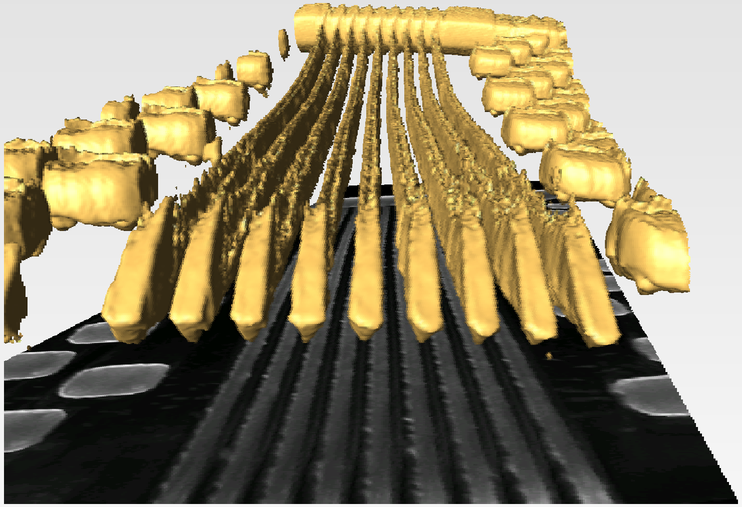
3D Imaging of Nanostructures Using Electron Tomography, and the Impact of Aberration Correctors



Peter Ercius

Huolin Xin

Varat Intaraprasonk

David Muller

Applied and Engineering Physics, Cornell University

Lynne Gignac

IBM T.J. Watson Research Center, SRC

Tomographic Reconstruction

Goal: *3D information from thick, crystalline, high atomic number materials*

- Measure structure thicknesses, x-sections, CDs

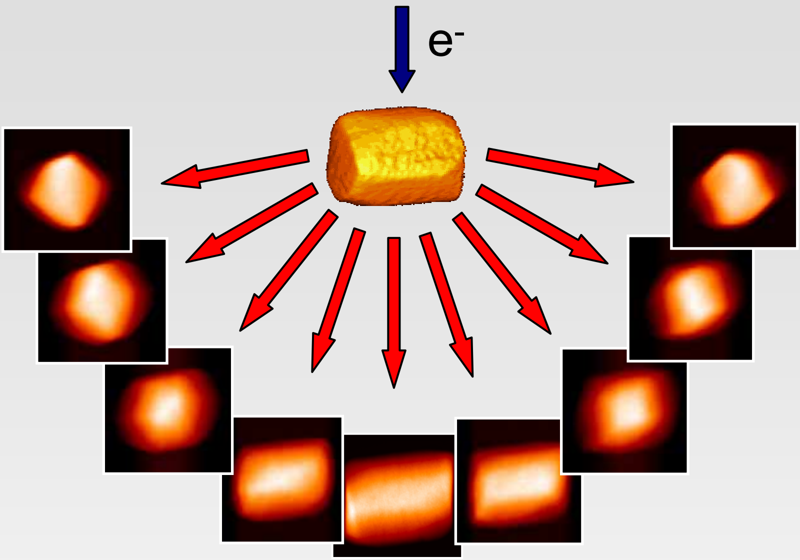
Challenges:

- Image intensities for electron tomography must be monotonic with thickness
  - ⇒ Not Conventional TEM
- Contrast reversal in HAADF Scanning TEM (Z-contrast)
  - ⇒ High mass-thickness materials appear dark at high tilts
- Samples must be tilted to ±70° to recover 3D information
  - ⇒ Tilting causes translations and rotations between images that must be corrected (post-processing)

Impact of aberration correctors:

- Lateral and depth resolution significantly improved
  - ⇒ Depth resolution < sample thickness

Tomography Experiment



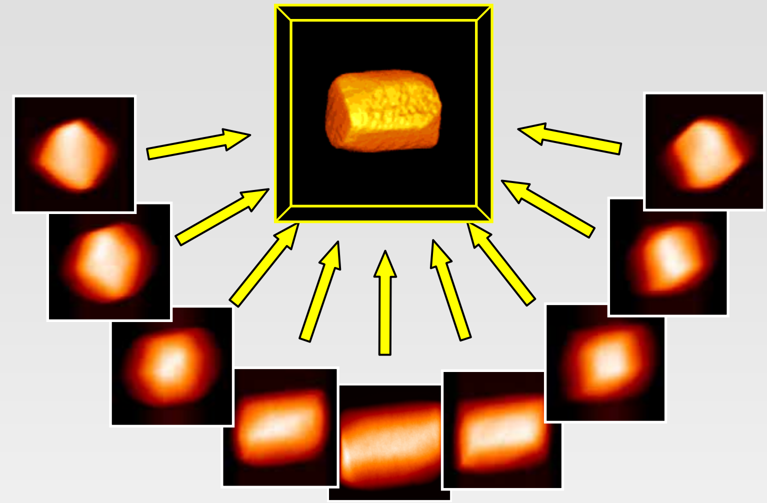
Acquisition

<u>For the best results</u>:

• Acquire many images over as large a tilt range as possible

⟶ One every 1-2° from ±70°

⟶ Filling Fourier Space



Reconstruction

<u>Requires</u>:

• Accurate spatial alignment

• Determination of tilt axis

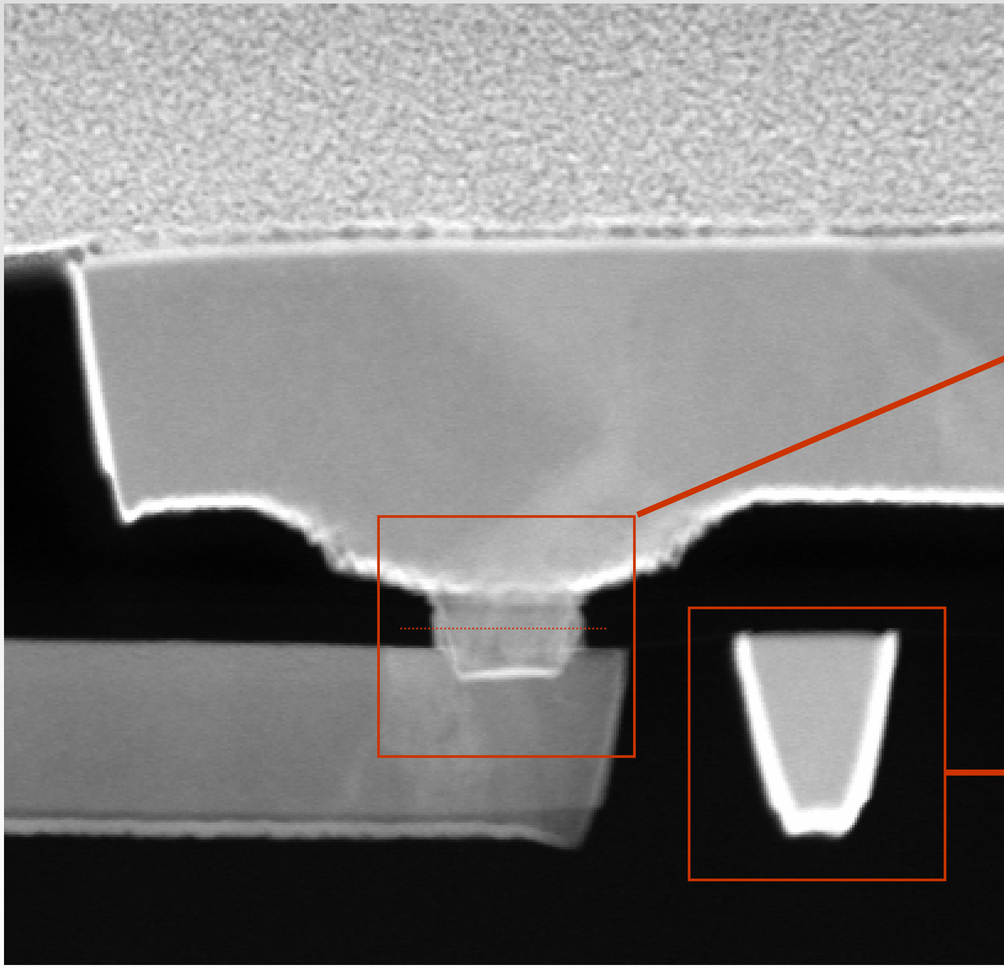
• Accurately spaced angular increments

CORNELL UNIVERSITY

SRC Semiconductor Research Corporation

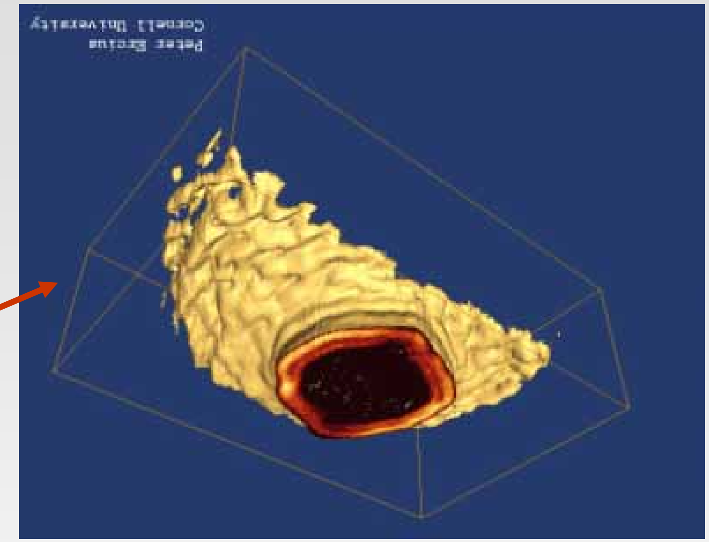
Peter Ercius, Cornell University

V2 Via Liner Layer by HAADF STEM



90nm Cu line width

Etch Roughness



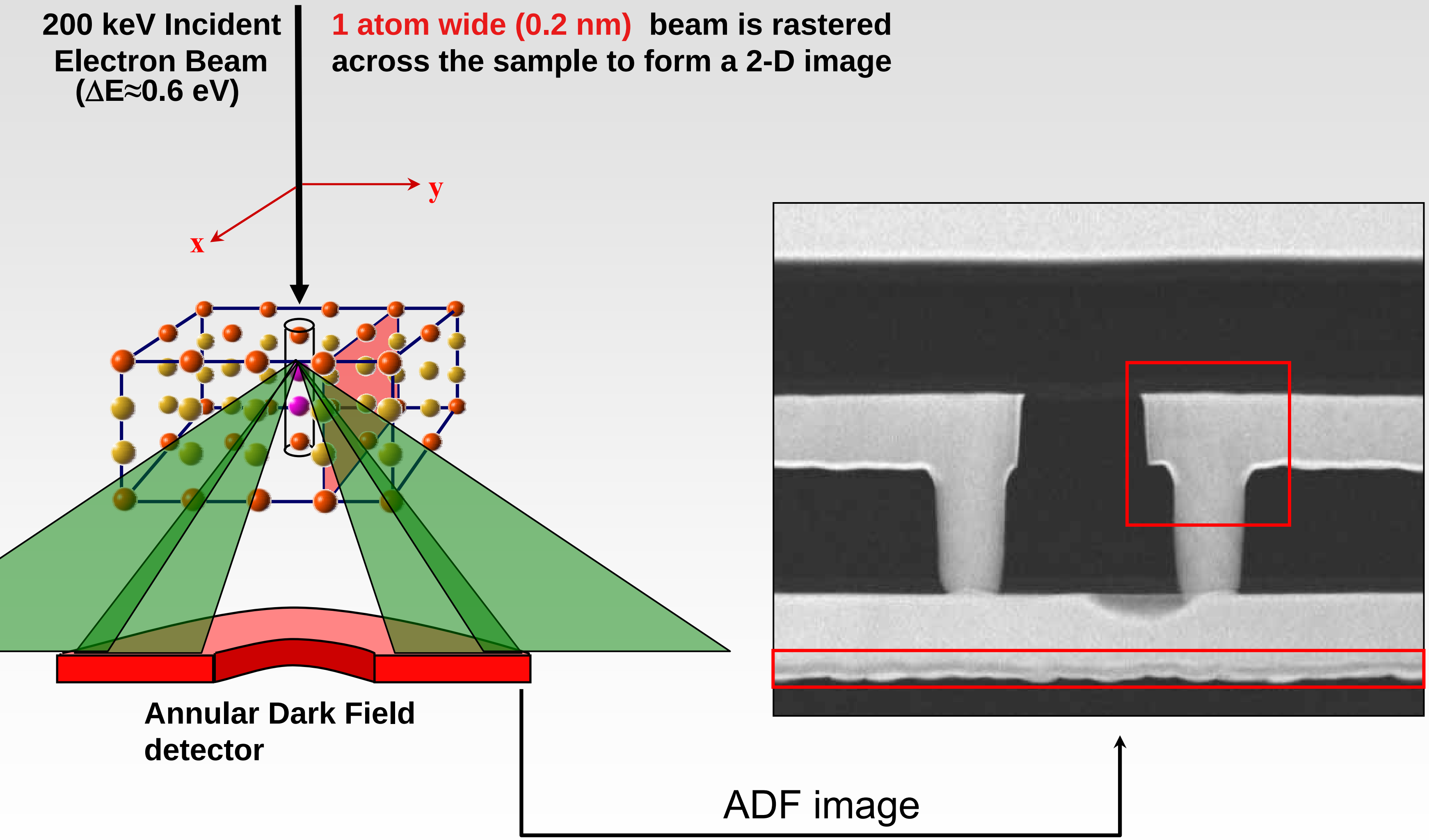
Lithography Roughness

Peter Ercius, Cornell University

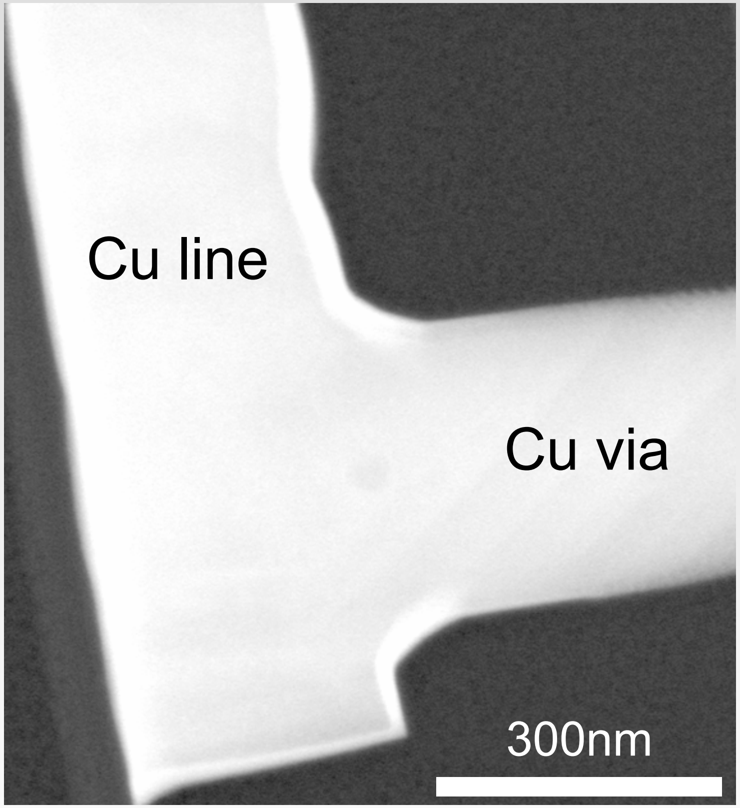
CORNELL UNIVERSITY

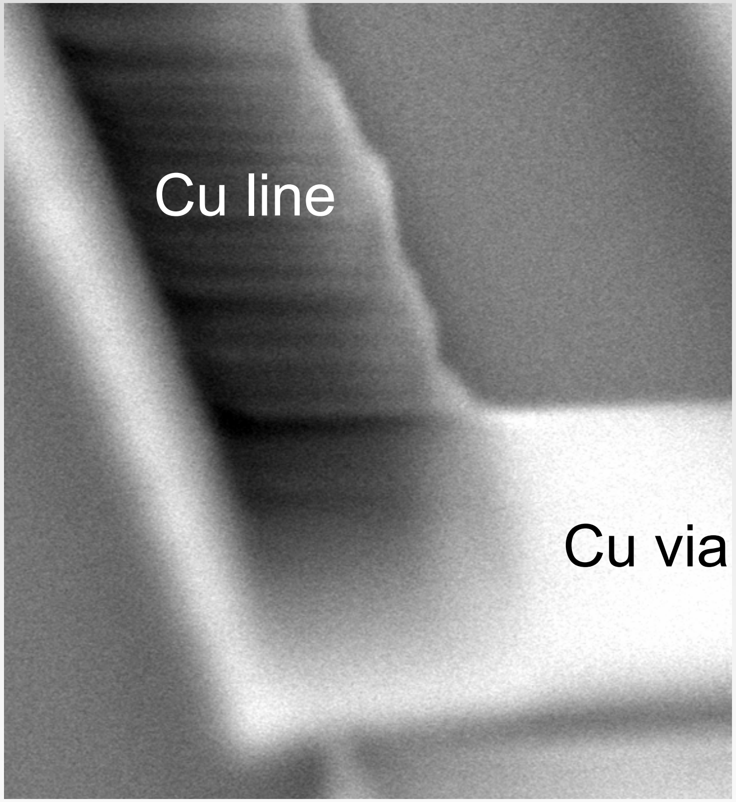
SRC Semiconductor Research Corporation

Contrast Reversal in HAADF STEM



Contrast Reversal with Thickness

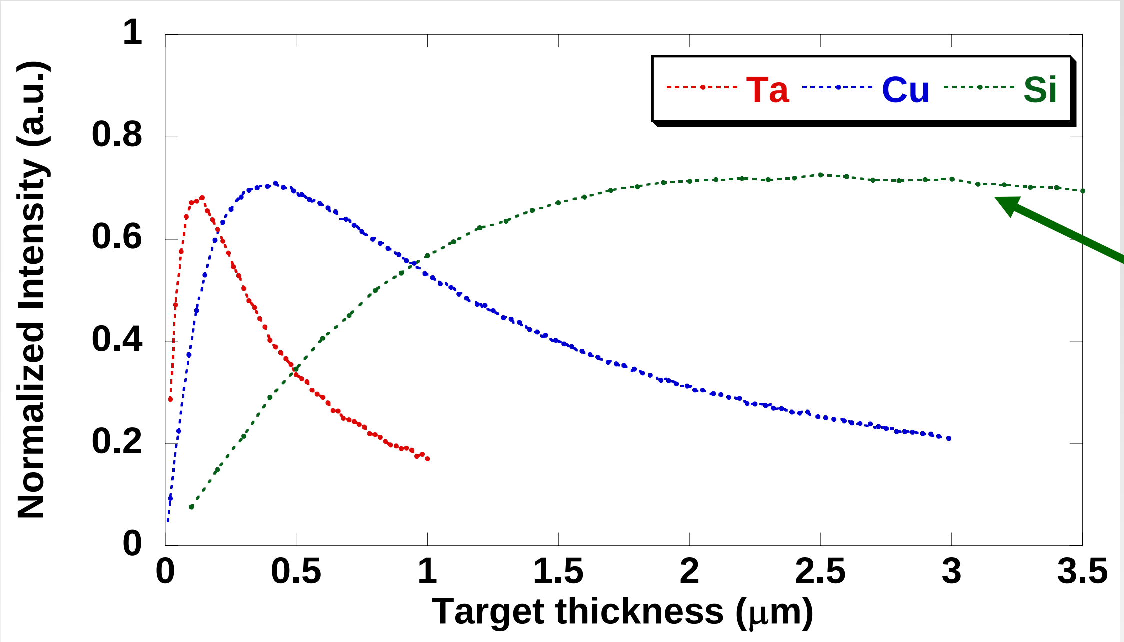




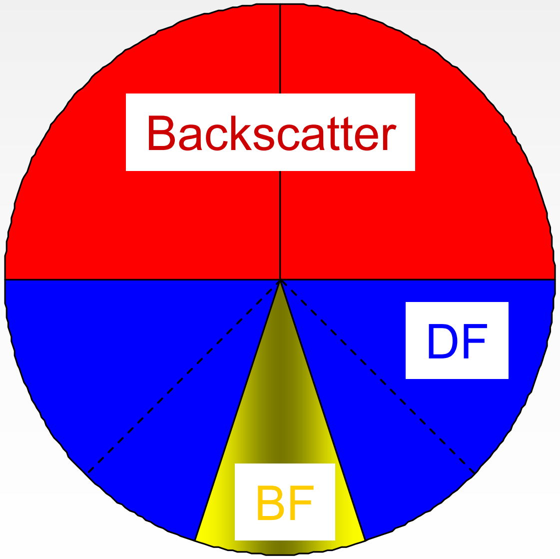
- HAADF STEM
- 0° tilt

- HAADF STEM
- 70° tilt

Why the Contrast Reversal in HAADF?



Signal drops when electrons scatter outside outer angle of detector (e.g. backscattering)

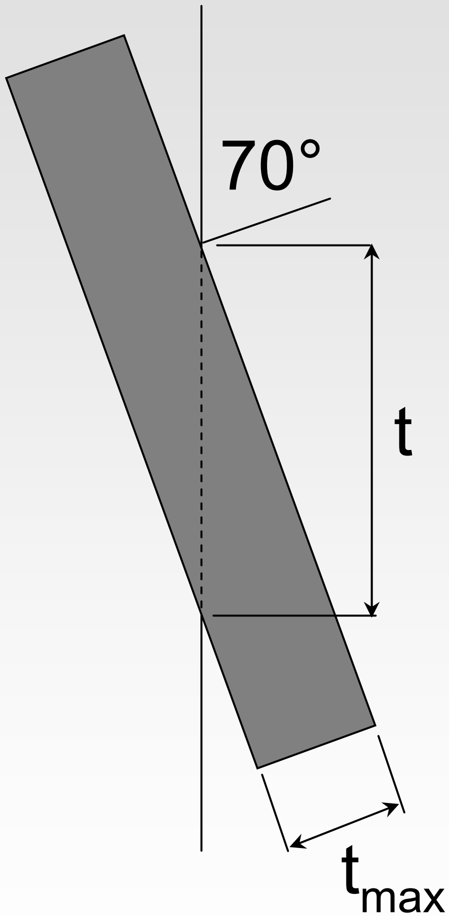


But no electrons stop in the sample:

$$R = \frac{K}{\rho} E_0^{\gamma} \cong 50\,\mu m \text{ in Cu for 200keV}$$

Maximum Material Thickness: HAADF vs IBF

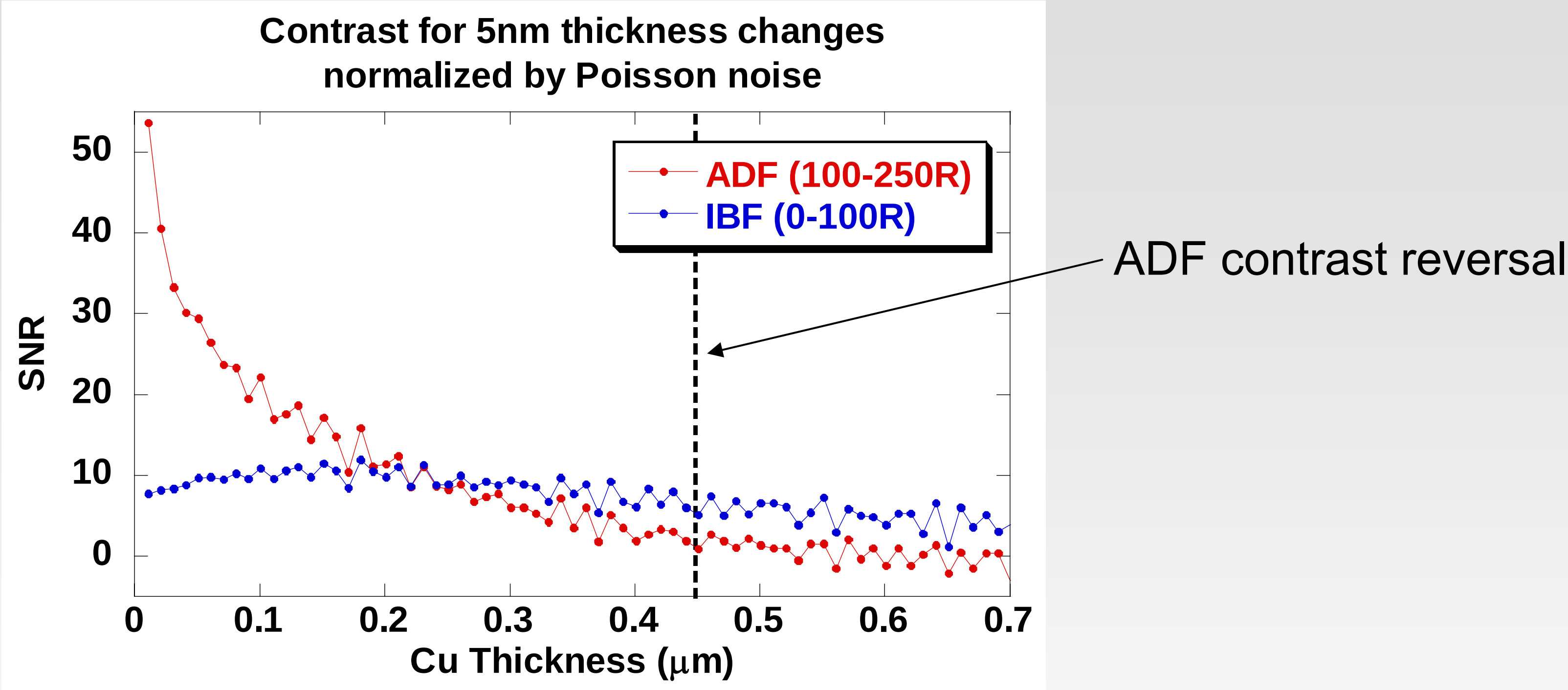
Apparent thickness is increased ~threefold by tilting



Maximum material thickness, t_{max} (in nm), for ±70° tilt

	HAADF	IBF
Tantalum	47	73±7
Copper	143	220±20
Silicon	855	1160±30

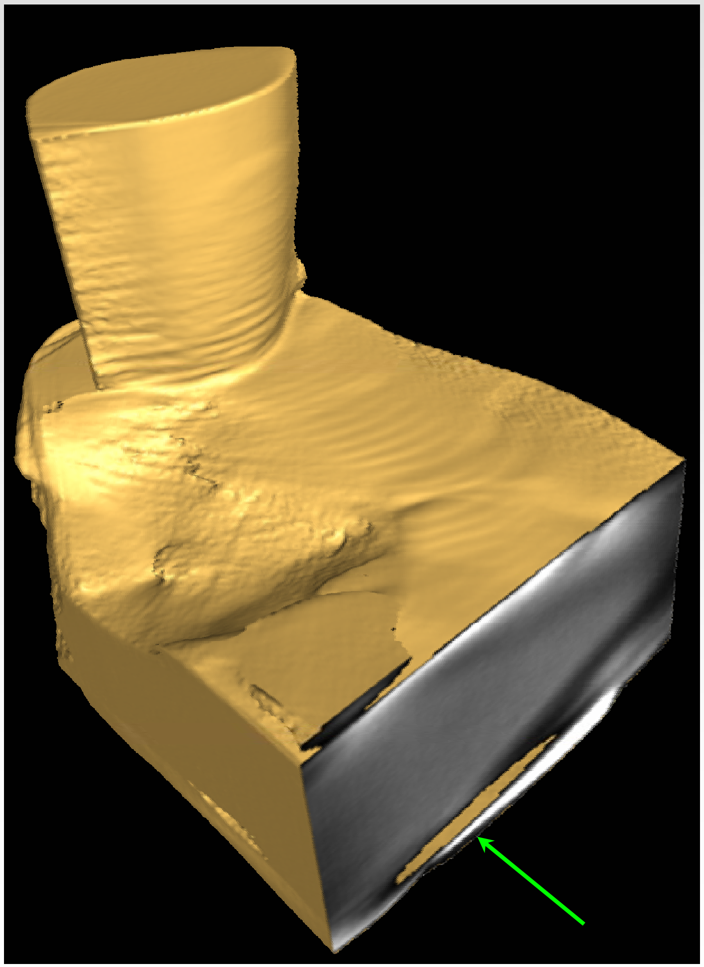
IBF vs. HAADF for Cu: SNR



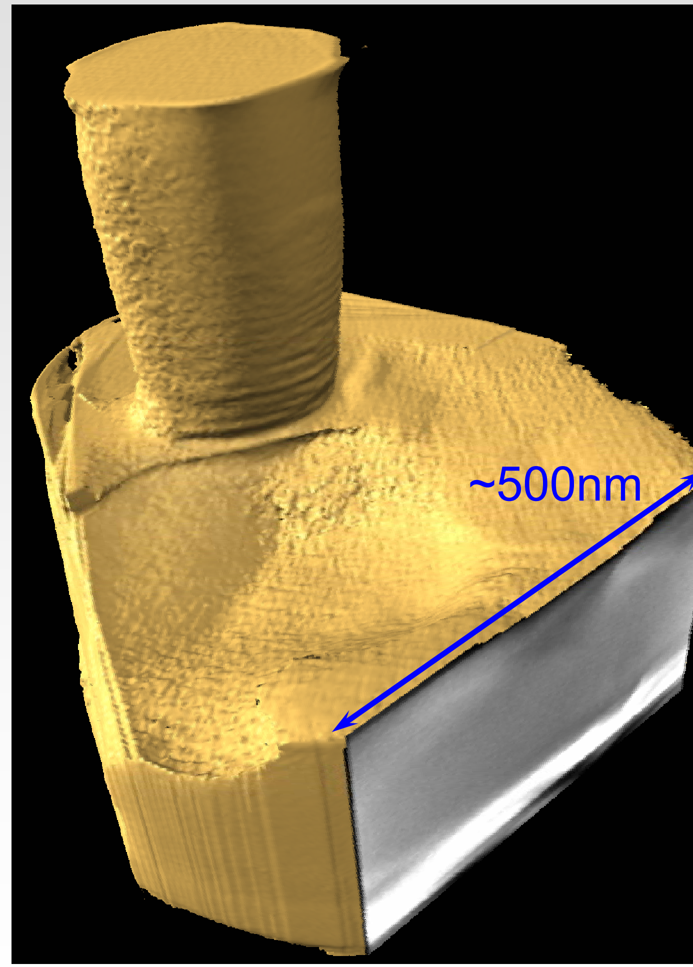
- Question: when does IBF become advantageous over HAADF?
  - Compare for Δt=5nm at relevant thicknesses
- IBF is better even before contrast reversal thicknesses are reached

