Exploring Strain in Nanoscale Semiconductors

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London Centre for Nanotechnology
Diamond Light Source

Lund University, Sweden
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Outline

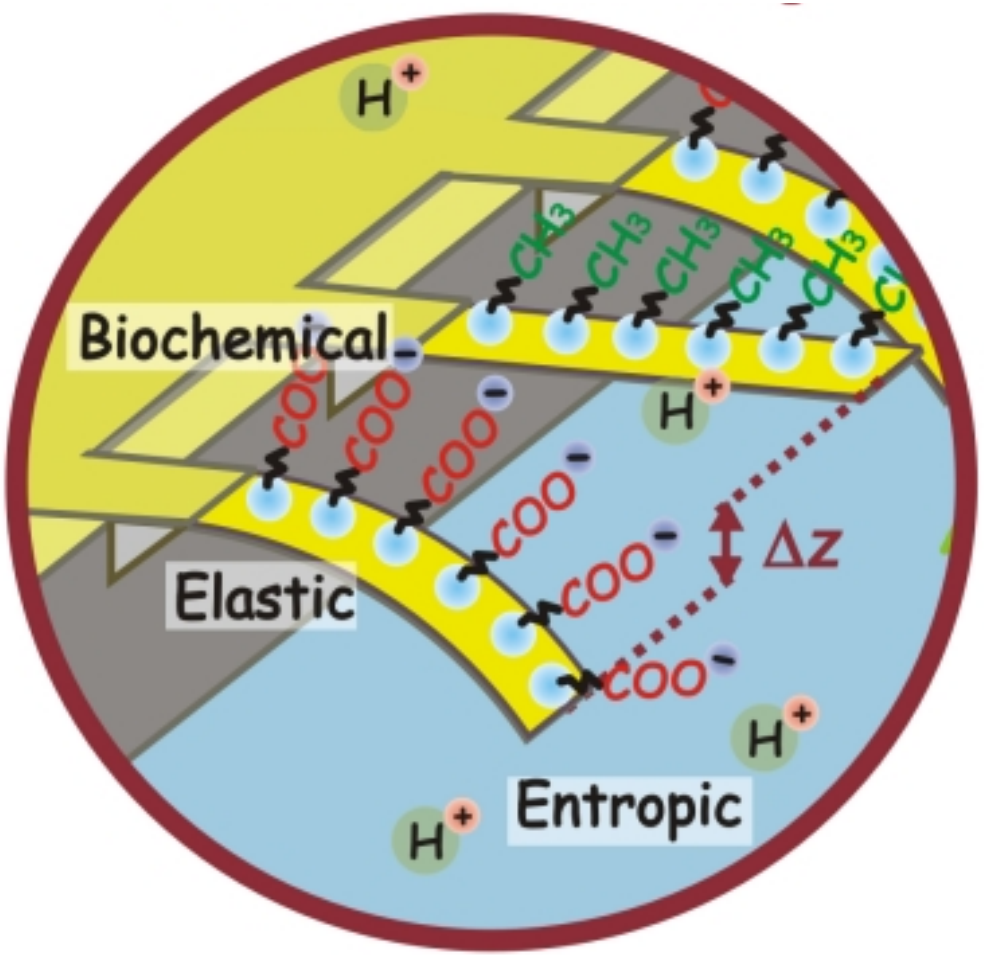
- Coherent x-ray diffraction
- CXD can solve the phase problem
- Nanocrystal structures
- Extension to phase objects
- Exploration of crystal strain
- Nanowire structures

London Centre for Nanotechnology

- Clean Rooms
- Low-T STM
- Lithography
- 3-beam FIB
- Visualisation
- CLS?

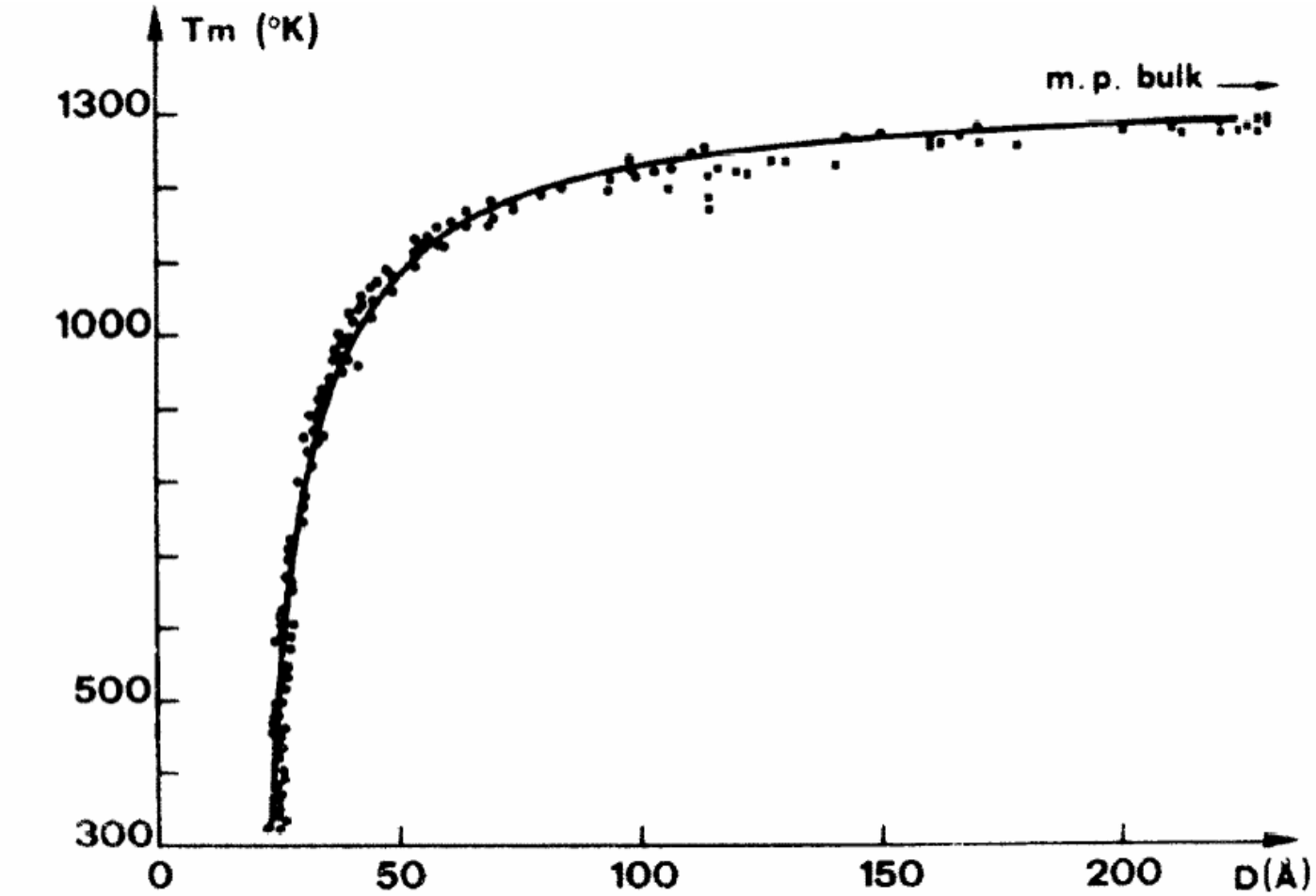
Nanocantilevers

Dr Rachel McKendrie

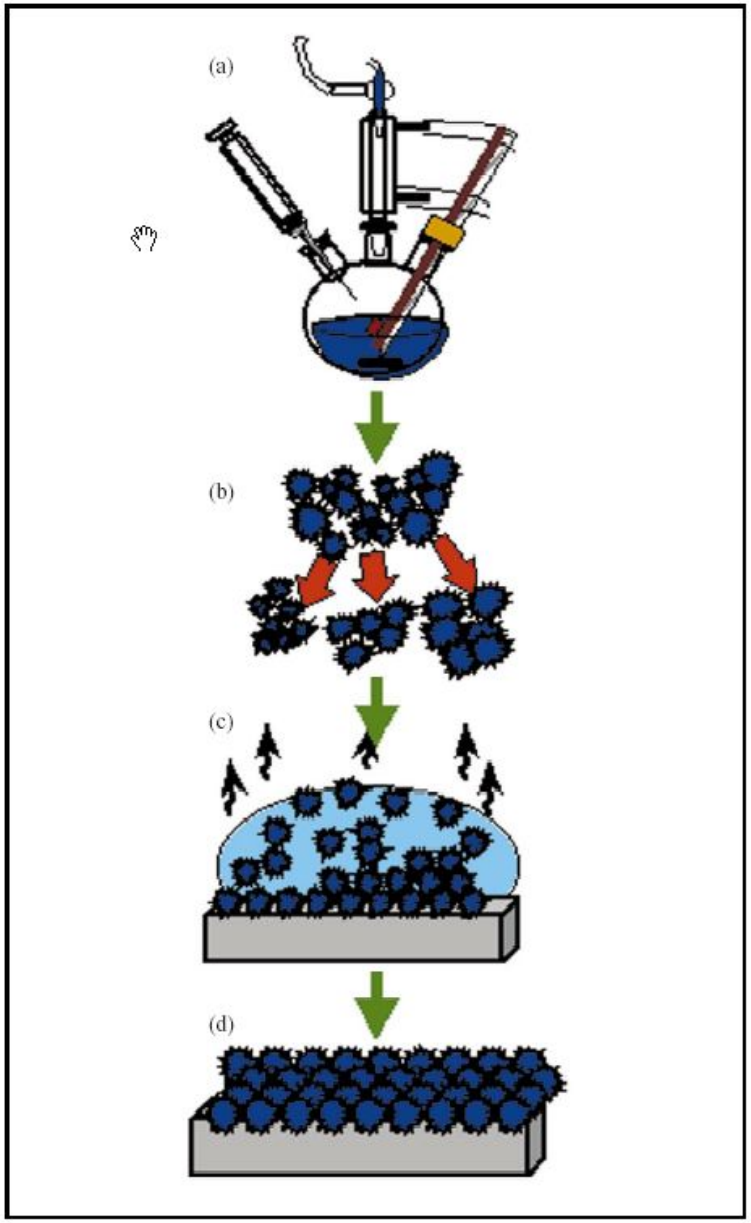


Size-dependent Melting of Au Particles

P. Buffat and J-P. Borel, Phys. Rev. A 2287-97 (1975)

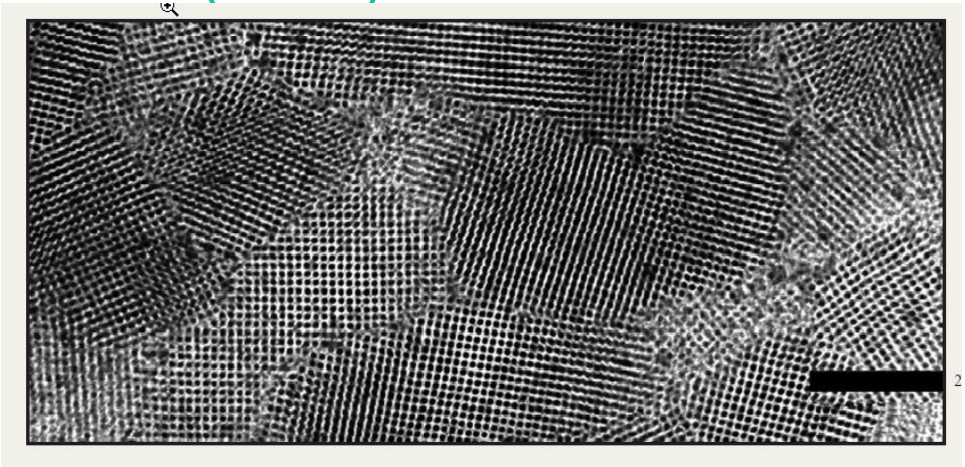


Chemical Synthesis of Nanocrystals



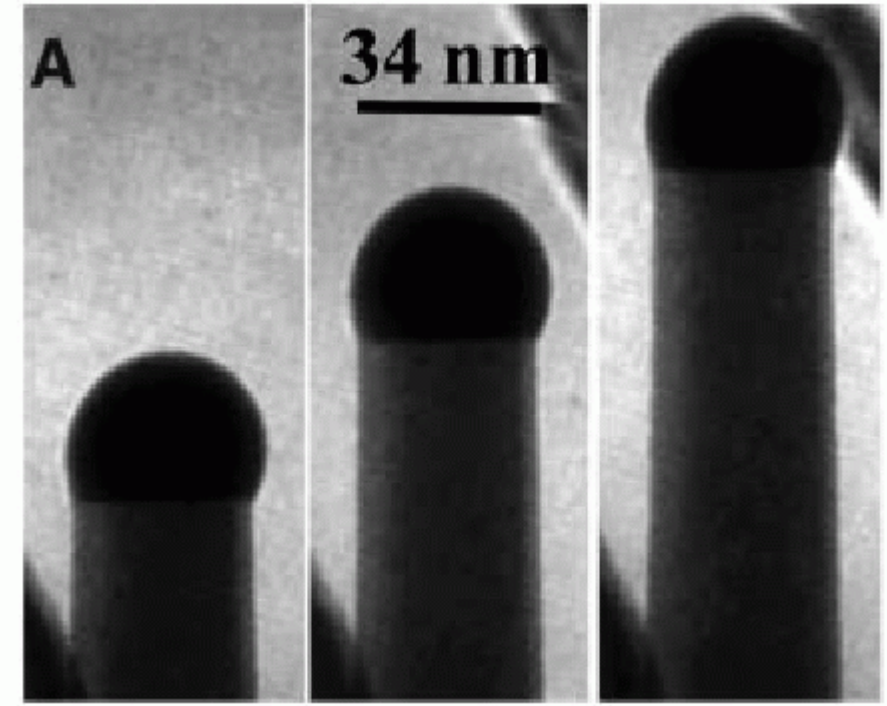
- Reactants introduced rapidly
- High temperature solvent
- Surfactant/organic capping agent
- Square superlattice (200nm scale)

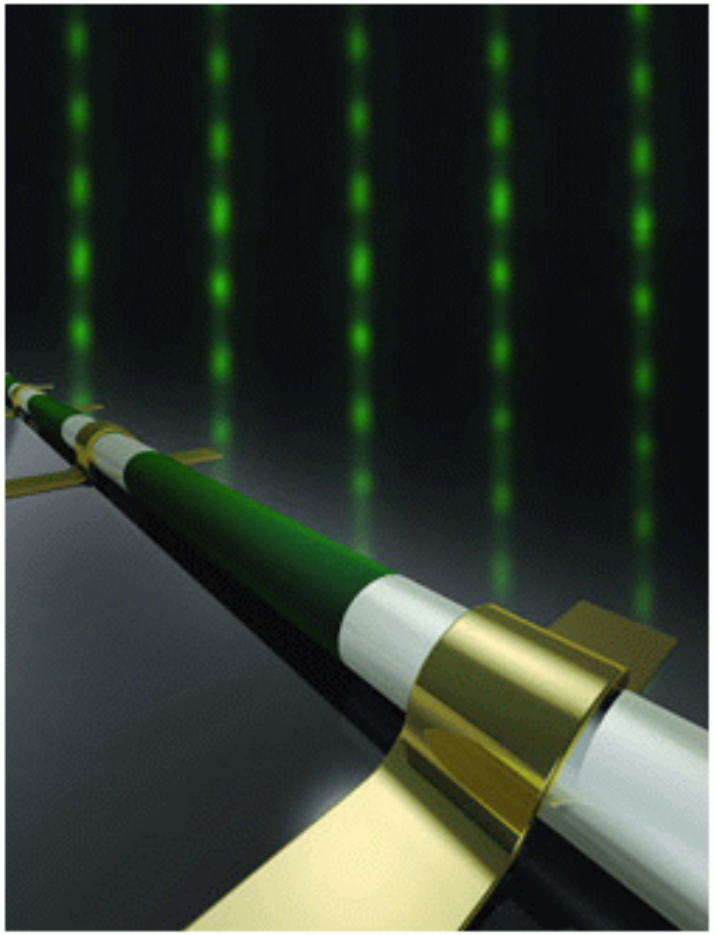
C. B. Murray, IBM J. Res. & Dev. **45** 47 (2001)



VLS growth of nanowires

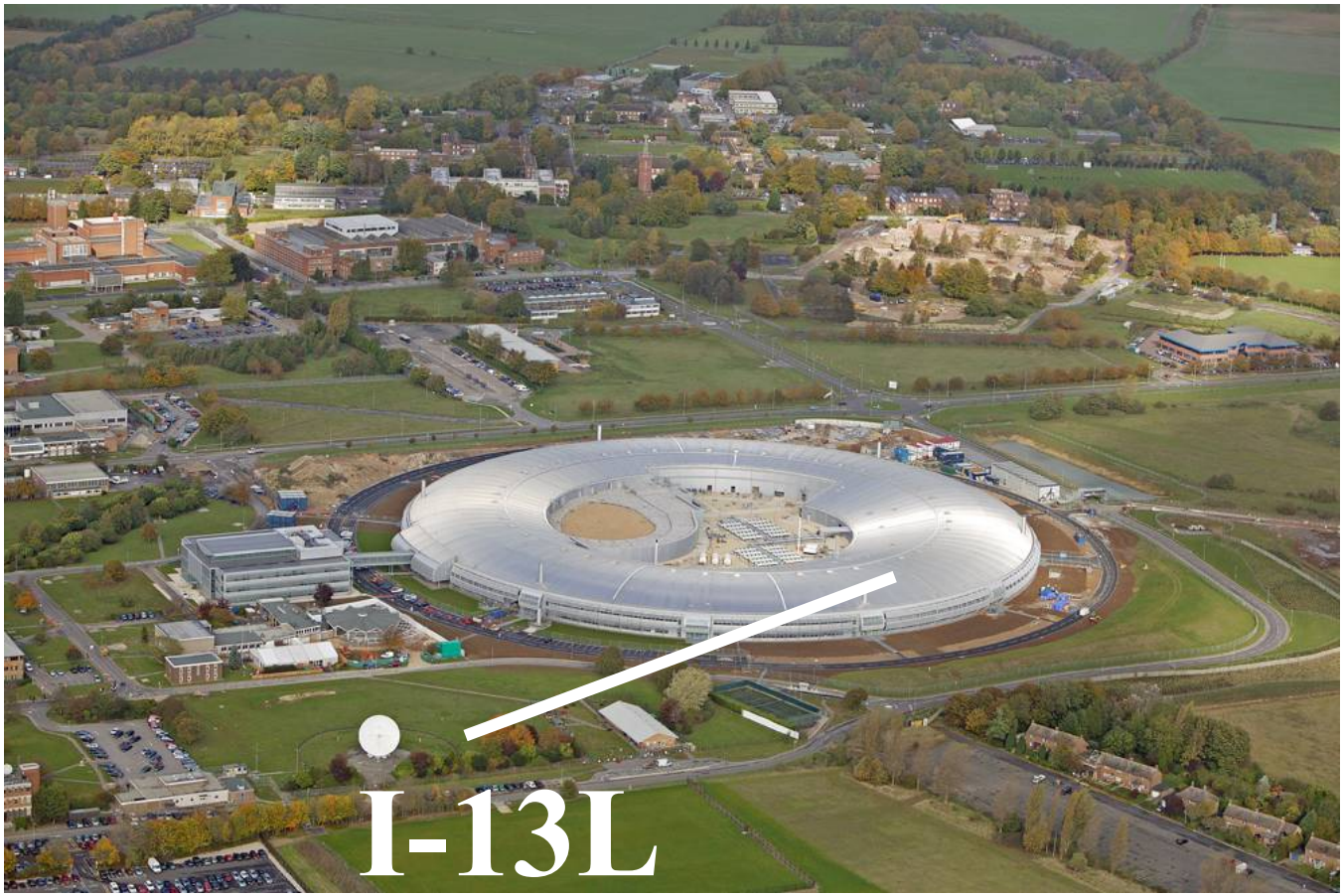
S. Kodambaka et al., Science 316 729 (2007)





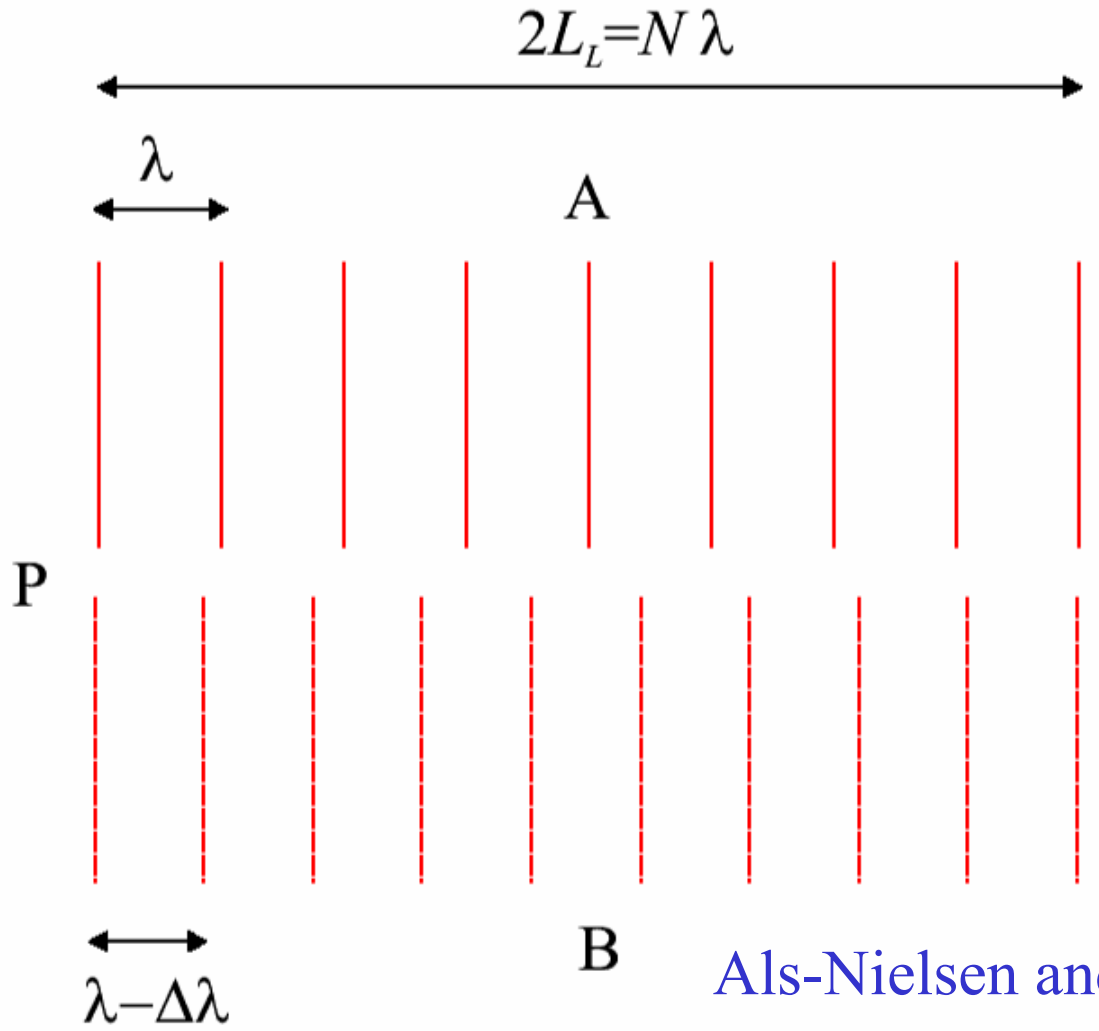
NiSi/Si nanowire heterostructure devices. *Nature* **430**, 61 (2004).

