Electron Microscopy

- 1930s (Ruska & Knoll)
  - 75 keV e- LINAC
  - Higher resolution than light microscopy
  - 

    Physics: MCMLXXXVI
- What’s happened since then?
- Where Accelerator R&D could help advance the state-of-the-art

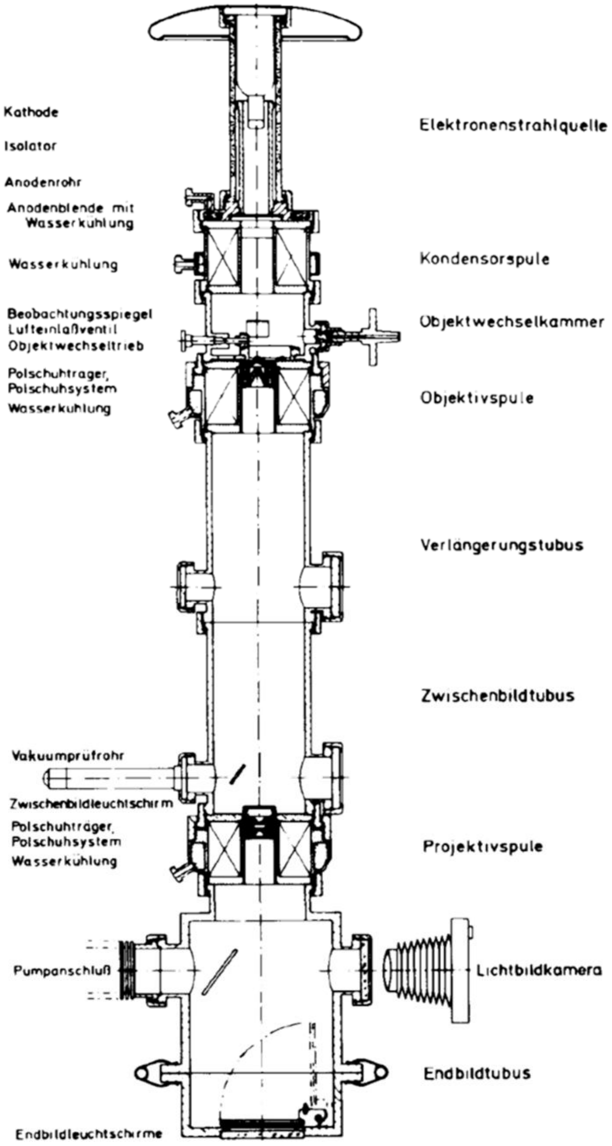


Fig. 5: First (two-stage) electron microscope magnifying higher than the light microscope. Cross-section of the microscope column (Re-drawn 1976) [15].

Synergies

- Describe potential synergies and connections to other GARD thrusts and other SC offices (BES, NP, QIS, FES, etc)

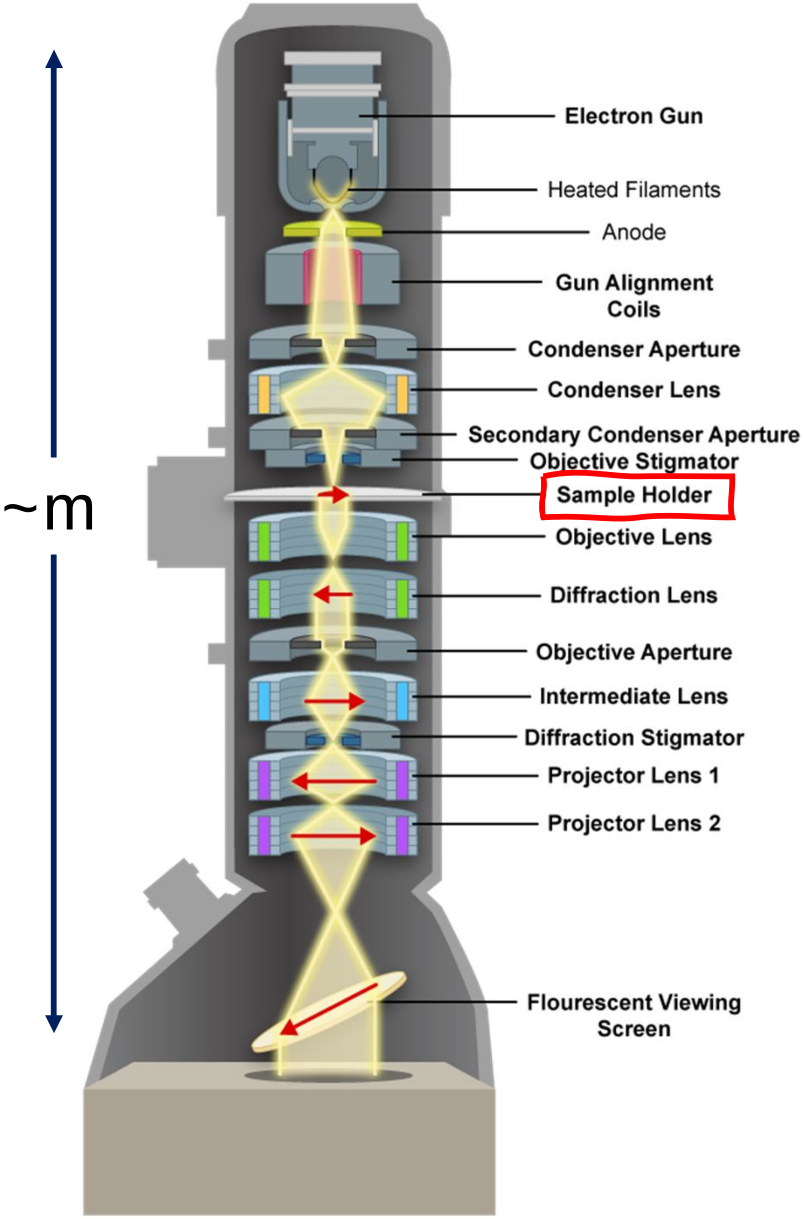
There are many types of ‘electron microscopes’
Concentrate here on those with beam energies sufficient for atomic resolution
And on real space imaging (diffraction – generally – averages over sample)

Connections: EM is a key discoverytool for materials science and structural biology

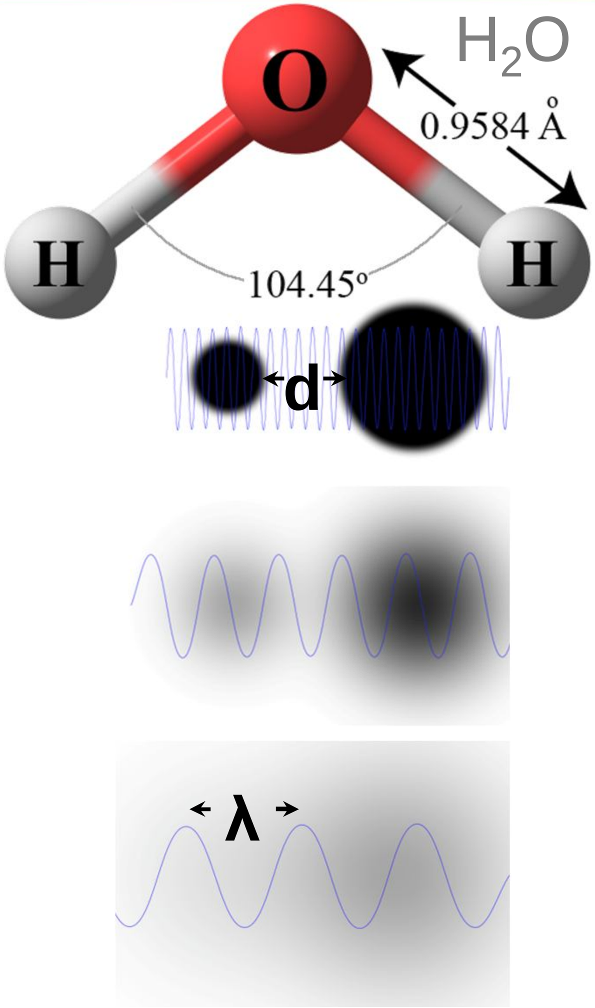
- **Motivation (why EM?)**
- **Challenges**

Conventional TEM

- $E \sim 10^5\ eV$
- $I \lesssim nA$
  - →1 e^- in column at a time
  - → ~~space charge~~
- At 300 keV
  - $\lambda \sim 0.02\ \text{Å}$
  - $\beta \sim 0.8$



Seeing Atoms



Resolve atoms – spaced d ~ 1 Å apart

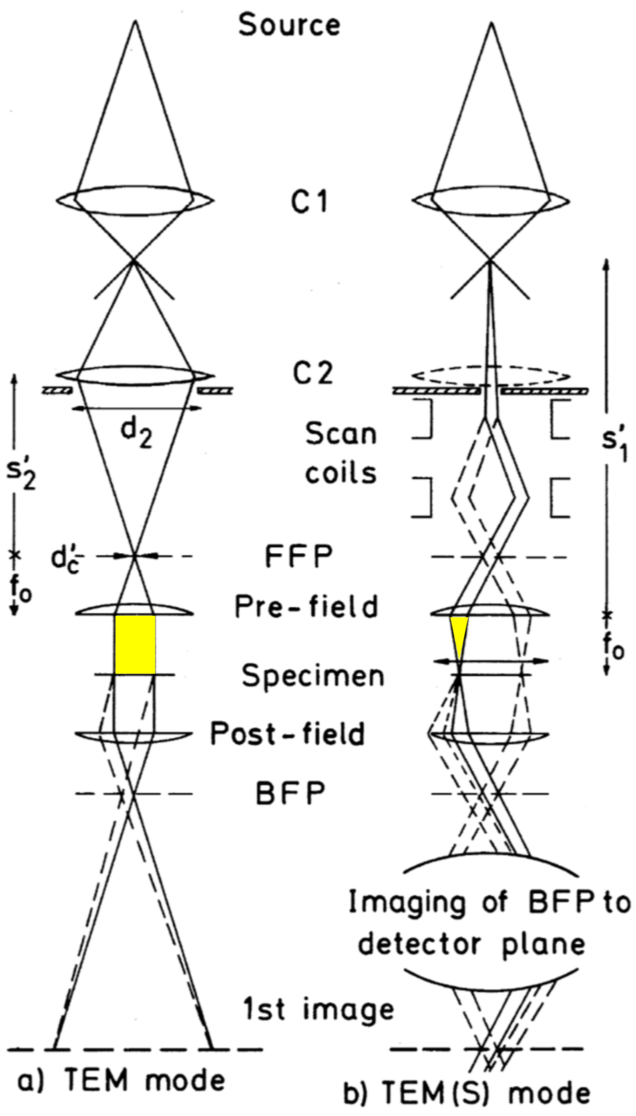
Diffraction Limit: λ < d

Microscope	λ [Å]
Visible light	4,000
Soft X-ray	≤10
Hard X-ray	≤1
Electron	≪0.1

Electron Microscopy continues to be the best way to image at the atomic (or near-atomic) scale

