M. Strobl - Neutron Imaging & Activation Group :: Paul Scherrer Institut

Neutron Imaging - Principles

AUNIRA, TUM, Aug. 2017

markus.strobl@psi.ch

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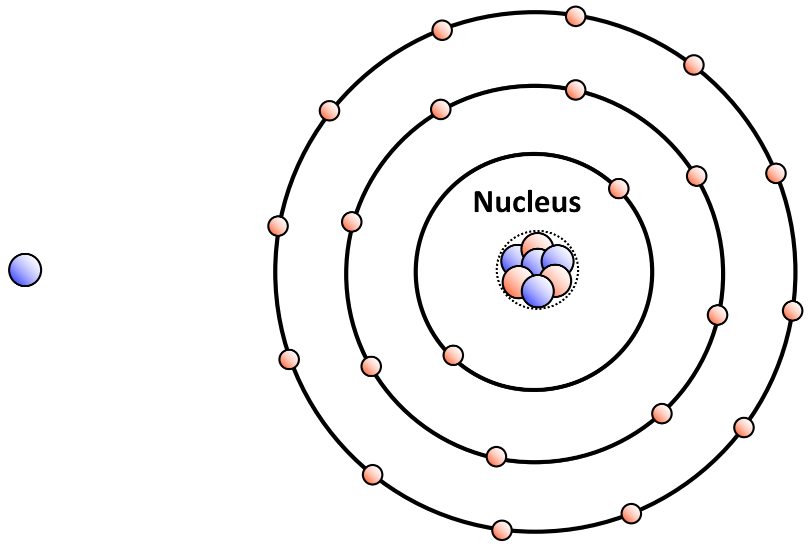
The Neutron

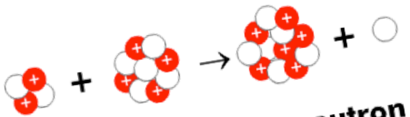


Classification	Baryon
Composition	1 up quark, 2 down quarks
Statistics	Fermionic
Interactions	Gravity, weak, strong, electromagnetic
Symbol	n, n^0, N^0
Antiparticle	Antineutron
Theorized	Ernest Rutherford[1] (1920)
Discovered	James Chadwick[2] (1932)
Mass	$1.674\,927\,471(21) \times 10^{-27}$ kg[3] 939.565 4133(58) MeV/c^2[3] 1.008 664 915 88(49) u[3]
Mean lifetime	881.5(15) s (free)
Electric charge	0 e $(-2 \pm 8) \times 10^{-22}$ e (experimental limits)[4]
Electric dipole moment	$< 2.9 \times 10^{-26}$ $e \cdot$cm (experimental upper limit)
Electric polarizability	$1.16(15) \times 10^{-3}$ fm^3
Magnetic moment	$-0.966\,236\,50(23) \times 10^{-26}$ J·T^{-1}[3] $-1.041\,875\,63(25) \times 10^{-3}$ μ_B[3] $-1.913\,042\,73(45)$ μ_N[3]
Magnetic polarizability	$3.7(20) \times 10^{-4}$ fm^3
Spin	$\frac{1}{2}$

Neutron Sources

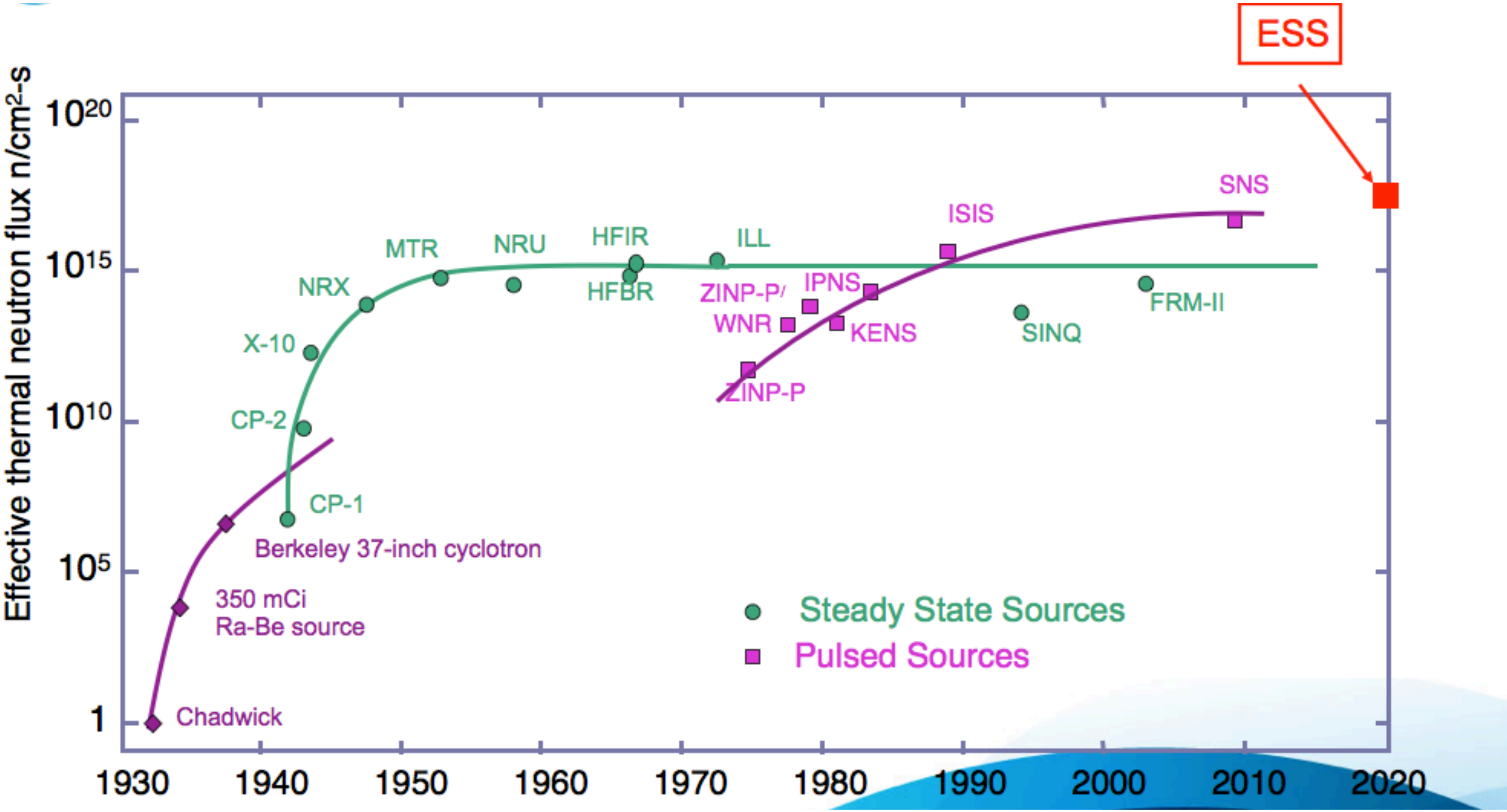
n

- Use Polonium as alpha emitter on Beryllium

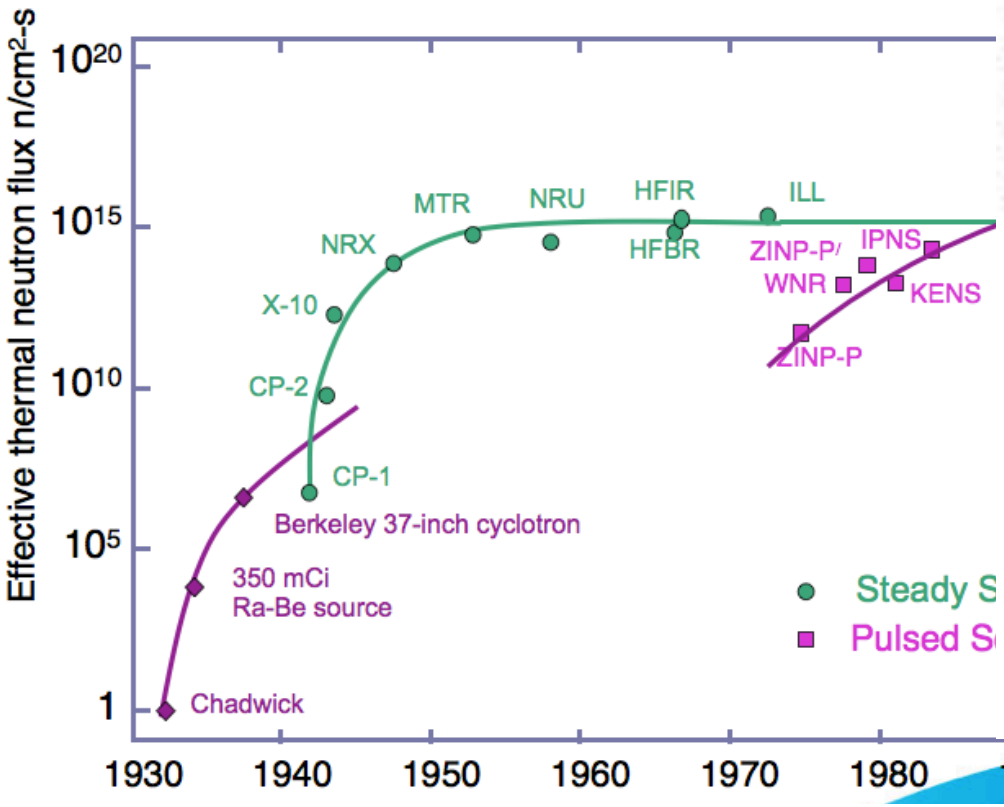


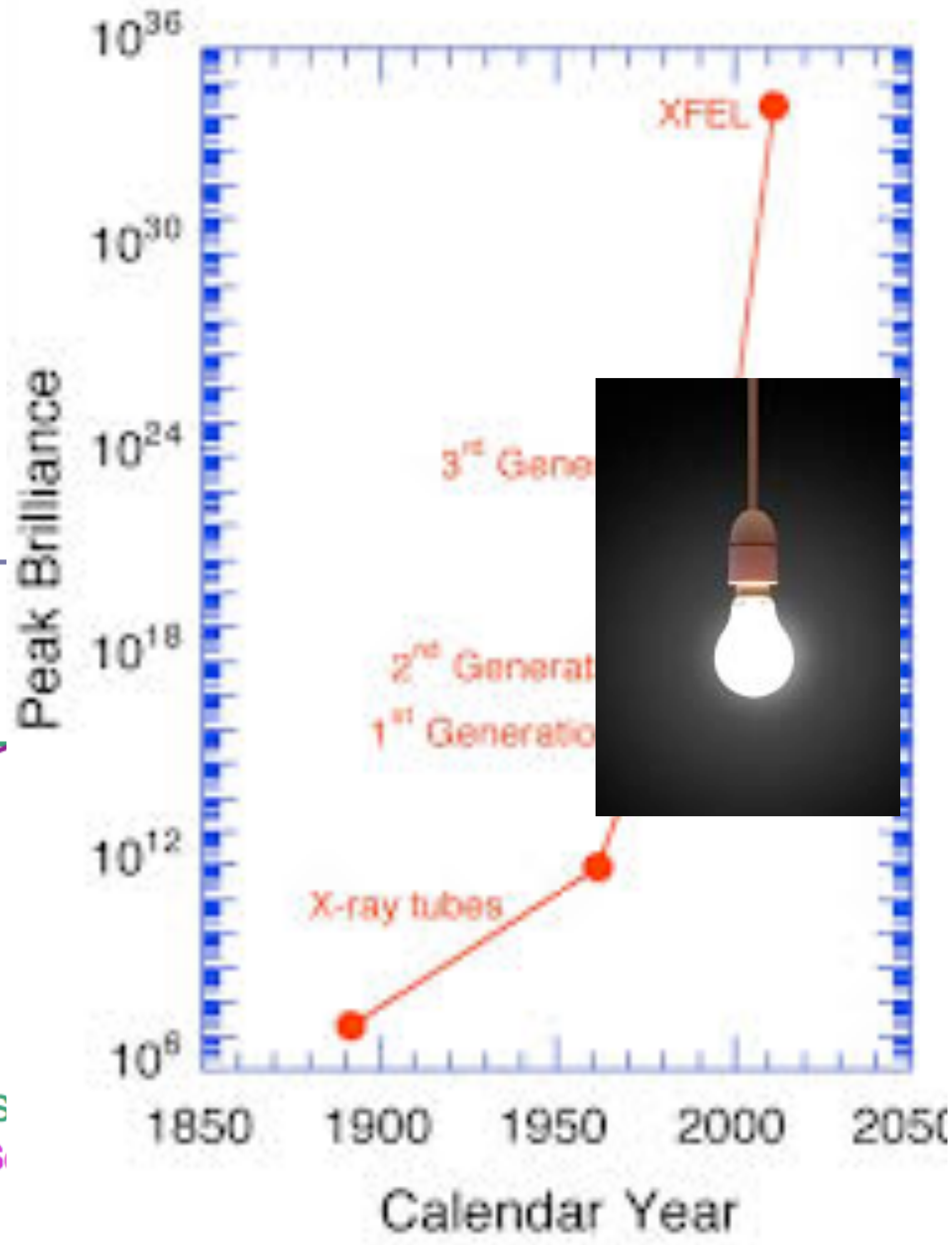
$^{4}He + ^{9}Be \rightarrow ^{12}C + \text{neutron}$

Neutron Sources



Neutron Sources





Fundamental for Imaging

- Spatial Resolution

    Geometry

    Detectors

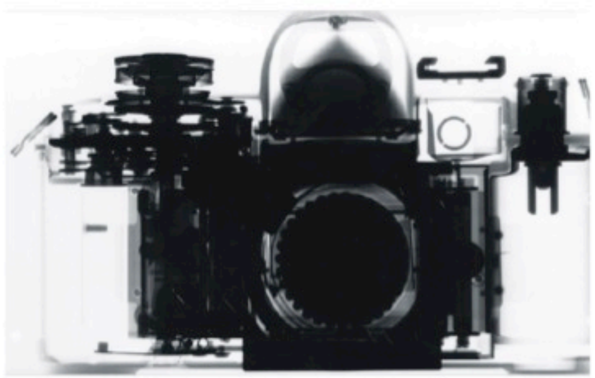
- Contrast

    Interactions

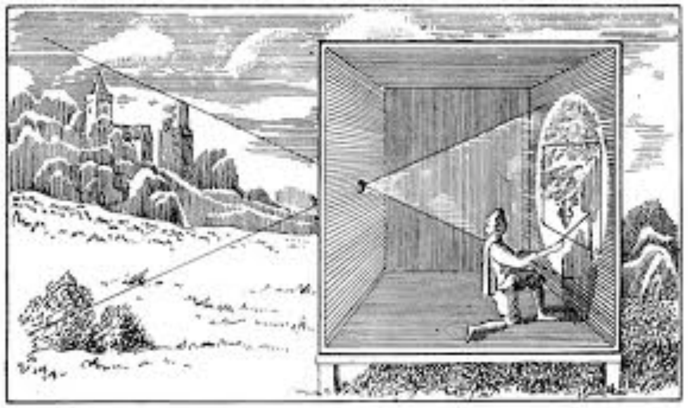
    Techniques

Imaging with Neutrons

No optics?