Diamond Light Source (RAL)



Diamond in-vacuum X-ray Undulator

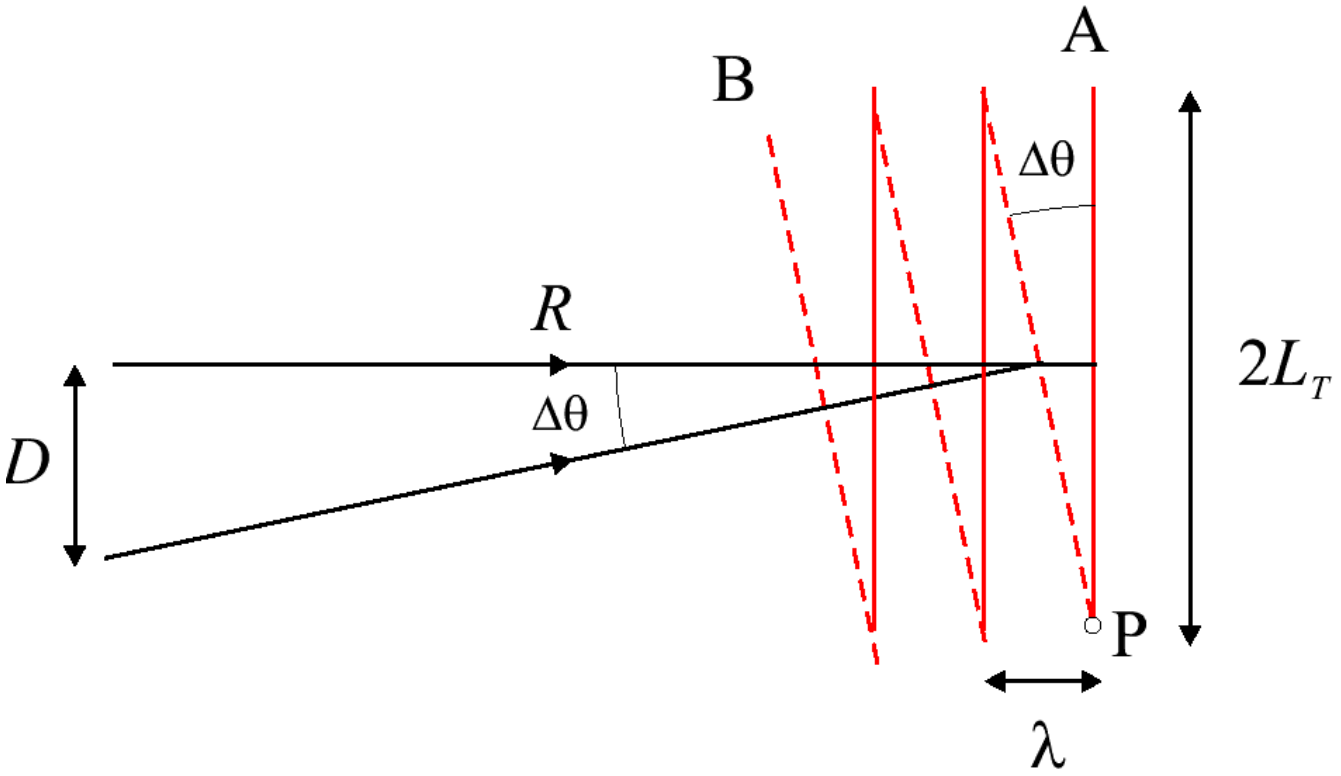
Longitudinal Coherence



$$L_L = \frac{1}{2}\frac{\lambda^2}{\Delta\lambda}$$

Als-Nielsen and McMorrow (2001)

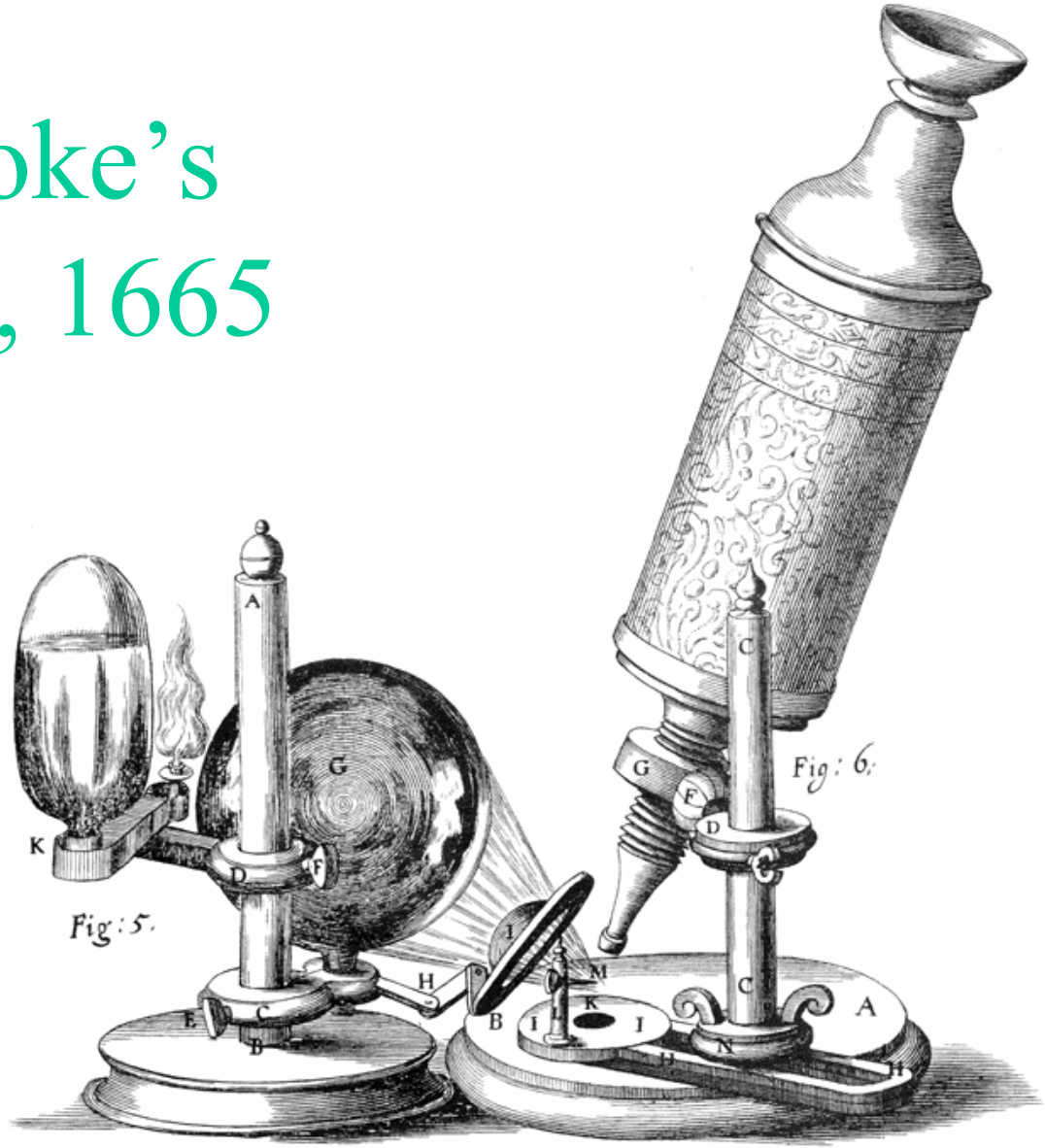
Lateral (Transverse) Coherence



$$L_T = \frac{\lambda}{2}\frac{R}{D}$$

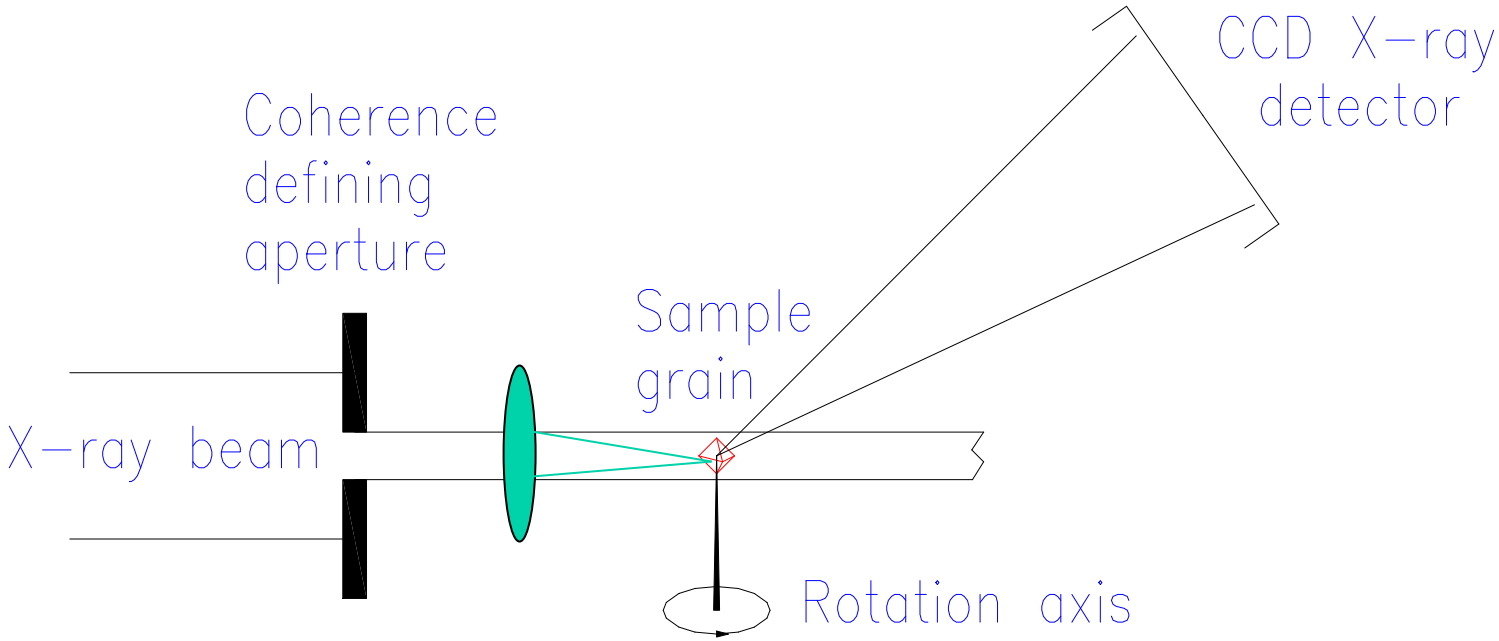
Als-Nielsen and McMorrow (2001)

Robert Hooke's microscope, 1665

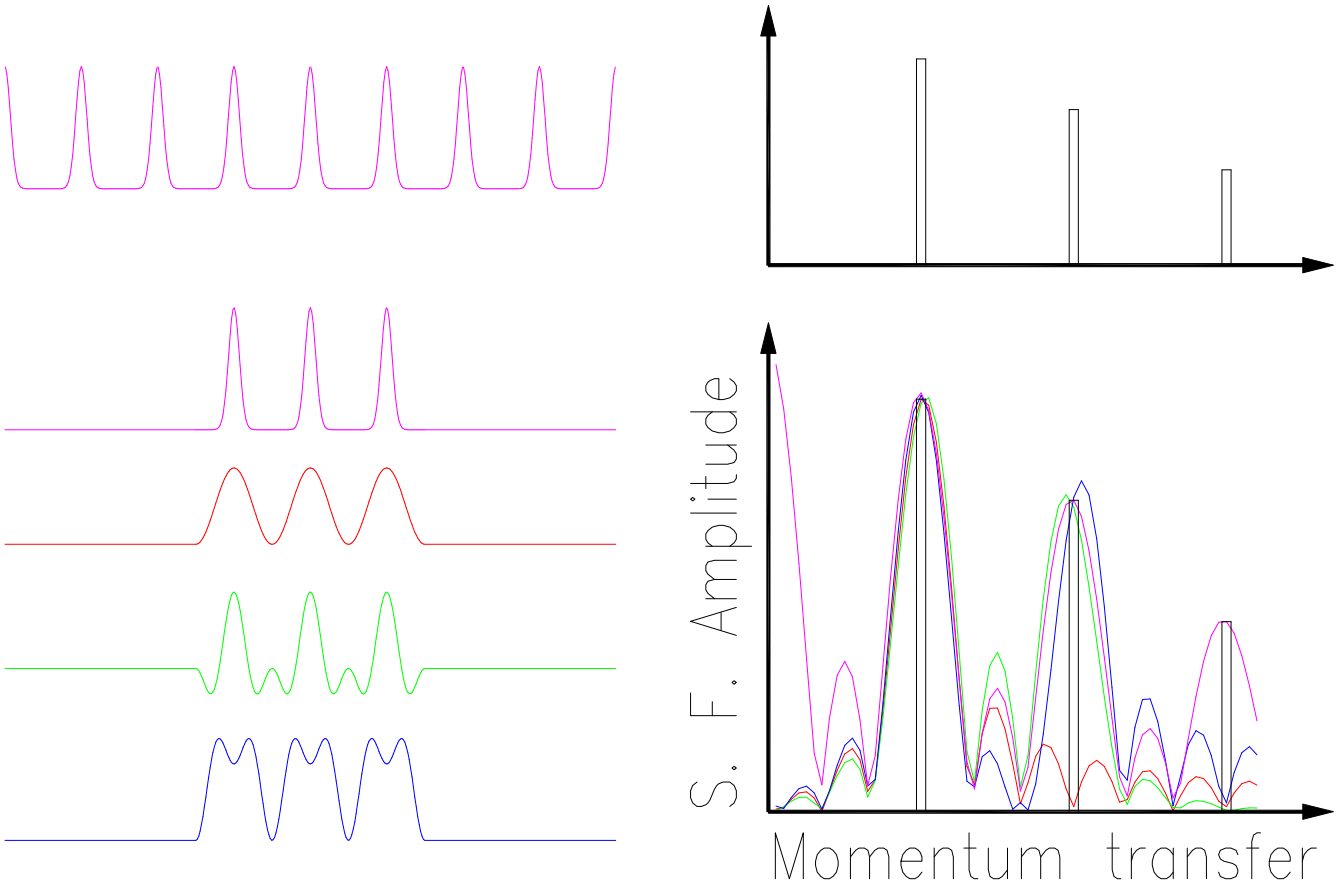


National Museum of Health and Medicine, Washington DC

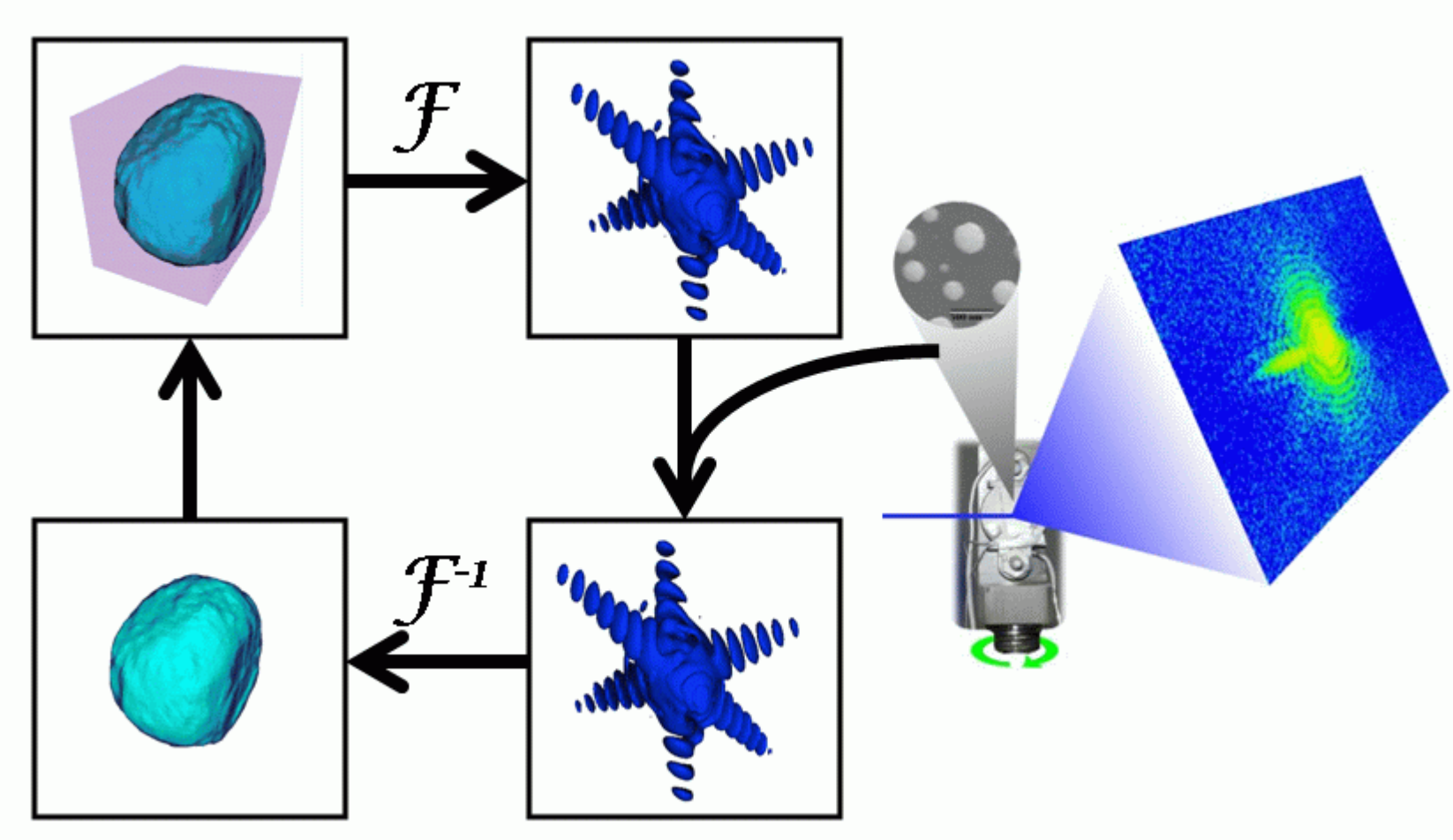
Lensless X-ray Microscope, 2003



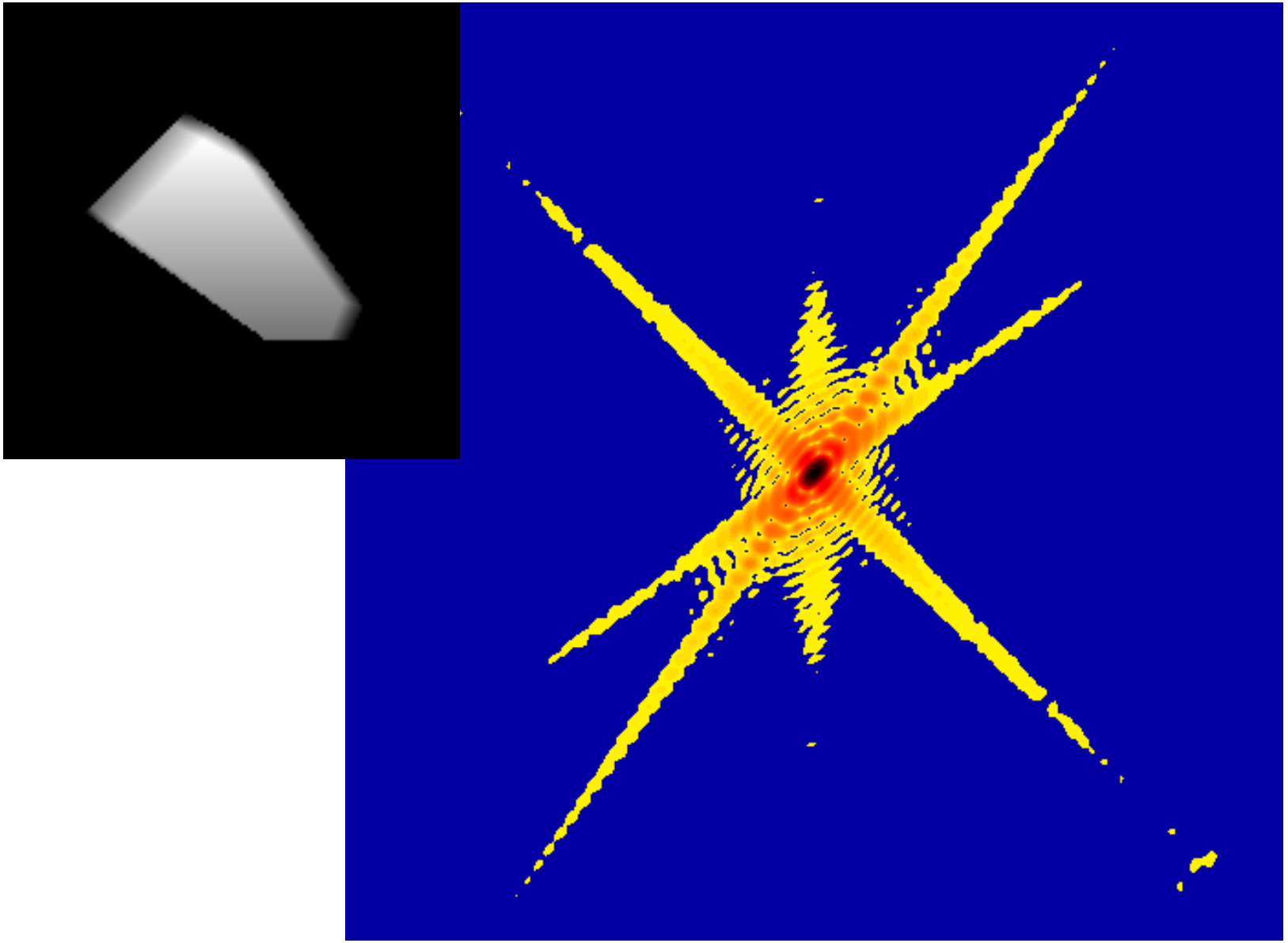
Oversampling solves Phase Problem



Generic "Error Reduction" method

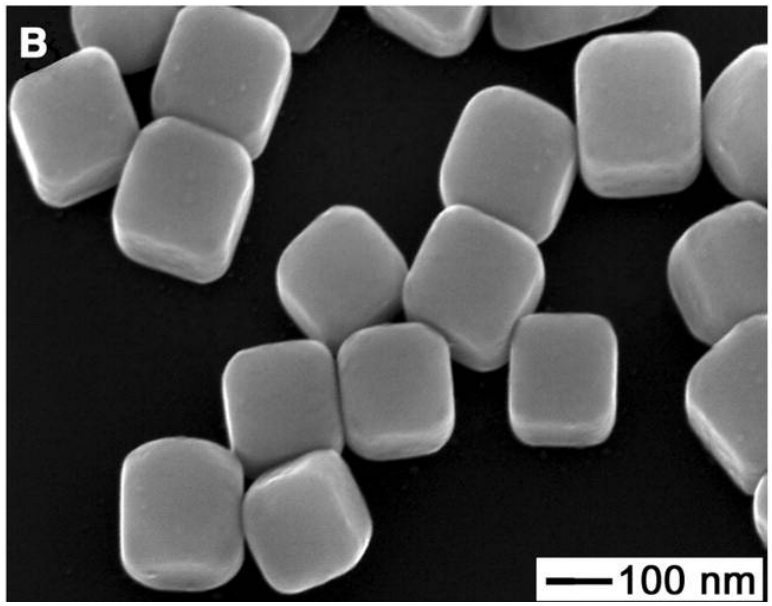


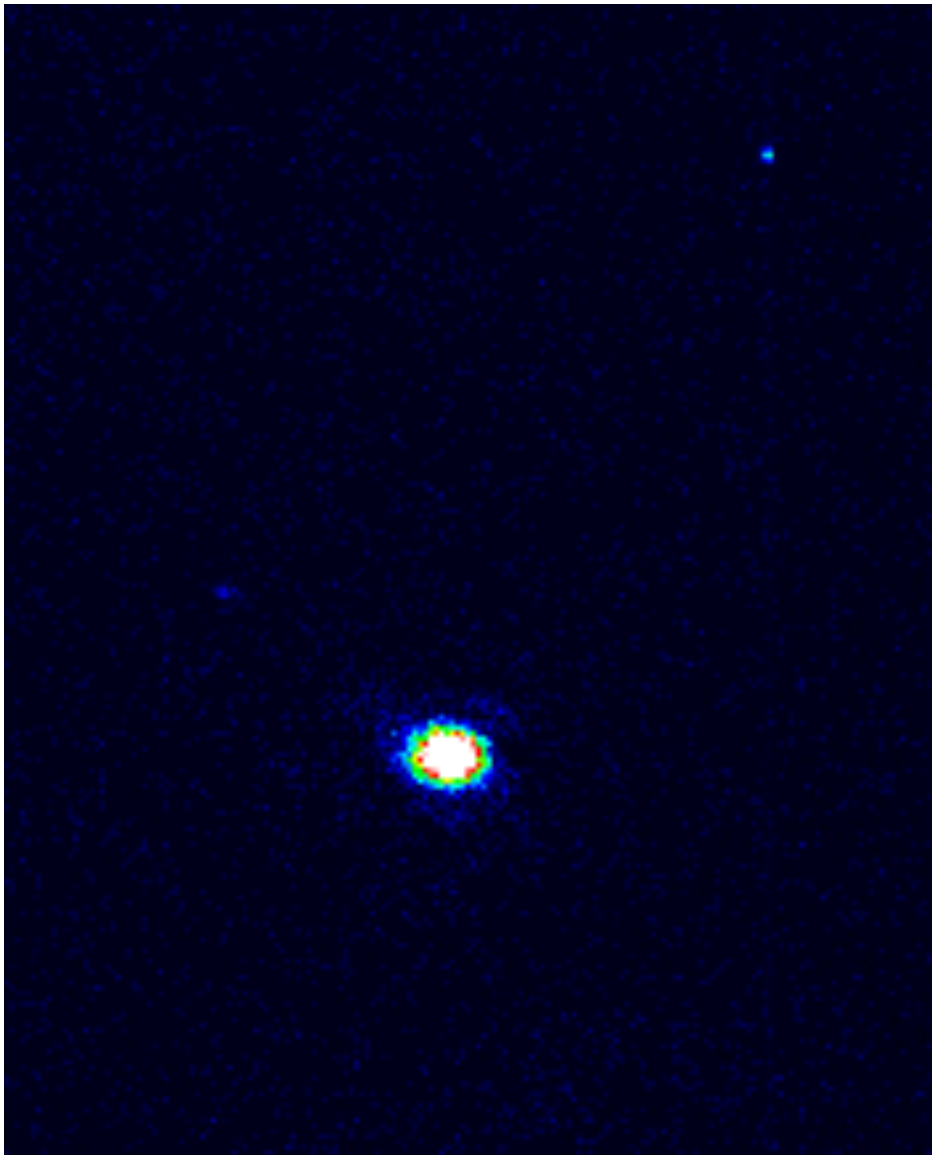
J. R. Fienup Appl. Opt. 21 2758 (1982)
R. W. Gerchberg and W. O. Saxton Optik 35 237 (1972)