(S)TEM – “equivalent”

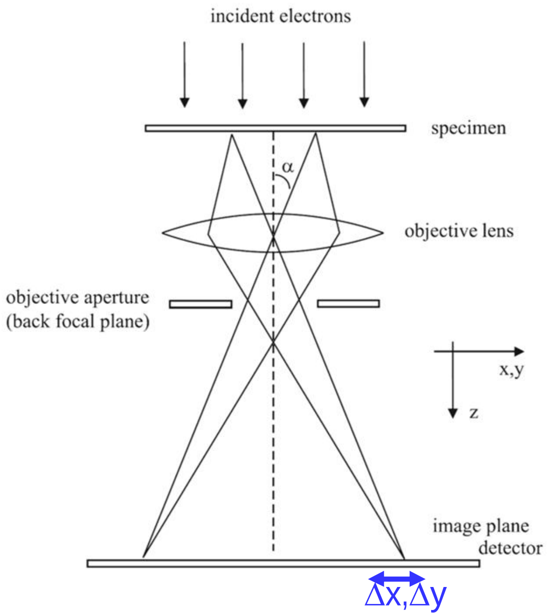
TEM: parallel beam on sample

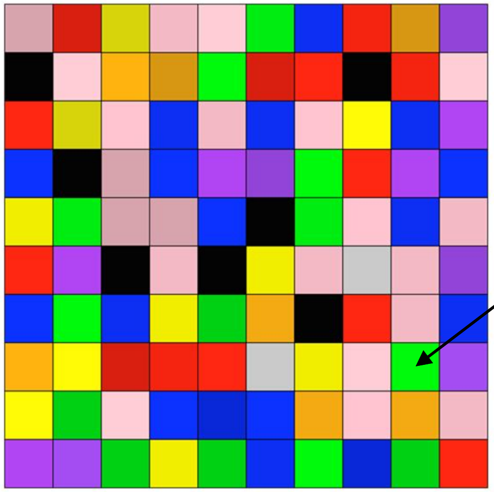


STEM: point-like beam on sample

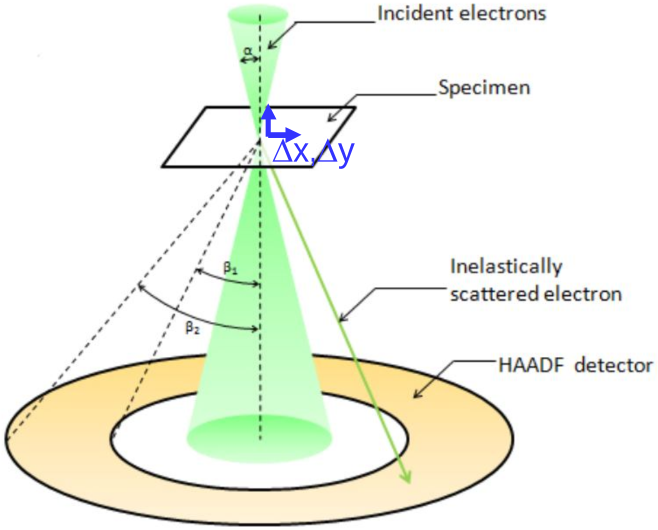
From Reimer, Transmission Electron Micrsocopy

