Three-Dimensional Imaging with Atomic Resolution in Phase TEM

- ***Migrating Nano-Science Toward Nanotechnology of Energy Saving Windows and E-paper***

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奈米物理特論, 物理館019教室, 12/24/2009

Better electron microscopes

NTHU

It would be very easy to make an analysis of any complicated chemical substance; all one would have to do would be to look at it and see where the atoms are.

The only trouble is that the electron microscope is one hundred times too poor.

Develop new tool to discover new science !

-Richard F. Feynman
-12.29.1959 American Physics Society, CIT

My talk will cover

(a) Toward atomic resolution tomography (Dirk Van Dyck and Christian Kisielowski)

(b) Development of "phase (plate)/ wet cell TEM"

(c) Migration from nano-science toward nano-technology: Smart Window for Energy Saving and e-paper

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- scaling up the nano-materials

hypothesis of deBroglie (1929, Nobel Prize)

Particle-Wave Duality

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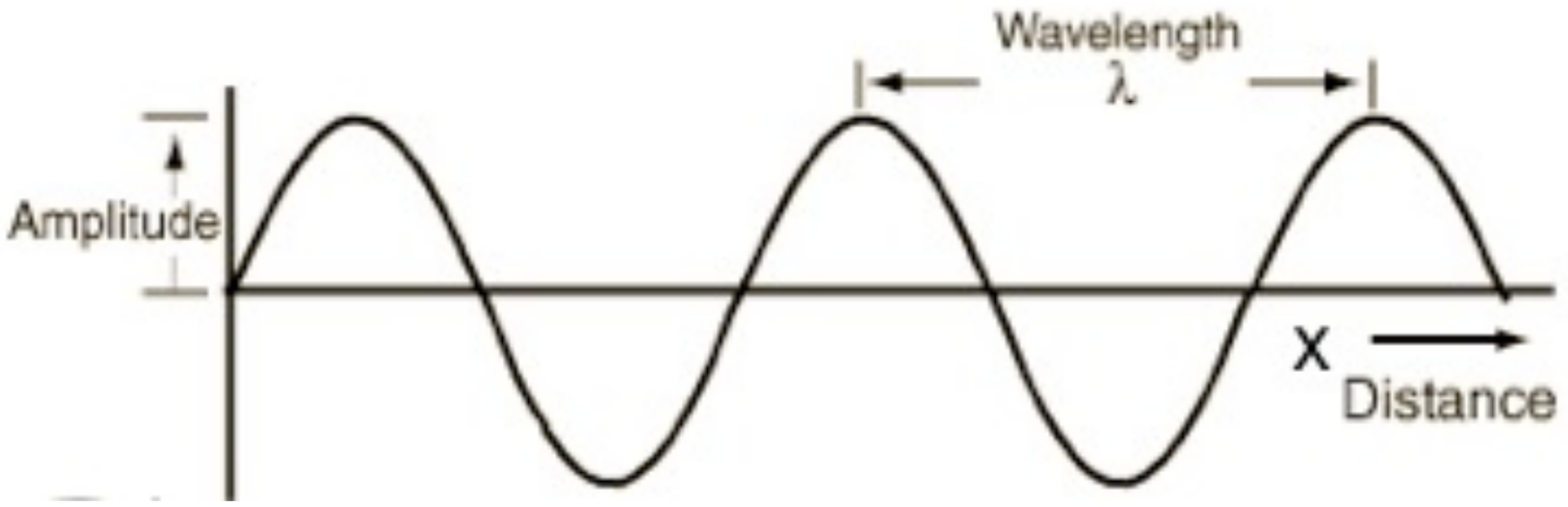
Particle-Wave Duality



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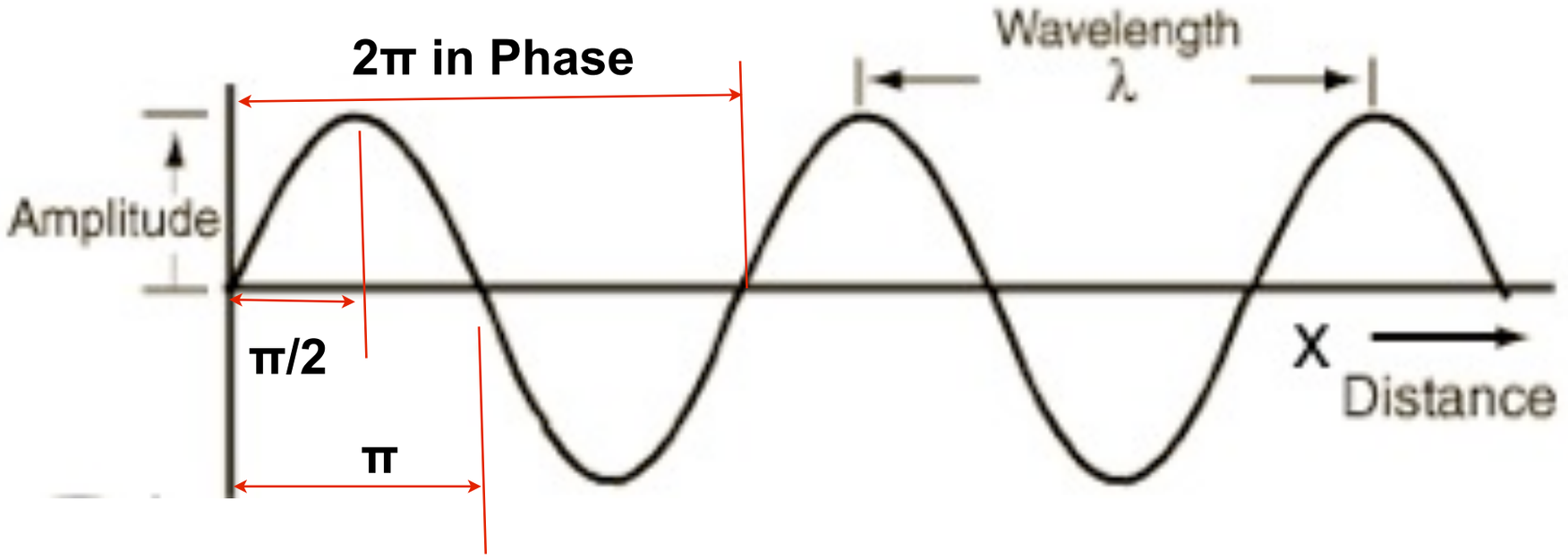

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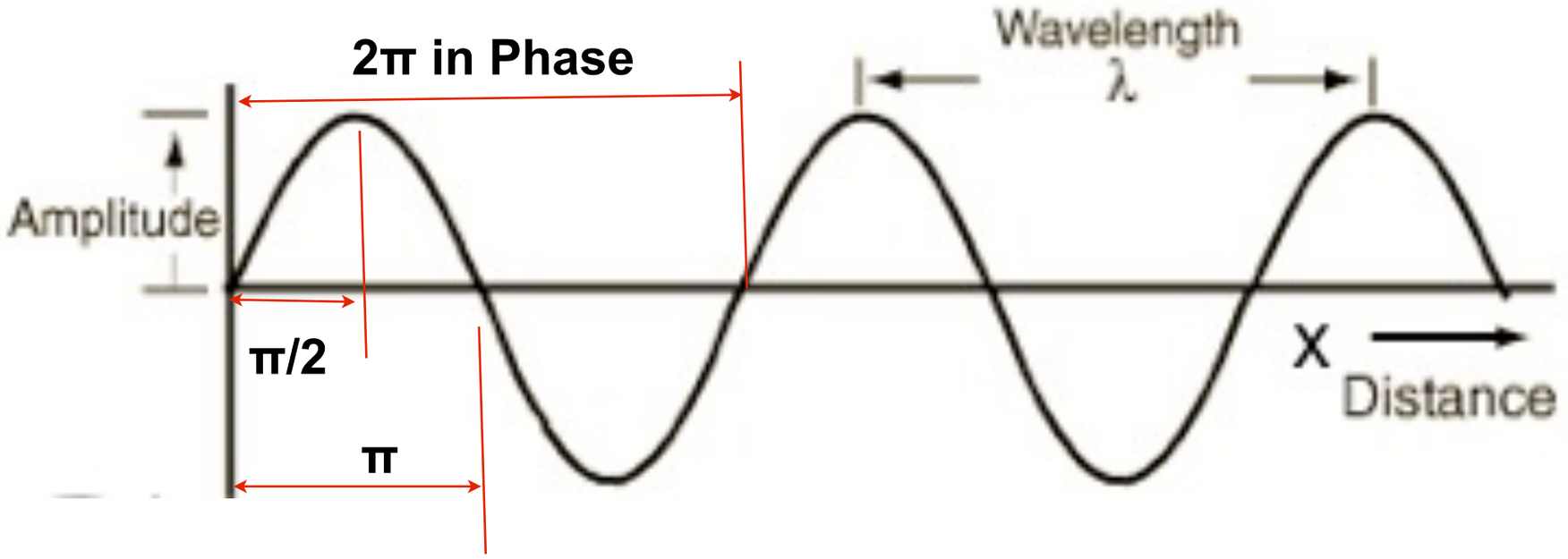
Particle-Wave Duality

$$\psi = A\sin(2\pi x/\lambda - \omega t) \quad \text{or} \quad \psi = A\sin(kx - \omega t)$$

Amplitude

Phase



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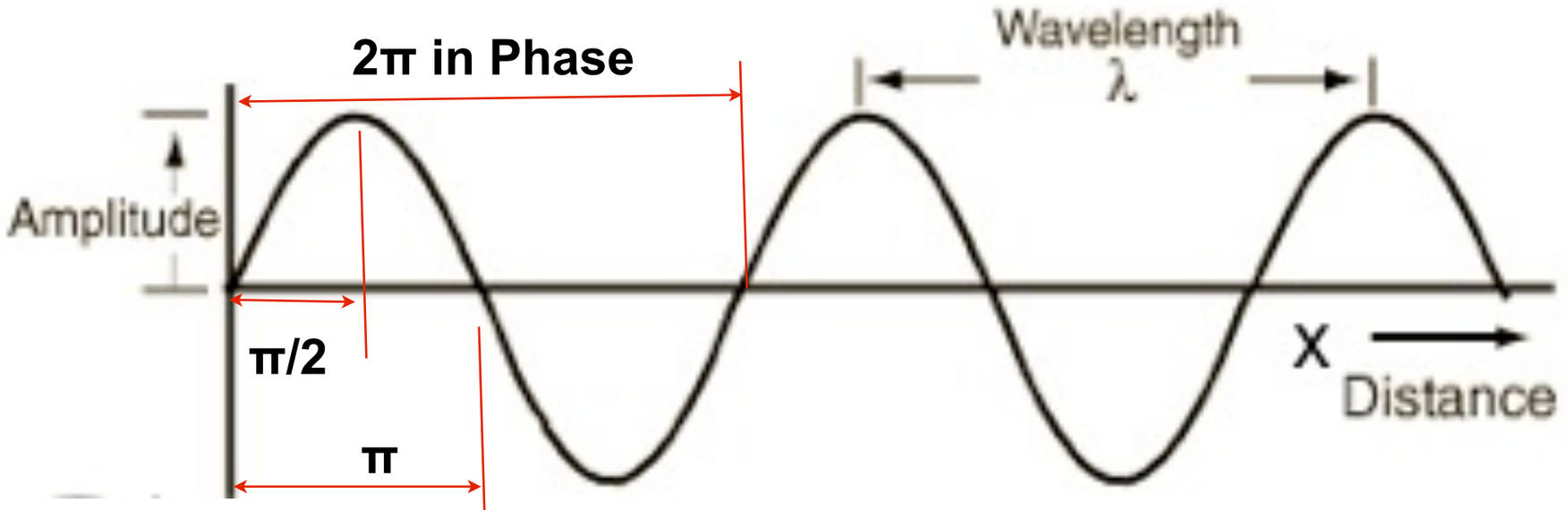

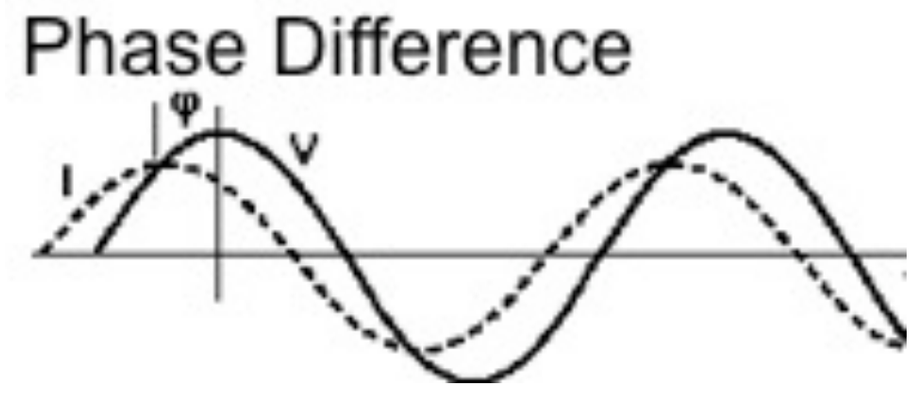

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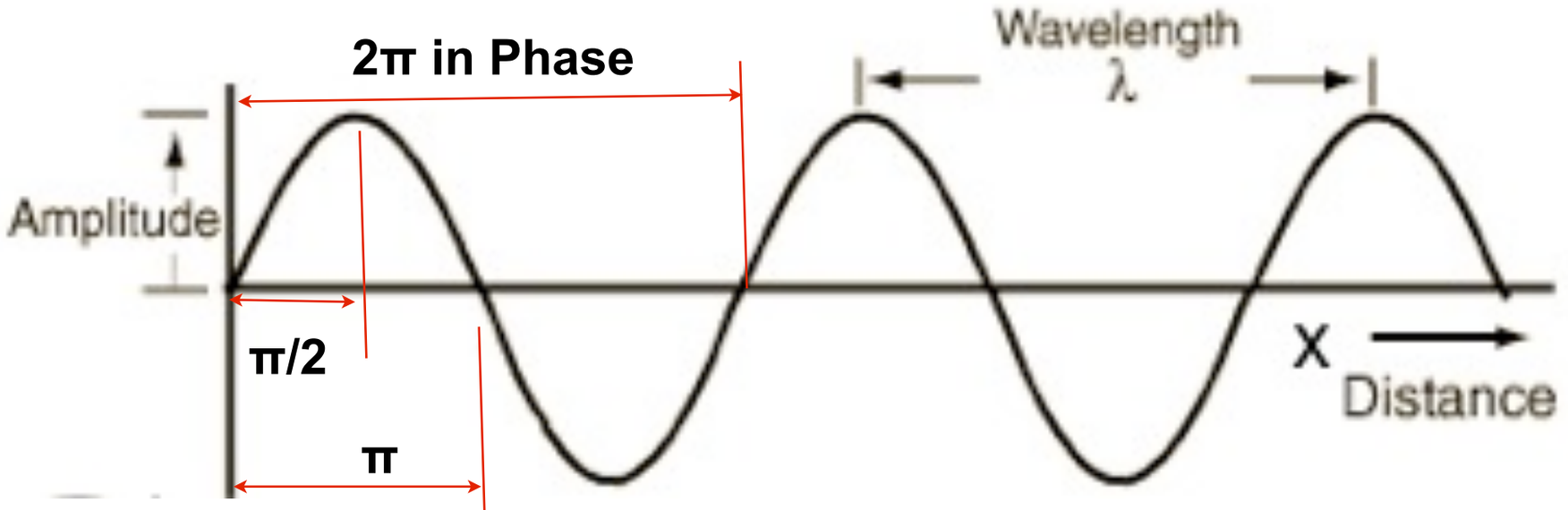
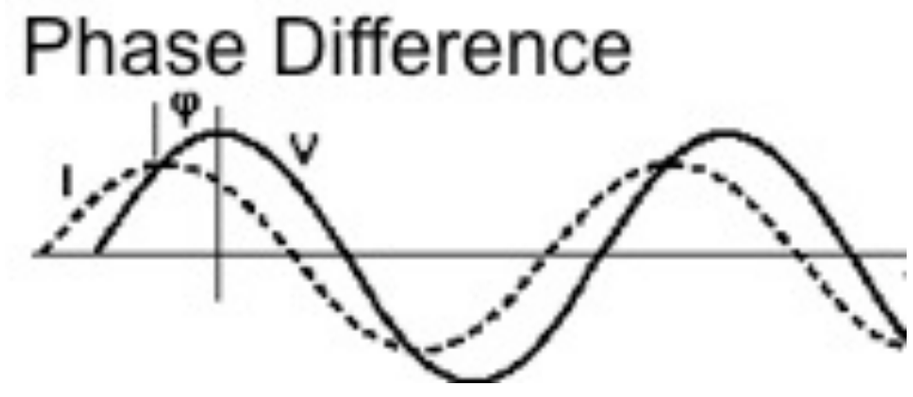
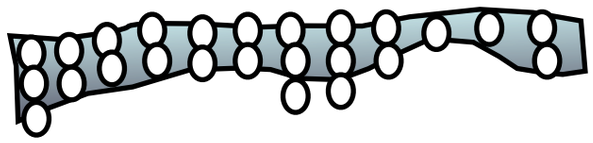




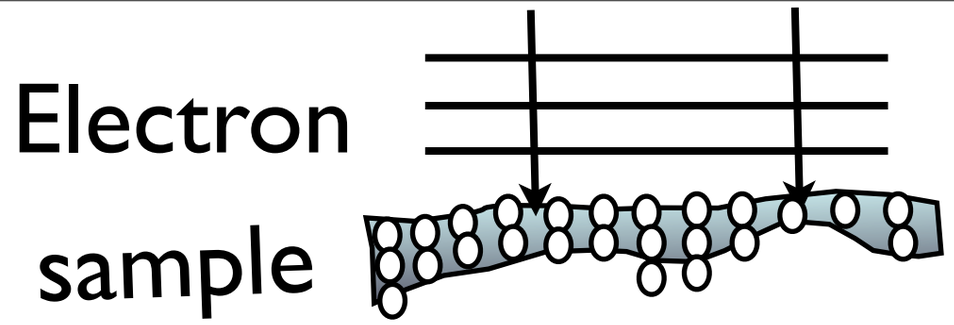
$$I = \psi\psi^* = |A|^2$$

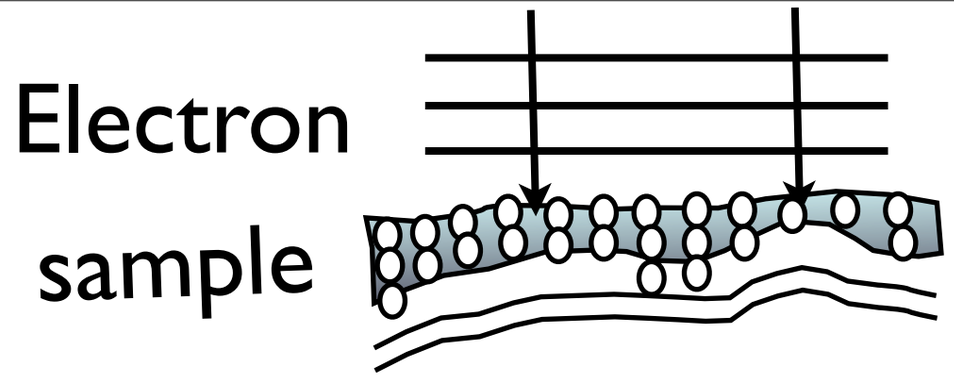
(a) Toward atomic resolution tomography

Phase Problem in TEM

sample 

Phase Problem in TEM



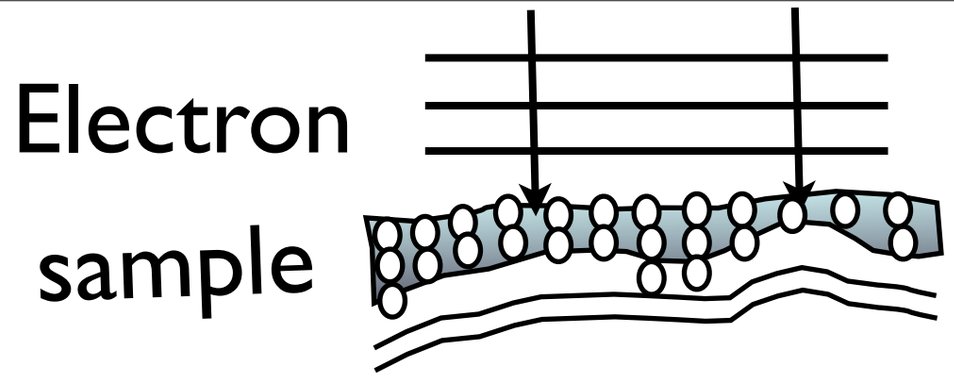


Phase Problem in TEM

Dynamics scattering

exit wave $\Psi=A\exp(-i\phi)$

Phase Problem in TEM



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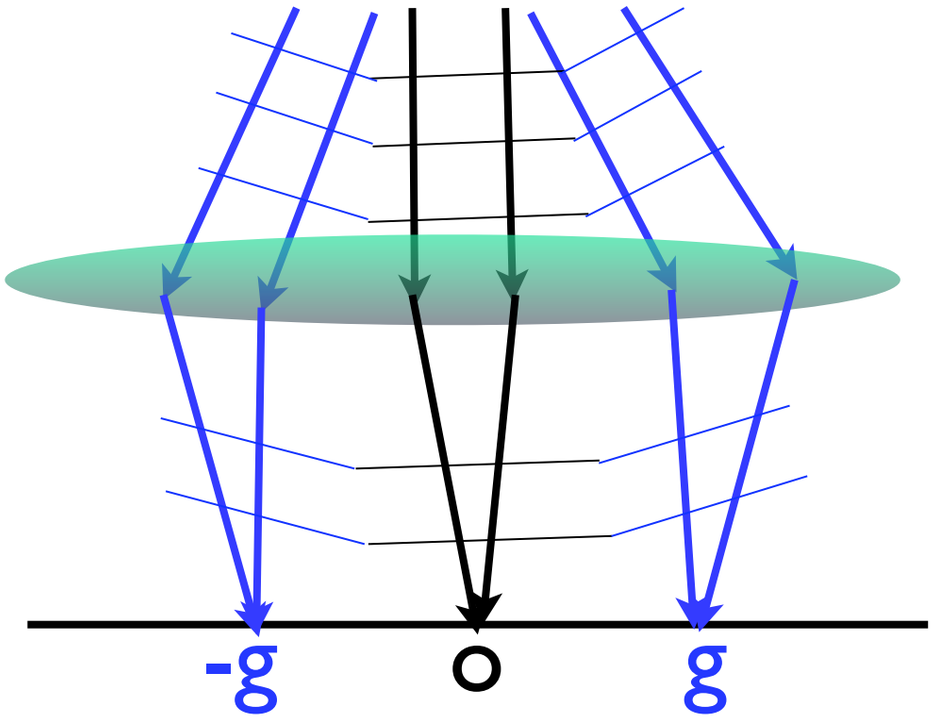

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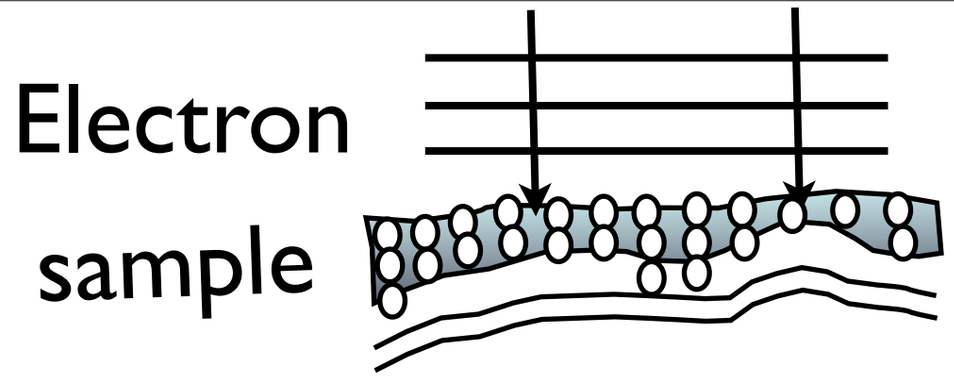

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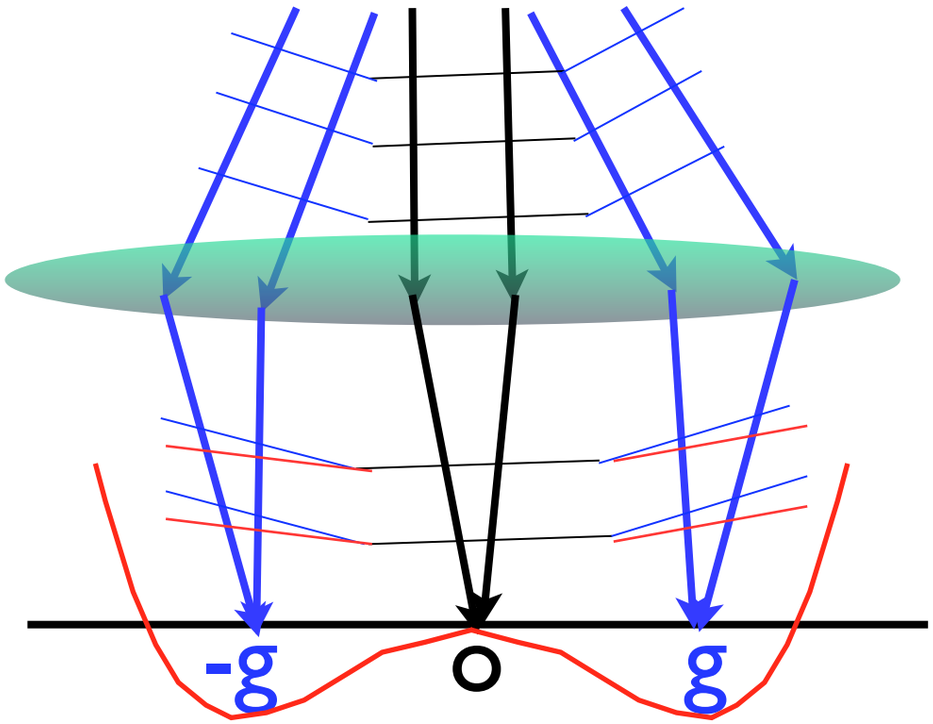
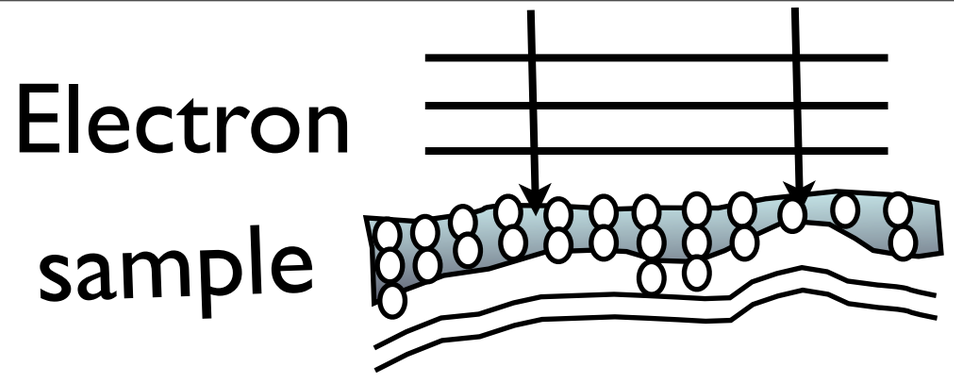


Lens Aberration

phase plate

$$\chi = \pi\lambda\Delta f g^2 + \frac{\pi}{2} C_s \lambda^3 g^4$$

Phase Problem in TEM



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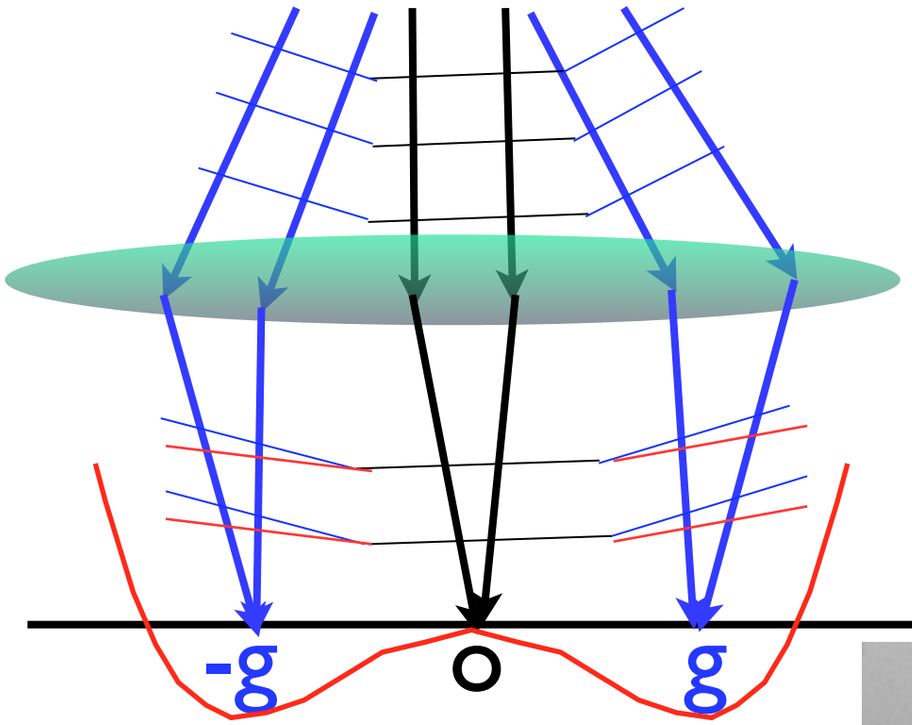

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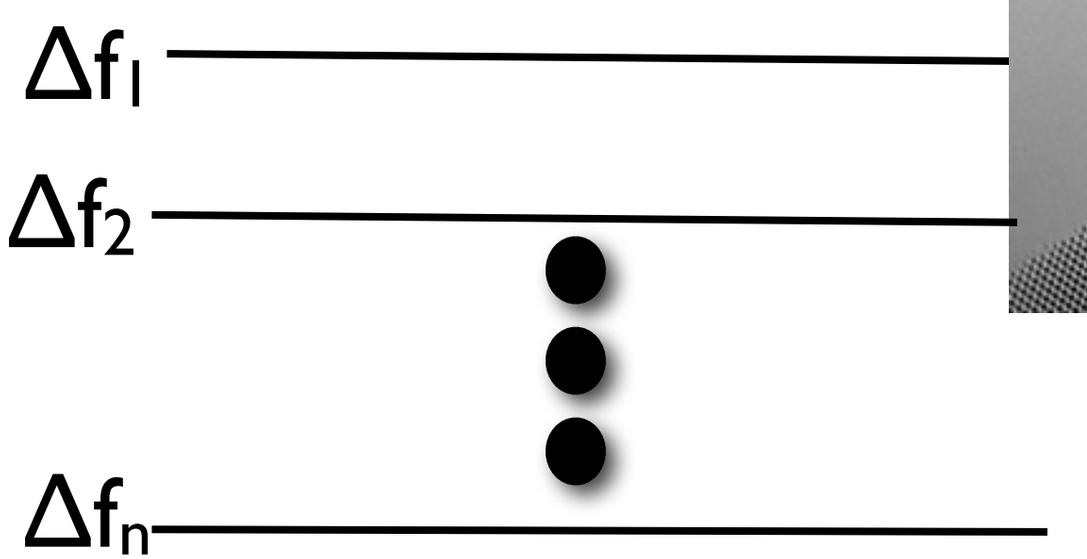

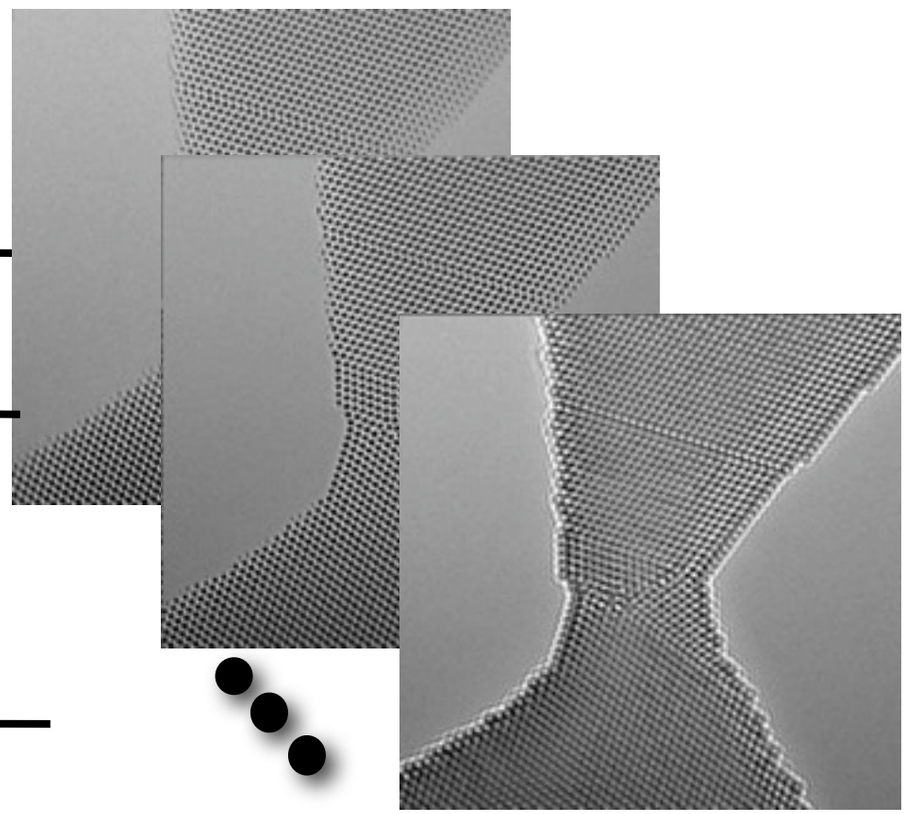

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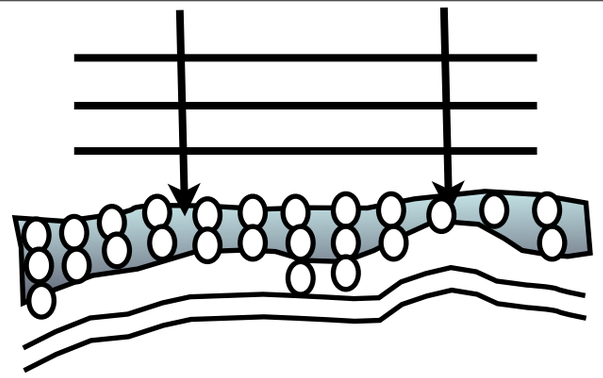

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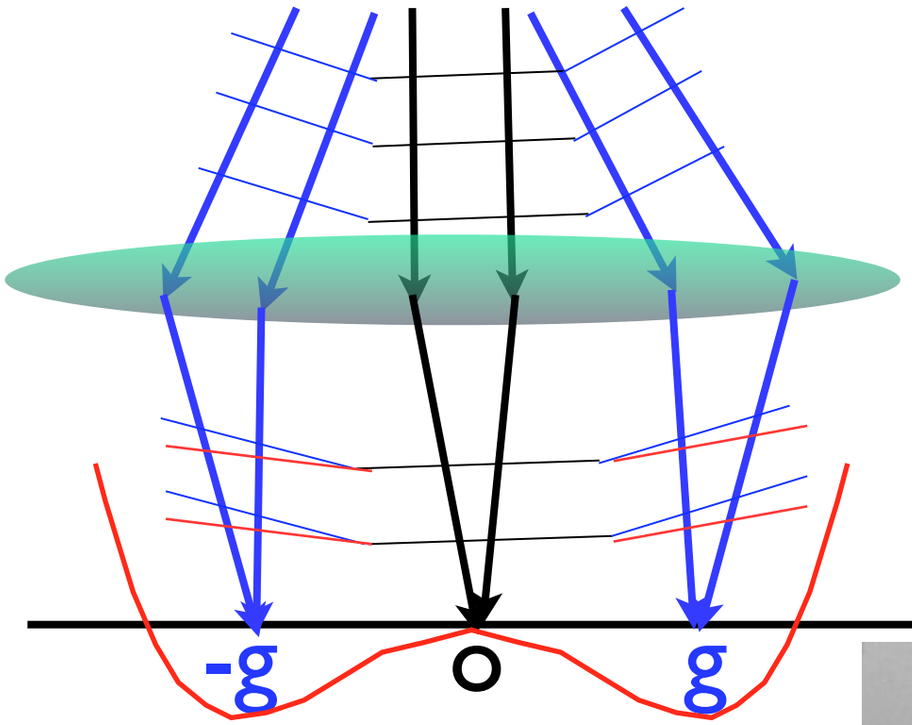


Lens Aberration

phase plate

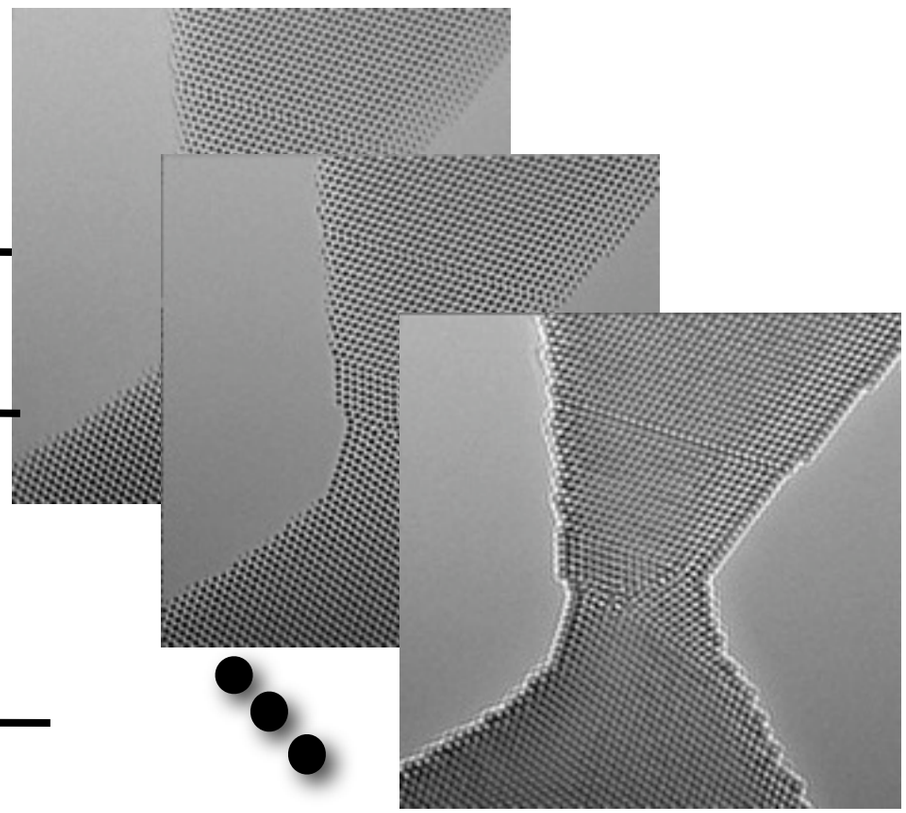
$$\chi = \pi\lambda\Delta f g^2 + \frac{\pi}{2} C_s \lambda^3 g^4$$

Fourier
Transform
(linear Image)

Δf_1

Δf_2

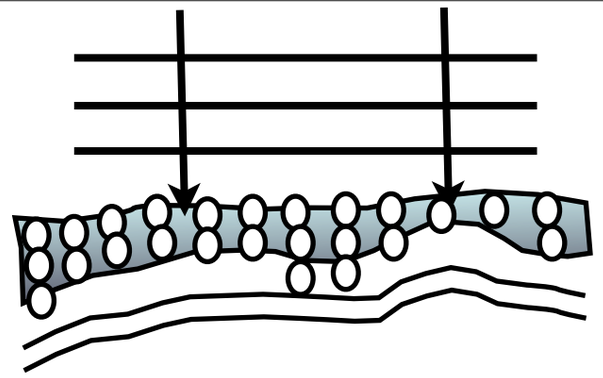
Δf_n



Phase Problem in TEM

Electron

sample



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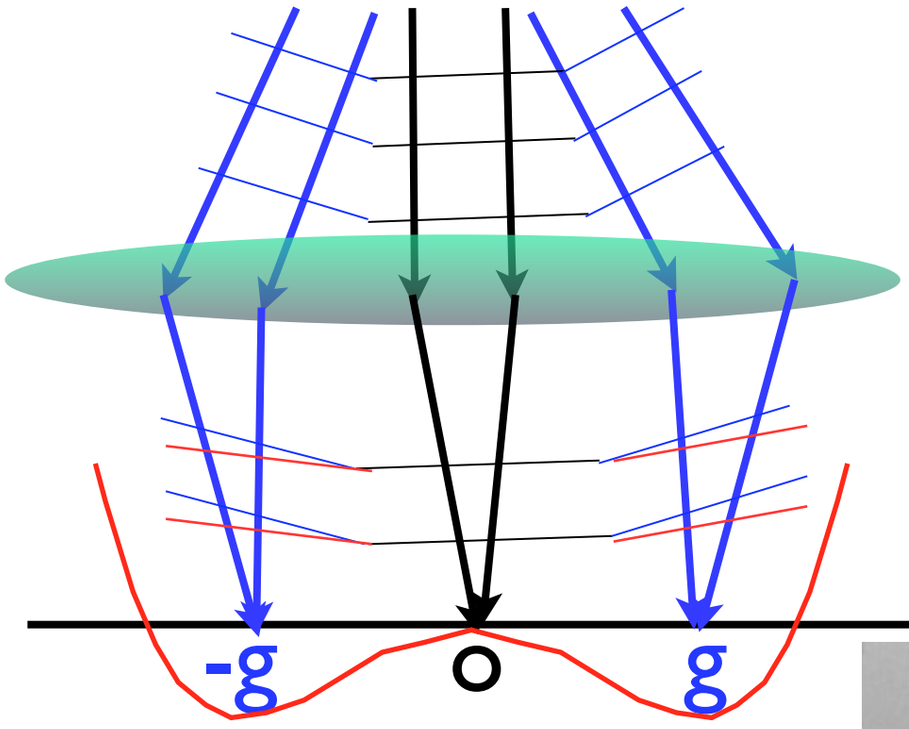

Lens Aberration

phase plate

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Phase Lost

I(g)

Fourier

Transform

(linear Image)

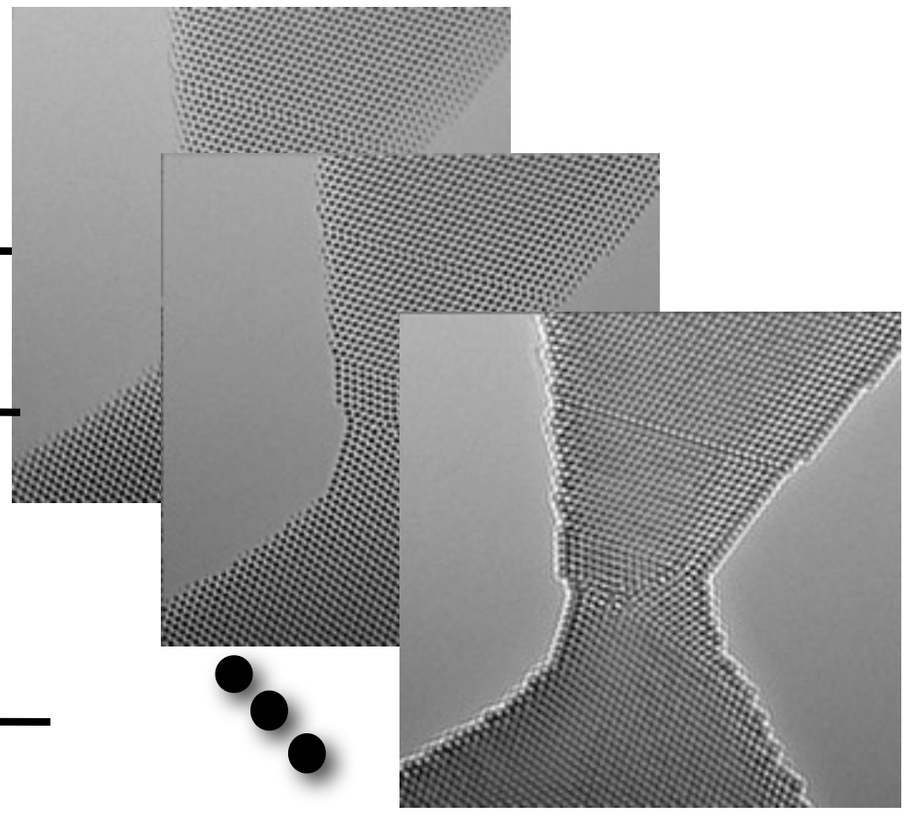
Phase Lost

I(r)

Δf_1

Δf_2

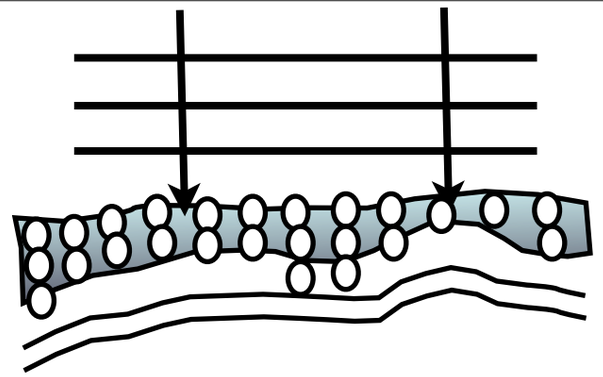
Δf_n



Phase Problem in TEM

Electron

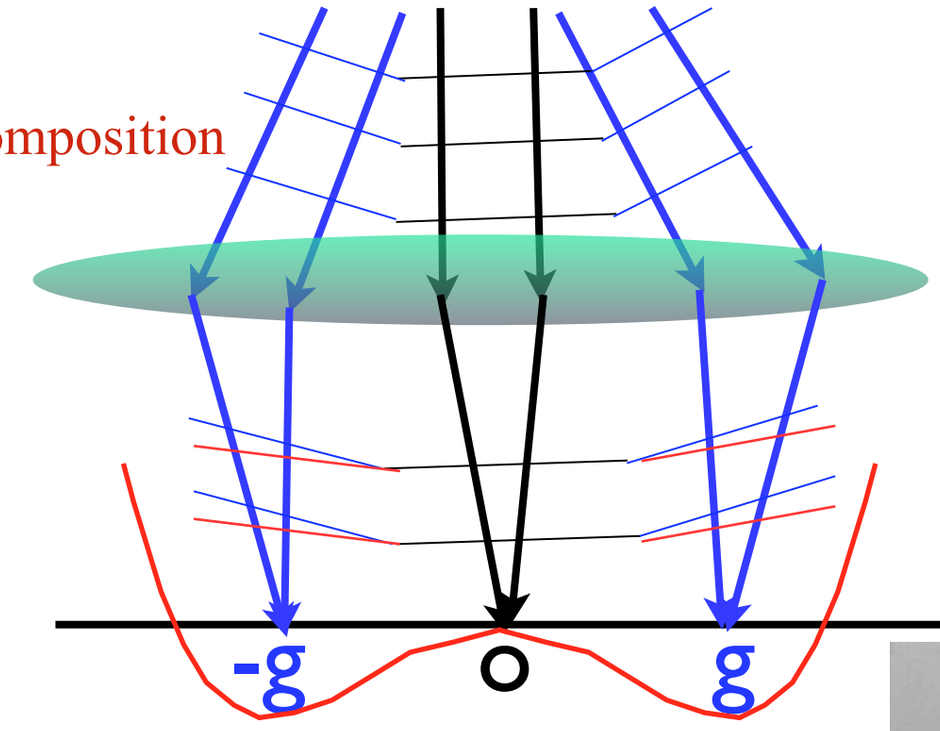
sample



Dynamics scattering

exit wave $\Psi=A\exp(-i\phi)$

1. Atomic structure is heavily encoded in images
2. Little information about composition and thickness(
3. 2-D projection



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phase plate

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Phase Lost

I(g)

Fourier Transform (linear Image)

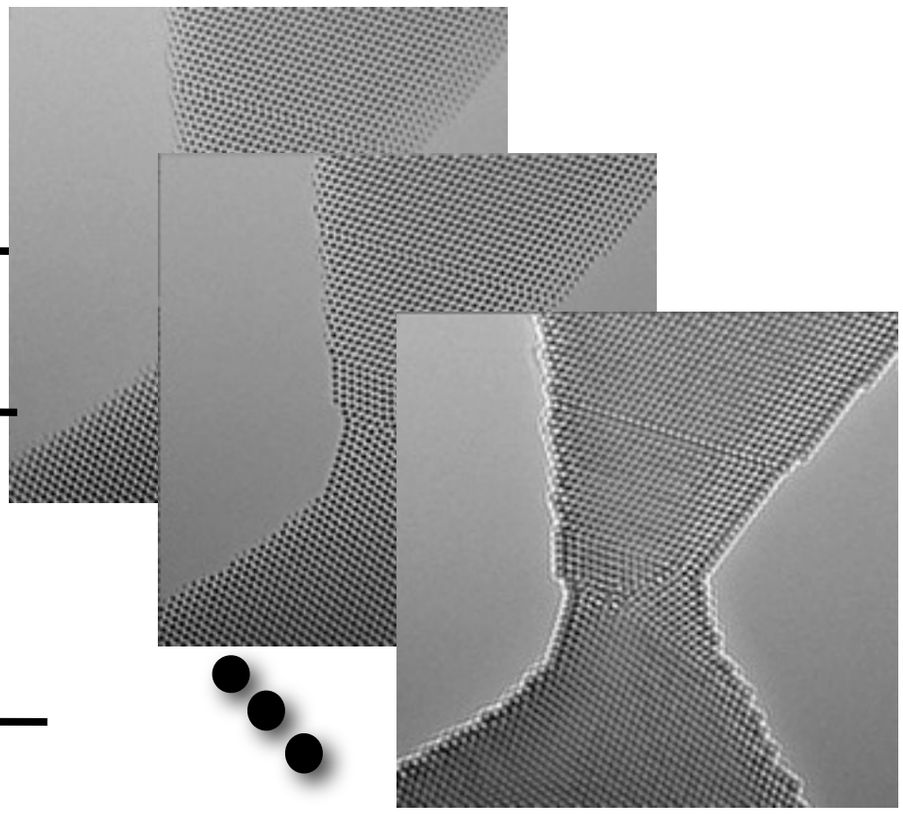
Phase Lost

I(r)

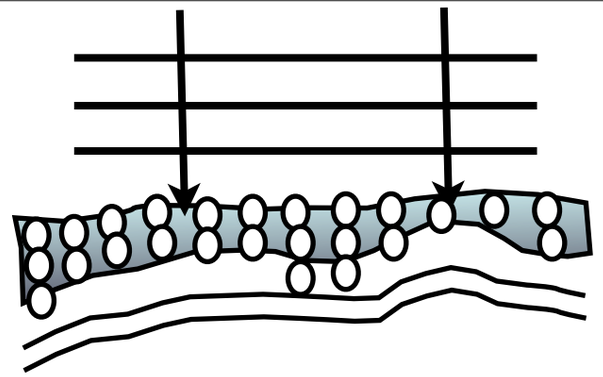
Δf_1

Δf_2

Δf_n



Phase Problem in TEM



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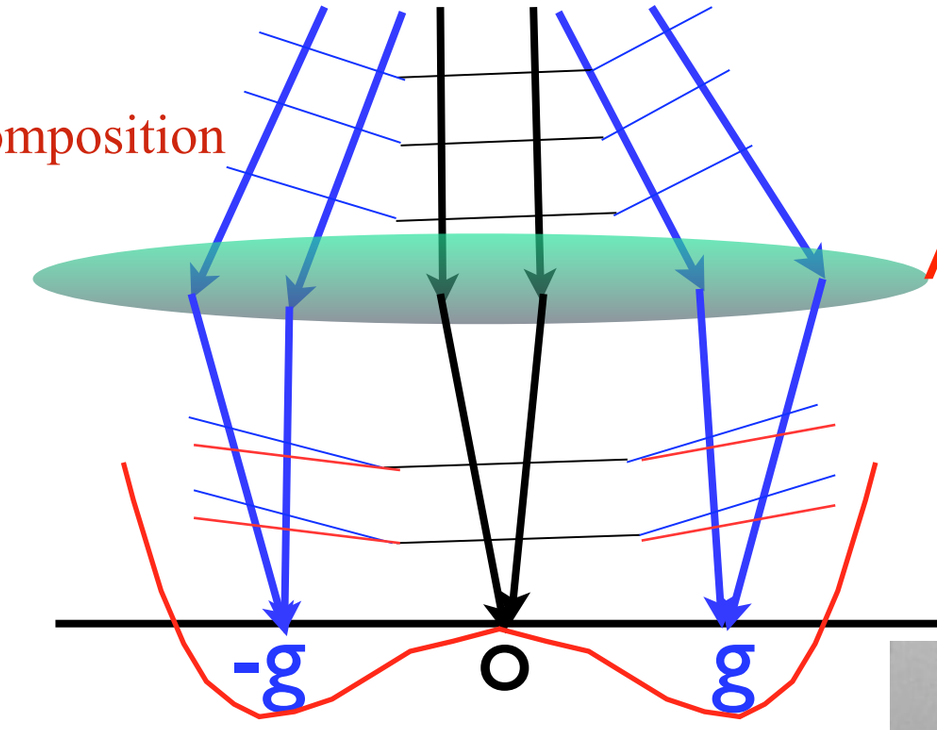


Aberration Corrector

phase plate → 0

$$\chi = \pi\lambda\Delta f g^2 + \frac{\pi}{2} C_s \lambda^3 g^4$$

Phase Lost

I(g)

Fourier Transform (linear Image)

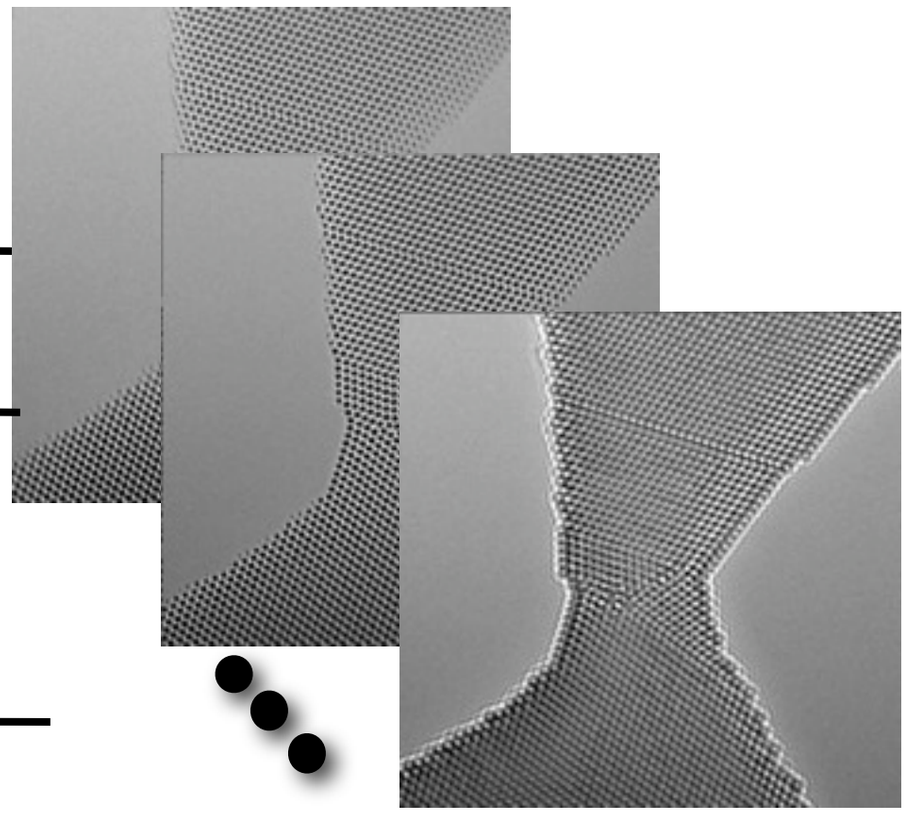
Phase Lost

I(r)

Δf_1

Δf_2

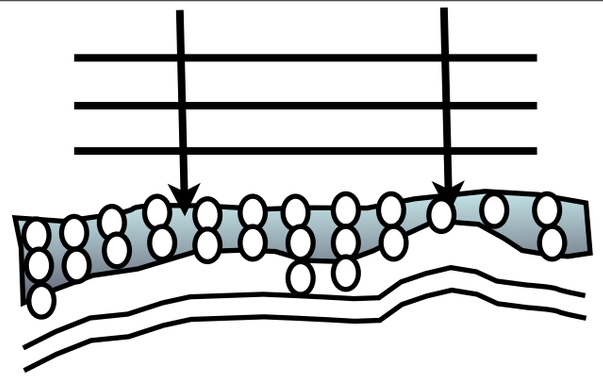
Δf_n



Phase Problem in TEM

Electron

sample

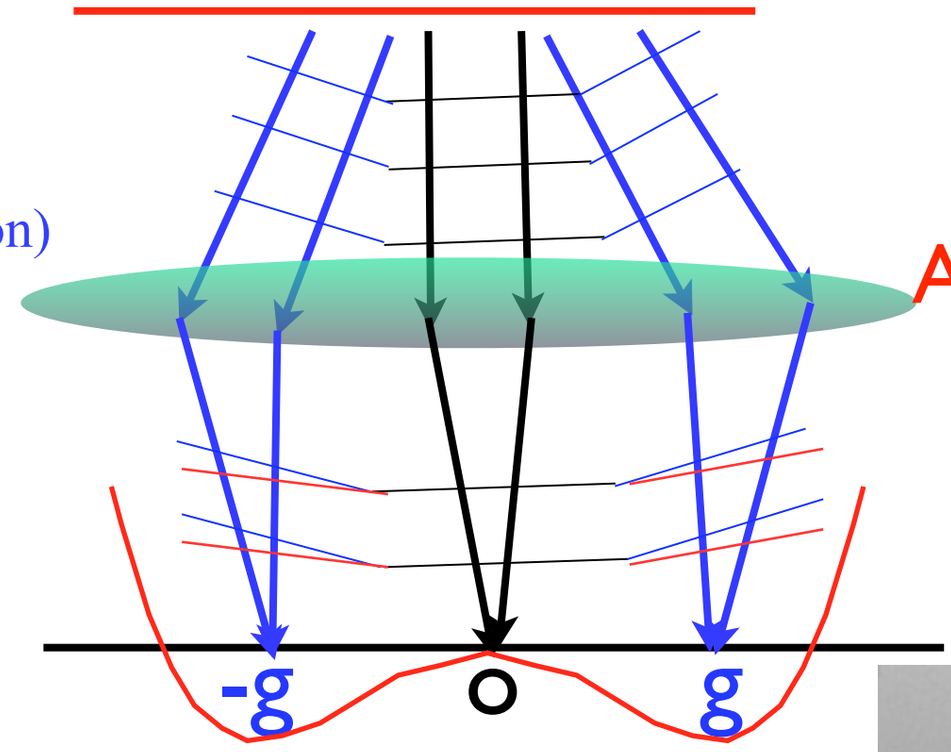


Dynamics scattering

exit wave $\Psi=A\exp(-i\phi)$

(aberration correction:

exit wave reconstruction)



Aberration Corrector

phase plate

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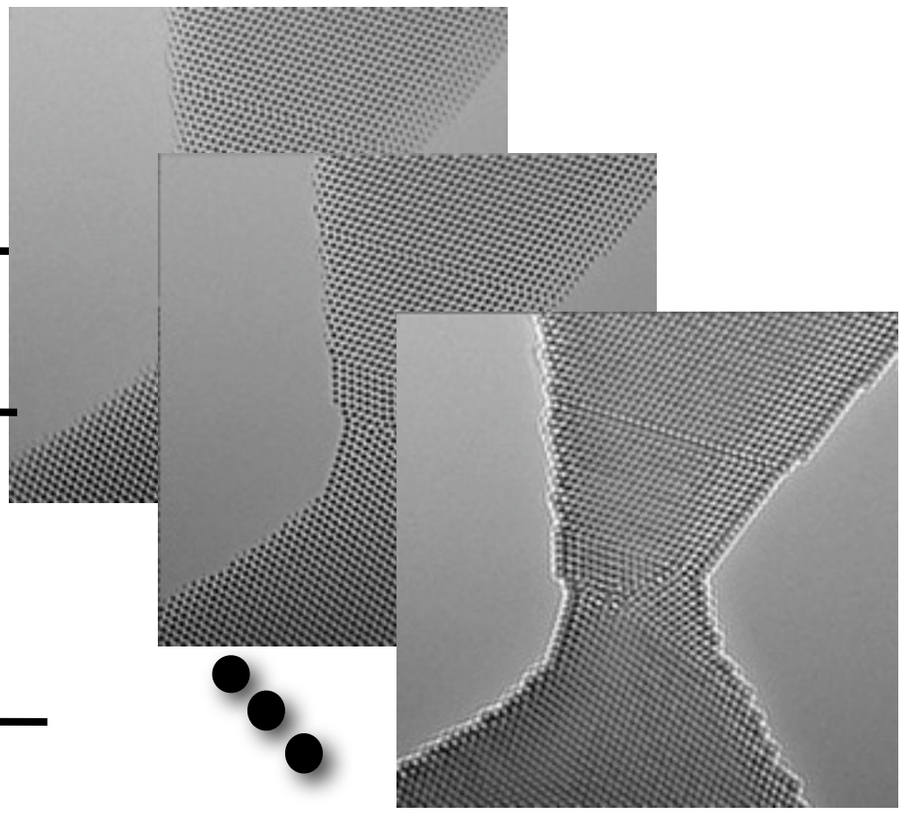
0

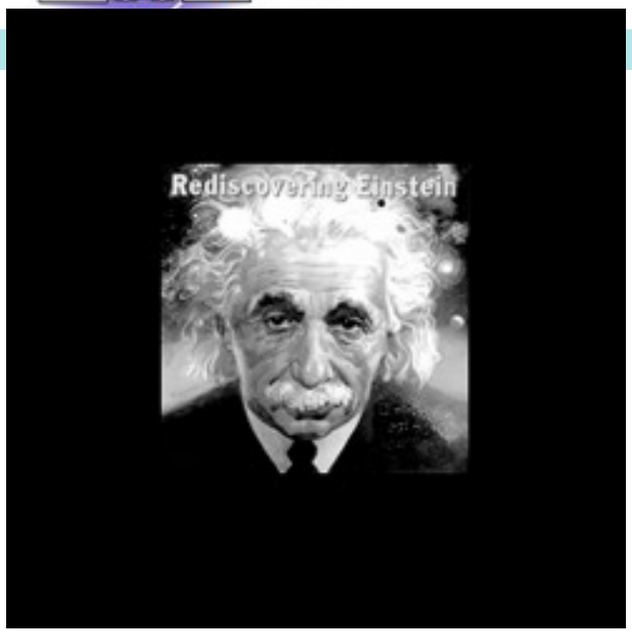
Δf_1

Δf_2

Δf_n



Phase Problem



object 1

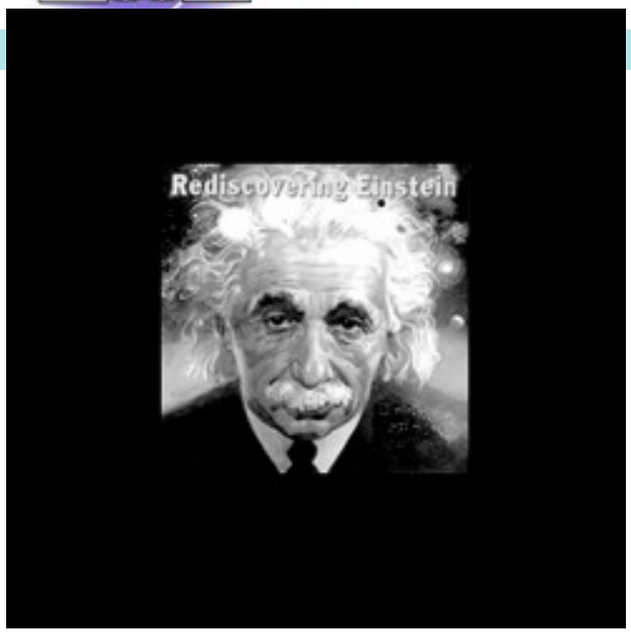
Diffraction Plane

image 1

Object 2

image 2

Phase Problem



object 1

FFT

Diffraction Plane

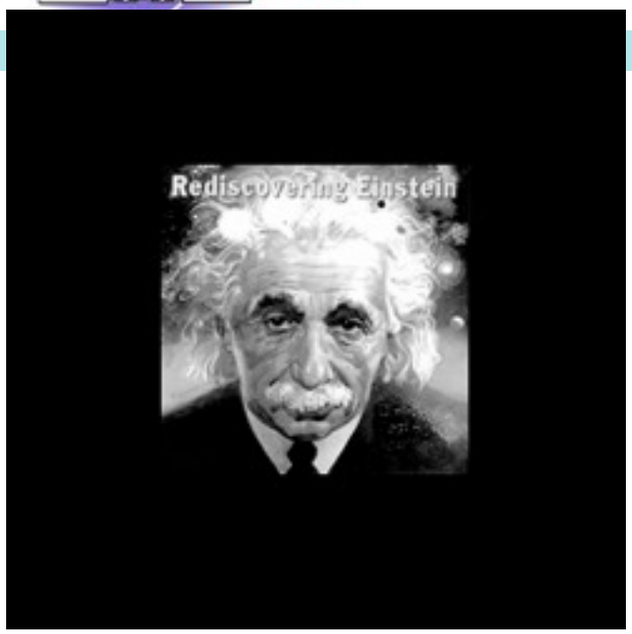
image 1

Object 2

FFT

image 2

Phase Problem



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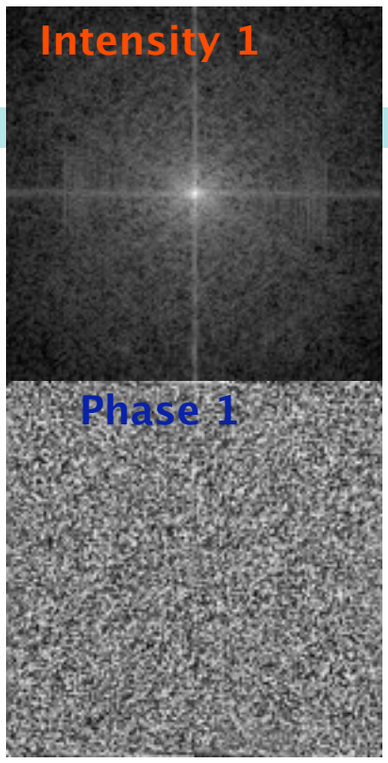


Diffraction Plane

image 1

Object 2

FFT

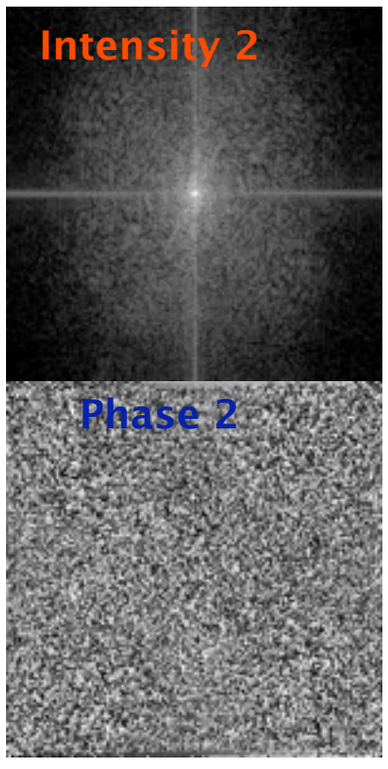
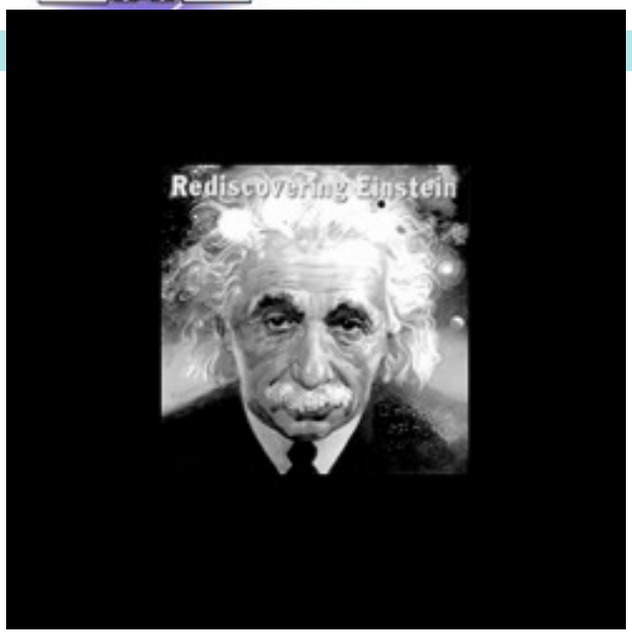


image 2

Phase Problem

TEM CENTER

NTHU



object 1

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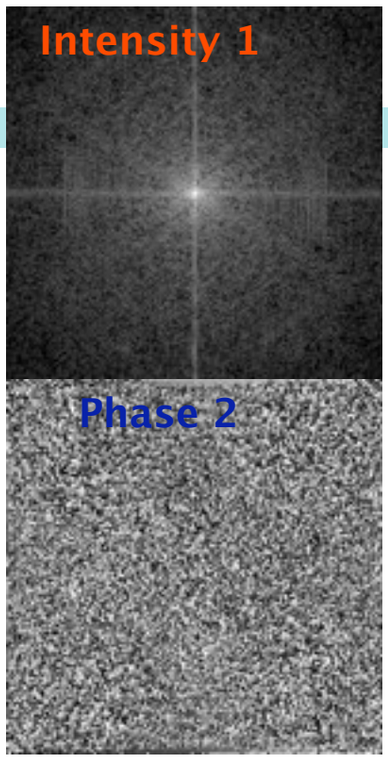


Diffraction Plane

image 1

Object 2

FFT

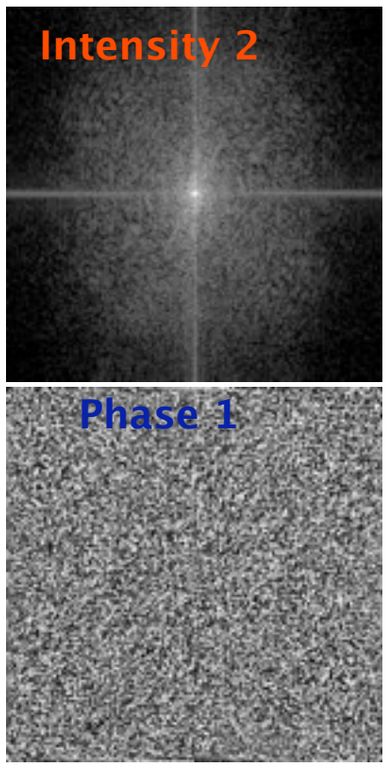
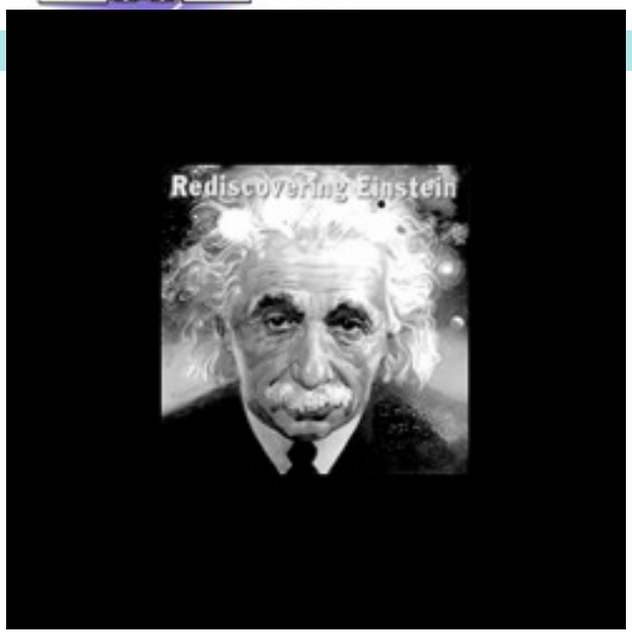


image 2

Phase Problem



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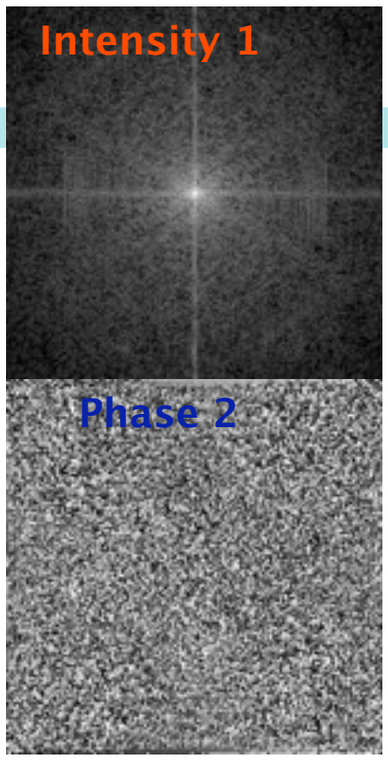


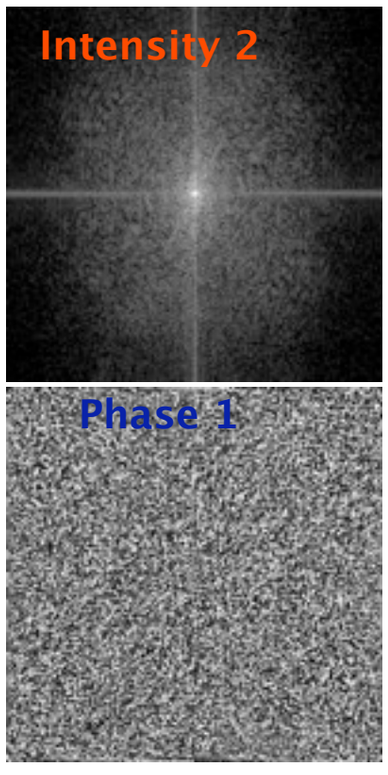
Diffraction Plane

FFT^{-1}

image 1

Object 2

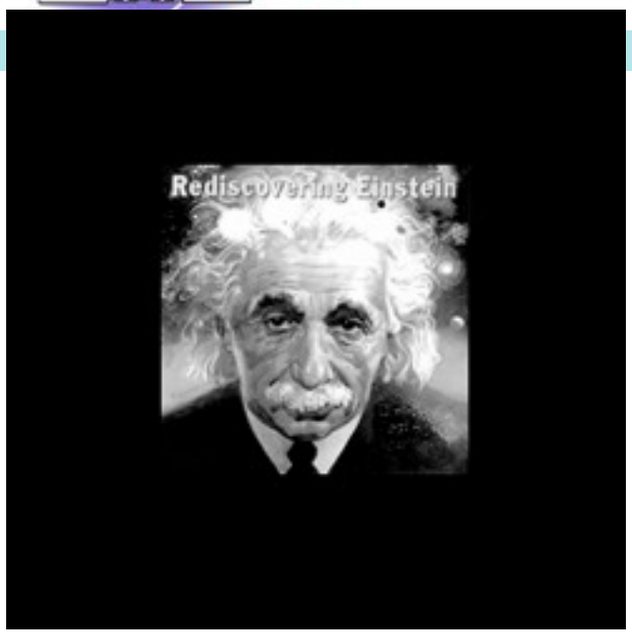
FFT



FFT^{-1}

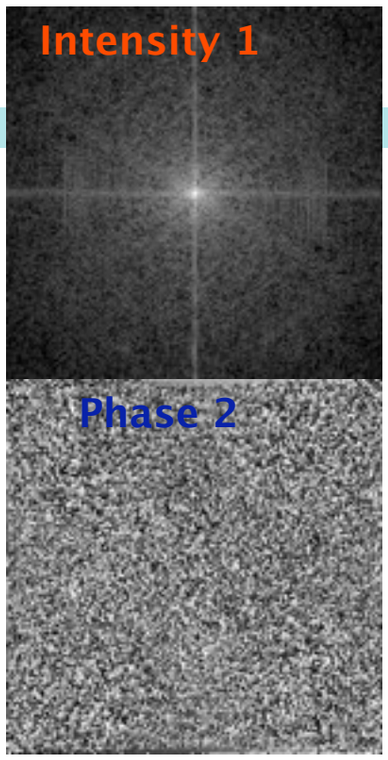
image 2

Phase Problem



object 1

FFT



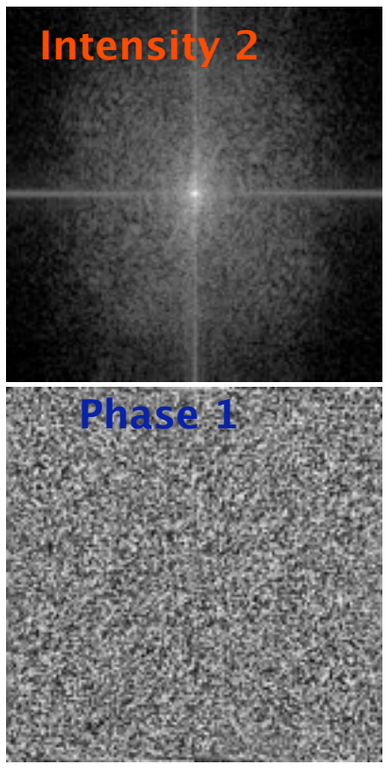
Diffraction Plane

FFT^{-1}

image 1

Object 2

FFT



FFT^{-1}

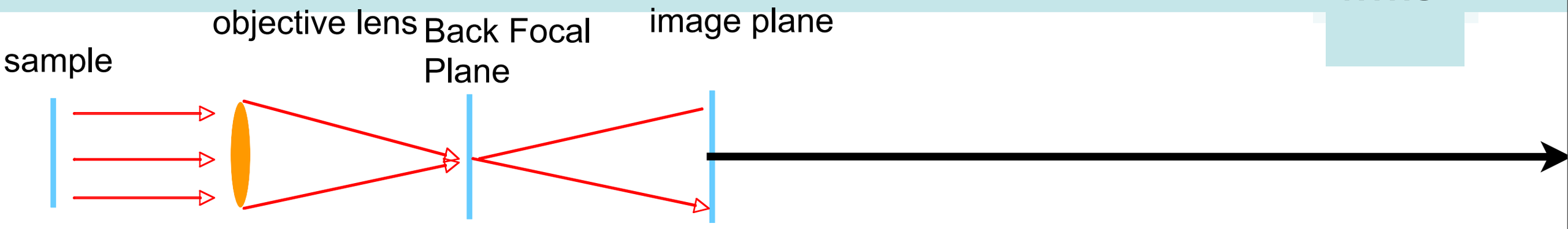
image 2

Transport Intensity Equation

(TIE non-interference method)