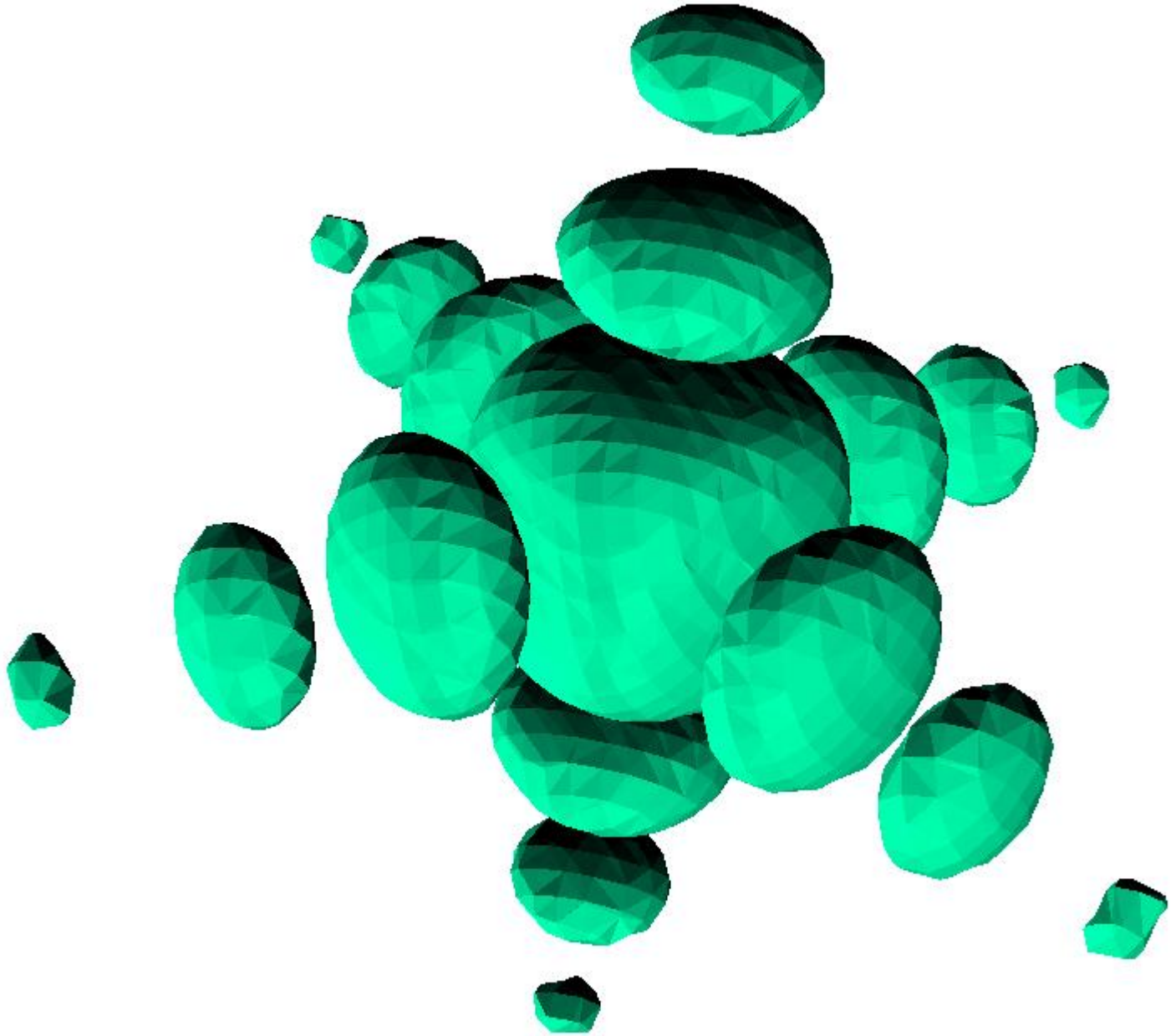


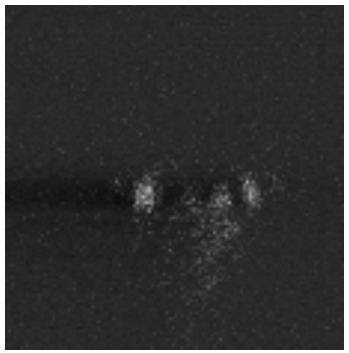
Chemically Synthesized Silver Nanocube Rock with 0.01° steps

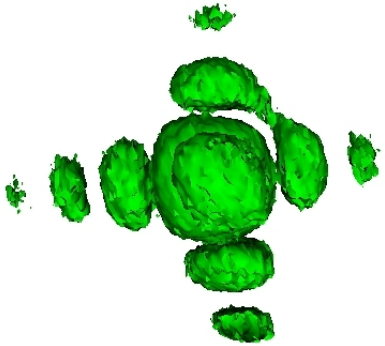
Yugang Sun and Younan Xia, Science 298 2177 (2003)

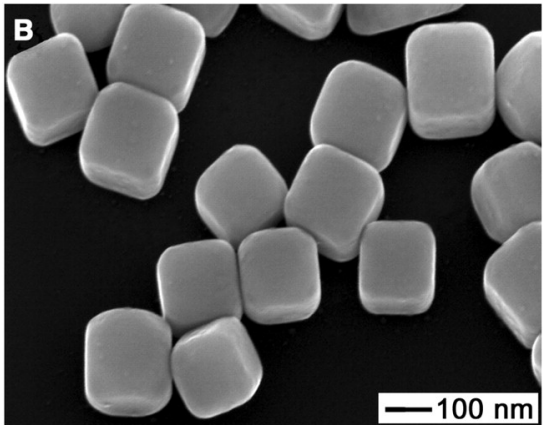


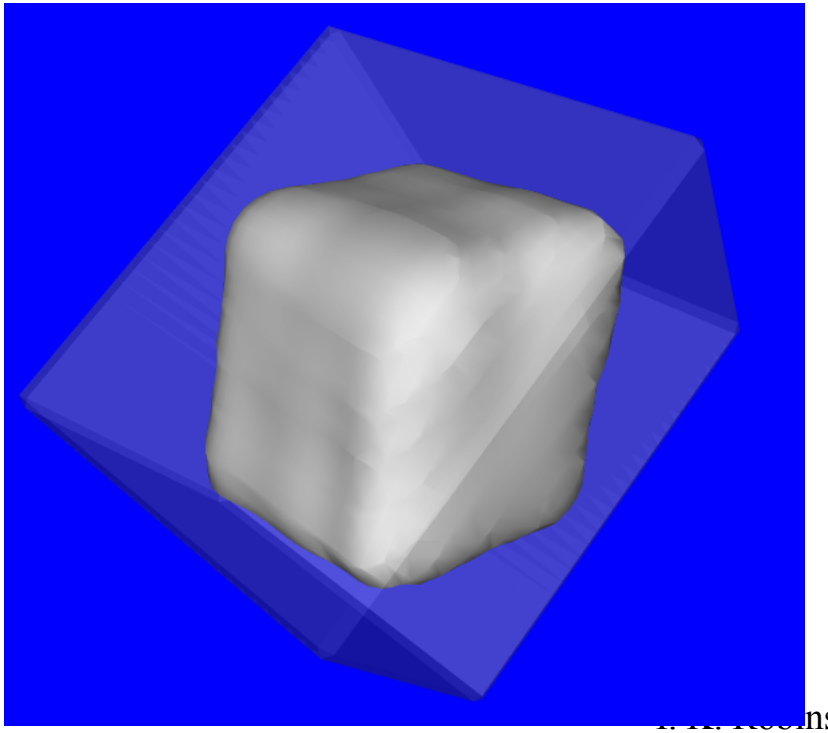


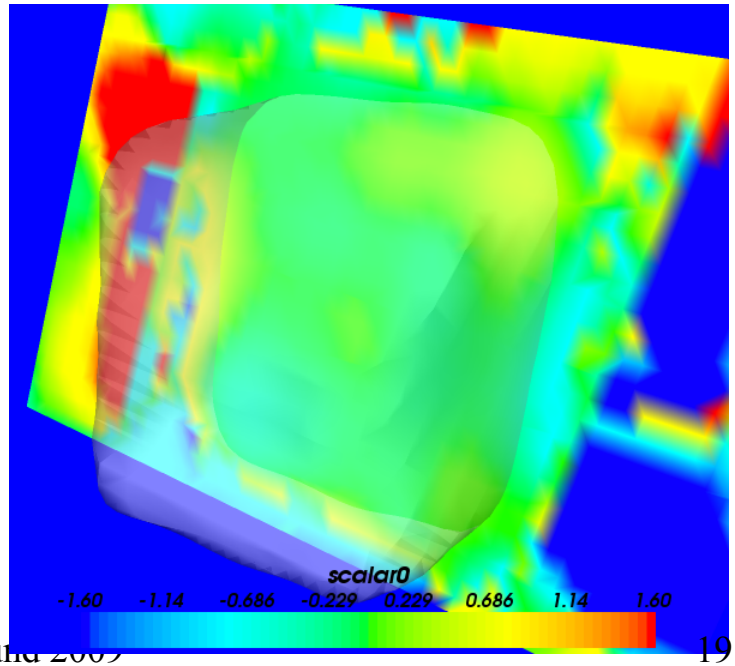






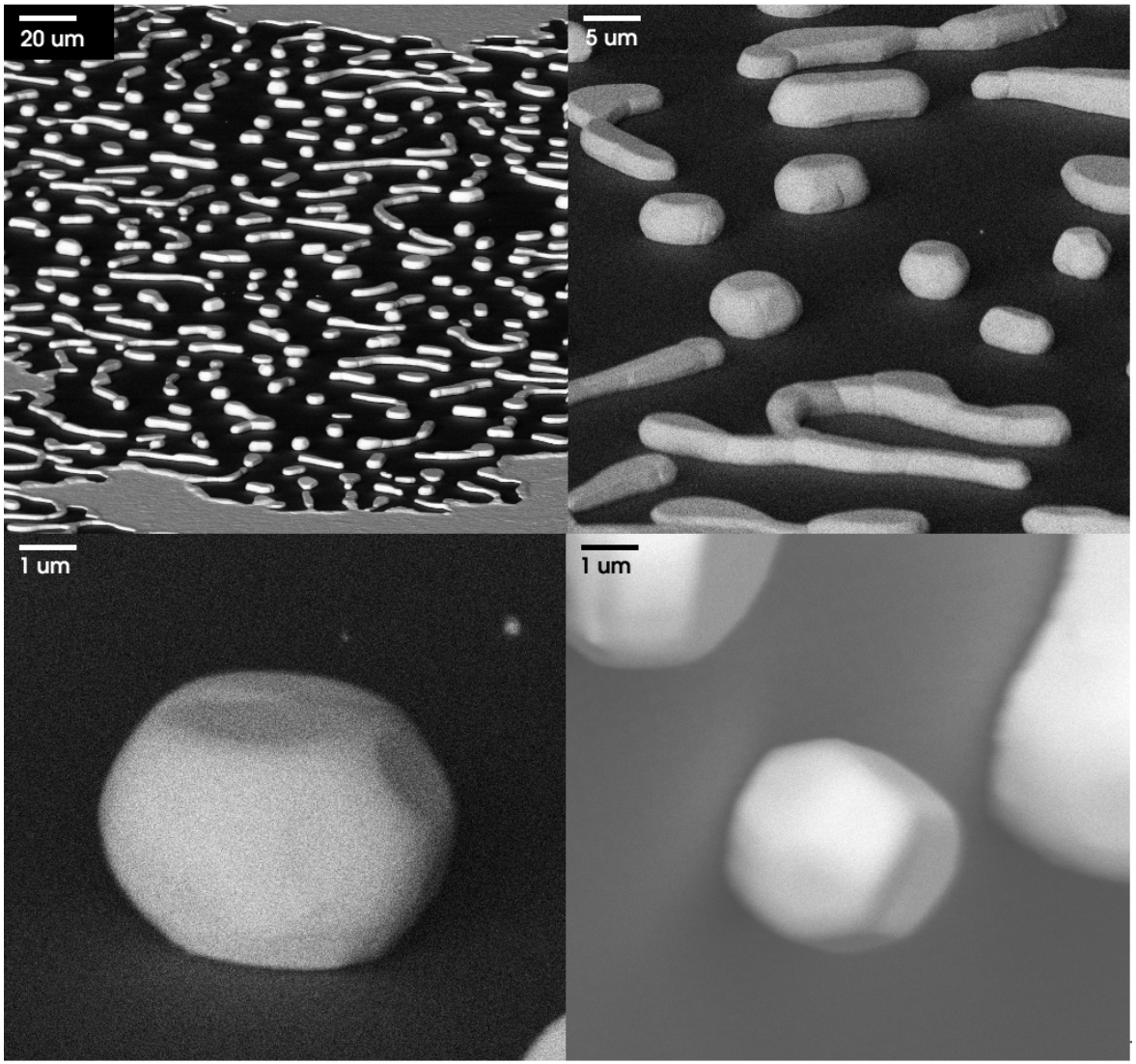

B
100 nm




scalar0
-1.60 -1.14 -0.686 -0.229 0.229 0.686 1.14 1.60

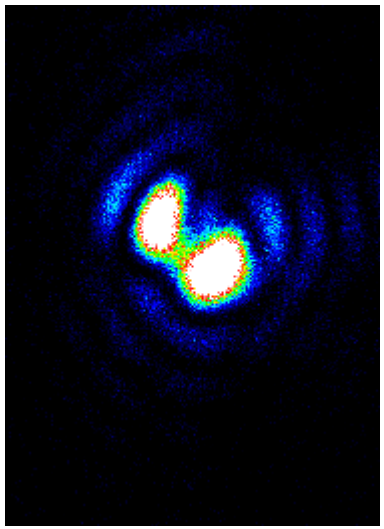
SEMS

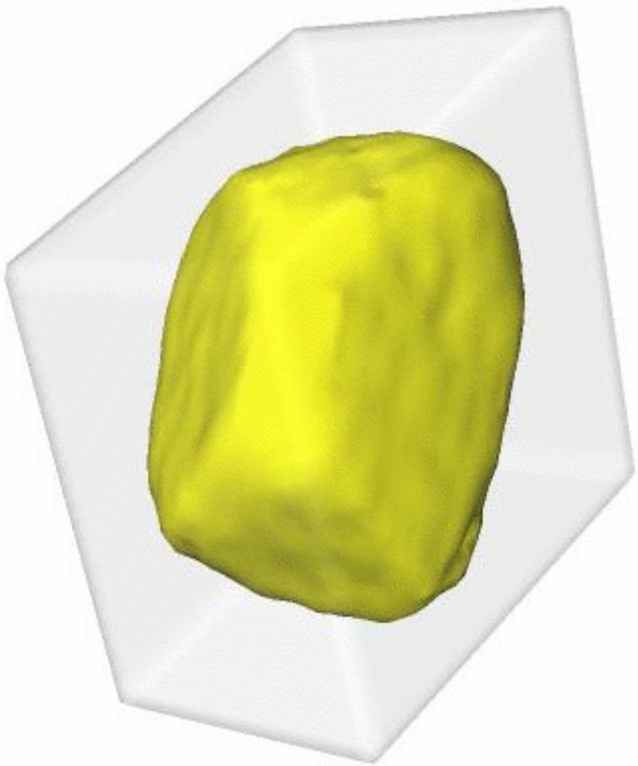
- Au blanket film
- Quartz substrate
- Annealed at 950°C for 70 hrs.



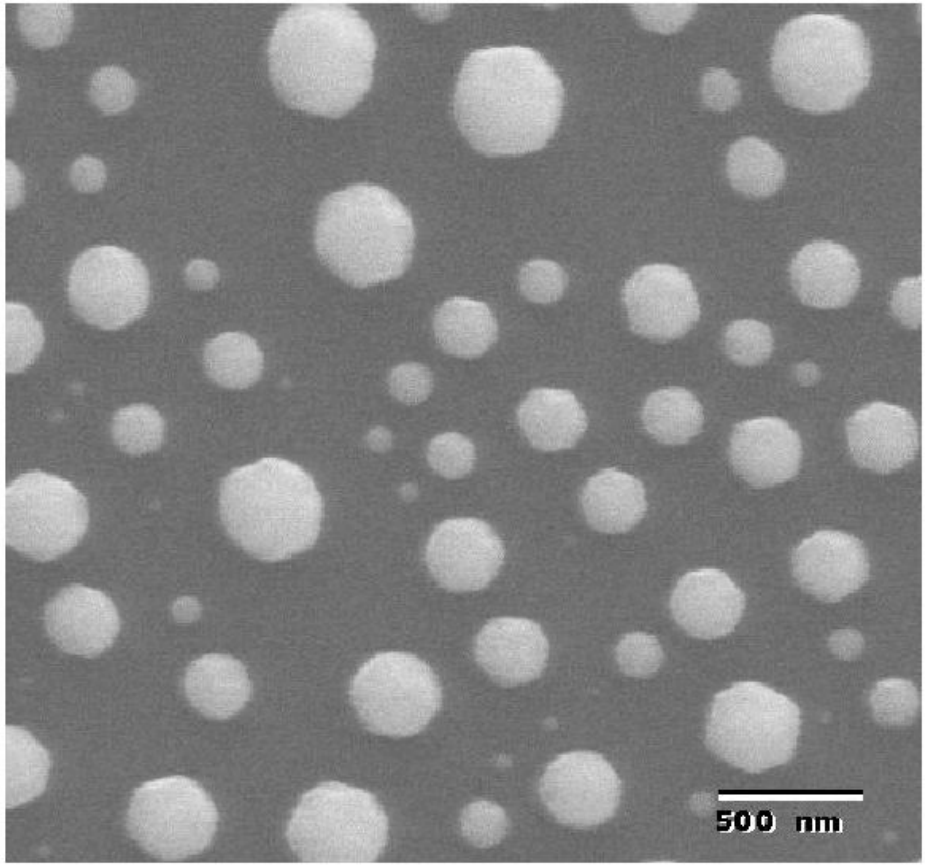
Gold nanocrystal reconstruction

showing support used for 20 HIO followed by 10 ER

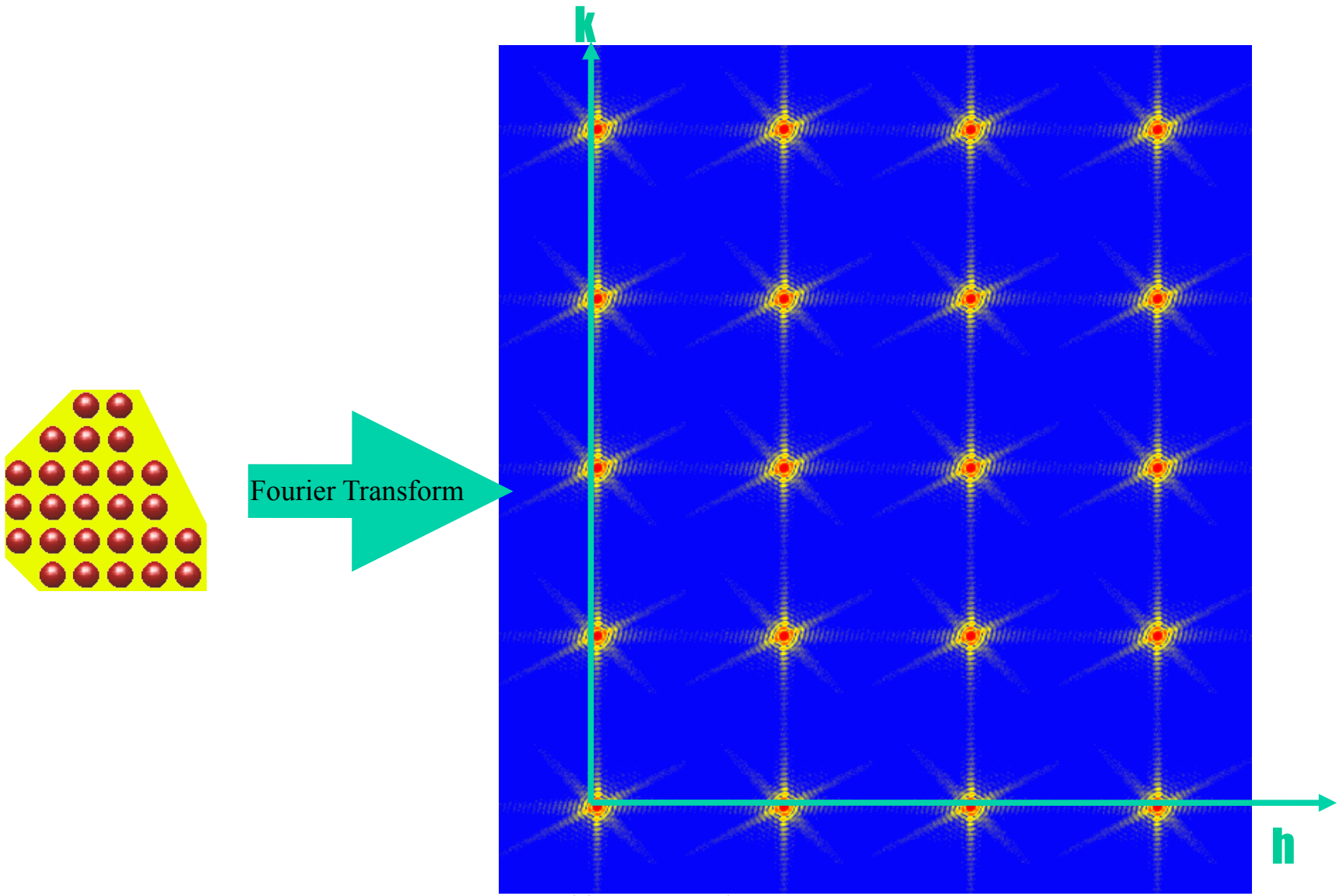




In situ growth of Pb crystals

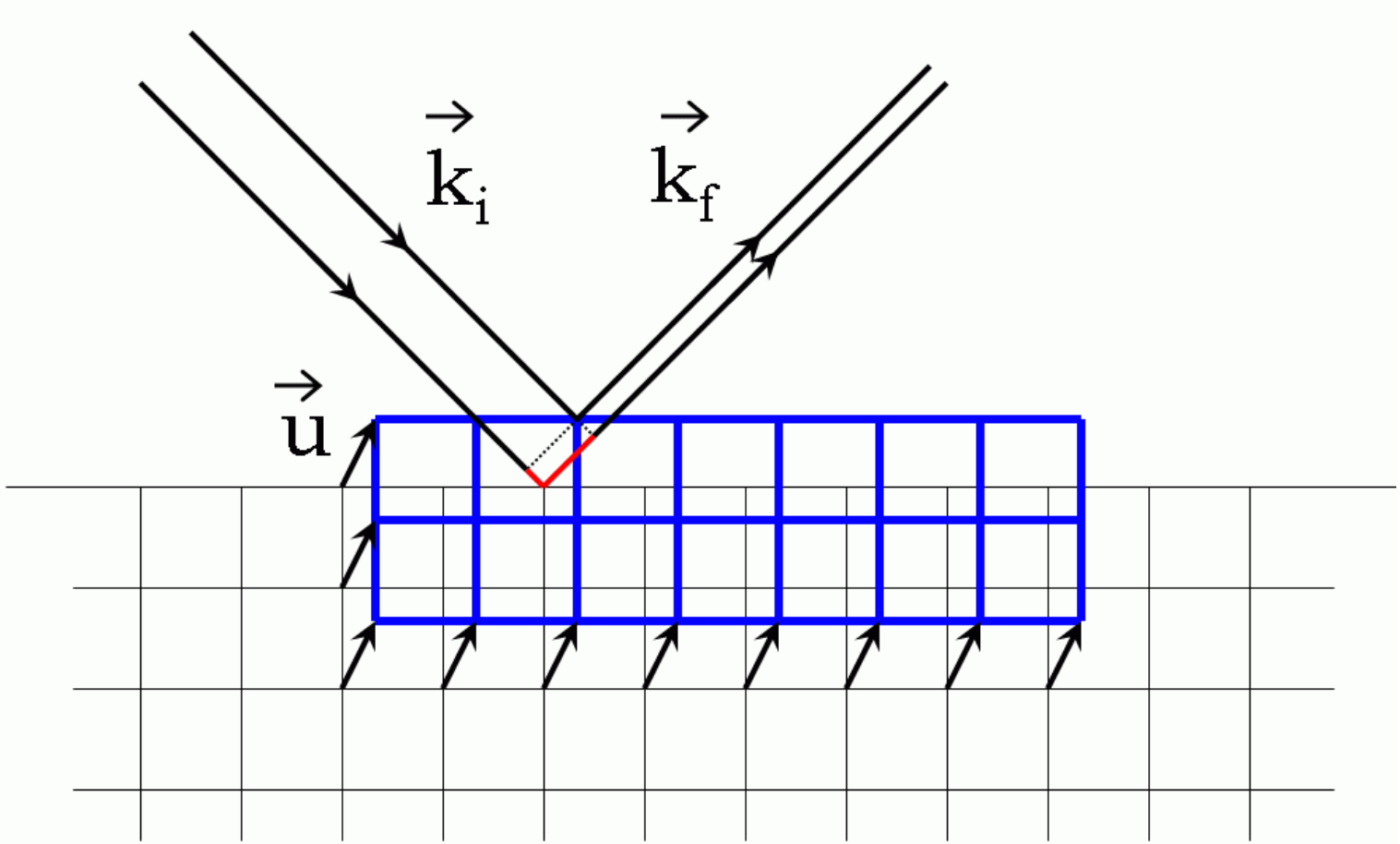


Coherent Diffraction from Crystals



Sensitivity to strain

$$\Delta\varphi = \mathbf{k}_f \cdot \mathbf{u} - \mathbf{k}_i \cdot \mathbf{u} = \mathbf{Q} \cdot \mathbf{u}$$



