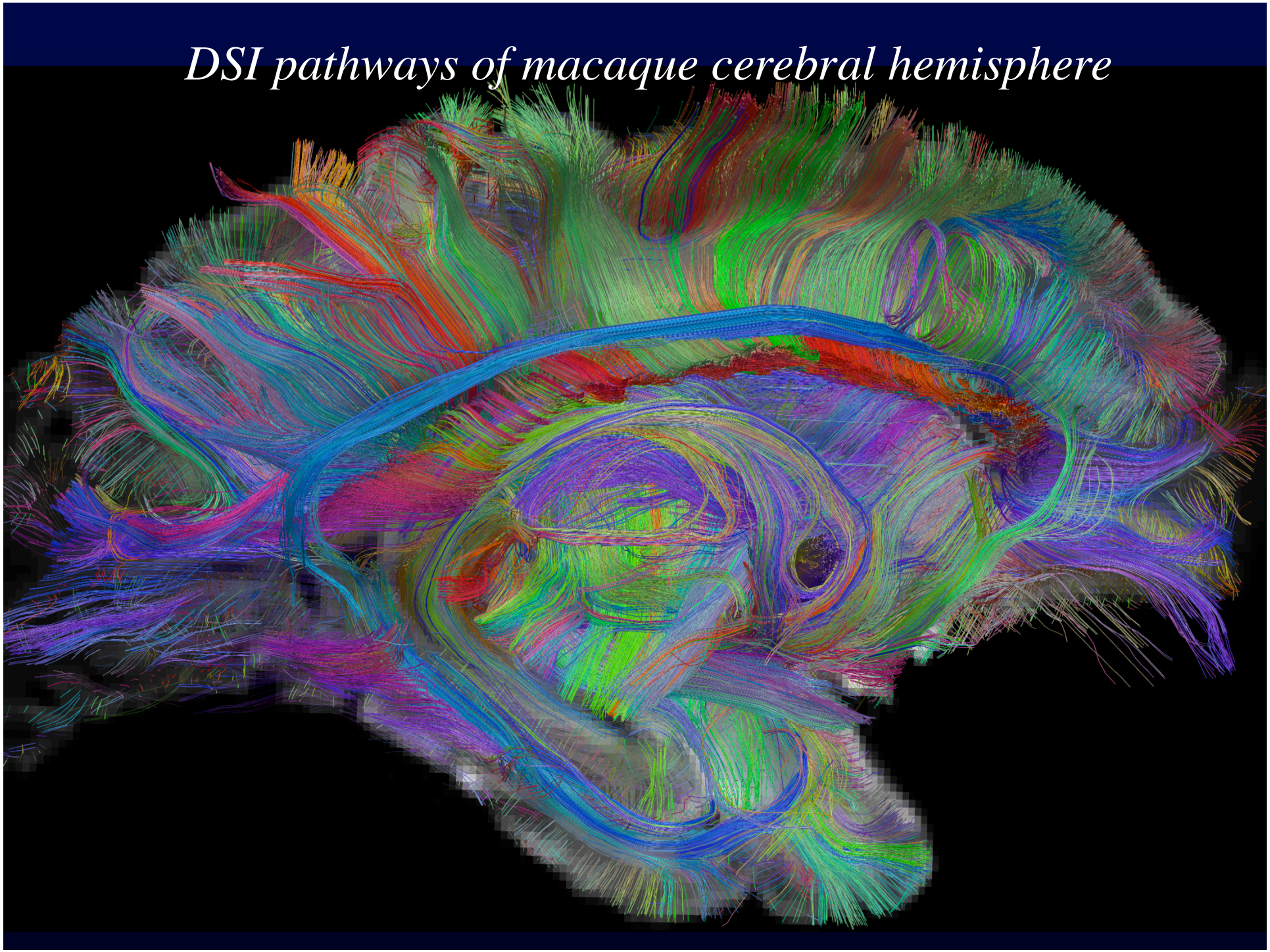
Rat DSI paths of a saggital slice



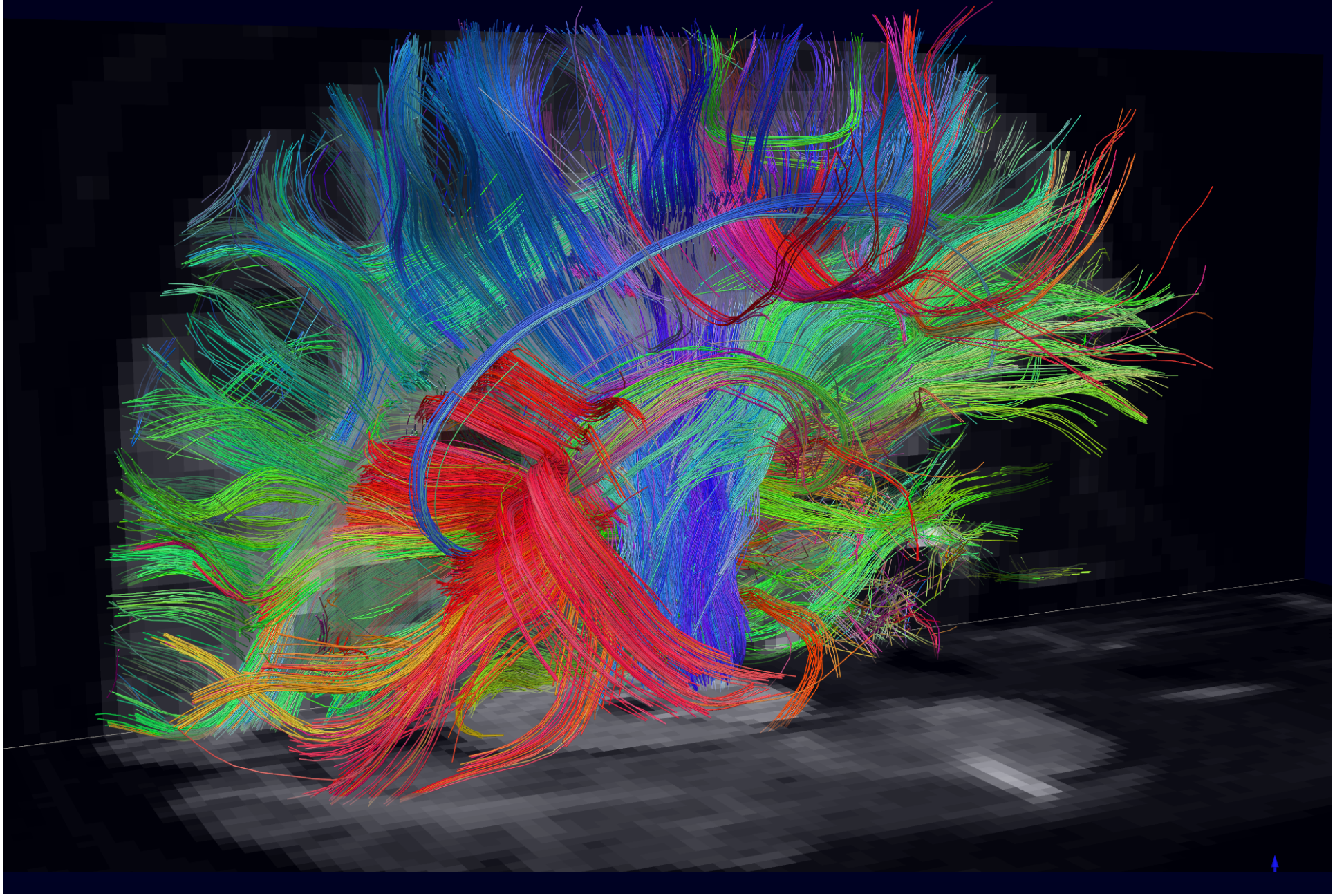
Owl monkey DSI - 3D paths of 1 slice



DSI pathways of macaque cerebral hemisphere

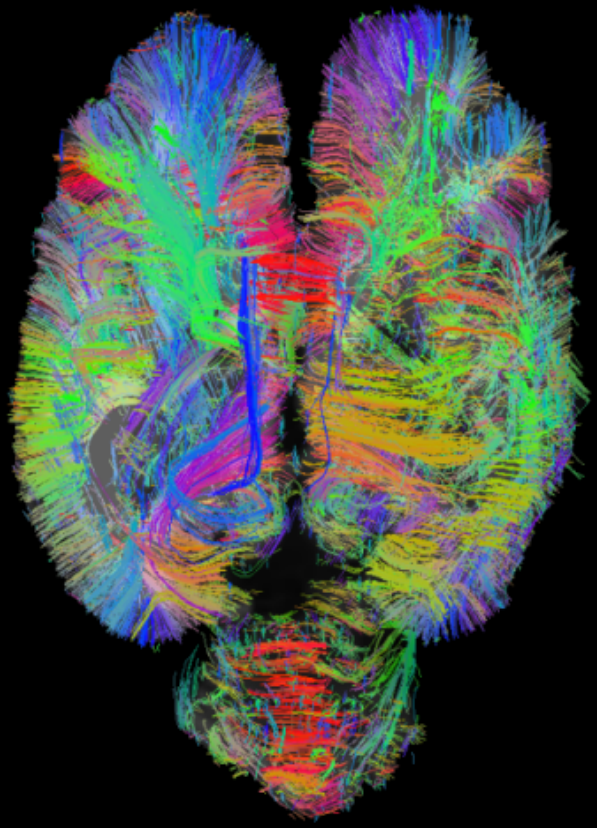


DSI human in vivo 3T



Cat DSI

birth



day 100

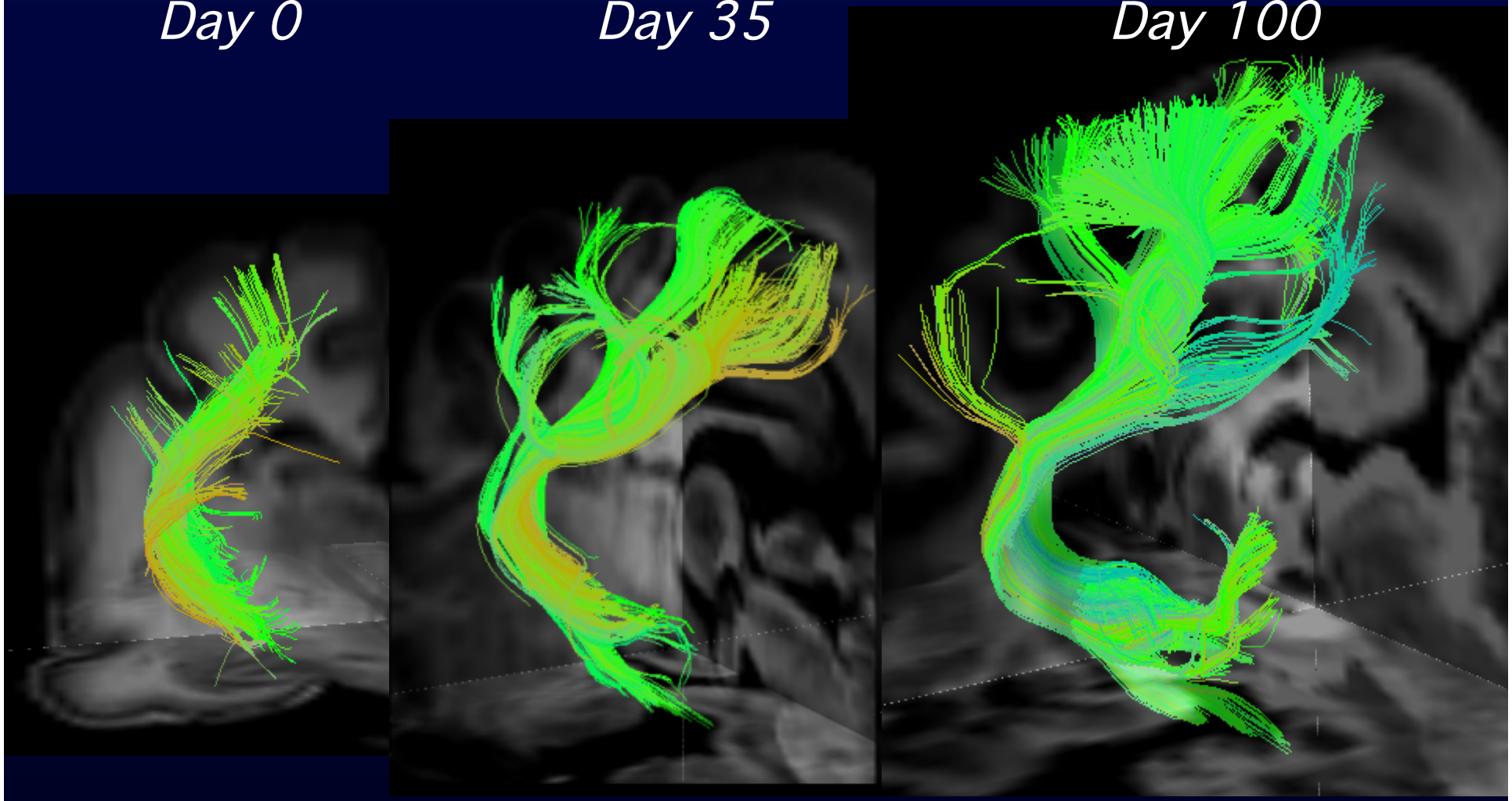
Takahasi et al ISRMR 2008

Development of cortico-thalamic tracts in cat

Day 0

Day 35

Day 100



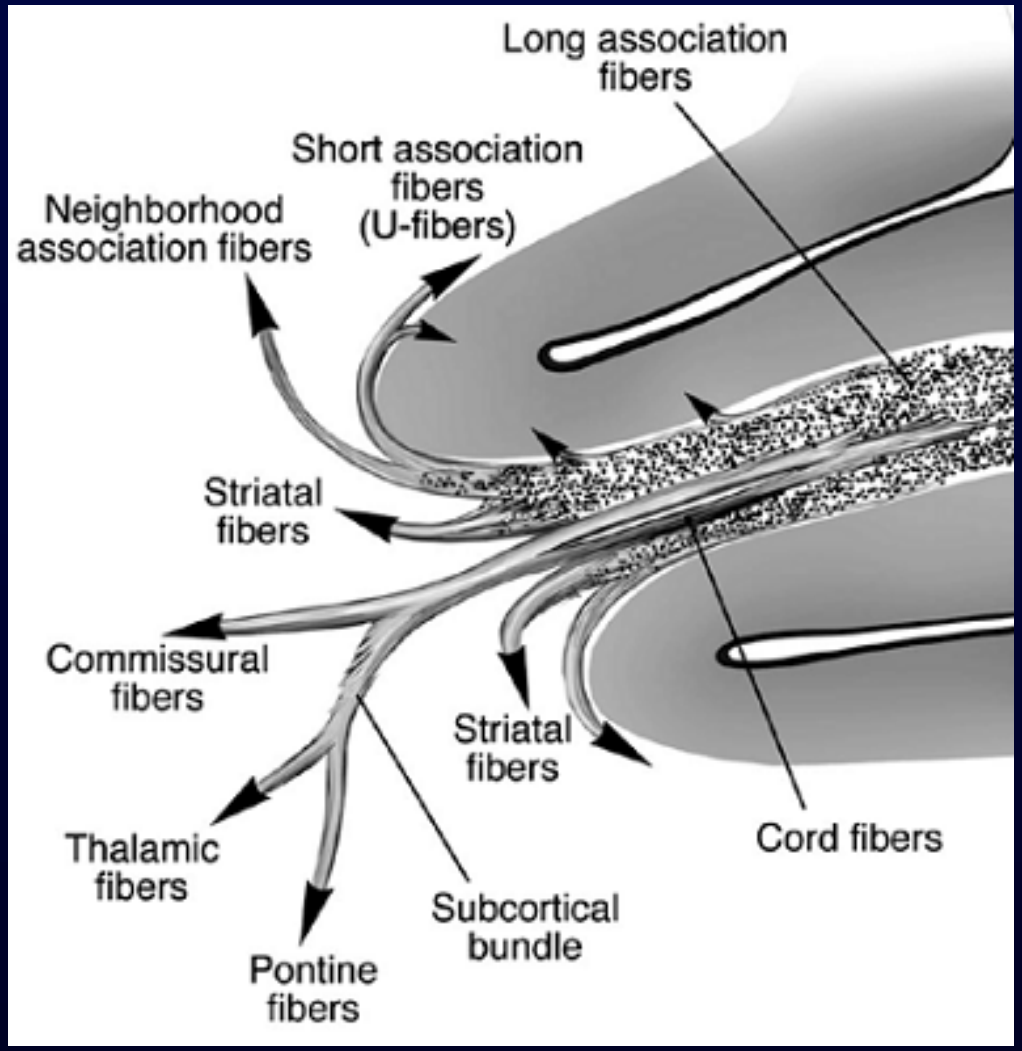
Takahasi et al ISRMR 2008

