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Eberhard H. Lehmann
:: Neutron Imaging & Activation Group :: Paul Scherrer Institut

Neutron Imaging
… and options for quantification …

19th HERCULES Specialized Course on «Quantitative Imaging»

Eberhard H. Lehmann

German, working in Switzerland

Education: reactor physicist

PhD: physics of the fast breeder reactor

Active in neutron imaging since 1995

Group leader «Neutron Imaging & Activation»

Operating facilities at the Swiss spallation source

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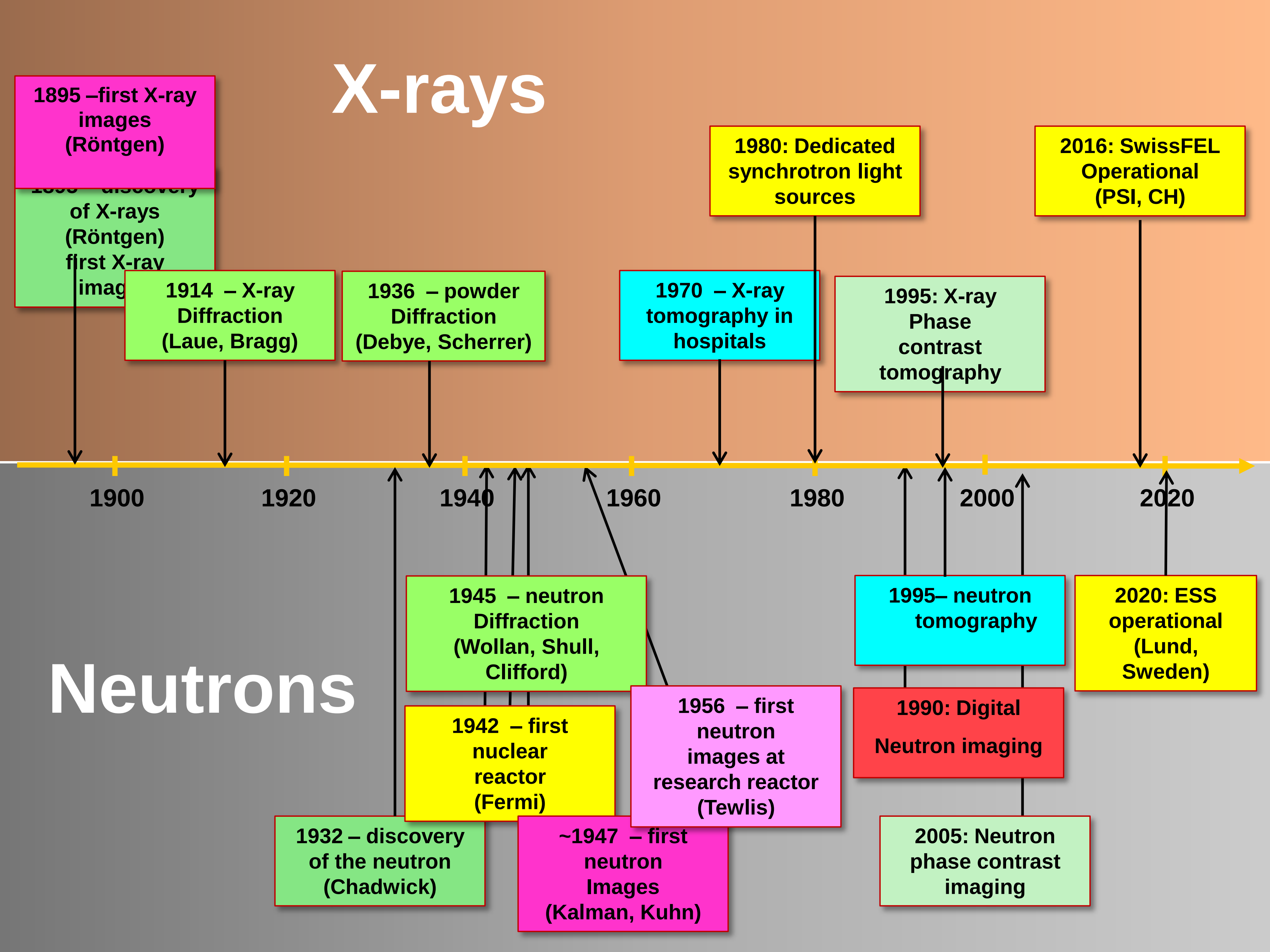
OUTLINE

1. Historical background: X-rays vs. Neutrons - the “mirrored” techniques
2. Neutrons and their interaction with matter
3. Setup of a neutron imaging facility
4. Status in a world-wide context
5. Methods in neutron imaging - overview
6. Data processing - Quantification
7. Fields of applications
8. Future developments

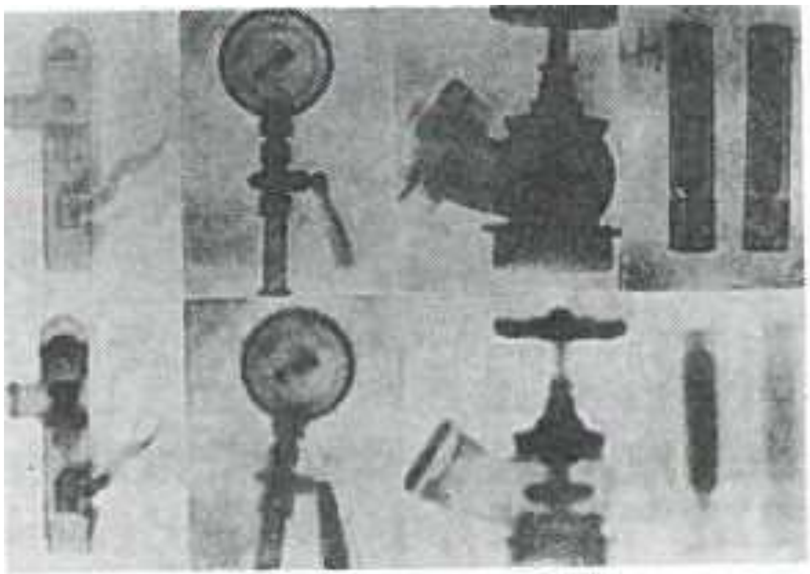
9. Summary & Conclusions


X-rays
1895 –first X-ray images (Röntgen)
of X-rays
(Röntgen)
first X-ray
1914 – X-ray Diffraction (Laue, Bragg)
1936 – powder Diffraction (Debye, Scherrer)
1970 – X-ray tomography in hospitals
1980: Dedicated synchrotron light sources
1995: X-ray Phase contrast tomography
2016: SwissFEL Operational (PSI, CH)
1900
1920
1940
1960
1980
2000
2020
Neutrons
1932 – discovery of the neutron (Chadwick)
1942 – first nuclear reactor (Fermi)
1945 – neutron Diffraction (Wollan, Shull, Clifford)
~1947 – first neutron Images (Kalman, Kuhn)
1956 – first neutron images at research reactor (Tewlis)
1990: Digital Neutron imaging
1995– neutron tomography
2005: Neutron phase contrast imaging
2020: ESS operational (Lund, Sweden)

X-rays vs. neutrons

- free neutrons were discovered **37 years** after the X-rays were found
- neutron imaging started **50 years** after first X-ray images were made
- neutron diffraction comes **30 years** later than X-ray diffraction
- neutron tomography comes **25 years** later than X-ray tomography in hospitals
- phase contrast imaging with neutrons comes **10 years** later than with X-rays
- neutron imaging is **now** a competitive and complementary method compared to the X-ray techniques

From radiography to tomography



H. Kallmann (reported by O. Peter) **about 1947**
Film radiography using an accelerator based neutron source

2015: high resolution tomography at the Swiss spallation source SINQ (Y. Wang)

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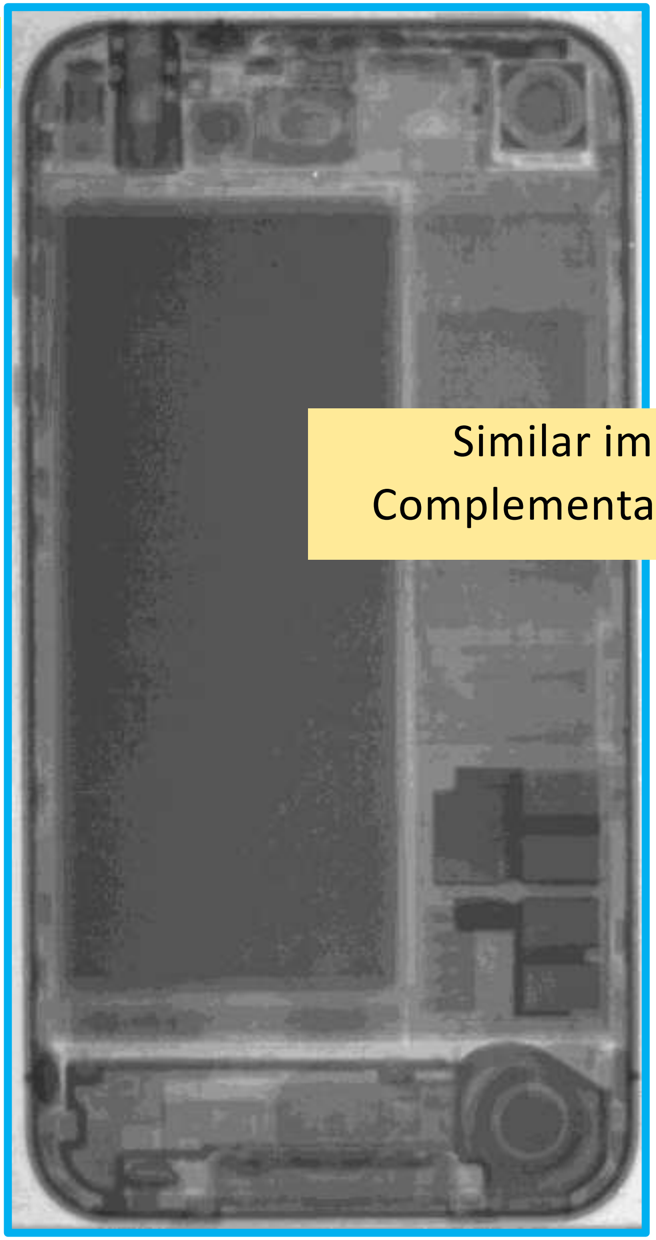
Smartphone

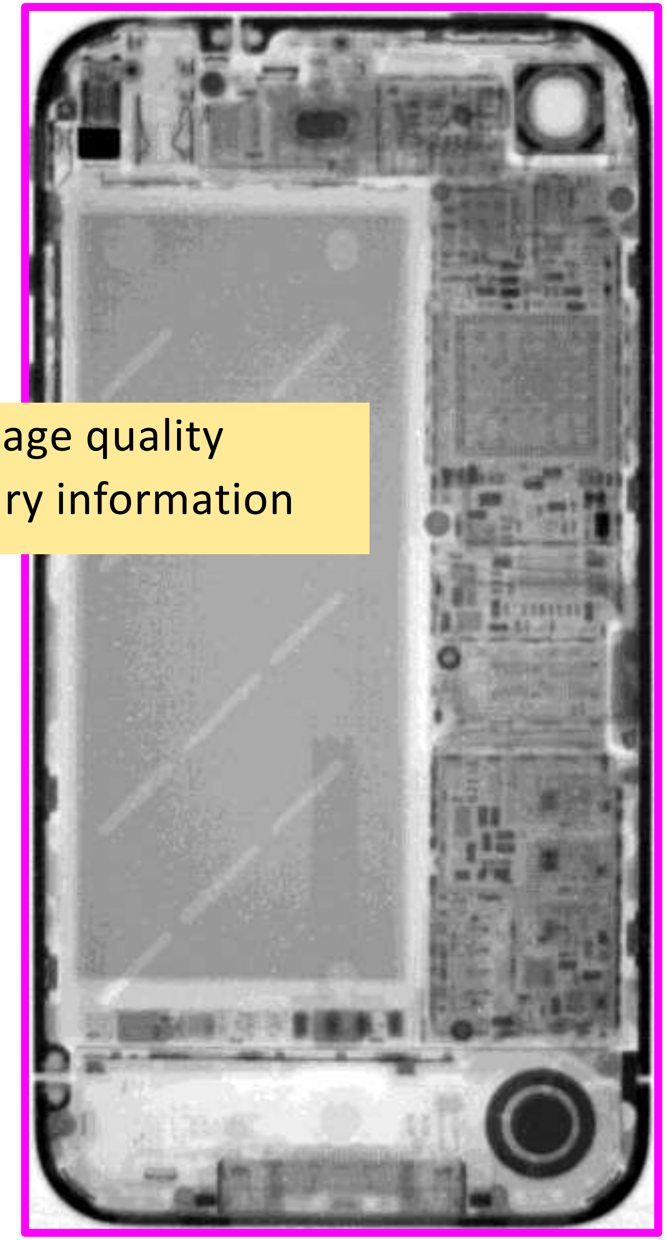
destructive imaging

Smartphone: Radiography mode

neutrons

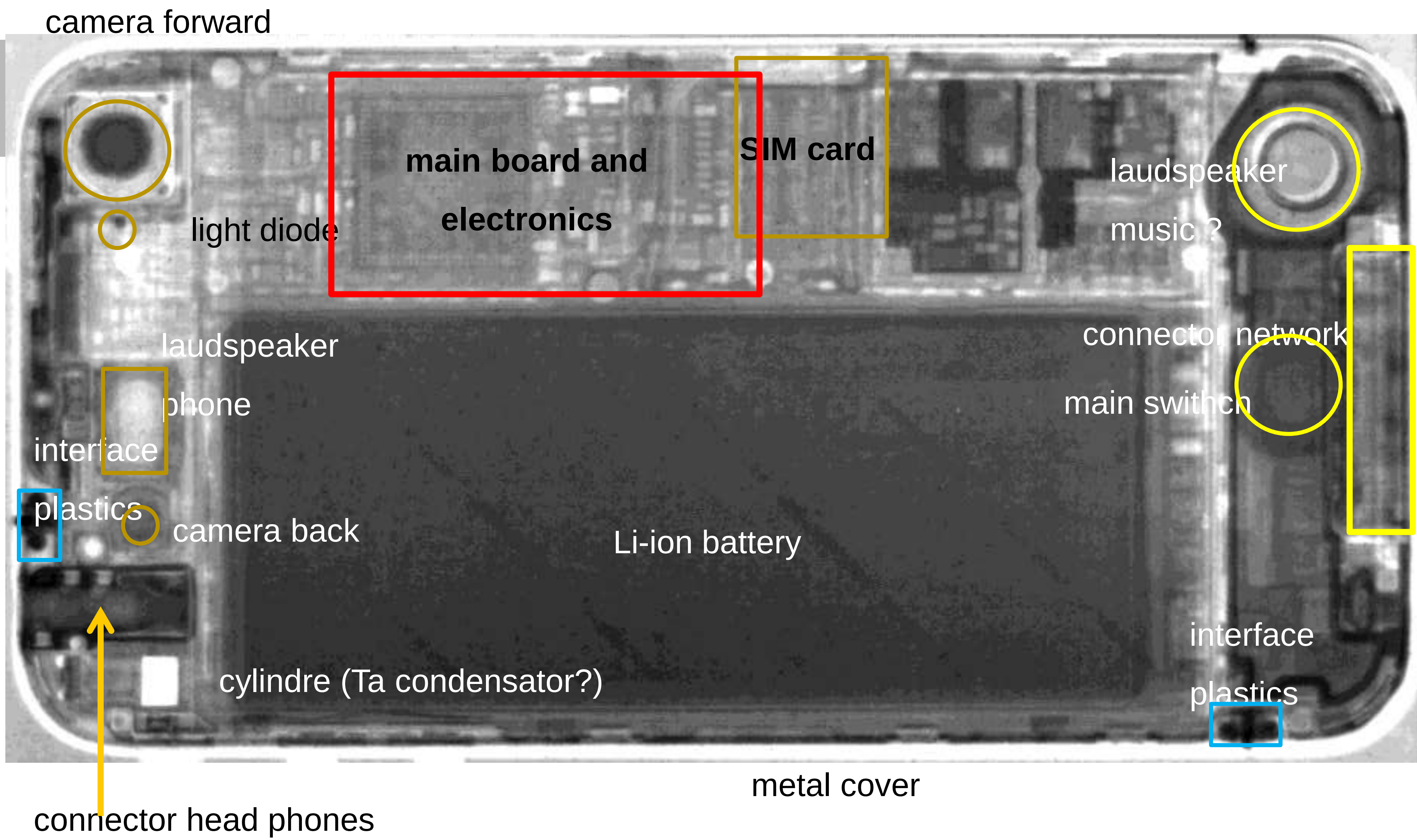


Similar image quality
Complementary information

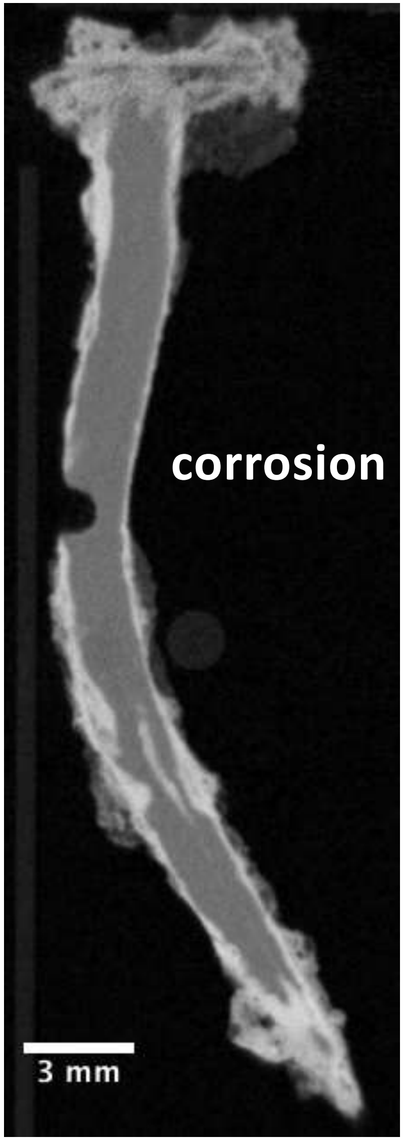


X-rays

Combined N and X: components visible



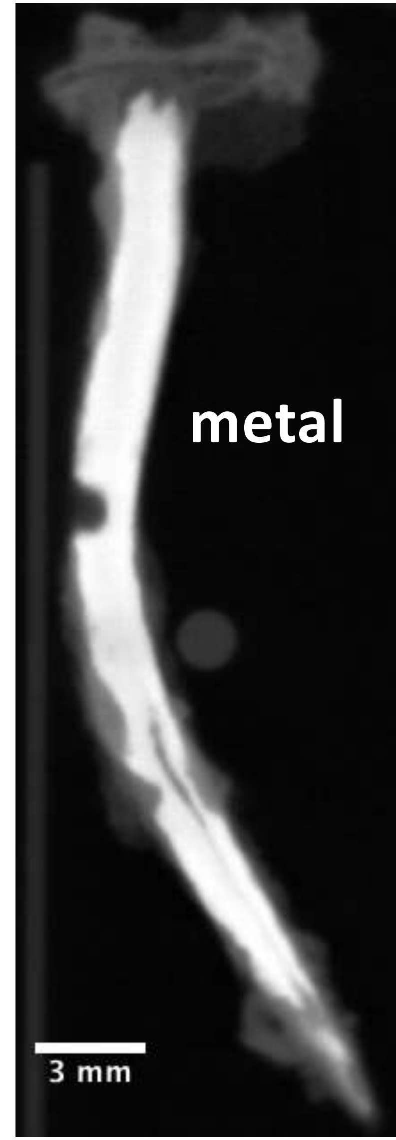
Neutrons & X-ray Imaging



Neutron-CT

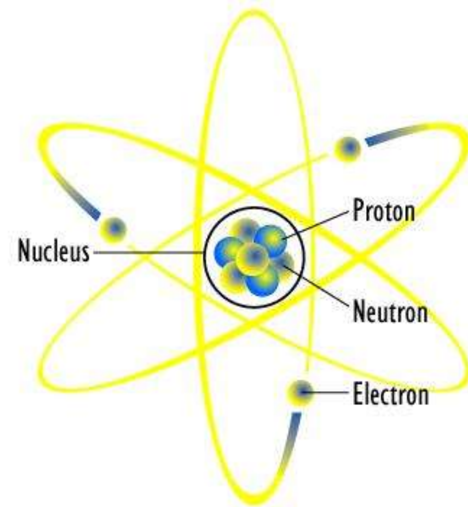
Heavily corroded nail from the Roman period (age: 2000 years)

- → Same image quality
- → Complementary information
- → High resolution
- → Tomography (now standard)
- → Option for «data fusion»

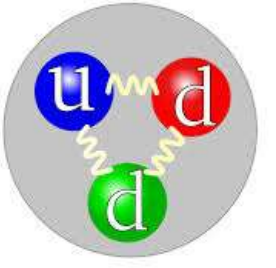


X-ray-CT

Properties of the free neutron



- **Size:** $1.6 * 10^{-15}$ m
- **Mass:** $1.674927351(74) * 10^{-27}$ kg
- **Charge:** 0
- **Spin:** ½ (two states possible)
- **Velocity:** few m/s (ultra cold) to speed of light (very fast)
- **Elementary composition:** 3 Quarks up-down-down
- **Magnetic moment:** $-1.913\ \mu_N$
- **Interaction with matter:** nuclear reactions: absorption, scattering, fission
- **Classification:** Baryon, Fermion
- **Half-life:** 881.5 s



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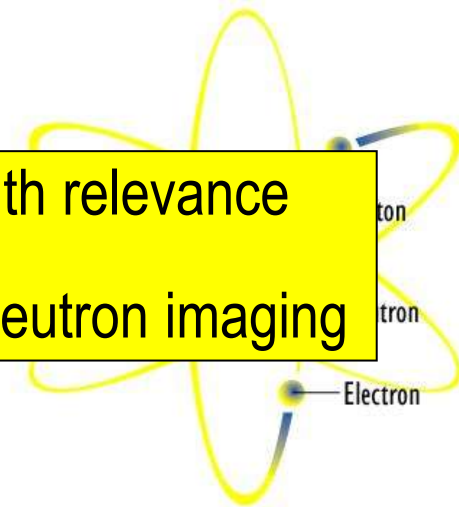
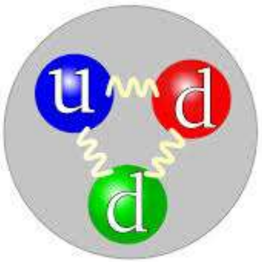
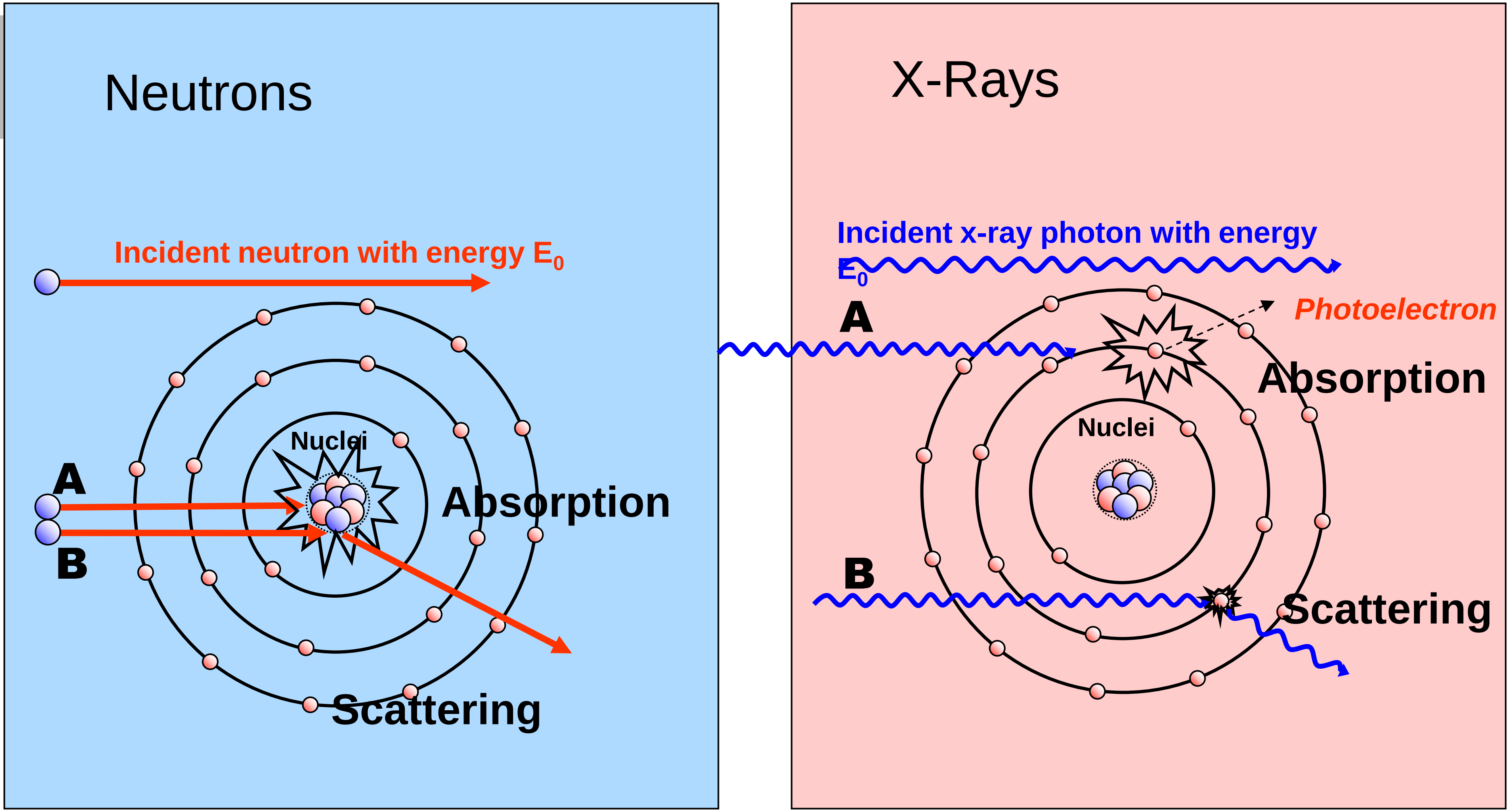


with relevance
for neutron imaging

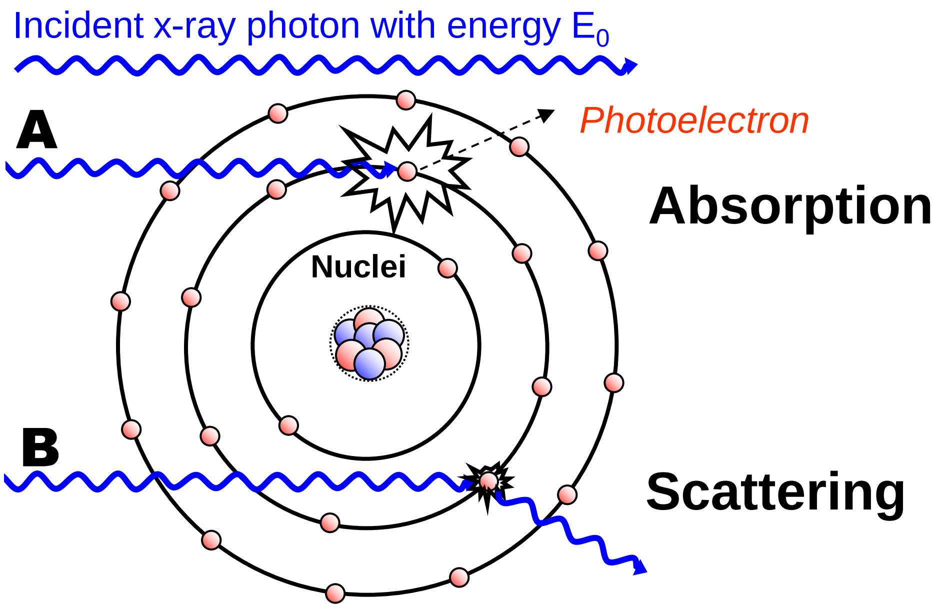


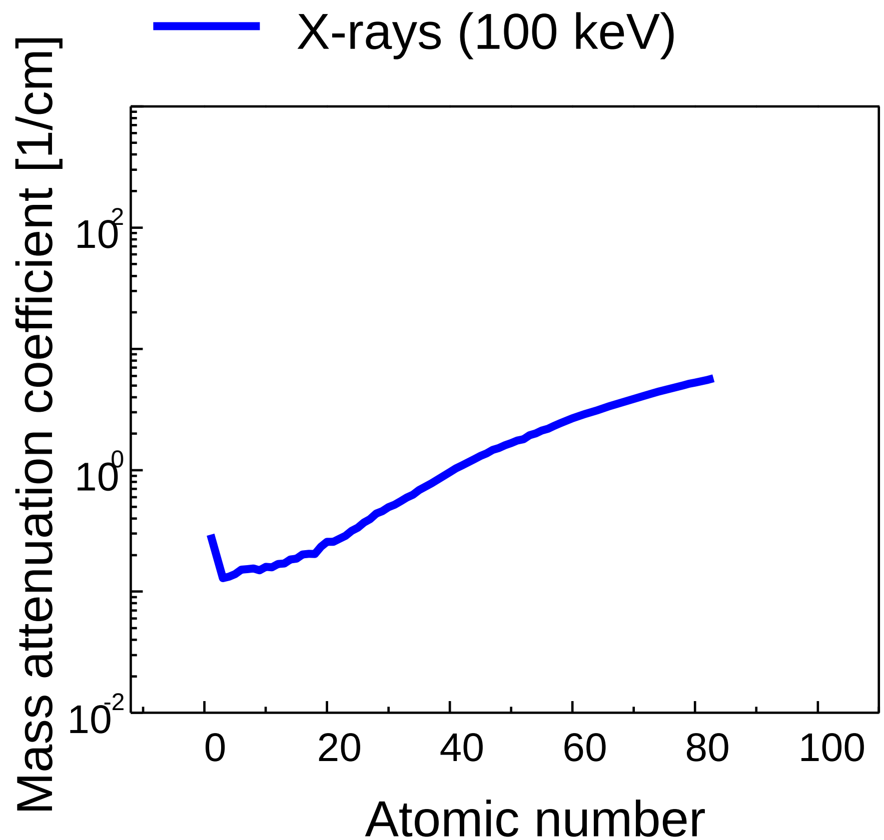
Neutrons vs. X-rays (interaction scheme)