Good statistics, 3D diffraction data

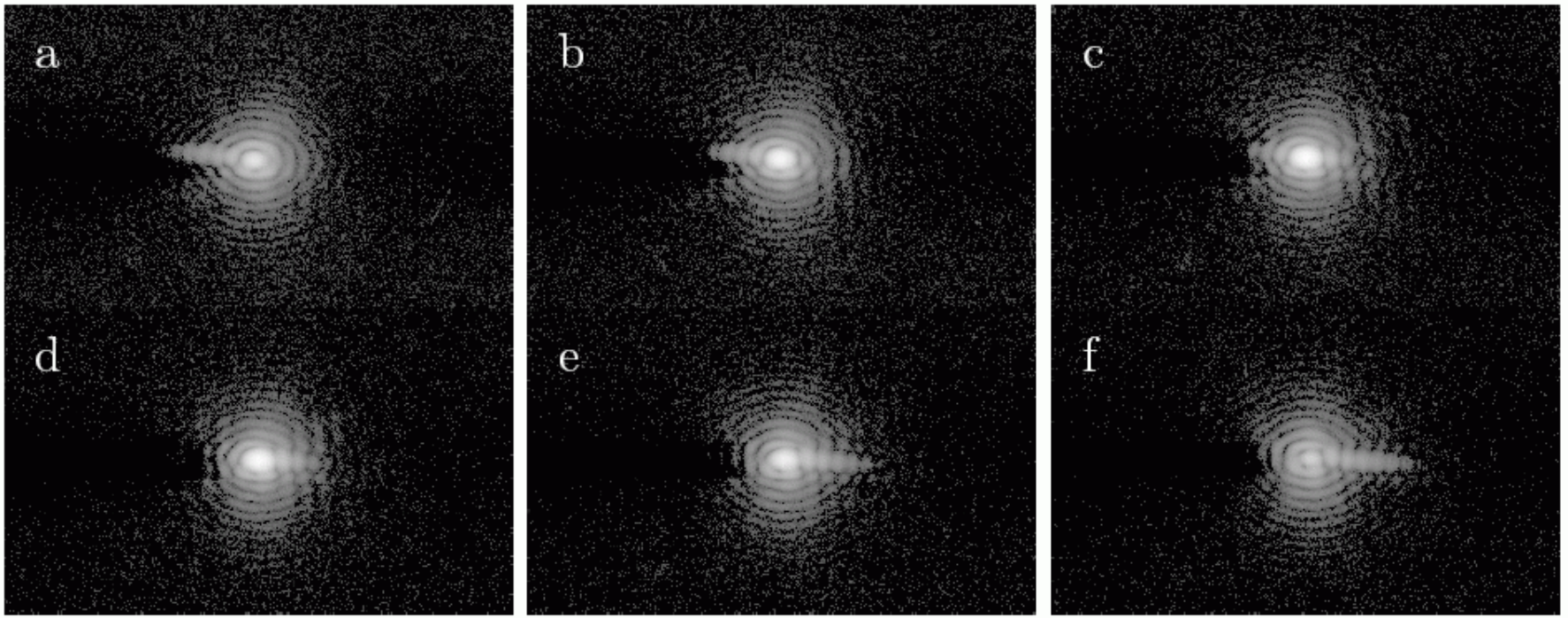
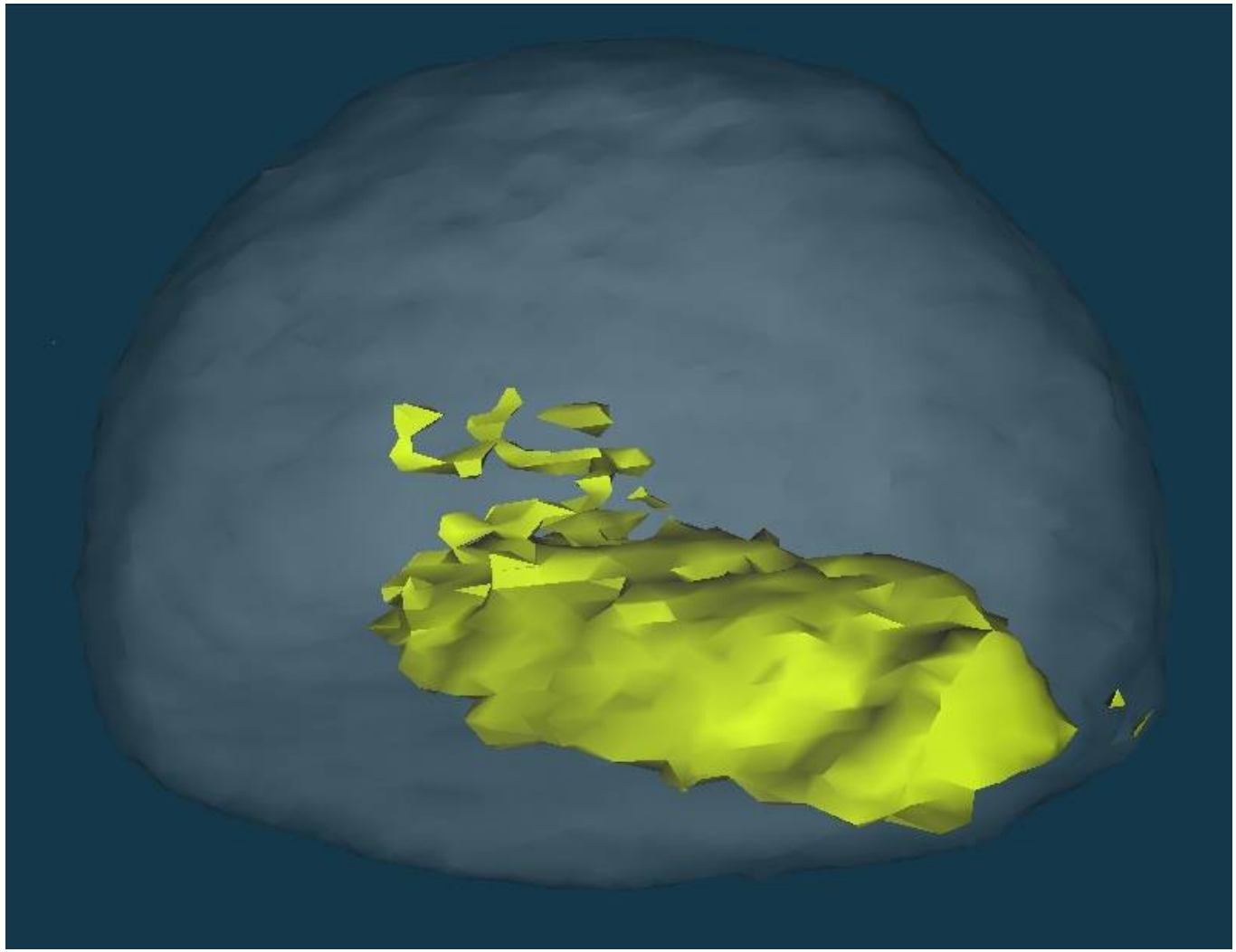
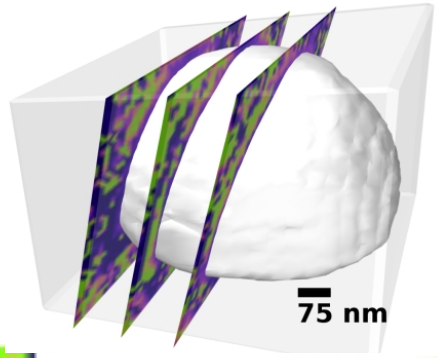


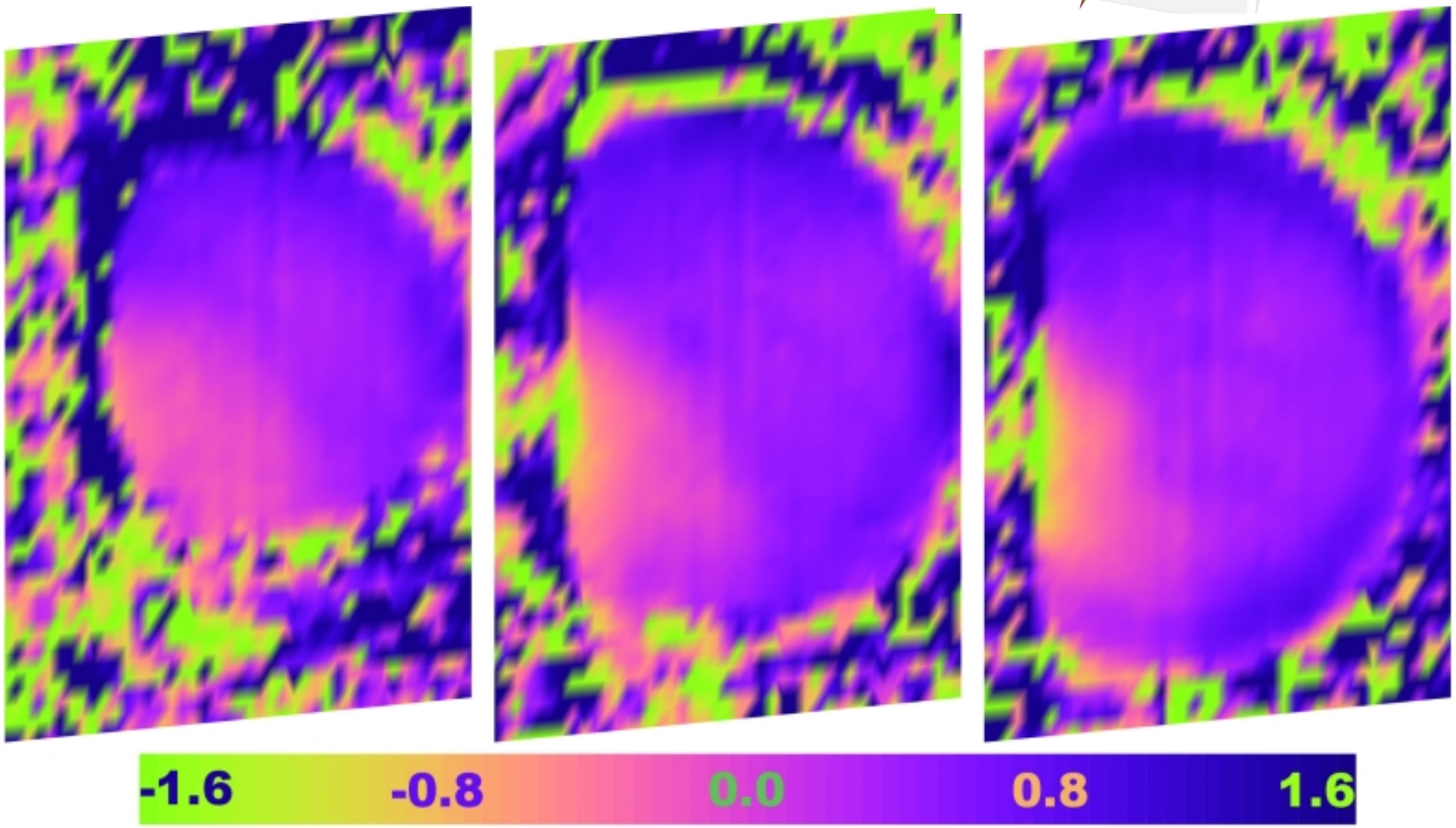
Figure 4.12: Center slices from 3D CXD pattern from Pb sample, on a log scale. Data file 296 from 10/03.

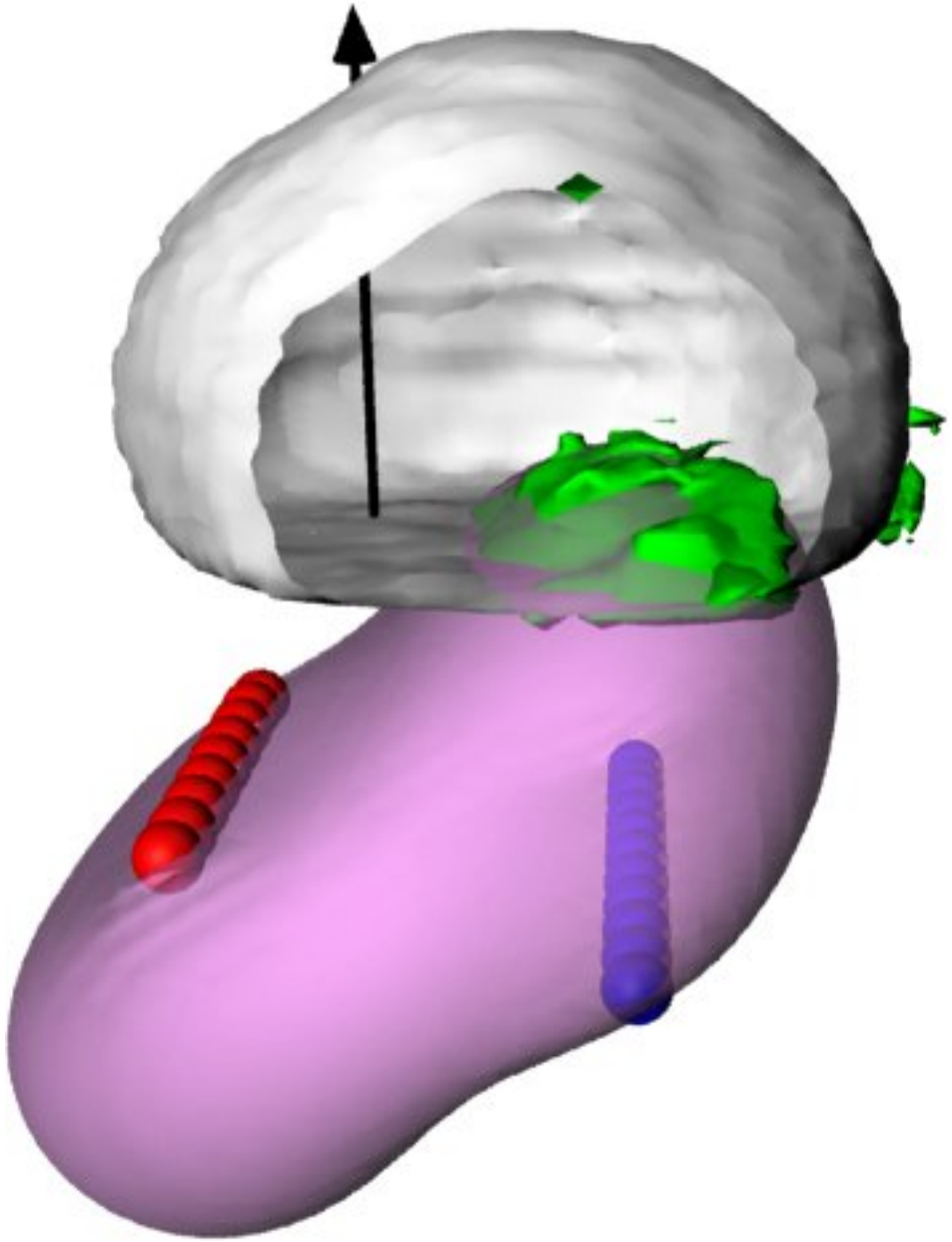
Modeling of 3D Phase Bump



3D phase map sections





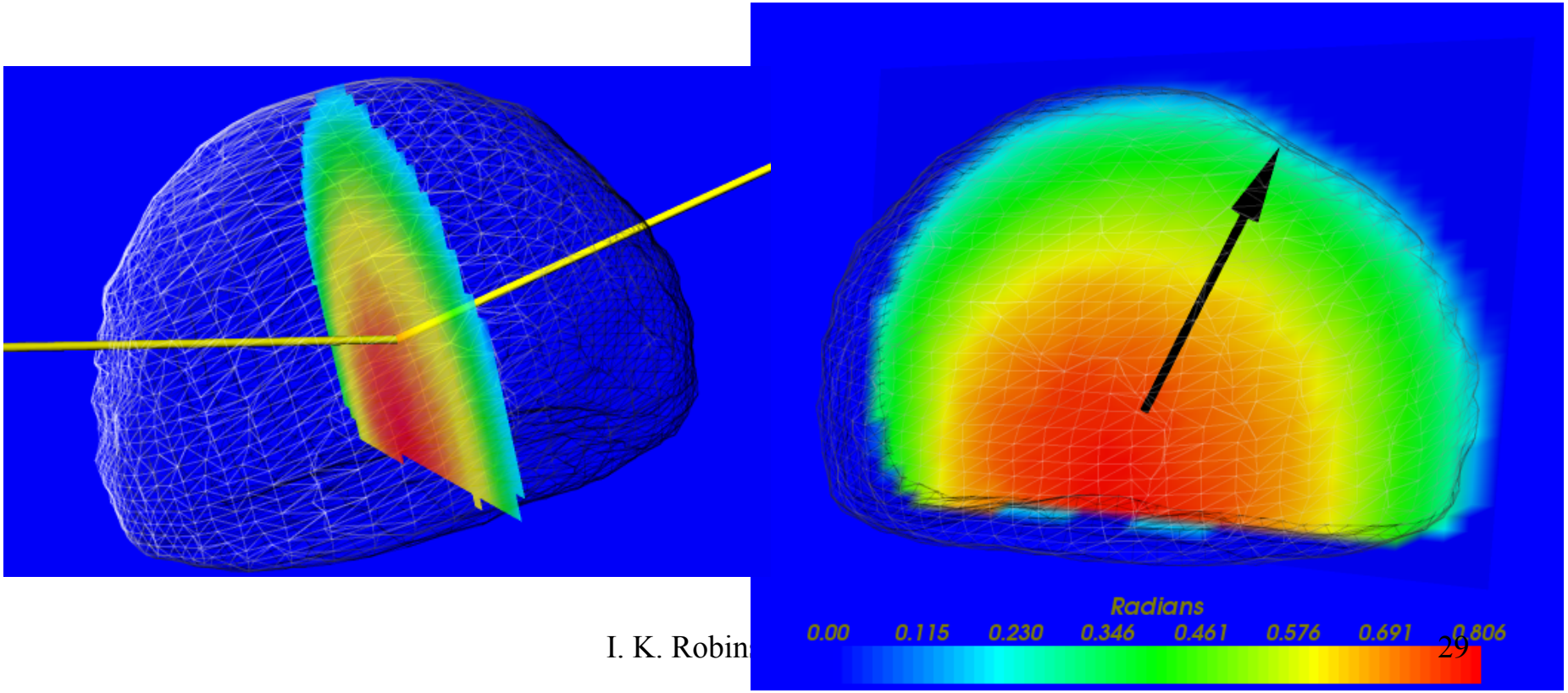


Refraction effects in Lead at 8.9keV

Phase accumulation due to refraction along scattering path

$$n=1-\delta+i\beta$$

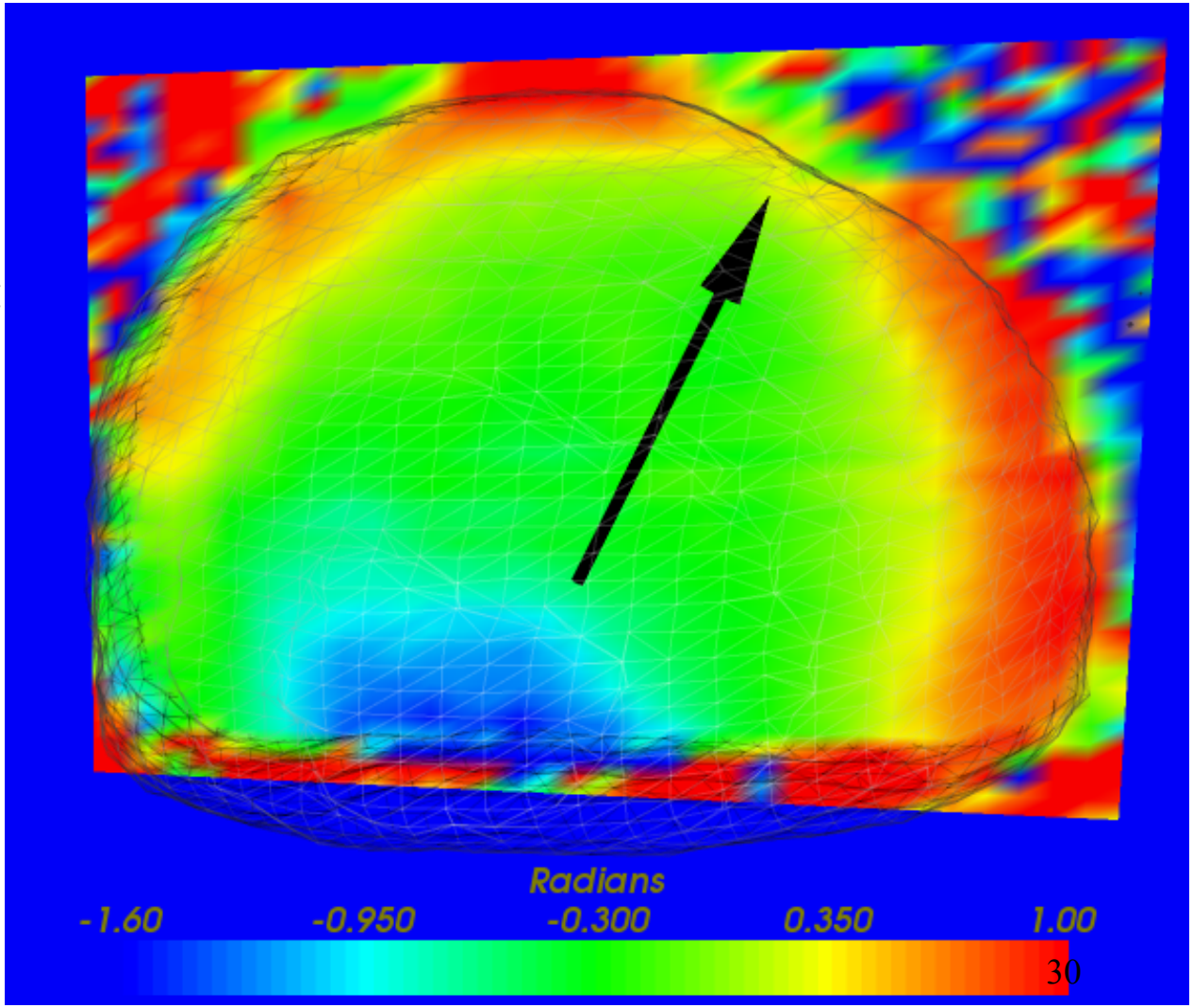
$$\delta=2.23\text{x}10^{-5}$$
$$\beta=2.19\text{x}10^{-6}$$



