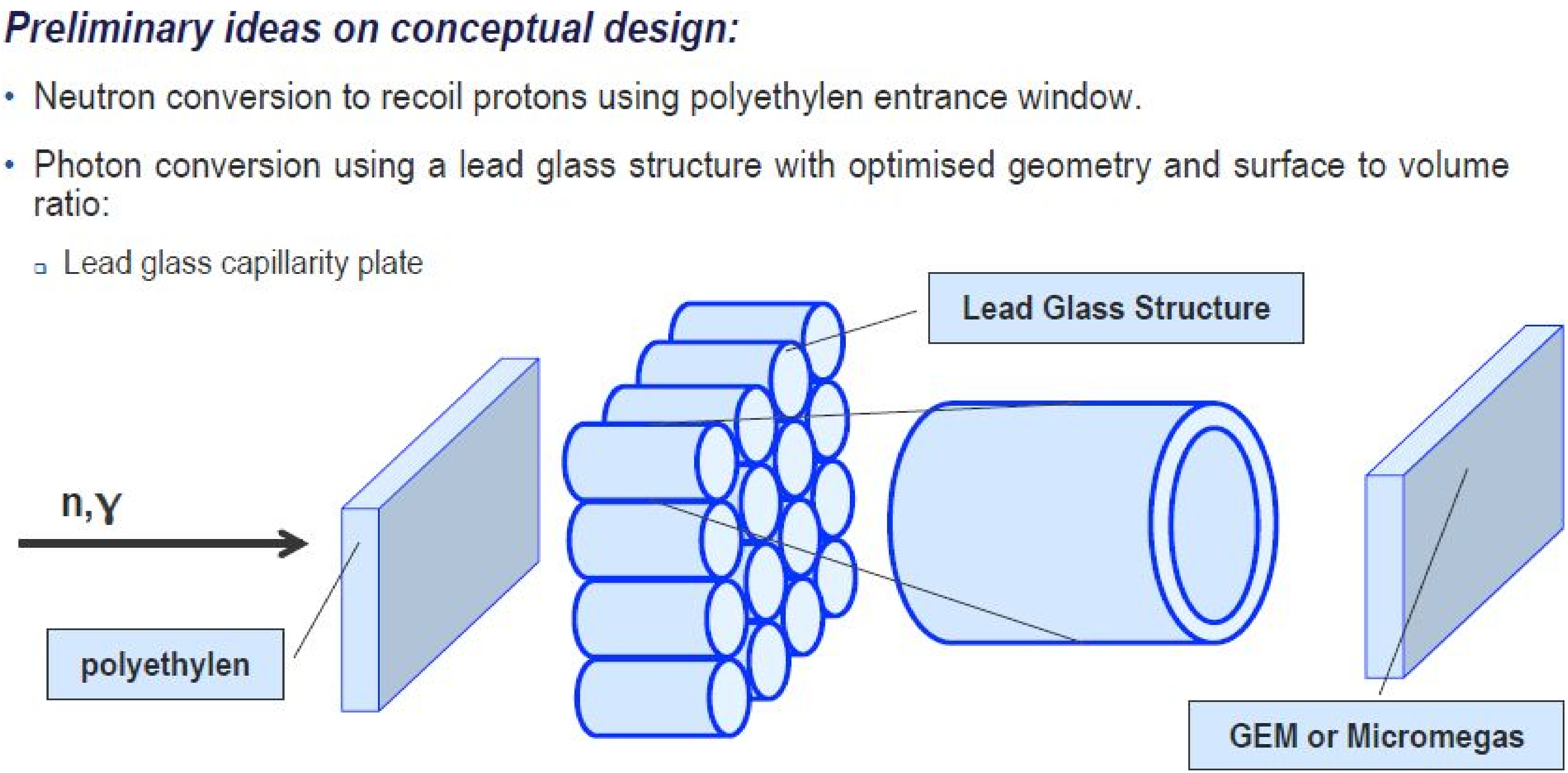
Cargo scanner

Detection mechanism

Sources of efficiency loss

Material requirements

The idea



Preliminary ideas on conceptual design:

- Neutron conversion to recoil protons using polyethylen entrance window.
- Photon conversion using a lead glass structure with optimised geometry and surface to volume ratio:
  - Lead glass capillarity plate

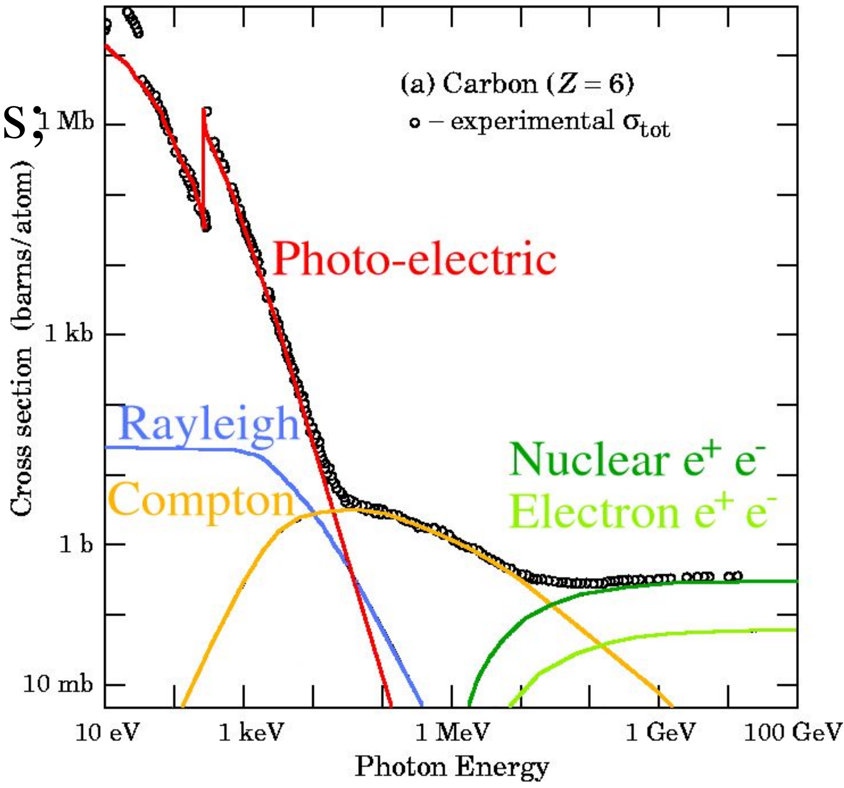
- More detail: Hartmut Hillemanns' presentation in WG1.

Photon detection

- Four-step process:
  - Compton scattering of the γ producing a recoil e^-, or e^+e^- production in the nuclear field;
  - e^- traverses the absorber and enters the gas;
  - transport of the e^- through the gas;
  - amplification and detection.
- Losses occur at all stages.

Interactions of photons

- Photons interact via:
  - $\epsilon_\gamma <$ few eV: molecular interactions;
  - $\epsilon_\gamma < 1$ MeV: photo-electric effect;
  - $\epsilon_\gamma < 1$ MeV: Rayleigh scattering;
  - $\epsilon_\gamma \sim 1$ MeV: Compton scattering;
  - $\epsilon_\gamma > 1$ MeV: pair production;
  - $\epsilon_\gamma > 1$ MeV: nuclear interactions.



[Adapted from the PDG, 2004 edition]

Cross section terms

- At $\epsilon_\gamma = 3$ MeV, Compton scattering dominates.
- At higher ϵ_γ and high Z, pair production in the nuclear field takes over.
- The photo-electric effect is a smaller contribution at lower γ energy, which matters mainly for secondary γ's.

