Enhancing the Spatial Resolution of Hyperpolarized Carbon-13 MRI of Human Brain Metabolism using Structure Guidance

Matthias J. Ehrhardt

Department of Mathematical Sciences, University of Bath, UK

November 11, 2021

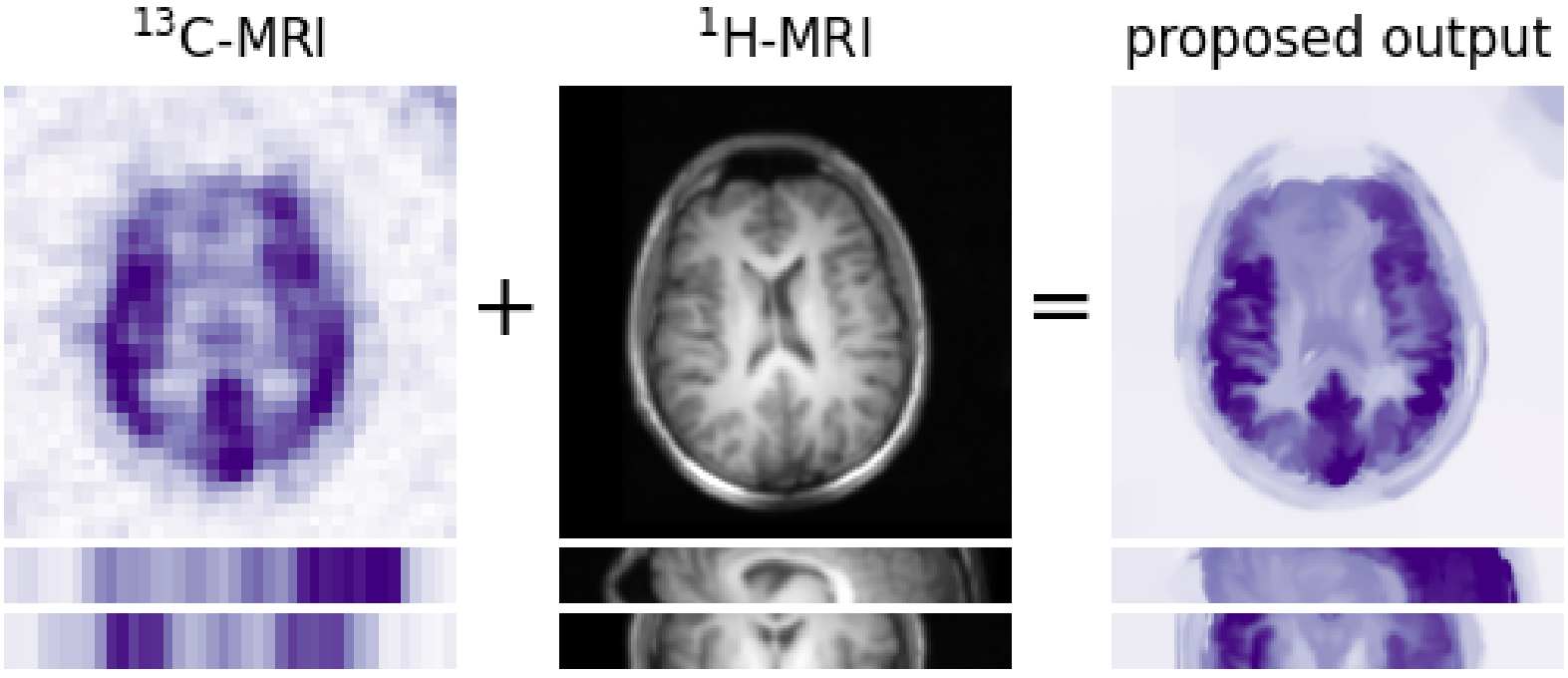
Joint work with:
F. Gallagher, M. McLean, C.-B. Schönlieb (all Cambridge, UK)

