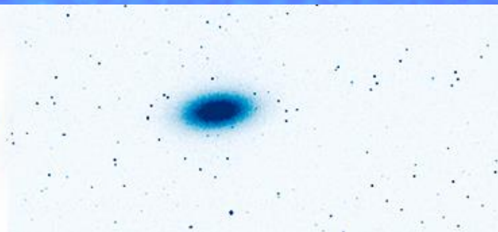
Topical Workshop on Emittance Measurements for Light Sources and FELs
January 29th–30th, 2018
Session: Monday Afternoon II



Beam Size Measurements Using Heterodyne Speckle Fields

M. Siano, B. Paroli, M. A. C. Potenza
University of Milan, Department of Physics

U. Iriso, A. A. Nosych, C. S. Kamma-Lorger
ALBA-CELLS Synchrotron Radiation Facility

G. Trad, S. Mazzoni
CERN

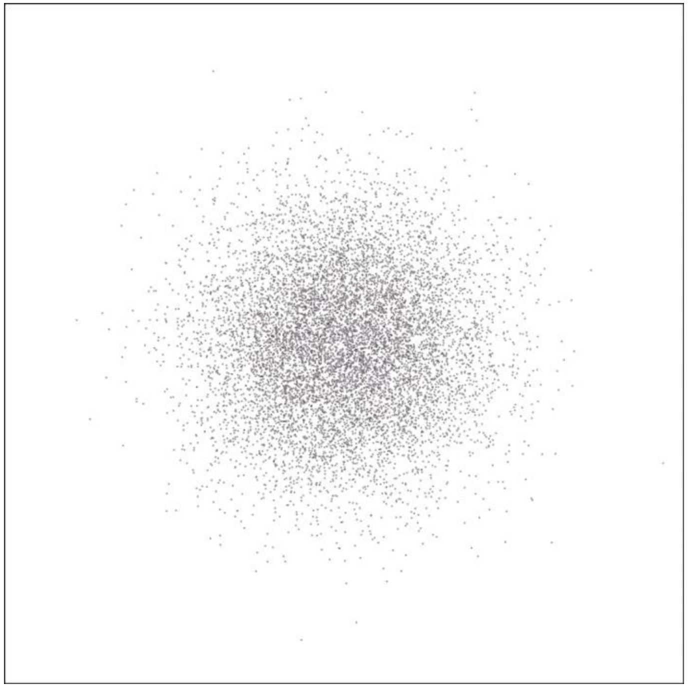
Outline

- Introduction to coherence-based beam size measurements
- The Heterodyne Near Field Speckle (HNFS) technique
- Experimental results at NCD beamline (ALBA)
- Conclusions and perspectives

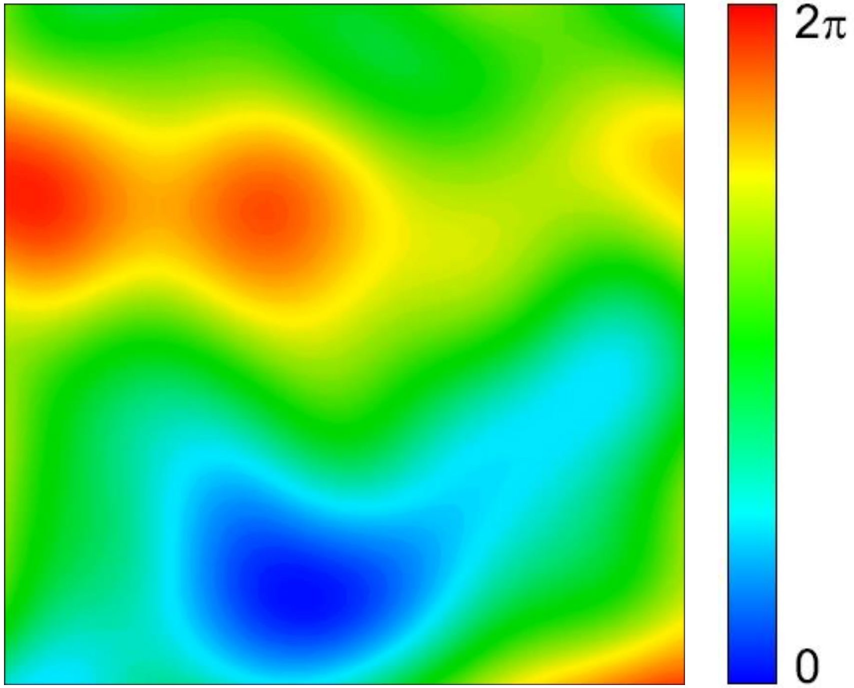
Introduction to coherence-based beam size measurements

Transverse coherence in third-generation light sources

$$\vec{E}_{tot}(\vec{r}_P, t) = \sum_{j=1}^{N} \vec{E}_j(\vec{r}_P, t, \vec{l}_j, \vec{\eta}_j, t_j)$$



e⁻ bunch transverse distribution



SR phase distribution

Transverse coherence in third-generation light sources

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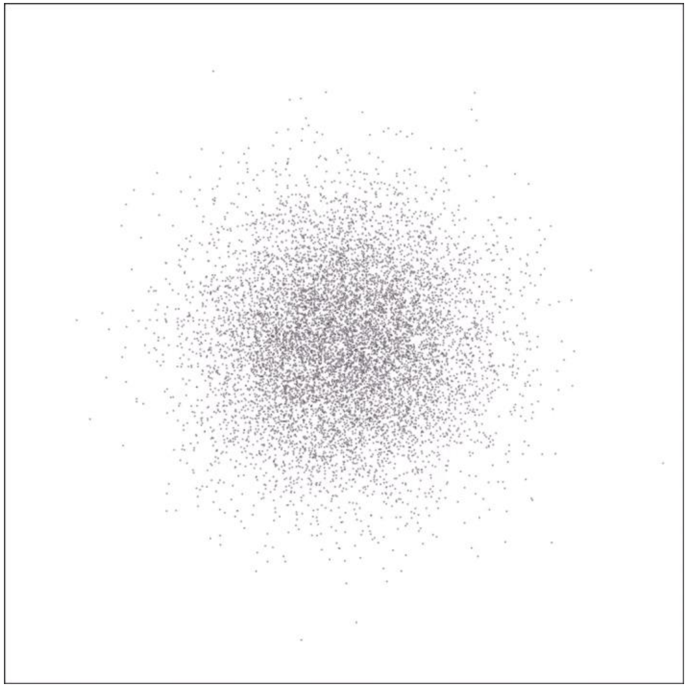
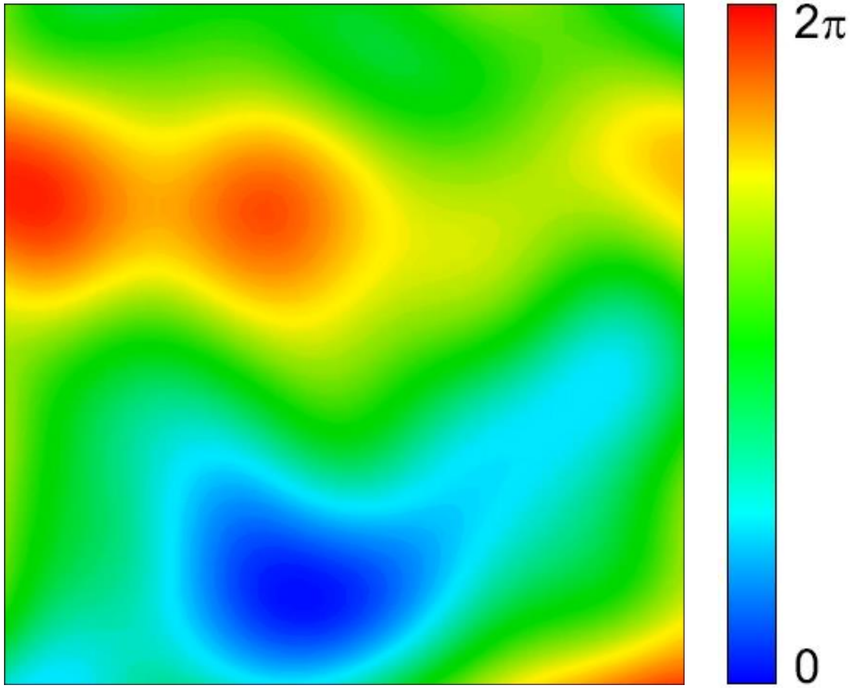


e^- bunch transverse distribution

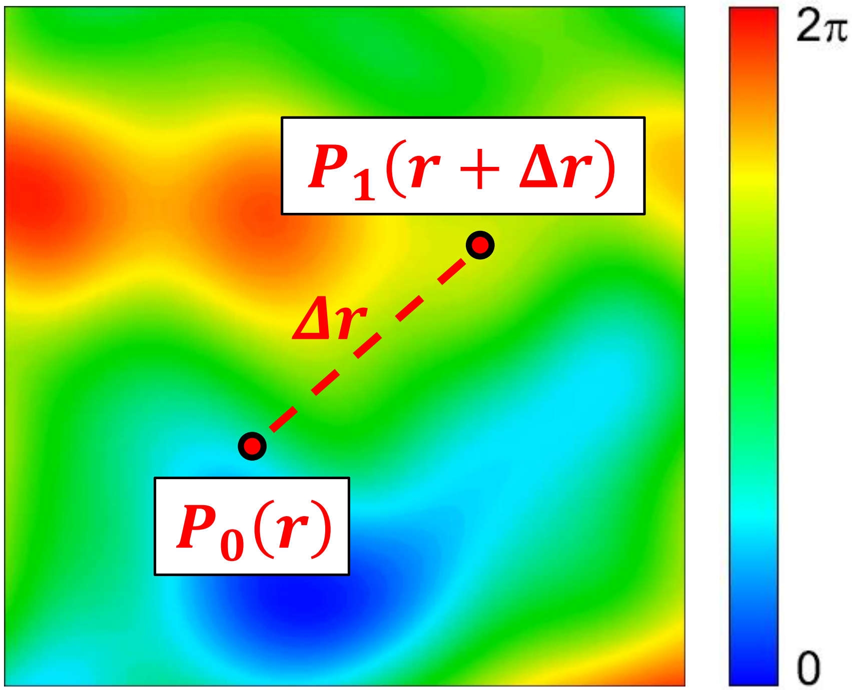


SR phase distribution

Transverse coherence in third-generation light sources

$$\mu(\Delta r) = \frac{\langle E(r)E^*(r+\Delta r)\rangle}{\sqrt{\langle I(\vec{r}_1)\rangle\langle I(\vec{r}_2)\rangle}}$$

Complex Coherence Factor (CCF)



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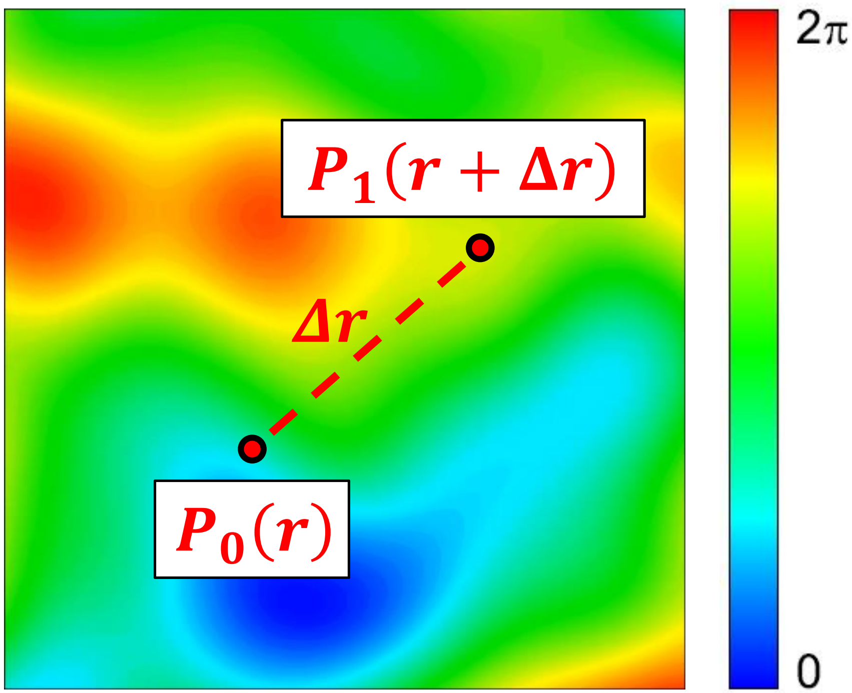
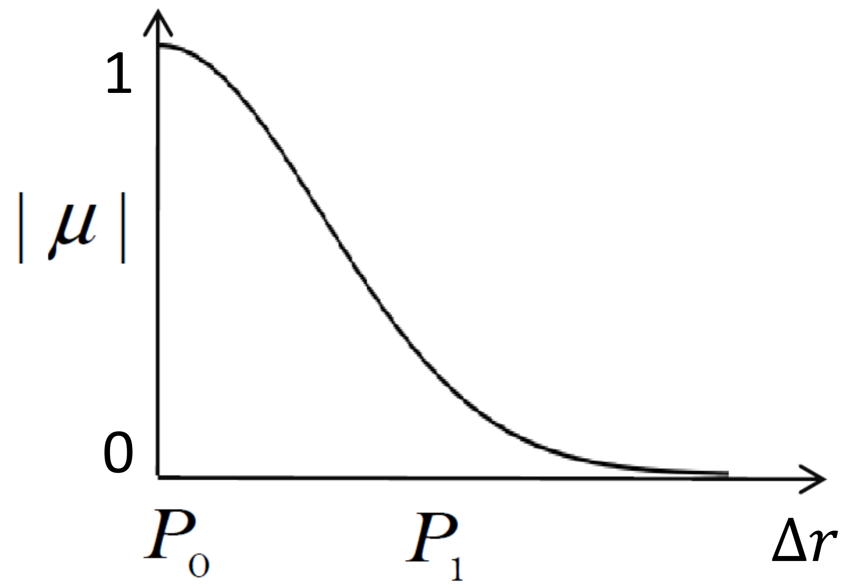
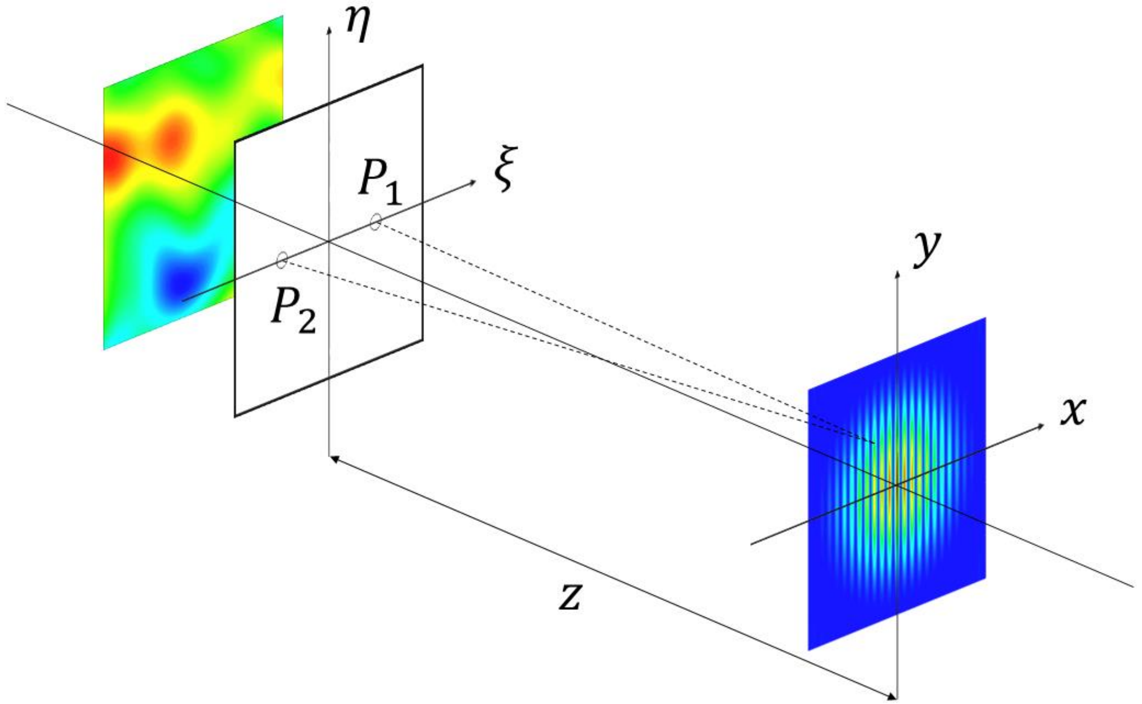


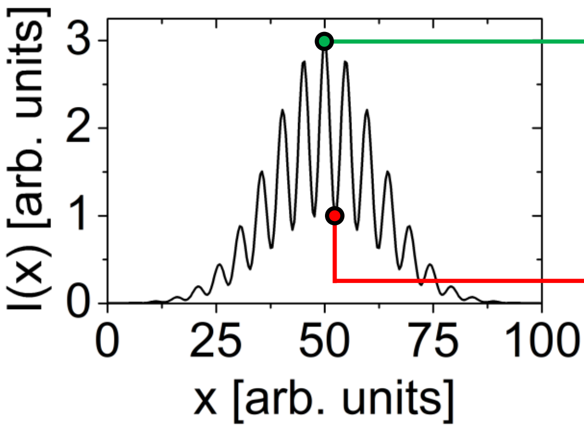


$$\sigma_{coh} = \int_{-\infty}^{+\infty} |\mu(\Delta r)|^2 \, d\Delta r \propto \frac{\lambda z_0}{\sigma}$$

(Van Cittert-Zernike theorem)

Interference: a manifestation of coherence

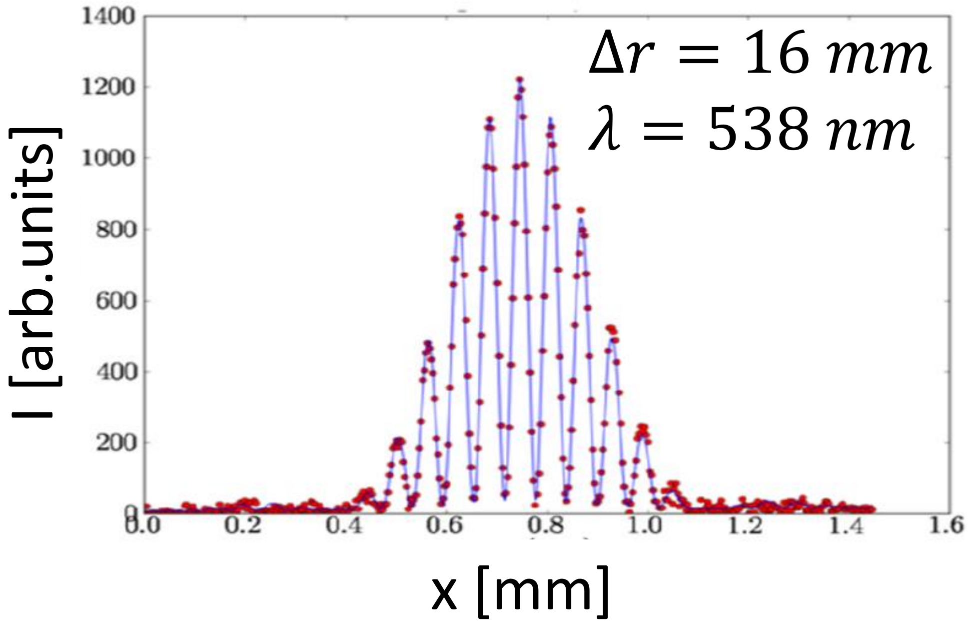




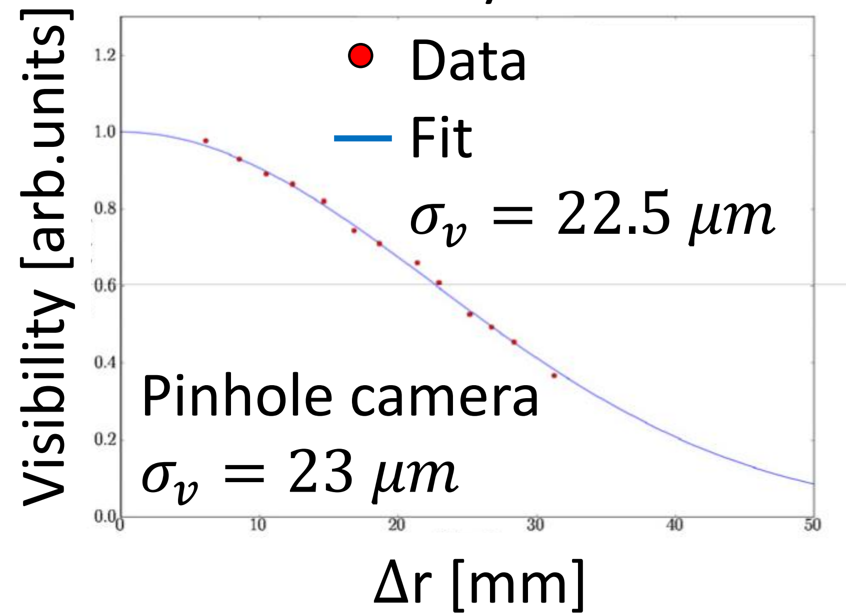
$$\mathcal{V} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = |\mu(\Delta r)|$$

Coherence-based beam size measurements

Young interferogram



Visibility curve

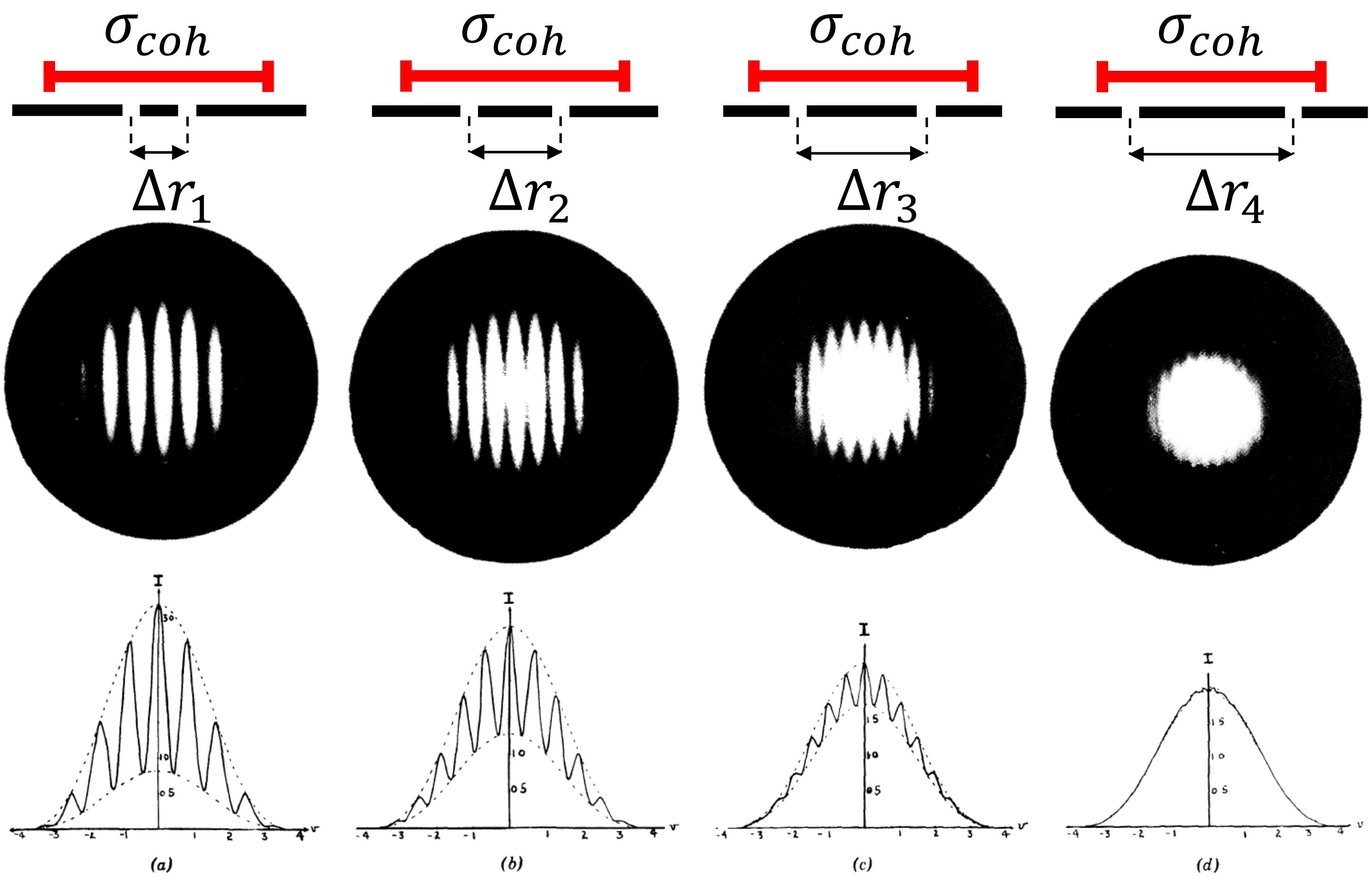


- Non-invasive diagnostics for the particle beam
- Well-established with visible SR