Compton cross section – Klein Nishina

- Total cross section:

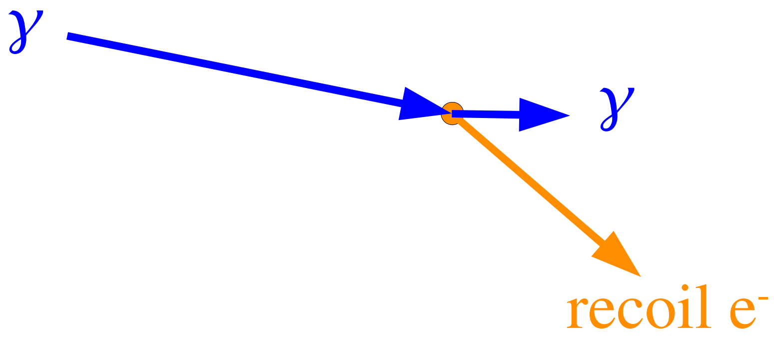
$$2\pi\left(\frac{q_e^2}{4\pi\epsilon_0 m_e c^2}\right)^2\left(\frac{1+a}{a^2}\left(2\frac{1+a}{1+2a}-\frac{\log(1+2a)}{a}\right)+\frac{\log(1+2a)}{2a}-\frac{1+3a}{(1+2a)^2}\right)$$

- where:

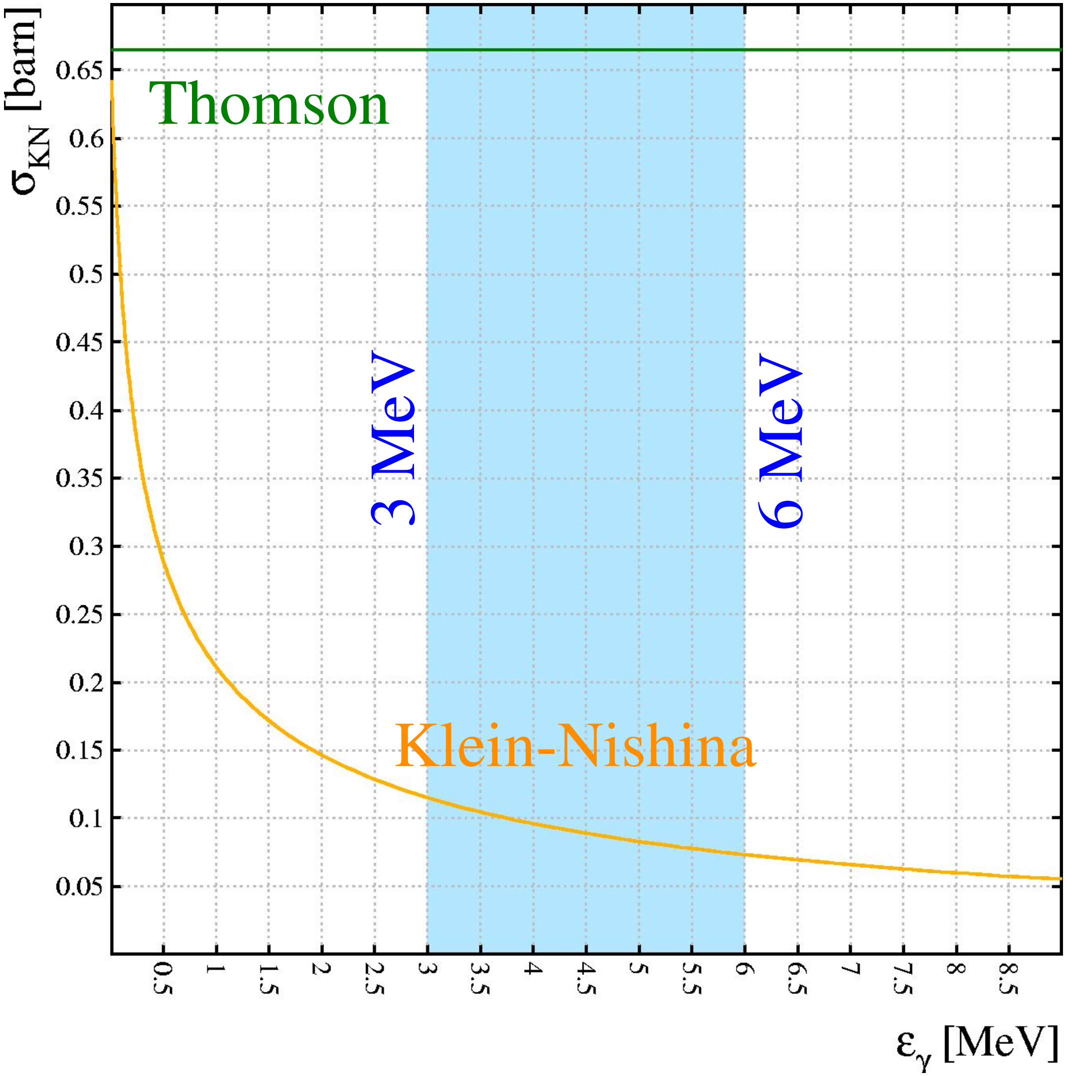
$$a=\epsilon_\gamma/m_e$$

Compton scattering cross section

- Scattering of a γ on a quasi-free e^-:



- Cross section at scanner energies: $\sigma \sim 0.1$ barn/e^-



Compton mean free path

- Try to estimate the mean free path λ via the e^- density:

  n [e^-/cm^3] = Z [e^-/atom] × N_0 [atoms/mol] × ρ [g/cm^3] ÷ A [g/mol]

- Which gives as Compton mean free path for Pb:

  $n = 82 \times 6.022\ 10^{23}$ atoms/mol $\times\ 11.34$ g/cm^3 $\div\ 207.2$ g/mol

  $= 2.70\ 10^{24}$ e^-/cm^3

  $\lambda = 1/(\sigma\, n)$

  $= 4.5$ cm [$\sigma_{KN} = 0.083$ barn at $\epsilon_\gamma = 5$ MeV]

- The mean free path for $\epsilon_\gamma = 5$ MeV is:

  $\lambda = 2.1$ cm ! [NIST calculation]

- Pair-production (and the photo-electric effect) can not be neglected, nor can corrections for the atomic structure.

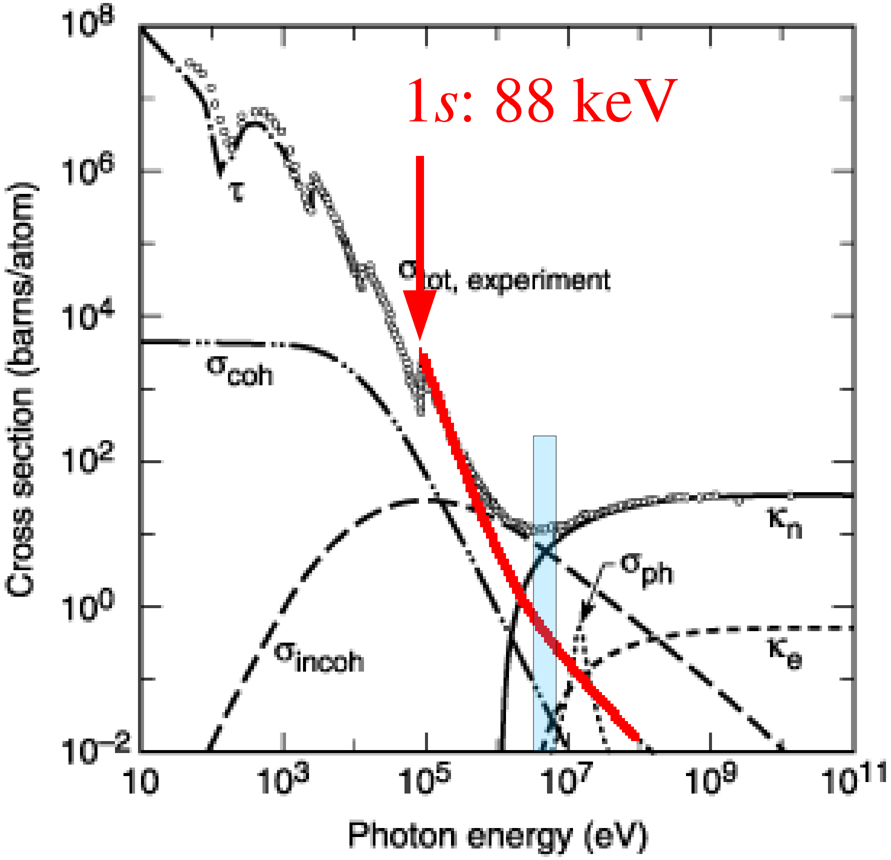
e^+e^- Pair-production

- Nuclear field pair-production dominates the γ cross section at $\epsilon_\gamma = 6$ MeV in high Z materials.