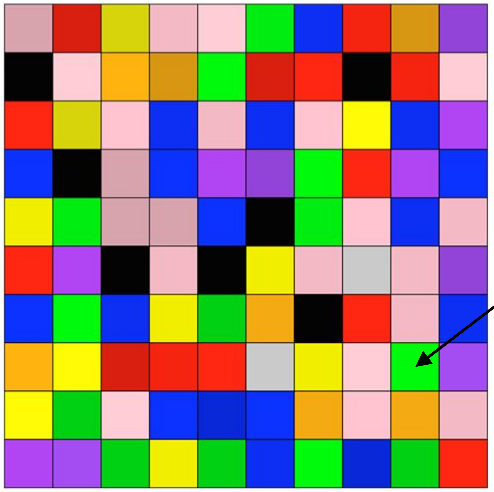
(S)TEM



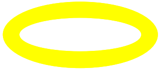


$$\left(\sum_{\Delta x,\Delta y} e^{-}\right) \times \mathit{factors}$$



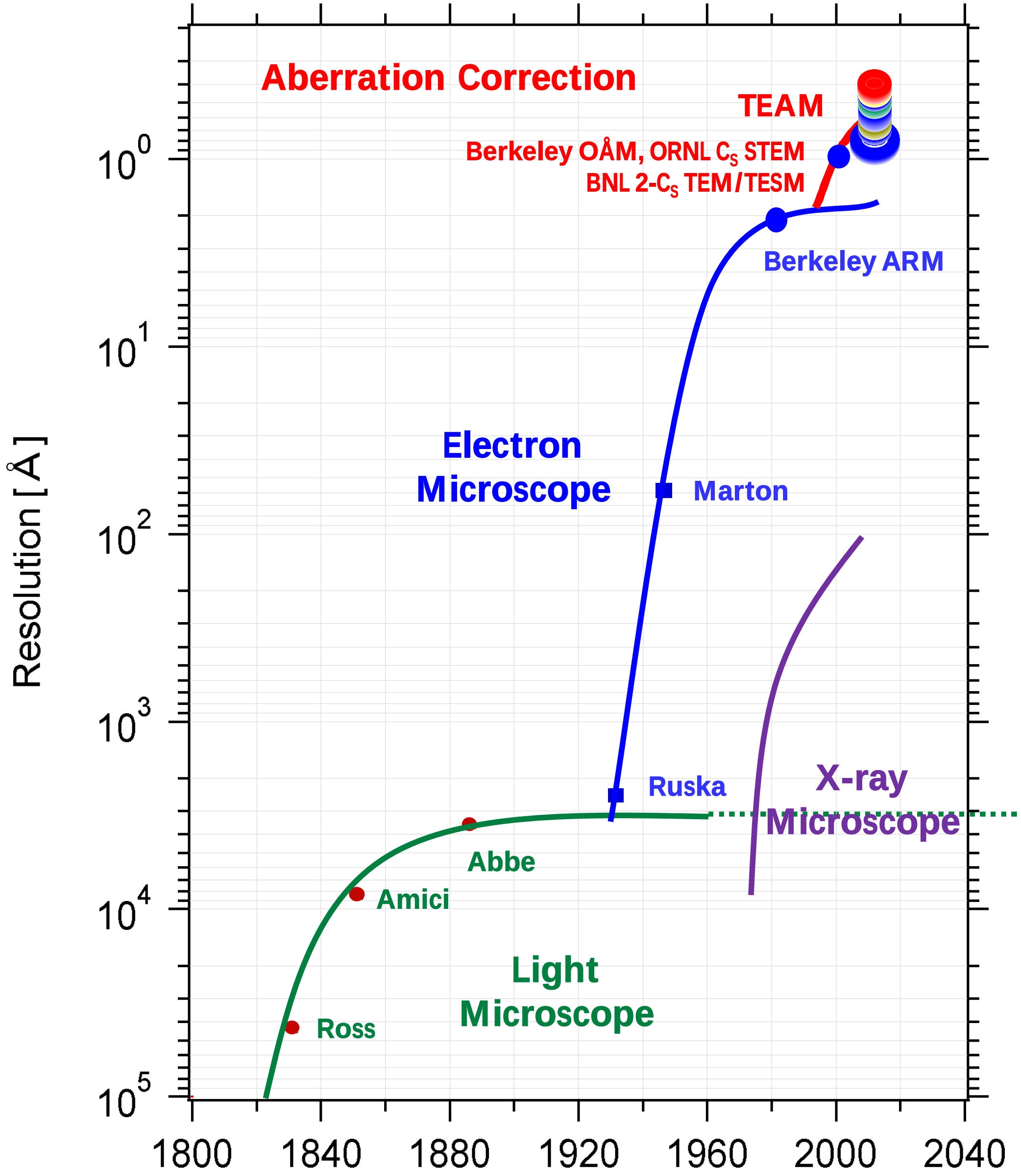


$$\left(\sum_{\Delta x,\Delta y} e^{-}\right) \times \mathit{factors}$$



From Kirkland – Advanced Computing in Electron Microscopy

Optics



δx

Aberration correction

Technology gets better

- Better power supplies
- Improved designs
- …

Computers

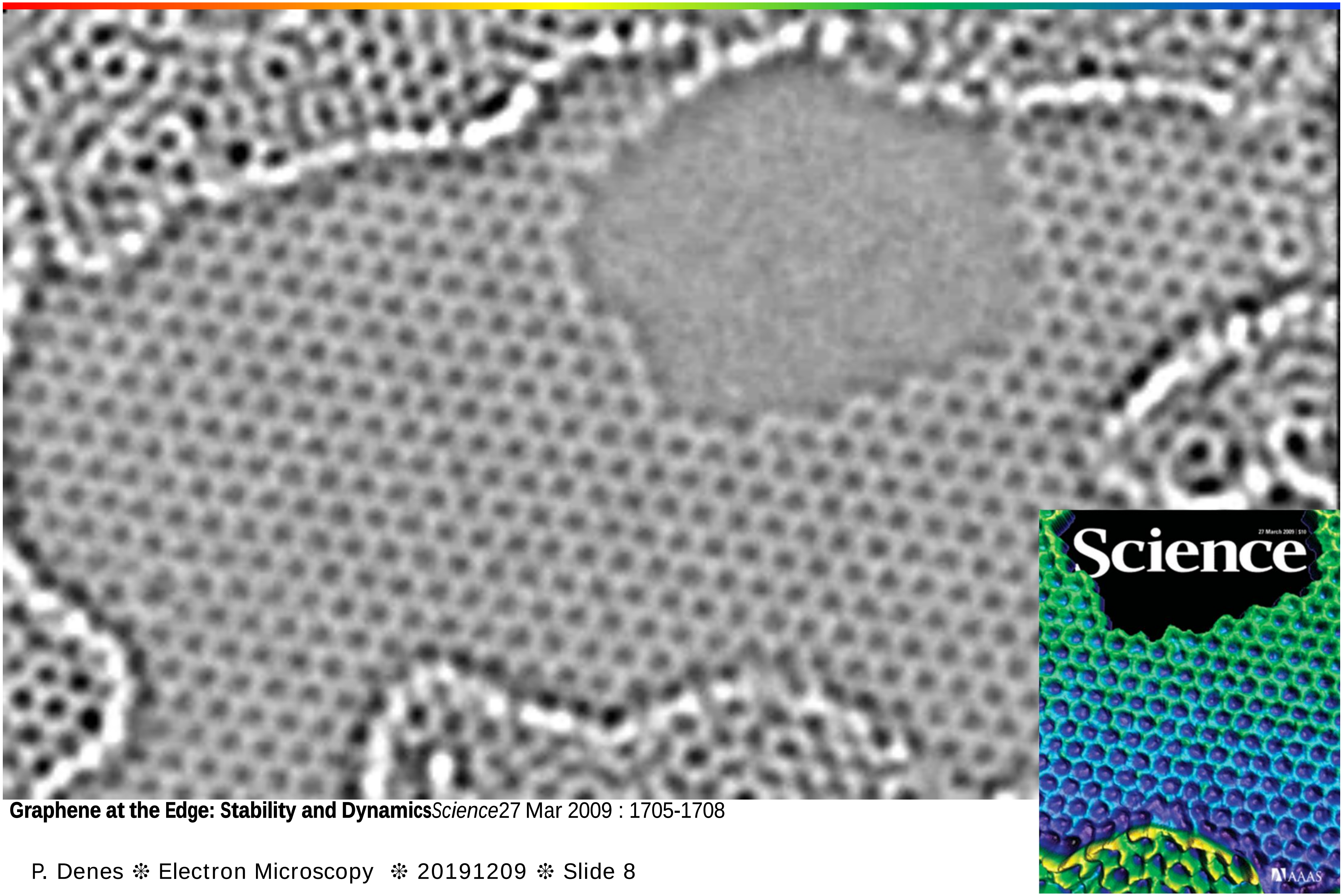
Light microscopy at the diffraction limit

Can sometimes be improved by *super-resolution*

Chemistry: MMXIV

EM: After Rose
X-ray: Kirz and Jacobsen XRM2008

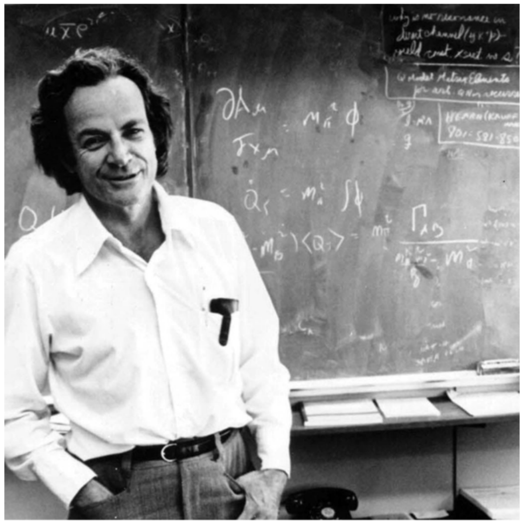
Graphene on TEAM 0.5



Graphene at the Edge: Stability and Dynamics*Science*27 Mar 2009 : 1705-1708

Challenge

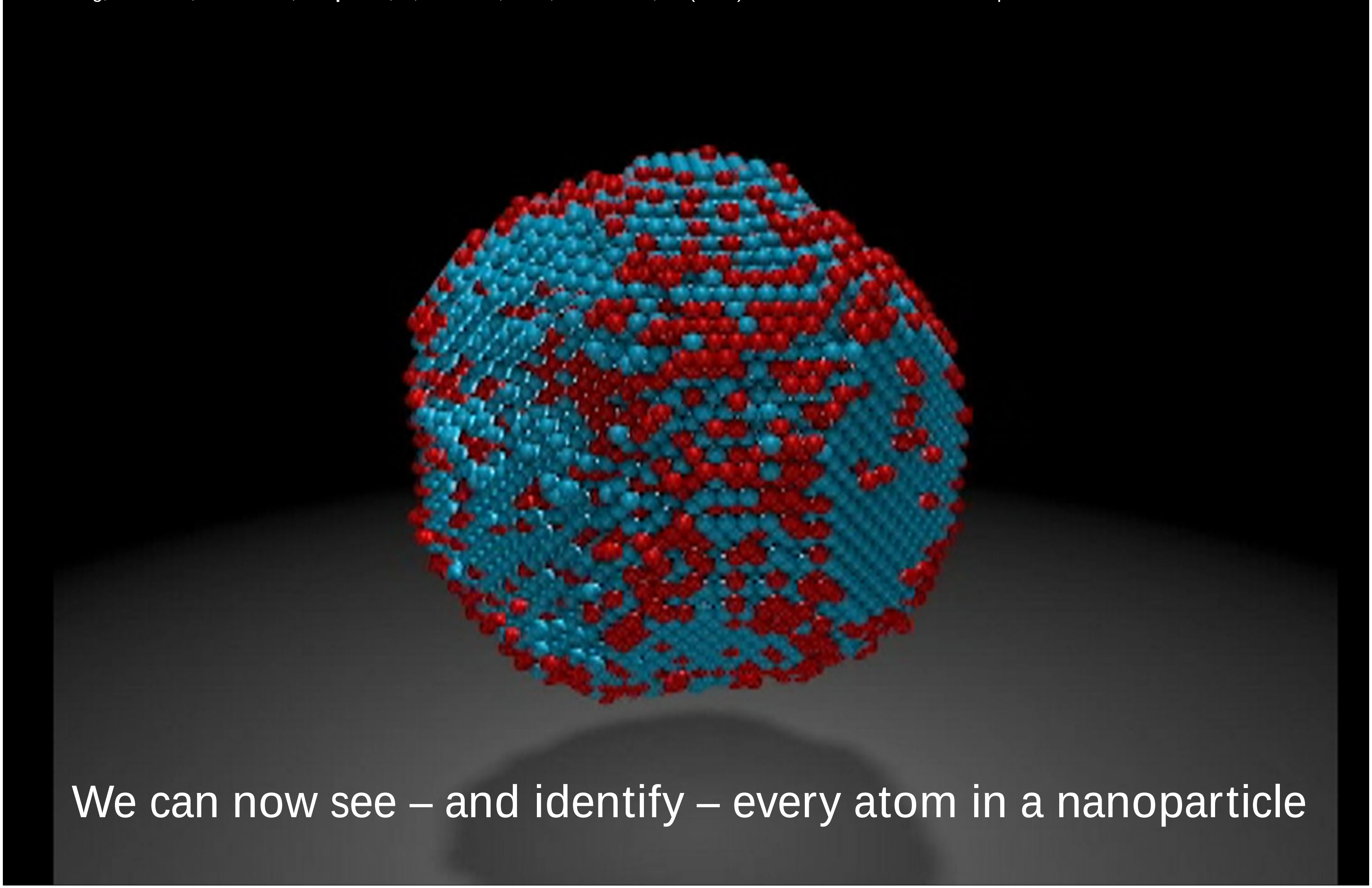
"It would be very easy to make an analysis of any complicated chemical substance; all one would have to do would be to look at it and see where the atoms are. The only trouble is that the electron microscope is one hundred times too poor … I put this out as a challenge: Is there no way to make the electron microscope more powerful?"



