MRI as a Probe of Tissue Microstructure

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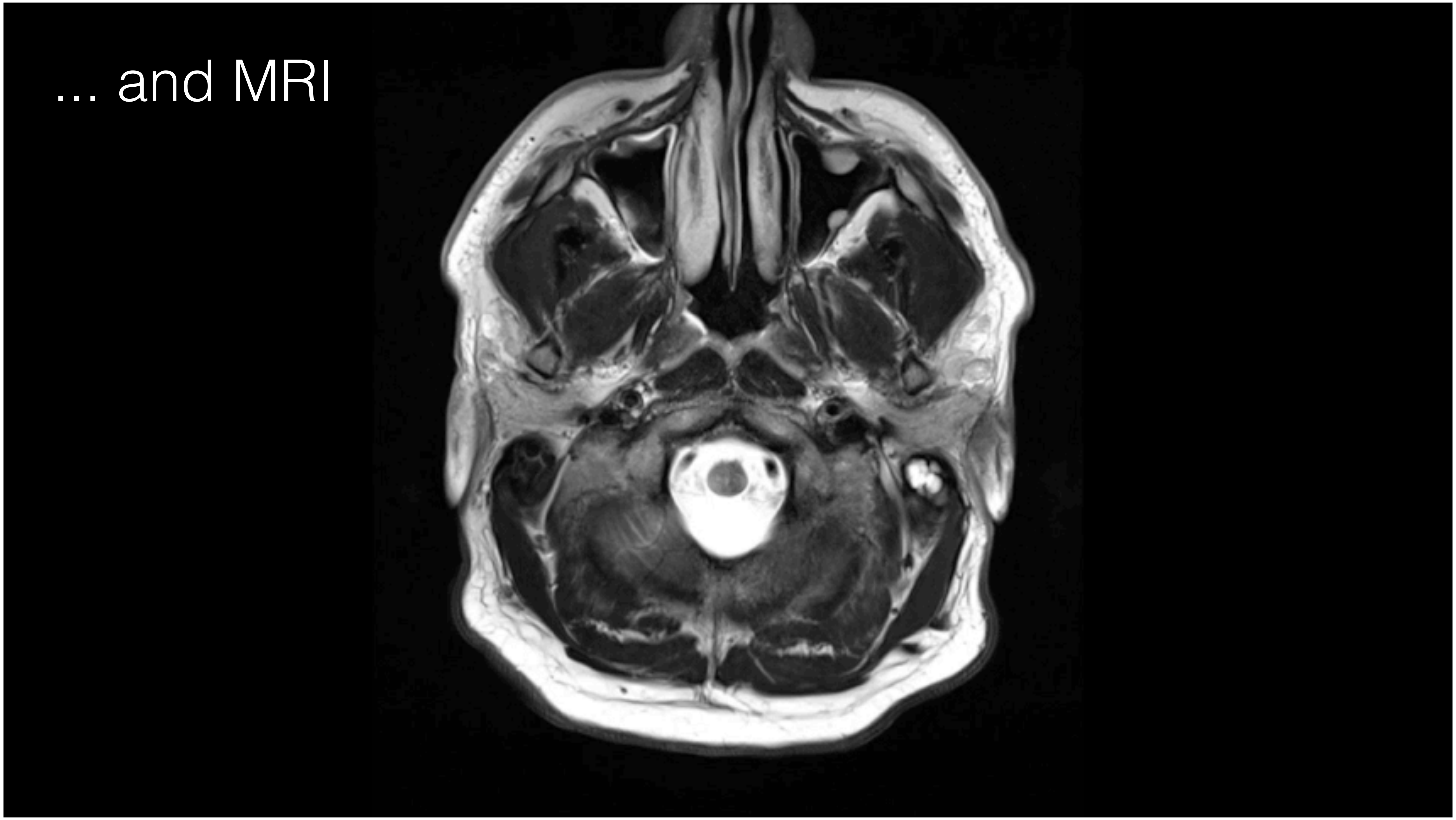
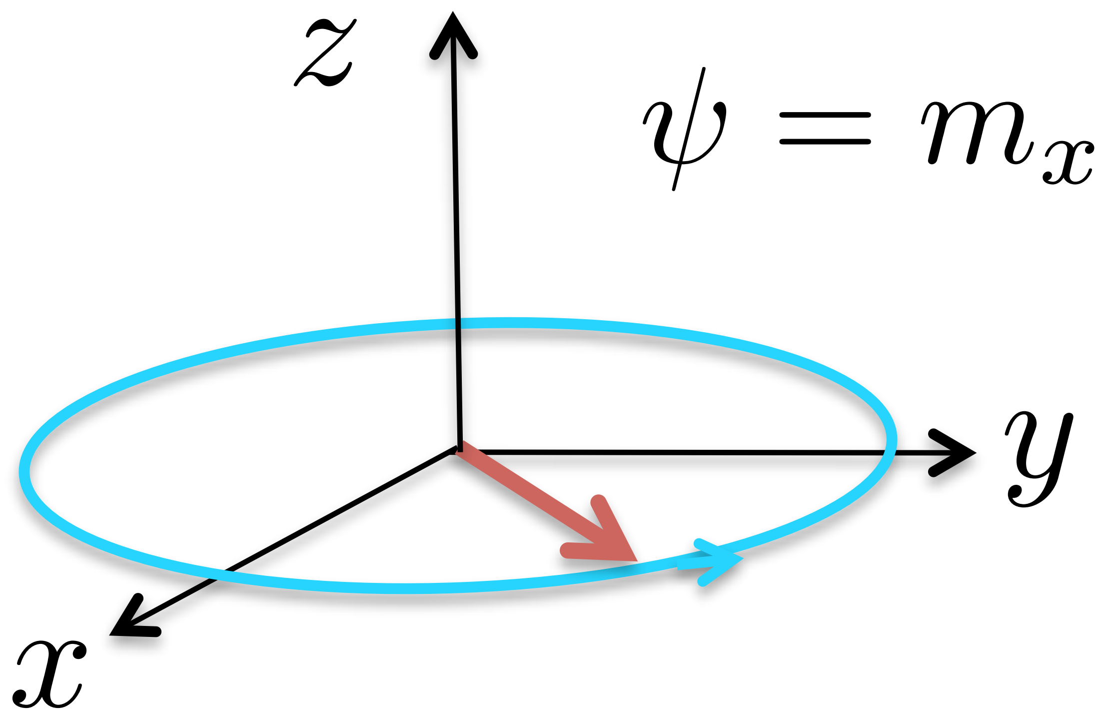
There is medicine...



MRI in brief



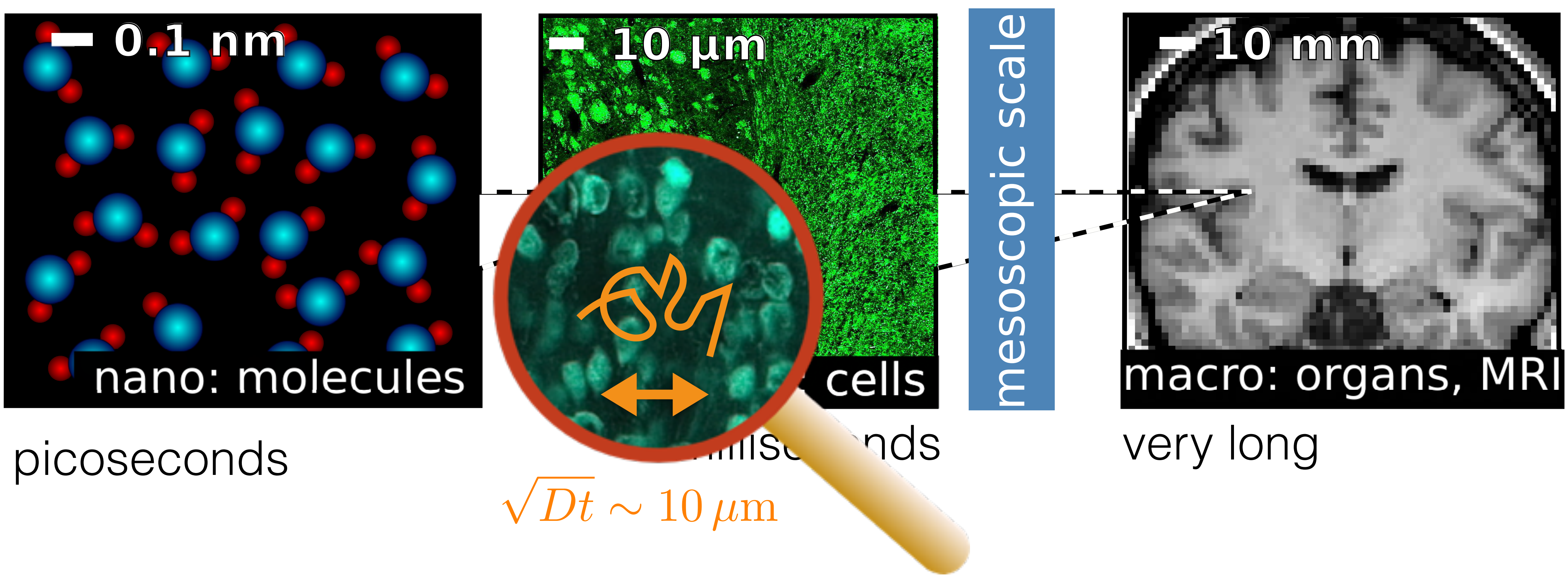
$$\psi = m_x + i m_y \; = e^{i\varphi}$$

$$S = \langle e^{i\varphi} \rangle$$

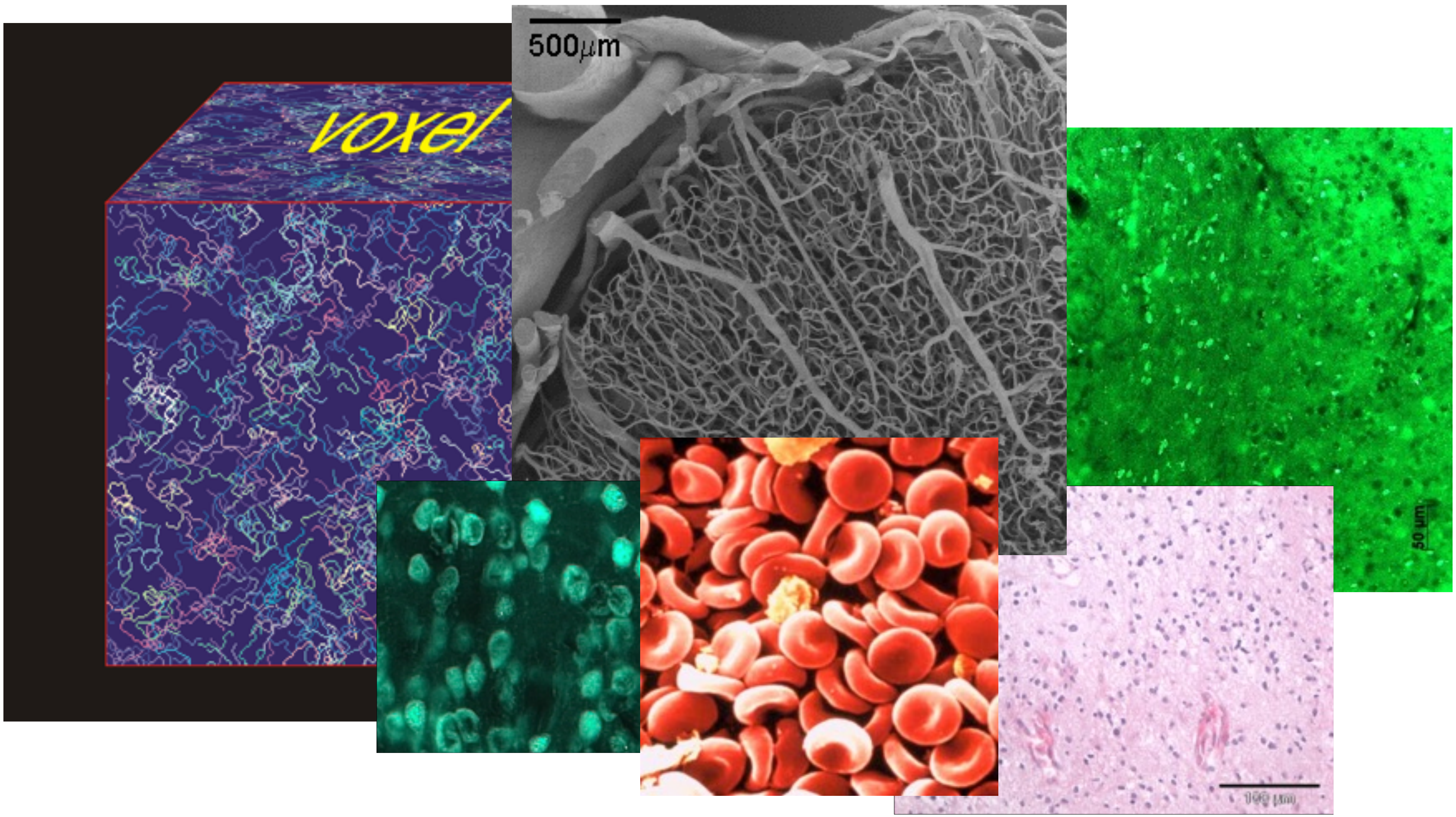
3 tools of MRI:

- RF
- gradients of the main field
- do nothing

Tissue microstructure



More of tissue microstructure



vessels: Courtesy of B.Weber and N.Logothetis

...and even more...

