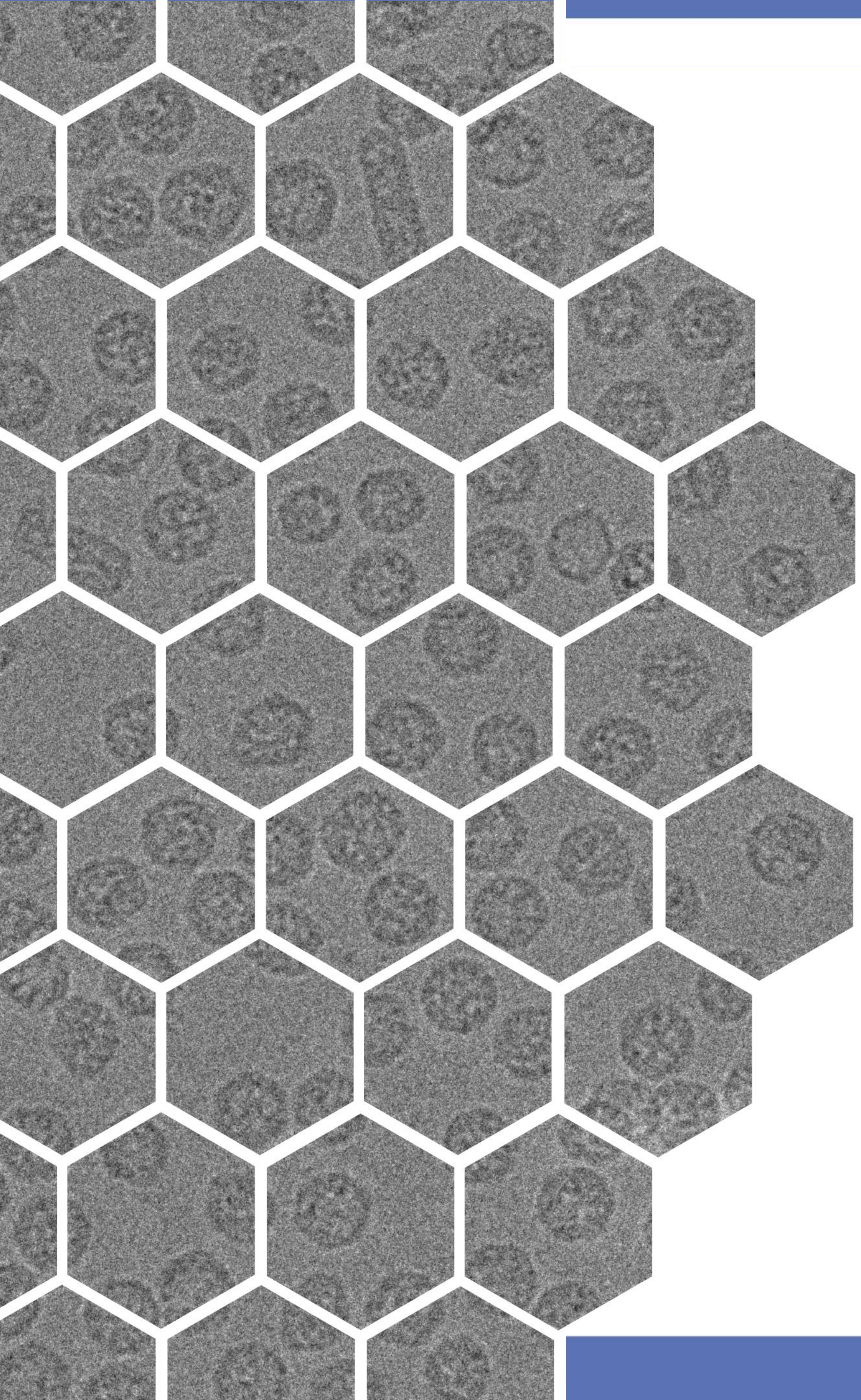
2025 Spring cryoEM course

Welcome and Anatomy of an EM

January 22, 2025

NYSBC SEMC



- Course outline
- Student survey
- Anatomy of an EM

Welcome to SEMC

20th year of the course

SIMONS ELECTRON MICROSCOPY CENTER • GUILD OF MICROSCOPISTS •

Course logistics: main website

https://semc.nysbc.org/workshops/2025-em-course/

SIMONS ELECTRON MICROSCOPY CENTER

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WORKSHOPS & COURSES

CURRENT/UPCOMING COURSES | PAST COURSES

EM Courses:

2024
2023
2022
2021
2020
2019
2018
2017
2016

The Winter-Spring 2025 EM Course

About the course

Electron microscopy in combination with image analysis is increasingly powerful in producing 3D structures of individual molecules and large macromolecular complexes that are unapproachable by other methods. This course is focused on the concepts and theories behind electron microscopy. Each week guest lecturers and SEMC staff lead discussions on the practice of solving molecular structures by electron microscopy. Students will be responsible for watching relevant sections from Getting Started in Cryo-EM and cryoEM101 ahead of attending the lectures.

The course will be held at the New York Structural Biology Center at 89 Convent Ave (133rd St).

Course Schedule

Classes in NYSBC A-11 seminar room (Mondays 3:30-5pm and select Wednesdays 3:30-5pm)

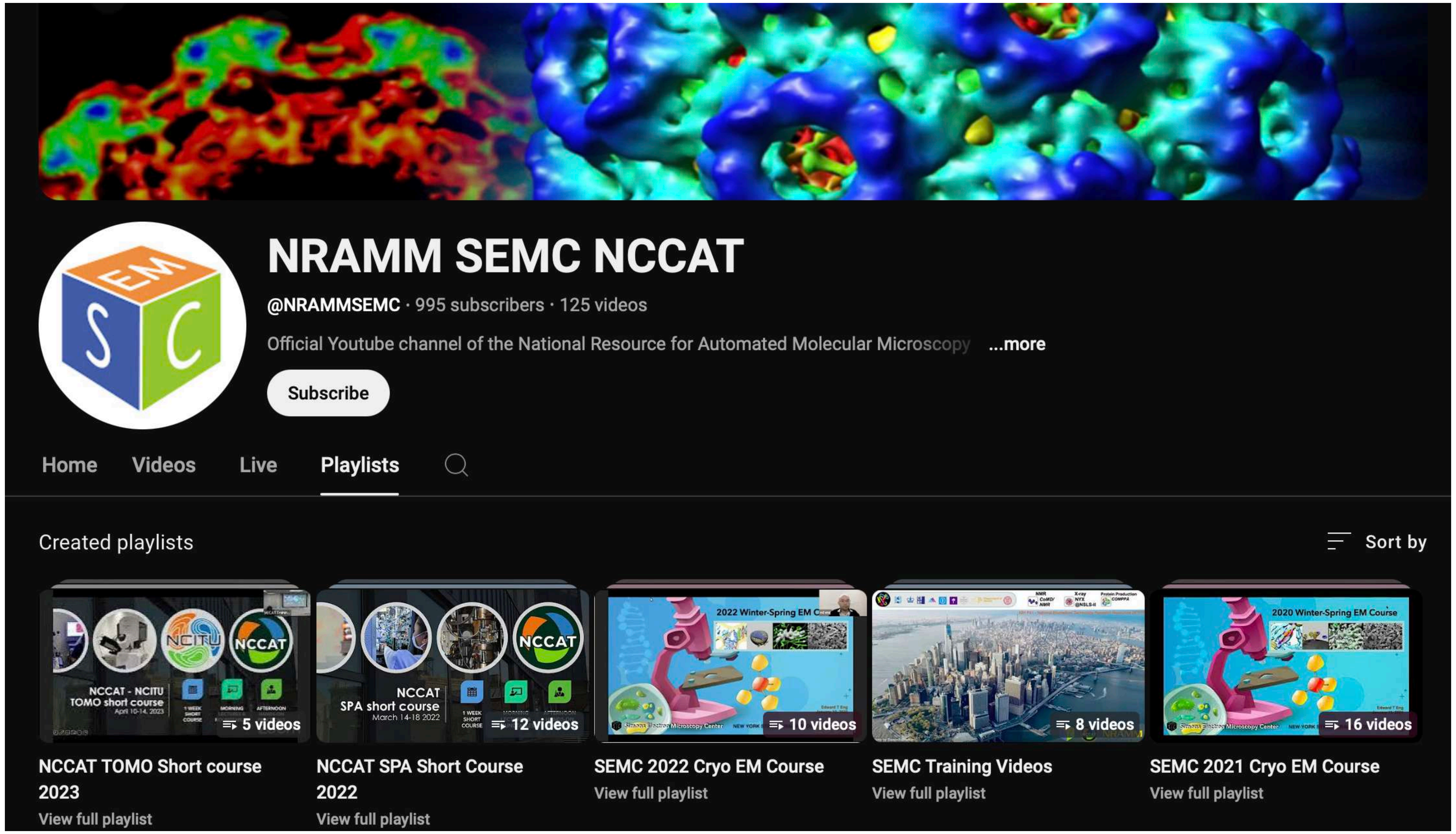
EM fundamentals section
Jan 20: Martin Luther King Holiday (no class)
Jan 22: Lecture – Introduction & Basic anatomy of the electron microscope (Ed Eng – NYSBC/SEMC & SEMC staff)
Jan 27: Lecture – New cryoEM hardware and supporting a facility (Michael Alink – NYSBC/SEMC)
Jan 29: Practical – TEM use (SEMC staff [worksheet])
Feb 3: Lecture – Considerations for biological cryoEM (Ed Eng – NYSBC/SEMC & SEMC staff)
Feb 5: Practical – Sample Preparation & Support films (SEMC staff [worksheet])

- Course Administrator:
  - Ed Eng (NYSBC)

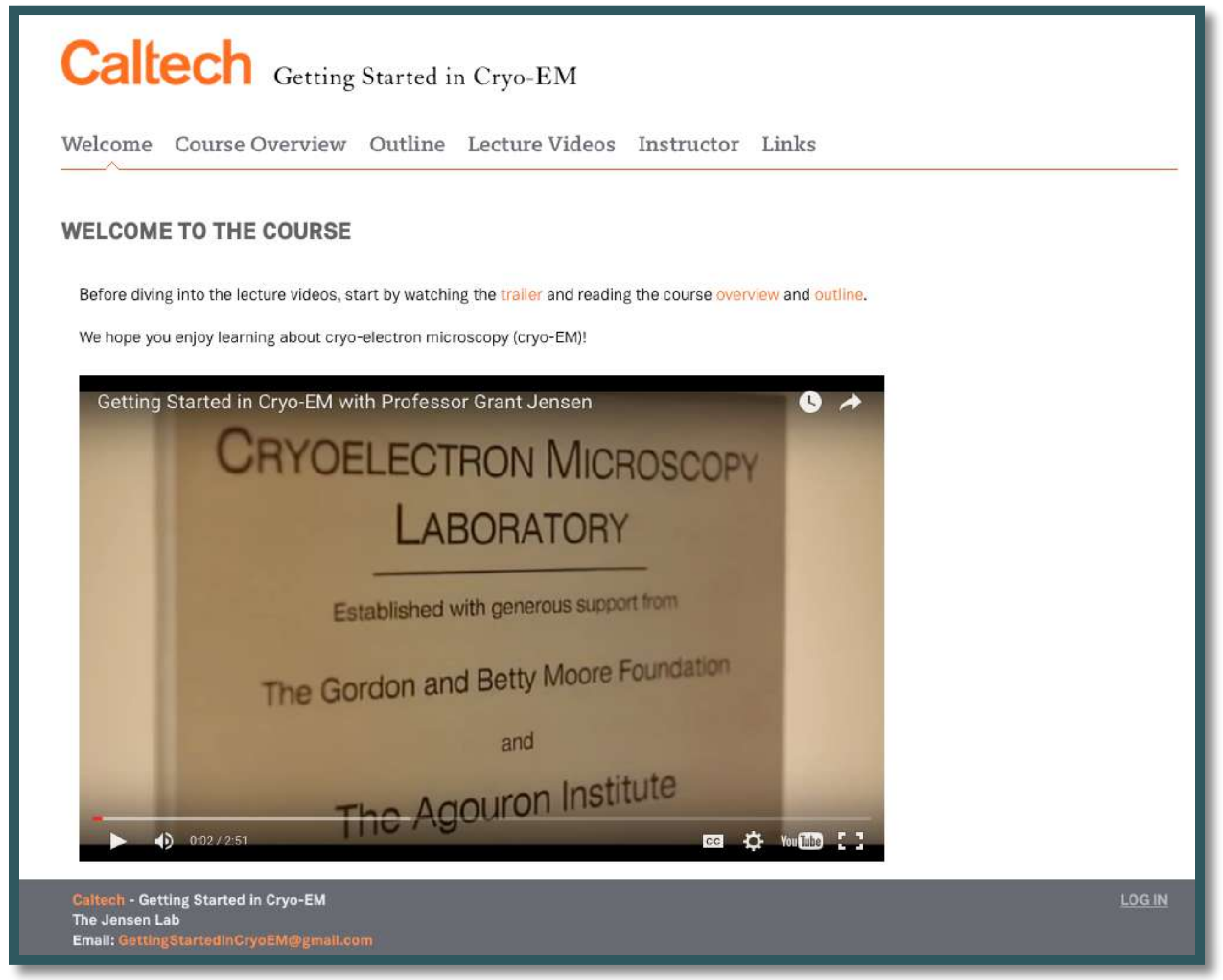
- Teaching Assistants:
  - Mahira Aragon (NYSBC)
  - Alex Flynn (NYSBC)
  - Shubhangi Agarwal (NYSBC)
  - Kasahun Neselu (NYSBC)

Course logistics: additional resources

youtube.com/nrammsemc



cryo-em-course.caltech.edu/videos



cryoem101.org

Course logistics: main topics

Section 1 : EM fundamentals

Section 2 : EM crystallography

Section 3 : Single Particle Analysis

Section 4 : Tomography Short Course
March 31-April 4

Section 5 : Future perspectives

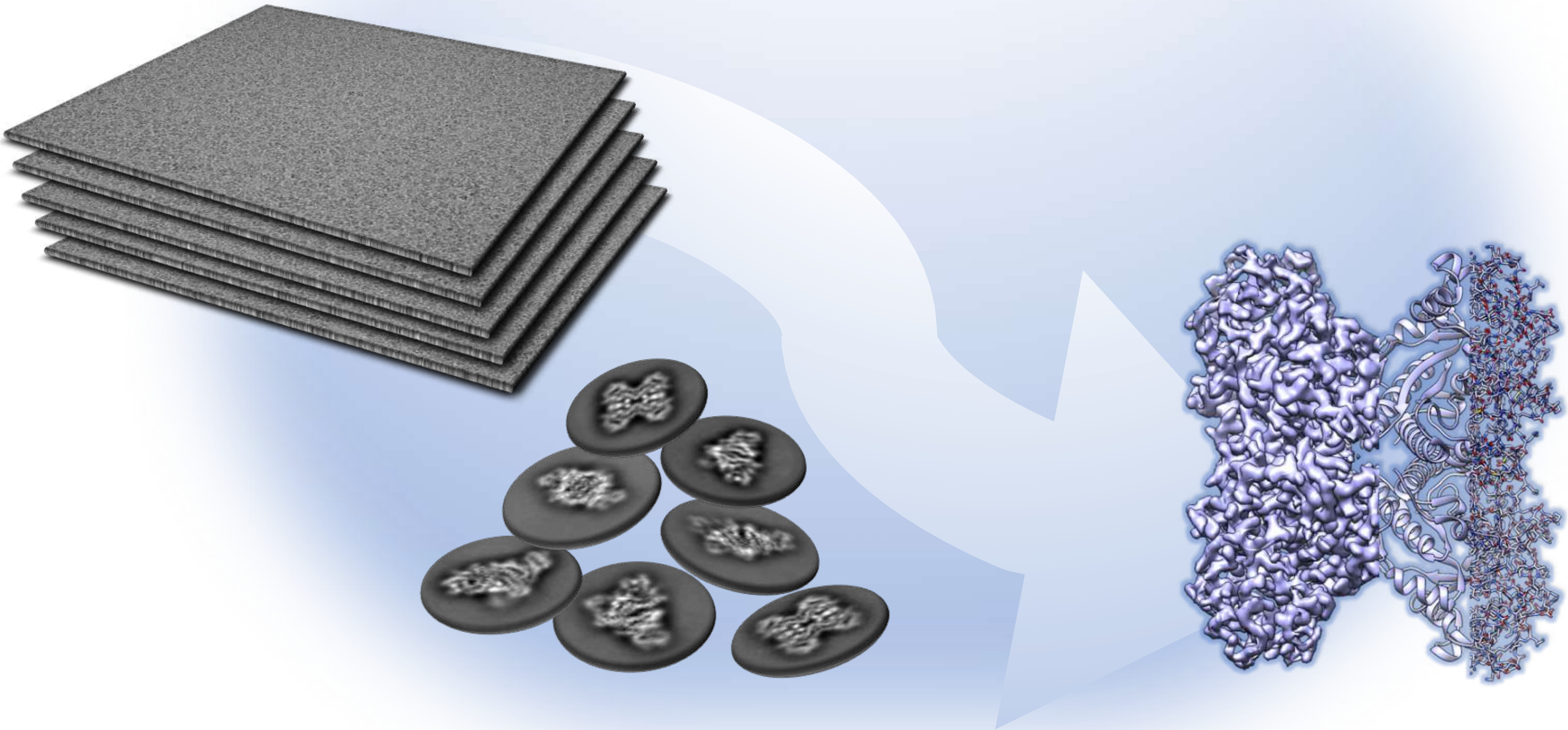
Course logistics: main topics

Course logistics: class for credit

Component	Percentage
Recitation/Participation	50%
- *JC/HW/questions*	
Practicals	10% x 3
Attendance	20%


atoms
1 Å
Small molecules
1 nm
Biological macromolecules
10-100 nm
Organelles prokaryotic cells
0.1-5 µm
Eukaryotic cells
5-100 µm
Neurons
mm
organs & organisms
cm-m
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Neutrons
AFM
Human eye
X-Rays
Light microscopy
NMR
Electron microscopy

What is possible today?



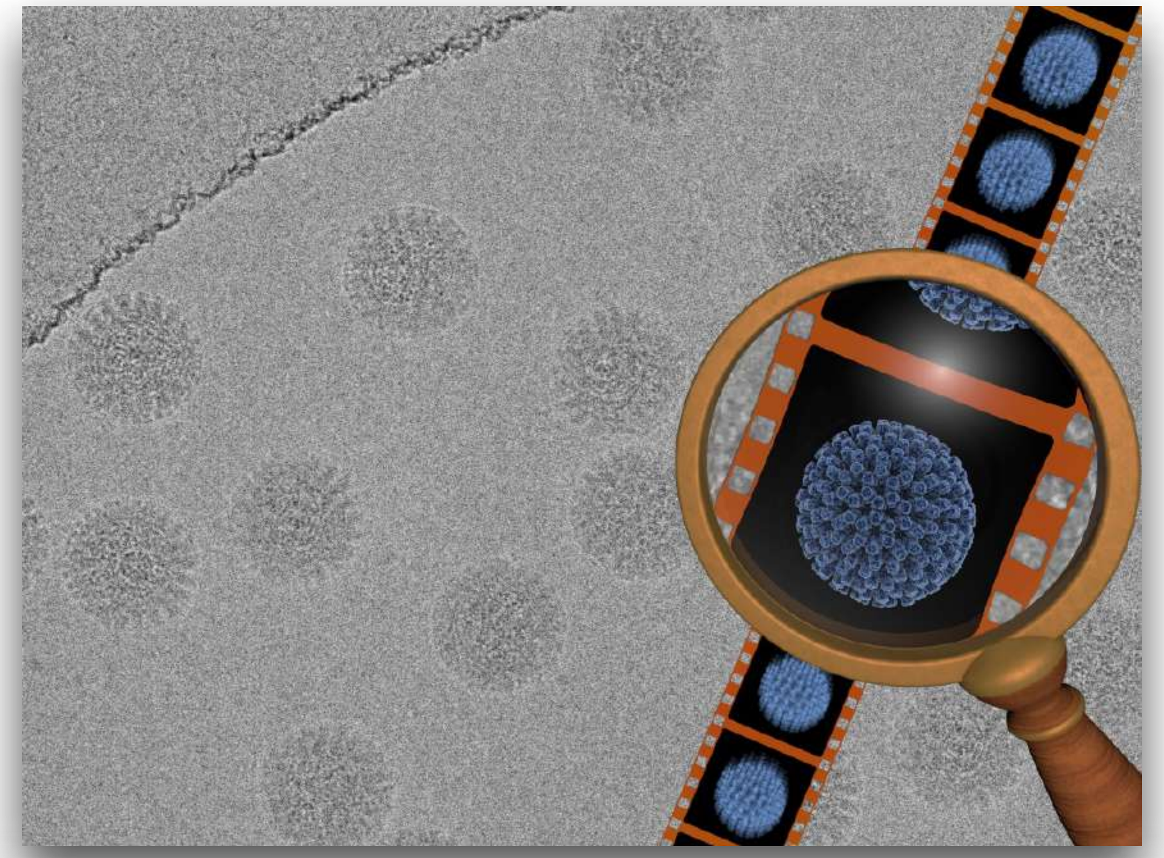
What brought about the resolution revolution?

(~2012-2014)

Hardware

Microscopes

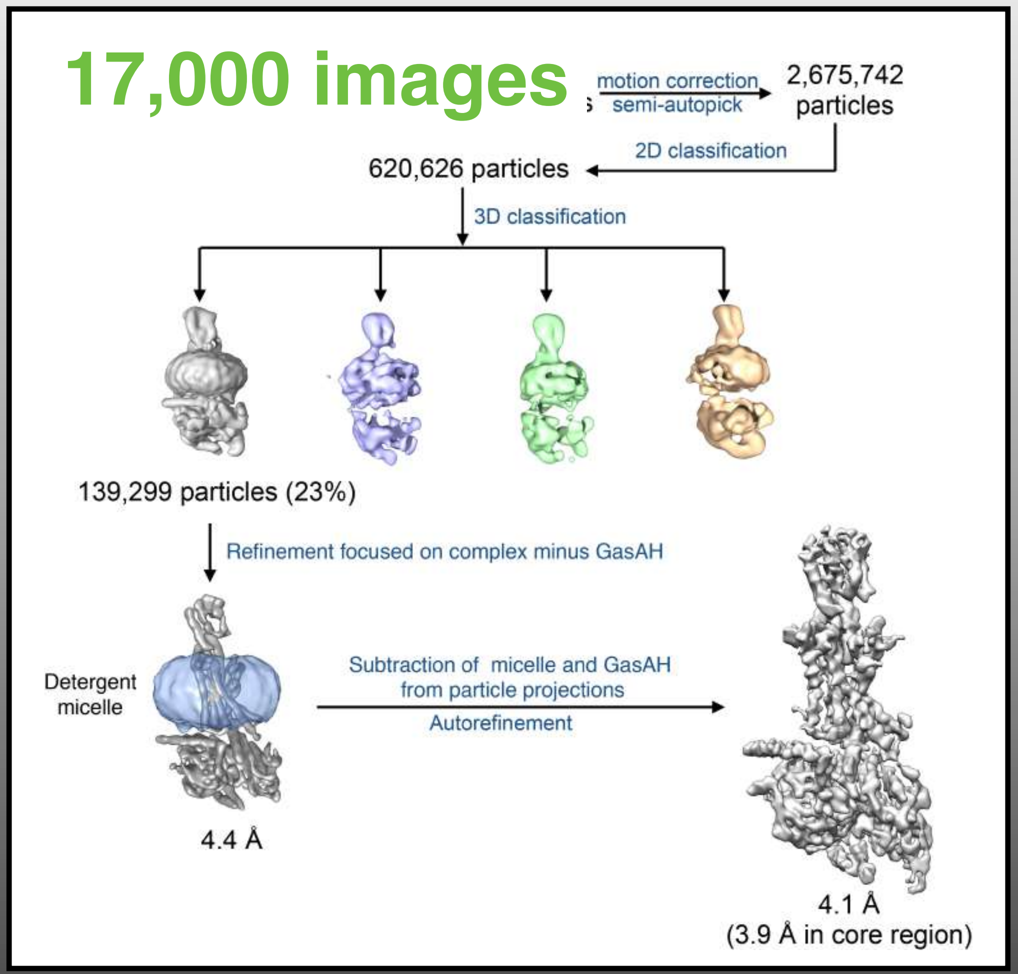
Direct Detectors



Computers

2012->2017
Cost reduced by 100x

Software



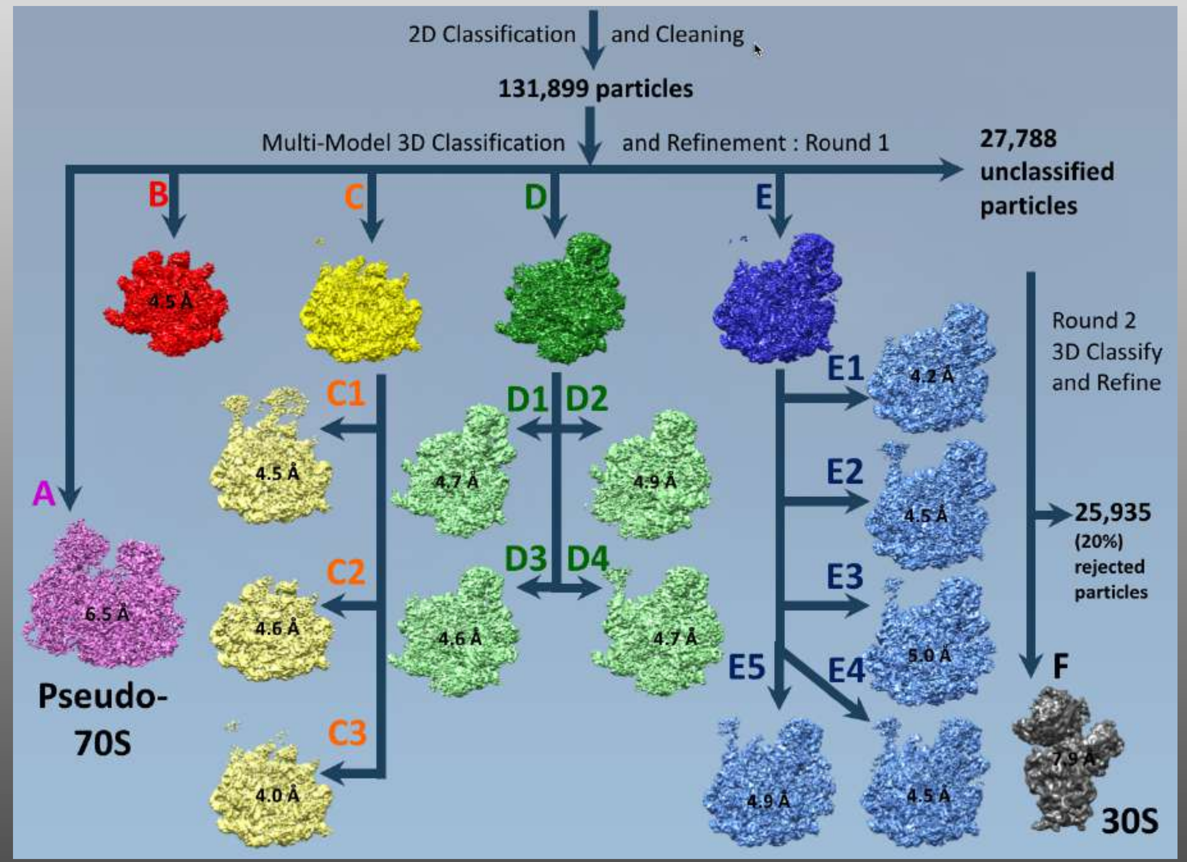
5% used in map!

