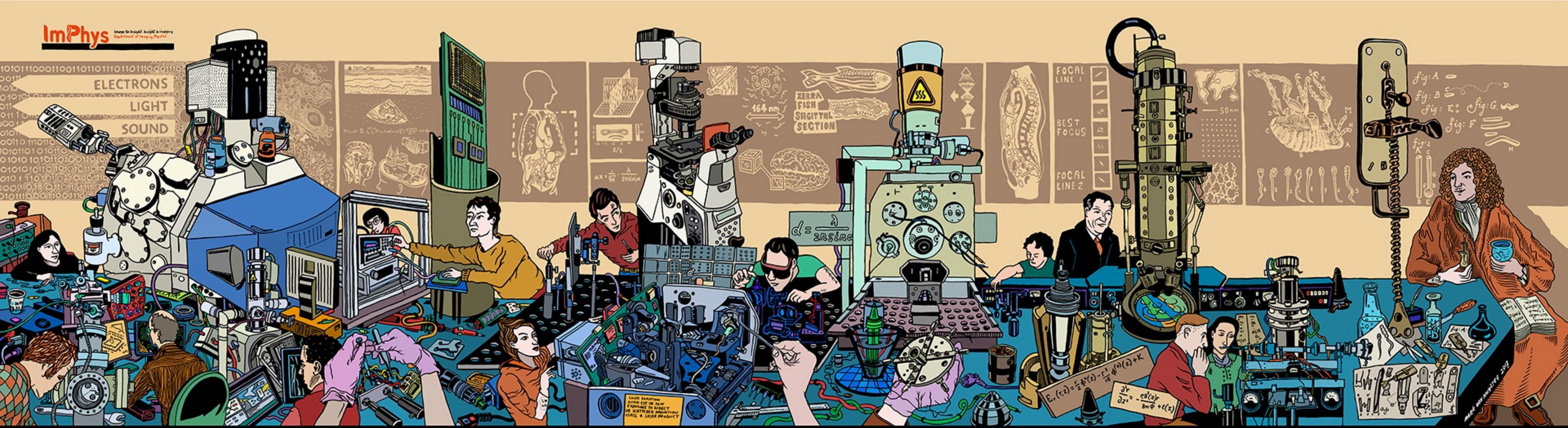
NEBULA, a simulation tool for electron beam imaging and lithography

Kees Hagen and co-workers, TU-Delft



← VLLAIR: VAN LEEUWENHOEK LAB FOR ADVANCED IMAGING RESEARCH

History of electron-matter interaction simulations in Delft

Kieft and Bosch [Philips]
J. Phys. D: Appl. Phys. 41 (2008) 215310
MC code based on GEANT4

Theulings (NIKHEF and TU-Delft) - 2020
Model improvements in Kieft and Bosch code
GEANT4 platform

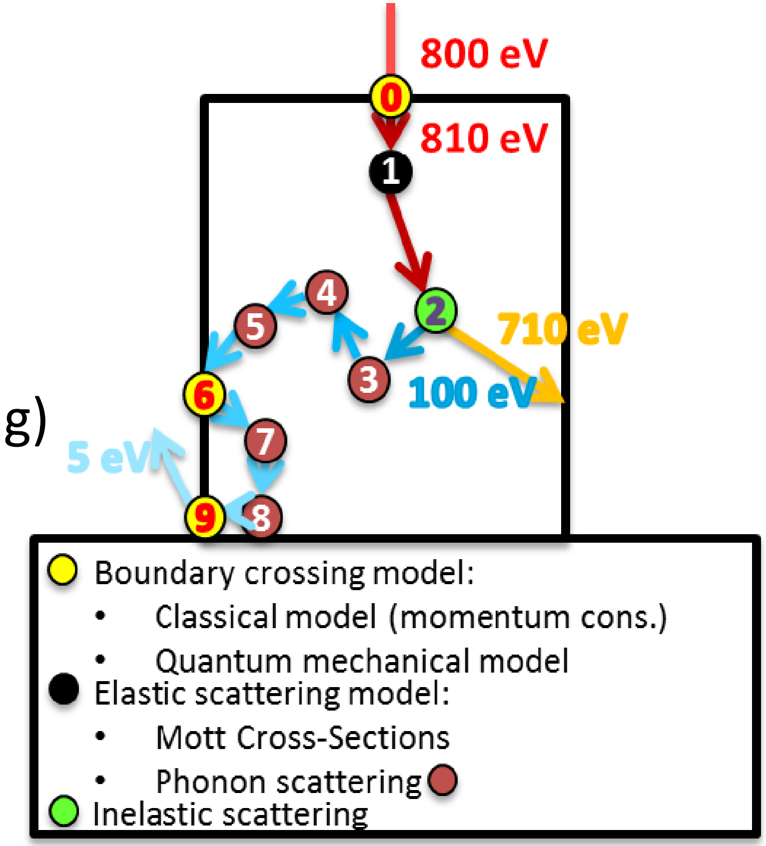
Verduin (TU-Delft) - 2016
Developed the code from scratch
e-scatter (C++/CUDA for CPU and GPU)

Arat (TU-Delft, Raith, GenISys) - 2021
- De-bugged e-scatter
- Implemented the physics models in VirtualSEM (GenISys, proprietary) – contains charging models
- Application to imaging and lithography use-cases

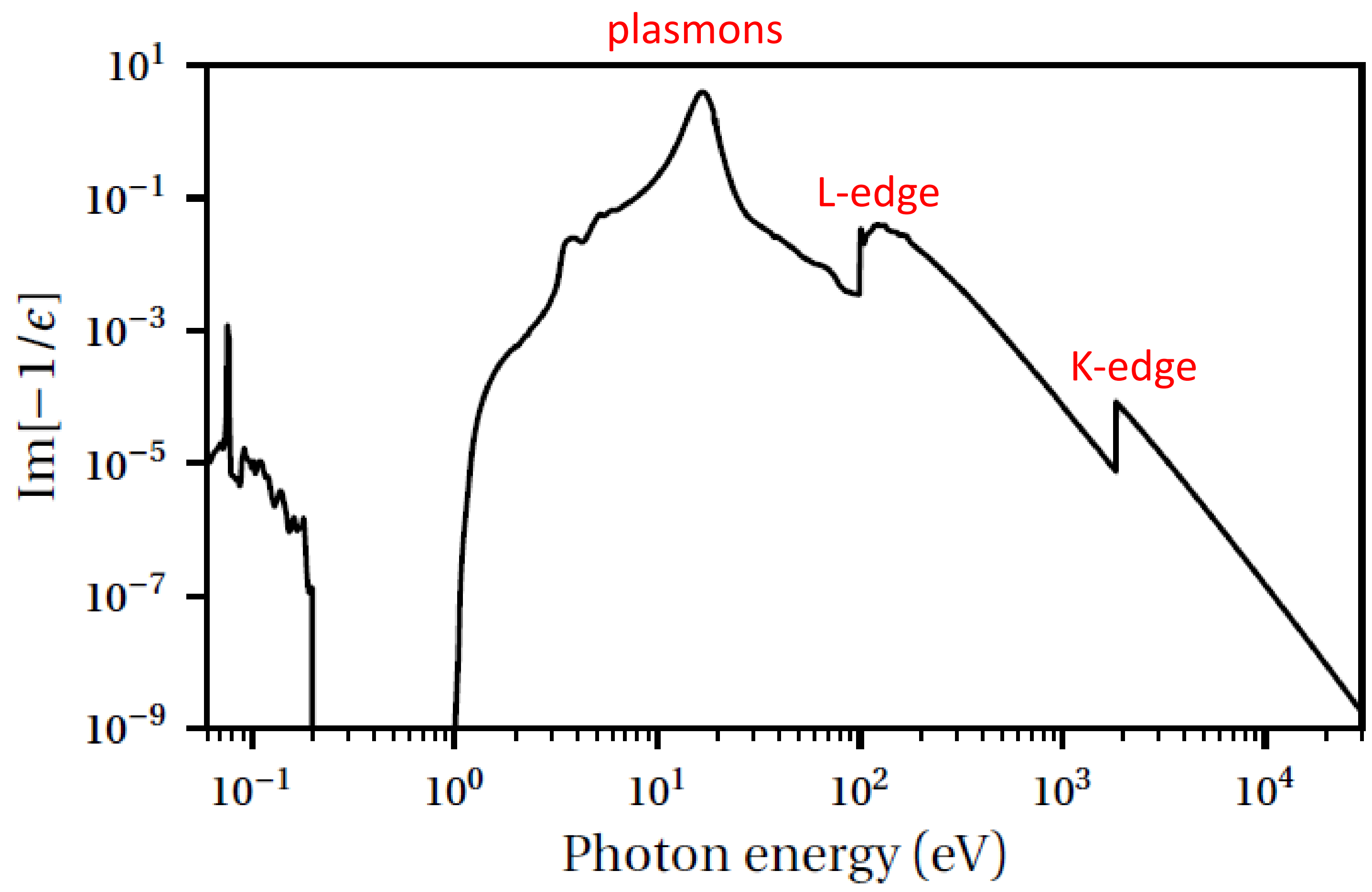
Van Kessel (TU-Delft, ASML) - 2022
Model improvements in e-scatter (surface plasmons, Penn model, inner shell excitations)
NEBULA (C++/CUDA for CPU and GPU)

