The Response of Energy Dispersive X-Ray Detectors

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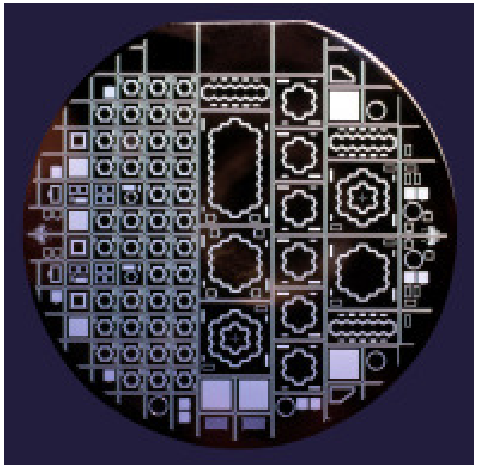
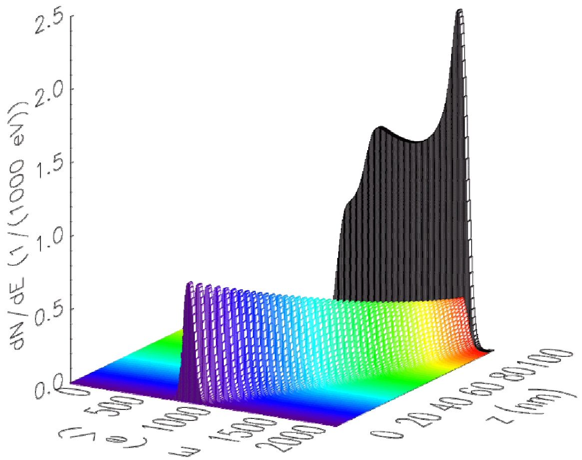
The Response of Energy Dispersive X-Ray Detectors



Part A   Principles of Semiconductor Detectors

1. Basic Principles
2. Typical Applications
3. Planar Technology
4. Read-out Electronics



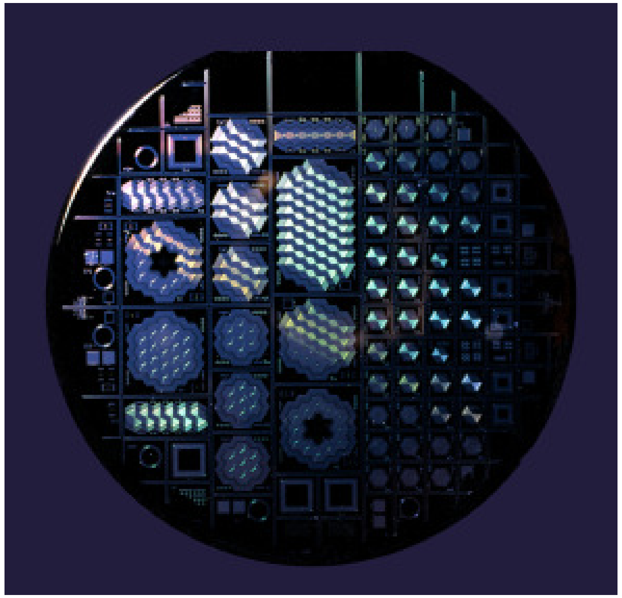
Part B   Response of Silicon Drift Detectors

1. Silicon Drift Detectors
2. Low Energy Measurements/Experimental Setup
3. Calculation of Spectral Contributions
4. Results
5. Resume

Motivation

- Many discoveries and results of fundamental research are closely related to the quality of the instruments used
- Telescopes, Microscopes, Cameras
- New detector concepts enabled the discovery of many elementary particles: e^+, ν, J/ψ
- Results are only reliable if the instrument is well understood
- Response function needed
- Detailed characterization and understanding of detector properties are important for both, users and manufacturers

Why Semiconductor Detectors?



- Photons and charged particles ionize matter
- Gases: electron ion pairs are produced
- Semiconductors: electron hole pairs are produced
- Measurement of position and energy
- Pair creation energy in SC << ionization energy in gases
- High density of solids → high interaction probability
- Integration of transistors and read-out electronics

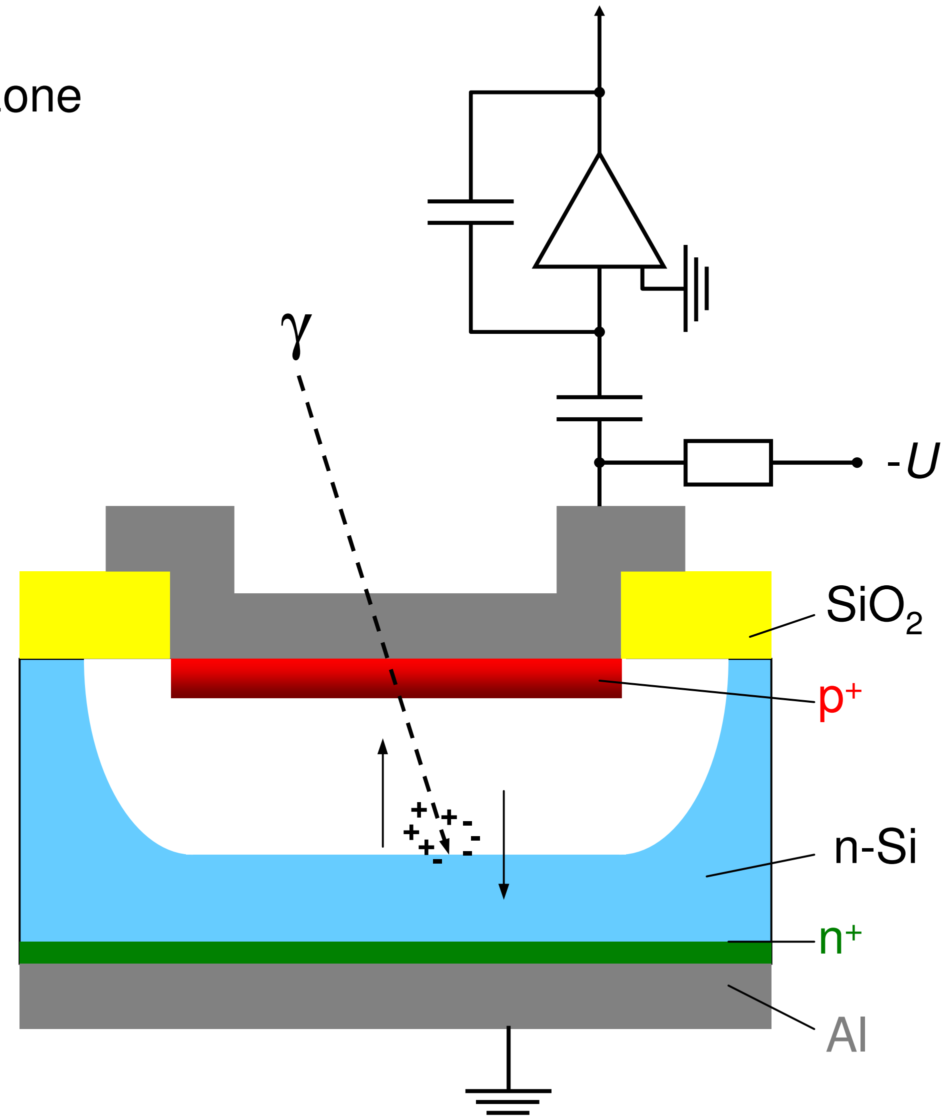
Semiconductor Detectors

p-i-n configuration → depletion zone

Al → saturation of free bonds
→ contacts p^+
→ reflects visible light

p^+ → maximum at the surface
→ no dead layer
→ high electric field strength

- e^--hole pairs generated by radiation
- charge separated and collected
- current mode: current prop. to flux and energy
- single photon counting: signal amplitude $U=q/C$



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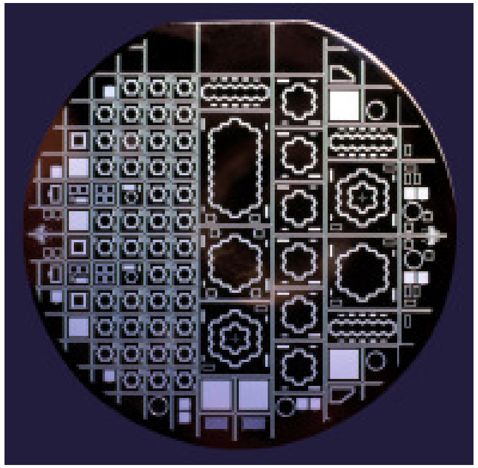

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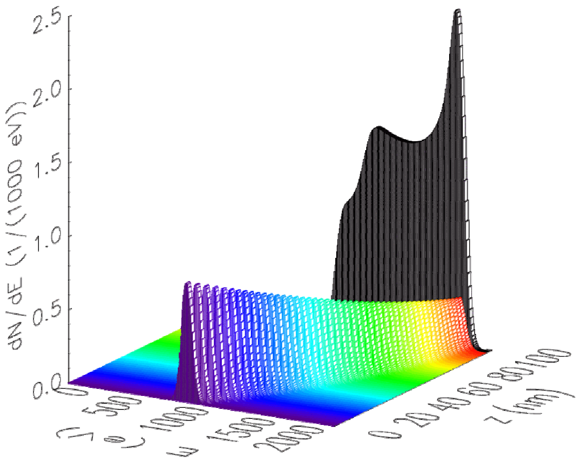

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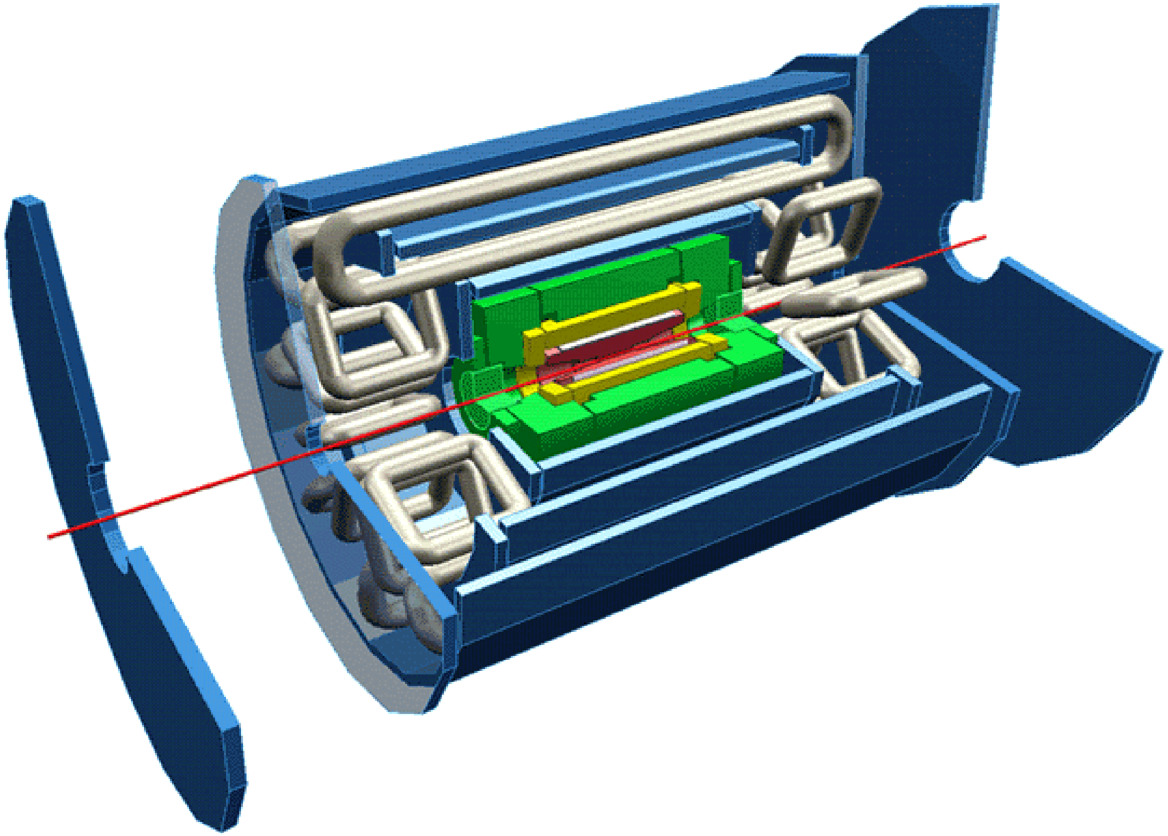
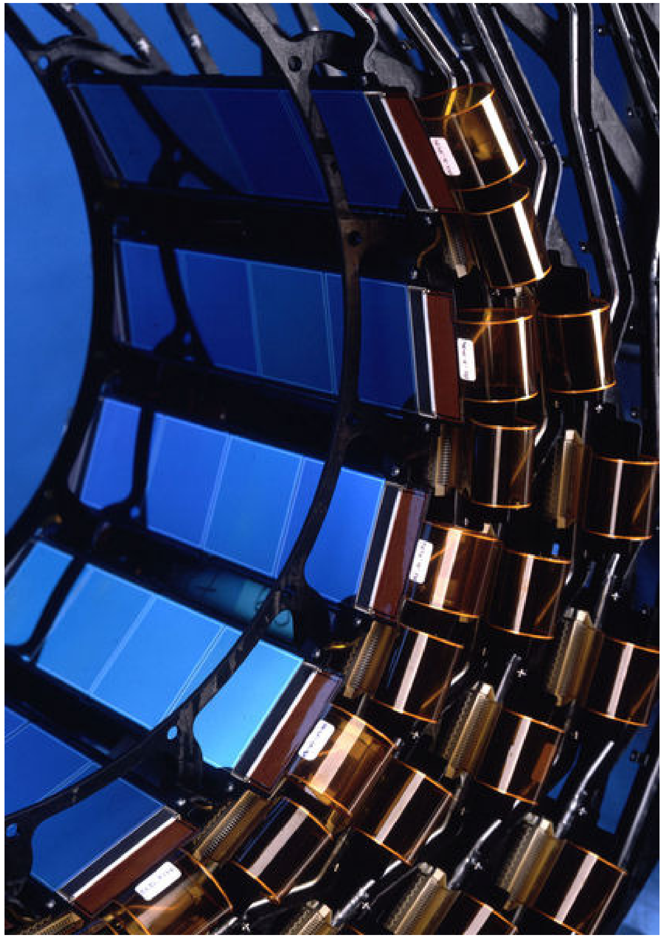
Applications in Basic Research

High Energy Physics

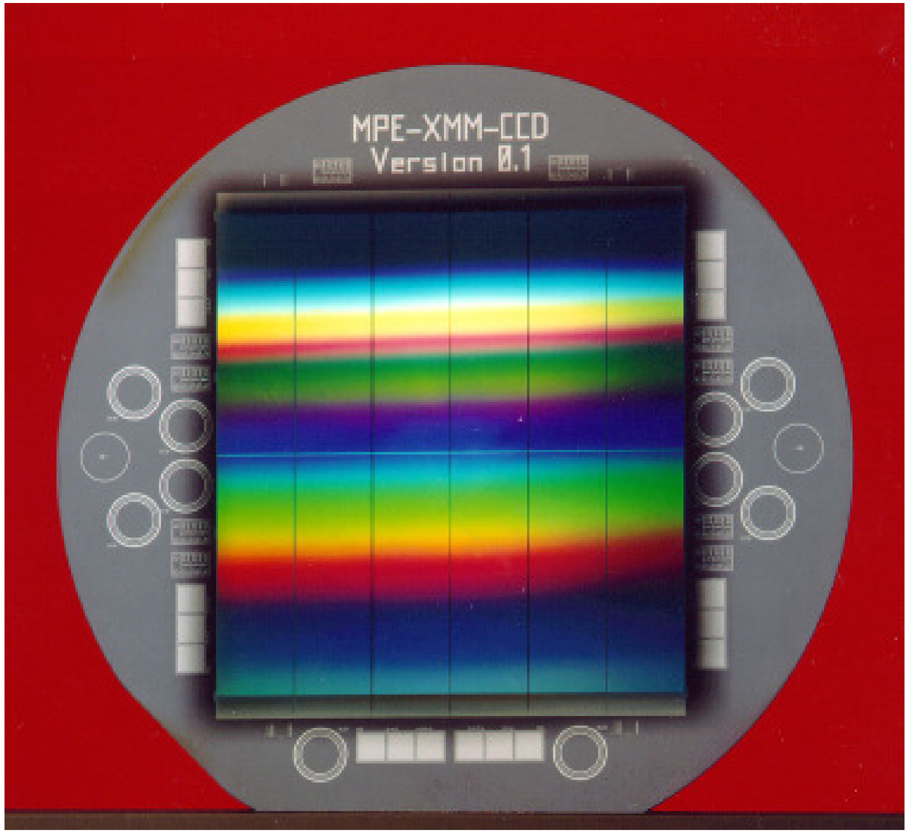


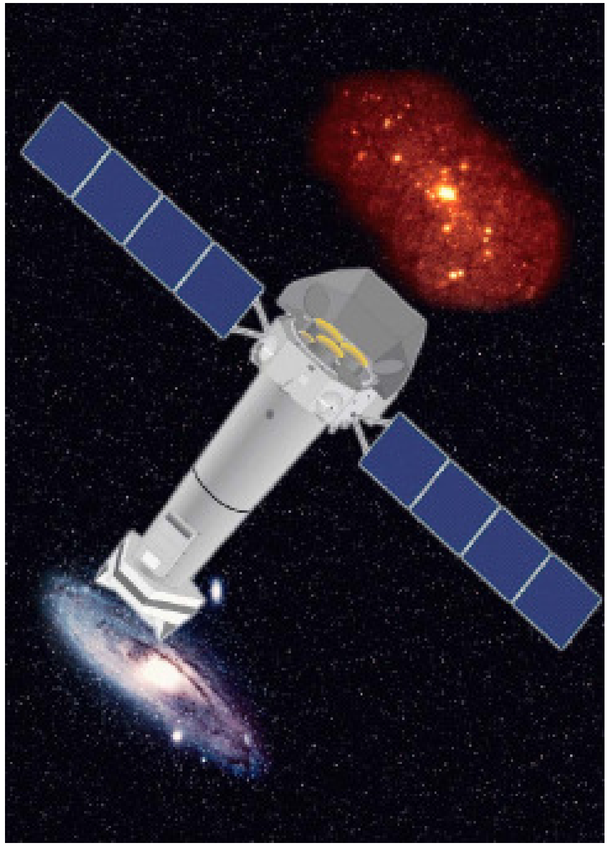


Strip or pixel detectors as inner trackers → position resolution

Applications in Basic Research

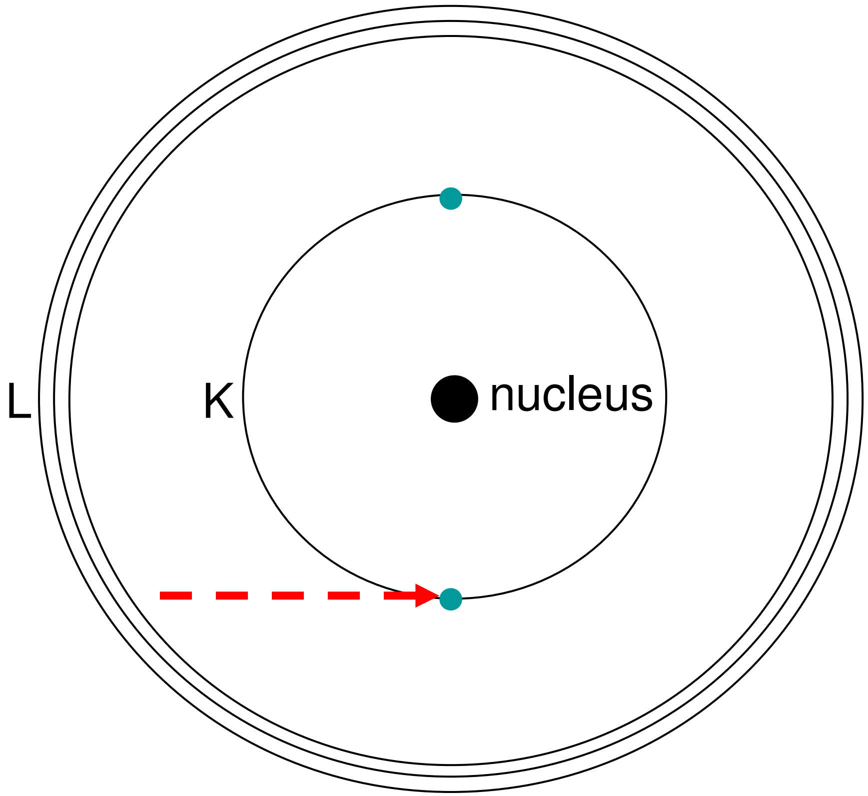
X-Ray Astronomy





Spectroscopy of cosmic x-ray sources
Fully depleted pn-CCD on ESA's x-ray multi-mirror mission (XMM)

X-Ray Fluorescence



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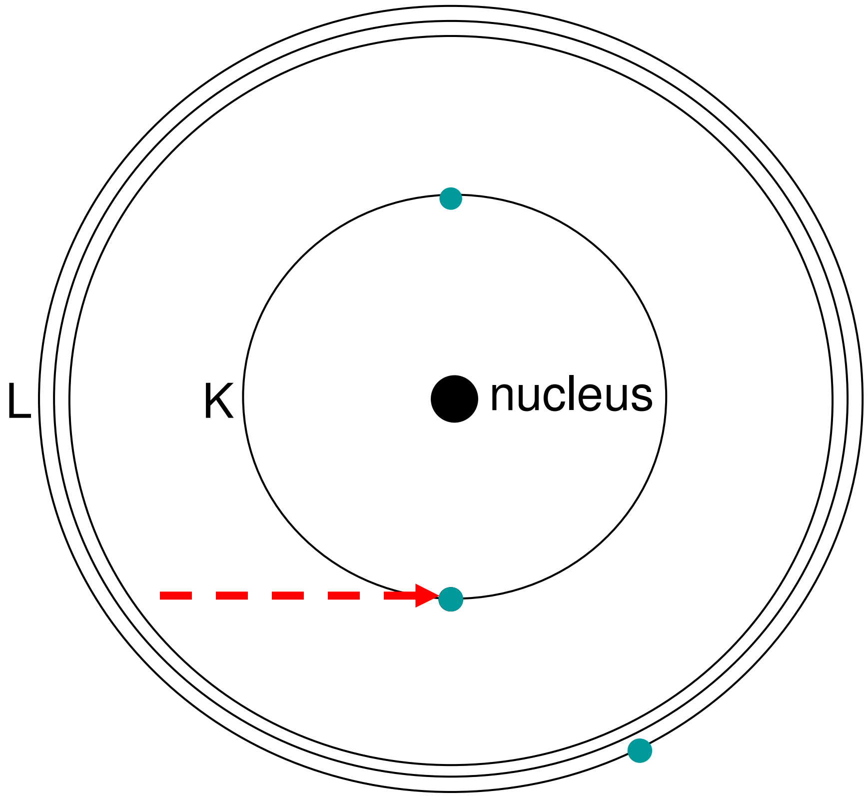

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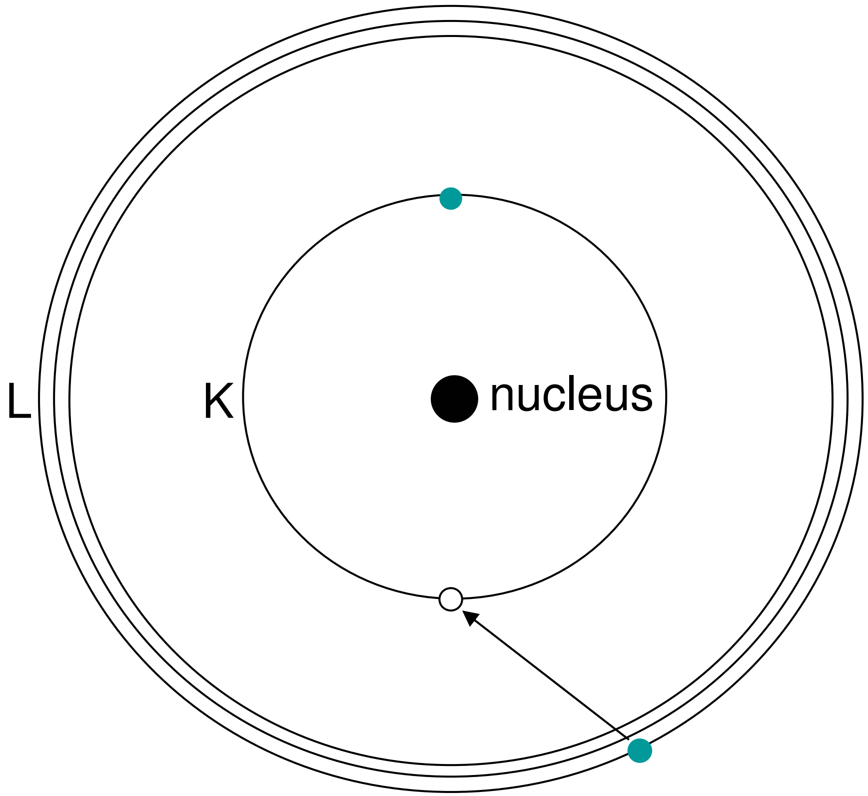

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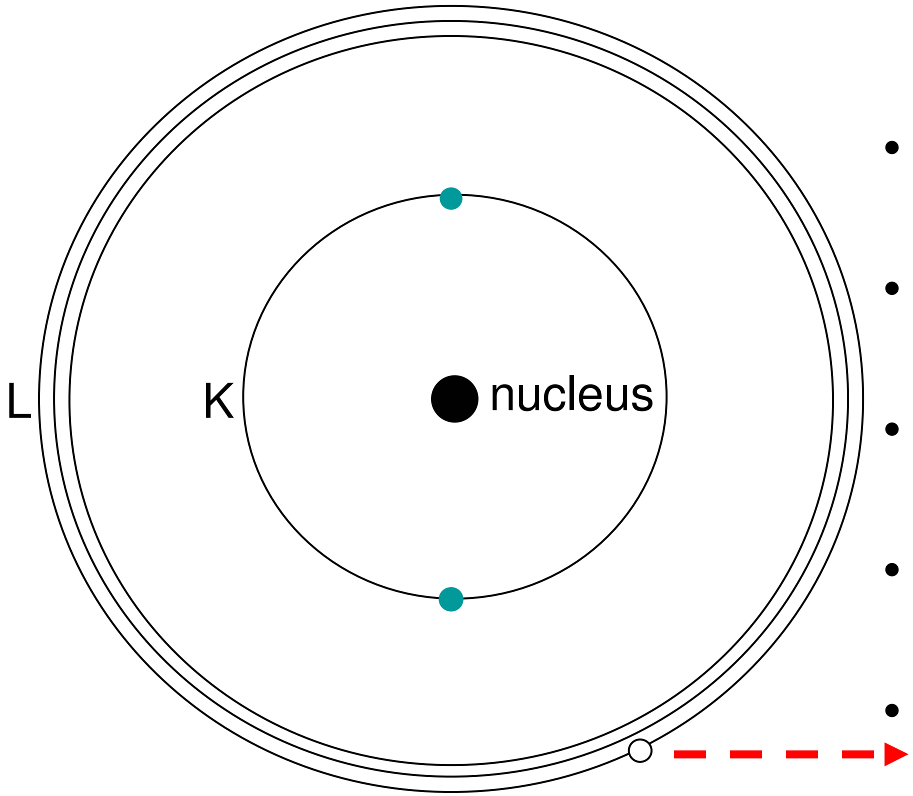
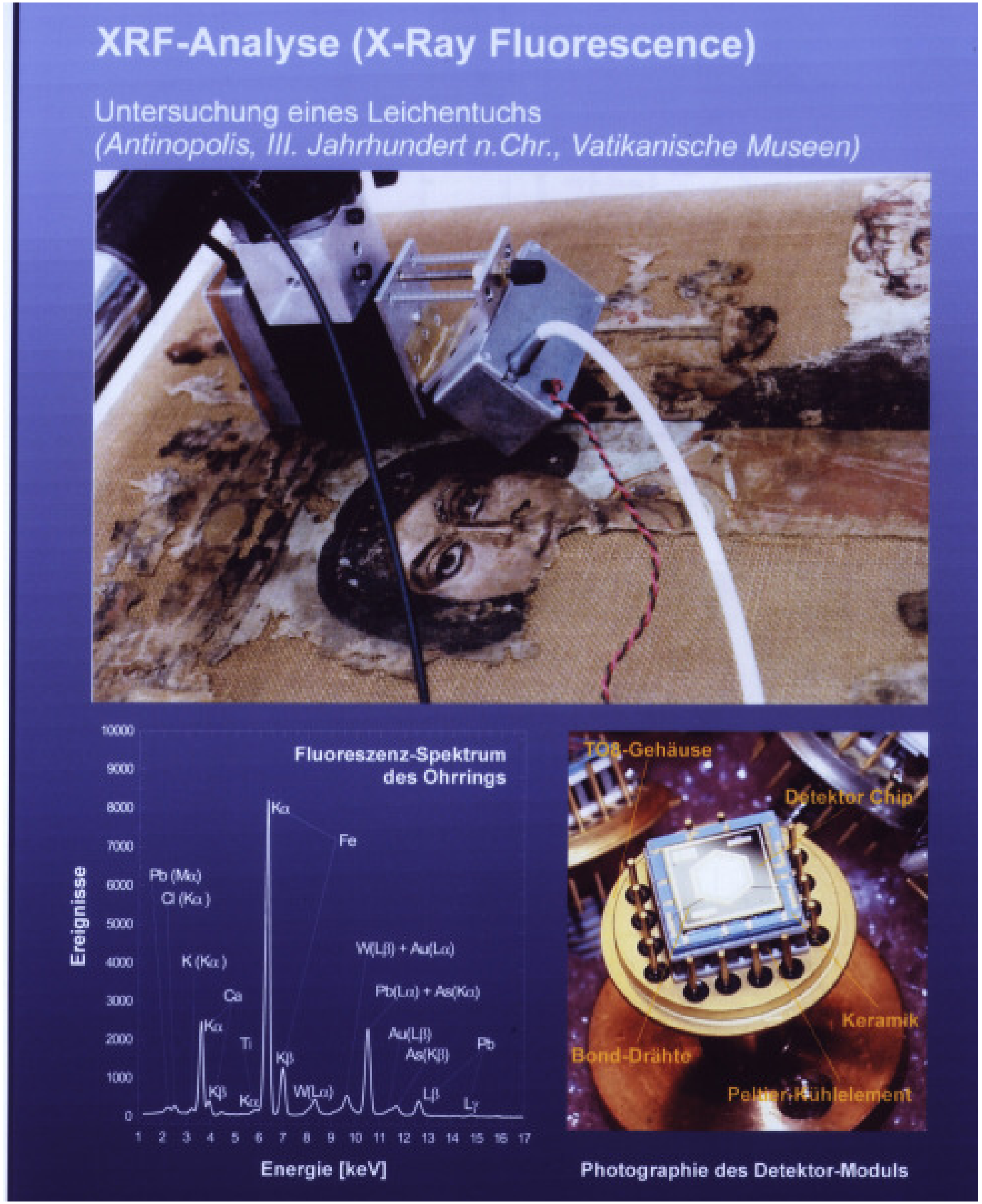


- Energy of fluorescence photon = difference of binding energies
- Moseleys Law:
  E_F prop. to Z^2
- Many transitions possible
- Transitions into K-shell: $K_{\alpha, \beta}$ photons ("peaks")
- Transitions into L-shell: $L_{\alpha, \beta, \gamma, \eta, L}$ photons
- Higher fluorescence yield for high Z elements