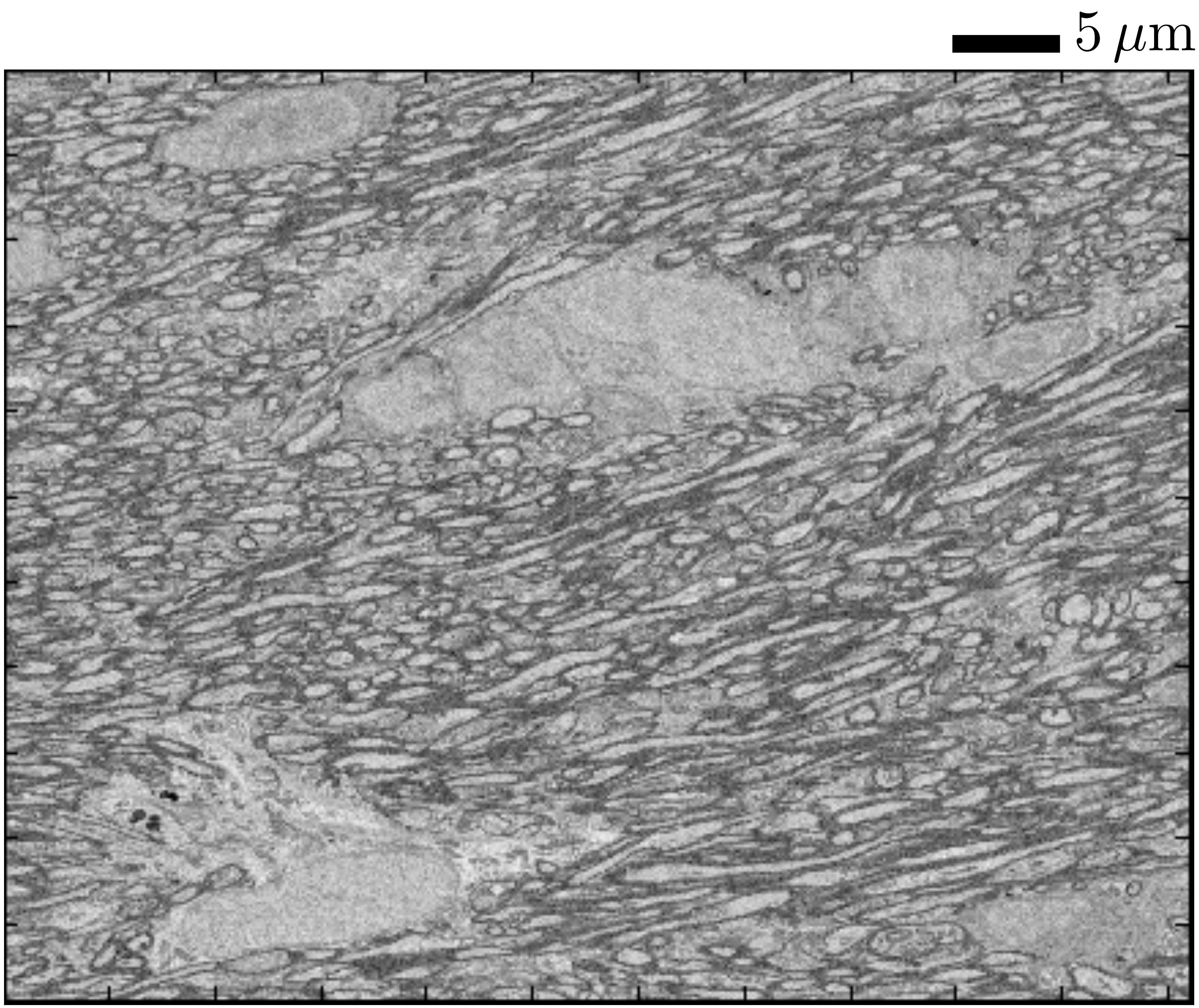
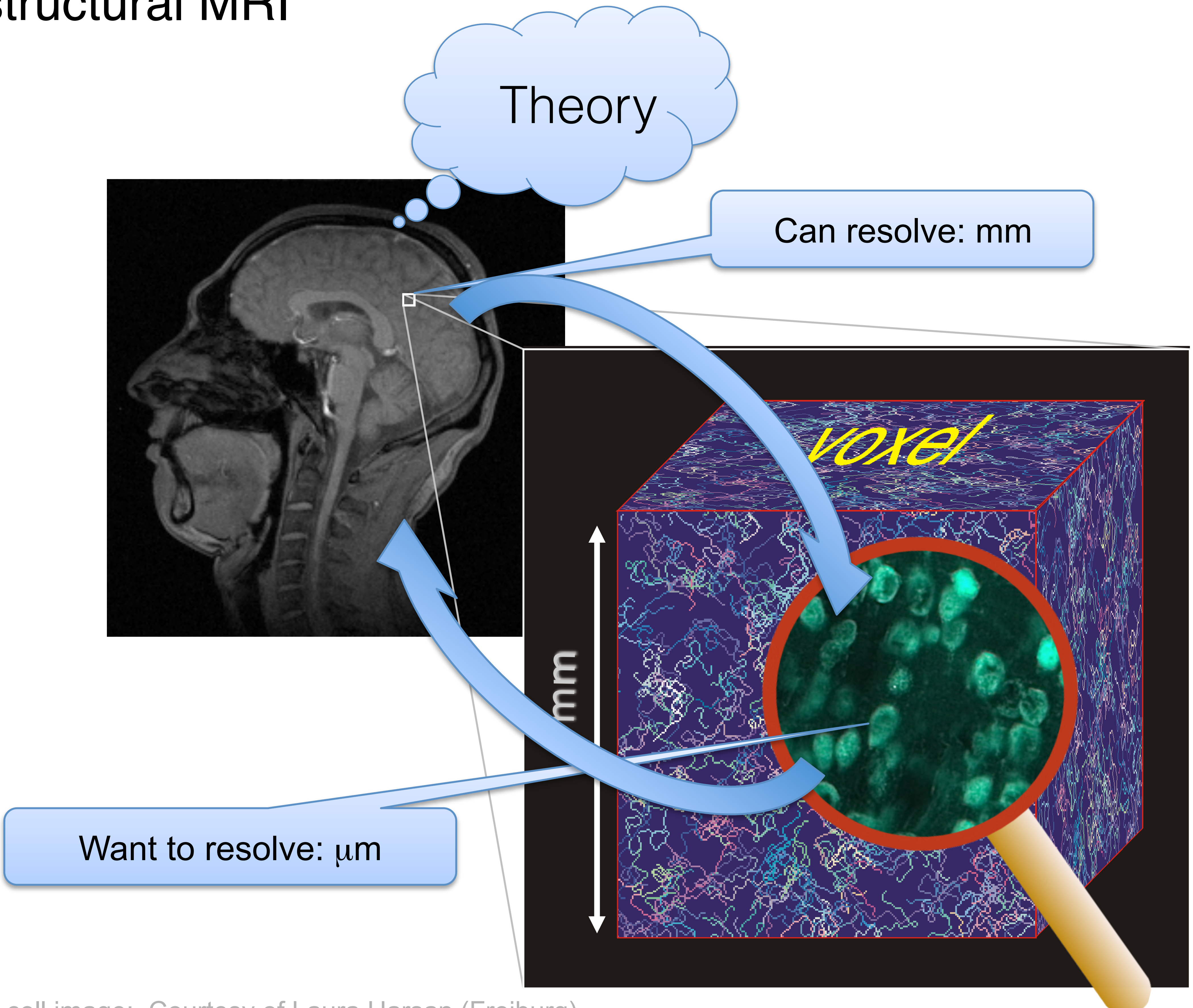


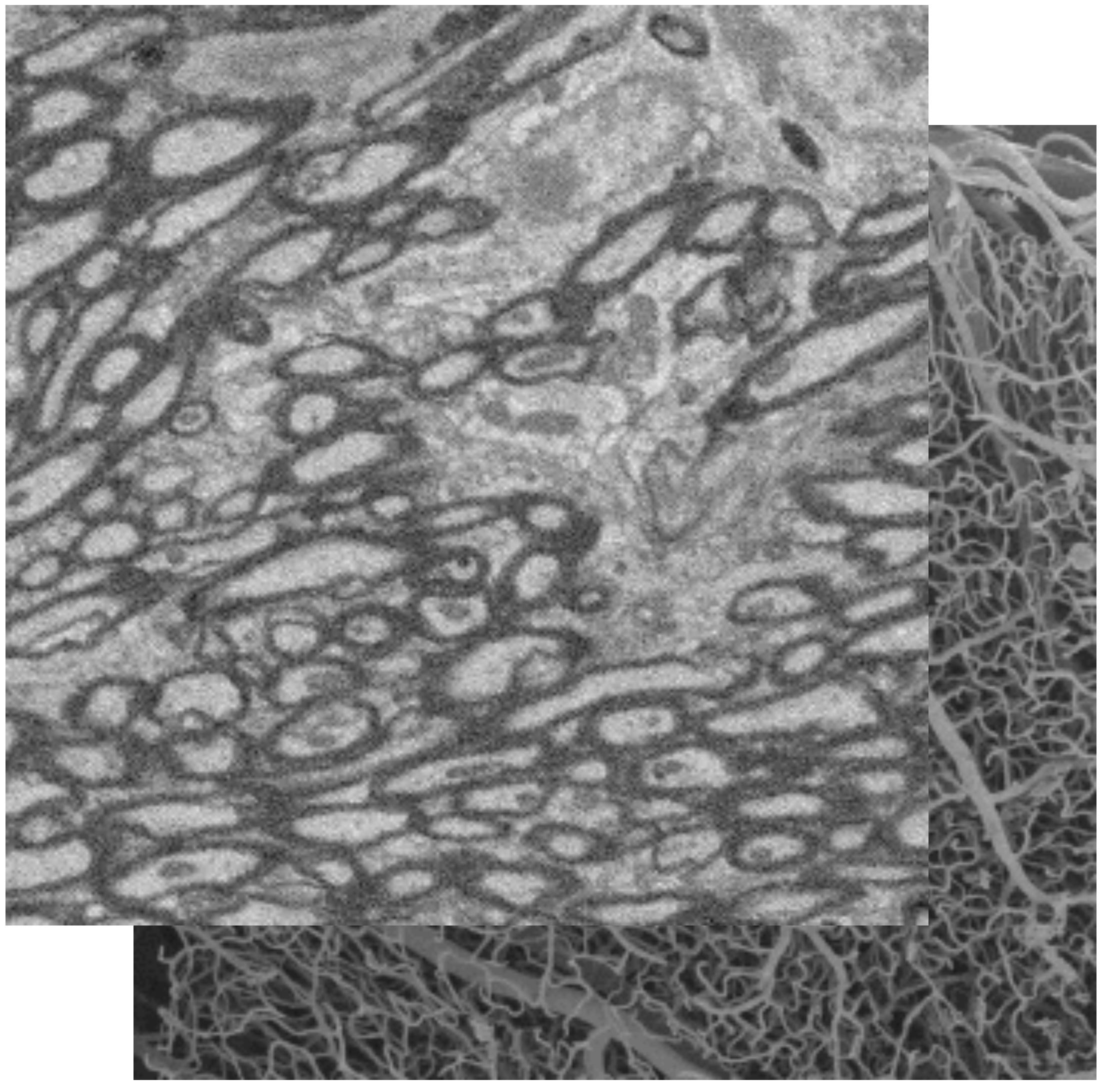
Image courtesy: A.S Lopez, Olli Gröhn et al.