T. Mitsuhashi, *Proceedings of the 6th International Particle Accelerator Conference (IPAC 2015)*

Interference: a manifestation of coherence

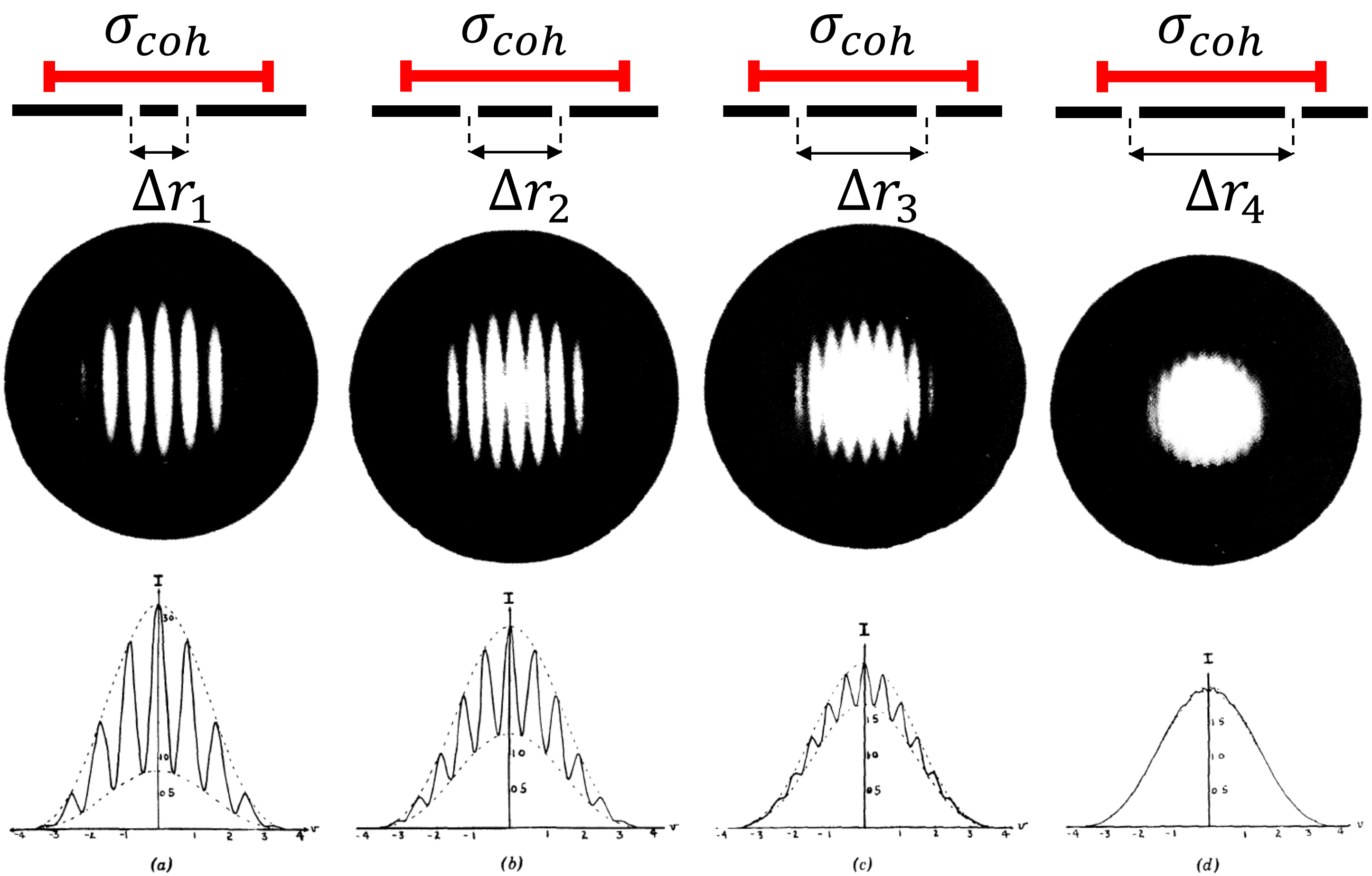
Coherence: the ability of the radiation of writing stable interference fringes



J. W. Goodman, *Statistical Optics*

Interference: a manifestation of coherence

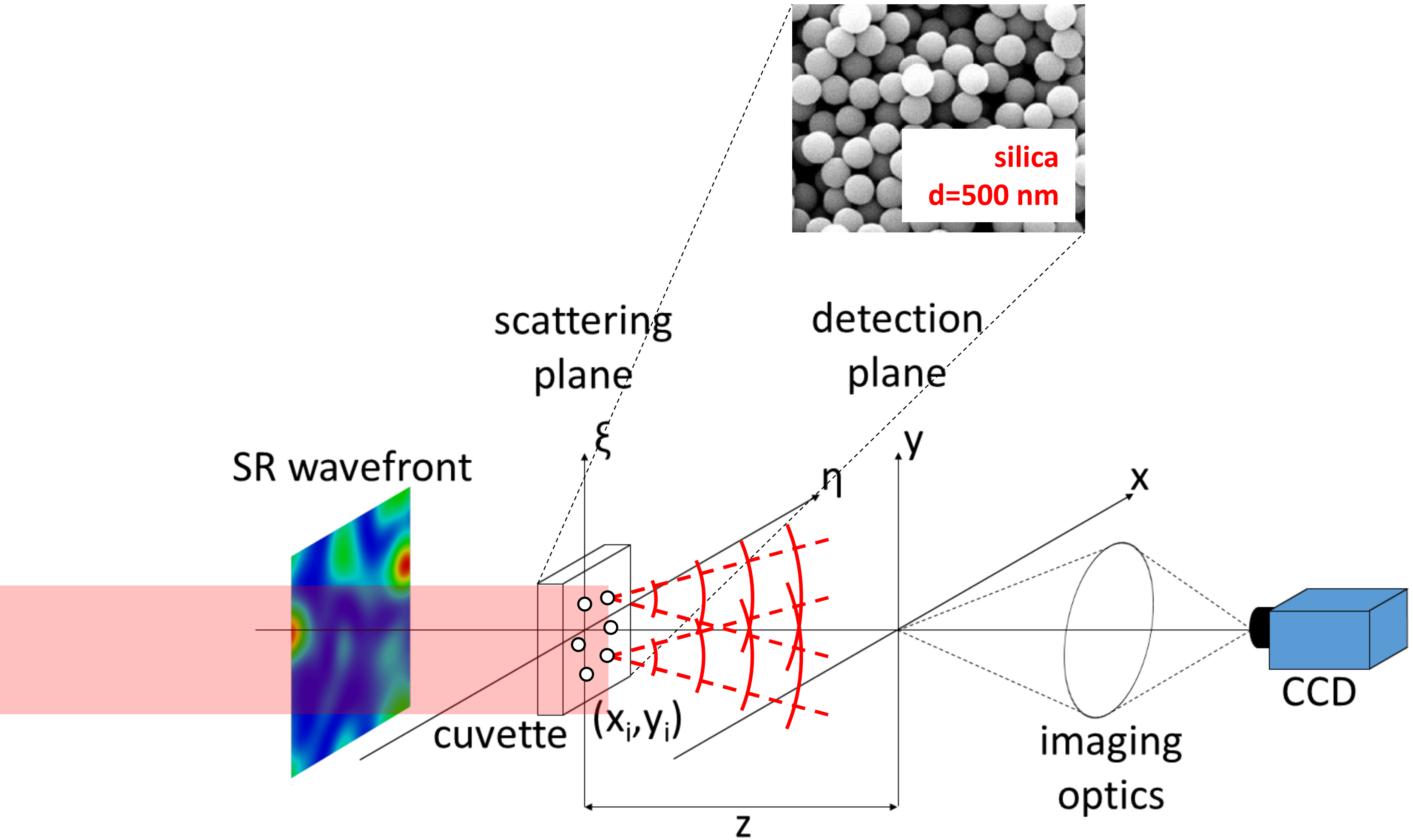
Coherence: the ability of the radiation of writing stable **high-frequency** interference fringes



J. W. Goodman, *Statistical Optics*

The Heterodyne Near Field Speckle (HNFS) technique

The Heterodyne Near Field Speckle (HNFS) technique: setup



F. Ferri *et al.*, *Phys. Rev. E* **70**, 041405 (2004)

S. Mazzoni *et al.*, *Rev. Sci. Instrum.* **84**, 043704 (2013)

HNFS: scattering from a single particle

$$I(x,y) = \langle |E_0(x,y) + E_s(x,y)|^2 \rangle$$
$$= \langle |E_0(x,y)|^2 \rangle + 2\Re e \langle E_0(x,y) E_s^*(x,y) \rangle + \langle |E_s(x,y)|^2 \rangle$$

(heterodyne term) (heterodyne conditions)

$$E_s(x,y) \propto e^{i\frac{k}{2z}(x^2+y^2)}$$

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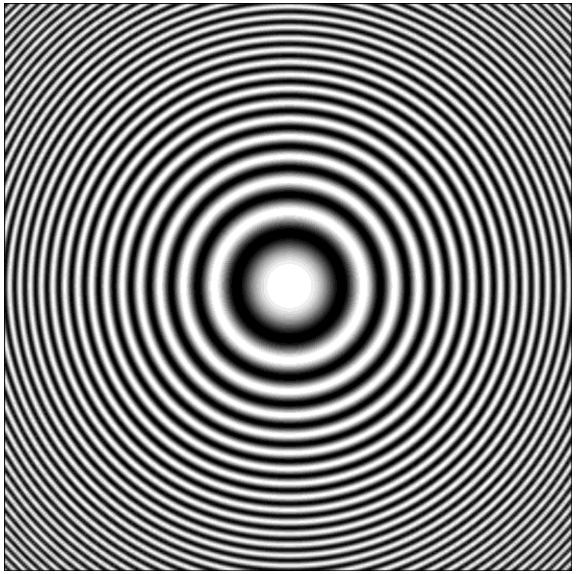

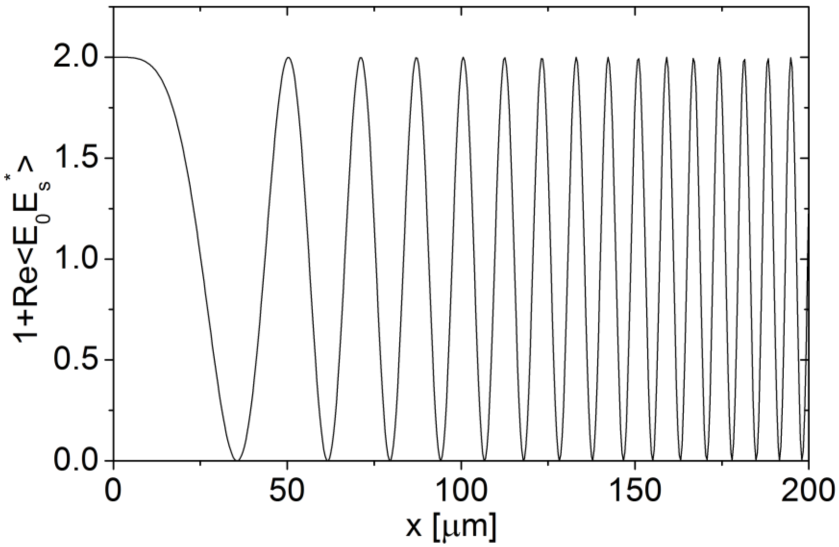

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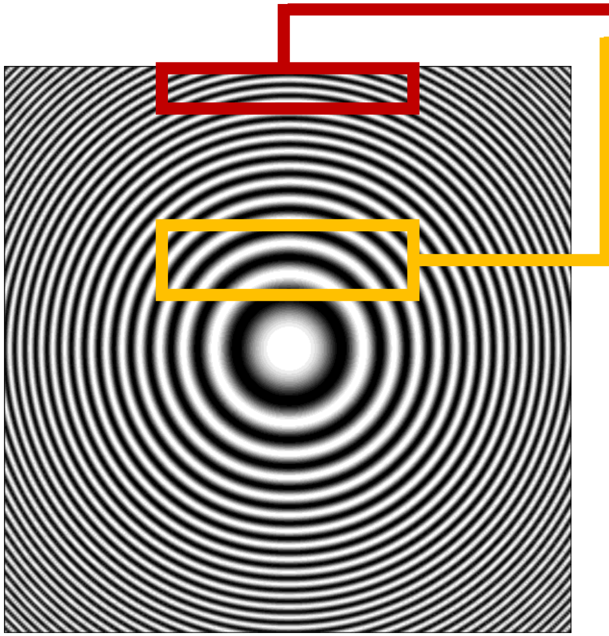

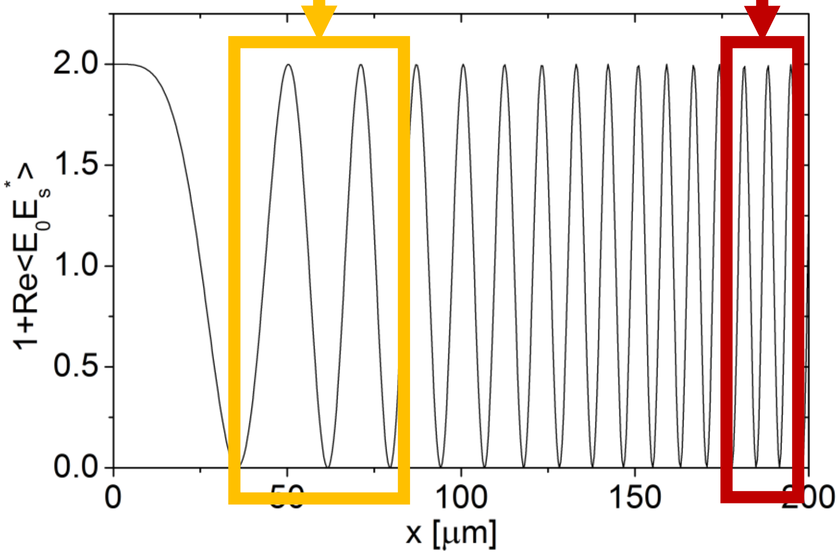

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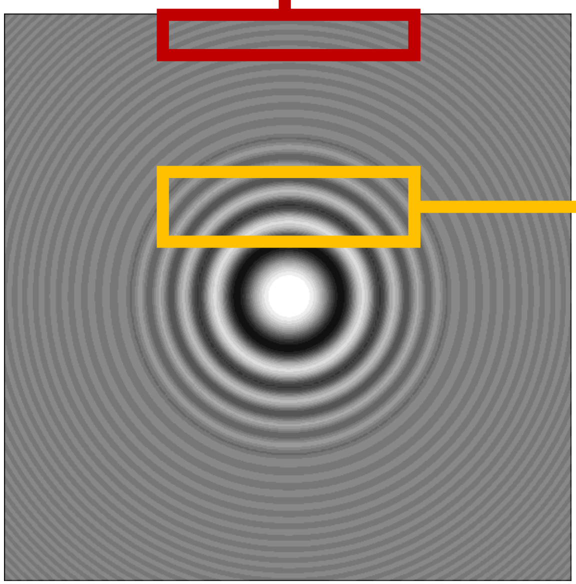

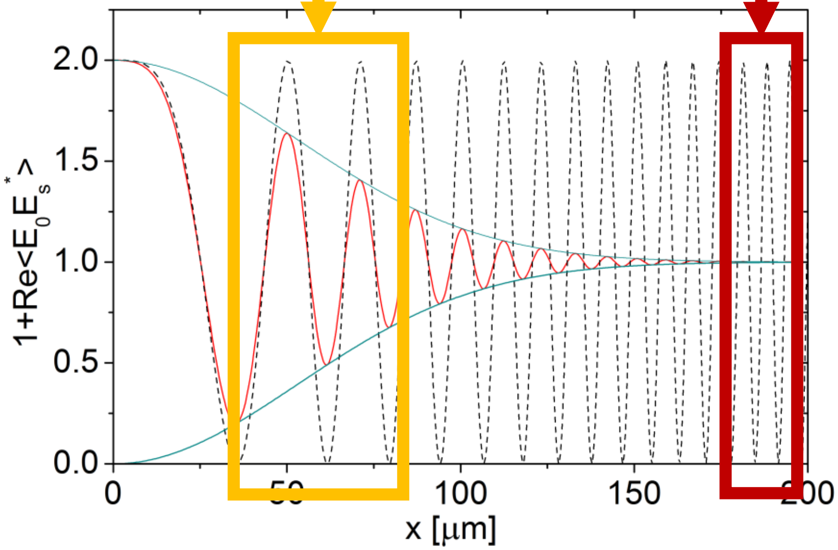

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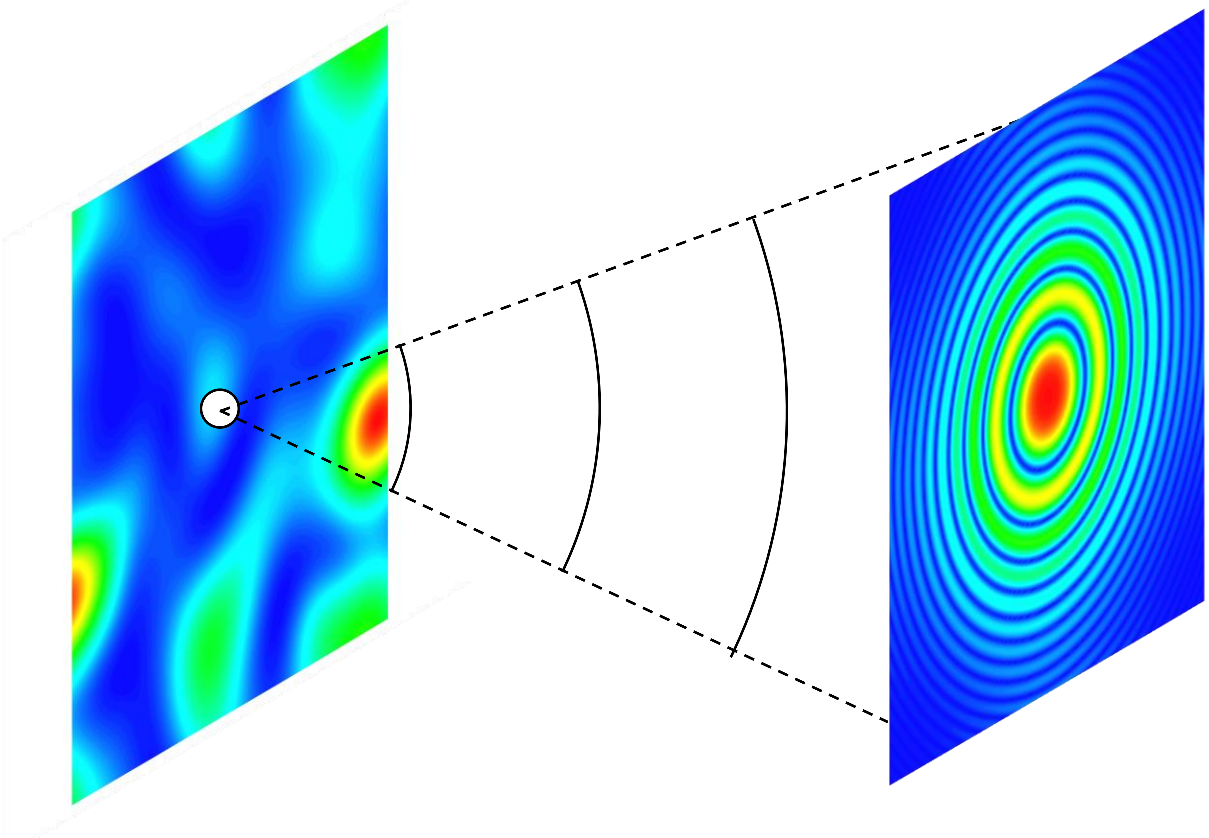

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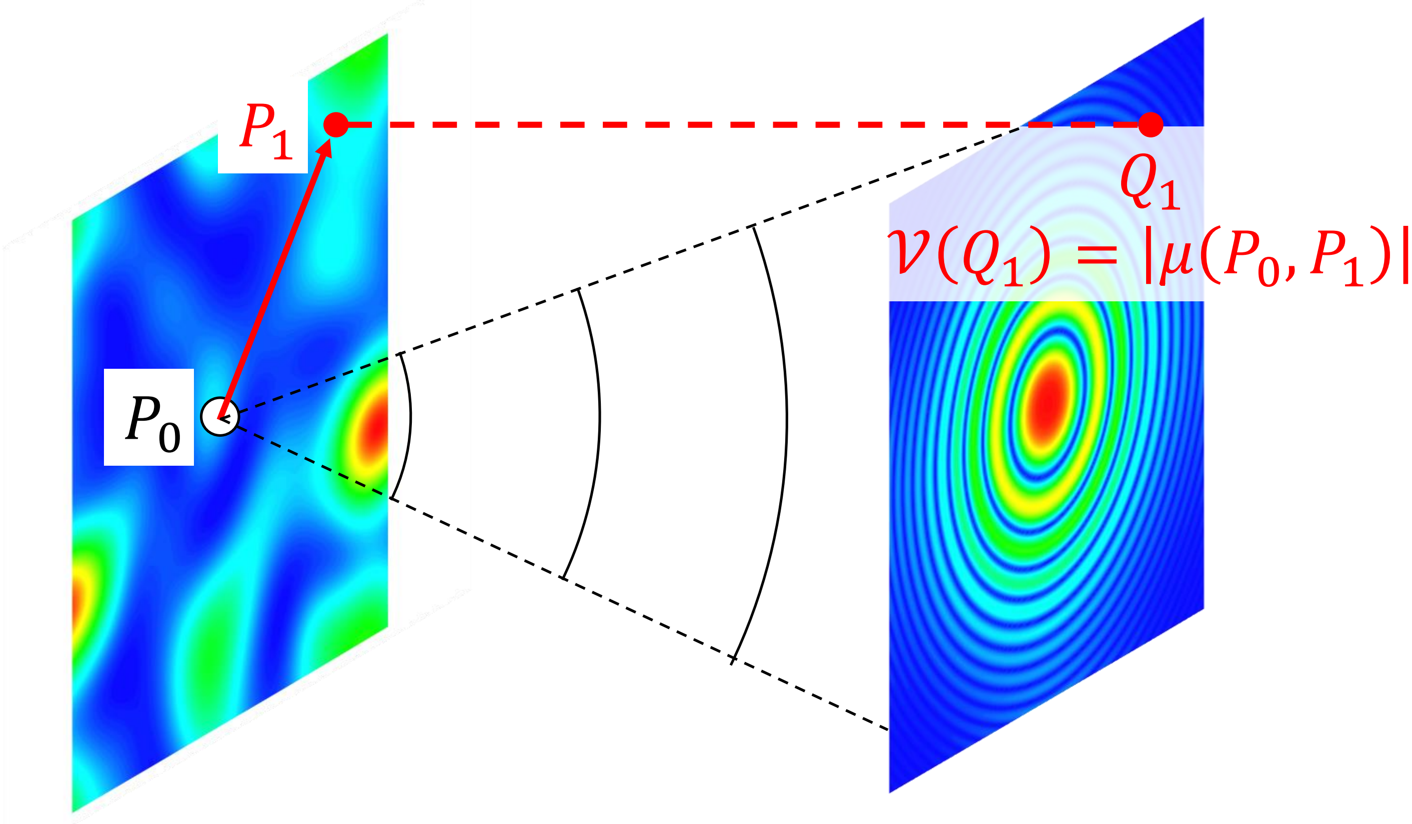

