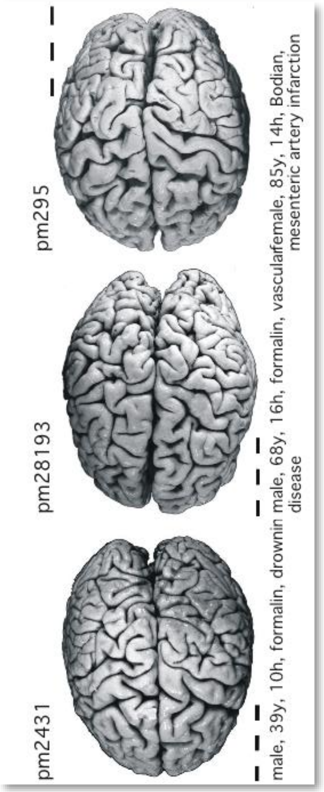
Pushing Global Brain Tractography towards Micrometer Resolution with Exascale Computing

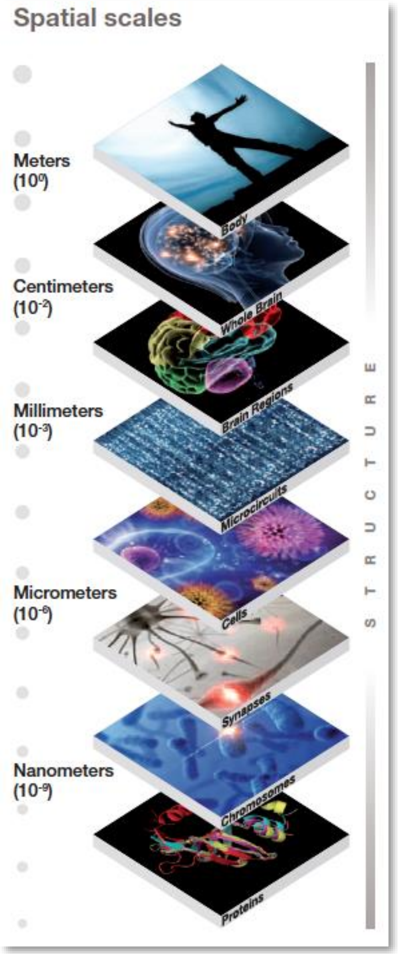
21.09.22 I Felix Matuschke I Institute of Neuroscience and Medicine (INM-1)

AI Data Analytics and Scalable Simulations

JÜLICH Forschungszentrum

The Human Brain





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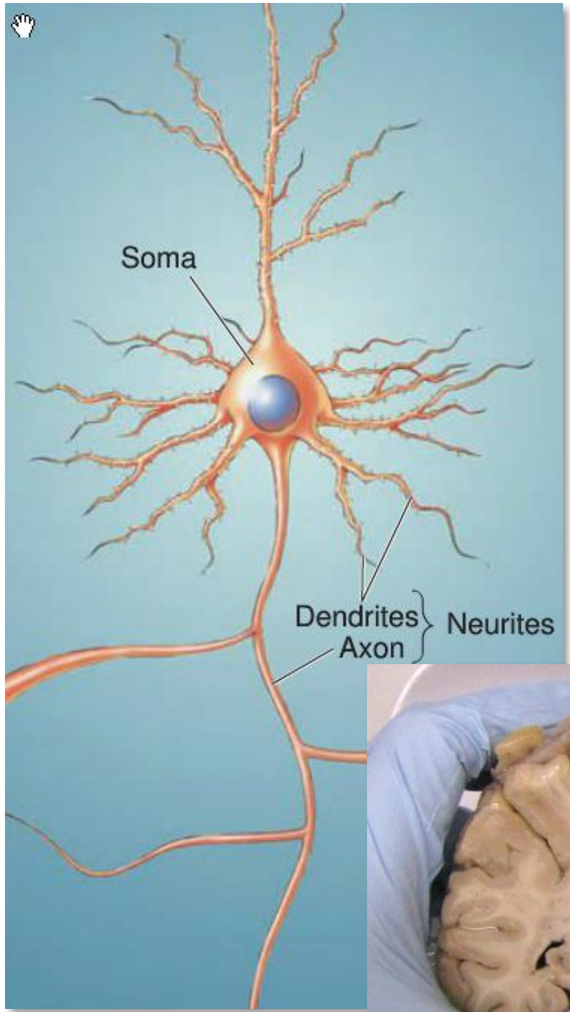
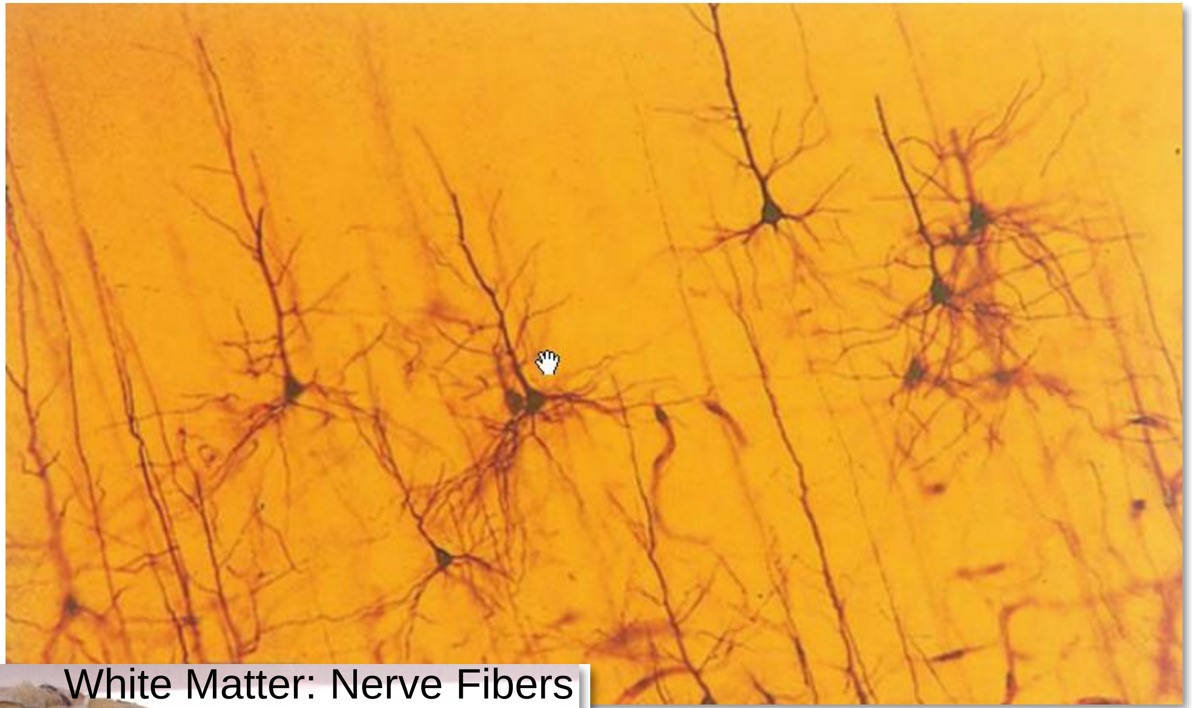
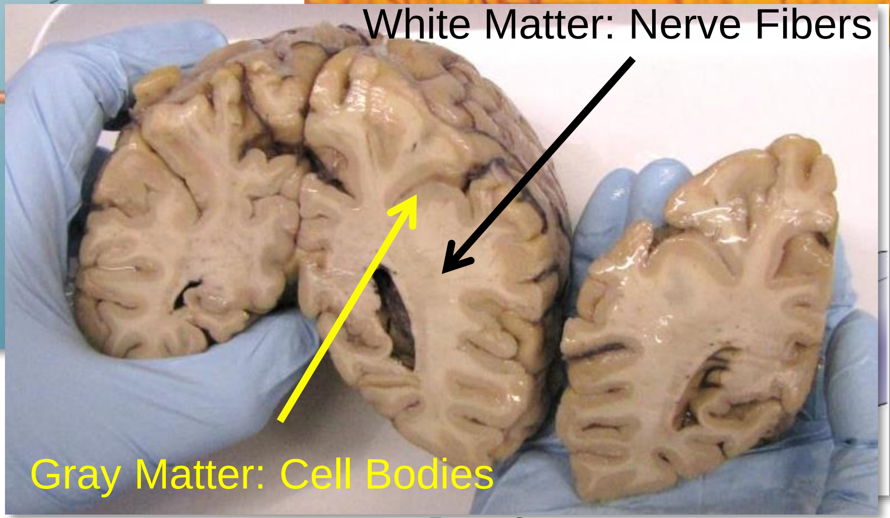