Microstructural MRI



cell image: Courtesy of Laura Harsan (Freiburg)

Back to physics: Relevant phenomena



$$\Omega(x) \quad R_2(x) \quad \text{“}D(x)\text{”}$$

$$\frac{\partial}{\partial t}\psi = -\nabla j - i\Omega(x)\psi - R(x)\psi$$

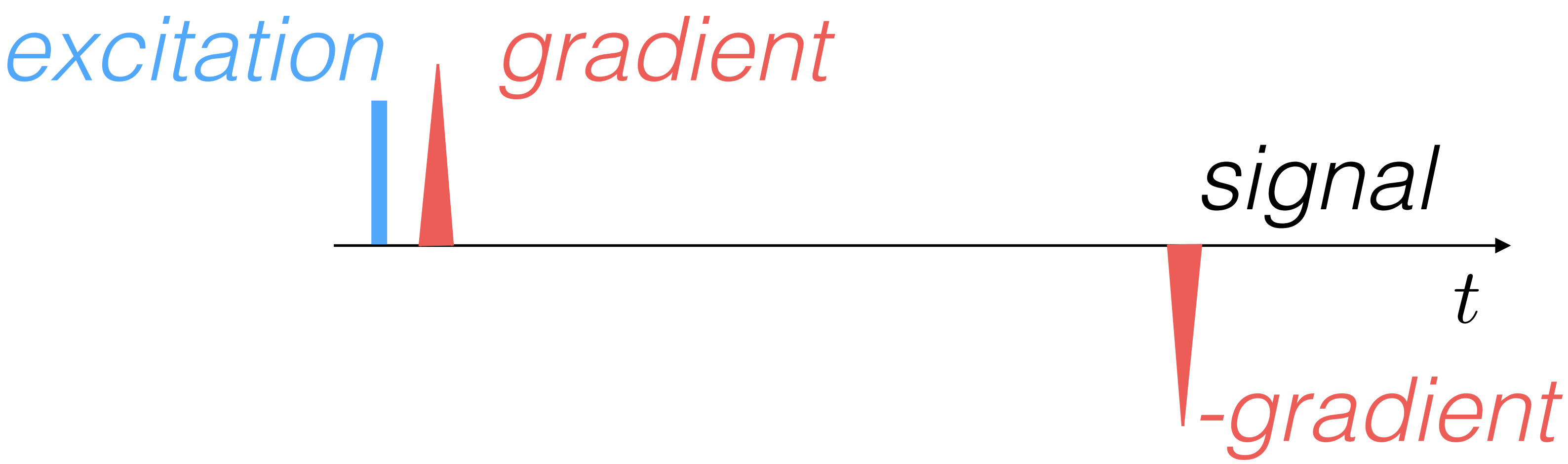
$$j = -D(x)\nabla\psi$$

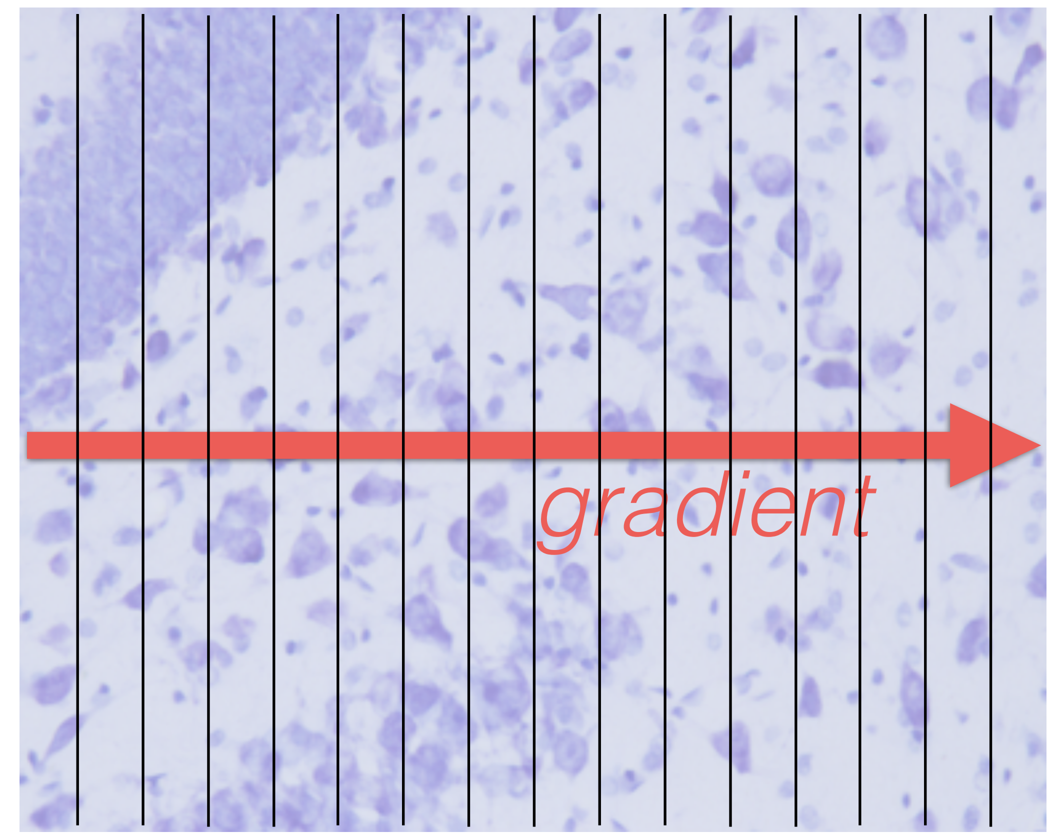
$$\frac{\partial}{\partial t}\psi = -\left[\nabla D(x)\nabla - i\Omega(x) - R(x)\right]\psi$$

$$\left[\frac{\partial}{\partial t} + \nabla D(x)\nabla + i\Omega(x) + R(x)\right]\mathcal{G} = \delta(t)\delta(x - x_0)$$

Vessel image courtesy: B.Weber and N.Logothetis

A typical MR trick





$$\psi \longrightarrow \psi\, e^{iqx}$$

$$S(t) = \int \frac{dx_0}{V} dx\, e^{iqx_0} \mathcal{G}(t, x, x_0) e^{-iqx}$$

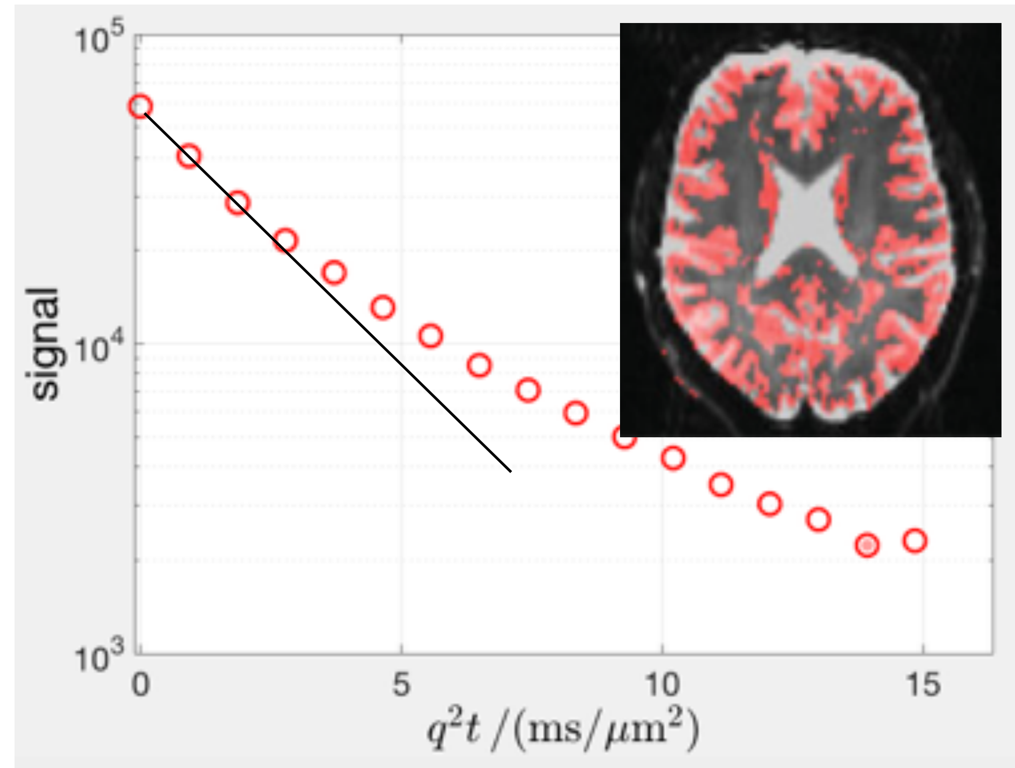
$$= \int dx\, e^{-iq(x-x_0)} G(t, x - x_0) \quad = G(t, q)$$