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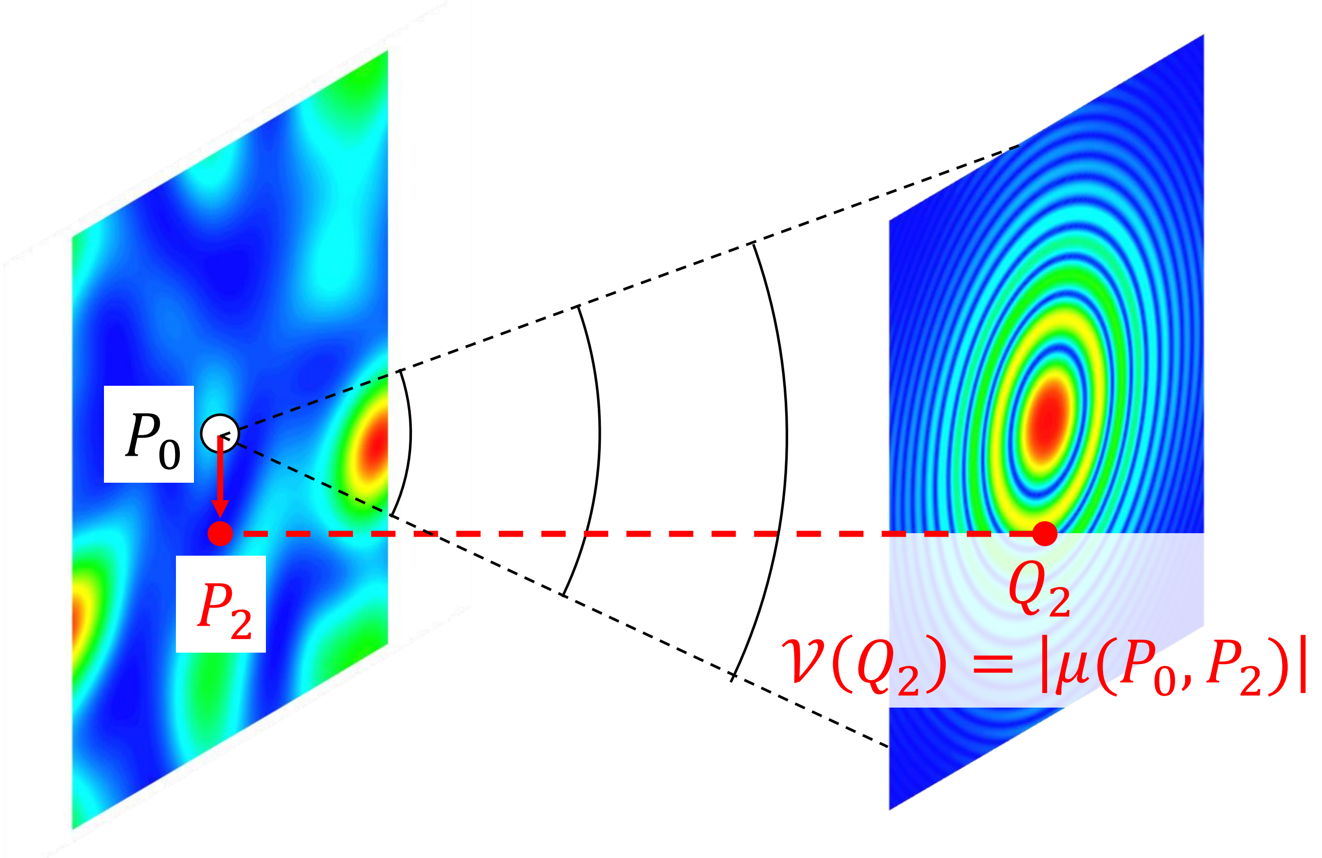

HNFS: scattering from a colloidal suspension

$$I(x,y) = \langle |E_0(x,y) + E_s(x,y)|^2 \rangle$$
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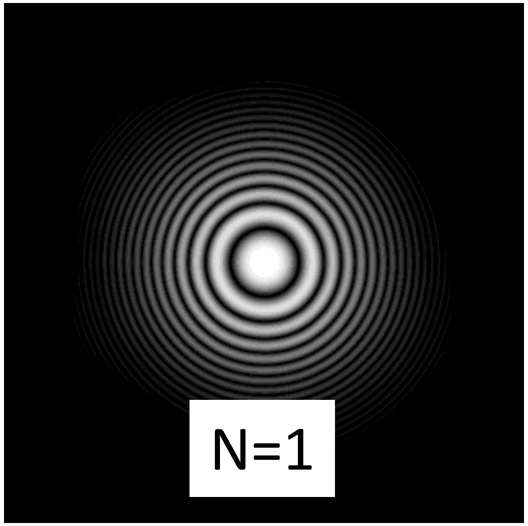
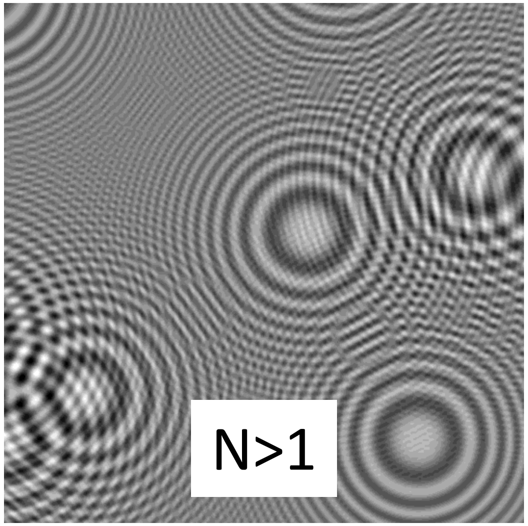
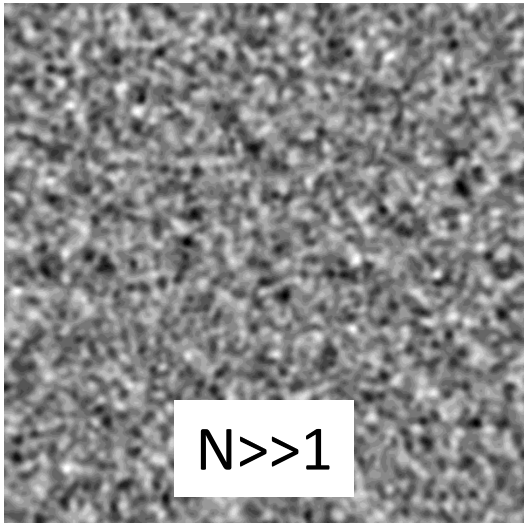
(heterodyne term) (heterodyne conditions)

$$E_s(x,y) = \sum_{j=1}^{N} \frac{E_0(x_j,y_j)}{ikz} S(0) e^{ikz} e^{i\frac{k}{2z}\left[(x-x_j)^2+(y-y_j)^2\right]}$$







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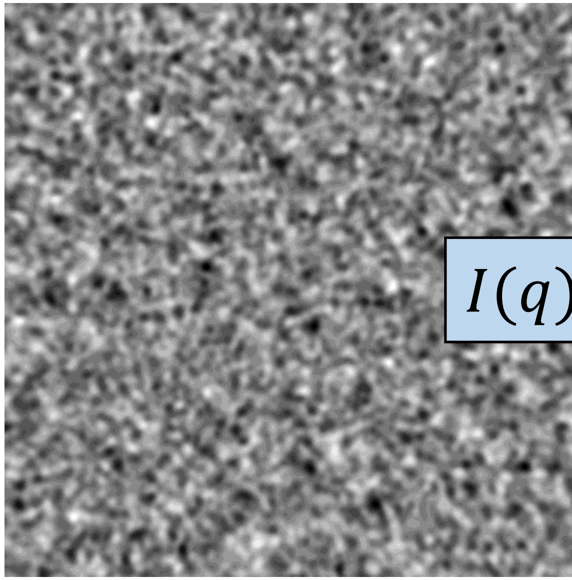
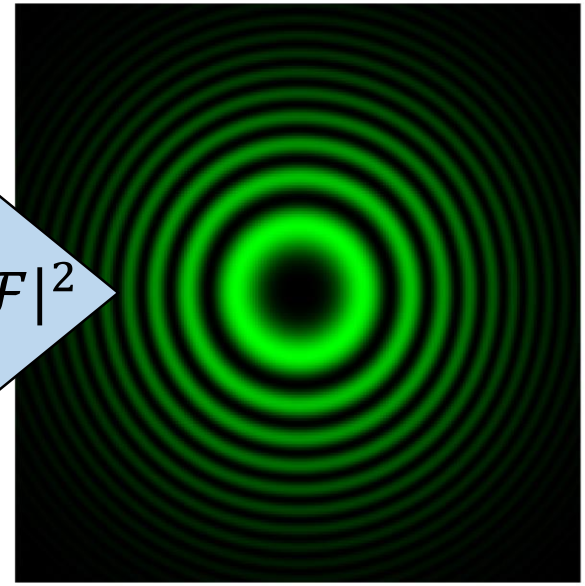


$$I(q) = |\mathcal{F}|^2$$



$$I(q) = T(q)C(q)$$

Talbot transfer function

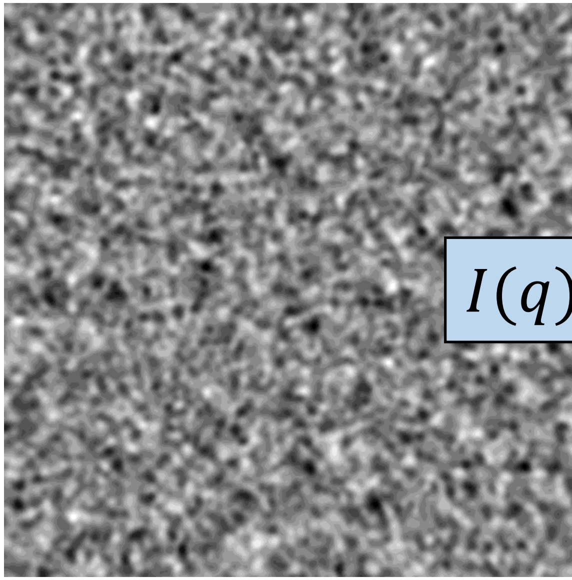
$$T(q) = \left[\sin\left(\frac{zq^2}{2k}\right)\right]^2$$

CCF (squared modulus)

M. D. Alaimo *et al.*, *Phys. Rev. Lett.* **103**, 194805 (2009)

M. A. C. Potenza *et al.*, *Phys. Rev. Lett.* **105**, 193901 (2010)

HNFS: scattering from a colloidal suspension



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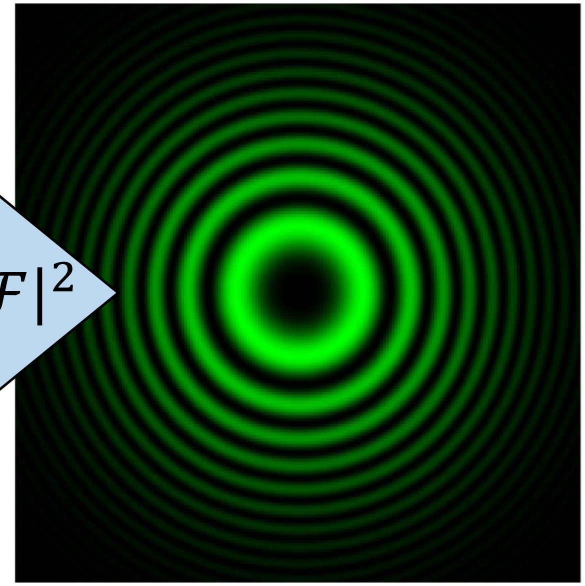


$$I(q) = S(q)T(q)C(q)H(q) + P(q)$$

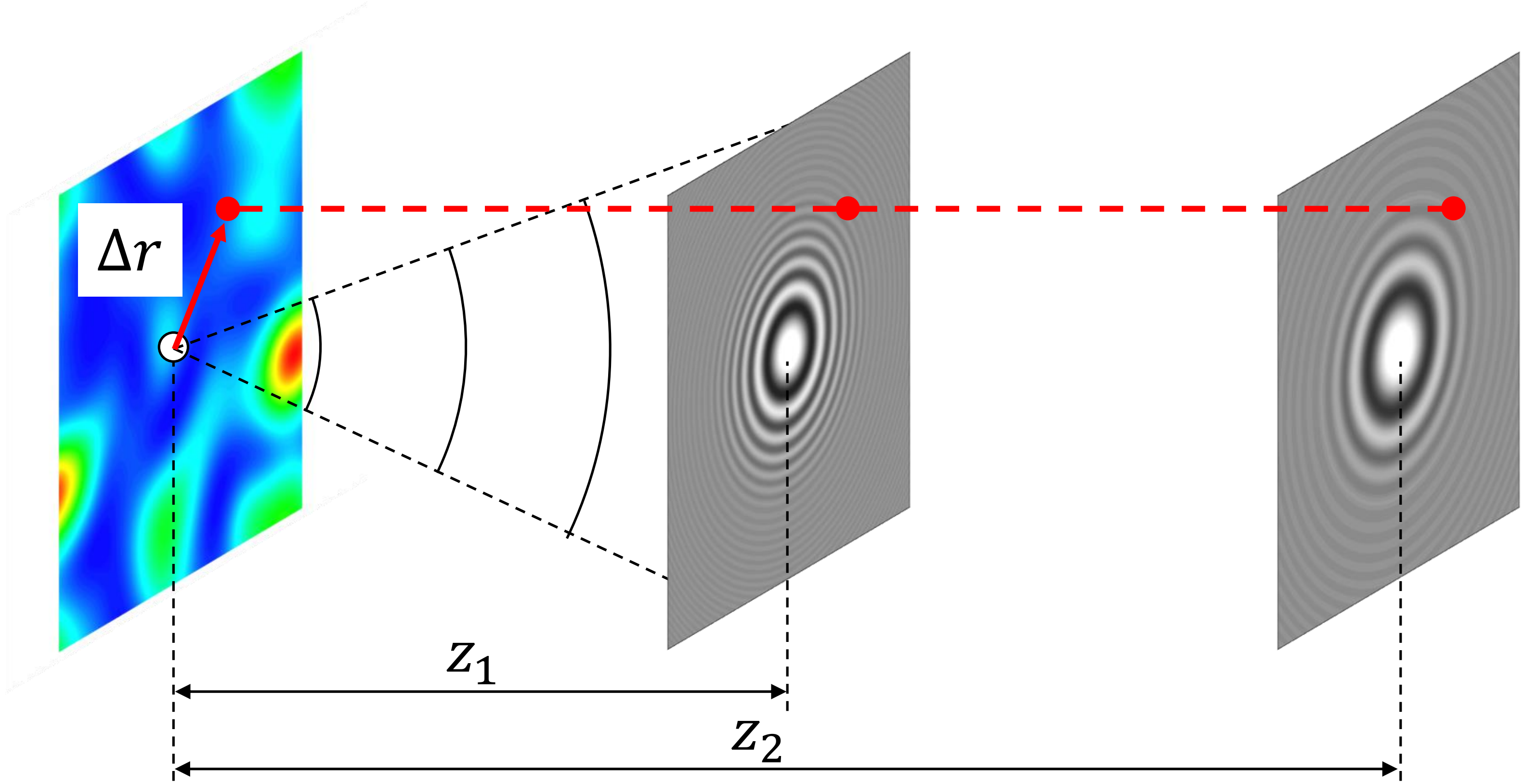
- $S(q)$: particle form factor (Mie theory)
- $T(q)$: Talbot transfer function
- $C(q)$: CCF (squared modulus)
- $H(q)$: optics transfer function (PSF)
- $P(q)$: noise contribution

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

M. D. Alaimo *et al.*, *Phys. Rev. Lett.* **103**, 194805 (2009)

M. A. C. Potenza *et al.*, *Phys. Rev. Lett.* **105**, 193901 (2010)

Spatial scaling and spatial master curve



$$q = k\frac{\Delta r}{z}$$

Spatial scaling and spatial master curve

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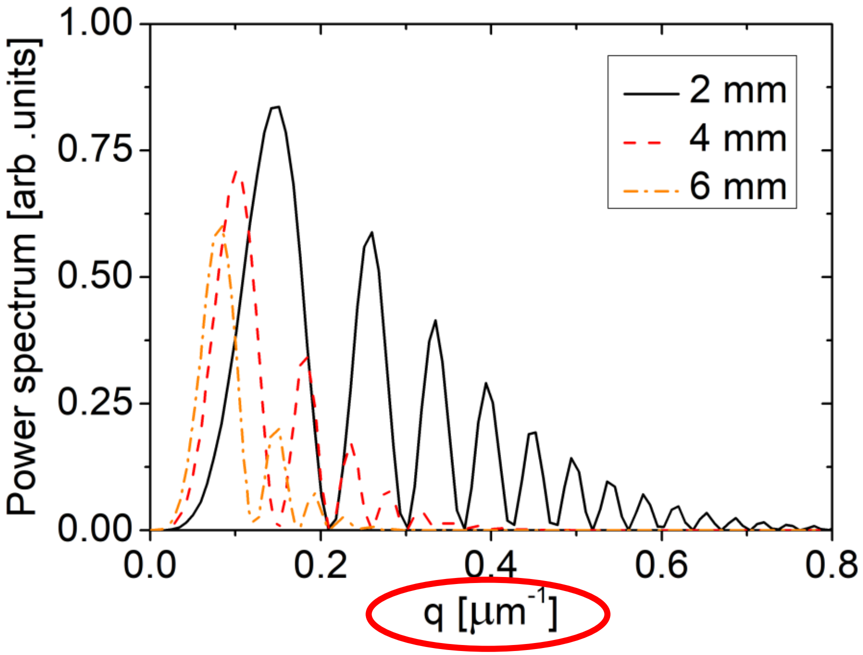


M. D. Alaimo *et al.*, *Phys. Rev. Lett.* **103**, 194805 (2009)

M. D. Alaimo *et al.*, *Opt. Express* **22**, 30013 (2014)

M. Siano *et al.*, *Phys. Rev. Accel. Beams* **20**, 110702 (2017)

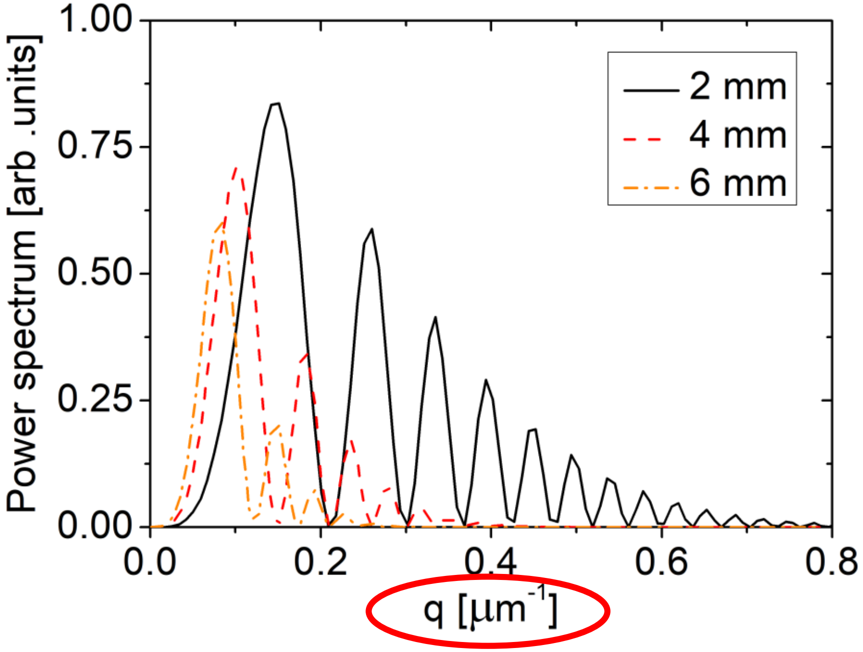
Spatial scaling and spatial master curve

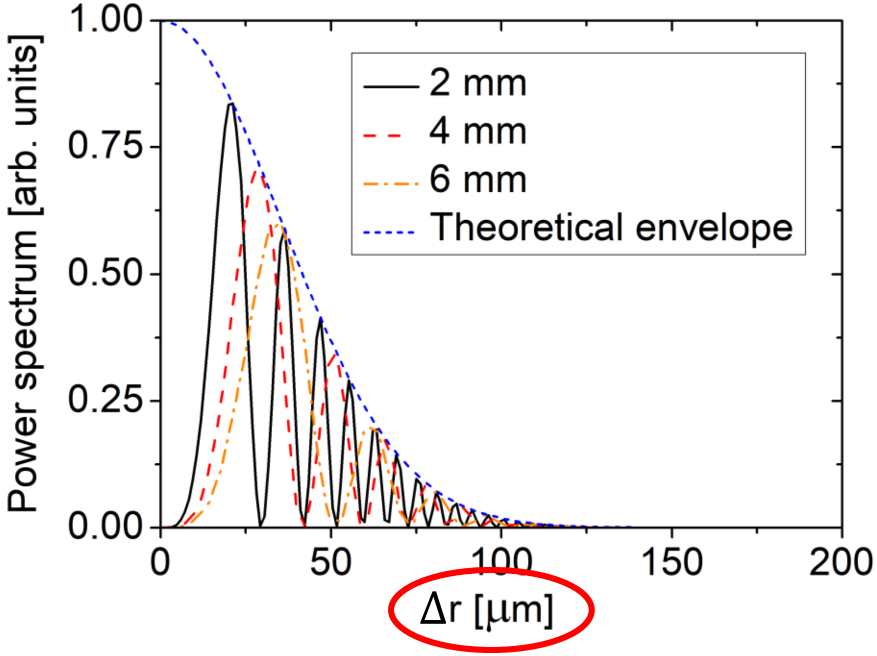
$$q = k\frac{\Delta r}{z}$$

spatial scaling

$$\Delta r = z\frac{q}{k}$$

spatial master curve





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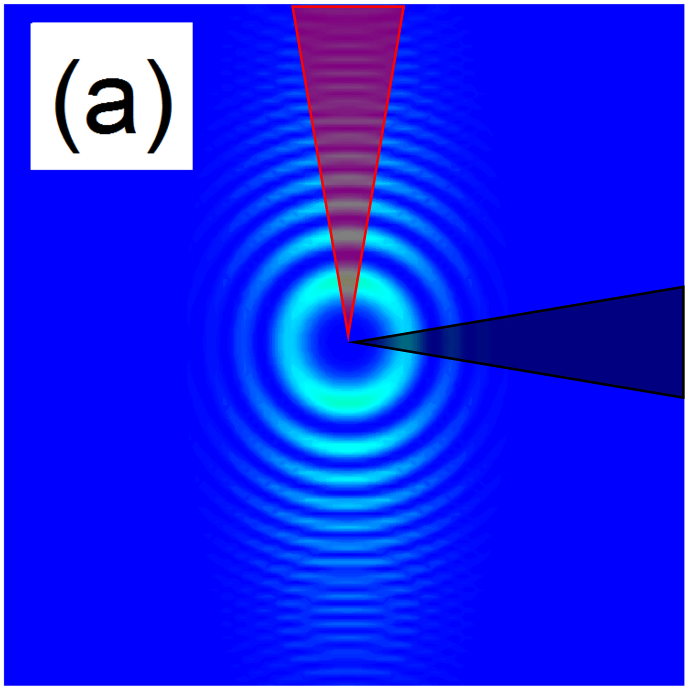
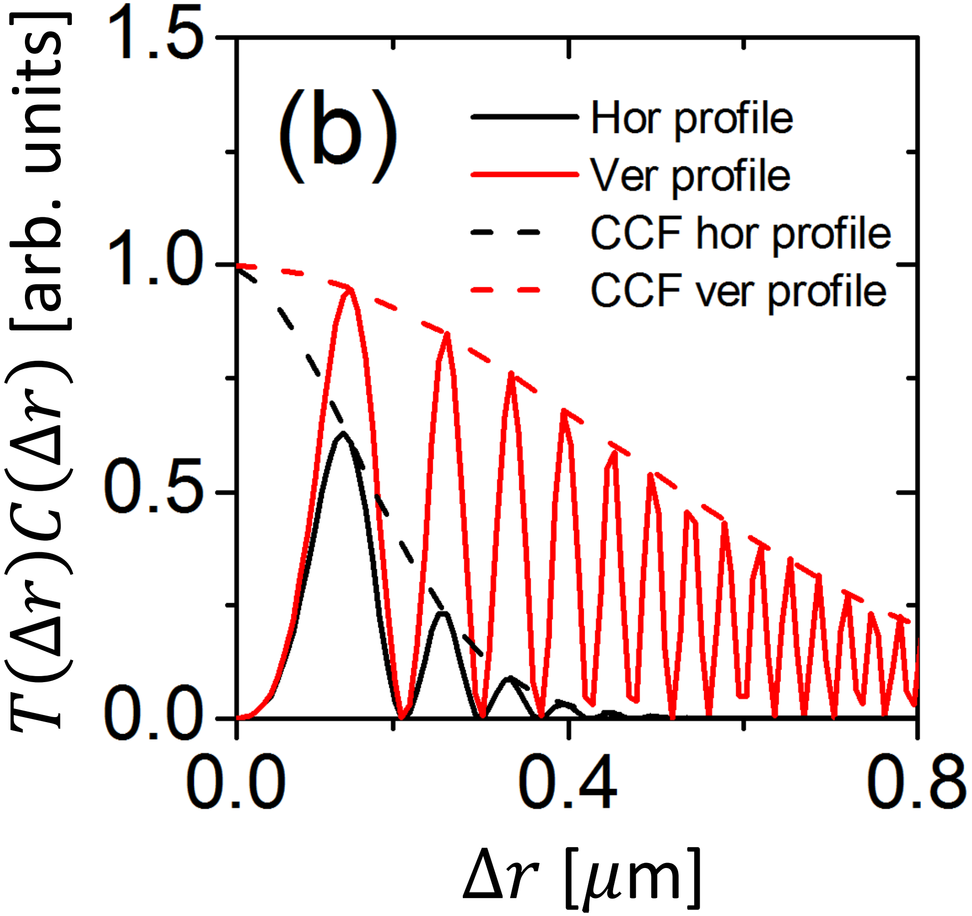
M. Siano *et al.*, *Phys. Rev. Accel. Beams* **20**, 110702 (2017)

