Coherence and partial coherence – what do we need?

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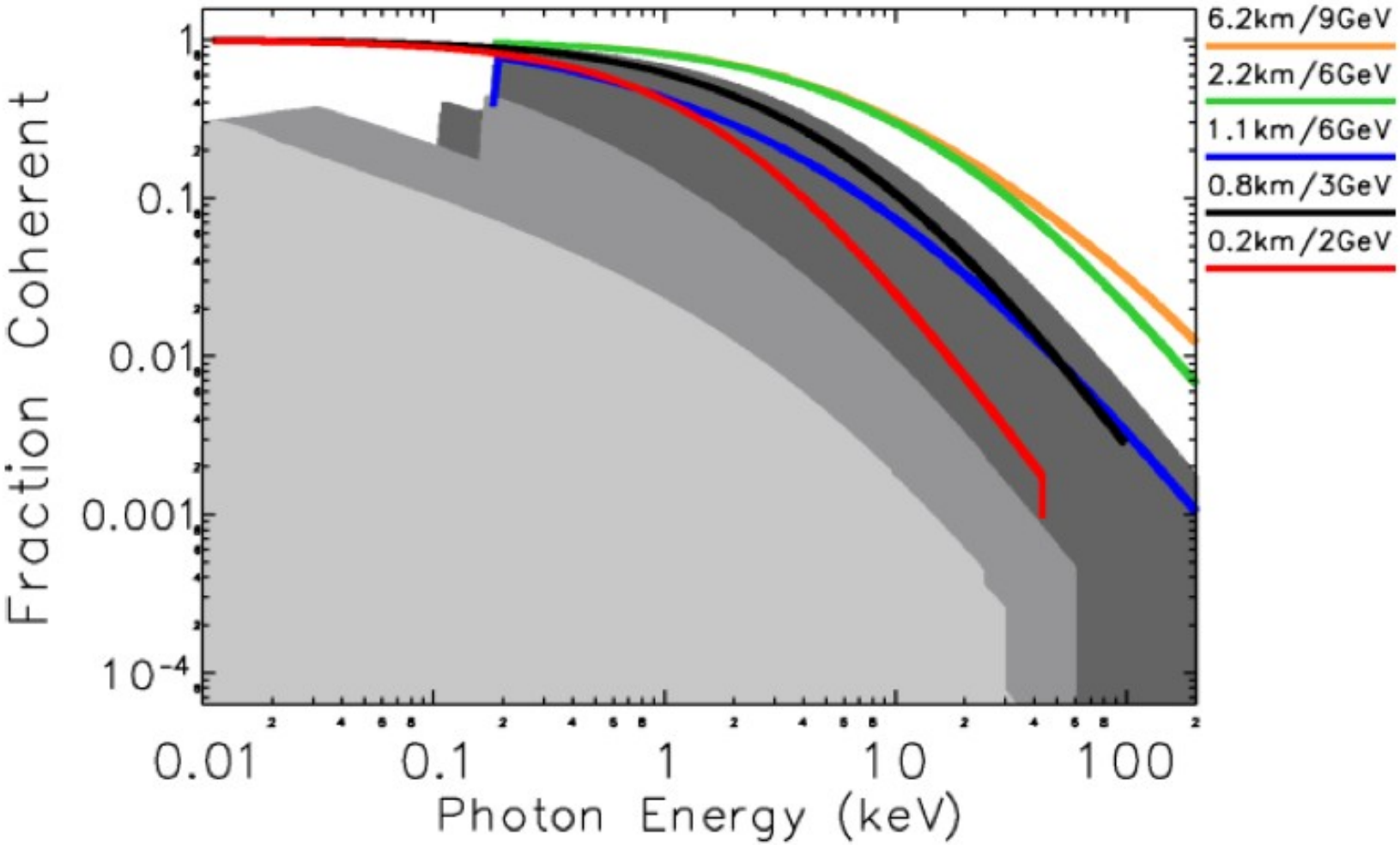
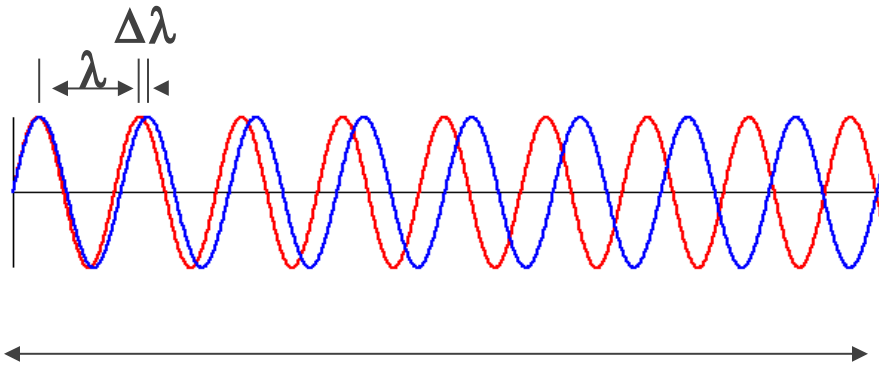
Coherent fraction of proposed DLSR's



