CRYOEM 001 :
EM COMPATIBLE SAMPLES

NCCAT Embedded Training – Master Class series

February 1, 2023

NATIONAL CENTER FOR
CRYOEM ACCESS & TRAINING

New York Structural
Biology Center

SIMONS ELECTRON
MICROSCOPY CENTER

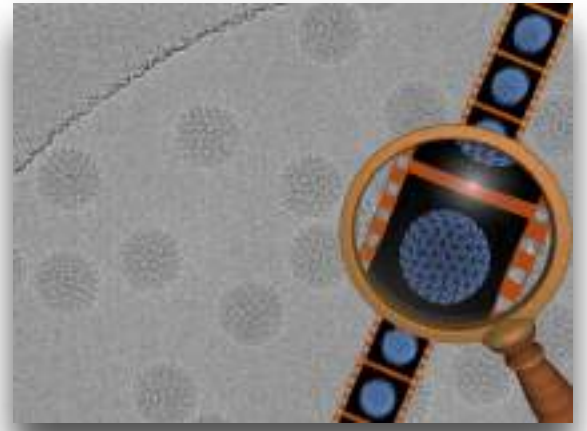
WHAT BROUGHT ABOUT THE RESOLUTION REVOLUTION

(~2012-2014)

Hardware

Microscopes

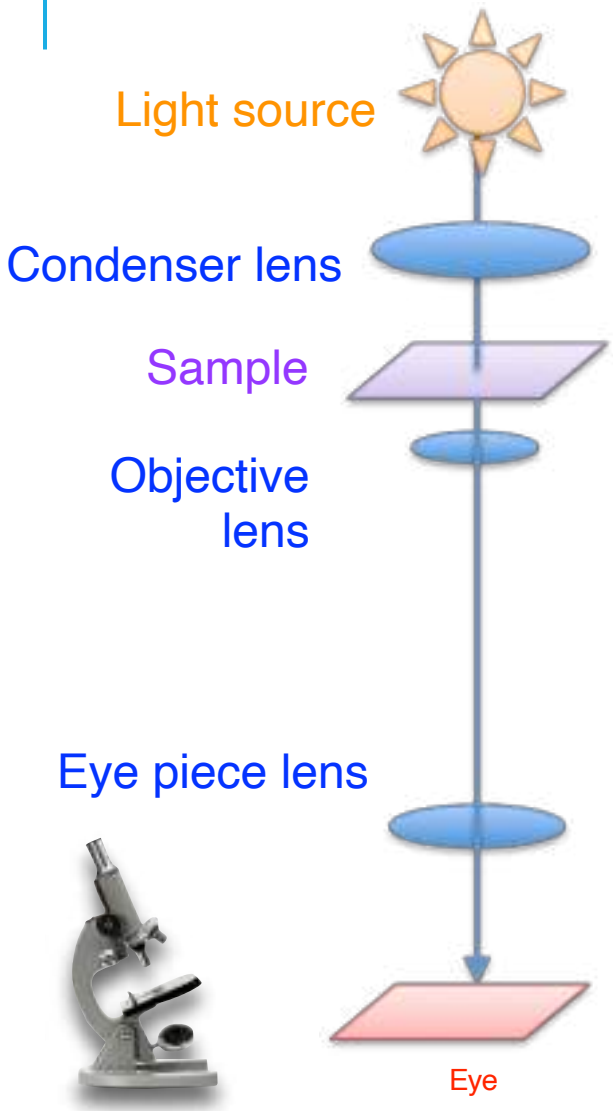
Direct Detectors

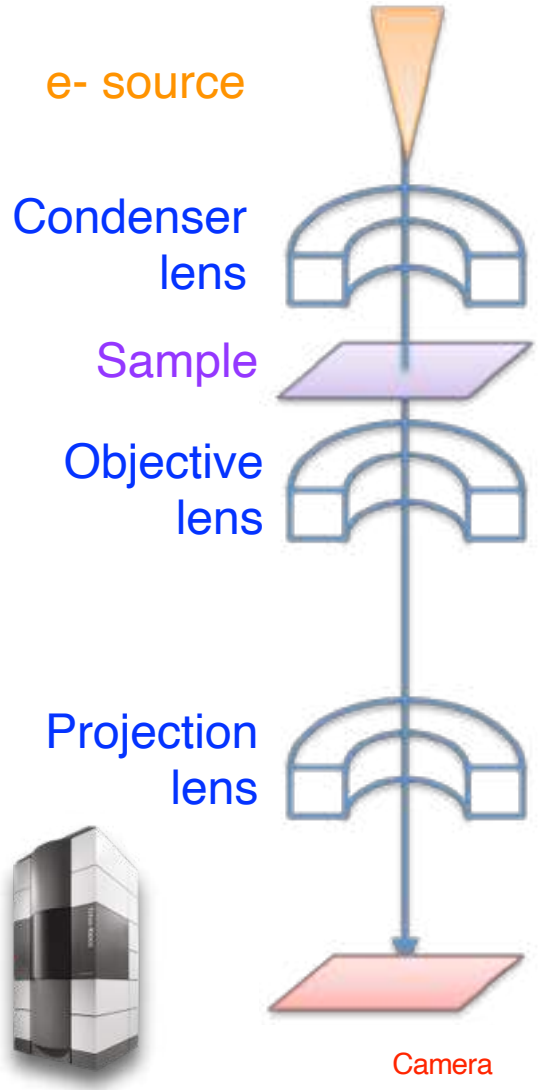


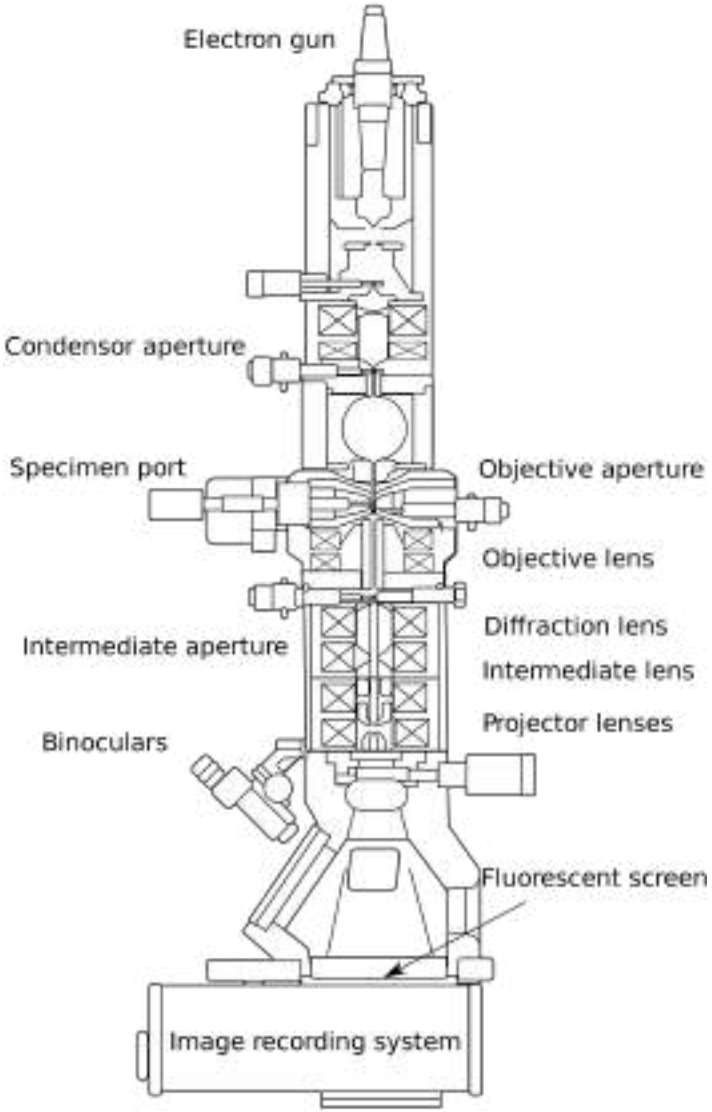
Computers

2012->2017
Cost reduced by 100x

CRYOEM TOOLS

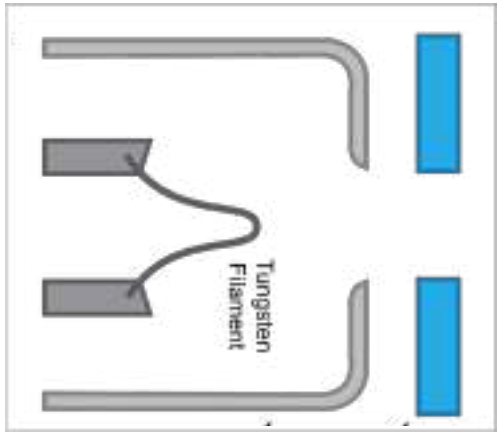


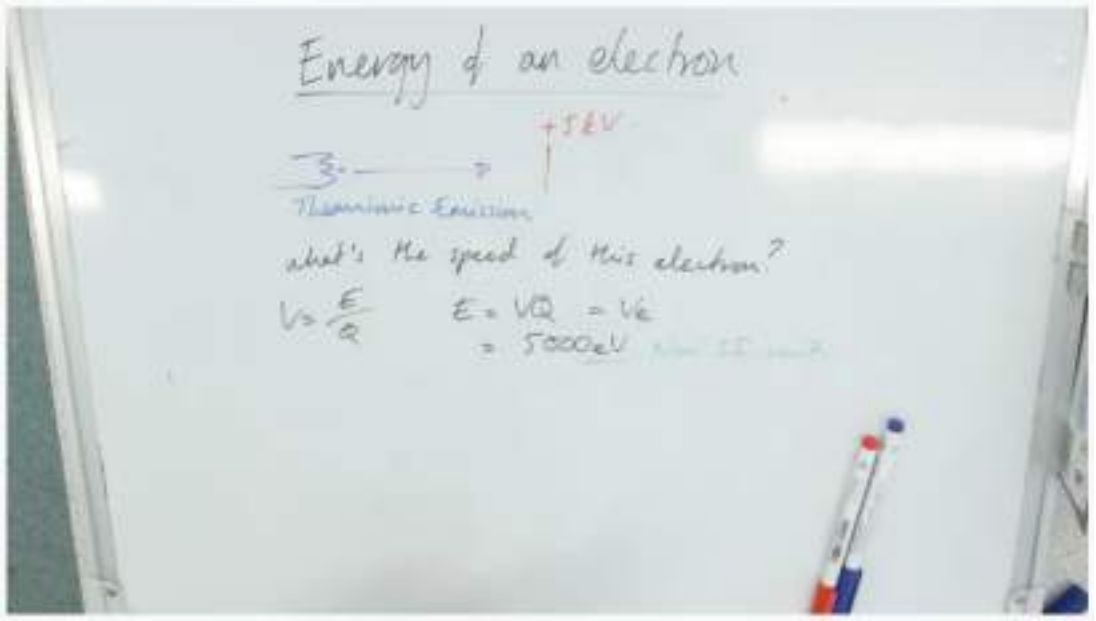




ELECTRON SOURCES

How fast are the electrons moving?

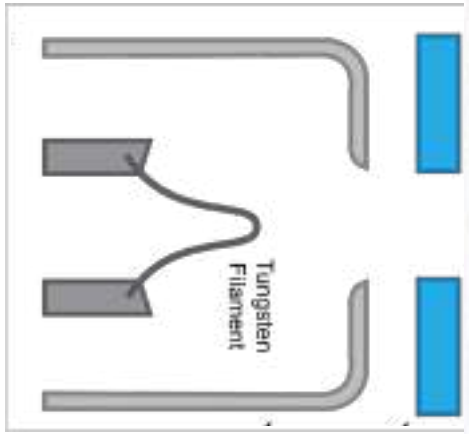


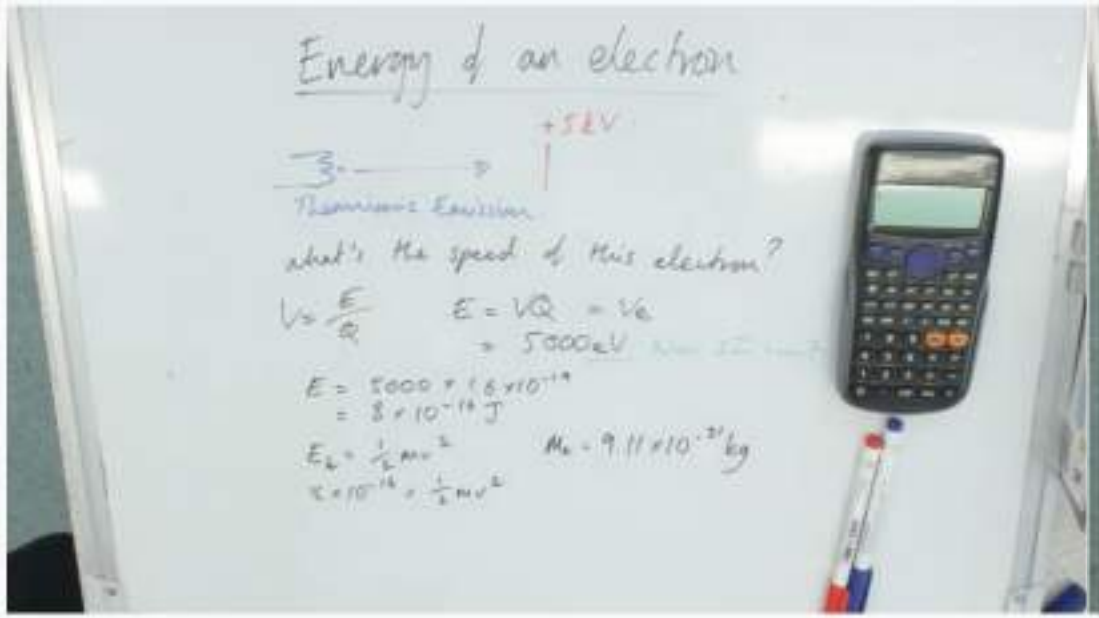


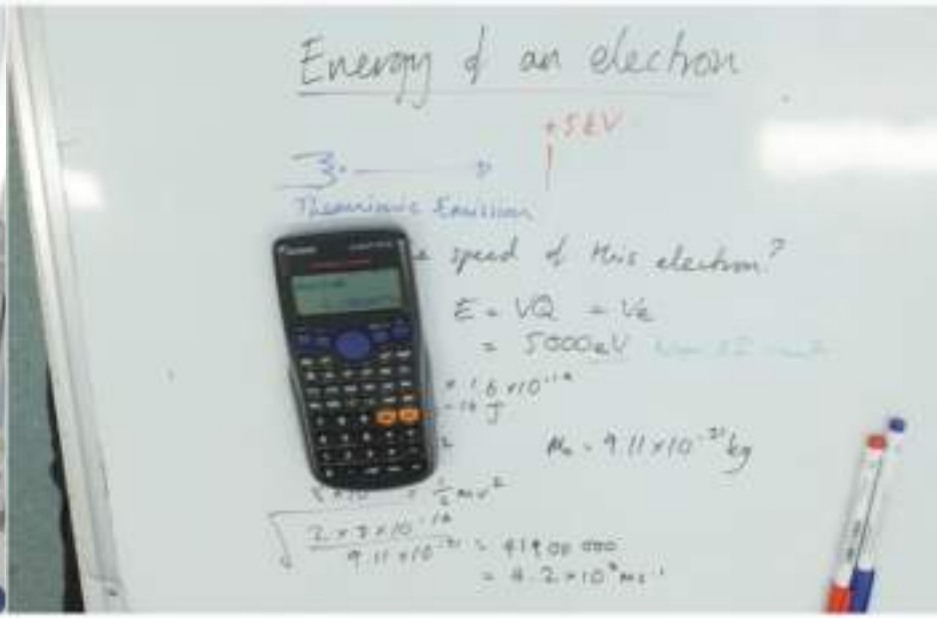
https://www.youtube.com/watch?v=tYCET6vYdYk

ELECTRON SOURCES

How fast are the electrons moving?