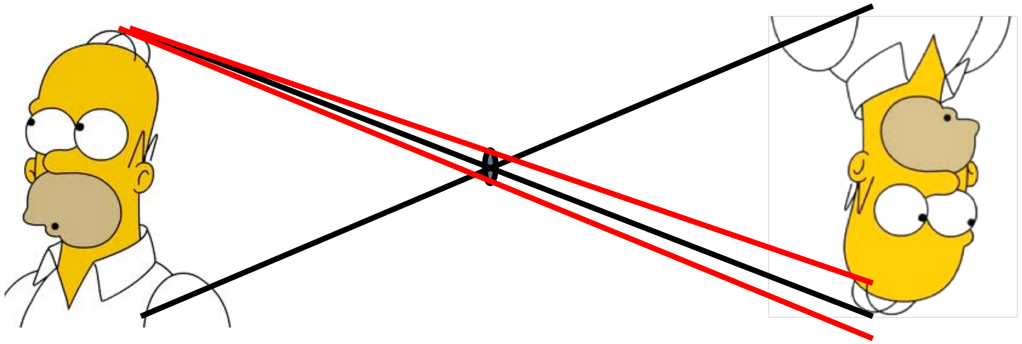


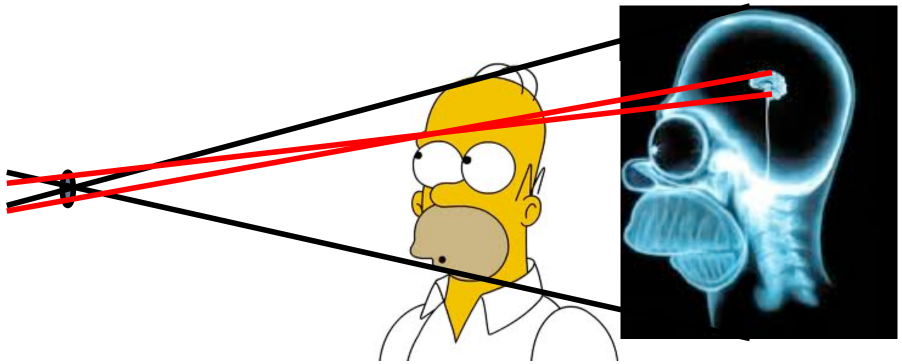
Spatial resolution



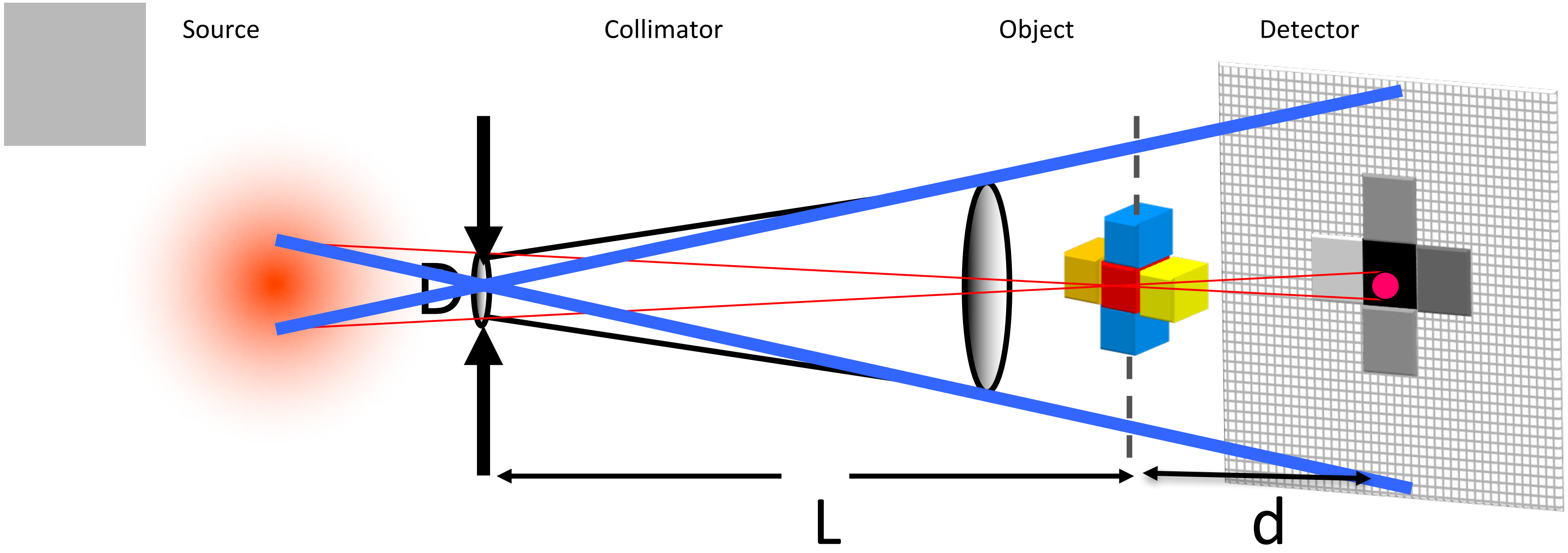
Camera obscura

No optics





Spatial resolution

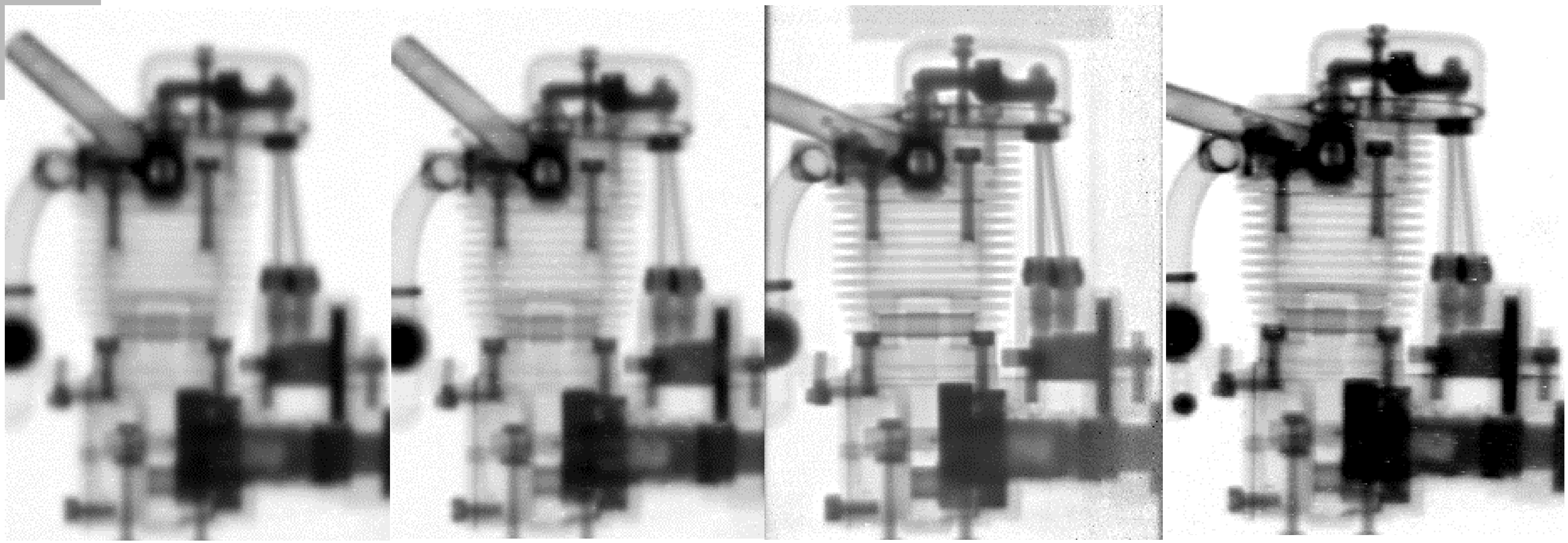


blur
collimation ratio

$$b = \frac{d}{L/D}$$

typical: several 100

Spatial resolution

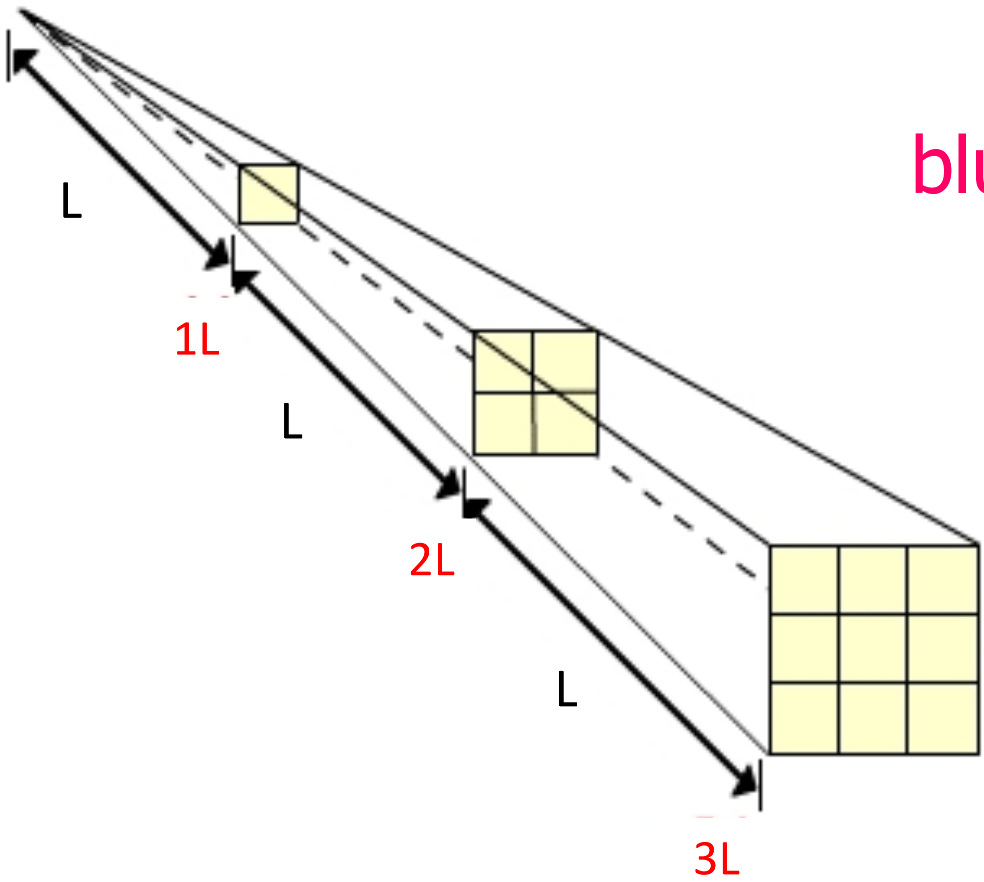


L/D=71 L/D=115 L/D=320 L/D>500.

Radiographs of a small motor taken at different beam positions with different L/D ratios.

Resolution → limit geometry/flux

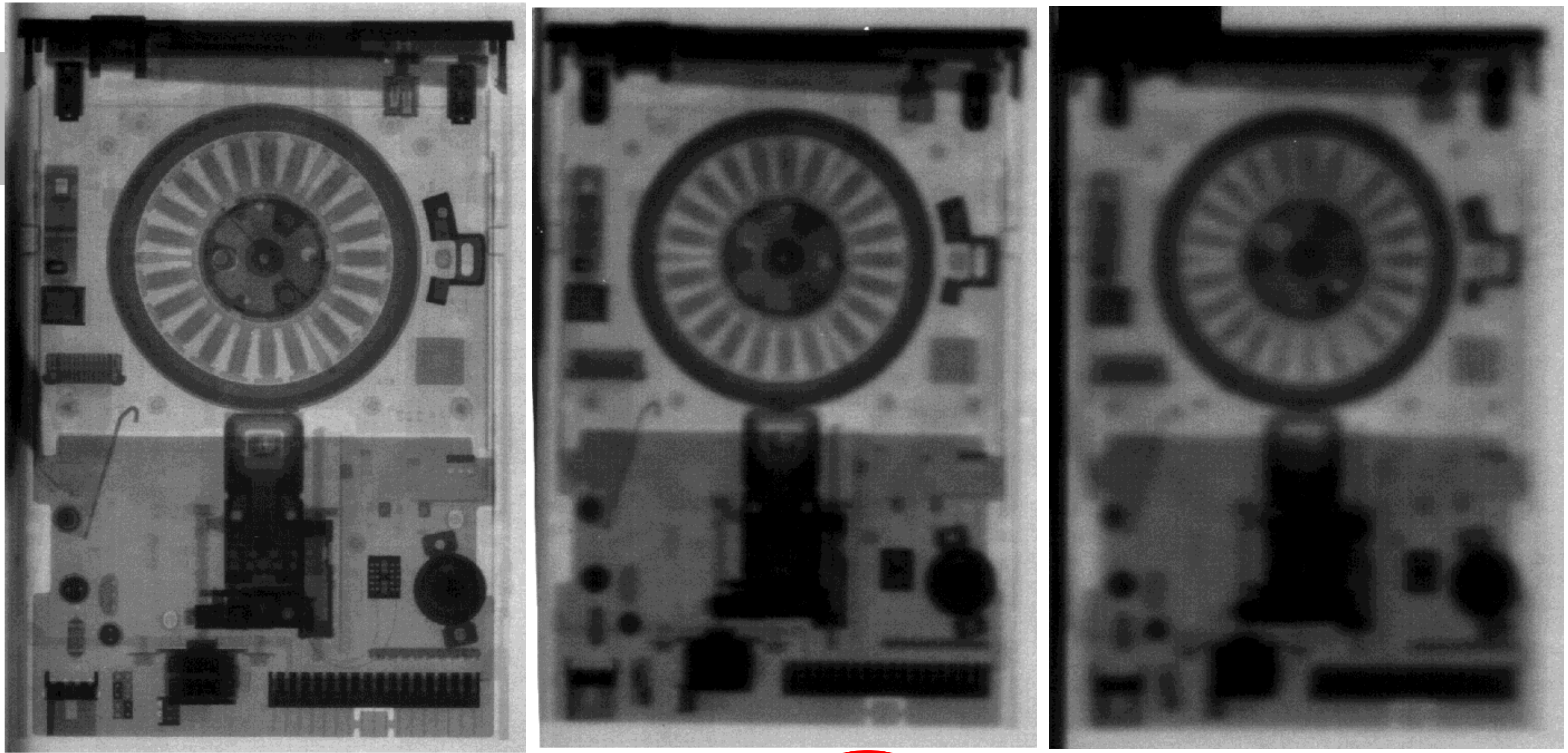
flux limitations $10^9\ cm^{-2}s^{-1}$



blur $b = \frac{d}{L/D}$

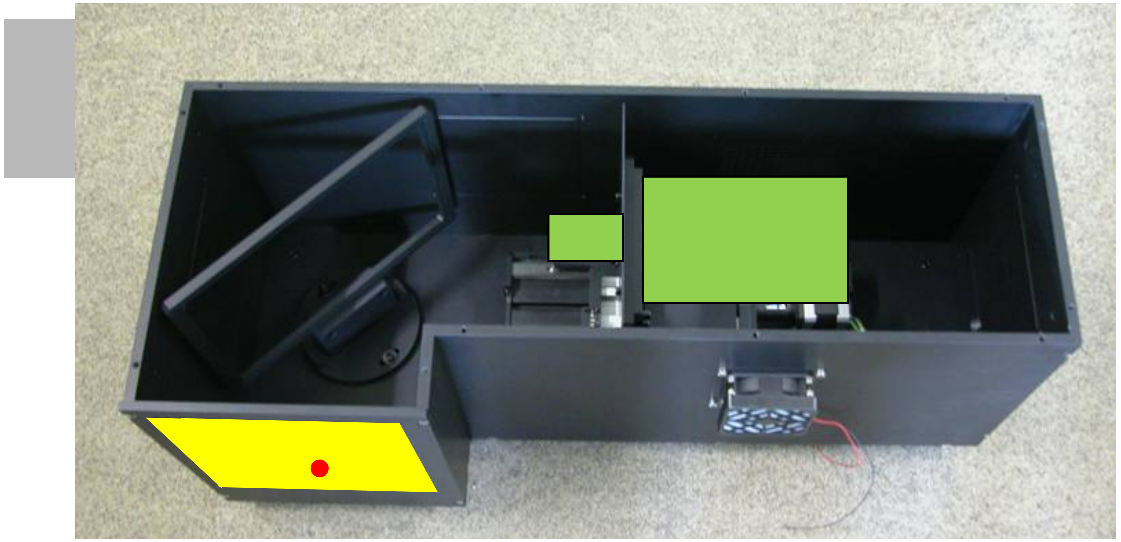
Intensity ∝ D^2 & Intensity ∝ $1/L^2$

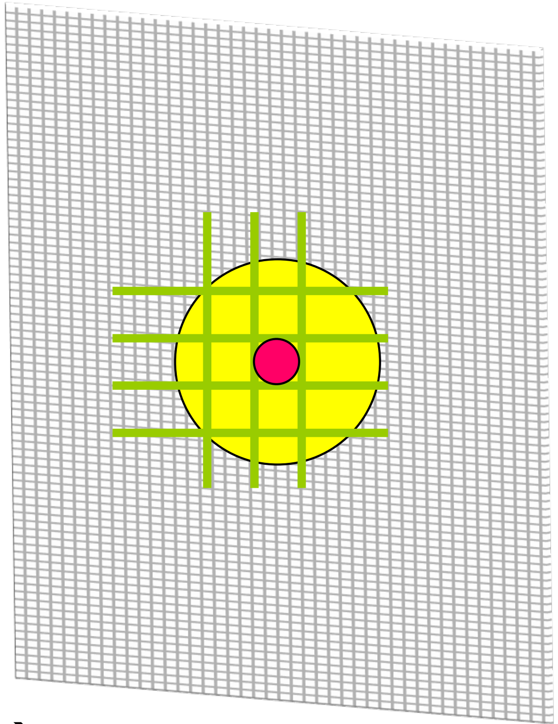
Spatial resolution



Radiographs of a 3,5" floppy drive in 0 cm, 10 cm and 20 cm distance from a film + Gd sandwich taken at a cold neutron guide with *L/D*=71.

