Topical Workshop on “Scintillation Screens and Optical Technology for Transverse Profile Measurements”

Krakow, Poland - April 1 to 3, 2019

Characterization of the spatial frequency response of a scintillator for beam size measurements using Heterodyne Near Field Speckles

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Outline

- The Heterodyne Near Field Speckle (HNFS) technique
- The role of the scintillator
- Recent results at ALBA
- Conclusions and perspectives

The Heterodyne Near Field Speckle (HNFS) technique

General framework

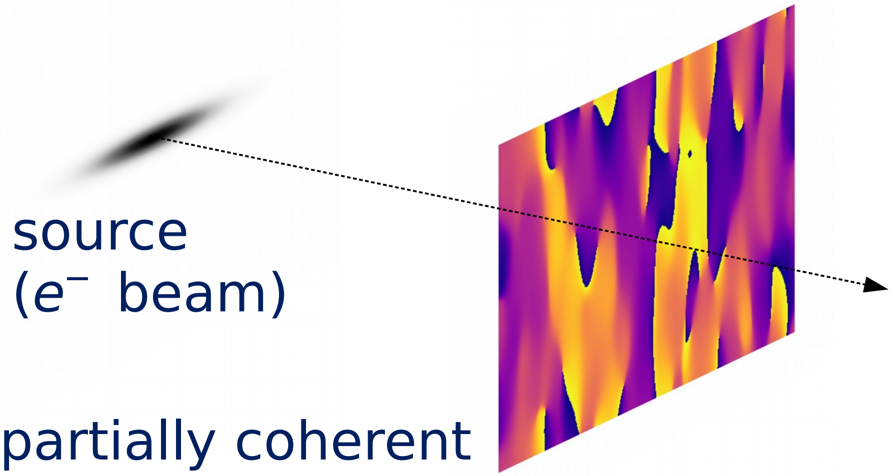
The Heterodyne Near Field Speckle (HNFS) technique

The role of the scintillator

Recent results at ALBA

Conclusions and perspectives

Interferometric beam size measurements



source
(e^- beam)

partially coherent
X-ray SR

Complex Coherence Factor **(CCF)**:

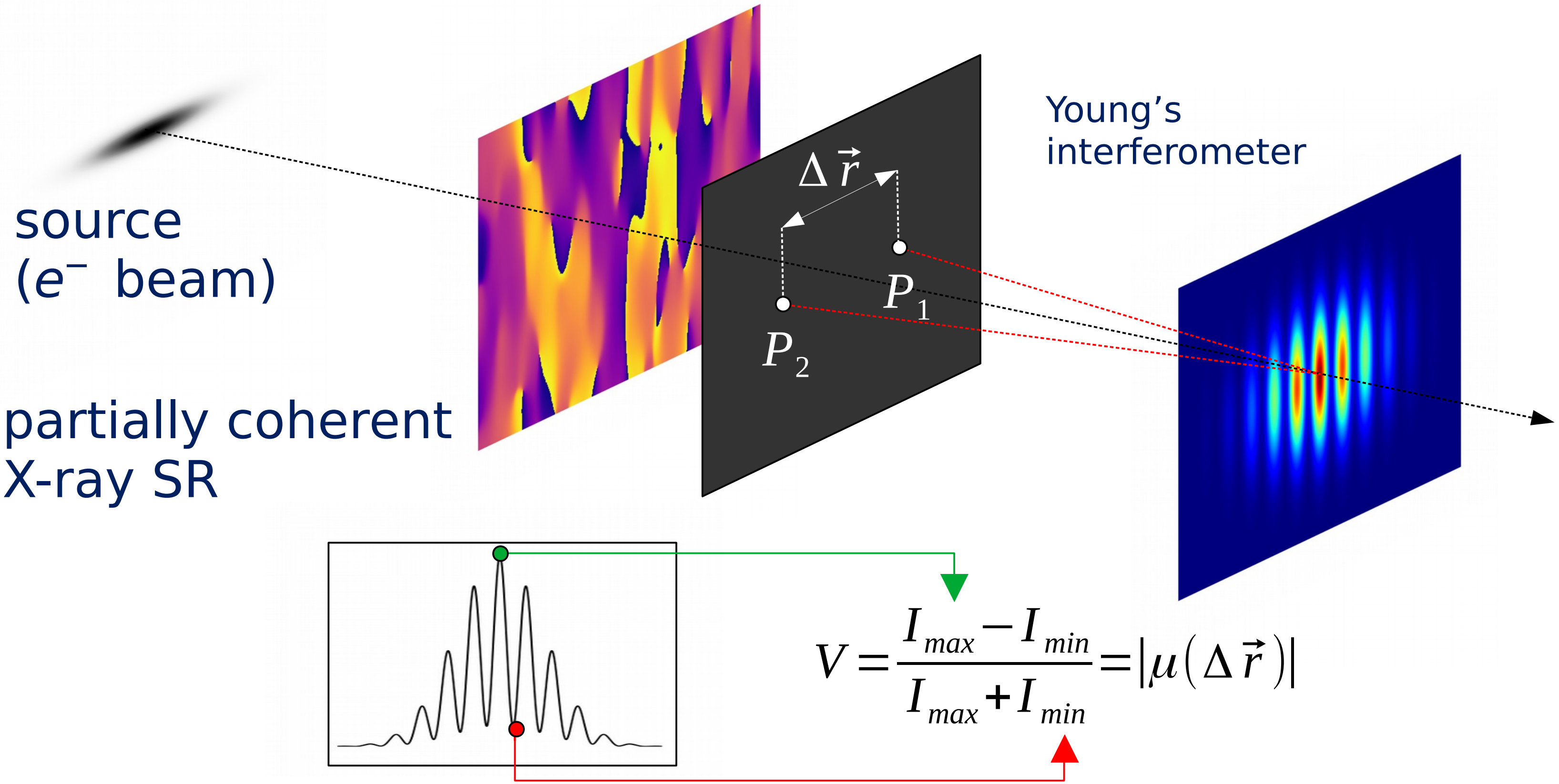
$$\mu(\Delta\vec{r}) = \frac{\langle E(\vec{r})E^*(\vec{r}+\Delta\vec{r})\rangle}{\sqrt{\langle I(\vec{r})\rangle\langle I(\vec{r}+\Delta\vec{r})\rangle}}$$

Free-space propagation,
Van Cittert – Zernike theorem:

source intensity distribution $\xrightarrow{\text{FT}}$ radiation CCF

General framework

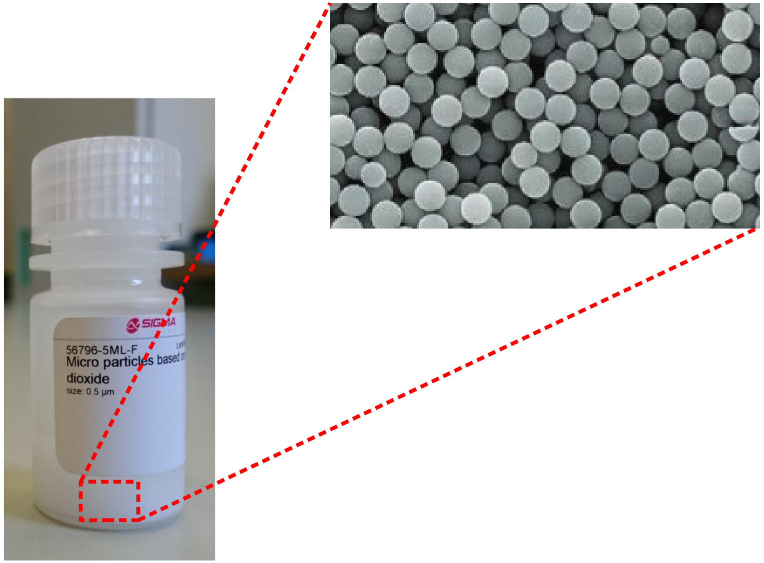
Interferometric beam size measurements

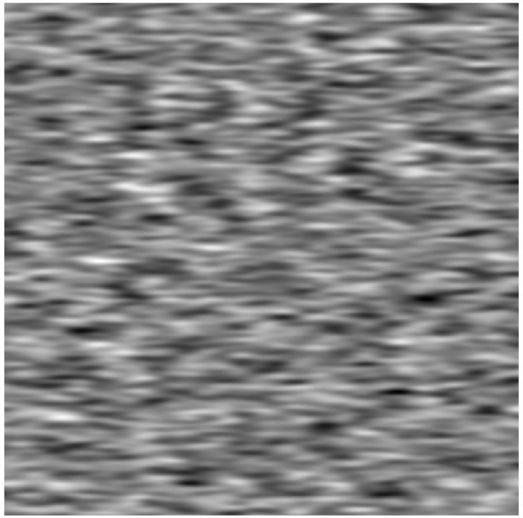


$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = |\mu(\Delta\vec{r})|$$

Colloids

Colloids: a **<u>cloud</u>** of spherical particles suspended in water, **<u>randomly moving and wiggling</u>**, generating a **<u>stochastic, noisy-like</u>** intensity distribution known as speckles.





Single-particle scattering

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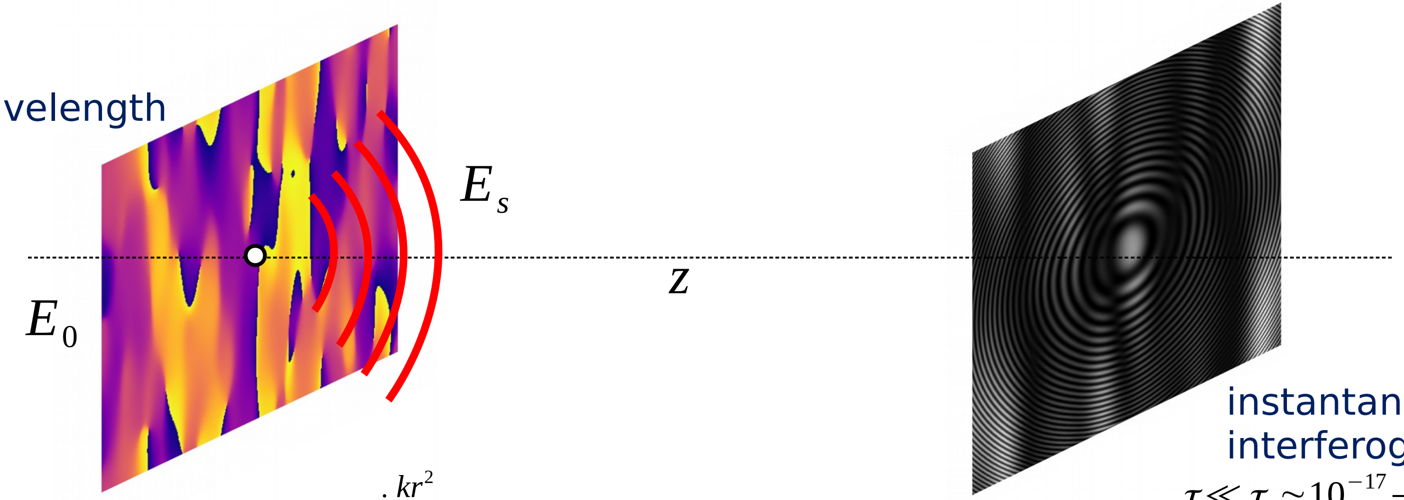
$k = \frac{2\pi}{\lambda}$

