Diffusion MRI of Brain Tissue

Importance of Axonal Trajectory

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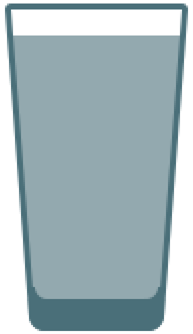
Introduction: Magnetic Resonance Imaging

- Imaging modality.
- Probes magnetic properties of tissue.
- Probes properties of water.
- Most MR methods study macrostructure.
- dMRI aims at probing microstructure.



[1]

Conventional MR image of head

[2]

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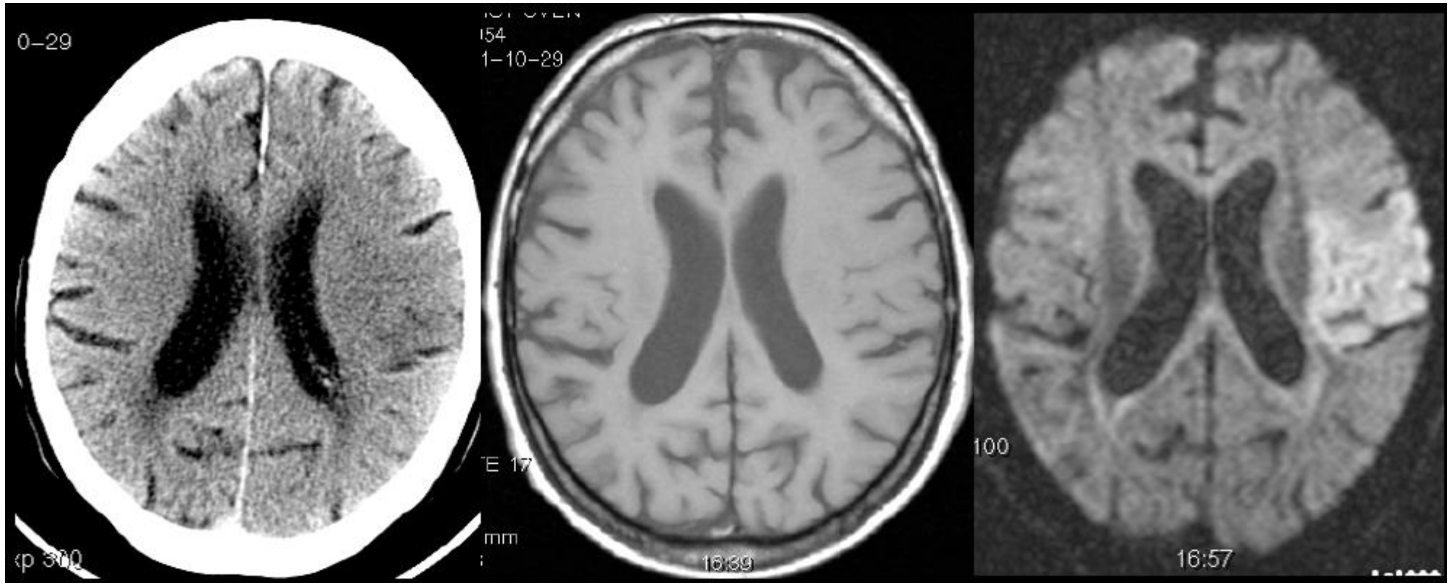
[1] Koziel (2016), *bhcamouflage.us*; [2] Neuroskeptic (2014), *blogs.discovermagazine.com*

Introduction: Clinical application of dMRI

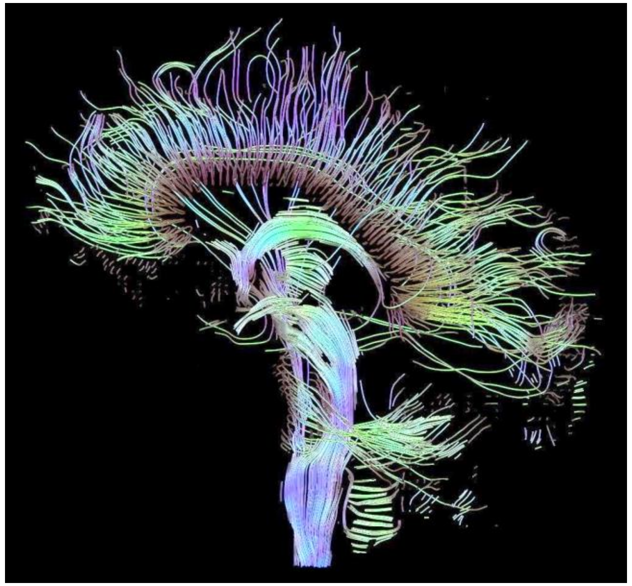
Stroke Diagnostics

CT T1W DWI [1]



Neurosurgery Planning

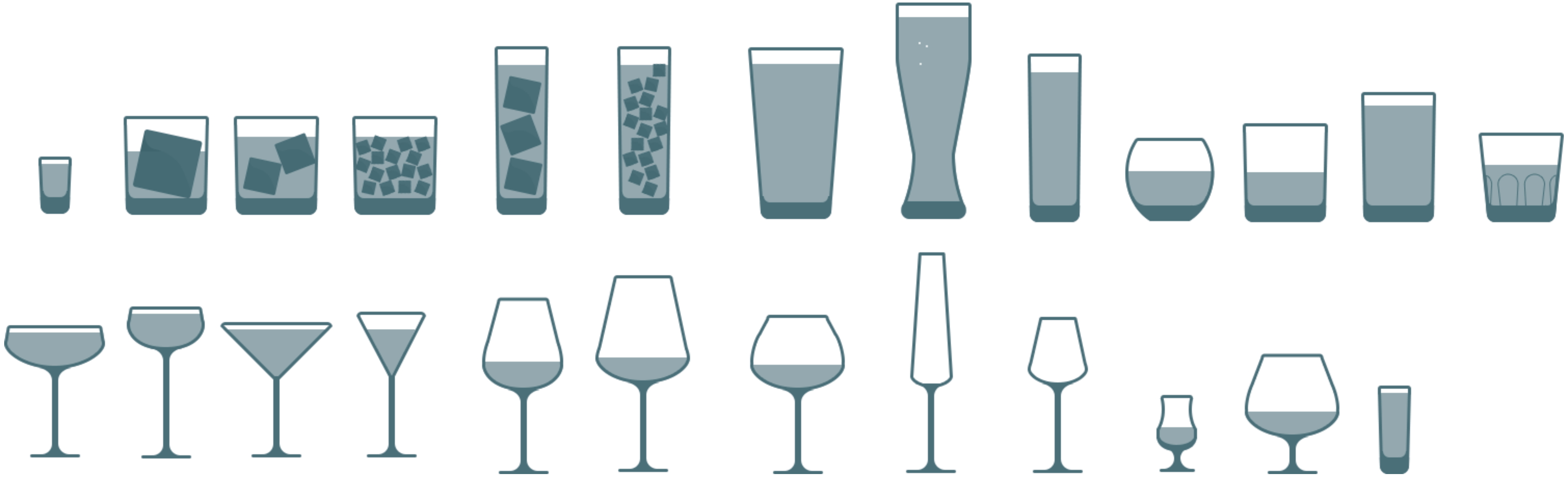
Tractography [2]



[1] In-house Lund data; [2] Schultz (2006), *Wikimedia*

Introduction: Principles of dMRI

- Diffusion MRI studies diffusion of water.
- Diffusion is modulated by surrounding environment.
- Diffusion MRI contains indirectly information on the geometry of the environment.
- Different geometries can be linked to different functions/pathological conditions.



[1]

[1] Koziel (2016), *bhcamouflage.us*

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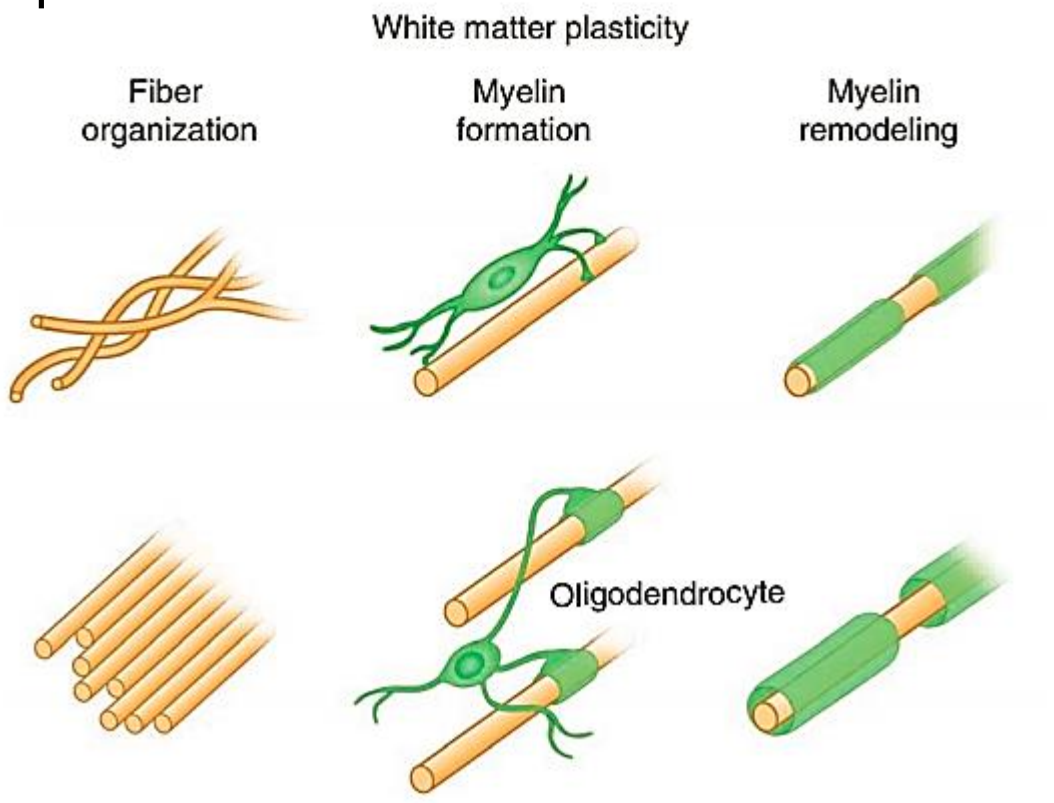
Introduction: Axon structure ↔ function

- Convey information as electrical impulses.
- Projections of nerve cells.
- Part of brain white matter.