The Leverhulme Trust

UKRI Engineering and Physical Sciences Research Council

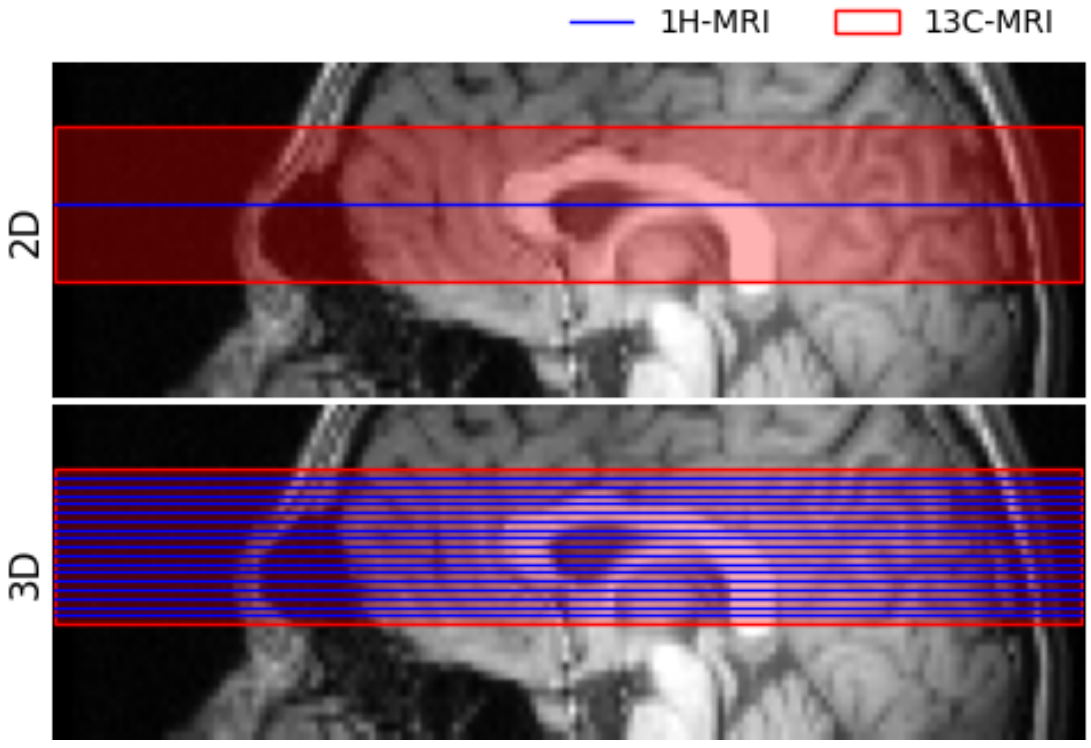
UNIVERSITY OF BATH

Motivation



- **Carbon-13** Magnetic Resonance Imaging (^{13}C-MRI) has a relatively **low spatial resolution**
- **enhance ^{13}C-MRI resolution** with **structural information** of Hydrogen-1 MRI (^{1}H-MRI)

Novelty



- **Superresolution** of ^{13}C-MRI using ^{1}H-MRI gained increased interest recently Farkash et al. MRM 2019, Dwork et al. Magn Res Mat Phys Bio Med 2021, Ma and Park Tomography 2020
- **Novelty 1: 2D v 3D anatomical data**
- **Novelty 2: improved mathematical model (dTV)**

Proposed Method

3D-dTV

$$\hat{x} = \arg\min_x \left\{ \|Sx - y\|_2^2 + \lambda \mathcal{R}(x) \right\}$$

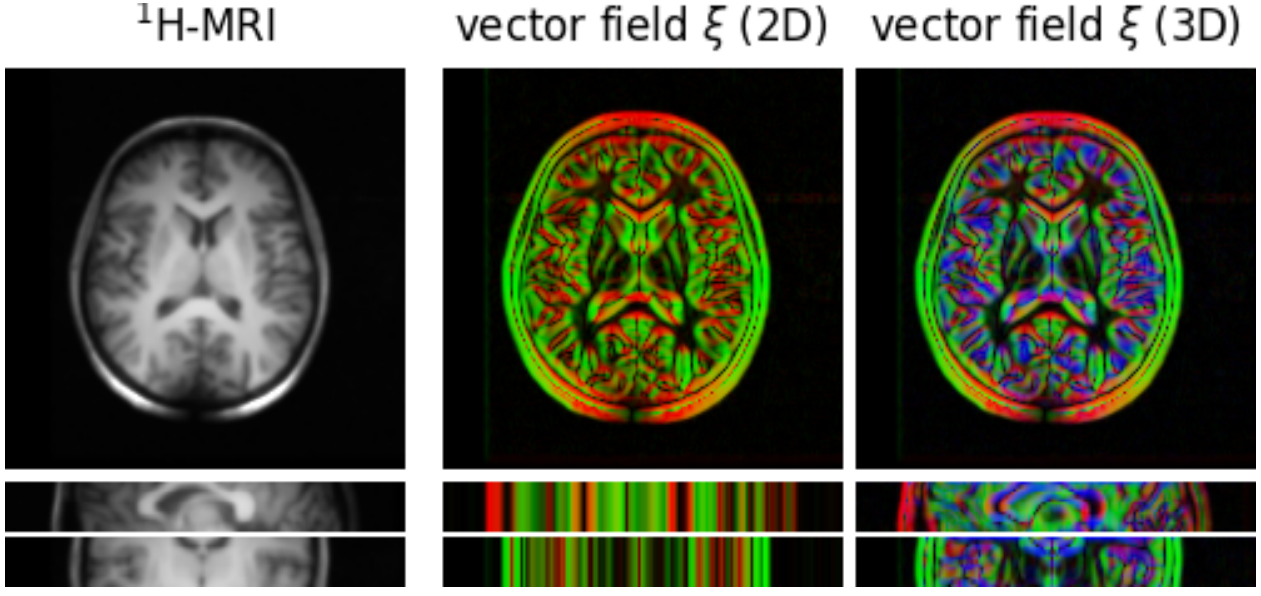
- x : desired high-resolution ^{13}C-MRI image
- y : low-resolution ^{13}C-MRI image
- S : resolution model; 3D high-res to 2D low-res