Stress Void Reconstructions

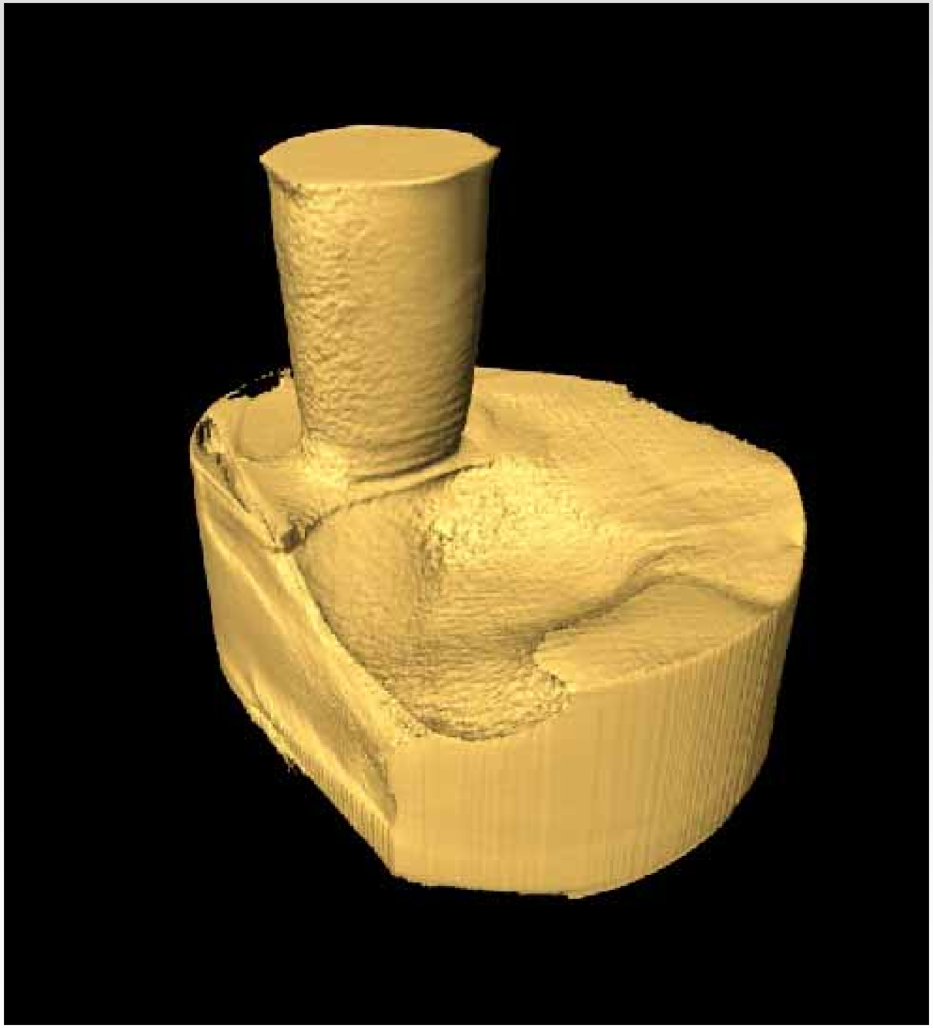
HAADF



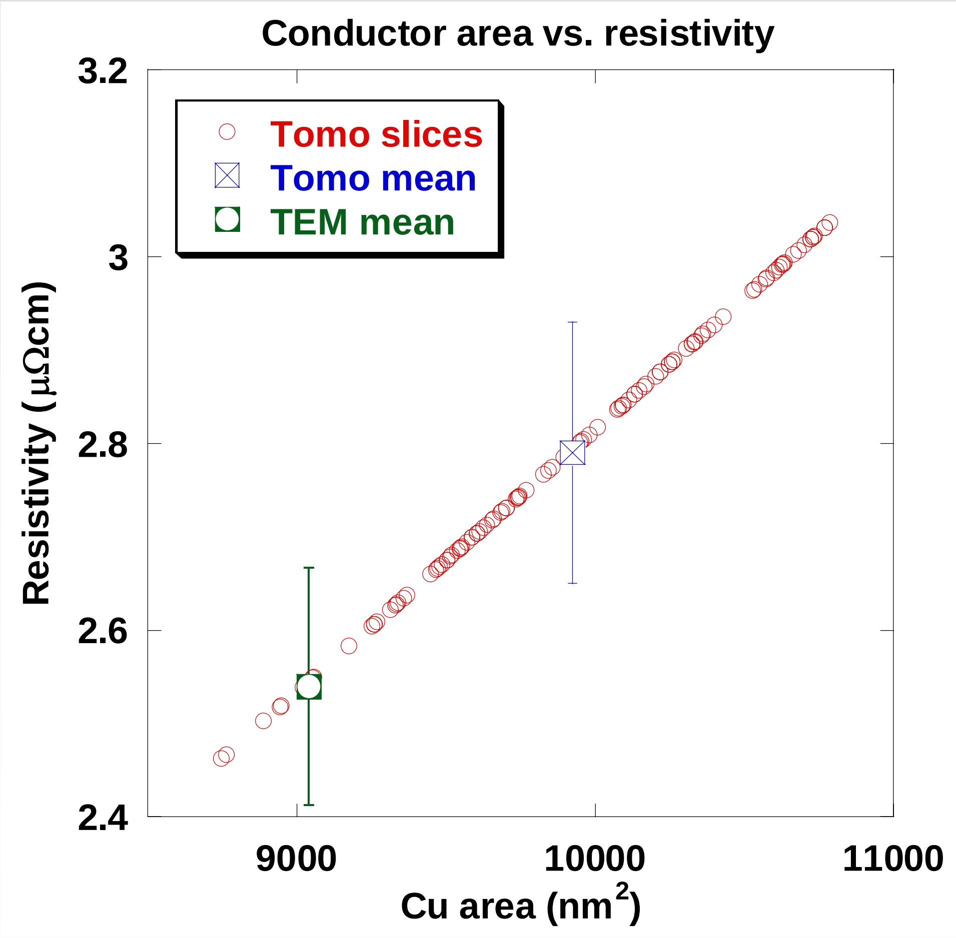
IBF

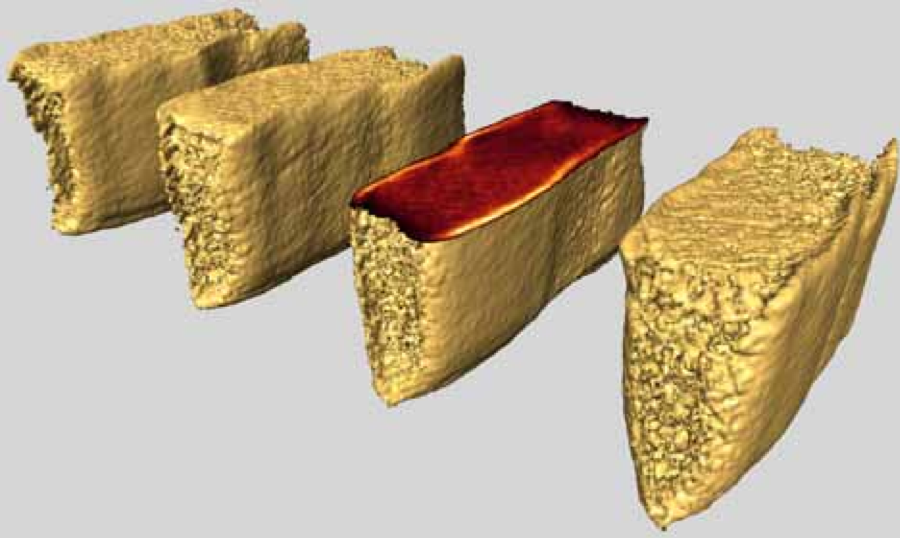


Stress Void and Via Reconstruction



Copper Line Resistivity





- TEM data from L. Gignac

• By preparing one sample for tomography we can gain information about ~2nm slices of each line.

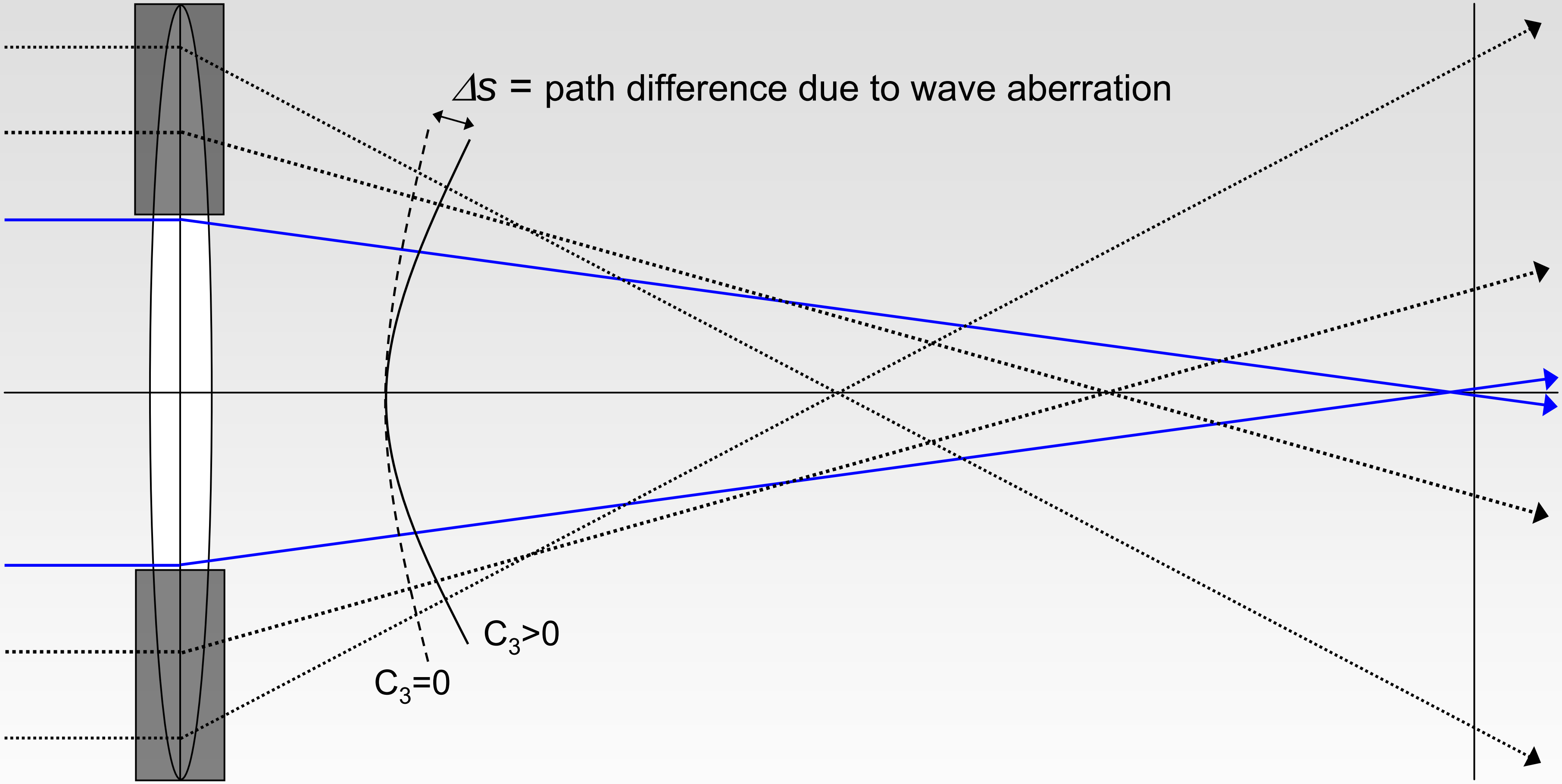
• Getting the same information by CTEM requires preparation and measurement of many samples.

CORNELL UNIVERSITY

SRC Semiconductor Research Corporation

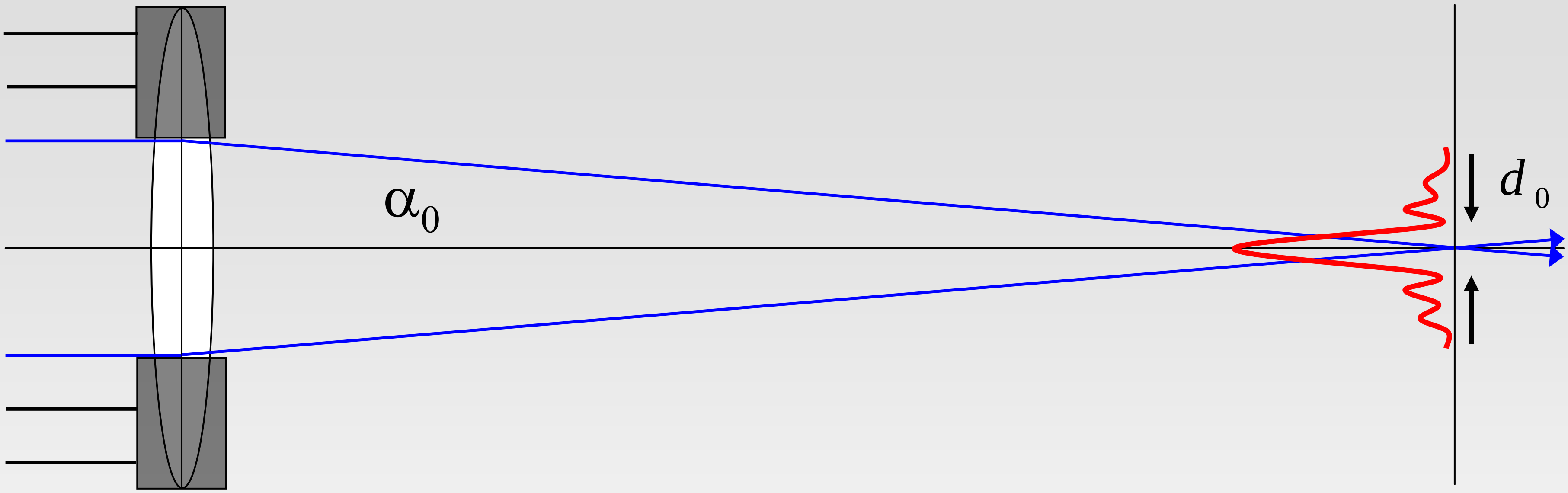
Peter Ercius, Cornell University

Electron Lens Aberrations



• Use circular aperture to cutoff electrons with a large phase shift Δs across the lens