2D transverse coherence measurements





HNFS: image acquisition and data processing

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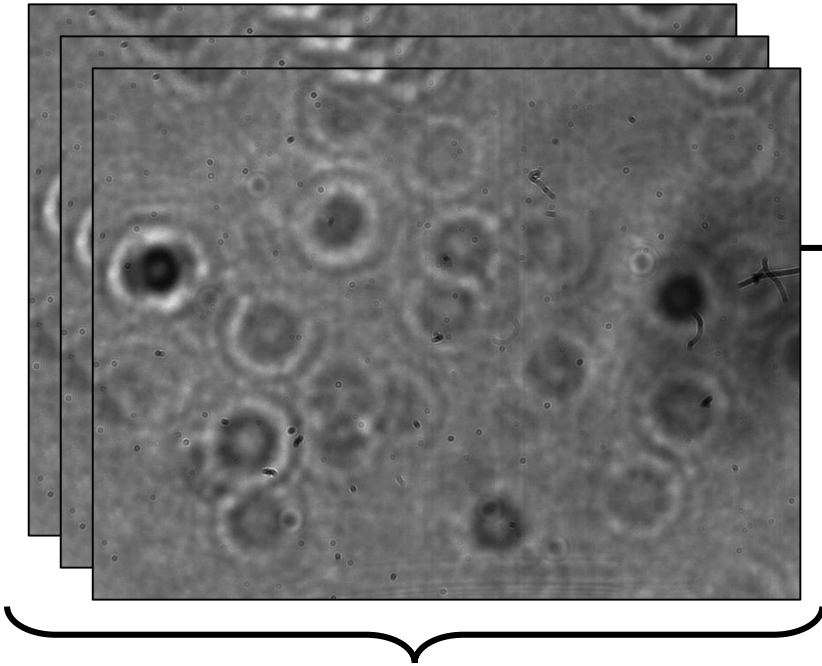
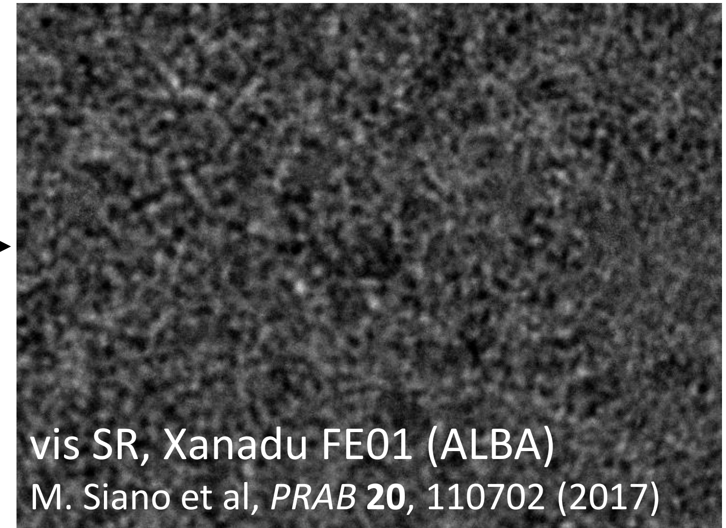


average frame



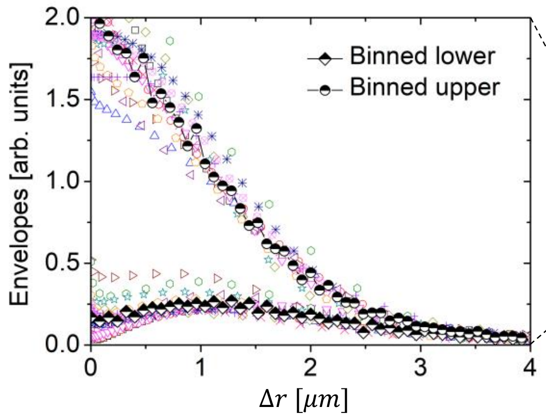
average power spectrum

profile

T(q)C(q)

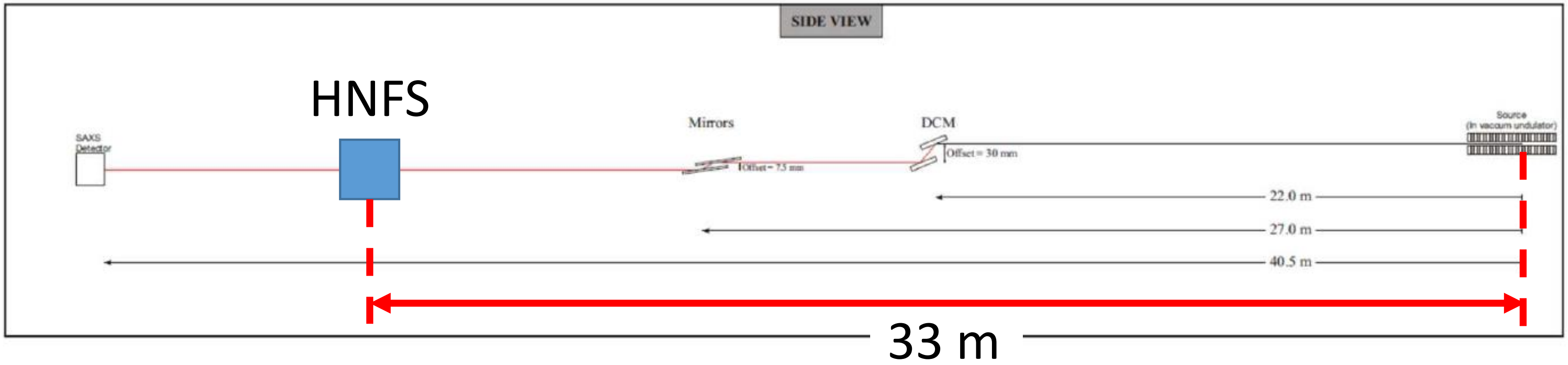
upper and lower envelopes

C(Δr) as envelopes average



Experimental results at NCD beamline (ALBA)

The NCD beamline (BL11) at ALBA



e^- beam energy = 3 GeV
$\gamma = 6000$

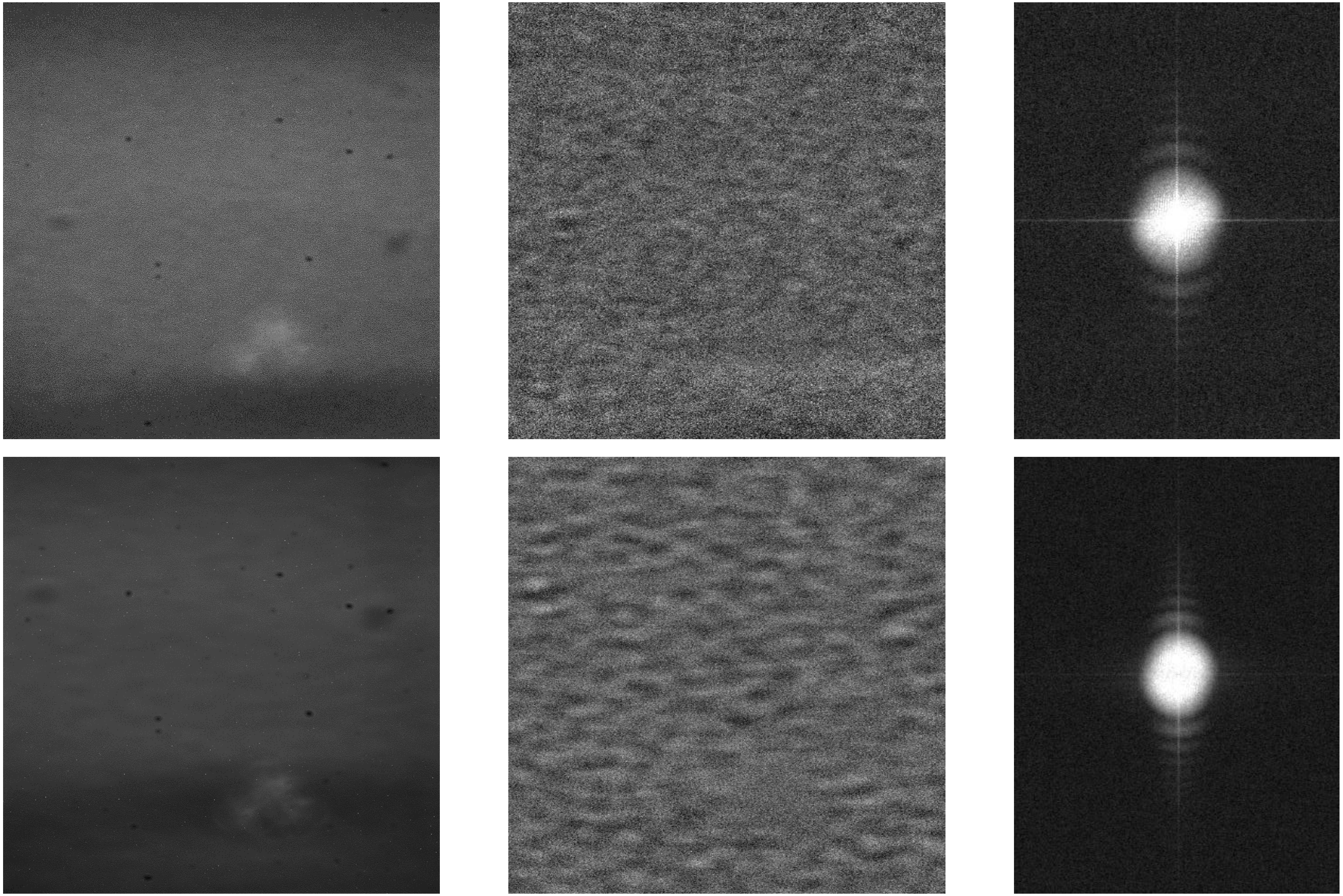
$K = 1.2 \div 1.3$
$\lambda = 1$ Å
ph. energy = 12.4 keV
Resonant 5th harm.

z = 15 cm, 35 cm, 55 cm

Beamline specification			
Wavelength range	λ	0.9 Å- 1.9 Å	
Energy range	-	6.5 keV - 13 keV	
Flux at sample position	-	$2 \cdot 10^{12}$ ph/s	
Monochromator relative bandpass	$\Delta E/E$	$< 10^{-4}$	

Undulator source			
Wiggler wavelength	λ_w	21.3 mm	
Number of wigglers	N_w	92	
K at minimum gap	$K_{\min}$	1.6	
Hor. beam size (FWHM)	σ_x	309 μm	(132)
Ver. beam size (FWHM)	σ_y	18 μm	(7.7)
Hor. divergence (FWHM)	σ'_x	112 μrad	(48)
Ver. divergence (FWHM)	σ'_y	28-22 μrad	(12-9.3)

HNFS experimental results at BL11



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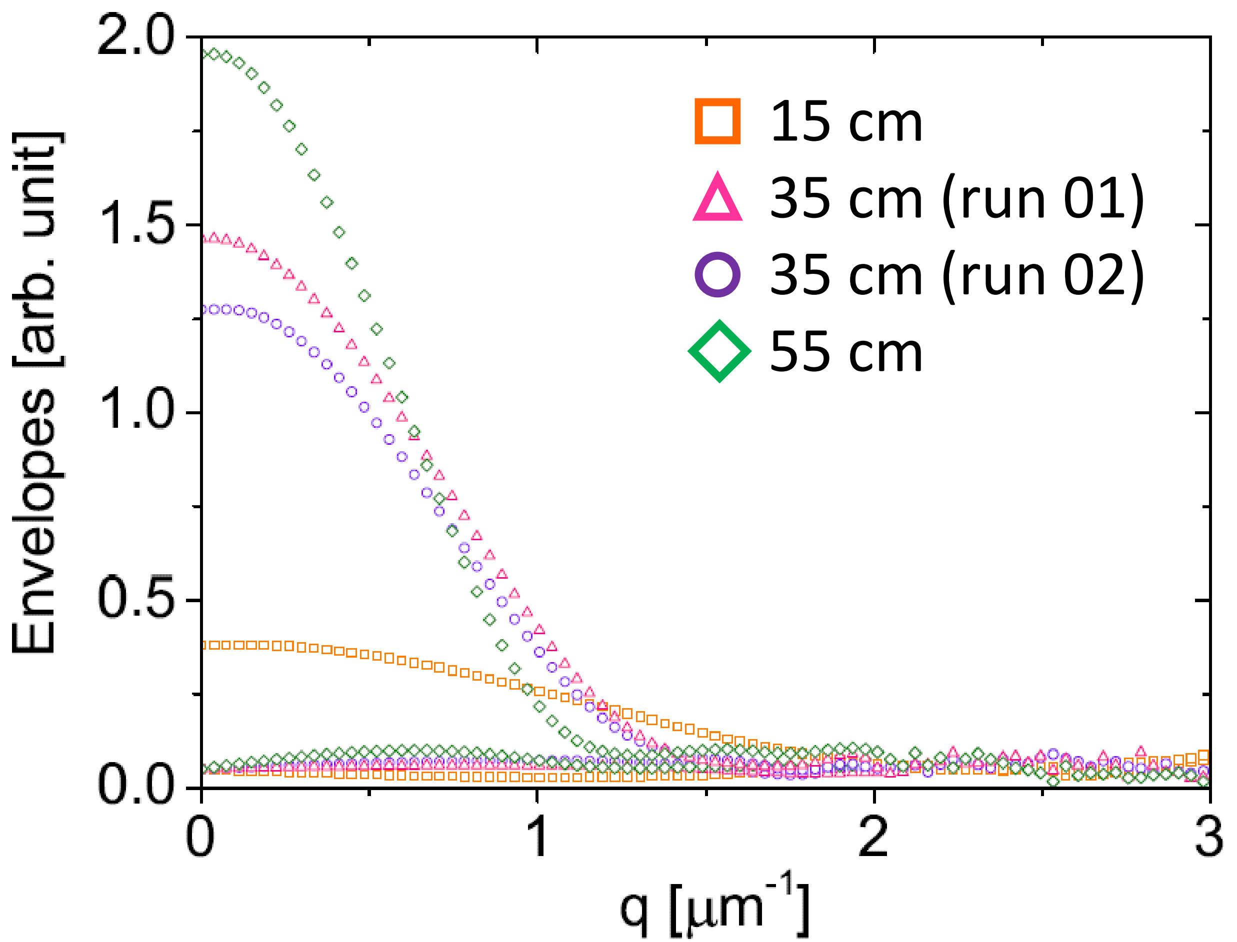
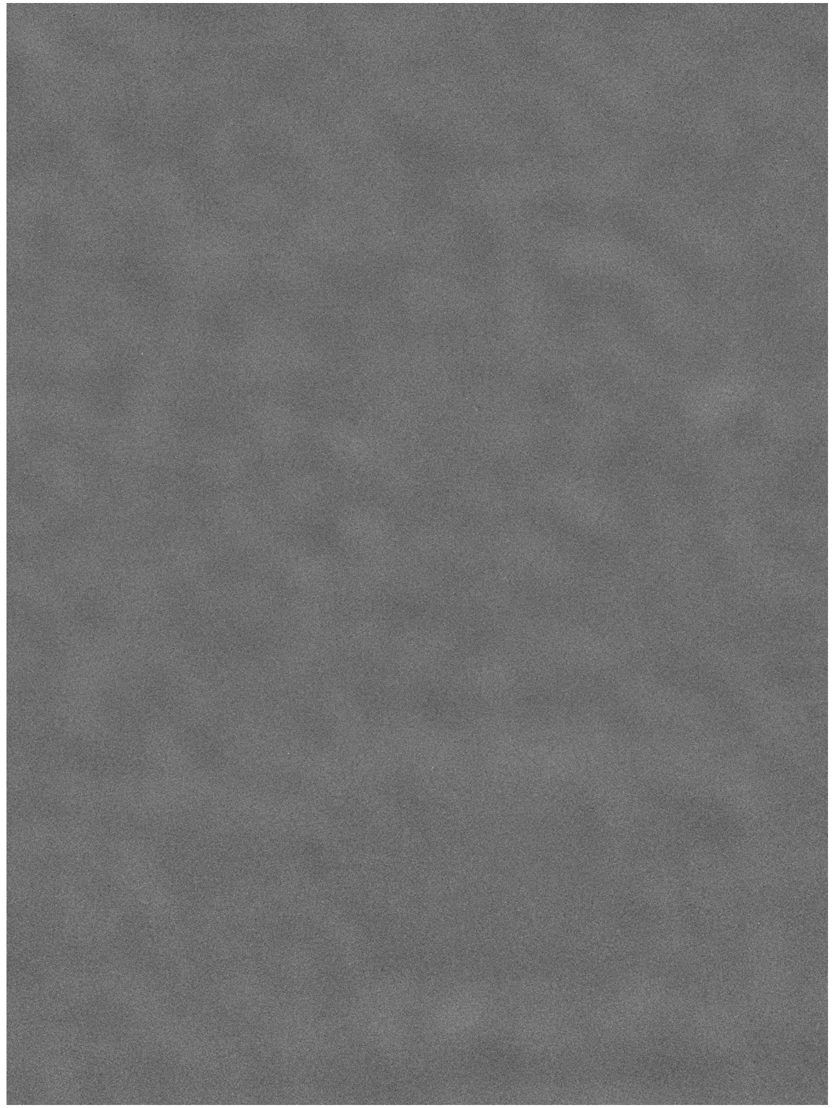


Power spectra instabilities at BL11



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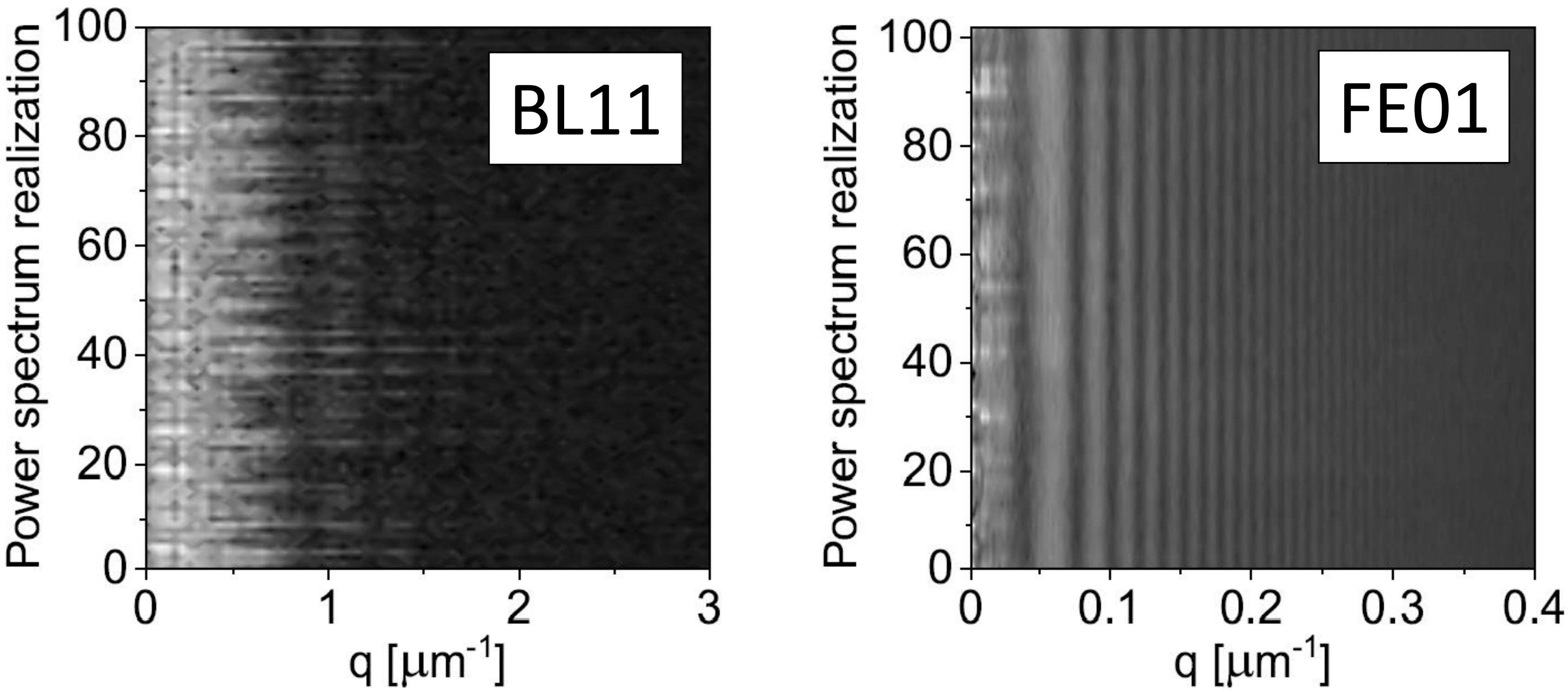

