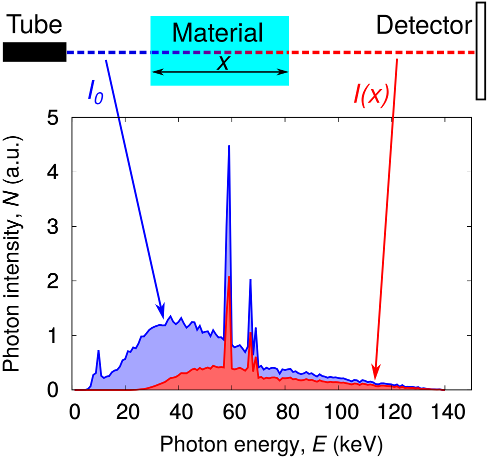
FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

Institute for Multiscale Simulation MSS

X-ray radiography of granular systems – particle densities and dynamics



PhD thesis
Manuel Baur

Funded by the German Federal Ministry for Economic Affairs and Energy, grant number 50WM 1653

Granular flows - are ubiquitous

replace text by images:

- Granular flows - fluidized bed reactors
- optically opaque
- X-ray reveal the inside
- Tomography: full 3D information - but slow (no dynamics)
- Radiography: single projections - knowledge on imaging physics
- Here two techniques to quantify: densities & dynamics

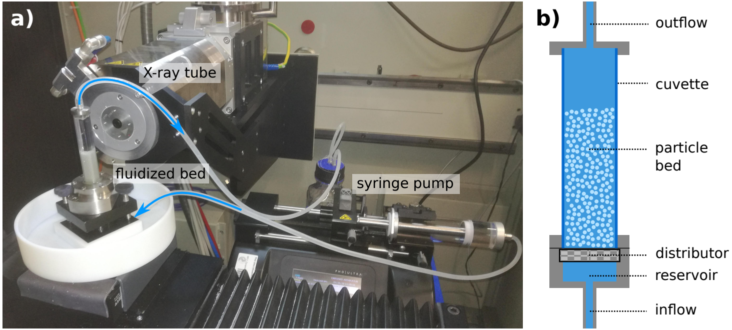
Granular flows - are ubiquitous

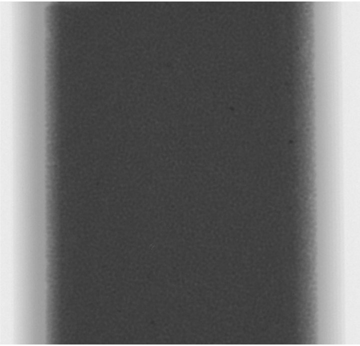
Study of granular flows difficult, because opaque: optically not possible
Video of Welm Pätzold's Master thesis - only boundary observable
here X-rays

X-ray Digital Fourier Analysis (X-DFA)

A technique to measure granular dynamics

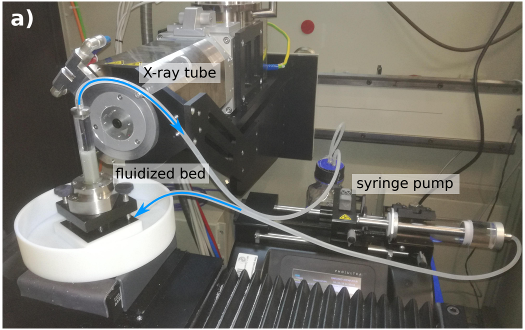
Experiments

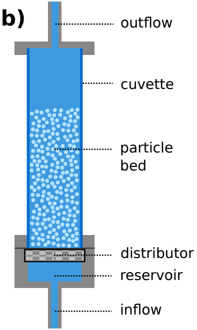


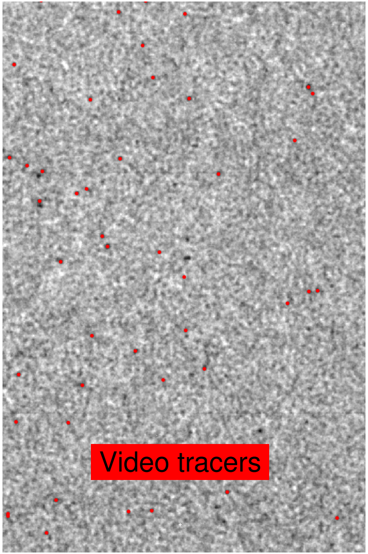


- volume fraction: $0.45 < \Phi < 0.56$
- control dynamics and Φ via pump rate

Experiments







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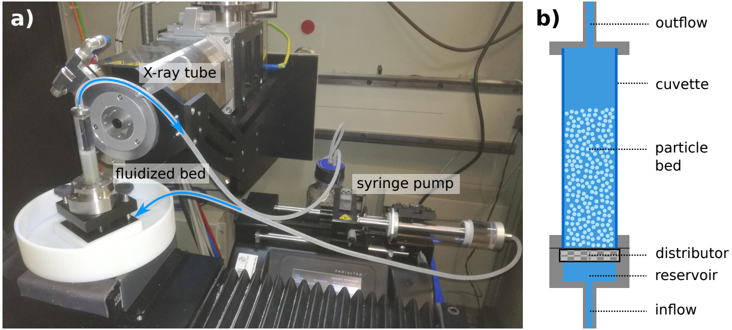

