Introduction to Diffusion Imaging: MRI of the Brain's Connections

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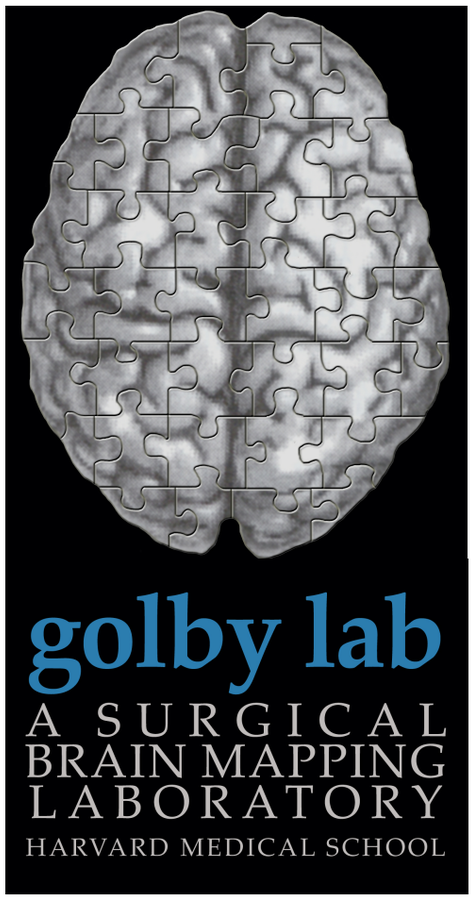
Collaborations



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Outline

- White Matter
- Diffusion MRI
- Neurosurgical Tractography
- Research Challenges

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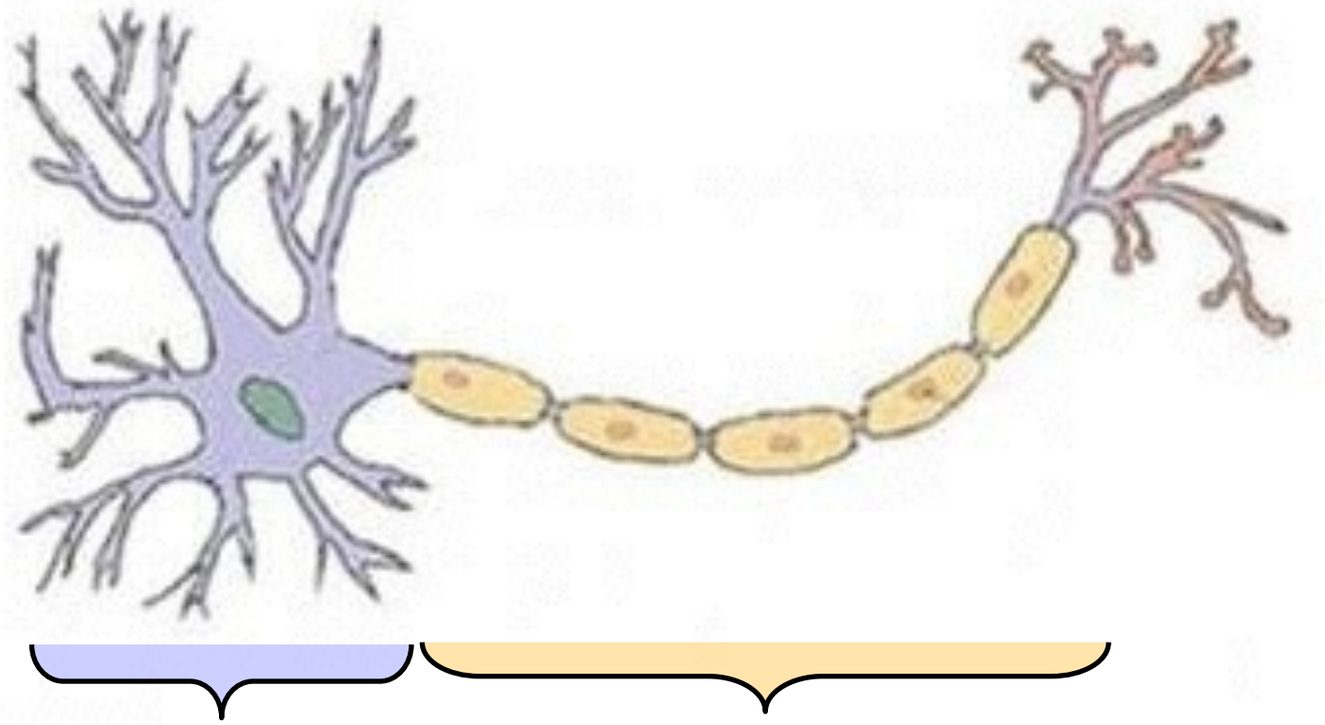
White Matter

- Neurons send and receive information



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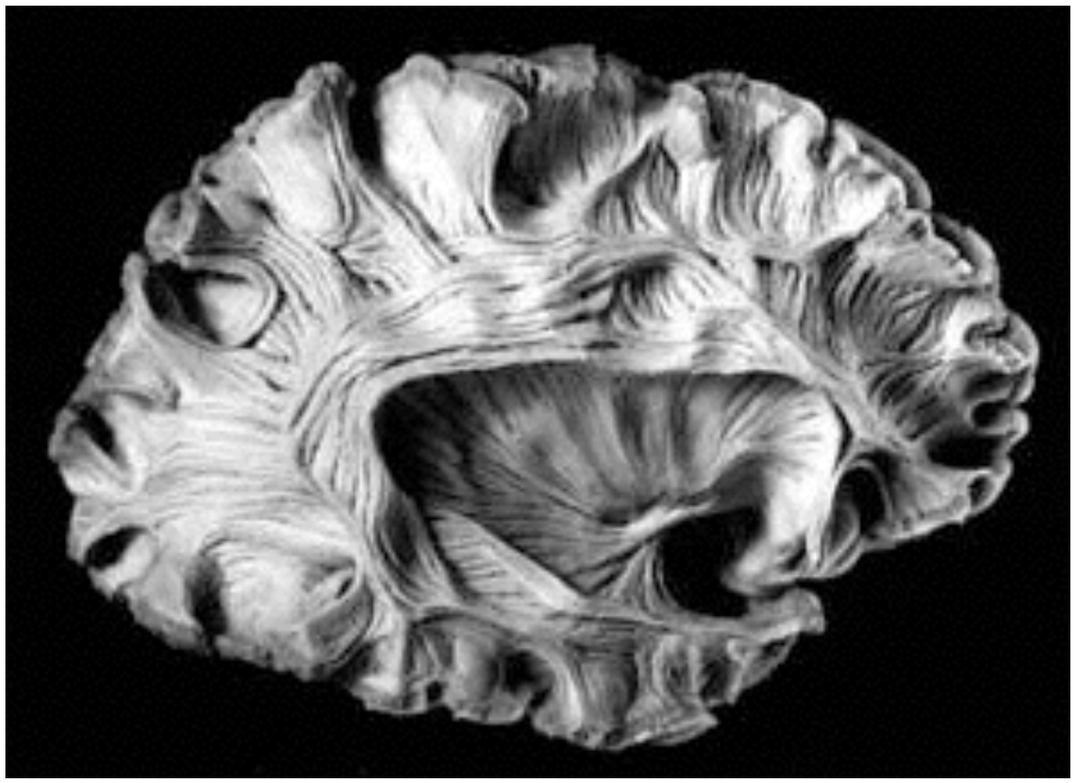
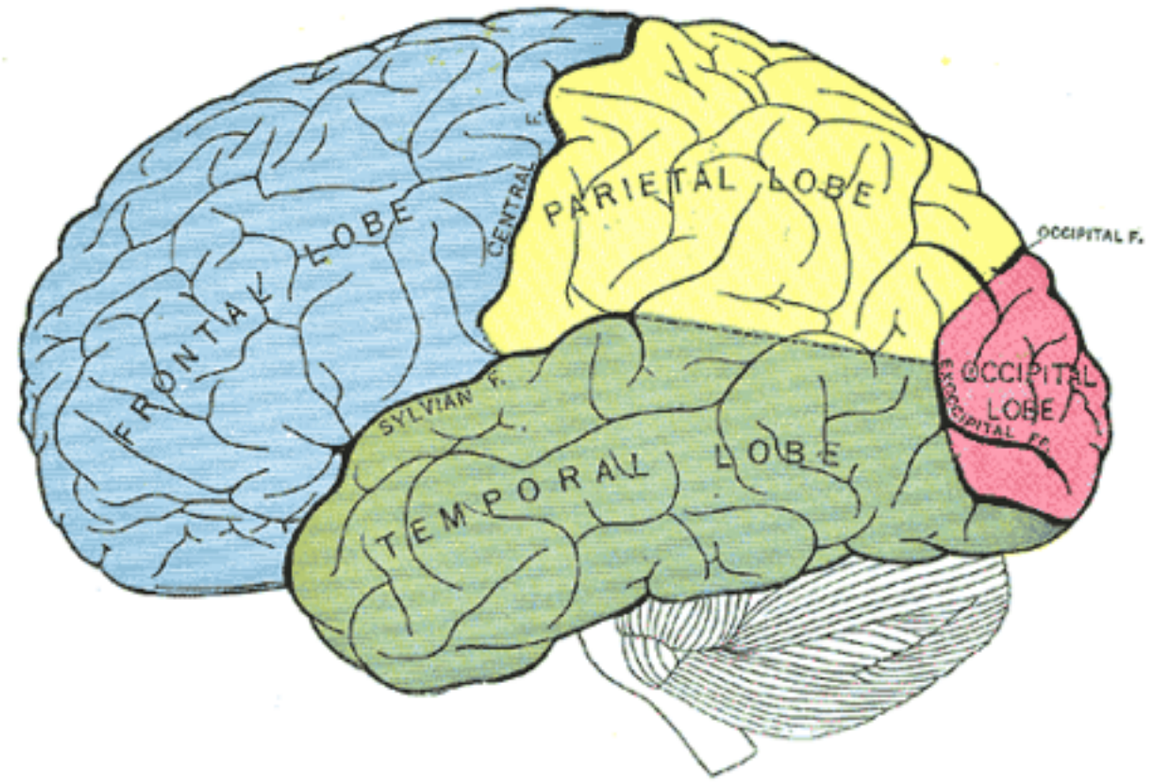
White Matter Fiber Tracts



Elaborate white matter dissection



Lobes of the brain

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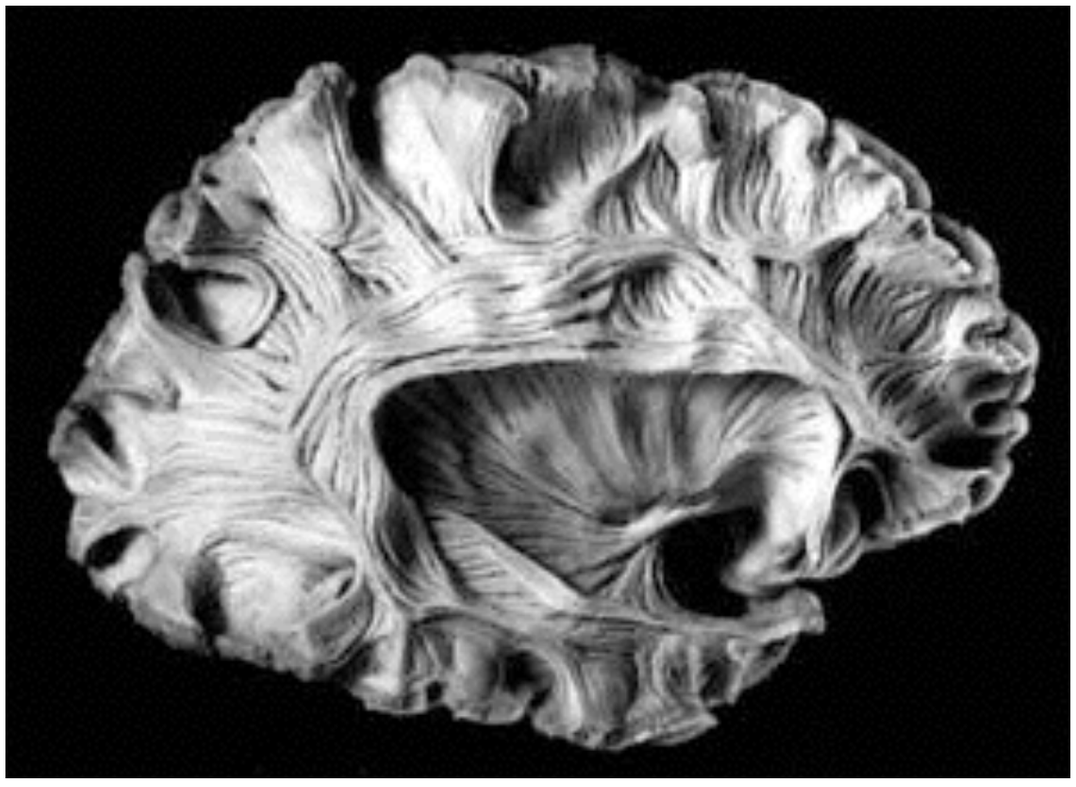
White Matter Fiber Tracts