X-rays vs. Neutrons

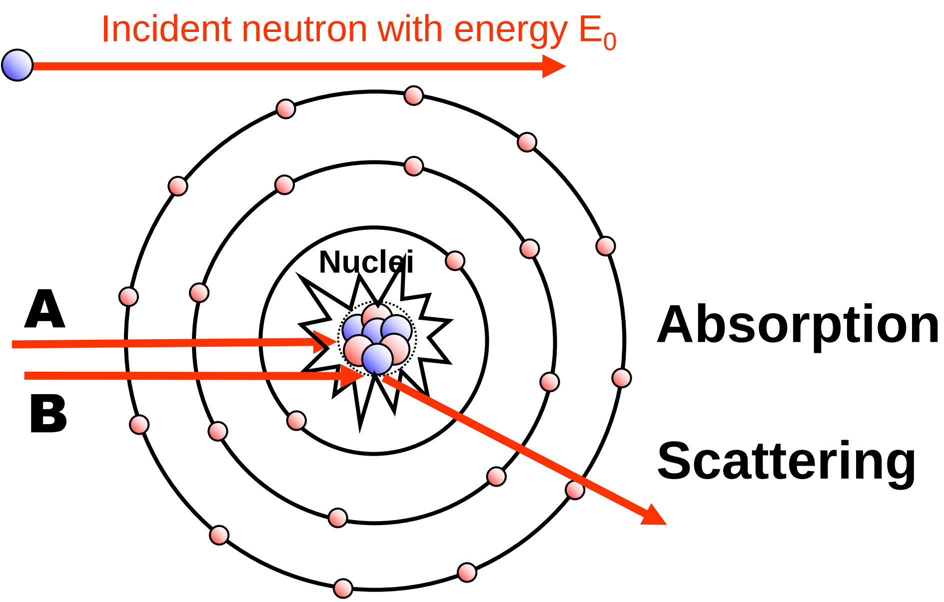
X-Rays

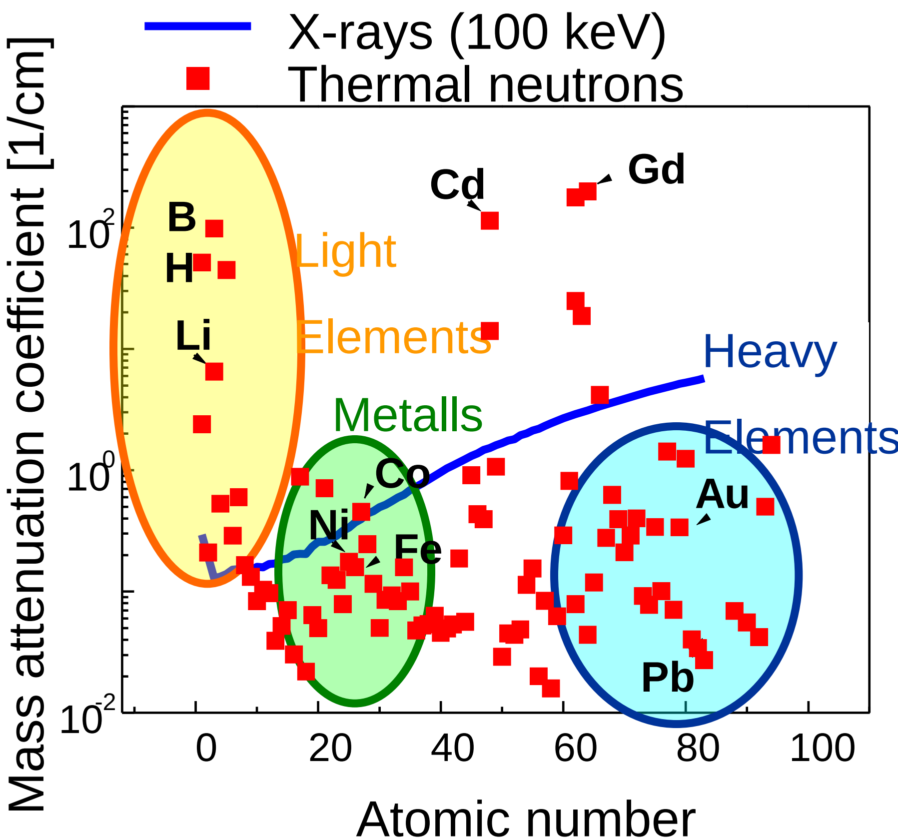




X-rays vs. Neutrons

Neutrons





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PSI

Attenuation of X-rays (100 keV)

Group → / ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	H 0.02																	He 0.02
2	Li 0.06	Be 0.22											B 0.28	C 0.27	N 0.11	O 0.16	F 0.14	Ne 0.17
3	Na 0.13	Mg 0.24											Al 0.38	Si 0.33	P 0.25	S 0.30	Cl 0.23	Ar 0.20
4	K 0.14	Ca 0.26	Sc 0.48	Ti 0.73	V 1.04	Cr 1.29	Mn 1.32	Fe 1.57	Co 1.78	Ni 1.96	Cu 1.97	Zn 1.64	Ga 1.42	Ge 1.33	As 1.50	Se 1.23	Br 0.90	Kr 0.73
5	Rb 0.47	Sr 0.86	Y 1.61	Zr 2.47	Nb 3.43	Mo 4.29	Tc 5.06	Ru 5.71	Rh 6.08	Pd 6.13	Ag 5.67	Cd 4.84	In 4.31	Sn 3.98	Sb 4.28	Te 4.06	I 3.45	Xe 2.53
6	Cs 1.47	Ba 2.73		Hf 19.70	Ta 25.47	W 30.49	Re 34.47	Os 37.92	Ir 39.01	Pt 38.61	Au 35.94	Hg 25.88	Tl 23.23	Pb 22.81	Bi 20.28	Po 20.22	At -	Rn 9.77
7	Fr -	Ra 11.80		Rf -	Db -	Sg -	Bh -	Hs -	Mt -	Ds -	Rg -	Uub -	Uut -	Uuq -	Uup -	Uuh -	Uus -	Uuo -

Lanthanides	La 5.04	Ce 5.79	Pr 6.23	Nd 6.46	Pm 7.33	Sm 7.68	Eu 5.66	Gd 8.69	Tb 9.46	Dy 10.17	Ho 10.17	Er 11.70	Tm 12.49	Yb 9.32	Lu 14.07
Actinides	Ac 24.47	Th 28.95	Pa 39.65	U 49.08	Np -	Pu -	Am -	Cm -	Bk -	Cf -	Es -	Fm -	Md -	No -	Lr -

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Attenuation of thermal neutrons

Group → / ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	H 3.44																	He 0.02
2	Li 3.30	Be 0.79											B 101.6	C 0.56	N 0.43	O 0.17	F 0.20	Ne 0.10
3	Na 0.09	Mg 0.15											Al 0.1	Si 0.11	P 0.12	S 0.06	Cl 1.33	Ar 0.03
4	K 0.06	Ca 0.08	Sc 2.00	Ti 0.60	V 0.72	Cr 0.54	Mn 1.21	Fe 1.19	Co 3.92	Ni 2.05	Cu 1.07	Zn 0.35	Ga 0.49	Ge 0.47	As 0.67	Se 0.73	Br 0.24	Kr 0.61
5	Rb 0.08	Sr 0.14	Y 0.27	Zr 0.29	Nb 0.40	Mo 0.52	Tc 1.76	Ru 0.58	Rh 10.88	Pd 0.78	Ag 4.04	Cd 115.1	In 7.58	Sn 0.21	Sb 0.30	Te 0.25	I 0.23	Xe 0.43
6	Cs 0.29	Ba 0.07		Hf 4.99	Ta 1.49	W 1.47	Re 6.85	Os 2.24	Ir 30.46	Pt 1.46	Au 6.23	Hg 16.21	Tl 0.47	Pb 0.38	Bi 0.27	Po -	At -	Rn -
7	Fr -	Ra 0.34		Rf -	Db -	Sg -	Bh -	Hs -	Mt -	Ds -	Rg -	Uub -	Uut -	Uuq -	Uup -	Uuh -	Uus -	Uuo -
Lanthanides				La 0.52	Ce 0.14	Pr 0.41	Nd 1.87	Pm 5.72	Sm 171.47	Eu 94.58	Gd 1479.0	Tb 0.93	Dy 32.42	Ho 2.25	Er 5.48	Tm 3.53	Yb 1.40	Lu 2.75
Actinides				Ac -	Th 0.59	Pa 8.46	U 0.82	Np 9.80	Pu 50.20	Am 2.86	Cm -	Bk -	Cf -	Es -	Fm -	Md -	No -	Lr -

Duality of neutrons – visible in imaging

de Broglie: λ=h/(m·v)

neutron as particle

- single neutrons can be counts on the detector
- description with Monte-Carlo codes (cross-sections as interaction probability) per neutron
- scattering and absorption adequately confirmed

neutron as wave

- phase effects at edges – refraction or total reflection
- refraction index based on wave functions
- interference of waves as interpretation
- coherence can play an essential role

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Interaction principle of neutrons with matter

- Neutrons interact with the **nuclei** of the atoms only

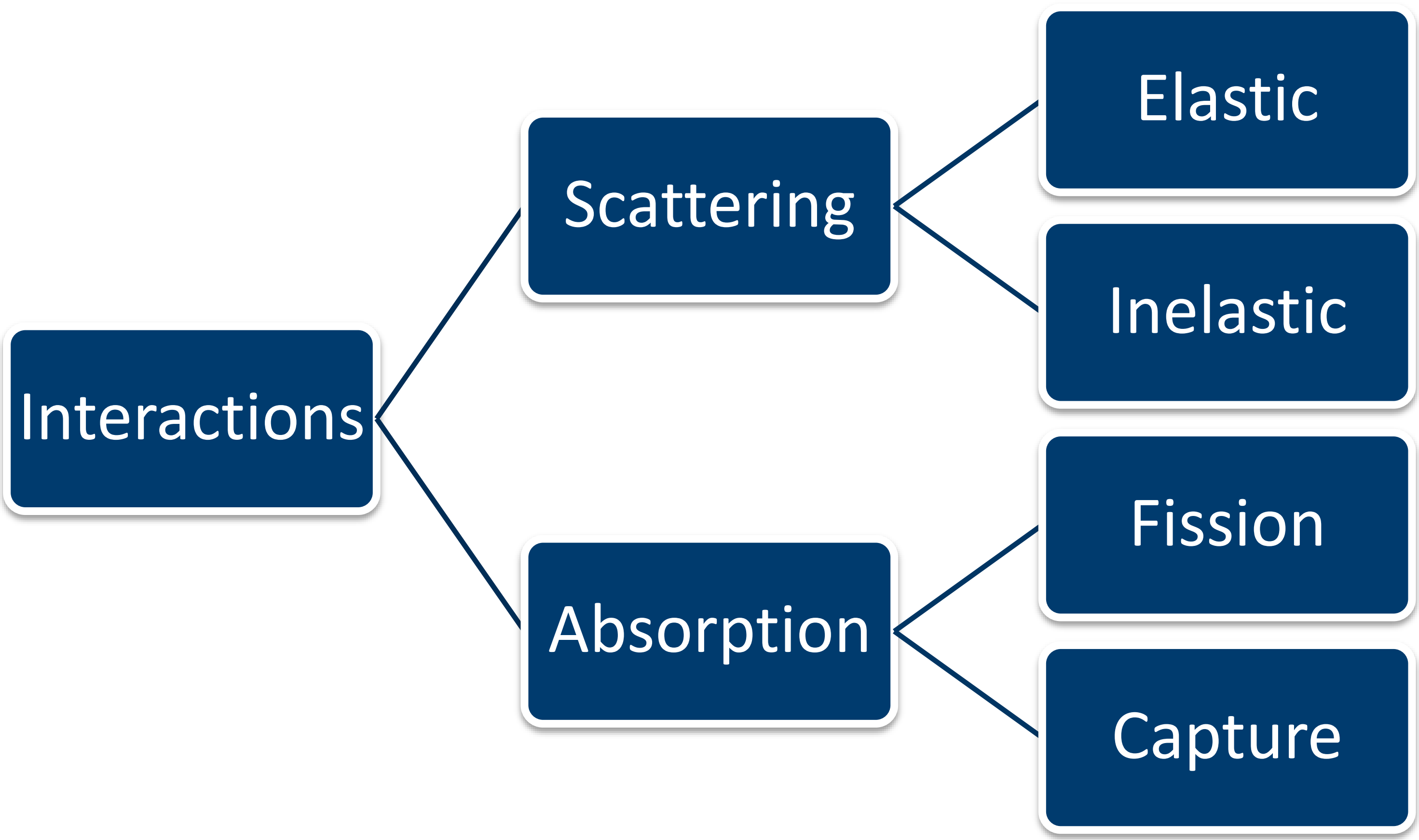
- The interaction can be: **collision** (scattering), **absorption** (creation of radioactive isotopes) or **fission** (with fissile materials)

- The strength of the interaction with matter is expressed by *„microscopic cross-sections“* – **σ** , the unit is „barn = 10^{-24} cm^{-2}“

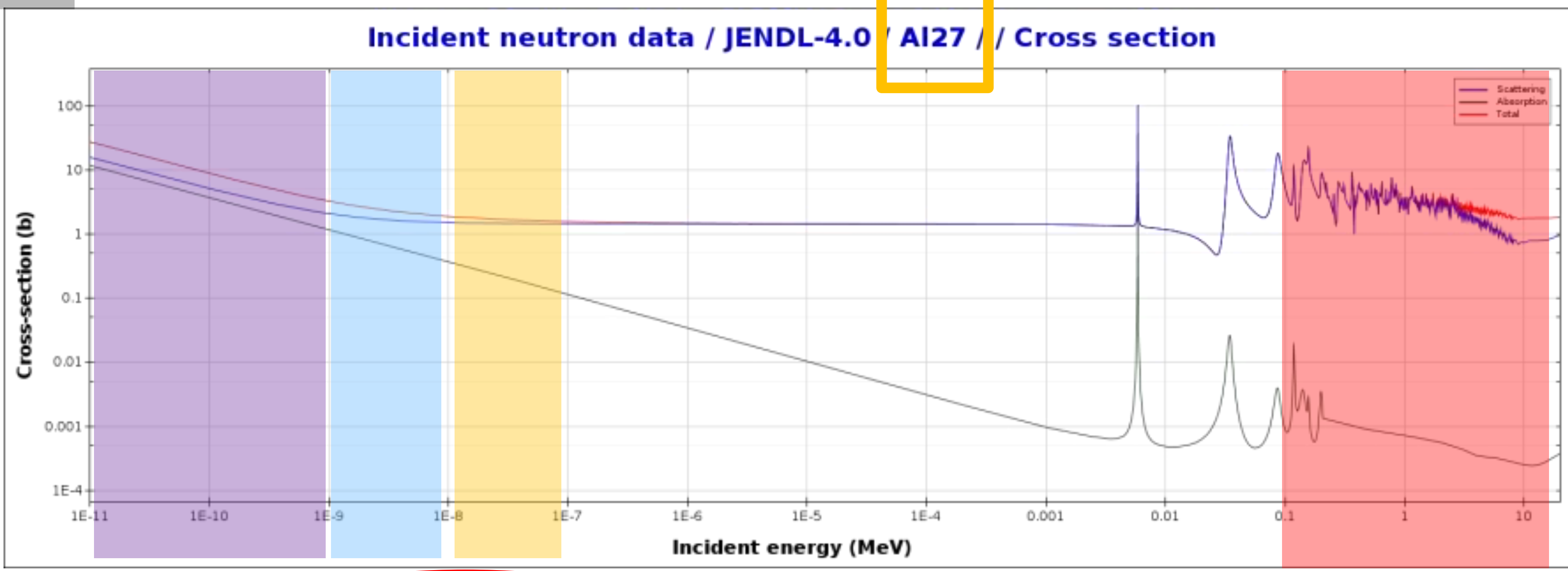
- The *“macroscopic cross-section”* Σ, also called *“attenuation coefficient”* is defined as : **Σ= N* σ**, the unit is cm^{-1}

- N = nuclear density = **(ρ*A)/M** (A=Avogadro‘s number, M=mass)

Neutron interactions with matter



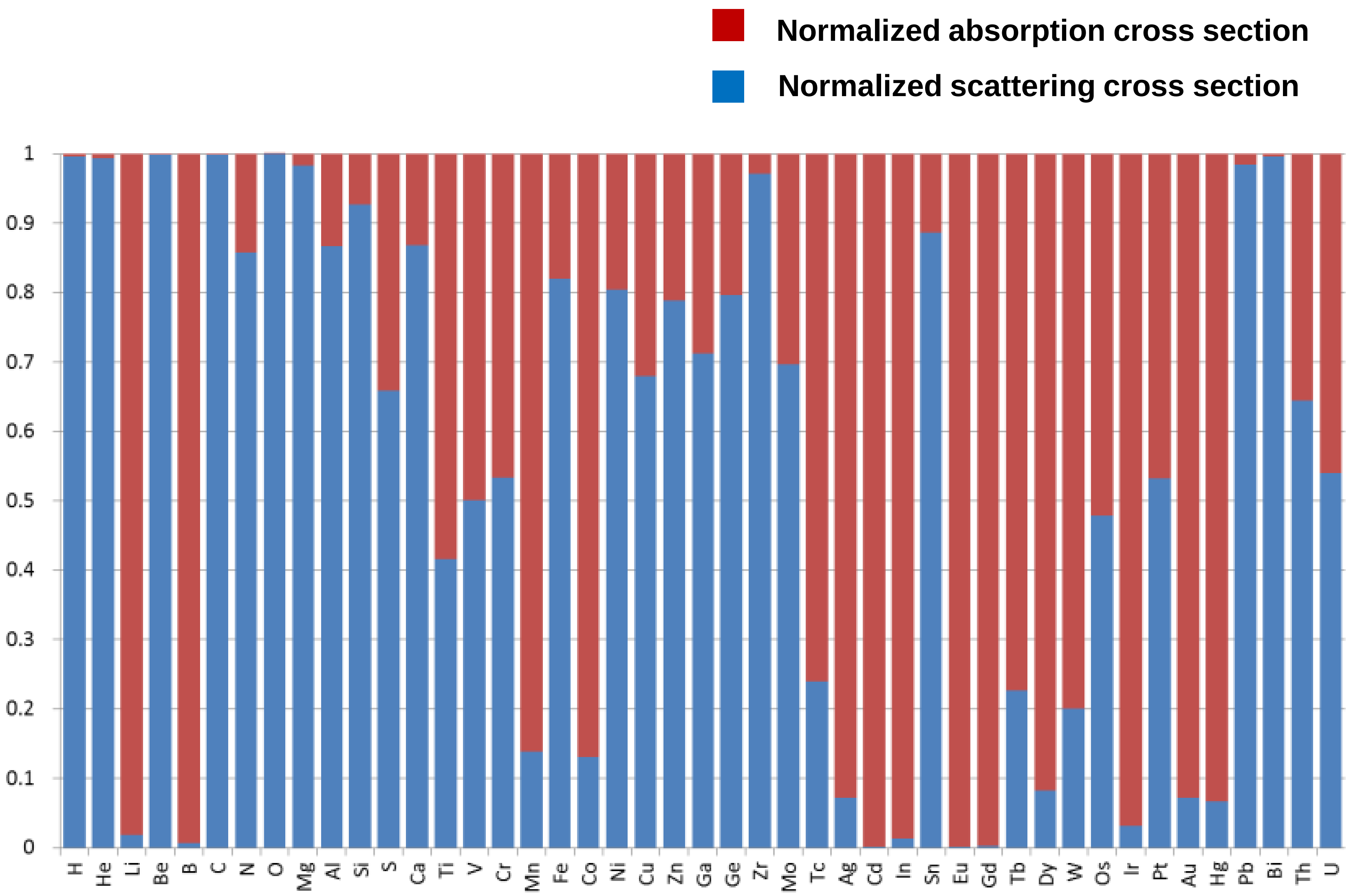
Neutron interactions with matter



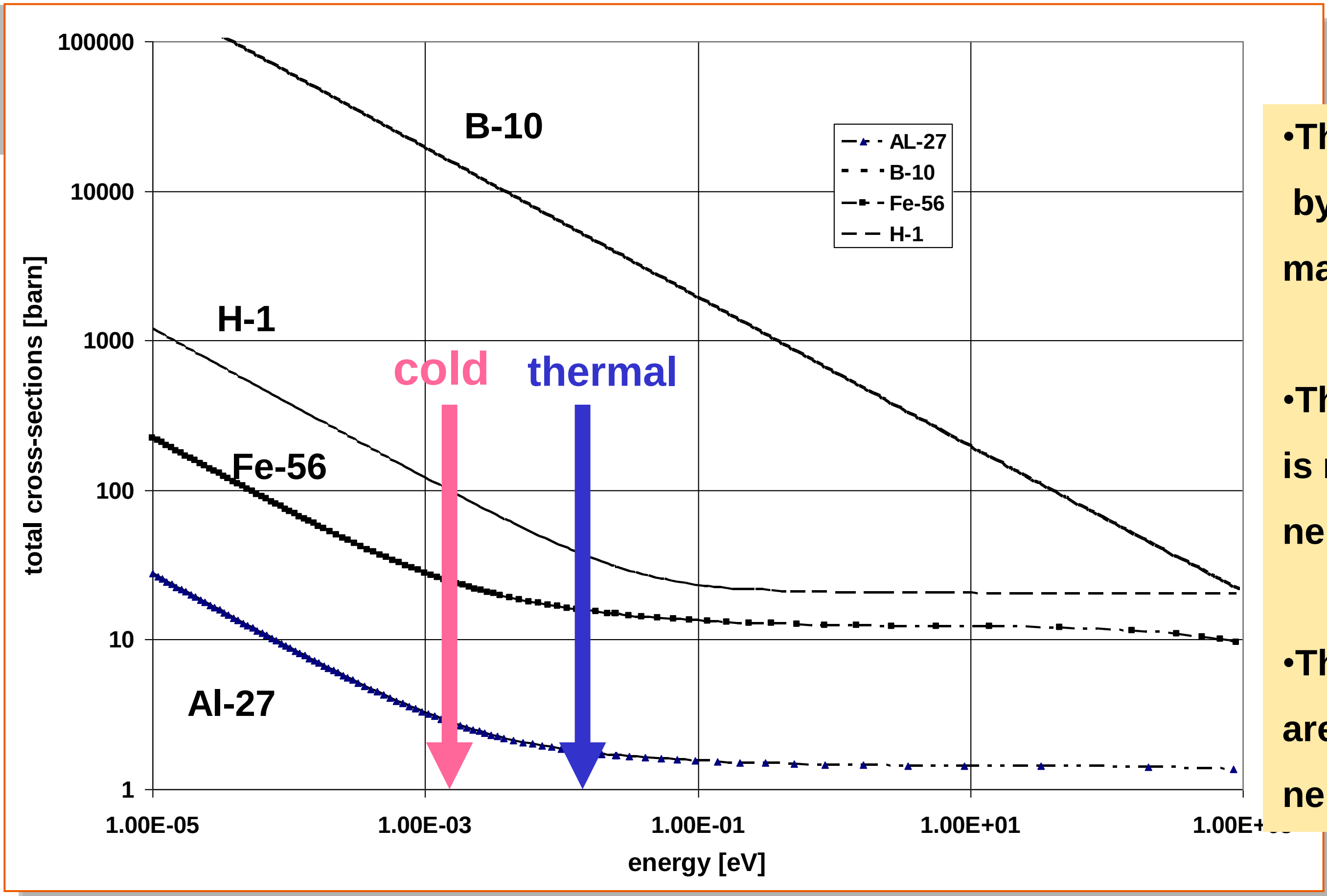
Ultra cold Cold Thermal ← Fission and spallation

Moderation

Neutron interactions with matter absorption vs. scattering



Interaction principle of neutrons with matter



- •The cross-sections can differ by orders of magnitude from material to material
- •The interaction probability is much higher for slow neutrons
- •Thermal and cold neutrons are the preferred tools in neutron imaging (E~meV)

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Neutron Utilization for Research

ADVANTAGES

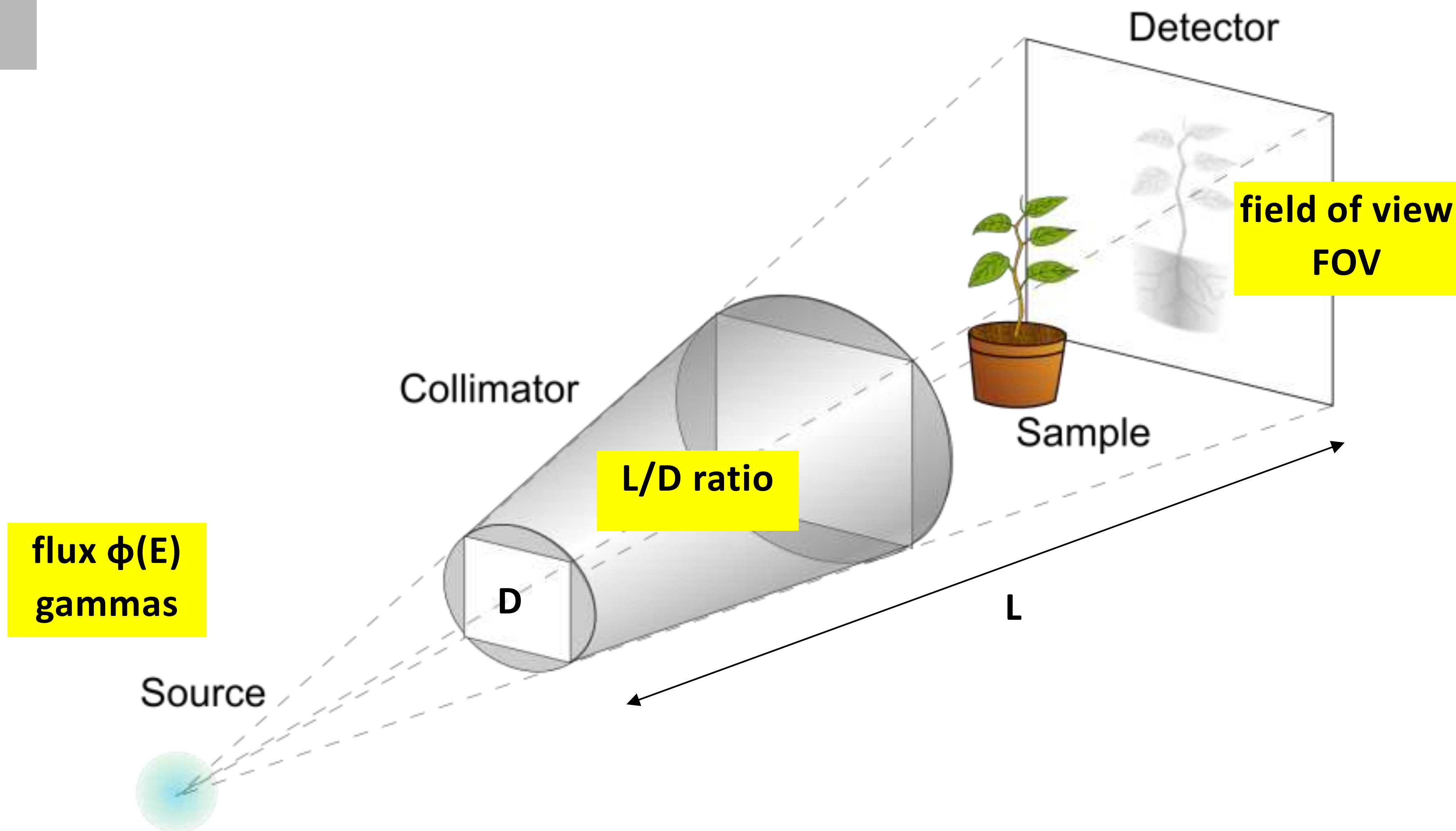
- no charge: often deeper penetration
- magnetic moment: magnetic interaction with nuclei → polarized neutrons
- high sensitivity for light elements
- different isotopes can be distinguished (D:H, B-10:B-11, Li-6: Li-7, U-235:U-238)
- energy selection using time-of-flight (at pulsed sources)

DISADVANTAGES

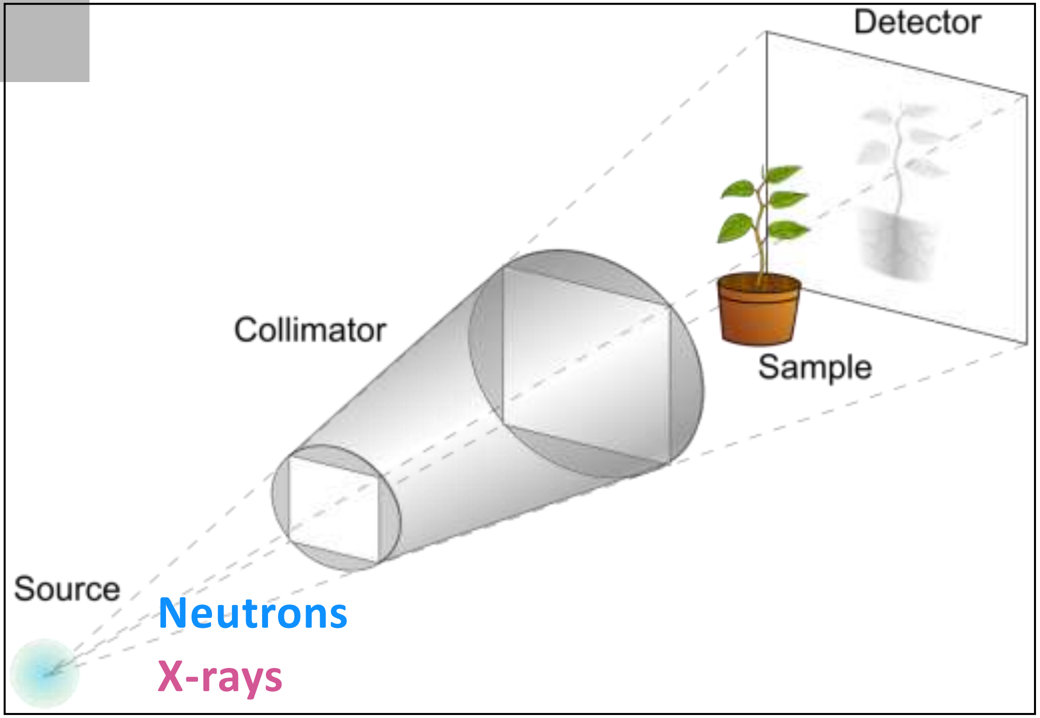
- neutron intensity limited
- no direct detection – a secondary process is needed (limiting spatial resolution)
- no charge: no focusing and guiding by el.-magnetic fields possible
- activation risks of samples