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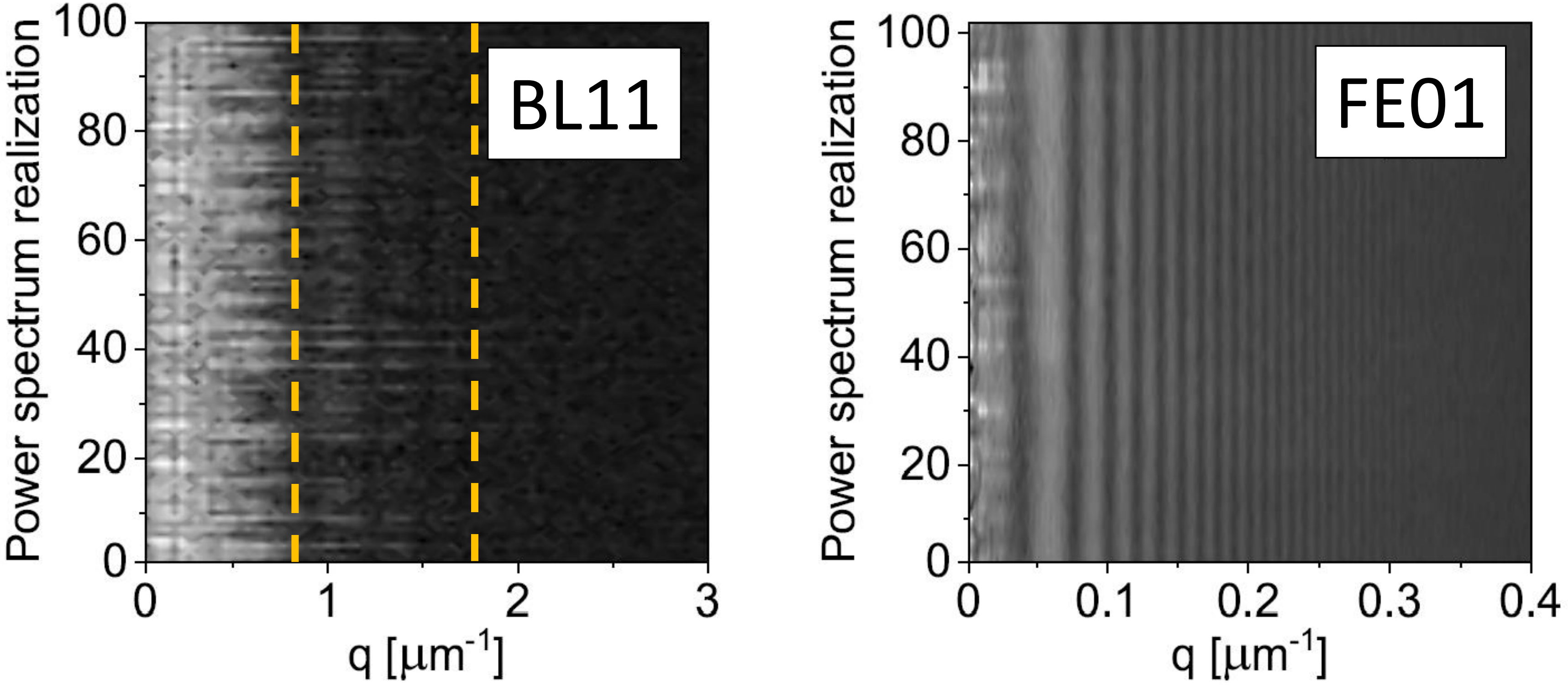
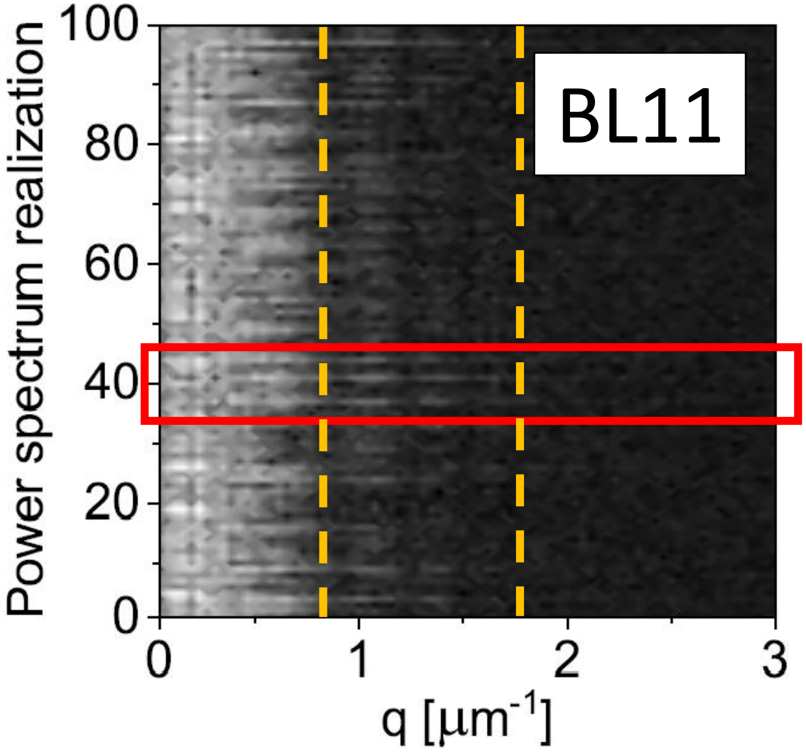
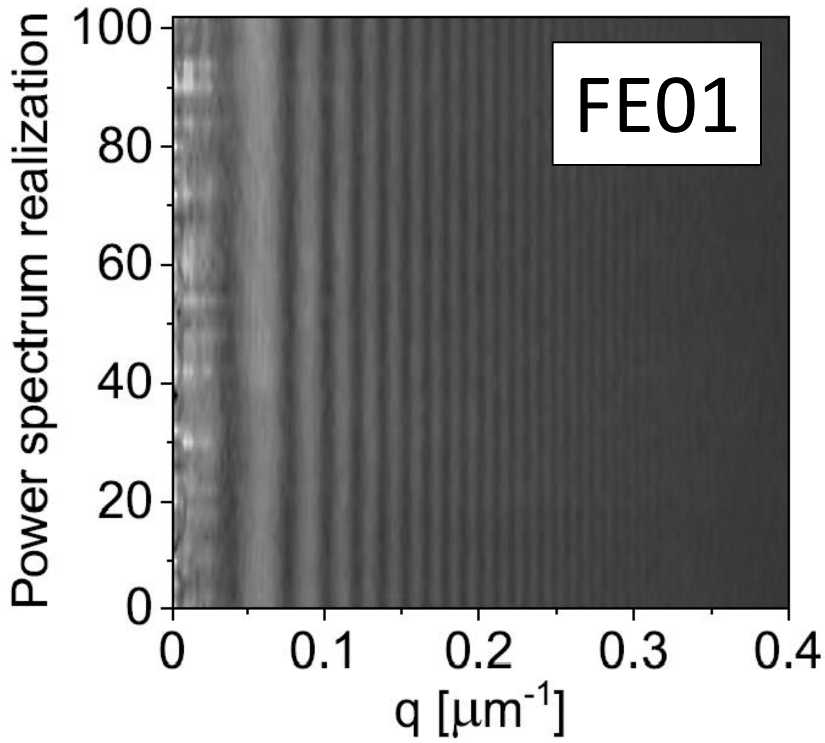


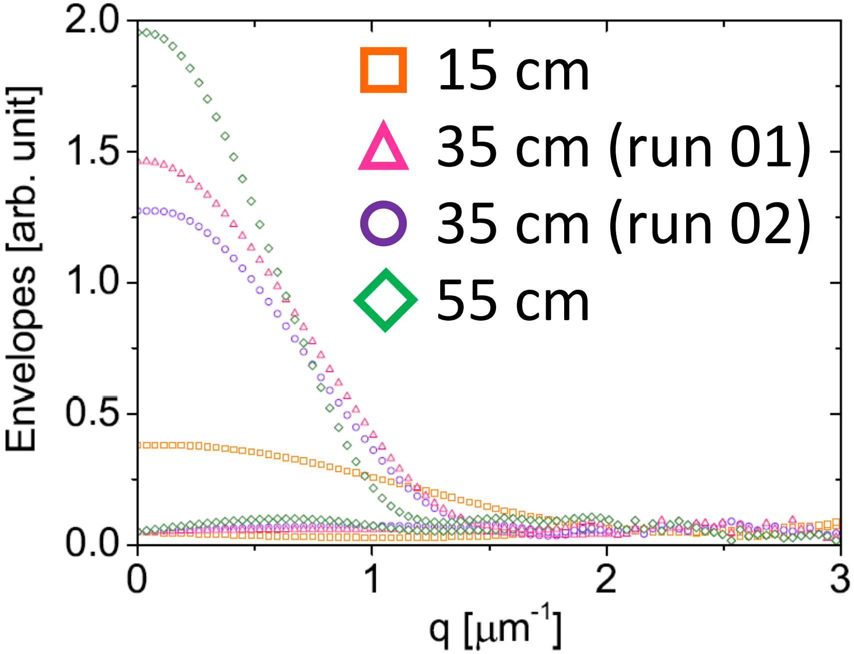
Power spectra instabilities at BL11



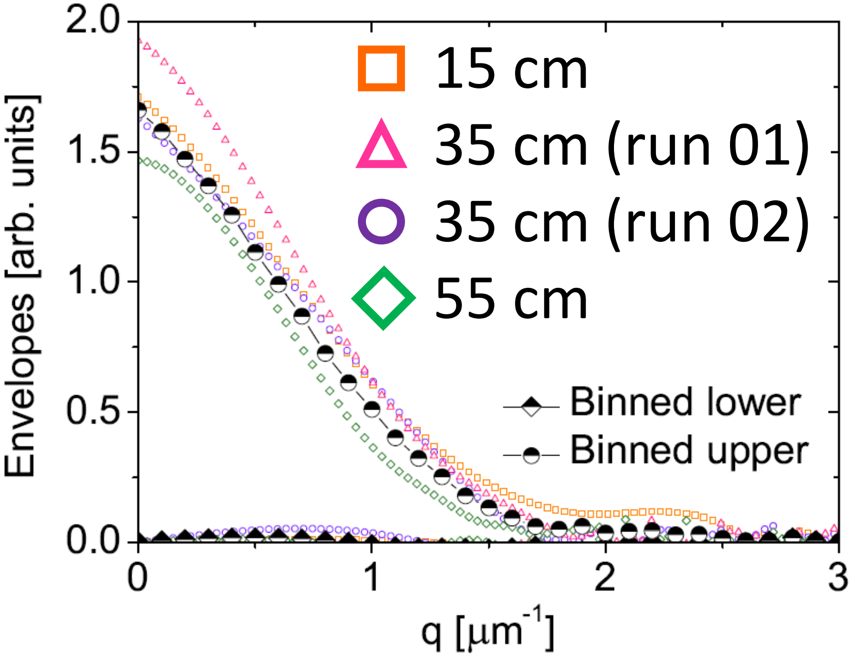


Results along the vertical direction at BL11

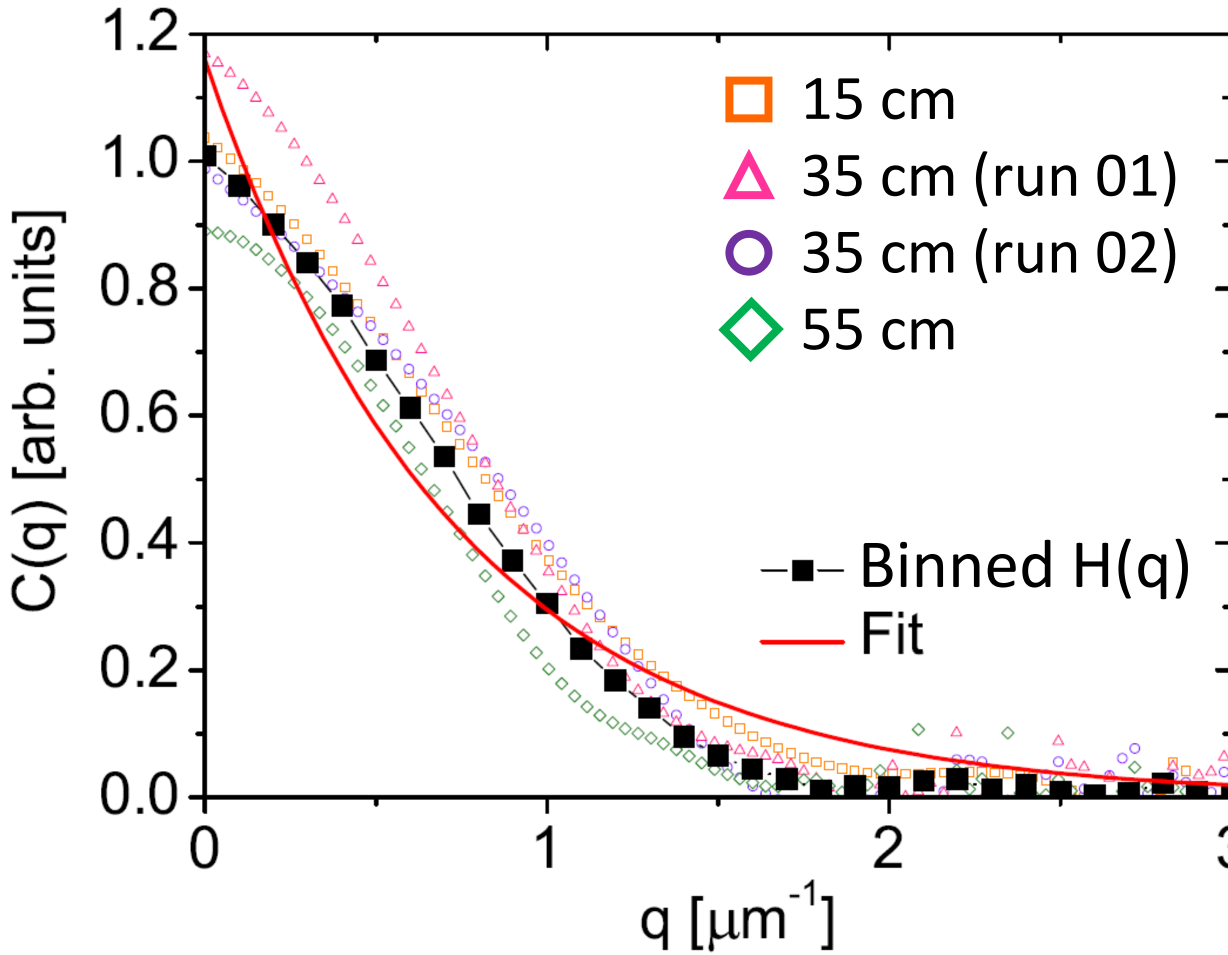
All



Selected



Results along the vertical direction at BL11

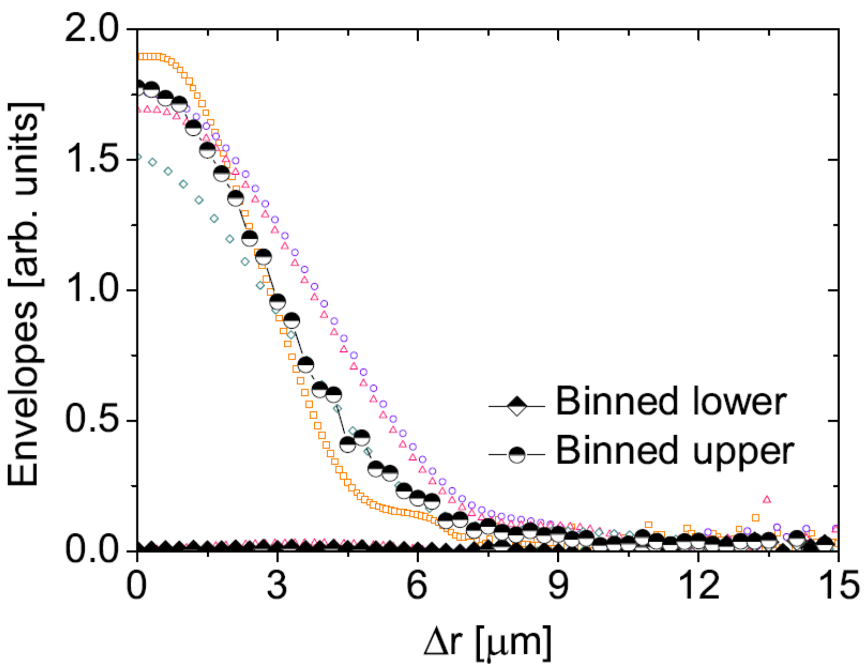


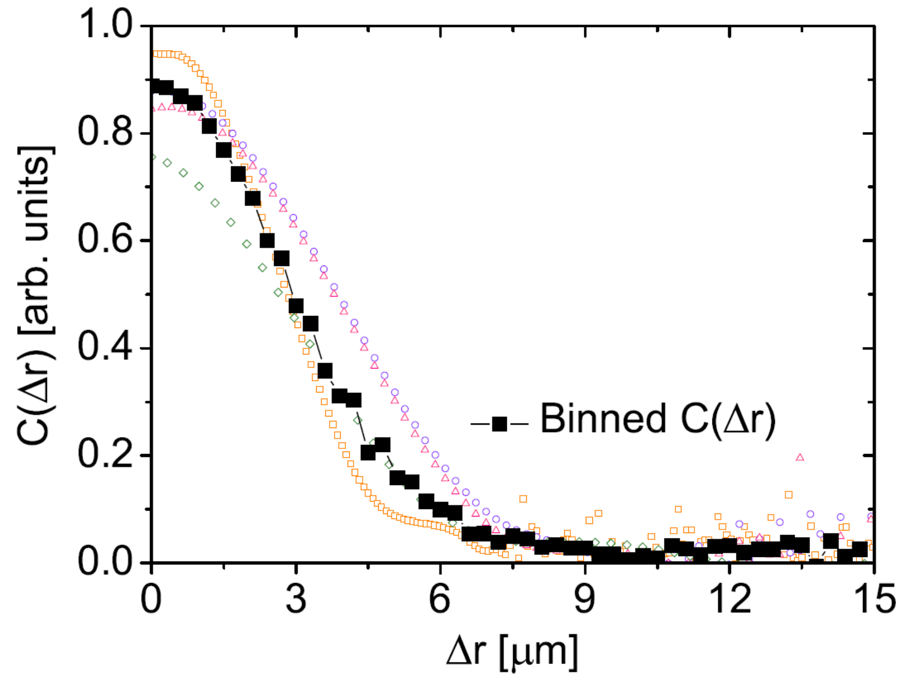
$$\sigma_{coh,y} > z_{max}\frac{q_{max}}{k} = 18\ \mu m$$

VCZ →

$$\sigma_y < 50 \div 55\ \mu m$$

Results along the horizontal direction at BL11



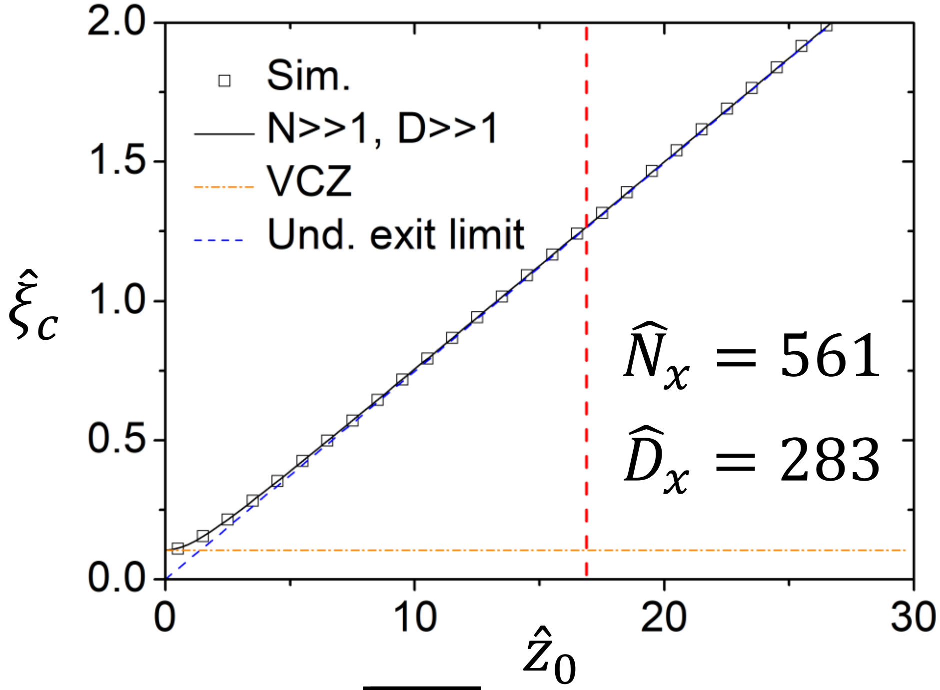


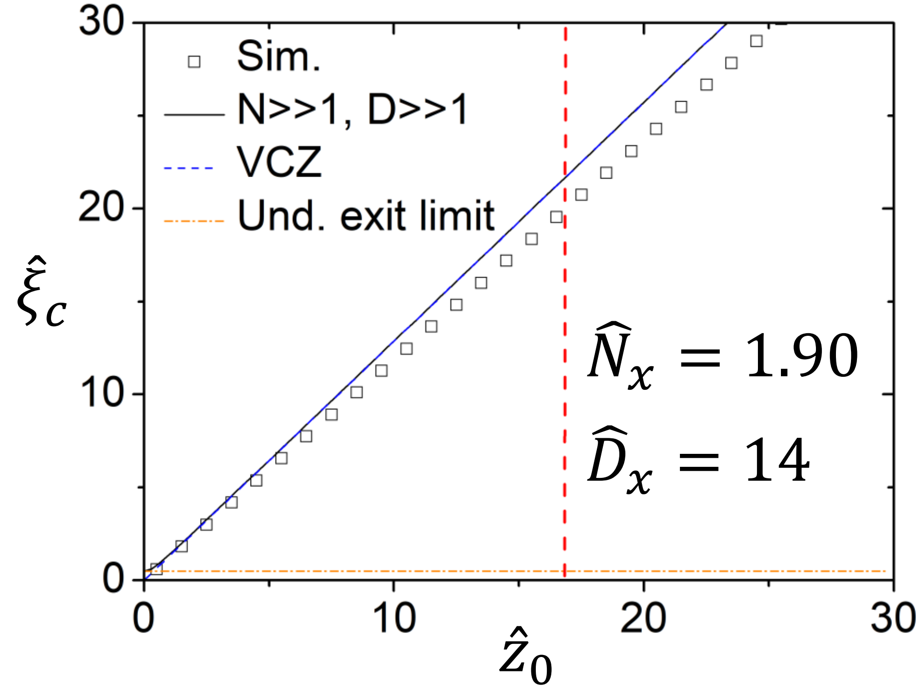
$$\sigma_{coh,x} = \int_{-\infty}^{+\infty} |\mu(\Delta r)|^2 \, d\Delta r = 2 \int_{0}^{+\infty} C(\Delta r) \, d\Delta r = (6.9 \pm 1.3) \;\mu m$$