Elaborate white matter dissection

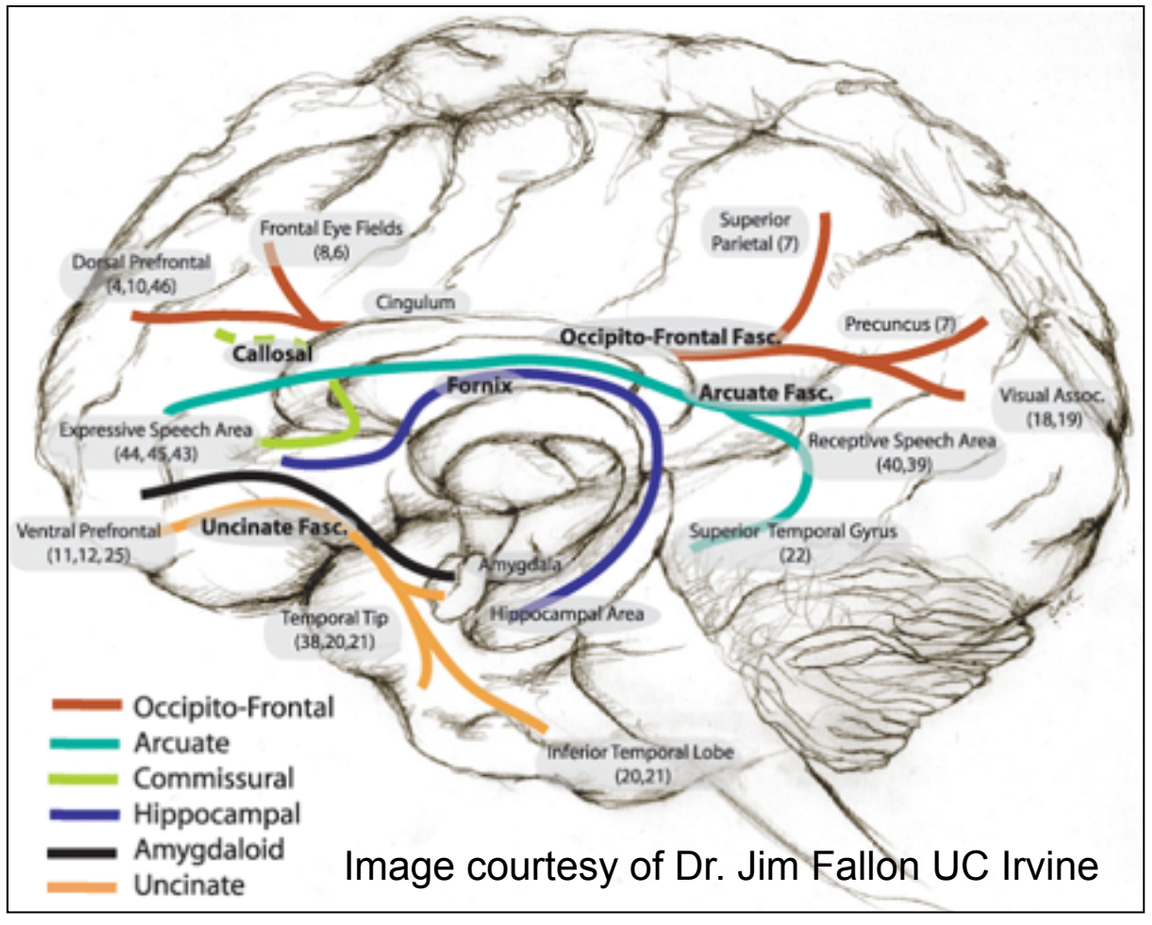


Image courtesy of Dr. Jim Fallon UC Irvine

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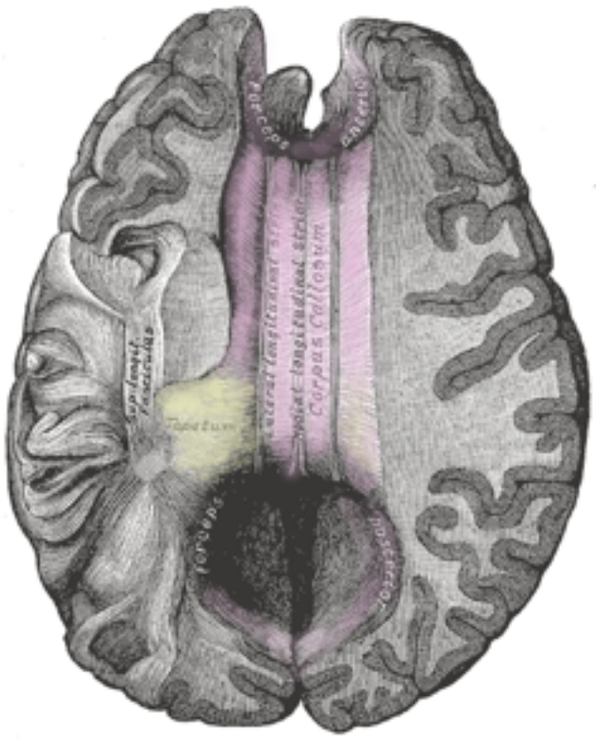
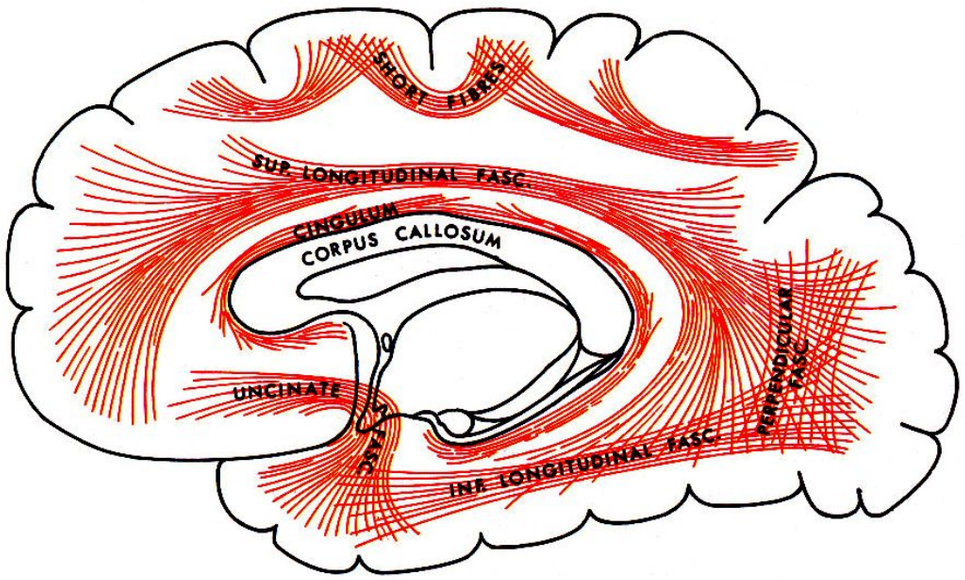
Types of Fiber Tracts

- Commissural
  - connect related regions of the two hemispheres
- Association
  - connect regions in the same hemisphere
  - within cortex, between gyri, or between lobes
- Projection
  - connect the cortex and subcortical structures
    - thalamus, basal ganglia, spinal cord (and cerebellum)

Commissural, Association, Projection





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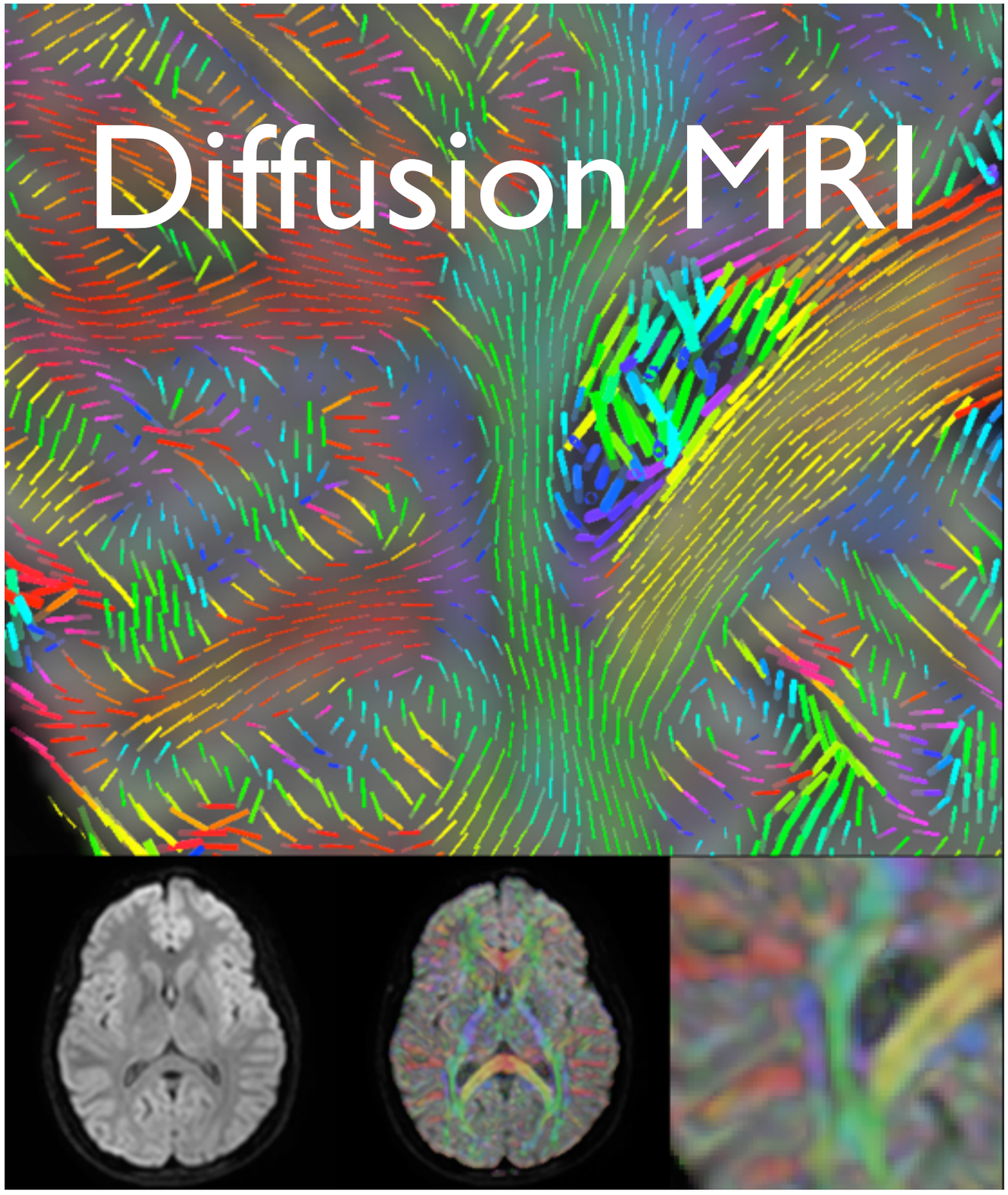
Diffusion MRI



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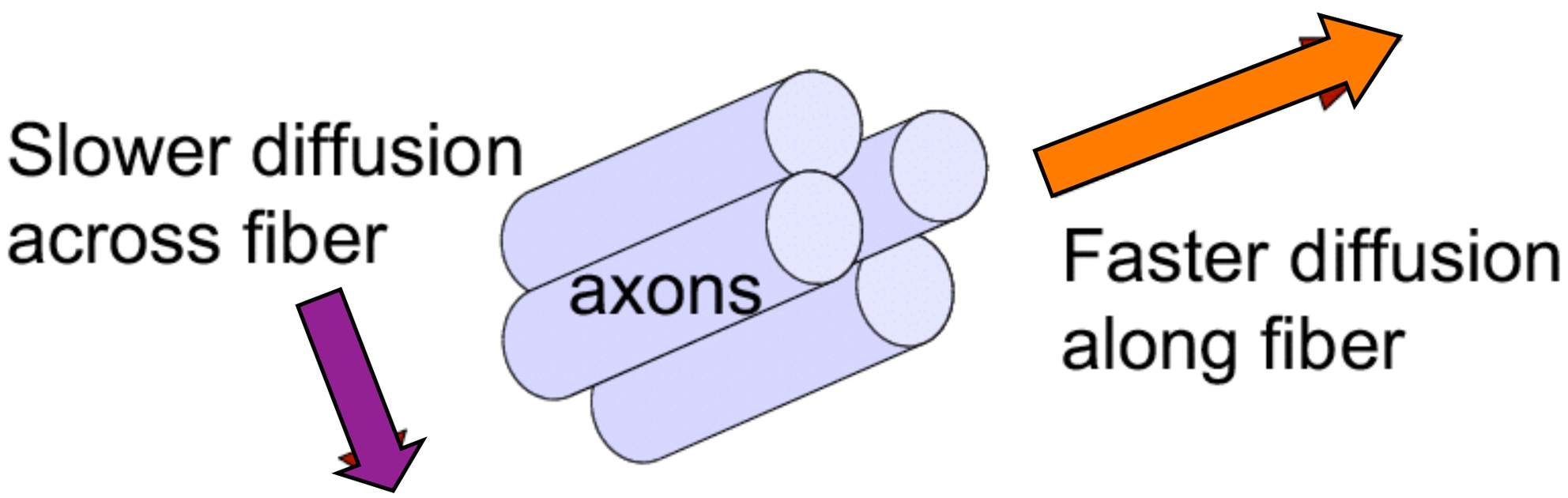
Diffusion MRI