Application

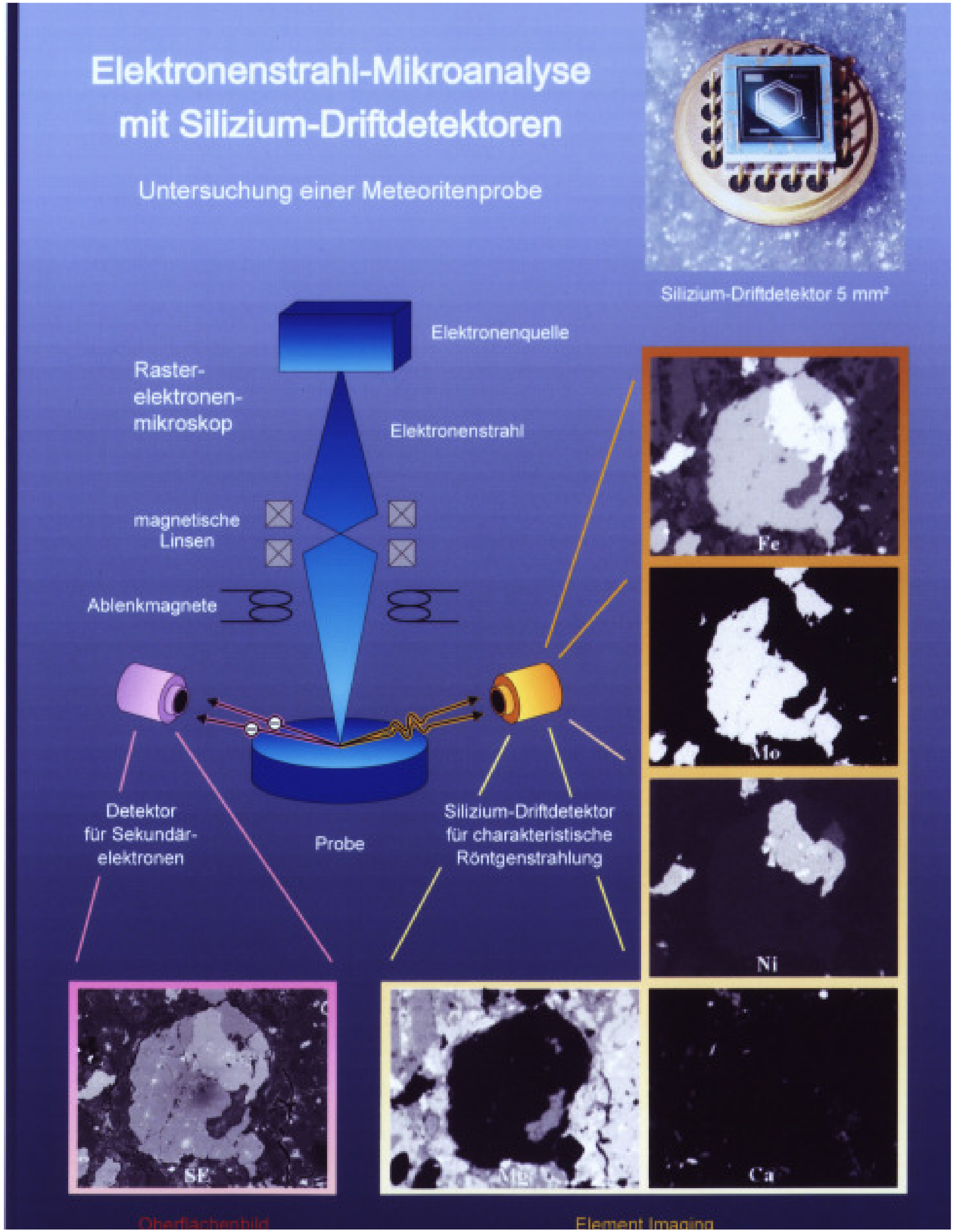
X-Ray Fluorescence Analysis (XRF)

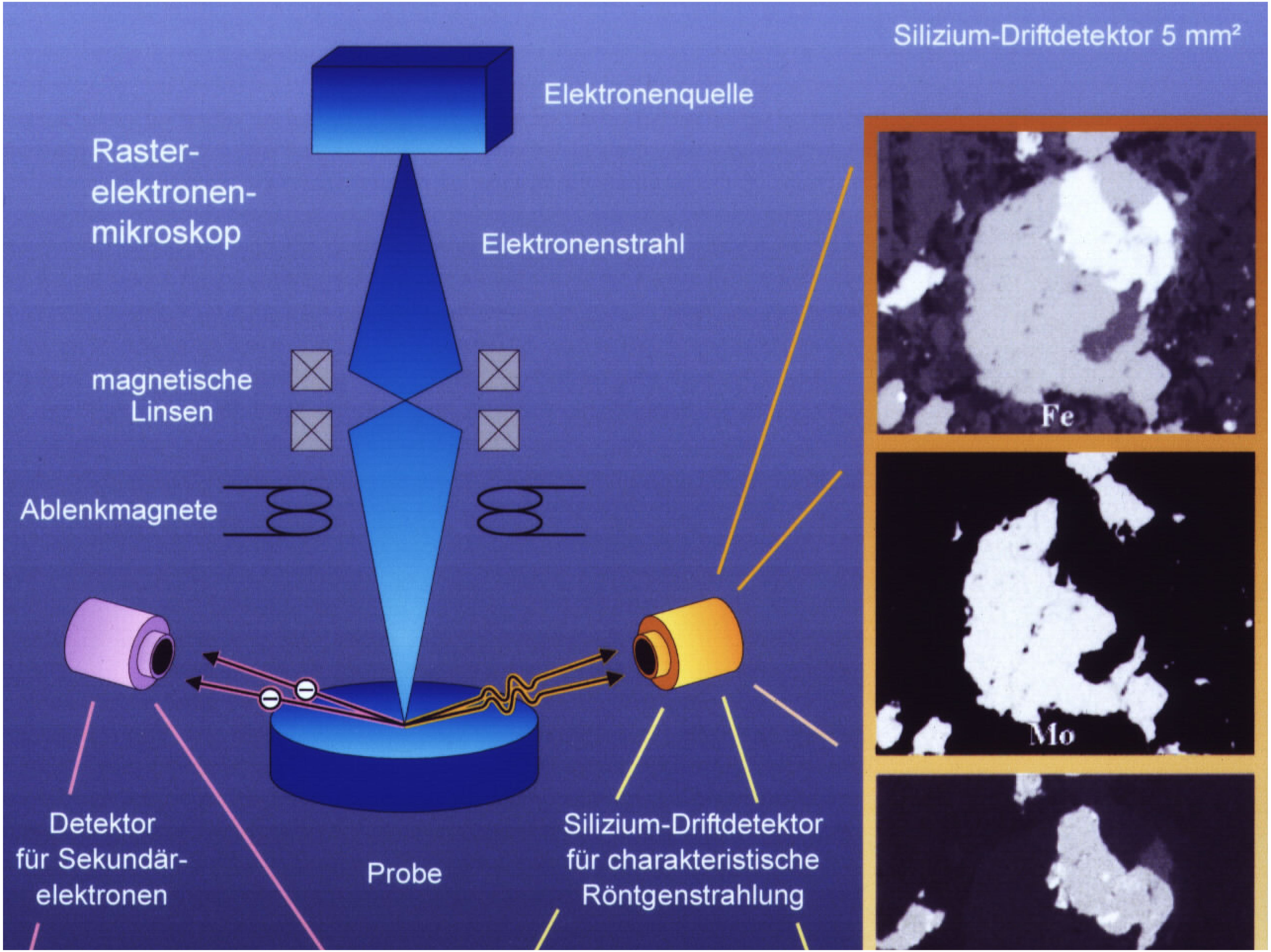
Excitation of sample with X-rays



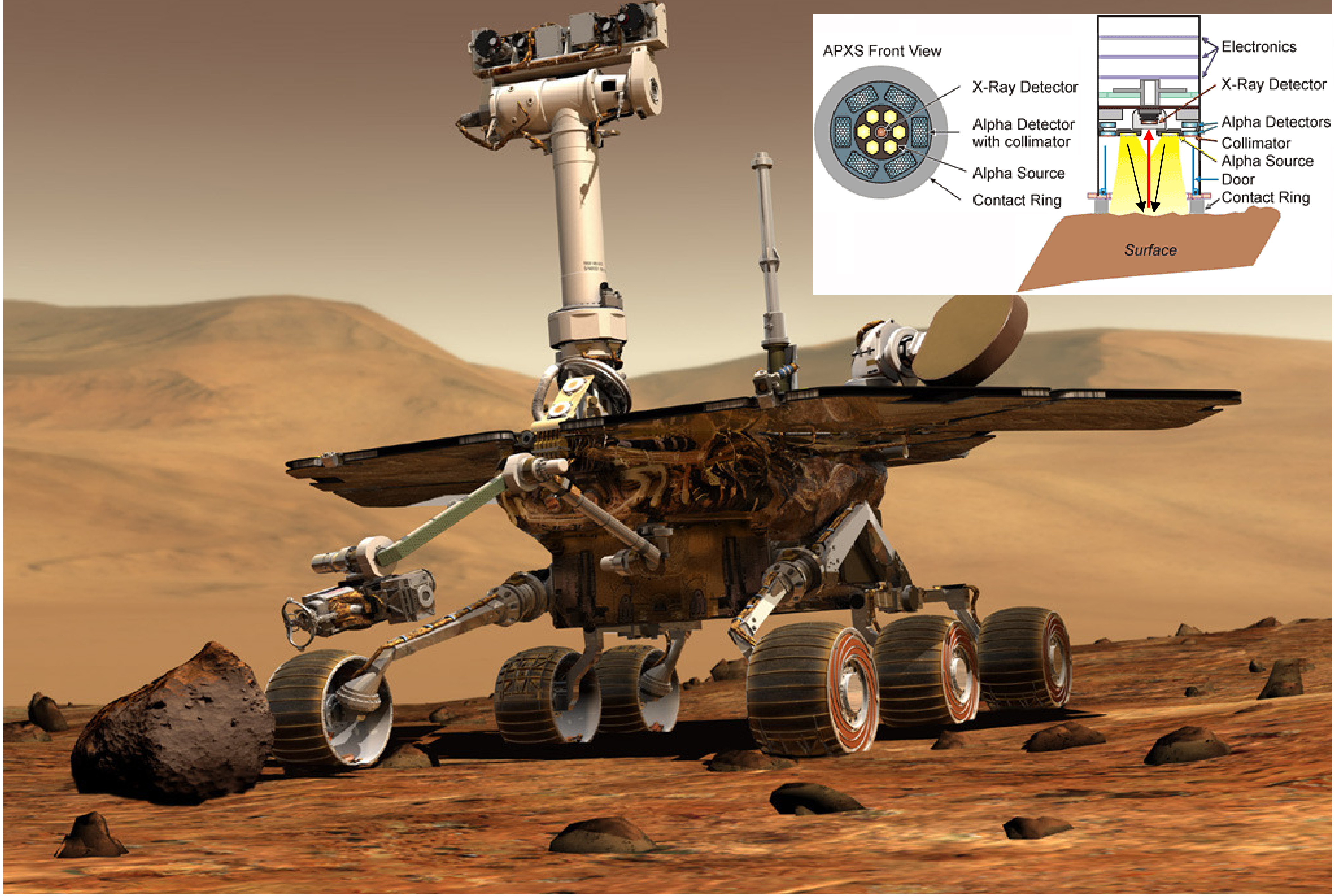
Application
XRF with scanning electron microscopes

Excitation of sample with electrons




Silizium-Driftdetektor 5 mm²
Elektronenquelle
Raster-
elektronen-
mikroskop
Elektronenstrahl
magnetische
Linsen
Ablenkmagnete
Fe
Mo
Detektor
für Sekundär-
elektronen
Probe
Silizium-Driftdetektor
für charakteristische
Röntgenstrahlung

NASA Mars Rovers



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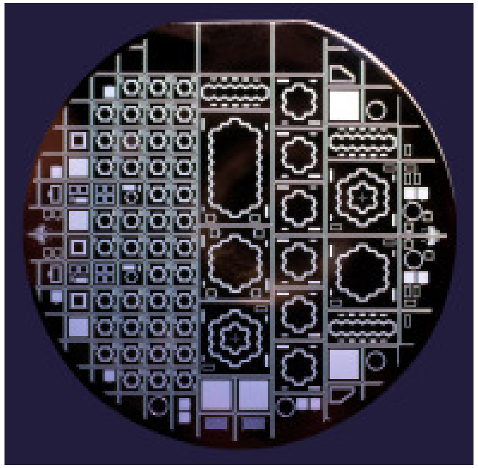

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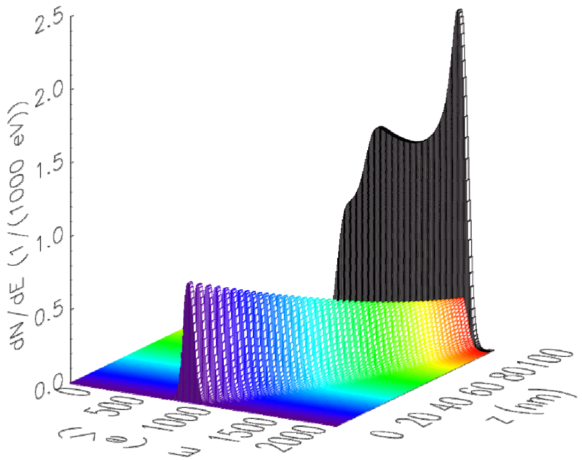

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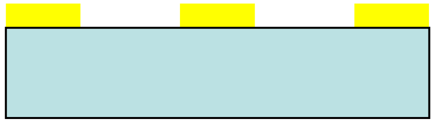
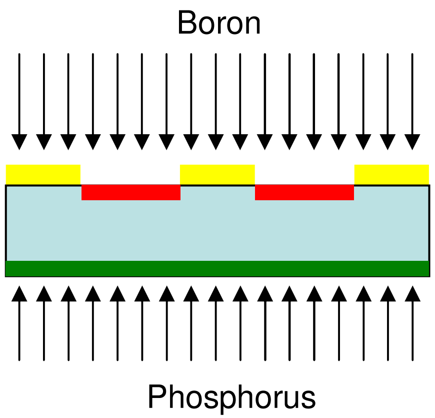
Planar Technology

n⁻-Si wafer

Thermal oxidation

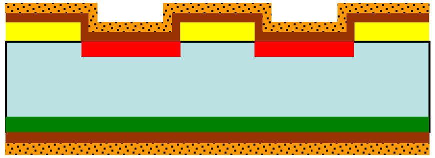


Opening of windows

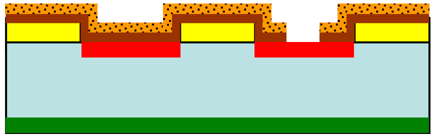


Doping by ion implantation and annealing at 600 °C

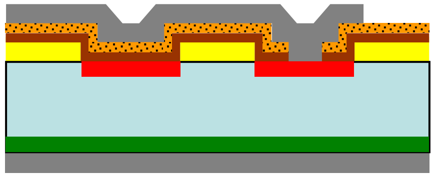
B: 15 keV, 5×10^{14} cm^{-2} P: 30 keV, 5×10^{15} cm^{-2}



Deposition of LPCVD-Nitride and LPCVD-Oxide



Opening of contact holes



Metal deposition and patterning

Differences to conventional planar technology

→ Wafer structured on both sides, larger structures

→ Low temperature processes

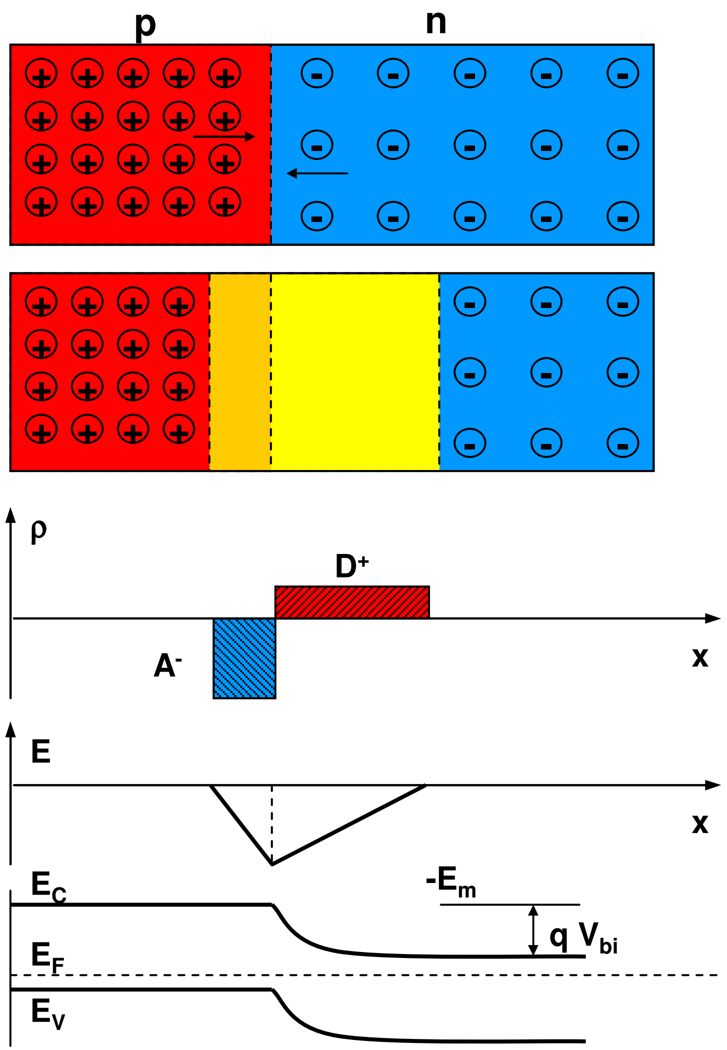
→ Less diffusion of impurities

→ Low leakage currents and high charge carrier life-times

Important Semiconductor Properties

		Si	Ge	GaAs	SiC
atomic number		14	32	31 / 33	14 /12
atomic weight		28.09	72.59	144.63	40
density	g / cm^3	2.33	5.33	5.32	3.21
band gap (RT)	eV	1.12	0.66	1.42	3.0
energy for e-h pair	eV	3.65	2.85	4.2	~ 8.5
electron mobility μ_e	cm^2/Vs	1500	3900	8500	~ 1000
hole mobility μ_h	cm^2/Vs	450	1900	400	~ 100
minority carrier lifetime τ	s	$2.5 \cdot 10^{-3}$	10^{-3}	$\sim 10^{-8}$	$\sim 10^{-6}$
$\mu\tau$ – product (e)	cm^2/V	2 – 5	5	$\sim 10^{-4}$	$\sim 10^{-3}$
$\mu\tau$ – product (h)	cm^2/V	1 – 2	2	$\sim 10^{-5}$	$\sim 10^{-4}$
intrinsic resistivity	Ωcm	$2.3 \cdot 10^5$	47	10^8	$> 10^{12}$
intrinsic carrier conc.	cm^{-3}	$1.45 \cdot 10^{10}$	$2.5 \cdot 10^{13}$	$1.8 \cdot 10^6$	10^{-6}

pn-Junction for Detector Applications



diffusion of majority carriers

formation of depletion layers

fixed space charge of acceptors (A^-) and donors (D^+)

electric field due to space charge

band bending of the junction
built in voltage

Properties of Si pn-Junction Detectors

Depletion layer thickness d

$d/\mathrm{cm} = 5 \cdot 10^{-3} (\rho\ U/(\Omega\mathrm{cmV}))^{1/2}$

ρ resistivity
U bias voltage

Capacitance C

$C/\mathrm{pF} = 2 \cdot 10^{4}\ A/\mathrm{cm}^2 (\rho\ U/(\Omega\mathrm{cmV}))^{-1/2}$

A junction area

Reverse current I_R

$I_R = I_D + I_S + I_G$

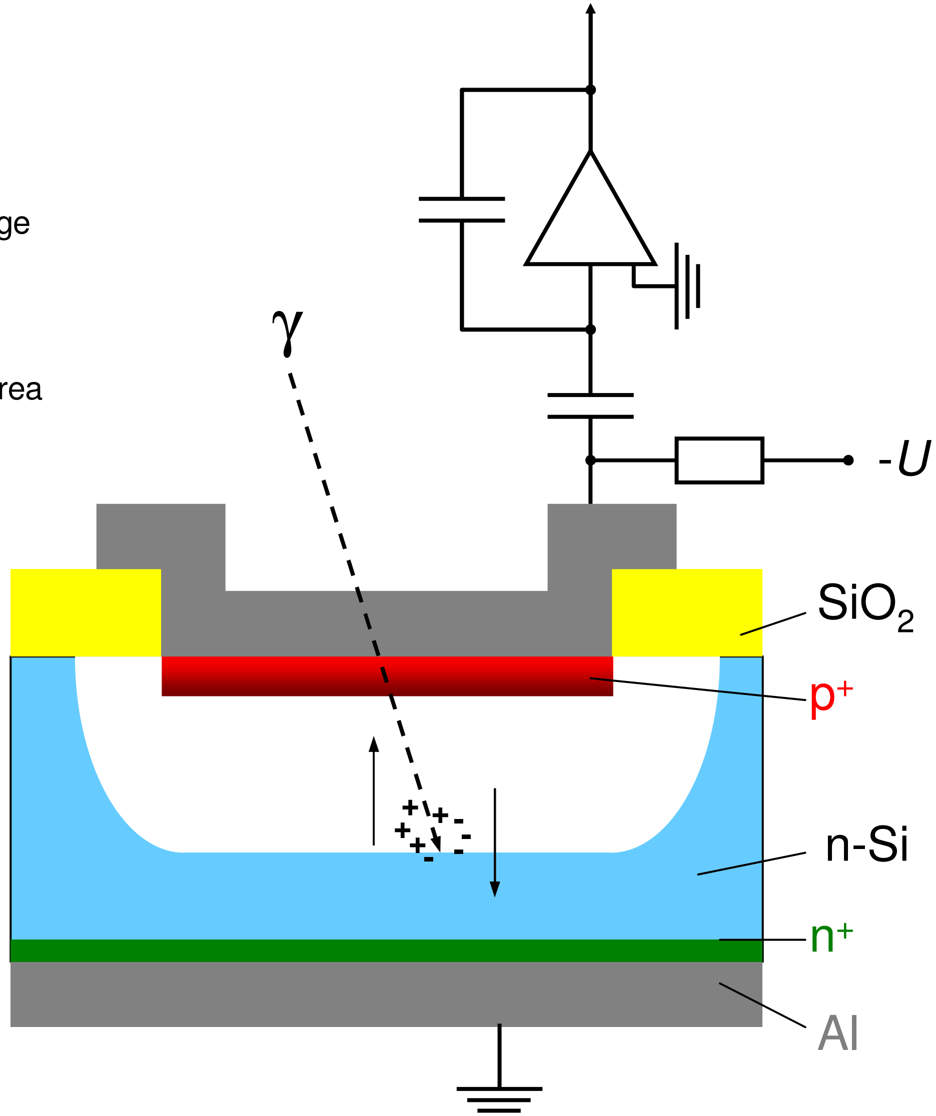
I_D diffusion current
I_S surface leakage c.
I_G generation current

For thick depletion layers

$I_R = I_G = q\,(n_i/\tau) A\, 5 \cdot 10^{-3} (\rho\ U)^{1/2}$

$I_R \sim U^{1/2}/\tau$

n_i $1.5\cdot10^{10}\ \mathrm{cm}^{-3}$ intrinsic carrier conc.
τ minority carrier lifetime
q $1.6\mathrm{x}10^{-19}$ As



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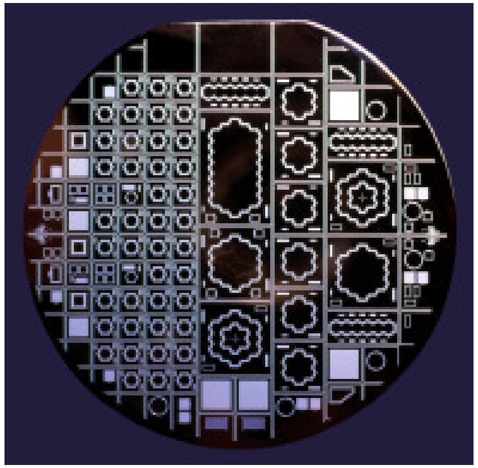

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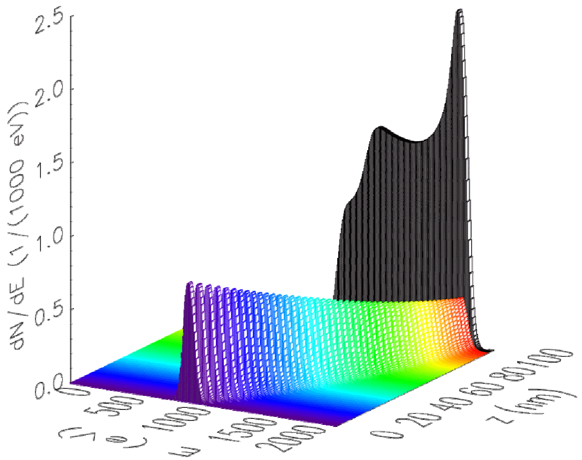

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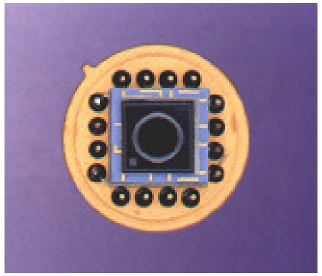
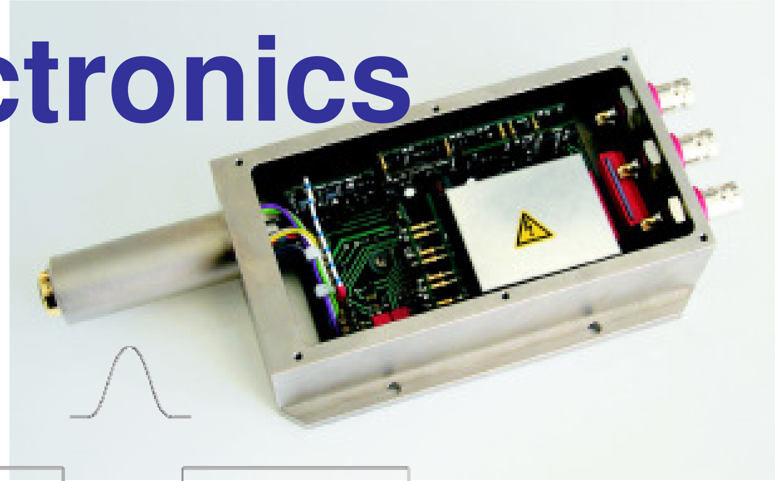
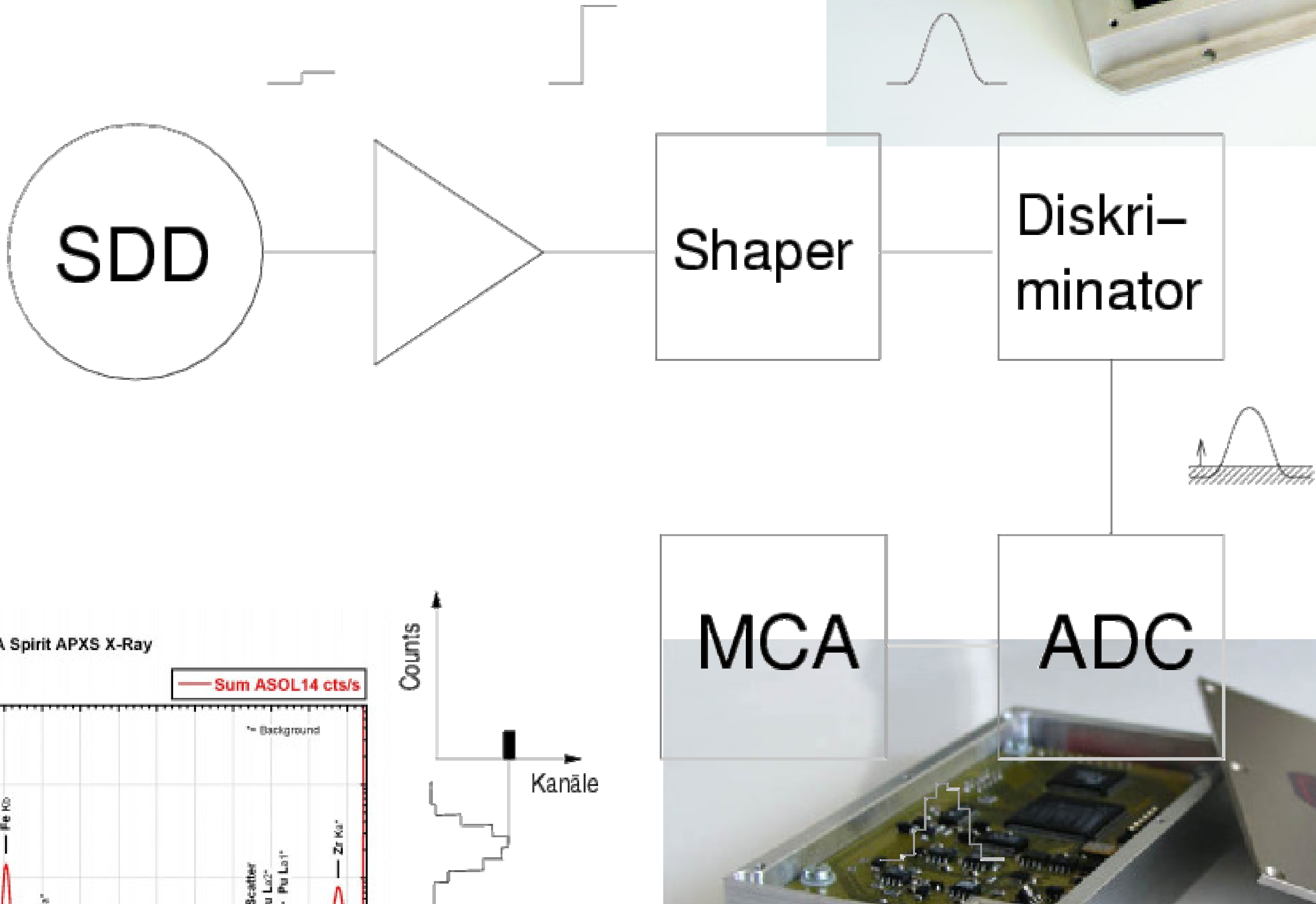
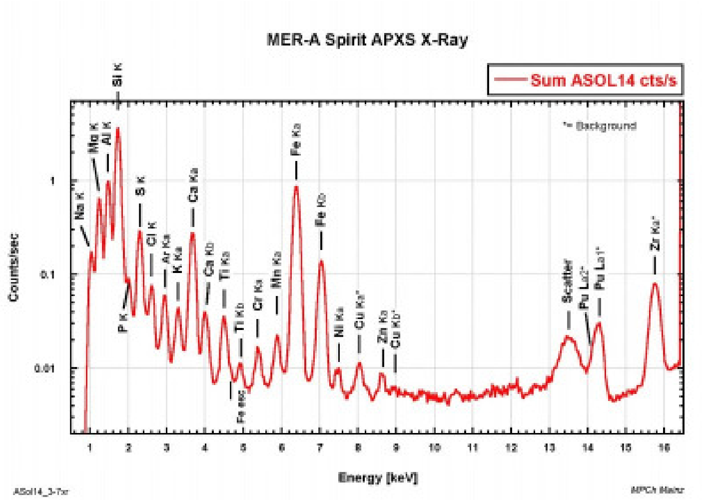
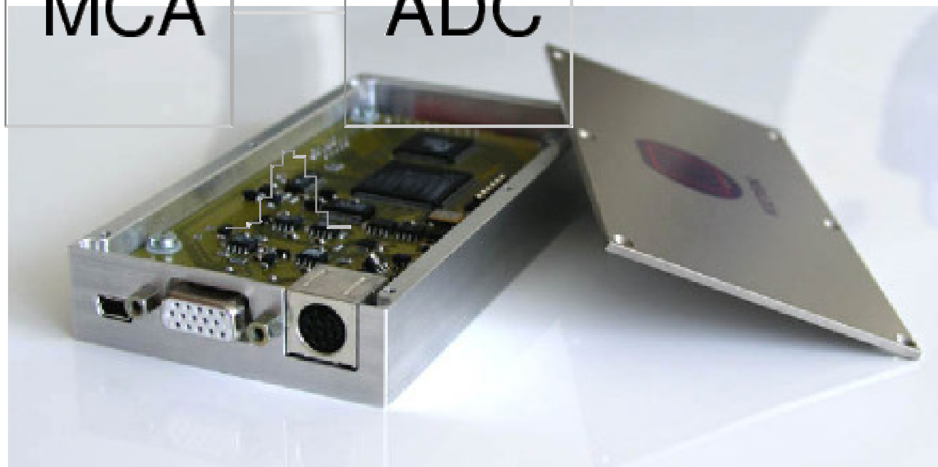
Read Out Electronics





