

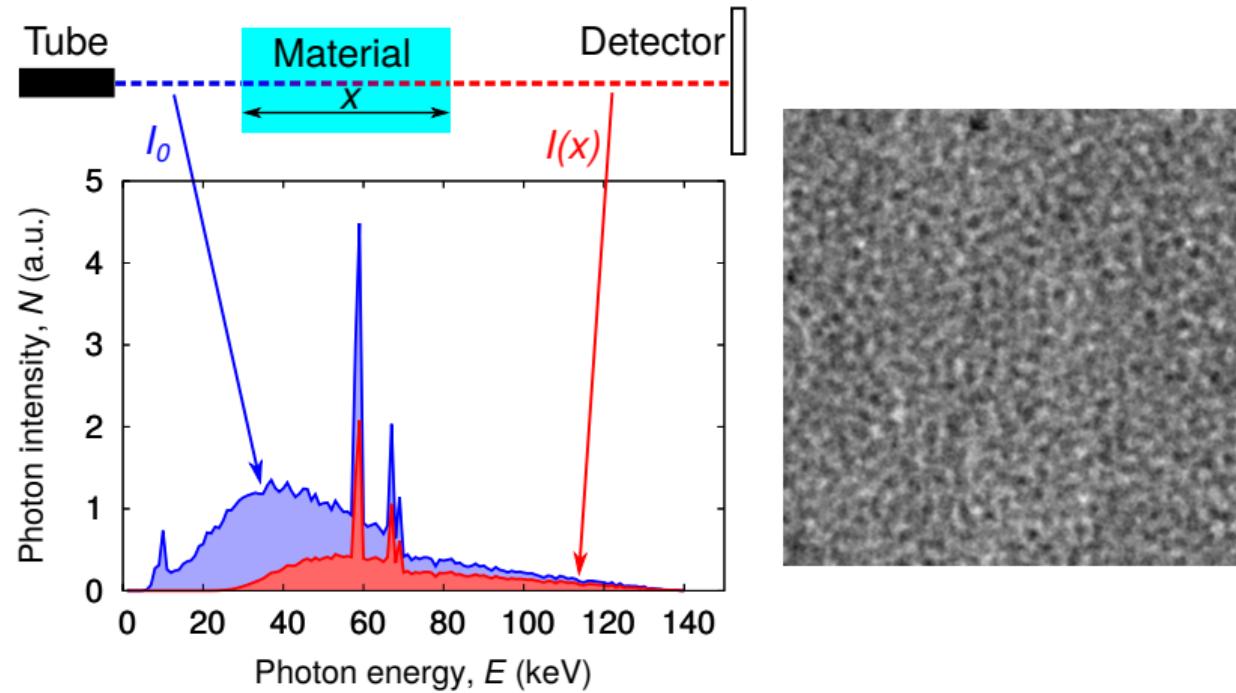


PhD defense
Manuel Baur

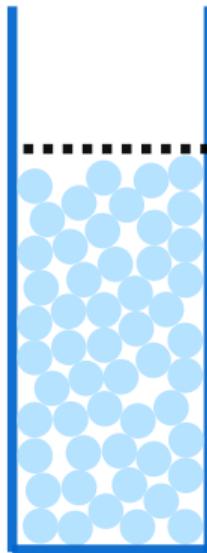
Funded by the German
Federal Ministry for
Economic Affairs and
Energy, grant no. 50WM

1653

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

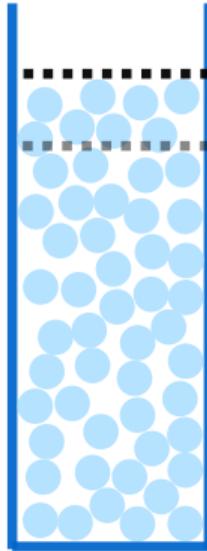


X-ray radiography of granular systems – particle densities and dynamics



$$\Phi = \text{RLP}$$

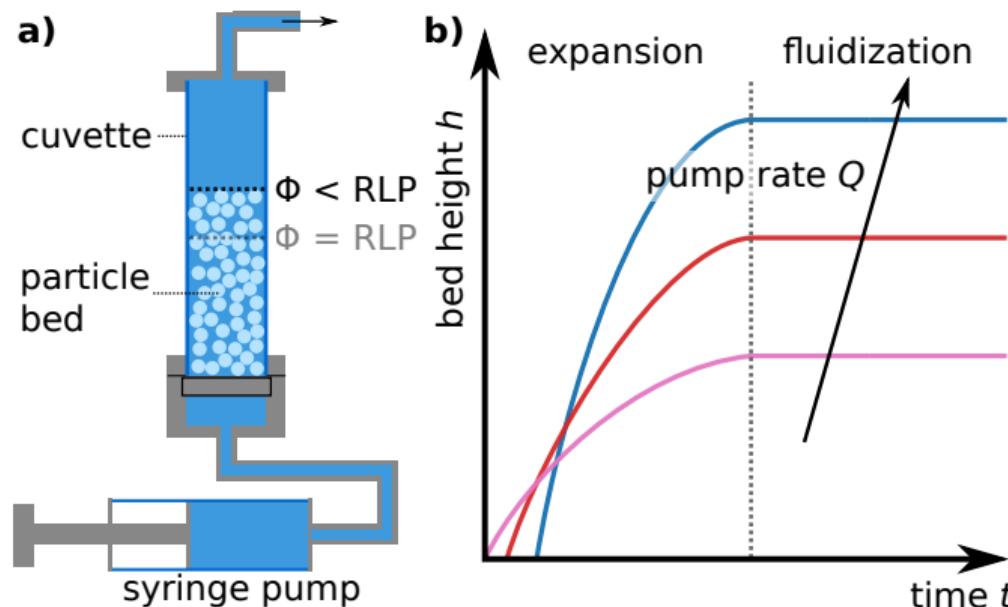
X-ray radiography of granular systems – particle densities and dynamics



$\Phi < \text{RLP}$
 $\Phi = \text{RLP}$

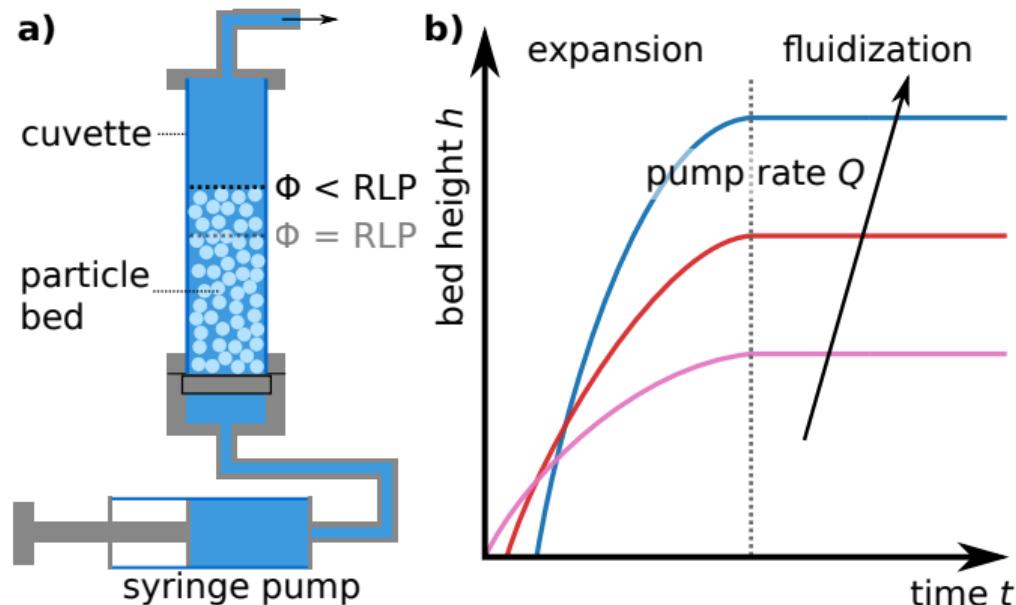
X-ray radiography of granular systems – particle densities and dynamics

Fluidized bed



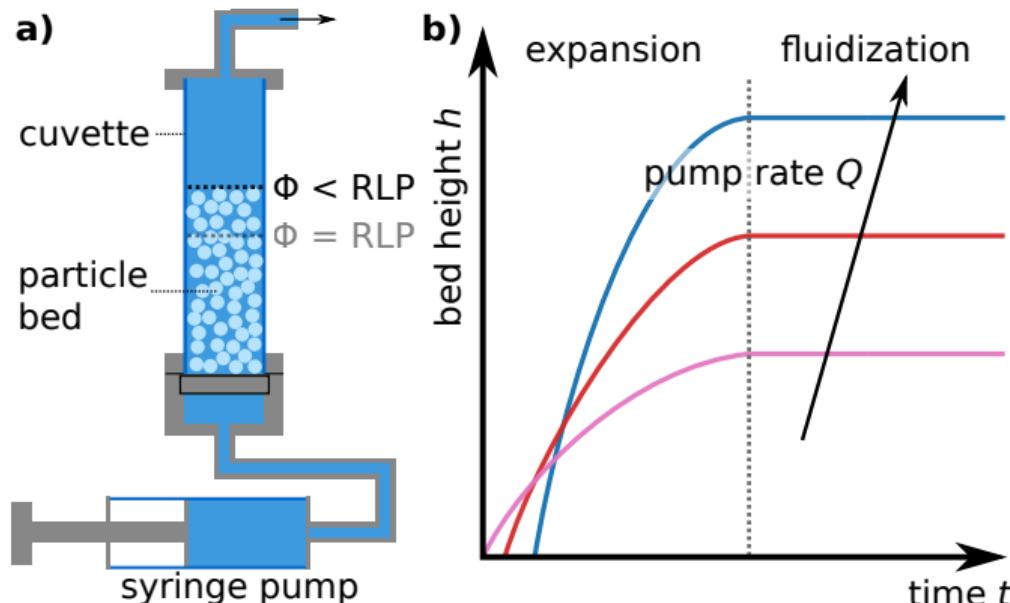
X-ray radiography of granular systems – particle densities and dynamics

Fluidized bed



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

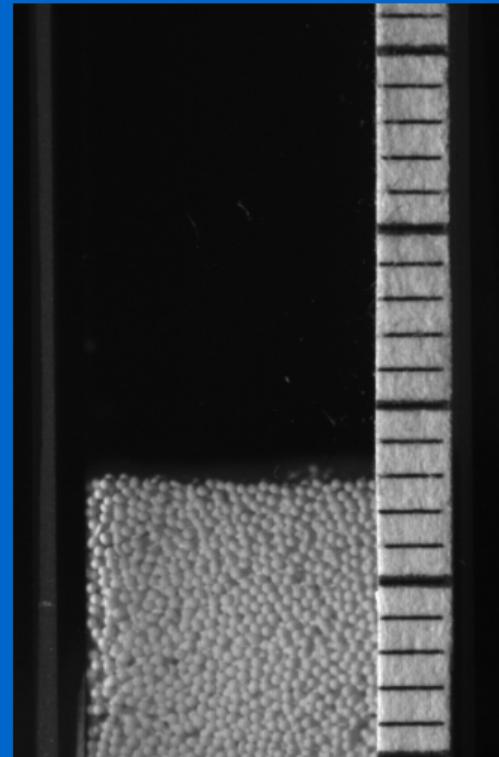
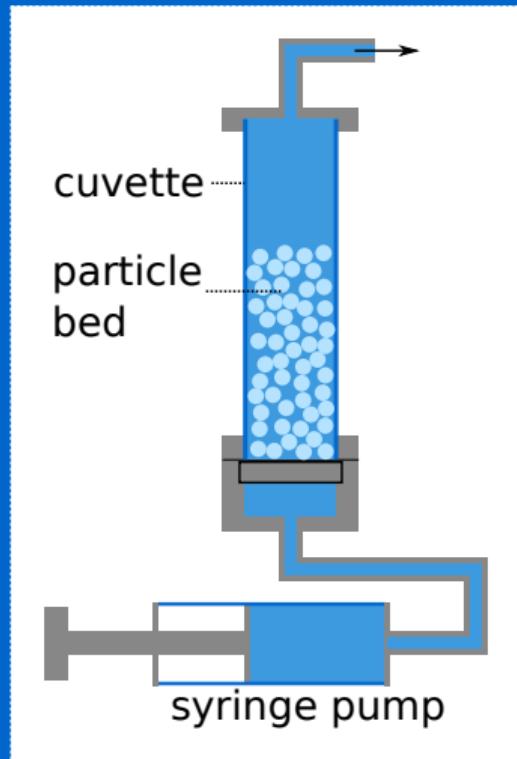
Fluidized bed



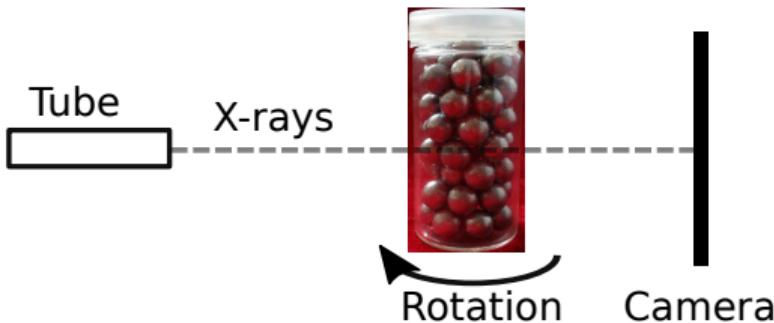
Fluidized bed reactor

"Lack of understanding:
It is very difficult to predict and calculate the **complex mass** [...] **flows** within the bed."

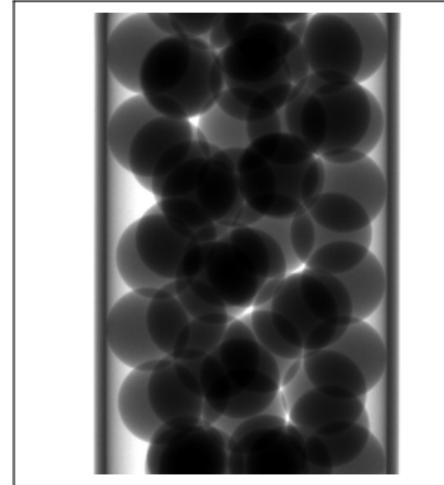
Particulate flows are **opaque**



X-ray radiography

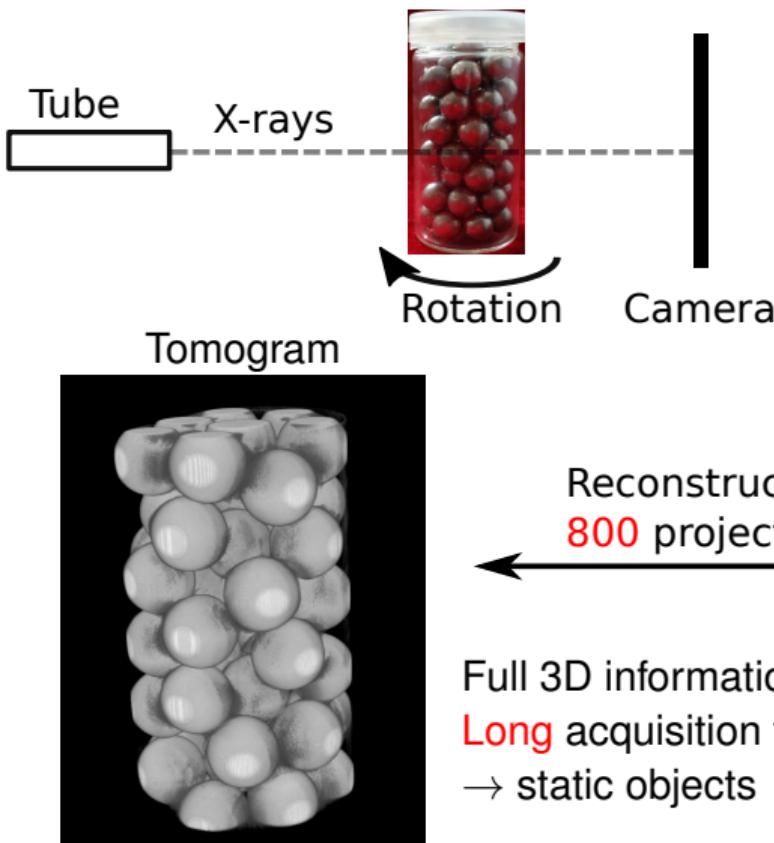


Radiogram

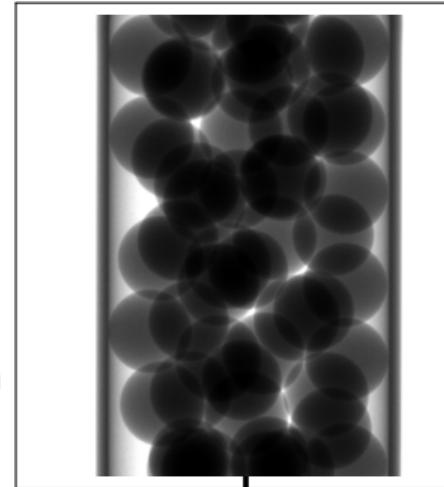


2D projections of 3D object
Short acquisition time

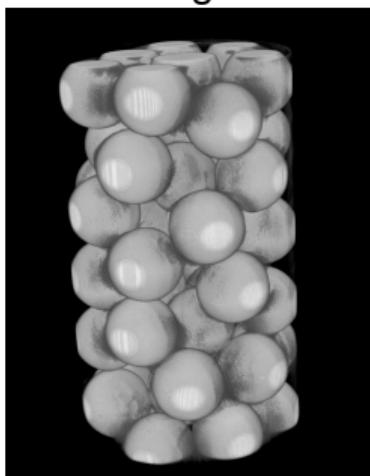
X-ray radiography



Radiogram



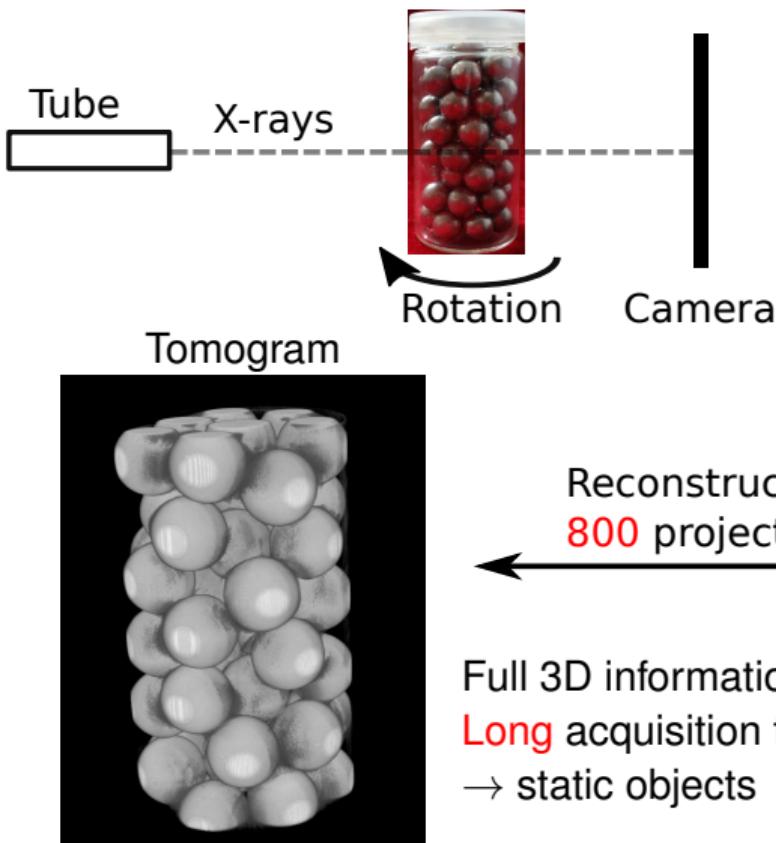
2D projections of 3D object
Short acquisition time



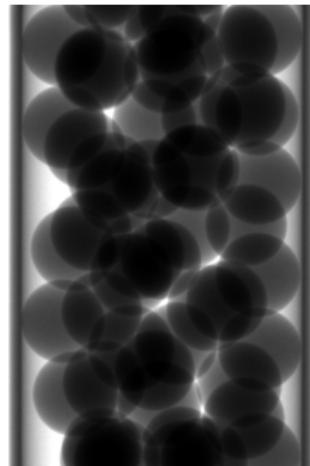
Full 3D information
Long acquisition time
→ static objects

Reconstruction from
800 projections

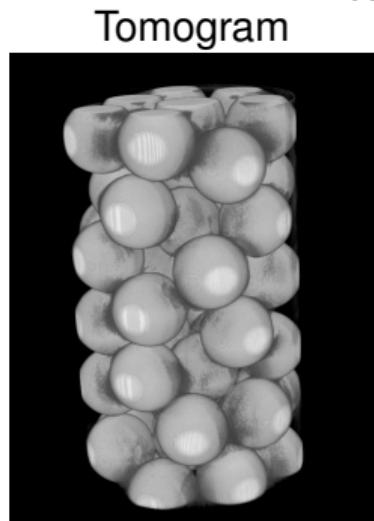
X-ray radiography



Radiogram

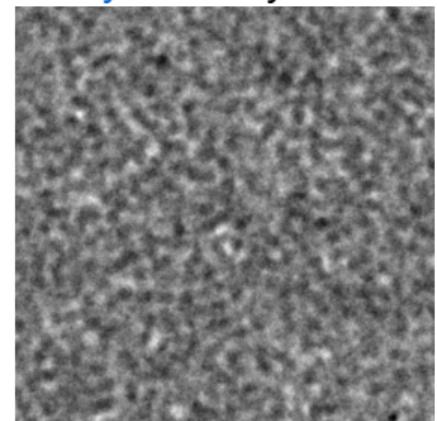


2D projections of 3D object
Short acquisition time

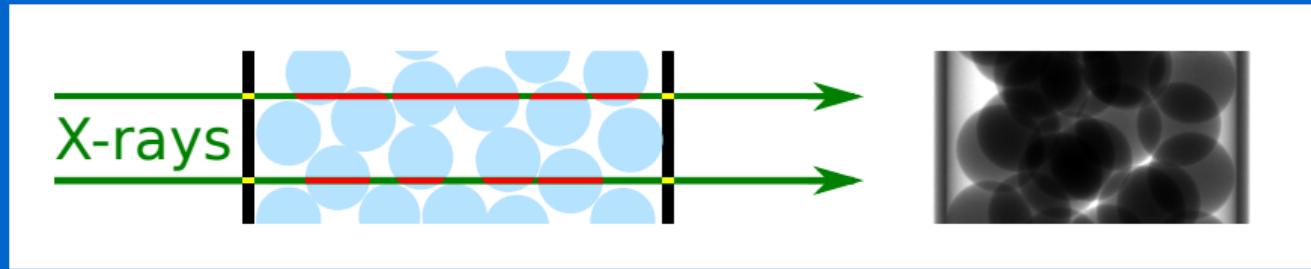


Full 3D information
Long acquisition time
→ static objects

Dynamic system



Measuring the volume fraction of **dynamic** granular systems

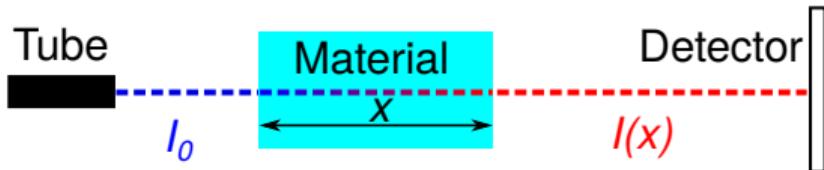


Correction of beam hardening
in X-ray radiograms

Baur *et al*, *Rev. Sci. Instrum.* (2019)