Refraction corrected phase map

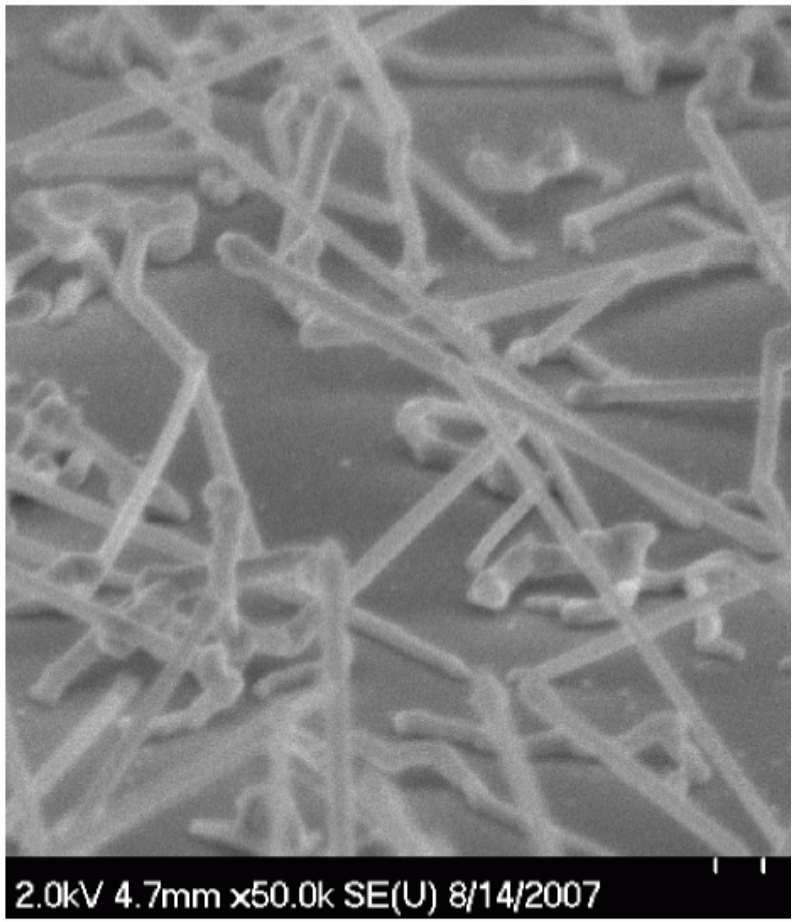
Max phase = 1.15rad
= 0.052nm

Phase on the (111) facet:
= 0.47 rad
= 0.02nm

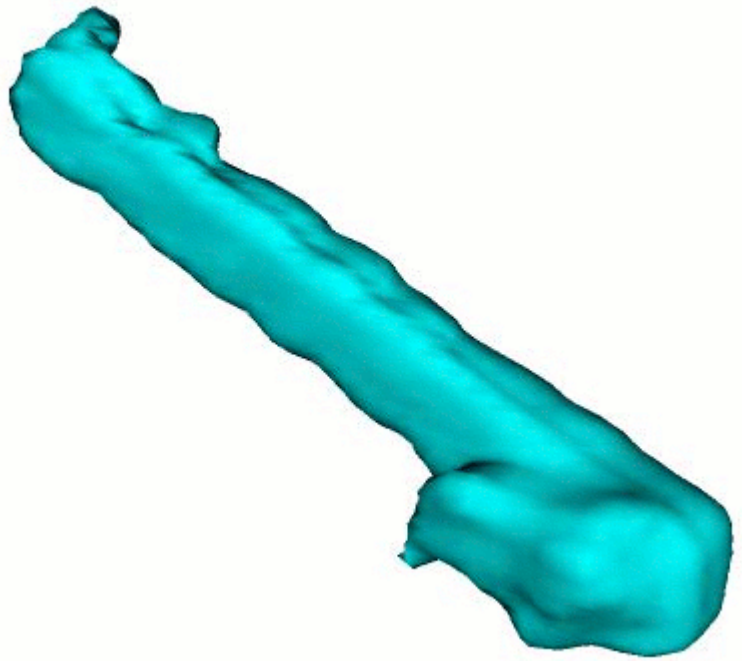


Reconstruction of InP nanowire

CVD on Si, Suneel Kodambaka, UCLA

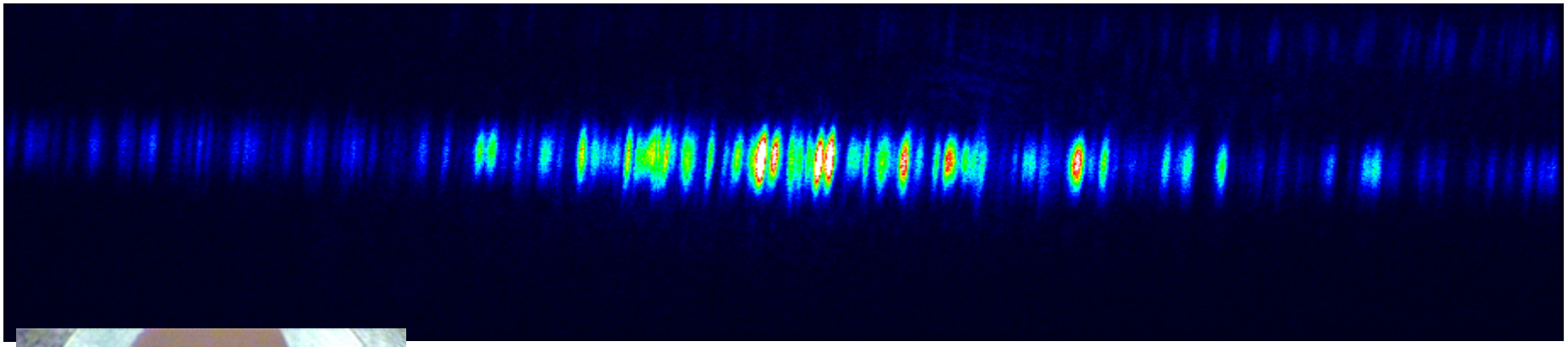


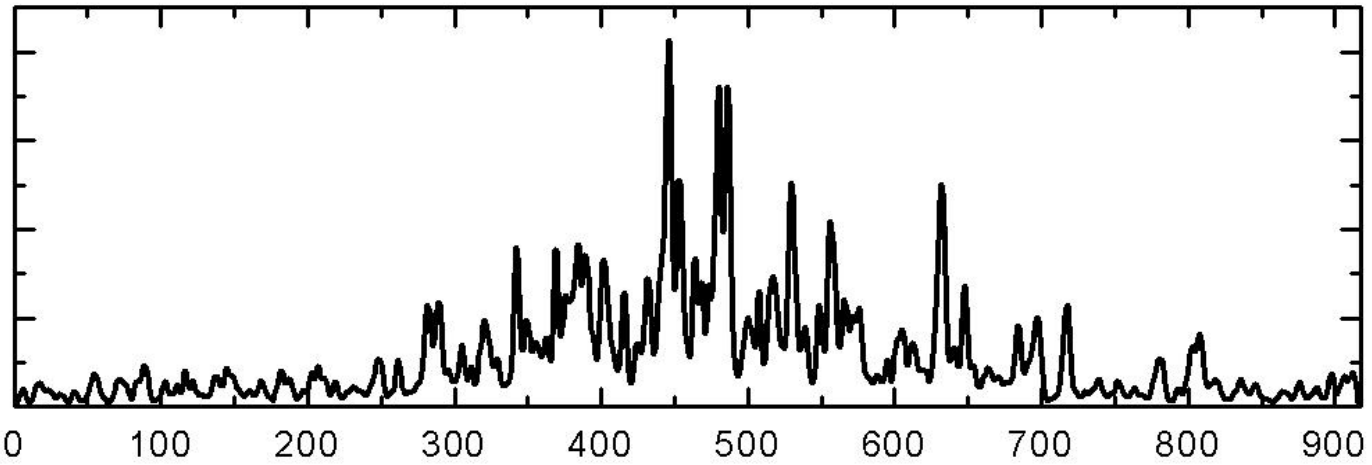
InP nanowires grown on Si (111)



GaAs Nanowire "Barcode"

Vincent Favre-Nicolin, Joel Eymery (CEA),
Rienk Algra (Philips), Ross Harder



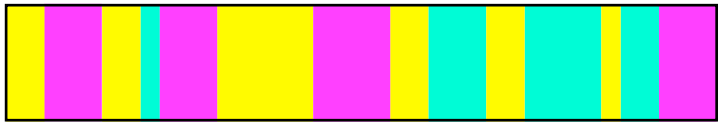


GaAsNW1106-22.spe
B9348 from Philips

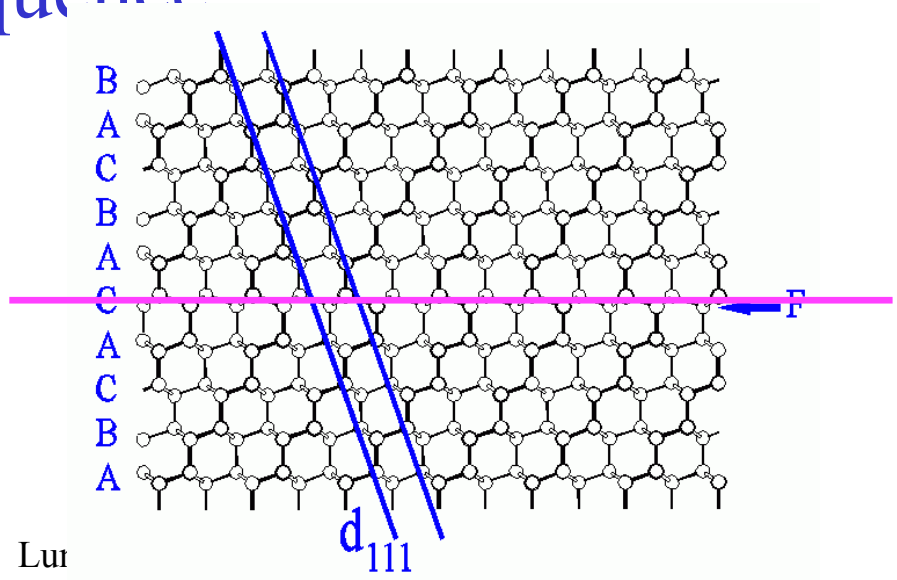
Models of Barcode Diffraction

(111) wires at (11-1) reflection

- Twinned stacking sequence

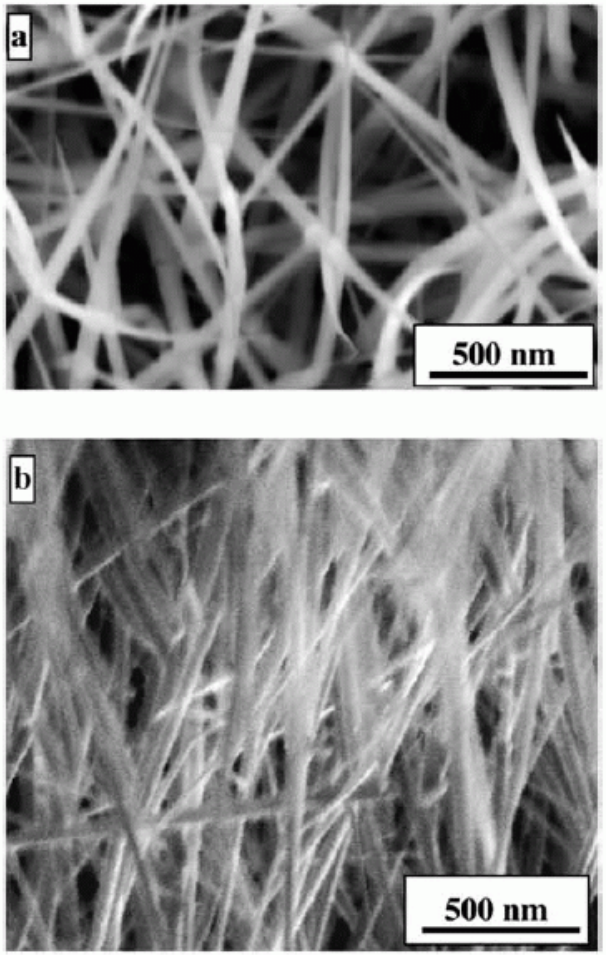


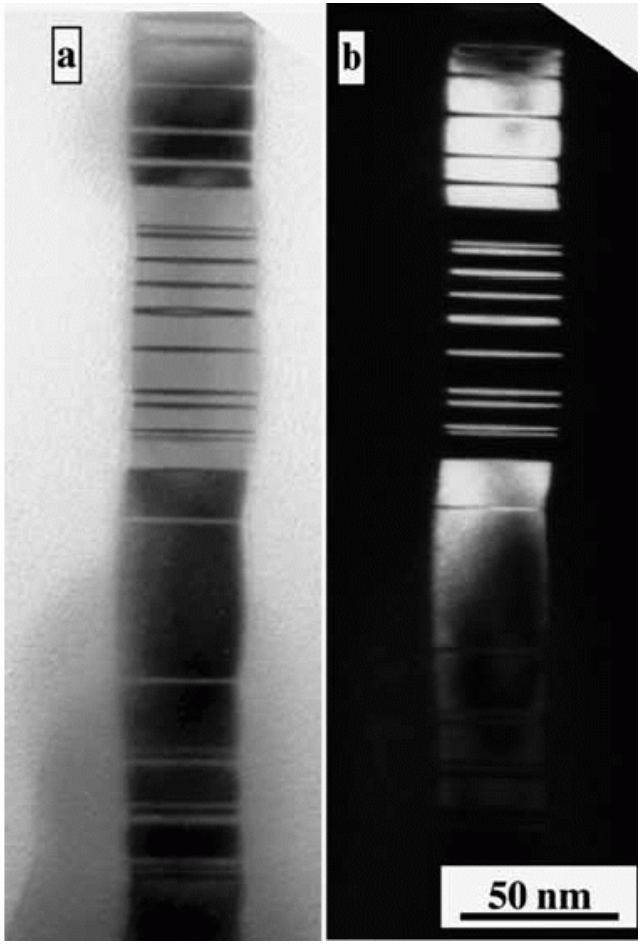
- Deformation faults



Dark Field TEM of GaAs Nanowires

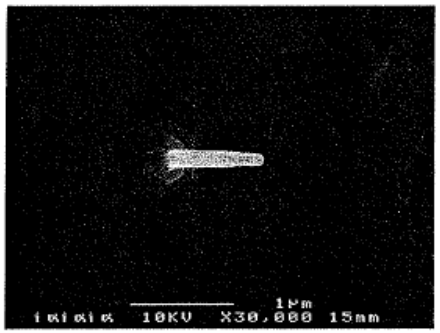
R. Banerjee et al, Phil. Mag. Lett. 86 807 (2006)





Lund sample 2657 InAs/InP NW

Jonas Johansson & Lars Samuelson SOI-nov09-98.spe



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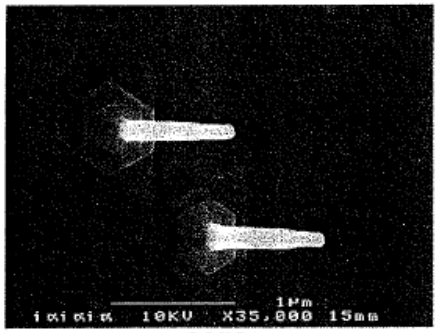

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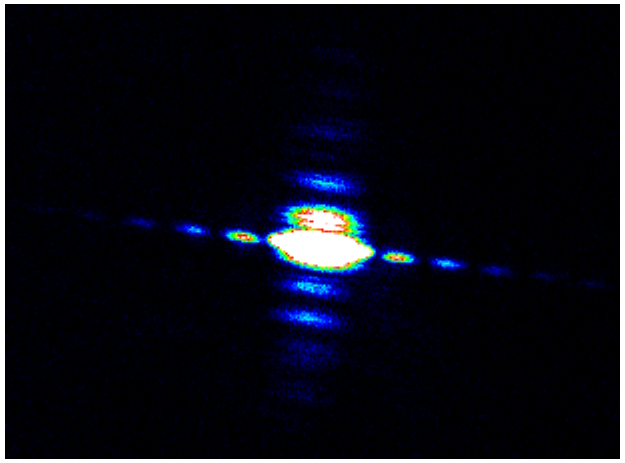

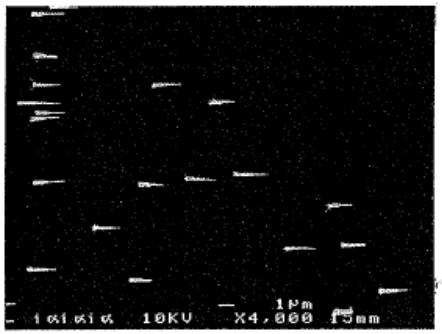

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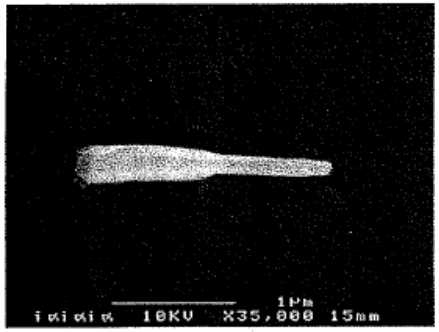

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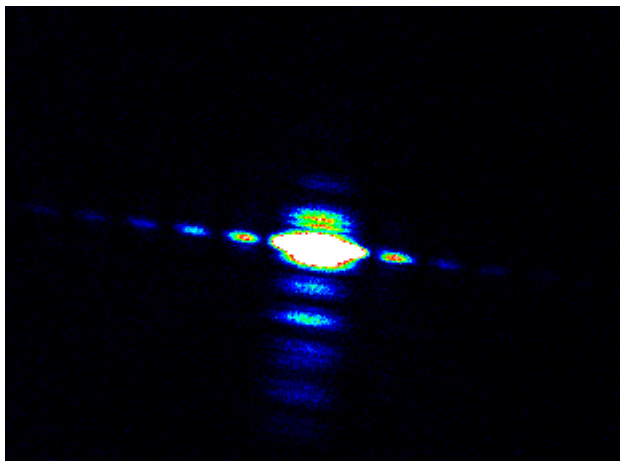
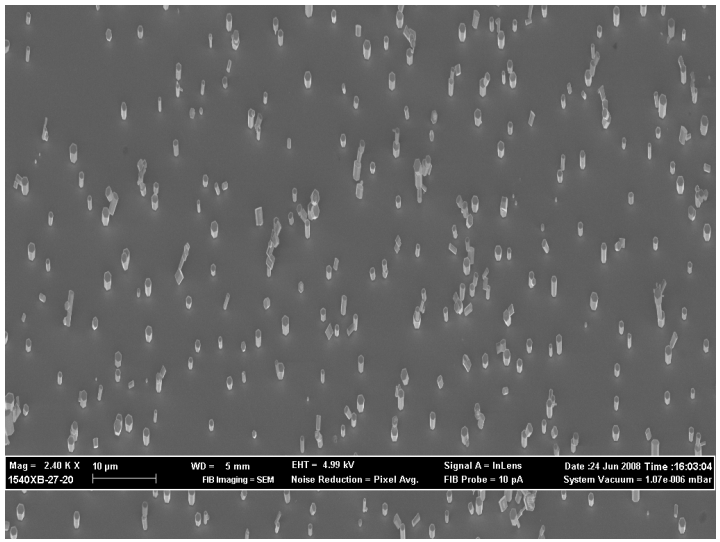
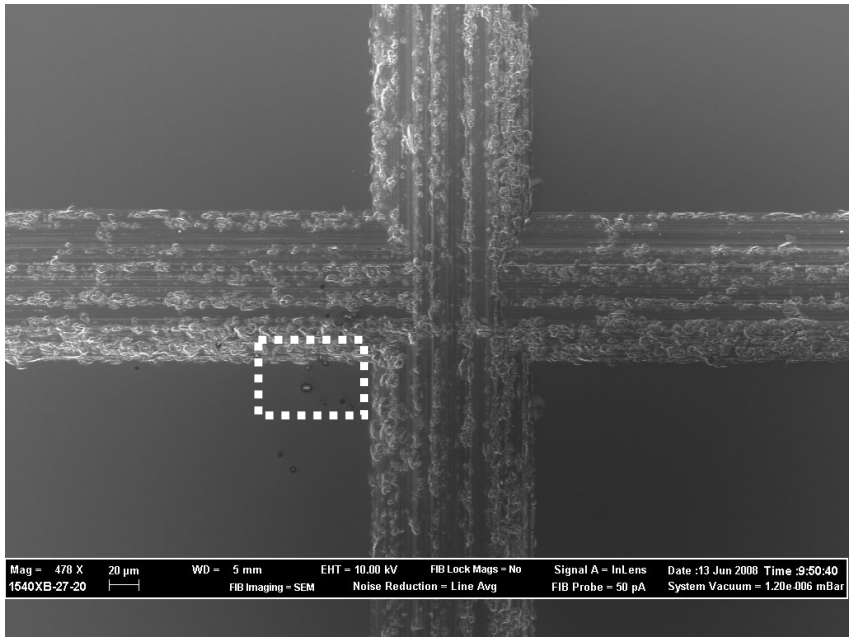
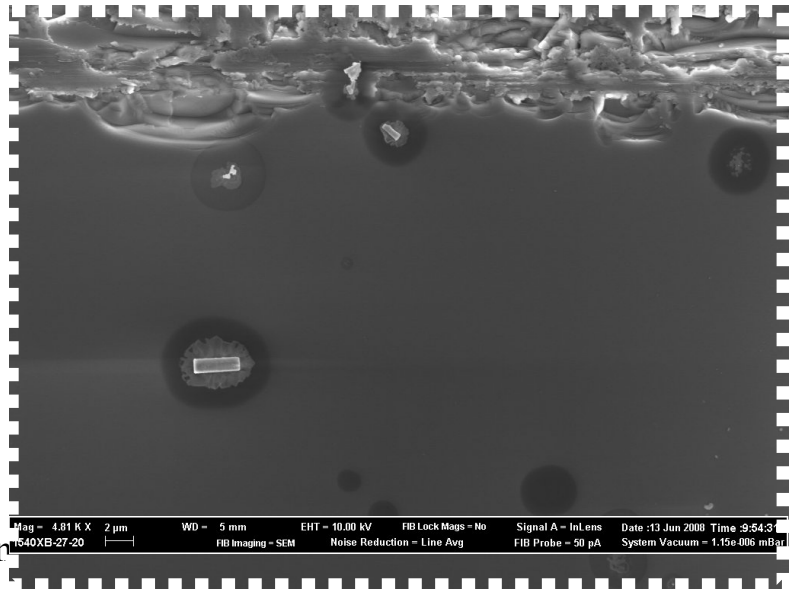