$\lambda \rightarrow$ wavelength



instantaneous interferogram

$\tau \ll \tau_c \sim 10^{-17} - 10^{-14}$ s

$$E_s(\vec{r}, z) \propto E_0(\vec{0}) \frac{e^{ikz} e^{i\frac{kr^2}{2z}}}{z}$$

$$\underbrace{|E_s| \ll |E_0|}_{\text{heterodyne conditions}} \Rightarrow I = |E_0 + E_s|^2 = |E_0|^2 + 2\Re\{\underbrace{E_0 E_s^*}_{\text{heterodyne term}}\} + \underbrace{\cancel{|E_s|^2}}_{\text{homodyne term}}$$

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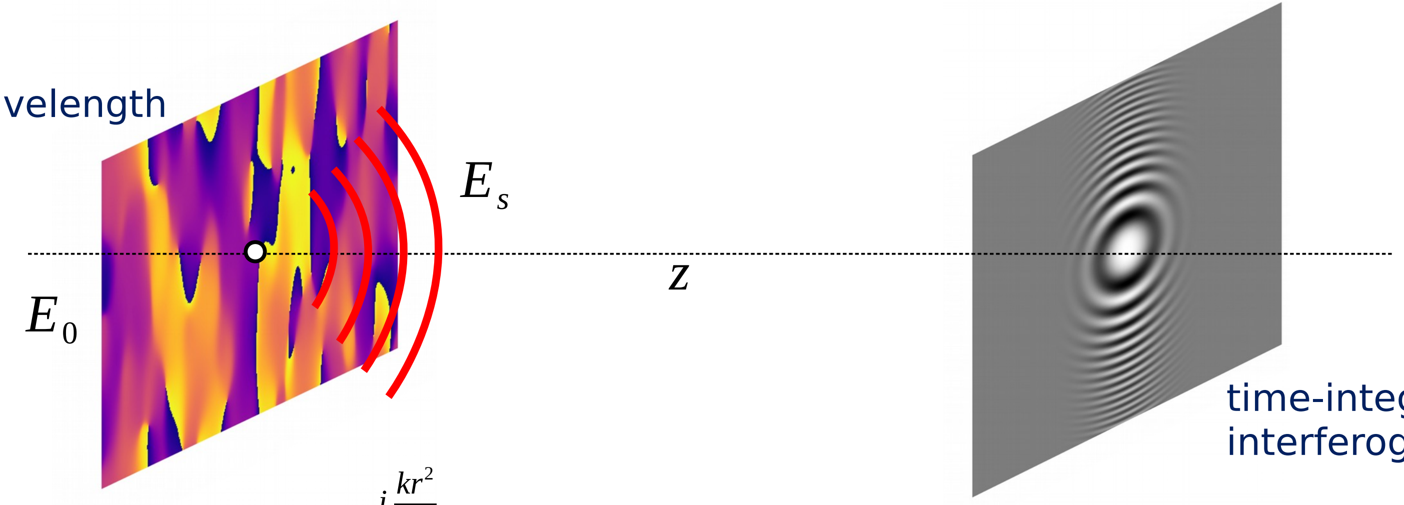
$k=\frac{2\pi}{\lambda}$

λ → wavelength



$$E_s(\vec{r}, z) \propto E_0(\vec{0})\,\frac{e^{ikz}\, e^{i\frac{kr^2}{2z}}}{z}$$

$$\Re\left\{\left\langle E_0 E_s^* \right\rangle\right\} \propto \left|\mu(\Delta\vec{r})\right| \cos\left[\frac{k\,\Delta r^2}{2z}\right]$$

Scattering from a single particle: paradigmatic layout to probe coherence between a selected point (the position of the particle) and **all** the others

Many-particles scattering

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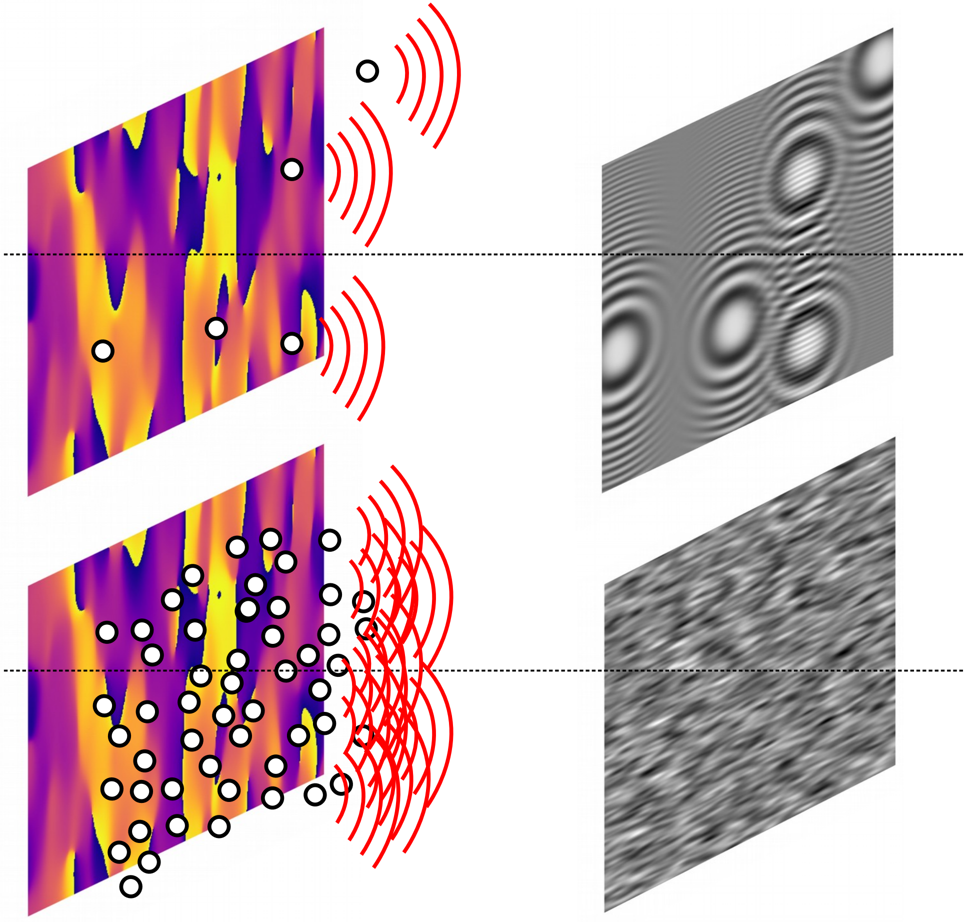

$$E_s(\vec{r},z) \propto \sum_{i=1}^{N} E_{s,i}(\vec{r},z)$$

$$\Re\left\{\left\langle E_0 E_s^{*}\right\rangle\right\} = \sum_{i=1}^{N} \Re\left\{\left\langle E_0 E_{s,i}^{*}\right\rangle\right\}$$

Heterodyne speckles: **intensity sum** of many **equal** single-particle **interference images**

The power spectrum

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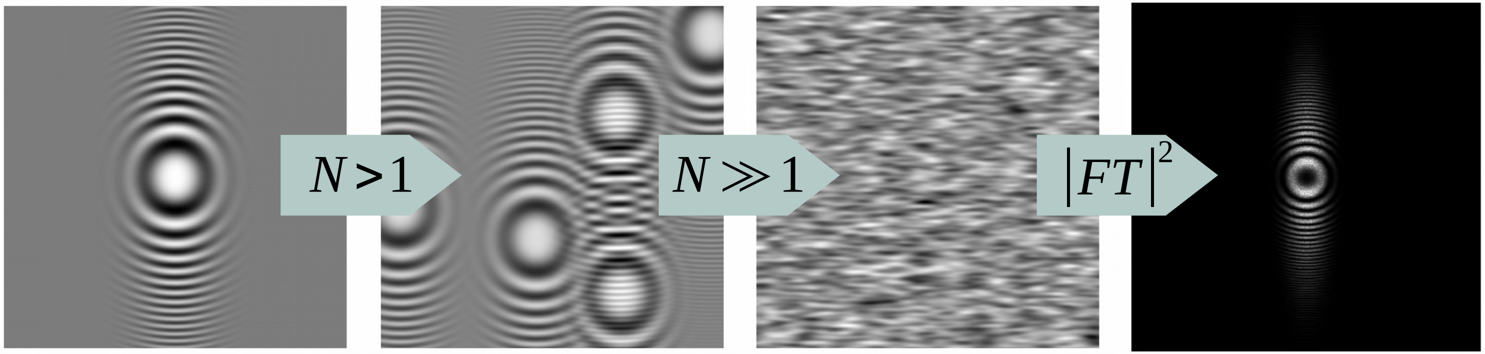

$$I(\vec{q})=T(q)C(\vec{q})$$

Power spectrum

$$C(\vec{q})=|\mu(\vec{q})|^2$$

Radiation CCF

$$T(q)=2\sin^2\left[\frac{zq^2}{2k}\right]$$

Talbot Transfer Function (TTF)

Spatial power spectrum of heterodyne speckles **directly** provides the interferometric information on **2D transverse coherence**

The spatial master curve

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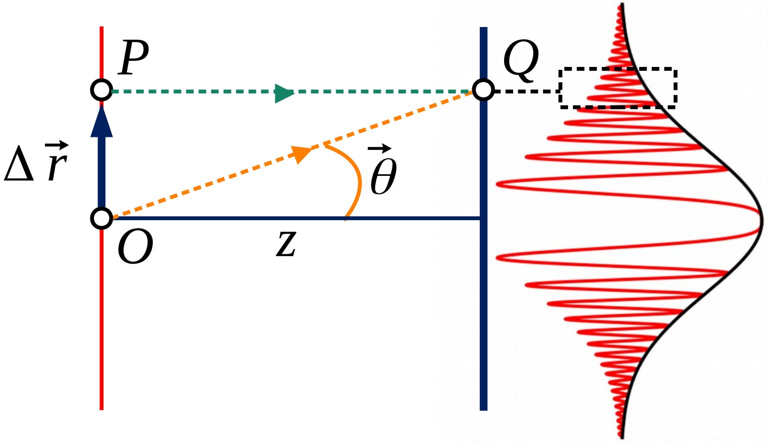
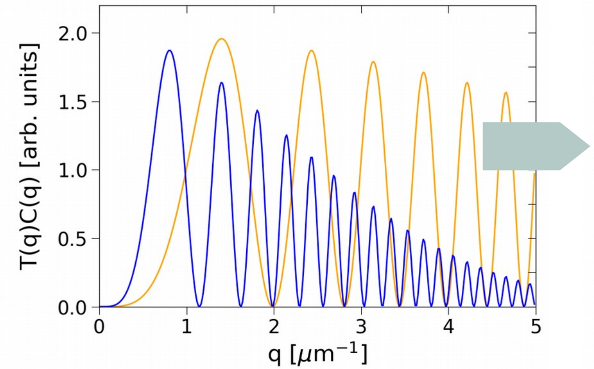