(medium resolution ~ 100 nm)

NTHU

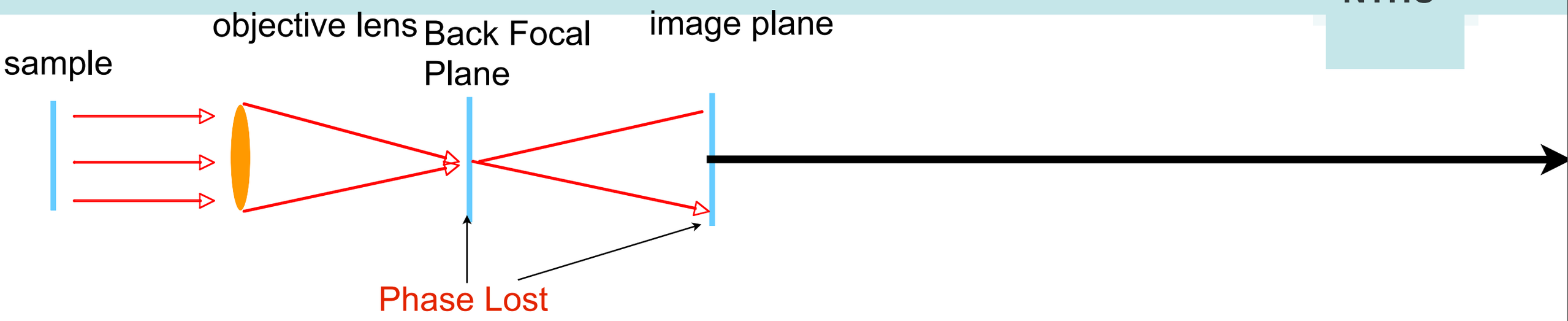


Transport Intensity Equation

(TIE non-interference method)

(medium resolution ~ 100 nm)

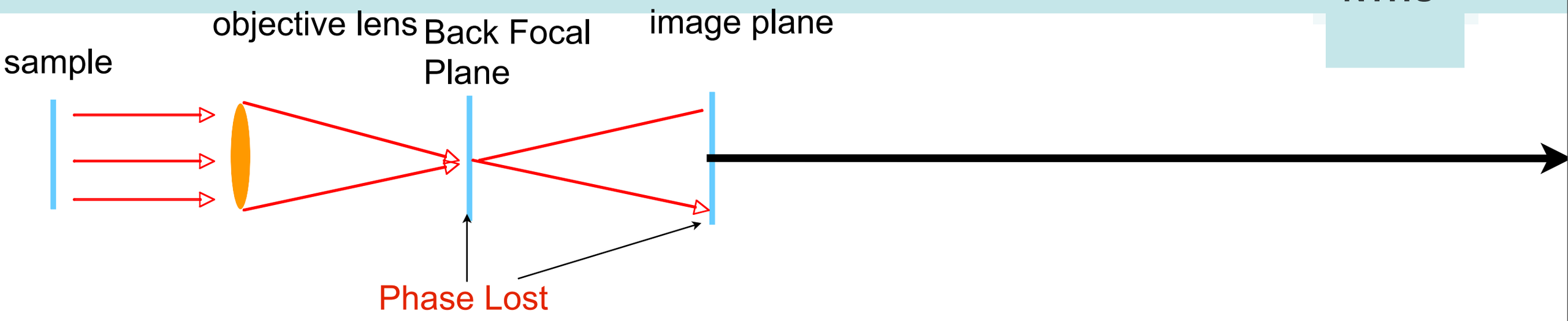
NTHU



Transport Intensity Equation

(TIE non-interference method)
(medium resolution ~ 100 nm)

NTHU

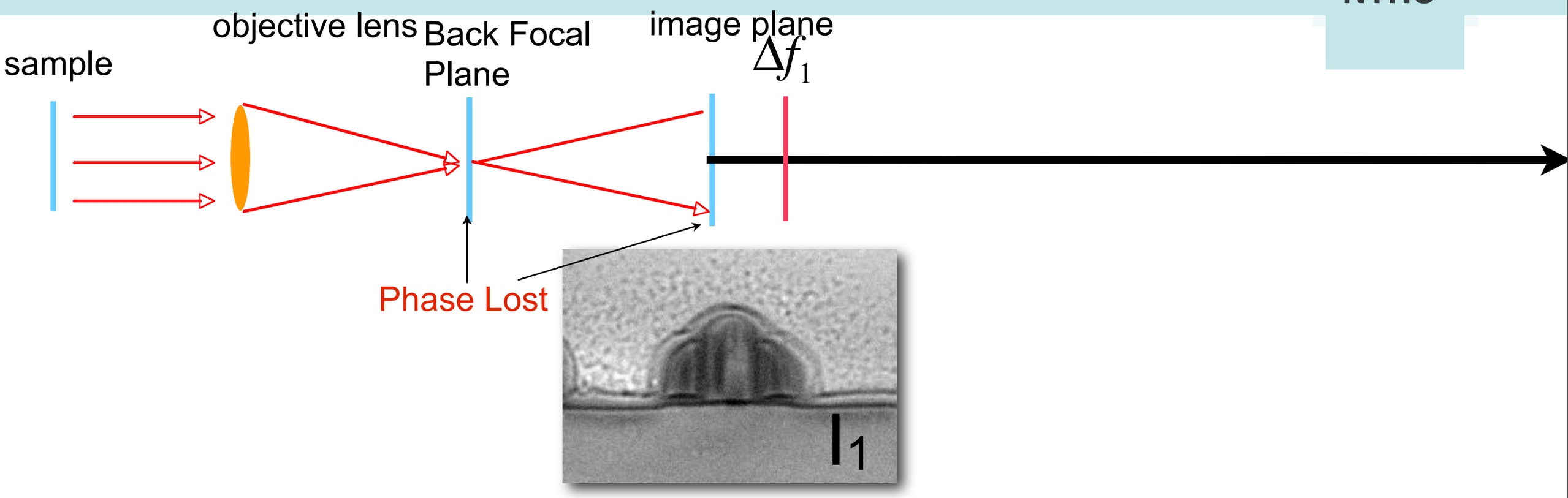


TIE : The phase is encoded in the “Gradient” of Image intensity

Transport Intensity Equation

(TIE non-interference method)
(medium resolution ~ 100 nm)

NTHU

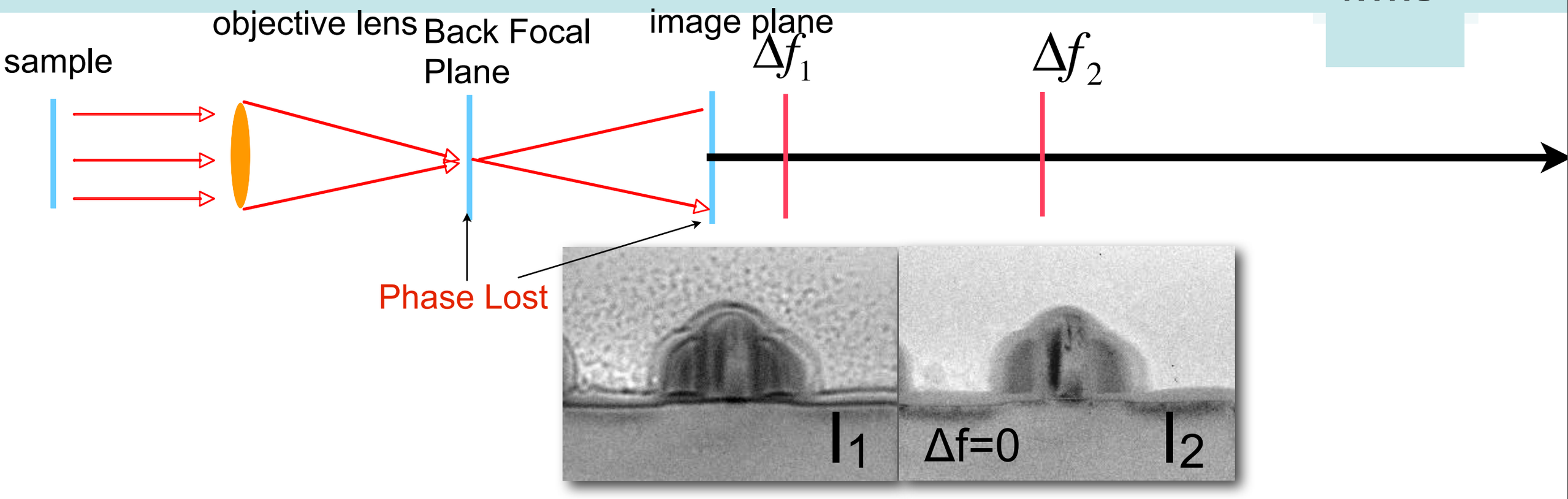


TIE : The phase is encoded in the “Gradient” of Image intensity

Transport Intensity Equation

(TIE non-interference method)
(medium resolution ~ 100 nm)

NTHU

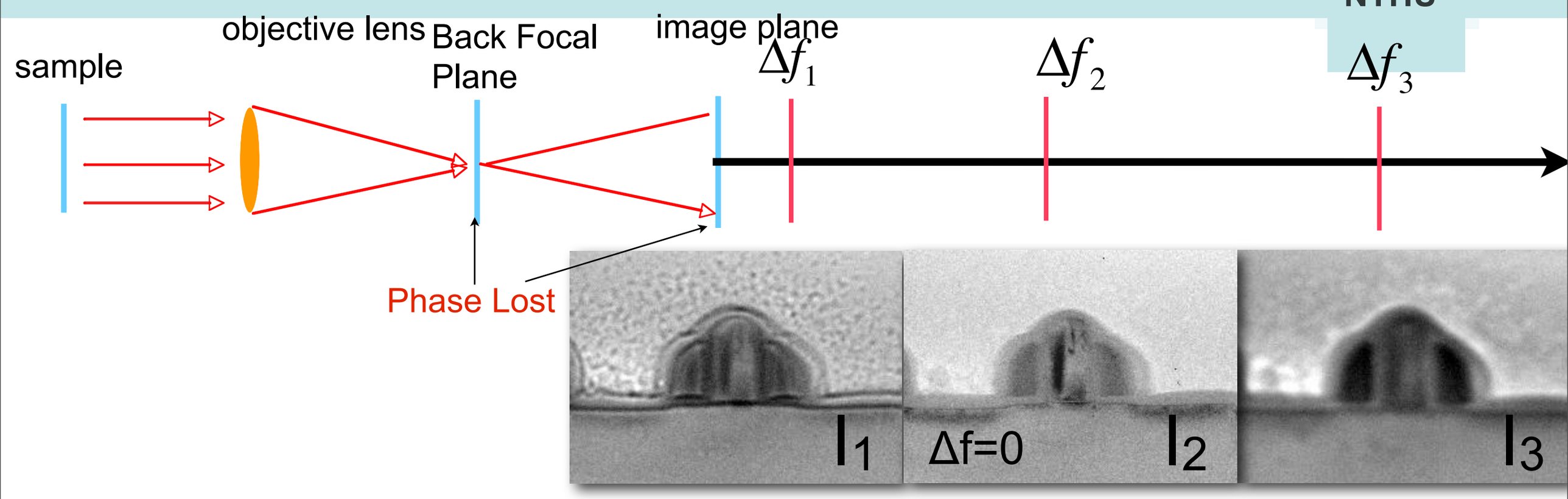


TIE : The phase is encoded in the “Gradient” of Image intensity

Transport Intensity Equation

(TIE non-interference method)
(medium resolution ~ 100 nm)

NTHU

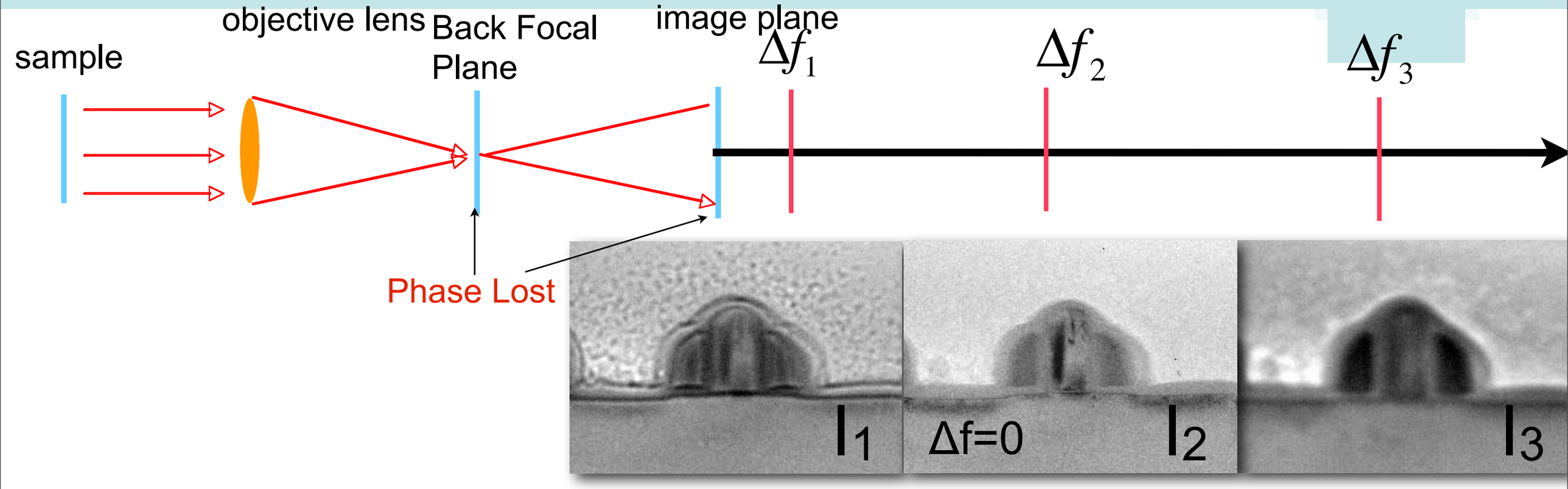


TIE : The phase is encoded in the “Gradient” of Image intensity

Transport Intensity Equation

(TIE non-interference method)
(medium resolution ~ 100 nm)

NTHU



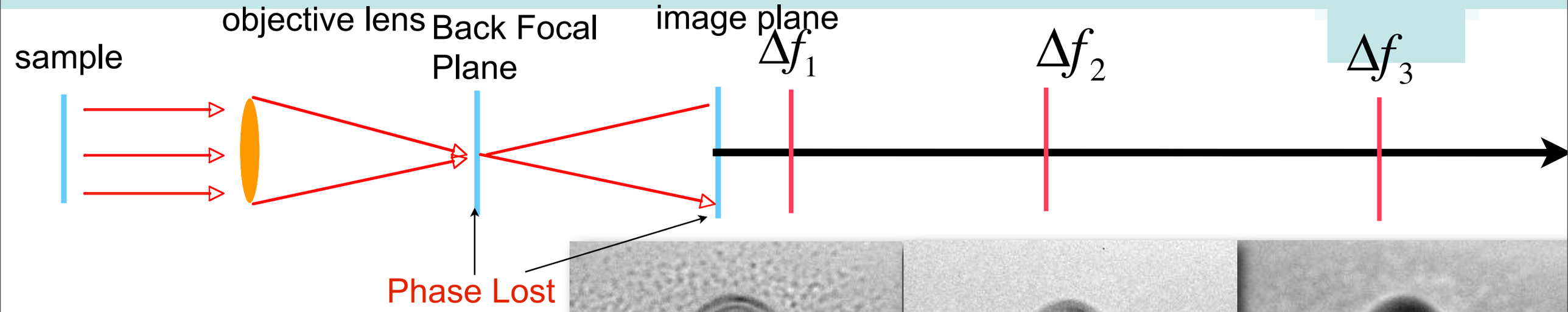
TIE : The phase is encoded in the "Gradient" of Image intensity

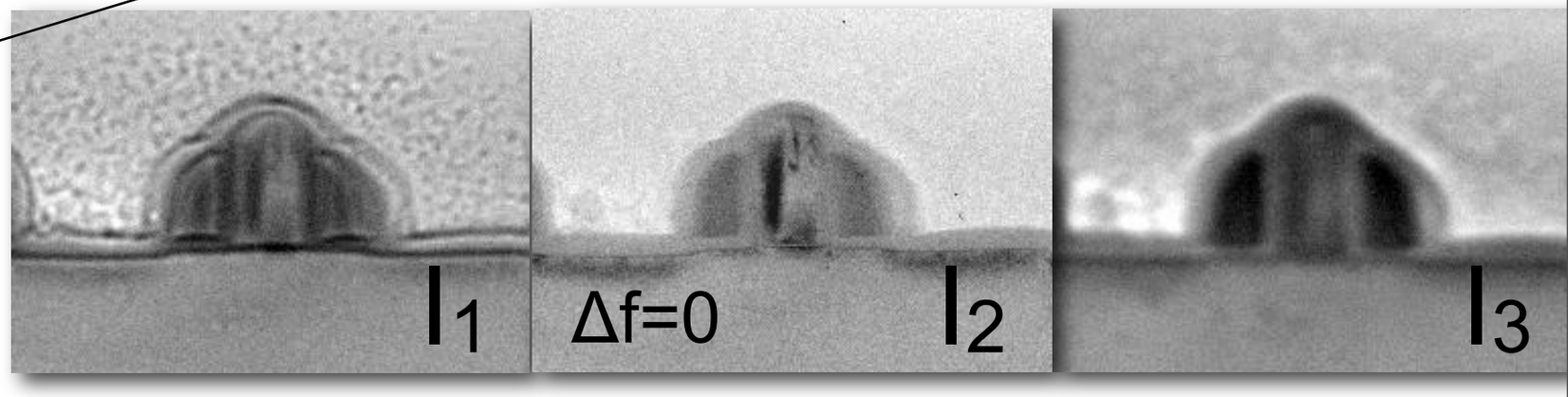
$$\nabla_\perp \bullet (I(r_\perp,0)\ \nabla_\perp \varphi) = -k\partial_z I(r_\perp,z)$$

Transport Intensity Equation

(TIE non-interference method)
(medium resolution ~ 100 nm)

NTHU





TIE : The phase is encoded in the "Gradient" of Image intensity

$$\nabla_\perp \bullet (I(r_\perp,0)\ \nabla_\perp \varphi) = -k\partial_z I(r_\perp,z)$$

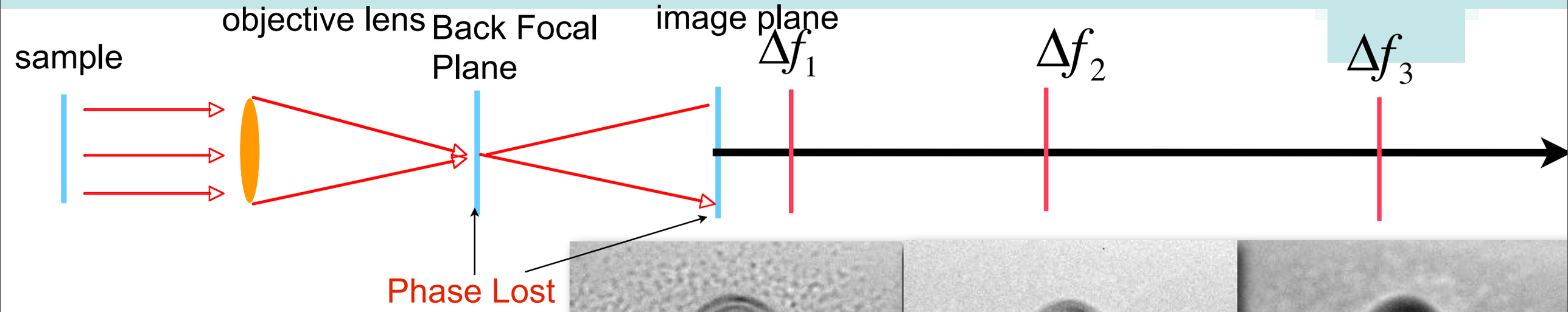
$$\frac{I_3 - I_1}{\Delta f_3 - \Delta f_1}$$

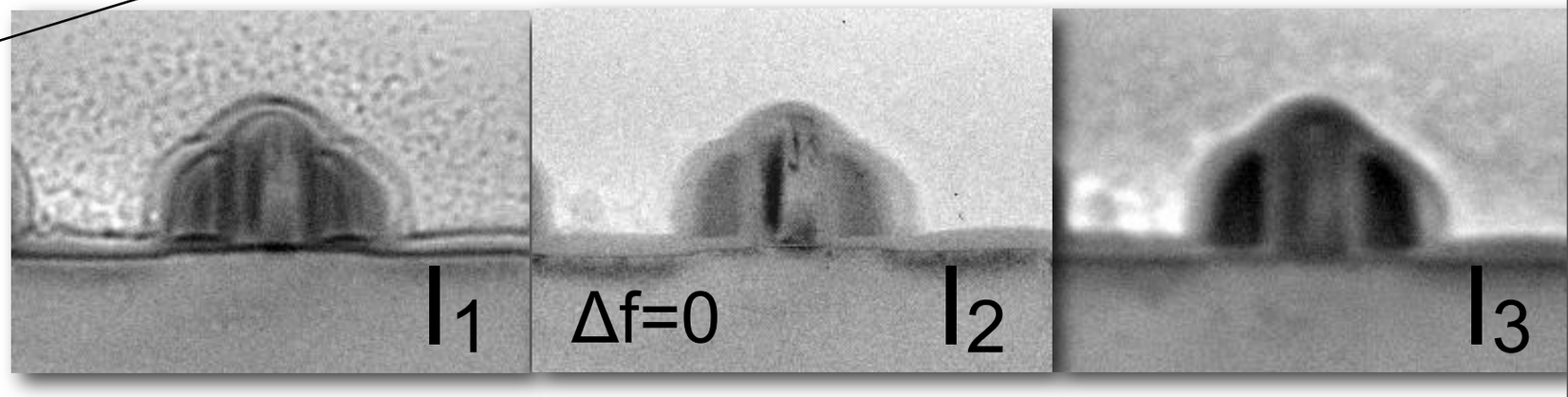
Two de-focus images

Transport Intensity Equation

(TIE non-interference method)
(medium resolution ~ 100 nm)

NTHU





TIE : The phase is encoded in the "Gradient" of Image intensity

$$\nabla_\perp \bullet (I(r_\perp,0)\ \nabla_\perp \varphi) = -k\partial_z I(r_\perp,z)$$

$$\frac{I_3 - I_1}{\Delta f_3 - \Delta f_1}$$

in-focus image

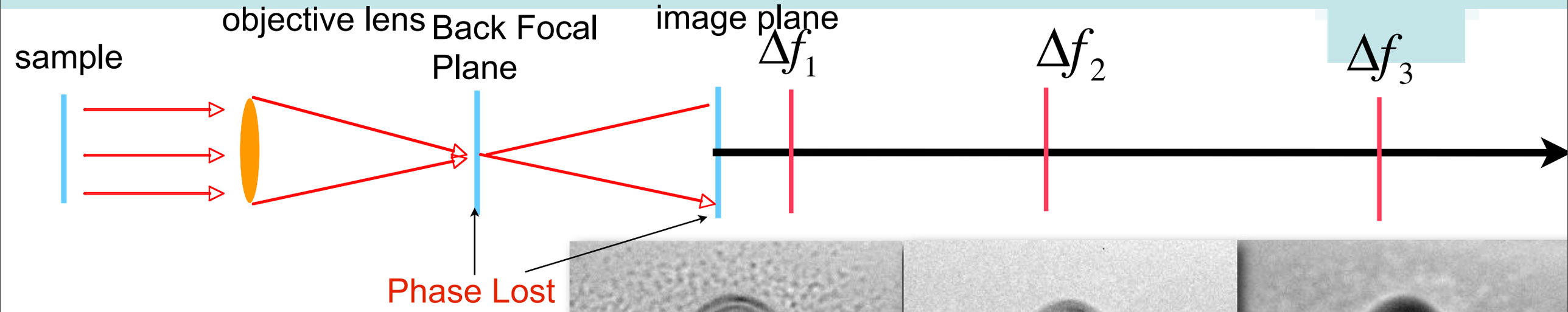
I_2

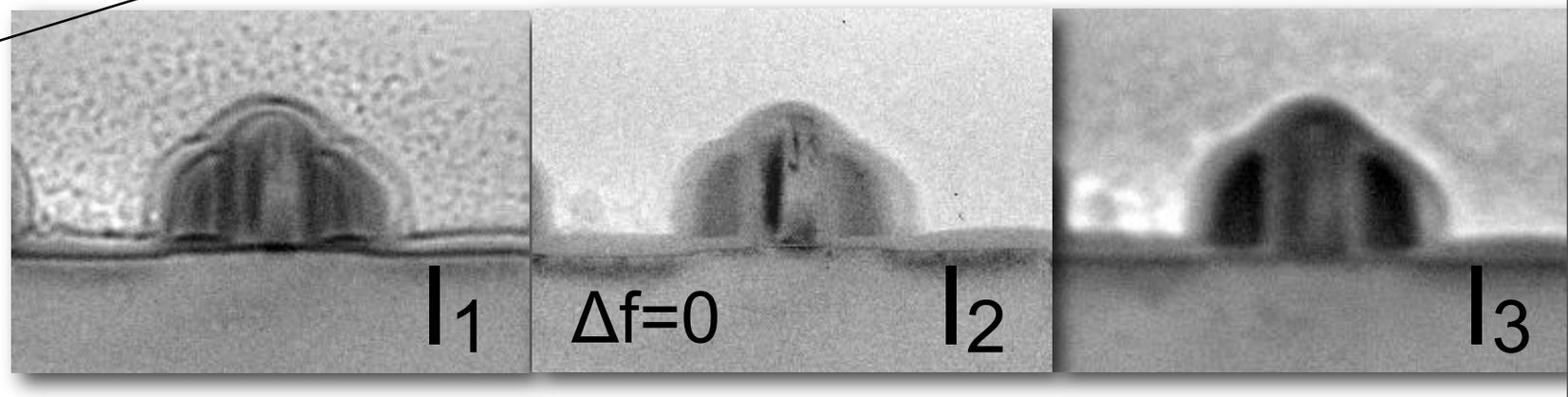
Two de-focus images

Transport Intensity Equation

(TIE non-interference method)
(medium resolution ~ 100 nm)

NTHU





TIE : The phase is encoded in the "Gradient" of Image intensity

$$\nabla_\perp \bullet (I(r_\perp,0)\ \nabla_\perp \varphi) = -k\partial_z I(r_\perp,z)$$

$$\frac{I_3 - I_1}{\Delta f_3 - \Delta f_1}$$

in-focus image I_2

Two de-focus images

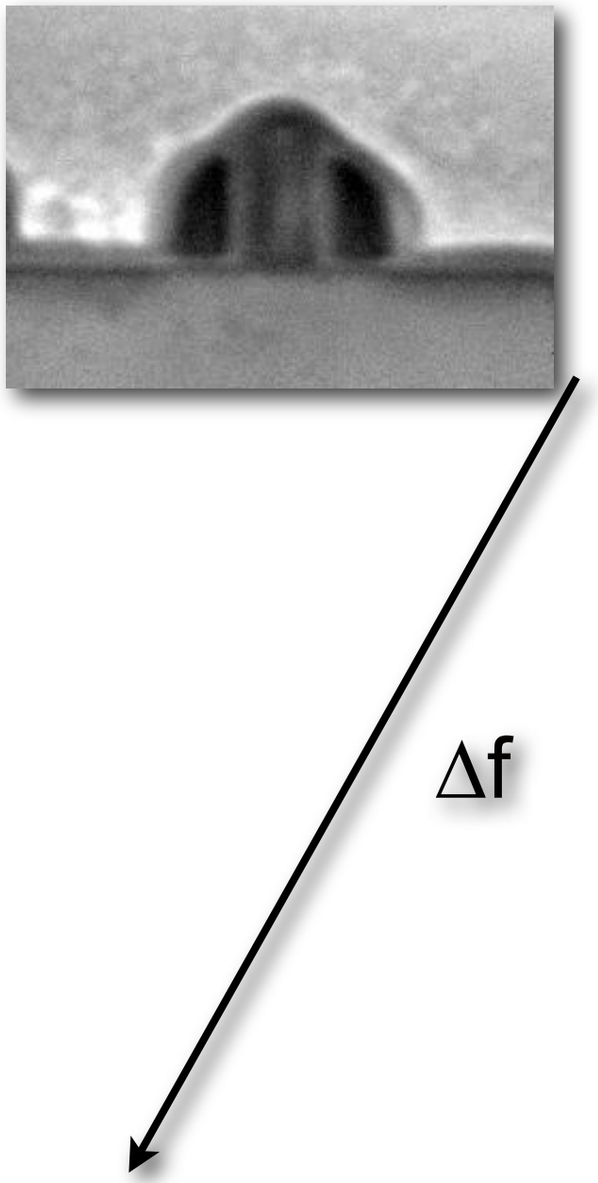
$\varphi(\mathbf{r}_\perp,z)$ is phase

$k = 2\pi/\lambda$ wave vector

pn- junction profile

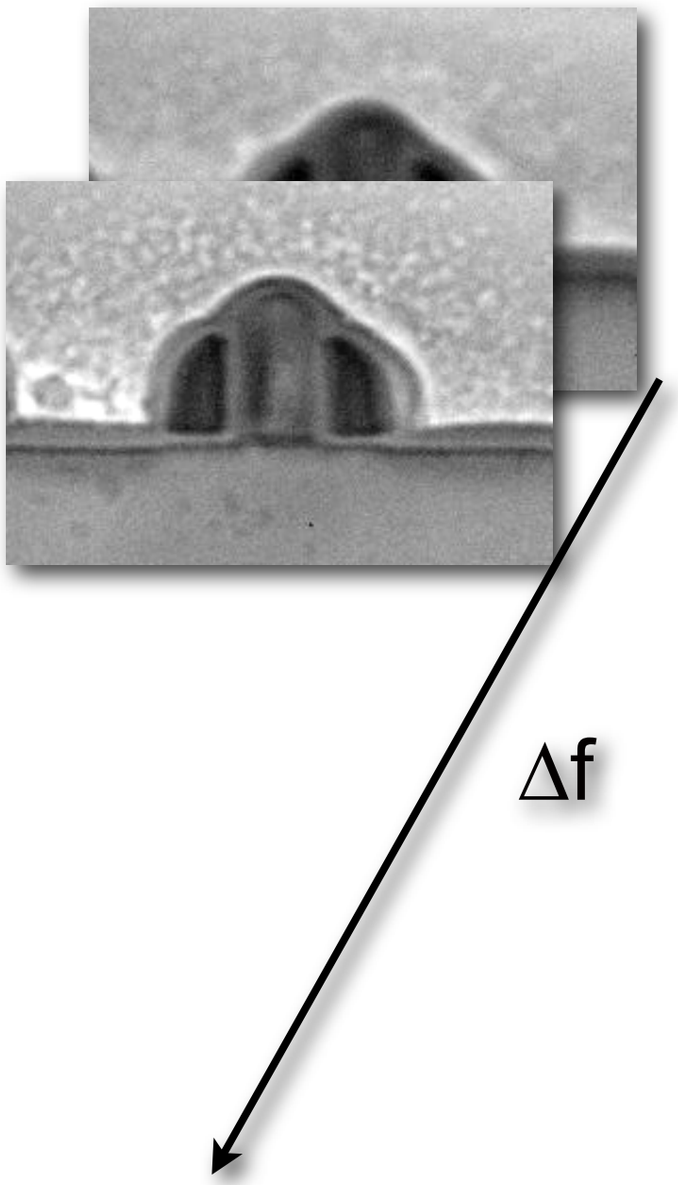
NTHU

pn- junction profile



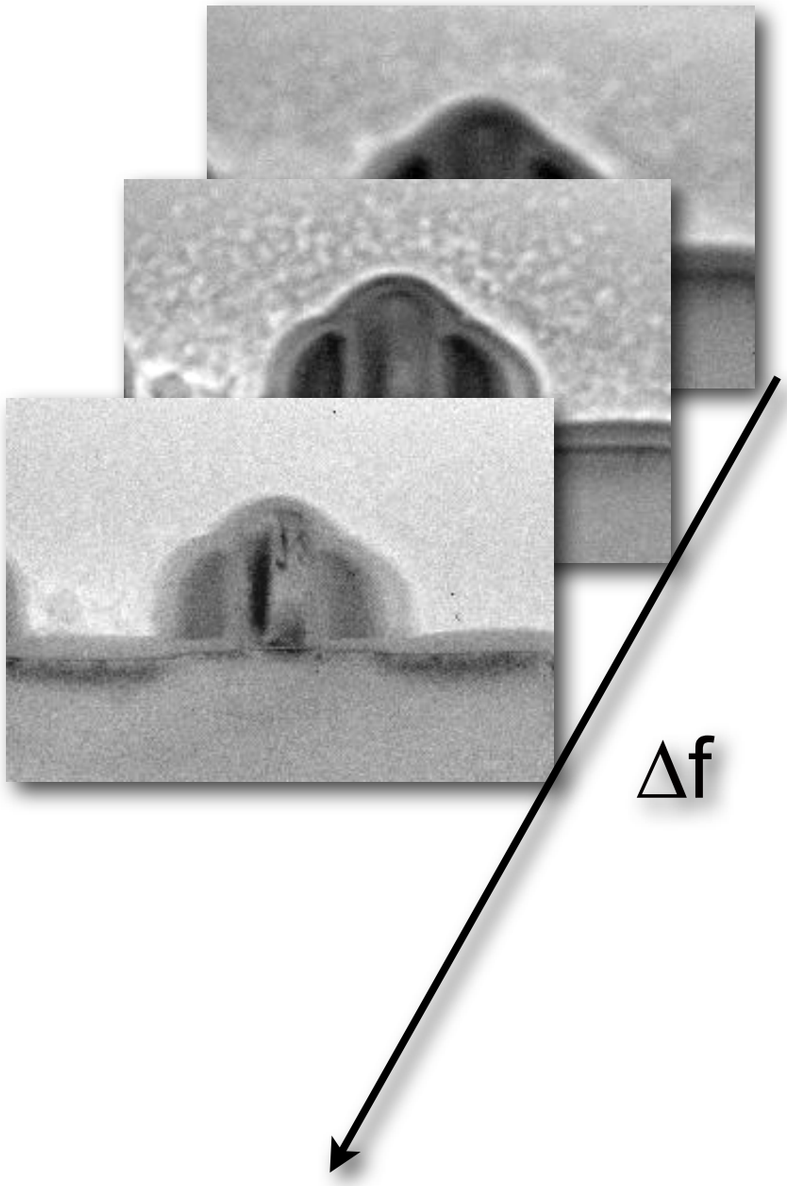
pn- junction profile

NTHU



pn- junction profile

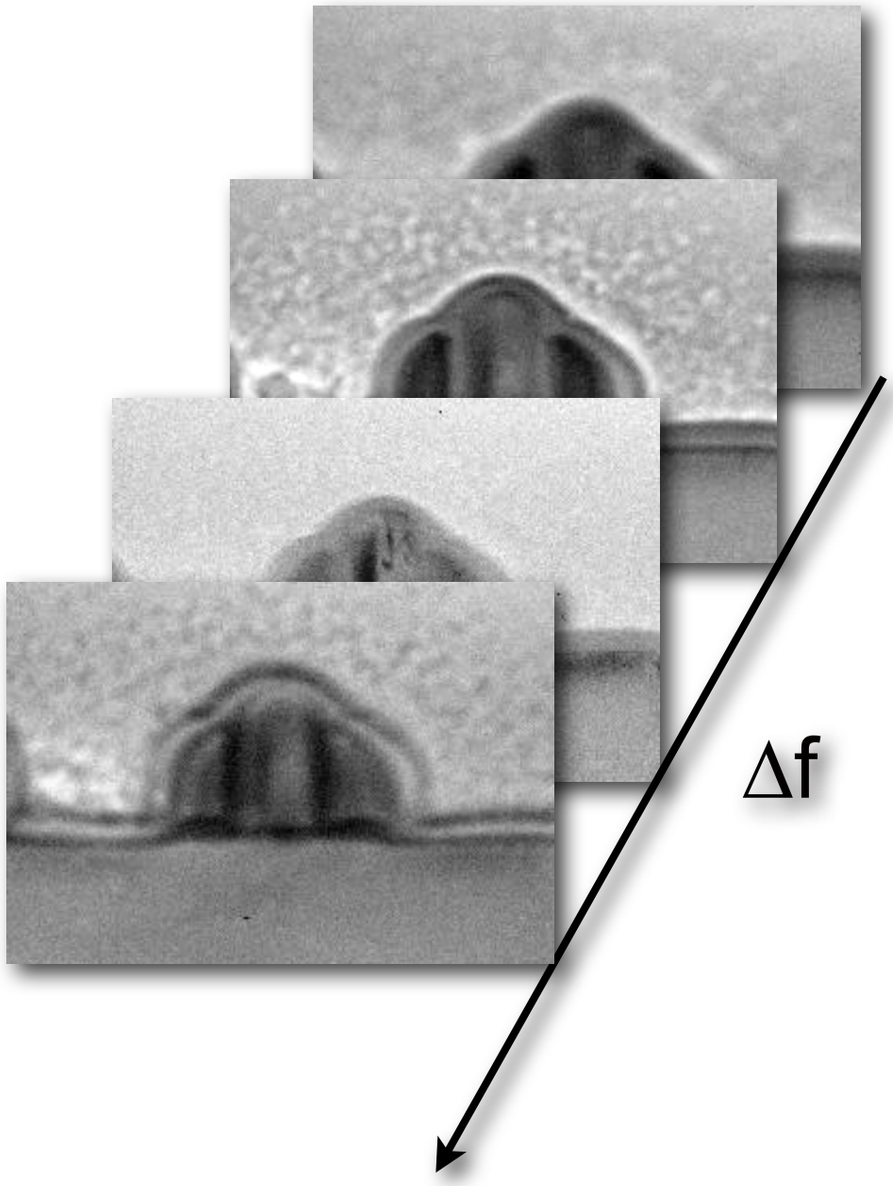
NTHU



TEM CENTER

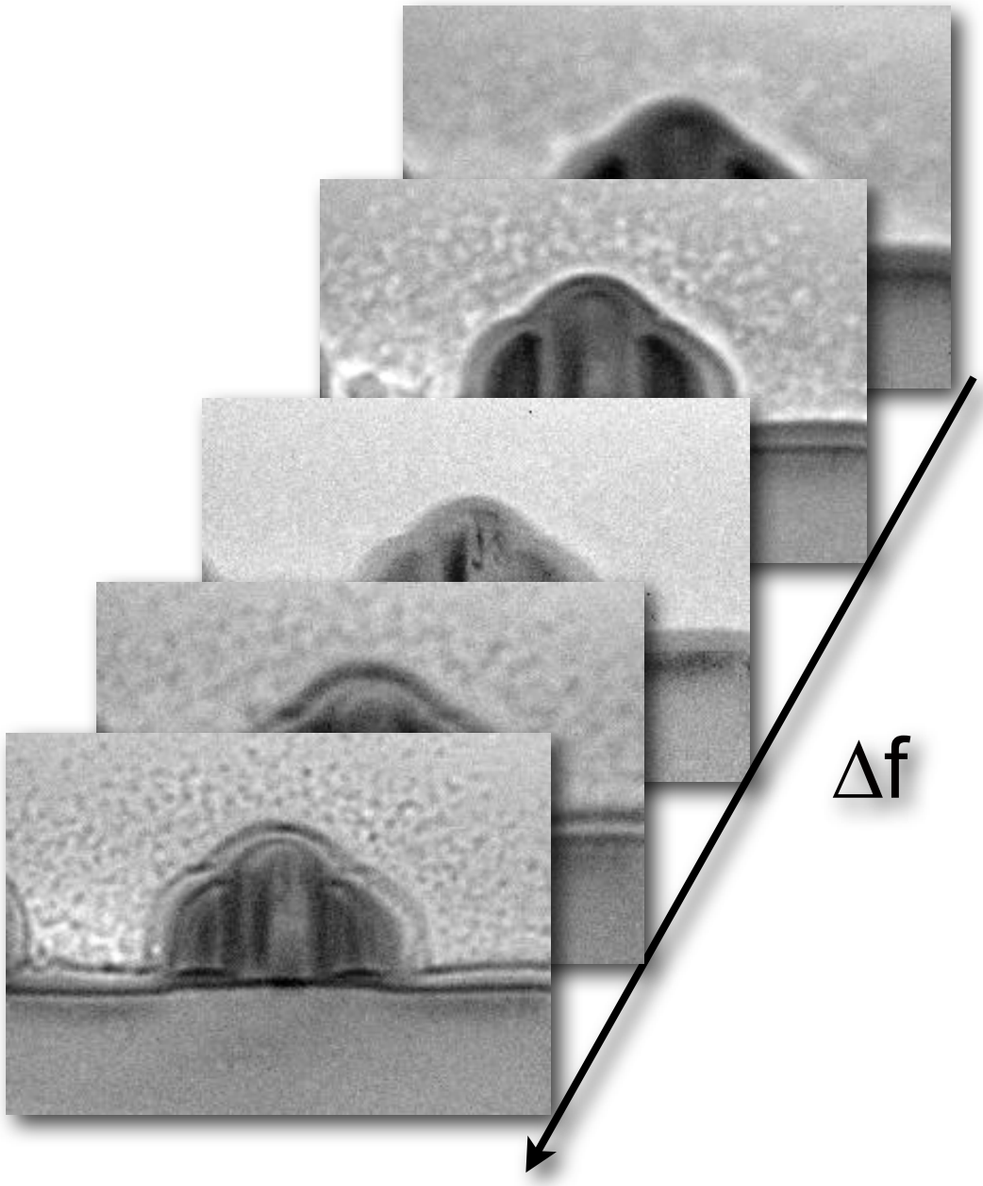
pn- junction profile

NTHU



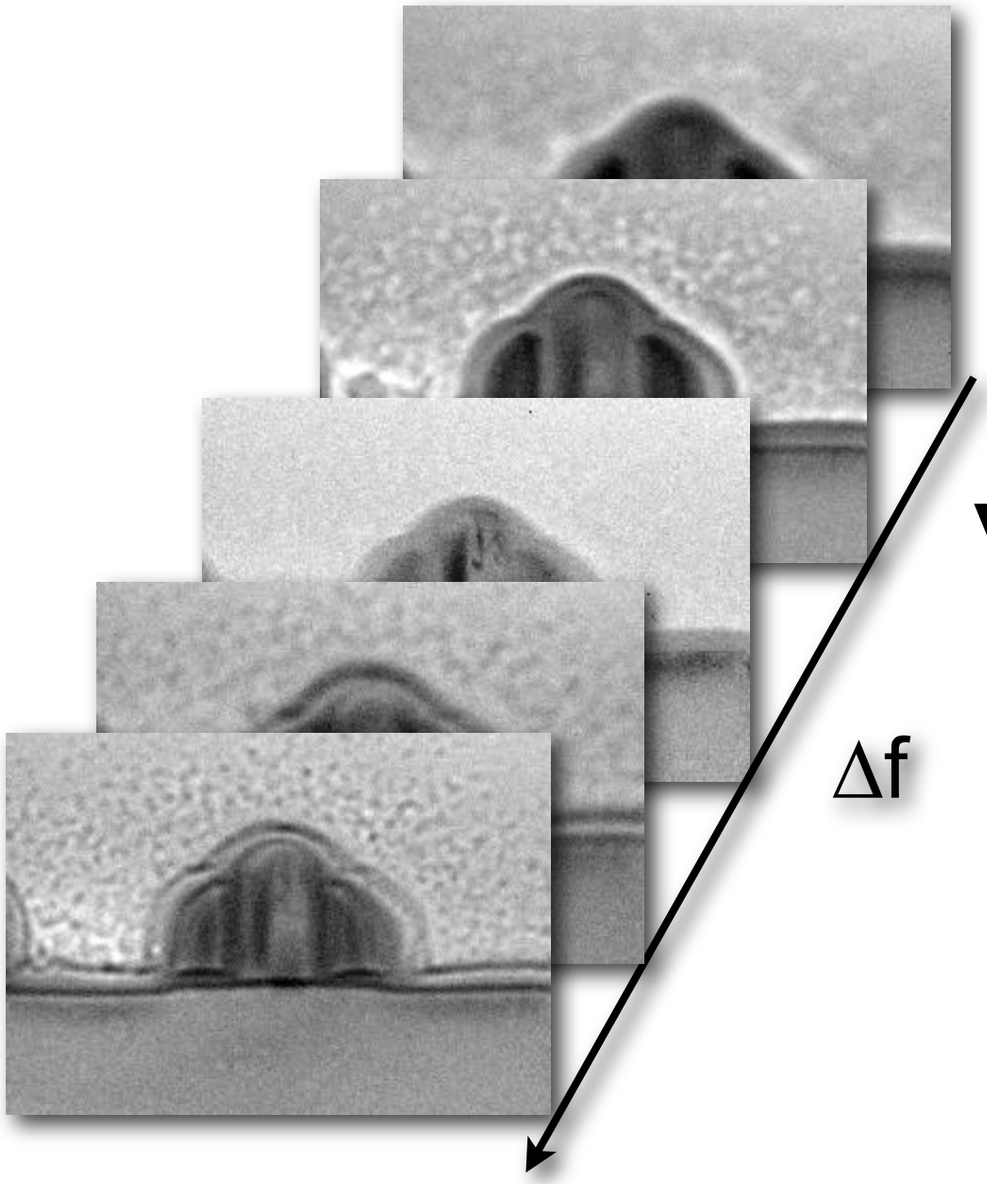
pn- junction profile

NTHU



pn- junction profile

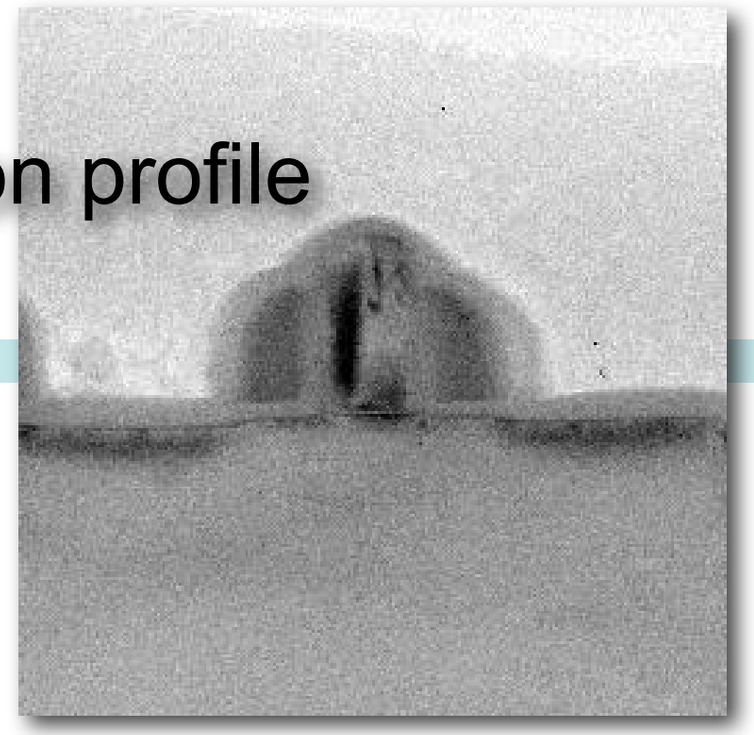
NTHU



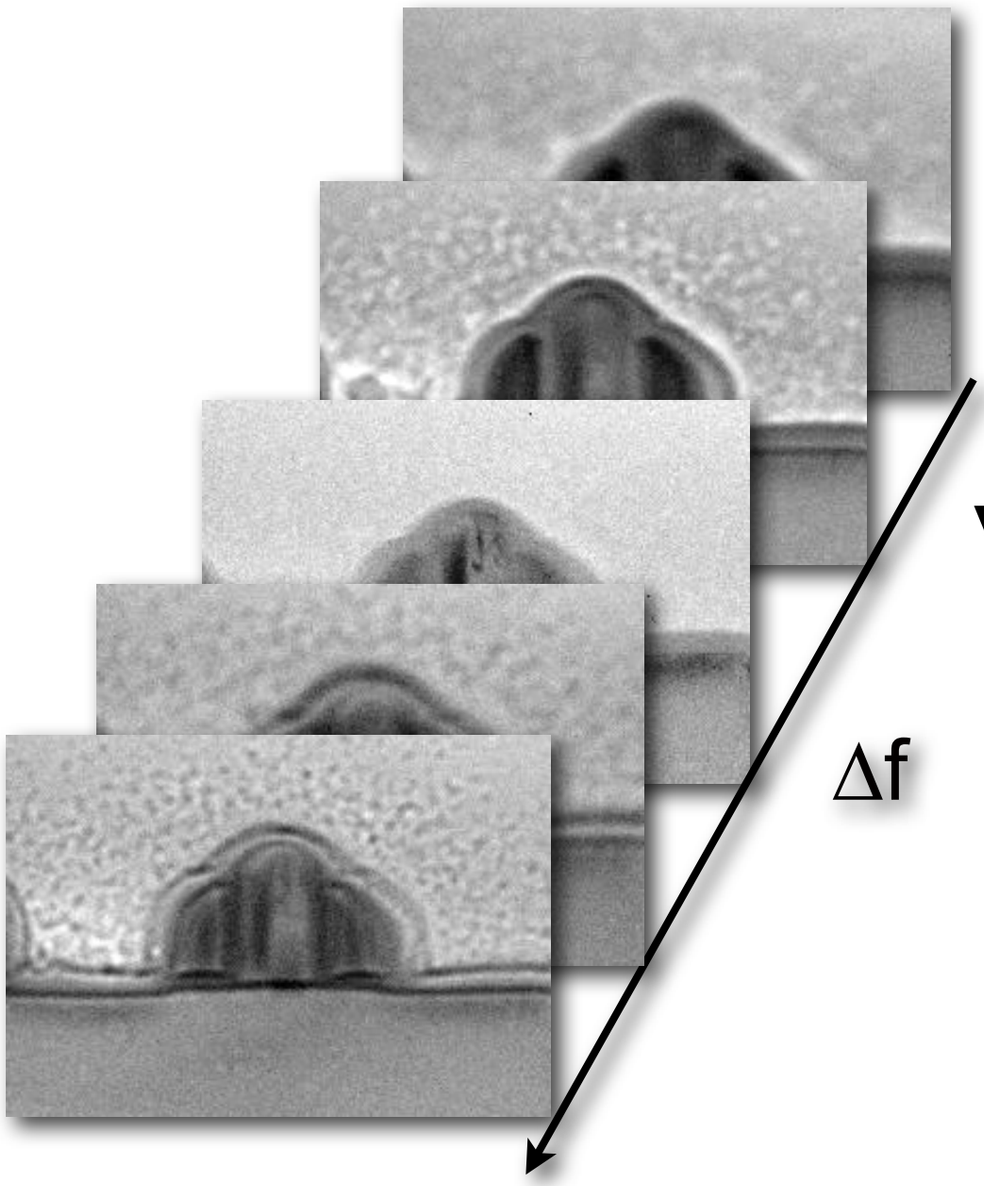
Δf

$$\nabla_\perp \bullet (I(r_\perp,0)\ \nabla_\perp \varphi) = -k\partial_z I(r_\perp,z)$$

pn- junction profile



modulus at exit surface

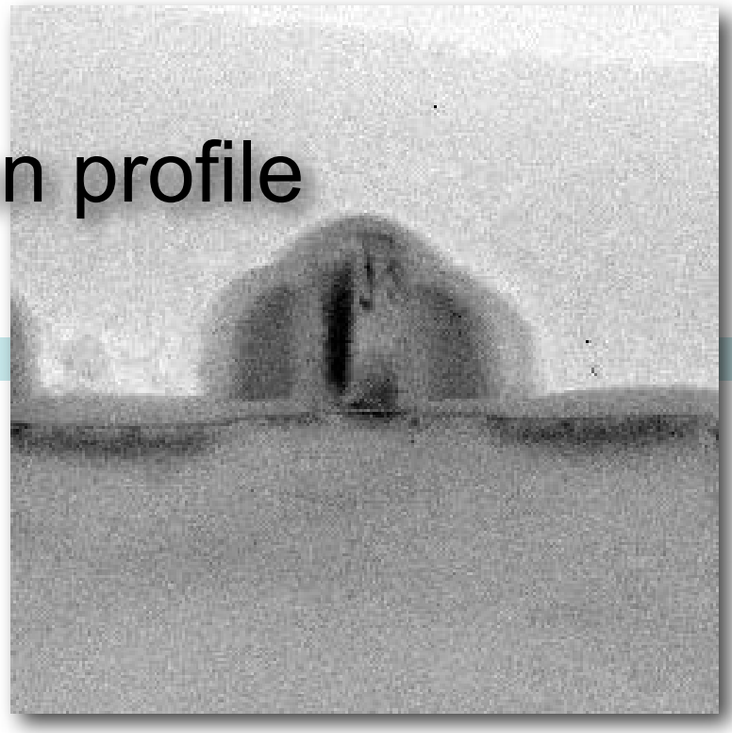


Δf

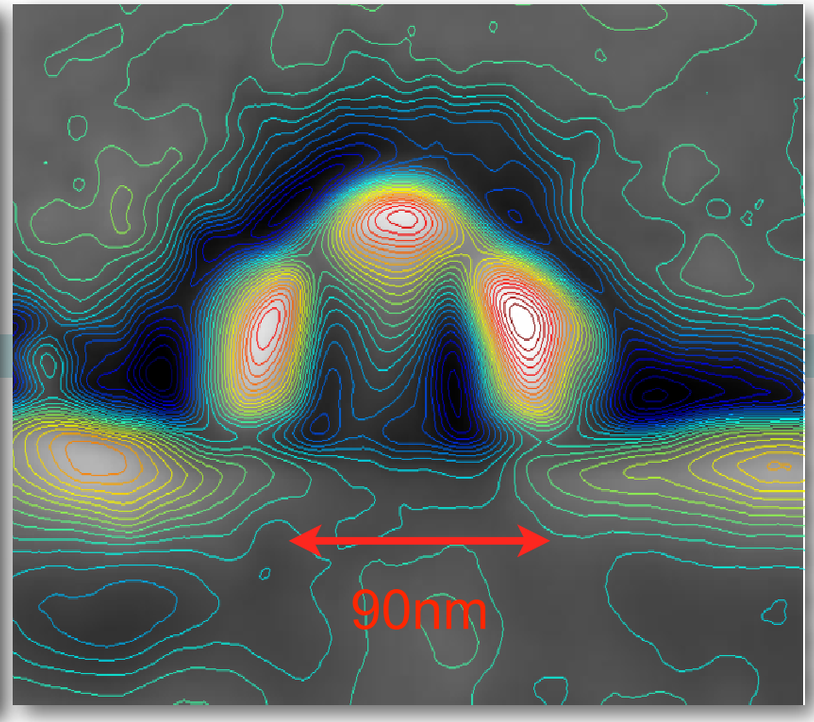
$$\nabla_\perp \bullet (I(r_\perp,0)\ \nabla_\perp \varphi) = -k \partial_z I(r_\perp,z)$$

TEM CENTER

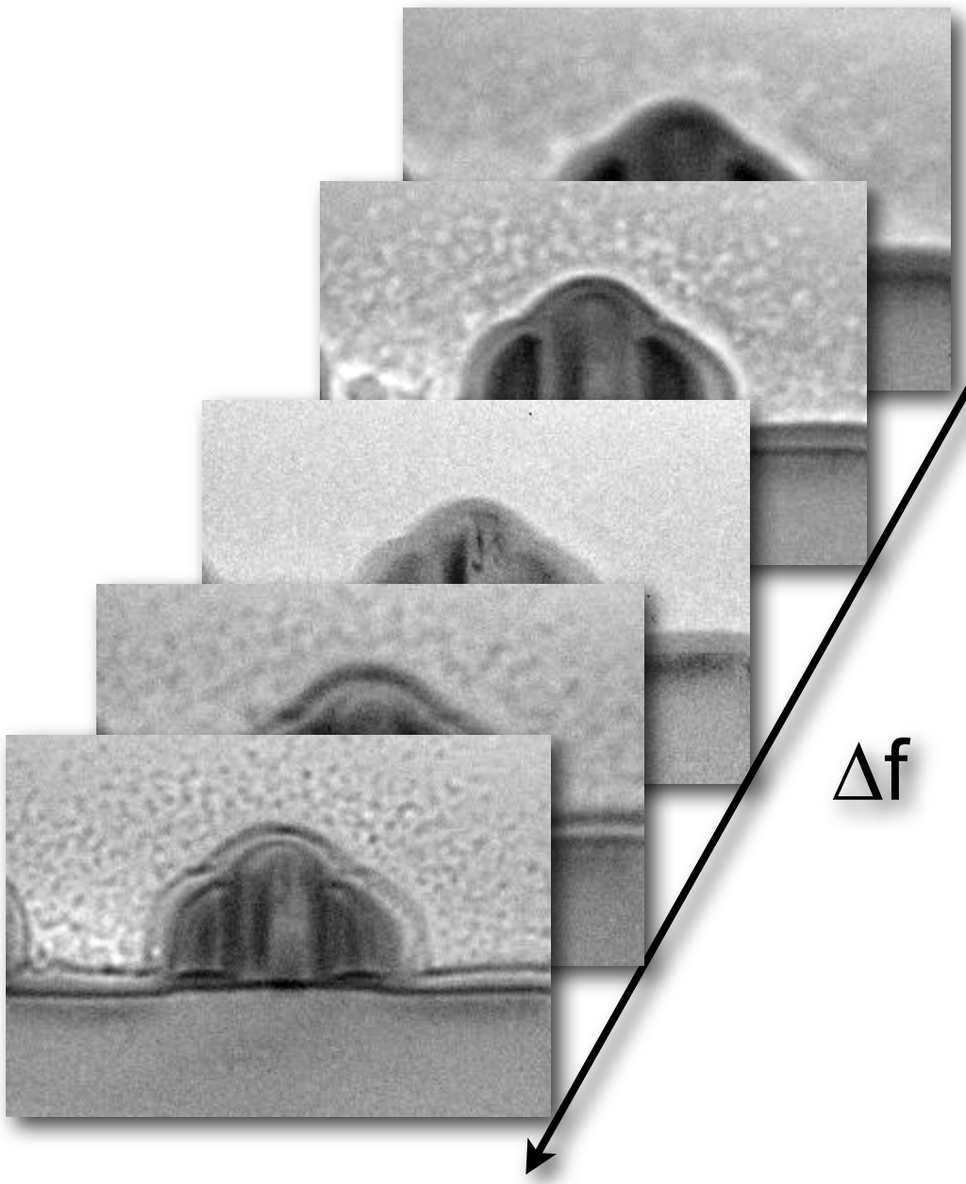
pn- junction profile



modulus at exit surface



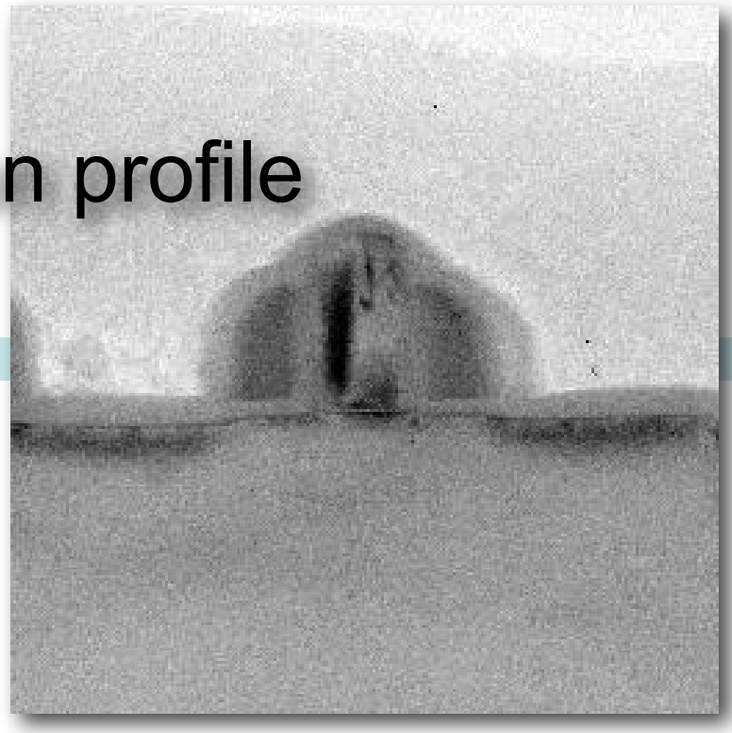
retrieved phase at exit surface



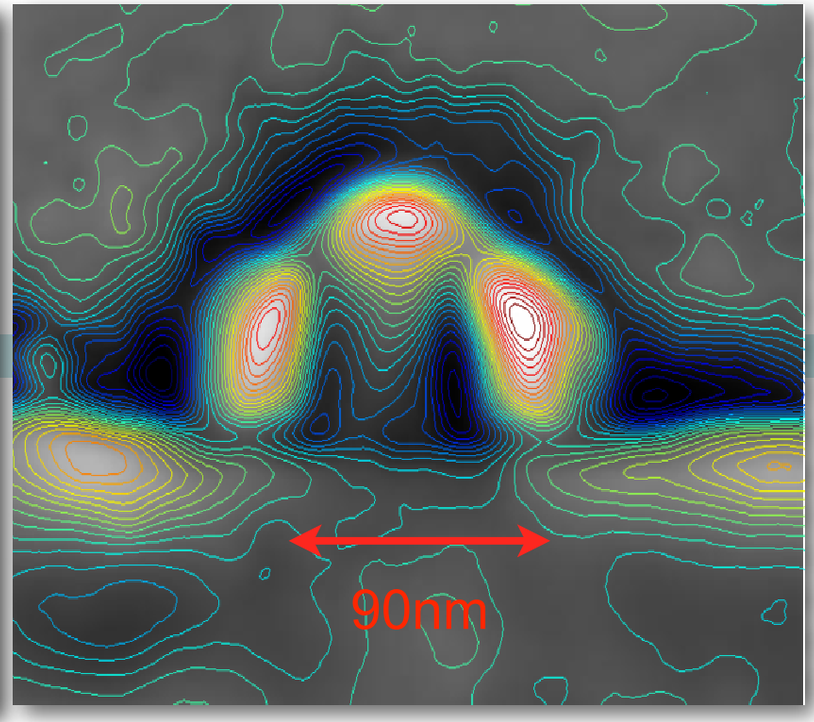
Δf

$$\nabla_\perp \bullet (I(r_\perp,0)\ \nabla_\perp \varphi) = -k \partial_z I(r_\perp,z)$$

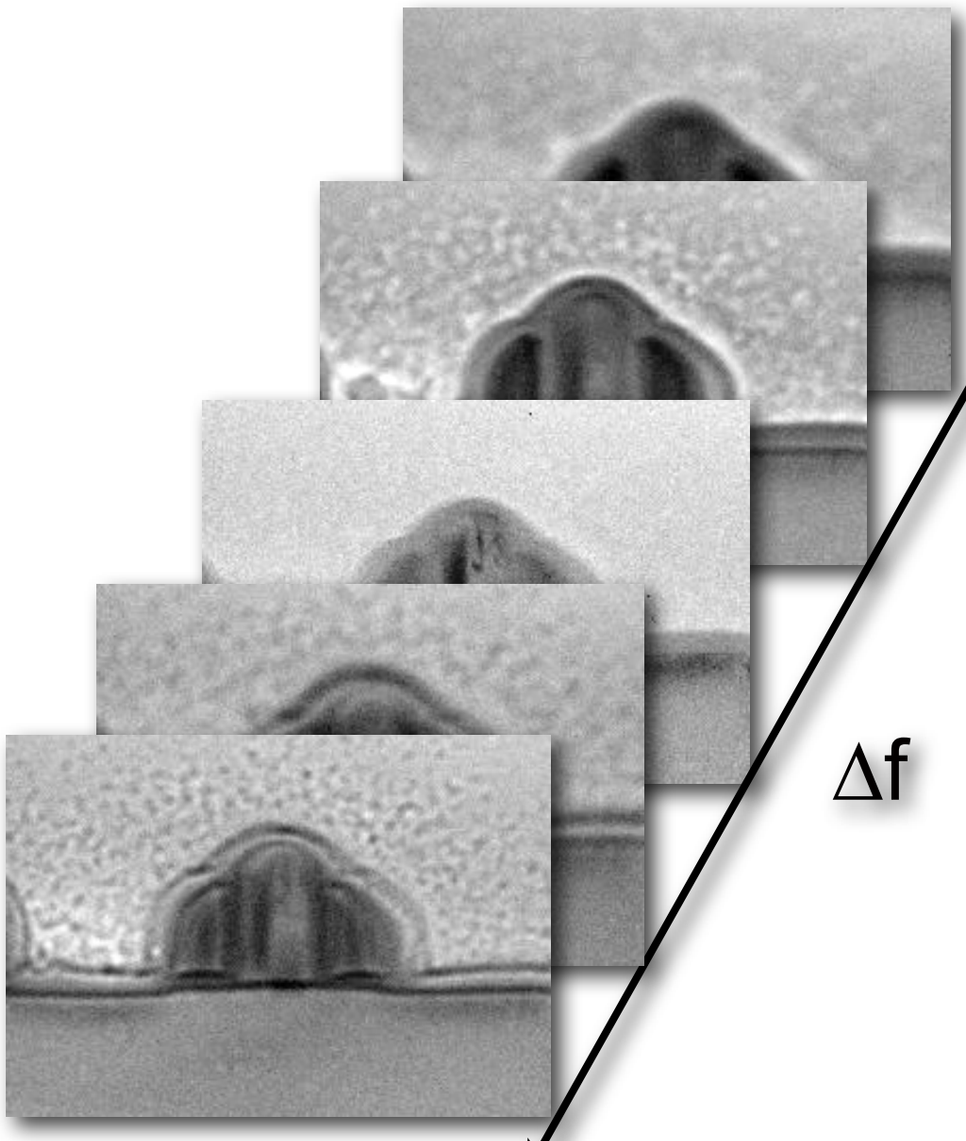
pn- junction profile



modulus at exit surface



retrieved phase at exit surface

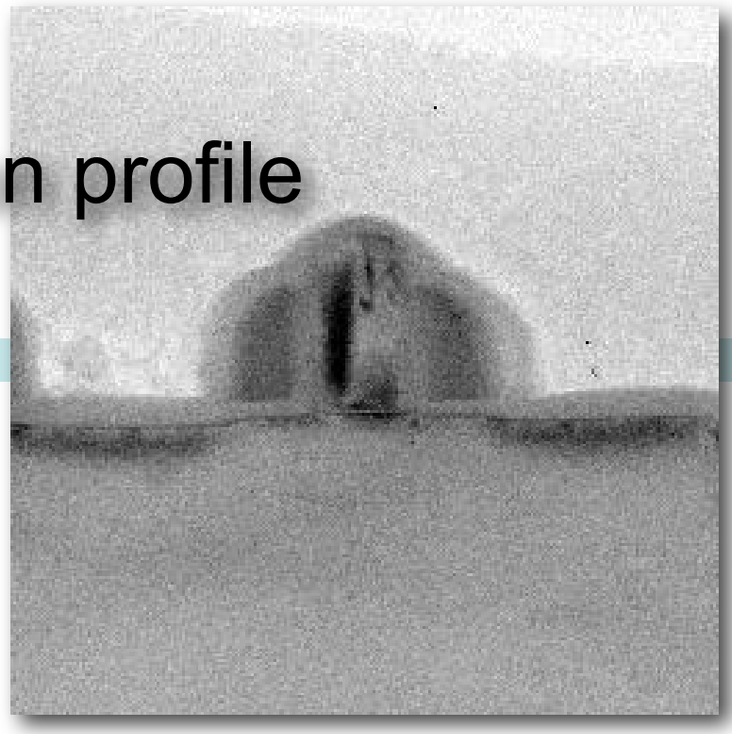


Δf

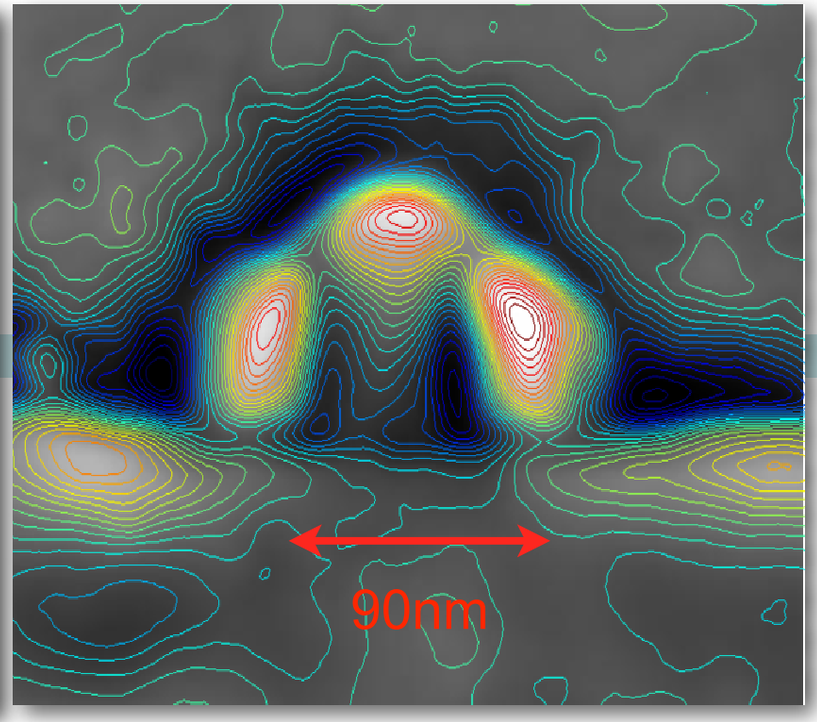
$$\nabla_\perp \bullet (I(r_\perp,0)\ \nabla_\perp \varphi) = -k\partial_z I(r_\perp,z)$$

$$\phi(x,y) = C_E \int V(x,y)dz - \frac{e}{h}\int \overrightarrow{B(x,y)}dAdz - \frac{\pi}{\lambda E_o \varepsilon}\int \overrightarrow{P(x,y)}drdZ$$

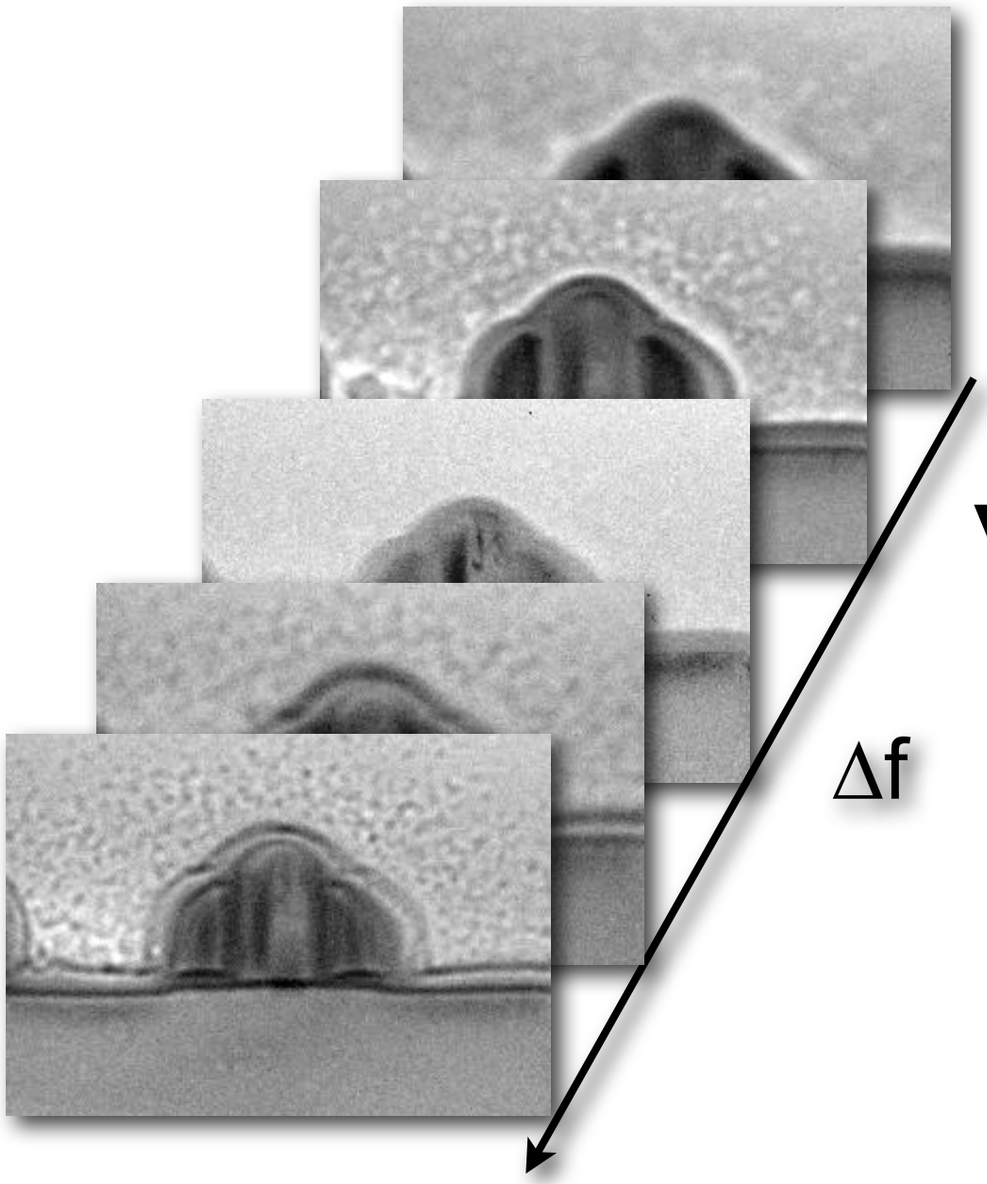
pn- junction profile



modulus at exit surface

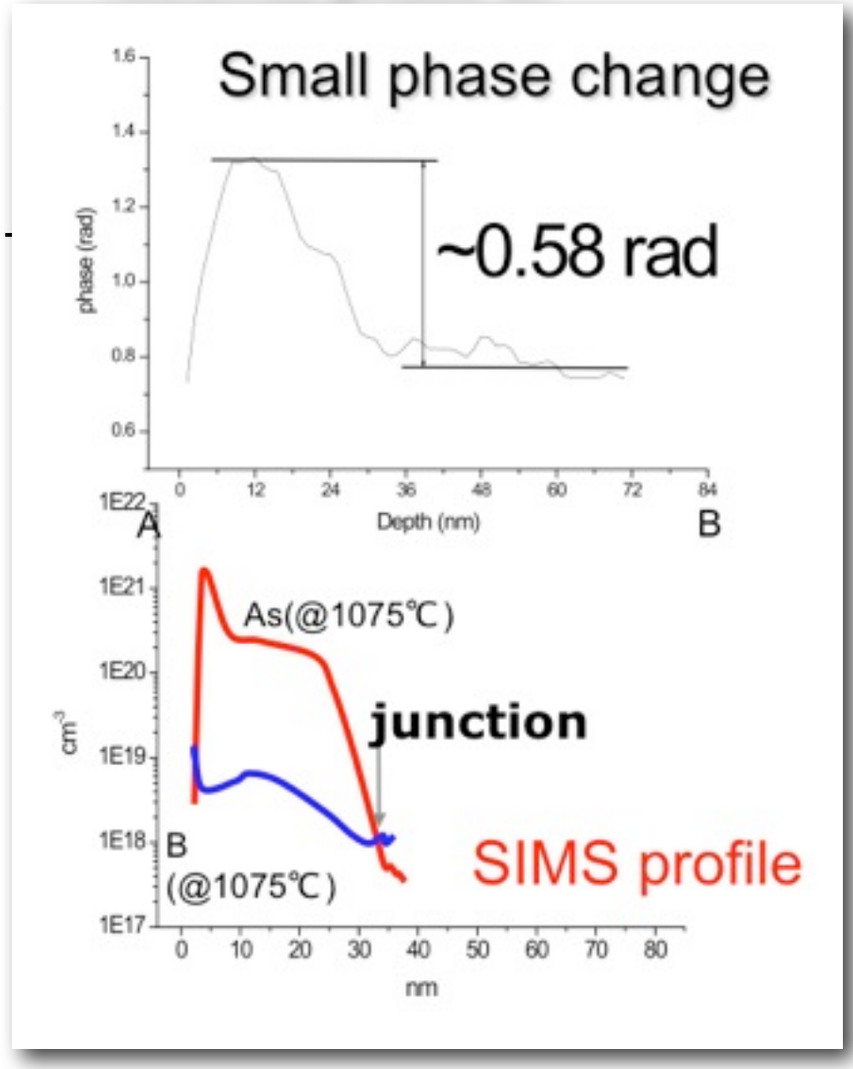


retrieved phase at



Δf

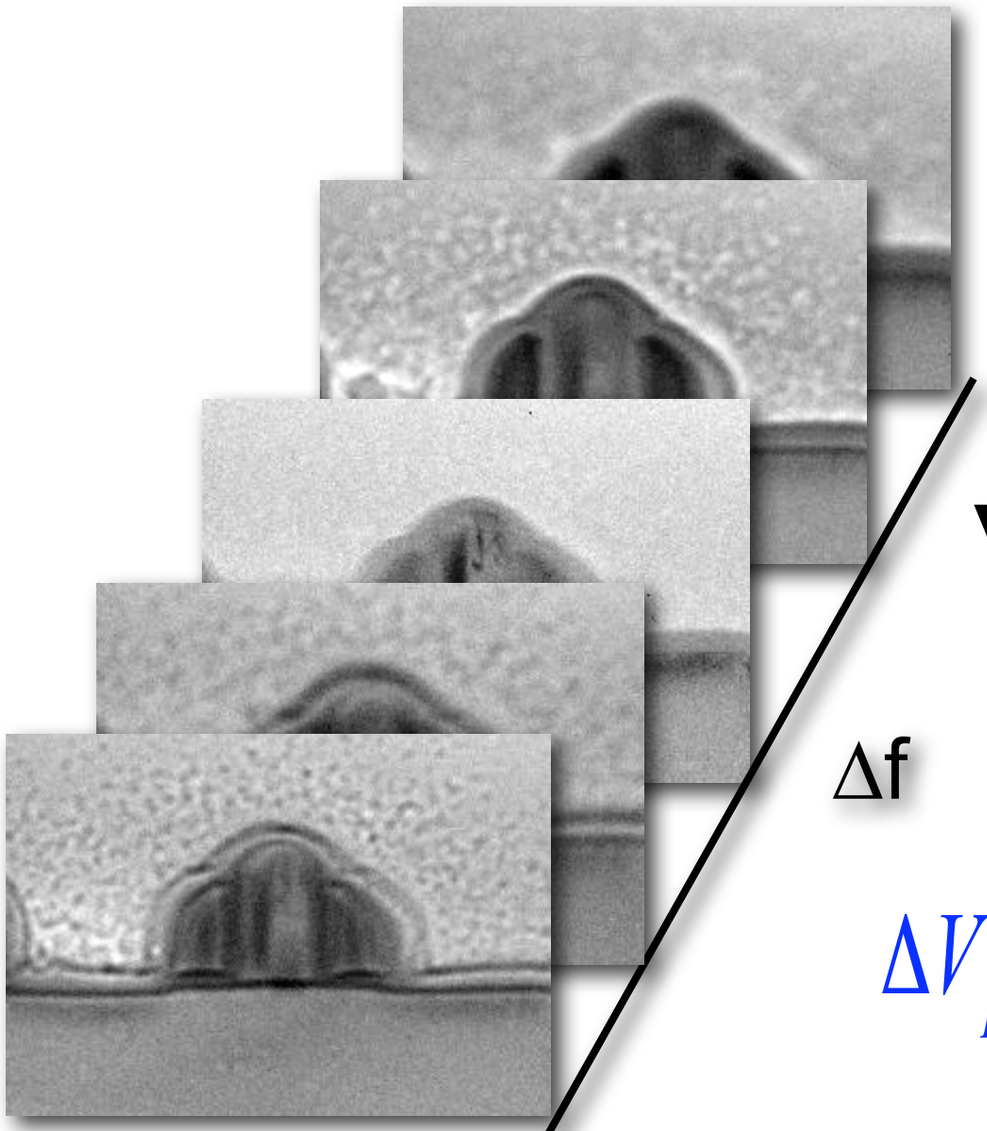
$$\nabla_{\perp}\bullet(I(r_{\perp},0)\ \nabla_{\perp}$$