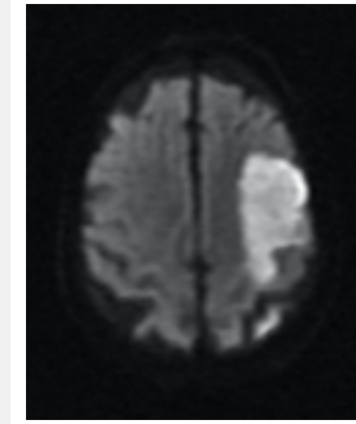
$$\boxed{S(t) = G(t, q)}$$

Signal anatomy

$$S = \langle e^{i\varphi} \rangle = G(t, q)$$

$$S = e^{-D(t)q^2 t + W(t) q^4 + \ldots}$$



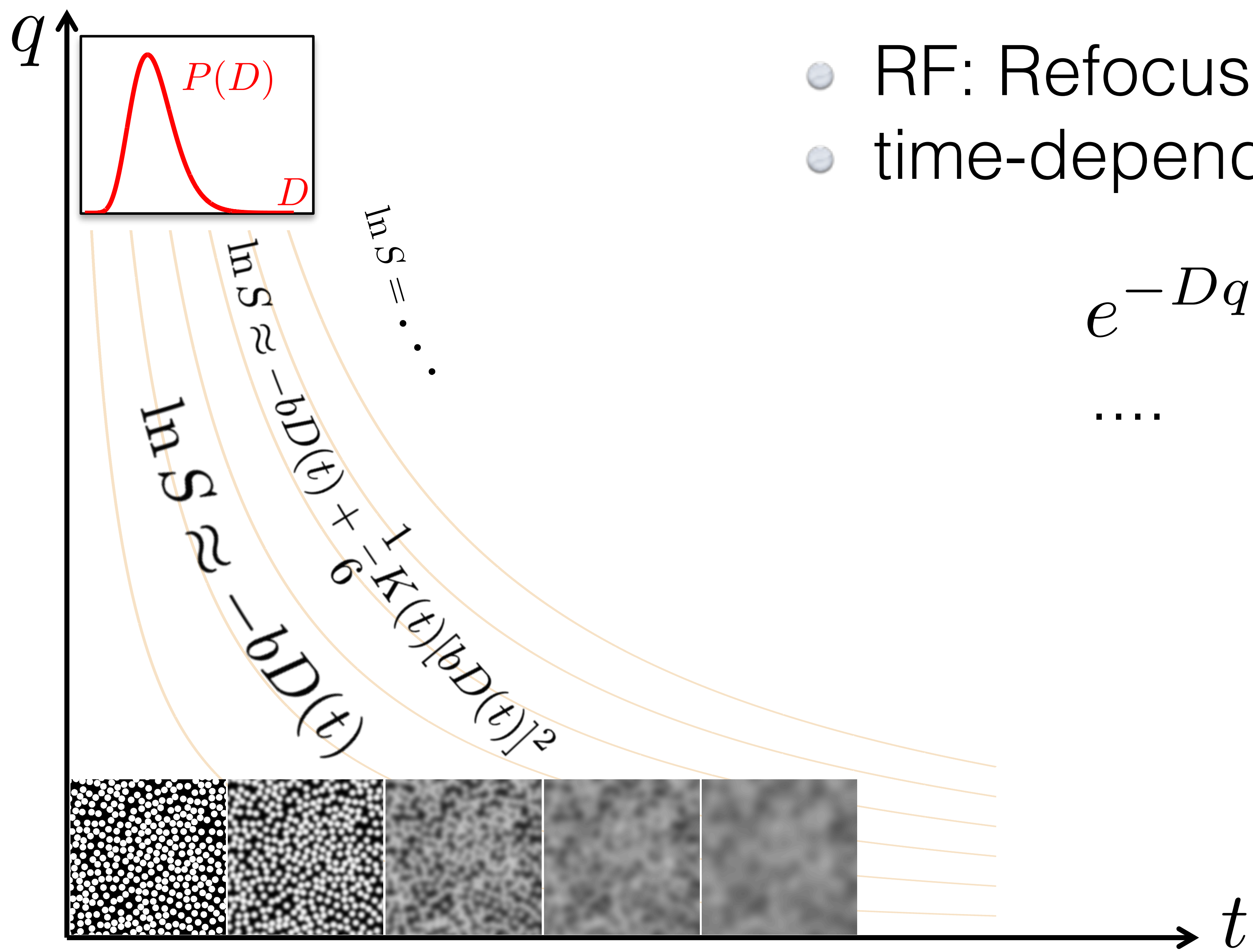


$$q(t) = \int_0^t dt'\, g(t')$$

$$S = \exp\left[-\frac{1}{2} \int dt_1 dt_2 \underbrace{\langle v(t_1) v(t_2) \rangle}_{\mathcal{D}(t_2 - t_1)} q(t_1) q(t_2) + \ldots \right]$$

$$= \exp\left[-\frac{1}{2} \int \frac{d\omega}{2\pi} \mathcal{D}(\omega) |q(\omega)|^2 + \ldots \right]$$

Number of controlling parameters = 2+++



- RF: Refocusing
- time-dependent gradients

$$e^{-Dq^2t} \to e^{-\mathrm{Tr}\, bD}$$

....

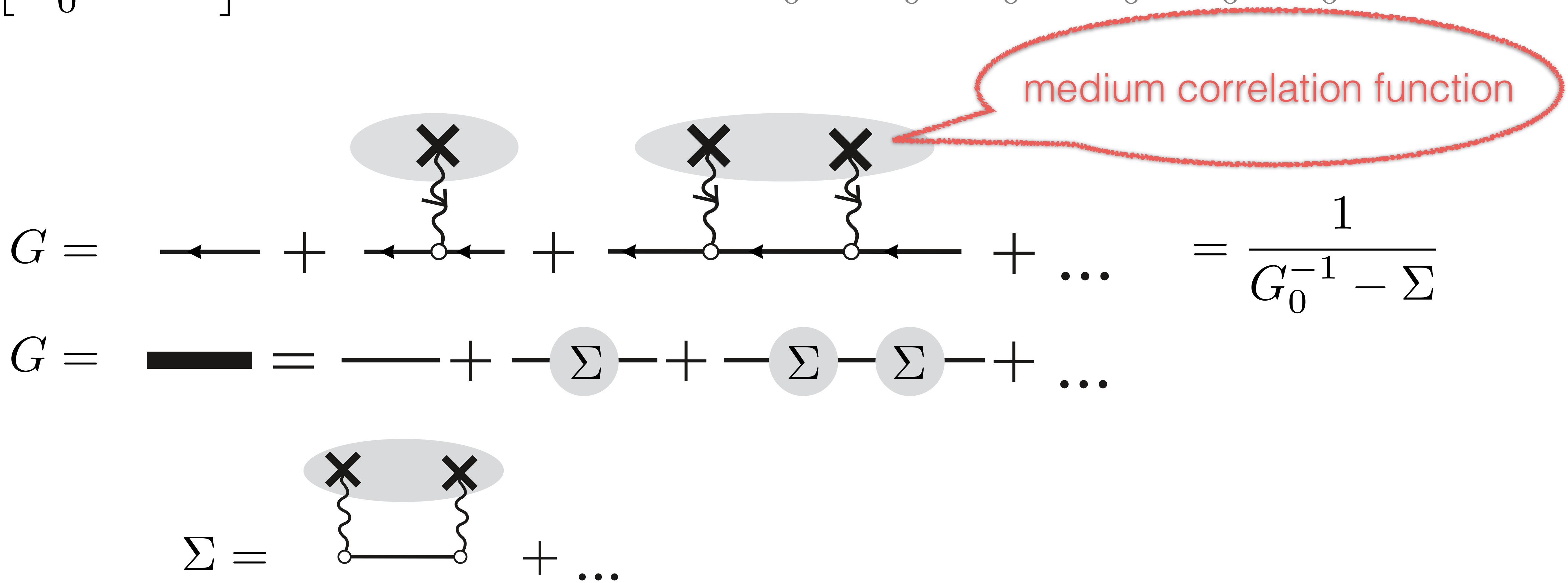
Novikov et al. arXiv 1612.02059

$G \neq$ microstructure

Averaging over the medium

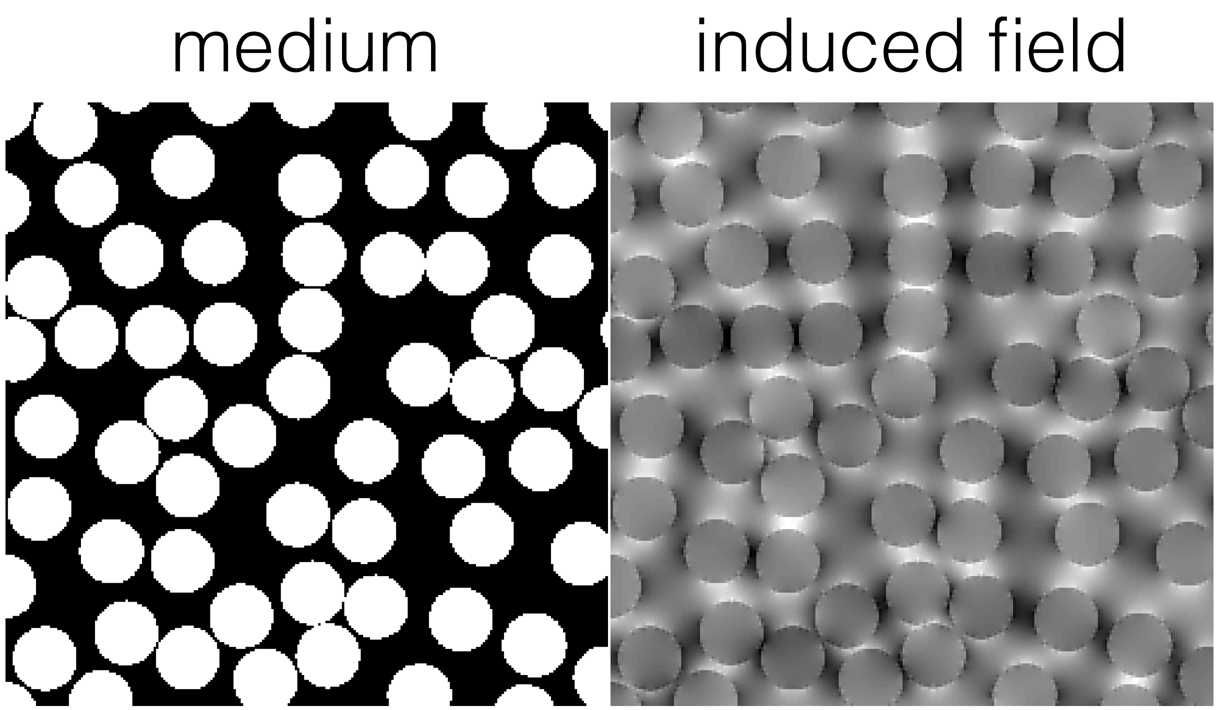
$$\left[\frac{\partial}{\partial t} + D_0\nabla^2 + R_0 - U(x)\right]\mathcal{G} = \delta(t)\delta(x - x_0)$$

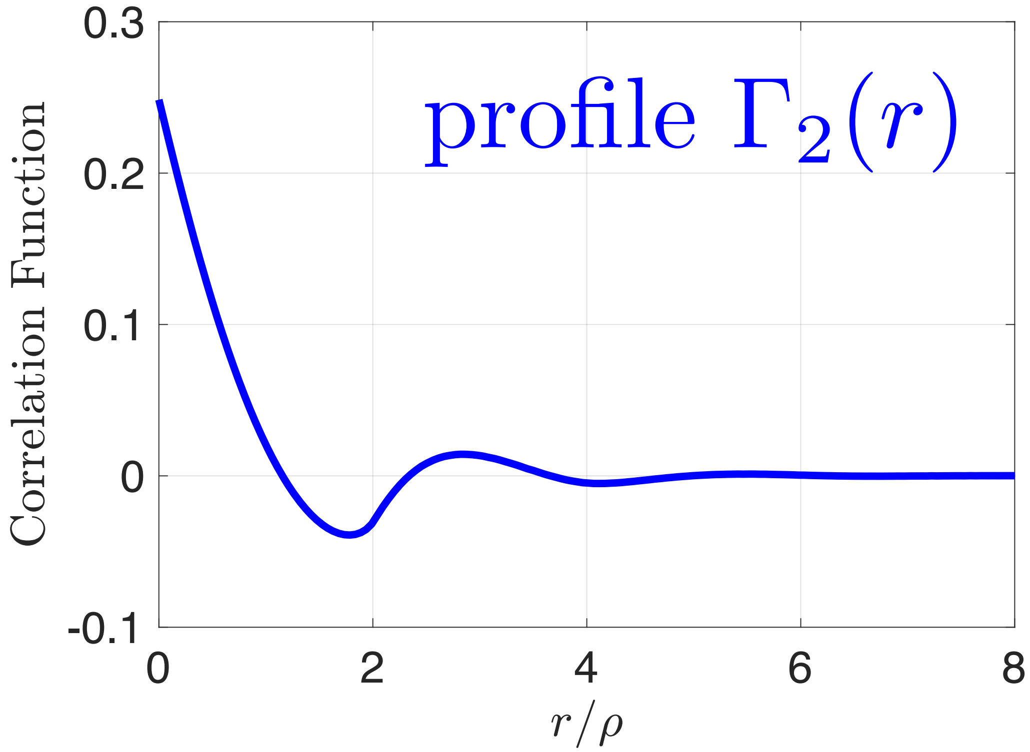
$$\left[G_0^{-1} - U\right]G = 1 \qquad G = G_0 + G_0UG_0 + G_0UG_0UG_0 + \ldots$$