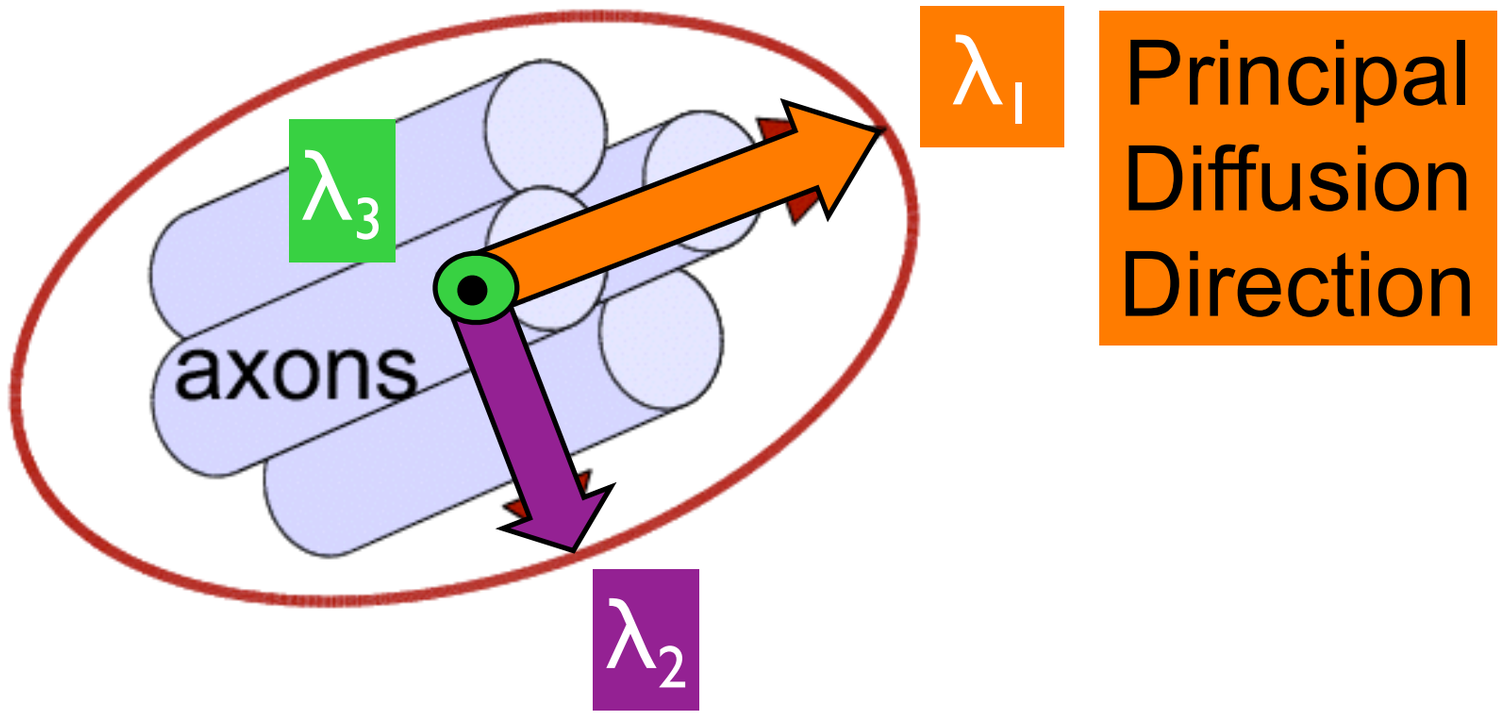
- Only in-vivo method to measure white matter tracts
- Indirect measure
  - water diffusion causes MRI signal loss
  - affected by cell membranes, myelin
  - 3D shape of water diffusion

Diffusion MRI



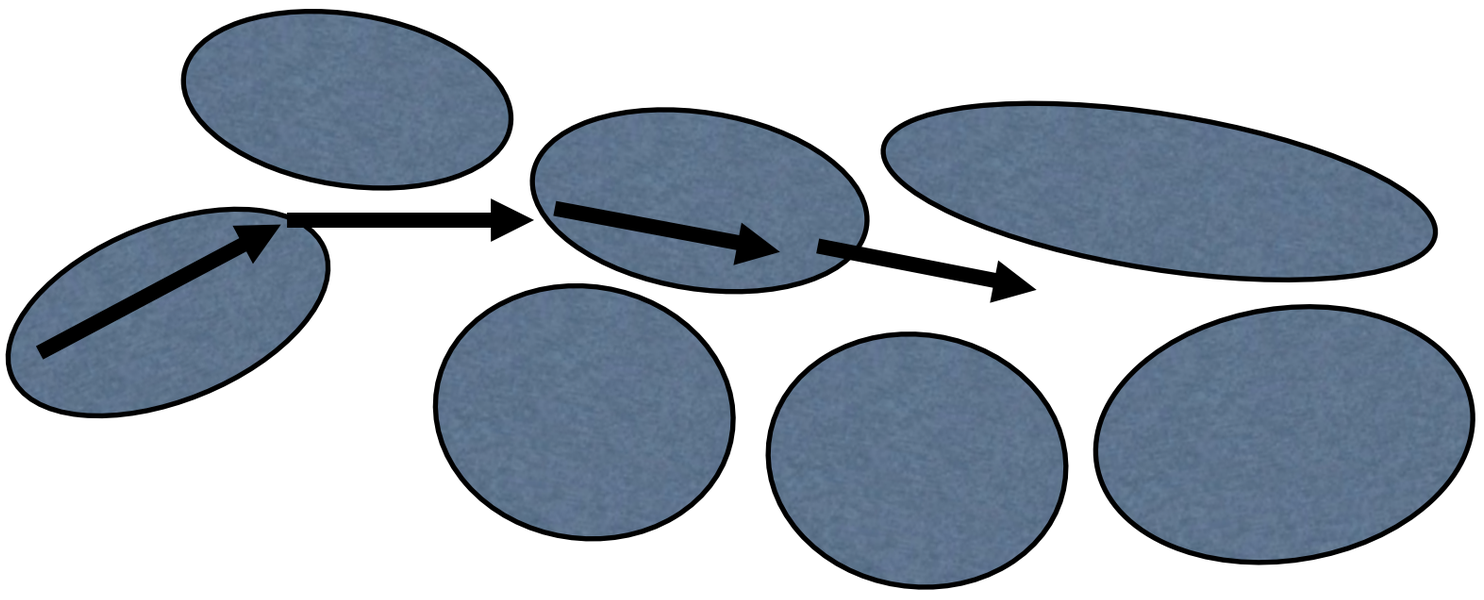
Diffusion Tensor MRI

$$S_k = S_0 \mathrm{e}^{-b\hat{g}_k^T \mathbf{D} \hat{g}_k}$$

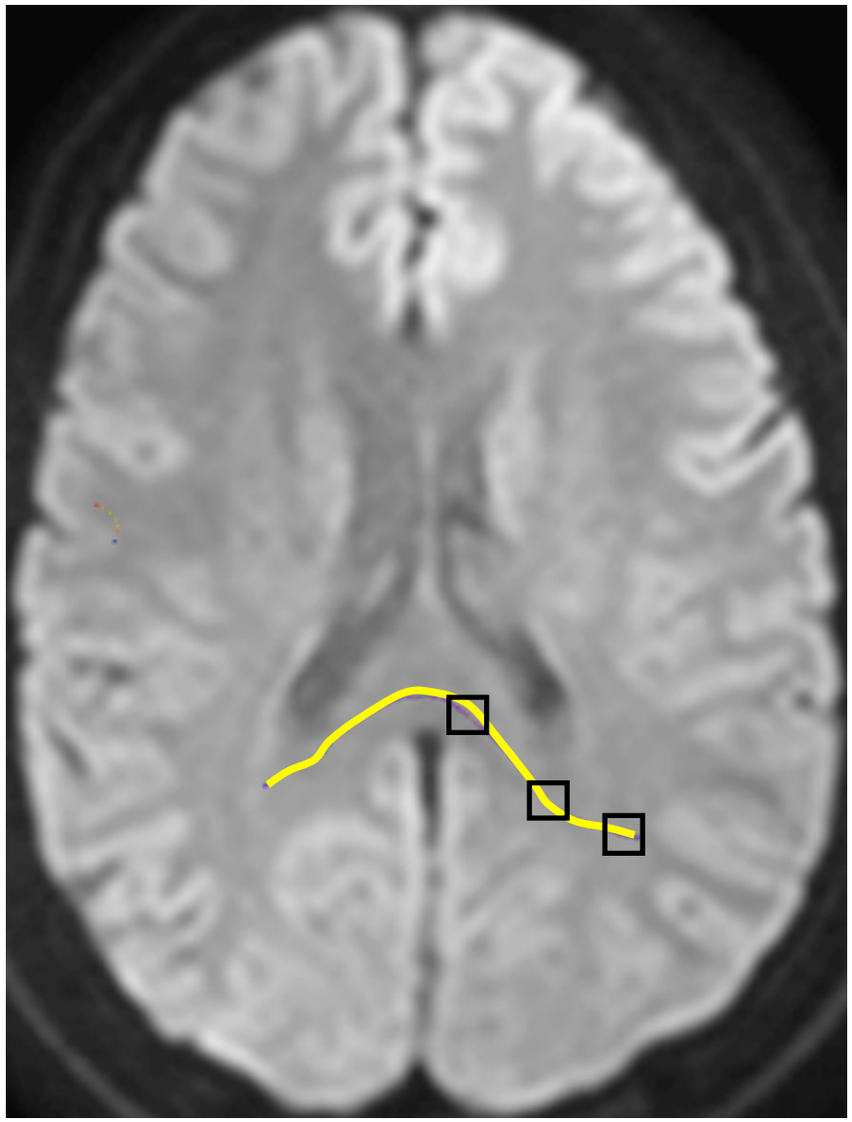


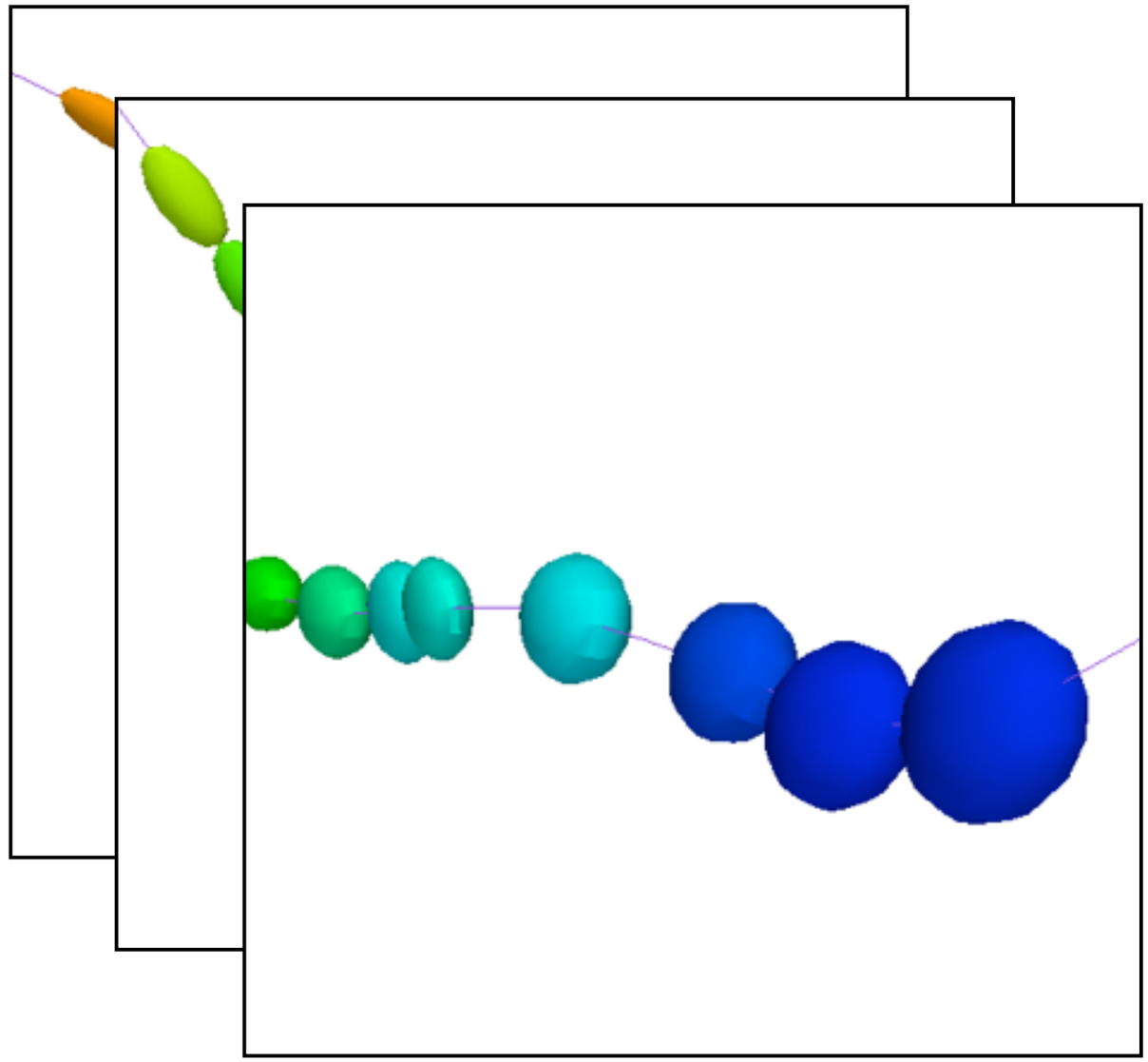
Tractography

- Estimate fiber trajectories in white matter
  - –streamline tractography
  - –Follow principal diffusion direction