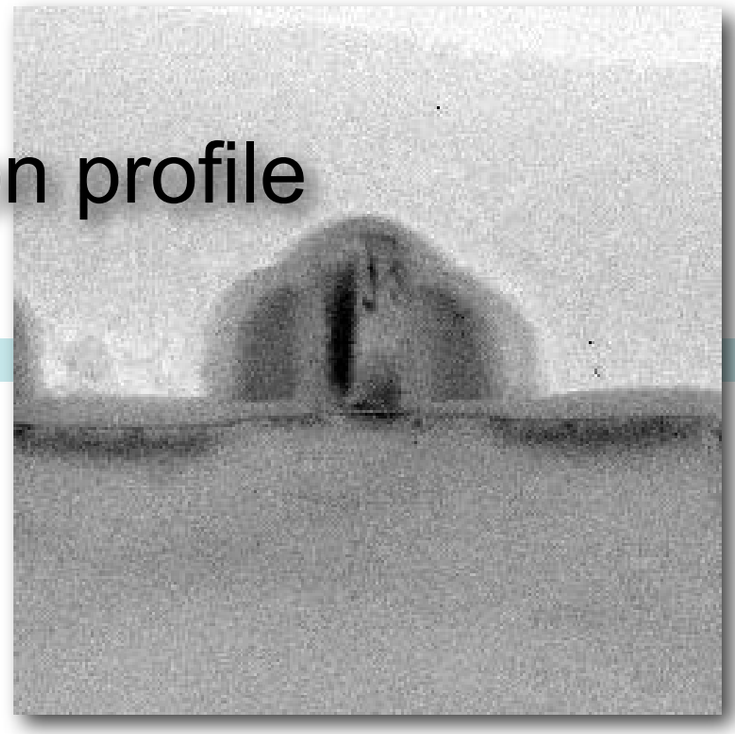


$$\phi(x,y) = C_E \int V(x,y)dz - \frac{e}{h}\int \overrightarrow{B(x,y)}dAdz - \frac{\pi}{\lambda E_o \varepsilon}\int \overrightarrow{P(x,y)}drdZ$$

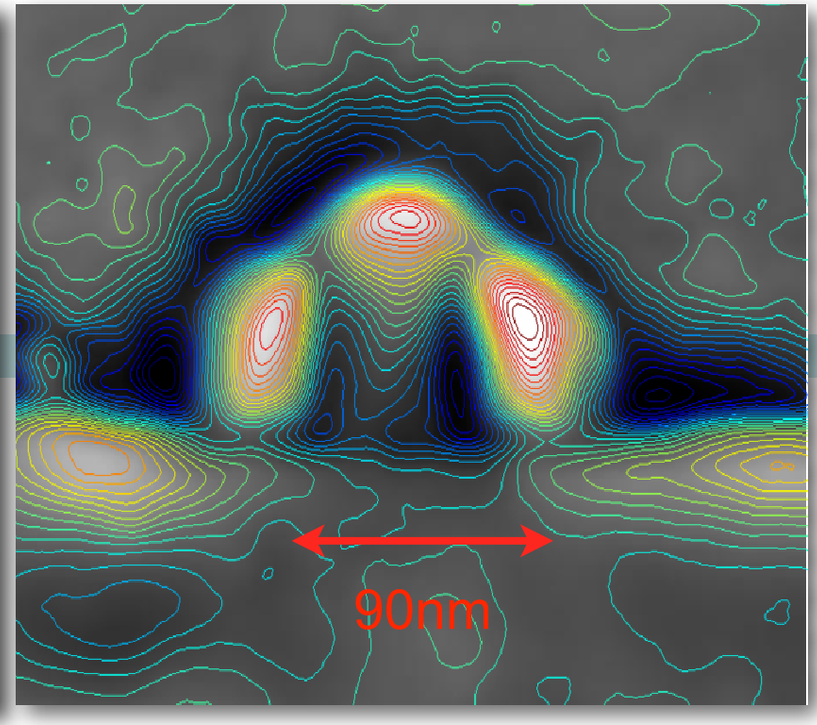
TEM CENTER

pn- junction profile





modulus at exit surface



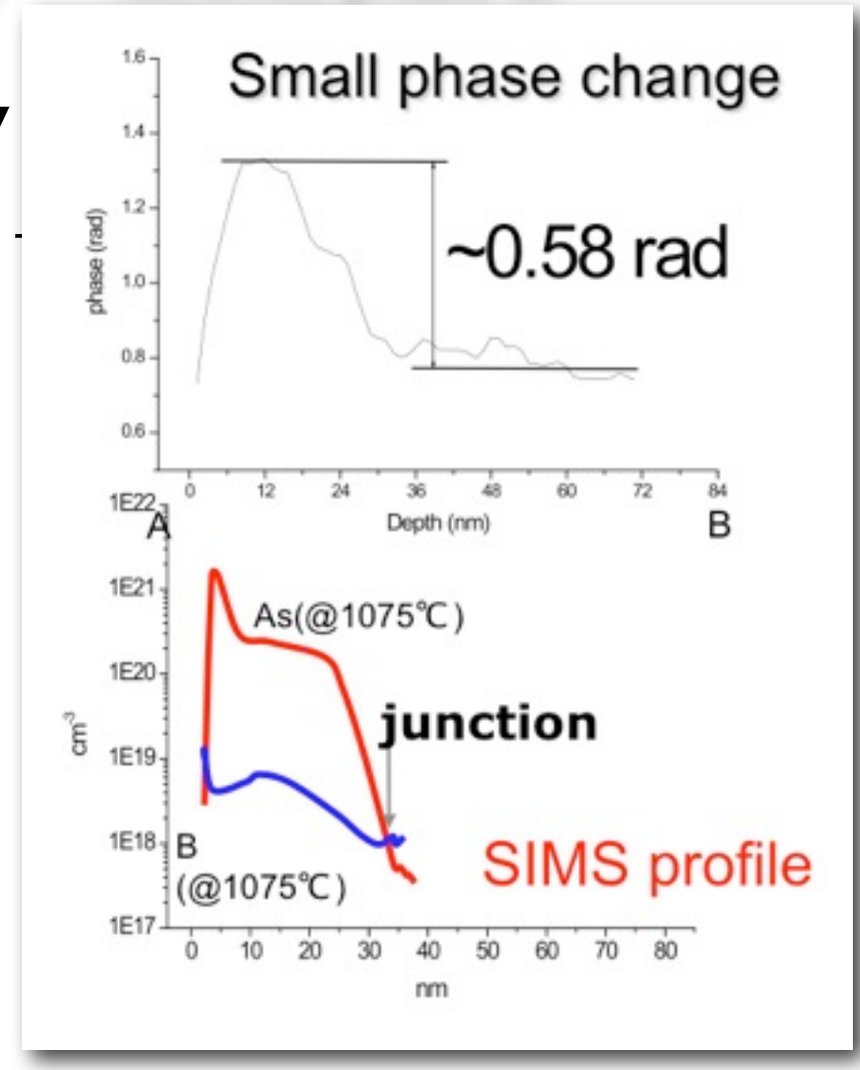
retrieved phase at

$$\nabla_{\perp}\bullet(I(r_{\perp},0)\ \nabla$$

Δf

$$\Delta V_{pn} = \frac{\Delta\varphi}{C_E t} = 0.91V$$

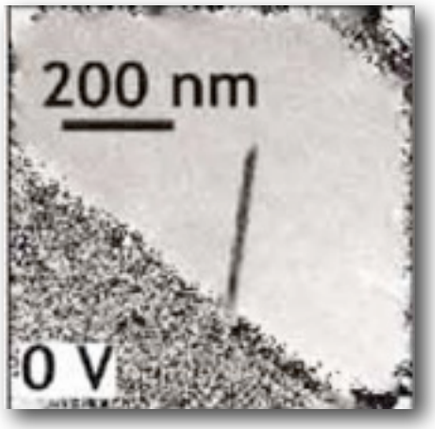
$$\phi(x,y) = C_E \int V(x,y)dz - \frac{e}{h}\int \overrightarrow{B(x,y)}dAdz - \frac{\pi}{\lambda E_o \varepsilon}\int \overrightarrow{P(x,y)}drdZ$$



Equi-Potential Map around Nano-Tip

TEM CENTER

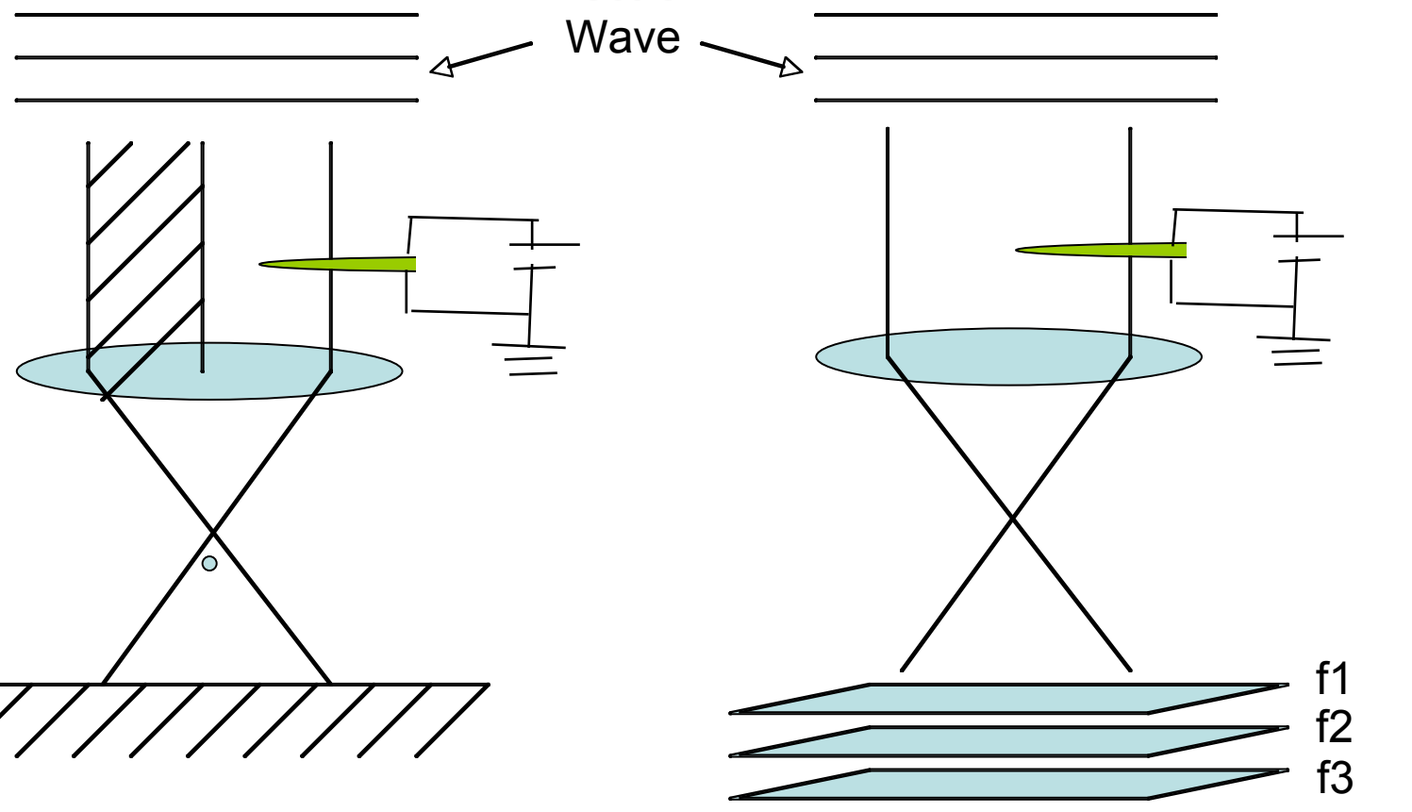
NTHU

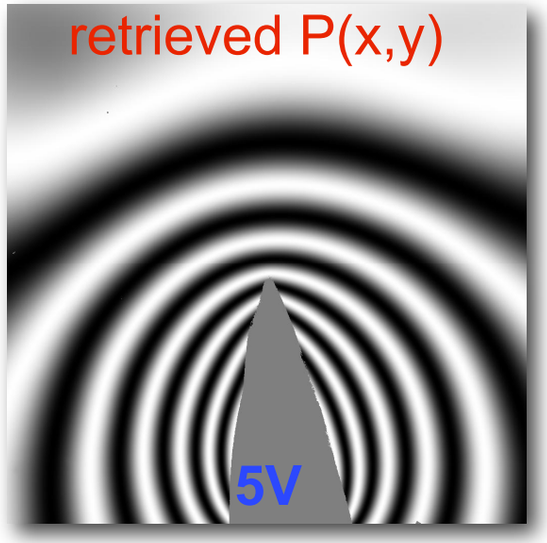


Electron Holography

Electron Wave

Transport of Intensity Equation



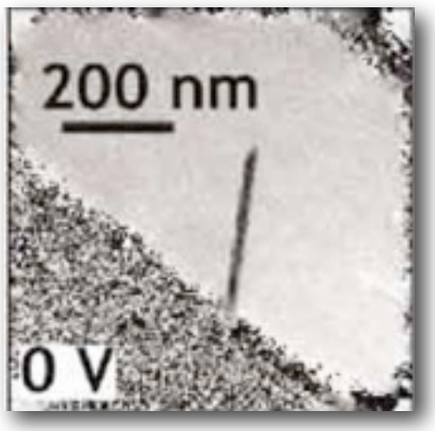


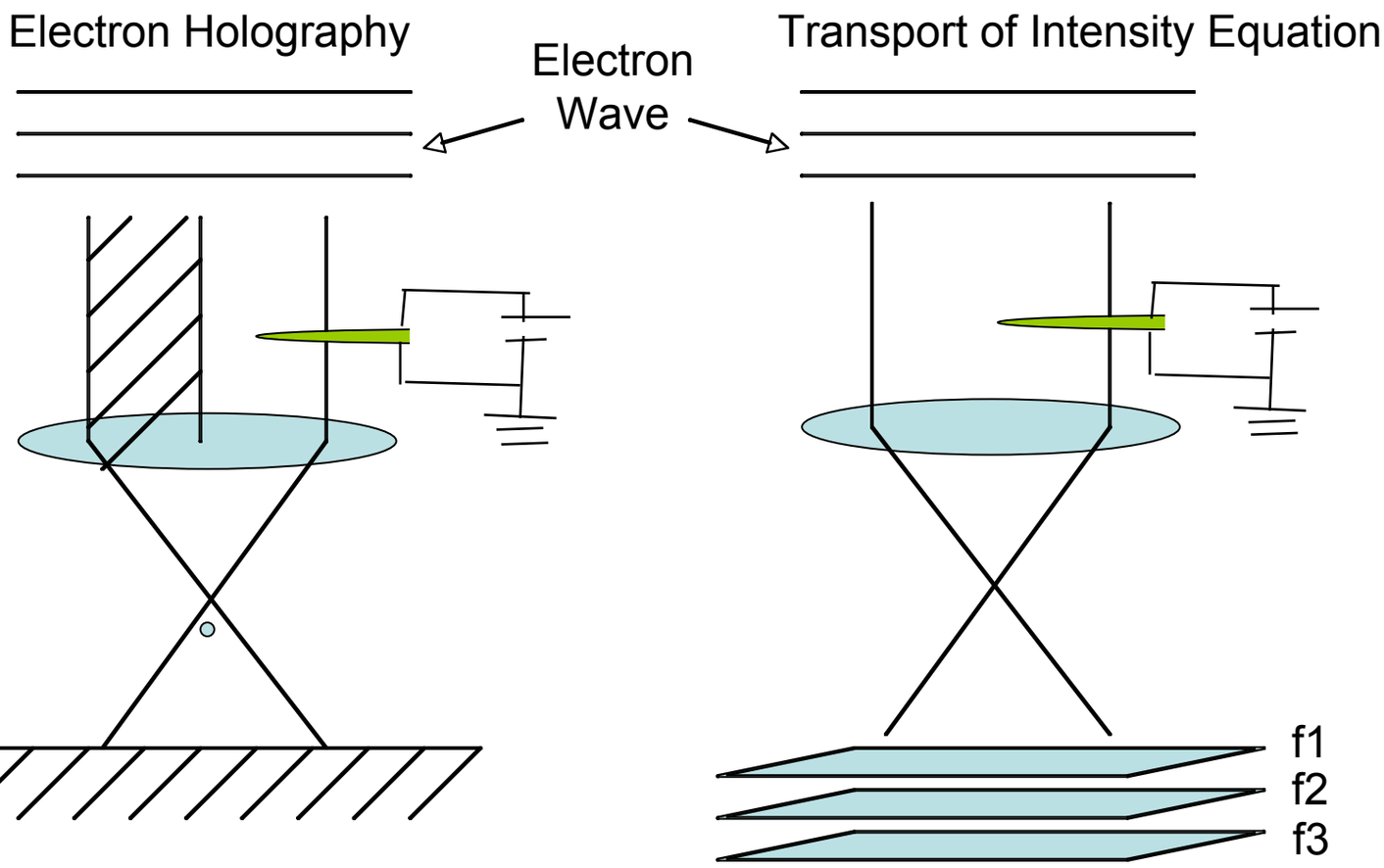
simulated P(x,y)

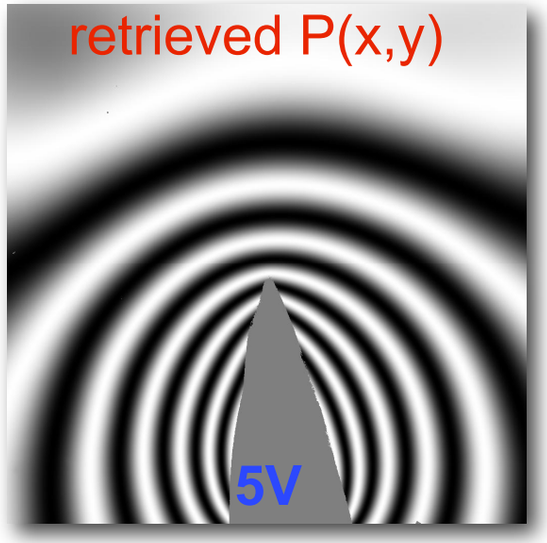
Equi-Potential Map around Nano-Tip

$$\phi(x,y) = C_E \int V(x,y)dz - \frac{e}{h}\int \overrightarrow{B(x,y)}dAdz - \frac{\pi}{\lambda E_o \varepsilon}\int \overrightarrow{P(x,y)}drdZ$$

NTHU





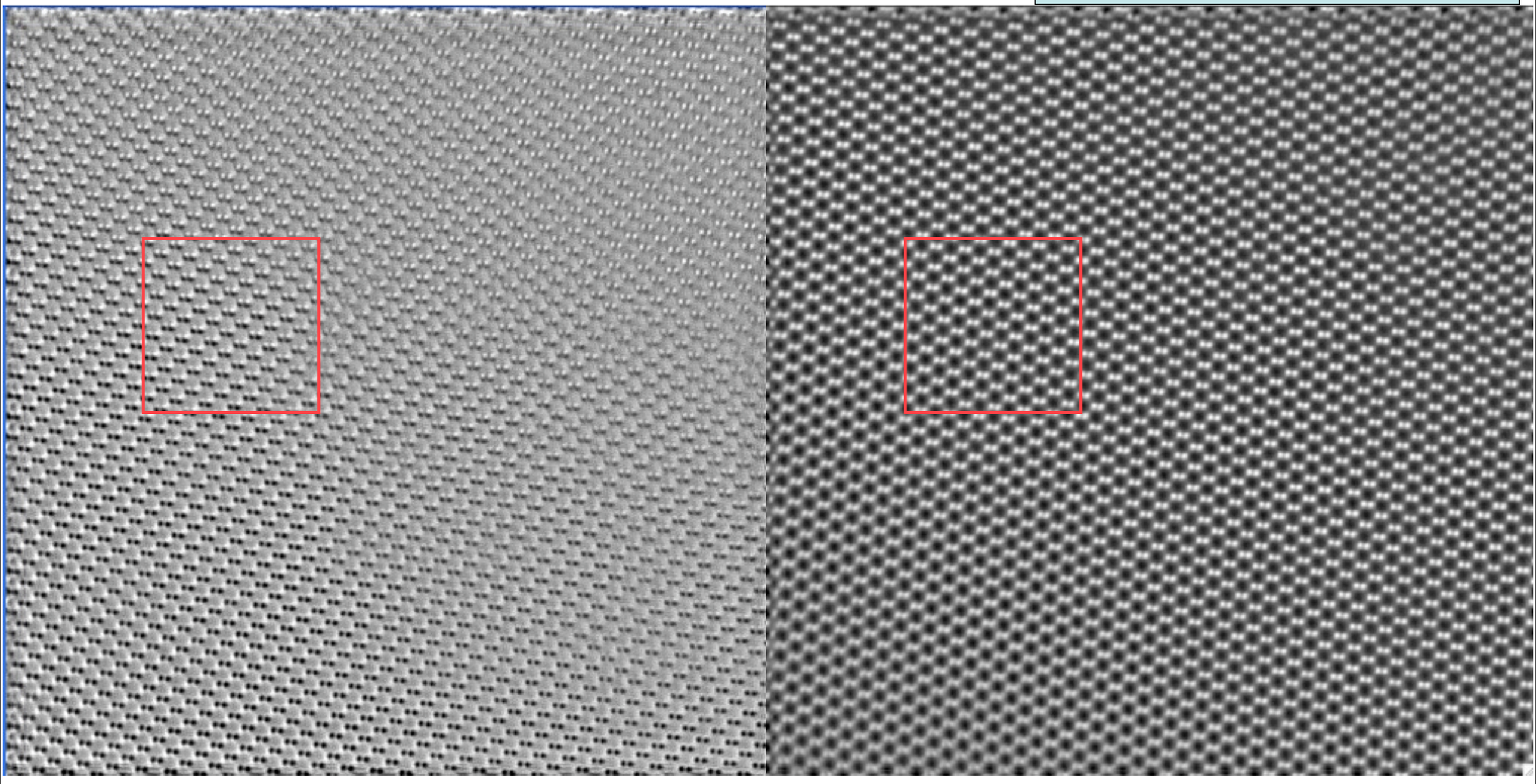


simulated P(x,y)

Reconstructed Exit Wave of Ge

- from de-focal series of Cs corrected HRTEM images

C_s=0.003mm	Δf=0nm
δf=2nm	
α=0.15mrad	step=-2nm
C_s5=5mm	35 images



modulus phase

de-focal series Images contribute from Christian Kisielowski, NCEM, Berkeley

Reconstructed Exit Wave of Ge

- from de-focal series of Cs corrected HRTEM images

C_s=0.003mm	Δf=0nm
δf=2nm	
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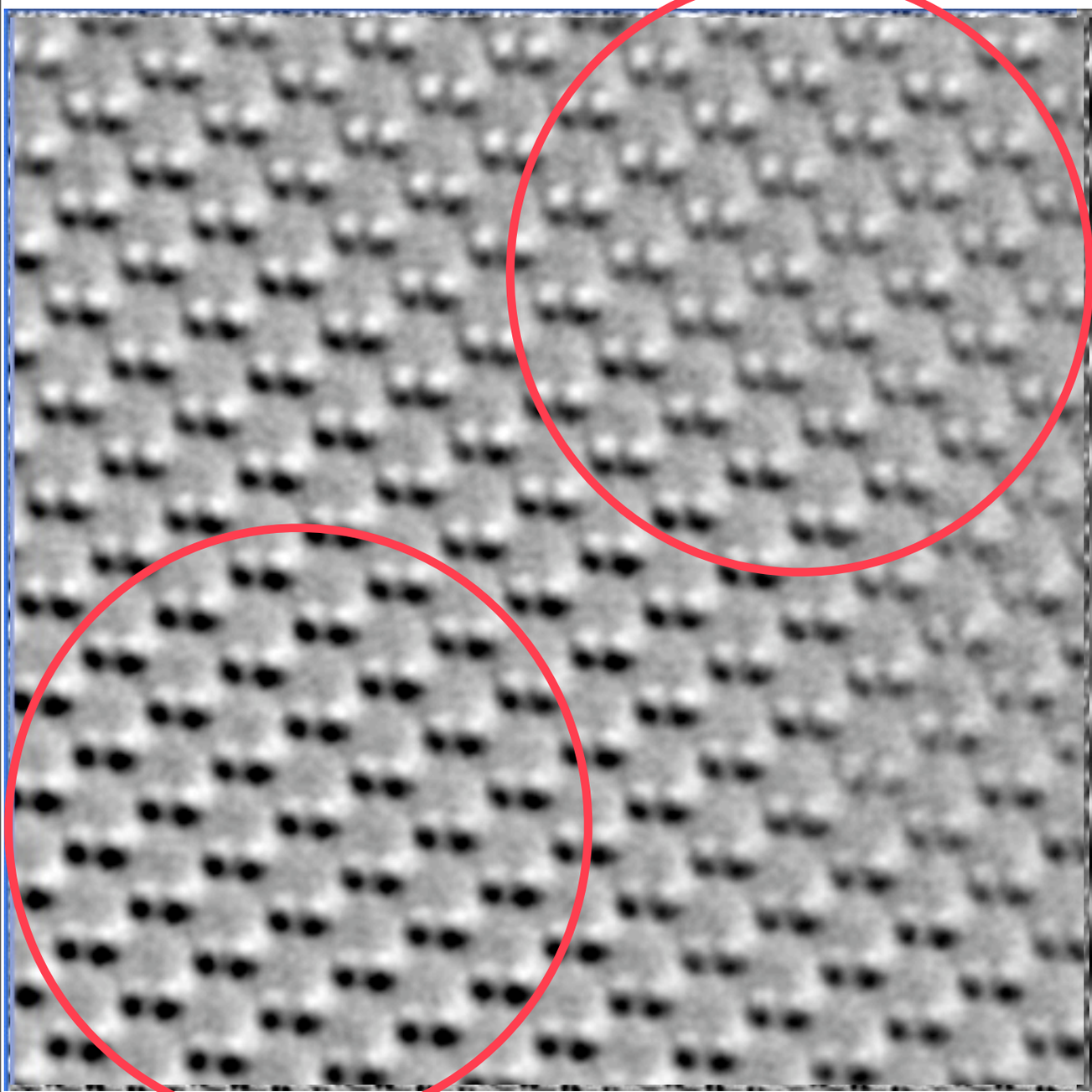


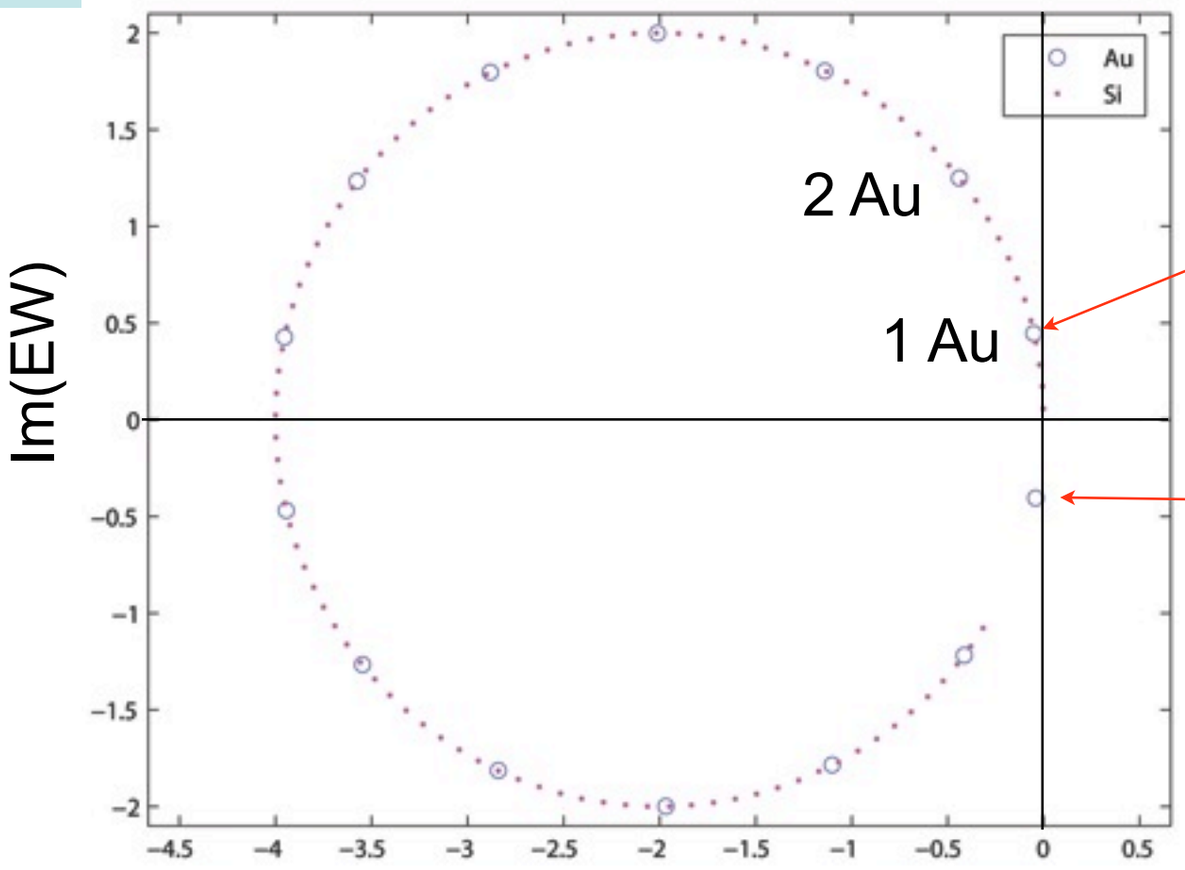
modulus

phase

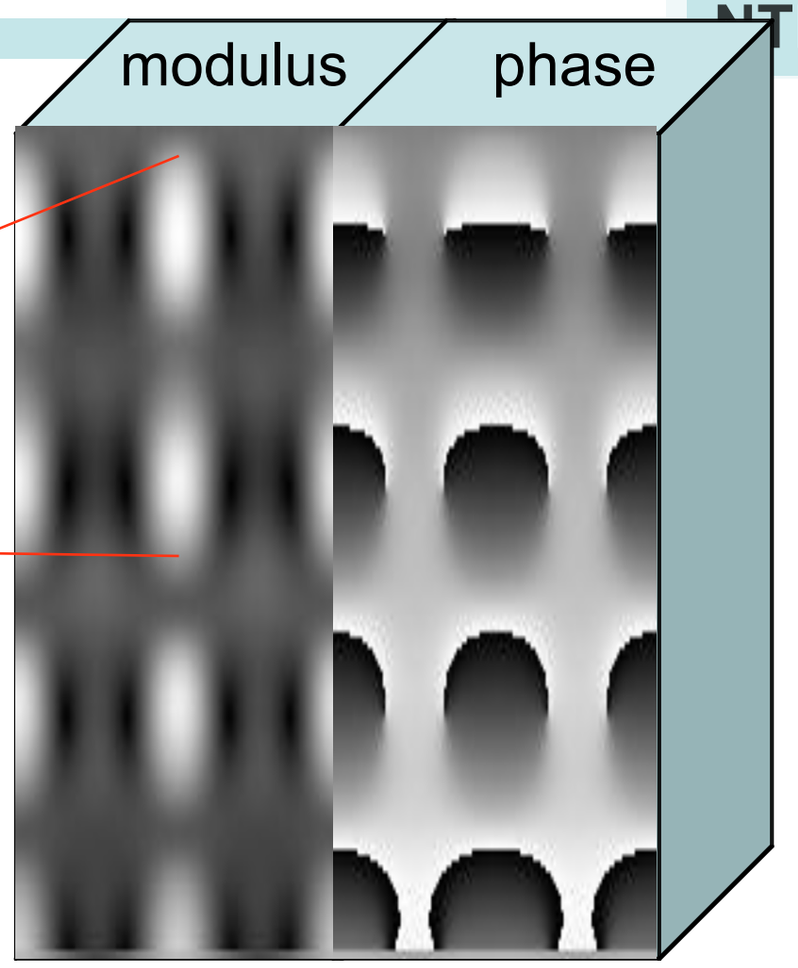
de-focal series Images contribute from Christian Kisielowski, NCEM, Berkeley

Propagation of Electron Wave inside Crystal (Channeling, 1s state wave)

Argand Plot for Exit Wave



Au

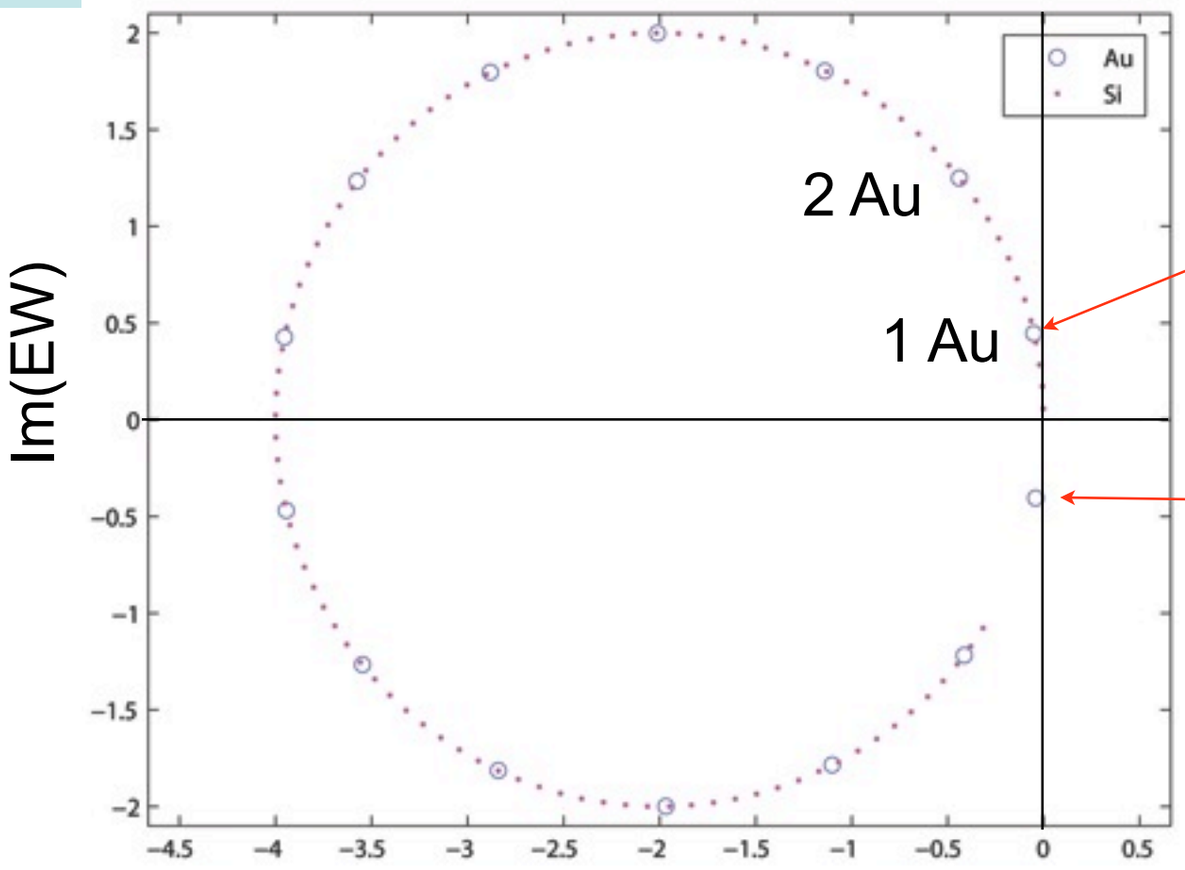


$$\mathrm{Re}(\psi(r,z)-1) = -2C_{1s}\sin^2(\pi\frac{E_{1s}}{E_0}\frac{k}{2}z)\phi_{1s}$$

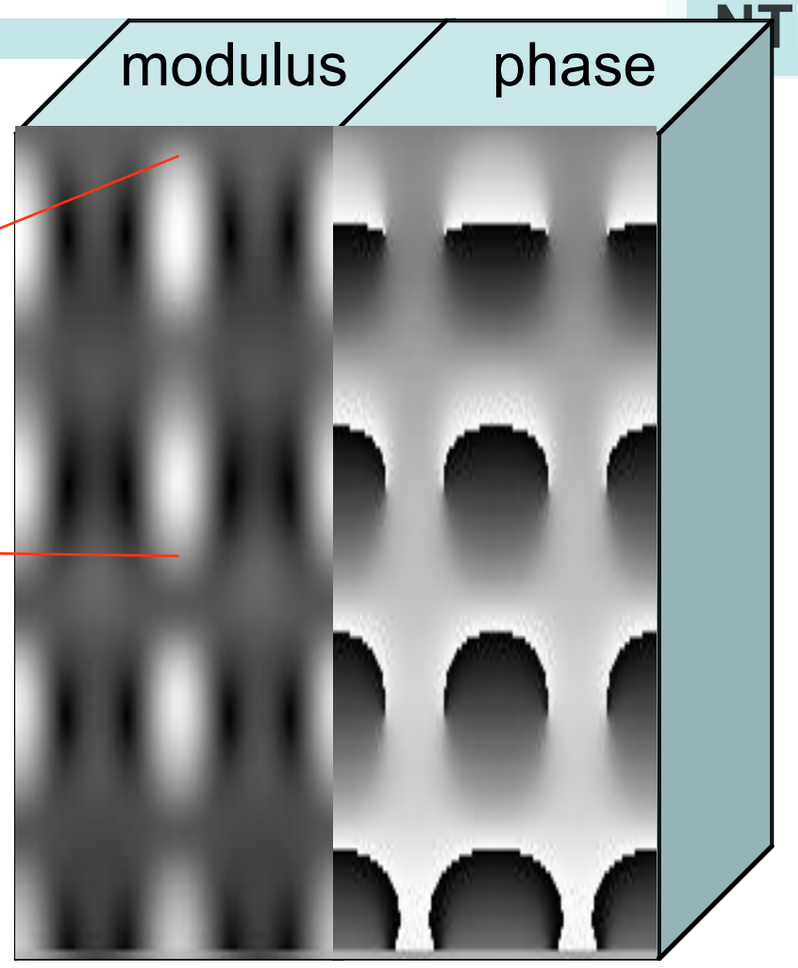
$$\mathrm{Im}(\psi(r,z)-1) = -2C_{1s}\sin(\pi\frac{E_{1s}}{E_0}\frac{k}{2}z)\cos(\pi\frac{E_{1s}}{E_0}\frac{k}{2}z)\phi_{1s}$$

Propagation of Electron Wave inside Crystal (Channeling, 1s state wave)

Argand Plot for Exit Wave



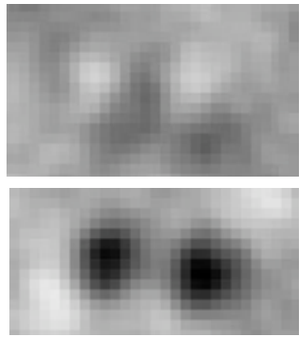
Au



$$\mathrm{Re}(\psi(r,z)-1) = -2C_{1s}\sin^2(\pi\frac{E_{1s}}{E_0}\frac{k}{2}z)\phi_{1s}$$

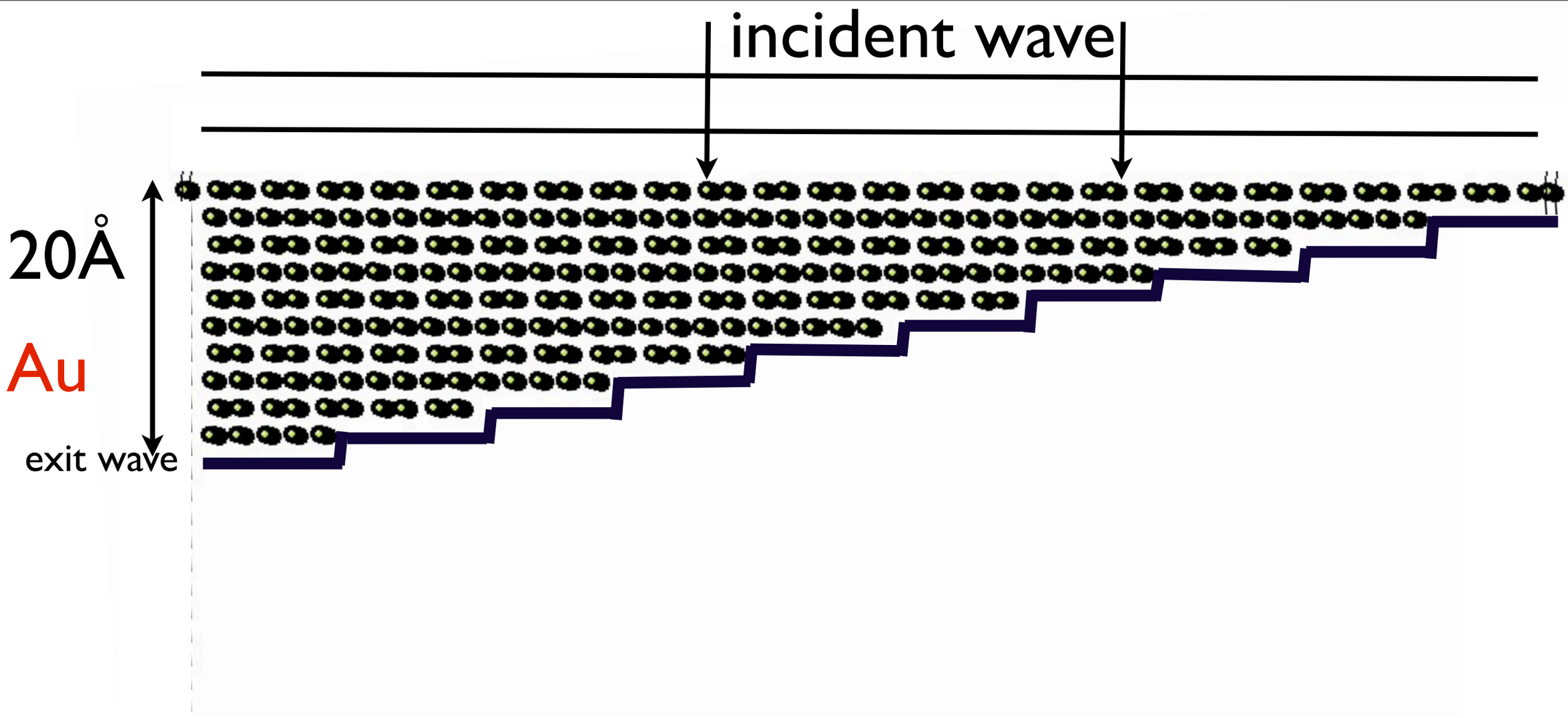
$$\mathrm{Im}(\psi(r,z)-1) = -2C_{1s}\sin(\pi\frac{E_{1s}}{E_0}\frac{k}{2}z)\cos(\pi\frac{E_{1s}}{E_0}\frac{k}{2}z)\phi_{1s}$$

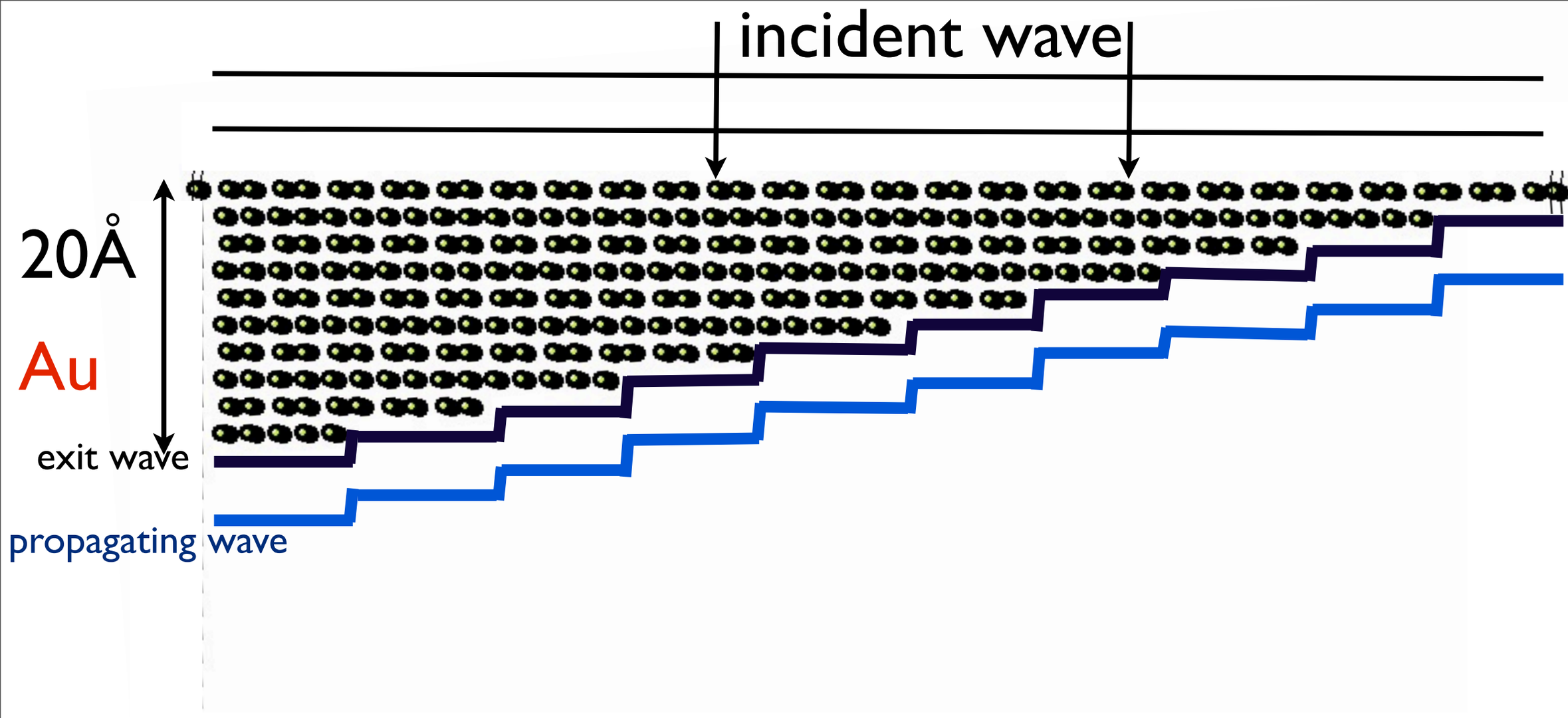
Atomic column acts as “positive” electro-static lens