Proposed Method

3D-dTV

$$\hat{x} = \arg\min_x \left\{ \|Sx - y\|_2^2 + \lambda \mathcal{R}(x) \right\}$$

- $\|Sx - y\|_2^2$: data fidelity, can be related to noise statistics
- $\mathcal{R}$: **directional total variation (dTV)** encourages similarity to ^{1}H-MRI and smoothness Ehrhardt and Betcke 2016
- $\lambda \geq 0$: balances fit-to-data and regularity



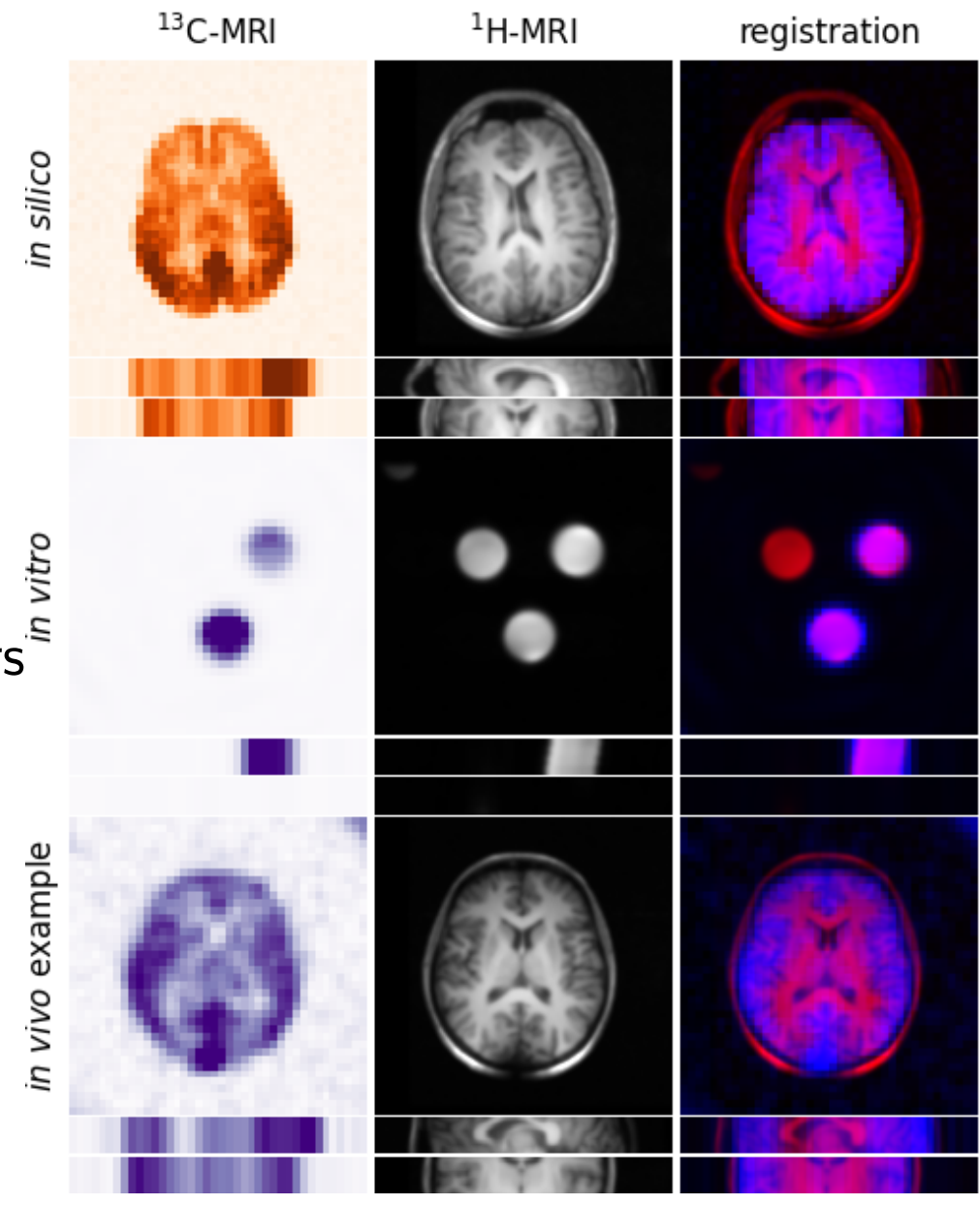
Overview of Data

- 1x *In silico:* GM/WM $\approx$ 4, smooth variations
- 1x *In vitro:* 3 tubes

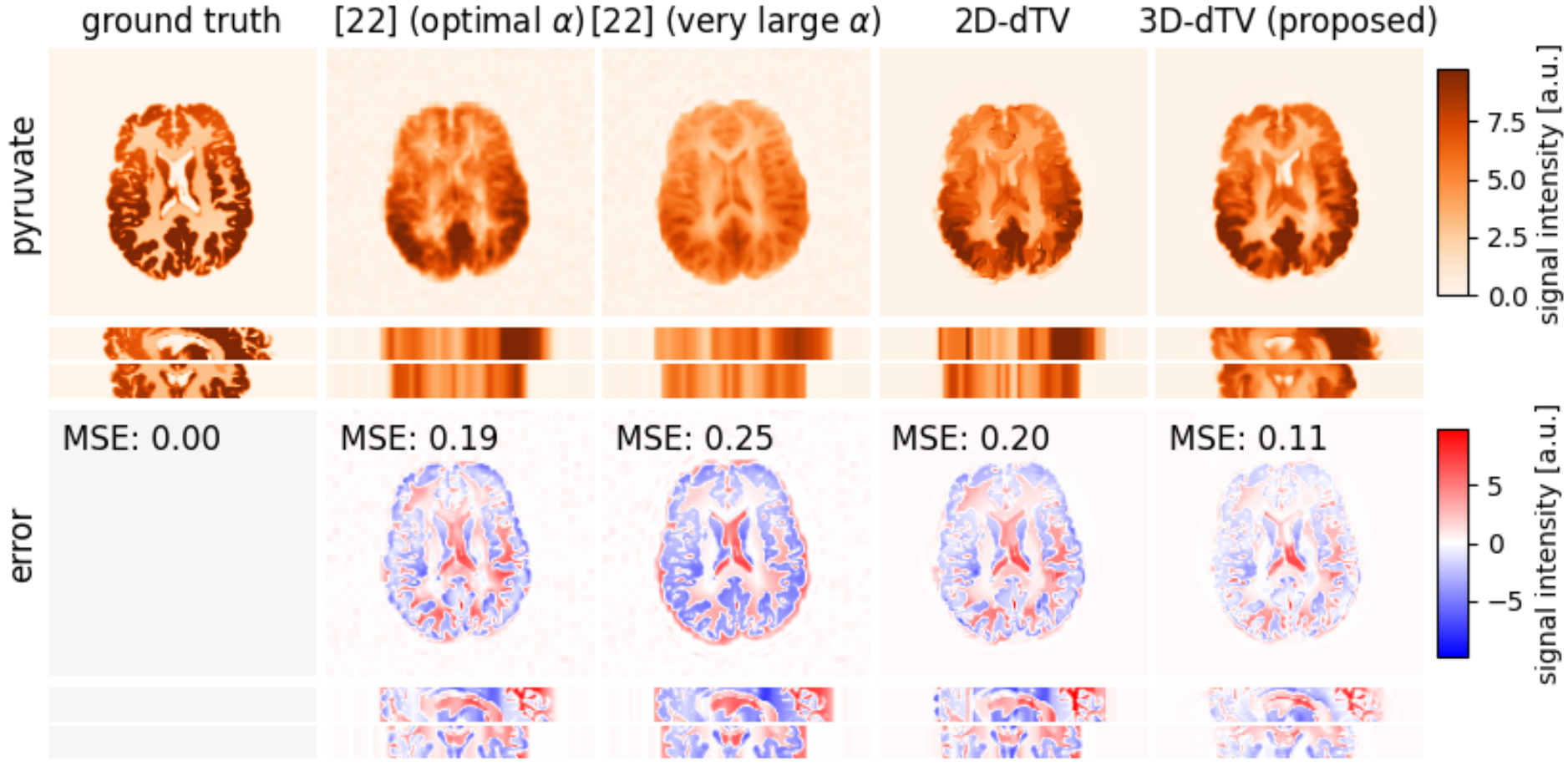
  Daniels et al. NMR Biomed 2016
- 4x *In vivo:* healthy volunteers

  Grist et al. NeuroImage 2019

Images need to be **registered**!