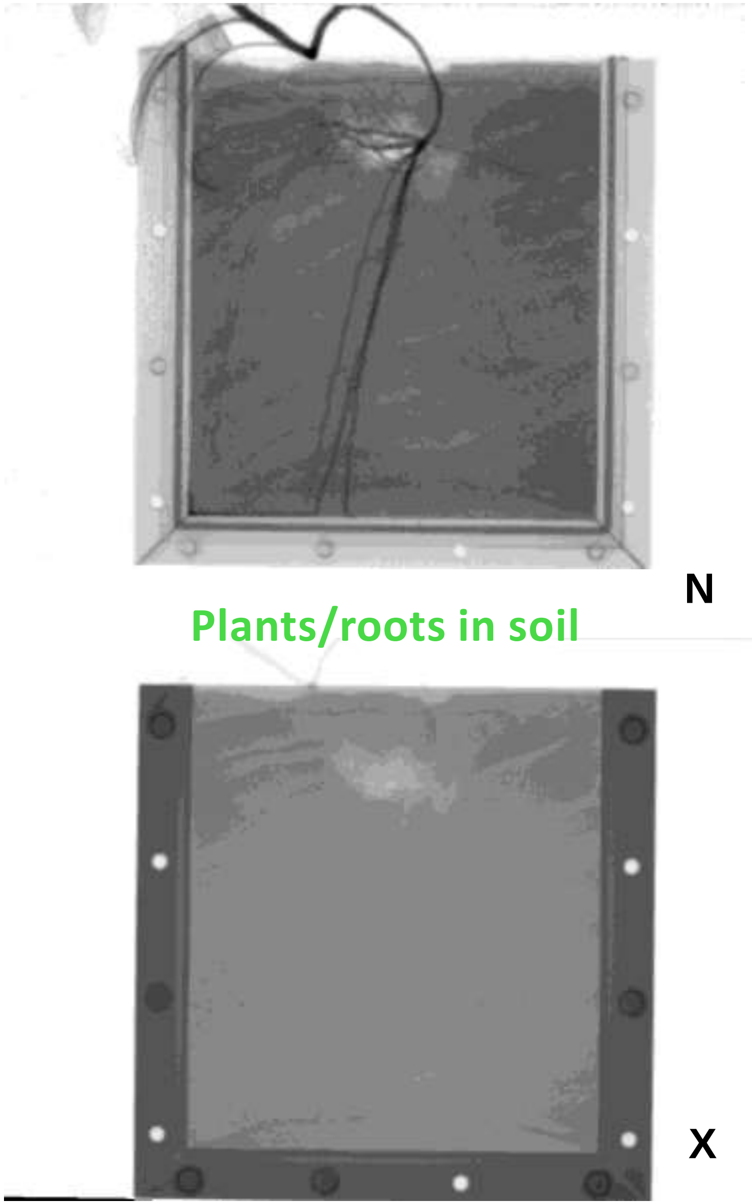
Neutron Imaging Principle

simplified setup for imaging in transmission mode



Transmission process



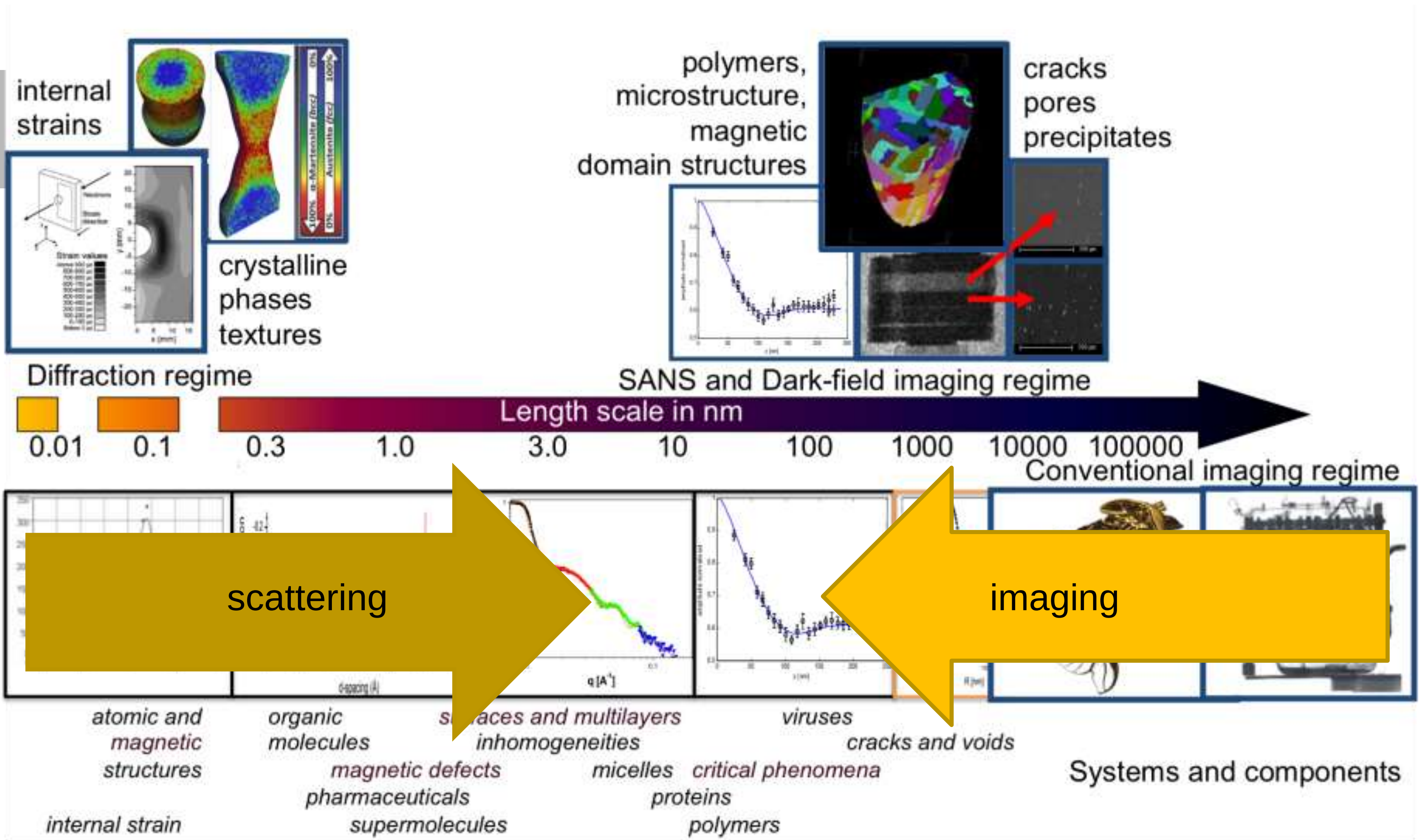


- direct attenuation
- no phase effects
- interpretation with the particle picture

Neutron Imaging Principle

- To use the interaction of (thermal / cold) neutrons with matter to get information about composition, structure and status of the object on the **macro scale**
- It is mostly the attenaution of a wide, homogenous beam by the object and the analysis of the transmitted beam fraction to be analyzed
- The efficient detection of the transmitted beam component determines the performance of the neutron imaging setup
- Advanced NI methods deal with the scattered neutrons also

Lenght scale in neutron research



Courtesy: M. Strobl ESS

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Some Terminology

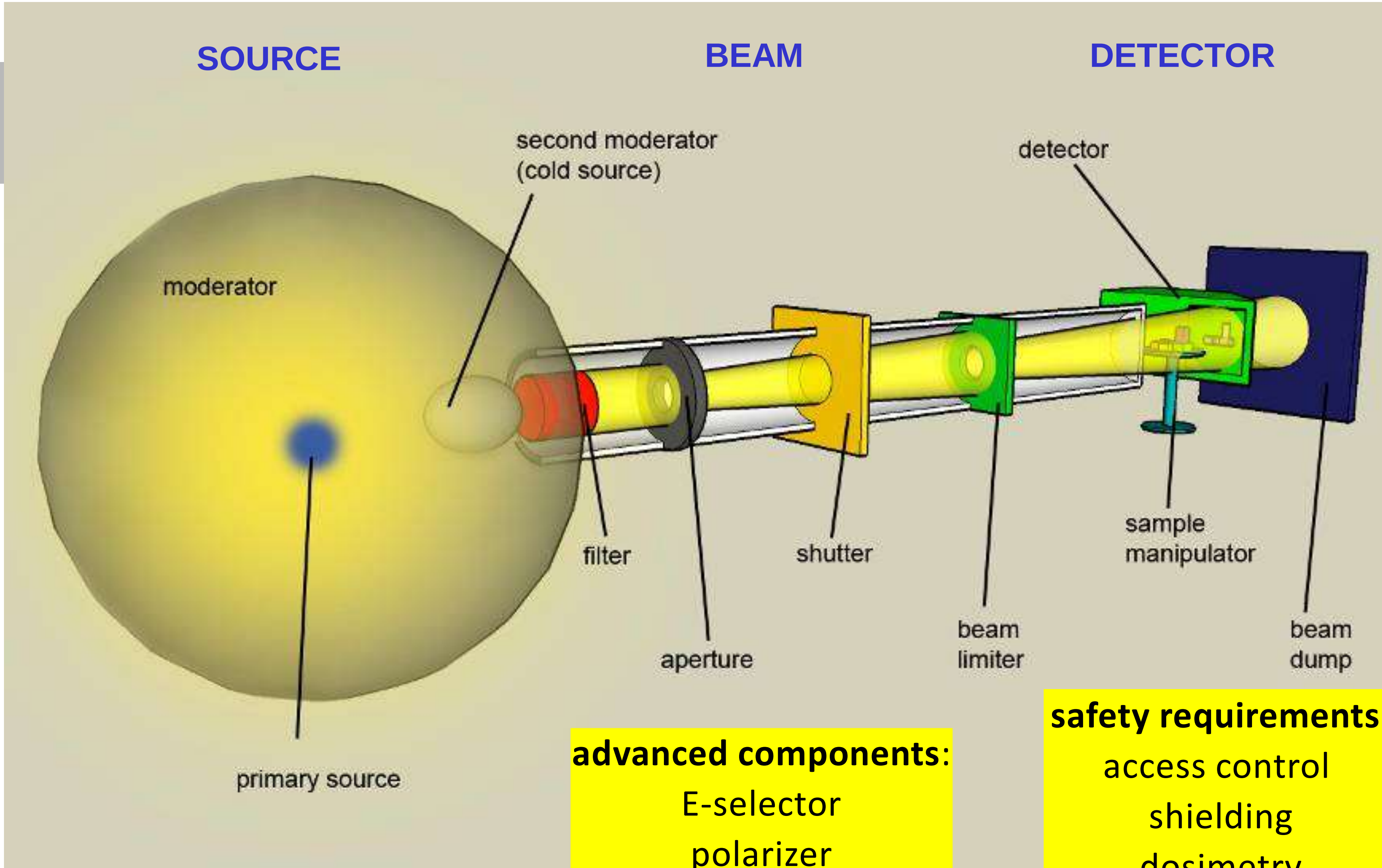
- **In the past:** **Neutron Radiography** = a method for non-destructive testing

- **Now:** **Neutron Imaging** **=**research tool for many fields of scientific applications, including material research, using more advanced methods too

- **New aspects:** digital output, data sets more than «pictures»

importance of image-processing

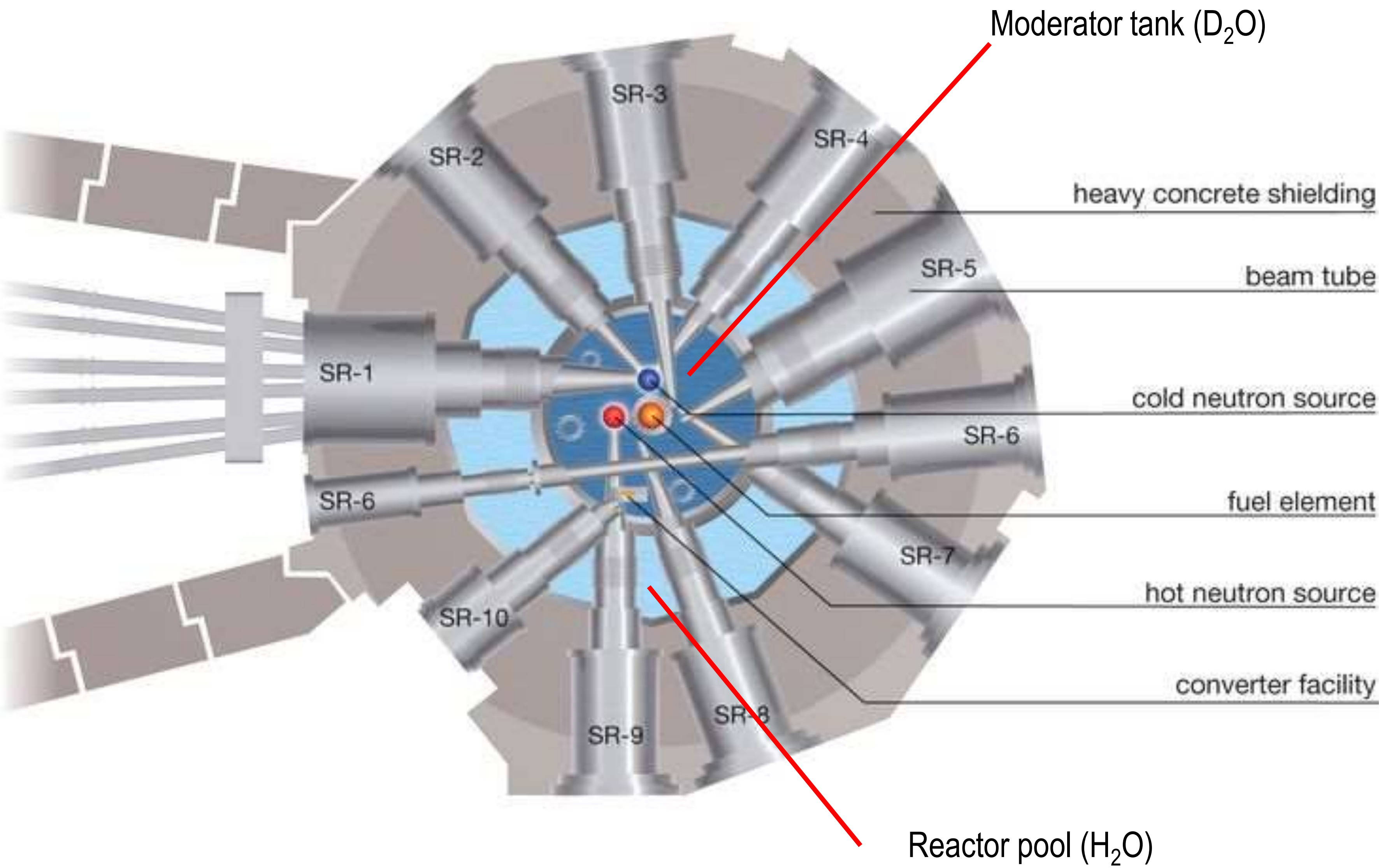
Neutron Imaging – Setup & Components



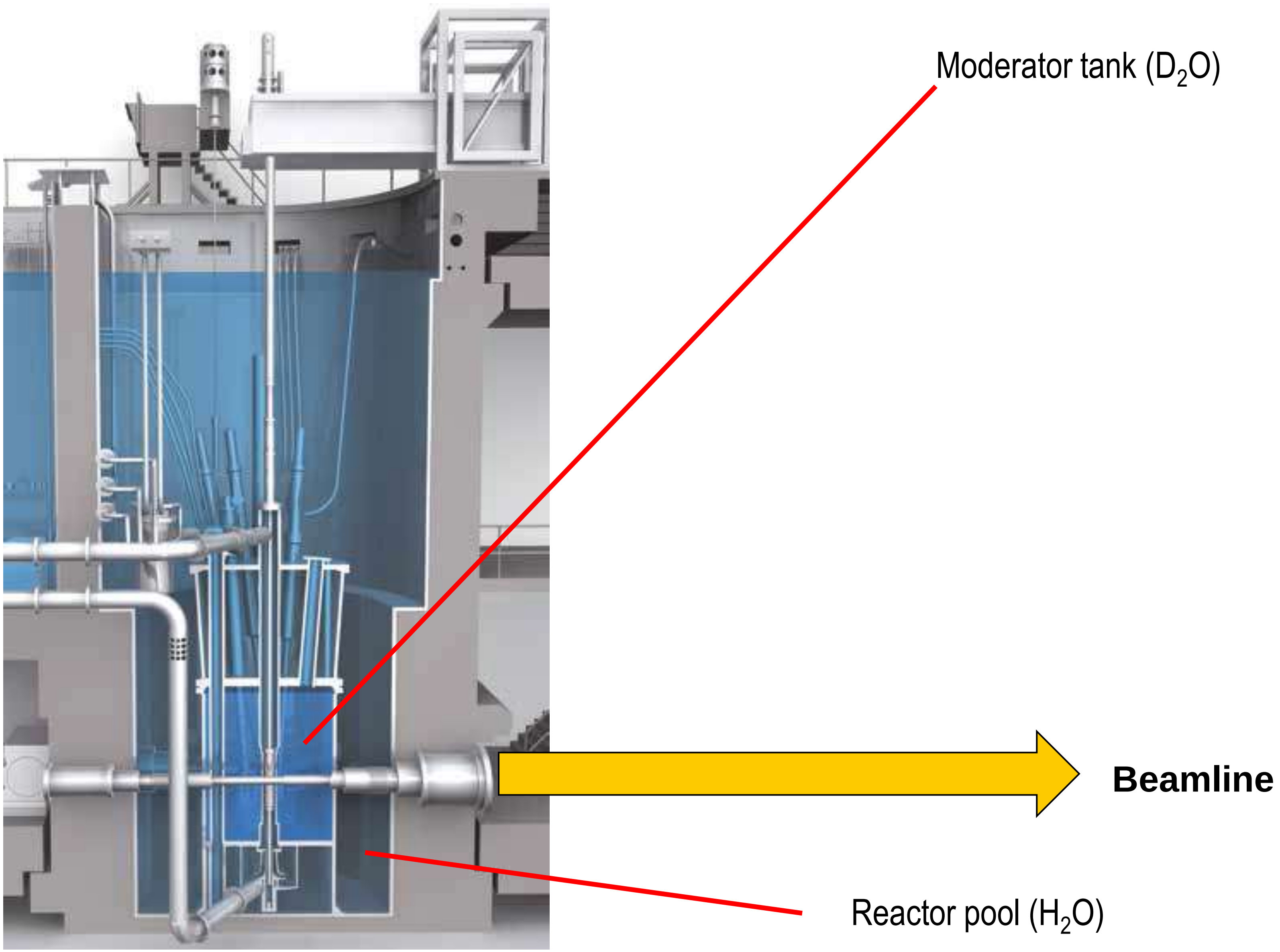
advanced components:
E-selector
polarizer
grating interferometer

safety requirements:
access control
shielding
dosimetry

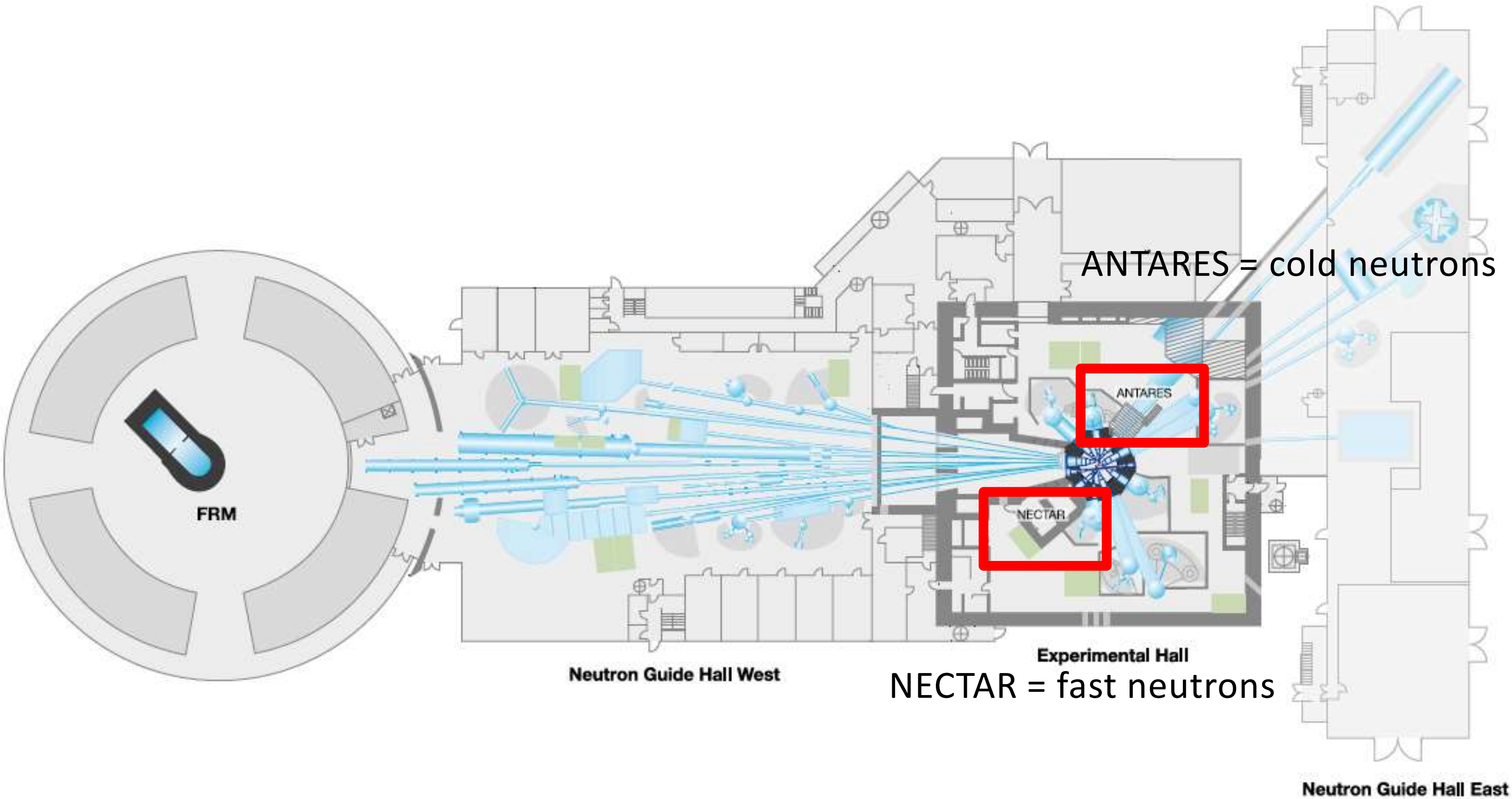
Research Reactors – Design (example FRM-2)



Research Reactors – Design (example FRM-2)



ANTARES and NECTAR @ FRM-2



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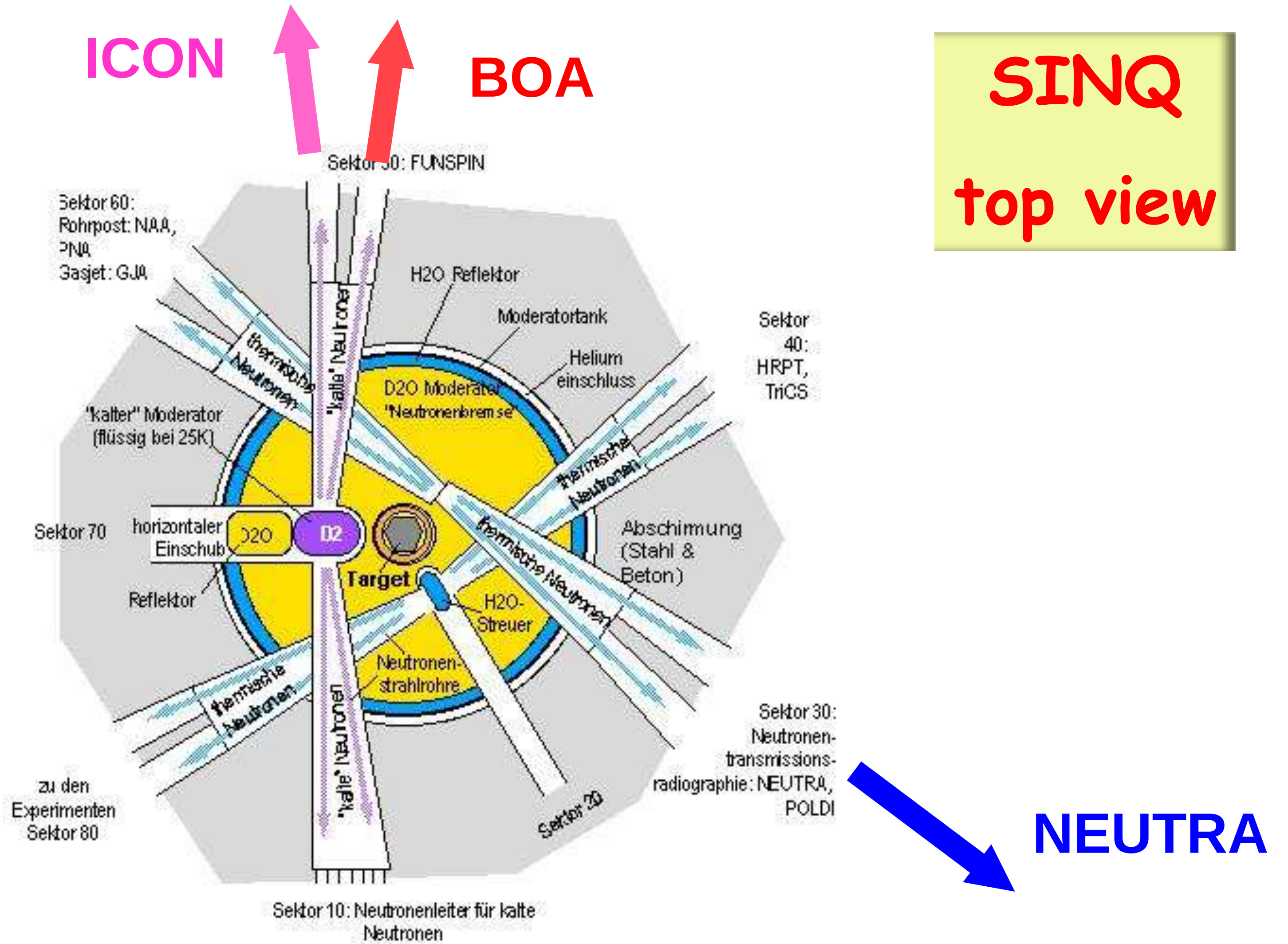
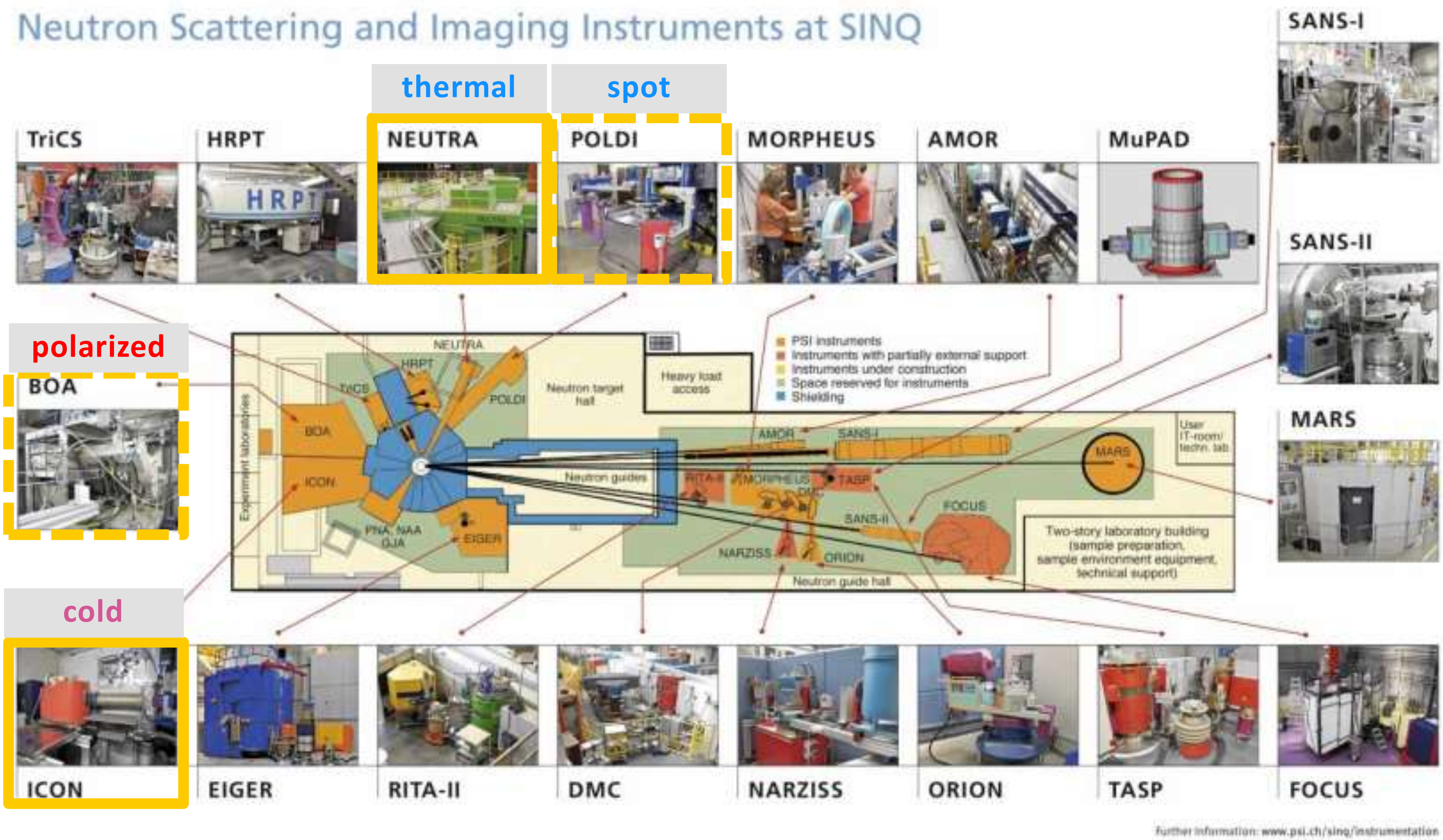
Spallation Neutron Source – example SINQ, PSI

