Anomalous diffusion stretched exponential γ-imaging model provides new information on spinal cord microstructure

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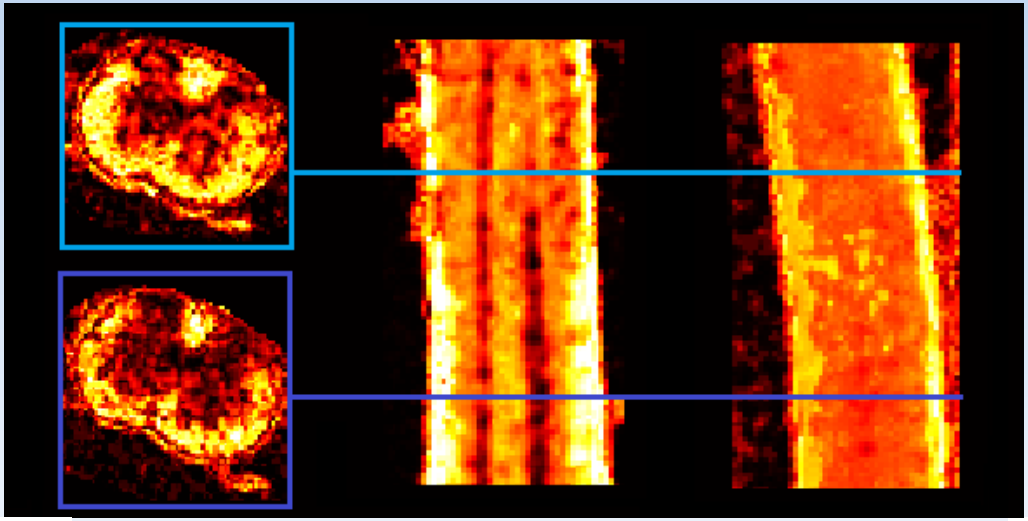
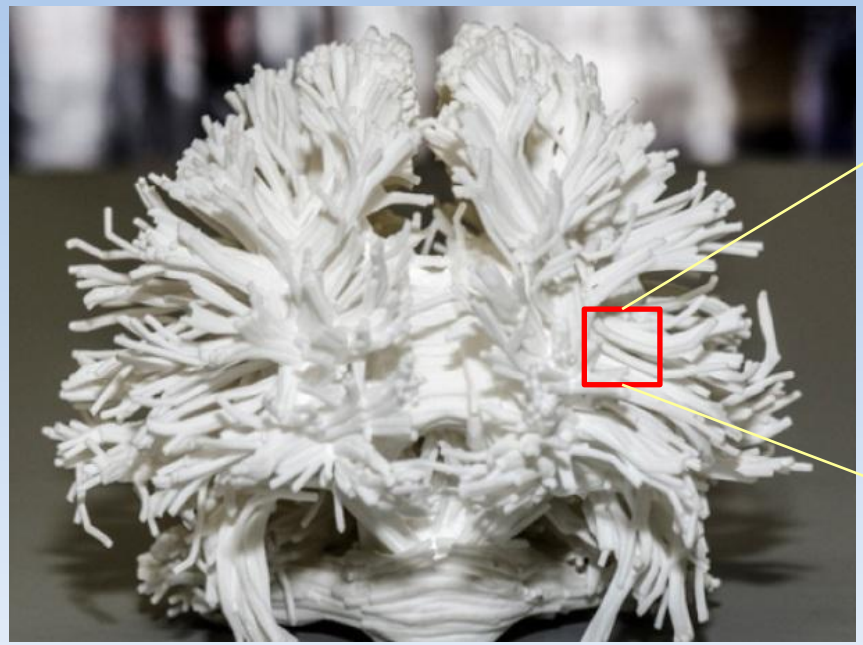


Goal

- Investigate the potential of γ-imaging model to obtain information about white matter arrangement in the Spinal Cord

White Matter

Anomalous diffusion stretched exponential γ-imaging model provides new information on spinal cord microstructure



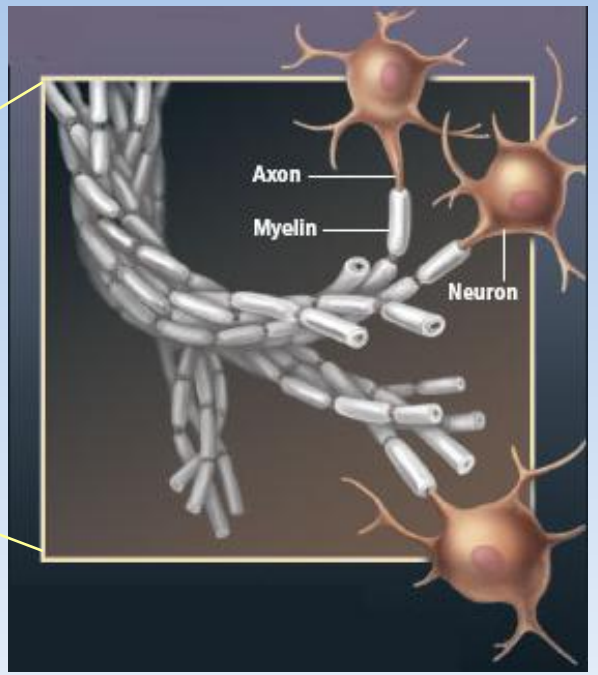


Illustration by Jen Christiansen
in Scientific American 2008

White Matter

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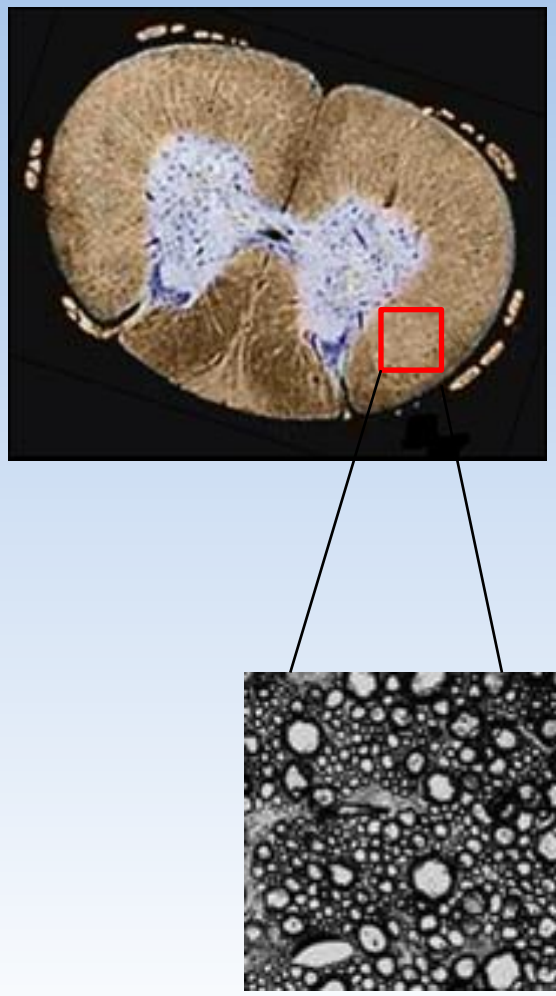

Anomalous Diffusion

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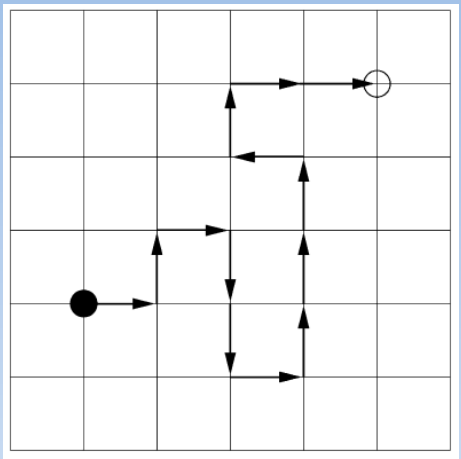
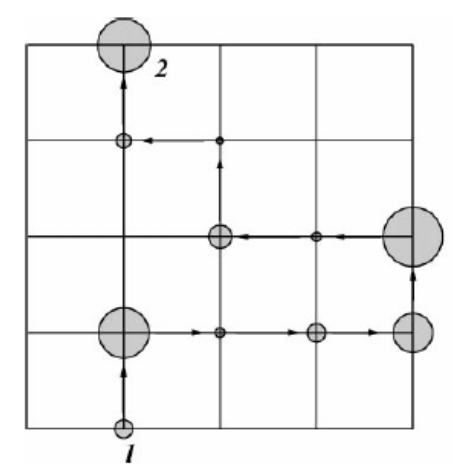