Resolution → limit detection





$^{3}He + {}^{1}n \Rightarrow {}^{3}H + {}^{1}p + 0.77$ MeV

$^{6}Li + {}^{1}n \Rightarrow {}^{3}H + {}^{4}He + 4.79$ MeV

LiF-ZnS/Ag → 25 µm

$^{10}B + {}^{1}n \Rightarrow {}^{7}Li + {}^{4}He + 2.78$ MeV (7%)

$\Rightarrow {}^{7}Li^{*} + {}^{4}He + 2.30$ MeV (93%)

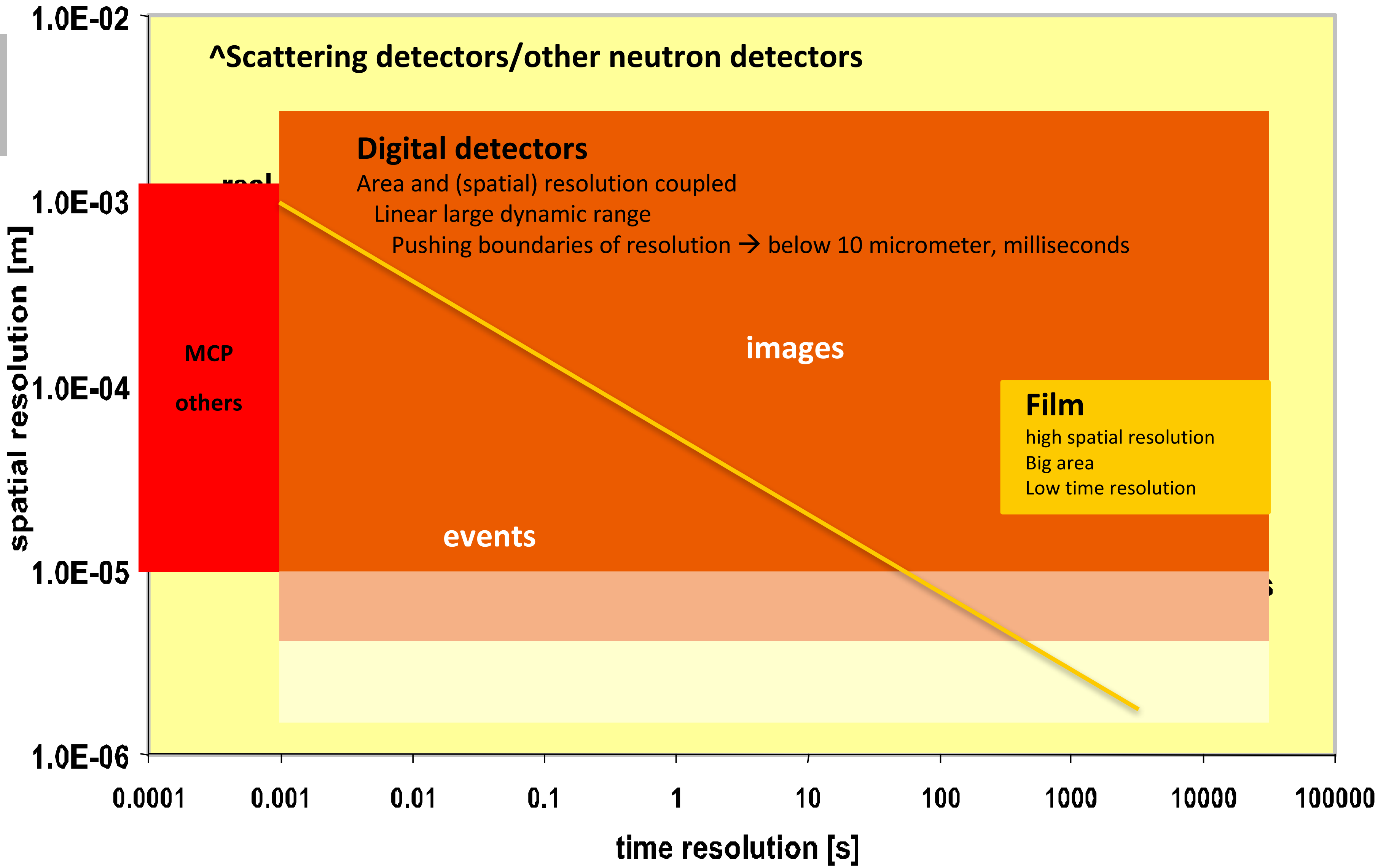
$^{155}Gd + {}^{1}n \Rightarrow {}^{156}Gd + \gamma's + CE's$ (7.9 MeV)

GADOX → 10 µm

$^{157}Gd + {}^{1}n \Rightarrow {}^{158}Gd + \gamma's + CE's$ (8.5 MeV)

^{235}U, ^{239}Pu $^{1}n \Rightarrow$ fission products + 80 MeV

Resolution → limit detection

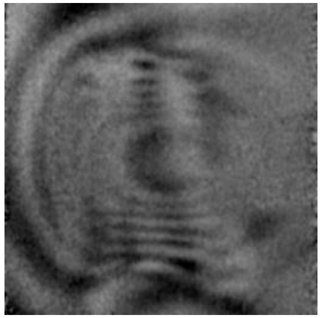


Digital → time resolution &...

kinetic

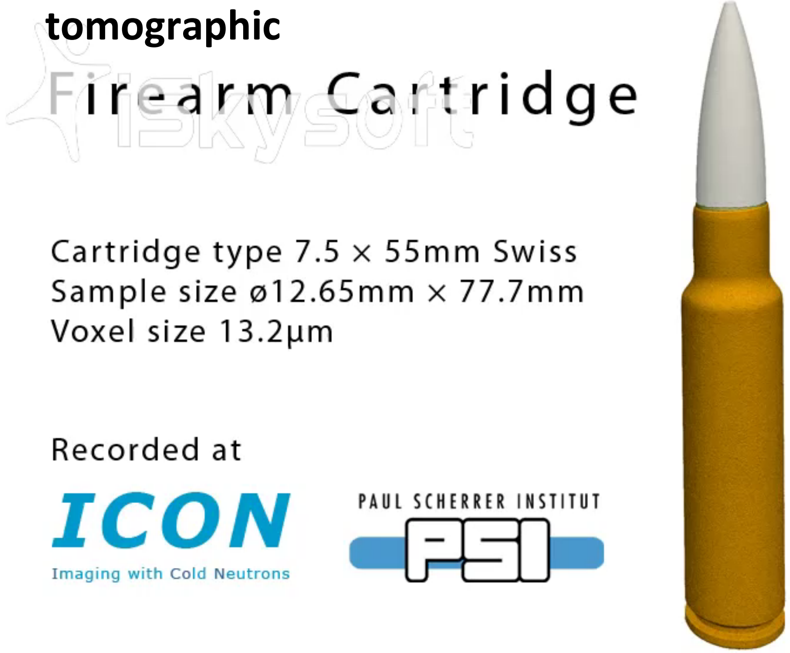
(10) milliseconds

stroboscopic



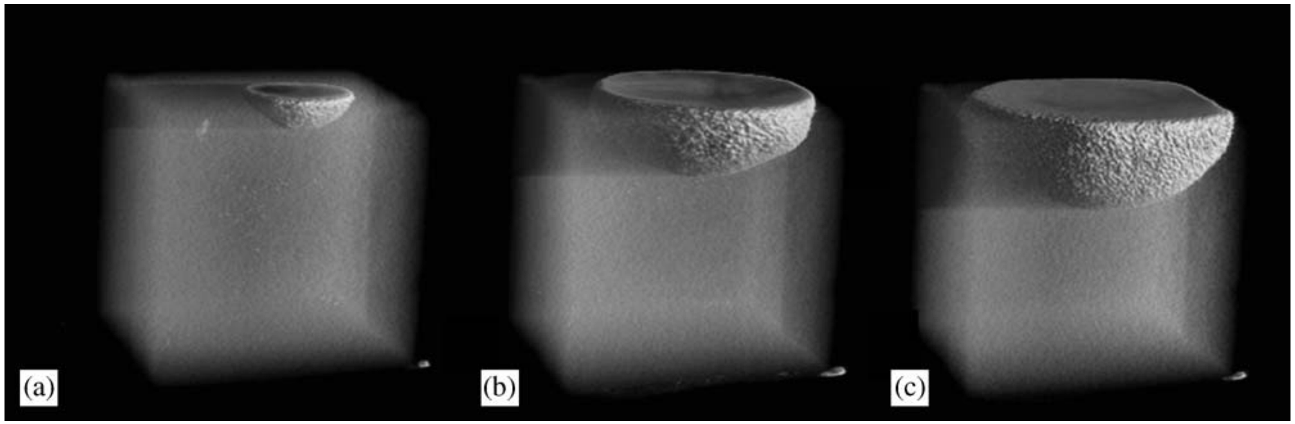
microsecs

tomographic



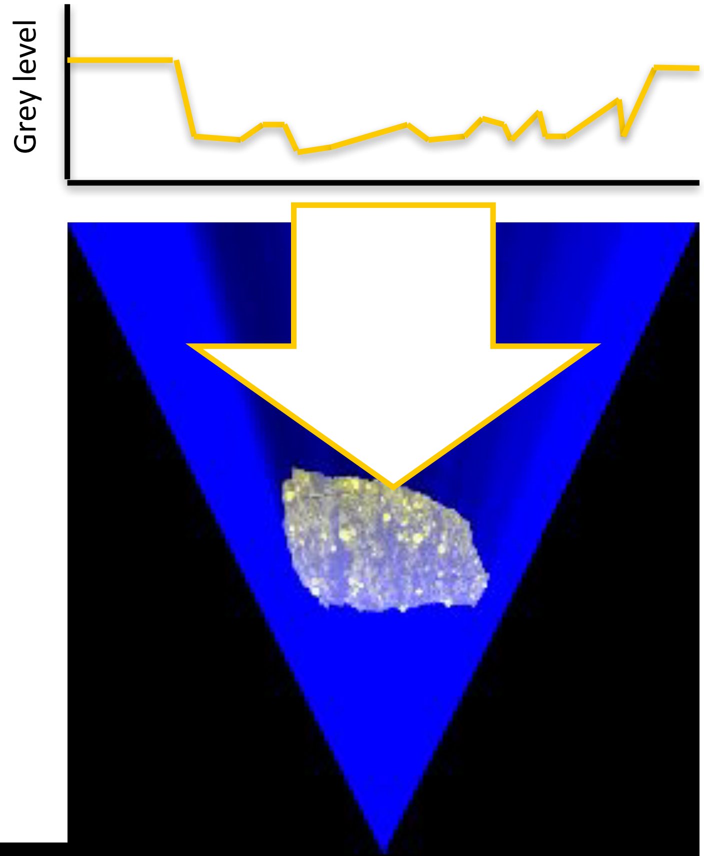
3D

kinetic tomographic



(10) seconds

Tomography



Radon

Transform

Fourier

Slice

Theorem

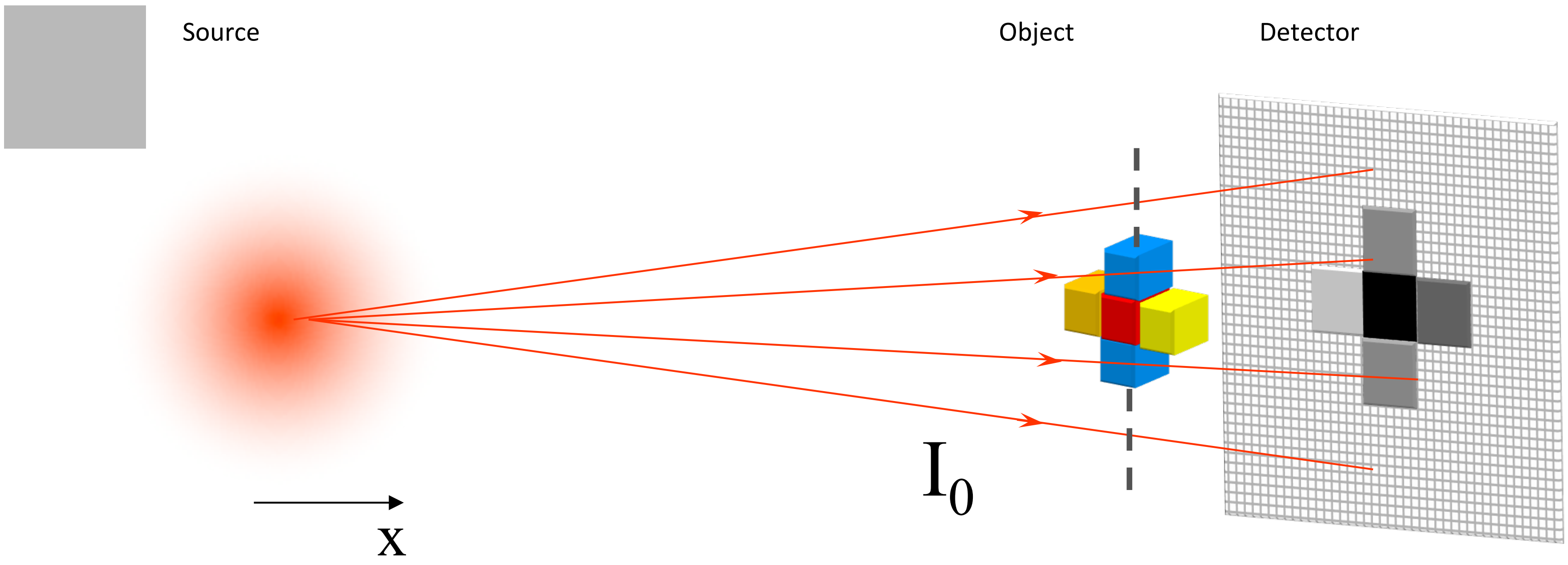
→

backprojektion

Fundamental for Imaging

- Spatial Resolution
  - Geometry
  - Detectors
- Contrast
  - Interactions
  - Techniques