[1] Zatore et al. (2012), *Nat. neuroscience*

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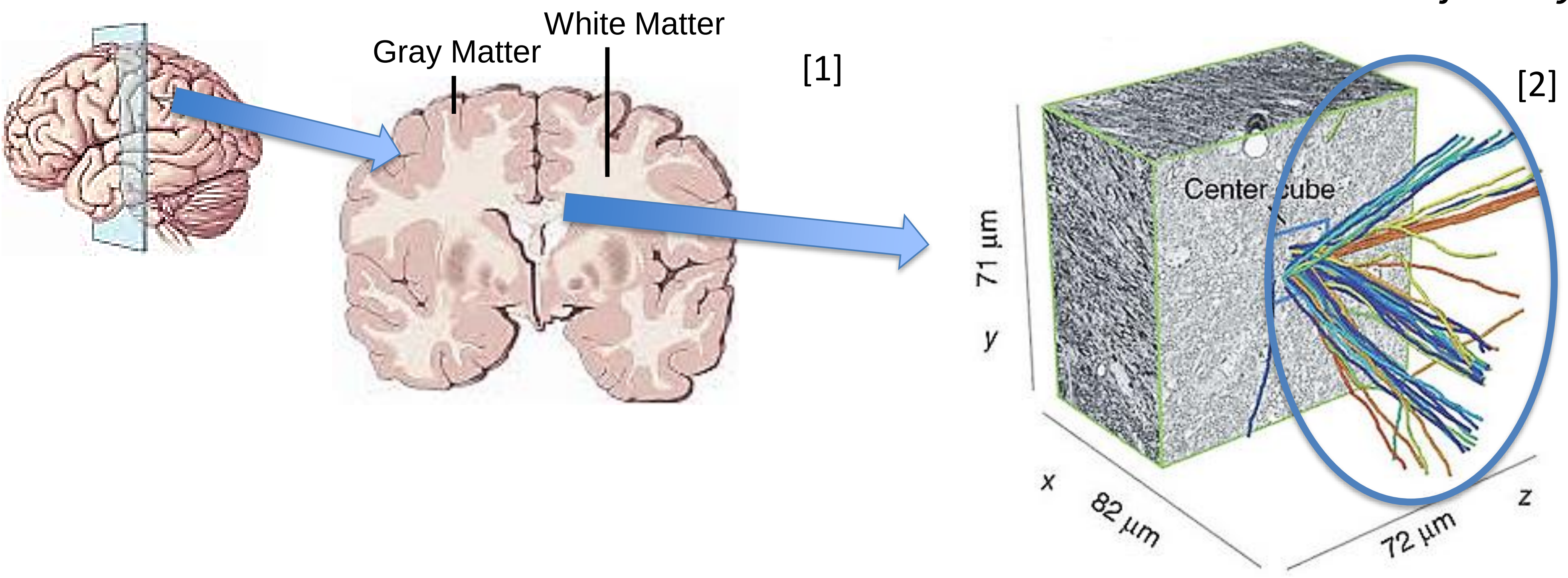
Introduction: Axons ↔ wiring of the brain

- Architecture is called *axonal trajectory.*

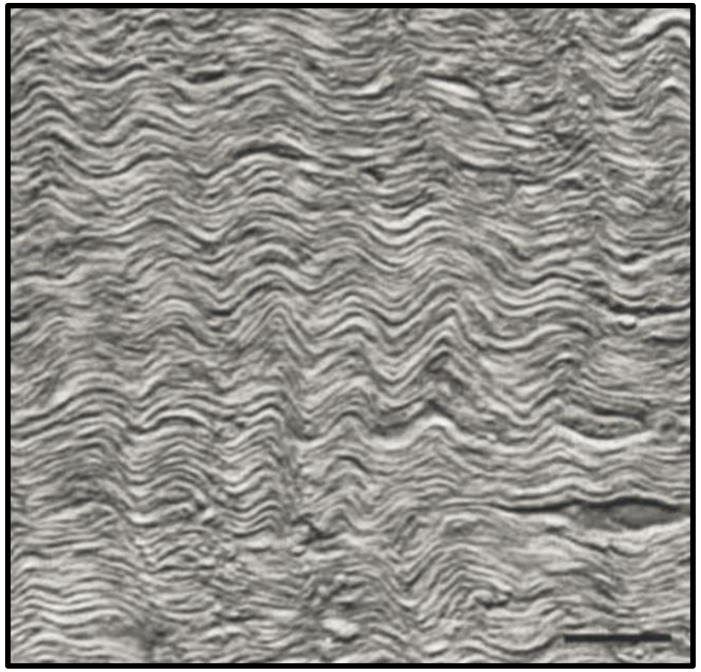
Axons:
their architecture:
axonal trajectory



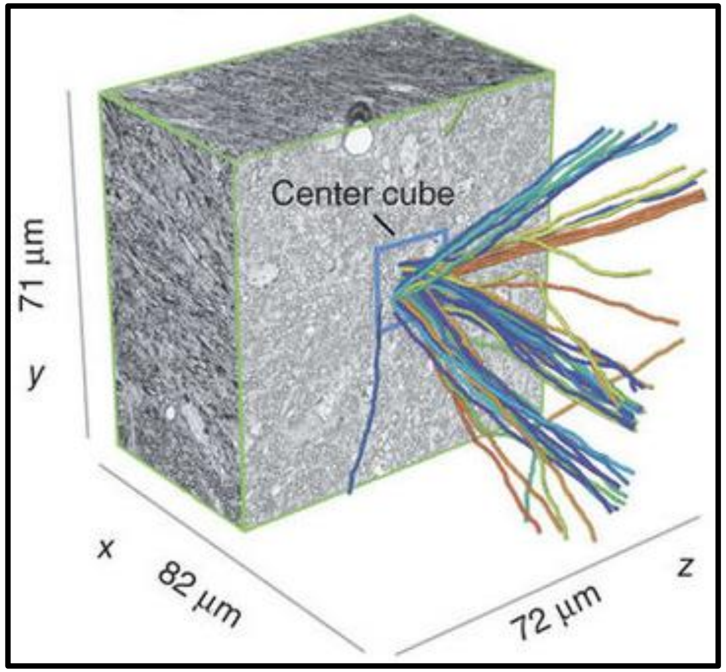
[1] AliceD (2015), *Stackexchange*; [2] Mikula et al. (2012), *Nat. Methods*

Introduction: Undulations are ubiquitous

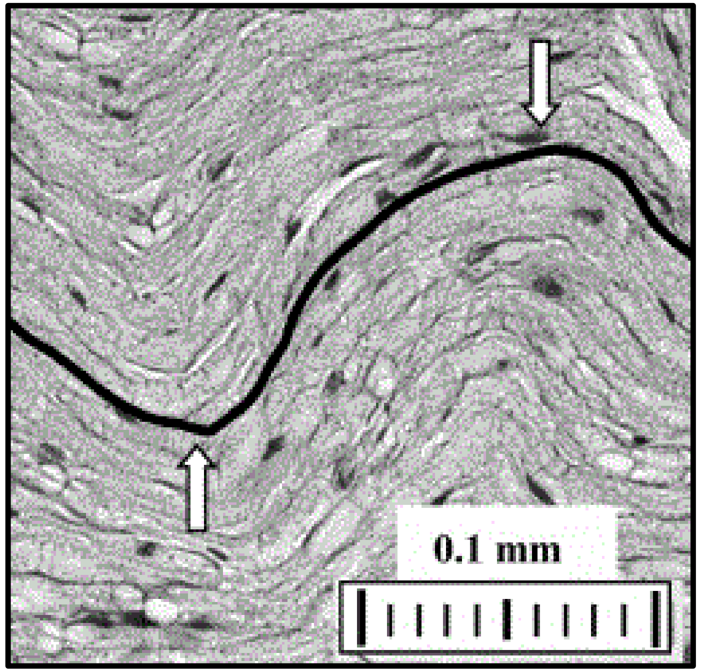
Optic Nerve [1]



Corpus Callosum [2]

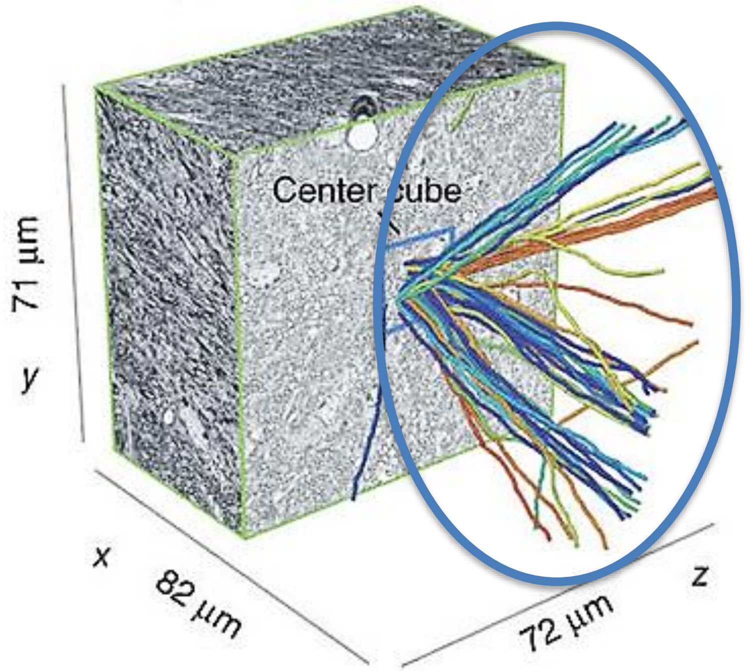


Phrenic Nerve [3]



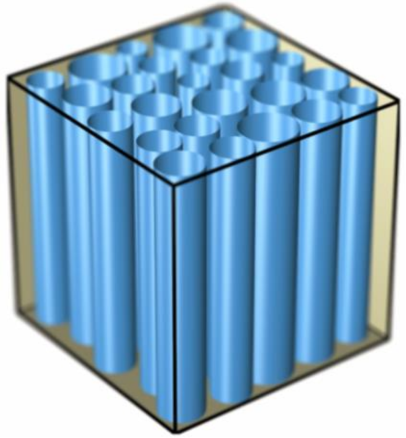
[1] Jeffery (1996), *J. Comp. Neurol*; [2] Mikula et al. (2012), *Nat. Methods*; [3] Lontis (2009), *IEEE Trans. Biomed. Eng.*

The Problem: How to model axons?