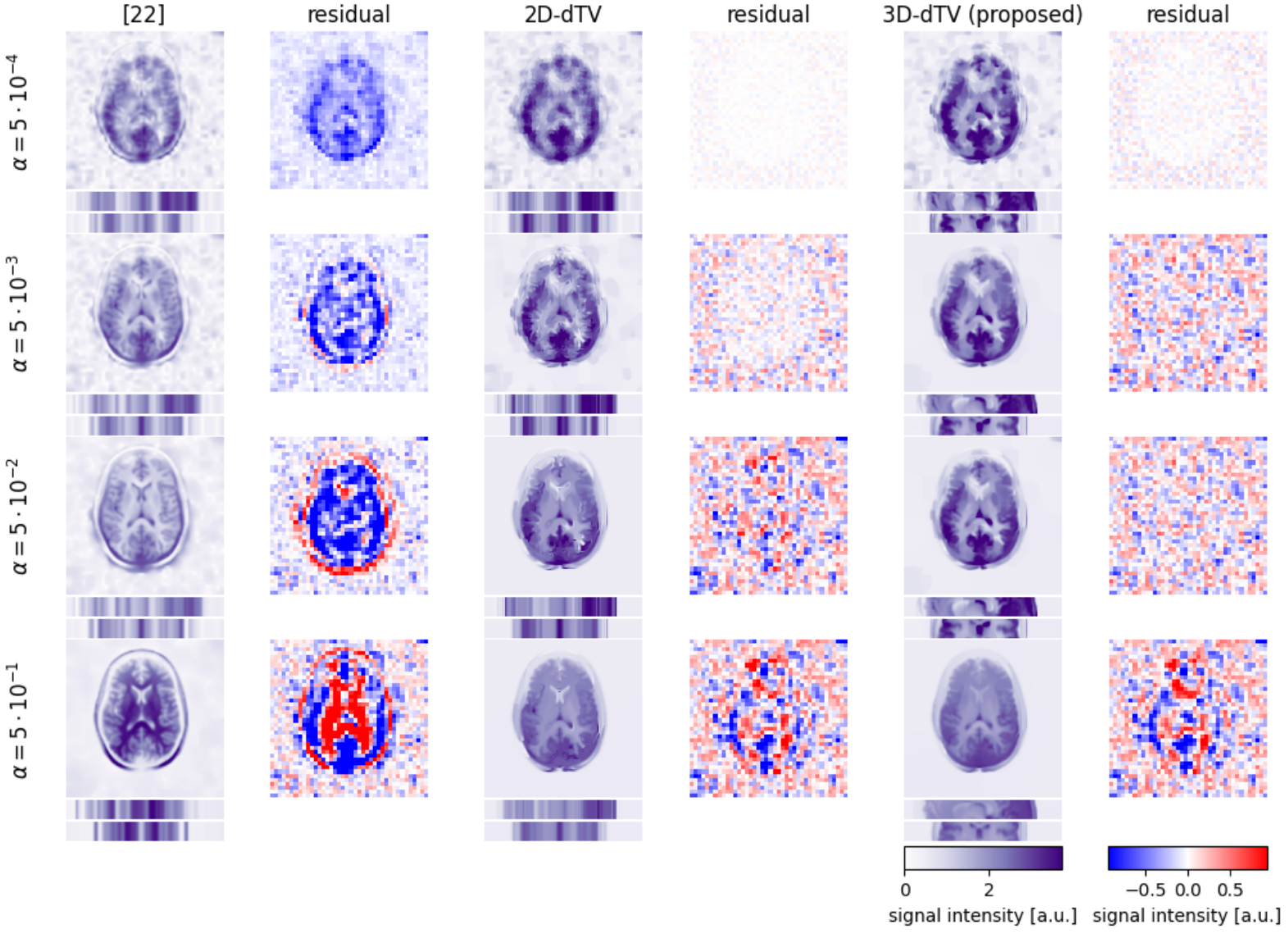


Compare methods: *In Silico*



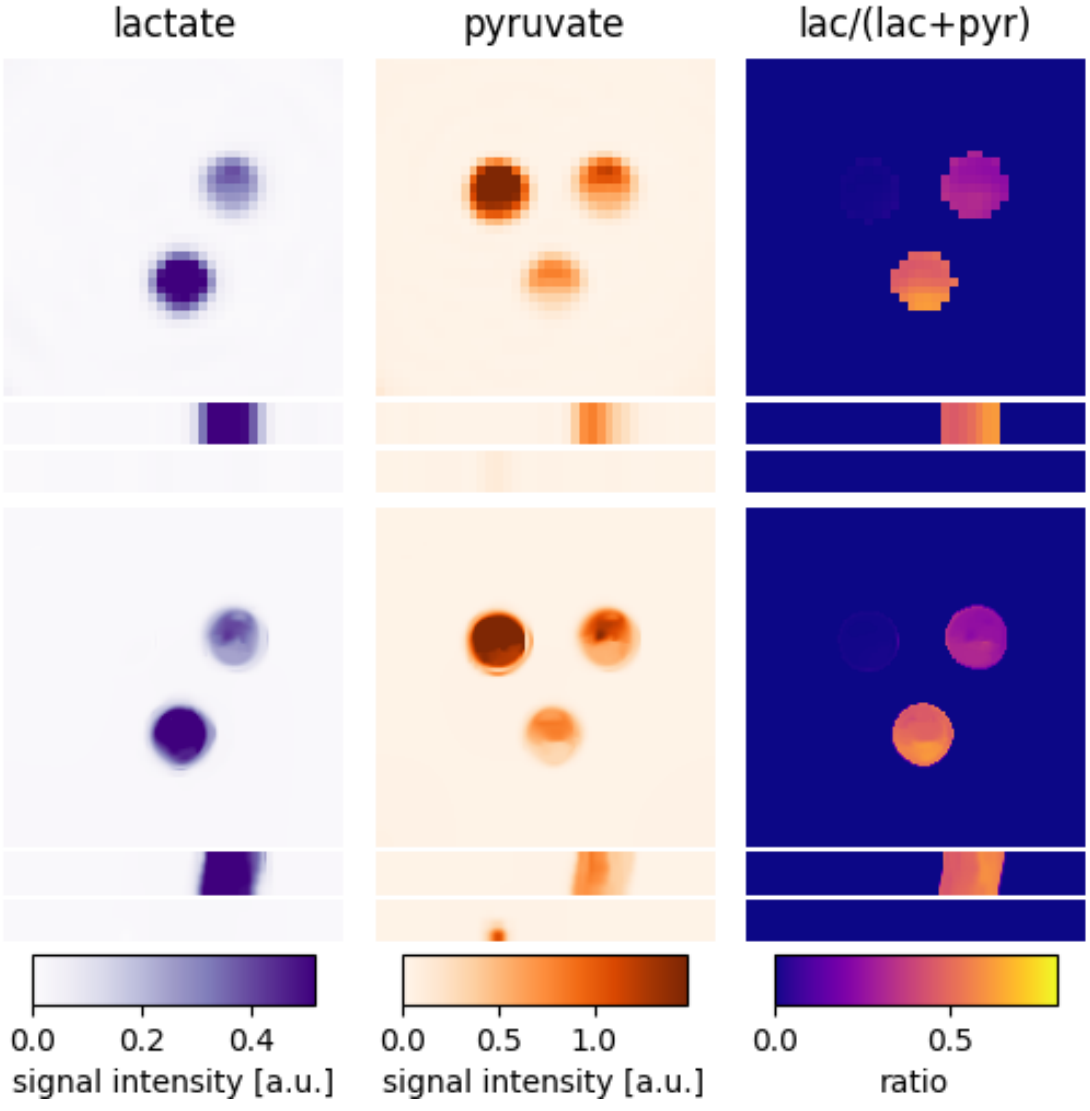
- [22] = Dwork et al. 2021 enforces ^{13}C-MRI and ^{1}H-MRI globally to **either have positive or negative correlation** (see CSF for large α)
- **3D-dTV** leads to **anatomically better-defined structures** compared to **2D-dTV**