Contrast



$$\sim \; I_0 e^{-\int \Sigma(x)dx}$$

I_0 – primary beam

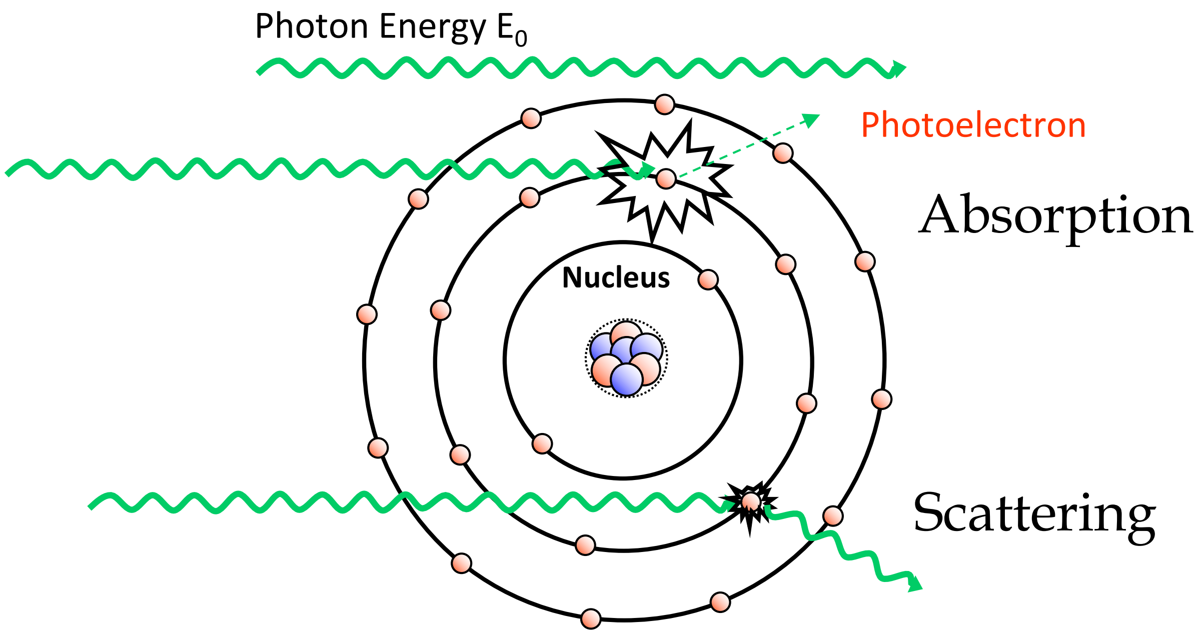
$\Sigma(x)$ – attenuation coefficient

x – propagation direction

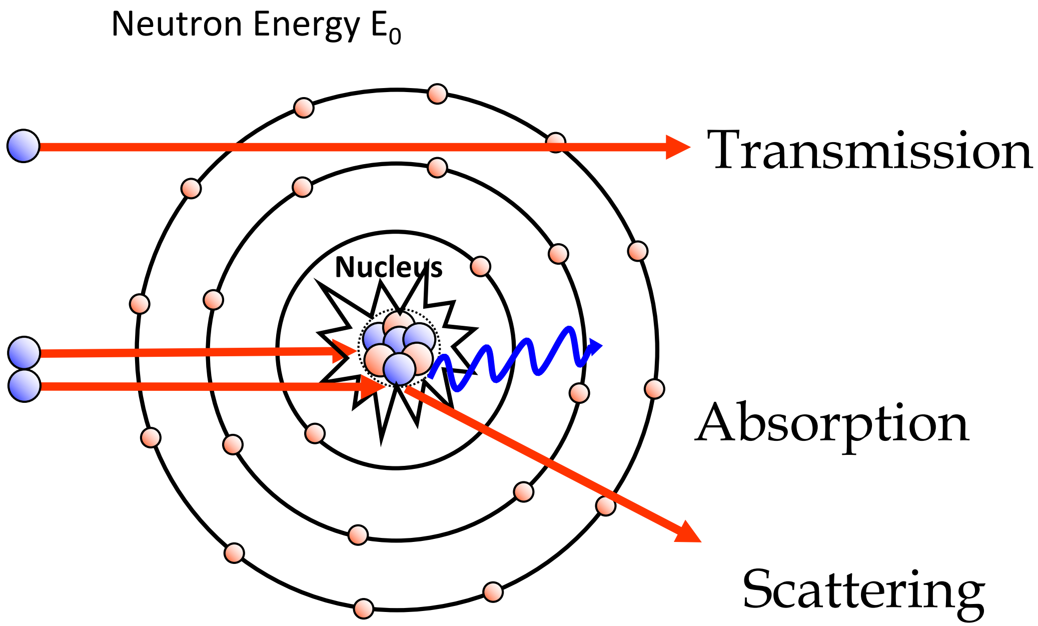
$$\Sigma[cm^{-1}] = N \cdot \sigma$$

$$\sigma[barn = 10^{-24} cm^2] = \sigma_a + \sigma_s$$

X-ray interaction with matter



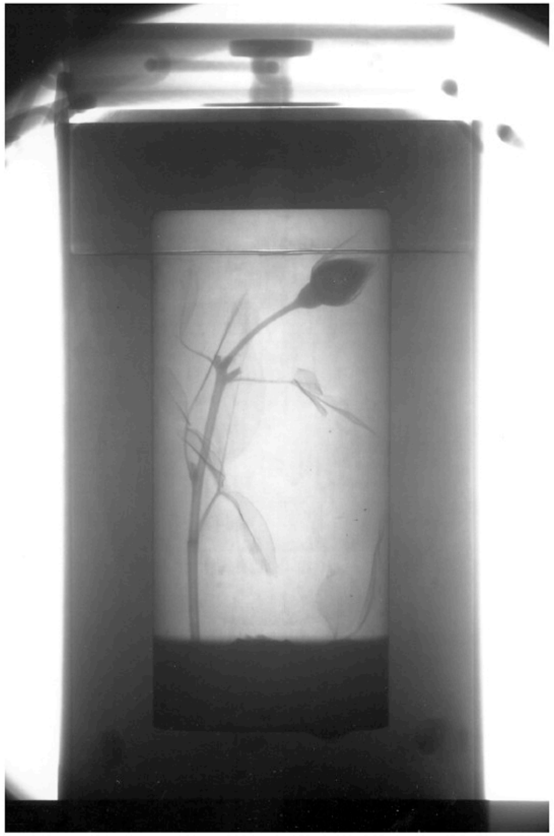
neutron interaction with matter



Contrast

Some advantages:

→ **High penetration power**

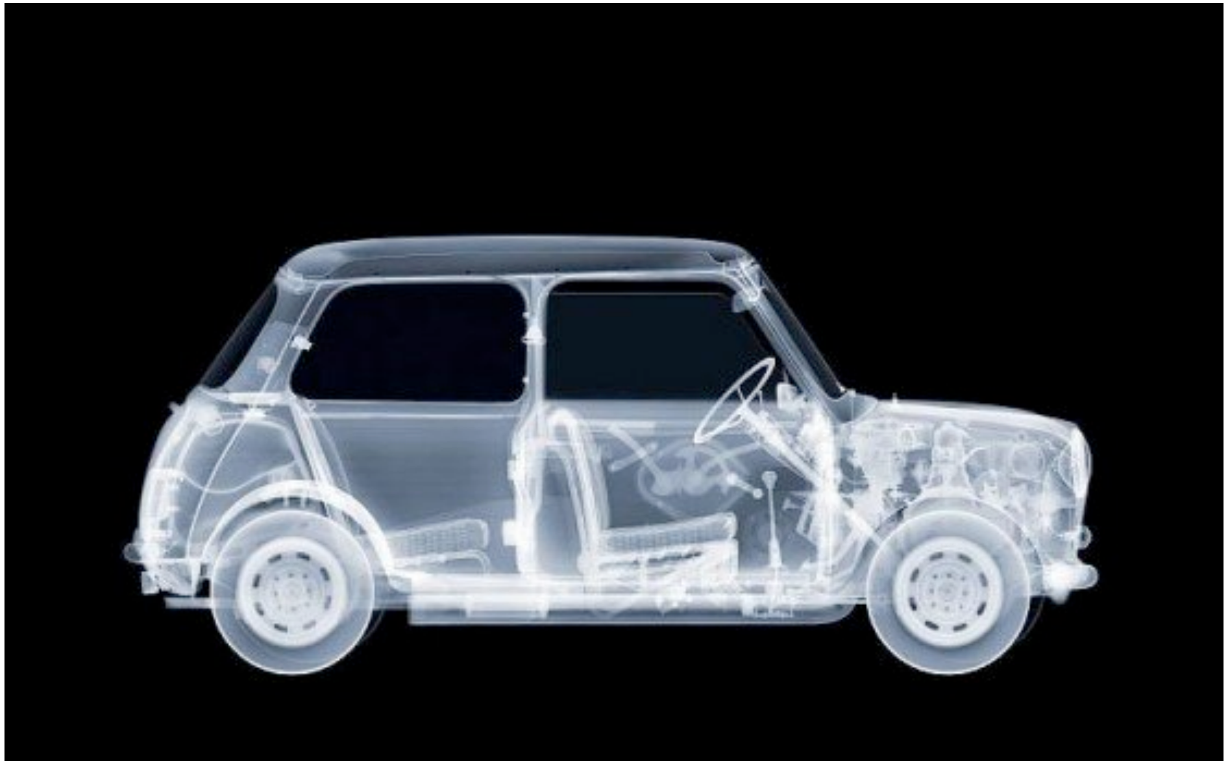


Contrast

Some advantages:

- High penetration power

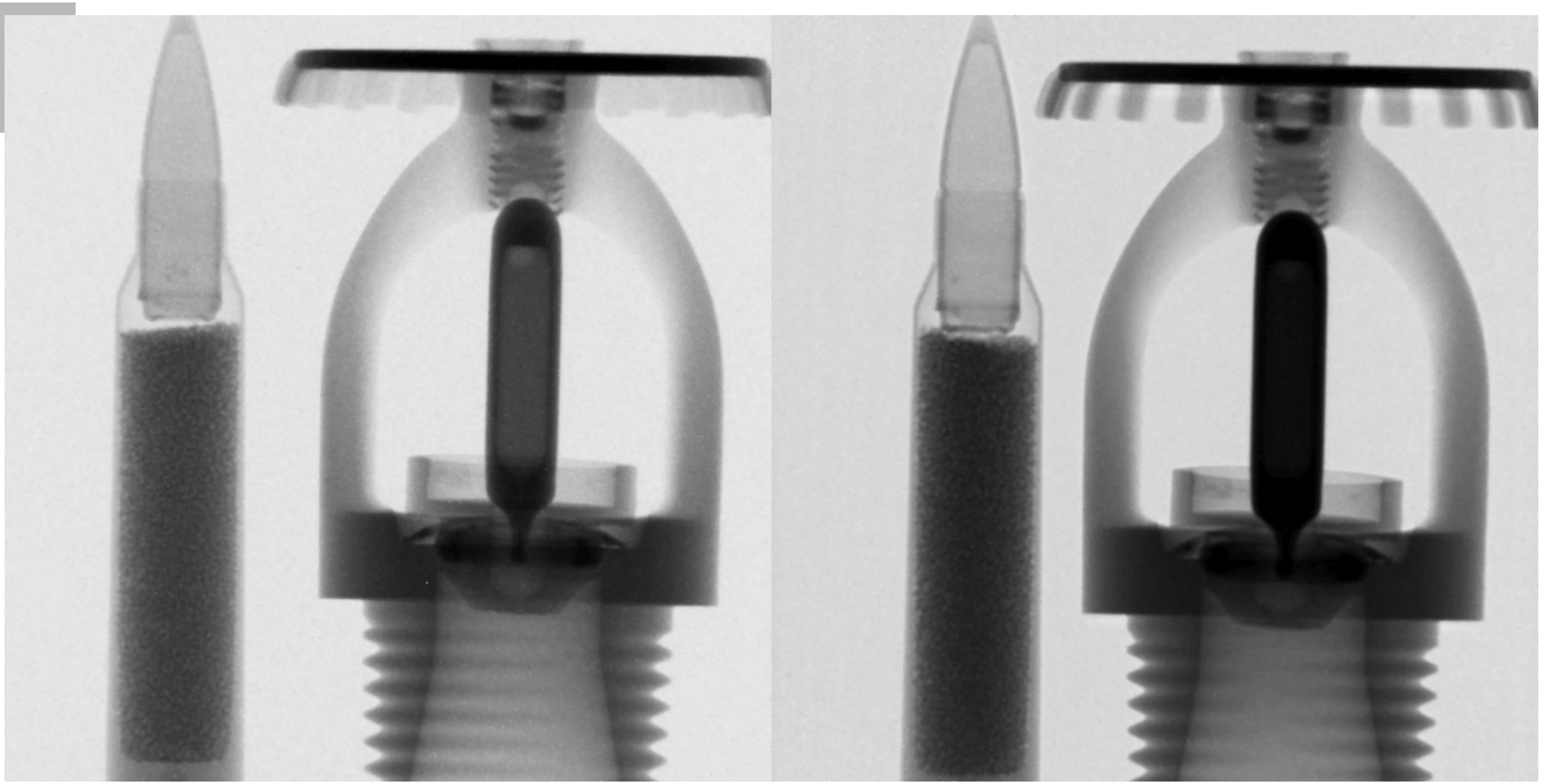
→ **Scattered contrast**



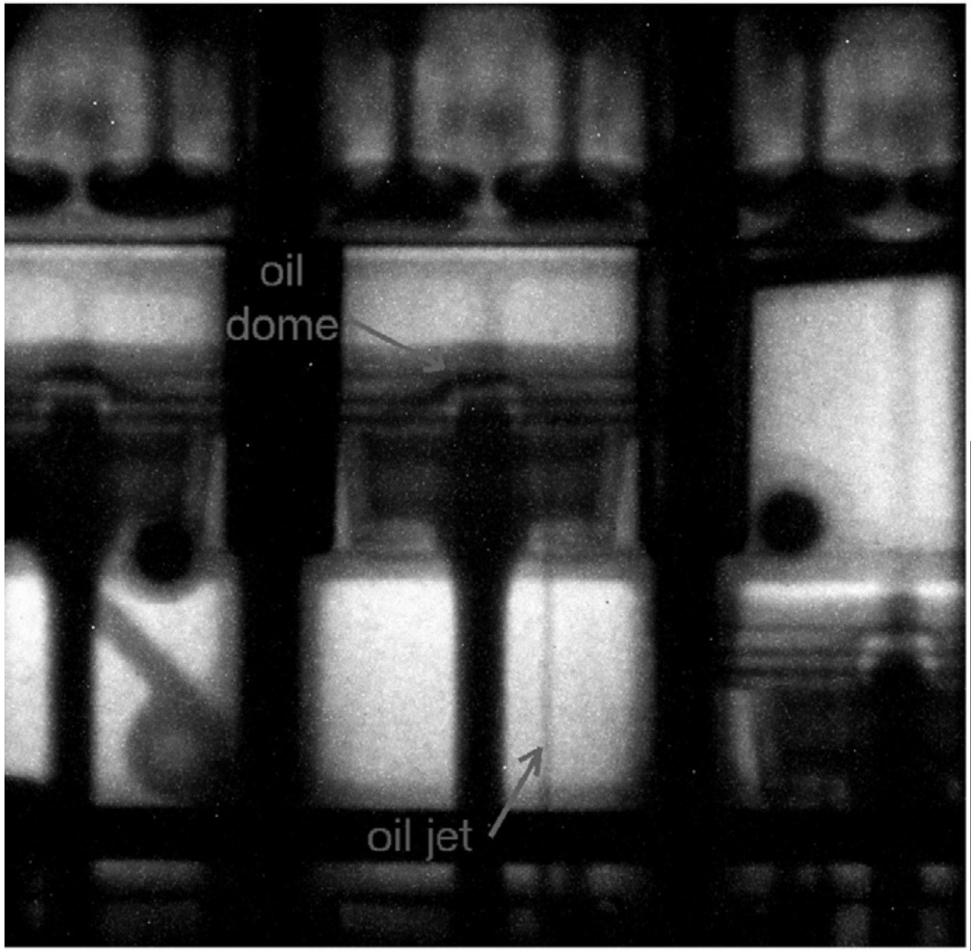
Contrast

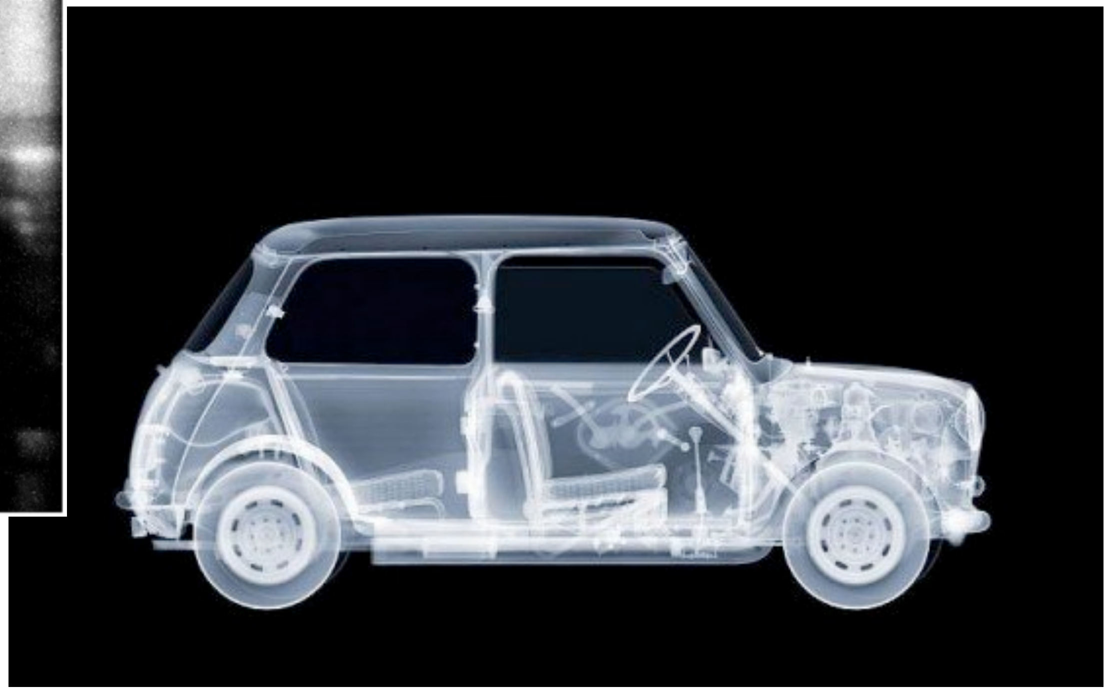
Thermal neutrons

Cold neutrons

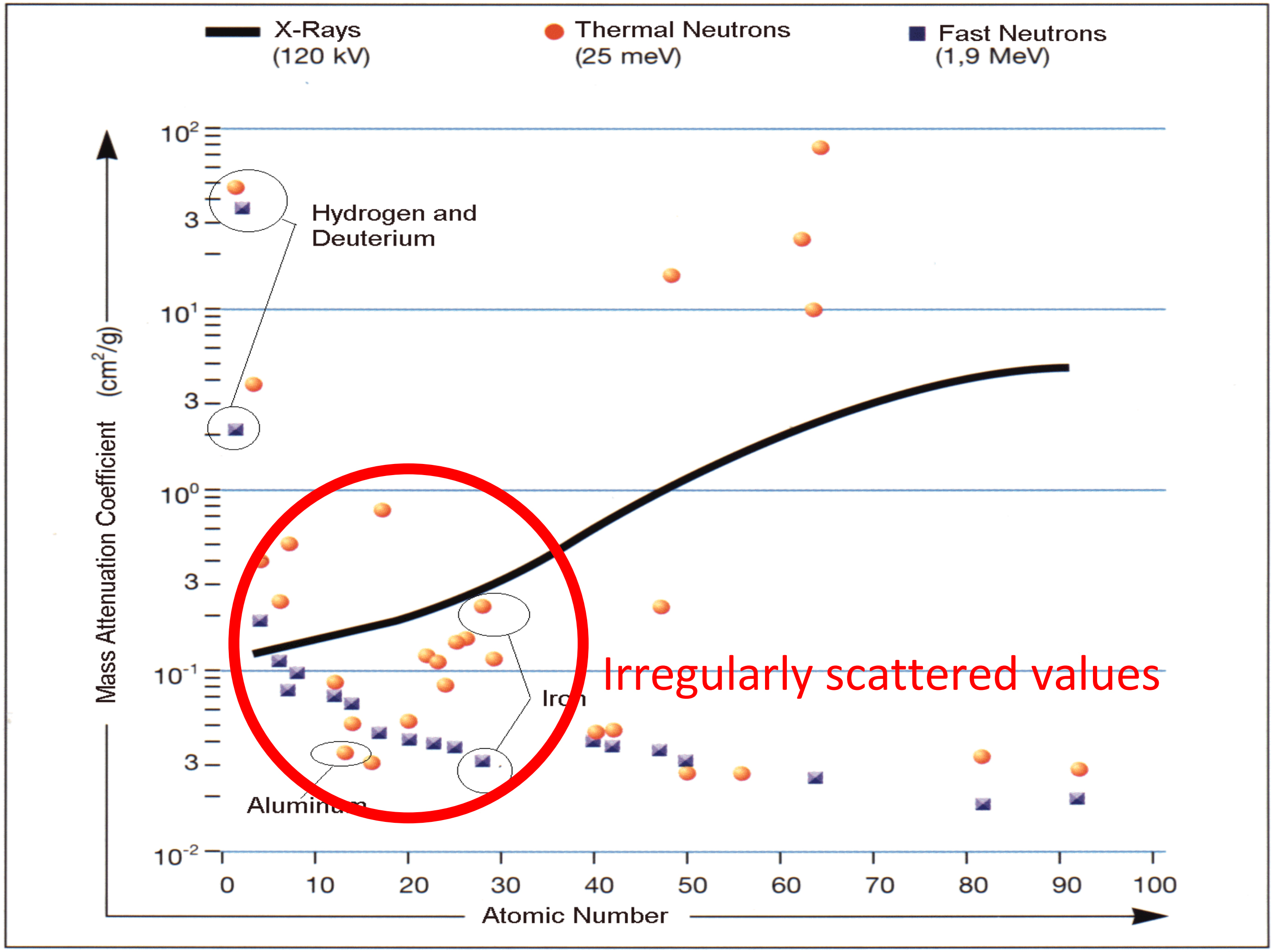


Contrast





Contrast


X-Rays
(120 kV)
Thermal Neutrons
(25 meV)
Fast Neutrons
(1,9 MeV)
Hydrogen and
Deuterium
Iron
Aluminum
Irregularly scattered values
Mass Attenuation Coefficient (cm²/g)
Atomic Number
10²
3
10¹
3
10⁰
3
10⁻¹
3
10⁻²
0
10
20
30
40
50
60
70
80
90
100

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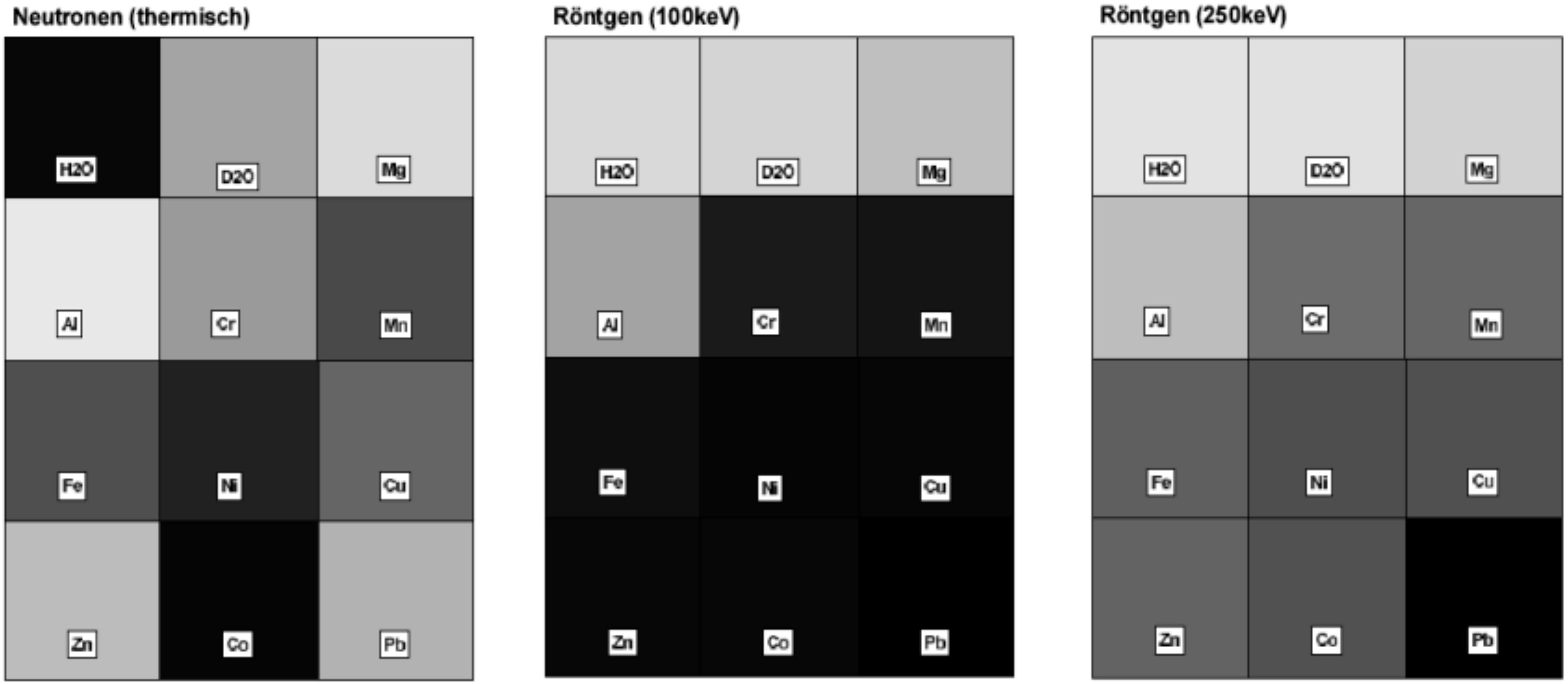
Contrast

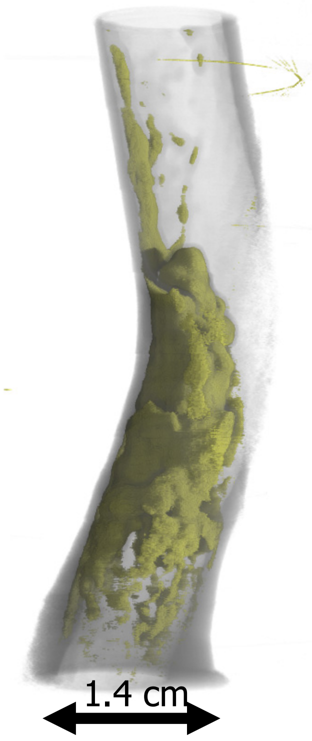


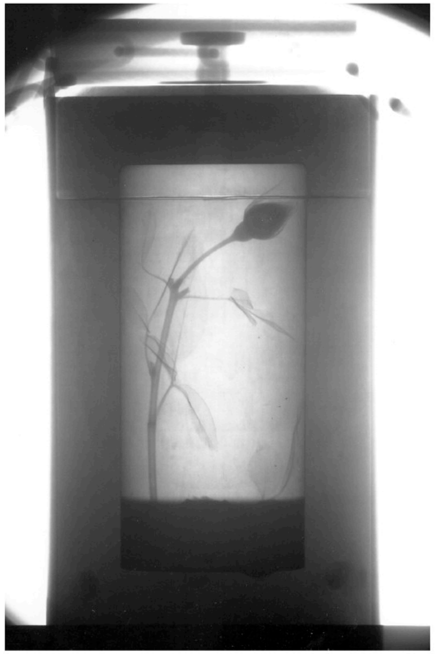
Contrast

Some advantages:

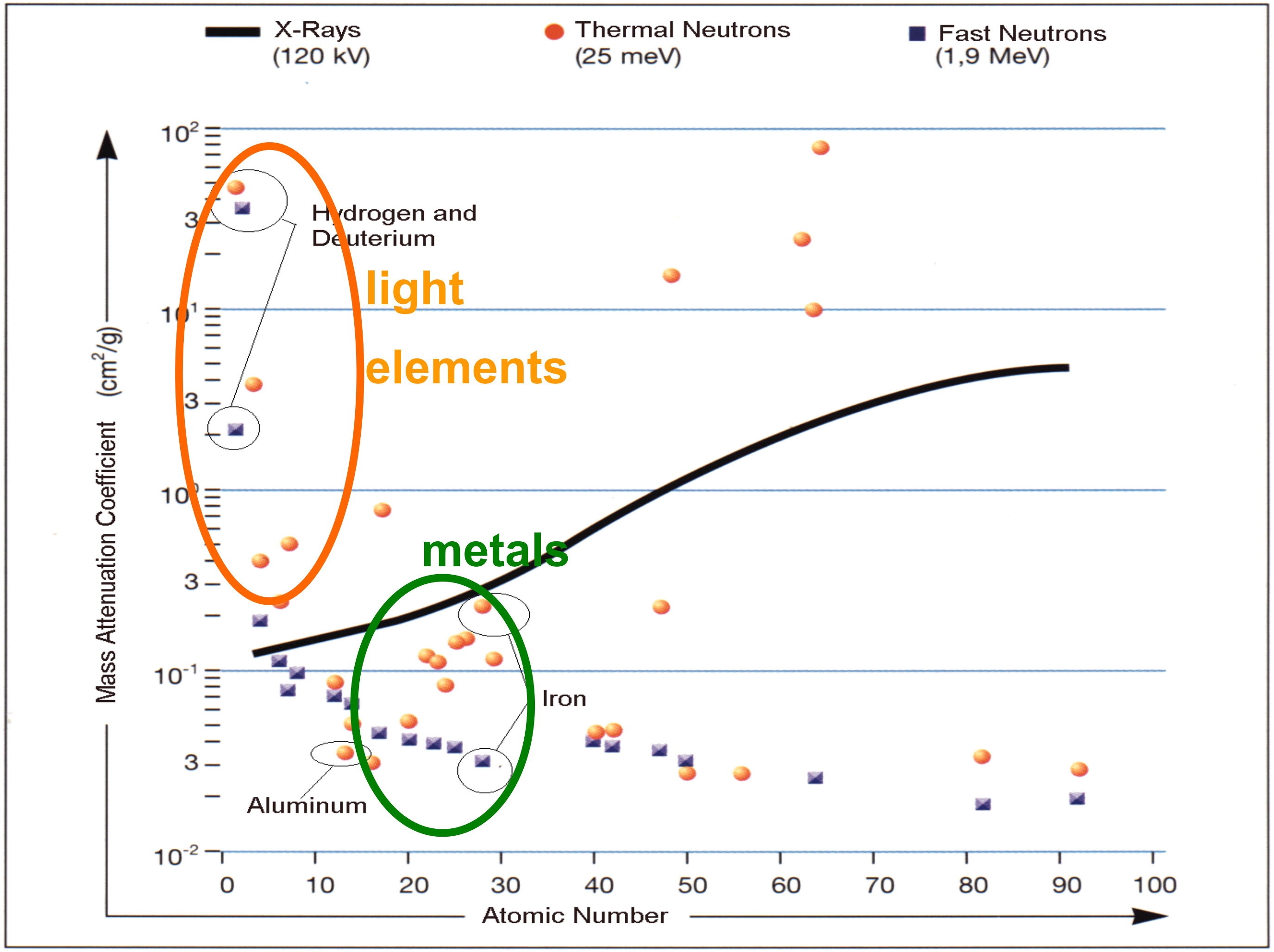
- High penetration power
- Scattered contrast