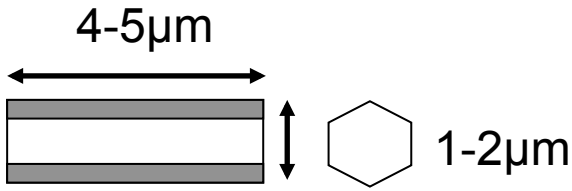
ZnO Sample Preparation







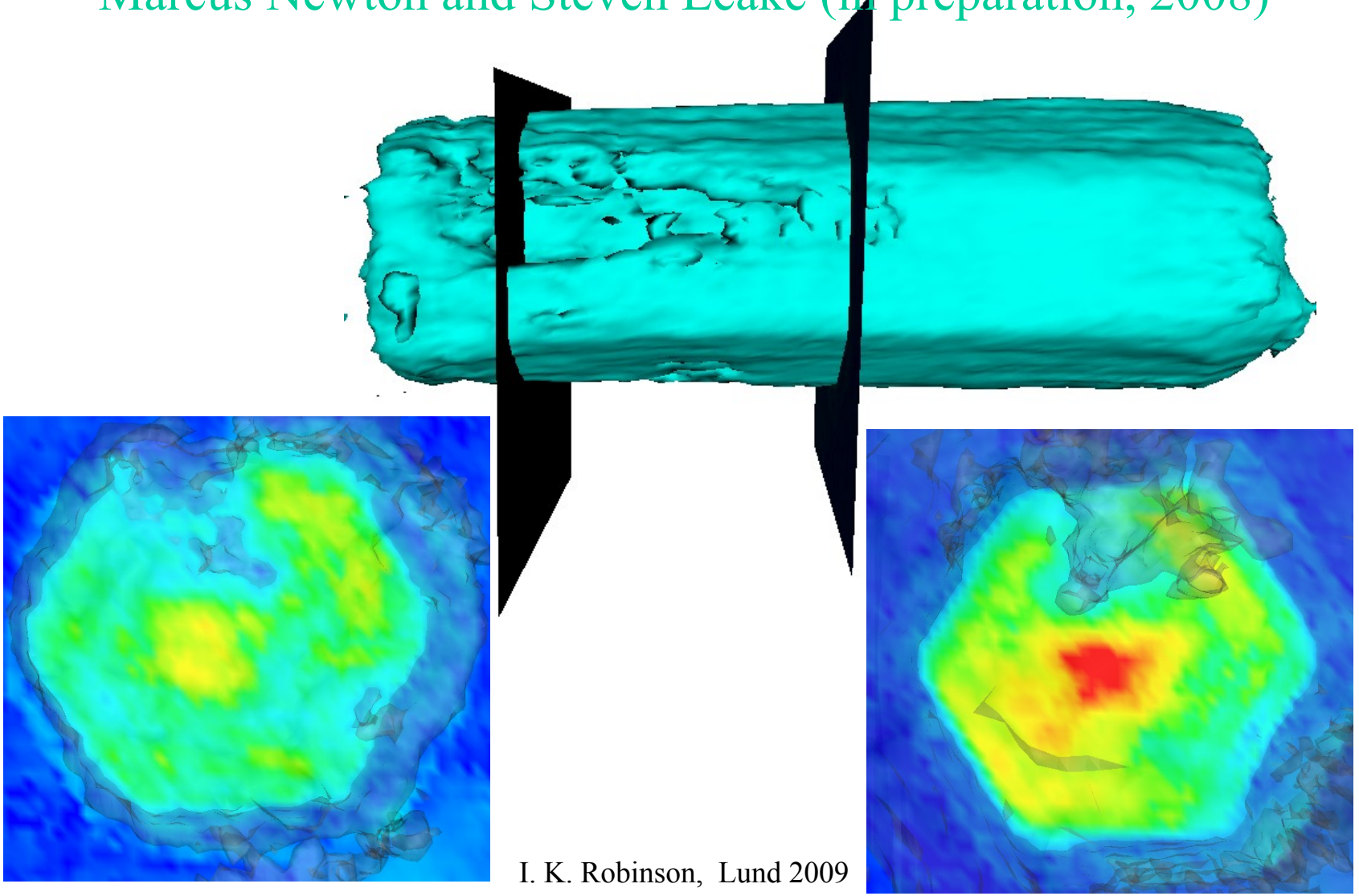
Dimensions:



I. K. Robinson, Lun

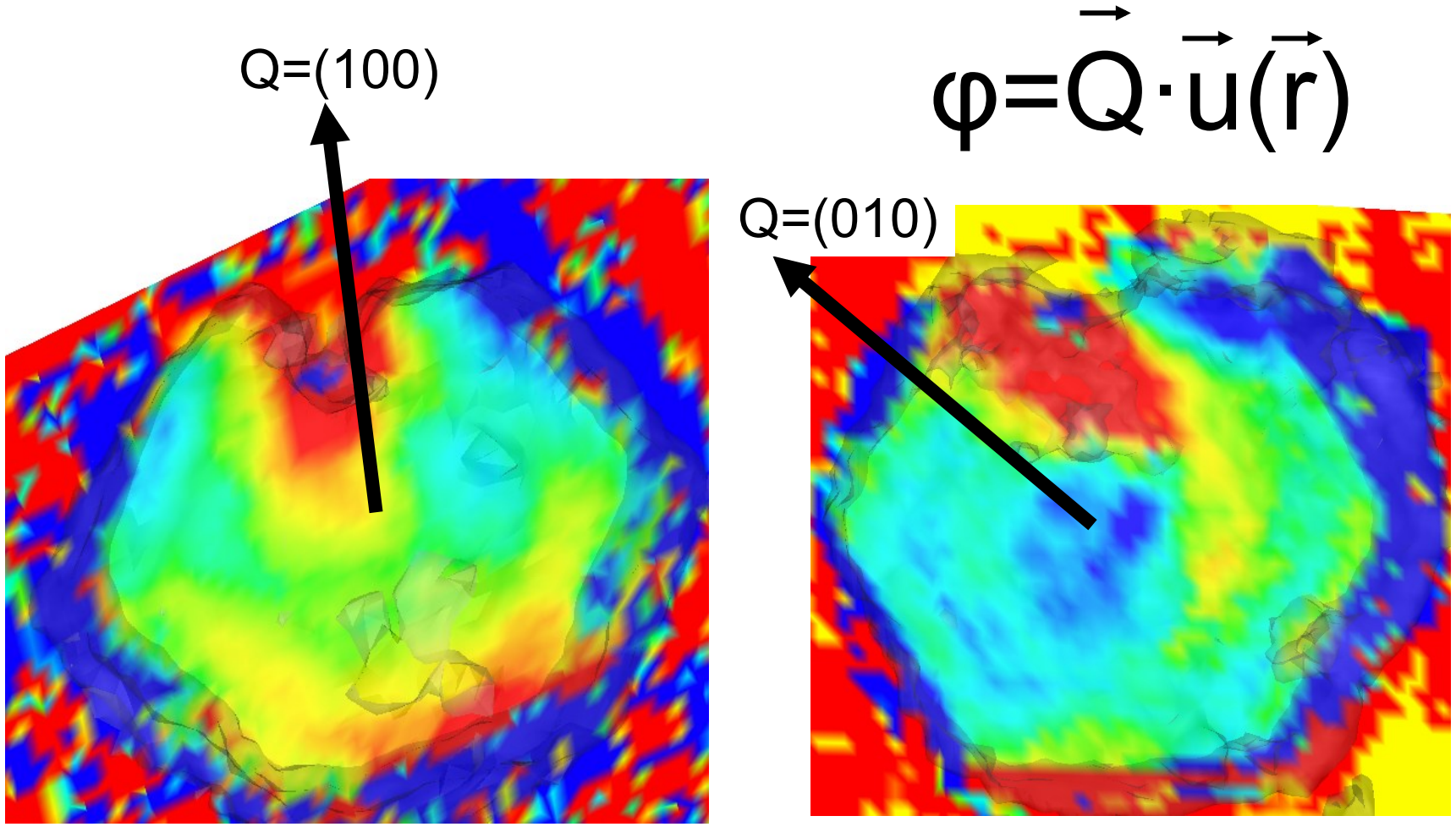
Density sections ZnO-39 (010)

Marcus Newton and Steven Leake (in preparation, 2008)