In collaboration with Norman Uhlmann, Fraunhofer EZRT

Attenuation of X-rays

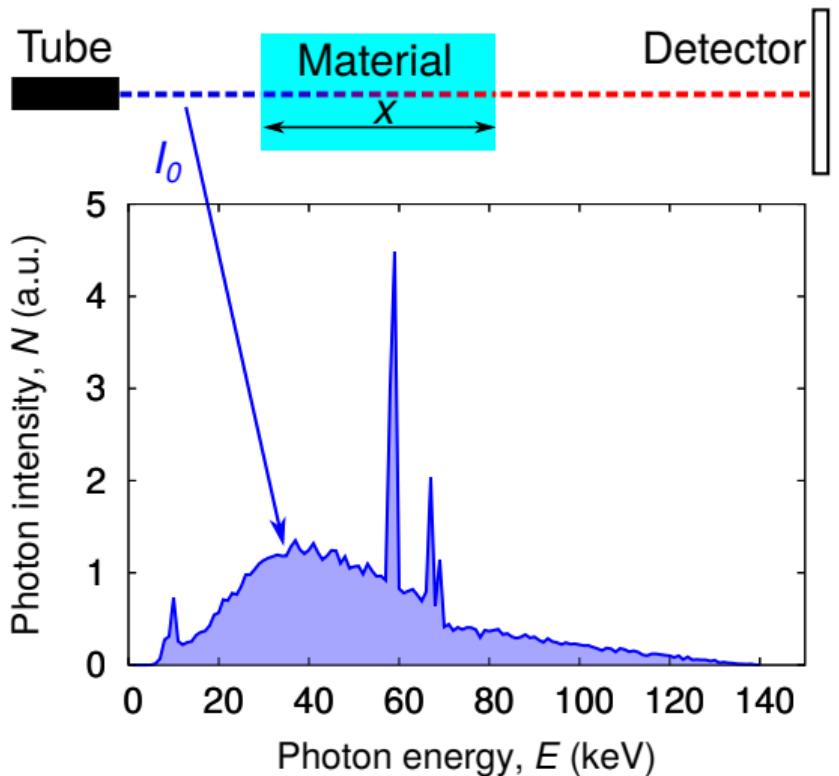


Beer-Lambert's law

$$I(x) = I_0 \exp(-\mu x)$$

$$\text{Thickness: } x = -\frac{1}{\mu} \ln \frac{I(x)}{I_0}$$

Attenuation of X-rays

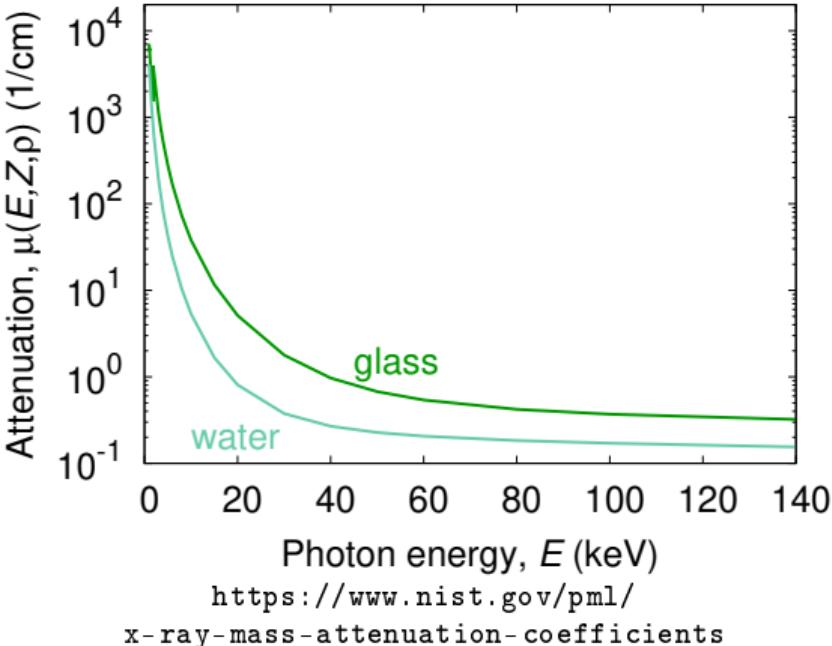


Beer-Lambert's law

$$I(x) = I_0 \exp(-\mu(E, Z, \rho)x)$$

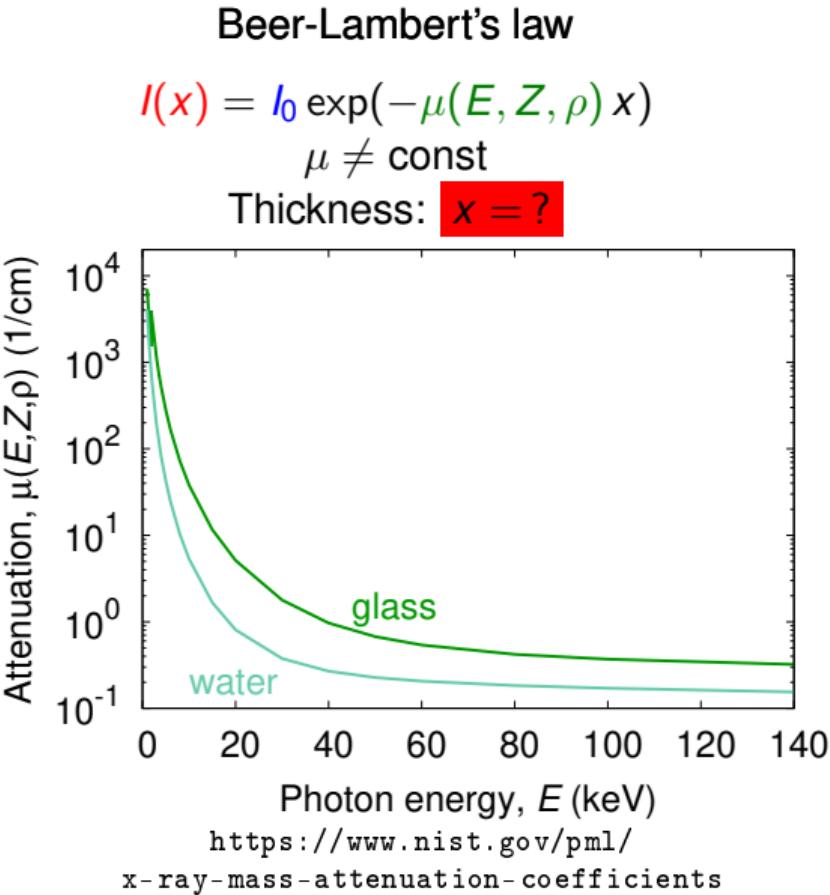
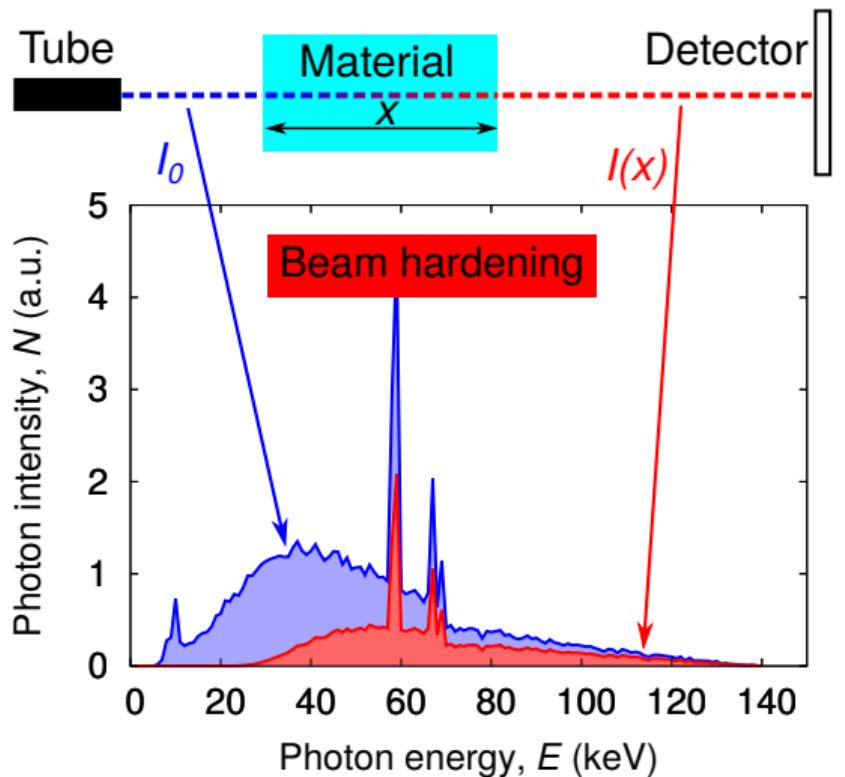
$\mu \neq \text{const}$

Thickness: $x = ?$

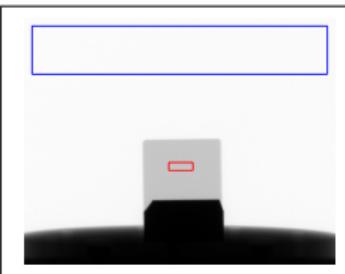
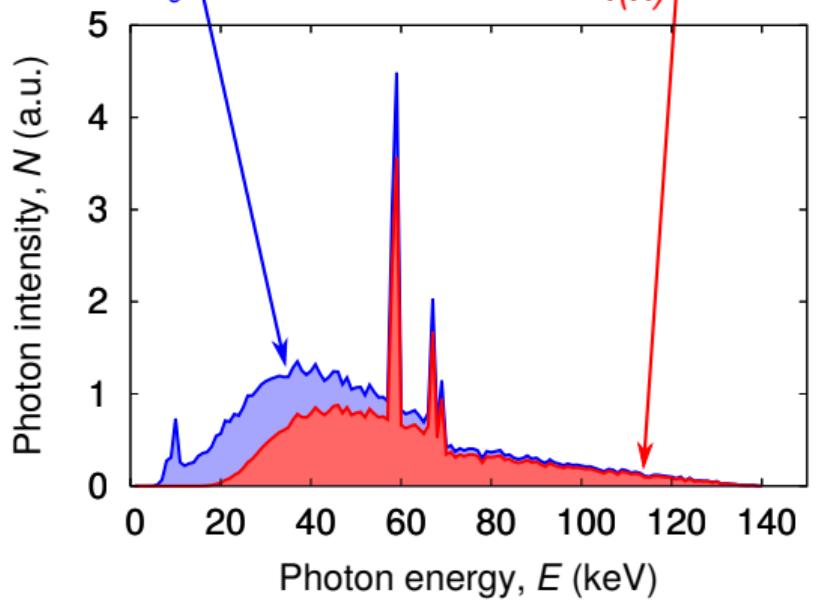


[https://www.nist.gov/pml/
x-ray-mass-attenuation-coefficients](https://www.nist.gov/pml/x-ray-mass-attenuation-coefficients)

Attenuation of X-rays

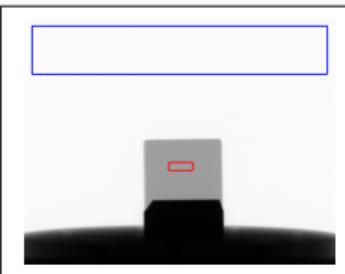
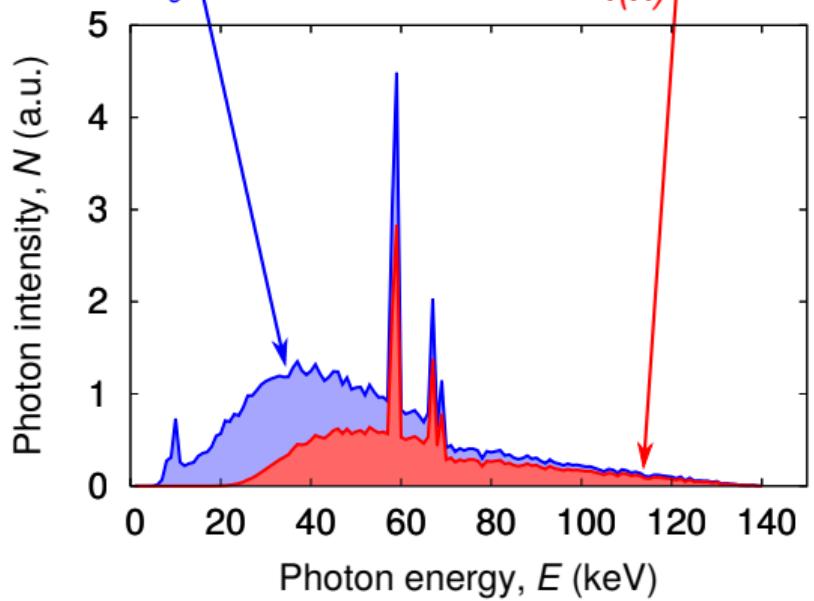
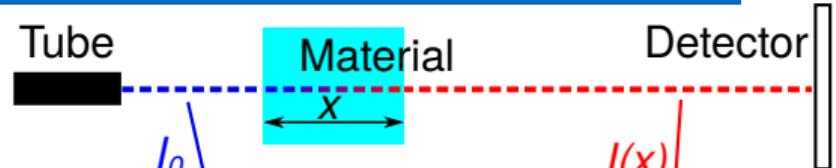


The effective attenuation, μ_{eff}



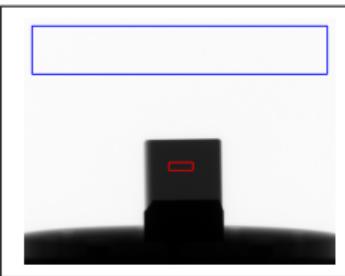
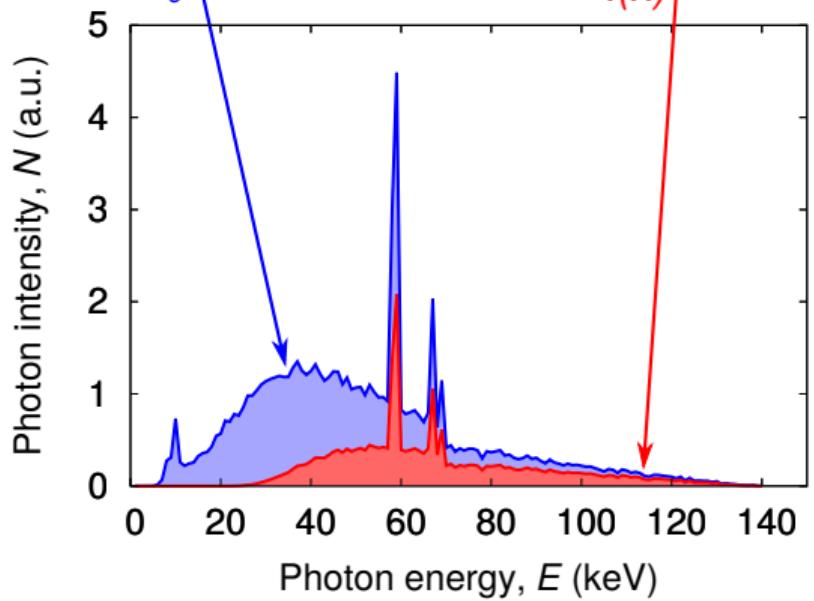
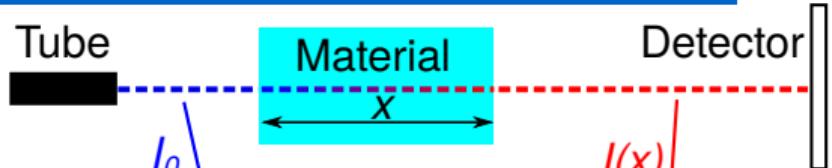
effective attenuation:
 $I(x) = I_0 \exp(-\mu_{\text{eff}}(x) x)$

The effective attenuation, μ_{eff}



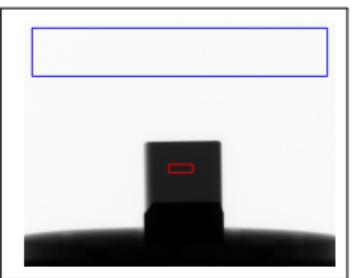
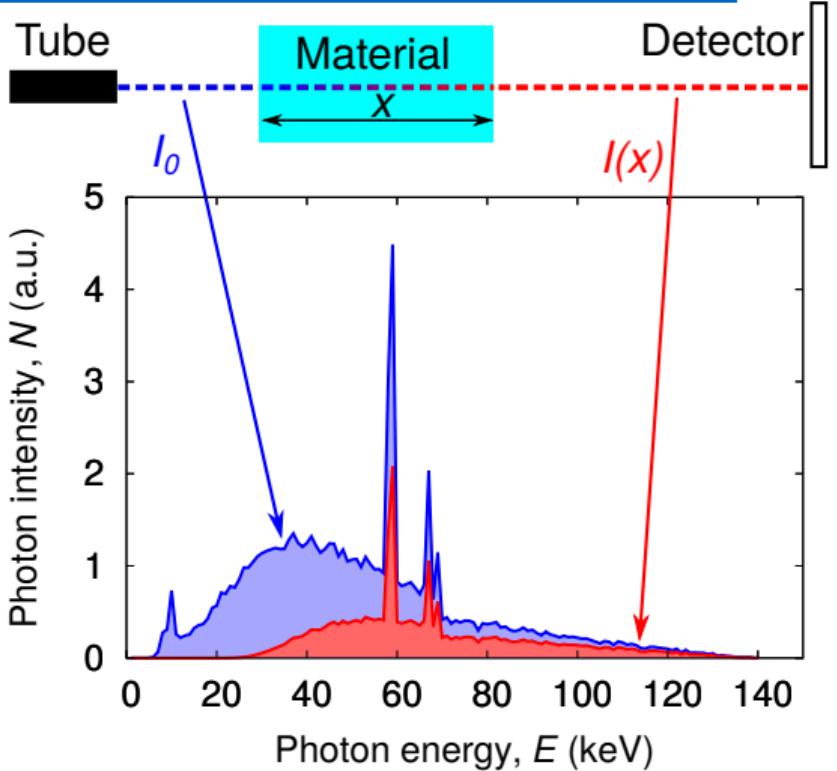
effective attenuation:
 $I(x) = I_0 \exp(-\mu_{\text{eff}}(x) x)$

The effective attenuation, μ_{eff}



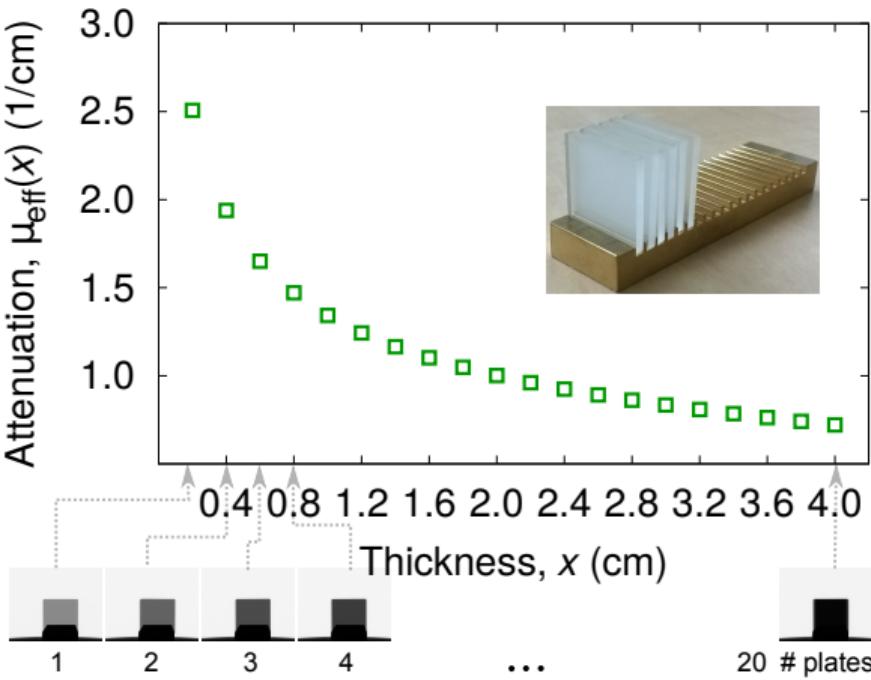
effective attenuation:
 $I(x) = I_0 \exp(-\mu_{\text{eff}}(x) x)$

