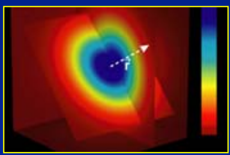
From Diffusion MR Image Analysis to Whole Brain Connectivity Simulation



Jean-Philippe Thiran

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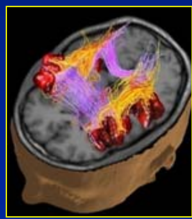

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EPFL - Lausanne

- HPC in life sciences at EPFL
  - *The Blue Brain project:*
    - create a biologically accurate, functional model of the brain using IBM's Blue Gene supercomputer
    - 8192 processors
  - *Several other projects*
  - *Including MR image anaylsis*

Blue Brain Project

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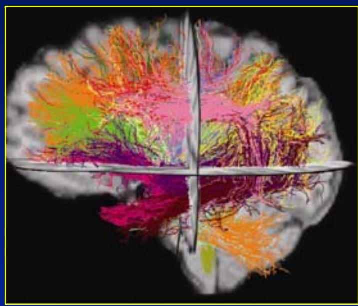
Motivation

- MR imaging is now established as the most important modality in neuro-imaging
- Recent advances allow to obtain *in vivo* information on the architecture of the (brain) tissues
  - New MR sequences
  - New algorithmic developments
- This opens new perspectives in fundamental neurosciences as well as in clinical practice



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Outline

- Basics of diffusion
- Imaging the diffusion by MRI
- From Diffusion MRI to Fiber Tracking
- Applications to Brain Connectivity Analysis

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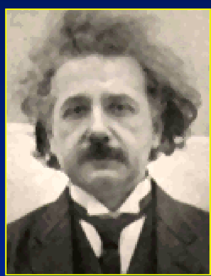
Basics of diffusion

- Molecular diffusion – Brownian motion
  - First formally described in 1905 by A. Einstein
  - We will consider water molecule diffusion
    - *Example: in a glass of water, molecules diffuse randomly and freely, only constrained by the boundaries of the container*



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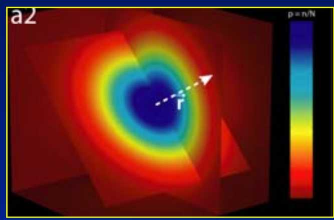
Basics of diffusion

- For a 3D volume,
  - 3D diffusion *pdf*
  - we use here the color-coding of the *pdf*
- For homogeneous media, this diffusion is an isotropic Gaussian
  - With $\sigma^2=2D\Delta$
  - D is the diffusion coefficient
    - *Function of medium viscosity, t°, …*



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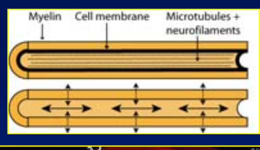
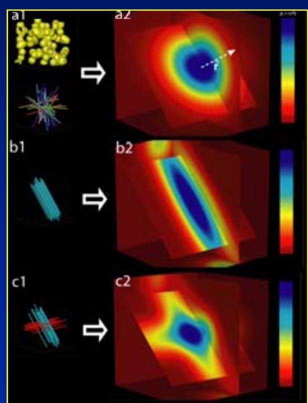
Diffusion in complex media

- Neuronal tissues: fibrillar structure
  - Tightly packed, coherently aligned axons
  - Diffusion more restricted in direction perpendicular to the axonal orientation than along its parallel direction
  - This is called anisotropic diffusion, as opposed to isotropic diffusion
- fiber crossings:
  - Certainly not a Gaussian pdf then.





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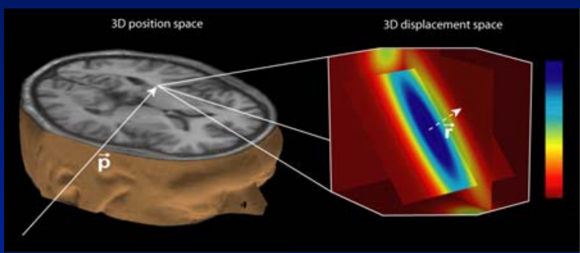
Diffusion imaging

- Imaging the diffusion of the 3D volume would ideally give a 6D data set



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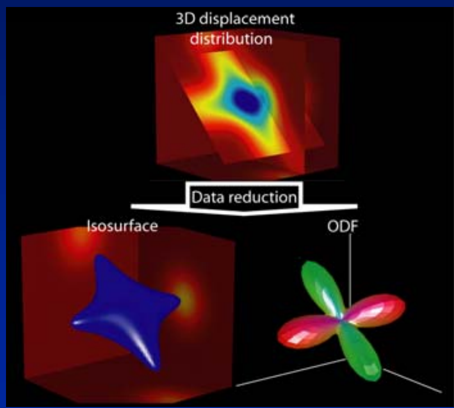
Diffusion imaging