$\langle r^2(t)\rangle = 2NDt$

$\langle r^2(t)\rangle \sim t^{\gamma}$

R. Metzler and J. Klafter, 339 Phys Rep (2000) 1-77

How to perform Anomalous-Diffusion MRI

Anomalous diffusion stretched exponential γ-imaging model provides new information on spinal cord microstructure

$$\frac{S(b)}{S_0} = e^{-Ab^{\gamma}} \propto W(q,t)$$

$$q = \gamma \delta G$$

(γ = 42.576 MHz/T)

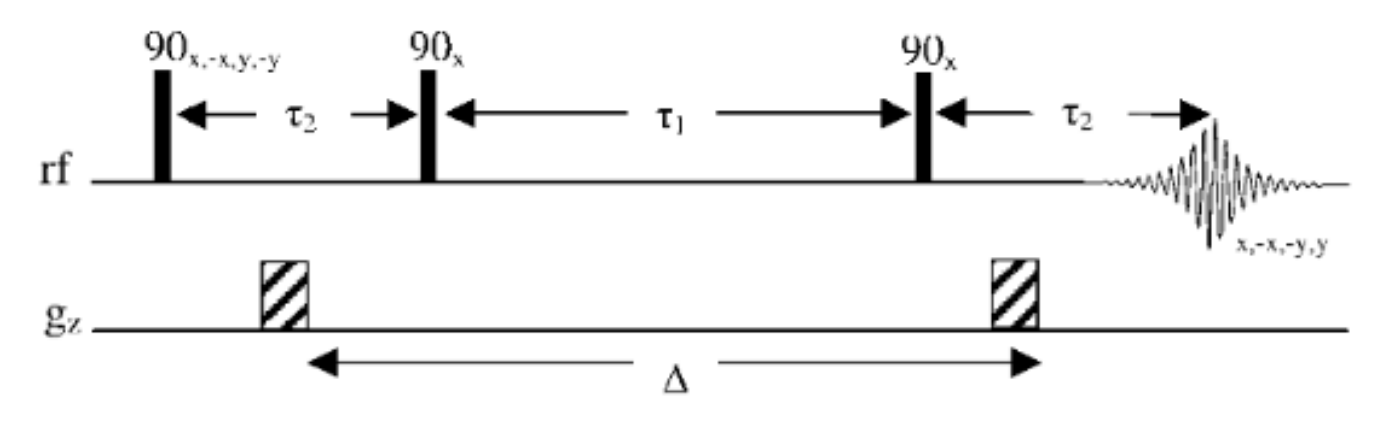
Pseudo Super-diffusion

$$W(q,t,\gamma) \sim e^{-D_{gen} q^{2\gamma} t}$$

PGSE or PGSTE

varying q, Keeping Δ constant

PGSTE



Tanner, J Chem Phys 52, 1970

Validation in phantoms

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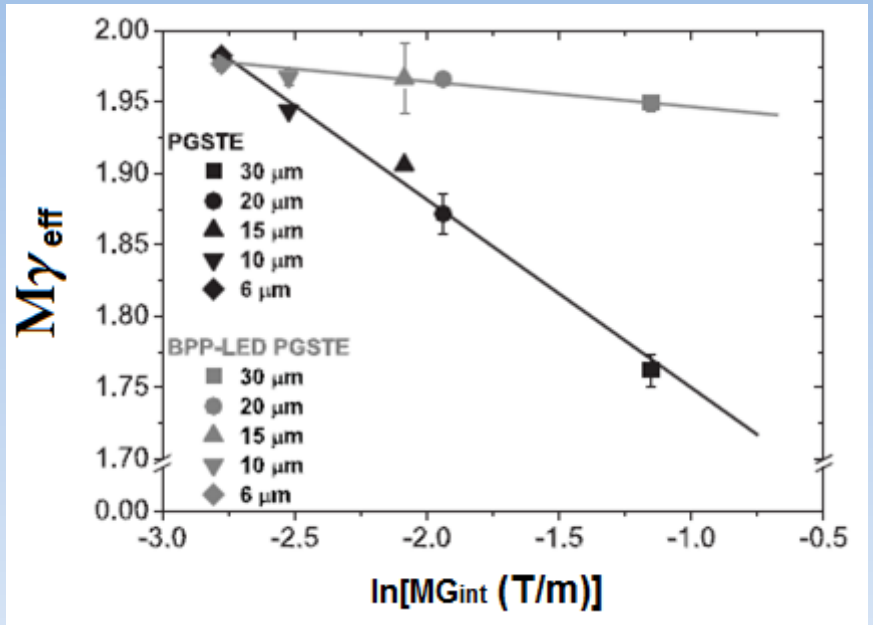
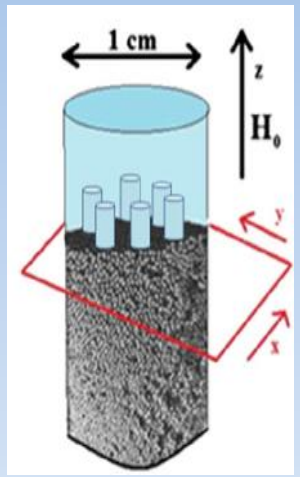




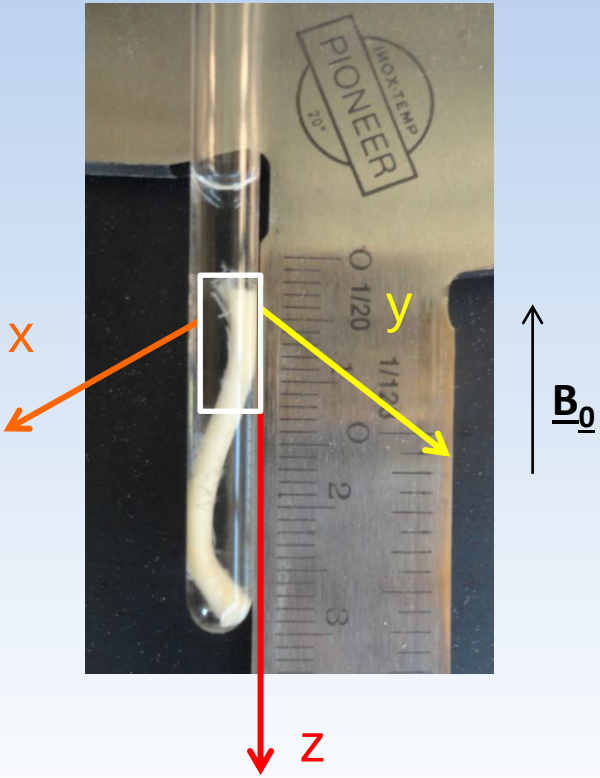
$$\Delta\chi_m \approx 1.56\,ppm$$

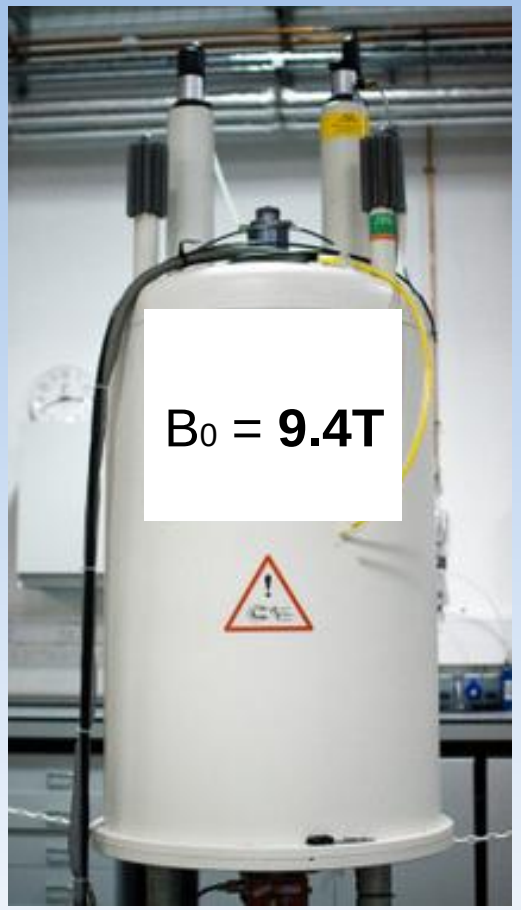
- γ is influenced by ΔX_m at the interface between micro-beads and diffusing water
- γ reflects micro-beads sizes