The effective attenuation, μ_{eff}

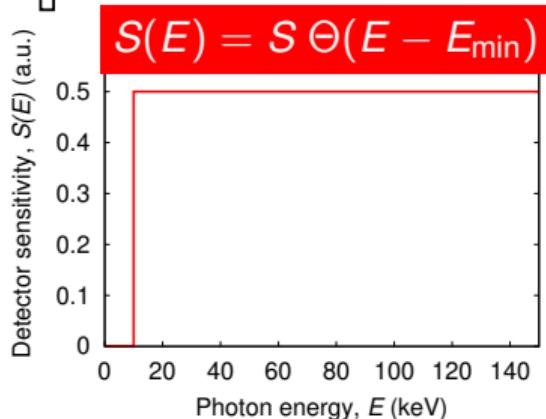
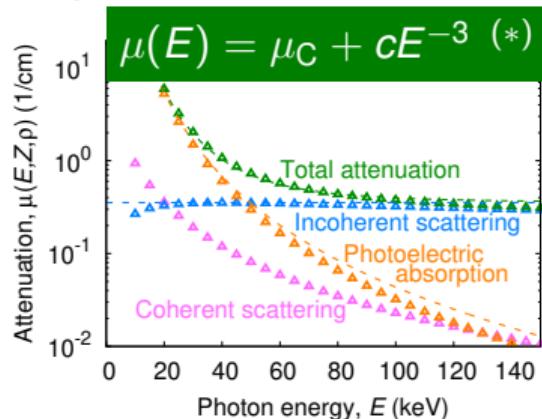
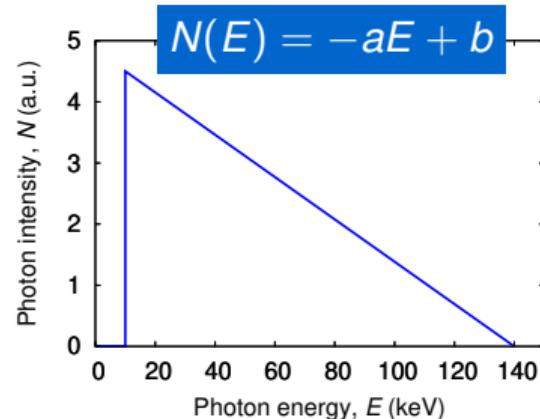
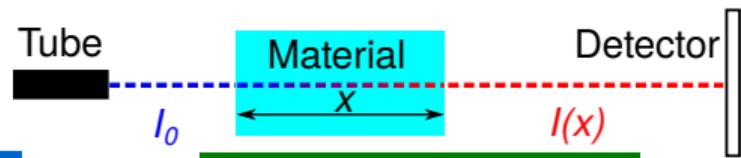


effective attenuation:
 $I(x) = I_0 \exp(-\mu_{\text{eff}}(x) x)$

$$\mu_{\text{eff}}(x) = -\frac{1}{x} \frac{I(x)}{I_0}$$



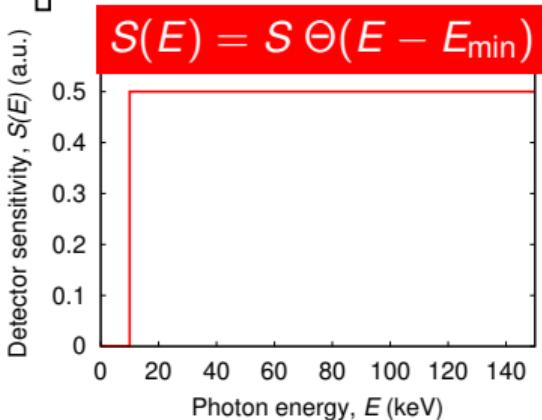
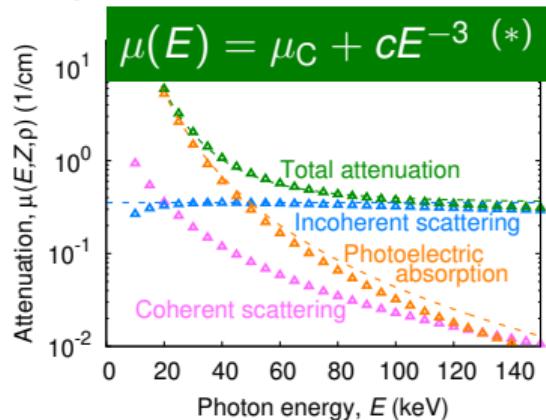
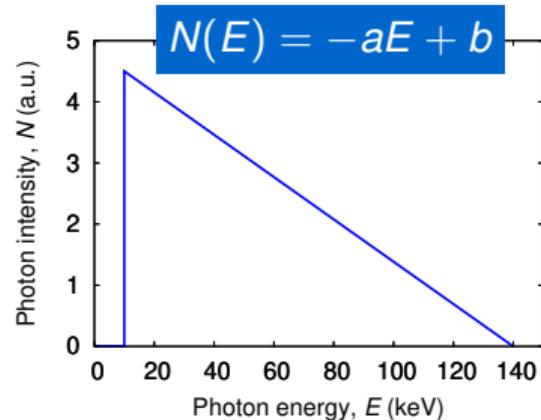
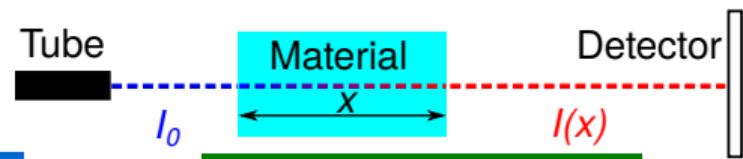
Modeling of μ_{eff}



$$I(x) \propto \int N(E) \exp\{-\mu(E, Z, \rho)x\} S(E) dE$$

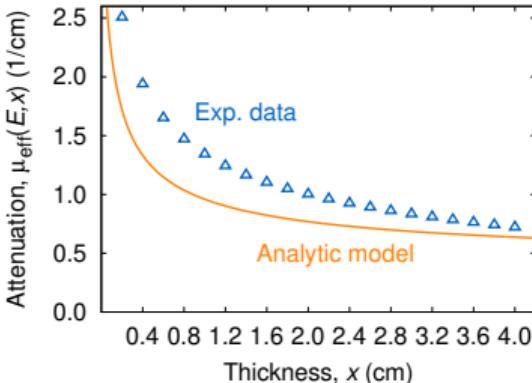
(*) XCOM supplied by NIST

Modeling of μ_{eff}



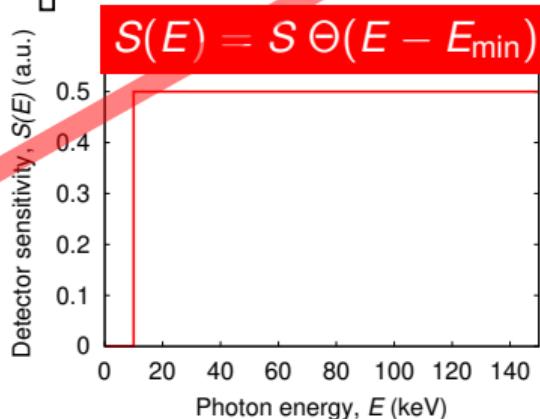
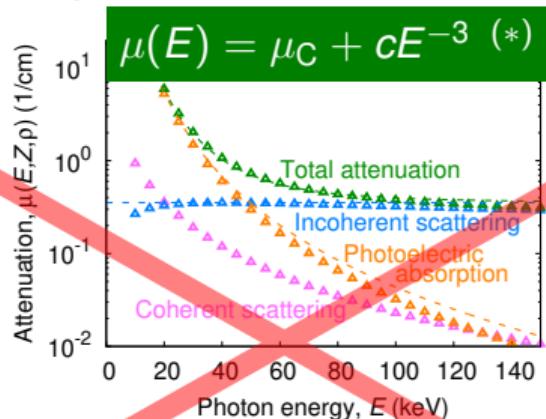
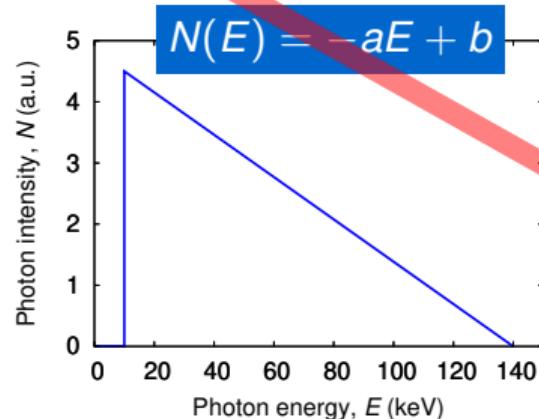
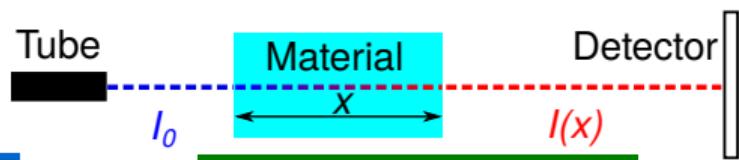
$$I(x) \propto \int N(E) \exp\{-\mu(E, Z, \rho)x\} S(E) dE$$

$$\propto S \int_{E_{\min}}^{E_{\max}} (-aE + b) \exp\{-(\mu_C + cE^{-3})x\} dE$$



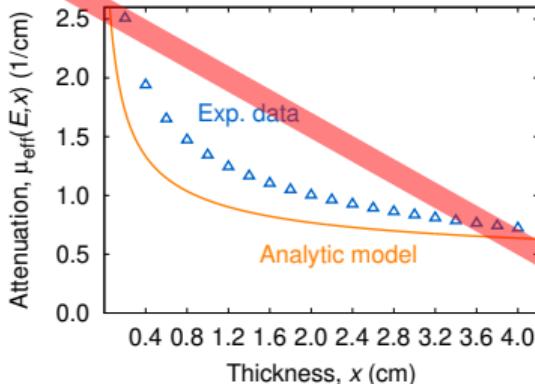
(*) XCOM supplied by NIST

Modeling of μ_{eff}

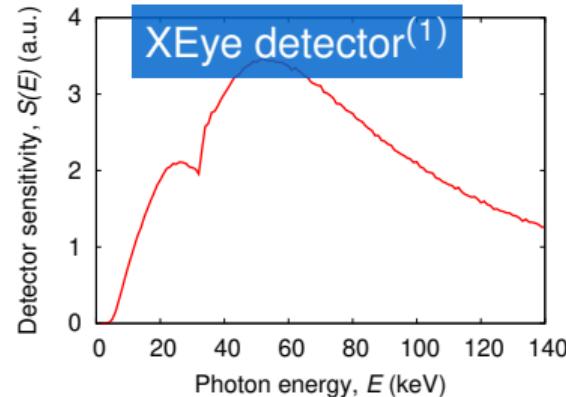
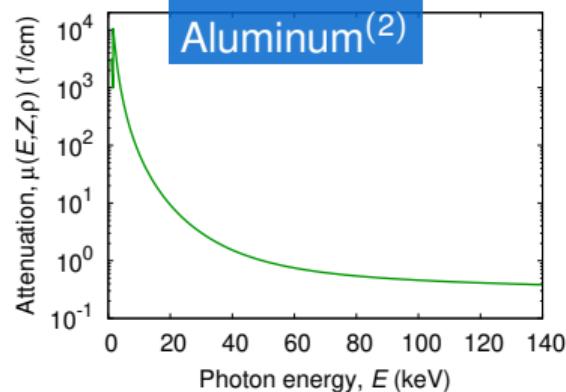
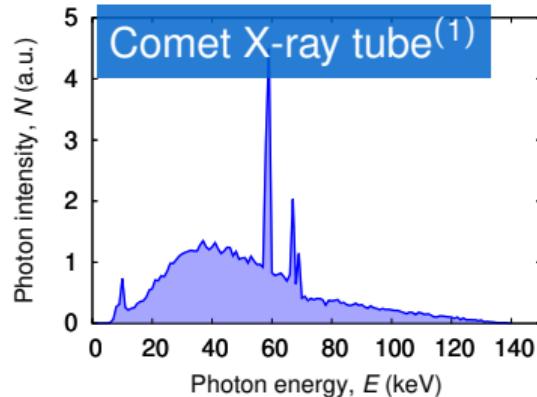
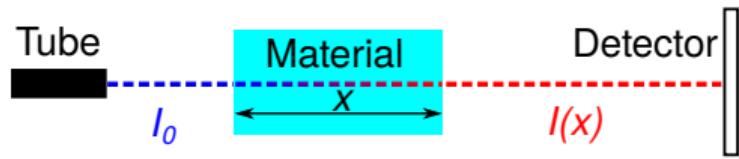


$$\begin{aligned} I(x) &\propto \int N(E) \exp\{-\mu(E, Z, \rho)x\} S(E) dE \\ &\propto S \int_{E_{\min}}^{E_{\max}} (-aE + b) \exp\{-(\mu_C + cE^{-3})x\} dE \end{aligned}$$

(*) XCOM supplied by NIST



Numerical approx. of μ_{eff}

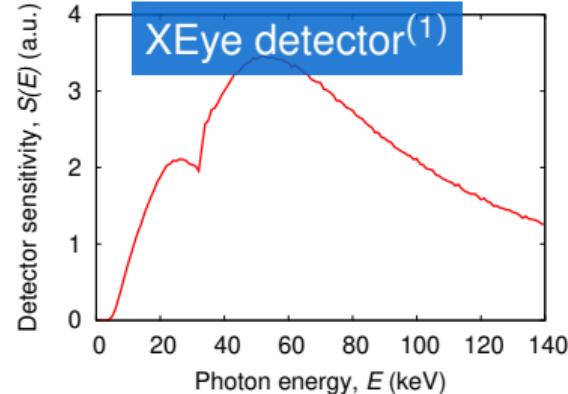
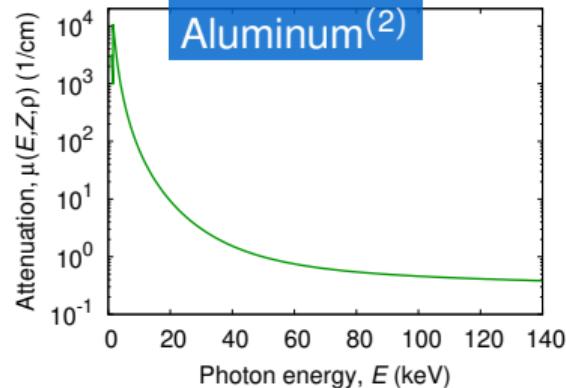
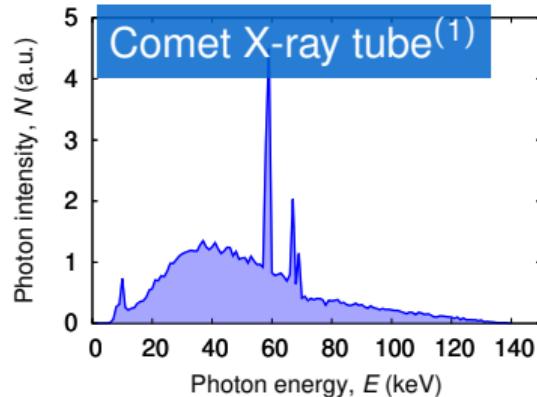
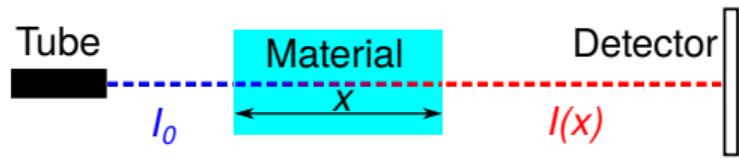


$$I(x) \propto \int N(E) \exp\{-\mu(E, Z, \rho)x\} S(E) dE$$
$$\int \rightarrow \sum$$

(1) Supplied by Norman Uhlmann, Fraunhofer EZRT

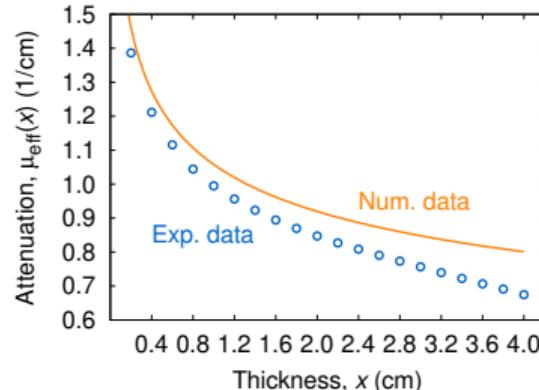
(2) XCOM supplied by NIST

Numerical approx. of μ_{eff}



$$I(x) \propto \int N(E) \exp\{-\mu(E, Z, \rho)x\} S(E) dE$$

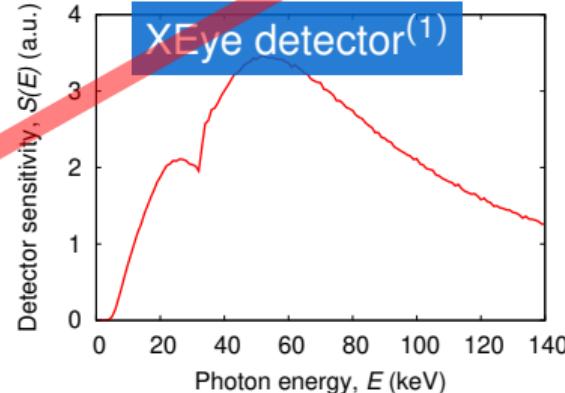
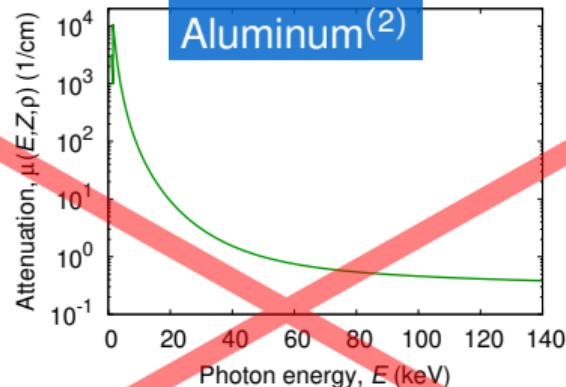
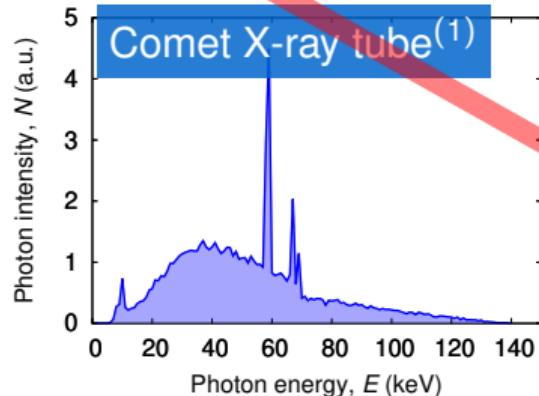
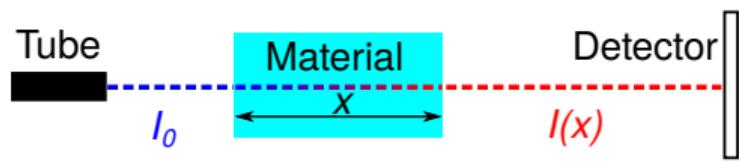
$$\int \rightarrow \sum$$



(1) Supplied by Norman Uhlmann, Fraunhofer EZRT

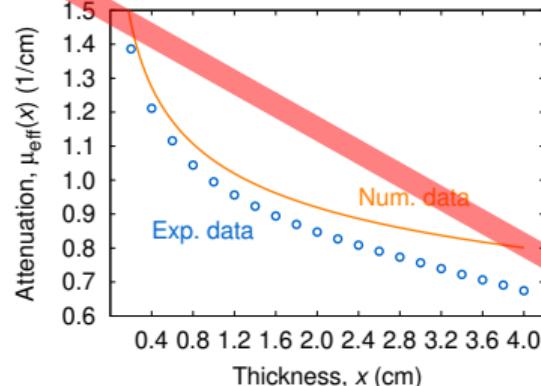
(2) XCOM supplied by NIST

Numerical approx. of μ_{eff}



$$I(x) \propto \int N(E) \exp\{-\mu(E, Z, \rho)x\} S(E) dE$$

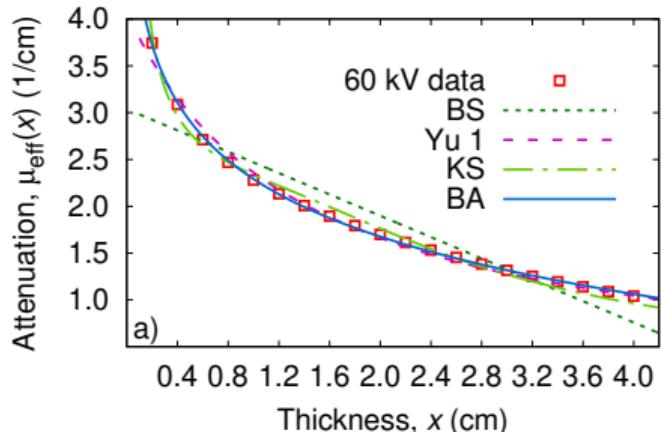
$$\int \rightarrow \sum$$



(1) Supplied by Norman Uhlmann, Fraunhofer EZRT

(2) XCOM supplied by NIST

Heuristic model functions for μ_{eff}



$$\mu_{\text{eff}}(x) = \mu_0 - \lambda x$$

Bjärngard & Shackford
(1994)

$$\mu_{\text{eff}}(x) = \frac{\mu_0}{1 + \lambda x}$$

Yu *et al.* (1997)

$$\mu_{\text{eff}}(x) = \mu(E_{\text{max}}) + \frac{2\mu_1}{x\sqrt{-\lambda_1^2+4\lambda_2}} \times$$

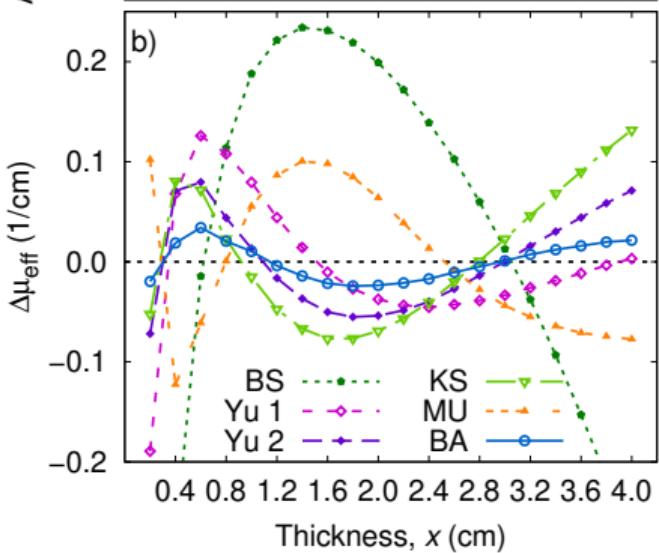
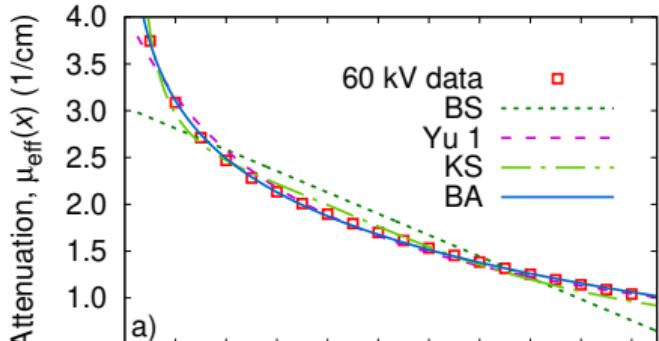
$$\left[\arctan\left(\frac{\lambda_1+2\lambda_2x}{\sqrt{-\lambda_1^2+4\lambda_2}}\right) - \arctan\left(\frac{\lambda_1}{\sqrt{-\lambda_1^2+4\lambda_2}}\right) \right]$$