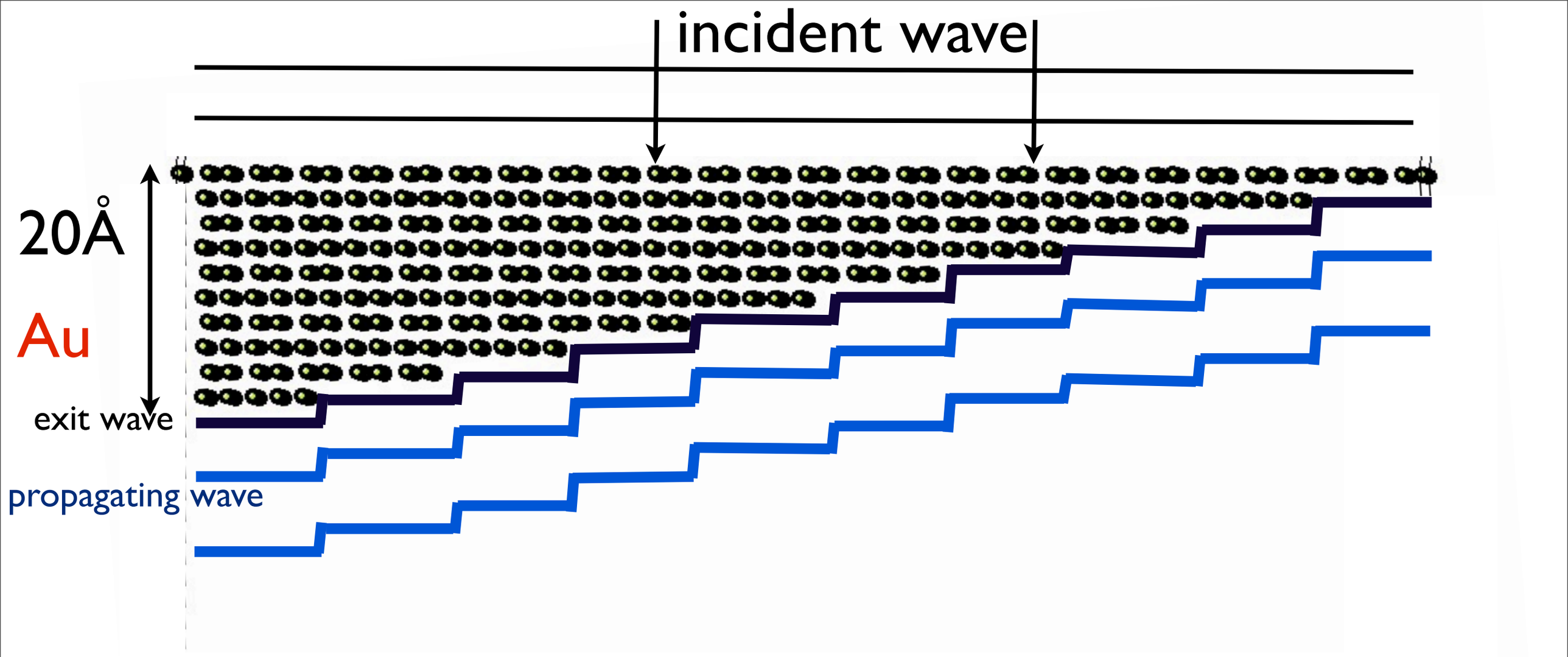


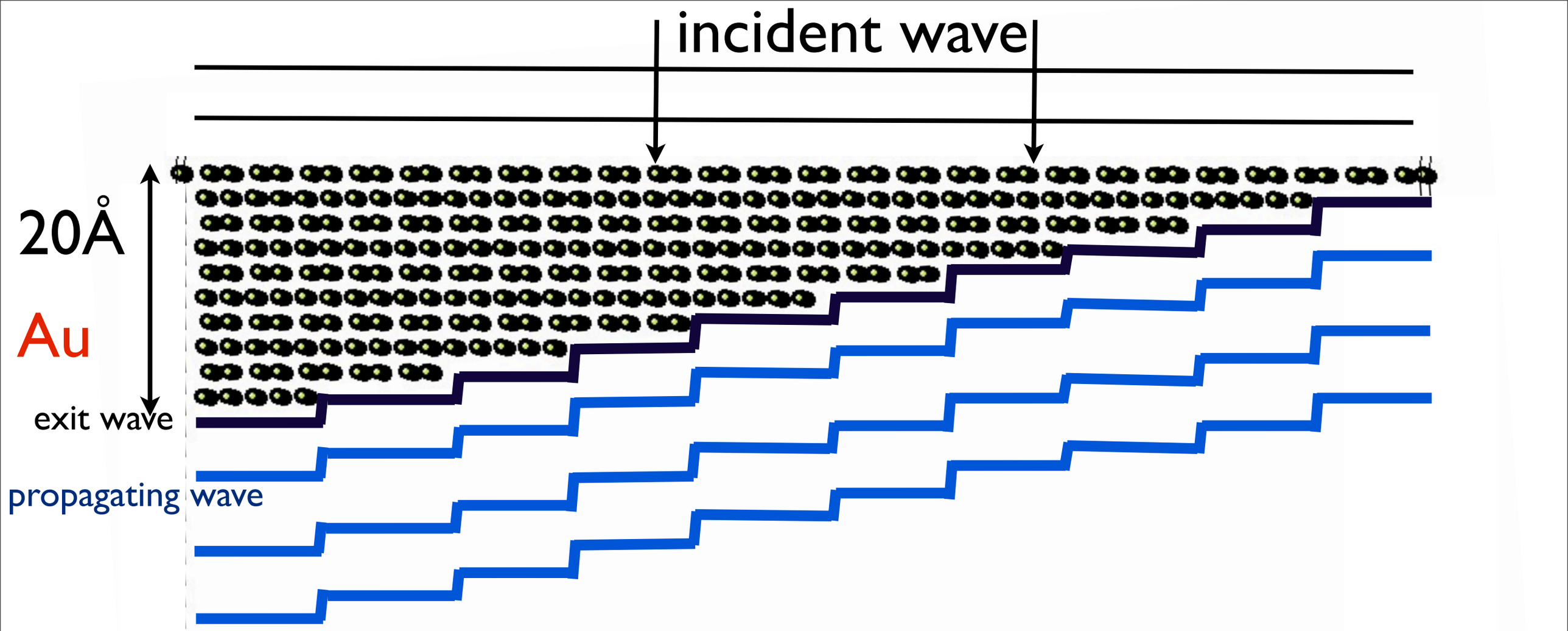
White atomic column ✓

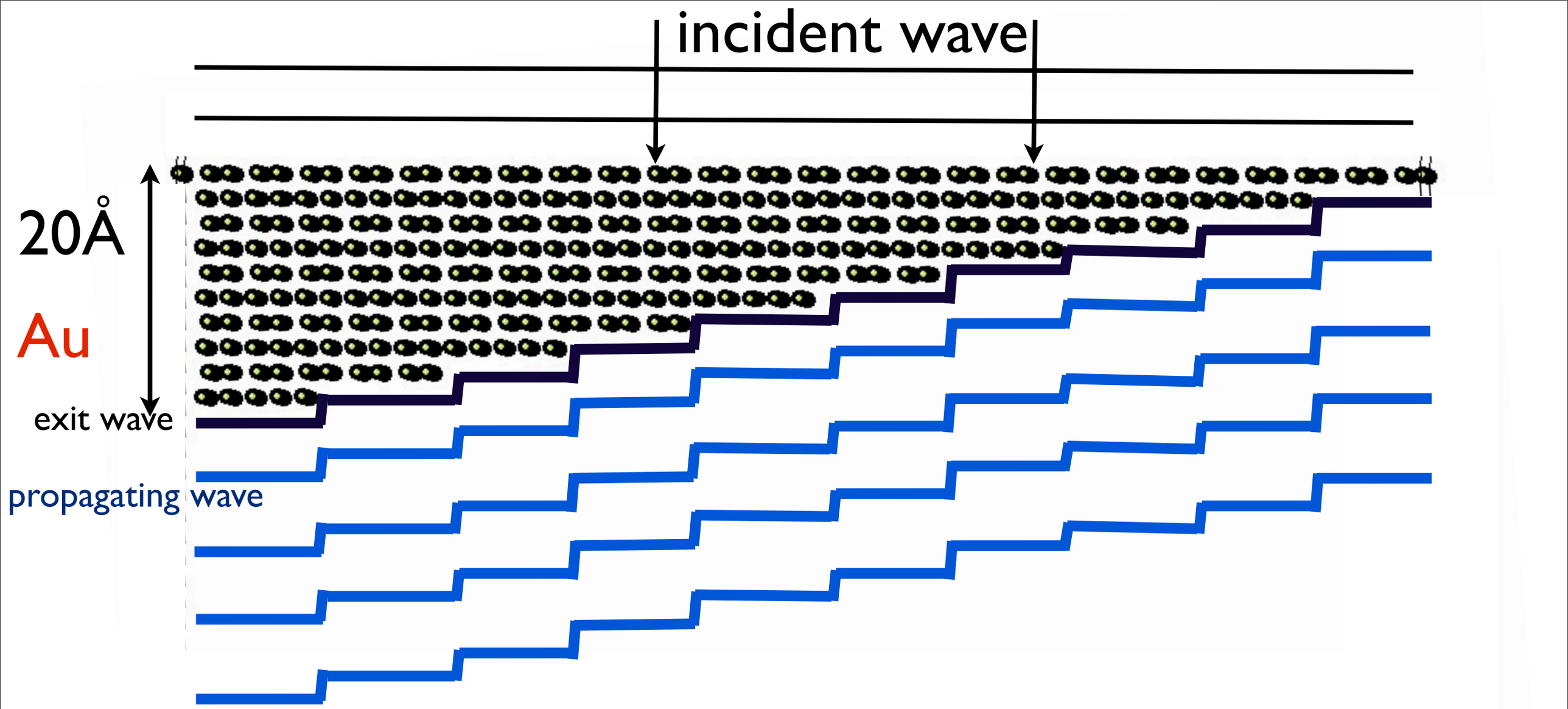
Black atomic column ✗

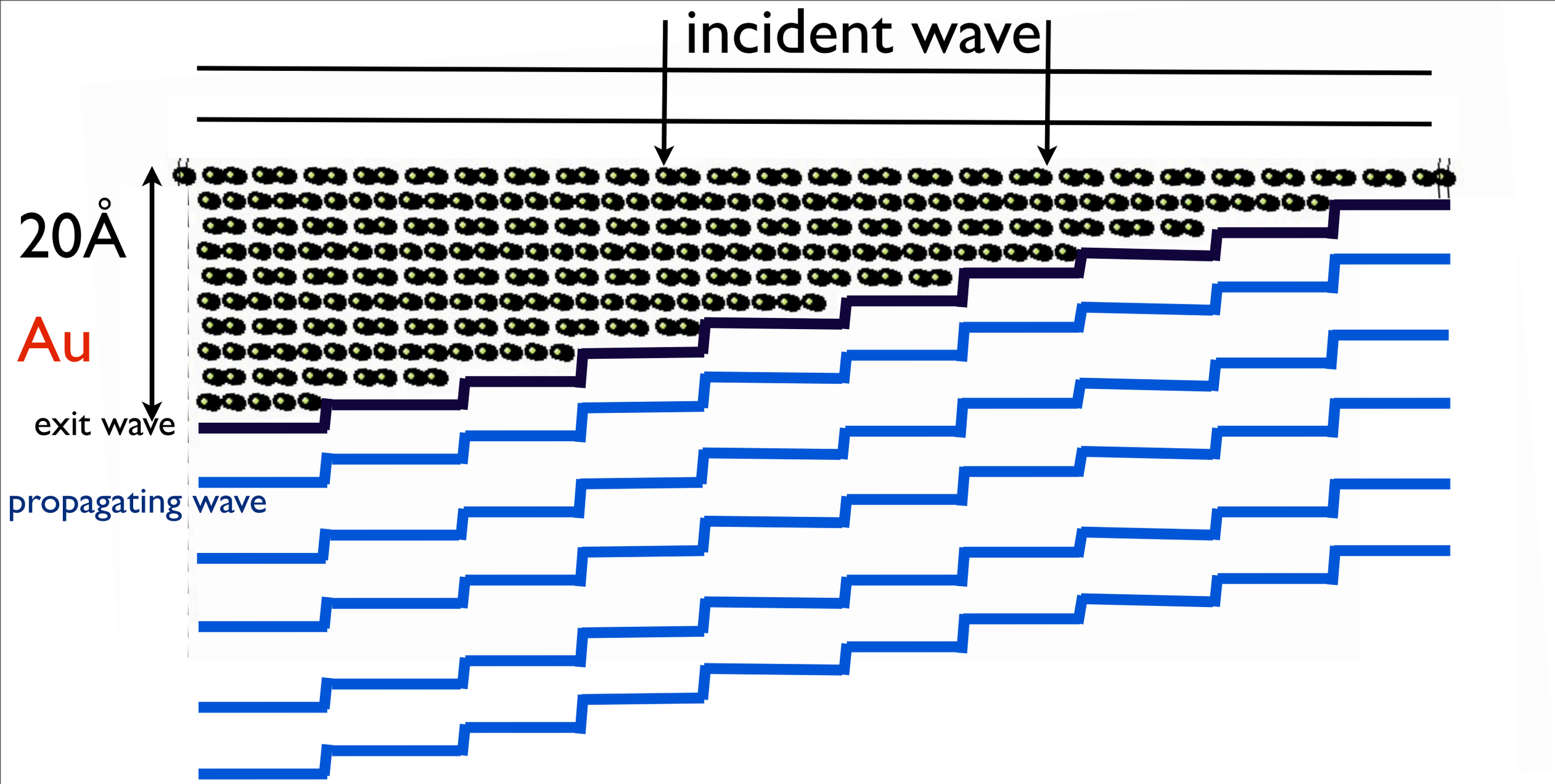

incident wave
20Å
Au
exit wave

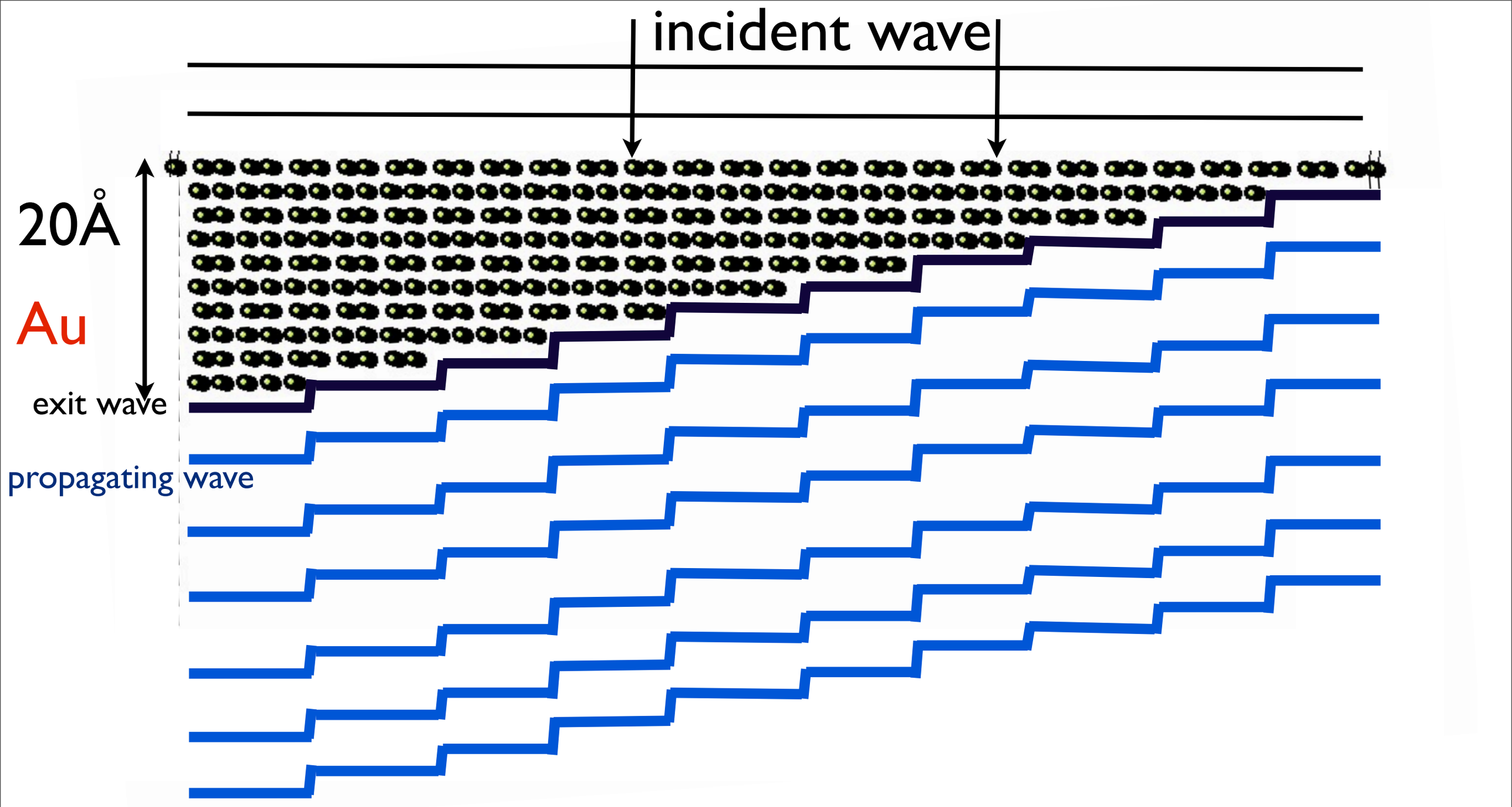

incident wave
20Å
Au
exit wave
propagating wave

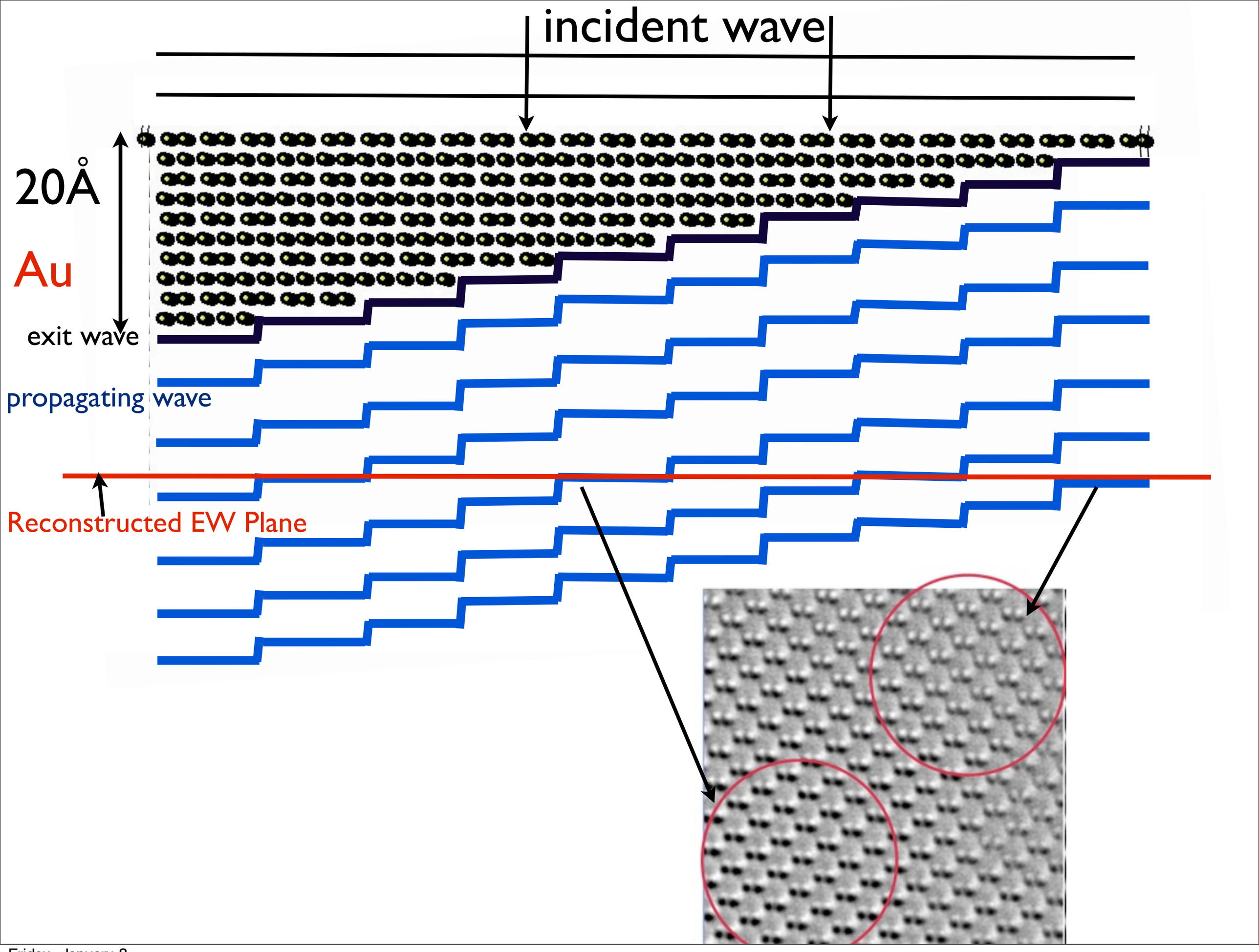

incident wave
20Å
Au
exit wave
propagating wave


incident wave
20Å
Au
exit wave
propagating wave


incident wave
20Å
Au
exit wave
propagating wave


incident wave
20Å
Au
exit wave
propagating wave


incident wave
20Å
Au
exit wave
propagating wave


incident wave
20Å
Au
exit wave
propagating wave
Reconstructed EW Plane

incident wave

20Å

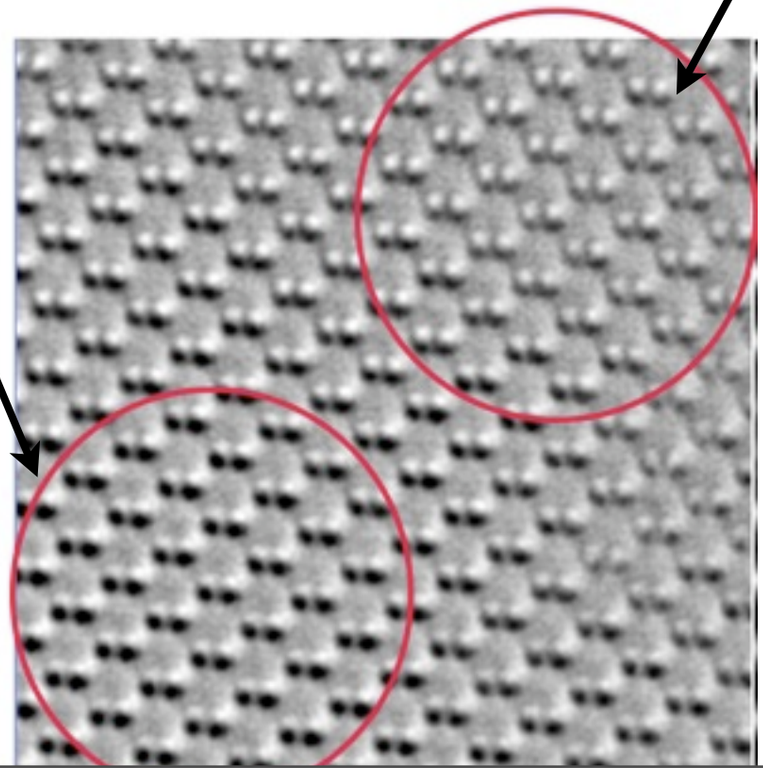
Au

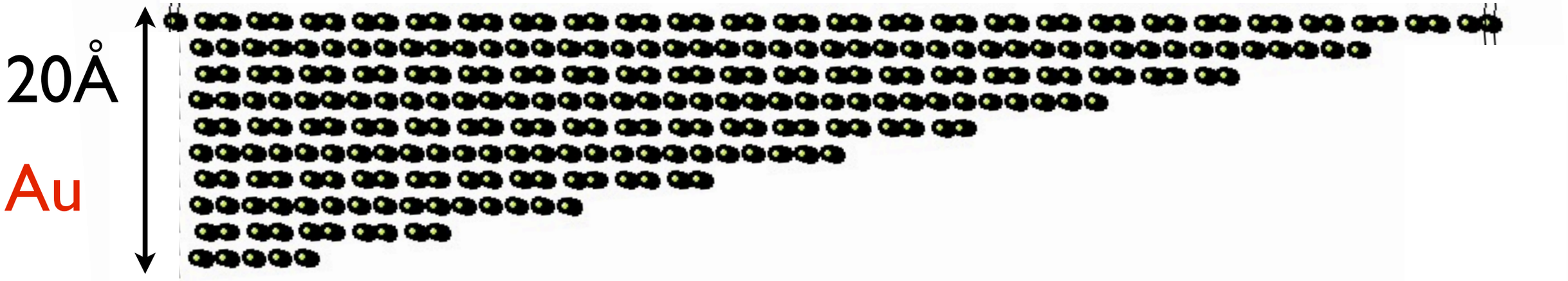
exit wave

propagating wave

Reconstructed EW Plane

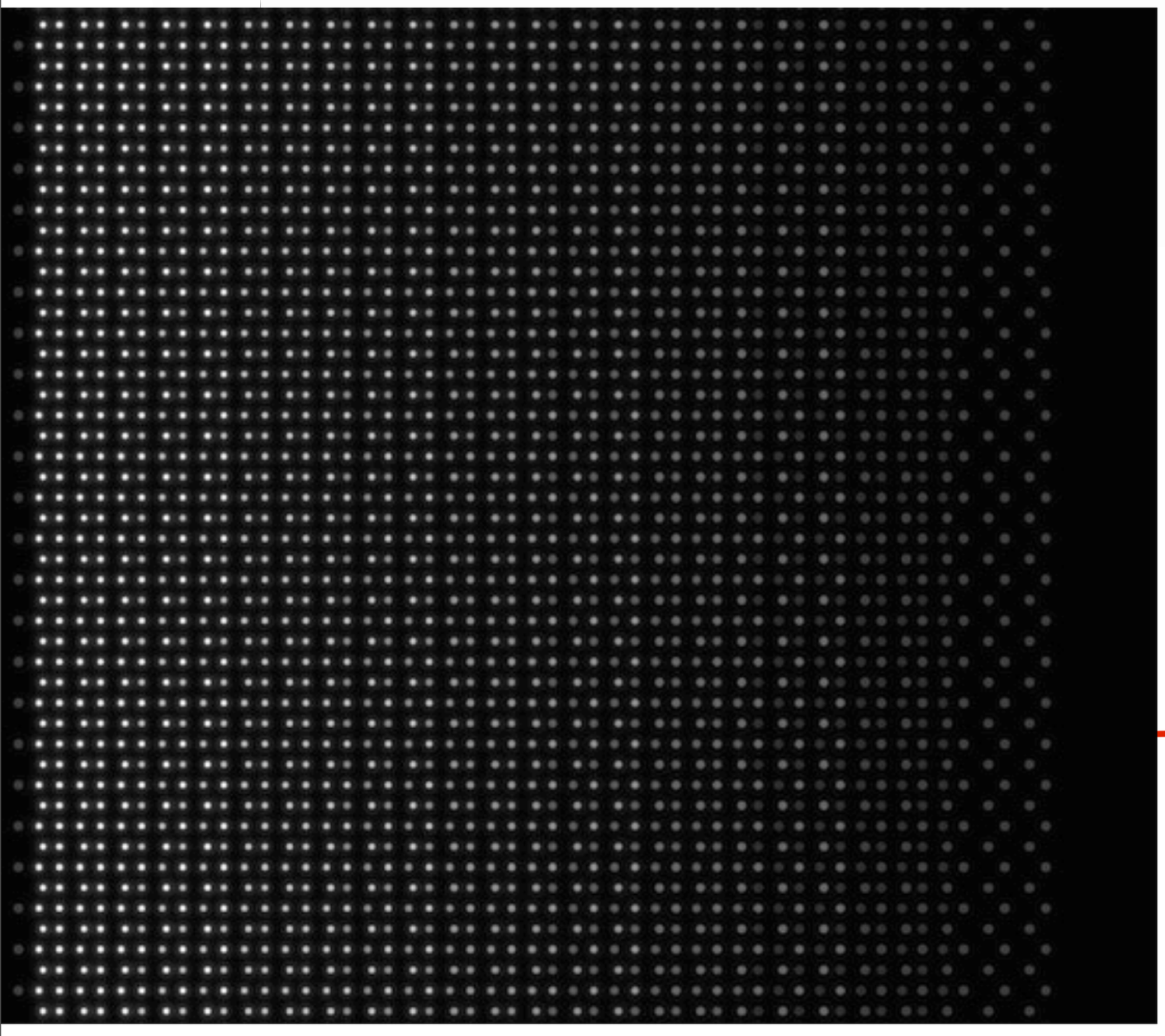
Z(r): focus plate




20Å
Au

20Å

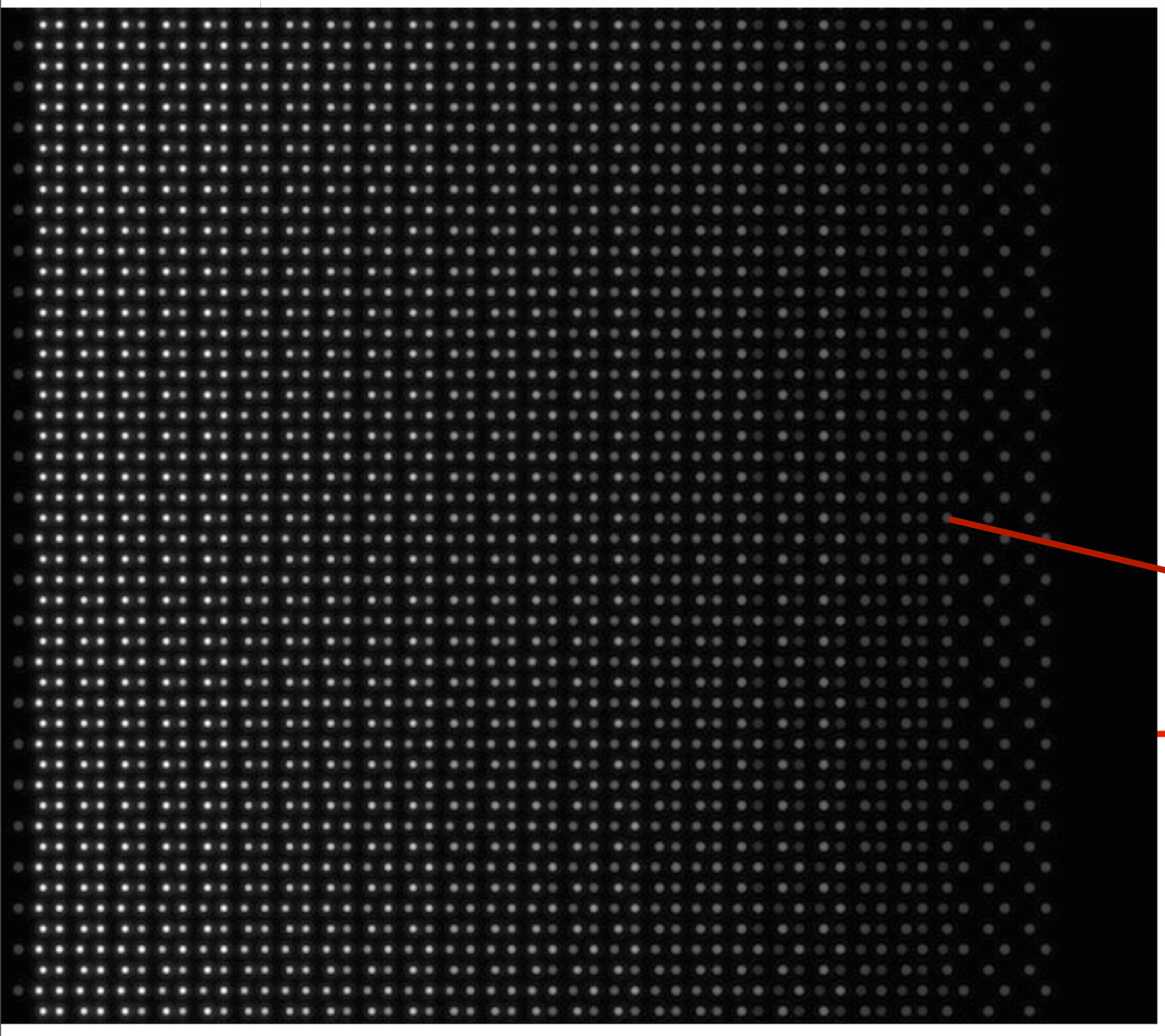
Au



Plane of Reconstructed EW

20Å

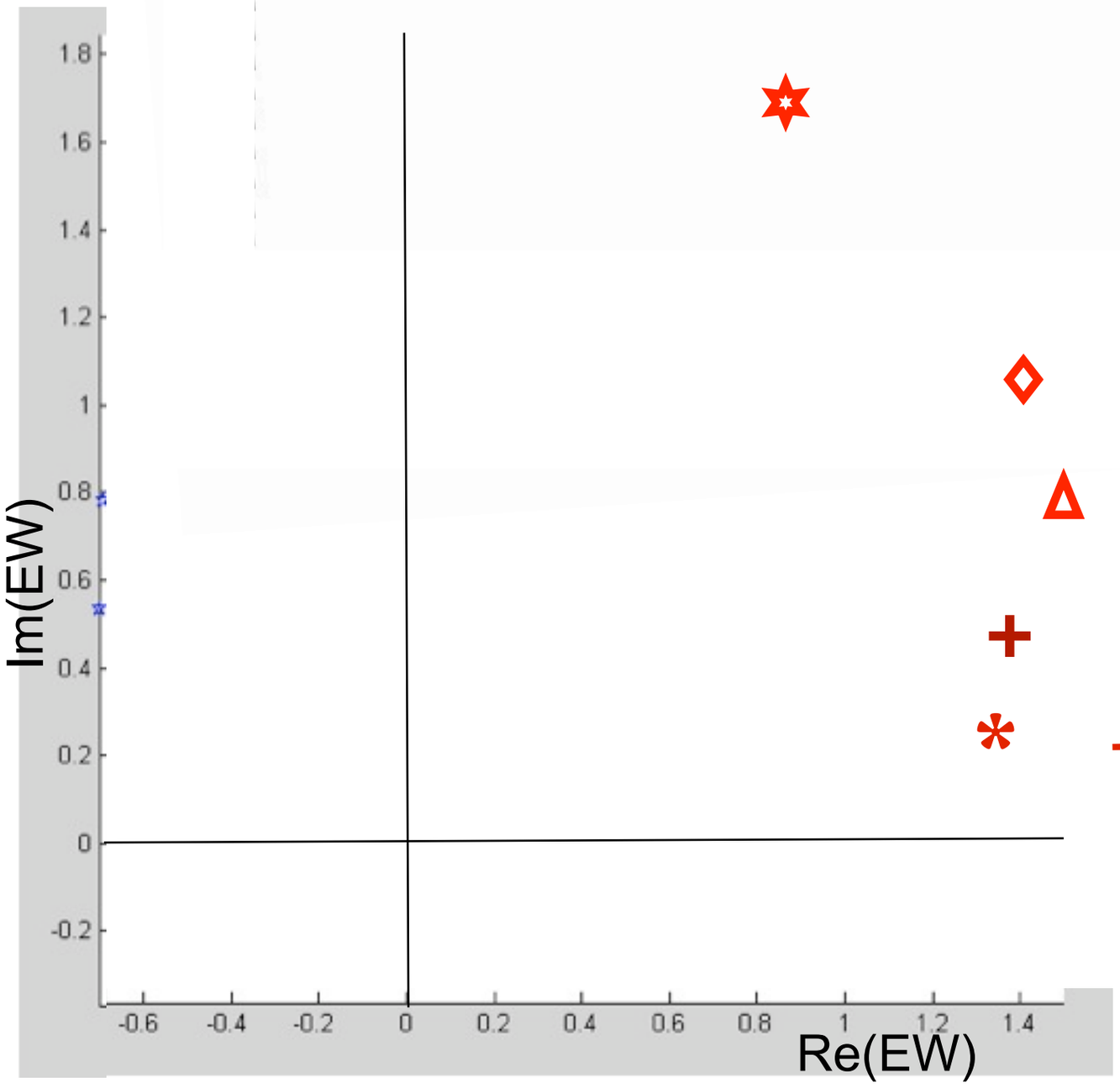
Au

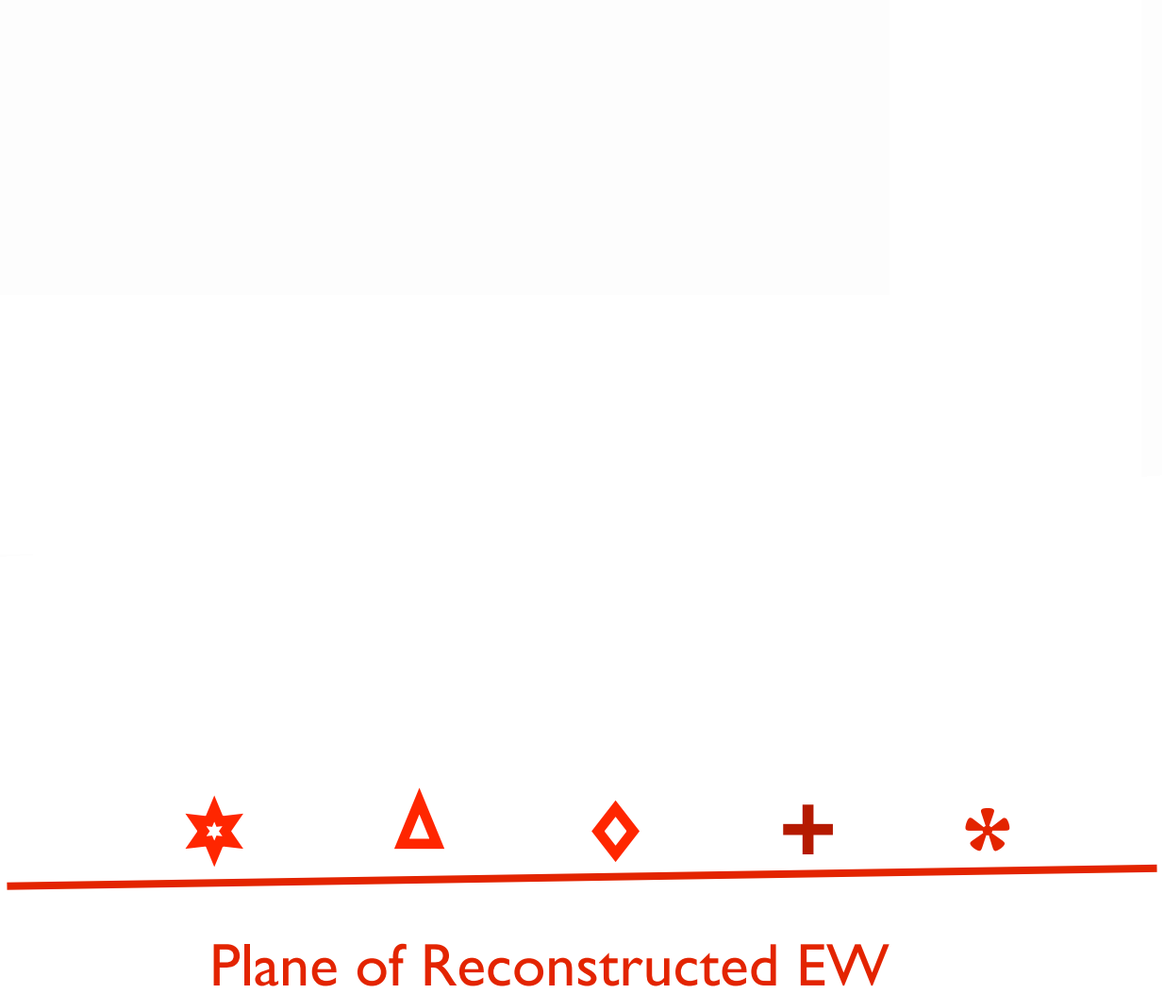


Plane of Reconstructed EW

20Å

Au

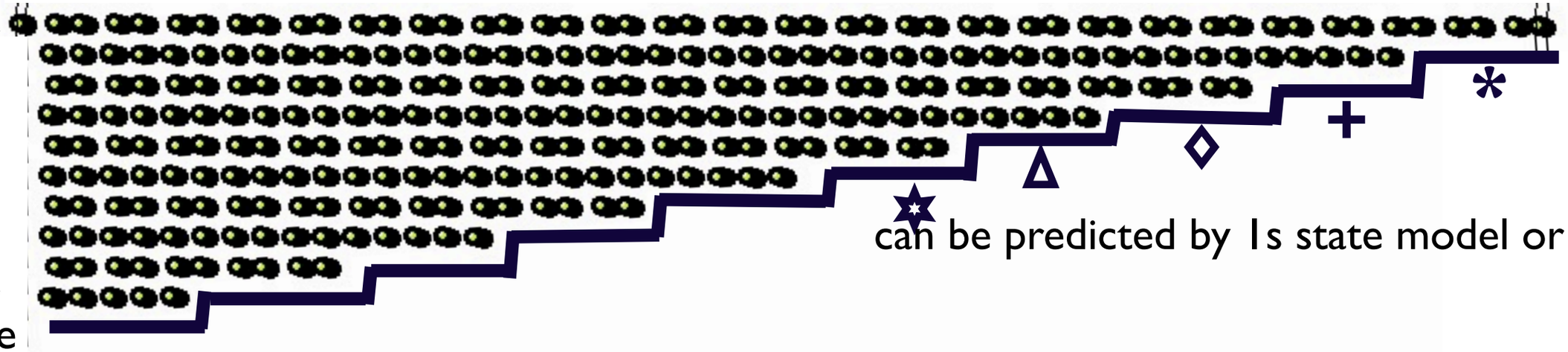

1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
Im(EW)
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Re(EW)


Plane of Reconstructed EW

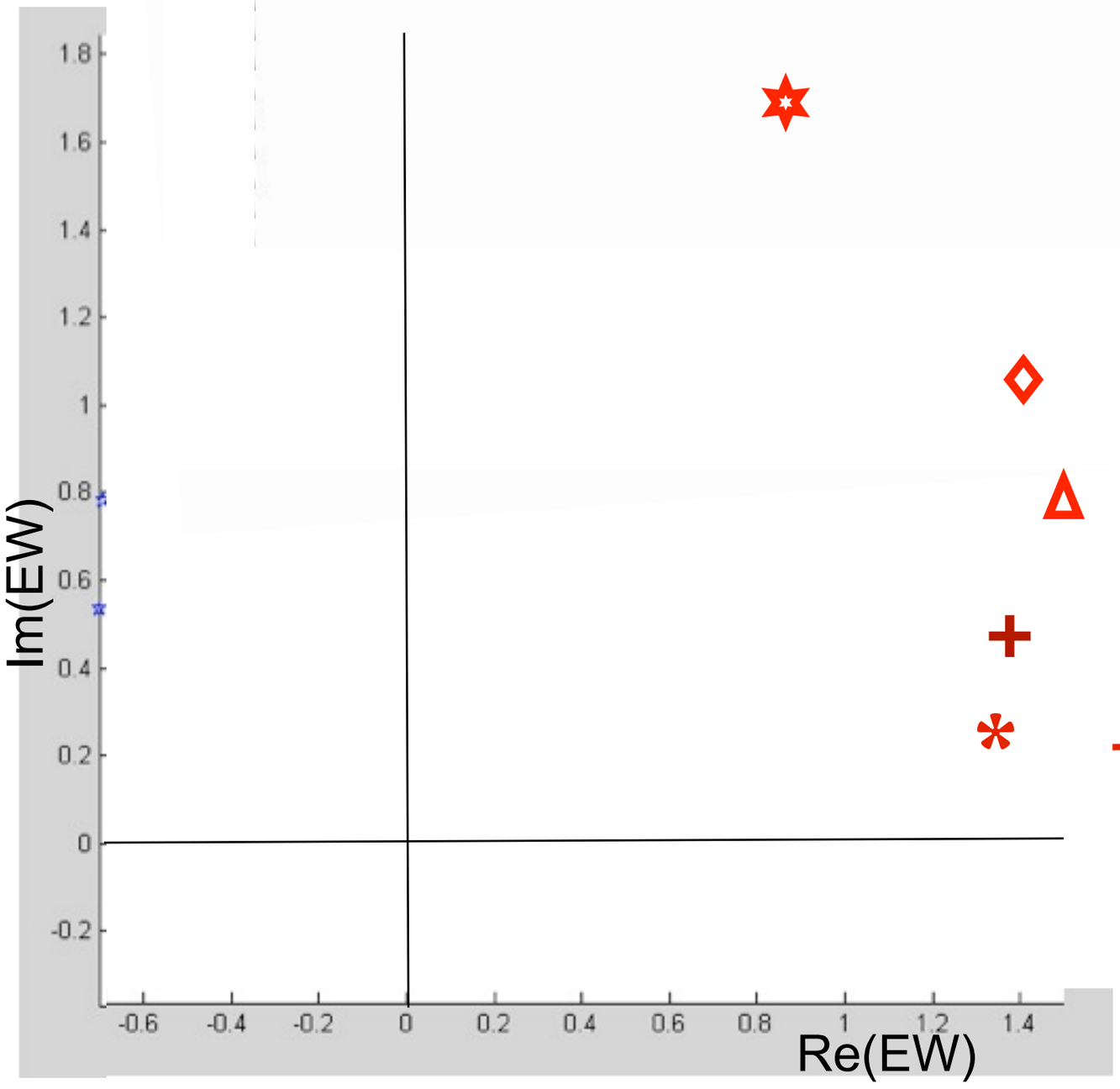
20Å

Au

exit wave



can be predicted by 1s state model or multisli

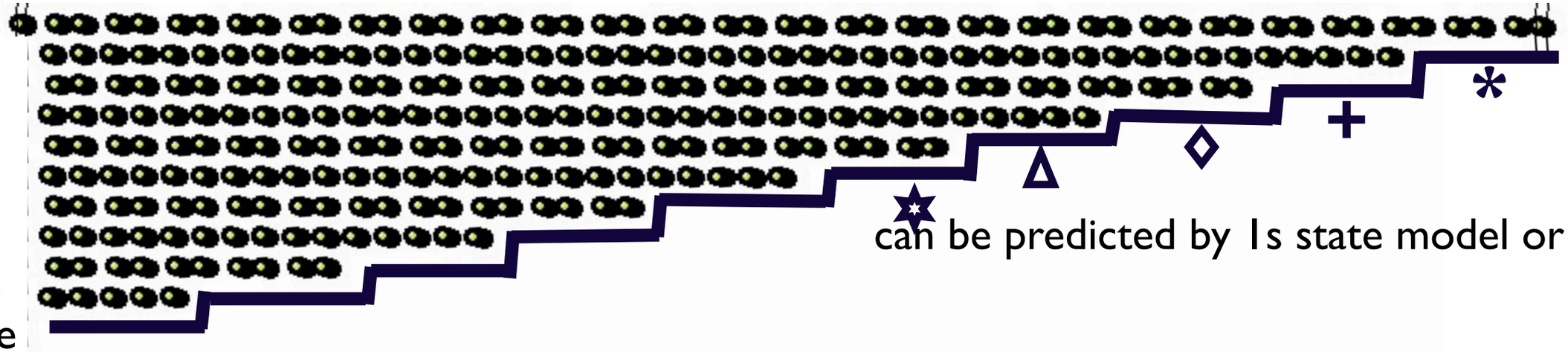


Plane of Reconstructed EW

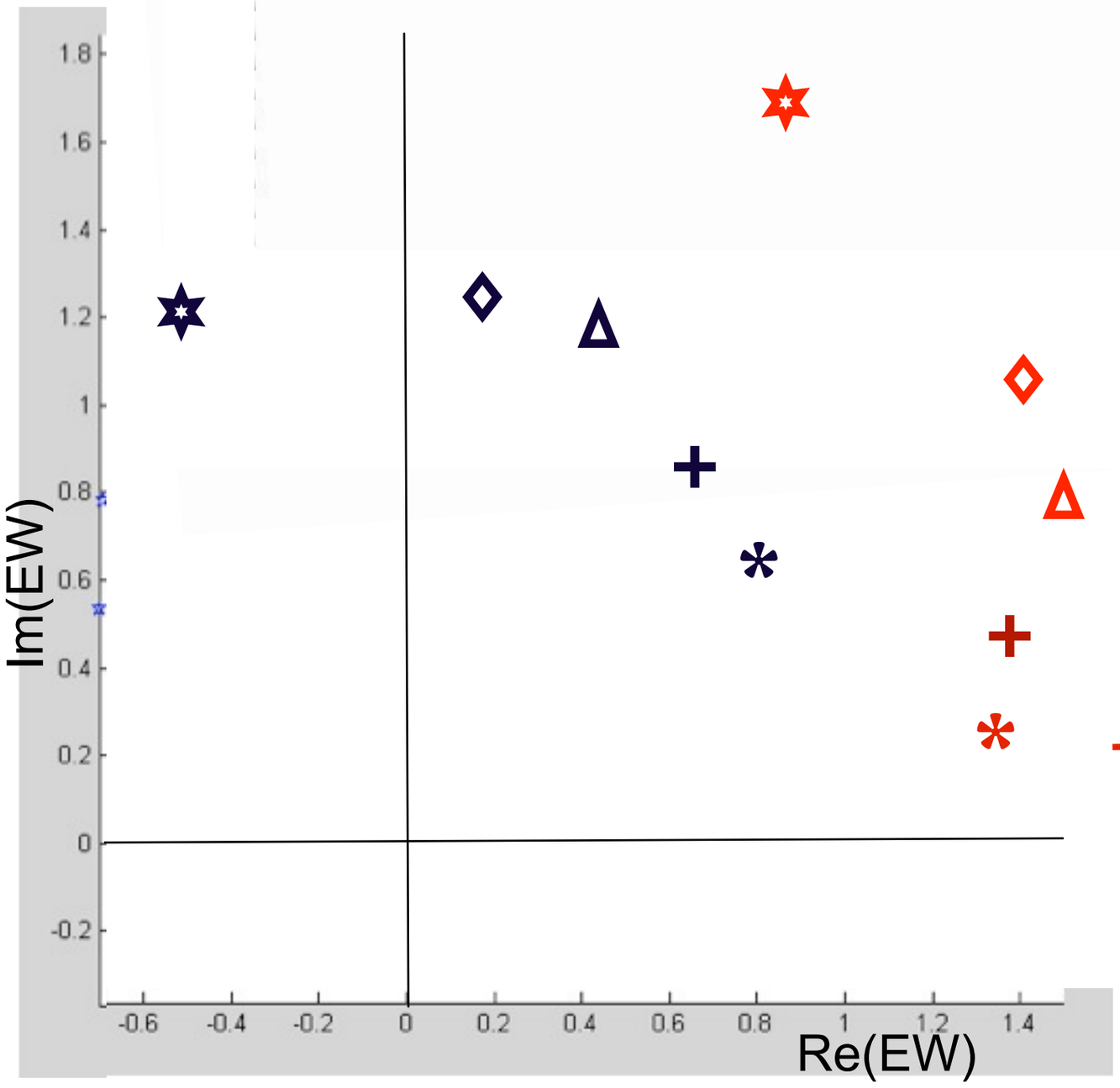
20Å

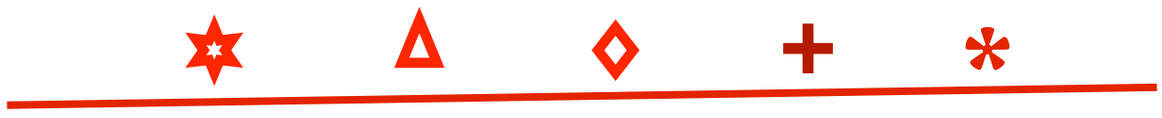
Au

exit wave



can be predicted by 1s state model or multisli



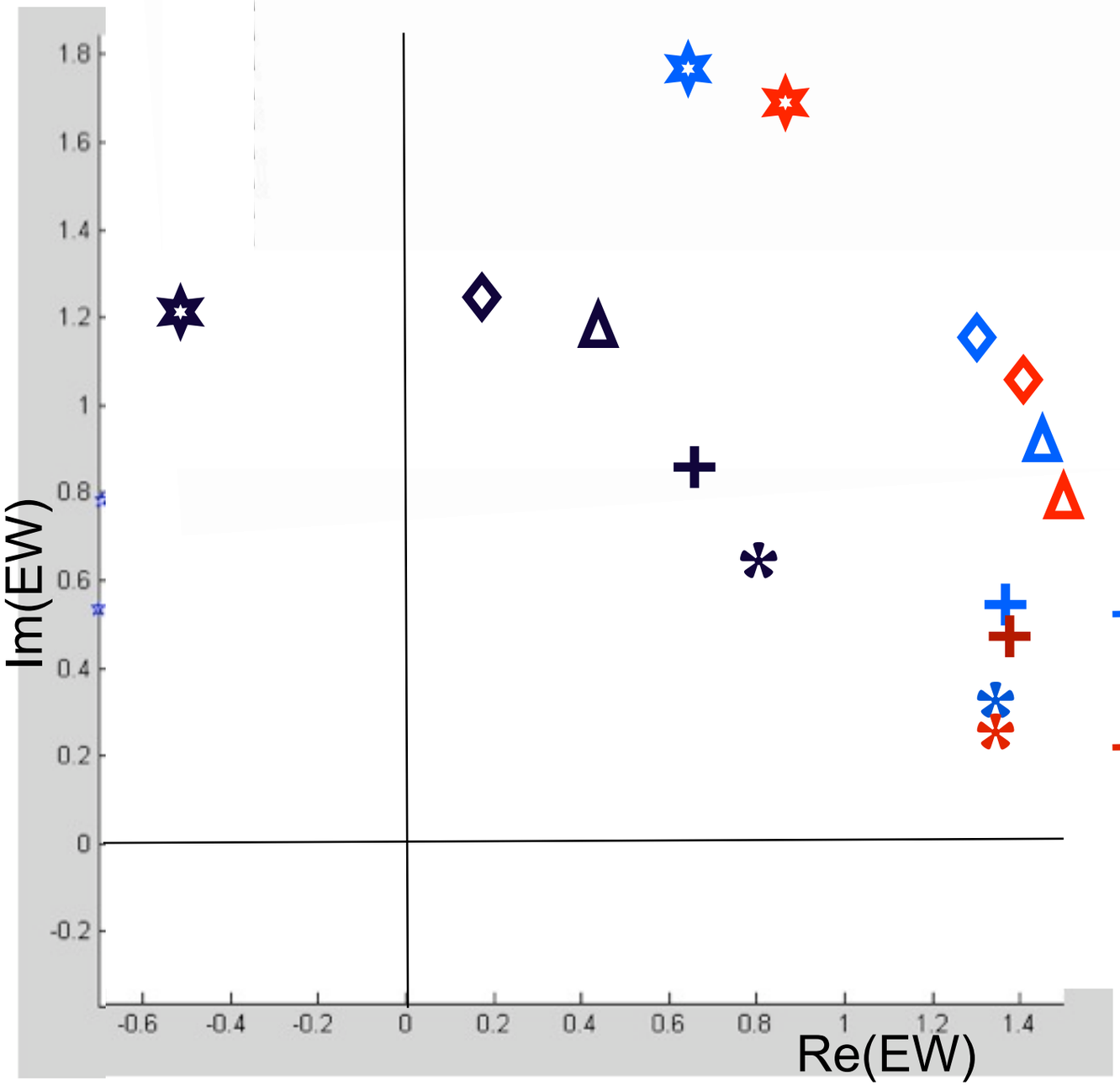


Plane of Reconstructed EW

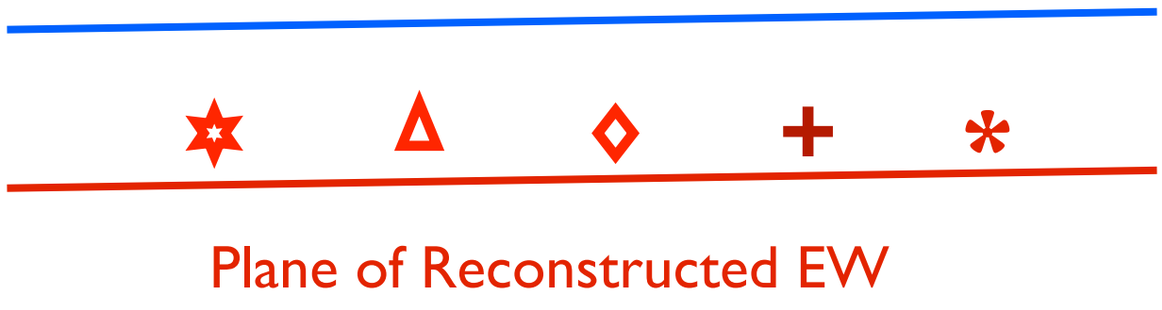
20Å

Au

exit wave



can be predicted by 1s state model or multisli

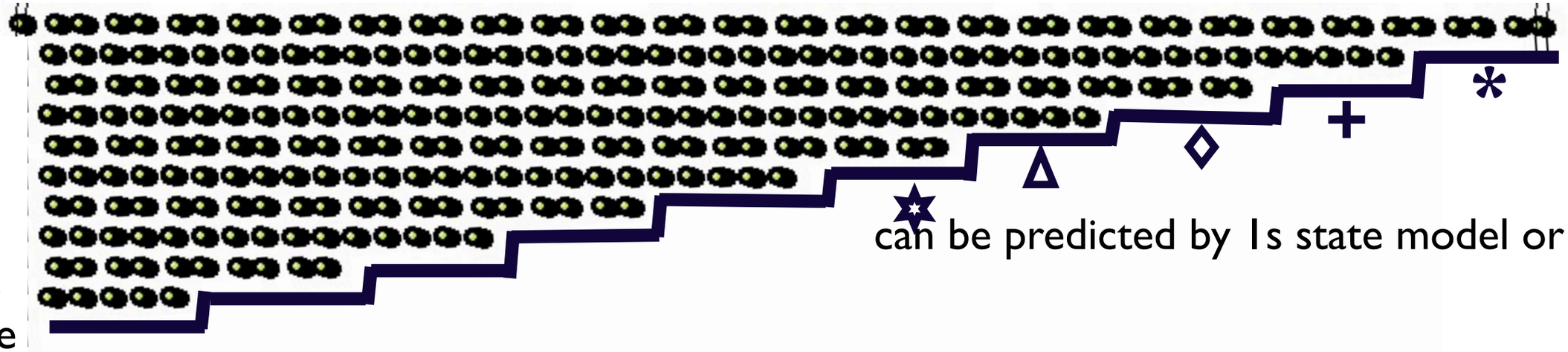


Plane of Reconstructed EW

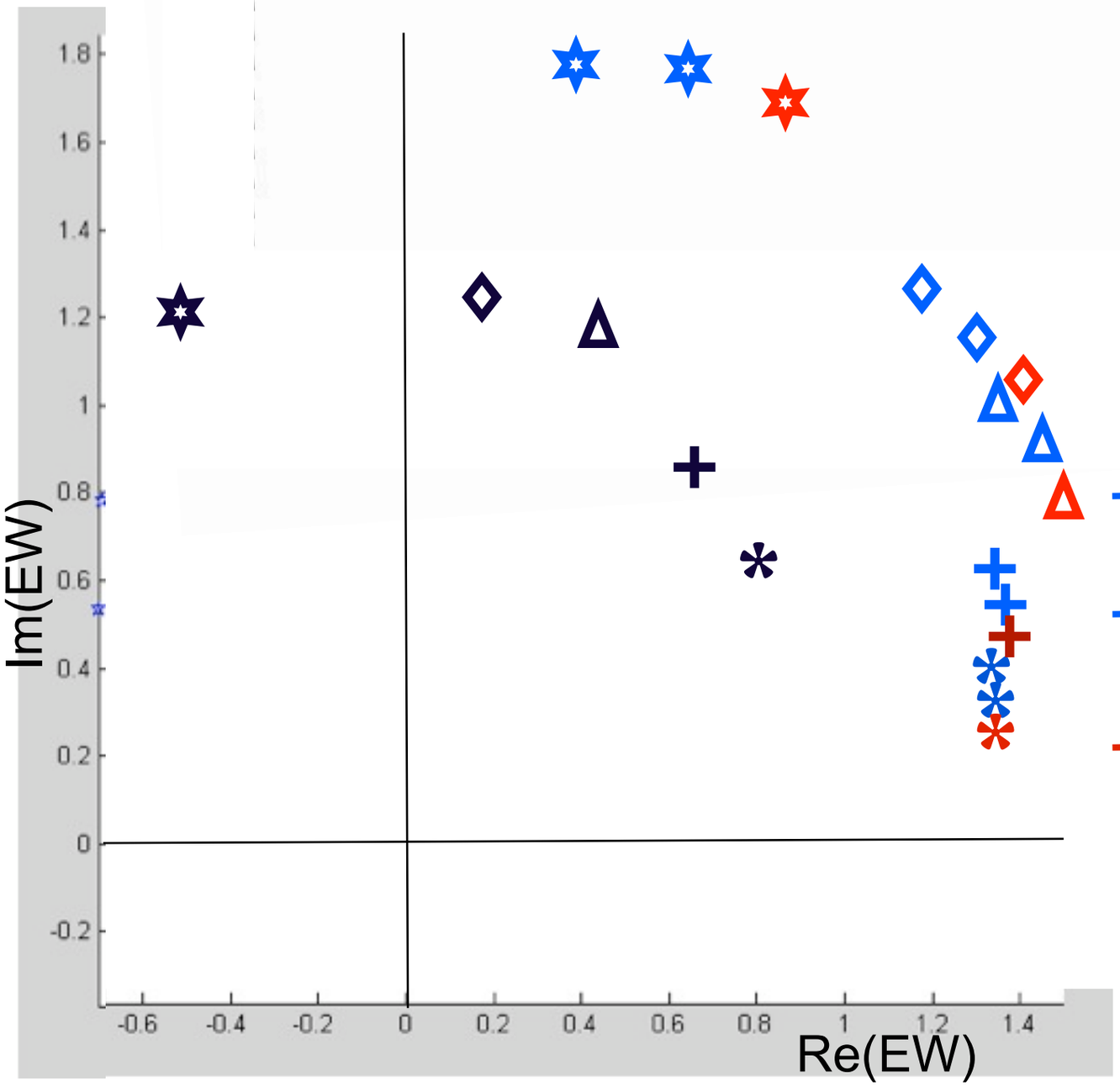
20Å

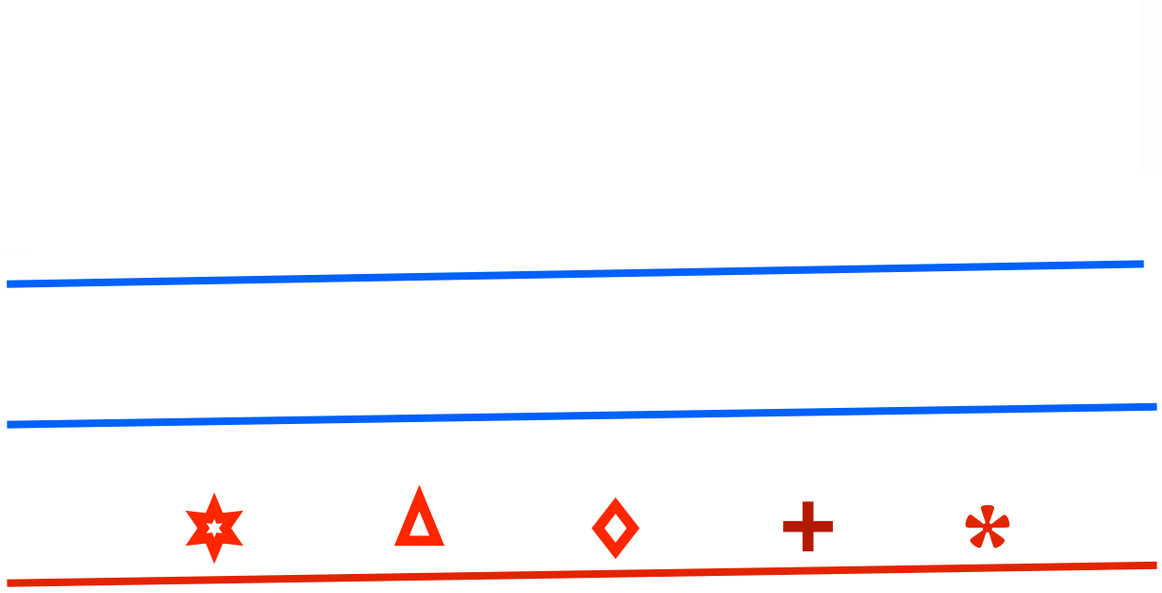
Au

exit wave



can be predicted by 1s state model or multisli



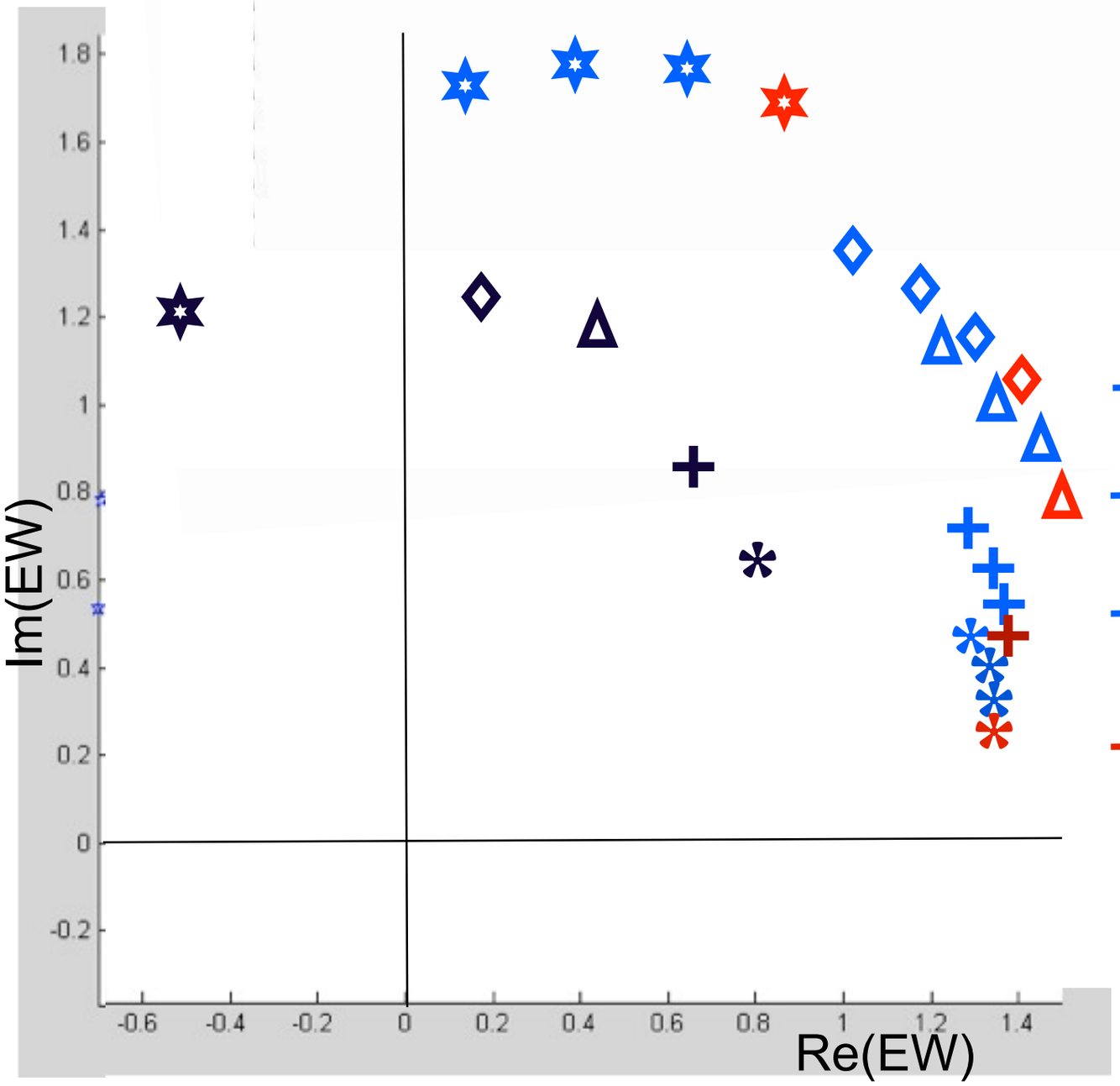


Plane of Reconstructed EW

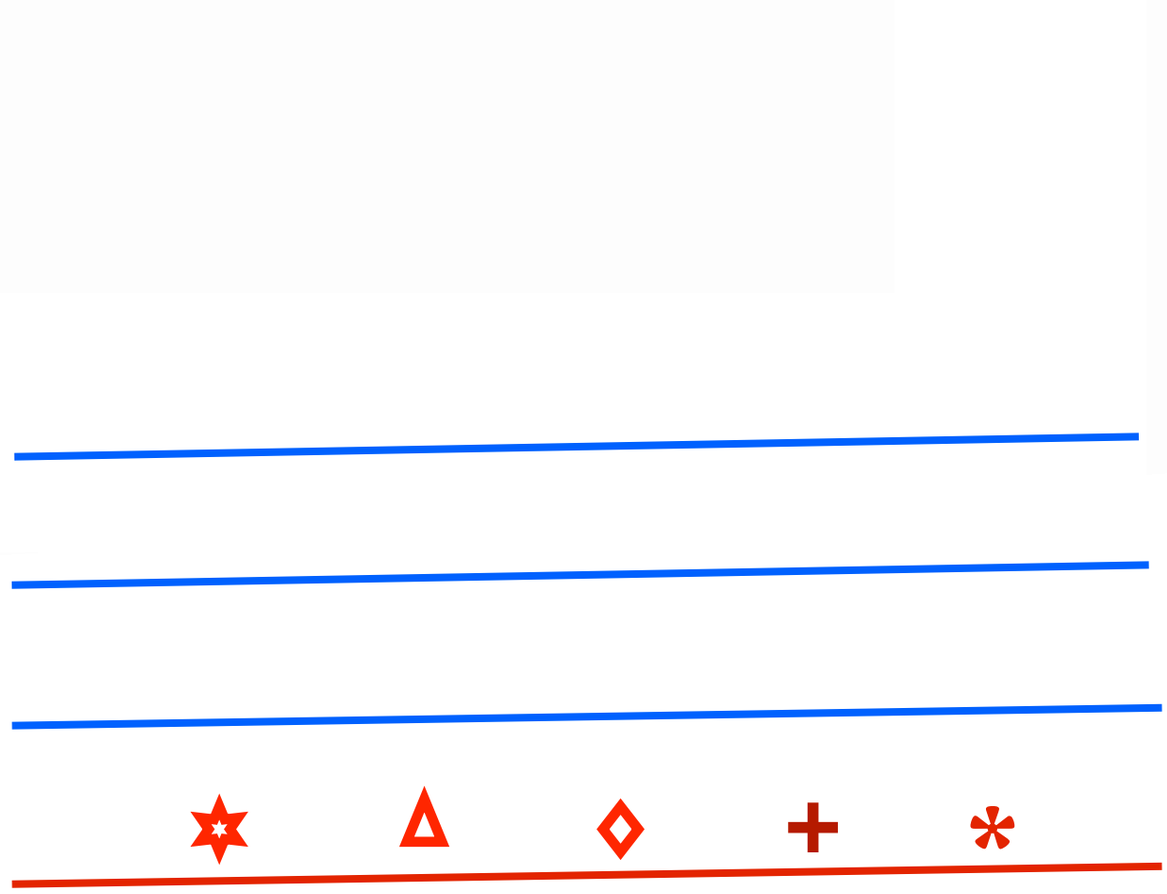
20Å

Au

exit wave



can be predicted by 1s state model or multisli

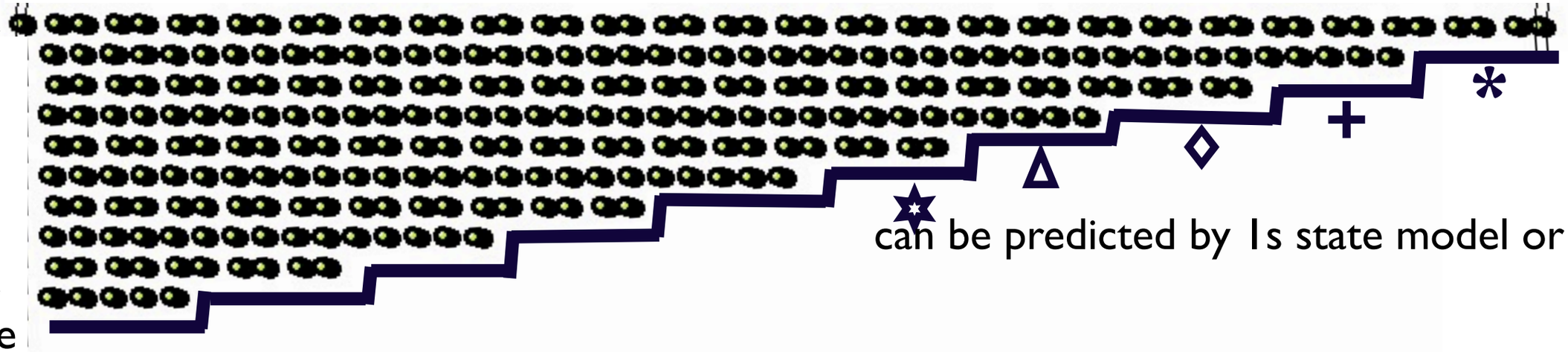


Plane of Reconstructed EW

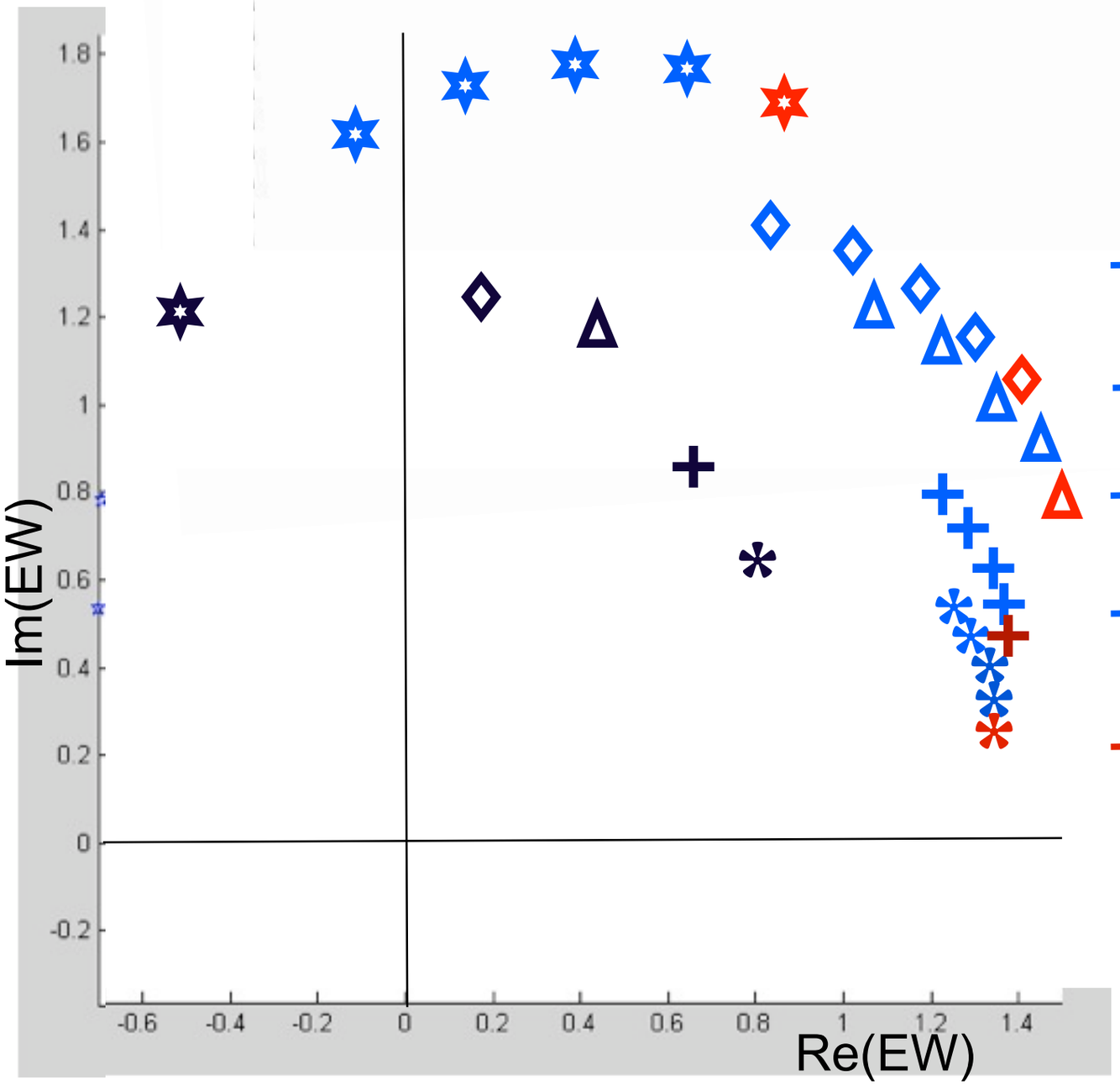
20Å

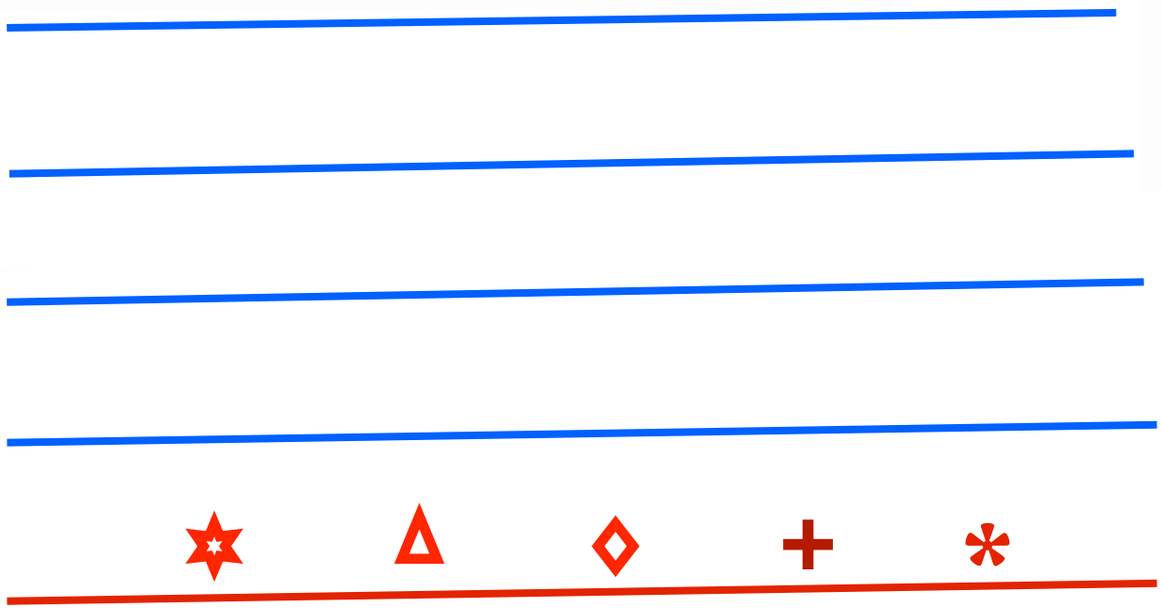
Au

exit wave



can be predicted by 1s state model or multisli



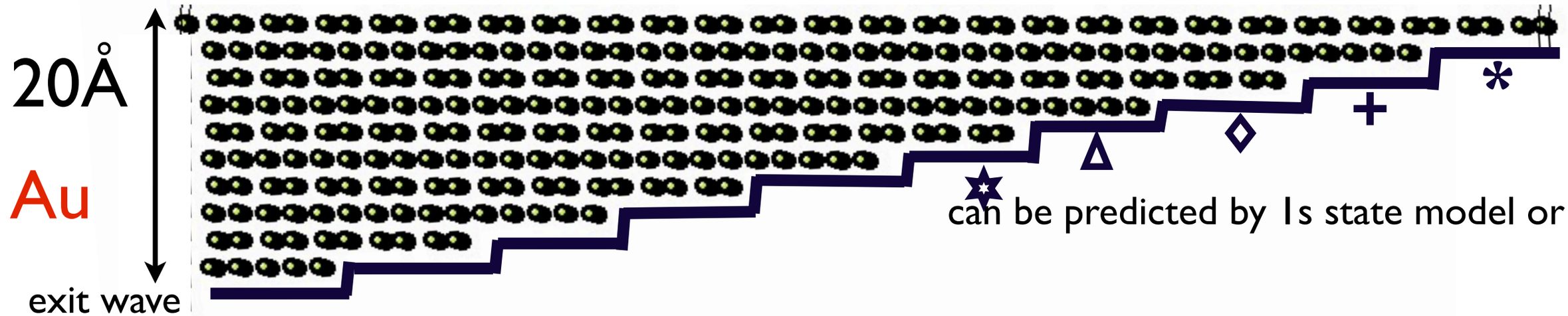


Plane of Reconstructed EW

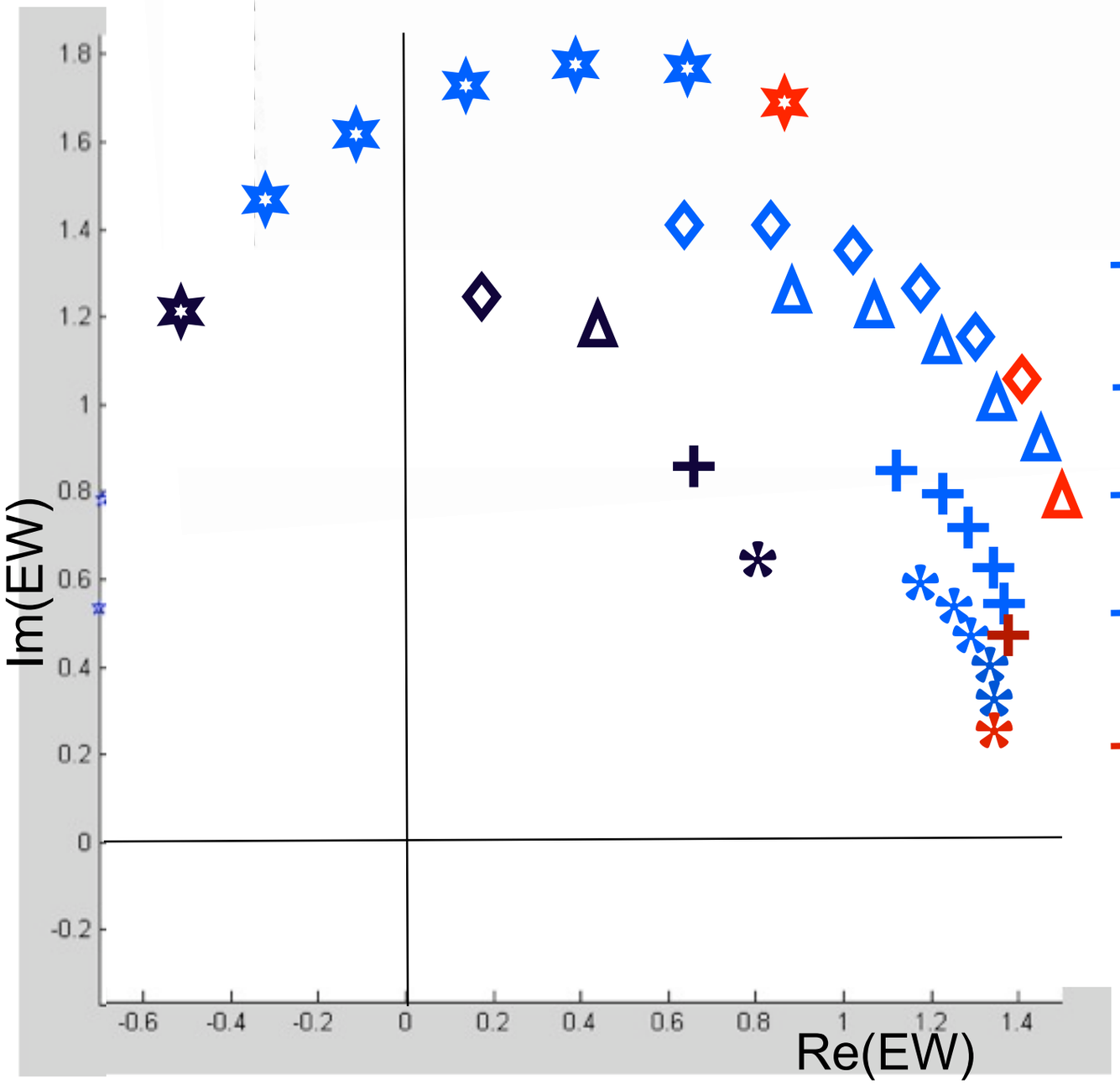
20Å

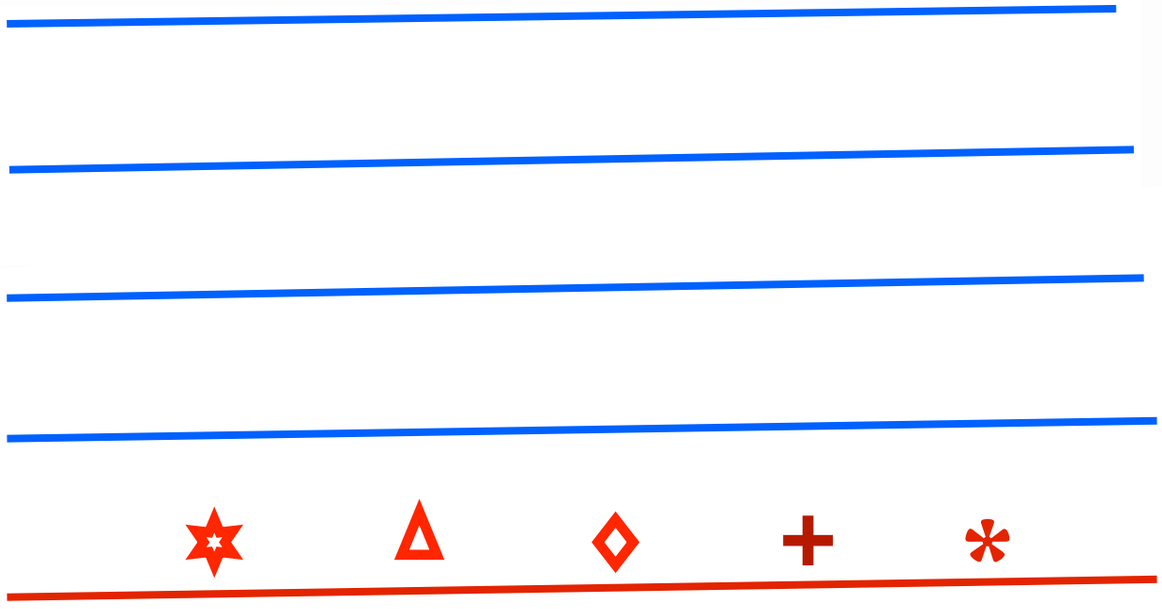
Au

exit wave



can be predicted by 1s state model or multisli



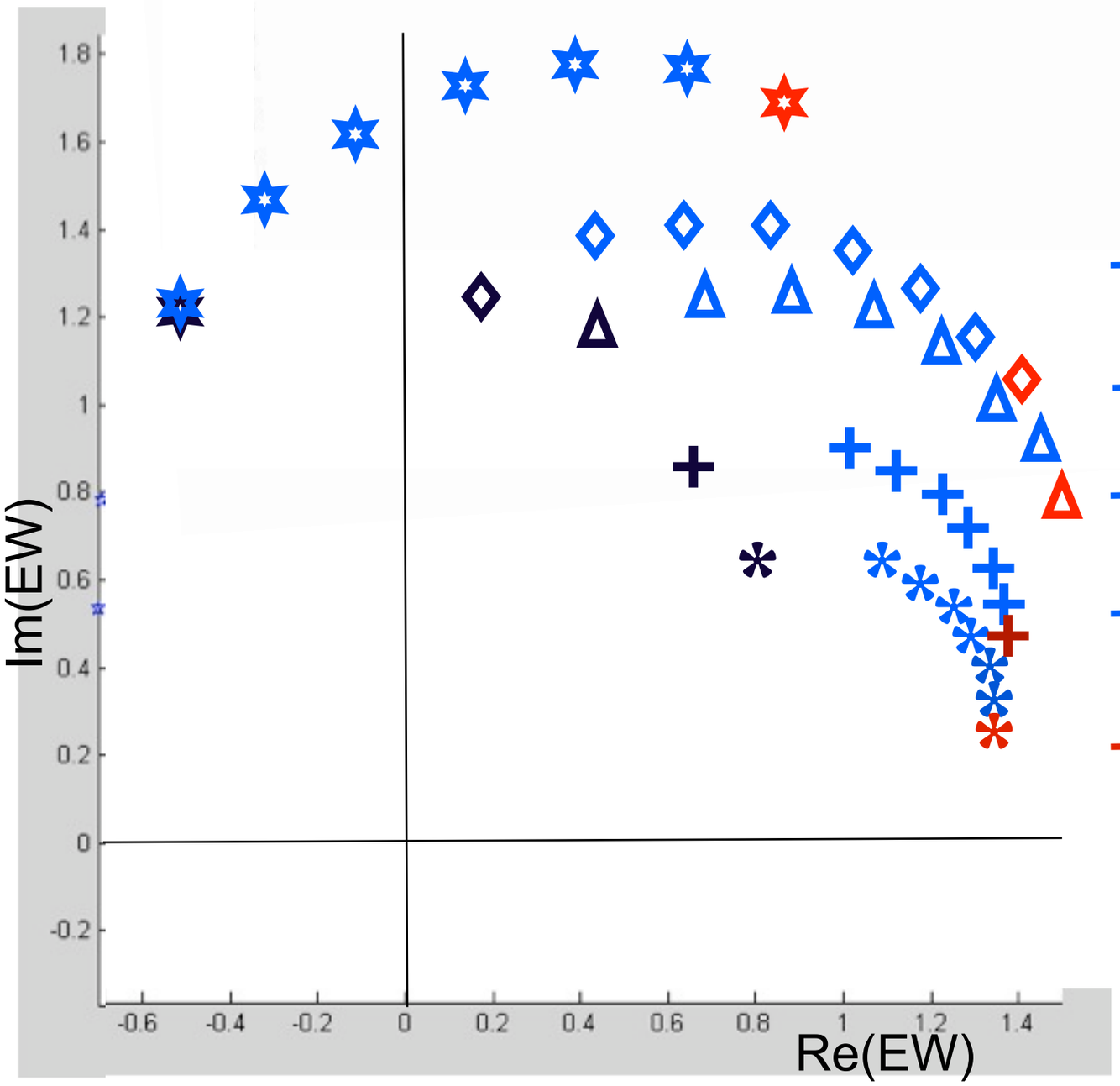


Plane of Reconstructed EW

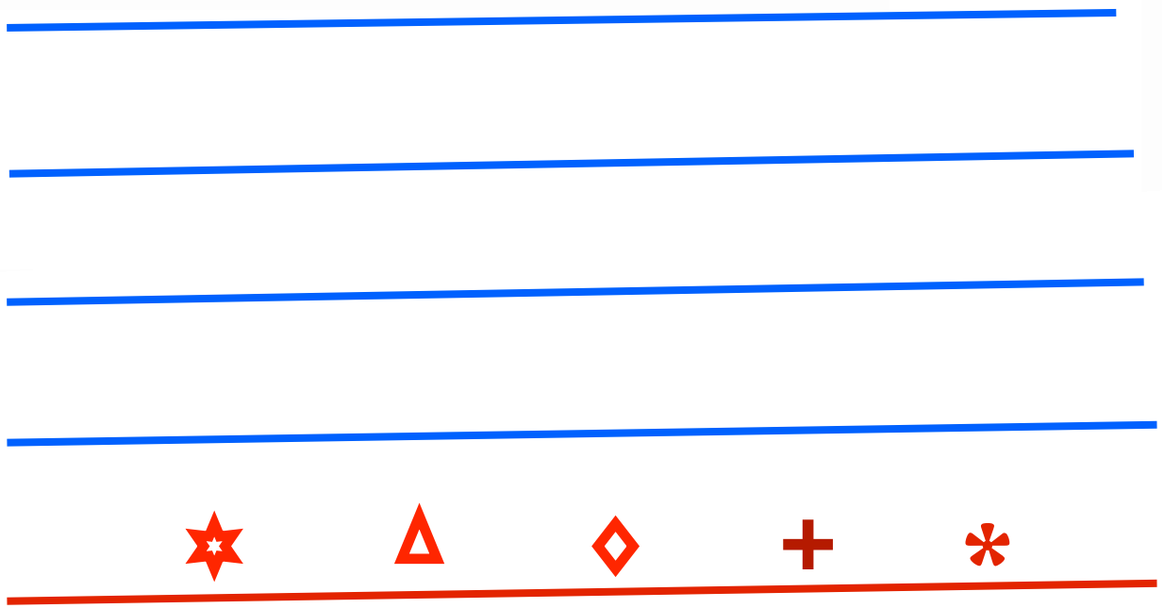
20Å

Au

exit wave



can be predicted by 1s state model or multisli

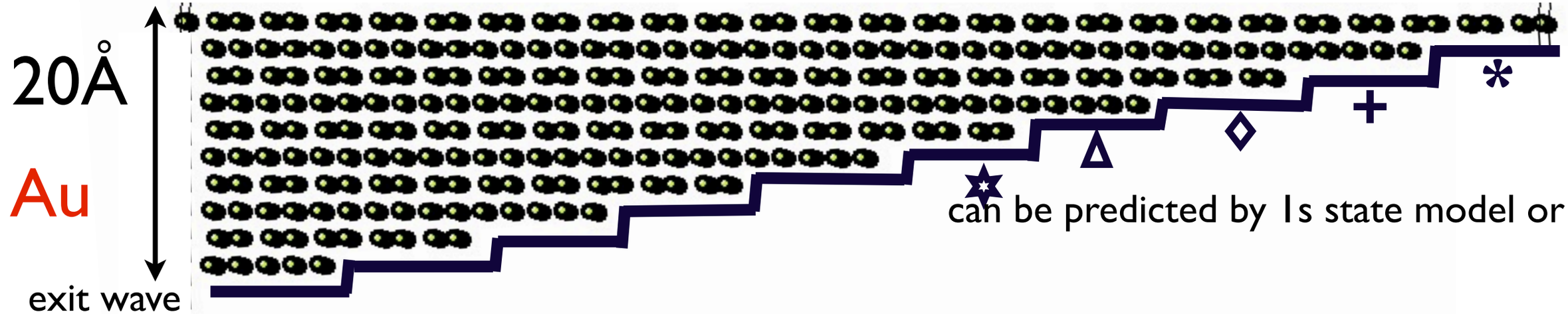


Plane of Reconstructed EW

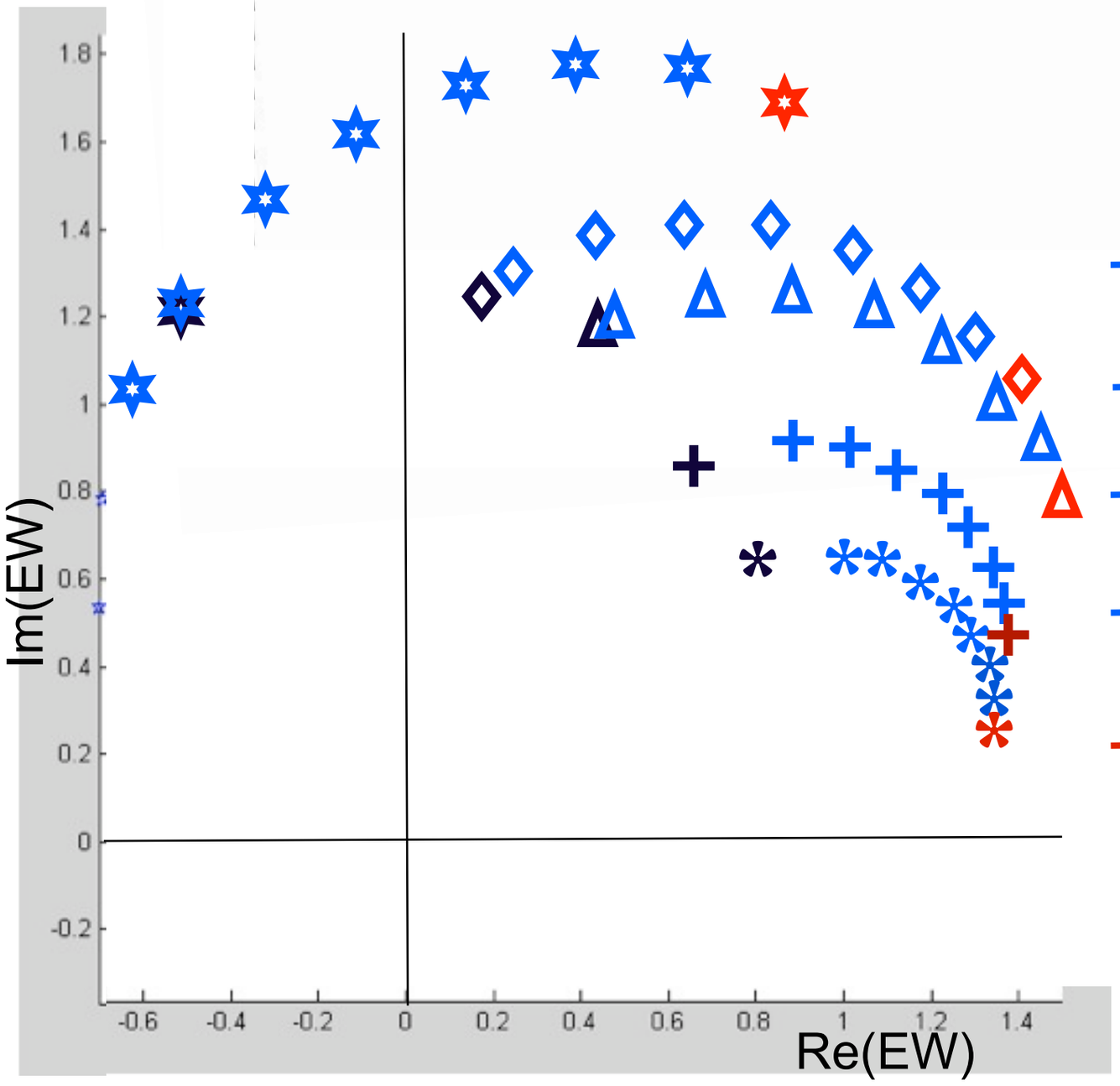
20Å

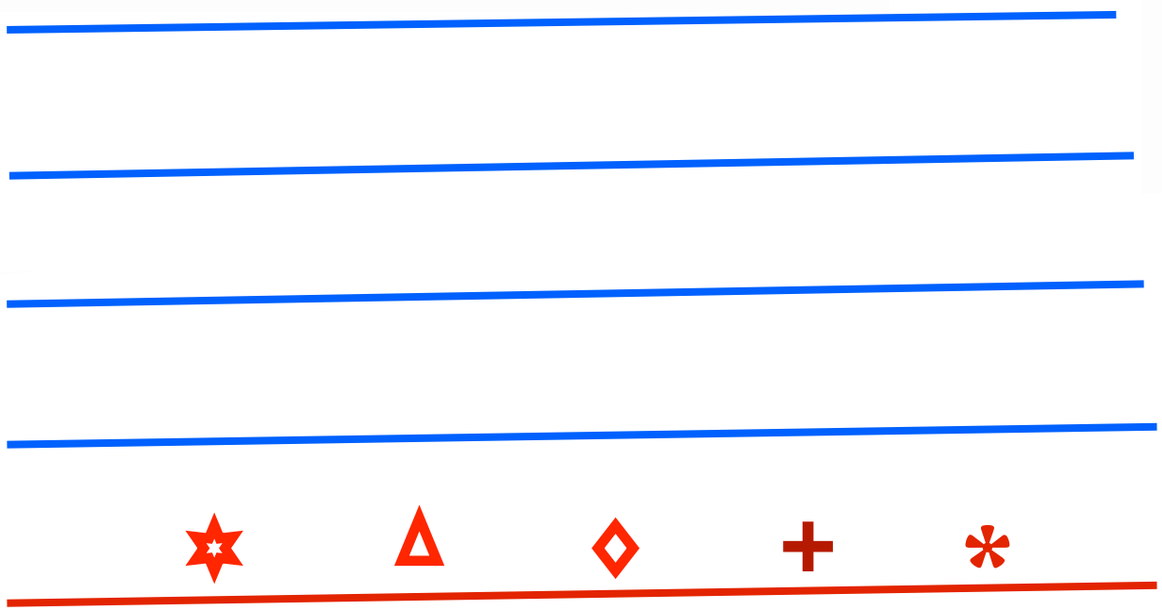
Au

exit wave



can be predicted by 1s state model or multisli



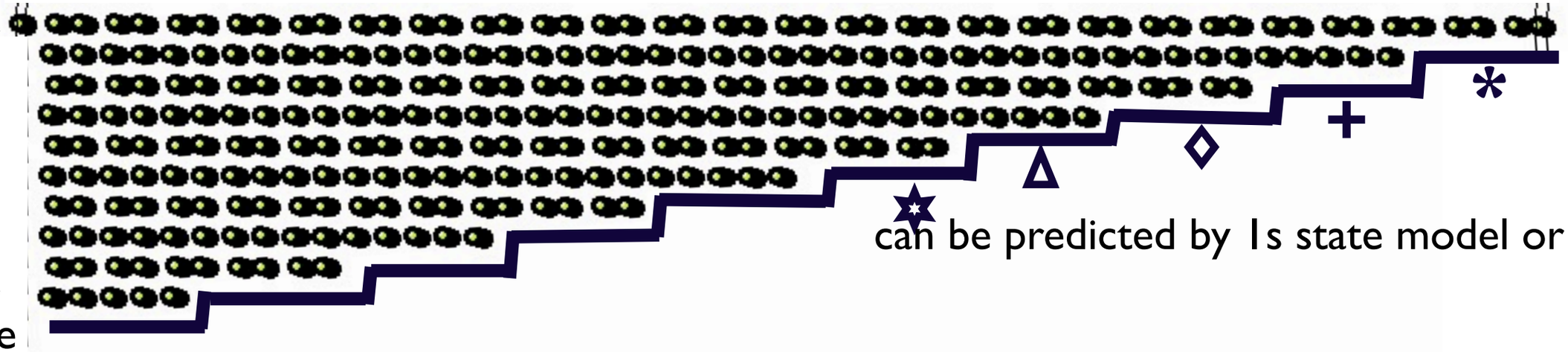


Plane of Reconstructed EW

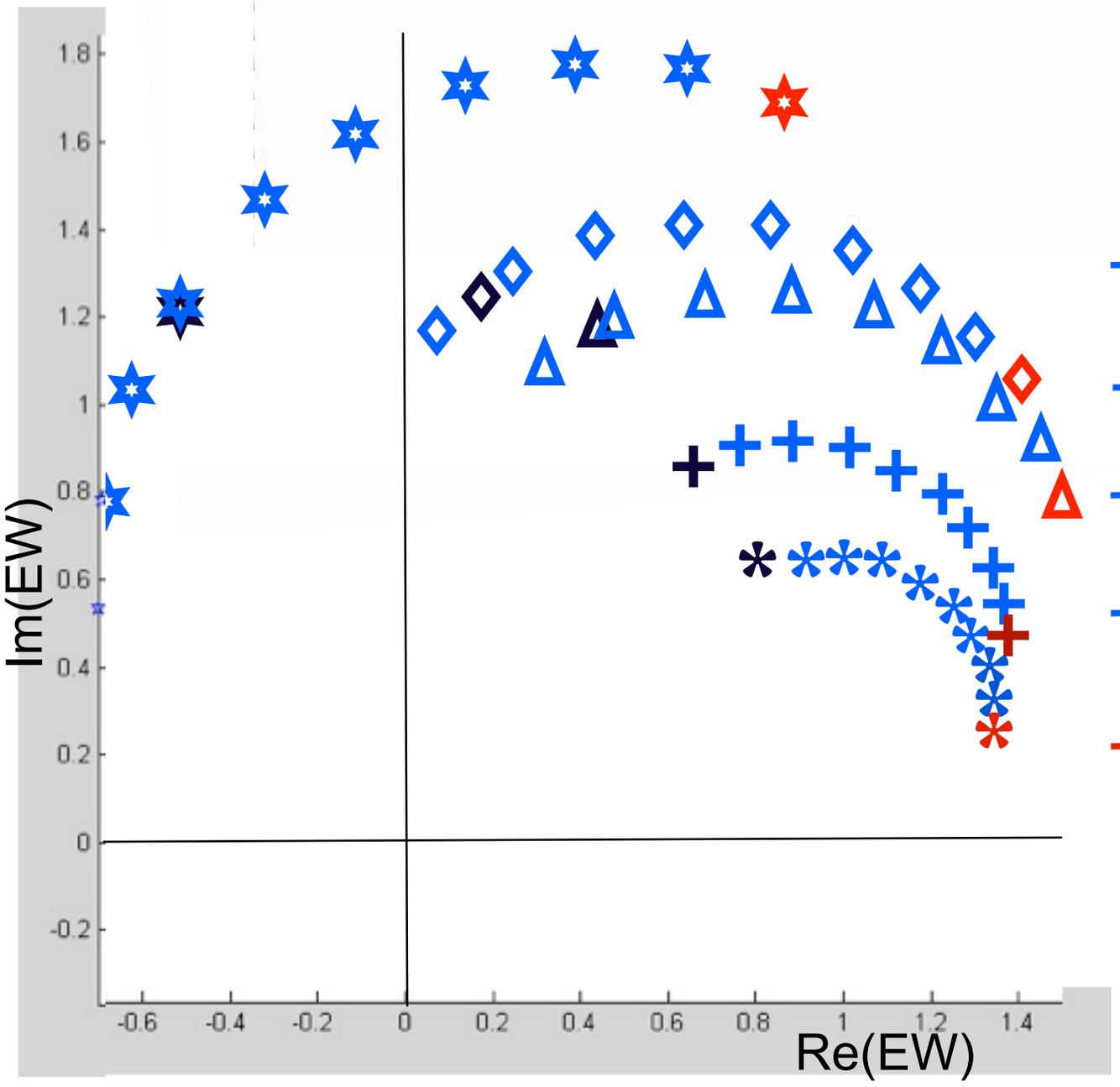
20Å

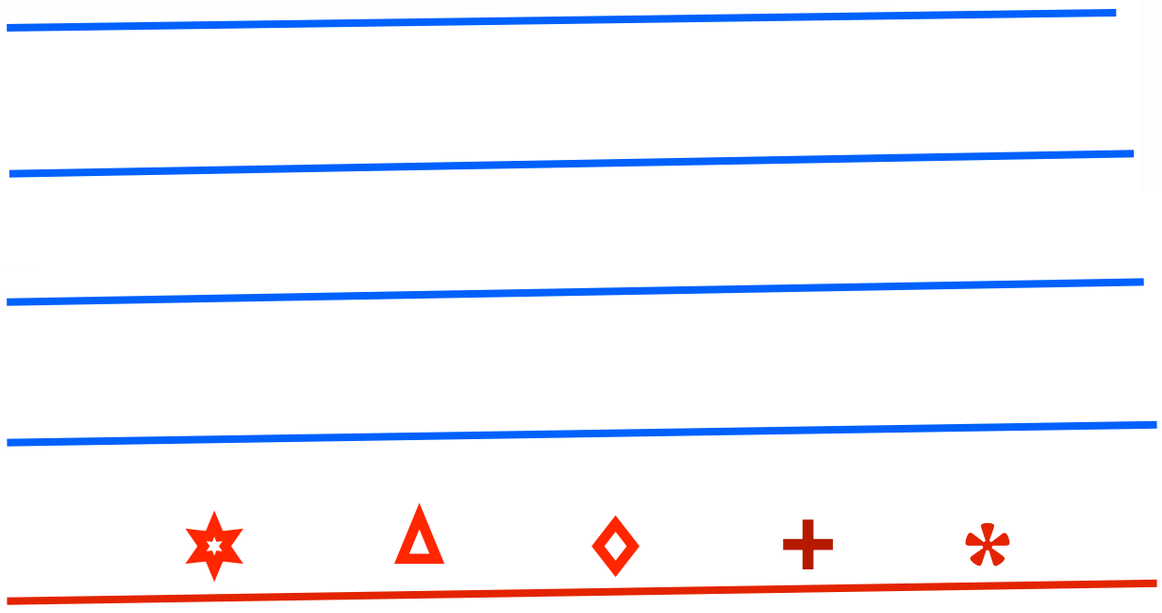
Au

exit wave



can be predicted by 1s state model or multisli



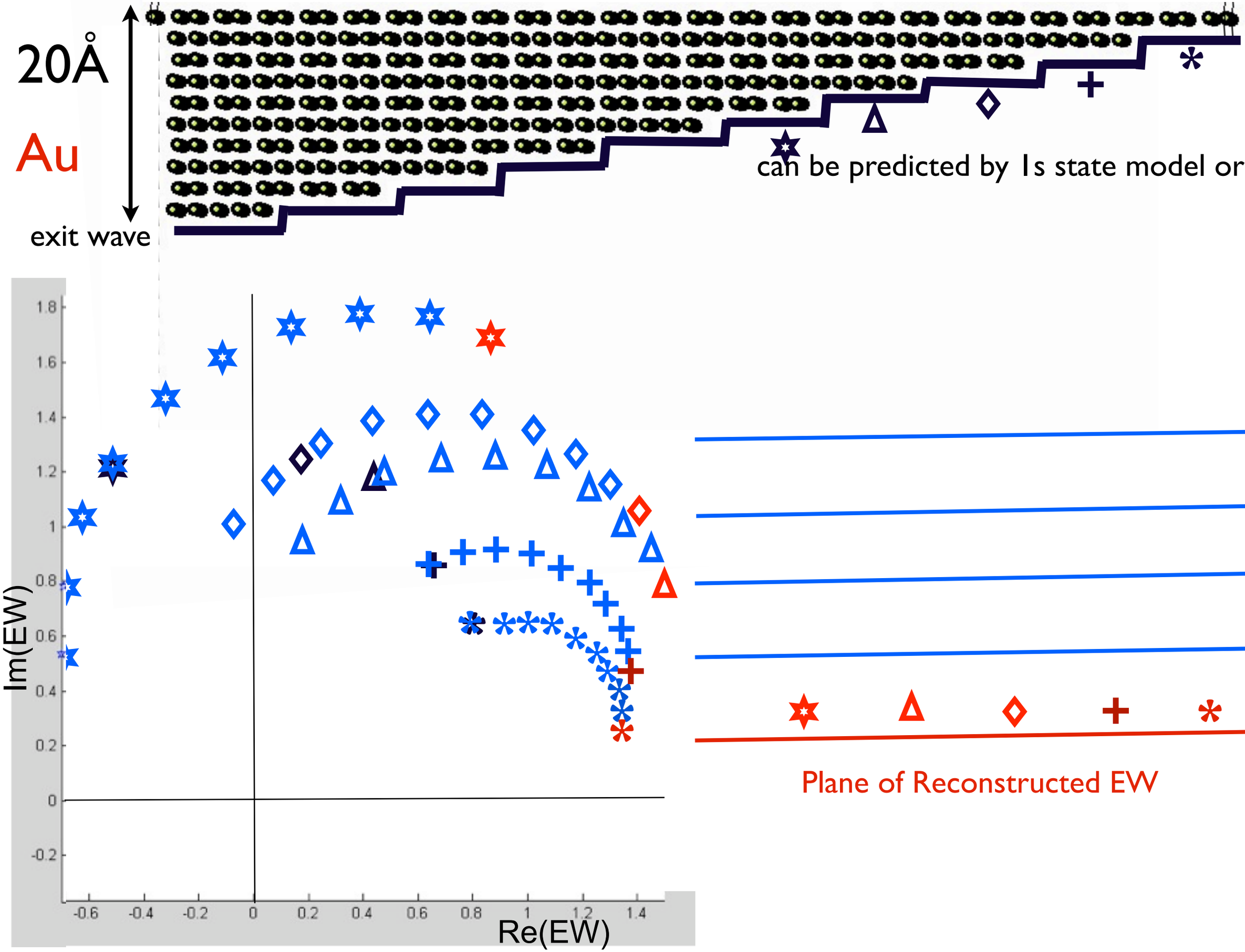


Plane of Reconstructed EW

20Å

Au

exit wave



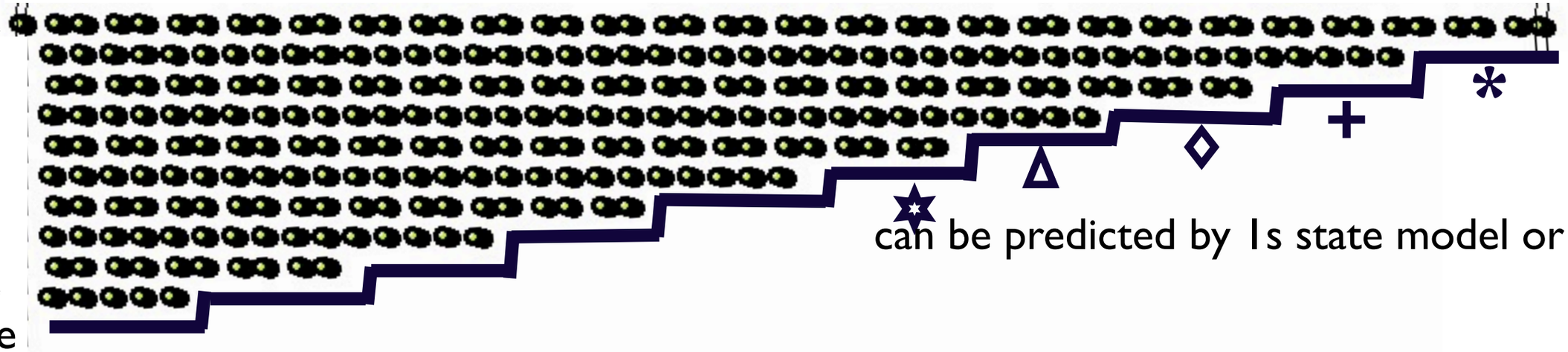
can be predicted by 1s state model or multisli