- Either the e^+ or the e^- will have an energy in excess of $\epsilon_\gamma / 2 =$ 1.5-3 MeV.

Photo-electric effect

- For Pb, the highest *Z* element to be plausibly used in this project, the photo-electric effect plays a role mainly for secondary interactions.



1*s*: 88 keV

[Graph from LBL]

γ-Mean free path in some materials

- As provided by NIST:

	λ 3 MeV [cm]	λ 4 MeV [cm]	λ 5 MeV [cm]	λ 6 MeV [cm]	Density [g/cm^3]	*Z/A* [-]
W	1.27	1.28	1.26	1.23	19.30	0.403
Pb	2.08	2.10	2.06	2.01	11.34	0.396
Lead glass	3.94	4.08	4.10	4.06	6.22	0.421
Pyrex	12.40	14.30	15.80	17.00	2.23	0.497
PET	19.50	22.80	25.60	28.10	1.38	0.520
Bakelite	21.30	24.90	28.00	30.80	1.25	0.528

Required thickness

- For a 20-25 % scattering probability, one needs ~$\lambda/4$:
  - Pb: ~ 5 mm,
  - W: ~ 3 mm, pure, more for typical alloys
  - Lead glass: ~ 1 cm, more for less dense glasses
  - PET: ~ 6 cm.

- The ideal Compton absorber has:
  - high density,
  - high Z/A.

Compton recoil electron properties

- At ϵ_{γ} = 3-6 MeV,
  - recoil e^- goes forward;
  - ϵ_e peaks just below ϵ_{γ}.

- This is independent of the absorber.

Klein Nishina formulae (cont'd)

- Electron energy distribution

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\epsilon_e}=\frac{\pi r_e^2}{a\epsilon_\gamma}\left(2-\frac{2\epsilon_e}{a(\epsilon_\gamma-\epsilon_e)}+\frac{\epsilon_e^2}{a^2(\epsilon_\gamma-\epsilon_e)^2}+\frac{\epsilon_e^2}{\epsilon_\gamma(\epsilon_\gamma-\epsilon_e)}\right)$$

- γ-Angular distribution: $p=\nu'/\nu=1/(1+a(1-\cos(\theta_\gamma)))$

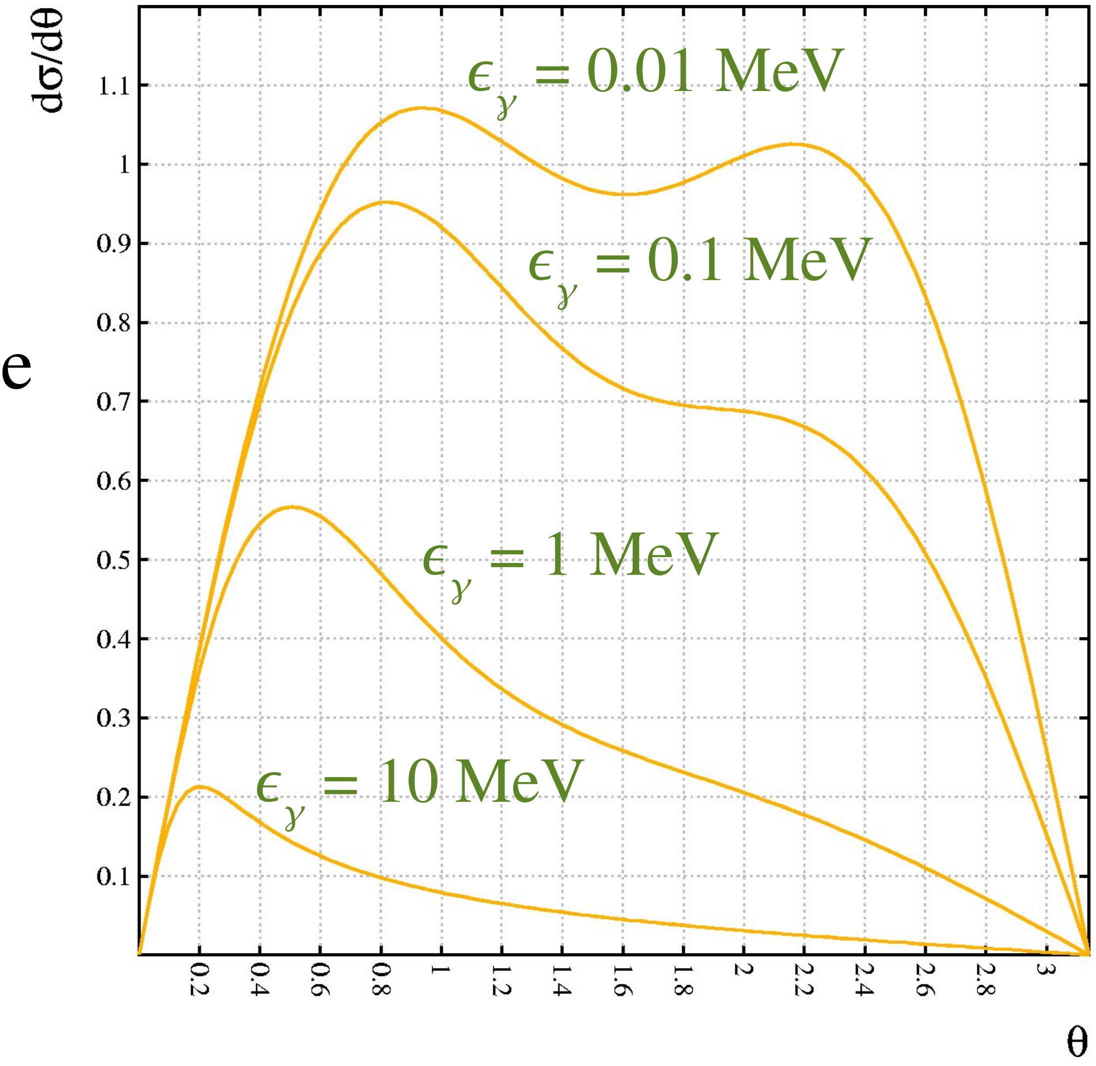
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\theta_\gamma}\propto p^2\left(p+\frac{1}{p}-\sin(\theta_\gamma)^2\right)\sin(\theta_\gamma)$$

- e$^-$-Angular distribution:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\theta_e}=\frac{\mathrm{d}\sigma}{\mathrm{d}\theta_\gamma}\frac{(1+a)\sin^2(\theta_\gamma/2)}{\cos^2(\theta_e)}$$