Coherence

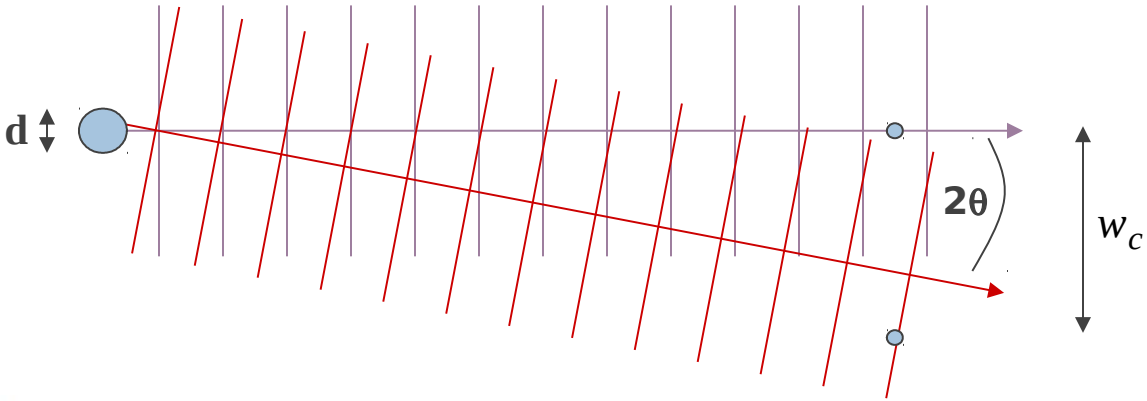
Temporal (longitudinal) coherence



$$l_c \sim \frac{\lambda^2}{\Delta\lambda}$$

$$\tau_c \sim \frac{\lambda^2}{c\Delta\lambda}$$

Spatial (transverse) coherence

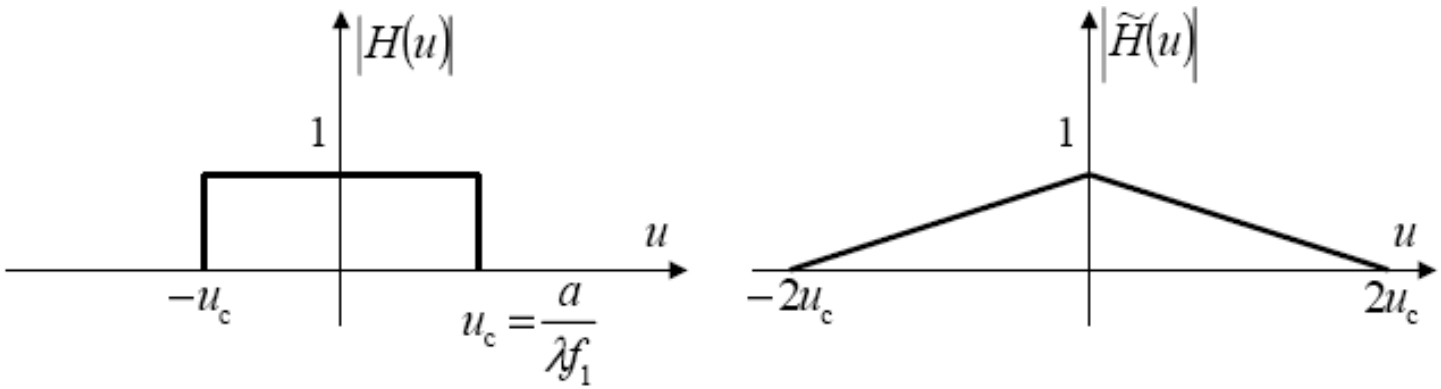


$$w_c \sim \frac{\lambda z}{d}$$

$$d \cdot \theta = \lambda / 2\pi$$

$$\Delta x \, \Delta p \geq h/2$$

Coherent vs. incoherent



Coherent illumination

Incoherent illumination

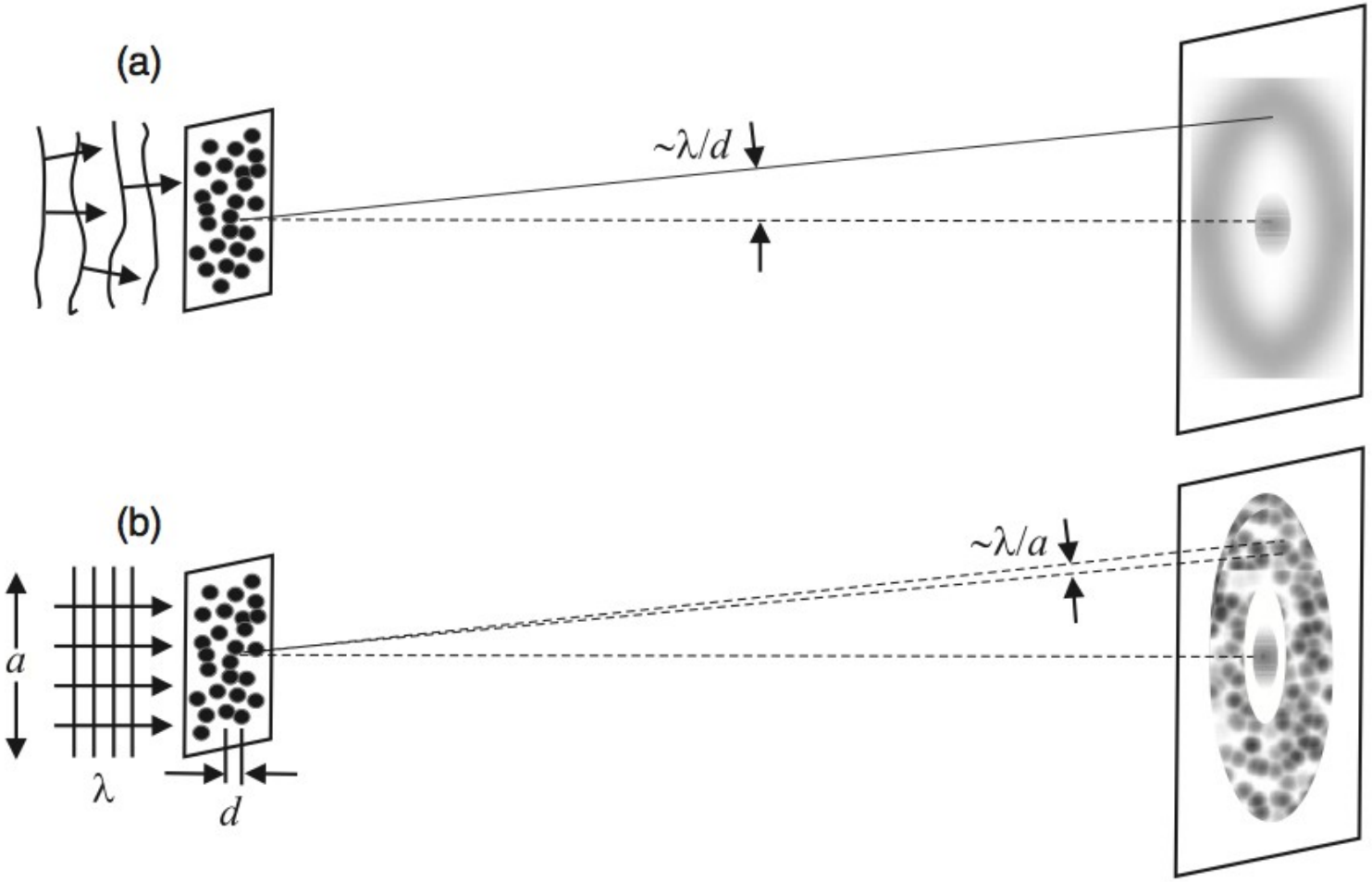
Scanning and full-field microscopy are *incoherent* methods

- Transfer function is linear in the field *intensities*