– Richard P. Feynman, 1959, "There's Plenty of Room at the Bottom"

Getting There

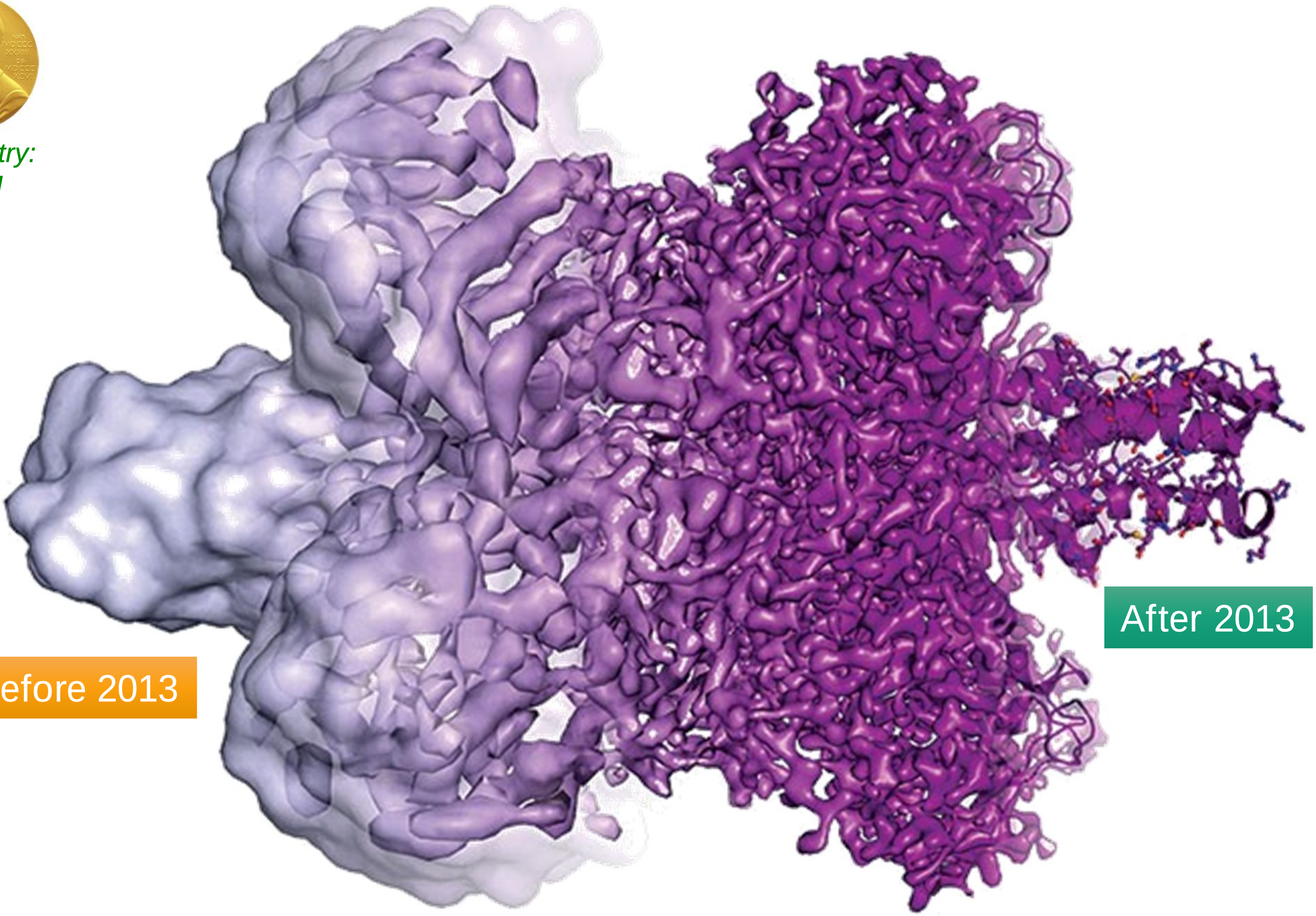
Y Yang, CC Chen, **MC Scott***, **C Ophus***,…, **P Ercius**, et al., Nature 542, 75 (2017) Movie from F Niekiel and C Ophus



We can now see – and identify – every atom in a nanoparticle

cryoEM

Chemistry: MMXVII

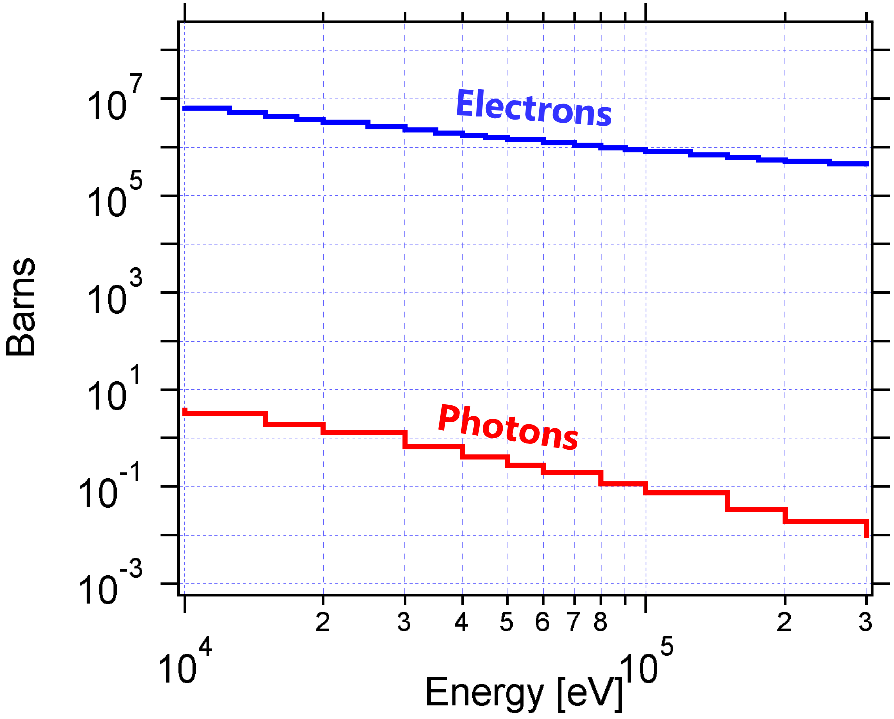


Before 2013

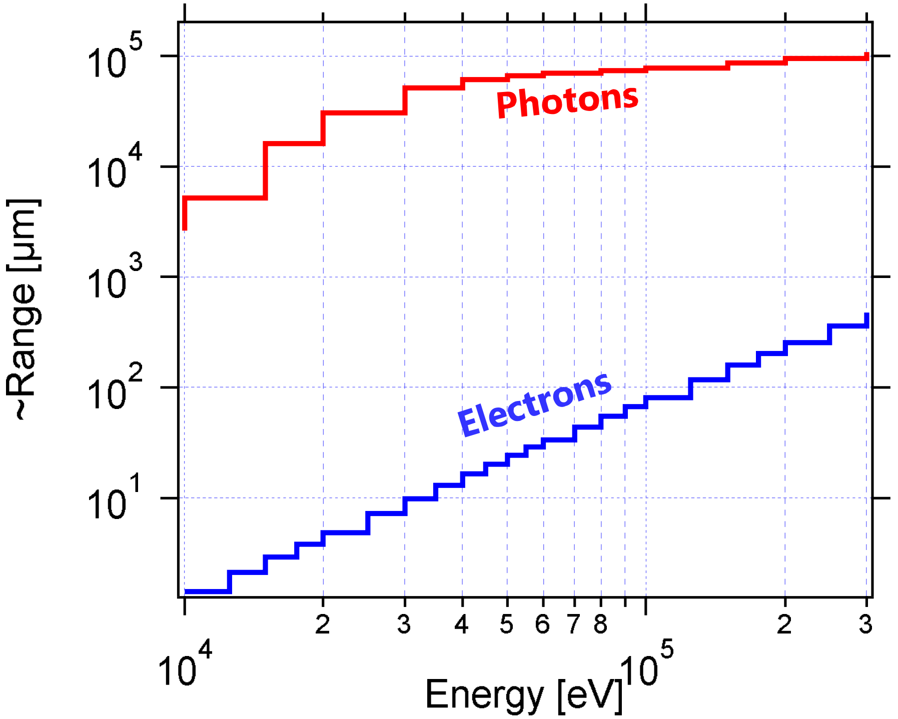
After 2013

Electrons vs. X-rays

Elastic Cross Section



Range



Carbon, here, as an example

Introduction: Grand challenges

For Electron Microscopy

- **Grand challenge #1 (beam intensity):** How do we increase beam intensities by orders of magnitude?
- **Grand challenge #2 (beam quality):** How do we increase beam phase-space density by orders of magnitude, towards quantum degeneracy limit?
- **Grand challenge #3 (beam control):** How do we control the beam distribution down to the level of individual particles?
- **Grand Challenge #4 (beam prediction):** How do we develop predictive “virtual particle accelerators”?

Challenges

δx

Spatial Resolution – largely solved
See atoms (under ideal observation conditions)

δE

Energy Resolution – source and optics
$\delta E \rightarrow 0$: Spectroscopy++

δt

Temporal Resolution – source+
$\delta t \rightarrow 0$: What are the limits?