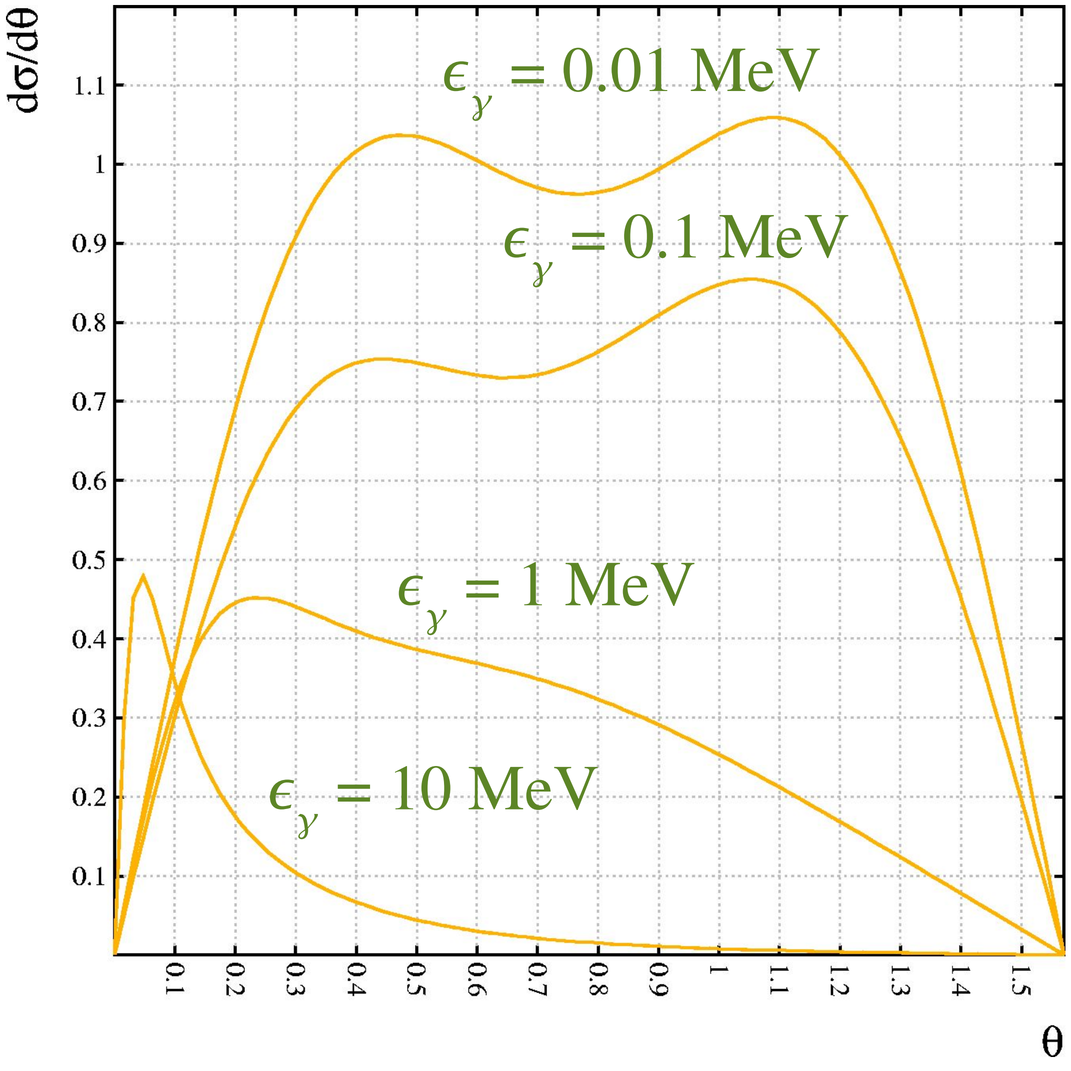
Compton photon deflection angle

- When ϵ_γ = 1-10 MeV, the γ is deflected little.
- This is independent of the absorber.



Compton recoil electron – direction

- Electrons of course only go forward.
- Distribution peaks even more forward than the γ at $\epsilon_\gamma > 1$ MeV.
- This is independent of the absorber.



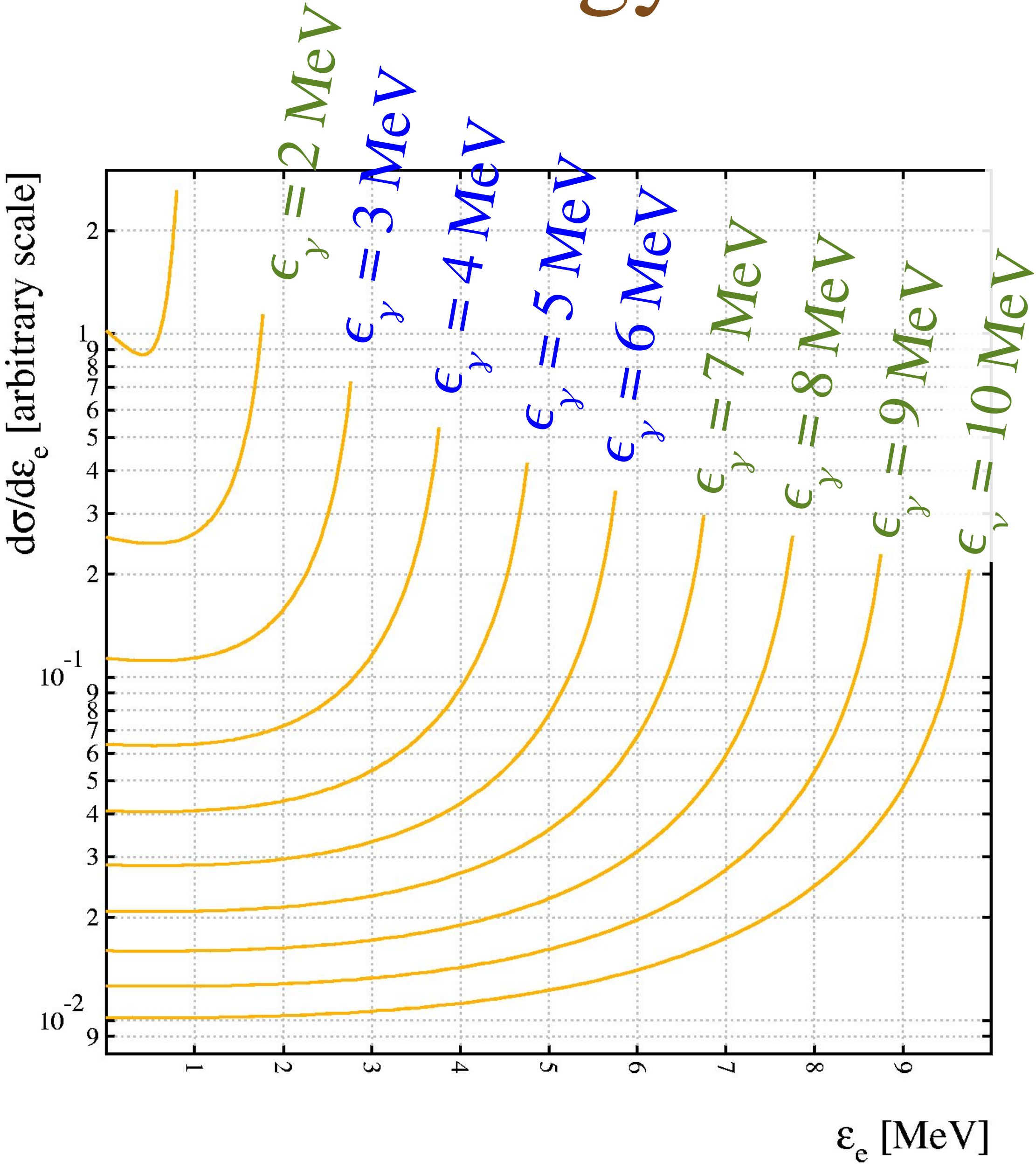
Compton recoil electron – energy

- The energy ϵ_e of the recoil e^- peaks at the kinematic maximum:

$$\epsilon_e^{max} = \epsilon_\gamma \frac{2a}{1+2a}$$

$$a = \epsilon_\gamma / m_e$$

- This is independent of the absorber.