- Characterized by sloping function down to 2NA

Diffraction and holographic microscopy are *coherent* methods

- Transfer function is linear in the field *amplitudes*
- Characterized by flat top, sharp cutoff at limiting NA

X-ray scattering from a disordered sample



X-ray diffraction from a disordered medium with particle distance d and object size a.
(a) **Incoherent scattering**, giving rise to a continuous diffraction ring.
(b) **Coherent scattering**, resulting in a speckled diffraction ring.

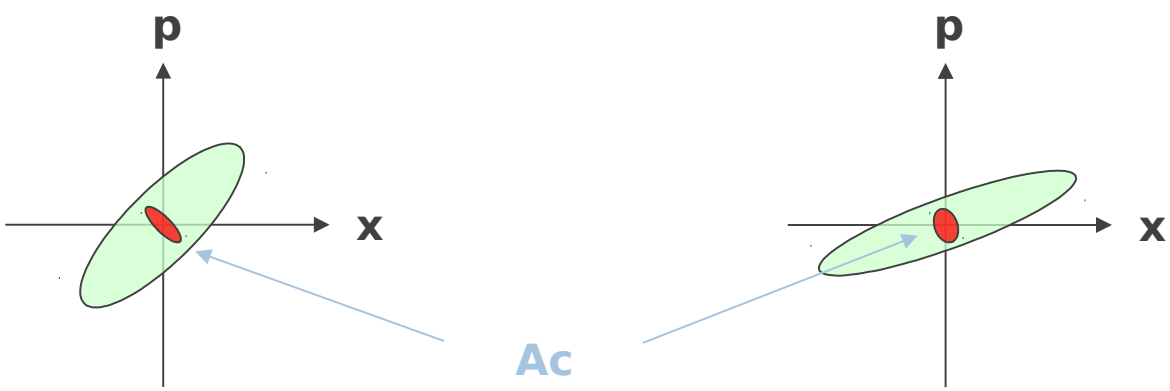
F. van der Veen, F. Pfeiffer, J. Phys. Cond. Mater. 16, 5003 (2004)