$\vec{q} = k\,\vec{\theta}$

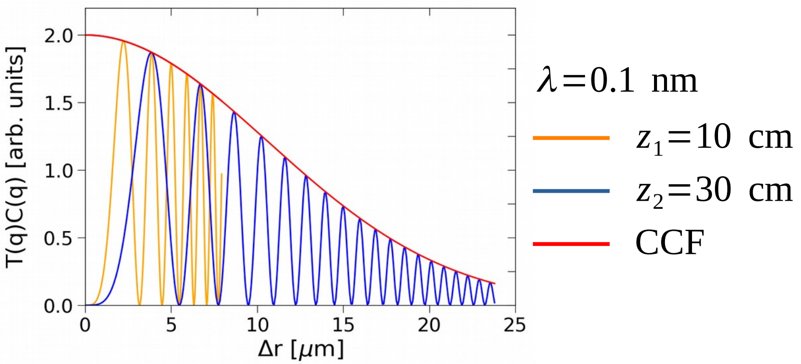
$$\boxed{\Delta\vec{r} = z\,\vec{\theta} = z\,\frac{\vec{q}}{k}}$$

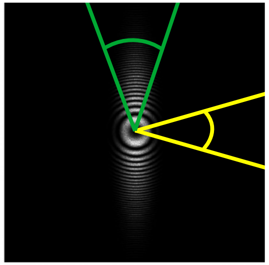
Spatial scaling

simulations



simulations





The role of the scintillator

HNFS @ NCD-SWEET (ALBA)

The Heterodyne Near Field Speckle (HNFS) technique

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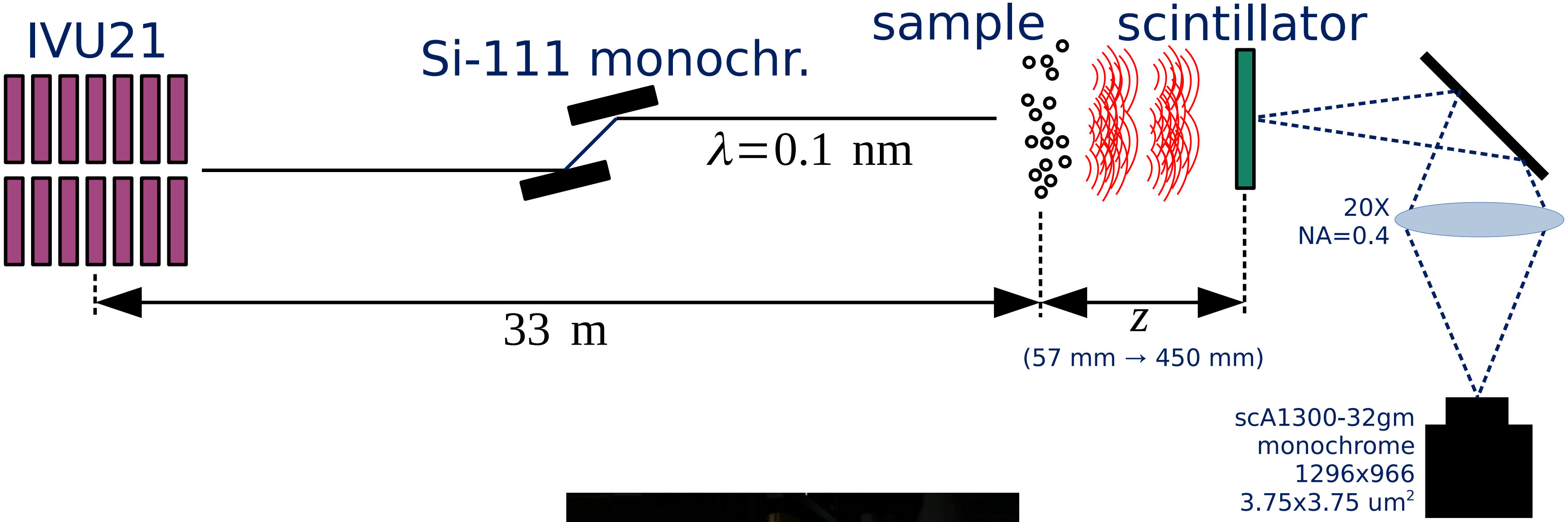
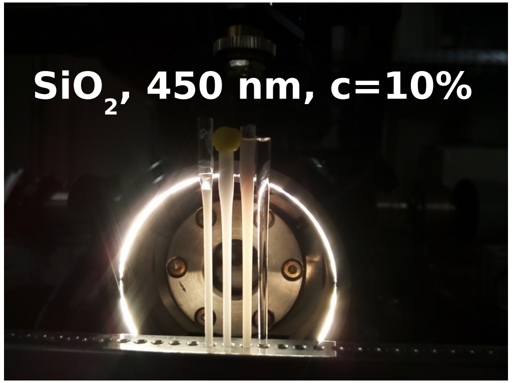
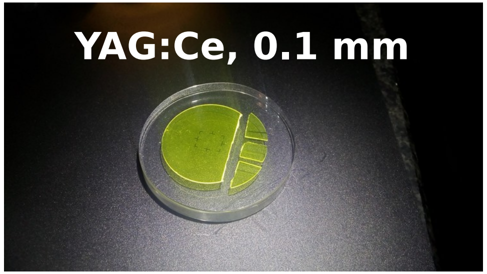


Period	21.3 mm
Number of periods	92
Gap	5.86 mm
Beam current	150 mA
Photon energy	12.4 KeV
Relative bandwidth	10^{-4}
SR source size	131x8 um^2 (HxV)


SiO_2, 450 nm, c=10%


YAG:Ce, 0.1 mm

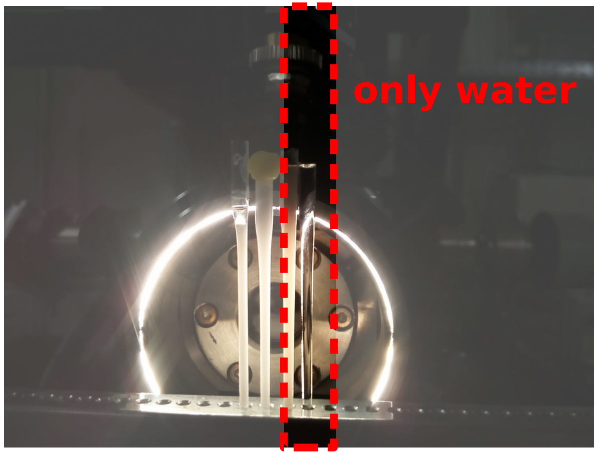
General formulation of HNFS

The **two-dimensional power spectrum** of speckled intensity distribution measured at a distance z from the sample can be expressed as:

$$\boxed{I(\vec{q},z)=T(q,z)C(\vec{q},z)\underbrace{H_0(\vec{q})S(q)}_{H(\vec{q})}+P(q)}$$

T = Talbot Transfer Function (TTF)
C = squared modulus of CCF
H_0 = frequency response (scintillator, optics, CCD, …)
S = particle form factor
P = noise contribution

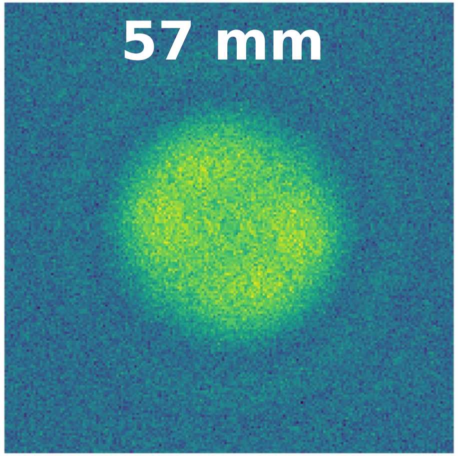
H = Instrumental Transfer Function (ITF)

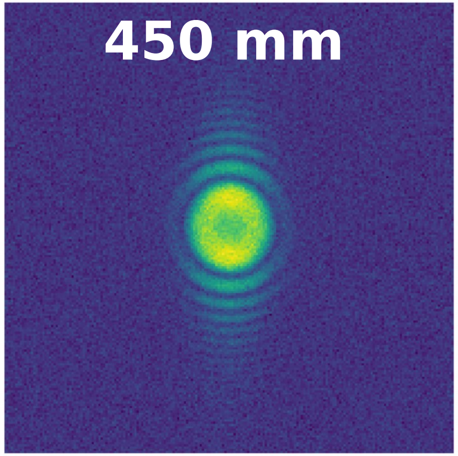


Measuring the ITF

z small $\left(|\Delta \vec{r}| < \sigma_{coh} \right)$

$$\Delta \vec{r} = z\,\vec{\theta} = z\,\frac{\vec{q}}{k} \;\rightarrow\; \Delta \vec{r} \sim \vec{0} \;\rightarrow\; C \sim 1$$