M. Palombo et al., 216 JMR (2012) 28-36

Methods

C57 BL6 mouse spinal cord fixed with 4%/2% glutaraldehyde/paraformaldehyde and stored in PBS

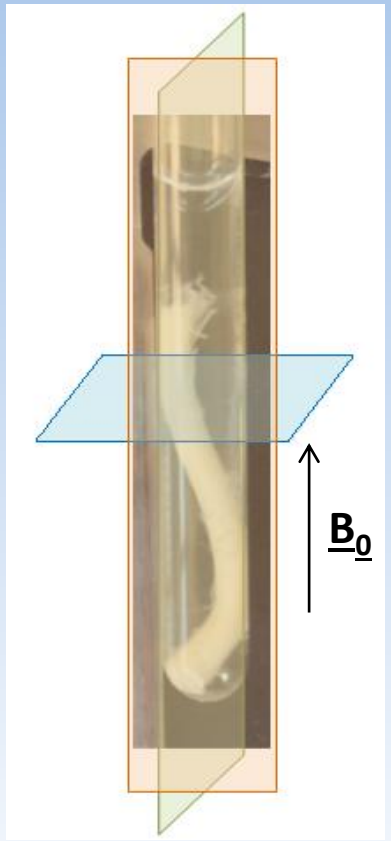




Methods

➢ Acquisition Protocol for the extraction of γ

- PGSTE (Δ = 40 ms)
- 10 b-values in the interval (100, 4000) s/mm^2 + 1 b0
- 10 G-values in the interval (50, 500) mT/m
- **3 orthogonal directions (x, y, z)**



➢ Conventional DTI protocol

- PGSTE with Δ/δ = 40/2 ms, b-value = 700 s/mm^2
- 6 directions

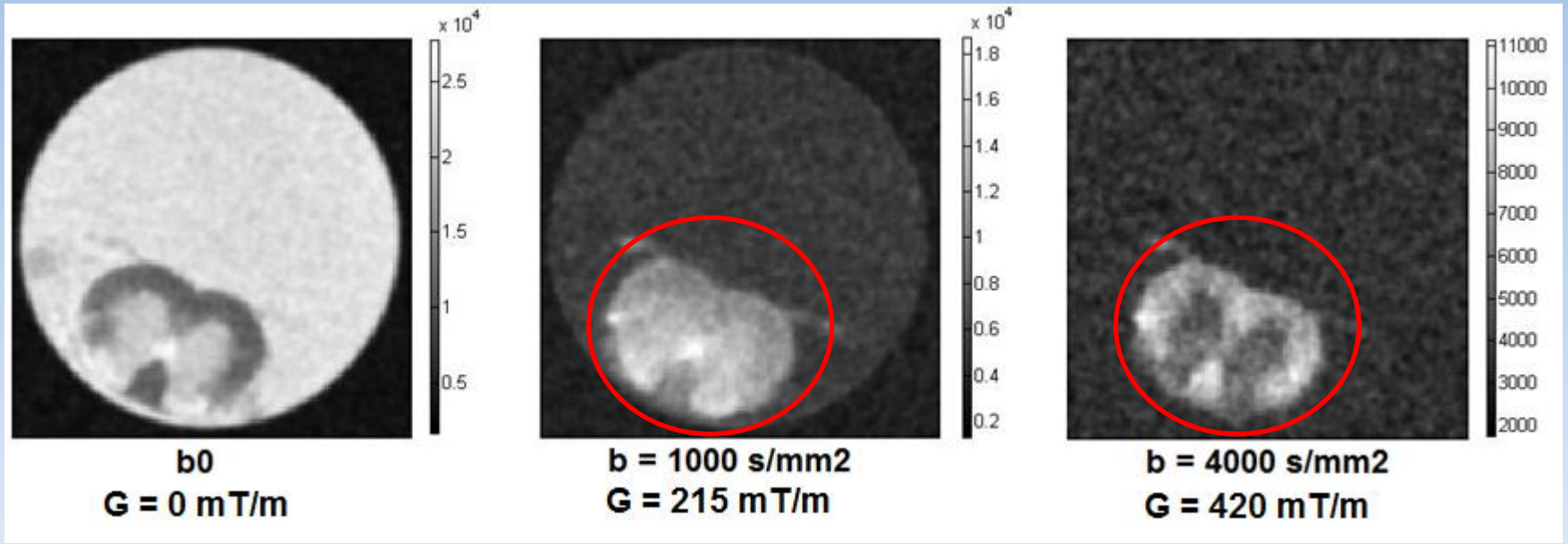
➢ Conventional T2* relaxometry

- GE with 13 TEs varying in the interval (2, 40) ms

Methods

Anomalous diffusion stretched exponential γ-imaging model provides new information on spinal cord microstructure

Diffusion weighted images at different G



The effective b0 is 154 s/mm^2

Δ = 40 ms for each DWI

The contrast between white matter and gray matter changes with increasing b

Methods

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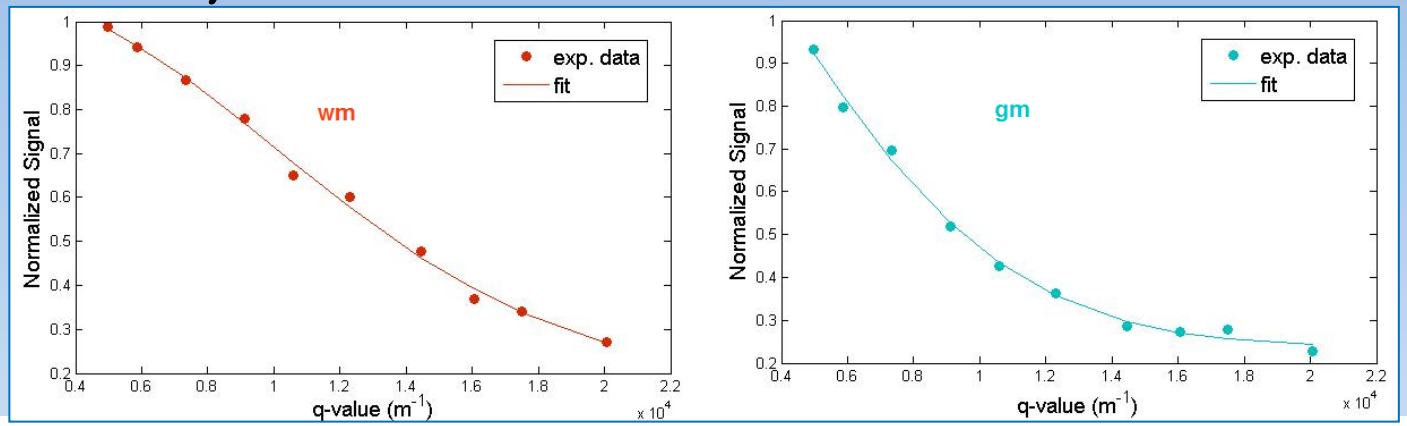
Extraction of γ from DWIs



$$S(q) = S(q_0) \cdot \exp\left(-D_{gen}|q|^{2\gamma}t\right)$$

$$S(q_0) = S(0) \cdot \exp\left(-D_0|q_0|^2 t\right)$$

$$\frac{S(q)}{S(q_0)} = \frac{S(q_0) \cdot \exp\left(-D_{gen}|q^{2\gamma}|t\right)}{S(0) \cdot \exp\left(-D_0|q_0|^2 t\right)} = \frac{S(q_0)}{S(0)} \cdot \exp\left(-\left(D_{gen}|q|^{2\gamma} - D_0|q_0|^2\right)t\right)$$

$$f(q) = A \cdot \exp\left[\left(-\left(D_{gen} \cdot q^{2\gamma} - D_0 \cdot q_0^2\right)\right] \cdot \Delta + c\right.$$