Kleinschmidt (1999)

$$\mu_{\text{eff}}(x) = a + \frac{b}{x^\alpha}$$

Baur *et al.* (2019)
(this work)

Heuristic model functions for μ_{eff}



$$\mu_{\text{eff}}(x) = \mu_0 - \lambda x$$

Bjärngard & Shackford
(1994)

$$\mu_{\text{eff}}(x) = \frac{\mu_0}{1 + \lambda x}$$

$$\mu_{\text{eff}}(x) = \frac{\mu_0}{(1 + \lambda x)^\beta}$$

Yu *et al.* (1997)

$$\mu_{\text{eff}}(x) = \mu(E_{\text{max}}) + \frac{2\mu_1}{x\sqrt{-\lambda_1^2 + 4\lambda_2}} \times \left[\arctan\left(\frac{\lambda_1 + 2\lambda_2 x}{\sqrt{-\lambda_1^2 + 4\lambda_2}}\right) - \arctan\left(\frac{\lambda_1}{\sqrt{-\lambda_1^2 + 4\lambda_2}}\right) \right]$$

Kleinschmidt (1999)

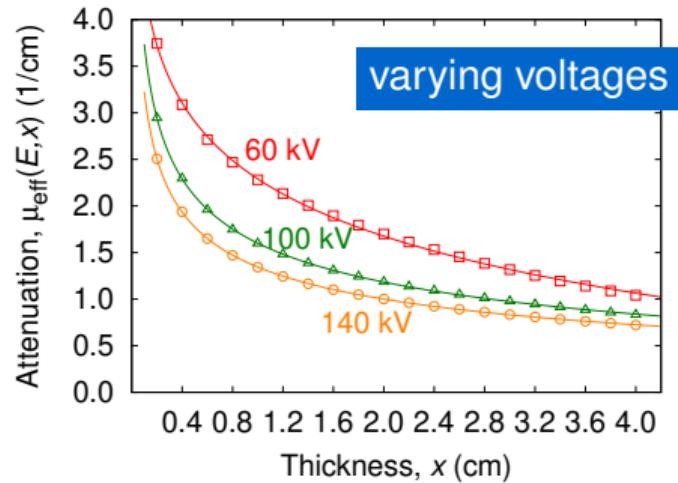
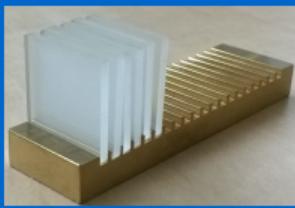
$$\mu_{\text{eff}}(x) = -\frac{1}{x} \ln [A + B \exp(-x/C)]$$

Mudde *et al.* (2008)

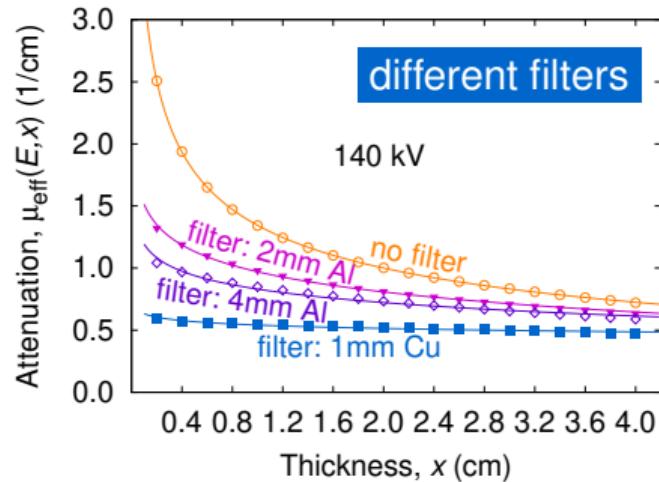
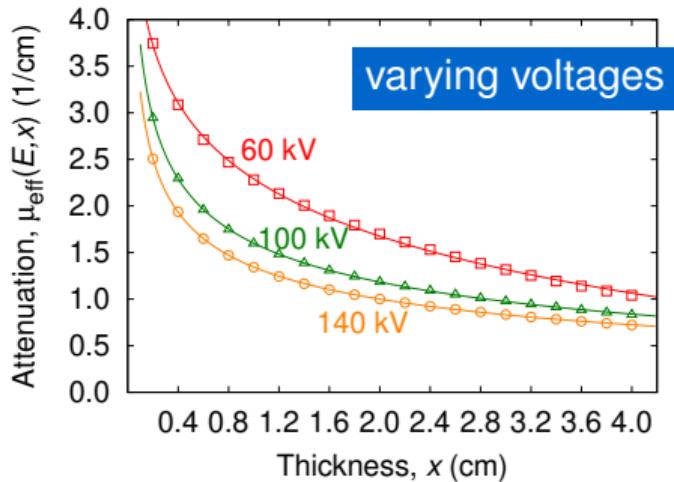
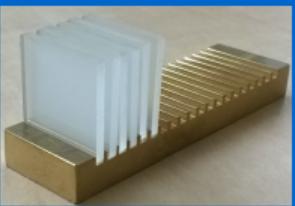
$$\mu_{\text{eff}}(x) = a + \frac{b}{x^\alpha}$$

Baur *et al.* (2019)
(this work)

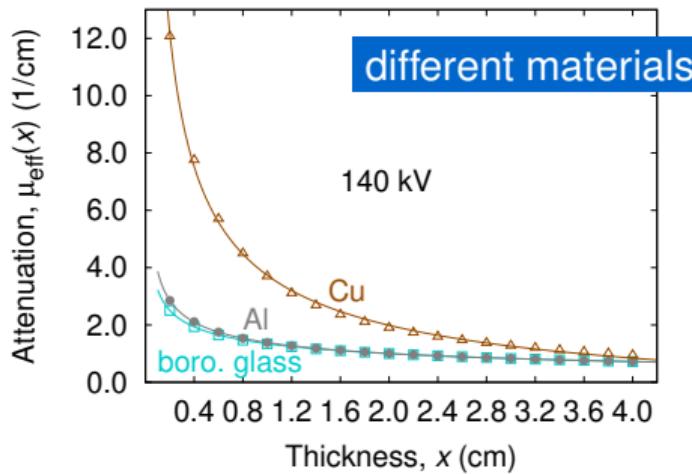
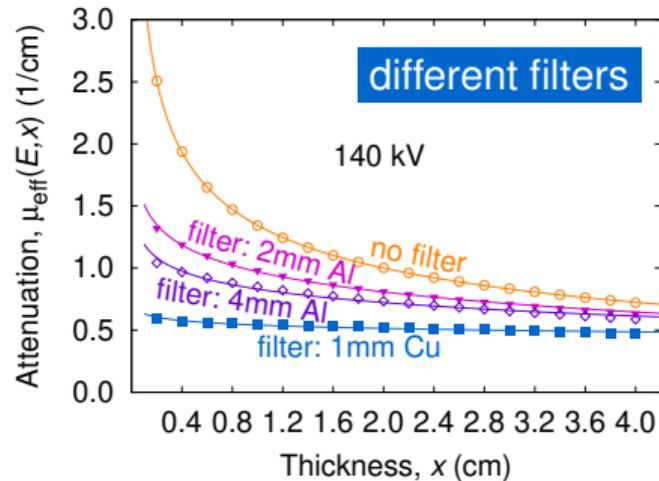
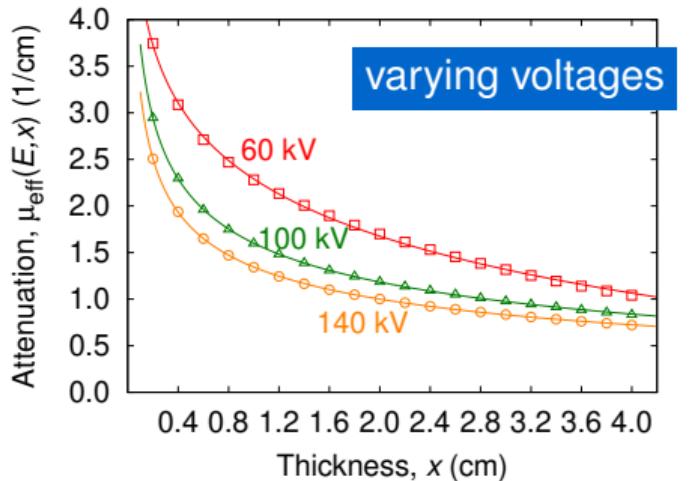
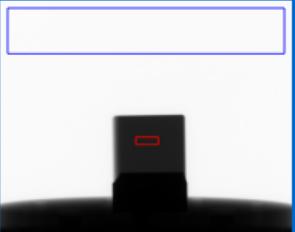
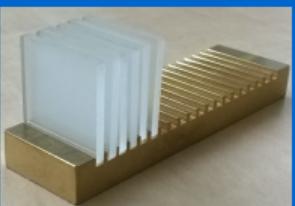
Universality of
 $\mu_{\text{eff}}(x) = a + \frac{b}{x^\alpha}$



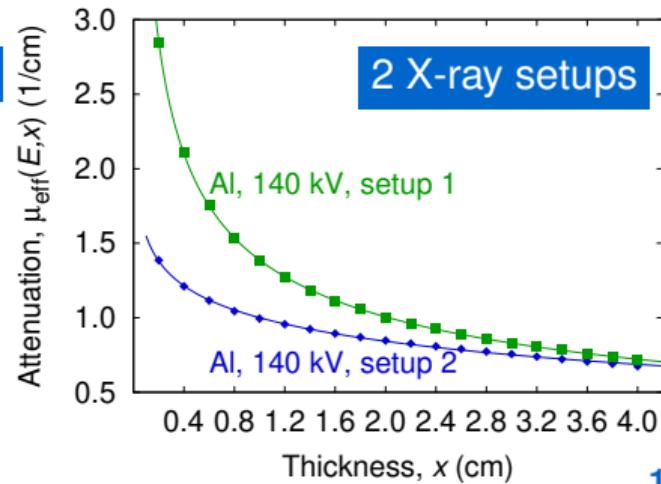
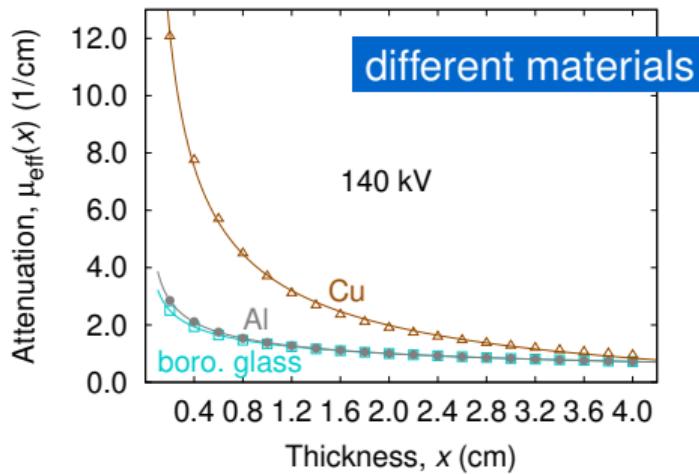
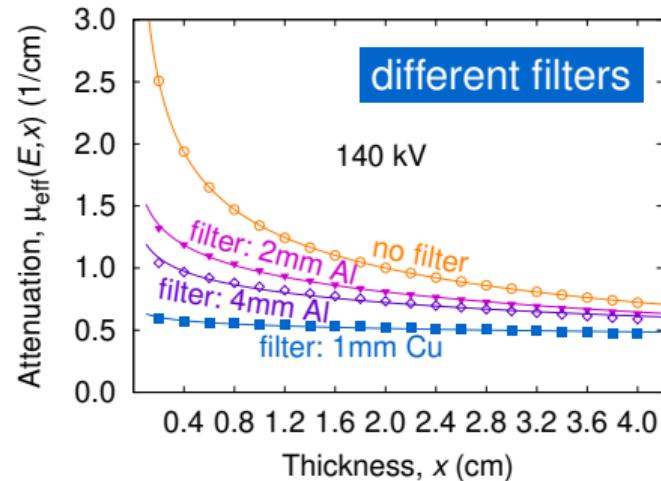
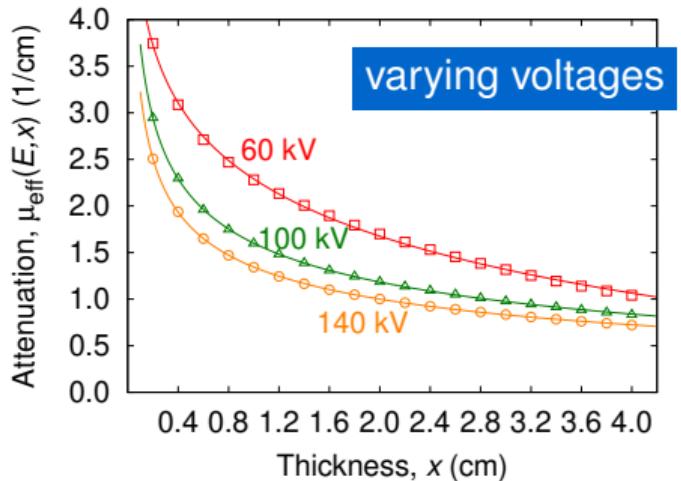
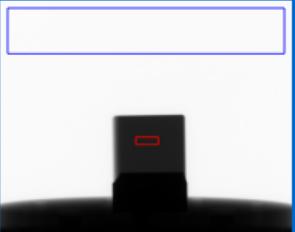
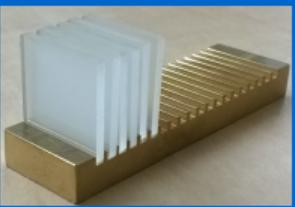
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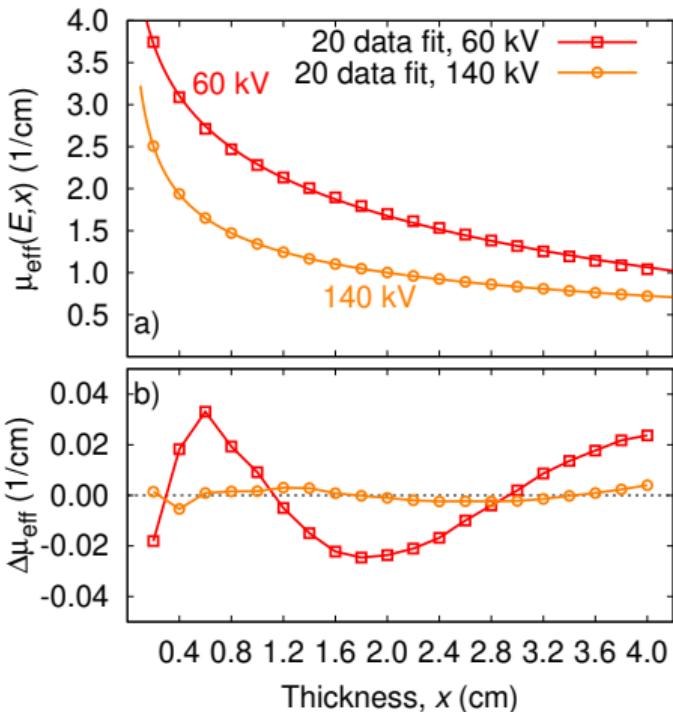
Determining the material thickness x

Generalized Beer-Lambert

$$I(x) = I_0 \exp(-\mu_{\text{eff}}(x) x)$$

Model function

$$\mu_{\text{eff}}(x) = a + \frac{b}{x^\alpha}$$



Determining the material thickness x

Generalized Beer-Lambert

$$I(x) = I_0 \exp(-\mu_{\text{eff}}(x) x)$$

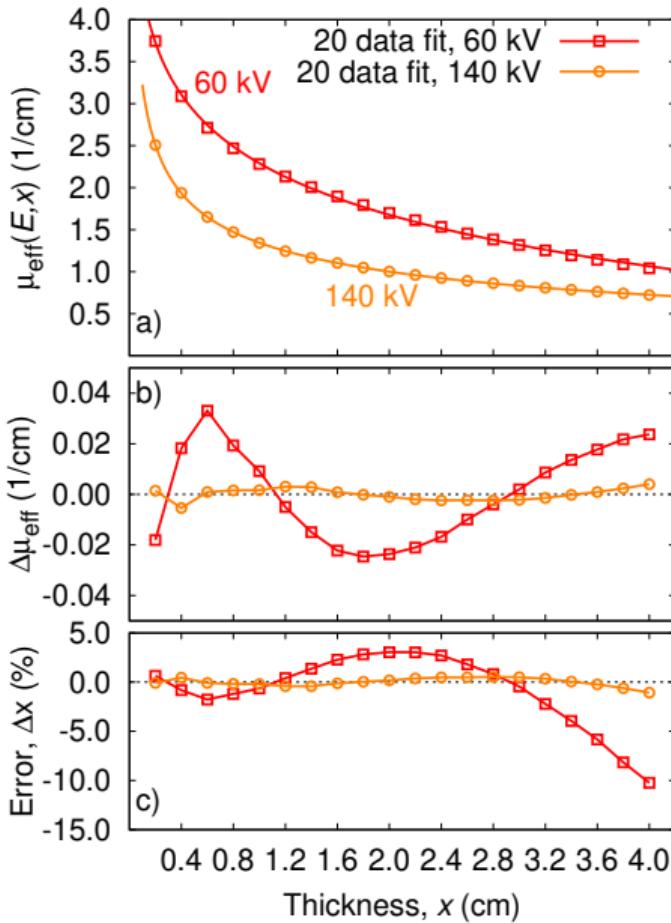
Model function

$$\mu_{\text{eff}}(x) = a + \frac{b}{x^\alpha}$$

Solve

$$ax + bx^{1-\alpha} + \ln\left(\frac{I(x)}{I_0}\right) = 0$$

e.g. Newton's method or look-up table



Determining the material thickness x

Generalized Beer-Lambert

$$I(x) = I_0 \exp(-\mu_{\text{eff}}(x) x)$$

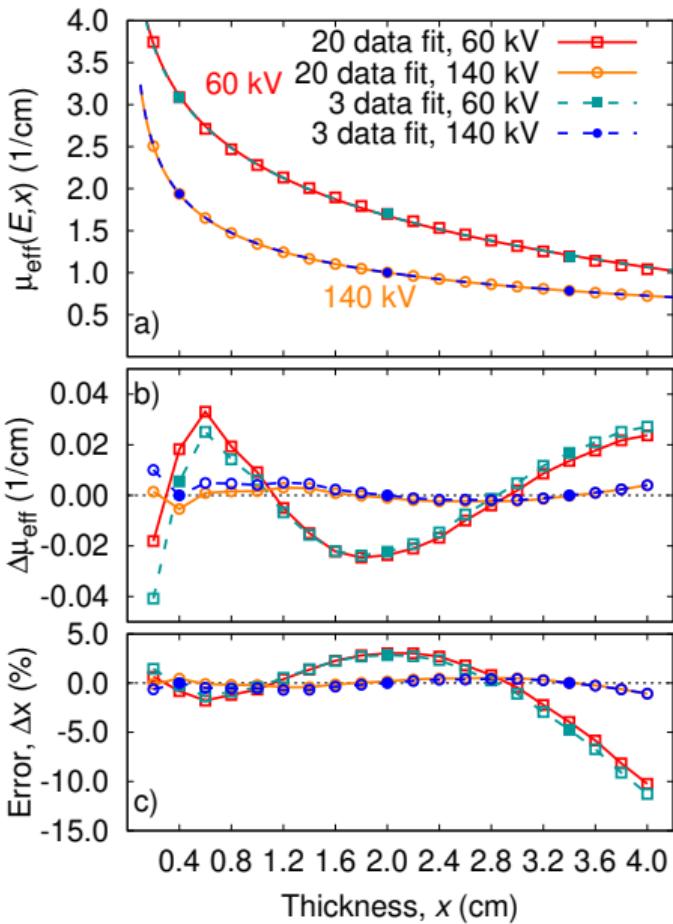
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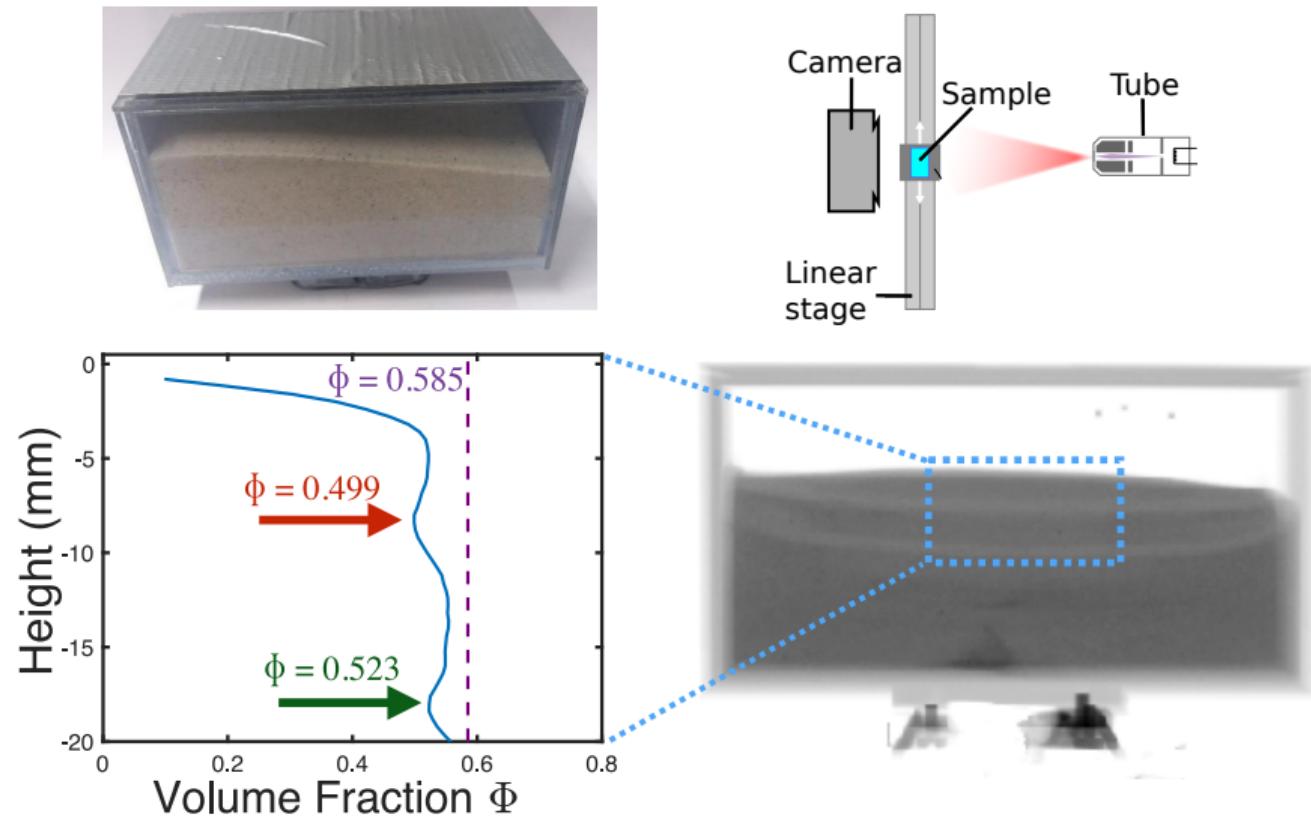
Solve

$$ax + bx^{1-\alpha} + \ln\left(\frac{I(x)}{I_0}\right) = 0$$

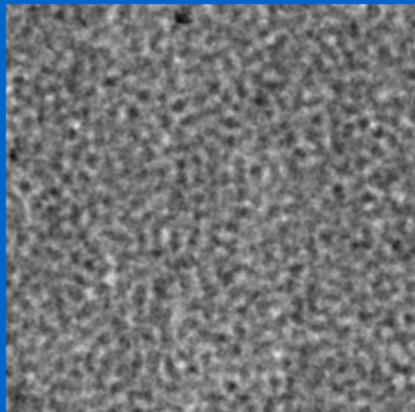
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Migrating shear bands in shaken granular matter, Kollmer *et al* (2020)