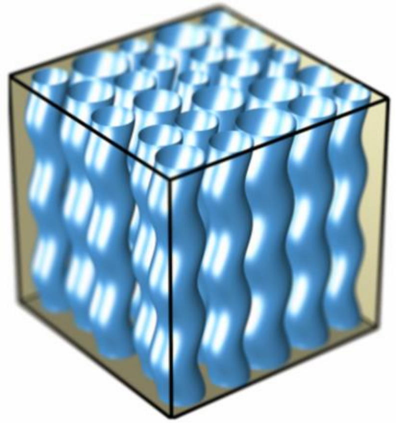


?

[1]

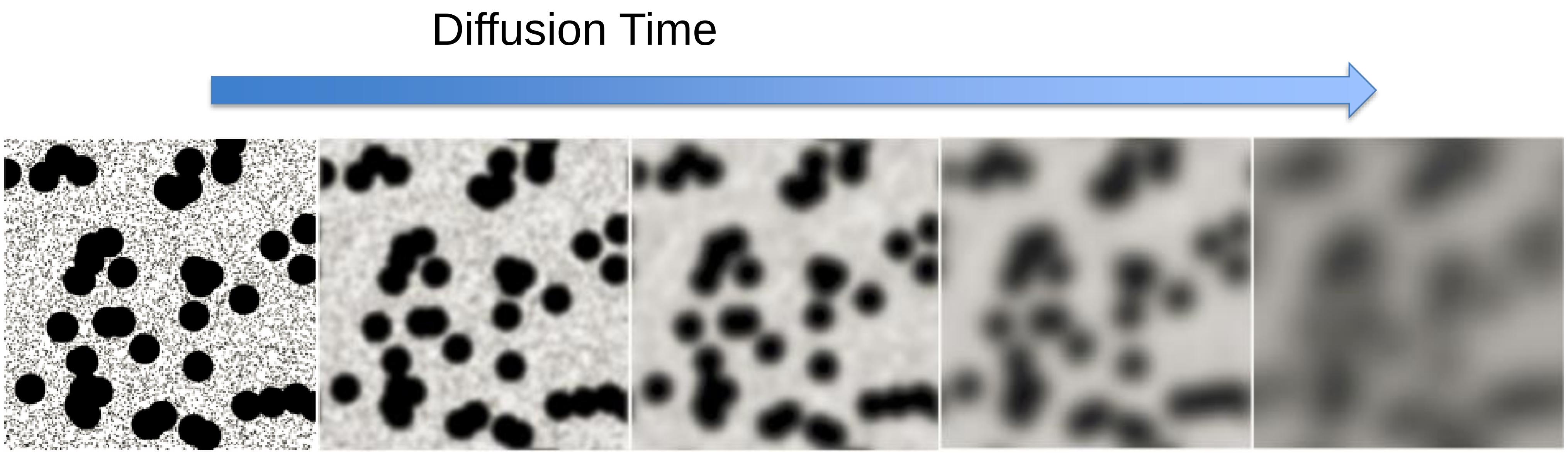


[1]



[1] Nilsson (2016), *Proc. ISMRM 24*

Methods: Physics at different diffusion times

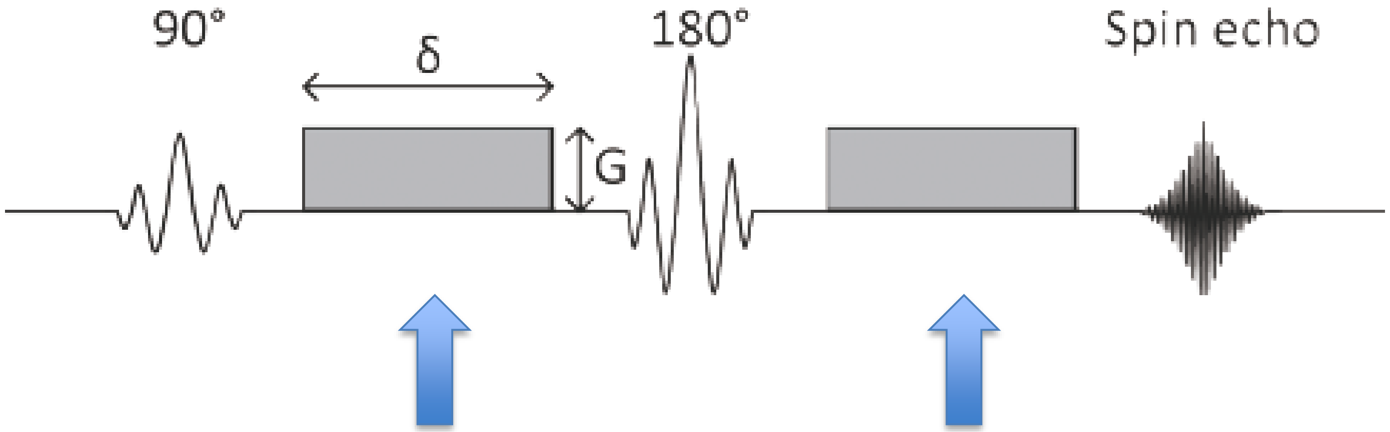


[1]

[1] Novikov (2016), *arXiv preprint*

Encoding information into signal

- Pulsed Gradient Spin Echo Sequence

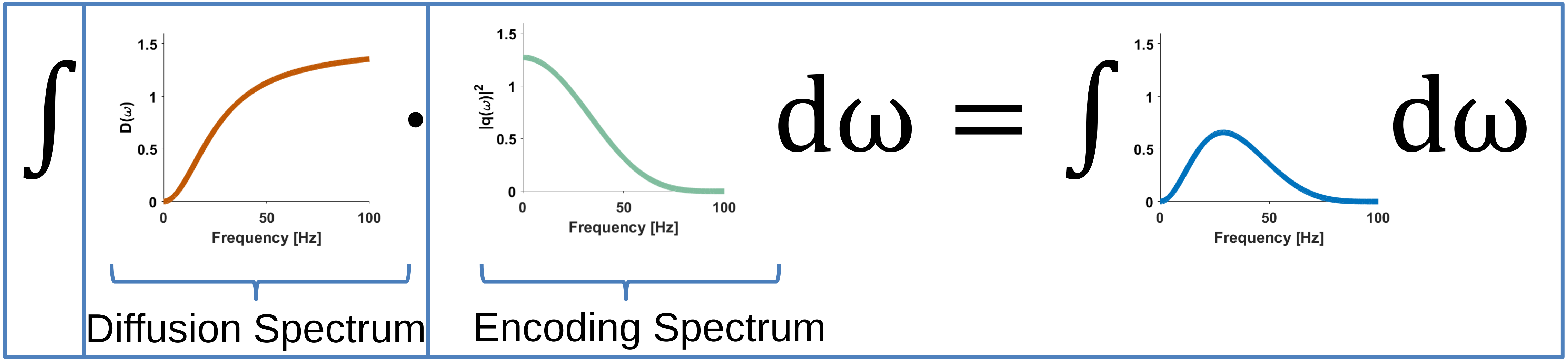


[1]