Undulator radiation

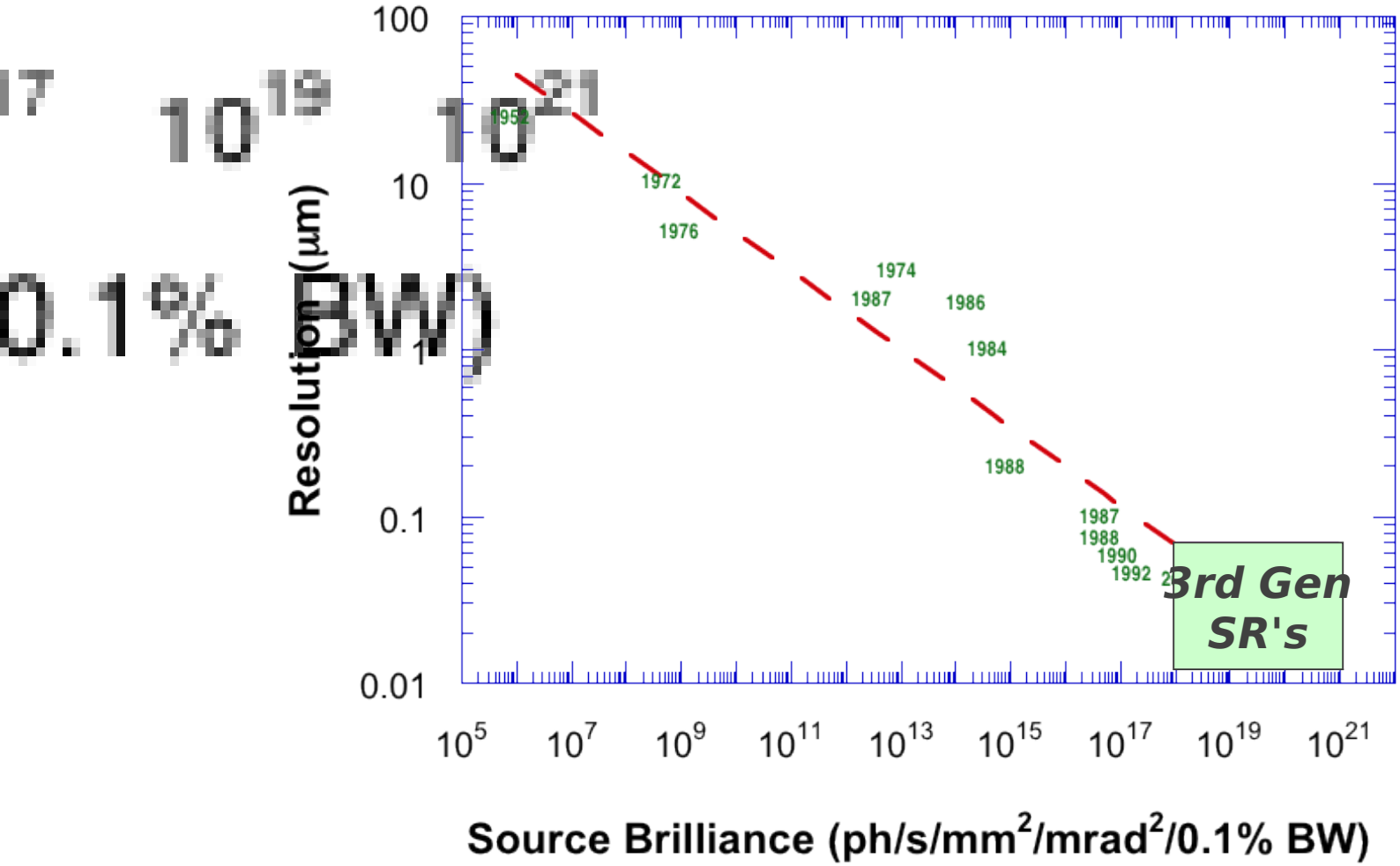
- SR sources (except FEL) are incoherent, but highly forward directed due to relativistic effects $\theta \sim 1/\gamma$

- Spatial and temporal filtering (pinholes, monochromators) are needed to select the coherent flux $Fc \sim \lambda 2\ B$

- Only the coherent flux can be focused into a diffraction-limited spot or be used to form interference fringes

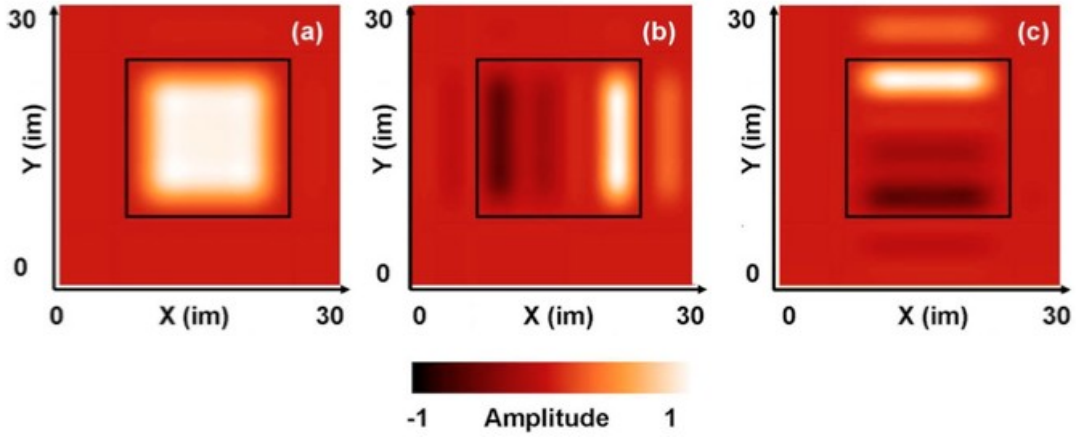


olution by x-ray holography



Partial coherent light can be treated as a distribution of coherent modes

$$J(\boldsymbol{r}_1, \boldsymbol{r}_2) = \sum_{n=1}^{N} \mu_n \psi_n(\boldsymbol{r}_1) \psi_n^*(\boldsymbol{r}_2),$$