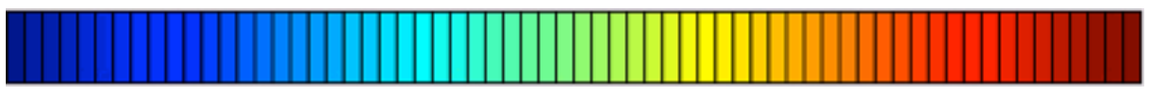


Tractography Example





Low anisotropy

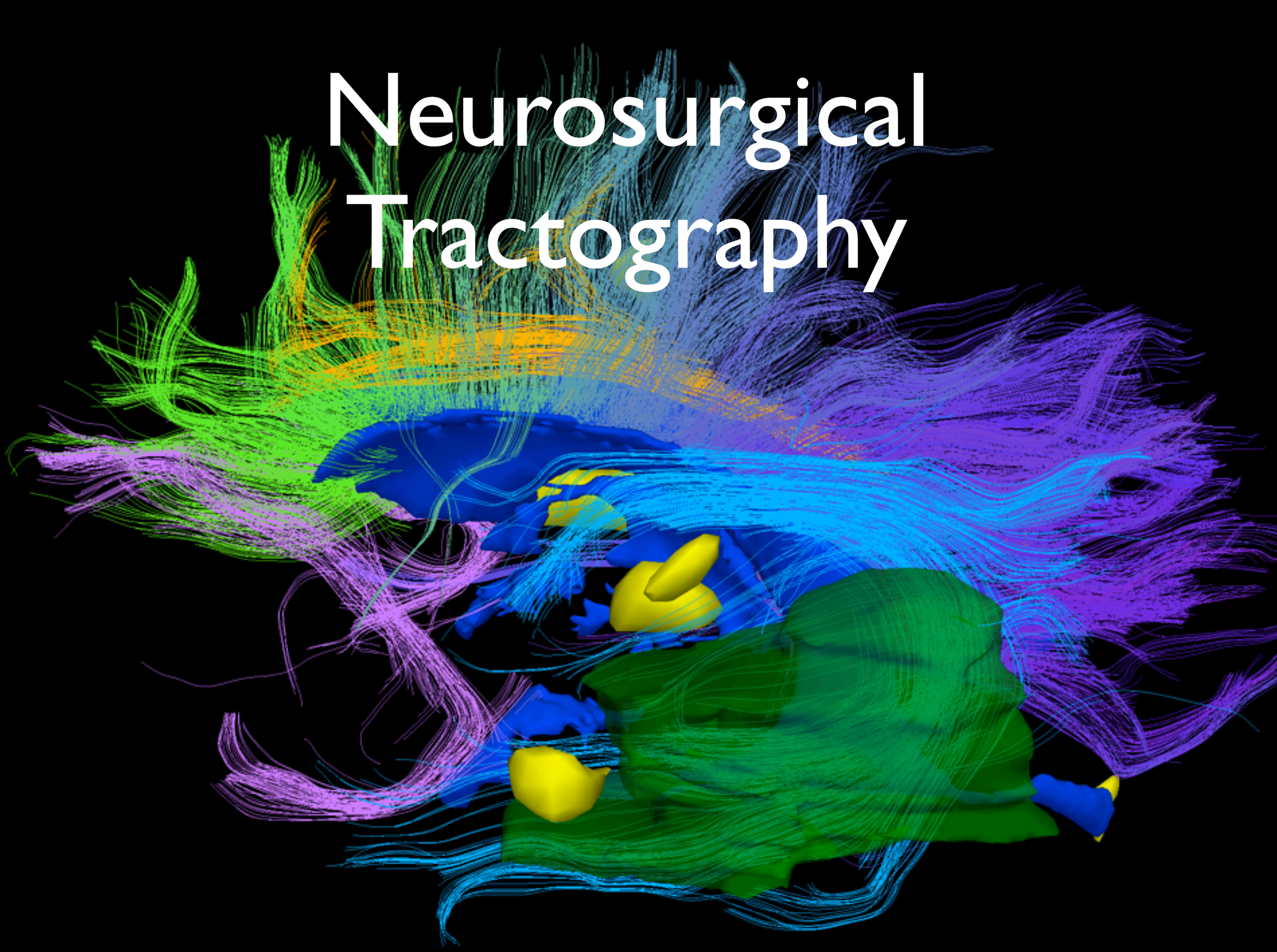


High anisotropy

Advanced dMRI...

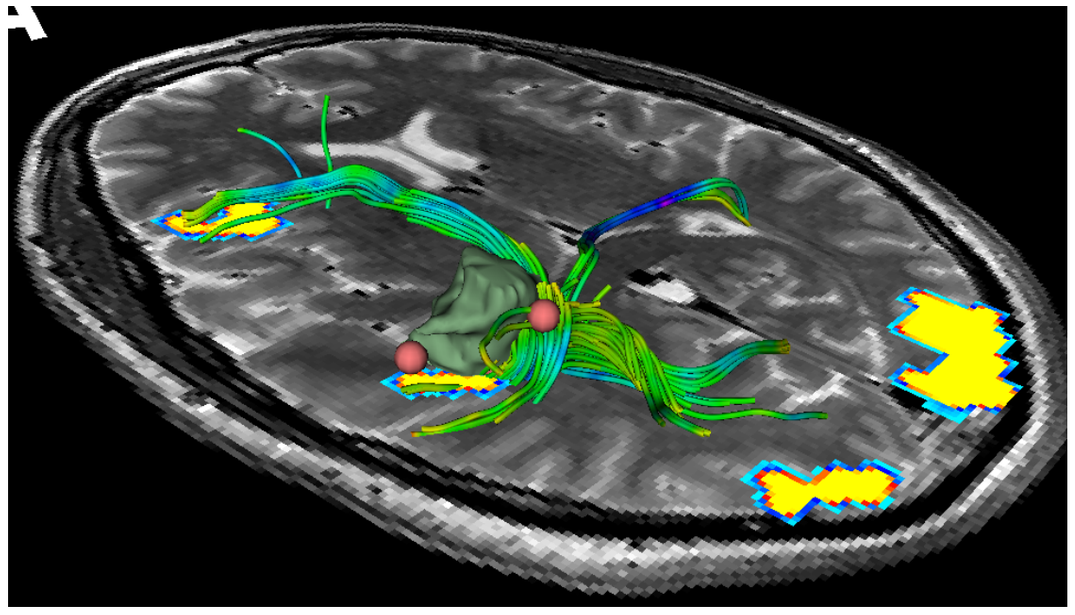
- acquisition
  - multishell, diffusion spectrum
- modeling
  - spherical harmonics, ball and sticks, multitensor
- tractography
  - deterministic vs probabilistic

Neurosurgical Tractography



Goals of image-guided neurosurgery

- Complete resection
- No neurologic injury
- Surgeon wants to see:
  - Lesion and margins
  - Critical structures
- To accomplish:
  - Pre-operative planning
  - Surgical decision-making



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Tractography Video

- Interactive DTI visualization for neurosurgical planning

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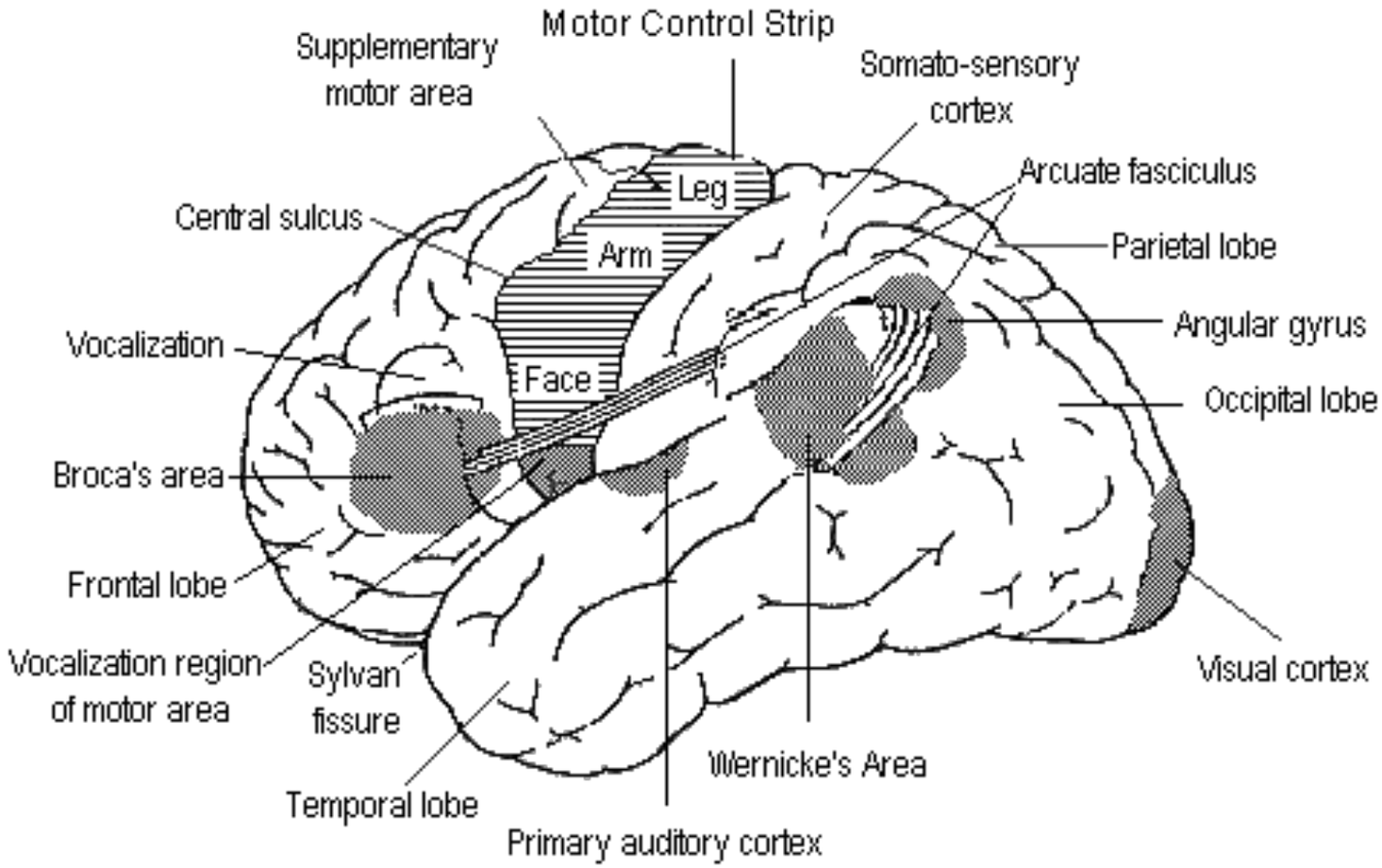
Important Tracts

- Three top tracts for neurosurgery
  - arcuate fasciculus (SLF IV): language
  - corticospinal tract: motor
  - optic radiations: vision
- Correspond to “eloquent cortex”

Eloquent Cortex



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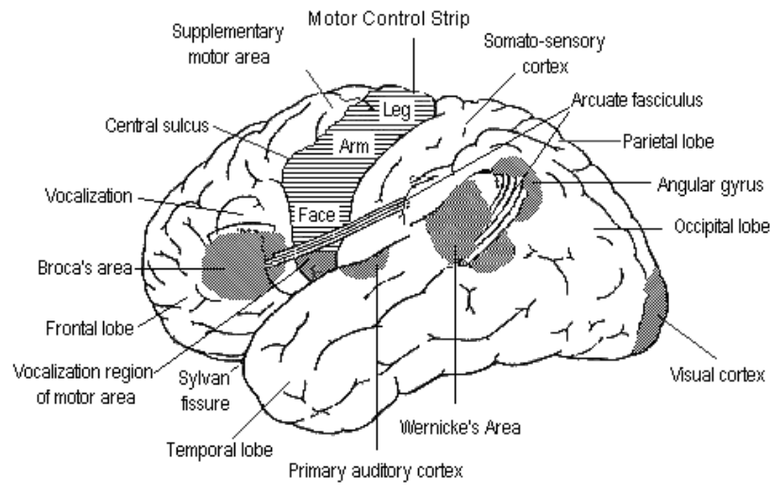
Language: Arcuate Fasciculus