[1] Winston (2012), *Quant Imaging Med Surg.*

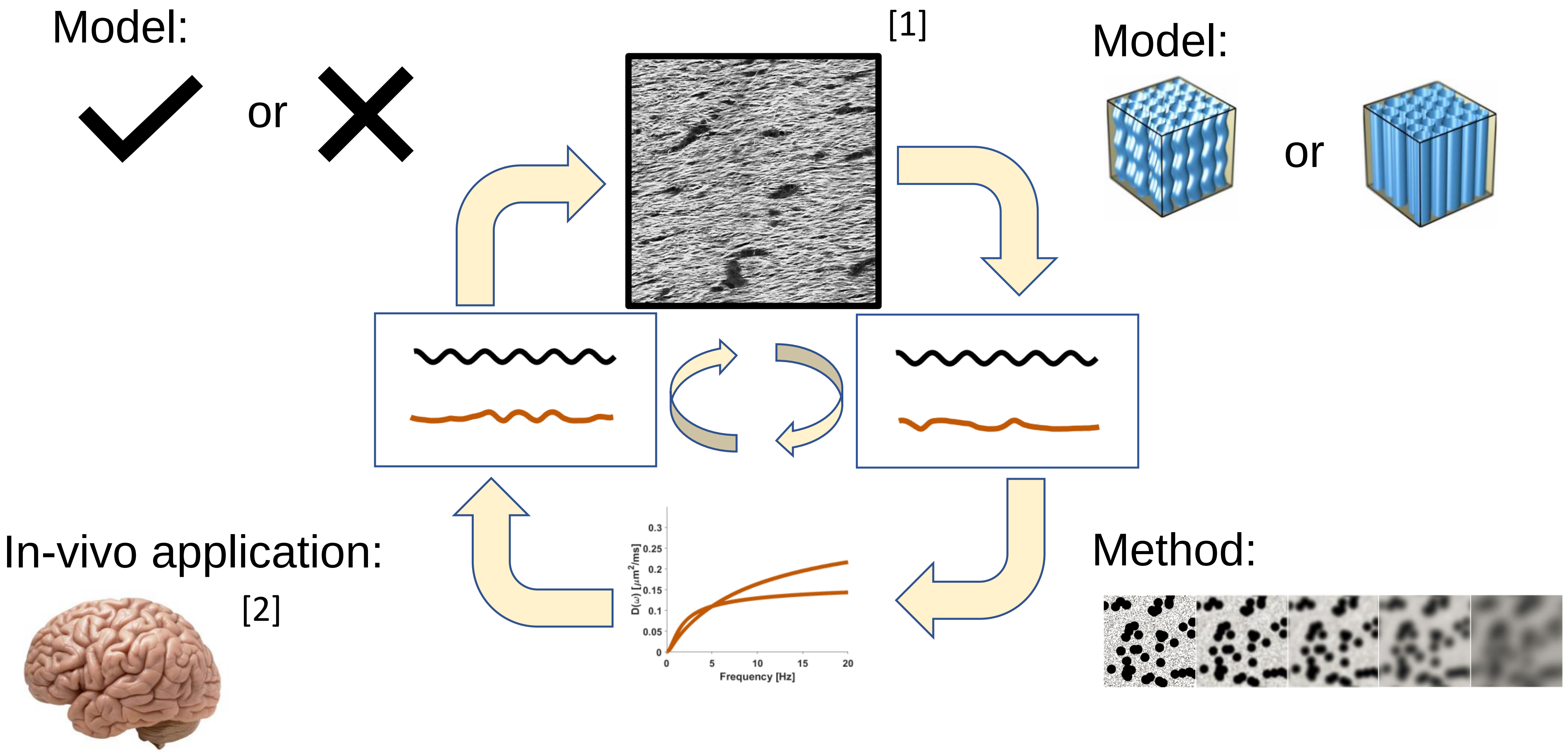
Signal = *f*(Diffusion Spectrum, Gradient Waveform)[1]

$$S = e^{-\int D(\omega)\cdot|q(\omega)|^2\, d\omega}$$



[1] Stepišnik (1993), *Physica B: Condensed Matter*

Aims

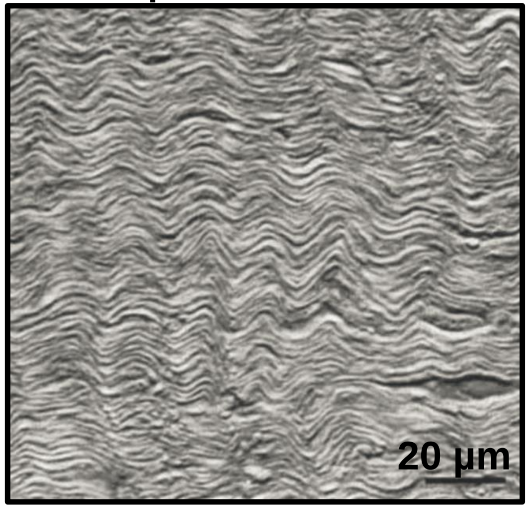


[1] Schilling (2018), *NeuroImage*; [2] _DJ_ (2005), *flickr.com*

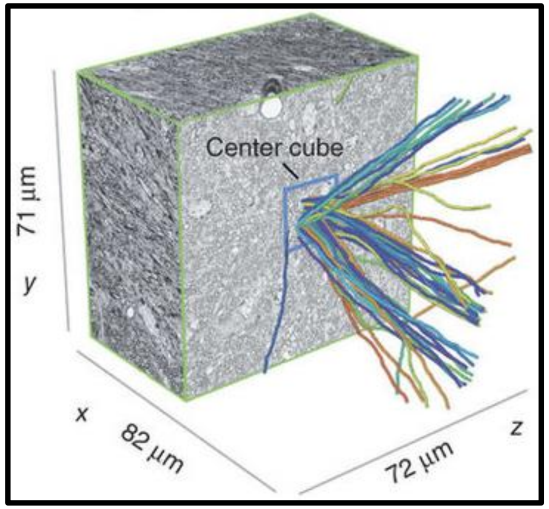
Model of axonal trajectory ↔ thin undulating wire

$$y(x) = a \cdot \sin(\Phi) = a \cdot \sin\left(2\pi \cdot \frac{x}{\lambda} + r(x)\right)$$

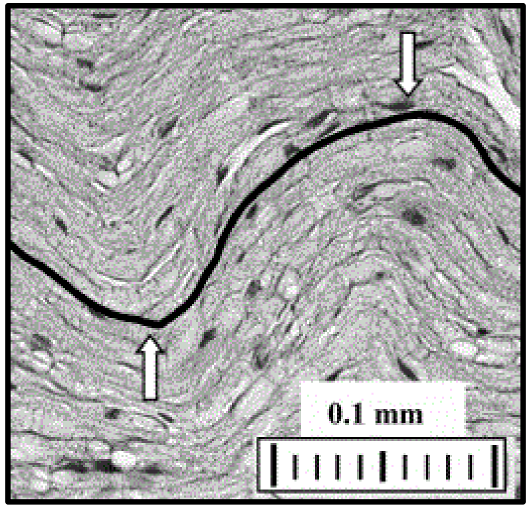
Optic Nerve



Corpus Callosum



Phrenic Nerve



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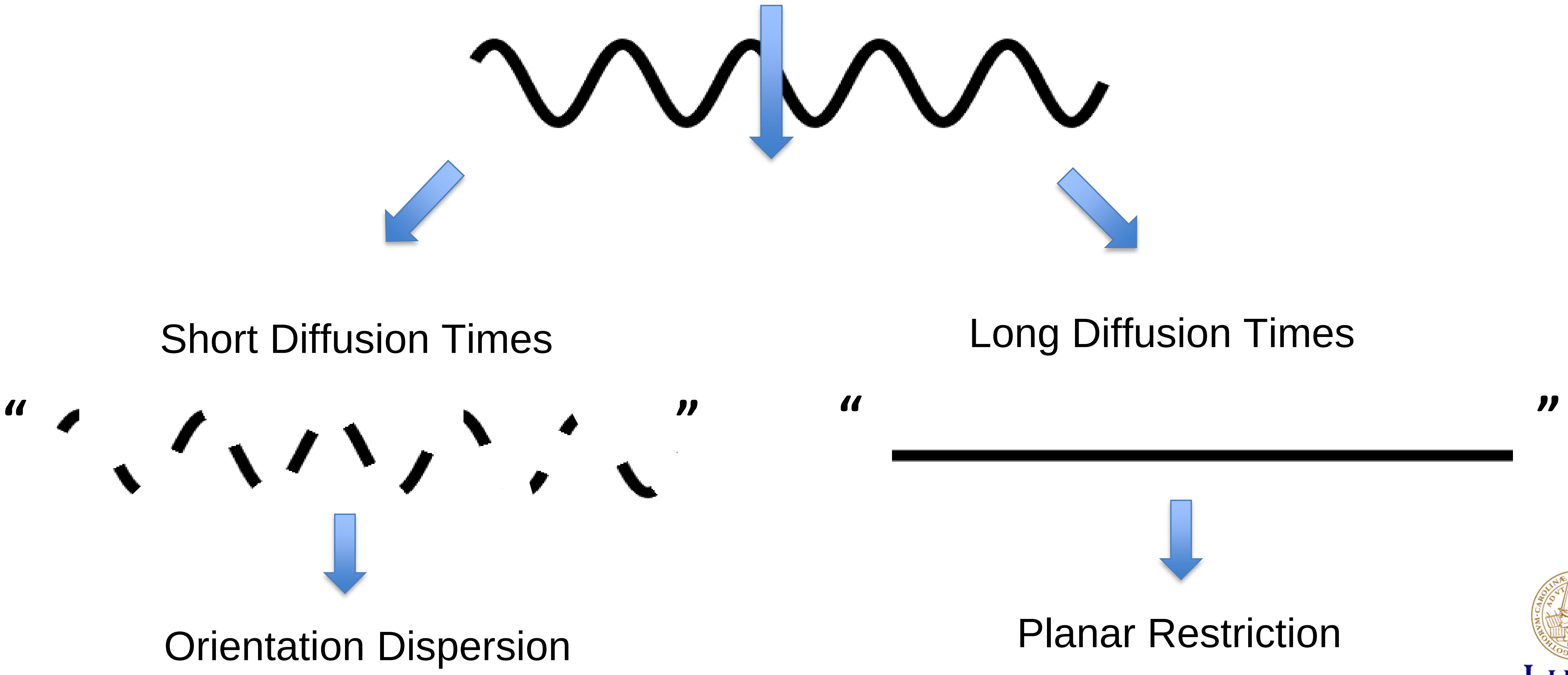
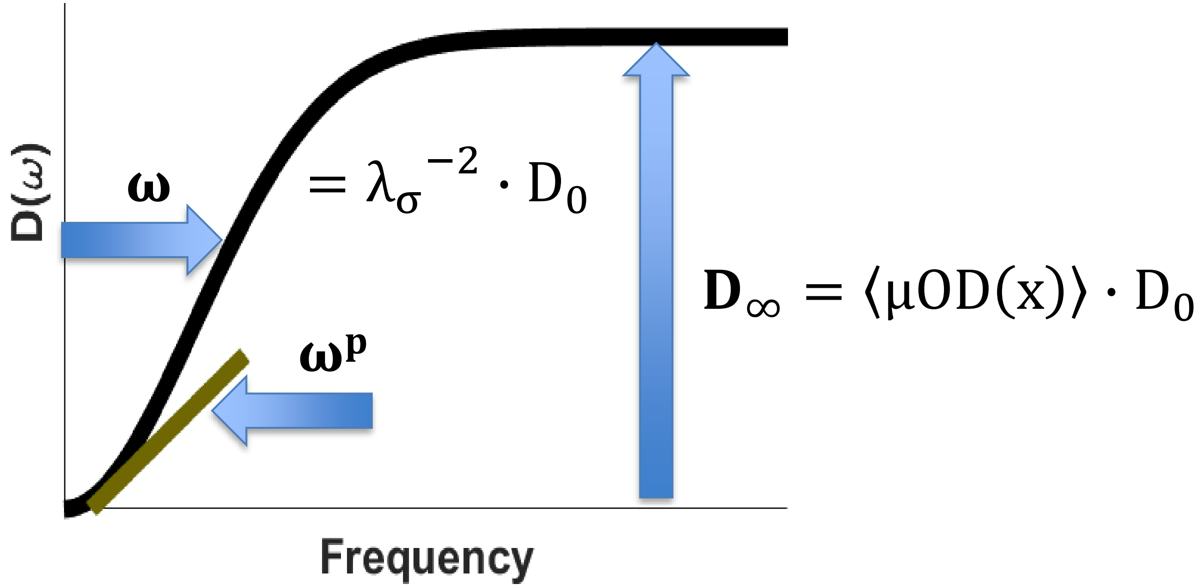
Diffusion in harmonic waves