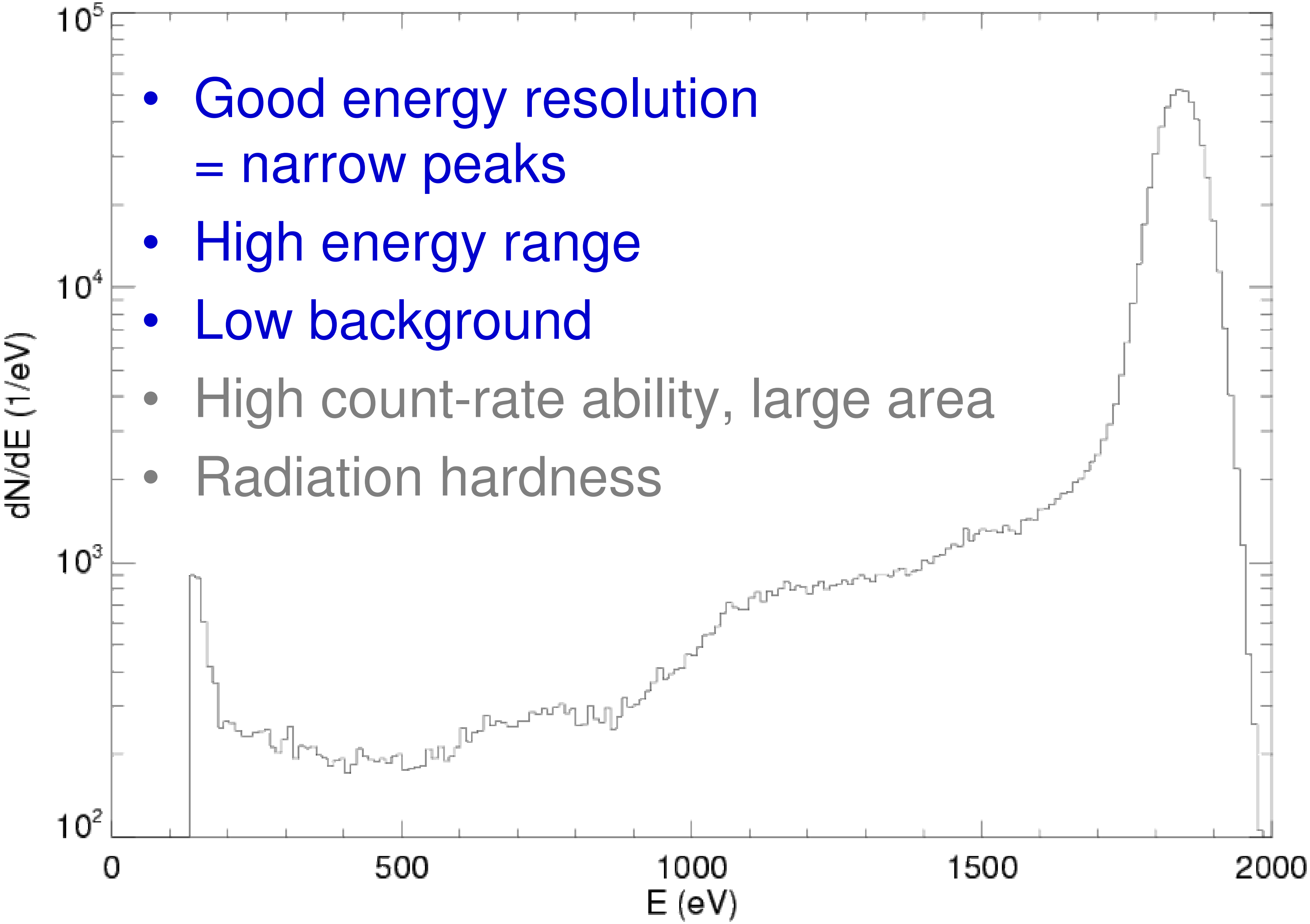




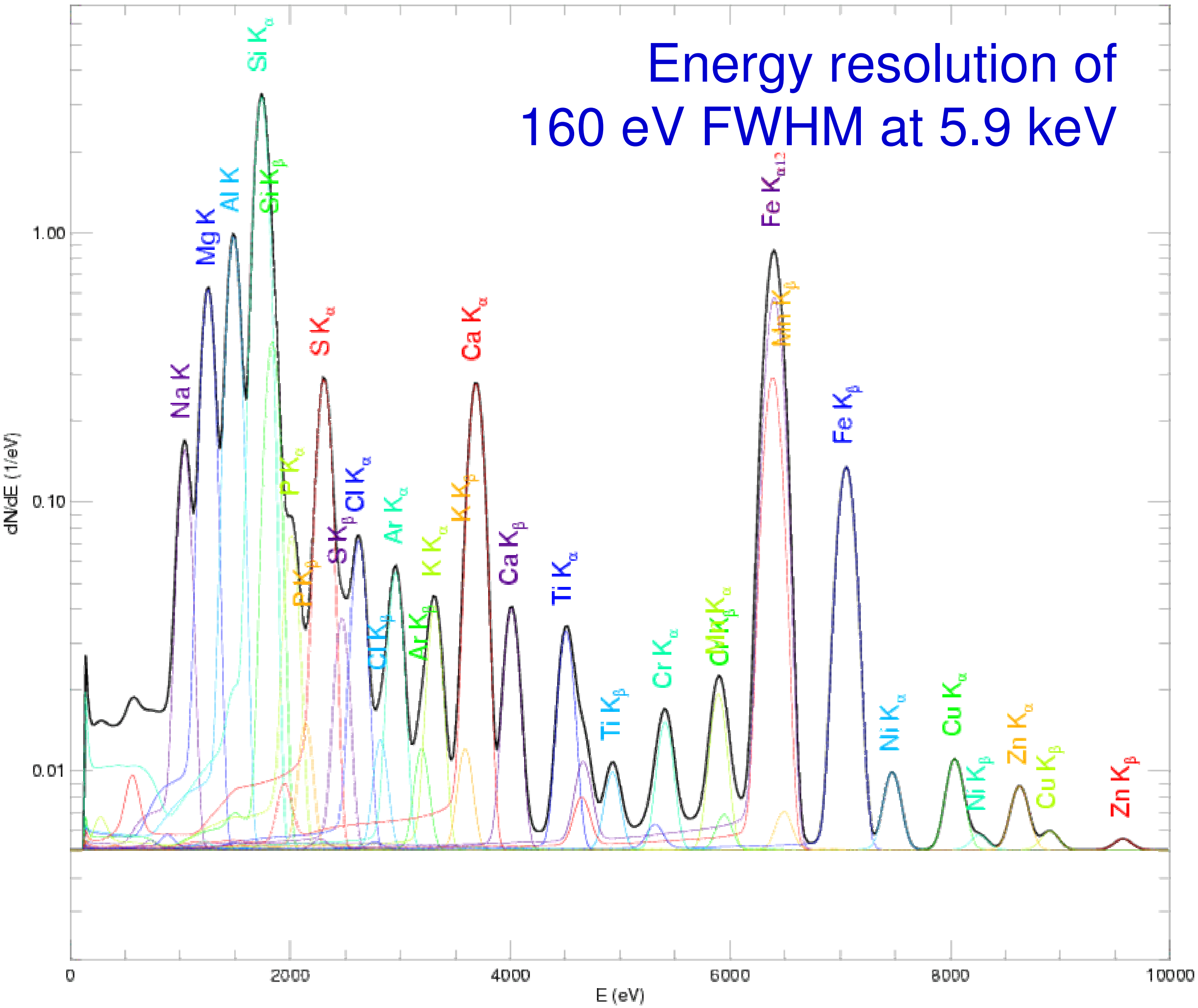


Requirements on Spectrometers

- Good energy resolution
  = narrow peaks
- High energy range
- Low background
- High count-rate ability, large area
- Radiation hardness



Spectrum of Martian Soil



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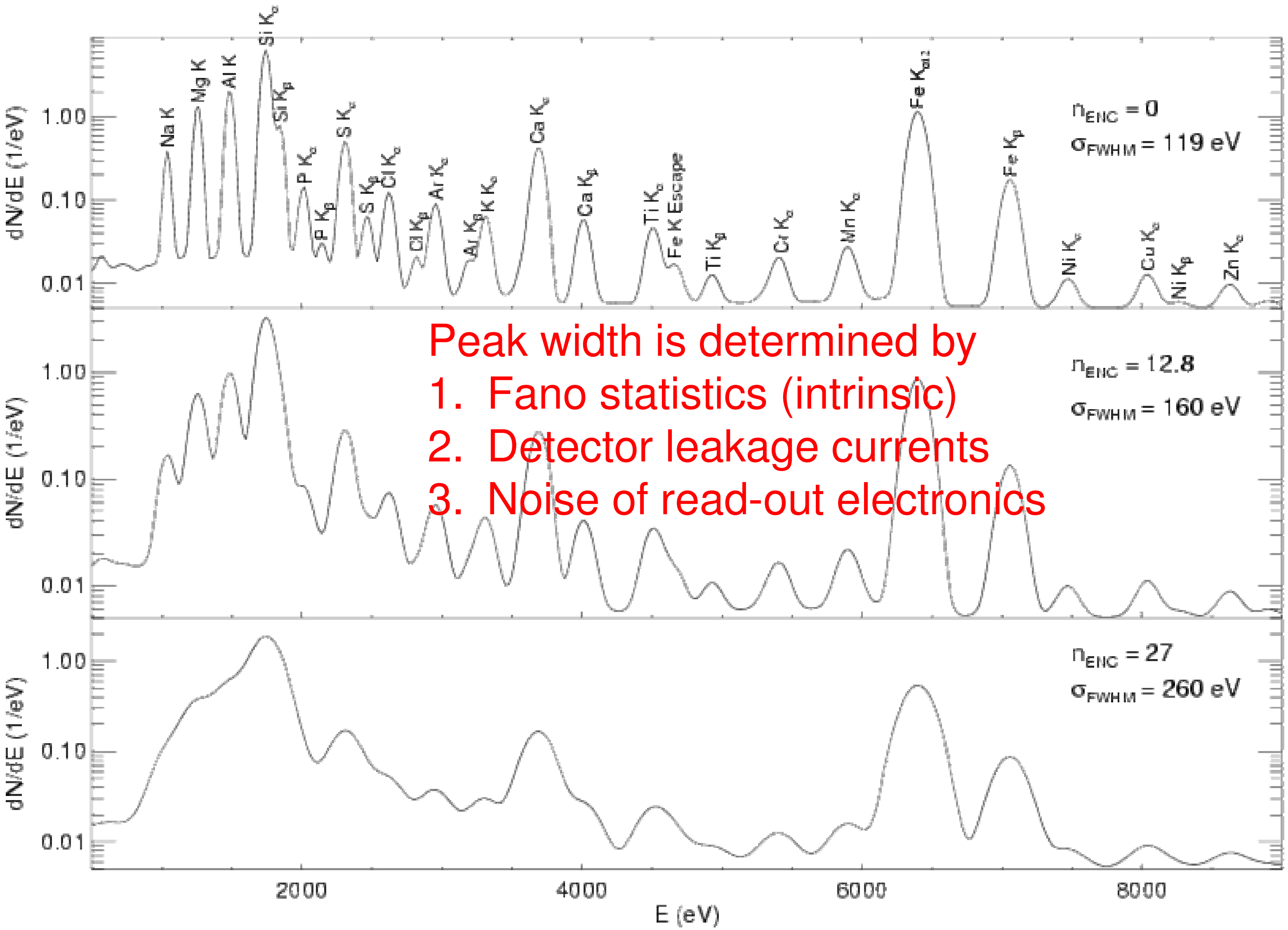
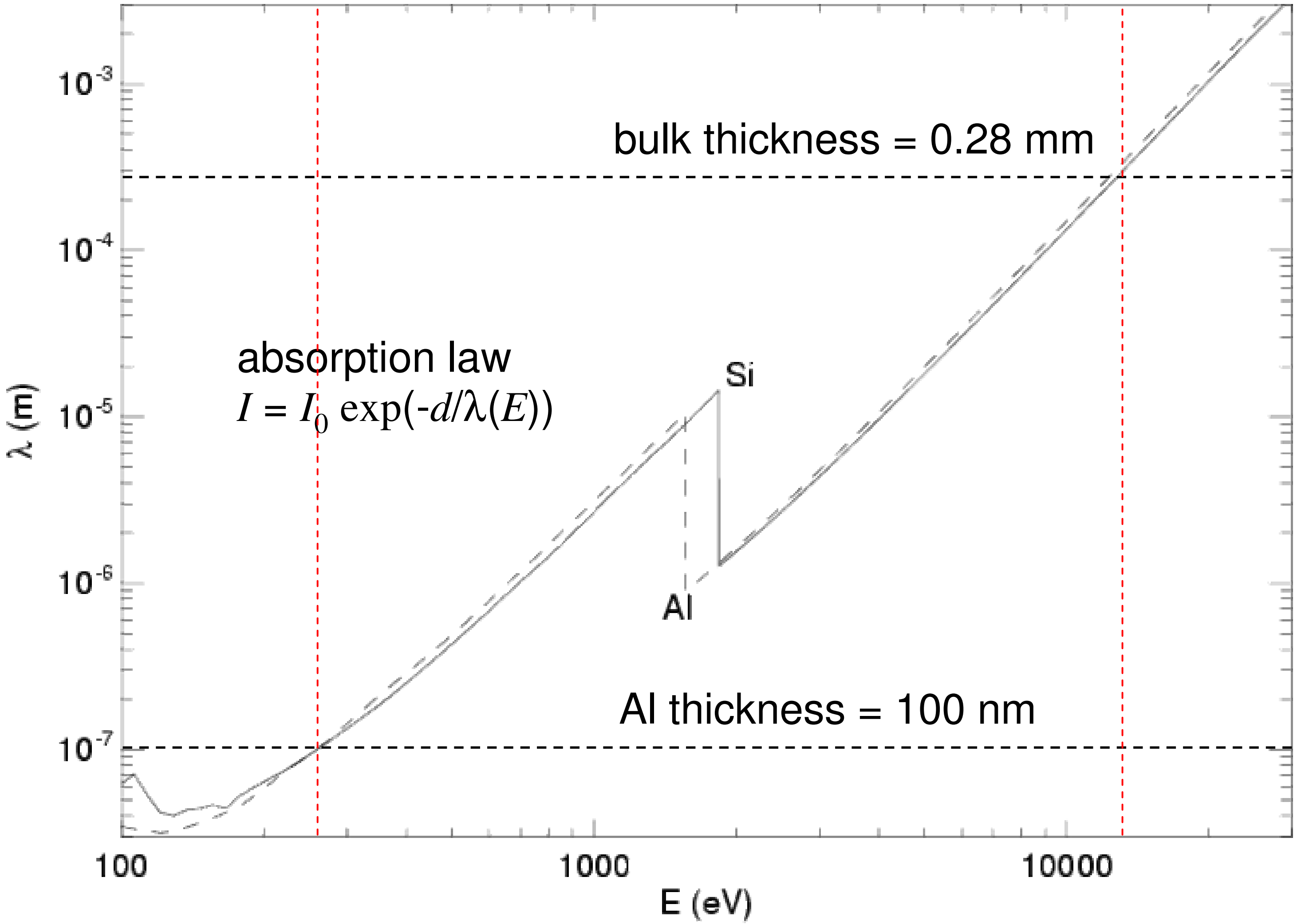


Peak width is determined by

1. Fano statistics (intrinsic)
2. Detector leakage currents
3. Noise of read-out electronics

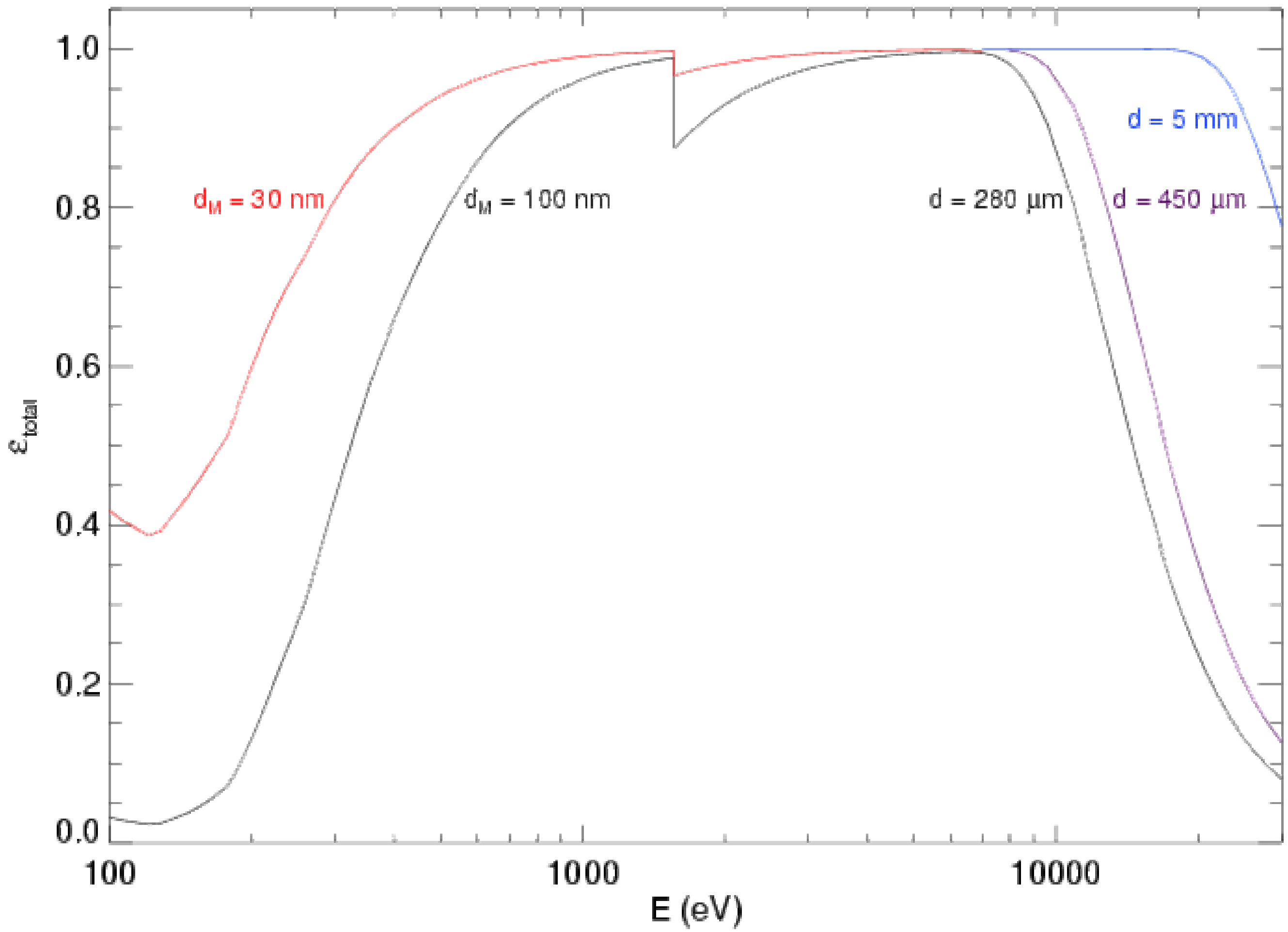
Absorption Lengths of Si + Al



Good efficiency from 250 eV to 11 keV
(20 keV)

Quantum Efficiency

ε = interaction probability within depletedSi bulk



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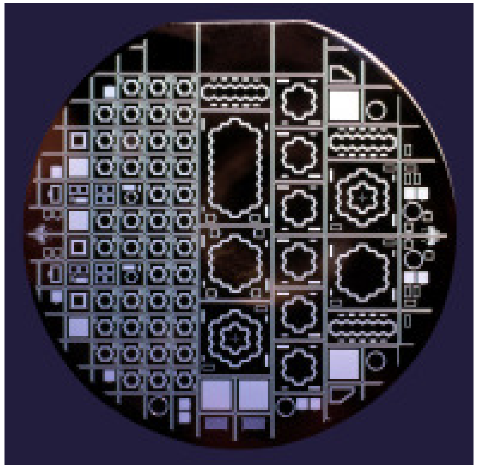

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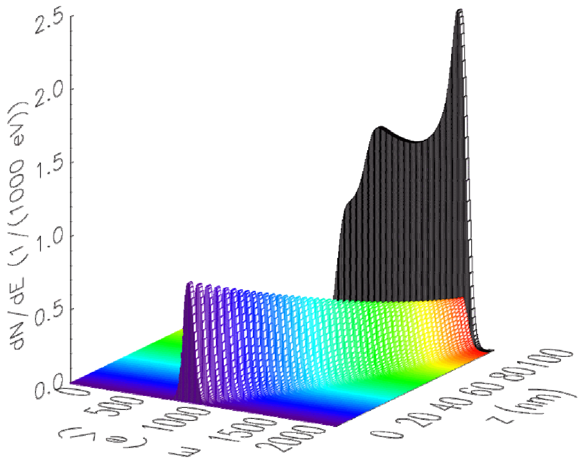

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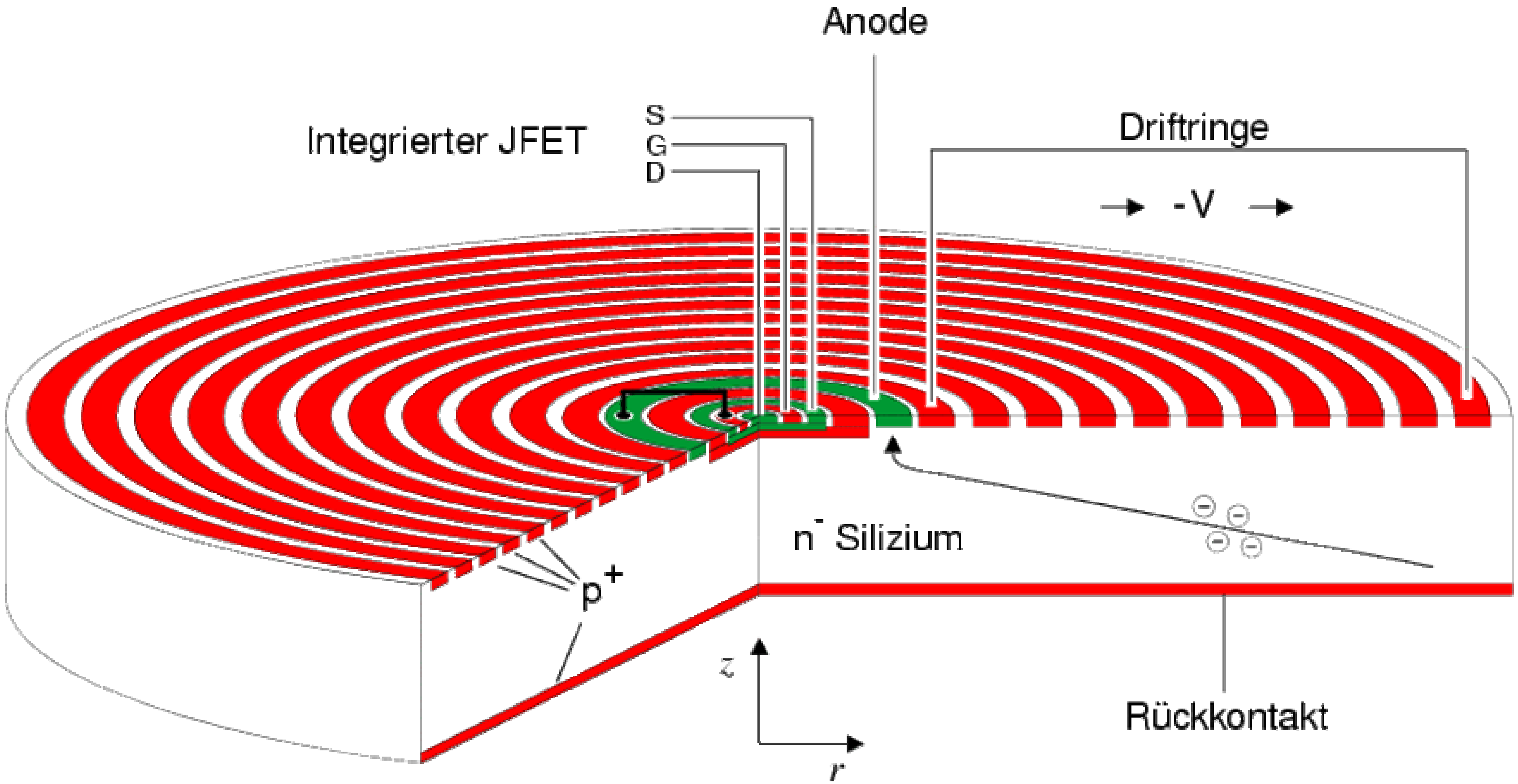
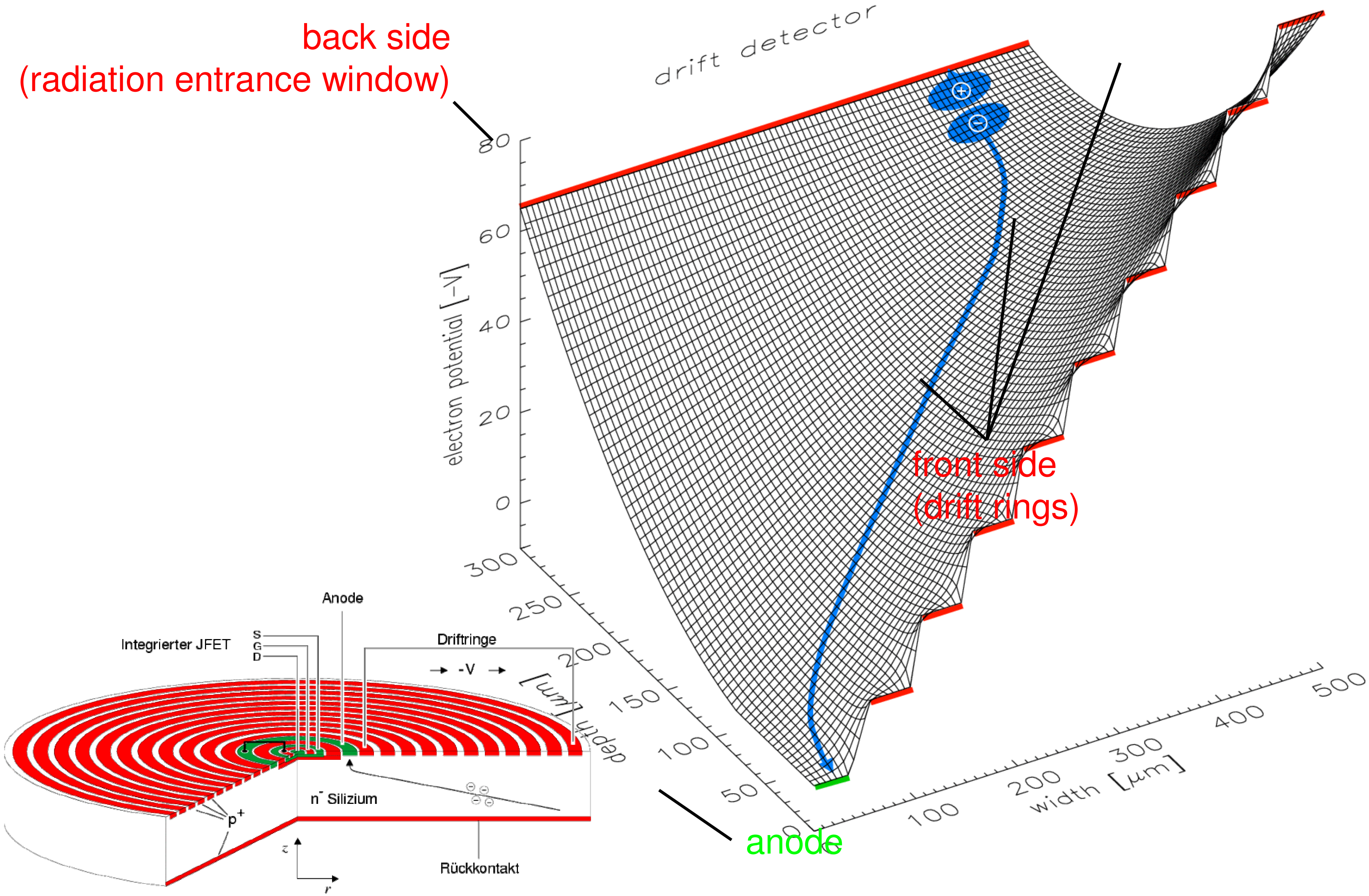
Silicon Drift Detector (SDD)

- Depletion from back contact towards bulk contact (n^+, not shown)
- Vertical and lateral drift field → small anode size → low capacitance
- High resistivity, high purity n-type silicon ($10^{12}/cm^3$)
- Drift rings at the front side, integrated voltage dividers
- Homogeneous entrance window at the back side