↓ VCZ

$$\sigma_x = (135 \pm 25)\mu m$$

GPU-based code for transverse coherence simulation



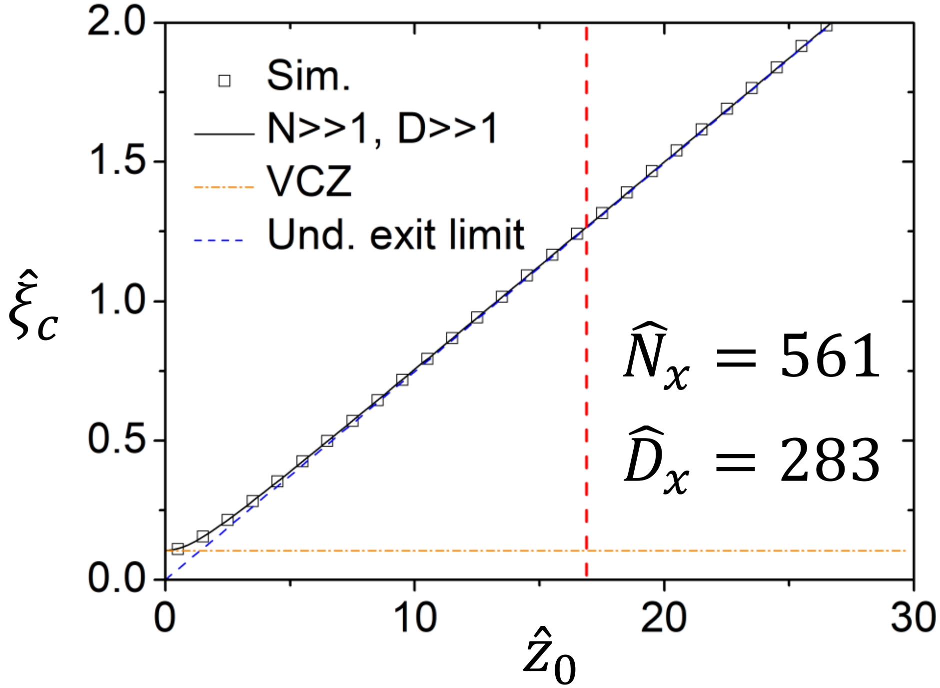


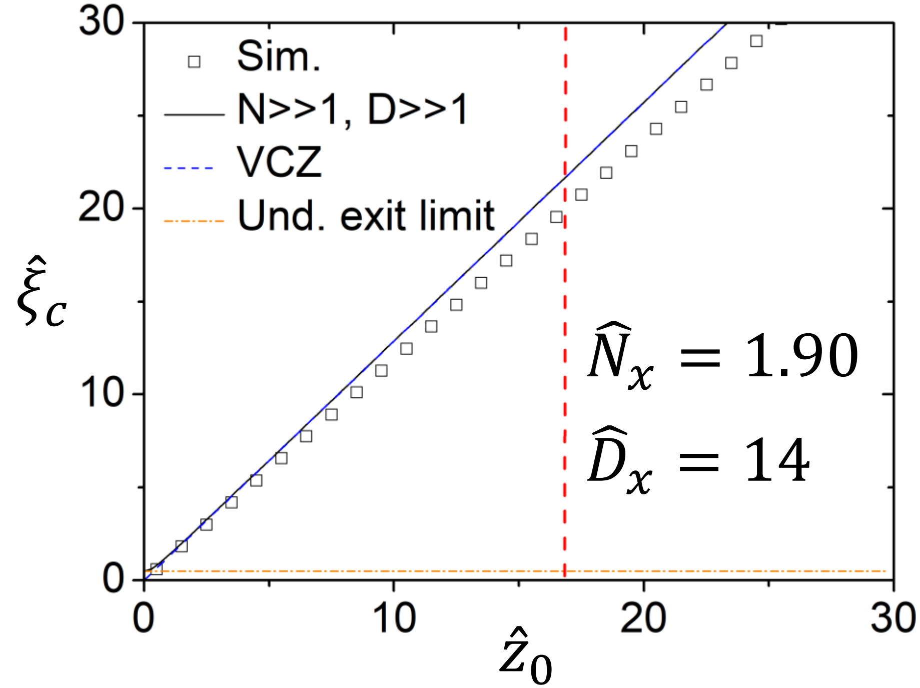
$$\hat{\xi}_c = \sigma_{coh}\sqrt{\frac{2\pi}{\lambda L_w}} \qquad \hat{z}_0 = \frac{z}{L_w} \qquad \hat{N} = \frac{2\pi\sigma^2}{\lambda L_w} \qquad \hat{D} = \frac{2\pi\sigma'^2}{\lambda / L_w}$$

$$\sqrt{\frac{\lambda L_w}{2\pi}} = 5.58\ \mu\text{m}$$

G. Geloni et al., *Nucl. Instrum. Methods Phys. Res., Sect. A* **588**, 463 (2008)

GPU-based code for transverse coherence simulation





$\sigma_x = 132\ \mu m$

$\hat{\xi}_{c,x} = 1.24$

$\sigma_{coh,x} = 7.1\ \mu m$

$\sigma_{coh,x,m} = (6.9 \pm 1.3)\ \mu m$

$\sigma_x = (135 \pm 25)\ \mu m$

$\sigma_y = 7.7\ \mu m$

$\hat{\xi}_{c,y} = 20$

$\sigma_{coh,y} = 112\ \mu m$

$\sigma_{coh,y,m} > 18\ \mu m$

$\sigma_y < 50 \div 55\ \mu m$

Conclusions and perspectives

Conclusions

- Aim: coherence-based beam size measurements in third generation light sources
- Probe 2D transverse coherence of SR by means of spatial power spectra of heterodyne speckle fields generated by scattering from spherical nanoparticles suspended in a liquid
- Simple setup, wavelength independent, suitable for X-rays without any dedicated optics, high statistics due to Brownian motions
- Scaling law and master curve criterion for spatial coherence
- Merge data at different distances (internal check + increased accuracy)

Conclusions

- Applied at the ALBA Synchrotron Light Source to retrieve the electron beam size from the probed transverse coherence of X-ray undulator radiation (λ=0.1 nm)
- Ver: limited by phosphor, upper limit to e^- beam size (σ_v<50 μm)
- Hor: first e^- beam size measurement with HNFS ⟶ σ_h=(135±25) μm
- Good agreement with nominal values and simulations
- VCZ does not hold in the ver direction

Perspectives

- Characterization of power spectra instabilities (likely due to vibrations)
- Increase S/N ratio hence accuracy
- Survey of colloidal particles and scintillator screens
- Probe transverse coherence in the ver direction and retrieve ver e^- beam size
- Further development and optimization of the simulation code
- Include detuning and energy spread effects, as well as treatment of even harmonics

Acknowledgements

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L. Torino (now at ESRF)
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S. Mazzoni
G. Trad
A. N. Goldblatt — CERN

M. Manfredda — ELETTRA Synchrotron
G. Geloni — European XFEL

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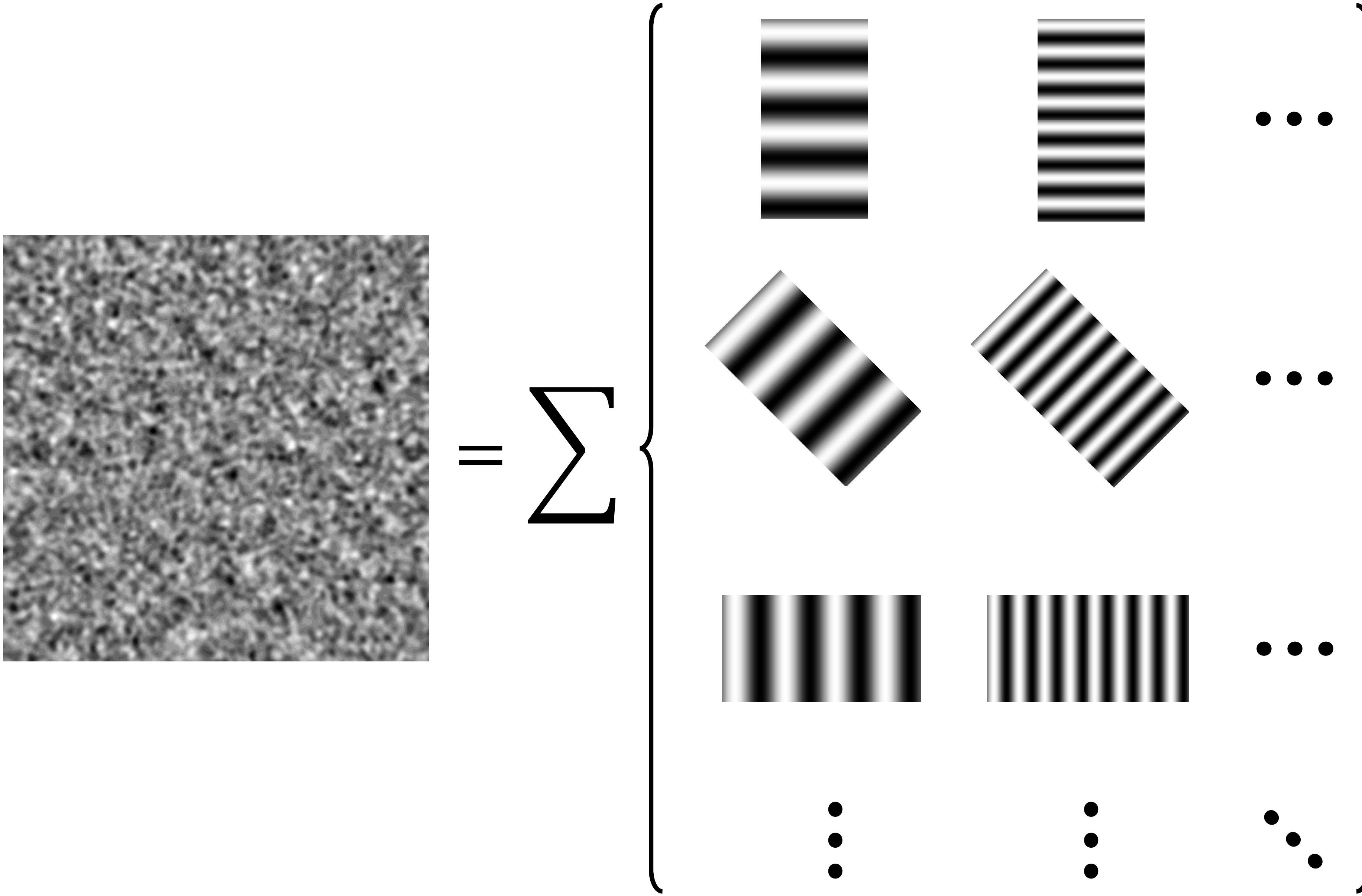
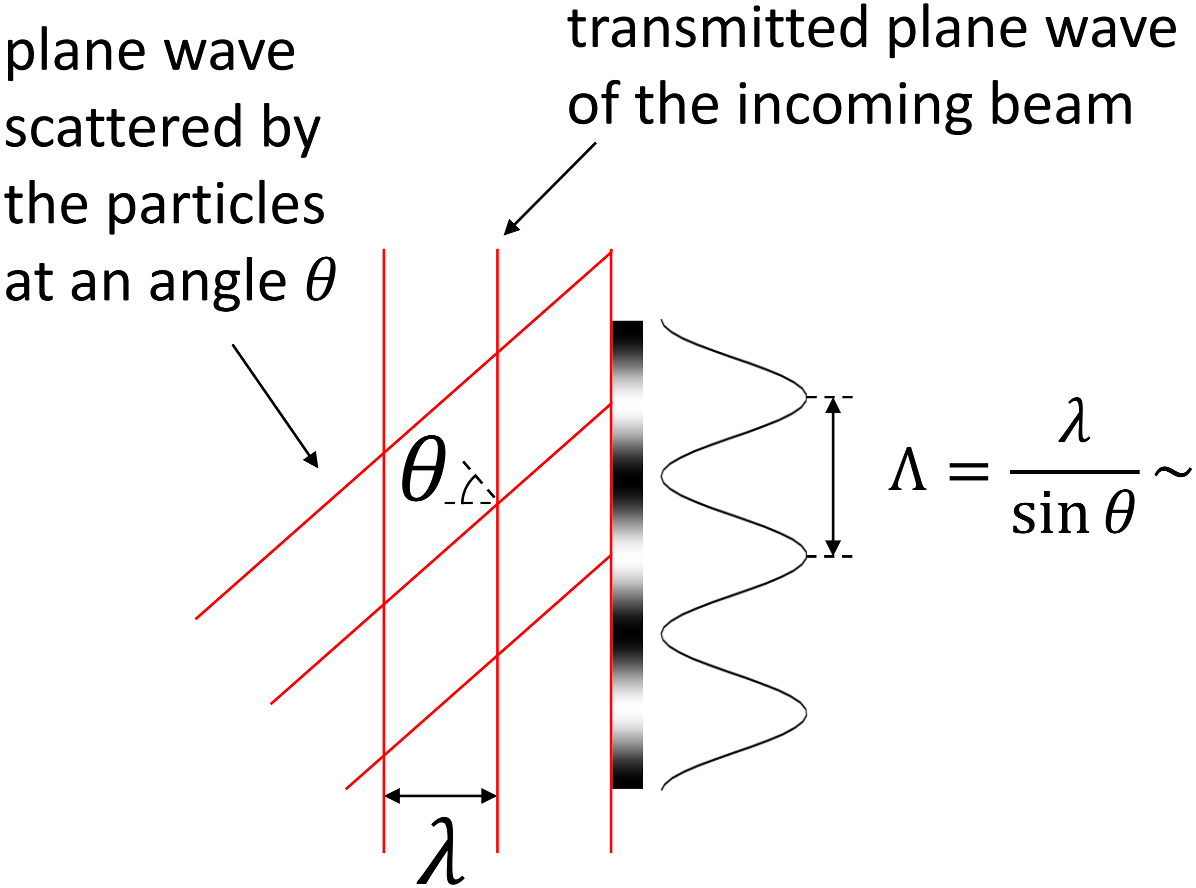
THANK YOU ALL
FOR YOUR KIND ATTENTION!

Extra slides

HNFS: a Fourier Optics approach



HNFS: a Fourier Optics approach

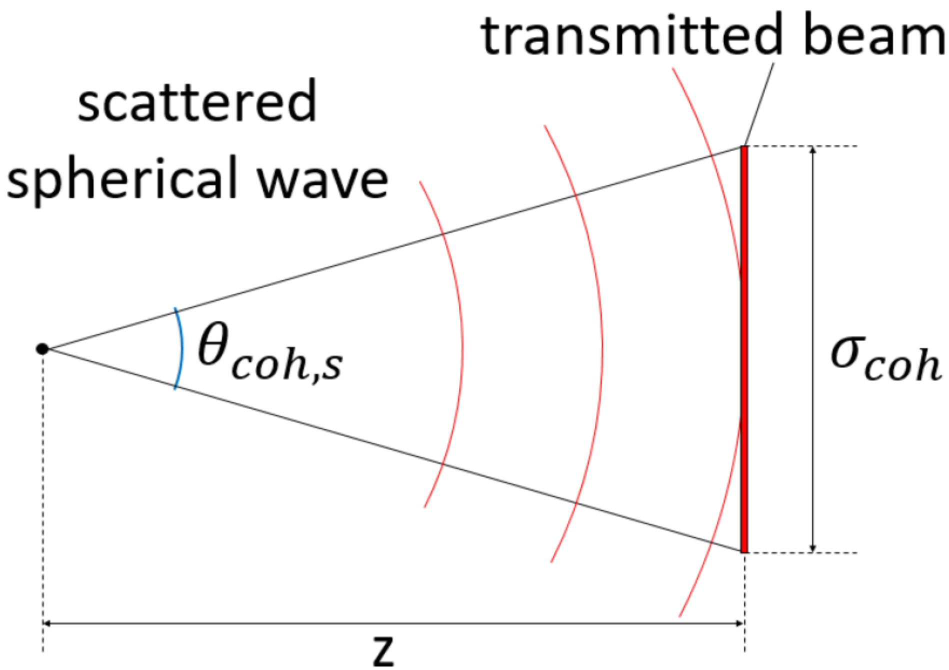


$$\Lambda = \frac{\lambda}{\sin\theta} \sim \frac{\lambda}{\theta} \rightarrow q = \frac{2\pi}{\Lambda} = k\theta$$

For a discrete detector of size $N_{pix}\left(\frac{d_{pix}}{M}\right)$, the minimum spatial frequency is given by $q_{min} = \frac{2\pi M}{N_{pix} d_{pix}}$.
The i-th pixel corresponds to $q_i = i q_{min}$.

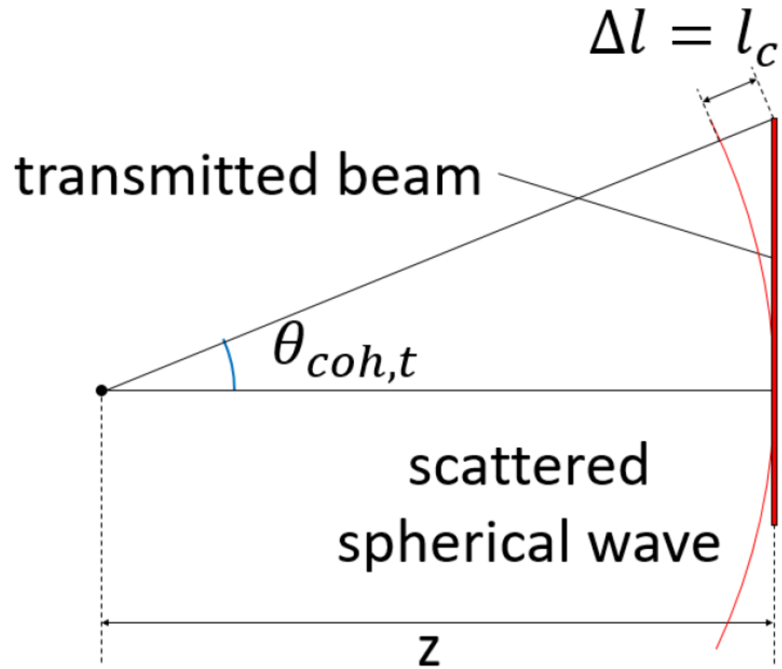
HNFS: a Fourier Optics approach

Limited spatial coherence



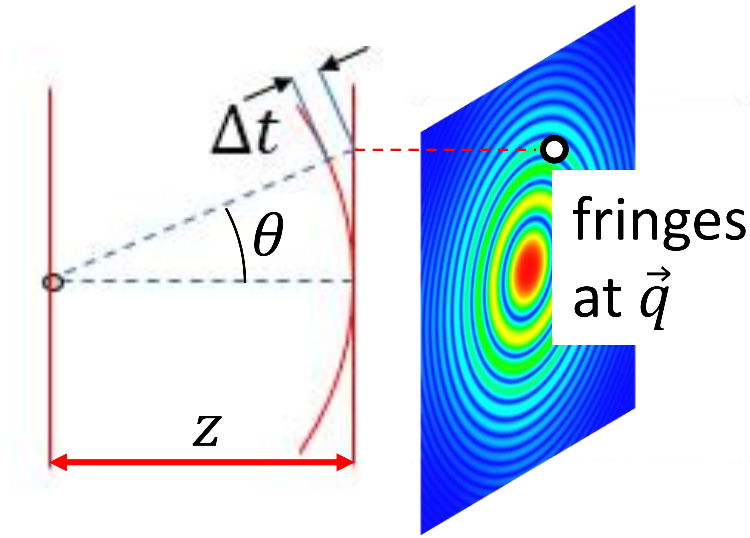
$$\theta_{max} = \frac{\sigma_{coh}}{z}$$

Limited temporal coherence



$$\theta_{max} = \sqrt{\frac{2 l_c}{z}}$$

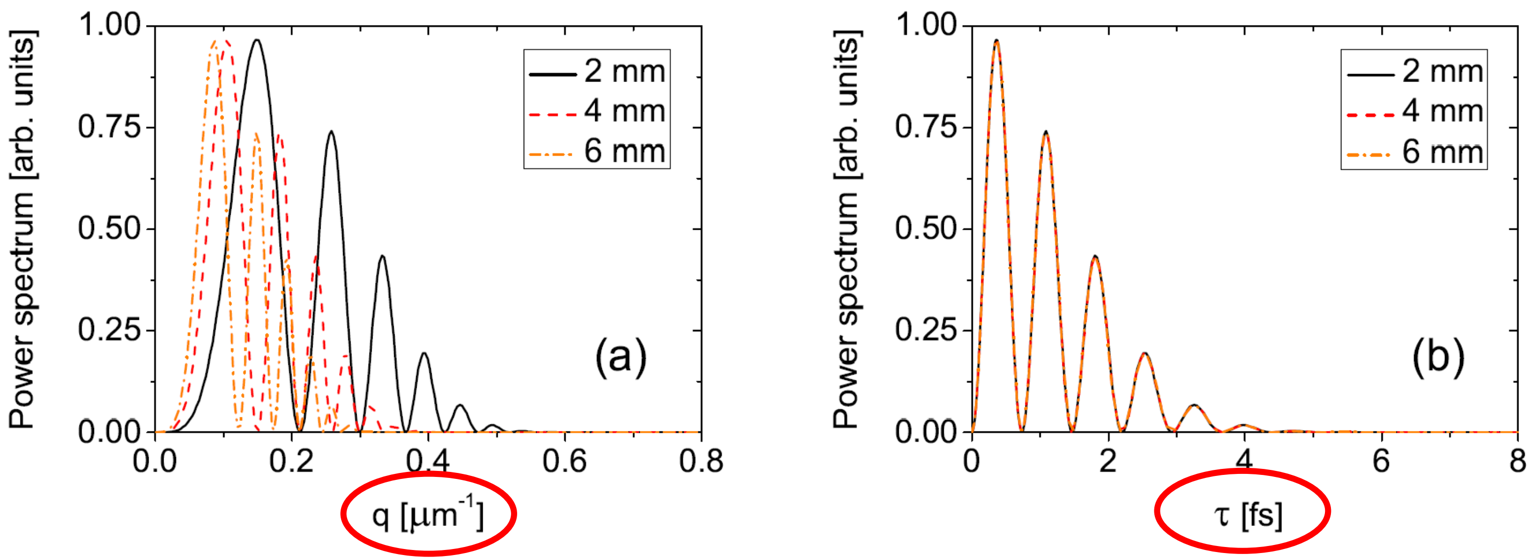
Temporal scaling and temporal master curve



temporal scaling

$$\tau = \frac{zq^2}{2ck^2}$$

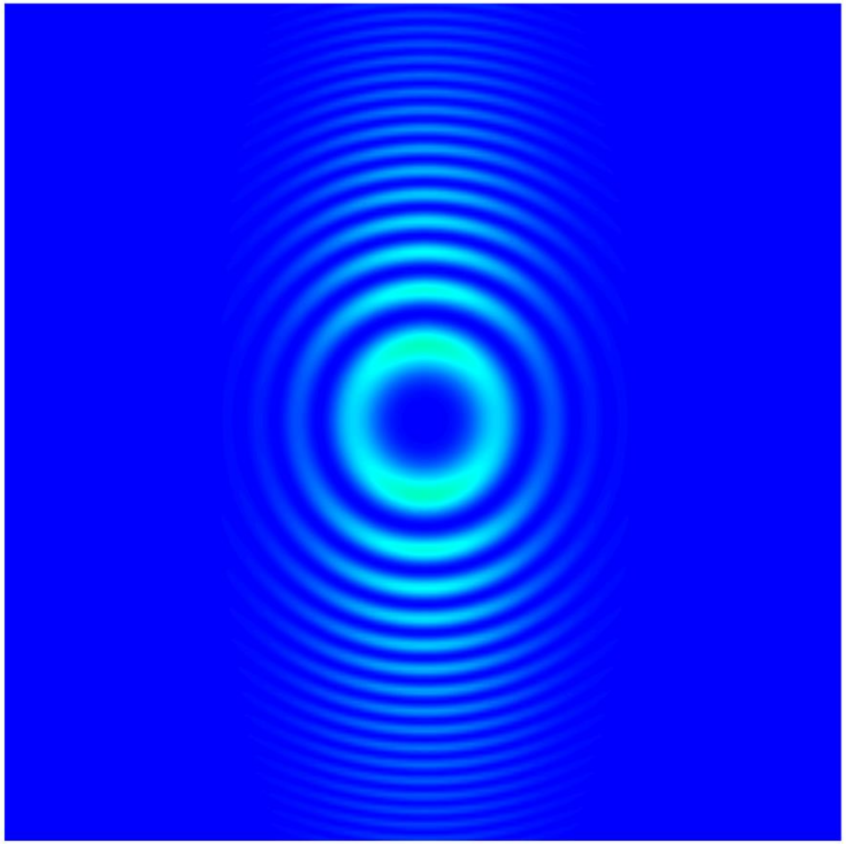
temporal master curve



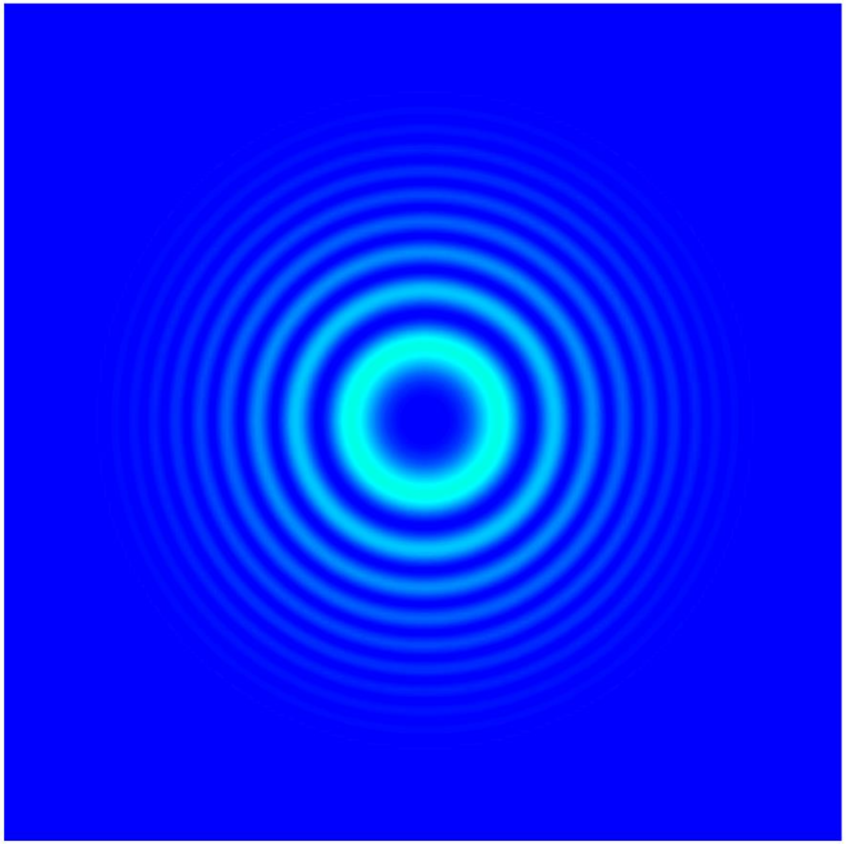
M. Siano *et al.*, *Phys. Rev. Accel. Beams* **20**, 110702 (2017)