- But this information is too complex to be analyzed and visualized
- Simplified representations
  - Isosurfaces
  - Orientation Distribution Functions (ODF)

    + color code for the orientation



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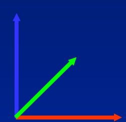
Diffusion imaging

Color-coding of the directions



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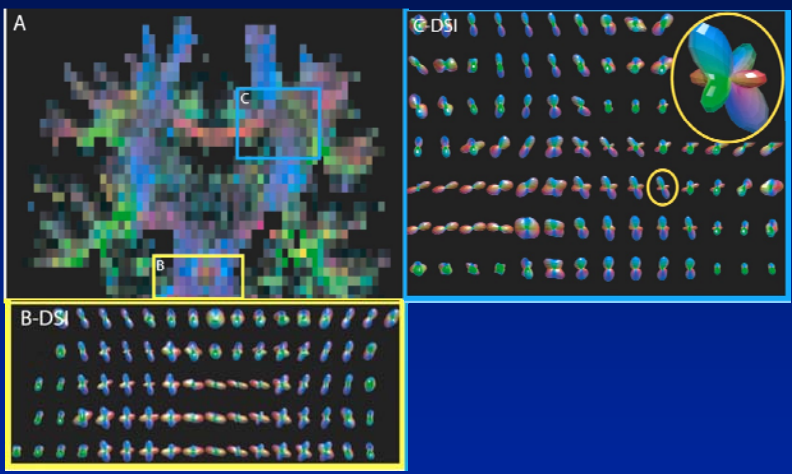
Diffusion imaging



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Outline

- Basics of diffusion
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  - Diffusion-Tensor MRI
- **From Diffusion MRI to Fiber Tracking**
- Applications to Brain Connectivity Analysis

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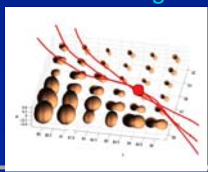
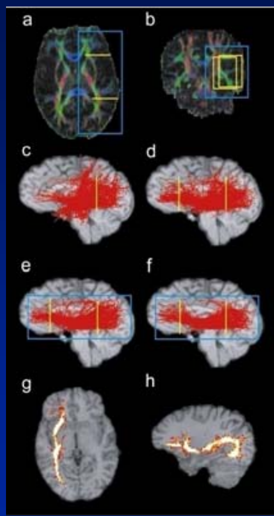
Tractography

- Fibre tracking
  - Infer axonal trajectories i.e. brain connectivity
  - Computation of trajectories following principal directions of diffusion
- Whole brain simulation
  - Trajectories are initiated all over the brain's WM
  - Result is an estimate of the whole brain connectivity (~100'000 lines)
- Tract selection, virtual dissection
  - Fibre selection using ROIs





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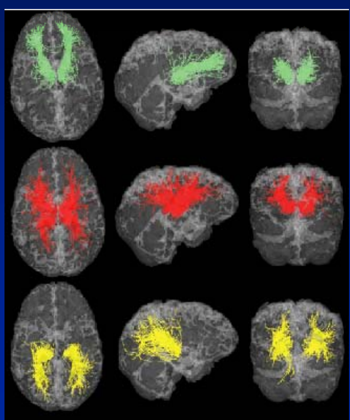
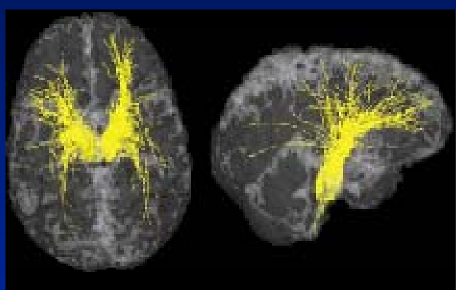
Fibre-tracking, results

- Thalamic projections
- Cortico-spinal and cortico-bulbar tracts





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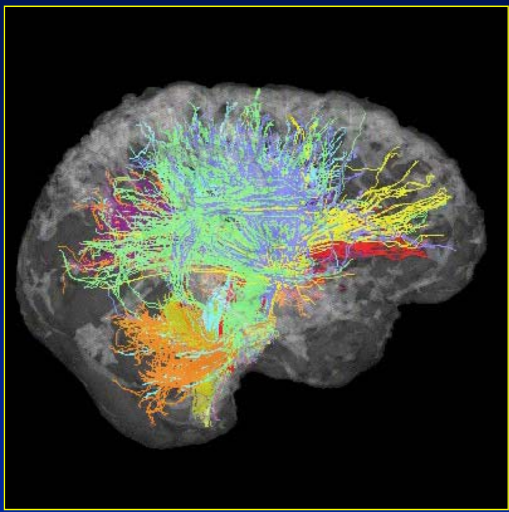
Fibre-tracking, results