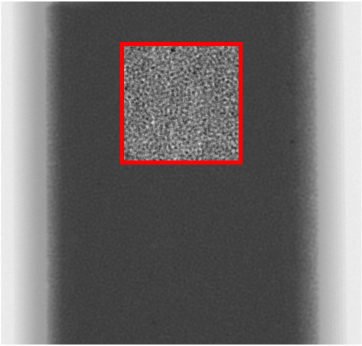

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Differential Dynamic Microscopy (DDM)

	up to now	**this work**
system	dispersion, gels	fluidized bed
particles	colloids	granulate
part. diameter	$< 1\ \mu\text{m}$	$\approx 200\ \mu\text{m}$
volume fraction	$\Phi \leq 0.33$	$0.45 < \Phi < 0.56$
imaging	light microscope	x-ray radiography
dynamics	Brownian motion, caging, glassy, collective motion	

Giavazzi *et al*, PRE **80**, 031403 (2009)

Extending Differential Dynamic Microscopy (DDM) to X-ray imaging

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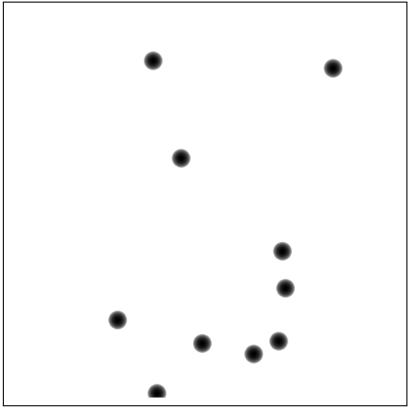
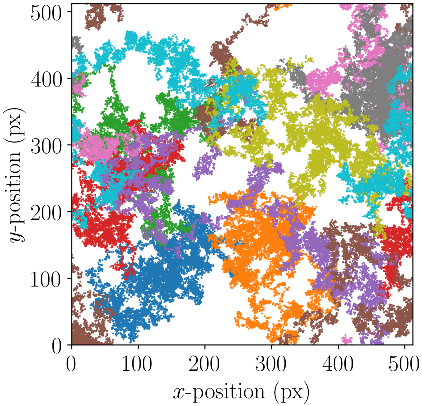
Digital Fourier Analysis of X-Ray Radiograms (X-DFA)

Giavazzi *et al*, PRE **80**, 031403 (2009)

Synthetic radiograms



Video 10 Particles



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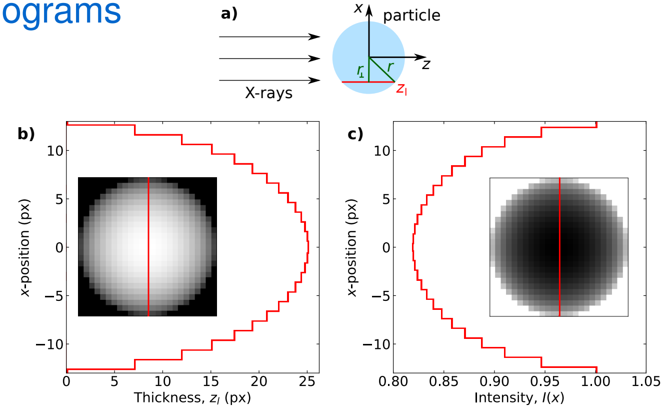
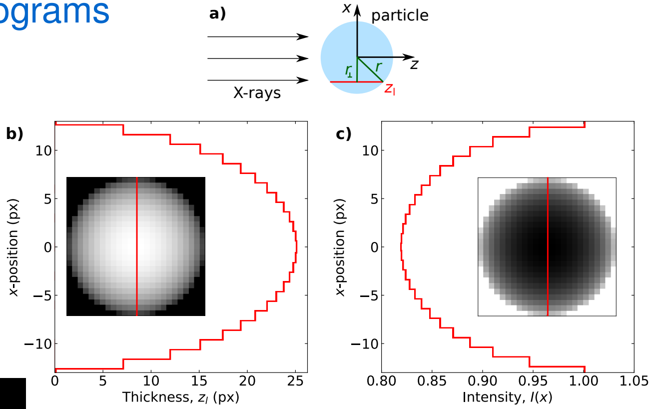
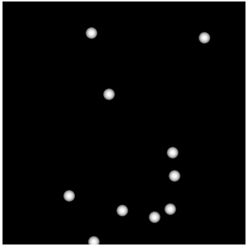