Results

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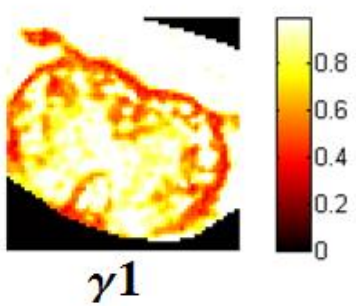
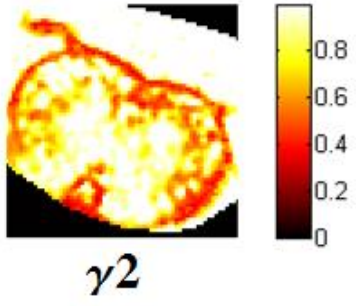
γ-imaging along 3 orthogonal directions

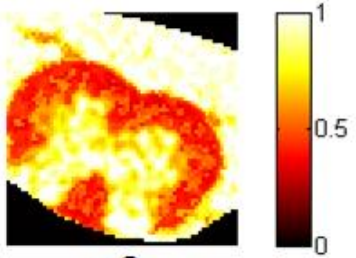
$$\gamma_{ort} = \frac{\gamma_1 + \gamma_2}{2}$$



$\gamma 1$



$\gamma 2$



$\gamma 3$

$$\gamma_{par} = \gamma_3$$

In plane resolution of 33 x 33 μm^2
Slice thickness: 0.7 mm

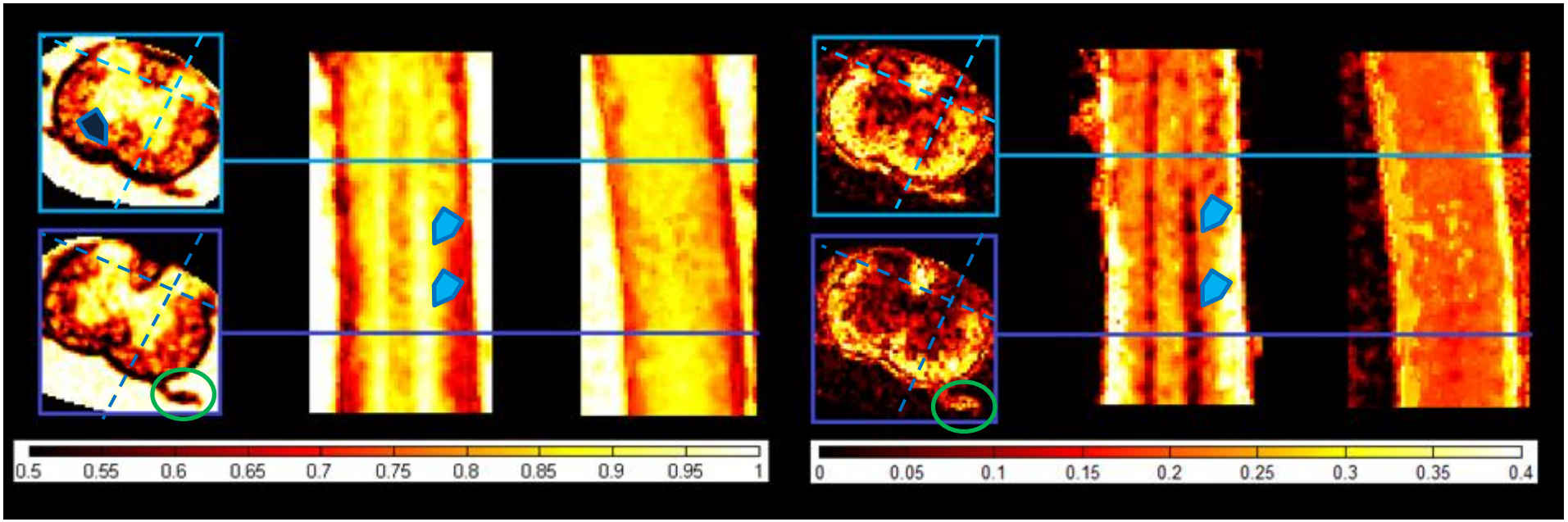
Results

Anomalous diffusion stretched exponential γ-imaging model provides new information on spinal cord microstructure

γ-imaging parametric maps

$$M\gamma = (\sum_{i=1,2,3} \gamma_i)/3$$

$$A\gamma = \sqrt{3\sum_{i=1,2,3}(\gamma_i - M_\gamma)^2 / 2\sum_{i=1,2,3}\gamma_i^2}$$



In plane resolution of 33 x 33 μm^2

Results

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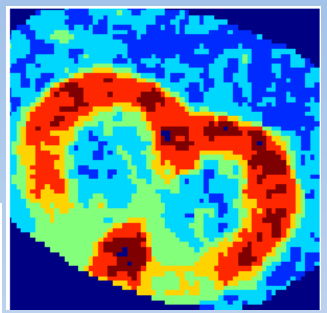
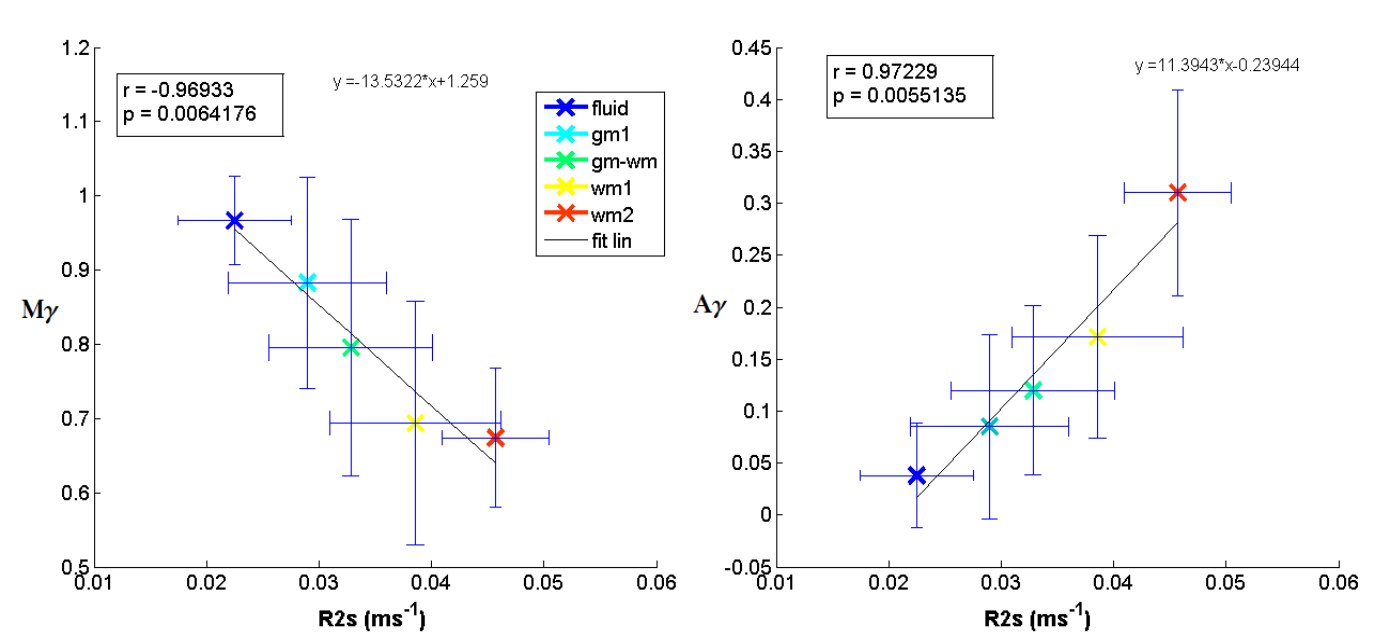
Mγ and Aγ correlate with R2*
In axial slices