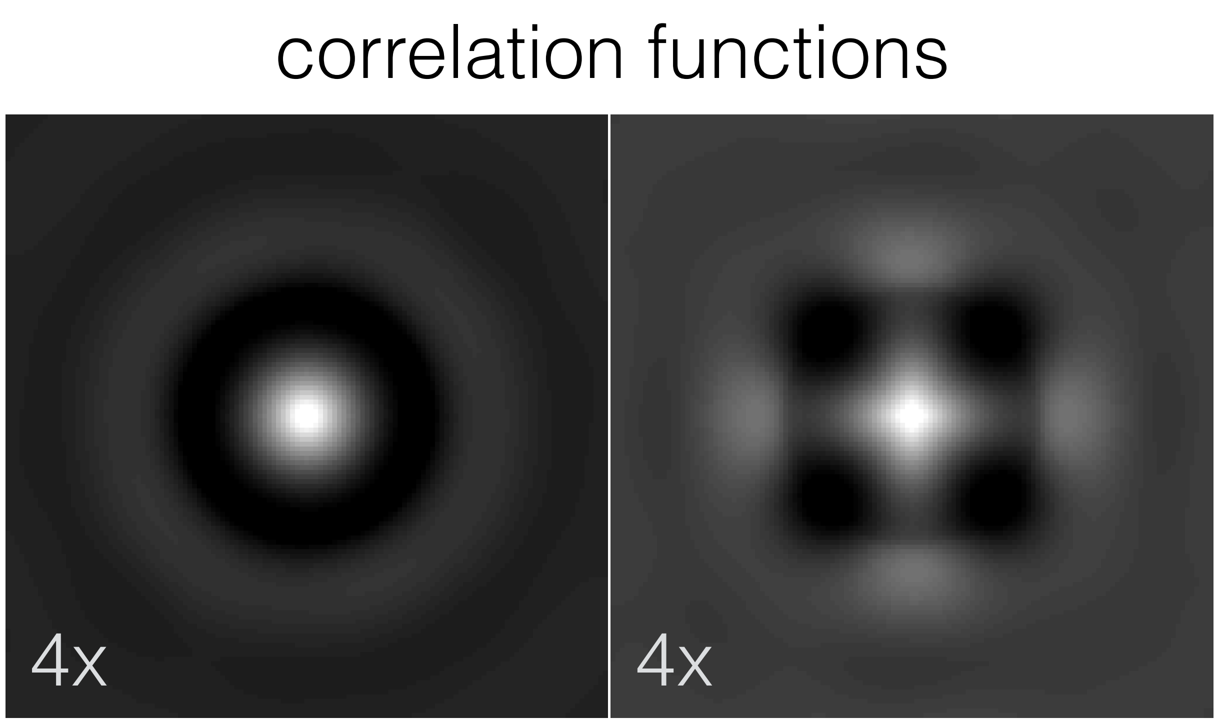


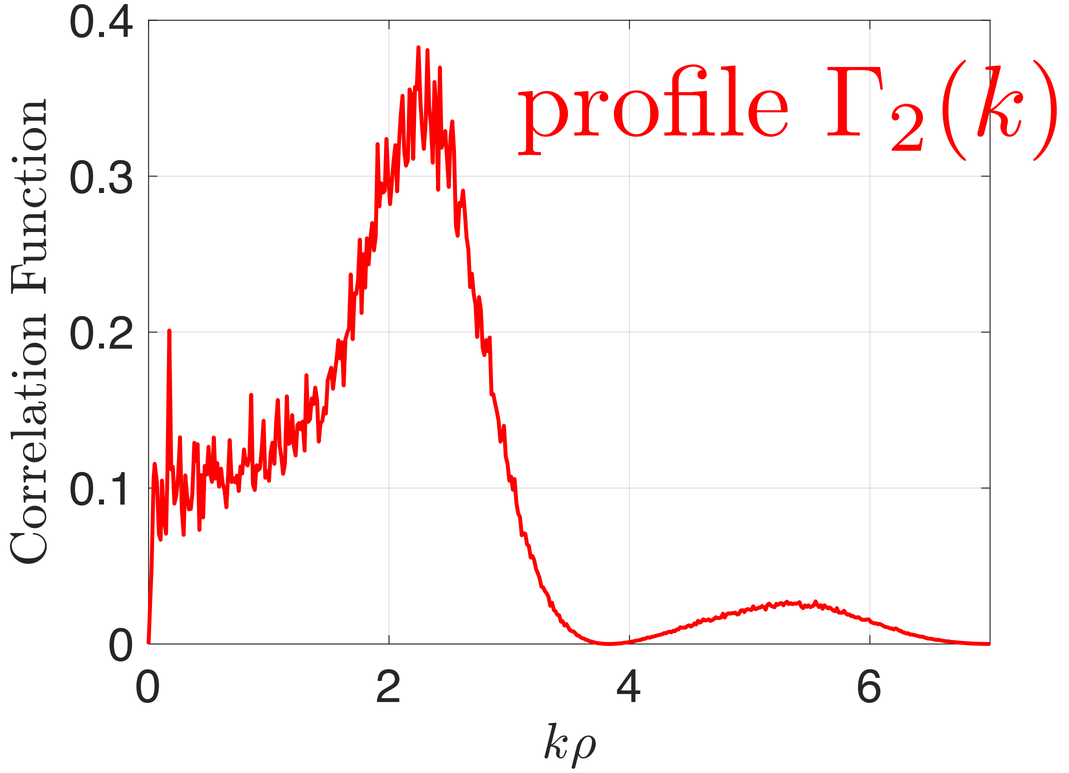
Novikov, Kiselev 2008

Medium correlation function









Novikov, Kiselev 2008

Effective medium theory

$$S(\omega, q) = \frac{1}{-i\omega + R + D_0 q^2 - \Sigma(\omega, q)}$$

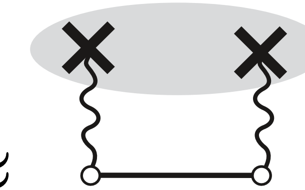
$$R \to R - \Sigma(\omega)$$

$$D_0 \to D_0 - \frac{1}{2}\Sigma''(\omega)$$

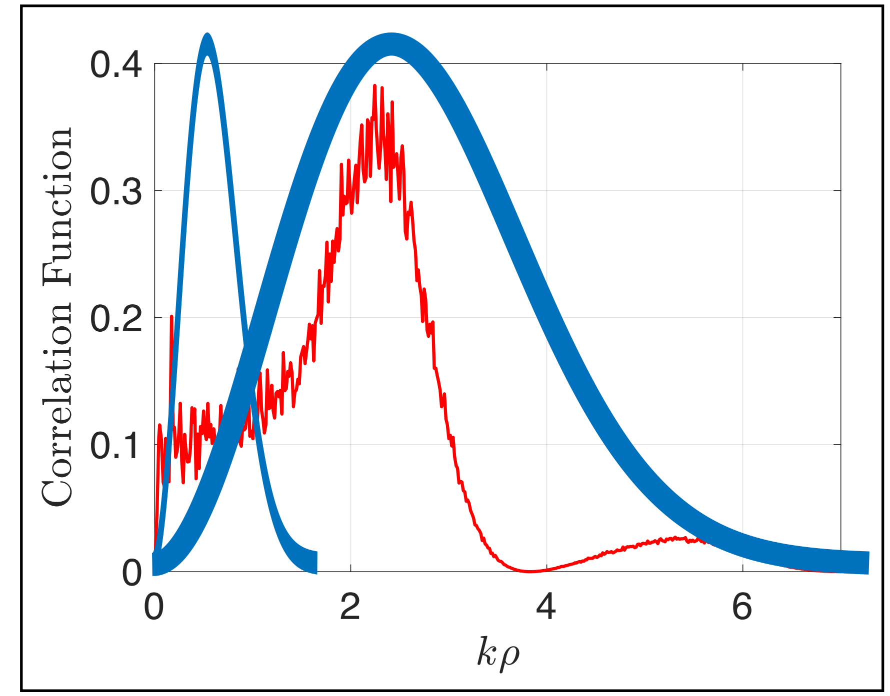
$$n(\omega) = n_1(\omega) + i n_2(\omega)$$

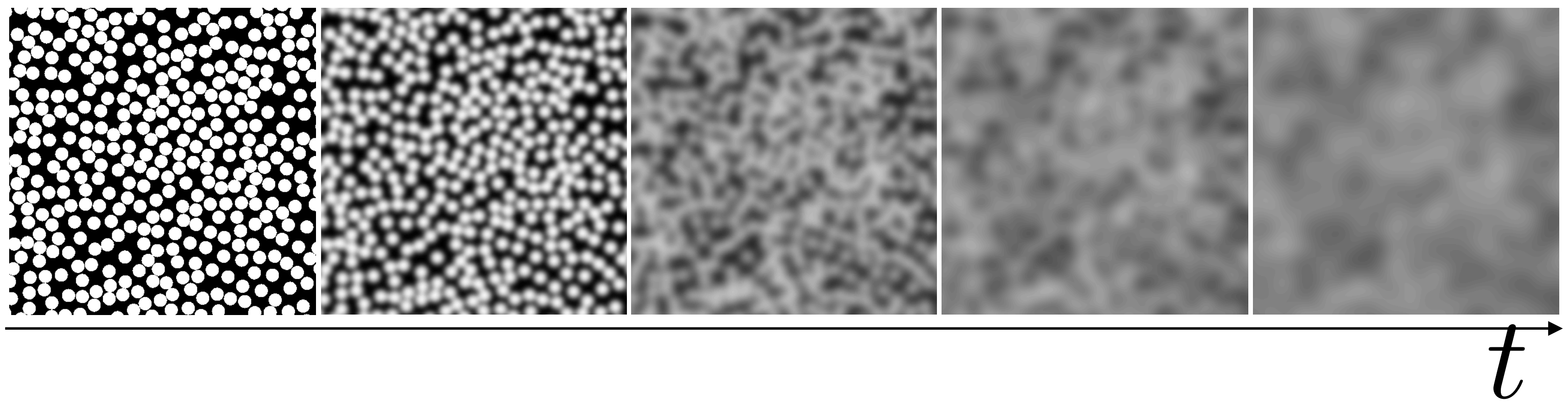
Novikov, Kiselev 2008, 2010

Perturbation theory

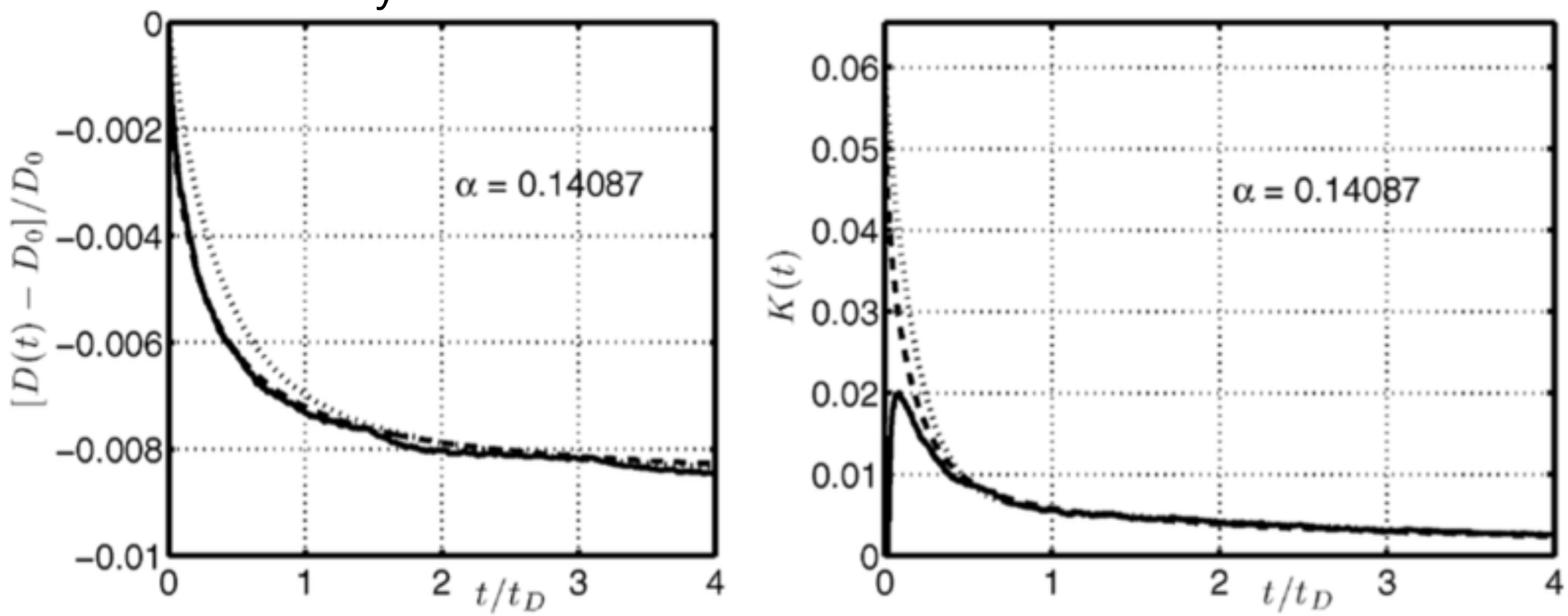
$\Sigma \approx$ 

$$D(t) \overset{t \gg \tau}{\approx} D_0 - \frac{1}{D_0 d} \int \frac{d^d k}{(2\pi)^d} e^{-D_0 k^2 t} \Gamma_2(k)$$