Physics models in the Monte Carlo simulator

- **Inelastic scattering**
  - Dielectric function model Im[-1/ε(q,ω)], to be found by combining measured optical data Im[-1/ε(0,ω)] with the full Penn model
  - Secondary electron generation by
    - Direct excitation of a valence electron
    - Excitation via plasmon decay
    - Inner-shell ionization (we apply a 50 eV energy threshold)
- **Elastic scattering**
  - Acoustic phonon scattering at <100 eV (Schreiber and Fitting)
  - Mott scattering at >200 eV (ELSEPA, Salvat et al.)
  - Interpolation between 100 and 200 eV
- **Boundary crossing: quantum mechanical model**

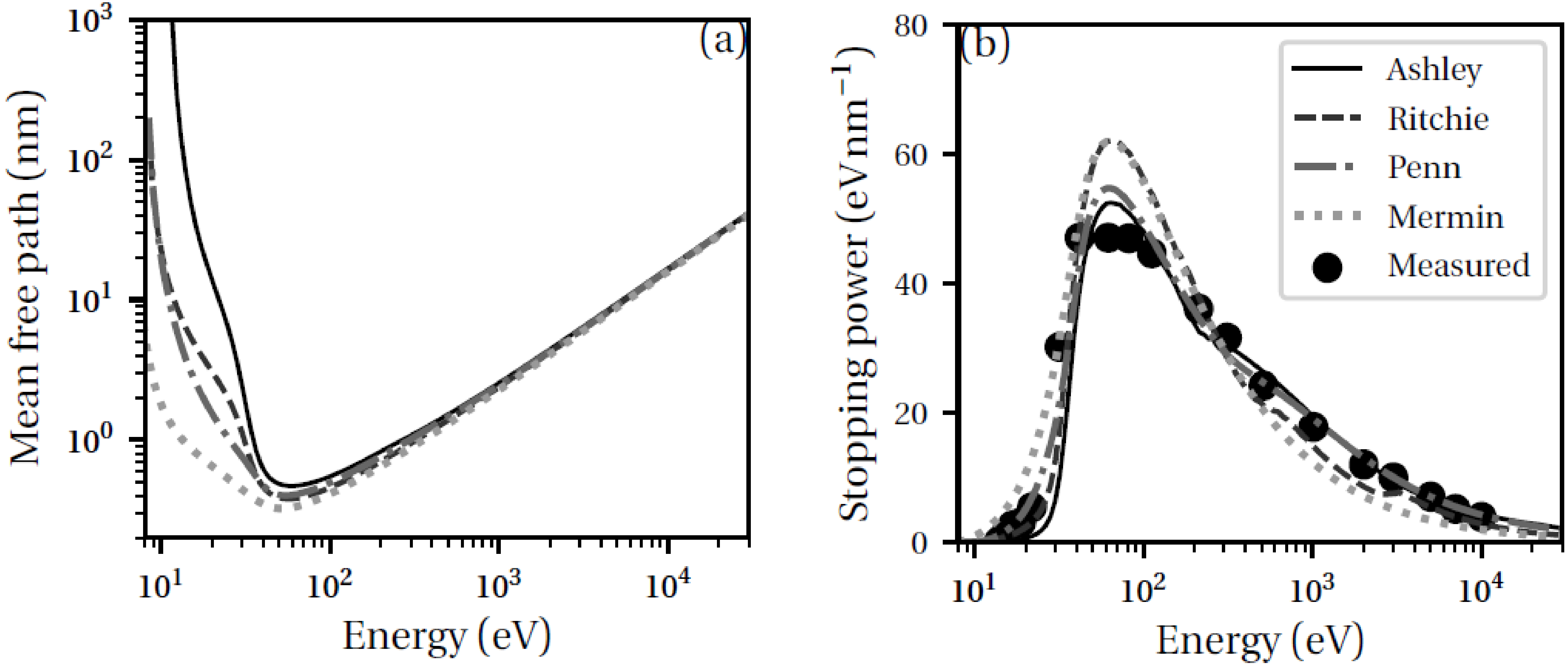


The energy-loss function for Silicon



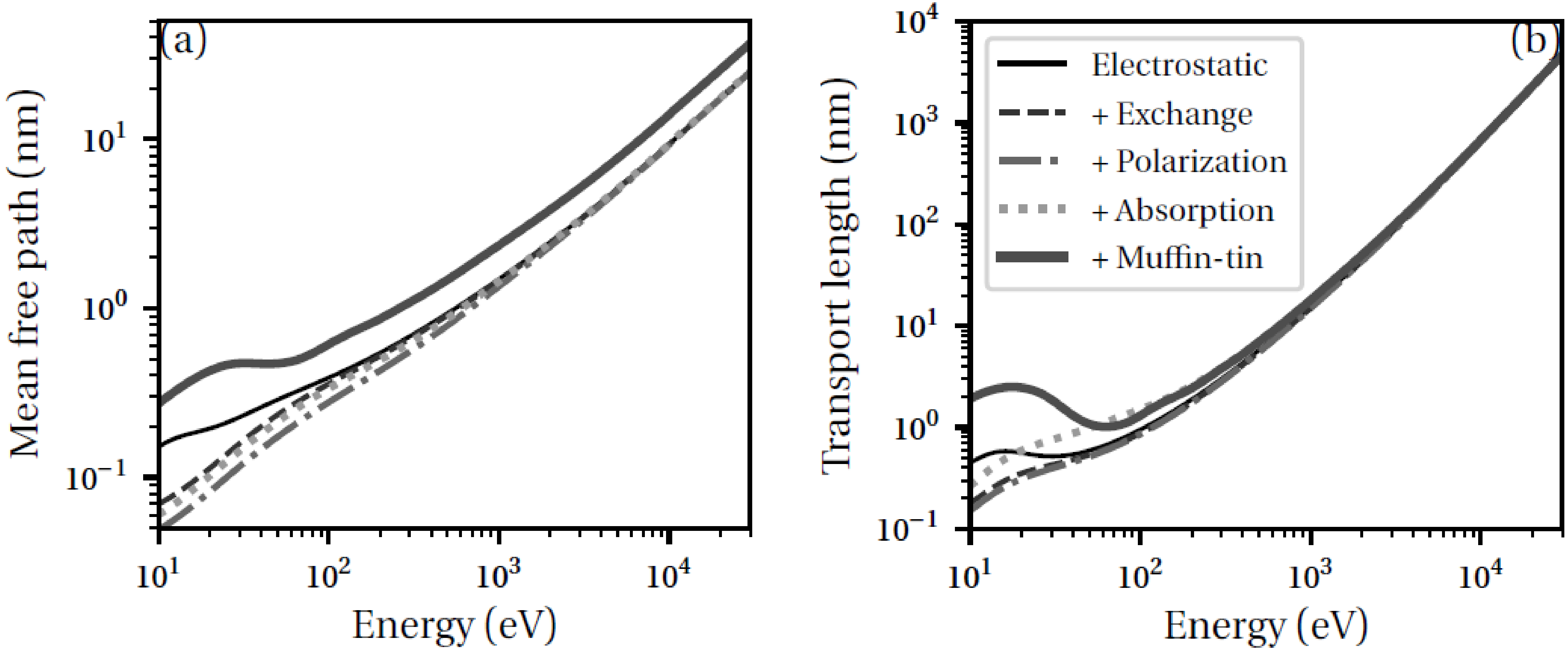
[Data was combined from various sources]

Inelastic mean free path and stopping power for various extension models for silicon