Principles of organization common to all cortical areas

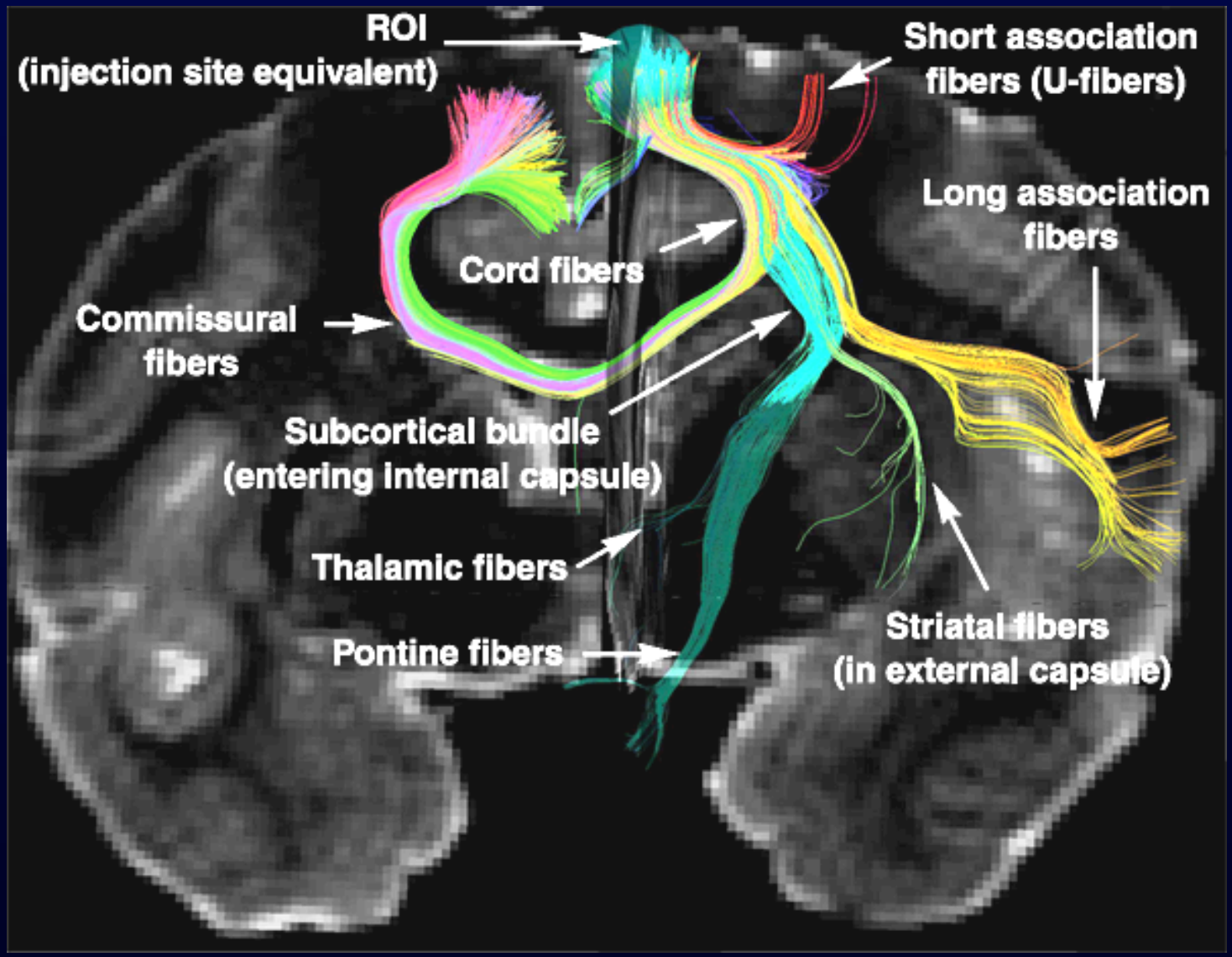
Association fibers
- *Local*
- *Neighborhood*
- *Long*

Cord
- *Commissural fibers*
- *Subcortical bundle*

Striatal fibers
- *Muratoff bundle*
- *External capsule*

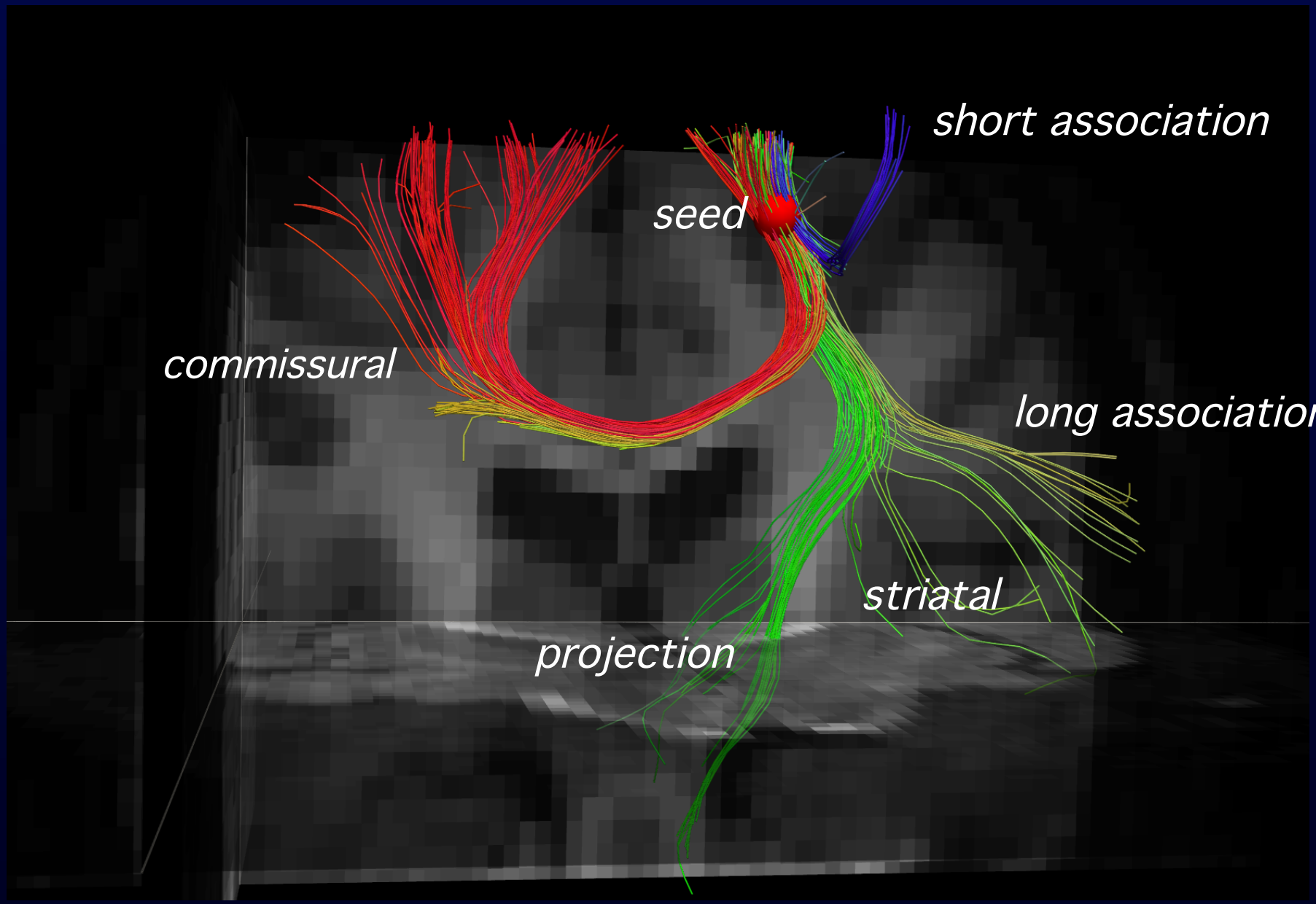


Connectional neuroanatomy with diffusion spectrum imaging

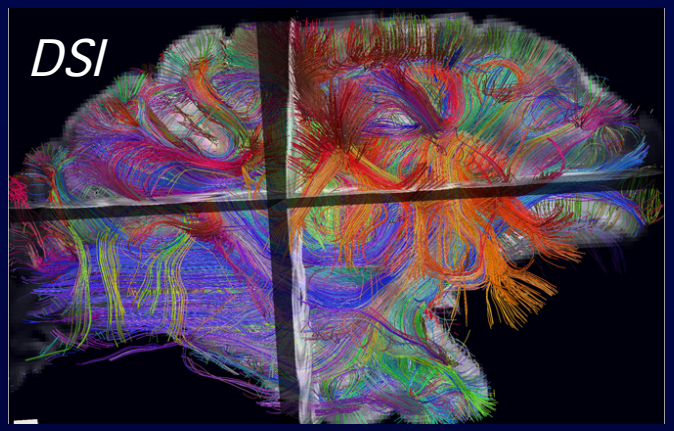


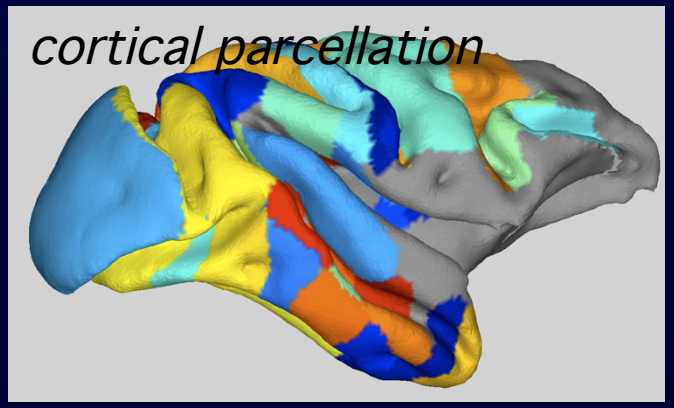
Schmahmann JD, Pandya DN, Wang R, Dai G, D'Arceuil HE, de Crespigny AJ, Wedeen VJ