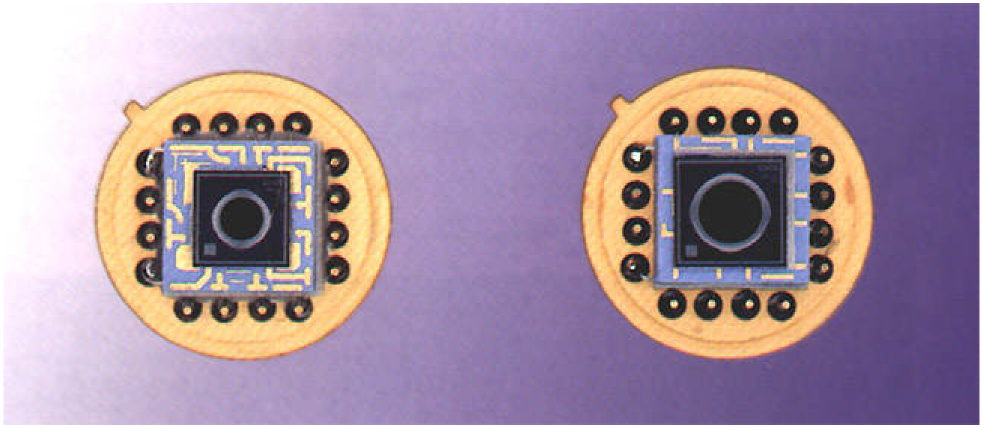


Drift Field Configuration

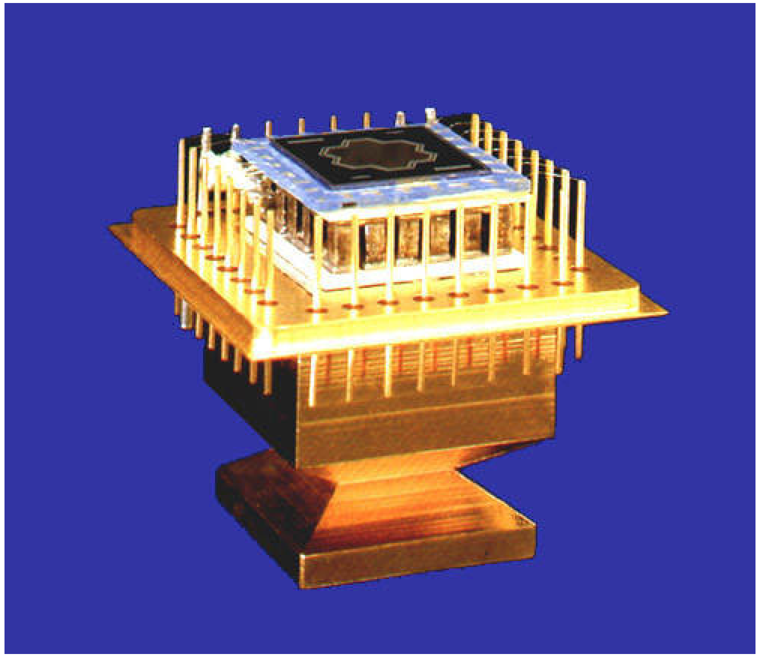


Mounted Devices

- 5 mm^2, 10 mm^2

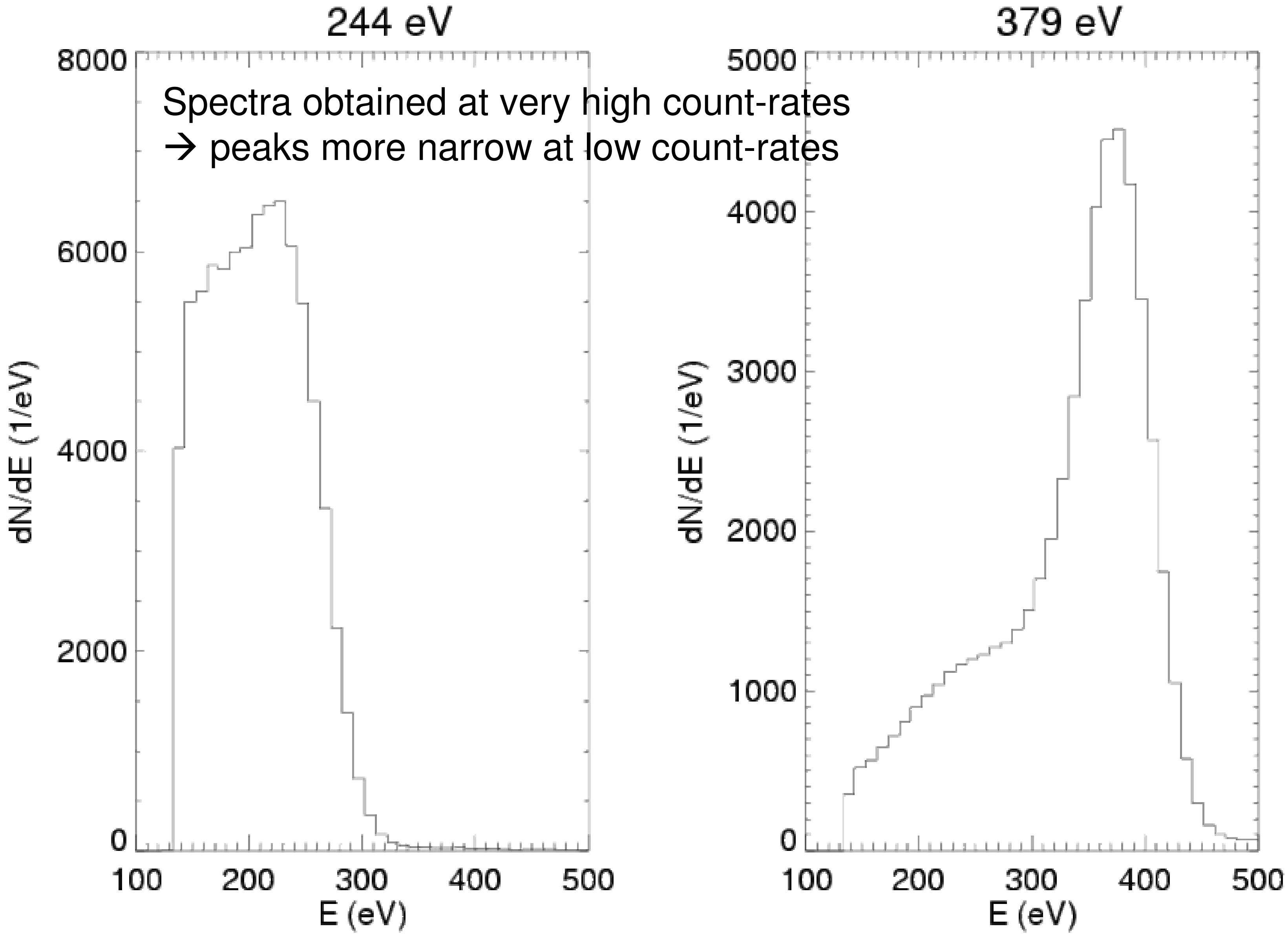


- 7 channel detector with 35 mm^2



Measured Low Energy Spectra

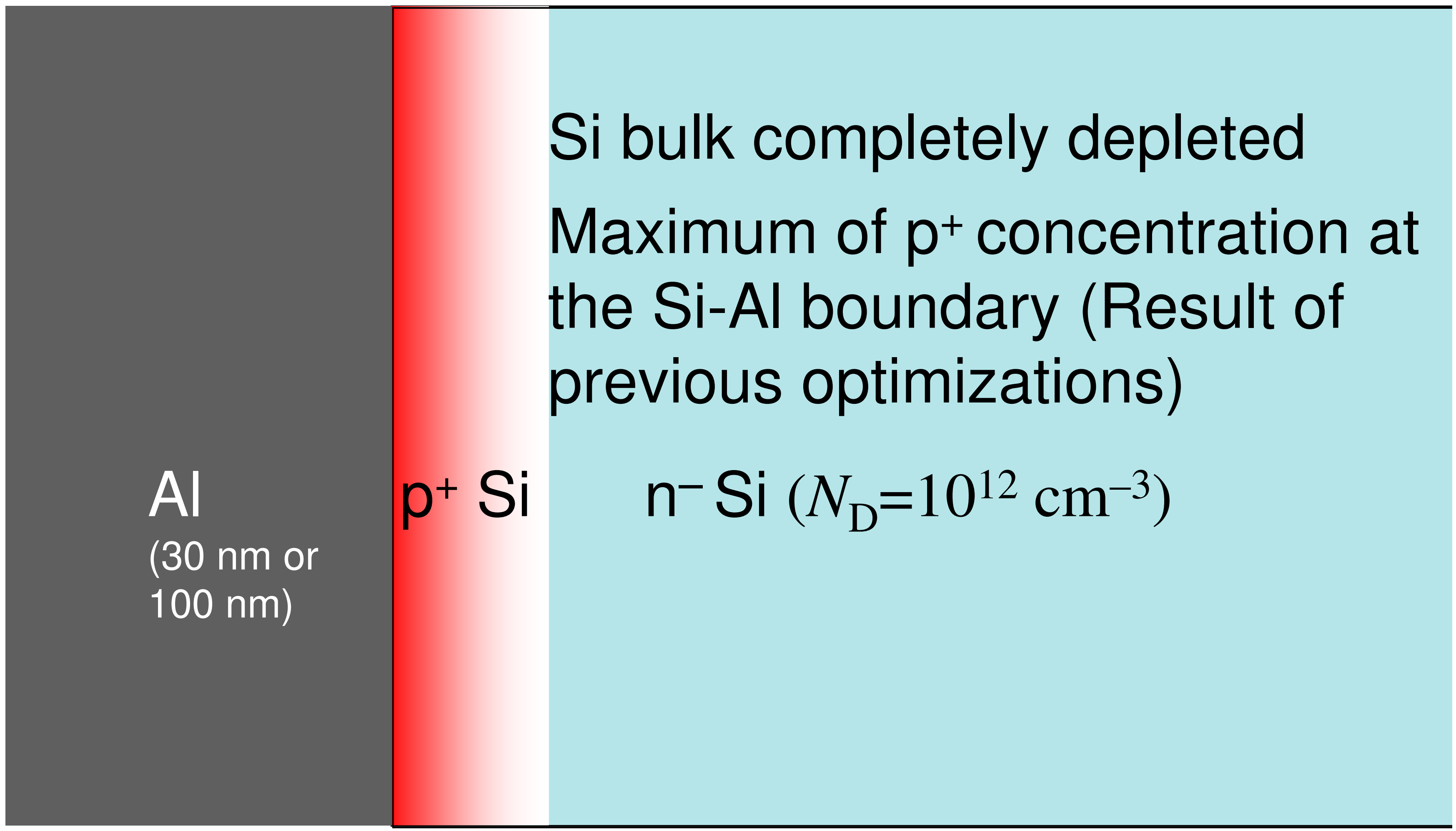
Spectra obtained at very high count-rates
→ peaks more narrow at low count-rates



Motivation

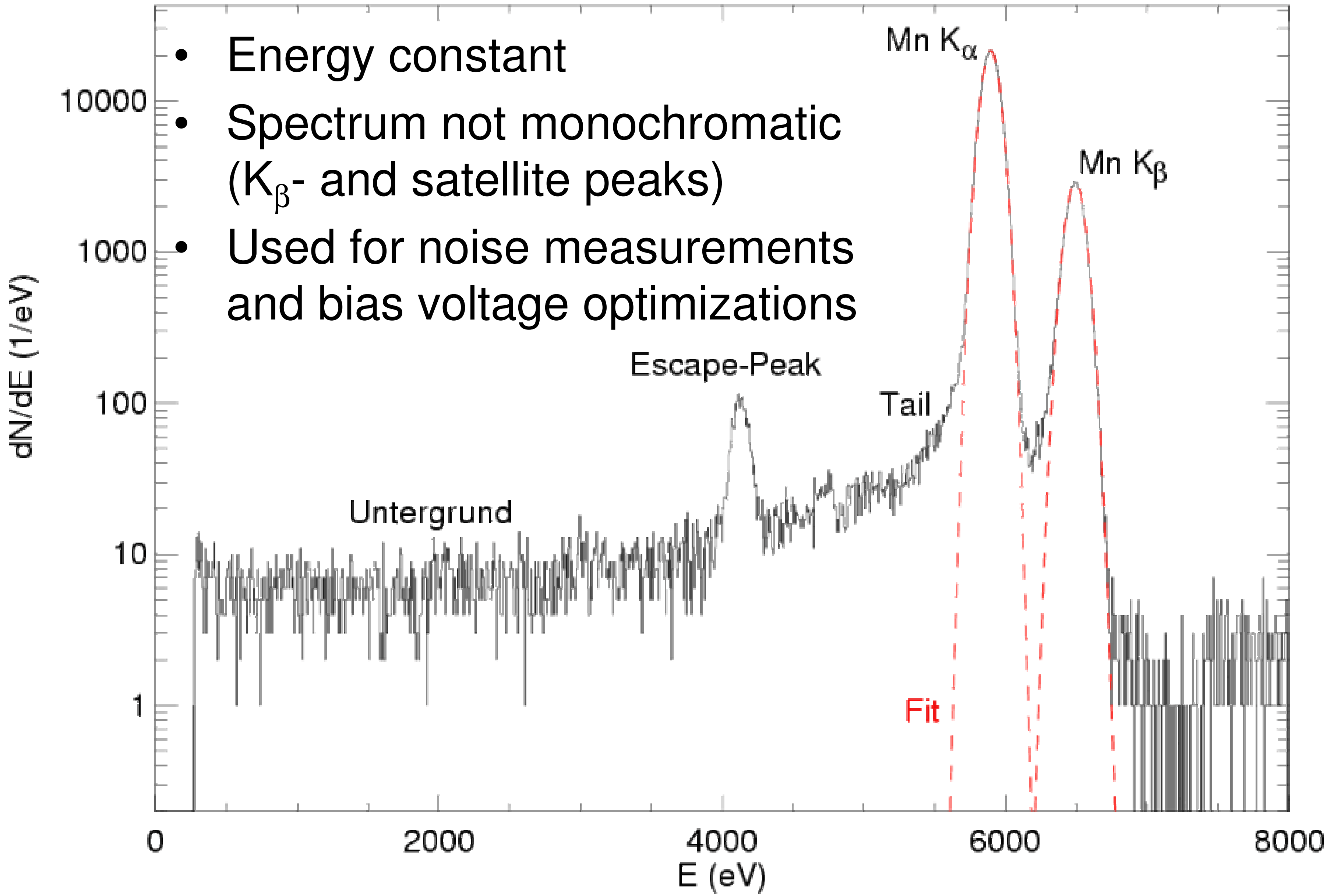
- What limits the detection of low energy X-rays?
- Is it noise?
- Is it the entrance window?
- Reasons for charge losses?
- Effect of aluminum coating?
- Effect of p^+-contact?
- How can the background be reduced?
- Previous models explain either losses of primary of *or* secondary electrons

Entrance Window Configuration



^{55}Mn Spectrum

- Energy constant
- Spectrum not monochromatic (K_β- and satellite peaks)
- Used for noise measurements and bias voltage optimizations



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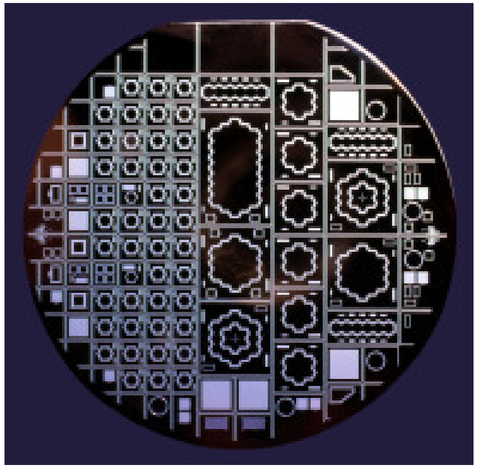

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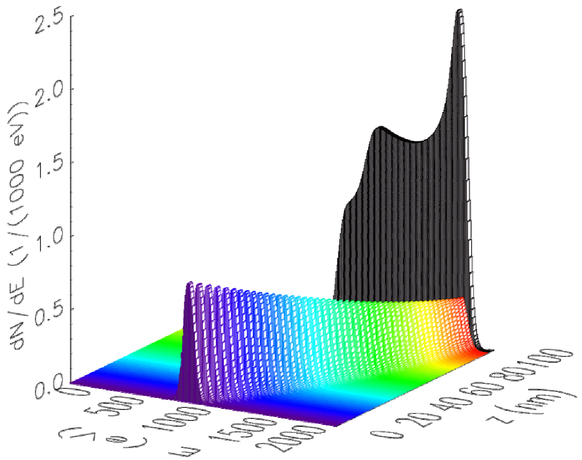

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Experiment

X-rays in the energy range 200 eV – 2 keV required

Radioactive sources > 5.9 keV

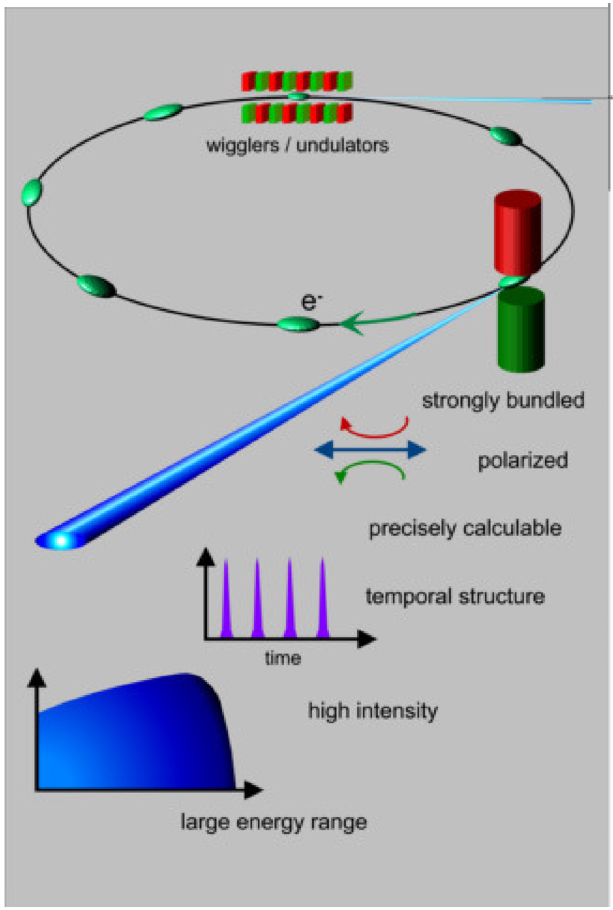
X-ray tubes: additional background due to bremsstrahlung
very low fluorescence yields

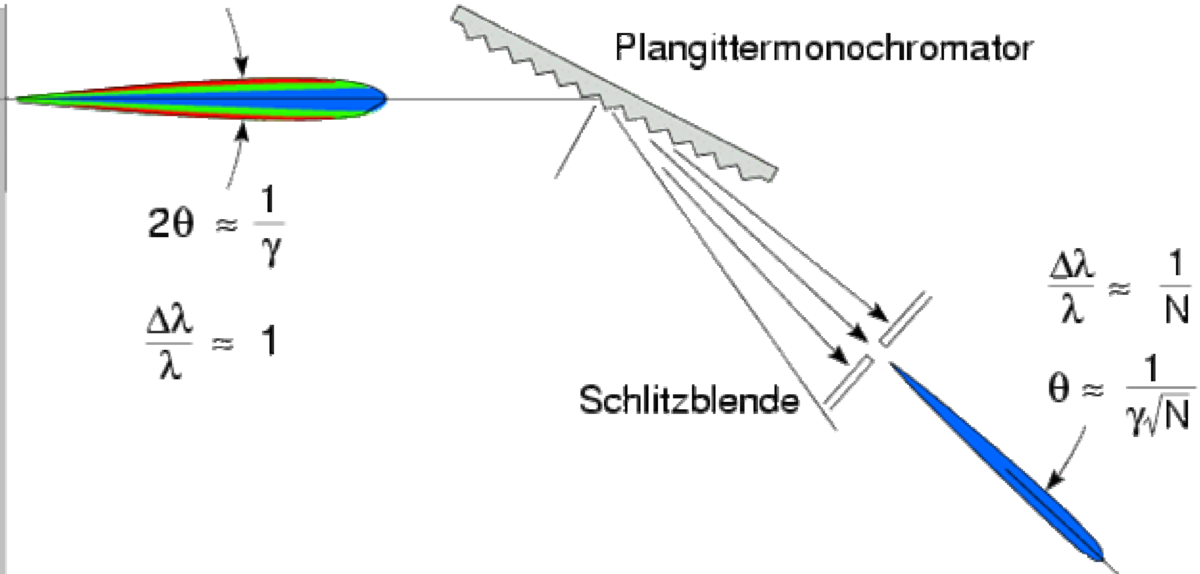
Synchrotrons are the cleanest X-ray sources

- Energy selectable
- High beam intensity
- Very low background
- Limited beam time

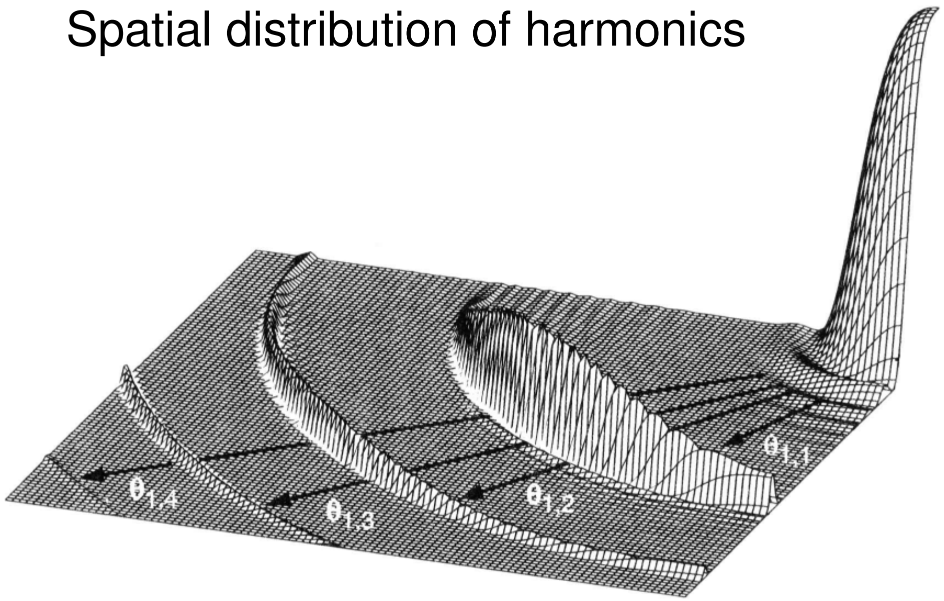
BESSY II

Experiment

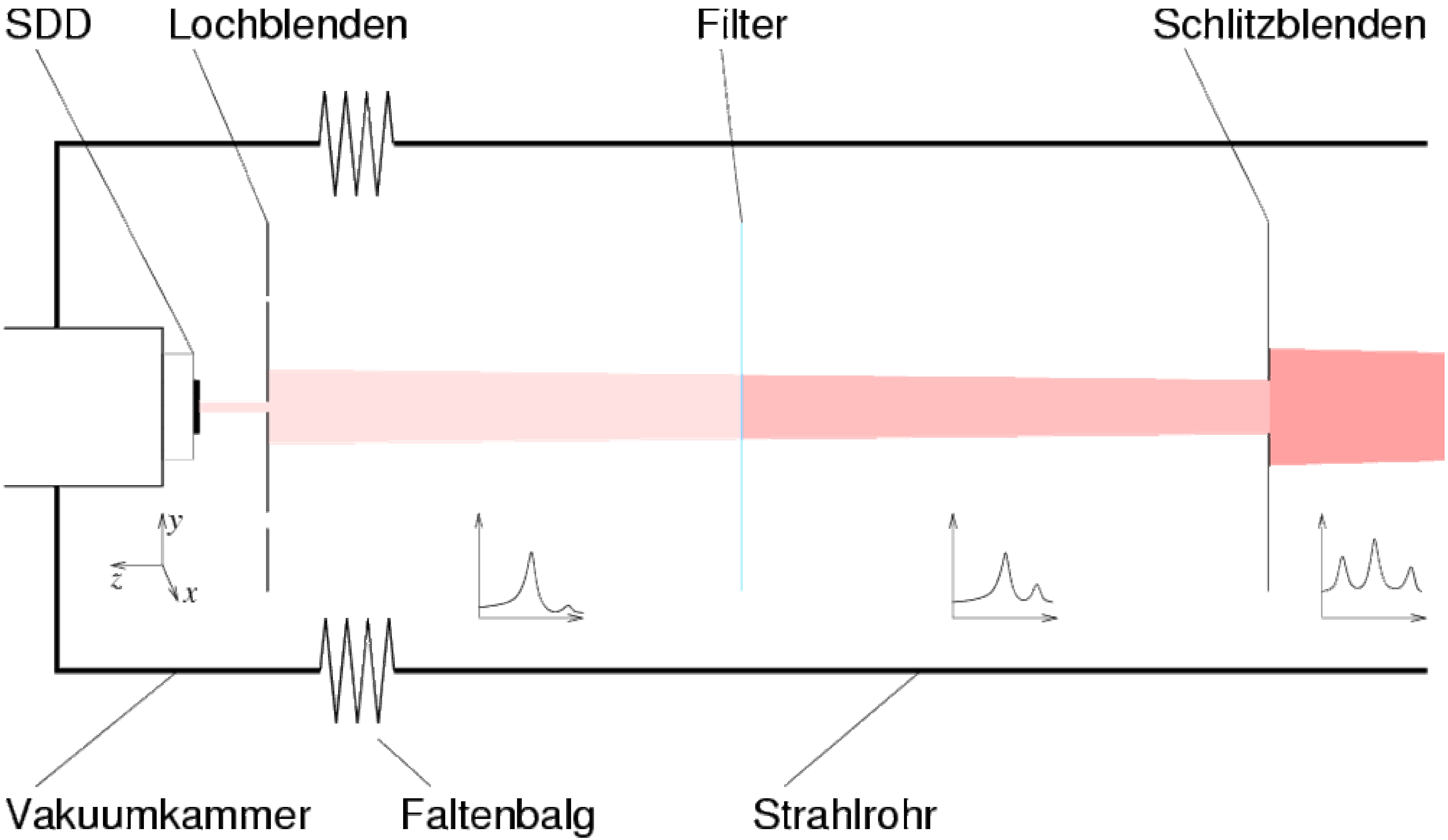




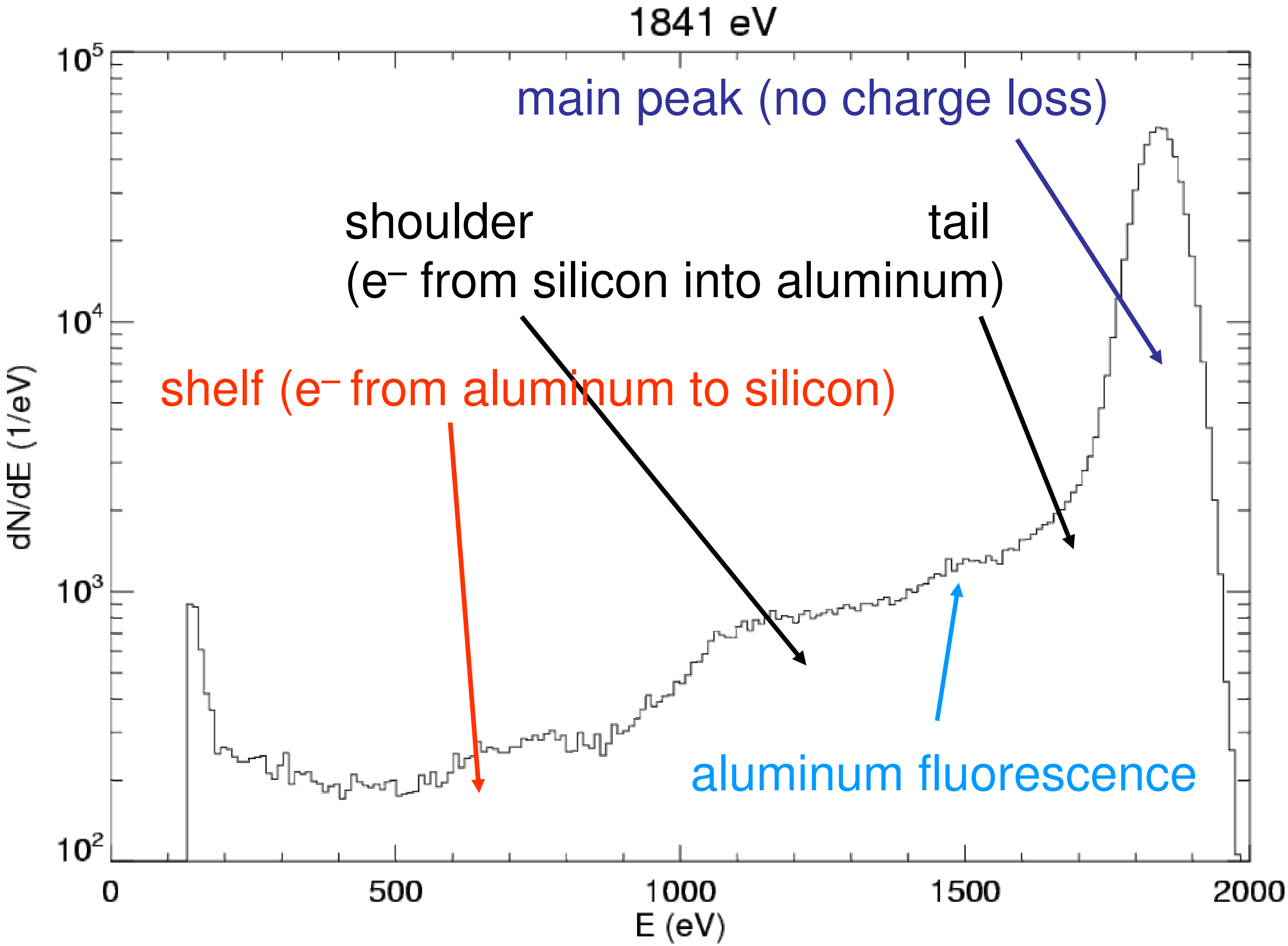
Spatial distribution of harmonics



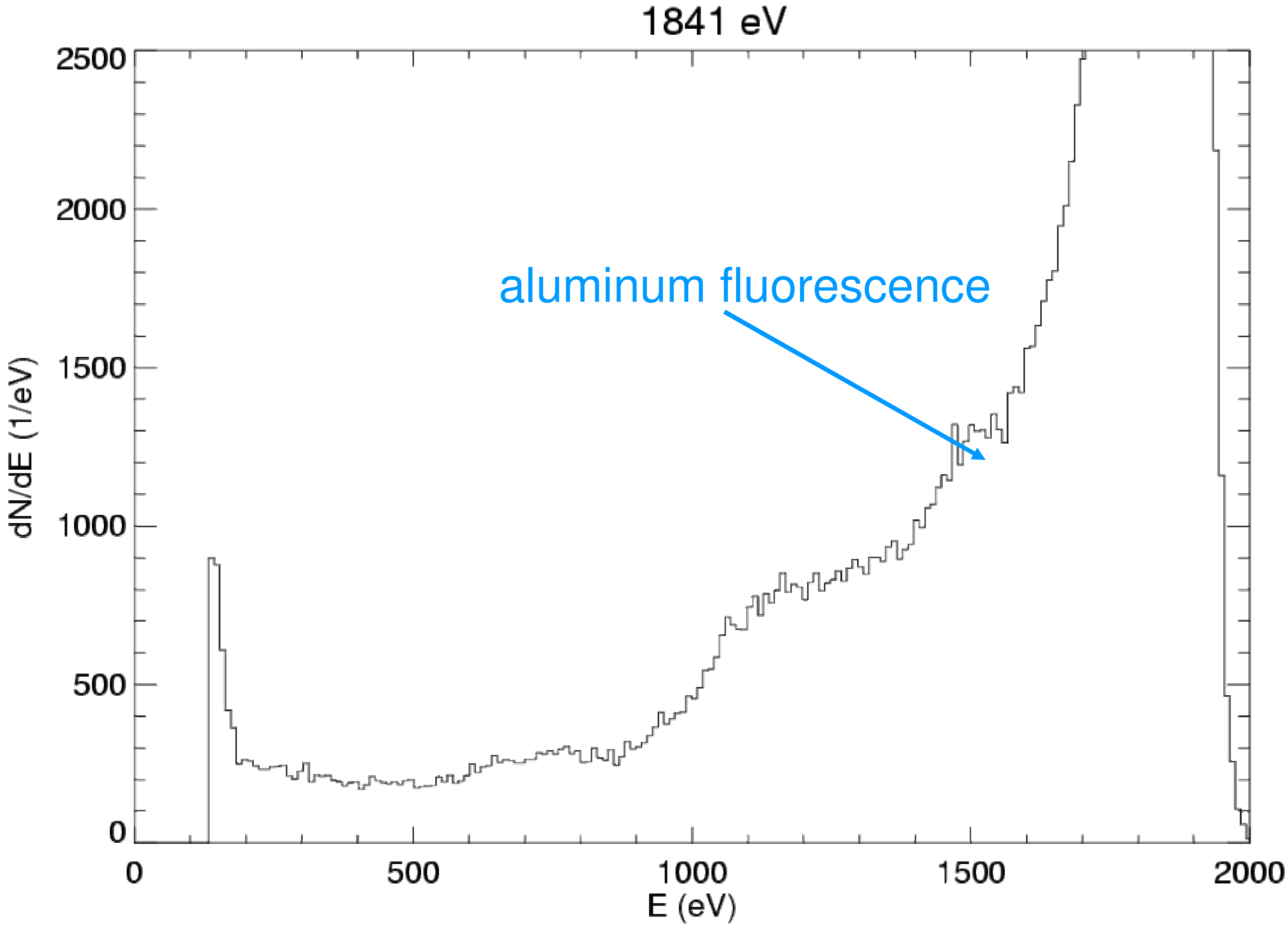
Experiment


SDD
Lochblenden
Filter
Schlitzblenden
y
z
x
Vakuumkammer
Faltenbalg
Strahlrohr

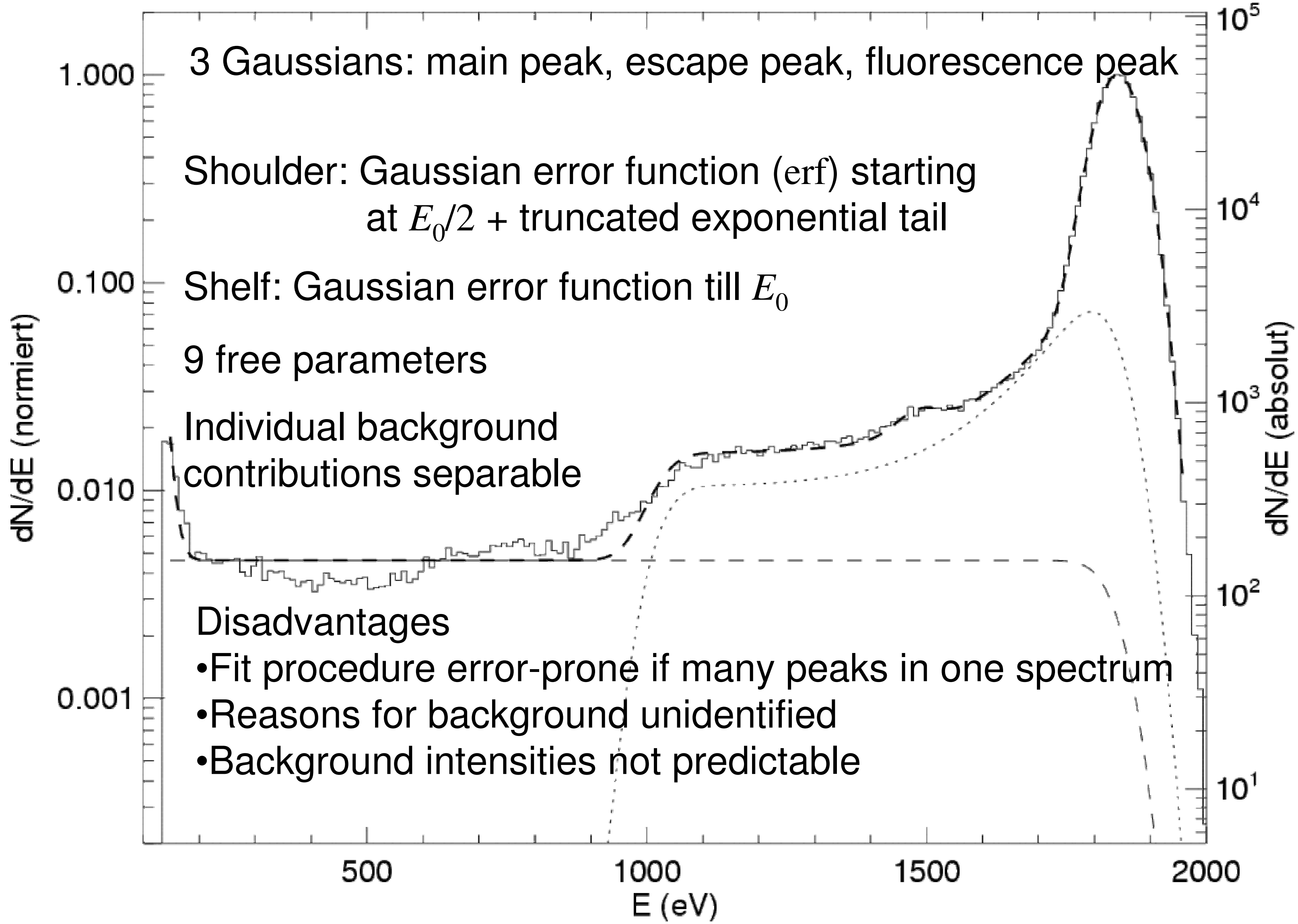
Typical Spectrum



Typical Spectrum



Fitting with an Analytical Function



3 Gaussians: main peak, escape peak, fluorescence peak

Shoulder: Gaussian error function (erf) starting at $E_0/2$ + truncated exponential tail