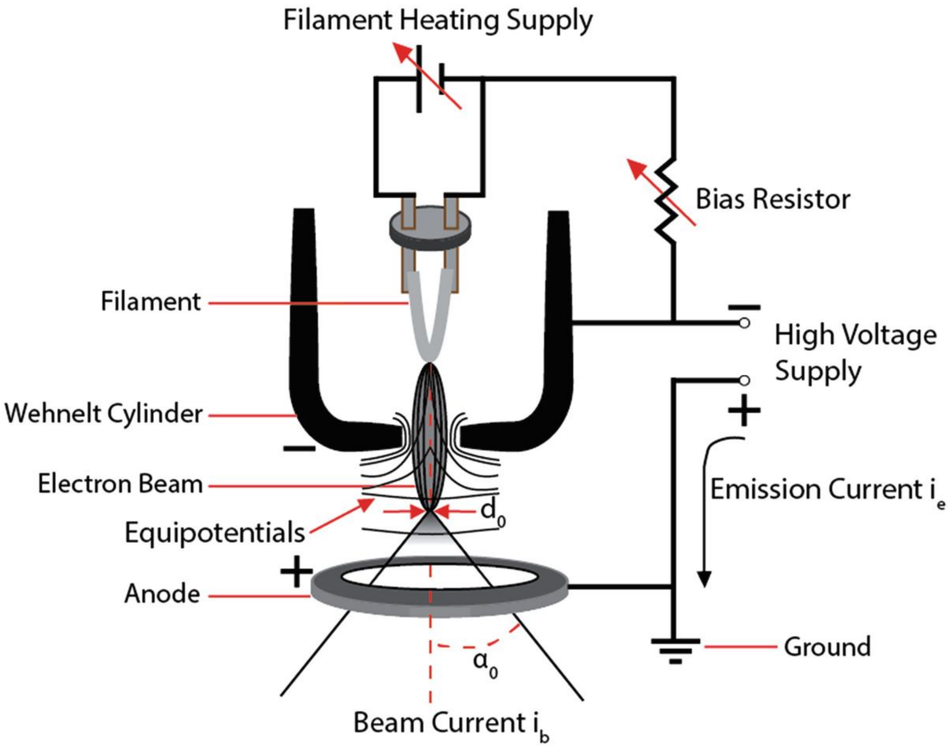
ε

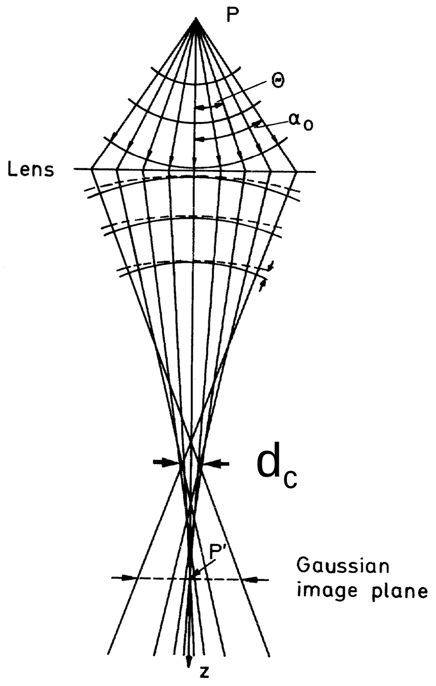
"Efficiency" – reduce sample damage
More buck for the bang

T

Temperatures other than room temperature
Atomic resolution at T ~ 0 (quantum phenomena)

The Source





Brightness: $\beta = \frac{I}{(\pi d_0 \alpha_0)^2}$

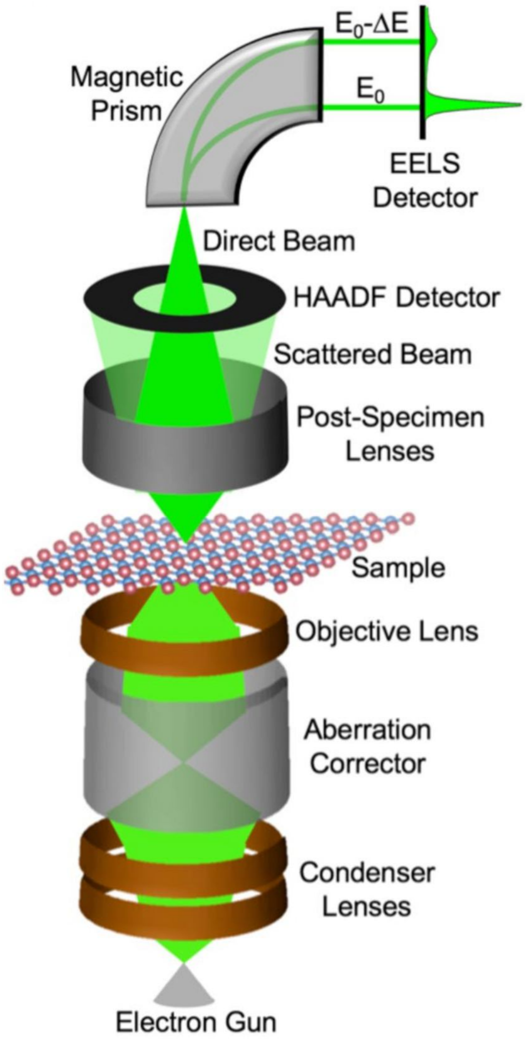
Source	β [A/m²Sr]
Thermionic	10^9
Schottky FEG	$5\text{x}10^{10}$
Cold FEG	10^{13}

Energy Spread:

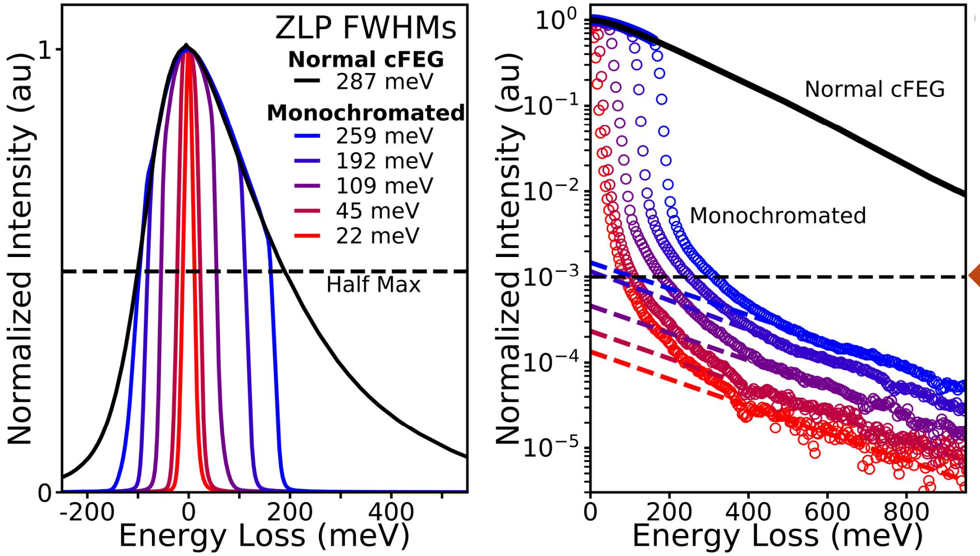
$$d_c = \frac{1}{2} C_c \frac{\Delta E}{E} \frac{1 + E/E_0}{1 + 2E/E_0} \alpha_0 M$$

$$\rightarrow \frac{\Delta E}{E} \sim 10^{-6}$$

Spectroscopy



- Inelastic scattering
- STEM
- (Today) beam monochromated to reduce ΔE
  - Reduction in beam current