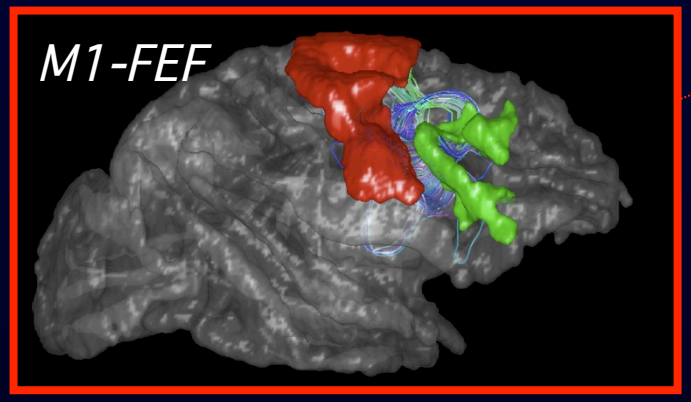
Connectivity of human superior frontal gyrus

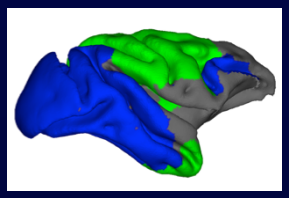


Connectivity matrices







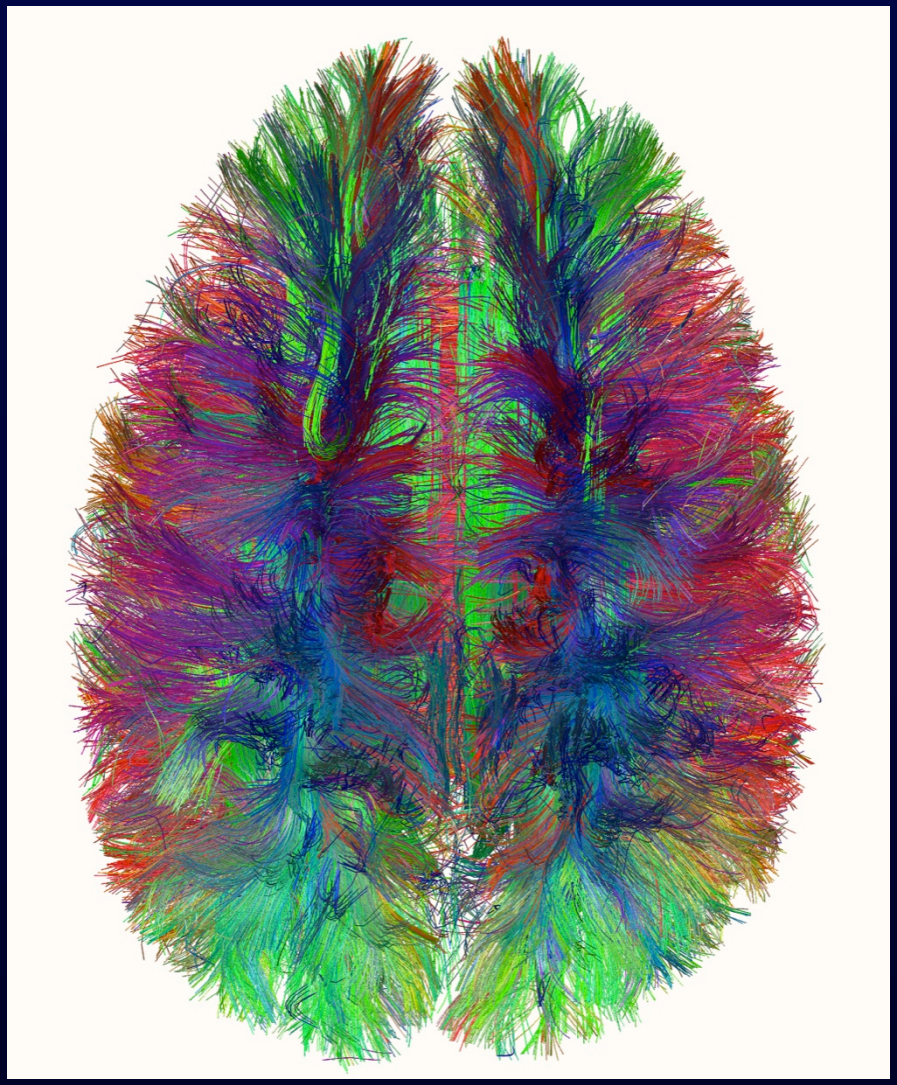


DSI
1 macaque

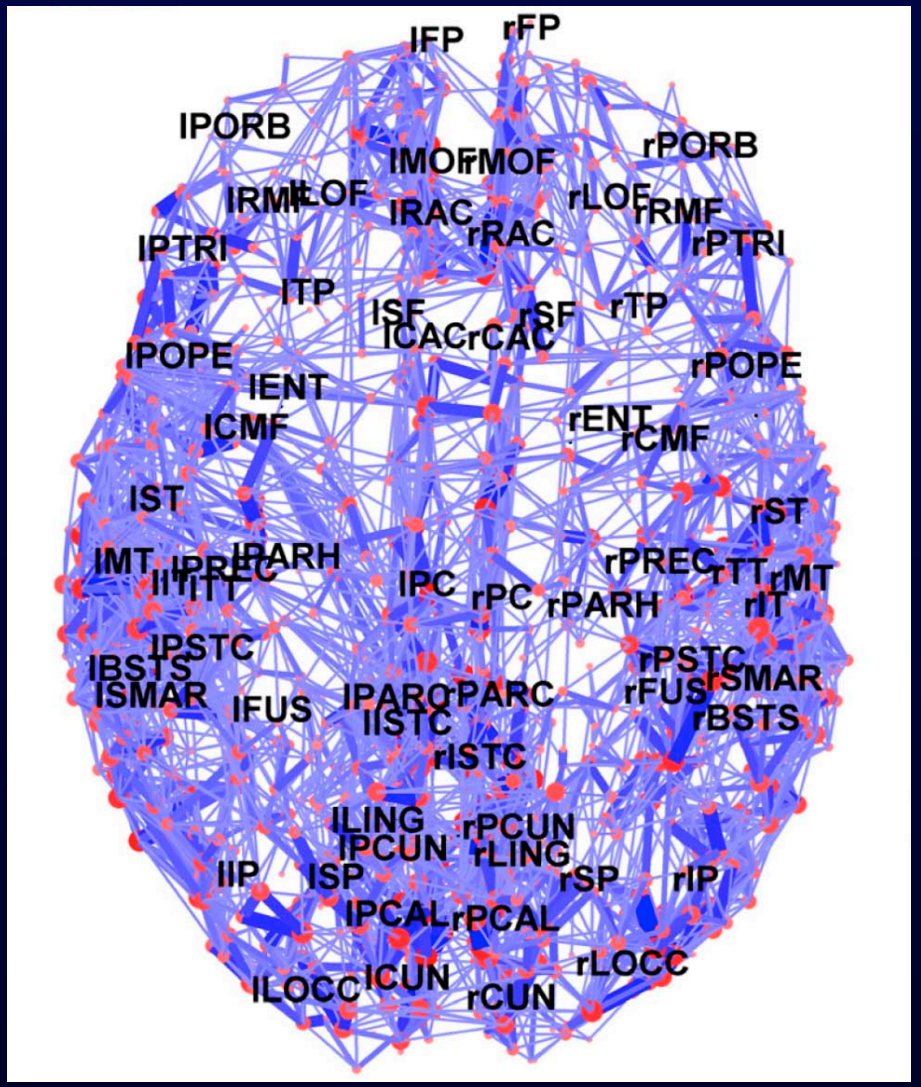
Cocomac
database

Sporns et al PLoS Biol 2008 in press

DSI in vivo human

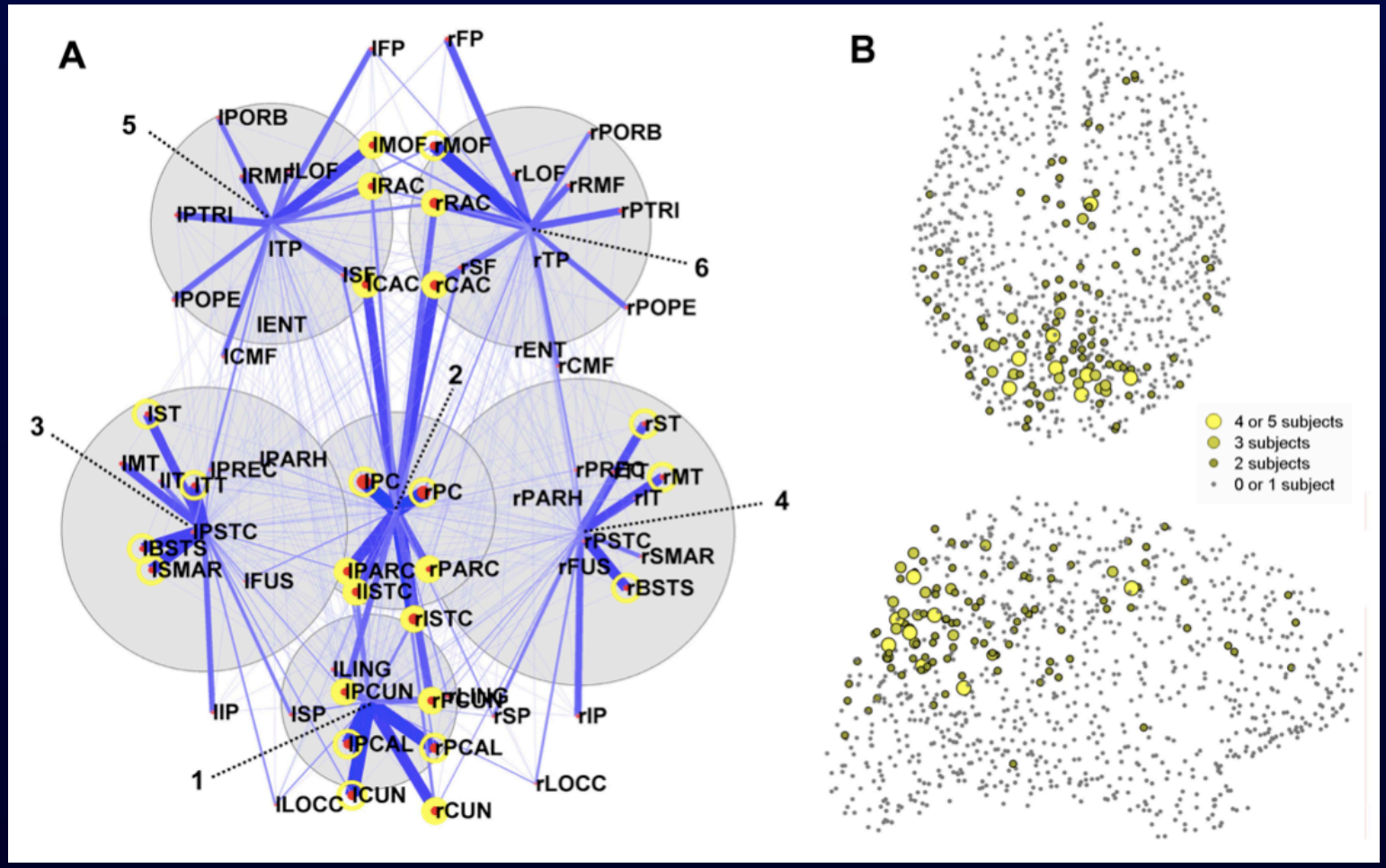


human connectome



Hagmann et al PLoS Biol 2008

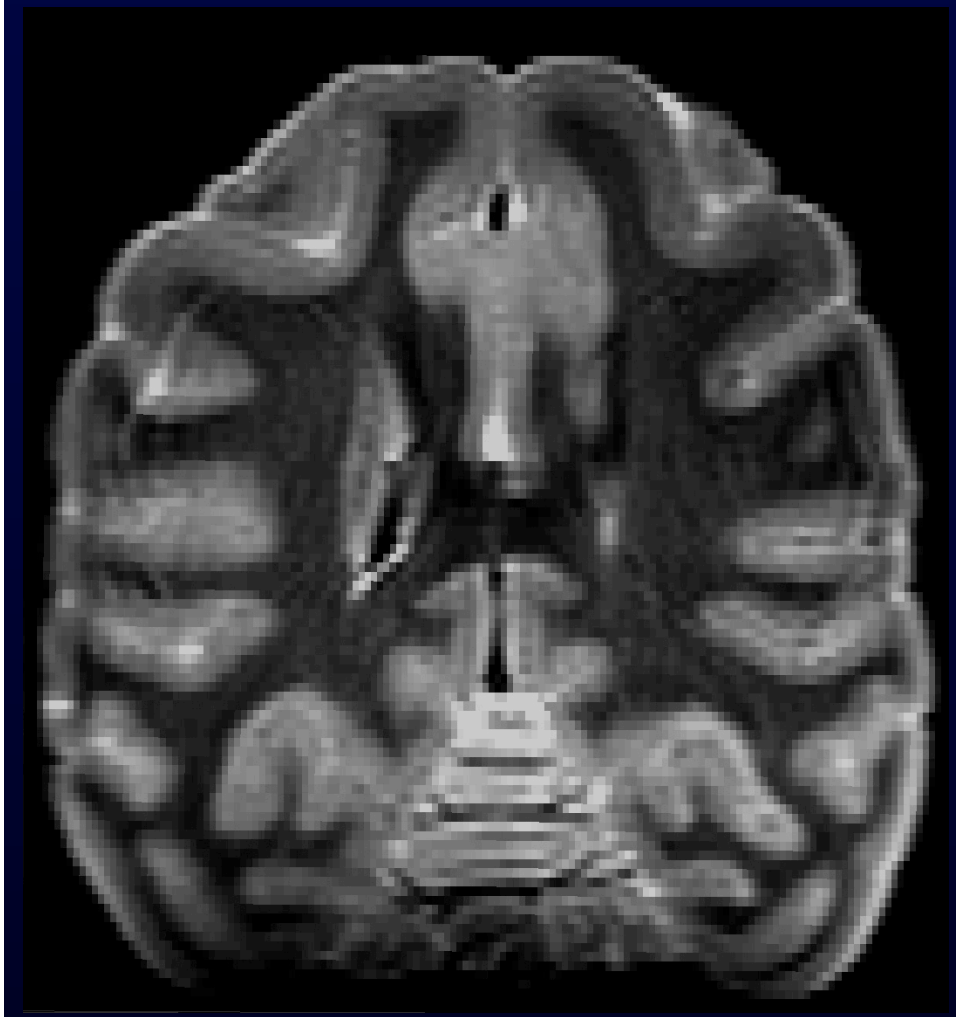