Length Nerve Fibers: µm – m

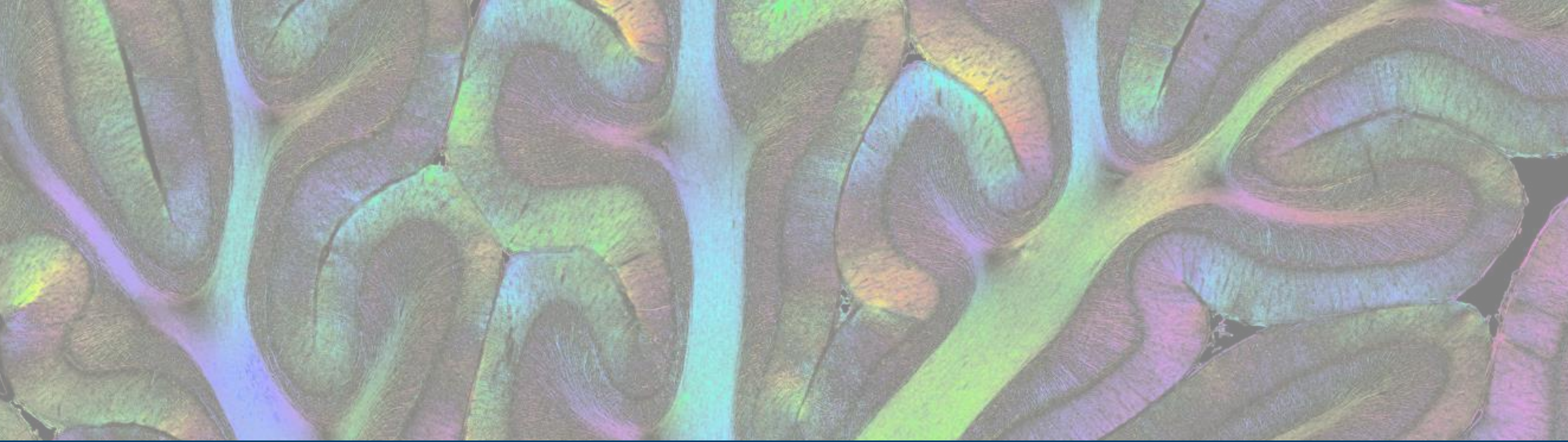
Ø Nerve Fibers: 1 – 20 µm

Ø Single Hair: 50 – 70 µm

100 Mrd. Neuronen

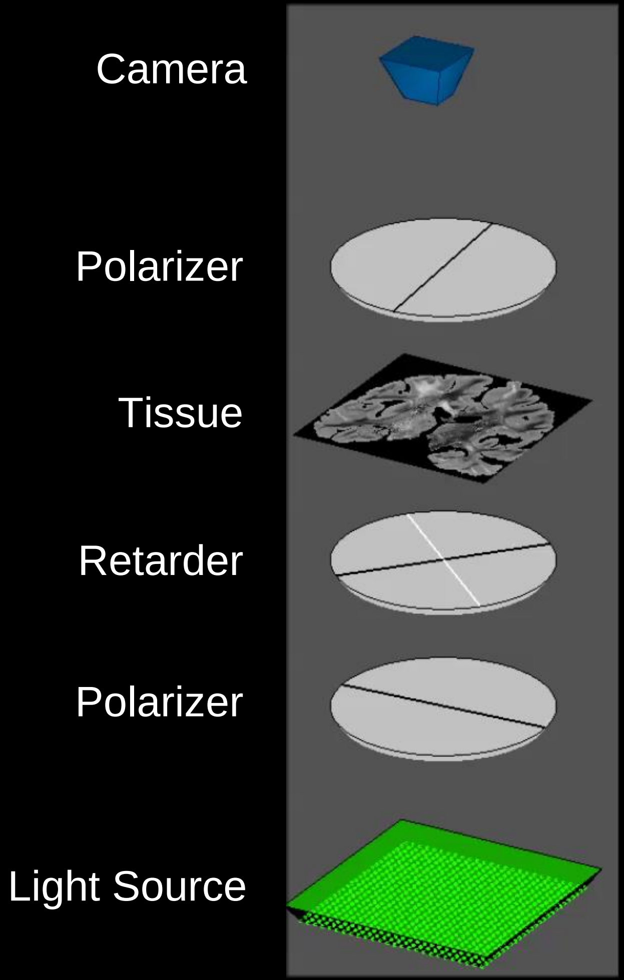
10.000 Synapsen pro Neuron

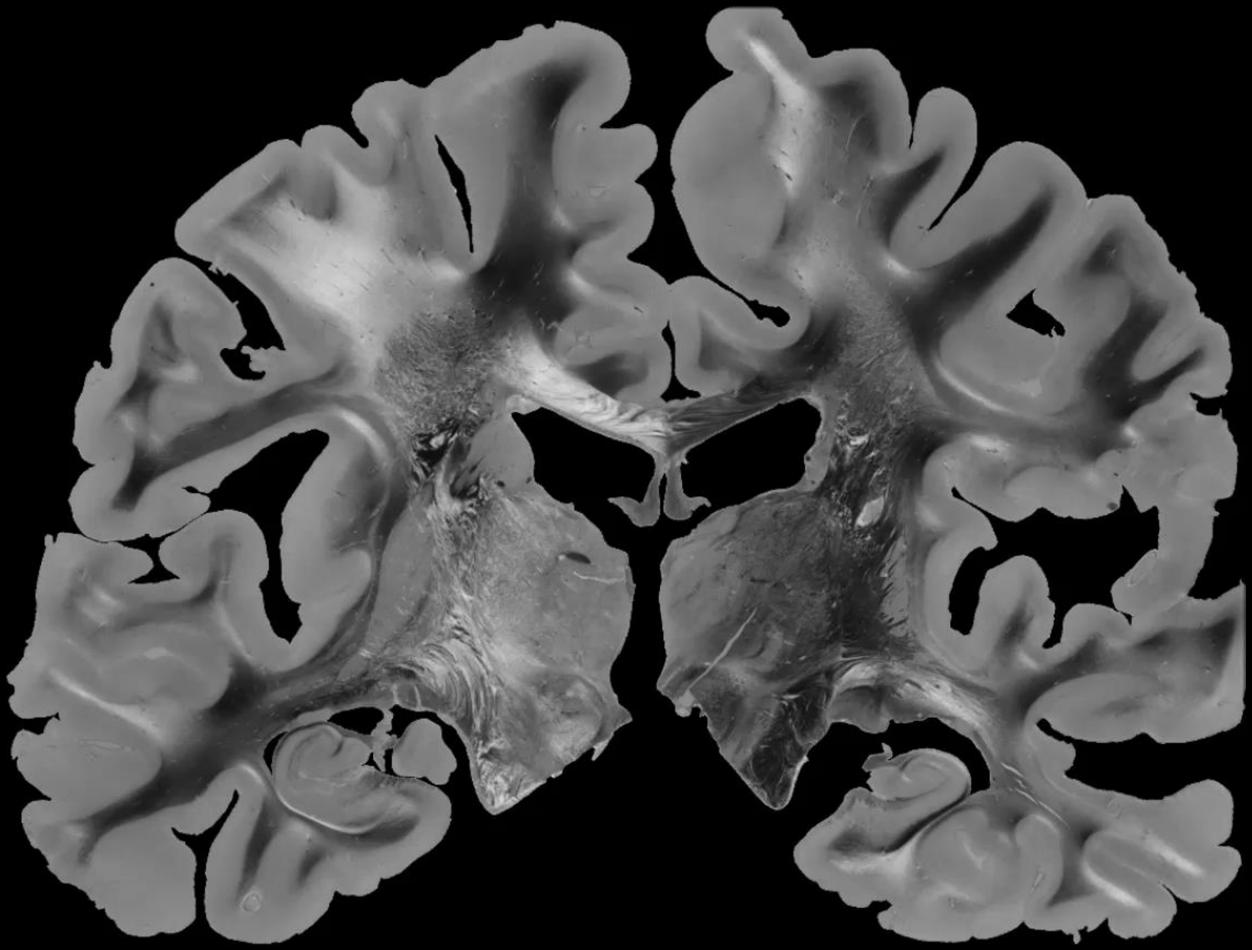
Quelle: Neuroscience: Exploring the brain, Bear, Wolters Kluver Verlag (2015)



3D – POLARIZED LIGHT IMAGING

3D - Polarized Light Imaging





INM-1 | Fiberarchitecture Group

3D - Polarized Light Imaging

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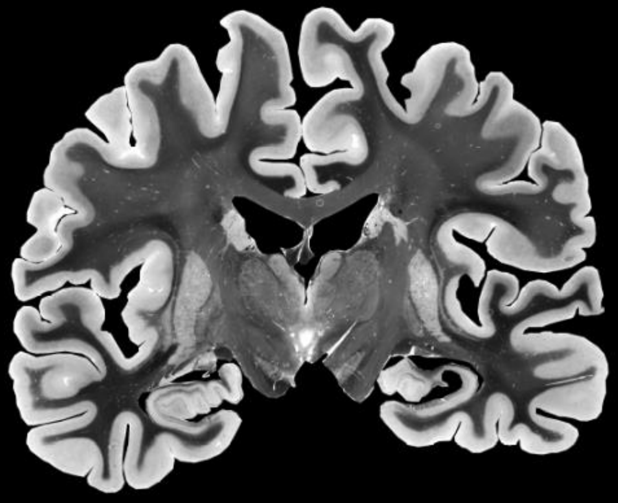
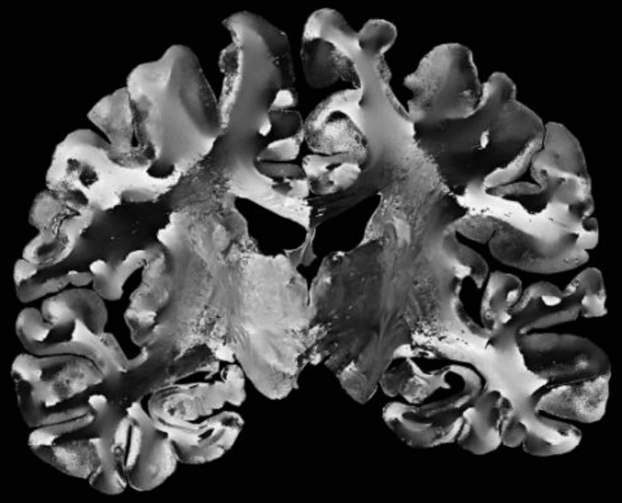
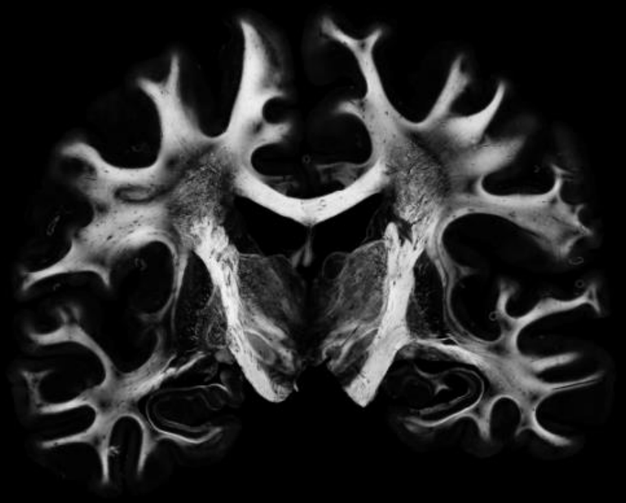