Beer-Lambert

$$I(z_l) = I_0 \exp(-\mu z)$$

Synthetic radiograms





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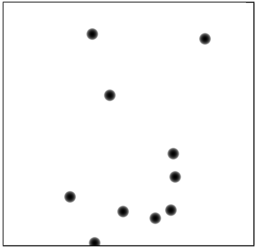
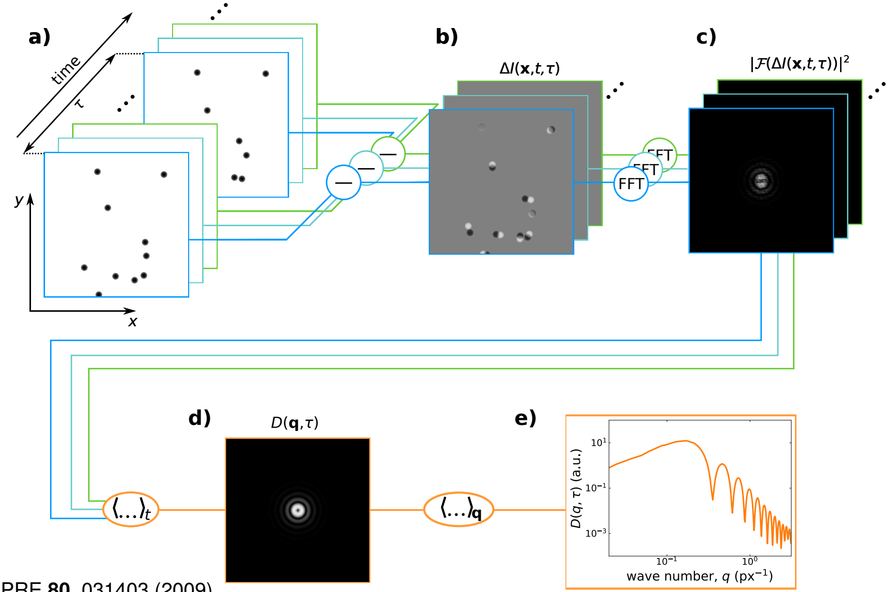


The image structure function $D(\mathbf{q}, \tau)$



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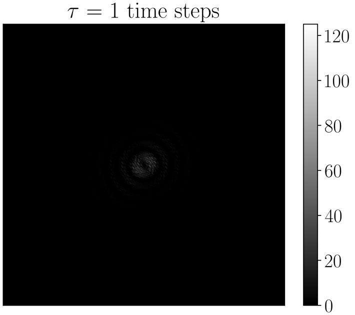

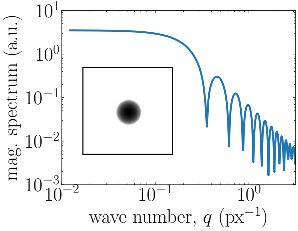

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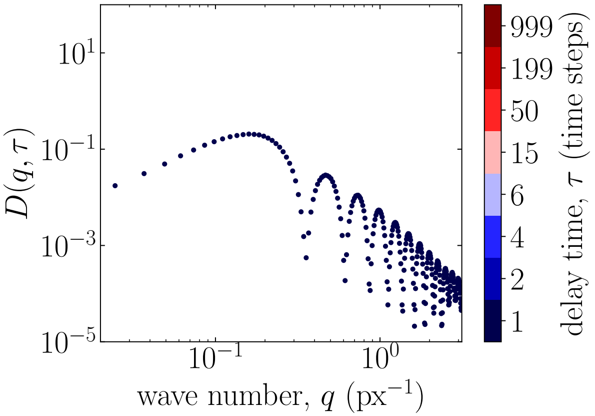
Azimuthal averaging: $D(\mathbf{q},\tau) \rightarrow D(q,\tau)$ ...