Leginon / SerialEM / EPU, …

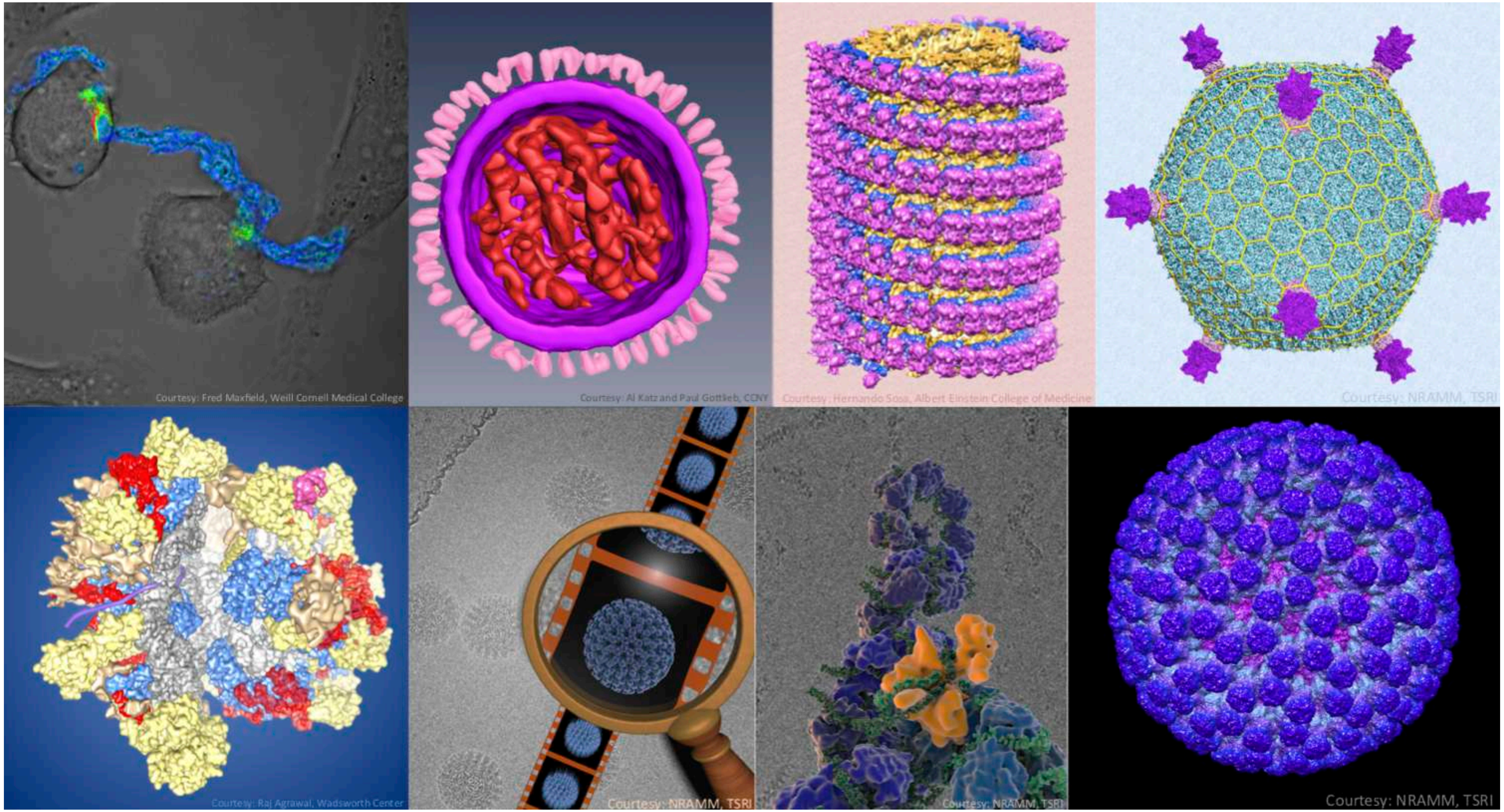
MotionCorr2, Unblur, …

RELION, FREALIGN/cisTEM, cryoSPARC
EMAN, Sparx, SPHIRE, XMIPP, …

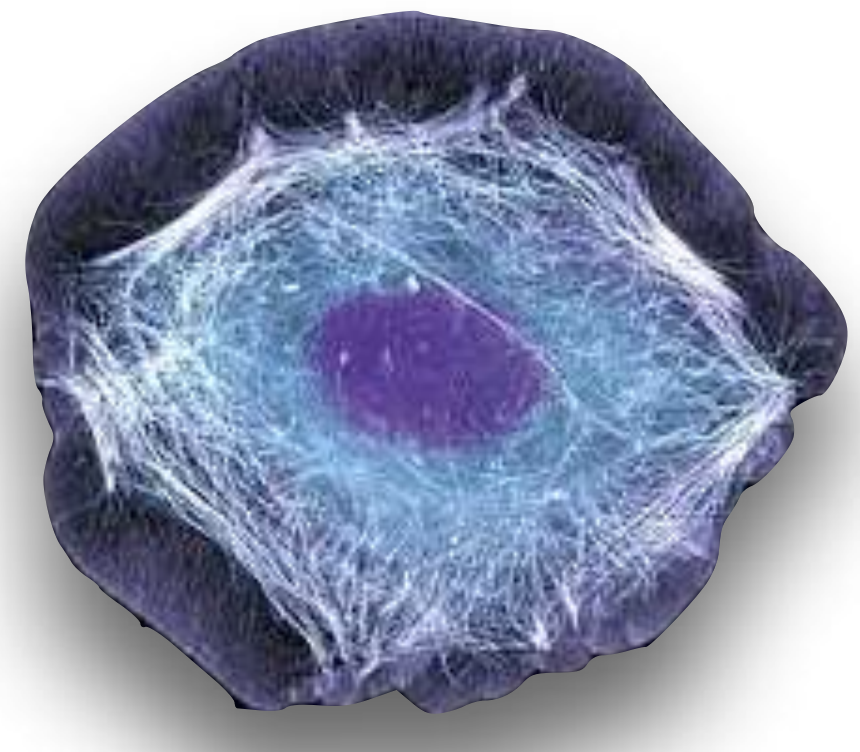
14 independent structures

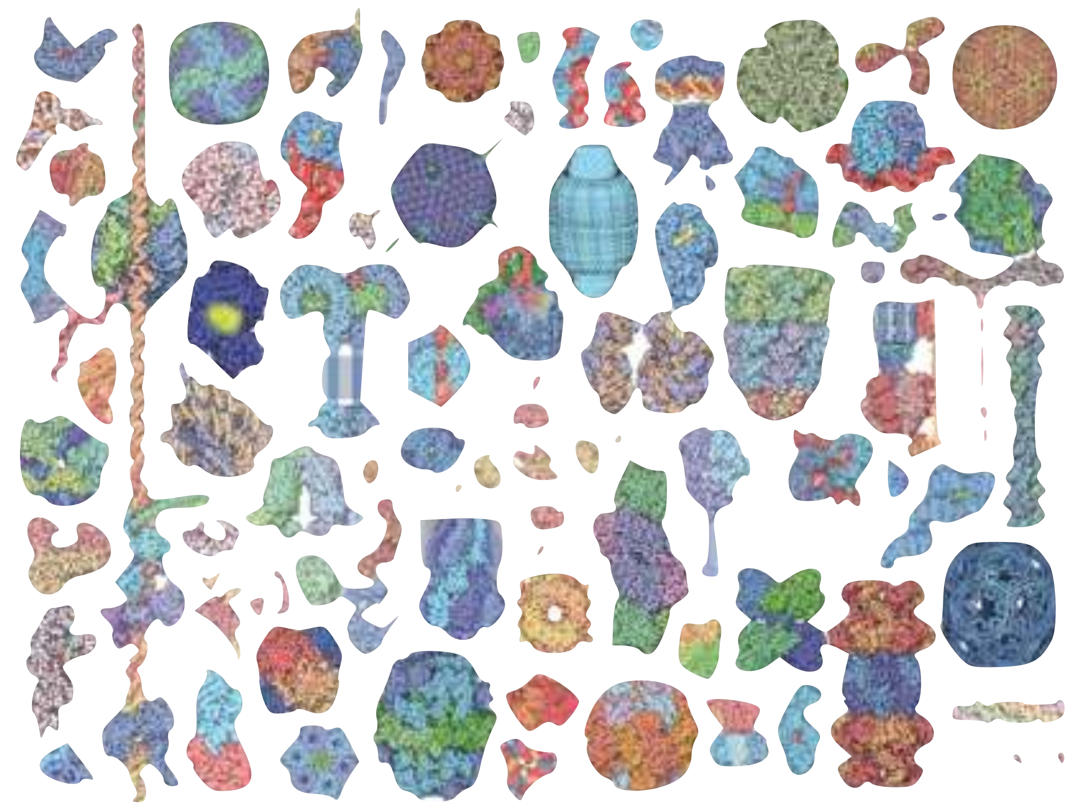


cryoEM: a technology on the rise



next steps

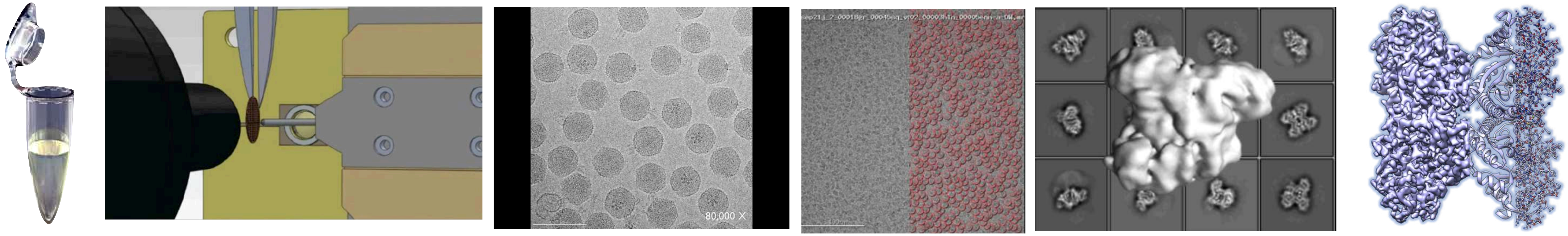


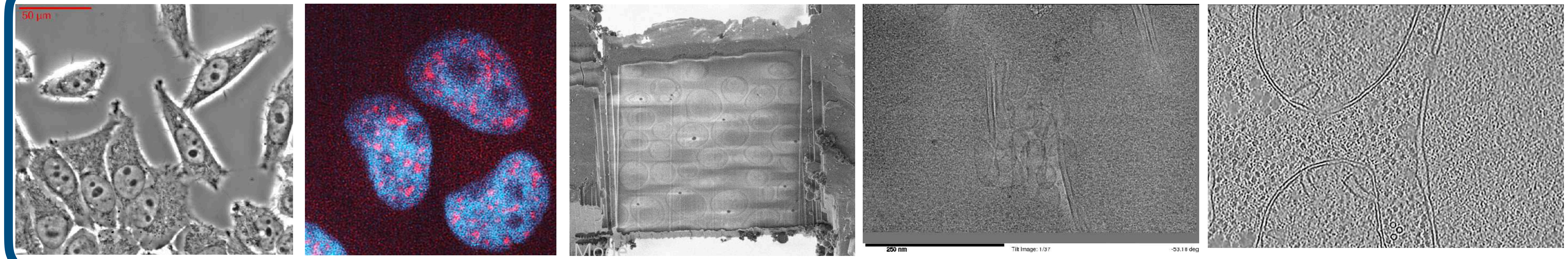


coming soon

cryoEM: a technology on the rise

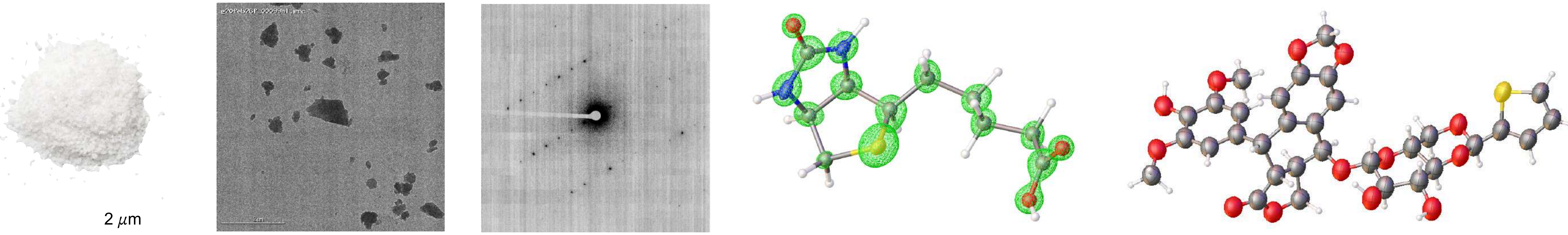
Single particle cryoEM





Cryo Electron Tomography (cryoET)

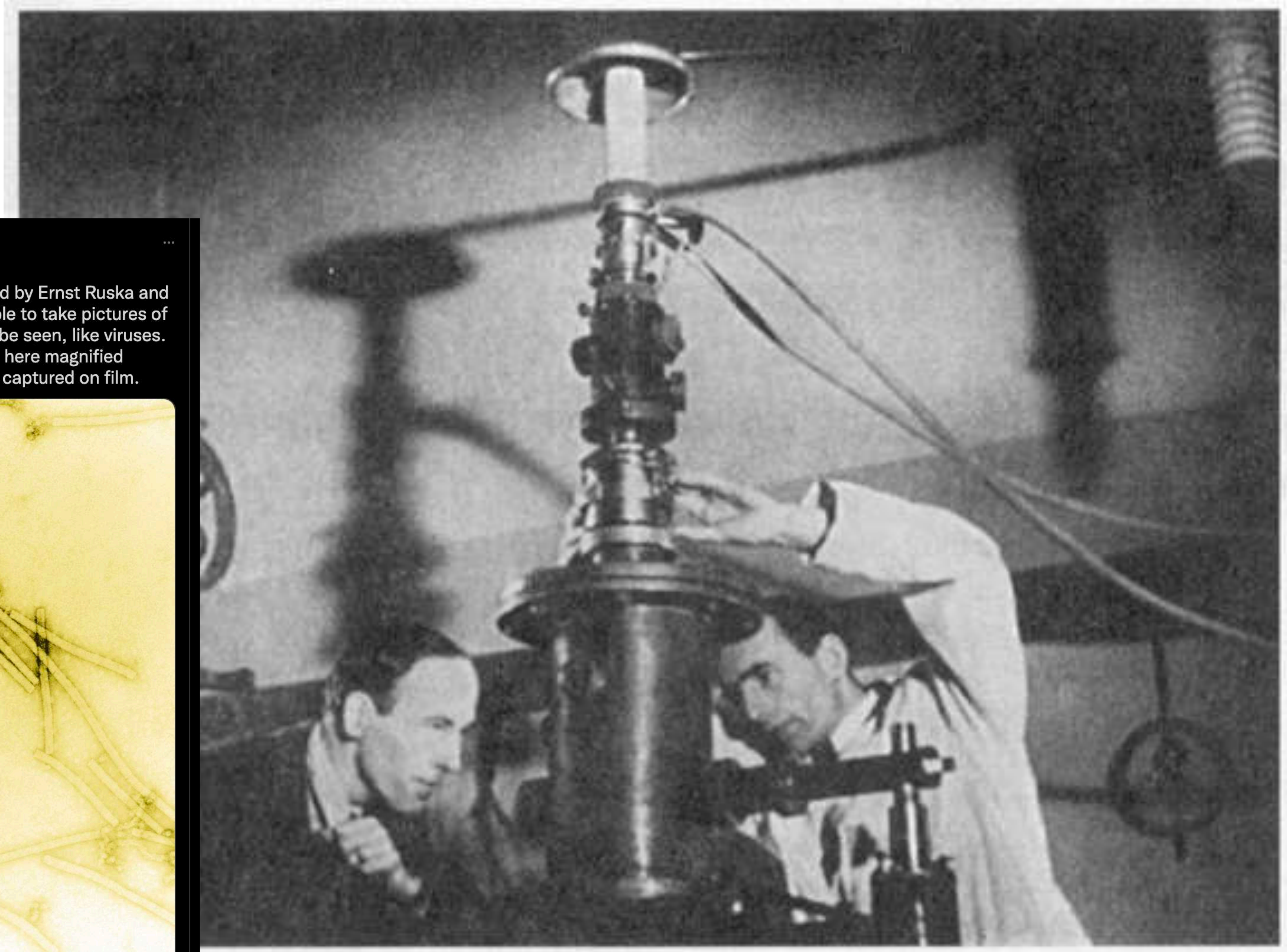
Micro crystal electron diffraction (microED)



The tool of our trade: EM

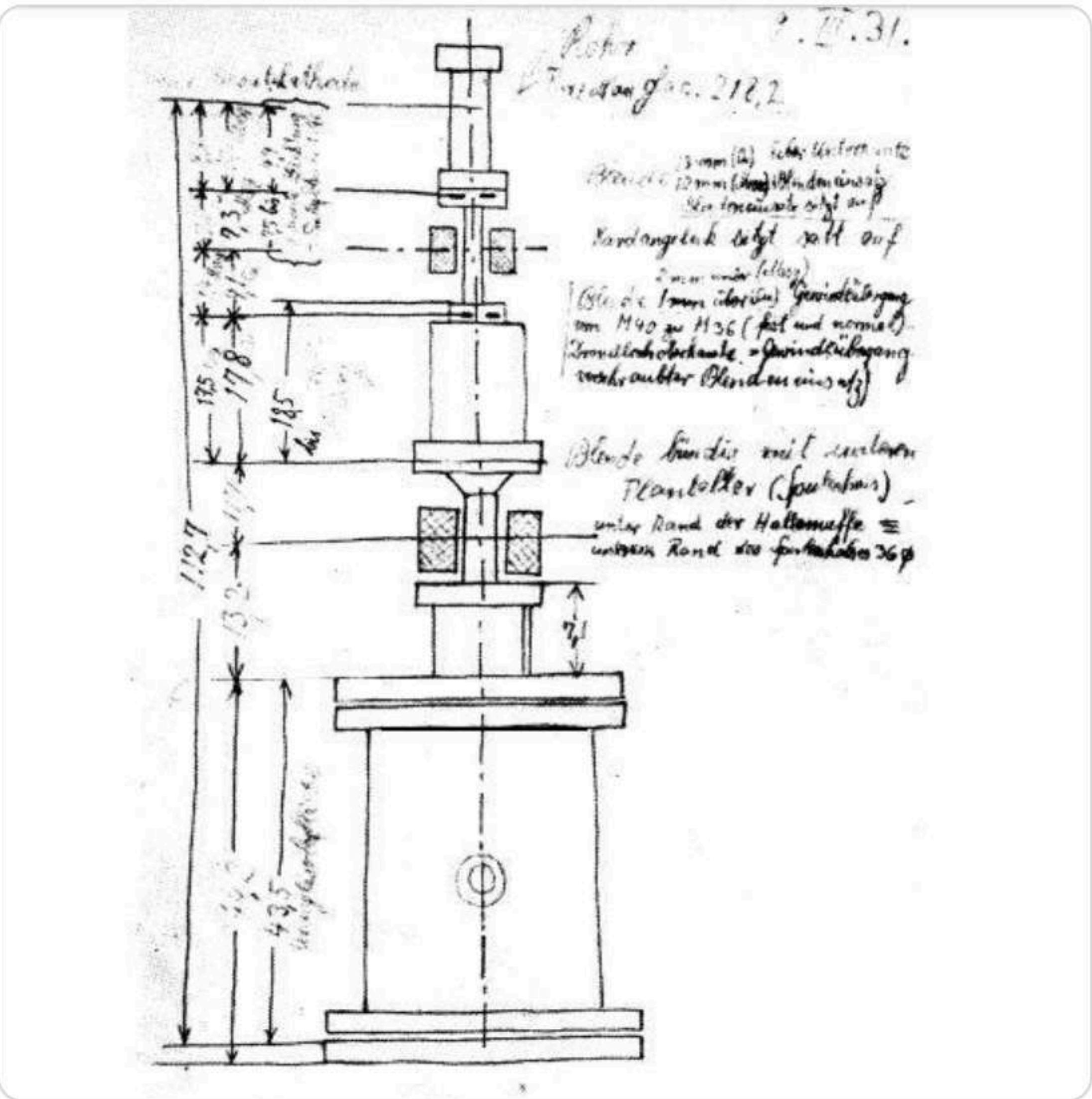
Ruska and Knoll in Berlin in the early 1930s

-Wikipedia



The Nobel Prize
@NobelPrize

Take a look at a sketch by physics laureate Ernst Ruska, dated 9 March 1931, of the cathode ray tube for testing one-stage and two-stage electron-optical imaging by means of two magnetic electron lenses (electron microscope). Ruska was awarded the 1986 physics prize for his work.



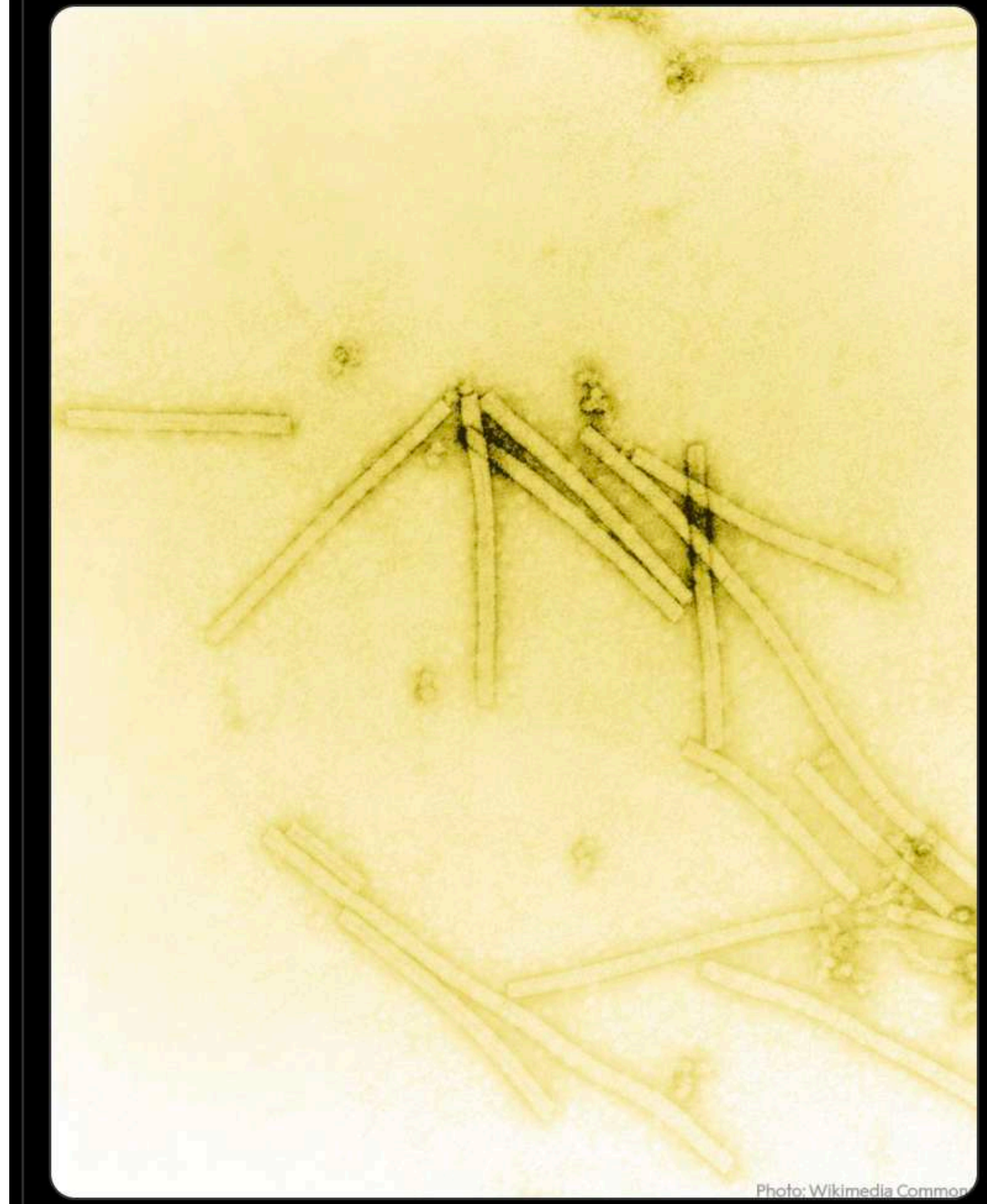
6:06 AM · Dec 25, 2021

725 Reply Copy link to Tweet

Read 8 replies

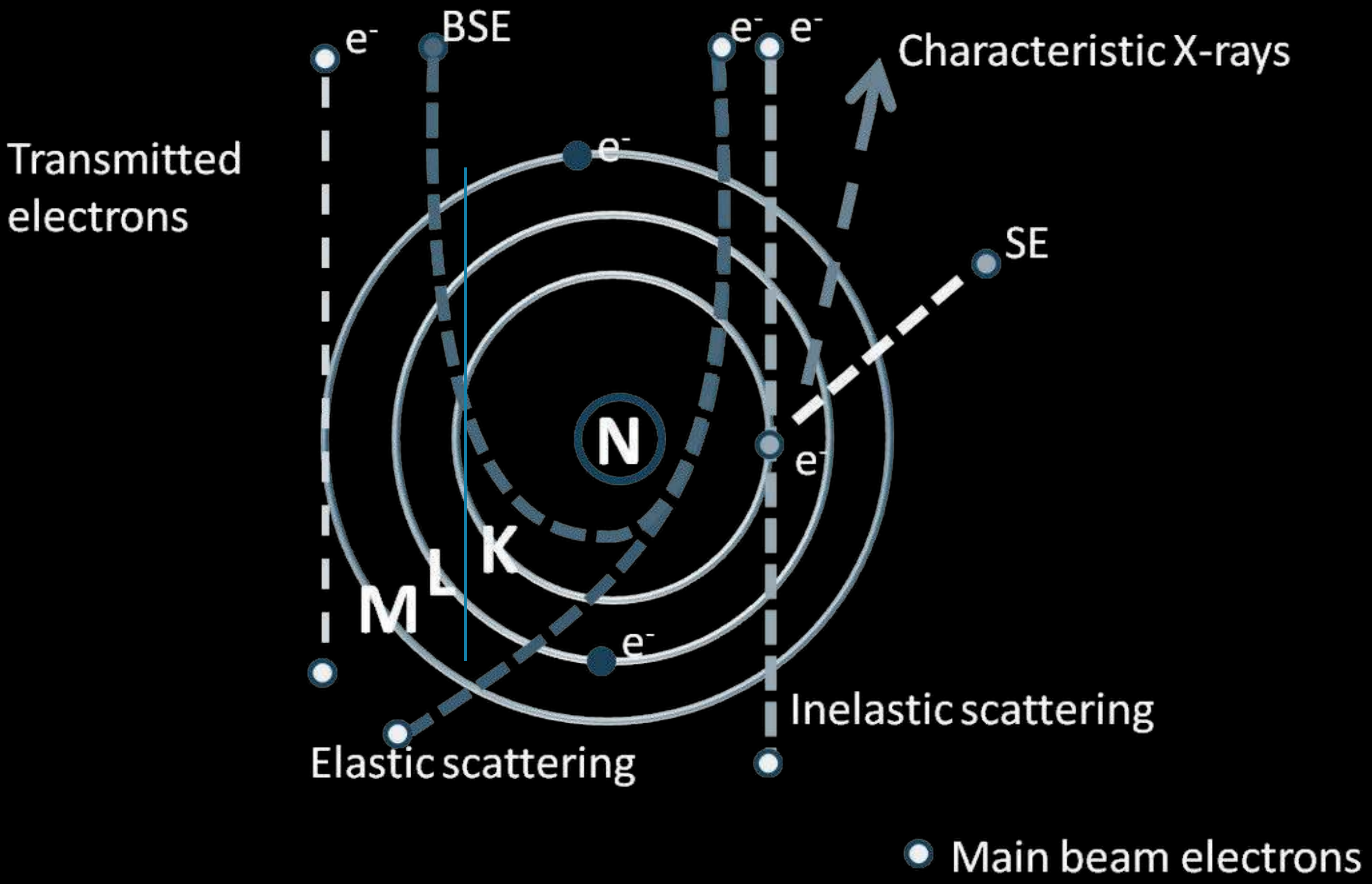
The Nobel Prize
@NobelPrize

The electron microscope, invented by Ernst Ruska and Max Knoll in 1933, made it possible to take pictures of objects that previously could not be seen, like viruses. The tobacco mosaic virus, shown here magnified 160,000 times was the first virus captured on film.



9:58 AM · Aug 22, 2021 · Sprout Social

Why electrons?



Why electrons?

Pros

Small wavelength

Can be focused

Cons

Damages sample

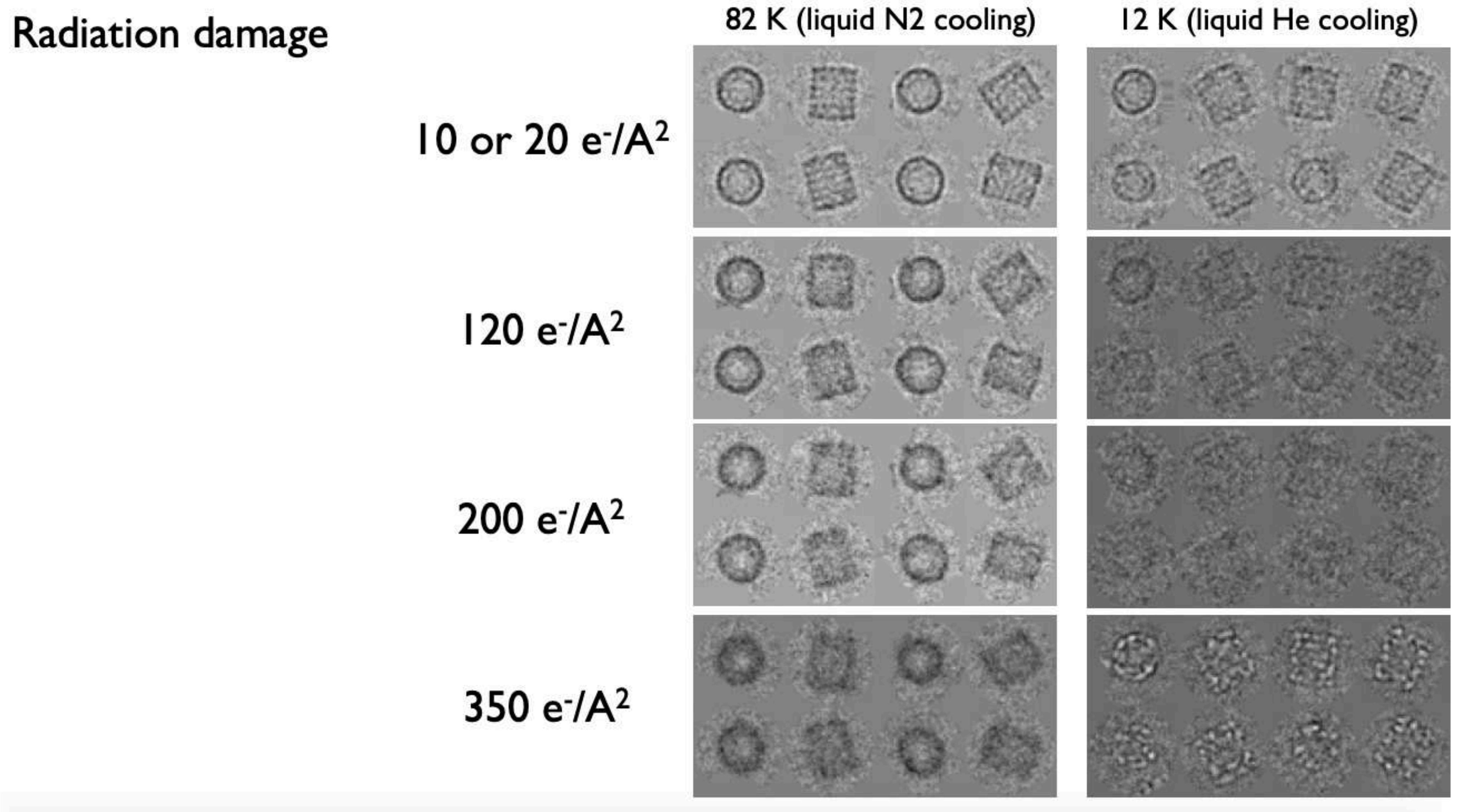
worse with faster electrons

Poor penetration

better with faster electrons

Why electrons?

Ideal dose for cryoEM?



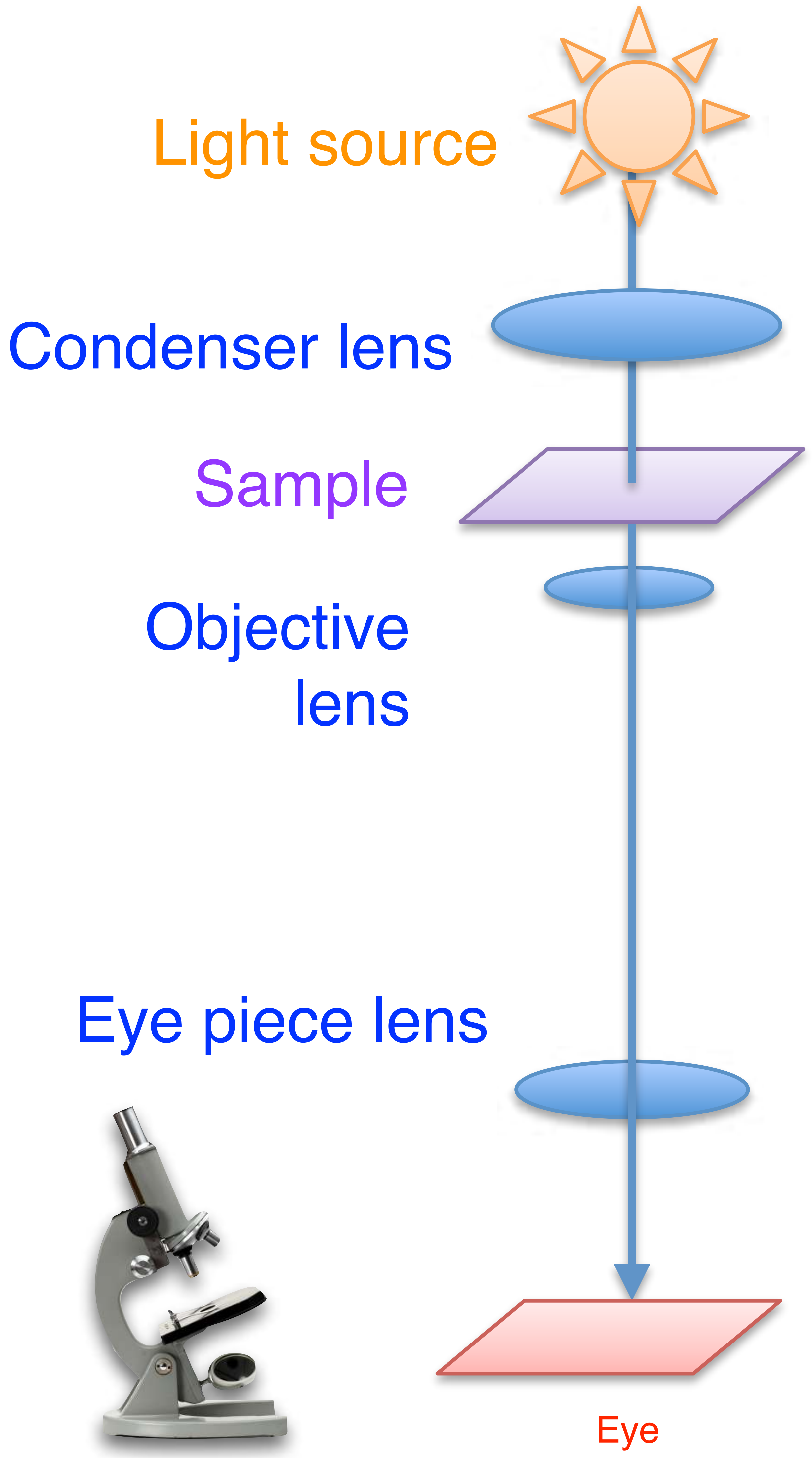
https://cryo-em-course.caltech.edu/

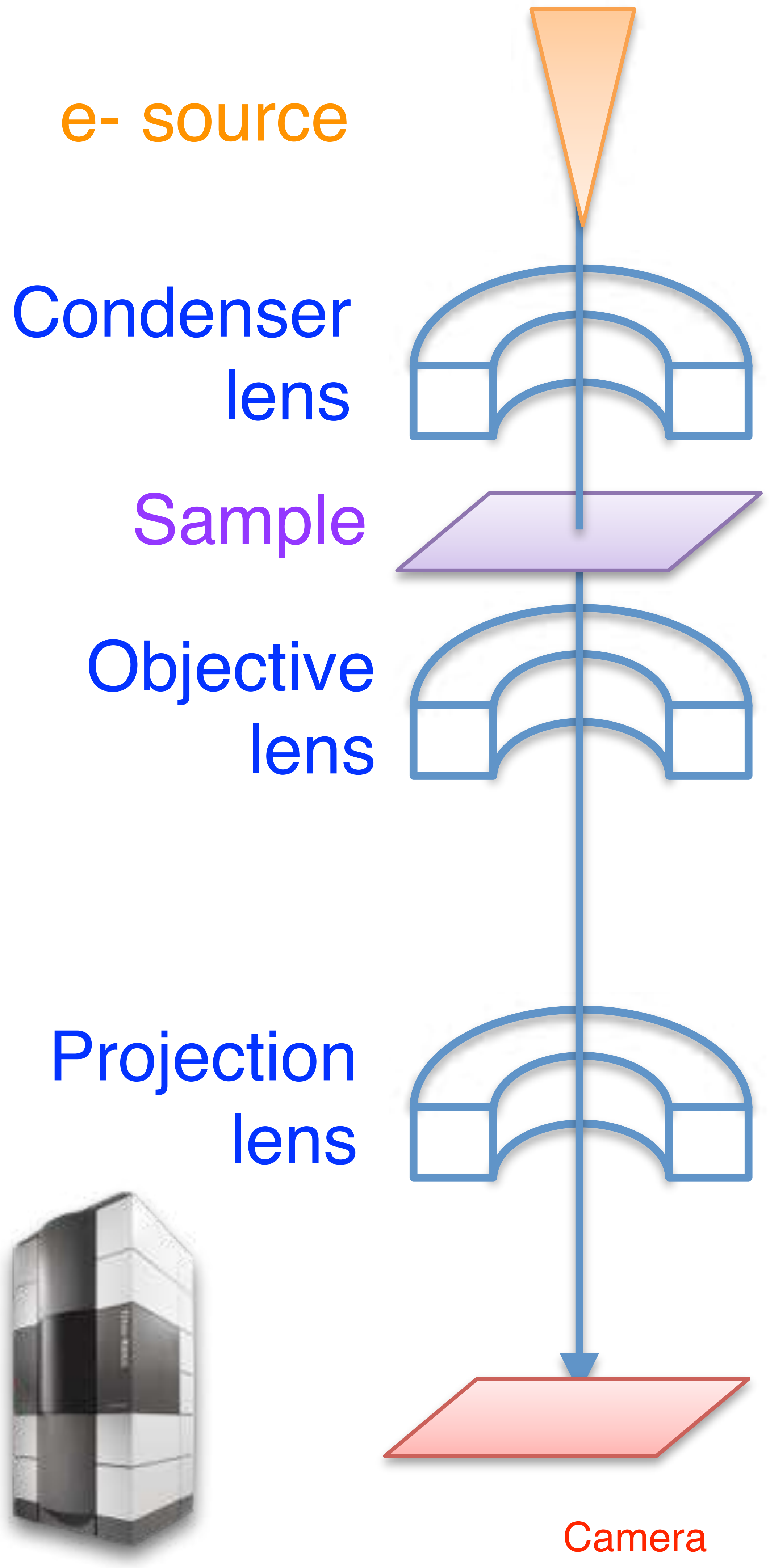
Specimen Behavior in the Electron Beam

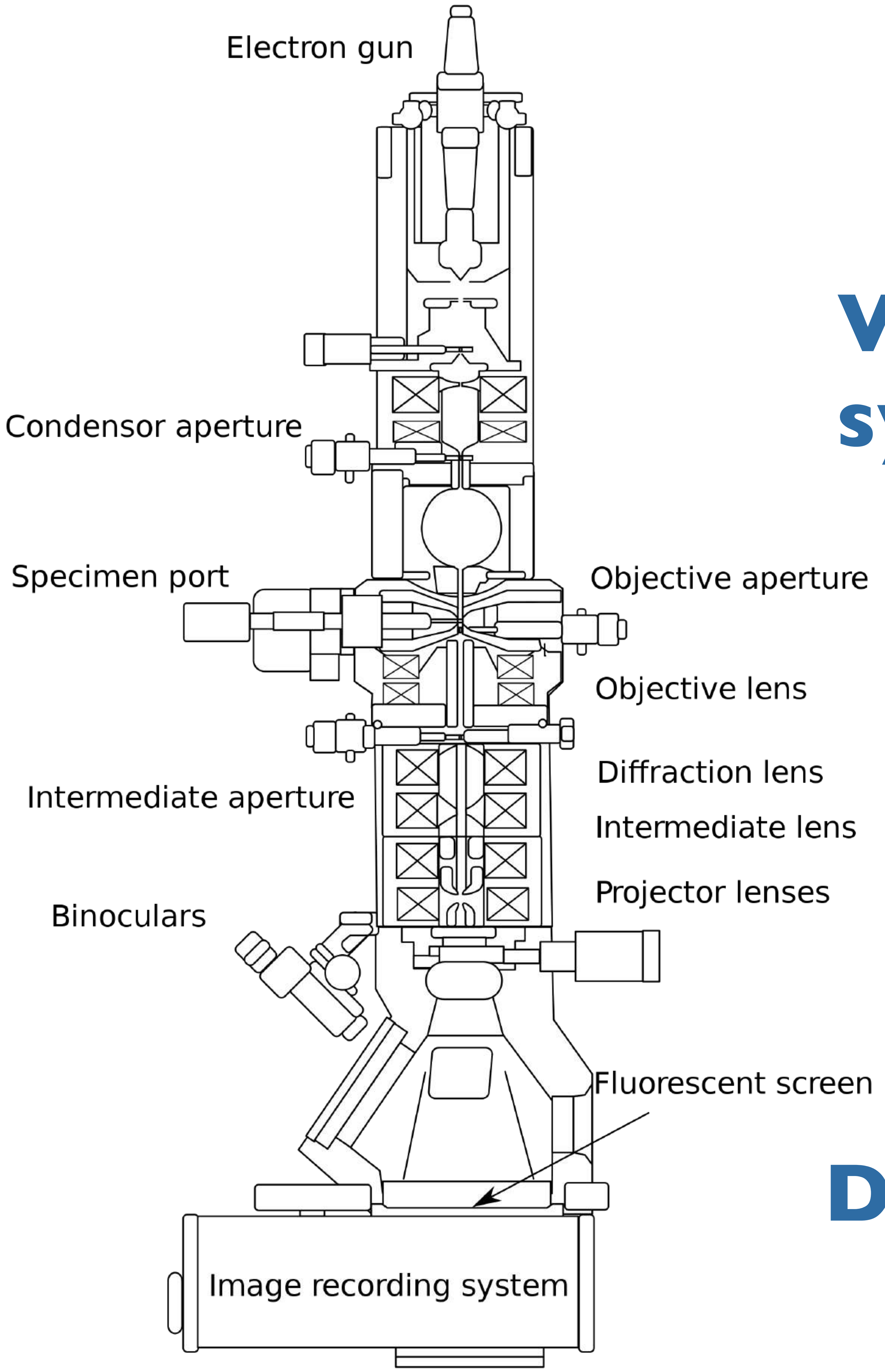
R.M. Glaeser[1]
Lawrence Berkeley National Laboratory, University of California, Berkeley, CA, United States
[1]Corresponding author: e-mail address: rmglaeser@lbl.gov

- The first noticeable bubbles appear after the accumulated exposure (for 300 keV electrons) is approximately 150 e/A . At this high exposure, high-resolution features would long since be destroyed, of course, but the macromolecular particles might still be visible.