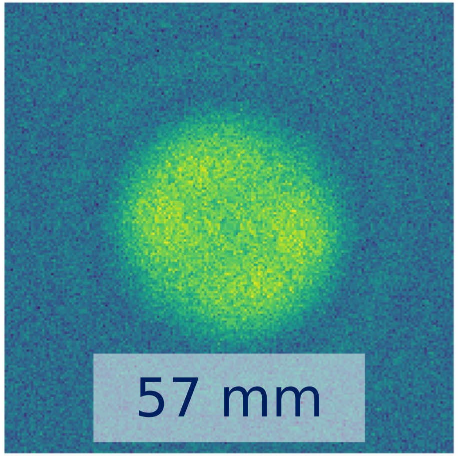


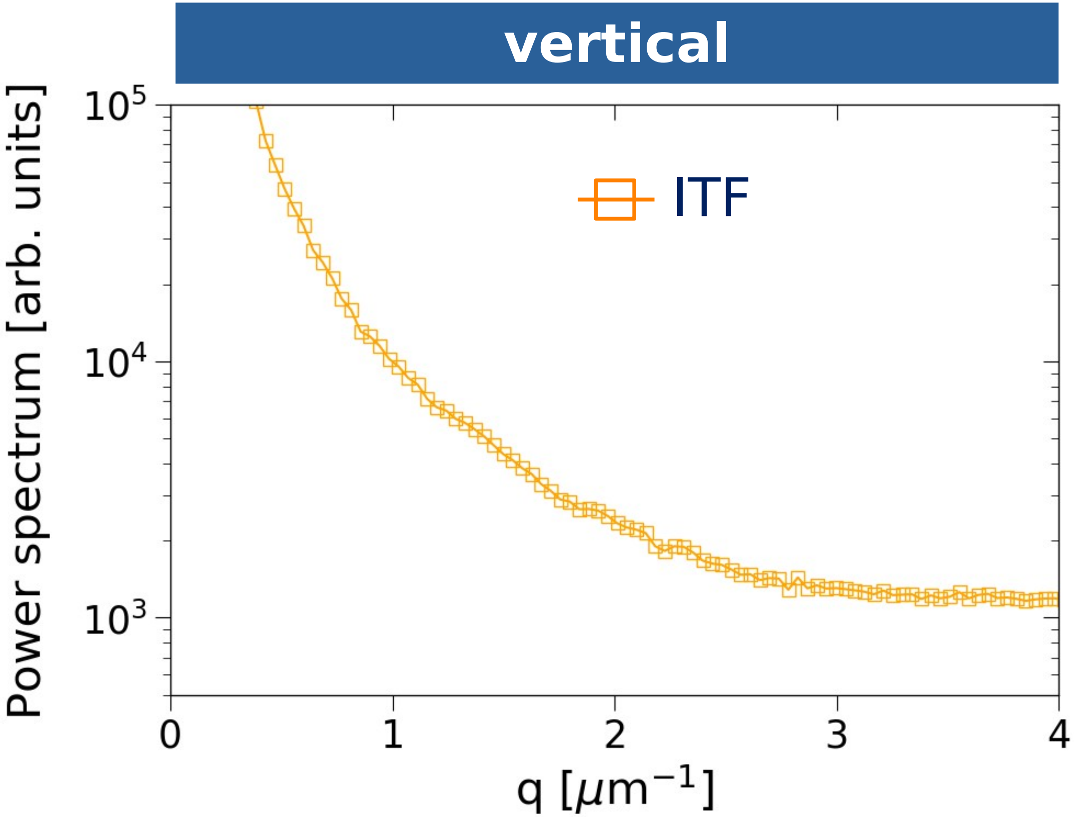


Short distances → isotropy → **ITF**
Large distances → anisotropy → **2D CCF**

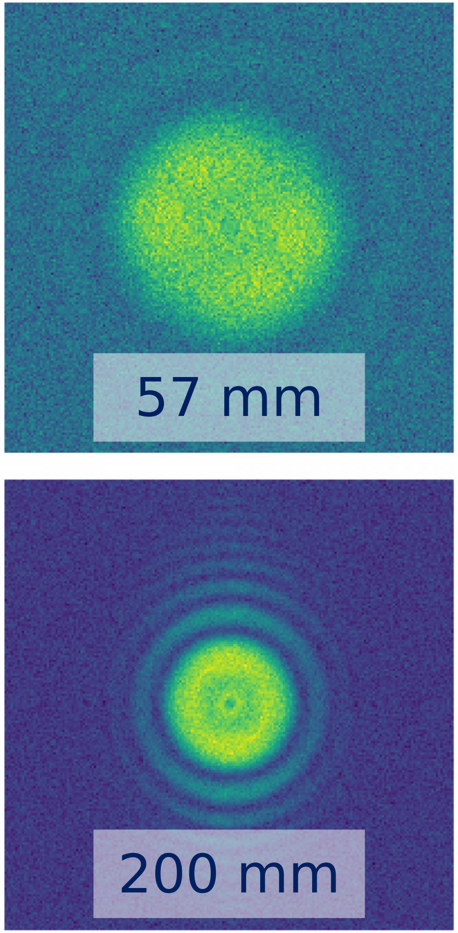
Recent results at ALBA

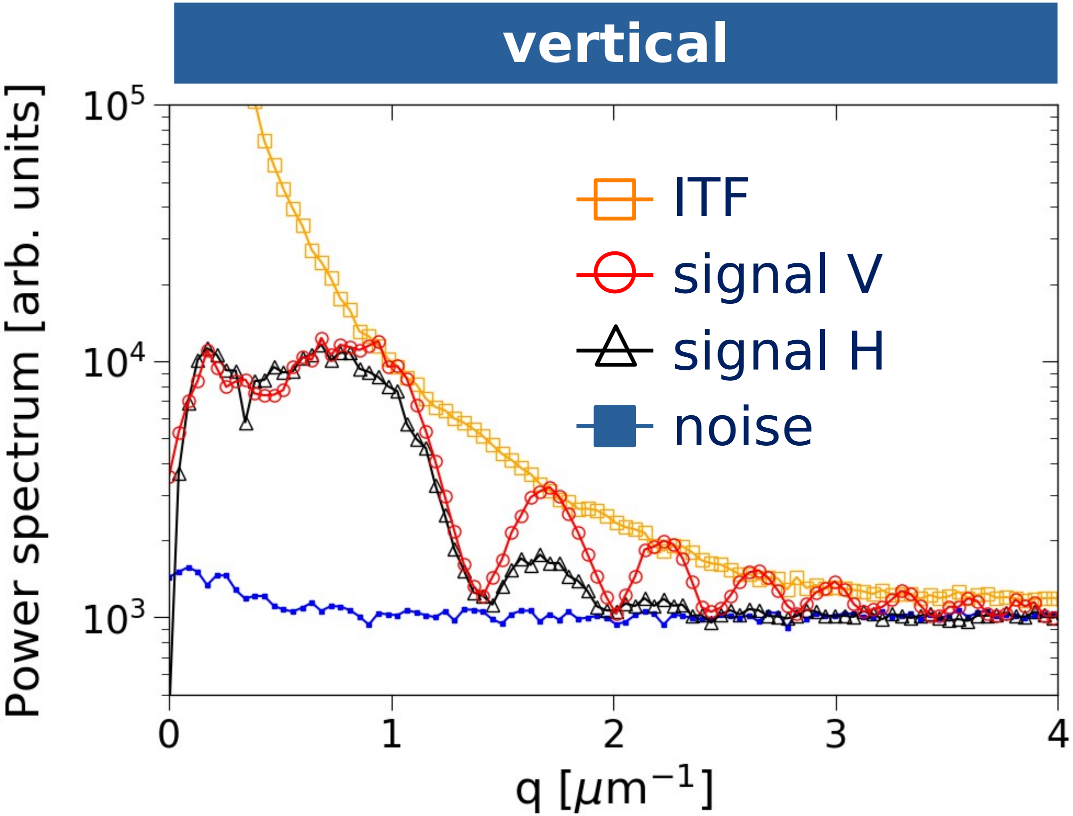
Signal overview



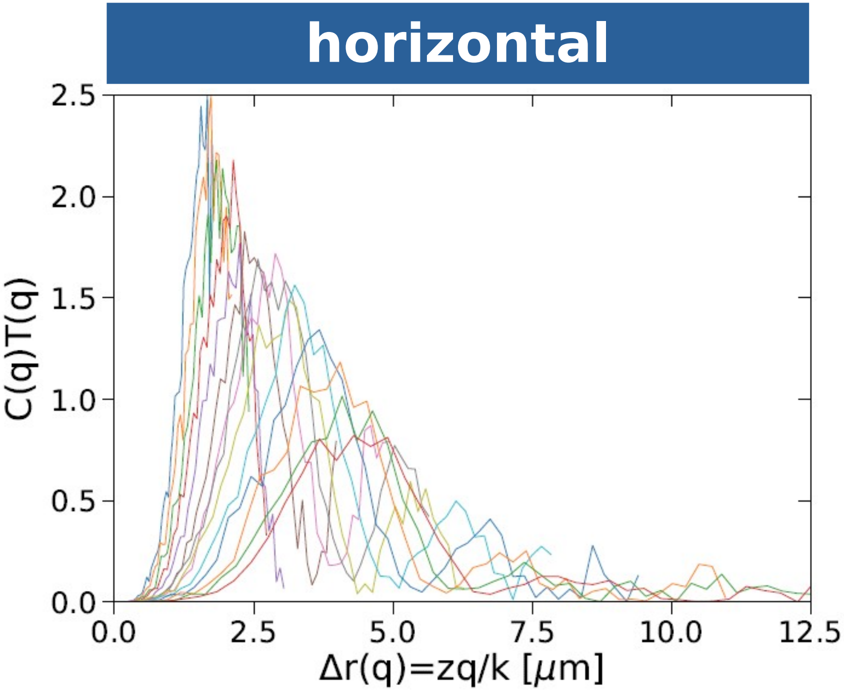


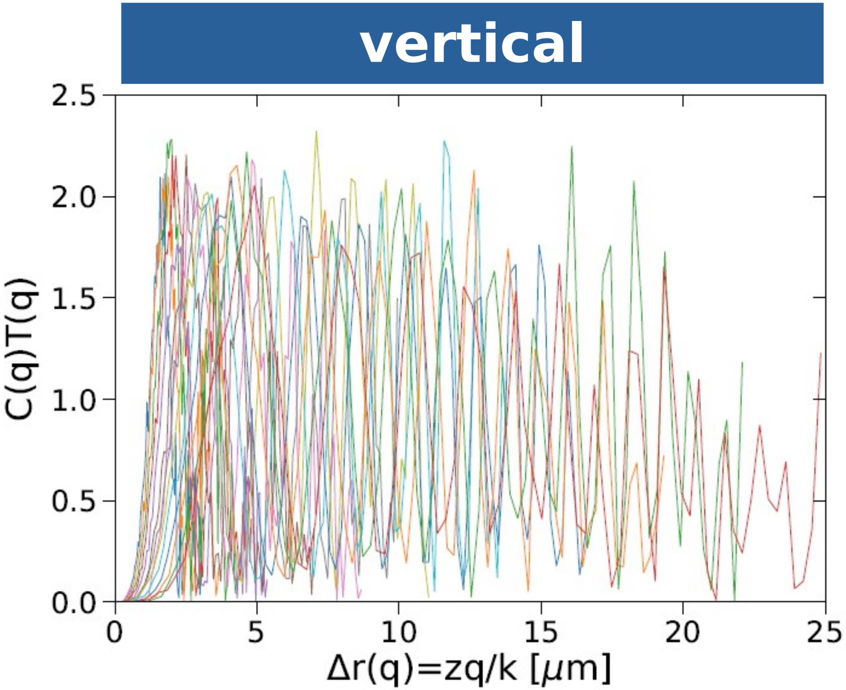
Signal overview





Reducing Talbot oscillations





Coherence and beam size

The Heterodyne Near Field Speckle (HNFS) technique

The role of the scintillator

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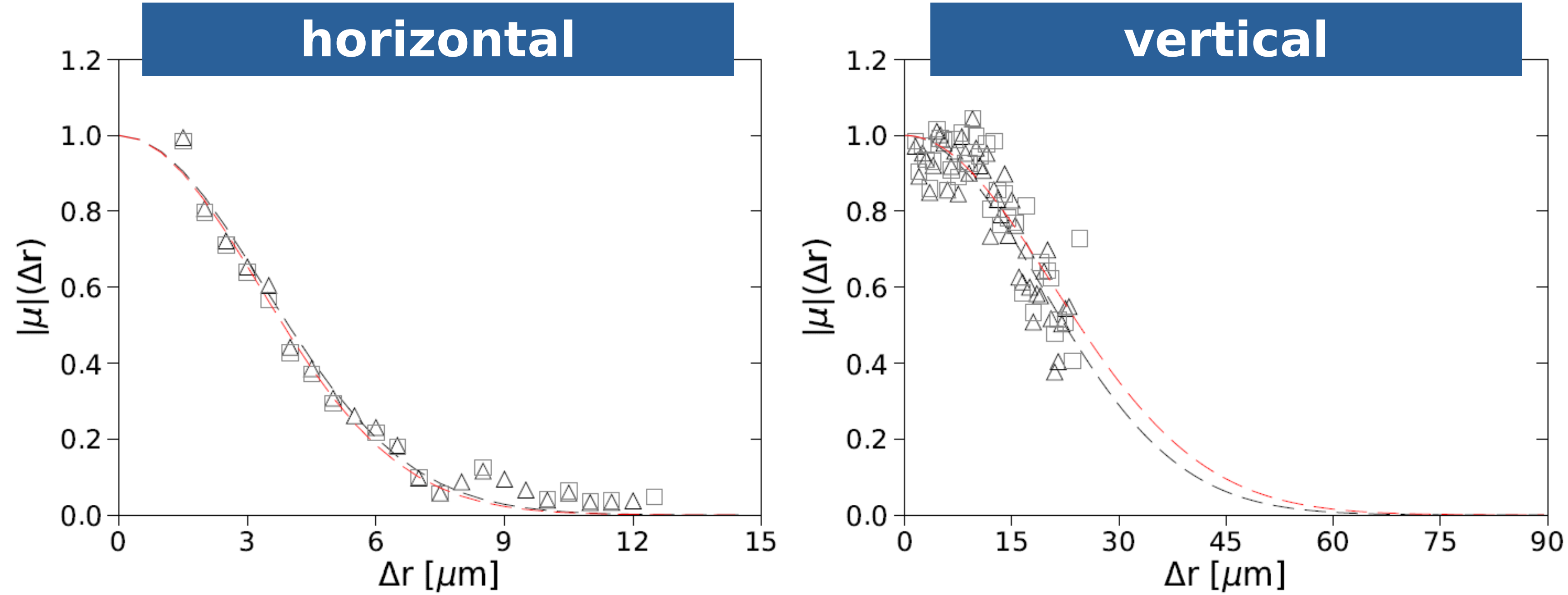