- installations for research with thermal and cold neutrons
- about 20 beam lines
- including 2.x for imaging
- approximately parallel beam

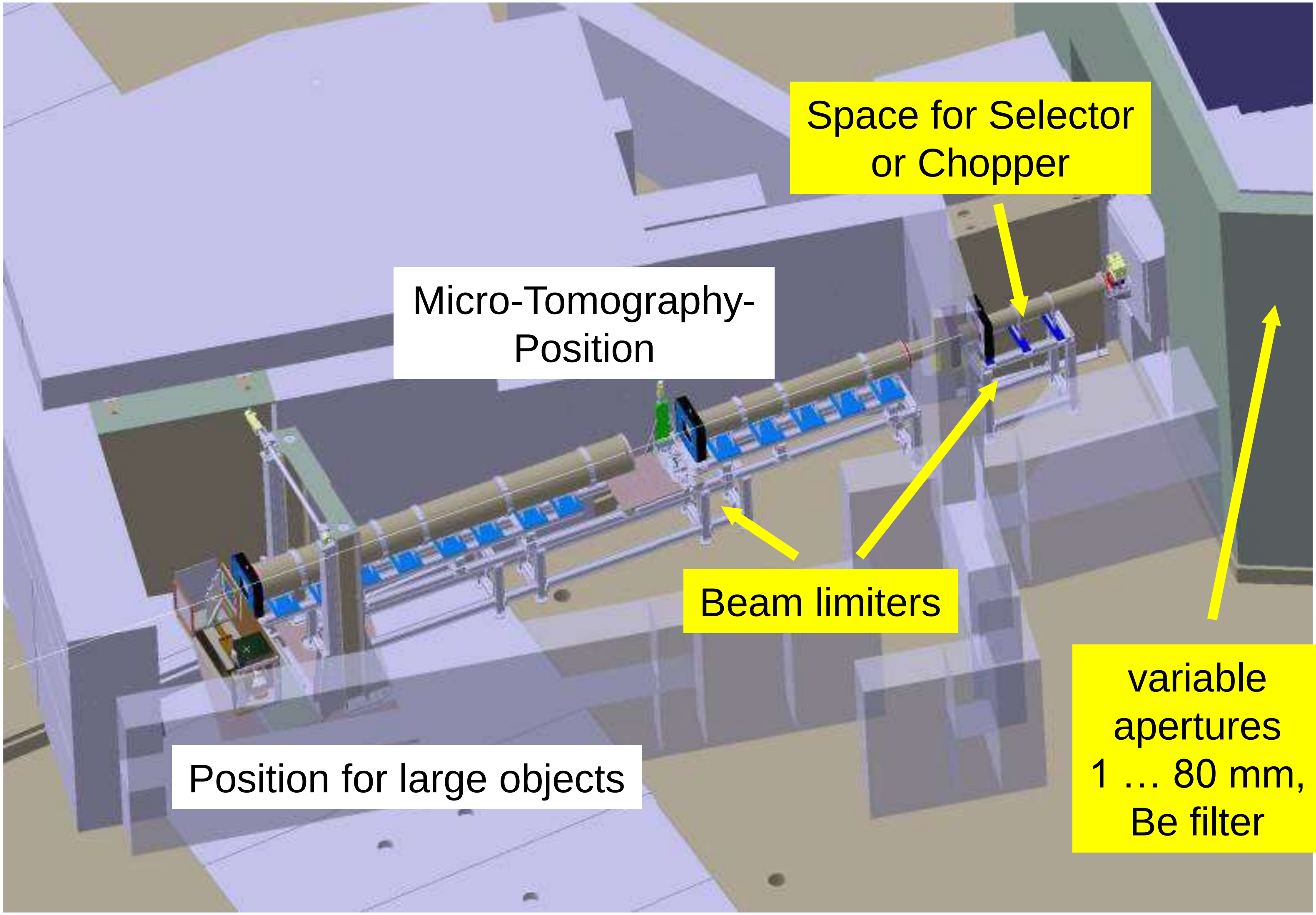
Beamlines layout



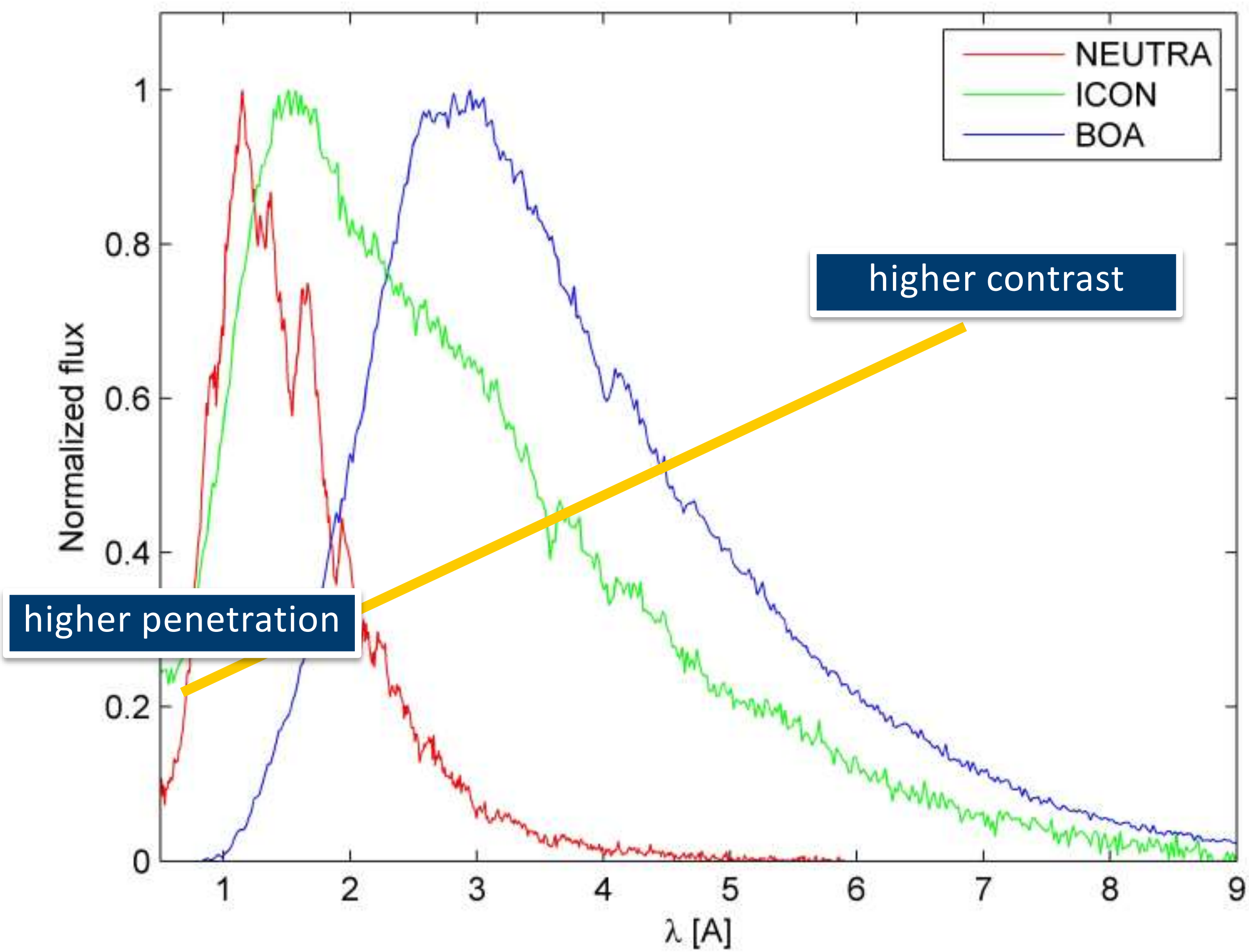


19 Instruments: 15 User facilities (>2 Imaging beam lines) + 4 Test facilities

ICON-beam line @ SINQ



Spectra at PSI/SINQ Neutron Imaging beamlines



State-of-the-art Neutron Imaging User Facilities **world-wide**

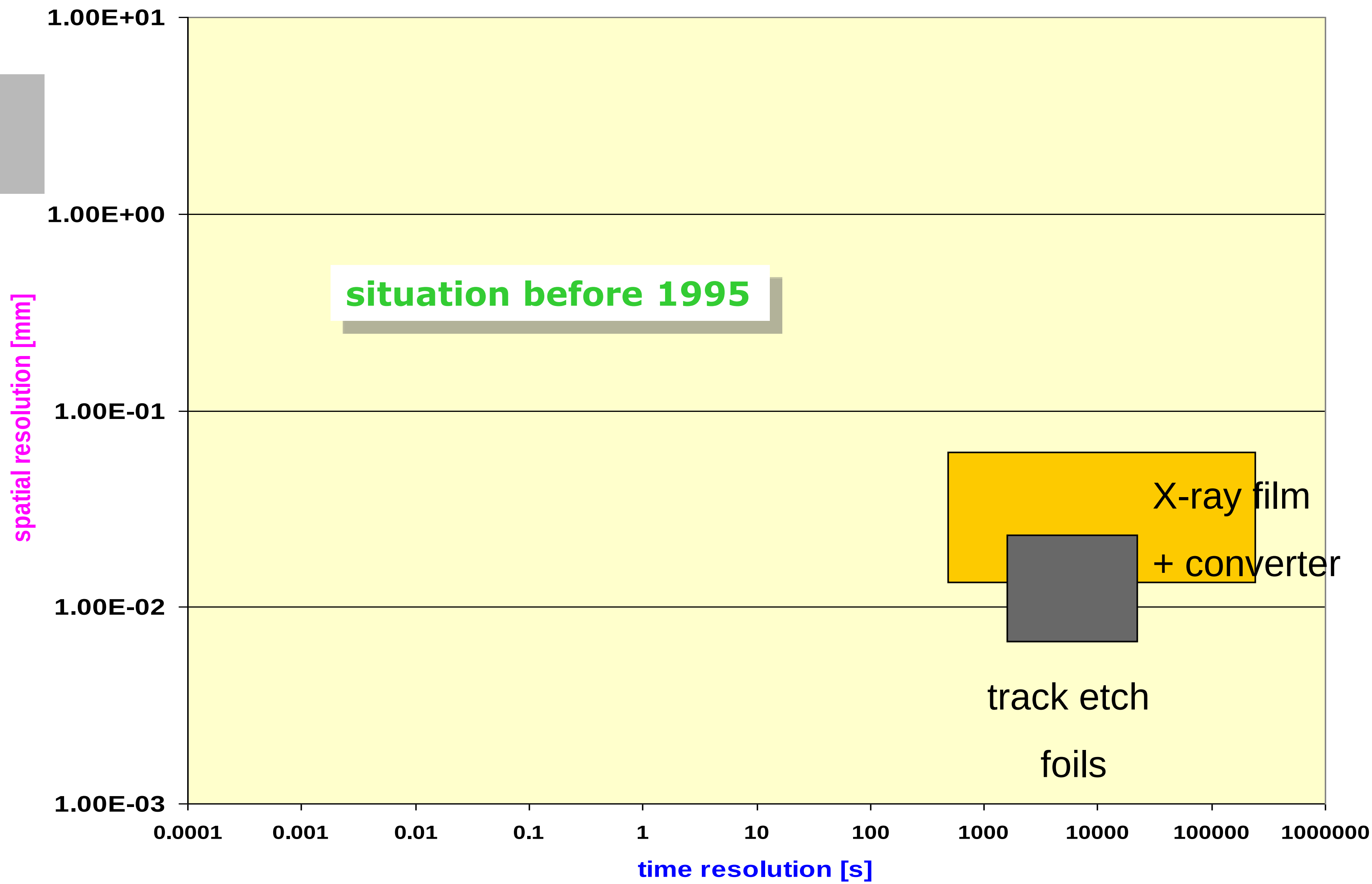
country	site	institution	facility	neutron source	spectrum	power [MW]	status
Australia	Sydney	ANSTO	DINGO	OPAL reactor	thermal	20	operational
Germany	Munich-Garching	TU Munich	ANTARES	FRM-2	cold	25	operational
Germany	Munich-Garching	TU Munich	NECTAR	FRM-3	fast	25	operational
Germany	Berlin	HZB	CONRAD	BER-2	cold	10	standby
Hungary	Budapest	KFKI	imaging beamline	WWS-M reactor	thermal	10	operational
Japan	Kyoto	Kyoto University	imaging beamline	MTR reactor	thermal	5	standby
Japan	Tokai	JAEA	imaging beamline	JRR-3M reactor	thermal	20	standby
Japan	Tokai	JAEA	RADEN	JPARC spallation	cold	0.3	operational
Korea	Daejon	KAERI	imaging beamline	HANARO reactor	thermal	30	operational
Switzerland	Villigen	PSI	NEUTRA	SINQ spallation	thermal	1	operational
Switzerland	Villigen	PSI	ICON	SINQ spallation	cold	1	operational
USA	Gaithersburg	NIST	BT-2	NBSR reactor	thermal	20	operational
USA	Sacramento	UC Davis	imaging beamline	TRIGA reactor	thermal	2	operational
USA	Oak Ridge	ORNL	CG-1D	HFIR reactor	cold	85	operational
South Africa	Pelindaba	NECSA	SANRAD	SAFARI reactor	thermal	20	operational

only about 15 TOP facilities available world-wide

among them, the performance is still different

It should be the goal for ILL to become member of the «club» !

Neutron Detectors for Imaging



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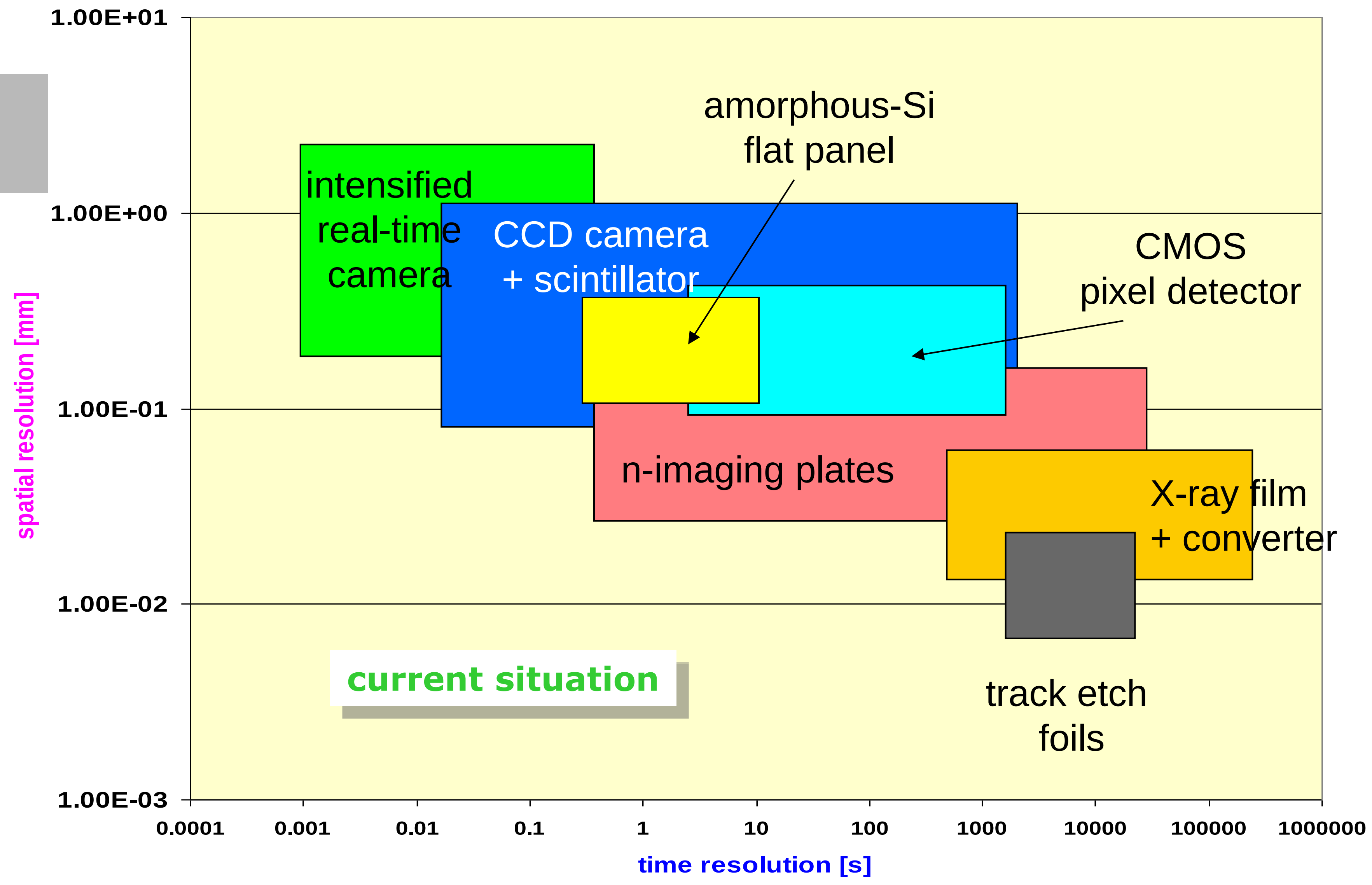
Analogue neutron imaging – 1 frame per hour

about 1994

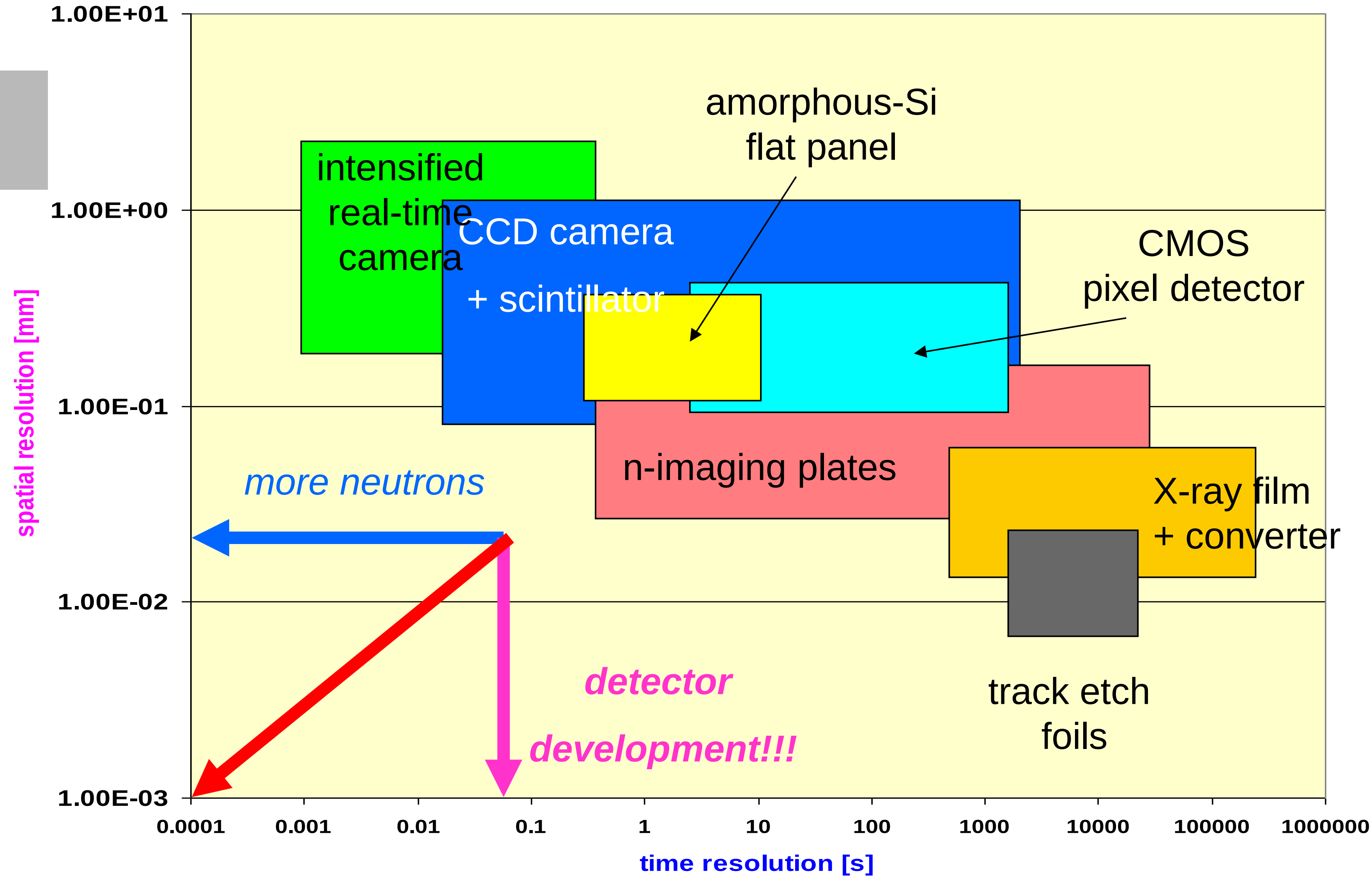
Neutron Detectors for Imaging



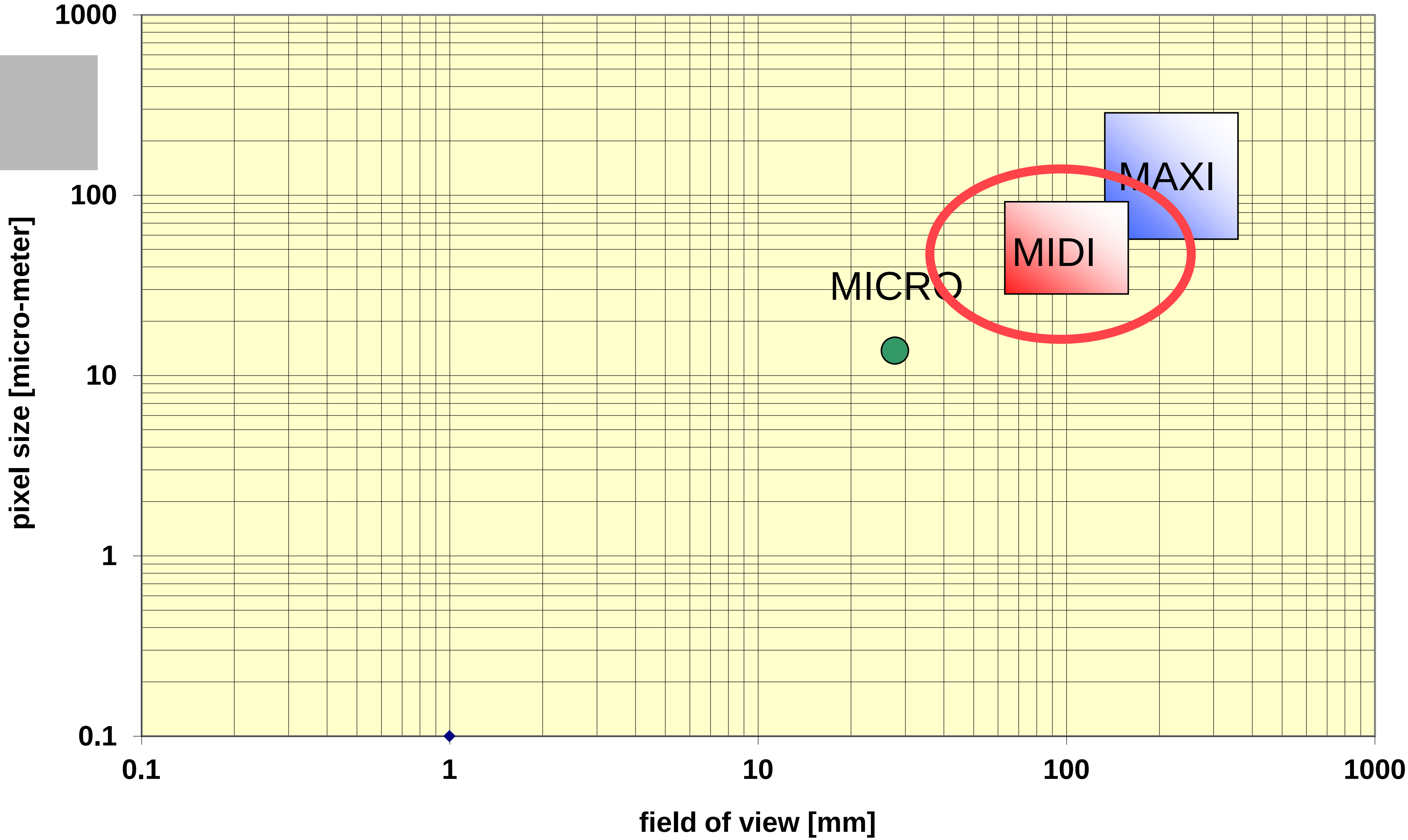
Digital – 1 frame per second

about 2012

Neutron Detectors for Imaging



Neutron Imaging: different settings wrt resolution



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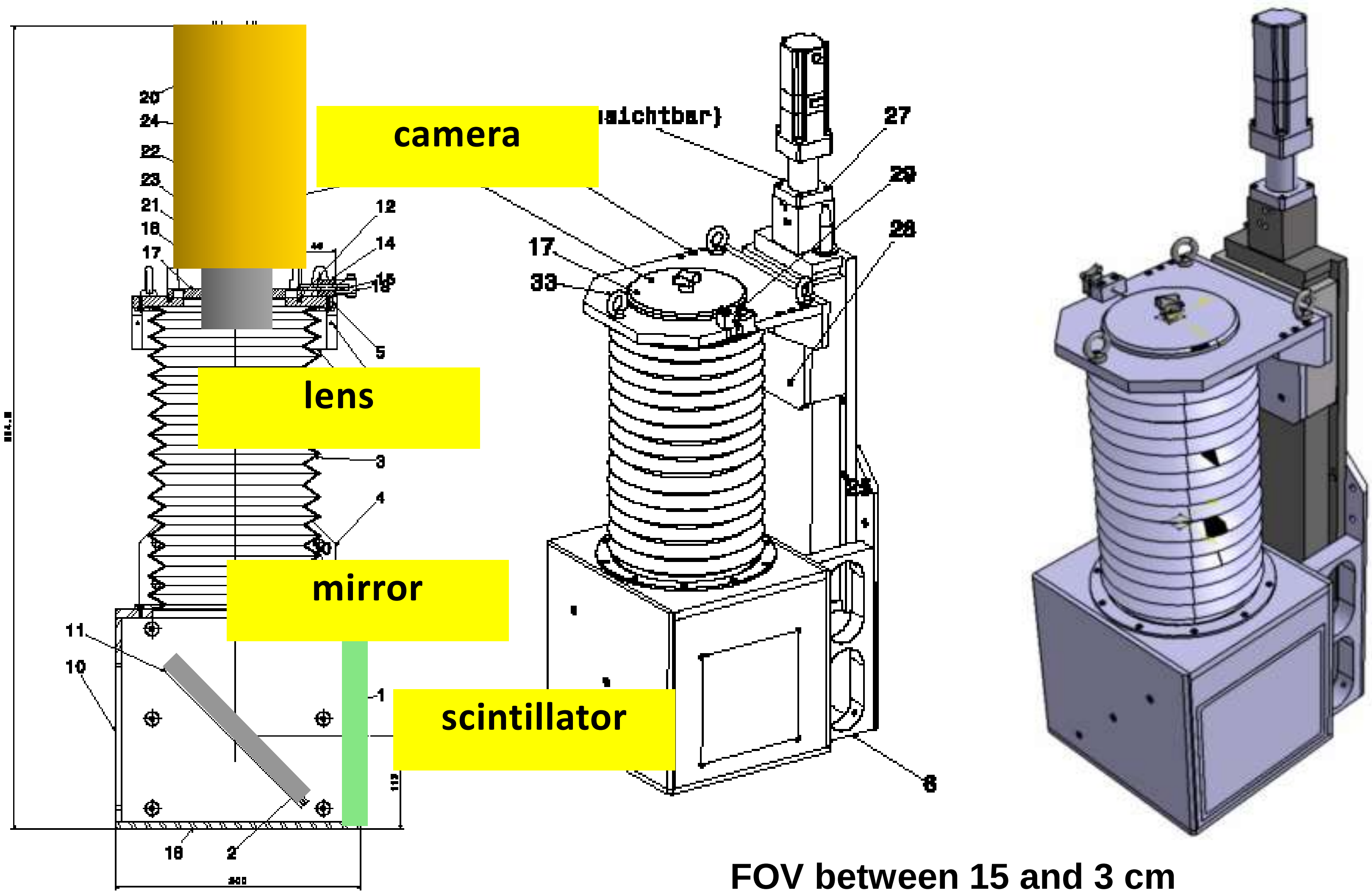
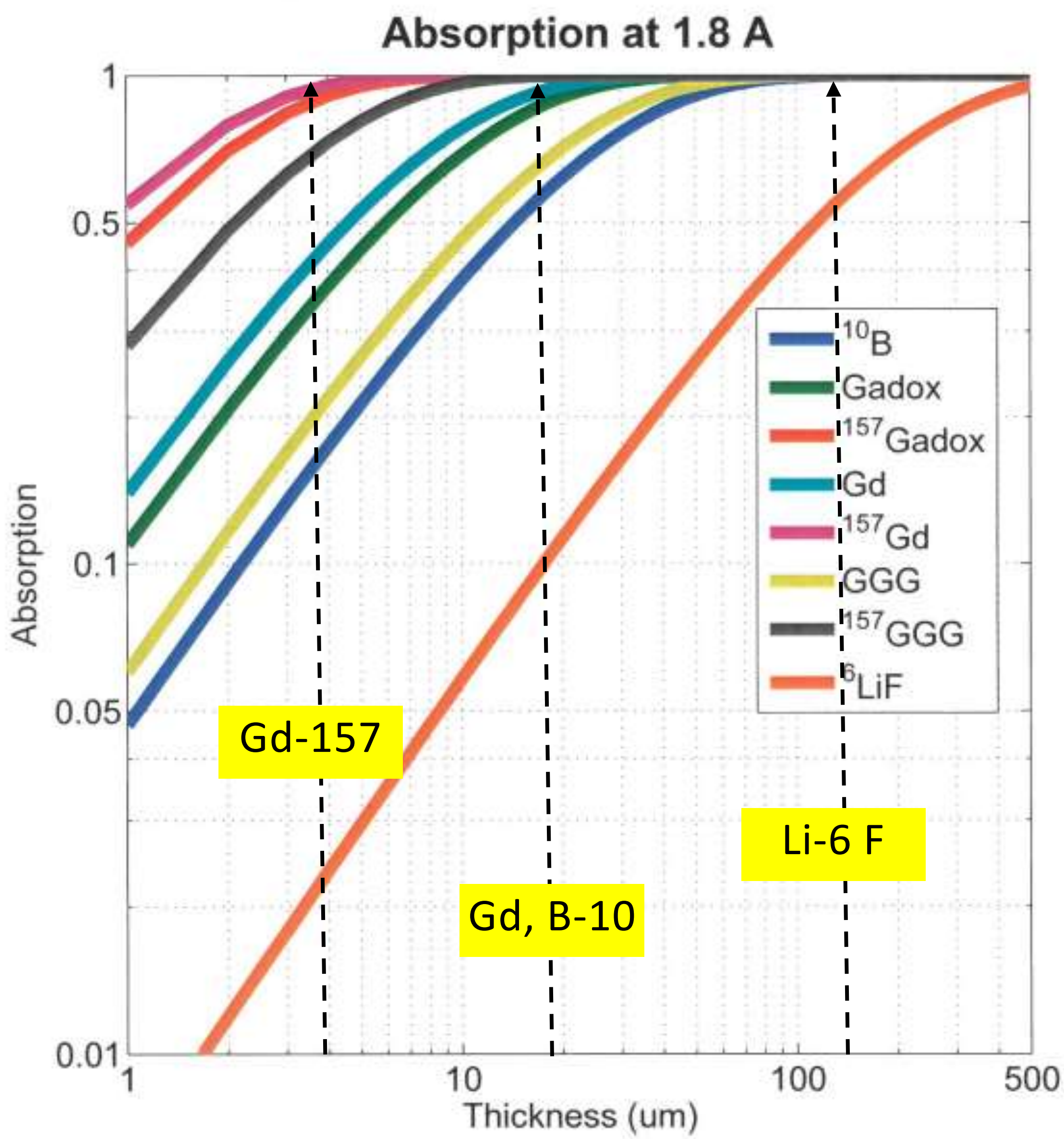
Camera-detector MIDI (medium FOV)