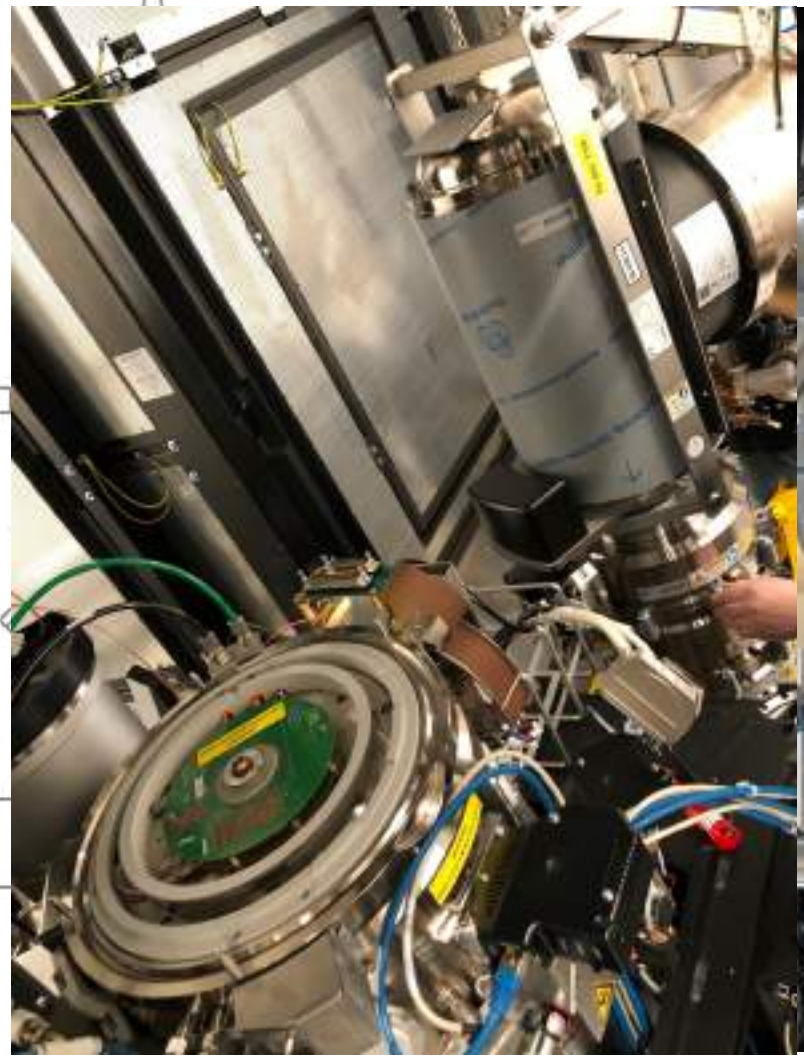


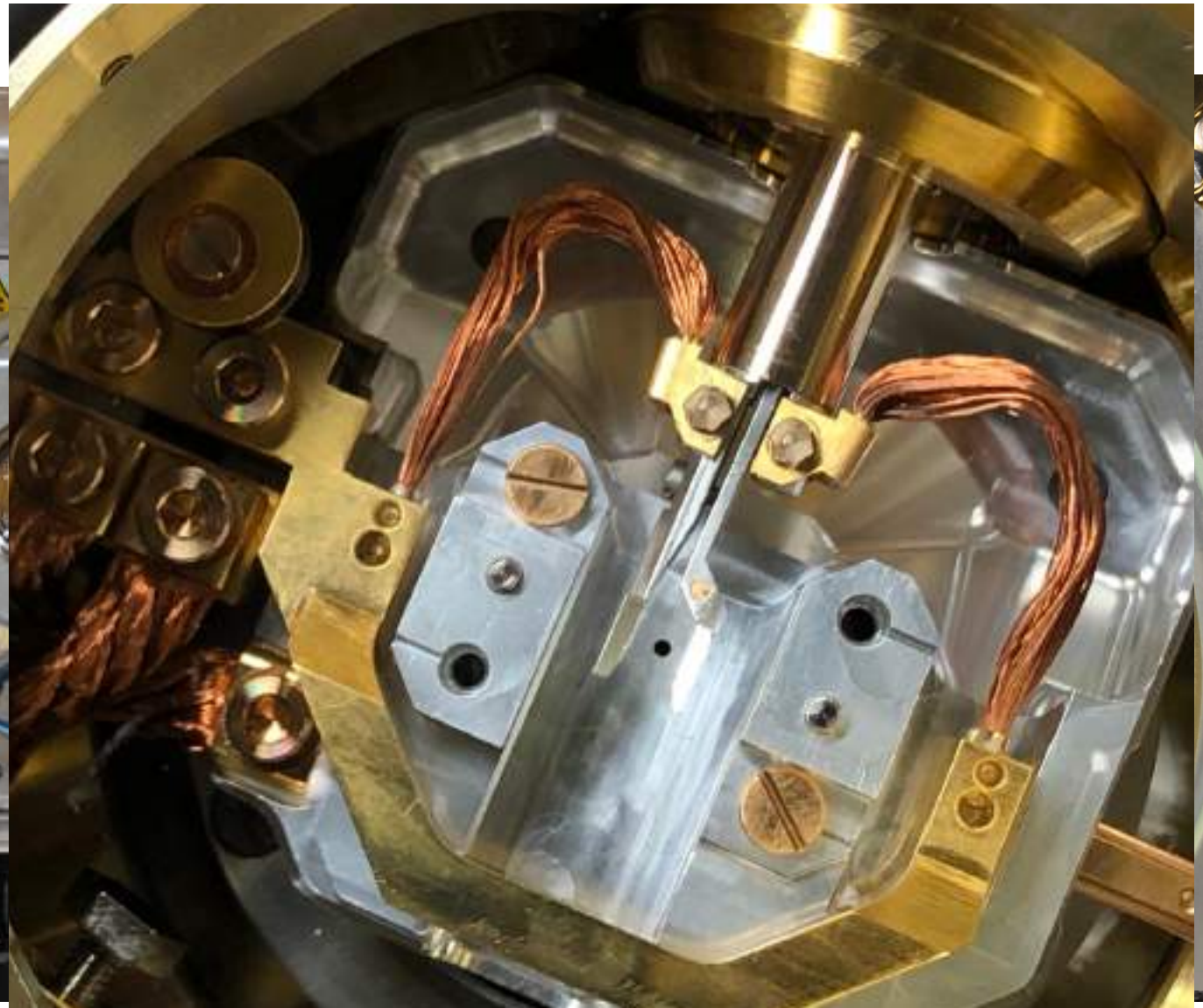




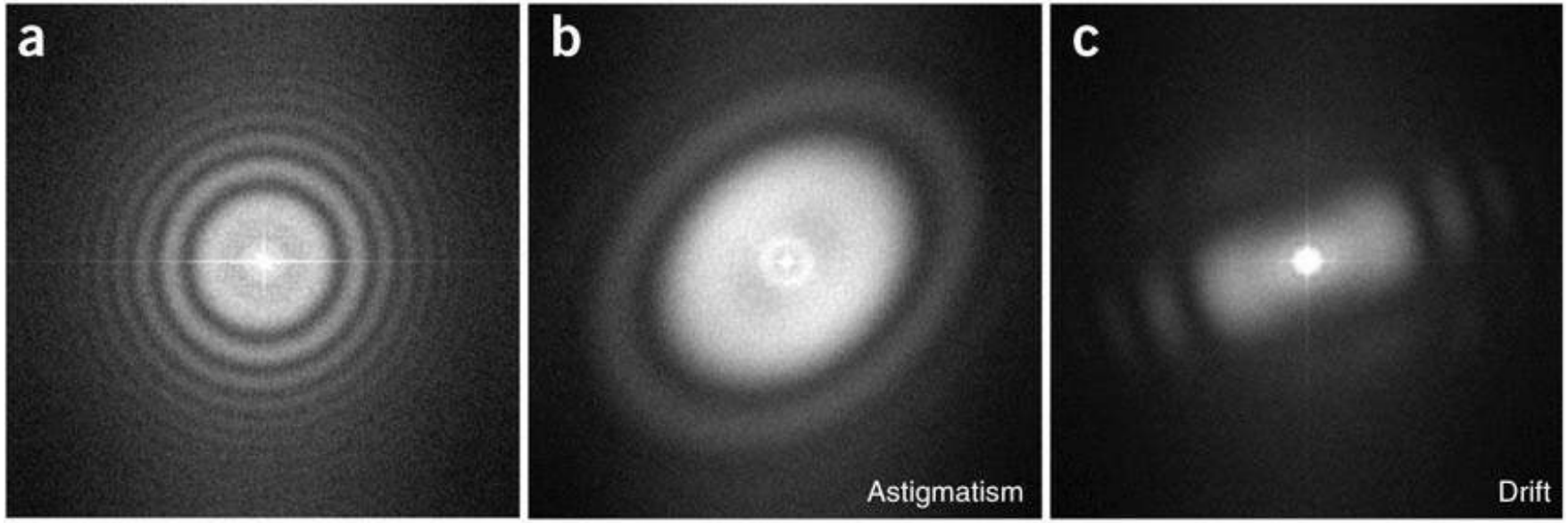
https://www.youtube.com/watch?v=tYCET6vYdYk

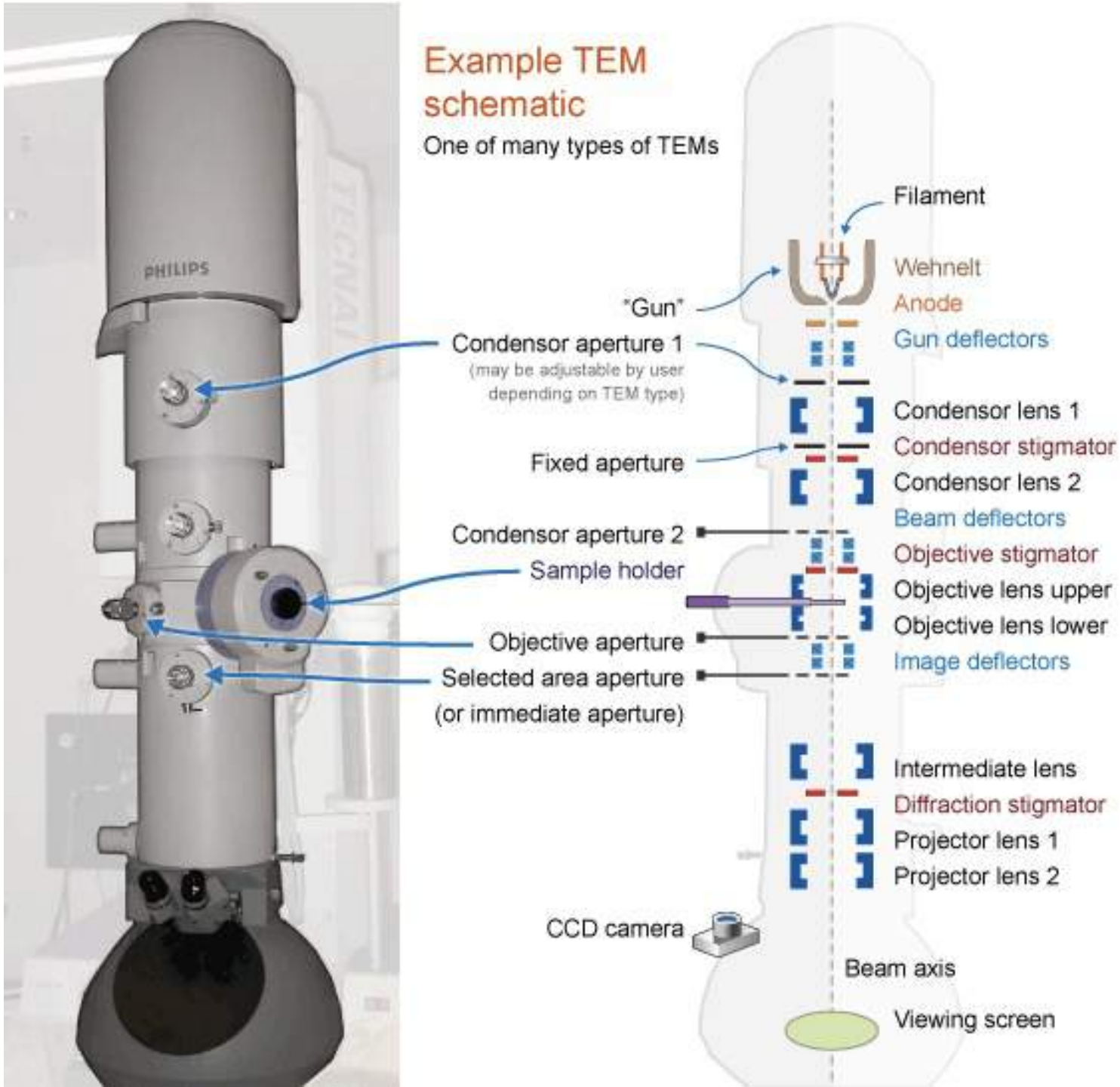
VACUUM SYSTEMS





CTF: WHY IS MONITORING THE CTF IMPORTANT IN OUR DATA COLLECTION?