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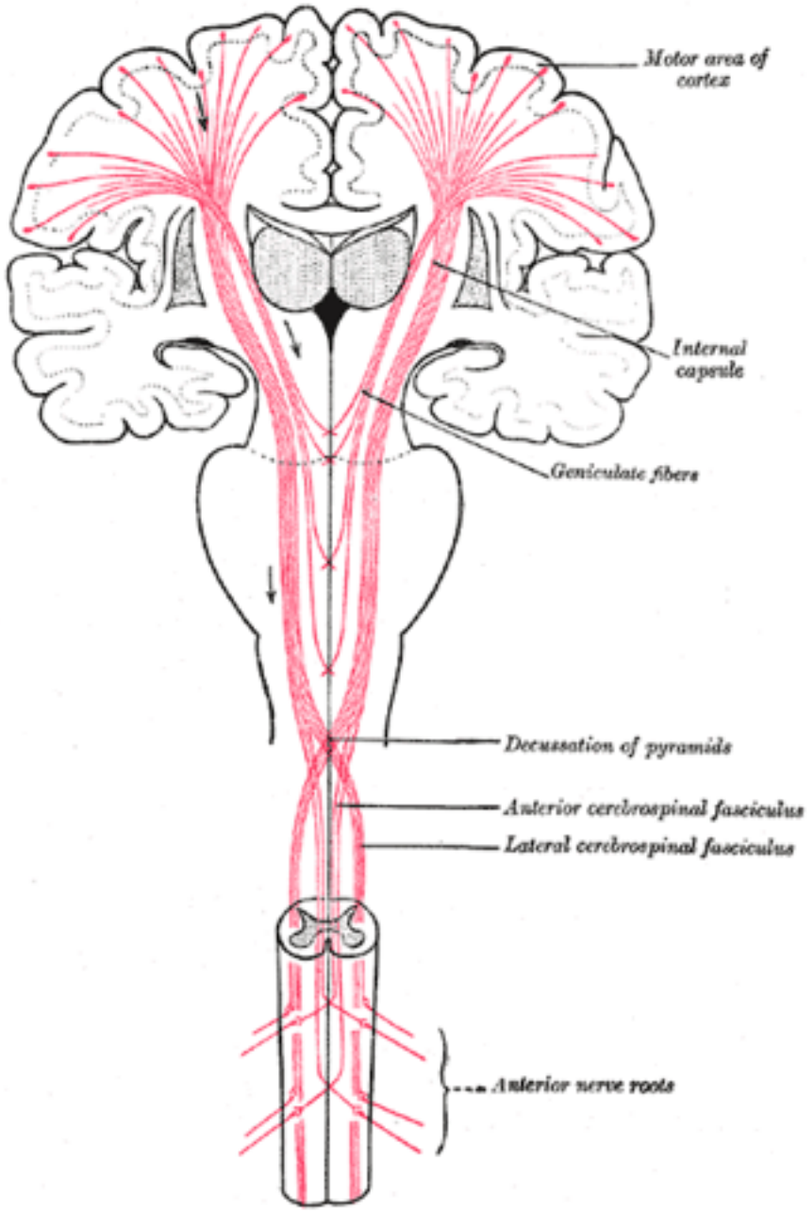
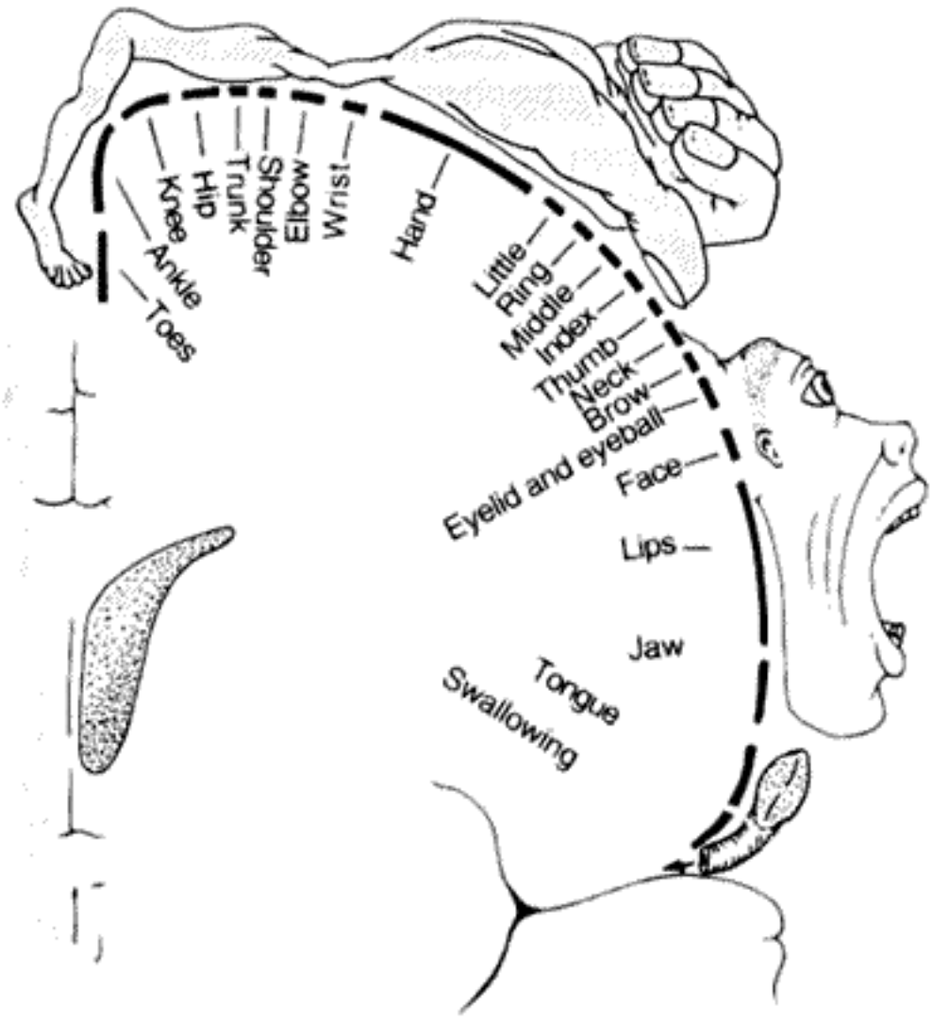
Motor: Corticospinal Tract





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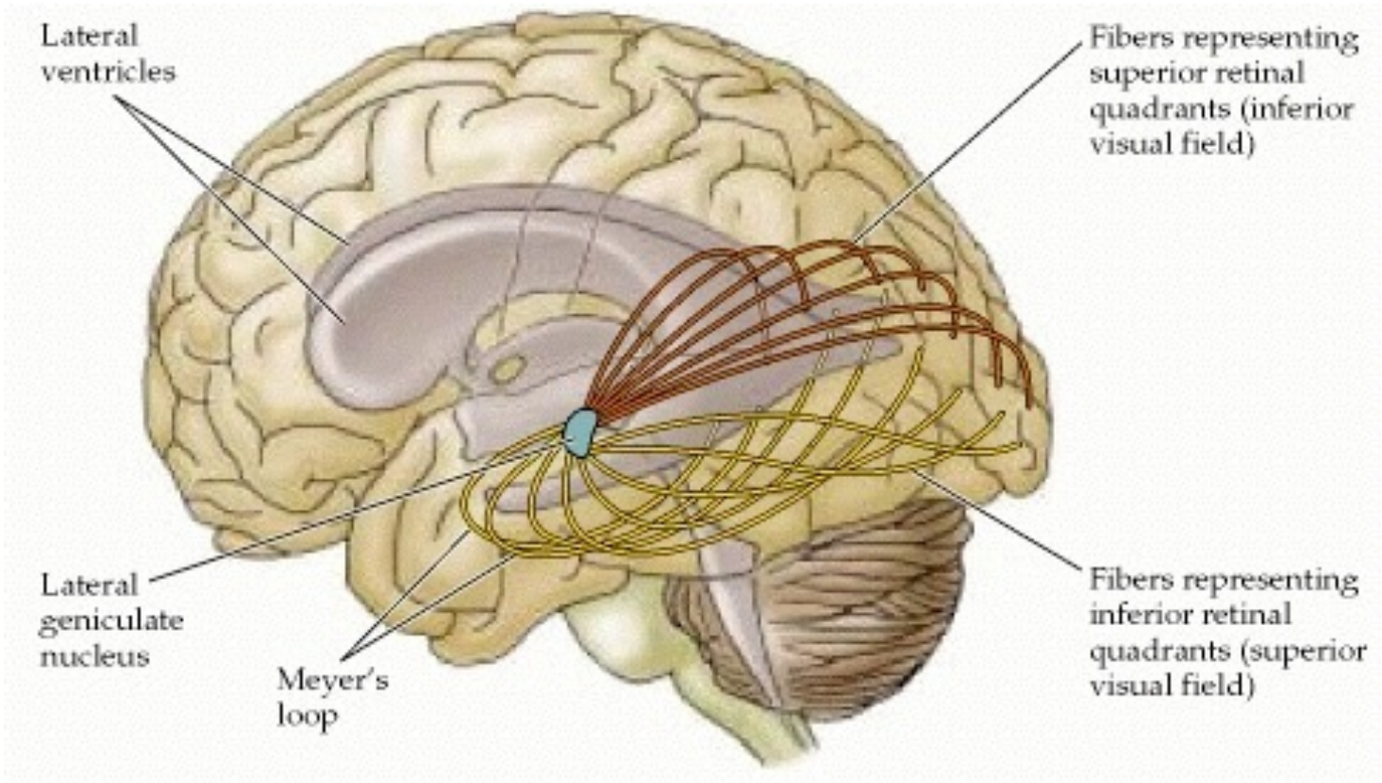
Vision: Optic Radiation



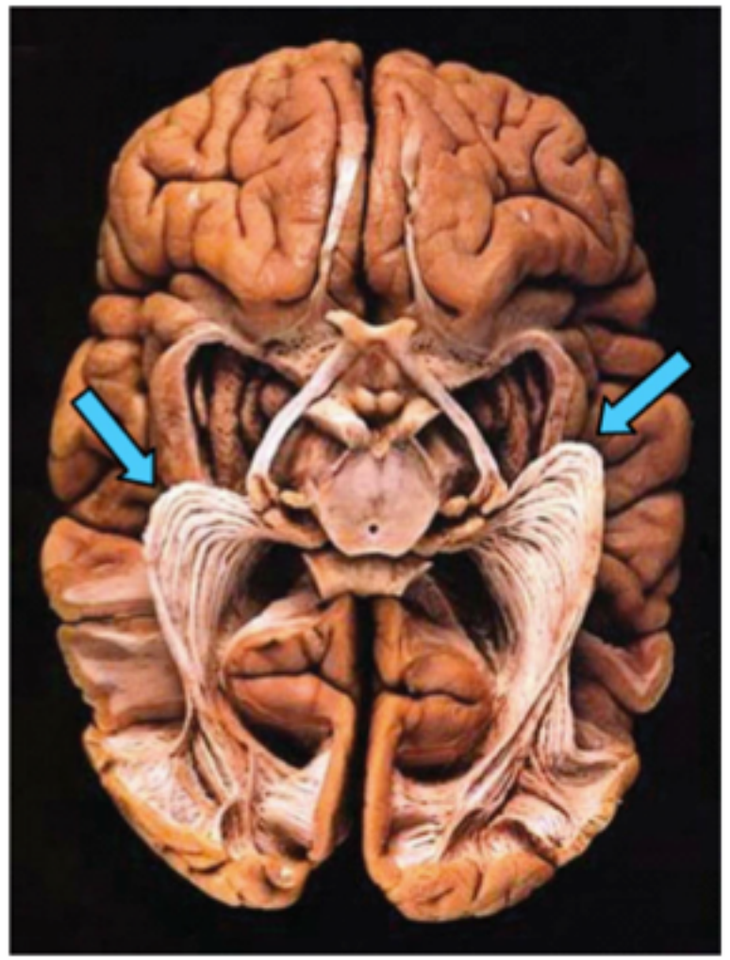


Figure 1. The optic radiation exposed (virtual hospital). A brain, viewed from below, is prepared using Klingler's fiber dissection technique. Meyer's loop, the anterior extension into the temporal lobe, is indicated by the arrows.

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During Neurosurgery

- Diffusion image data is useful because:
- Tracts are not visible
- Consistency of the tumor may be the same as white matter
- Electrical stimulation
  - Can identify cortical functional regions
  - Is less common/harder in white matter

AMIGO


VectorVision compact
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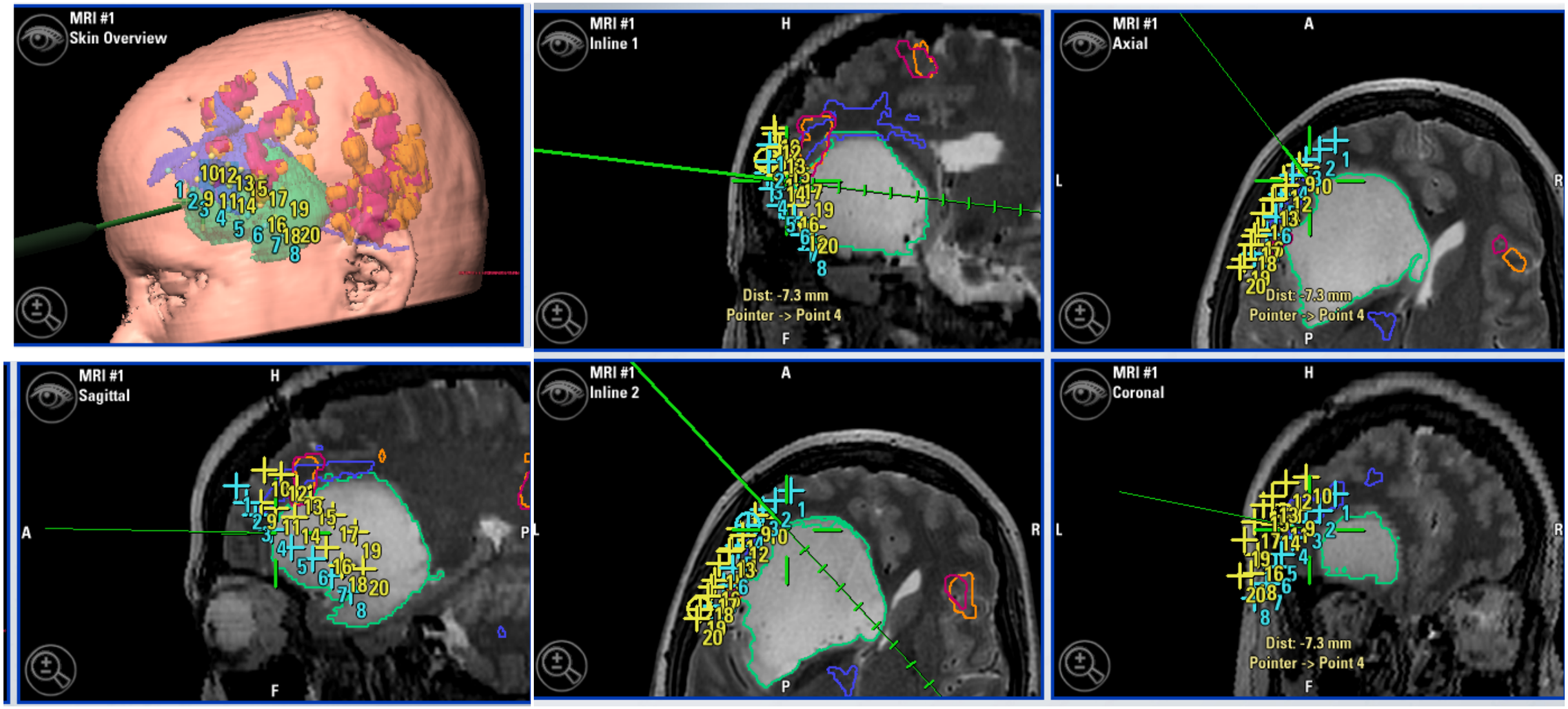
Neuronavigation



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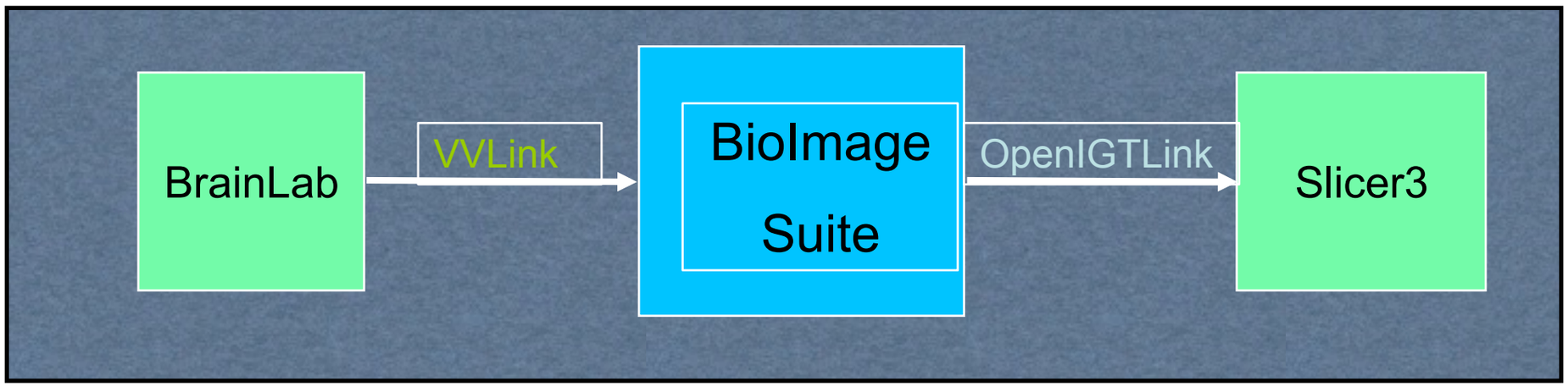
Integrating research and commercial platforms



- BrainLab sends real-time data from its tracking system and/or images to Slicer
- BrainLab tracker used to manipulate dynamic DTI visualization in Slicer.

slide courtesy Dr. Alexandra Golby

Tractography Video

- Intraoperative real-time querying of white matter tracts

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Research Challenges

- Accurate tractography is needed
  - Tensor model is too simple...
    - But is clinically available
- Data is clinically challenging to interpret
  - Can algorithms help?
  - Identification of key fiber tracts

Tractography Accuracy

- "Crossing fibers" in 30-90% of the brain
- Different models lead to different results
- Anatomical variability is high
- Clinical/neuroscientific results:
  - arcuate fasciculus, corticospinal tract

Arcuate Variability

- colocalization: <1 cm to **electrode contact that produced language disturbance** during cortical stimulation.

