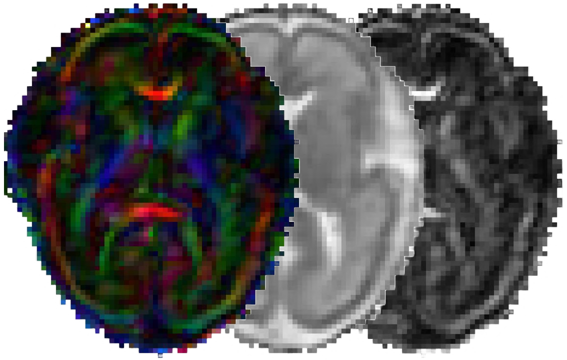
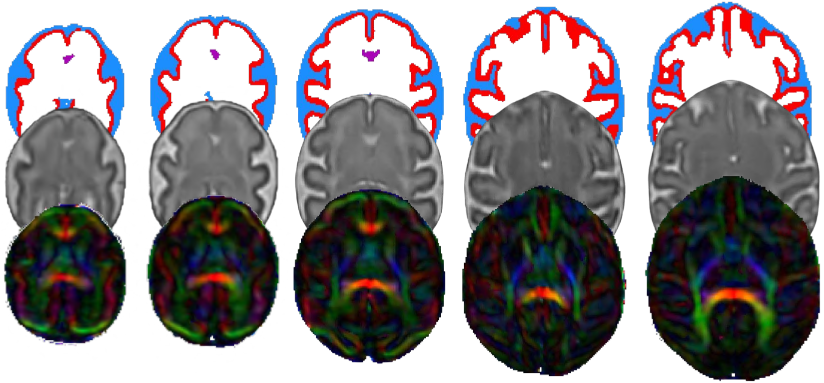
Processing and Analysis of Fetal Diffusion MRI

From Clinical Human Imaging to Longitudinal Baboon Research Data

Mattia Cazzolla





Neuroimaging meeting - CERIMED, 11 December 2025

int
institut de
neurosciences
de la timone

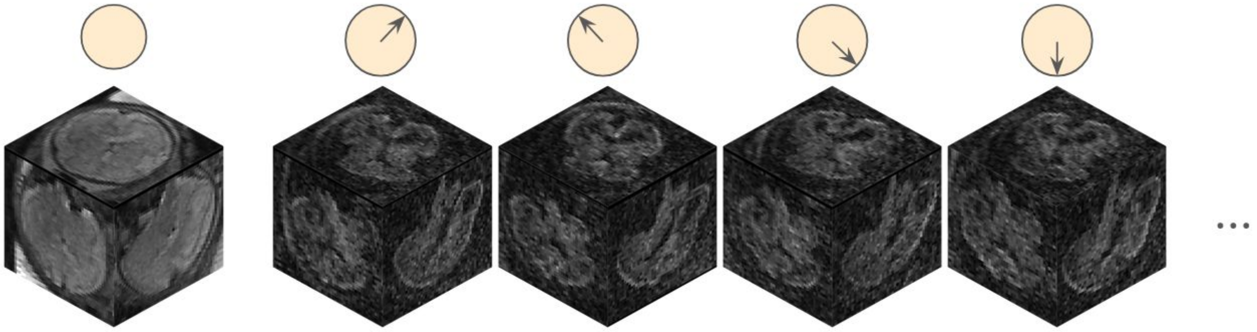
Outline

1. **Fetal Diffusion MRI:** opportunities and challenges
2. **MarsFet:** clinical human acquisitions
3. **BaboFet:** research baboon acquisitions

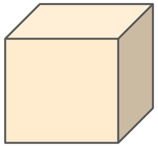
Fetal Diffusion MRI

Introduction

Diffusion MRI allow to study microstructural tissues information by measuring the **signal attenuation** caused by water **diffusion** in a specific direction



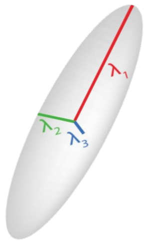
Voxel



(x,y,z)

b=0: [I_0]

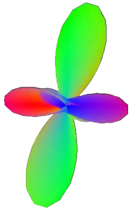
b=1000: [I_1 , I_2 , I_3 , ... , I]



Tensor model

$$S_{DWI} = S_{b=0} \times e^{(-b \times D)}$$

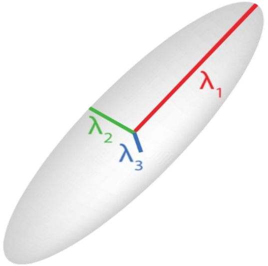
$$\mathcal{D} = \begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{zx} & D_{zy} & D_{zz} \end{bmatrix}$$



Higher order models

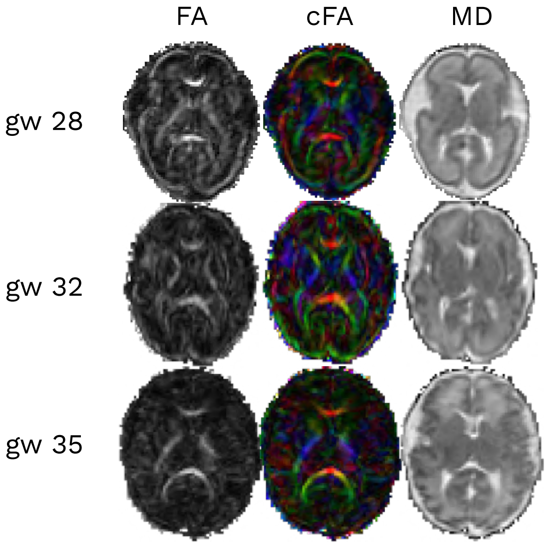
Fetal Diffusion MRI

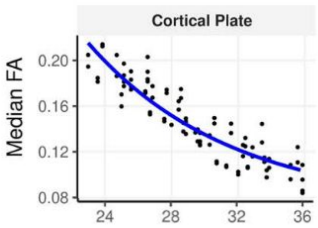
Introduction



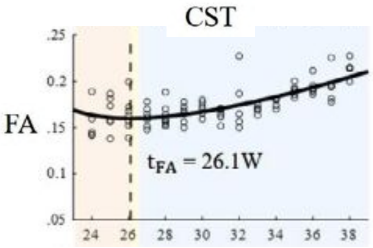
From the tensor can extract metrics:

- **Fractional Anisotropy** (dominant diffusion direction)
- **Mean Diffusivity** (proxy for water content)
- Axial and Radial Diffusivity





Calixto et al, Cerebral Cortex



Chen et al, Neuroimage

Do different cortical/white matter areas develop with different dynamic?

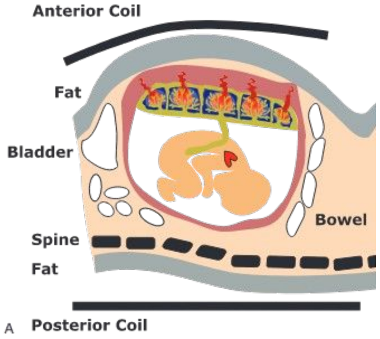
Fetal Diffusion MRI

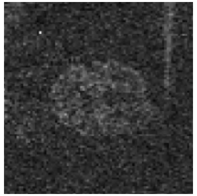
Challenges - ROI

Coils

Maternal tissue between fetal brain and MRI coils

low SNR

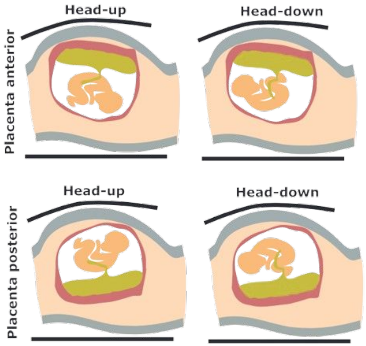


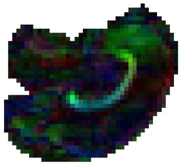


Non standard orientation

Non standard orientation relative to scanner

wrong color maps

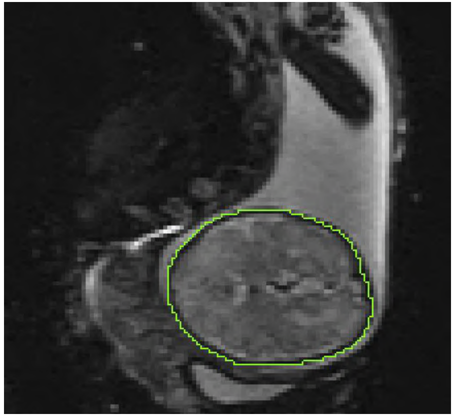




Brain extraction

Brain needs to be located and extracted

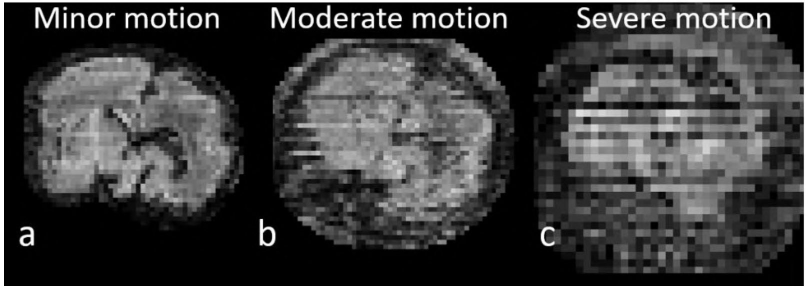
need for specific tools

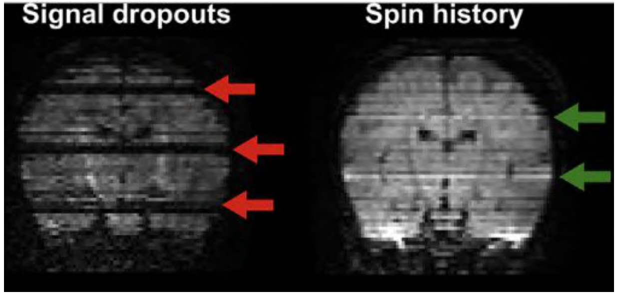


Christiaens et al., “In Utero Diffusion MRI: Challenges, Advances, and Applications,” Topics in Magnetic Resonance Imaging, 2019.