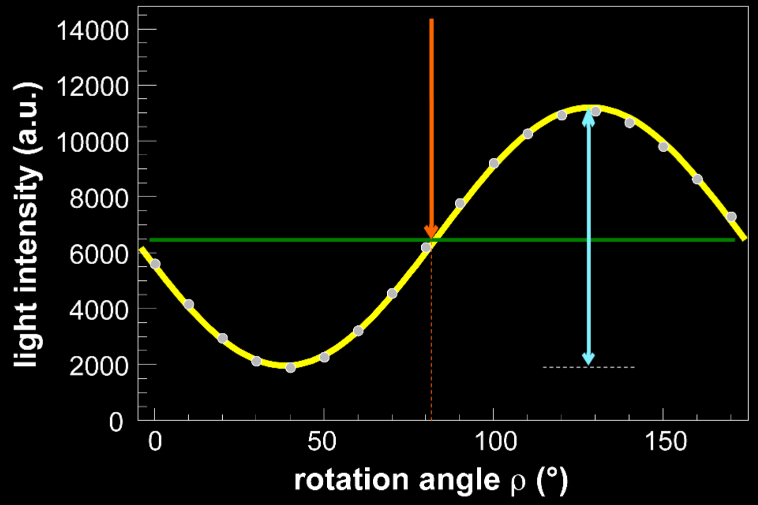
Transmittance



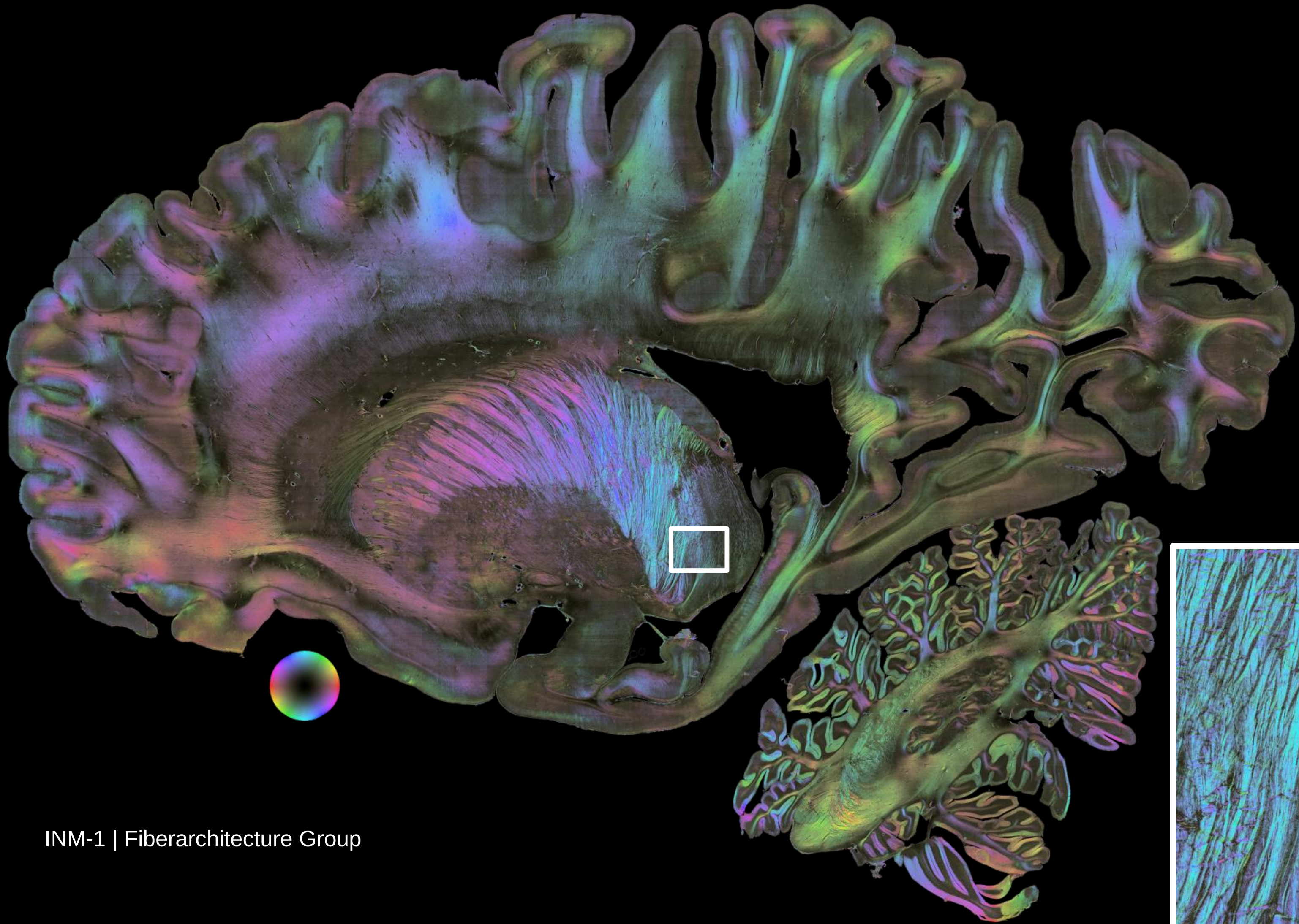
Direction

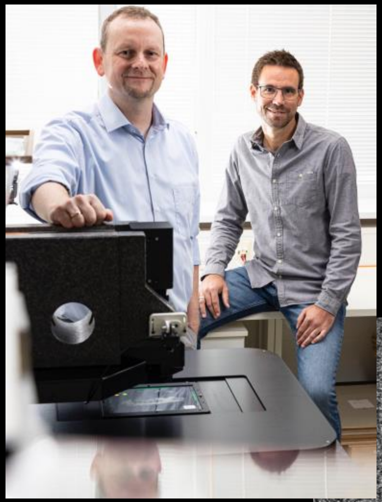


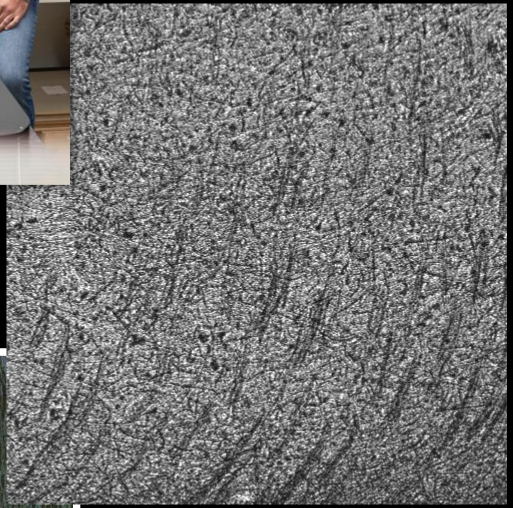
Retardation

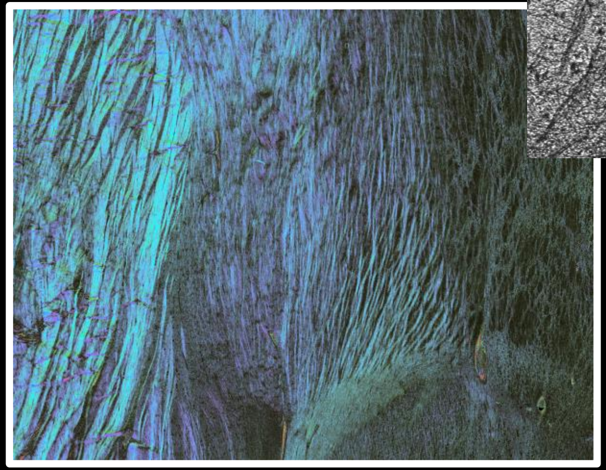


3D - Polarized Light Imaging









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3D-PLI - Volume Reconstruction

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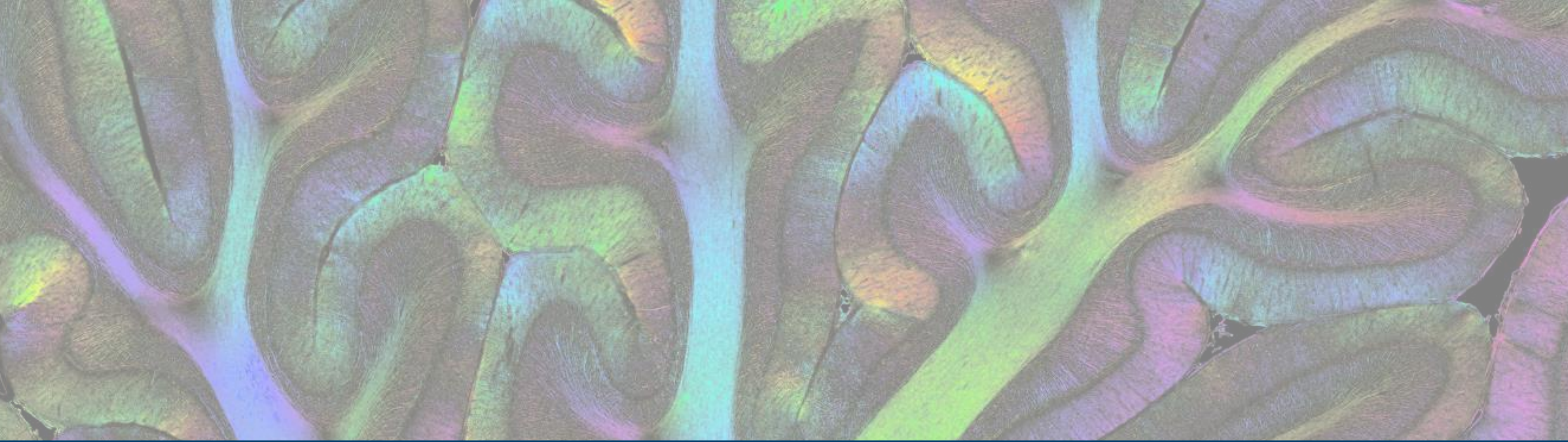
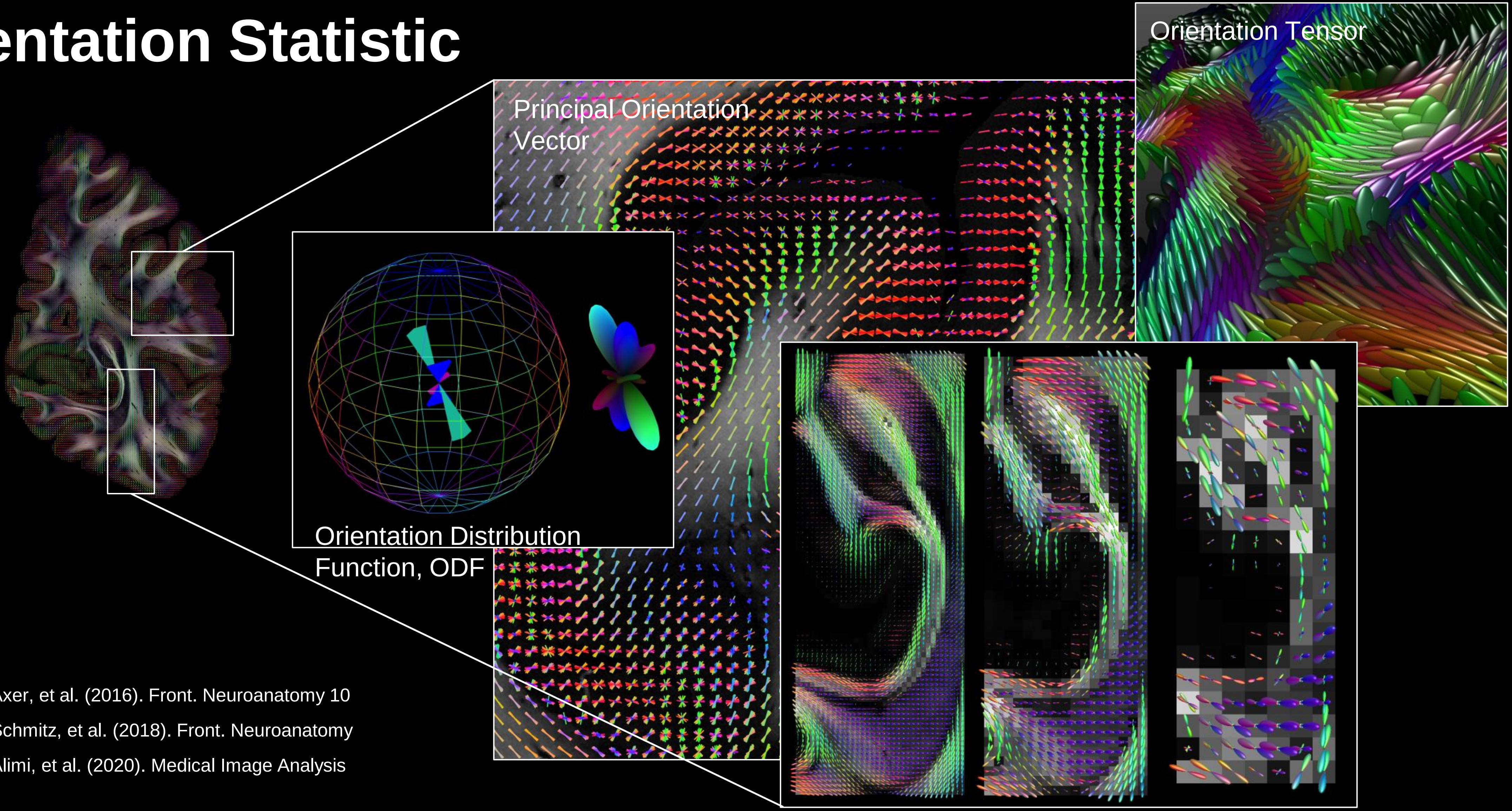