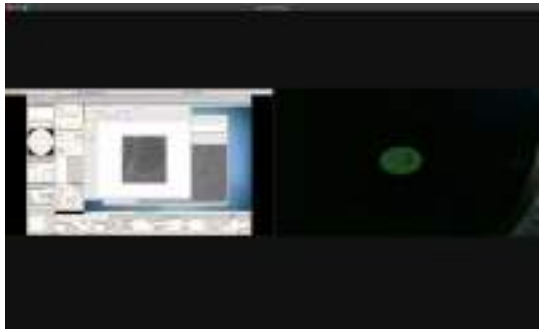


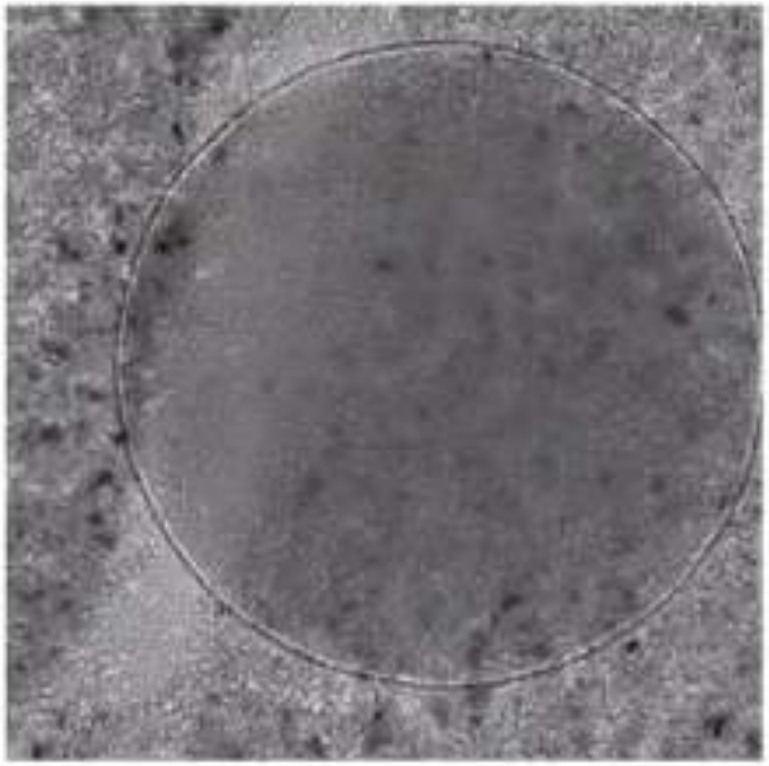
Example TEM schematic

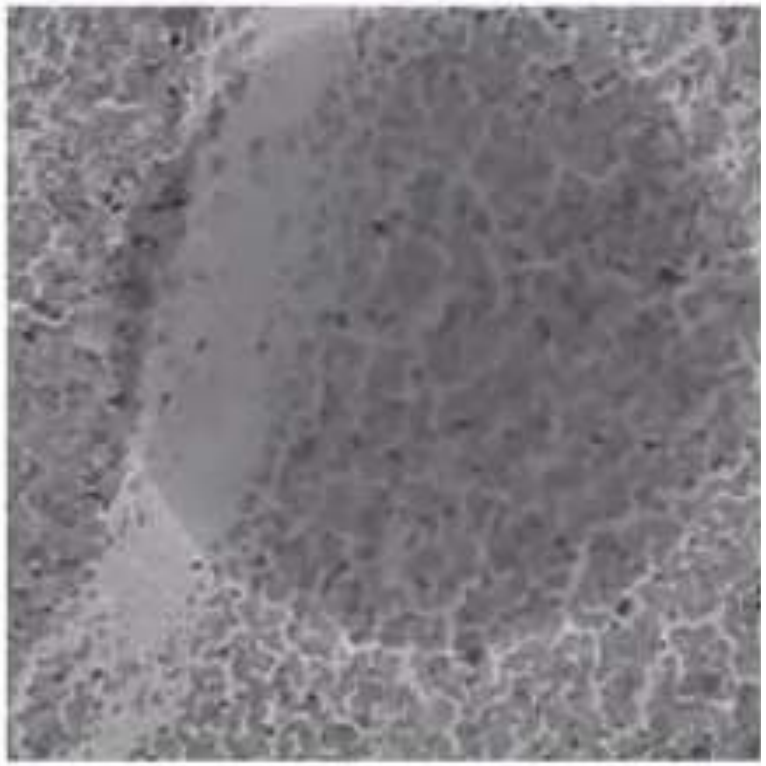
One of many types of TEMs

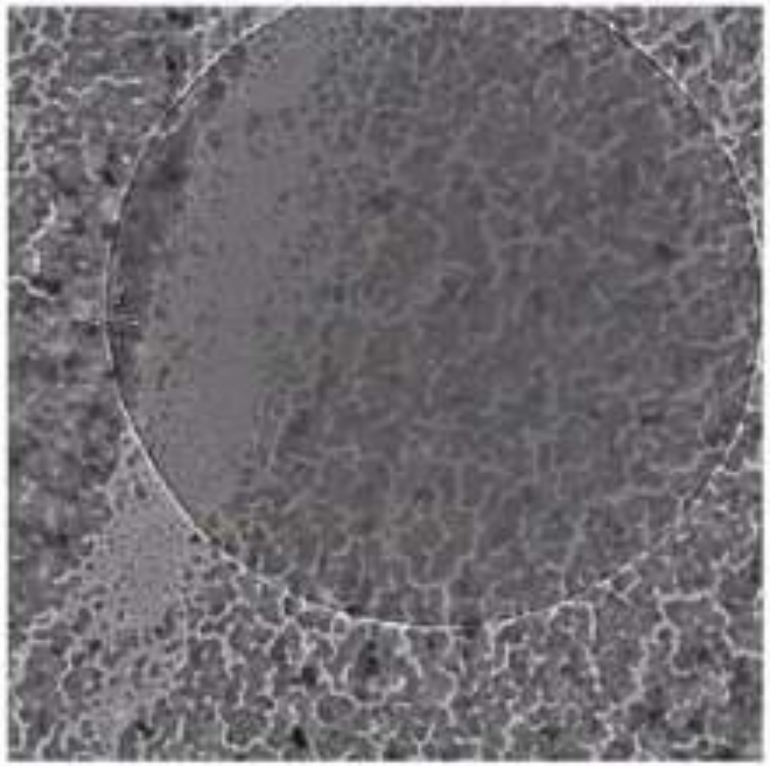
Filament
Wehnelt
Anode
"Gun"
Gun deflectors
Condensor aperture 1
(may be adjustable by user depending on TEM type)
Condensor lens 1
Condensor stigmator
Fixed aperture
Condensor lens 2
Beam deflectors
Condensor aperture 2
Objective stigmator
Sample holder
Objective lens upper
Objective lens lower
Objective aperture
Image deflectors
Selected area aperture
(or immediate aperture)
Intermediate lens
Diffraction stigmator
Projector lens 1
Projector lens 2
CCD camera
Beam axis
Viewing screen

FOCUS









- Transmission Electron Microscopy: A Textbook for Materials Science

By David B. Williams, C. Barry Carter

THE QUALITY OF YOUR DATA IS AT LEAST DIRECTLY PROPORTIONAL TO THE QUALITY OF YOUR SPECIMEN.

TECHNIQUES TO FRAME THE START

Cells

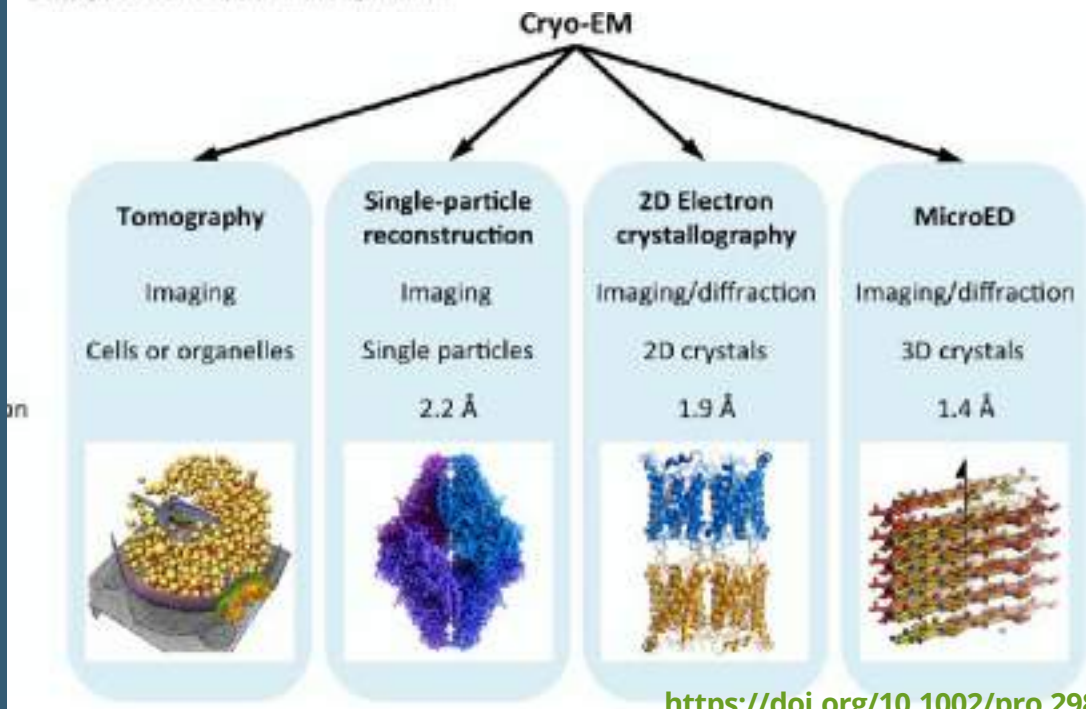
Organelles

3D Crystals

2D Crystals

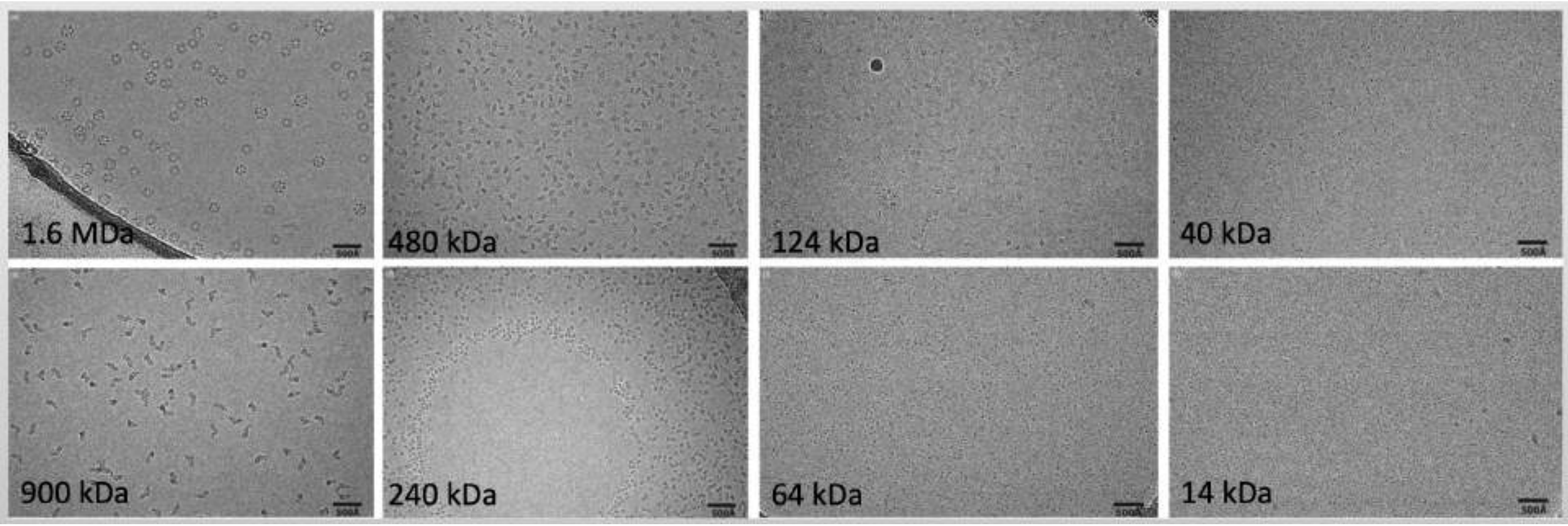
Individual Macromolecules

http://www.boruhealthmachine.org/what-is-meant-by-the-resolving-power-of-a-microscope.html



https://doi.org/10.1002/pro.29

DOES SIZE MATTER?



Kutti R. Vinothkumar *et al*., 2016

CONSIDERATIONS FOR SAMPLES THAT WILL BE ANALYZED BY CRYOEM

- specimens must be thin
- vacuum in the microscope
- radiation damage
- low signal:noise
- charging

SAMPLES SUITABLE FOR EM

A major limiting factor for structure determination is specimen preparation.

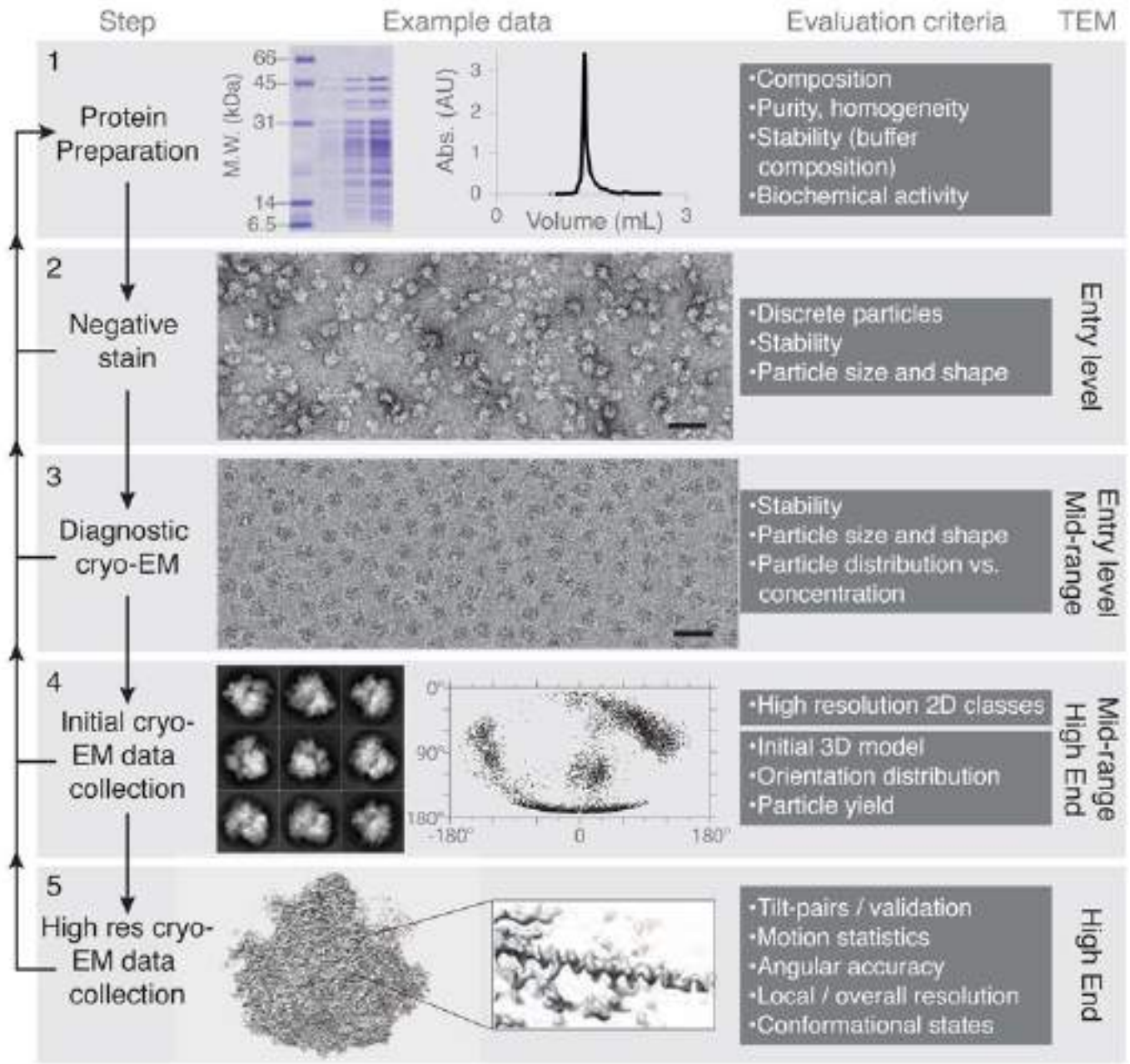
The origin of this limitation is two-fold in nature:

1. During the creation of a thin layer of water for vitrification and imaging, specimens are exposed to surfaces and conditions which are very different from the inside of a test tube or cell. The effects of these on the molecules and complexes are not known *a-priori*, and can be difficult to remedy if destructive to the specimen.
2. Specimen preparation for cryo-EM is a delicate process that still requires skilled handling and careful technique through a number of detailed preparation steps. This often confounds novice and experienced microscopists alike by making it difficult to distinguish problems with the specimen from problems in technique and methods.

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5140023/

THE OPTIMIZATION WORKFLOW

Structure determination by cryo-EM. A systematic approach to 3D structure determination is shown. In the left column, the major steps are listed. Each step should be performed successively and only after one has been completed successfully should the scientist move onto the next step. In the second column, example data are shown for ribosomes (details in text). Scale bars on the micrographs are 500 Å. Each step should be evaluated with the criteria listed in the third column, returning to earlier steps for troubleshooting.

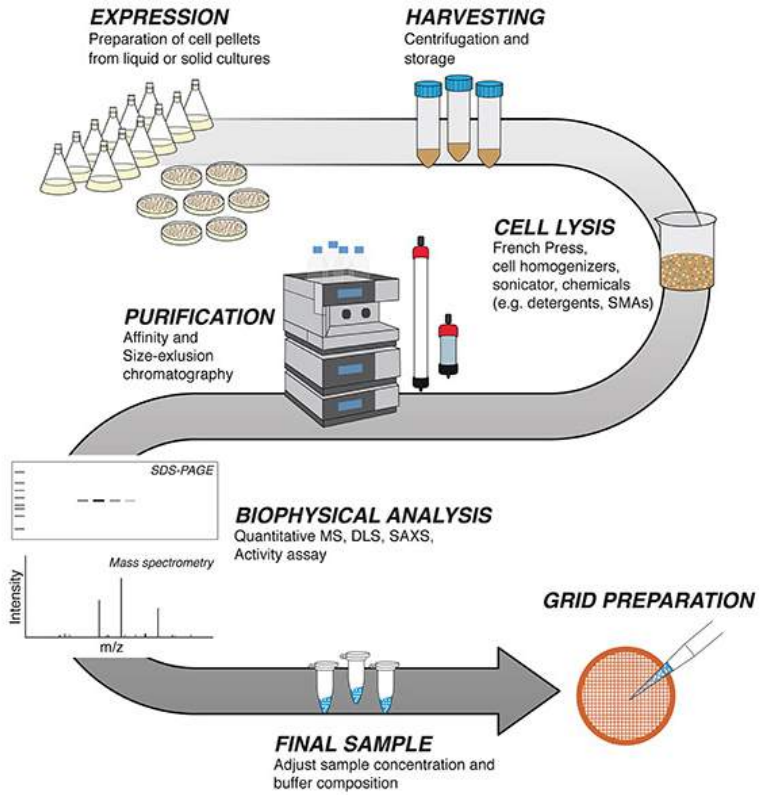


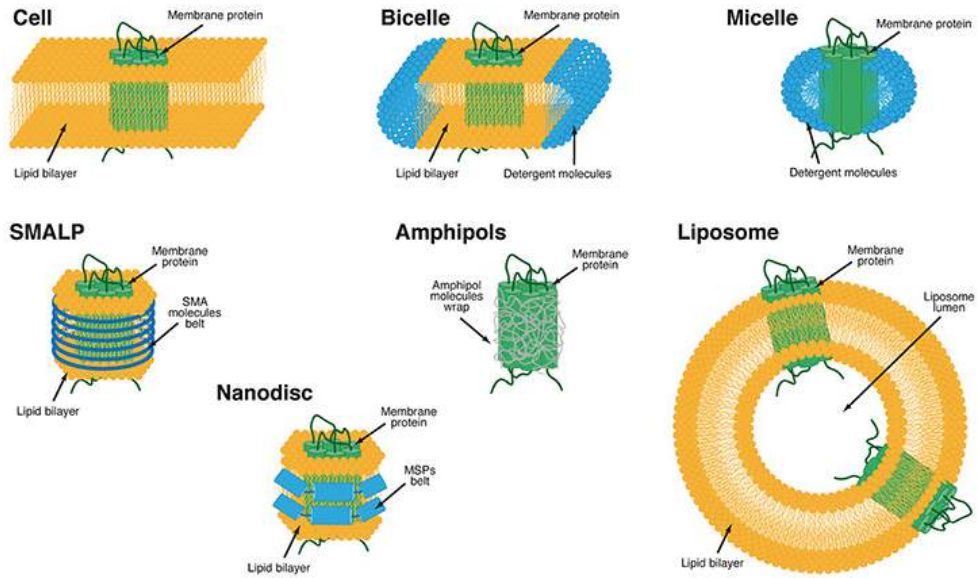
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5140023/

