UFO-3: Unsupervised Three-Compartment Learning for Fiber Orientation Distribution Function Estimation

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September 25, 2025

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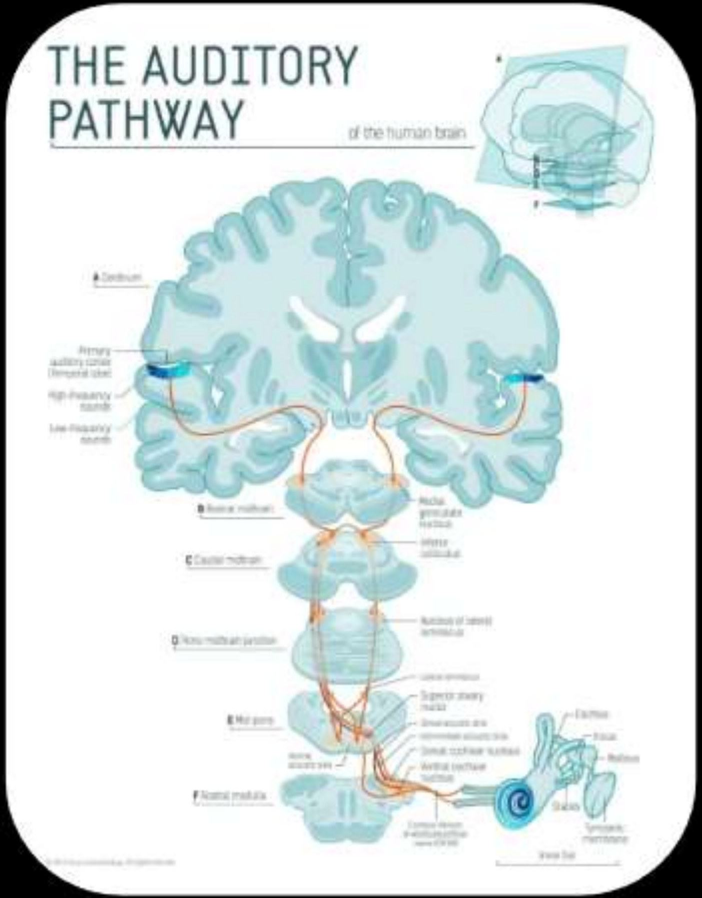
Three-Pound Universe in Your Brain

Listening[1]

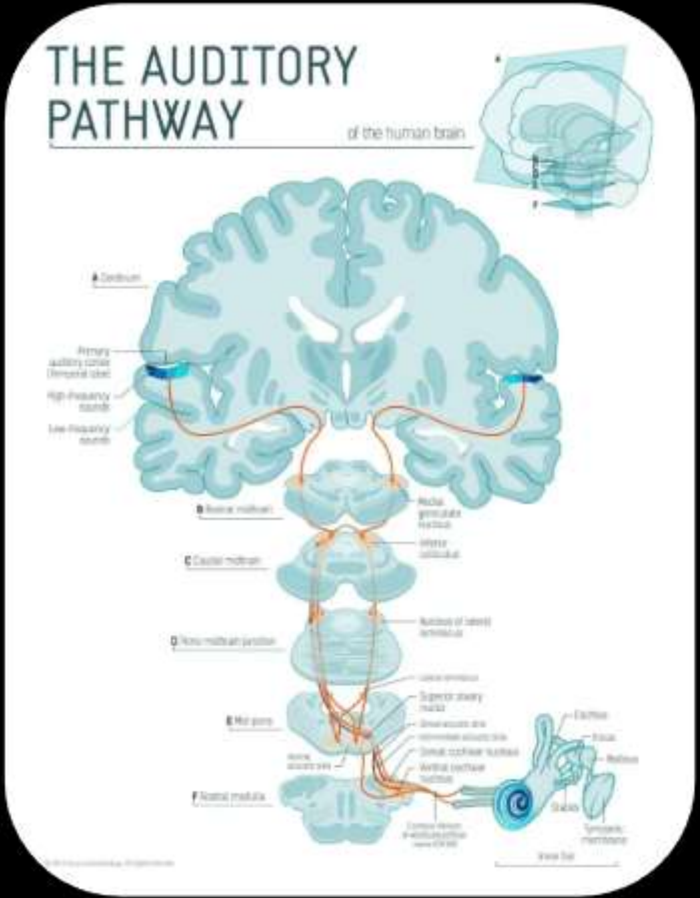


The auditory pathway[2]

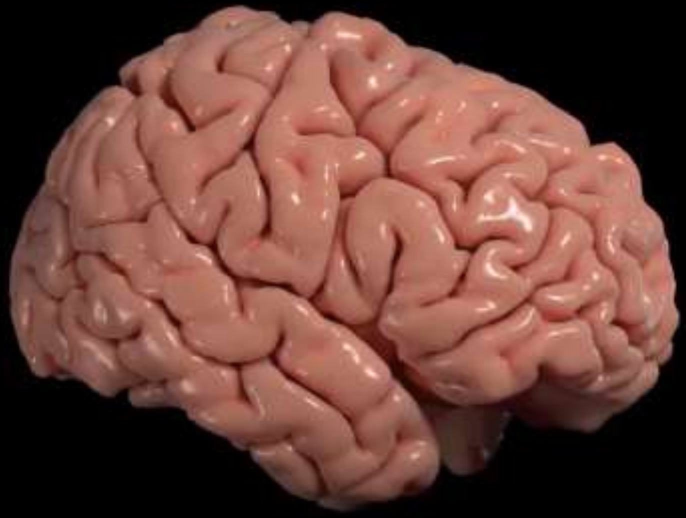
[1]Illustrative image from [Chapter 5: Understanding Context, Purpose & Audience – Academic Writing for Success Canadian Edition 2.0]
[2]Illustrative image from Inessa Stashkevich (2016), Auditory Pathway, https://inessaskaya.com/portfolio/auditory-pathway

Three-Pound Universe in Your Brain

Listening[1]



The auditory pathway[2]



Tractography[3]
(white matter connections in our brain)