TRACTOGRAPHY

Data Preparation

Orientation Statistic



Axer, et al. (2016). Front. Neuroanatomy 10

Schmitz, et al. (2018). Front. Neuroanatomy

Alimi, et al. (2020). Medical Image Analysis

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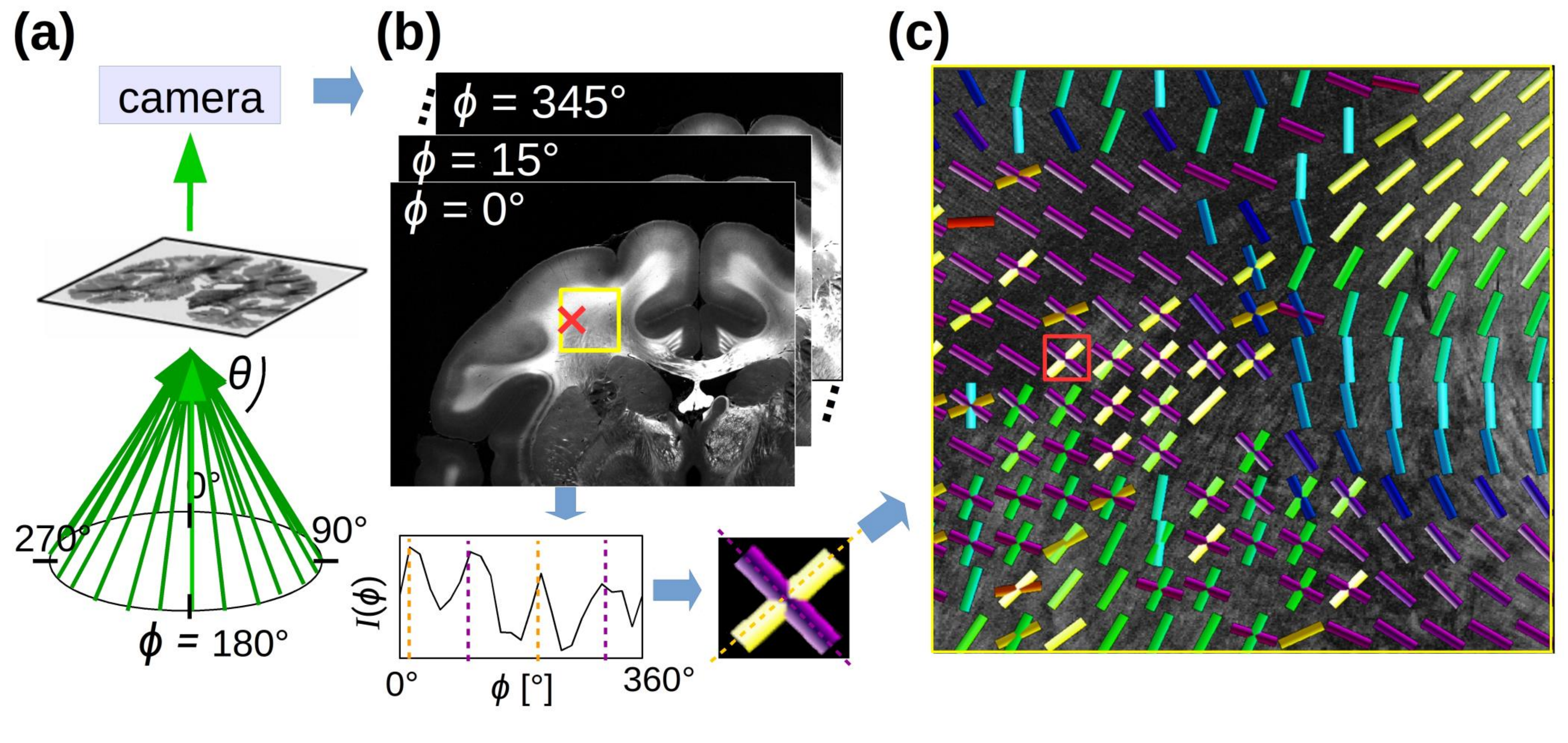
Orientation Statistic

Scattered Light Imaging



Menzel et al. NeuroImage (2021)

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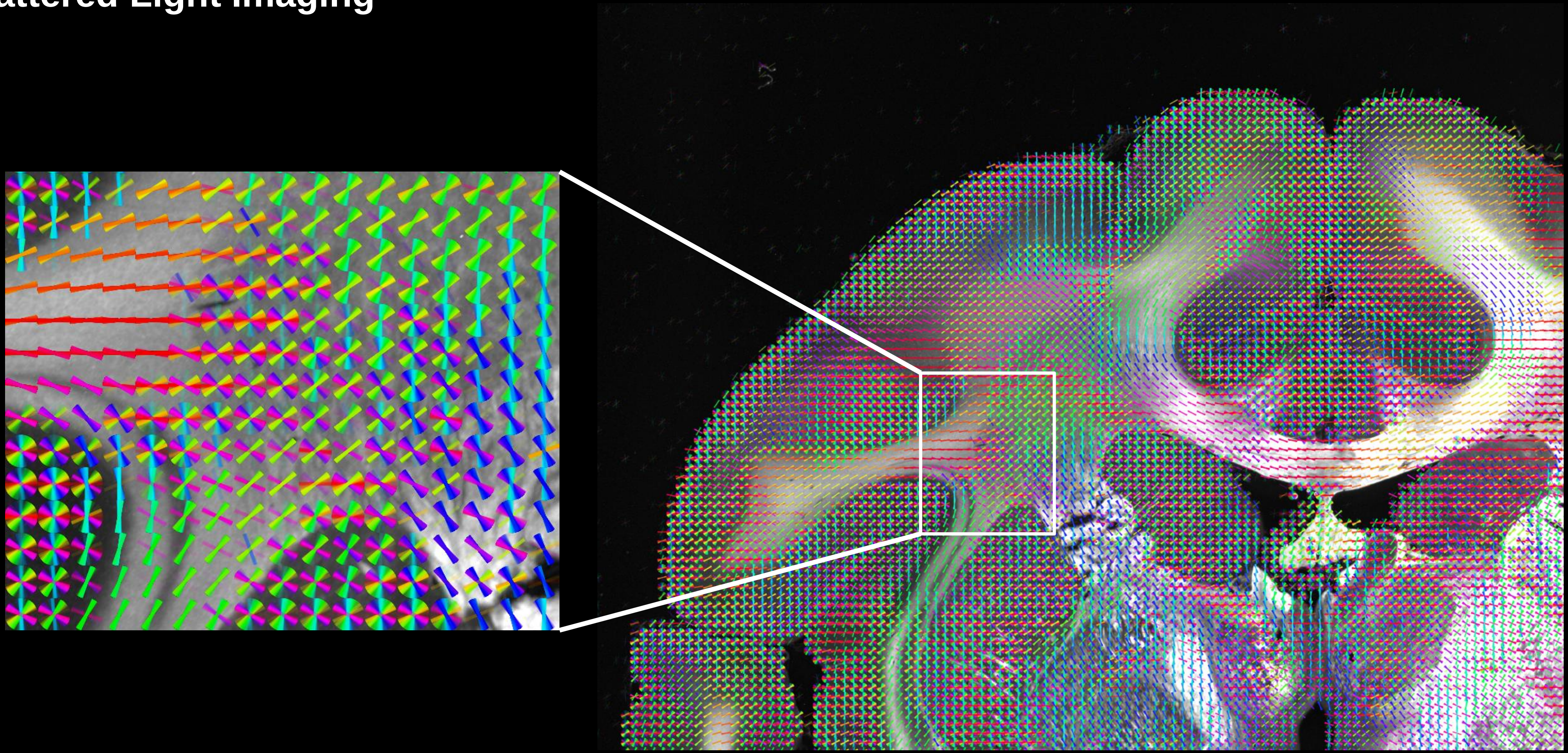
Orientation Statistic