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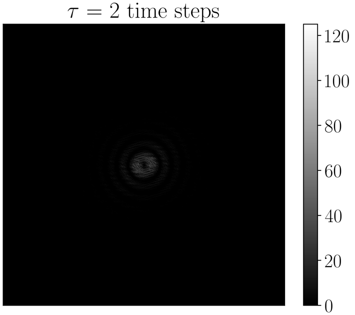

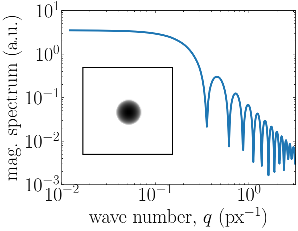

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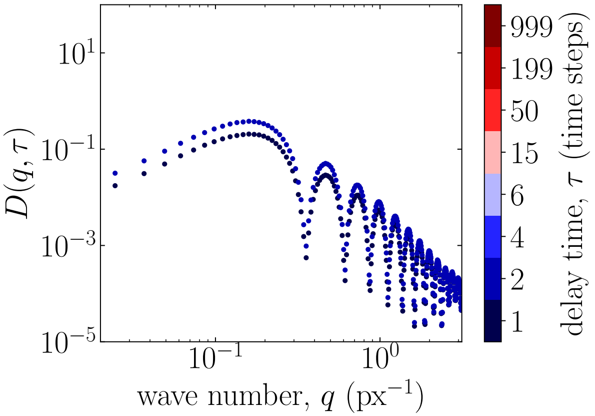

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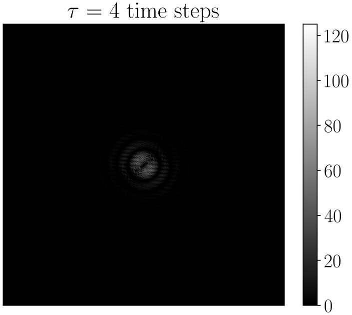

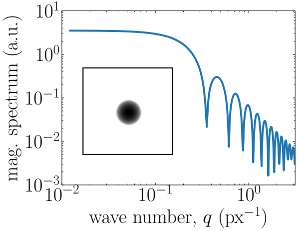

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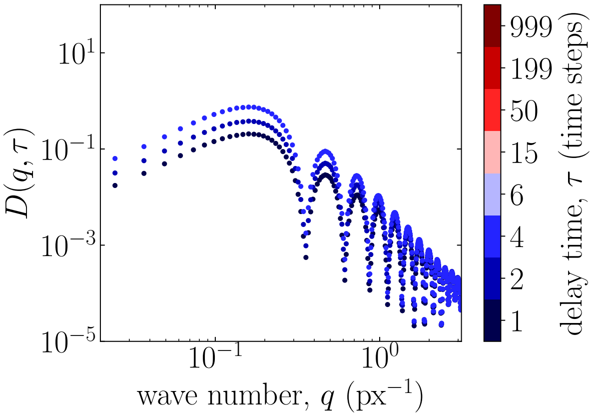

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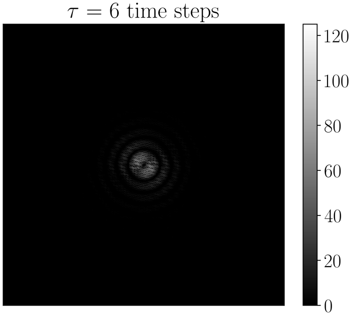

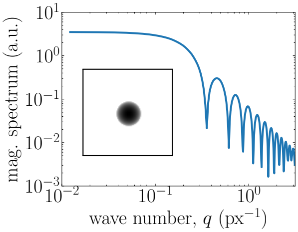

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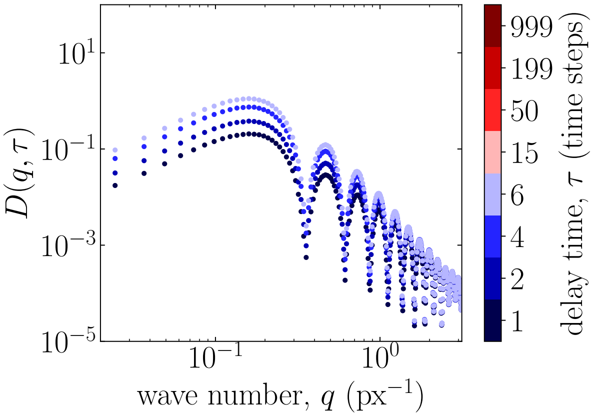

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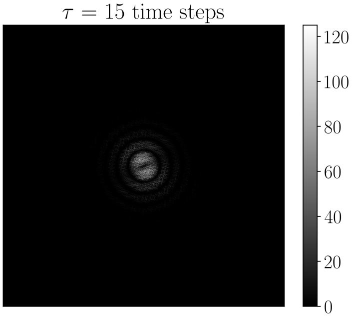