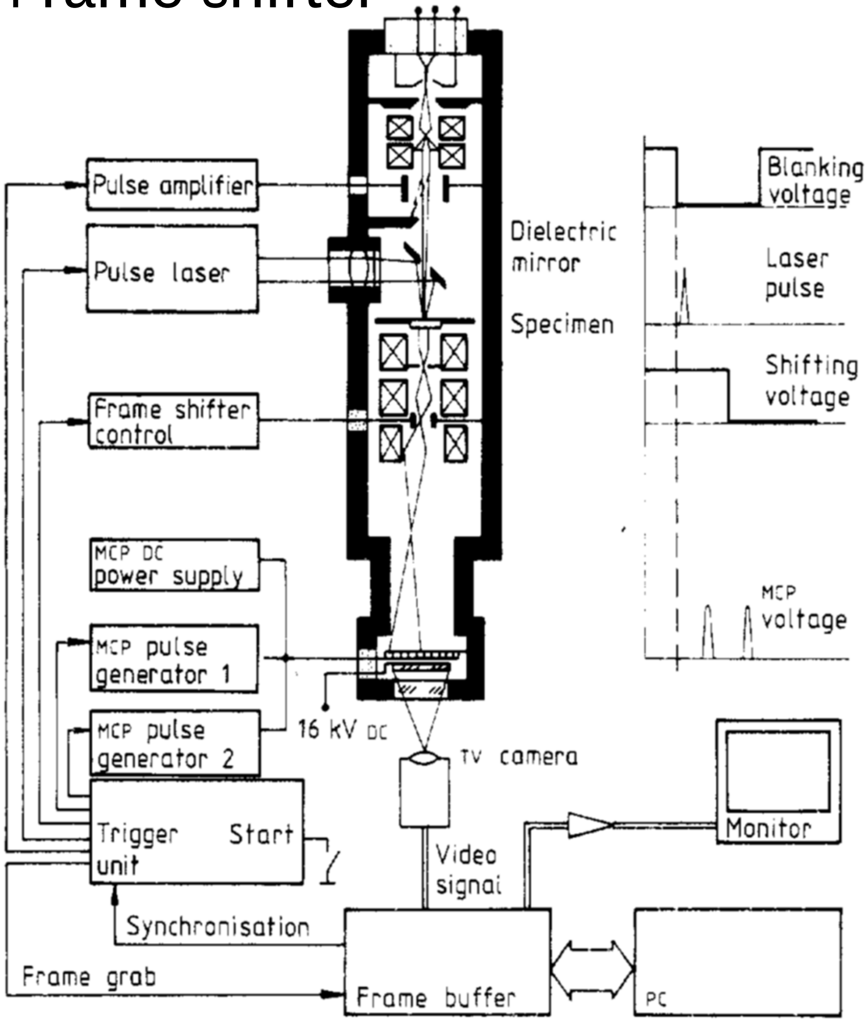


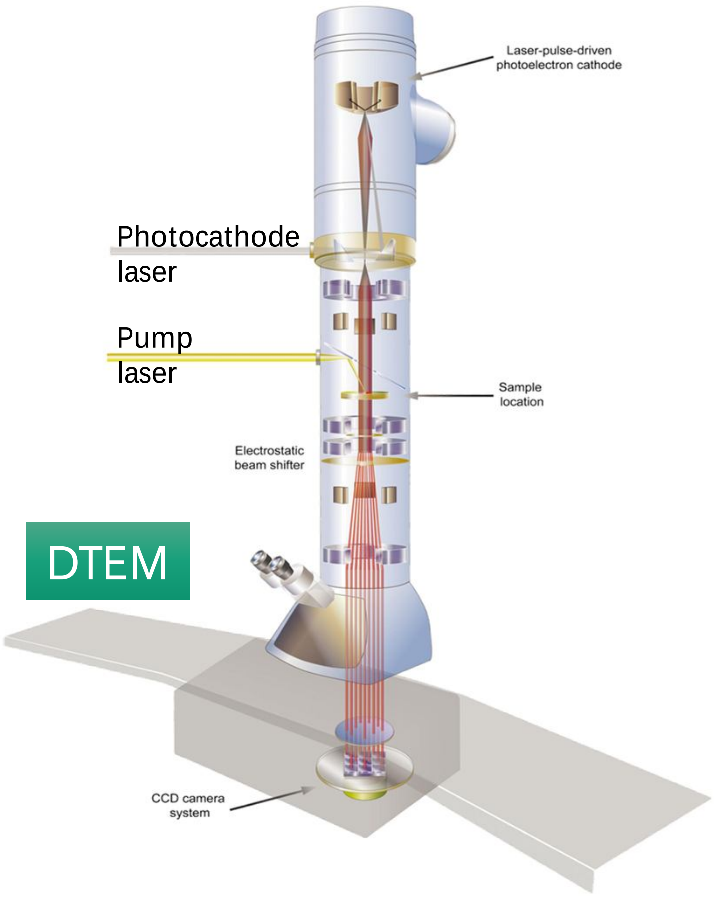
10^{-3}

Hachtel, Lupini & Idrobo, *Sci Rep* **8,** 5637 (2018)

Time Resolved [ns]

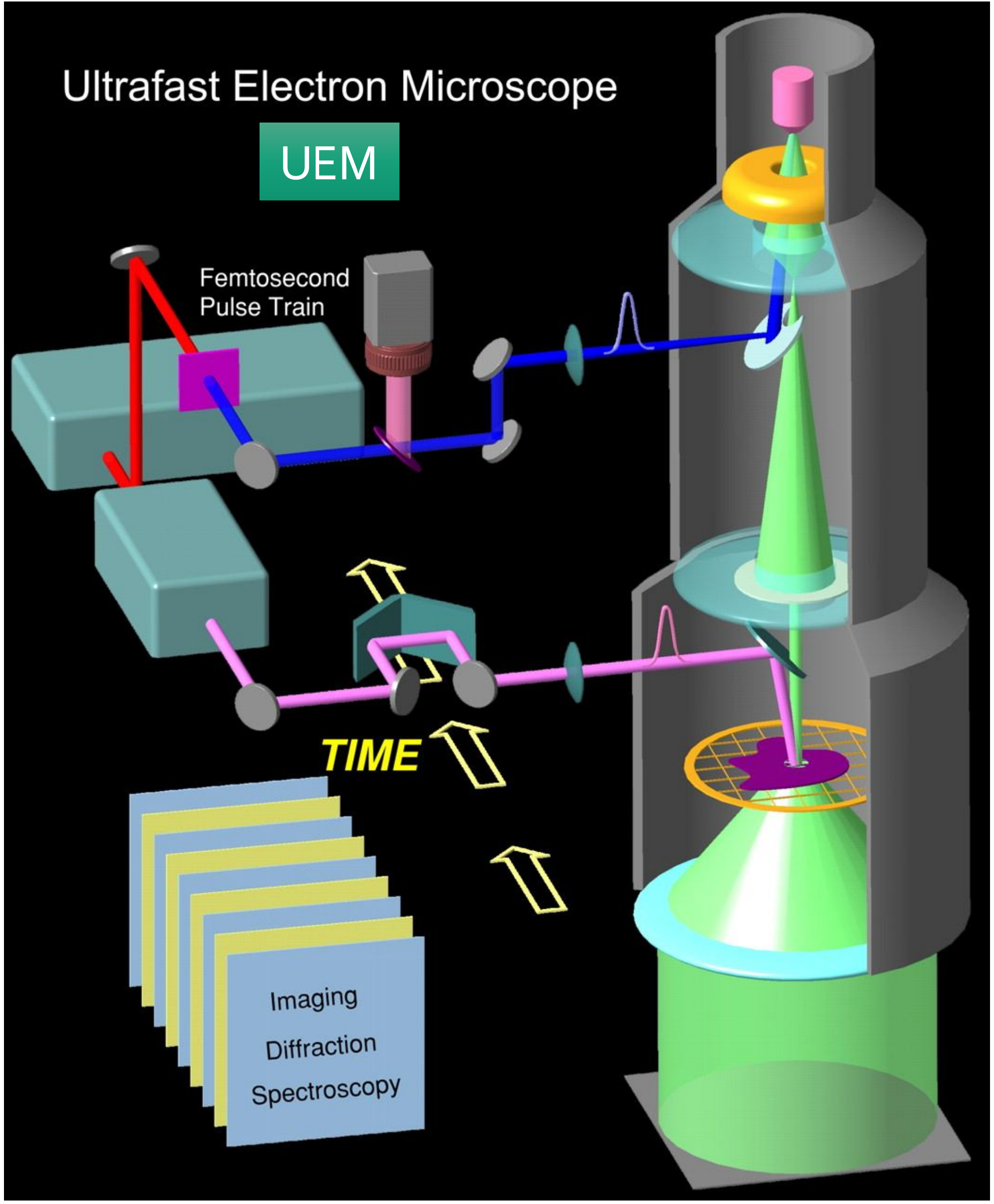
- Laser-driven photocathode
- Frame shifter





Bostanjoglo, *Ultramicroscopy* 1987
Bostanjoglo *J. Phys. E: Sci. Instrum. 1989*

Time Resolved [<ps]

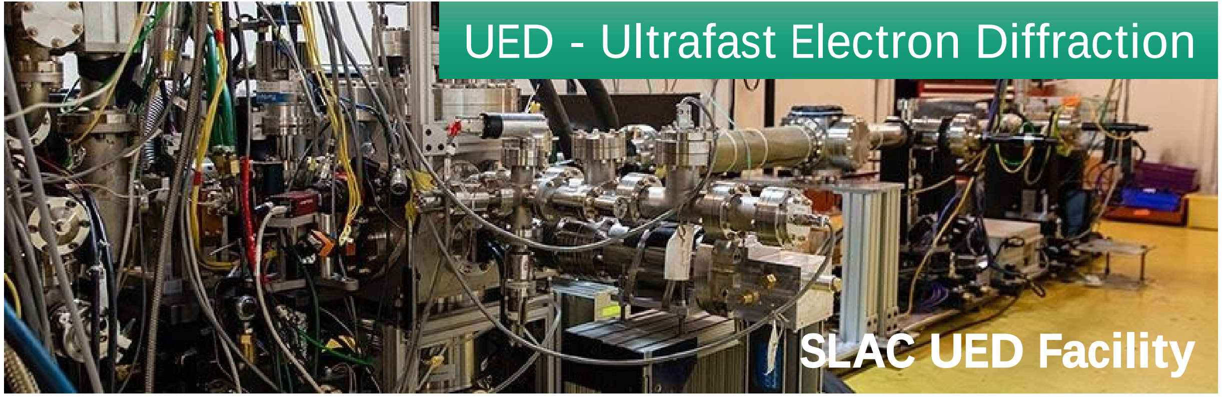


- DTEM
  - Pump
  - Probe-Probe-Probe
  - Many e- / Probe pulse
- UEM
  - Pump
  - Probe
  - ~1 e- / Probe pulse

Zewail, *Science* 2010

Time Resolved [<ps]

- FEL gun
- Bunch charge Q
- Bunch width δt
- E ~ MeV (space charge)


UED - Ultrafast Electron Diffraction

SLAC UED Facility

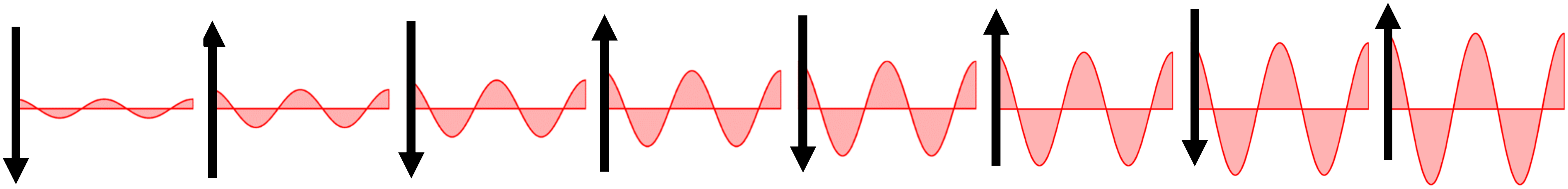
SLAC UED Facility		LBNL Hires
Parameter	**Value**	
Electron beam energy	2 - 4 MeV	730 keV
Repetition rate	Single shot → 360 Hz	≤ 1 MHz
Charge per pulse	1 - 100	0.1 - 10 fC
Bunch length	<150 fs FWHM*	~100 fs FWHM*
Beam spot size	100-200 um (typical), 10 um (FWHM) focused	50-200 um (typical)

*(depending on charge)