Balance Aberration and Diffraction

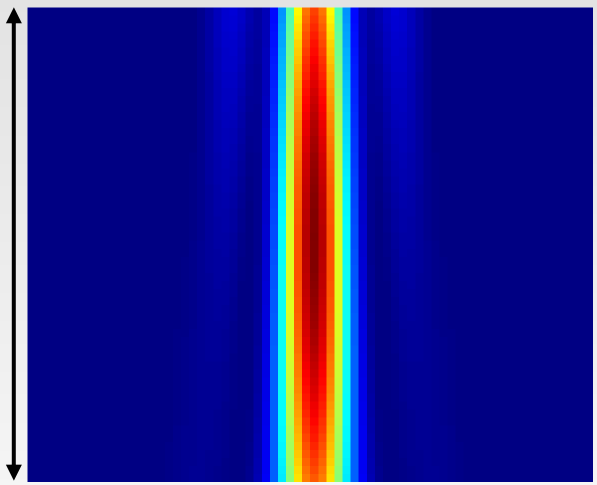


- The image of a point transferred through a lens with a circular aperture of semiangle α_0 is an Airy disk of diameter: $d_0 \propto 1/\alpha_0$
- Balance spherical aberration against the aperture's diffraction limit
    - Less diffraction with a larger aperture
- Design correctors to eliminate phase shift across the lens
    - Lens aberrations are a non-convergent power series
        - Correct $C_3 \rightarrow C_5$; Correct $C_5 \rightarrow C_7$; ETC…

Depth Point Spread Function (PSF)

C_3 limited:

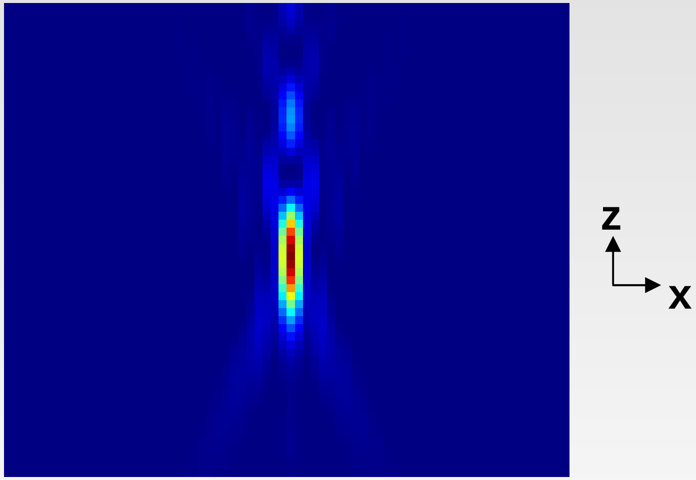
200nm



$$\Delta z \approx 33nm$$

200keV, α=9.6mRad,
C_3=1.2mm, Δf=550Å

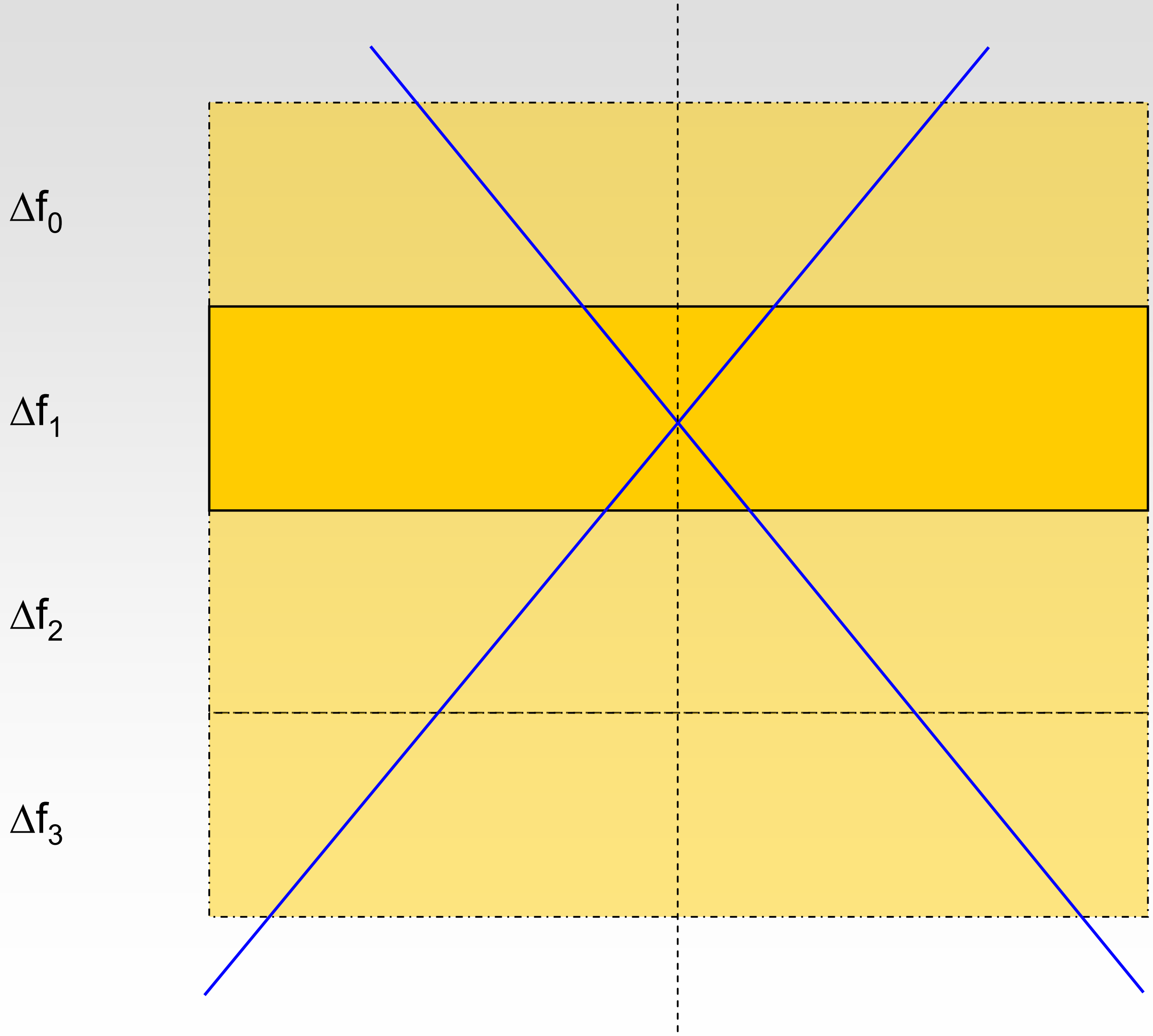
C_5 limited:



$$\Delta z \approx 3.6nm$$

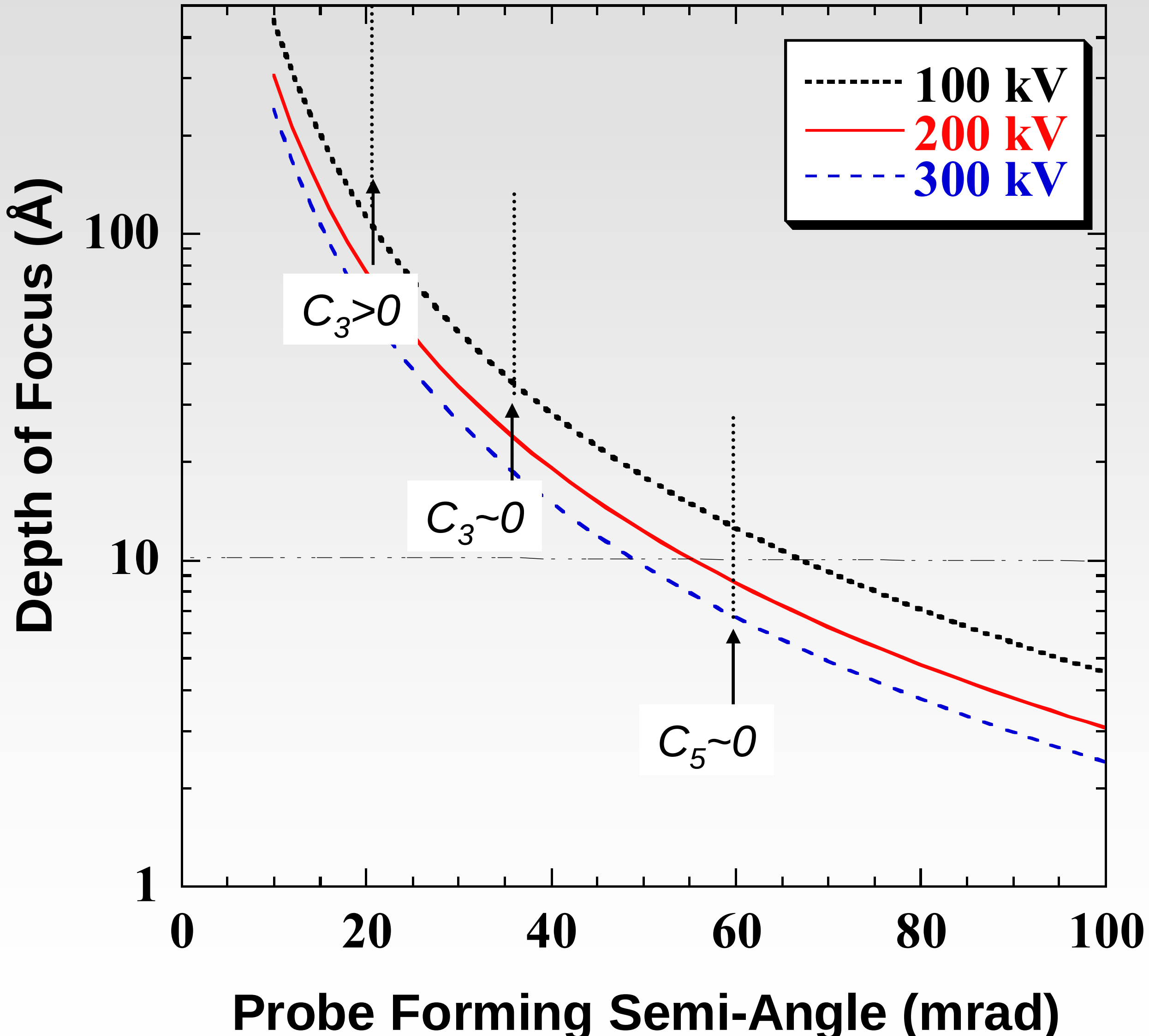
200keV, α=29.1mRad
C_3=-0.0842mm,
C5=100mm, Δf=-132Å

