Phase retrieval in tomography with Kirkpatrick-Baez mirrors

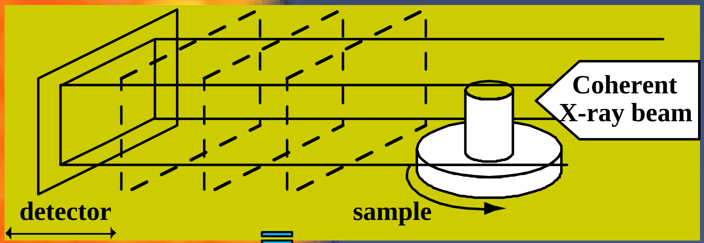
Rajmund Mokso

European Synchrotron Radiation Facility
Grenoble

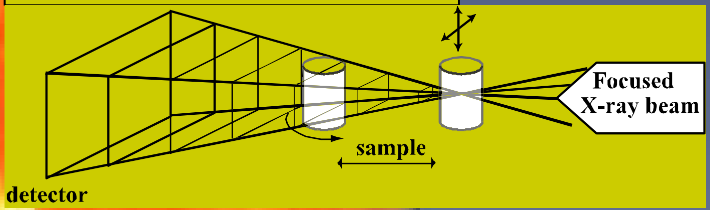
Collaborators: Peter Cloetens, Wolfgang Ludwig, Olivier Hignette, Eric Maire

Motivation

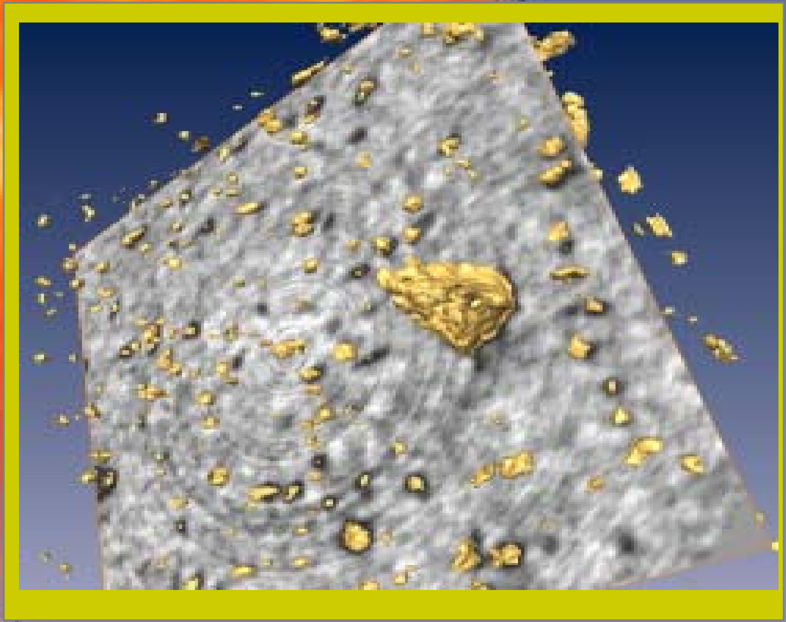
Improve the spatial resolution of tomographic scans



Projection microscopy



adapt phase retrieval algorithms to the focusing geometry



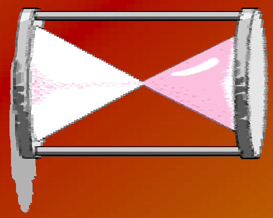
Outline

the geometry of the imaging setup

the nature of artefacts

outlook

HIGH SPATIAL RESOLUTION (KB FOCUSING)

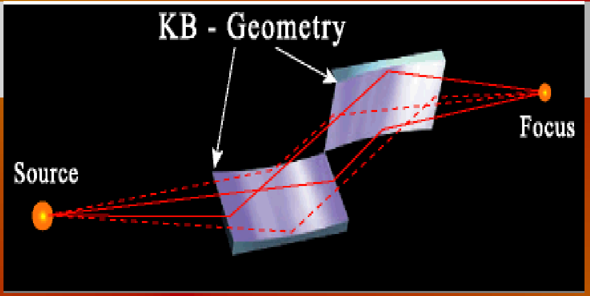


towards local tomography

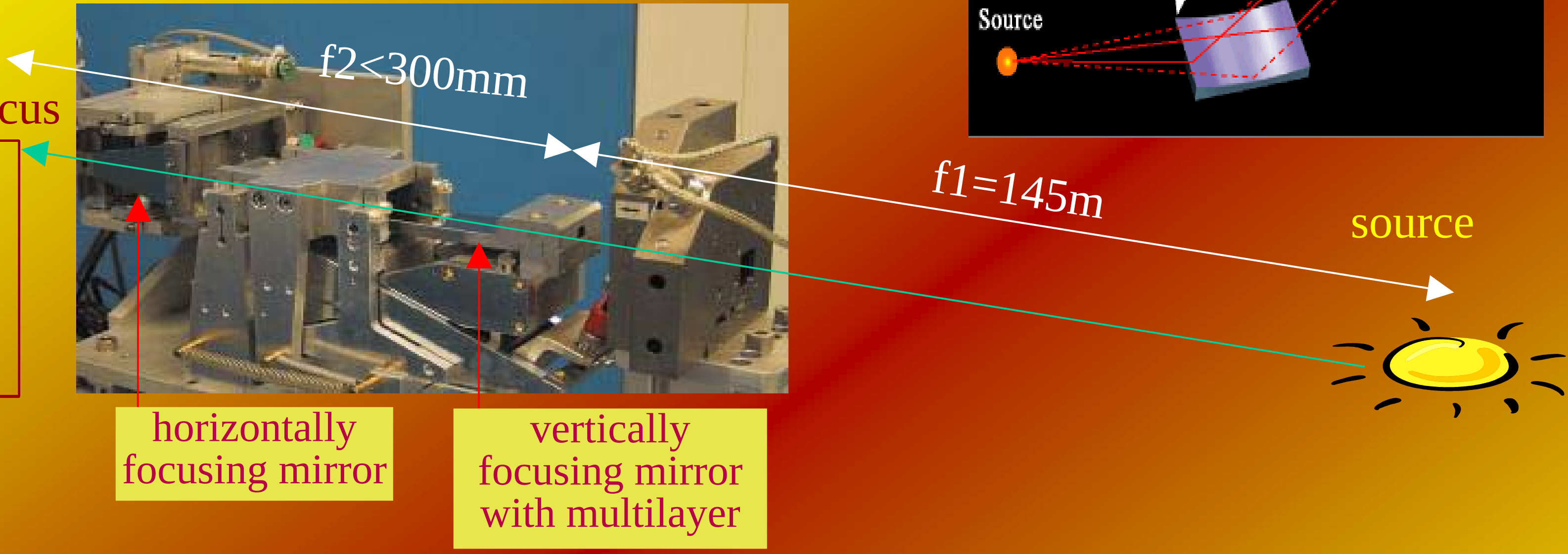
examples of results (3D rendering)

description of different phase retrieval approaches and their comparison on real data

THE GEOMETRY



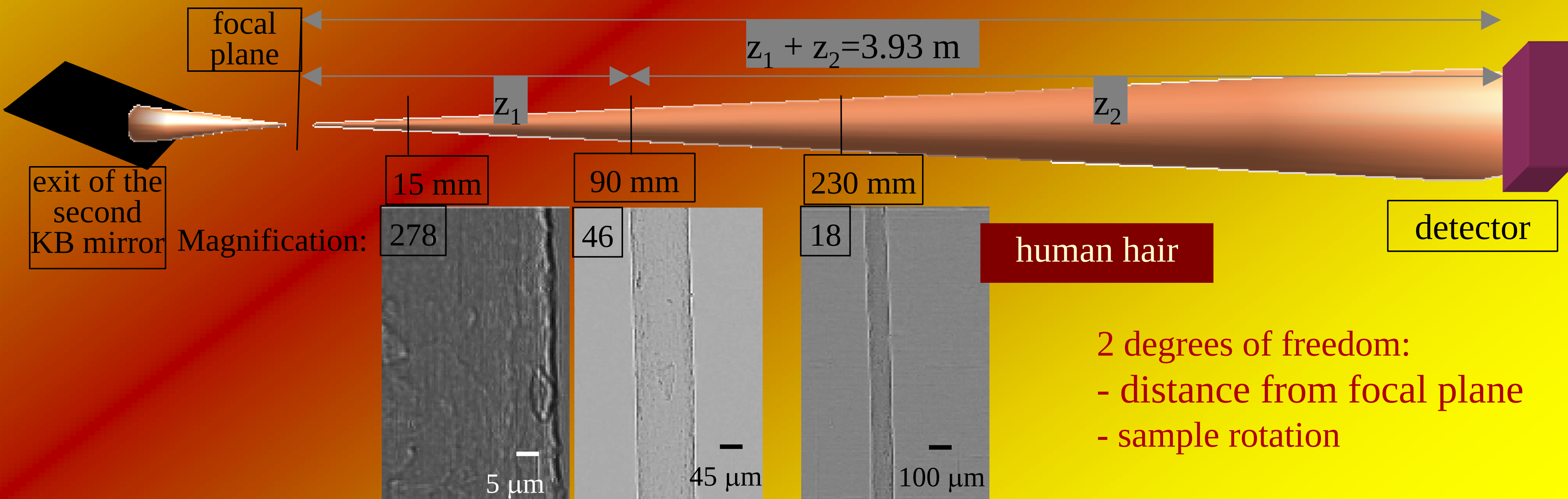
demagnification:
f1/f2 =>
theoretical best focus
spot= 87x45 nm