The electron microscope







Electron sources

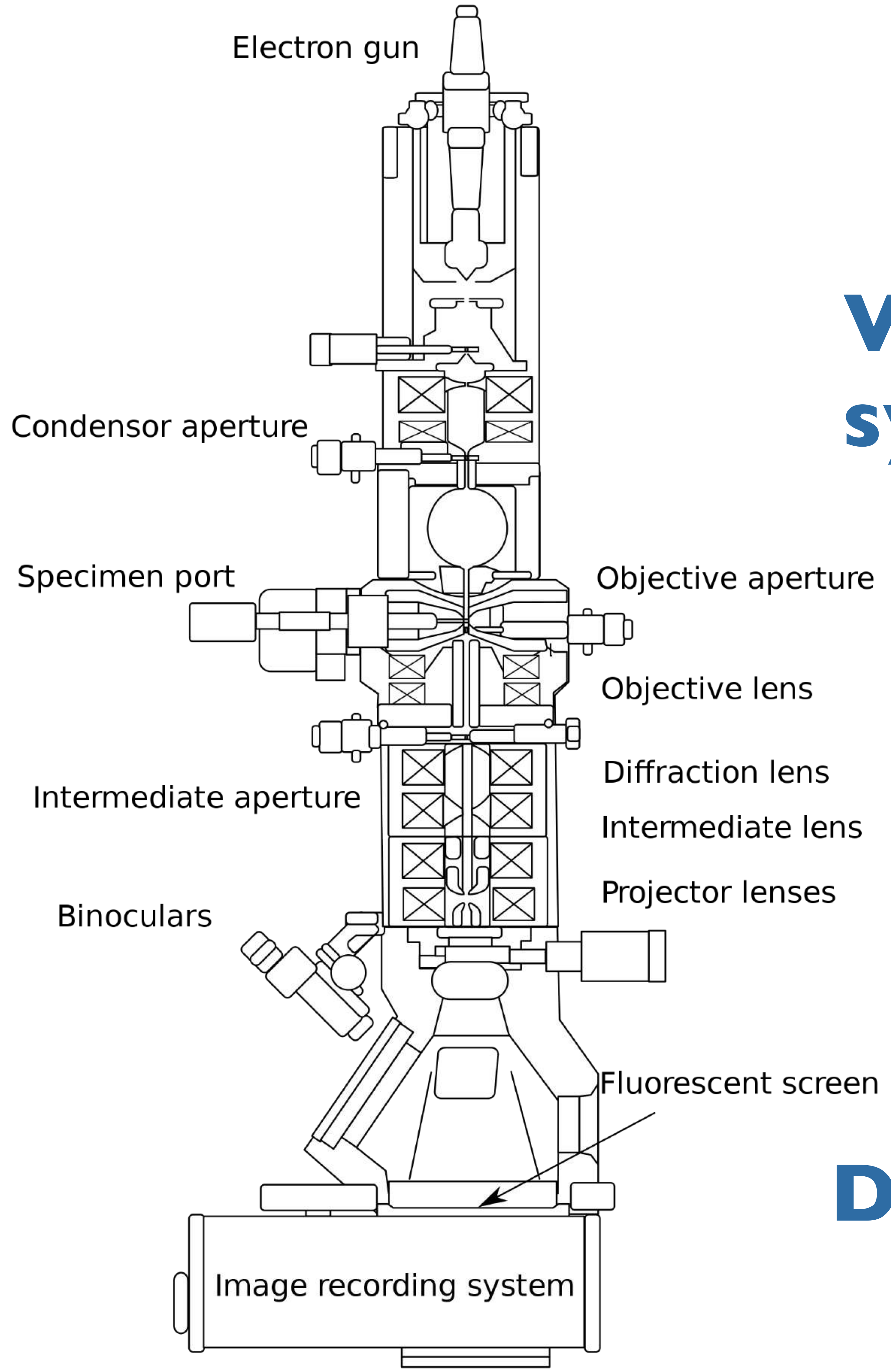
Vacuum systems

Lenses

Detectors

The electron microscope

e- gun	produces e-
accelerator	accelerate e- to high engergy
condenser	control illumination on sample
objective	sample and main imaging lens
Intermediate projection	controls mag and image/ diffraction mode
Flu-screen	Flu-screen image via camera
TEM camera	TEM detector



Electron sources

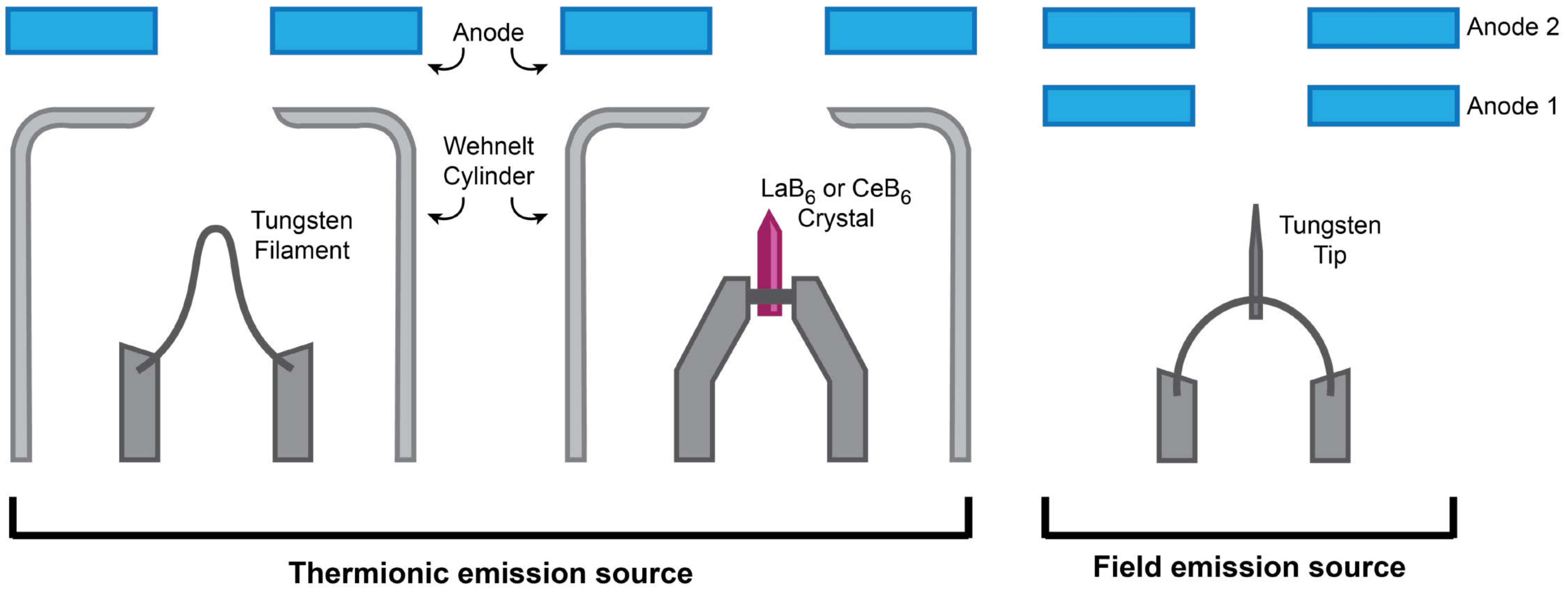
Vacuum systems

Lenses

Detectors

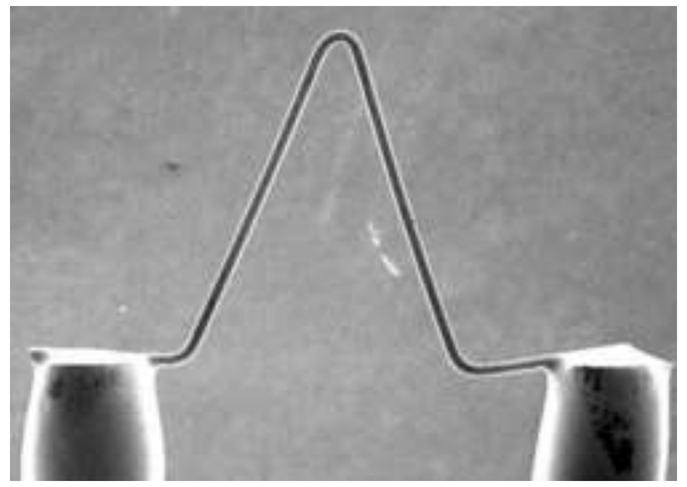
Electron sources

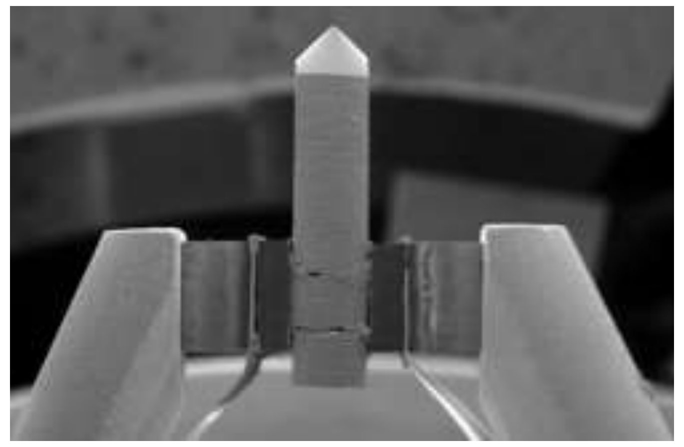
What are the 3 main kinds of electron sources?

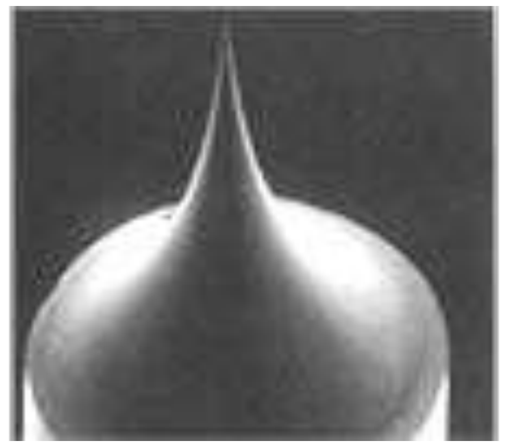


thermofisher.com

nanoscience.com

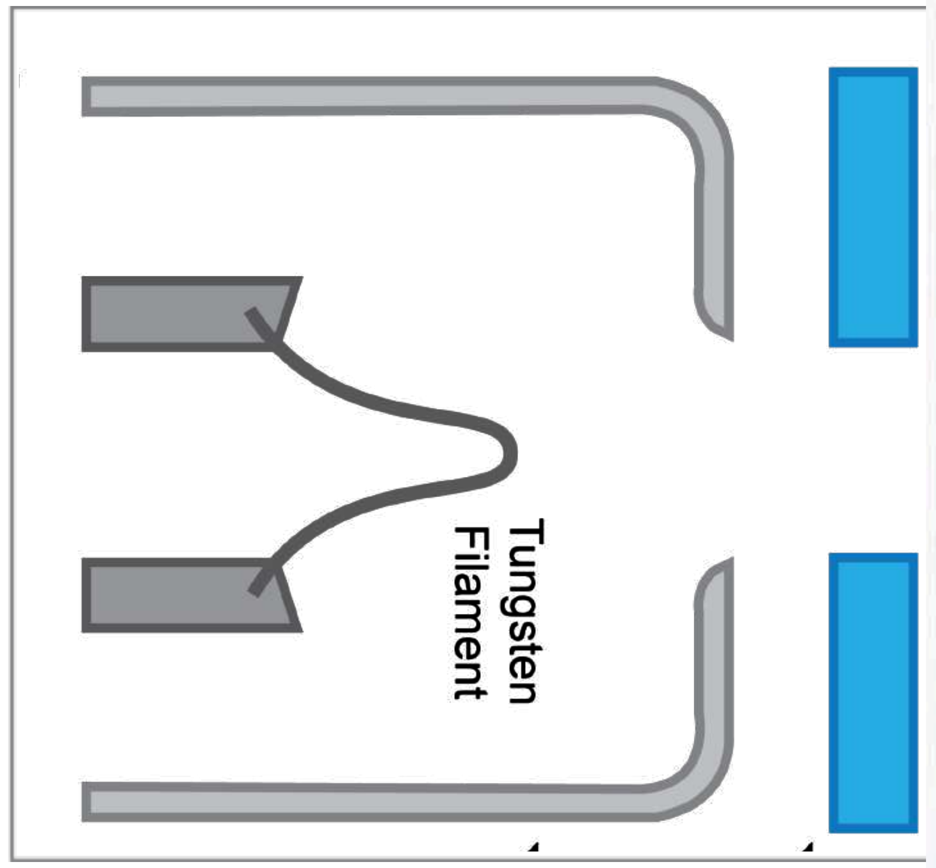


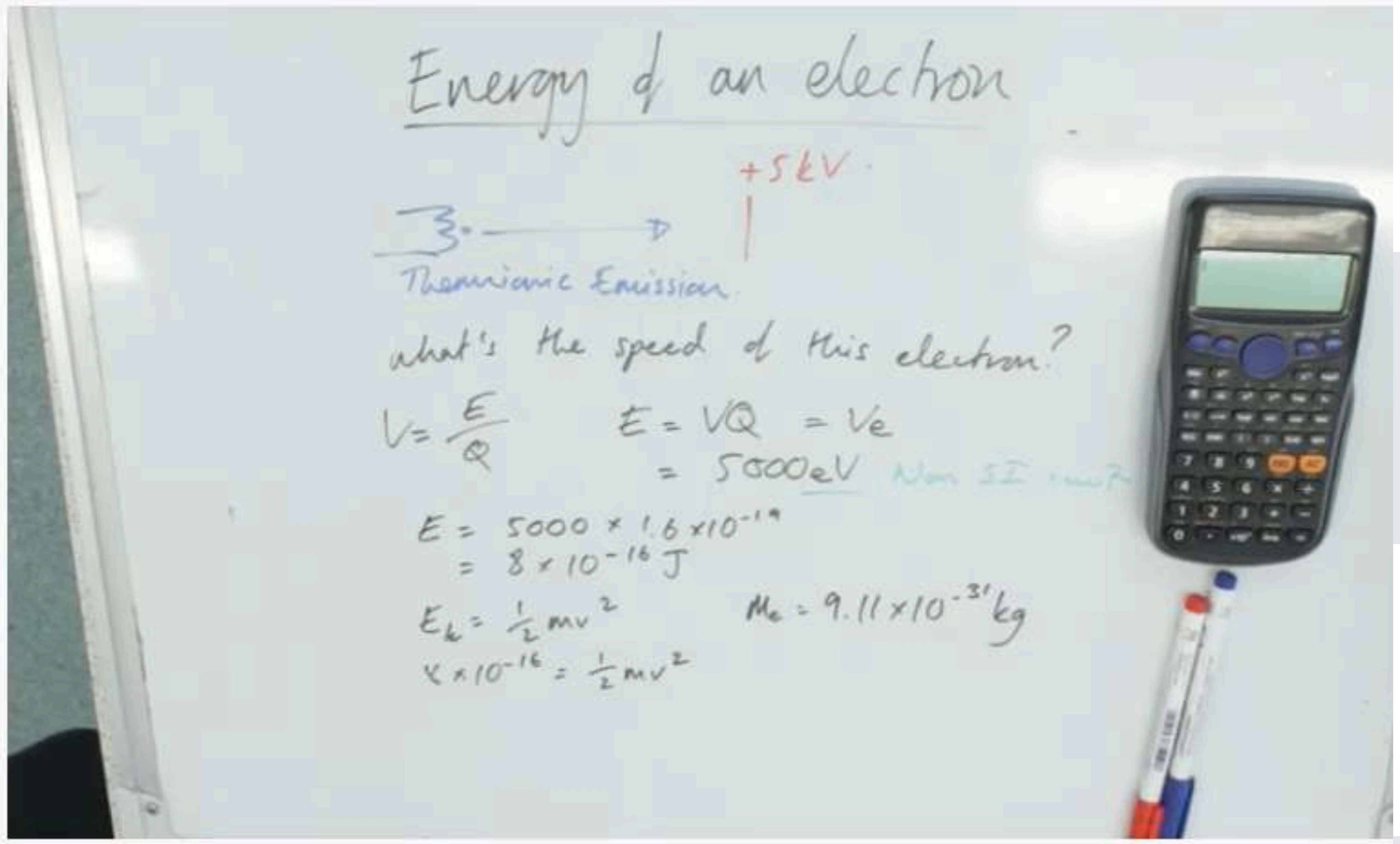




Electron sources

How fast are the electrons movi

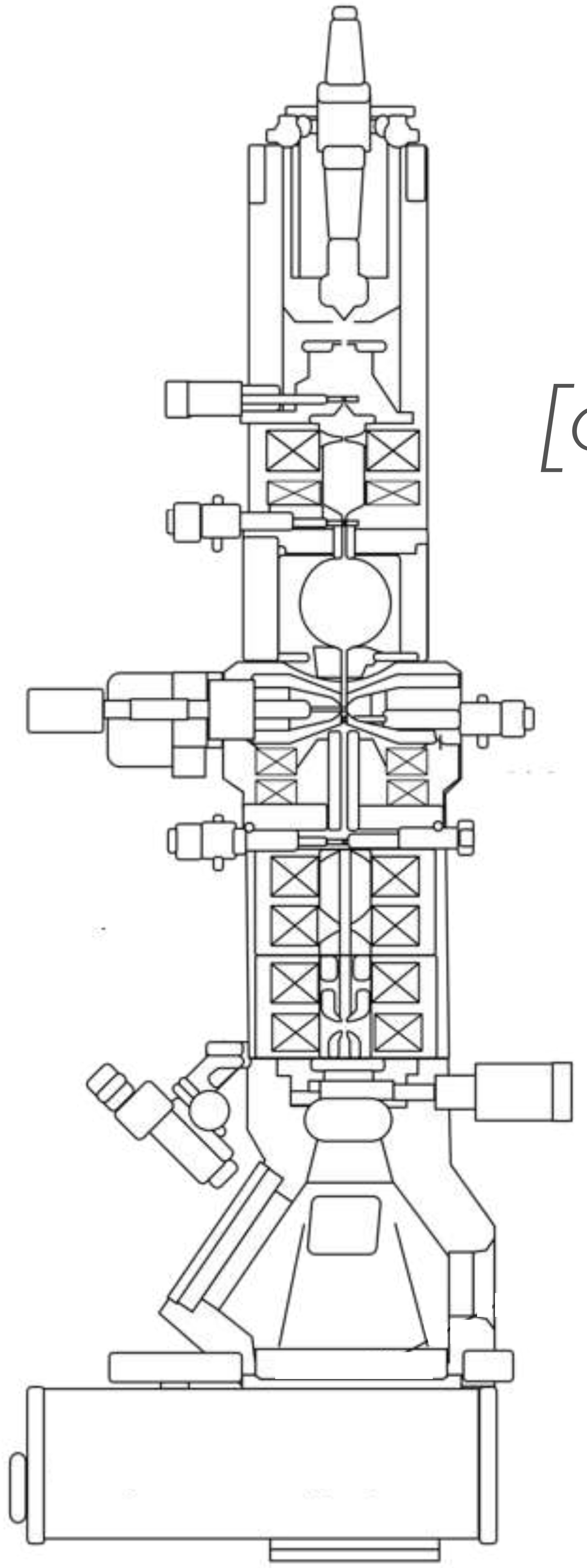




Light microscope	Transmission electron microscope
Visible light	Electrons
Glass lenses	Electron-magnetic lenses
450-650 nm	3.70 pm (100 keV) 2.51 pm (200 keV) 1.96 pm (300 keV.)
speed of light in vacuum c	0.548c (100 keV) 0.695c (200 keV) 0.776c (300 keV.)

https://www.youtube.com/watch?v=tYCET6vYdYk

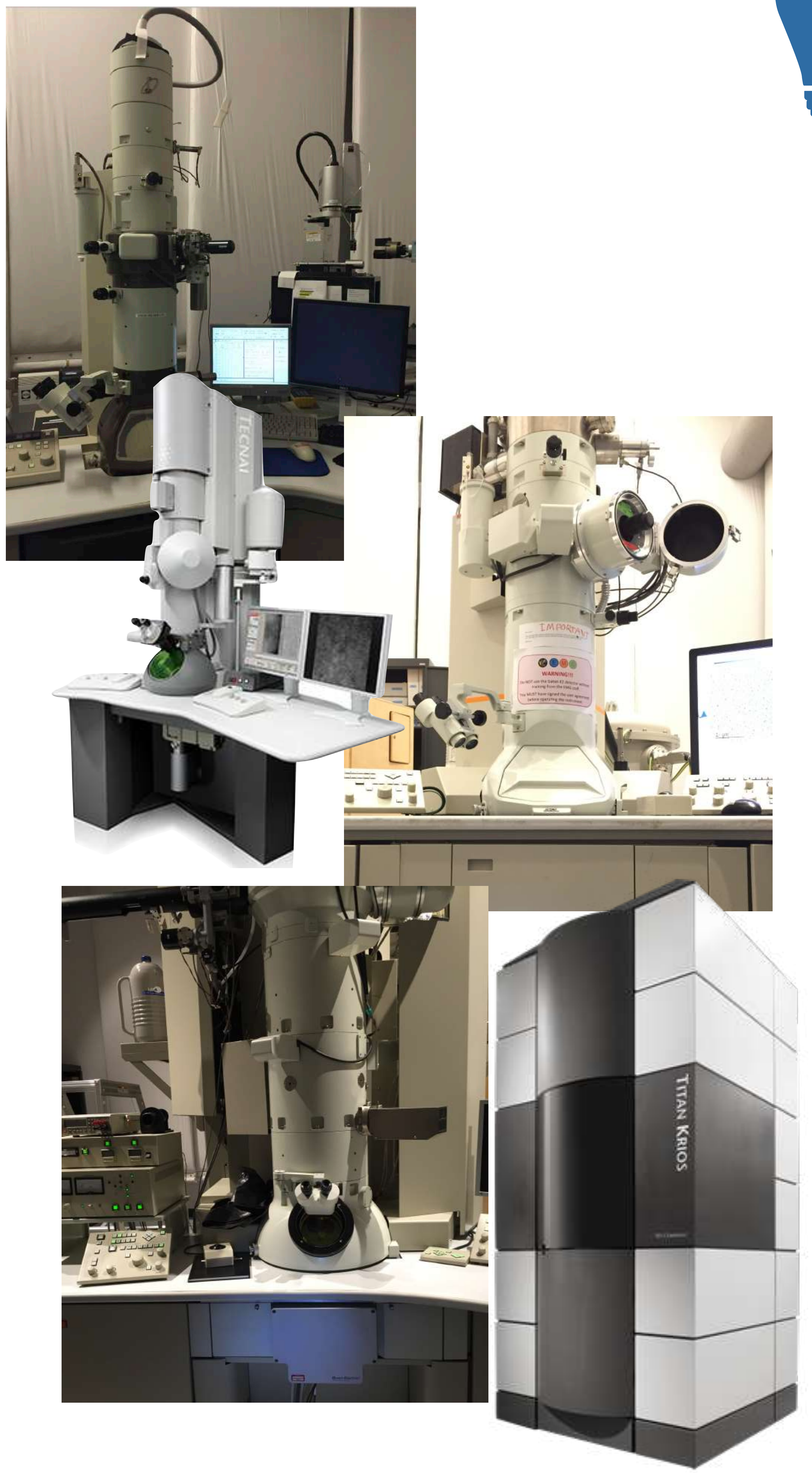
Electron sources



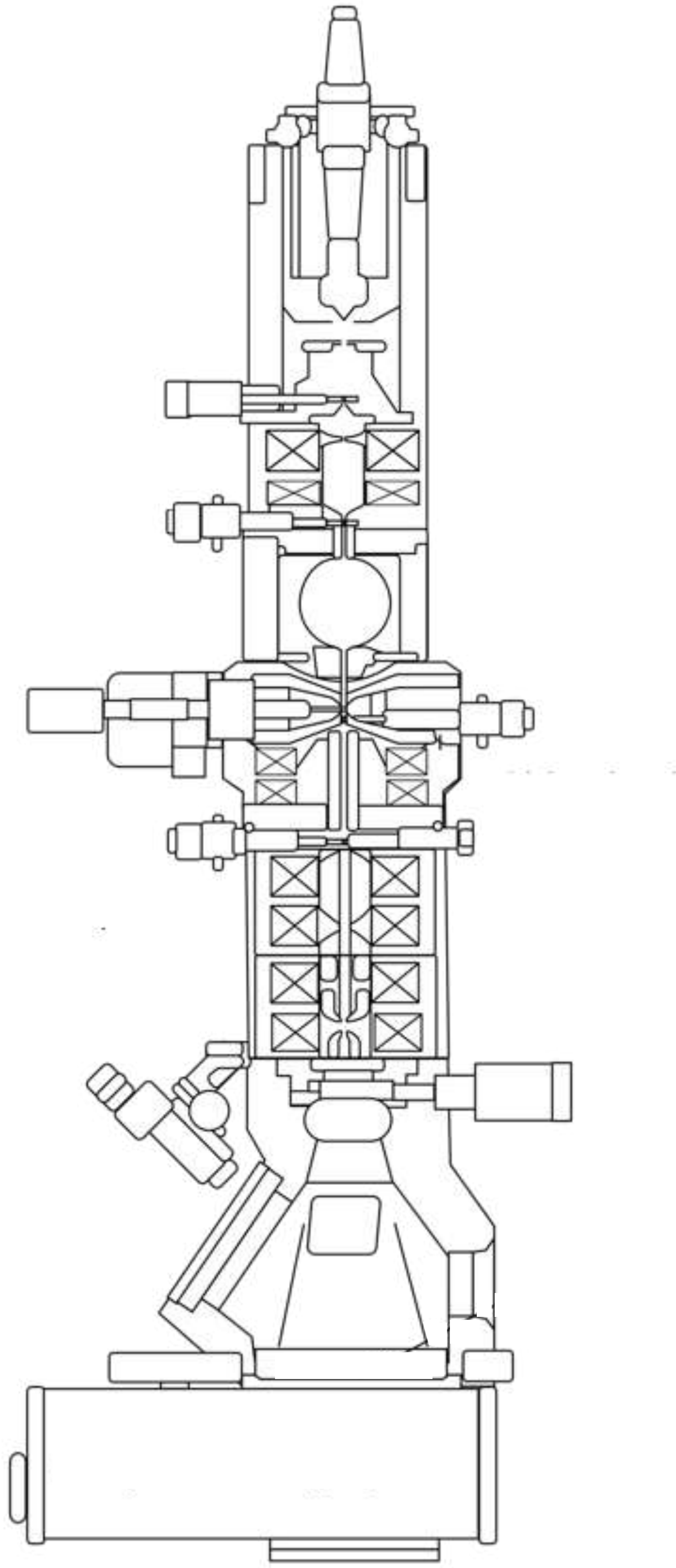
80-120 kV: Hitachi 7800, JEOL1400, TFS Talos120
W or LaB6
High contrast & robust
sub-nm resolution
[developments ongoing to push resolution with FEG systems]

200 kV: J2100F; TFS Tecnai, Glacios, Arctica
FEG
2+ Å resolution (3.5-4 Å)

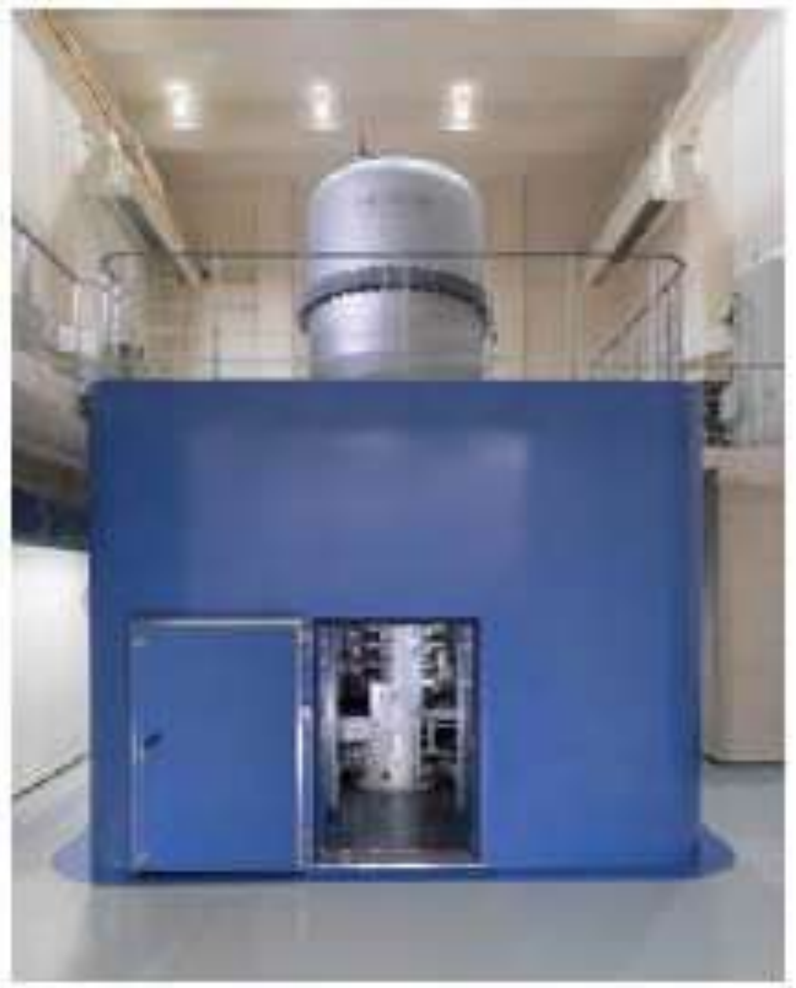
300 kV: JEOL3200FSC, cryoARM; TFS Krios, Halo
FEG
Smaller effect on unwanted lens aberrations
1.5-3 Å resolution