- "The AF ... colocalized well with anterior language areas, but less so with posterior language areas, inferring that the latter are more spatially dispersed."

- anterior 84% vs posterior 56%

- FACT algorithm (Mori)

  - single tensor tractography

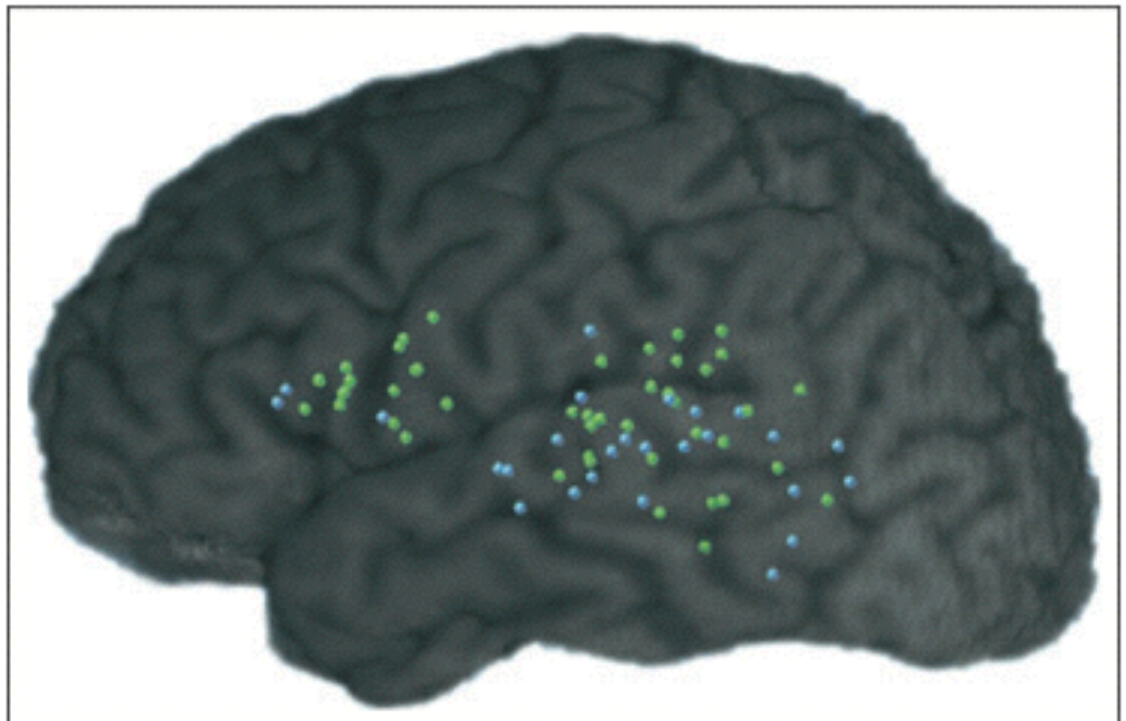
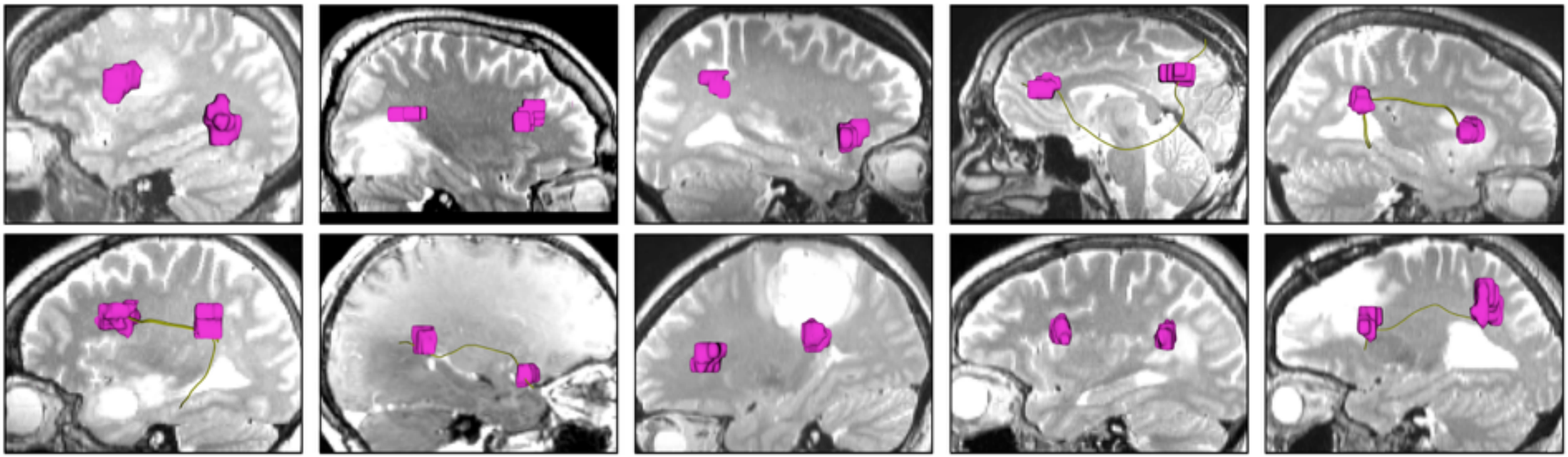


Figure 3.
Composite map of all electrode positions in 14 patients overlying language cortex. Displayed on a magnetic resonance imaging (MRI) scan of a normal control, in Montreal Neurological Institute space. The electrode positions overlying language cortex were rated as colocalizing well (green color code) with the arcuate fasciculus (AF), or not localizing well (blue).
Epilepsia © ILAE

Diehl et al. Cortical stimulation for language mapping in focal epilepsy: Correlations with tractography of the arcuate fasciculus. Epilepsia, 51(4):639–646, 2010

Clinical: 1 tensor



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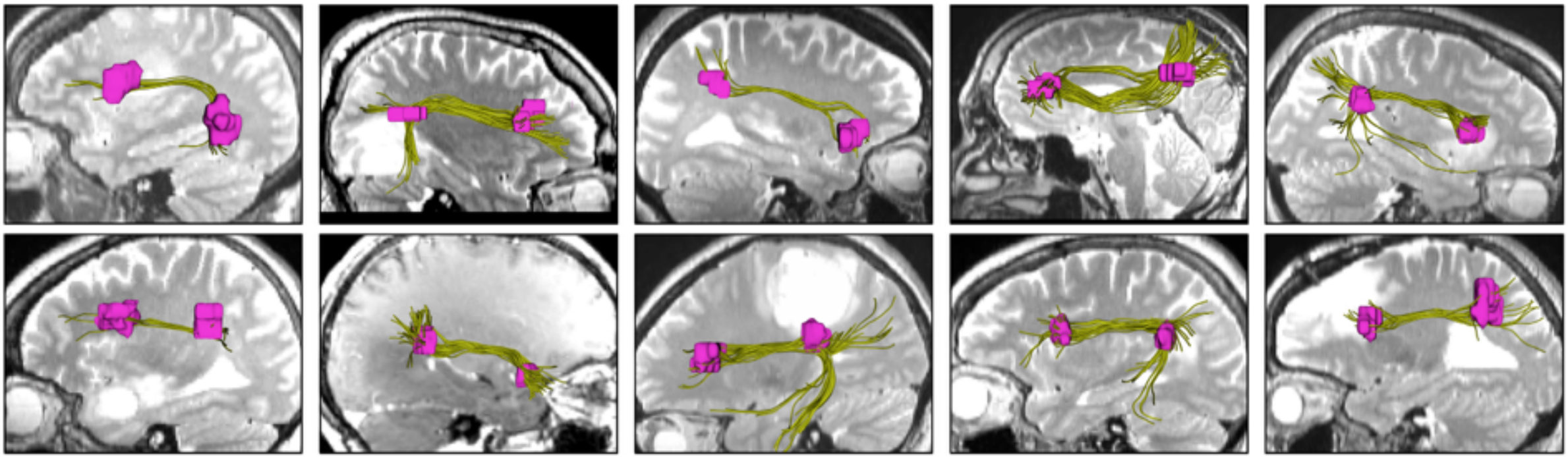
Clinical: 2 tensor



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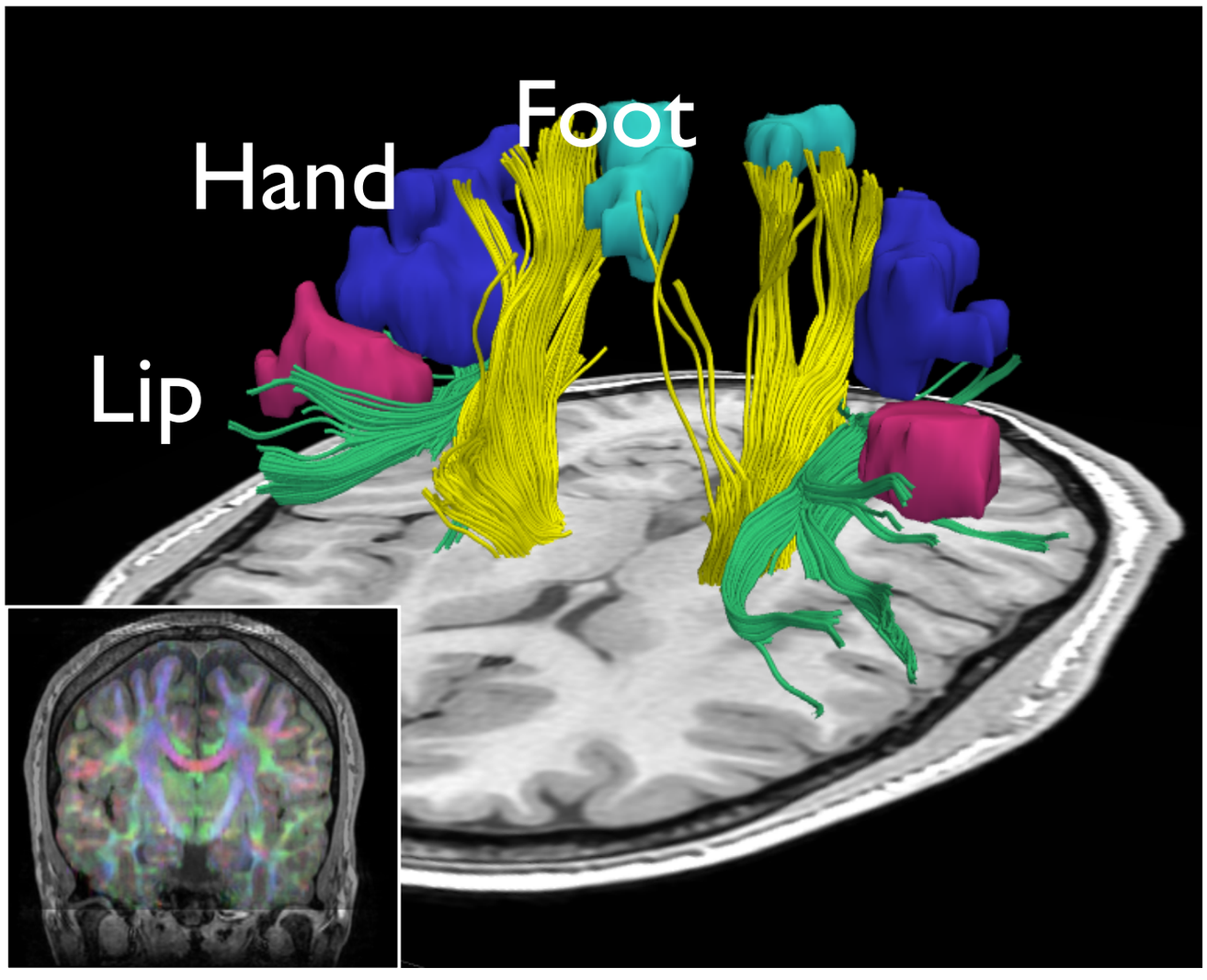
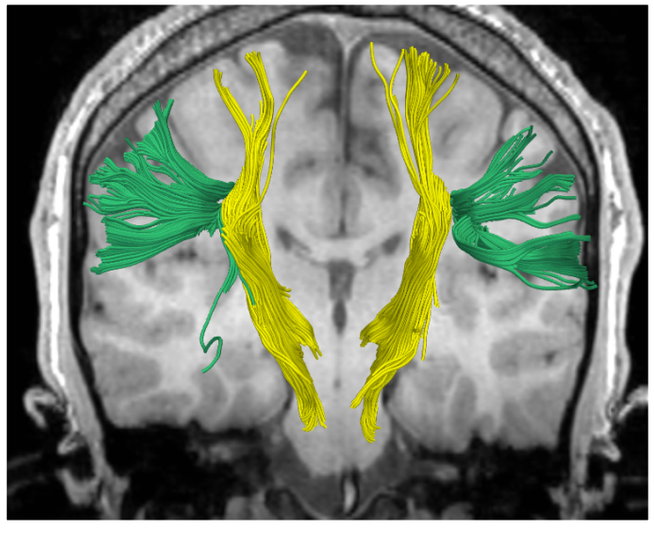
Corticospinal Tract