$$R_2^* = \frac{1}{T_2} + \gamma \cdot \Delta B_i$$



ROIs were selected thresholding FA maps



γ-metrics is sensitive to ΔXm

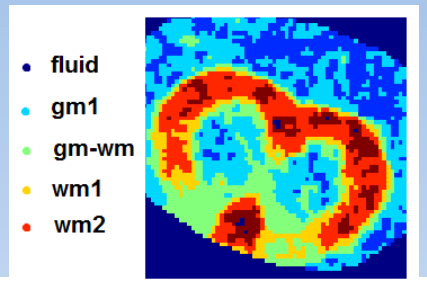
Water-myelin

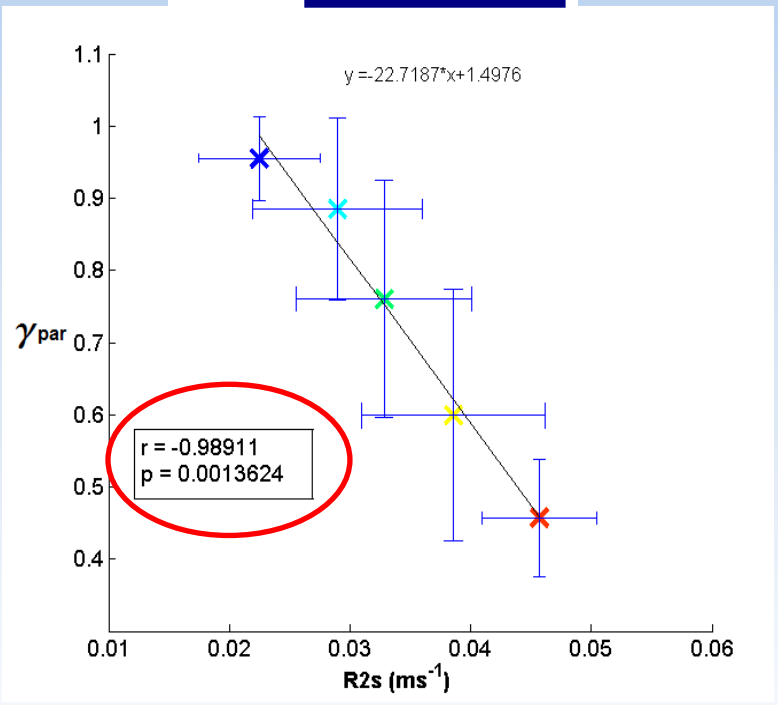
$$\Delta\chi_m \approx 10^{-2} - 10^{-3}\ ppm$$

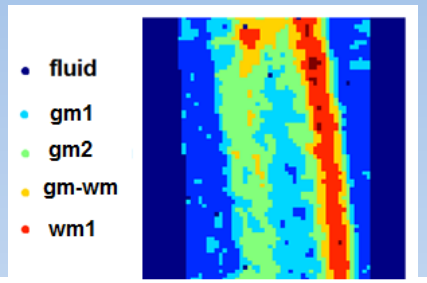
Results

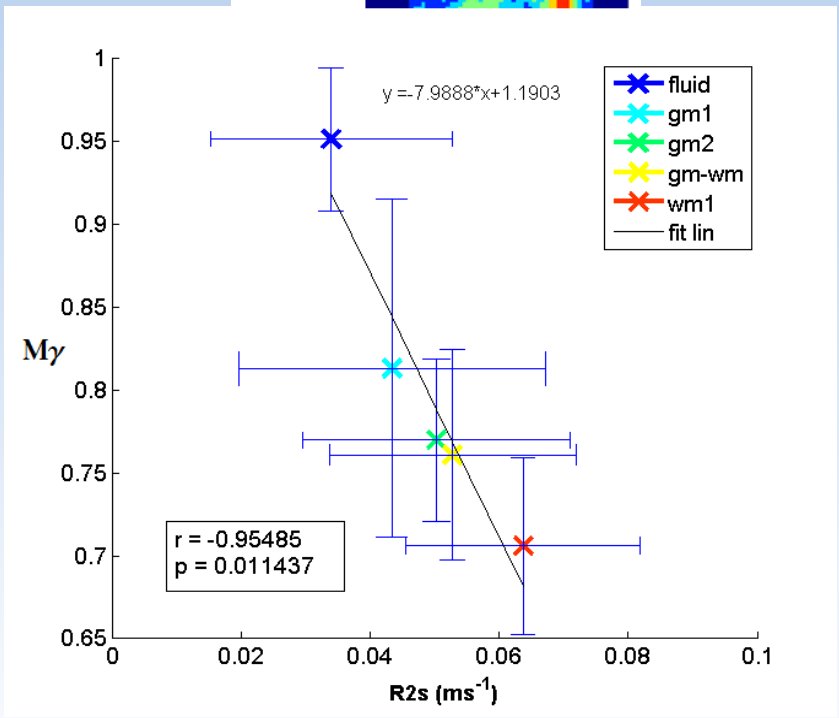
Anomalous diffusion stretched exponential γ-imaging model provides new information on spinal cord microstructure

γ_{par} correlates with R2* - Mγ with R2* also in sagittal sl.









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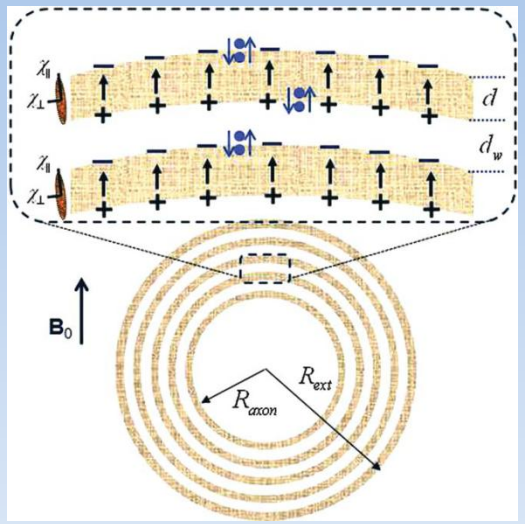
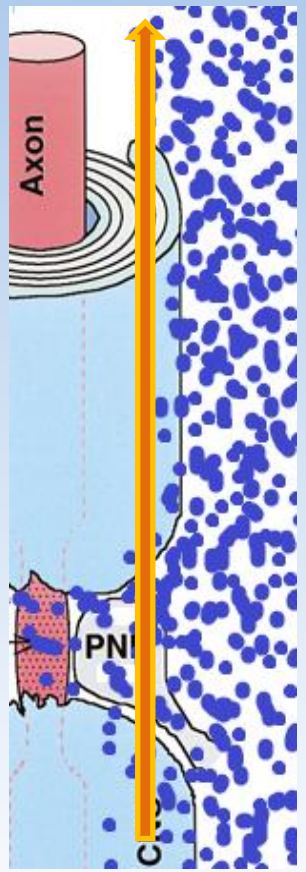


D.A. Yablonskiy and A.L. Sukstanskii
71 Mag Res Med (2014) 1956-1958

Ext. water diffusing in the Preferential orientation parallel to fibers encounters several ΔX_m along its trajectory

J.L. Salzer 18 Neuron (1997) 843-846

$$\Delta\chi_m \approx 10^{-2} - 10^{-3}\ ppm$$



The alternating proteo-lipid-protein in the presence of a static magnetic Field determines susceptibility differences At the surface

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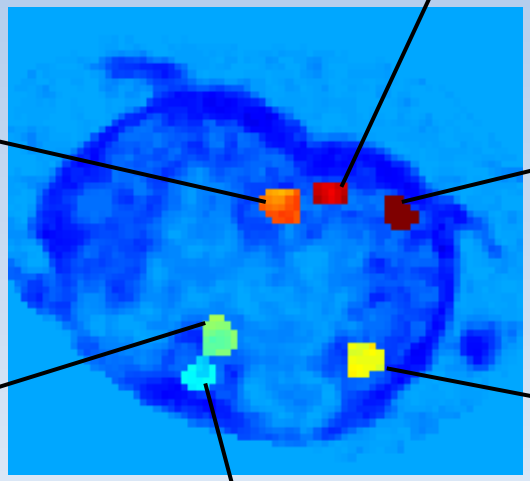
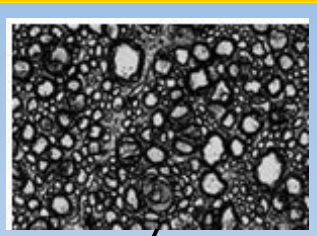
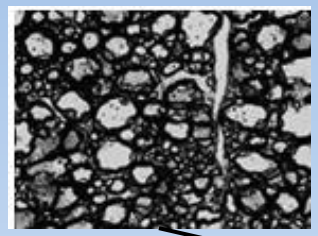
Wm microstructure in mouse SC

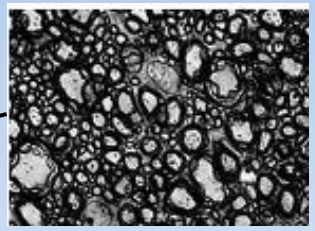




right Recto-spinal Tract (ReST)