$$\sigma_{coh} = \int_{-\infty}^{+\infty} |\mu(\Delta r)|^2 \, d\Delta r$$

$$= 2\int_{0}^{+\infty} C(\Delta r) \, d\Delta r$$

$$\sigma_{coh,x} = (8.1 \pm 0.2)\ \mu m$$

$$\sigma_{coh,y} = (60 \pm 6)\ \mu m$$

$$\sigma_x = (115 \pm 6)\ \mu m$$

$$\sigma_y = (16 \pm 2)\ \mu m$$

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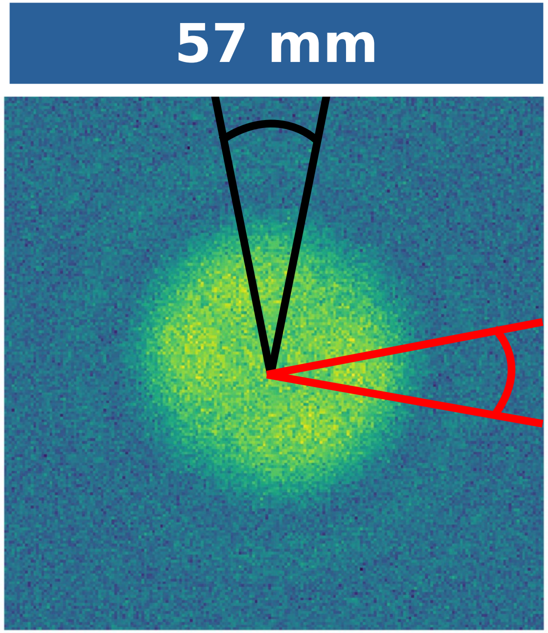
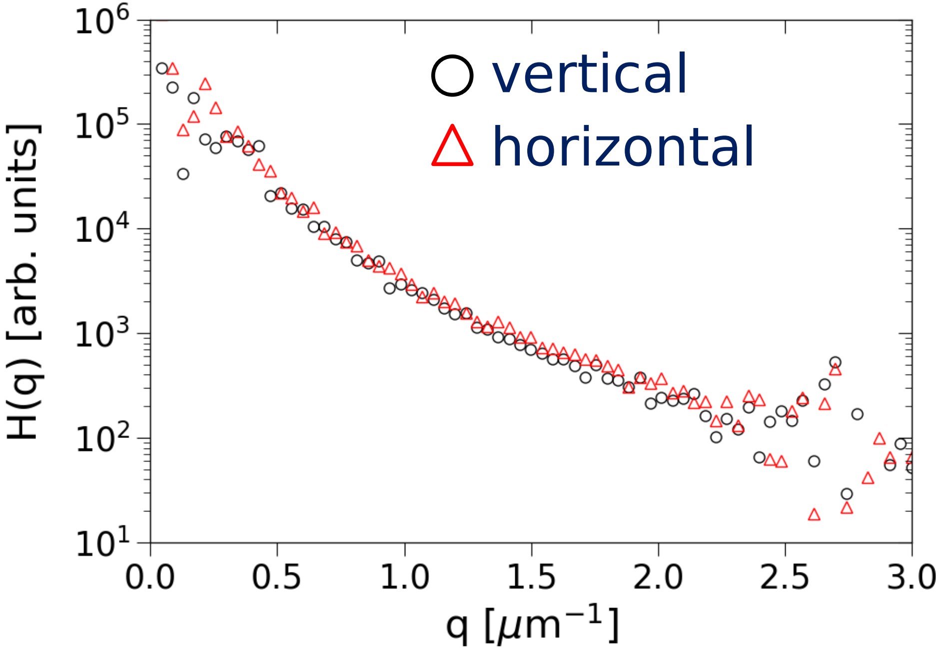
ITF: measurements

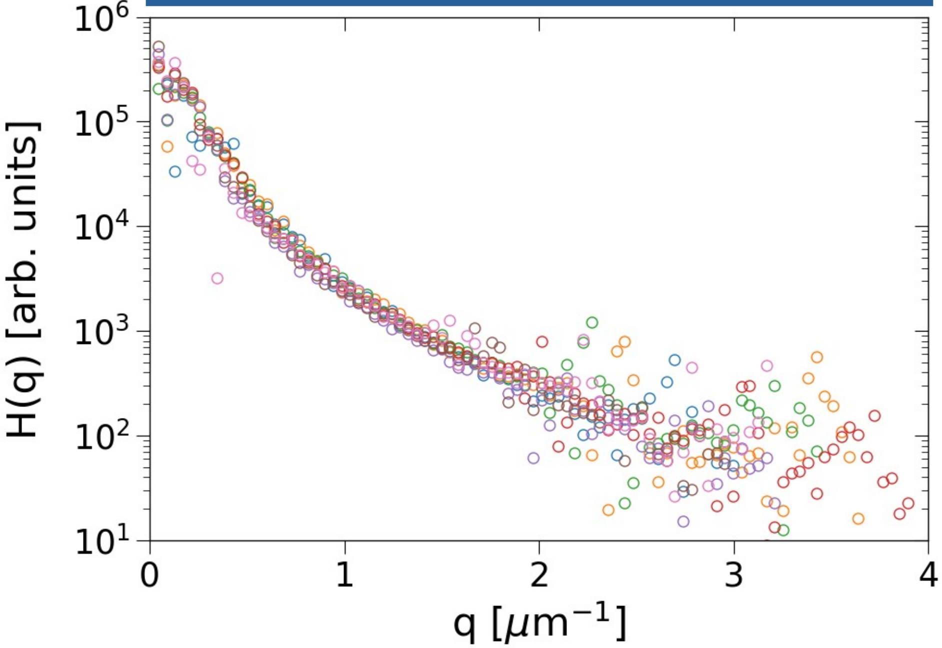
$$H(q)\overset{\text{z small, } C=1}{\downarrow =}\frac{I(q)-P(q)}{T(q)} \qquad T(q)=2\sin^2\left[\frac{zq^2}{2k}\right]$$