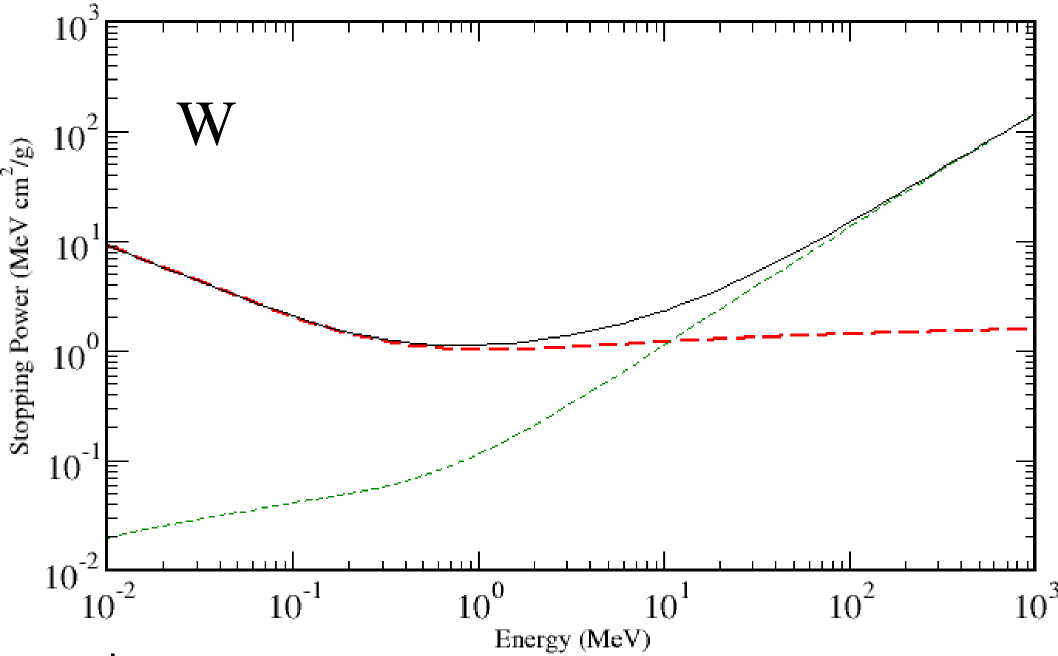
Energy loss of e^-

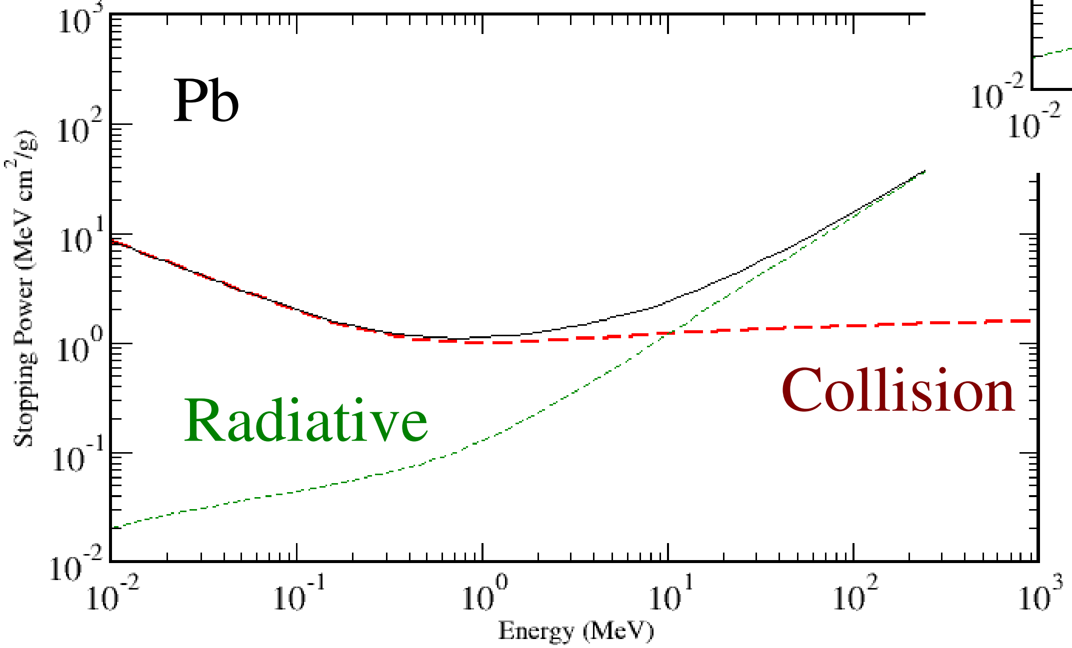
- Recoil and pair-production electrons have $\epsilon_e \sim$ a few MeV when produced and less when they enter the gas.

  - $\epsilon_e < E_{exc}$: elastic scattering, vibrations, rotations
    $E_{exc} \sim 11.5$ eV in Ar
  - $E_{exc} < \epsilon_e < E_c$: ionisation, excitation, attachment
    $E_c \sim 7$ MeV in Pb, $E_c \sim 40$ MeV in Ar
  - $E_c < \epsilon_e$: Bremsstrahlung

e⁻ Stopping power and range – NIST

- Collision stopping power: Average energy loss per unit path length, due to inelastic Coulomb collisions resulting in ionisation + excitation of atoms or molecules.



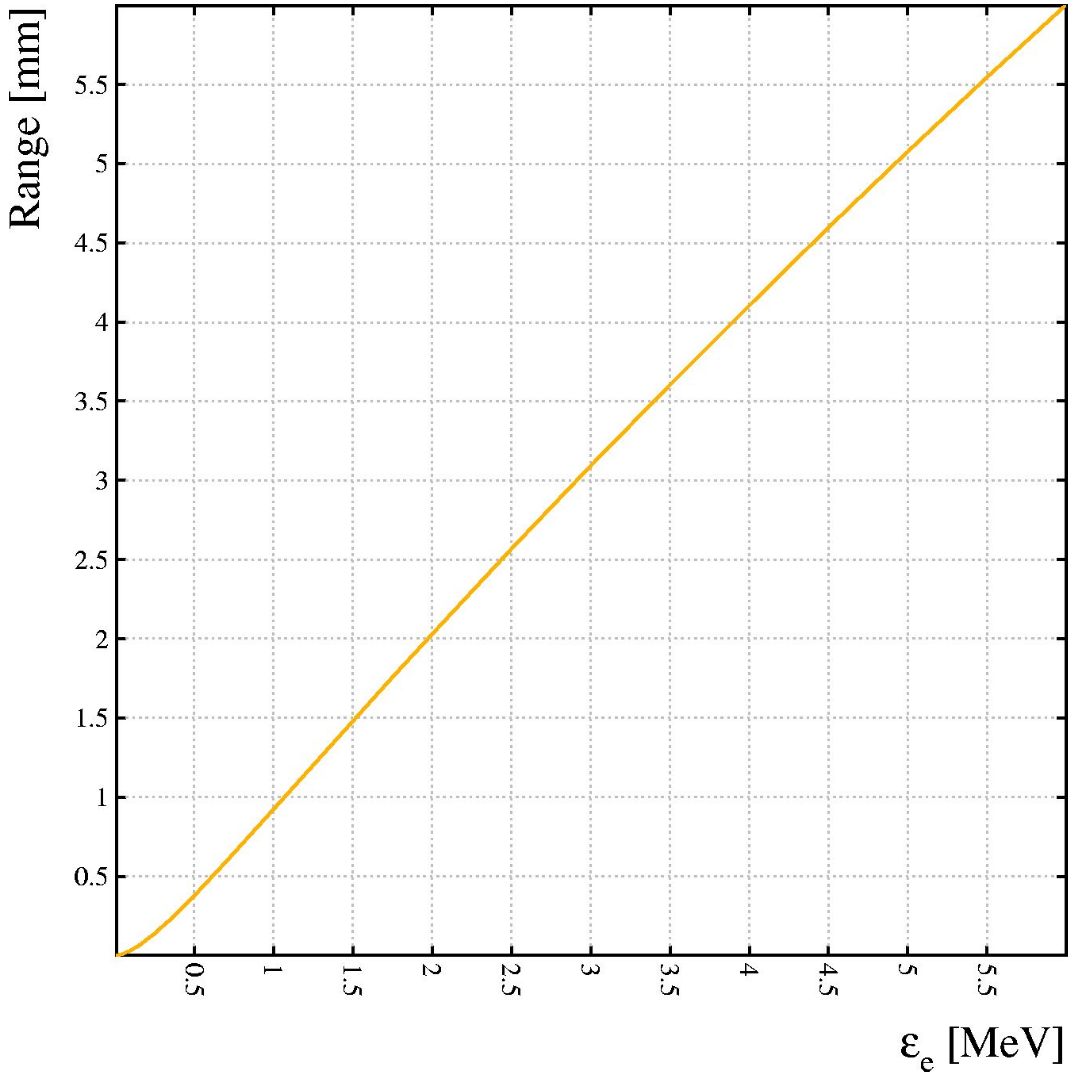


- CSDA range: Average path length travelled by a charged particle as it slows down to rest, calculated in the continuous-slowing-down approximation.