FOV between 15 and 3 cm

Detection Efficiency for Neutron Converters



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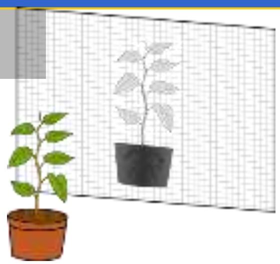
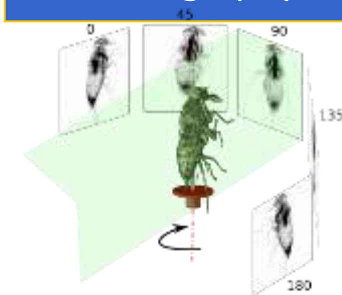
Neutron imaging methods @ PSI

Classic neutron imaging methods

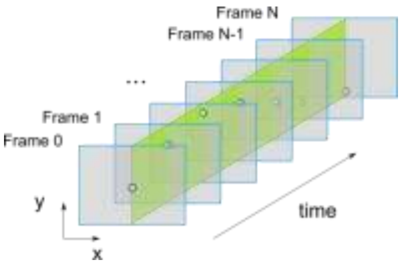
Radiography



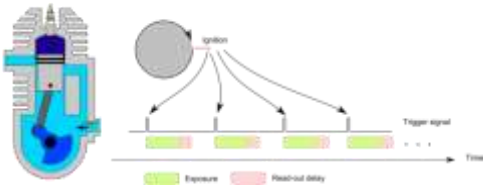
Tomography



Real-time imaging

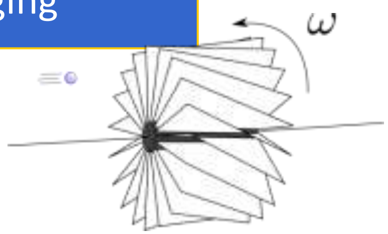


Stroboscopic imaging

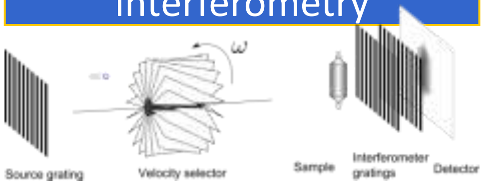


Advanced neutron imaging methods

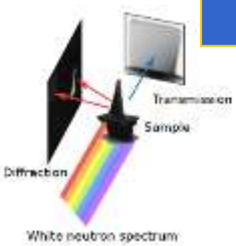
Energy selective imaging



Neutron grating interferometry



Diffraction imaging

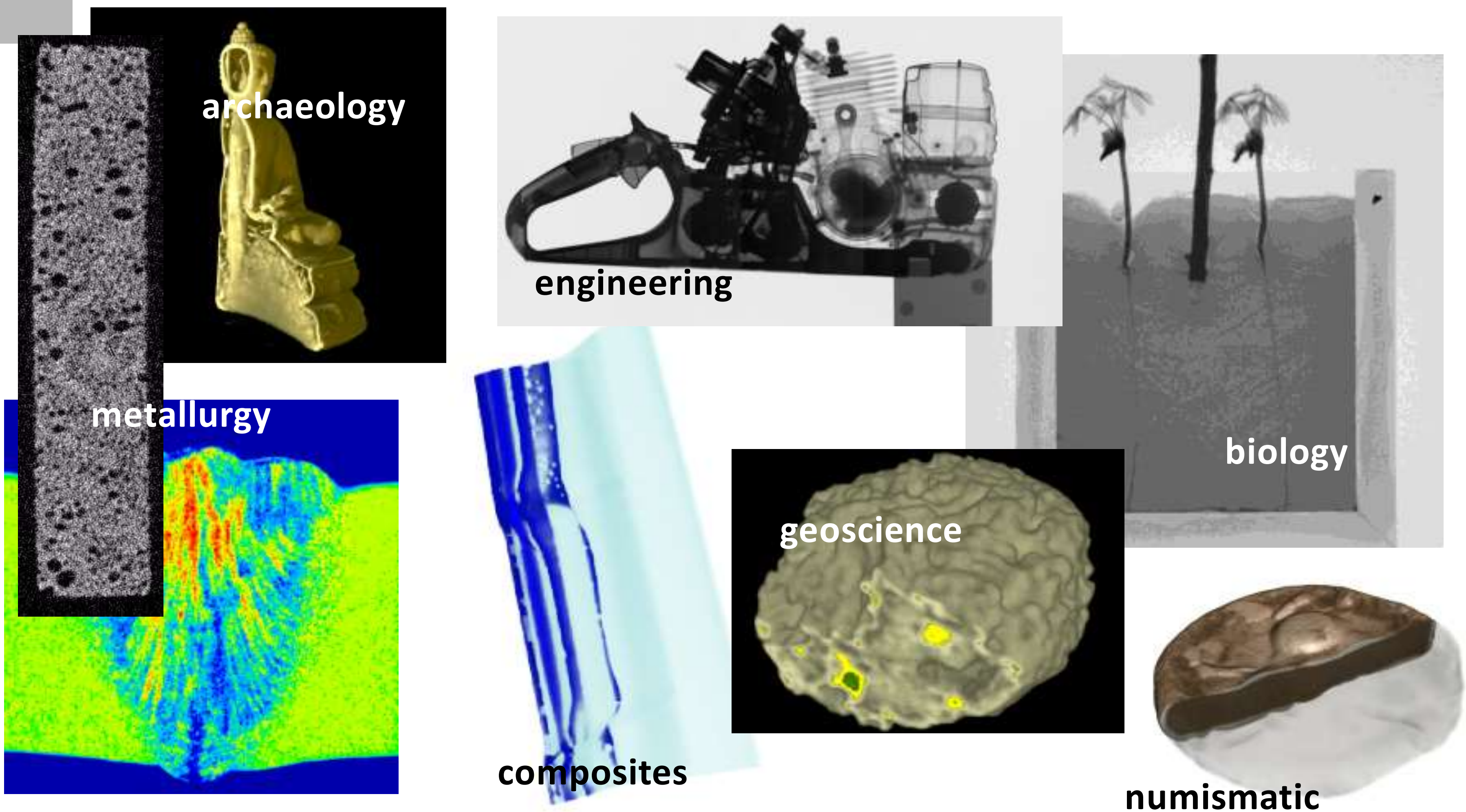


Under preparation:

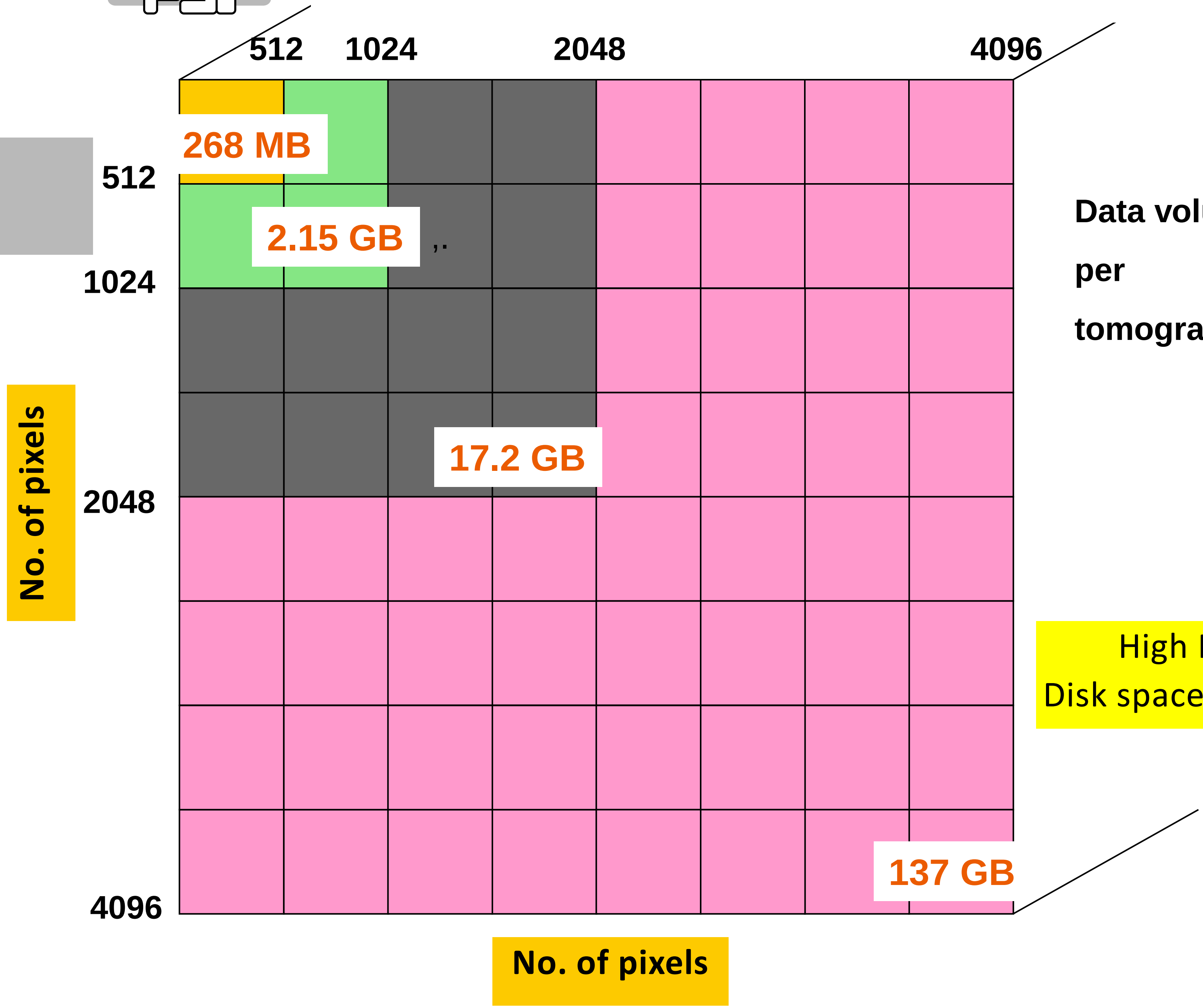
- Imaging with polarized neutrons (BOA)
- Project neutron microscope
- N/X data fusion

many

SCIENTIFIC CASES!



Increased Data Volume



Data volume

per

tomography set

High RAM and
Disk space requirements

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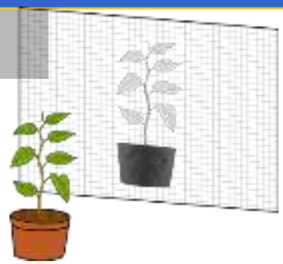
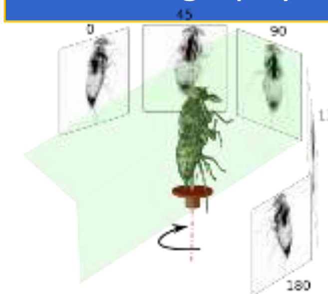
Neutron imaging methods @ PSI

Classic neutron imaging methods

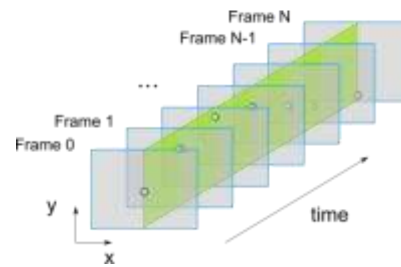
Radiography



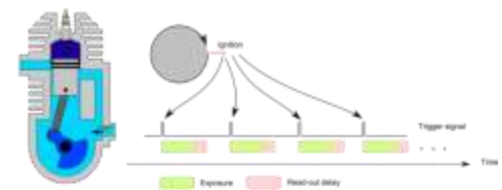
Tomography



Real-time imaging

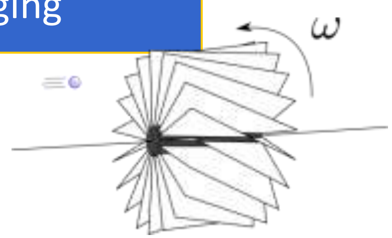


Stroboscopic imaging

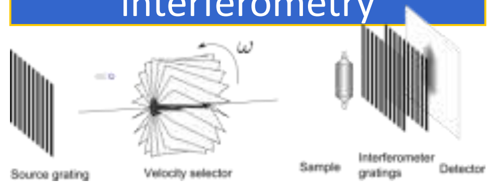


Advanced neutron imaging methods

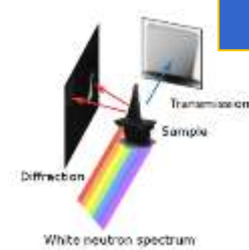
Energy selective imaging



Neutron grating interferometry



Diffraction imaging



Under preparation:

Imaging with polarized neutrons (BOA)

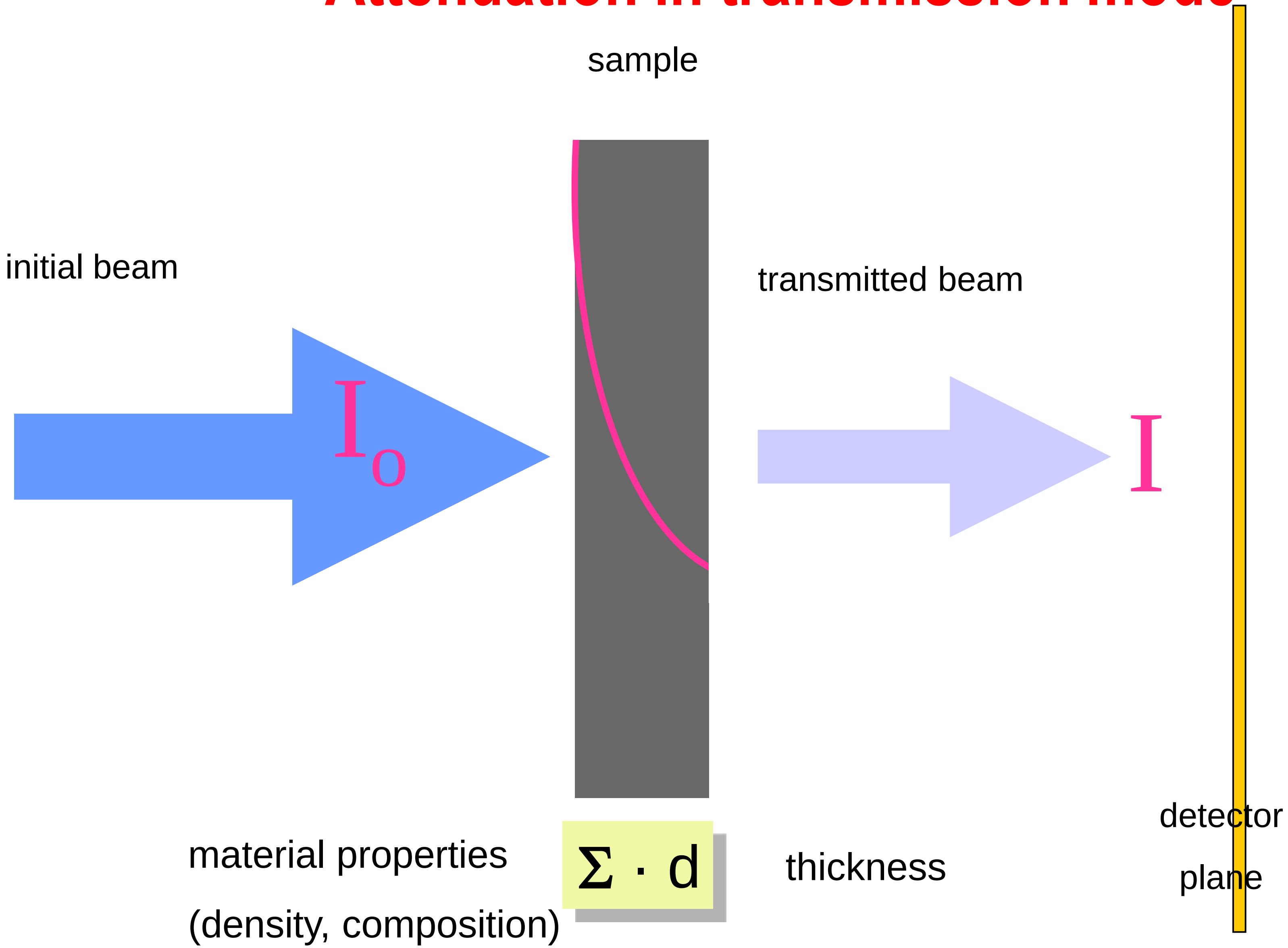
Project neutron microscope

N/X data fusion

Quantification in Neutron Imaging

= non-invasive determination of the sample's content

Attenuation in transmission mode



Analytical description of the transmission process

•Beer-Lambert law

Transmission

$$T = \frac{I}{I_0} = e^{-\Sigma \cdot d} = e^{-\sigma \cdot N \cdot d}$$

and inverted …

$$\Sigma \cdot d = \ln\left(\frac{I_0}{I}\right)$$

Thickness d can be obtained when Σ is known

Density or composition derived if thickness d is known

Final results of neutron imaging in transmission mode

Two dimensional ***pixel-matrix*** **Σ(x, y)** of

averaged macroscopic cross-sections

integrated over the length in beam direction z

$$\Sigma_{eff} = N \cdot \frac{\int_E dE \cdot \varepsilon(E) \cdot \sigma(E) \cdot \phi(E)}{\int_E dE \cdot \varepsilon(E) \cdot \phi(E)}$$

In the case of **neutron tomography** the

3rd dimension is resolved and a ***voxel-matrix***

Σ(x, y, z) can be derived

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Problems in Quantification

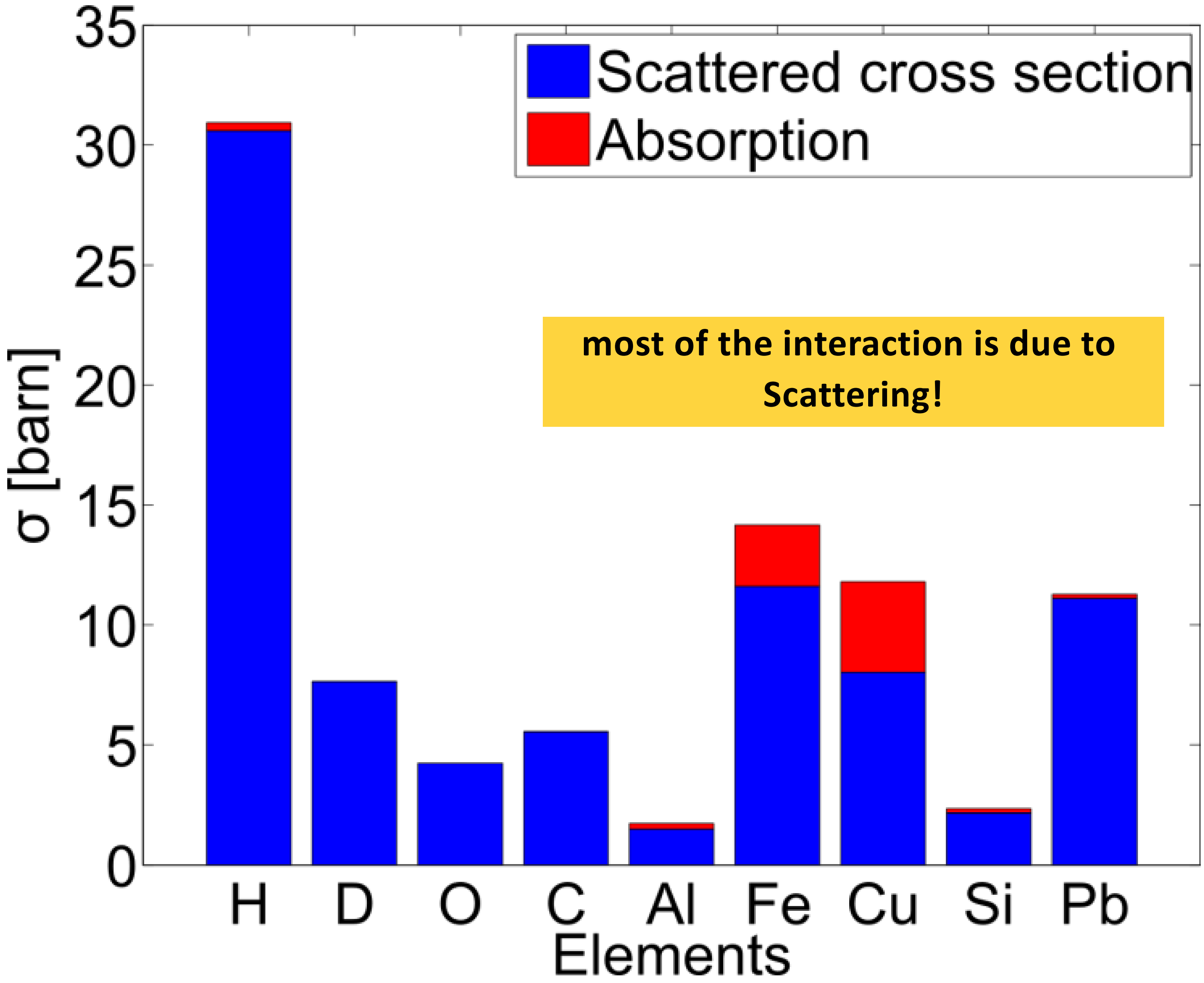
Physics:

- attenuation coefficients, detector response and flux distribution are energy dependent → beam hardening artifacts are possible
- multiple scattering in the sample can distort the result
- Cross-section data for comparison are complex (Bragg edges), depend on materials properties (e.g. texture) and have uncertainties

Imaging Technique:

- **Detector:** background of scattered light; afterglow of scintillator; background from gamma-radiation are disturbing
- **Signal/noise** ratio can limit the accuracy

The attenuation law assumes that the beam is absorbed … but



most of the interaction is due to Scattering!

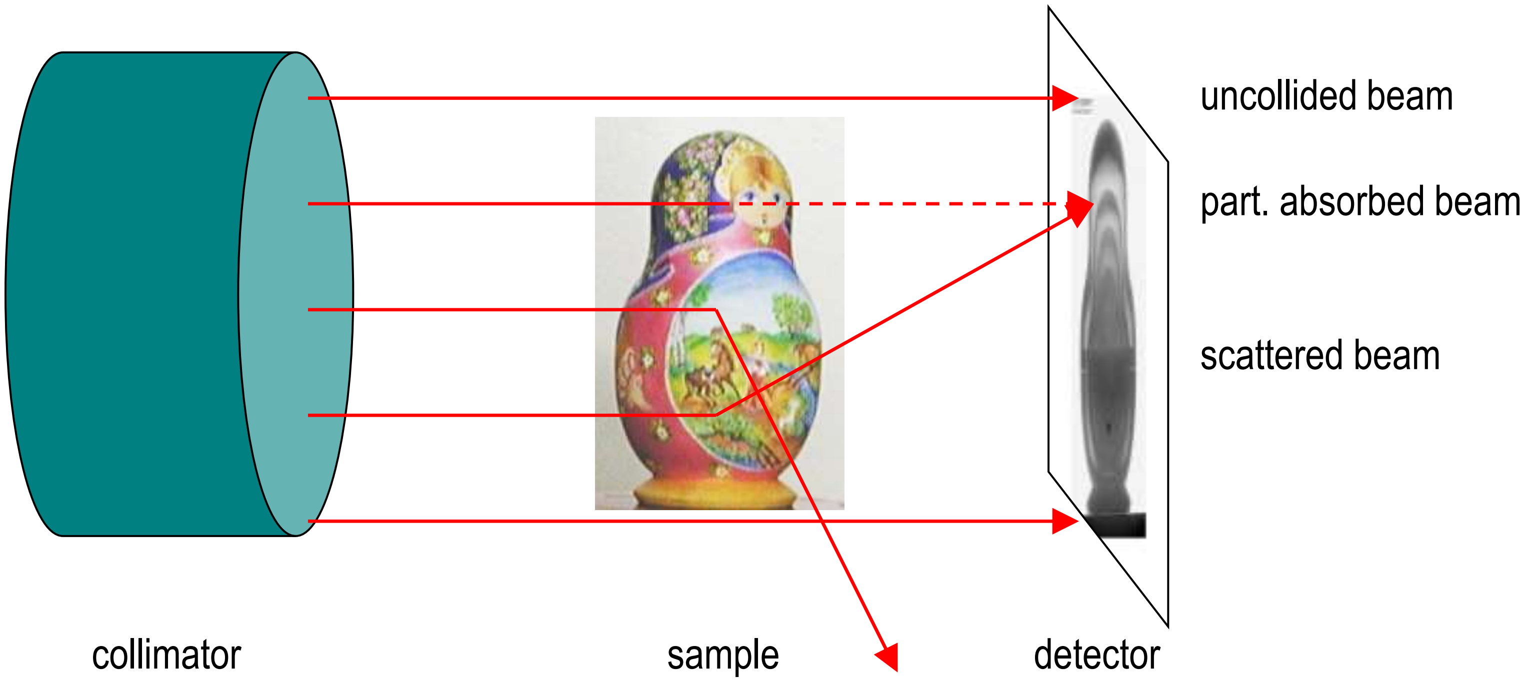
Ways to improve the quantitative accuracy

1. **Correction of the scattered neutrons** contributions by means of Monte-Carlo simulations (mainly focused on **hydrogen**)

2. **Changing sample-detector distances** for the determination of the scattering contribution

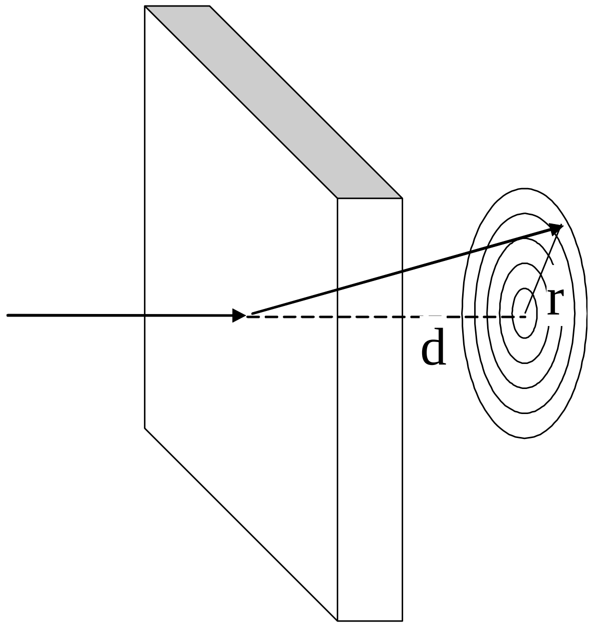
3. Using the **«black-body»** correction tools (cases of low transmission)

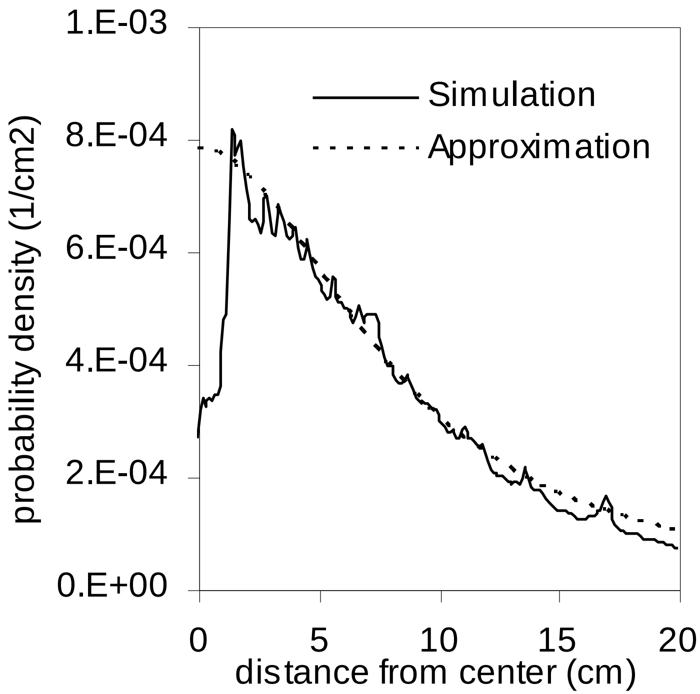
Perturbation by Sample Scattering



The scattering pretends a higher transmission value behind the sample, which is mistaken for less mass thickness