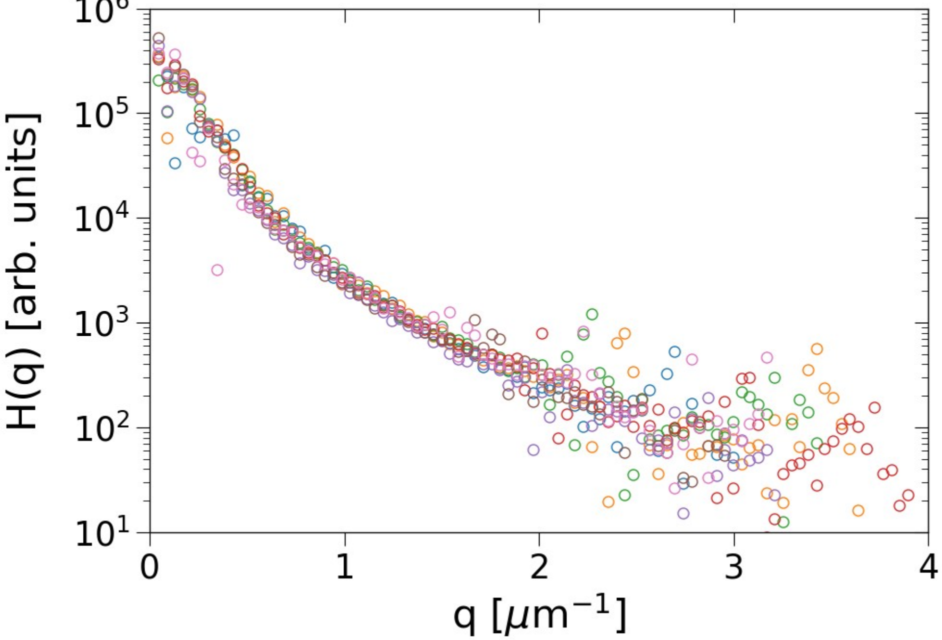
ITF: changing z

ver: 57 mm → 157 mm

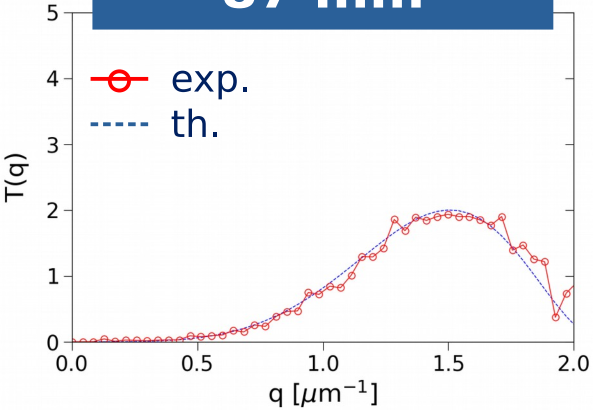


ITF: changing z

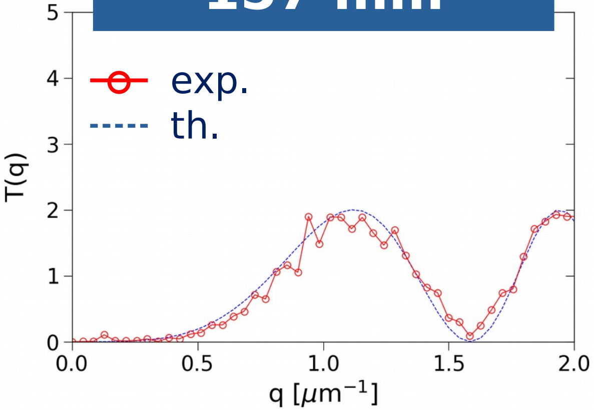
ver: 57 mm → 157 mm



87 mm



157 mm



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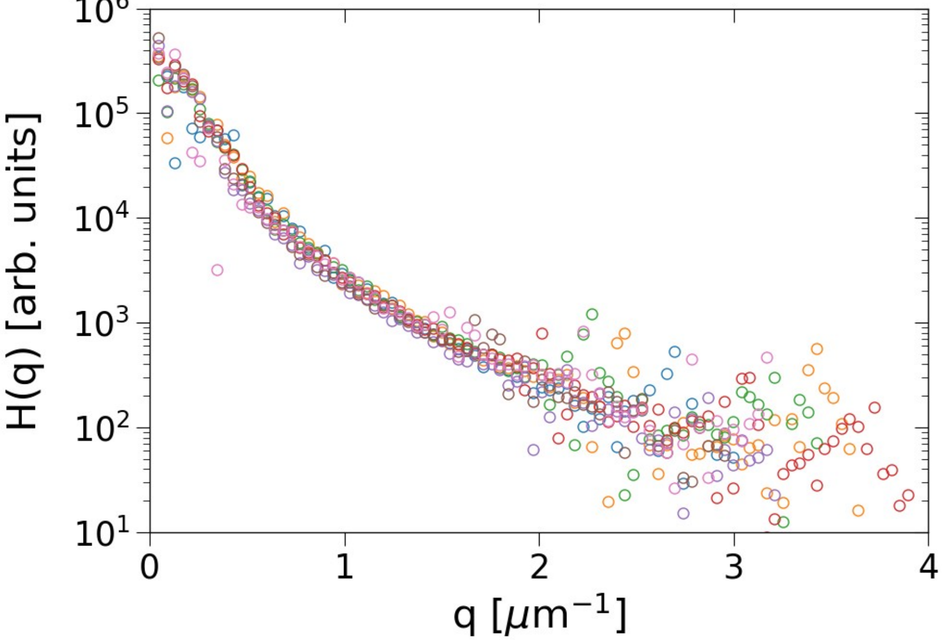
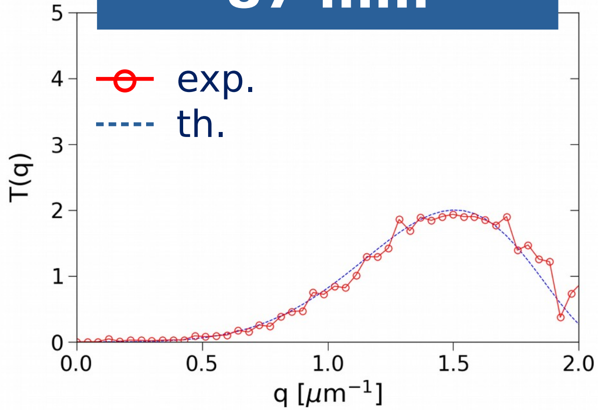
ITF: changing z

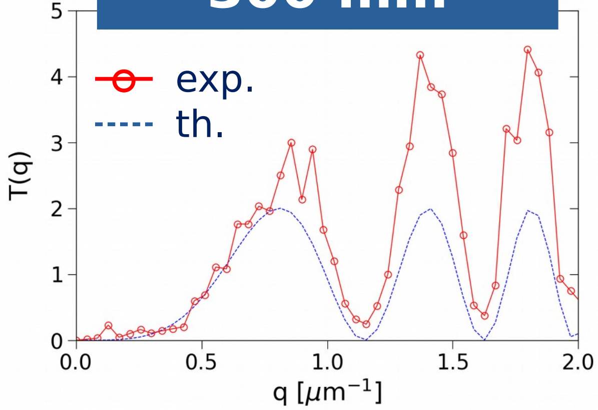
ver: 57 mm → 157 mm



87 mm



300 mm



ITF: changing z

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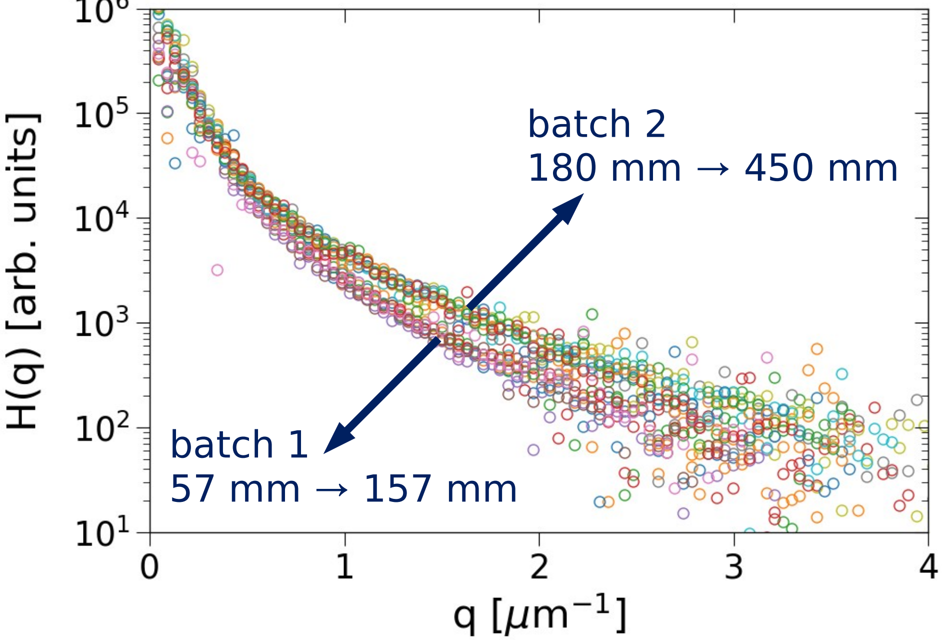
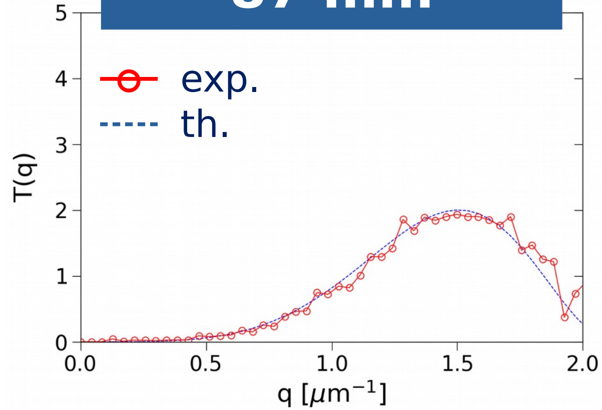
ver: 57 mm → 450 mm