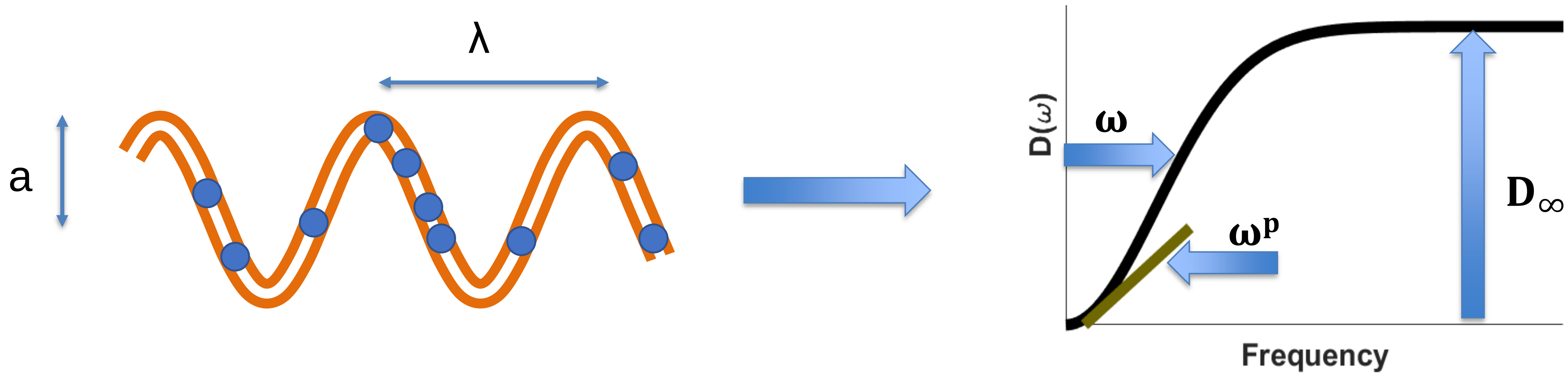


How to characterize diffusion spectrum?



$$D(\omega | D_\infty, \sigma, p) \; = \; D_\infty \left(1 - e^{-\frac{\omega^p}{\sigma^2}}\right)$$

Methods: Numerical Simulations



Descriptors of axonal Trajectories:

1) Amplitude a, wavelength λ
2) Microscopic orientation dispersion µOD, dispersion-weighted wavelength λ_σ

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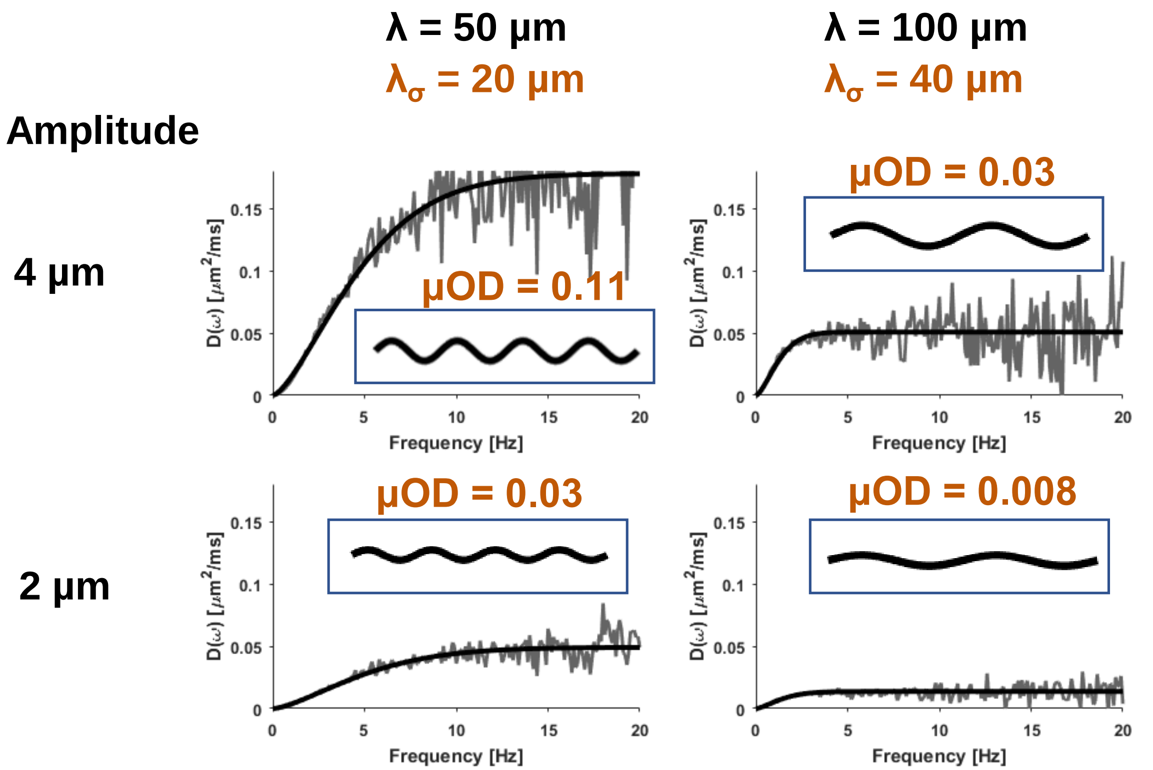
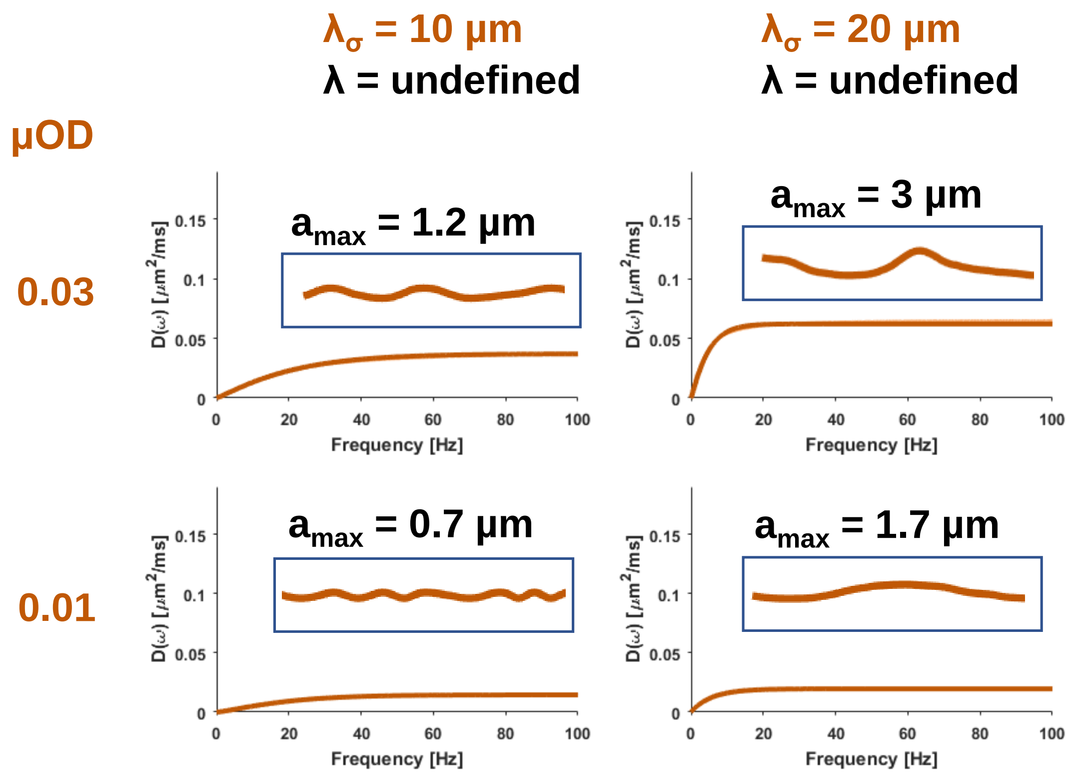
Results: Diffusion Spectra of Axonal Trajectories