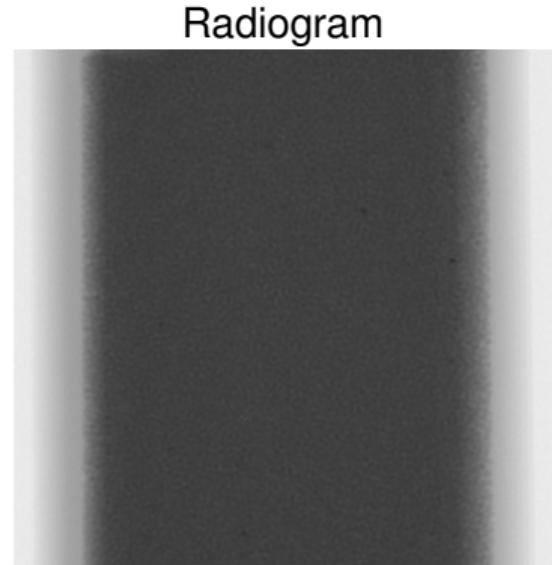
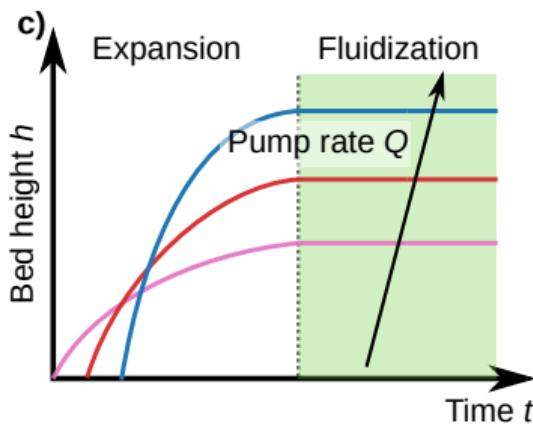
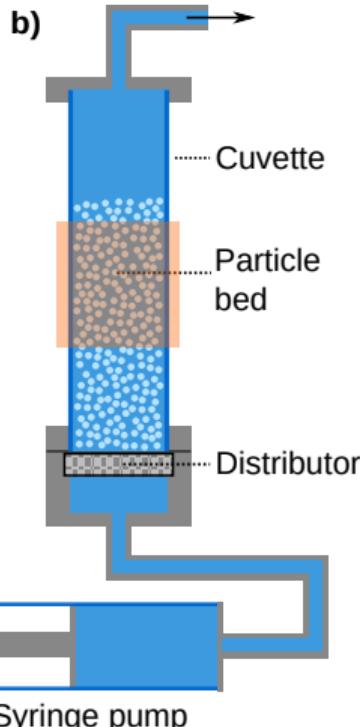
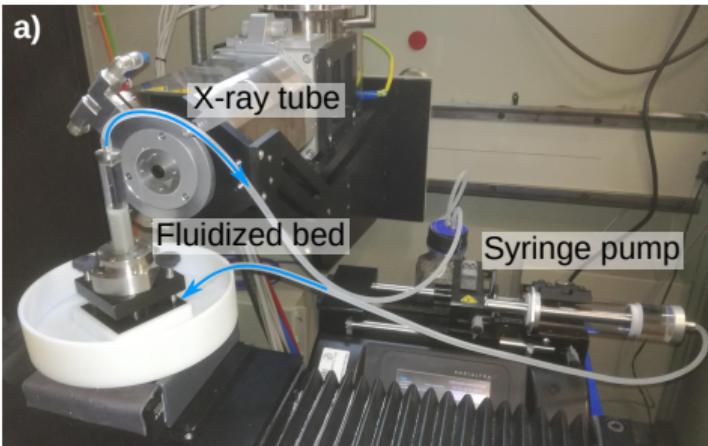


Measuring granular dynamics with X-ray Digital Fourier Analysis (X-DFA)

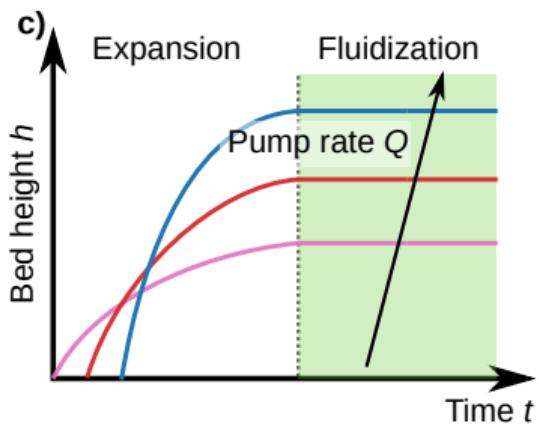
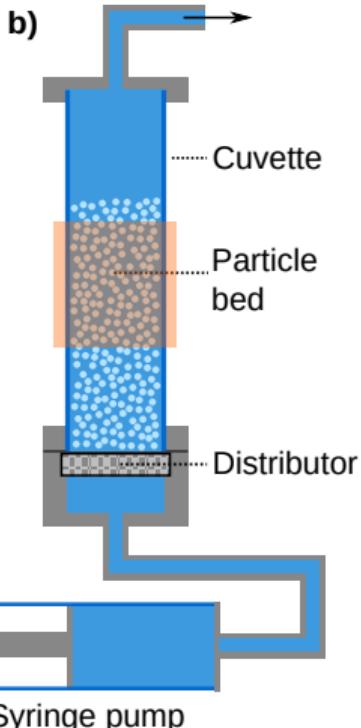
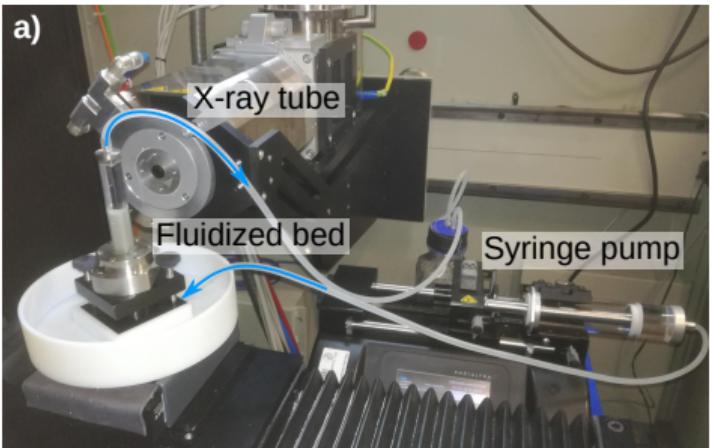


In collaboration with M. Escobedo & S. Egelhaaf, University of Düsseldorf

The system: A liquid fluidized bed

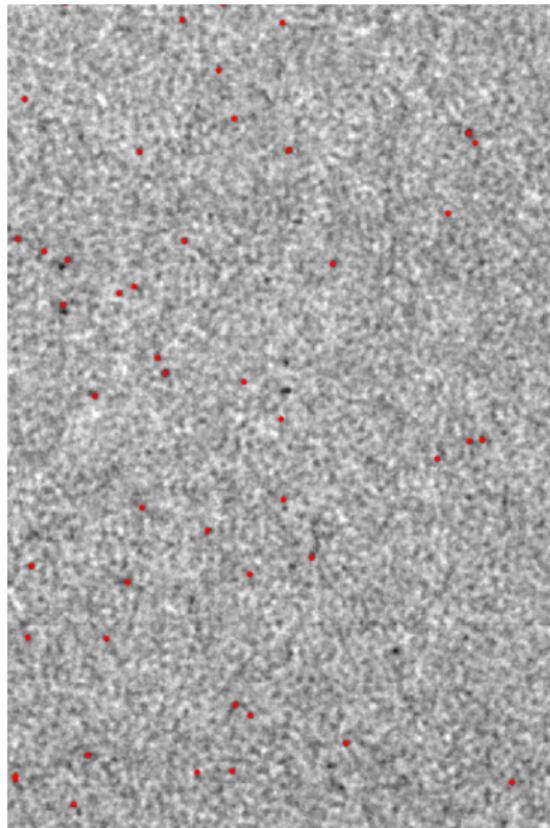


The system: A liquid fluidized bed

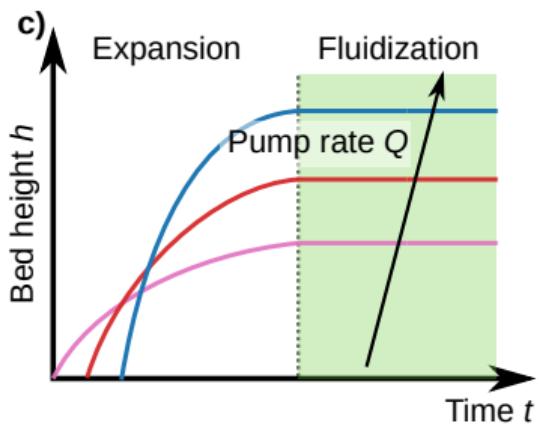
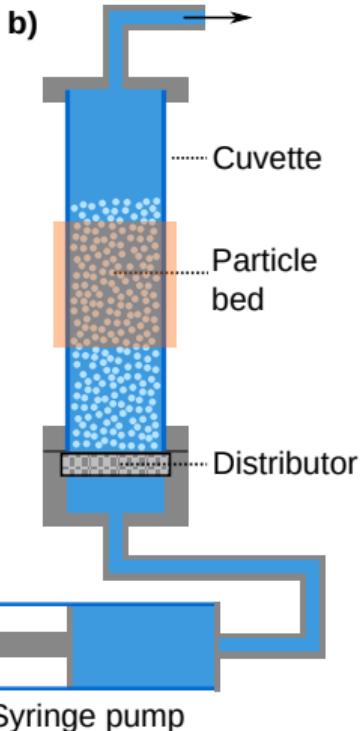
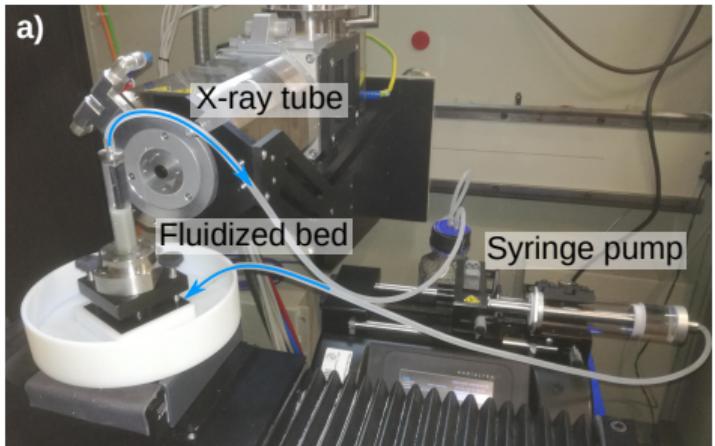


$$0.45 < \phi < 0.56$$

Particle tracking

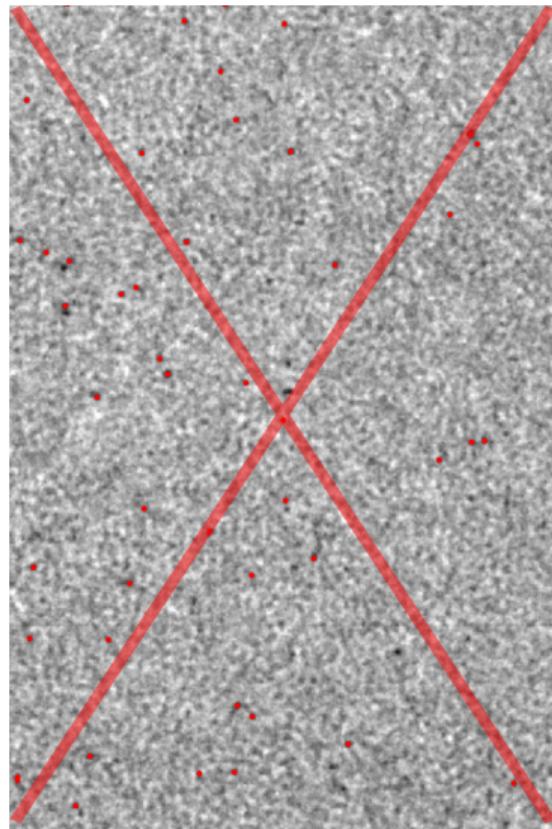


The system: A liquid fluidized bed

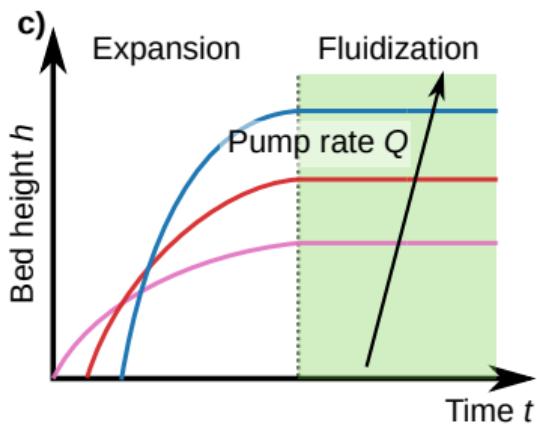
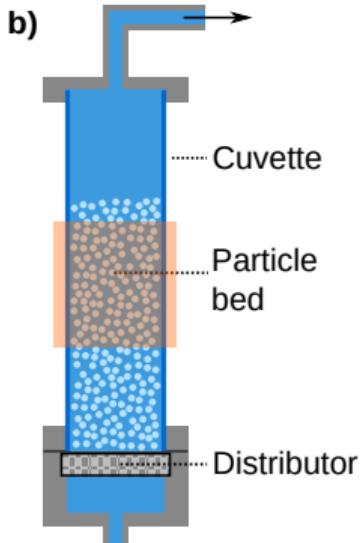
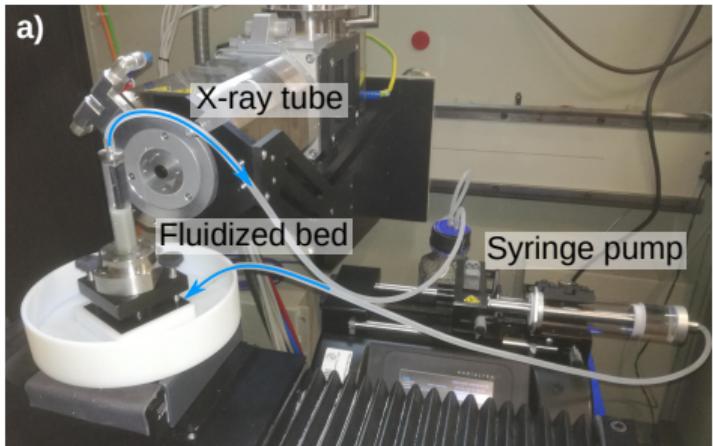


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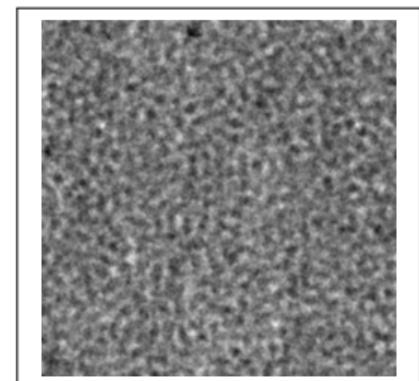
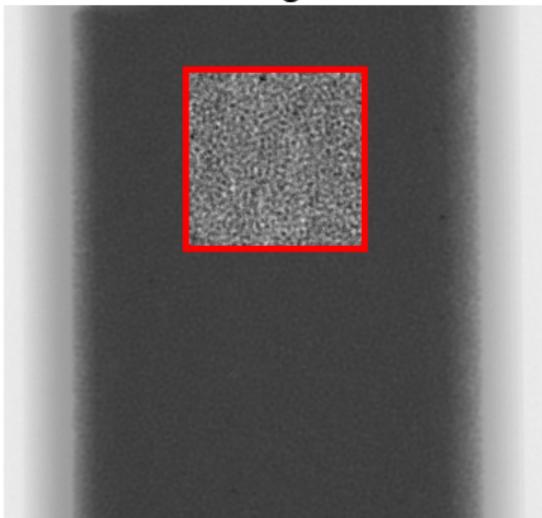


The system: A liquid fluidized bed



$$0.45 < \Phi < 0.56$$

Radiogram



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	

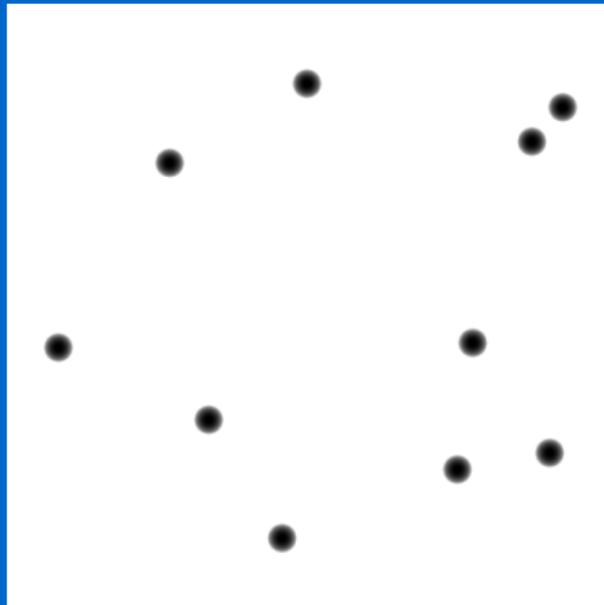
Extending Differential Dynamic Microscopy (DDM) to X-ray imaging

	up to now	this work
system	dispersion, gels	fluidized bed
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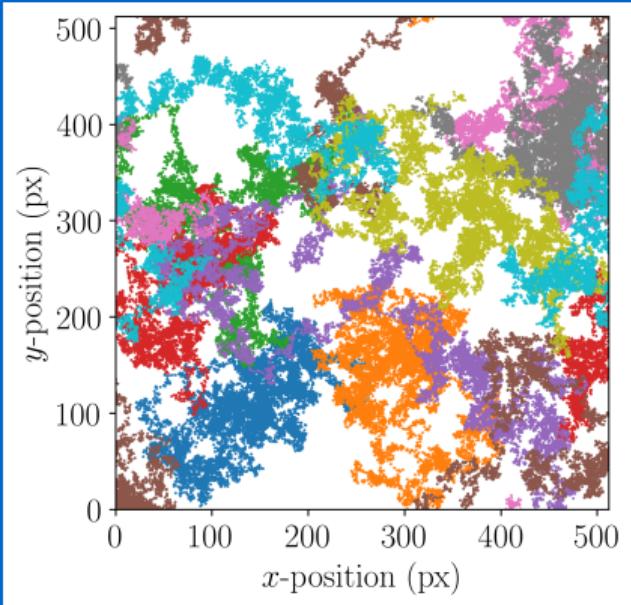
Digital Fourier Analysis of X-Ray Radiograms (X-DFA)

Introduction to Differential Dynamic Microscopy (DDM)