Compare methods: *In Vivo*



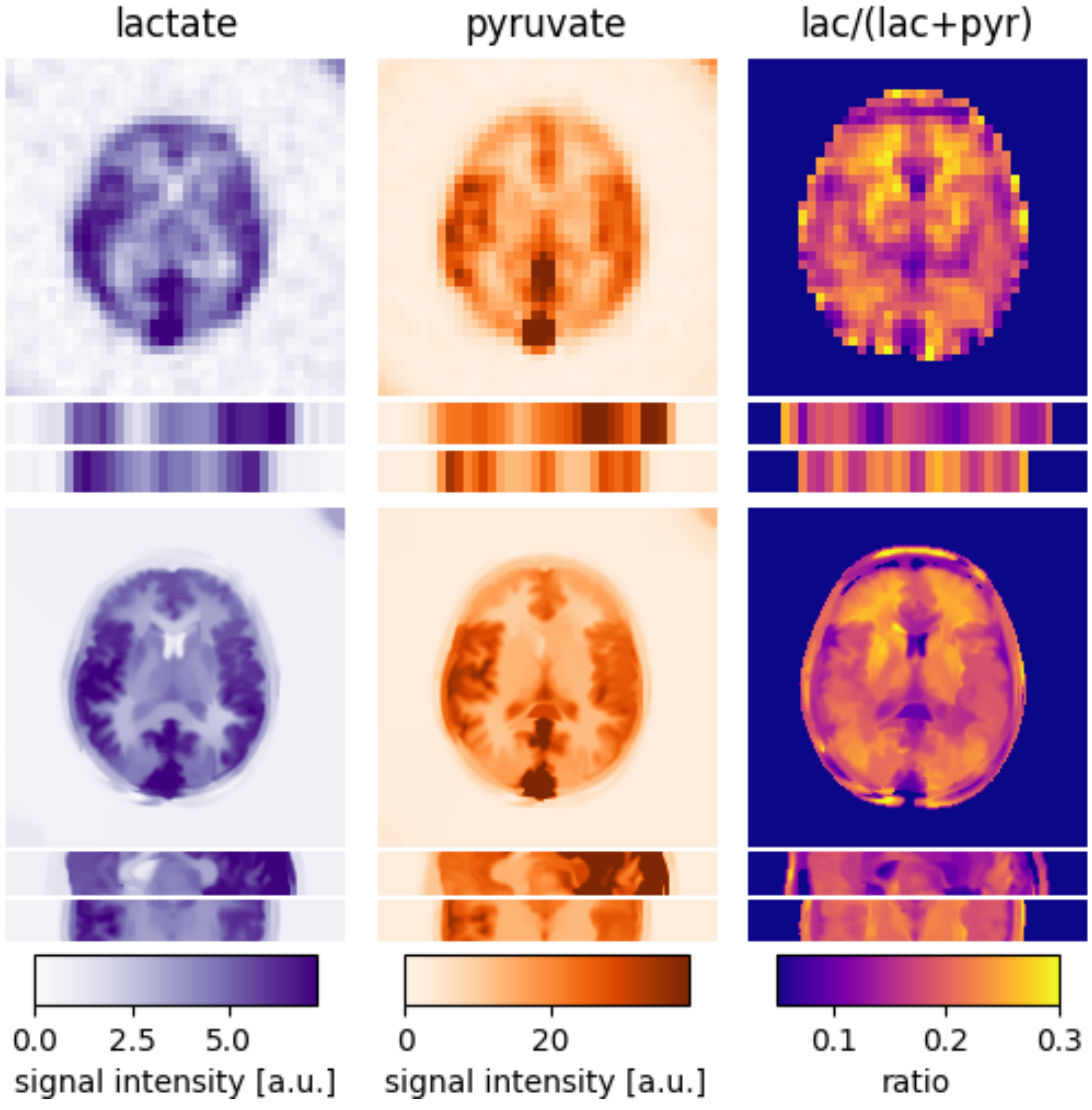
- **Similar observations** as for *in silico* data
- [22] = Dwork et al. 2021. **Bad fit to data**

Qualitative evaluation: *In Vitro*



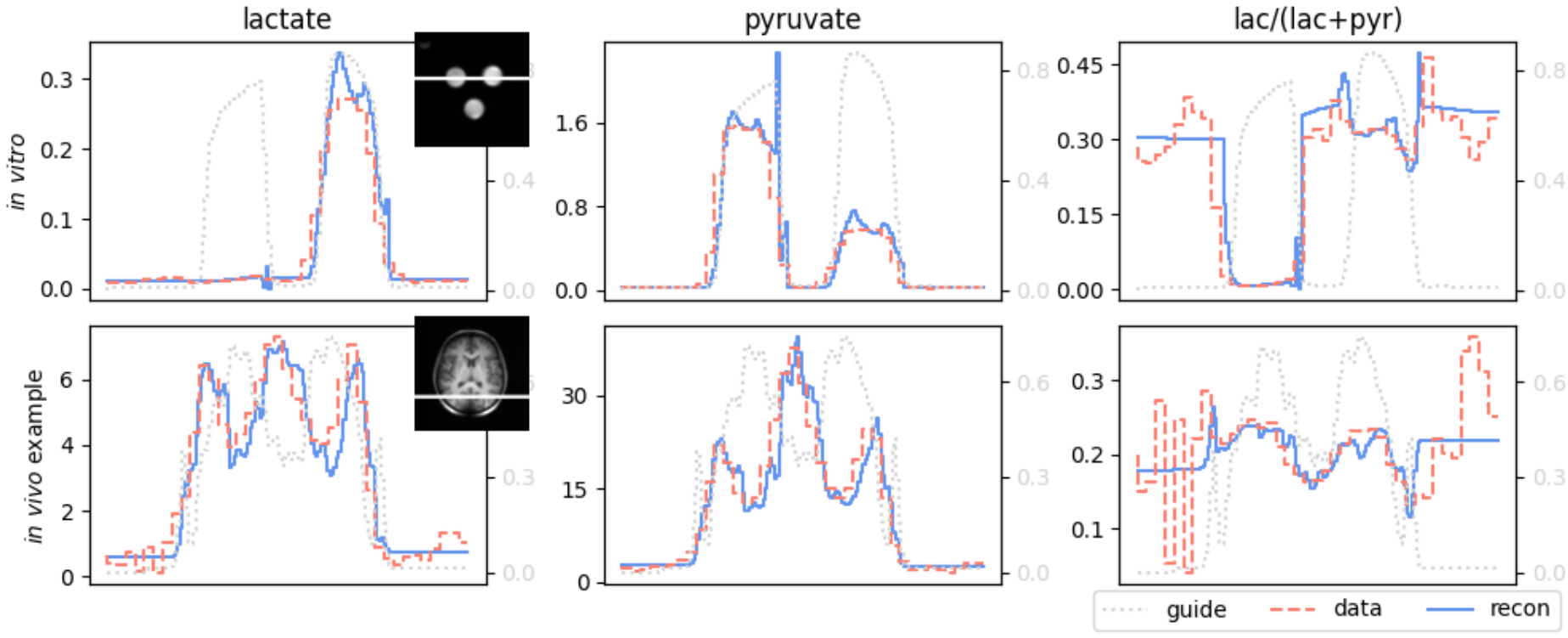
- **Higher resolution but preserves smooth variations**