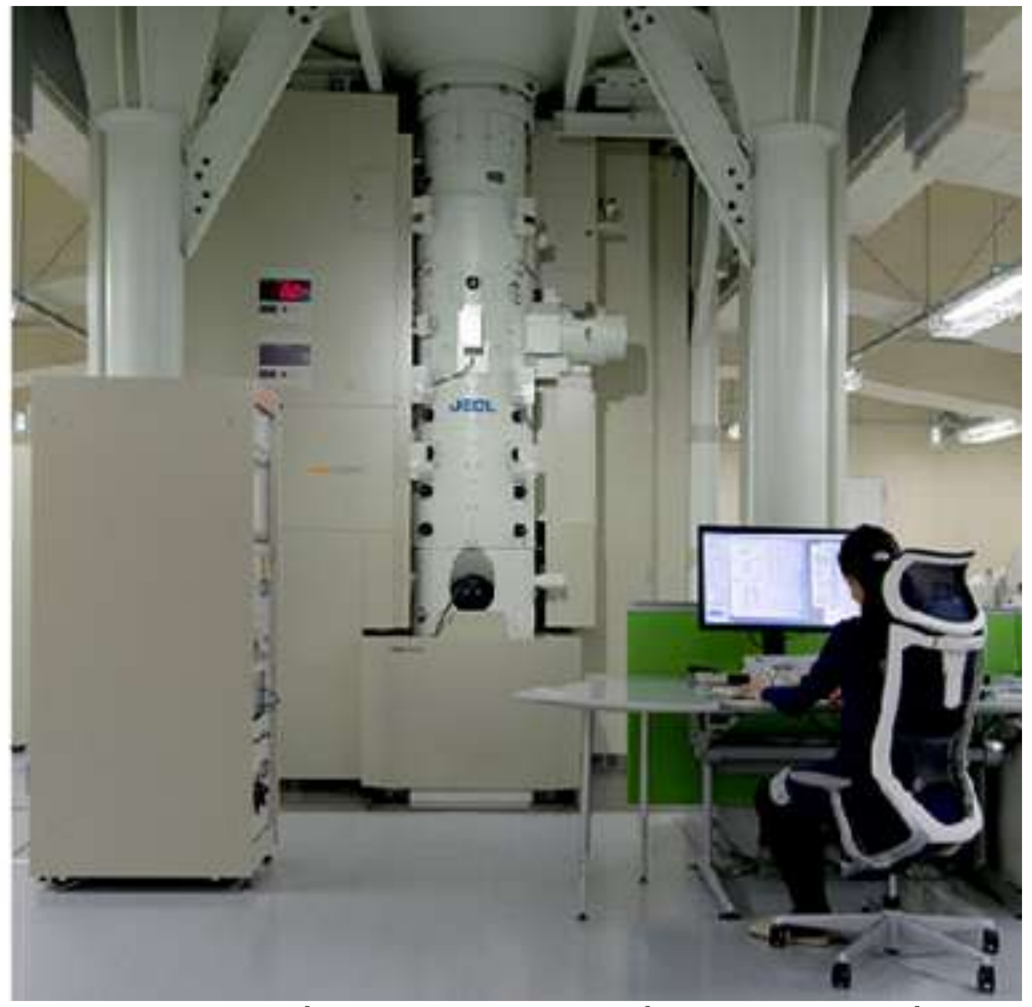


Electron sources



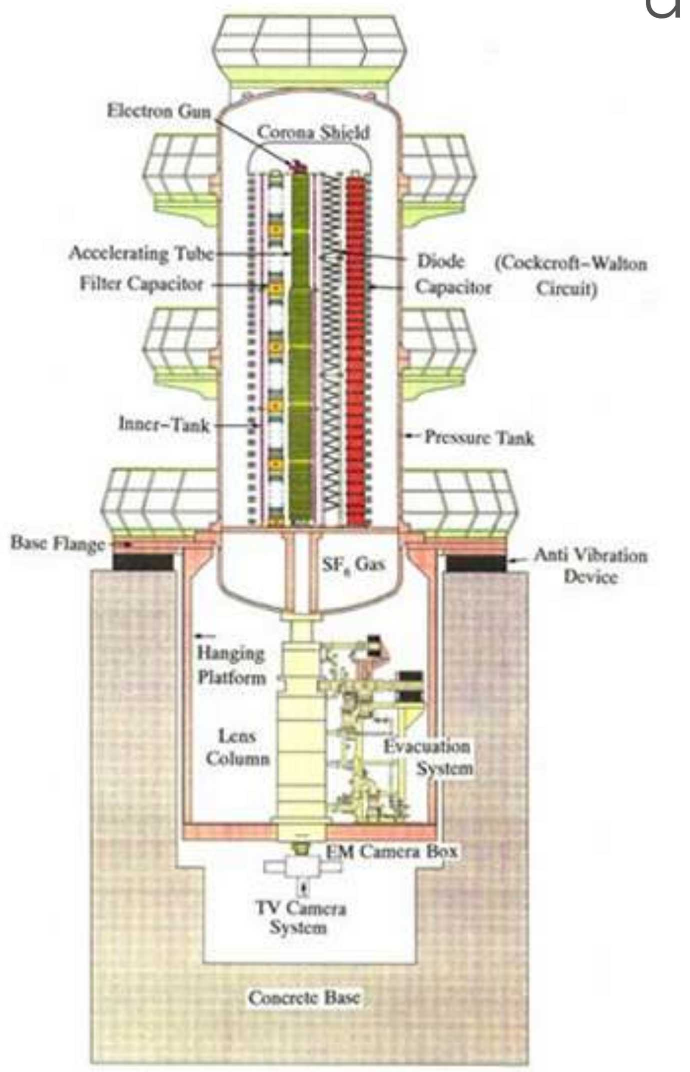
1-1.2 MV: Hitachi, JEOL
LaB6



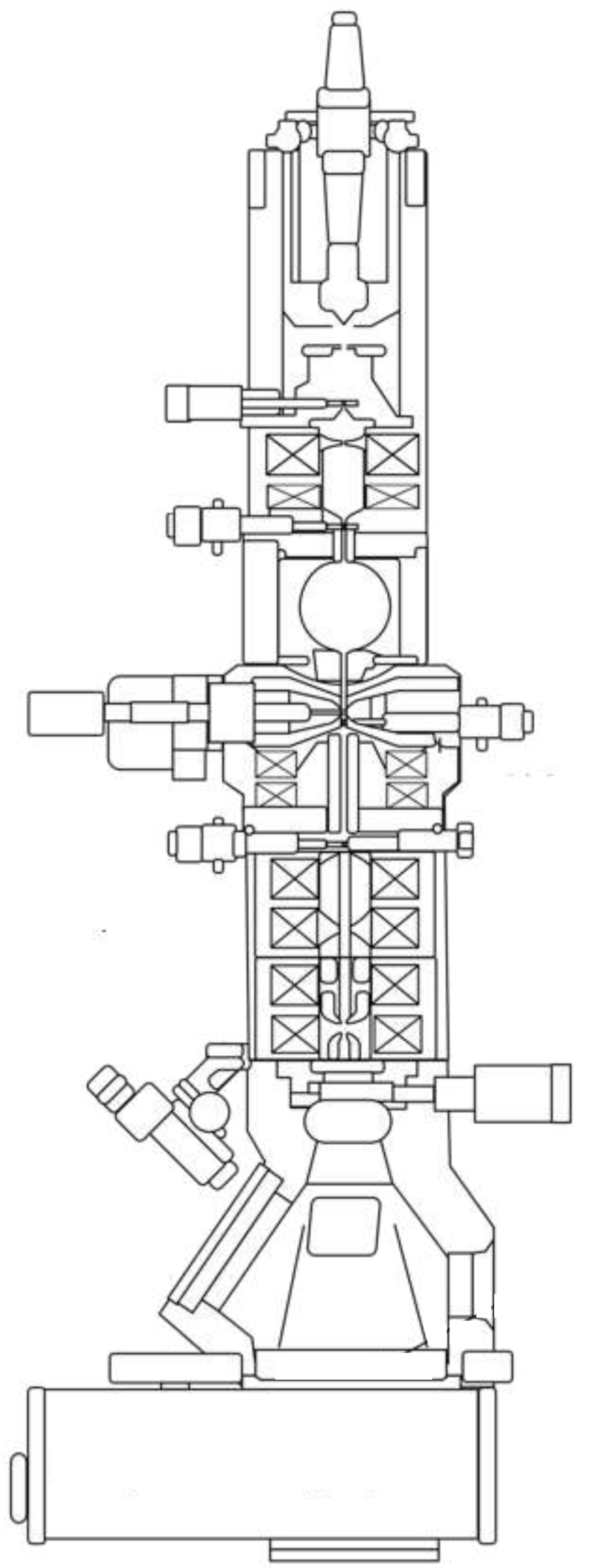


uhvem.osaka-u.ac.jp

3 MV: Hitachi H3000
LaB6



Vacuum systems



Why do we need a vacuum?

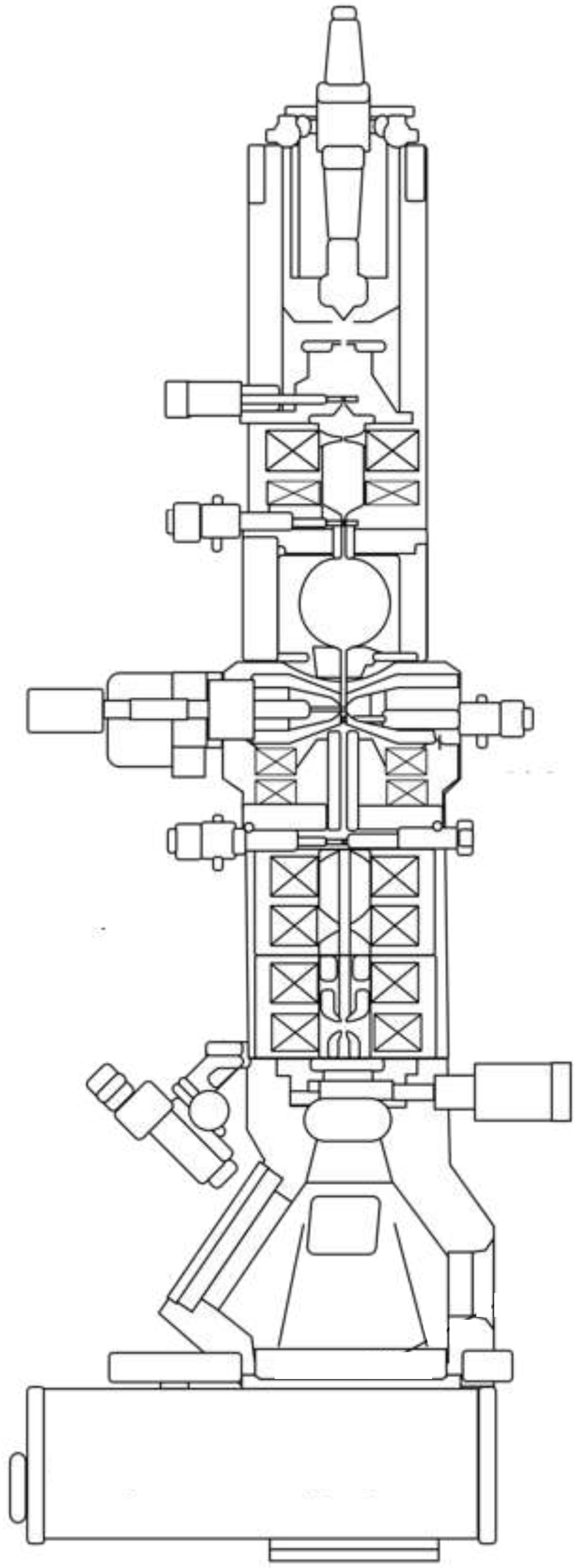
Beam coherence - at STP mean free path ~1 cm

Insulation - interaction between e- and air

Filament - O_2 will burn out source

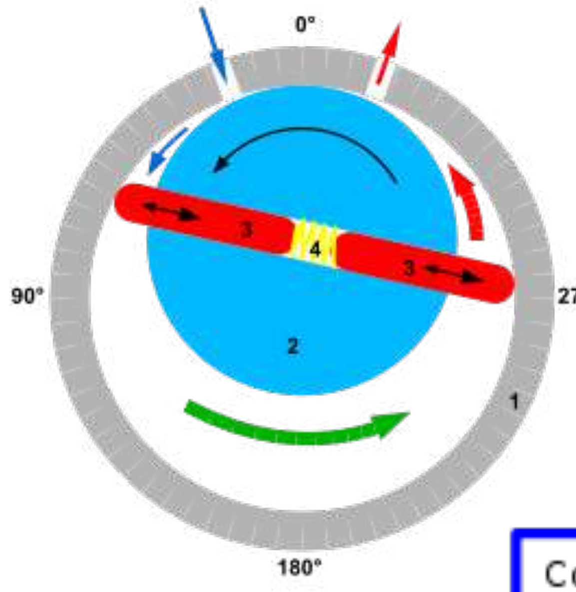
Contamination - reduce interaction gas, e-beam and sample

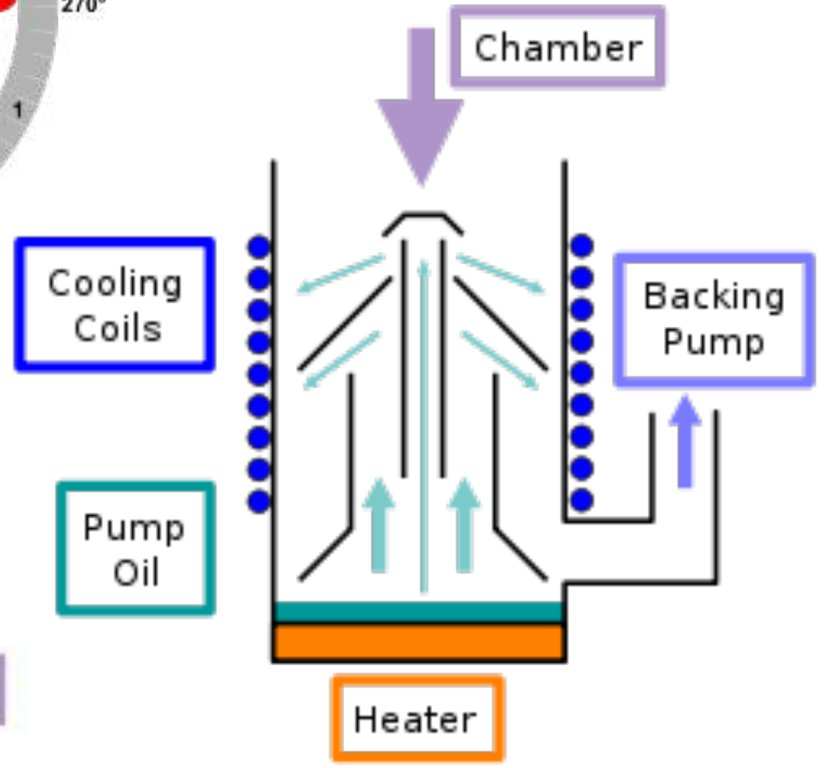
Vacuum systems

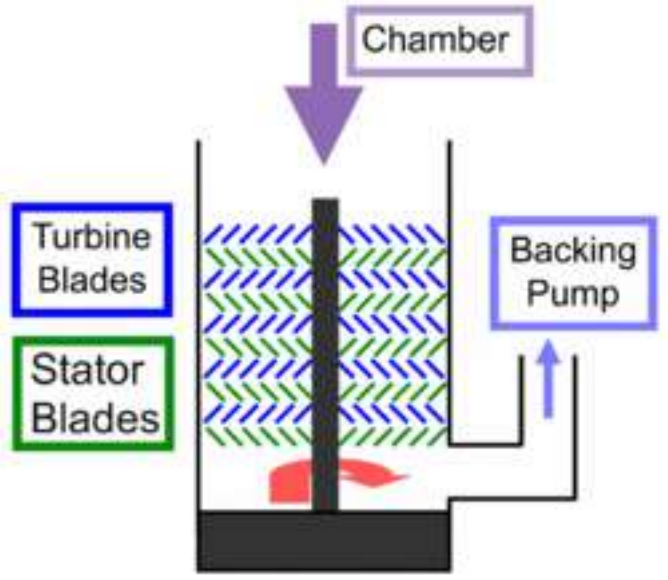


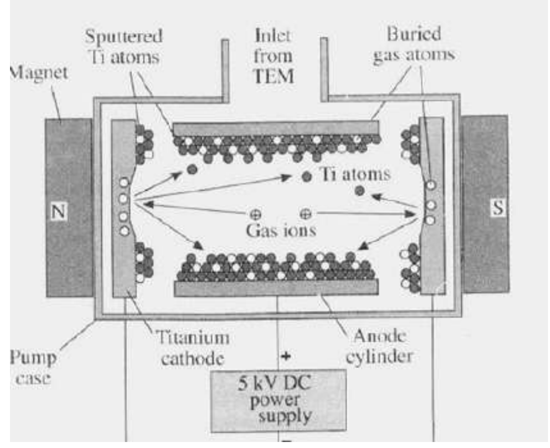
What types of pumps do we have?

1 mm Hg = 1 Torr = 10^2 Pa
1 atm = 760 Torr = 7.5×10^4 Pa









wikipedia.com

PVP / Rotary	$1\text{-}10^{-3}$ Torr	>0.1 Pa
Diffusion	$10^{-3}\text{-}10^{-6}$ Torr	$0.1\text{-}10^{-4}$ Pa
Turbo	$10^{-6}\text{-}10^{-9}$ Torr	$10^{-4}\text{–}10^{-7}$ Pa
IGP	$10^{-9}\text{-}10^{-12}$ Torr	$10^{-7}\text{-}10^{-9}$ Pa

Vacuum systems

1 mm Hg = 1 Torr = 10^2 Pa
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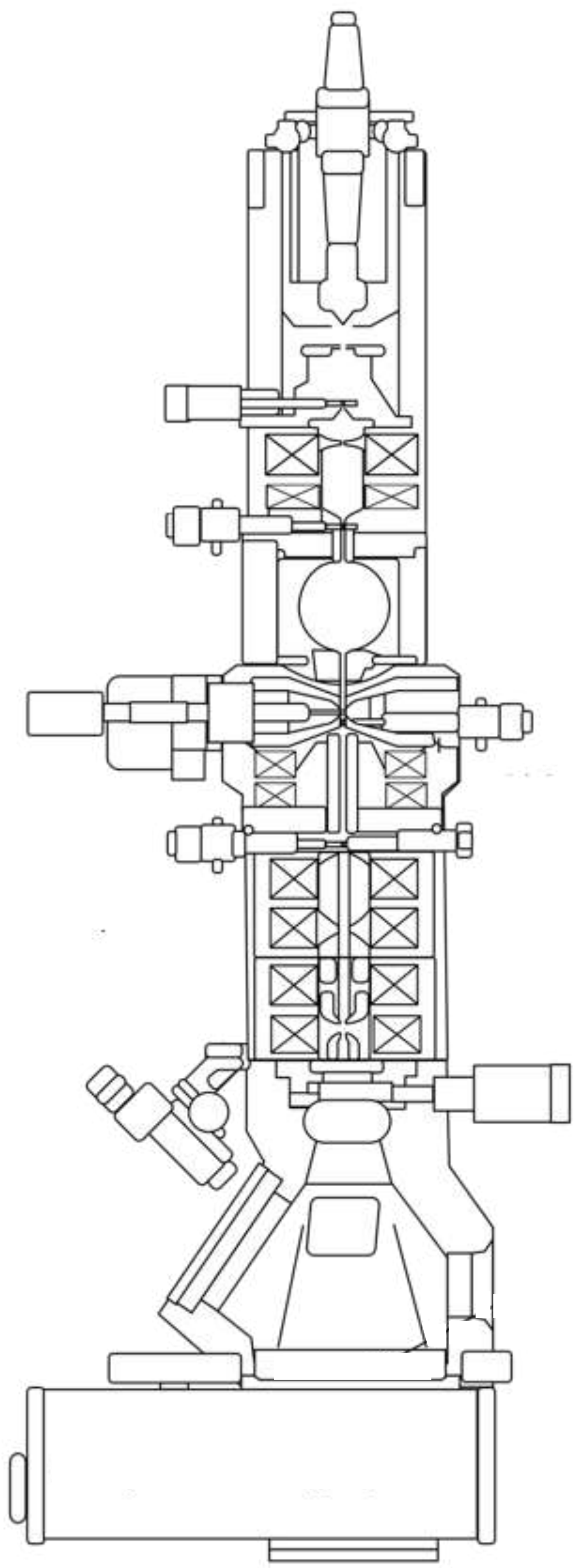
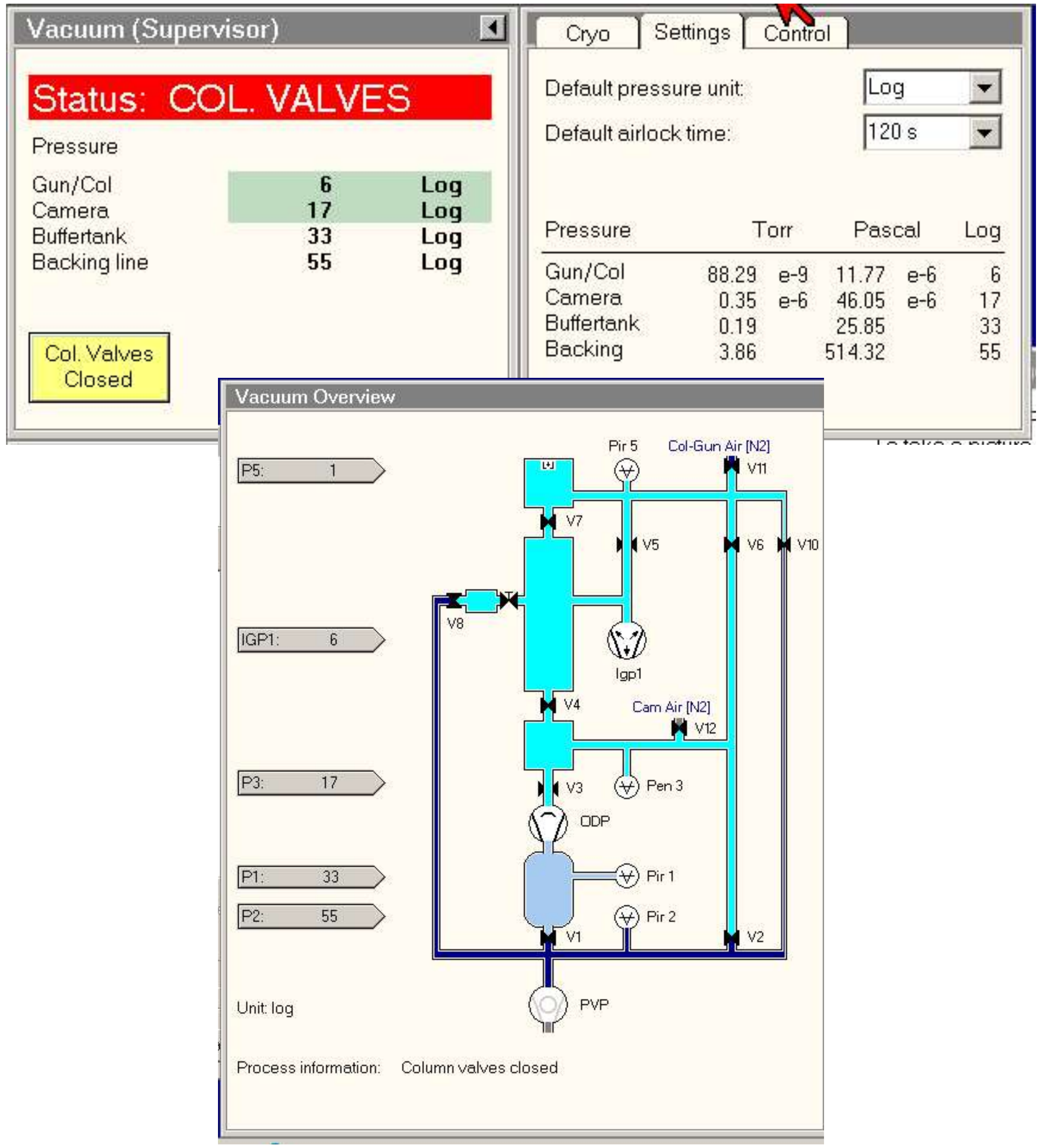
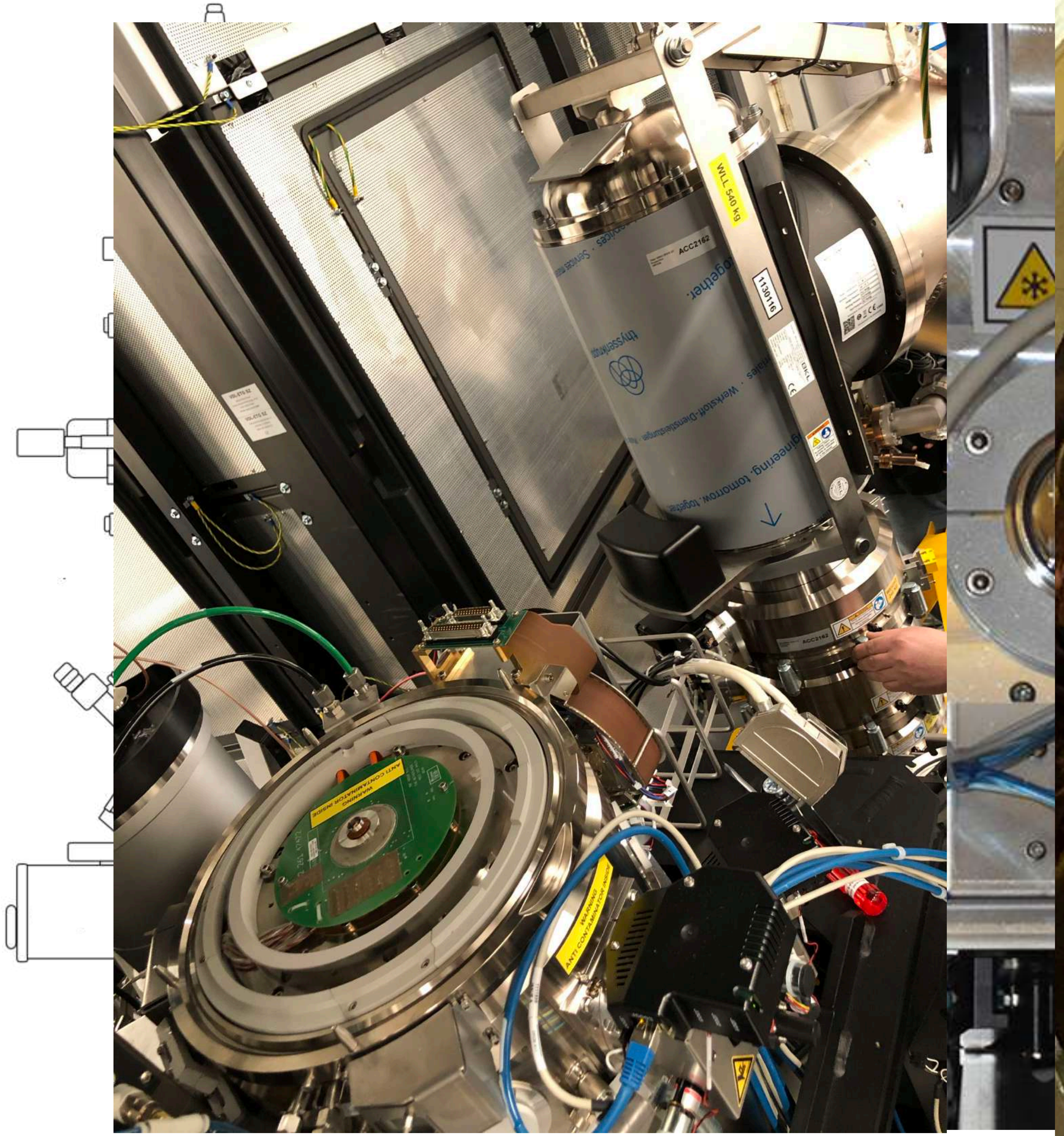


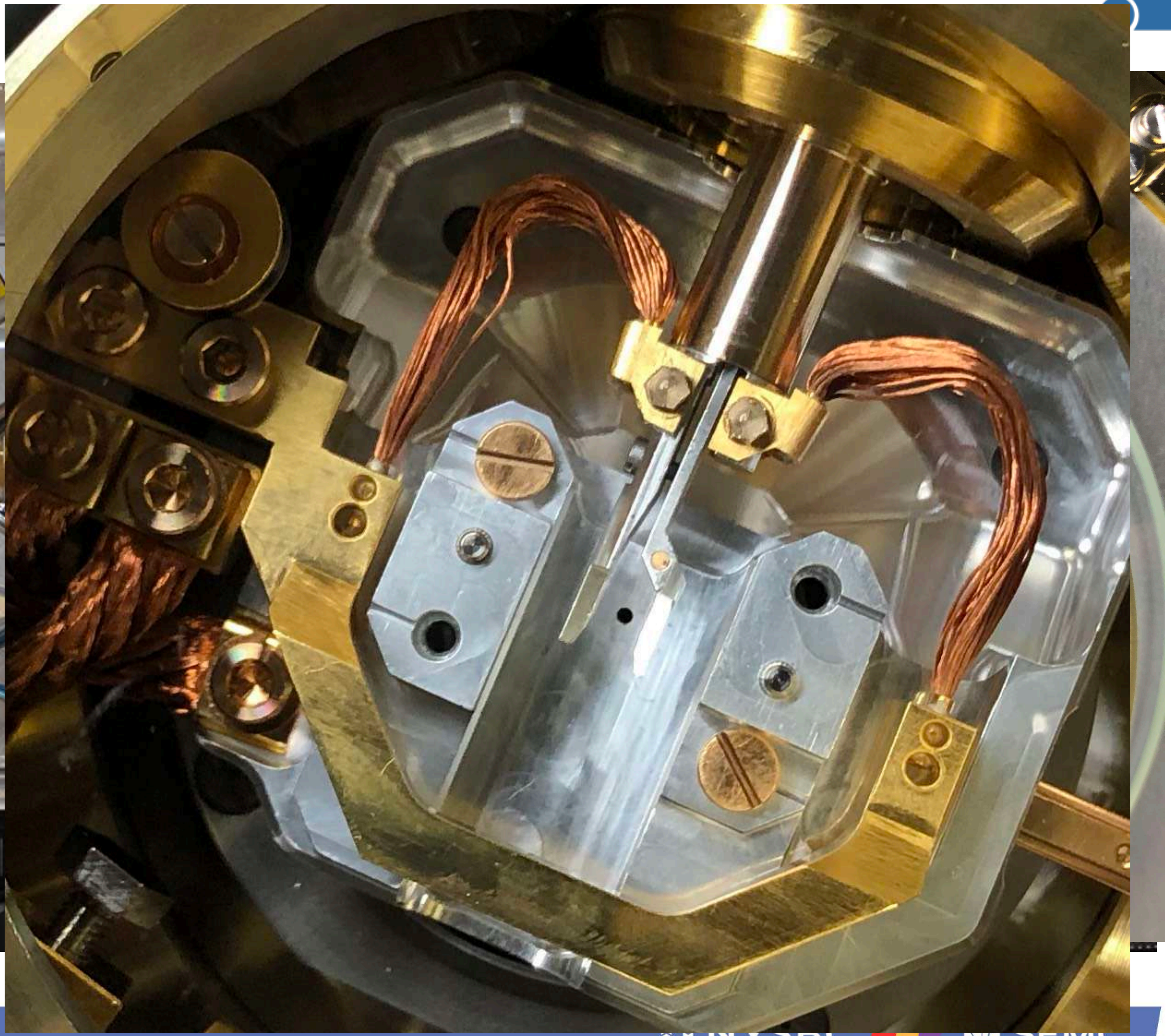
What types of pumps do we have?