Plane of Reconstructed EW

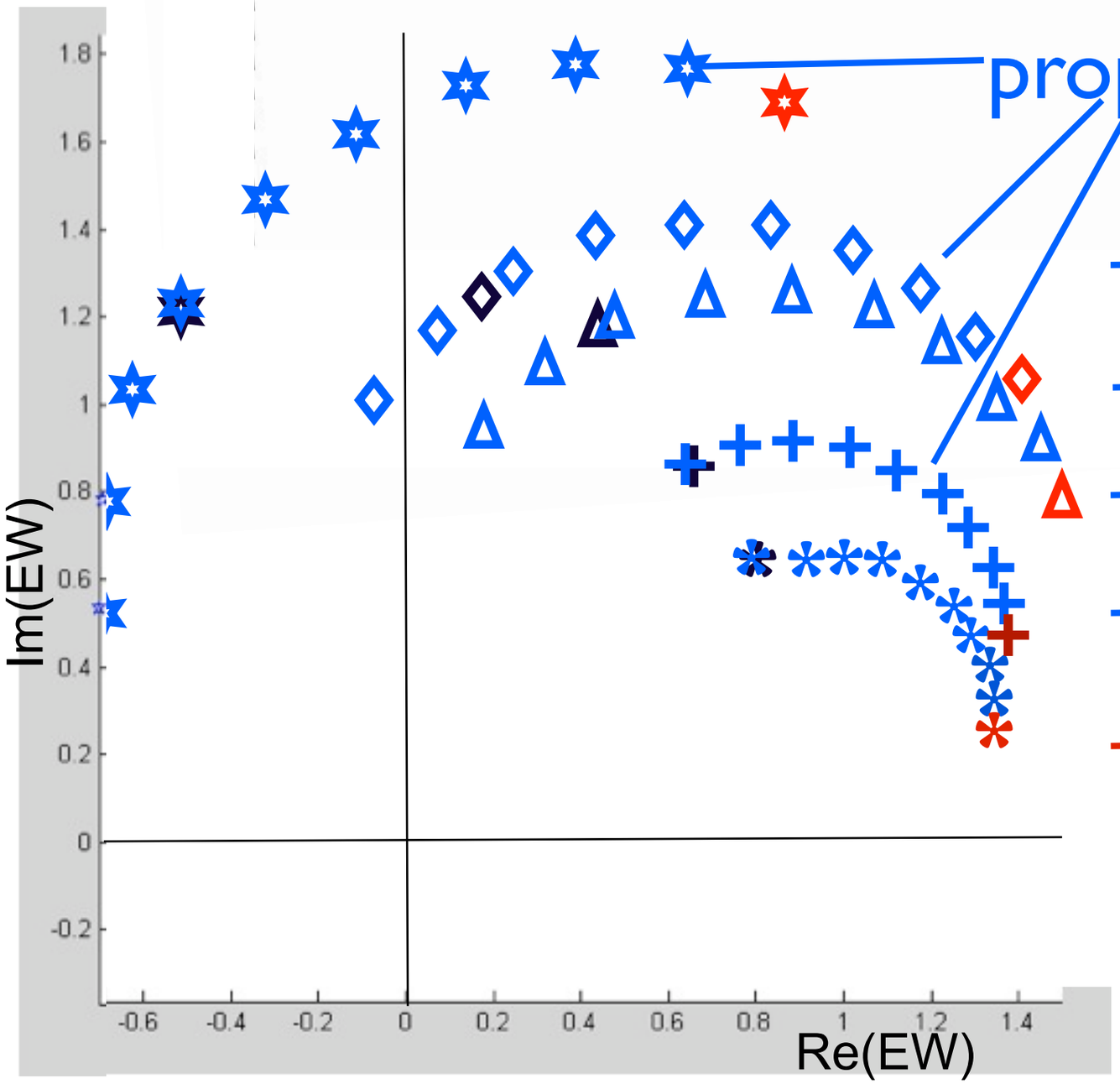
20Å

Au

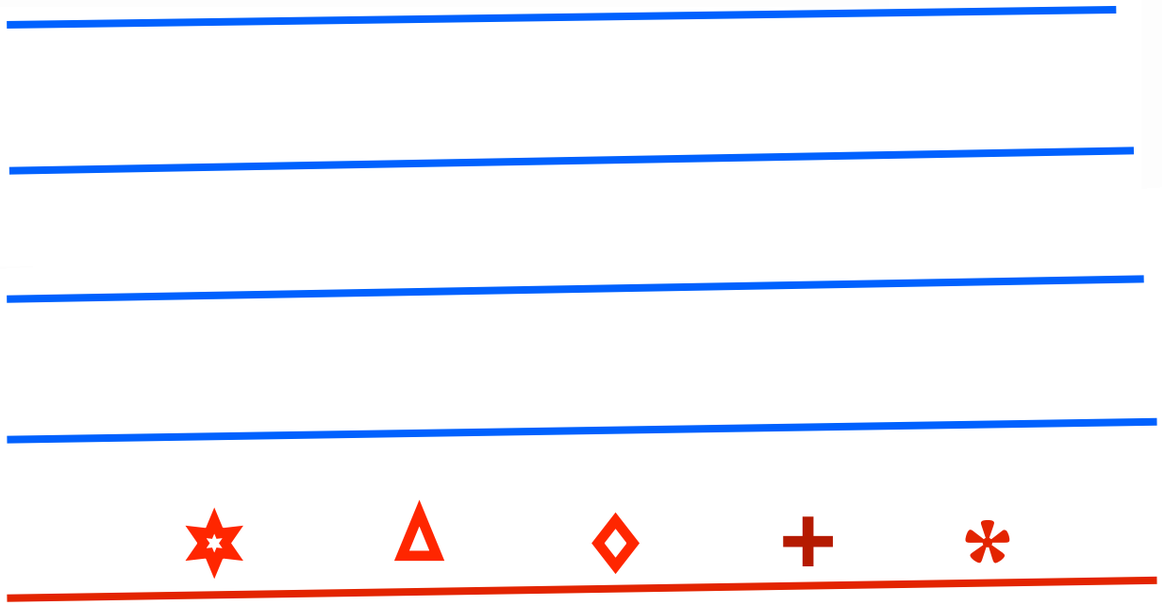
exit wave



can be predicted by 1s state model or multisli



propagation circle

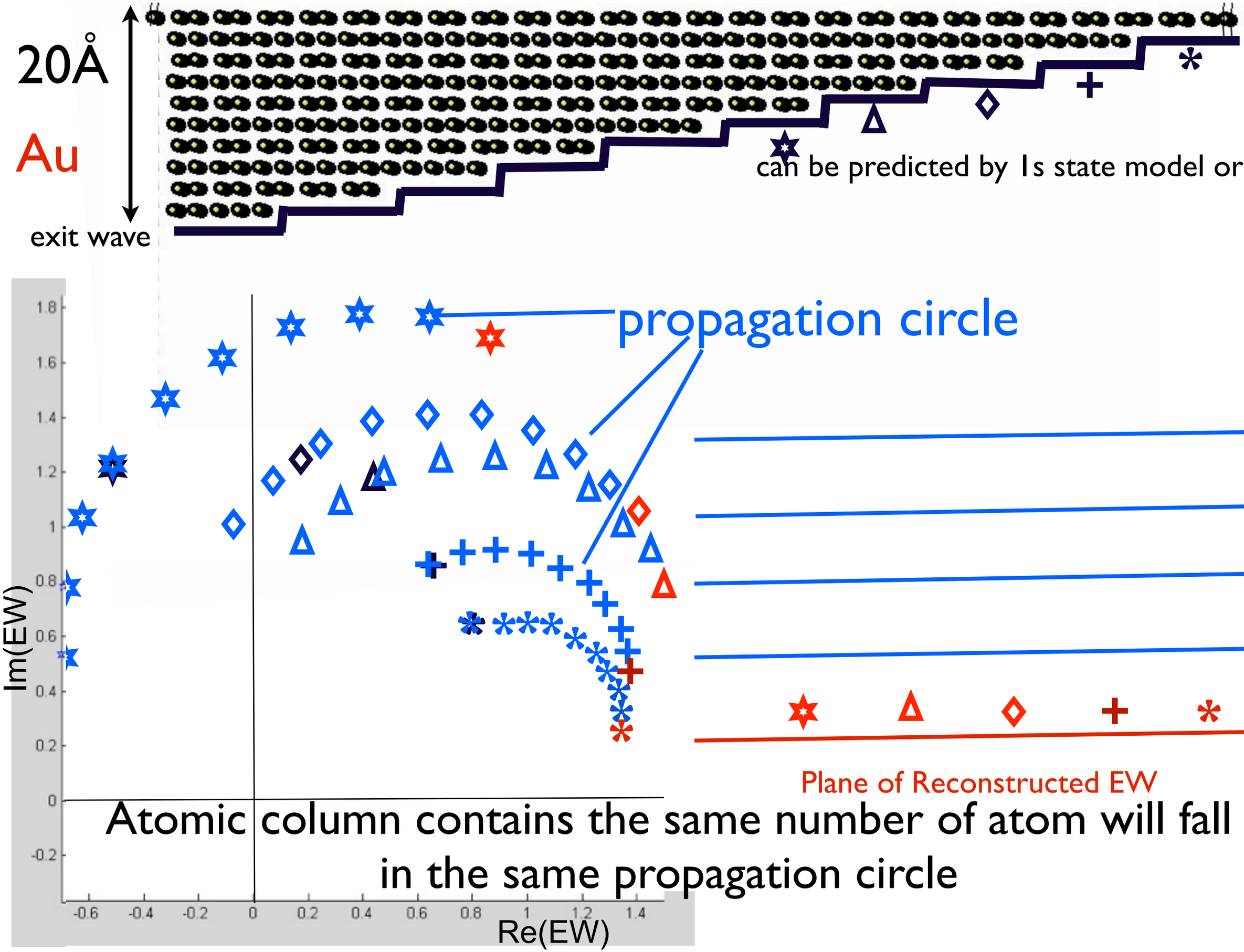


Plane of Reconstructed EW

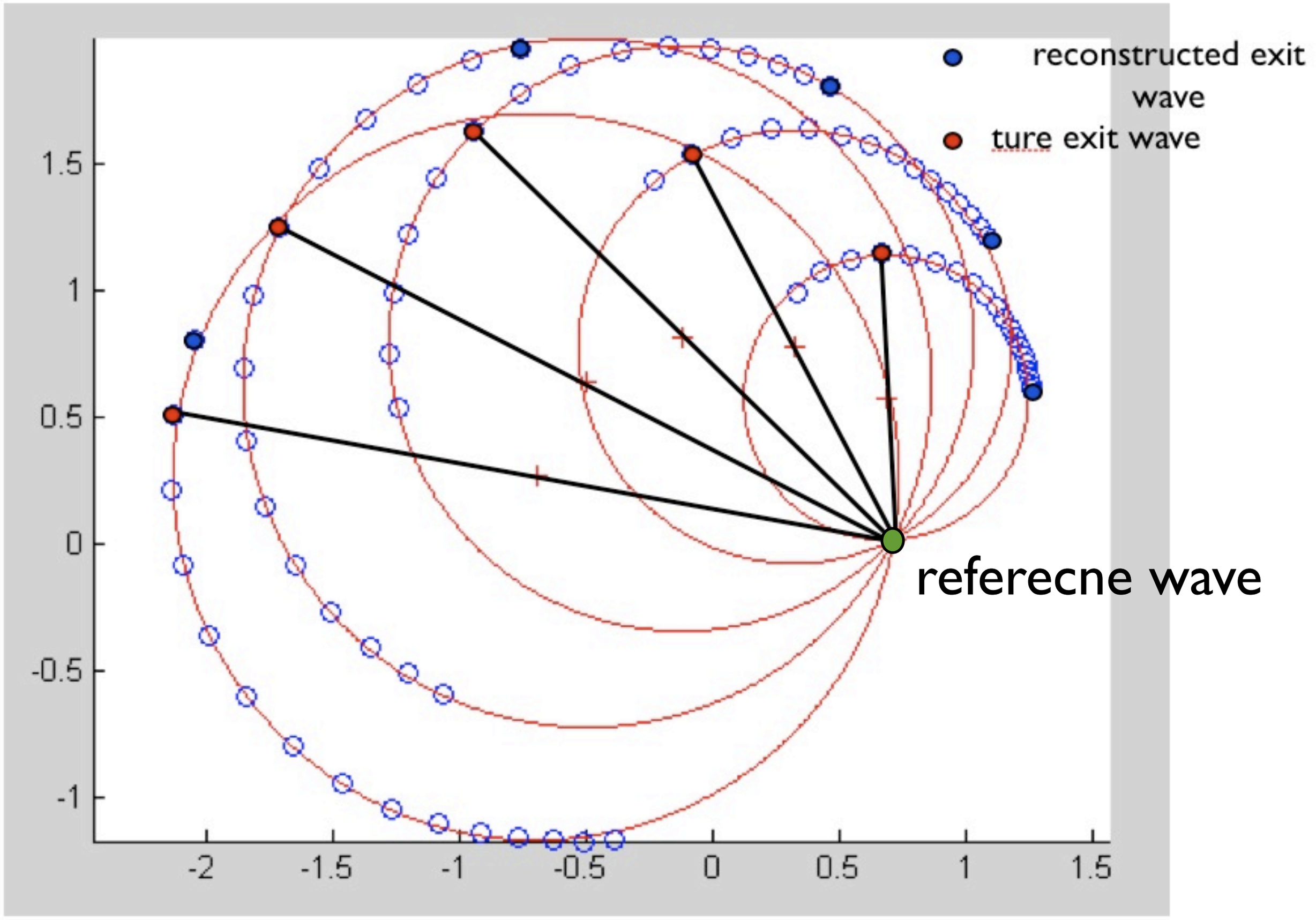
20Å

Au

exit wave

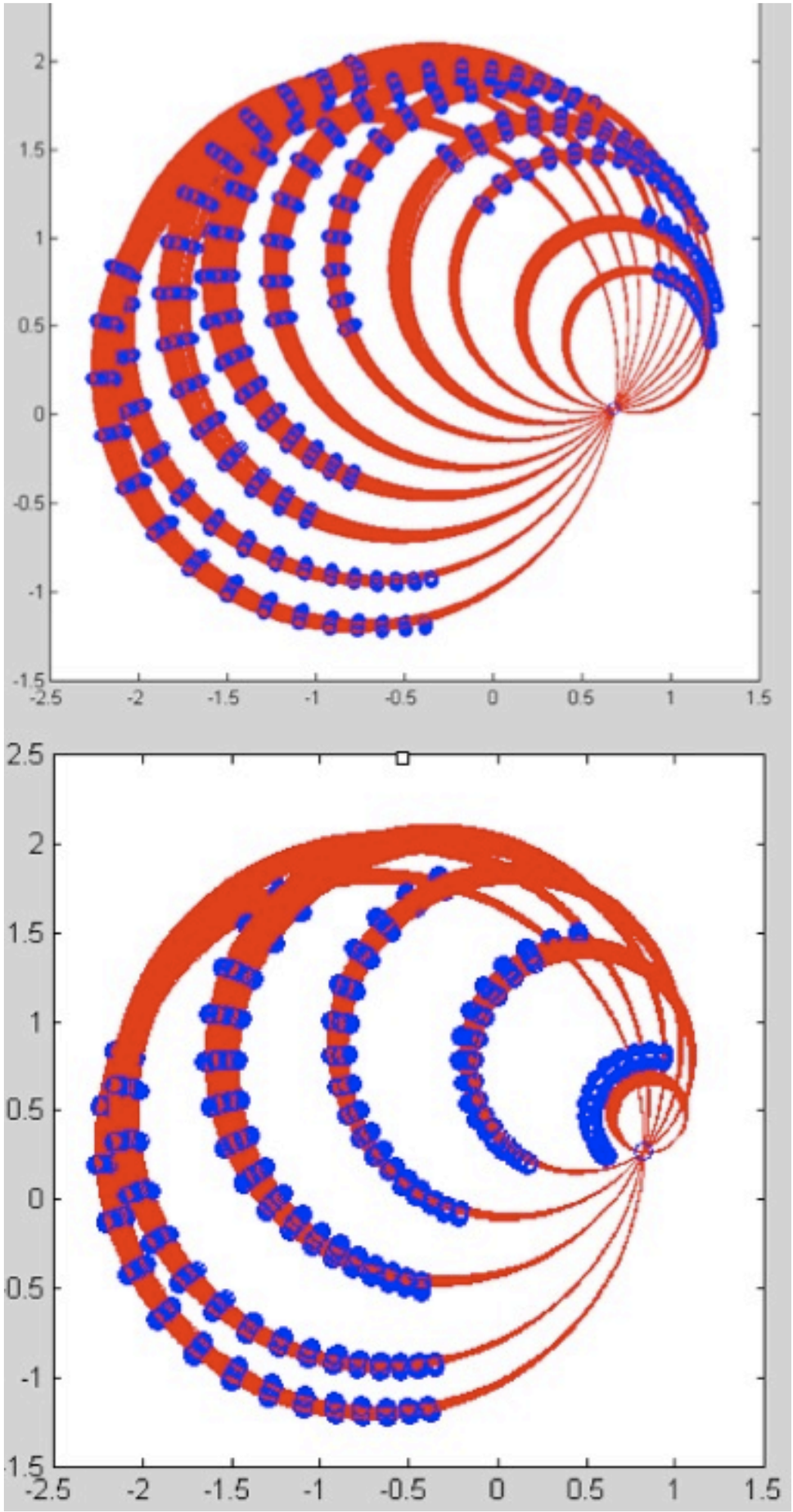


Atomic column contains the same number of atom will fall in the same propagation circle

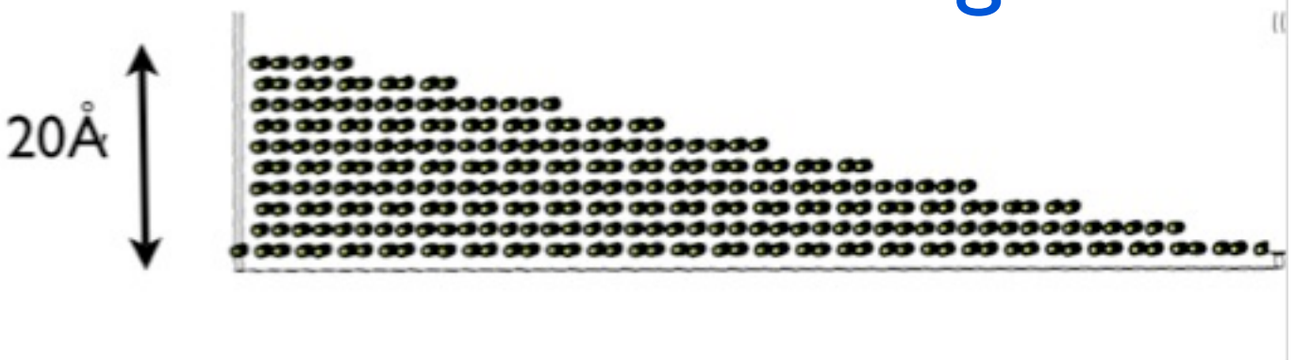

reconstructed exit wave
ture exit wave
referecne wave
1.5
1
0.5
0
-0.5
-1
-2
-1.5
-1
-0.5
0
0.5
1
1.5

flat top wedge

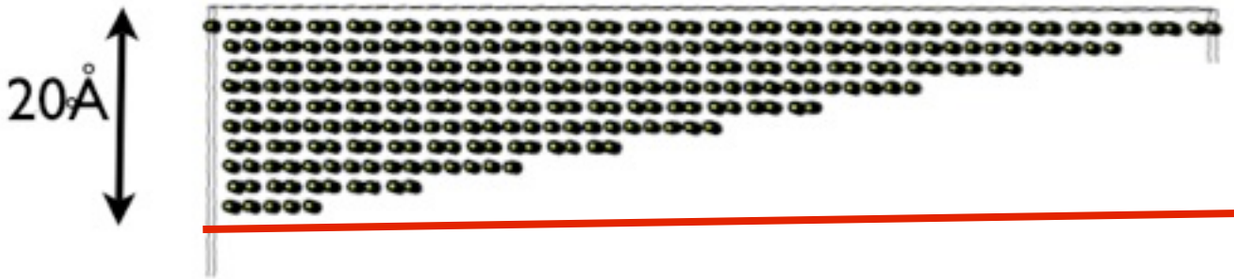
1441 atomic columns



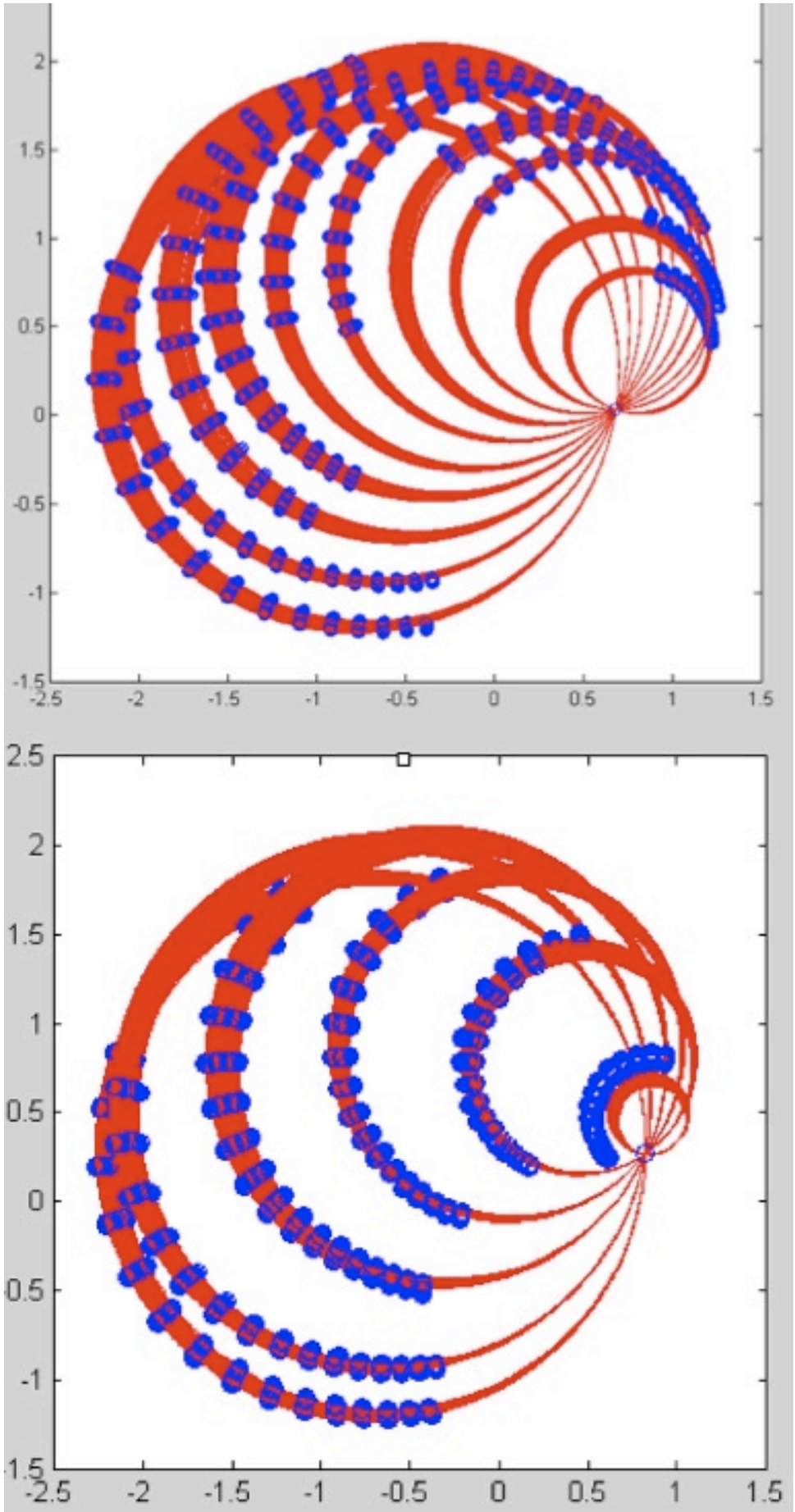
flat bottom wedge



flat top wedge

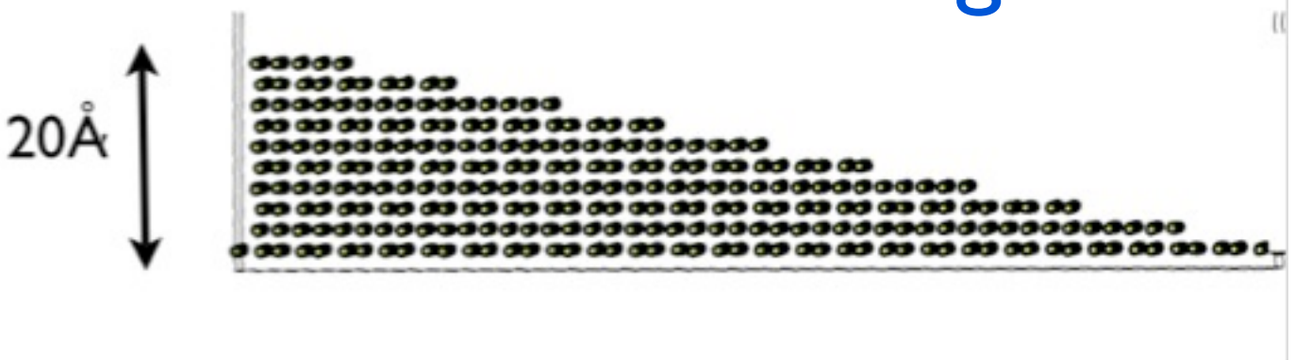


Plane of Reconstructed EW

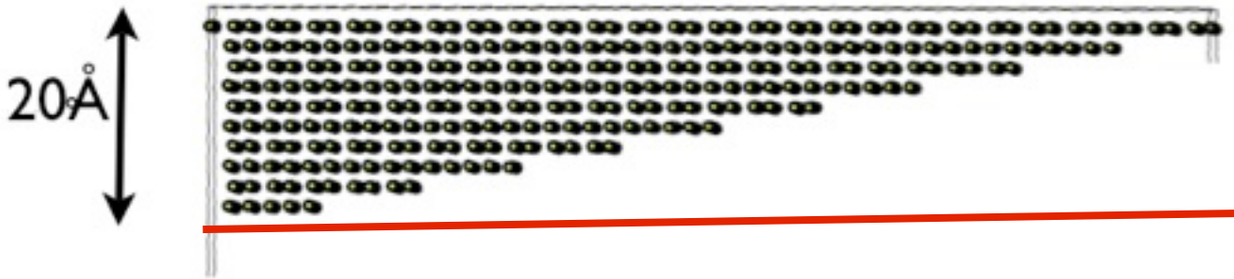


1441 atomic columns

flat bottom wedge

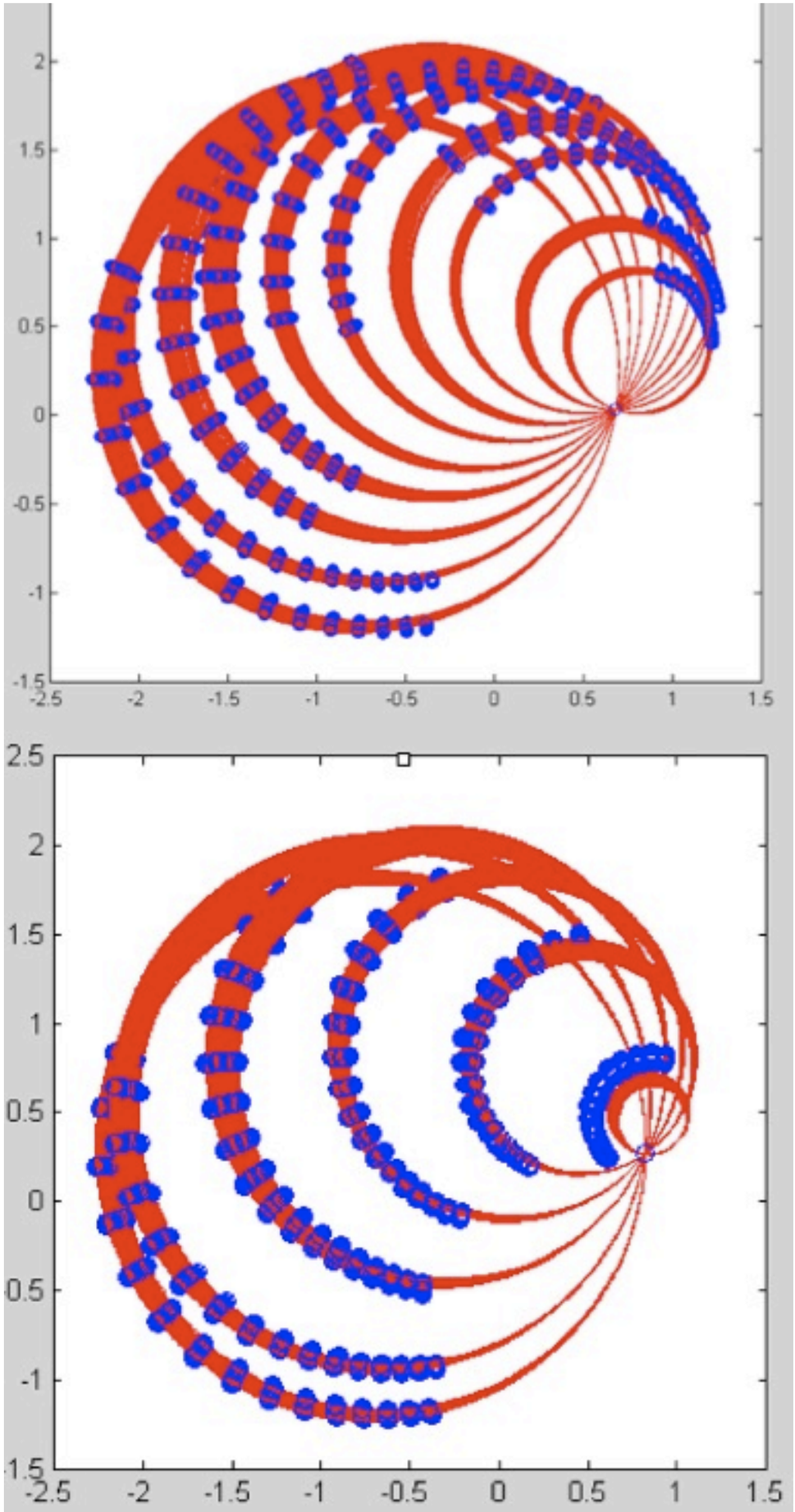


flat top wedge

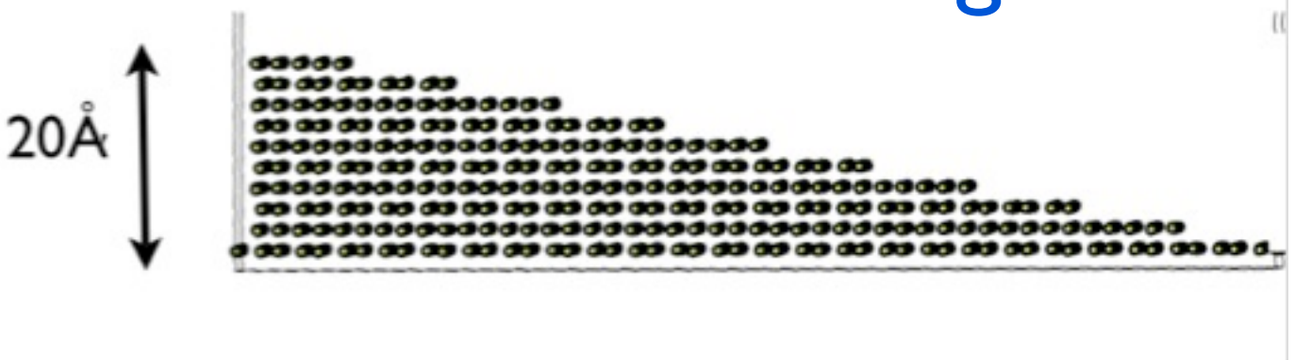


Plane of Reconstructed EW

1441 atomic columns

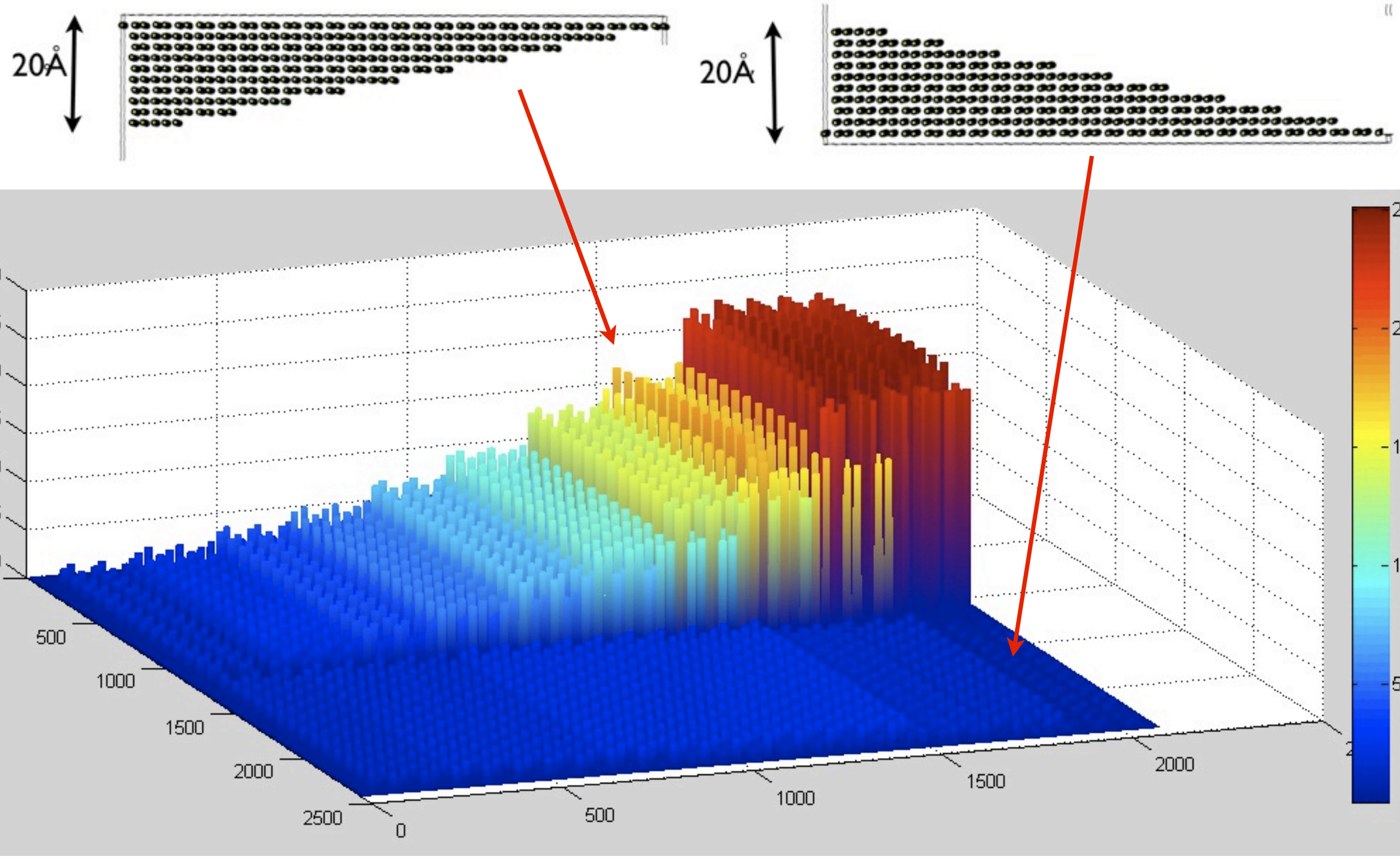


flat bottom wedge

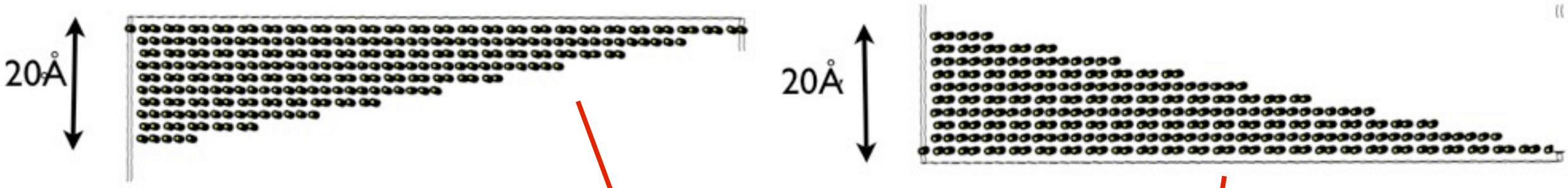


Plane of Reconstructed EW

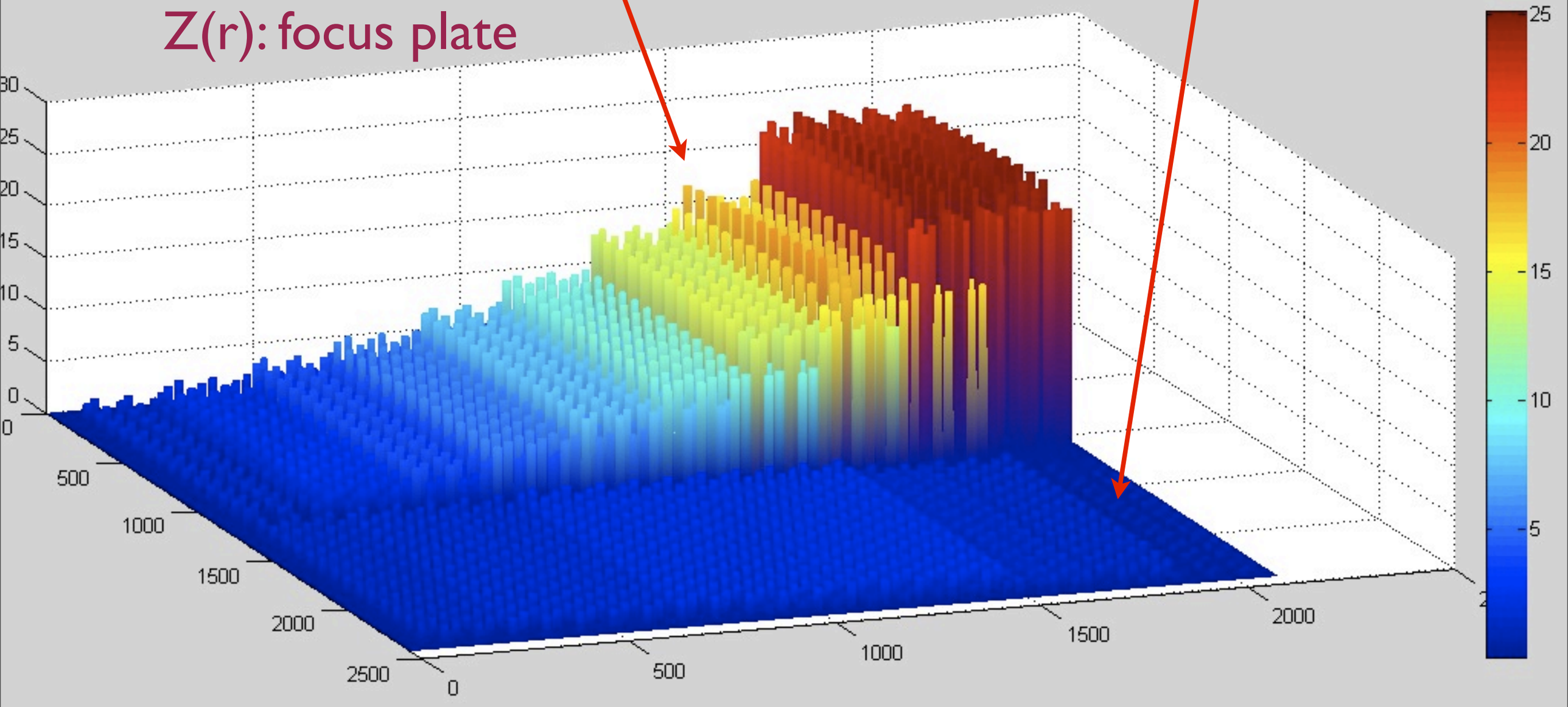
Au Wedge Crystal



Au Wedge Crystal

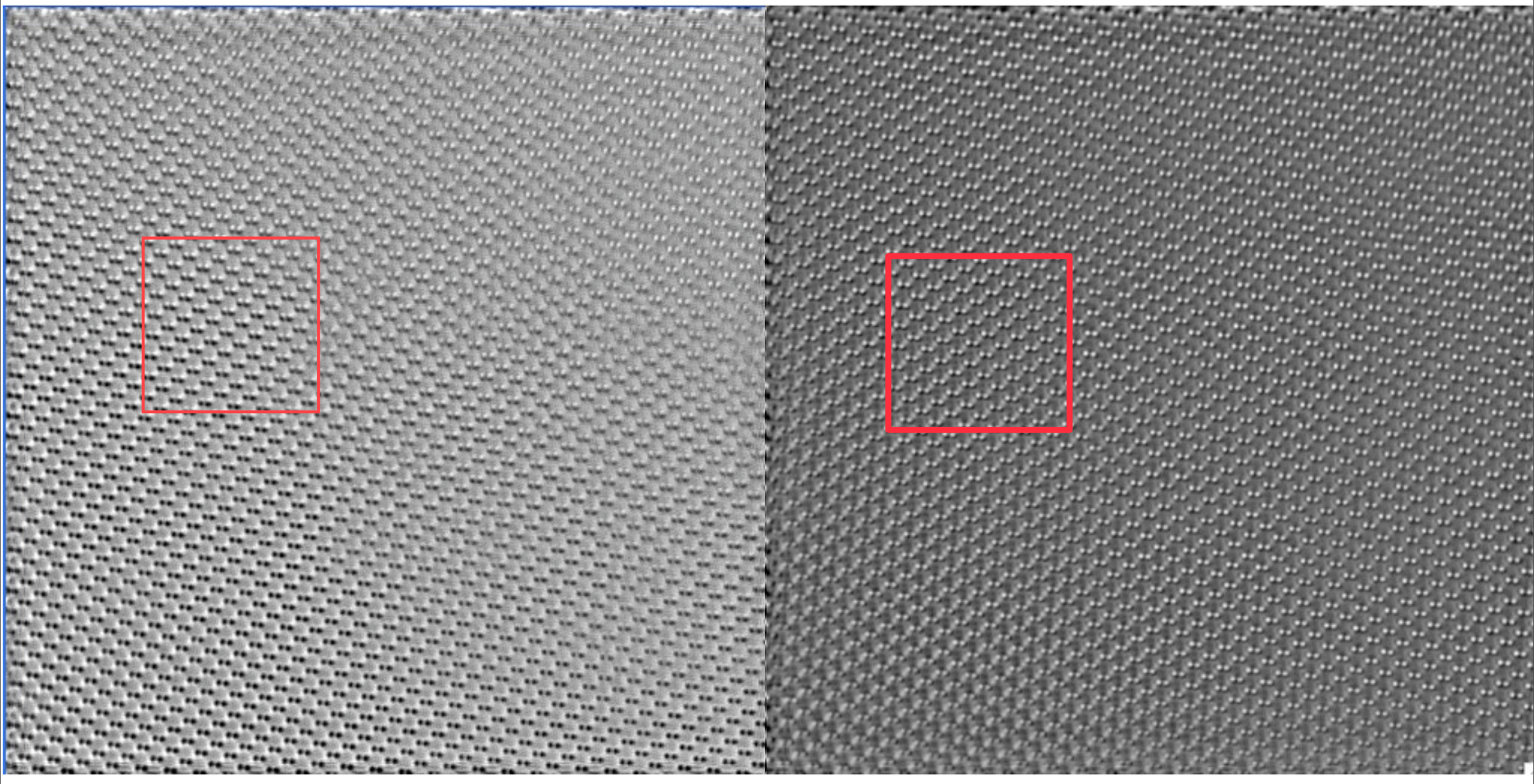


Z(r): focus plate



Focus Corrected EW

NTHU

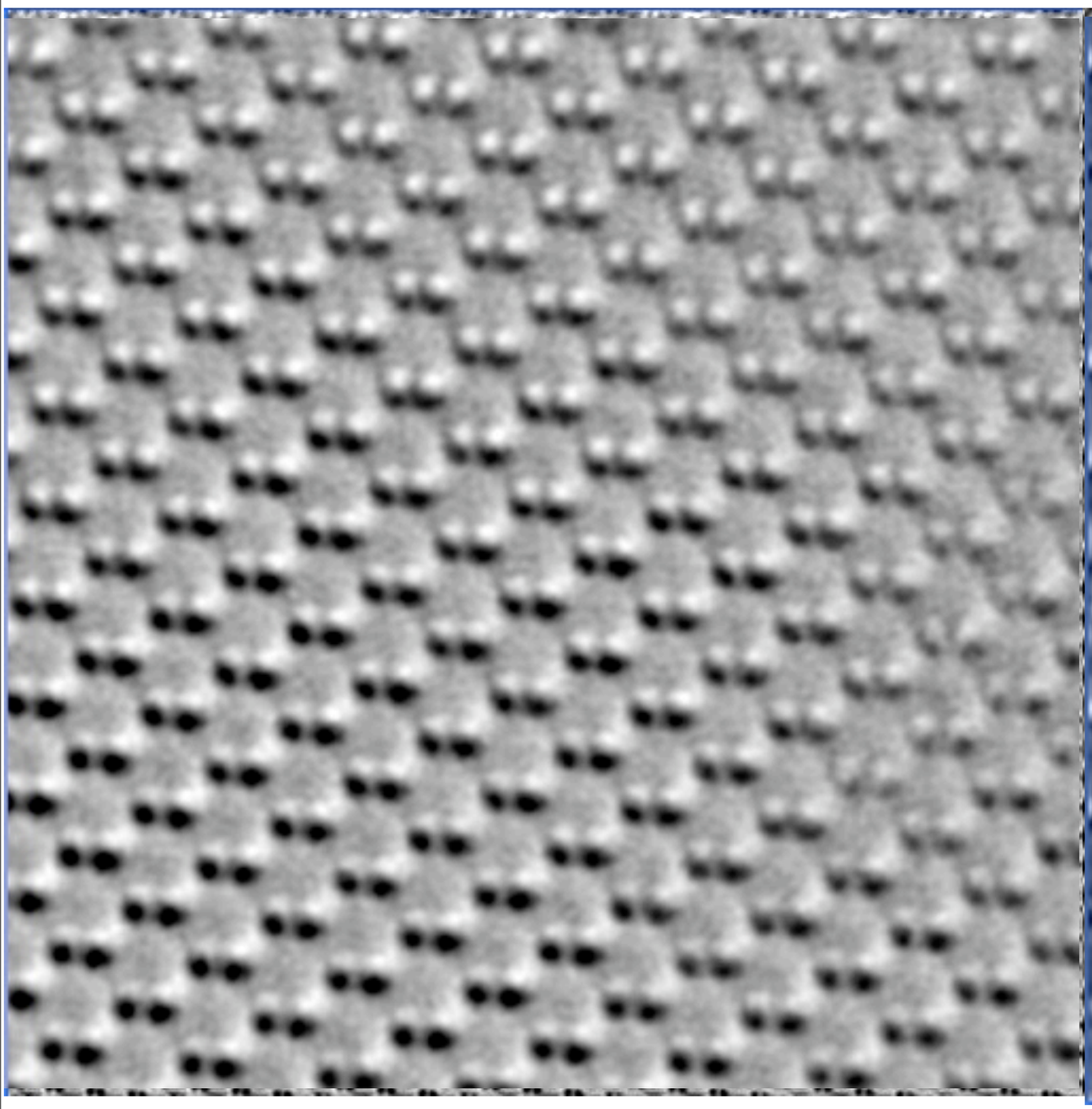


modulus of as reconstructed EW

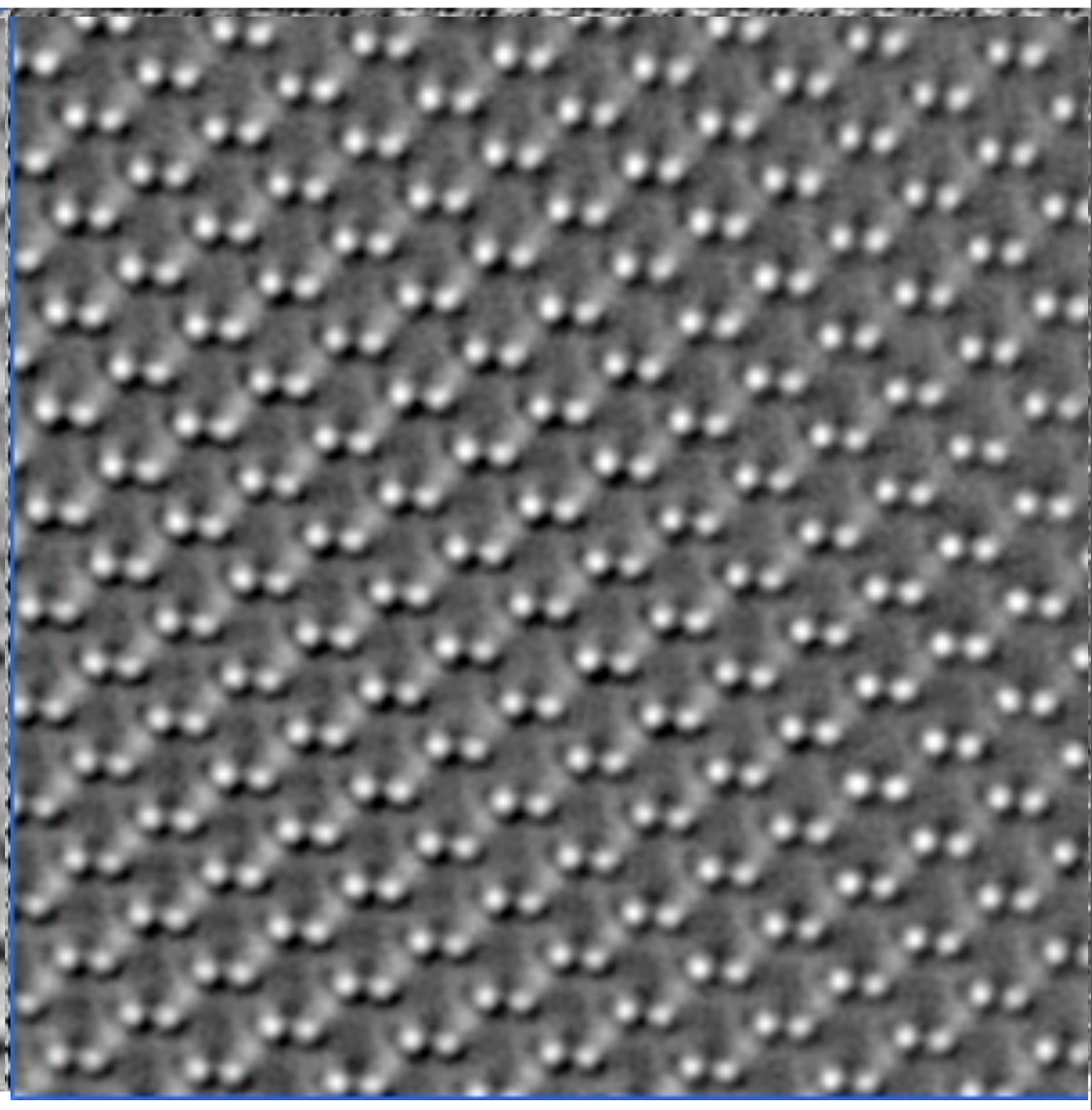
modulus of focus corrected EW

Focus Corrected EW

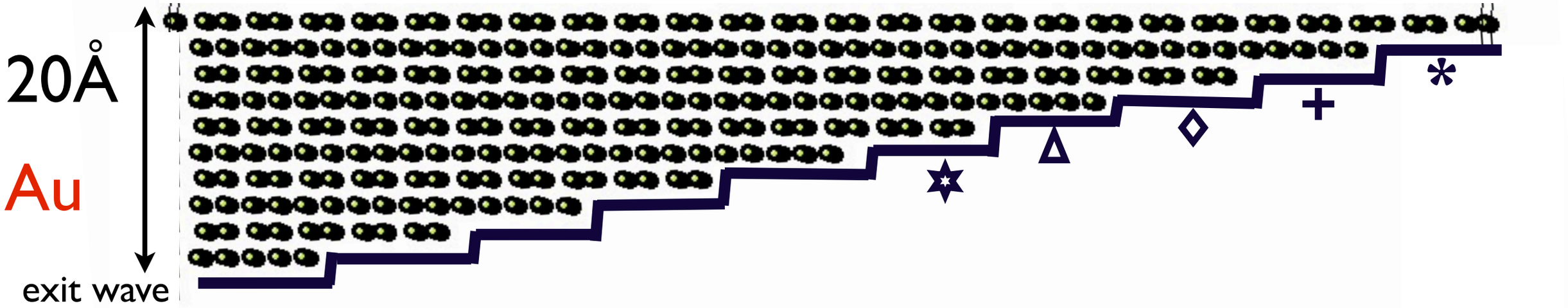
NTHU



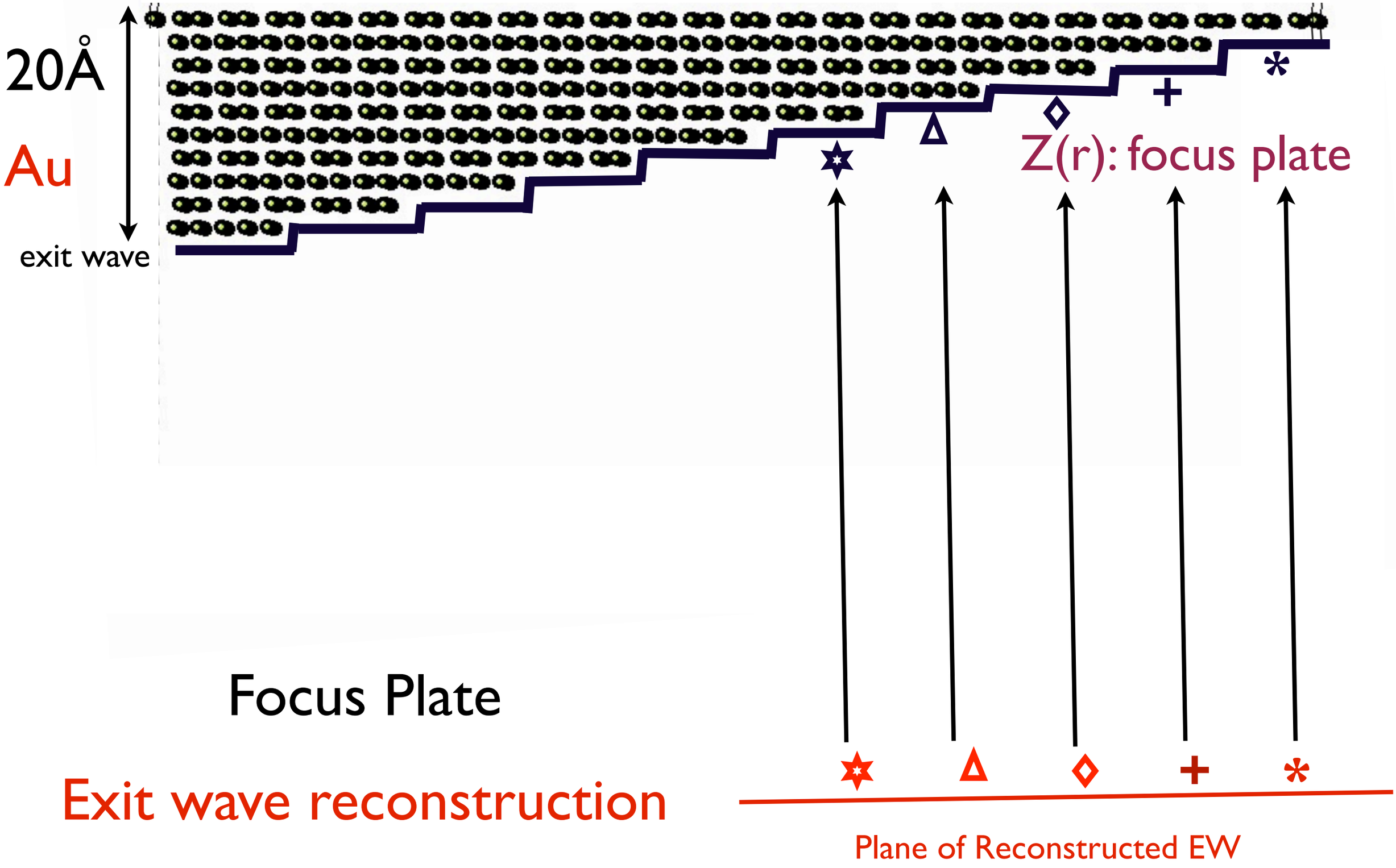
modulus of as reconstructed EW



modulus of focus corrected EW

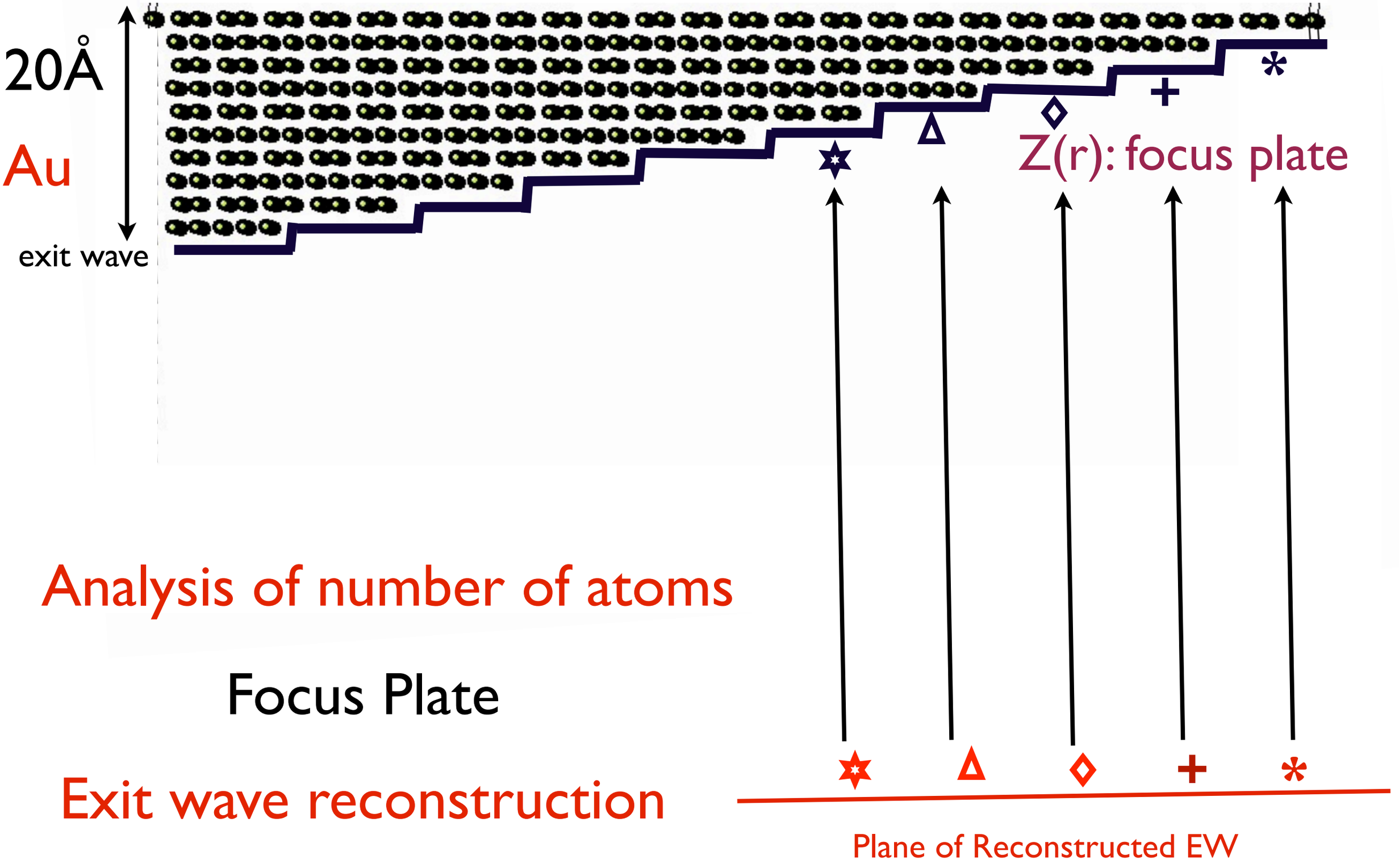


Exit wave reconstruction



Focus Plate

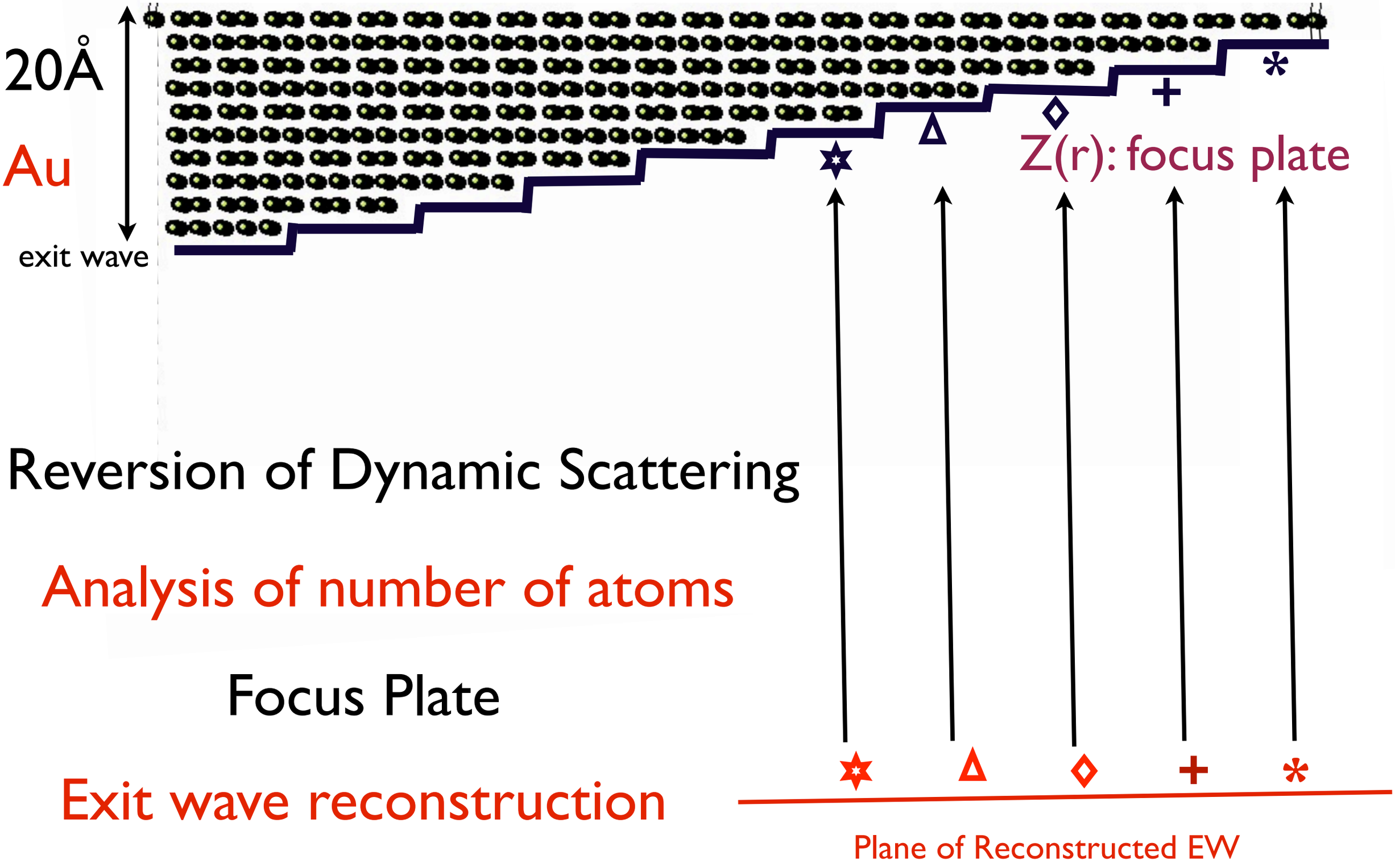
Exit wave reconstruction



Analysis of number of atoms

Focus Plate

Exit wave reconstruction

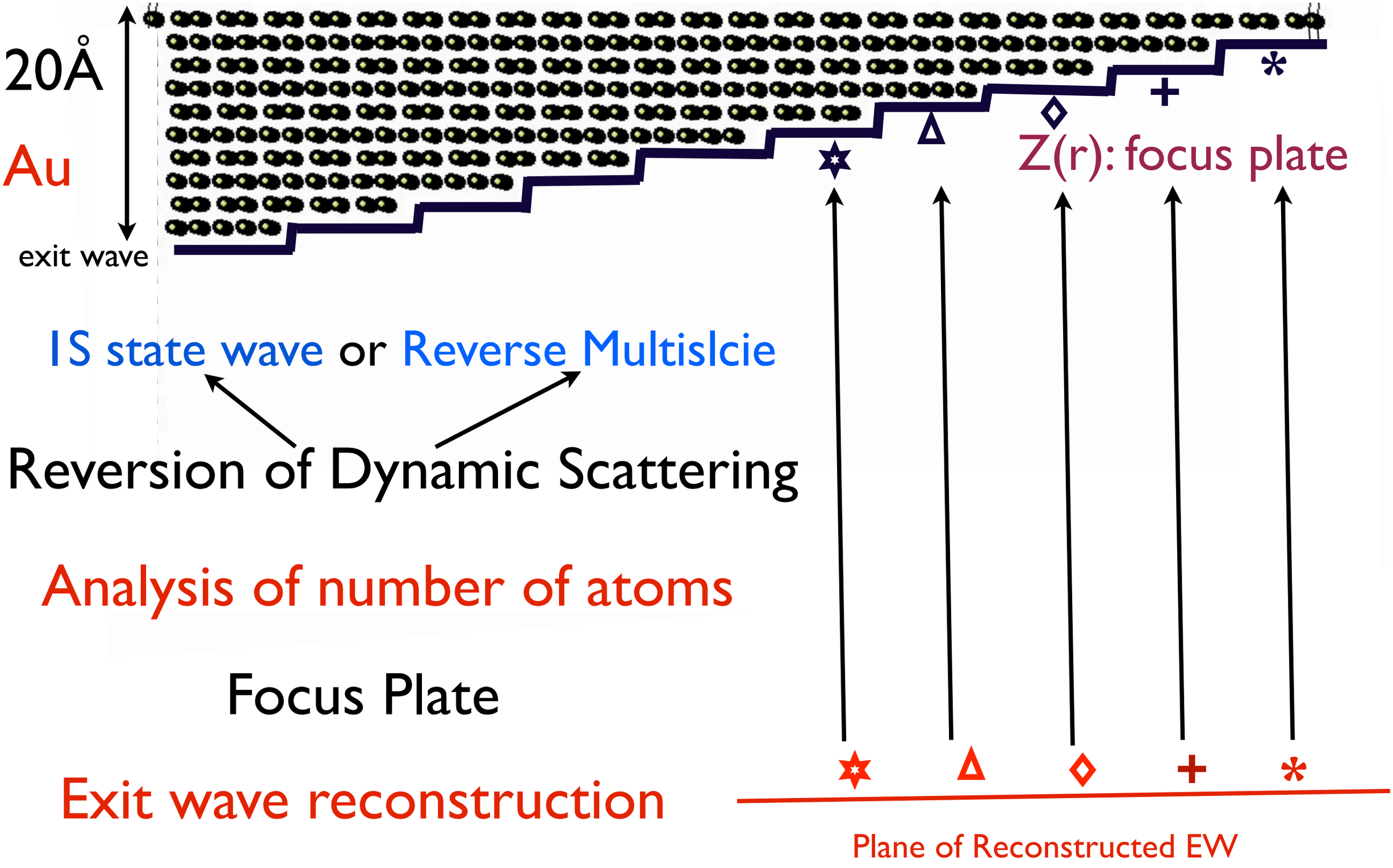


Reversion of Dynamic Scattering

Analysis of number of atoms

Focus Plate

Exit wave reconstruction


20Å
Au
exit wave
Z(r): focus plate
IS state wave or Reverse Multislcie
Reversion of Dynamic Scattering
Analysis of number of atoms
Focus Plate
Exit wave reconstruction
Plane of Reconstructed EW