dose efficient

overcome resolution of detector

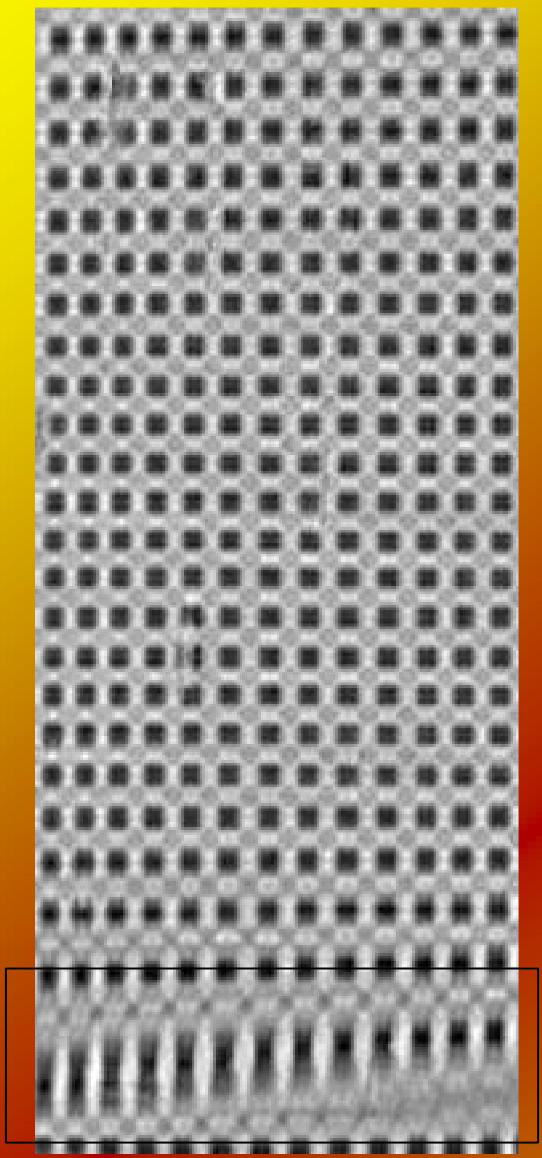
compatible with fluorescence

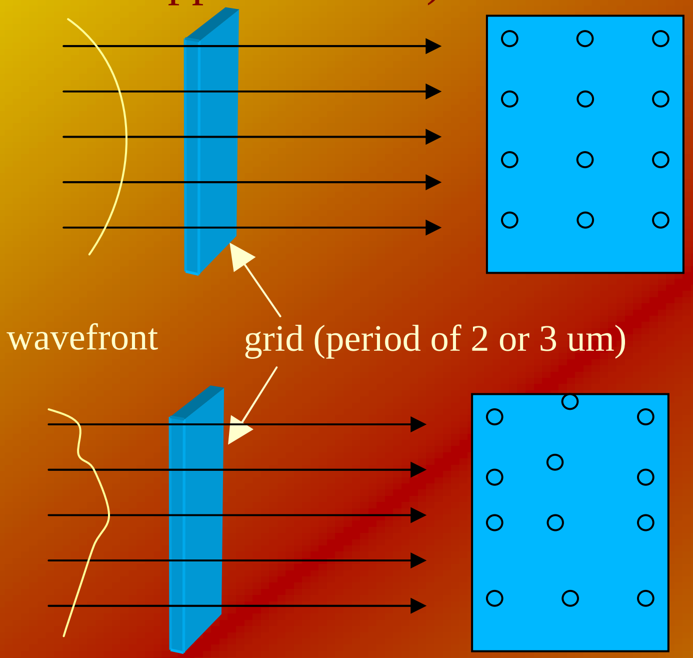


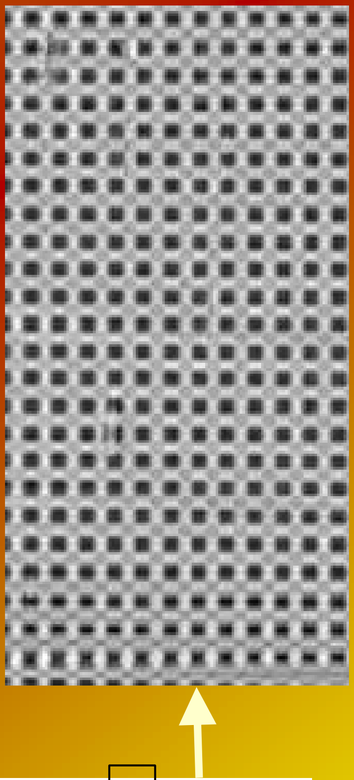
2 degrees of freedom:
- distance from focal plane
- sample rotation

THE DISTORTION

determination of wavefront abberations caused by mirror bending defects (geometrical approximation)

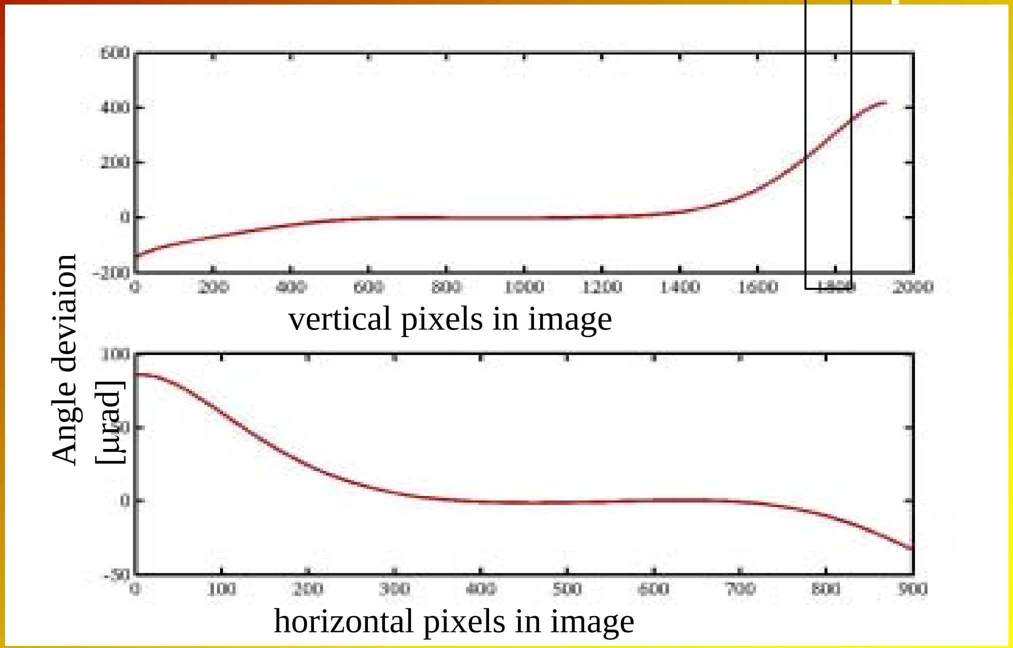






relation between the phase and the angle:

$$\alpha=(\lambda/2).\delta\phi/\delta z$$

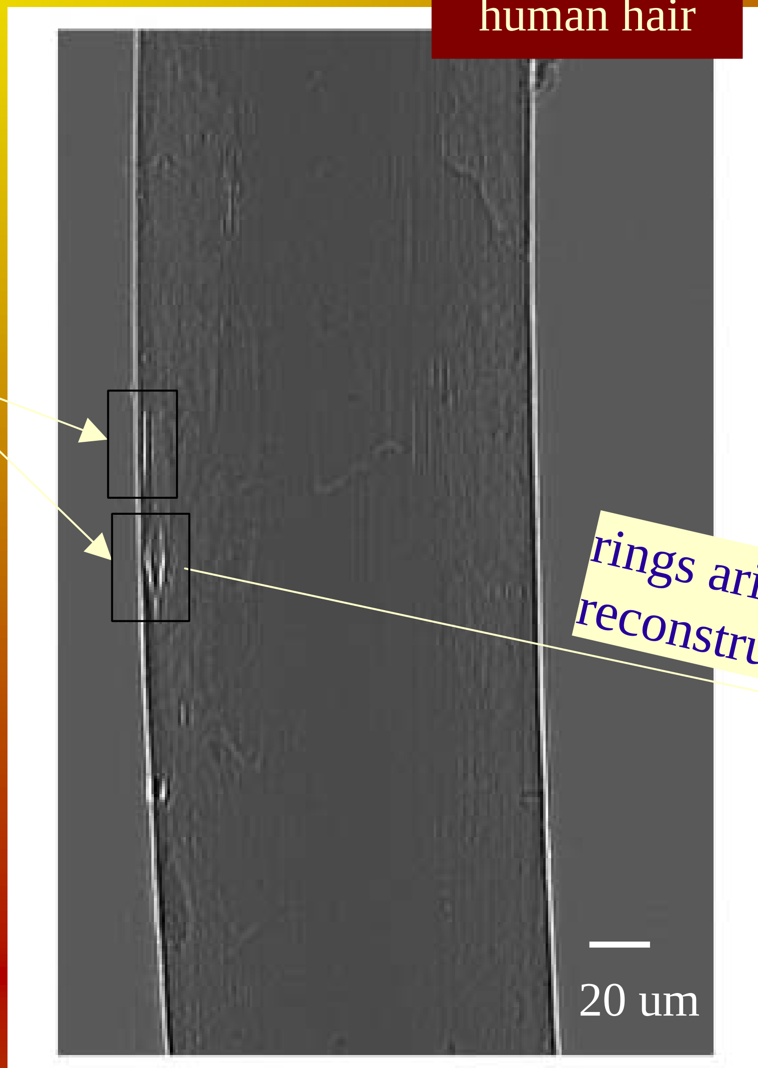


refraction by the sample

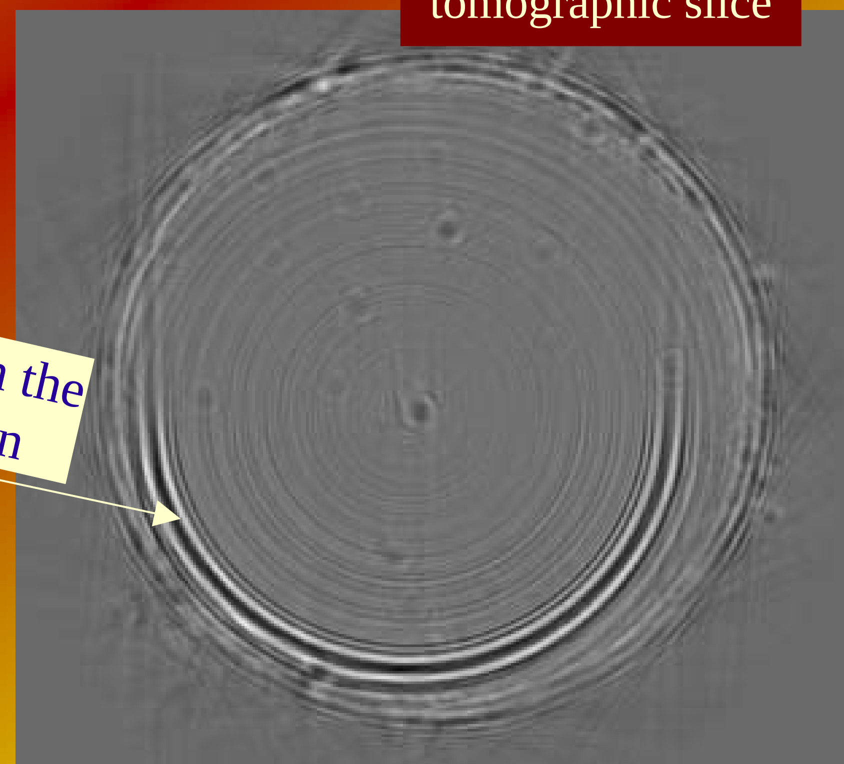
flat-field correction fails

$$I_{corr} = \frac{I_{obj}}{I_{ref}}$$

dust particles
on the mirror

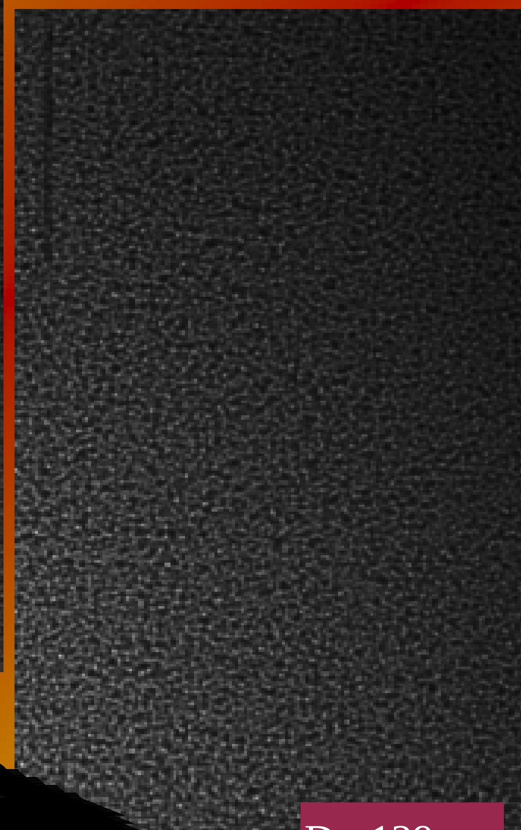


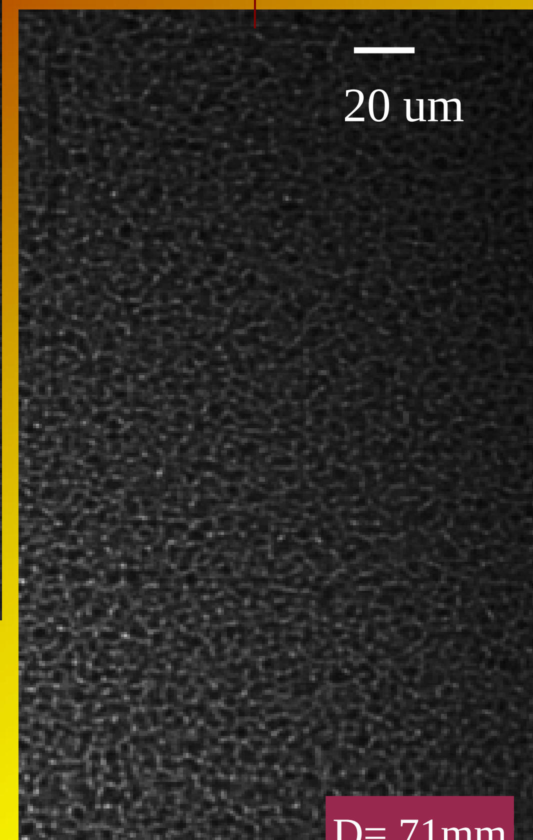
rings arise in the reconstruction

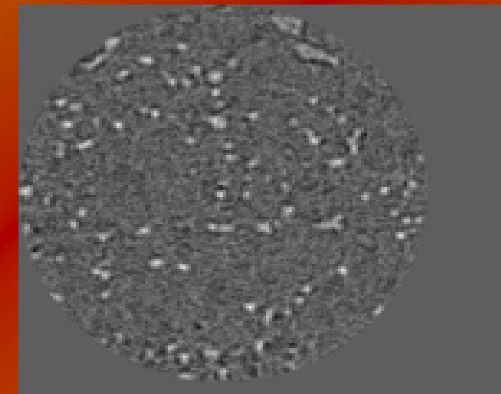


solution: LOCAL TOMOGRAPHY

Local tomography