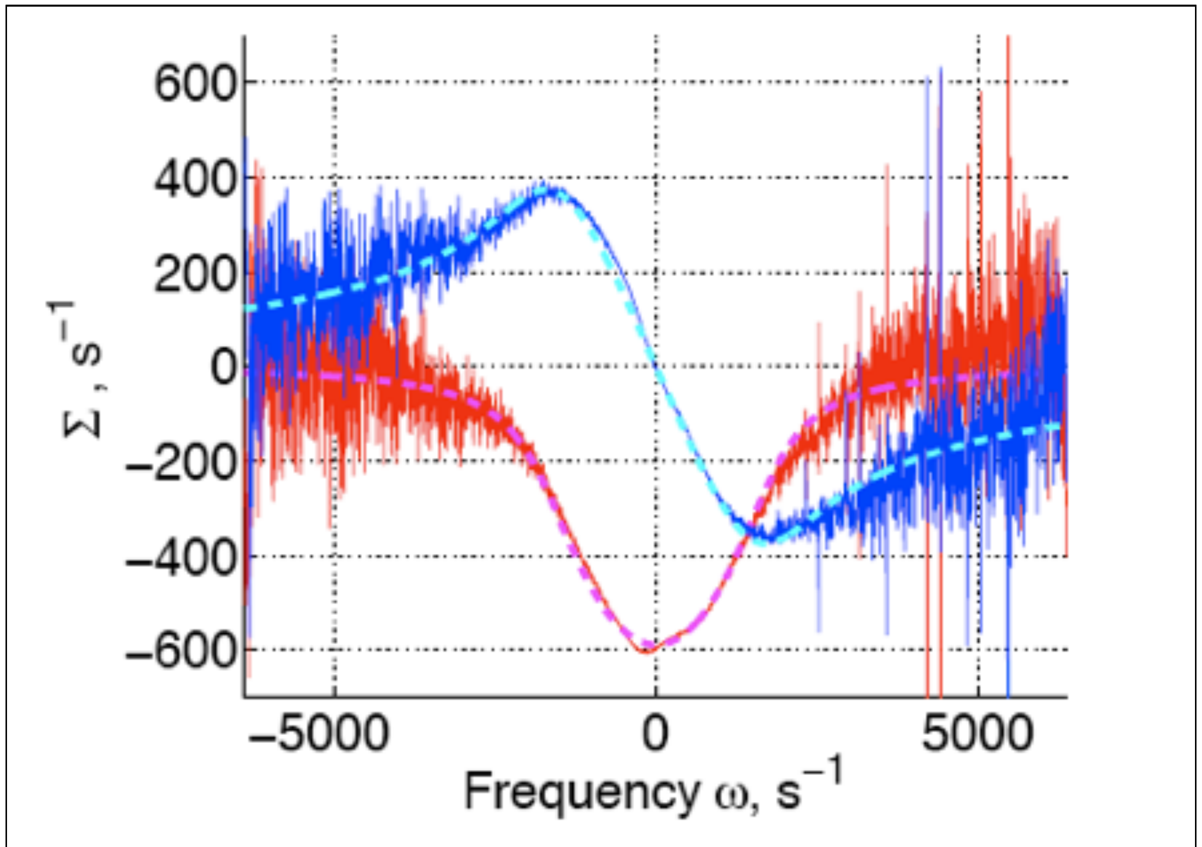
analytical result vs. Monte Carlo simulation



Novikov, Kiselev 2010

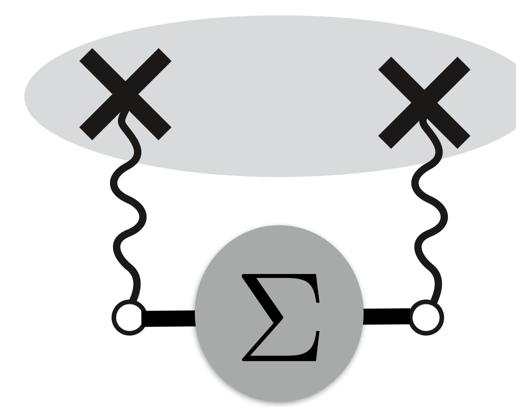
Beyond the perturbation theory

Blood spectral line shape



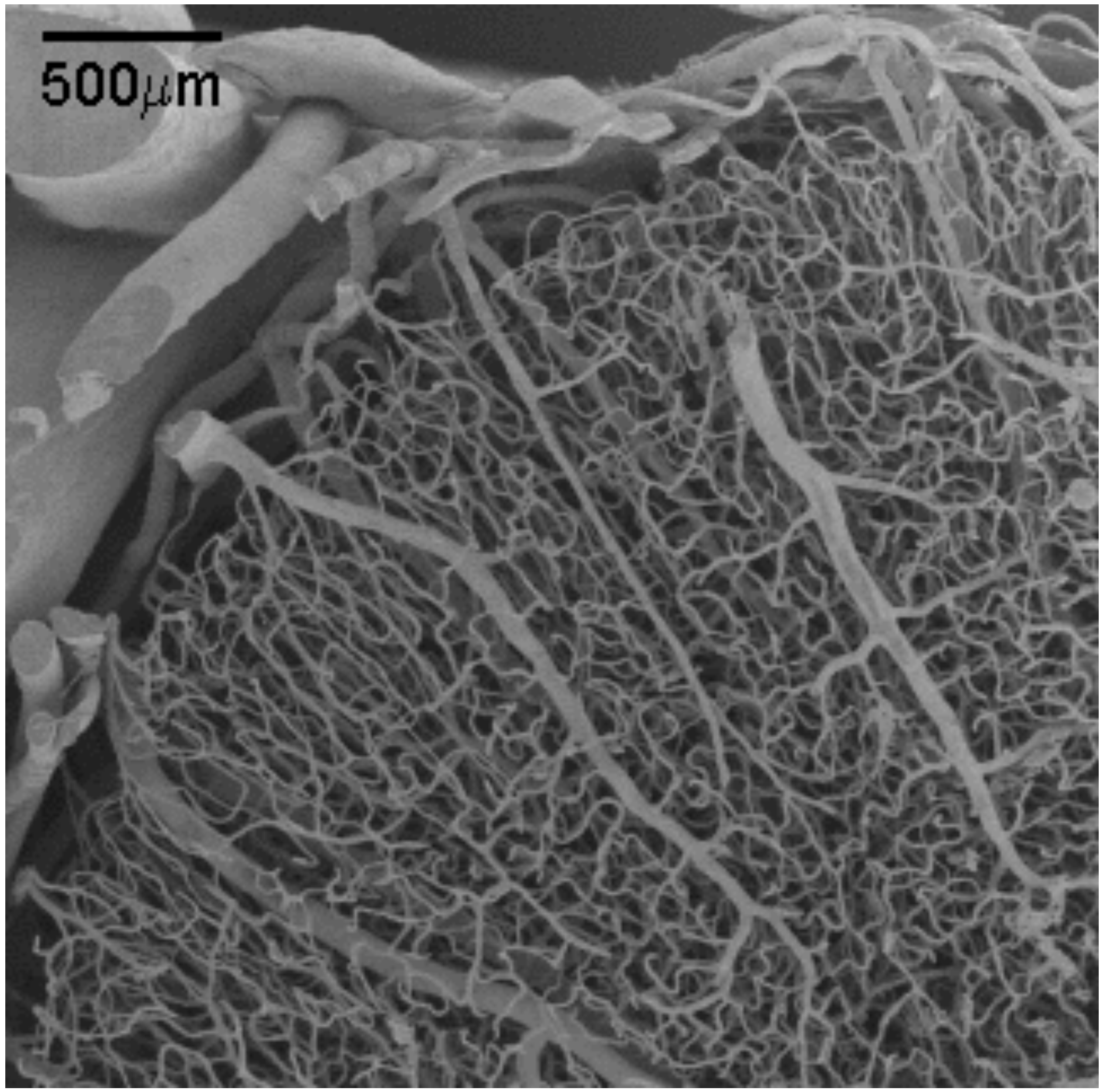
Self-consistent Born approximation:

$\Sigma \approx$

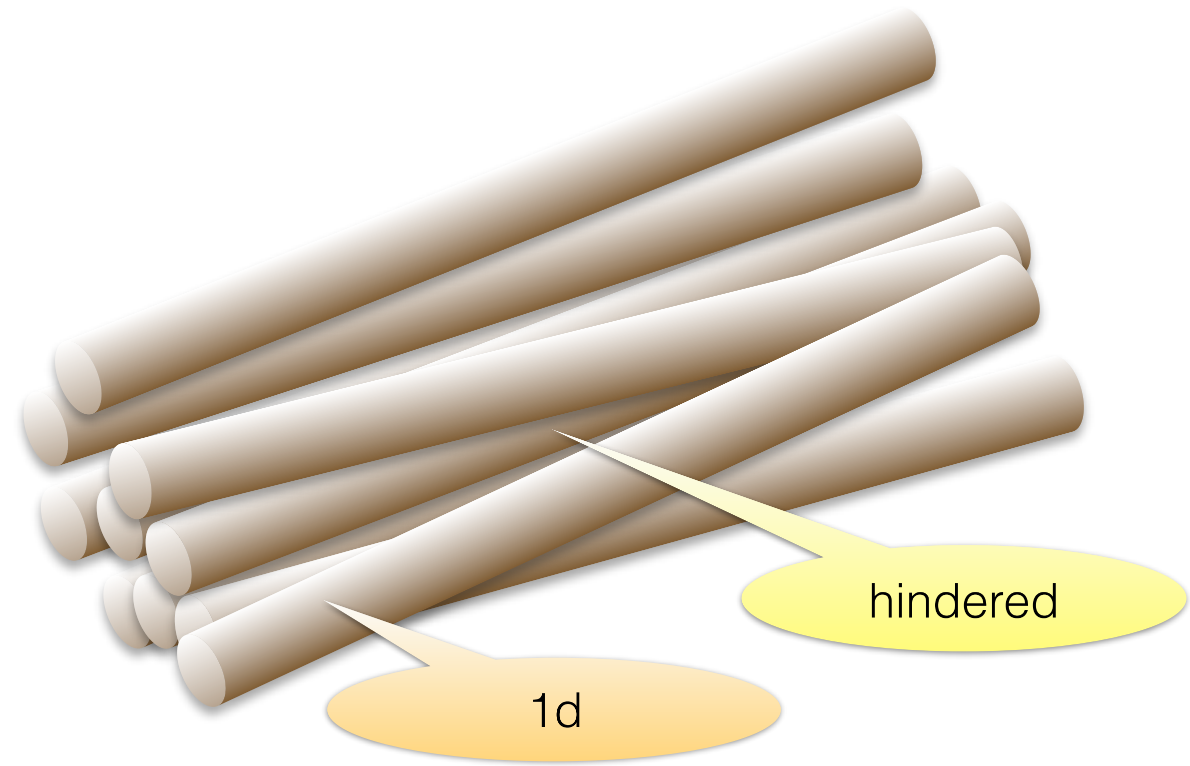


Novikov, Kiselev 2008

Beyond the perturbation theory...