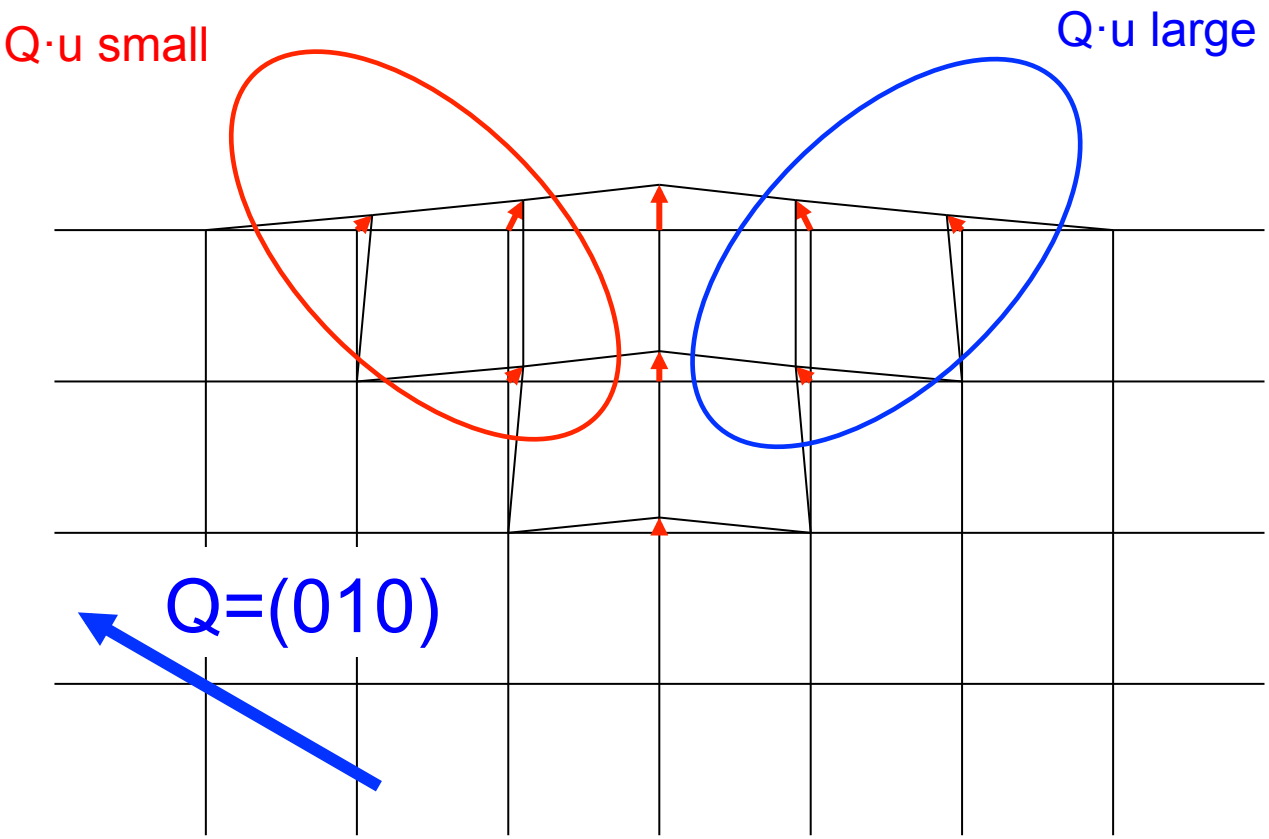


Phase maps from 2 Bragg peaks

Blue-Red is +2 radians. Slice at -1500nm from centre ZnO-5 -39

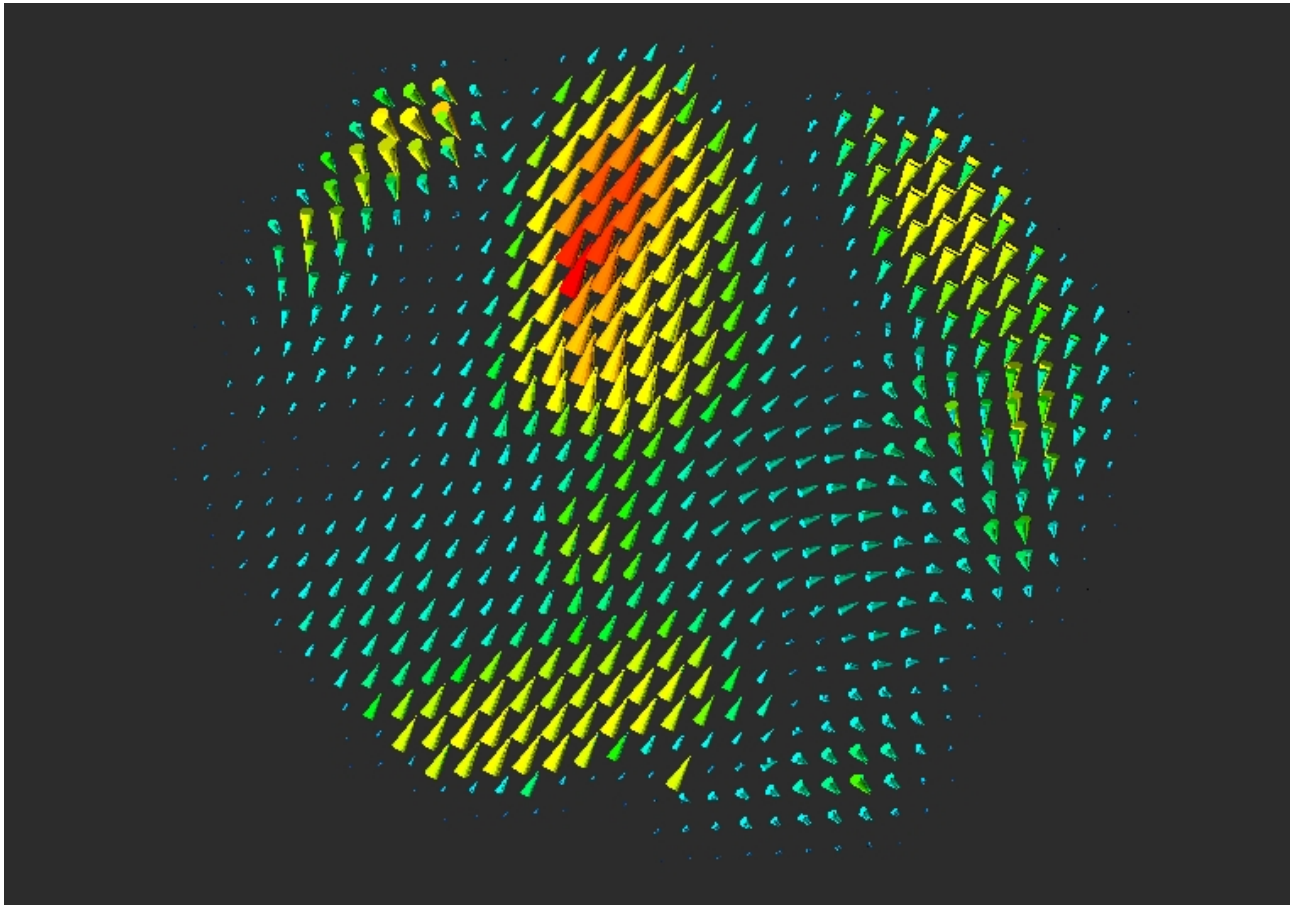


Typical displacement field

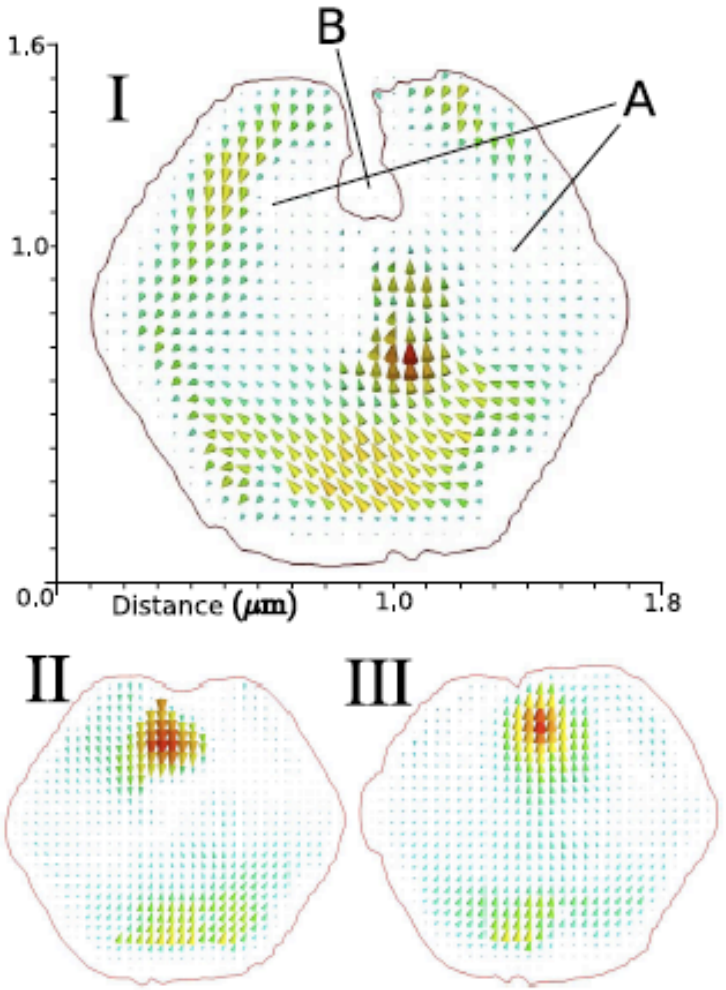


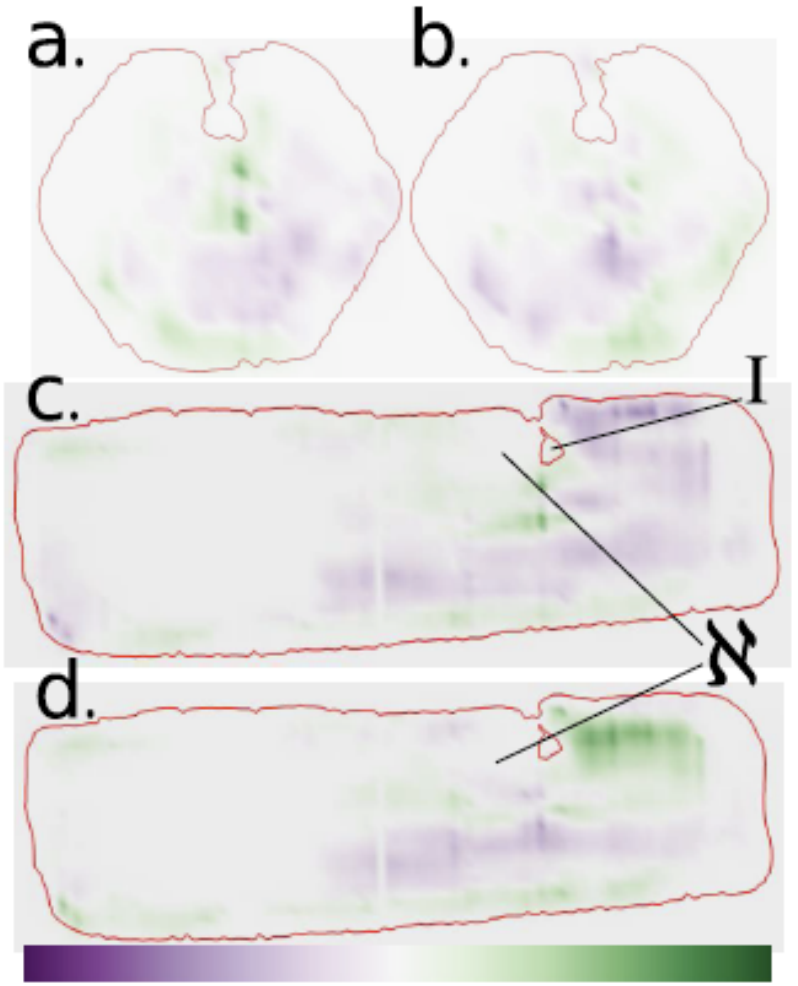
2D vector field of displacements

Marcus Newton, UCL, Jan 2009

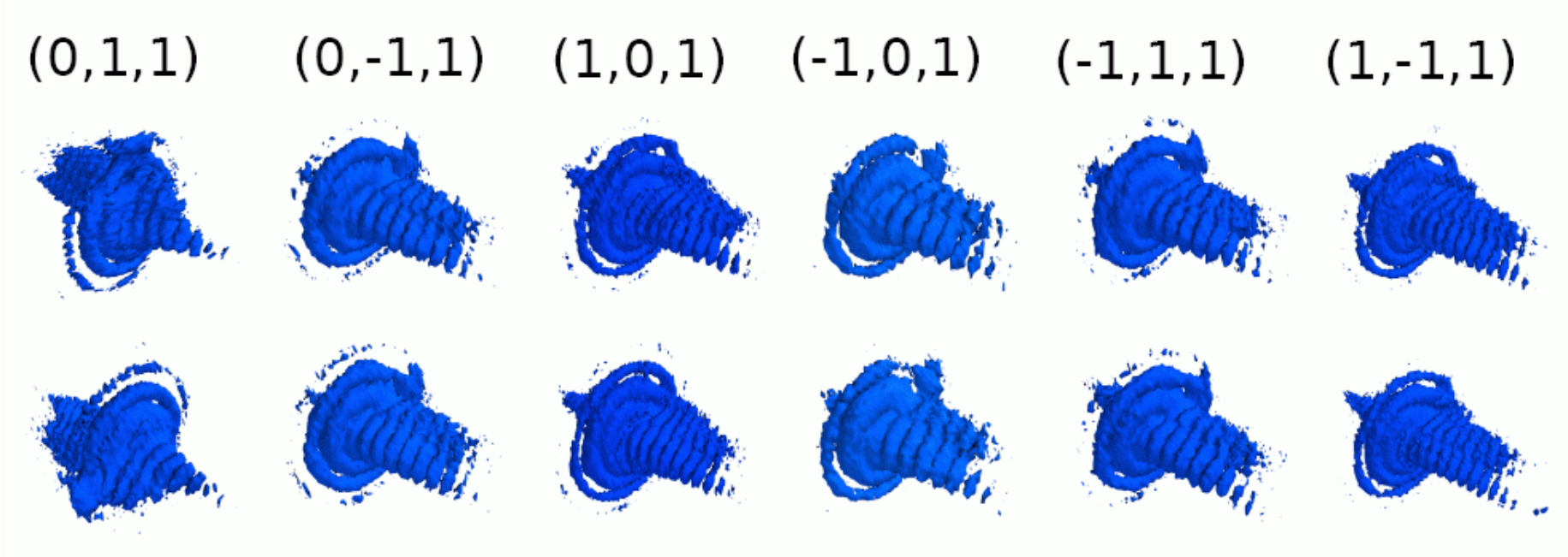


Strain and Rotation fields

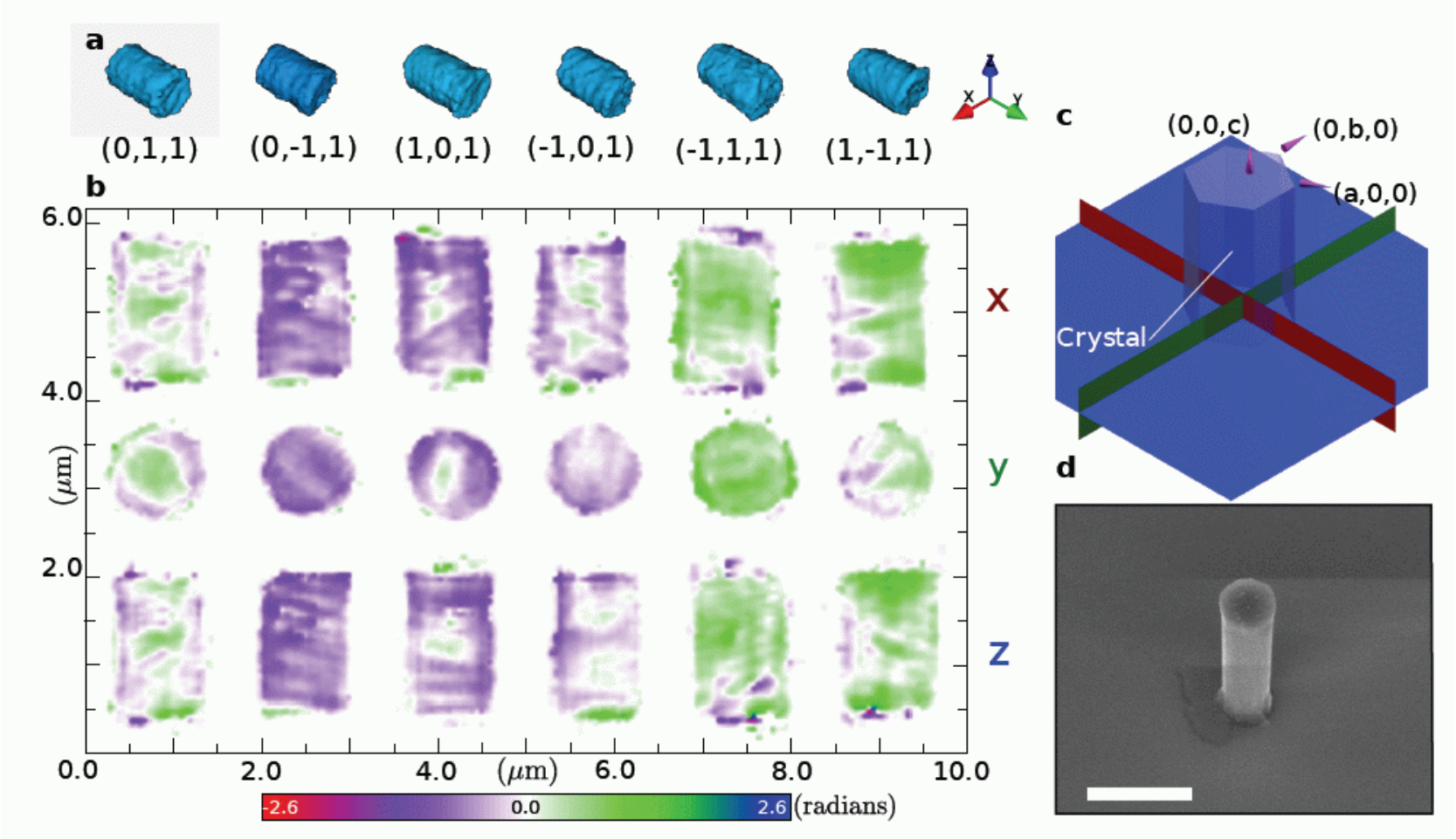




Extension to 6 Bragg Peaks

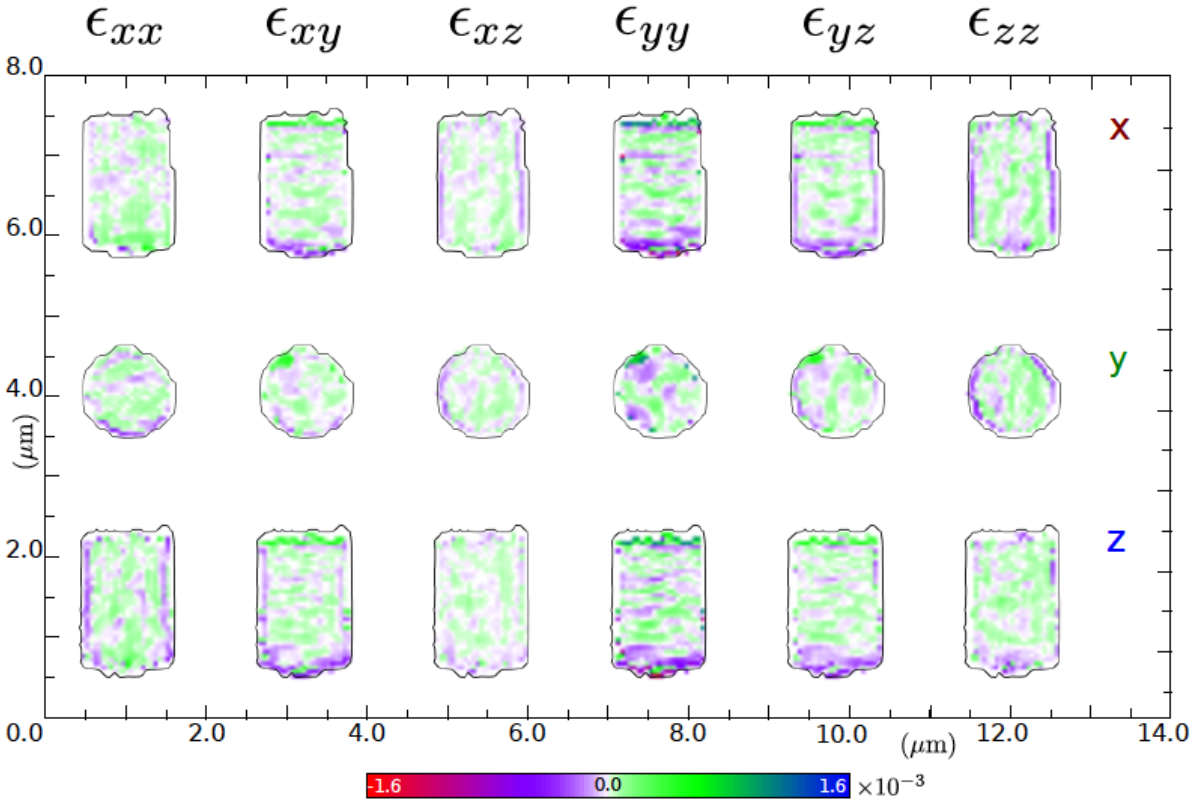


Extension to 6 Bragg Peaks

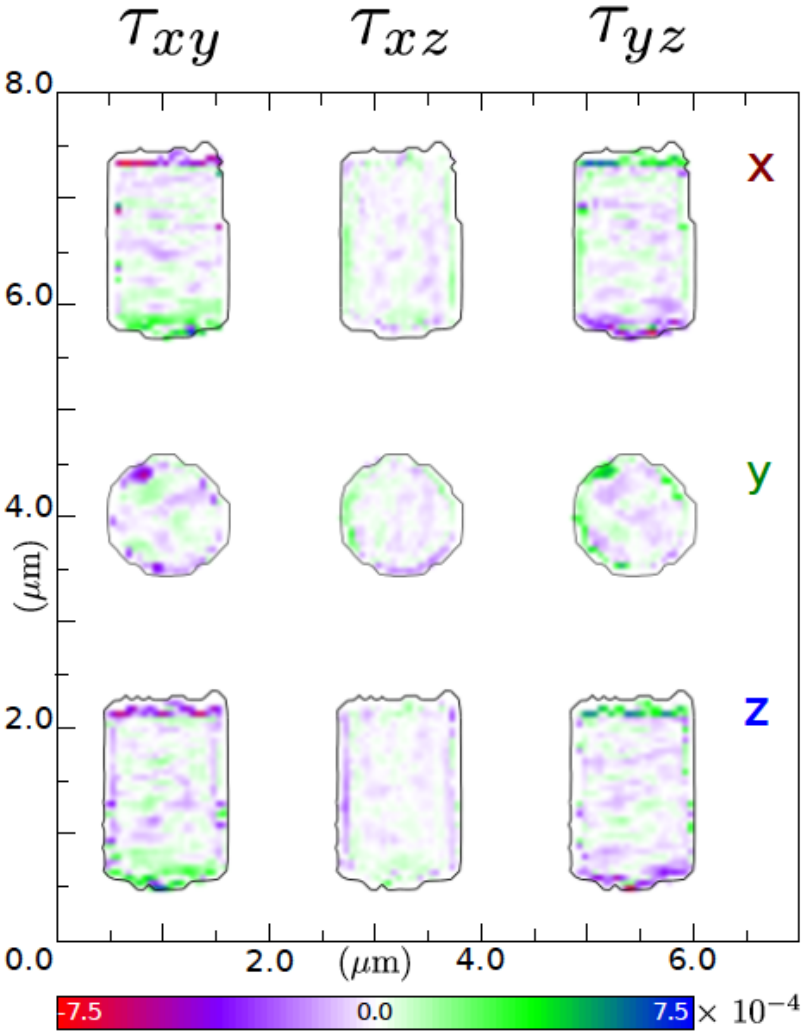


Full Strain Tensor

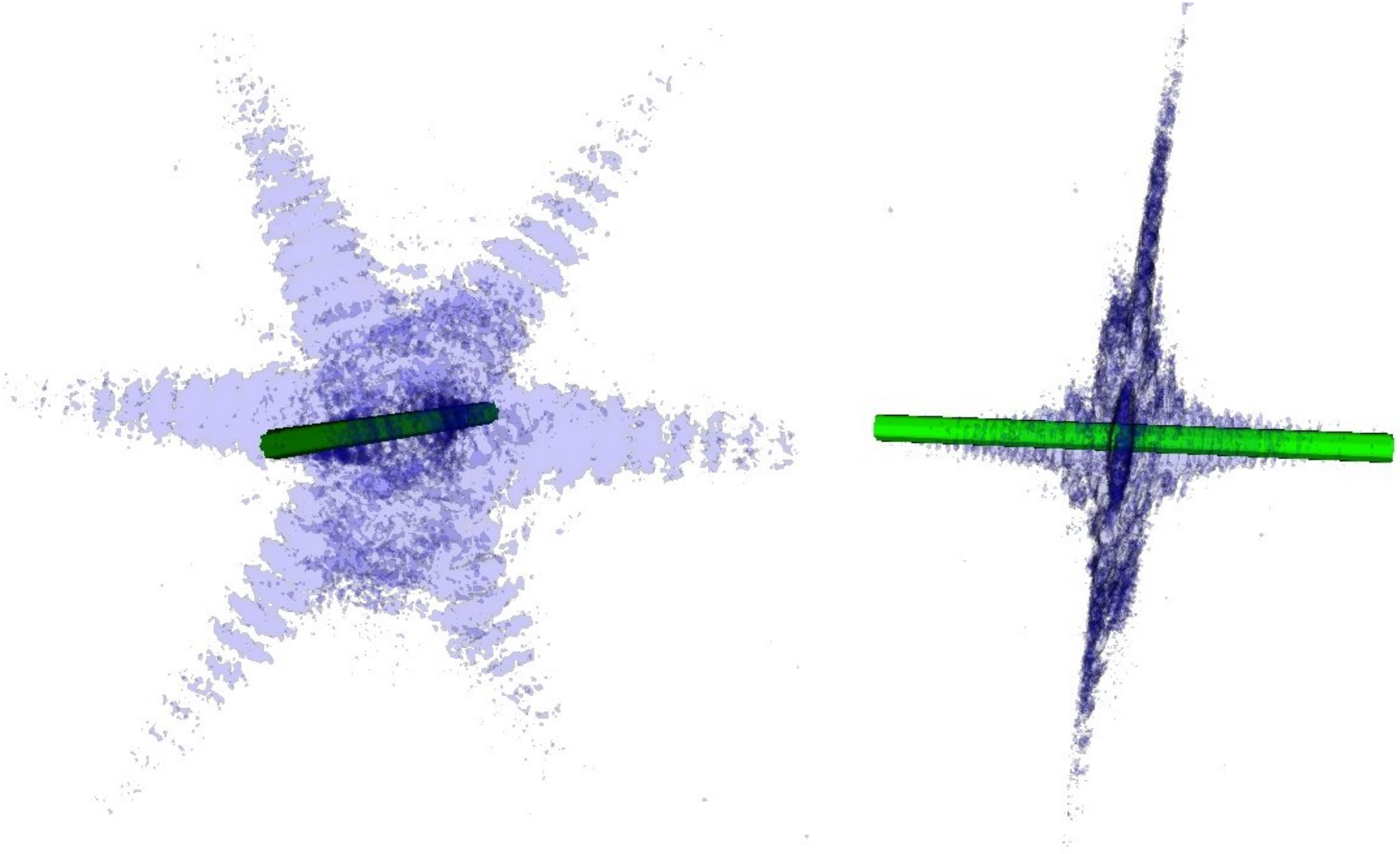
$$\epsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right) \quad , \quad \tau_{ij} = \left(\frac{\partial u_j}{\partial x_i} - \frac{\partial u_i}{\partial x_j}\right)$$

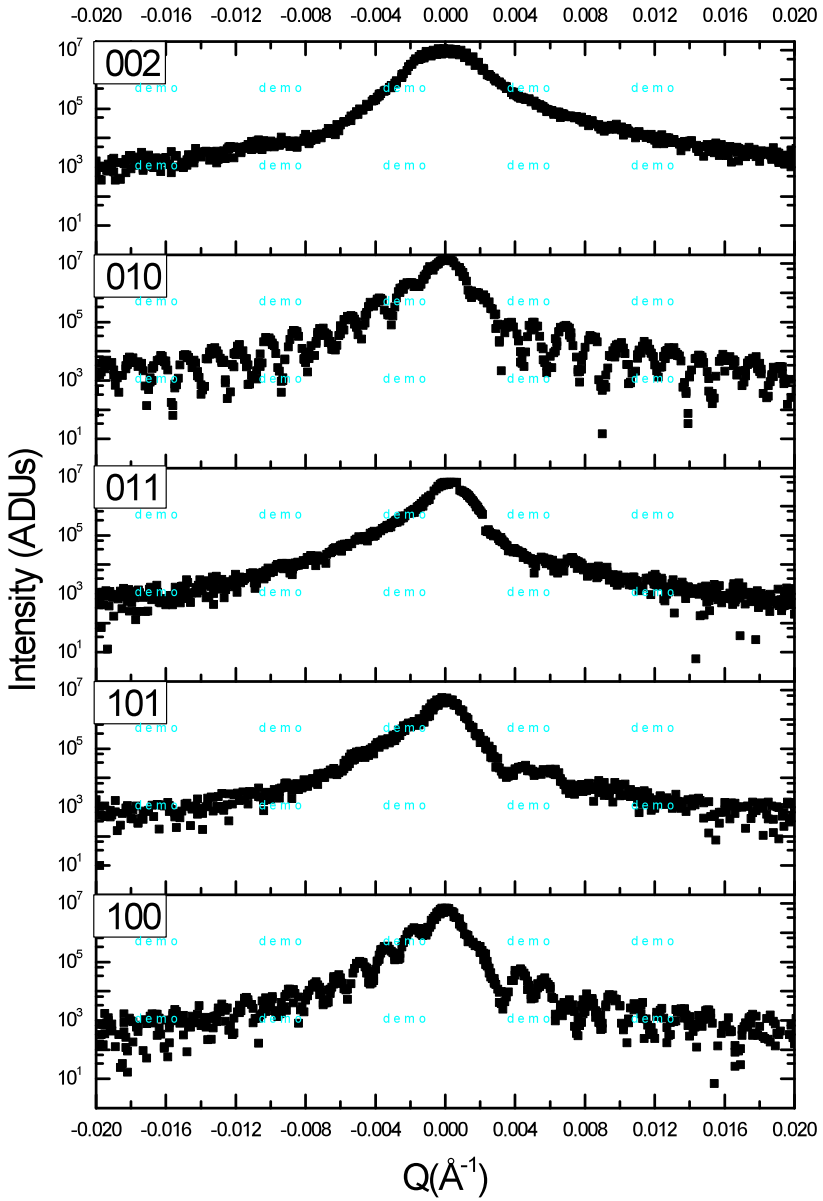


ZnO Rigid-body Rotations



How to extract the contrast data





Five Bragg peaks

002 no fringe visibility

010 & 100 good fringe visibility

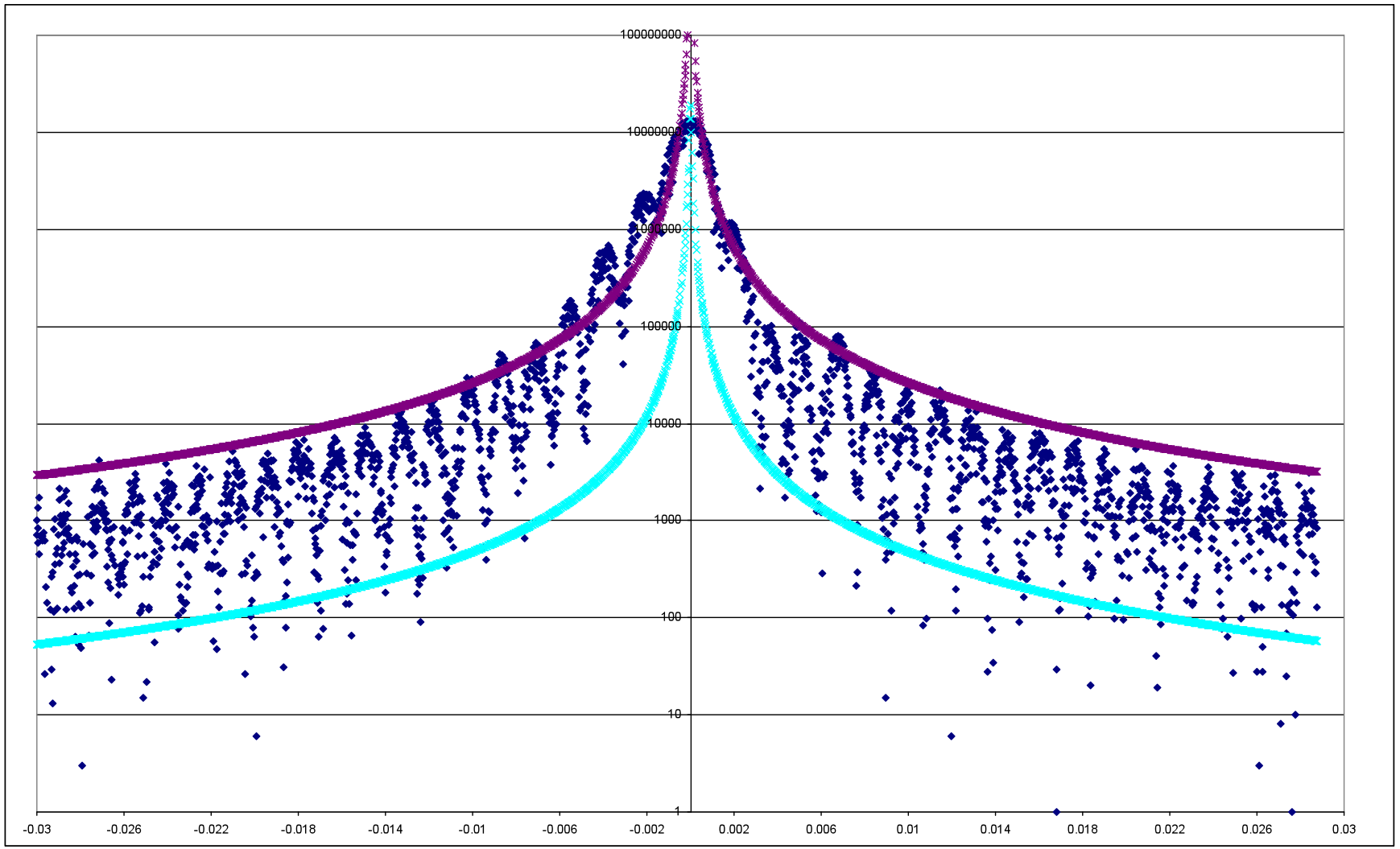
101 & 011 diminished fringe visibility
but fringes still evident

010:011 & 101:100
show complementary fringes
but not between each other

Error in coordinate transform ruled out

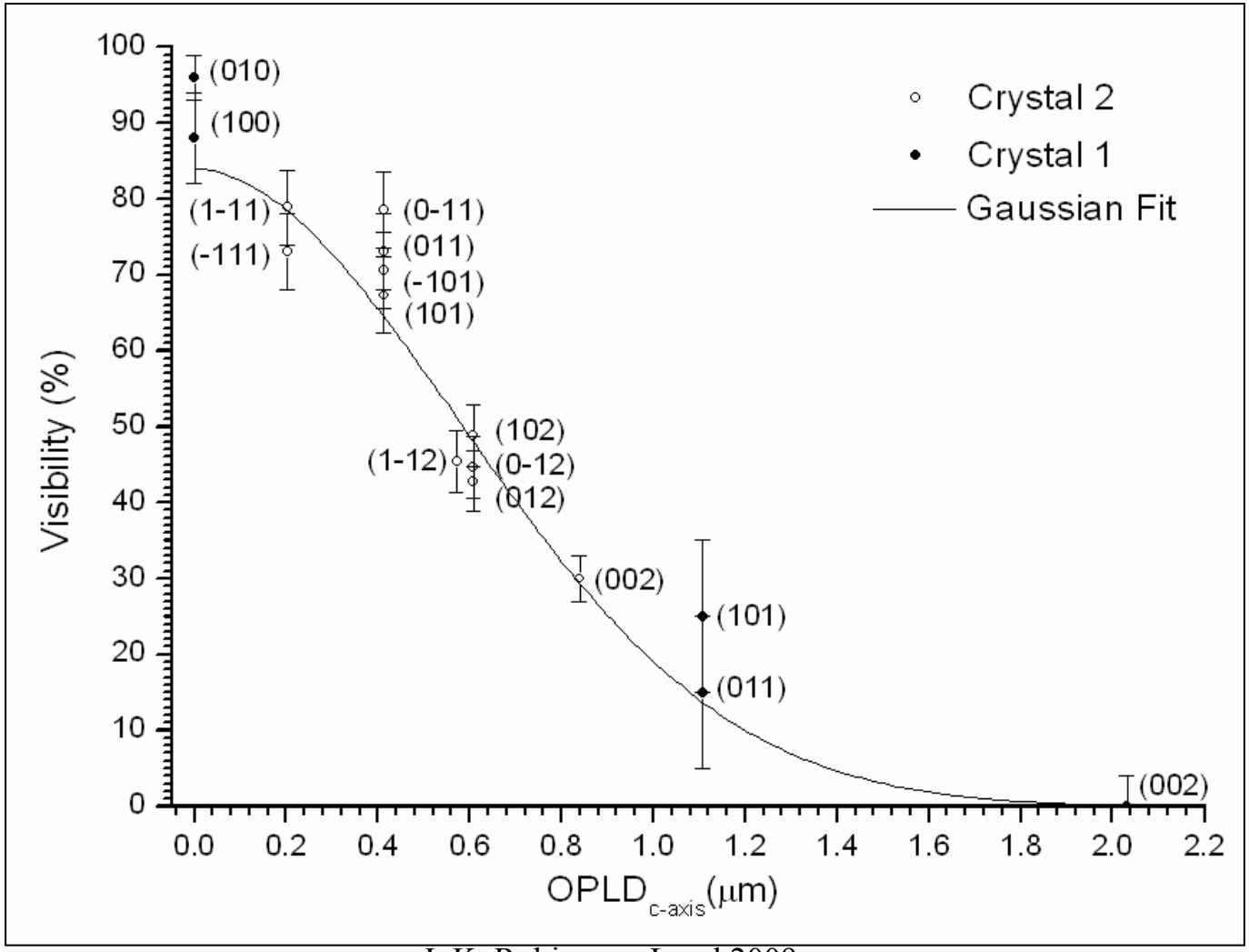
010 and 100 reflections fringe spacing
difference ~ 20%

Fringe Visibility 96±2% @010



Measured Longitudinal Coherence

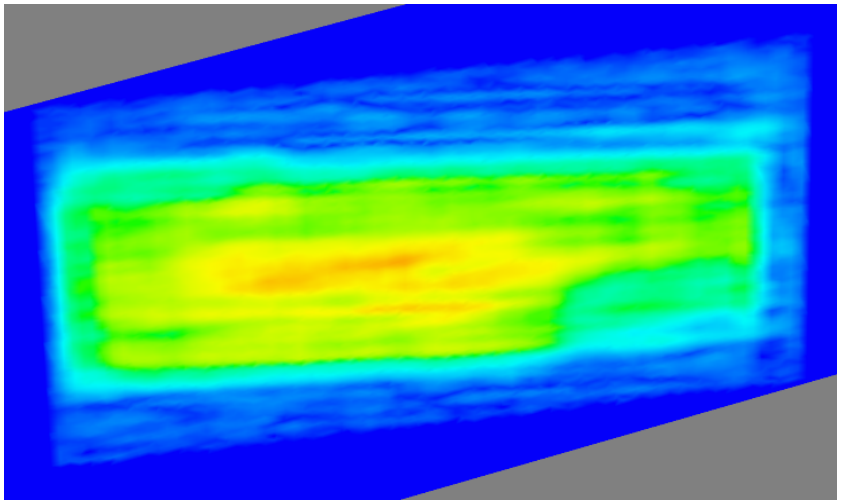
Steven Leake, Optics Express 17 15853 (2009)