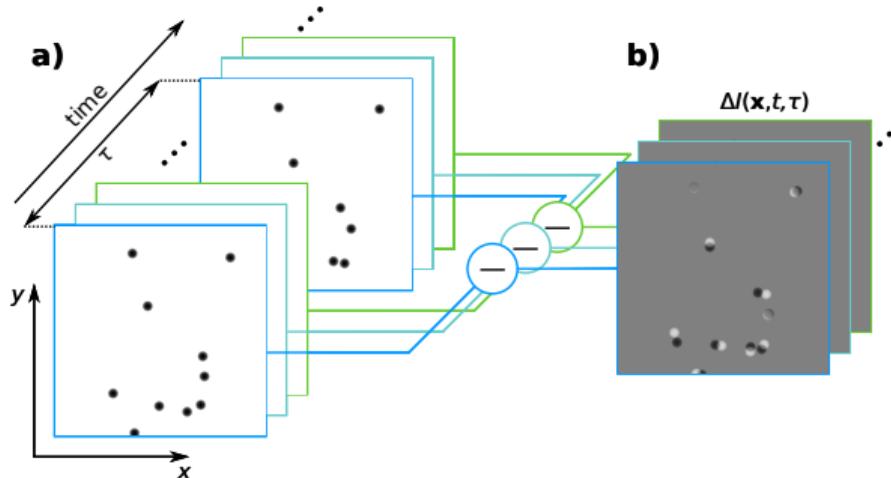
Synthetic radiograms



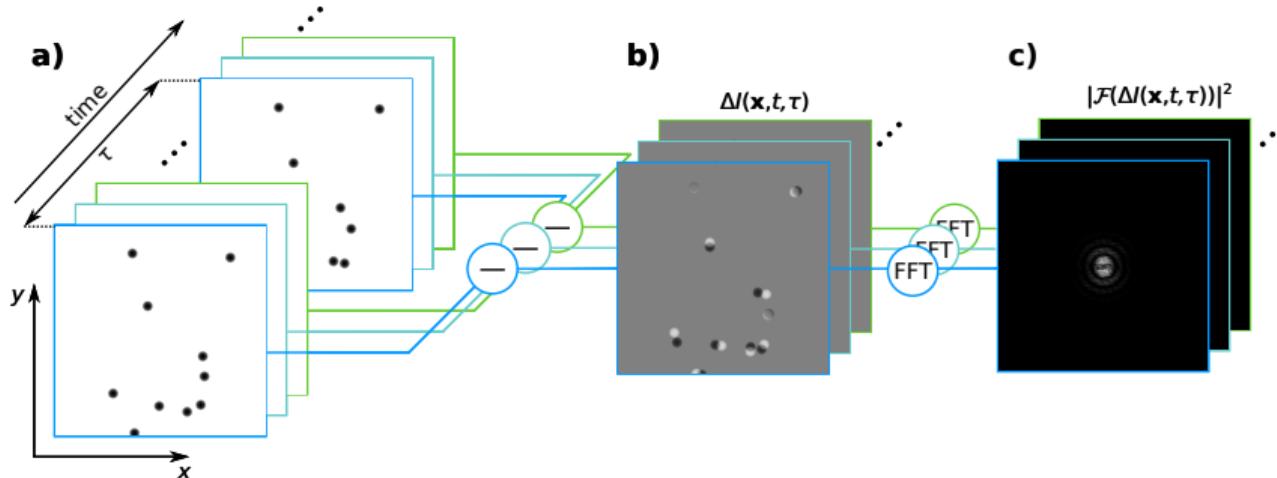
Particle trajectory



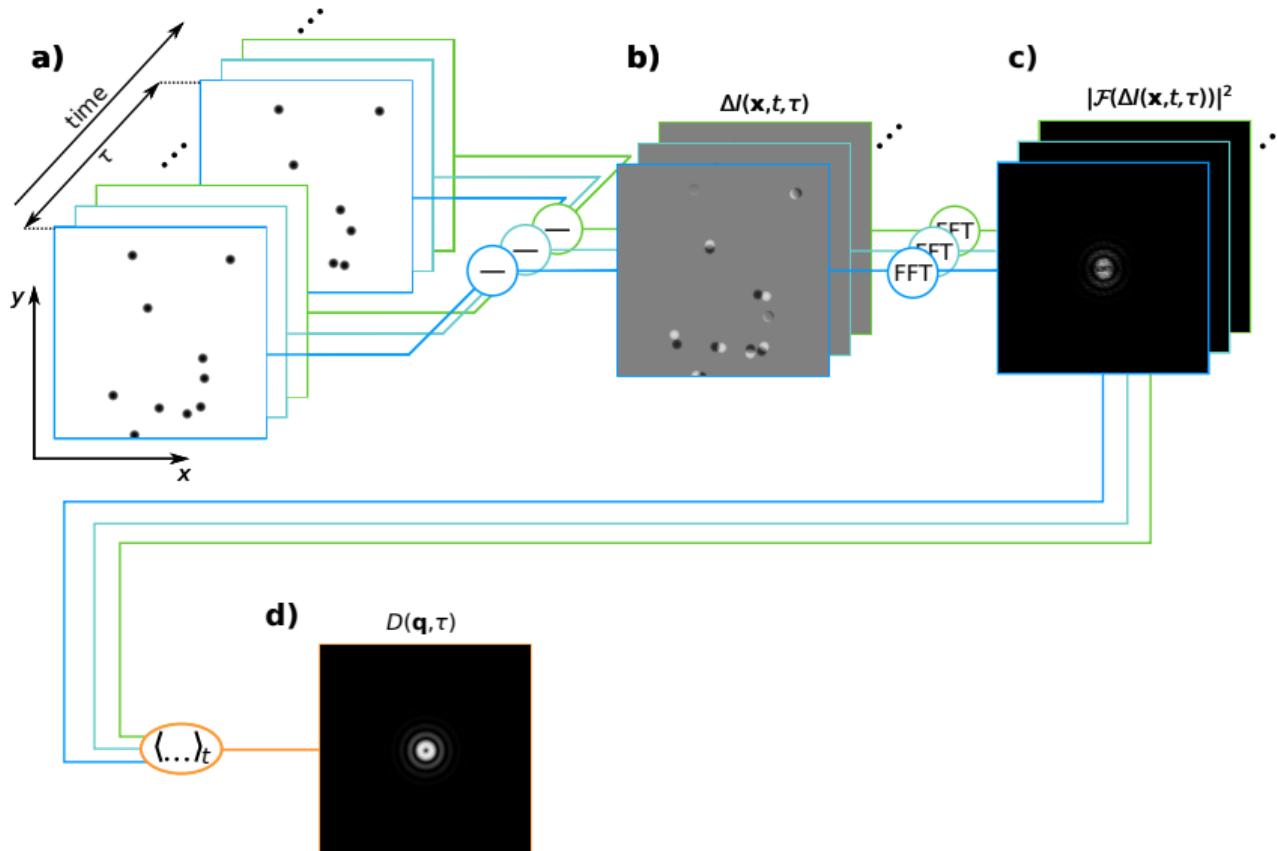
The image structure function $D(\mathbf{q}, \tau)$



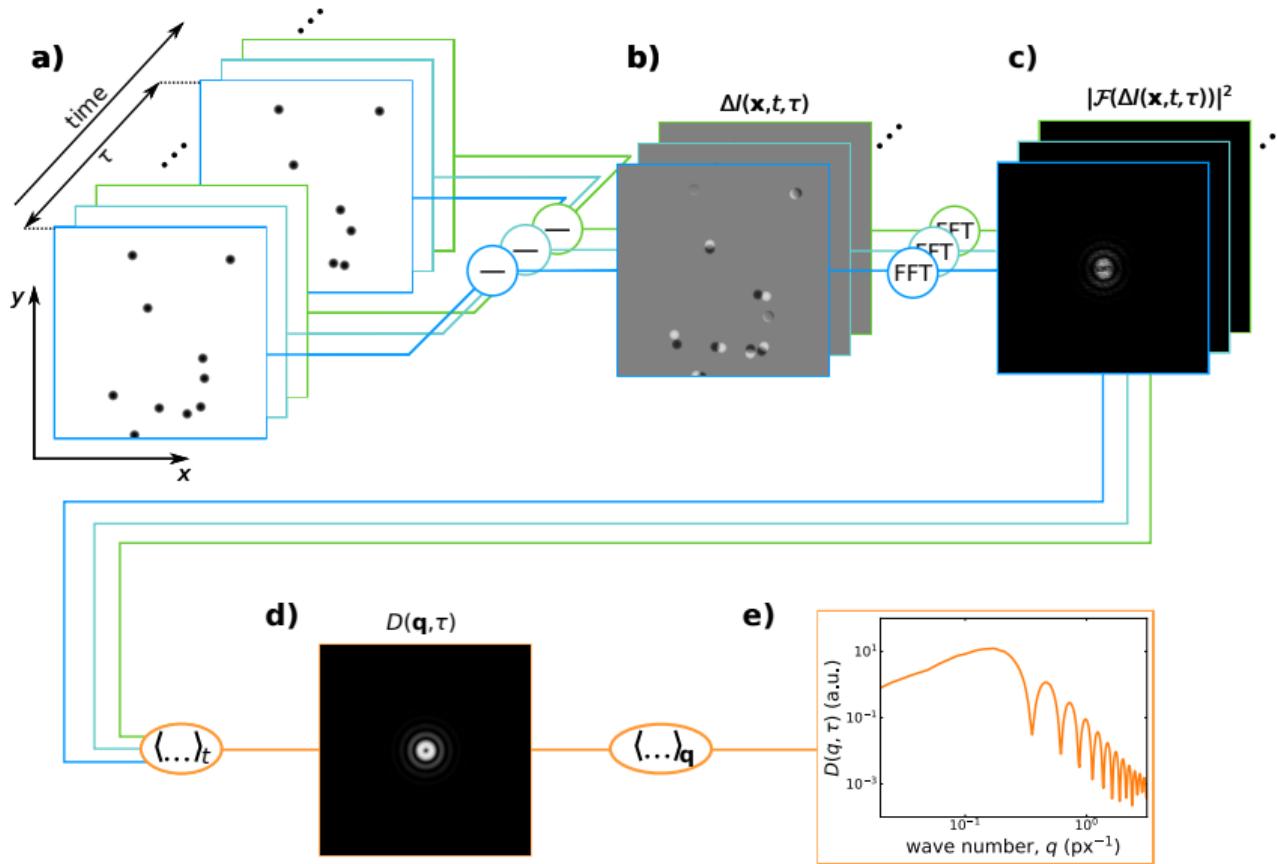
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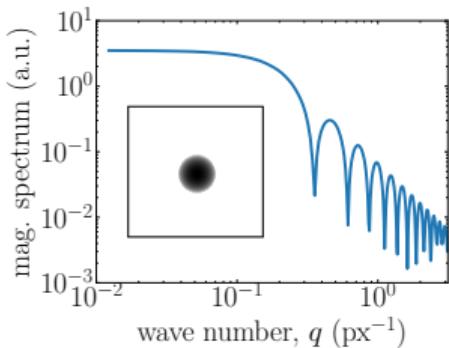
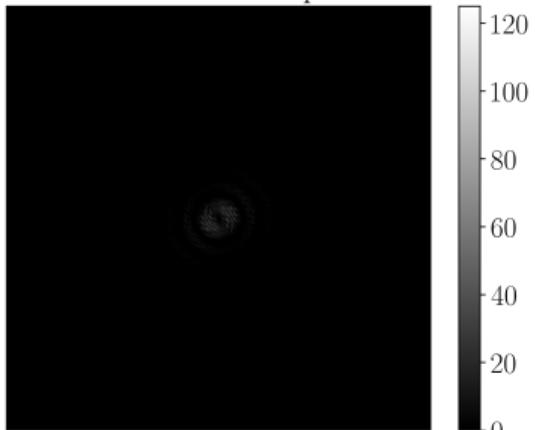


The image structure function $D(\mathbf{q}, \tau)$



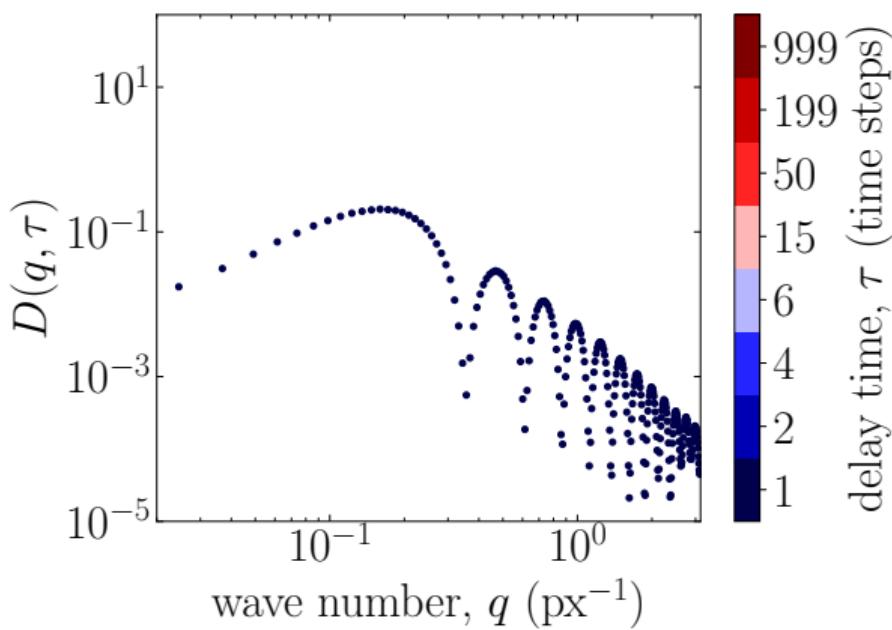
The image structure function $D(q, \tau)$

$\tau = 1$ time steps



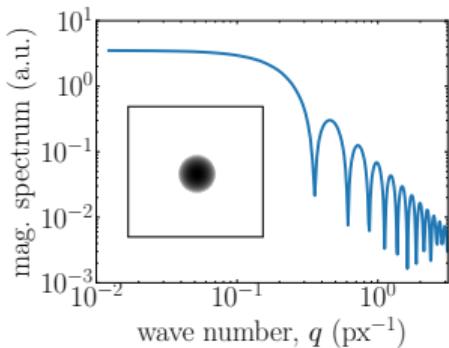
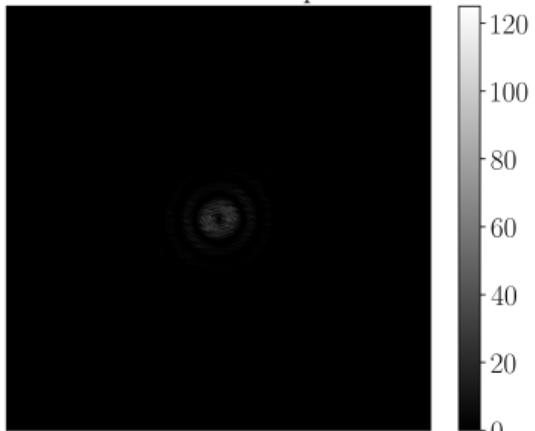
Time averaging: $D(\mathbf{q}, \tau) = \langle |\mathcal{F}(\Delta I)|^2 \rangle_t$

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



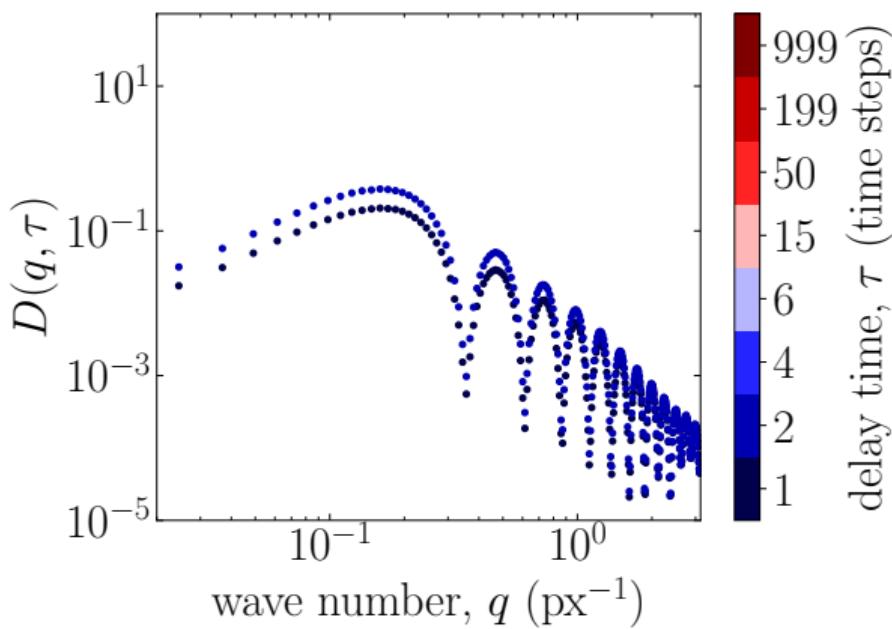
The image structure function $D(q, \tau)$

$\tau = 2$ time steps



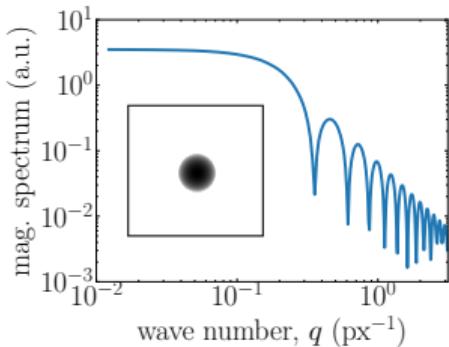
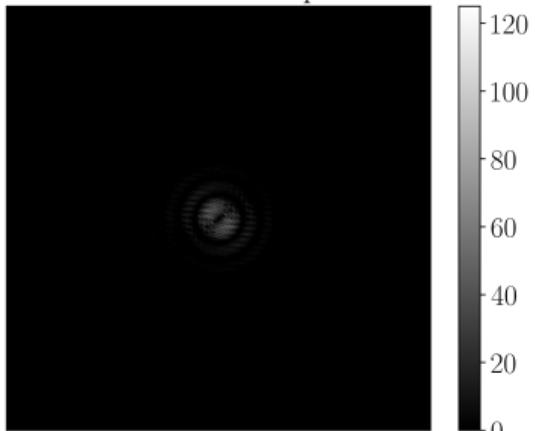
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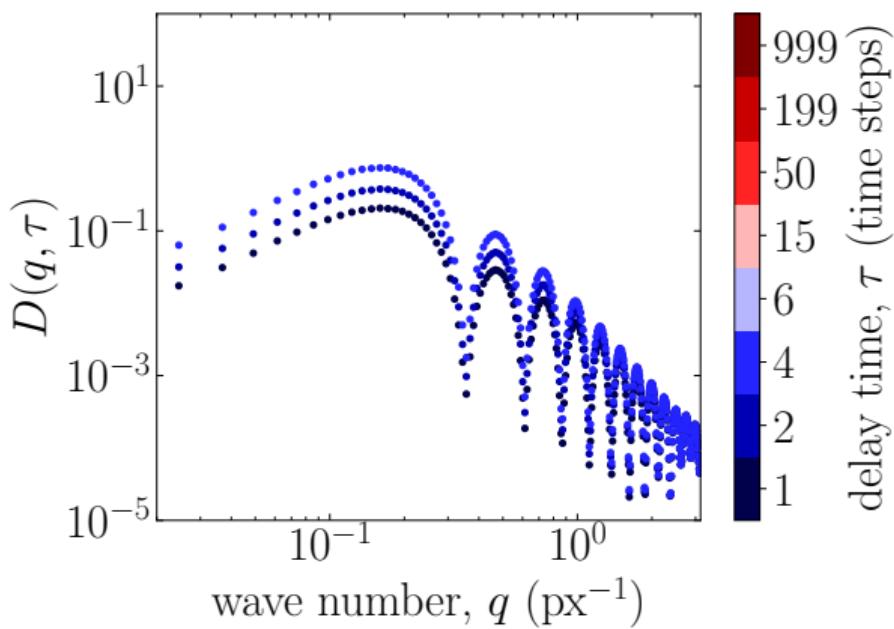
The image structure function $D(q, \tau)$

$\tau = 4$ time steps



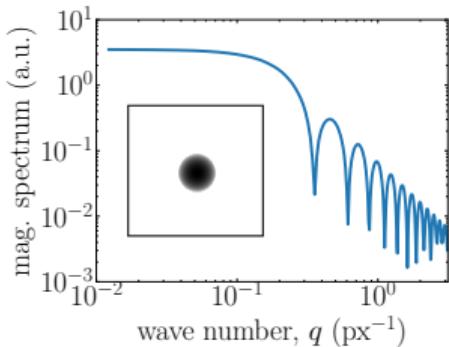
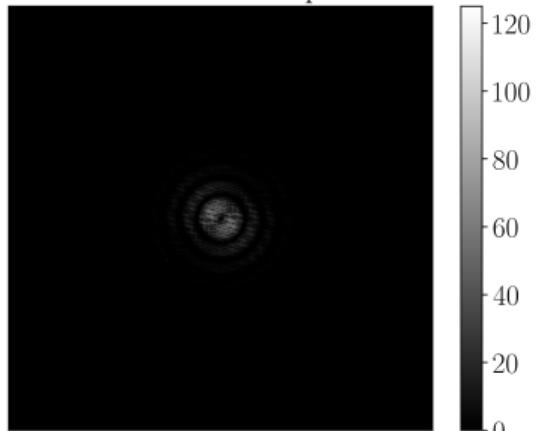
Time averaging: $D(\mathbf{q}, \tau) = \langle |\mathcal{F}(\Delta I)|^2 \rangle_t$

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



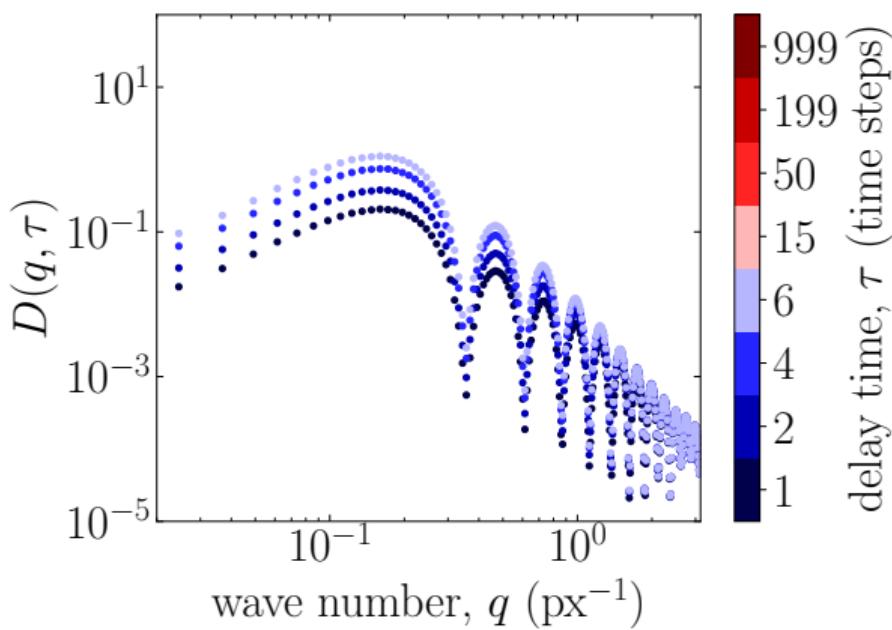
The image structure function $D(q, \tau)$