Human connectome hubs and core



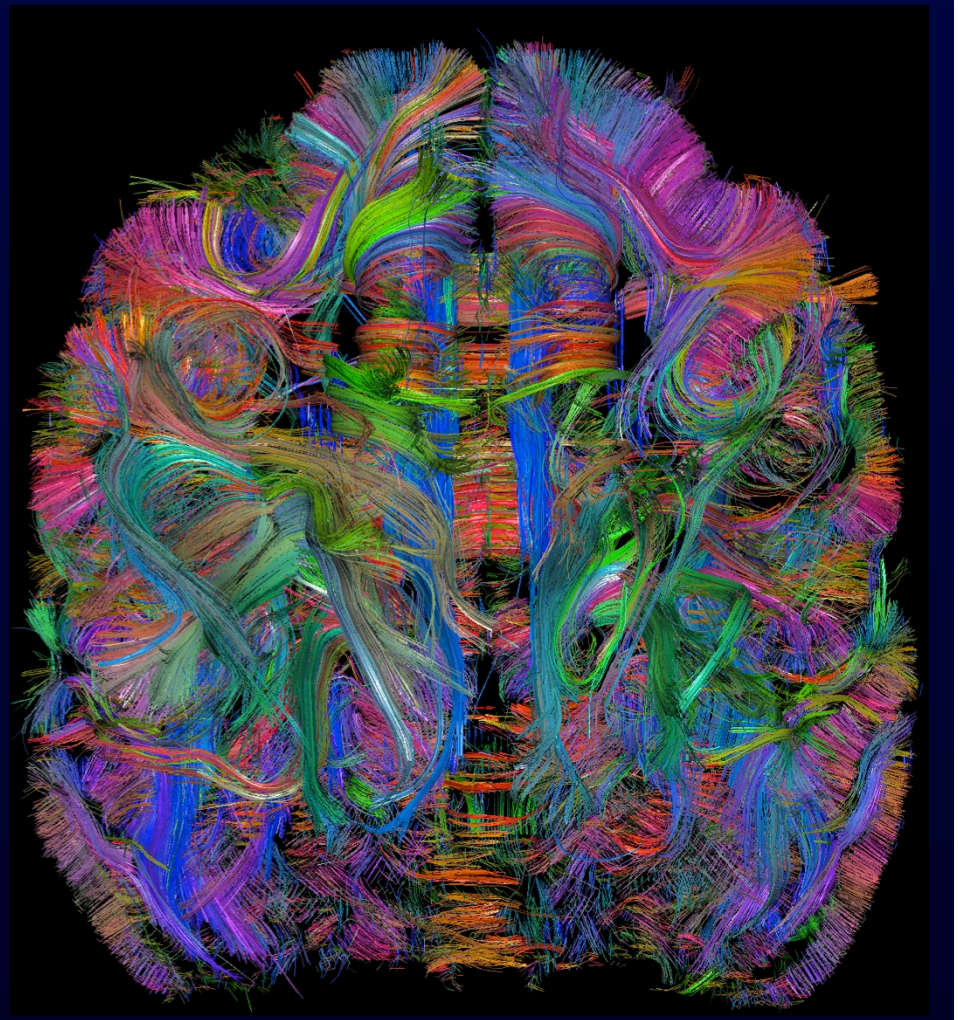
Hagmann et al PLoS Biol 2008

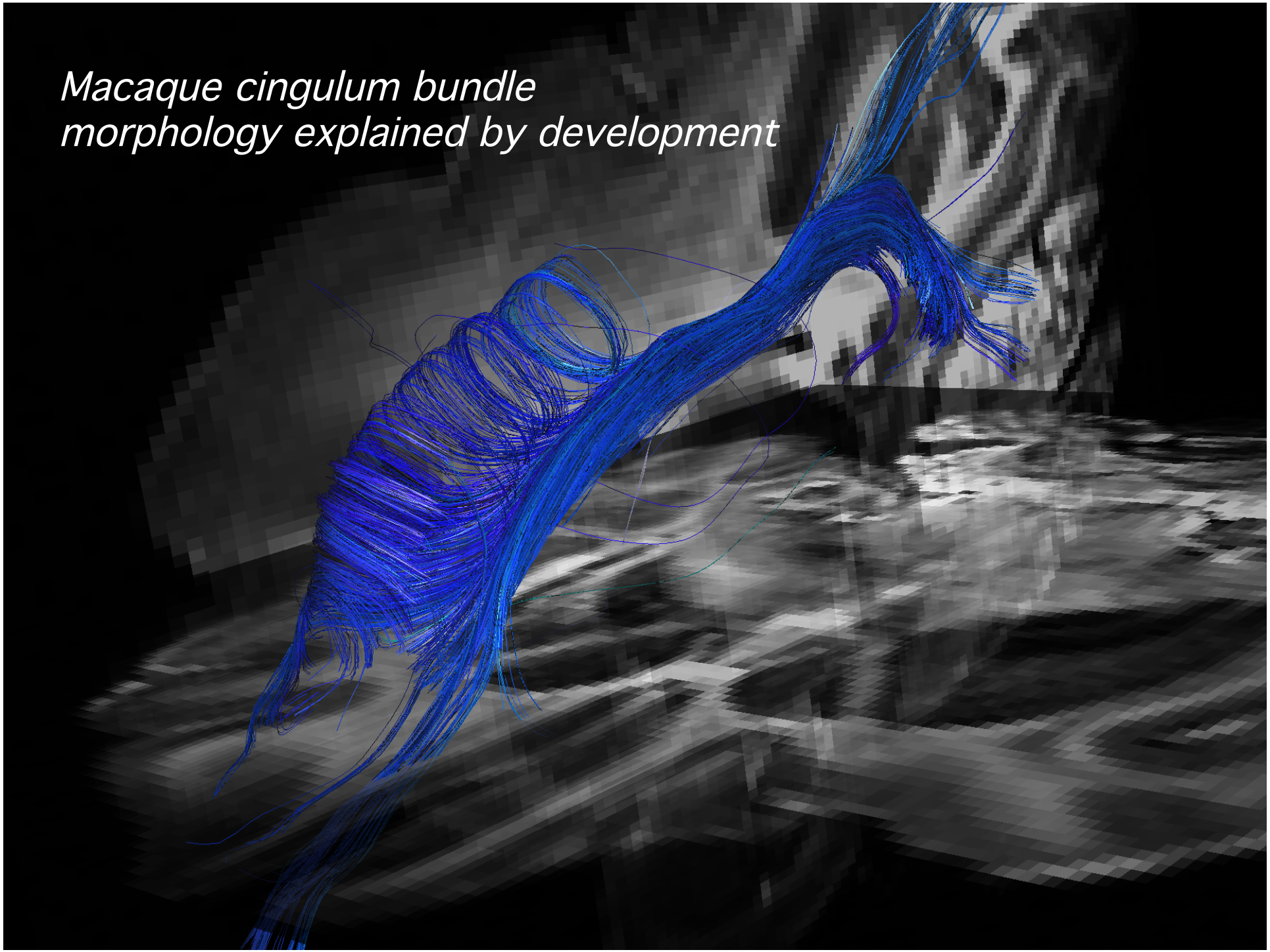
Macaque

3D MRI - paths superimpose

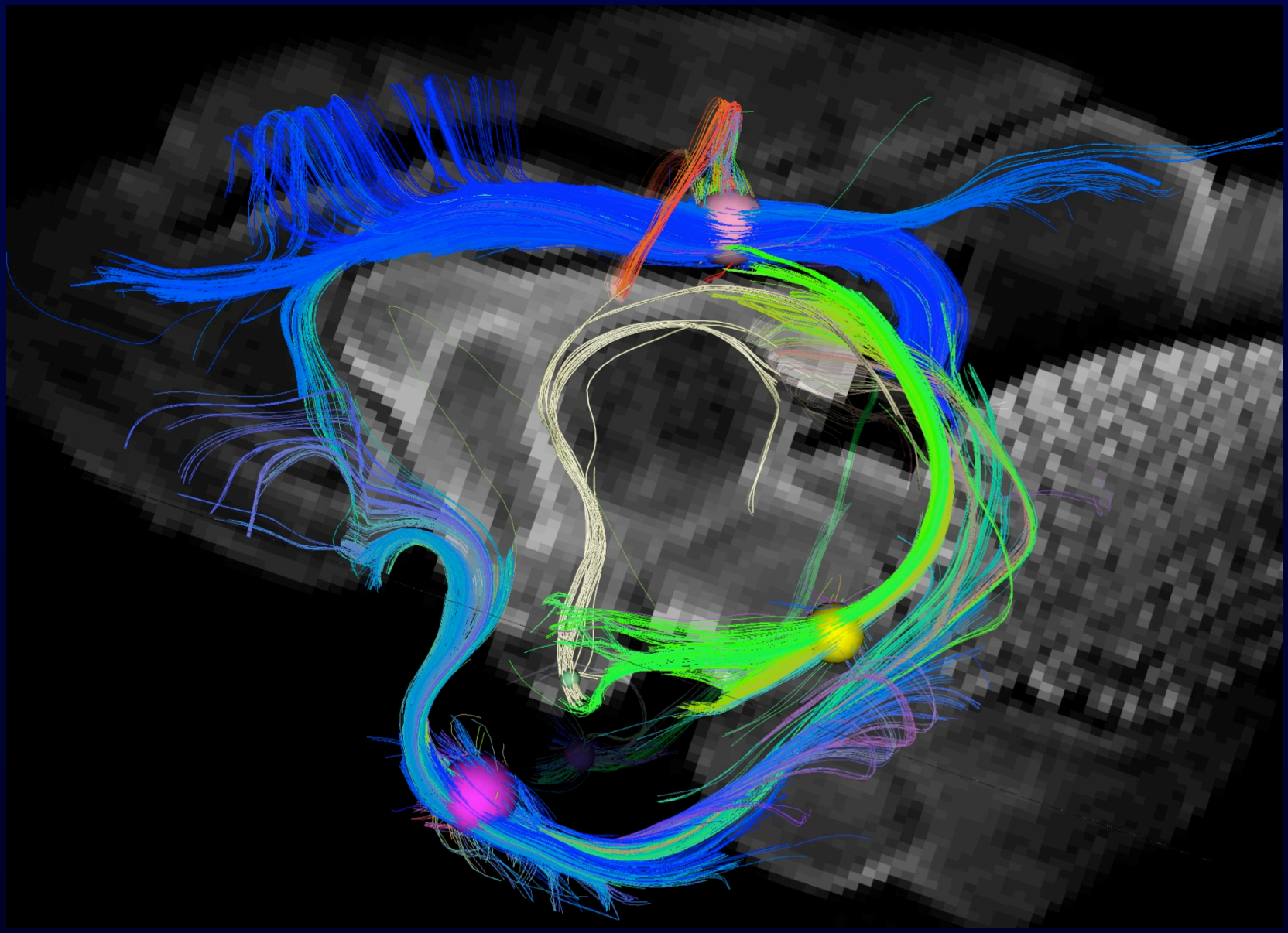


6D DSI - paths resolved

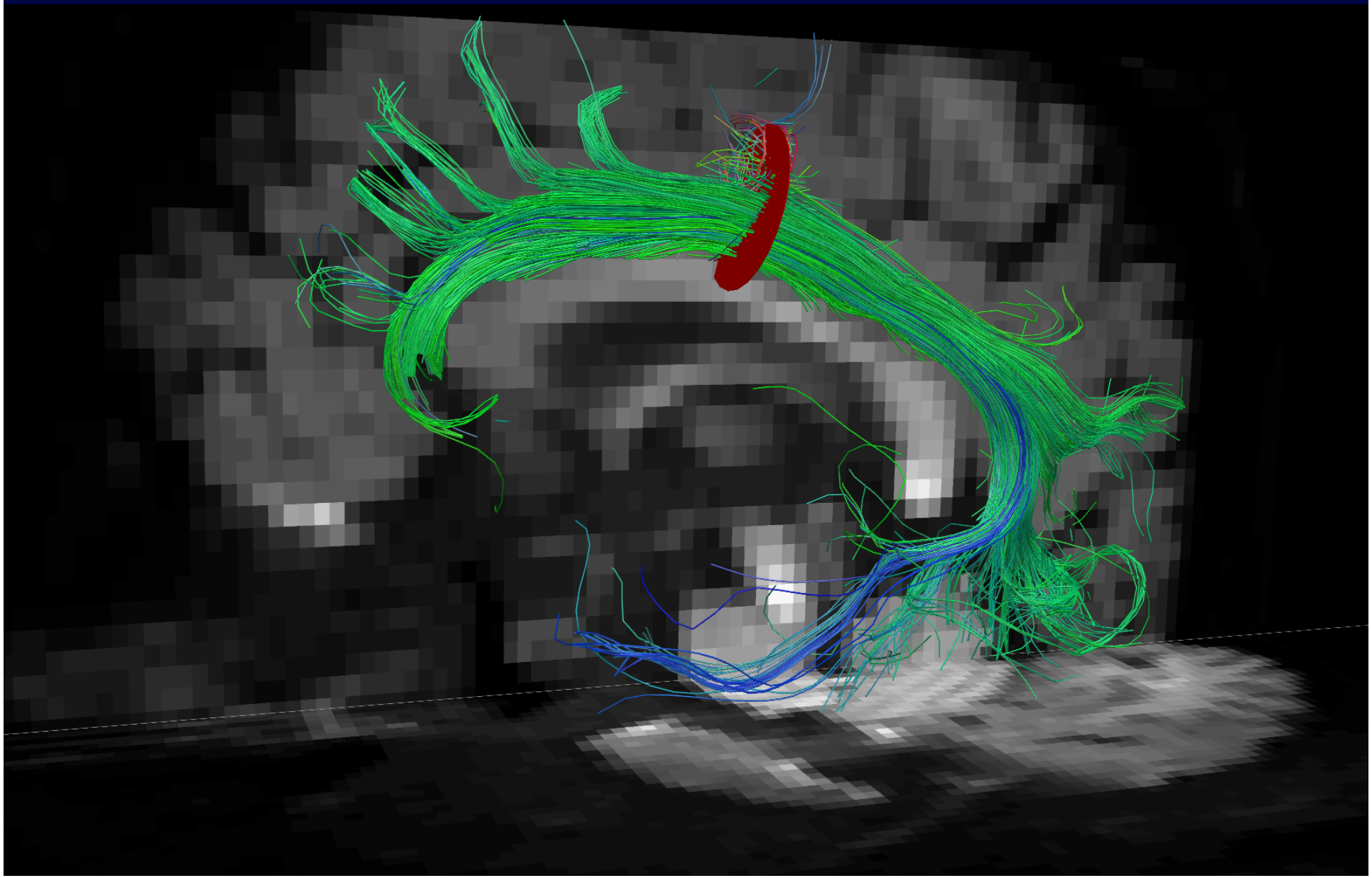



Macaque cingulum bundle
morphology explained by development

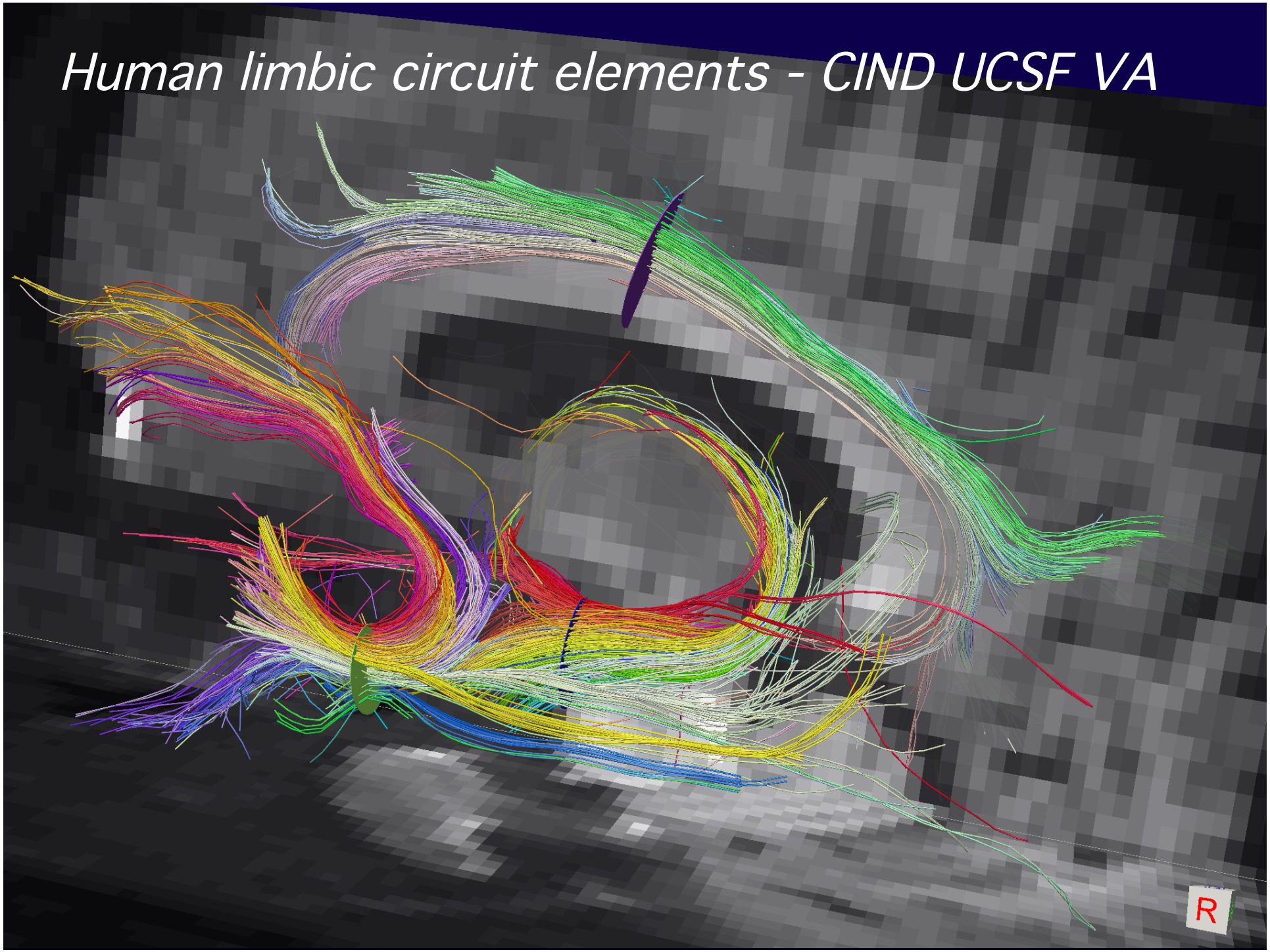
Macaque circuit of Papez ex vivo



Cingulum bundle human DSI in vivo 3T