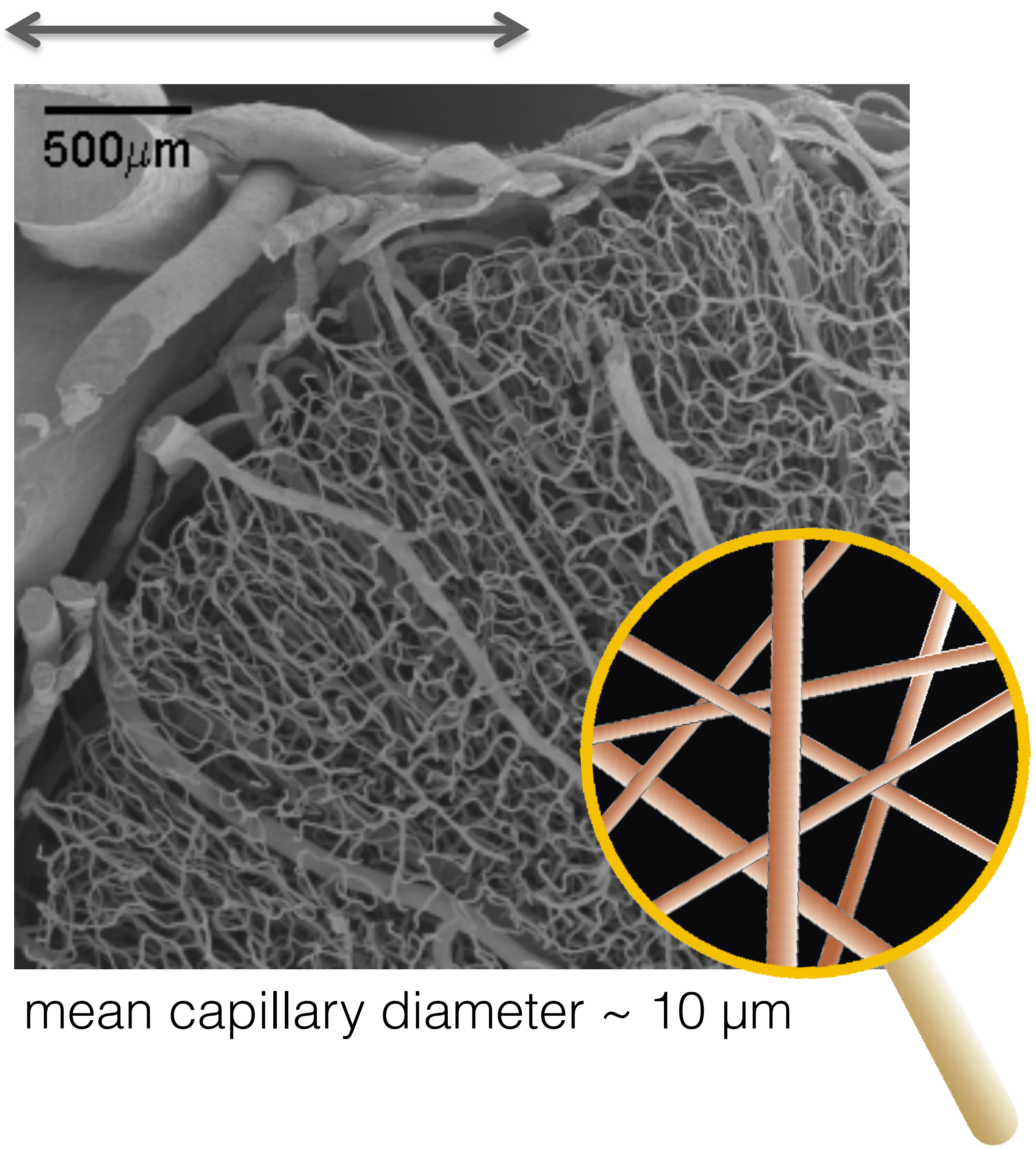
blood doped with contrast agent



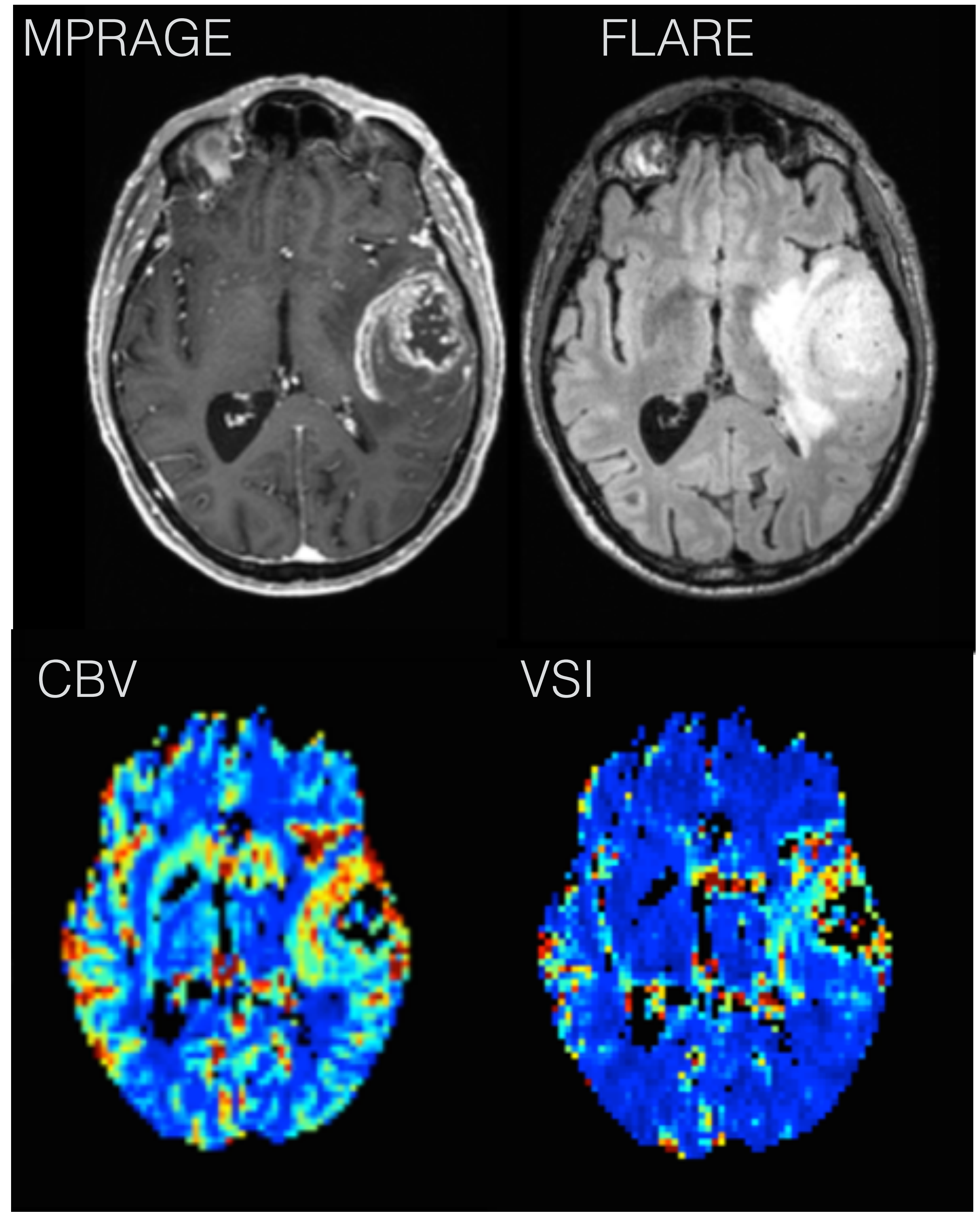
diffusion in complex geometry
(here white matter)