Fetal Diffusion MRI

Challenges - Motion





Caused by:

- maternal breathing
- fetal motion

Motion can be assumed frozen during the readout of each slice.

Motion can cause:

- signal dropout
- slice cross-talks artifacts

Christiaens et al., "In Utero Diffusion MRI: Challenges, Advances, and Applications," Topics in Magnetic Resonance Imaging, 2019.
Deprez et al., "Higher Order Spherical Harmonics Reconstruction of Fetal Diffusion MRI With Intensity Correction," IEEE Transactions on Medical Imaging, 2020.

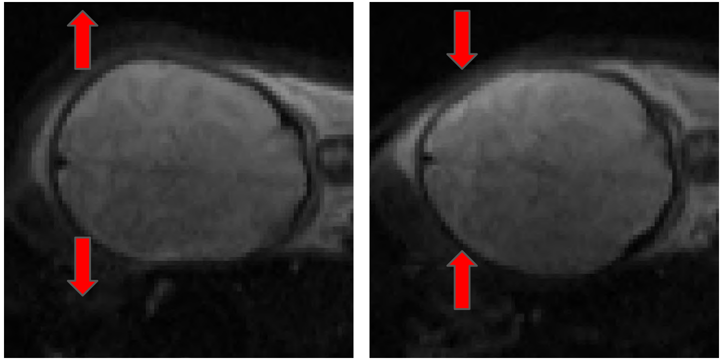
Fetal Diffusion MRI

Challenges - Geometrical distortions

Fetal dMRI rely on EPI (Echo Planar Imaging) for efficient data acquisition.
But EPI suffer from local geometric distortions:

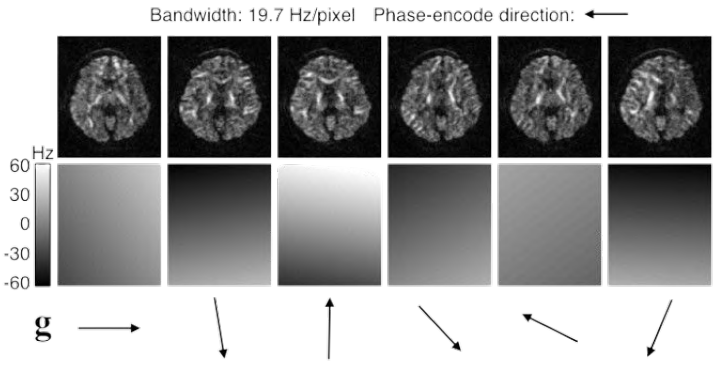
Magnetic Susceptibility

b0 with **AP** phase encoding | b0 with **PA** phase encoding



differences of **magnetic susceptibility** at tissue/air interface

Eddy currents



rapid switch of diffusion gradients generate currents in nearby conductors

https://fsl.fmrib.ox.ac.uk/fsl/docs/diffusion/eddy/index.html

Outline

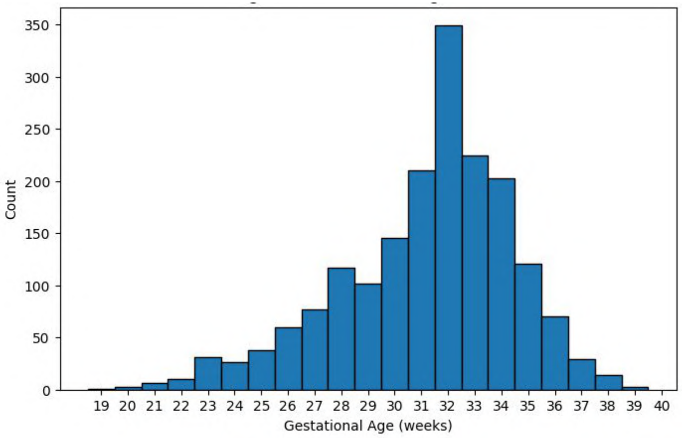
1. **Fetal Diffusion MRI:** challenges and limitations
2. **MarsFet:** clinical human acquisitions
3. **BaboFet:** research baboon acquisitions

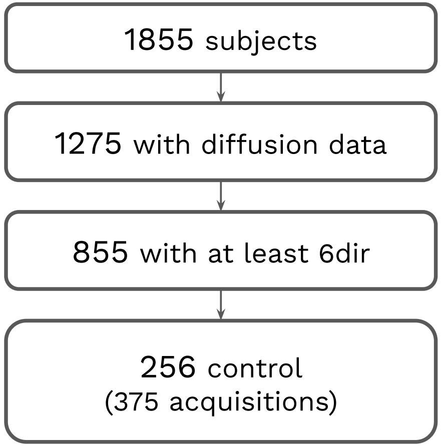
MarsFet

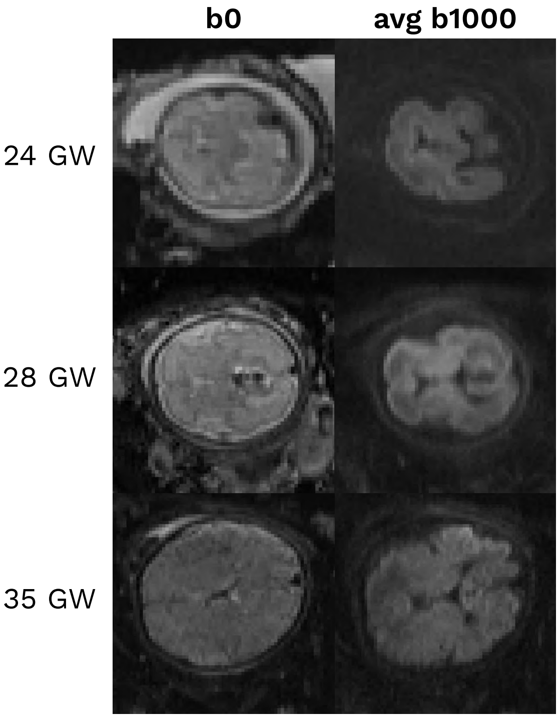
Dataset

Large-scale fetal MRI dataset acquired during routine clinical examinations at *La Timone University Hospital* (Marseille, France) between 2008 and 2021.

- more than 1800 subjects
- pathological cases precisely annotated





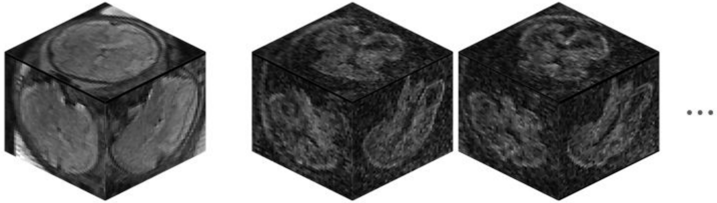


MarsFet
Acquisitions




int institut de neurosciences de la timone

Diffusion data



b0 b1000 b1000

MarsFet cohort is an heterogeneous dataset due to the multiple acquisition protocols utilized.

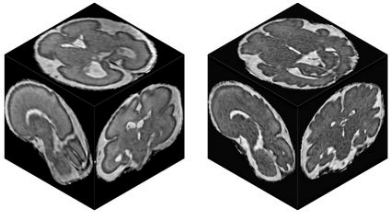
Variability:

- 4 different MRI scanners
- 1.5 and 3T
- 6, 12 or 30 directions
- TR and TE

Typical acquisition:

- one stack
- isotropic (2mm)
- single shell b=1000 s.mm-2
- no Reverse Phase Encoding

Anatomical data



Reconstructed T2w images are available but we decided not to use them

MarsFet

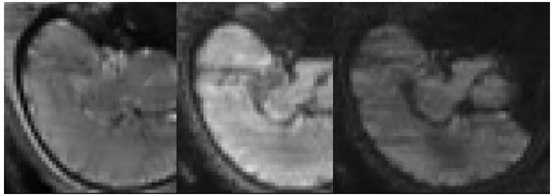
State of the art

dHCP data

253 high quality fetal data

- b=0 (15 volumes)
- b=400 (46 volumes)
- b=1000 (80 volumes)

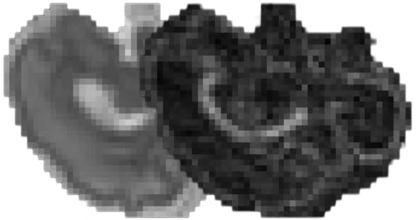
- SAFE sequence



dHCP pipeline

Code not available

1. Denoising
2. **Dynamic distortion correction**
3. Bias field correction
4. Brain mask
5. **Multi-shell reconstruction (SHARD)**



Need of pipeline suitable for clinical acquisitions

Christiaens et al., “Fetal diffusion MRI acquisition and analysis in the developing Human Connectome Project,” Proceedings, ISMRM, 2019