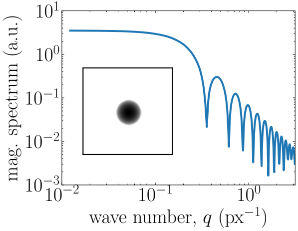

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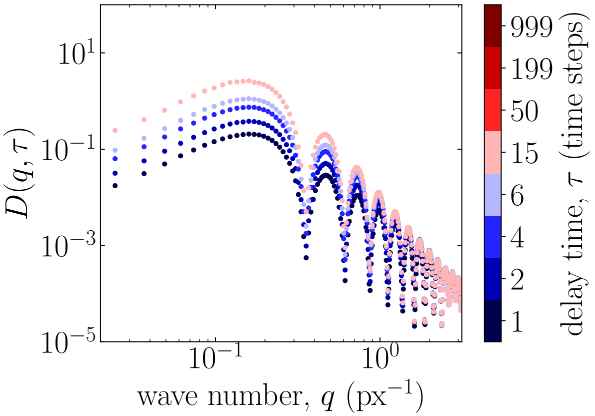

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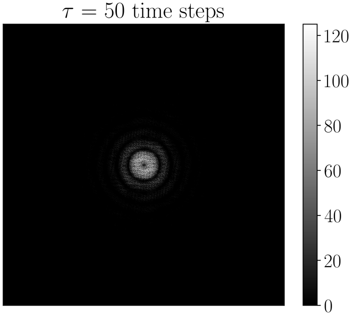

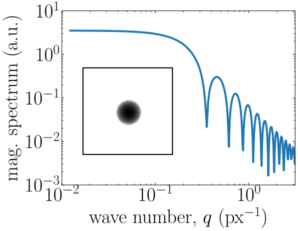

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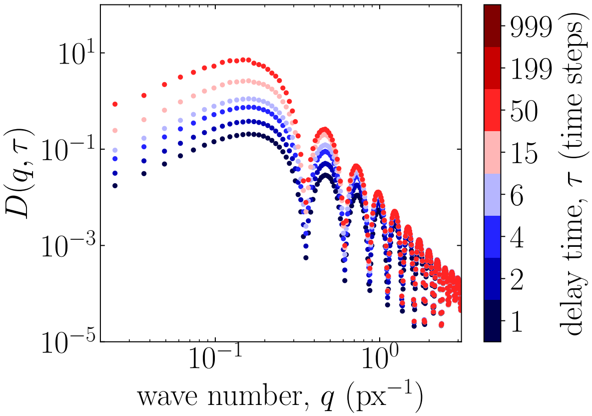

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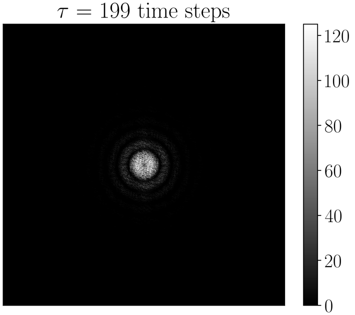

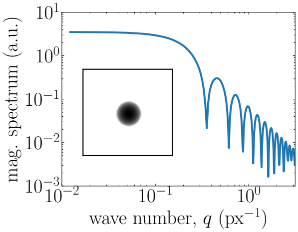

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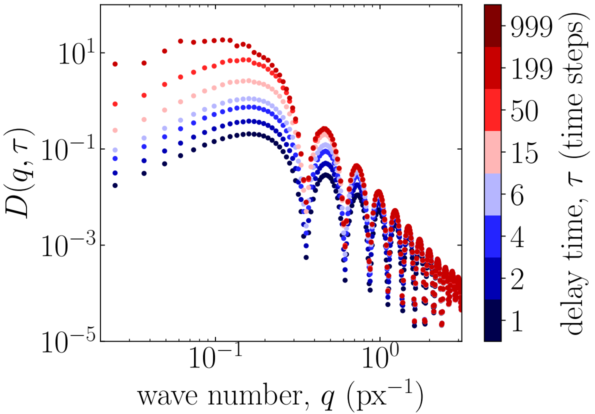

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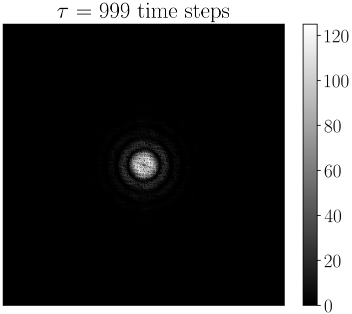

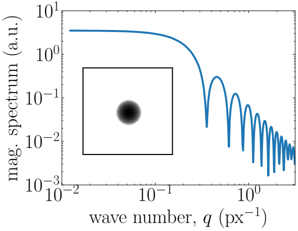

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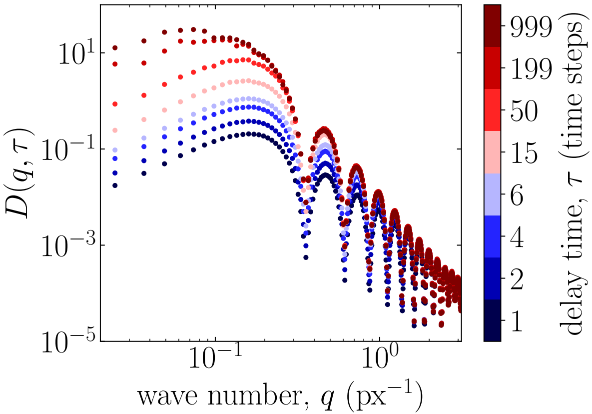