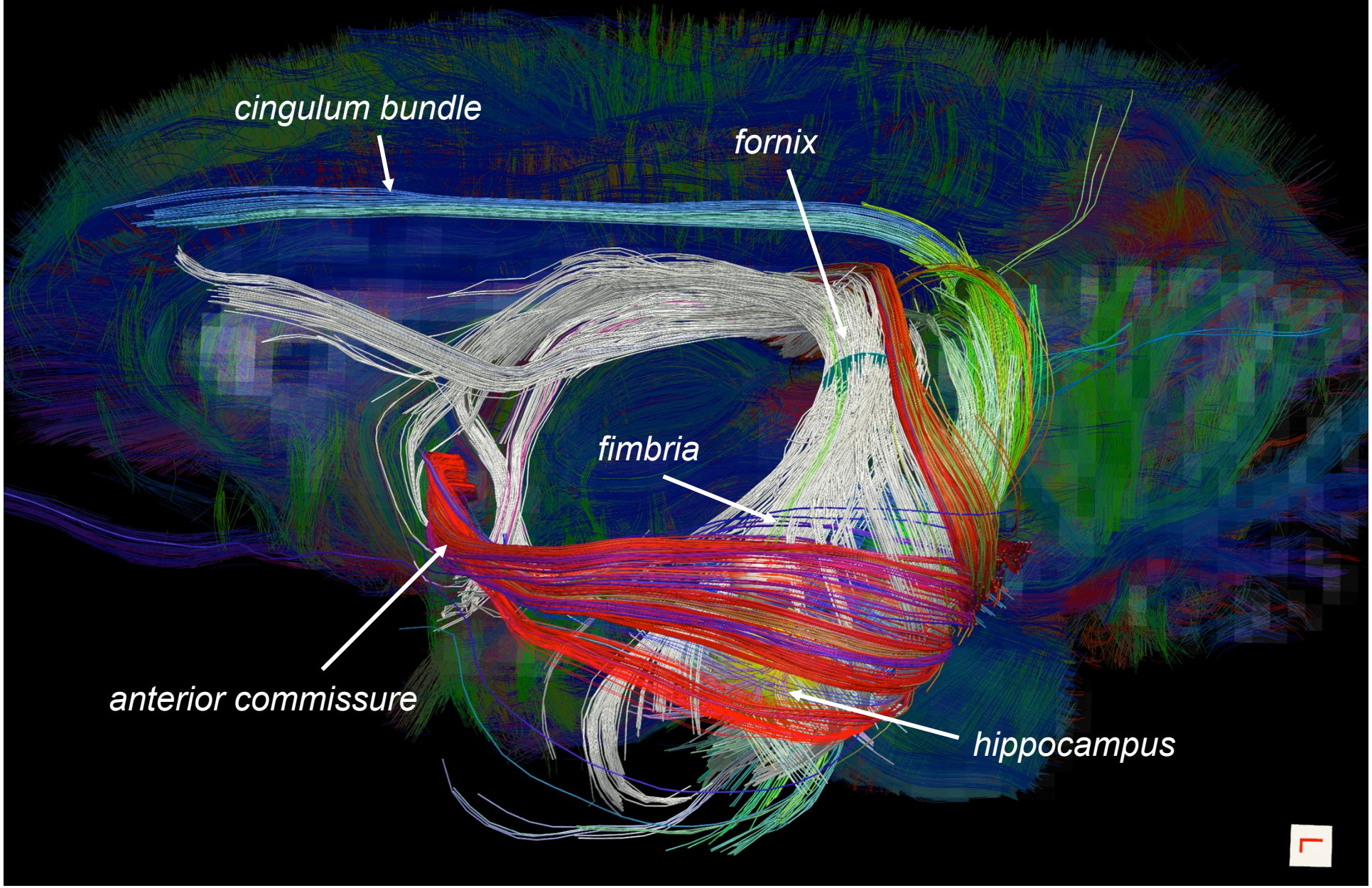


Human limbic circuit elements - CIND UCSF VA

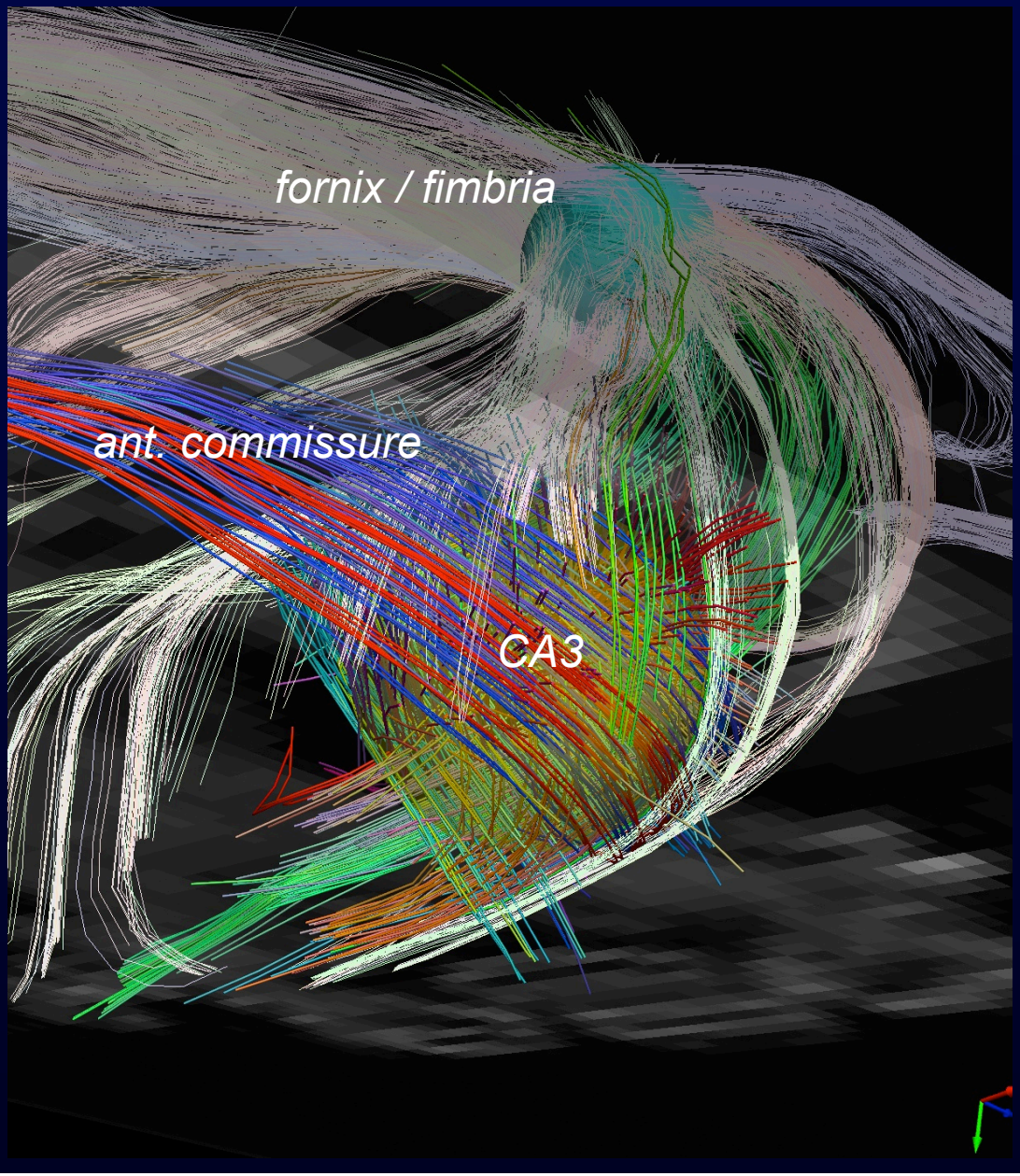


Owl monkey hippocampal associated pathways

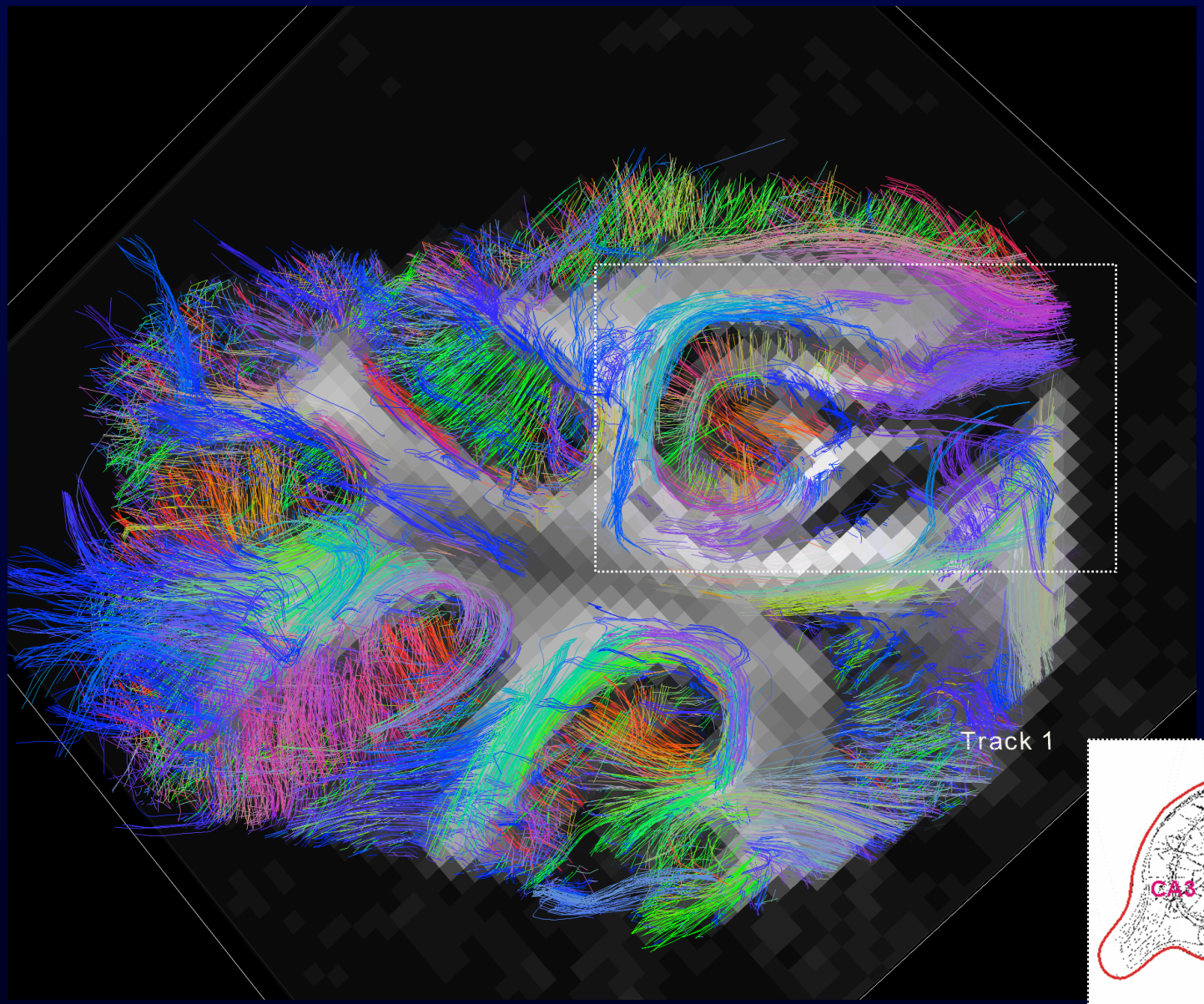
DSI ex vivo, left lateral view

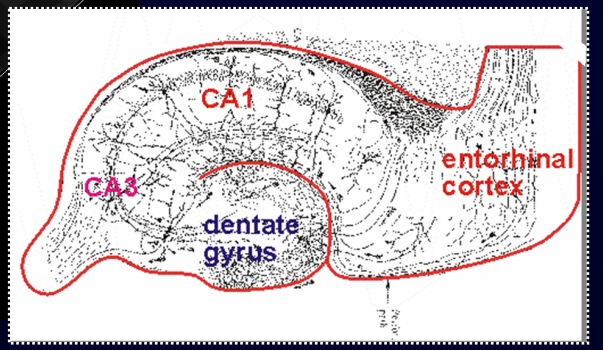


Owl monkey hippocampus ex vivo DSI

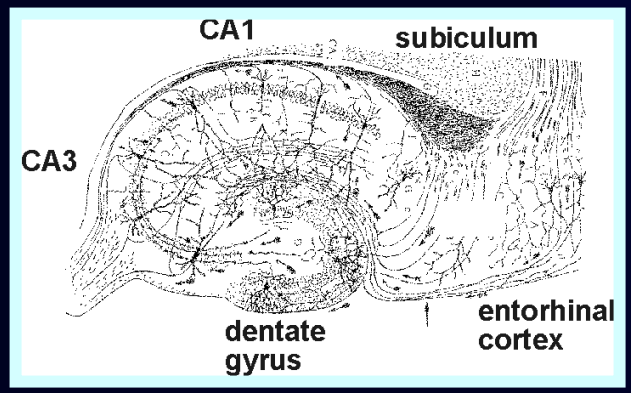


Human temporal lobe / hippocampus ex vivo

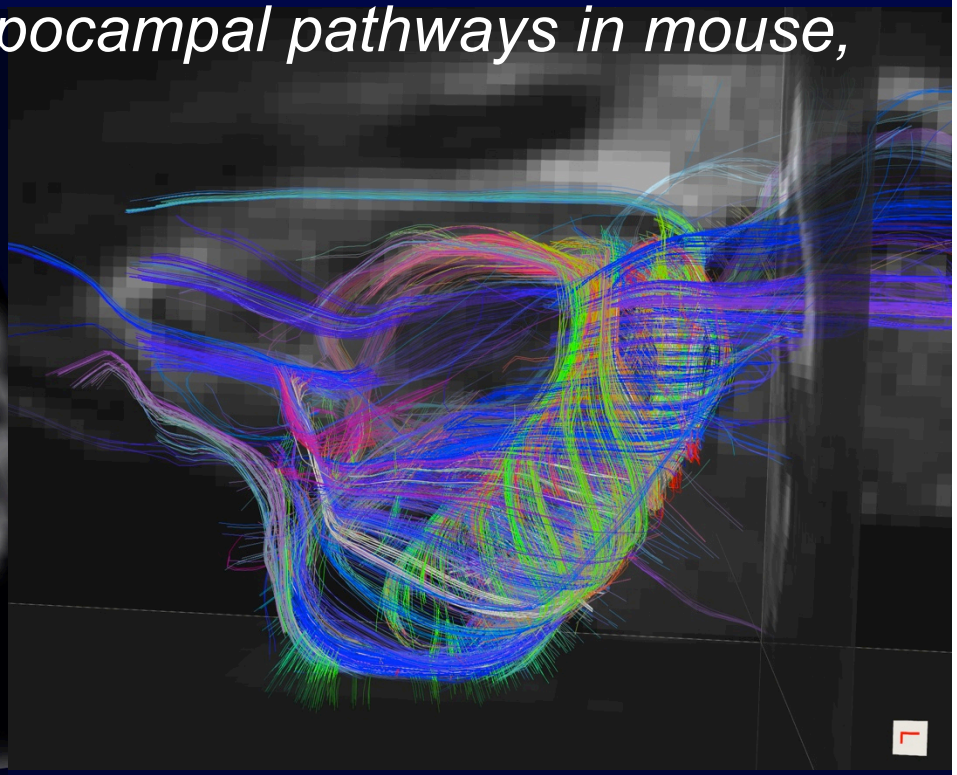


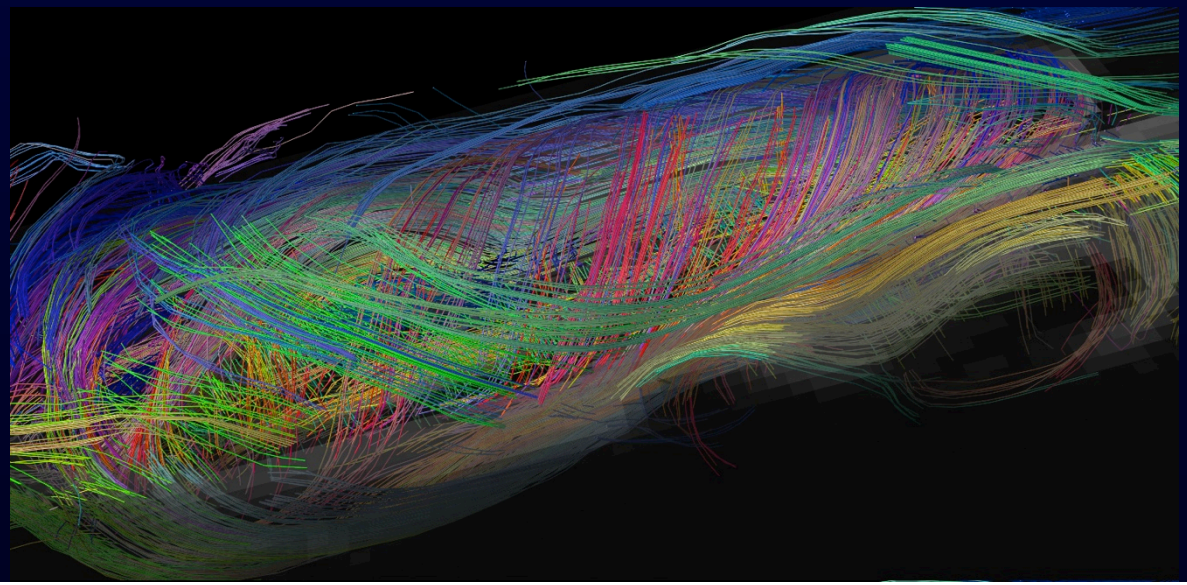


