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# Multi-Spherical MRI: Breaking the Boundaries of Diffusion Time



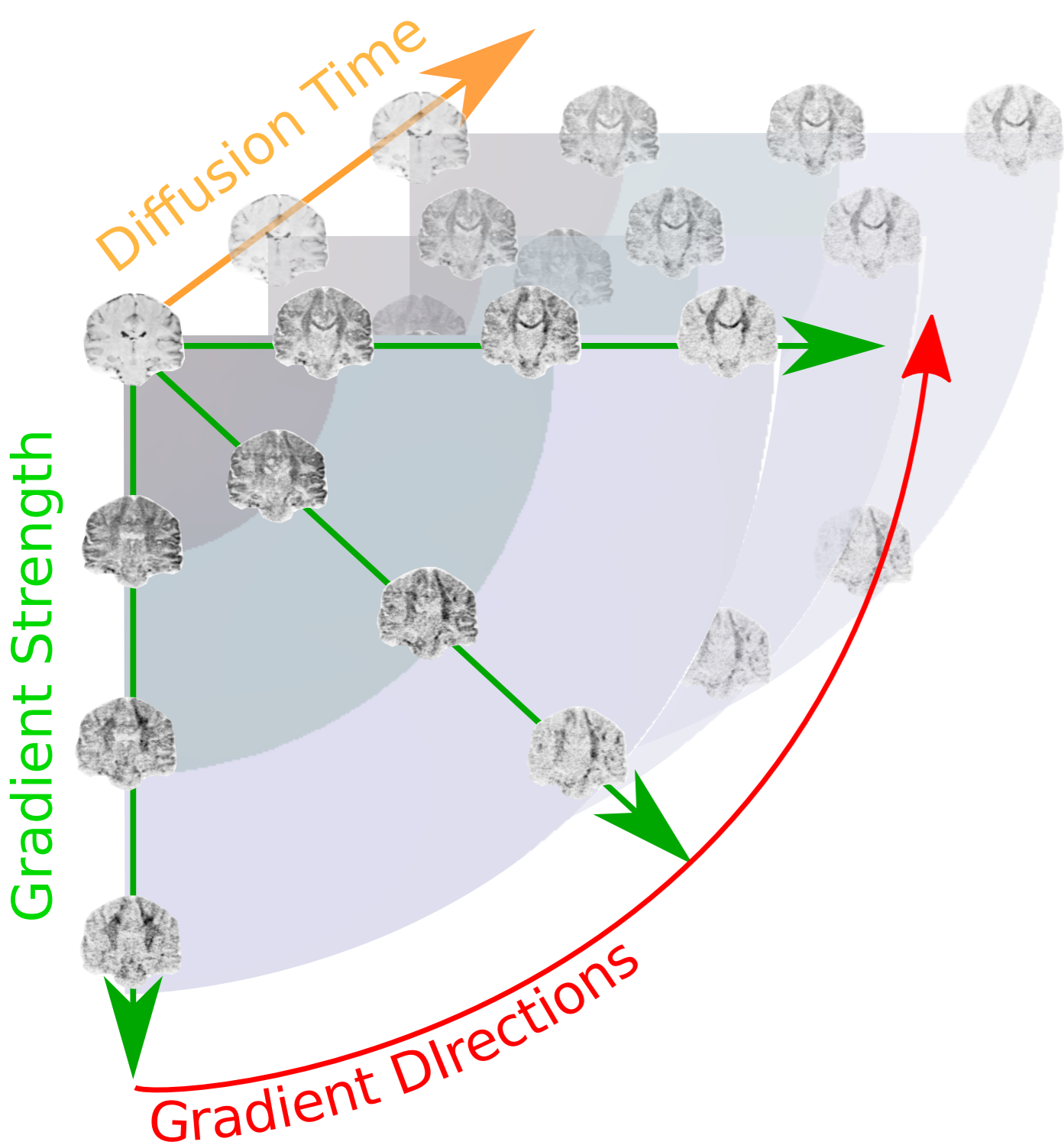
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**Abstract:** Effective representation of the diffusion signal's dependence on diffusion time is a sought-after, yet still unsolved challenge in diffusion MRI. We propose a functional basis approach that is specifically designed to represent the dMRI signal in this four-dimensional space - that we call the multi-spherical space. We provide regularization tools to drastically reduce the number of measurements we need to probe the properties of this multi-spherical space.