e^- Range in lead glass

- Assumes:
  - 25 % PbO, 75 % SiO_2,
  - $\rho = 6.22$ g/cm^3.

- Shown is the CSDA range calculated with ESTAR.



e^- Range in lead glass

- PbO (25 %) + SiO_2 (75 %) with density 6.22 g/cm^3:

Energy	Stopping power			Range	
	Collision	Radiation	Total	CSDA	
MeV	MeV cm^2/g	MeV cm^2/g	MeV cm^2/g	g/cm^2	mm
0.100	3.043	0.0152	3.058	0.020	0.03
1.000	1.395	0.0440	1.439	0.574	0.92
2.000	1.395	0.0828	1.478	1.263	2.03
3.000	1.424	0.1256	1.550	1.924	3.09
4.000	1.451	0.1711	1.622	2.554	4.11
5.000	1.474	0.2183	1.692	3.158	5.08
6.000	1.493	0.2669	1.760	3.737	6.01

- Catching electrons below 1 MeV is a challenge.

e^- Range in pure Pb and W

- Pb

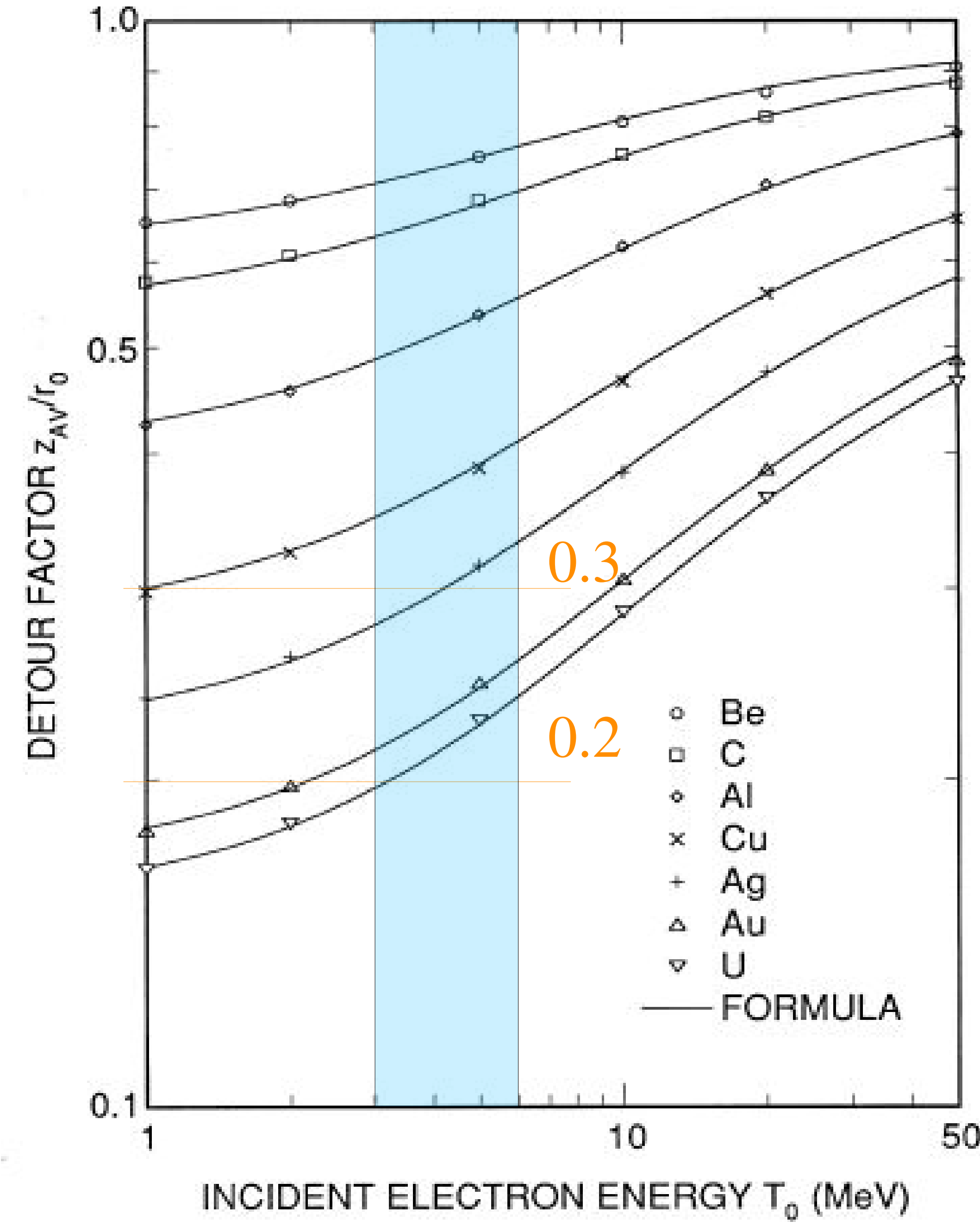
Energy	Stopping power			Range	
	Collision	Radiation	Total	CSDA	
MeV	MeV cm^2/g	MeV cm^2/g	MeV cm^2/g	g/cm^2	mm
3.000	1.063	0.3427	1.406	2.381	2.10
4.000	1.095	0.4582	1.553	3.057	2.70
5.000	1.120	0.5773	1.698	3.673	3.24
6.000	1.142	0.6991	1.841	4.239	3.74

- W

Energy	Stopping power			Range	
	Collision	Radiation	Total	CSDA	
MeV	MeV cm^2/g	MeV cm^2/g	MeV cm^2/g	g/cm^2	mm
3.000	1.072	0.3158	1.388	2.372	1.23
4.000	1.101	0.4248	1.526	3.059	1.59
5.000	1.126	0.5372	1.663	3.687	1.92
6.000	1.146	0.6523	1.798	4.265	2.22

Detour factor

- The projected distance covered by the electrons is smaller than the CSDA range by the *detour factor*.
- For heavy materials, the factor seems to be ~ 0.25.