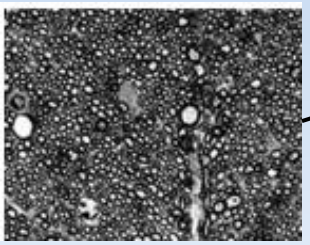
medial Vestibulo-spinal Tract (VST)

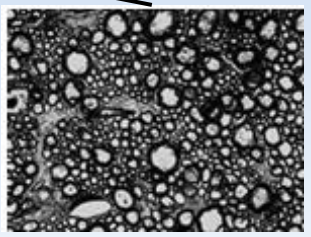




right Spino-Thalamic Tract (STT)

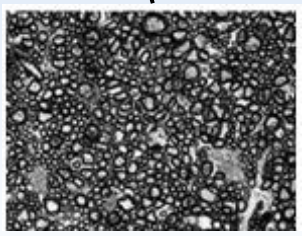
dorsal Cortico-spinal tract (dCST)





right Rubro-spinal Tract (RST)

Funiculus Gracilis (Fg)



Light microscopic images from
H.H. Ong et al., 40 Neuroim (2008) 1619-1632

Results

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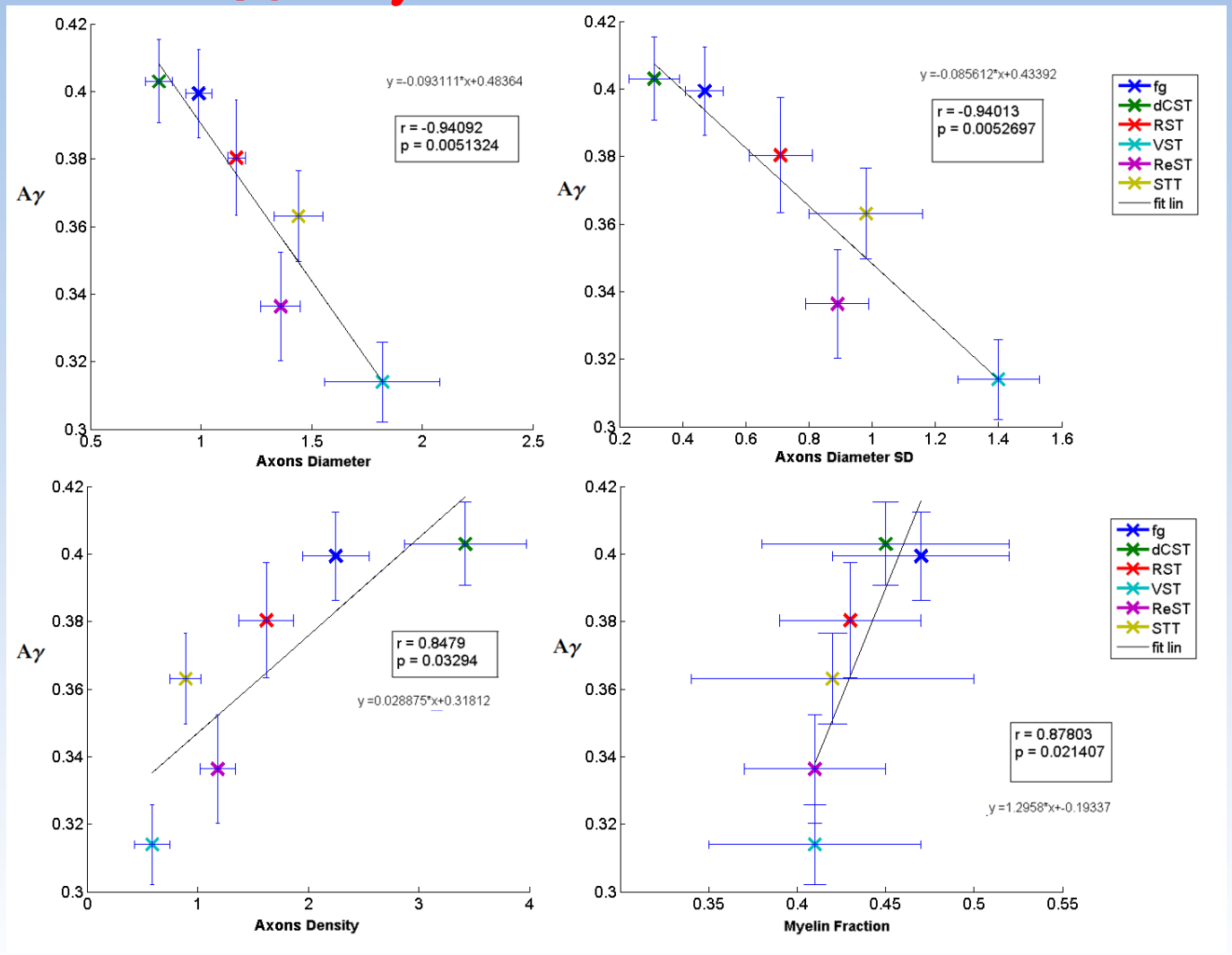
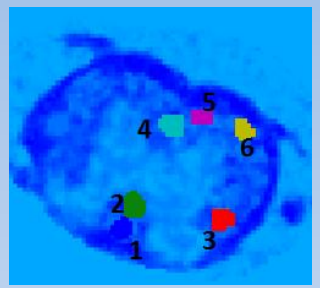
Anisotropy of γ and wm micro-structure





Aγ correlates with wm structural parameters!

conversely
MD, FA, T2*, R2*
DO NOT

Results

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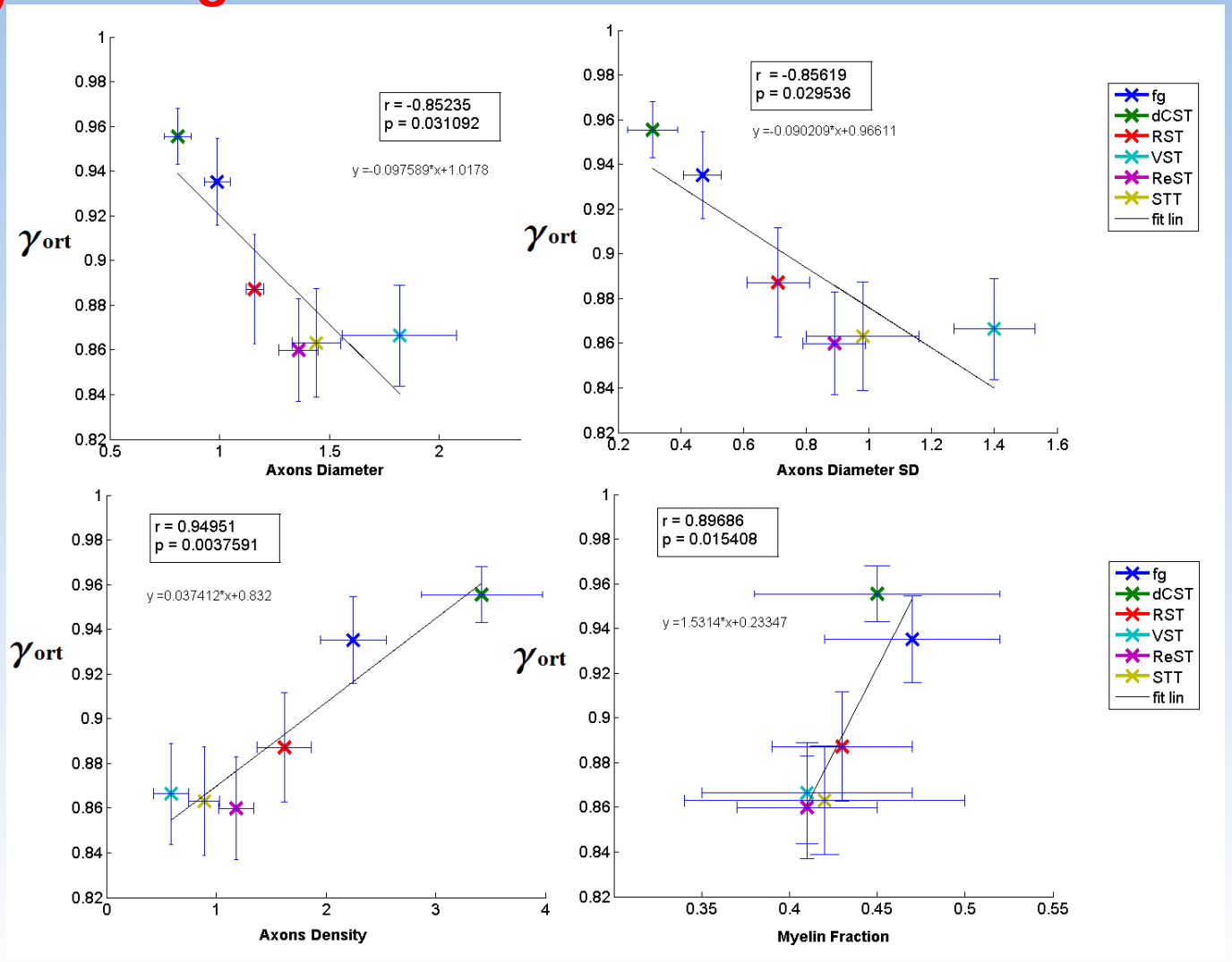
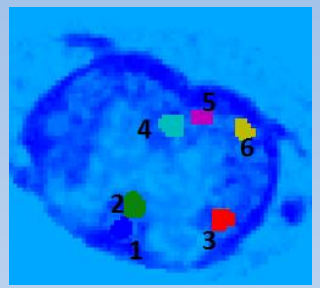
γ orthogonal to fibers and wm micro-structure