Coherent modes for the lower-coherence set of experimental data. The square delineates the edge of the physical aperture. (a) (0,0) mode, (b) (1,0) mode, (c) (0,1) mode.

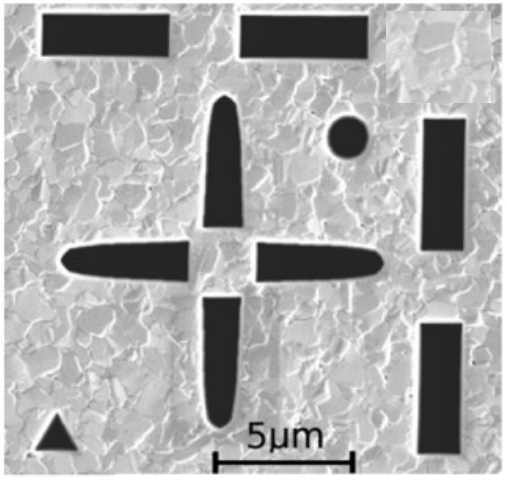
S. Flewett, *Opt. Lett* 34, 2198 (200

Diffractive imaging with partially coherent light

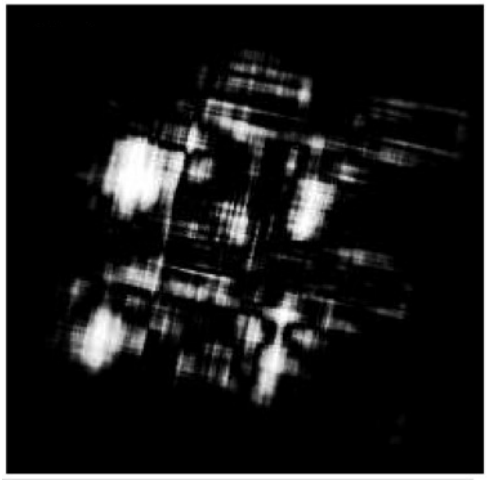
- Conventional phase retrieval algorithms that assume full coherence break down with partially coherent light

$$I(\boldsymbol{k}) = \sum_{n=1}^{N} \mu_n I_n(\boldsymbol{k}),$$

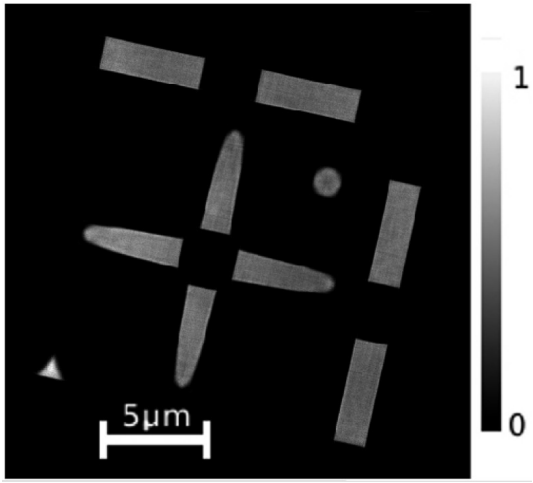
- If you know (or guess) the modal distribution (i.e. its weighting *μn*), you can fold this into the algorithm to optimize for each mode



SEM of Au test pattern



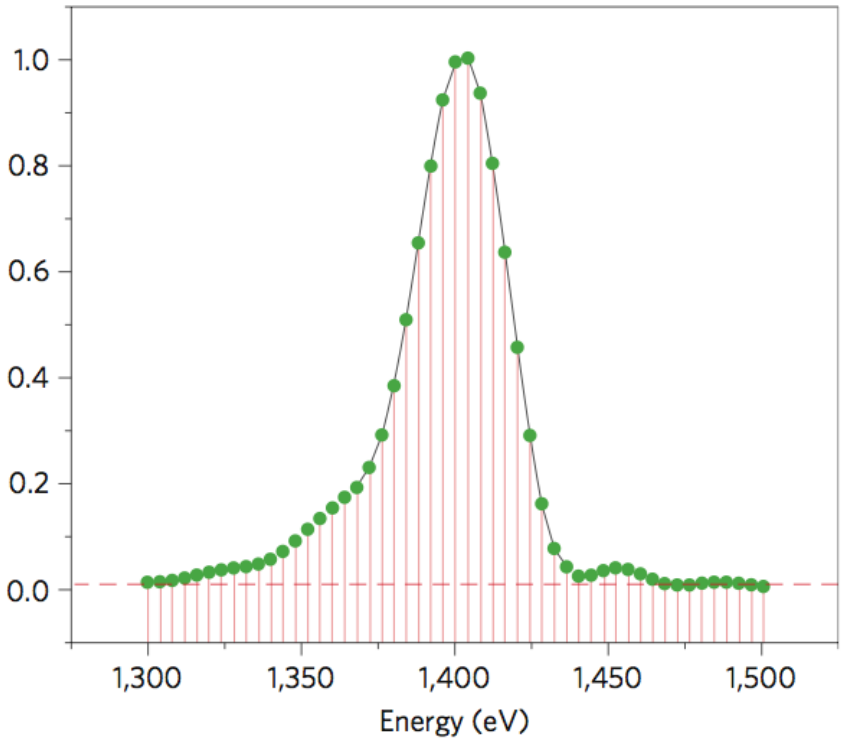
Conventional reconstruction with partial spatial coherence