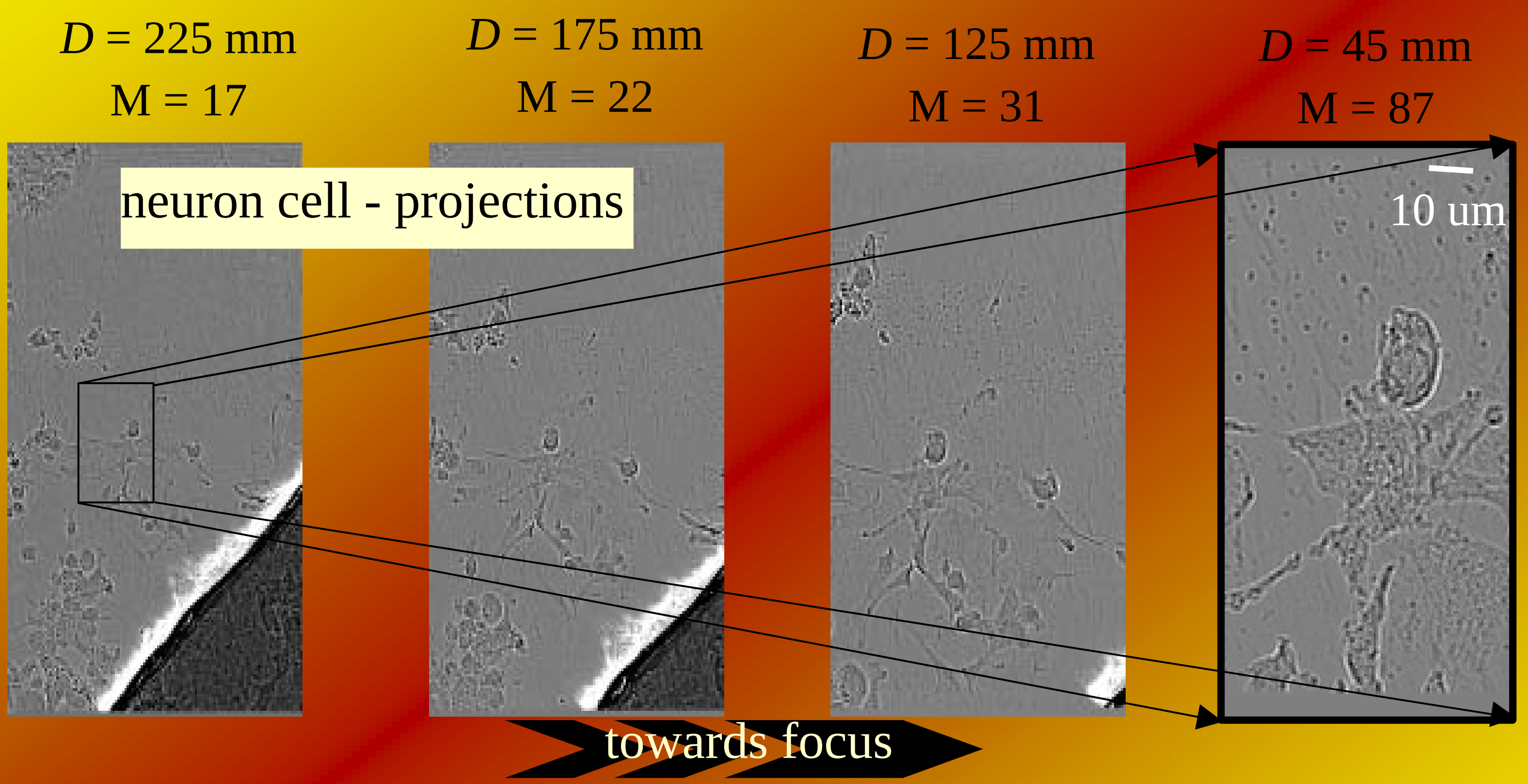




reconstruction - no phase retrieval

cylindrical sample of 7% Cu in Al much larger than the field of view

towards focus

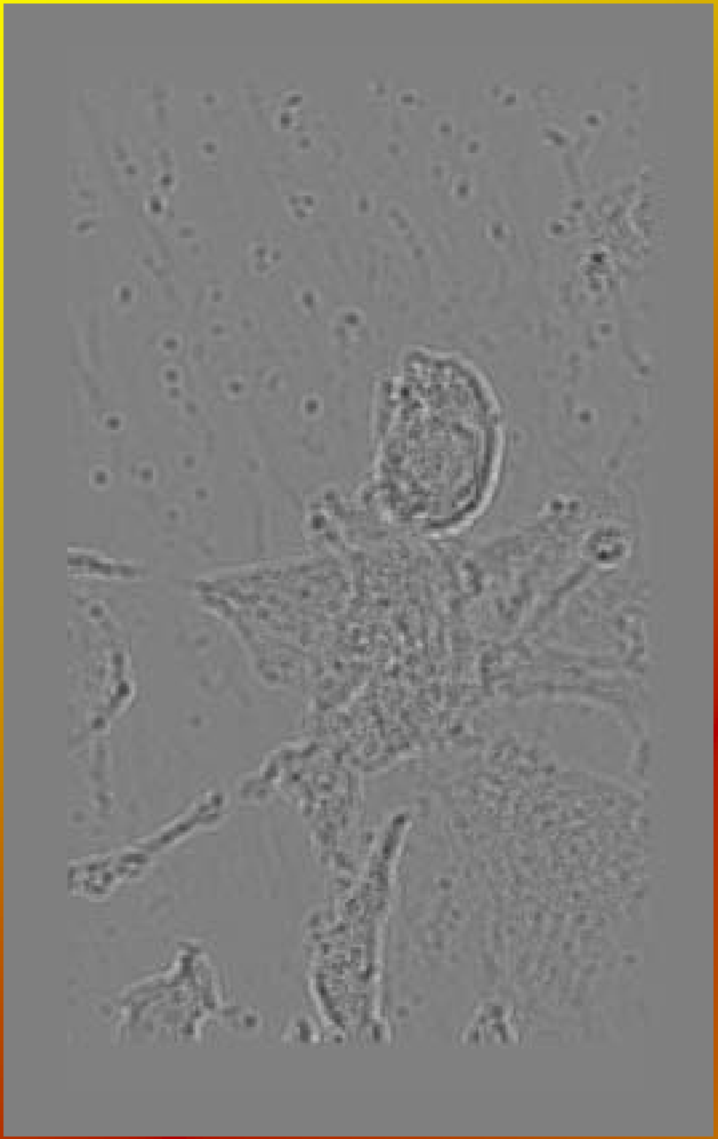


The equivalences between parallel and cone beam

$$D = \frac{z_1 . z_2}{z_1 + z_2}$$

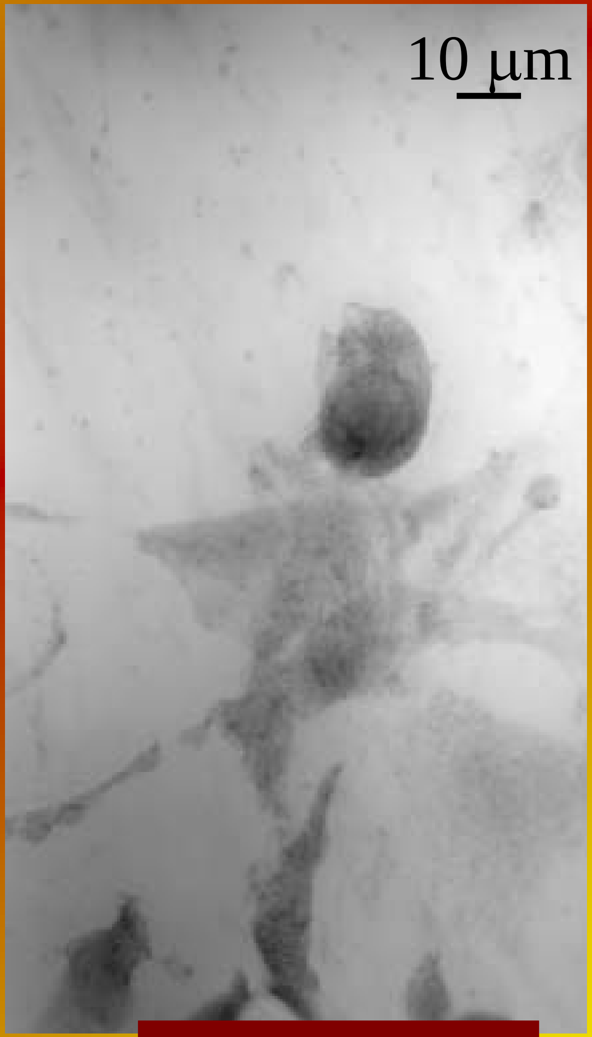
$$M = \frac{z_1 + z_2}{z_1}$$

Rel. phase map from magnified fresnel diffraction patterns



D = 475mm

5 dist.