## 1 The Multi-Spherical Space



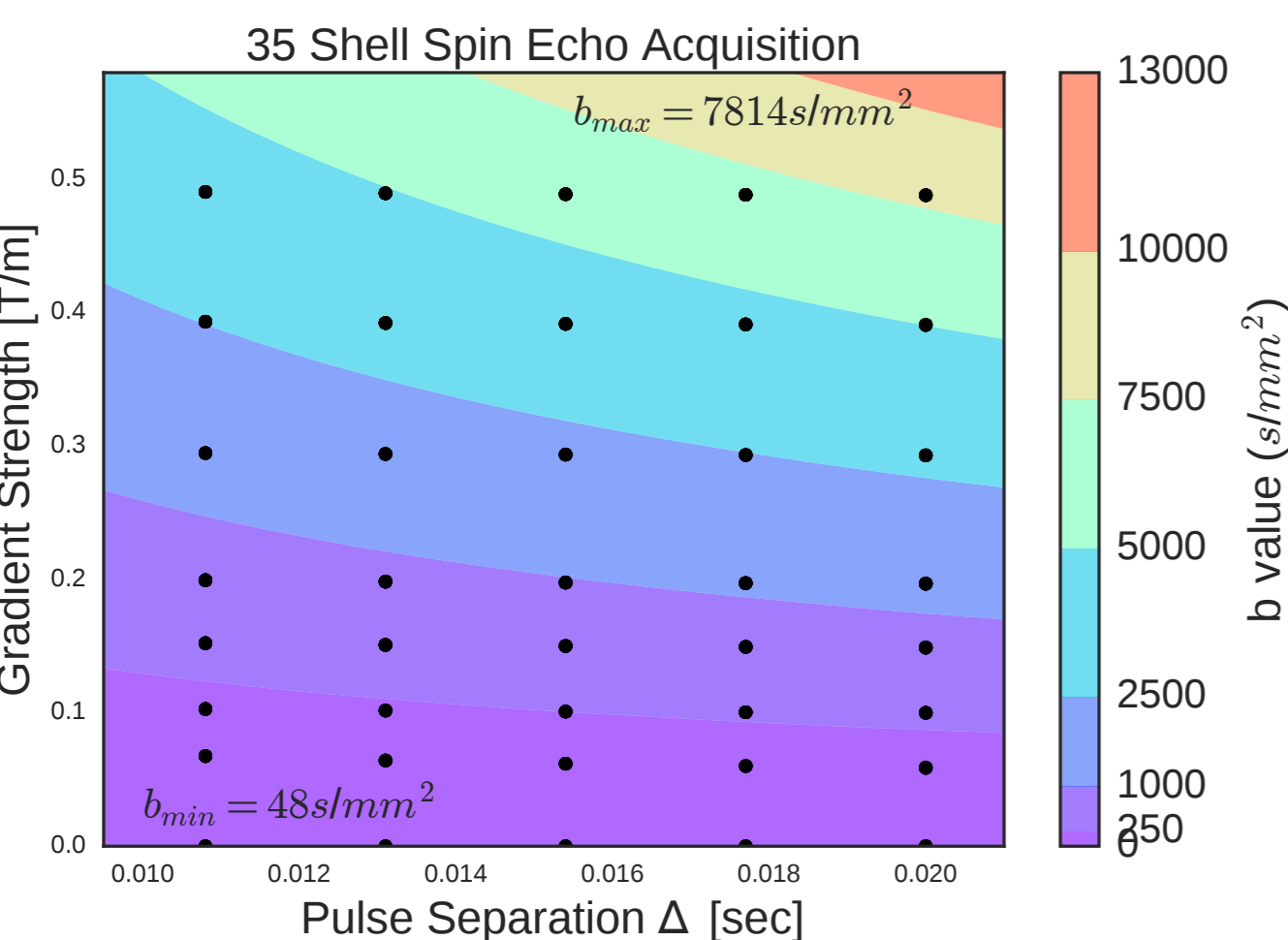
**Diffusion restriction** occurs when water diffusion is obstructed by tissue boundaries. The amount of restriction is **time-dependent**, meaning that the observed diffusion coefficient will change for varying diffusion times [1].

**Multi-Spherical MRI** [2] describes diffusion restriction by fitting the diffusion signals over varying:

- **Gradient strength (G)**
- **Gradient direction (g)**
- **Diffusion time (tau)**

We call this four-dimensional space the **Multi-Spherical Space**.

We sampled this space on 35 different "shells", varying only **g**, for different **G** ranging from [50-490] mT/m and **tau** ranging from [9.1-18.3] ms.