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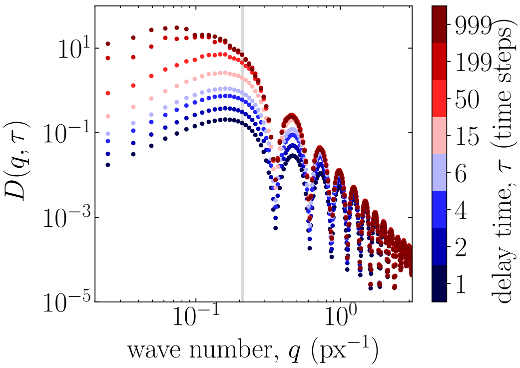

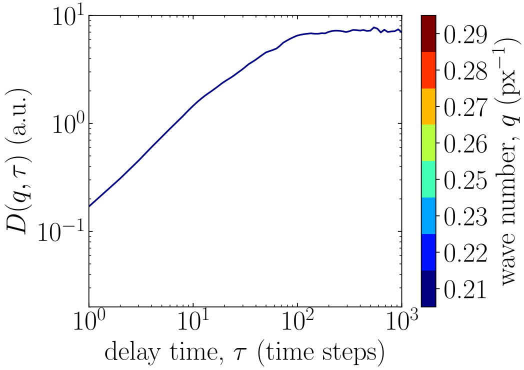

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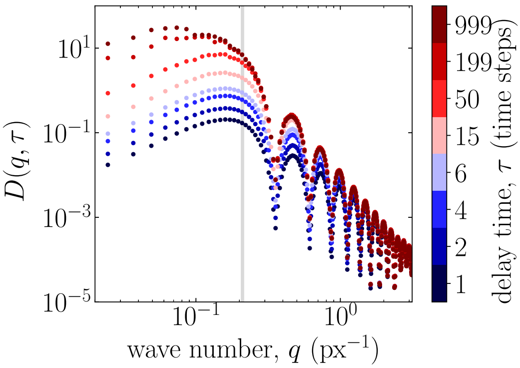

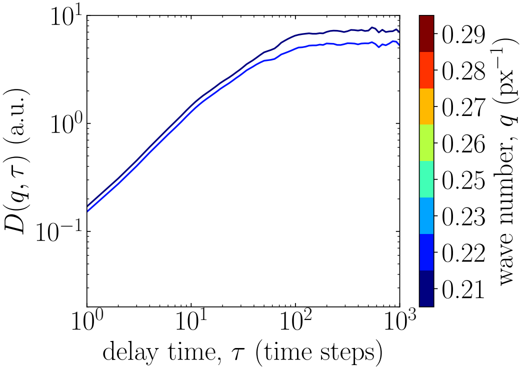

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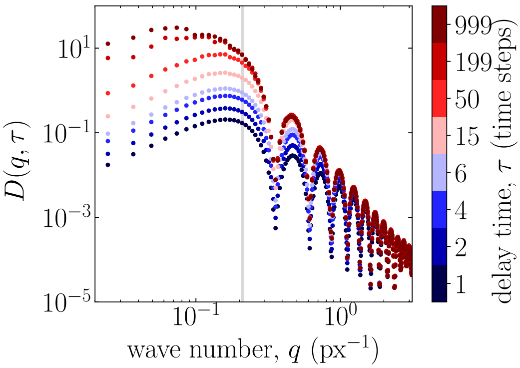

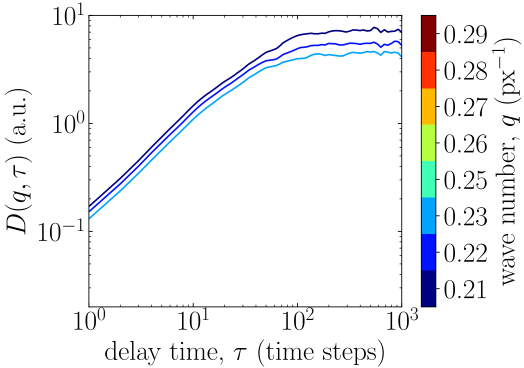

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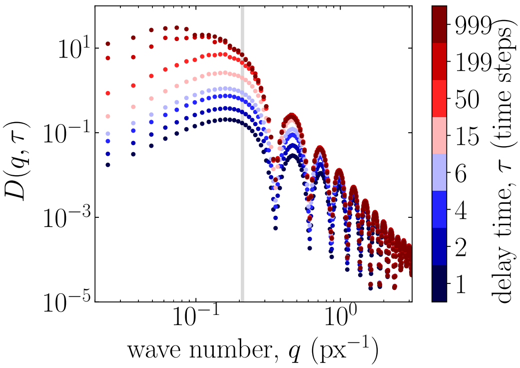