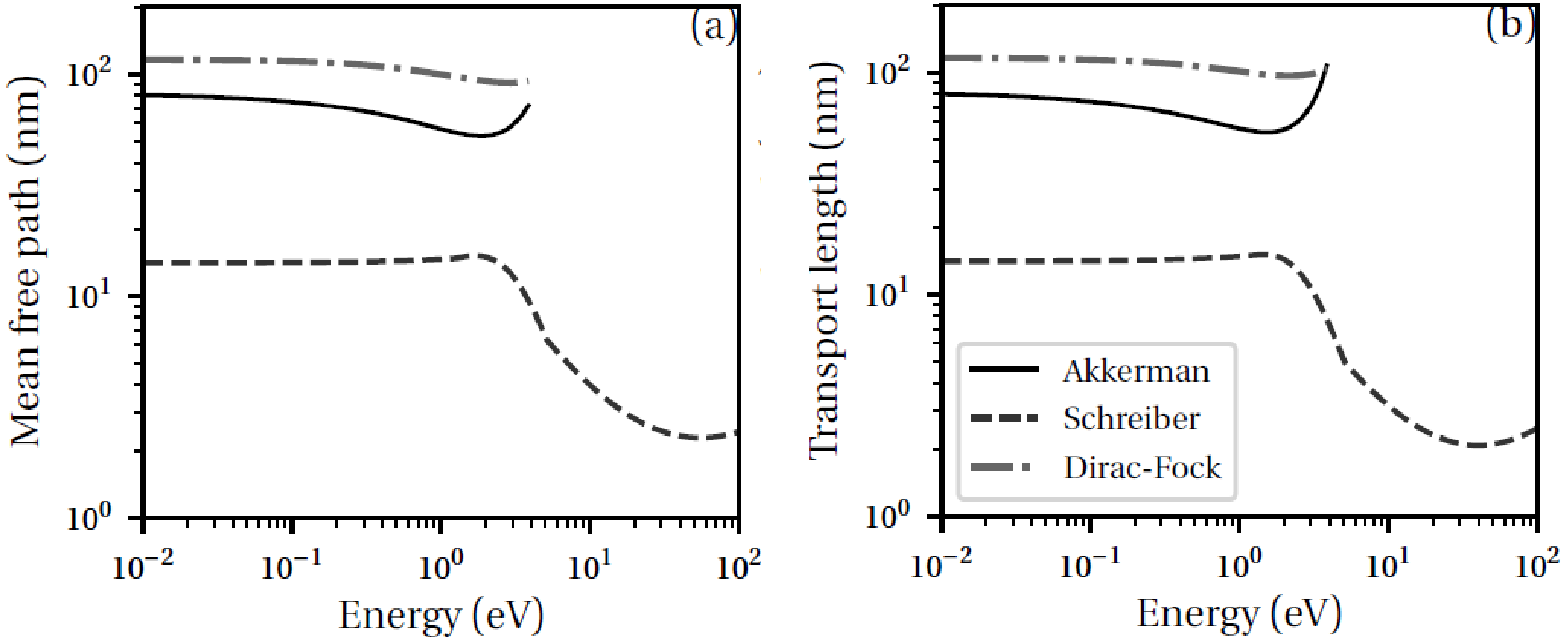


[● Measured data are from: D.C. Joy, Scanning 17 (1995) 270]

Elastic mean free path and transport length for silicon using ELSEPA

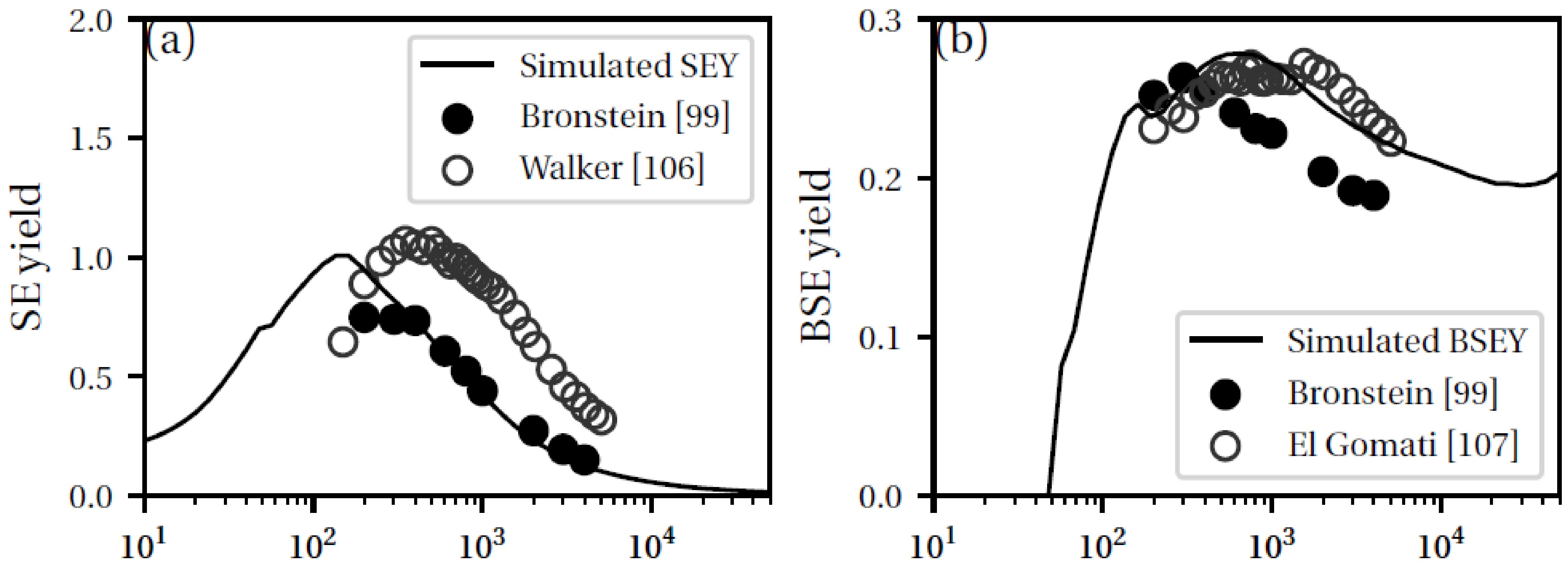


Mean free path and transport length for several electron-acoustical phonon scattering models for silicon



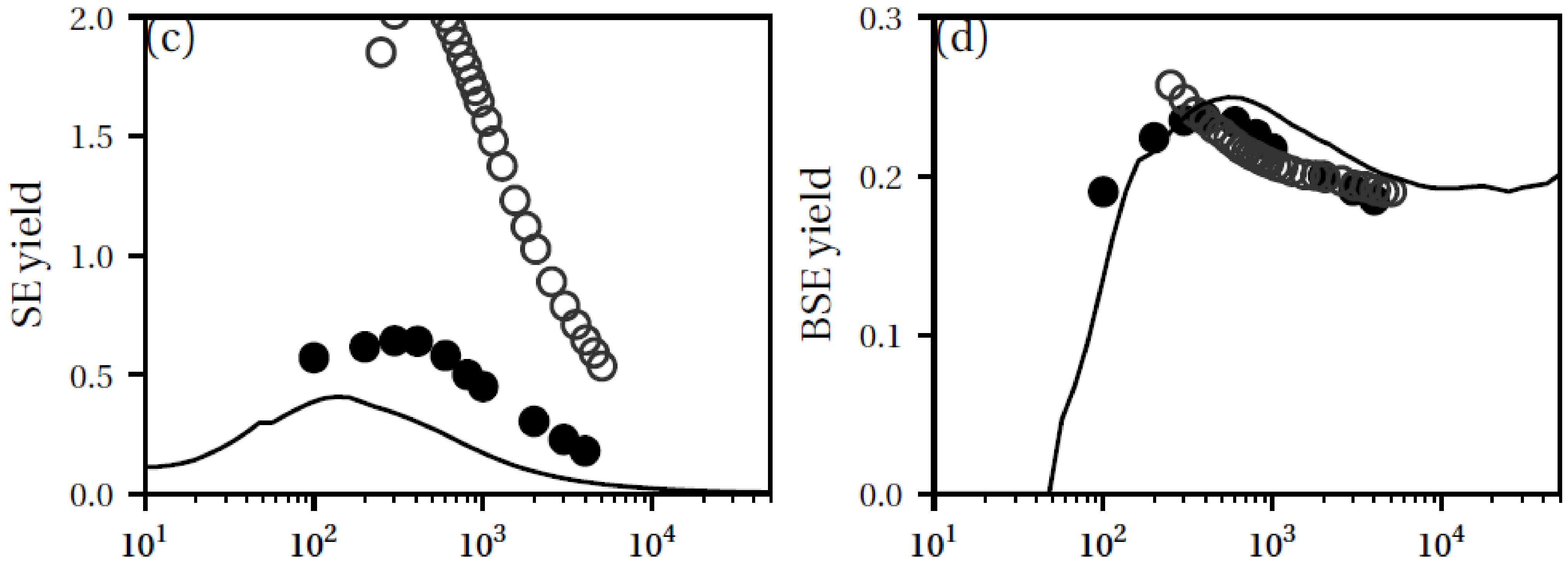
[Energies are referenced with respect to the bottom of the conduction band]

Measured and simulated electron yields (Si)



Closed symbols from: I.M. Bronshtein and B.S. Fraiman in Vtorichnaya elektronaya emissiya (Nauka, Moskva, 1969) 220, 340
Open symbols from: C.G. Walker et al., Scanning 30 (2008) 365 (SE yield) and M.M. El Gomati et al., Scanning 30 (2008) 2 (BSE yield)

Measured and simulated electron yields (Al)