CRYOEM IS STILL STRUCTURAL BIOLOGY

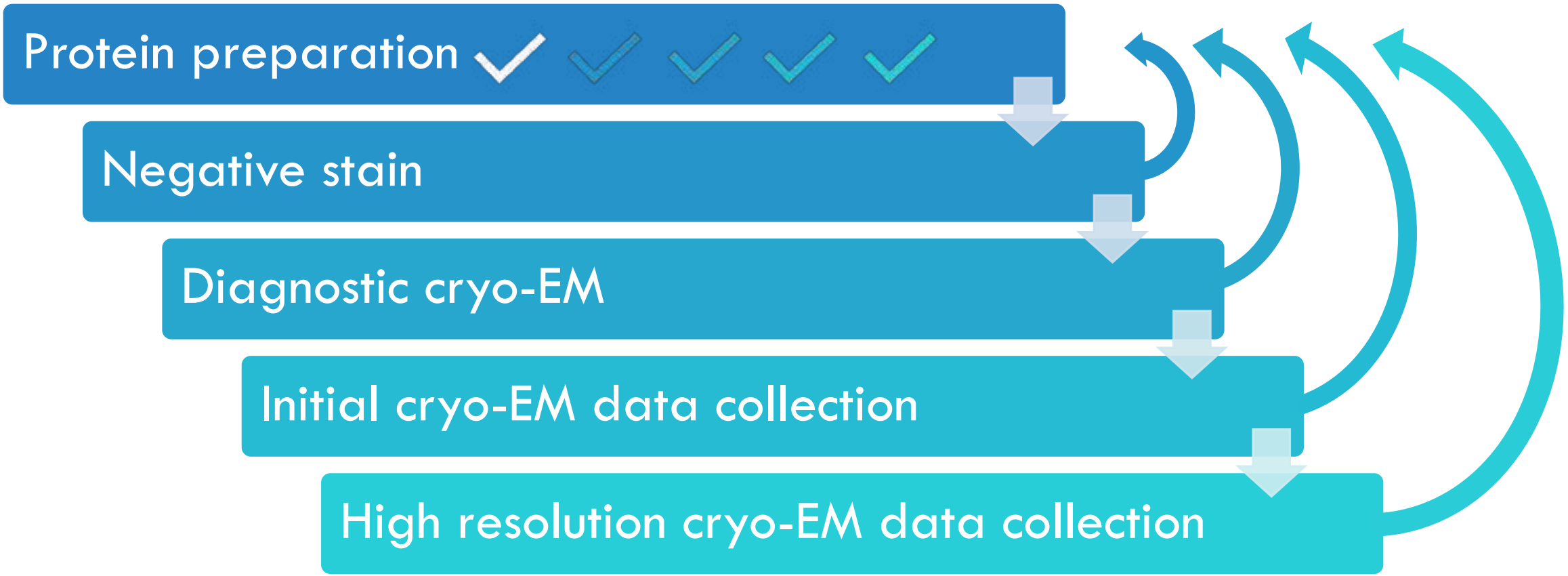
- The first step in a systematic approach is to evaluate several biochemical and biophysical aspects of the protein sample, such as composition, purity, homogeneity, stability, and biochemical activity.
- Contaminating proteins or degradation products may interfere with complex stability and subsequent computational analysis of the particle images, wasting resources on the more time-consuming and expensive cryo-EM data collection and image processing steps. Evaluation of sample homogeneity by negative staining electron microscopy before cryo-EM grid preparation will help not only to validate that the correct purification protocol has been followed, but will also ensure that no contaminants or degradation products are present in the protein sample.
- Prior knowledge of the protein molecular weight and oligomeric state(s), and buffer composition (salt concentration, pH, co-factors, cryo-protectants and other additives) in which the protein is stable can remarkably facilitate cryo-EM grid preparation.

https://www.frontiersin.org/articles/10.3389/fmolb.2018.00074/full

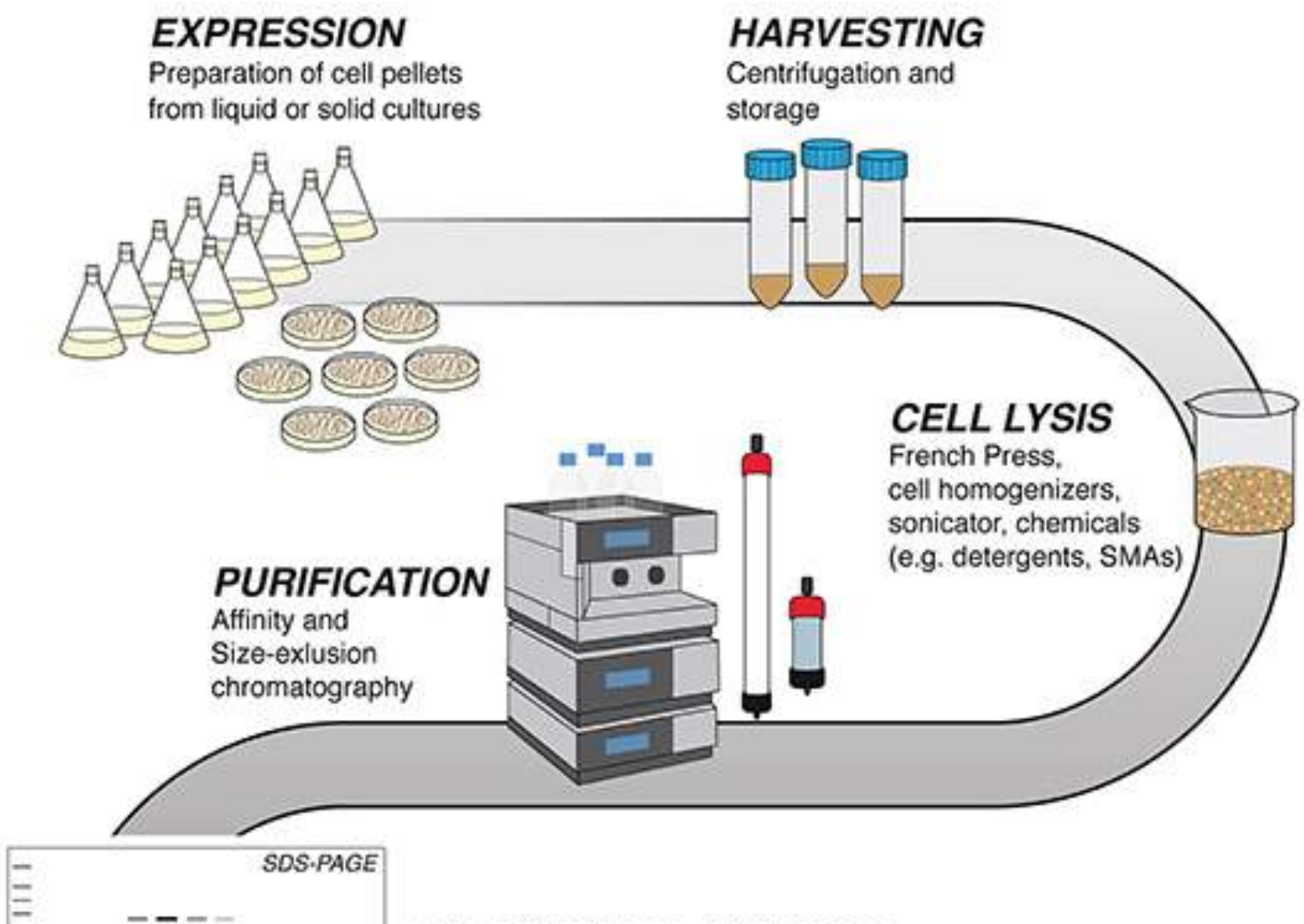




THE OPTIMIZATION WORKFLOW



PROTEIN PREPARATION



Molecular Biology

- Construct design
- Tags
- Genomic expansion
- Expression system

Biochemistry

- Composition
- Purity homogeneity
- Stability
- Biochemical activity

Markers

- Fabs/Nanobodies
- Fluorophores

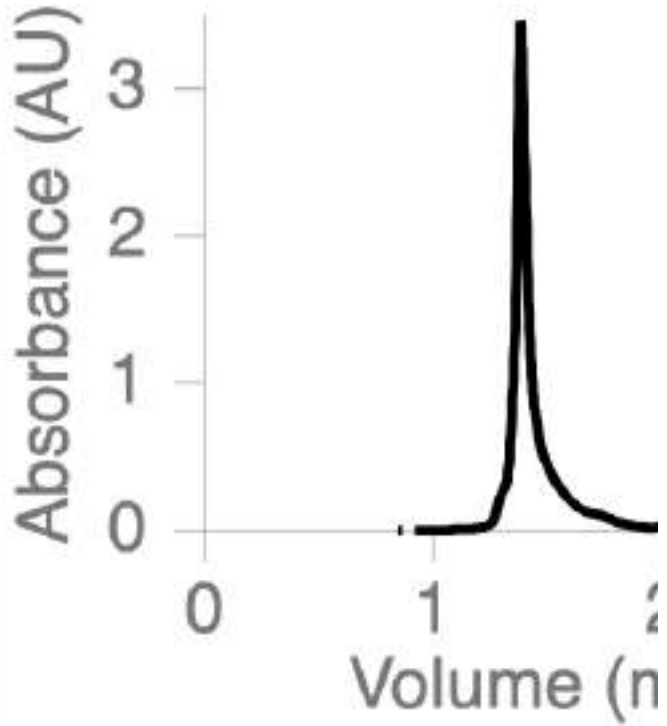
PROTEIN PREPARATION

Specimen homogeneity

SDS-polyacrylamide gel electrophoresis (PAGE), native-PAGE, Silver stain

size exclusion chromatography

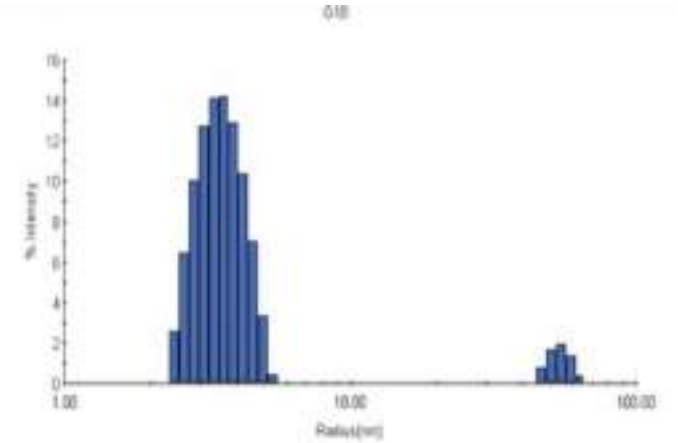
mass spectrometry



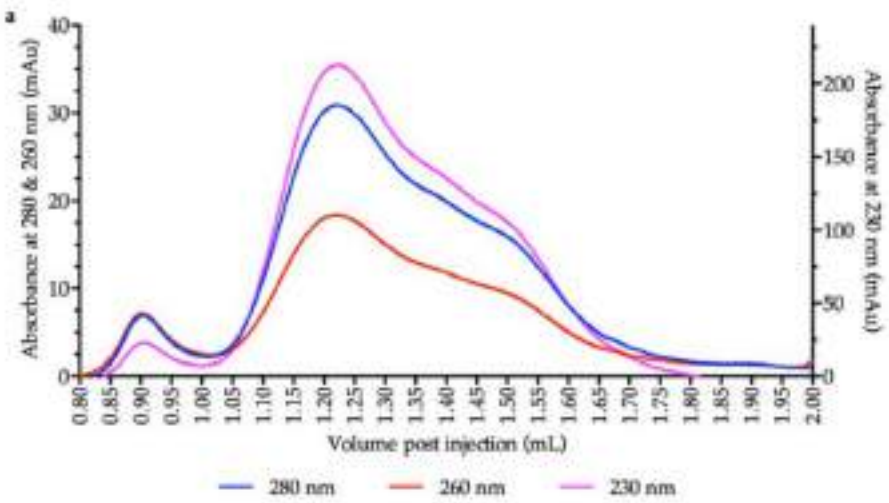
HOMOGENEITY OF SAMPLES

Optimize buffer conditions

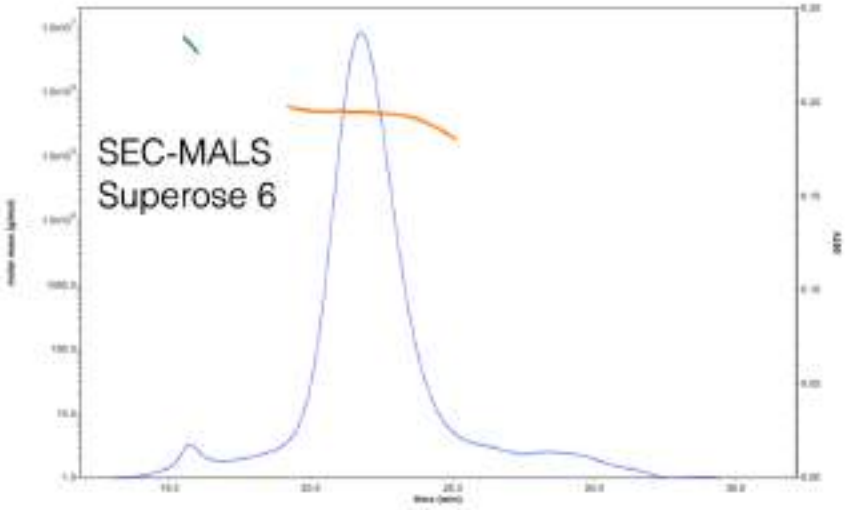
(salt, pH, detergent, etc…)