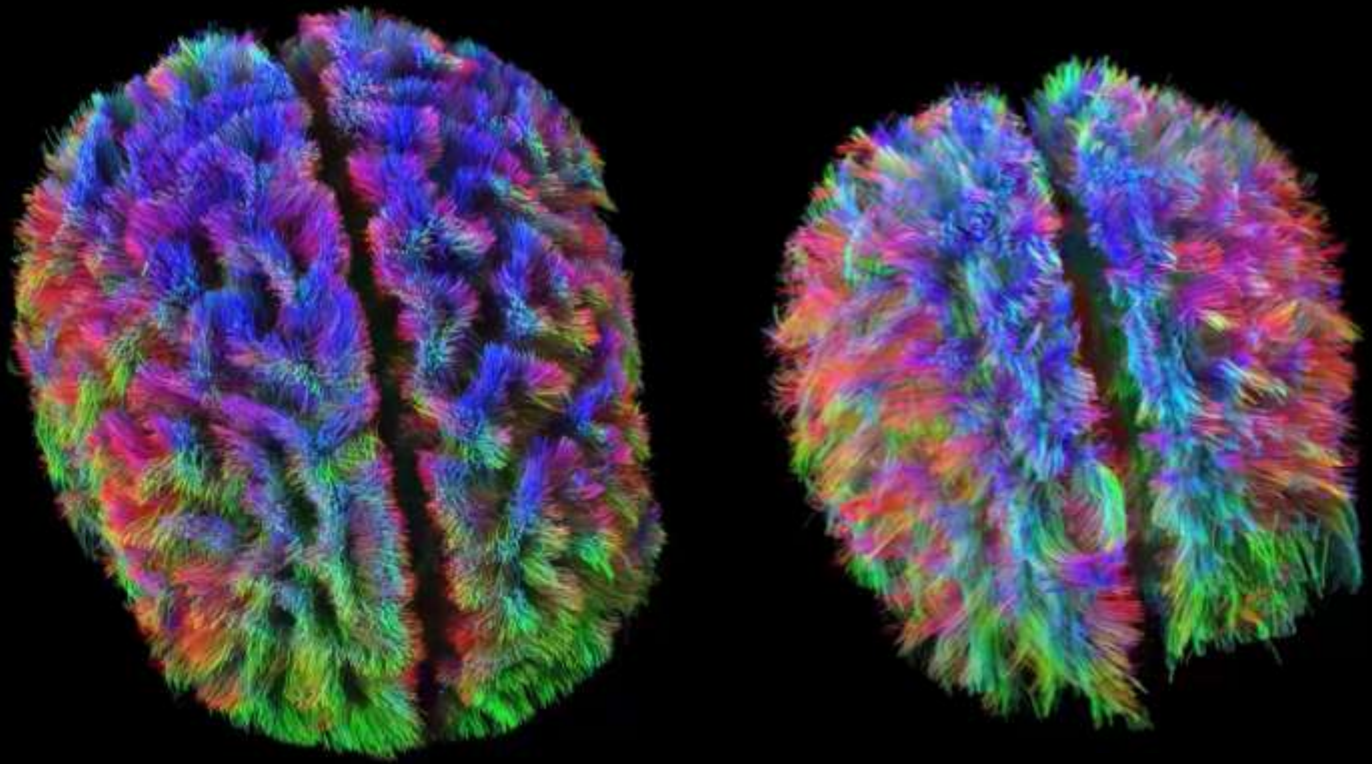
[1]Illustrative image from Chapter 5: Understanding Context, Purpose & Audience – Academic Writing for Success Canadian Edition 2.0
[2]Illustrative image from Inessa Stashkevich (2016), Auditory Pathway, https://inessaskaya.com/portfolio/auditory-pathway
[3]Illustrative video from Youtube @iniusc

Why Is Tractography Crucial?

1. Reveals White Matter Pathways[1]

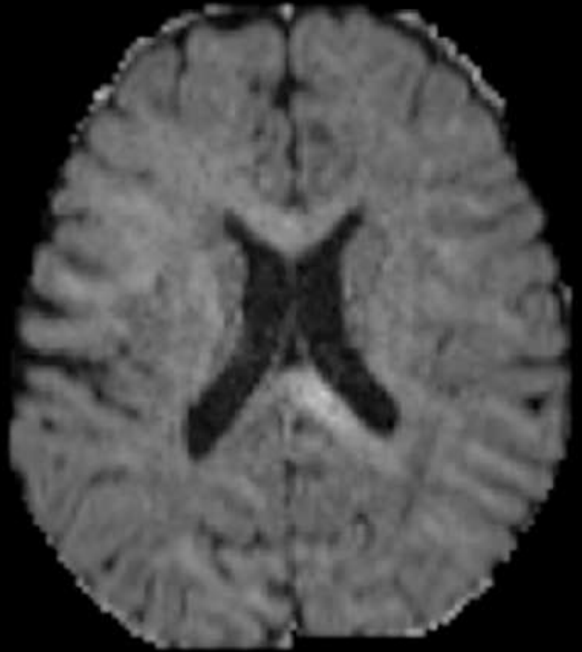
2. Surgical Planning[2]

Healthy **Injured**

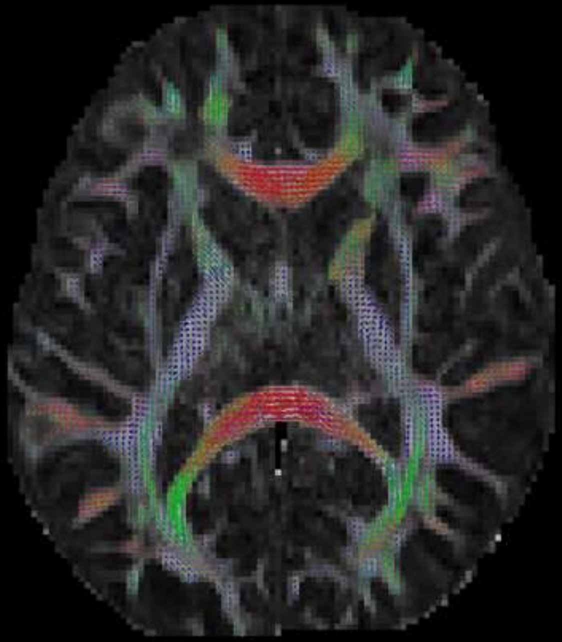


[1]Illustrative image from Youtube @iniusc
[2]Illustrative image from Instagram @medivis

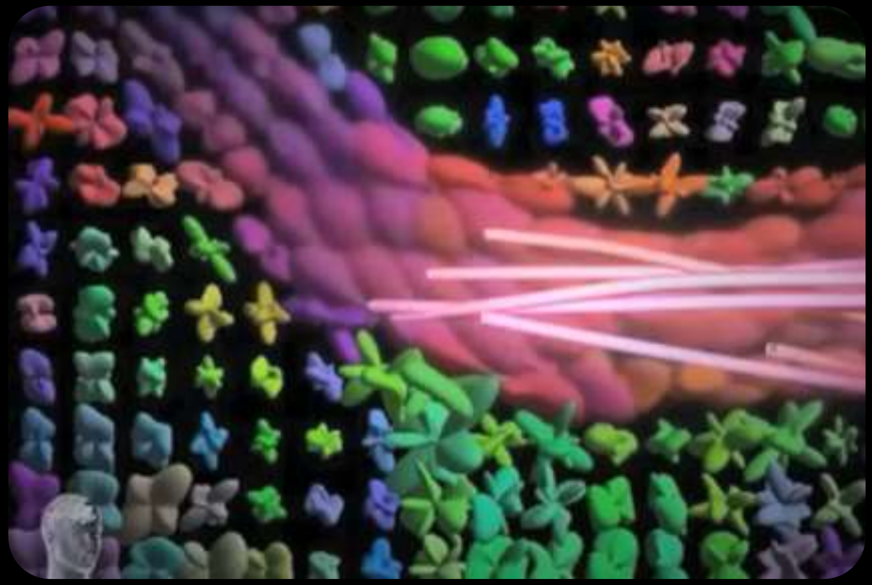
fODF (fiber Orientation Distribution Function): A Bridge from Signal to Tractography



Diffusion MRI



fODF



fODF →Tractography[1]

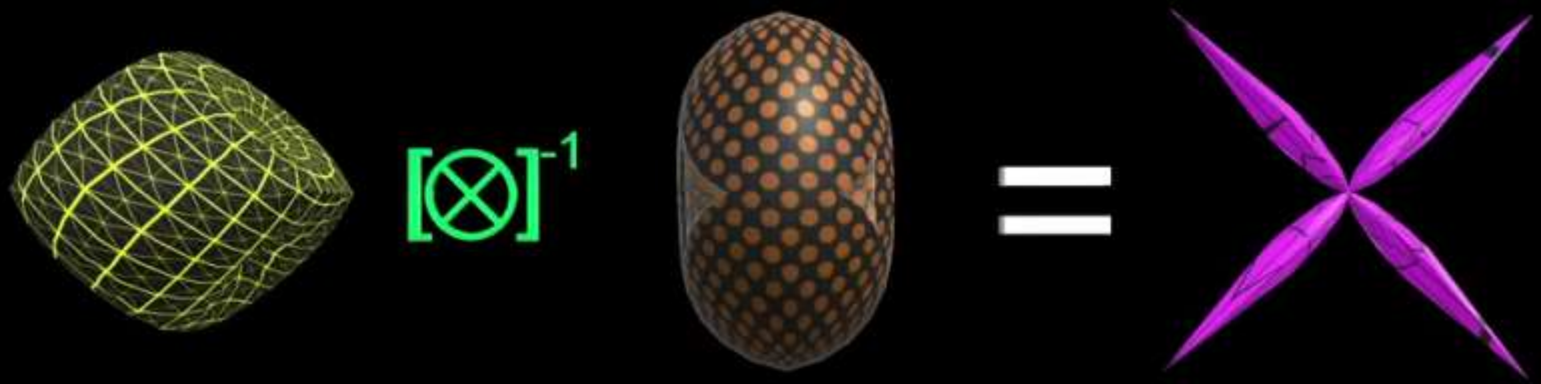
[1]Illustrative video from Youtube @iniusc