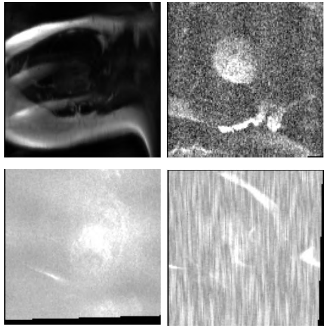
MarsFet

Processing pipeline

Initial QC

Visual inspection

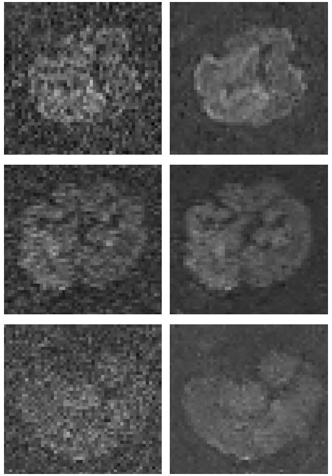
Exclusion of poor quality data (high noise and/or obvious artifacts)



~ 50 acquisition removed

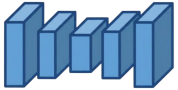
Denoising

Marchenko-Pastur PCA

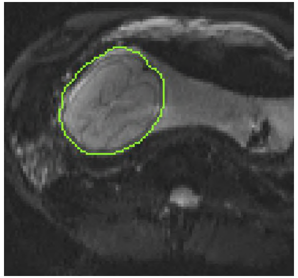


Brain extraction

FetalBET

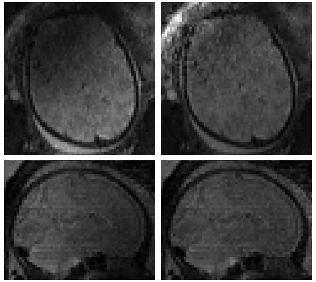


Brain mask extracted from the b0



Bias correction

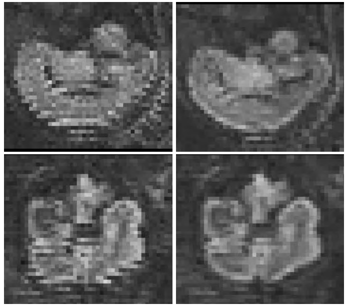
N4



Motion Correction

FSL Eddy

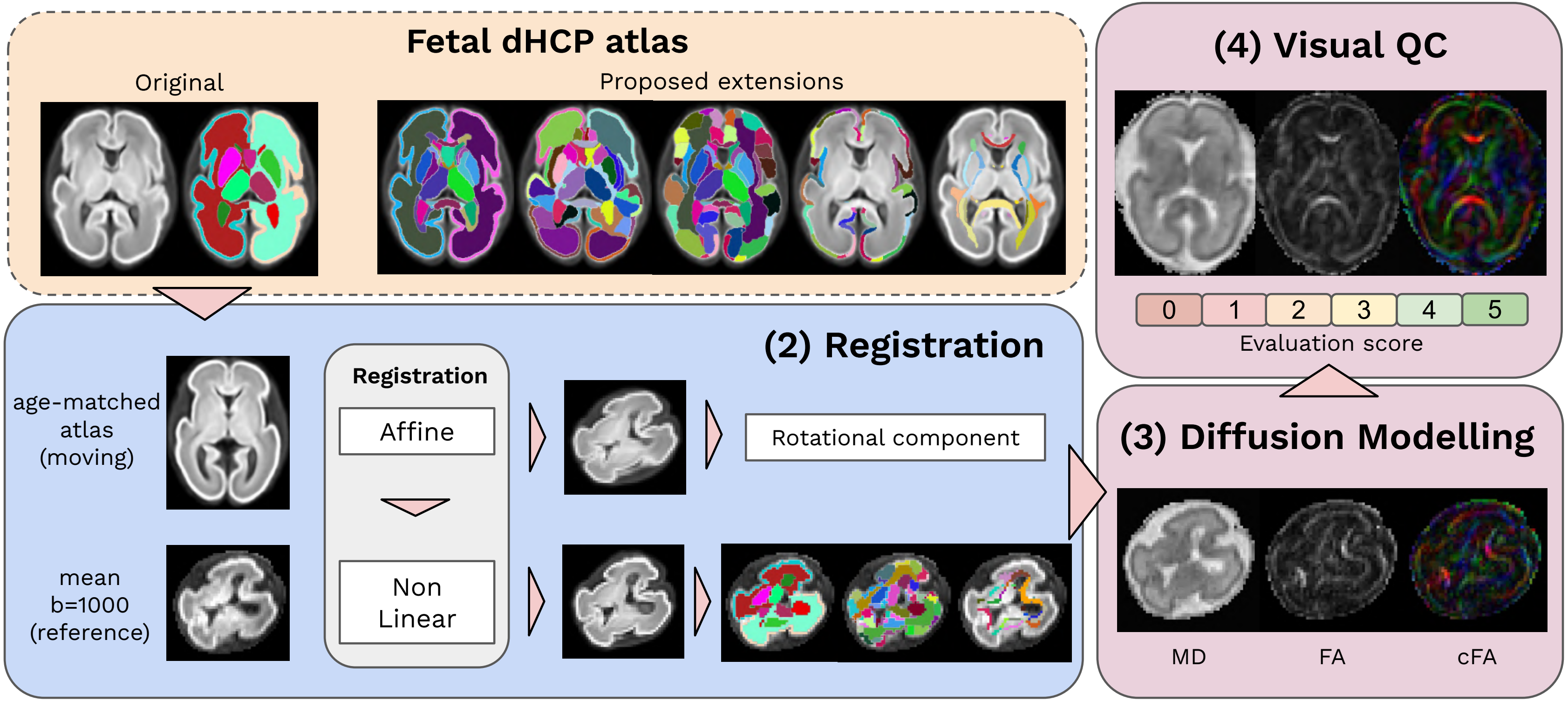
- Slice2Volume
- outlier replacement



Faghihpirayesh et al., “Fetal-BET: Brain Extraction Tool for Fetal MRI,” IEEE Open Journal of Engineering in Medicine and Biology, 2024.