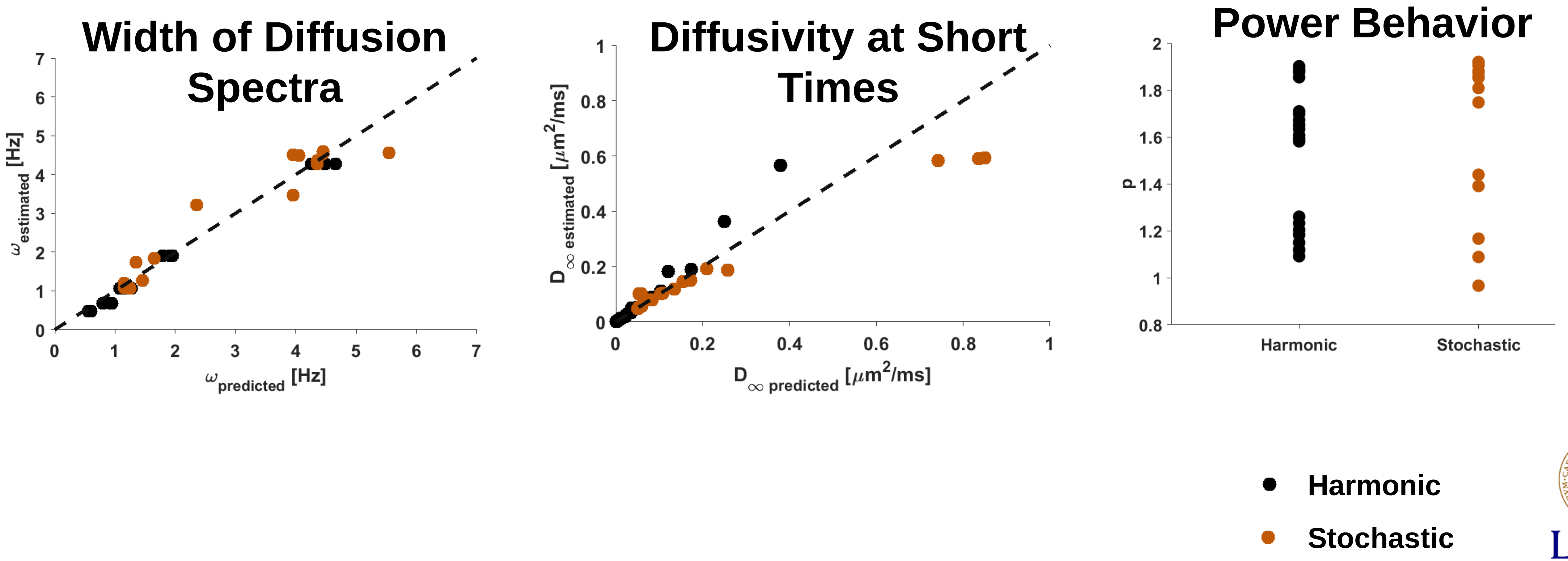
Harmonic Axonal Trajectories



Stochastic Axonal Trajectories

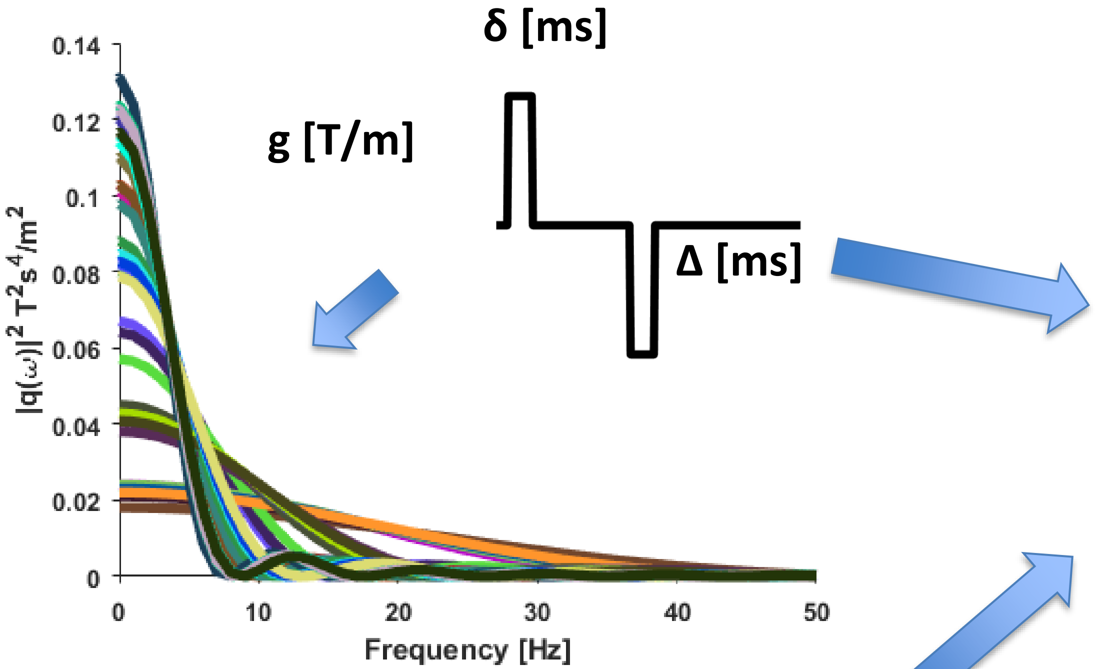


Results: Predicted vs. Estimated parameters



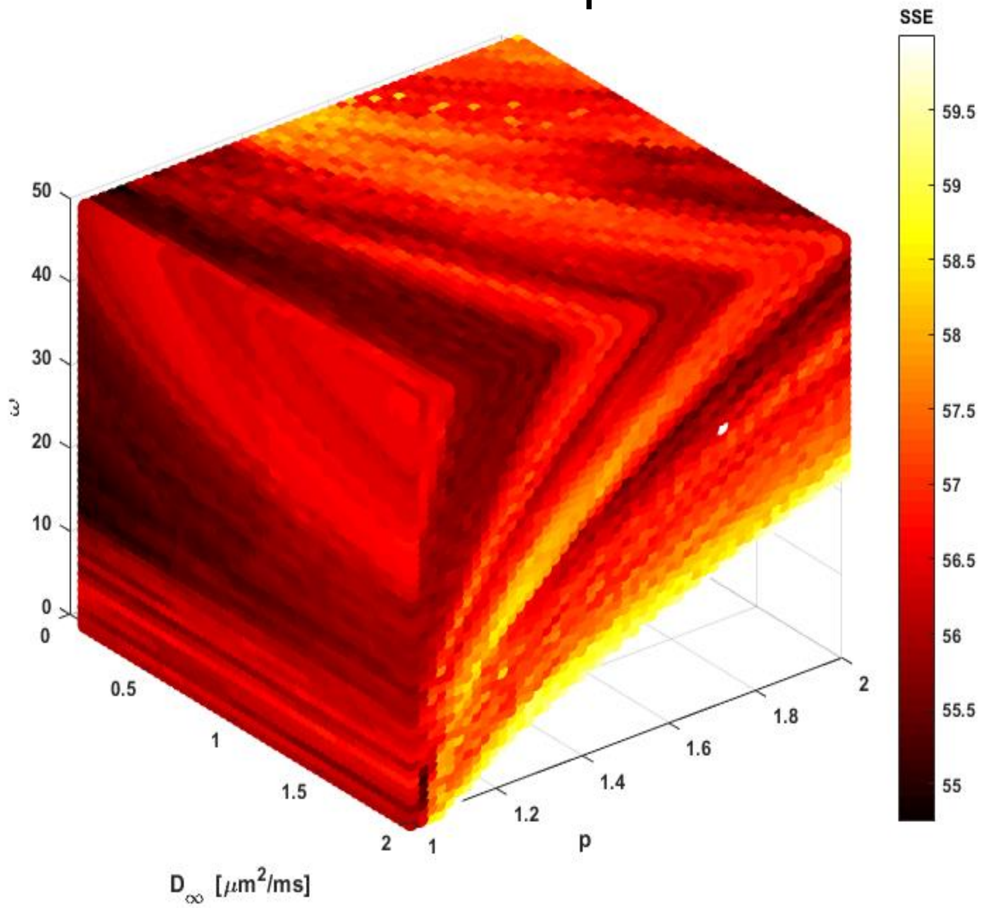
Results: Solving the inverse problem

Gradient Waveforms



dMRI Signal

Parameter Space



Results: Estimating Axonal Trajectories

ω = 10 Hz

↔

D_∞ = 0.1 µm²/ms

p = 2

λ_σ = 13 µm, µOD = 0.06

a = 1.8 µm
λ = 32 µm

a_{max} = 2.5 µm
λ = undefined

ω = 33 Hz

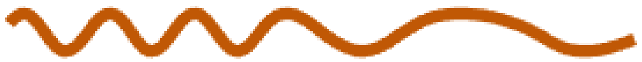
↔

D_∞ = 0.4 µm²/ms

p = 2

λ_σ = 7.2 µm, µOD = 0.24

a = 2.3 µm
λ = 18 µm



a_{max} = 3 µm
λ = undefined

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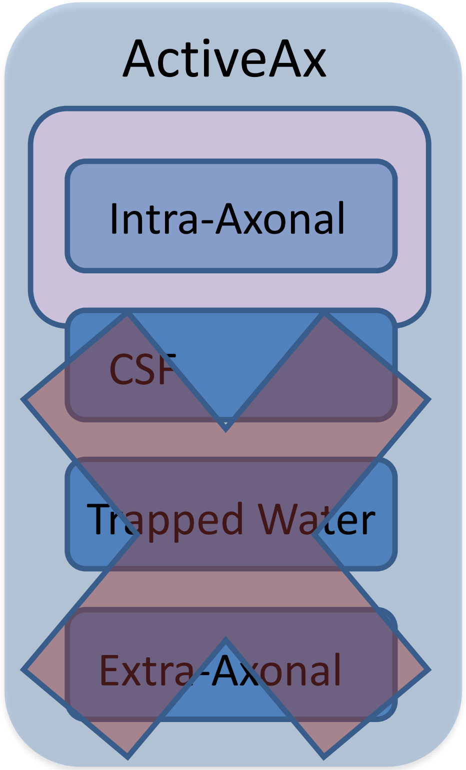
Are non-straight axonal trajectories necessary?