Depth Sectioning by Focal Series

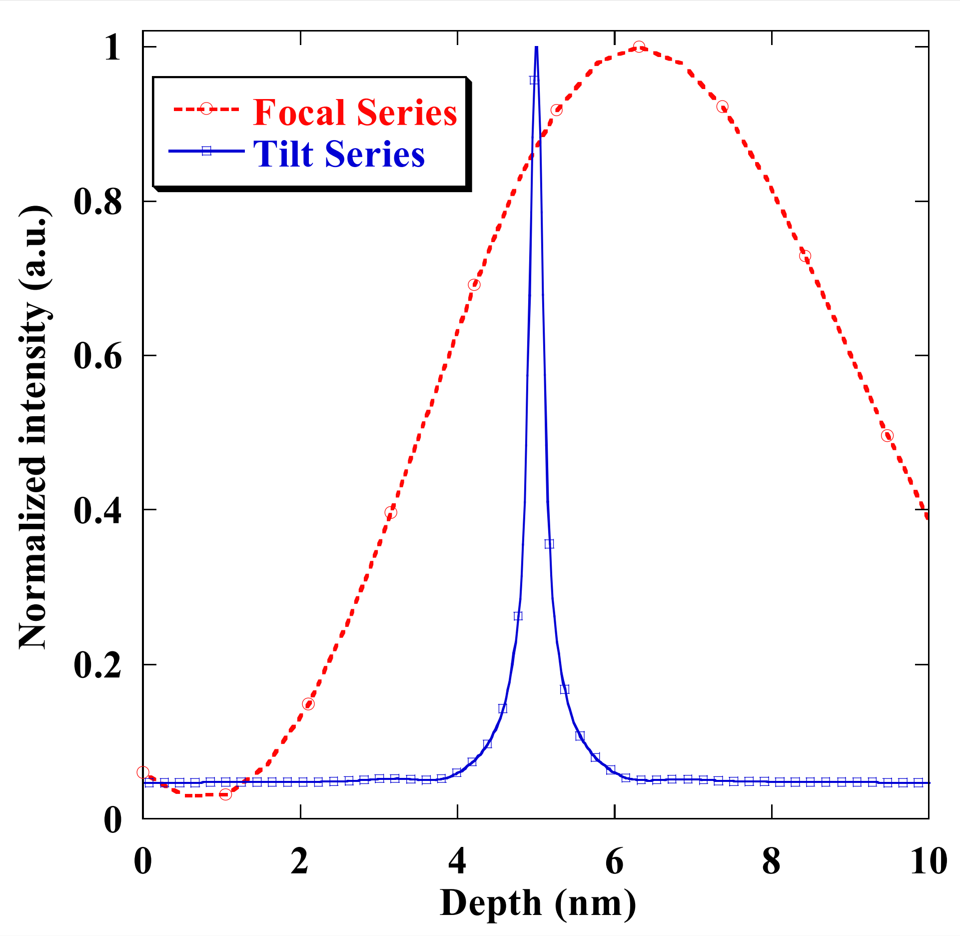


Prospects for Depth Sectioning

Current STEM correctors: Δz ~ 3-8 nm *Super STEM: Δz ~ 1 nm?*



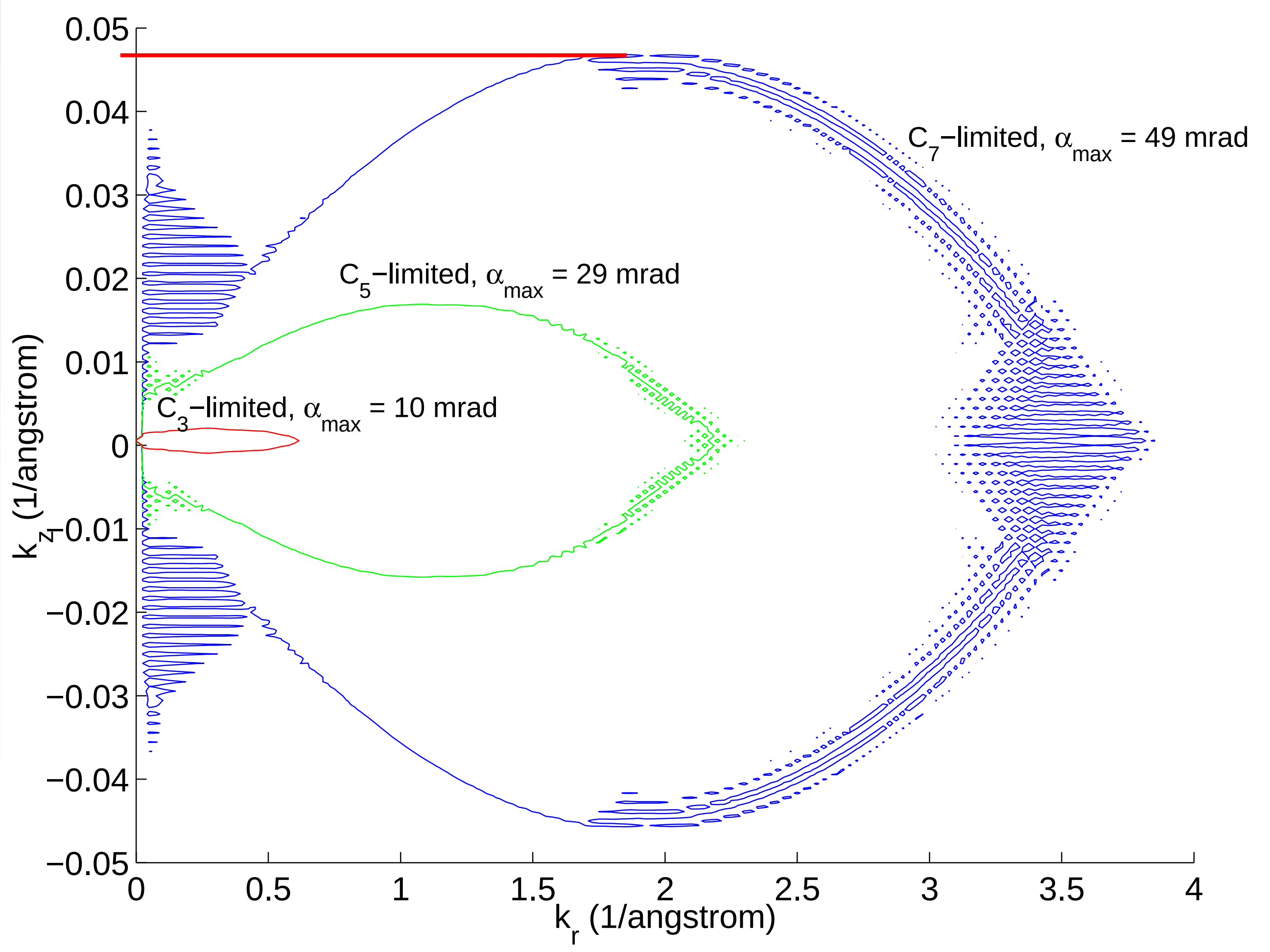
Tomography or Depth Sectioning



Focal Series: Change defocus to sample at different depths
Tilt Series: Tilt sample to fill Fourier-Space with projections

Information Limit for Depth Sectioning

Information limit: 0.05^{-1} = 20Å



Half-angle: $2\alpha_{max}$

k_r cutoff: $\dfrac{2\alpha_{max}}{\lambda}$

C_3 limited:

$9.6\text{mrad} = .55°$

$\text{covers}: 1.1°$

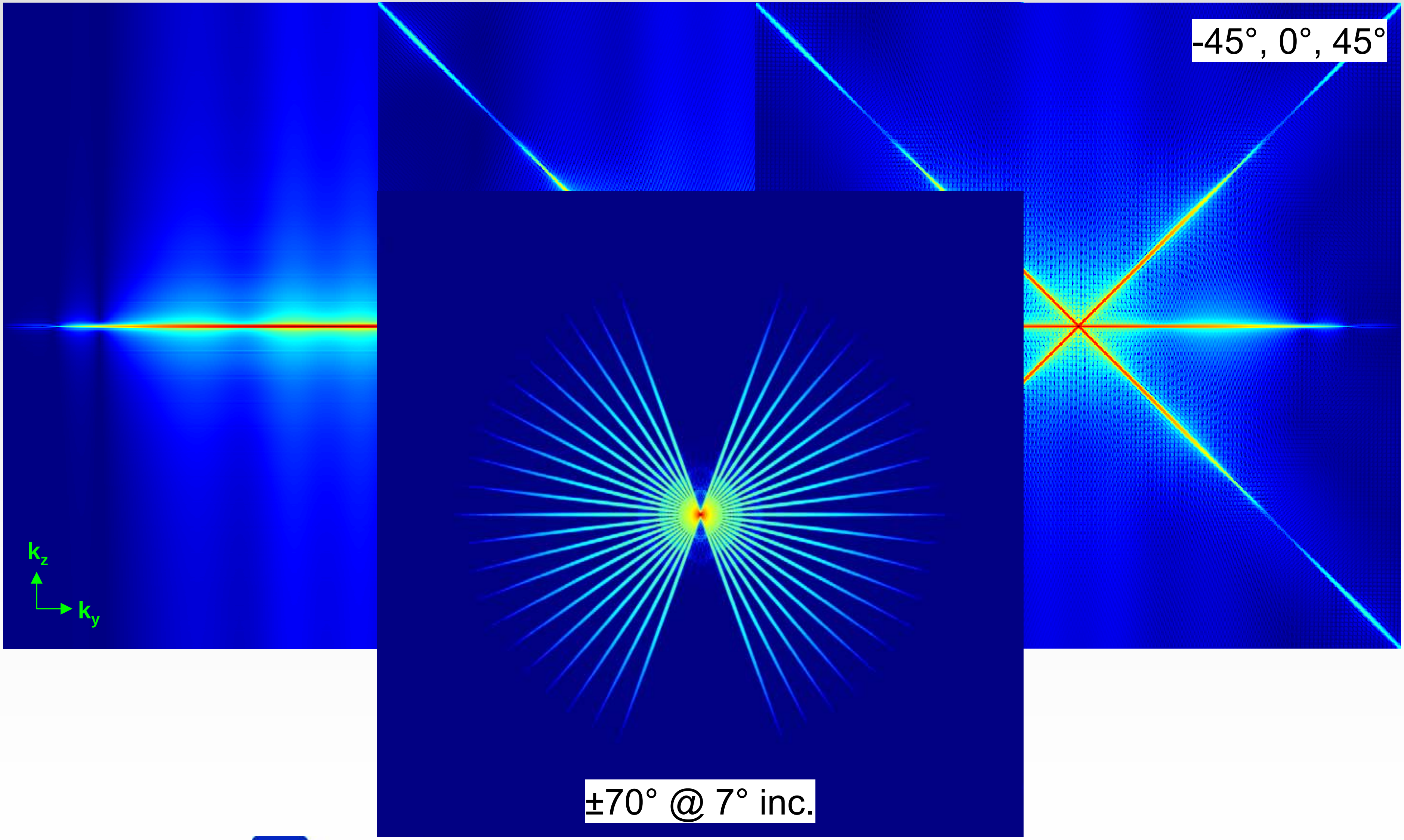
C_5 limited:

$29\text{mrad} = 1.66°$

$\text{covers}: 3.32°$

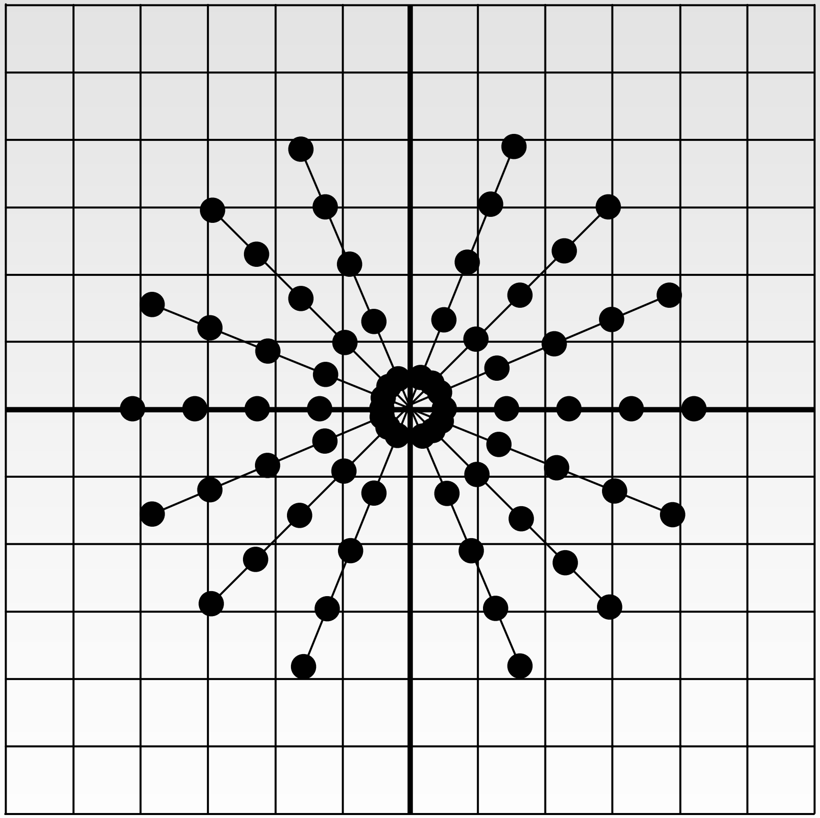
CORNELL UNIVERSITY
SRC Semiconductor Research Corporation
Peter Ercius, Cornell University