→ **High sensitivity to Hydrogen**



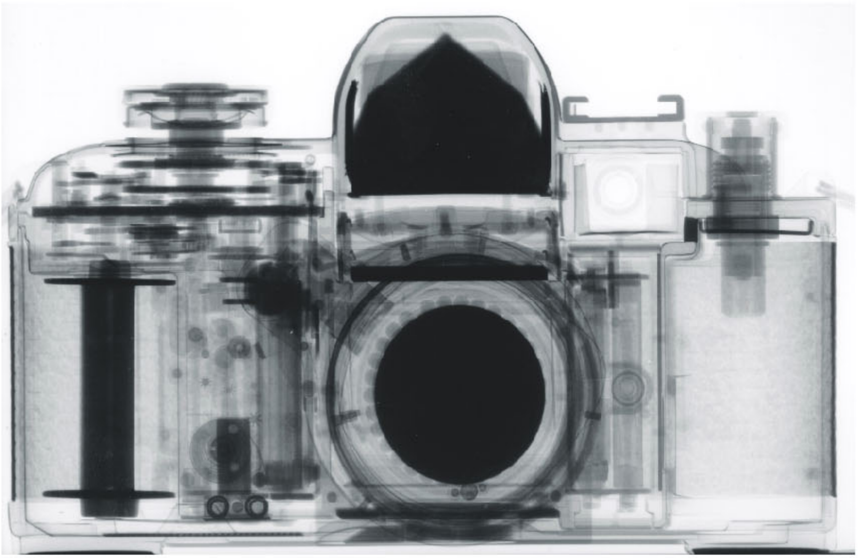


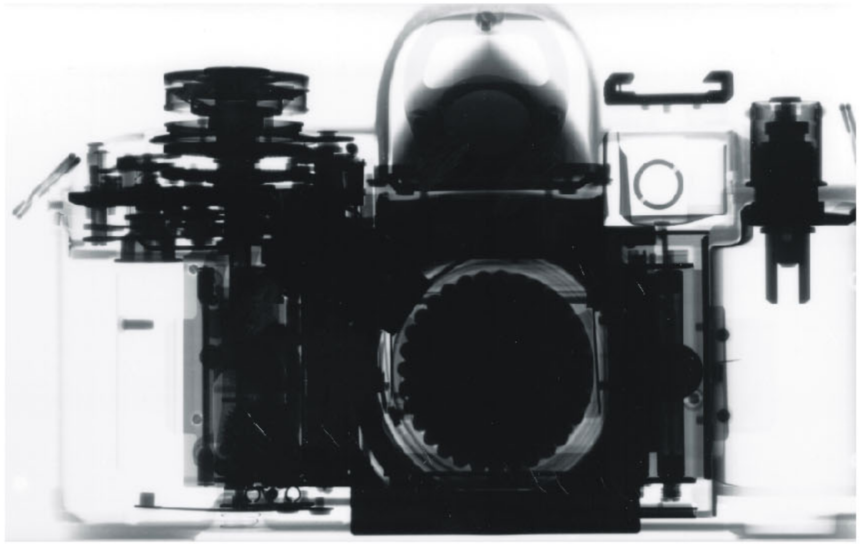
Contrast



X-Rays
(120 kV)
Thermal Neutrons
(25 meV)
Fast Neutrons
(1,9 MeV)
Hydrogen and
Deuterium
light
elements
metals
Iron
Aluminum
Mass Attenuation Coefficient (cm²/g)
Atomic Number
10²
3
10¹
3
10⁰
3
10⁻¹
3
10⁻²
0
10
20
30
40
50
60
70
80
90
100

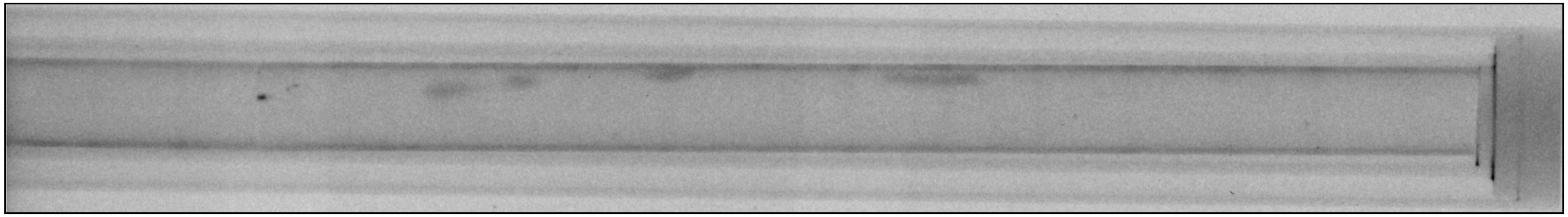
Contrast





Contrast

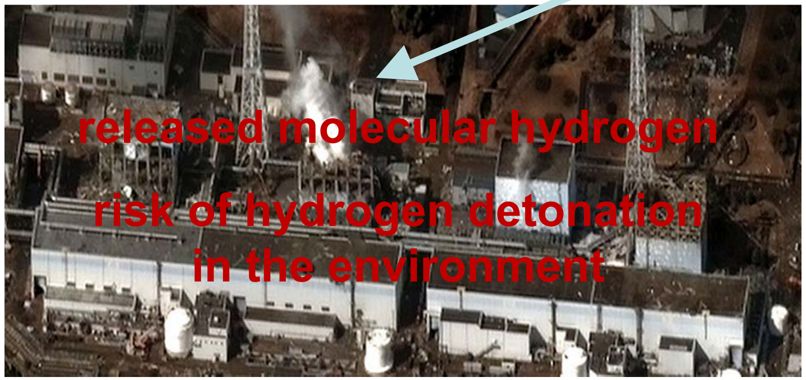
Zircaloy cladding only: ZrH_2 blisters



Emerging cooling of the overheated reactor core results in steam oxidation of the zirconium alloys used as fuel rod cladding material:

$$2\ H_2O + Zr \rightarrow ZrO_2 + 4\ H \text{ (very simplified)}$$

$$4\ H \rightarrow 2H_2\uparrow\ /\ 4\ H_{absorbed}$$



Fuel Cells

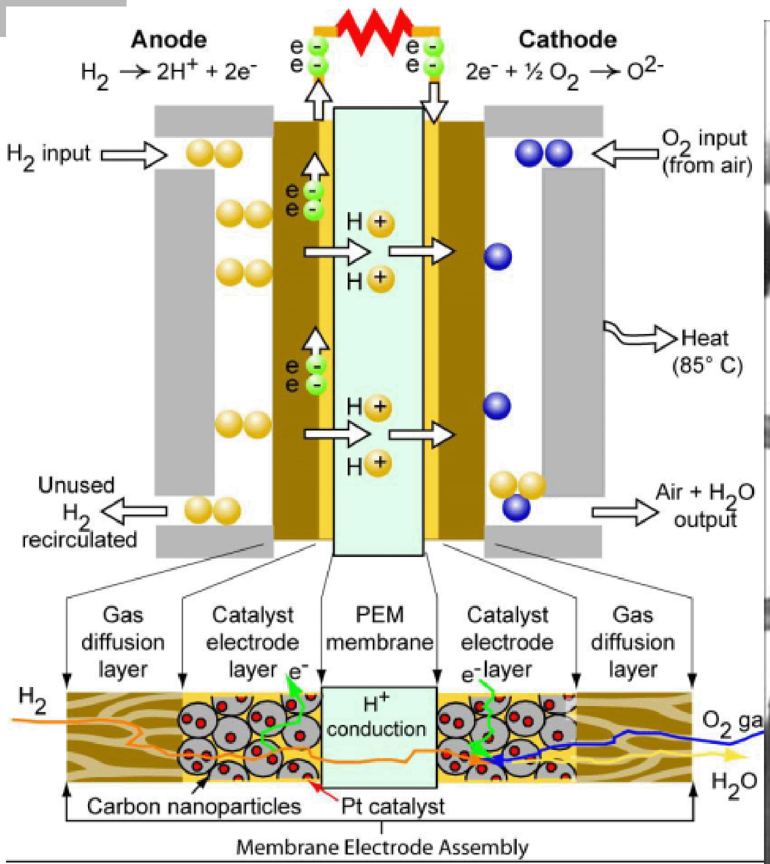
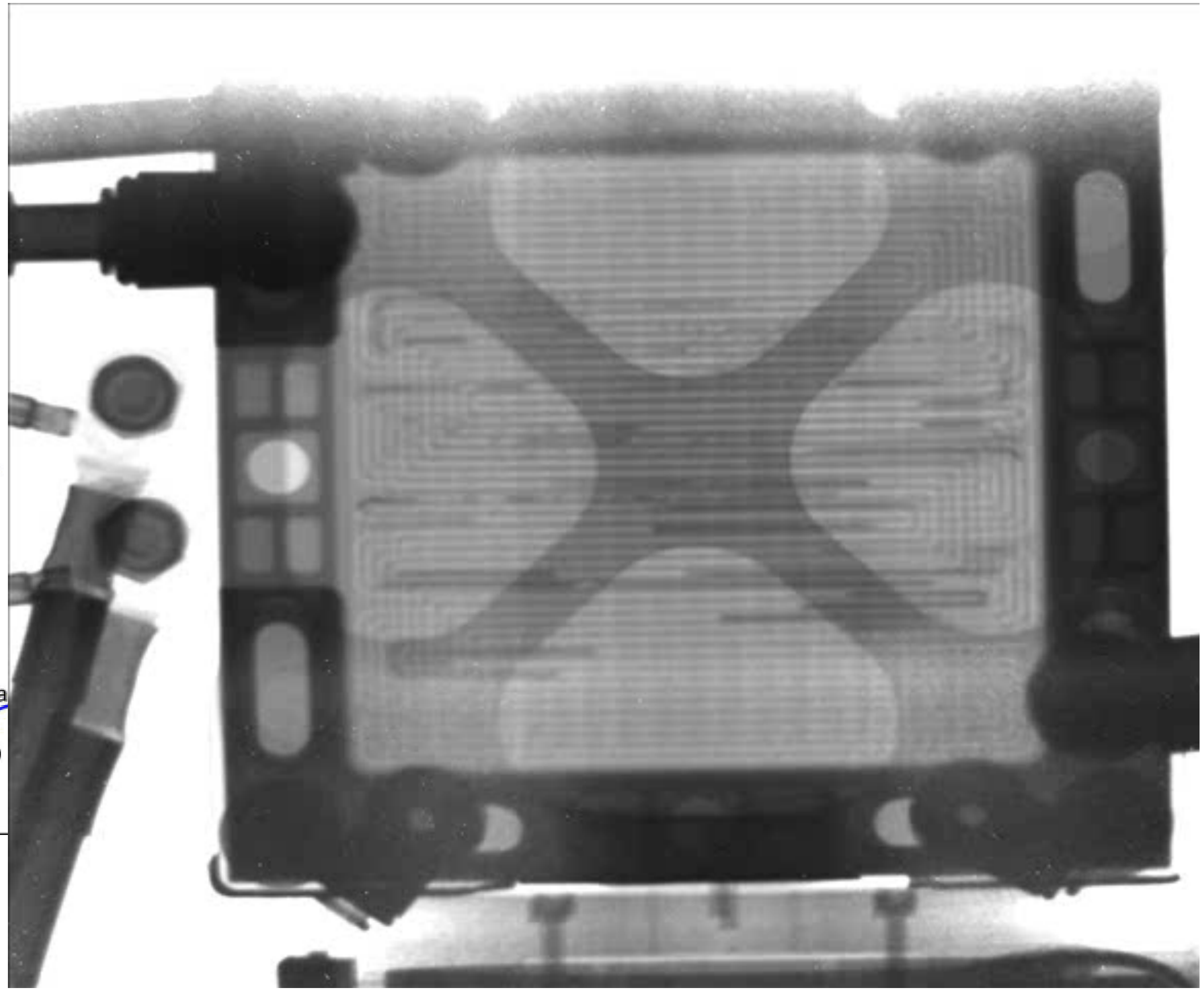


Figure 1. Schematic of a PEM Fuel Cell

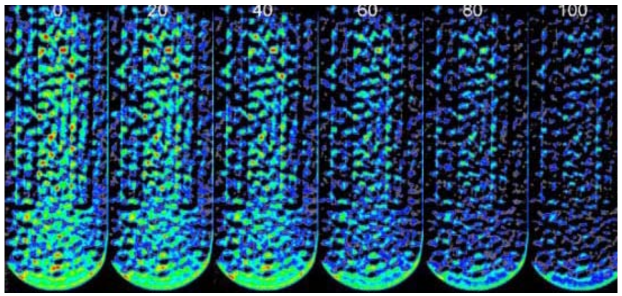


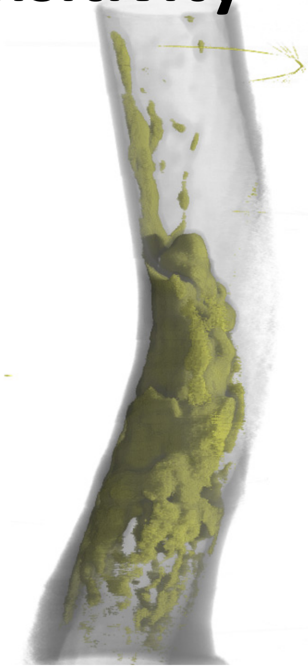
Contrast

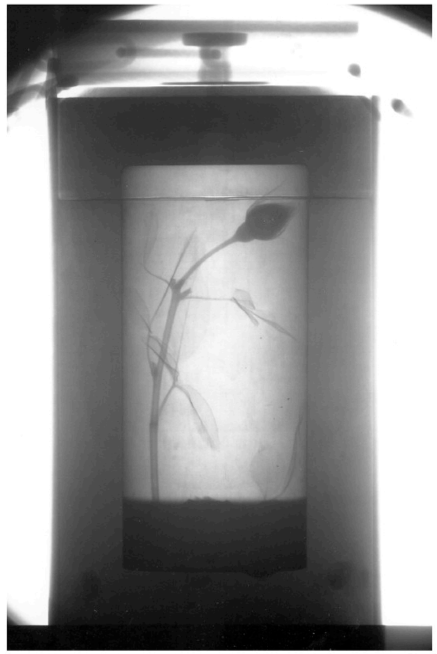
Some advantages:

- High penetration power
- Scattered contrast
- High sensitivity to Hydrogen

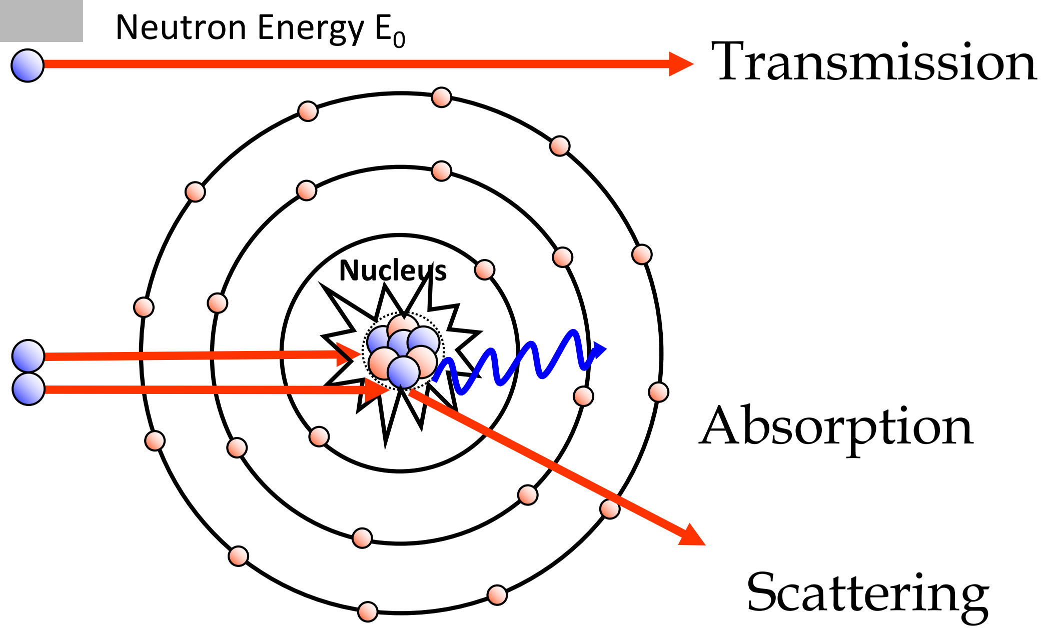
→ **Isotope sensitivity**

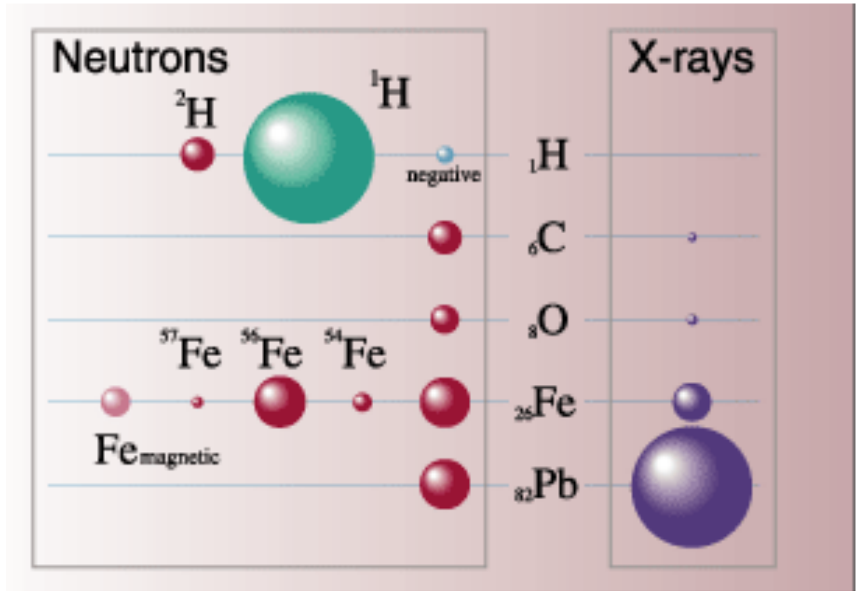






Contrast

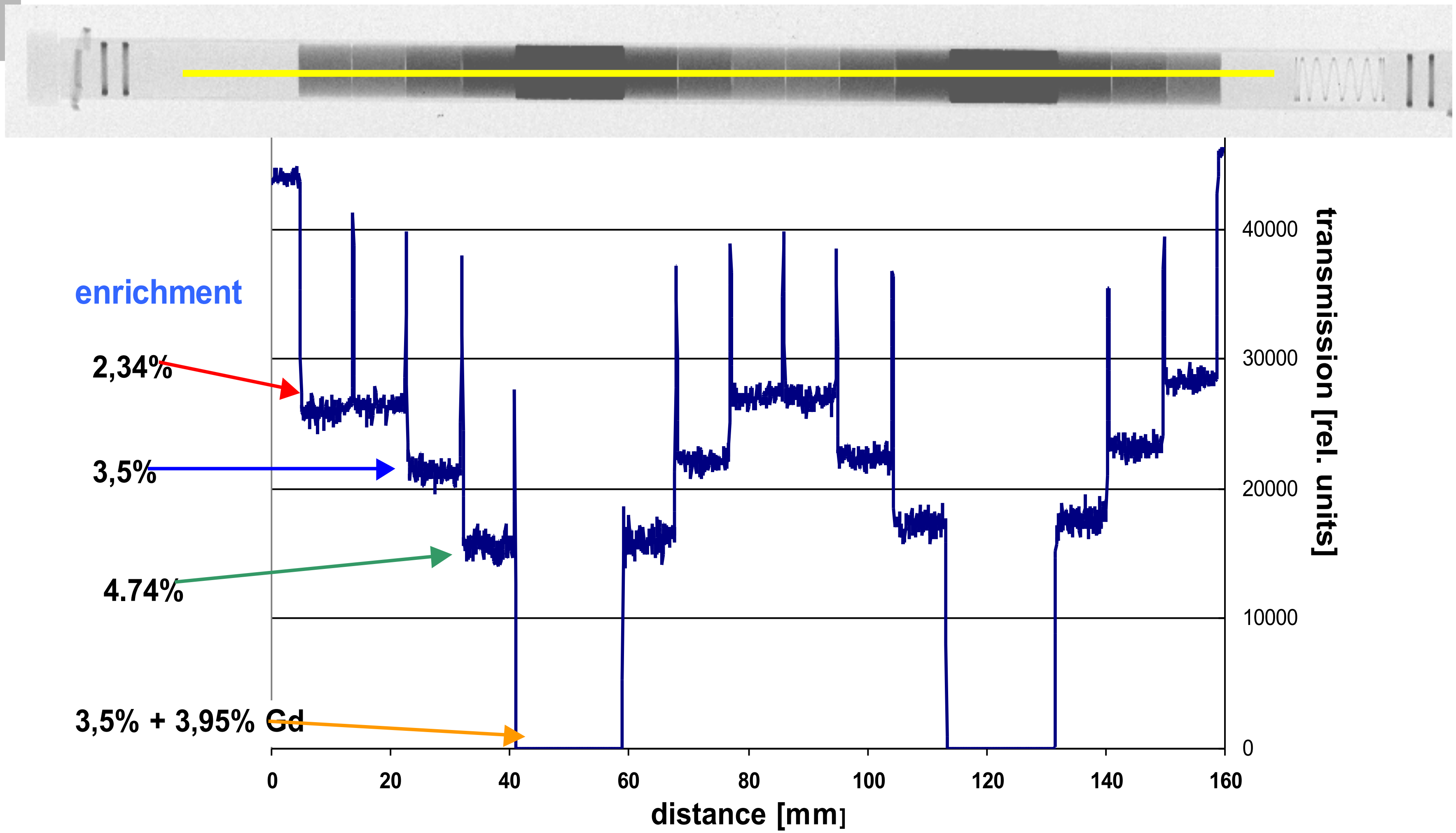




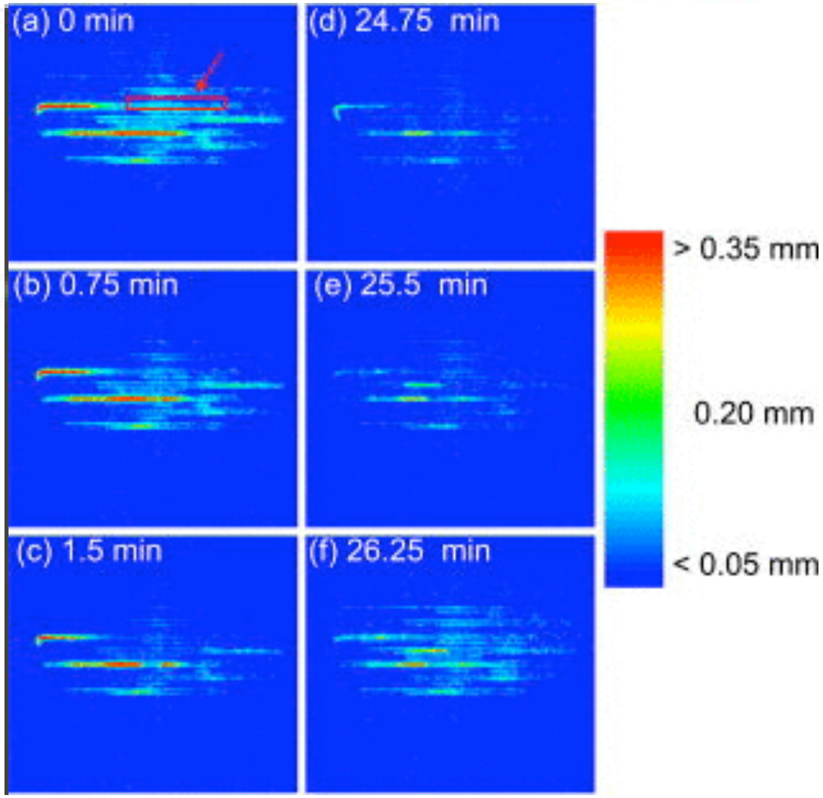
scattering cross sections

Contrast

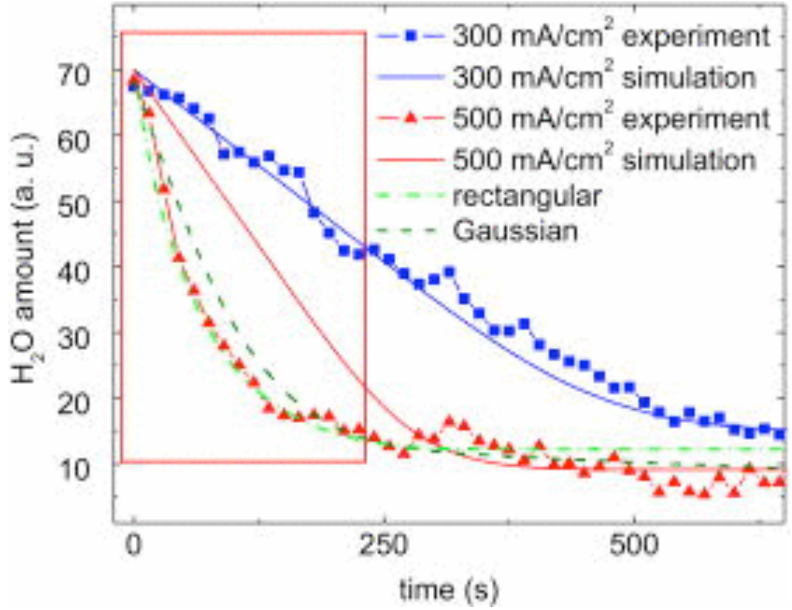
Determination of the U-235 content (enrichment) in nuclear fuel elements



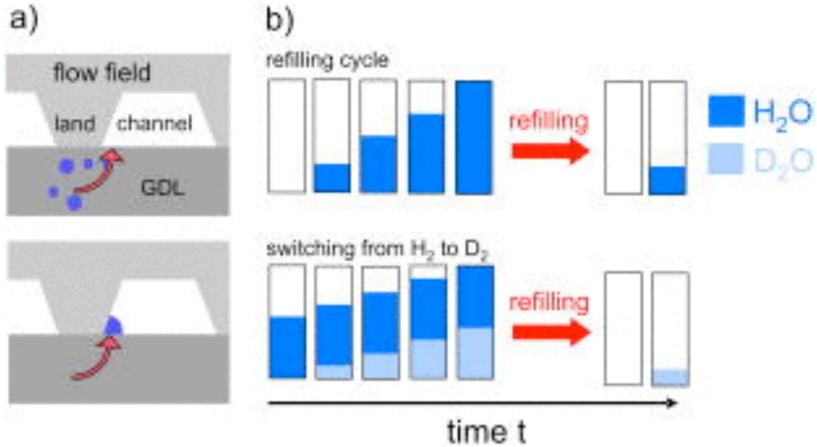
Contrast



(a) 0 min
(d) 24.75 min
(b) 0.75 min
(e) 25.5 min
(c) 1.5 min
(f) 26.25 min
> 0.35 mm
0.20 mm
< 0.05 mm

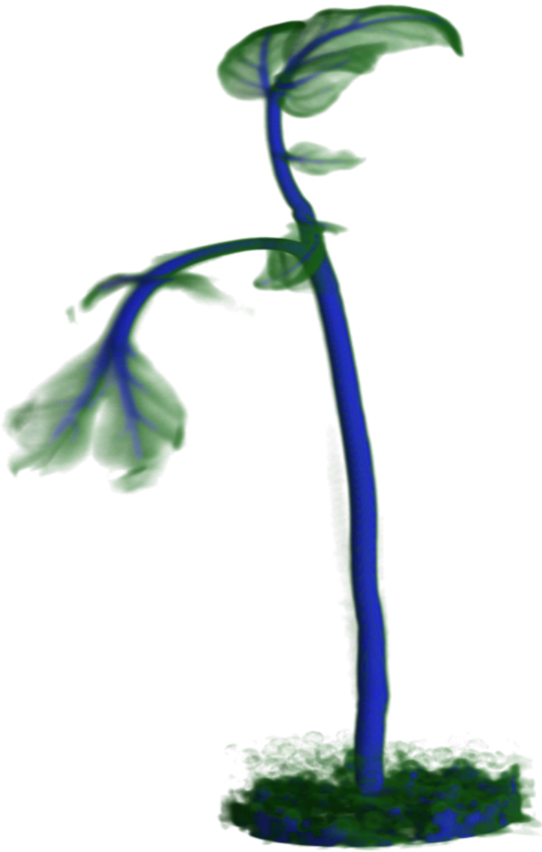


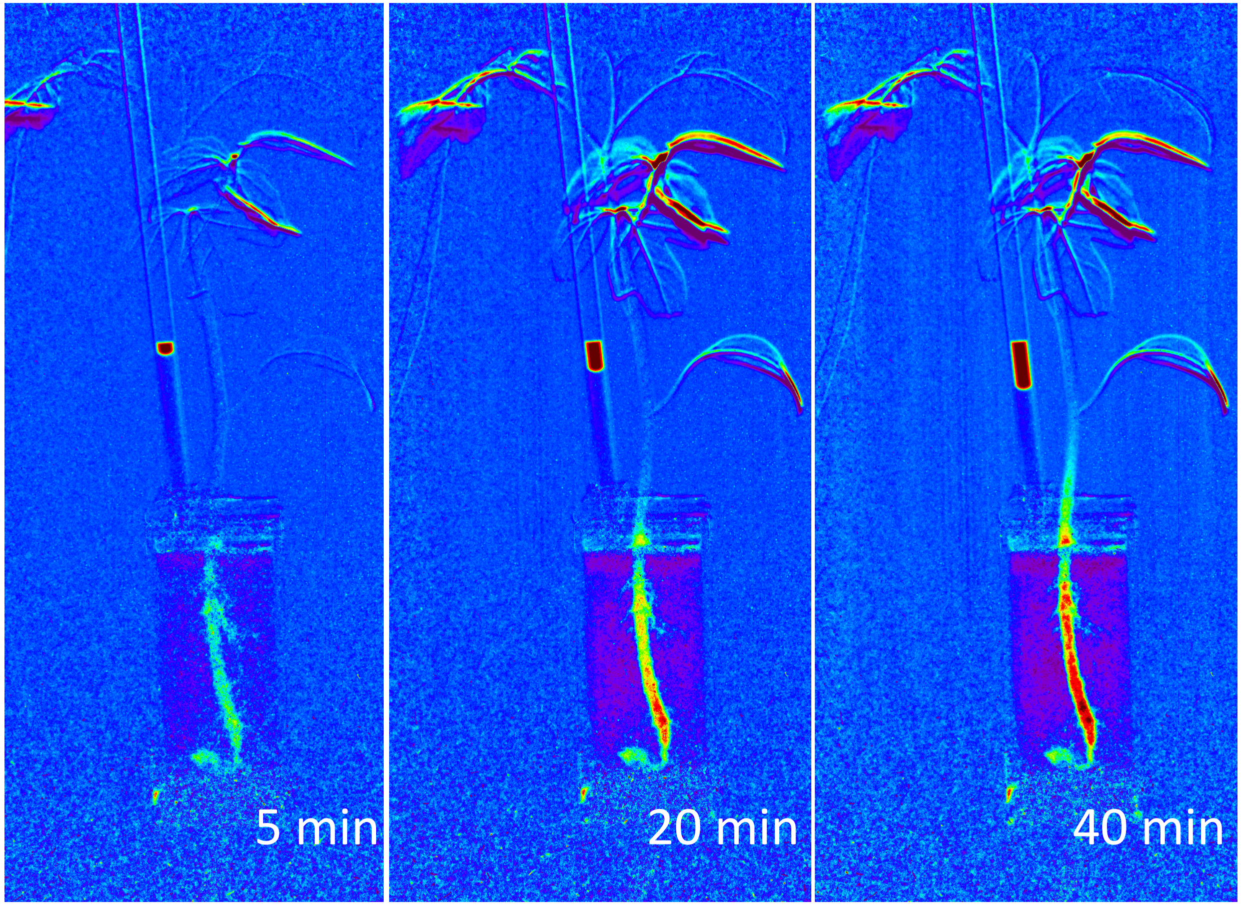
300 mA/cm² experiment
300 mA/cm² simulation
500 mA/cm² experiment
500 mA/cm² simulation
rectangular
Gaussian
H₂O amount (a. u.)
time (s)



a)
b)
flow field
land
channel
GDL
refilling cycle
refilling
H₂O
D₂O
switching from H₂ to D₂
refilling
time t