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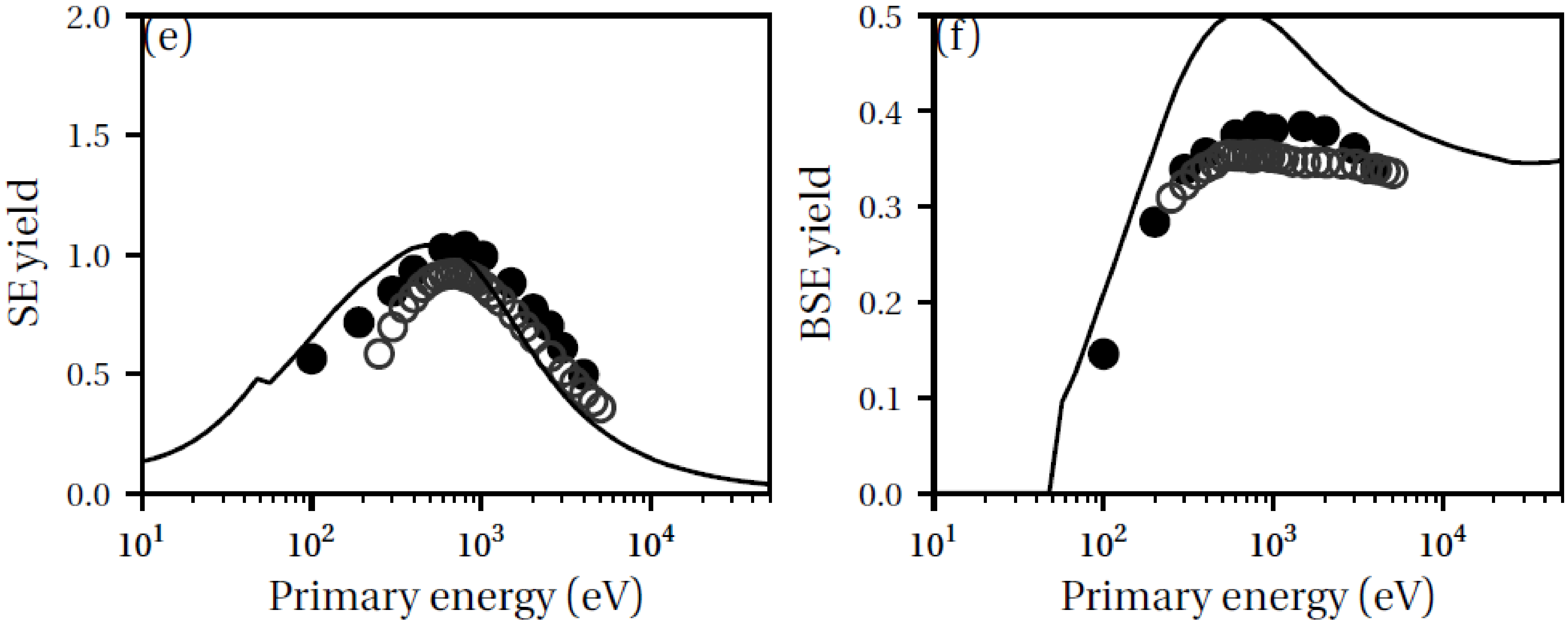
Open symbols from: C.G. Walker et al., Scanning 30 (2008) 365 (SE yield) and M.M. El Gomati et al., Scanning 30 (2008) 2 (BSE yield)

Measured and simulated electron yields (Cu)



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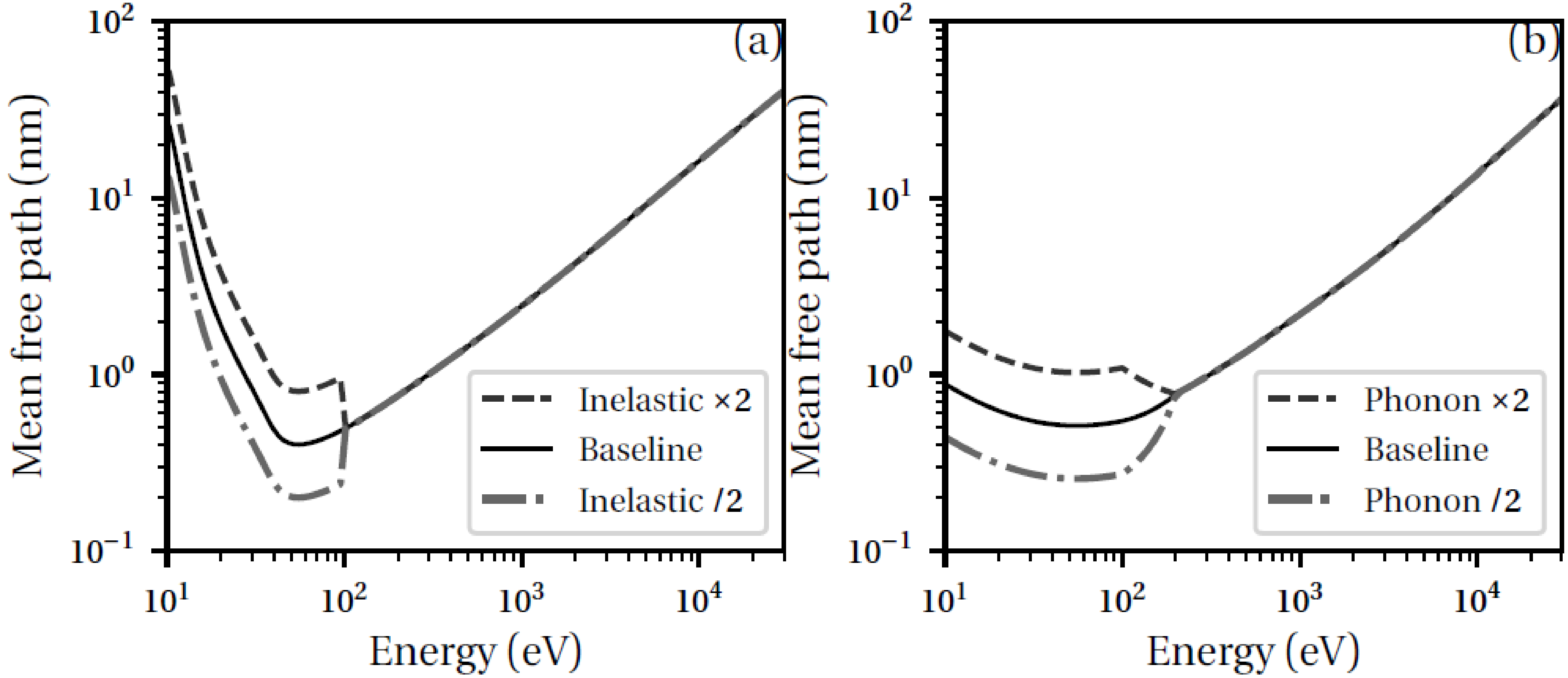
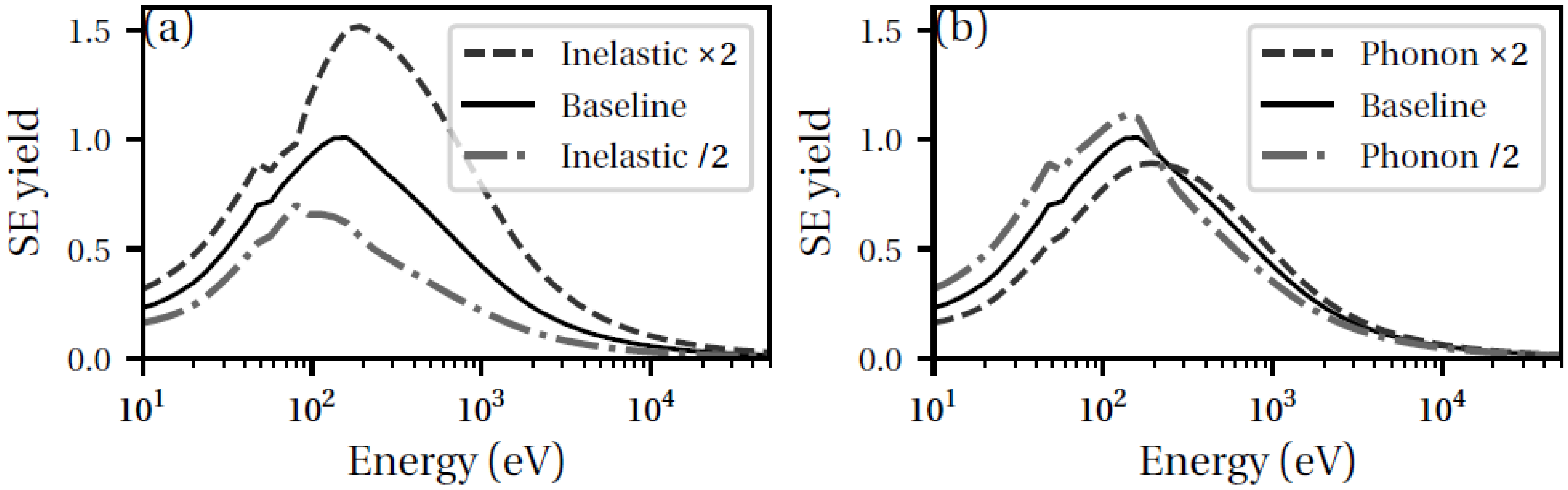
Open symbols from: C.G. Walker et al., Scanning 30 (2008) 365 (SE yield) and M.M. El Gomati et al., Scanning 30 (2008) 2 (BSE yield)