## 2 Modeling the Multi-Spherical Space

Multi-Spherical MRI uses a separable **Fourier Basis** to reconstruct diffusion propagator  $P(\mathbf{r}, \tau; \mathbf{c})$  from signal attenuation  $E(\mathbf{q}, \tau; \mathbf{c})$ , represented in coefficients  $\mathbf{c}$ .

$$\hat{E}(\mathbf{q}, \tau; \mathbf{c}) = \sum_i^{N_q} \sum_k^{N_\tau} c_{ik} \Phi_i(\mathbf{q}) T_k(\tau) \xleftrightarrow{FT} \hat{P}(\mathbf{r}, \tau; \mathbf{c}) = \sum_i^{N_q} \sum_k^{N_\tau} c_{ik} \Psi_i(\mathbf{r}) T_k(\tau)$$

$\Psi_i(\mathbf{r}) = FT(\Phi_i(\mathbf{q}))$ : 3D Fourier basis over  $\mathbf{q}$  and displacement  $\mathbf{r}$  [3].

$T_m(\tau)$ : Exponential diffusion time basis over  $\tau$  [4].

We constrain the fitting of  $\mathbf{c}$  to respect boundary conditions of the signal and impose **signal smoothness and sparsity**:

$$\operatorname{argmin}_{\mathbf{c}} \underbrace{\iint [E(\mathbf{q}, \tau) - \hat{E}(\mathbf{q}, \tau; \mathbf{c})]^2 d\mathbf{q}d\tau}_{(1) \text{ Data Fidelity}} + \underbrace{\iint [\nabla^2 \hat{E}(\mathbf{q}, \tau; \mathbf{c})]^2 d\mathbf{q}d\tau}_{(2) \text{ Smoothness}} + \underbrace{\|\mathbf{c}\|_1}_{(3) \text{ Sparsity}}$$

Where smoothness is imposed using **closed-form Laplacian regularization**.

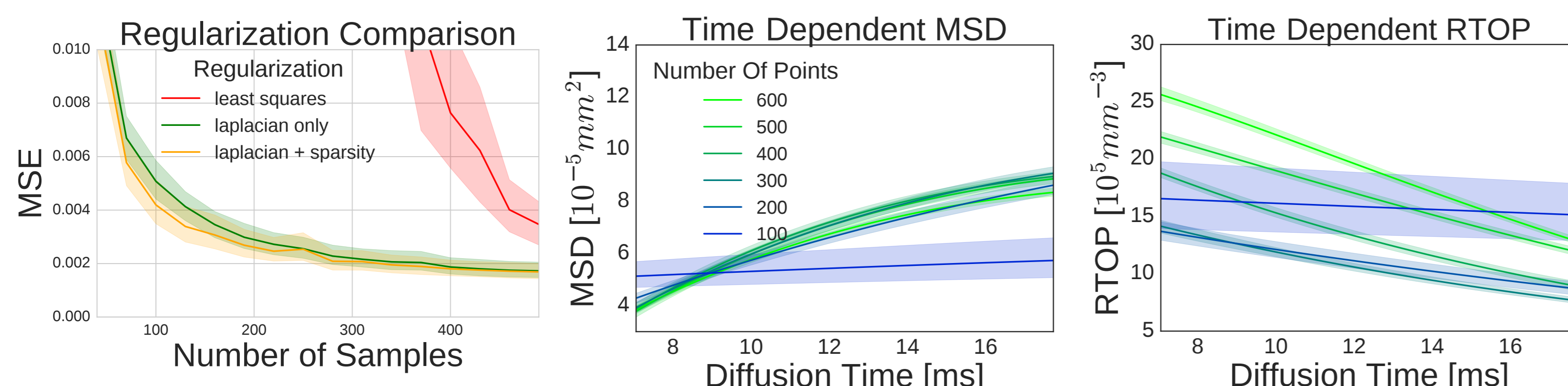
Once fitted, all q-space indices [3] can be estimated for any  $\tau$ . As examples we show:

- Mean Squared Displacement (MSD), related to restriction
- Return-To-Origin Probability (RTOP), related to cellularity

## 3 In-Silico results

We study fitting performance under random subsampling by simulating the multi-spherical diffusion signal from gamma-distributed axons using Camino [5].