Scattered Light Imaging



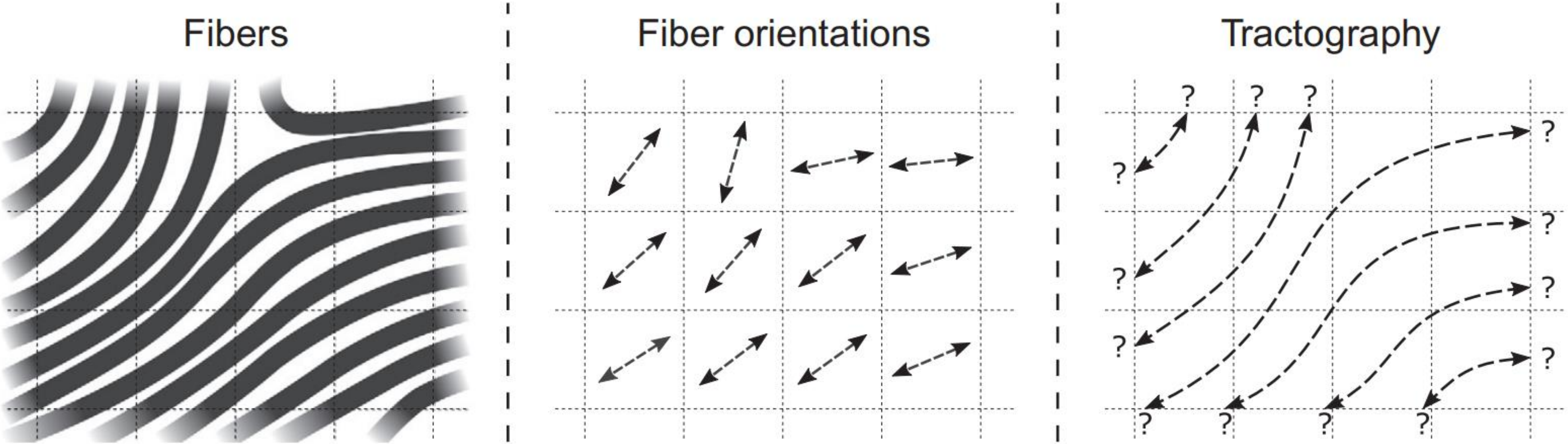
Jan Reuter & Miriam Menzel

TRACTOGRAPHY

The Basics

Tractography

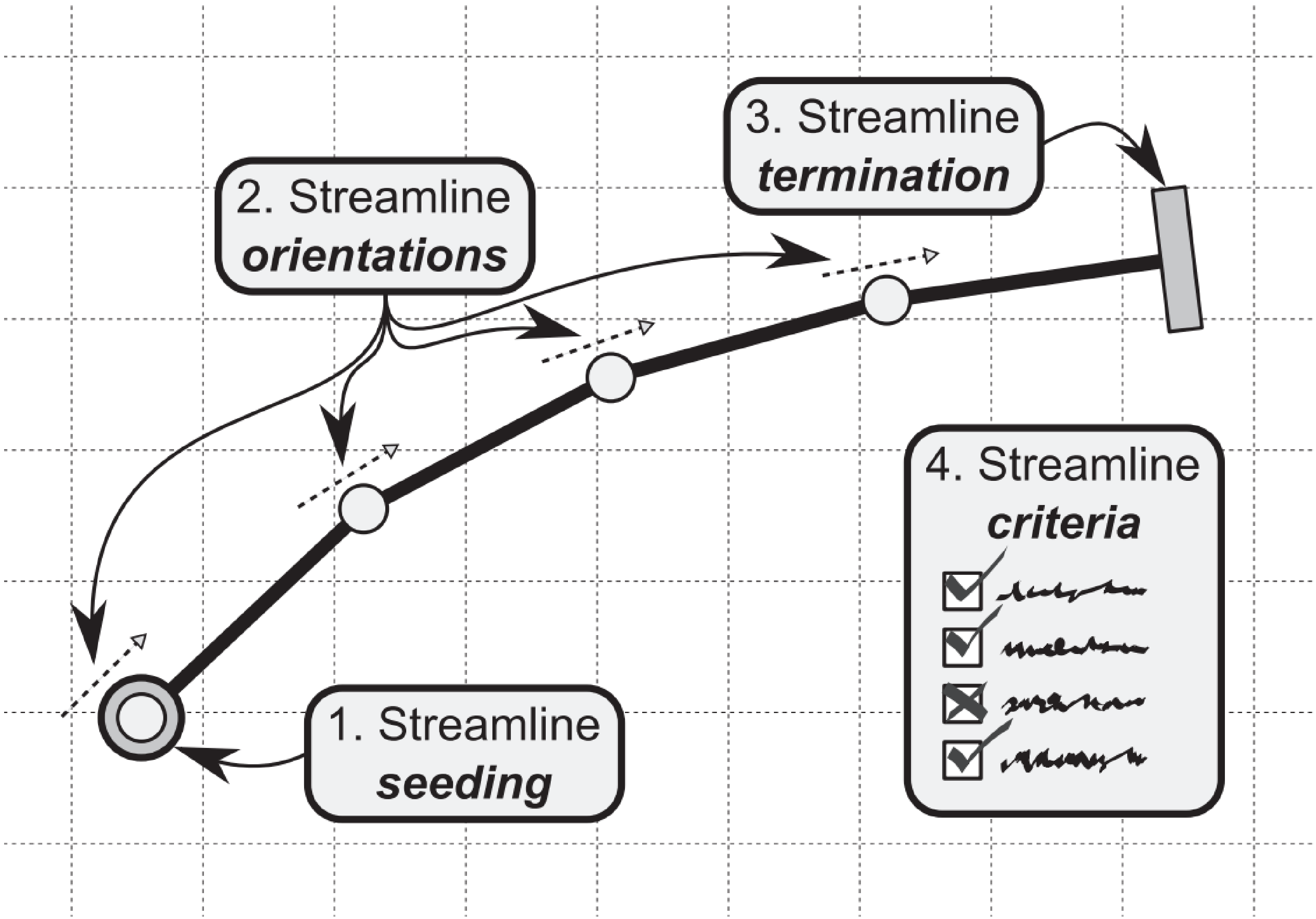
Basics



Smith et.al. - Diffusion MRI
Fiber Tractography - 2020

Tractography

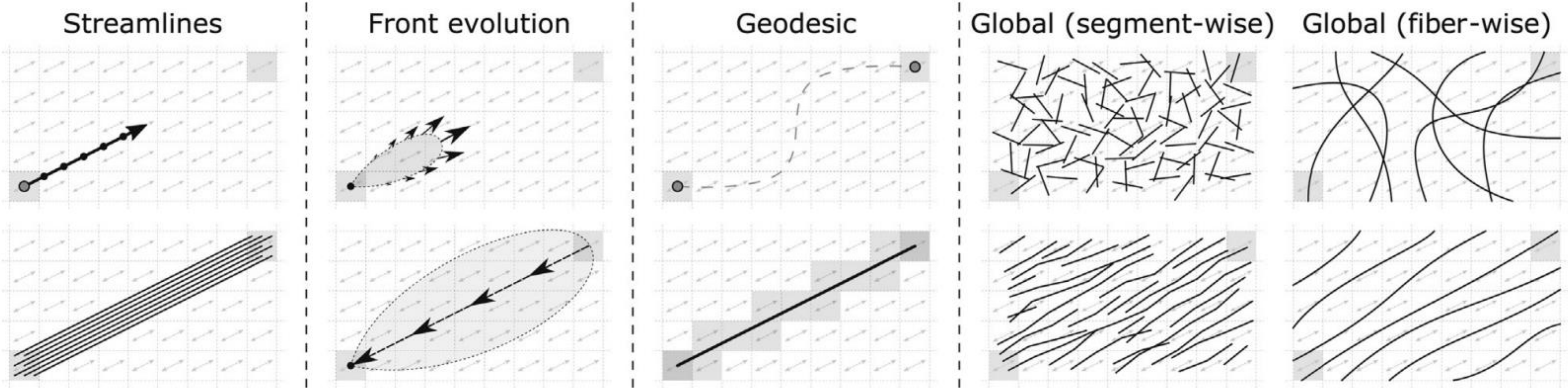
Basics



Smith et.al. - Diffusion MRI Fiber Tractography - 2020

Tractography

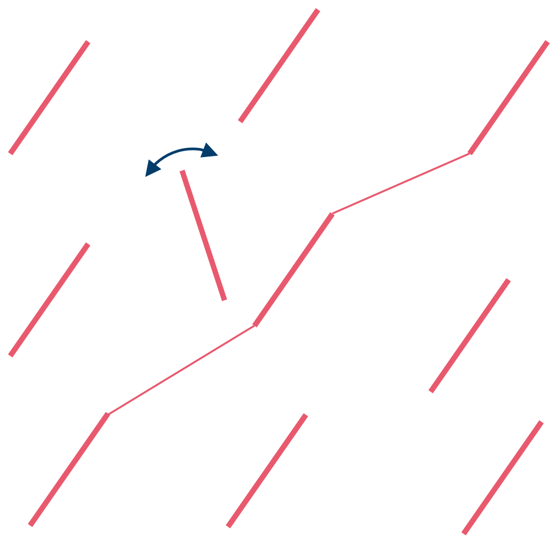
Basics



Smith et.al. - Diffusion MRI
Fiber Tractography - 2020

Global Tractography

From Particles to Fibers



Markov Random Strategy:

- Pick random Spins
- Sample a random orientation according to the data
- Randomly move Spin
- Check if connection is reasonable

Global Tractography

From Particles to Fibers

Markov Random Strategy:

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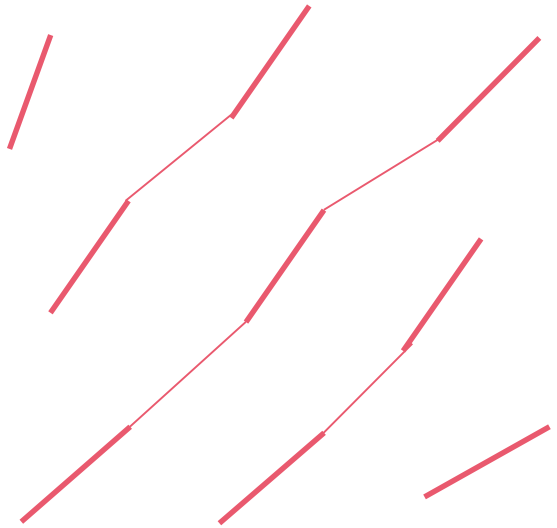
NeuroSpin AIDAS AI Data Analytics and Scalable Simulations JÜLICH Forschungszentrum

Global Tractography

Overcoming the Gab

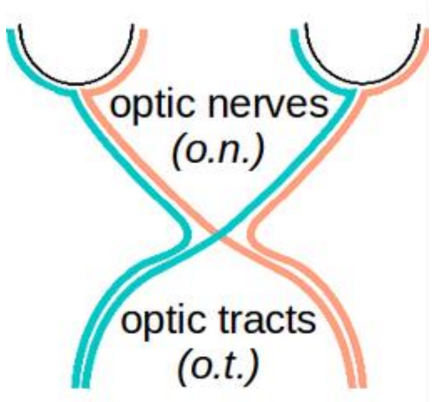


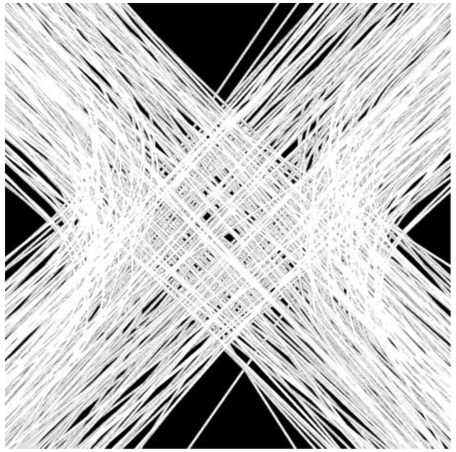
Markov Random Strategy:

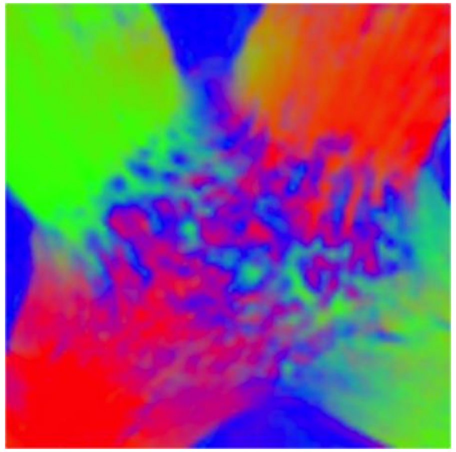
- Pick random Spins
- Sample a random orientation according to the data
- Randomly move Spin
- Check if connection is reasonable
- Fibers are allowed to grow