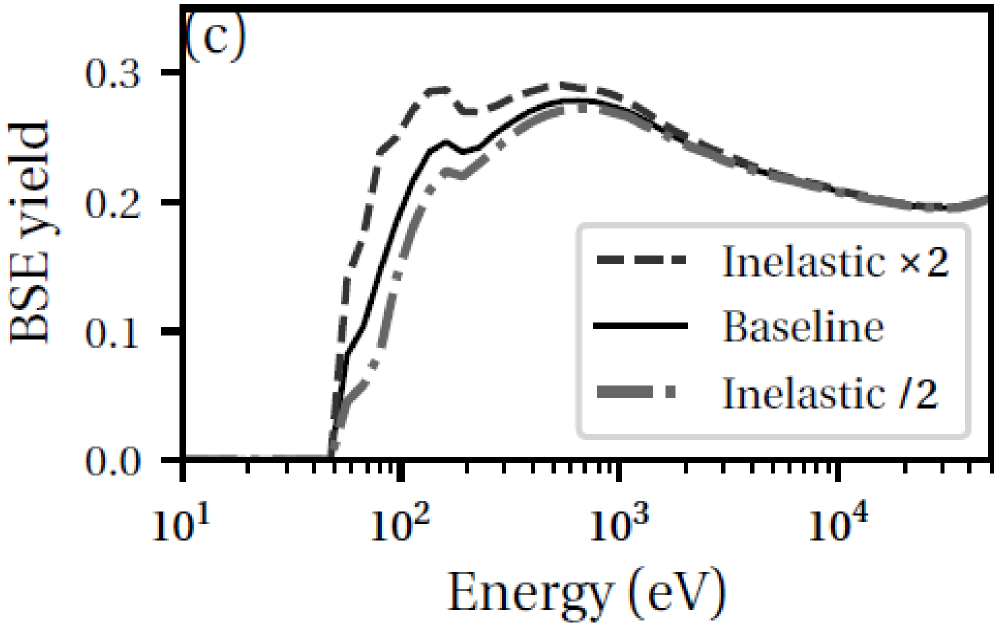
Modification of inelastic and phonon mfp's (Si)

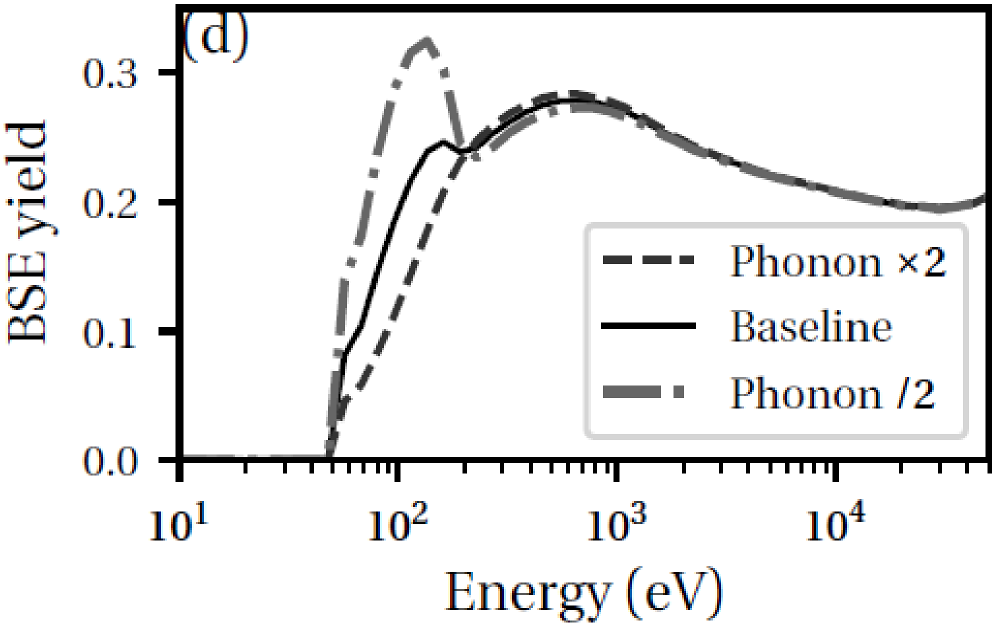


SE yields of Si using modified (a) inelastic and (b) phonon mfp’s

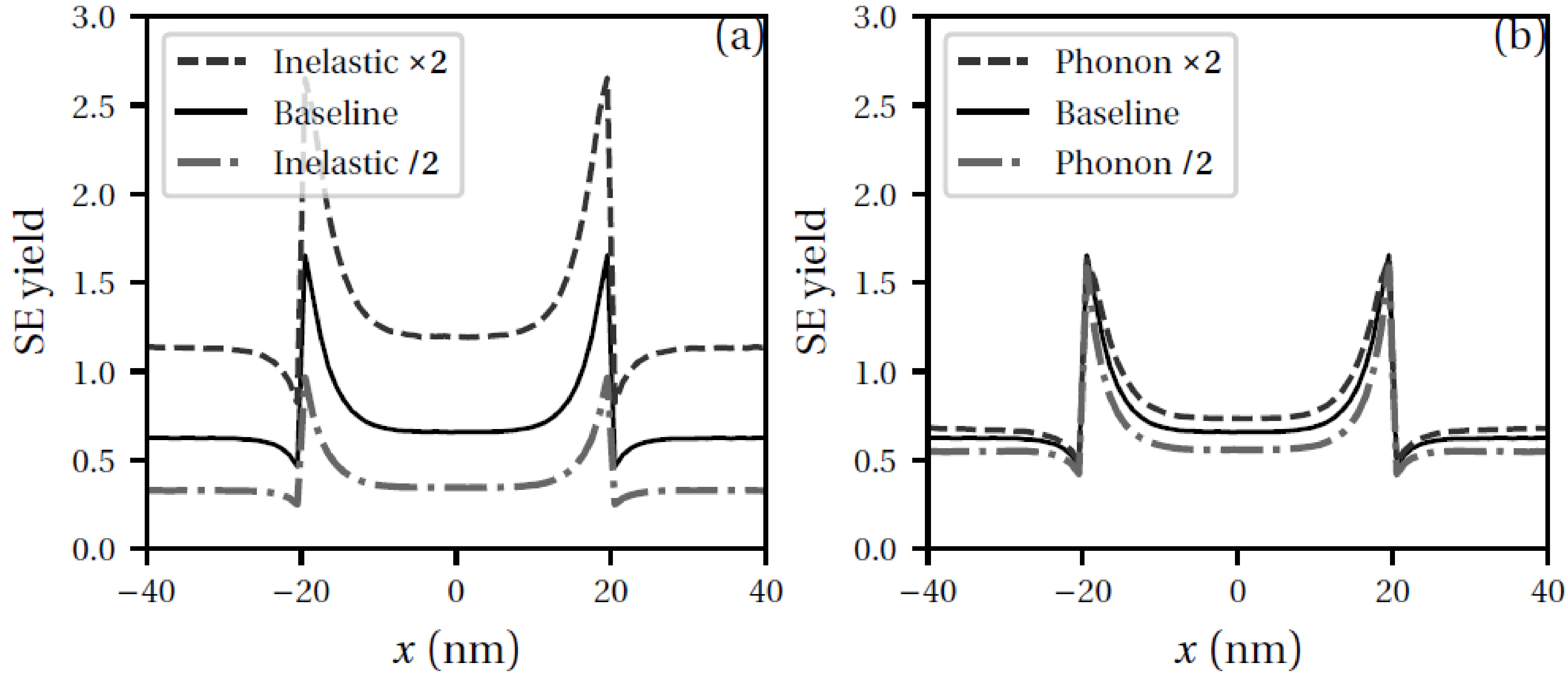


BSE yields of Si using modified (c) inelastic and (d) phonon mfp’s





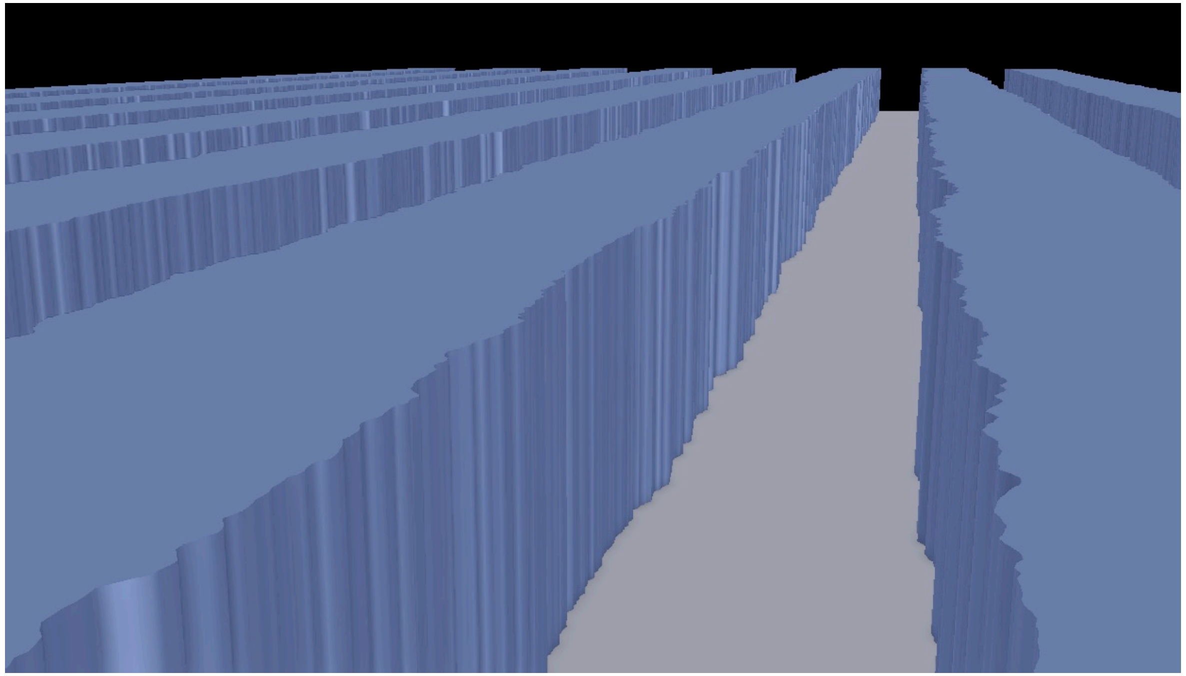
Linescan of an isolated 40 nm high and 40 nm wide Si line on a Si substrate. Zero-width electron beam of 500 eV. Modified inelastic and phonon mfp's.