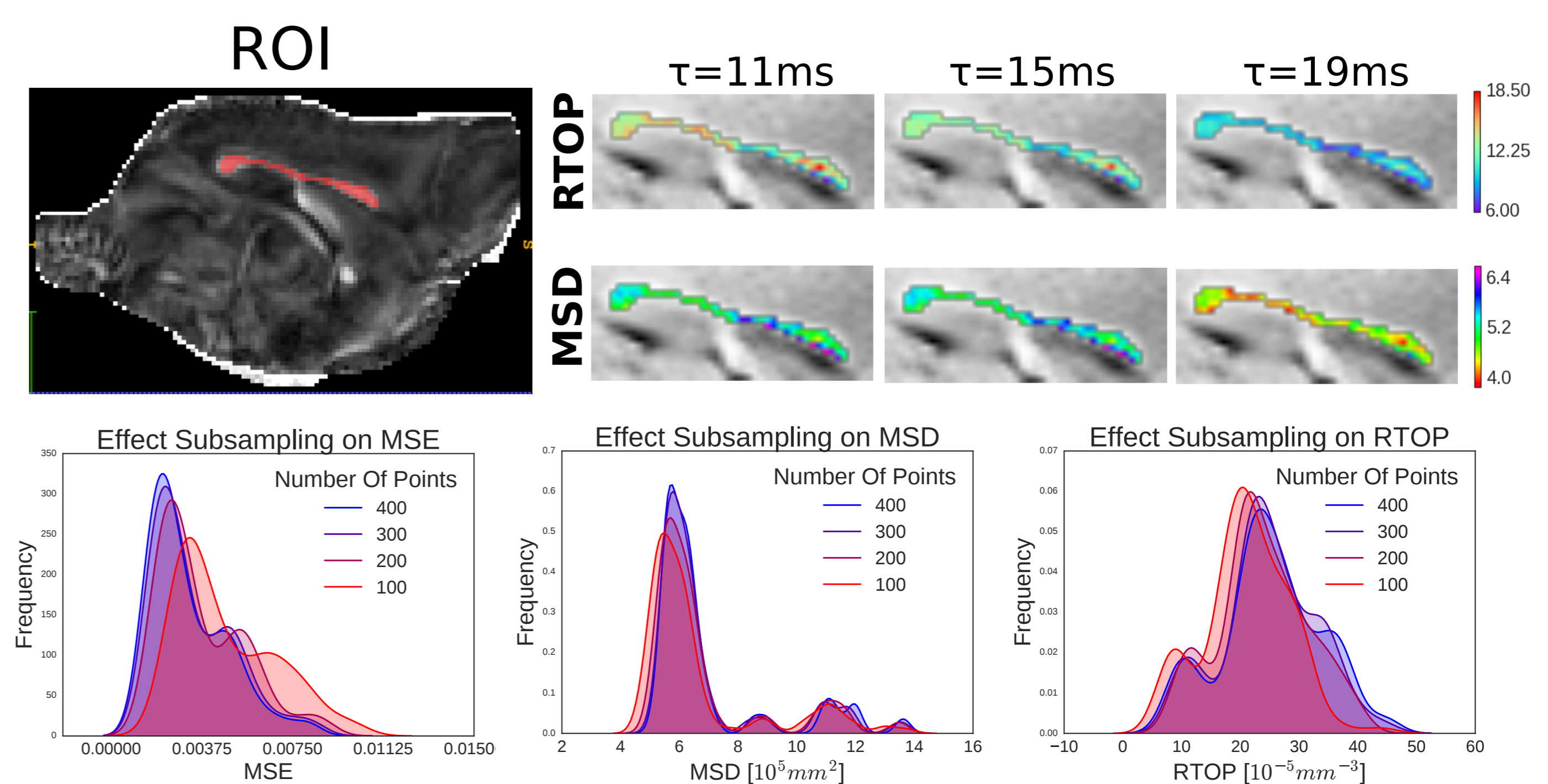
- Combined sparsity and Laplacian regularization produces the lowest fitting error (left).
- Time-dependent MSD and RTOP follow expected trends - MSD increasing and RTOP decreasing over time - down to about 200 DWIs (right two)



## 4 Application In-vivo Mouse Data

After eddy current correction, we chose an ROI of 173 voxels in Corpus Callosum. After subsampling we find

- Stable fitting errors from 400 down to 200 DWIs
- Expected trends for time-dependent MSD and RTOP



## 5 Discussion and Conclusions

- Multi-Spherical MRI allows for the characterization of diffusion restriction through time-dependent q-space indices.
- Through signal sparsity and smoothness, our approach can represent the multi-spherical signal with less samples, allowing more realistic acquisition schemes.
- Additional signal or propagator constraints can be conveniently included in the optimization.
- Through resampling, our approach could be used as a pre-processing for other methods studying properties of the multi-spherical space, e.g. axon packing [6].

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**References** [1] Fieremans et al. NeuroImage 129 (2016): 414-427. [2] Fick et al. CD-MRI 2016. [3] Özarslan et al. NeuroImage 78 (2013): 16-32. [4] Fick, Rutger, et al. IPMI 2015. [5] Cook et al. ISMRM, 2006. [6] Novikov et al. 111.14 (2014): 5088-5093.