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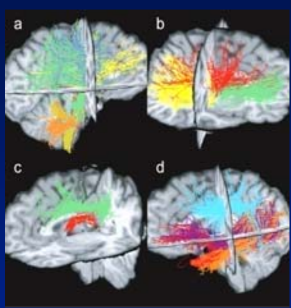
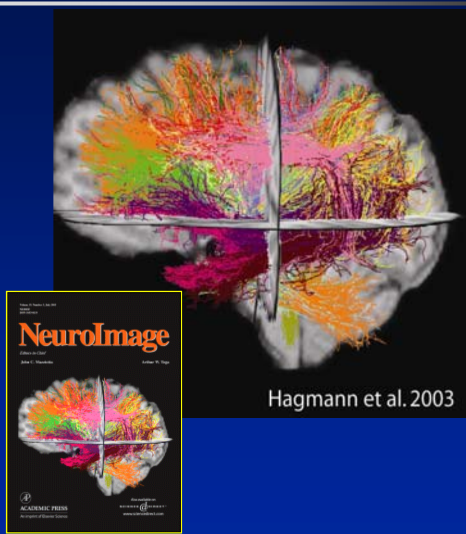
References





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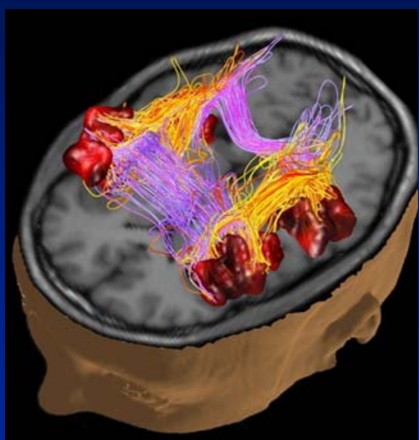
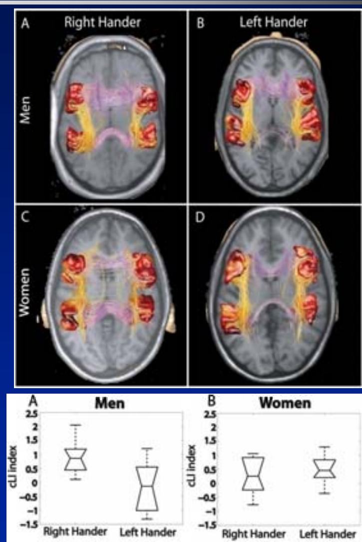
Application: study of language networks





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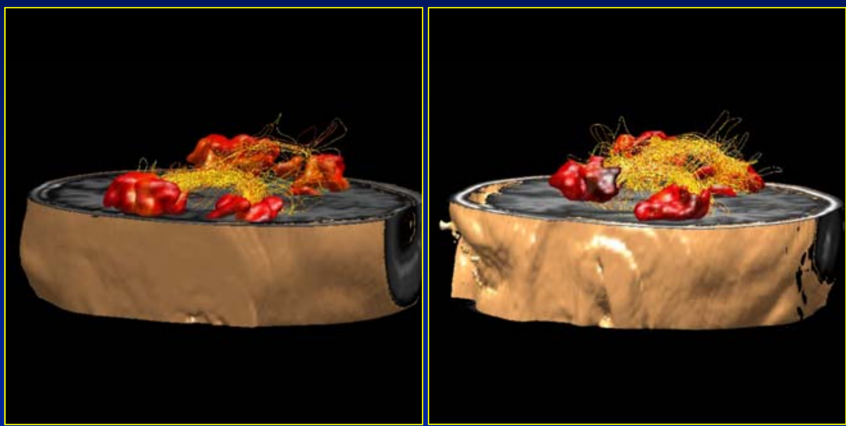
Application: study of language networks

- Language networks in right and left handers



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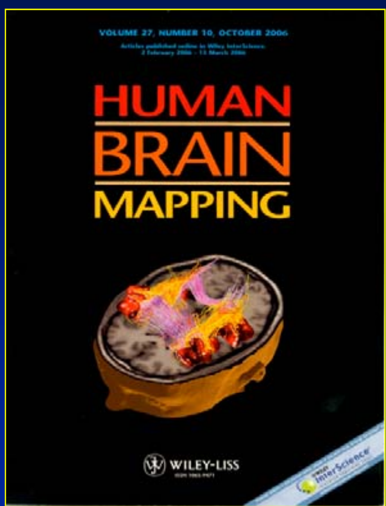
Application: study of language networks