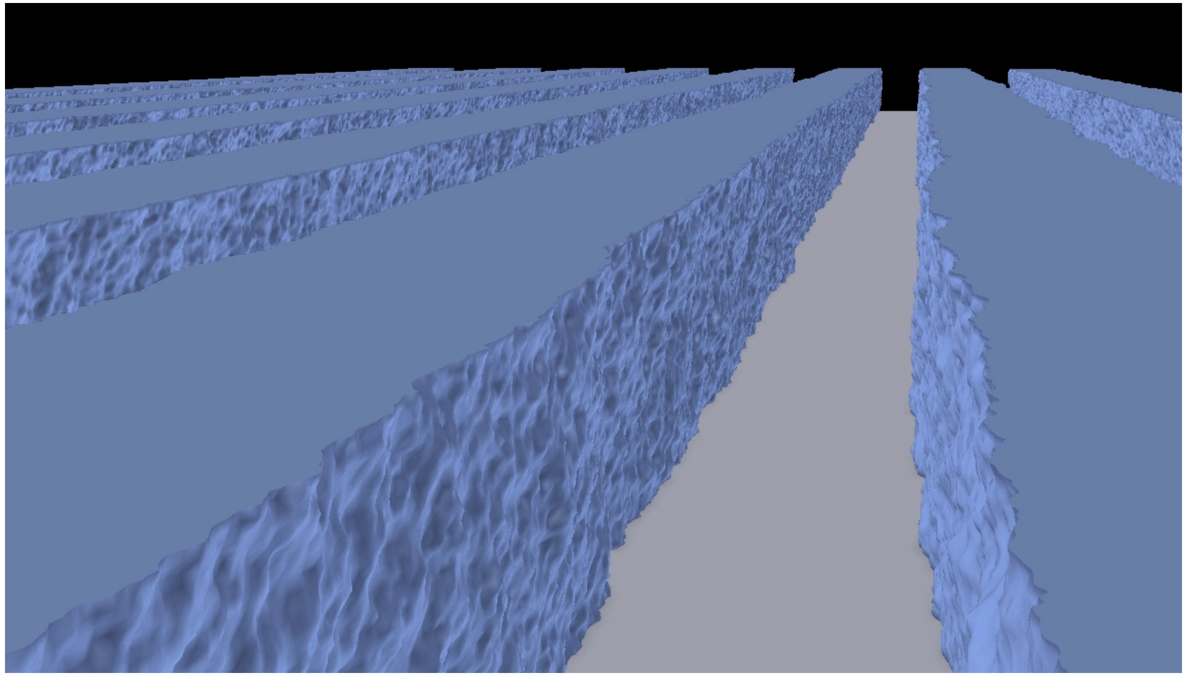
Mfp*2: 25% increase in edge blooming effect; Mfp/2: 20% decrease in edge blooming effect

Influence of sidewall roughness on observed line edge roughness in SEM images

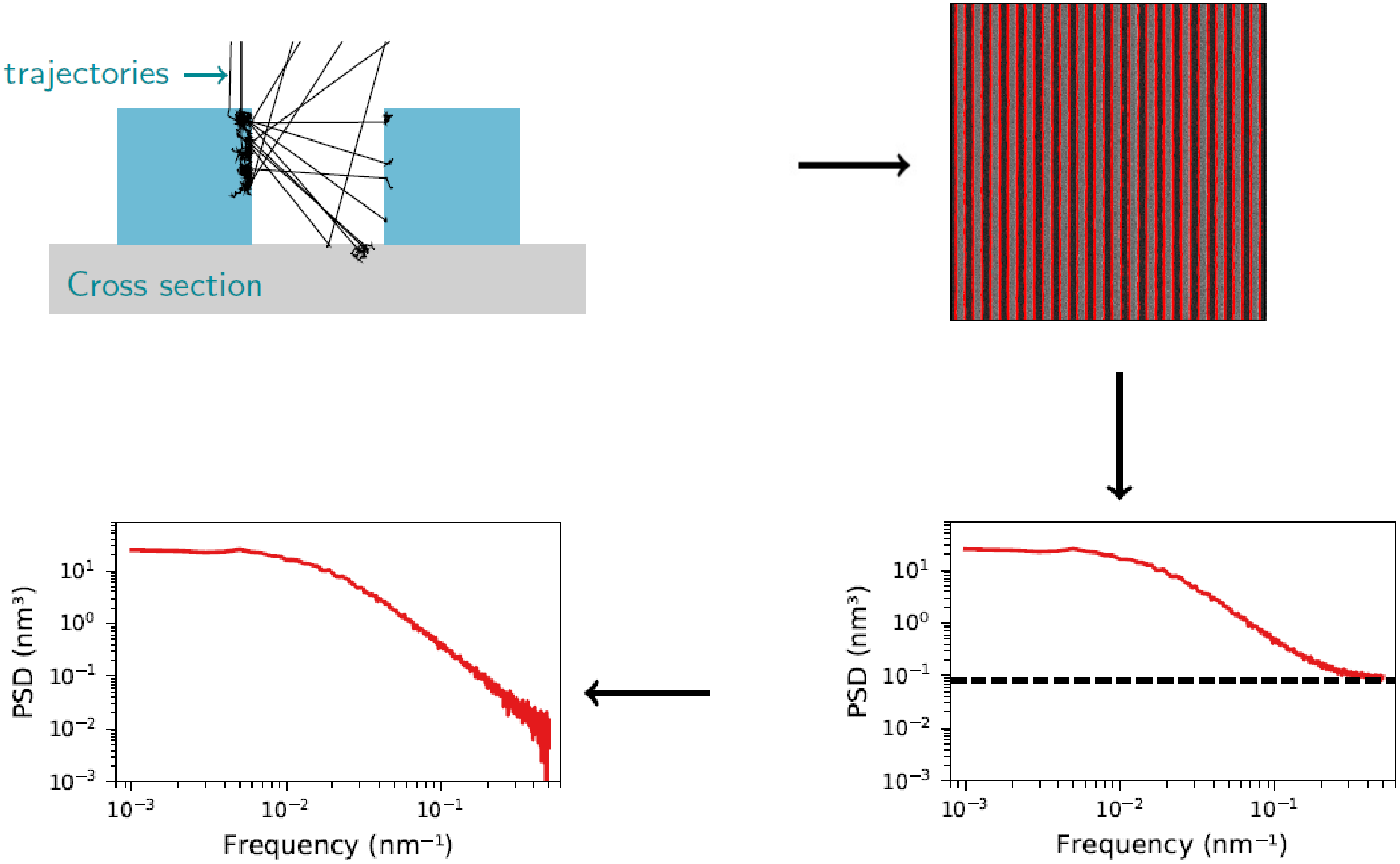
People assume LER looks like this ……



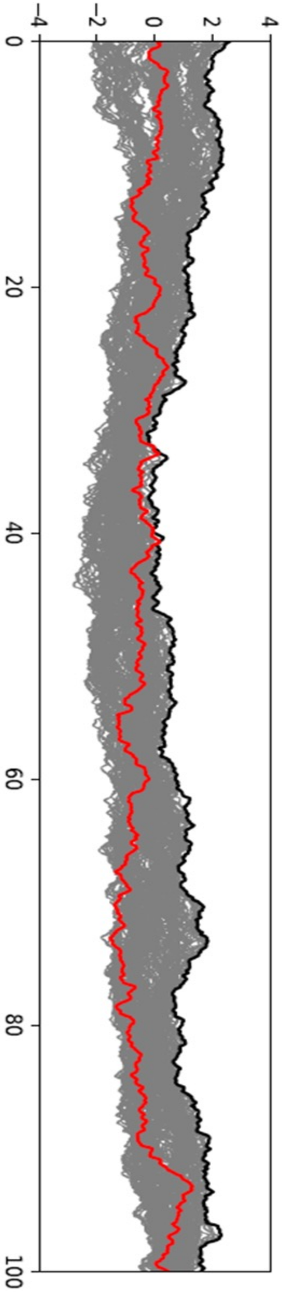
….. but resist often looks more like this