relative phase map

Rel. phase map from magnified fresnel diffraction patterns brought to same magnification

phase retrieval

The cost functional

$$C_s = \sum_d \left| \tilde{I}_d^{exp}(f) - \tilde{I}_d^{calc}\left(\tilde{T}(f)\right) \right|^2$$

Direct linear methods
(filtering)

linearization with respect to:

- slowly-varying phase — $\tilde{\varphi}$
- weak object — $\tilde{\varphi}, \tilde{B}$
- paraboloid method — $\tilde{T}$

Iterative method: no restrictions on object — Steepest descend to minimize the cost functional

Slowly-varying phase

the approximations

$$T(x) = e^{i\varphi(x)} \quad \& \quad \left|\varphi(\eta) - \varphi(\eta - \lambda D f)\right| << 1 \;\; \forall \eta$$

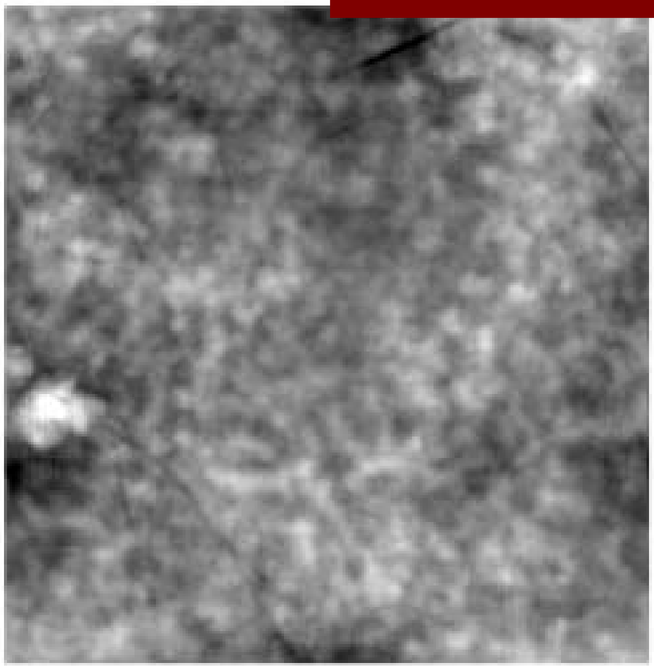
$\lambda D f$

the basic formula

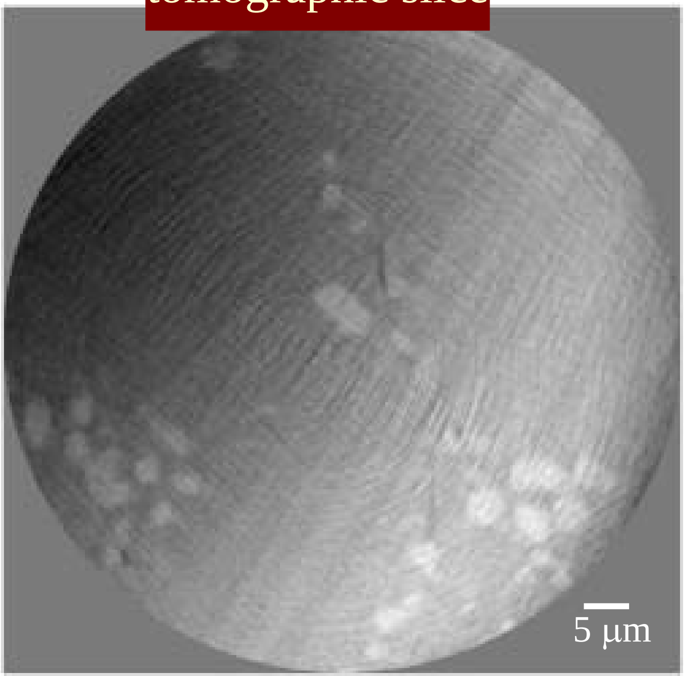
$$\tilde{I}_D(f) \approx \delta(f) + 2\sin(\pi \lambda D f^2) \cdot \tilde{\varphi}(f)$$

FT of intensity — **contrast factor** — FT phase

phase map



tomographic slice



5 distances
900 projections

Weak object approximation

the approximations

$$T = e^{-B(x)} . e^{i\varphi(x)}, \; B(x) << 1$$

the basic formula

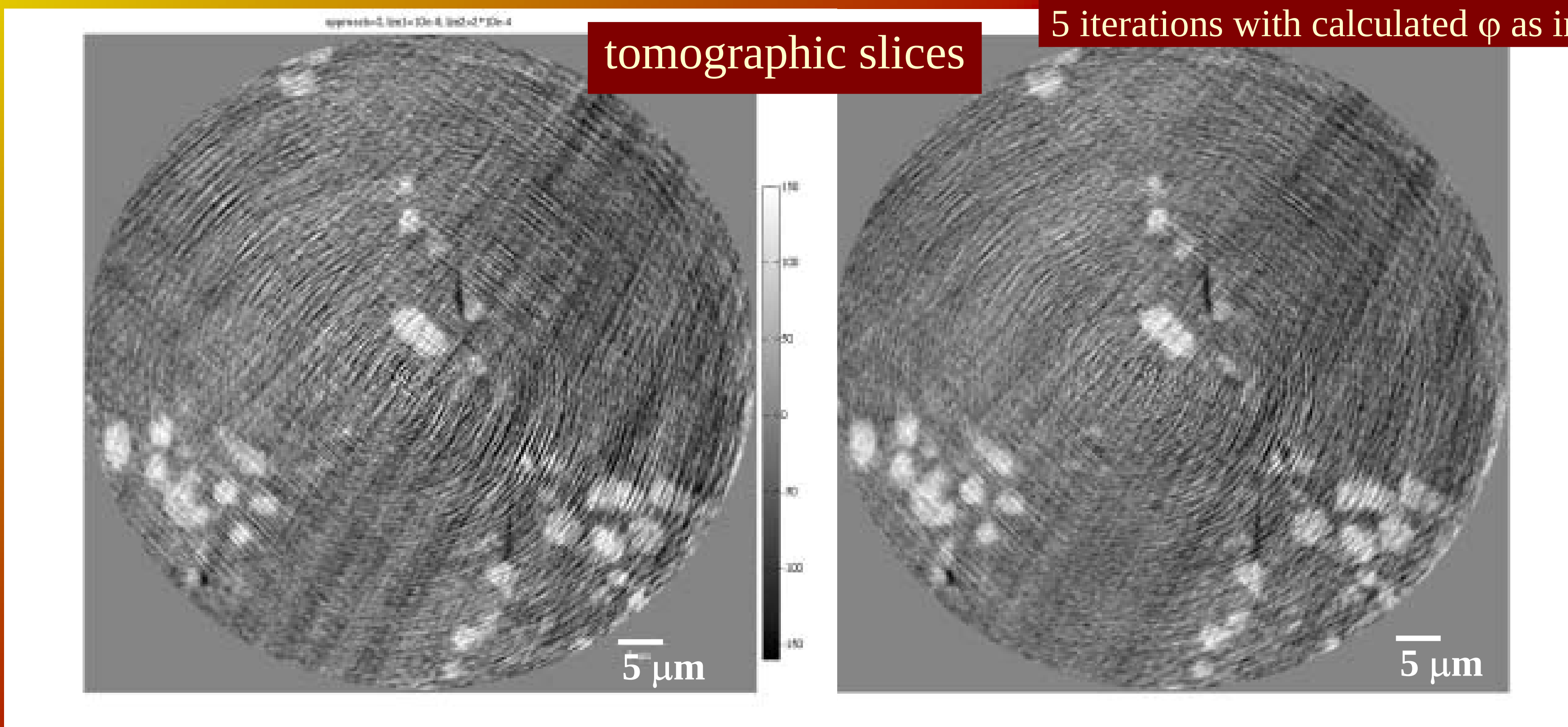
$$\tilde{I}_D(f) \approx \delta(f) \; + \; 2\underbrace{\sin(\pi\lambda D f^2)}_{\text{phase contrast factor}} . \tilde{\varphi}(f) \; - \; 2\underbrace{\cos(\pi\lambda D f^2)}_{\text{absorption contrast factor}} . \tilde{B}(f)$$