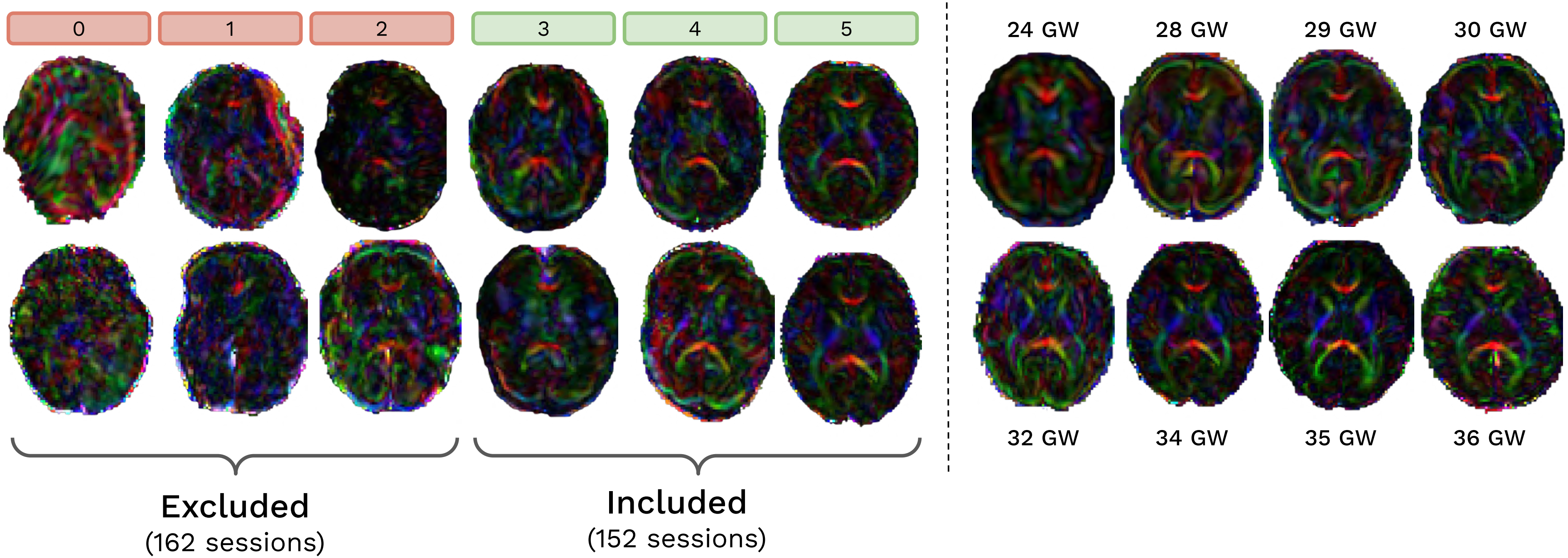
MarsFet

Processing pipeline



MarsFet

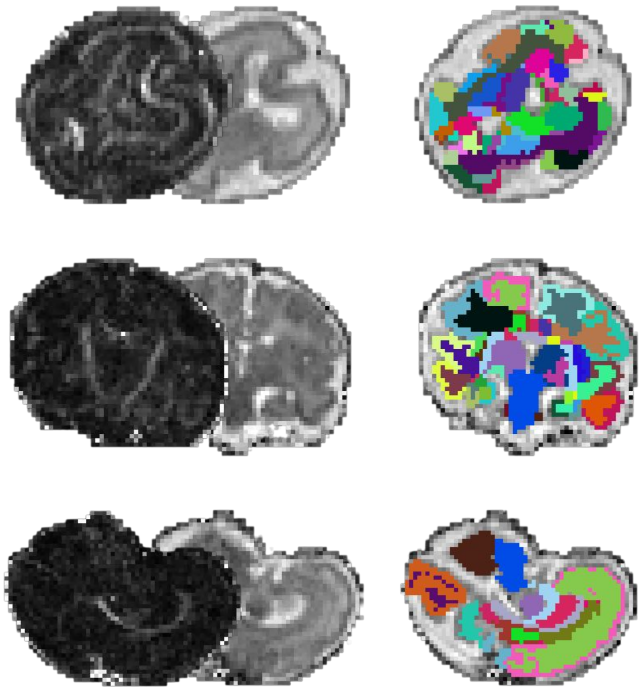
Results

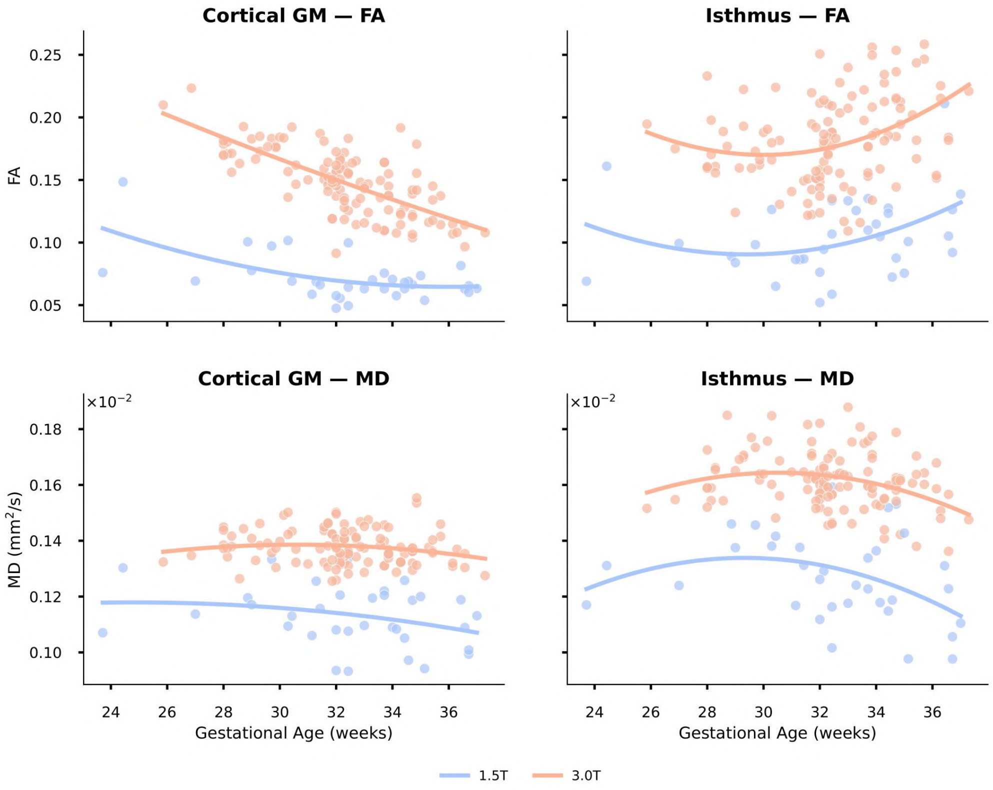


MarsFet

Trends

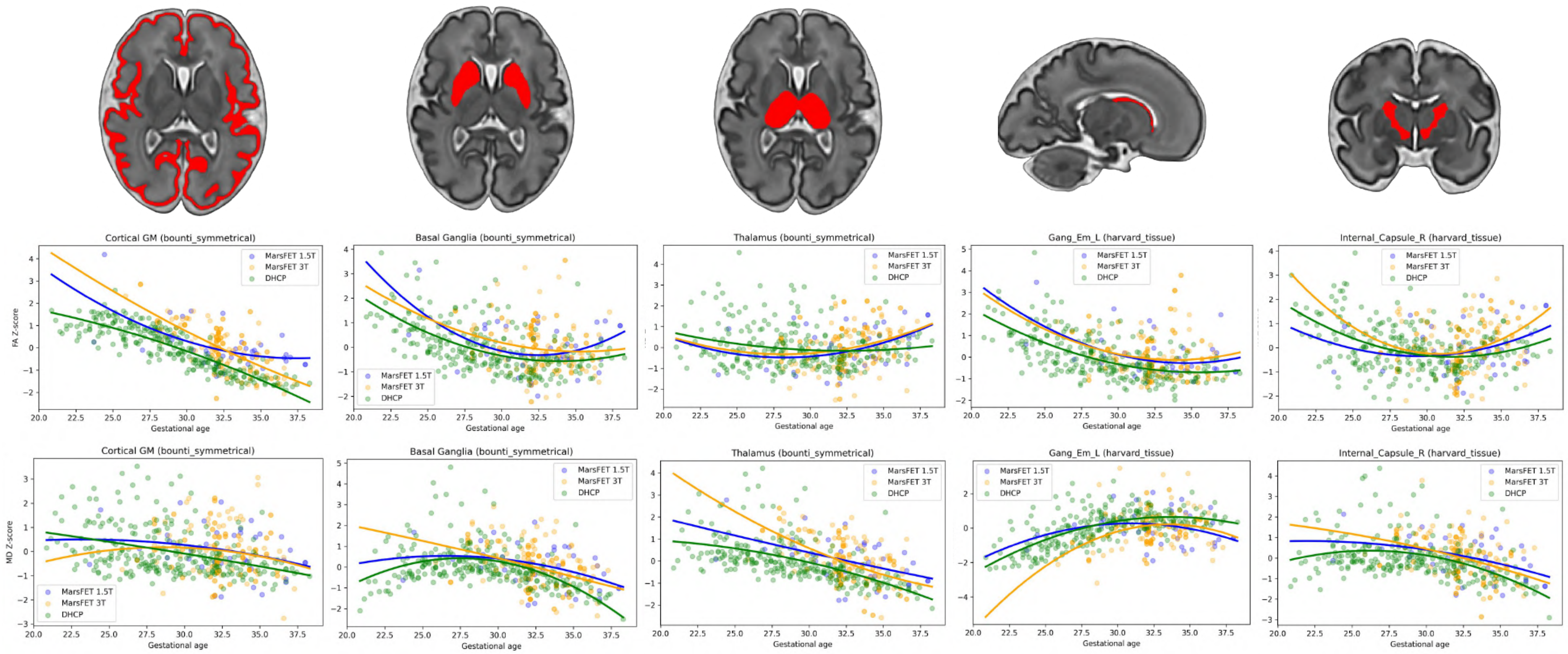
Tensor maps | Parcellations





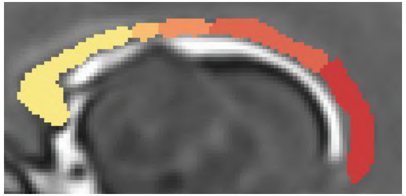
MarsFet

dHCP comparison

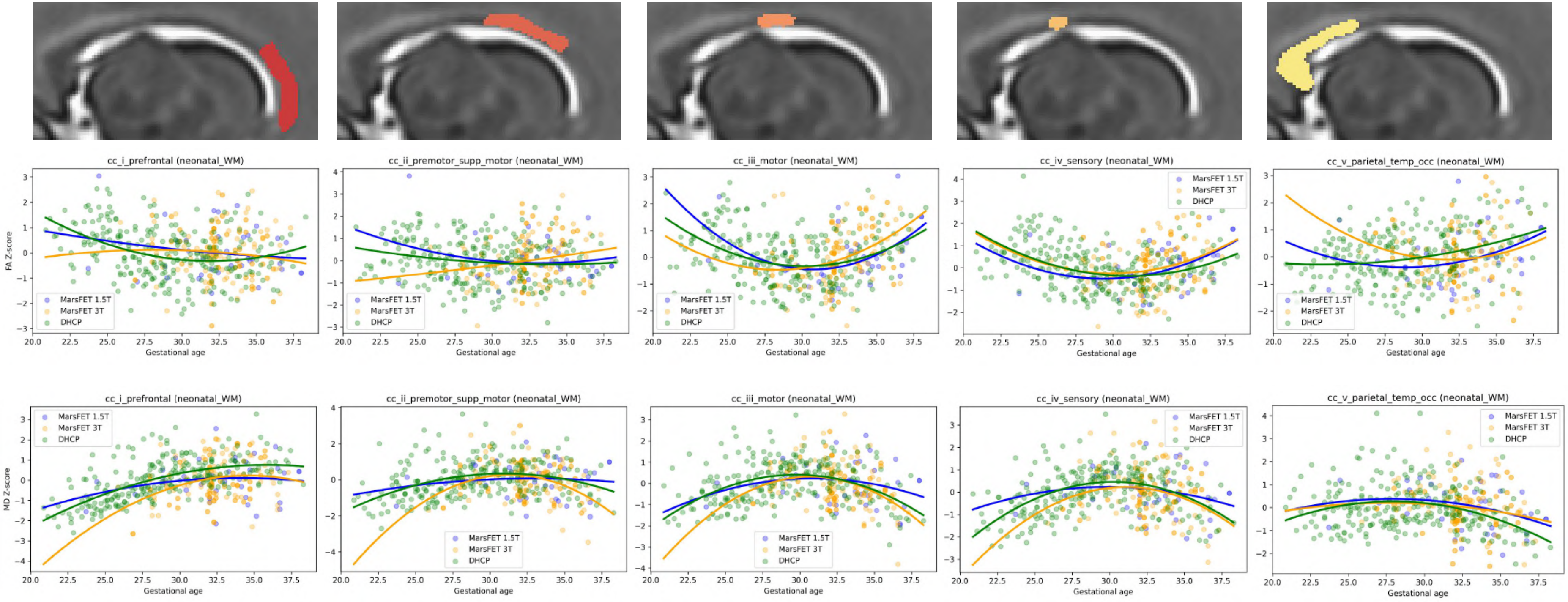


MarsFet

dHCP comparison



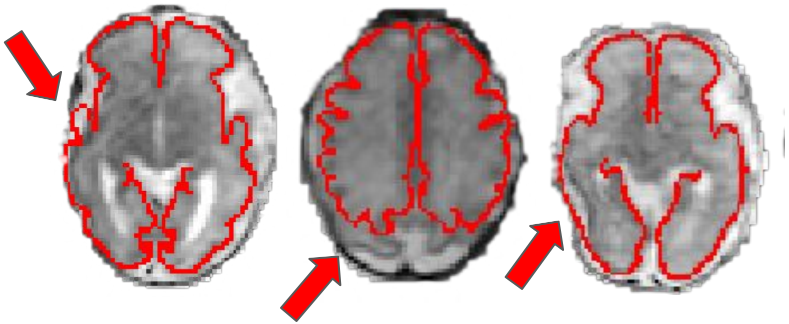
int
institut de
neurosciences
de la timone