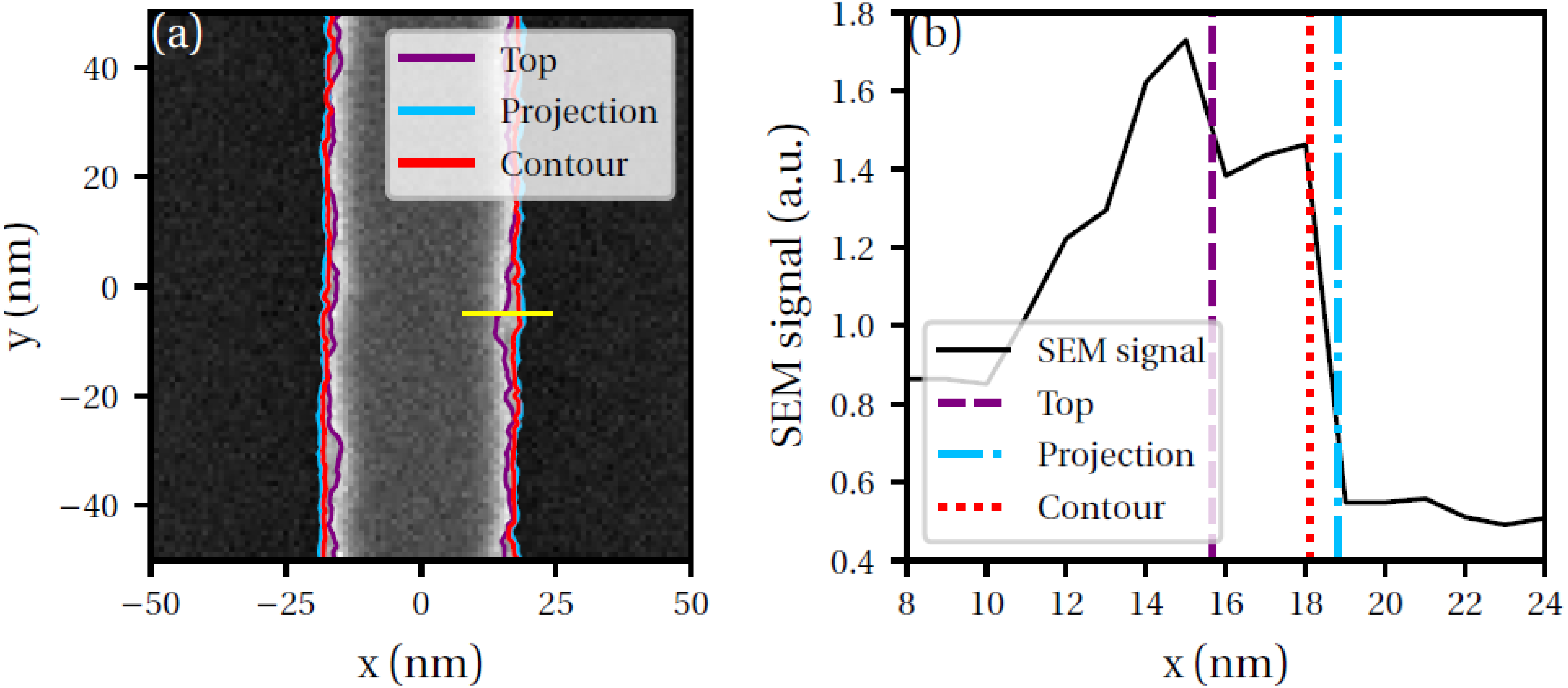


Method: simulate SEM images, compare measured to input roughness

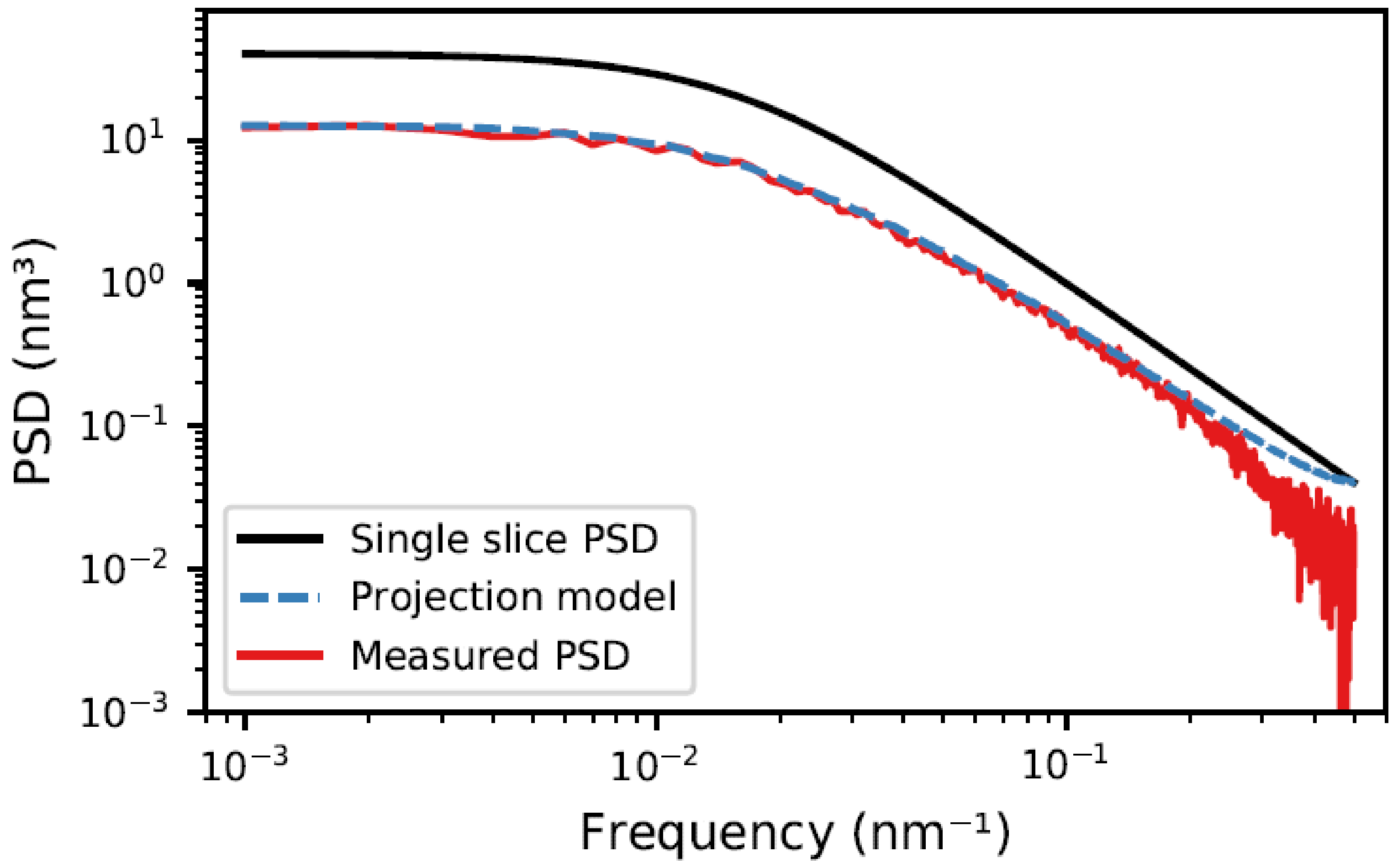


Contouring method

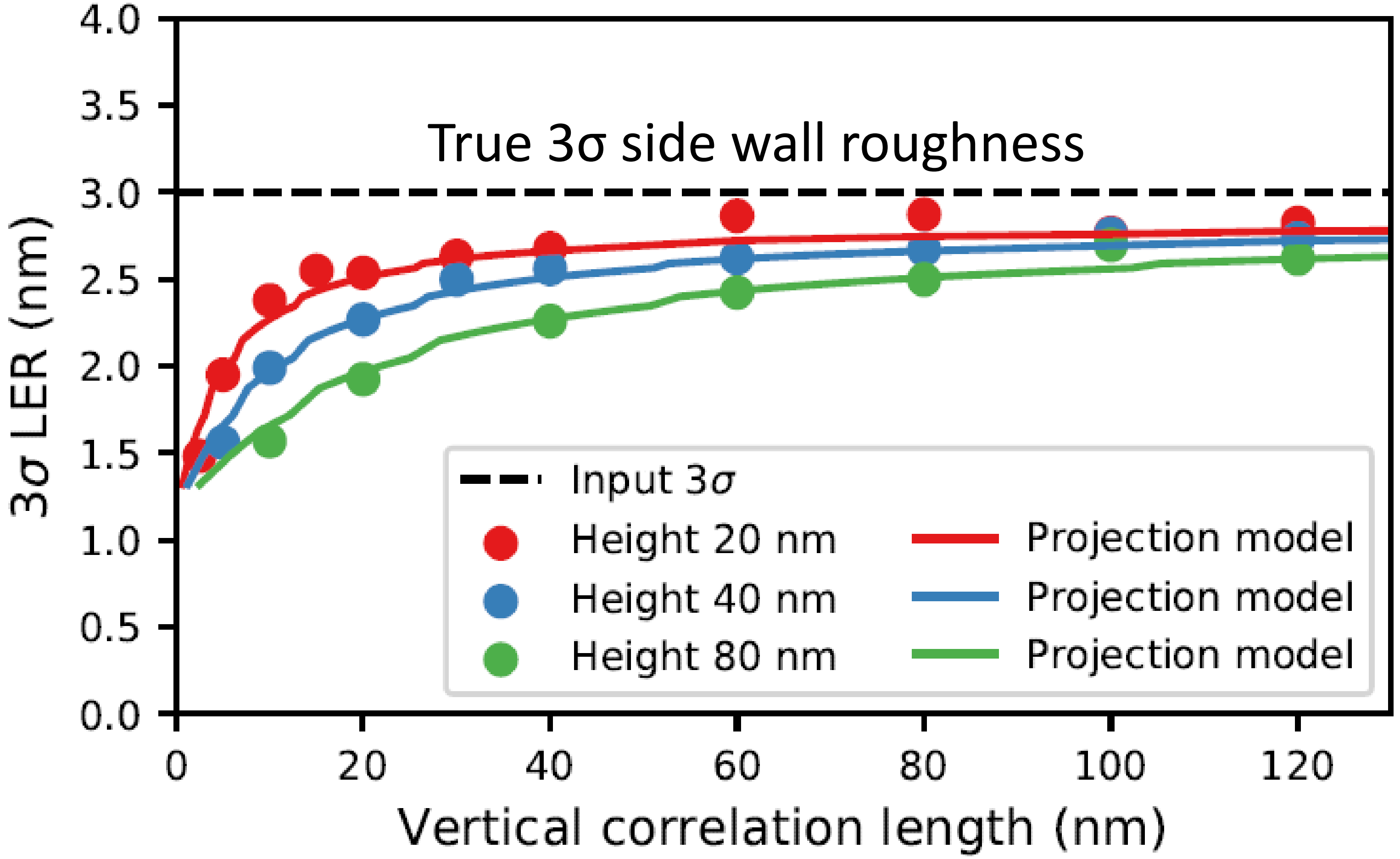




Projection model predicts the PSD from full simulations very well (for isolated lines)



Bias in LER with respect to the true SWR



What is missing in our simulations?

Three categories of uncertainties

- Imperfect modelling
  - Dielectric function (1^{st} Born approximation, exchange effects, tensor (anisotropic materials), extension to non-zero momentum
  - Inner-shell excitations
  - Low-energy elastic scattering
  - Wave and band structure effects (diffraction, band bending, anisotropy)
  - Defects, trapping, delocalisation
  - Interface effects (electric fields, work function potential, surface states)
  - Charging (electric fields, charge diffusion, electron-beam-induced current, voltage breakdown)
- Imperfect assumptions about the sample
  - Idealized structure and geometry (homogeneous, isotropic, atomically flat)
  - Native oxides
  - Surface contamination
  - Sample damage (ionization, bond breaking, excitation, heating, atom displacement)
- Imperfect experimental conditions
  - Cleanliness (vacuum level)
  - Vibrations and electromagnetic fields

Foundations for electron beam metrology & inspection


Jacob Hoogenboom


Kees Hagen