Hagmann et al. Human Brain Mapping, 2006

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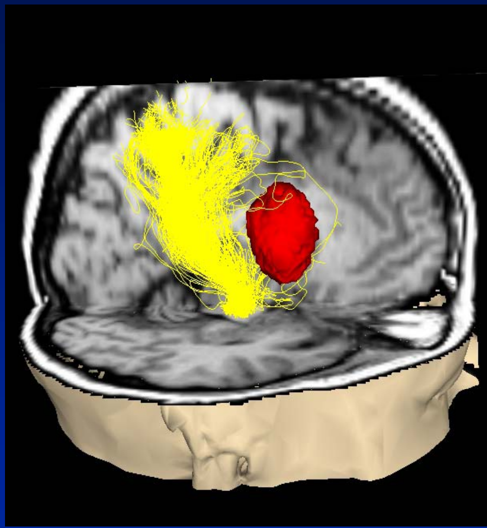
Application: diagnosis and therapy



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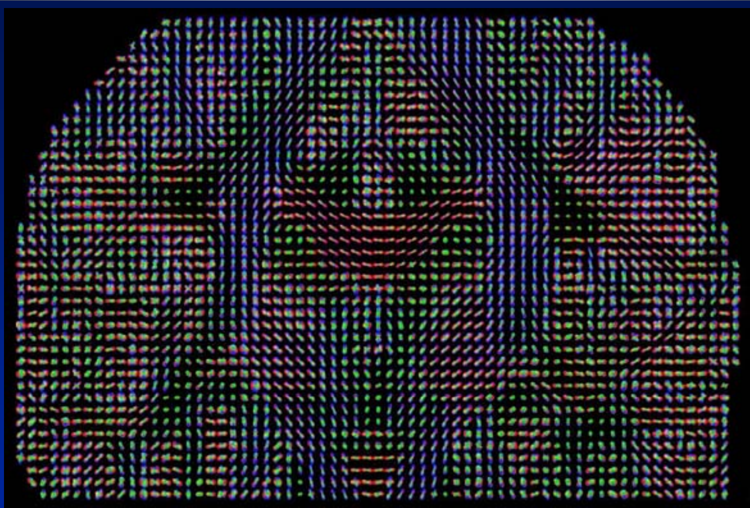
Fast-Marching Tractography (Fast-TraC)



Orientation Distribution Function map (coronal section)

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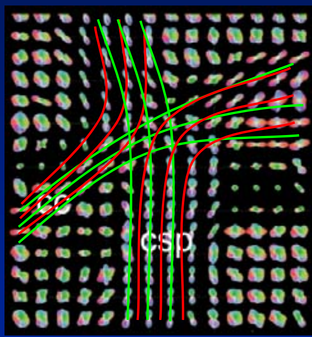
Fast-Marching Tractography (Fast-TraC)

- Motivation
  - Classical tractography algorithms: not accurate in complex fiber crossings regions, because fibers follow locally the most linear trajectories.
- Goal
  - Design a tractography algorithm able to map complex fiber crossings in the brain WM using a Fast-Marching approach.



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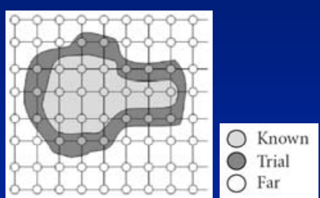
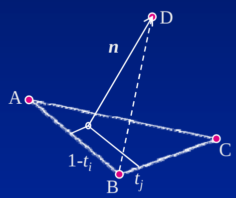
Fast-Marching Tractography (Fast-TraC)

- Front propagation
  - 3D Anisotropic Fast Marching (shifted grid, 26 neighbors, Qingfen Lin 2003)





$$u_D = (1-t_i)u_A + (t_i - t_j)u_B + t_j u_C + \min\{|\boldsymbol{n}\times \boldsymbol{s}_1|,\ldots,|\boldsymbol{n}\times \boldsymbol{s}_N|\}$$

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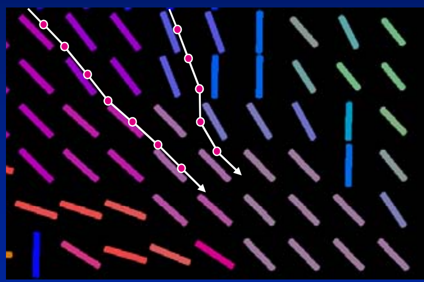
Fast-Marching Tractography (Fast-TraC)