[Tatsuo Tabata and Pedro Andreo, 10.1016/S0969-806X(98)00184-4]

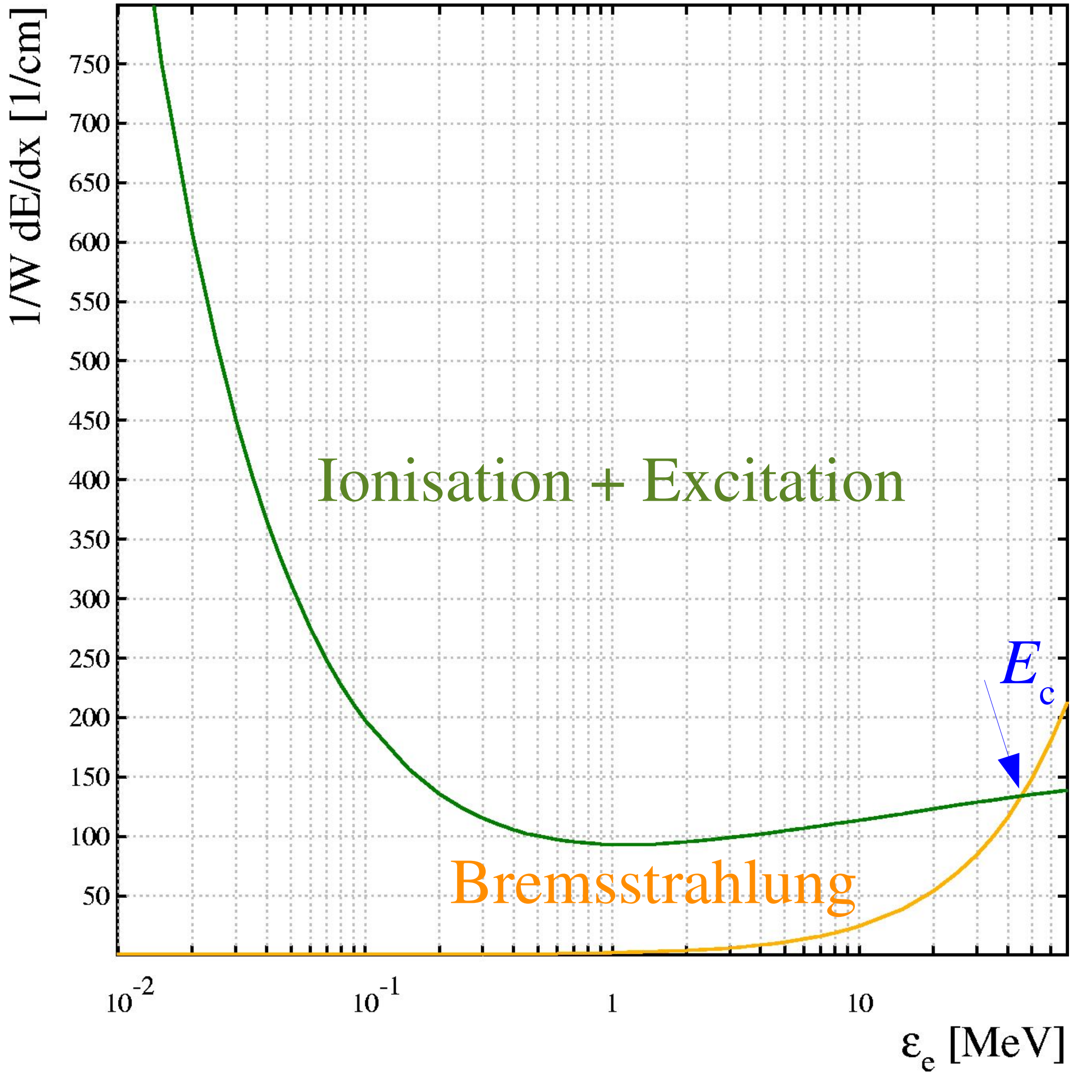
Required granularity

- The precise projected range remains to be worked out. Assuming a detour factor of 0.25 and a CSDA range of 4 mm (lead glass), absorber material more than 1 mm from a gas channel is likely to be inefficient.

- Higher density absorbers require finer granularity.

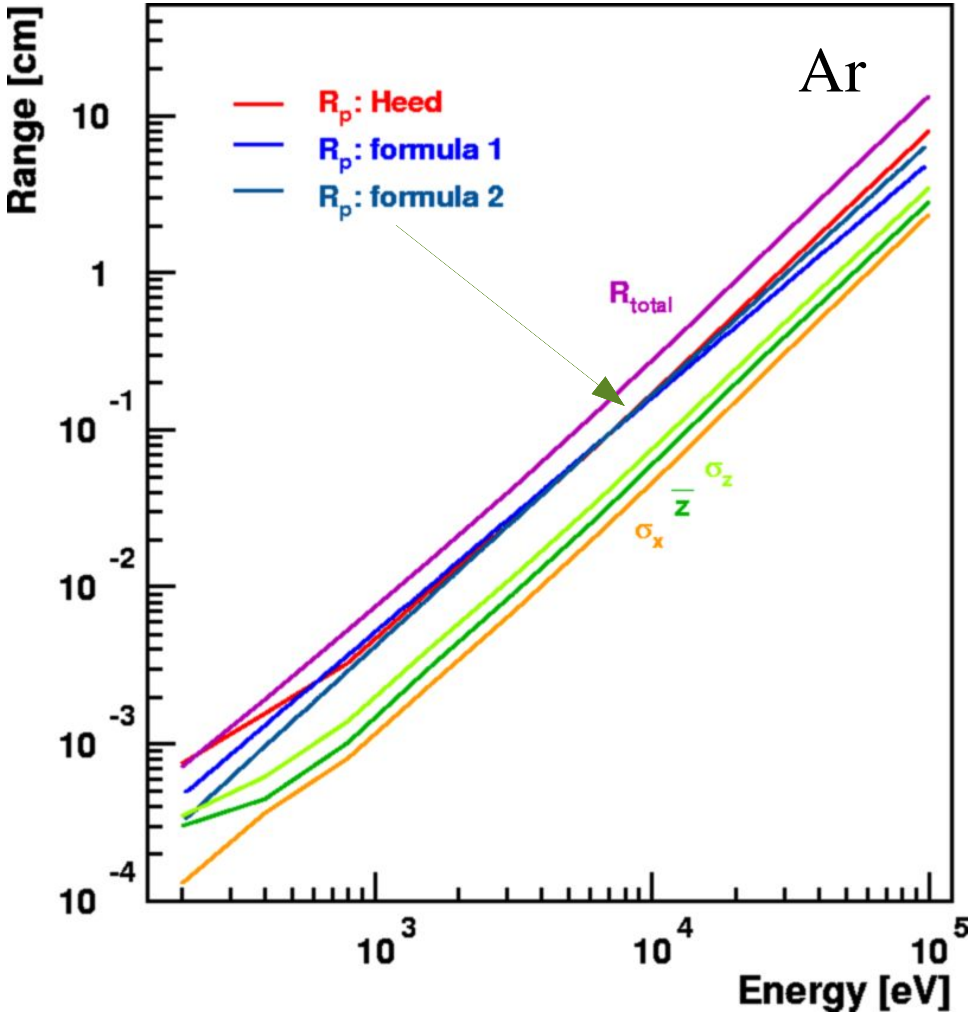
Energy loss of high-energy e^- in Ar

- Secondary e^- production is minimal at ϵ_e ~ 1 MeV with ~8 e^-/mm.
- At ϵ_e ~ 10 keV, an e^- is absorbed within 1 mm.
- Calculated with ESTAR.