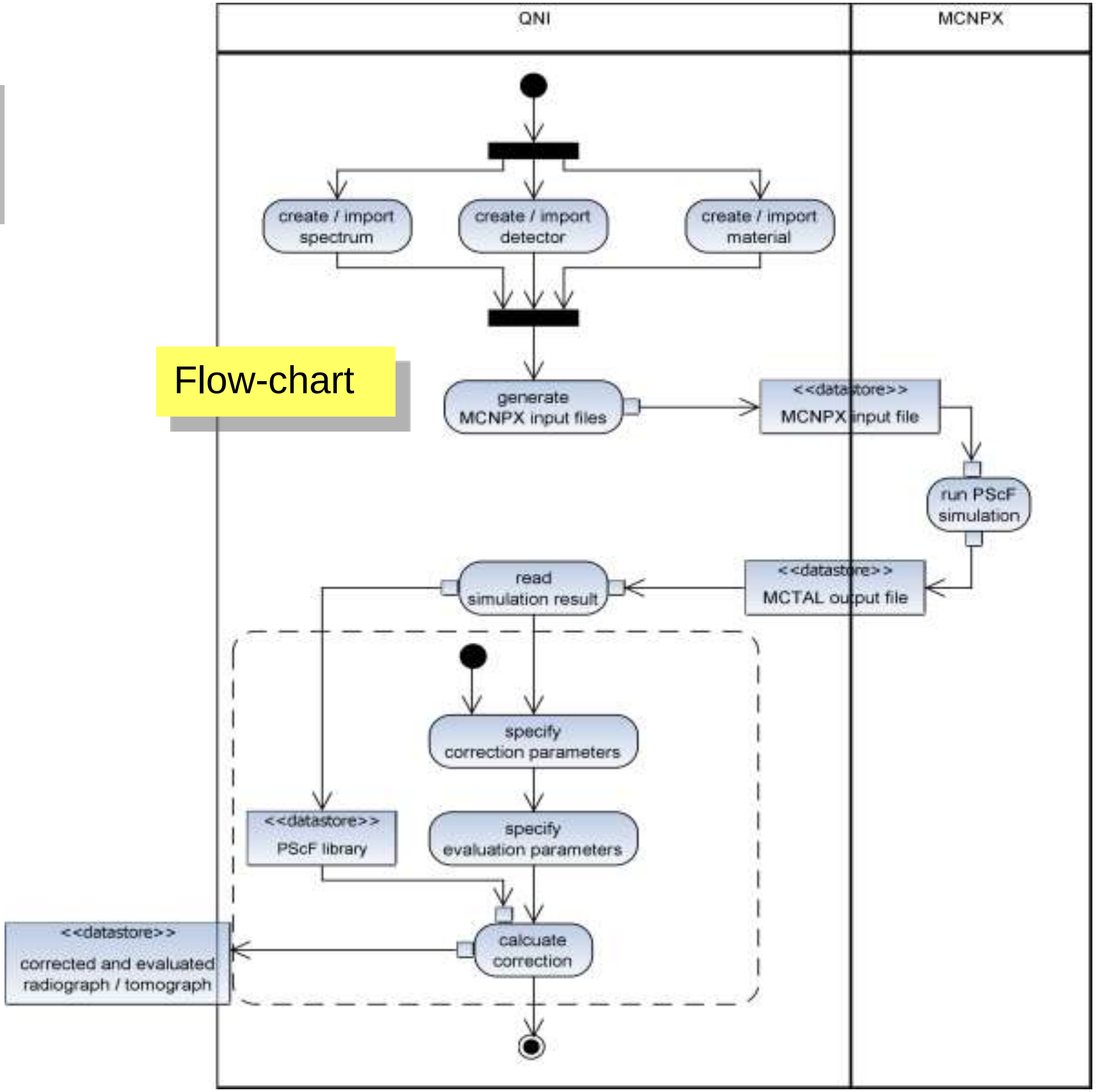
Approximation of the Point Scattered Functions





$$\mathrm{PScF}(r) = S_{\mathrm{A}} \cdot \frac{d_{\mathrm{A}}}{4\pi(d_{\mathrm{A}}^2 + r^2)^{3/2}} \cdot \frac{1 - e^{-\Sigma_{\mathrm{D}} \cdot s_{\mathrm{D}} \cdot \sqrt{d_{\mathrm{A}}^2 + r^2} / d_{\mathrm{A}}}}{1 - e^{-\Sigma_{\mathrm{D}} \cdot s_{\mathrm{D}}}}$$

QNI – the correction tool



Flow-chart

Basic principle:
superposition of
the «point scattering functions»

Based on PhD work of

Rene Hassanein

- MCNP based
- Programmed in IDL
- Available for other users

QNI - Iterative Algorithm

- **Corrected transmission image = radiography – sample scattering**
- With the corrected image, a more precise base for the choice of the PScF is available and the computation is repeated.
- After about 4 iterations the algorithm converges in the range of ±1 %.

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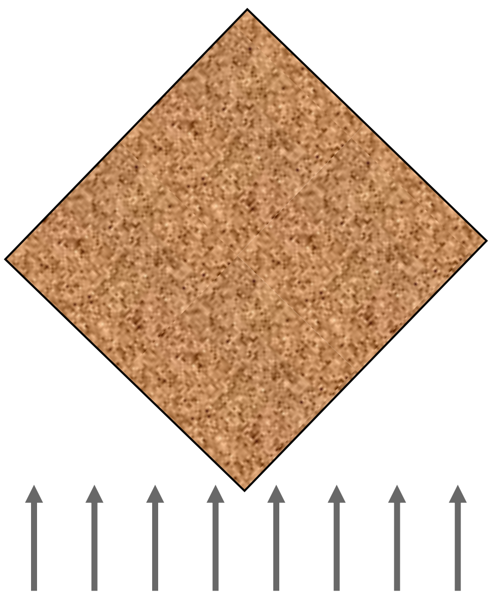
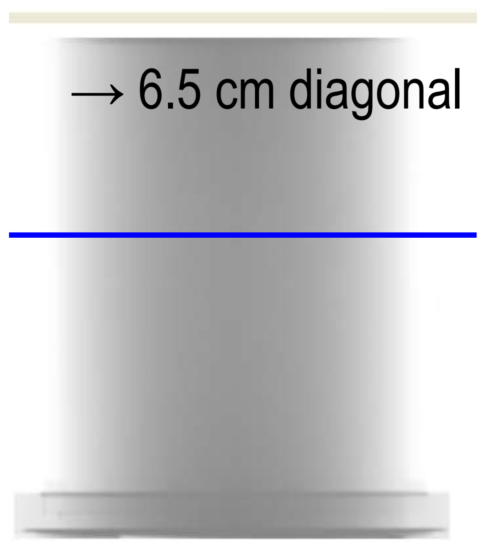
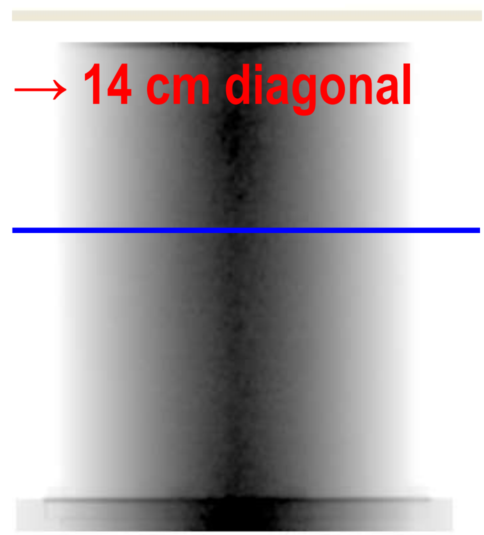
Water Content in Sand Columns (radiography mode)

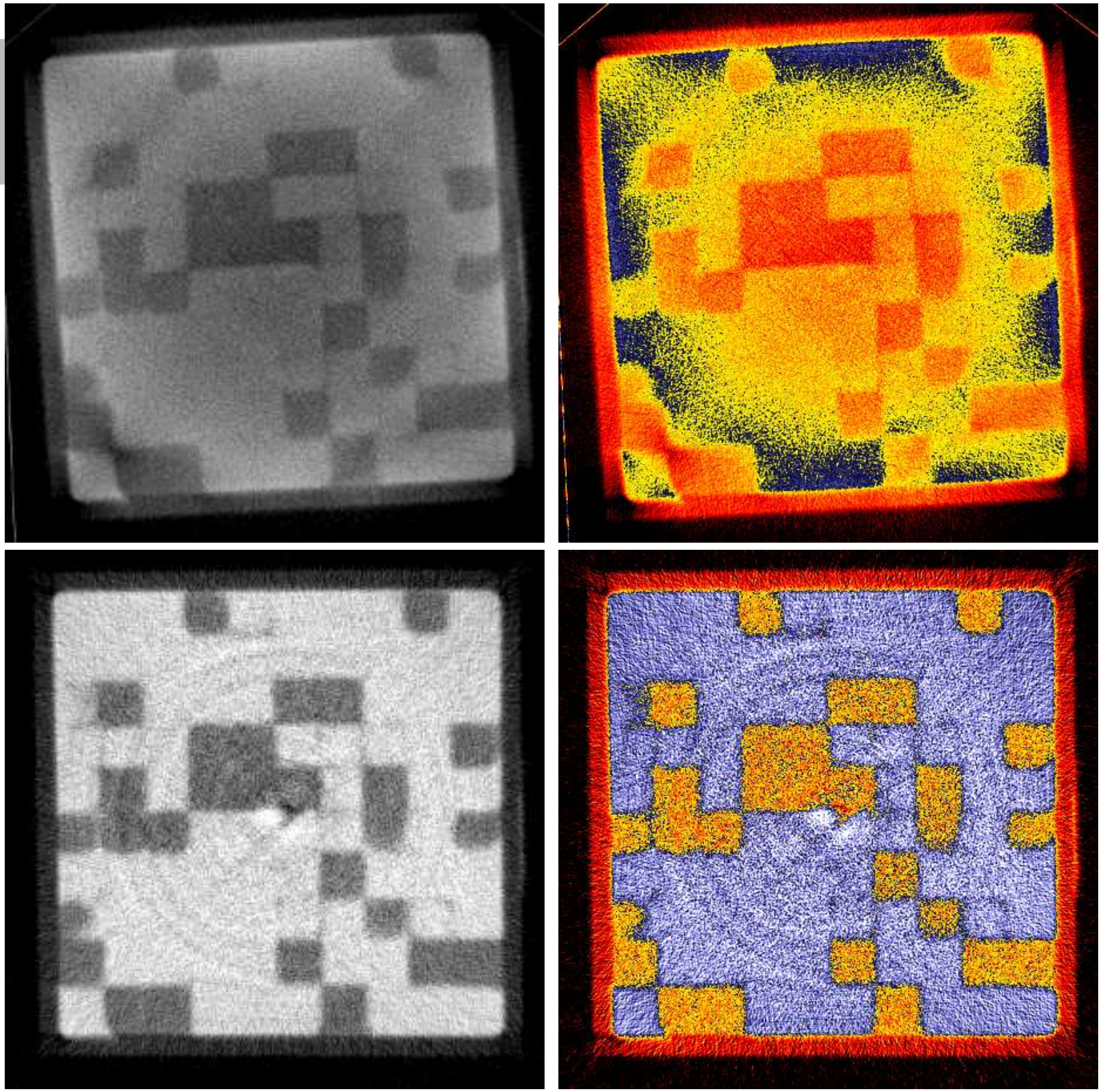
45° view: before after correction



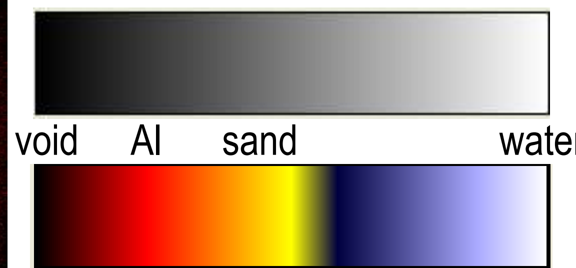




Water Content in Sand Columns (tomography mode)



uncorrected slice

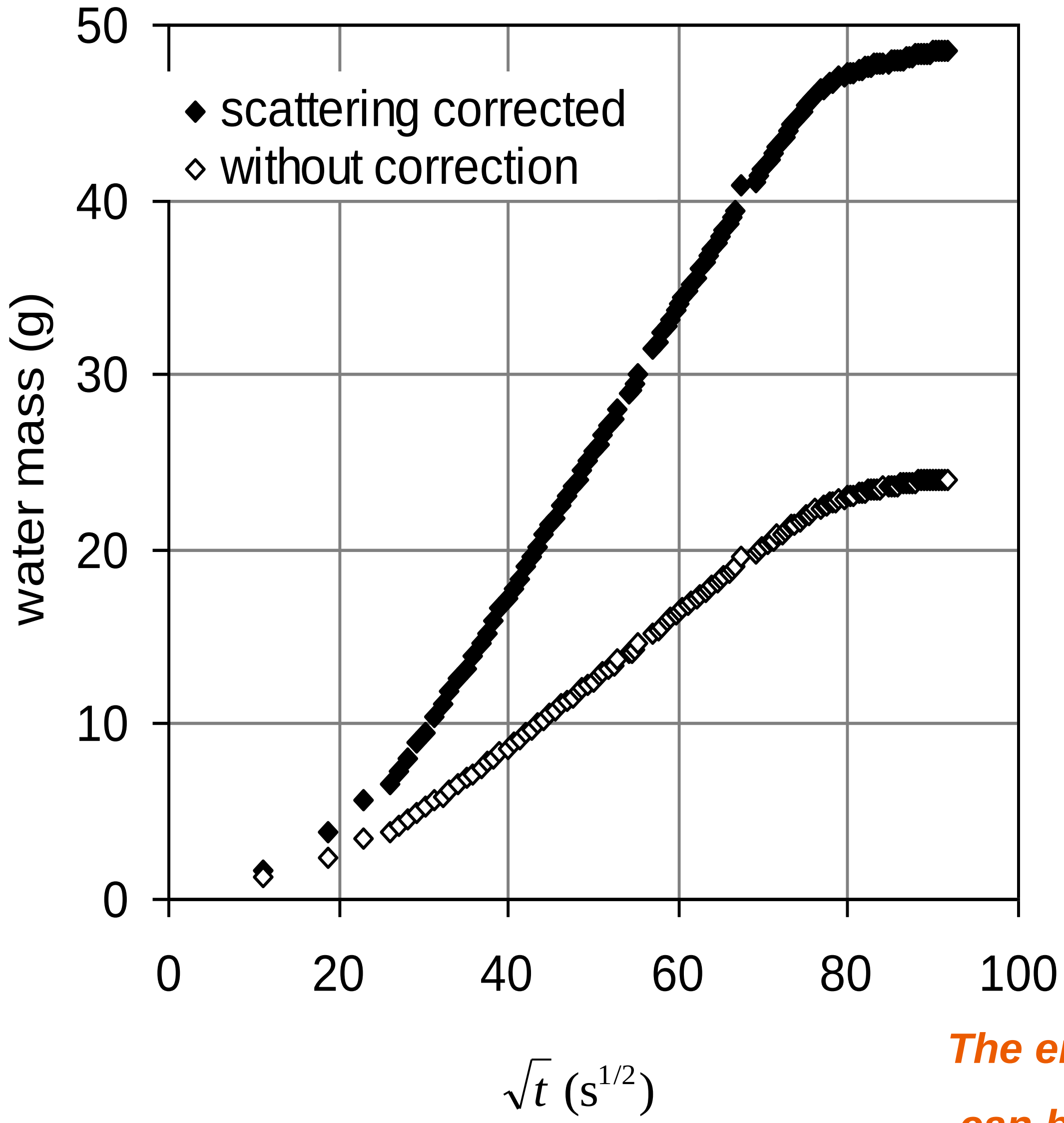


corrected slice

but:

- more noise induced
- Some more artefacts

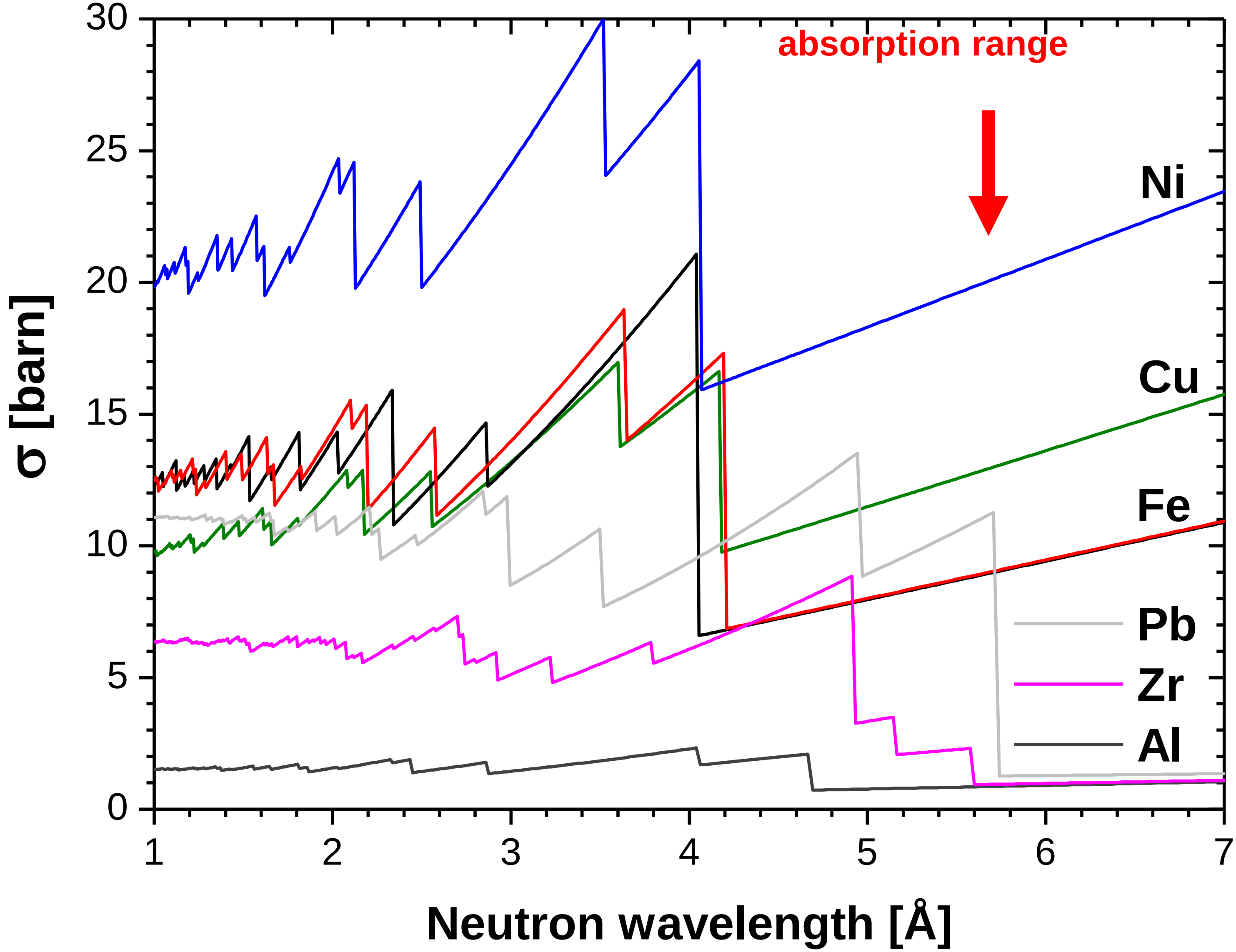
Water migration in sandstones



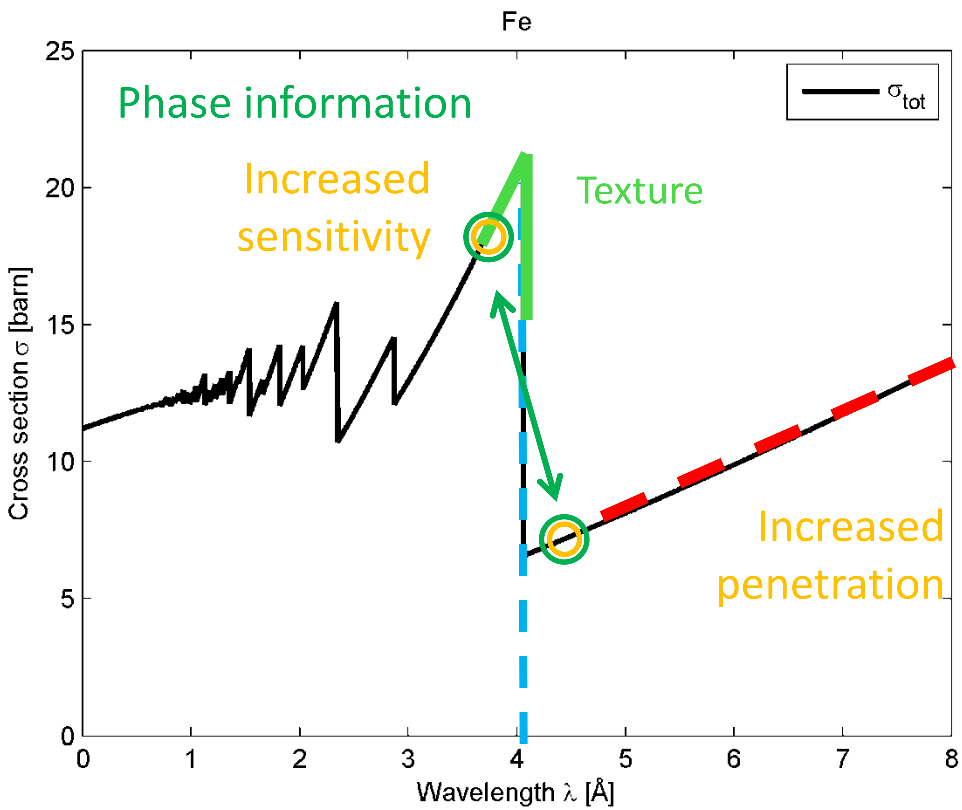
The error in the quantification can be up to 100%!

Structural materials

Cross-sections of crystaline structural materials



Energy-selective Imaging



Absorption range

(quantification)

Strain Imaging

Spatially resolved

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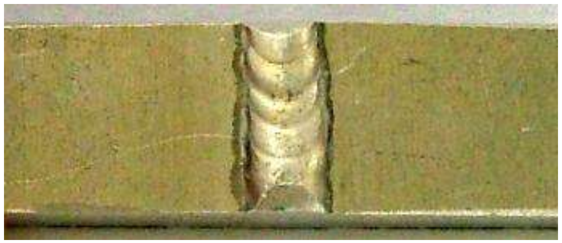
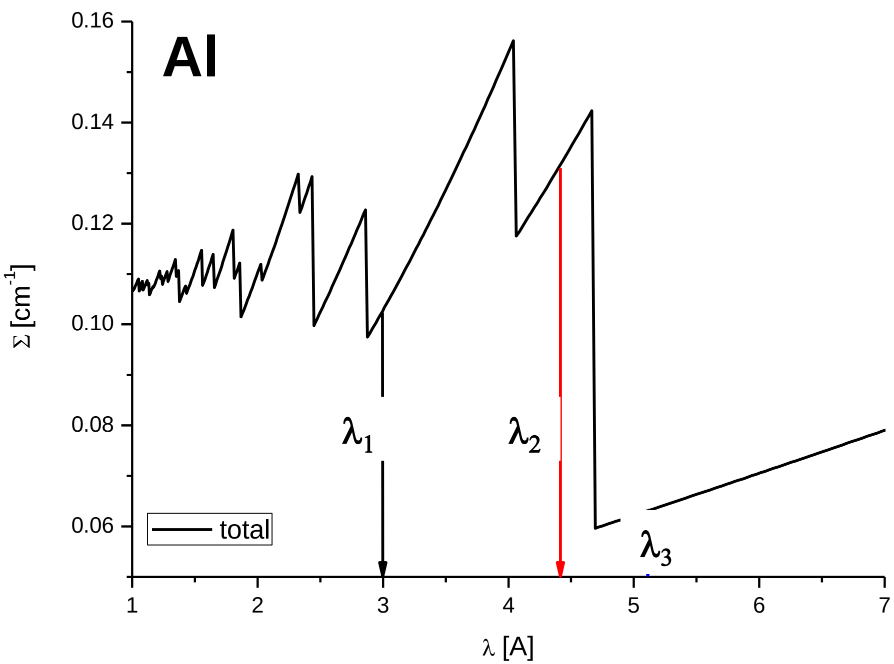
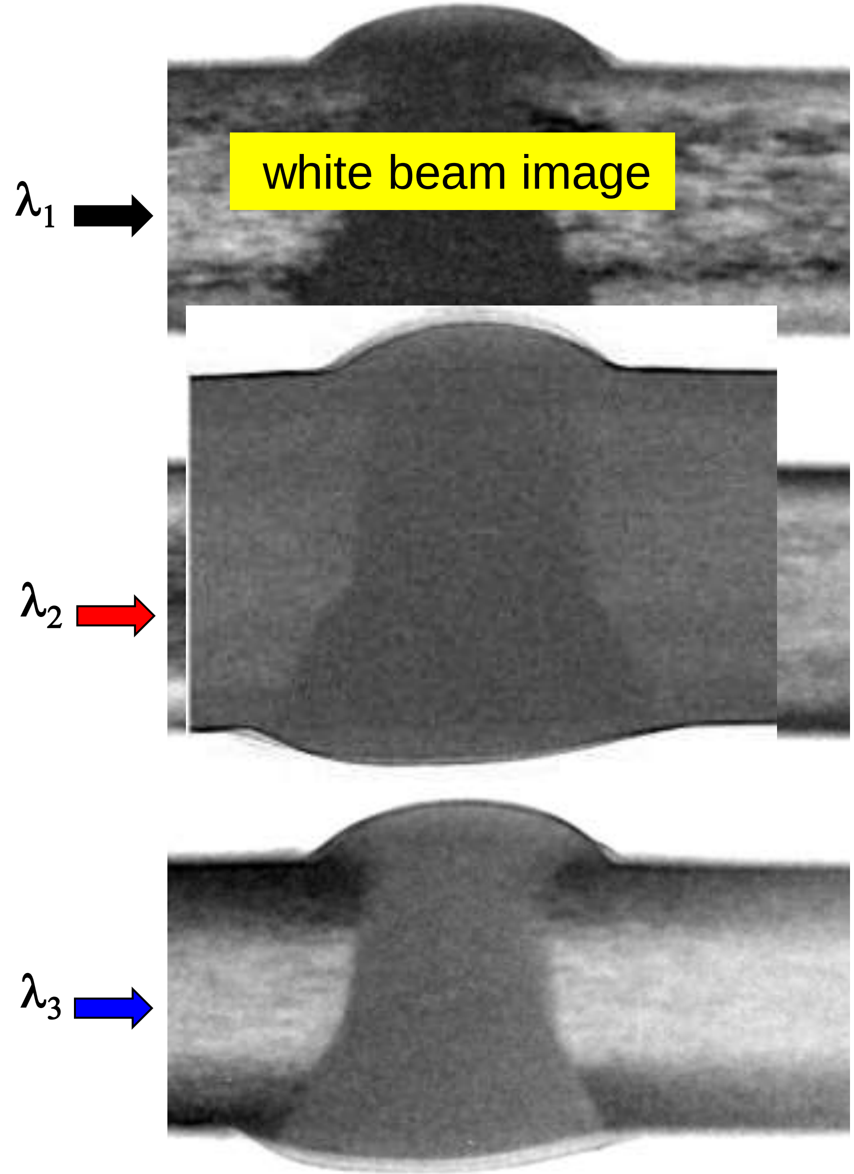
rolled Al plate (with weld) – texture analysis