Weathersby..Wang, *RSI* 2015

Multipass (“Quantum”) EM

Consider a weak phase signal:  ϕ_0 max phase shift



Do 1 pass m times. $Intensity \propto m\phi_0^2$

Do m passes 1 time. $Intensity \propto m^2\phi_0^2$

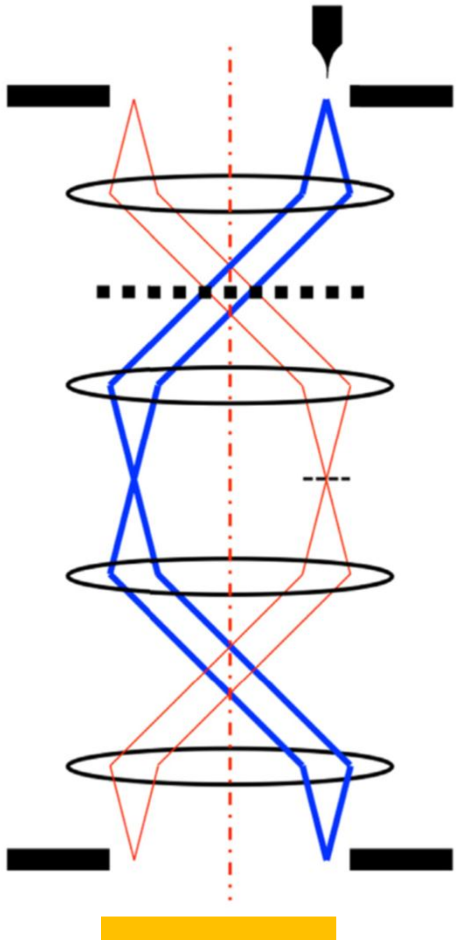
In each case, the sample sees m electrons. “Figure of merit”:

$Intensity/Dose \propto \phi_0^2$ – single pass

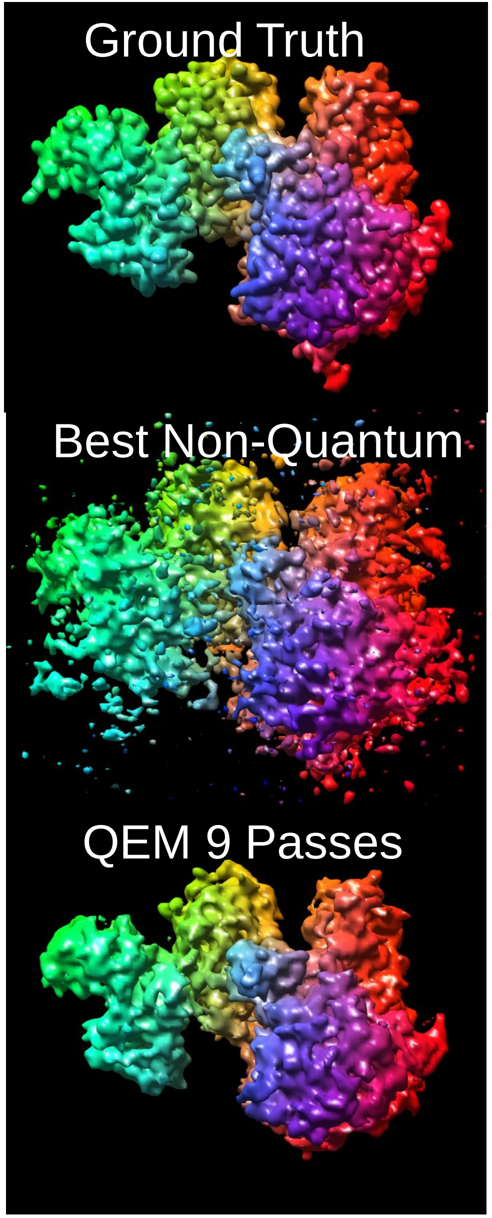
$Intensity/Dose \propto \mathbf{m}\phi_0^2$ – single pass

From Colin Ophus, NCEM/Molecular Foundry

Multipass (“Quantum”) EM


electron source
barn door
lens
coupler
lens
sample
lens
lens
barn door
detector

P. Kruit … M. Kasevitch *Ultramicroscopy* 2016


Ground Truth
Best Non-Quantum
QEM 9 Passes

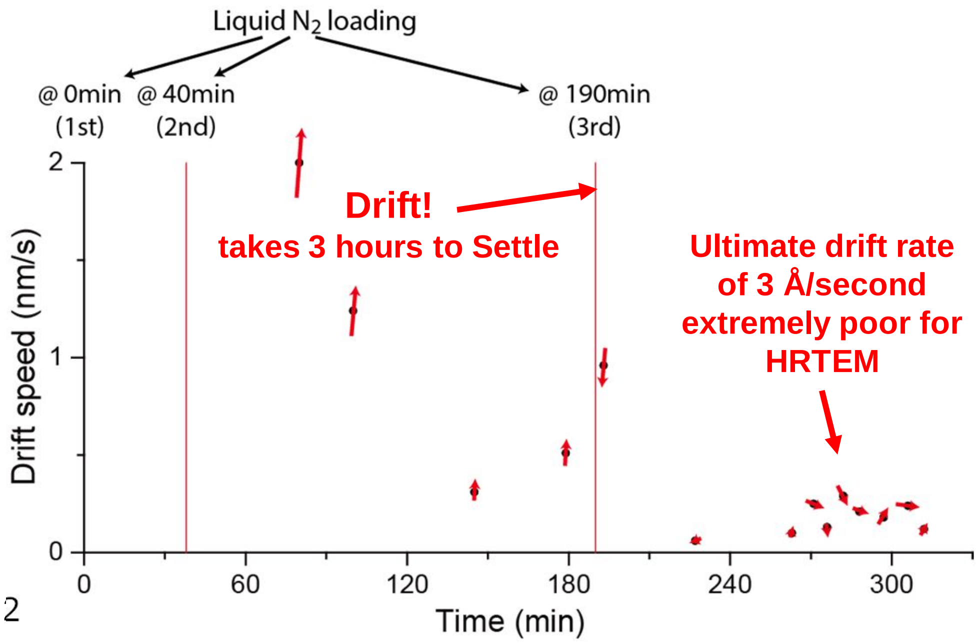
Multipass TEM Simulation at 32 $e^-/Å^2$: - Colin Ophus

Temperature and Stability

Atomic resolution at (very low temperatures)

- Electron-Lattice Coupling
  - exploration of novel phases in temperature regimes not currently possible at atomic resolution
- Single photon quantum emitters / optical coupling / QIS
  - spectroscopy at low temperature - similar to STM, but for bulk samples.
- In-situ studies
  - stability → multimodal atomic characterization of both hard and soft materials

Drift on TEAM-I at 77K

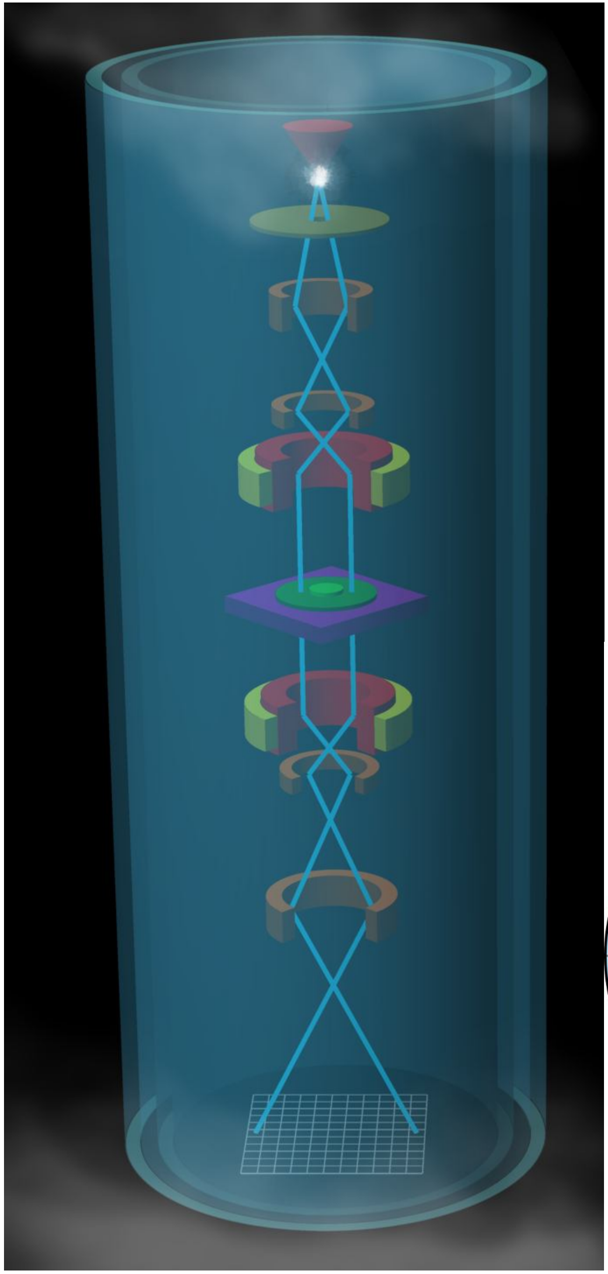


Drift!
takes 3 hours to Settle

Ultimate drift rate of 3 Å/second extremely poor for HRTEM

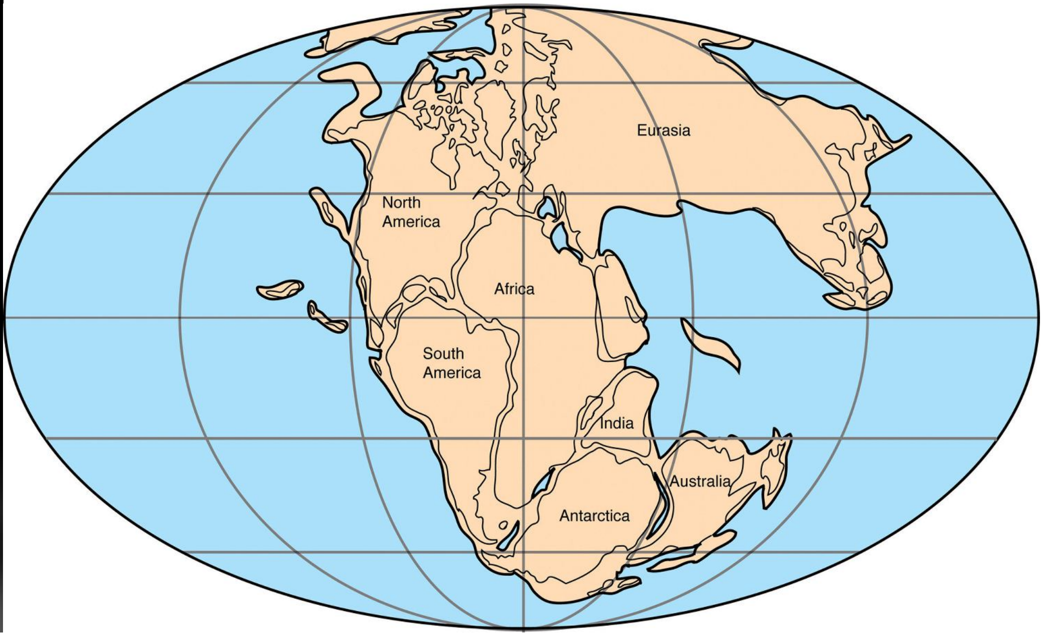
Drift data from TEAM I - W.C. Lee, J. Ciston, P. E. Ercius, et al.
Similar to CryoTEM results from other facilities
(i.e.- L. Kourkoutis @ Cornell and Y. Zhu @ BNL)