Reconstruction incorporating 3 spatially coherent modes

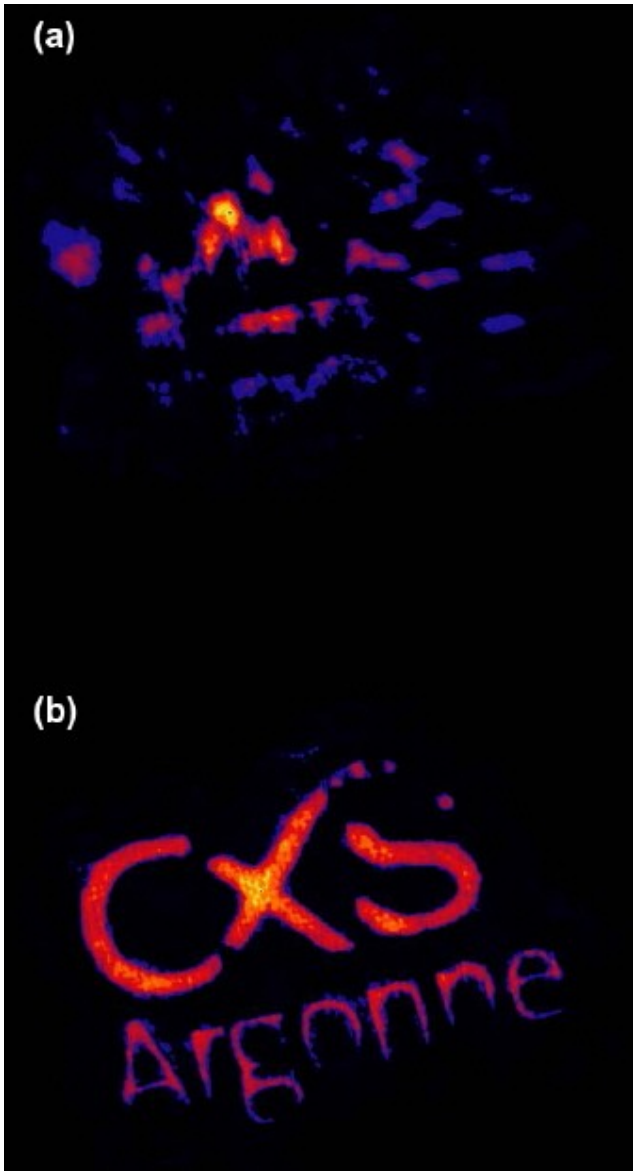
L. Whitehead, *PRL* 103, 243902 (2009

Going broadband: use polychromatic light

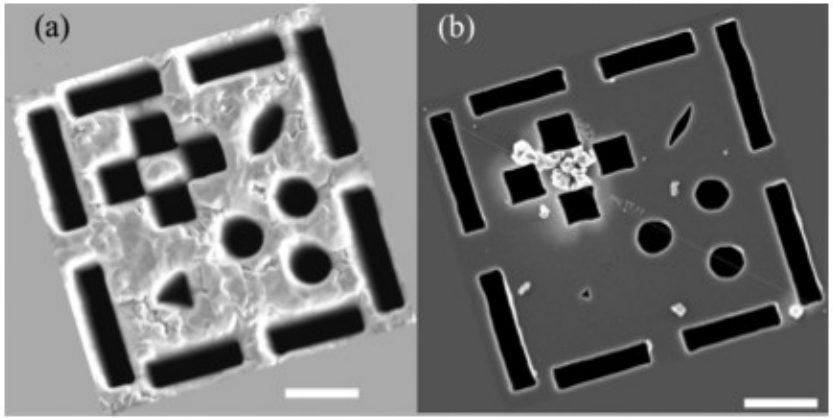


Use of entire first undulator harmonic (~2.5% BW) gives 60x gain in measurement speed.