HNFS: power spectra for spatial and temporal coherence

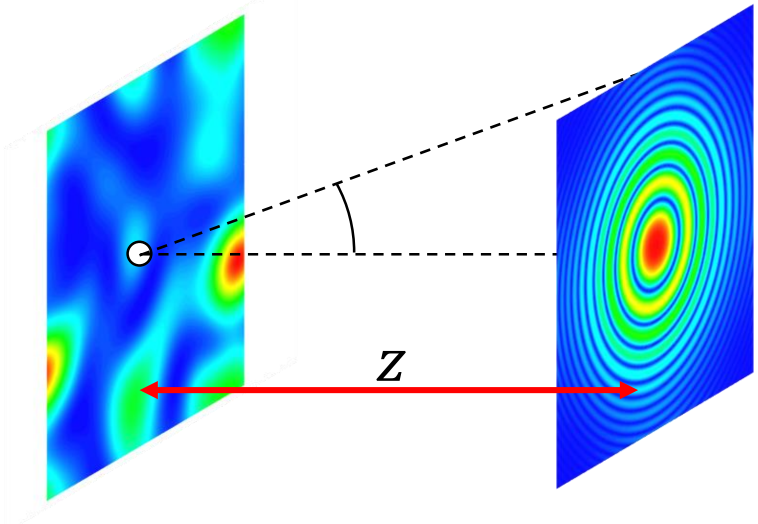
spatial coherence



temporal coherence



HNFS conditions

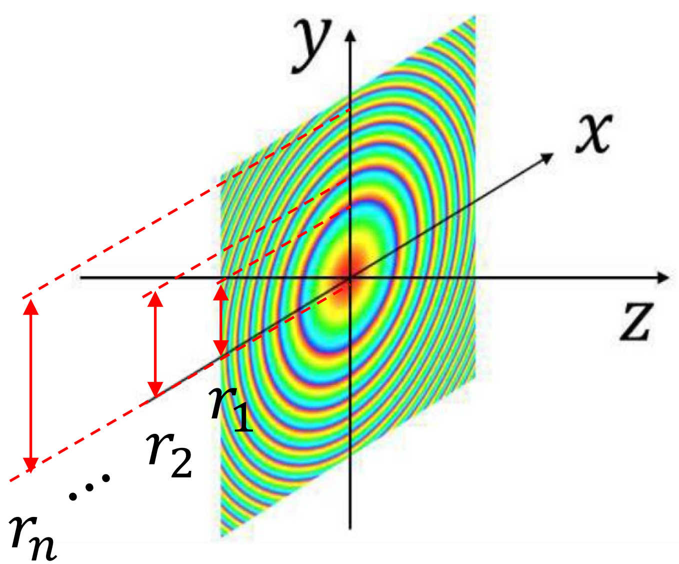


Coherence areas ≡ plane waves

$$z < \frac{\sigma_{coh}^2}{\lambda}$$

Near field of the radiation beam [1]

$$z_{det} < \frac{\phi^2}{\lambda}$$



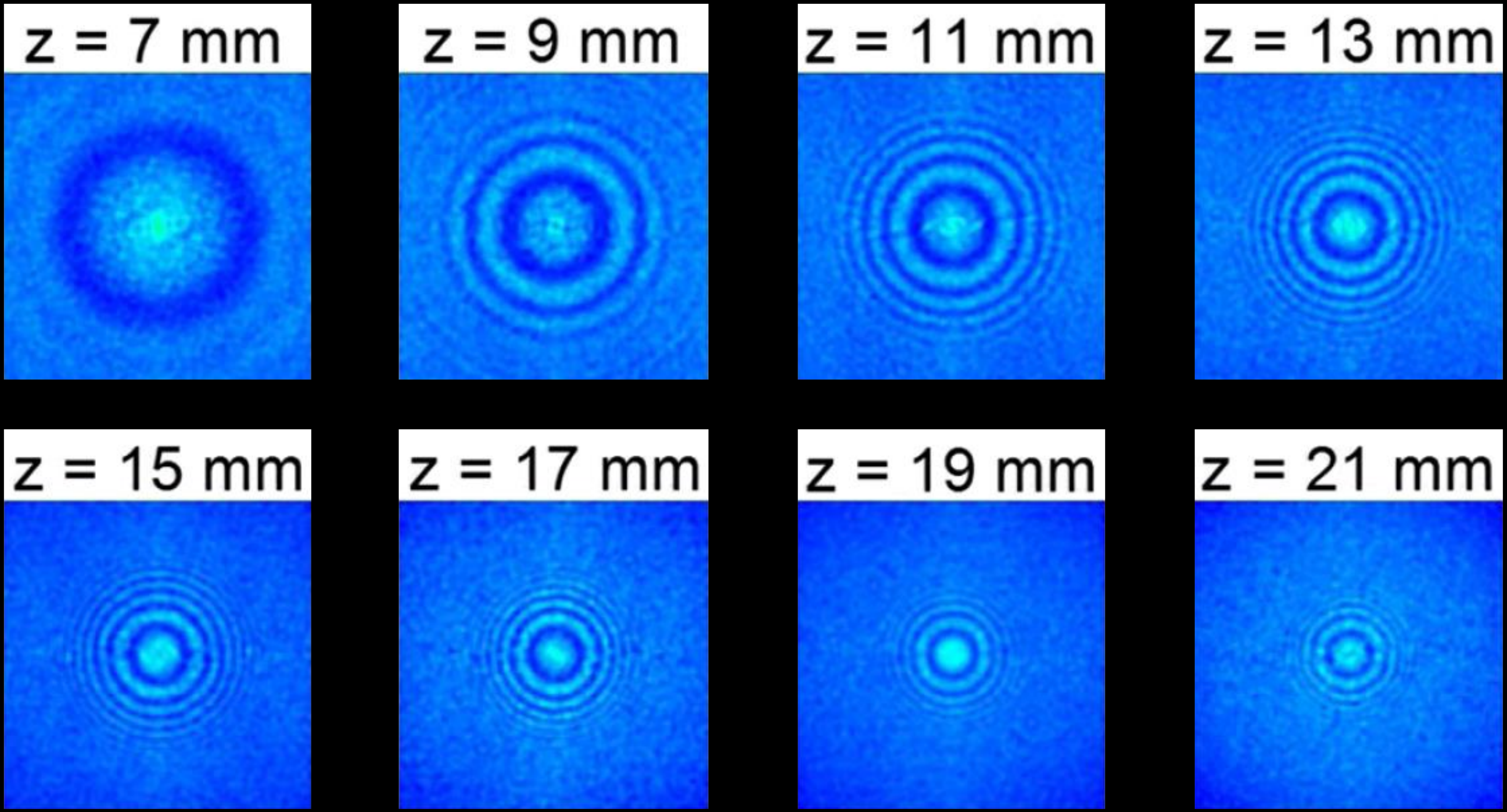
$$\begin{cases} l_c = c\tau_c = n\lambda \\ \sigma_{coh} \end{cases}$$

$\sigma_{coh} < \sqrt{n\lambda z}$ spatial coherence

$\sigma_{coh} > \sqrt{n\lambda z}$ temporal coherence

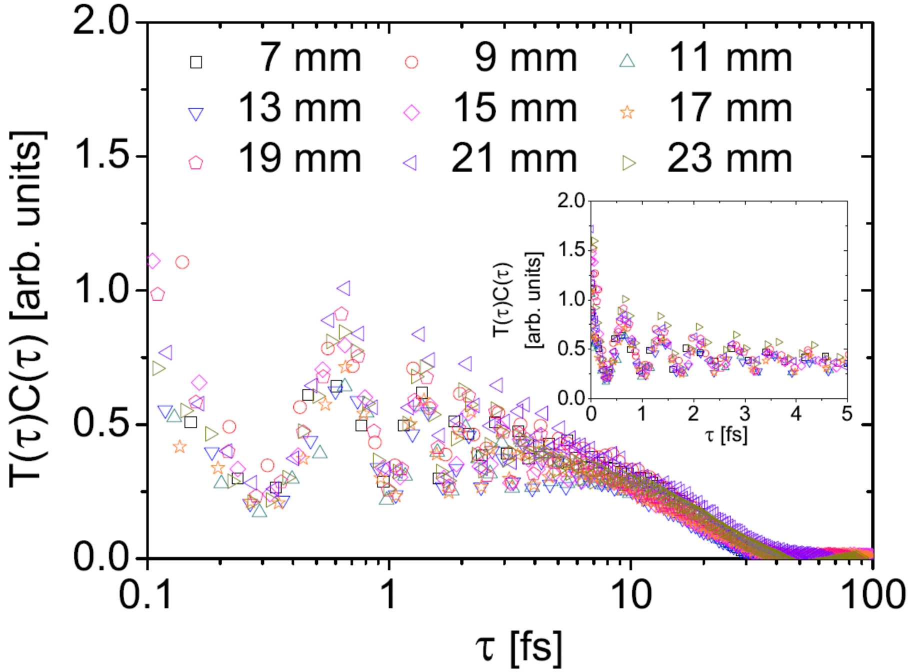
$$z > (<) \frac{\sigma_{coh}^2}{n\lambda}$$

Probing temporal coherence of narrowband SR beams

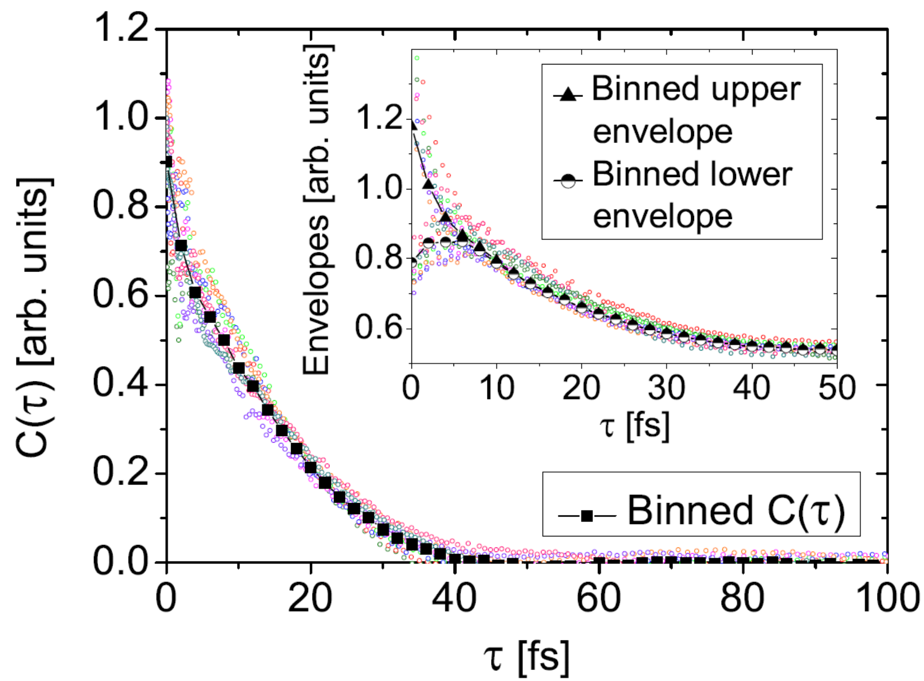


M. Siano *et al.*, *Phys. Rev. Accel. Beams* **20**, 110702 (2017)

Probing temporal coherence of narrowband SR beams

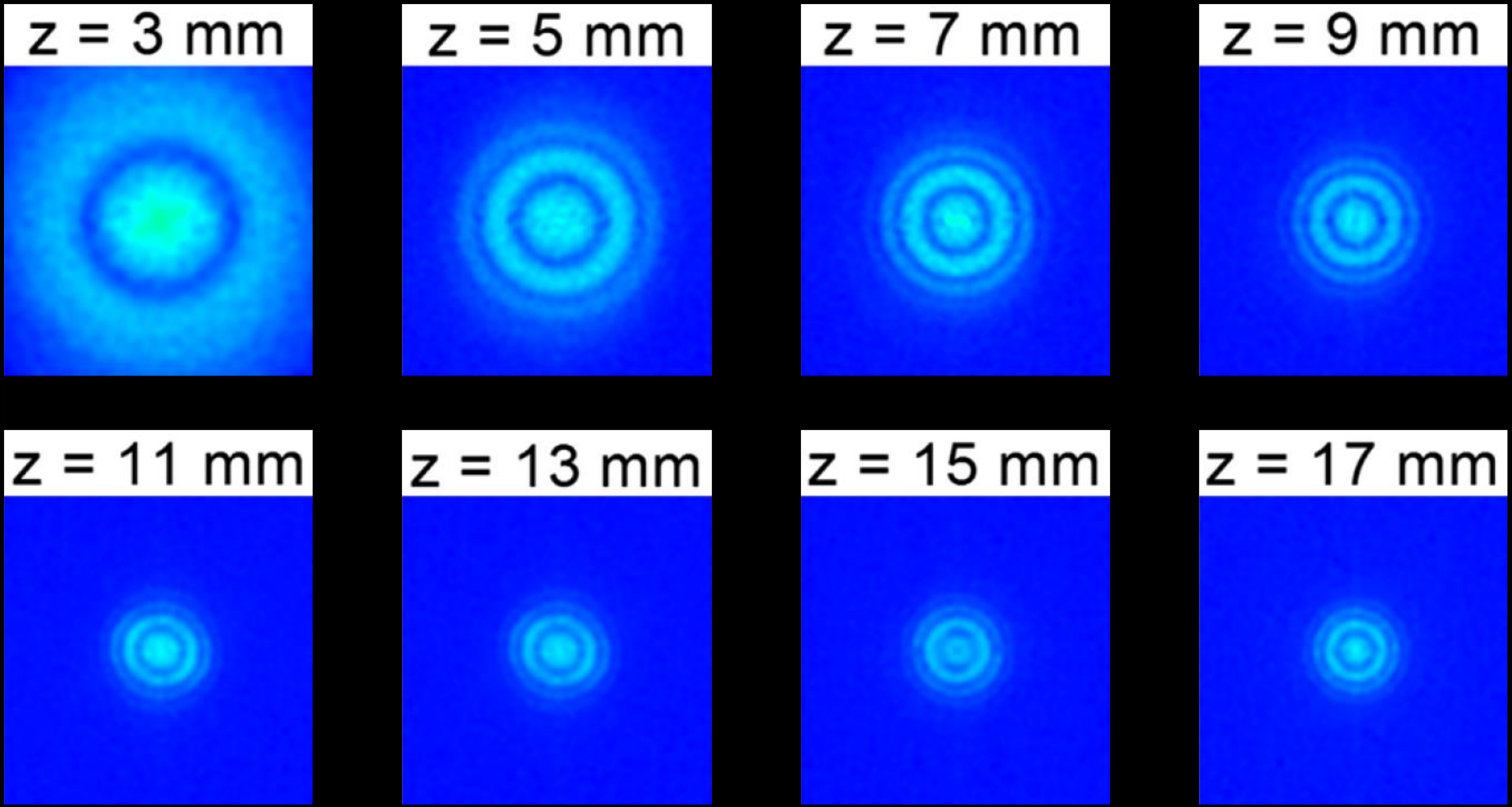


$$\tau_c = (40 \pm 10)\ \text{fs}$$



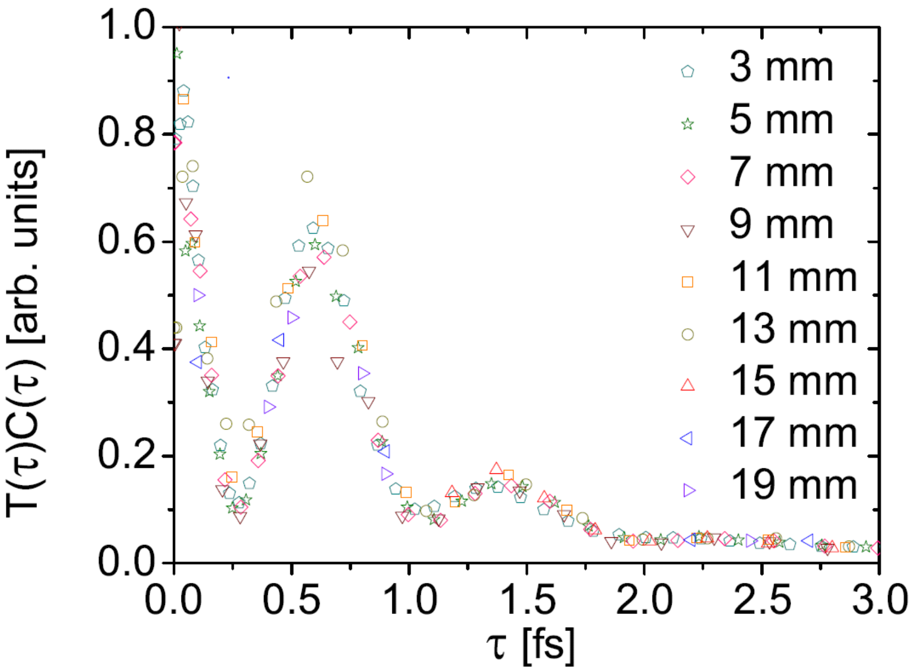
M. Siano *et al.*, *Phys. Rev. Accel. Beams* **20**, 110702 (2017)

Probing temporal coherence of white SR beams

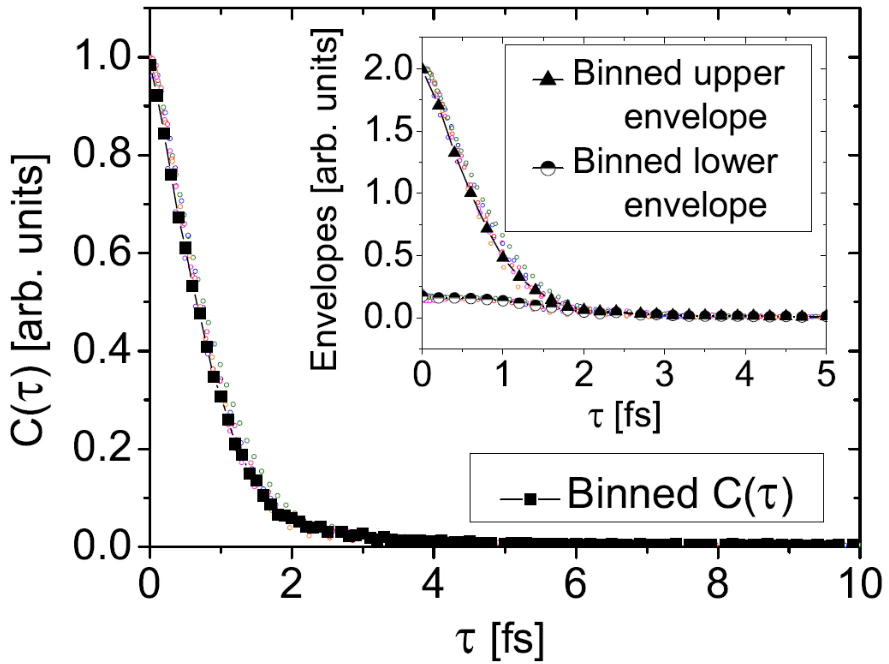


M. Siano *et al.*, *Phys. Rev. Accel. Beams* **20**, 110702 (2017)

Probing temporal coherence of broadband SR beams



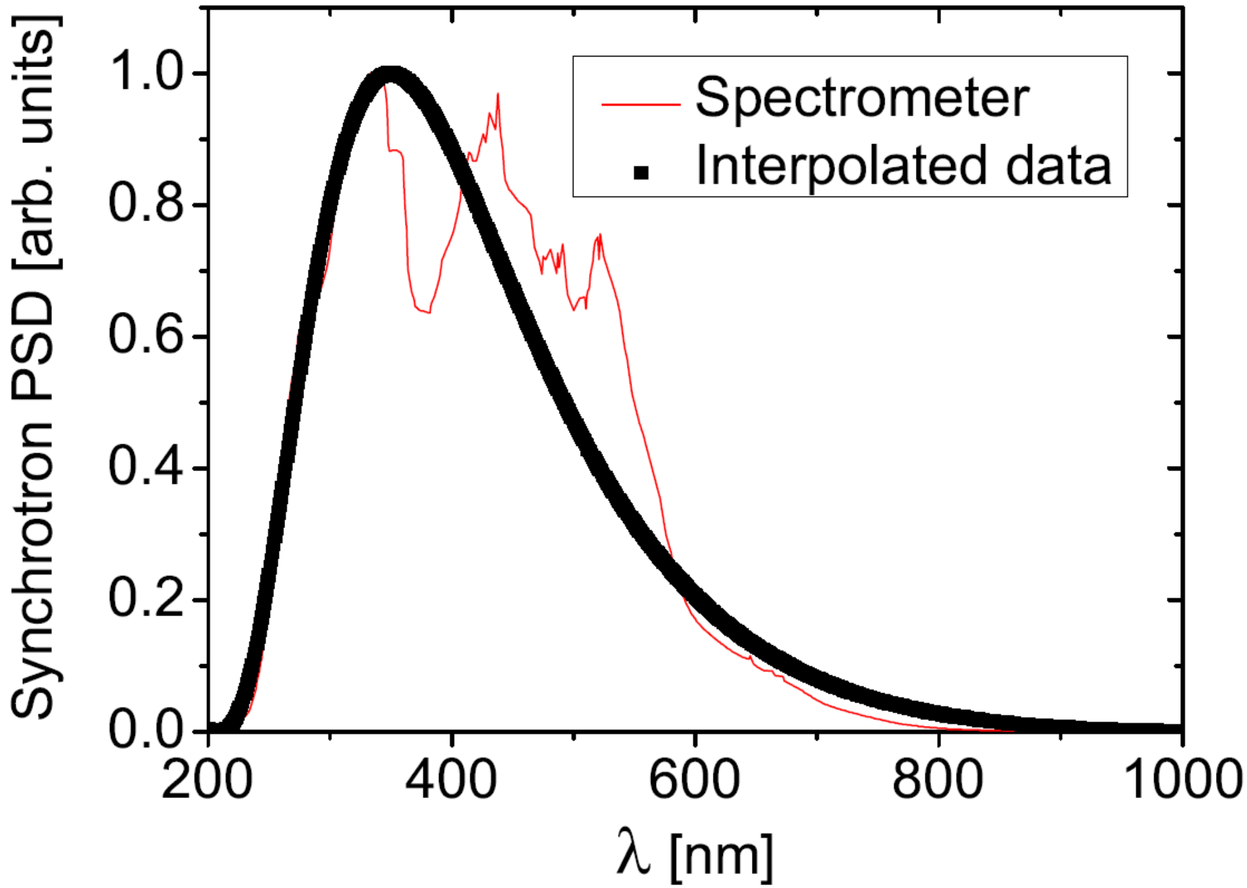
$\tau_c = (1.7 \pm 0.4)$ fs



M. Siano *et al.*, *Phys. Rev. Accel. Beams* **20**, 110702 (2017)

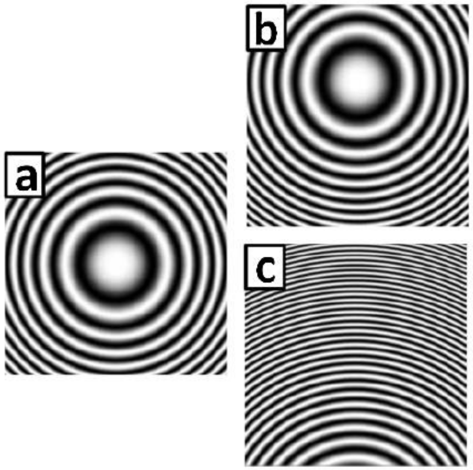
Retrieving SR power spectral density

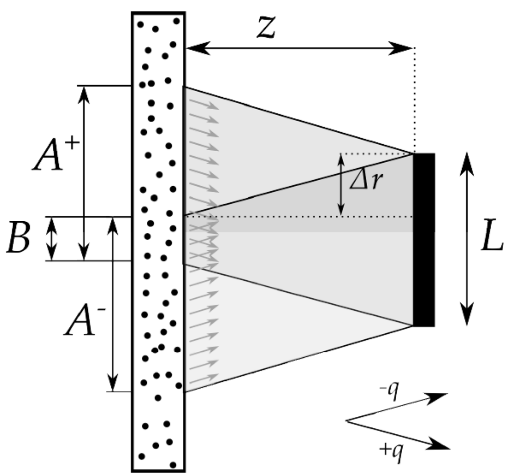
$$S(\upsilon) = \int_0^{+\infty} |\gamma(\tau)| \cos[(\upsilon - \bar{\upsilon})\tau]\, d\tau = \int_0^{+\infty} \sqrt{C(\tau)} \cos[(\upsilon - \bar{\upsilon})\tau]\, d\tau$$