From Exit wave to Structure

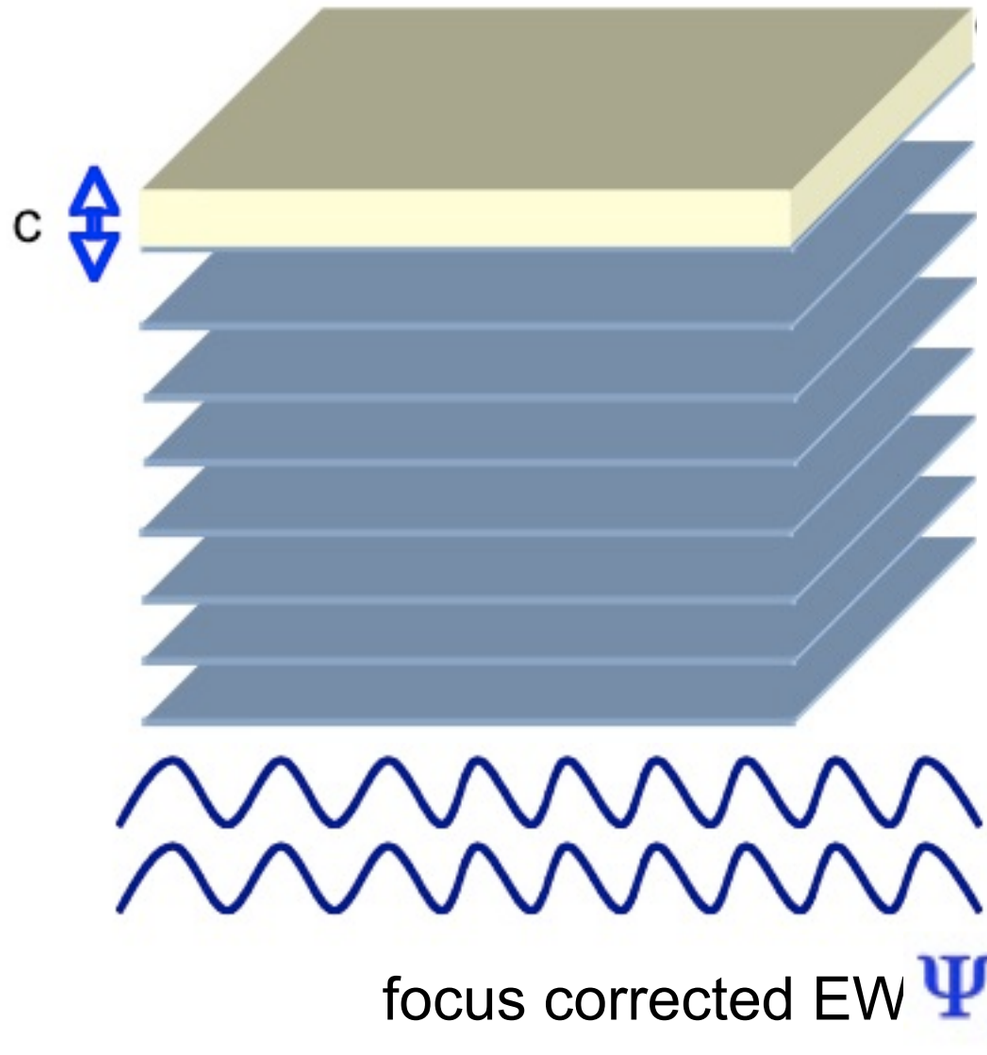
Reverse Multislice Method

focus corrected EW Ψ_e

From Exit wave to Structure

Reverse Multislice Method

specimen can be subdivided into thin slices of phase grating



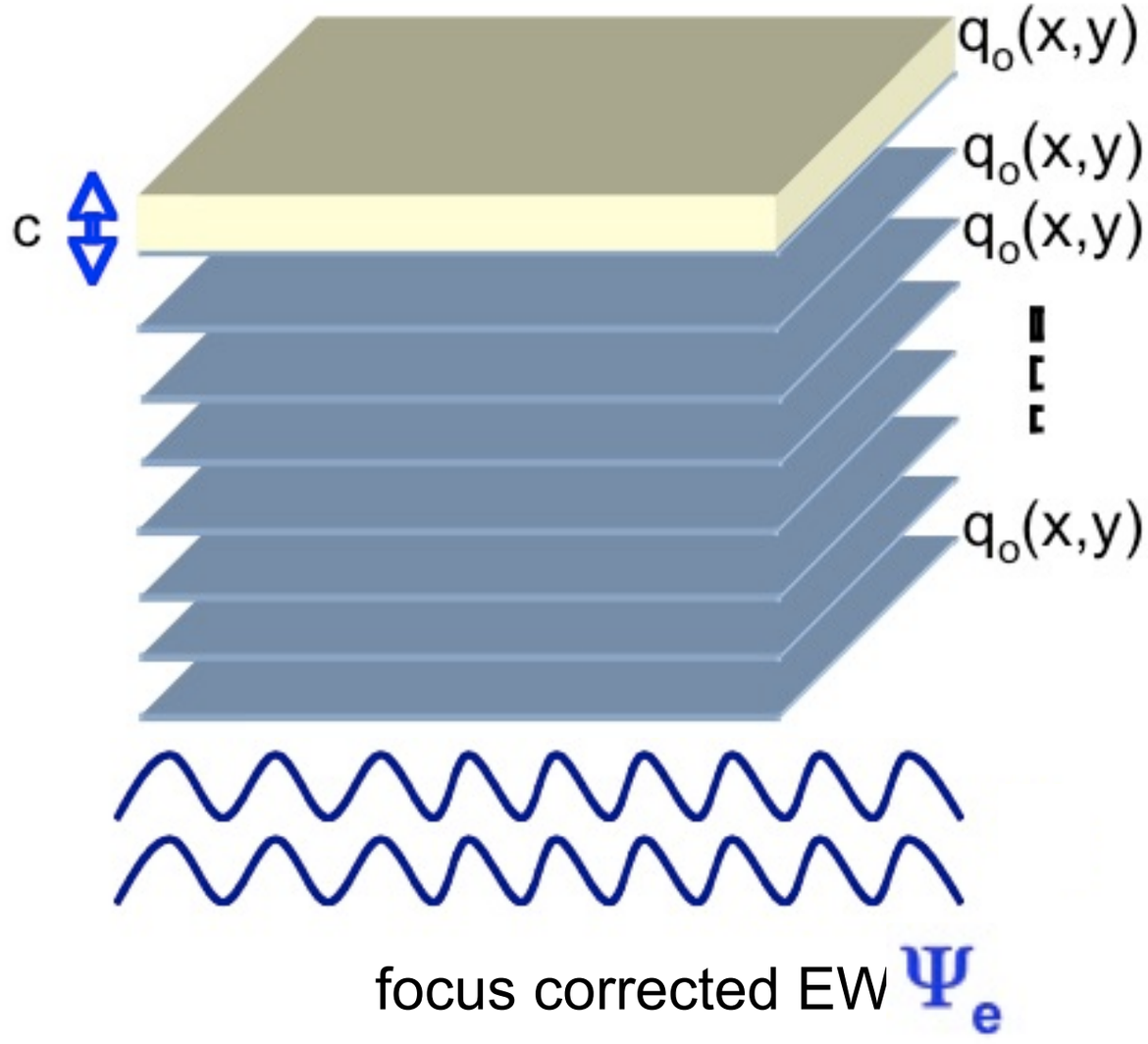
focus corrected EW Ψ_e

From Exit wave to Structure

Reverse Multislice Method

specimen can be subdivided into thin slices of phase grating

$$q_o(x,y)=\exp\{iC_E V(x,y)c\}$$

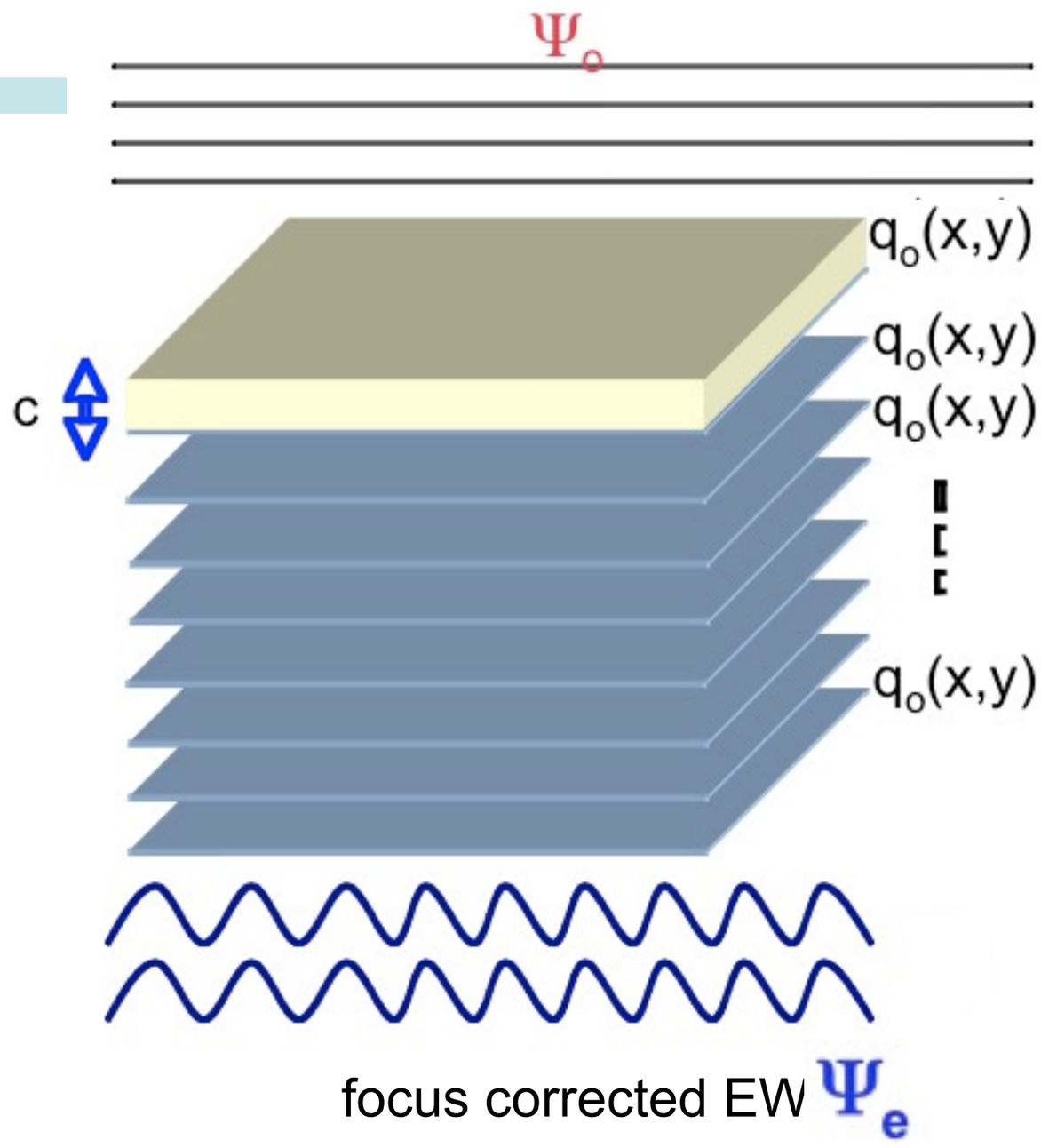


From Exit wave to Structure

Reverse Multislice Method

specimen can be subdivided into thin slices of phase grating

$$q_o(x,y)=\exp\{iC_E V(x,y)c\}$$

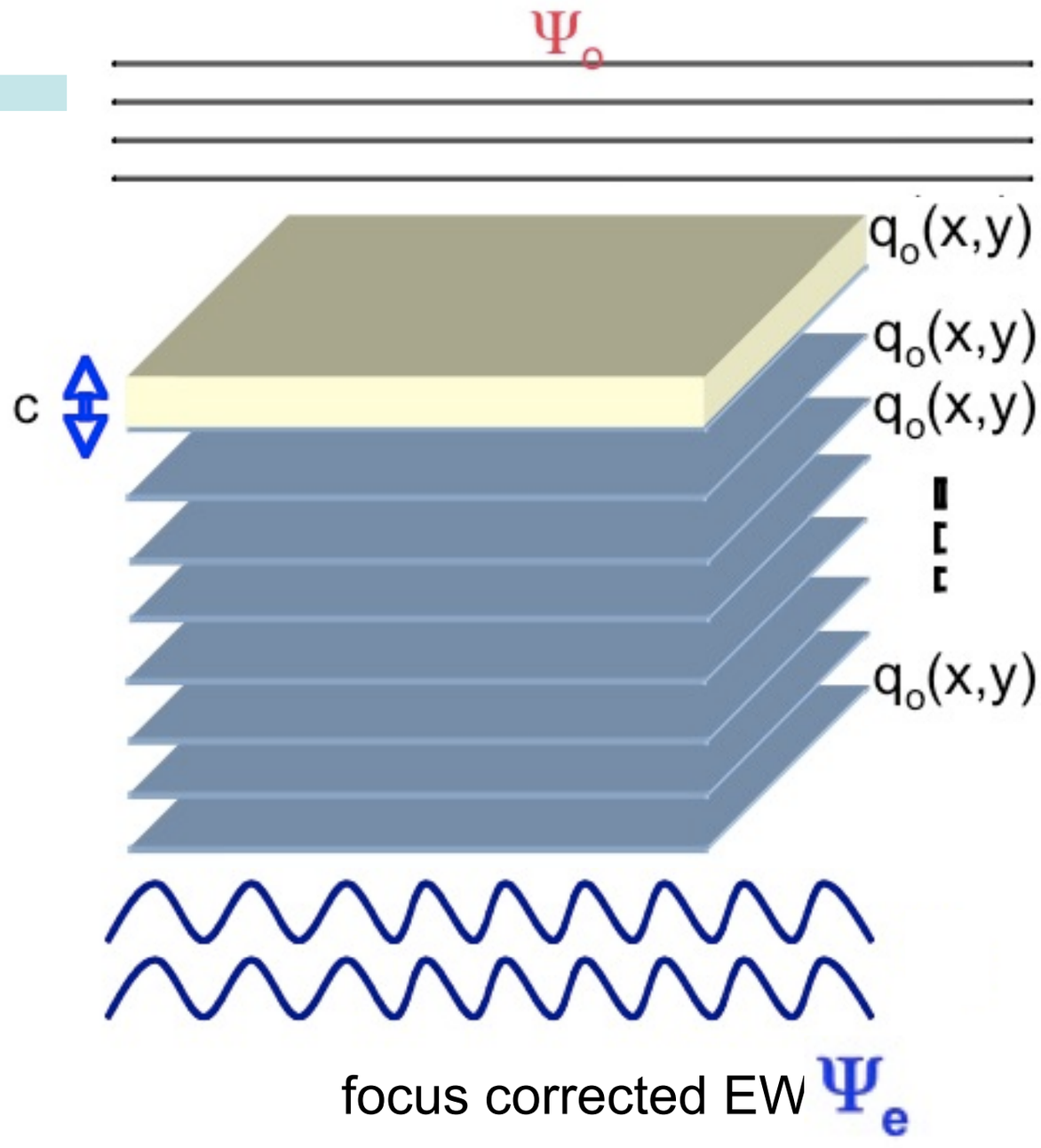


From Exit wave to Structure

Reverse Multislice Method

specimen can be subdivided into thin slices of phase grating

$$q_o(x,y)=\exp\{iC_E V(x,y)c\}$$



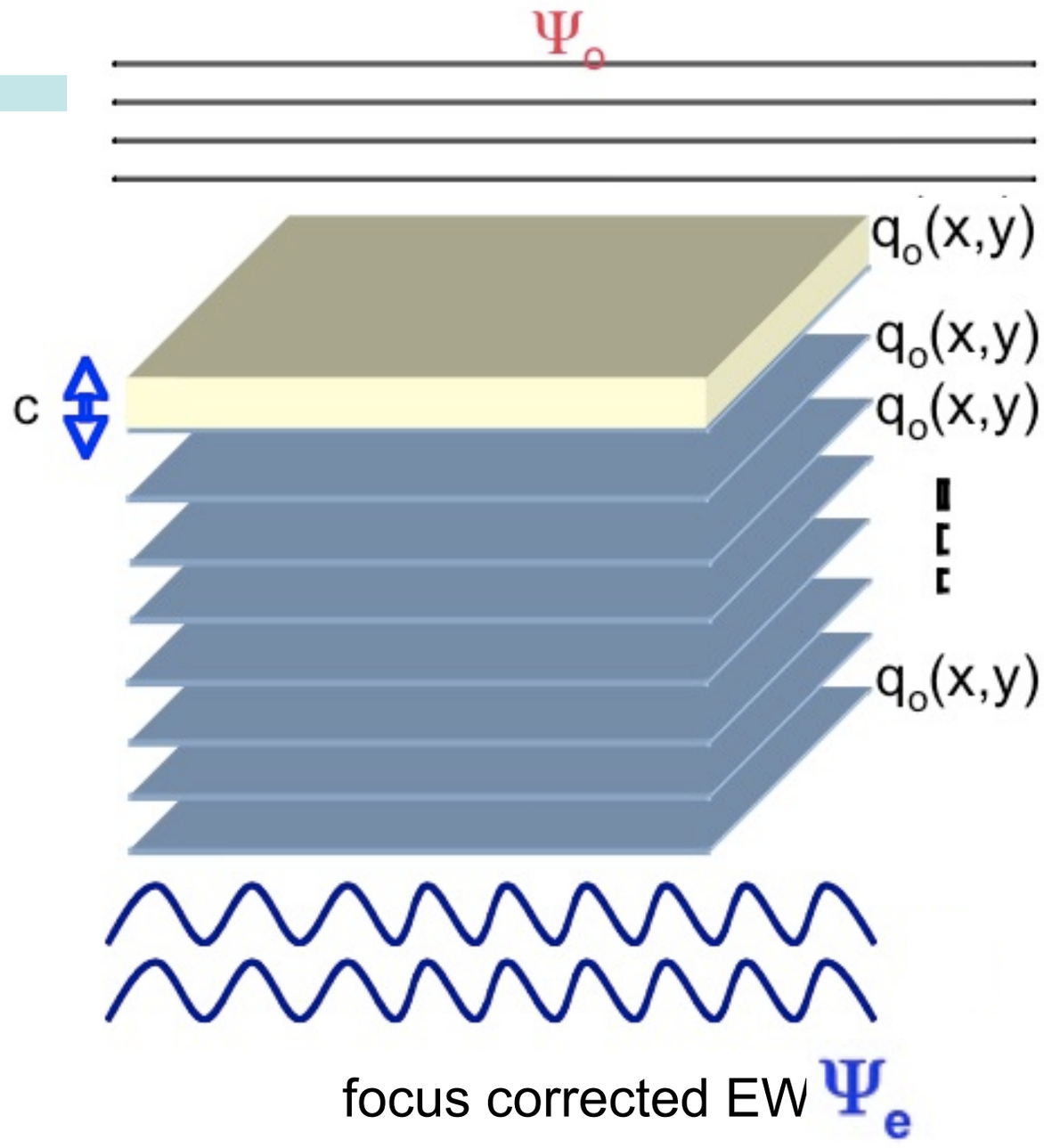
$$(\Psi_o \cdot q_o(x,y)$$

From Exit wave to Structure

Reverse Multislice Method

specimen can be subdivided into thin slices of phase grating

$$q_o(x,y)=\exp\{iC_E V(x,y)c\}$$



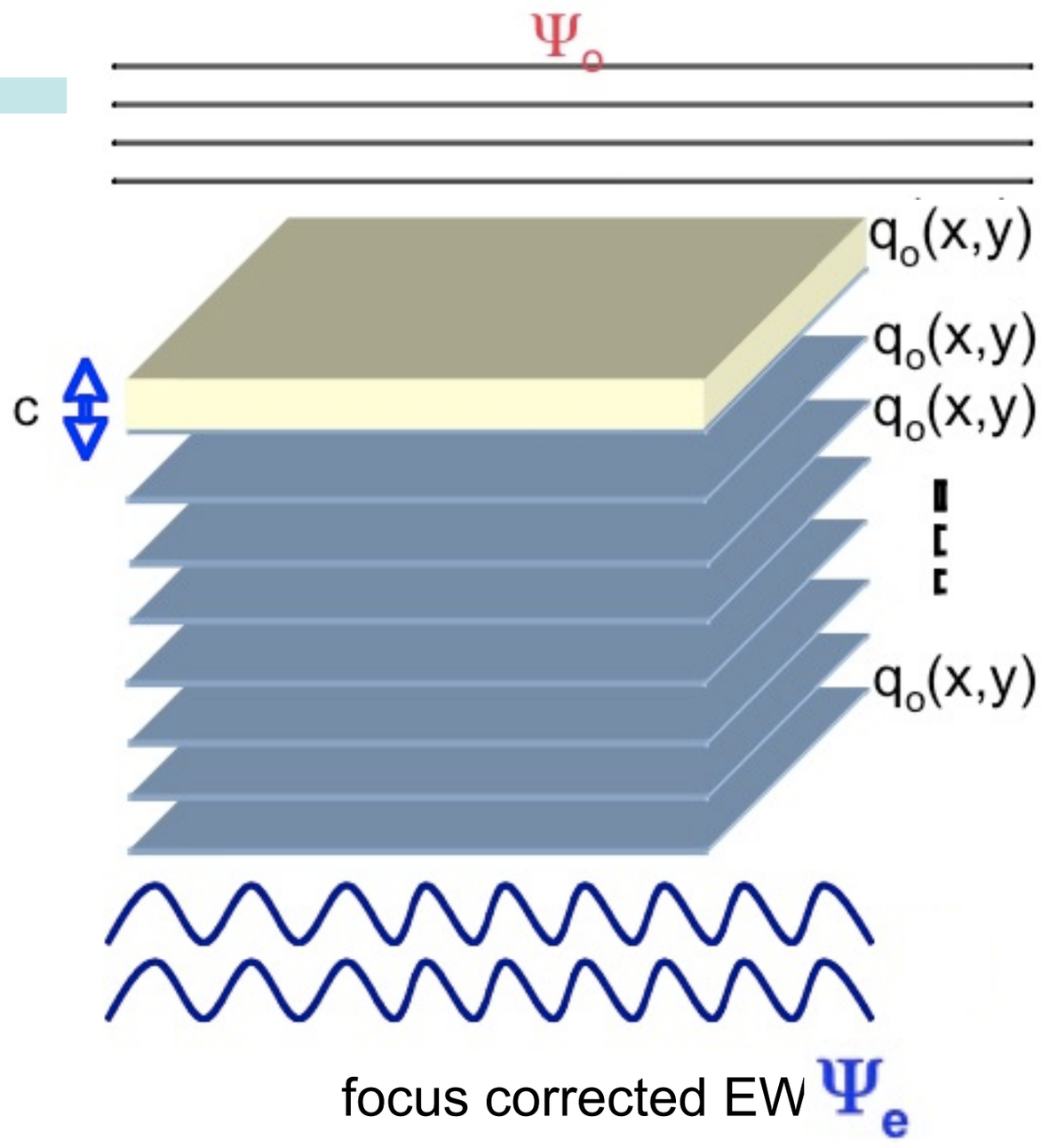
$$(\Psi_o \cdot q_o(x,y)) \otimes p(x,y)]$$

From Exit wave to Structure

Reverse Multislice Method

specimen can be subdivided into thin slices of phase grating

$$q_o(x,y)=\exp\{iC_E V(x,y)c\}$$



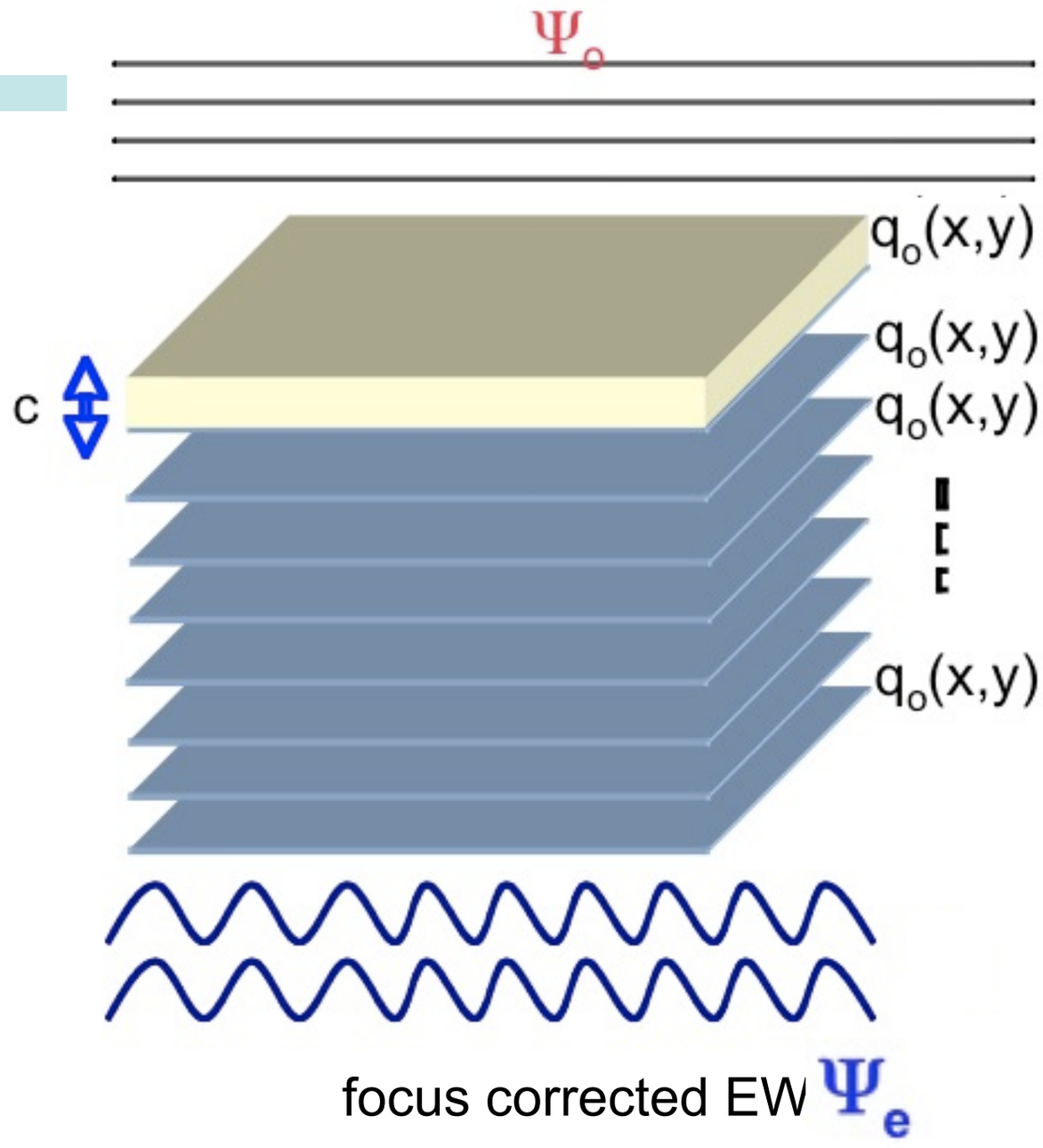
$$(\Psi_o \cdot q_o(x,y)) \otimes p(x,y)]\, q_o(x,y))$$

From Exit wave to Structure

Reverse Multislice Method

specimen can be subdivided into thin slices of phase grating

$$q_o(x,y)=\exp\{iC_E V(x,y)c\}$$



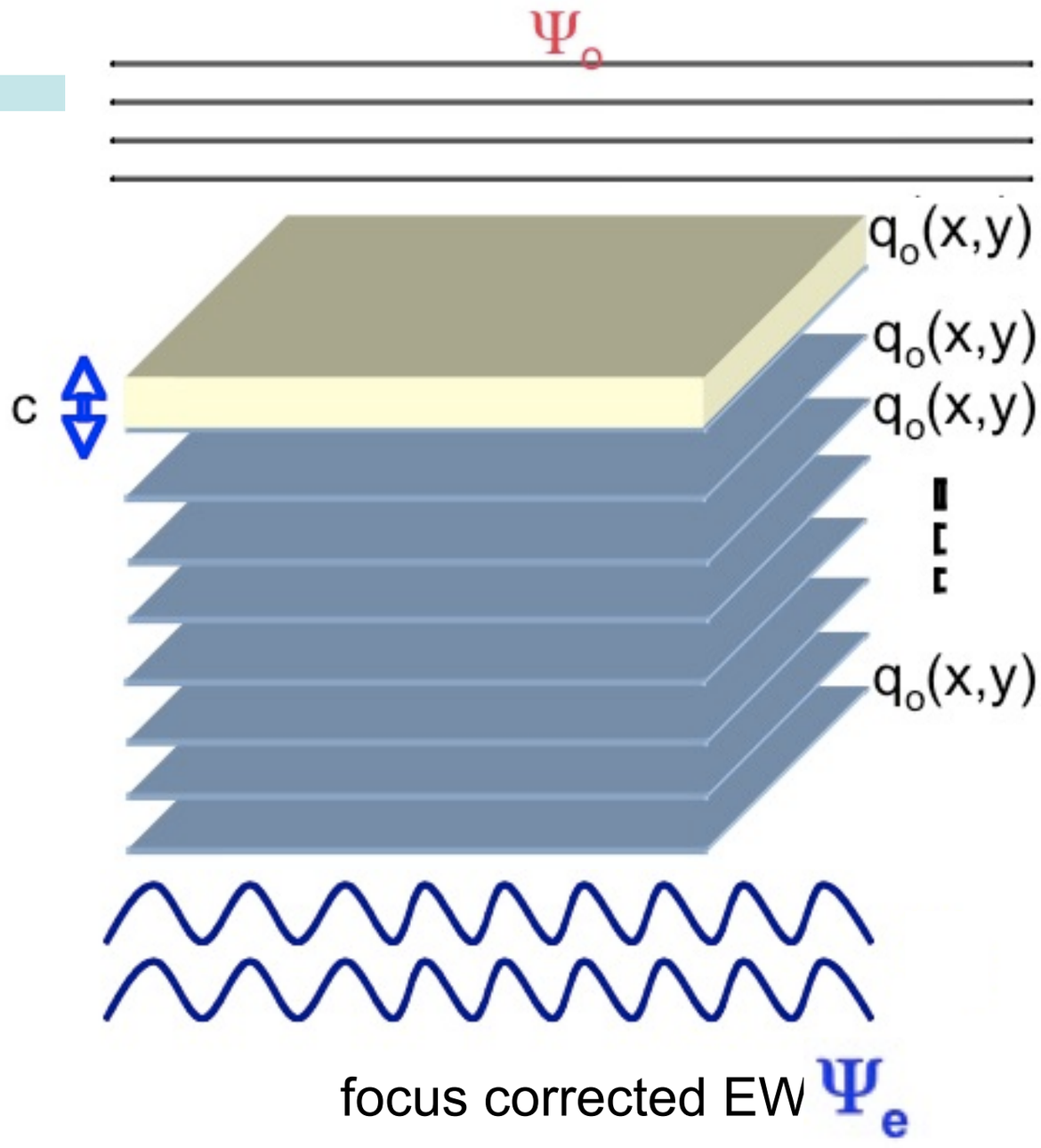
$$(\Psi_o \cdot q_o(x,y)) \otimes p(x,y)]\, q_o(x,y))\ldots)\, q_o$$

From Exit wave to Structure

Reverse Multislice Method

specimen can be subdivided into thin slices of phase grating

$$q_o(x,y)=\exp\{iC_E V(x,y)c\}$$



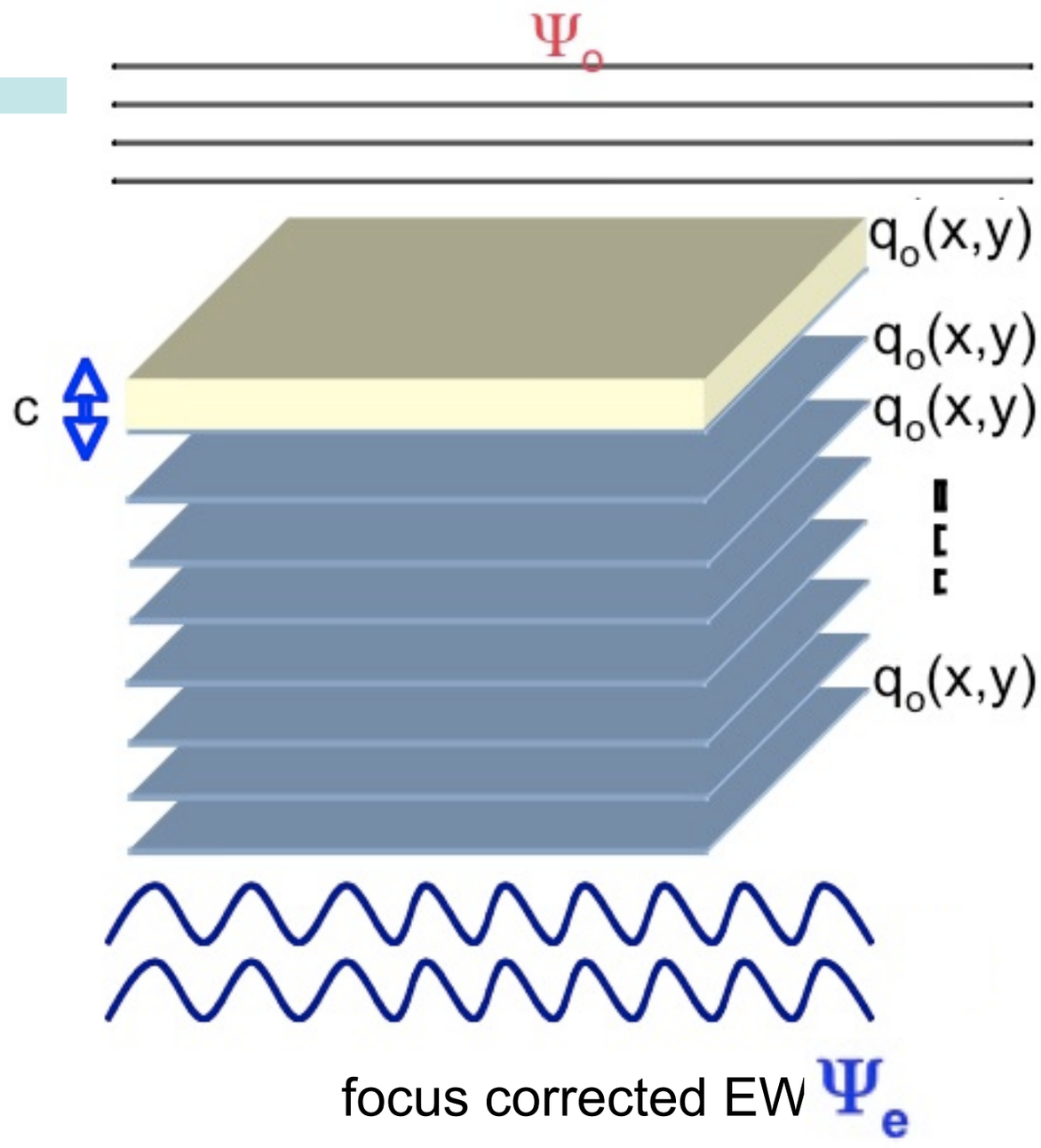
$$(\Psi_o \cdot q_o(x,y)) \otimes p(x,y)]\, q_o(x,y))\ldots)\, q_o(x,y) - \Psi_e$$

From Exit wave to Structure

Reverse Multislice Method

specimen can be subdivided into thin slices of phase grating

$$q_o(x,y)=\exp\{iC_E V(x,y)c\}$$



$$\chi^2 = \{ (\Psi o \cdot q_o(x,y)) \otimes p(x,y)] \, q_o(x,y))\ldots) \, q_o(x,y) - \Psi_e \}^2$$

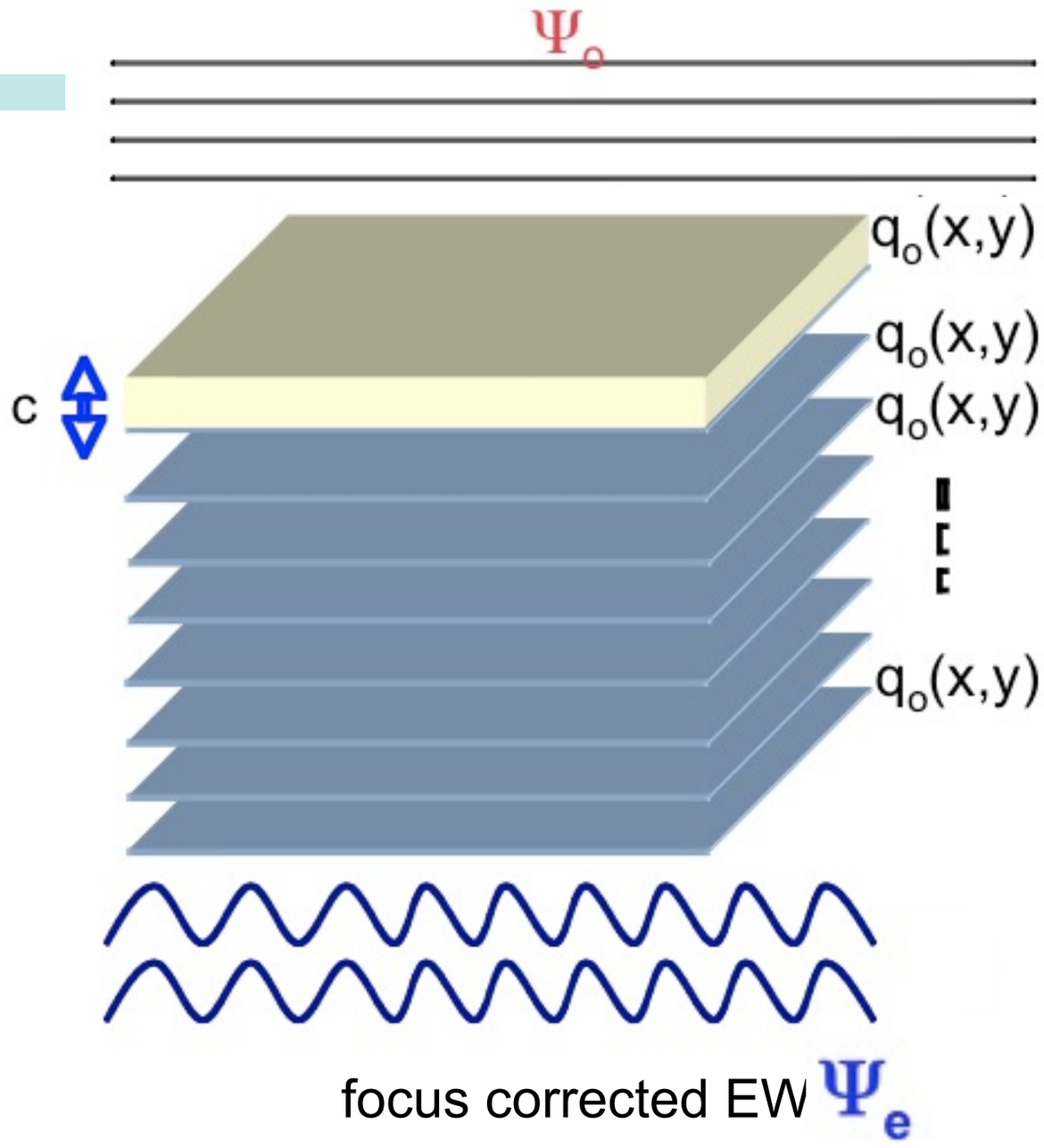
From Exit wave to Structure

Reverse Multislice Method

specimen can be subdivided into thin slices of phase grating

$$q_o(x,y)=\exp\{iC_E V(x,y)c\}$$

$$\partial\chi^2/\partial V(x,y)=0$$



$$\chi^2=\{\,(\Psi_o \cdot q_o(x,y)\,)\otimes p(x,y)]\,q_o(x,y)\,)\ldots)\,q_o(x,y)-\Psi_e\}^2$$

From Exit wave to Structure

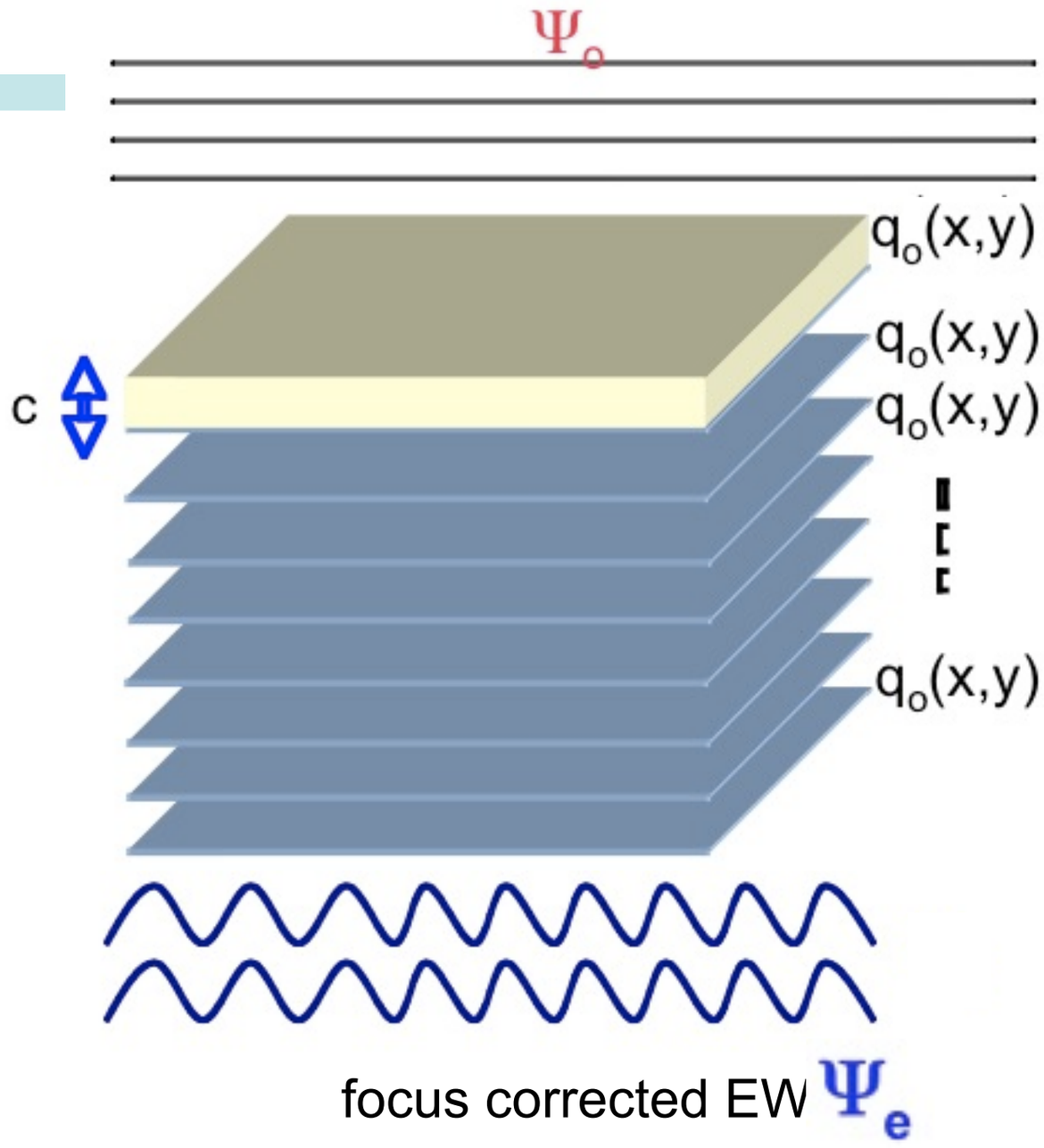
Reverse Multislice Method

specimen can be subdivided into thin slices of phase grating

$$q_o(x,y)=\exp\{iC_E V(x,y)c\}$$

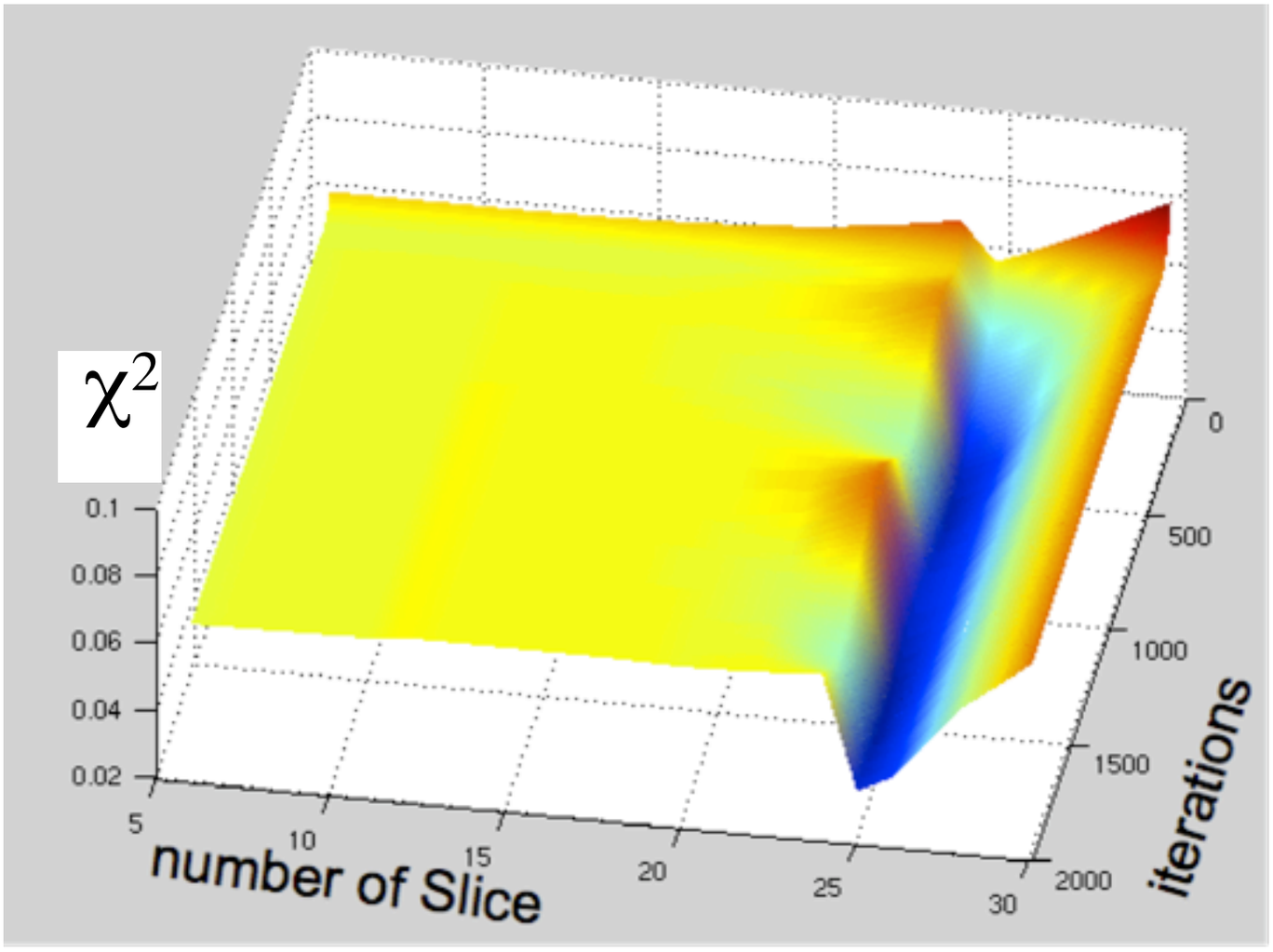
$$\partial\chi^2/\partial V(x,y)=0$$

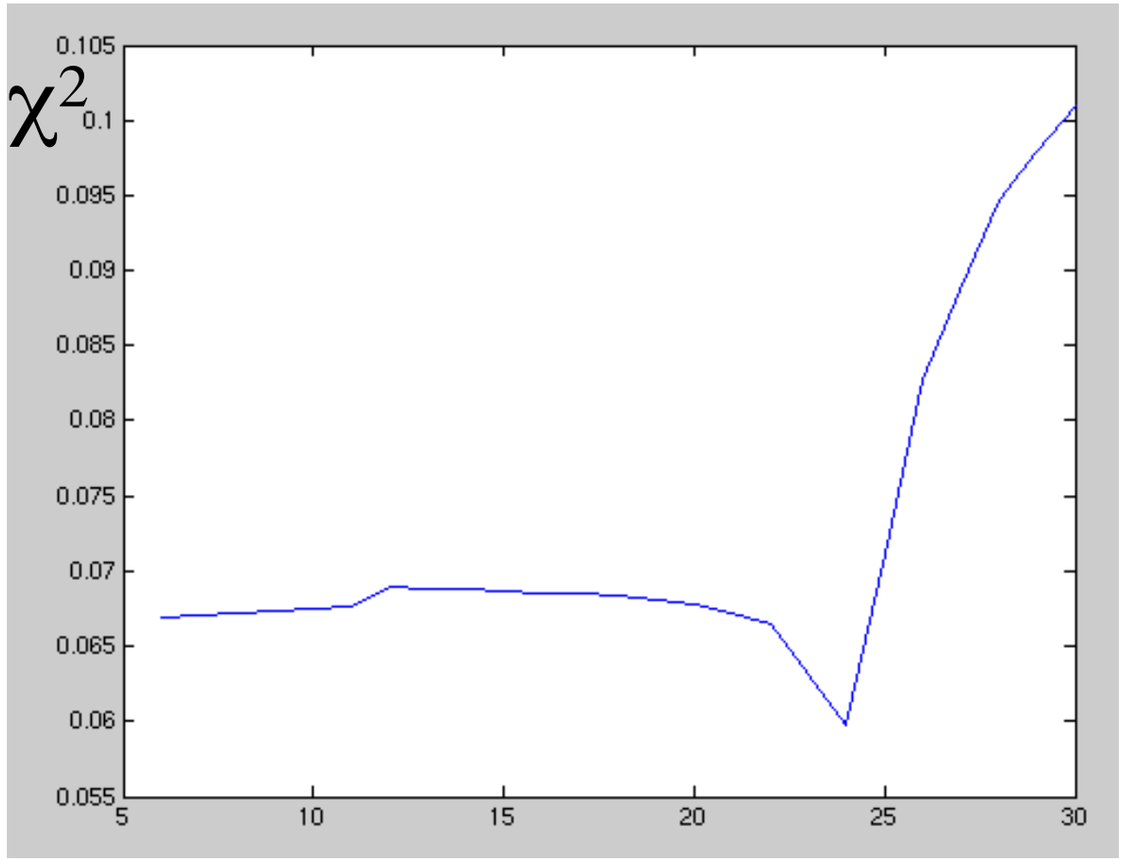
Potential Map



$$\chi^2=\{\ (\Psi o\cdot q_o(x,y)\ )\otimes p(x,y)]\ q_o(x,y)\ )\ldots)\ q_o(x,y)\ -\Psi_e\}^2$$

Analysis of EW Atomic Column by column

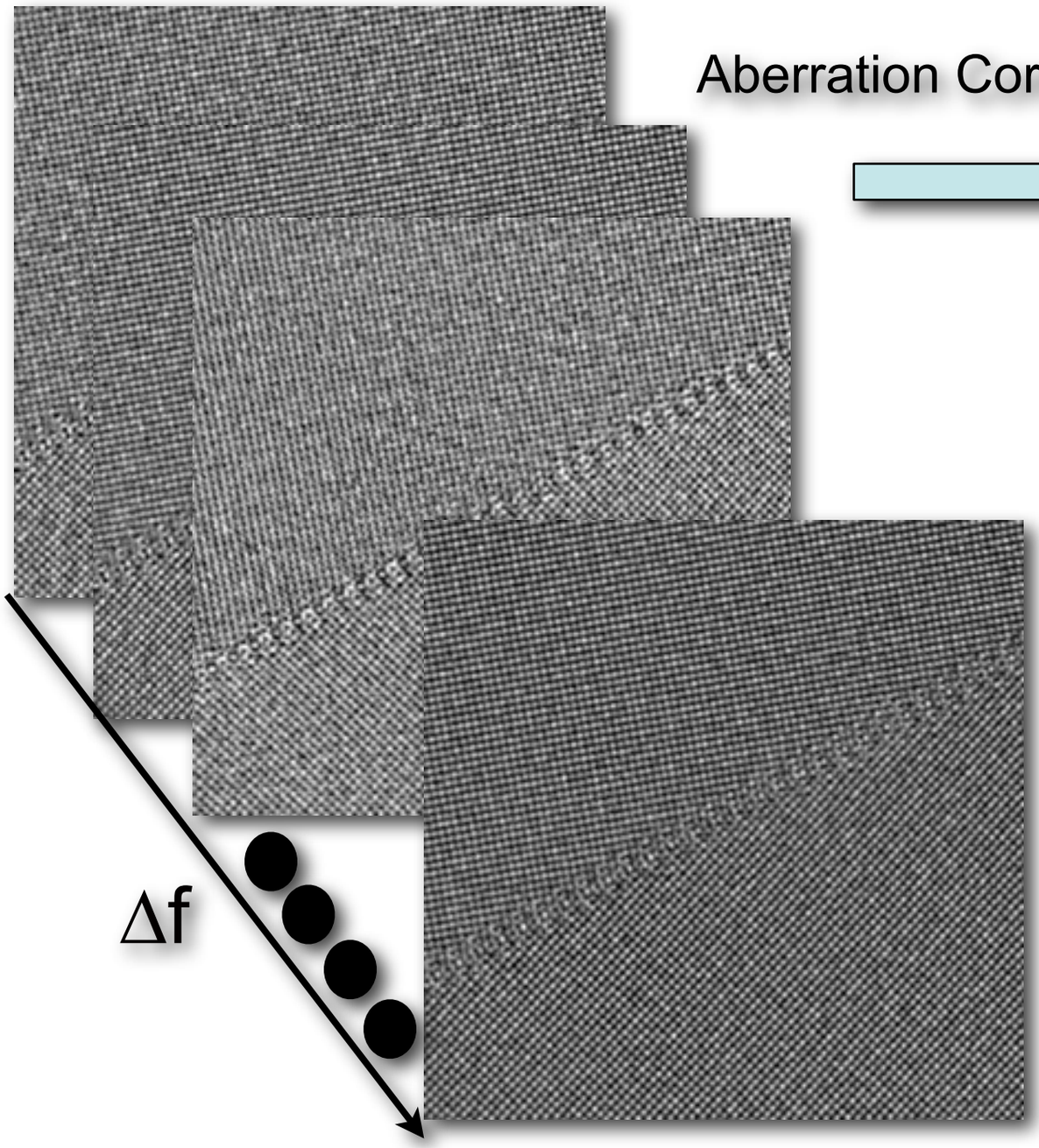




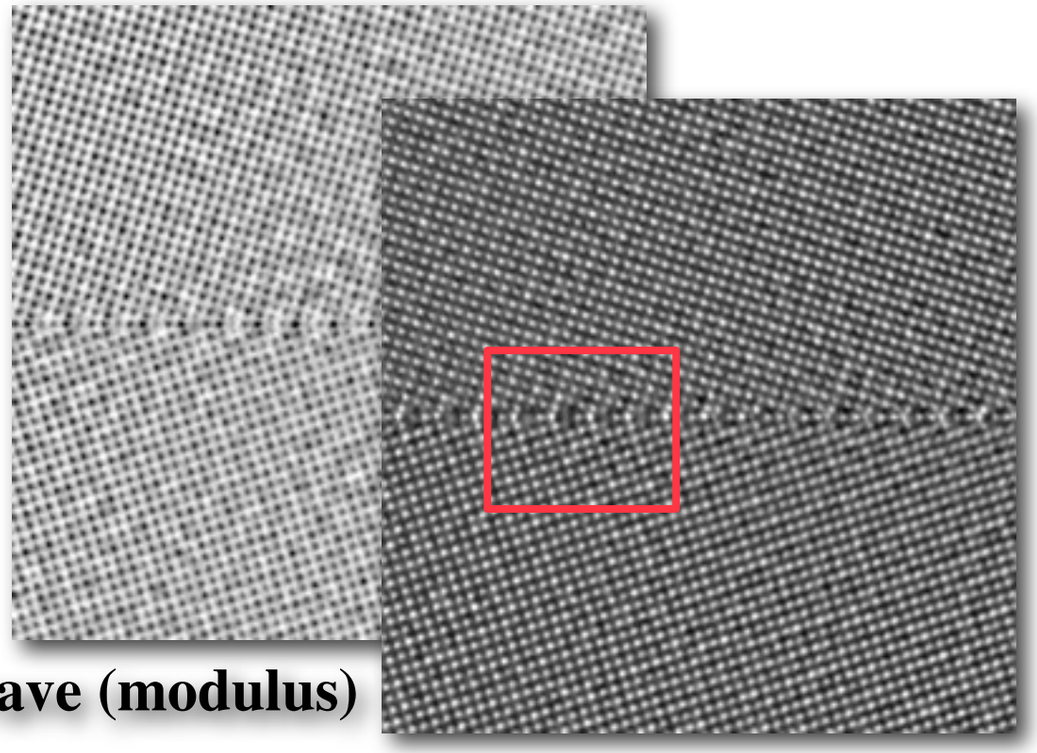
χ^2 map vs iterations and number of slices for input EW

Segregation of Cu in Σ5 Grain Boundary in Al

NTHU

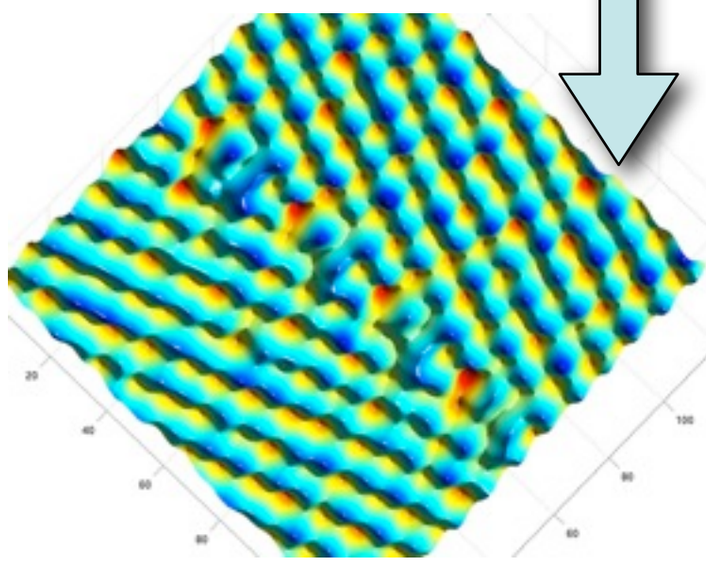


Aberration Correction



Exit wave (modulus)

Exit wave (phase)



Potential Map

Fu-Rong Chen1, Christian Kisielowski, Joerg R. Jinschek

	EXP	Retrived
x_{cu}	1%	0.8%

NTHU

$V_o = x_{Al} V_{o,Al} + x_{cu} V_{o,Cu}$

$V_o(x,y) = X_{Al}(x,y) V_{o,Al} + X_{Cu}(x,y) V_{o,Cu}$

$V_{o,Cu}$=23.5eV, $V_{o,Al}$=17eV

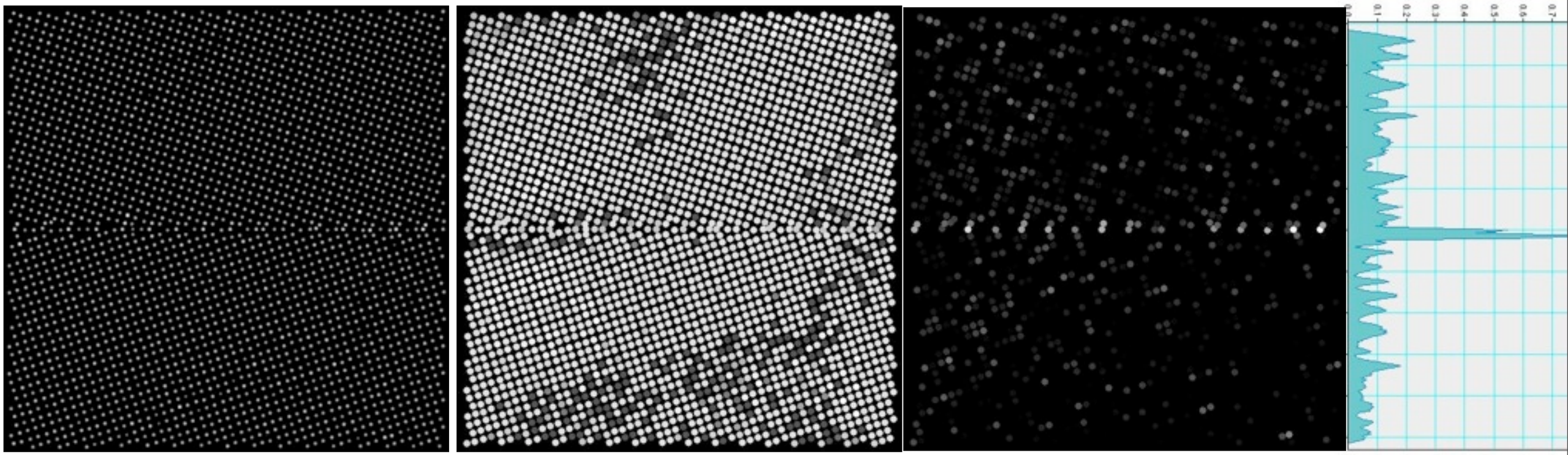
$$X_{Al}(x,y) = \frac{V_{o,Cu} - V_o(x,y)}{V_{o,Cu} - V_{o,Al}}$$

$$X_{Cu}(x,y) = \frac{V_o(x,y) - V_{o,Al}}{V_{o,Cu} - V_{o,Al}}$$

$V_o(x,y)$

$X_{Al}(x,y)*t(x,y)$

$X_{Cu}(x,y)*t(x,y)$



	EXP	Retrived
x_{cu}	1%	0.8%

Bonding Energy of Al Grain Boundary to Cu Solute

$$X_{Cu}^{b} = \frac{X_{cu}\exp(Q/kT)}{(1-X_{cu})+X_{cu}\exp(Q/kT)}$$

X_{cu}^{b} : the concentration of Cu at grain boundary

X_{cu} : the concentration of Cu in matrix

Q : the bonding energy of grain boundary to solute atom Cu

T: temperature

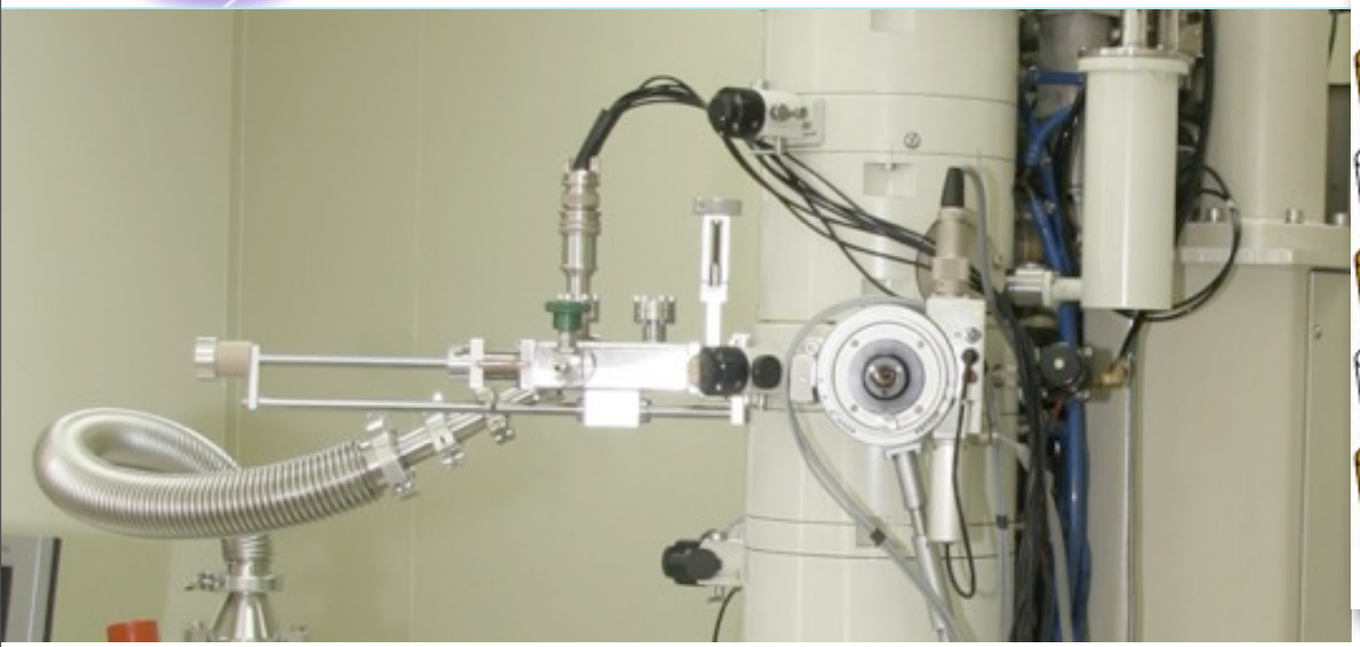
Calculated Q =0.02eV/atom

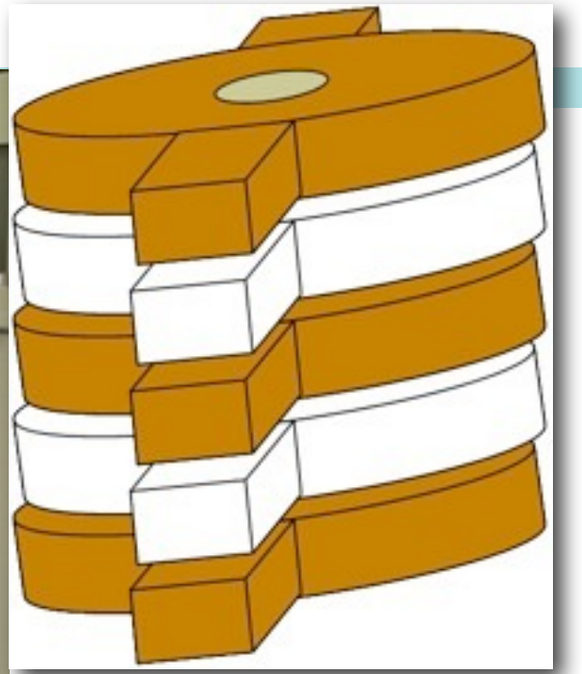
Conclusions

- Focal plate: determination of the geometry of exit surface of sample
- Correction of dynamic scattering is an important issue for quantification of the structure (Reverse multislice or 1s state model)
- For sample containing single element, it is possible to reconstruct 3-d structure with focal series images...Au wedge case
- We are working on the REWs from experimental cases

- (b) Development of “phase (plate)/ wet cell TEM”

Phase Plate/ Wet Cell Microscopy:





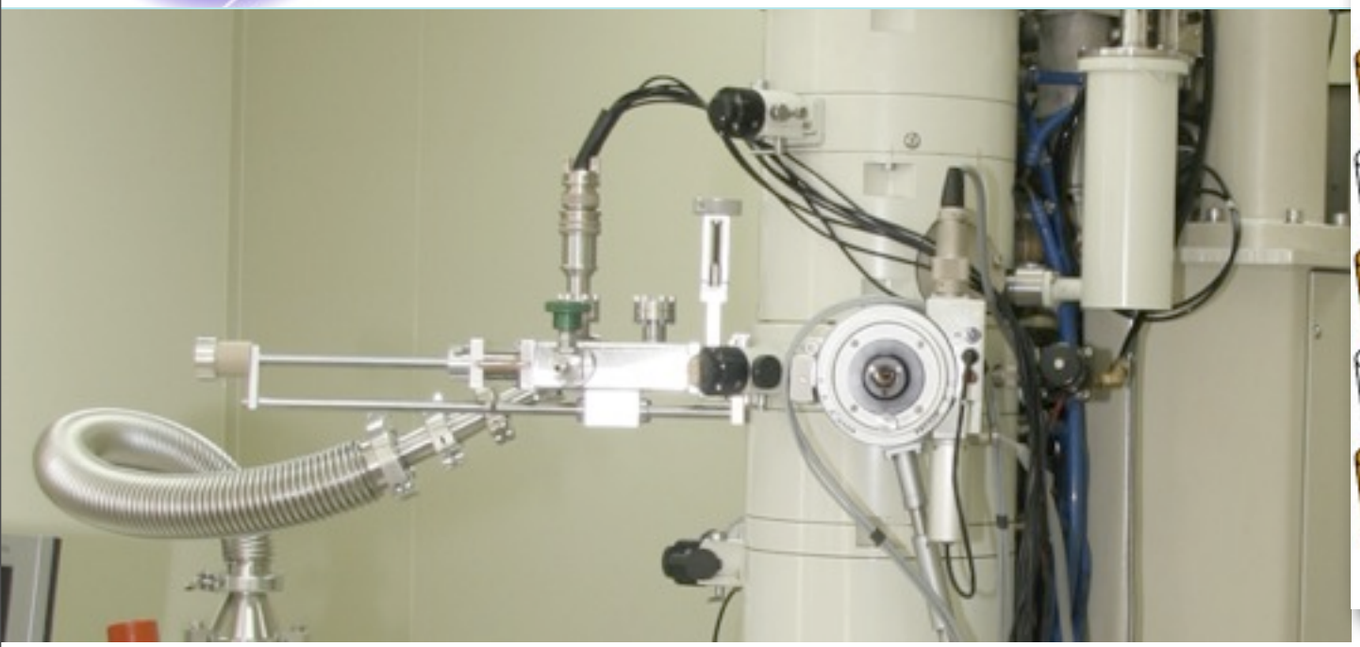
Phase Plate

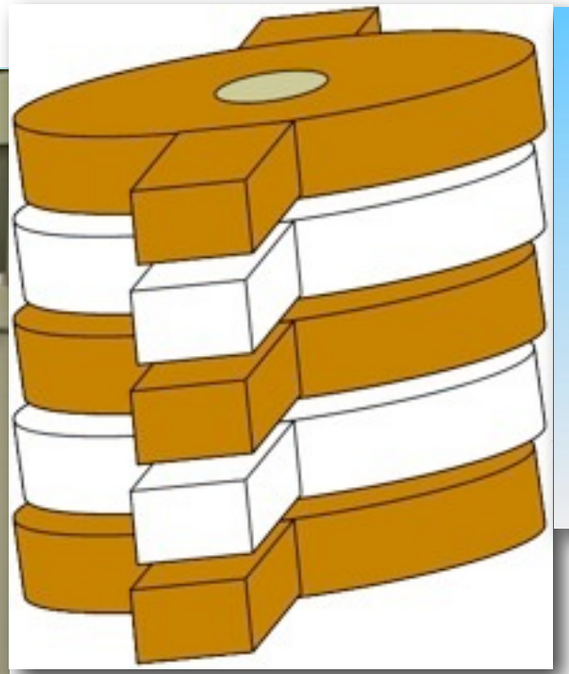
Wet cell

MEMs fabrication

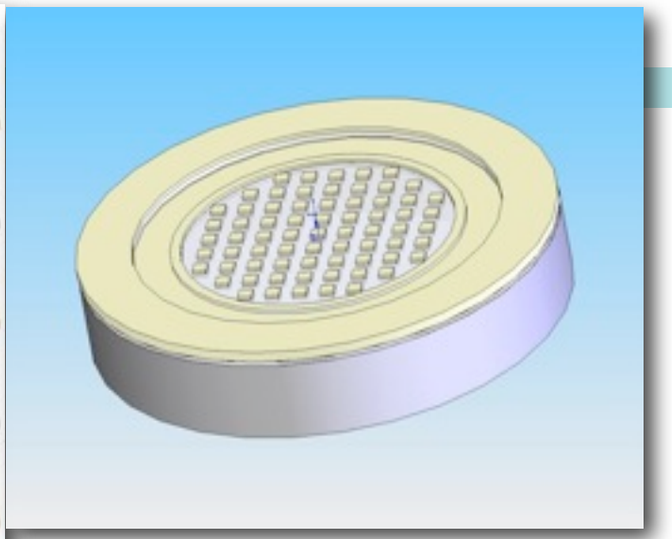
Bottlenecks for Biological Imaging

Phase Plate/ Wet Cell Microscopy:





Phase Plate

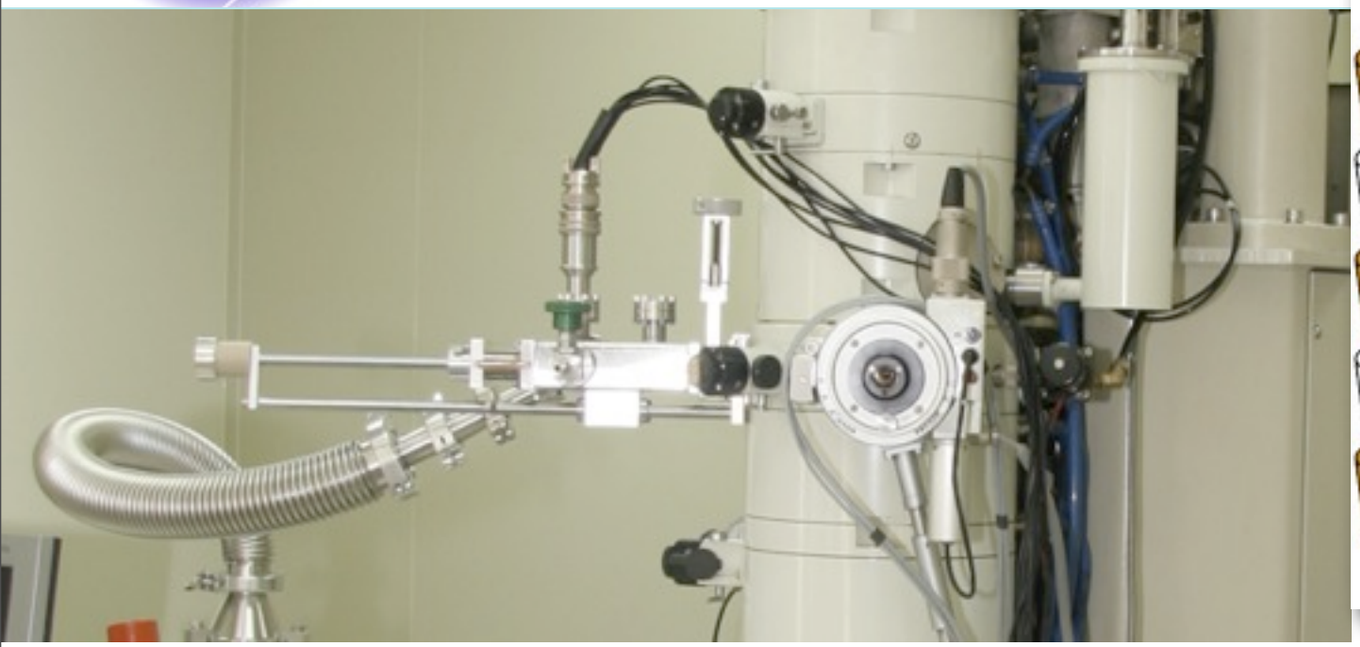


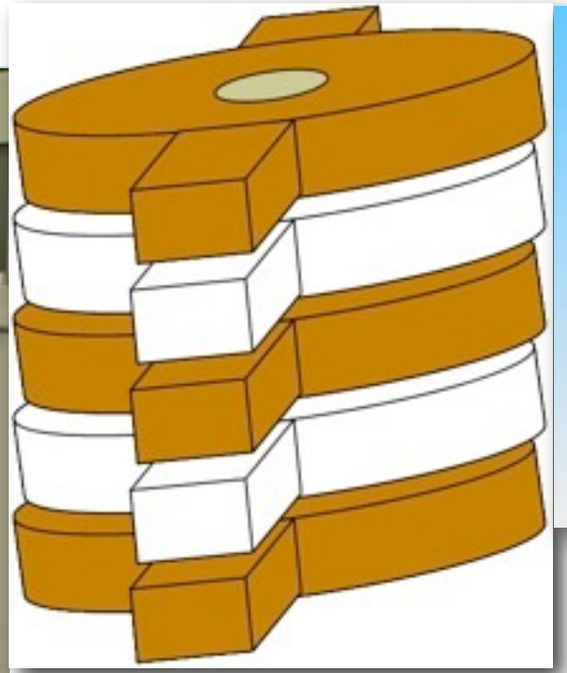
Wet cell

MEMs fabrication

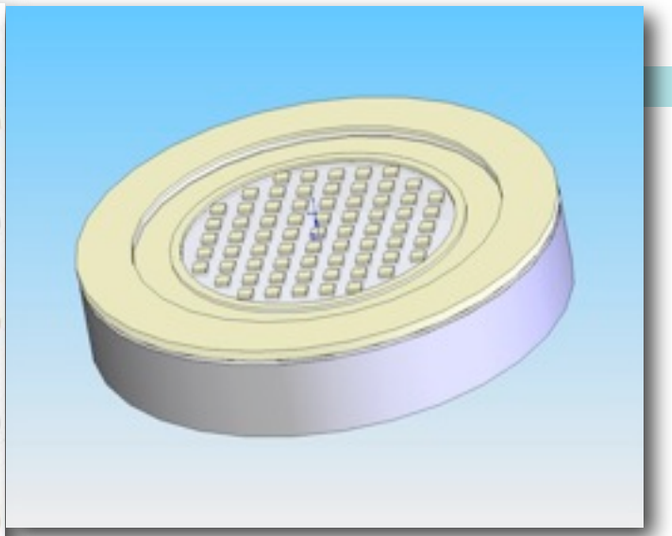
Bottlenecks for Biological Imaging

Phase Plate/ Wet Cell Microscopy:





Phase Plate



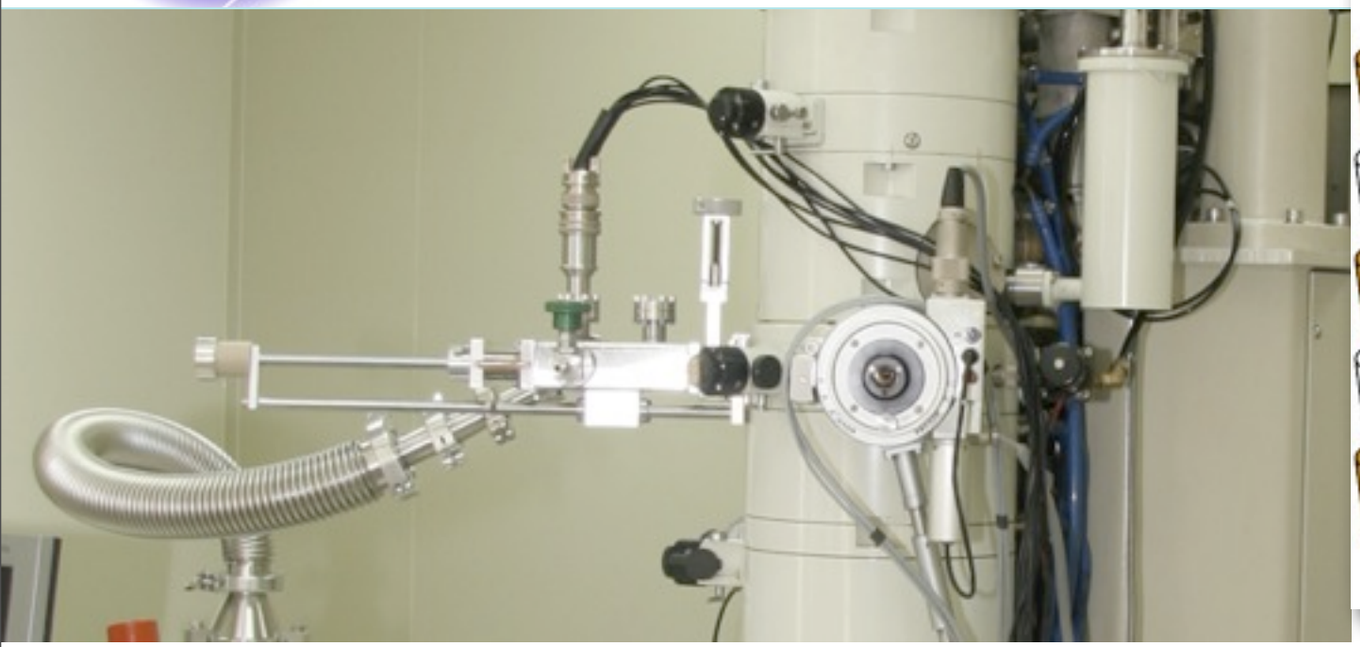
Wet cell

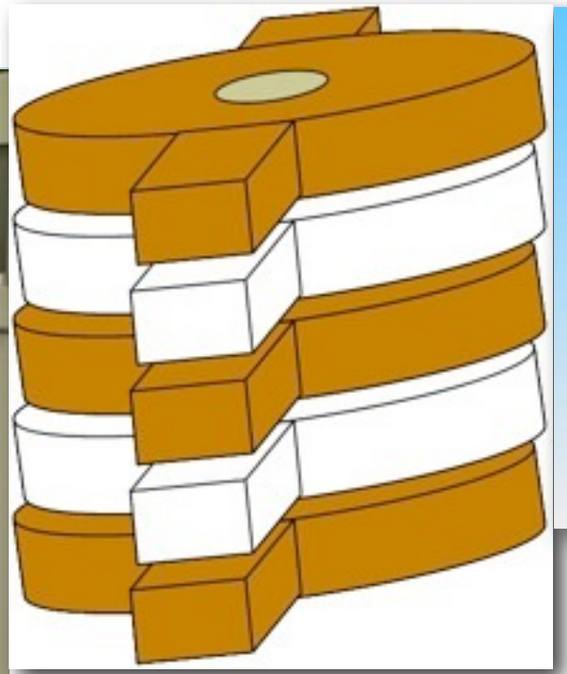
MEMs fabrication

Bottlenecks for Biological Imaging

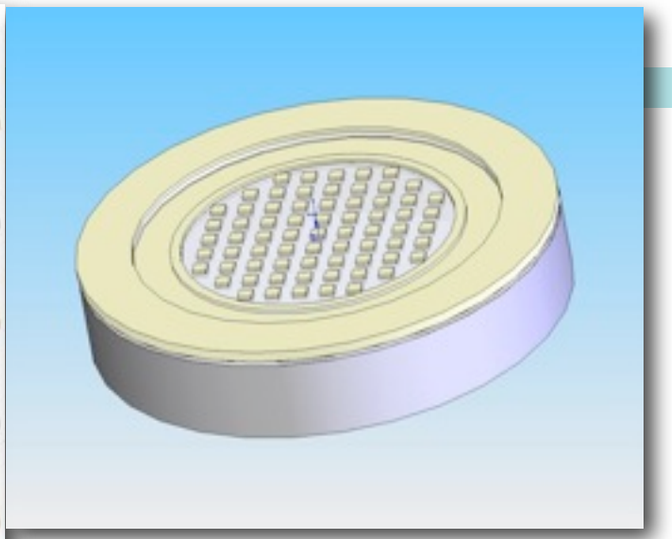
a) Lack of contrast:

Phase Plate/ Wet Cell Microscopy:





Phase Plate



Wet cell

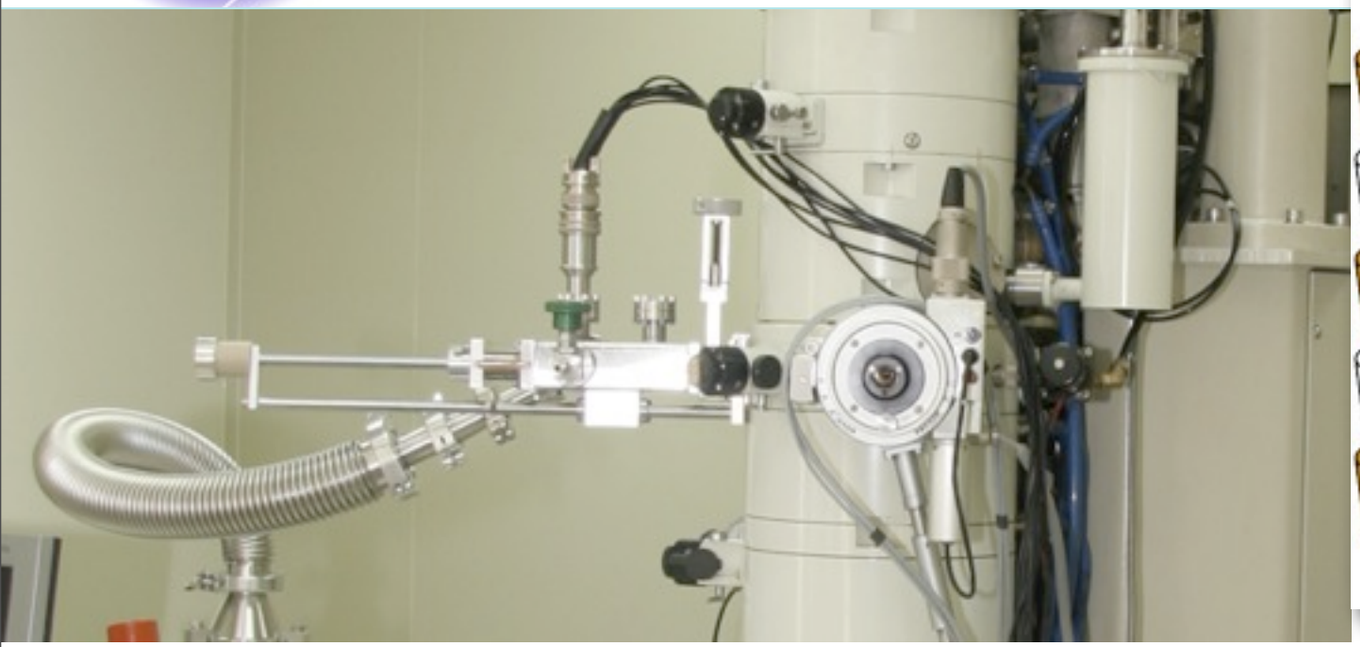
MEMs fabrication

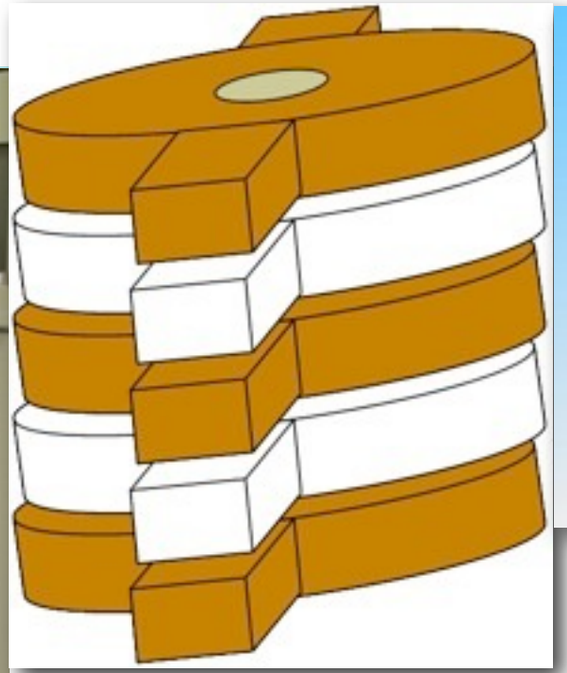
Bottlenecks for Biological Imaging

a) Lack of contrast:

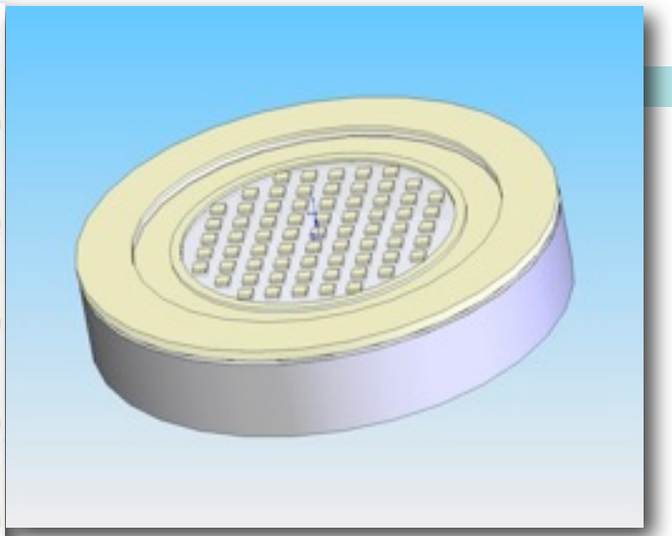
b) Only dry sample is allowed:

Phase Plate/ Wet Cell Microscopy:





Phase Plate



Wet cell

MEMs fabrication

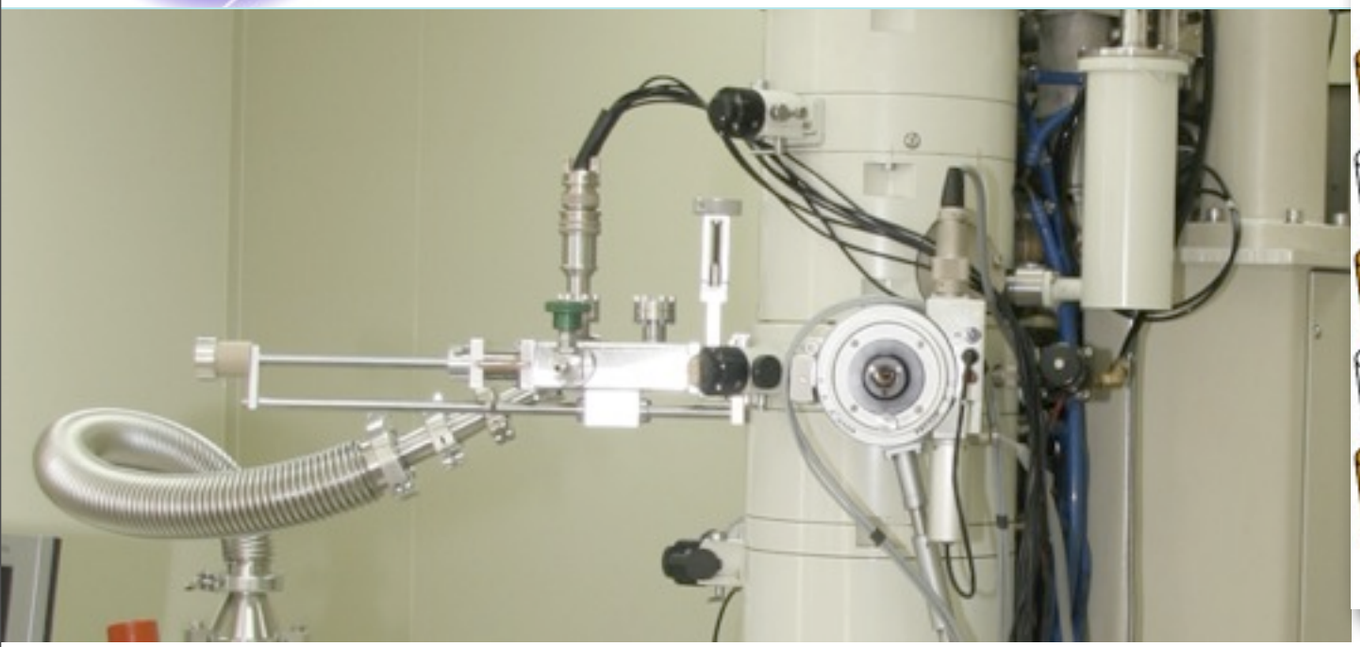
Bottlenecks for Biological Imaging

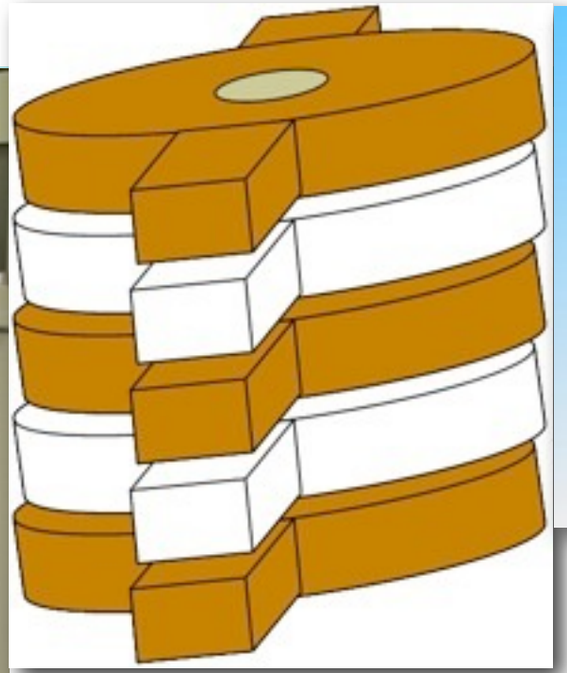
a) Lack of contrast: Zernike Phase Plate

(alternate the phase of electron wave in focal plane)

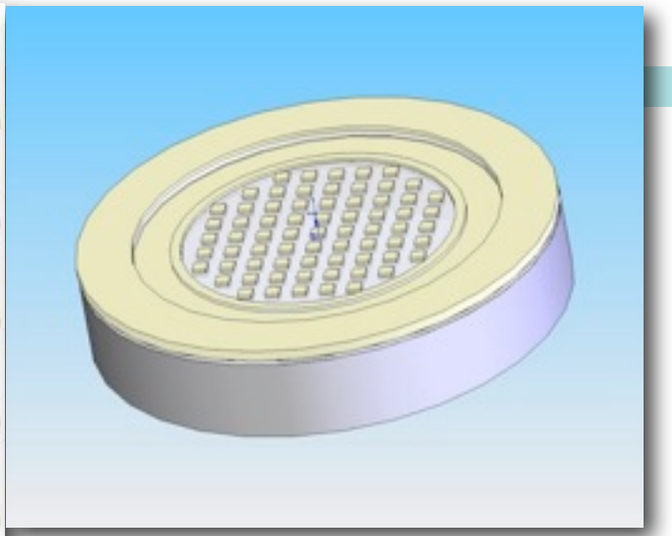
b) Only dry sample is allowed:

Phase Plate/ Wet Cell Microscopy:





Phase Plate



Wet cell

MEMs fabrication

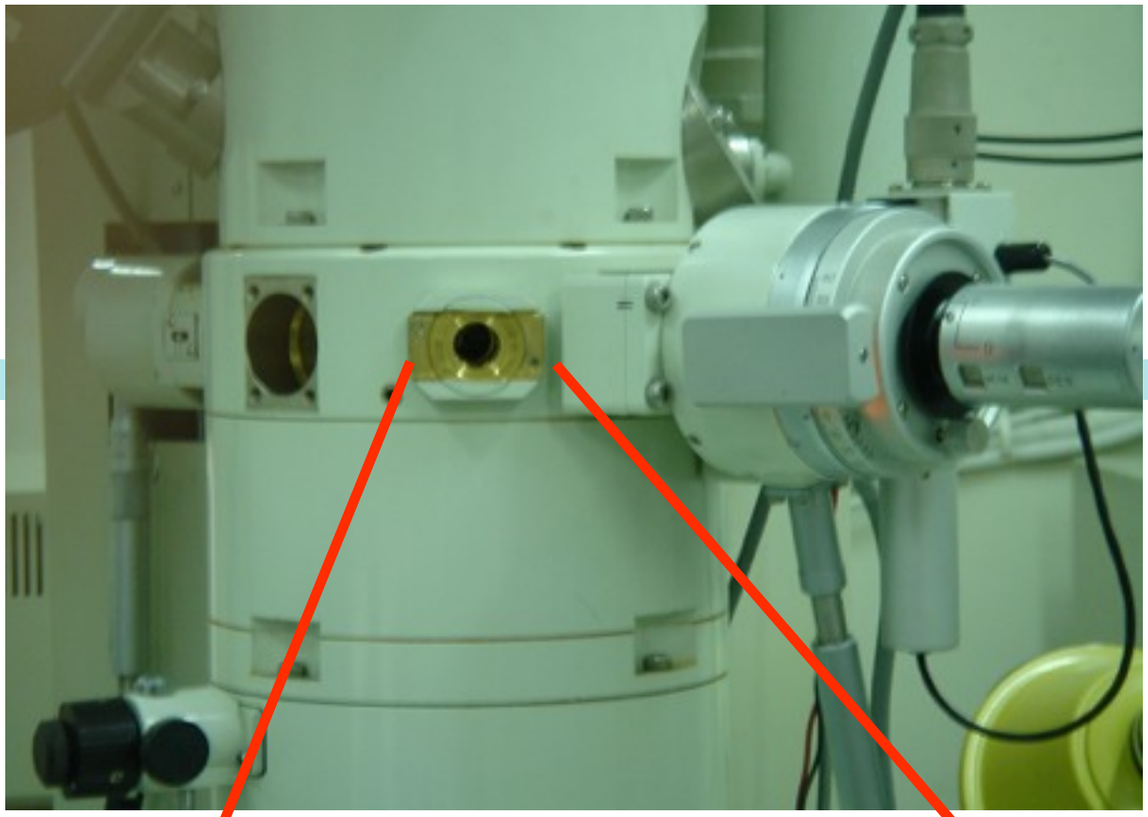
Bottlenecks for Biological Imaging

a) Lack of contrast: Zernike Phase Plate

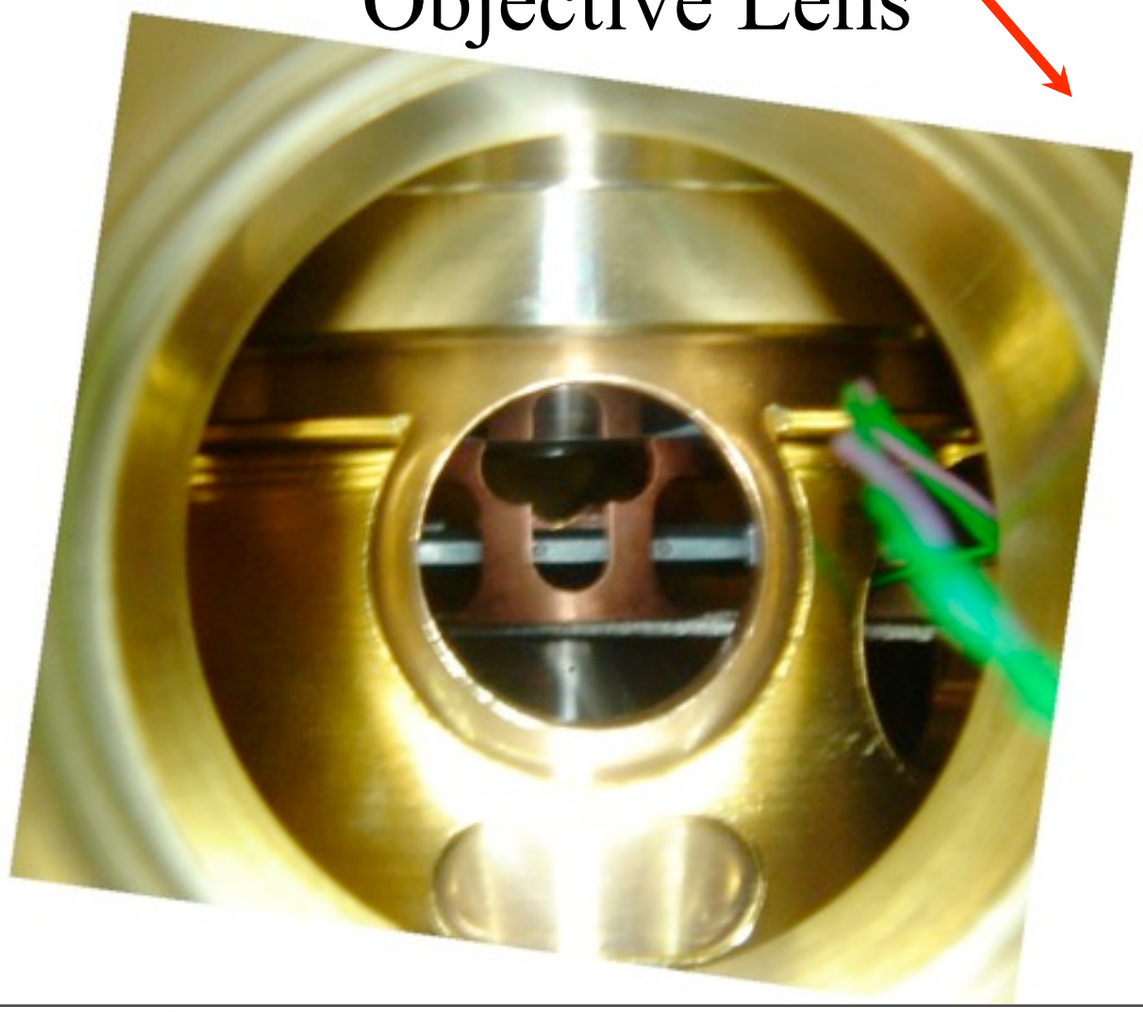
(alternate the phase of electron wave in focal plane)

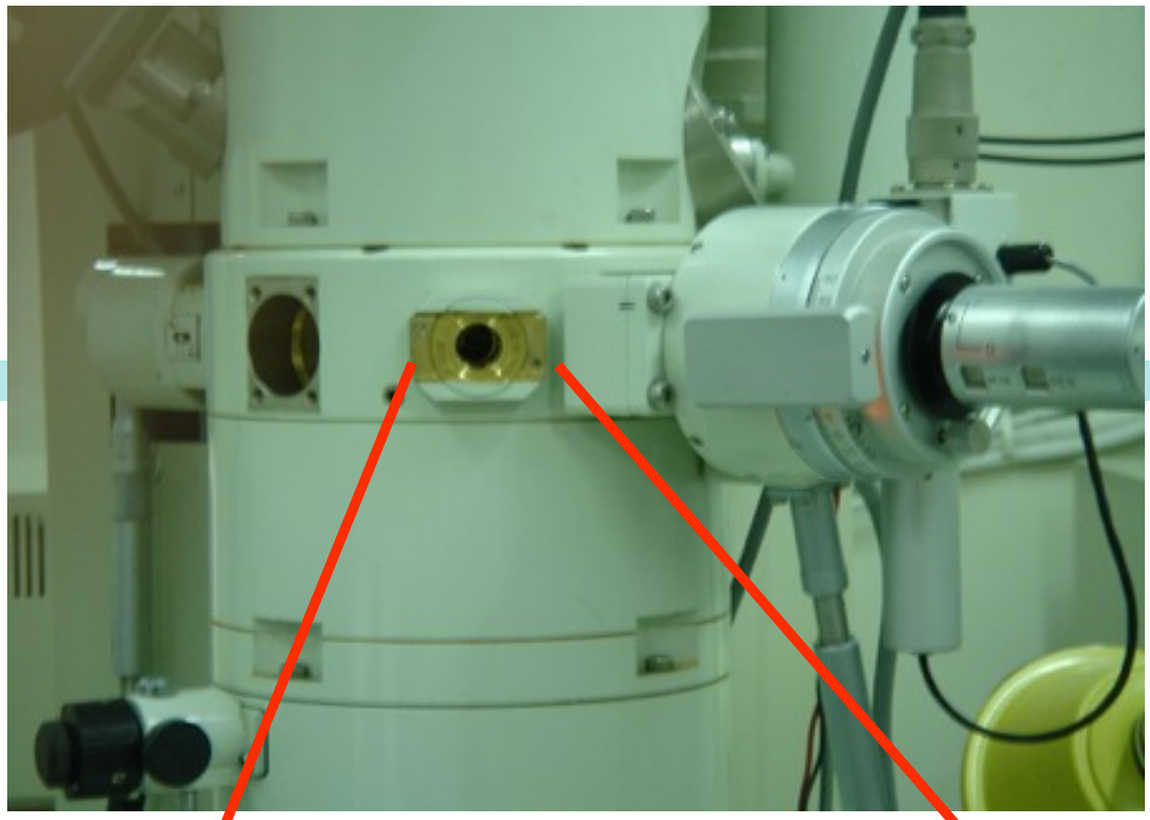
b) Only dry sample is allowed: Wet Cell

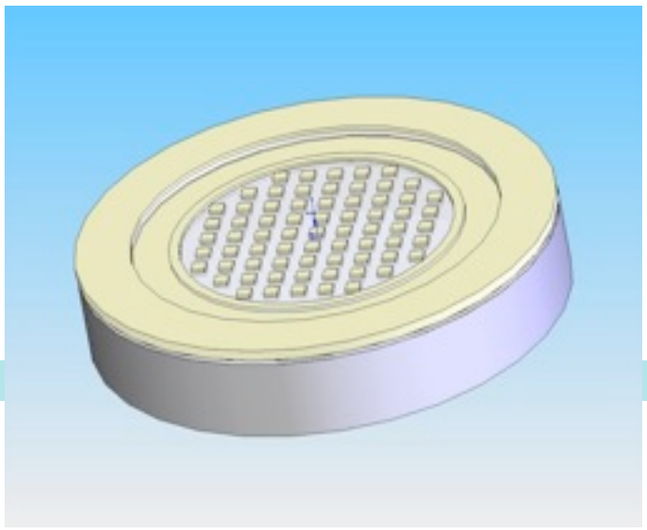
Motivation



Objective Lens

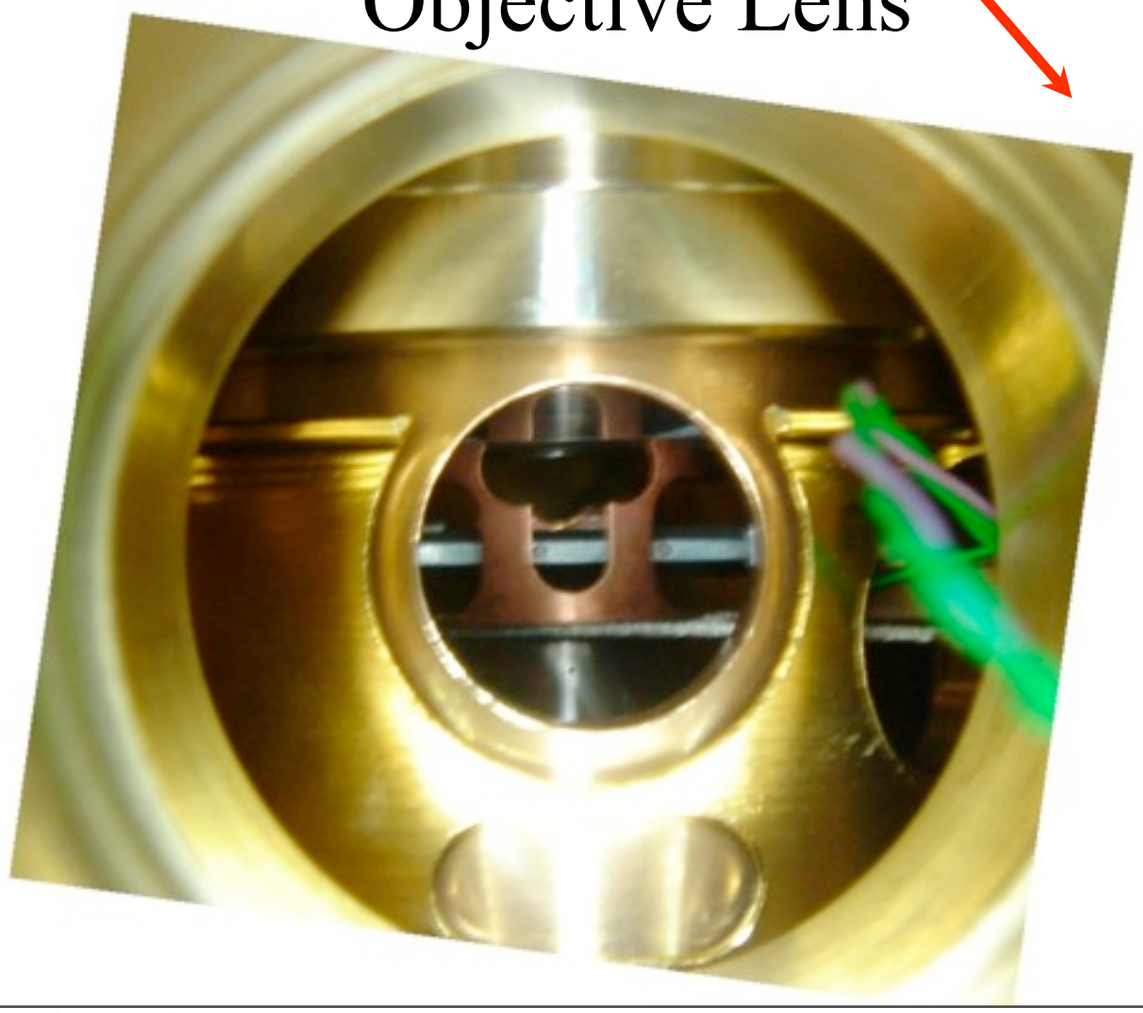




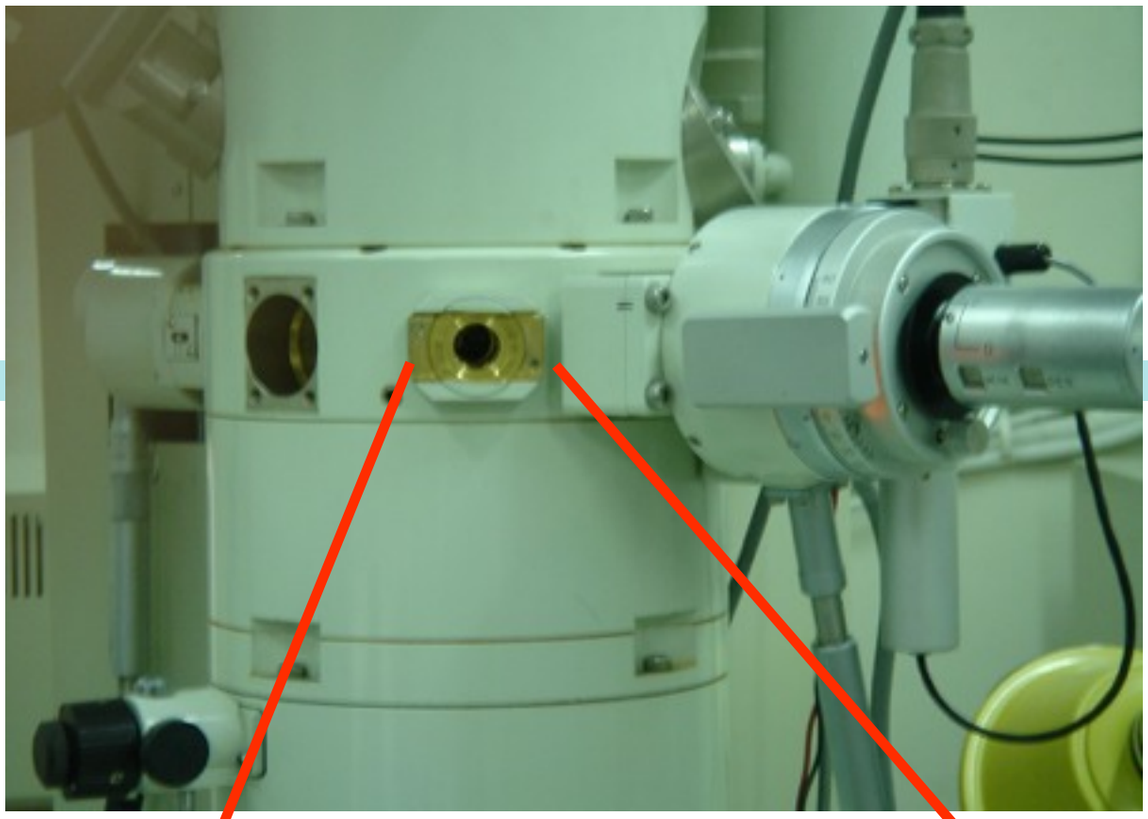


Wet cell:
bio-sample in liquid environment

Objective Lens



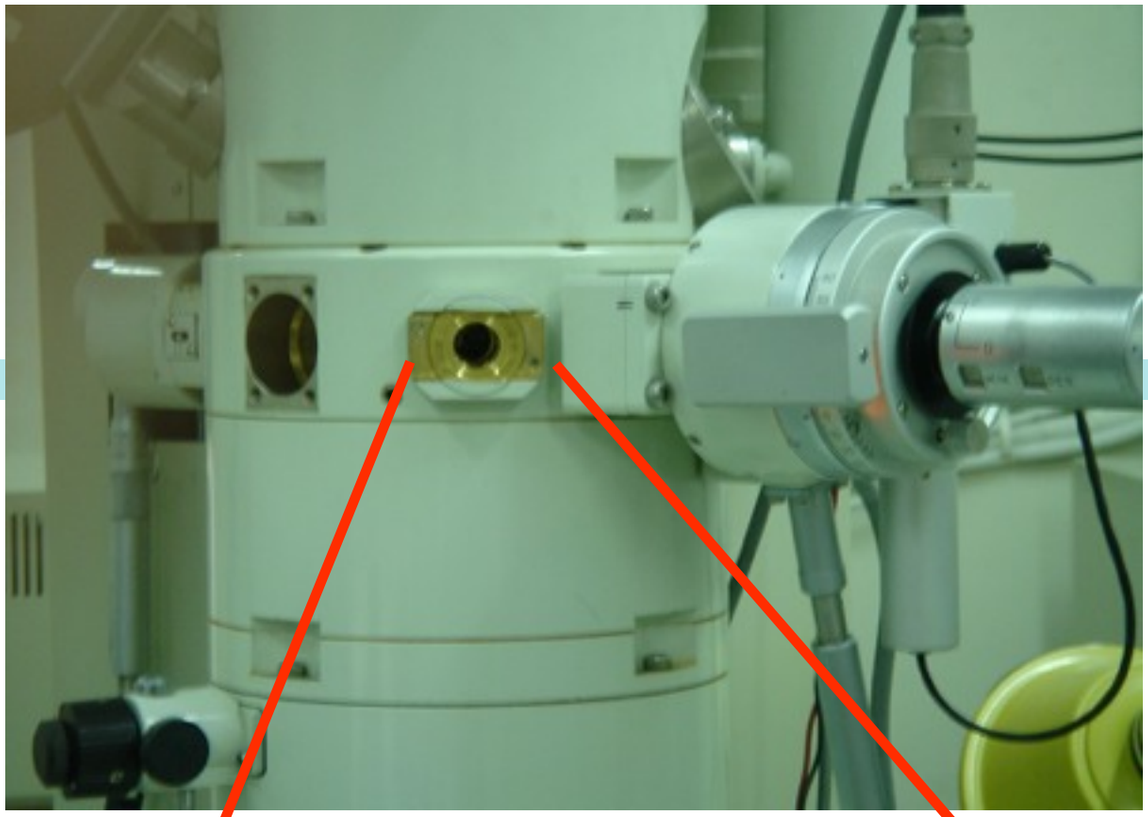
Motivation



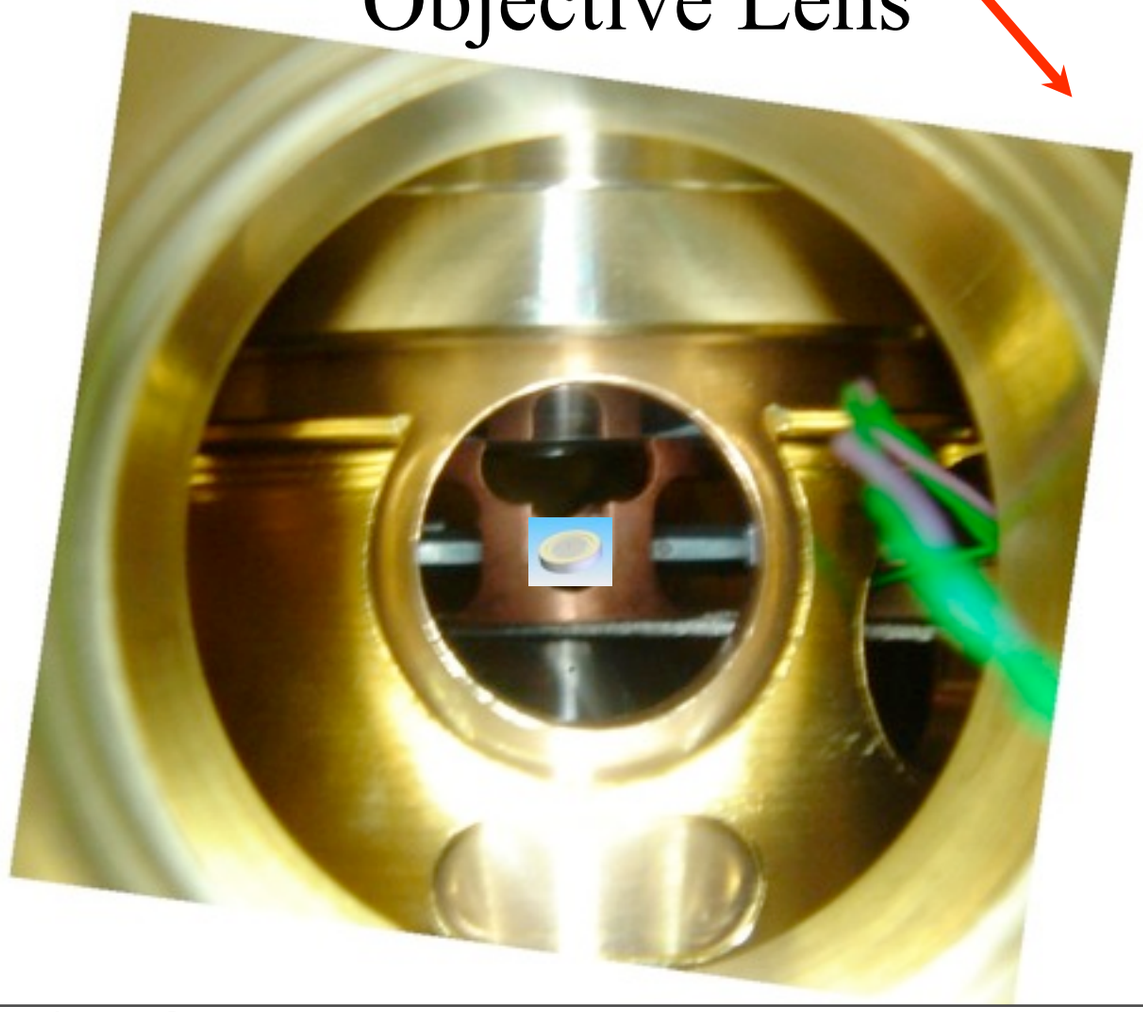
Objective Lens

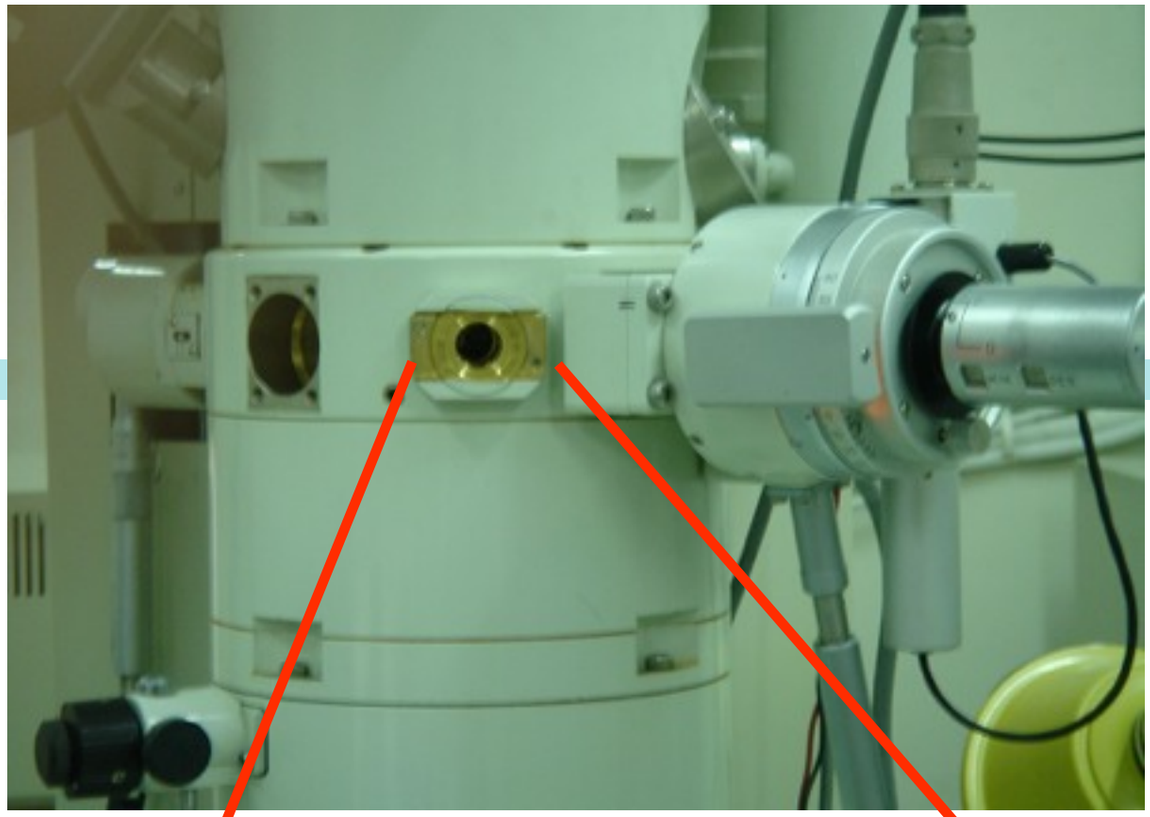
Wet cell:
bio-sample in liquid environment

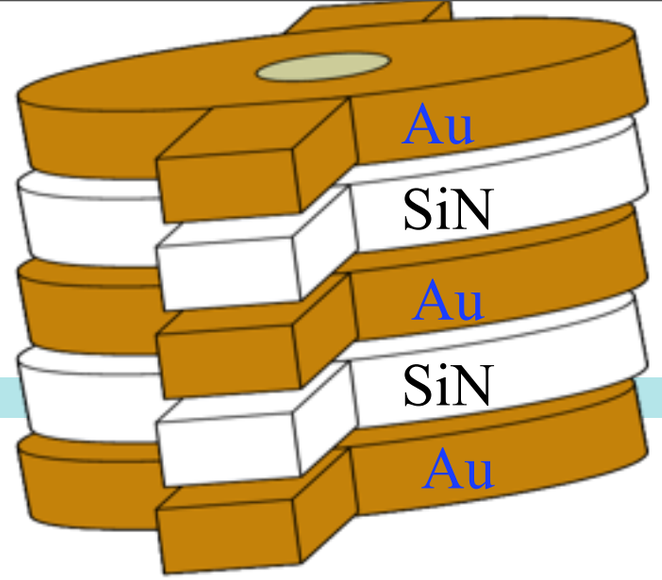
Motivation



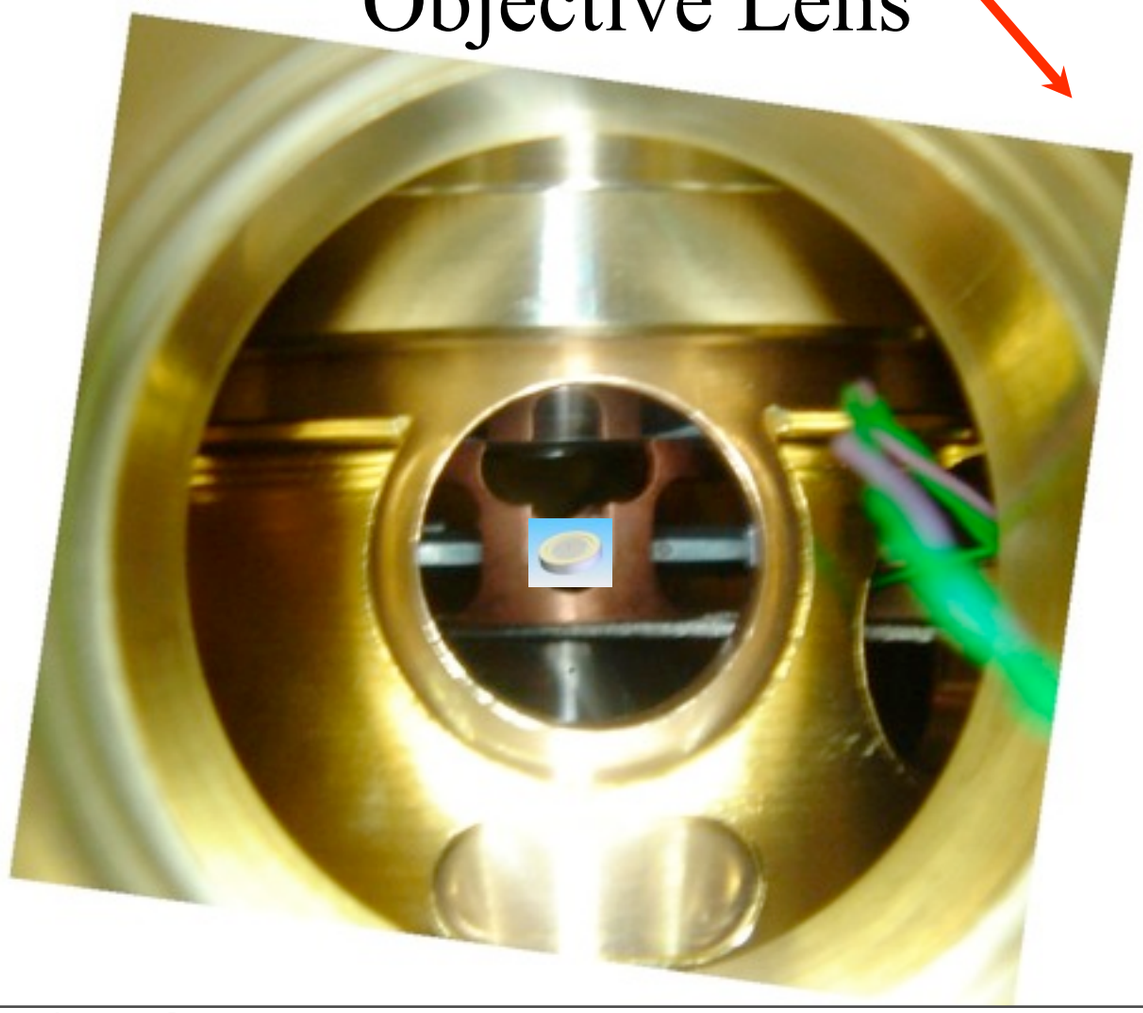
Objective Lens





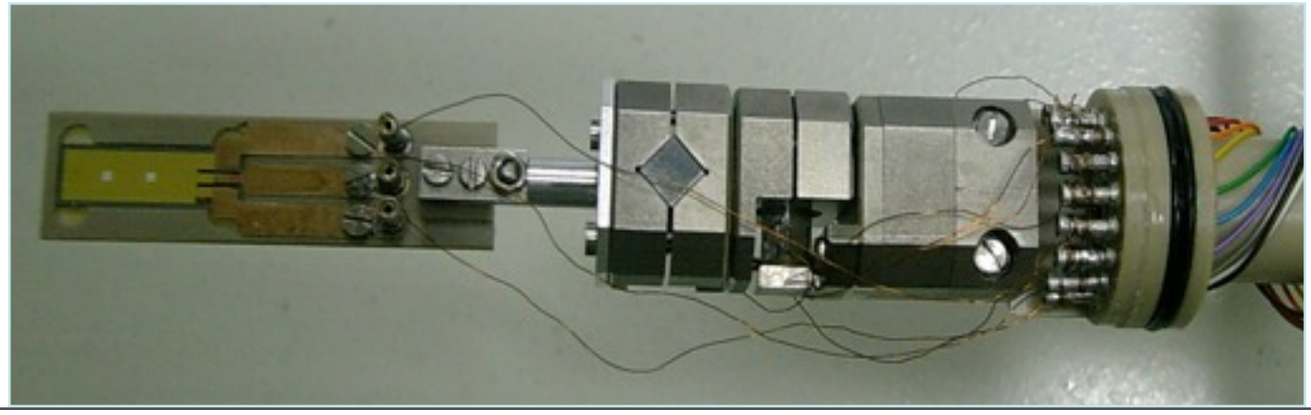


Objective Lens

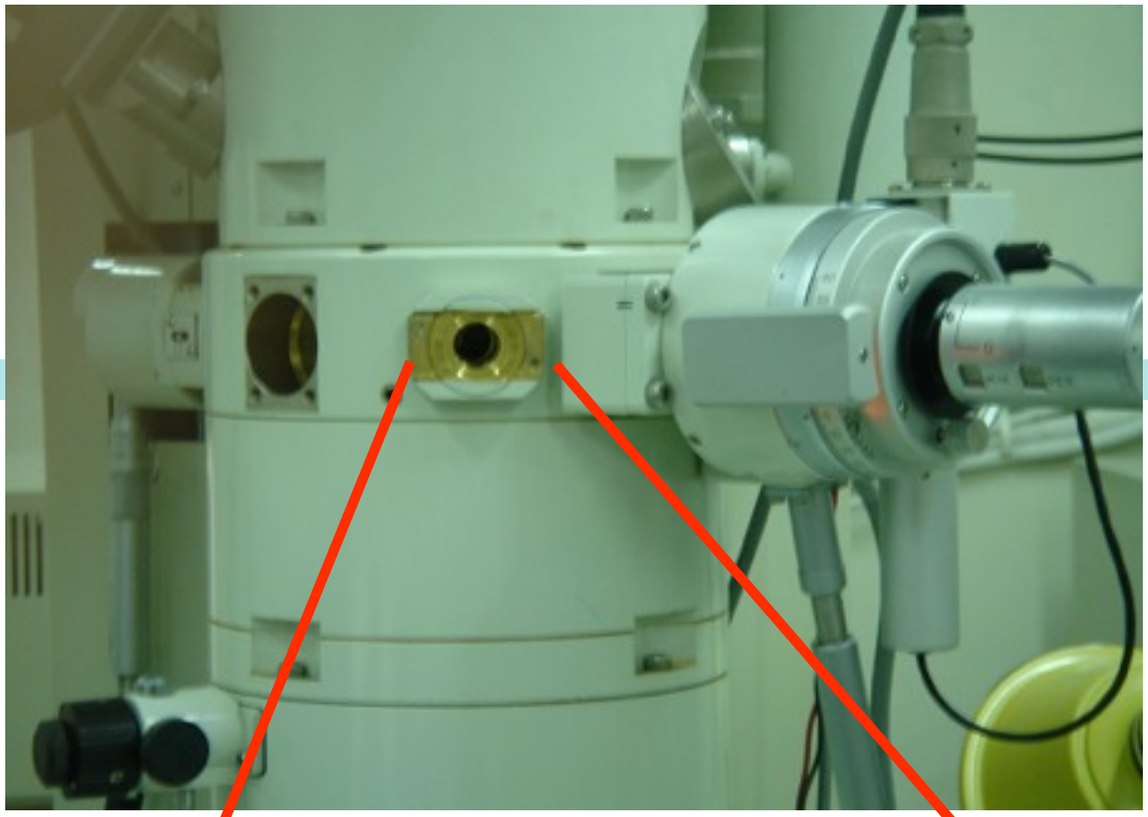


Enhance Phase Contrast

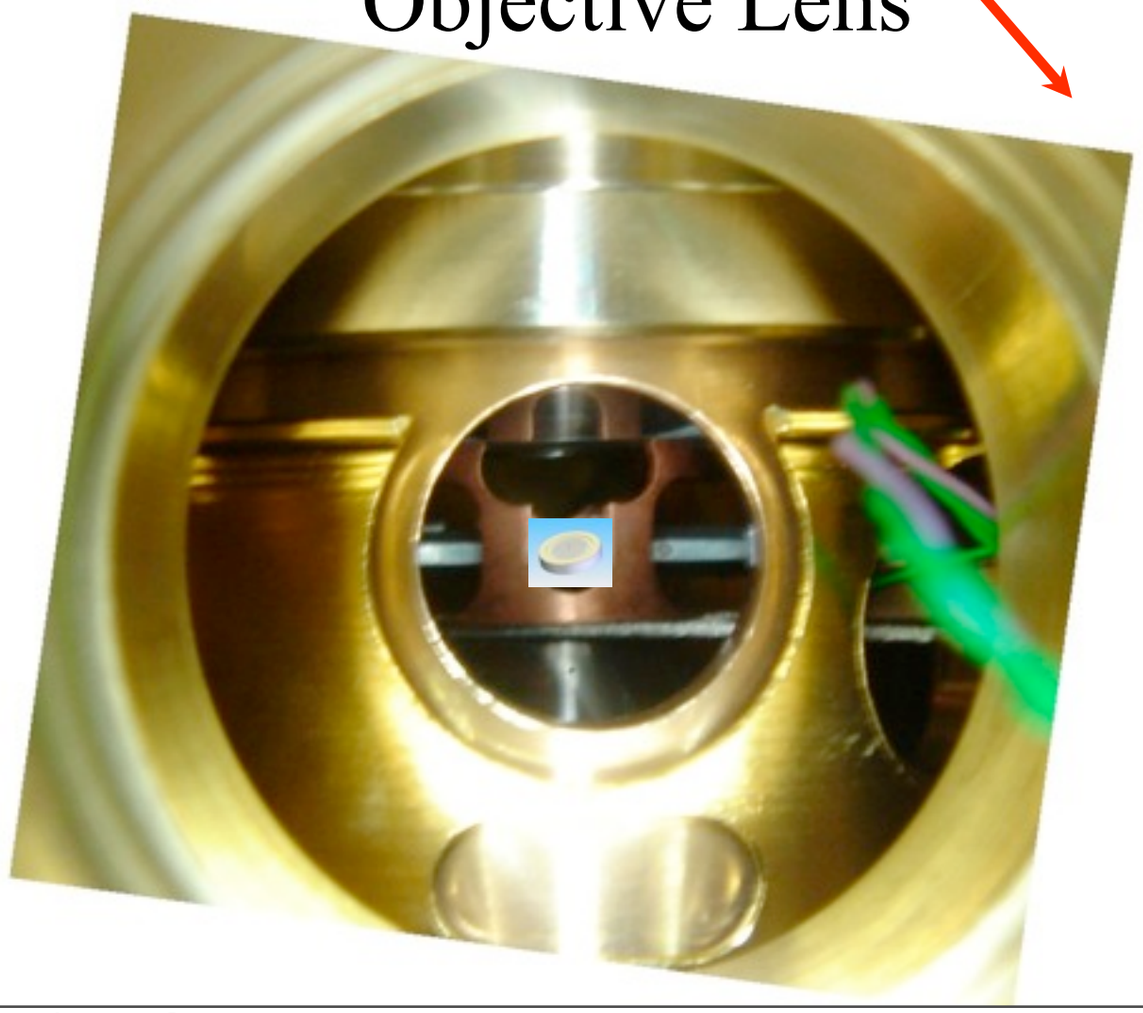
piezo-driven holder



Motivation

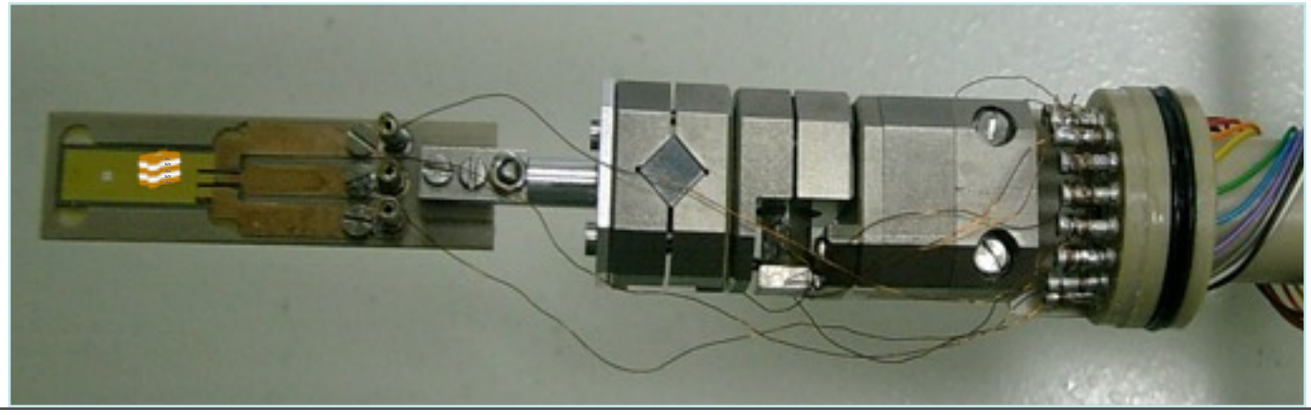


Objective Lens

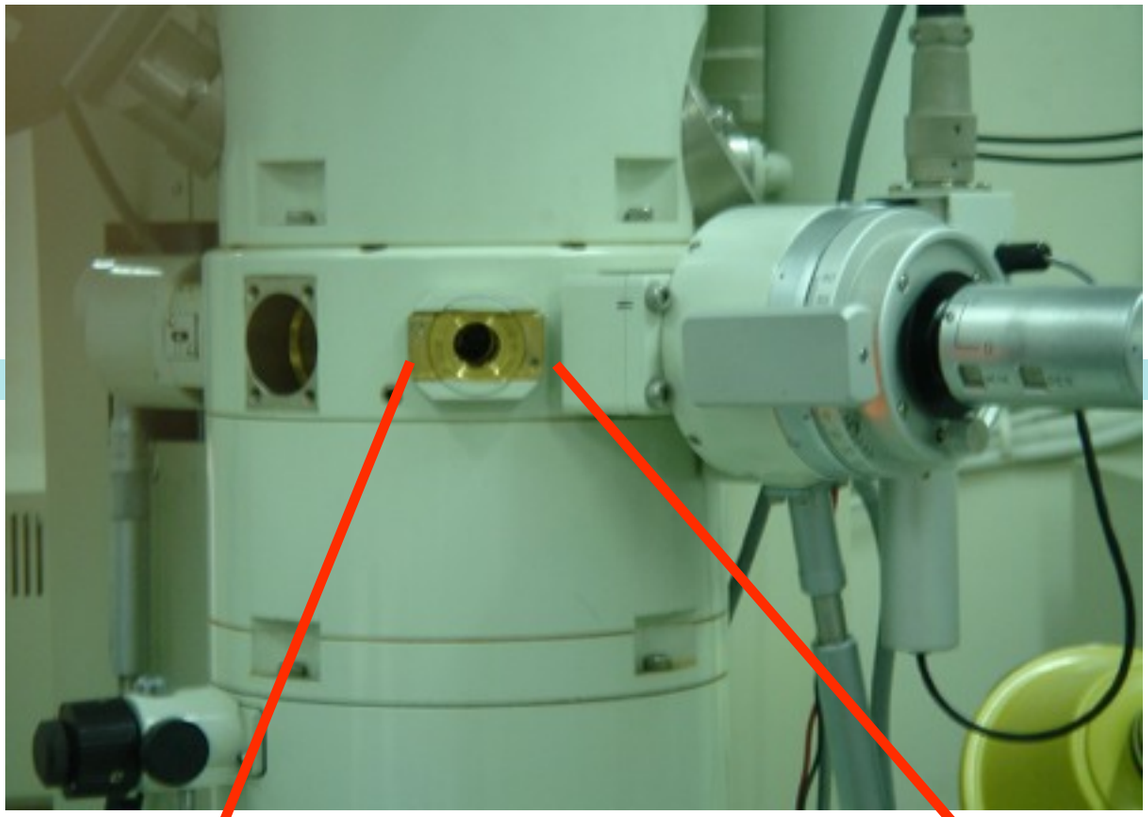


Enhance Phase Contrast

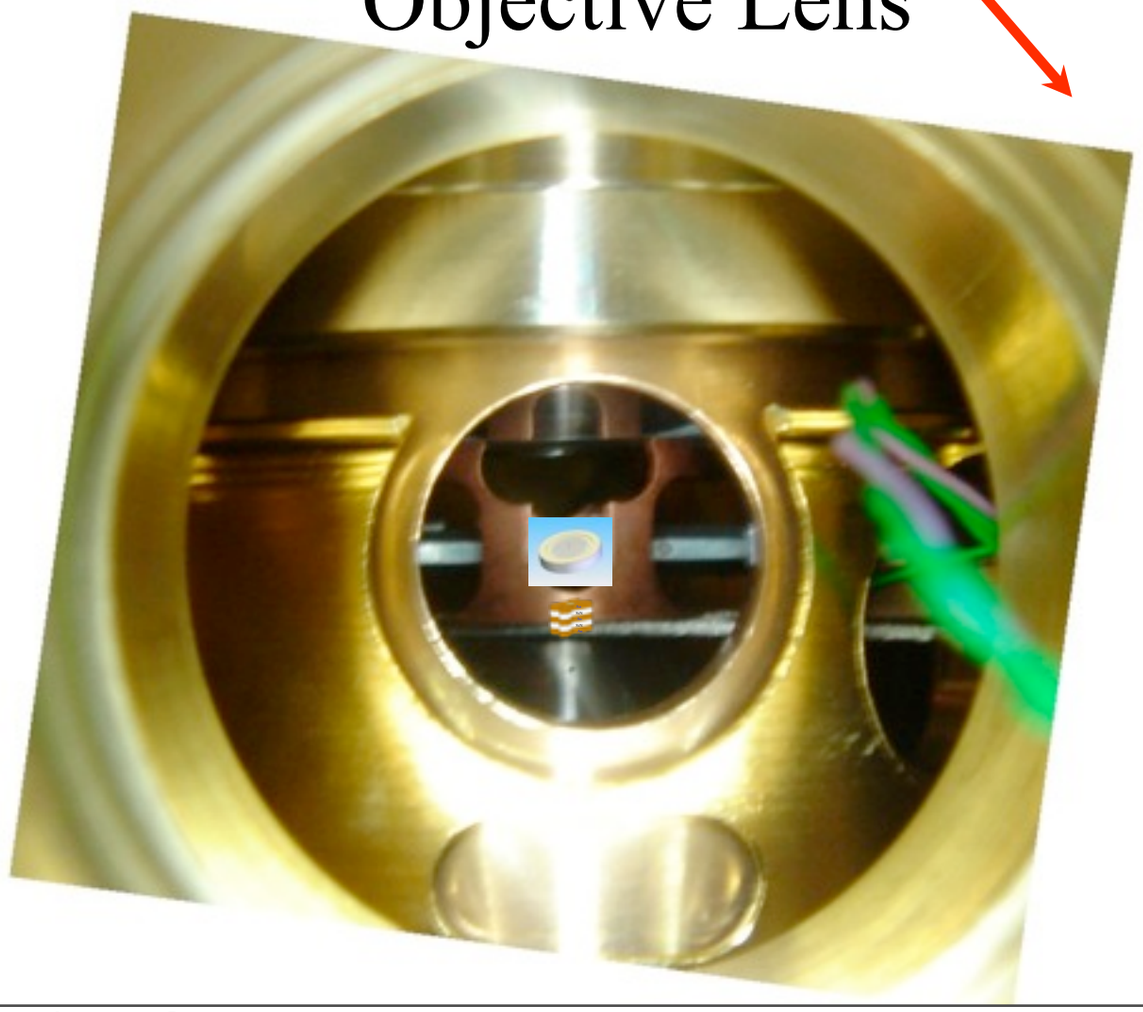
piezo-driven holder

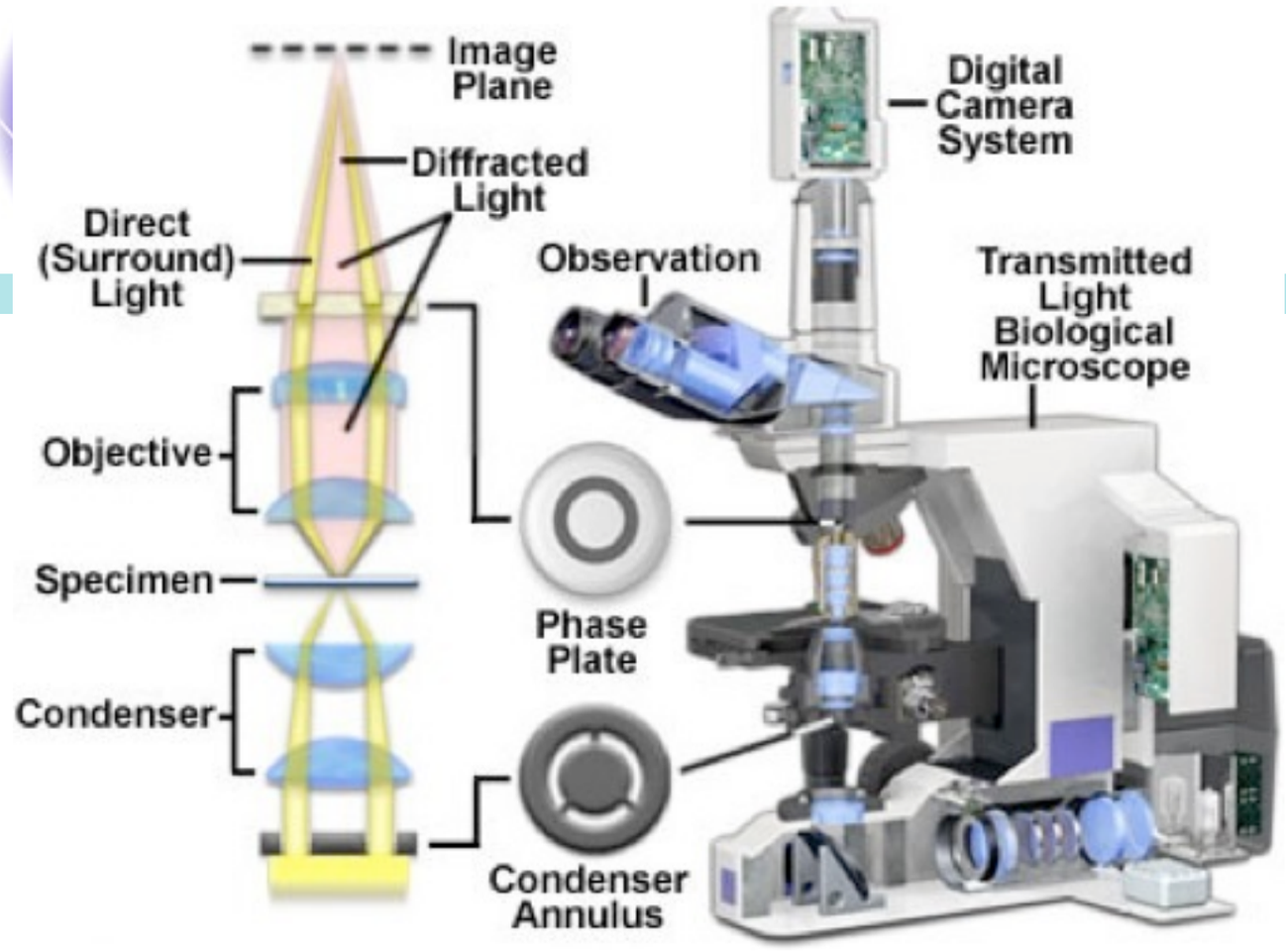


Motivation

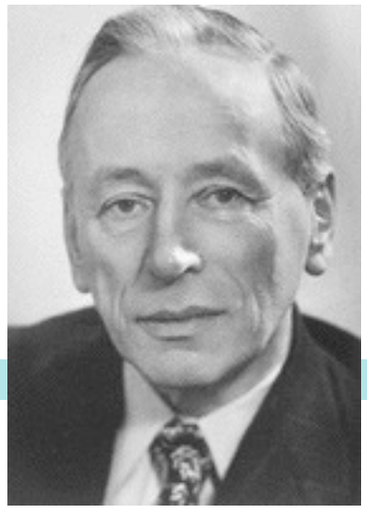


Objective Lens

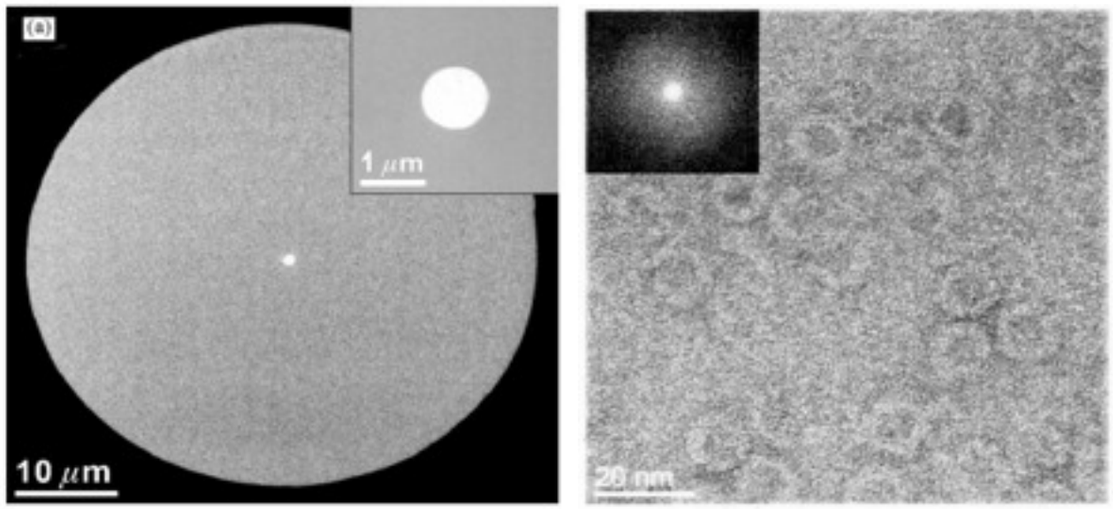


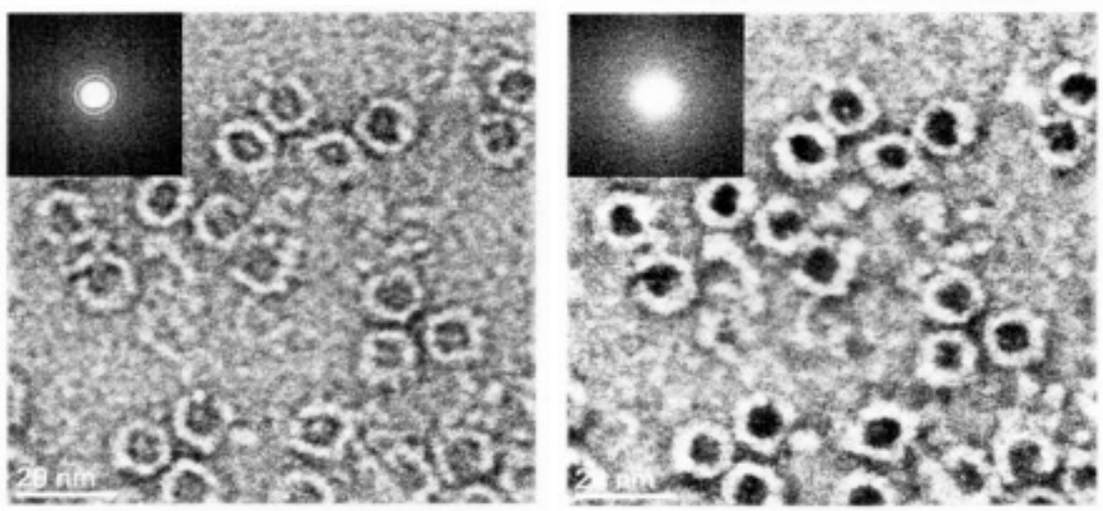


Zernike Phase Plate
Nobel Prize (1953)



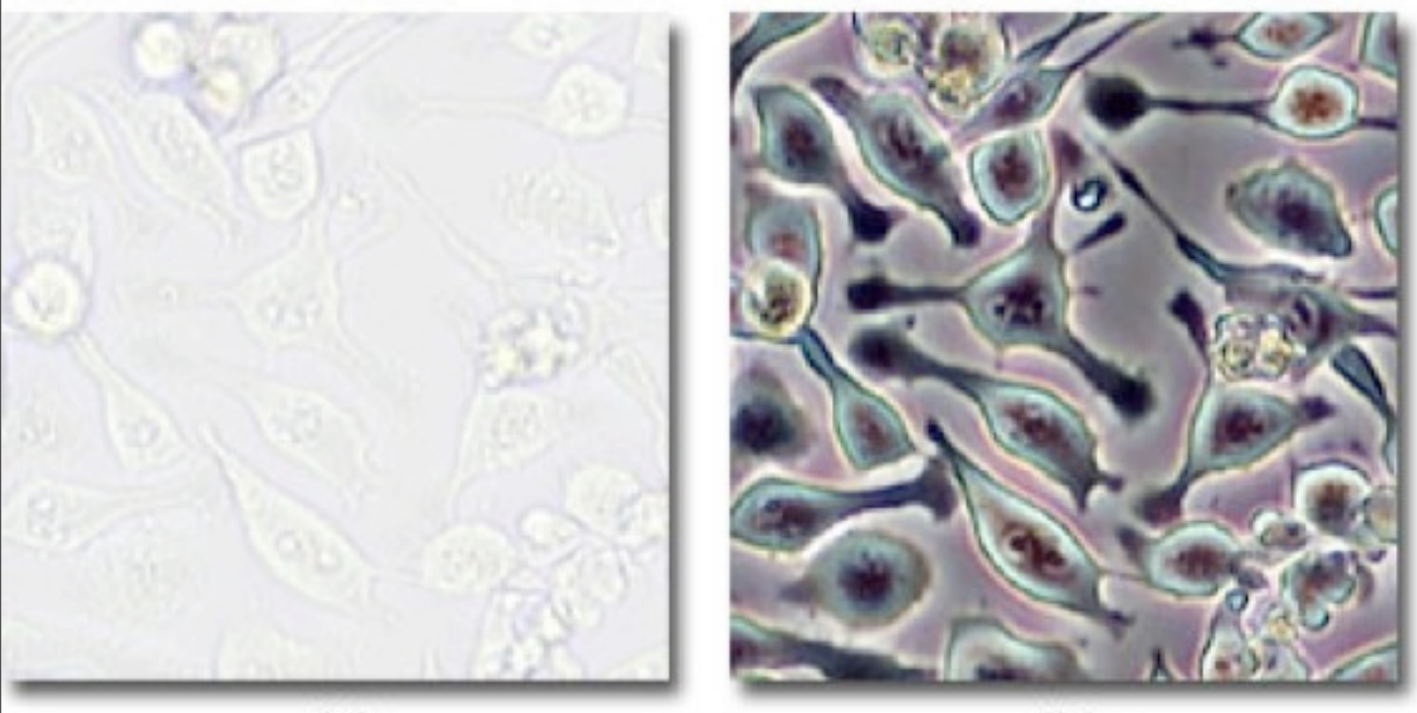
-120 nm





-4050 nm

Phase plate

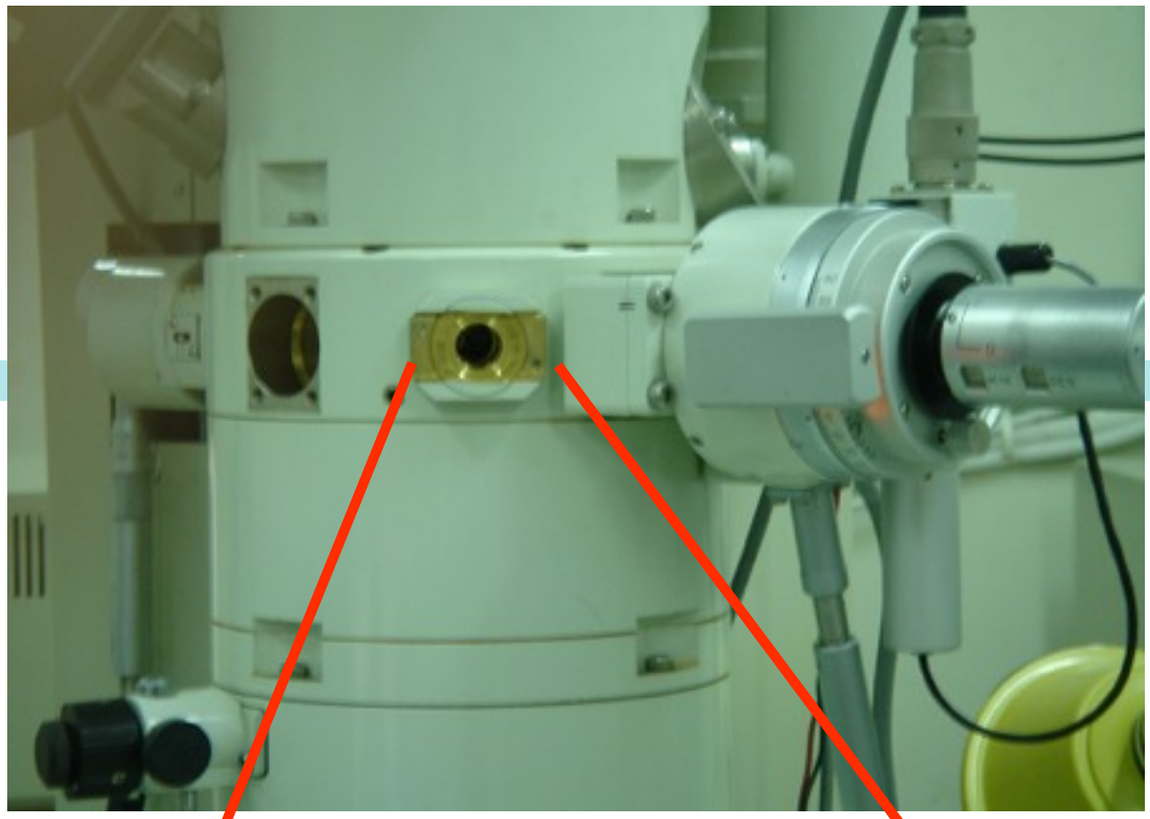


(a)