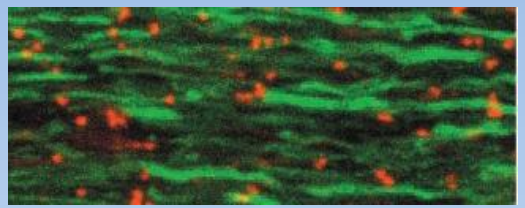


γ_{ort} correlates with wm structural parameters!

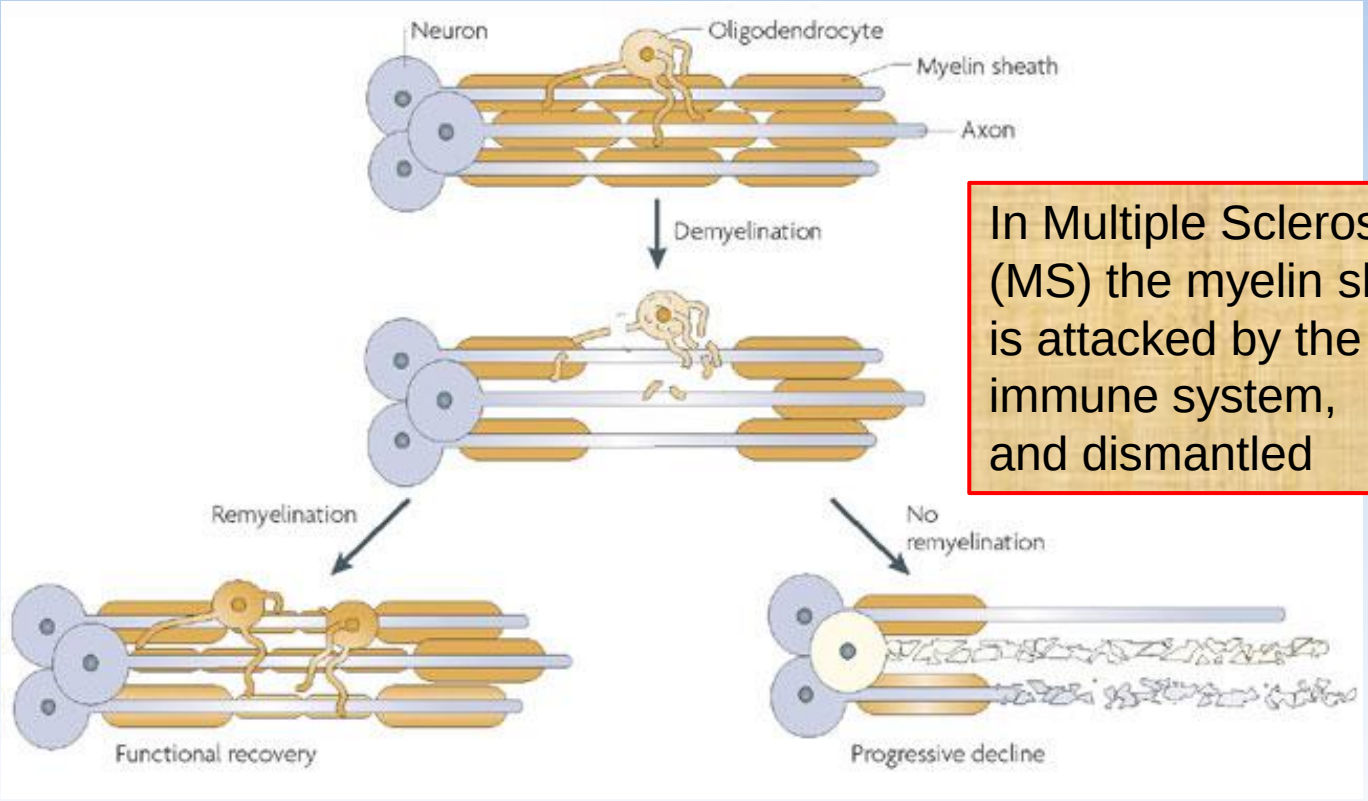
CONVERSELY
'No correlation was found between tADC and axon diameter'
Schwartz et al.,
16 Neuroreport (2005) 73-76

Discussion

Anomalous diffusion stretched exponential γ-imaging model provides new information on spinal cord microstructure



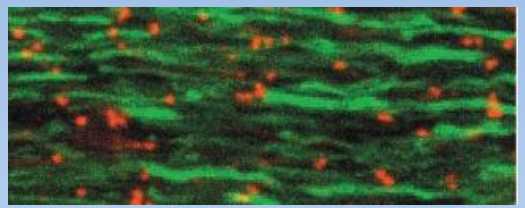
Fluorescence of CNS
J.C. Rios et al.,
23 J of NeuroSc (2003) 7001-7011



In Multiple Sclerosis (MS) the myelin sheath is attacked by the immune system, and dismantled

Discussion

Anomalous diffusion stretched exponential γ-imaging model provides new information on spinal cord microstructure