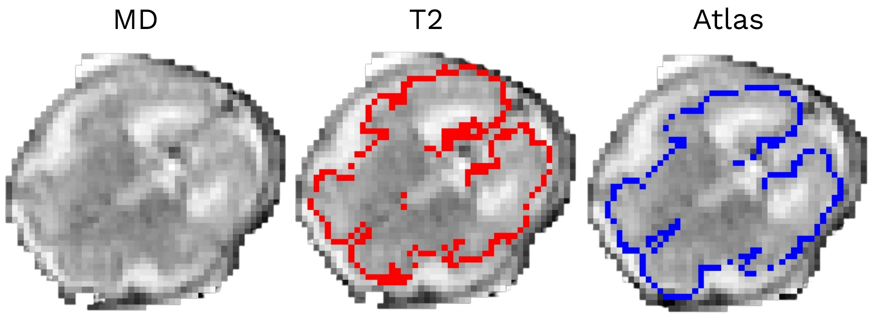


MarsFet

Future works

Improve parcellations in diffusion space using the subject reconstructed T2





Need good quality anatomical reconstruction and segmentations

Outline

1. **Fetal Diffusion MRI:** challenges and limitations
2. **MarsFet:** clinical human acquisitions
3. **BaboFet:** research baboon acquisitions

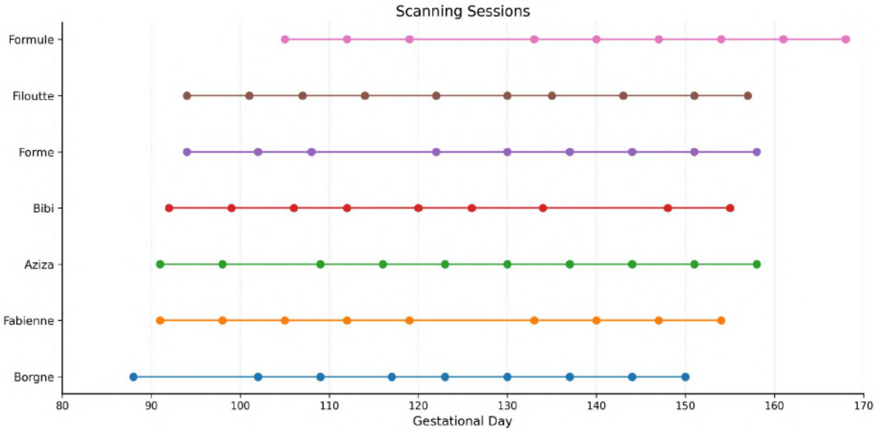
BaboFet

Dataset

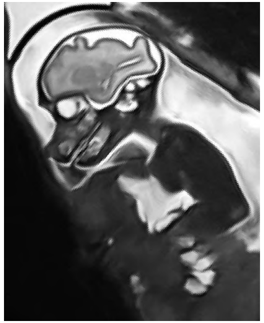
L. Renaud M. Clémenceau

Dataset of 7 pregnant baboons scanned longitudinally, once a week for 10 weeks, between 13wGA and 24wGA, acquired at CERIMED (Marseille, France).

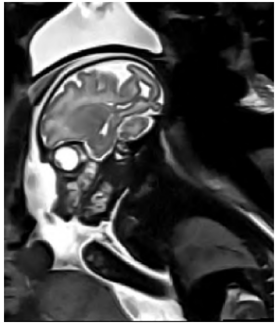
- **Anatomical**: 2D T2 HASTE 0.63x0.63x2 mm³
- **Diffusion**: 2D Spin Echo EPI, 1.1x1.1x3 mm³, 30 directions, b=1000s.mm-2
- **Functional:** 2D Gradient-recalled Echo EPI, 2.5x2.5x2.5 mm³, TR/TE=2000/30ms



14w



18w



22w

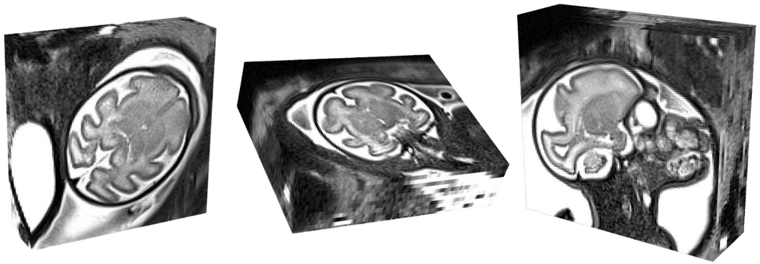
BaboFet

2D stacks

L. Renaud M. Clémenceau

Six 2D stacks of thick slices, 2 per plane with half voxel overlap.
Allow for super-resolution reconstruction