- centrum semiovale
- crossing fibers
  - CST, AF, corpus





Typical Streamline Tractography
One-Tensor Model Result

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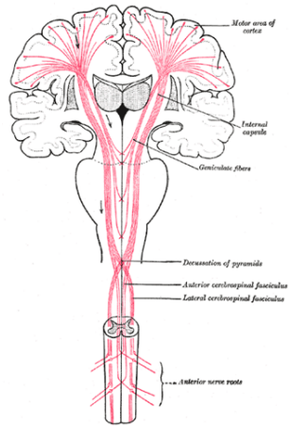
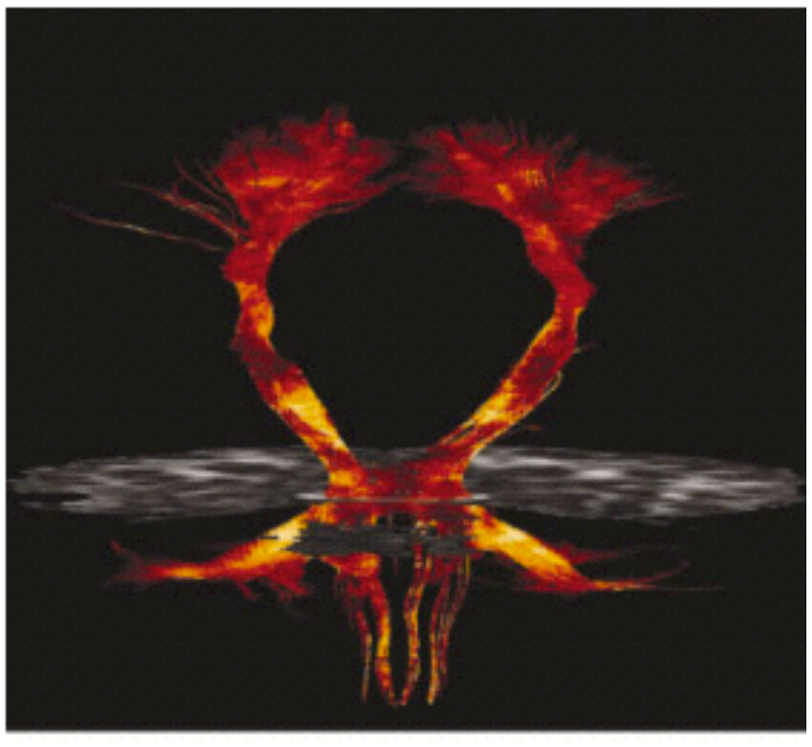
CST Tracing Methods

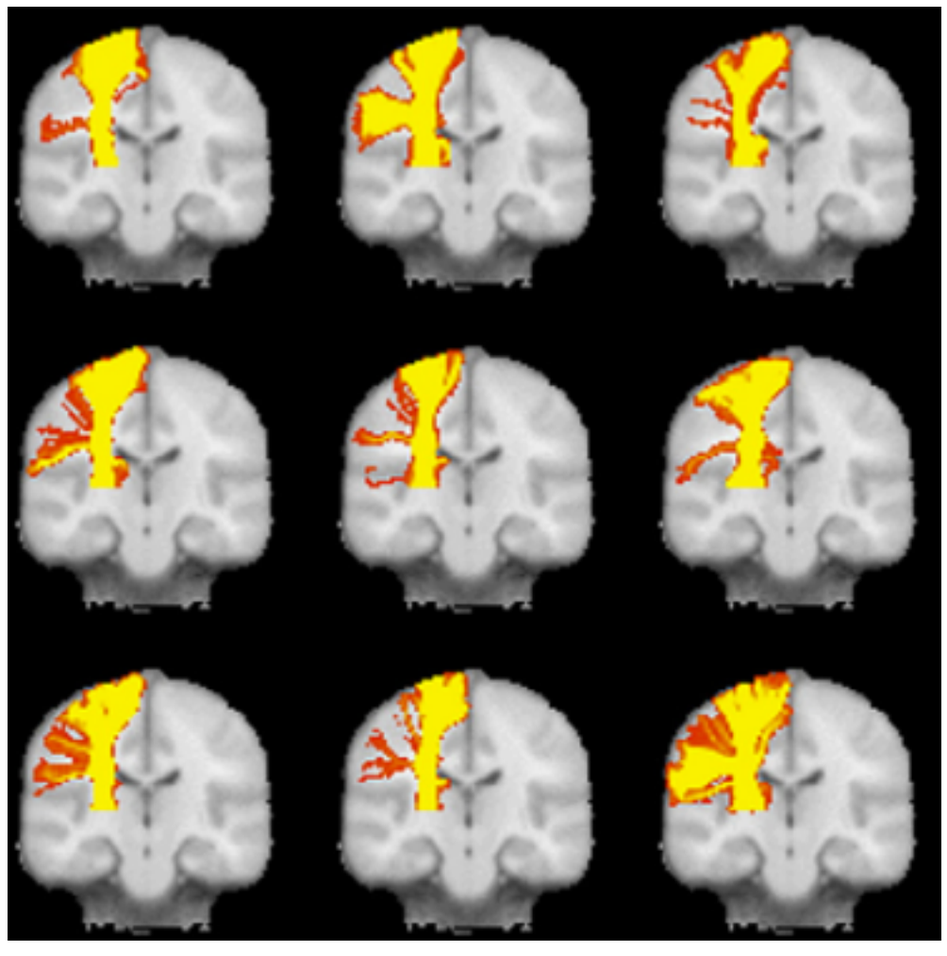


Lazar M et al. White matter tractography using diffusion tensor deflection. Human brain mapping 18(4) 306-321. 2003



(a)

Behrens TE et al. Probabilistic diffusion tractography with multiple fibre orientations: What can we gain? Neuroimage 34(1):144–55. 2007.



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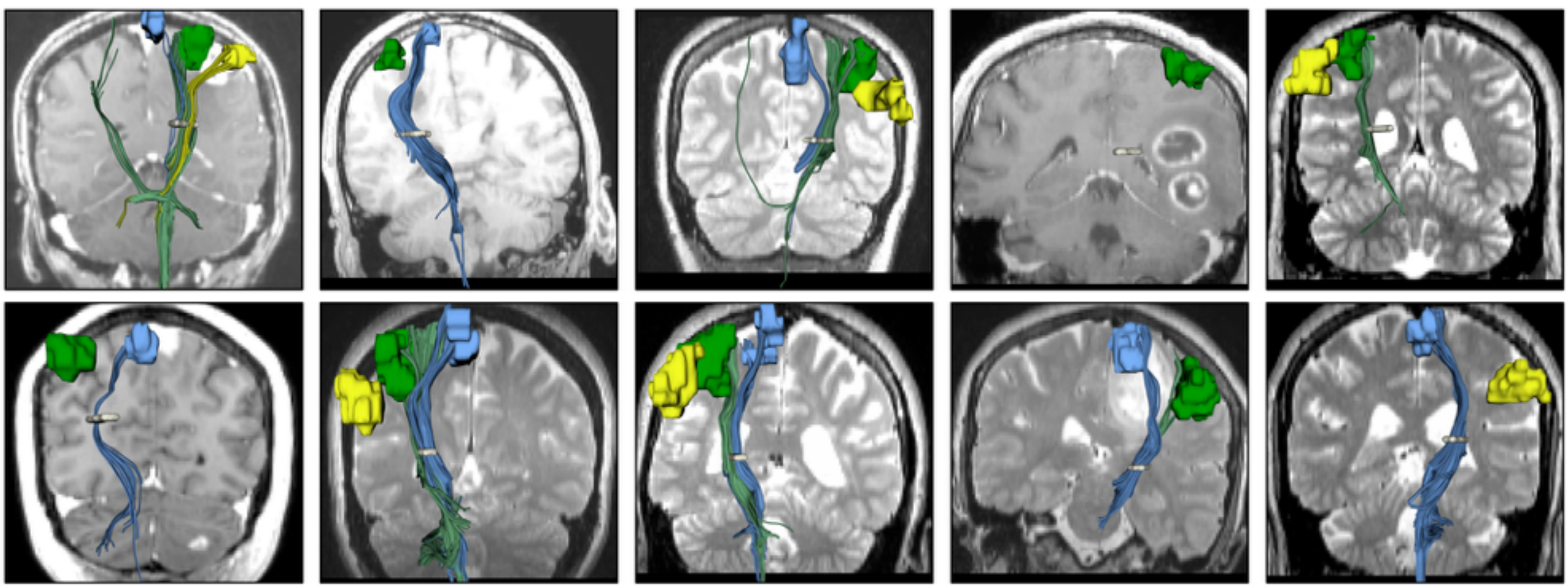
Clinical: 1 tensor



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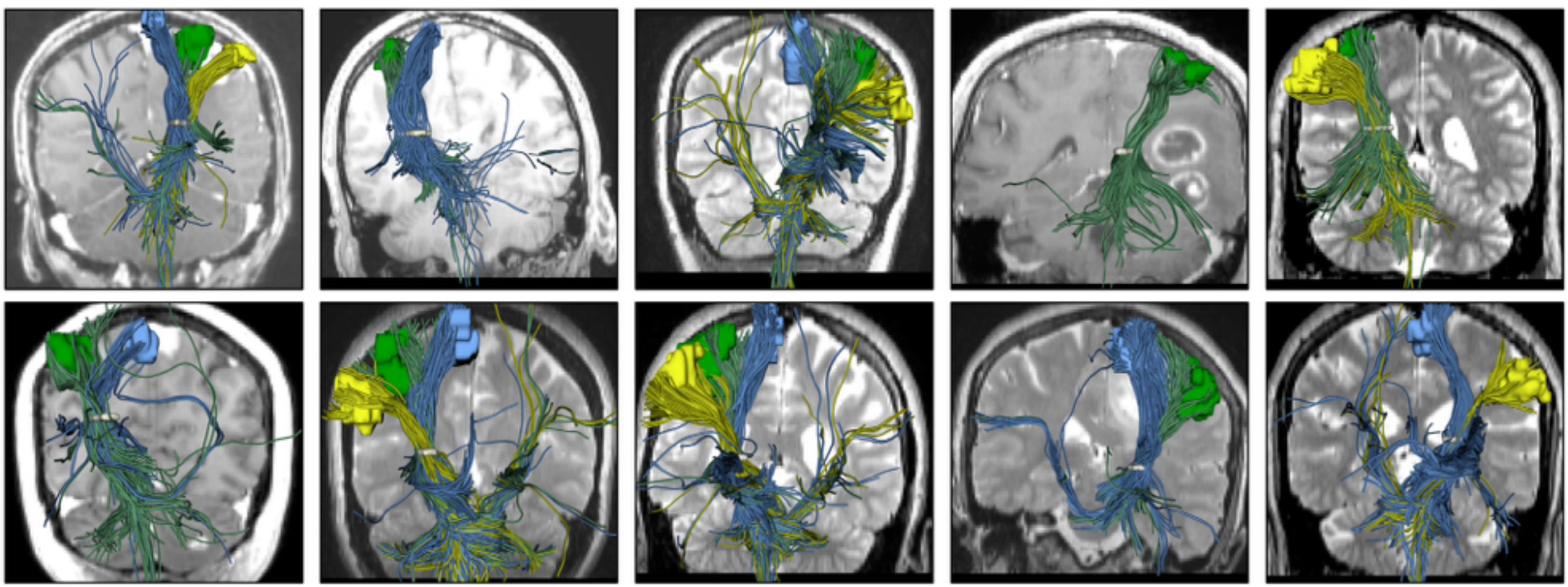
Clinical: 2 tensor