phase contrast factor

absorption contrast factor

tomographic slices

5 iterations with calculated φ as initial guess



S. Zabler, P. Cloetens, J.-P. Guigay, J. Baruchel, M. Schlenker, Rev. Sci. Ins., in press

paroboloid method

the approximations

neglect the non-linear contributions to the intensity

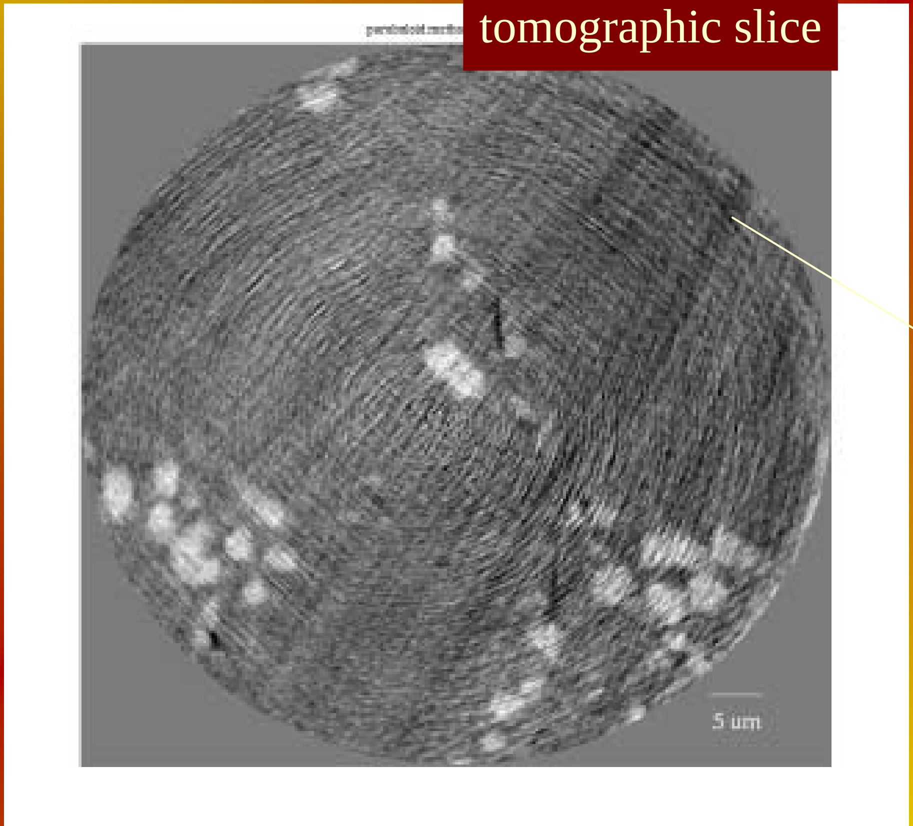
the basic formulas

decomposition of the object: $T(x) = \alpha + \psi(x)$

$$ = \alpha^2 .\delta(f) + \exp(-i\pi\lambda D f^2) \;.\; \alpha \quad + \exp(i\pi\lambda D f^2) \;.\; \alpha \quad + N.L. $$

Fourier transform intensity — FT object — FT c.c. object — non-linear terms

tomographic slice



large objects enter the field of view

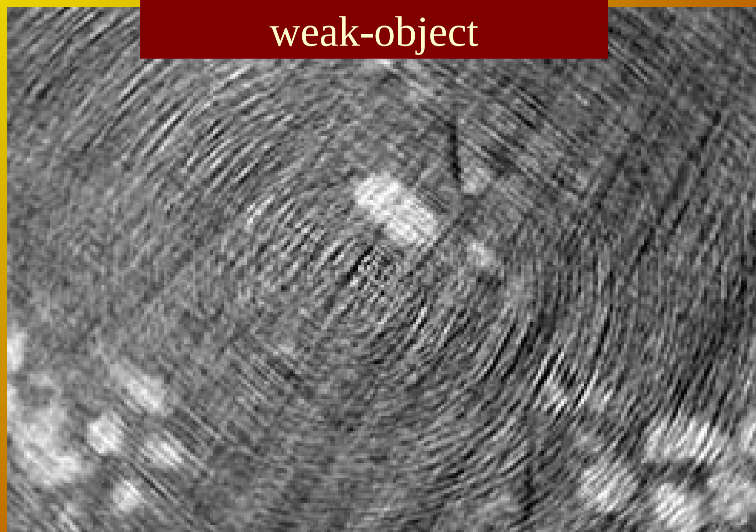
- phase unwrapping needed

M.Op de Beeck, D. Van Dyck and W. Coene, Ultramicroscopy 64,167 (1996)

comparing the different approaches

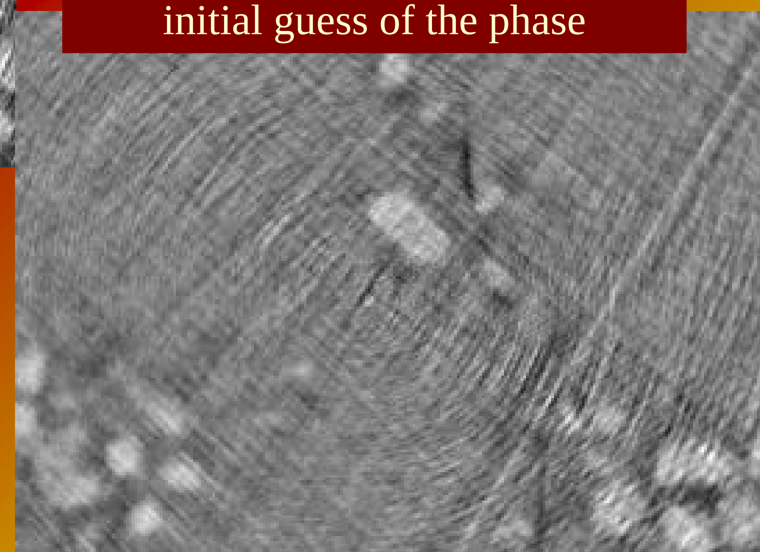
weak-object followed by 5 iterations

weak-object



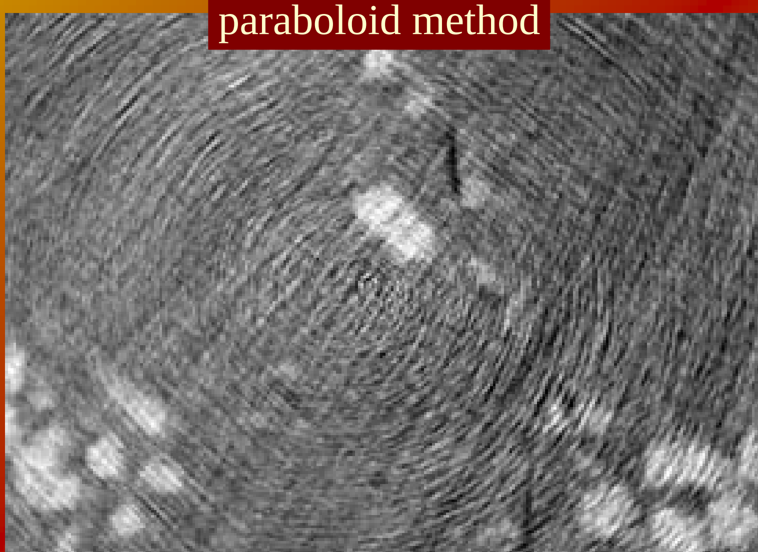
- the design of the filter amplifies ring artefacts