Gun	10^{-9} Torr
Specimen	10^{-6} - 10^{-7} Torr
Chamber and Camera	10^{-5} - 10^{-6} Torr

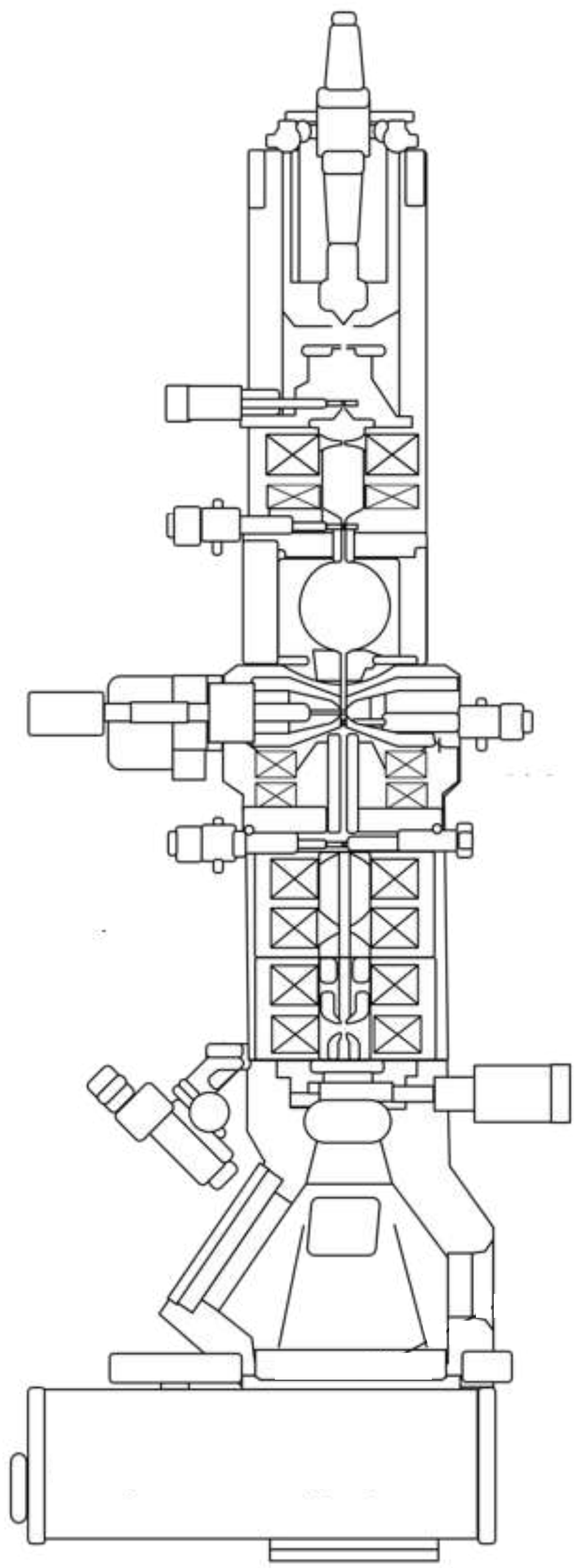


Vacuum systems

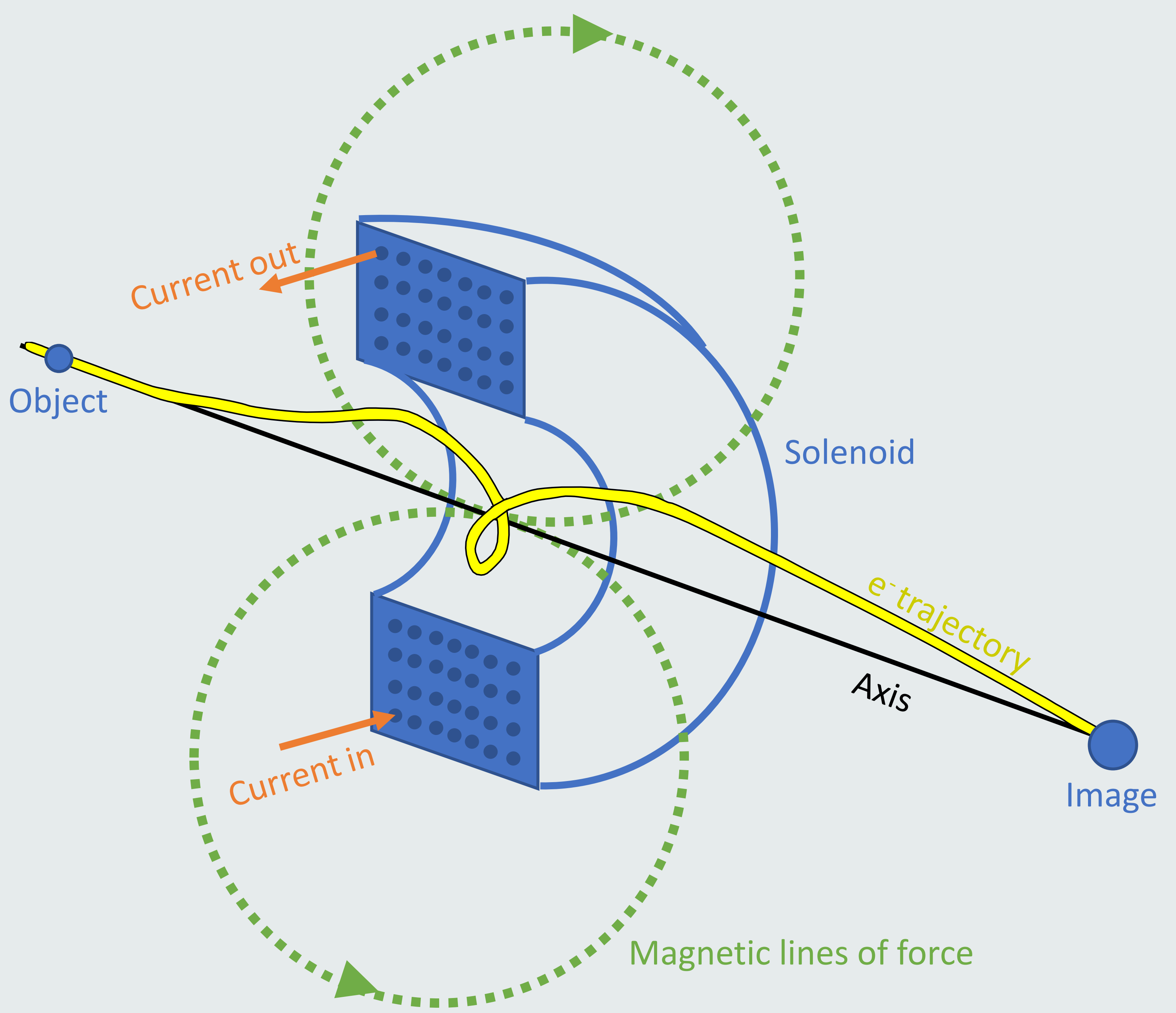




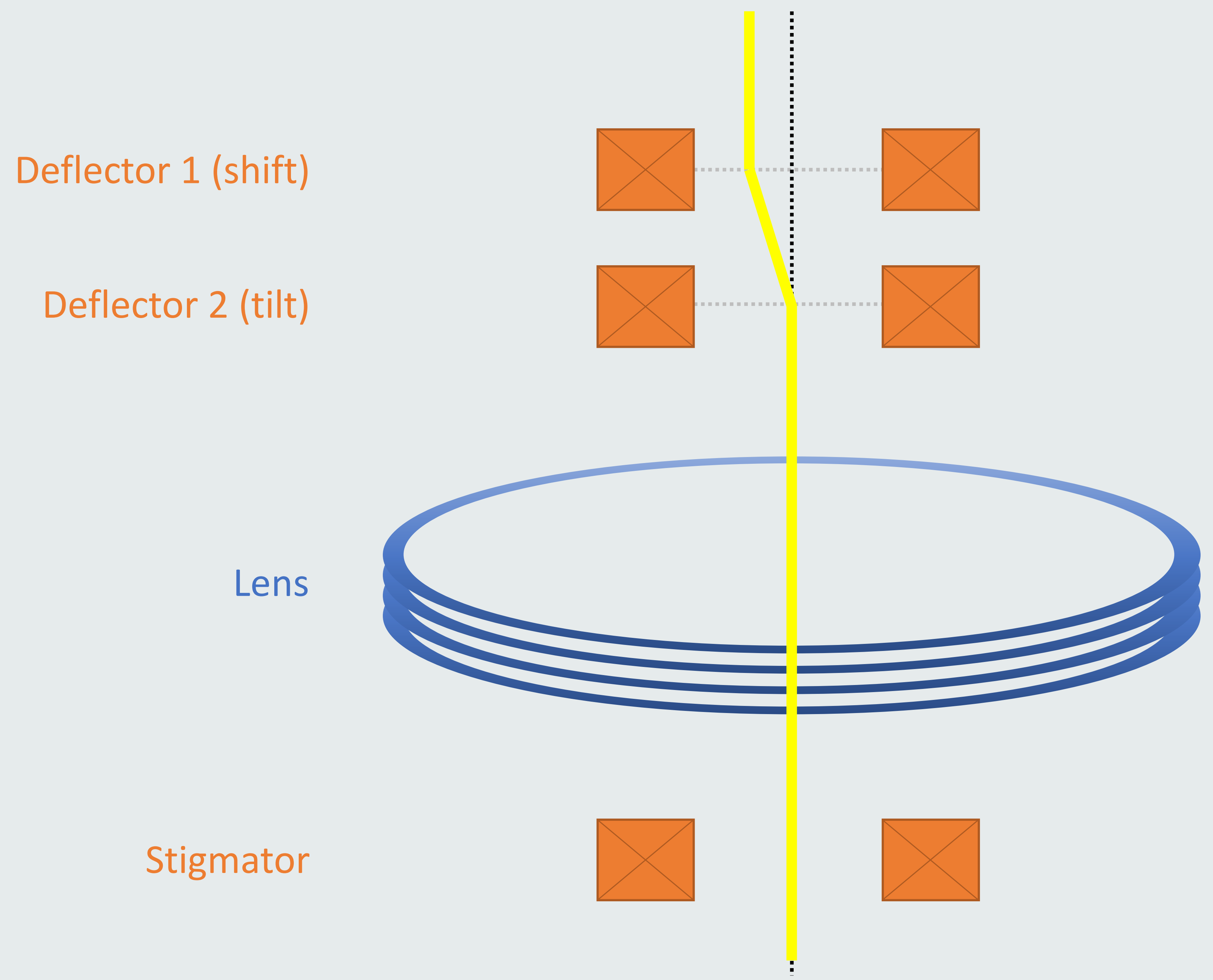
Lenses



What types of lenses do we have?

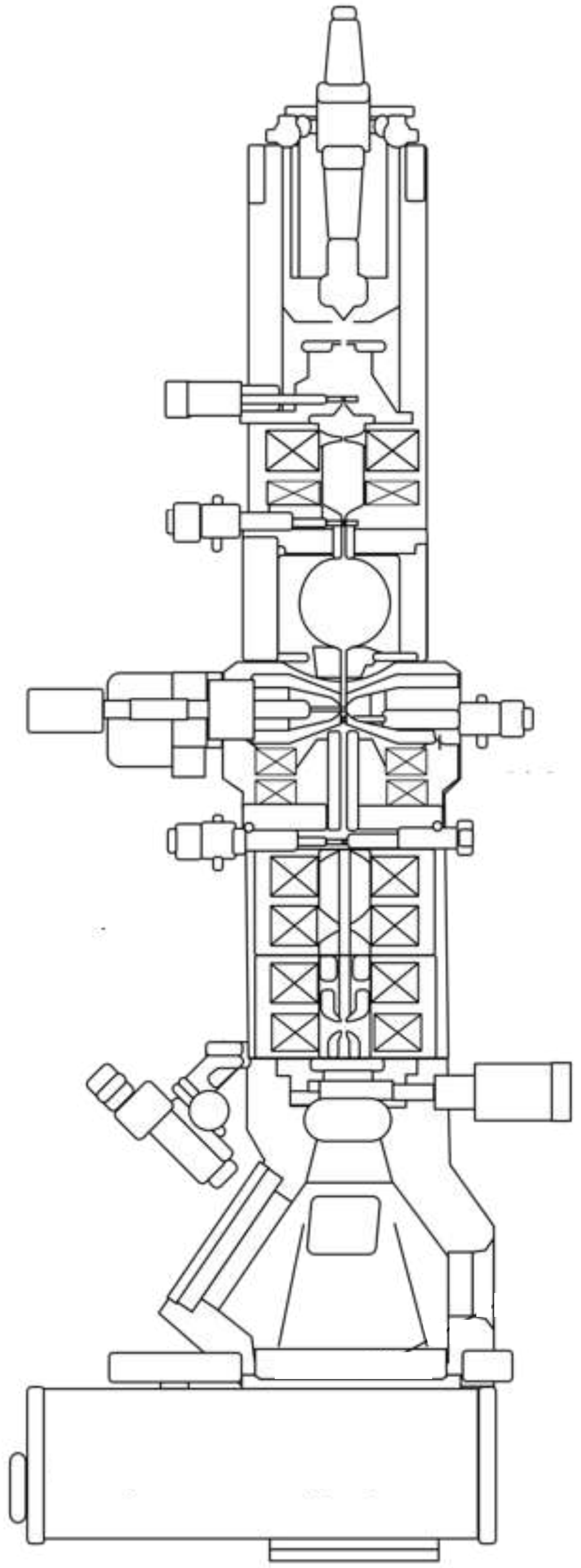


- Focus
- Magnify
- Rotate

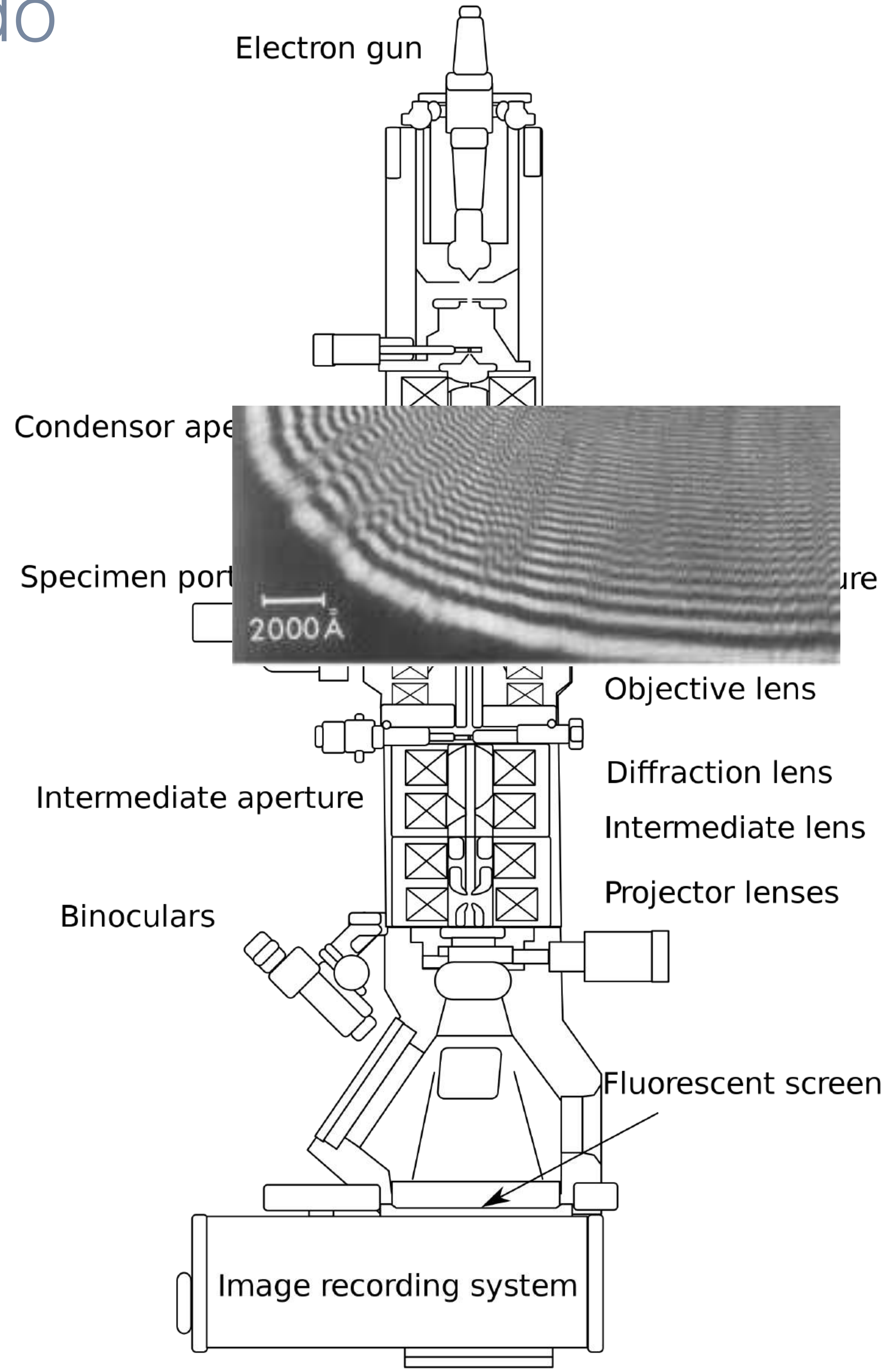


Lenses

Microscope Alignments
What to do & what not to do



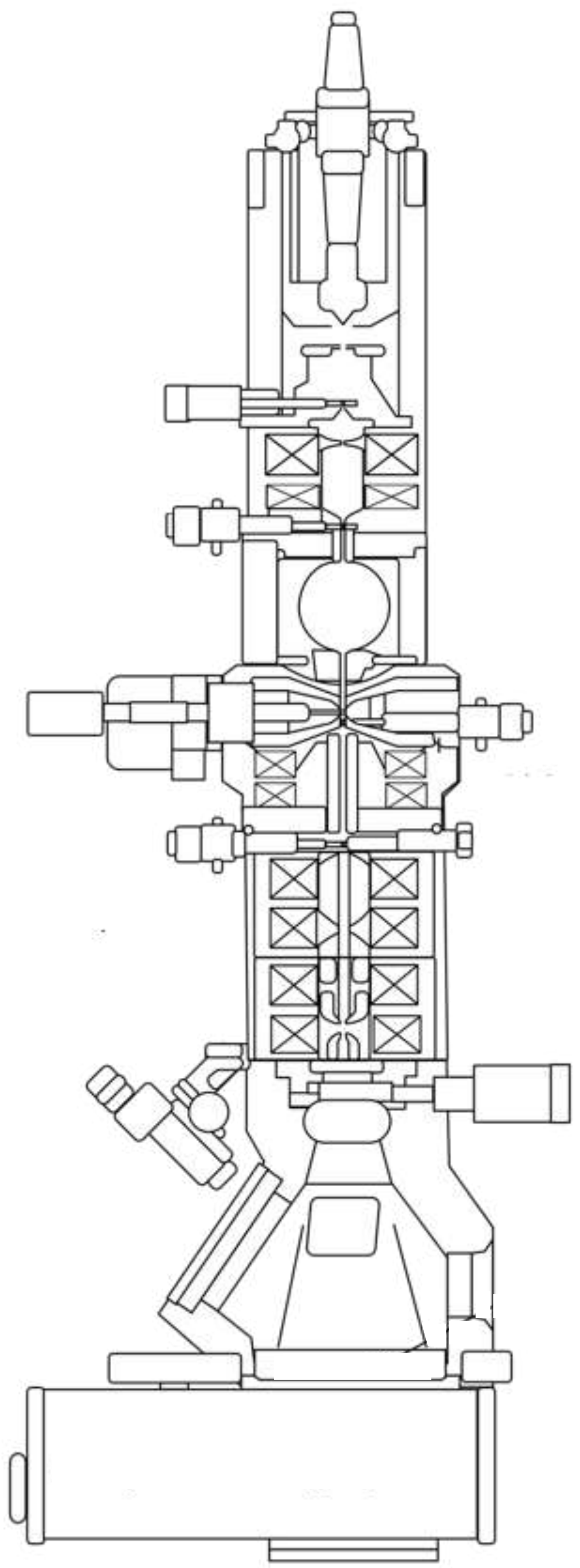
- Do:
  - Start at eucentric height and focus
  - Check if it is already good before attempt
  - Align from top to bottom
- Not to do:
  - ~~Align without a way to undo~~
  - ~~Align when TEM is not stable (i.e., temperature)~~

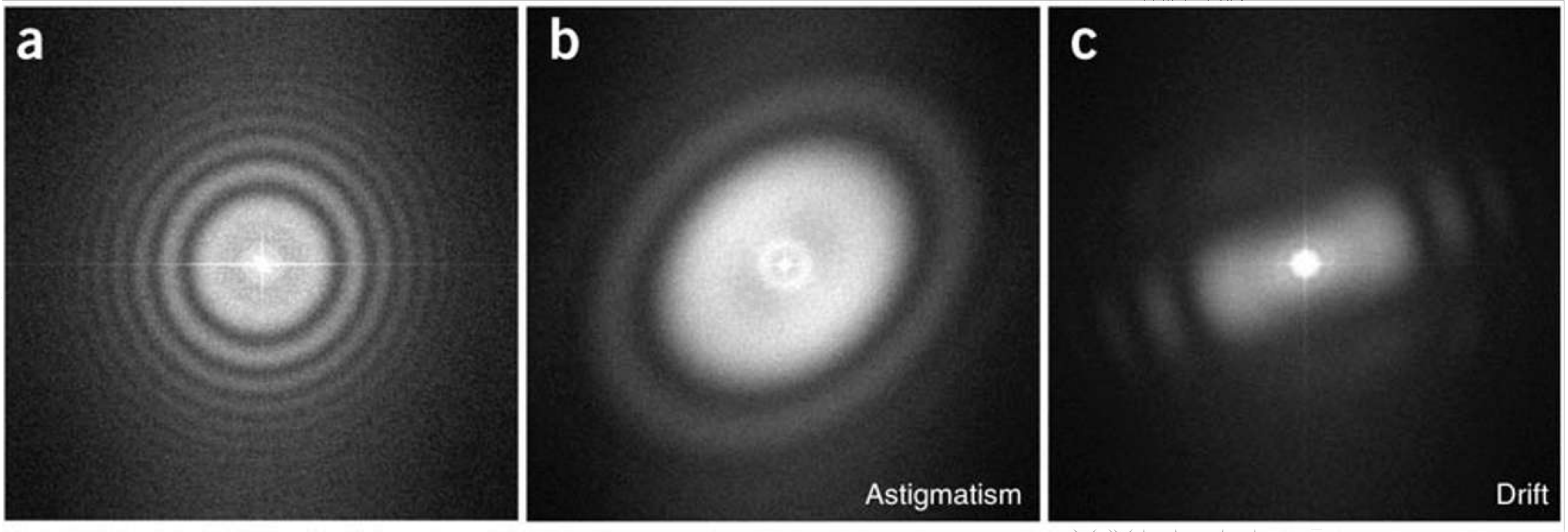


Lenses

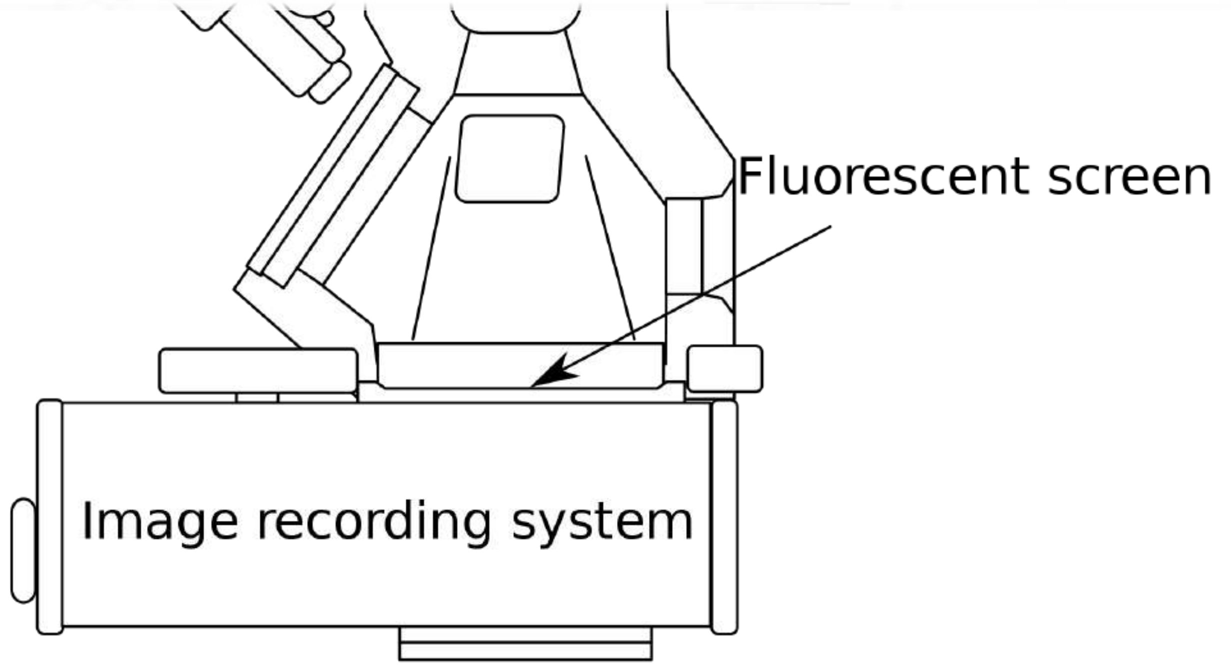
Microscope Alignments
What to do & what not to do

- Do:

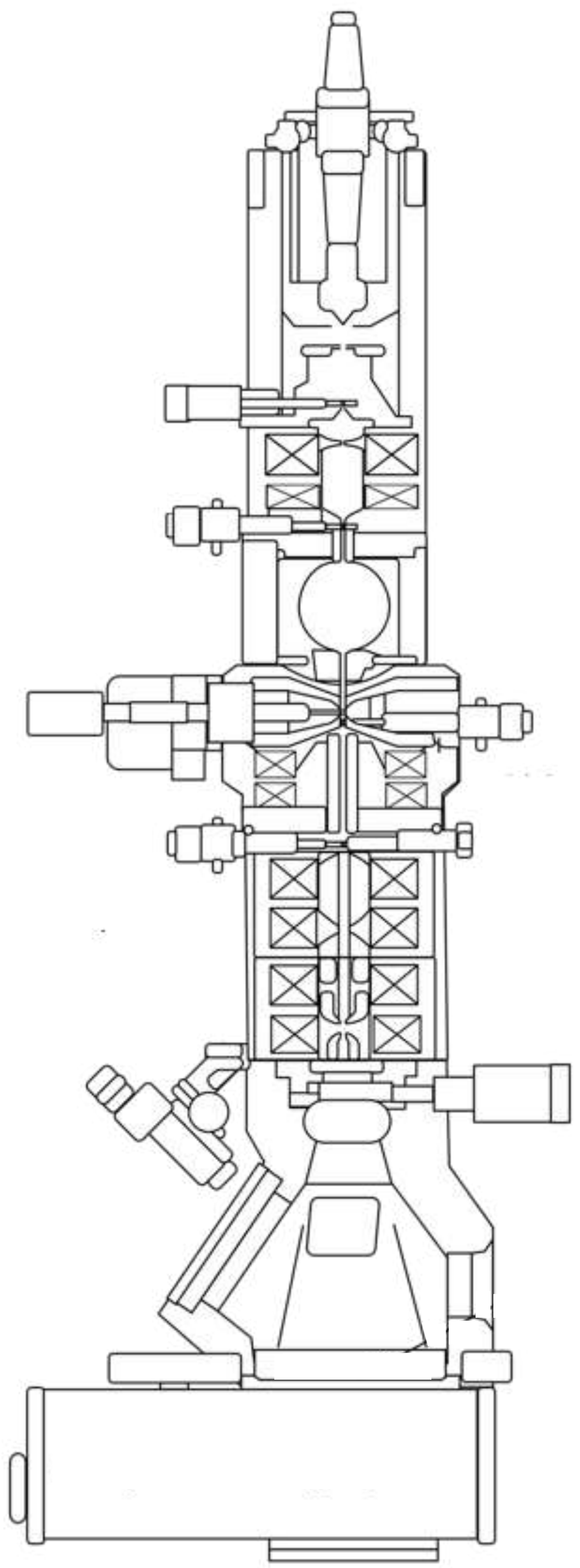




- ~~Align without a way to undo~~
- ~~Align when TEM is not stable (i.e., temperature)~~



CTF



The **contrast transfer function** (**CTF**) mathematically describes how aberrations in a transmission electron microscope (TEM) modify the image of a sample

The phase shift (phase distortion function) due to the objective lens can be combined into a single phase factor χ, given by,

$$\chi(|g|) = \left(\frac{1}{2}\pi C_s \lambda^3 |g|^4 - \pi \Delta f \lambda |g|^2\right) \text{ -------------- [4236a.a]}$$

$$= \frac{2\pi}{\lambda}\left(\frac{1}{4}C_s \alpha^4 - \frac{1}{2}\Delta f \alpha^2\right) \text{ -------------- [4236a.b]}$$

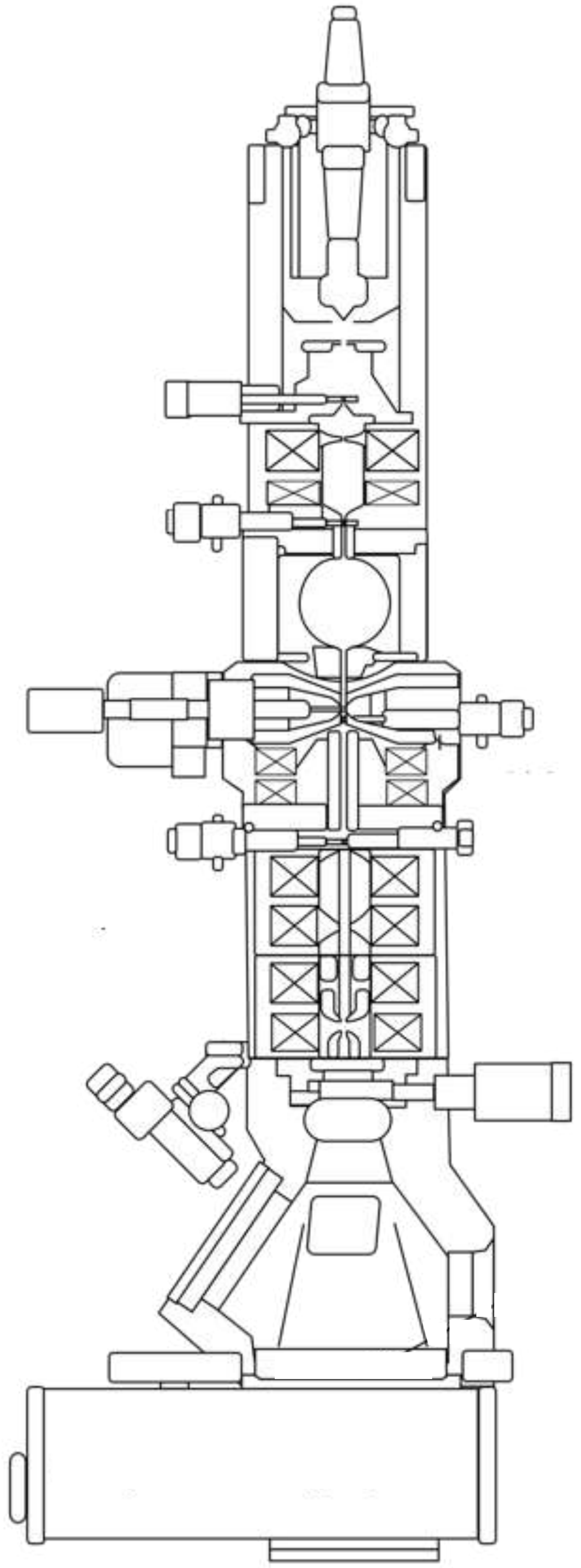
where,

C_s -- The spherical aberration coefficient, defining the quality of objective lens,
λ -- The wave-length,
Δf -- The defocus value,
|g| -- The spatial frequency,
α -- The convergence semi-angle.

https://www.globalsino.com/EM/page4236.html

Lenses

CTF



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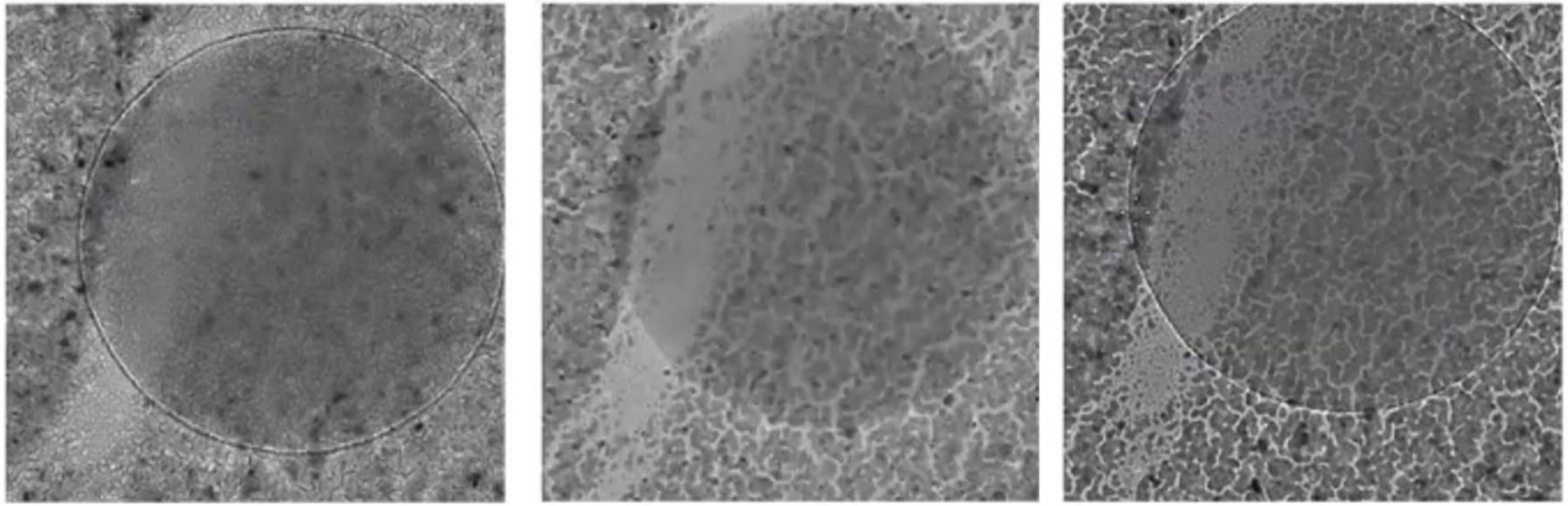


Lenses

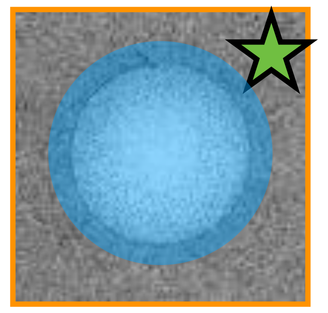
How to increase efficiency?