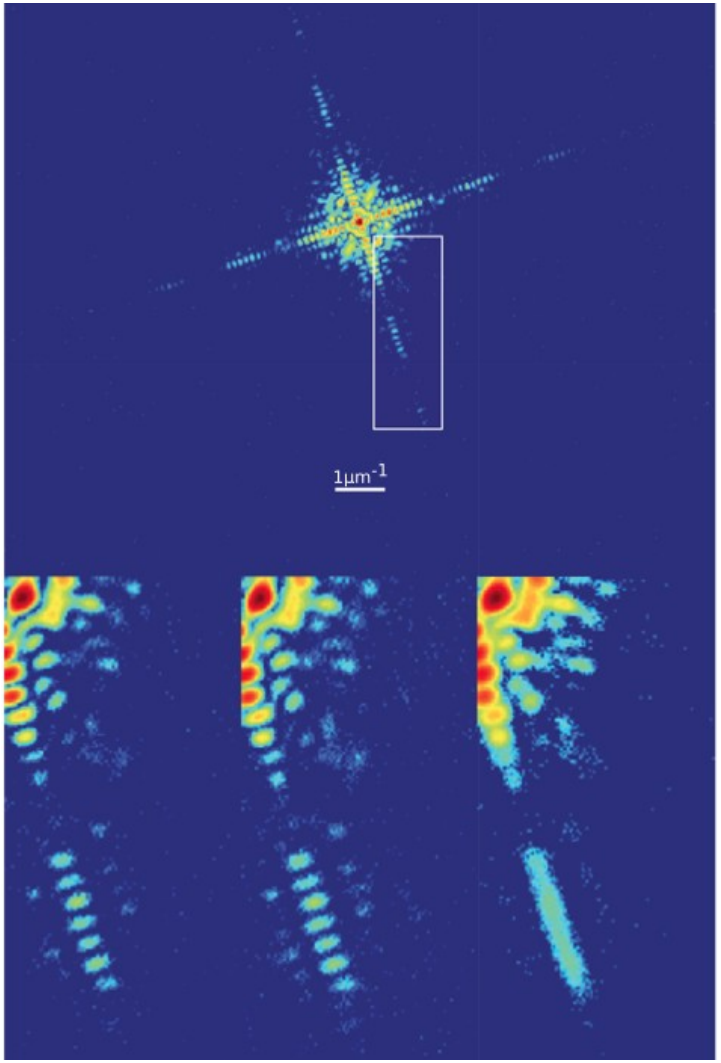
B. Abbey, *Nature Photonics* 5, 420 (2011)