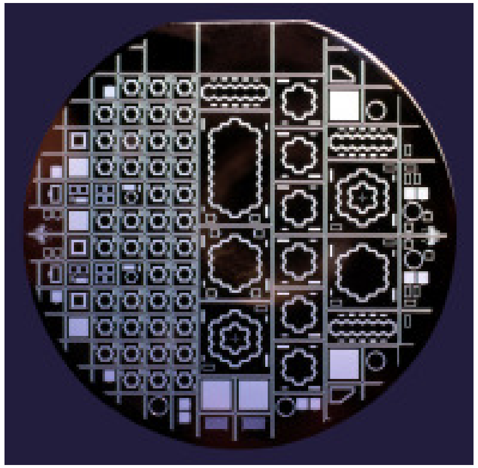
Shelf: Gaussian error function till E_0

9 free parameters

Individual background contributions separable

Disadvantages
- Fit procedure error-prone if many peaks in one spectrum
- Reasons for background unidentified
- Background intensities not predictable

The Response of Energy Dispersive X-Ray Detectors



Part A Principles of Semiconductor Detectors

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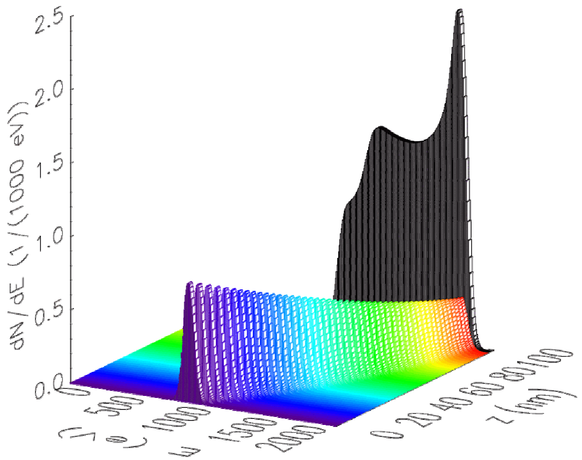

Part B Response of Silicon Drift Detectors

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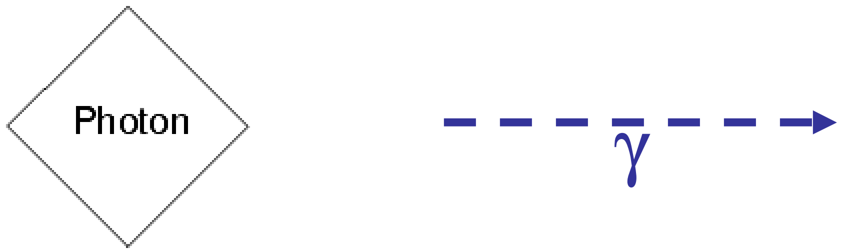
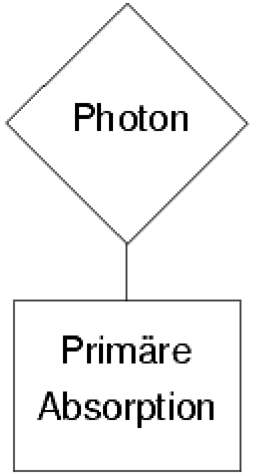
X-ray photon hits detector

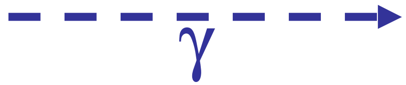


Interaction always by
photoelectric effect

Compton effect unlikely

e^-e^+ pair creation impossible



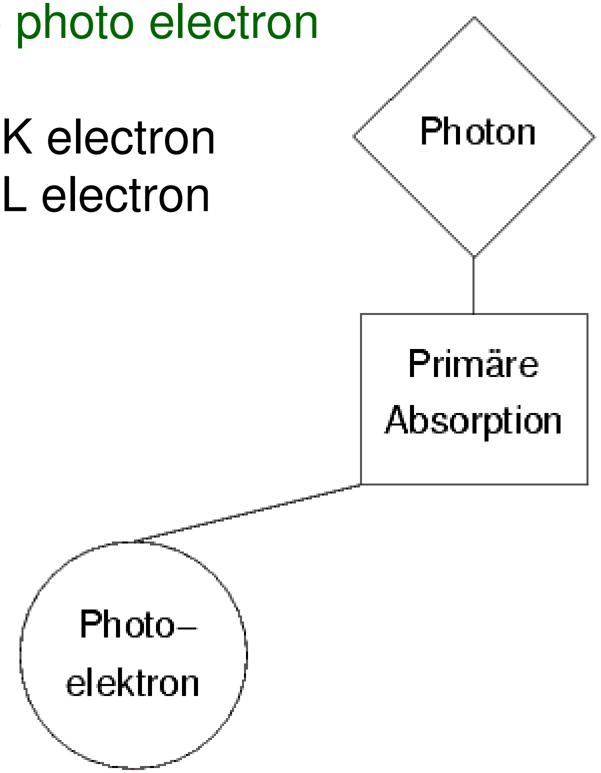


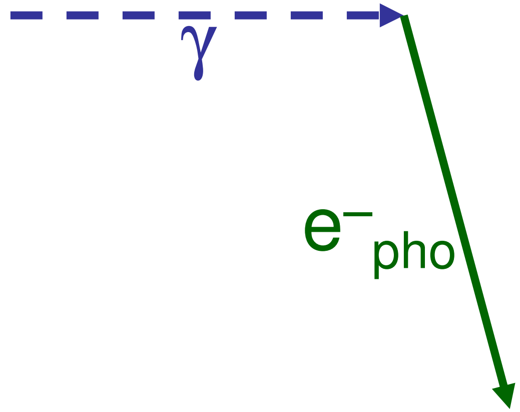
Creation of one photo electron

$E = E_0 - E_B$

E_0 > Si K shell: K electron

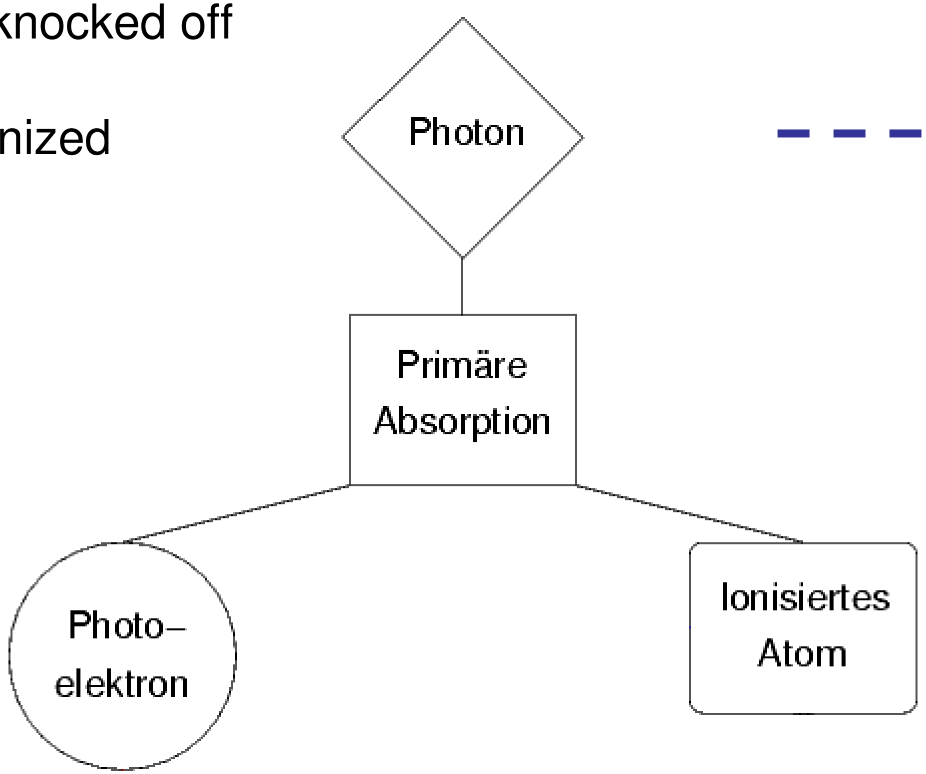
E_0 < Si K shell: L electron

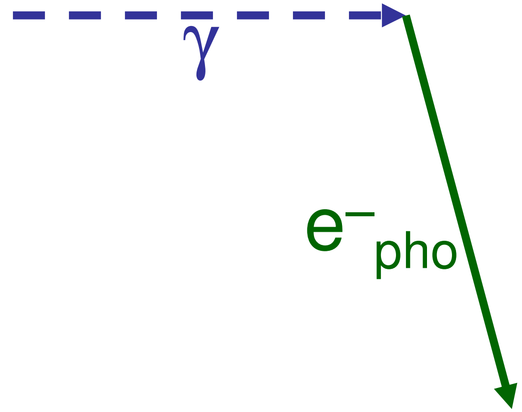




K or L electron knocked off its shell

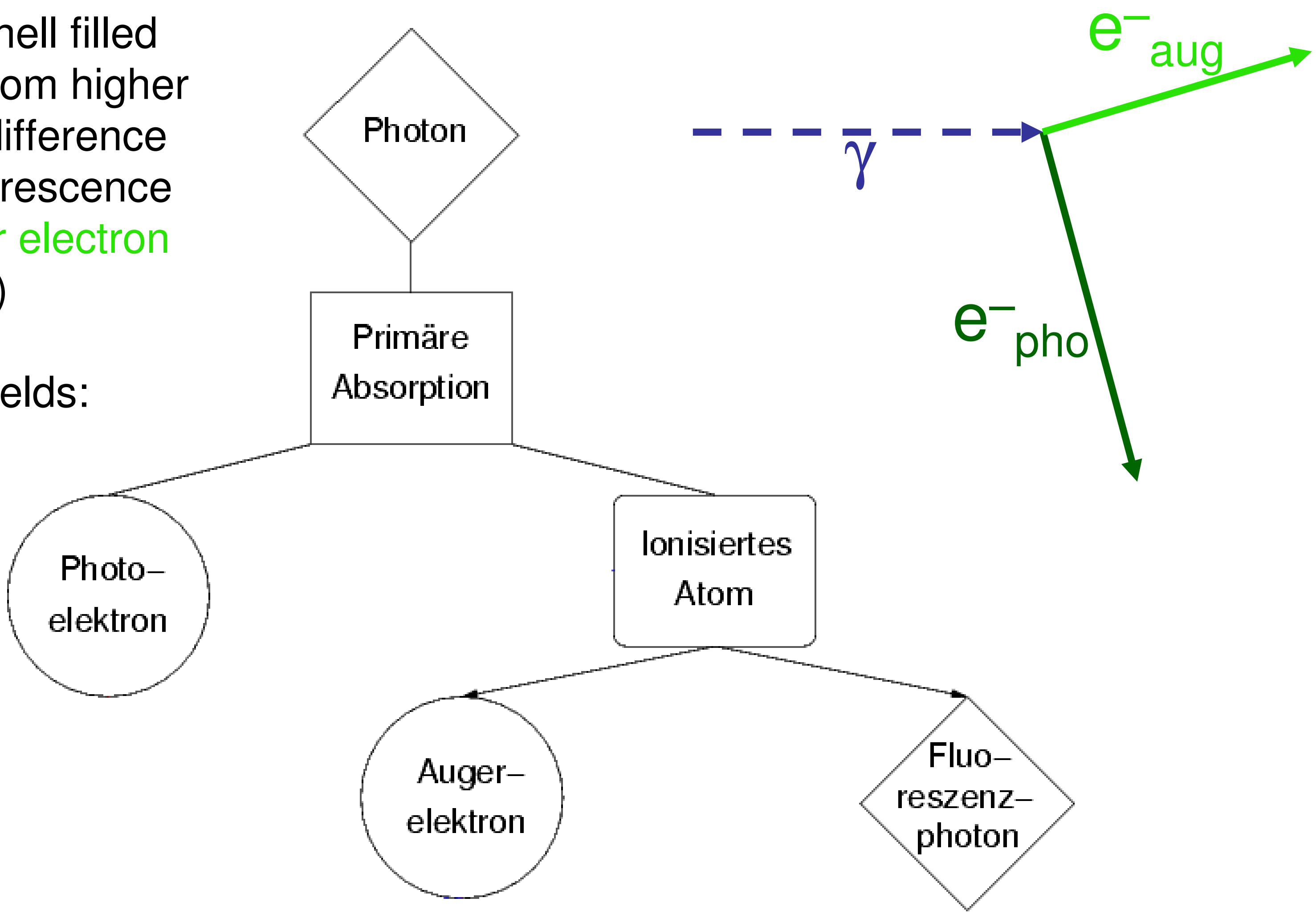
➢atom single ionized



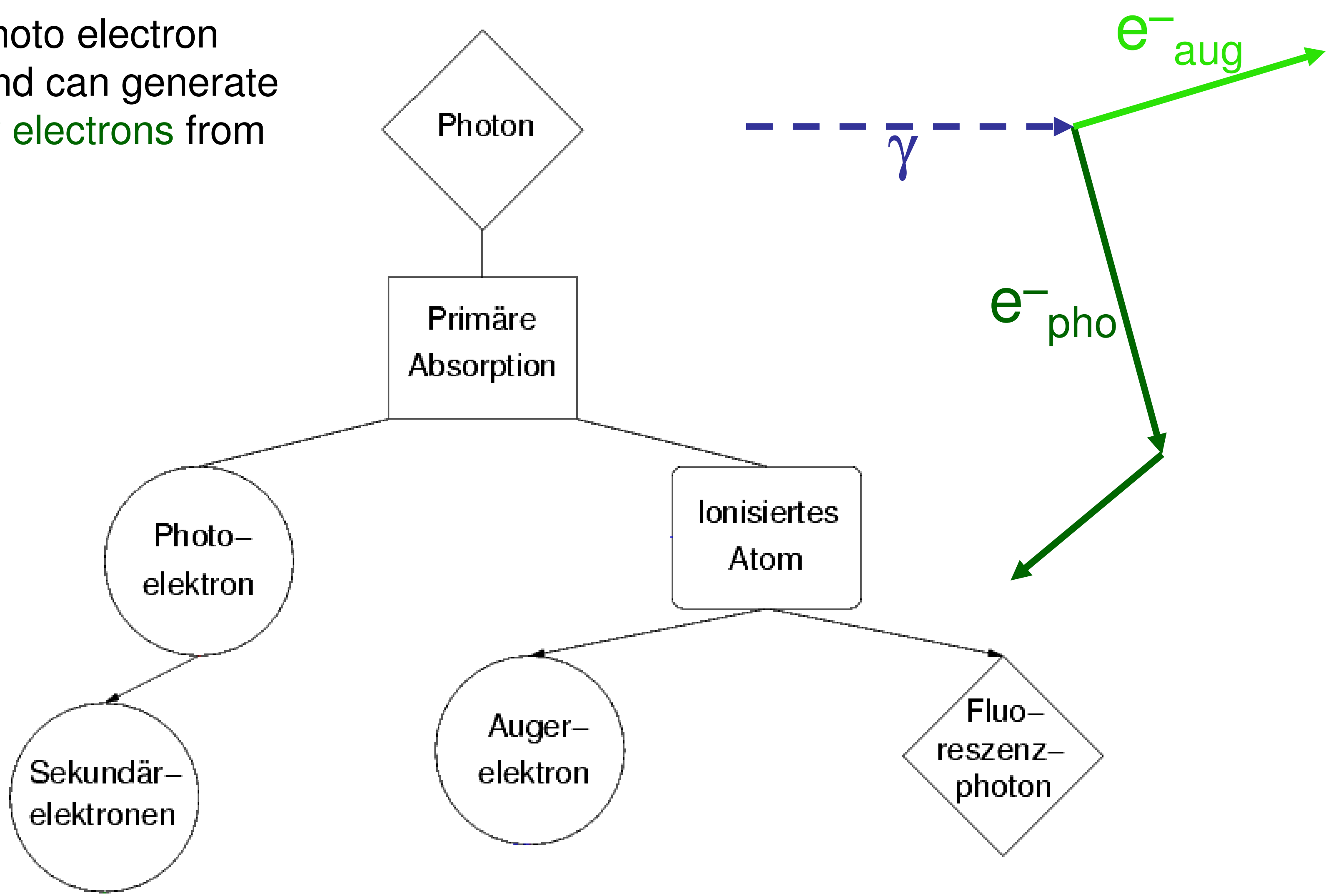


Hole in K or L shell filled with electrons from higher shells. Energy difference assigned to fluorescence photon or Auger electron (of fixed energy)

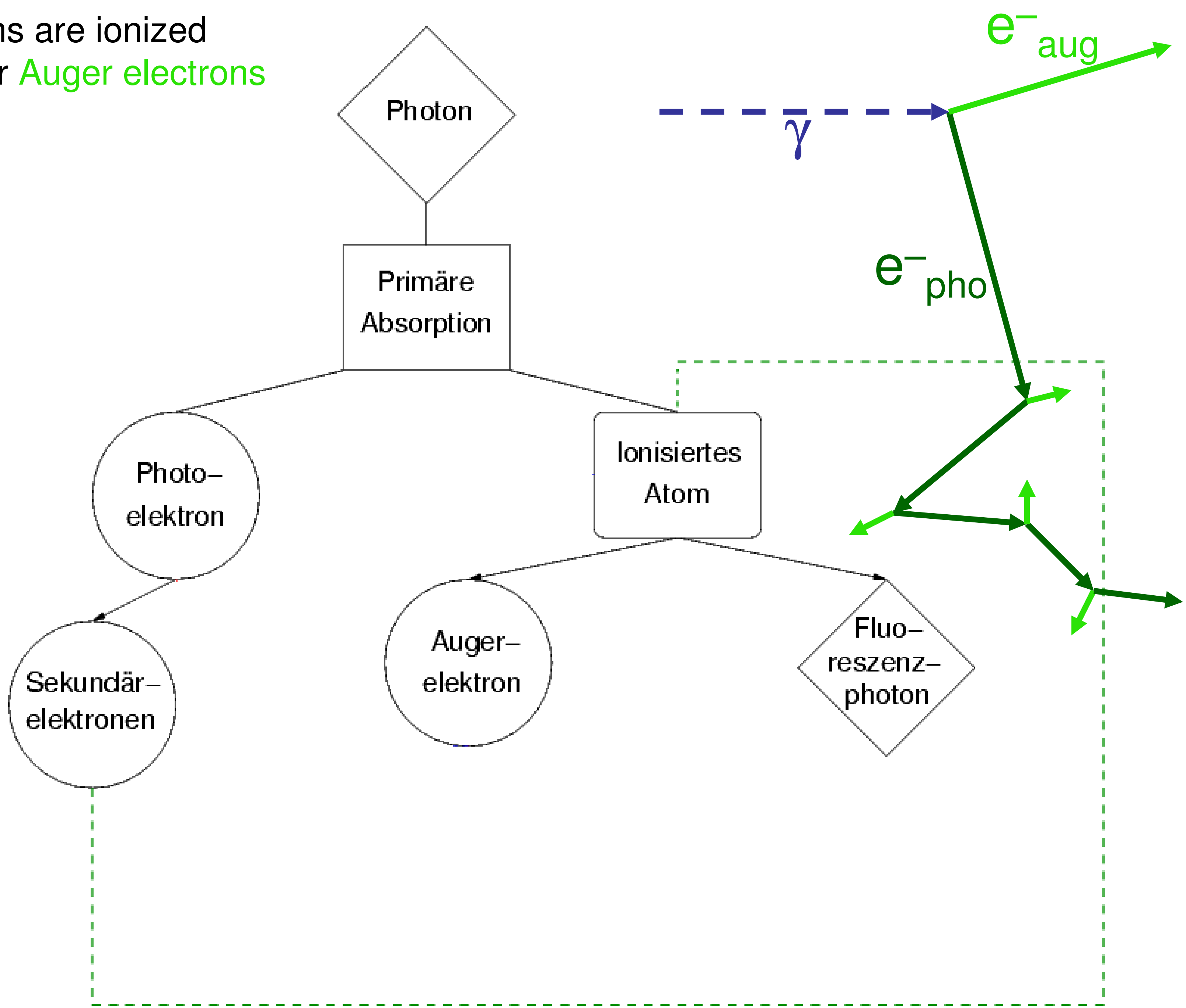
Fluorescence yields:
L shell: 0%
K shell: 4%



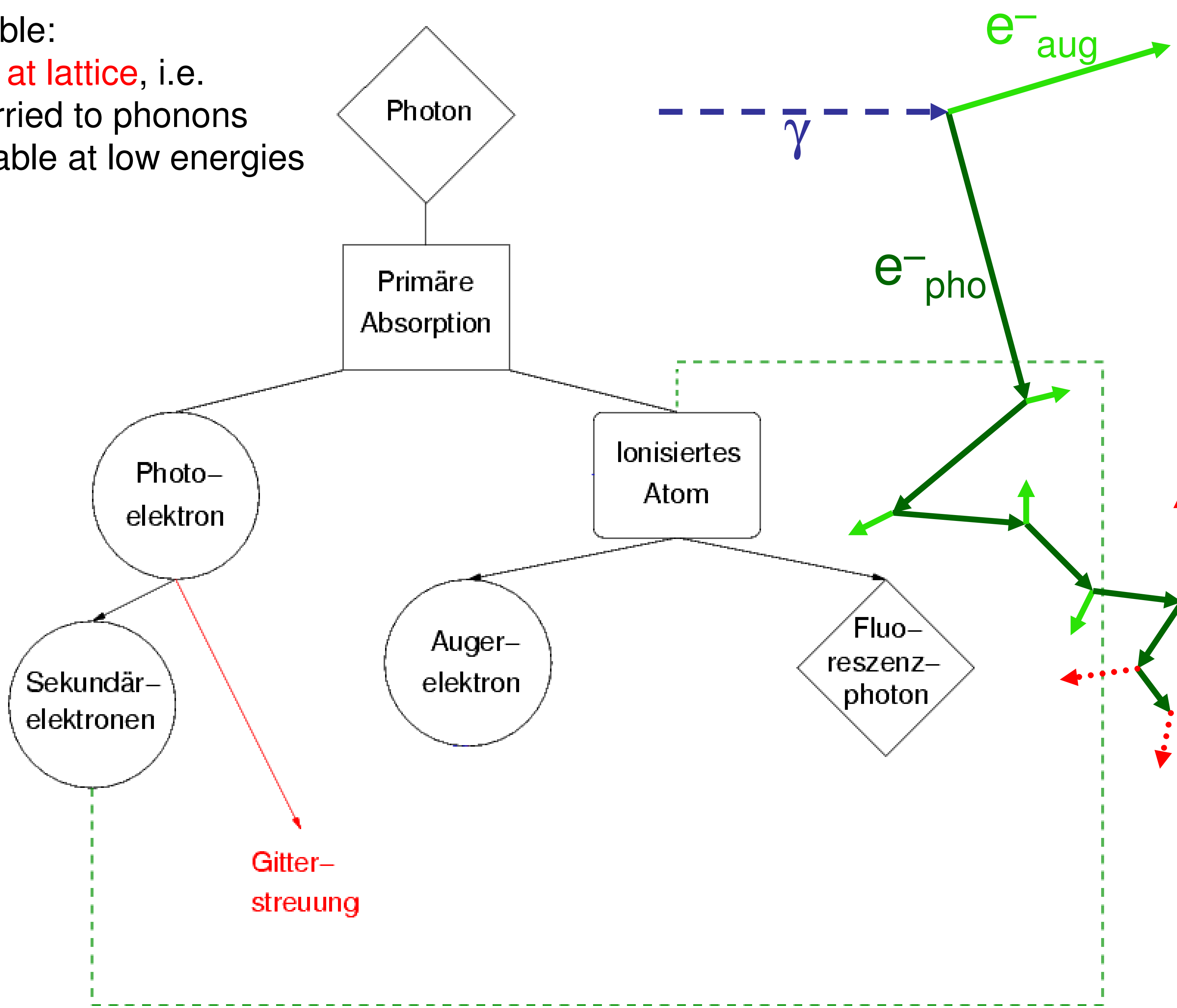
Primary photo electron scatters and can generate secondary electrons from Si atoms



More atoms are ionized and further Auger electrons emerge

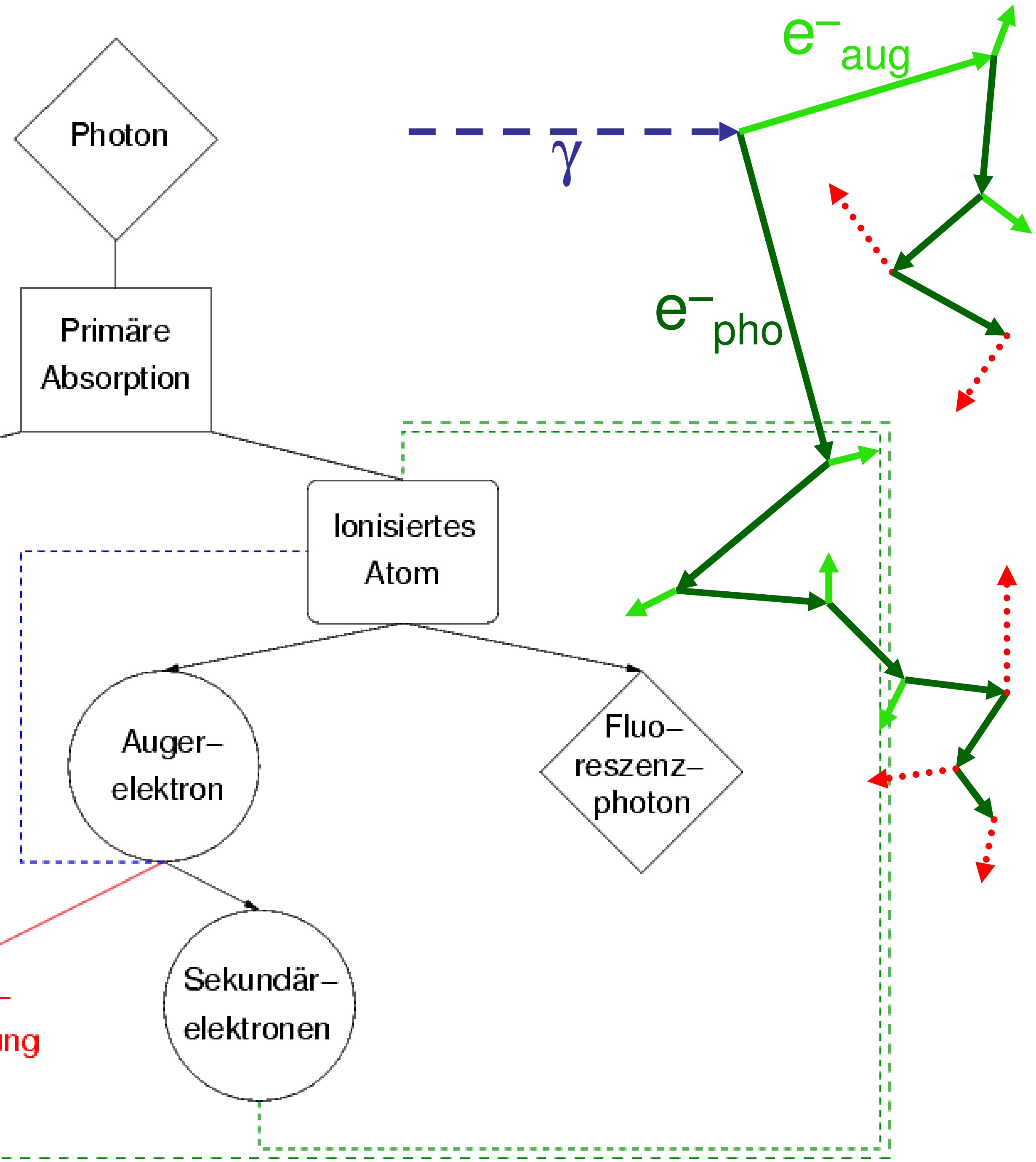


Also possible:
Scattering at lattice, i.e.
energy carried to phonons
Very probable at low energies