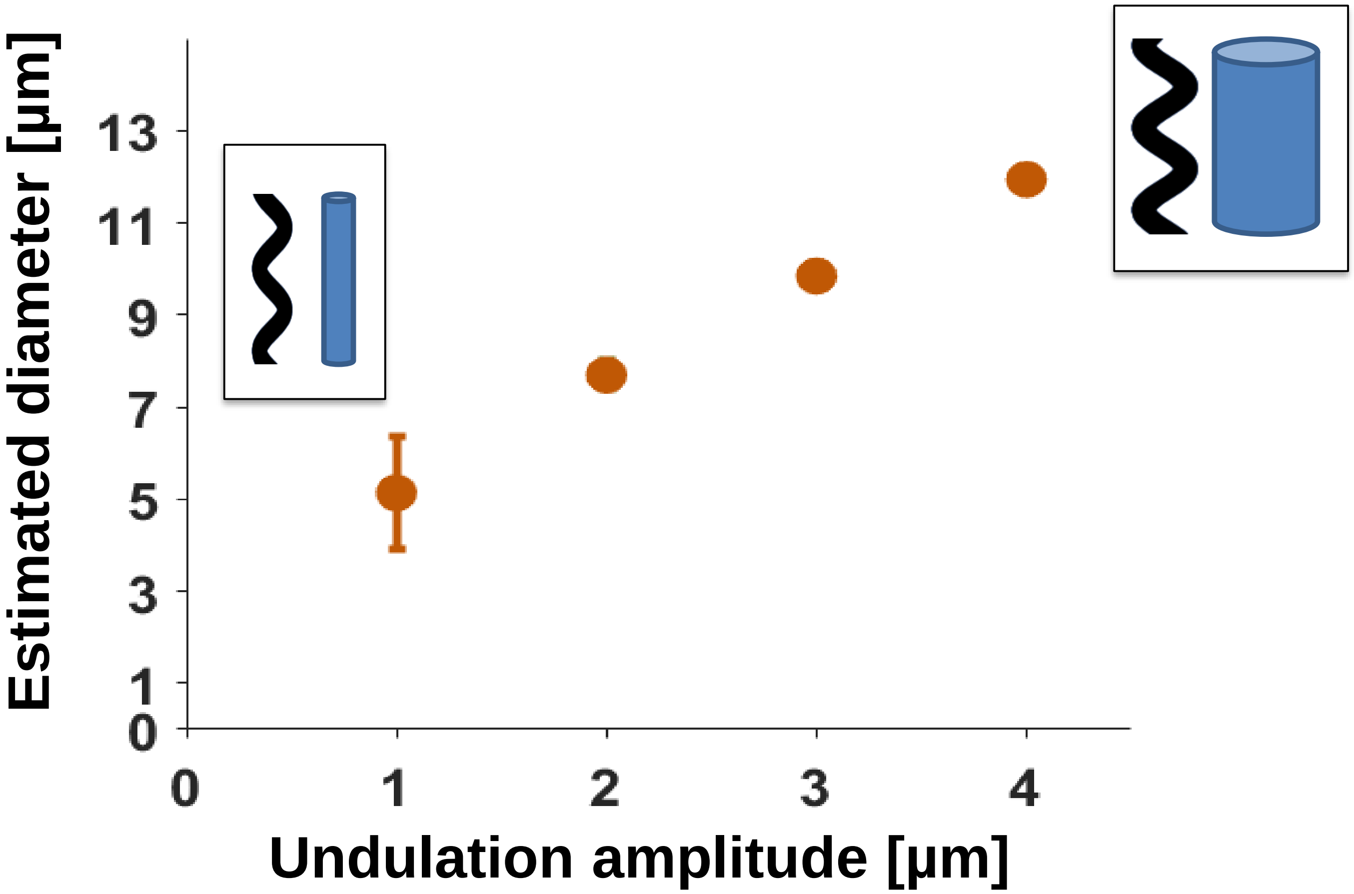
- Questions:
  - Do undulations bias axon diameter estimation in models that assume straight cylinders? [1]
  - Can the bias be explained?

- Signal and diffusion spectra from Monte Carlo.
- Restricted diffusion compartment model constrained to intra-axonal part only [2].
- Gradient waveforms with short & long diffusion times [2].
- Explanation through diffusion spectra.

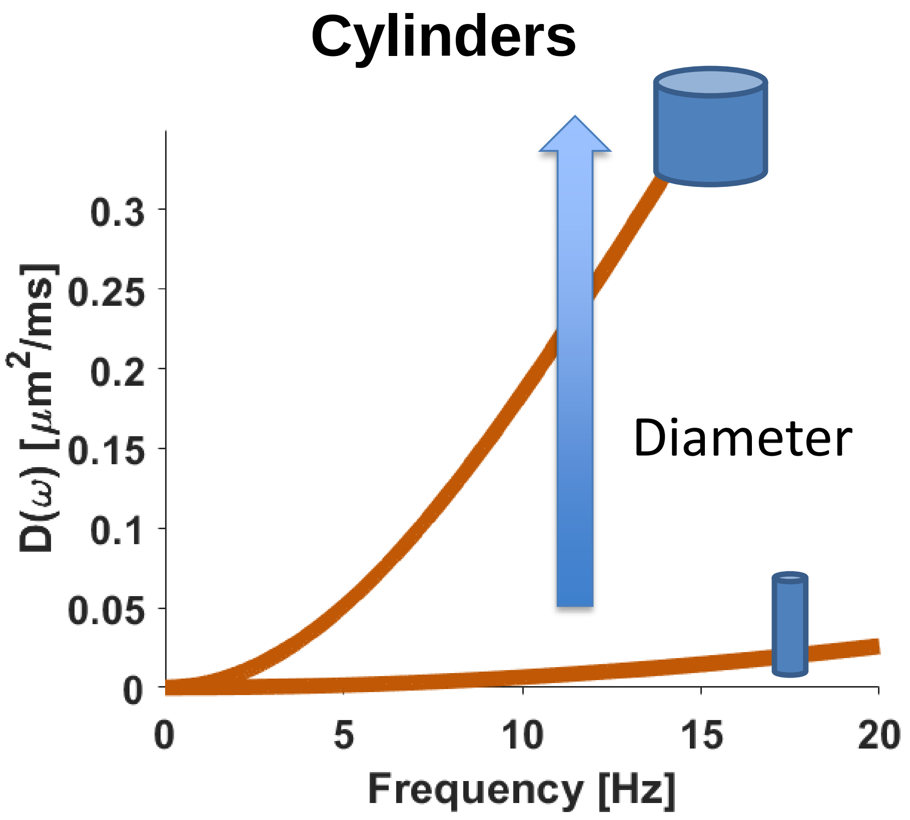


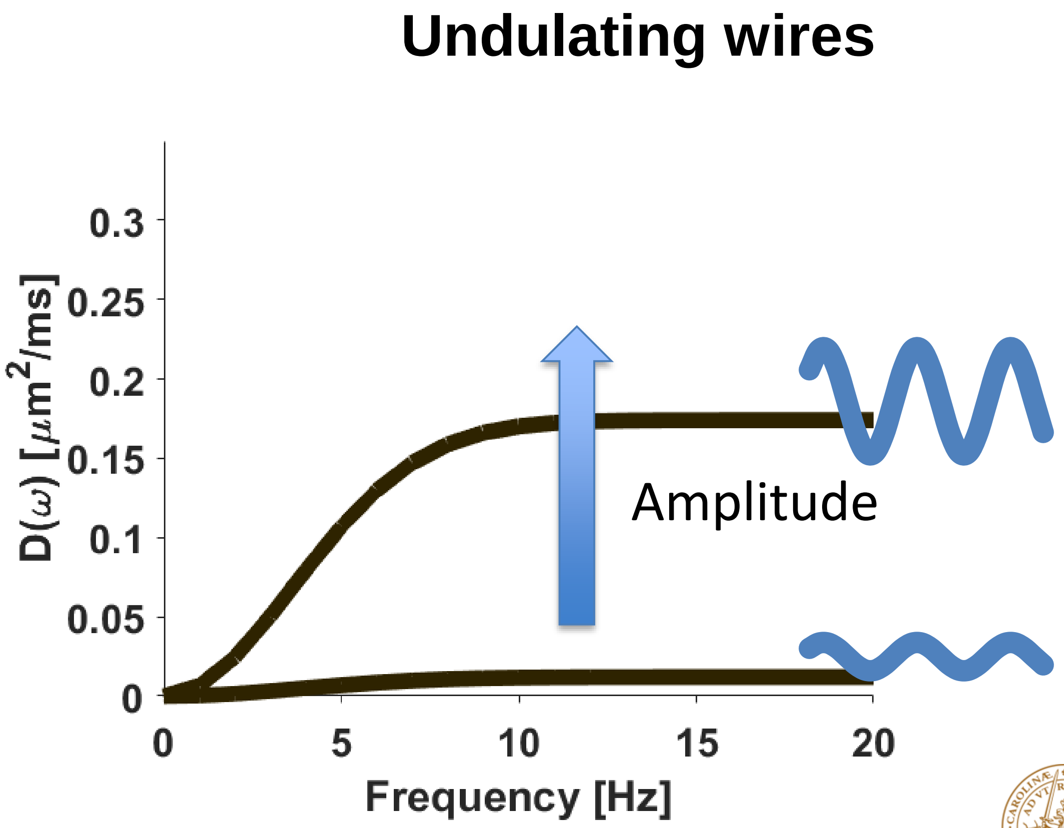
[1] Nilsson et al. (2012), *NMR Biomed*; [2] Alexander et al. (2010), *NeuroImage*