Quantitative exploration



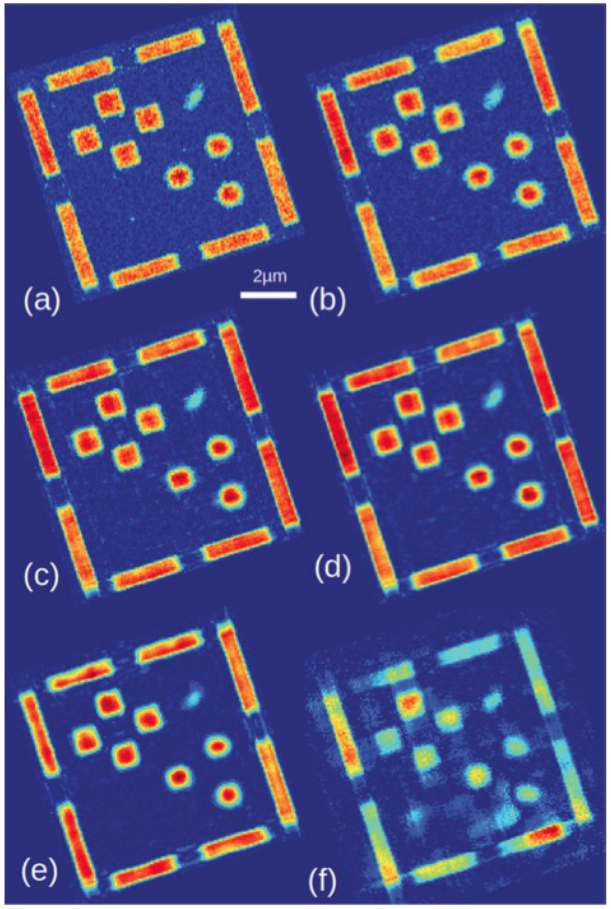
Gold test pattern

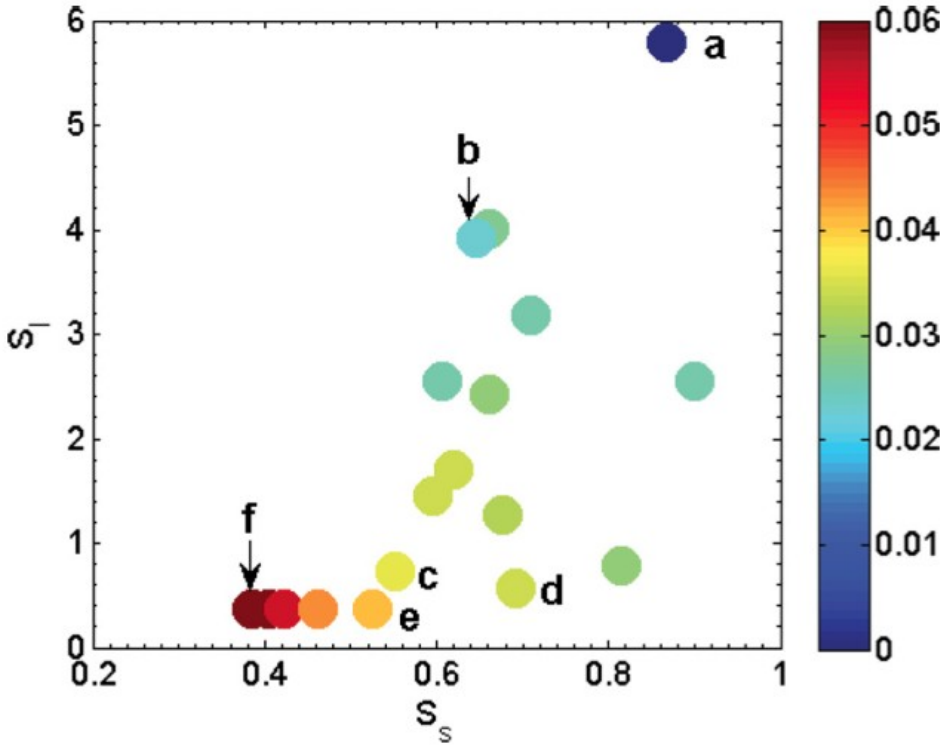


Diffraction pattern (1.4 keV) recorded with decreasing degree of coherence (open up the beamline slits)

Limits of partial coherence on phase recovery

$$S_s = \frac{\sigma_{s,x}}{2L} \qquad S_l = 2\sigma_l \frac{\delta}{\lambda L}$$





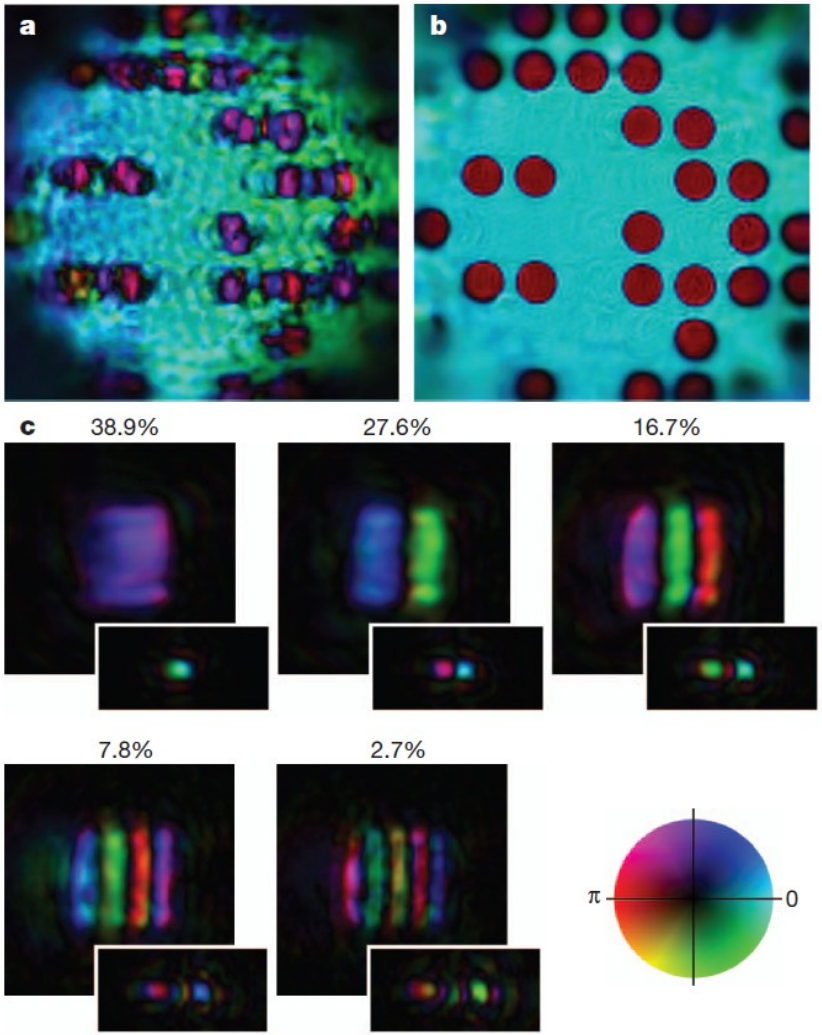
B. Chen et al., *Phys. Rev.* B 86, 235401 (2012)

Approach is more general than it might appear

- Fringe blurring can also be thought of as being due to sample vibration, drift, detector resolution function, etc.

- New methods for handling blurring (e.g. Gaussian approx., quantum state approach), look even more promising.

- These methods seem to work best when the number of modes ≤ 10 ***-> well suited to hard x-rays from an MBA lattice***



J. Clark, *Appl. Phys. Lett.* 99, 154103 (2011)
J. Clark, *Nature Comms.* 3, 993 (2012)
P. Thibault, *Nature* 494, 68 (2013)

Summary

- X-ray beams from the proposed APS DLSR based on an MBA Lattice are only coherent up to ~2 keV
- By incorporating models for coherence into phase retrieval algorithms we can make use of partial spatially and temporally coherent light
- These approaches also appear useful for handling beam-sample motion and other dynamic processes … perhaps even damage
- *Smarter use of multi-mode light enables access to higher energies and shorter time scales*