Fourier Reconstruction with Depth Sectioning at Different Tilts

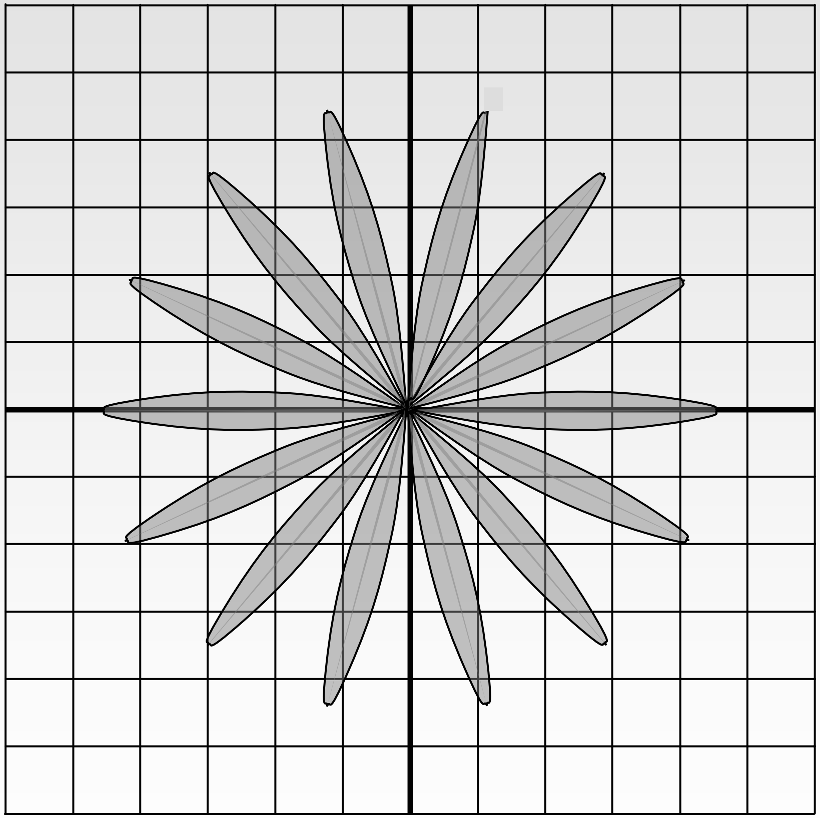


Fourier Reconstruction Methods

Tilt Series



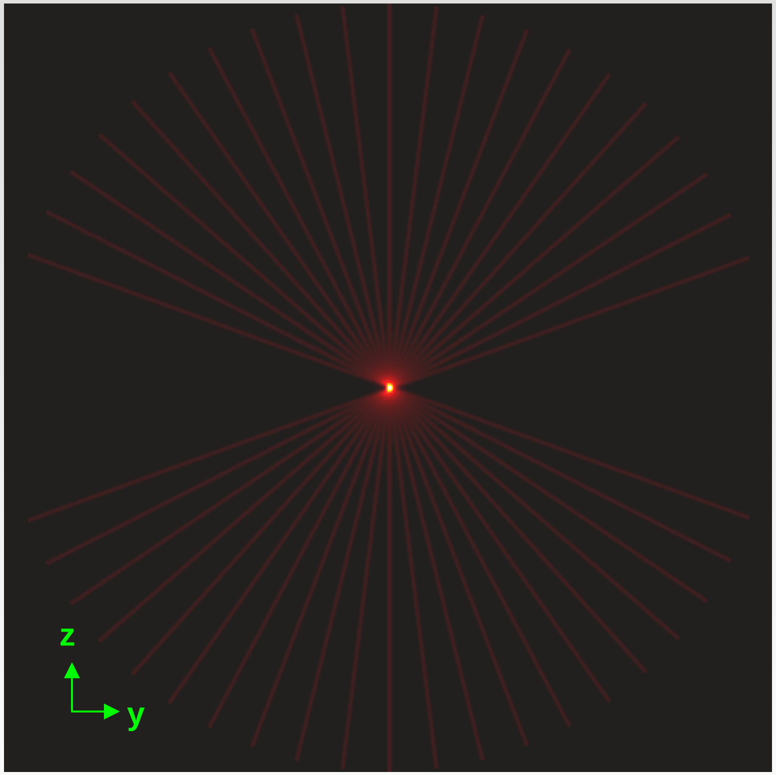
Focal & Tilt Series



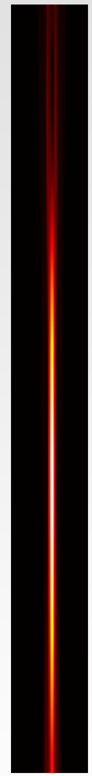
Peter Ercius, Cornell University

Convolution Simulation: PSF

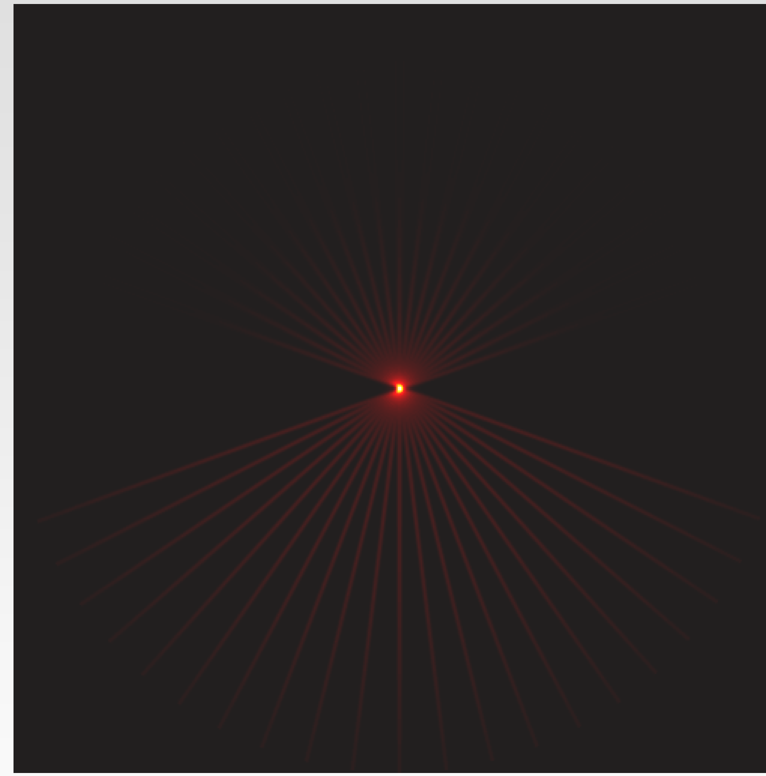
Tilt Series



Focal Series



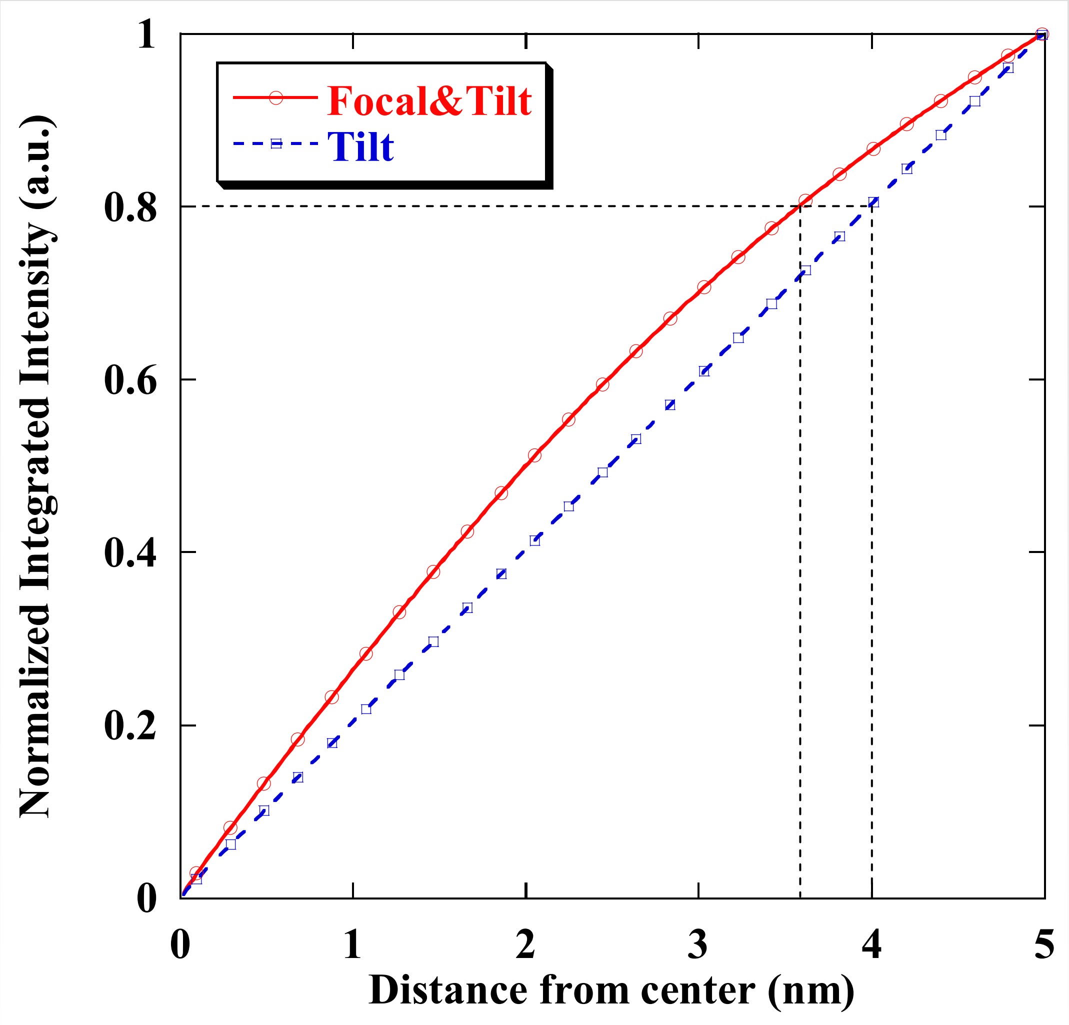
Focal &Tilt Series



200keV, C_3=-0.0842mm, C_5=100mm, f_0=-132, α=29.1mRad
±70° @ 7° increments

Peter Ercius, Cornell University

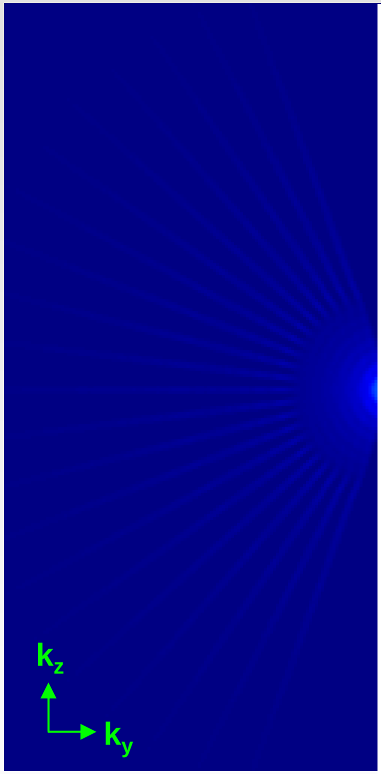
Spread of PSF Intensity

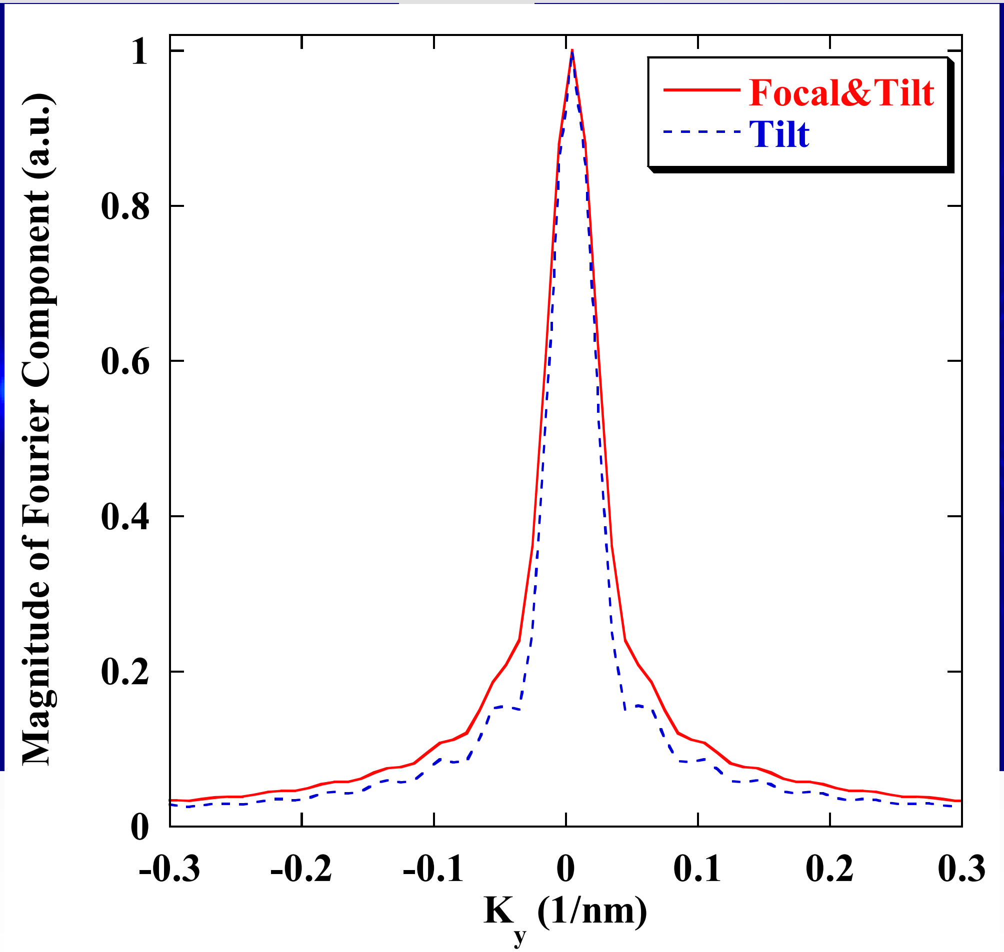


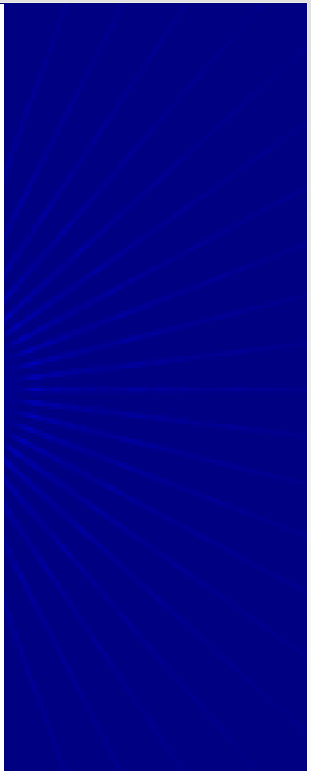
- Intensity is decentralized for both methods

Convolution Simulation: CTF

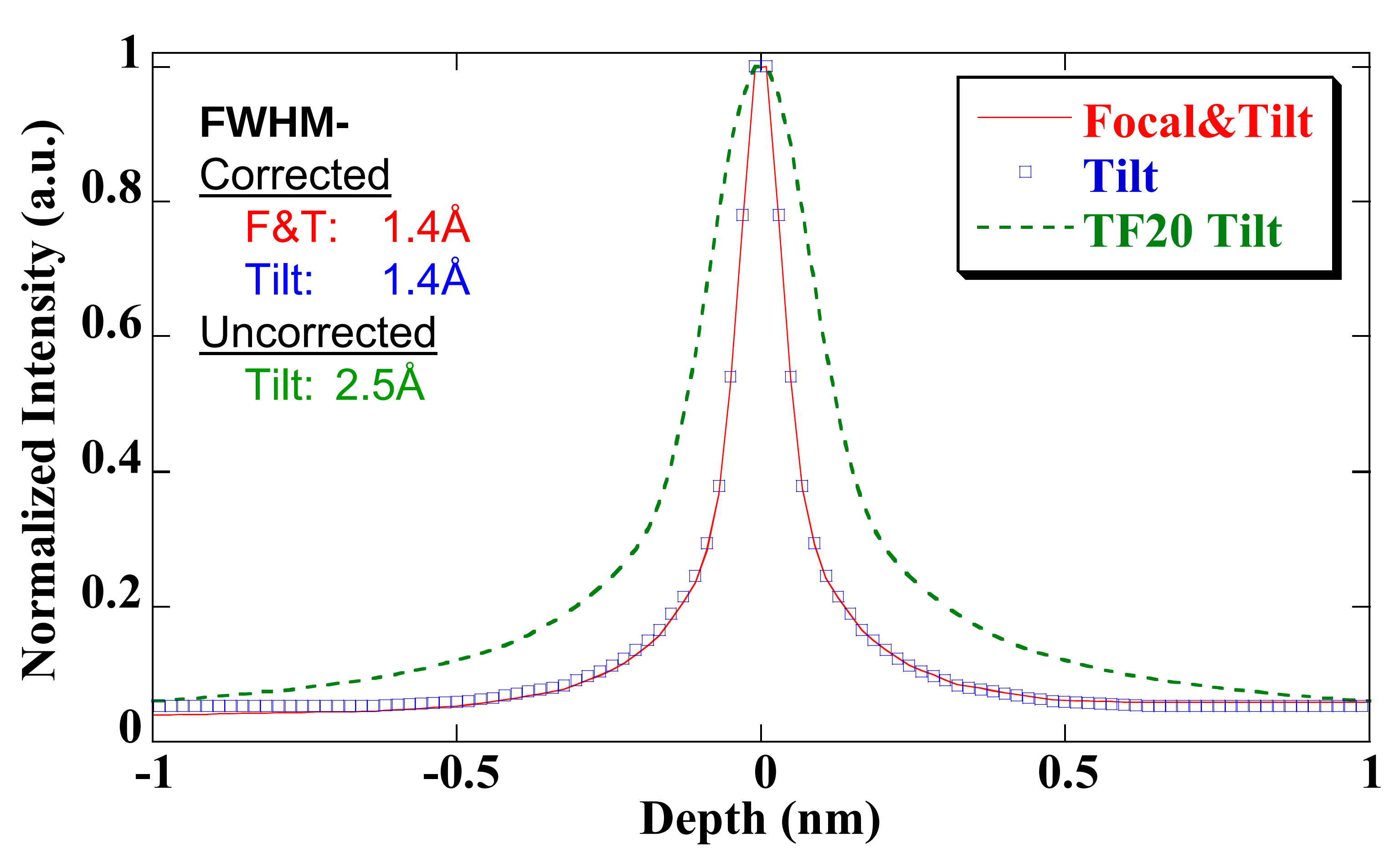
Focal & Tilt Series | **Tilt Series**







Depth Resolution

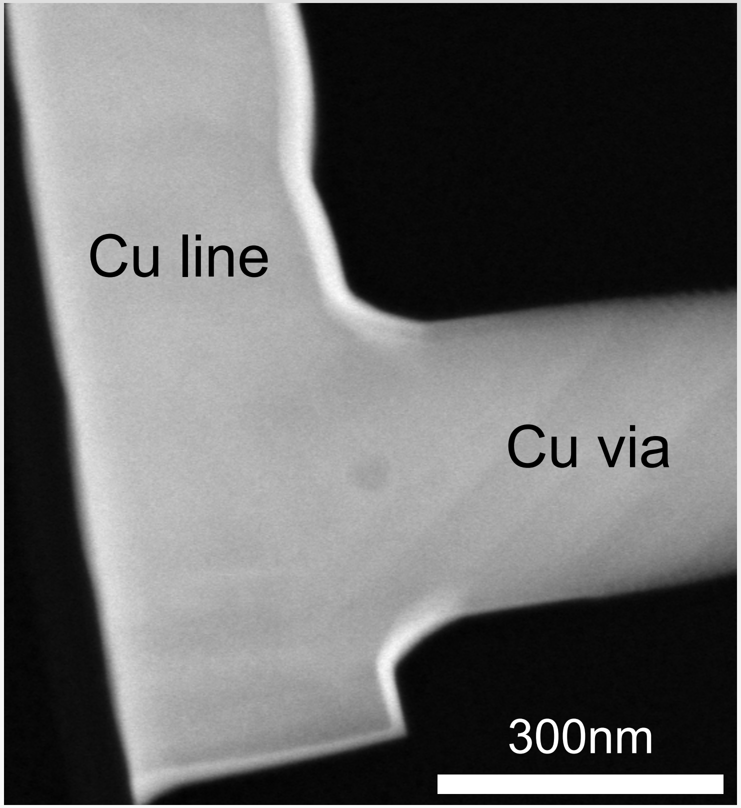


- Depth information from focal series does not add to depth resolution
- Tomography resolution: experiment is 1-2nm (Why!?)
  - Tomography yields 10x worse resolution in practice
    Alignment, stage movement (low mag)