$\tau = 6$ time steps

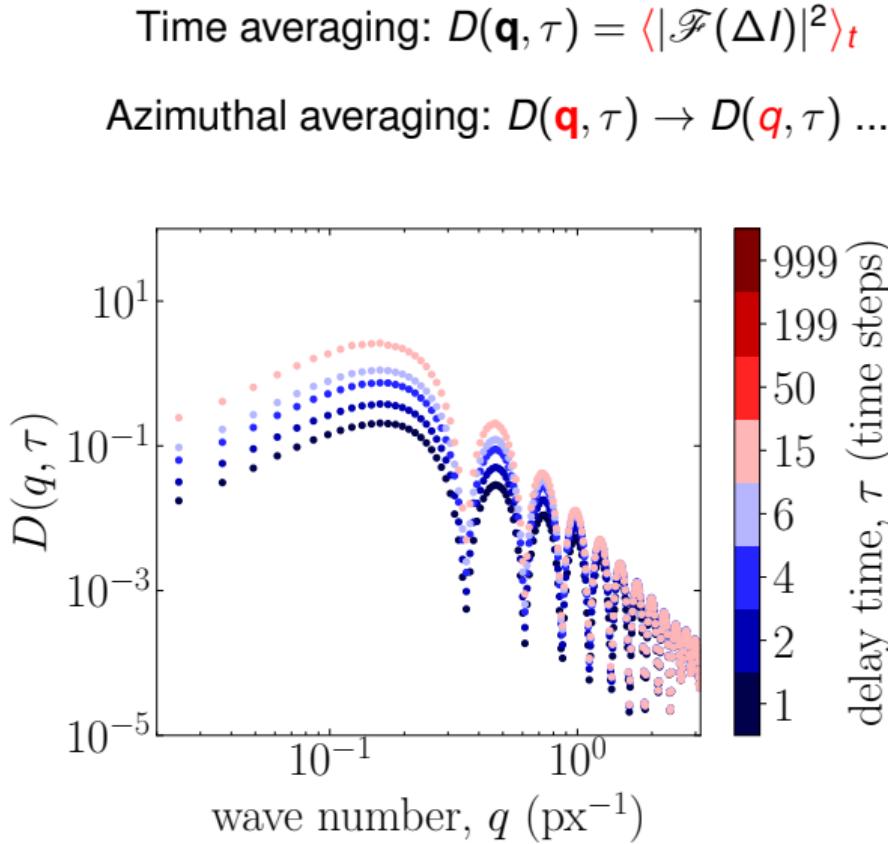
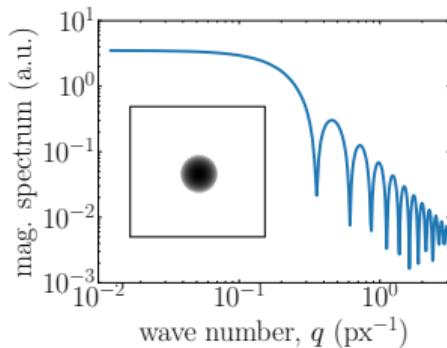
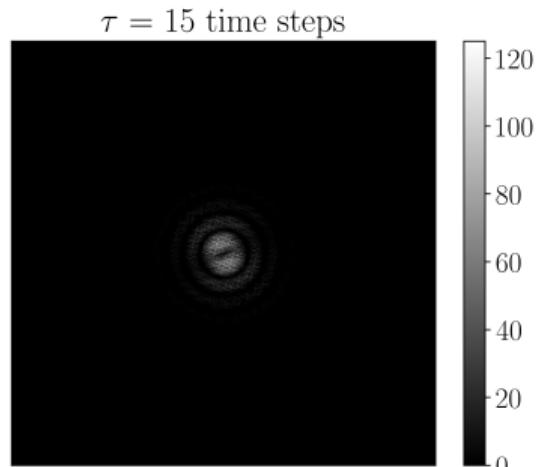


Time averaging: $D(\mathbf{q}, \tau) = \langle |\mathcal{F}(\Delta I)|^2 \rangle_t$

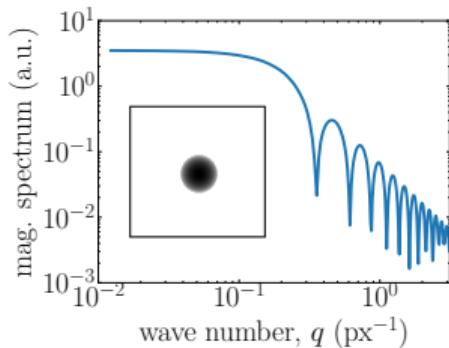
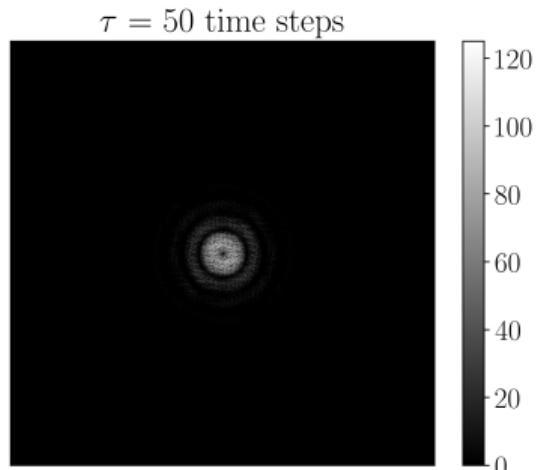
Azimuthal averaging: $D(\mathbf{q}, \tau) \rightarrow D(\mathbf{q}, \tau) \dots$



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

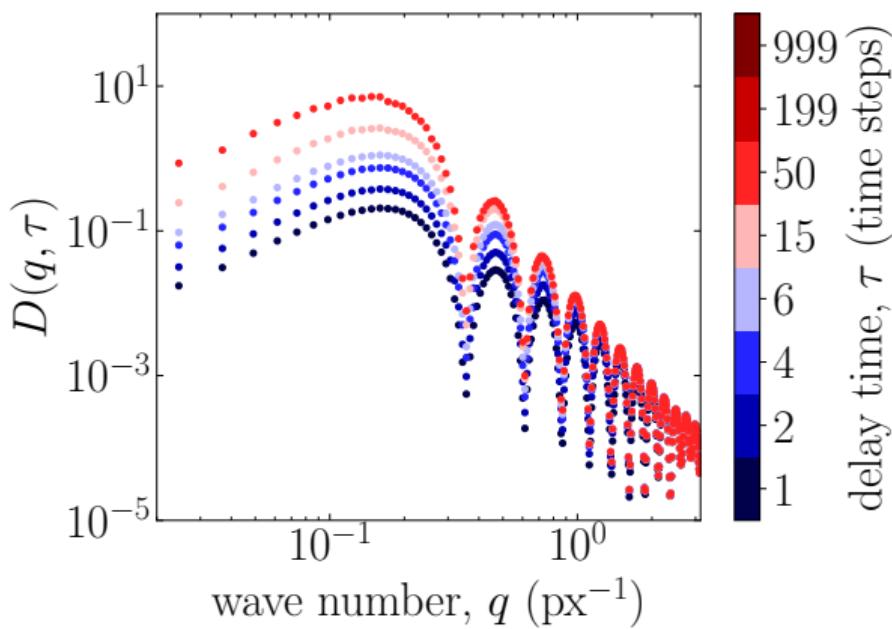


The image structure function $D(q, \tau)$

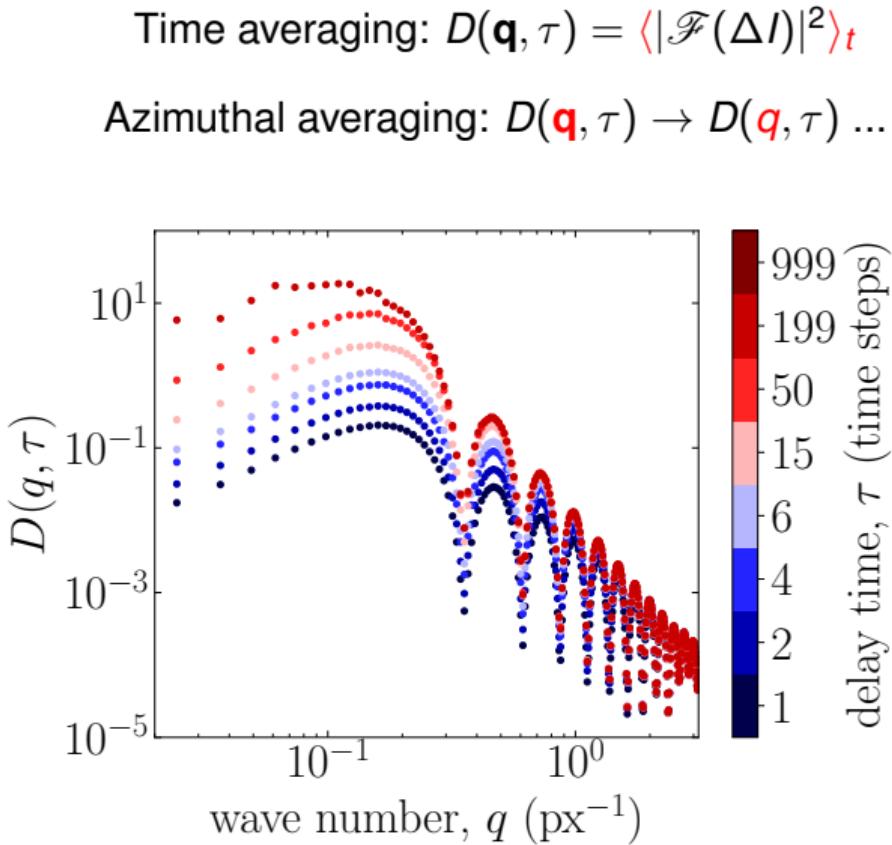
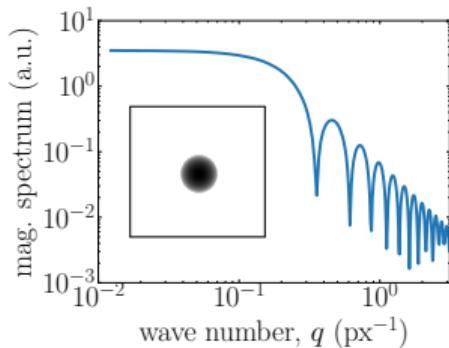
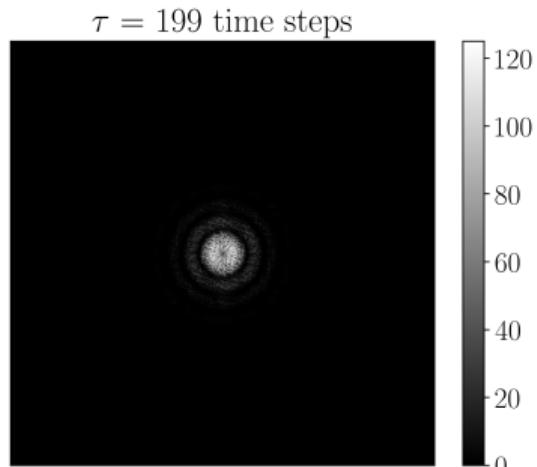


Time averaging: $D(\mathbf{q}, \tau) = \langle |\mathcal{F}(\Delta I)|^2 \rangle_t$

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

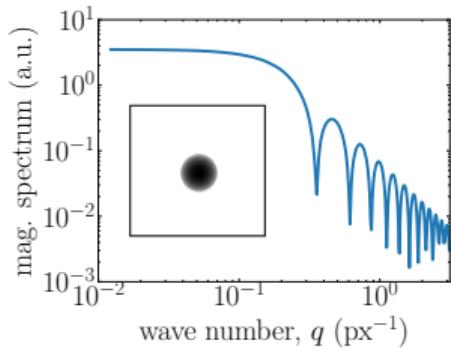
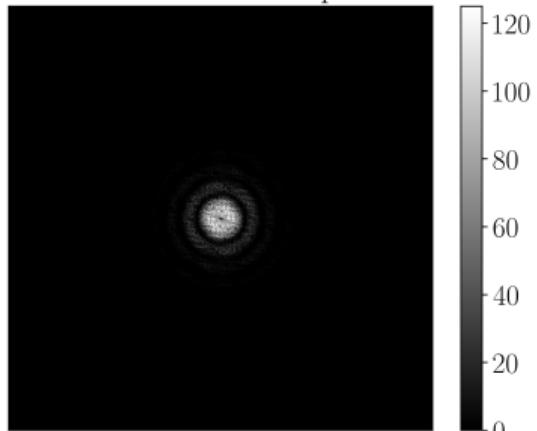


The image structure function $D(q, \tau)$



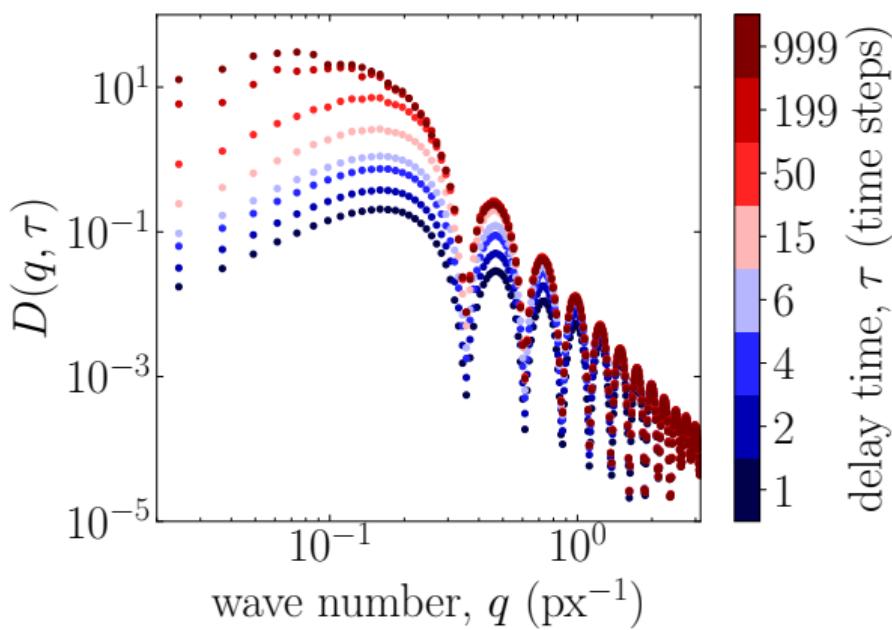
The image structure function $D(q, \tau)$

$\tau = 999$ time steps

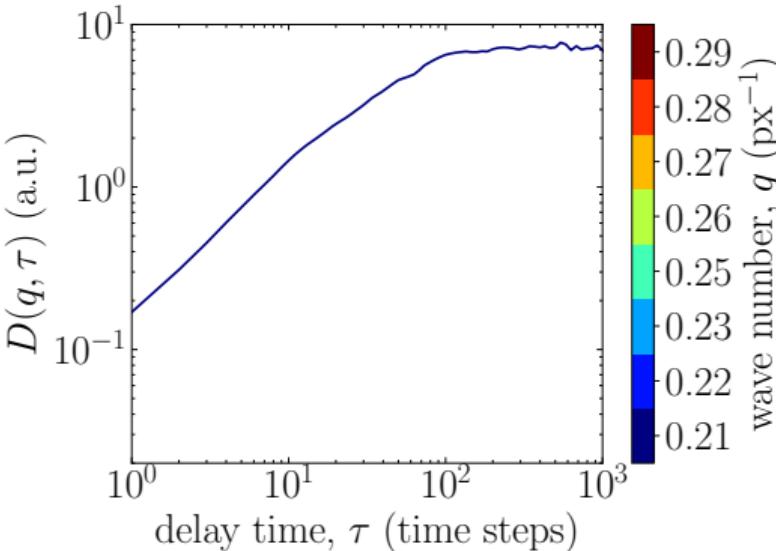
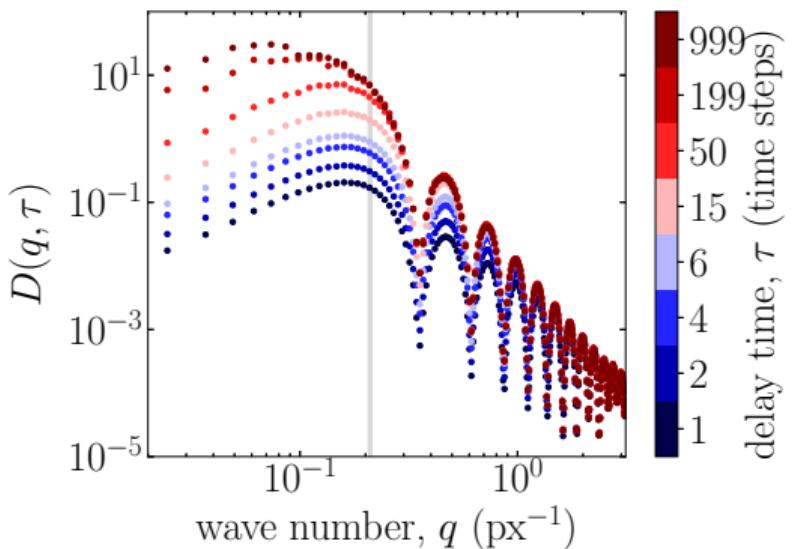


Time averaging: $D(\mathbf{q}, \tau) = \langle |\mathcal{F}(\Delta I)|^2 \rangle_t$

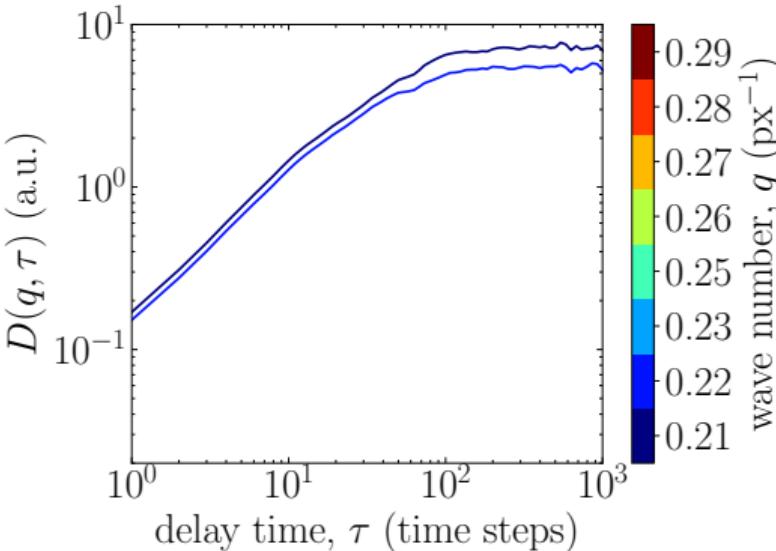
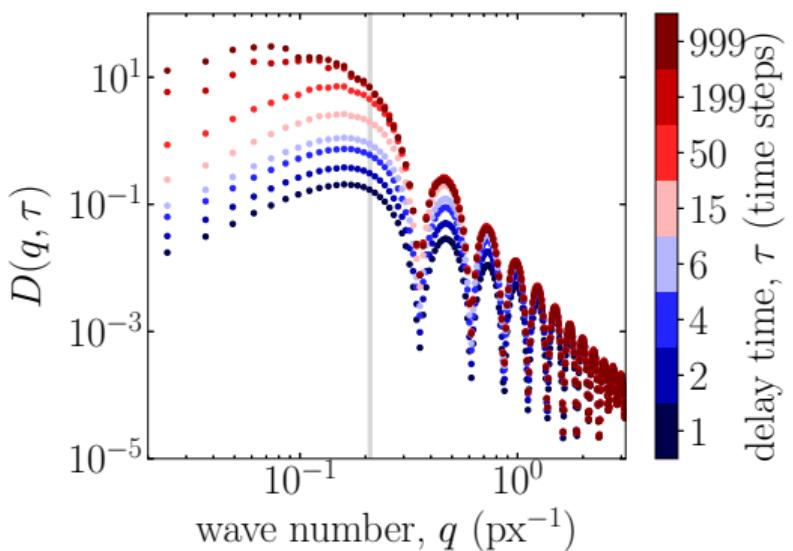
Azimuthal averaging: $D(\mathbf{q}, \tau) \rightarrow D(\mathbf{q}, \tau) \dots$



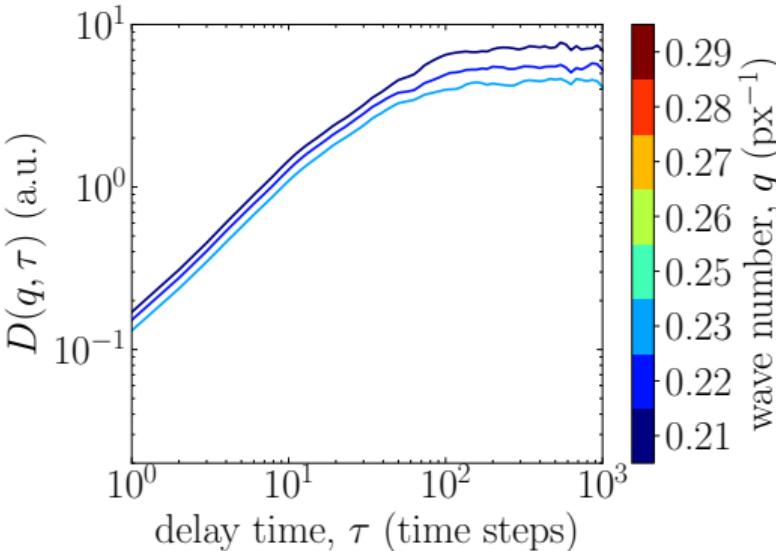
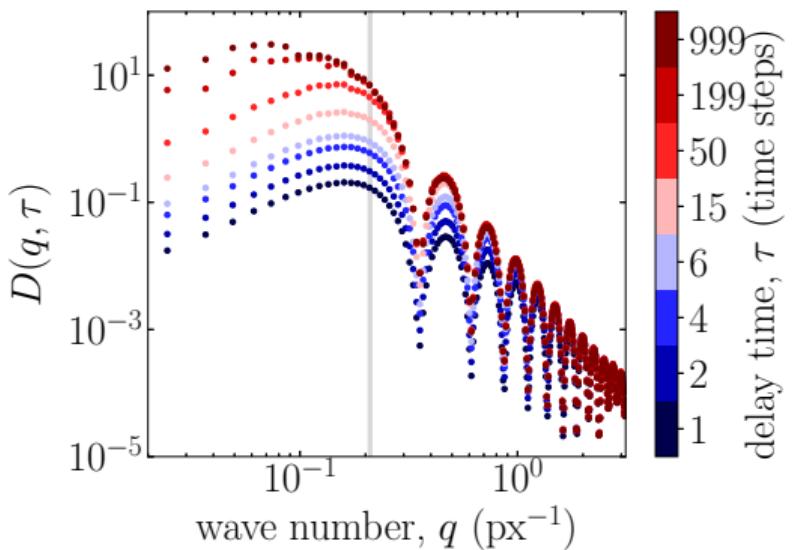
The image structure function $D(q, \tau)$