Results: Undulations interpreted as cylinders



Tissue Parameters ↔ Diffusion Spectrum





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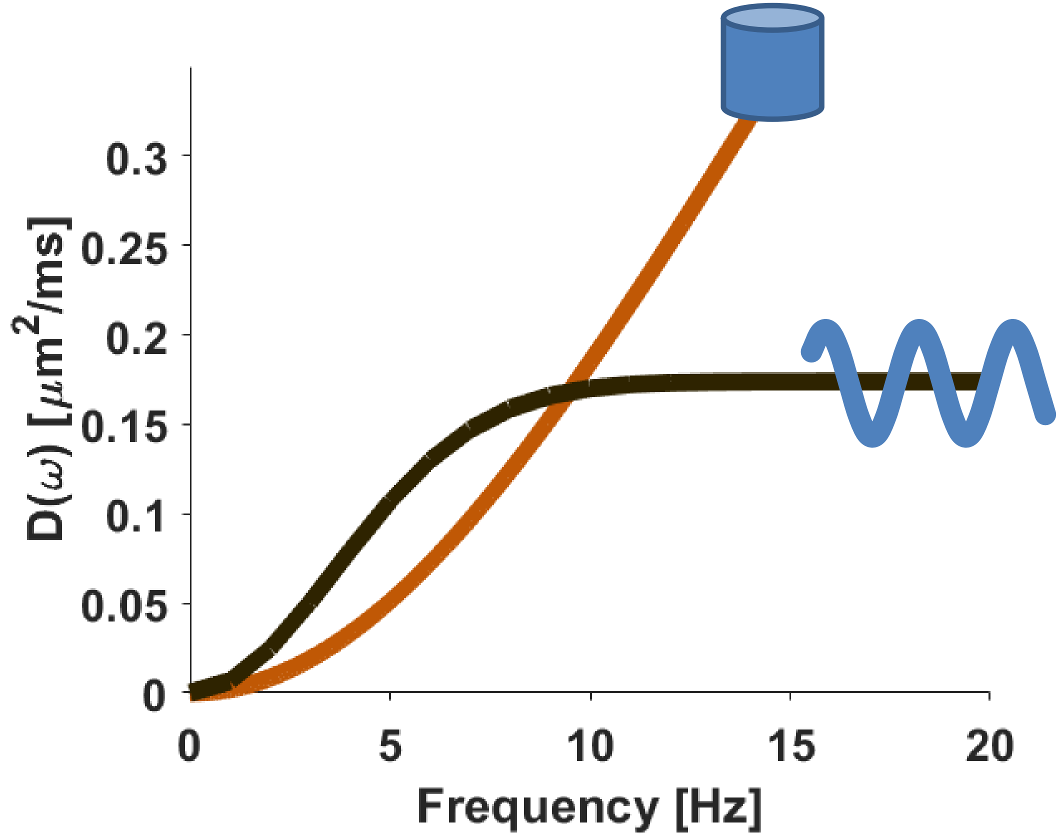
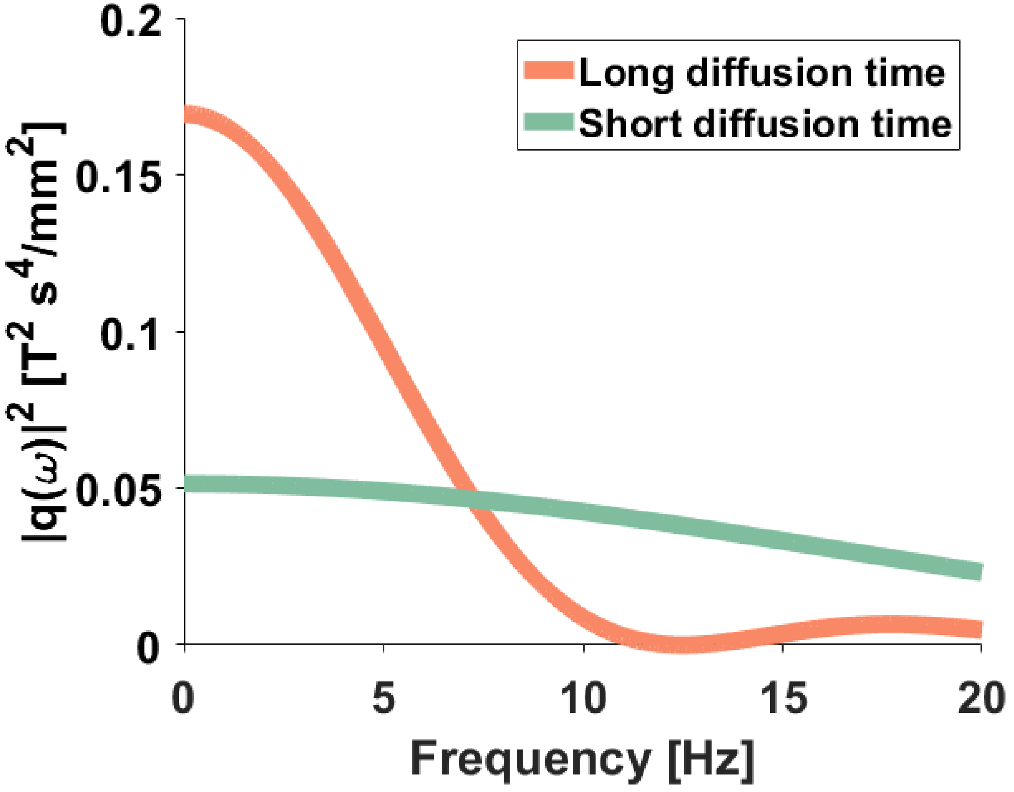
What & Where is Fitted?



Diffusion Spectra



Encoding Spectra

Conclusions

- Axonal trajectory model is congruent with histology, unlike models that assume parallel straight cylinders.

ω = 10 Hz

$\leftrightarrow$

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λ_σ = 13 μm, μOD = 0.06

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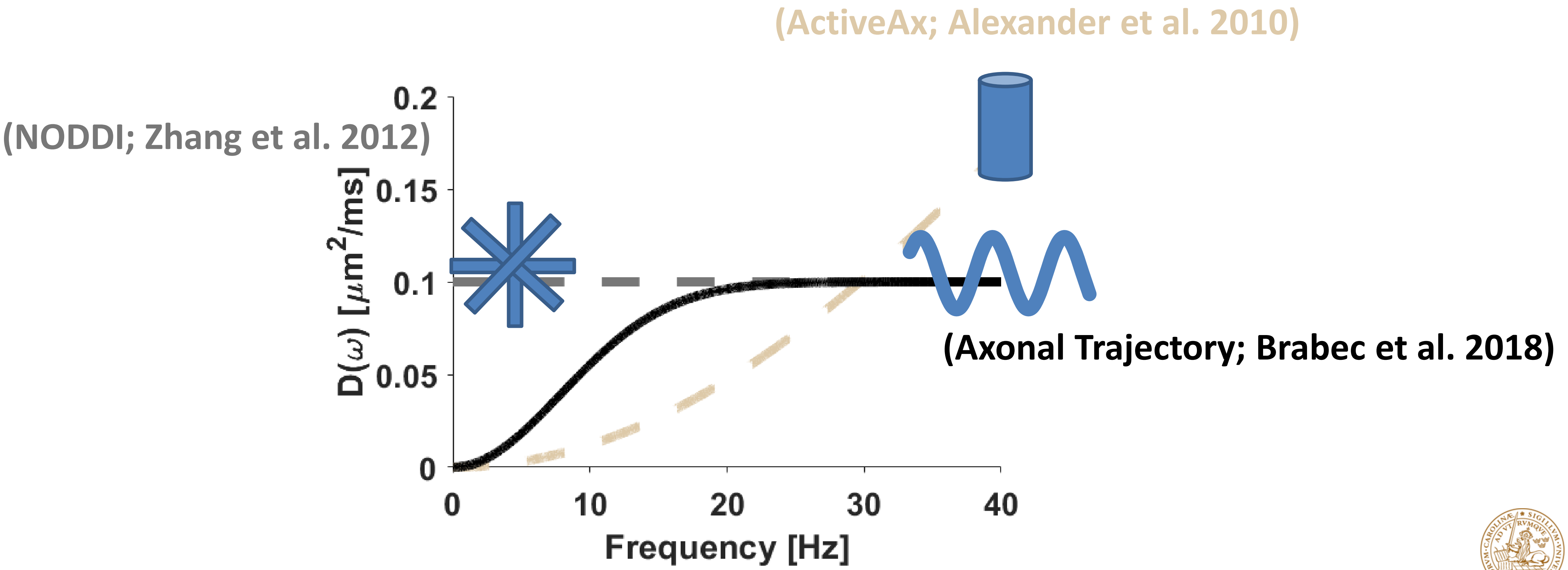
Conclusions



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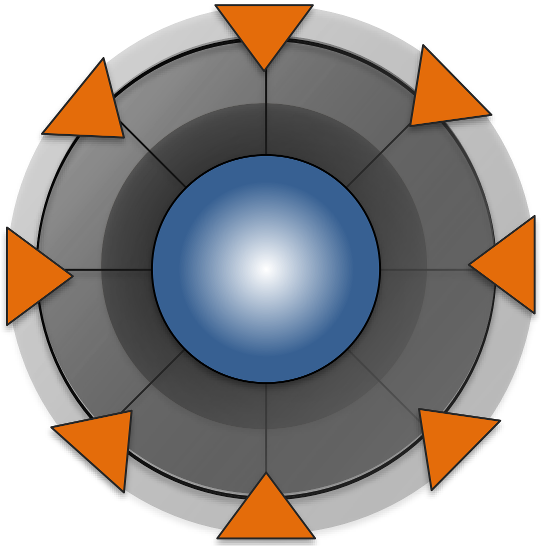
Importance of Physics

- A simple 1D-toy model with far-reaching consequences.
- Scientific fields are no longer separate.

Thank you for your attention



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