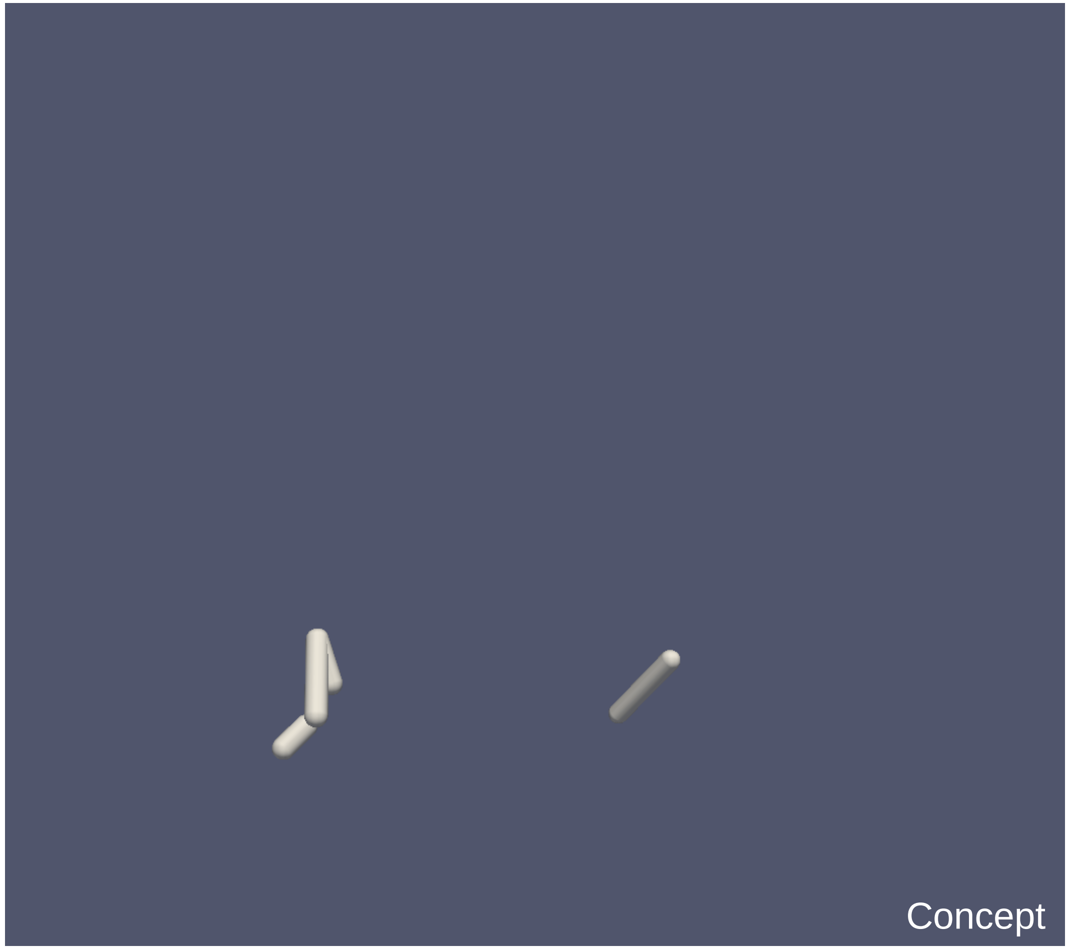
An Example

Optic Chiasm

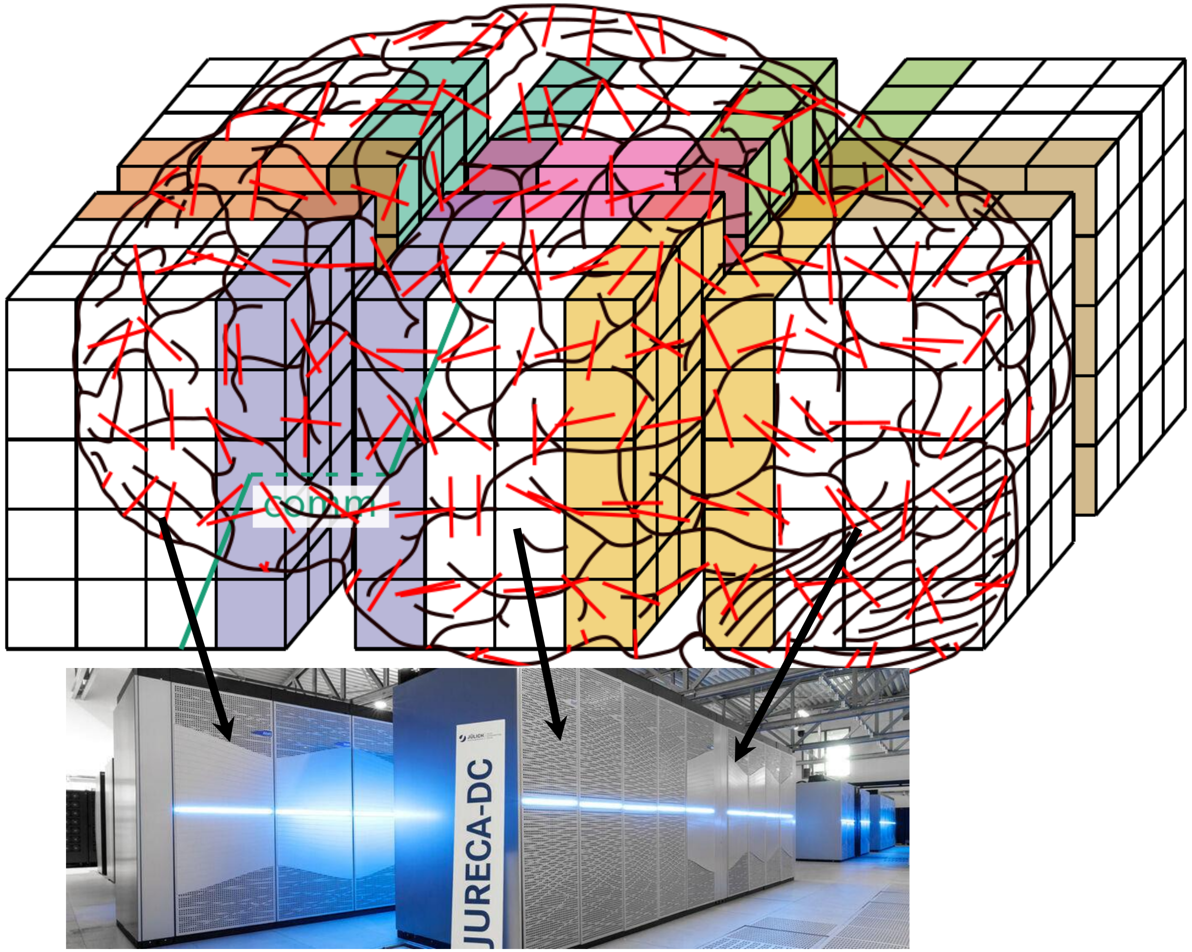


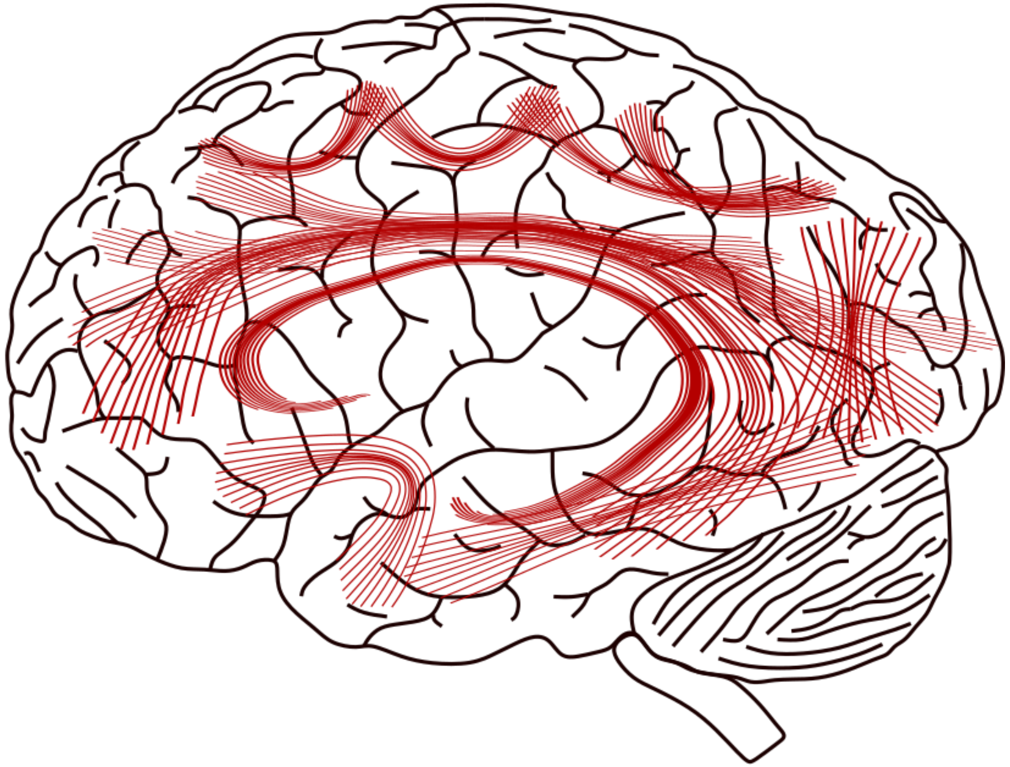


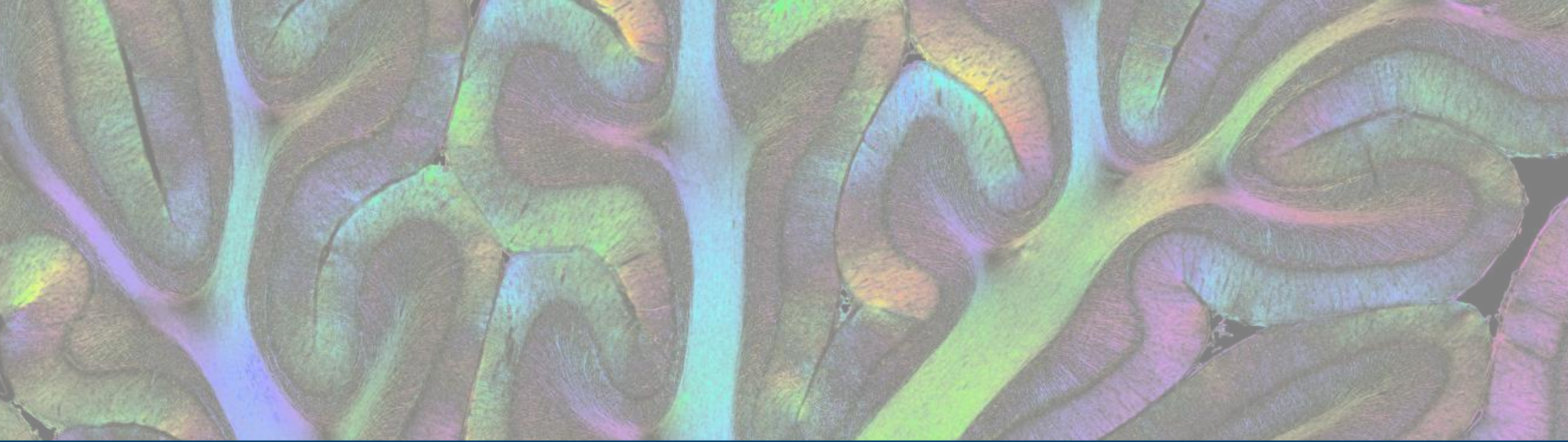




Global Tractography





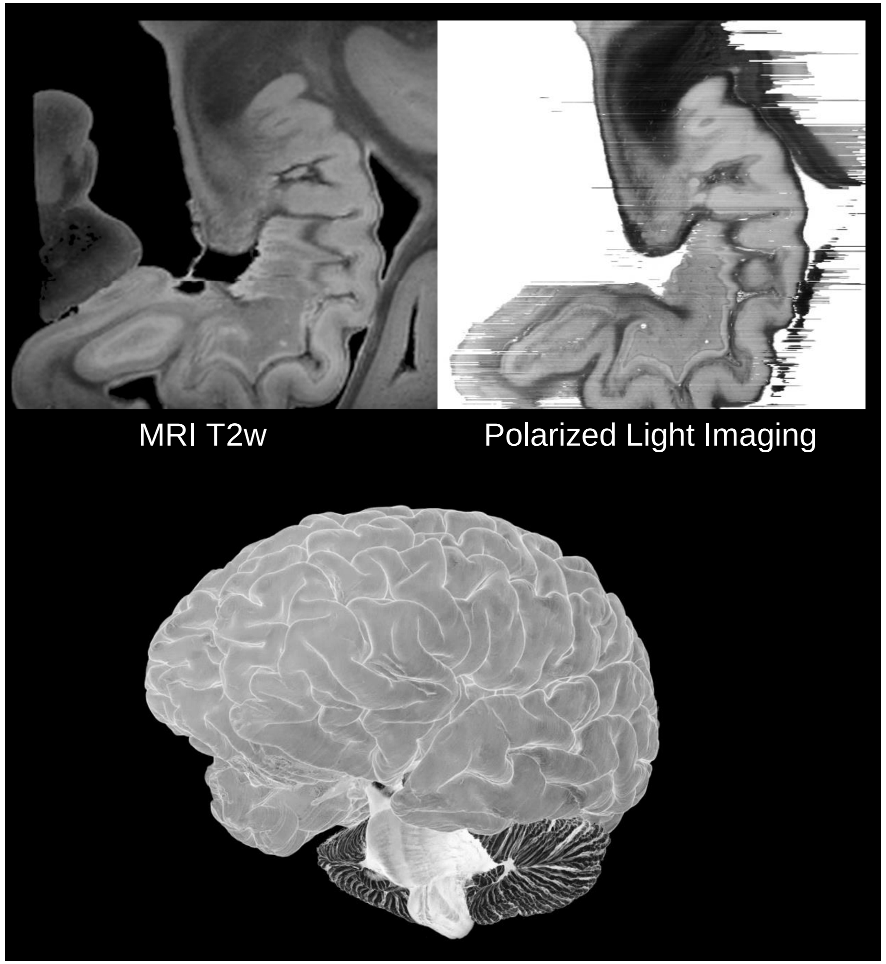


TRACTOGRAPHY

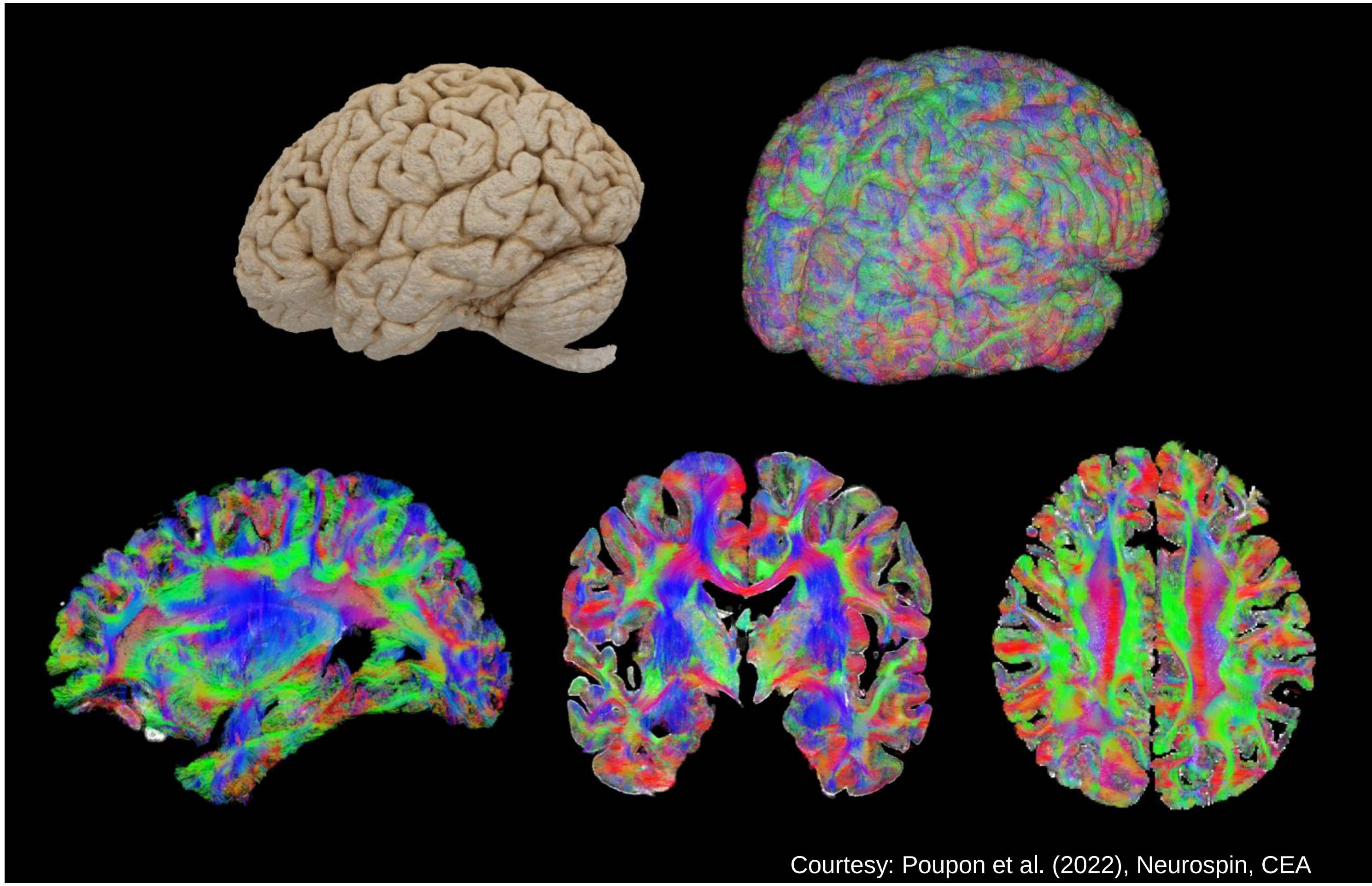
The Human Datasets

Human Datasets

Hippocampus



Whole-brain postmortem diffusion MRI at 200µm resolution



Human Data Sets

Towards a Nerve Fiber Atlas

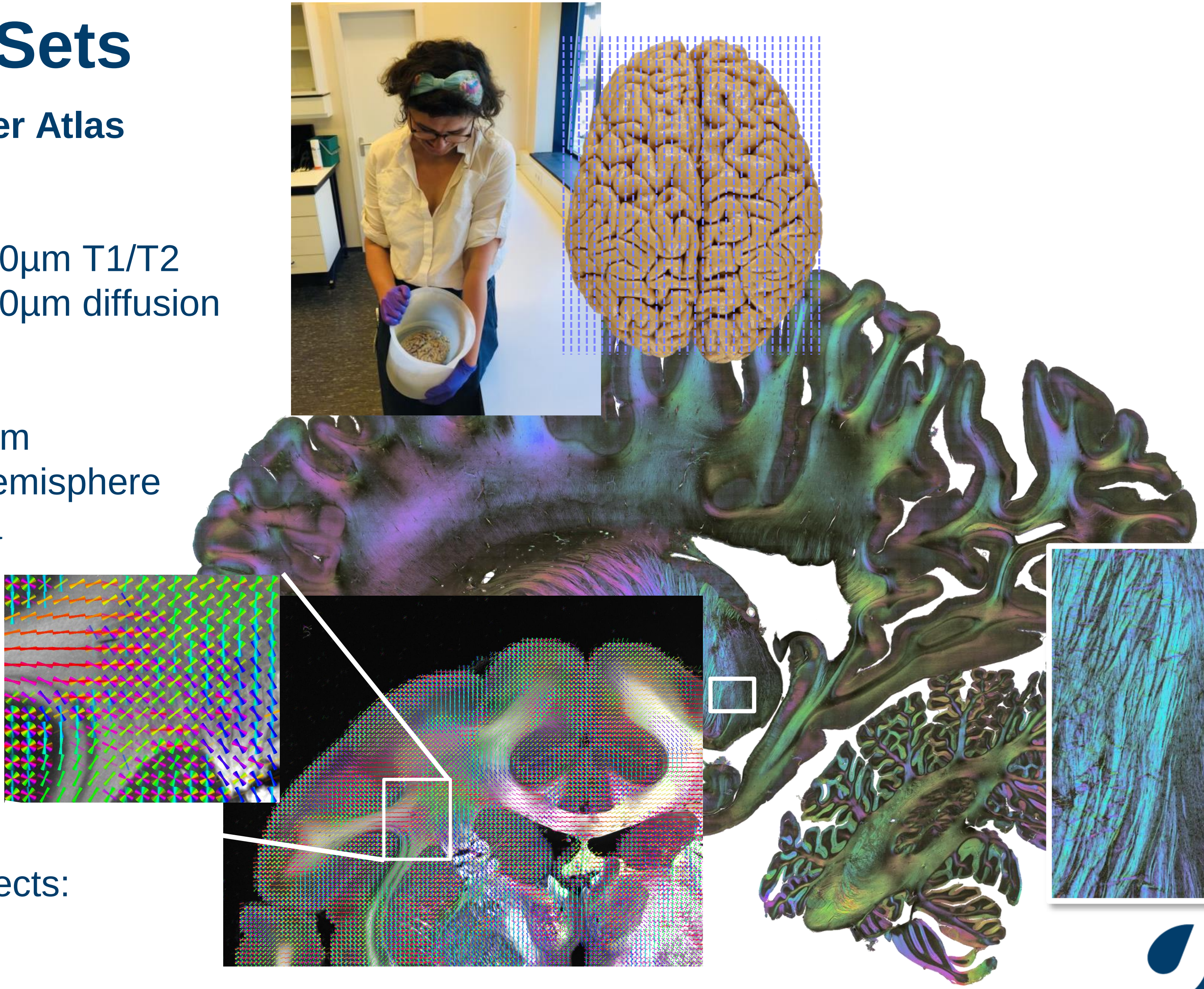
High Resolution dMRI:
- 200µm x 200µm x 200µm T1/T2