Anatomical



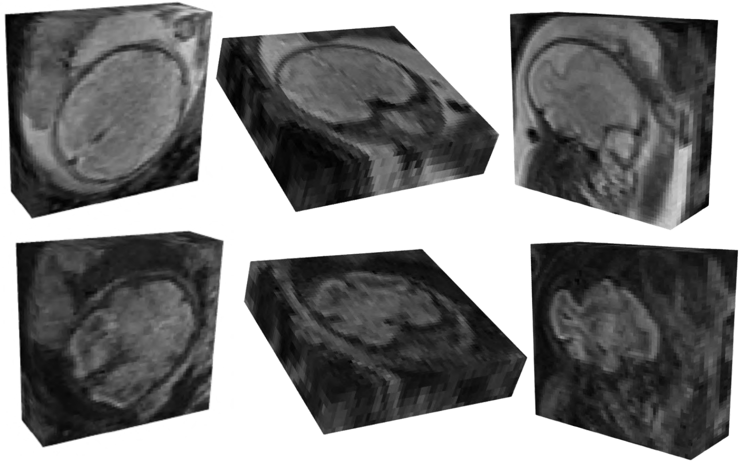
Axial Coronal Sagittal

x2

Diffusion

b0

dwi

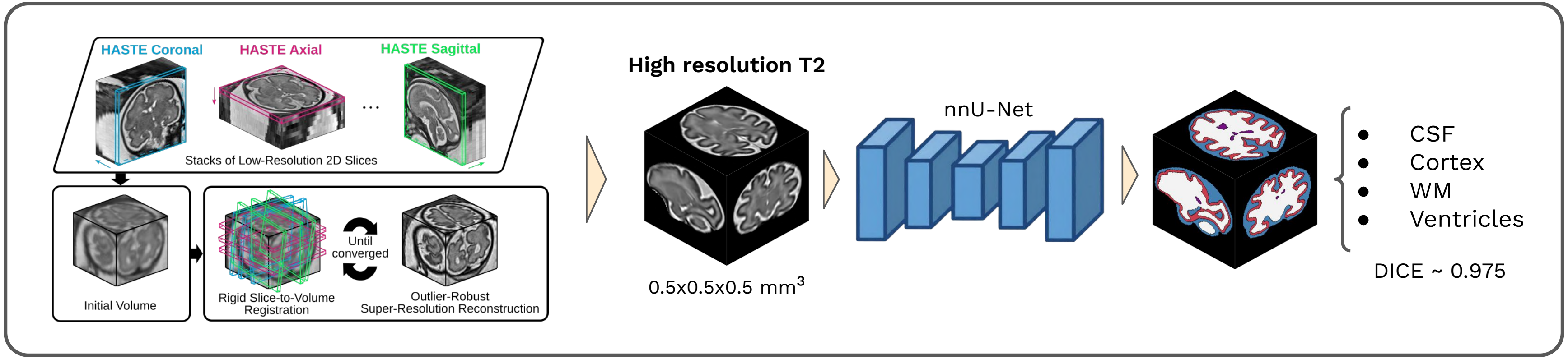


Axial Coronal Sagittal

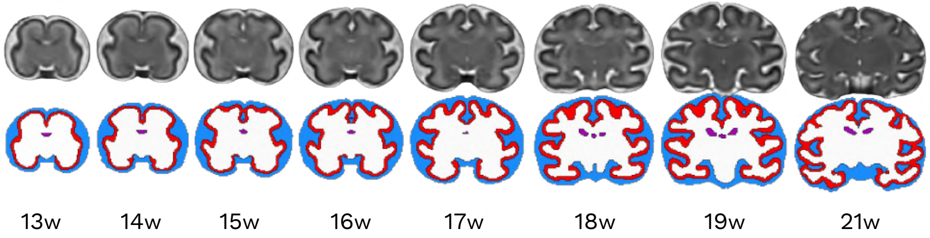
x2

BaboFet

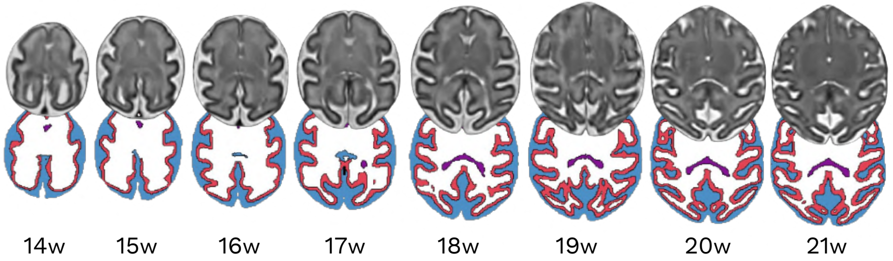
Processing pipeline - anatomical



Sub-Bibi



Sub-Borgne



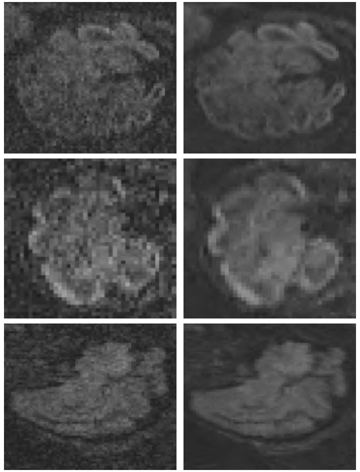
Ebner et al., "An automated framework for localization, segmentation and super-resolution reconstruction of fetal brain MRI", Neuroimage, 2020
Isensee et al., "nnU-Net: a self-configuring method for deep learning-based biomedical image segmentation," Nature Methods, 2021

BaboFet

Processing pipeline - diffusion

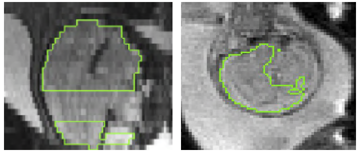
Denoising

Marchenko-Pastur PCA
and
Gibbs ringing removal

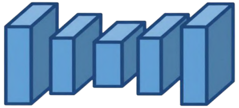


Brain extraction

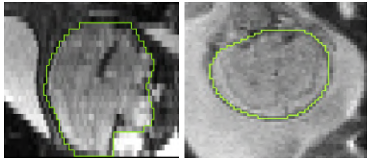
FetalBET struggles with baboons



Trained **nnUNet** on 359 b0 volumes

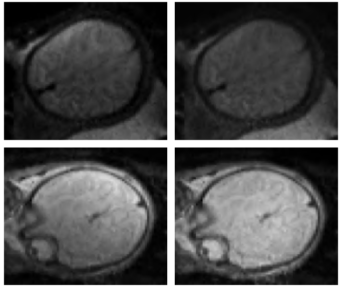


Dice: 0.959 ± 0.017



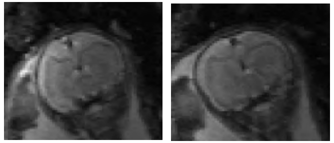
Bias and Distortion correction

N4 Bias correction



Topup

AP **PA**

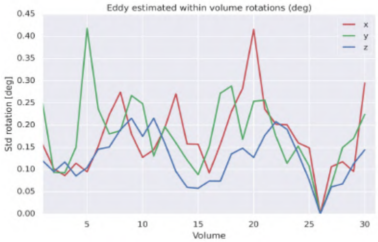


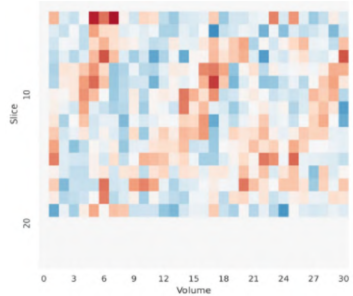
Field

Motion Correction

FSL Eddy

- Slice2Volume
- outlier replacement

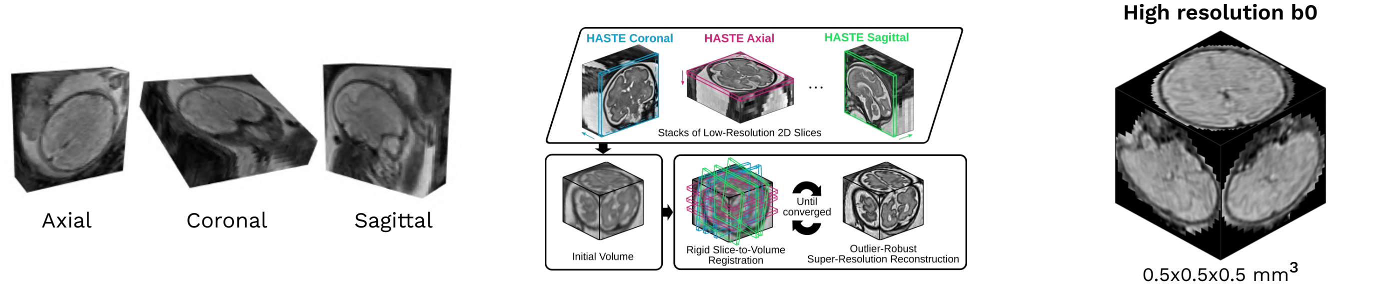




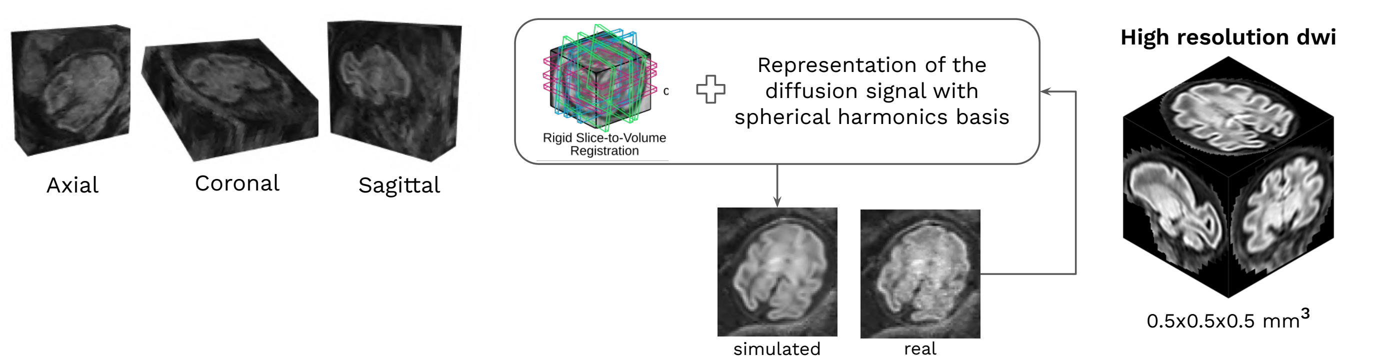
BaboFet

Super-resolution reconstruction

b0



dwi



Uus et al, “Retrospective motion correction in foetal MRI for clinical applications: existing methods, applications and integration into clinical practice”, British Journal of Radiology, 2022.
Deprez et al., “Higher Order Spherical Harmonics Reconstruction of Fetal Diffusion MRI With Intensity Correction,” IEEE Transactions on Medical Imaging, 2020.