All-Superconducting TEM



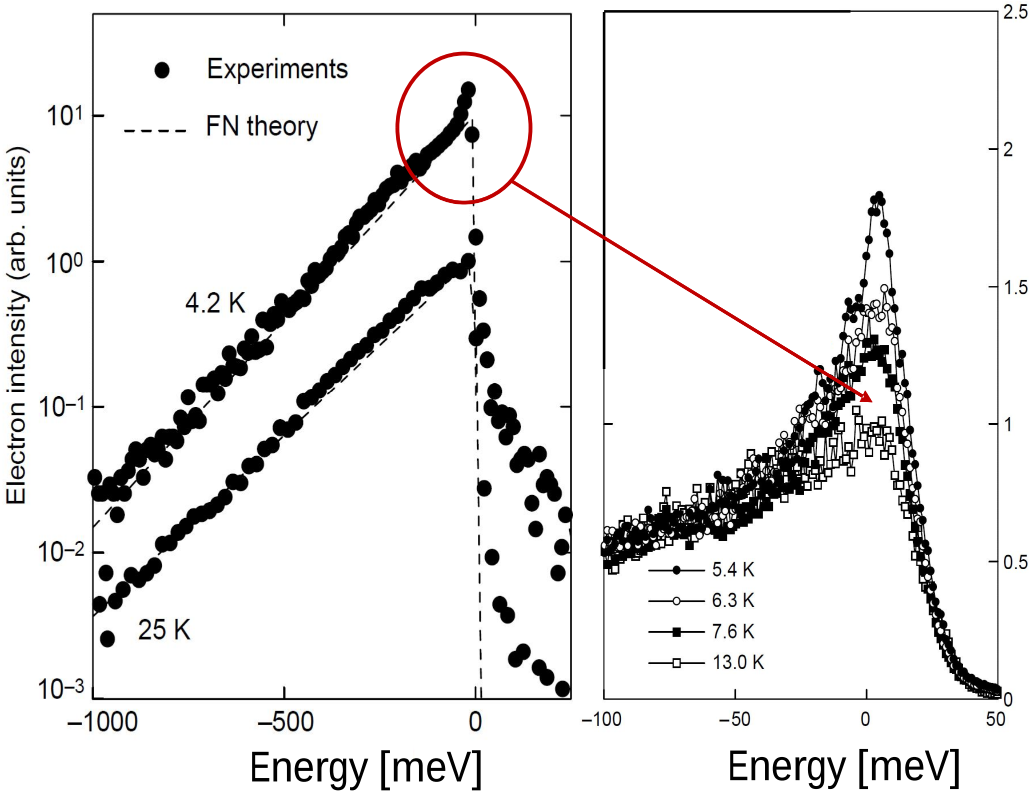
- Conceptual R&D at LBNL
- $\frac{\Delta I}{I}$ – SC persistent currents
- $\frac{\Delta x}{x}$ – CTE → 0 at T → 0

Continental drift ~ 1 Å / 0.1 s

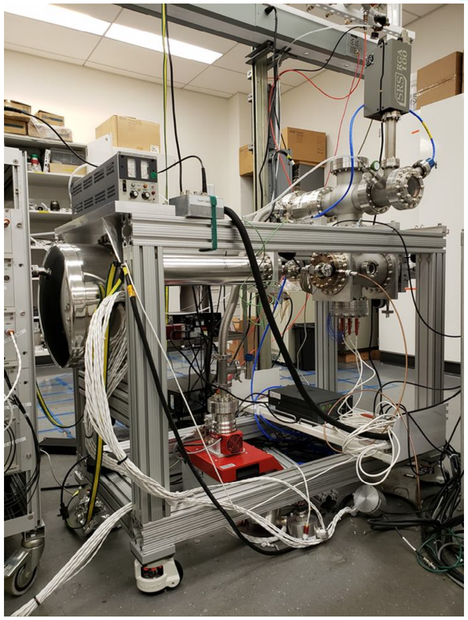


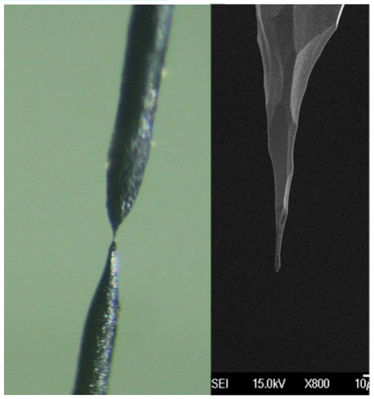
Superconducting Field Emitters

Field emission from superconducting Ni tip (<9.2 K)

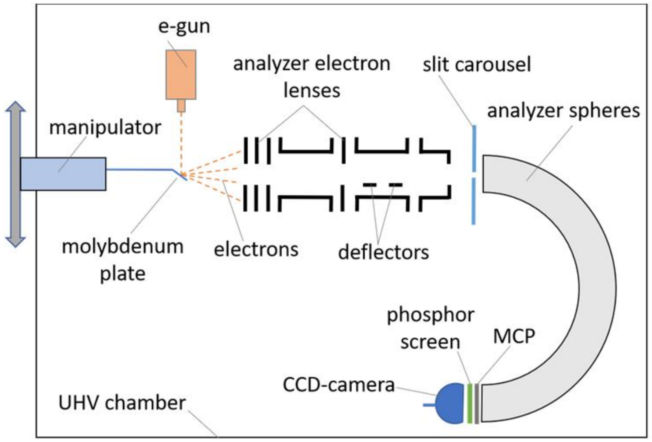


- 10-fold increase in intensity
- 10-fold smaller energy distribution (20 meV)





Tip fab: r~10 nm



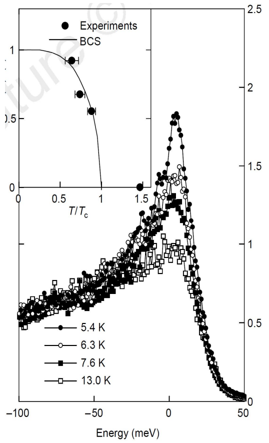
Ni tip test UHV setup at the Molecular Foundry

K. Nagaoka et al, Nature 1998
K. Yuasa et al, Phys. Rev. B 2009

Challenges

- DTEM – **many e-/bunch** **δt~ns** **δx~nm**
  - Resolution limits
  - “Slow”: Speed of sound ~ 1 Atom / 100 fs
- UED – **many e-/bunch** **δt~f/ps** **δx~µm**
  - Resolution limits
  - *Diffraction* (not imaging)
- UEM – **1 e-/bunch** **δt~f/ps** **δx~Å**
  - Pump-Probe
  - Many shots needed
    - Sample needs Δt to relax before next shot
- Can we have it all?

Challenges

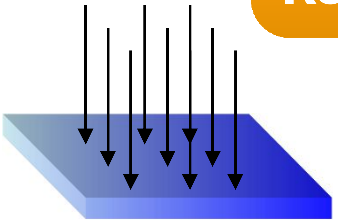


- Can we get a high-brightness source (?) with
  - δE ~ 0 – improves every aspect of microscopy
    - Especially spectroscopy
  - "Controllable" δt (with δE ~ 0)
    - At what current?
- Can we increase the beam current?
  - While preserving all other properties
  - XFELs → MHz
  - EM imaging: ~100 fC / shot

Challenges

- How does EM “outrun” damage?

Poisson statistics: $\Delta N = \sqrt{N}$
Contrast $C \propto \Delta N/N$
Rose Criterion: $C \geq k$ ($k = 5$)



$N = f \times D \times d^2$
D = Dose = ptcl/s/Area x Time
f = factor for scattering and detection efficiency
→ $D \sim k^2/f \times C^2 \times d^2$
But $C \sim d$ → **$D \sim 1/f \times d^4$**

  - **Factor 2 in resolution = 16 x Dose**

- Can we employ “entanglement”?
  - $\frac{1}{\sqrt{N}} \rightarrow \frac{1}{N}$
- How to realize?

Rose, A., J. Soc. Mot. Picture Eng. 1946

- The electron microscope is a
  - Low energy
  - Low current
  - Quasi-relativistic

linear accelerator

- But remarkably successful

- Fertile common ground to explore

- *The ABP thrust explores and develops the science of accelerators and beams to make future accelerators better, cheaper, safer, and more reliable. Particle accelerators can be used to better understand our universe and to aid in solving societal challenges.*