- Back propagation of the fibers
  - Gradient descent through cost map u(**r**)
  - Initialization points: one in each GM voxel



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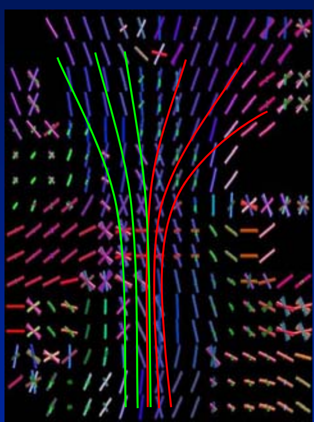
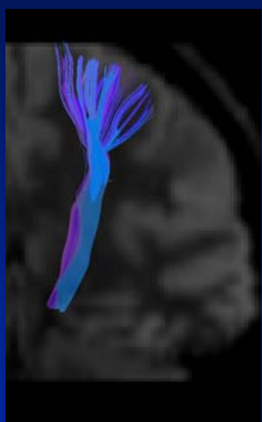
Fast-Marching Tractography (Fast-TraC)

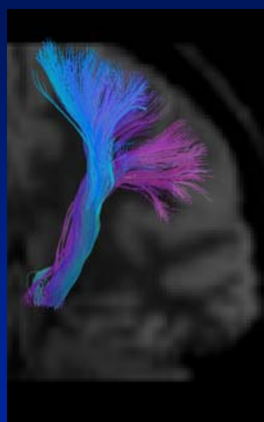
- Results: cortico-spinal tract



Local maxima of the ODF map



Classical streamline tractography (posterior view)



Fast-TraC (posterior view)

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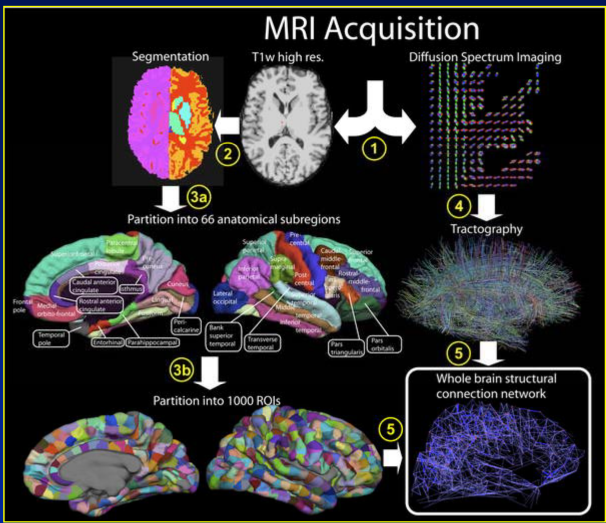
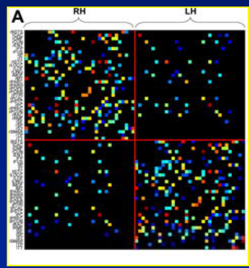
Towards brain connectivity analysis





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Computational complexity

- Front propagation
  - Volume of interest (WM): ~450cm^3
  - Resolution: 1x1x1 mm^3

  => Number of voxels : ~450'000

  In each of these voxels, we have to minimize u_D
  - Regions of Interest: ~1000
  - One front propagation per ROI

  => 998 front propagations
- Back propagation
  - Computed trajectories: 1 – 20 millions

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Computational complexity

- Computation time
  - Approx. 20 hours (P4 3.8GHz, C++ code)
  - Each front propagation is independent, the algorithm is highly parallelizable
- What would we gain with HPC ?
  - Ideally, we should perform one front propagation for every voxel of the WM-GM interface
  - WM-GM interface: ~200'000 voxels
  - Estimated computation time without parallelization: 4000 hours!

Fast-Marching Tractography (Fast-TraC)

- Discussion
  - New methodology for whole brain tractography, able to solve fiber crossings and branchings
  - Increases the global connectivity in the brain WM
  - Preliminary results obtained on the premotor cortex show a strong improvement of tractography results compared to classical streamline
  - Need for HPC to improve the resolution of the tractography

Conclusions

- Diffusion MRI & adapted tractography are useful tools to study brain connectivity analysis *in vivo*
- The *connectome* gives both a visual and quantitative representation of the brain connectivity
  - Normal subjects
  - Pathologies
    - *Schizophrenia*
    - *Epilepsy*
    - *…*
  - Brain development

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  - Prof. Reto Meuli
  - Dr Claudio Pollo
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  - Prof. Olaf Sporns (Indiana University, Bloomington, Indiana)
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  - Lausanne-Geneva Center for Biomedical Imaging (CIBM)

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