Photo



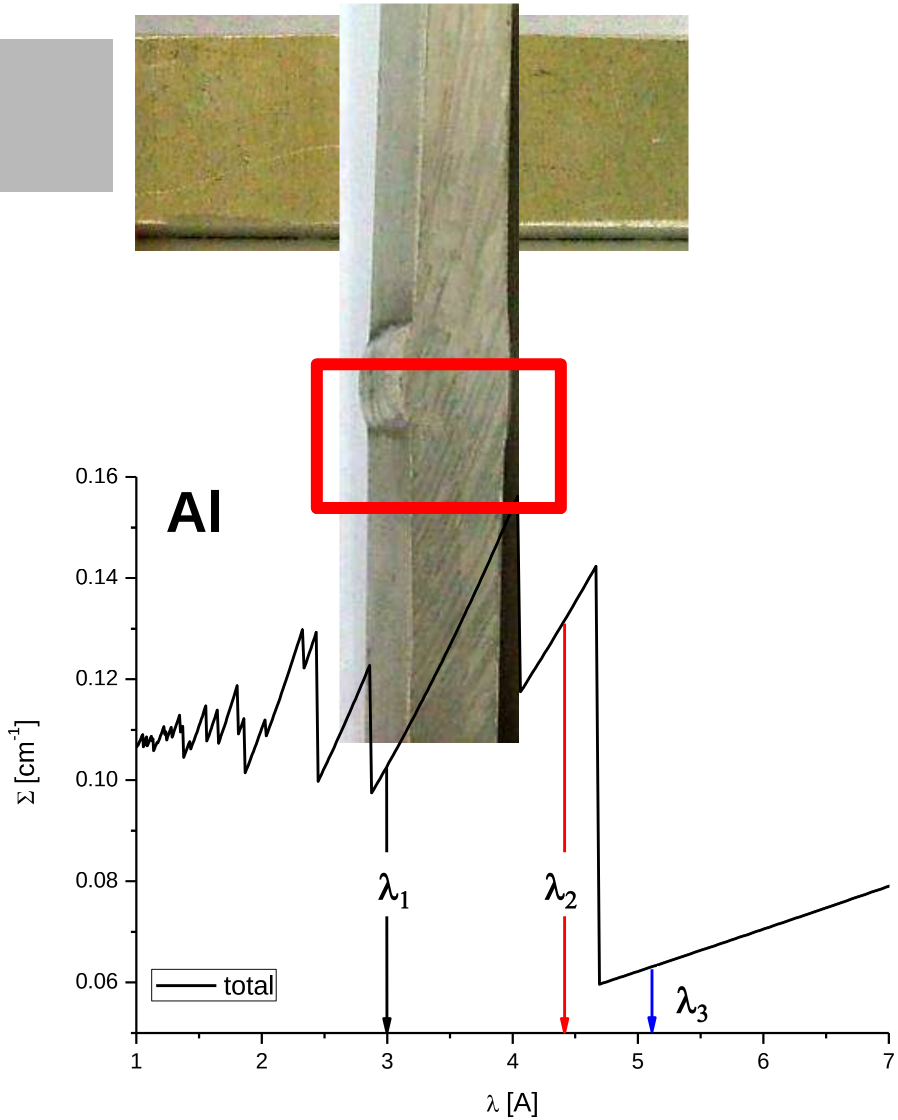


Neutron radiography images

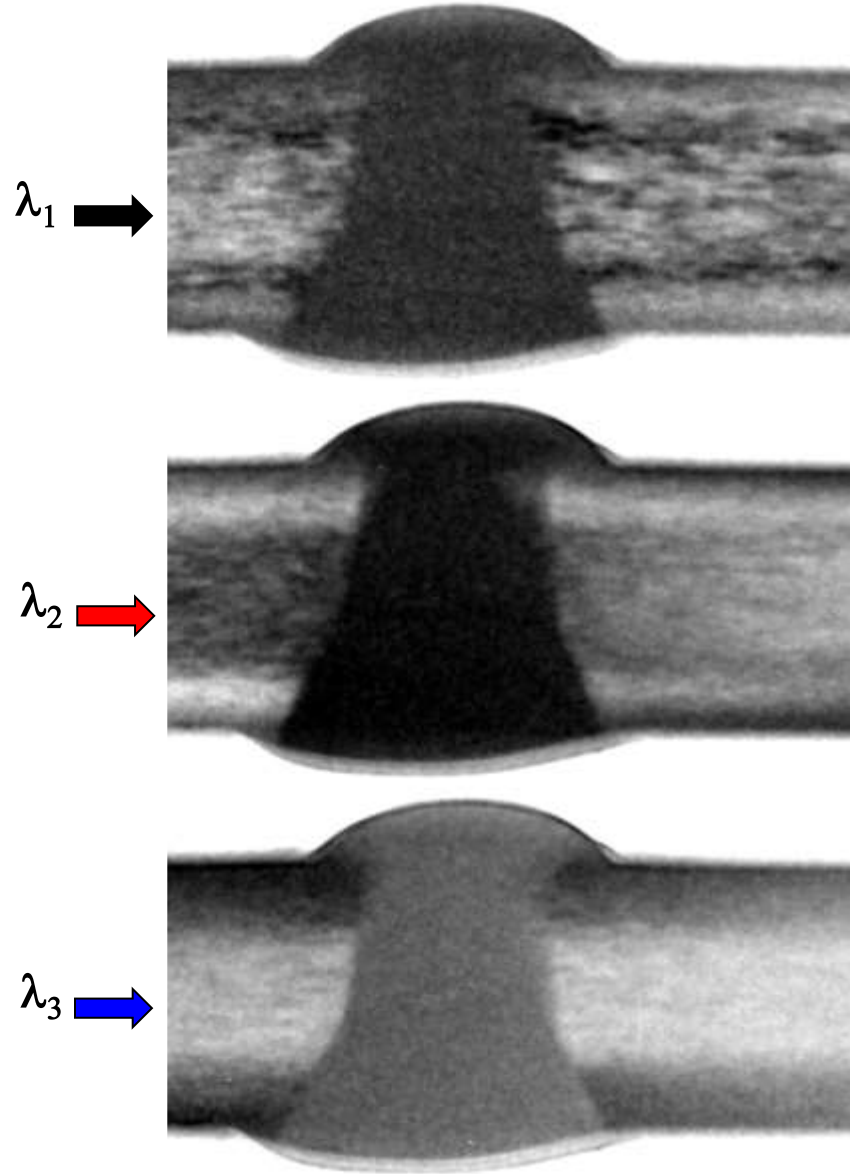


rolled Al plate (with weld) – texture analysis

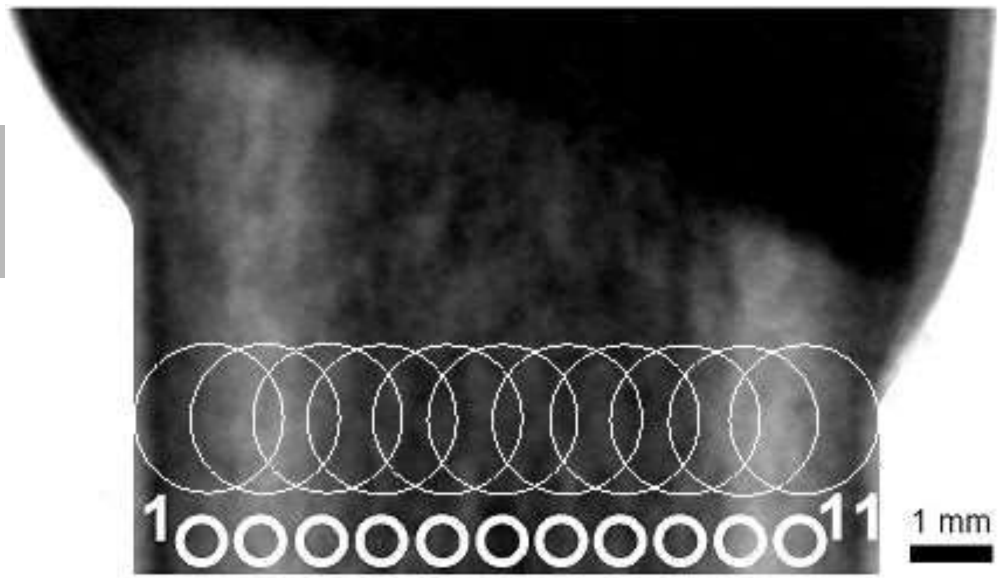
Photo



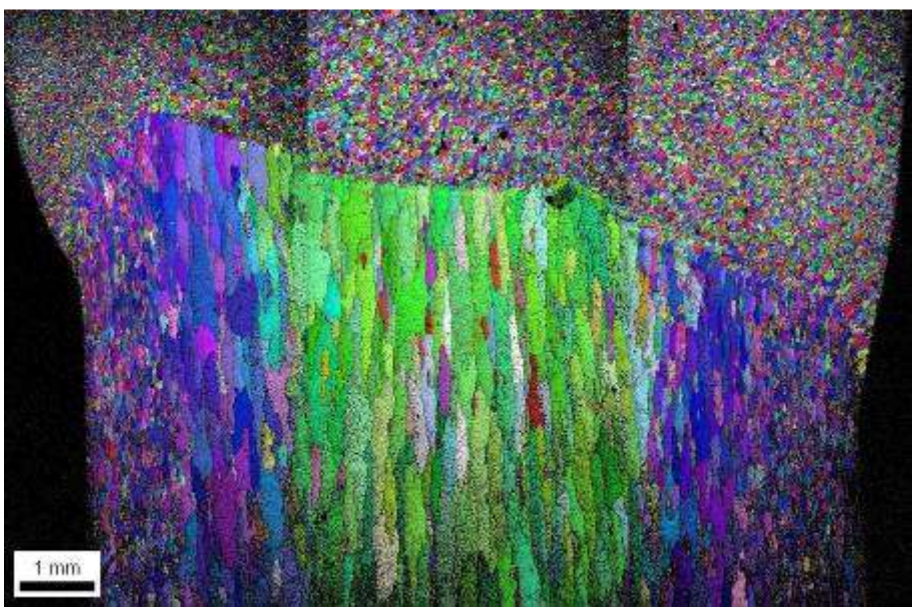
Neutron radiography images



Al structure – and their interpretation



transmission image at 4.8 Å



EBSD – measurement at the surface

→Different grain size and orientation in bulk and weld

Data: L. Josic, H.Leber, PSI

Measurements in «white beam» conditions
- Quantification -

- To avoid geometrical blurring , the samples have to measured **close to the detector**
- To avoid the high contribution of scattered neutrons to the signal, the samples have to be measured **in a certain distance**

→ To **combine both approaches** helps to overcome the problems in quantification for the observed materials Fe, Cu. V, …

Why is scattering correction needed?

Photography of a copper cylinder

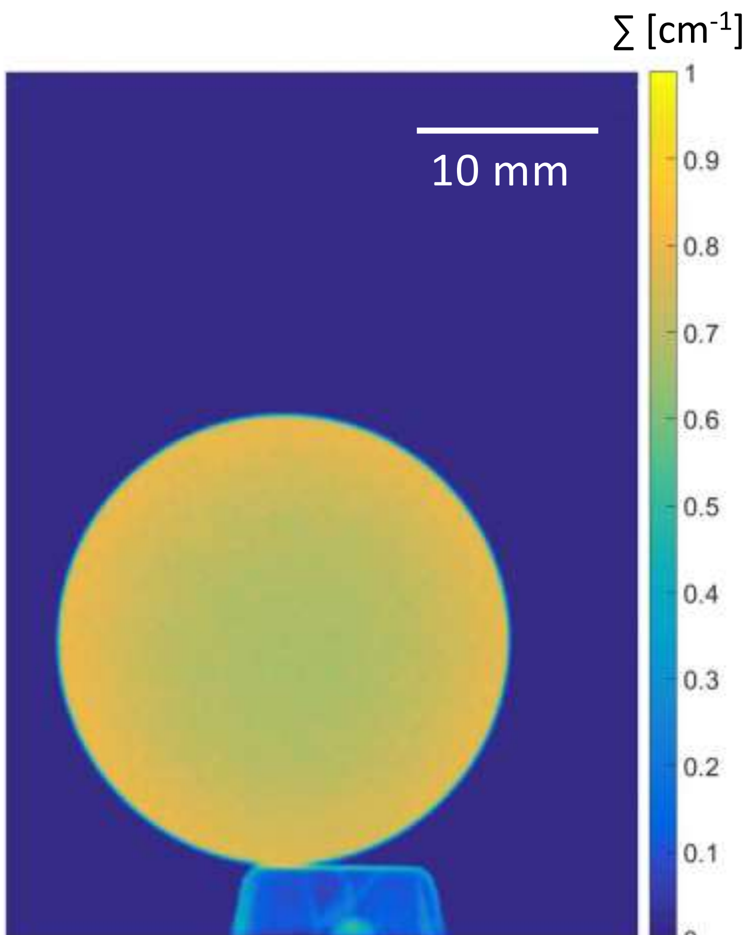
ETP Copper
r = 12.5 mm
t = 10 mm

Why is scattering correction needed?

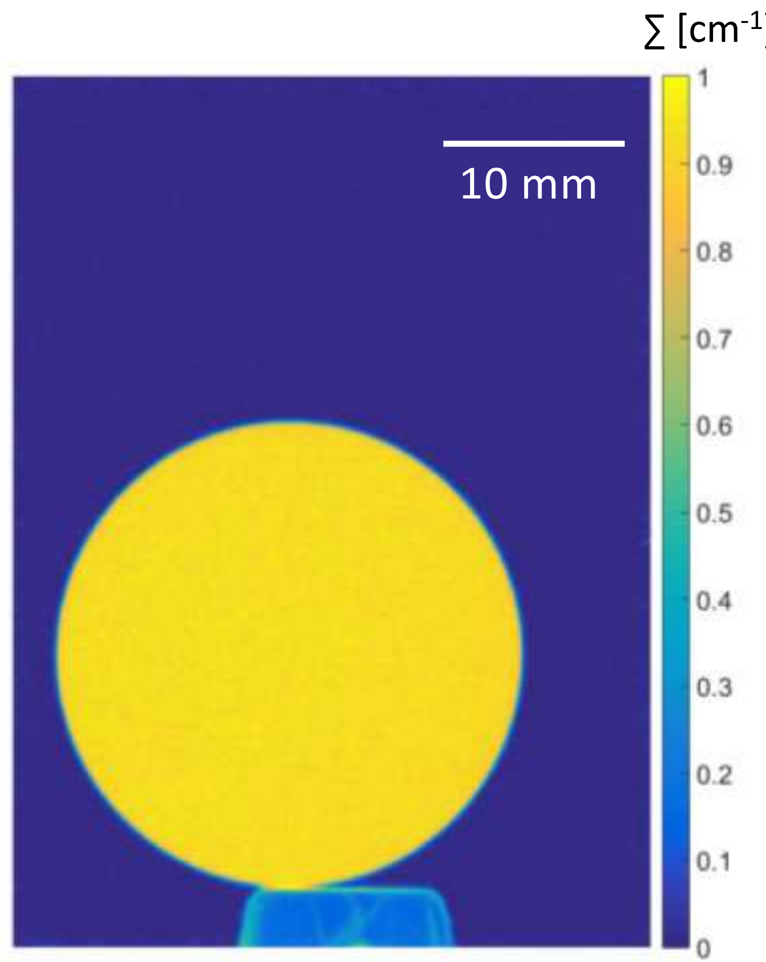
$$\frac{I}{I_0} = e^{-\Sigma t} \longrightarrow \Sigma = ln\left(\frac{I}{I_0}\right)\frac{1}{t}$$

ETP Copper
r = 12.5 mm
t = 10 mm

Sample at distance = 0 mm



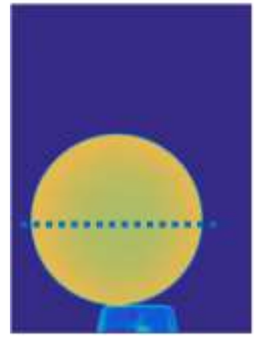
Sample at distance = 55 mm



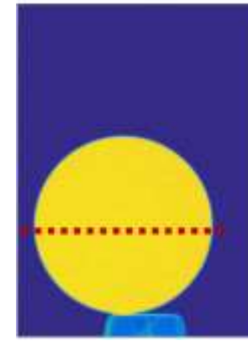
Why is scattering correction needed?

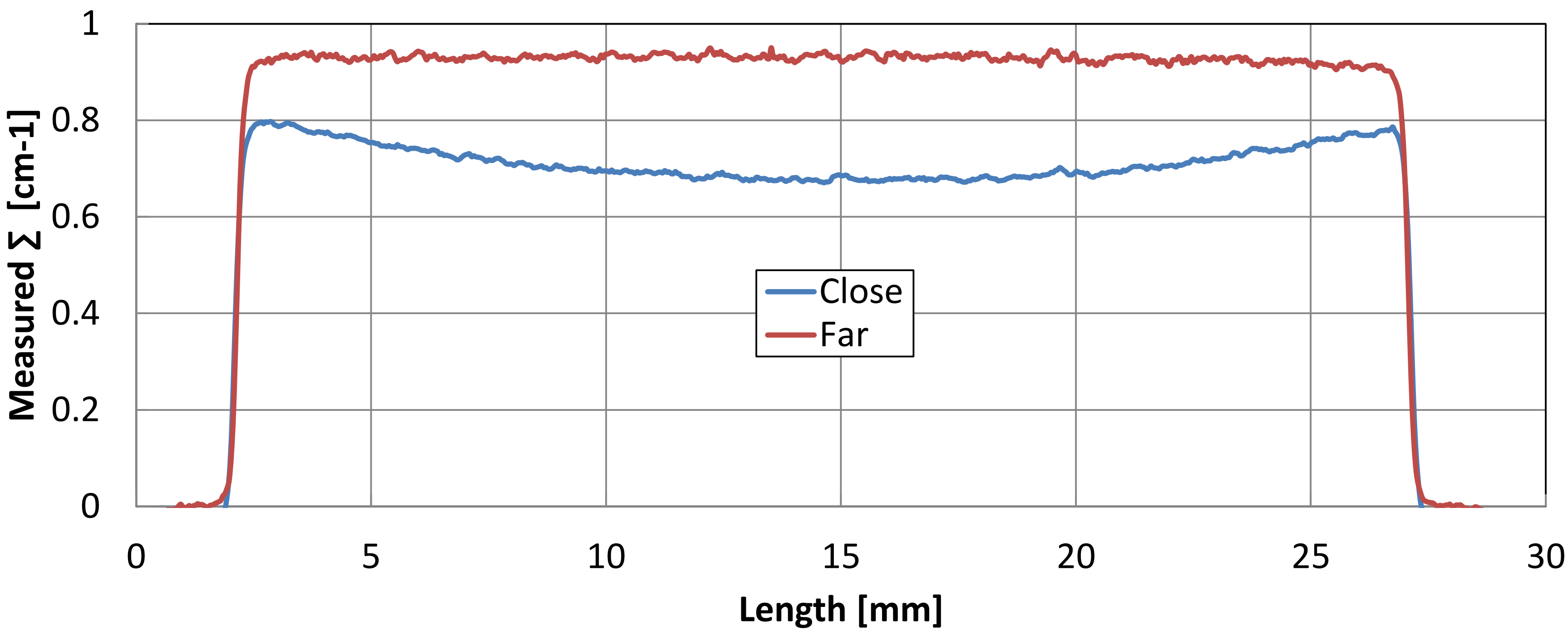
Photograph

Distance = 0 mm



Distance = 55 mm





Forward scattering for coherent scatterers

Bragg law

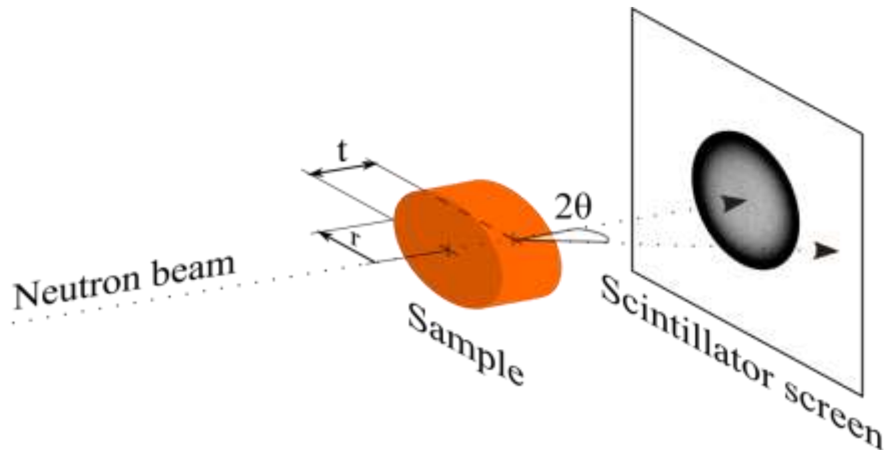
$$n\lambda = 2d \cdot sin(\theta) \rightarrow 2\theta = 2asin\left(\frac{n\lambda}{2d}\right)$$

λ=1Å
n=1

	Largest d-spacing [Å]	Smallest 2θ [°]
Copper	2.08	28
Iron	2.02	29
Aluminium	2.33	25
Titanium	2.55	23

Examples of minimum scattering angles for structural metals

Forward scattering for coherent scatterers



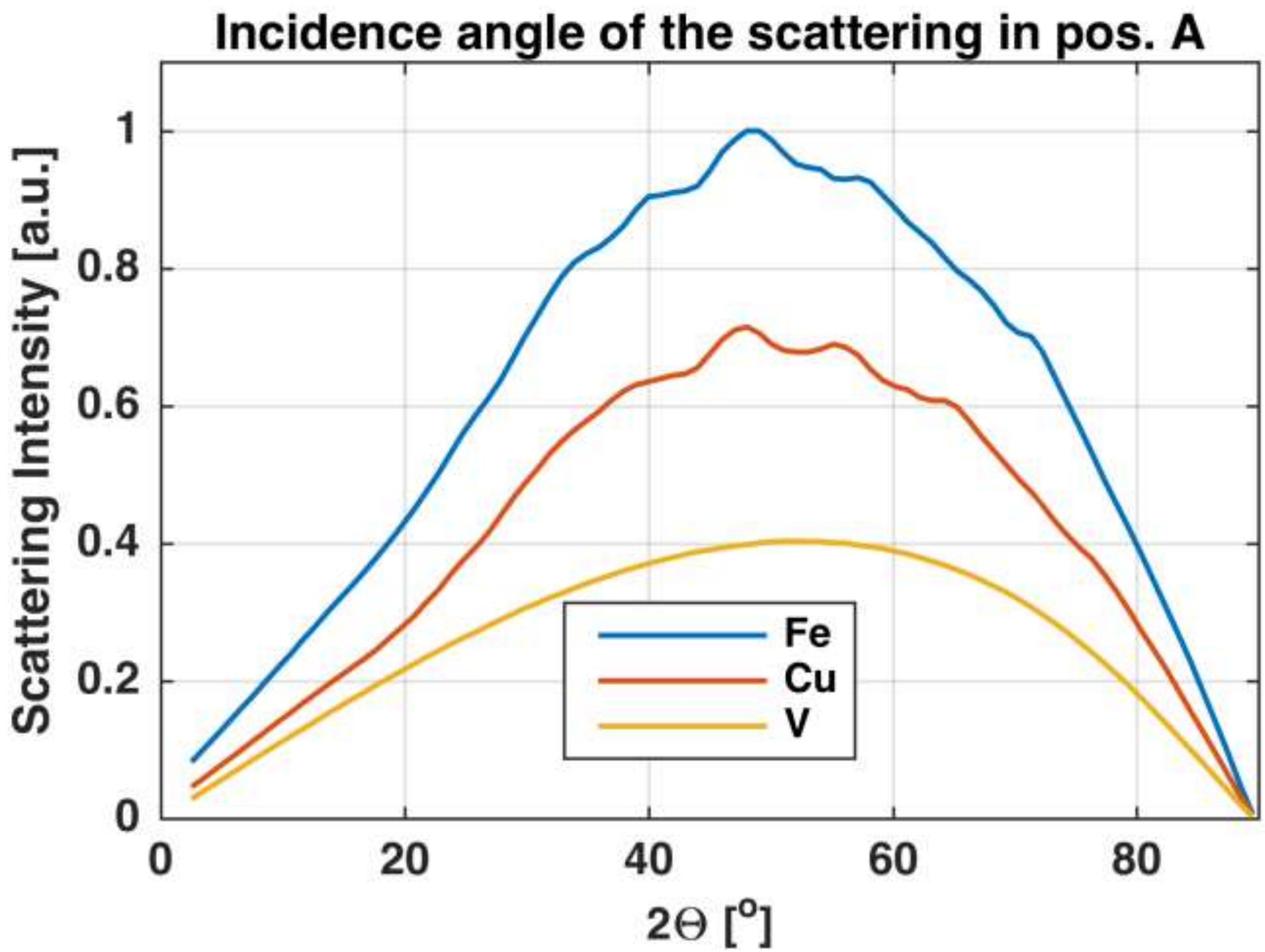
λ=1Å

n=1

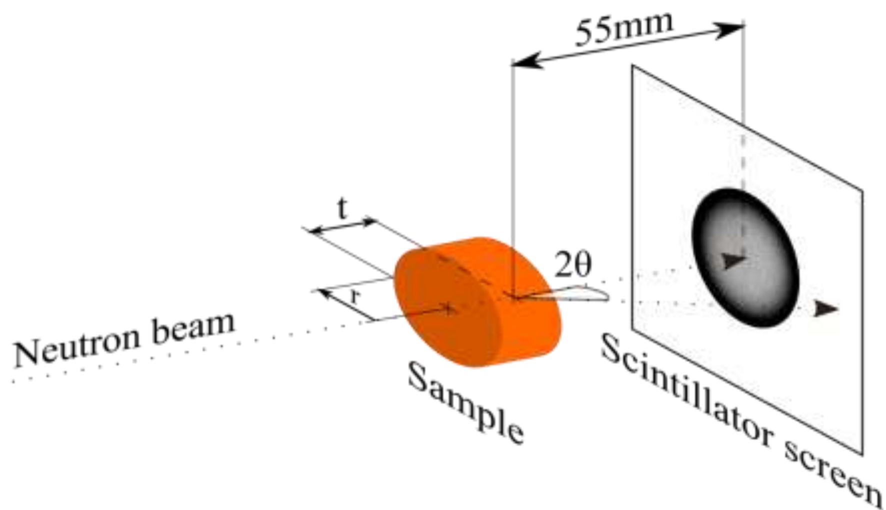
	Largest d-spacing [Å]	Smallest 2θ [°]
Copper	2.08	28
Iron	2.02	29
Aluminium	2.33	25
Titanium	2.55	23

Examples of minimum scattering angles for structural metals

Angular distribution of the scattered neutrons

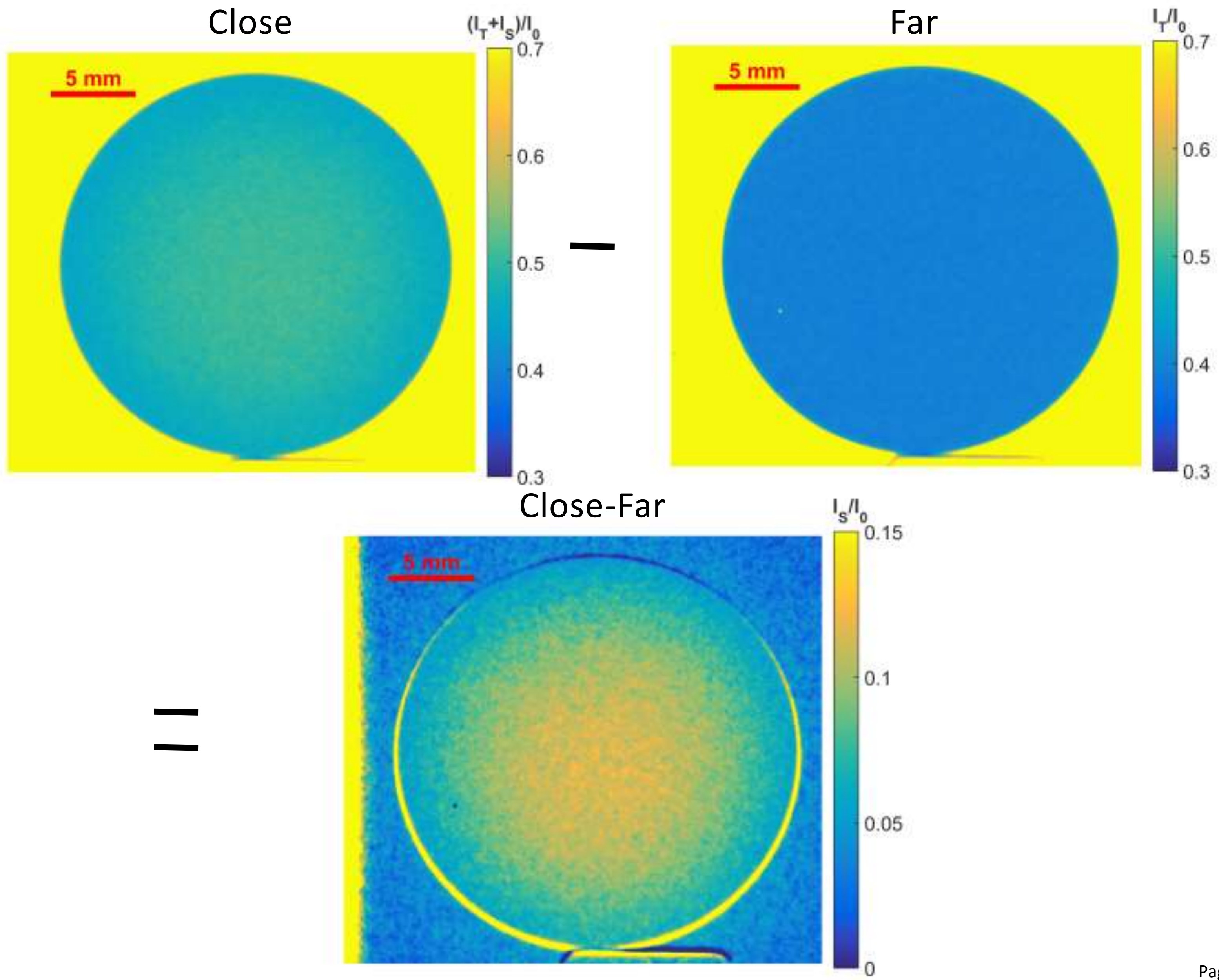


Quantifying the scattering

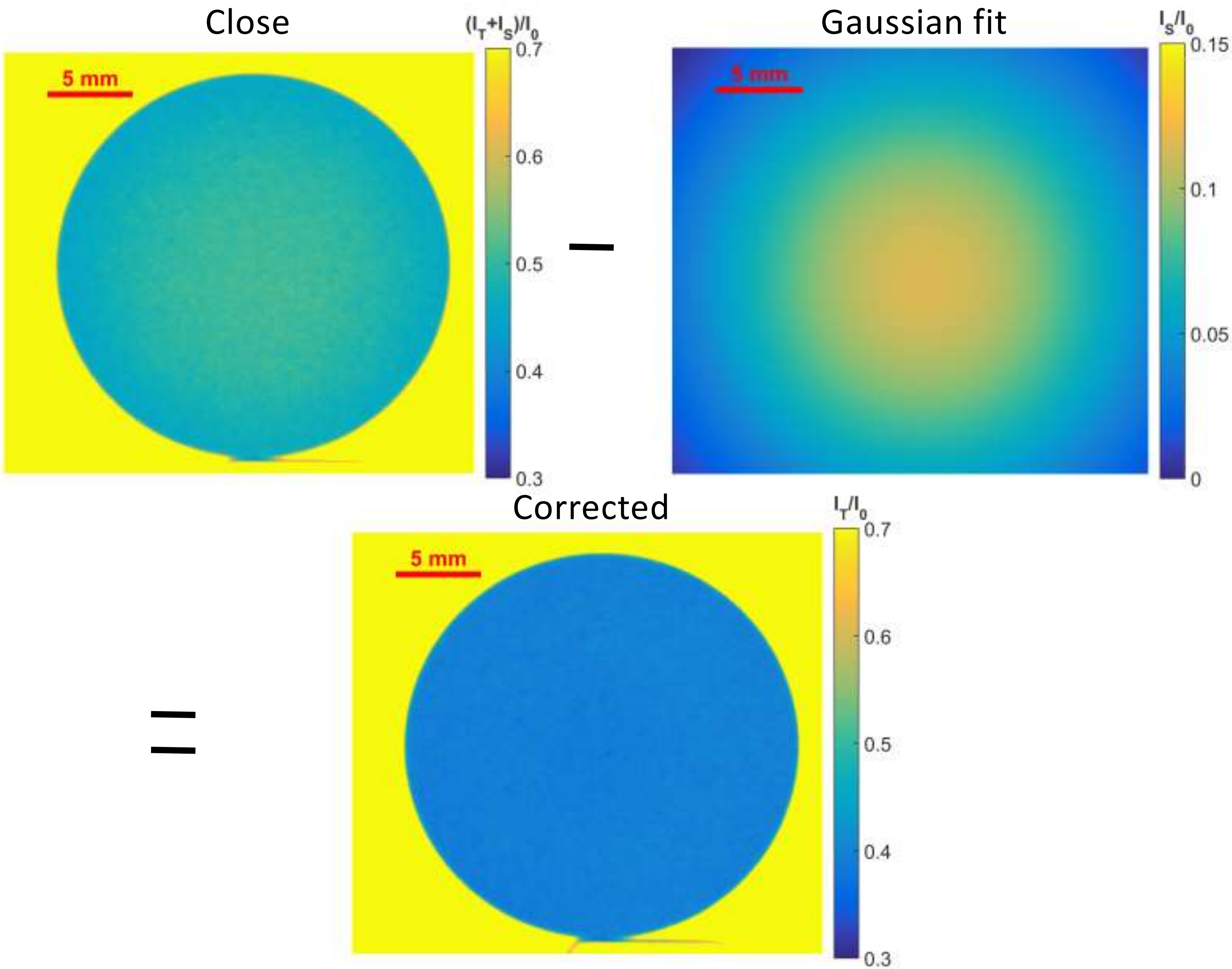


- Close, Distance = 0 cm $$\frac{I_{Transmitted} + I_{Scattered}}{I_0}$$
- Far, Distance = 55 mm $$\frac{I_{Transmitted}}{I_0}$$
- Close - Far $$\frac{I_{Scattered}}{I_0}$$