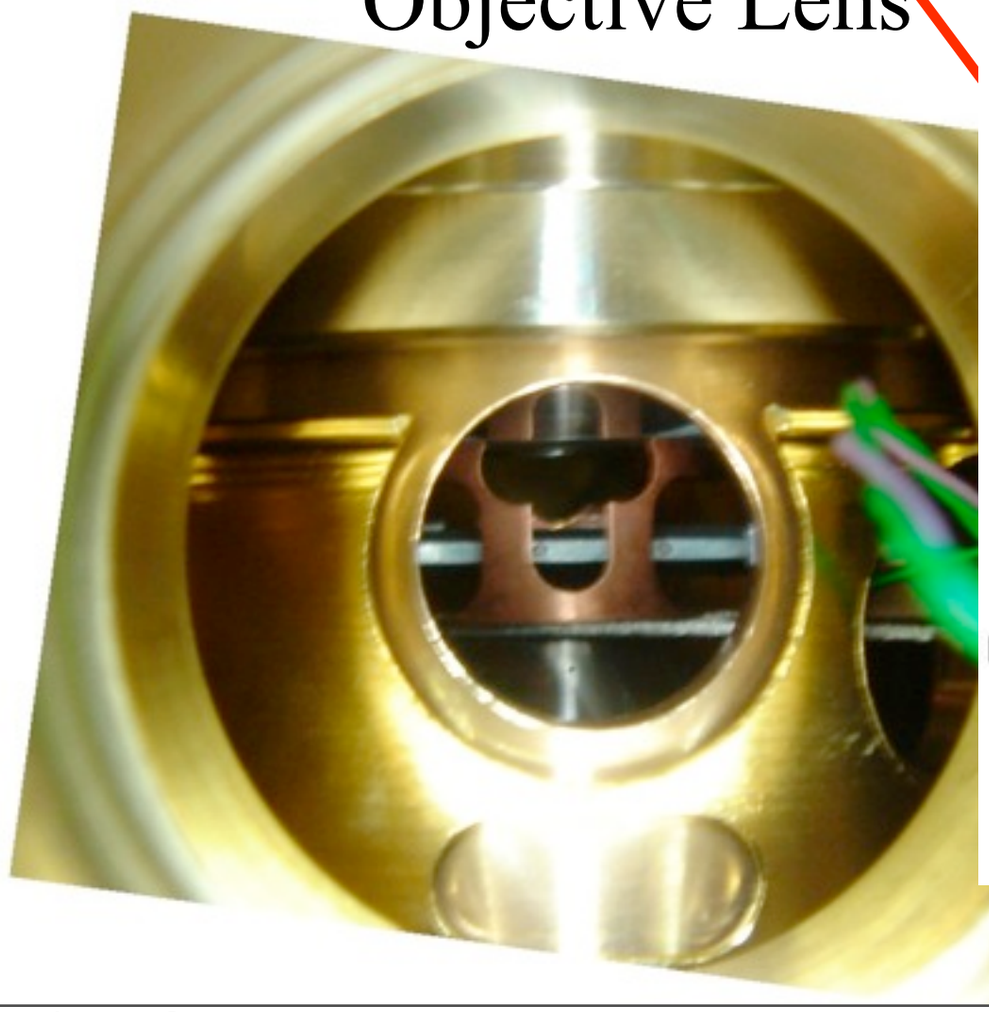
(b)

Radostin Danev, Kuniaki Nagayama
Ultramicroscopy 88(2001) 243-212

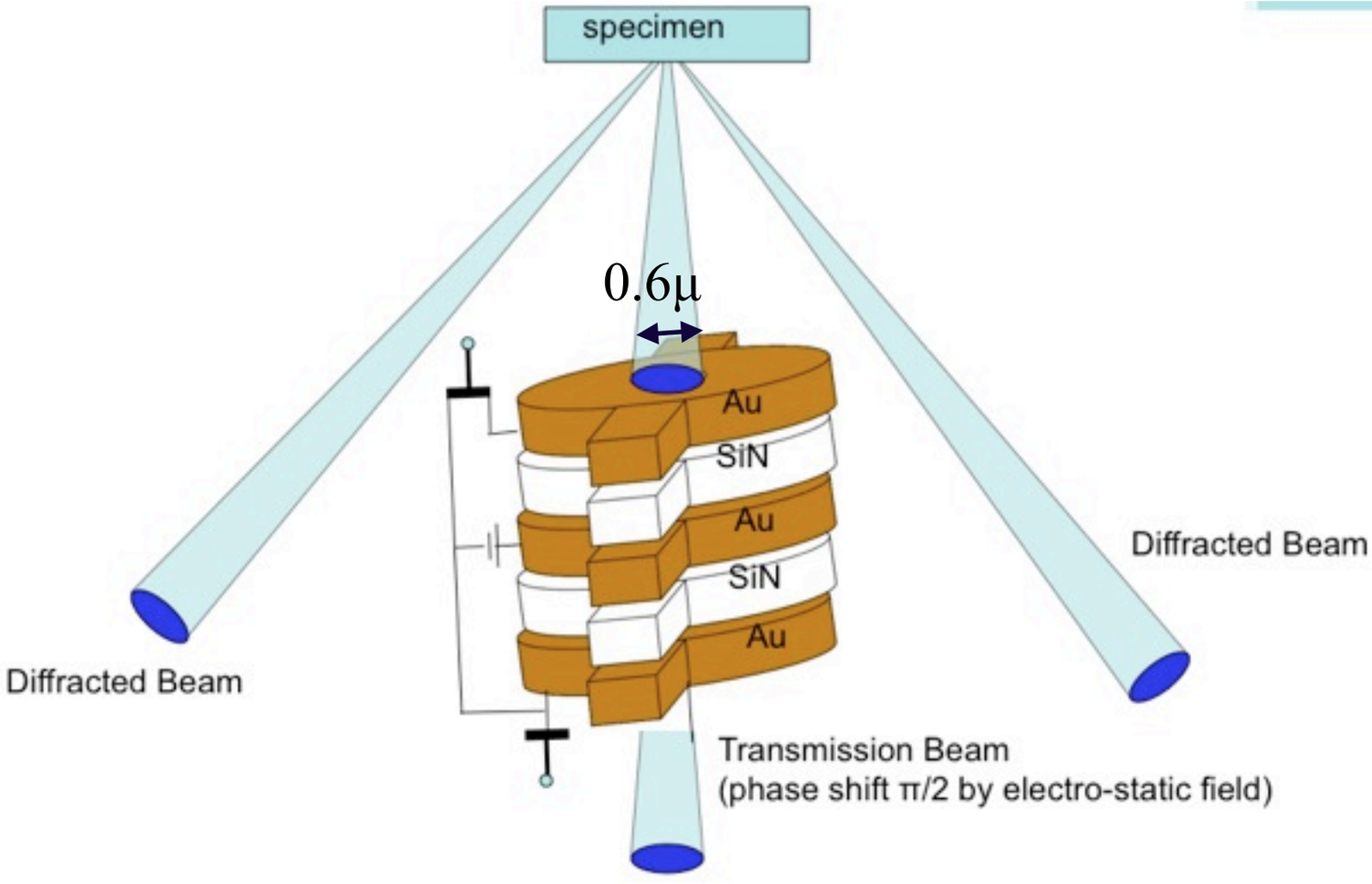
Motivation

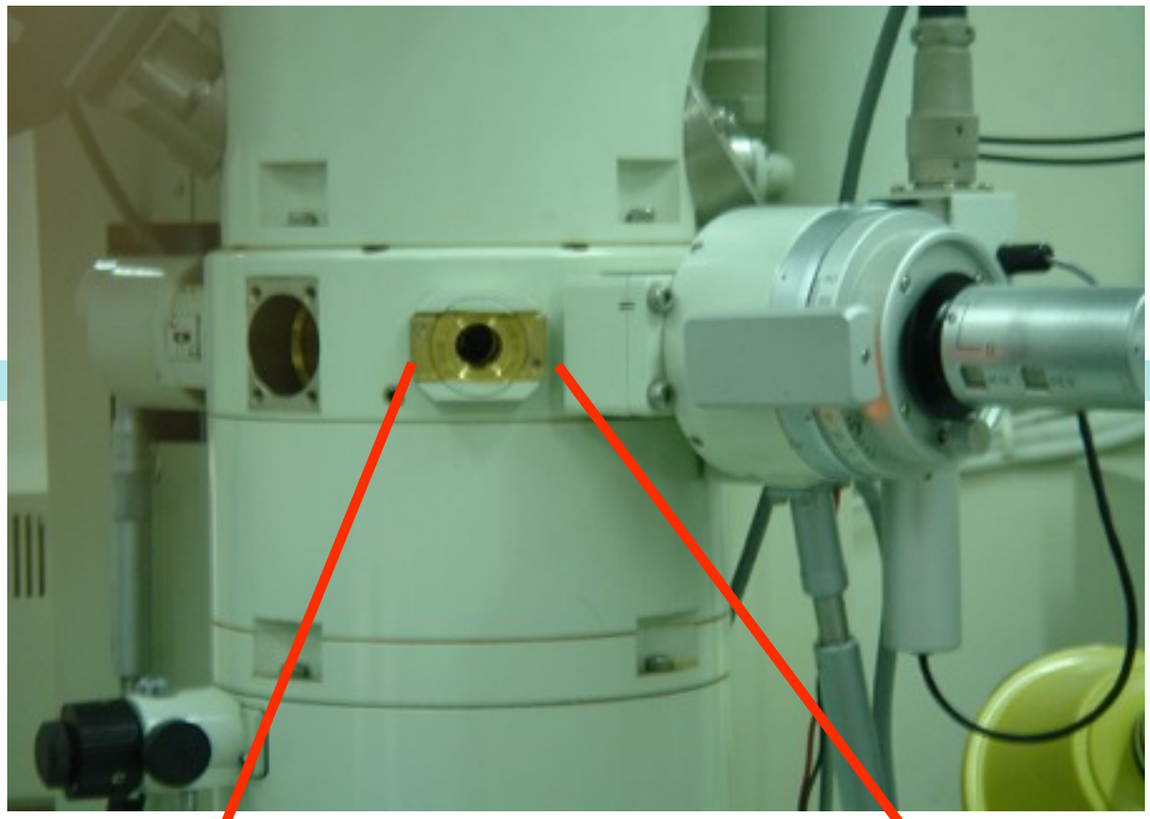


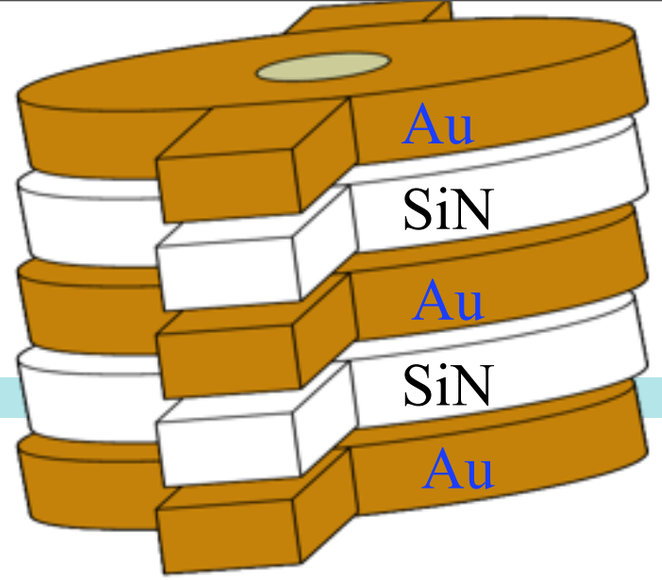
Objective Lens



Boersch Phase Plate:
Tunable Phase Contrast ⟶ Wave



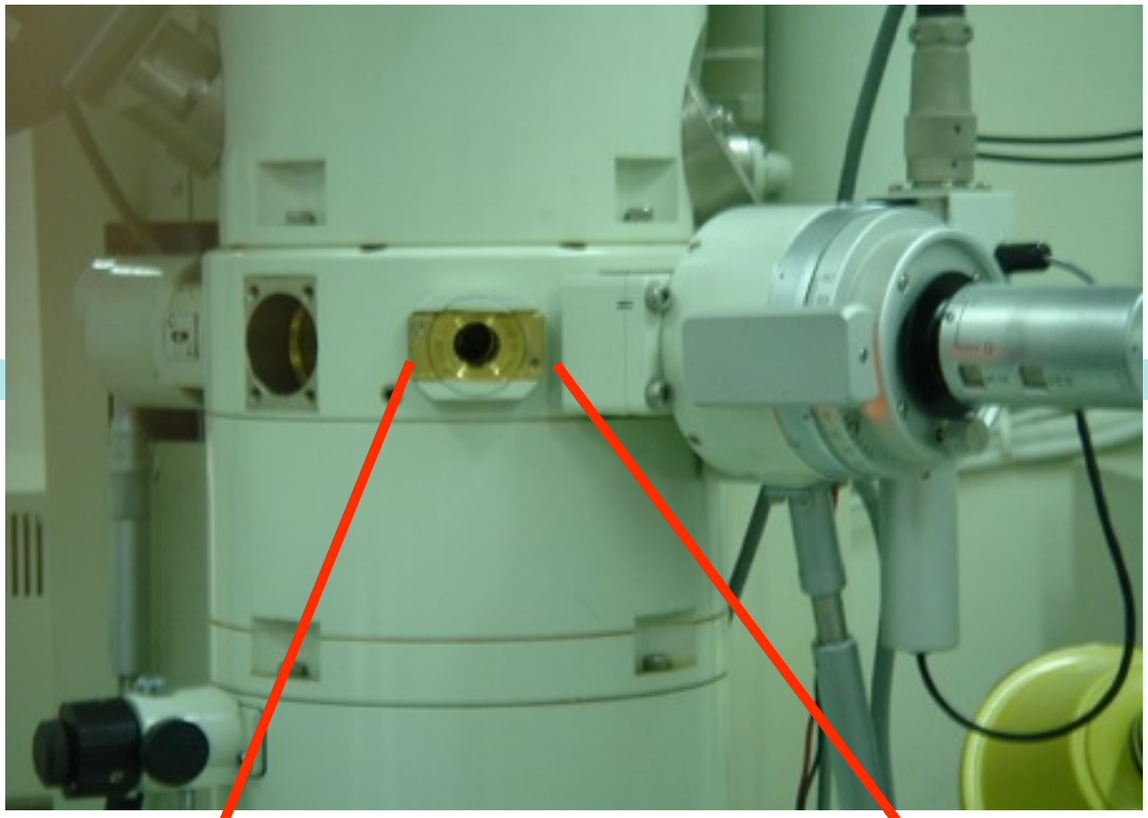




Objective Lens

piezo-driven holder

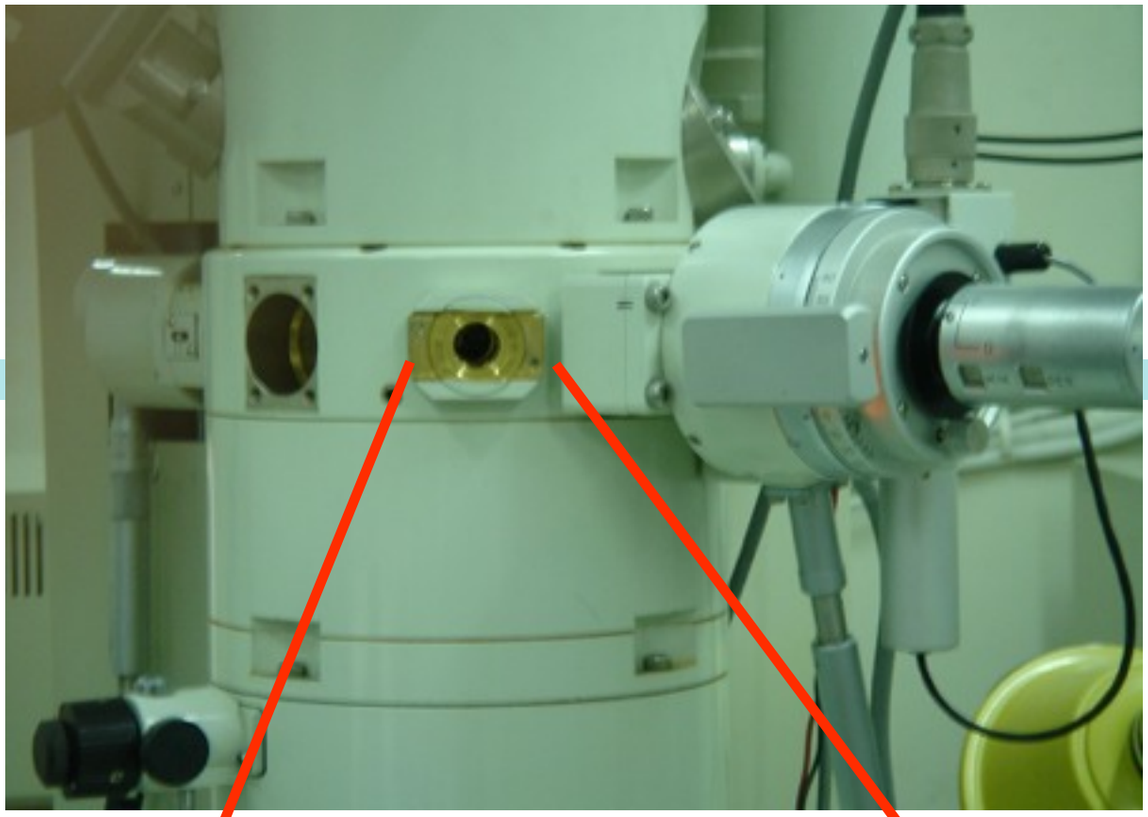
Motivation



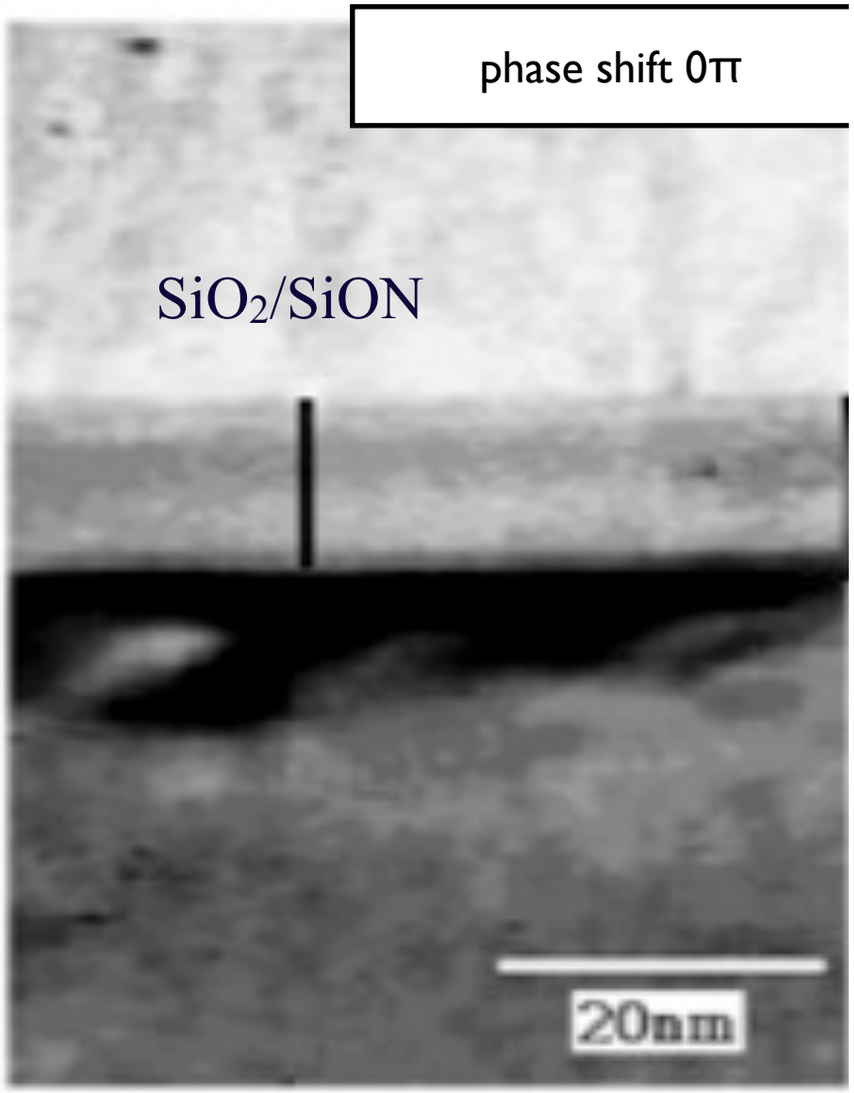
Objective Lens

piezo-driven holder

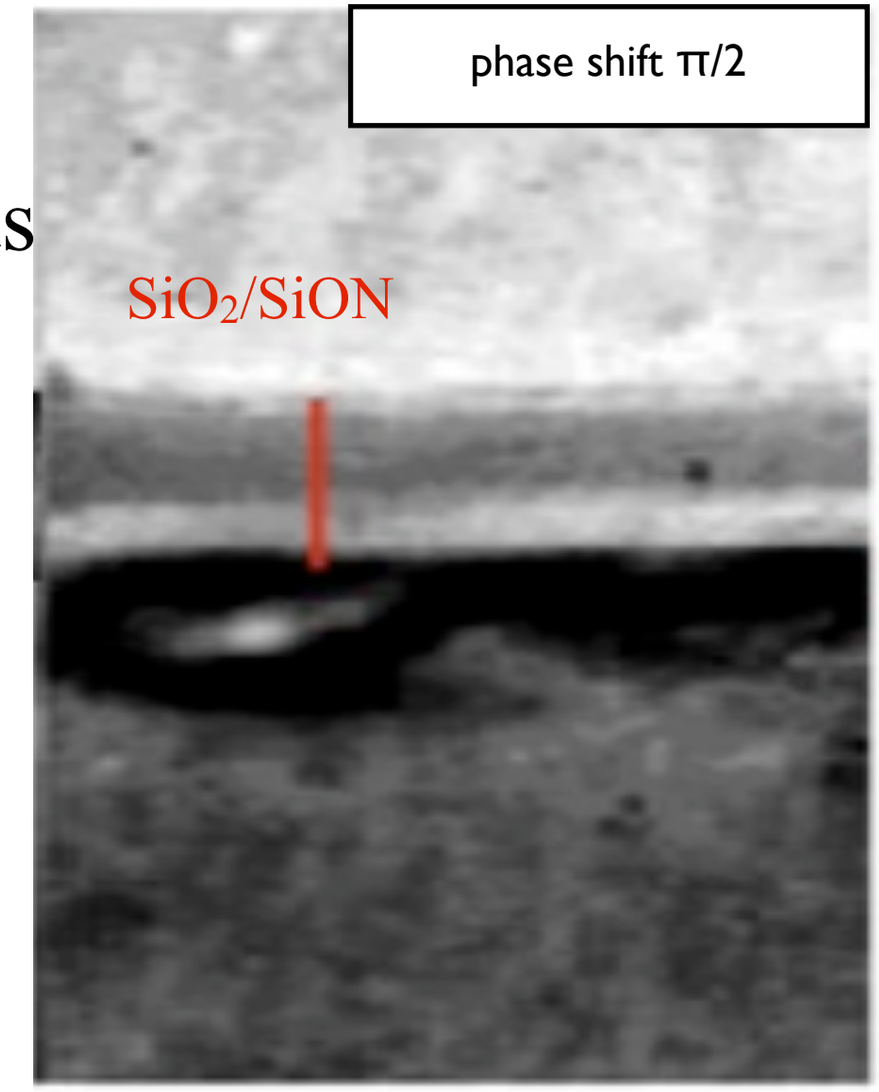
Motivation



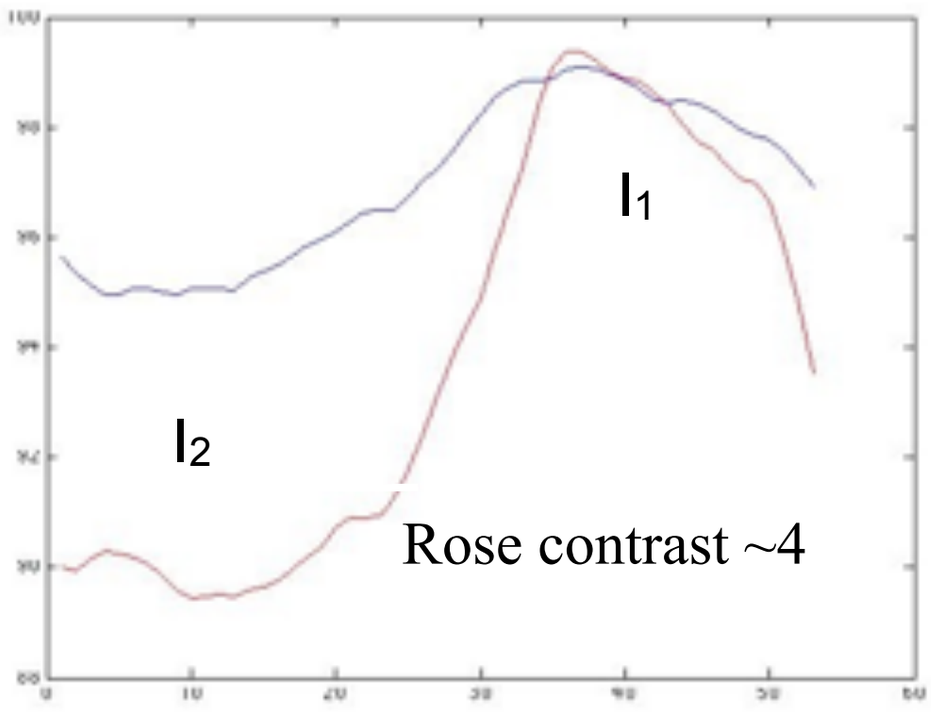
Objective Lens



Δf=0, in focus



Phase image of gate oxide

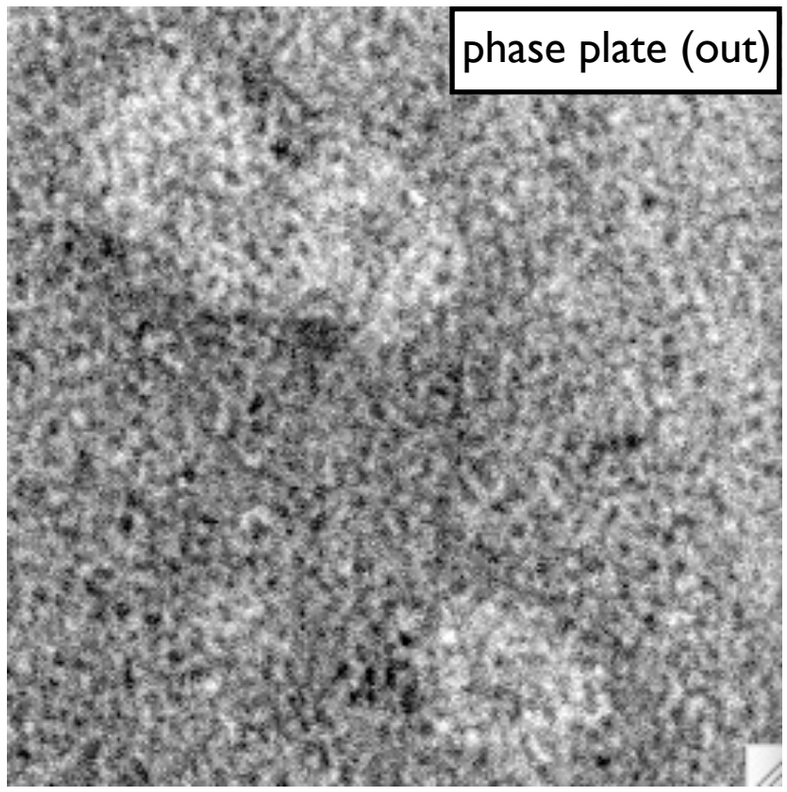


$$\text{Rose Contrast} = \frac{I_1 - I_2}{I_1 - I_2} \times \frac{(\sigma_1^2+\sigma_2^2)^{1/2}}{(\sigma_1^2+\sigma_2^2)^{1/2}}$$

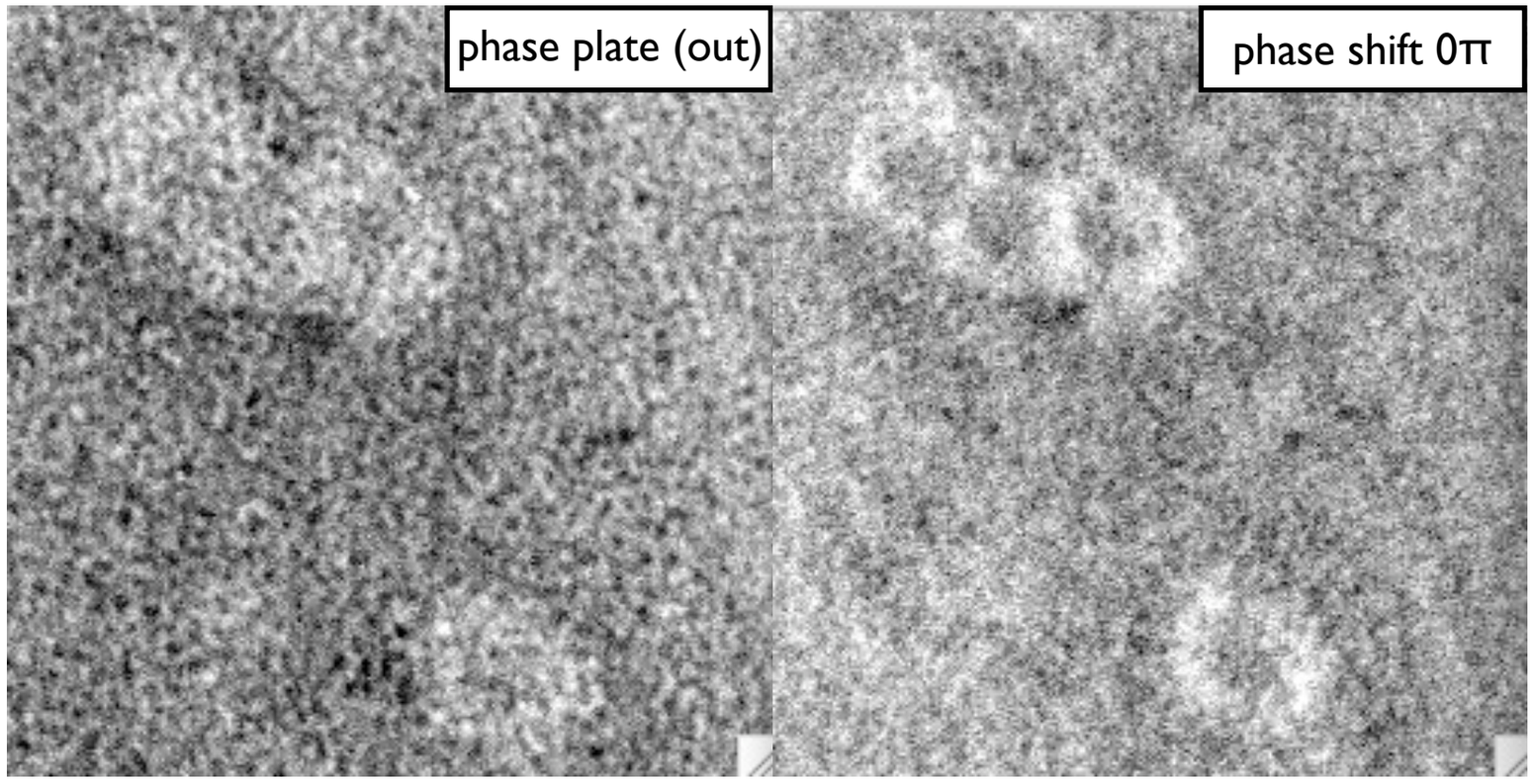
)urnal of Electron Microscopy 55: 273-280 (2006)

Phase Image of Ferritin $\Delta f=0$, in focus

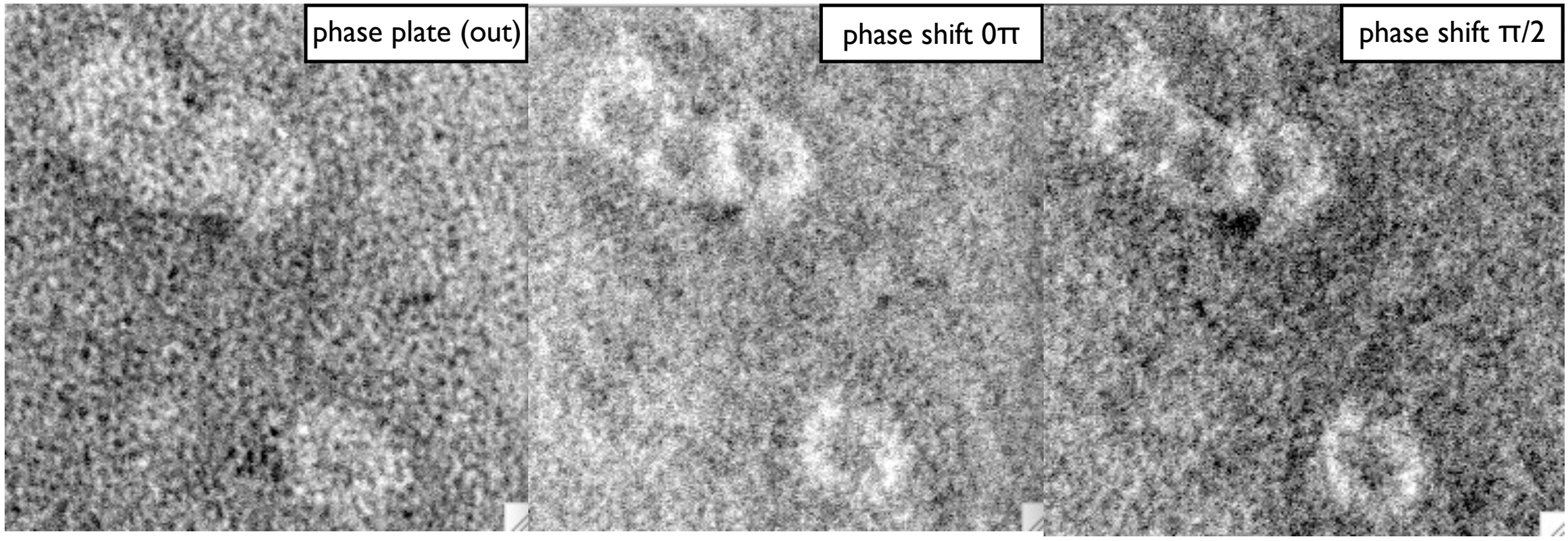
Phase Image of Ferritin $\Delta f=0$, in focus



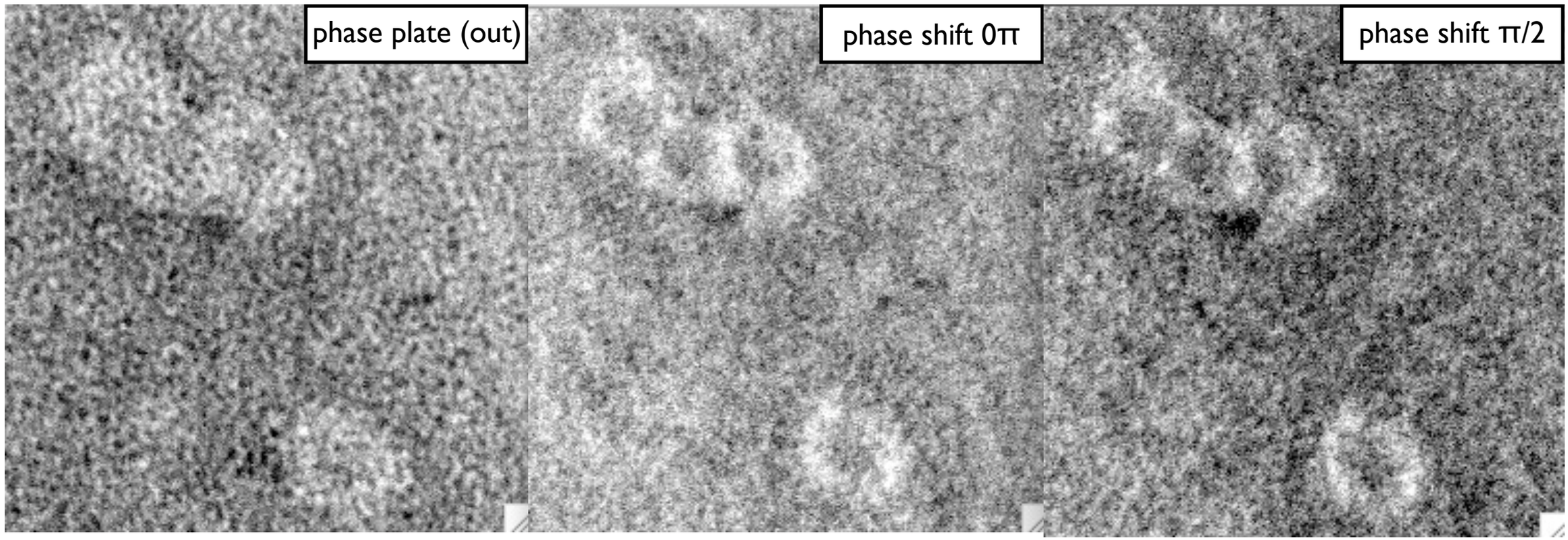
Phase Image of Ferritin $\Delta f=0$, in focus

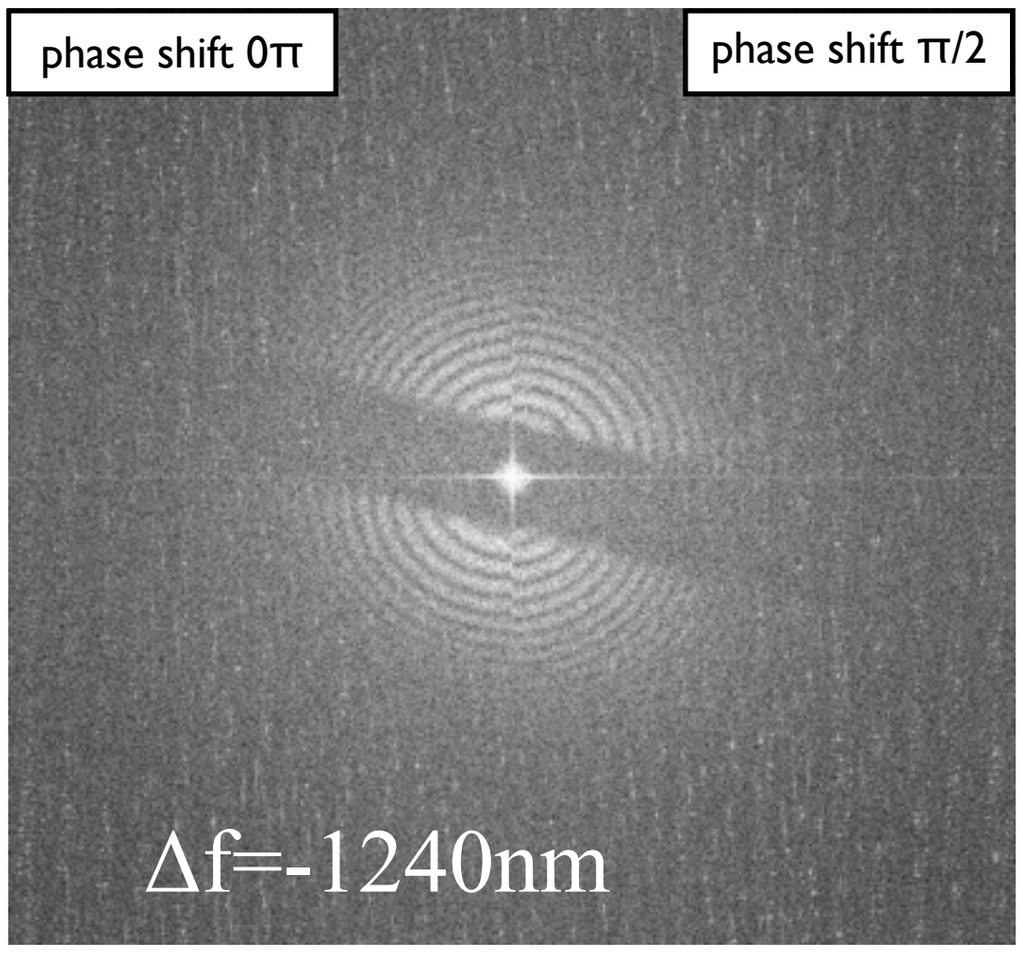


Phase Image of Ferritin $\Delta f=0$, in focus

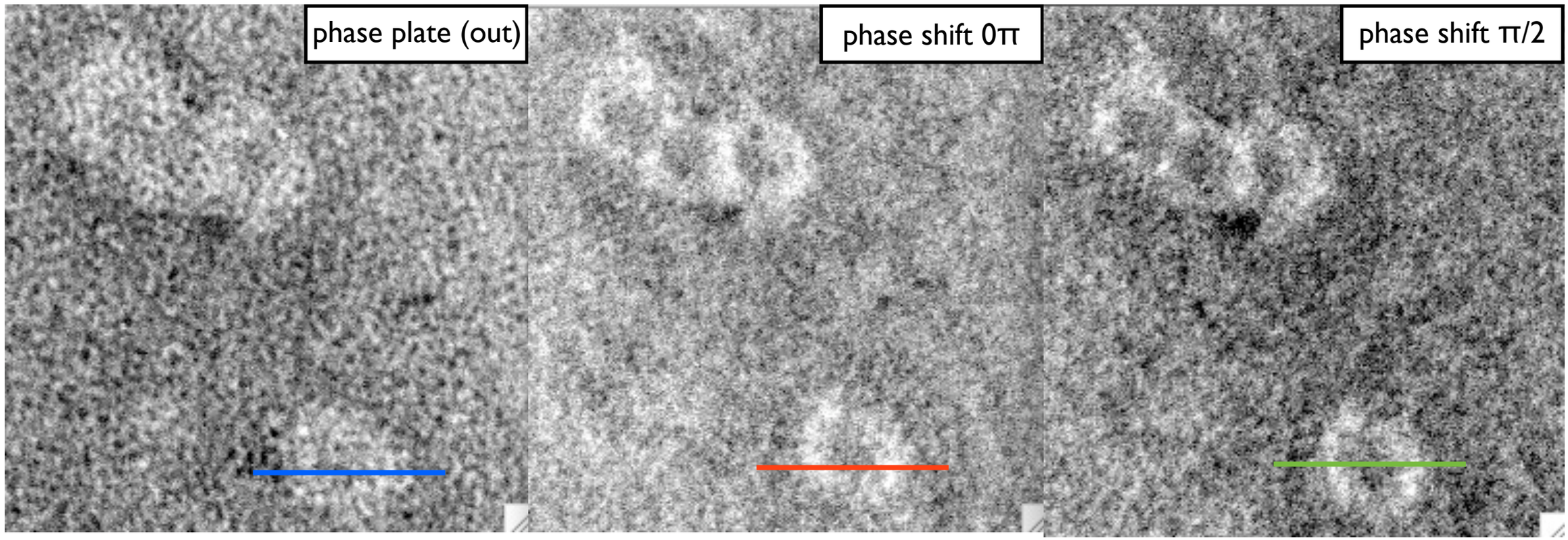


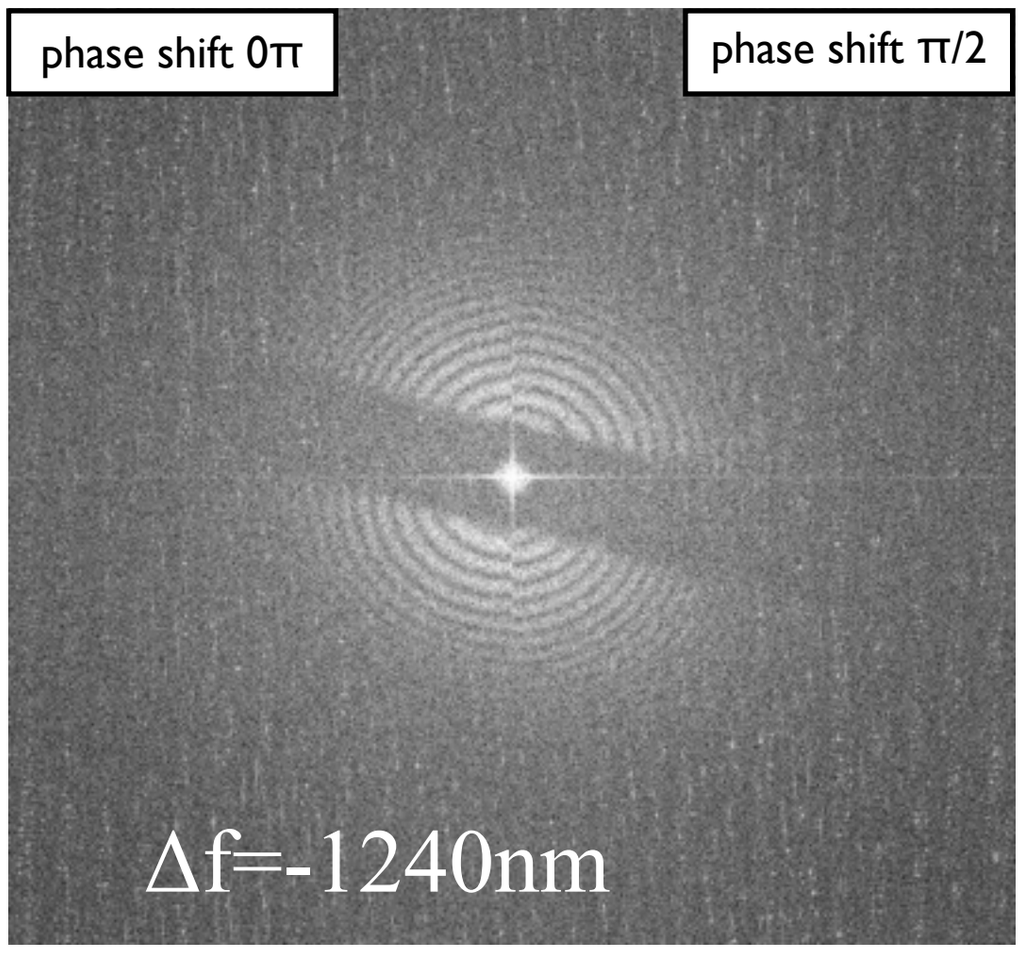
Phase Image of Ferritin Δf=0, in focus



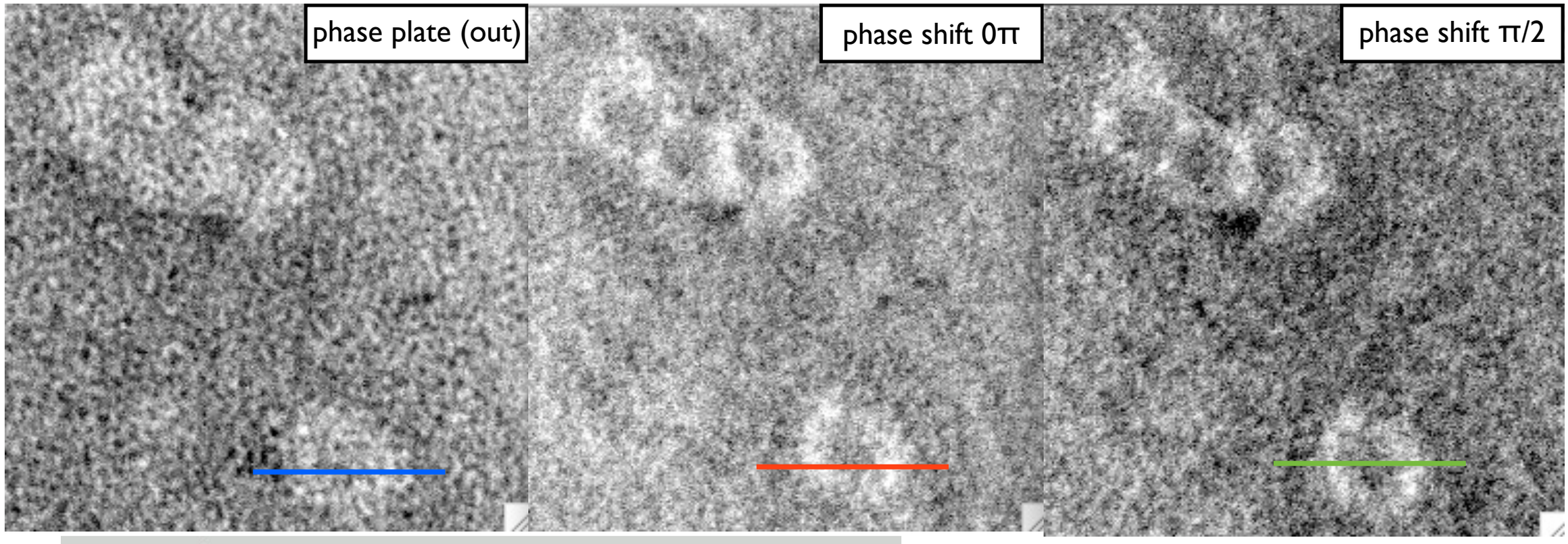


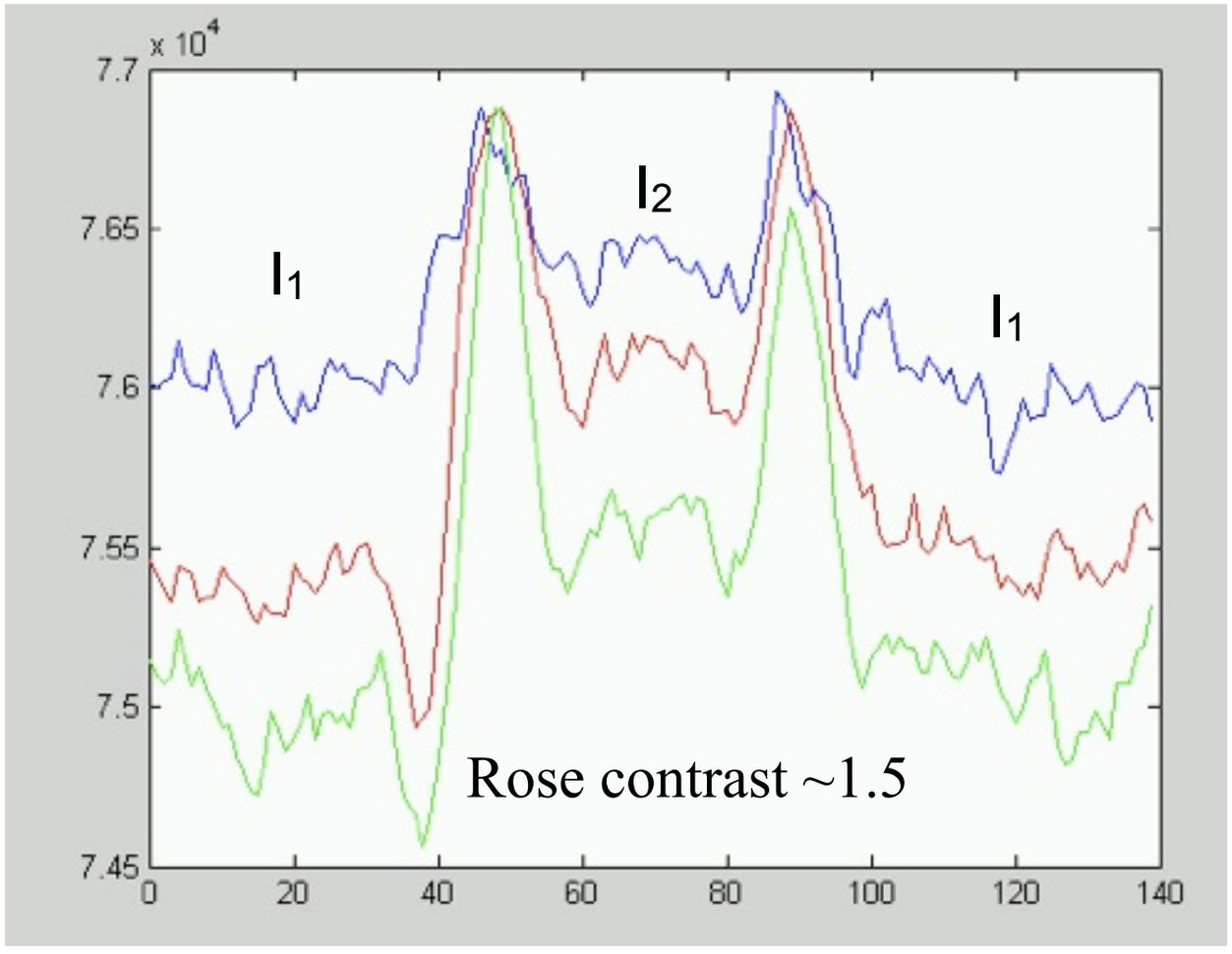
Phase Image of Ferritin Δf=0, in focus

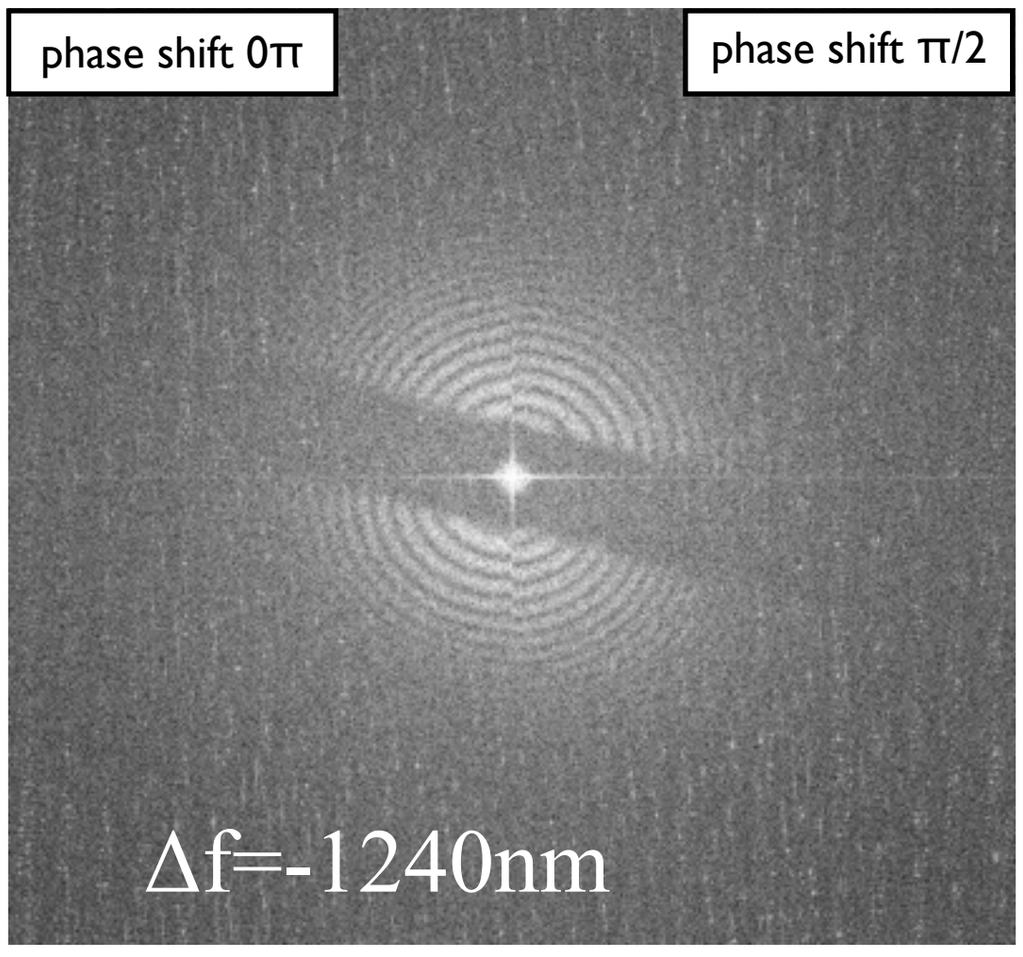




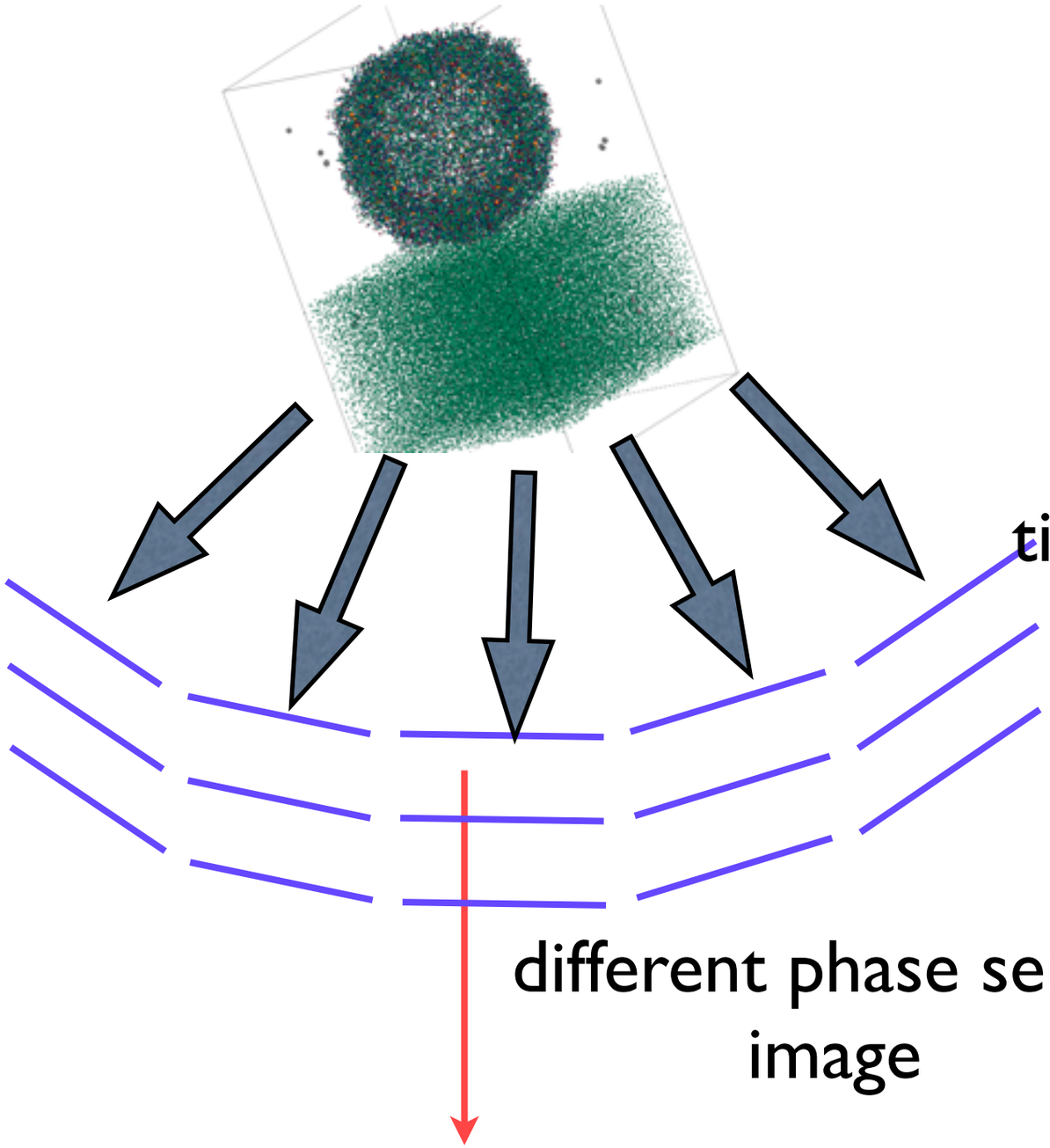
Phase Image of Ferritin $\Delta f=0$, in focus







Proposed Phase Tomography in TEM



Ferritin~12 nm

Carbon film~12 nm

tilt series of phase contrast image

different phase series image

Phase Tomography

1) High phase efficiency
2) low "absorption" contrast
3) good stability and long life

Phase Problems
Conclusions

- Diffractive Imaging (recover the phase in diffraction plane)
- Recover the phase in the real space (TIE)
- Aberration Correction/ Exit Wave Reconstruction

- Focal plate: determination of the geometry of exit surface of sample
- Phase Plate: Alternating the phase to improve the contrast for biological sample

Conclusion

(a) Stable Boesch Phase Plate (Einzel lens) under electron beam (no damage and no charge)

(b) New design of Phase plate and integration with the electron optics of TEM is being carried out to improve the phase efficiency and reducing the absorption effect

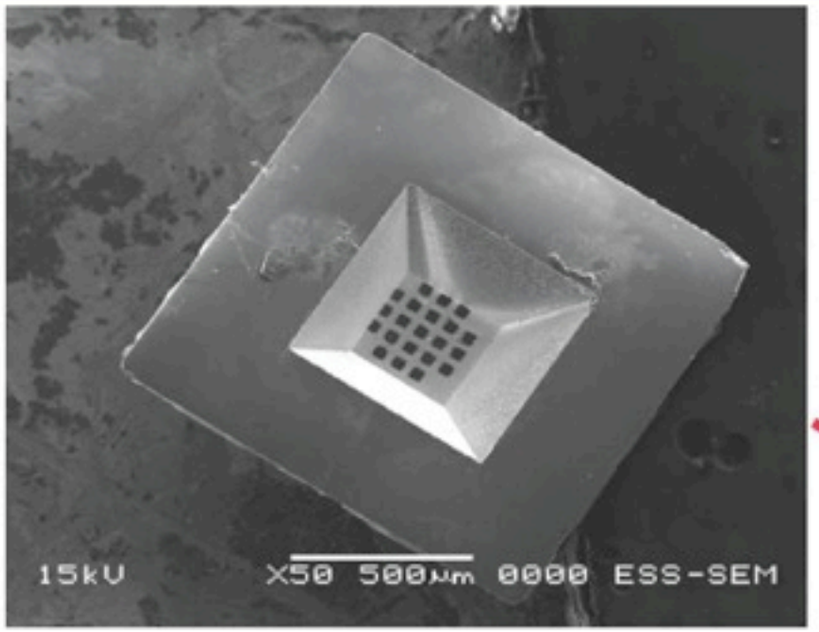
(c) Alignment of optical axes of Phase Plate and Objective lens

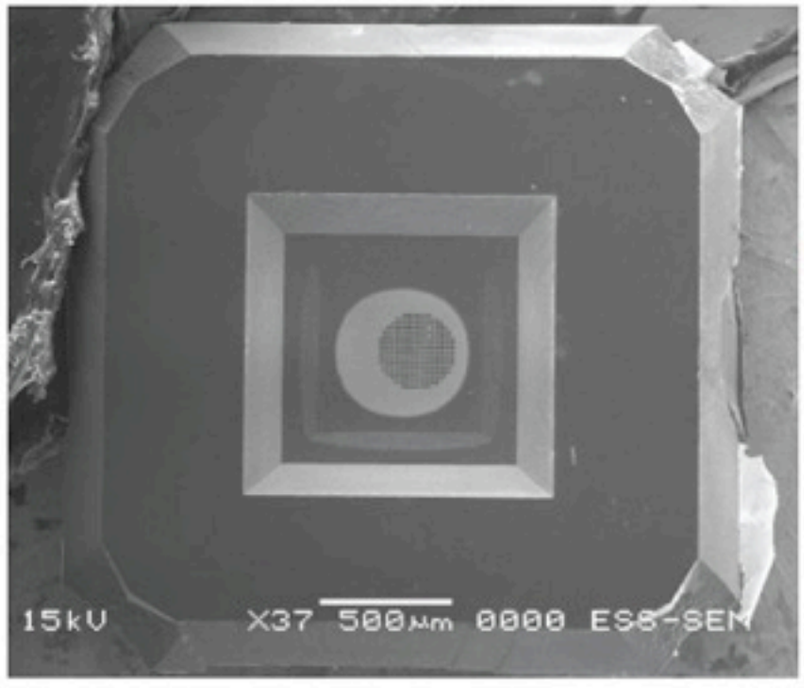
Wet Cell Fabricated by MEMS

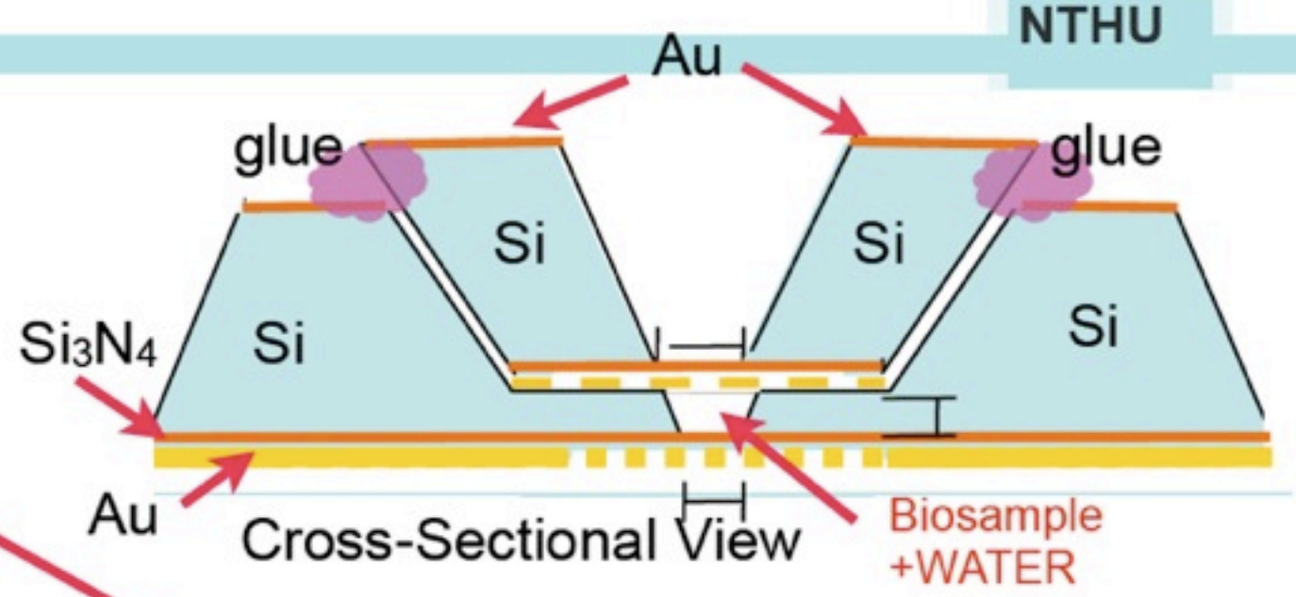
(without modification of TEM)

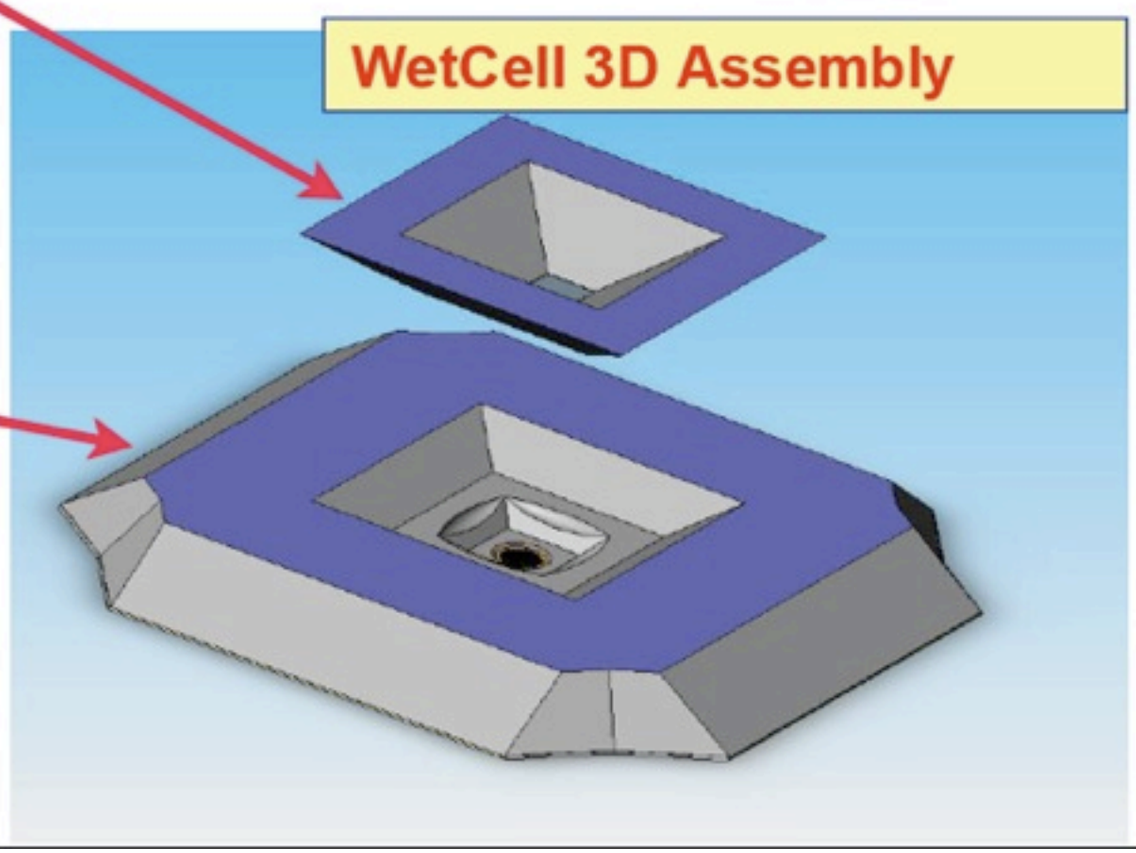
TEM CENTER

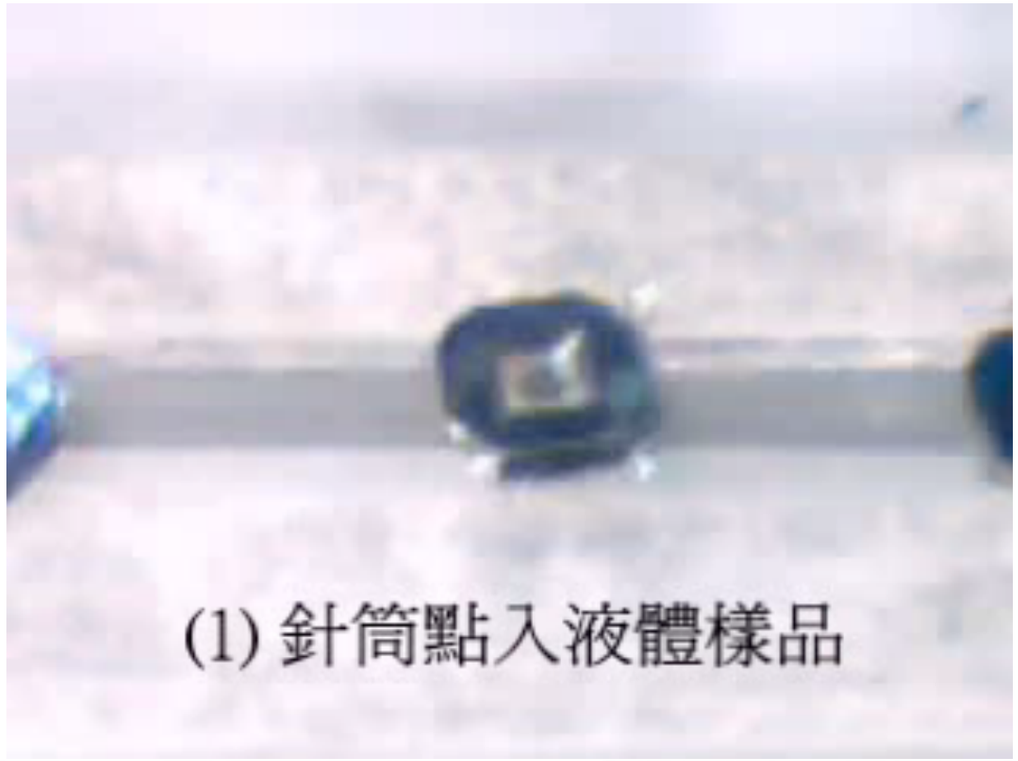
NTHU



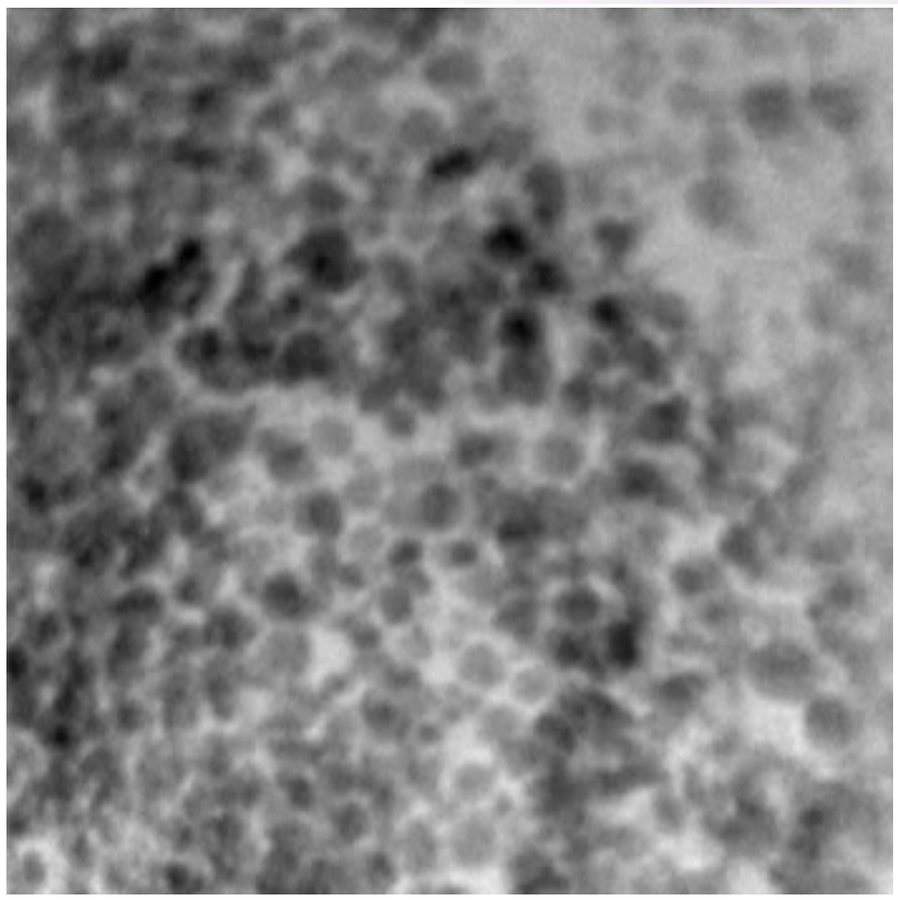




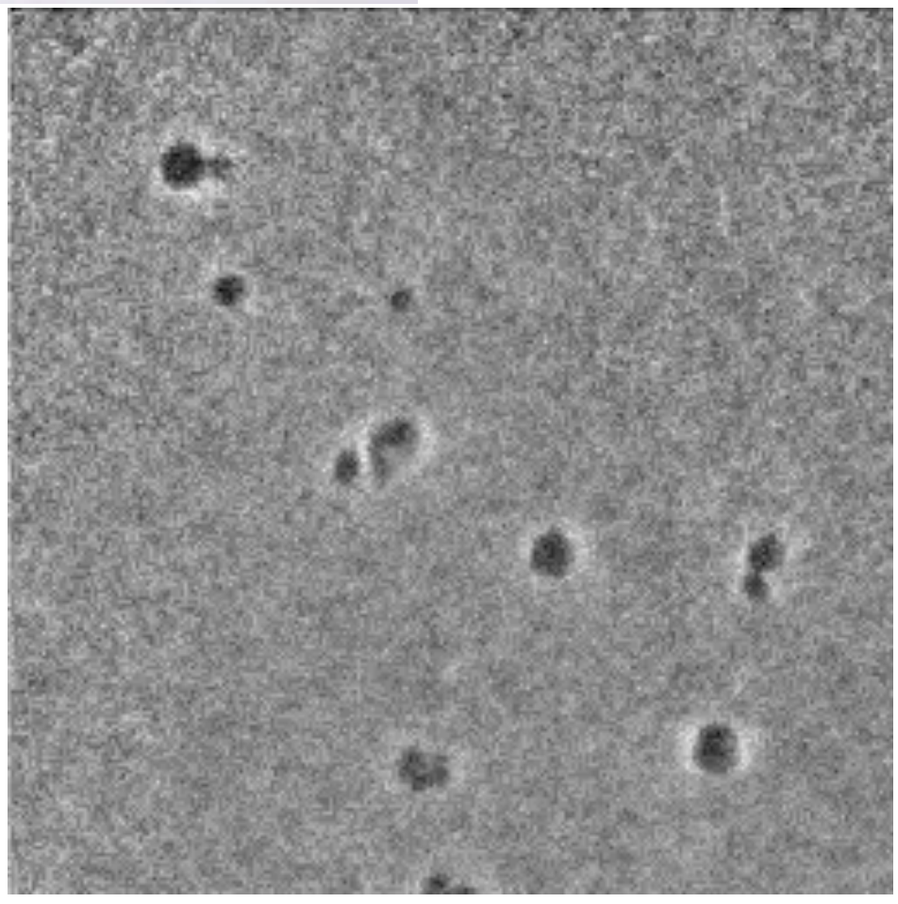




sealing of wet cell



Au particle in water



Au particles in Glycerol