Our Goal, Spherical Deconvolution: fODF Estimation from Diffusion MRI

Diffusion MRI Signal (s)

Response Function $(\mathbf{A}_{+})$

fODF



Ill-posed inverse problem

Illustrative image from Youtube @iniusc

Traditional Model-Driven Methods for fODF Estimation

Constrained Spherical Deconvolution (CSD)[1]

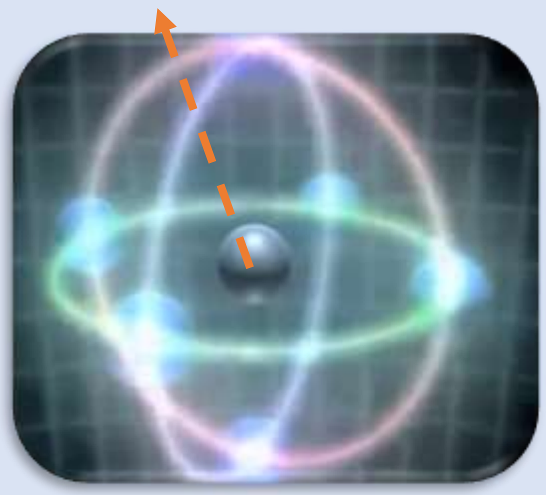
Multi-Shell Multi-Tissue CSD (MSMT-CSD)[2]

Single-Shell 3-Tissue CSD (SS3T-CSD)[3]

Three-Compartment Model[4]

Assumption

Water Molecule



Isotropically

Cell Wall

Anisotropically

Modeling

Response function

Solver:

$$fODF_{k+1} = T(fODF_k; dMRI)$$

with stop test $\|r_k\| < \tau$

Iter 1

Iter 2

Iter 3

Iter 4

Iter 5

……

[1]Tournier, J.-D. et al, NeuroImage, 2007 [2]Jeurissen, B. et al, NeuroImage, 2014 [3]Jeurissen, B. et al, NeuroImage, 2016 [4]Tran, G., Shi, Y., IEEE Trans Med Imaging, 2015

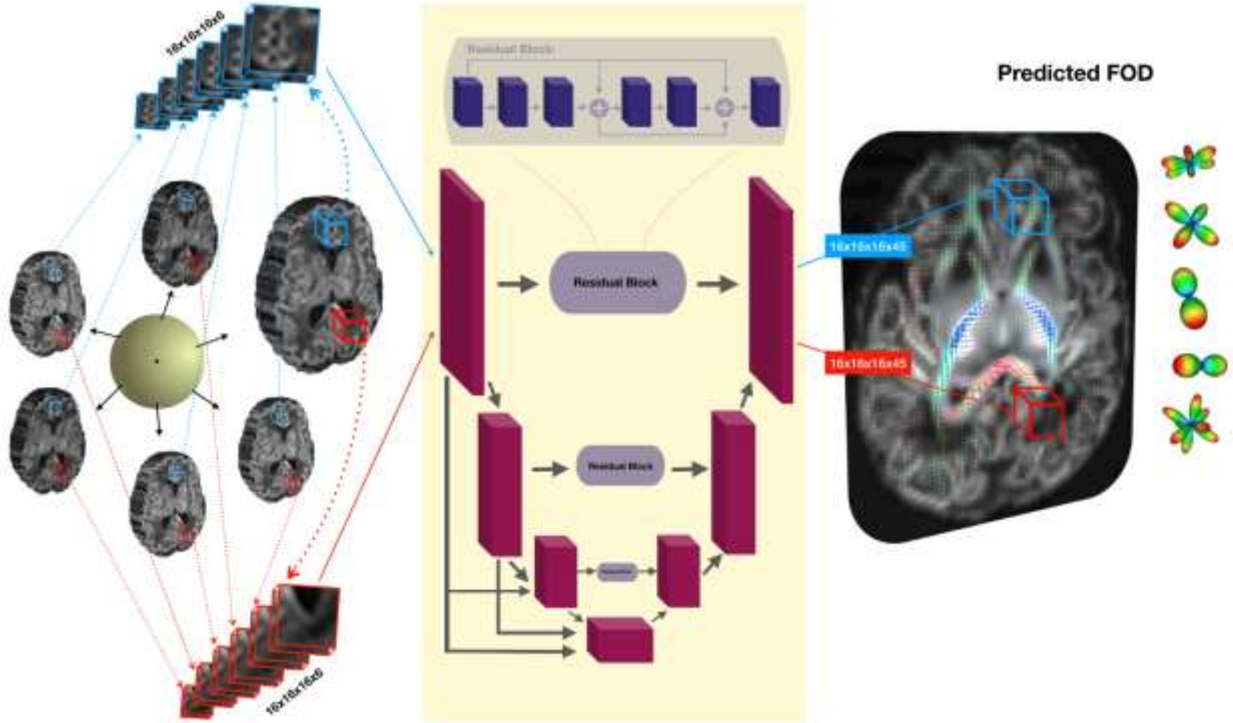
Supervised Learning:
Efficient Estimation from Limited Data

Constrained Spherical Deconvolution (CSD)[1]

Ground truth: MSMT-CSD[2]-estimated fODF

Single-Shell 3-Tissue CSD (SS3T-CSD)[3]

Three-Compartment Model[4]



Supervised framework[5]

[1]Tournier, J.-D. et al, NeuroImage, 2007 [2]Jeurissen, B. et al, NeuroImage, 2014 [3]Jeurissen, B. et al, NeuroImage, 2016 [4]Tran, G., Shi, Y., IEEE Trans Med Imaging, 2015
[5]Kebiri, H. et al, Medical Image Analysis (2024)