13.6MP

Cheng A, Eng ET, Alink L, Rice WJ, Jordan KD, Kim LY, Potter CS, Carragher B. High resolution single particle cryo-electron microscopy using beam-image shift. J Struct Biol. 2018;

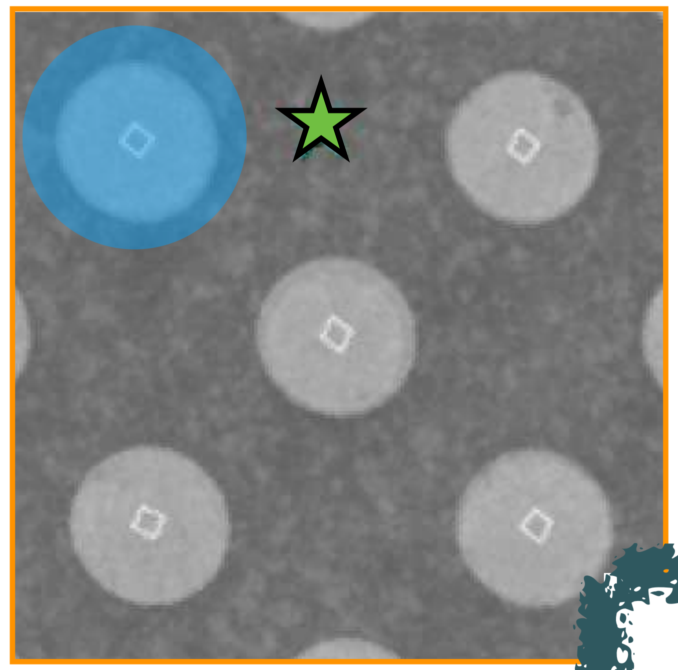
Anchi Cheng

1 target/setup
80 s/image
~1000 images/day



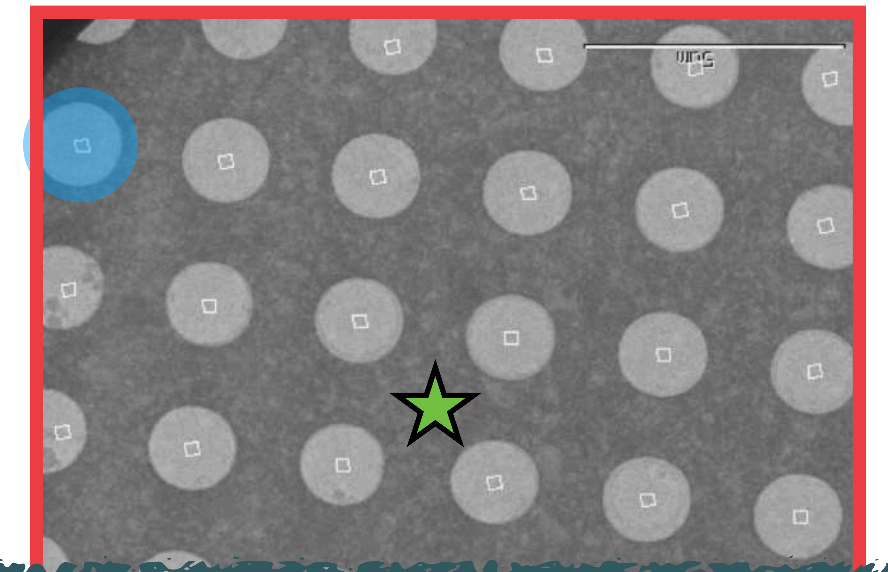
beam tilt
0 mrad

5 targets/setup
35 s/image
~2500 images/day

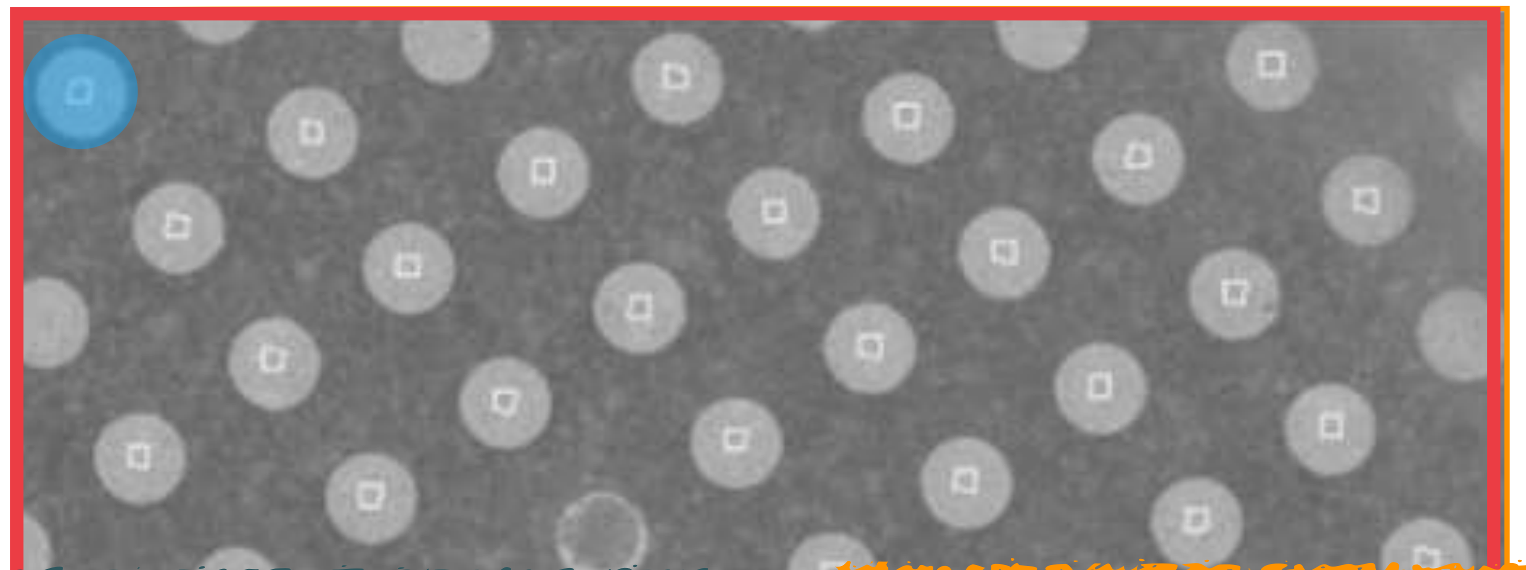


beam tilt
0.5 mrad

30 targets/setup
22 s/image
~3800 images/day



70 targets/setup
18 s / image
~ 4800 images/day

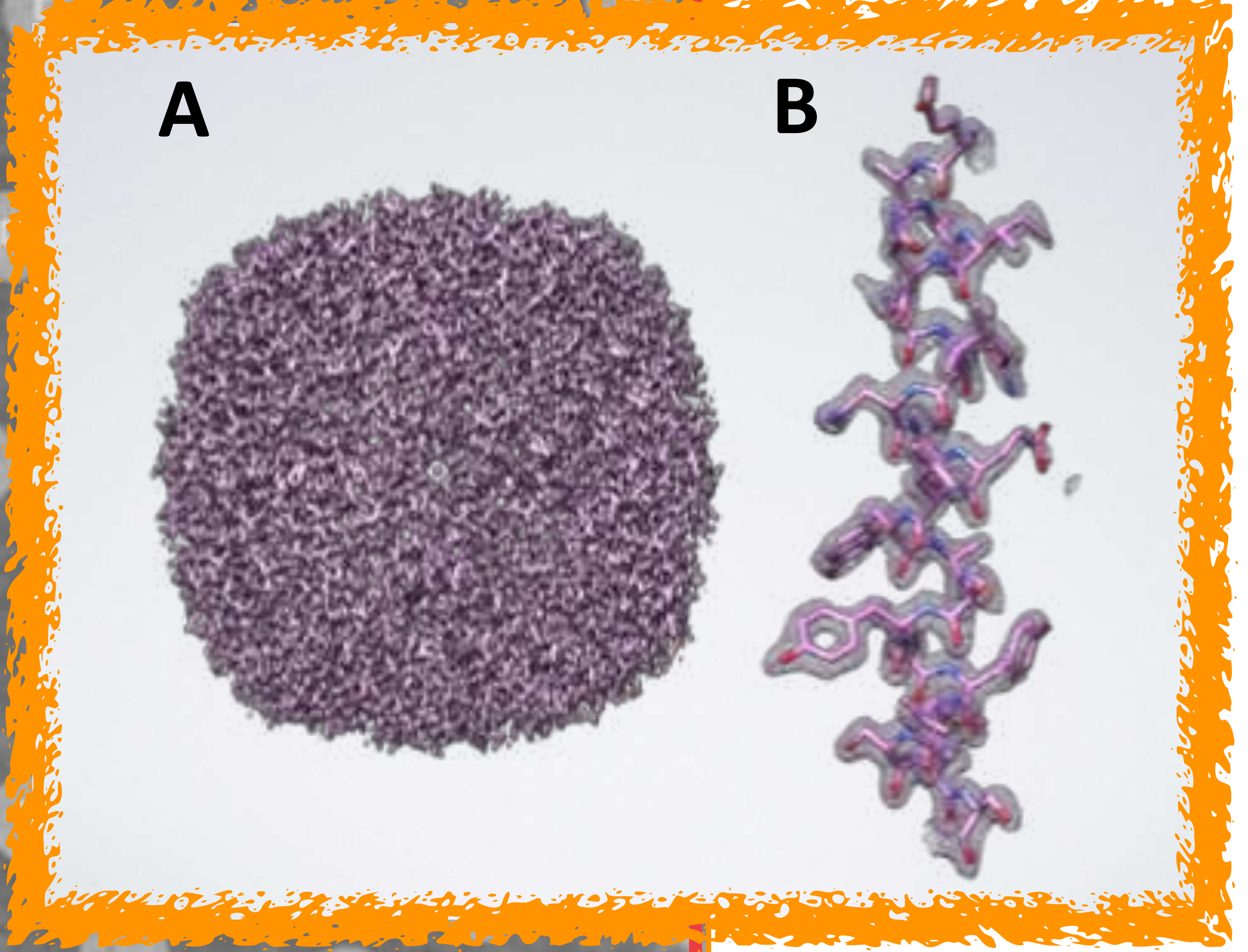


beam tilt
~3 mad

But… image shift ind

so… implement hardwar

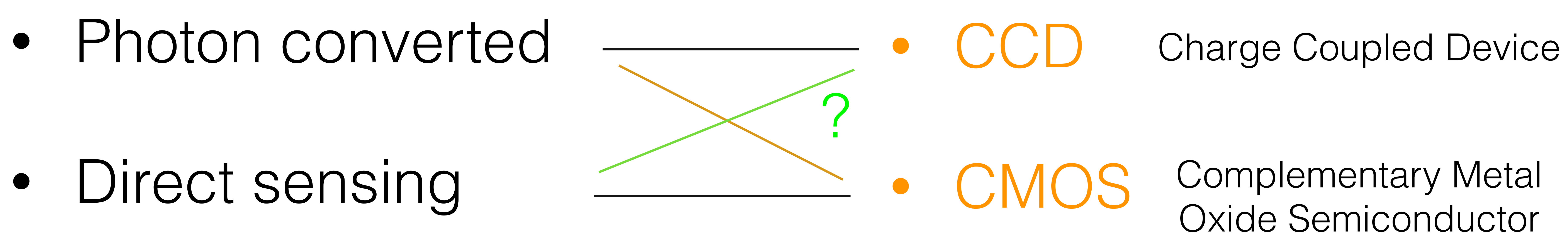
Upgrade to K3
24MP
3.75x the
framerate of K2

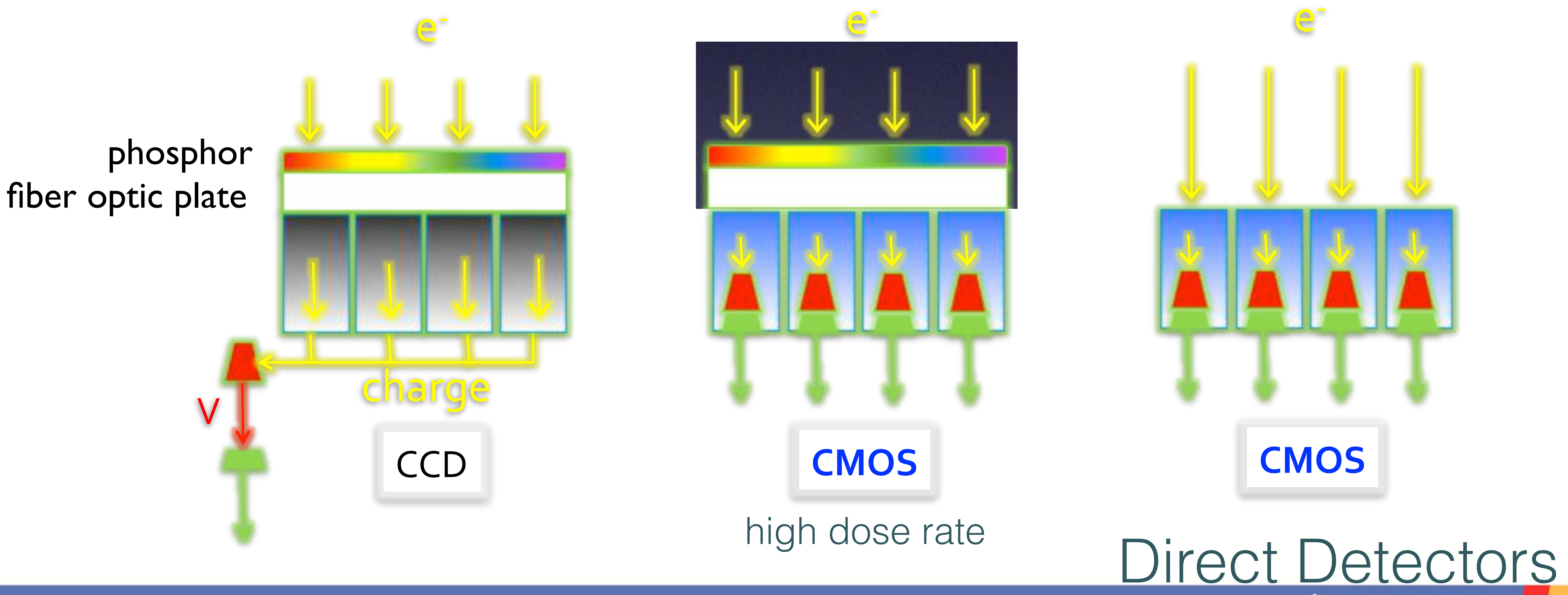


Overhead
30 s stage move and settling
30 s focus and drift check
20s for K2 40 frame movie to save

Detectors

Digital Cameras for TEM

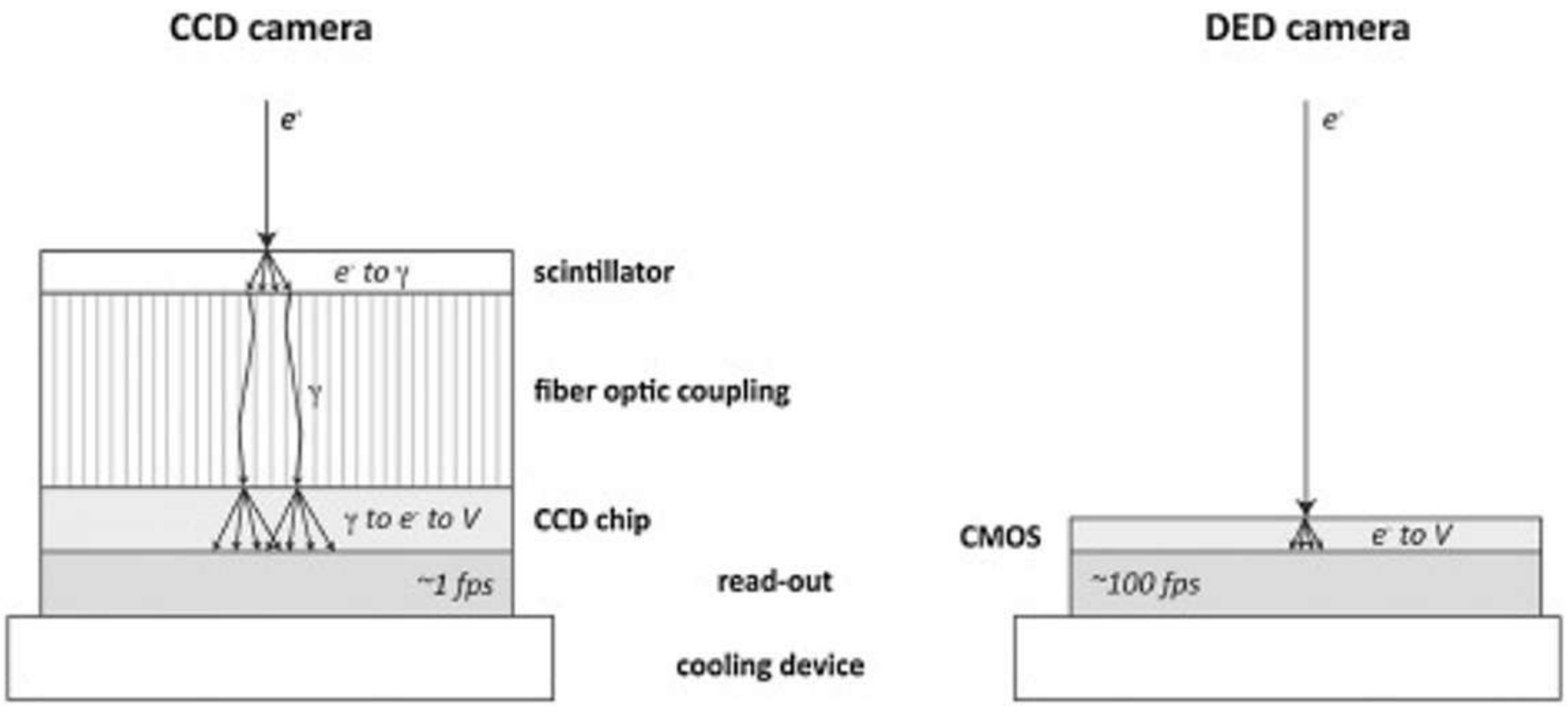




Anchi Cheng

Detectors

Digital Cameras for TEM

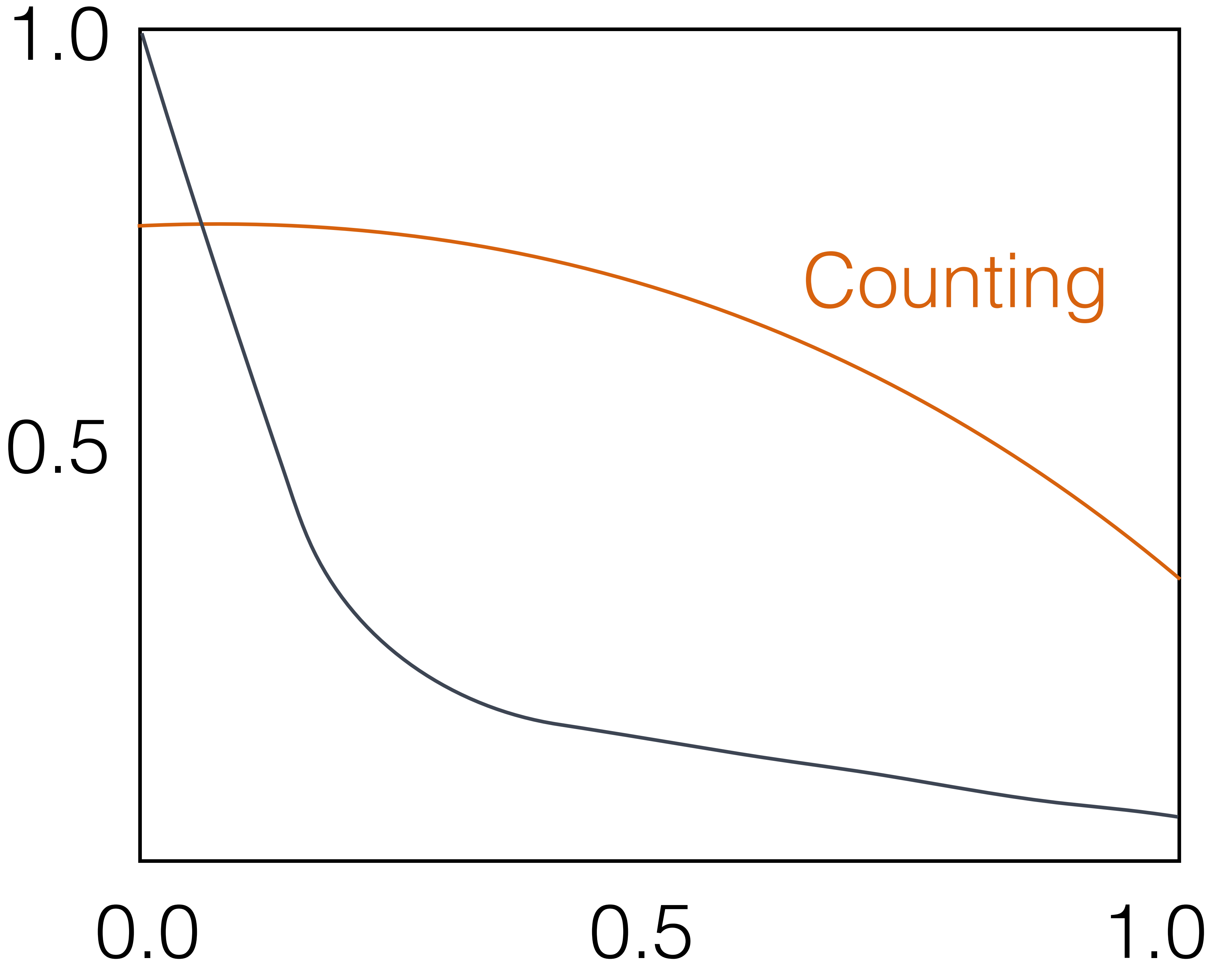


Koning et al. Ann. Anatomy 2018

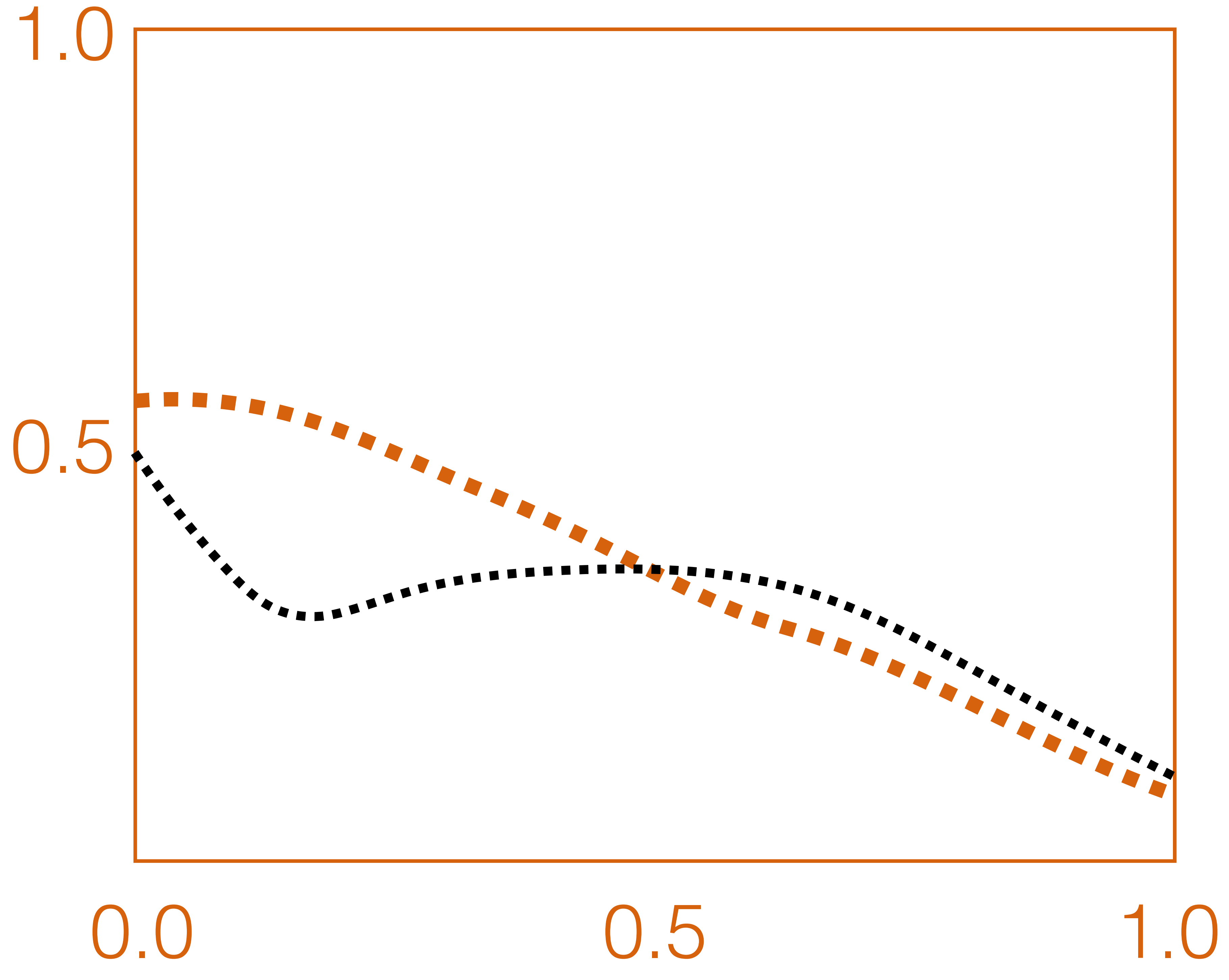
Detectors

Detector Performance Characterization

- MTF (Modulation Transfer Transform)
  - contribute to signal envelope



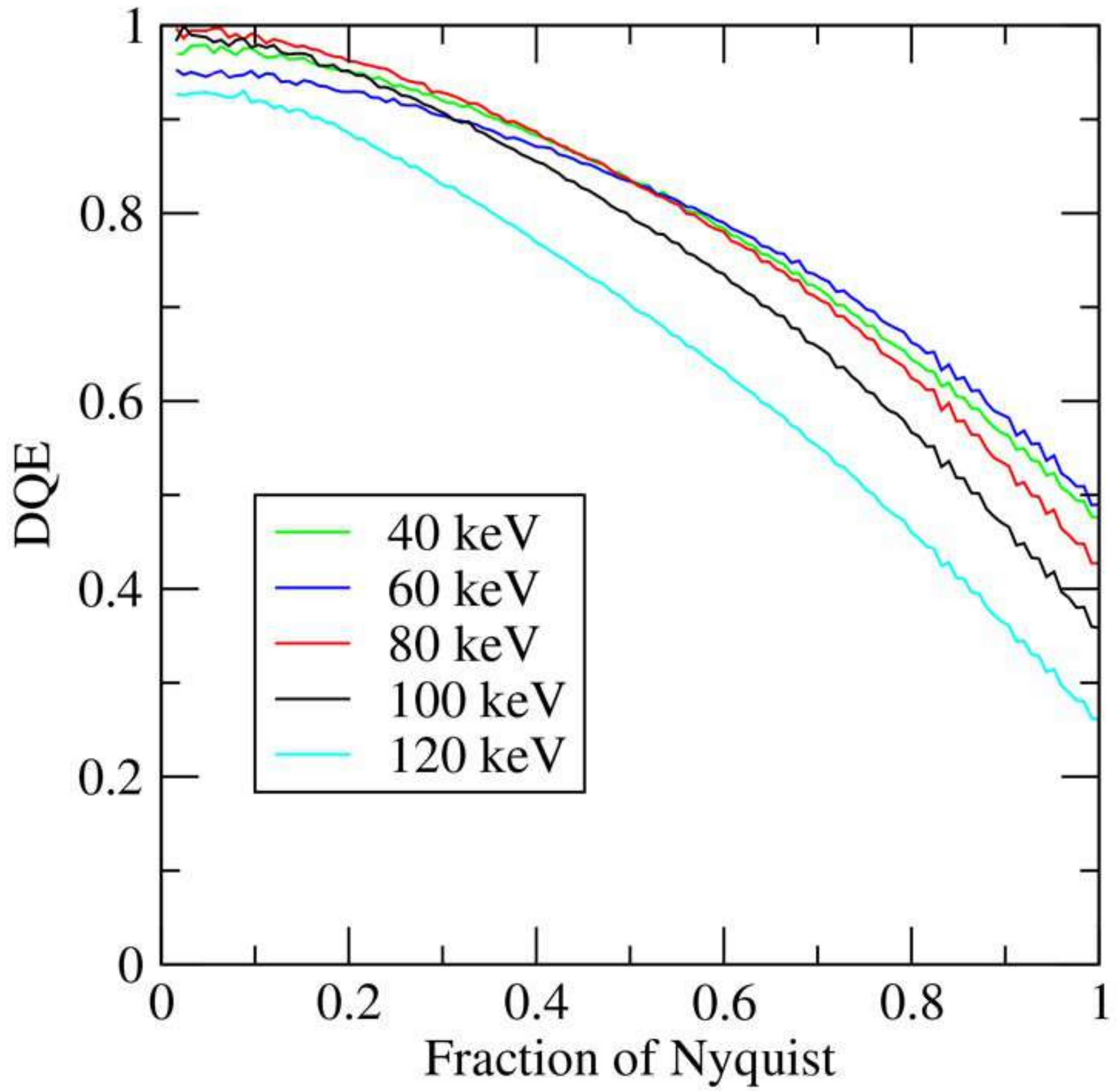
- DQE (Detector Quantum Efficiency)
  - S/N over spatial frequency range



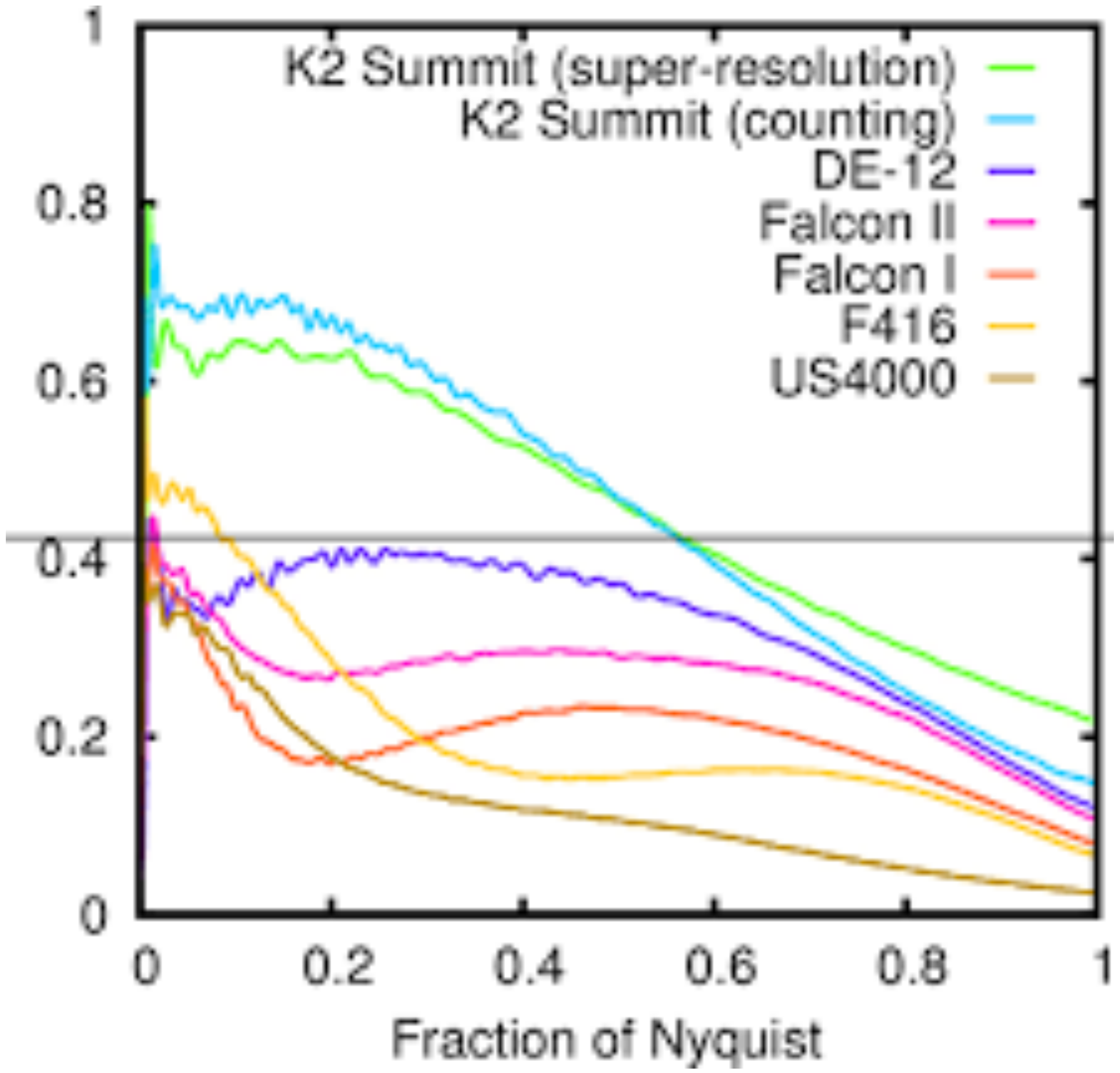
PSF: the point spread function describes the response of an imaging system to a point source or point object.
MTF: the modulation transfer function, is defined as the Fourier transform of the point spread function