Human hippocampus ex vivo DSI digital dissection

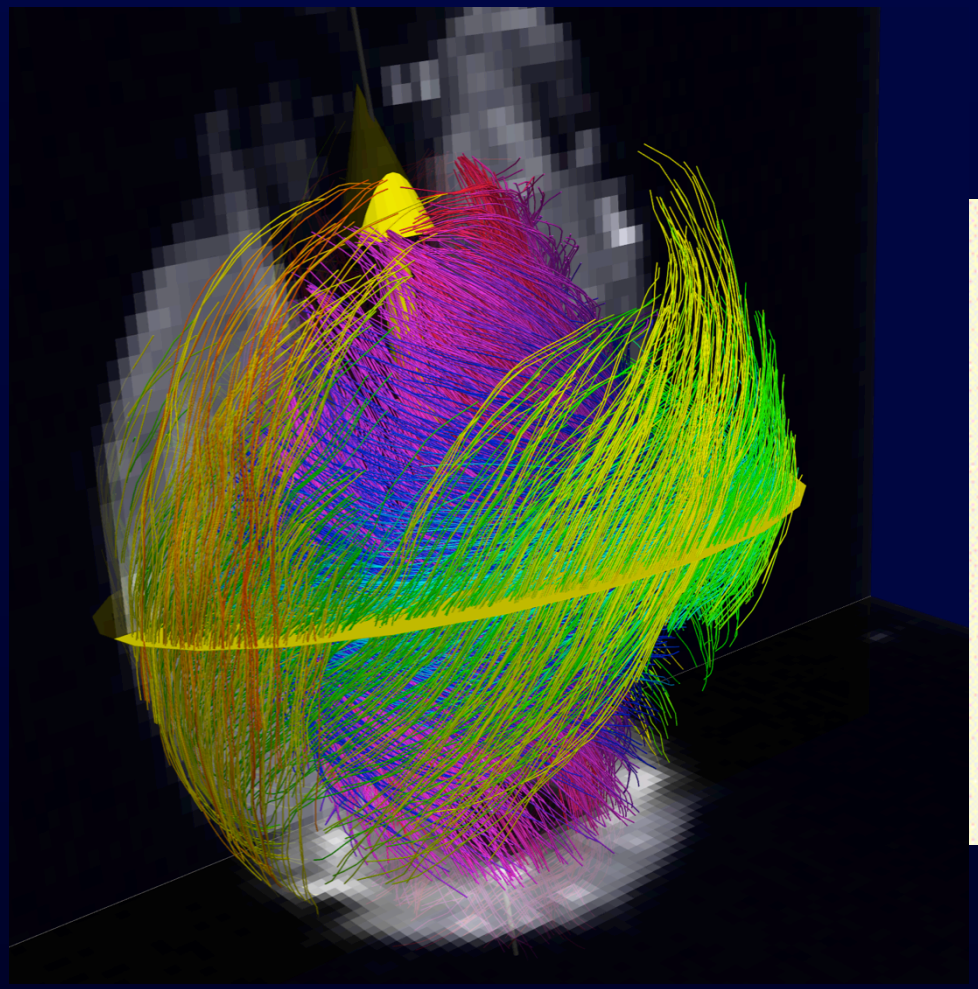


Homologous woven motif of hippocampal pathways in mouse, owl monkey, and human

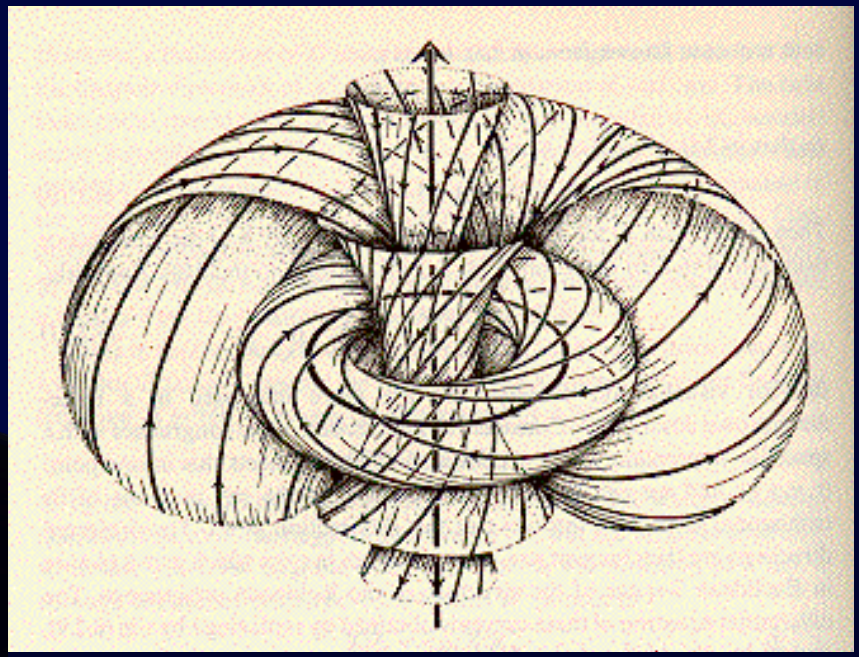




Myocardial fiber geometry for optimum efficiency

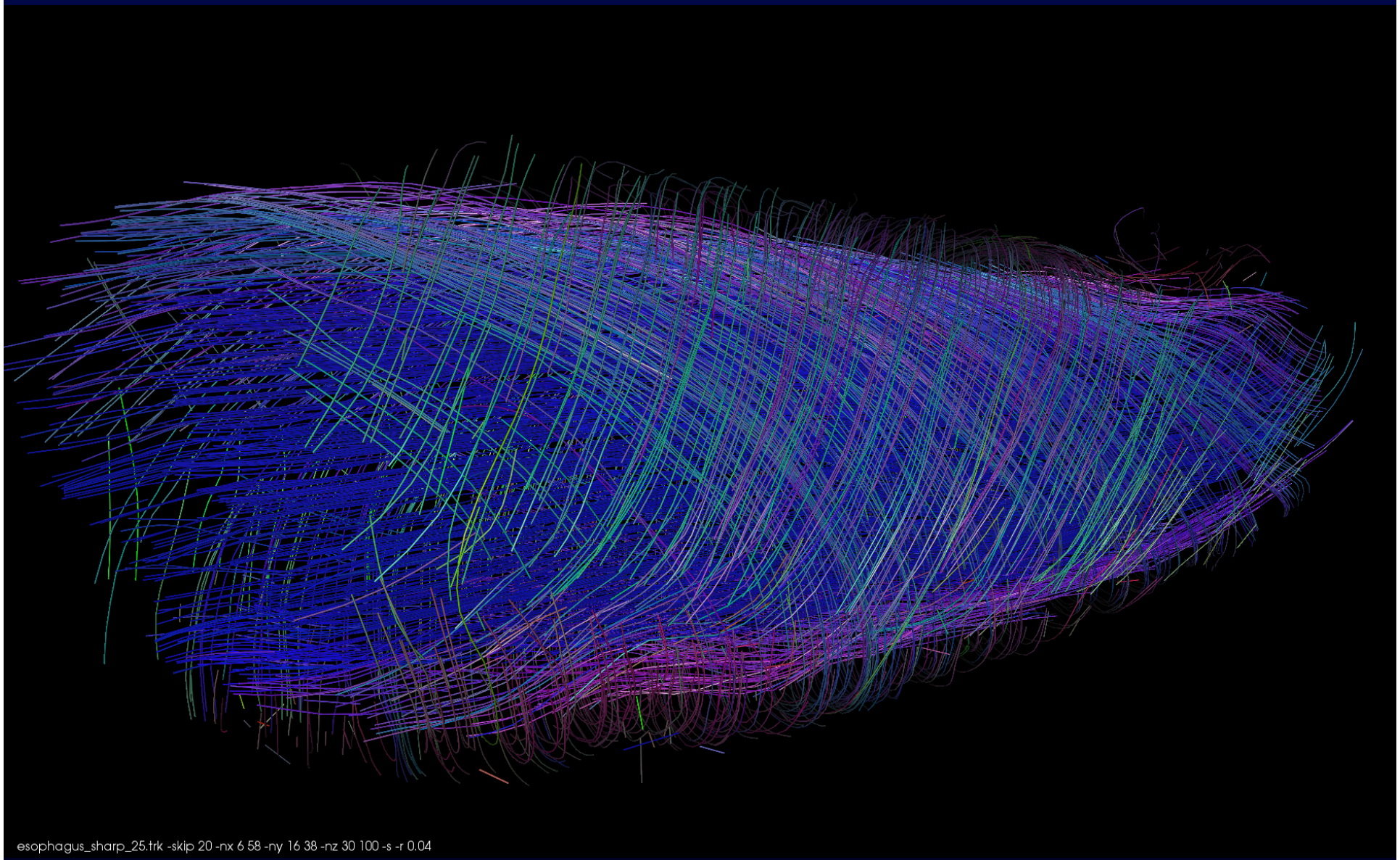


rat left ventricle

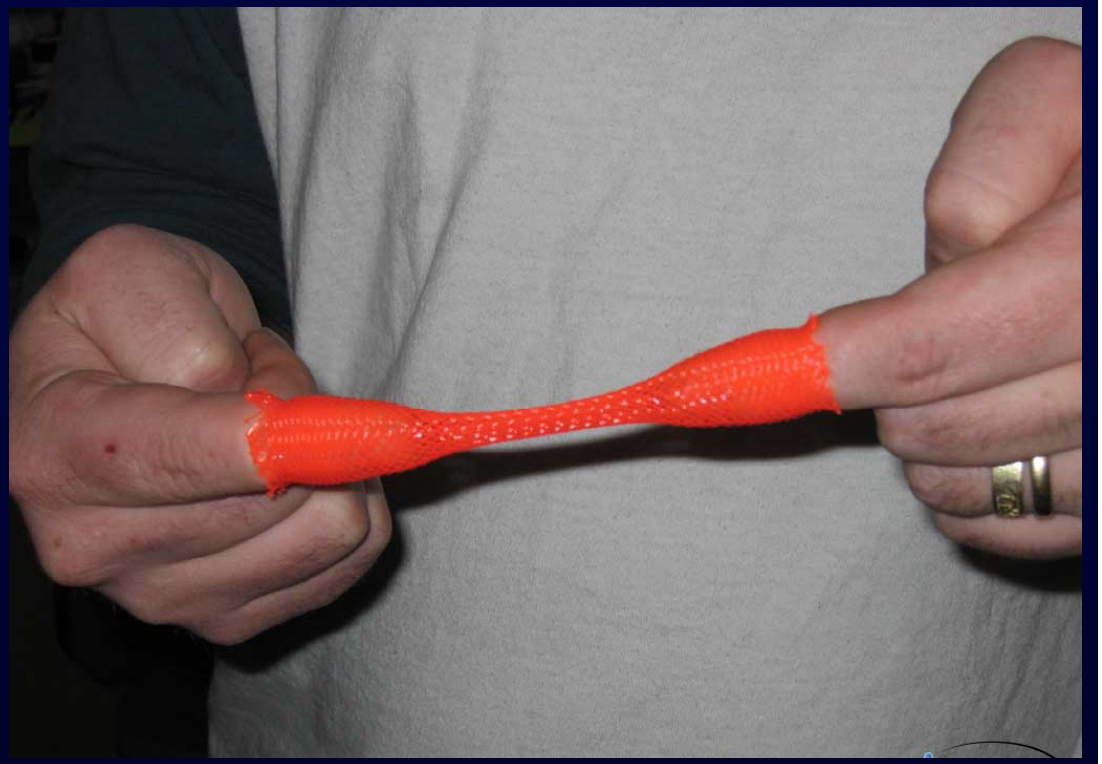


hyper-complex numbers

Esophagus fiber structure - like Chinese finger cuffs