- 400µm x 400µm x 400µm diffusion

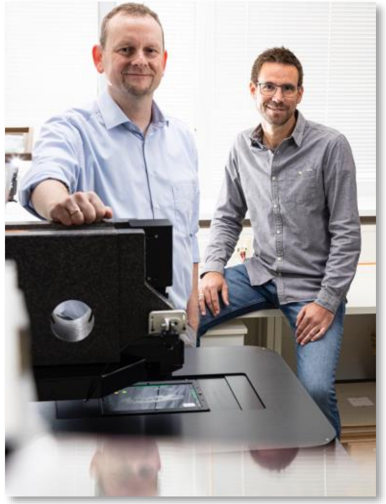
3D-PLI:
- 1.3µm x 1.3µm x 50µm
- ~1.500 section per hemisphere
- ~2 **PBytes** Raw Data

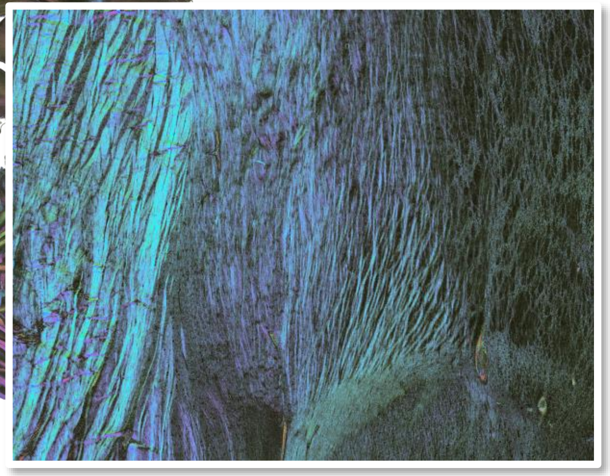
SLI:
- ~10th section

Immunohistochemistry:
- ~10th section

Multimodal Partner Projects:
- …







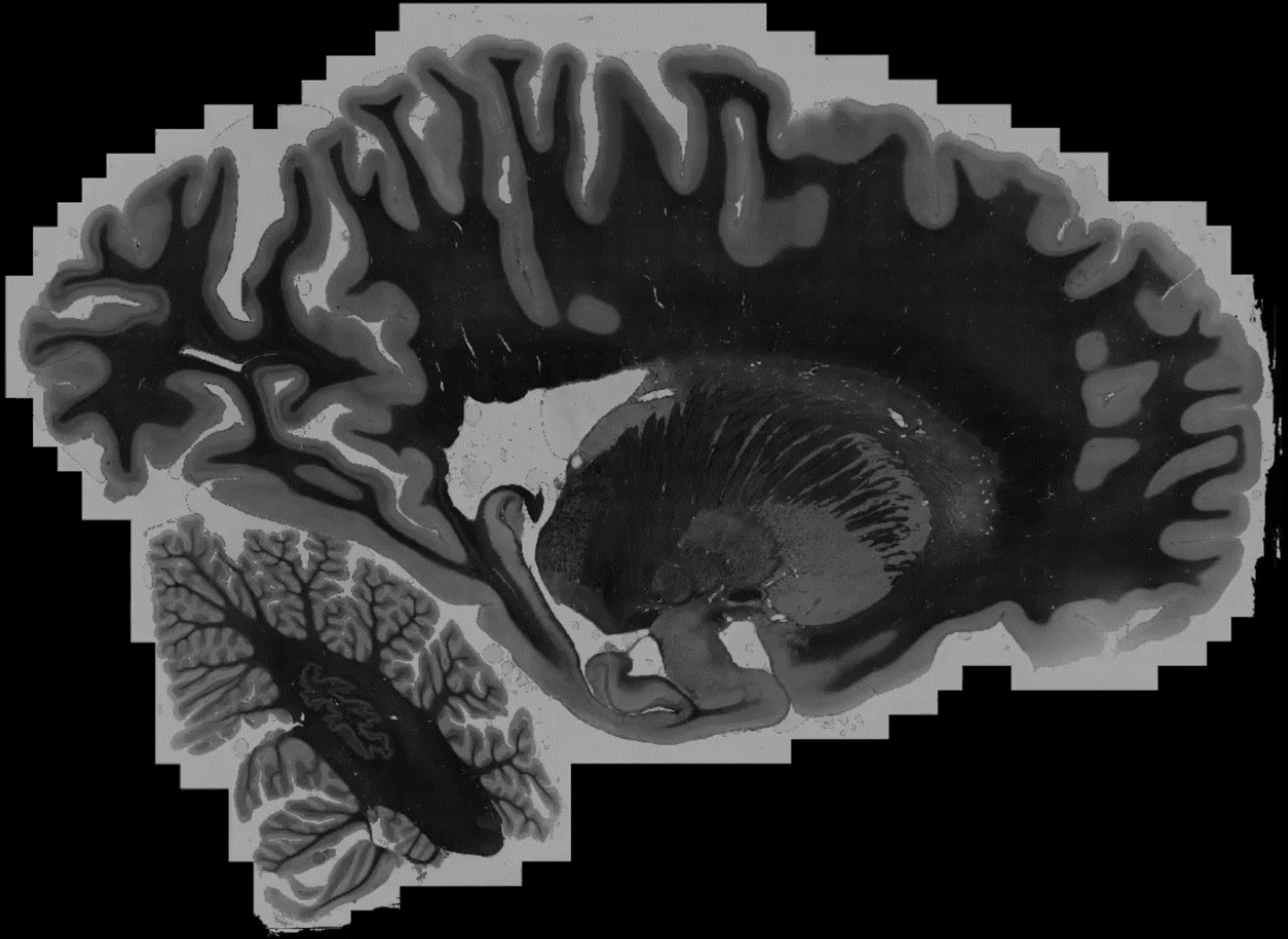
JSC for the rescue

192 accelerated compute nodes:

- 2× AMD EPYC 7742, 2× 64 cores, 2.25 GHz
- 512 (16× 32) GB DDR4, 3200 MHz
- 4× NVIDIA A100 GPU, 4× 40 GB HBM2e
- 2× InfiniBand HDR (NVIDIA Mellanox Connect-X6)