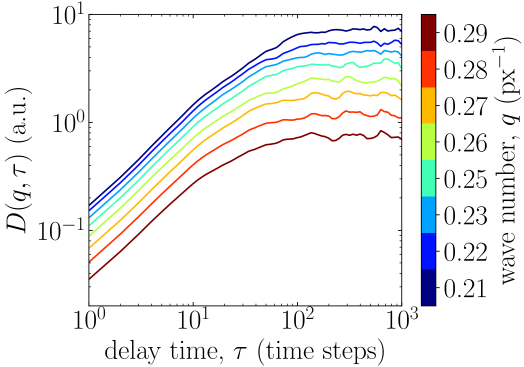

$$
\begin{aligned}
D(q, \tau) &= \left\langle \left| I(q, t+\tau) - I(q, t) \right|^2 \right\rangle_t \\
&= A(q) \left[1 - \frac{\left\langle I^*(q, t) I(q, t+\tau) \right\rangle_t}{\left\langle |I(q, t)|^2 \right\rangle_t} \right] + B(q)
\end{aligned}
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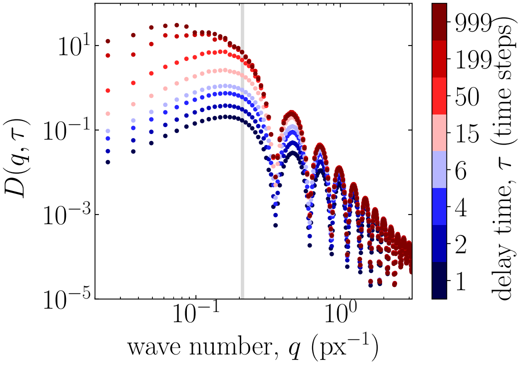

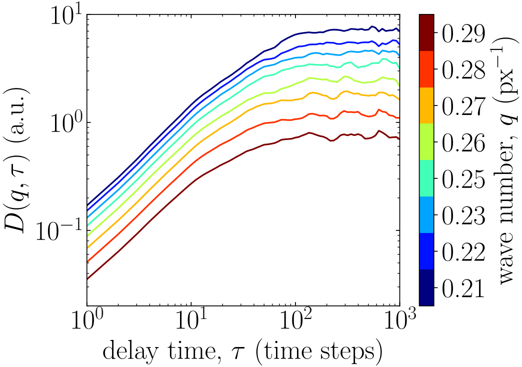

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Linear space invariant imaging

image correlation function

$$g(\mathbf{q}, \tau) = \frac{\langle I^*(\mathbf{q}, t) I(\mathbf{q}, t + \tau) \rangle_t}{\langle |I(\mathbf{q}, t)|^2 \rangle_t}$$

Linear space invariant imaging

image correlation function

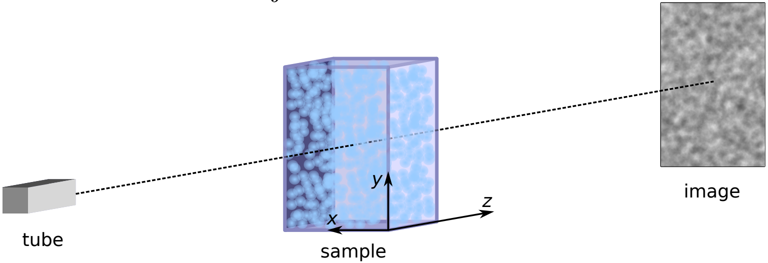
$$g(\mathbf{q},\tau) = \frac{\langle I^*(\mathbf{q},t) I(\mathbf{q},t+\tau)\rangle_t}{\langle |I(\mathbf{q},t)|^2\rangle_t}$$