5 iteration without restrictions on initial guess of the phase



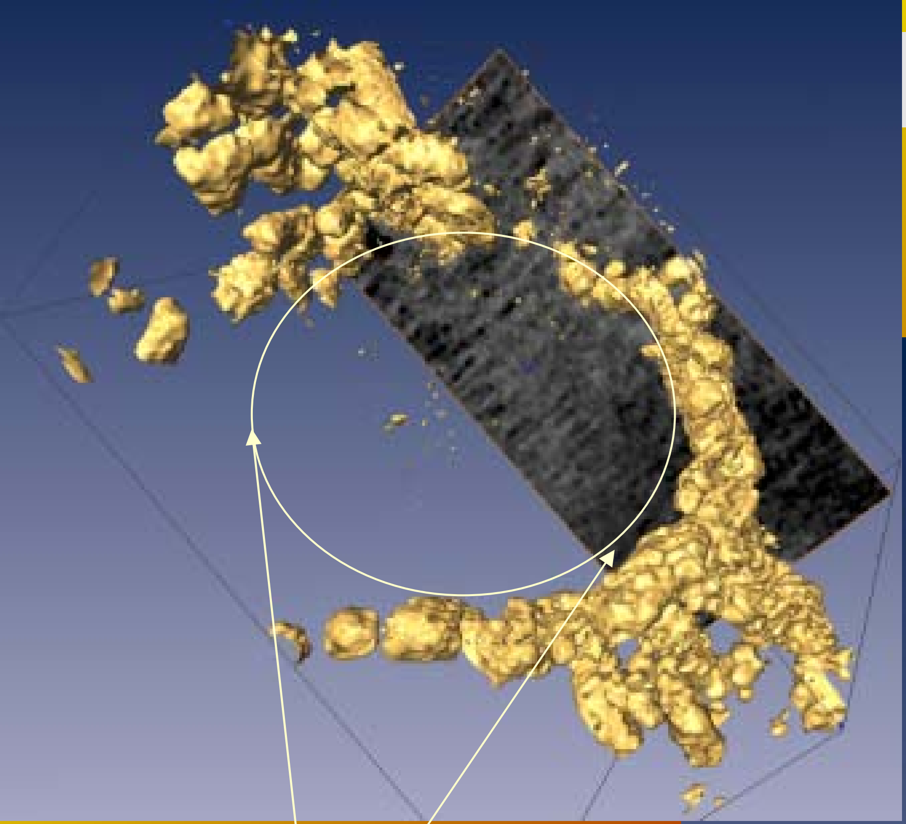
5 µm

paraboloid method



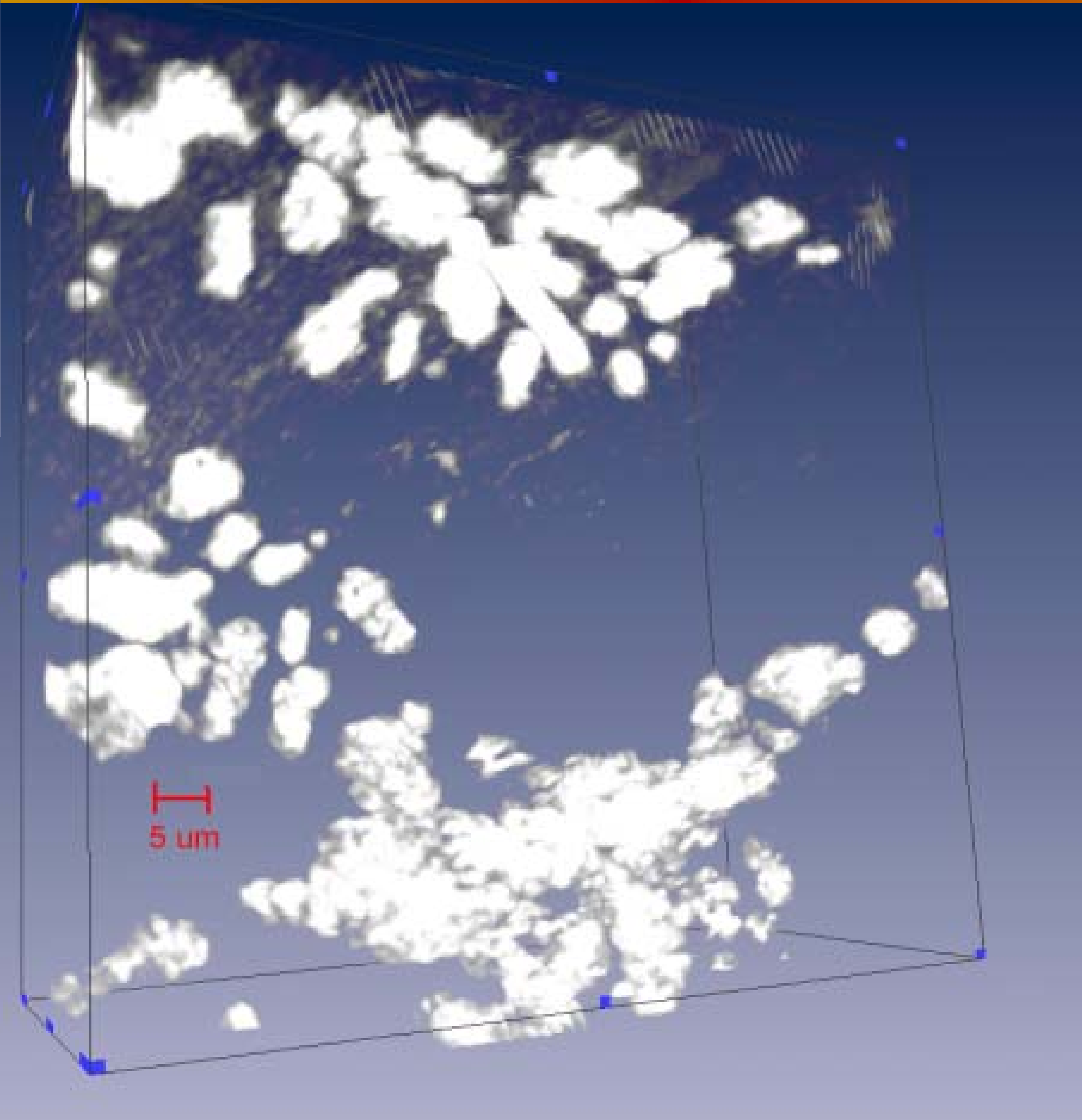
quality of images implies the use of image processing tools in order to obtain 3D volumes that can be segmented