Chinese finger trap



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Collaborators

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Doug Rosene	*BU*

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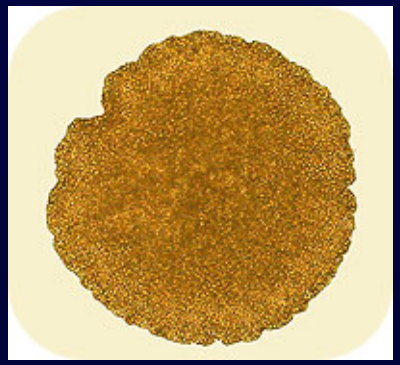
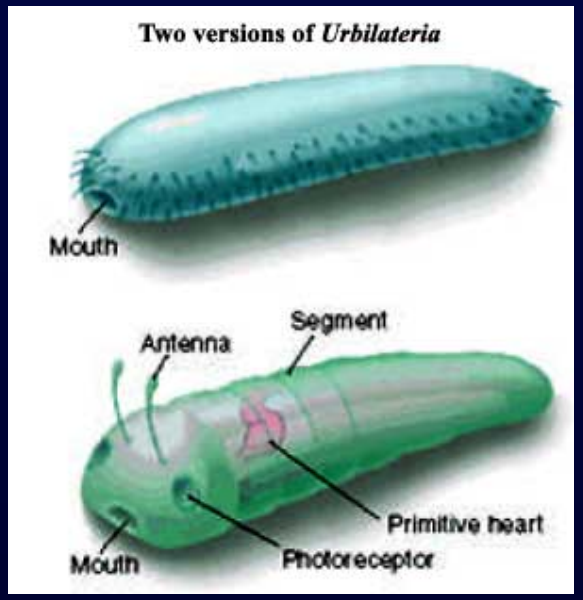
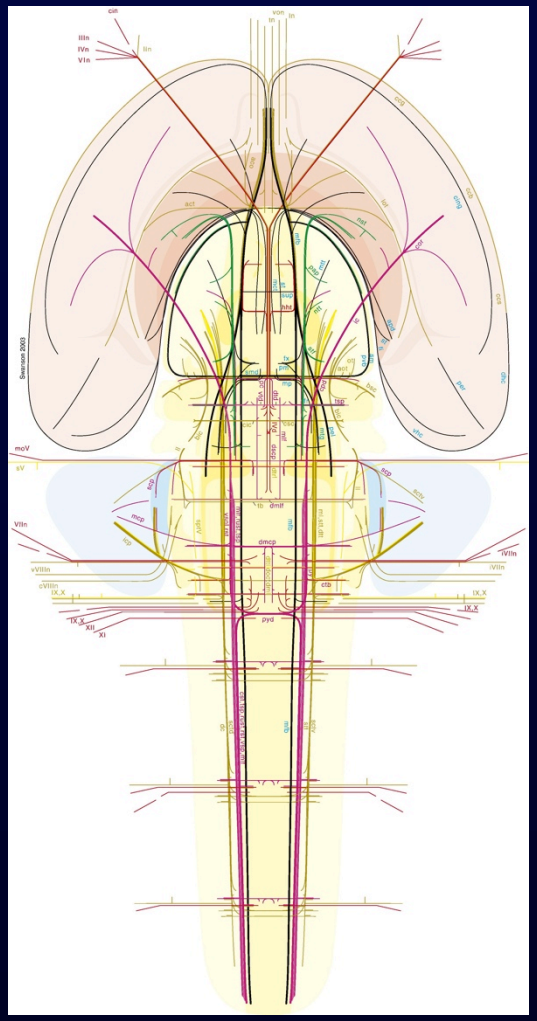
placazooan



ur-bilaterian

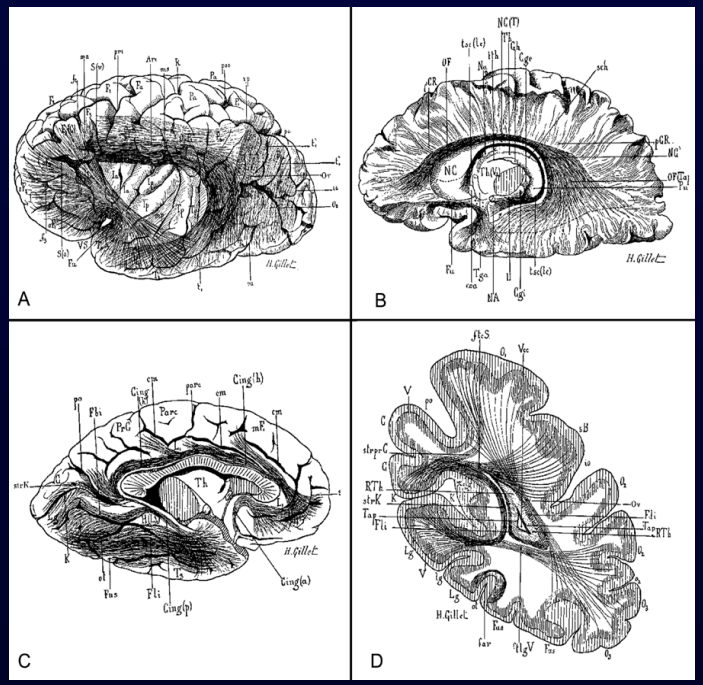


vertebrate

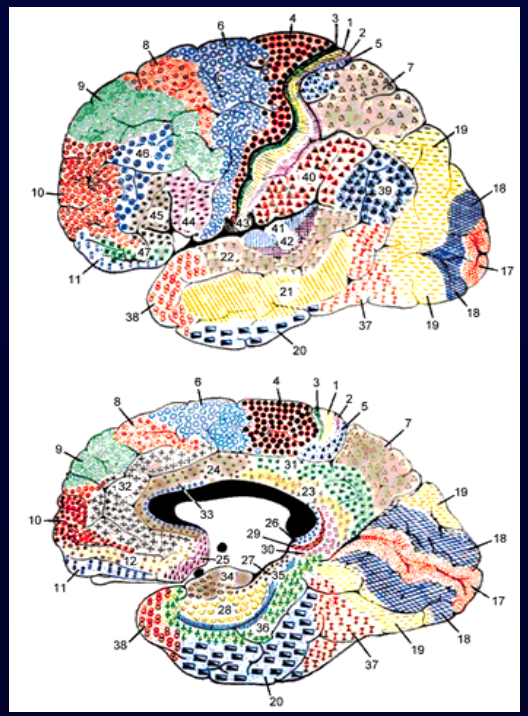