DLS
Dynamic Light Scattering



SEC
Size Exclusion Chromatography

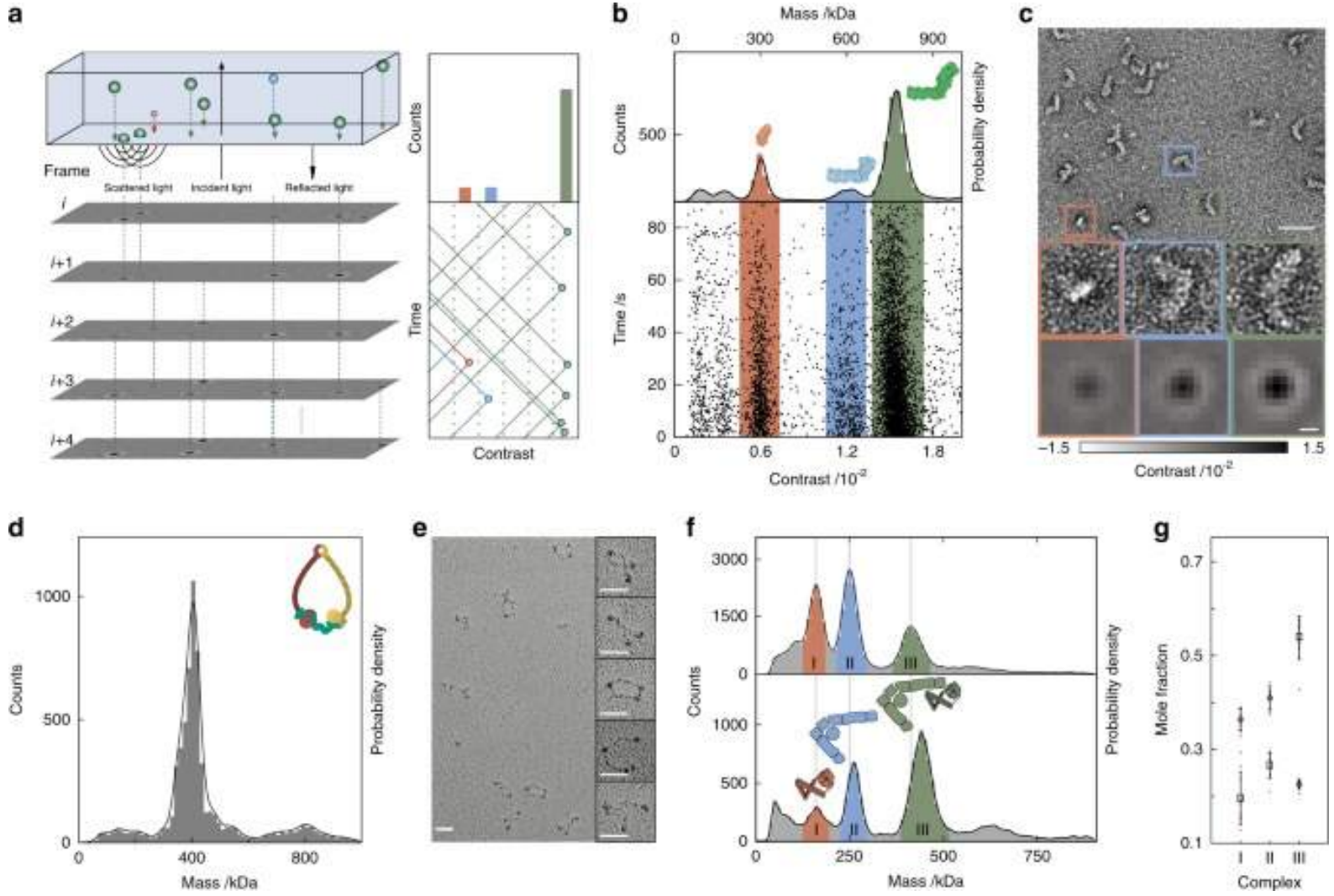


SEC-MALS
Size Exclusion Chromatography coupled to Multi Angle Light Scattering

HOMOGENEITY OF SAMPLES

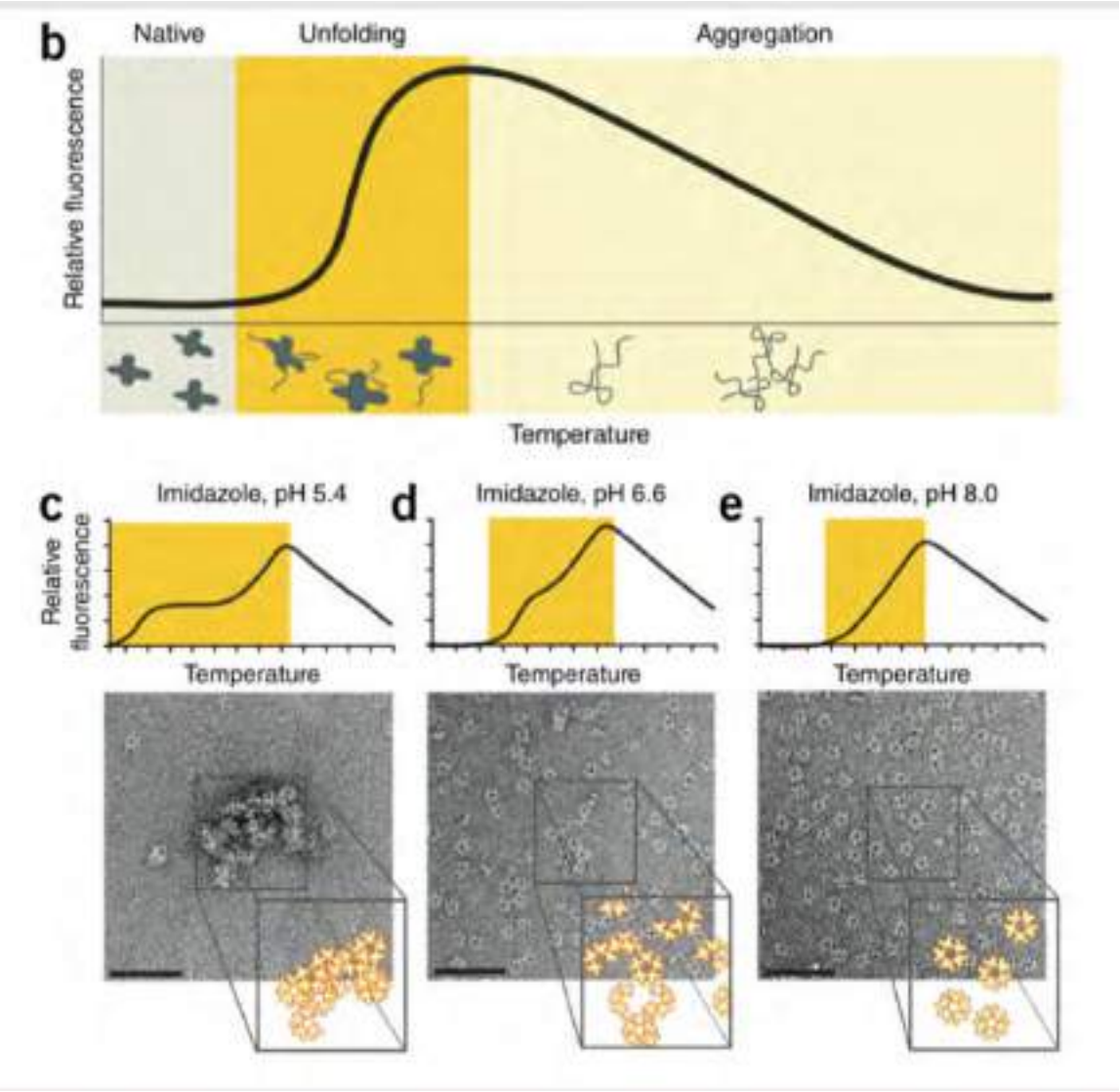
Mass photometry as a general method for characterizing biomolecular heterogeneity.

https://www.nature.com/articles/s41467-020-15642-w



SCREENING BUFFER CONDITIONS

sample stability can then be optimised by changing buffer conditions (e.g. salt, pH, detergent)



ProteoPlex thermal stability assay.

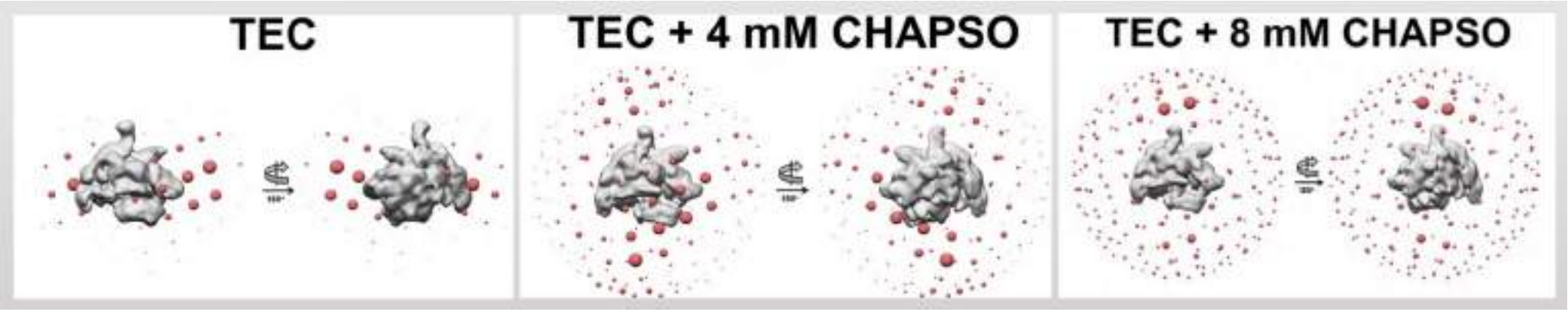
Holger Stark: Max Planck Institute for Biophysical Chemistry, Göttingen, Germany

Ashwin Chari et al., 2015

BUFFER COMPATIBILITY

Detergents can be used to relieve preferred orientation at air-water interface

- CHAPSO helps TEC (a bacteria RNA polymerase) distribute into diverse orientation.



James Chen et al., 2019

HOW MUCH SAMPLE IS NEEDED

Rules of thumb:

2 – 4 µl / grid

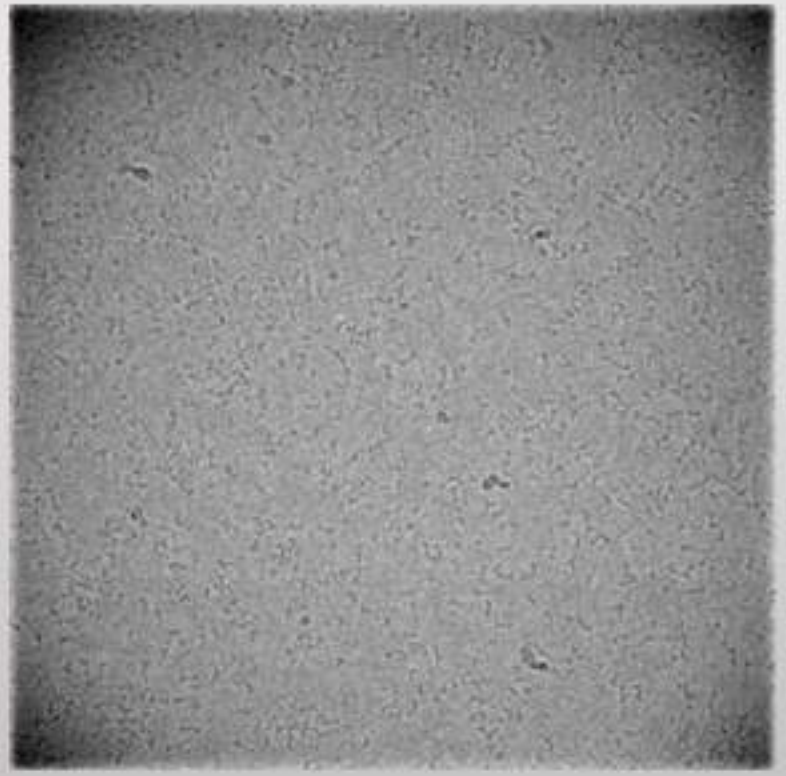
50 nM – 5 µM concentration

EM specimens are typically prepared using 3 µl protein solution at a concentration of 0.05 – 5 µM. Thus, it is essential for the protein complex to remain intact at these concentrations. If the dissociation constant (Kd) for the subunits is known, one can calculate whether it is expected to remain intact . Experimentally, one can run the protein complex on a size exclusion column repeatedly, at decreasing concentrations, to ensure it will not dissociate at the concentration required for cryo-EM.

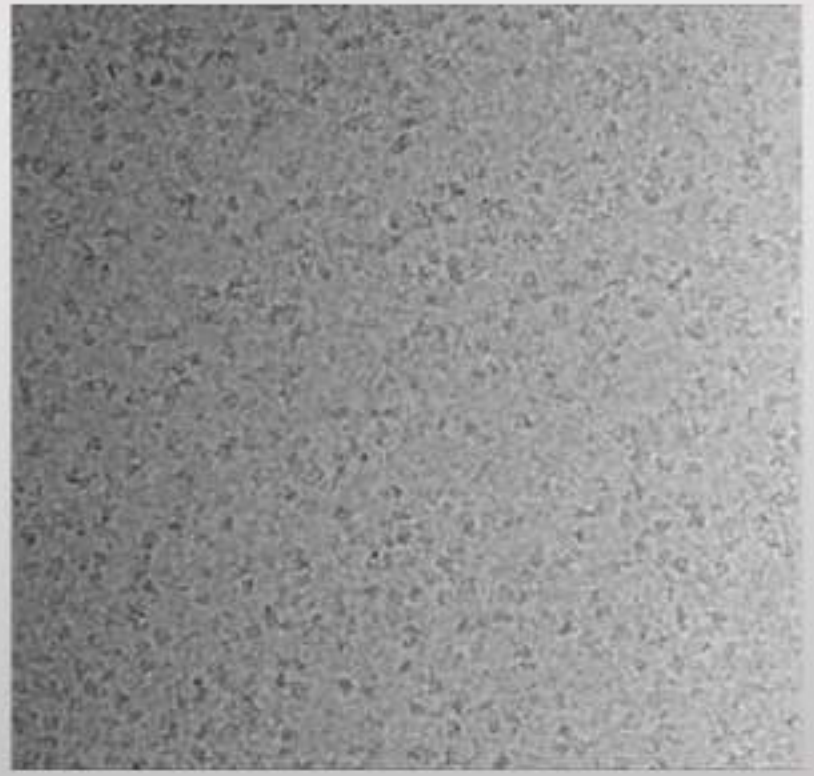
HOW MUCH SAMPLE IS NEEDED

For negative staining, 0.01-0.05 mg/ml.

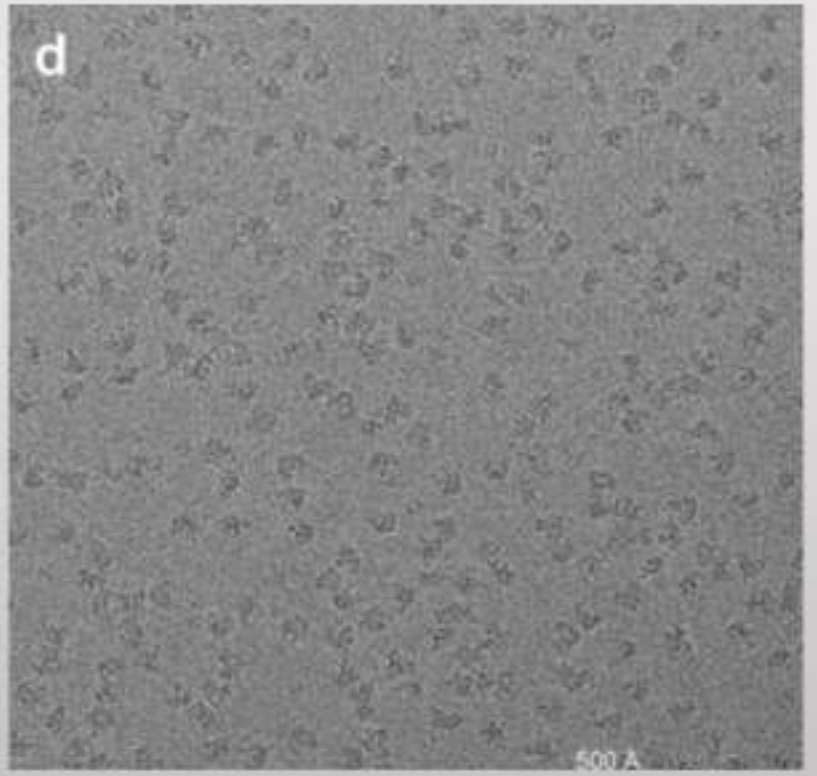
For cryo-EM, 0.1-5 mg/ml.



CTF3 complex, 130 kDa
0.2 mg/ml



Cas12a-AcrVA4/5 complex, 200 kDa
3 mg/ml



APC/C complex, 1.2 MDa
0.1 mg/ml on continuous carbon film

-slide from Leifu Chang

WHAT IF MY COMPLEX DISSOCIATES AT LOW CONCENTRATIONS?