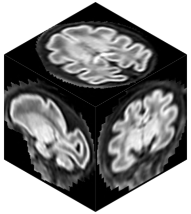
BaboFet

Diffusion models

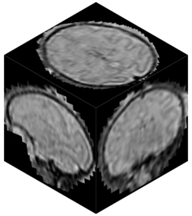
Spatially aligned

Rigid registration
b0 → T2 → dwi

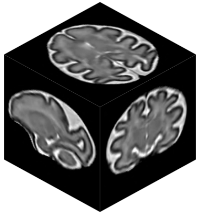
dwi



b0

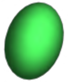


T2

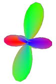


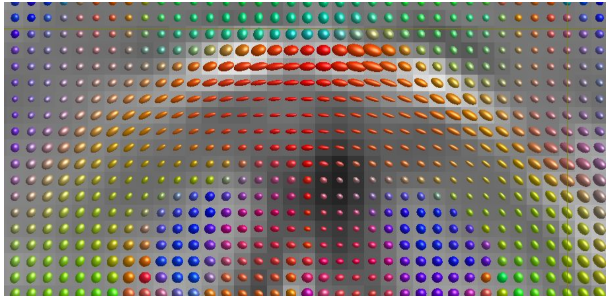
Diffusion models

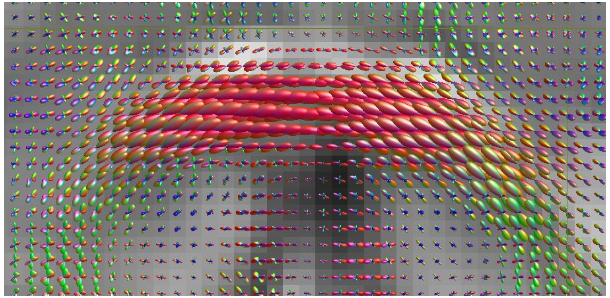
Tensor



FOD

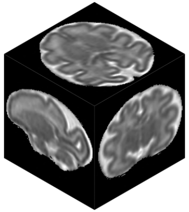




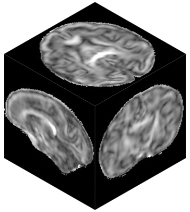


with Constrained Spherical Deconvolution

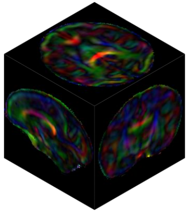
Metrics are derived from the tensor



MD

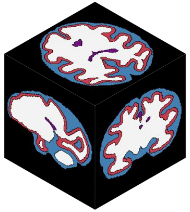


FA



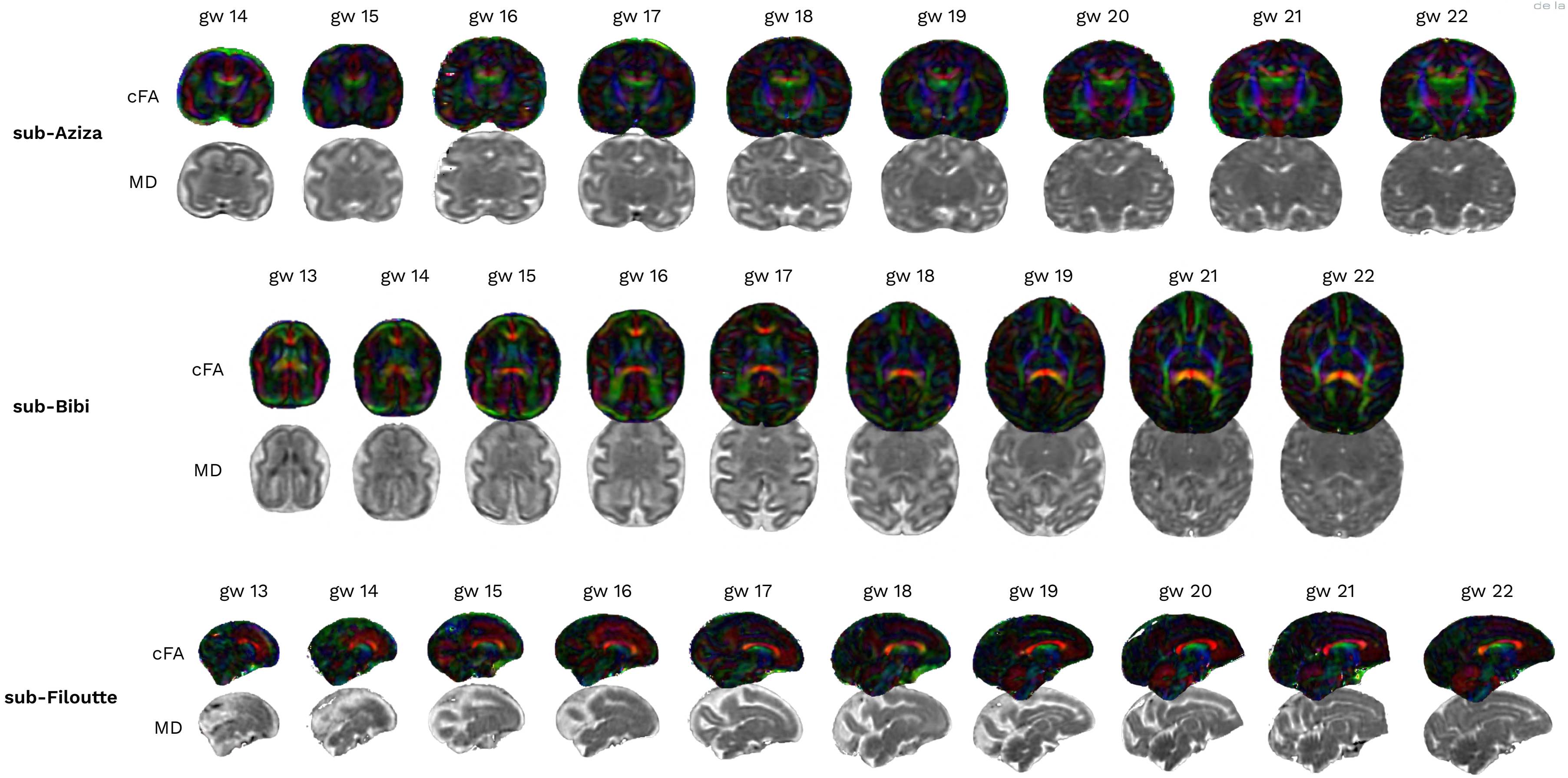
cFA

Propagate the T2w masks



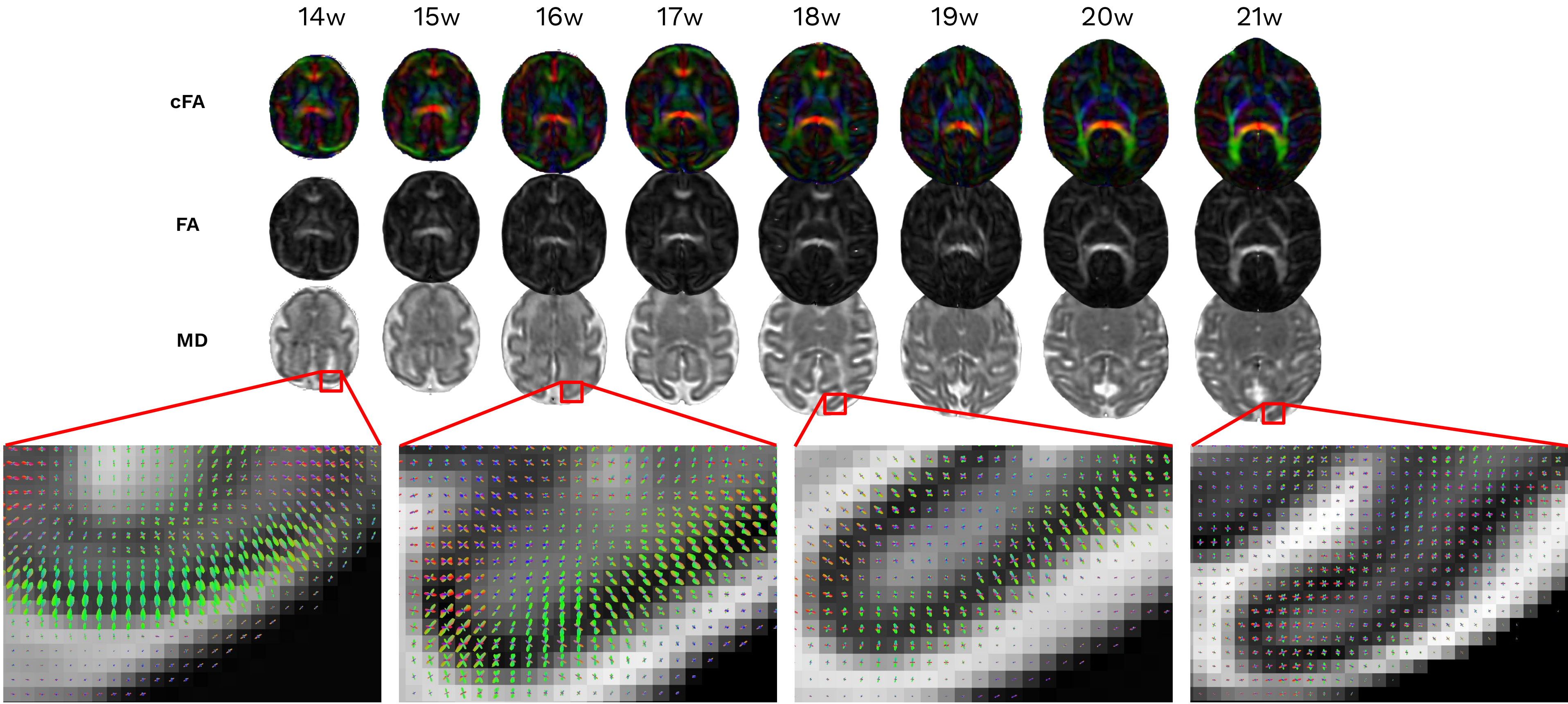
BaboFet

Results



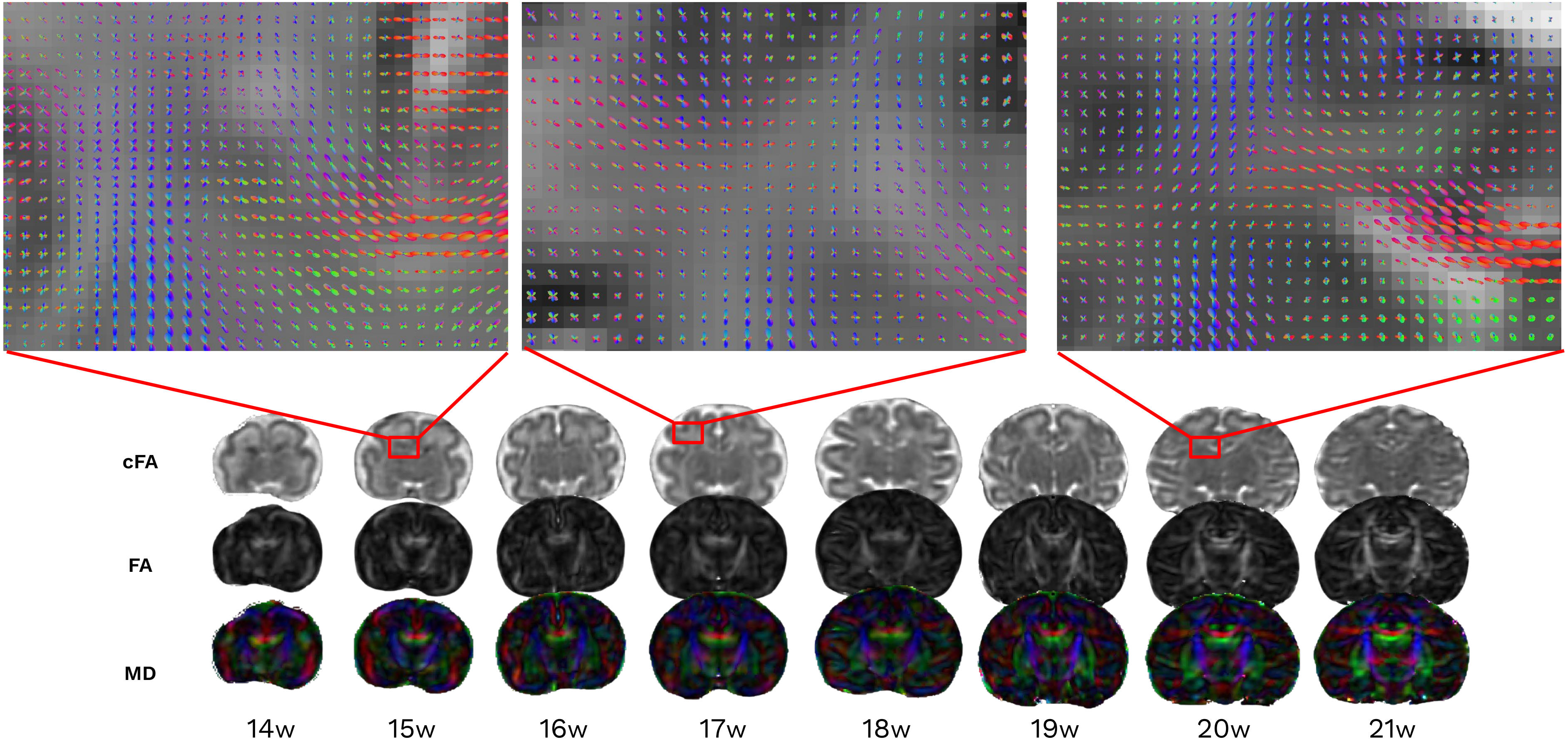