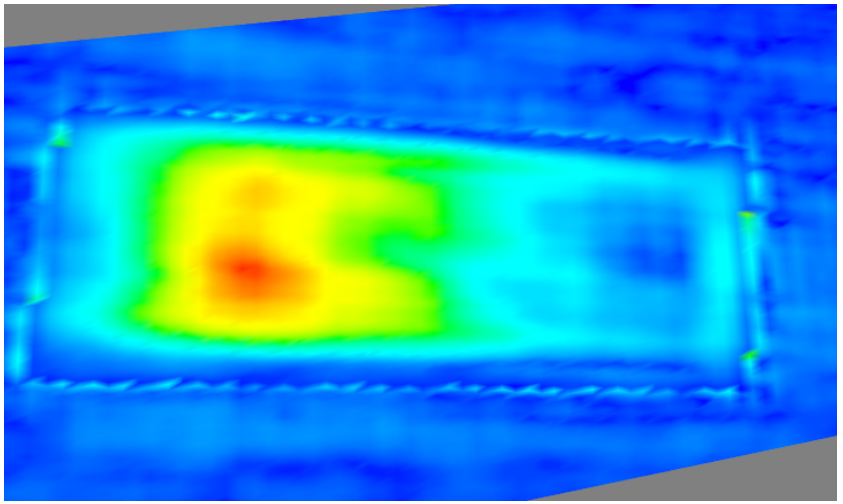


Density Section of Reconstruction using 100 and 101 reflections

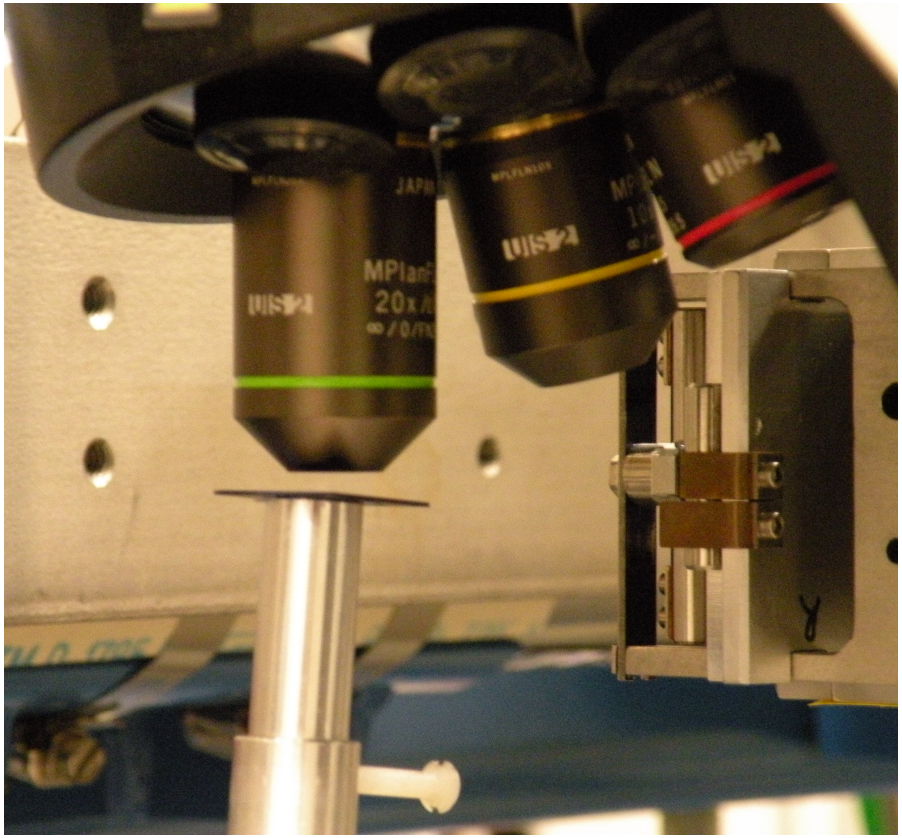
"hot spot" more developed for limited coherence

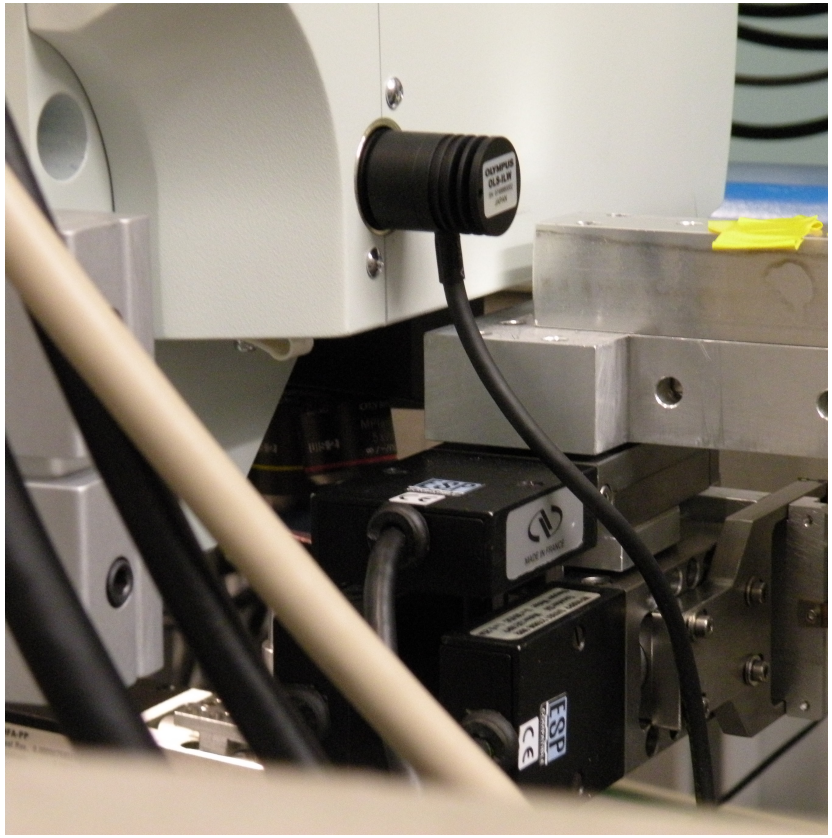
Steven Leake, Optics Express 17 15853 (2009)



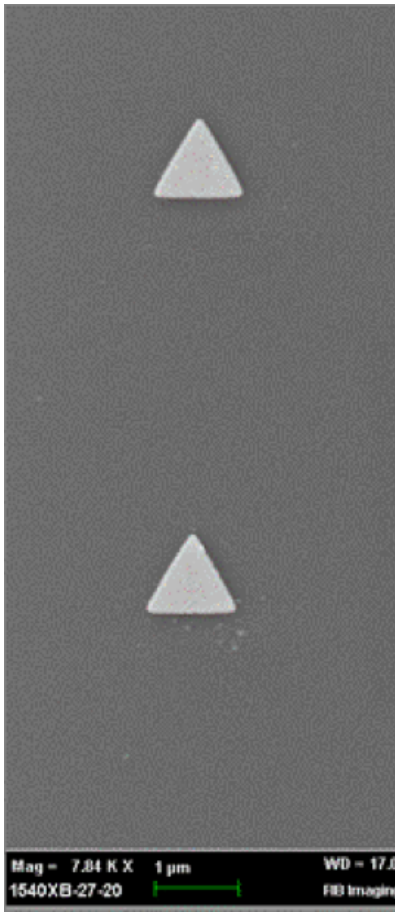


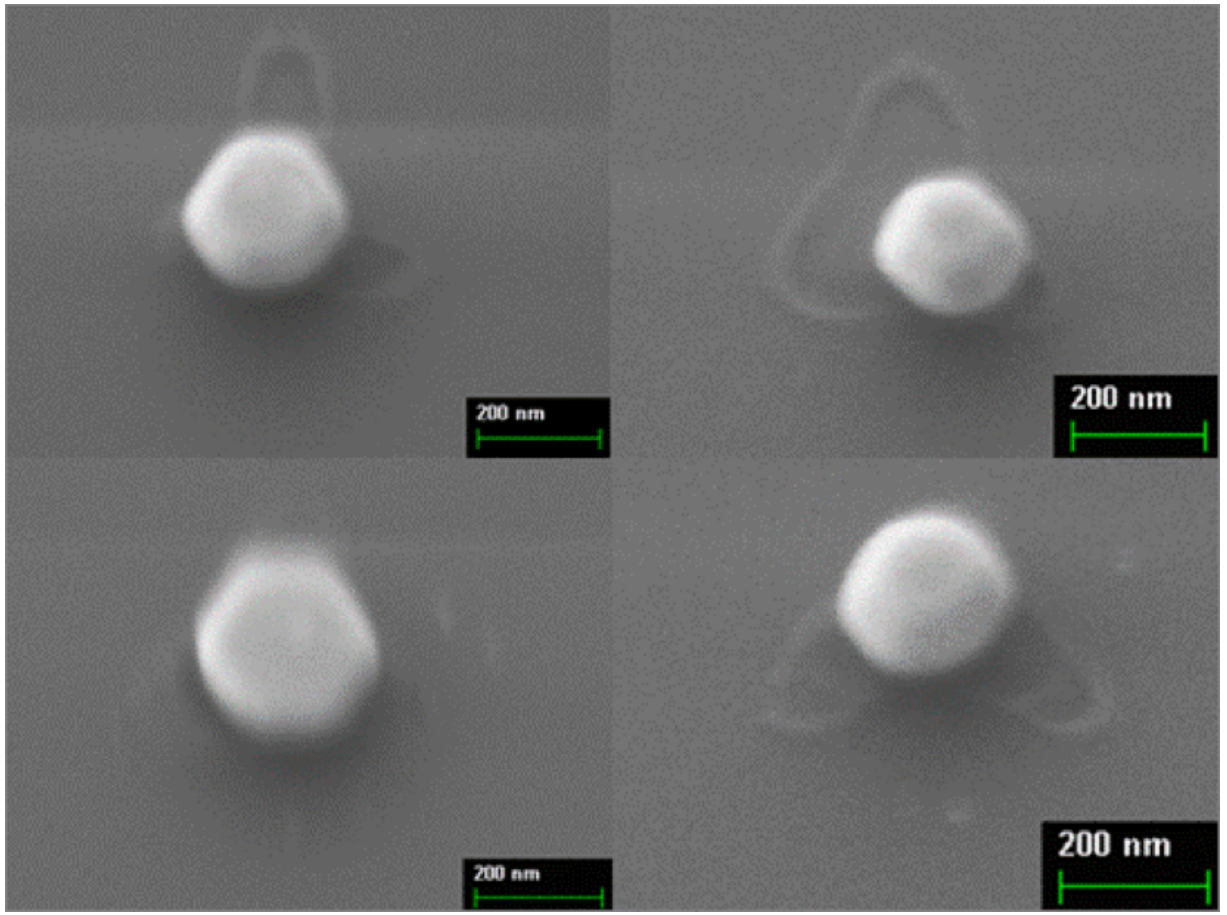
Confocal Alignment Microscope





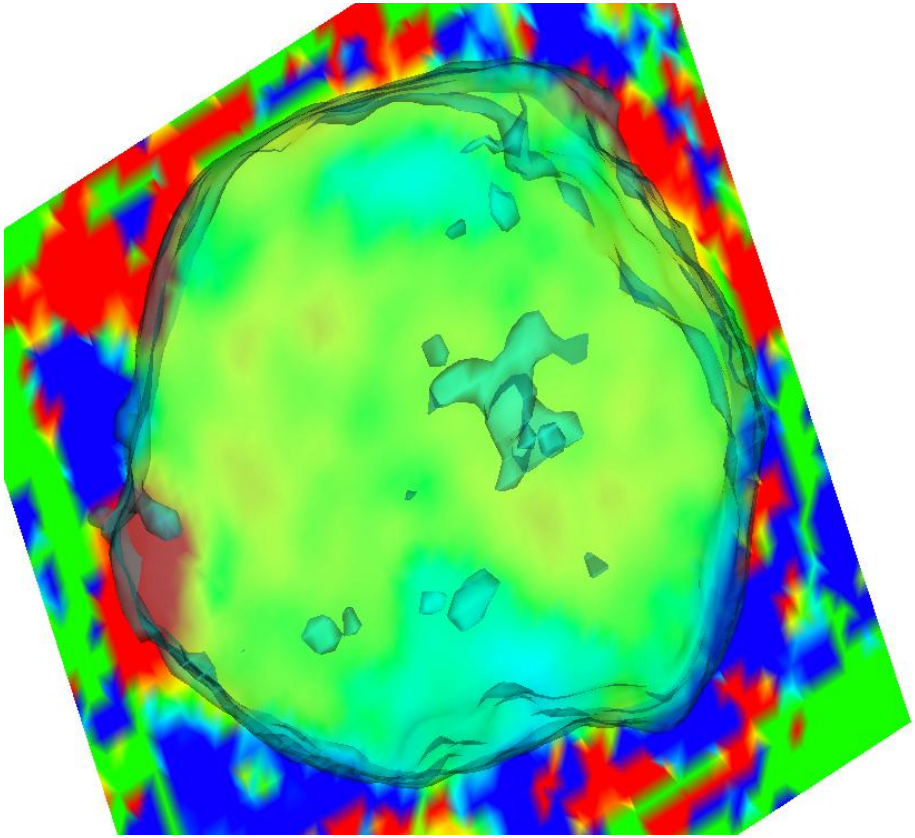
Single Au nanocrystal synthesis

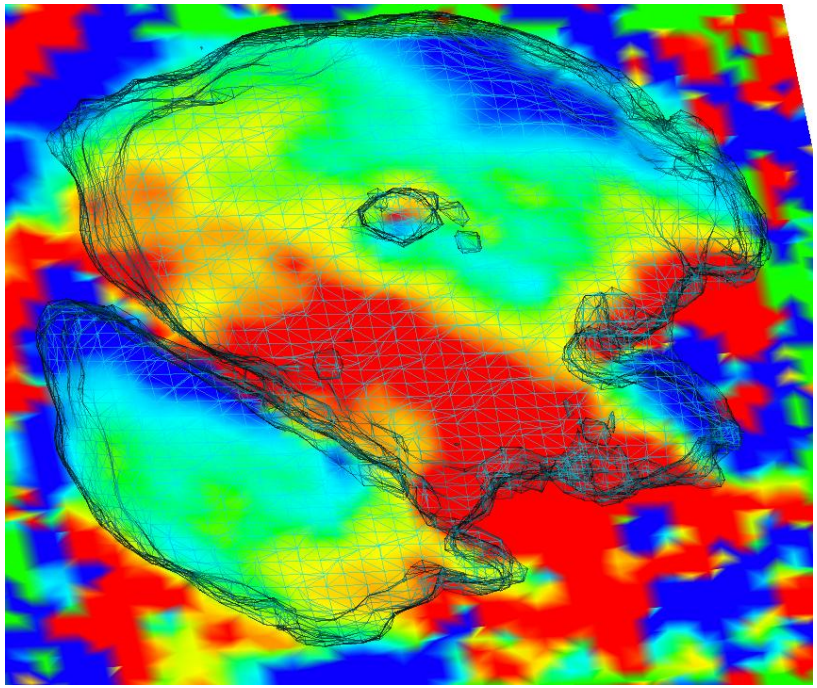


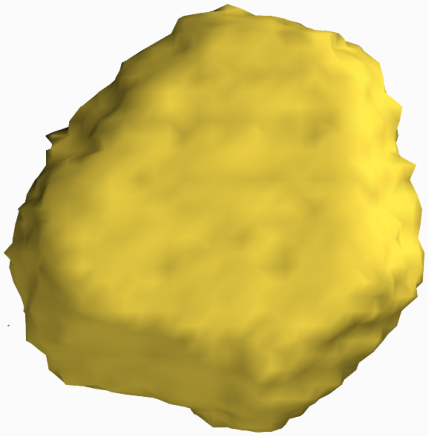


Two views of strain in Au NC

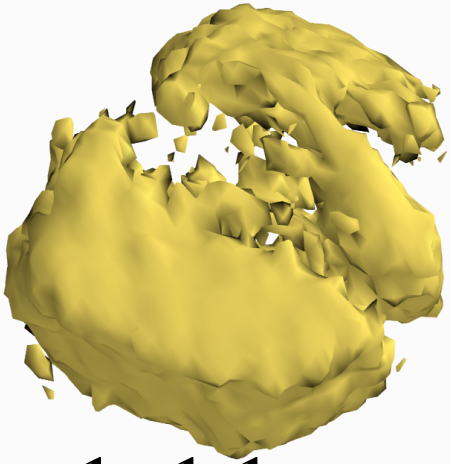
Au409B-52 (11-1) and Au409B-60 (200)



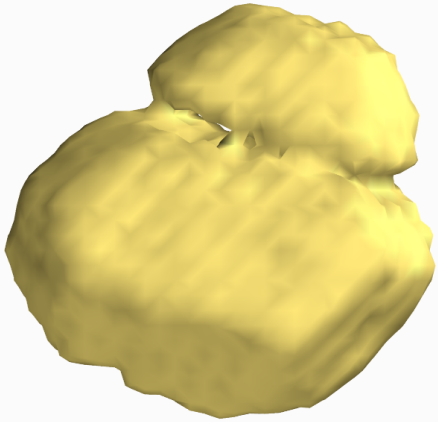




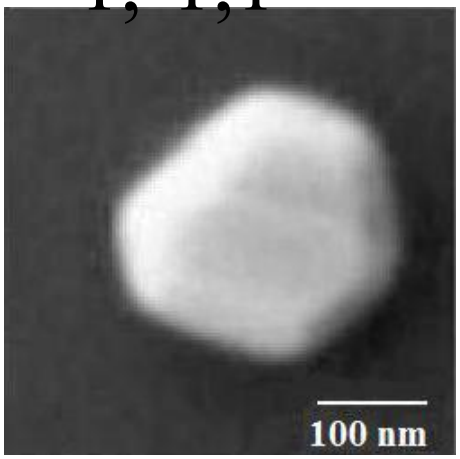
1,1,-1



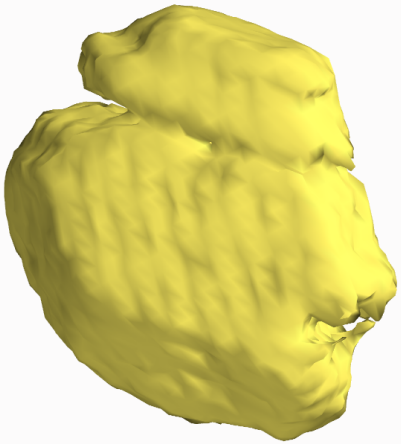
1,-1,1

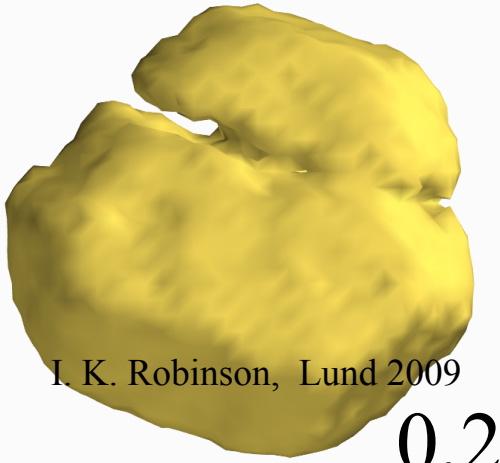


-1,1,1



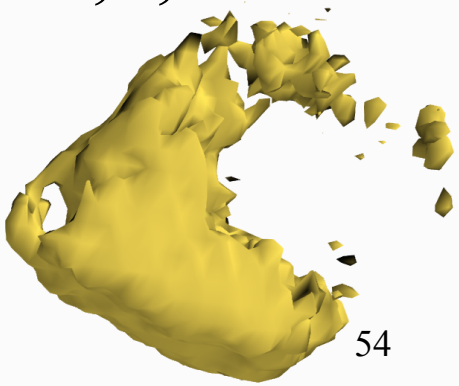
2,0,0





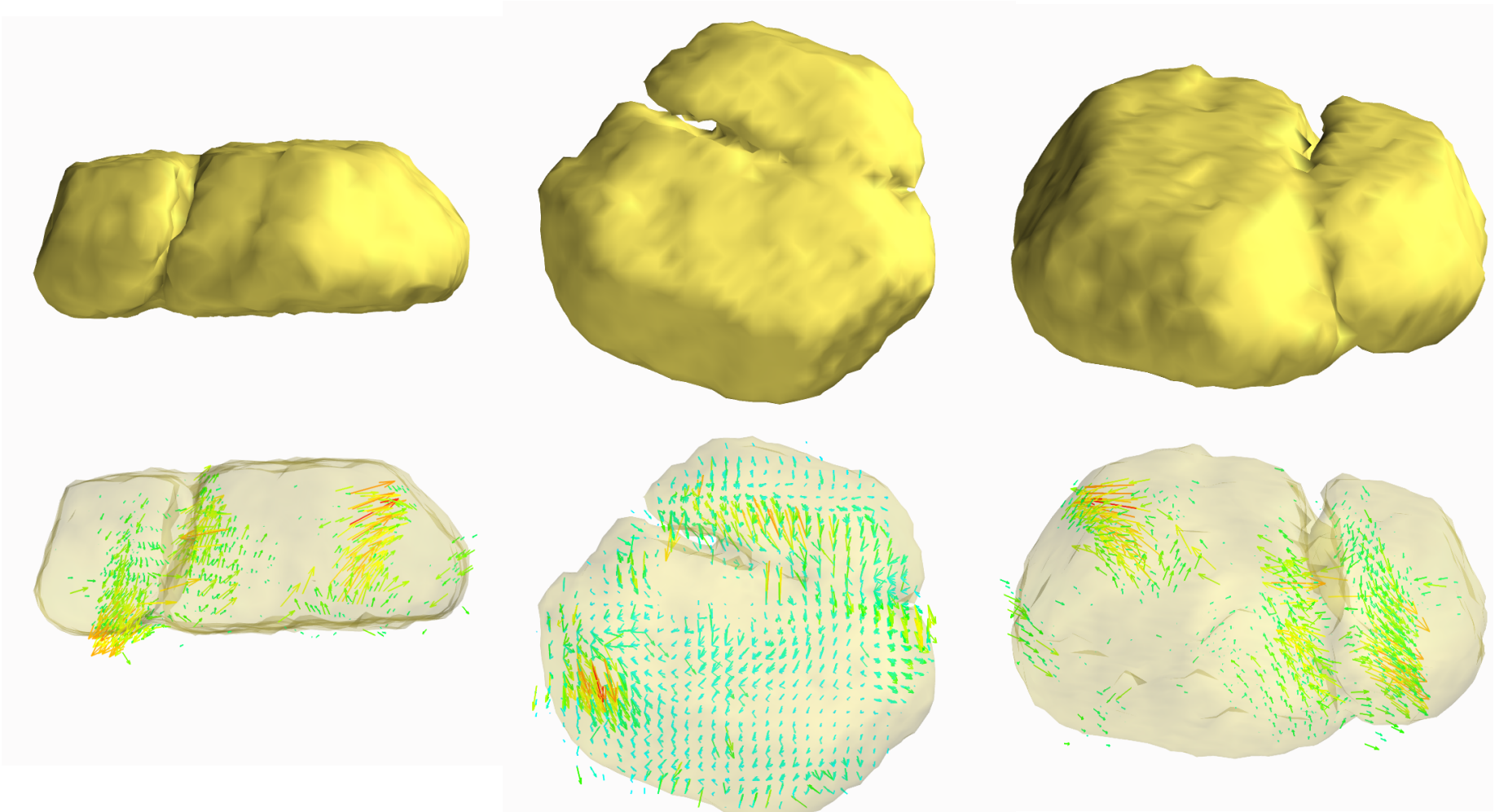
0,2,0

0,0,2



Vector displacement field

Merged reconstructions from (11-1) (020) and (-111)



Conclusions

- Internal structure of Nanocrystals
- 3D imaging of faults in Nanowires
- Phasing by computation instead of lens
- Strain fields imaged from asymmetric patterns
- Contact Forces and Surface Strains
- Plan to look at operating electronic devices