Qualitative evaluation: *In Vivo*



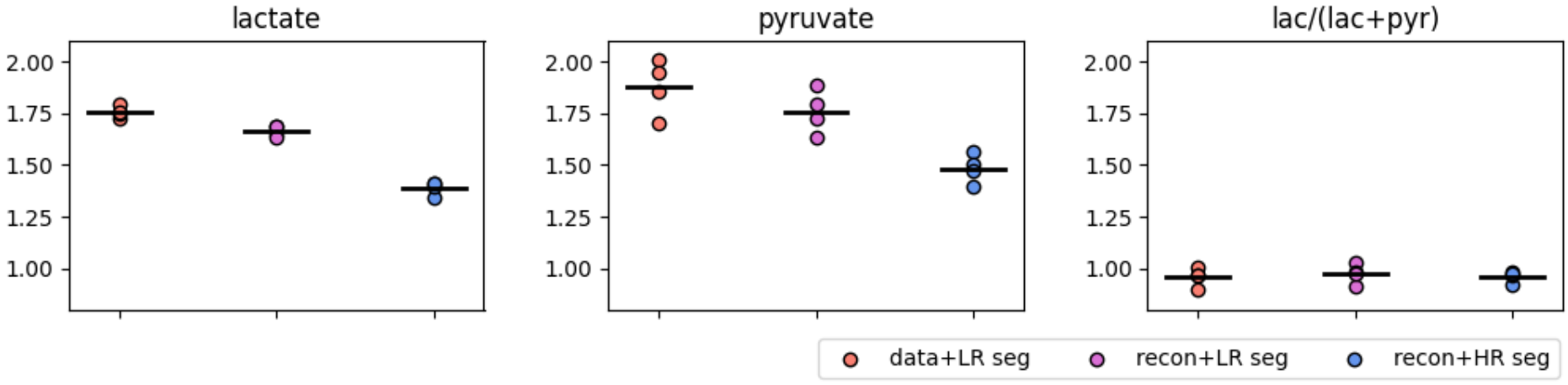
- **Anatomically well-defined** images
- **not constant within anatomical regions** (e.g. GM, WM)

Line plots



- Some visual evidence that **quantification is preserved**
- Intensities are **not hallucinated**, see e.g. lactate *in vitro*

Quantitative evaluation



- Ratio of mean values in GM/WM
- **Ratios in lactate and pyruvate reduced**: largely due to better segmentation
- **Normalized ratios constant**

Conclusions and Outlook

Conclusions

- **Directional total variation well-suited** for ^{13}C-MRI superresolution (allows locally changing correlations)
- **3D guide image** better than 2D (as it reflects anatomy)
- visually **higher resolution** with largely **preserved quantification**
- **ratio of means down** (perhaps more accurate?)
- **Computation:** $<$ 2 min on 3-year old MacBook Pro
- **Parameters**: 1 important parameter ($+4$ with robust default)

Conclusions and Outlook

Conclusions

- **Directional total variation well-suited** for ^{13}C-MRI superresolution (allows locally changing correlations)
- **3D guide image** better than 2D (as it reflects anatomy)
- visually **higher resolution** with largely **preserved quantification**
- **ratio of means down** (perhaps more accurate?)
- **Computation:** $<$ 2 min on 3-year old MacBook Pro
- **Parameters**: 1 important parameter ($+4$ with robust default)

Future work

- **Validation, validation, validation ...** e.g. *in vivo* data sets with tissue samples
- **Better modelling of data**, e.g. by using k-space data