Detectors

Detector Performance Characterization



dectris.com

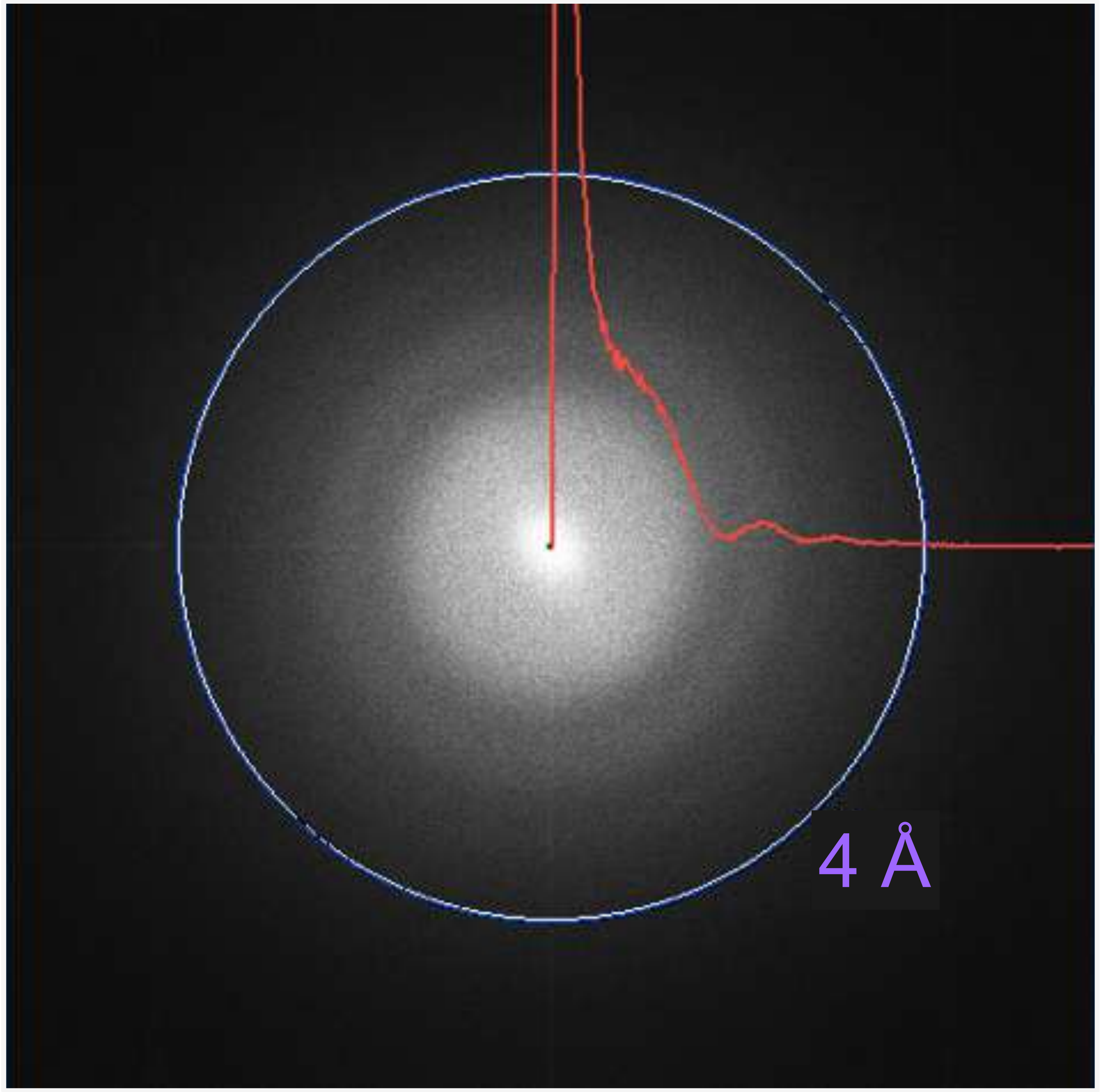


Ruskin, et al JSB

Detectors

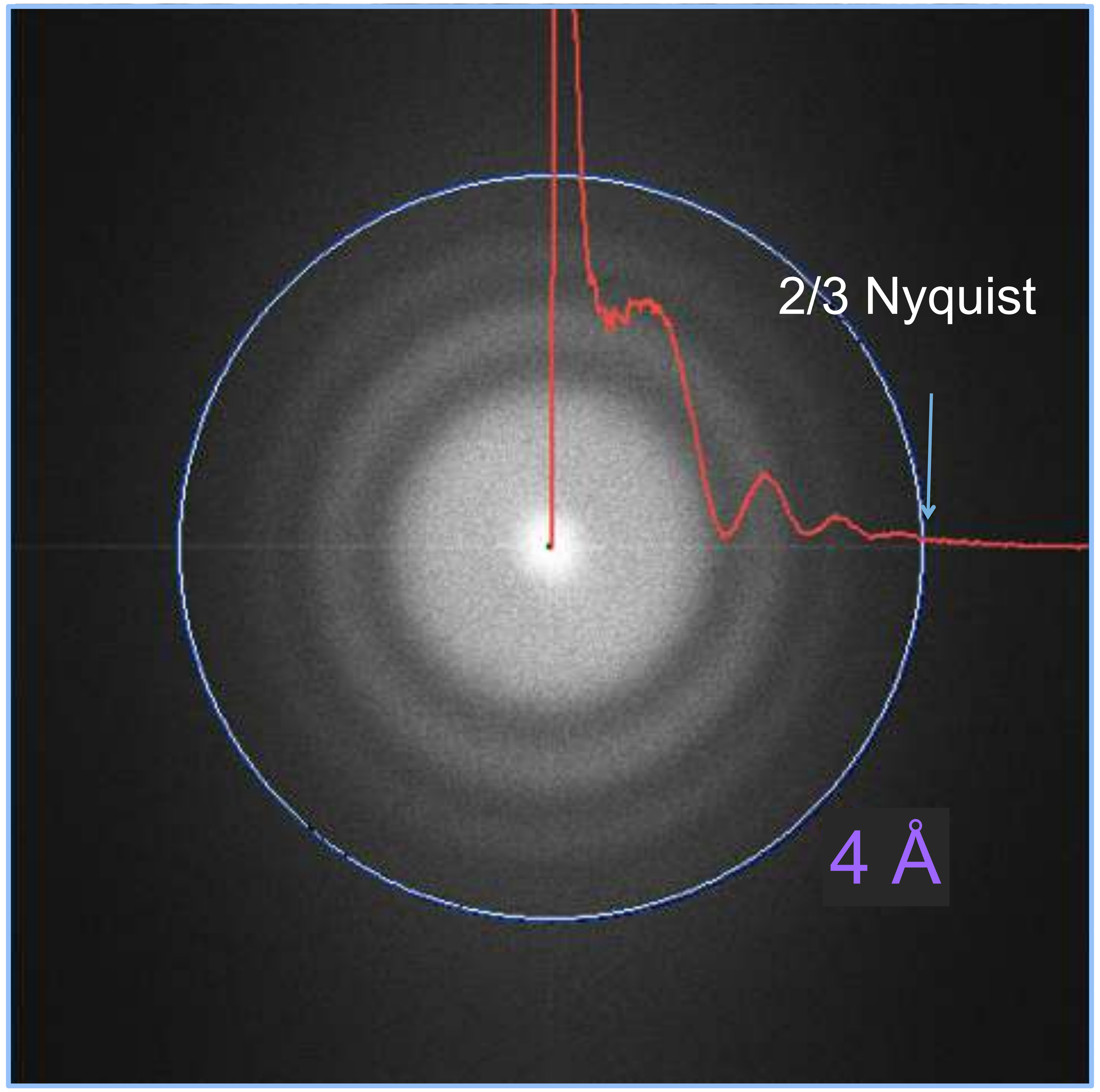
Improving the resolution:
Detecting electrons instead of photons

CCD



1.37 Å/pixel

DDD



1.38 Å/pixel

200KeV ; 20 e-/Å^2 ; carbon film ;
3k x 3k image

Detectors

Improving the resolution:
Detecting electrons instead of photons

K3 specs

https://www.gatan.com/K3

Specifications

	K3	K3 Base
TEM operating voltage (kV)	200 / 300	
Sensor size (pixels)	5,760 x 4,096	3,456 x 4,096
Readout modes	Counting Super-resolution	Counting
Max. image size (pixels)	11,520 x 8,184 Super-resolution	3,456 x 4,096
Performance relative to physical Nyquist (DQE)		
Peak	>0.87 / >0.83	>0.8
0.5	>0.53 / >0.53	>0.5
Sensor read-out (full fps)	>1500	
Transfer speed to computer (full fps)	>75	>25
Motion correction	Inline	
Gatan Microscopy Suite® software	Included	
Automation support	Latitude and other third-party software	

Specifications are subject to change without notice.

Detectors

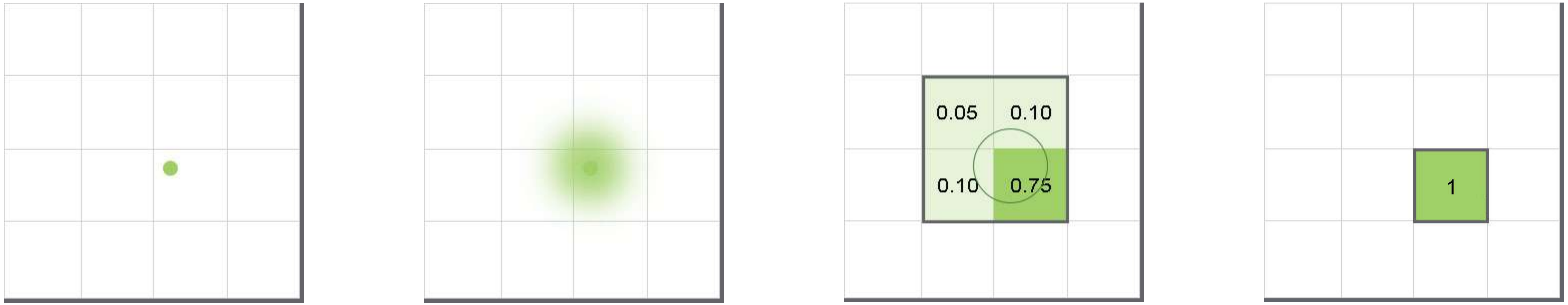
Improving the resolution:
Detecting electrons instead of photons

5,760 x 4,096 px

↓

11,520 x 8,184 px

Counting mode



Electron enters detector.

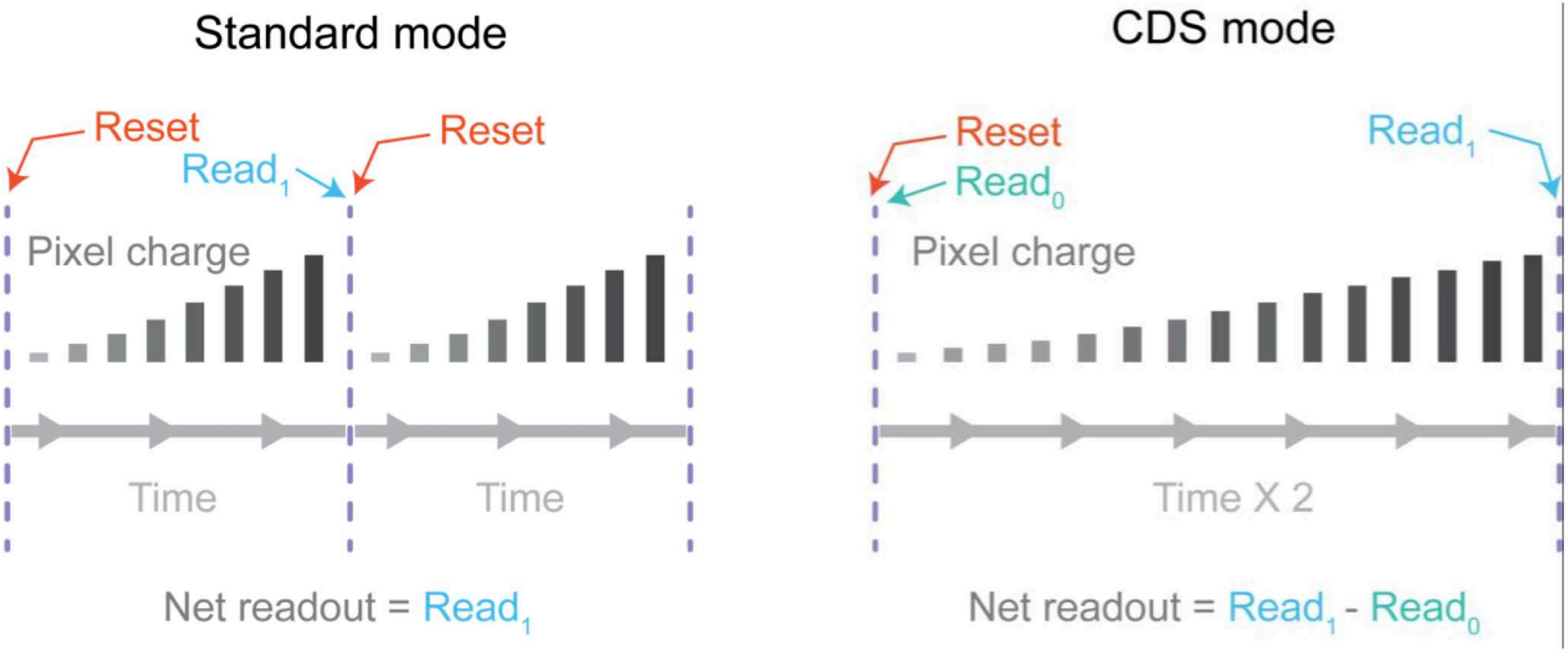
Electron signal is scattered.

Charge collects in each pixel.

Events reduced to highest charge pixels.

https://www.gatan.com/improving-dqe-counting-and-super-resolution

K3 lowers Read Noise with Correlated Double Sampling (CDS)

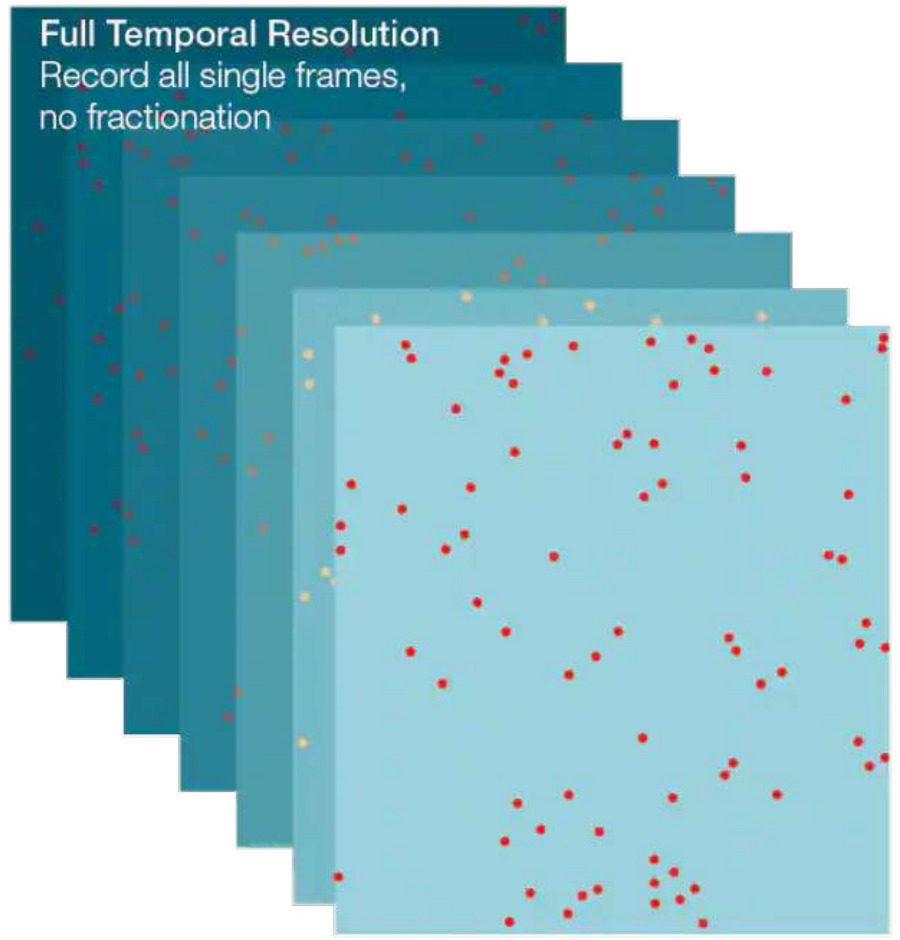


https://www.gatan.com/

Detectors

Improving the resolution:
Detecting electrons instead of photons

Falcon4 specs



Full Spatial Resolution
All localized events

Coordinates	
x	y
3953.24	2845.63
919.78	1447.39
3864.43	348.13
3606.05	1539.54
1758.86	2971.55
...	...
3983.58	531.96

Counted events of all raw frames with full temporal resolution (320 fps) and spatial resolution (events are localized to one-sixteenth of a pixel).

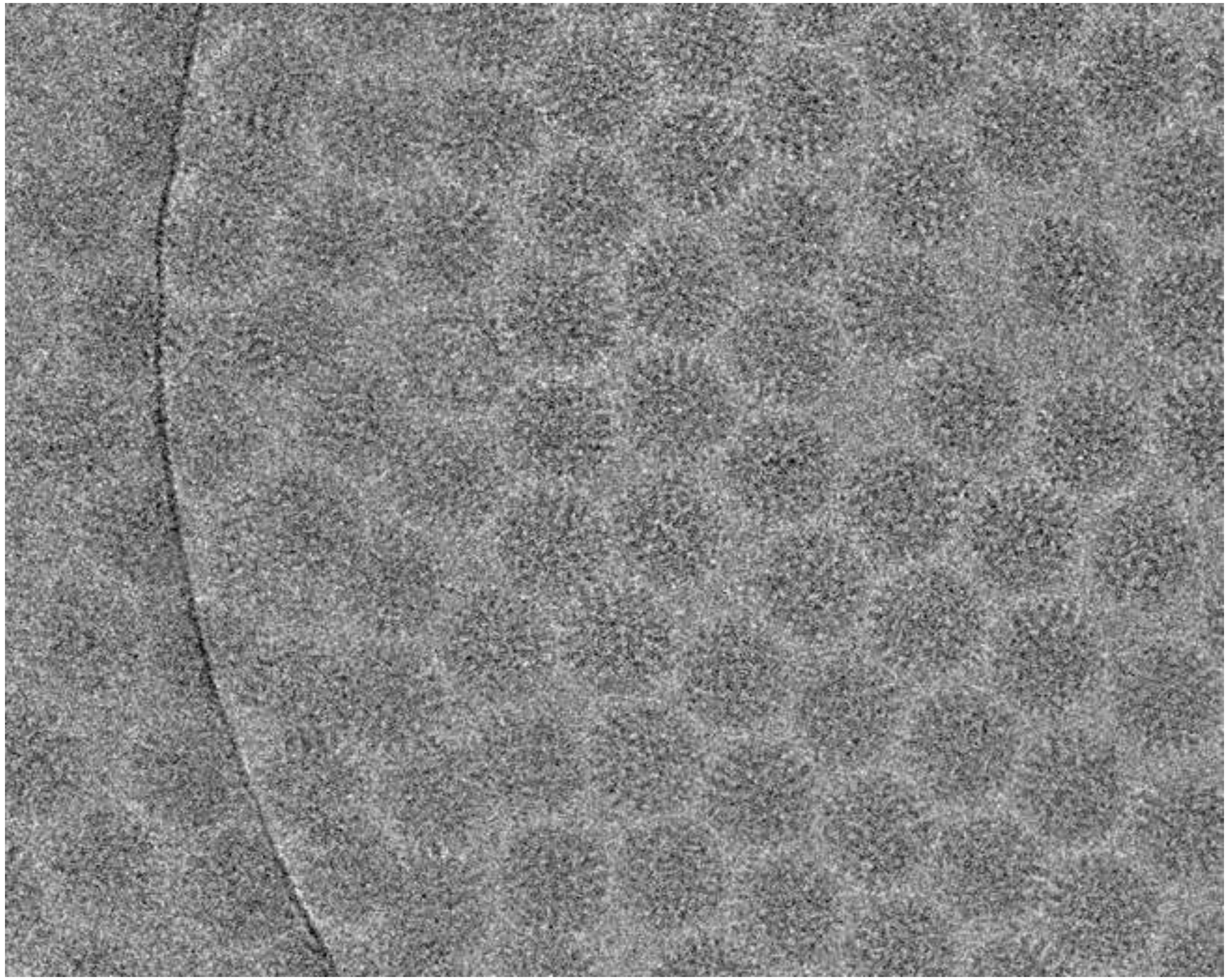
Camera architecture	Direct electron detection	
Sensor size	4,096 × 4,096 pixels, ~ 5.7 x 5.7 cm^2	
Pixel size	14 x 14 μm^2	
TEM Operating voltage	200 kV, 300 kV	
Internal frame rate	320 fps	
Frame rate to storage	320 fps (EER mode)	
Camera Overhead time	0.5 s per acquisition	
File formats	EER (native), MRC, TIFF, LZW TIFF	
Lifetime (<10% DQE degradation)	5 years in normal use (1.5Ge/px)	
Detection Modes	Electron counting mode Survey mode (fast linear mode)	
Imaging performance in EER mode (4k x 4k)	300 kV	200 kV
DQE (0)	0.92	0.91
DQE (½ Nq)	0.72	0.62
DQE (1 Nq)	0.50	0.33

Electron-event representation (EER)

https://www.thermofisher.com/us/en/home/electron-microscopy/products/accessories-em/falcon-detector.html

Detectors

Images are movies



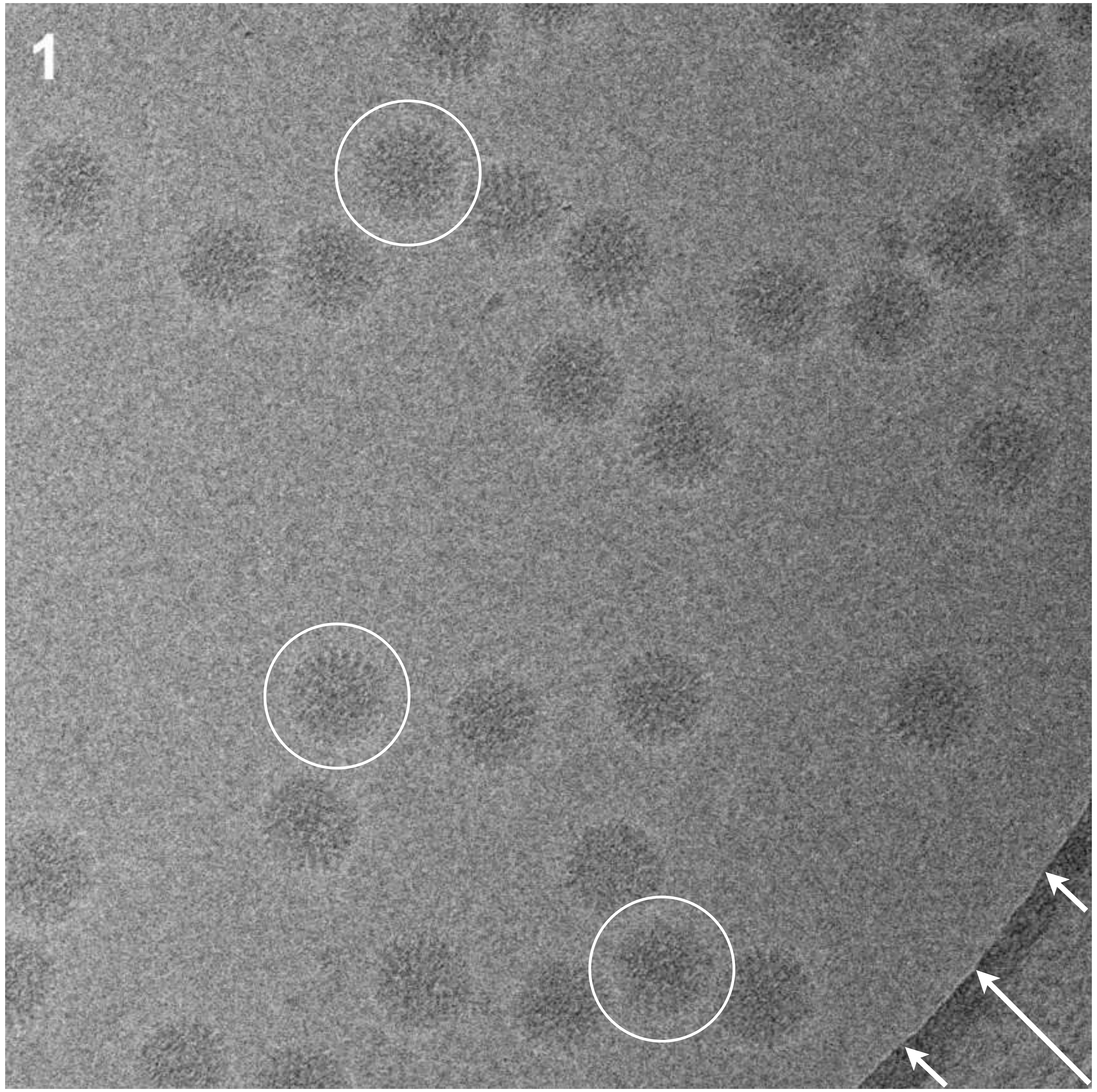
0.5 $e^-/Å^2$/frame

Image = Frame1 + Frame2 + Frame3 + Frame4 + Frame5

We can use DDD movies to examine (and correct) “beam induced motion”

Detectors

Images are movies



10 frame averages

Each averaged frame corresponds to 0.25 s.

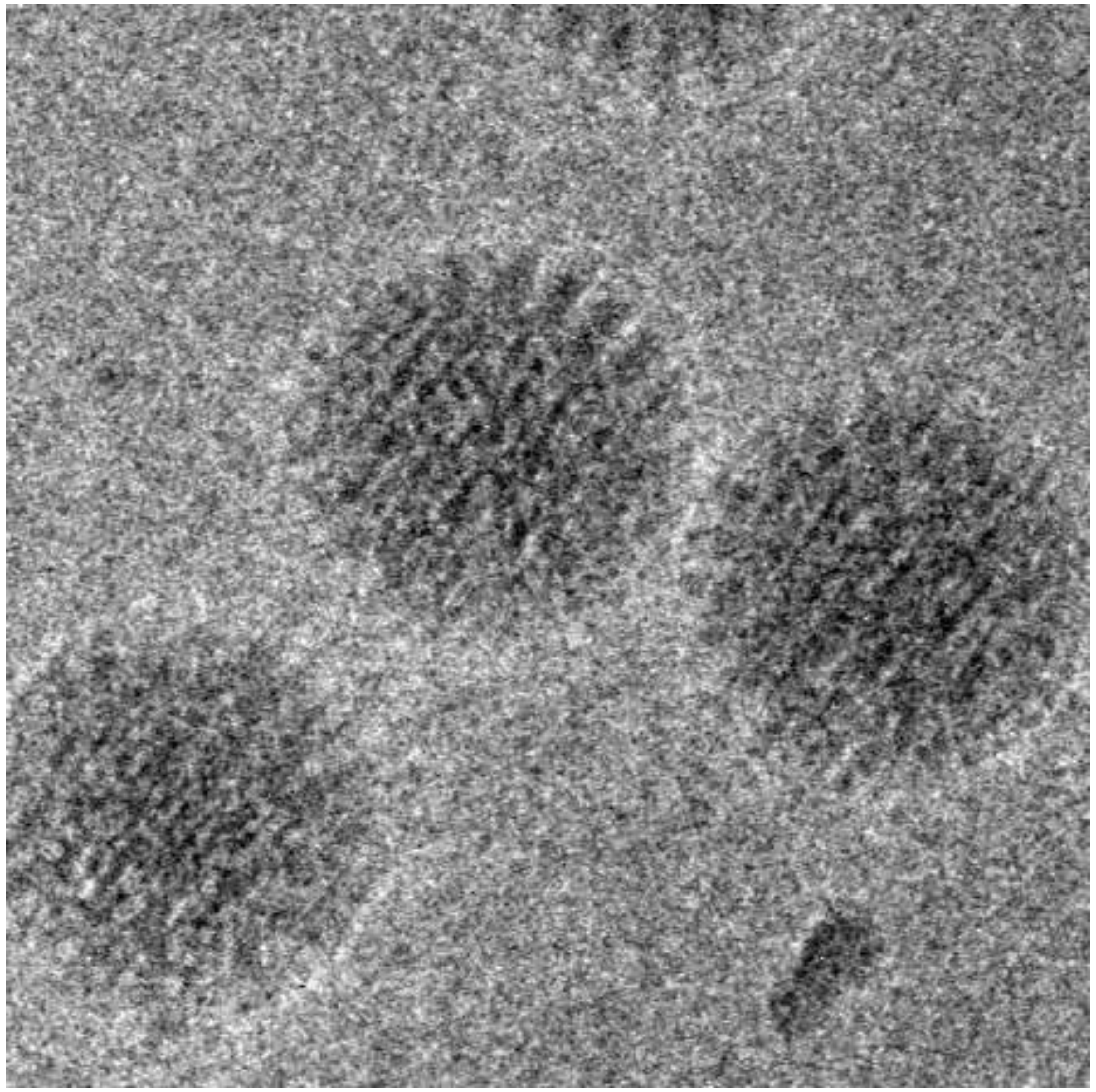
Dose/frame = 5 $e^-/Å^2$

A “movie” of rotavirus exposed to electron beam

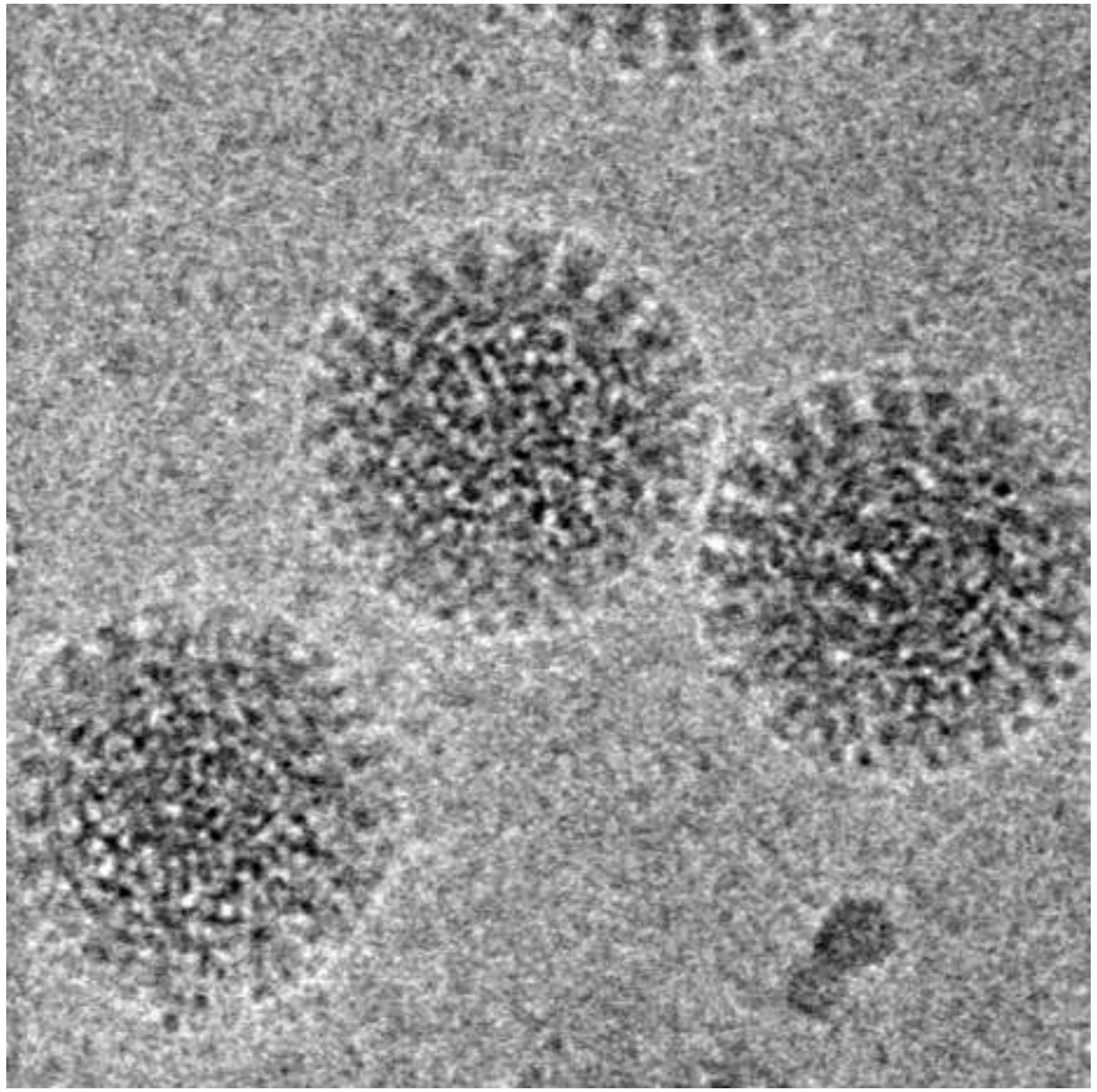
Brilot C.F. et al. (2012) J Struct Biol.

Correcting for movement

60-frame average
(no alignment)



60-frame average
(translational alignment)



Brilot C.F. et al. (2012) J Struct Biol.