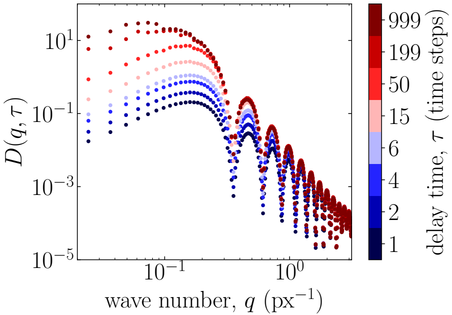
intermediate scattering function

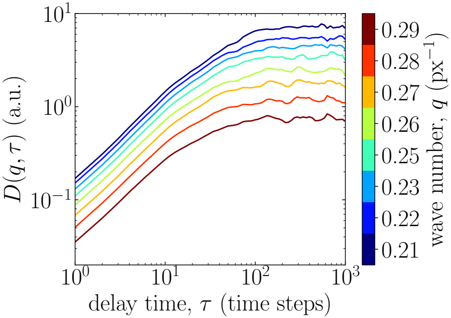
$$f(\mathbf{q},\tau) = \frac{\langle \rho^*(\mathbf{q},t) \rho(\mathbf{q},t+\tau)\rangle_t}{\langle |\rho(\mathbf{q},t)|^2\rangle_t}$$

Linear space-invariant imaging:

$$I(\mathbf{r},t) = I_0 + \int \mathrm{d}\mathbf{r}'\, \mathrm{d}z'\, T(\mathbf{r}-\mathbf{r}', -z') c(\mathbf{r}', z', t)$$







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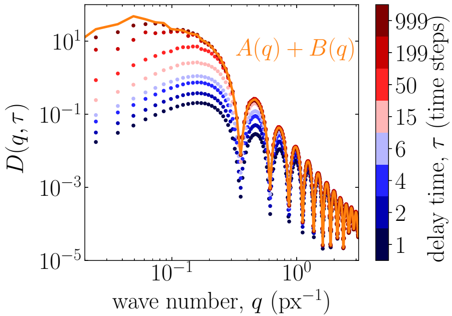

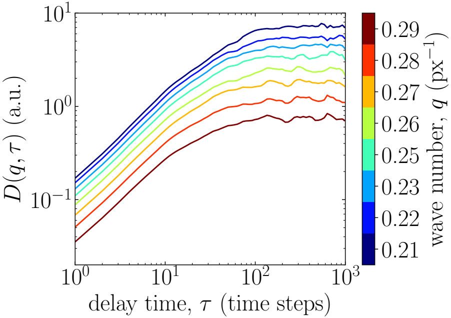

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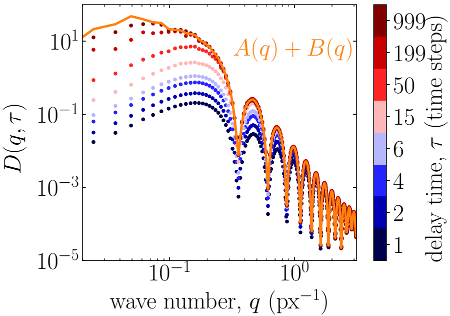

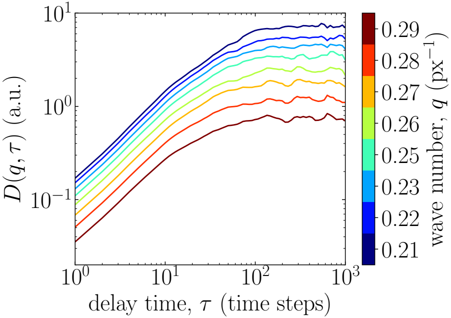

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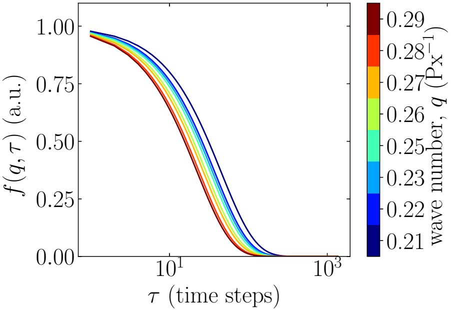
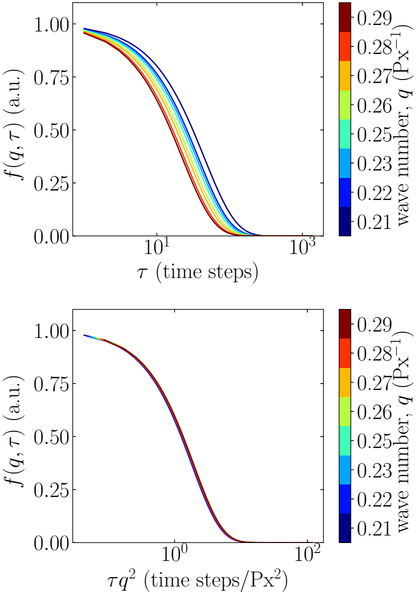
- $d(q,\tau \to 0) = B(q) = 0$
- $d(q,\tau \to 0) = A(q) + B(q)$



Intermediate scattering function $f(q, \tau)$



Brownian motion:

$$f(q,\tau) = \exp(-q^2\tau/\tau_\mathrm{D})$$

Accuracy: 2% - 6%