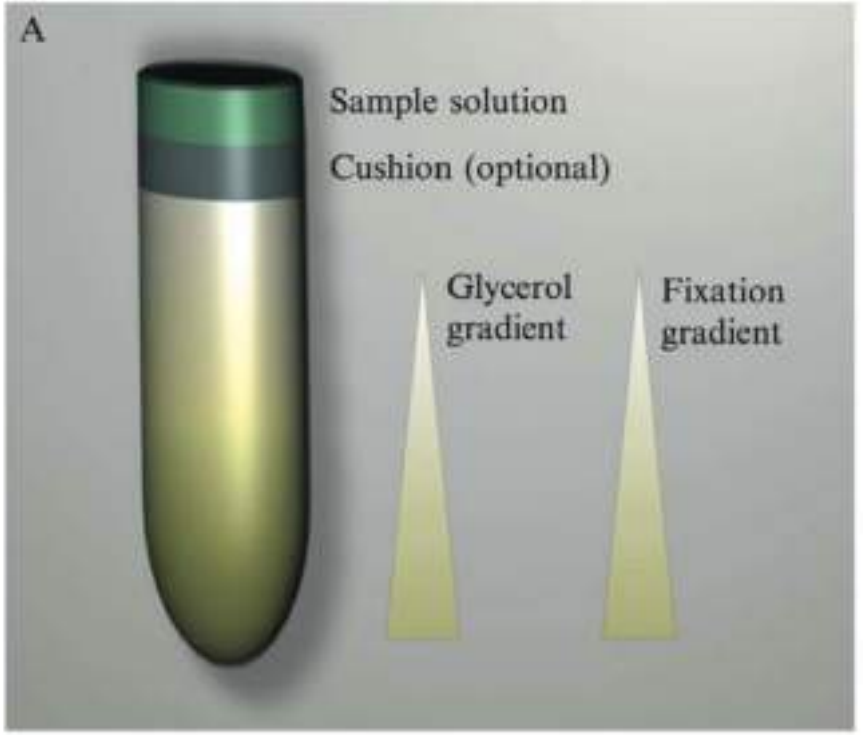
• Work at higher concentrations, adjust plasma and blotting

• Buffer conditions

• Crosslinking can stabilize protein- protein interactions (between subunits or domains)

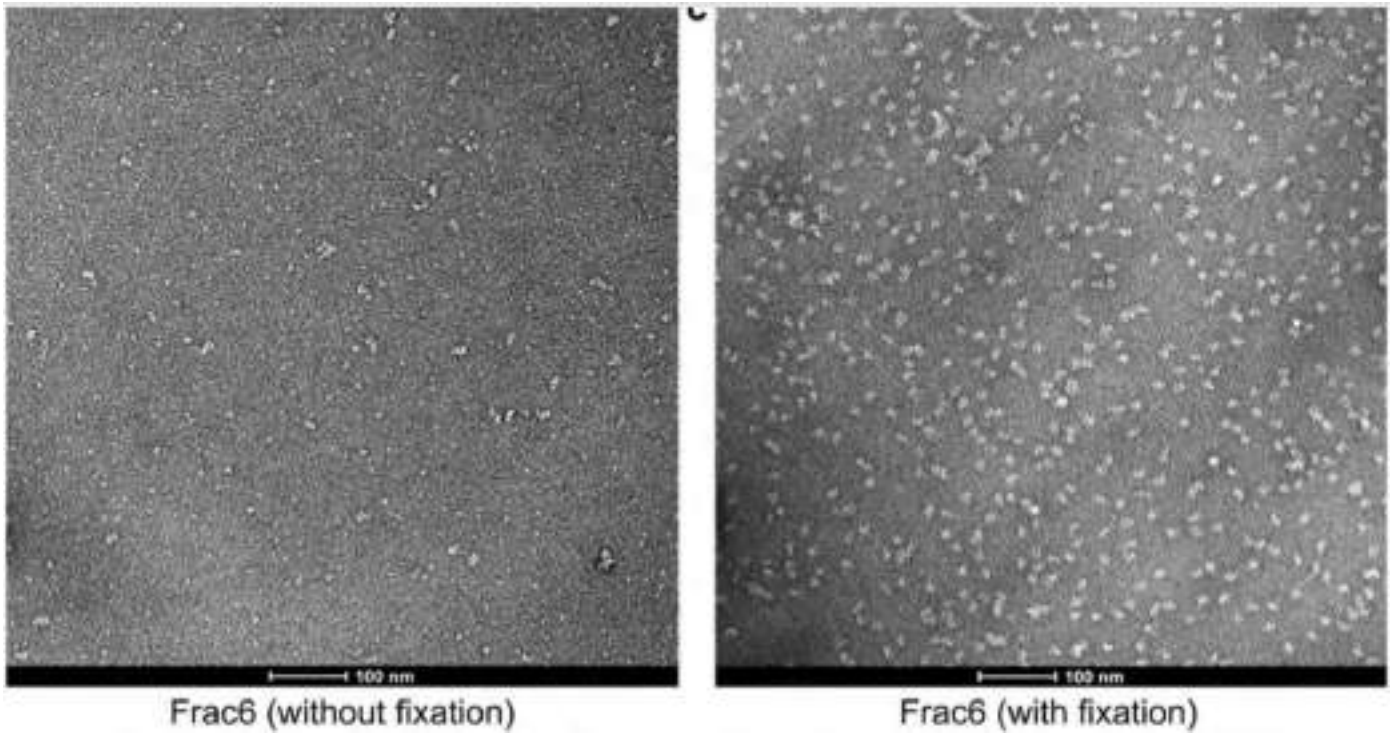
– Changes surface properties so can change particle orientations on grid

– Must minimize or remove aggregates due to intra-complex crosslinks



Kastner *et al*, 2008 | Stark, 2010

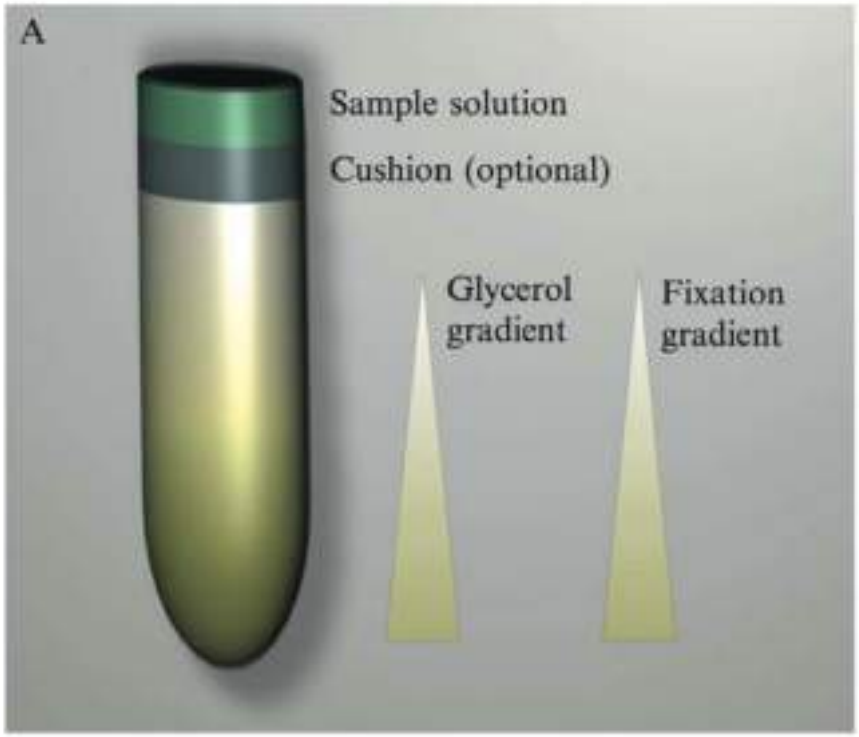
WHAT IF MY COMPLEX DISSOCIATES AT LOW CONCENTRATIONS?



Frac6 (without fixation)

Frac6 (with fixation)

Li *et al*, 2018



Kastner *et al*, 2008 | Stark, 2010

ADDITIONAL CONSIDERATIONS: MEMBRANE PROTEINS

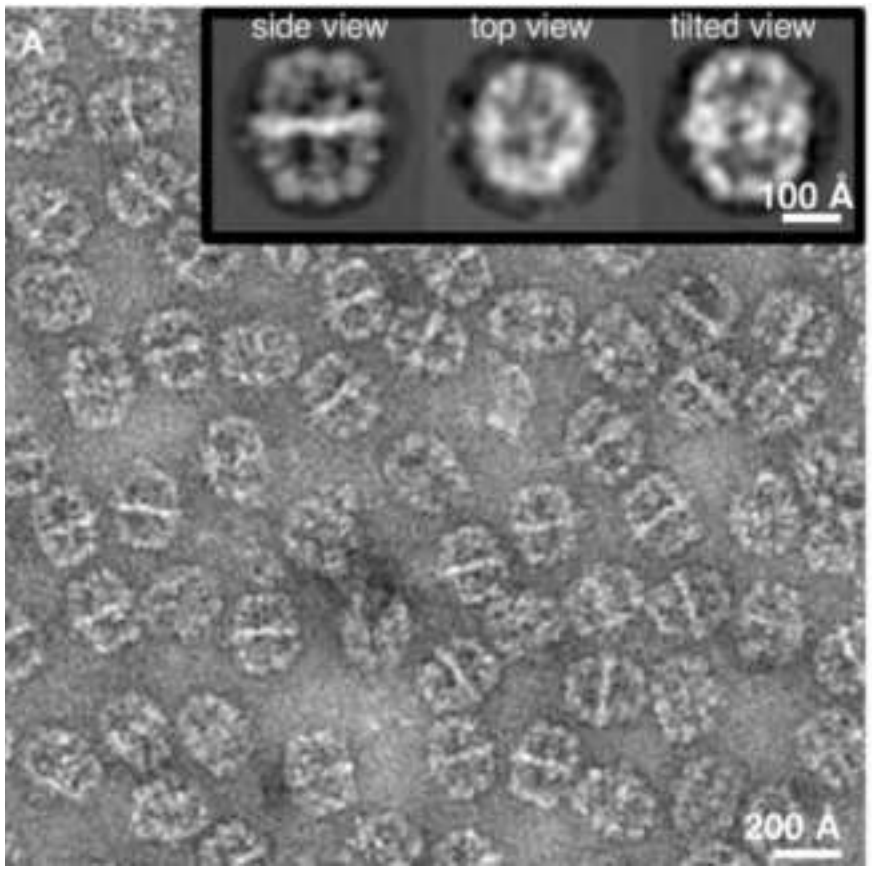
Choice of Detergents

- Amphipols: a hydrophilic backbone and hydrophobic side chains
- Amphipols have been successfully used in cryo-EM for many membrane proteins

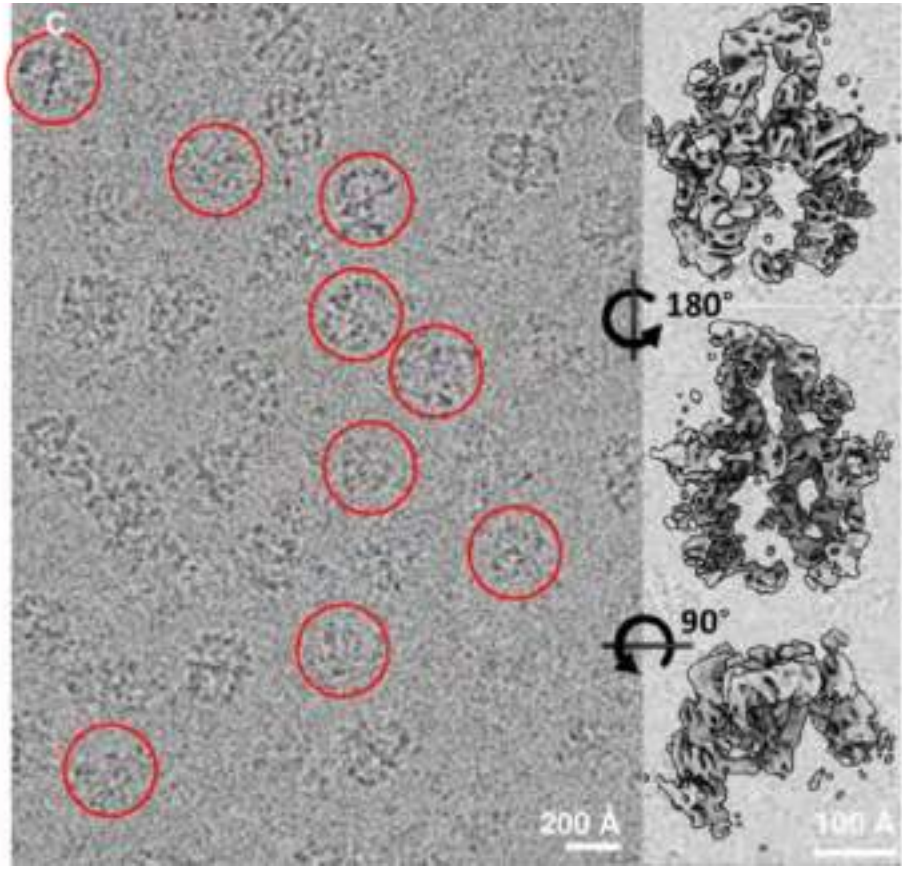
Nanodiscs

- MSP- Nanodiscs can stabilize proteins and offer membrane proteins a native bilayer.
- SMALPS- Endogenous bilayers may be used