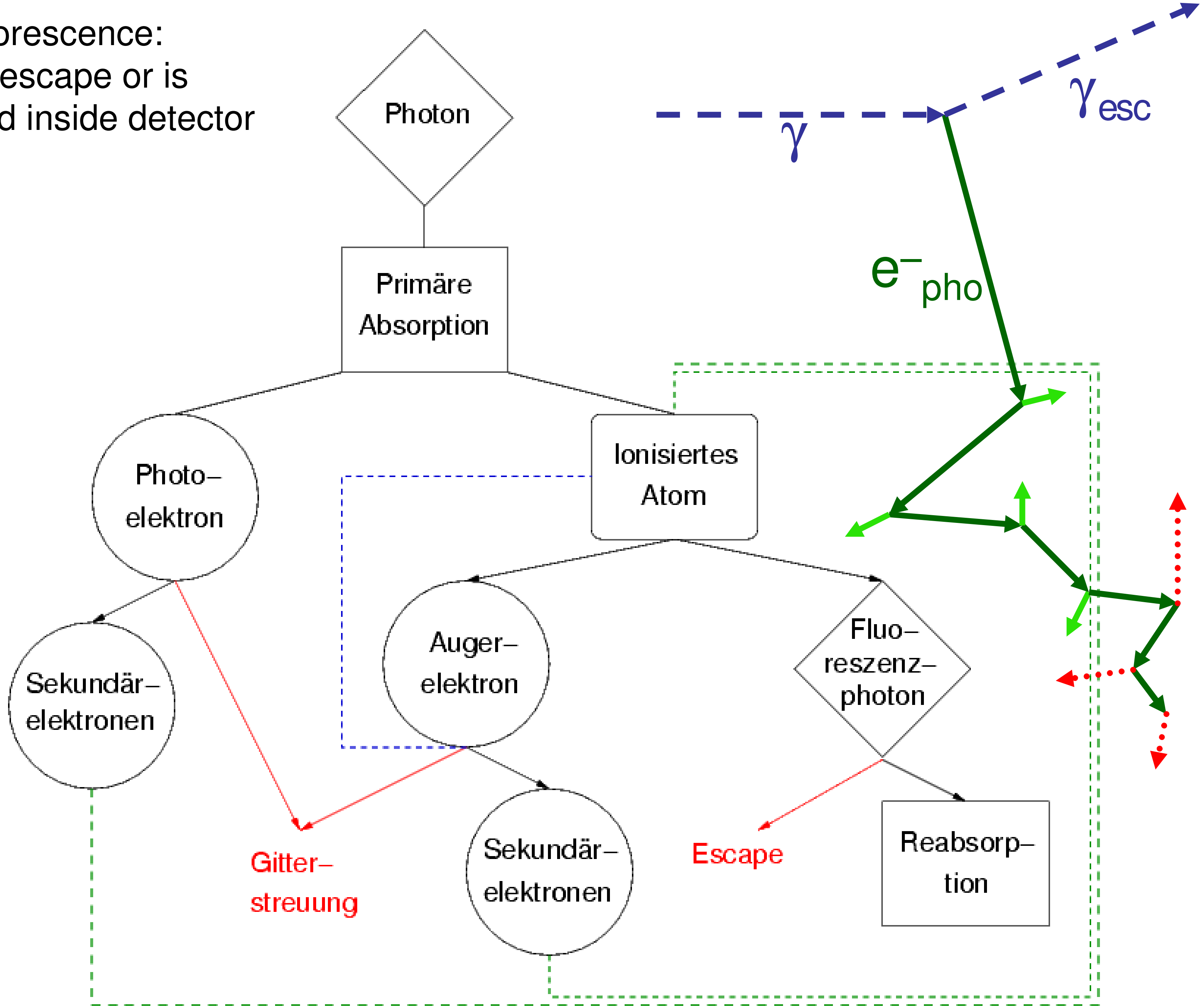


The primary Auger electron also produces secondaries and phonons

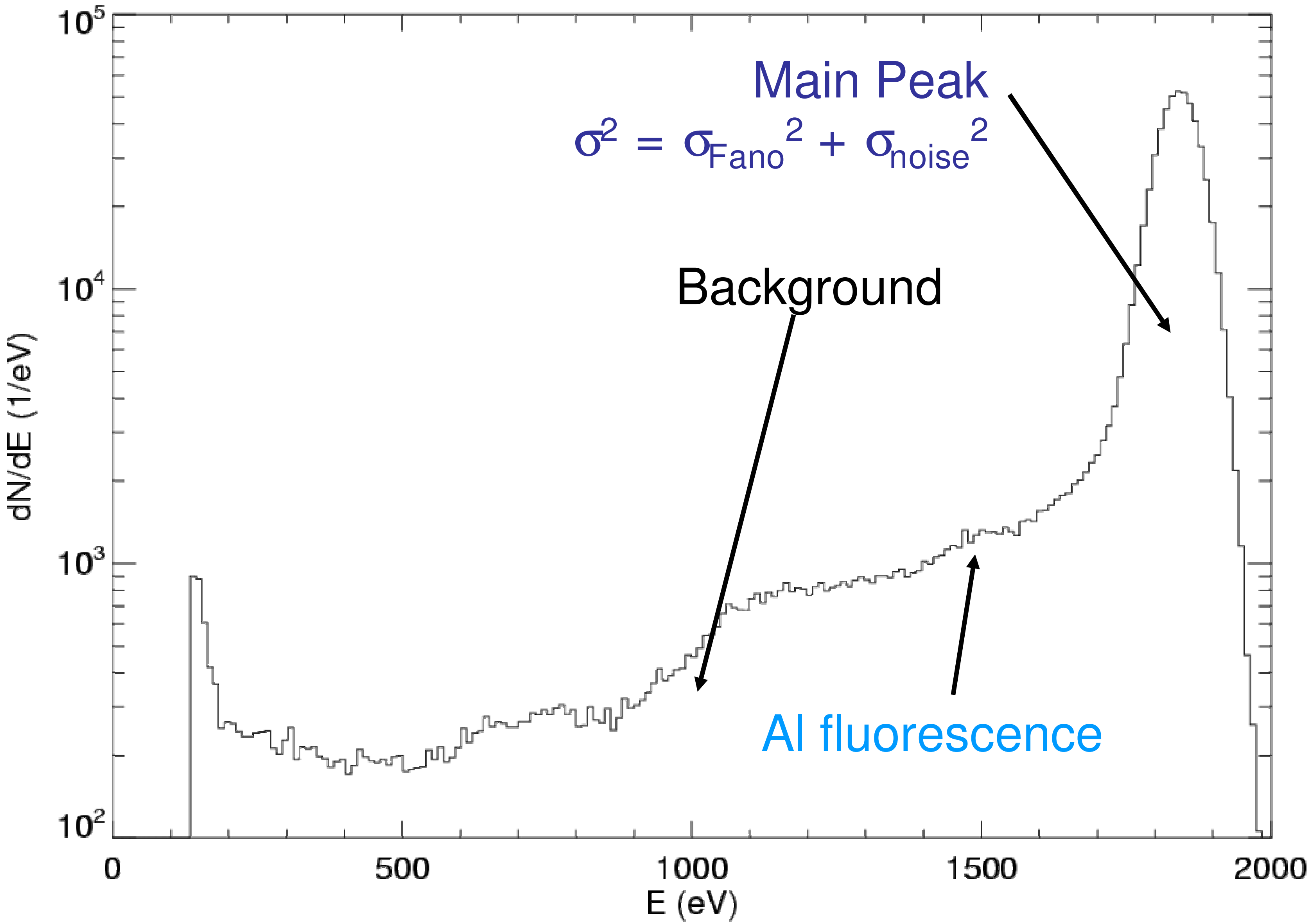
Number of electrons generated: Ionization/Fano statistics



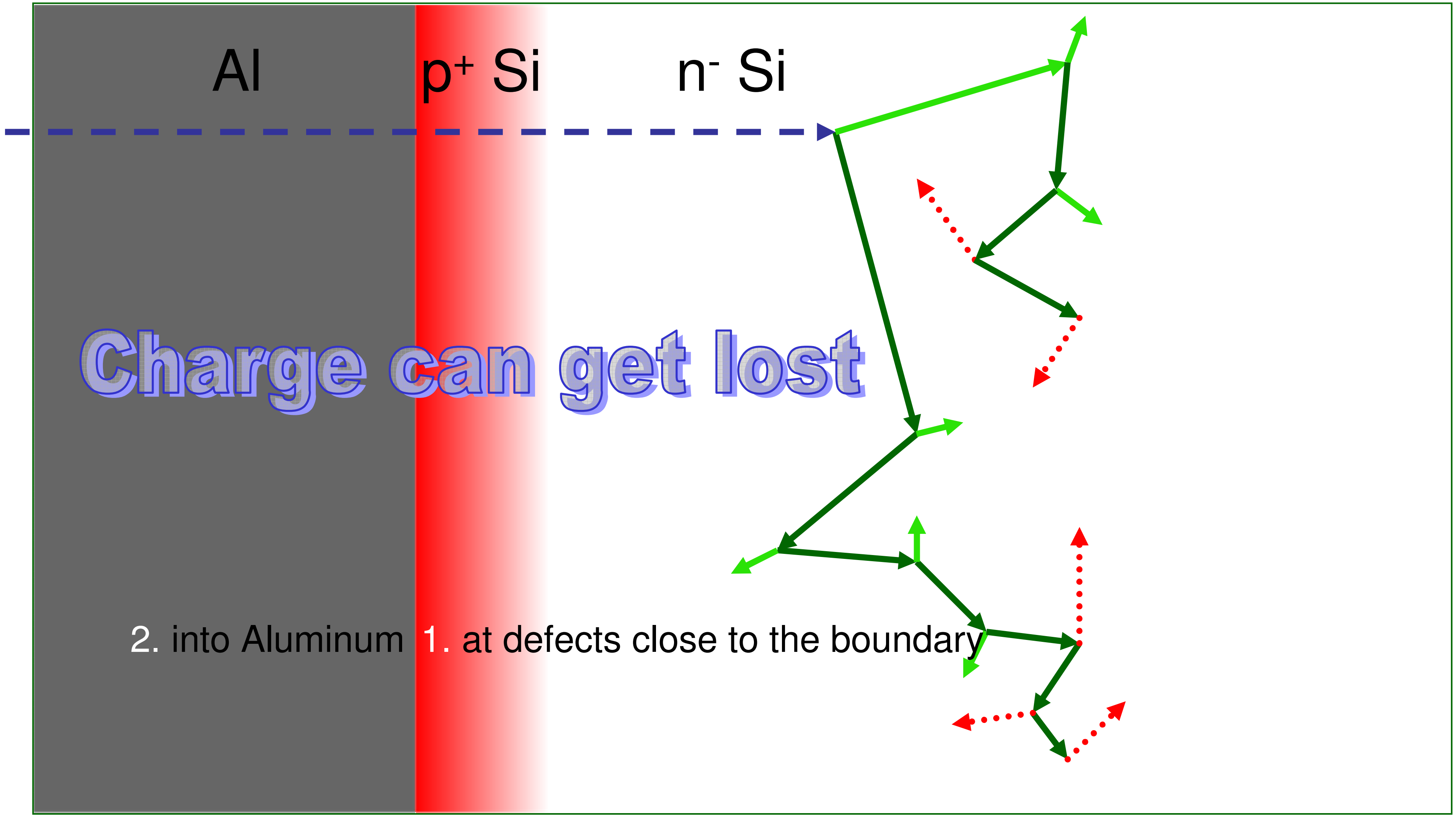
K shell fluorescence:
X-ray can escape or is
reabsorbed inside detector



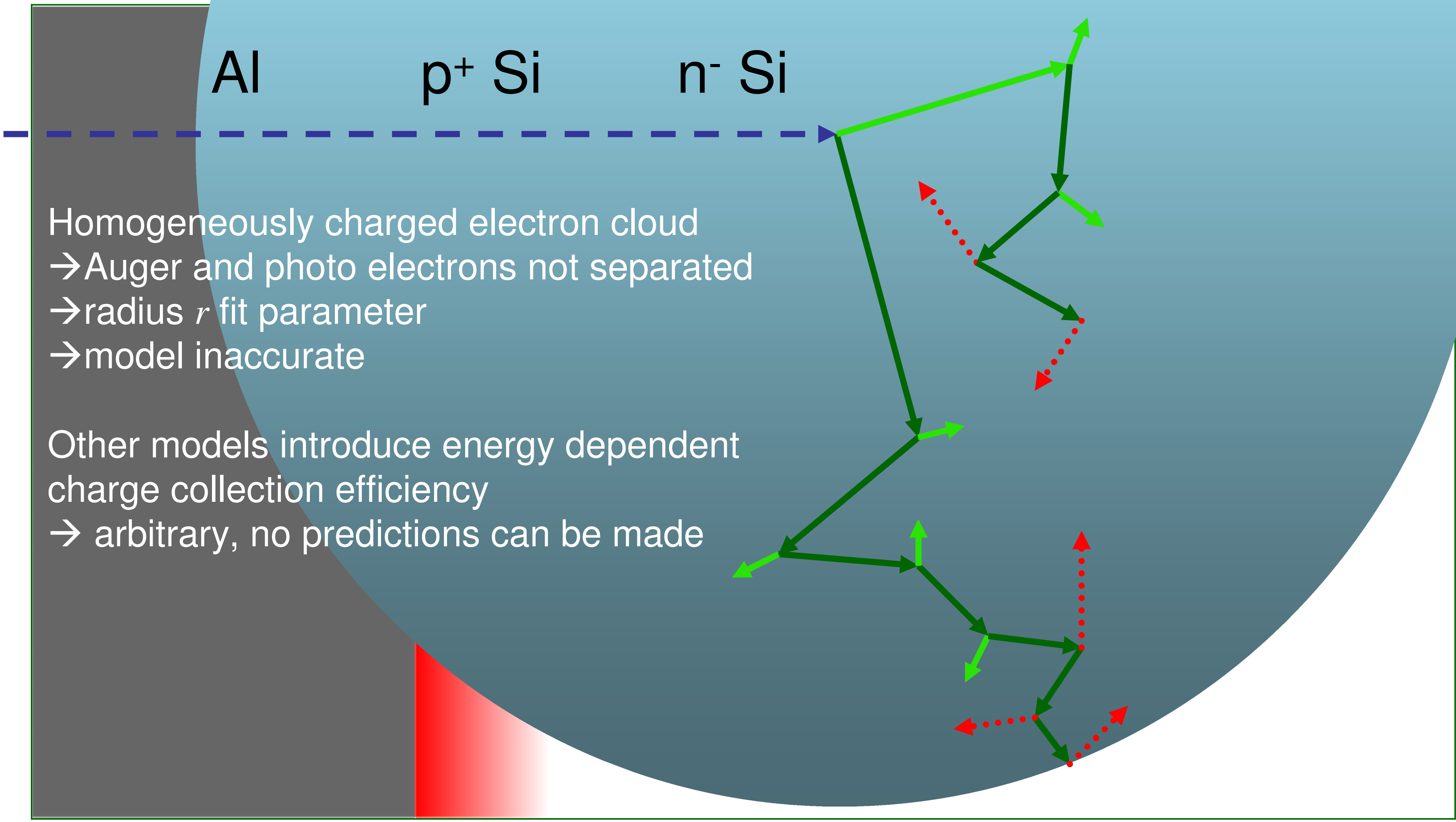
Calculation of Spectra



Absorption Near the Boundary



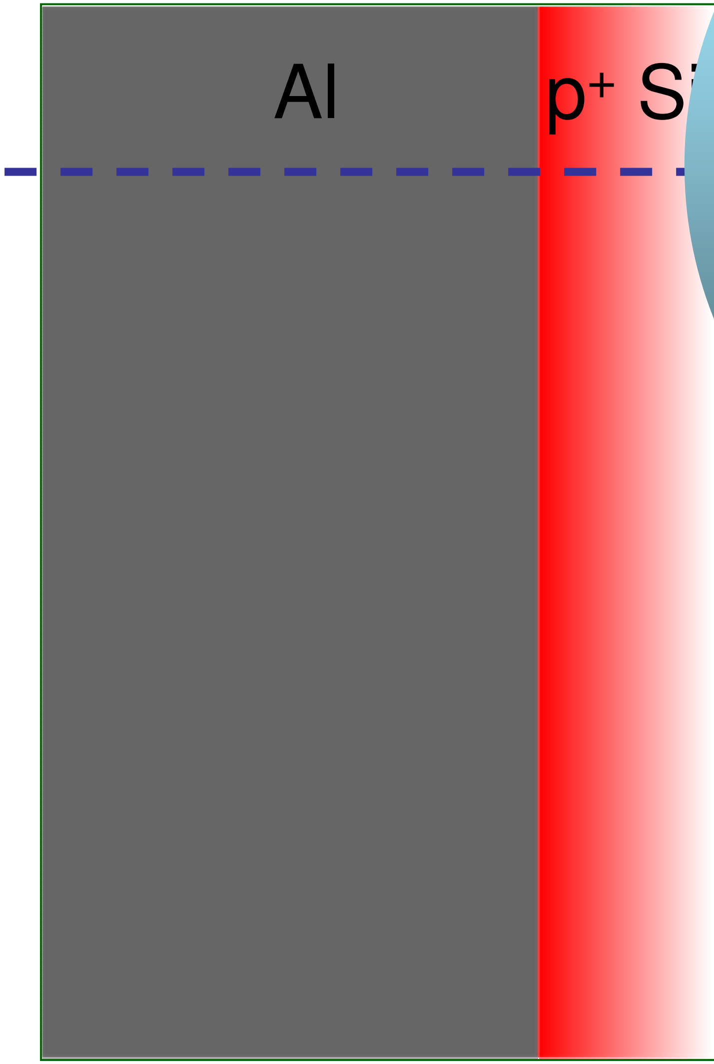
Absorption Near the Boundary



Homogeneously charged electron cloud
→Auger and photo electrons not separated
→radius r fit parameter
→model inaccurate

Other models introduce energy dependent charge collection efficiency
→ arbitrary, no predictions can be made

New



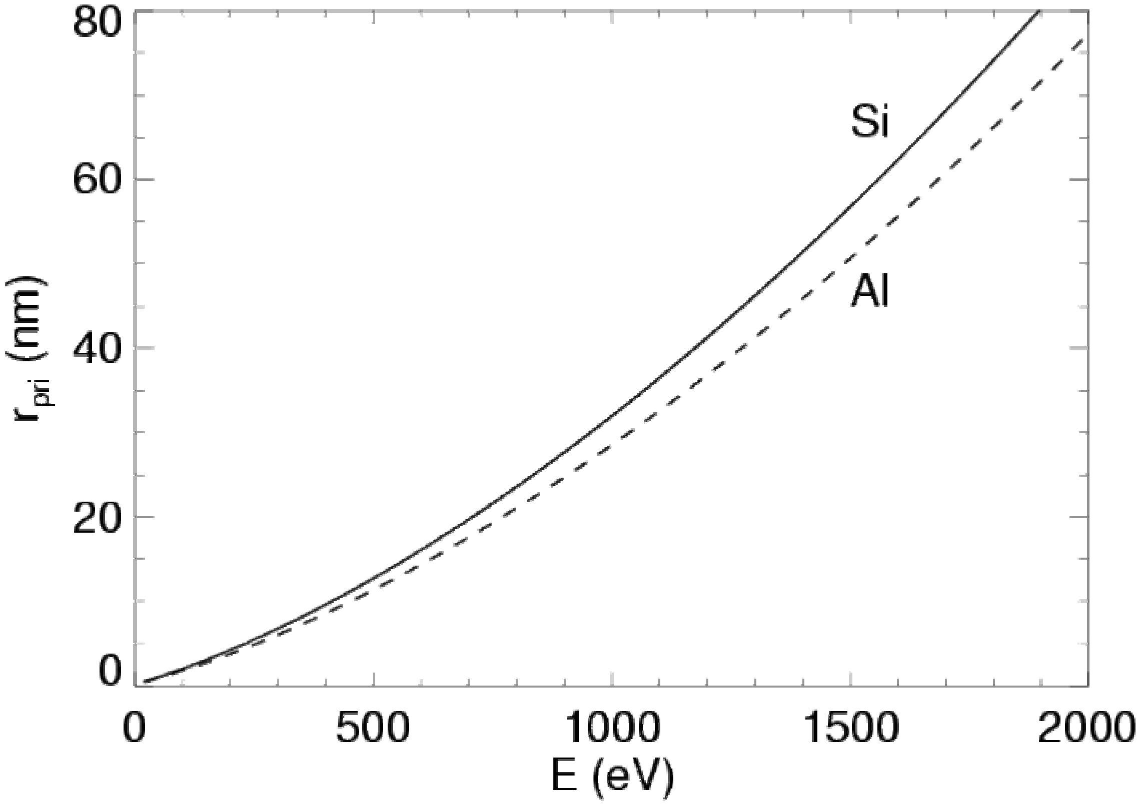
primaries
ferential tracks
rting point
harge
$\mathrm{d}E/\mathrm{d}R$

charge cloud radius
free parameter

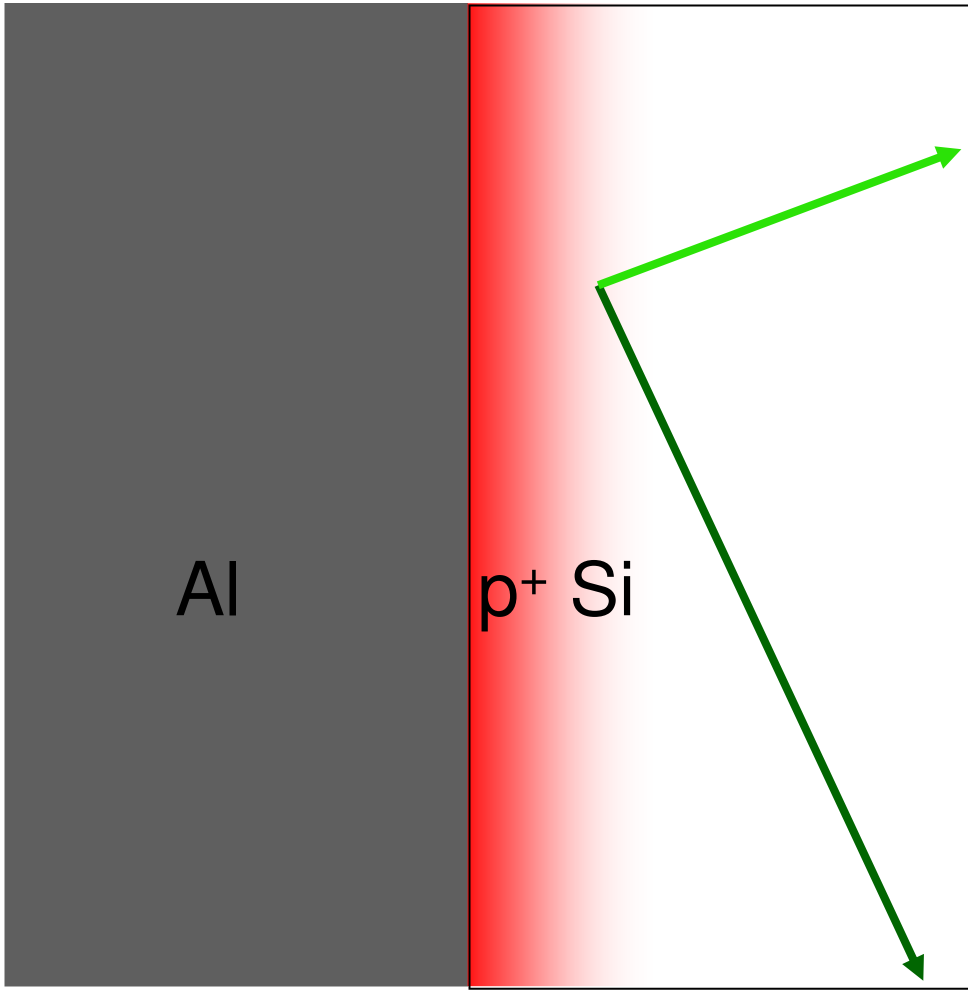
primary track can propagate in any direction

Electron Ranges

„Projected“ ranges (after *Iskef*)
Valid for primary electrons



Primary Electrons



Secondary electron charge clouds not shown

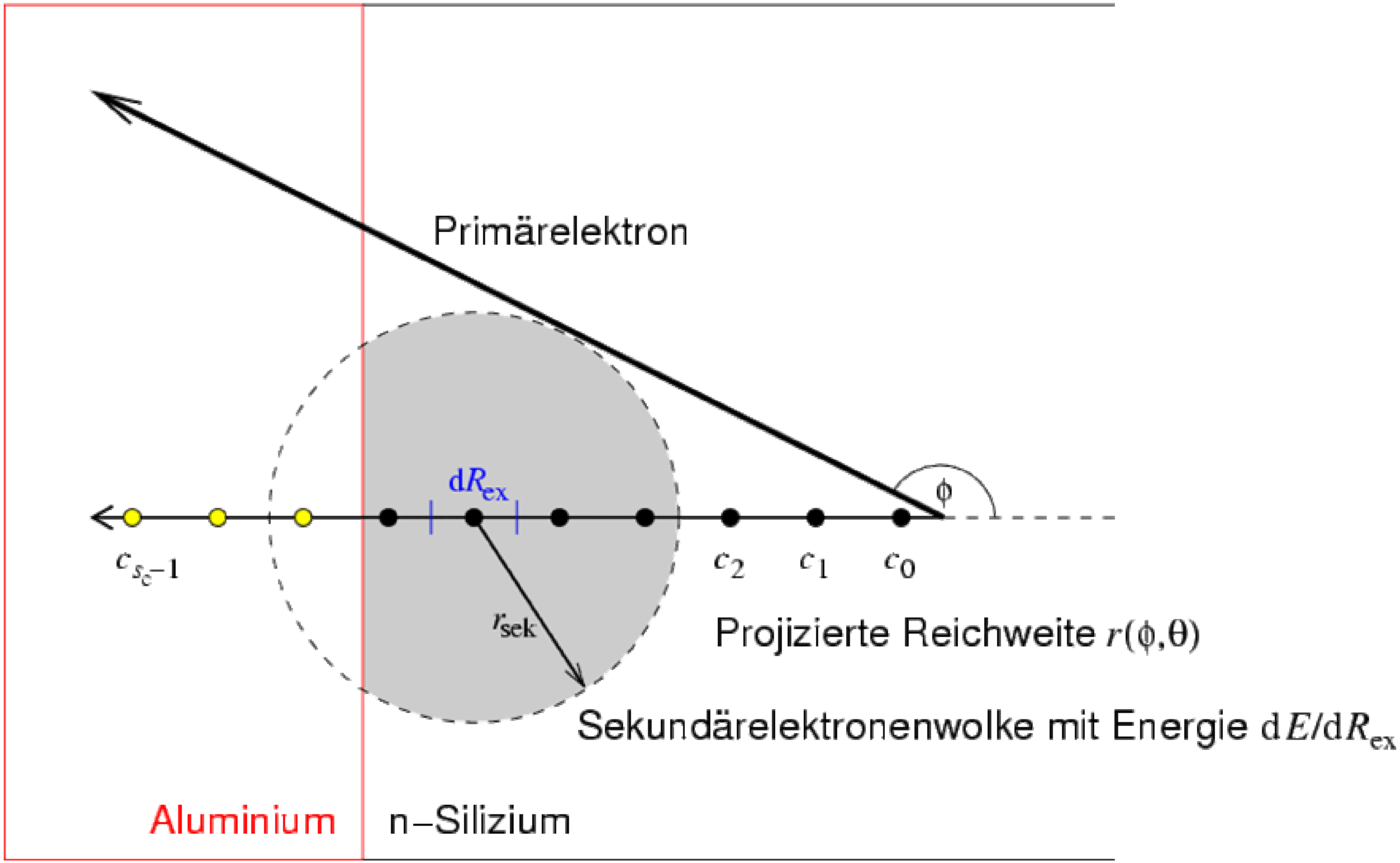
Calculation of collected charge for 2 primary electrons and the angles $\phi = 0, \ldots, \pi/2, \; \theta = 0, \ldots, \pi$

No charge collection in Al

Each possible combination summed up

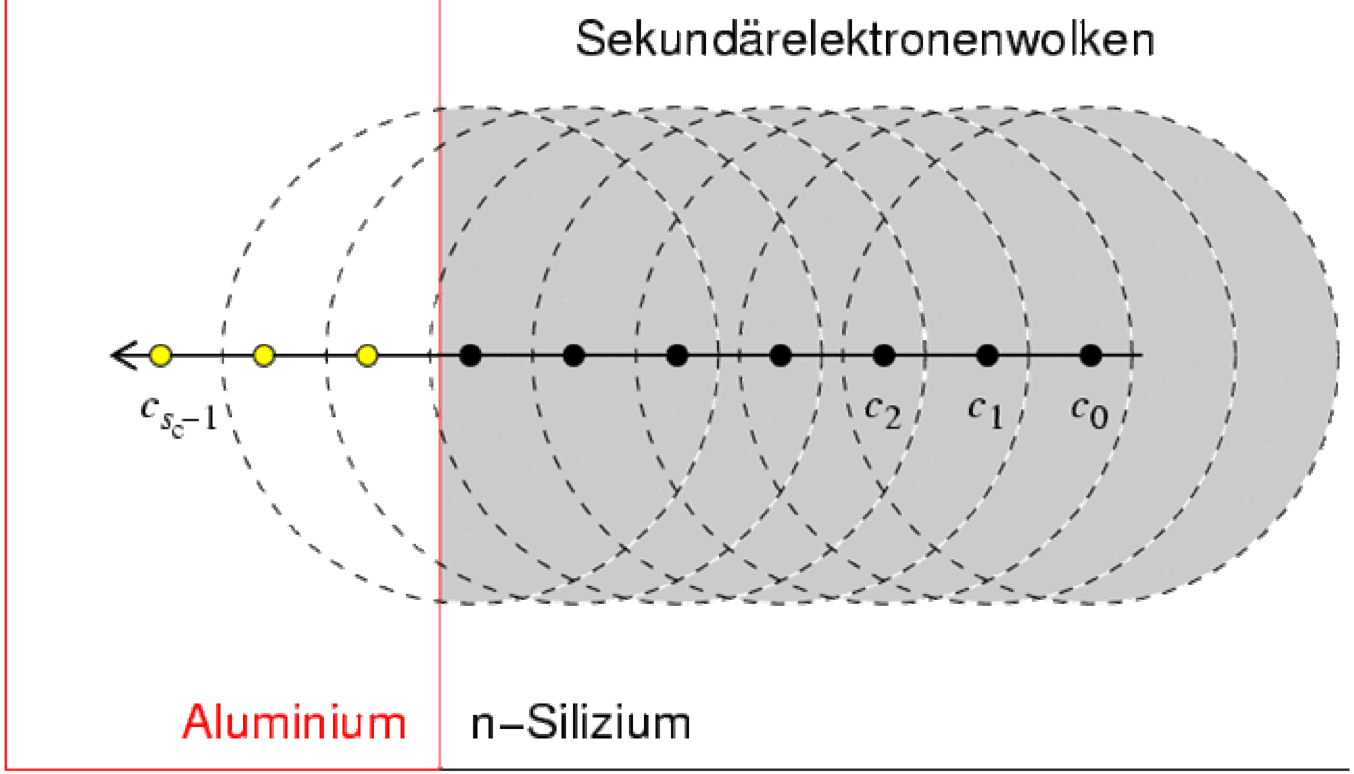
Calculation done for several absorption depths and weighted with absorption probabilities

Primary Electrons



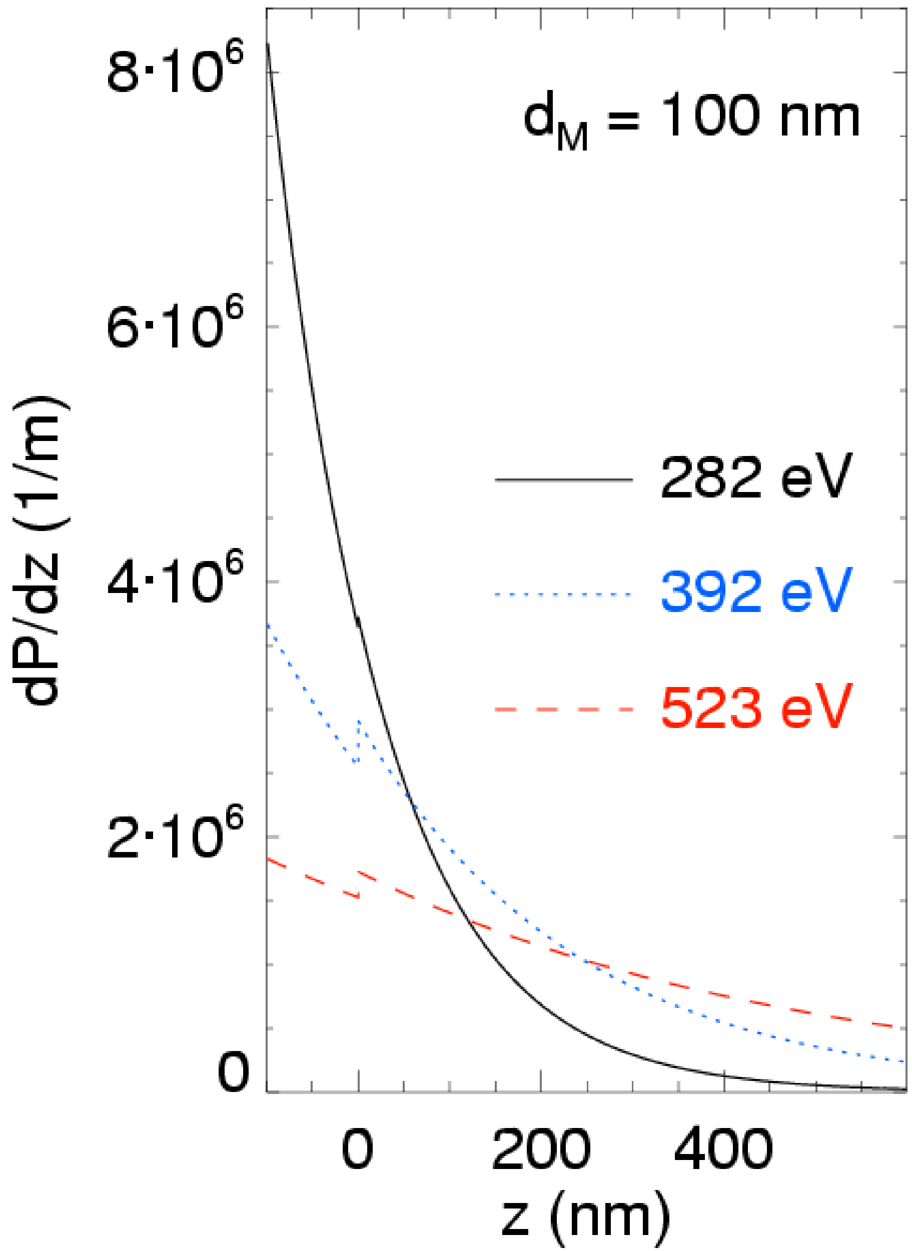
Secondary Electrons

Statistics of charge carrier generation well-known
Fano noise + electronic noise = peak width
→considered by σ
Calculation of *spatial distribution* of charge