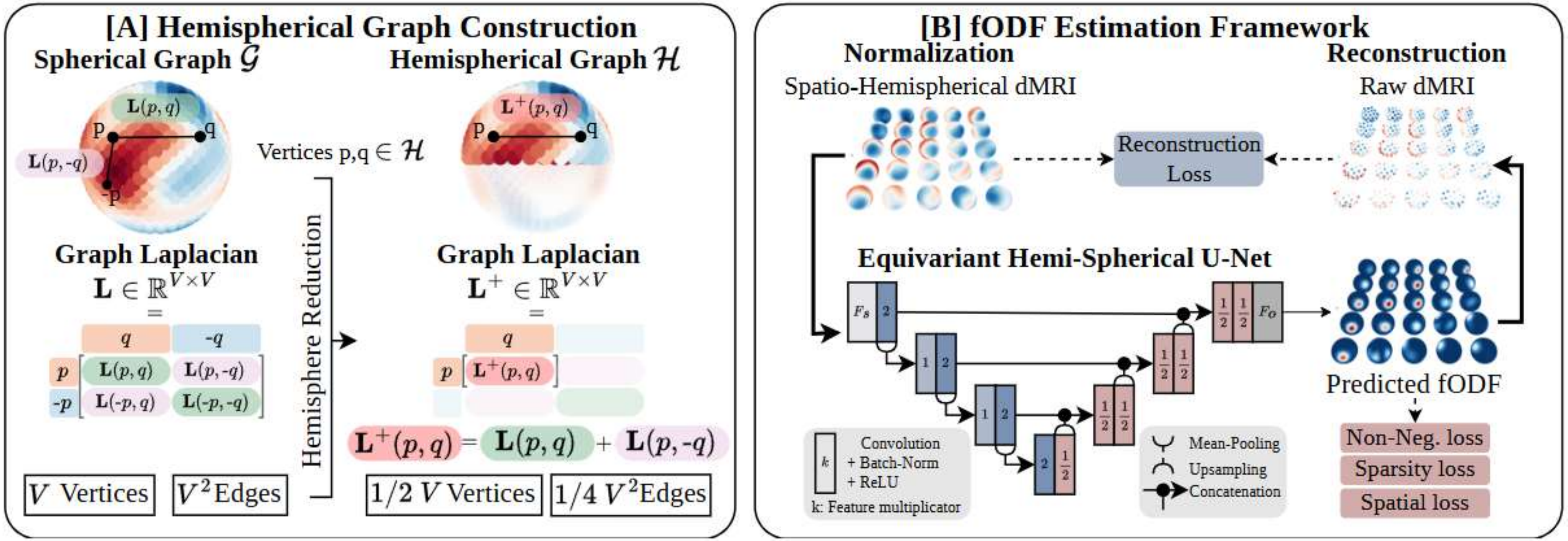
Unsupervised Learning:
Label-free

Constrained Spherical Deconvolution (CSD)[1]

Modeling as MSMT-CSD[2]

Single-Shell 3-Tissue CSD (SS3T-CSD)[3]

Three-Compartment Model[4]



Unsupervised framework SHD-TV[5]

[1]Tournier, J.-D. et al, NeuroImage, 2007 [2]Jeurissen, B. et al, NeuroImage, 2014 [3]Jeurissen, B. et al, NeuroImage, 2016 [4]Tran, G., Shi, Y., IEEE Trans Med Imaging, 2015
[5]Elaldi, A. et al, NeurIPS, 2024

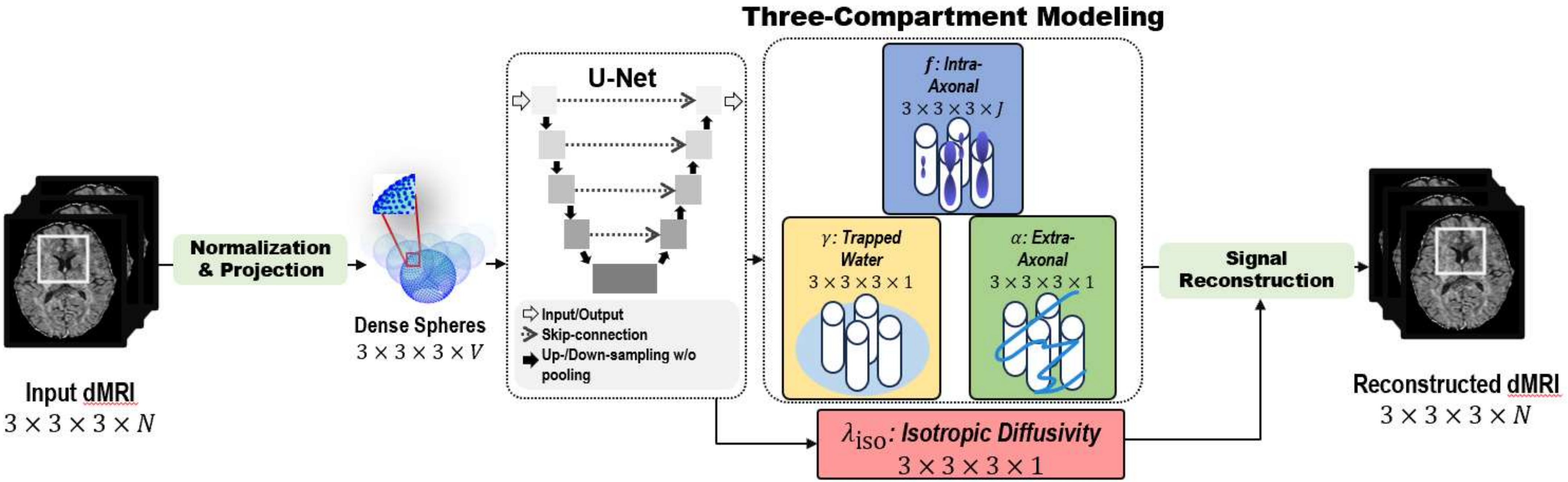
UFO-3: Unsupervised Three-Compartment Learning

Constrained Spherical Deconvolution (CSD)[1]

Multi-Shell Multi-Tissue CSD (MSMT-CSD)[2]

Single-Shell 3-Tissue CSD (SS3T-CSD)[3]

Modeling as Three-Compartment Model[4]



Train+Inference time ↓ to 0.5 h **Joint optimization of response function** **High sensitivity to crossing fibers**

[1]Tournier, J.-D. et al, NeuroImage, 2007 [2]Jeurissen, B. et al, NeuroImage, 2014 [3]Jeurissen, B. et al, NeuroImage, 2016 [4]Tran, G., Shi, Y., IEEE Trans Med Imaging, 2015

Three-Compartment model

The diffusion signal $s \in \mathbb{R}^N$ is modeled as[1]:

$$\boldsymbol{s} = \mathbf{A}_{+}[\boldsymbol{f}\ \alpha\ \gamma]^{\top} + n,$$

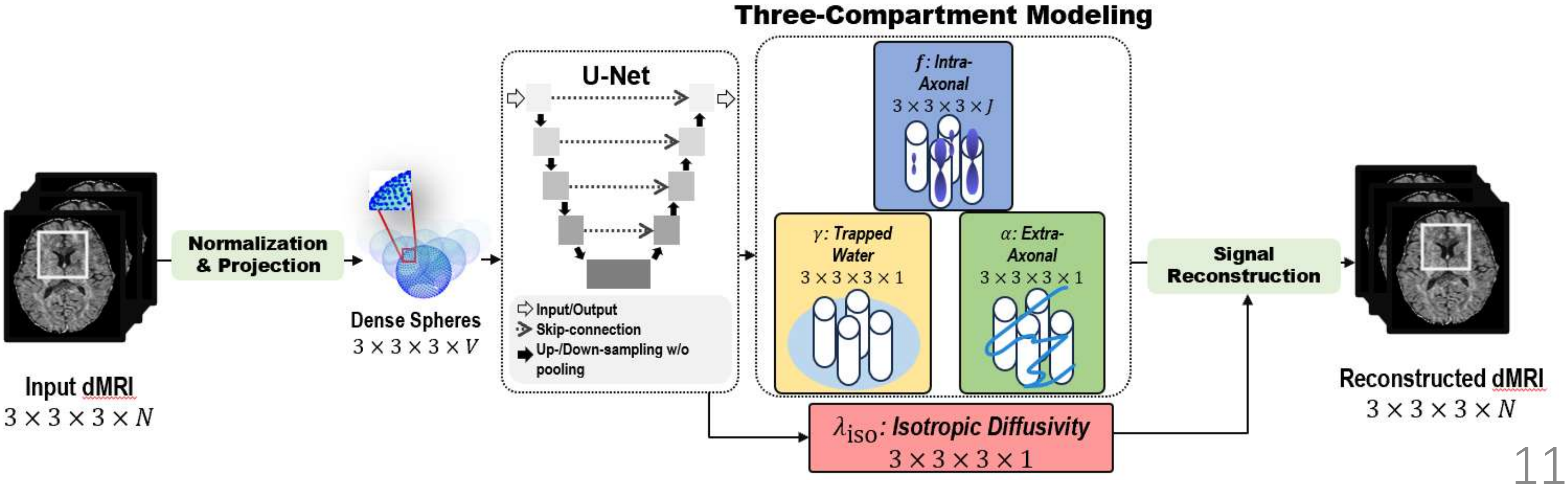
$$\mathbf{A}_{+} = [\mathbf{A}\ \boldsymbol{\beta}\ \boldsymbol{e}]$$

where $\boldsymbol{\beta} = \left[e^{-b_1\lambda_{\text{iso}}}\ \ldots e^{-b_N\lambda_{\text{iso}}}\right]^{\top}$ and $\boldsymbol{e} = \mathbf{1}_N$.