ADDITIONAL CONSIDERATIONS: DENATURATION



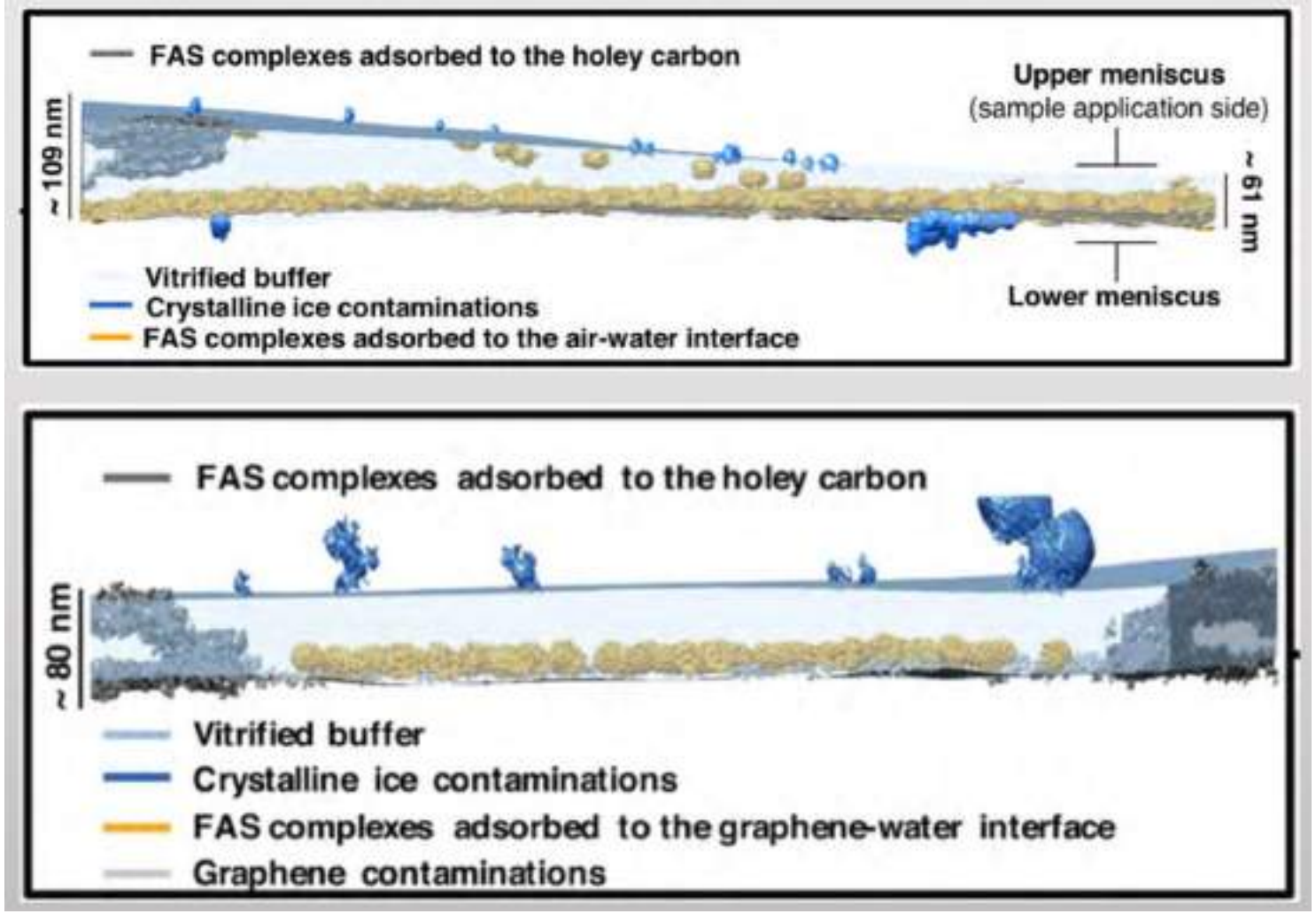
negative stain



cryoEM

D'Imprima *et al.*, 2019

ADDITIONAL CONSIDERATIONS: DENATURATION



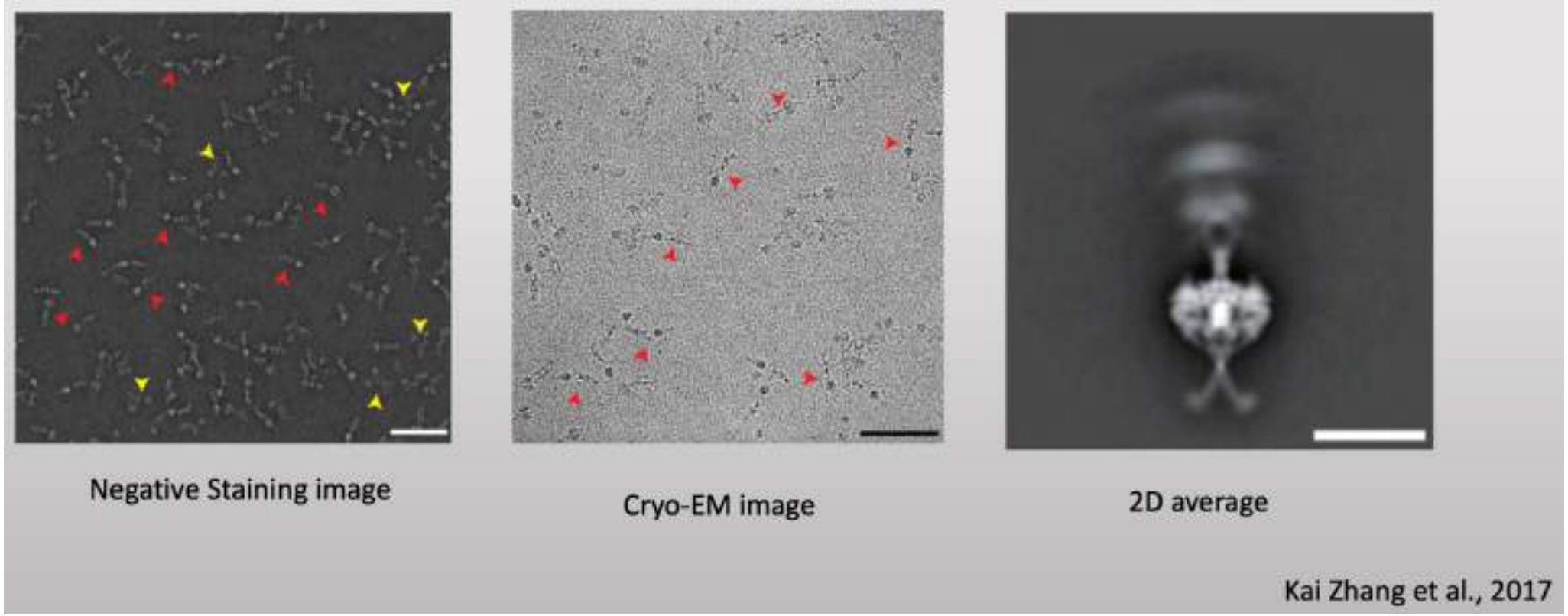
without graphene

with graphene

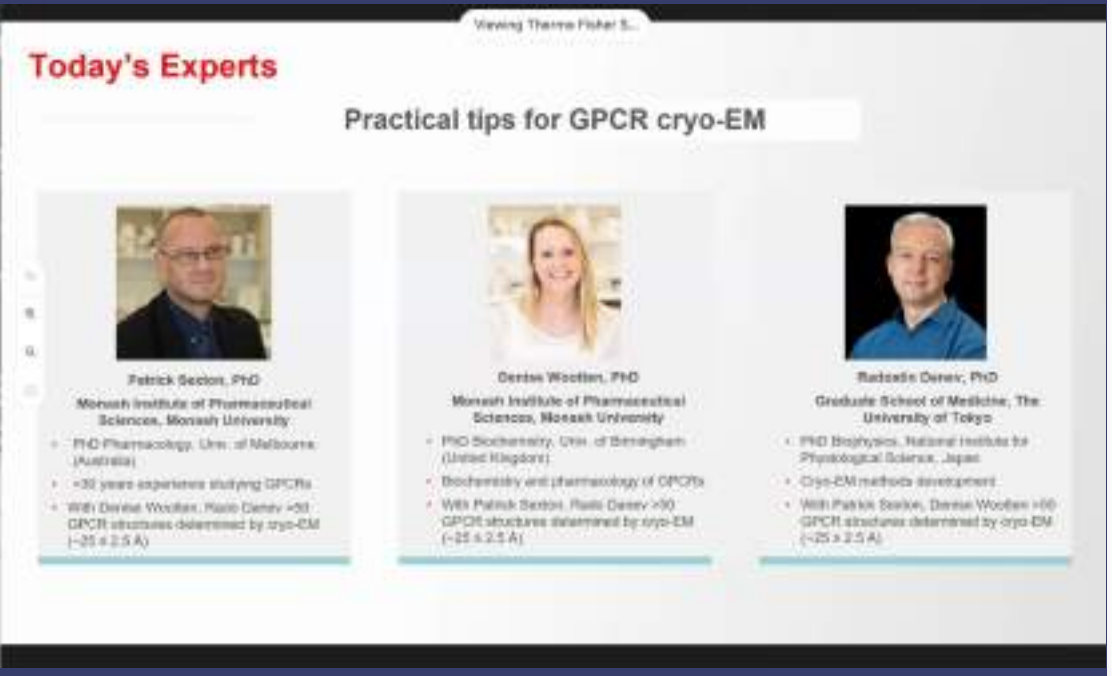
D'Imprima *et al.*, 2019

ADDITIONAL CONSIDERATIONS: FLEXIBILITY

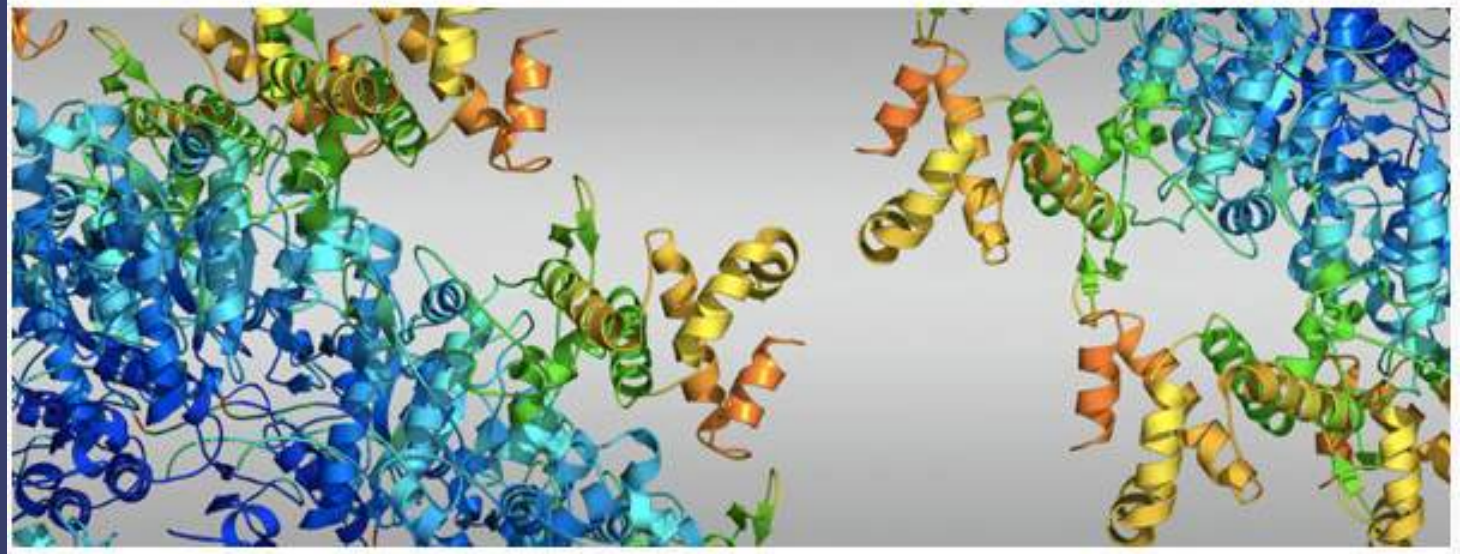
Dynein has a globular motor domains and flexible tail.



ROUTINE USE OF SPA



ThermoFisher SCIENTIFIC



Join a discussion on sub-2.5 Å cryo-EM structure determination of GPCRs for drug design

Wed, Sep 9, 2020, 8 p.m. EDT | 5 p.m. PDT | 10 a.m. AEST | 9 a.m. JST

Attend our upcoming *Ask the Experts* Q&A session on routine sub-2.5 Å cryo-EM structure determination of GPCRs for drug design. This rapidly developing field is constantly producing new and exciting biological and pharmacological discoveries. Ask questions and get answers from leading academic investigators in the field.

You'll learn about:

- GPCR biochemistry and purification for cryo-EM
- GPCR sample preparation for cryo-EM
- High-resolution single-particle cryo-EM imaging and 3D reconstruction of GPCRs

TIPS AND TRICKS FOR

Viewing Thermo Fisher S...

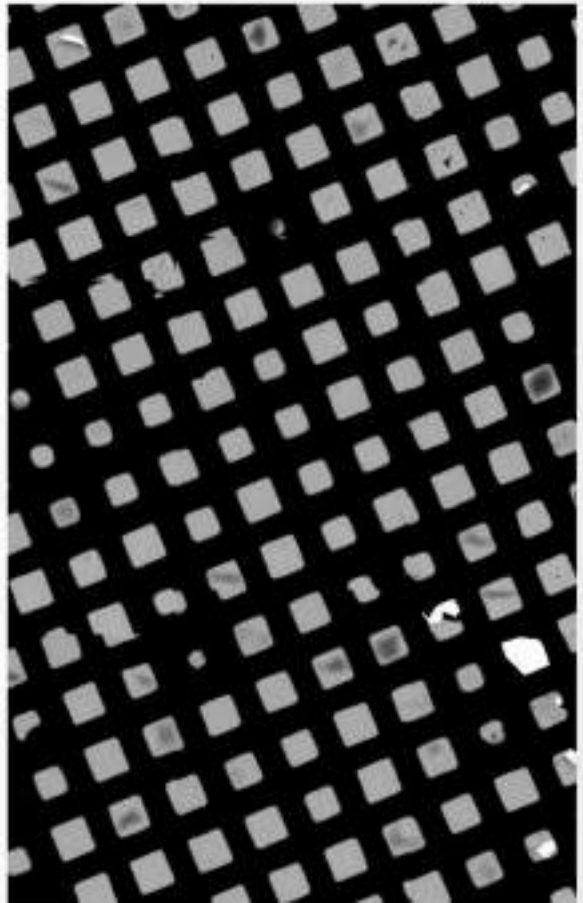
Cryo-EM sample preparation

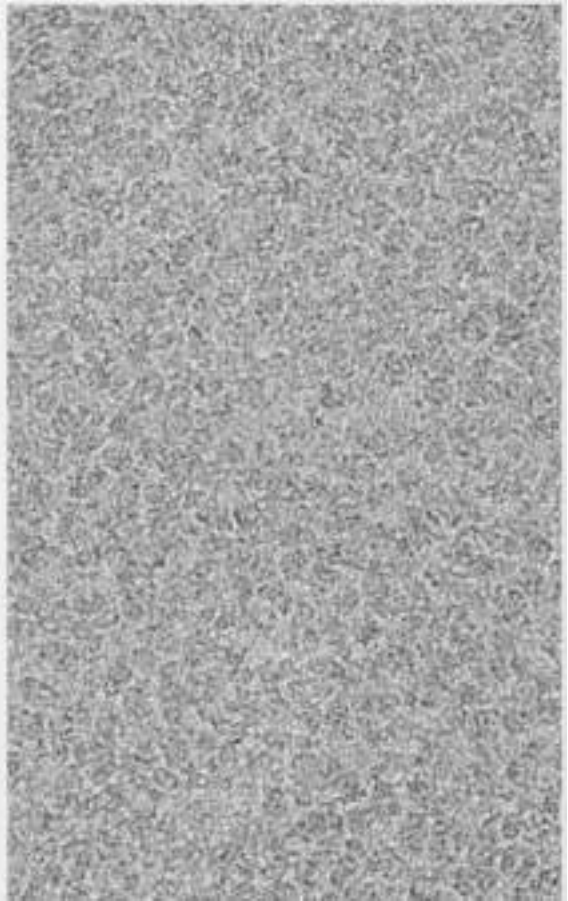
MONASH University

東京大学 THE UNIVERSITY OF TOKYO

- **The quality of the cryo-EM sample governs the outcome of the experiment!**

- We optimized the plunging parameters for ice thickness consistency and grid coverage
- Our blot time is relatively long: 10 s
- For every new sample, depending on the initial concentration, we prepare 2-3 grids with 2x dilution in-between
- GPCR sample concentrations in the range 3 – 7 mg/ml work best.
- Avoid as much as possible lower concentrations!
- Gold foil grids (UltrAuFoil) improved the consistency of getting uniformly thin ice and reduce beam-induced motion.





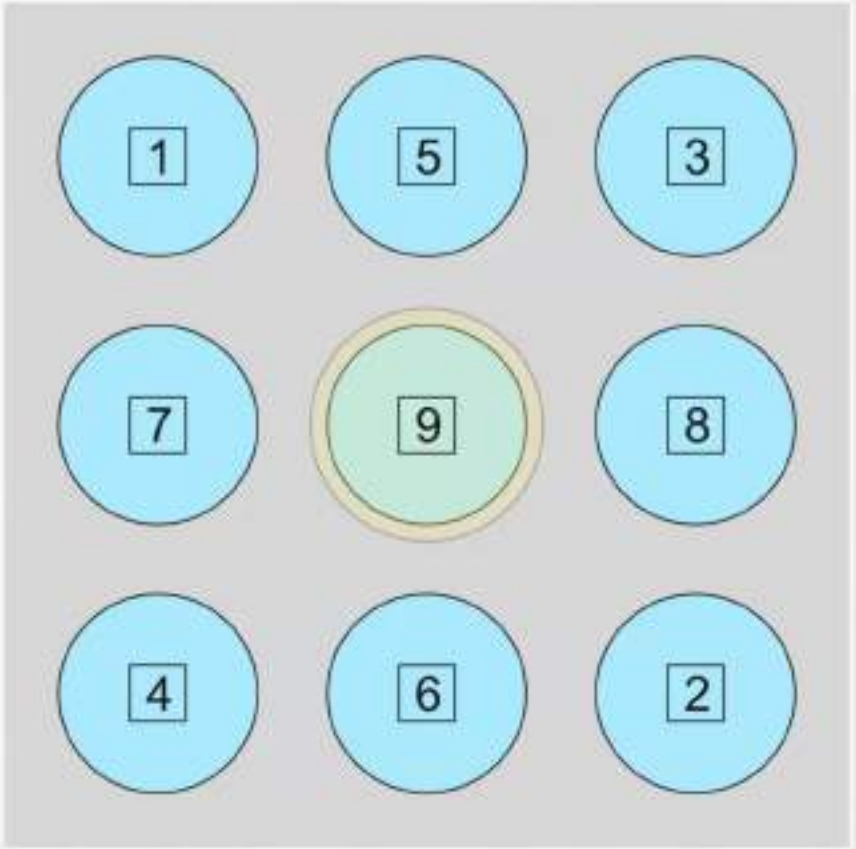
DATA COLLECTION

Viewing Thermo Fisher S...