Timon Fliervoet


Roland Bliem


Paul Planken

Goal

Improve reliability, resolution, and acquisition speed at low landing energies, low contamination and damage levels

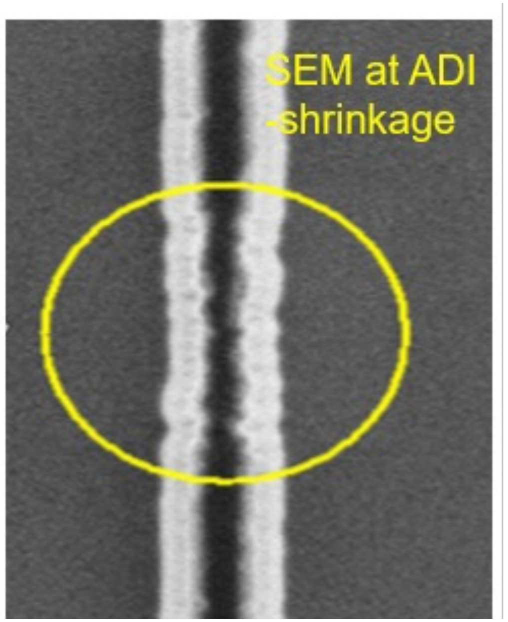
Main application areas

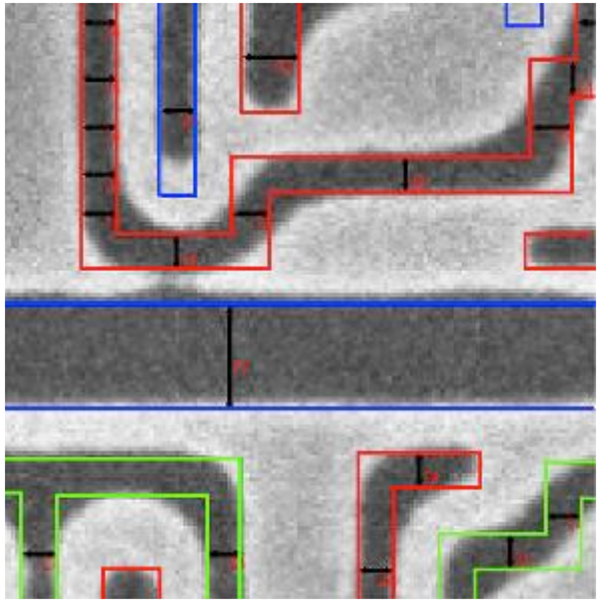
Metrology: accurate measurement of location, size and roughness of features printed on wafer

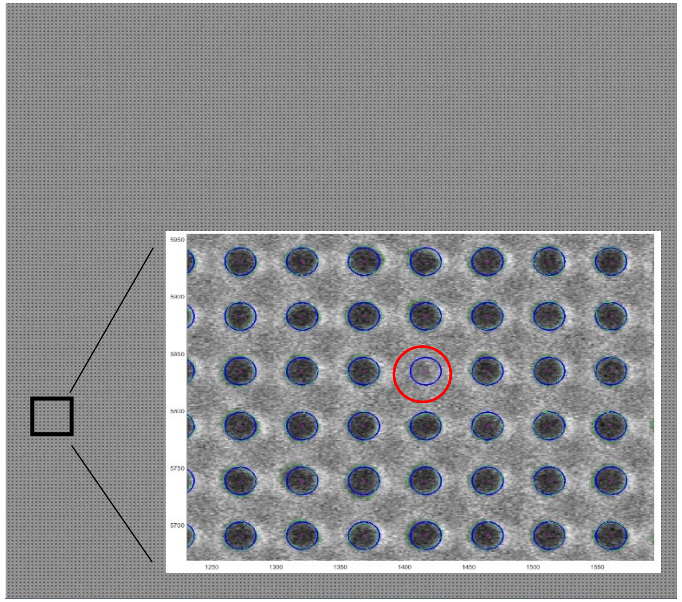
Inspection: detection and classification of (buried) defects on wafer

Central question: How does one ensure that an electron image provides the 'correct' information?

Why are we interested in electron beam technology?





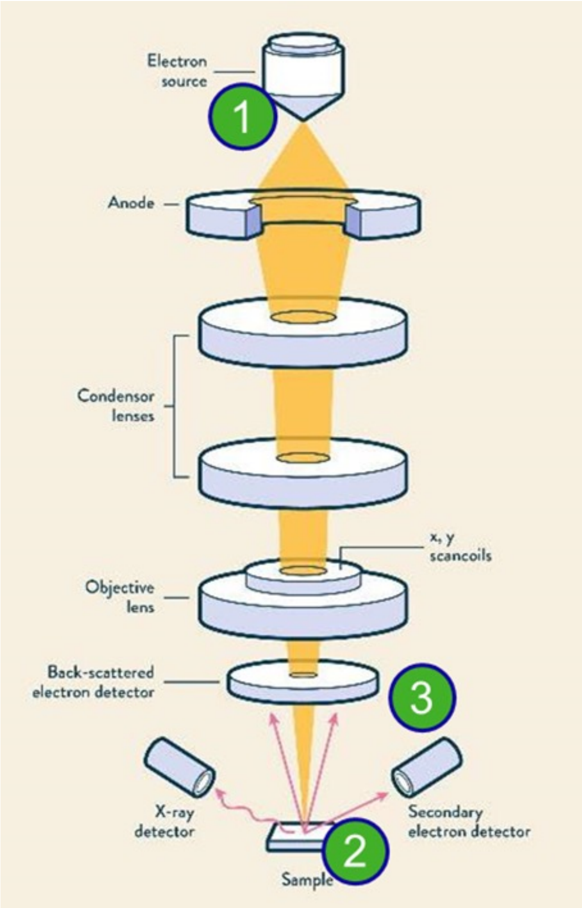


Program description

6 / 7 PhDs + 3 PostDocs ; 5 yr program, starting January 2024. Hiring now!

Three research lines (application driven)

- **Instrumentation** 1
  - Applications requirements & research into SEM design
  - Ultraclean vacuum (mini) environment
  - Application optimized SEM instrumentation (sources, corrector)
- **Electron target interaction, with focus on low landing energy** 2
  - Simulation models on charging & damage
  - Experimental characterization on electron induced damage & charge diffusion
- **Signal generation and detection** 3
  - Artefact and charging damage removal
  - Novel detector concepts
  - Experimental validation: the holistic approach



Thank you for listening