$$\mathbf{A} = \mathbf{Y} \odot \mathbf{G}$$

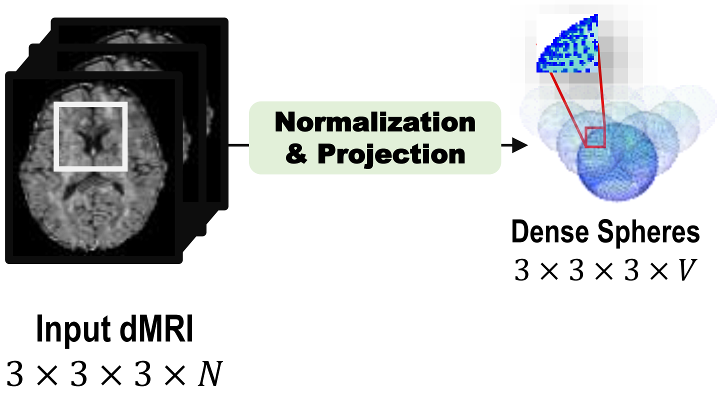
$\mathbf{Y}$: real even-order SH basis functions at sampling directions.

$\mathbf{G}$: values from Legendre polynomials with exponential decay, repeated per order.

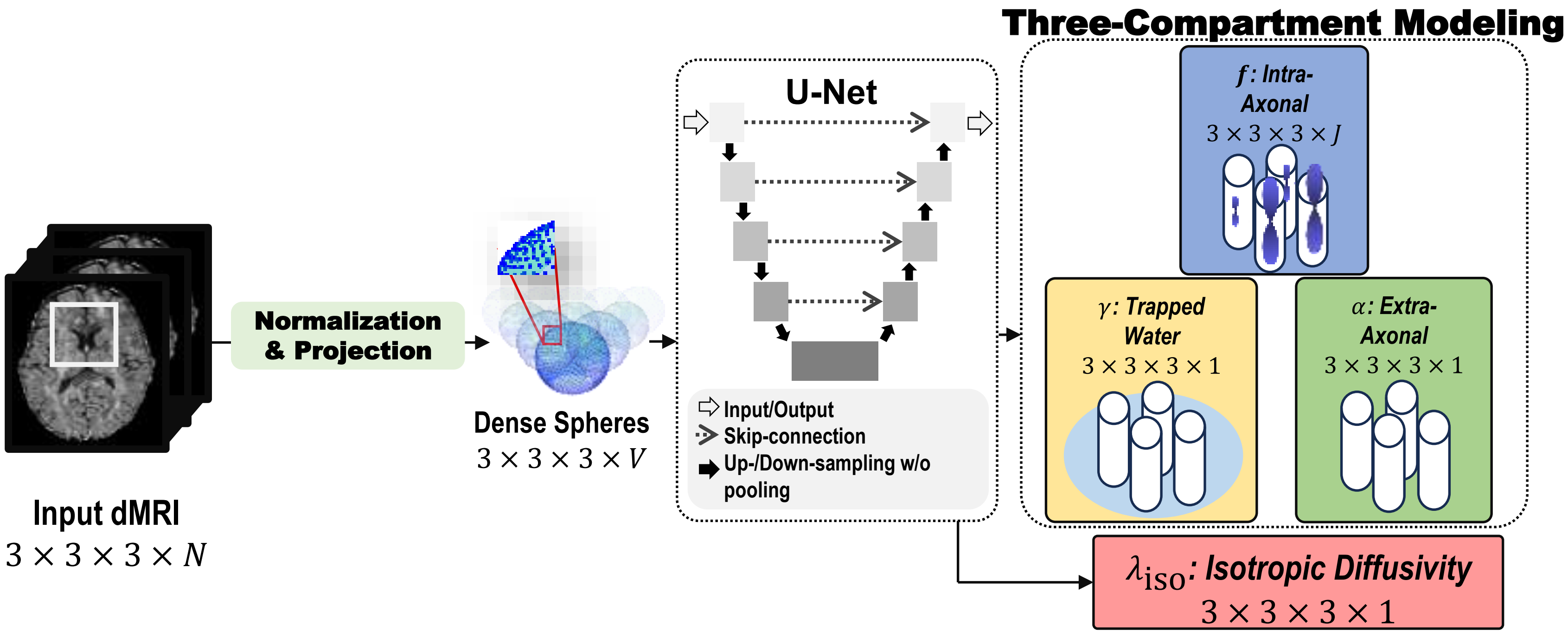


[1]Tran, G., Shi, Y., IEEE Trans Med Imaging, 2015

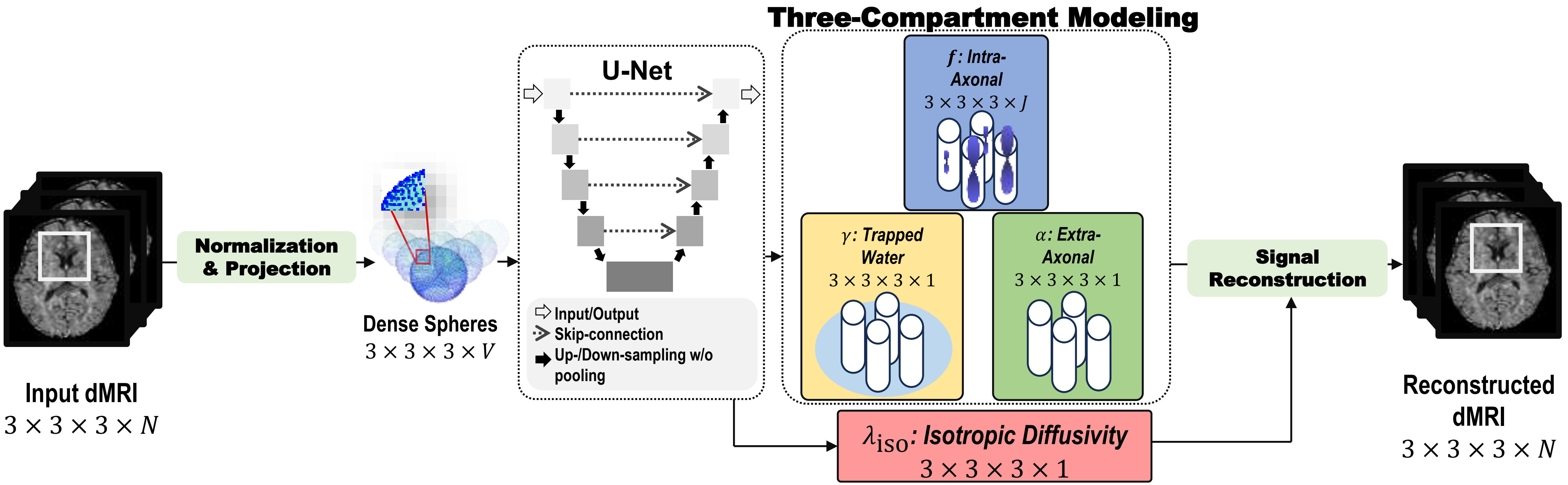
Framework: UFO-3



Framework: UFO-3



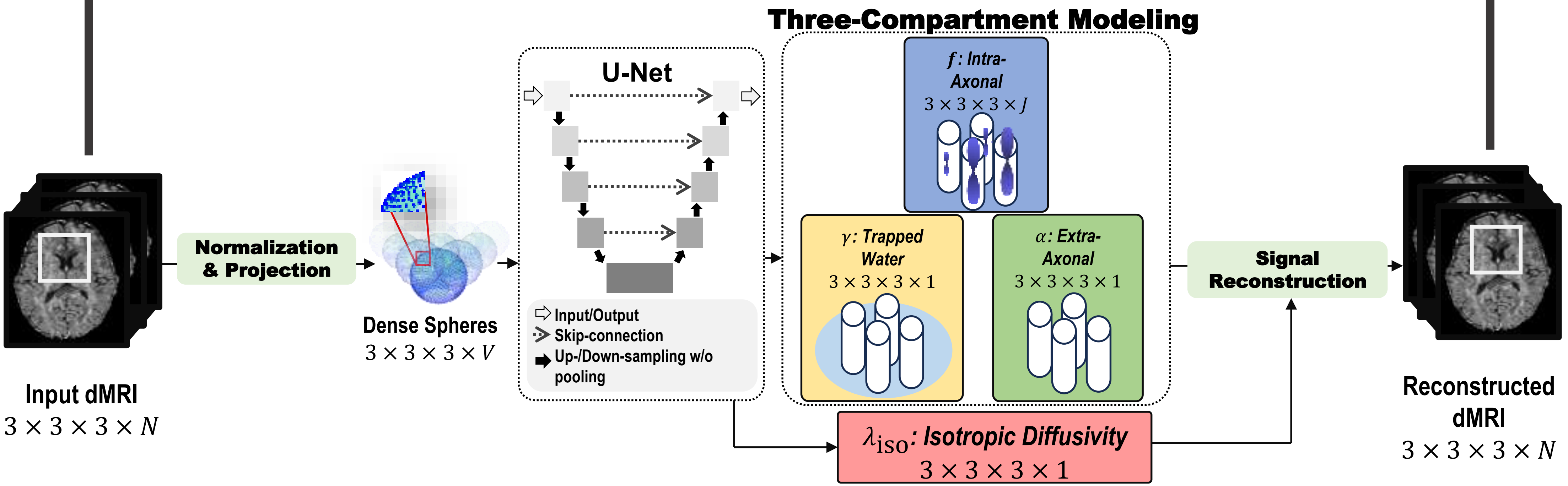
Framework: UFO-3



Framework: UFO-3

Loss: Data consistency term + Regularization term

$$\min \quad \frac{1}{2}\left\| s - \mathbf{A}_{+}(\lambda_{\text{iso}})[\boldsymbol{f} \quad \alpha \quad \gamma]^{\top} \right\|_2^2 + \xi \mathrm{Reg}(\mathbf{C}_M \boldsymbol{f})$$