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Prospective Study: Success

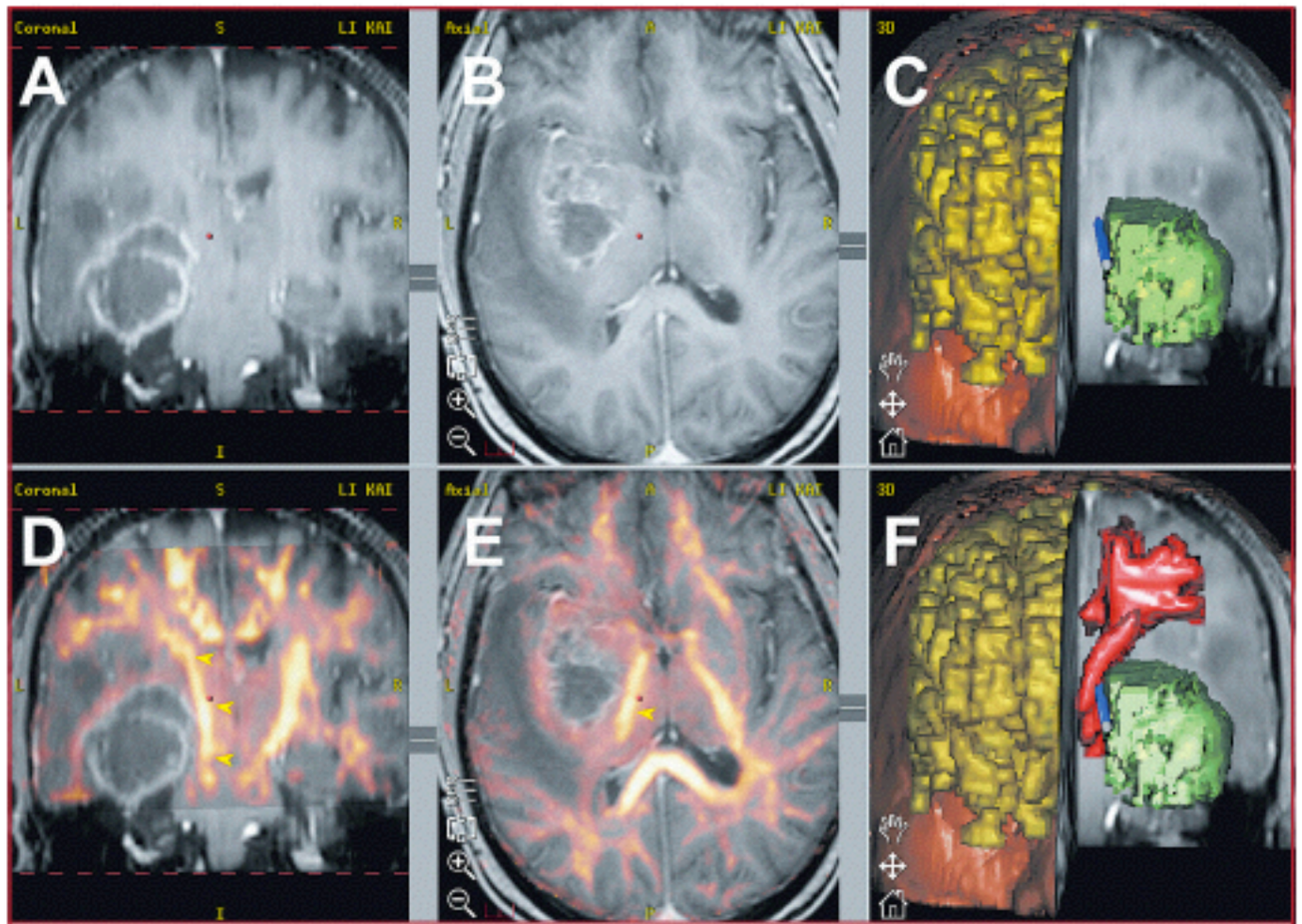


FIGURE 1. *MRI scans from a 63-year-old man with a left deep-seated temporal glioblastoma multiforme (WHO Grade IV).* **A**, *coronal T1-weighted enhanced MRI scan (3-D fast spoiled gradient recalled);* **B**, *axial T1-weighted enhanced MRI scan (3-D fast spoiled gradient recalled);* **C**, *segmentation and 3-D reconstruction of the scalp (brown), cortex (yellow), and tumor (green). In the routine neuronavigational images (***A–C***), no PT was visible.* **D** *and* **E**, *corresponding FA maps were merged into images* **A** *and* **B**. *PT was displayed clearly in heat pseudocolor mode depicting the relationship between tumor and neighboring inward shifting PT (yellow arrows) distinctively;* **F**, *additional manual segmentation and 3-D reconstruction of PT (red) were performed for optimal visualization.*

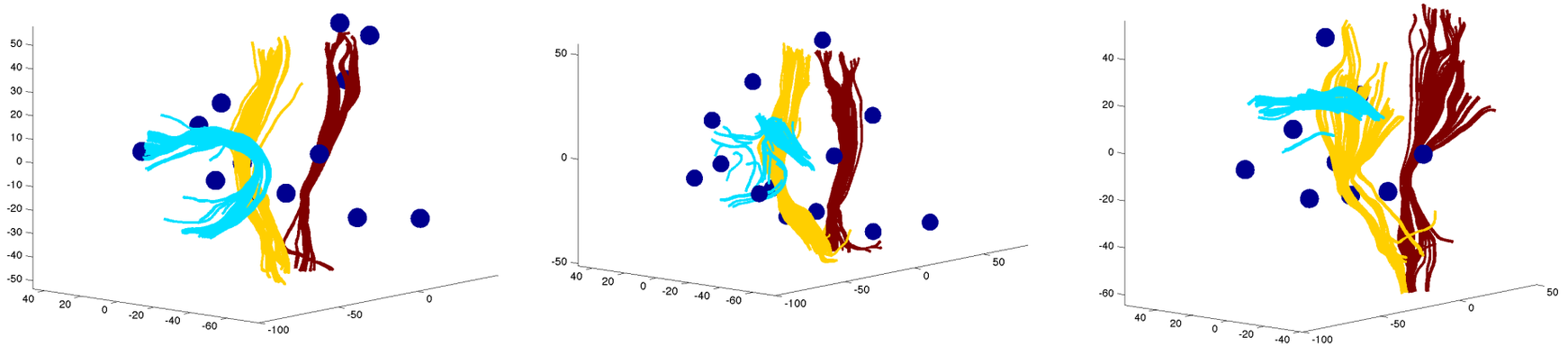
Wu, J., Zhou, L., Tang, W., Mao, Y., Hu, J., Song, Y., Hong, X., and Du, G. (2007). Clinical evaluation and follow- up outcome of diffusion tensor imaging-based functional neuronavigation: a prospective, controlled study in patients with gliomas involving pyramidal tracts. Neurosurgery, 61(5):935

- 238 patients:118 DTI, 120 control
- median survival 21 vs 14 months
- not all had tractography: expert segmentation

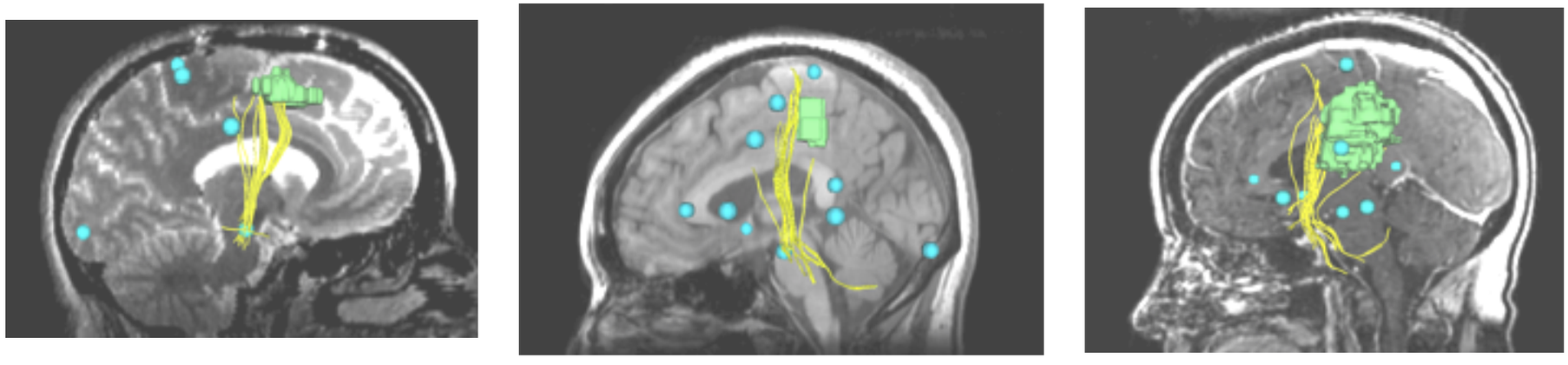
Current Research

- Building models to help identify crucial fiber tracts in neurosurgical patients
- Using fMRI and dMRI information
- Goal: detect tracts and give additional information
- Is tract "normal"? Displaced? Working?

Using model to detect fibers in patients with lesions



Tumor in RHem | Edema near AF | Tumor near AF



LJ O'Donnell et al. fMRI-DTI modeling via landmark distance atlases for prediction and detection of fiber tracts. NeuroImage 60 (1), 456-70. 2012

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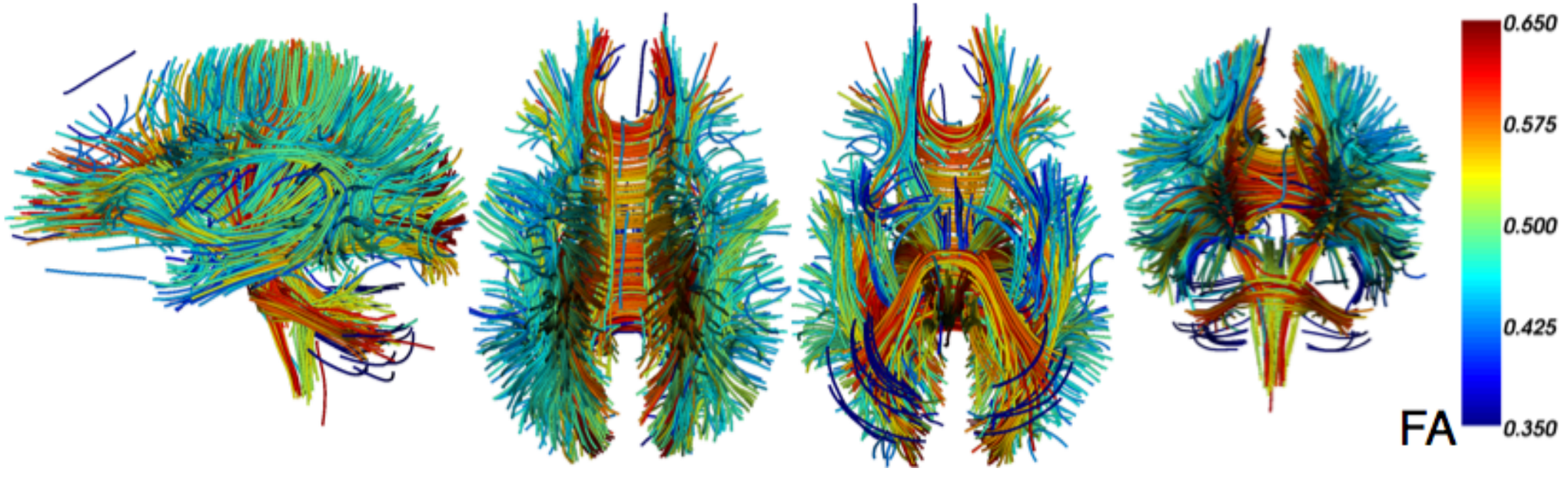
Registration using Tractography

- Unbiased group fiber tract registration method
- Atlas model: probability density over fiber tracts



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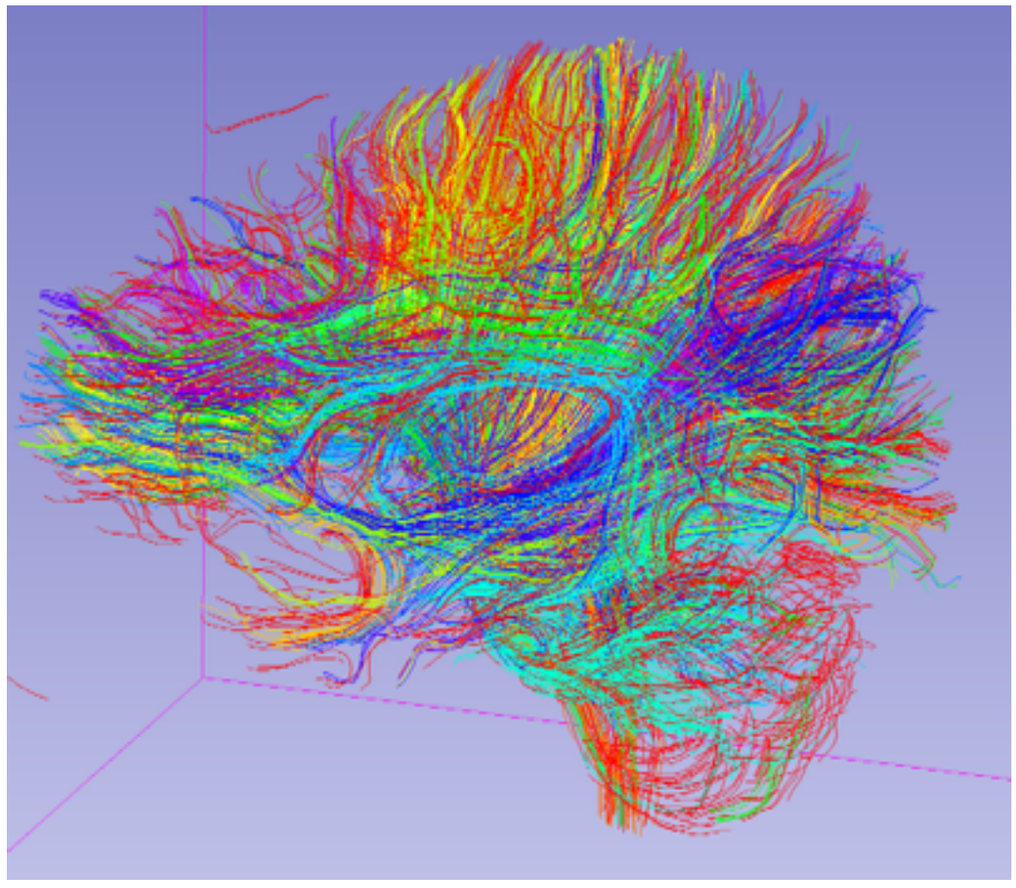
Software

- Clustering and atlas labeling of fiber tracts
- Python package



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Automatic tractography segmentation using a high-dimensional white matter atlas
LJ O'Donnell, CF Westin
Medical Imaging, IEEE Transactions on 26 (11), 1562-1575. 2007

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Thank You!

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