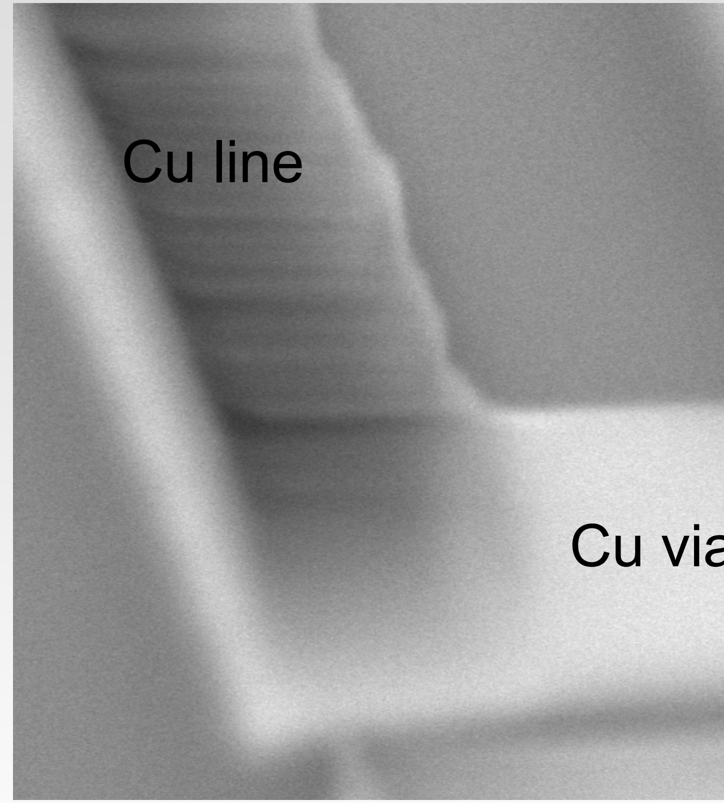
Conclusions: Tomography & Correctors

- ***Electron Tomography***
  - Quantitative measurements of 3D objects
  - Incoherent Bright Field (IBF) STEM
    - high ρ*Z and *t*
- ***Impact of Correctors***
  - Improved lateral and depth resolution
  - Focal and Tilt series
    - necessary for corrected instruments
    - 3x fewer tilts needed → Faster!
  - Resolution limits
    - No considerable increase in resolution predicted
    - Tilt stage quality, alignment, blurring

Contrast Reversal with Thickness

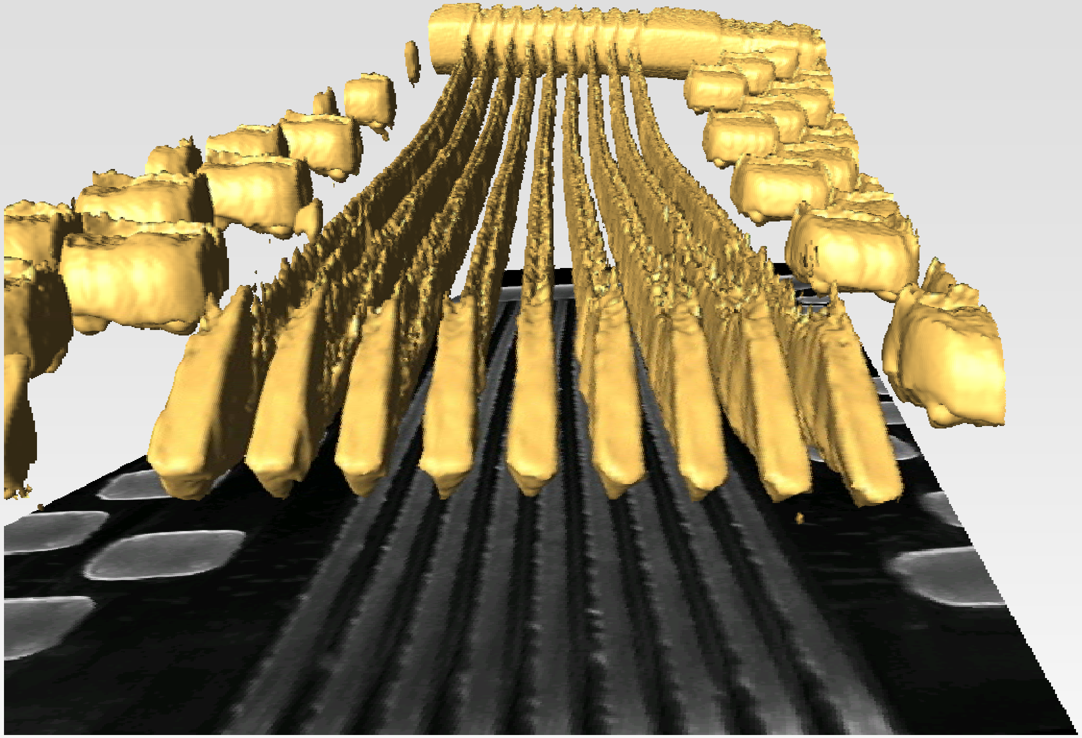


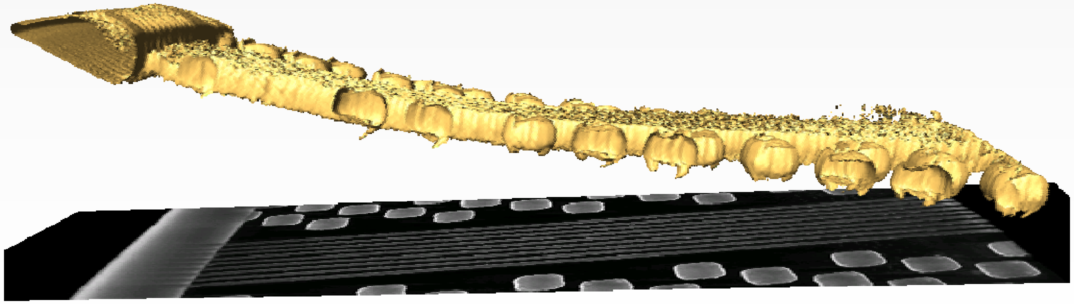
- HAADF STEM
- 0° tilt



- HAADF STEM
- 70° tilt

Cu lines: Planview



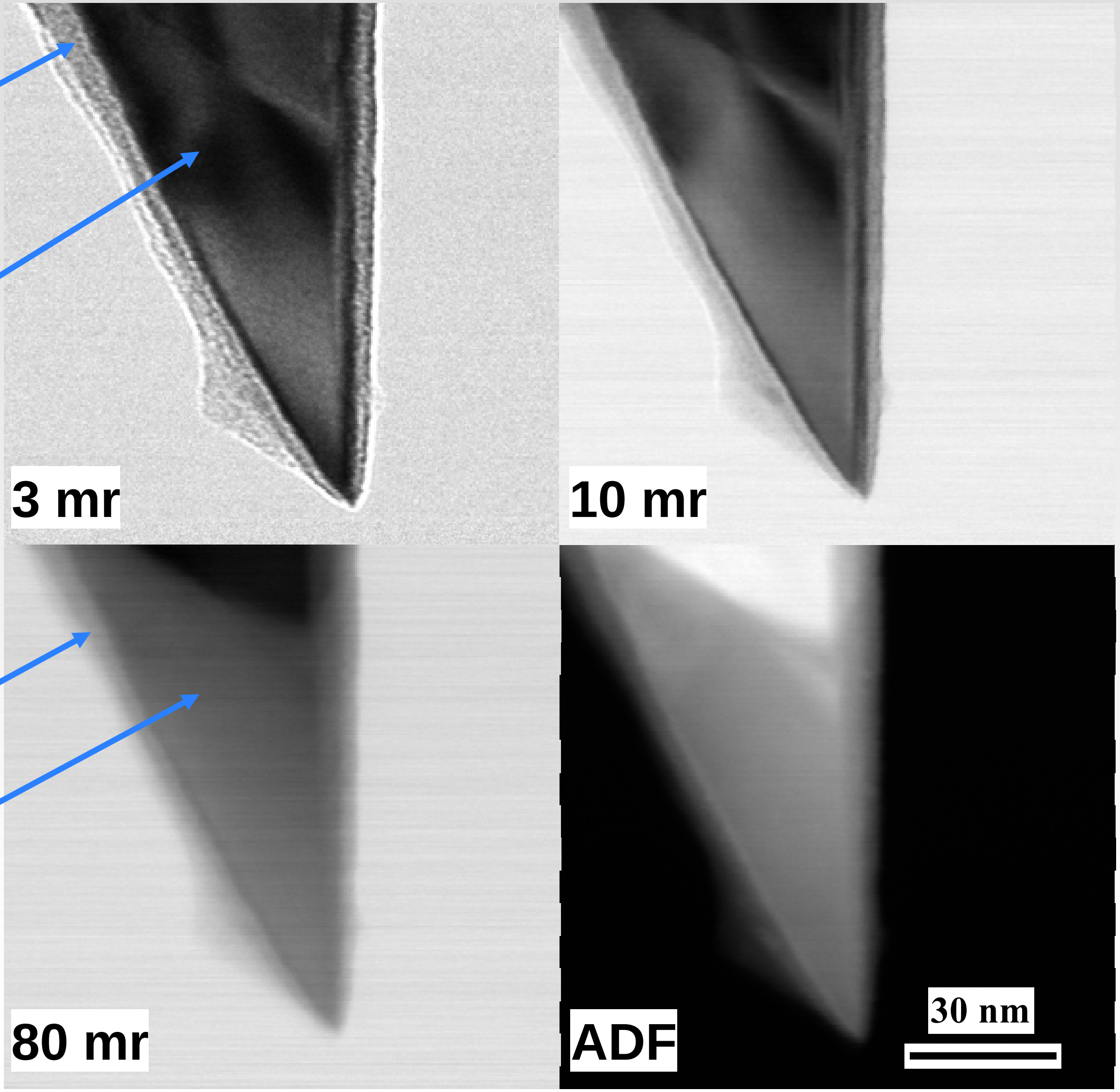


Peter Ercius, Cornell University

Increasing the Collector Angle (θ_c)

$\theta_c << \theta_{obj}$

- Phase contrast
- Diffraction contrast



$\theta_c \approx \theta_{obj}$

- No Phase contrast
- Diffraction contrast

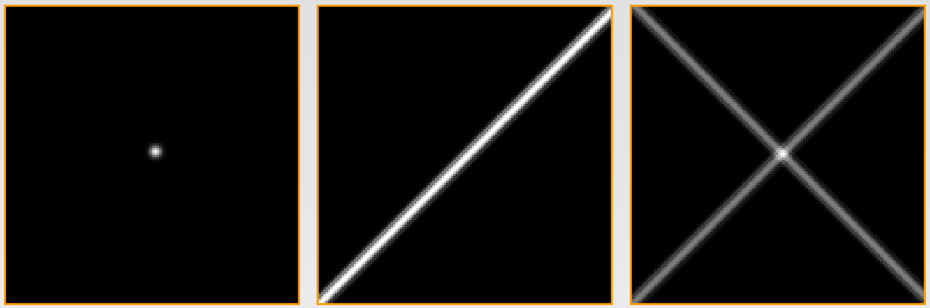
$\theta_c >> \theta_{obj}$

- No Phase contrast
- No Diffraction contrast

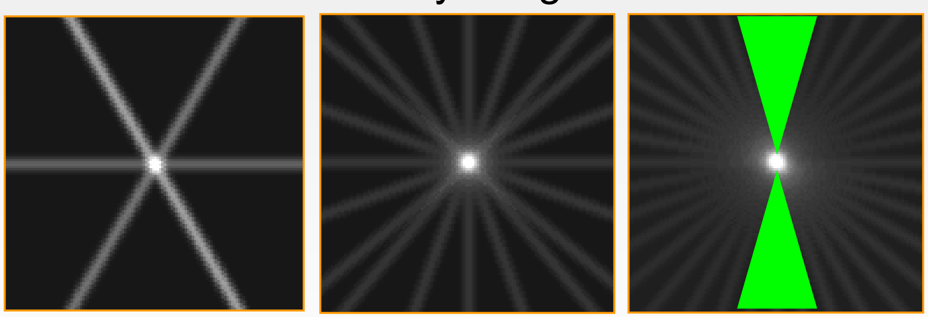
The incoherent BF image is the complement of the ADF image

Fourier Reconstruction

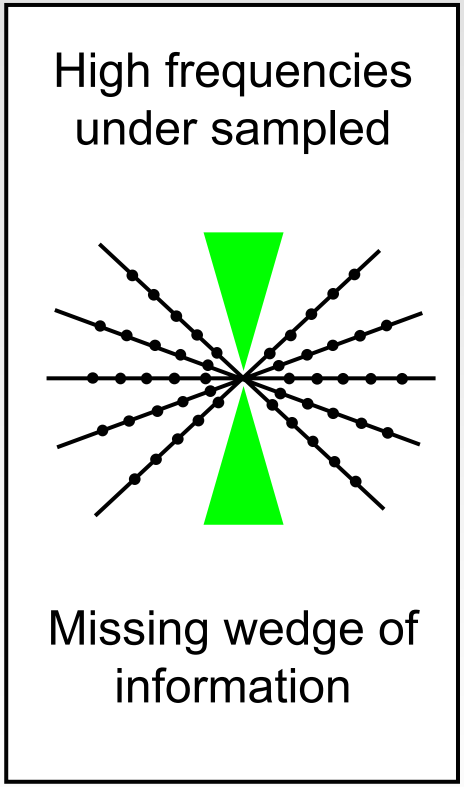
"A 2D projection of a object is equivalent to a 2D slice through the Fourier transform of that object at the angle of projection."