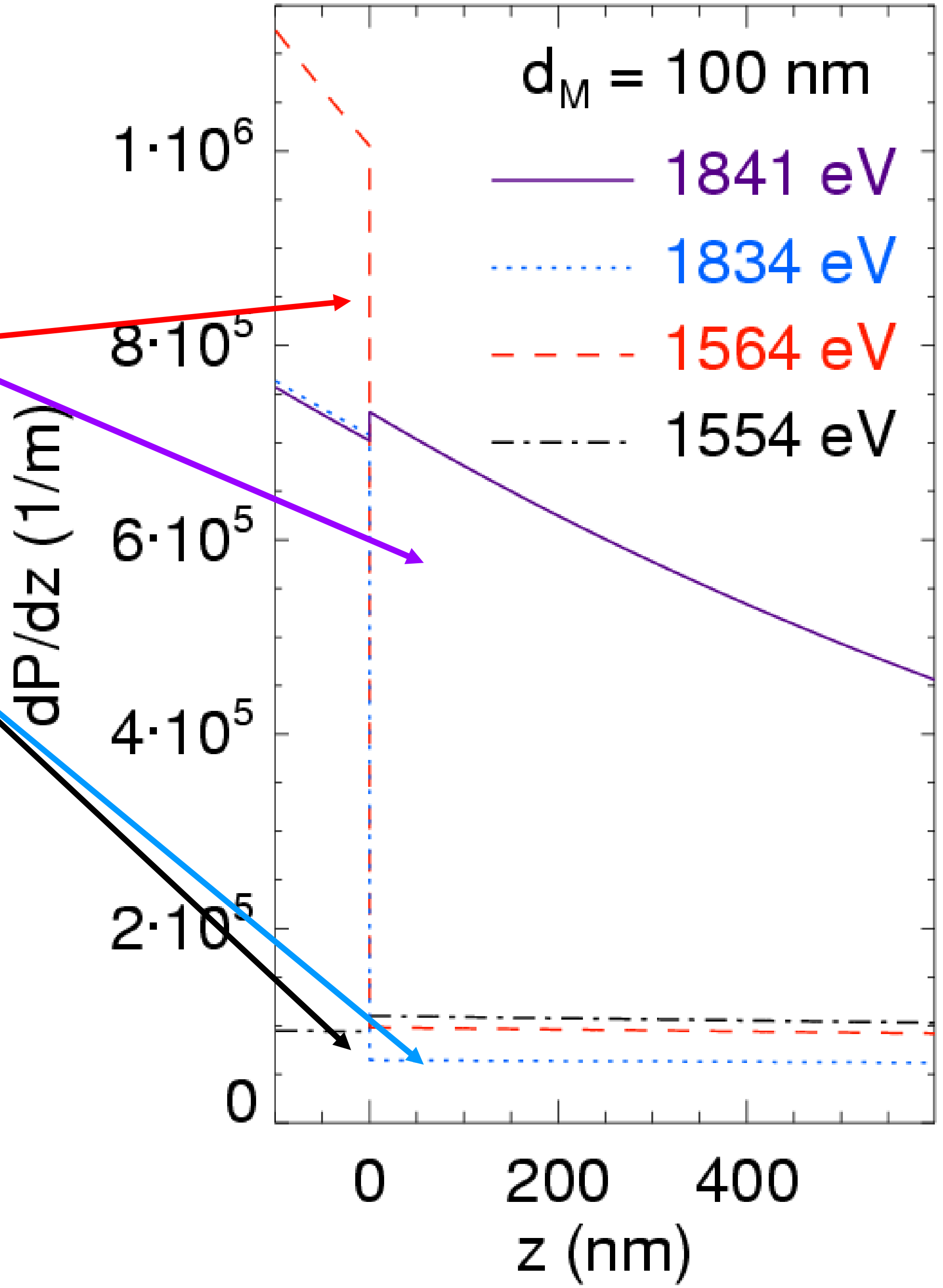
Absorption Probability Densities

$$dP/dz = \exp(-d/\lambda)/\lambda$$



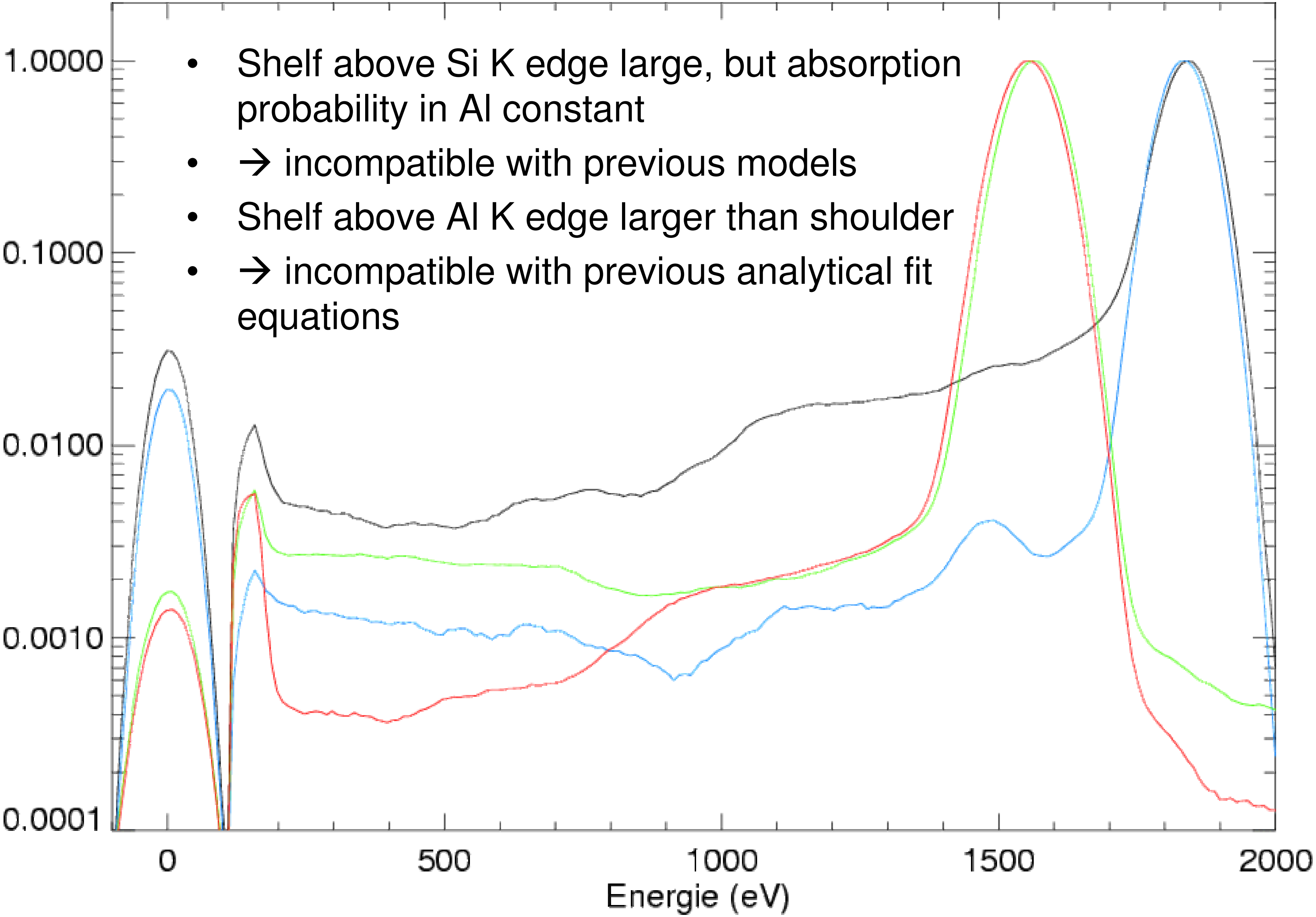
Largest absorption probabilities above K edges

Smallest absorption probabilities below K edges

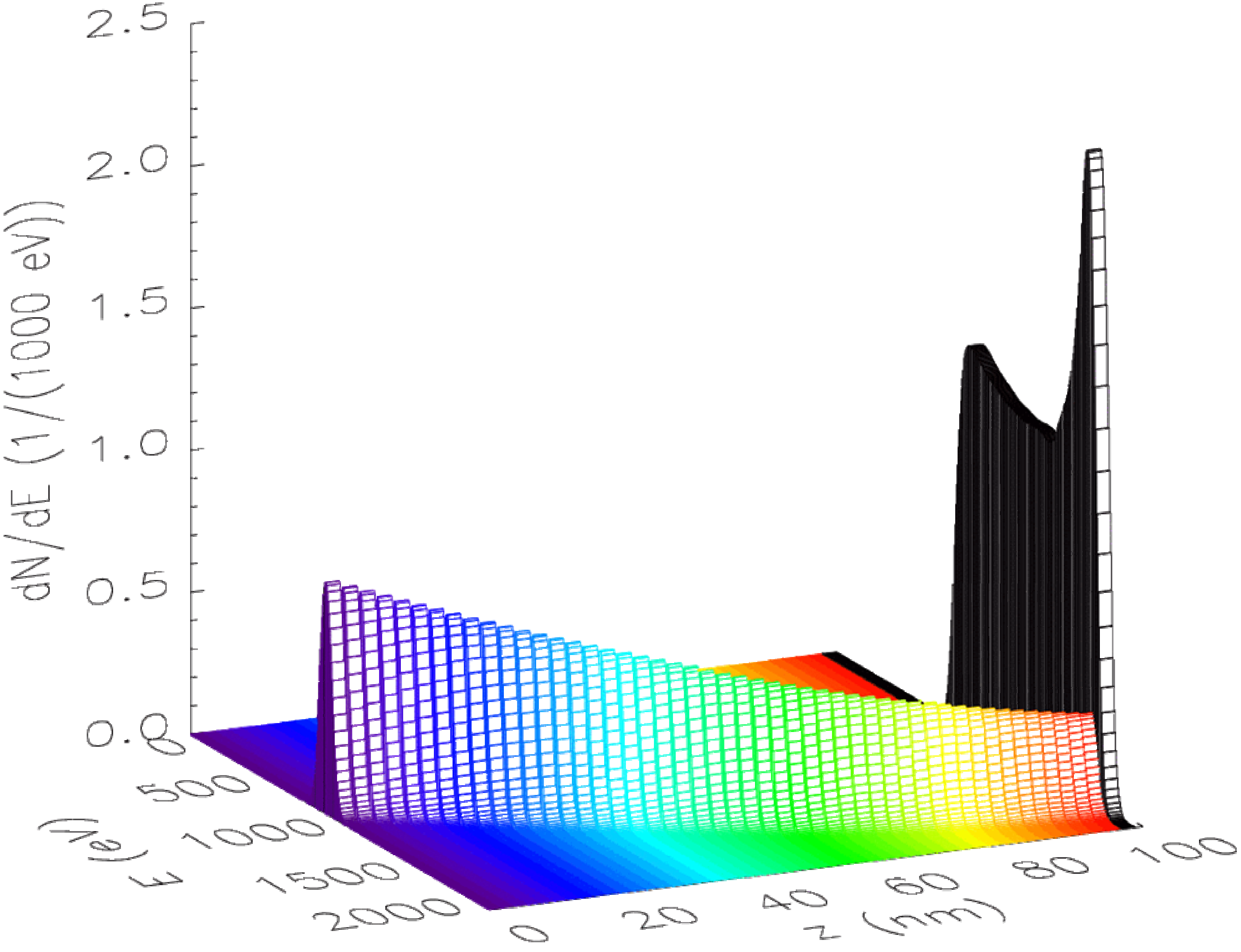


Spectra at the Al and Si K edges

- Shelf above Si K edge large, but absorption probability in Al constant
- → incompatible with previous models
- Shelf above Al K edge larger than shoulder
- → incompatible with previous analytical fit equations



Calculation of Background Spectra

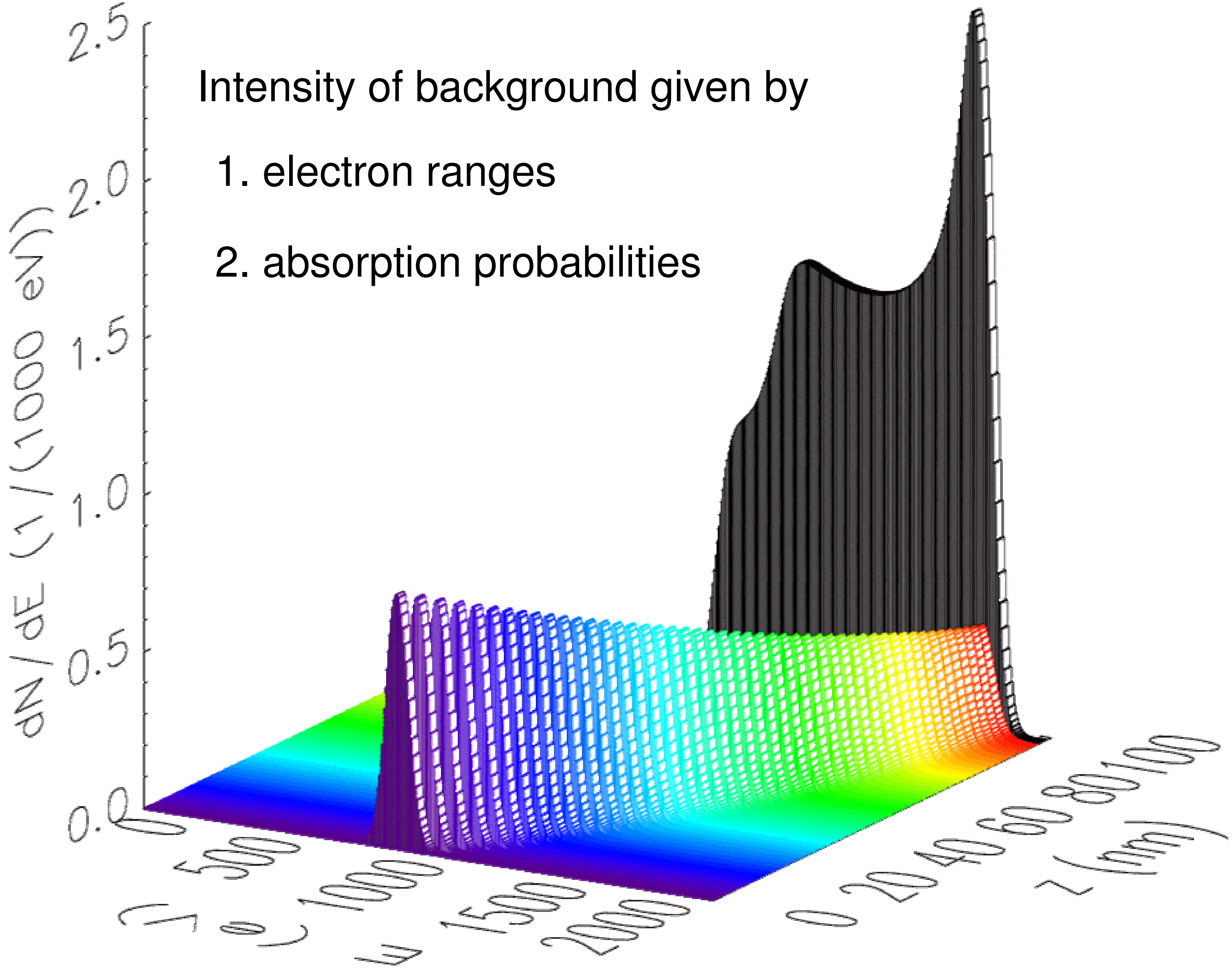


Calculation of Background Spectra

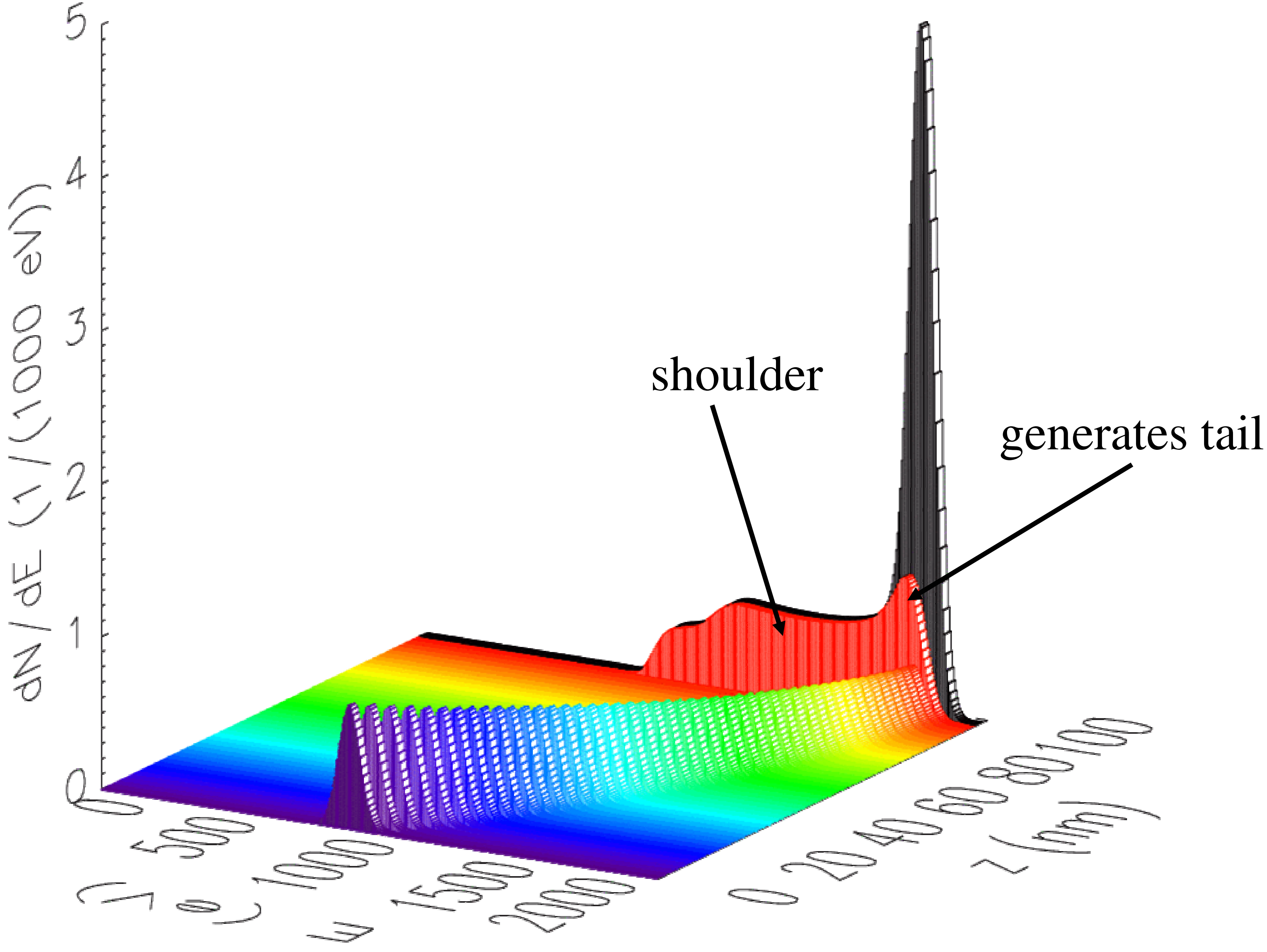
Intensity of background given by

1. electron ranges

2. absorption probabilities



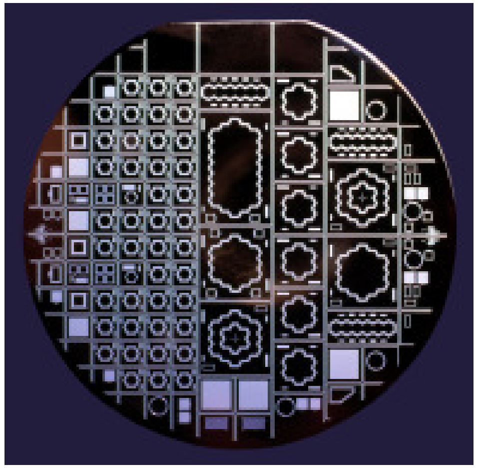
Background and Main Peak



Calculation of Response

- X-ray energy E_0 is known
- Fano noise = $(F\ w\ E_0)^{1/2}$
- Electronic noise measured separately
- Only secondary electron charge cloud radius is varied in the fit procedures
- Input: beam energy, noise, number of counts
- Output: intensities and spectral distribution of all features (main peak, background, escape peak)
- Uncertainty in primary electron ranges ≈ 25 %
- p^+ may reduce charge collection efficiency close to the boundary

The Response of Energy Dispersive X-Ray Detectors



Part A Principles of Semiconductor Detectors

1. Basic Principles
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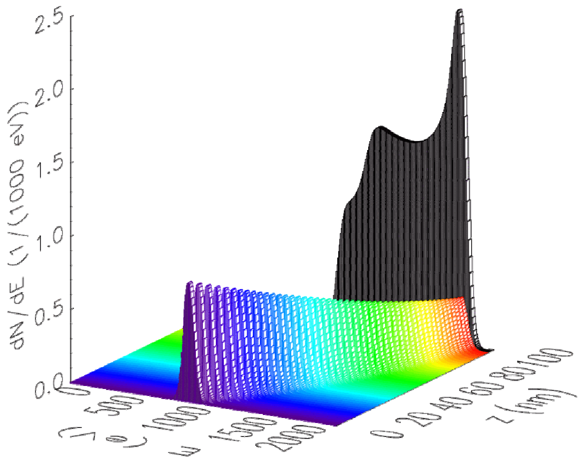
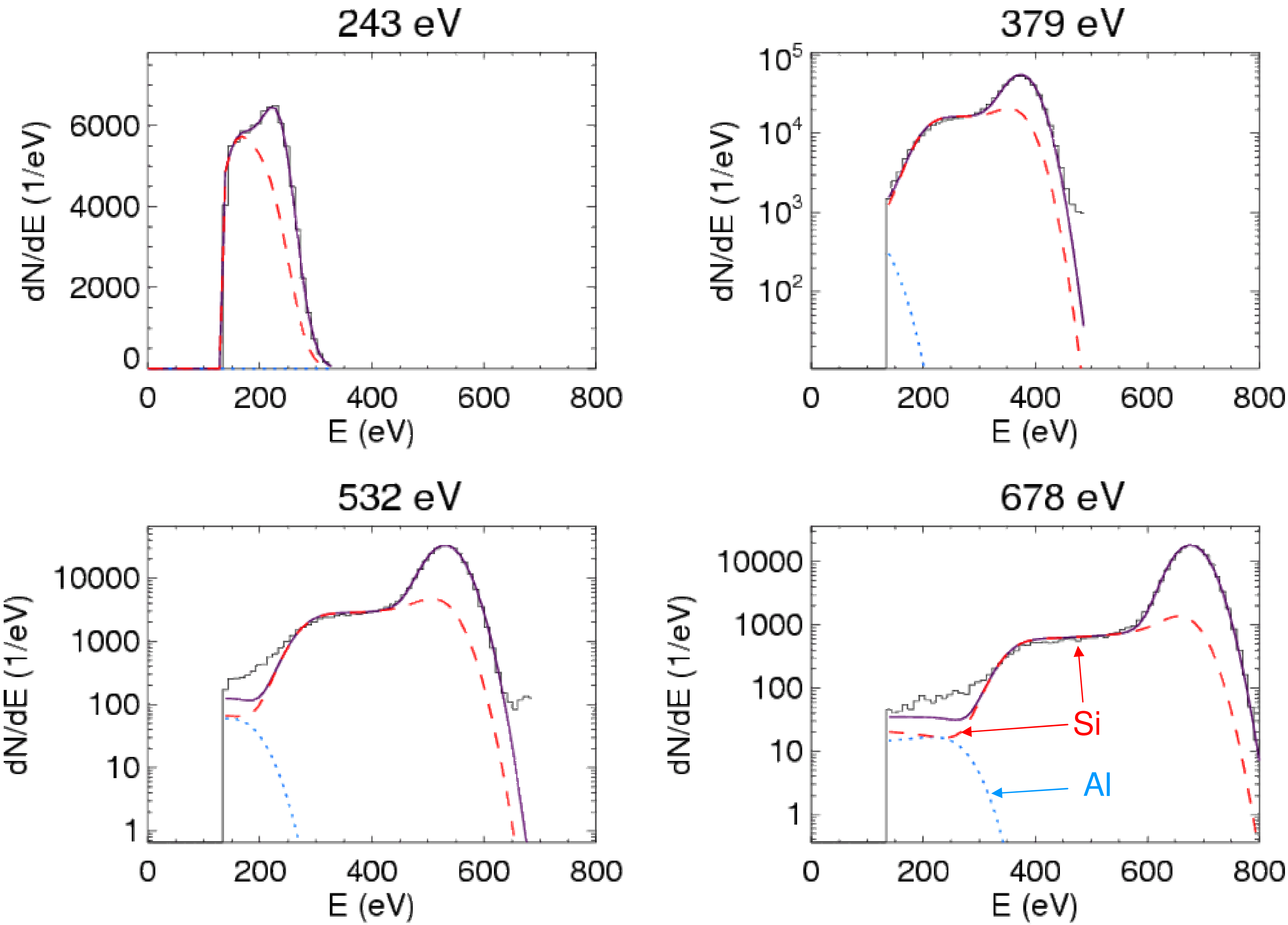
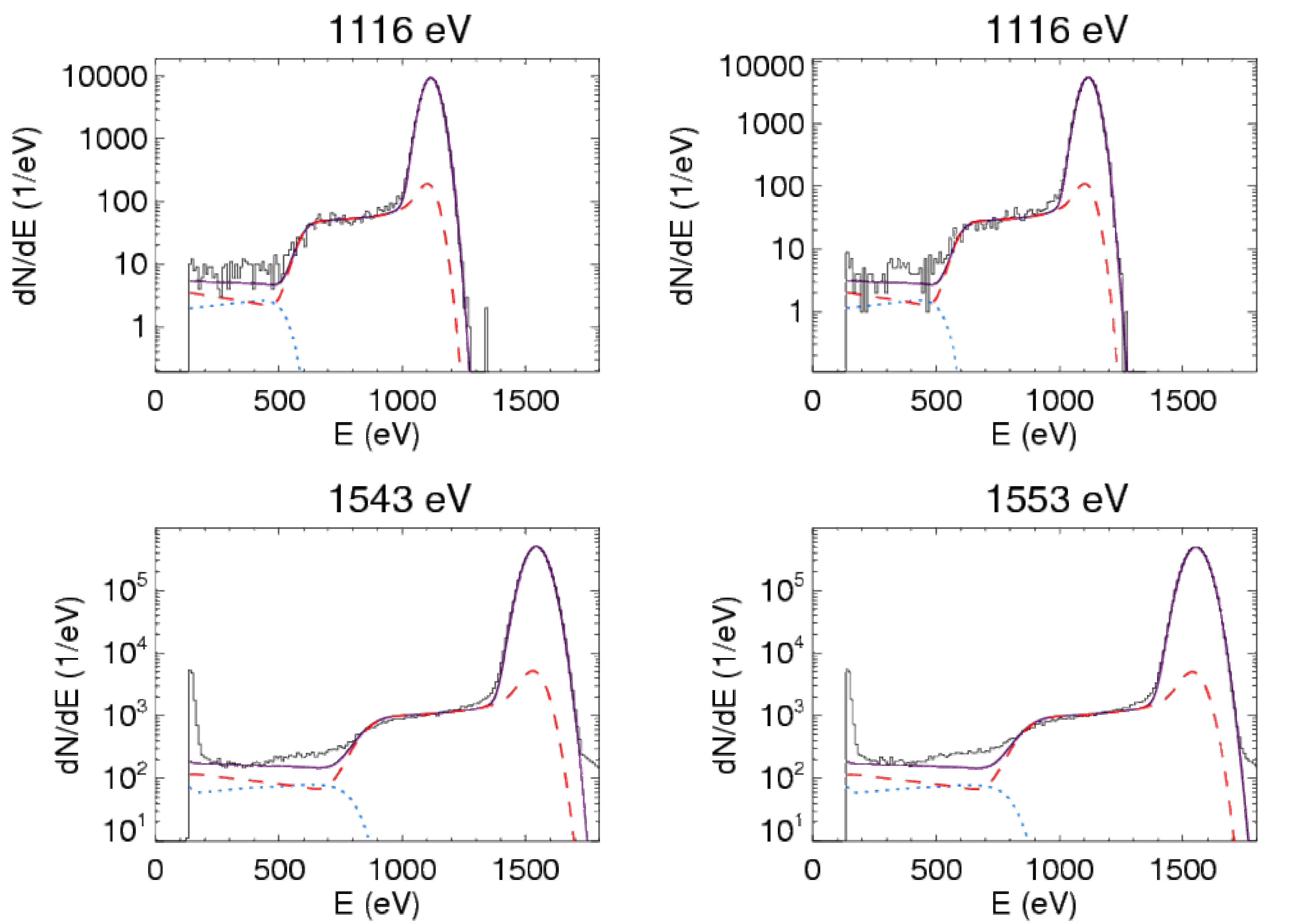


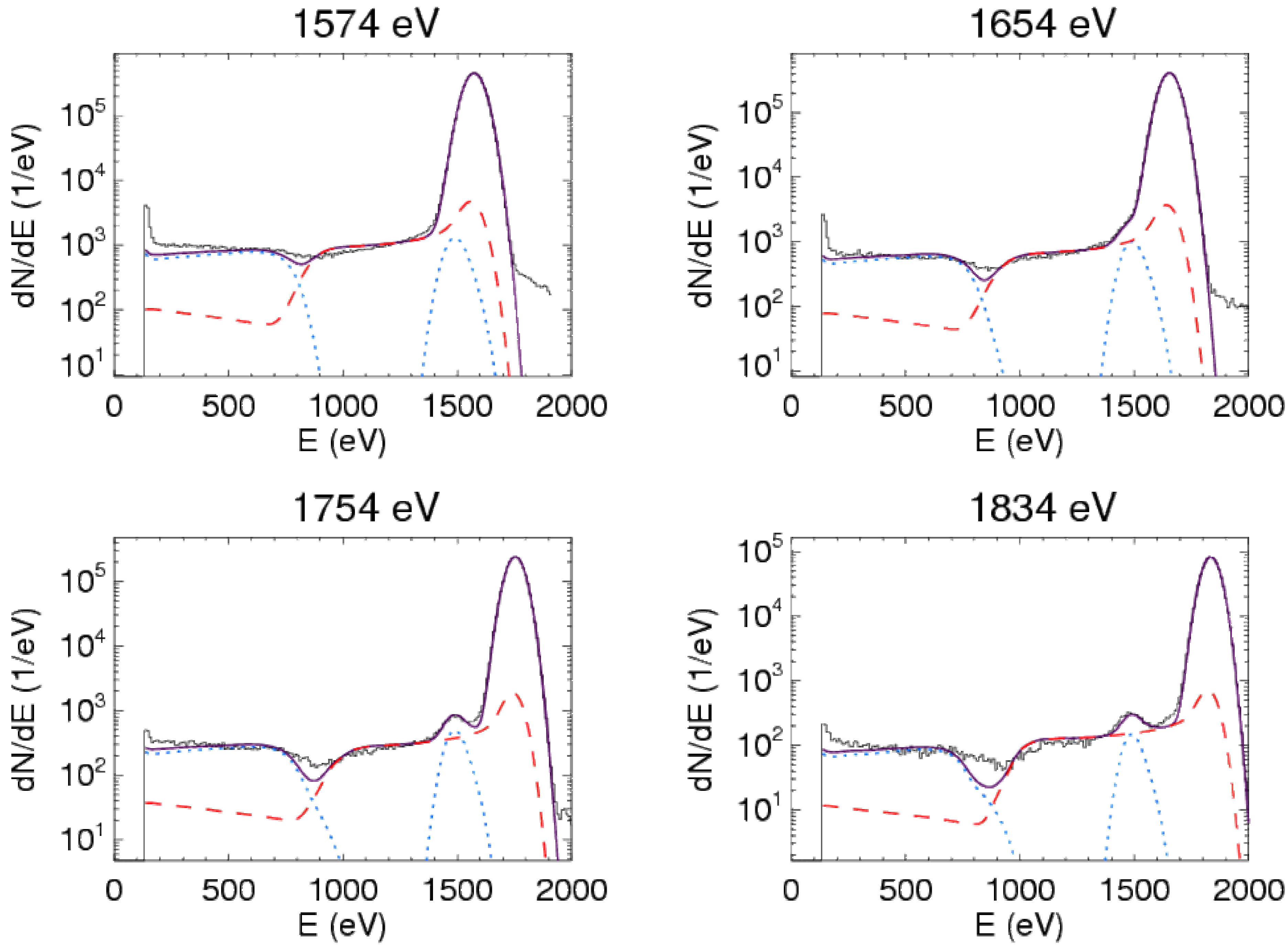
Part B Response of Silicon Drift Detectors