BaboFet

Results - cortex organization



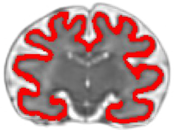
BaboFet

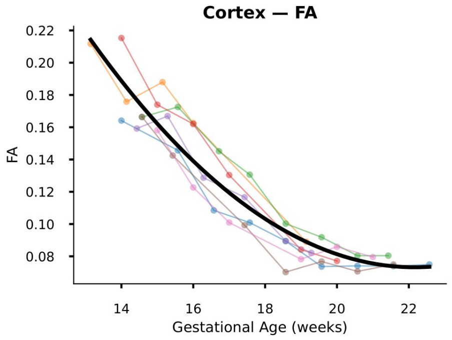
Results - crossing fibers

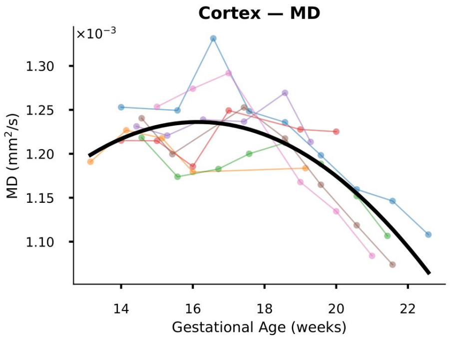


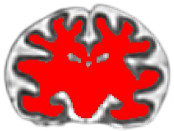
BaboFet

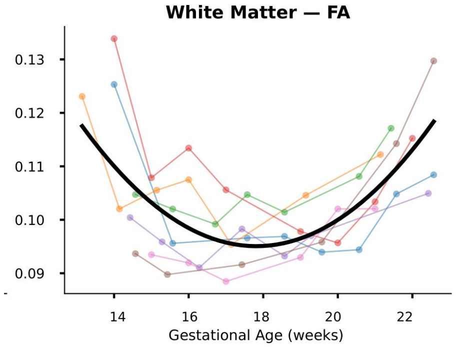
Trends

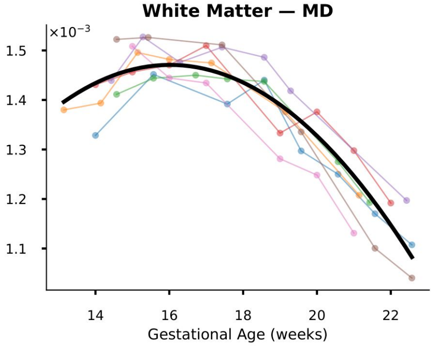






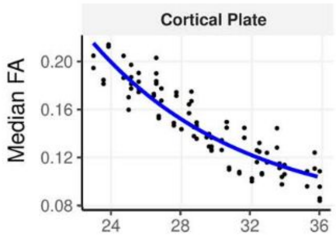




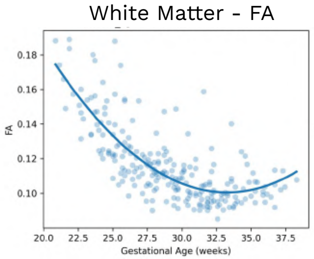


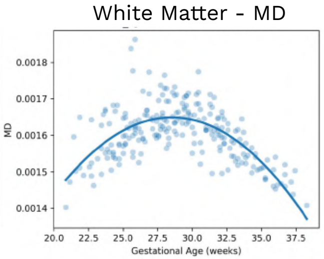
Literature

Calixto et al, Cerebral Cortex



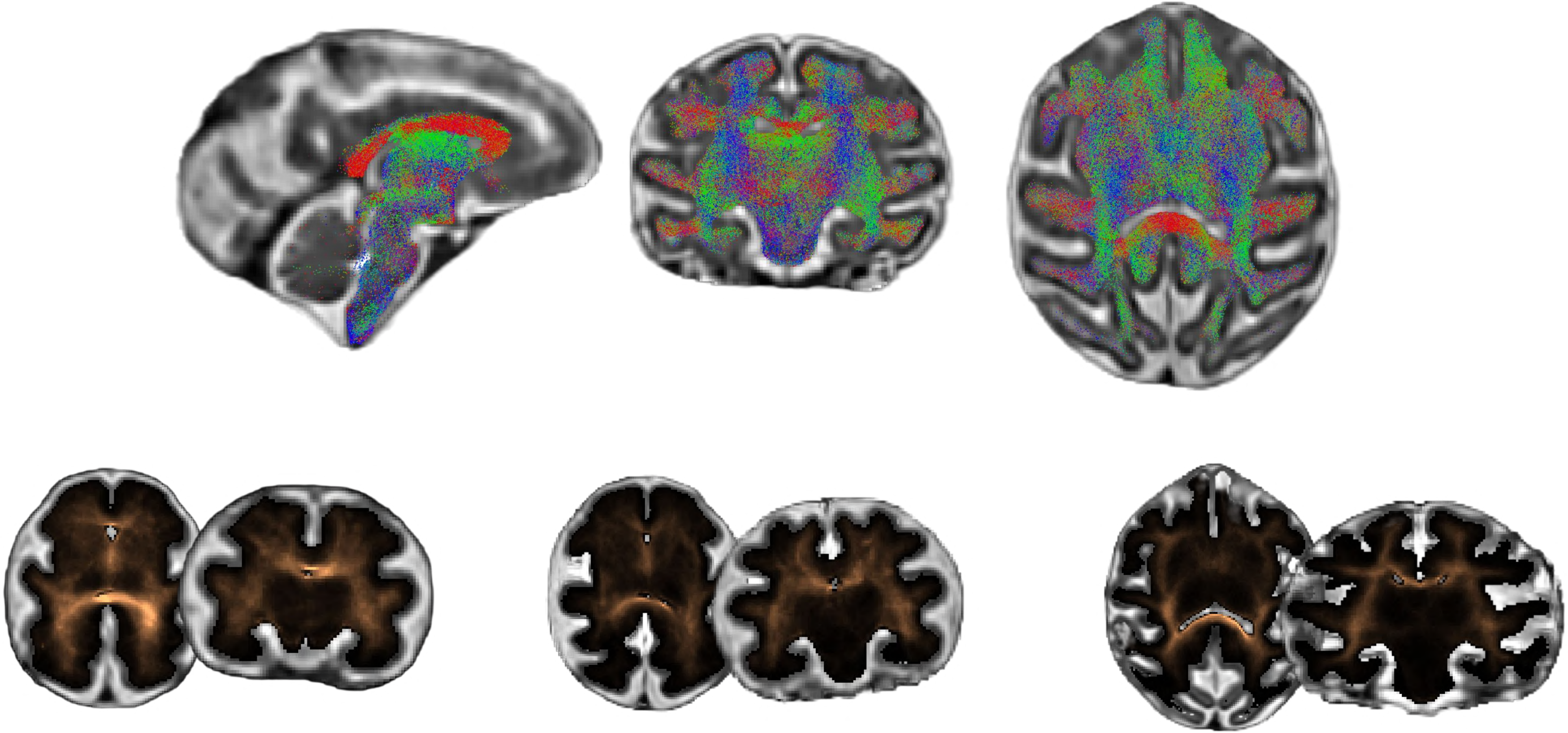
dHCP trends





BaboFet

Future work



THE PEOPLE


G. Auzias


O. Coulon


F. Rousseau


J. Sein


N. Girard


B. Leroux


D. Menieur


H. Dienye


M. Clémenceau


L. Renaud


L. Velly


A. Le Troter


B. Nazarian


J.-L. Anton


A. Manchon


M. Milh

THANK YOU!