3D visualisation



Si located at grain boundaries

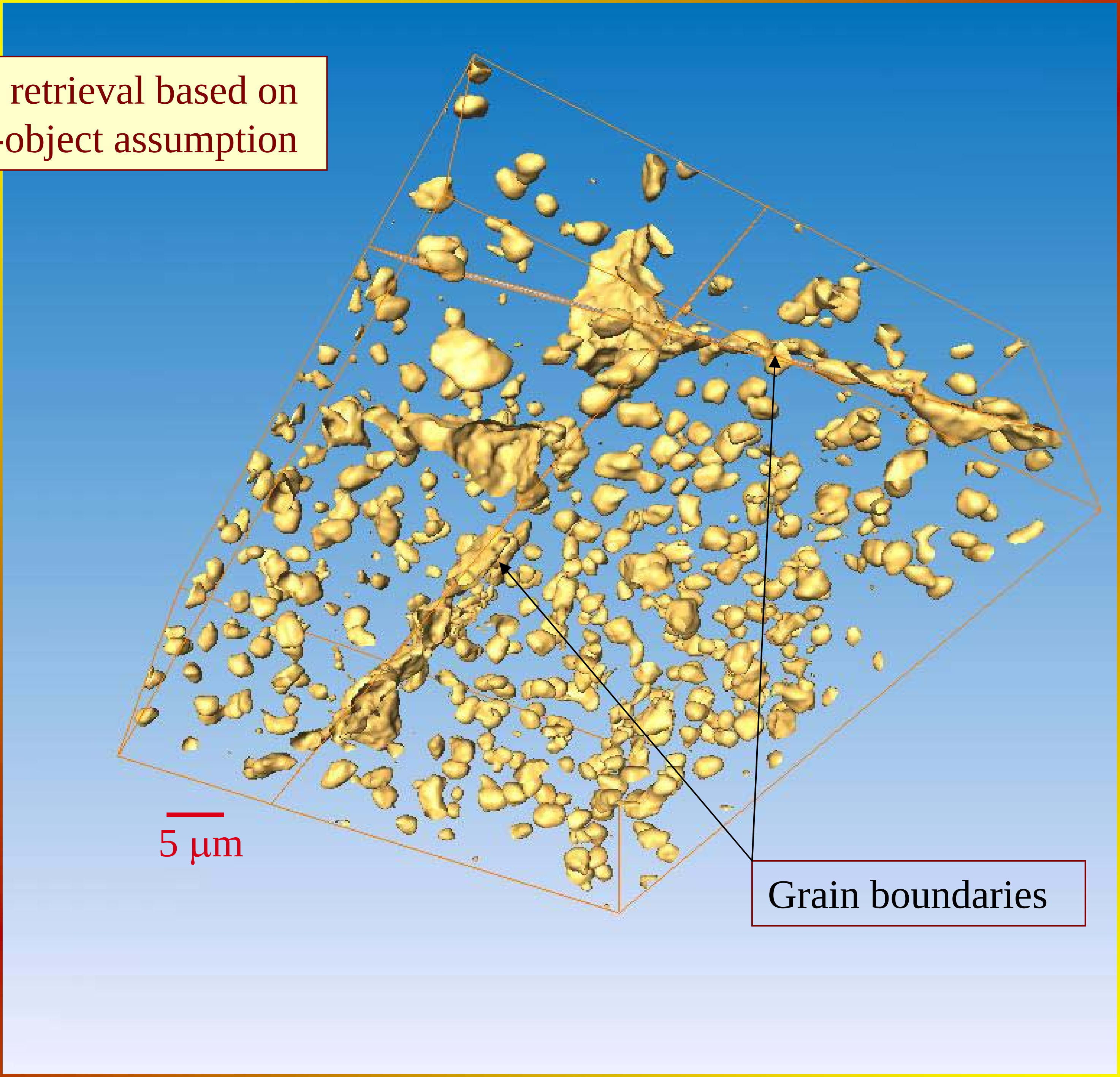
Paraboloid method



AlSi

Al_2Cu alloy in 3D

Phase retrieval based on weak-object assumption



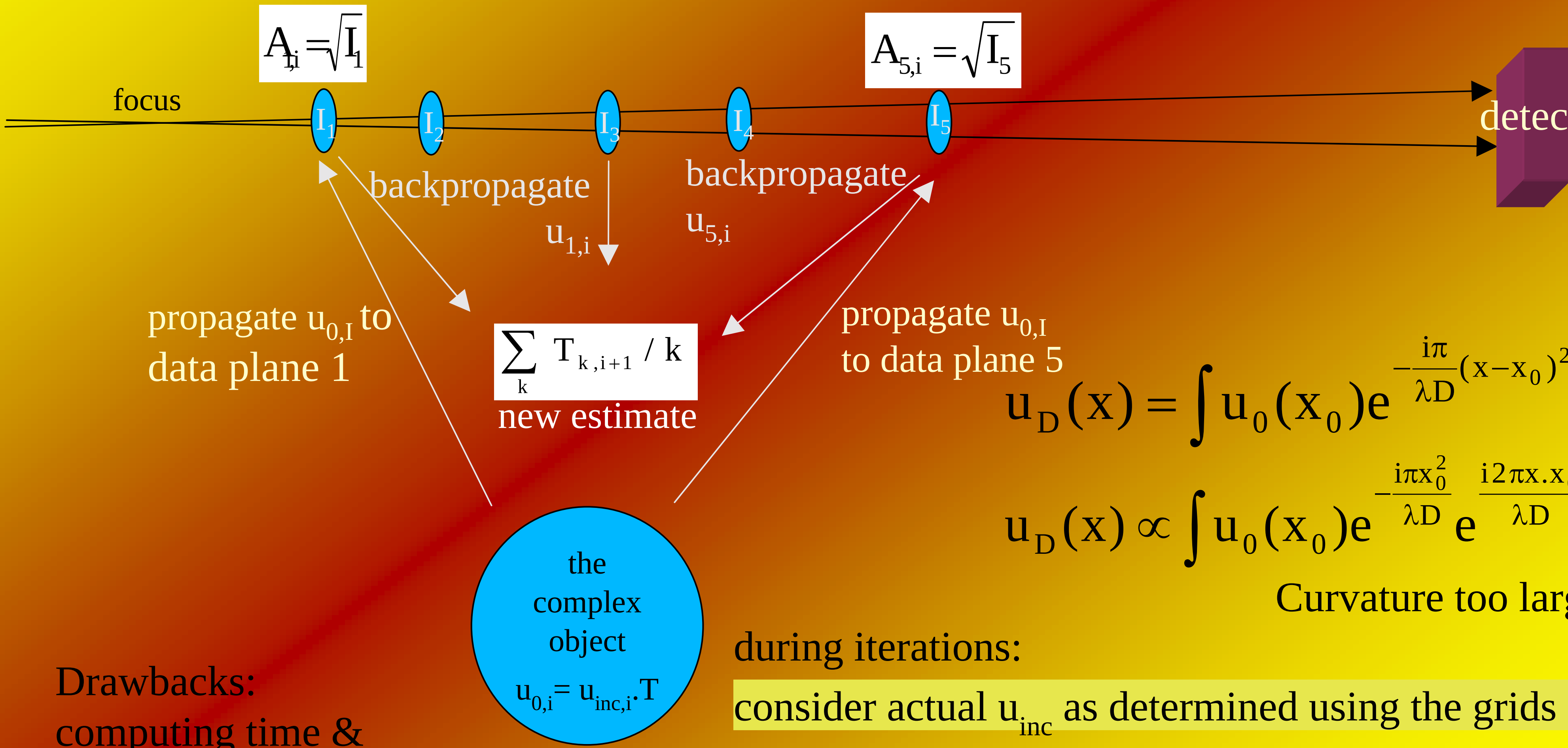
Outlook – iterative method

principle

The Gerchberg-Saxton-Fienup algorithm modified for:

- Fresnel diffraction
- multiple intensity measurements

See also: Curved wavefronts: Nugent, K.A. et. al., (2003). Phys. Rev. Let. 91,203902



$$u_D(x) = \int u_0(x_0) e^{-\frac{i\pi}{\lambda D}(x-x_0)^2} dx_0$$

$$u_D(x) \propto \int u_0(x_0) e^{-\frac{i\pi x_0^2}{\lambda D}} e^{\frac{i2\pi x.x_0}{\lambda D}} dx_0$$

Curvature too large?

during iterations:

consider actual u_{inc} as determined using the grids

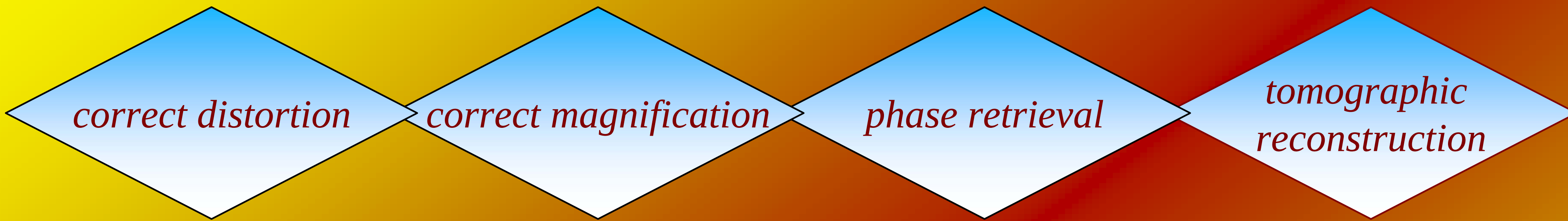
when iteration completed:

phase unwrapping

Drawbacks:
computing time &
strong curvature

summary & perspectives

- Overview of the processing for magnified tomography



- Artefacts: Perturbation of the wavefront introduced by the mirror shape
  Flatfield fails in case of strong phase gradients

- Local tomography offers the “easy” solution

- Phase retrieval on alloys with satisfactory results applying the weak-object approximation or the paraboloid method

-Implement different iterative approaches
consider as far-field with curvature
-Implement phase unwrapping

- Spatial resolution in tomography improved in comparison to the highest resolution optics