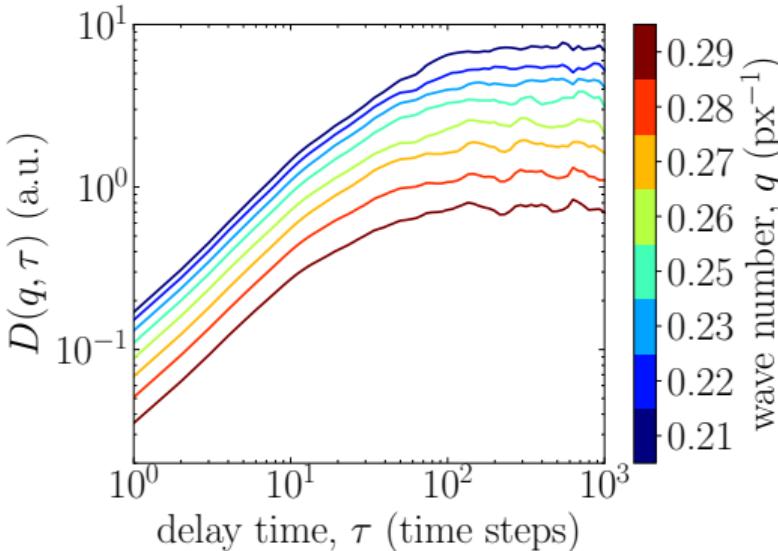
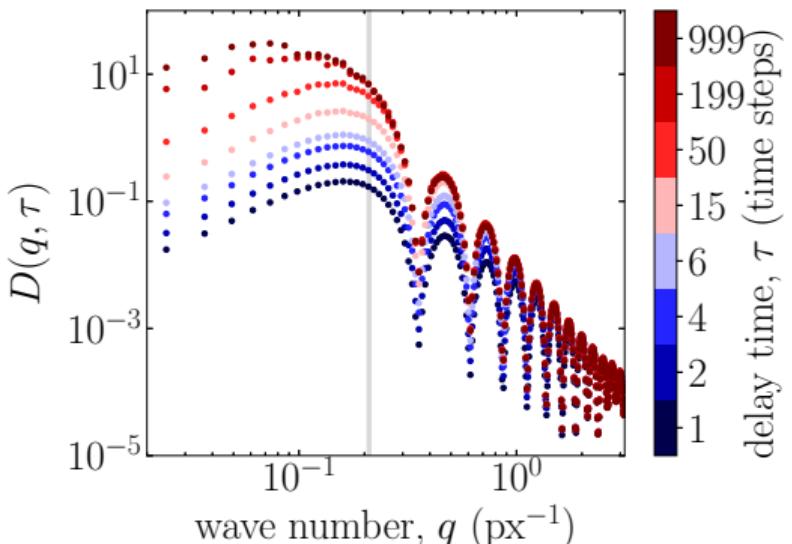
The image structure function $D(q, \tau)$



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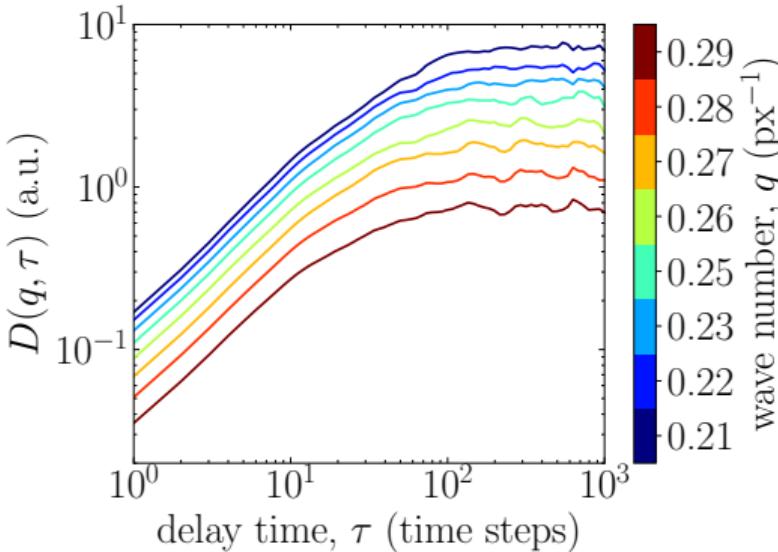
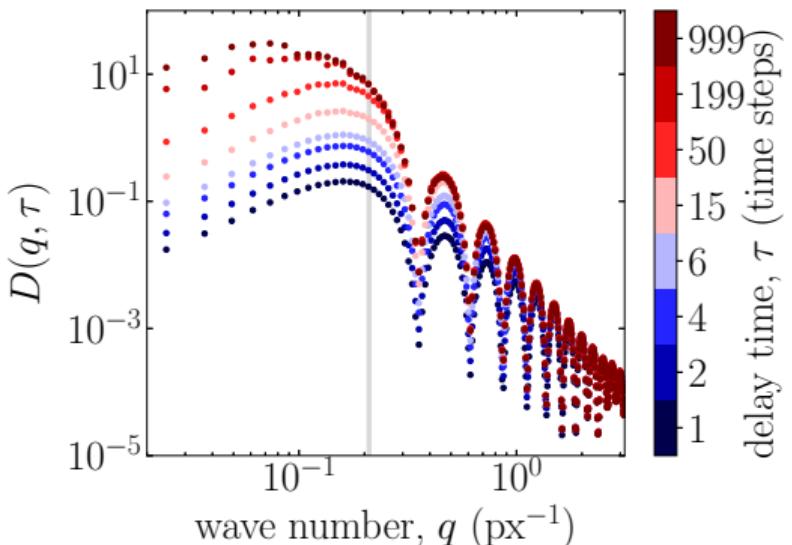


The image structure function $D(q, \tau)$

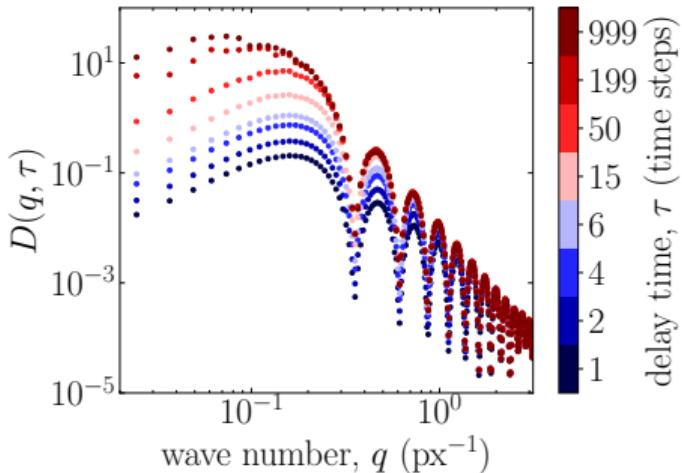


$$\begin{aligned} D(q, \tau) &= \left\langle |I(q, t + \tau) - I(q, t)|^2 \right\rangle_t \\ &= A(q) \left[1 - \frac{\left\langle I^*(q, t) I(q, t + \tau) \right\rangle_t}{\left\langle |I(q, t)|^2 \right\rangle_t} \right] + B(q) \end{aligned}$$

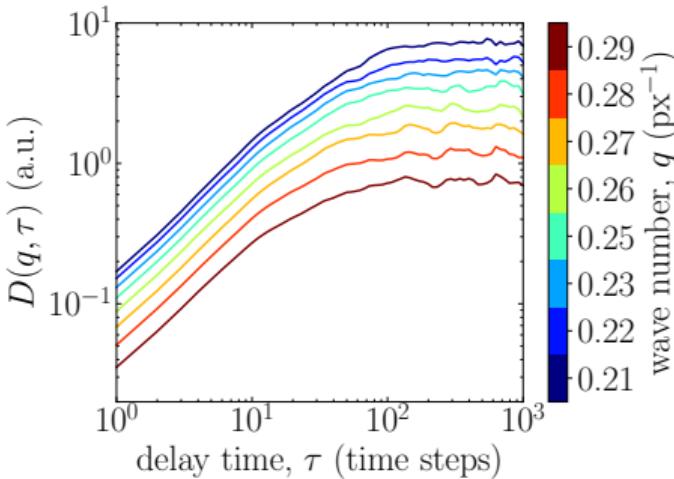
The image structure function $D(q, \tau)$



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



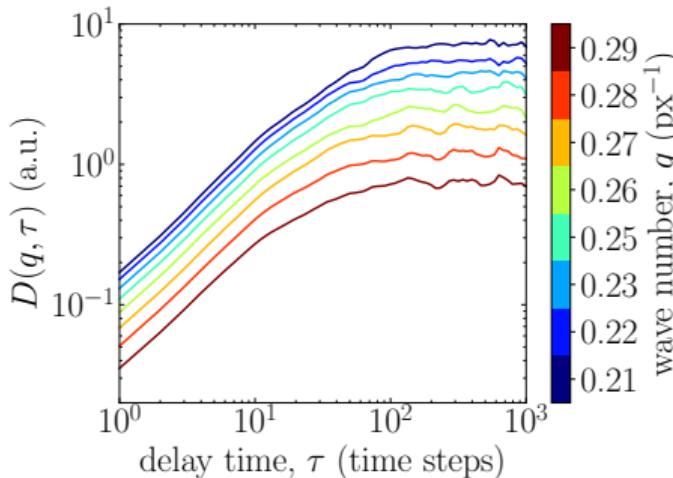
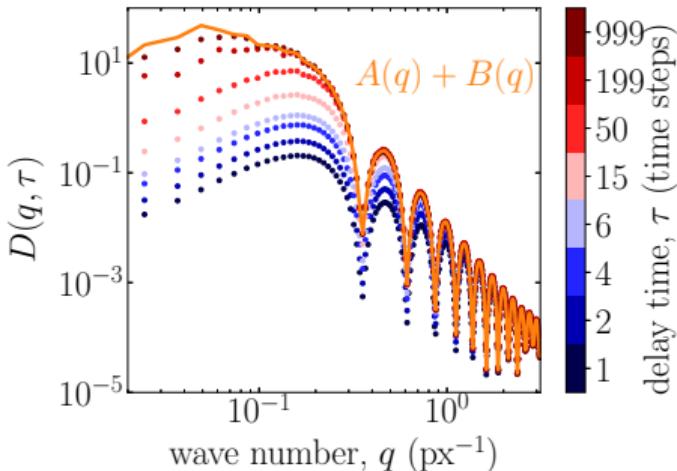
$$\begin{aligned}
 D(q, \tau) &= \left\langle |I(q, t + \tau) - I(q, t)|^2 \right\rangle_t \\
 &= A(q) \underbrace{\left[1 - \frac{\langle I^*(q, t) I(q, t + \tau) \rangle_t}{\langle |I(q, t)|^2 \rangle_t} \right]}_{\text{Image correlation function}} + B(q)
 \end{aligned}$$



Linear space invariant imaging

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

Intermediate scattering function



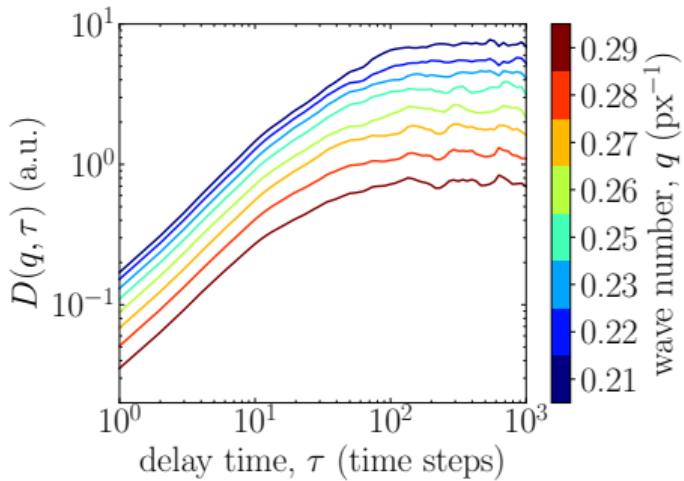
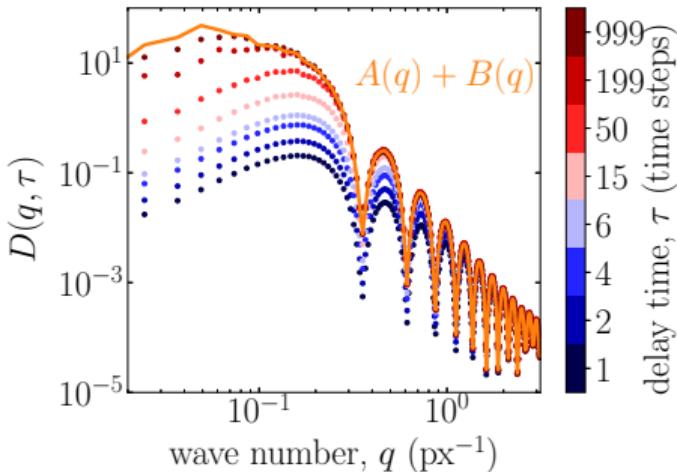
$$\begin{aligned}
 D(q, \tau) &= \left\langle |I(q, t + \tau) - I(q, t)|^2 \right\rangle_t \\
 &= A(q) \left[1 - \frac{\langle I^*(q, t) I(q, t + \tau) \rangle_t}{\langle |I(q, t)|^2 \rangle_t} \right] + B(q)
 \end{aligned}$$

- $D(q, \tau \rightarrow 0) = B(q) = 0$
- $D(q, \tau \rightarrow \infty) = A(q) + B(q)$

Linear space invariant imaging

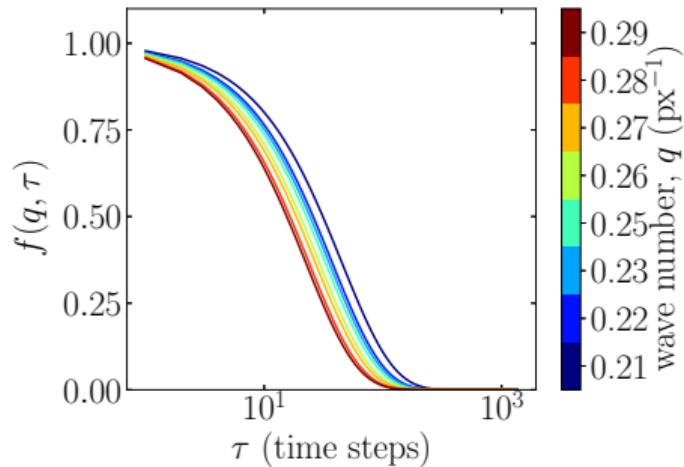
$$f(q, \tau) = \frac{\langle \rho^*(q, t) \rho(q, t + \tau) \rangle_t}{\langle |\rho(\mathbf{q}, t)|^2 \rangle_t}$$

Intermediate scattering function

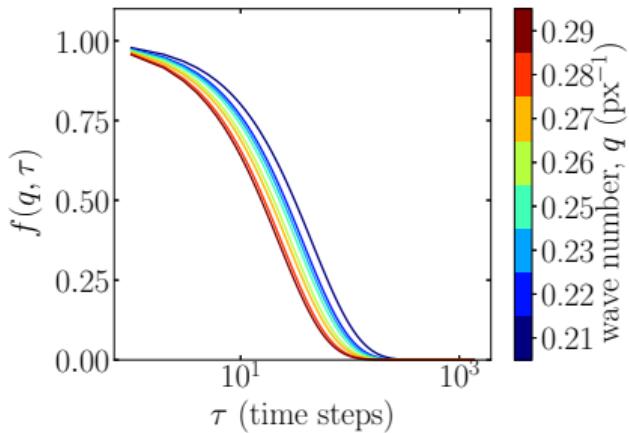


$$\begin{aligned} D(q, \tau) &= \left\langle |I(q, t + \tau) - I(q, t)|^2 \right\rangle_t \\ &= A(q) \left[1 - \frac{\langle I^*(q, t) I(q, t + \tau) \rangle_t}{\langle |I(q, t)|^2 \rangle_t} \right] + B(q) \end{aligned}$$

- $D(q, \tau \rightarrow 0) = B(q) = 0$
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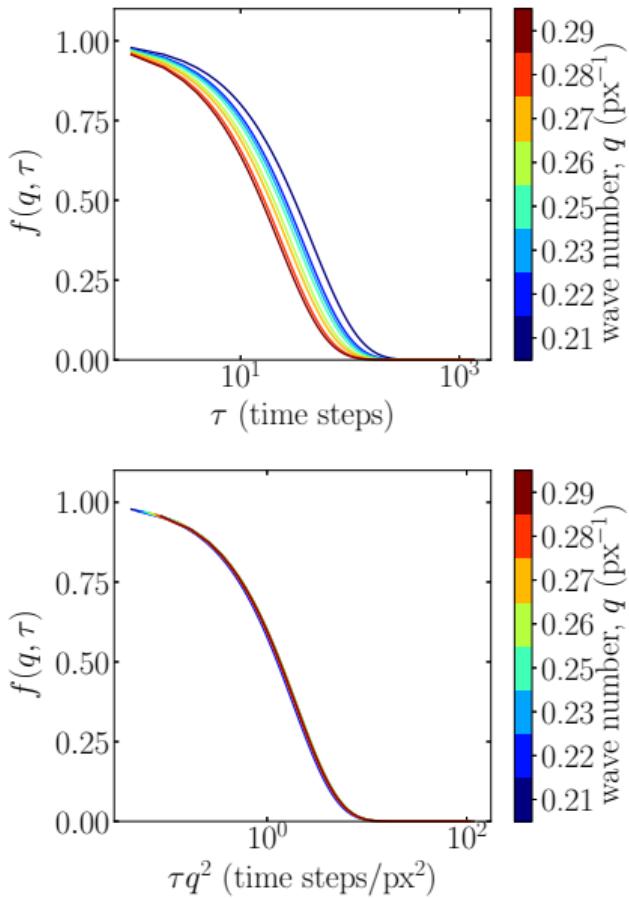


Intermediate scattering function $f(q, \tau)$

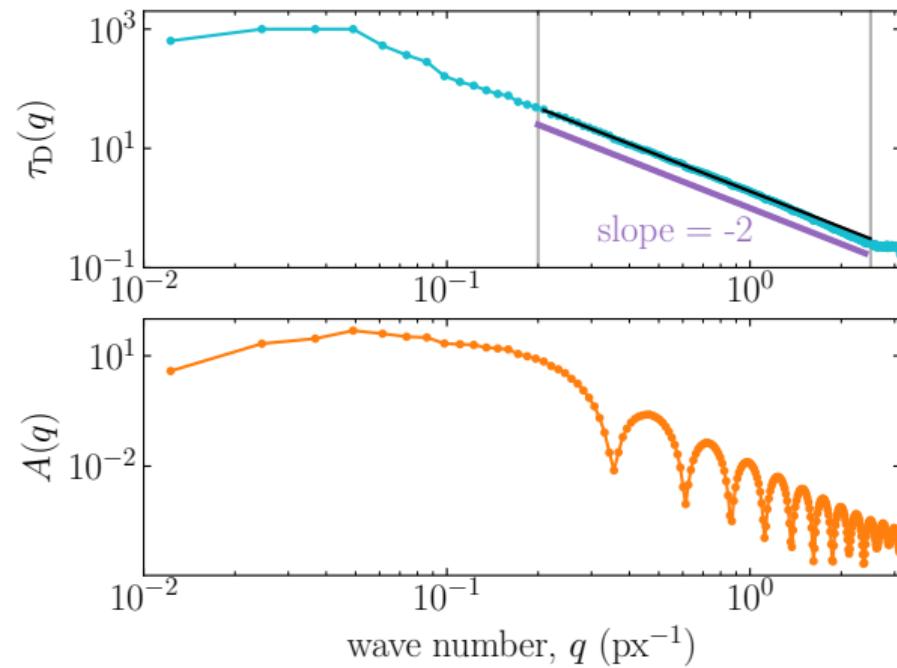


Brownian motion:
 $f(q, \tau) = \exp(-q^2\tau/\tau_D)$

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



Brownian motion:
 $f(q, \tau) = \exp(-q^2\tau/\tau_D)$

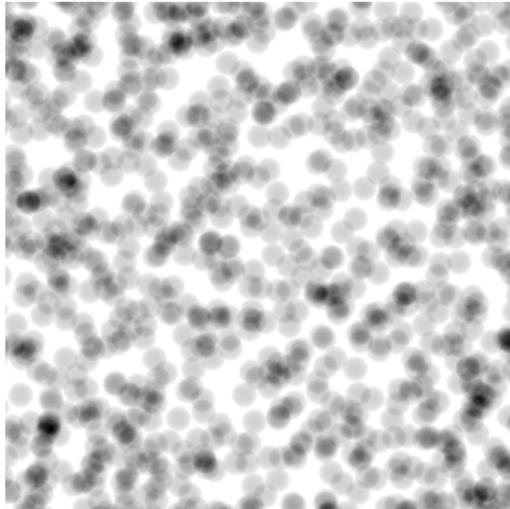


Accuracy of X-DFA: Varying the number of particles

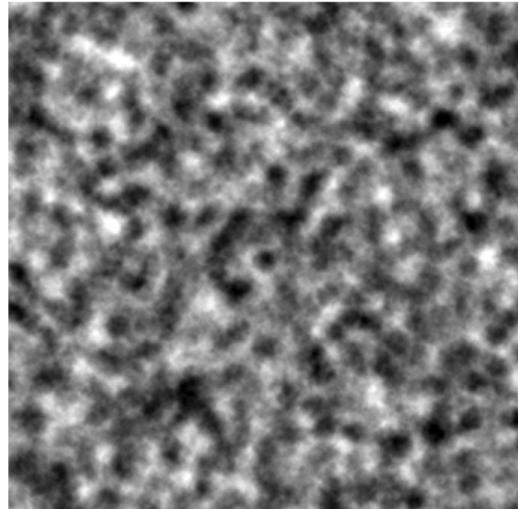
10 particles



1000 particles



100 000 particles



Deviation from the simulation input:

6%

2%

2%

PIV off by $\approx 650\%$