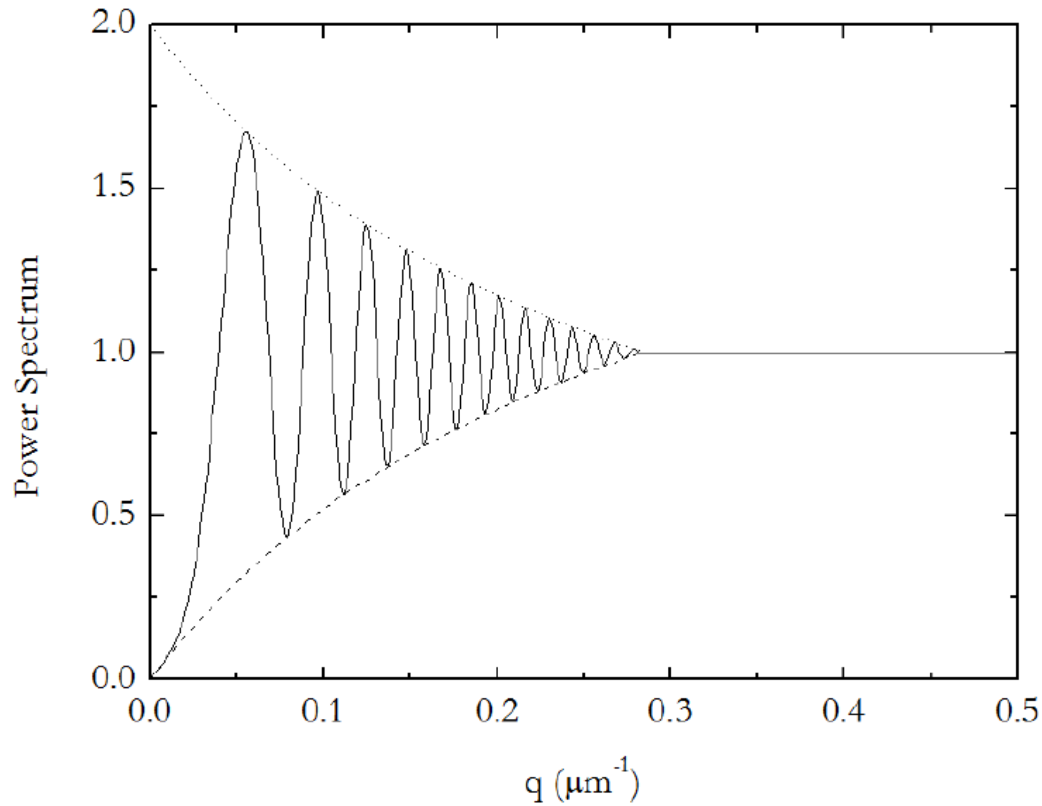


M. Siano *et al.*, *Phys. Rev. Accel. Beams* **20**, 110702 (2017)

Walkoff effect on Talbot oscillations



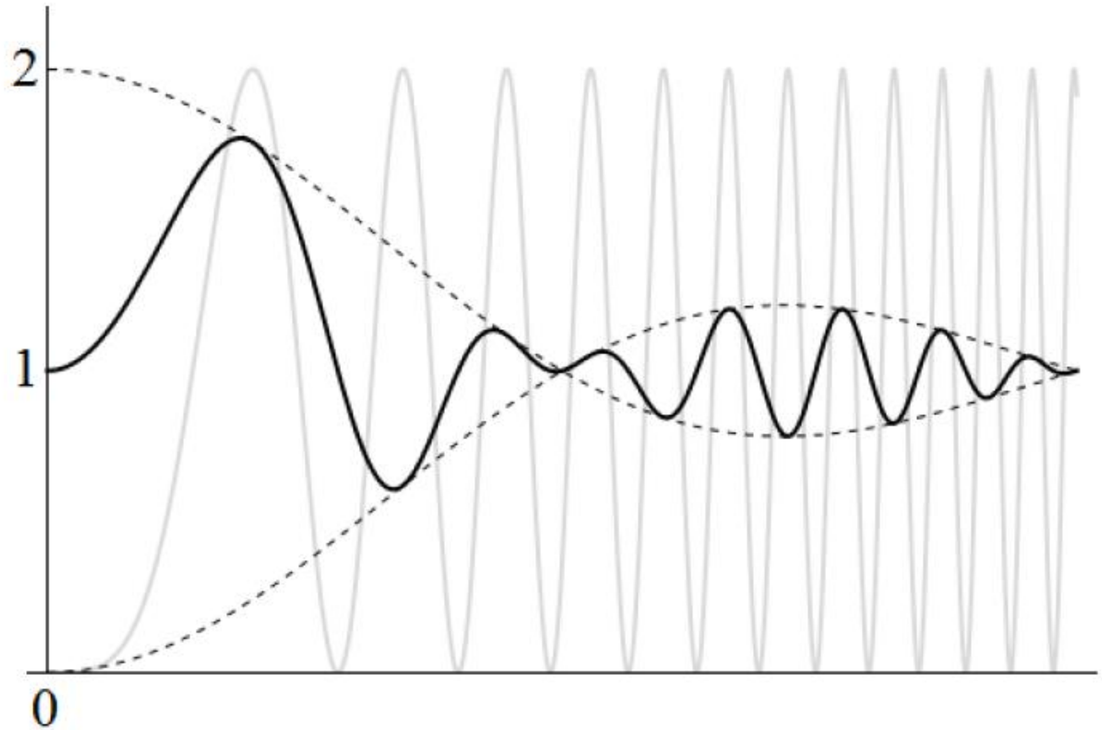




M. A. C. Potenza *et al.*, *Phys. Rev. Lett.* **105**, 193901 (2010)

M. Manfredda, *Ph.D. Thesis*, Universita’ degli Studi di Milano (2012)

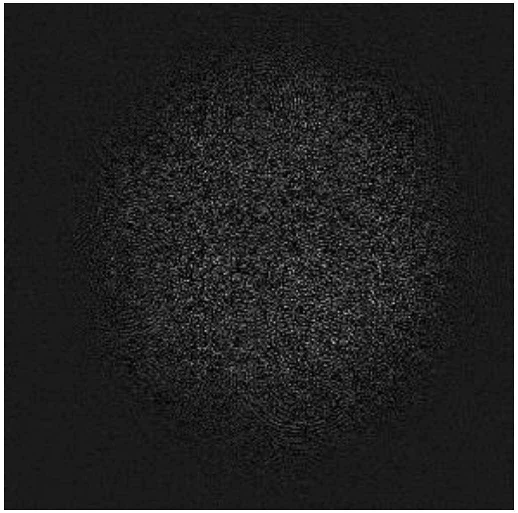
3D effect on Talbot oscillations

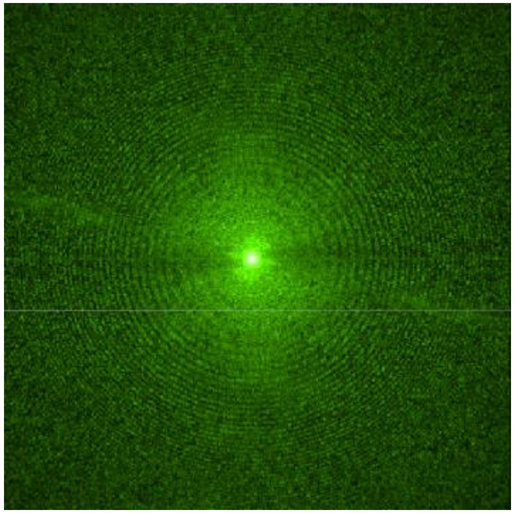


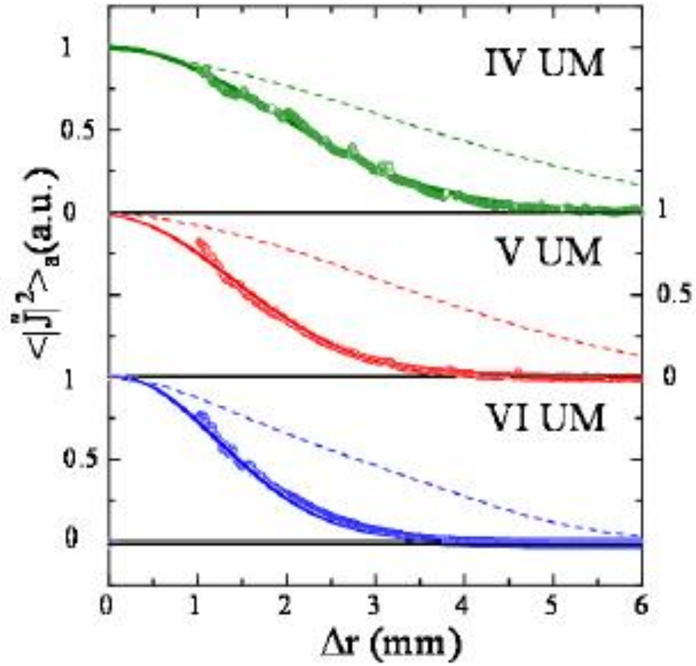
M. A. C. Potenza *et al.*, *Phys. Rev. Lett.* **105**, 193901 (2010)

M. Manfredda, *Ph.D. Thesis*, Universita' degli Studi di Milano (2012)

Results for a SASE FEL at SPARC-LAB

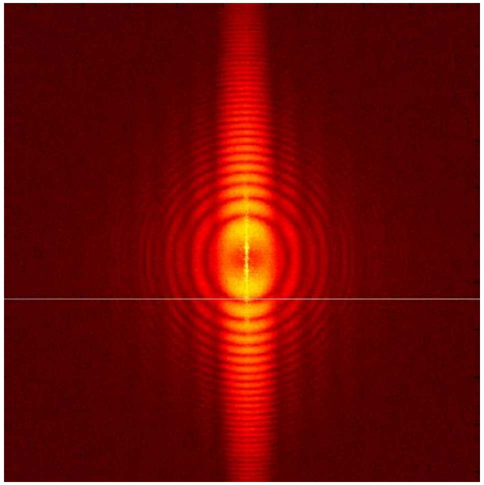


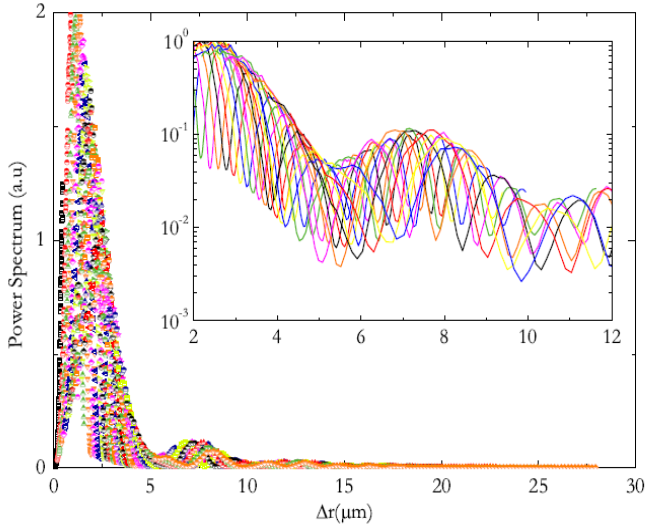


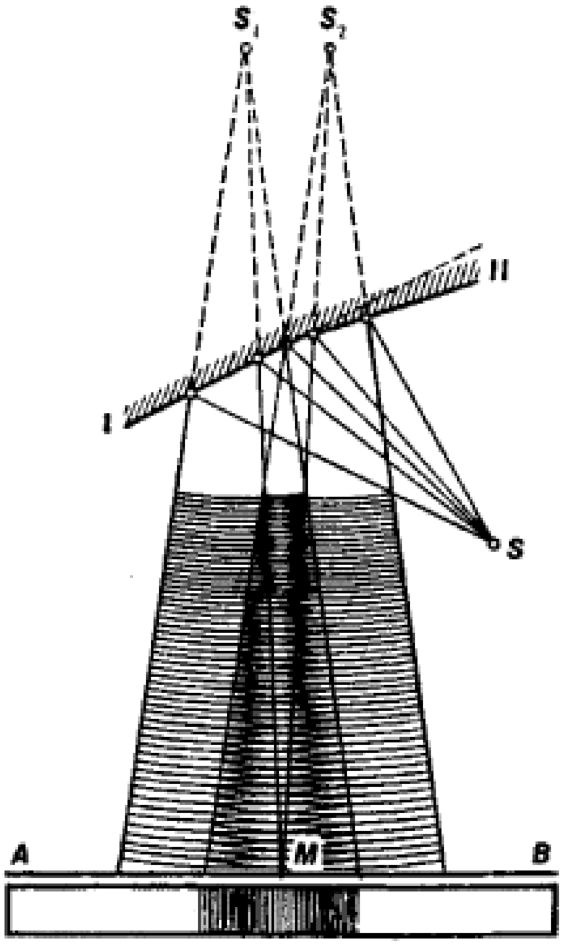


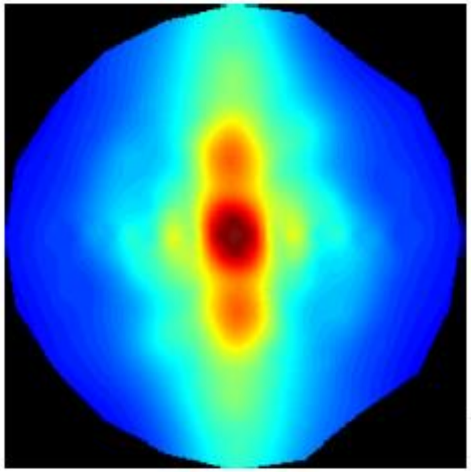
M. D. Alaimo *et al.*, *Opt. Express* **22**, 30013 (2014)

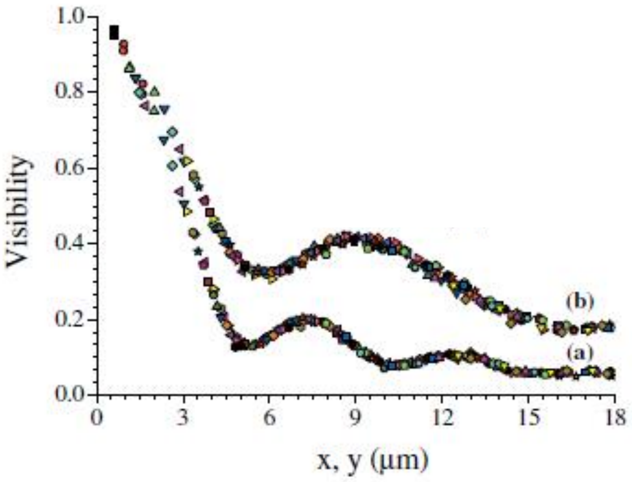
Results at ESRF







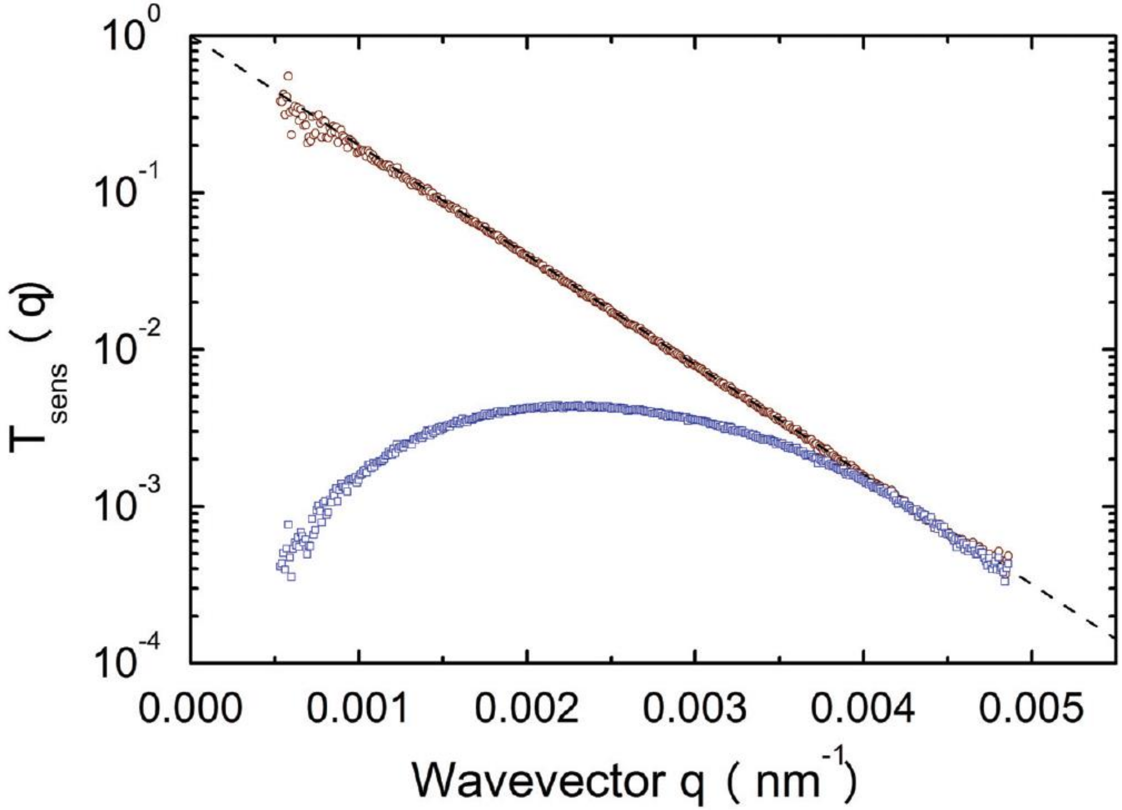




M. D. Alaimo *et al.*, *Phys. Rev. Lett.* **103**, 194805 (2009)

M. Manfredda, *Ph.D. Thesis*, Universita' degli Studi di Milano (2012)

Phosphor transfer function H(q) at ESRF



$$q_{scint} = 0.62\ \mu m^{-1}$$

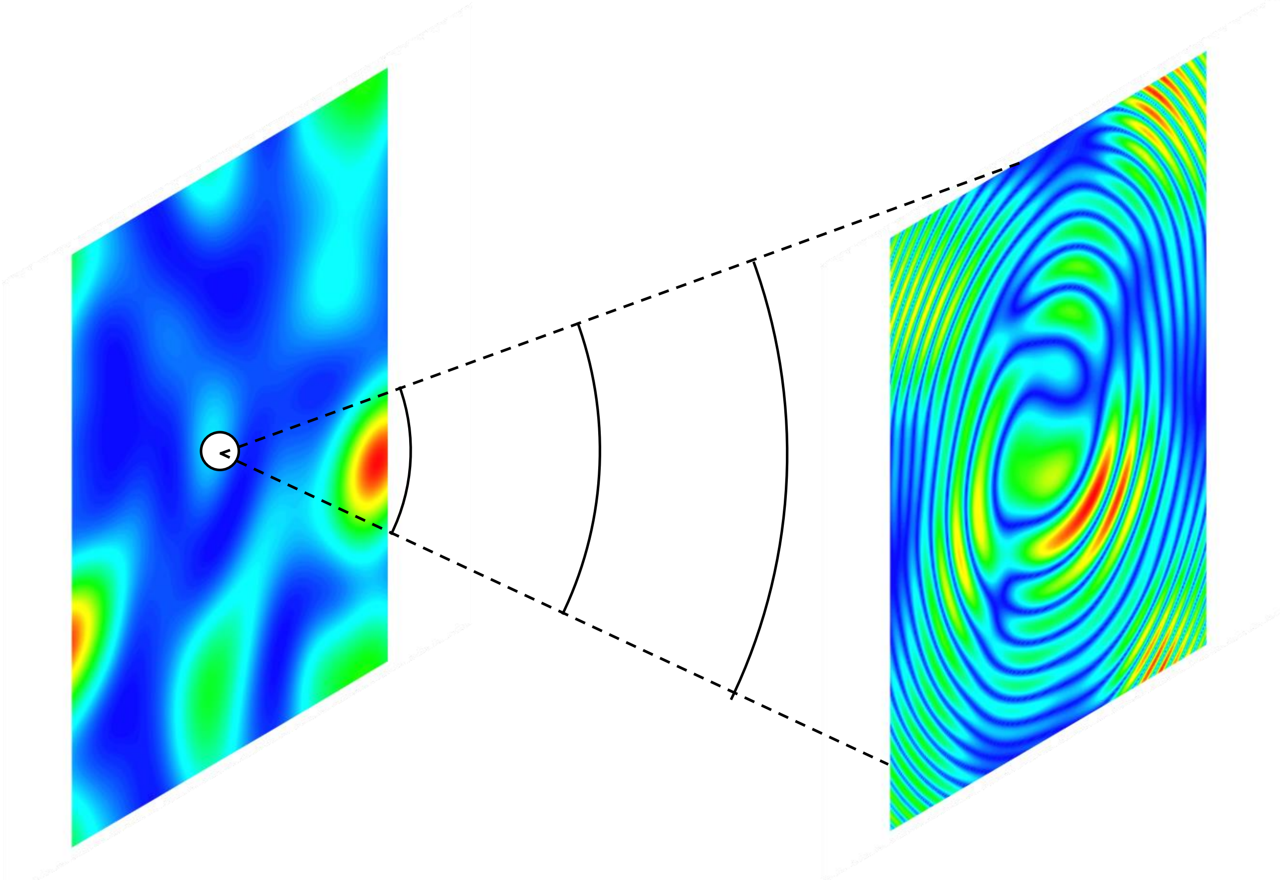
$$L_{min} = 10\ \mu m$$

R. Cerbino *et al.*, *Nat. Phys.* **4**, 238 (2008)

HNFS: scattering from a single particle

$$I(x,y) = \langle |E_0(x,y) + E_s(x,y)|^2 \rangle$$
$$= \langle |E_0(x,y)|^2 \rangle + 2\Re e \langle E_0(x,y) E_s^*(x,y) \rangle + \langle |E_s(x,y)|^2 \rangle$$

(heterodyne term) (heterodyne conditions)



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(heterodyne term) (heterodyne conditions)