NVIDIA CUDA

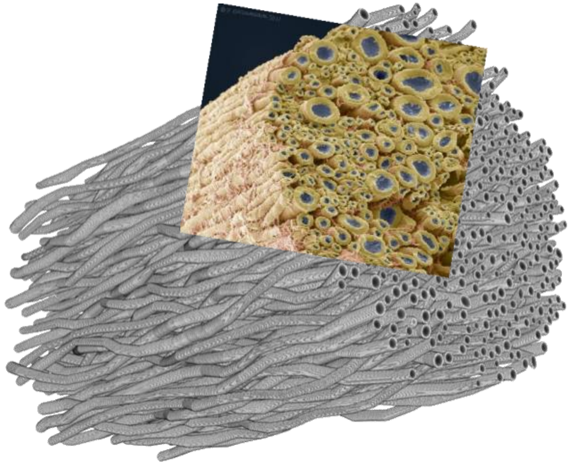
Exciting ♥

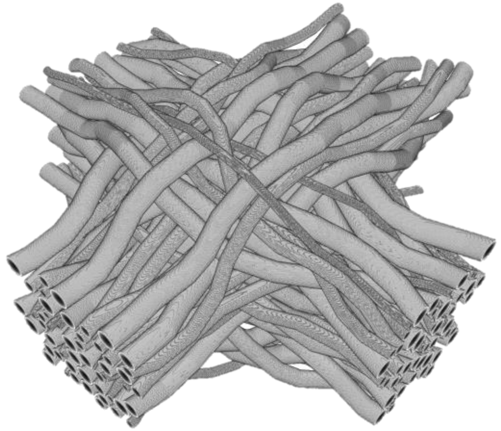


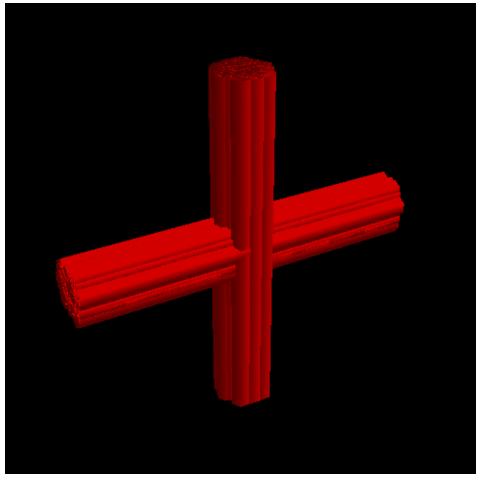
Transmittance

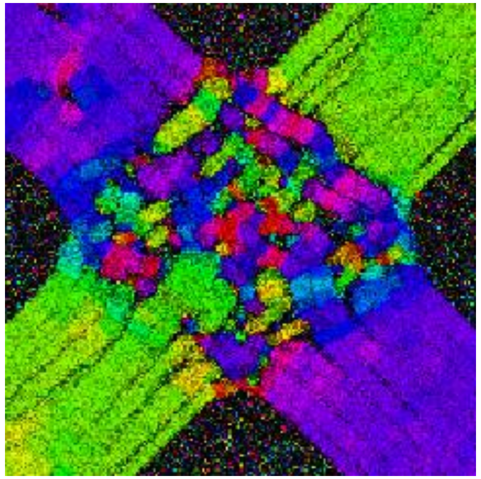
Synthetic Fiber Models

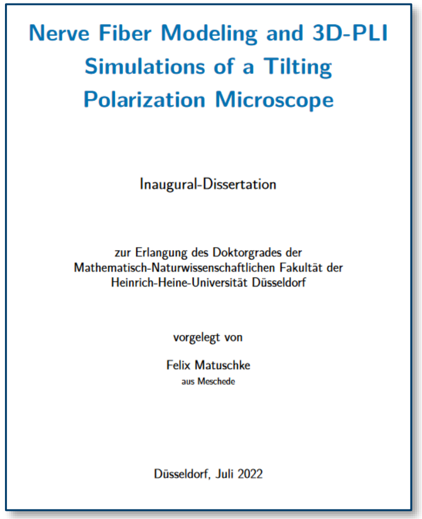
Modeling Collison Free Fiber Models










Nerve Fiber Modeling and 3D-PLI Simulations of a Tilting Polarization Microscope

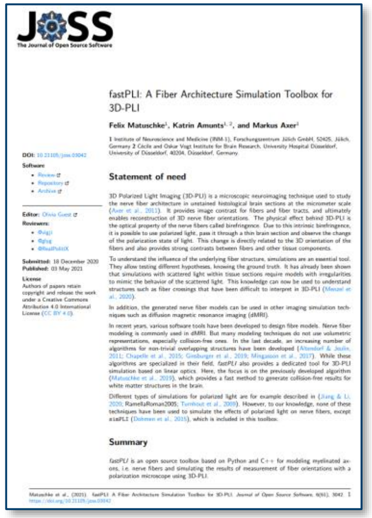
Inaugural-Dissertation

zur Erlangung des Doktorgrades der
Mathematisch-Naturwissenschaftlichen Fakultät der
Heinrich-Heine-Universität Düsseldorf

vorgelegt von

Felix Matuschke
aus Meschede

Düsseldorf, Juli 2022

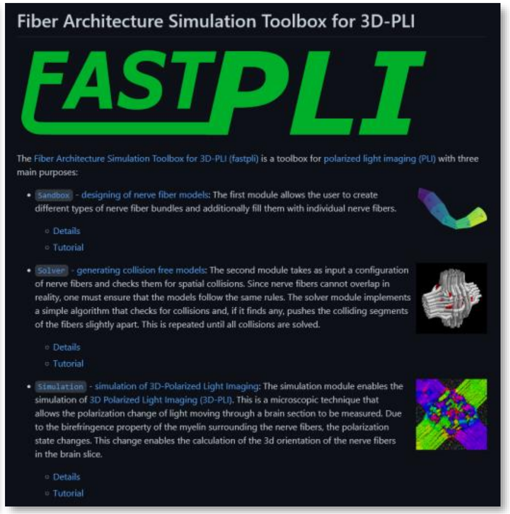

JOSS
The Journal of Open Source Software

fastPLI: A Fiber Architecture Simulation Toolbox for 3D-PLI

Felix Matuschke[1], Katrin Amunts[1, 2], and Markus Axer[1]

Statement of need

Summary


Fiber Architecture Simulation Toolbox for 3D-PLI

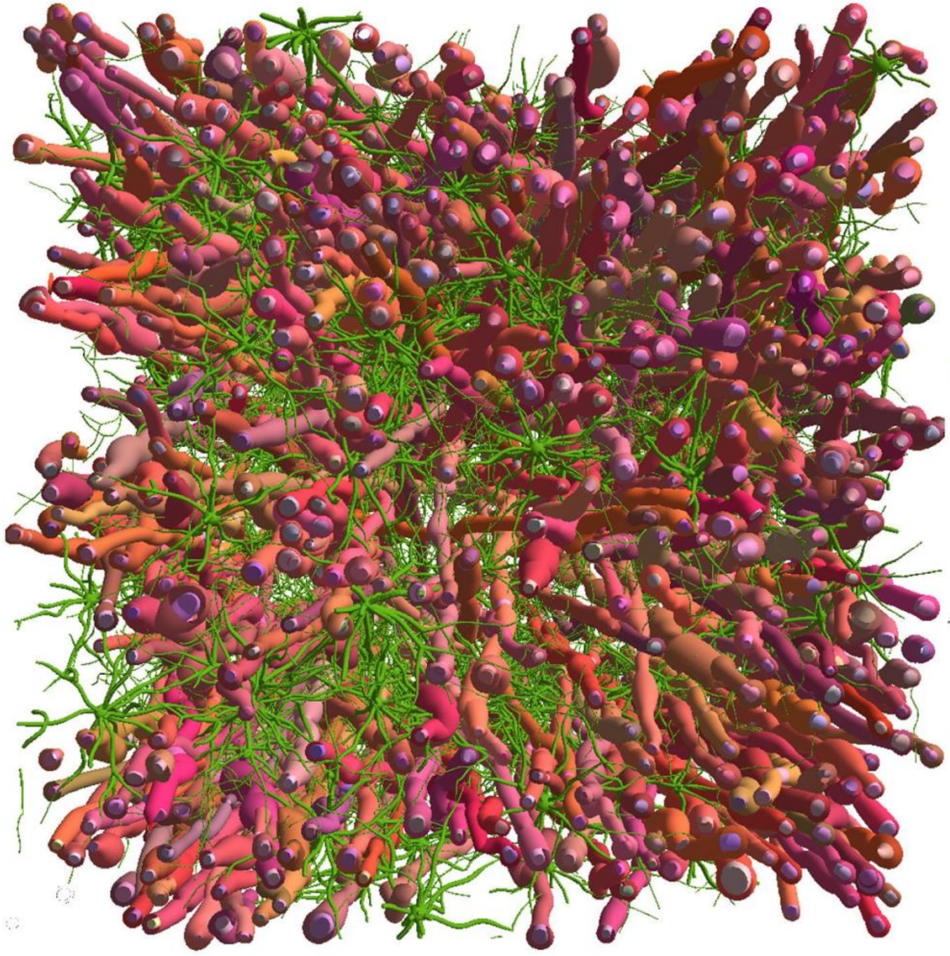
FASTPLI

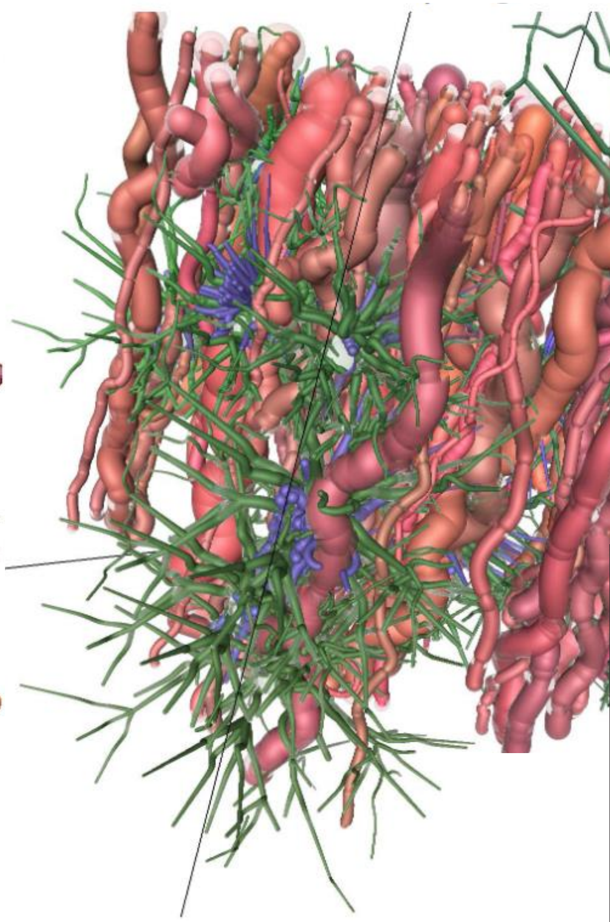
The Fiber Architecture Simulation Toolbox for 3D-PLI (fastpli) is a toolbox for polarized light imaging (PLI) with three main purposes:

- Sandbox - designing of nerve fiber models: The first module allows the user to create different types of nerve fiber bundles and additionally fill them with individual nerve fibers.
  - Details
  - Tutorial
- Solver - generating collision free models: The second module takes as input a configuration of nerve fibers and checks them for spatial collisions. Since nerve fibers cannot overlap in reality, one must ensure that the models follow the same rules. The solver module implements a simple algorithm that checks for collisions and, if it finds any, pushes the colliding segments of the fibers slightly apart. This is repeated until all collisions are solved.
  - Details
  - Tutorial
- Simulation - simulation of 3D-Polarized Light Imaging: The simulation module enables the simulation of 3D Polarized Light Imaging (3D-PLI). This is a microscopic technique that allows the polarization change of light moving through a brain section to be measured. Due to the birefringence property of the myelin surrounding the nerve fibers, the polarization state changes. This change enables the calculation of the 3d orientation of the nerve fibers in the brain slice.
  - Details
  - Tutorial

https://github.com/3d-pli

WM Modeling





Kevin Ginsburger, Felix Matuschke,
Cyril Poupon, Markus Axer, et al. (2019)

Outlook

- Juelich Brain Atlas
- AI driven tractography
- Open Source Code
  - Support of clinical Data
- Improvements of dMRI tractographies by better understanding the microscopic structure

Generating of a multimodal Nerve Fiber Atlas

Institute of Neuroscience and Medicine (INM-1) | Fiberarchitecture Group

Special thanks to:

- Markus Axer (FZJ | INM1)
- Jan Reuter (FZJ | INM1)
- Simon Legeay (CEA | Neurospin)
- Katrin Amunts (FZJ | INM1)
- Cyril Poupon (CEA | Neurospin)

Thanks!