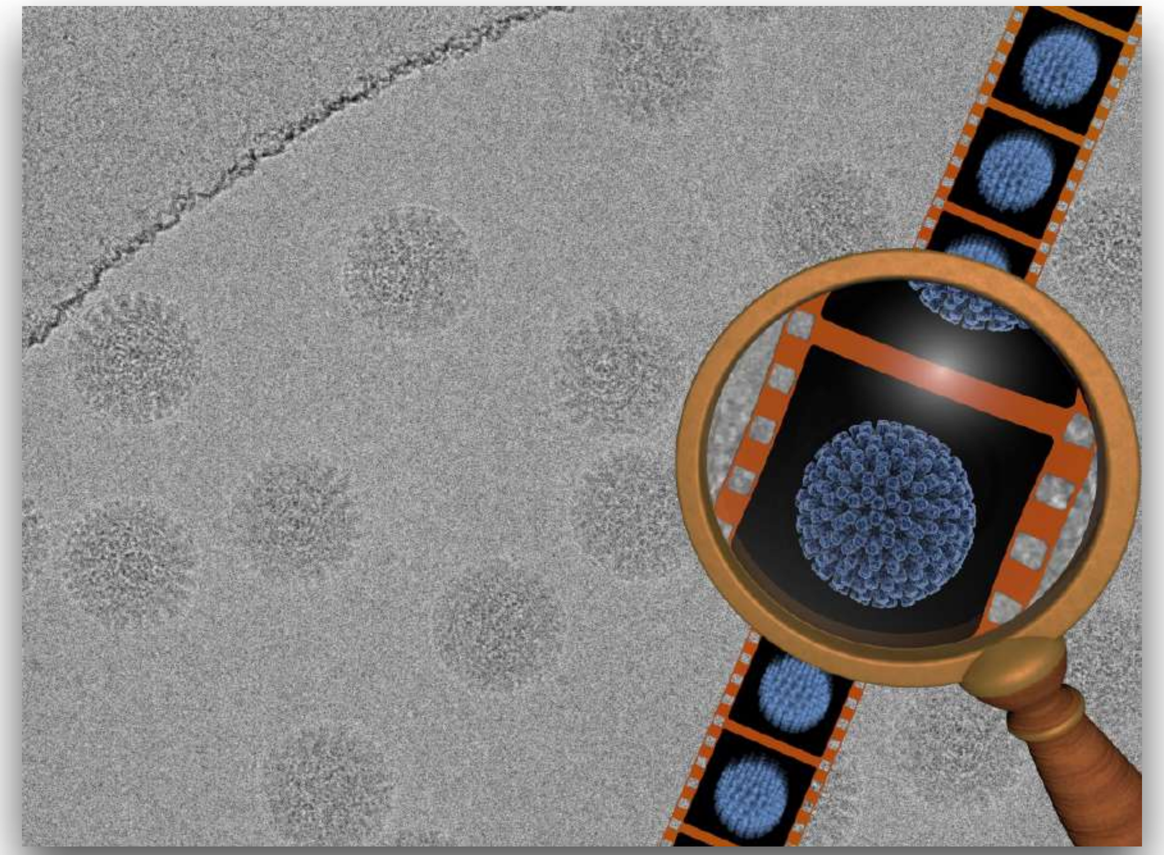
What brought about the resolution revolution?

(~2012-2014)

Hardware

Microscopes

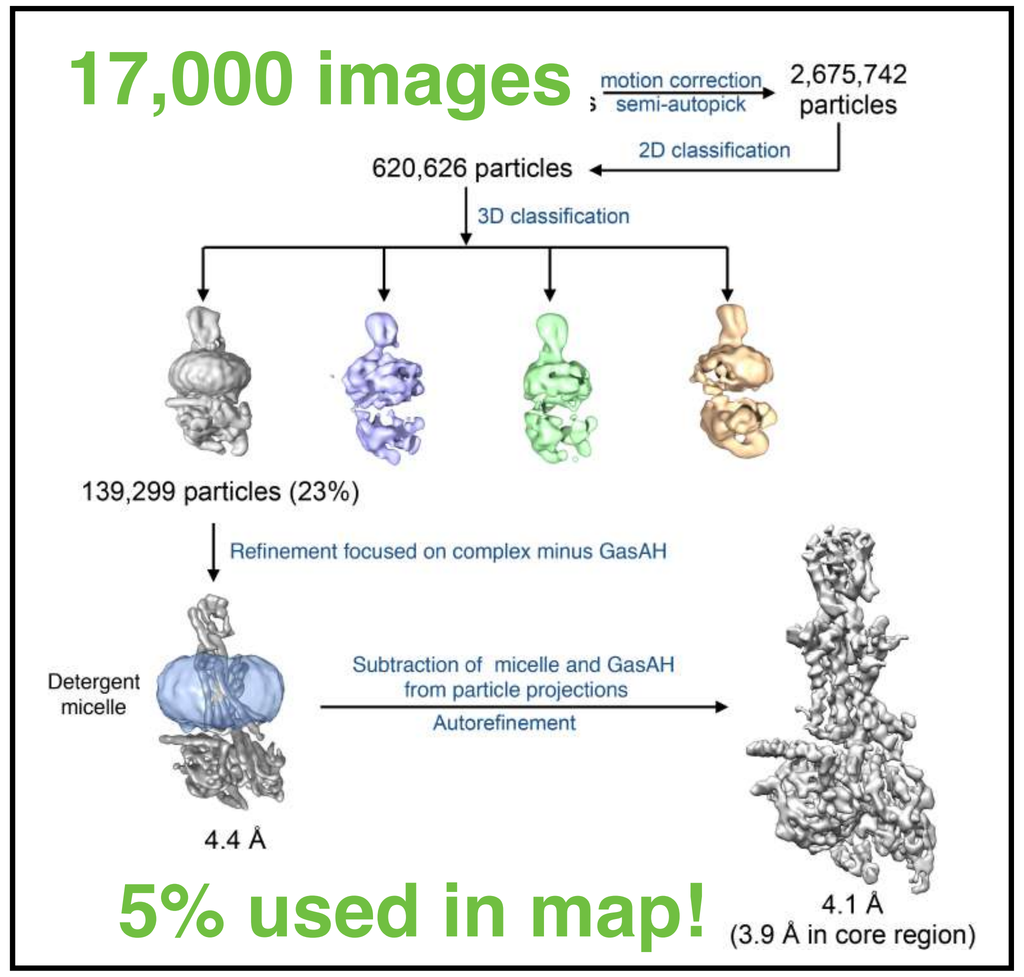
Direct Detectors



Computers

2012->2017
Cost reduced by 100x

Software

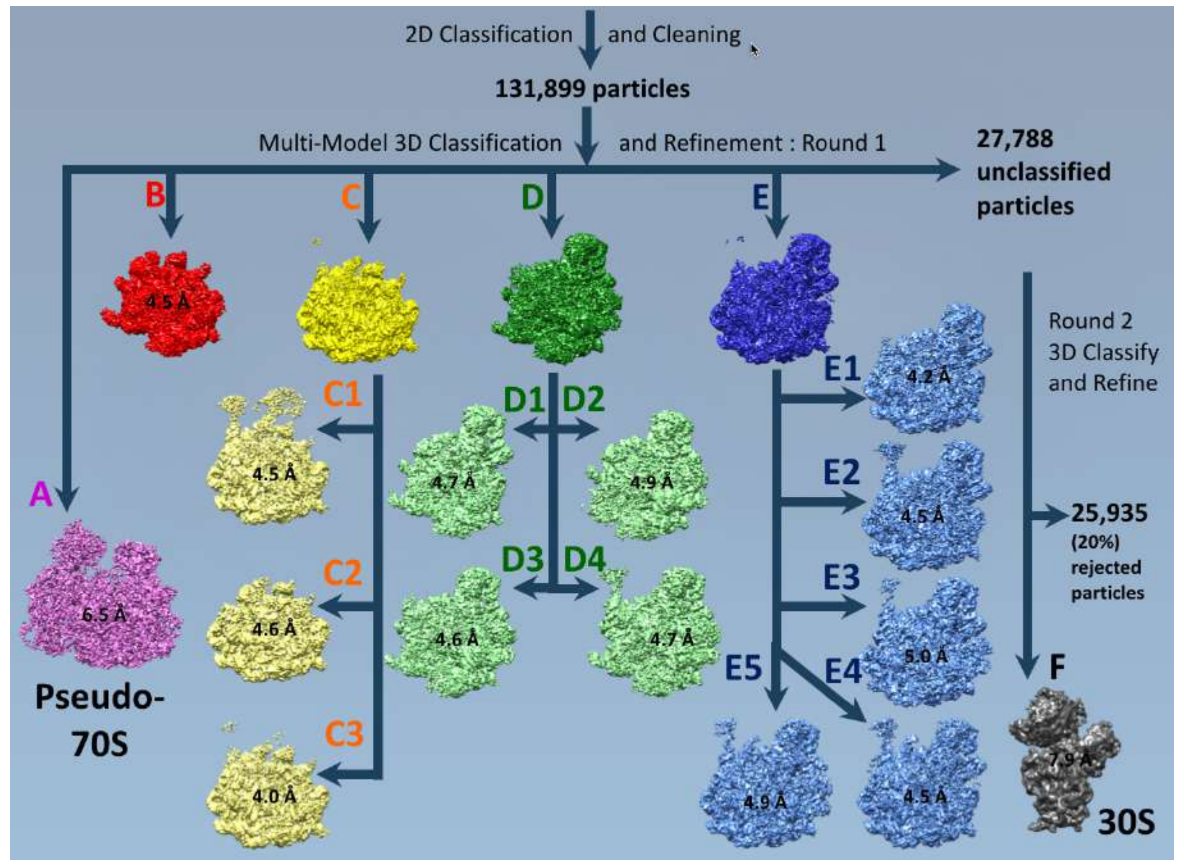


Leginon / SerialEM / EPU, …

MotionCorr2, Unblur, …

RELION, FREALIGN/cisTEM, cryoSPARC
EMAN, Sparx, SPHIRE, XMIPP, …

14 independent structures



What brought about the resolution revolution?

Hardware

Patrick Sexton, PhD

Monash Institute of Pharmaceutical Sciences, Monash University

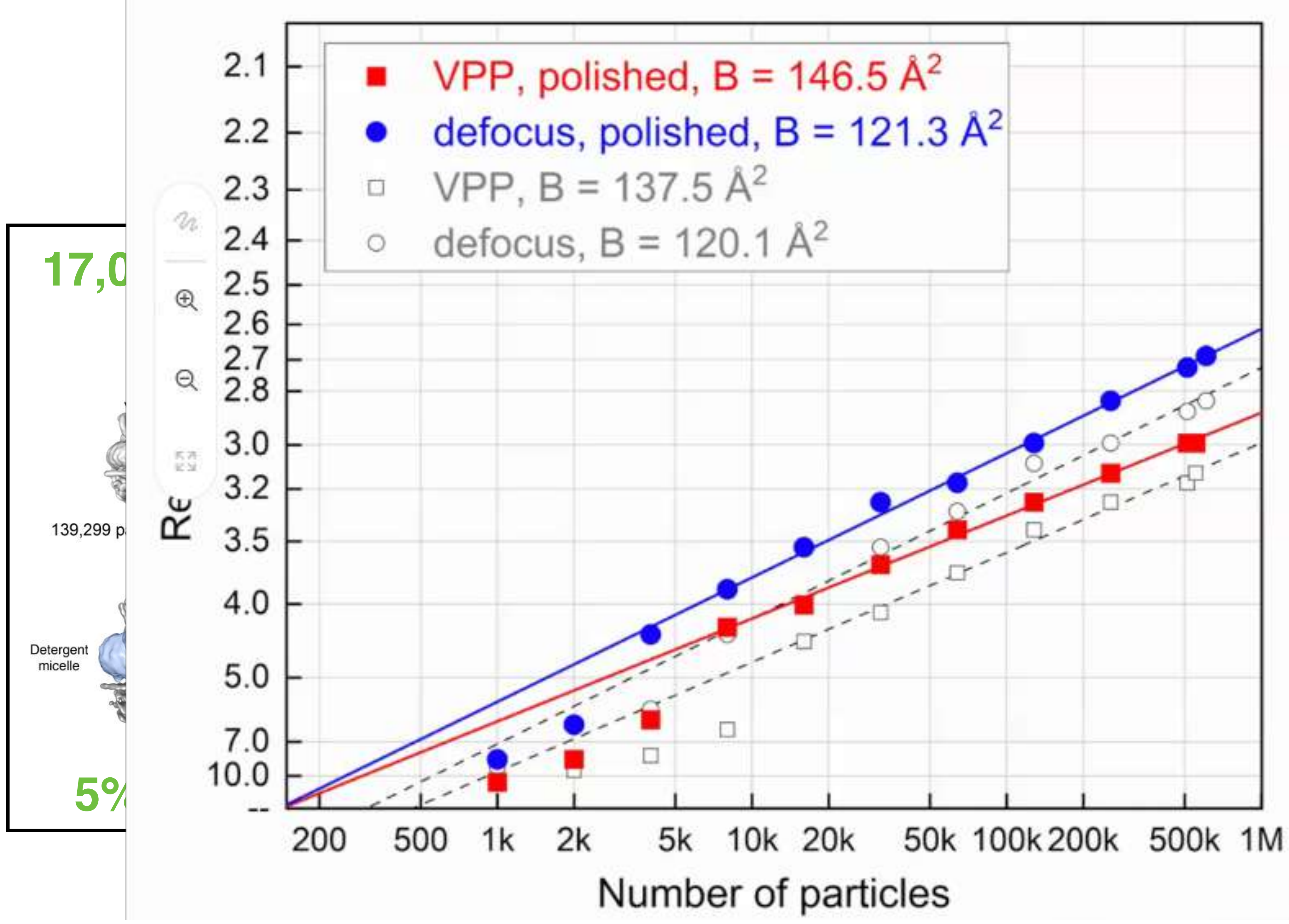
Denise Wootten, PhD

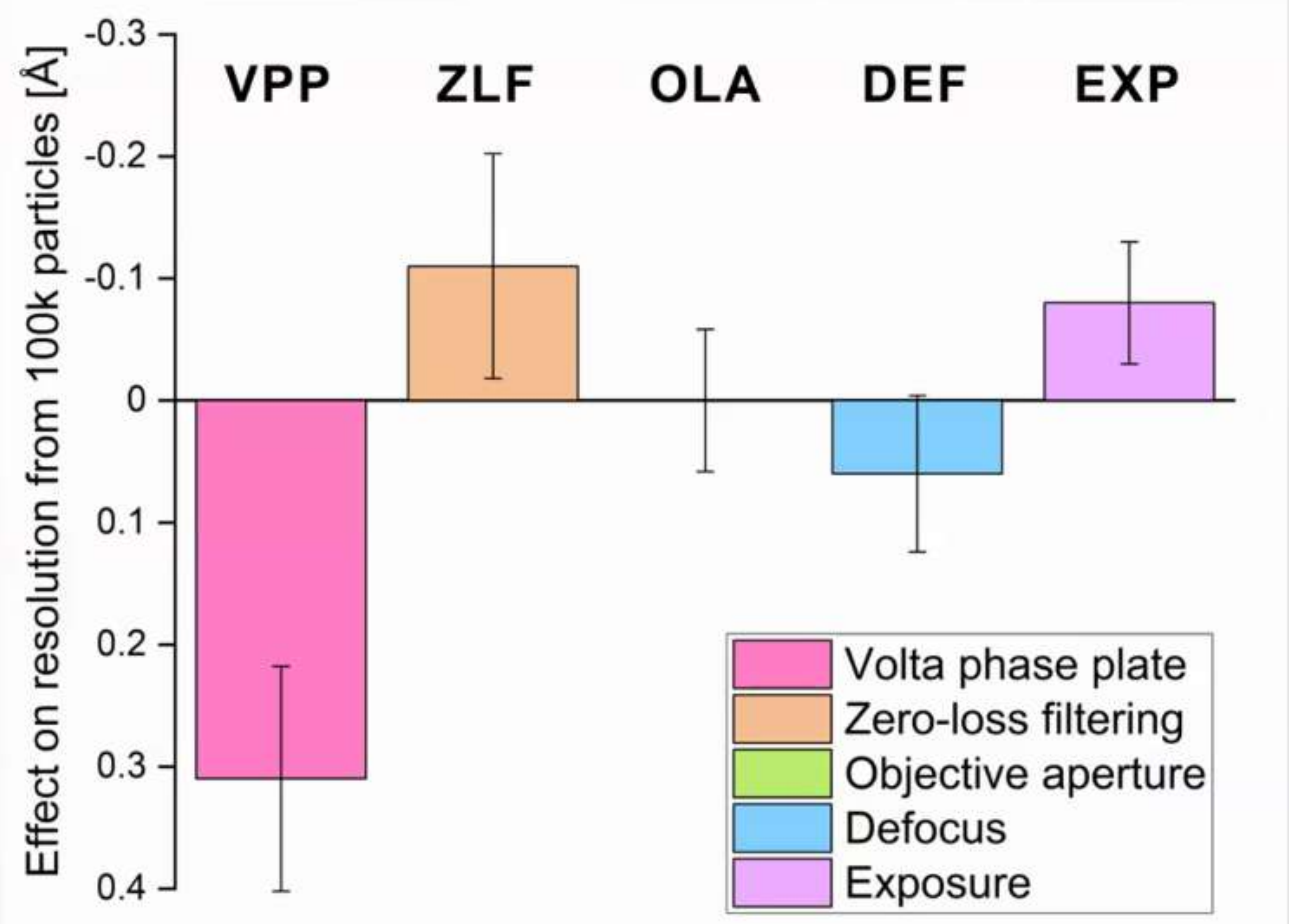
Monash Institute of Pharmaceutical Sciences, Monash University

Radostin Danev, PhD

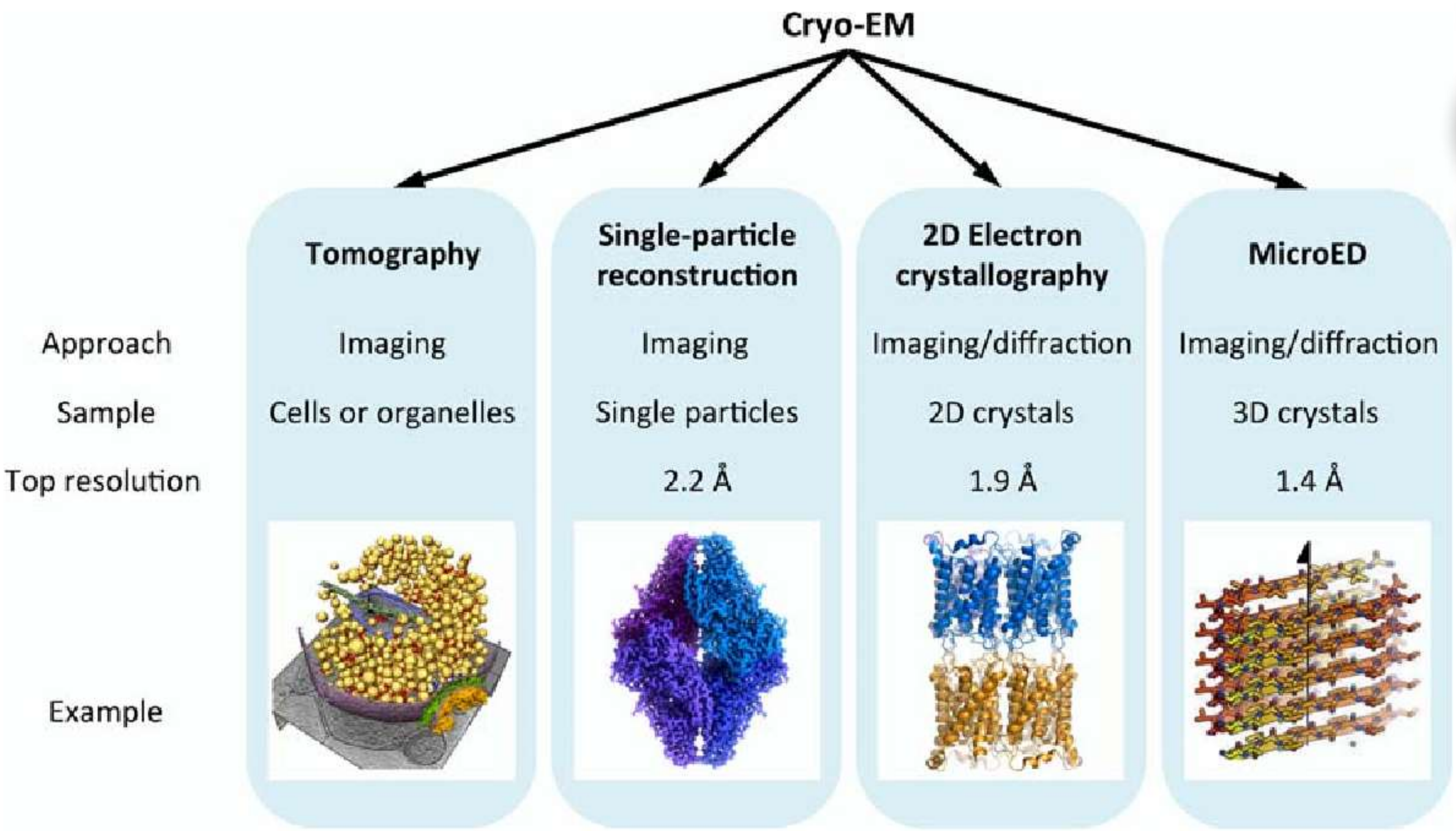
Graduate School of Medicine, The University of Tokyo

Software





Cryoem modalities and tools

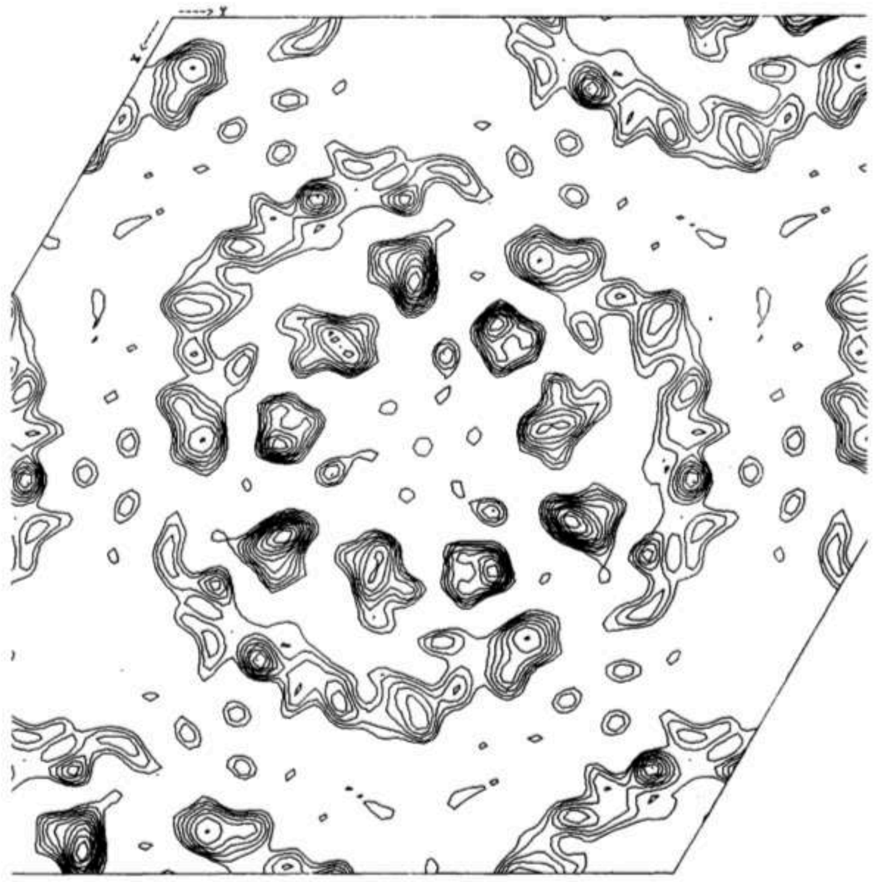


https://doi.org/10.1002/pro.2989

~3.4Å ~1.2Å ~1.9Å ~0.7Å

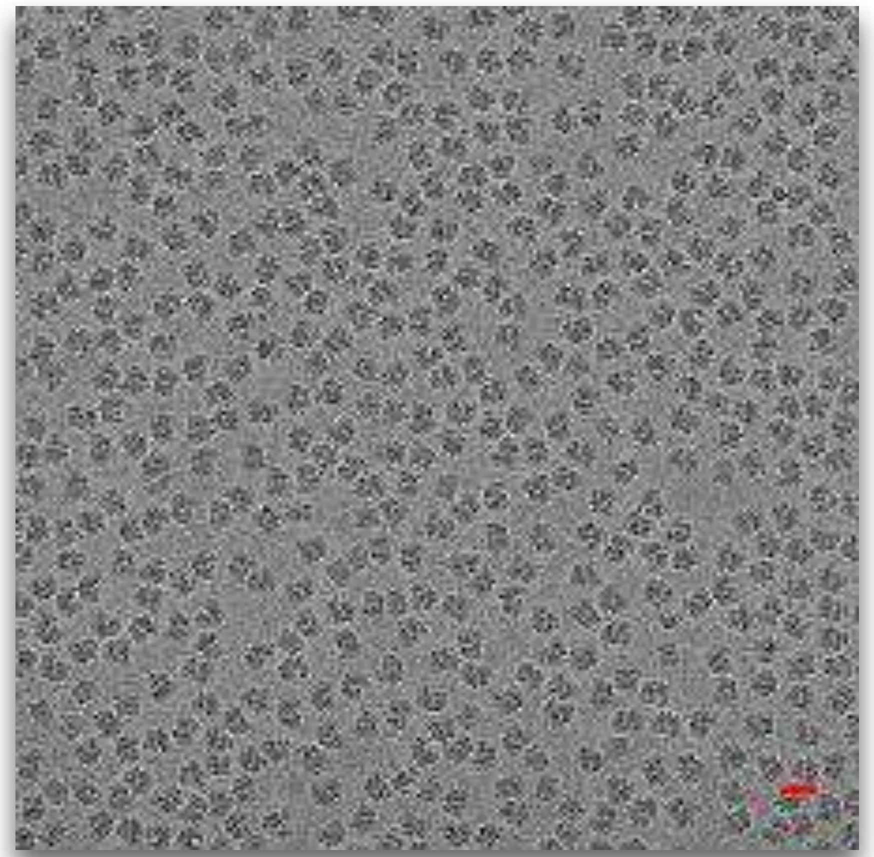
cryoEM: technology on the rise

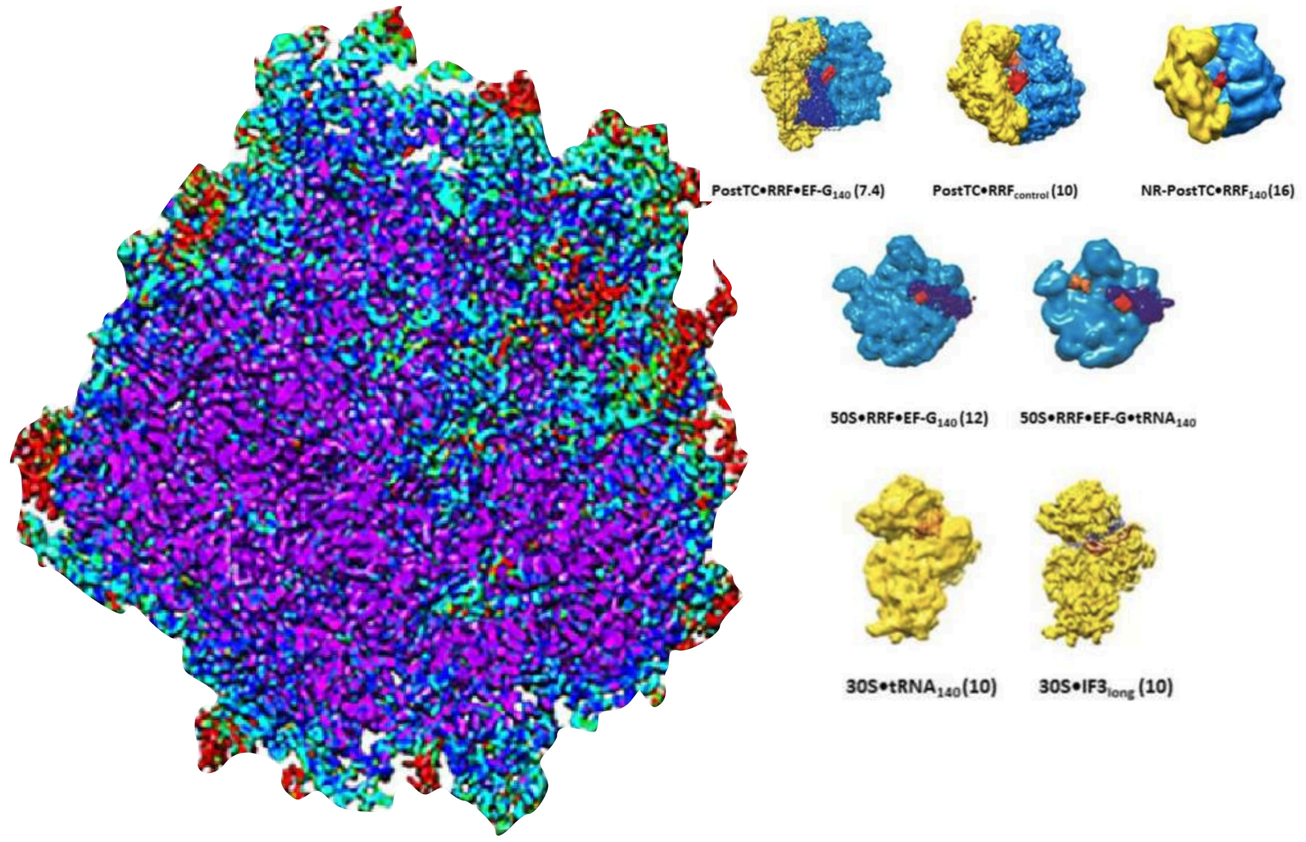
1986



Henderson et al. (1986)

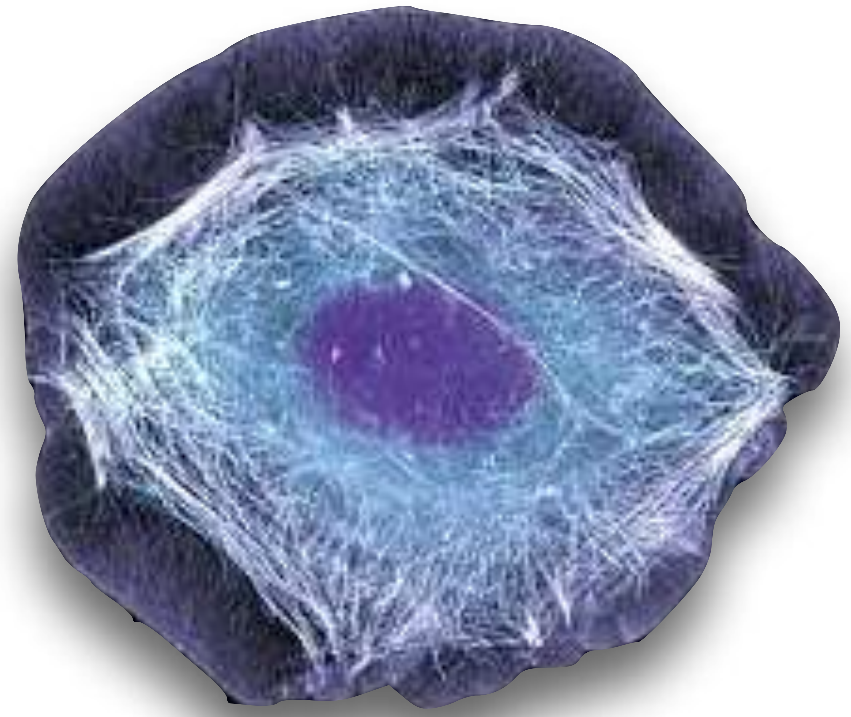
2017

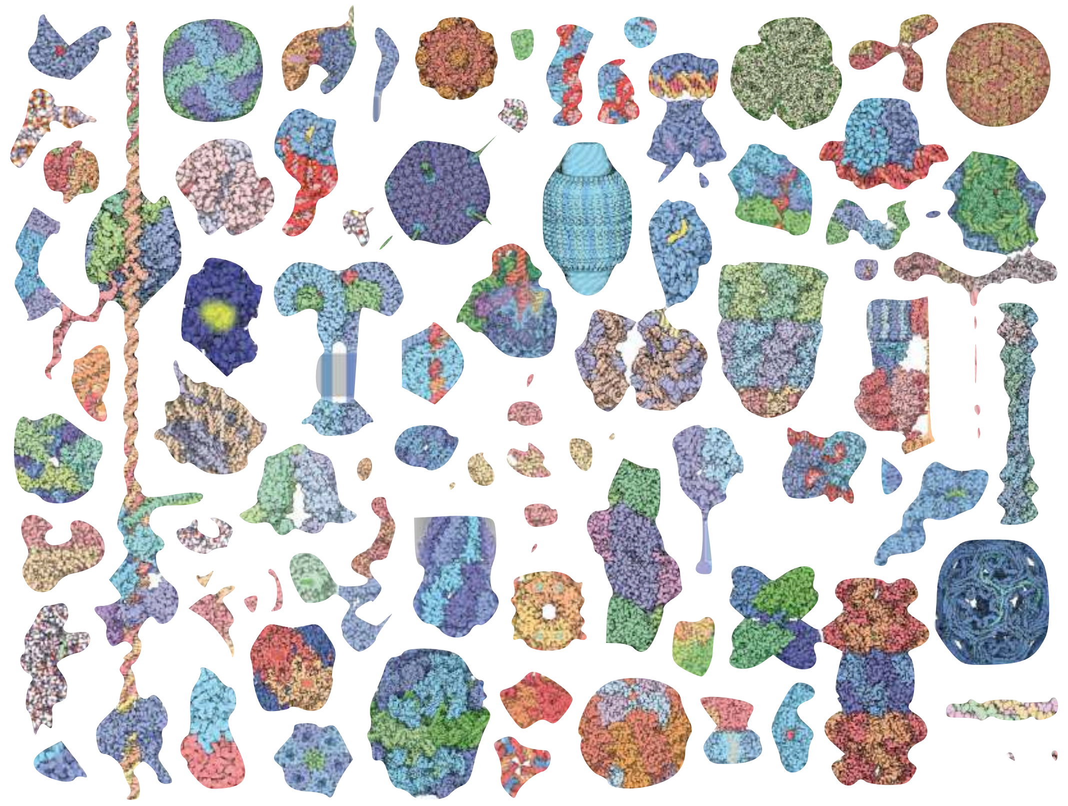




Frank et al. (2017)

in progress





the next chapter

And true “atomic” resolution is possible:

Nakane, et al. Single-particle cryo-EM at atomic resolution. Nature (2020).

How are samples prepared for cryoEM?

The start

Questions?