Experiment 1: fODF Estimation on Synthetic Data

UFO-3: sharp; accurate crossing fibers

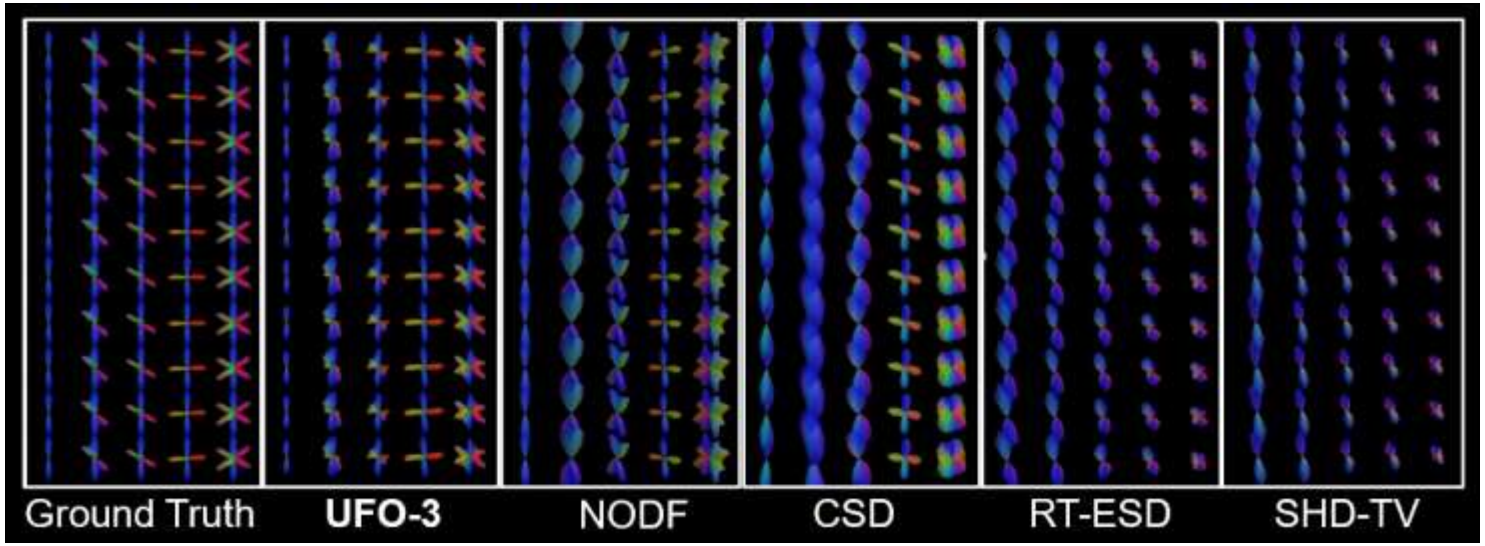


Fig. 2a. Synthetic data: fODF reconstruction comparison

Experiment 1: Synthetic fODF reconstruction

UFO-3: sharp; accurate crossing fibers

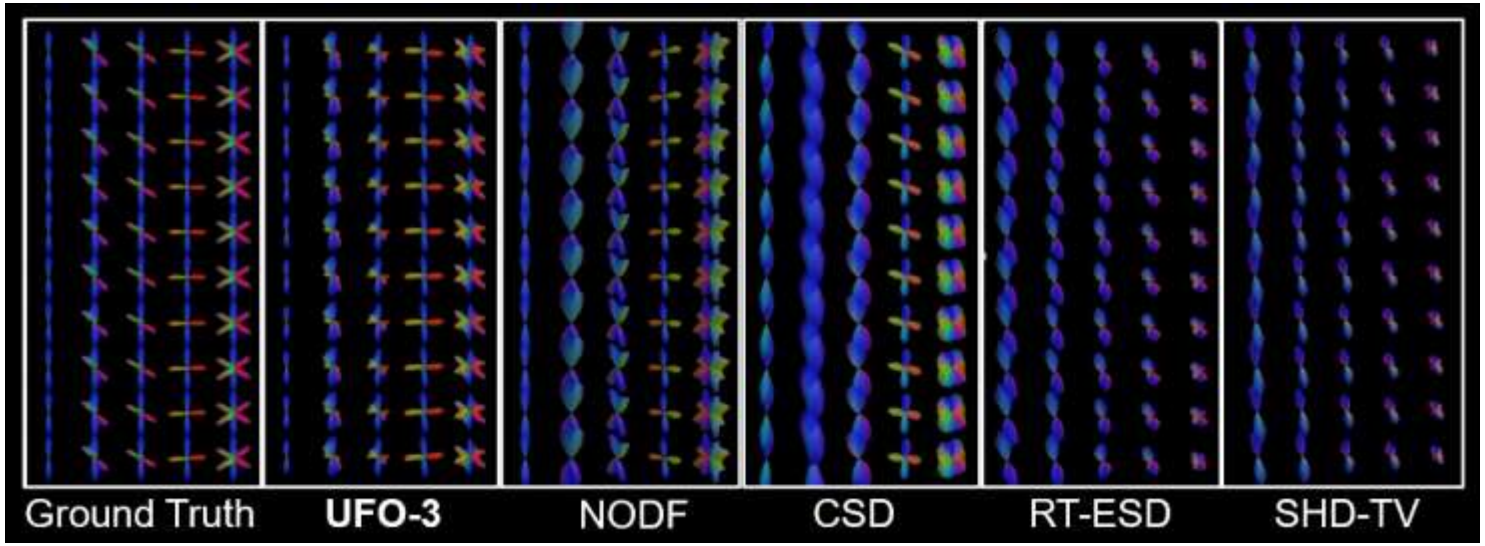


Fig. 2a. Synthetic data: fODF reconstruction comparison