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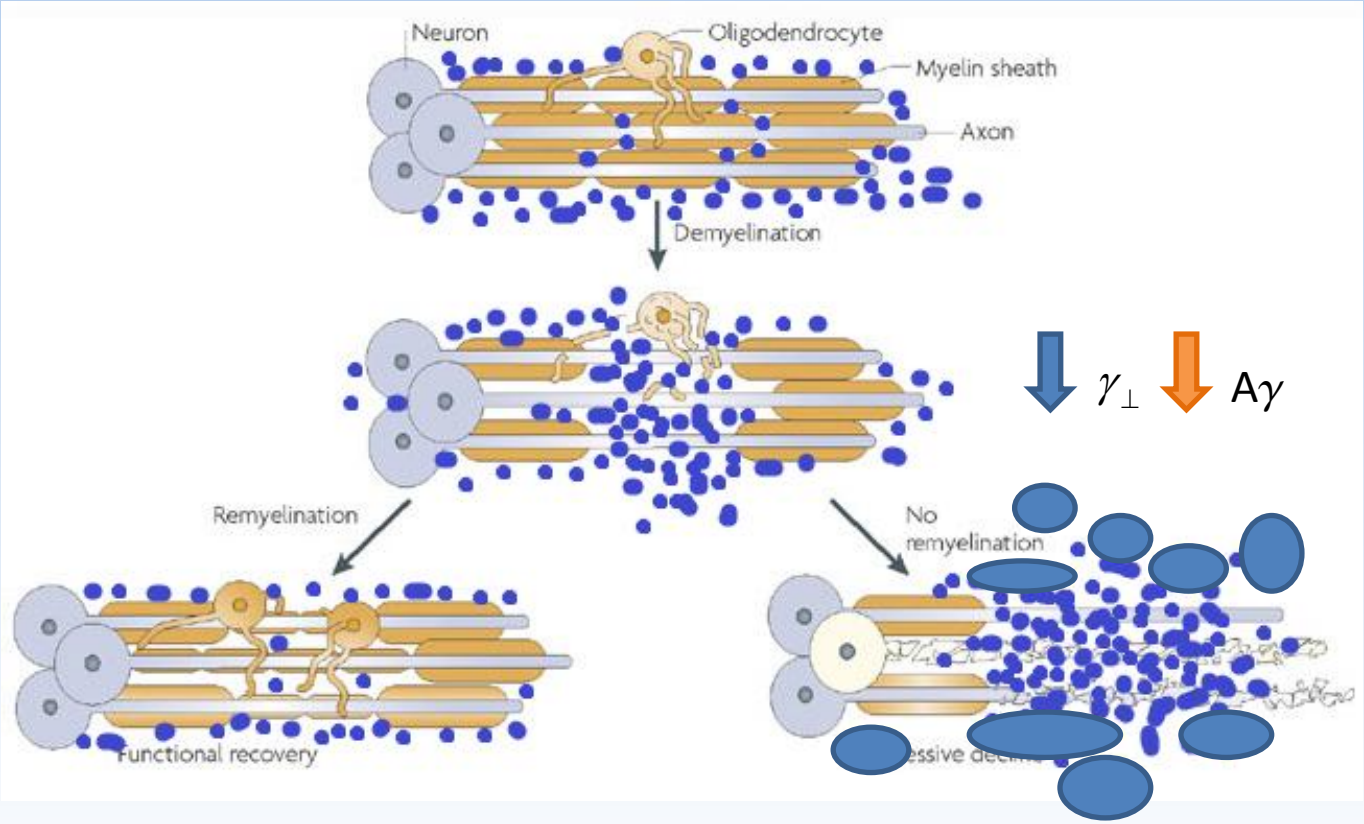
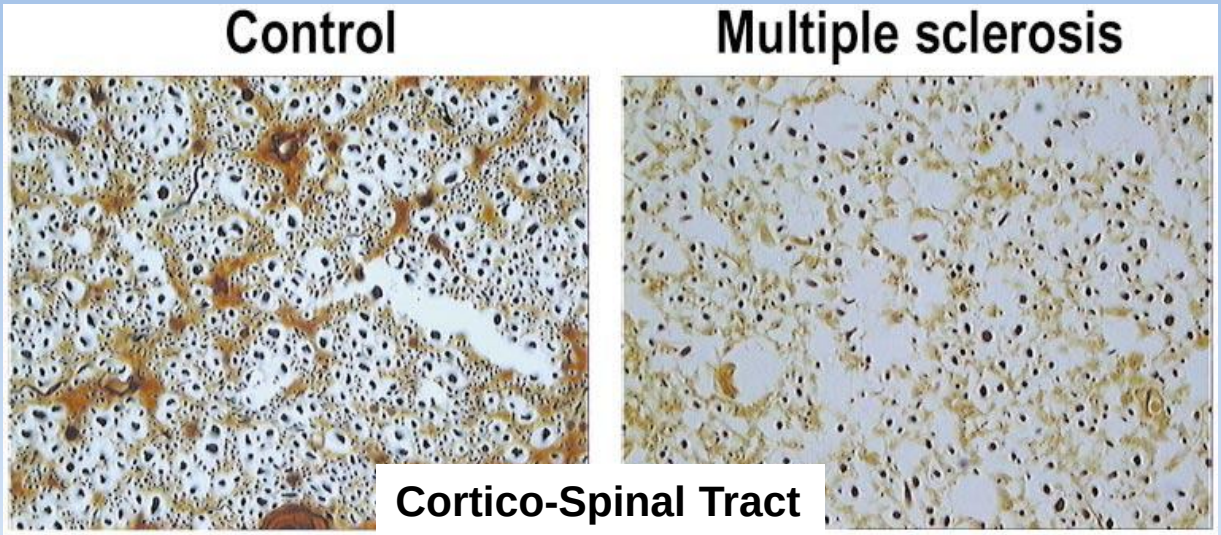


Example of application

Anomalous diffusion stretched exponential γ-imaging model provides new information on spinal cord microstructure

From literature:

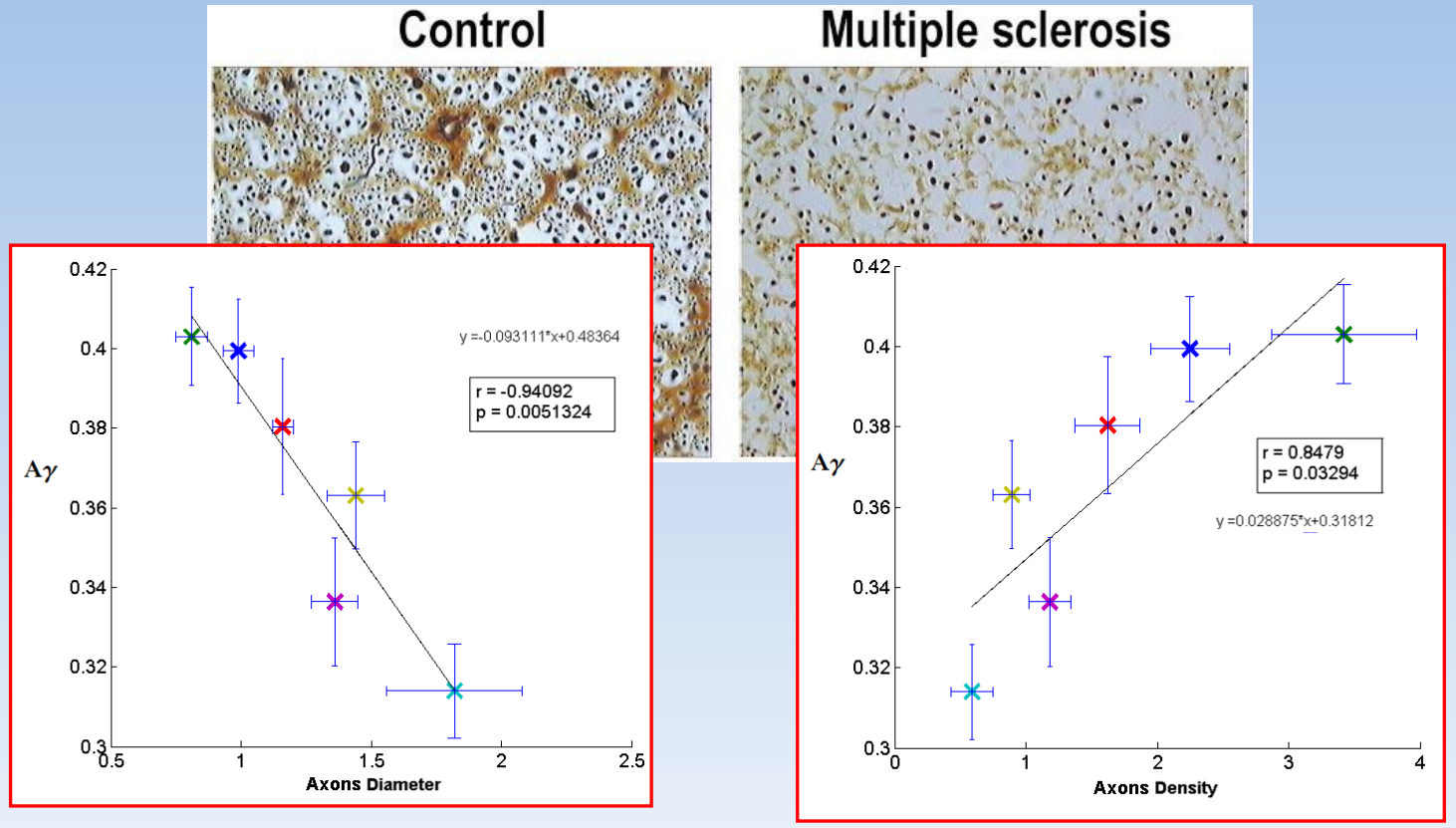


G.C. De Luca et al., 127 Brain (2004) 1009-1018

In Multiple Sclerosis axonal loss is widespread in both brain and Spinal Cord (SC), and its extent is **tract specific** and **size selective**

Example of application

Anomalous diffusion stretched exponential γ-imaging model provides new information on spinal cord microstructure



Conclusions

Anomalous diffusion stretched exponential γ-imaging model provides new information on spinal cord microstructure

- **The γ-parameters are sensitive to magnetic susceptibility inhomogeneities** at the interface between different tissues.

- **The γ-parameters (γort, Aγ) reflect micro-structure features of different white matter tracts**

- **In particular, γort, Aγ correlate with axon diameters and axon density.**

- **The γ-imaging technique may be useful to detect micrometric changes in patological white matter of SC tracts**

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