Contrast





H_2O ⇄ D_2O

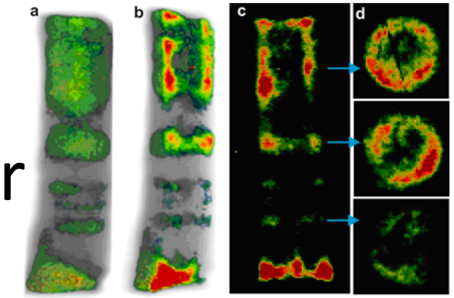
...and no stress!!

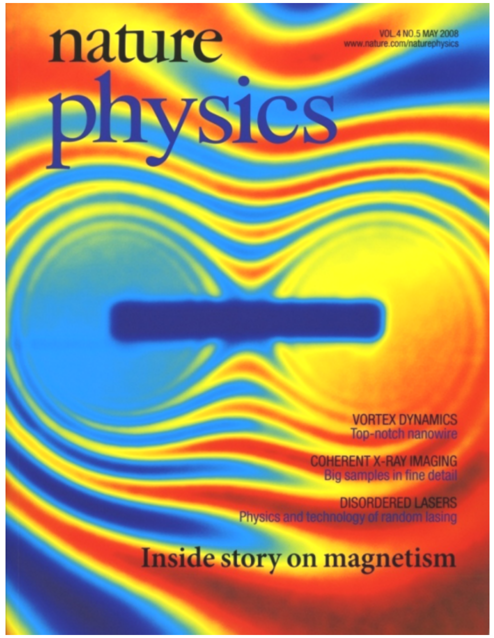
Contrast

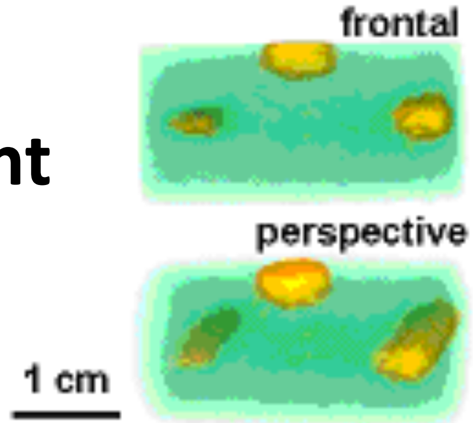
Some advantages:

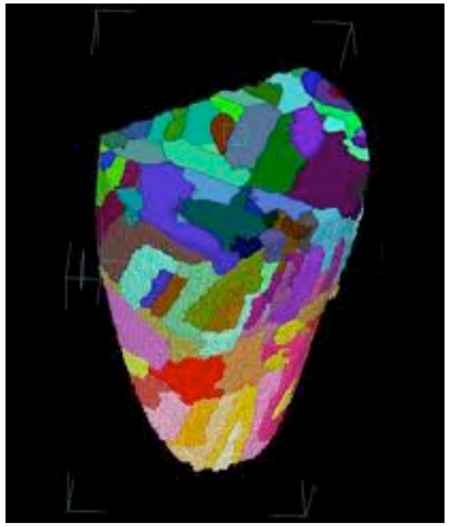
- High penetration power
- Scattered contrast
- High sensitivity to Hydrogen
- Isotope sensitivity

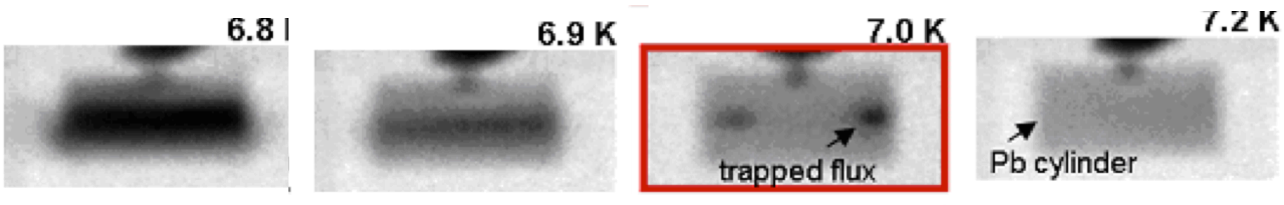
→ **Magnetic moment**











Contrast

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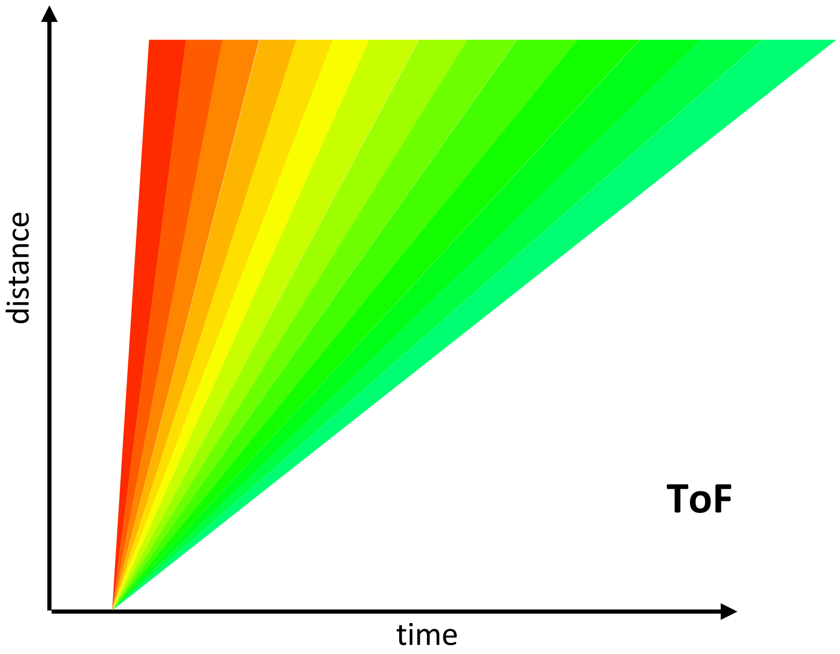
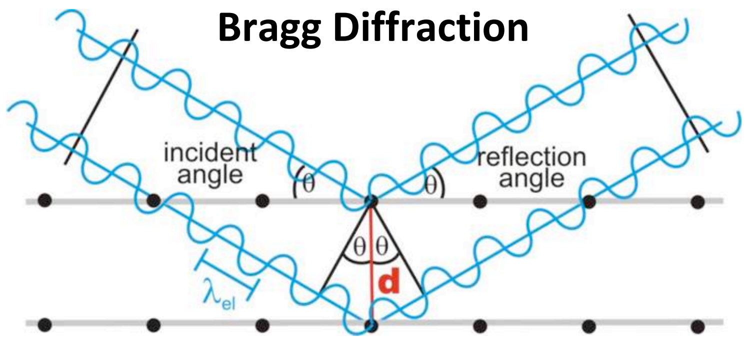
→ **Mass & wavefunction**





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Contrast

Some advantages:

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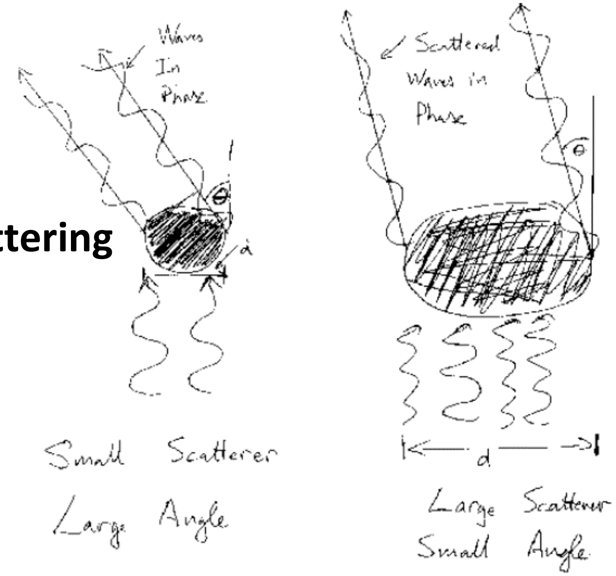
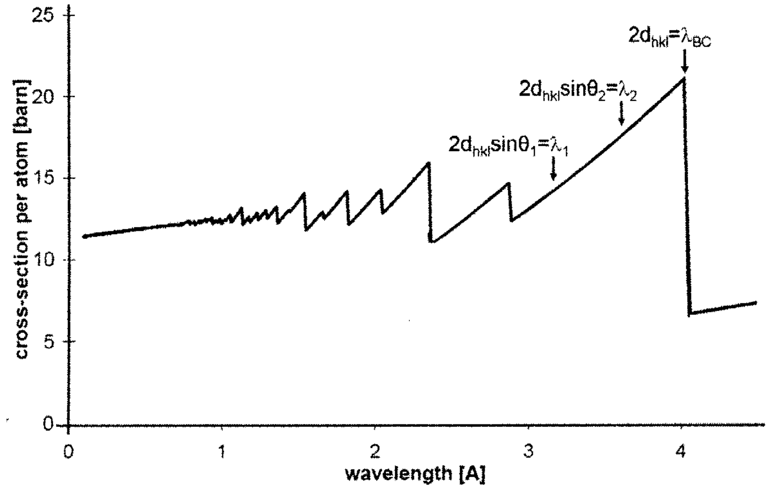
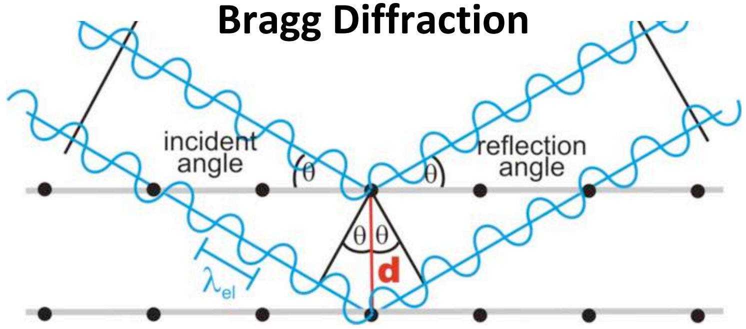
→ **Mass & wavefunction**

Small-Angle Scattering

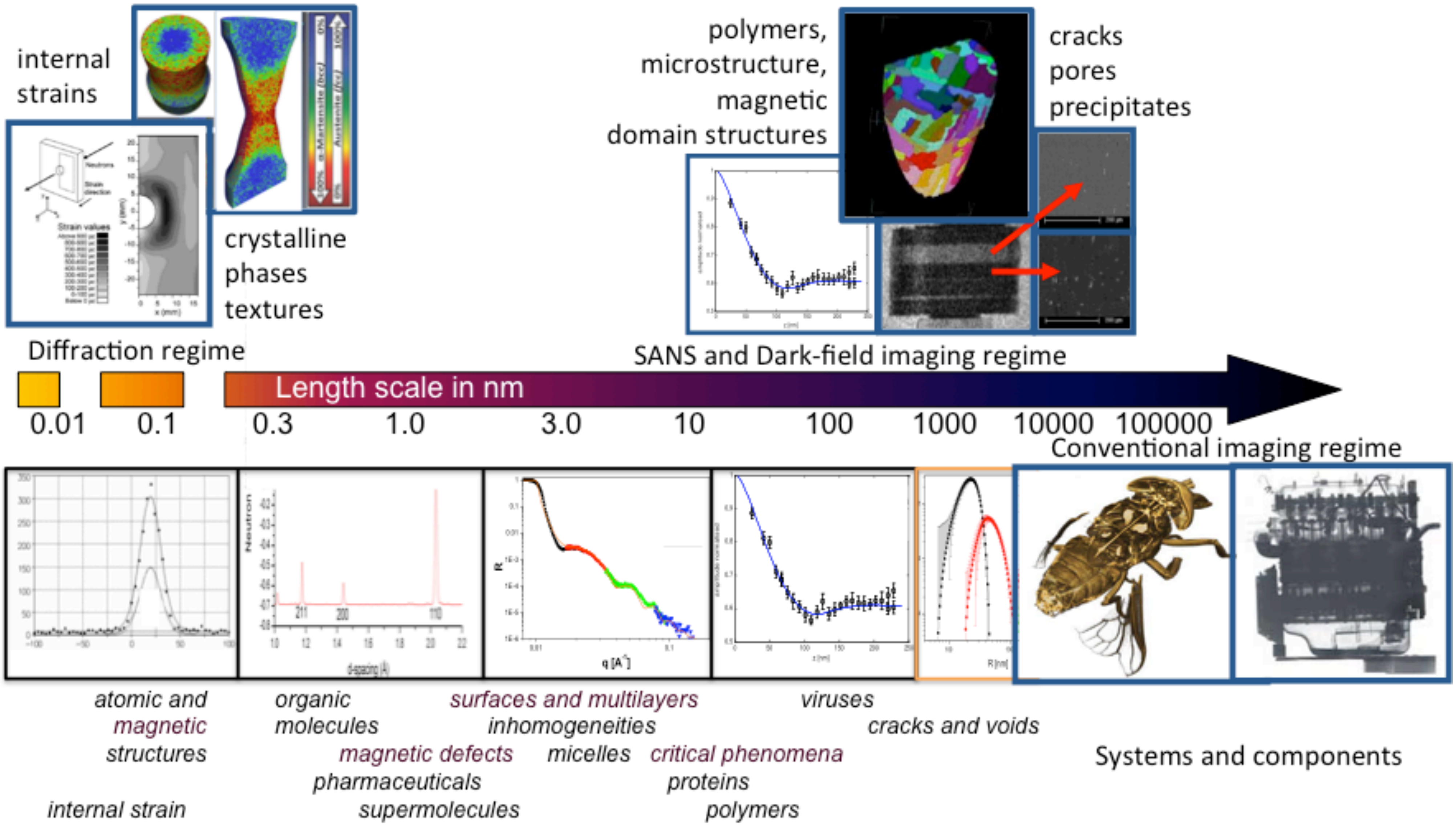




Bragg Diffraction



Neutron Imaging Today



Thank you

- Questions?