UFO-3: lowest MAE, highest ACC, Noise-Resilient

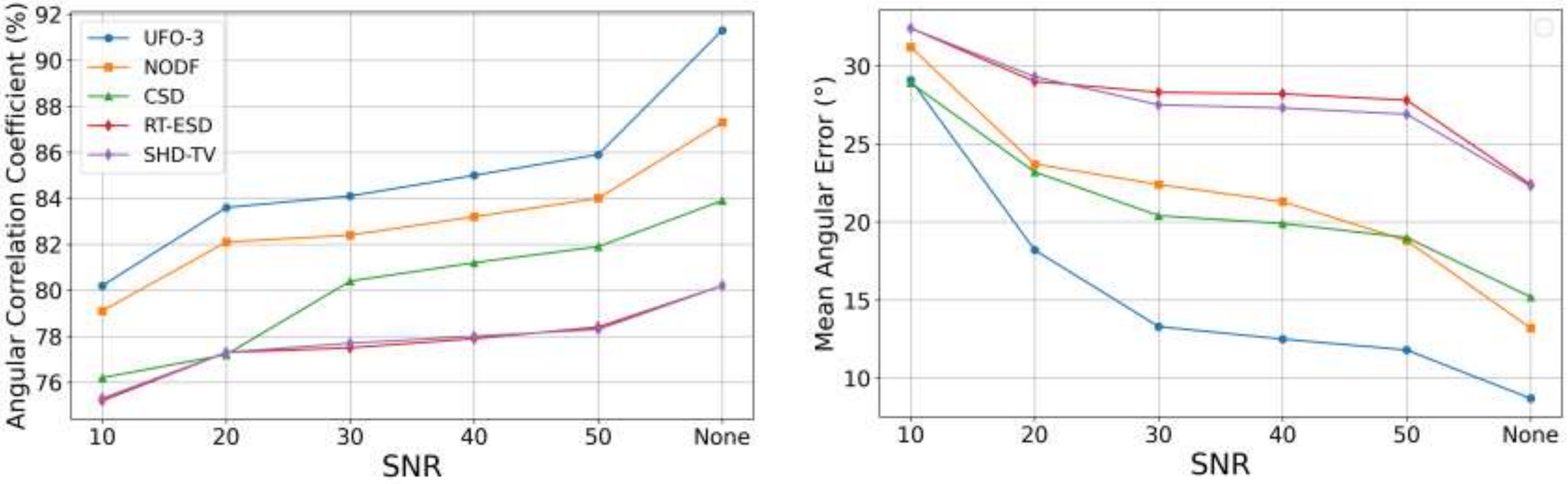


Fig. 2b. Synthetic data: ACC and MAE vs SNR

Experiment 2: In vivo human brain

UFO-3 matches multi-shell references, clear separation

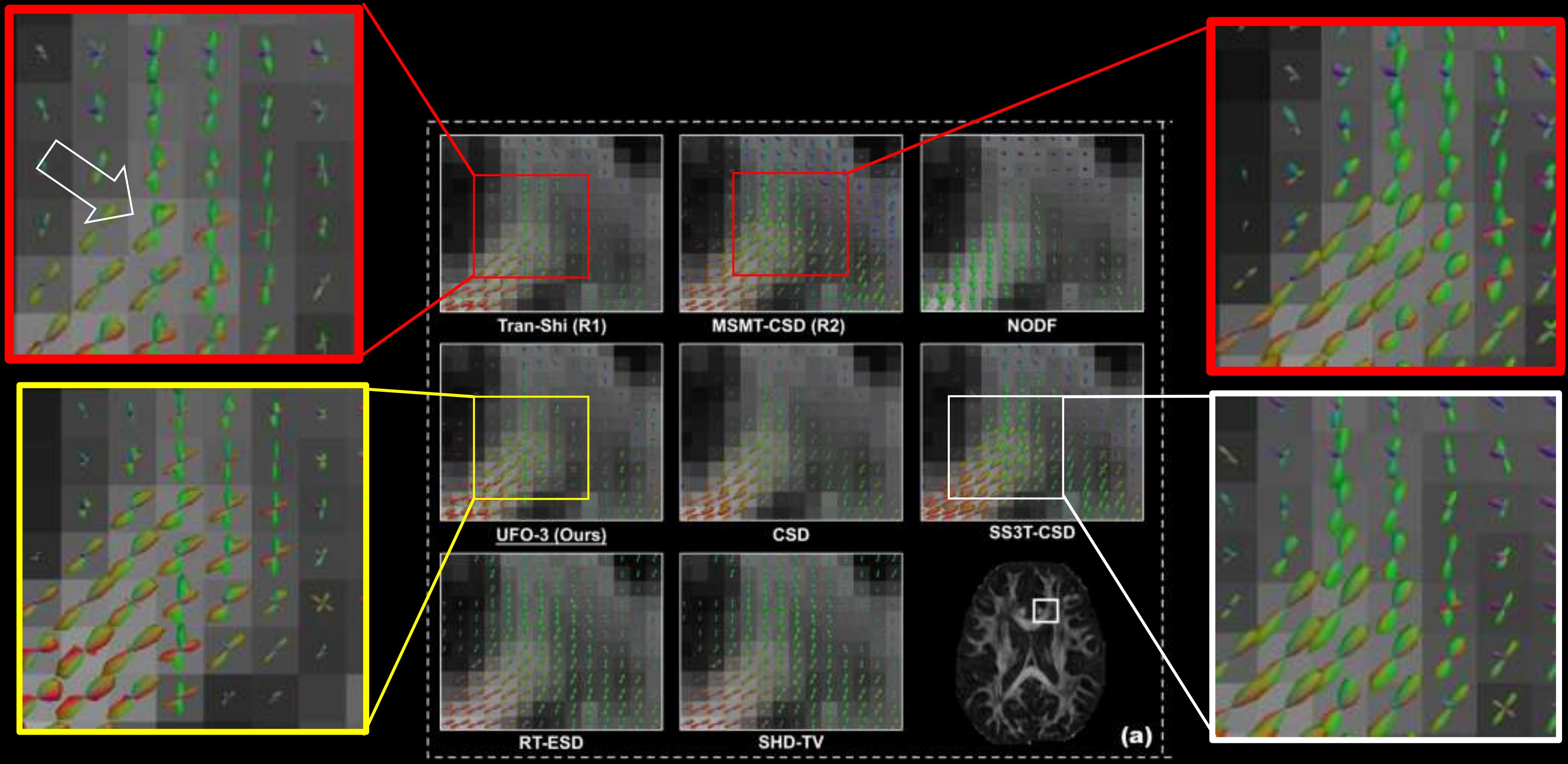
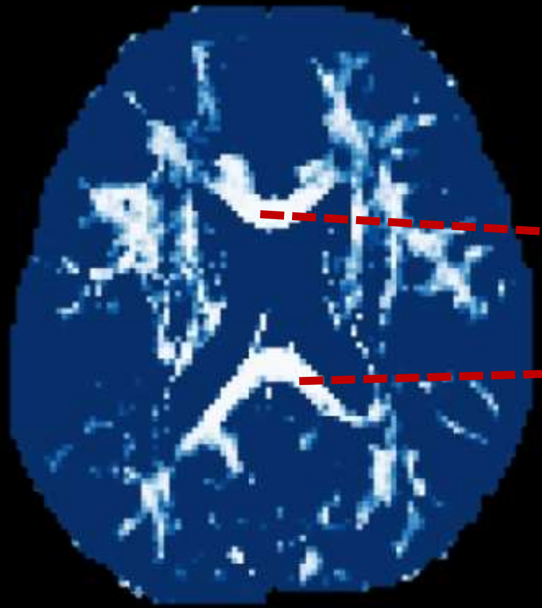
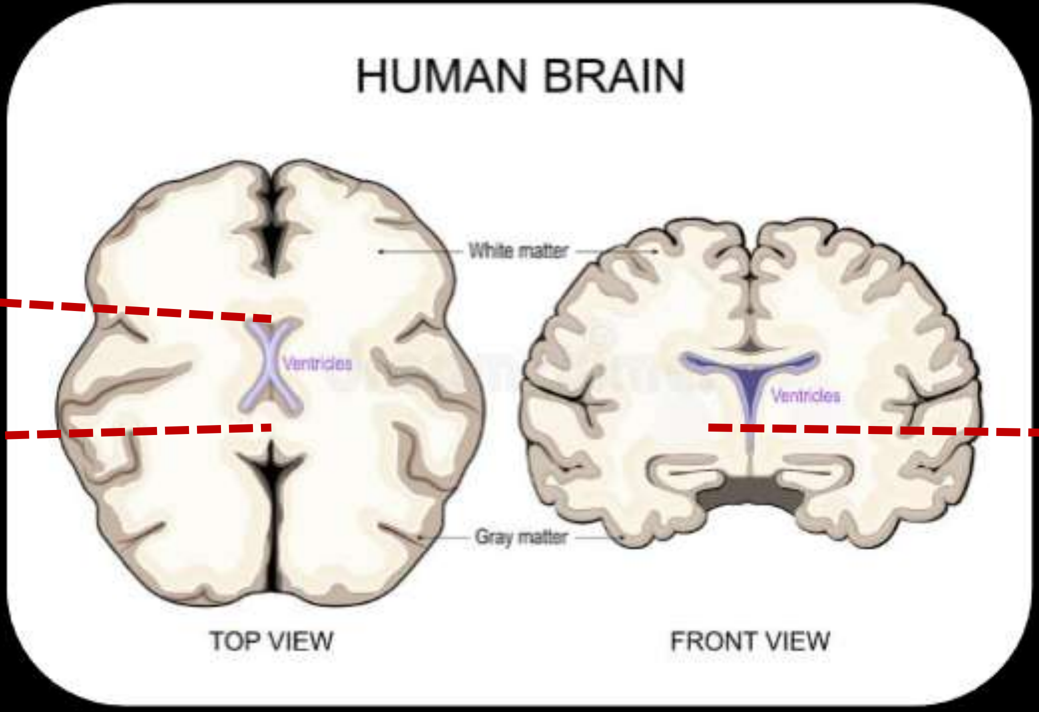