Object | 1 projection: the 'ray-integral' | 2 projections

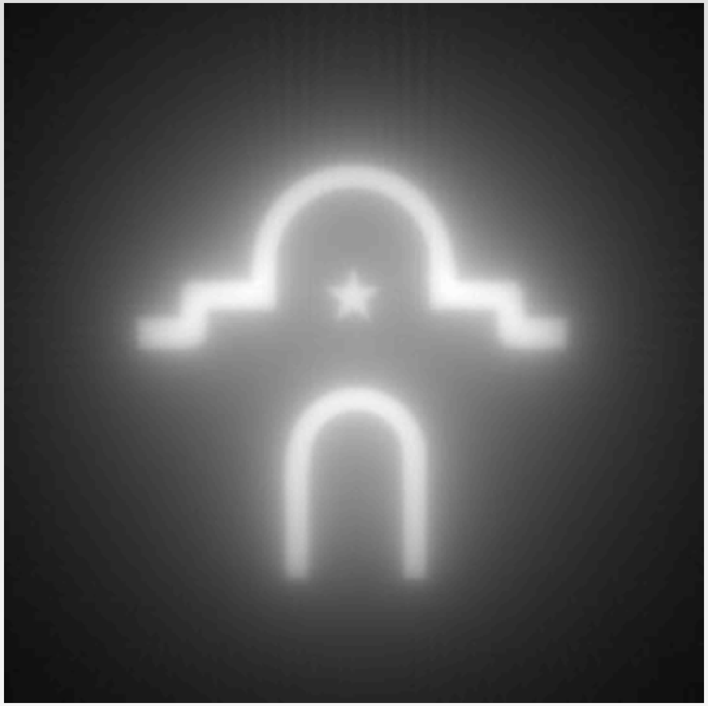


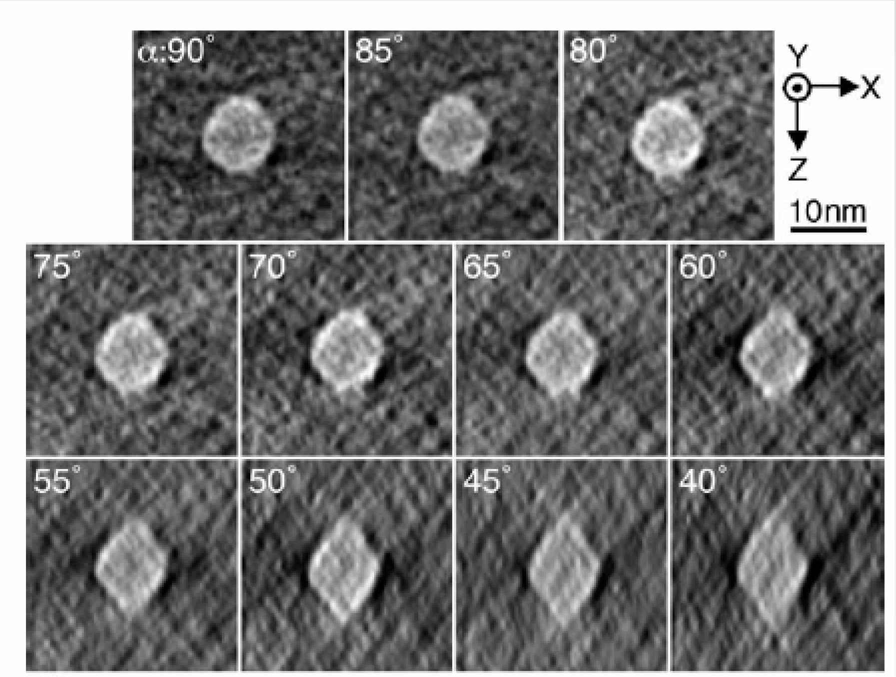
3 projections | 10 projections | 32 projections



Weighted backprojection: Backprojection can be made more accurate by restoring the correct distribution of the spatial frequencies using a weighting filter.

Tomographic Reconstruction





Under sampling

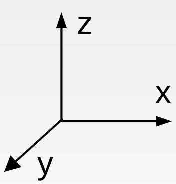
Yields a blurred reconstruction

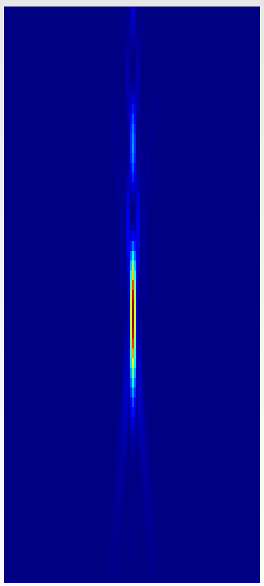
Missing wedge

Features perpendicular with the tilt axis are distorted

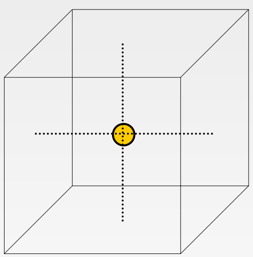
Z-contrast Simulation Method

PSF	$\delta(x, y, z)$	Focal Series
39 depth slices Depth: 5.1 Å/slice Lateral: .2 Å/pixel	$(100\text{Å})^3$	20 depth slices Δf: 5 Å

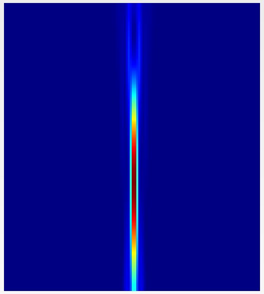




$\otimes$

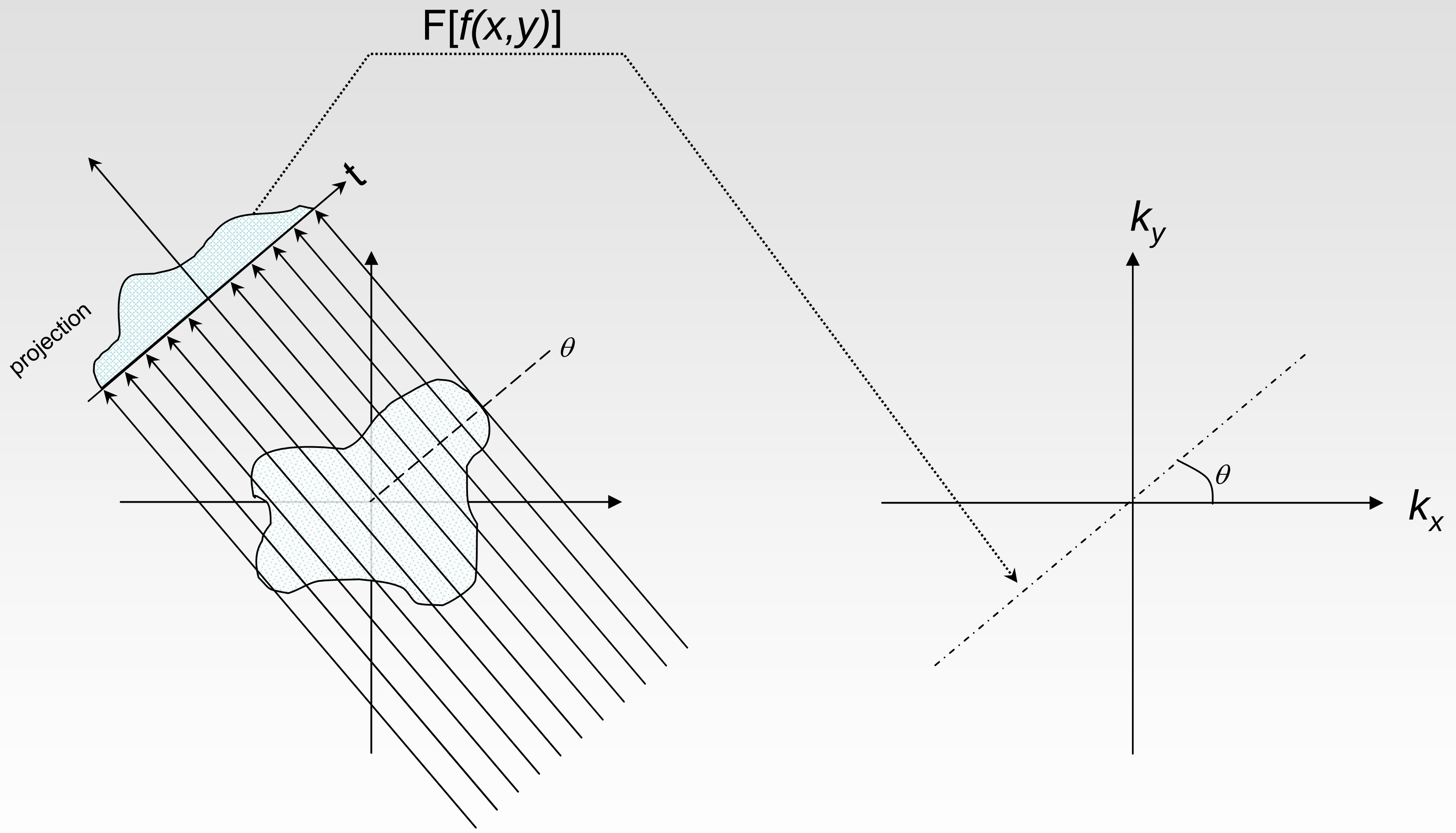


$=$



3D incoherent Z-contrast STEM imaging simulation

Fourier Slice Theory



Real space

Frequency space

Aberration Correctors

- Lens aberrations create phase shifts for e-'s incident at different angles

$$\chi(\alpha)=\frac{2\pi}{\lambda}\left(-\frac{1}{2}\Delta f\alpha^2+\frac{1}{4}C_3\alpha^4+\frac{1}{6}C_5\alpha^6+\frac{1}{8}C_7\alpha^8+\cdots\right)$$

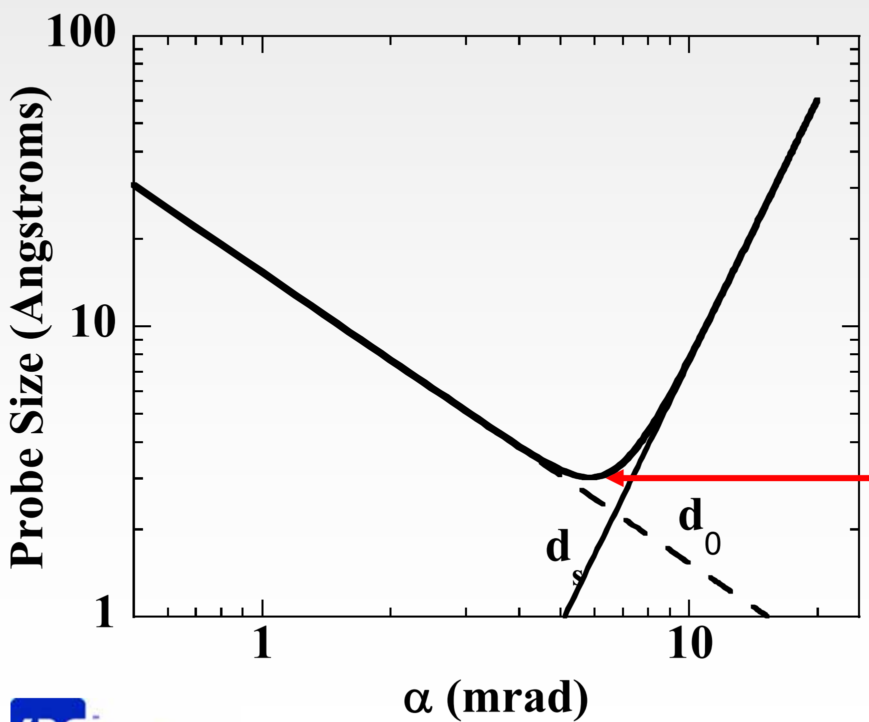
$$\chi_{\max}=\pi/2$$

- For given C-values…maximize α to maximize resolution
  - Including depth resolution Δz

$$\Delta z \propto \frac{1.22\lambda}{\alpha^2}$$

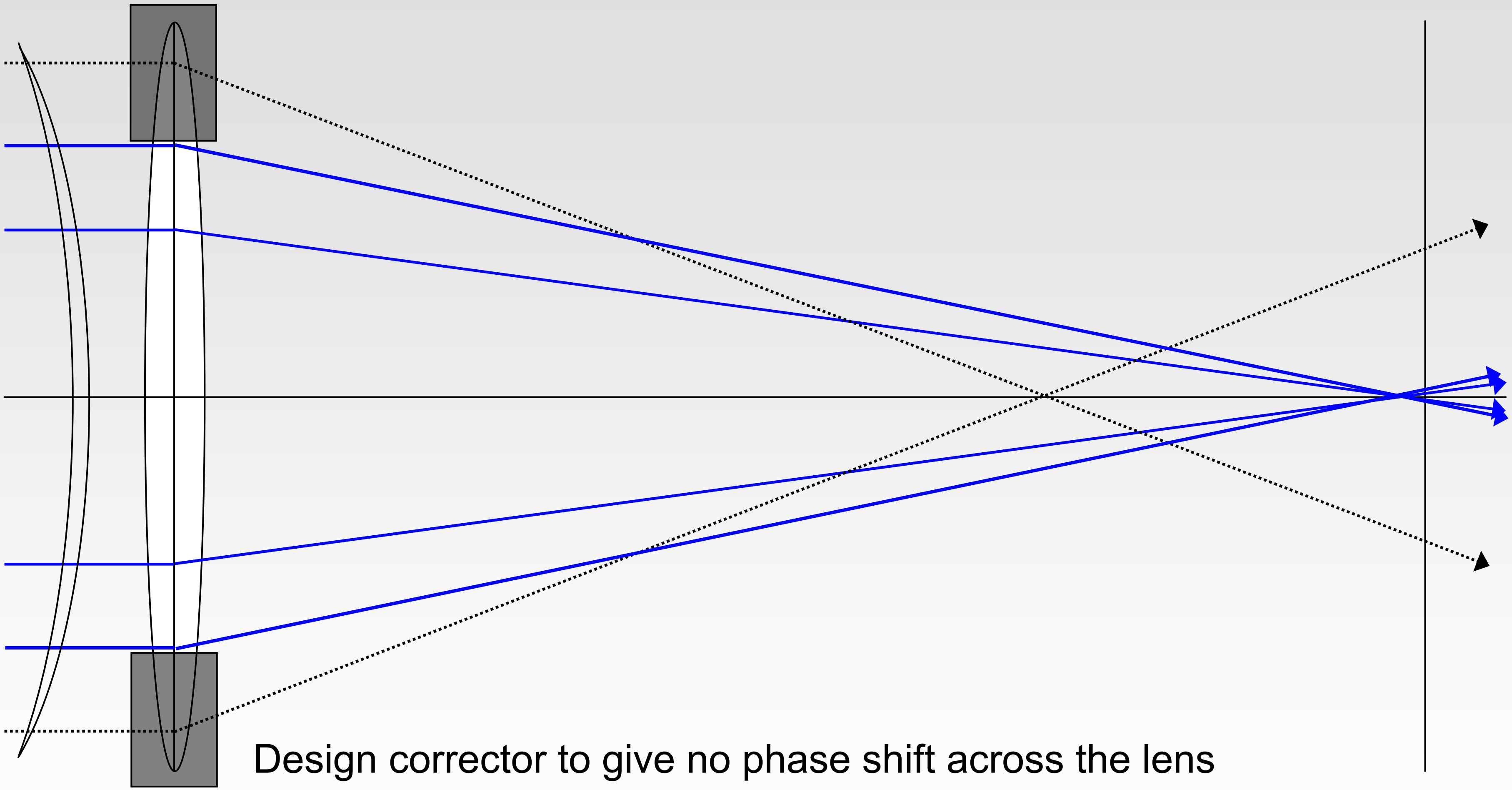
Balance Spherical Aberration Against Diffraction

- Balance sperical aberration against the aperture's diffraction limit
  - Less diffraction with a large aperture – must be balanced against C3
- For a rough estimate of the optimum aperture size, convolve blurring terms
  - Add in quadrature: $d_{tot}^2 \approx d_0^2 + d_s^2$



Optimal aperture
And minimum
Spot size

Electron Lens Aberration Correctors



Design corrector to give no phase shift across the lens
There are other higher order aberrations that limit resolution
Lens aberrations are a power series that does not converge
You can correct C3 but C5 limits you, correct C5 but C7 limits you, etc…