Vessel Size Imaging

image resolution ~ 2mm

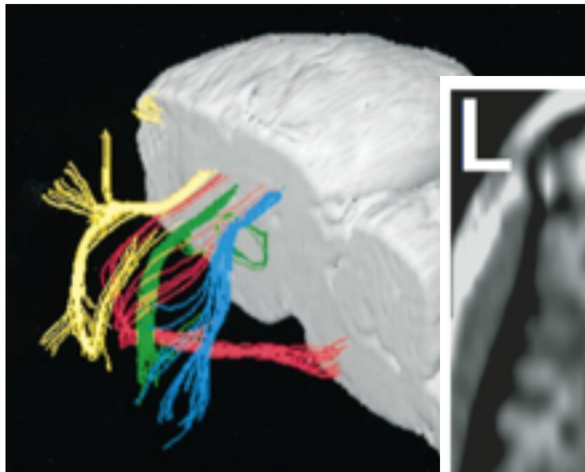


mean capillary diameter ~ 10 µm

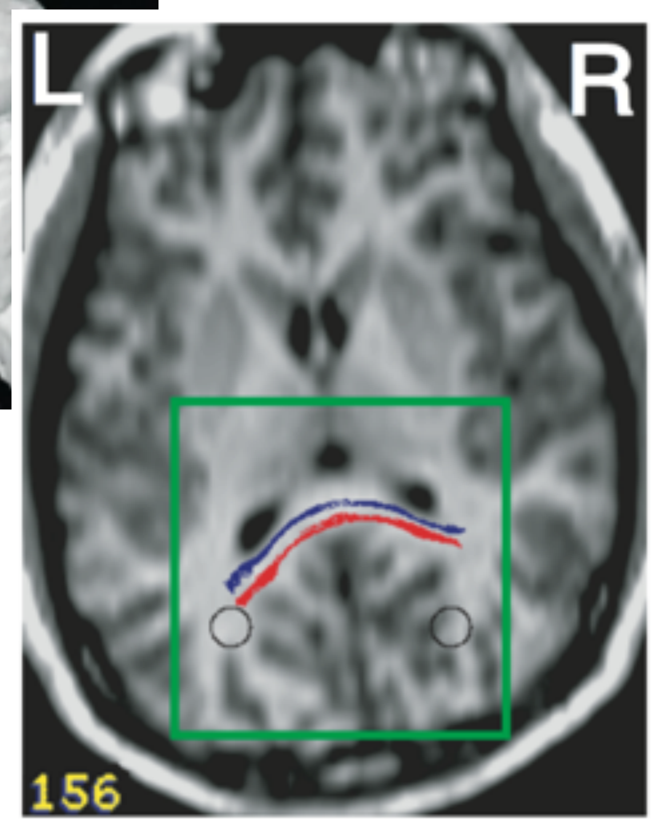


Kiselev et al. 2005

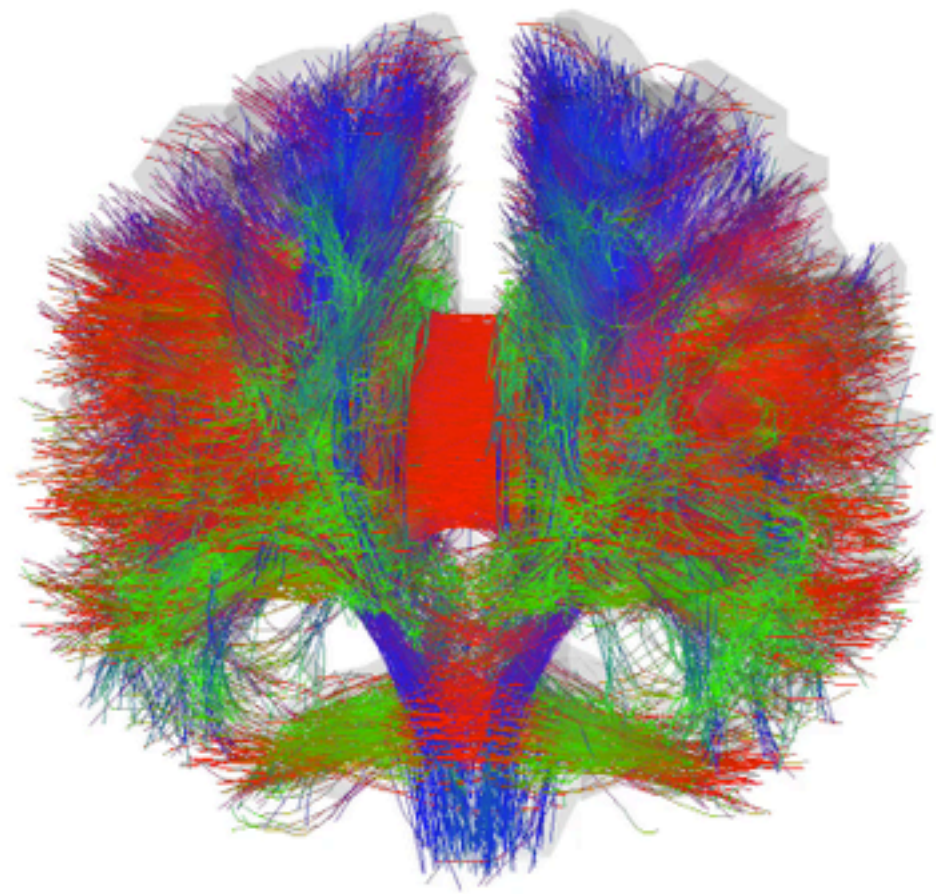
Fiber tracking



Mori et al. 1999

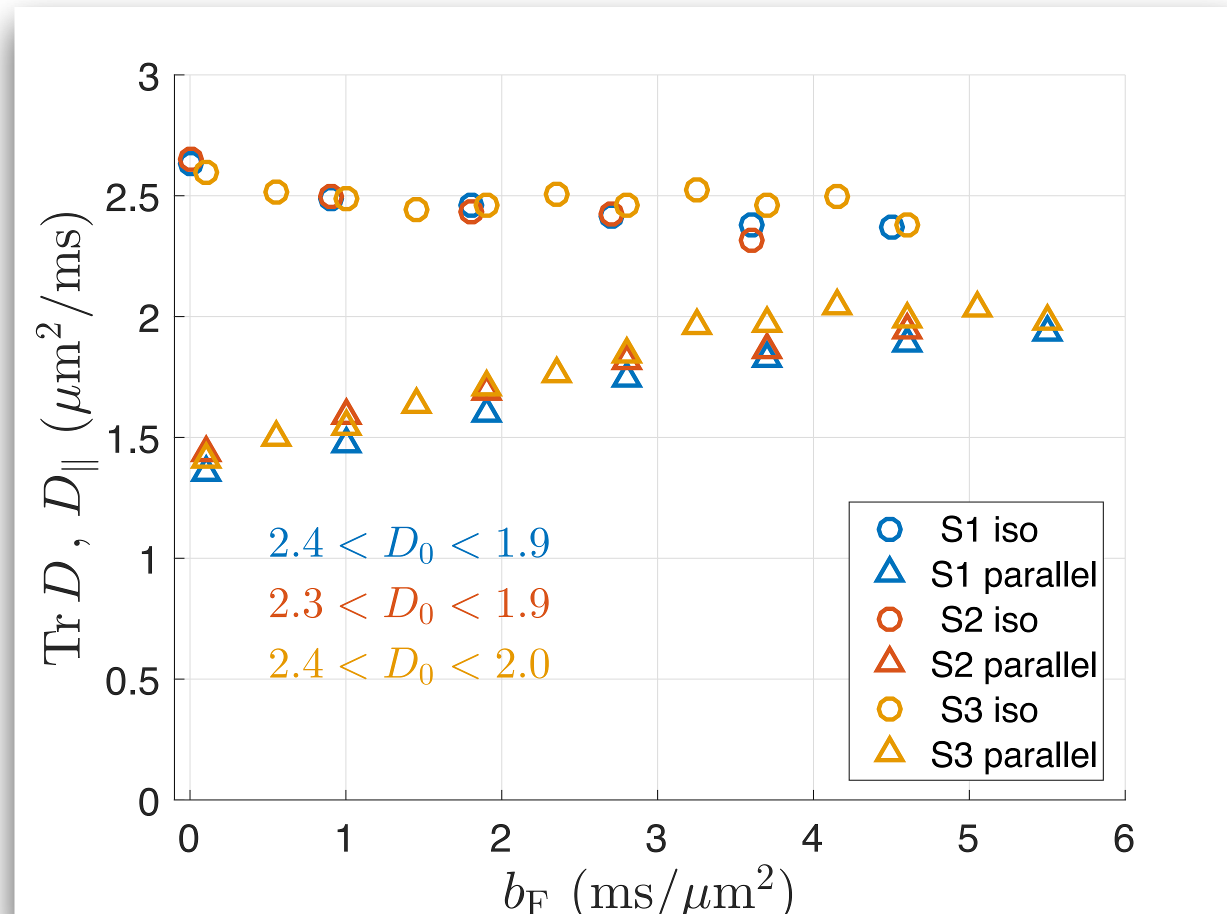


Conturo et al. 1999

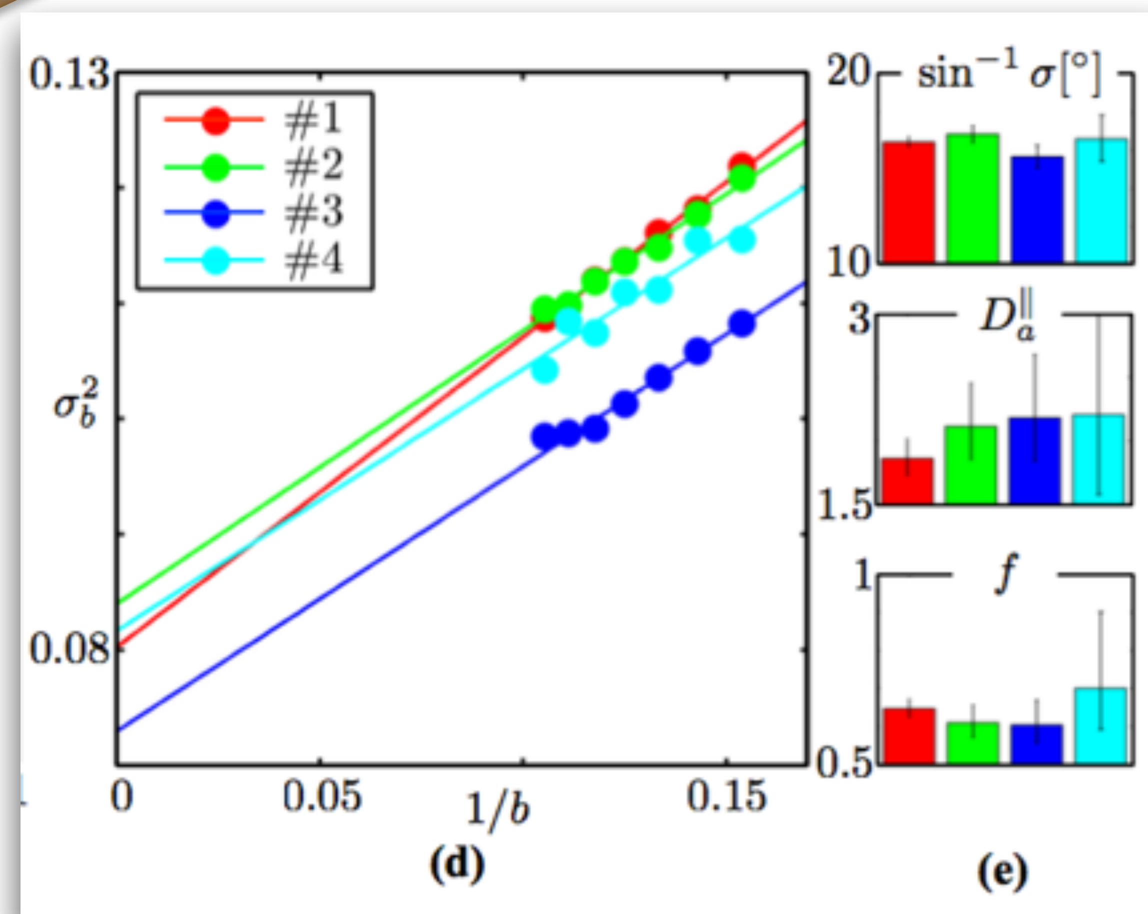


Reisert et al. 2011

Outlook: `In vivo MRI histology'

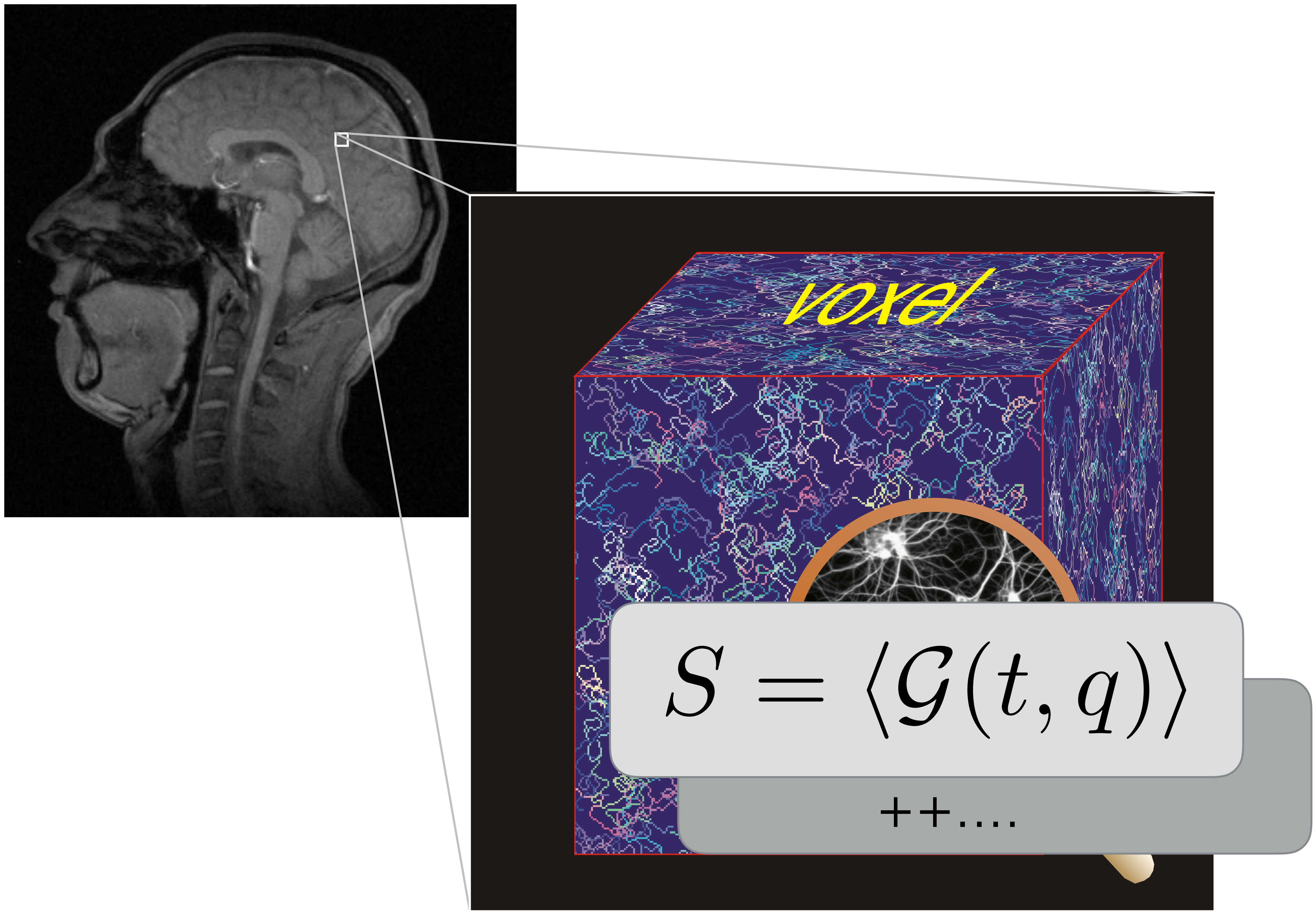


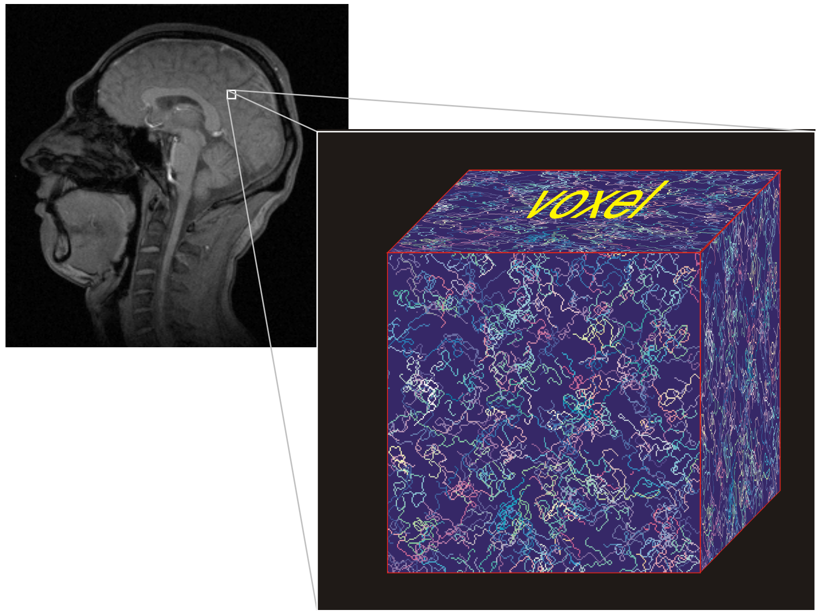
Dhital et al. in preparation



Veraart et al. arXiv:1609.09145v1

Conclusions





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