Cryo-EM data acquisition strategy

- **Collect on the thinnest possible ice that still has good particle coverage !**

- We used 3 x 3 = 9-hole beam-image shift data acquisition scheme, 1 image/hole, realized with home-made scripts in SerialEM
- Defocus range: 0.5 – 1.5 µm. Start at the high end on the first hole and reduce the defocus step-wise for each hole in the pattern, e.g. 1.4 → 1.3 → 1.2 → … → 0.6
- Use an energy filter with <15 eV slit
- Do not use super-res (K3), select pixel size ≈ 1/3 the resolution you are hoping to get. Use EER with Falcon 4.
- Throughput: 1 sample/day ≈ 1 structure/day; ~5,500 movies
- Collect non-gain-normalized compressed TIFFs/EER. prepare your own gain reference with Relion



WHAT FACTORS MATTER

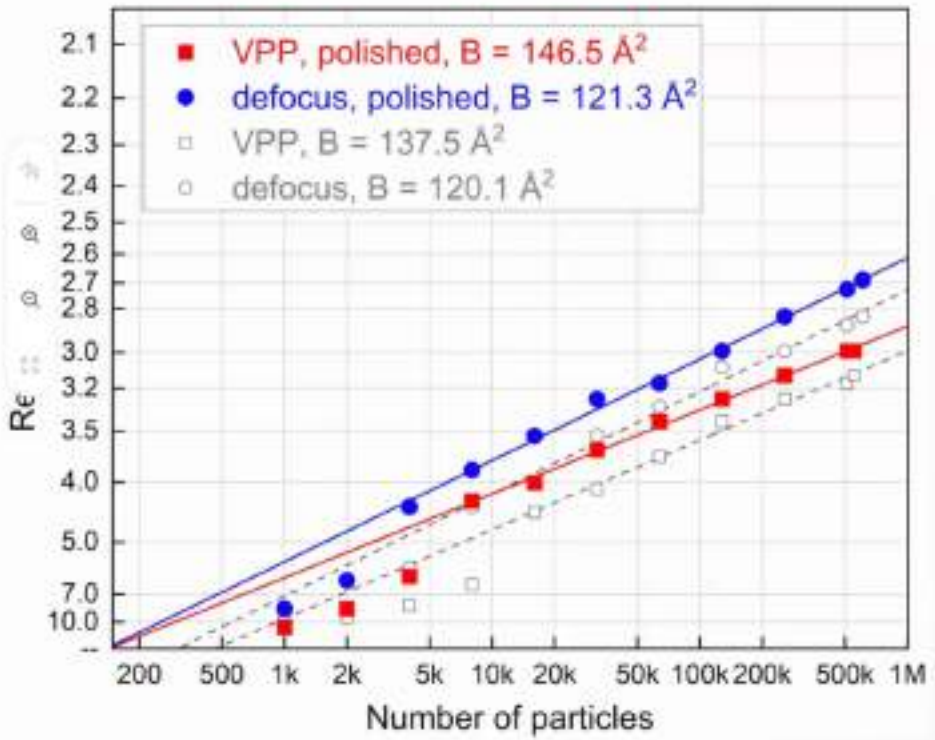
Viewing Thermo Fisher S...

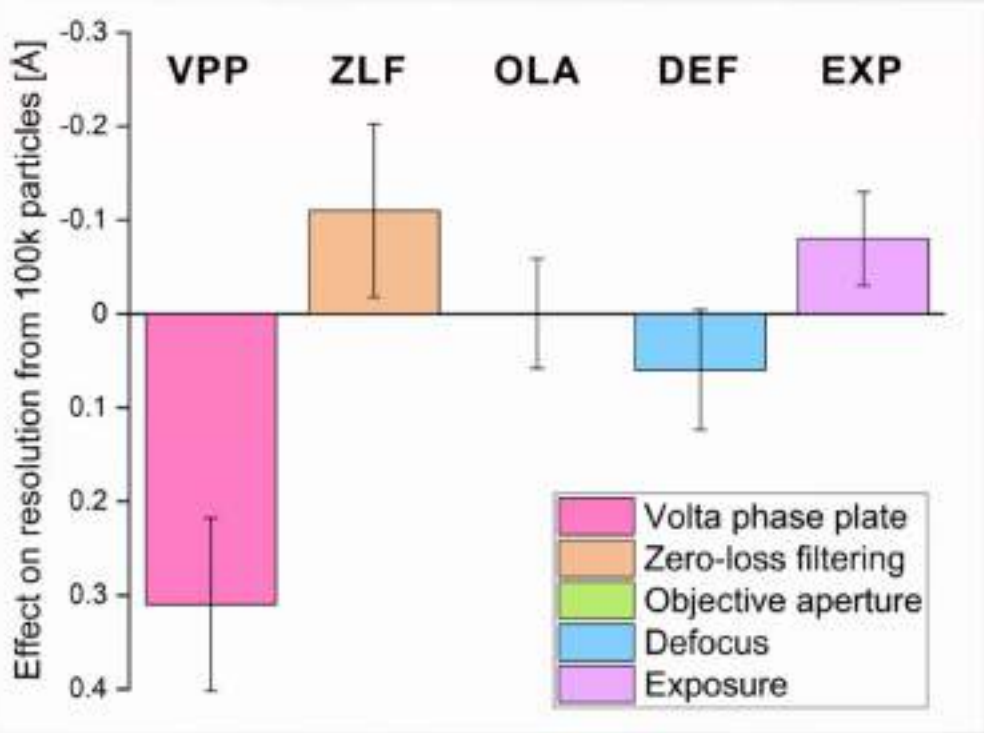
MONASH University

東京大学 THE UNIVERSITY OF TOKYO

Performance factors

- Do not use VPP; use zero-loss filtering; defocus <1.5 µm; total exposure ≥60 e/Å²





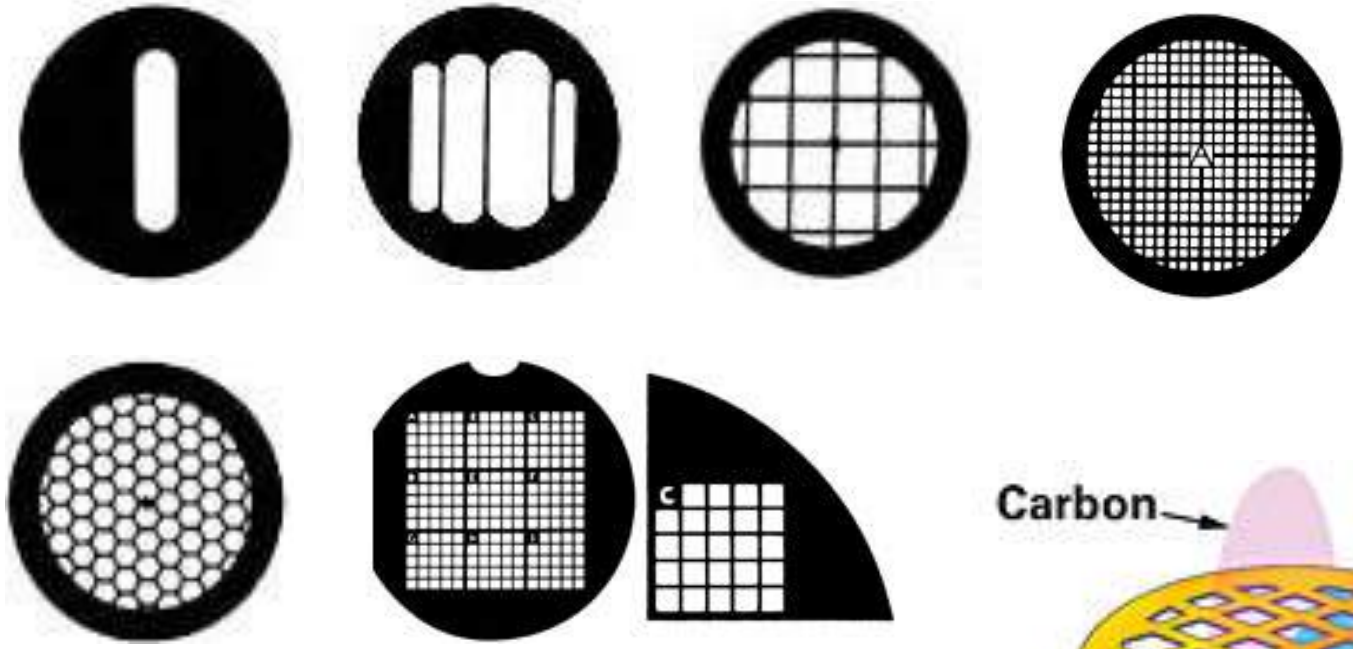
IMPACT OF GRIDS

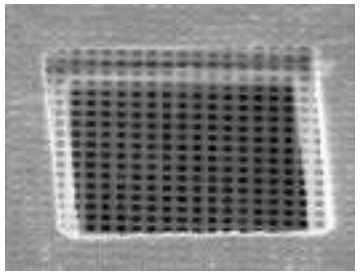
ED'S EM TOOLKIT

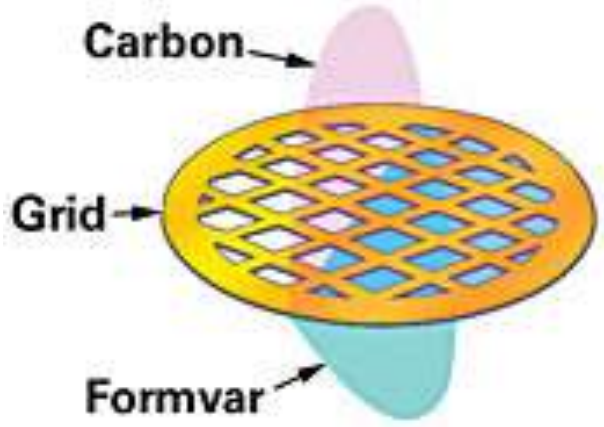
WHAT IS INSIDE?

If EM is a major part of your project or you become a regular EM user, you should have your own EM supplies and build an EM toolbox.

GRIDS







Common Materials

Copper

Nickel

Gold

Aluminum

Molybdenum

Titanium

Stainless Steel

https://www.tedpella.com/grids_html/

GRIDS: STATS

Rough grid parameters

Rim Width: 350-400µm.

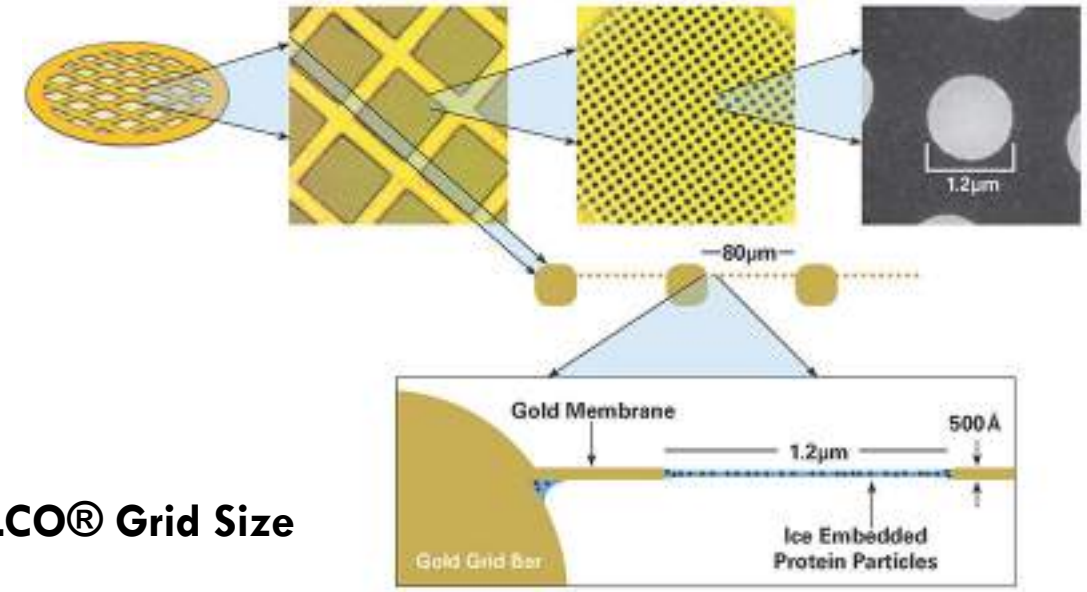
Thickness: PELCO® Grids are approximately 25µm thick.

Diameter: 3.0 to 3.05mm

Finish: Copper, Nickel and Gold grids have a matte finish on one side and a shiny finish on the other side.

Pitch: Is 1"/mesh or 25.4mm/mesh

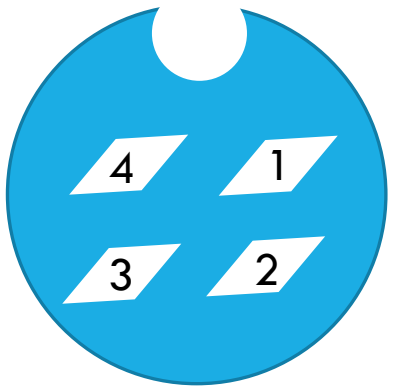
Example 200 mesh pitch = 25.4/200 = 127µm



PELCO® Grid Size

Square Mesh	Pitch µm	Hole µm	Bar µm	% Trans-mission
50	508	425	83	70
75	339	284	55	70
100	254	204	50	65
150	169	125	44	60
200	127	90	37	50
300	85	54	31	40
400	64	38	26	35
500	51	28	23	30

GRID BOXES

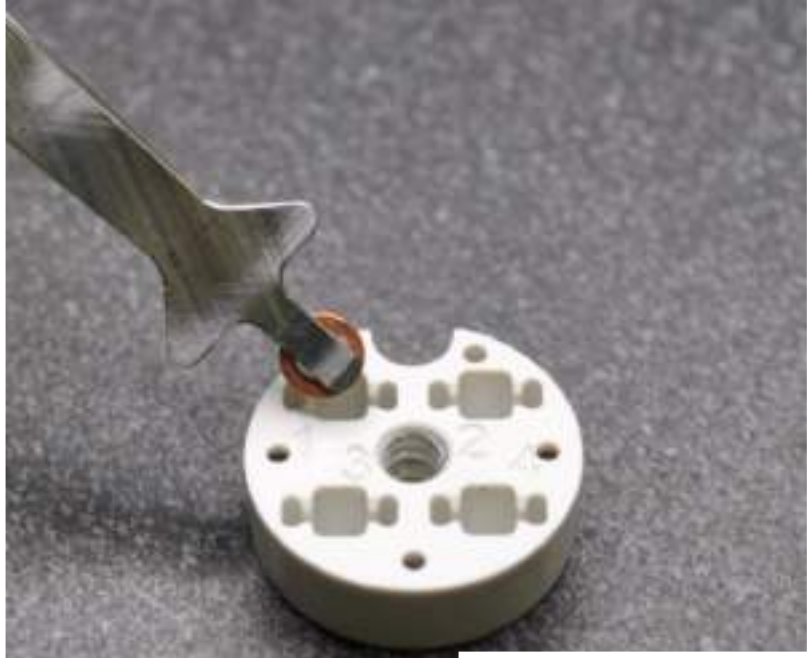


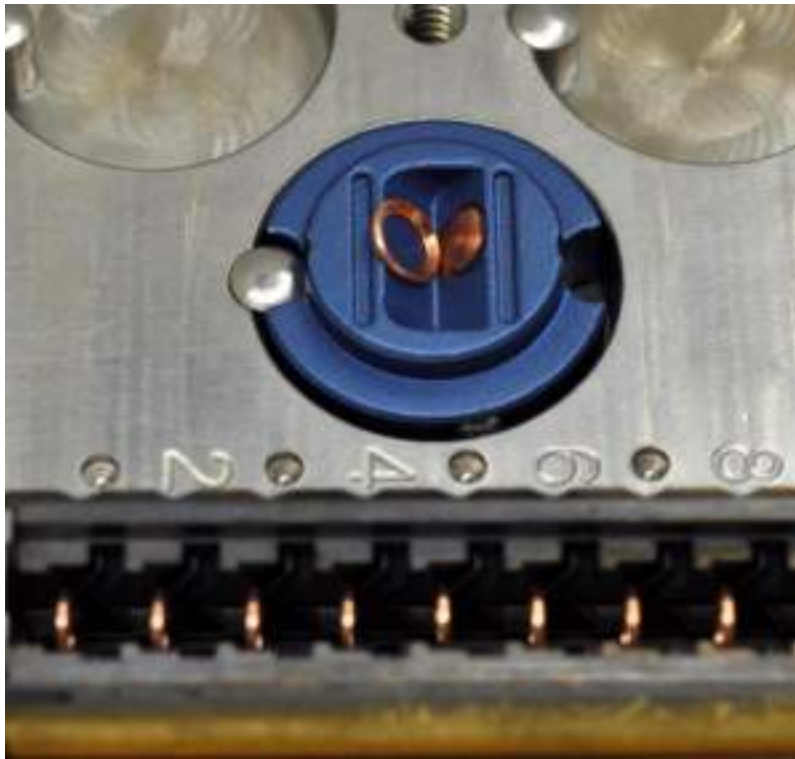
PUCKS – HIGH DENSITY STORAGE

CRYOGENIC DEWARS AND SHIPPERS

ADDITIONAL ACCESSORIES

negative stain accessories
vitrification accessories
grid clipping accessories
grid inspection accessories





EM VENDORS

There are several vendors where you may obtain the necessary equipment. A few of them that we use often are:

Electron Microscopy Sciences - http://www.emsdiasum.com/microscopy/

TedPella - http://www.tedpella.com/

SPI - http://www.microscopy.cc

SubAngstrom - https://subangstrom.com/Subangstrom

Protochips - https://www.protochips.com

Quantifoil - https://www.quantifoil.com

Nanosoft - https://www.nanosoftmaterials.com

EM COMPATIBLE SAMPLES

Moving from a **trial-and-error** process to a **controlled** and **reproducible** method

Questions?