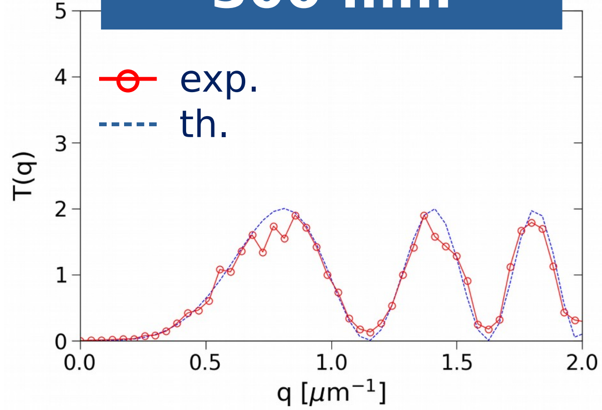
batch 2
180 mm → 450 mm

batch 1
57 mm → 157 mm

87 mm

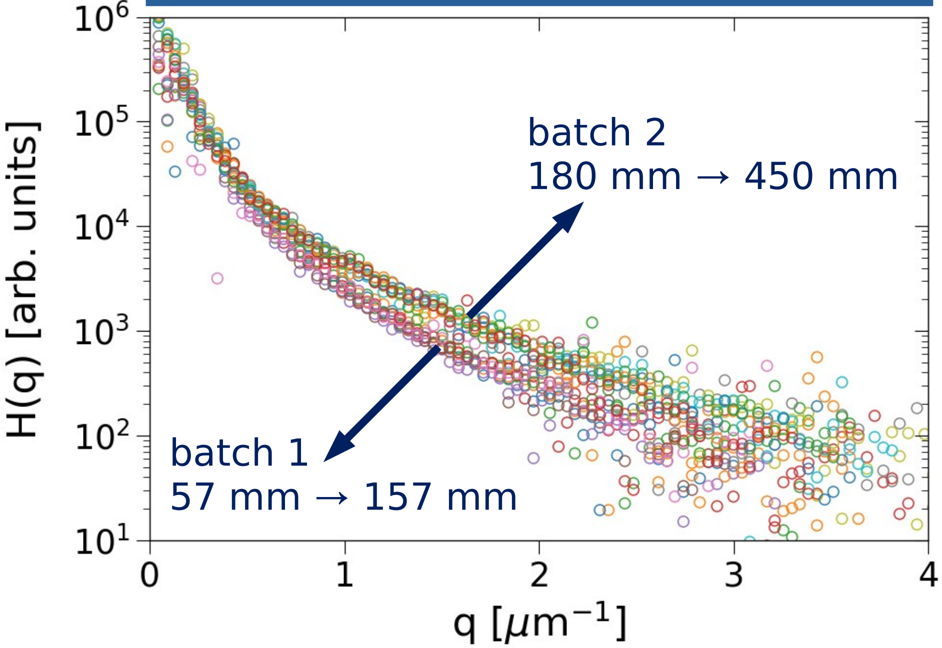


300 mm

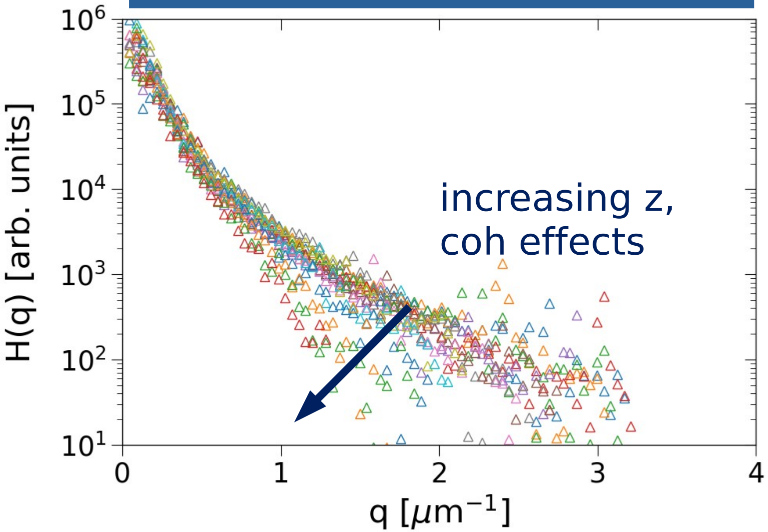


ITF: changing z

ver: 57 mm → 450 mm



hor



ITF: model

The Heterodyne Near Field Speckle (HNFS) technique

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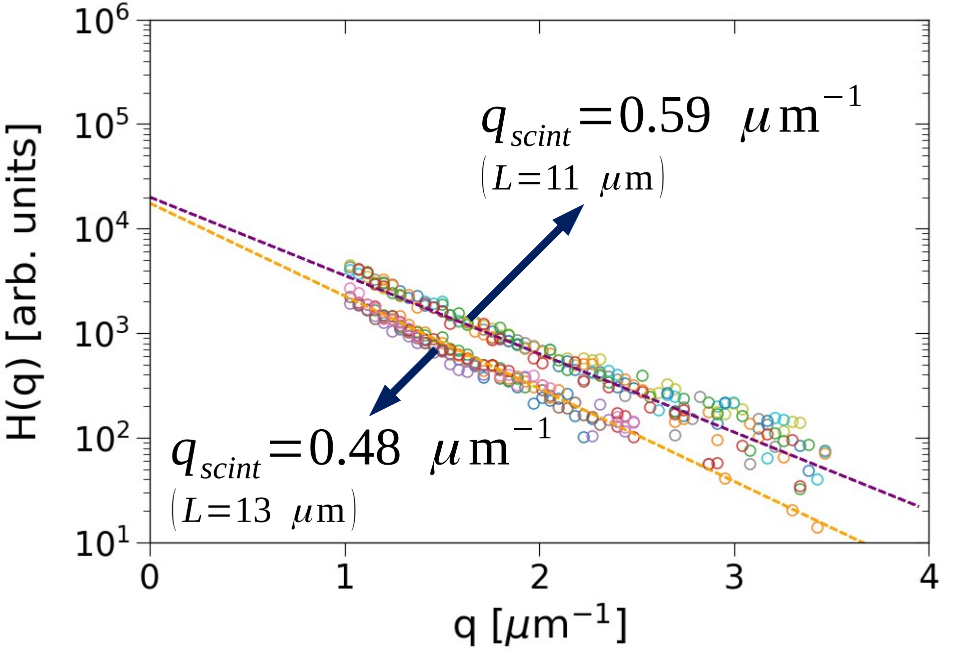
$$H(q) \propto e^{-\frac{q}{q_{scint}}}$$



$q_{scint} = 0.59\ \mu\mathrm{m}^{-1}$

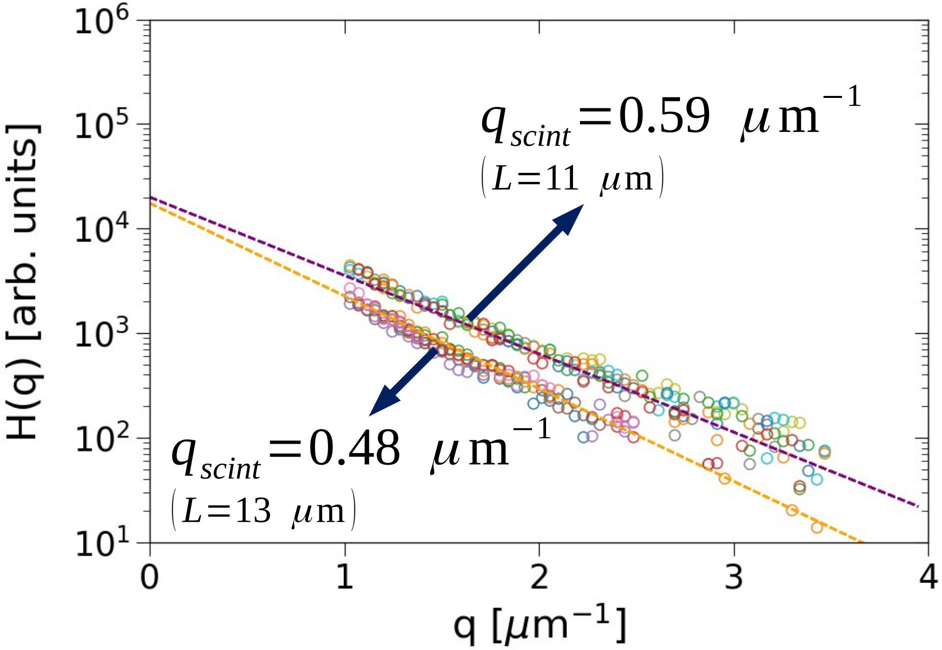
$(L = 11\ \mu\mathrm{m})$

$q_{scint} = 0.48\ \mu\mathrm{m}^{-1}$

$(L = 13\ \mu\mathrm{m})$

ITF: model

$$H(q) \propto e^{-\frac{q}{q_{scint}}}$$



Possible contributions:

1) particle form factor$^{(i)}$

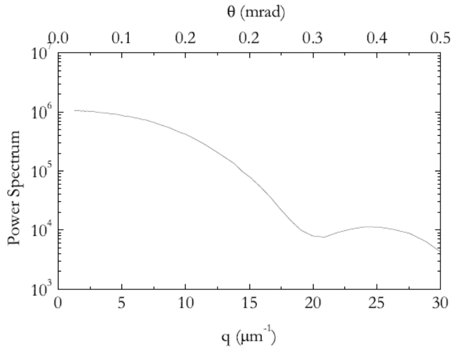


Figure 5.5: **Silica particle form factor**, Bonse-Hart measure

(i) M. Manfredda, PhD thesis

ITF: model

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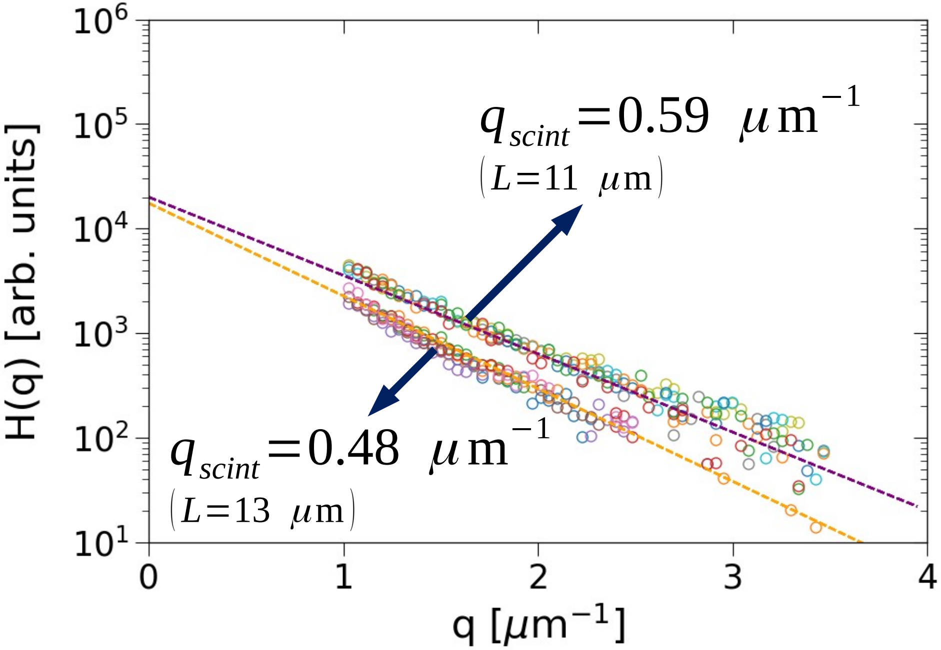
$$H(q) \propto e^{-\frac{q}{q_{scint}}}$$



Possible contributions:

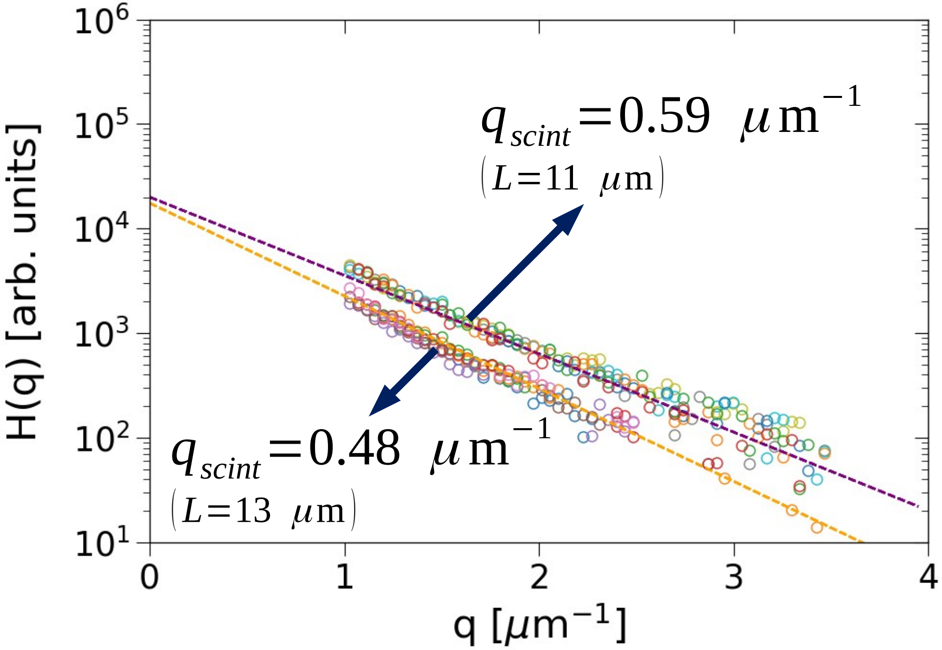
1) particle form factor$^{(i)}$

2) sample dynamics$^{(ii,iii,iv)}$

(i) M. Manfredda, PhD thesis
(ii) M. D. Alaimo et al, Phys. Rev. Lett. (2009)
(iii) R. Cerbino et al, Nat. Phys. (2008)
(iv) Y. Kashyap et al, Phys. Rev. A (2015)

ITF: model

$$H(q) \propto e^{-\frac{q}{q_{scint}}}$$



Possible contributions:

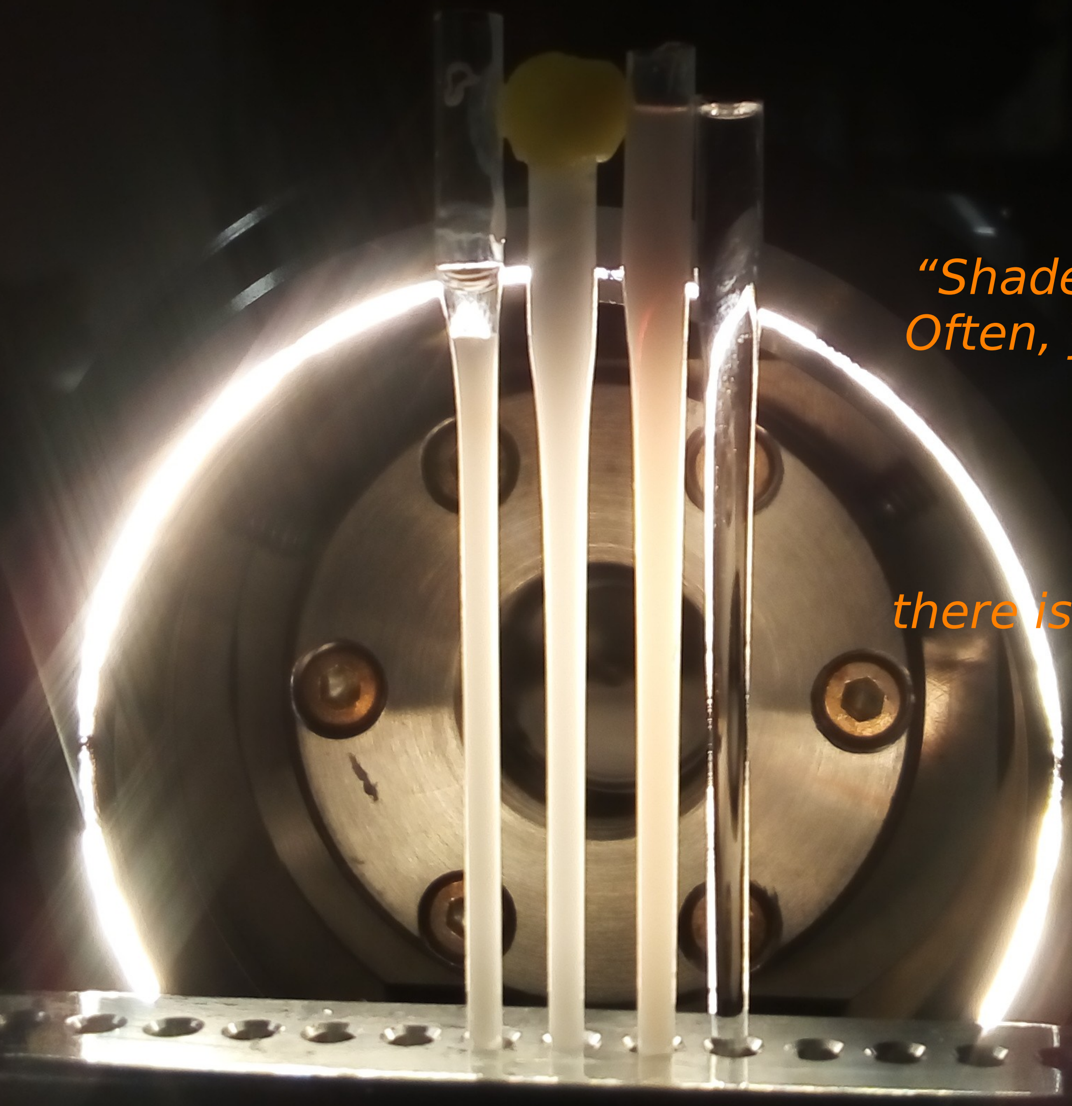
1) particle form factor(i)
2) sample dynamics(ii,iii,iv)
3) microscope
4) **scintillator**(ii,iii,iv)

(i) M. Manfredda, PhD thesis
(ii) M. D. Alaimo et al, Phys. Rev. Lett. (2009)
(iii) R. Cerbino et al, Nat. Phys. (2008)
(iv) Y. Kashyap et al, Phys. Rev. A (2015)

Conclusions and perspectives

Conclusions & perspectives

- Possibility of beam size measurements with HNFS: simple, inexpensive, robust, 2D information
- S/N optimization (CCD, sample, **scintillator**, …)
- **Essential** to precisely know the ITF
- Measurable with the same technique (no third-party instrumentation), mainly dictated by **scintillator** → higher resolution to probe finer fringes
- More accurate measurements, comparison with simulations (Fluka, Geant4, …)



"Wo wiel Licht, ist starker Schatten"

Goethe

"Shades are deeper where the light is stronger.
Often, yet, they're part of the same knowledge.
Shades and darkness are not the same,
for the first is cast by something,
but the latter is not.
Any time that a strong shadow appears,
there is a chance for the knowledge to advance.
Not necessarily by killing the shadow,
turning it into light, but simply by asking
where the shadow arises from.

Which may even be from the
superposition of two or many lights."

M. Manfredda

Backup slides

ITF at ESRF

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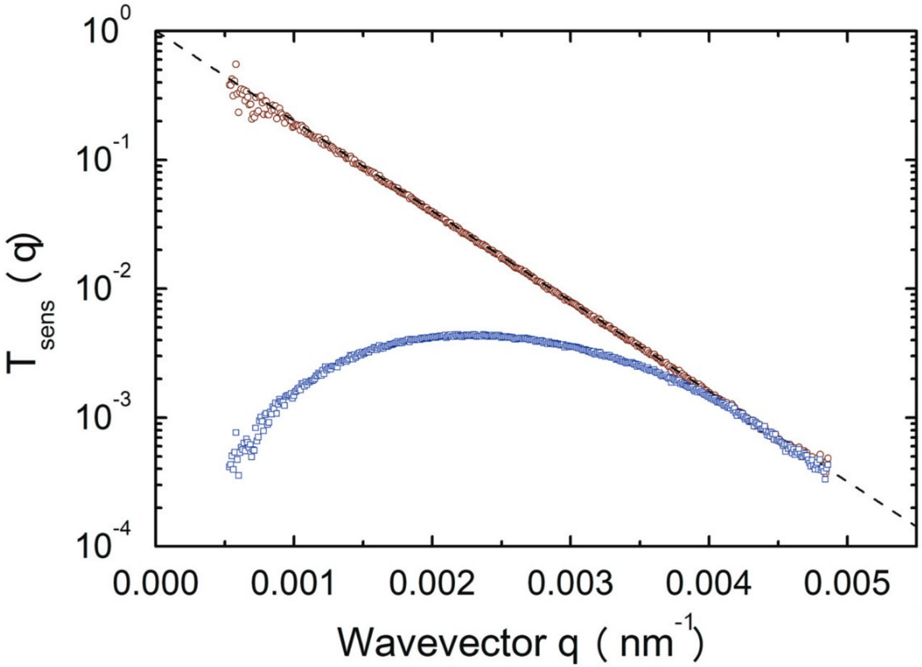
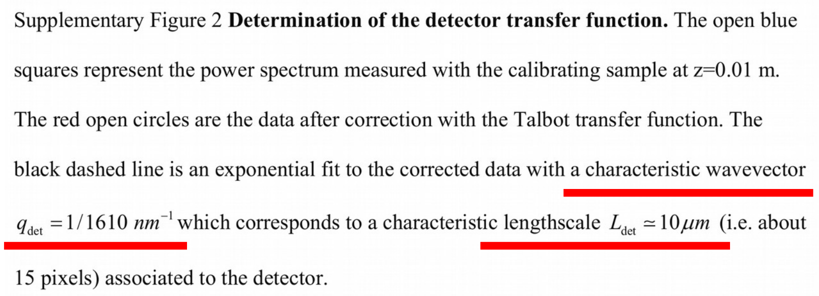


R. Cerbino et al, Nat. Phys. (2008)


Supplementary Figure 2 **Determination of the detector transfer function.** The open blue squares represent the power spectrum measured with the calibrating sample at z=0.01 m. The red open circles are the data after correction with the Talbot transfer function. The black dashed line is an exponential fit to the corrected data with a characteristic wavevector $q_{\det} = 1/1610\ nm^{-1}$ which corresponds to a characteristic lengthscale $L_{\det} \simeq 10 \mu m$ (i.e. about 15 pixels) associated to the detector.

Coherence at ESRF

The Heterodyne Near Field Speckle (HNFS) technique

The role of the scintillator

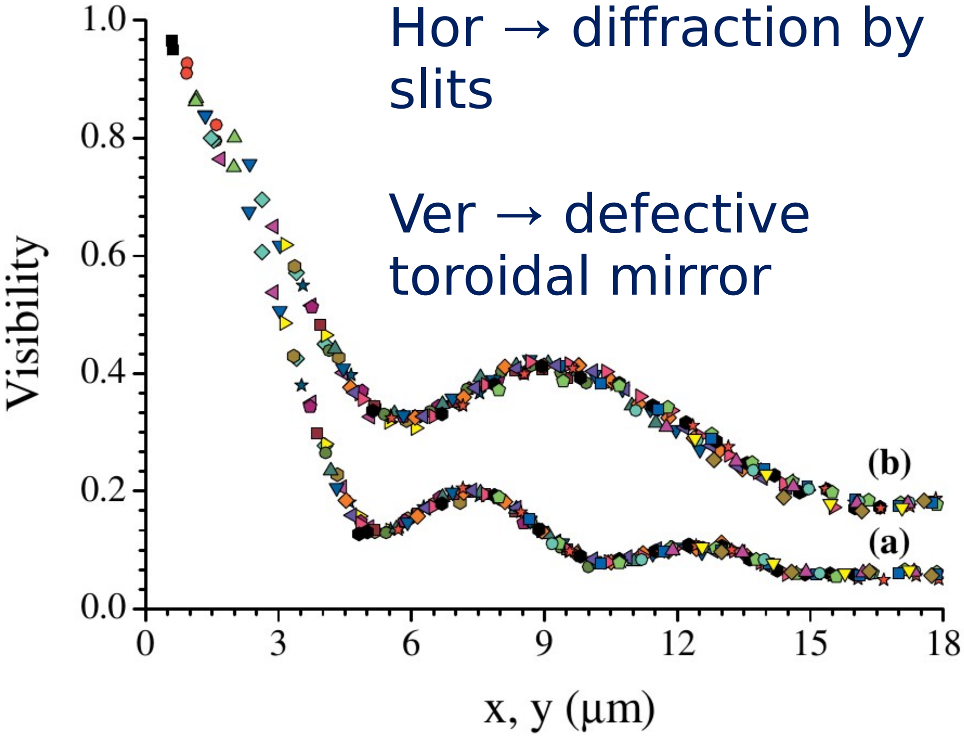
Recent results at ALBA

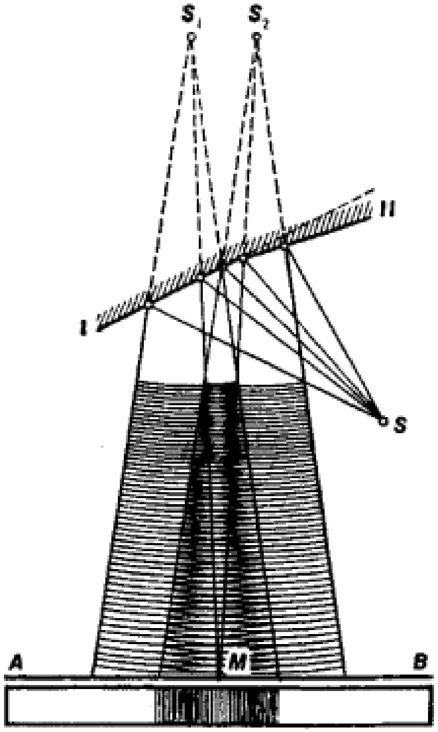
Conclusions and perspectives

M. D. Alaimo et al, Phys. Rev. Lett. (2009)

Hor → diffraction by slits

Ver → defective toroidal mirror





Walk-off effect

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