Fig. 3a. In vivo CHCP data: fODF comparison

Experiment 2: In vivo human brain

λ_{iso} shows anatomically plausible distribution





Reference[1]

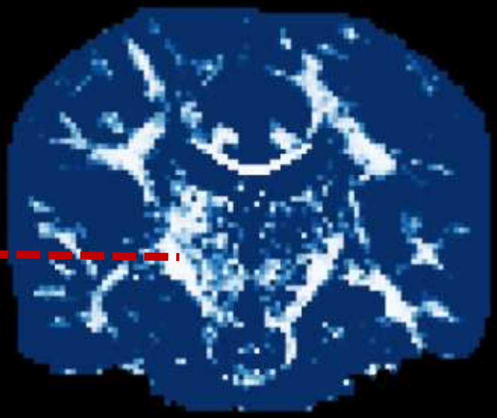


Fig. 3b. In vivo CHCP data: λ_{iso} diffusivity maps

[1]Brain Anatomy. White Matter and Gray Matter Stock Vector - Illustration of cross, matter: 326607647

Experiment 3: Tractography reconstruction analysis

UFO-3 captures more high-curvature fibers

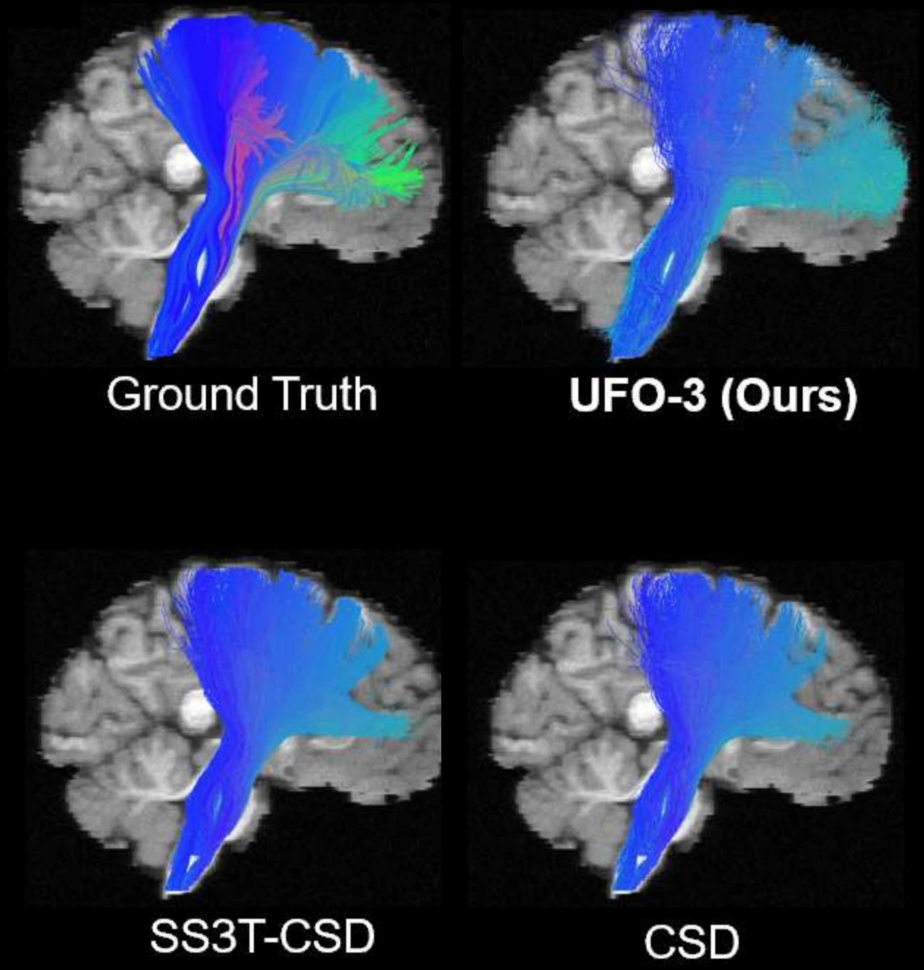


Fig. 4. ISMRM 2015 Tractometer challenge: brainstem tractography results

Conclusion

We proposed UFO-3:

- *Fast inference + joint response optimization*
- *Higher crossing-fiber sensitivity*
- *Biophysical interpre, unsupervised, subject-specific fODF*

Future work:

- *Broader validation*
- *Faster speed*

Thank you!

Poster: C289, Session 4, Fri-AM

ISTBI

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Daejeon Convention Center
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Seeking a PhD position. My page:

Paper

EPFL

LONI Laboratory of Neuro Imaging

The Chinese Human Connectome Project

Tractometer

NSFC

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