Range of electrons in Ar

- Electrons scatter in a gas.
- Measures of the range:
  - R_{total}: total path length
  - R_{p} : practical range
  - $\bar{z}$: cog in direction of initial motion
  - σ_{z}: RMS in direction of initial motion
  - σ_{x}: RMS transverse to initial motion



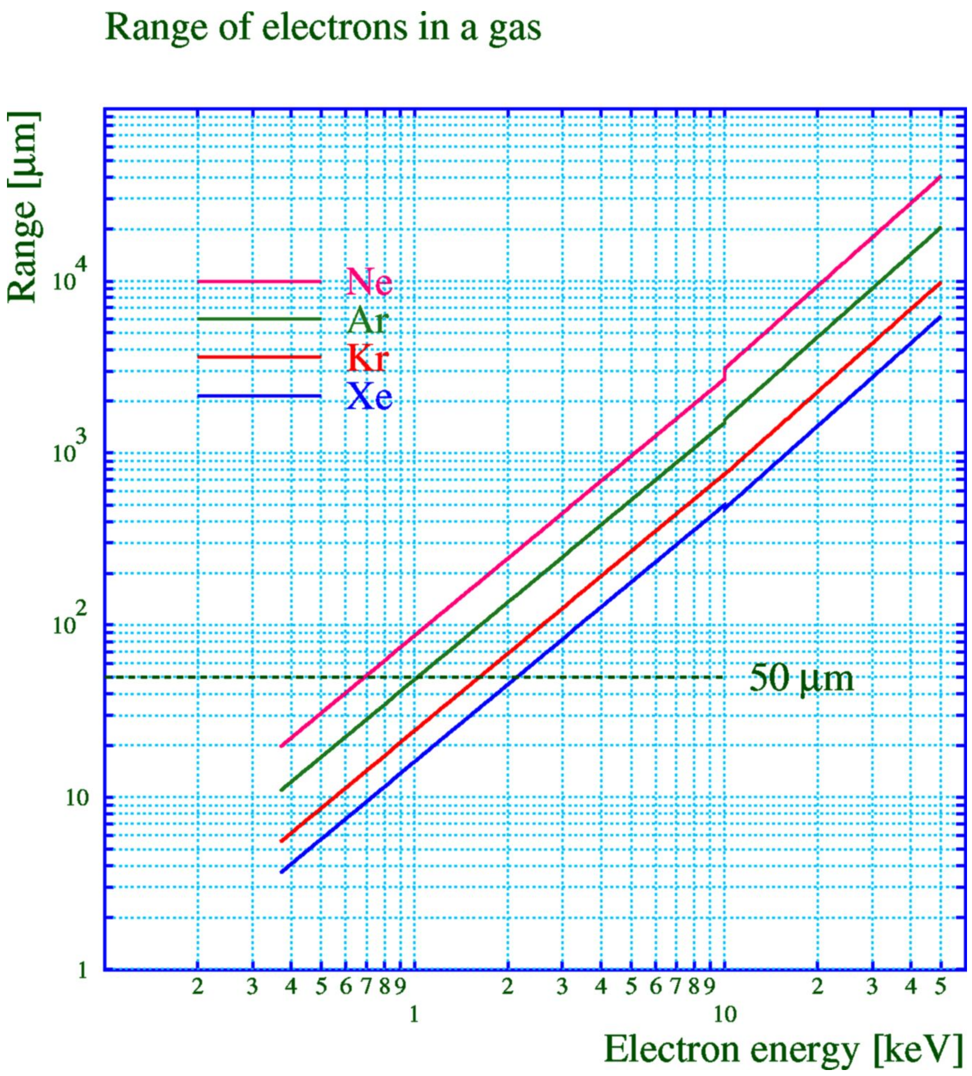
Practical range: distance at which the tangent through the inflection point of the descending portion of the depth- absorbed dose curve meets the extrapolation of the Bremsstrahlung background (ICRU report 35, 1984)

Range of electrons in noble gases

- The practical range
  - rises faster than linear with energy,
  - reciprocal in the density of the gas:

$$R_p = \begin{cases} 3.872\,10^{-3}\;\; A/Z\;\; E^{1.492}/\rho & (0.37\,\text{keV} < E < 10\,\text{keV}) \\ 6.97\,10^{-3}\;\; E^{1.6}/\rho & (10\,\text{keV} < E < 50\,\text{keV}) \end{cases}$$

Gas	A / Z	Density [g/l]
Ne	20.2 / 10	0.901
Ar	39.9 / 18	1.782
Kr	83.8 / 36	3.708


Range of electrons in a gas

[Formulae: L.P. Lapina *et al.*, PNPI preprint 2022 (1994)]

Electron transport

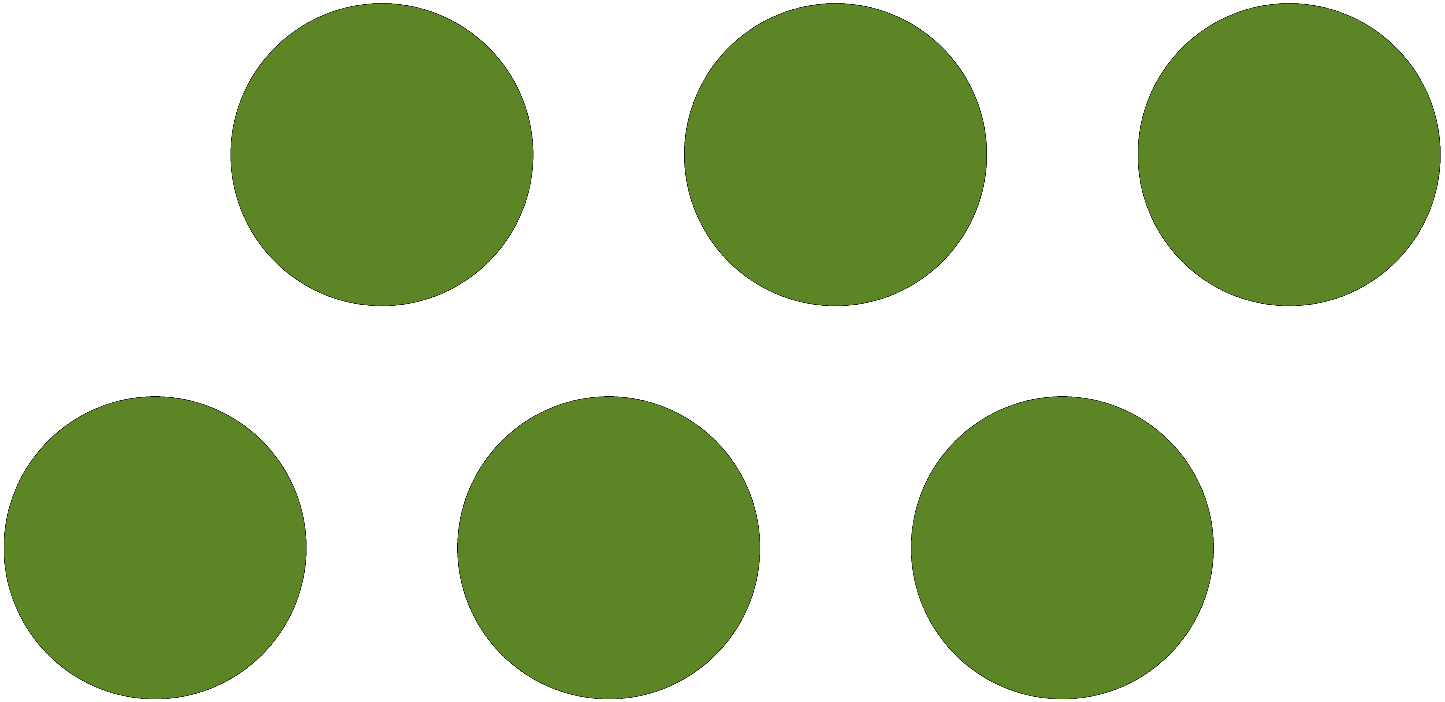
- Argon-based gases have σ_T ~ 250 µm for 1 cm of drift which for a channel of length *l* and radius *r* gives:

$$\text{losses} = e^{-\frac{r^2}{2 l \sigma_T^2}}$$

- E.g. with $r = 0.5$ mm and $l = 2$ cm, losses are 37 %, while they are 2 % for $r = 1$ mm.

Packing ratios

- Assuming $r = 1$ mm and 1 mm inter-hole distance, the absorber fraction would be 60 %.
- For 1 cm net absorber, one needs 1.6 cm overall thickness.



Summary

- Absorber:
  - Assuming a high-ρ lead glass, 25 % conversion efficiency requires > 1 cm of absorber (net).
- Gas channels:
  - in high-ρ lead glass, absorber material > 1 mm from a gas channel can go undetected;
  - channel diameter should be > 2 mm if length > 2 cm;
- Density scaling:
  - absorber thickness: $\propto \rho$,
  - channel diameter: $\propto \sqrt{\rho}$,
  - inter-channel gap: $\propto \rho$.