While gray matter has been mapped successfully for 100 years, white matter and connectivity remain problematic

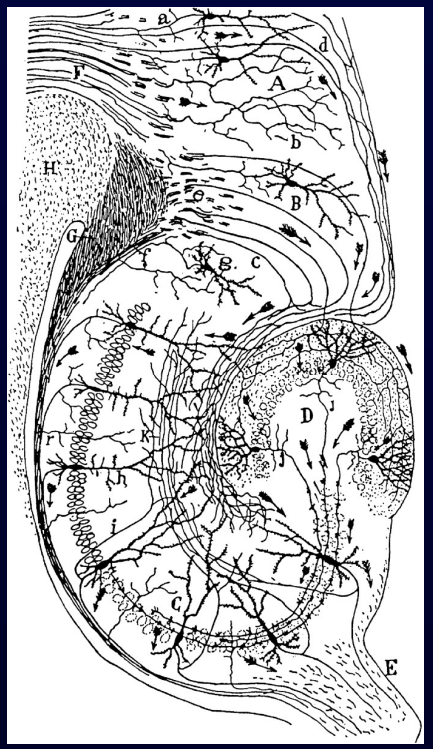
Dejerine 1895



Brodmann 1909



Cajal 1911



Wendell Krieg 1963 - human white matter by dissection

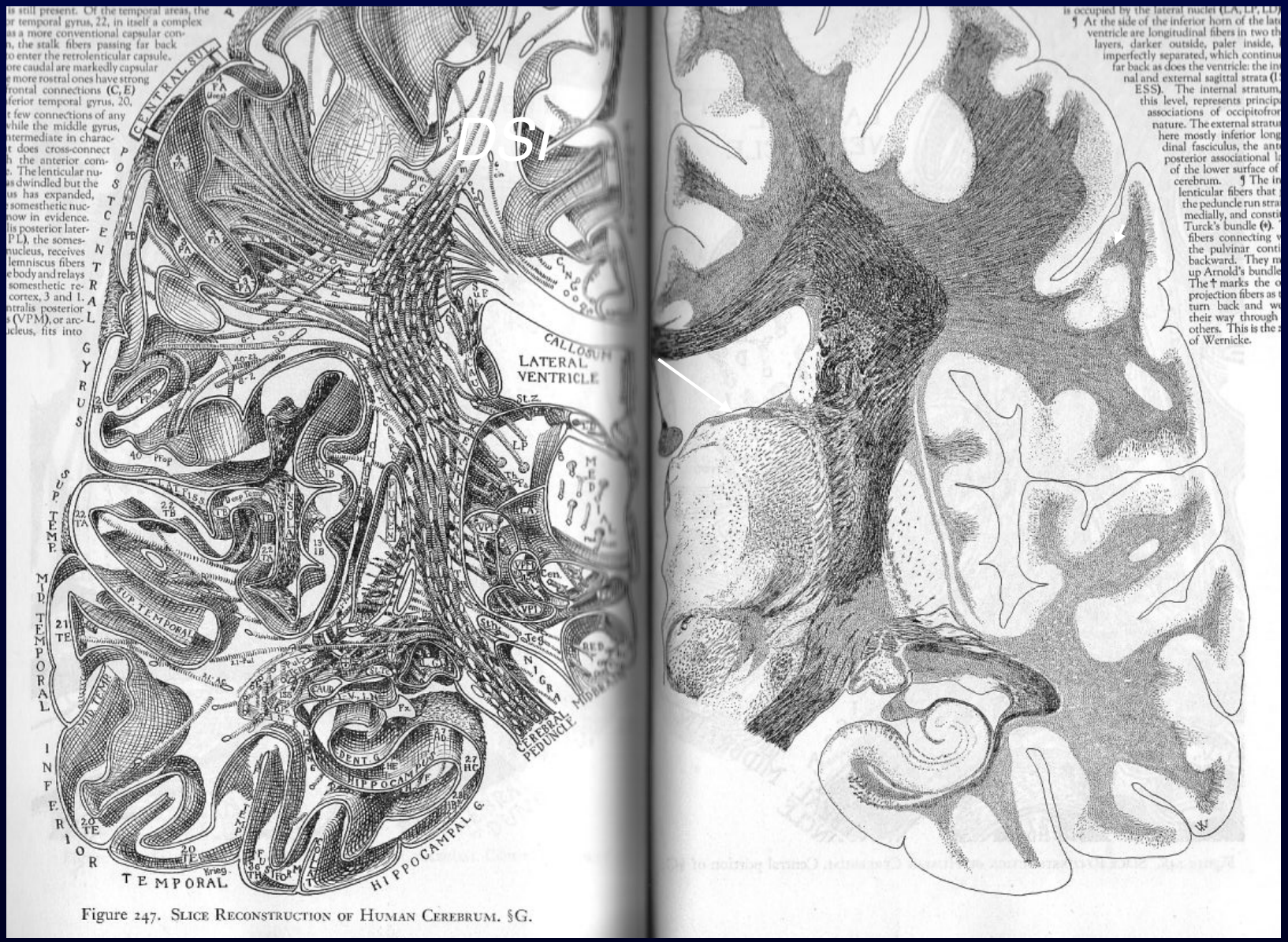


Figure 247. Slice Reconstruction of Human Cerebrum. §G.

The main reason neuro anatomy is more difficult to figure out than other kinds of anatomy - "fiber crossing" or overlap of structures in 3D