1. Silicon Drift Detectors
2. Low Energy Measurements/Experimental Setup
3. Calculation of Spectral Contributions
4. Results
5. Resume



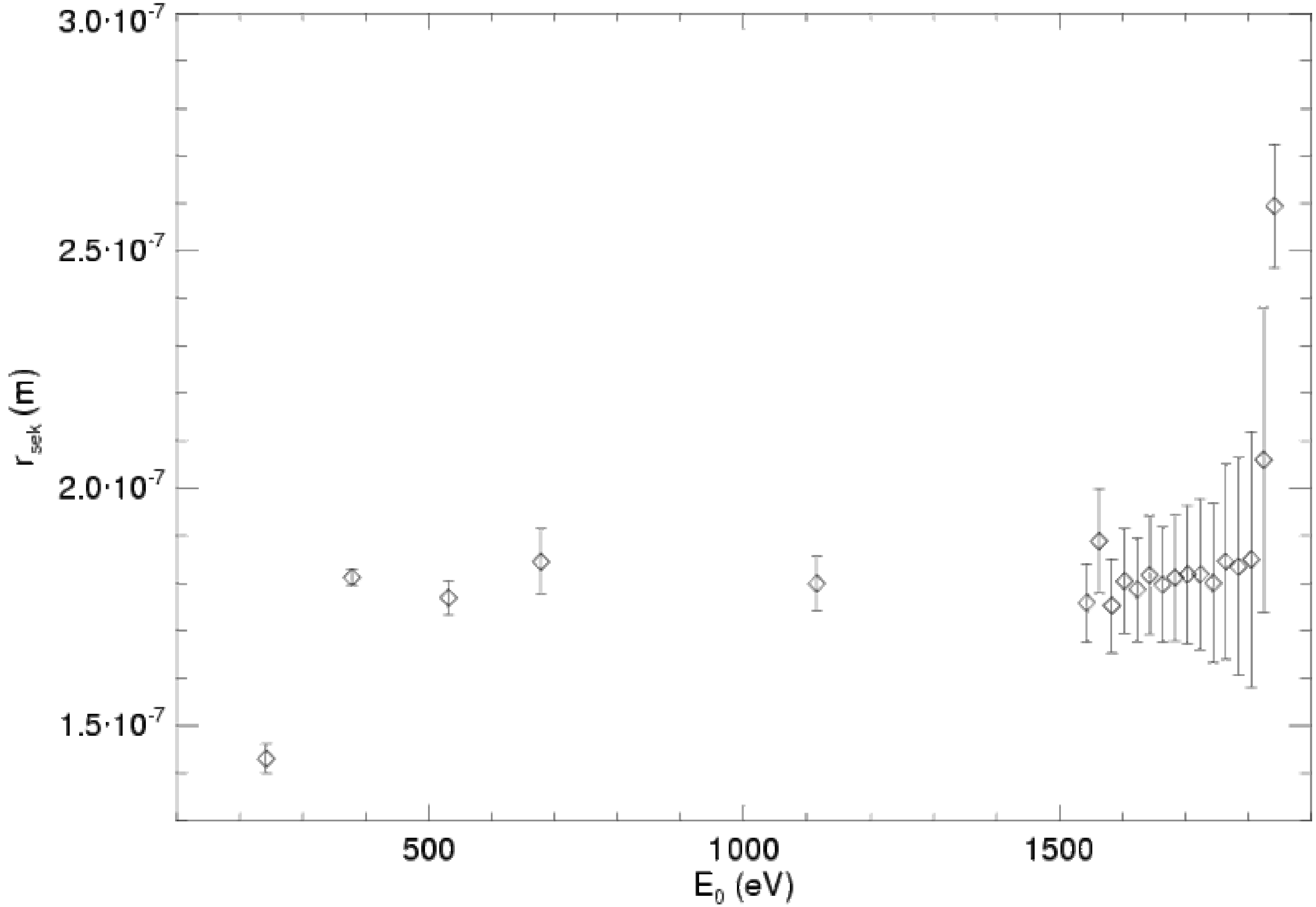
243 eV
379 eV
532 eV
678 eV
dN/dE (1/eV)
E (eV)
0
2000
4000
6000
200
400
600
800
10^2
10^3
10^4
10^5
1
10
100
1000
10000
Si
Al


1116 eV
dN/dE (1/eV)
10000
1000
100
10
1
0
500
1000
1500
E (eV)
1116 eV
dN/dE (1/eV)
10000
1000
100
10
1
0
500
1000
1500
E (eV)
1543 eV
dN/dE (1/eV)
10^5
10^4
10^3
10^2
10^1
0
500
1000
1500
E (eV)
1553 eV
dN/dE (1/eV)
10^5
10^4
10^3
10^2
10^1
0
500
1000
1500
E (eV)

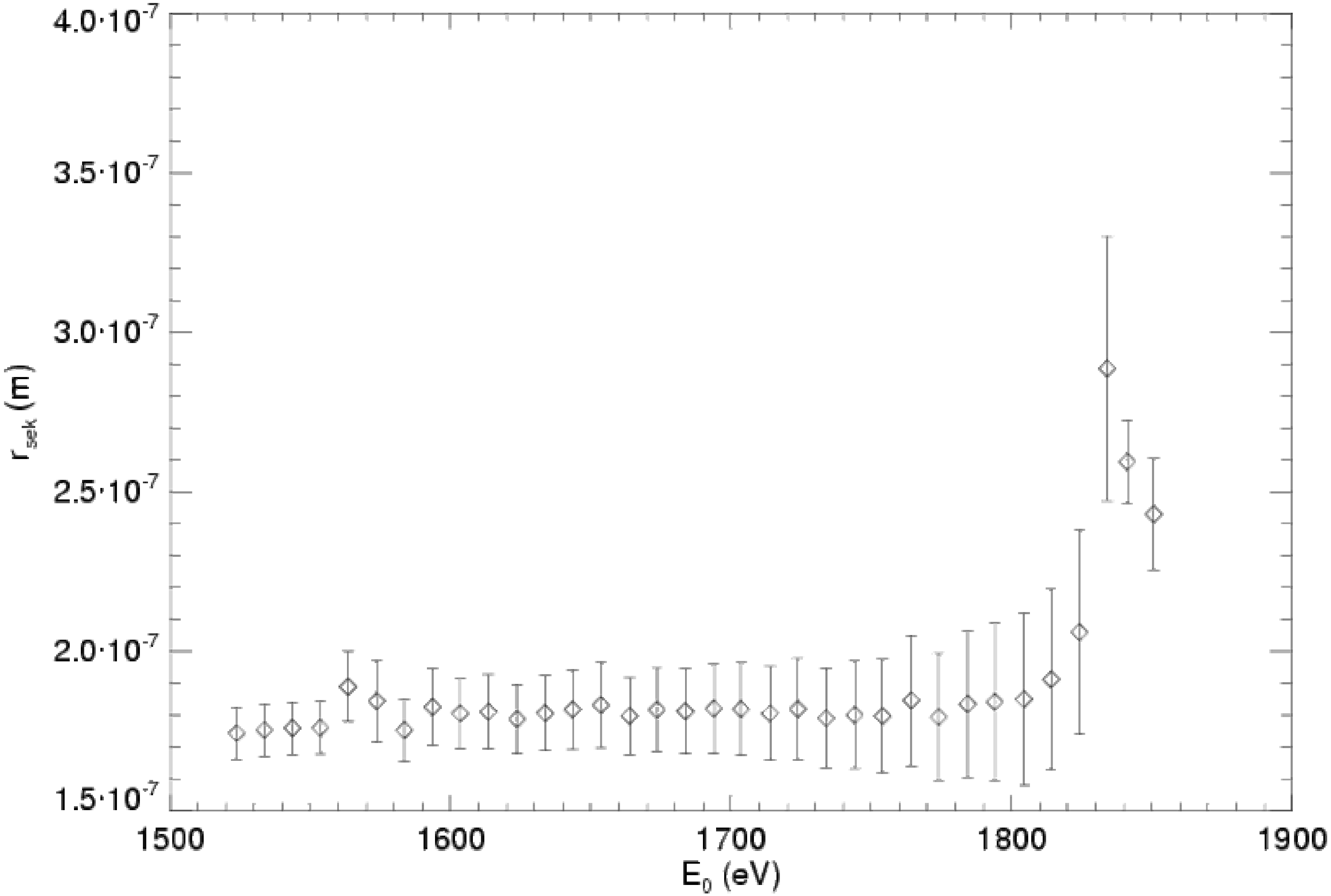


1574 eV
1654 eV
1754 eV
1834 eV
dN/dE (1/eV)
E (eV)

Radii of Secondary Electron Charge Clouds

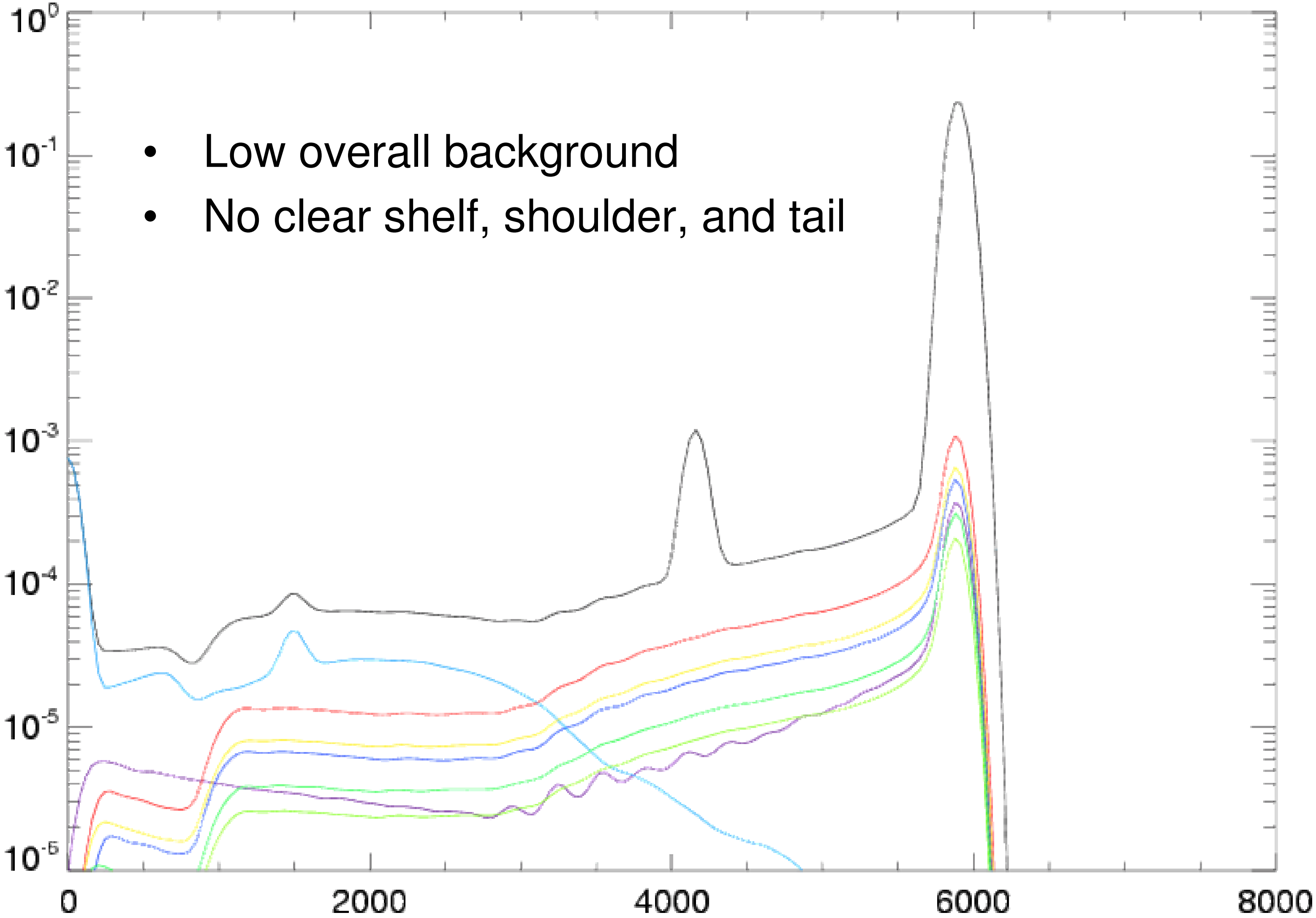


Radii of Secondary Electron Charge Clouds



^{55}Mn K_α 5.9 keV-Spectrum

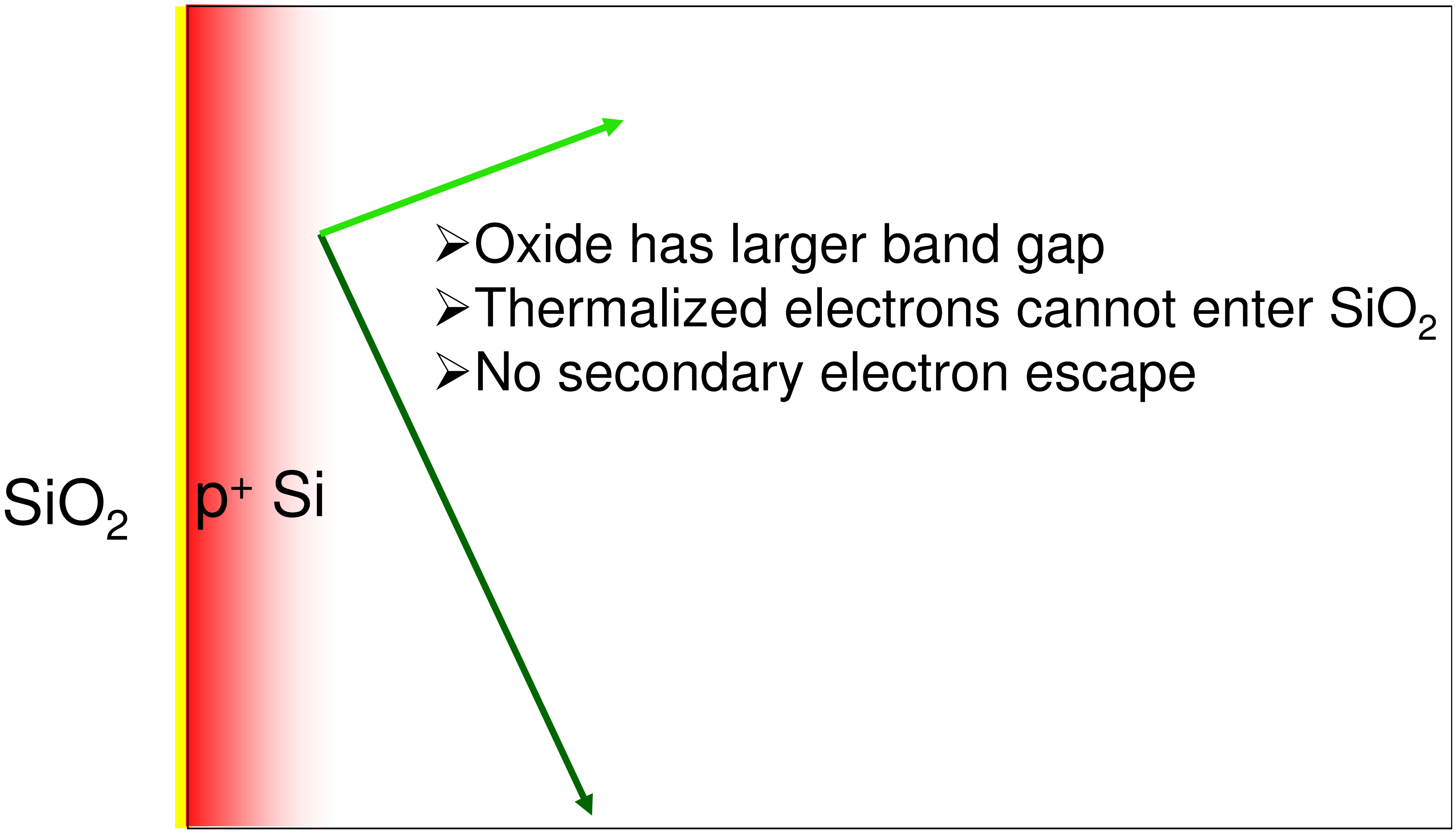
- Low overall background
- No clear shelf, shoulder, and tail



Results

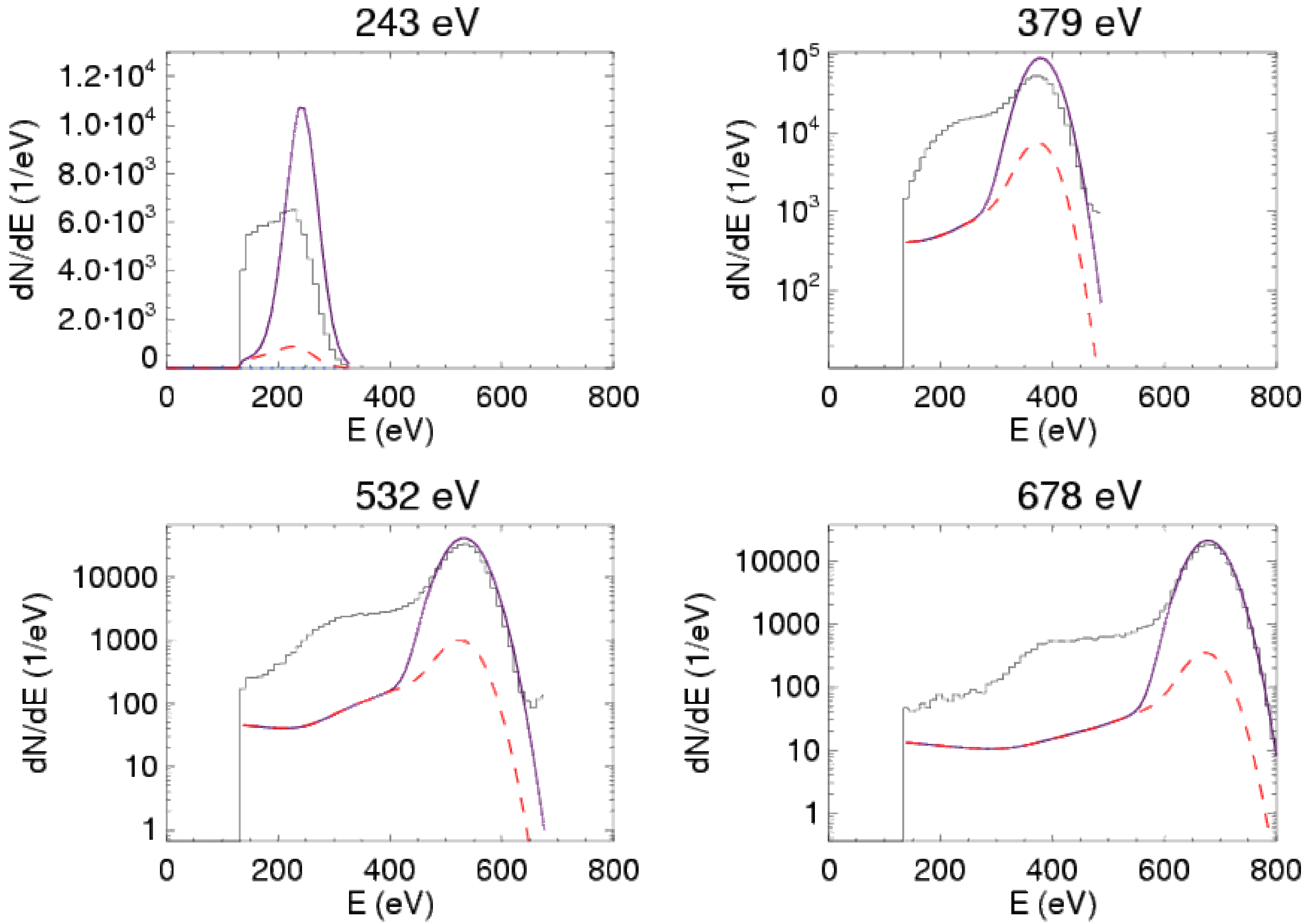
- Good agreement between measurements and calculated spectra
- Shelf and shoulder not calculated separately
- Distinction between layer, where ICC always occurs and layer, where ICC is possible
- Background dominated by secondary electron cloud with $r = (180 \pm 10)$ nm
- Thinner aluminum has only little effect

Proposed Configuration of Entrance Window



- Oxide has larger band gap
- Thermalized electrons cannot enter SiO_2
- No secondary electron escape

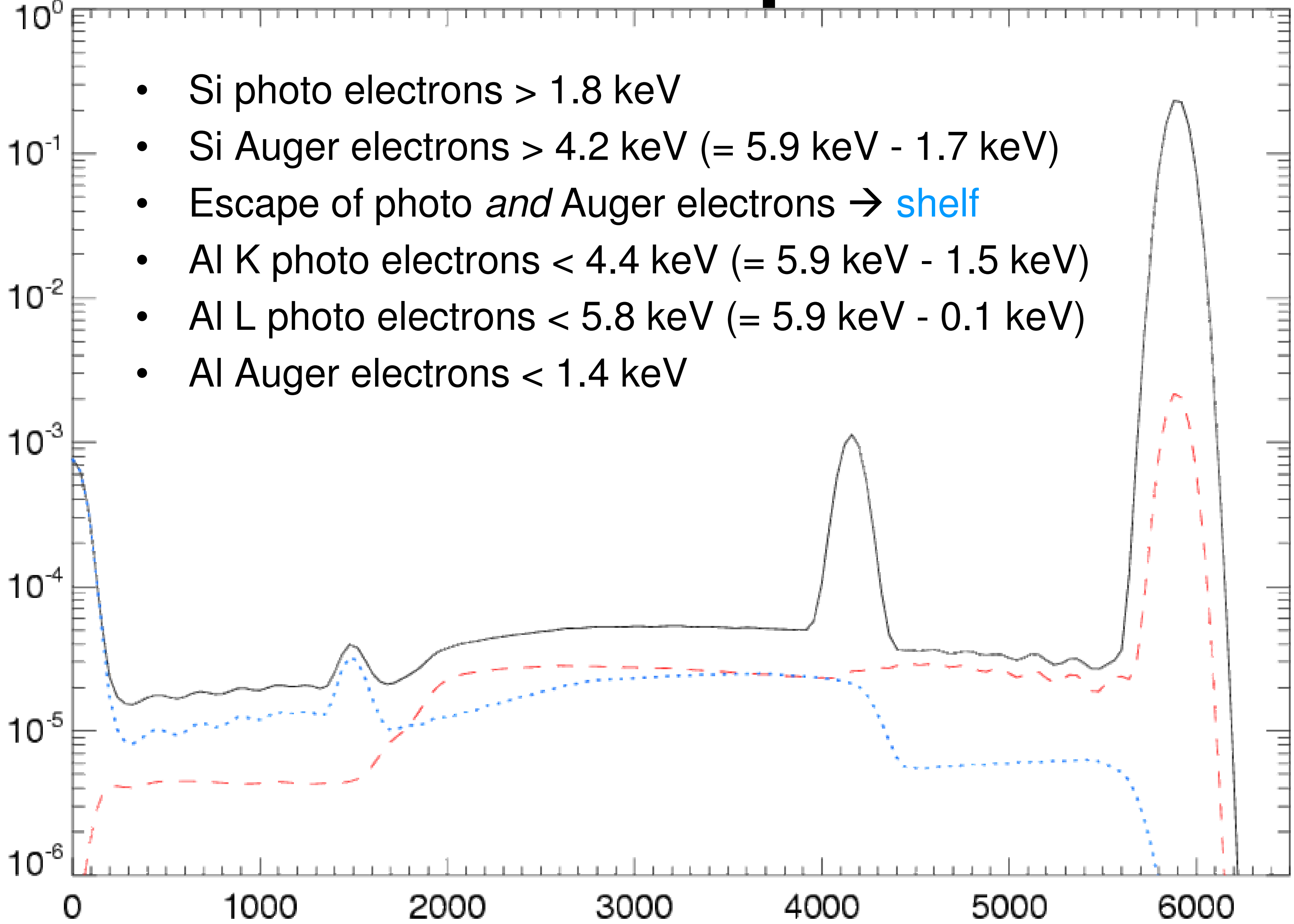
Expected Spectra



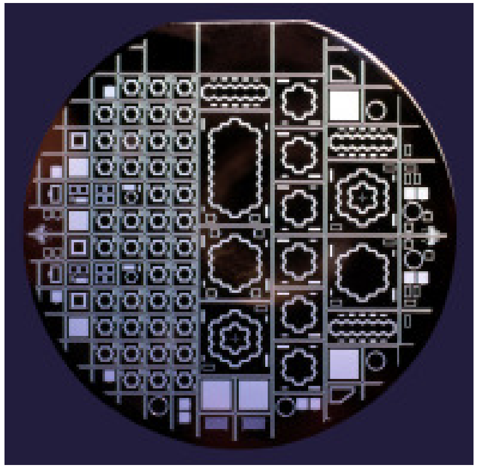
→ Much lower secondary electron background, no electrons from metallization

^{55}Mn 5.9 keV Spectrum

- Si photo electrons > 1.8 keV
- Si Auger electrons > 4.2 keV (= 5.9 keV - 1.7 keV)
- Escape of photo *and* Auger electrons → shelf
- Al K photo electrons < 4.4 keV (= 5.9 keV - 1.5 keV)
- Al L photo electrons < 5.8 keV (= 5.9 keV - 0.1 keV)
- Al Auger electrons < 1.4 keV



The Response of Energy Dispersive X-Ray Detectors



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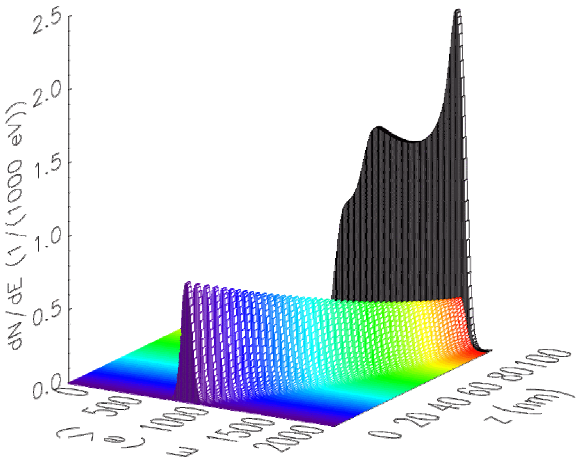

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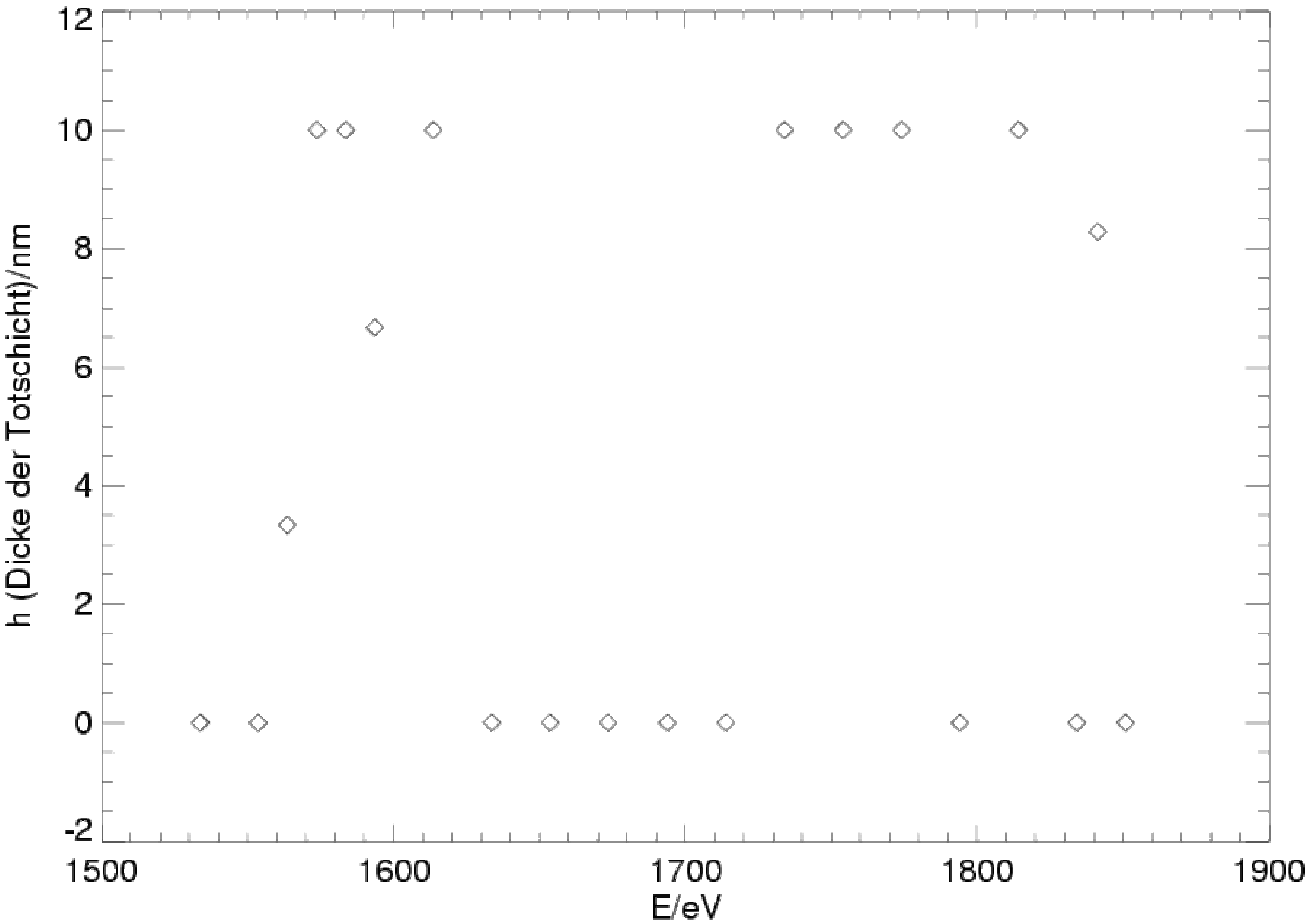
Resume

- Spectra with $E_0 <$ 300 eV deteriorated by background
- Model for background constructed
- Only one free parameter of the model
- Simulation successful → Responses of future devices can be predicted and are promising
- Model also suited for entrance window configurations of other detectors
- (no influence of p^+)
- More information: www.ketek.biz www.ketek.net

Dead layer thicknesses



Experiment

PGM beamline