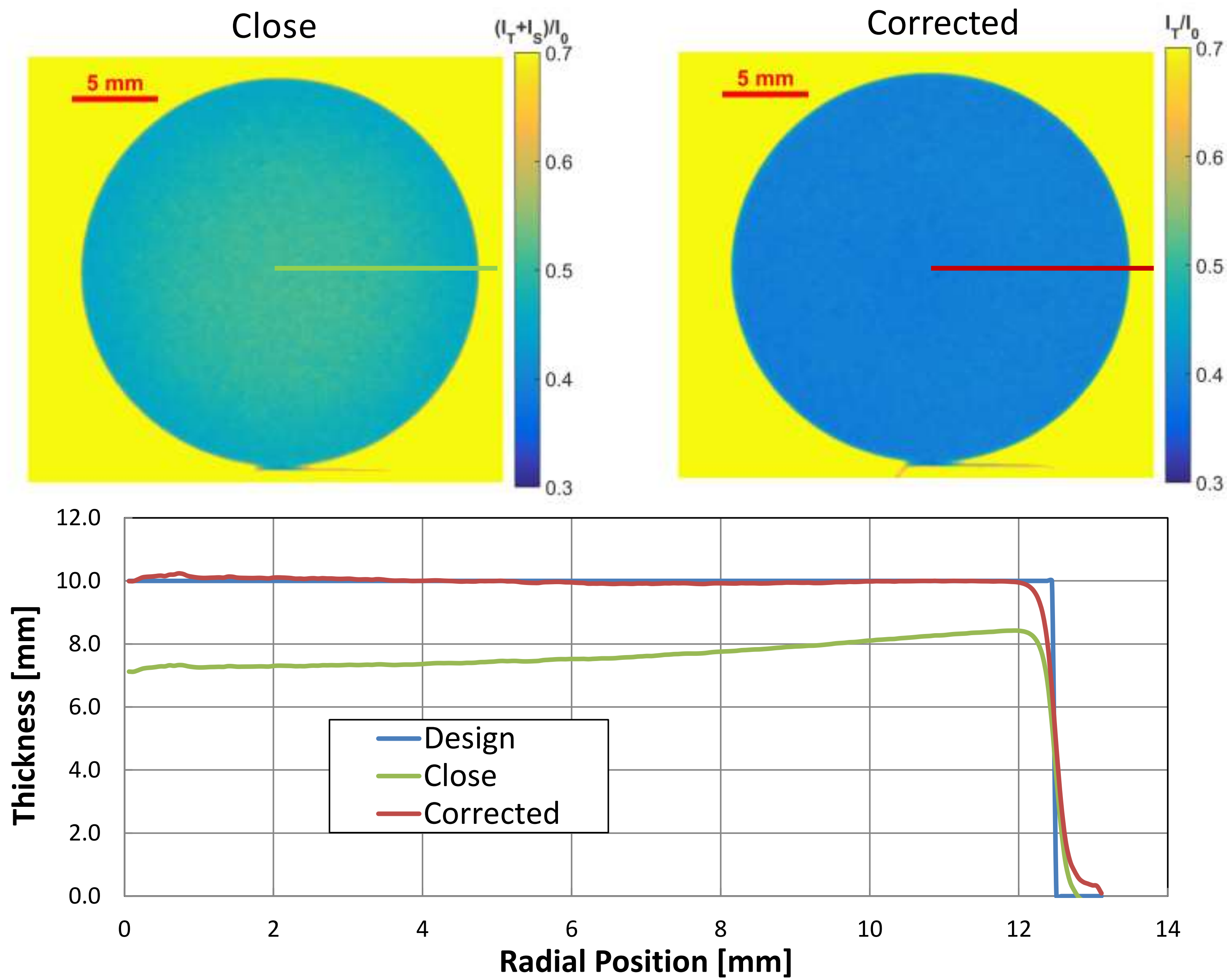
Quantifying the scattering: Coin



Quantifying the scattering: Coin



Correcting the scattering: Coin



The «black body» approach

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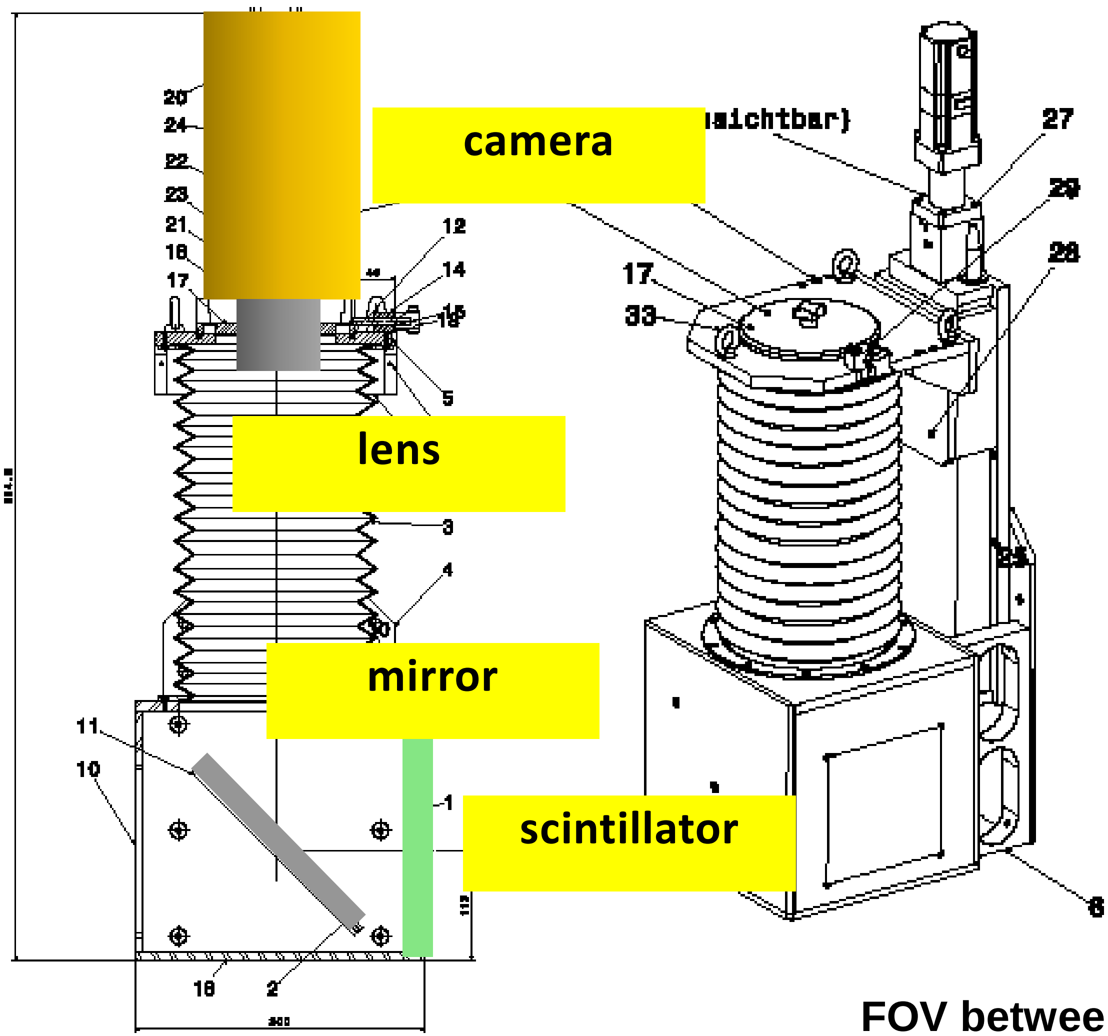
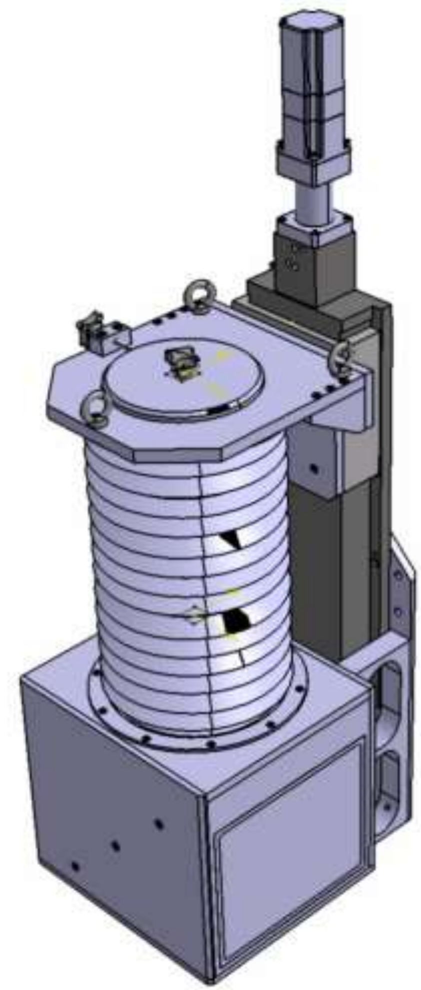
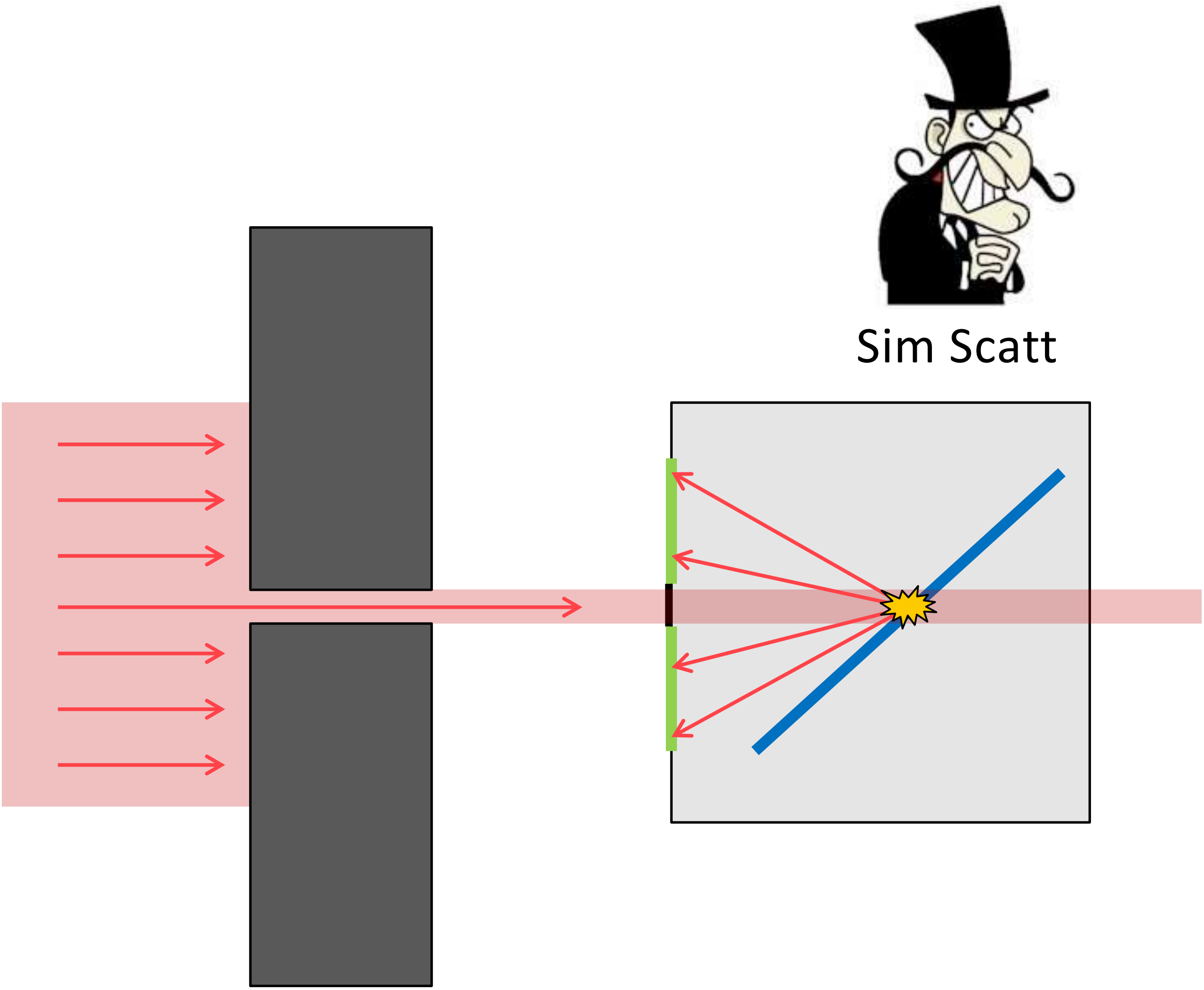
Camera-detector MIDI (medium FOV)



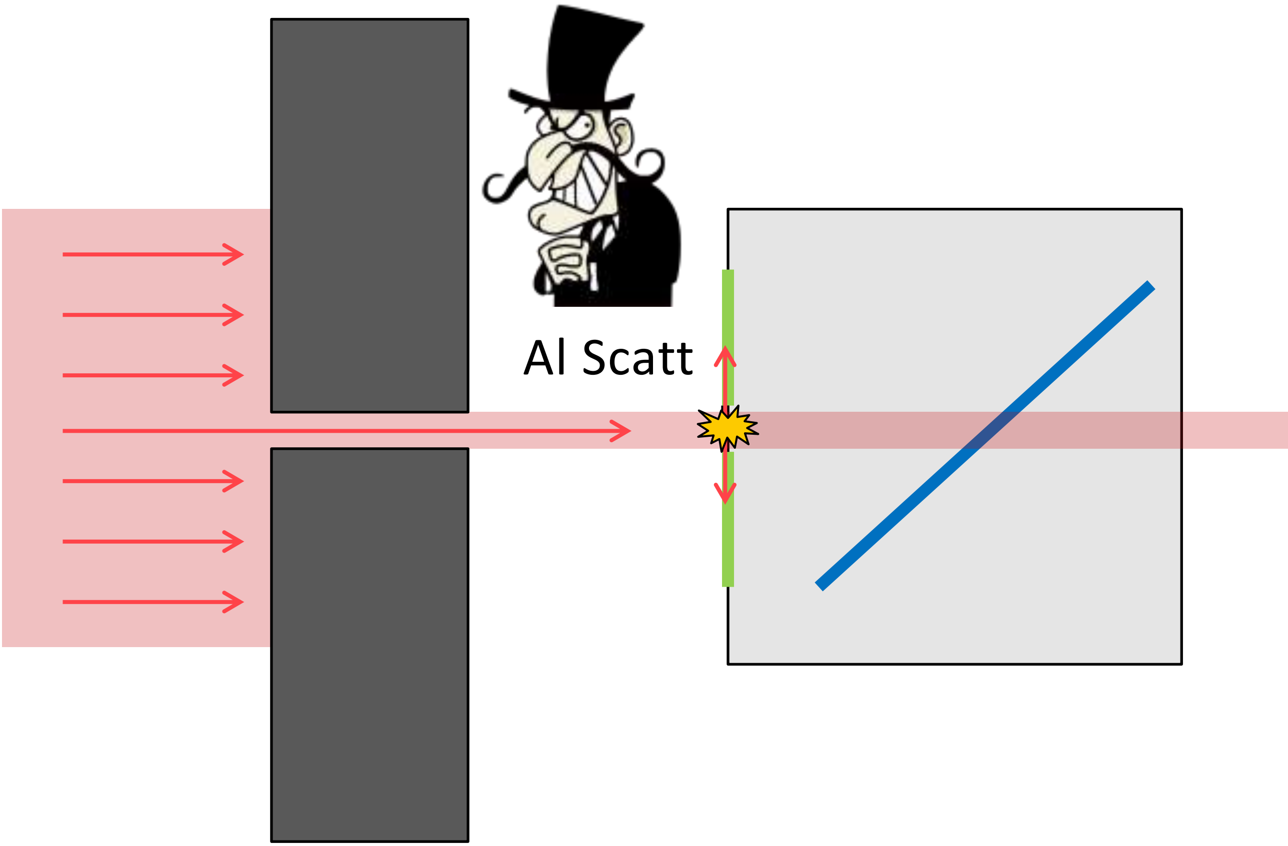


FOV between 15 and 3 cm

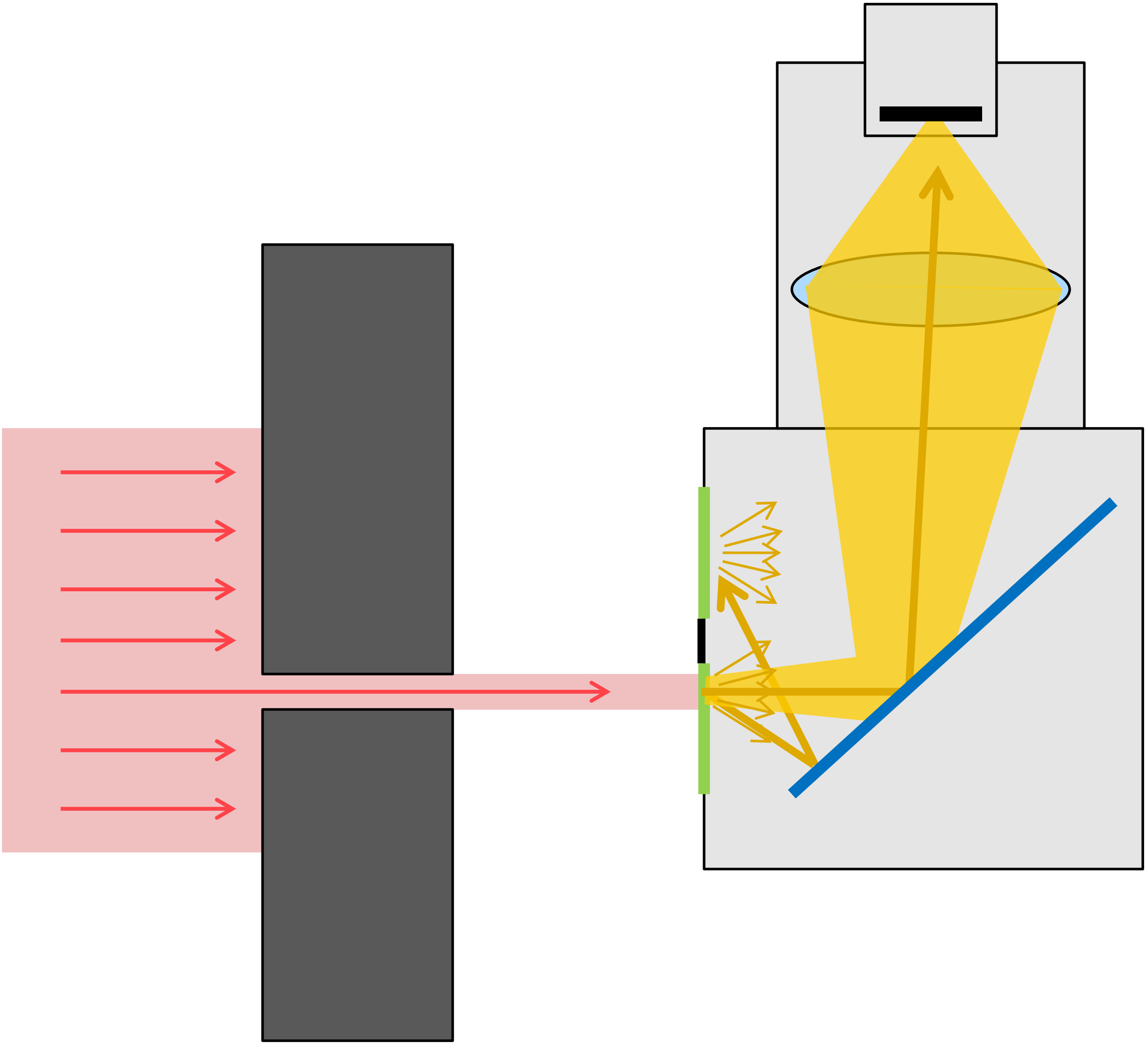
Mirror back-scattering

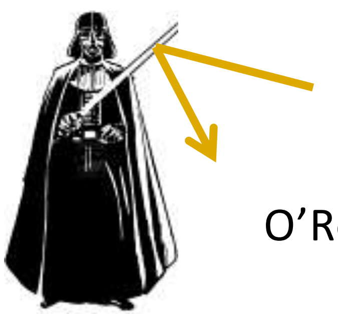


Scintillator substrate scattering



Special guest …





O'Ref

(= Optical Reflexion)

How much do they contribute ?

Elimination or Correction

WANTED

Sim Scatt

REWARD:

2%

Elimination or Correction

WANTED

Al Scatt

REWARD:

1%

Elimination or Correction

WANTED

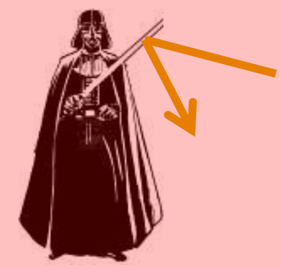
O'Blurry

REWARD:

< 0.5%

Elimination or Correction

WANTED



O'Ref

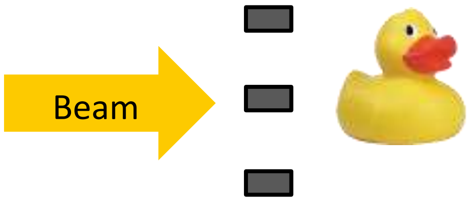
REWARD:

2%

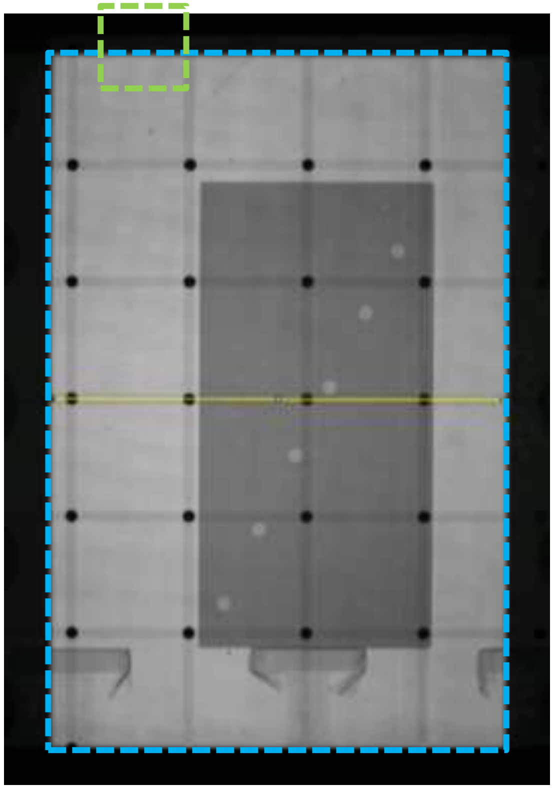
Up to 15-20% depending on setup !!!

Recomendation for the experiments

- Black body grid in front of the sample



- Dose correction region inside the grid



- **For tomographies**: Image of BB with open beam **<u>and</u>** image of BB at 25 different angles

- **For time series**: Image of BB with open beam **<u>and</u>** image of BB at one reference state

The correction process

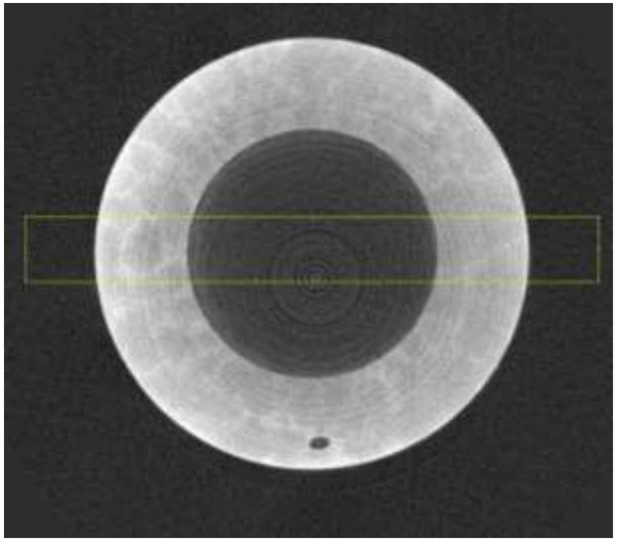
0 Nomenclature

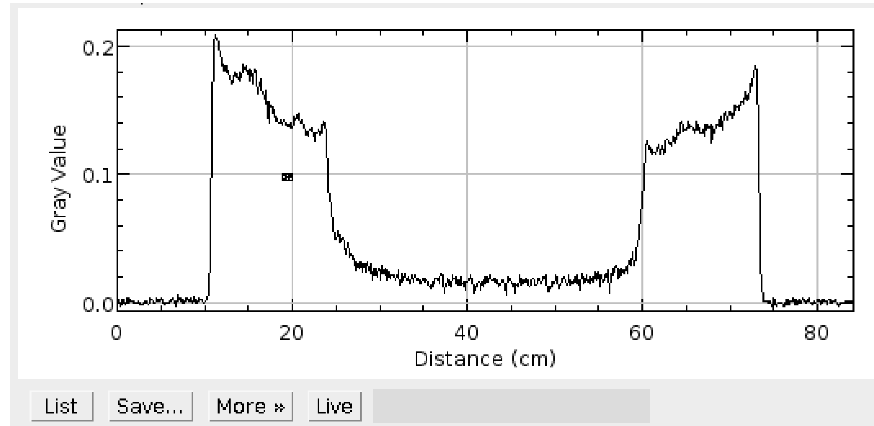
I_n^*	Measured sample image
I_n	True sample image
I_n^{BG}	Background of sample image
$\tilde{I}_n$	Normalised true sample image
$\tilde{I}_n^{BG}$	Normalised background of sample image
D	Dose operator (average value of normalising region)
I_{DC}	Dark current image
I_{OB}	Open beam image
$I_{n,BB}$	Sample image with black body pattern (mean pattern transmission $\tau_{BB} \in (0,1)$)
$I_{OB,BB}$	Open beam image with black body pattern (mean pattern transmission $\tau_{BB} \in (0,1)$)

$$\frac{\tilde{I}_n}{\tilde{I}_{OB}} = \frac{I_n^* - I_{DC} - I_{n,BB}^{BG} \dfrac{\mathrm{D}(I_n^* - I_{DC})}{\mathrm{D}\left(I_{n,BB}^* + \left(\dfrac{1}{\tau_{BB}} - 1\right) I_{n,BB}^{BG} - I_{DC}\right)\tau_{BB}}}{I_{OB}^* - I_{DC} - I_{OB,BB}^{BG} \dfrac{\mathrm{D}(I_{OB}^* - I_{DC})}{\mathrm{D}\left(I_{OB,BB}^* + \left(\dfrac{1}{\tau_{BB}} - 1\right) I_{OB,BB}^{BG} - I_{DC}\right)\tau_{BB}}} \cdot \frac{\mathrm{D}\left(I_{OB}^* - I_{DC} - I_{OB,BB}^{BG} \dfrac{\mathrm{D}(I_{OB}^* - I_{DC})}{\mathrm{D}\left(I_{OB,BB}^* + \left(\dfrac{1}{\tau_{BB}} - 1\right) I_{OB,BB}^{BG} - I_{DC}\right)\tau_{BB}}\right)}{\mathrm{D}\left(I_n^* - I_{DC} - I_{n,BB}^{BG} \dfrac{\mathrm{D}(I_n^* - I_{DC})}{\mathrm{D}\left(I_{n,BB}^* + \left(\dfrac{1}{\tau_{BB}} - 1\right) I_{n,BB}^{BG} - I_{DC}\right)\tau_{BB}}\right)}$$

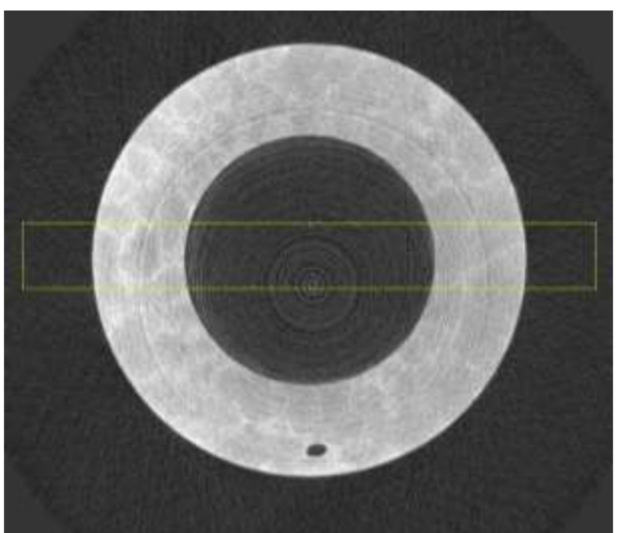
Example – Lead Sphere Tomo

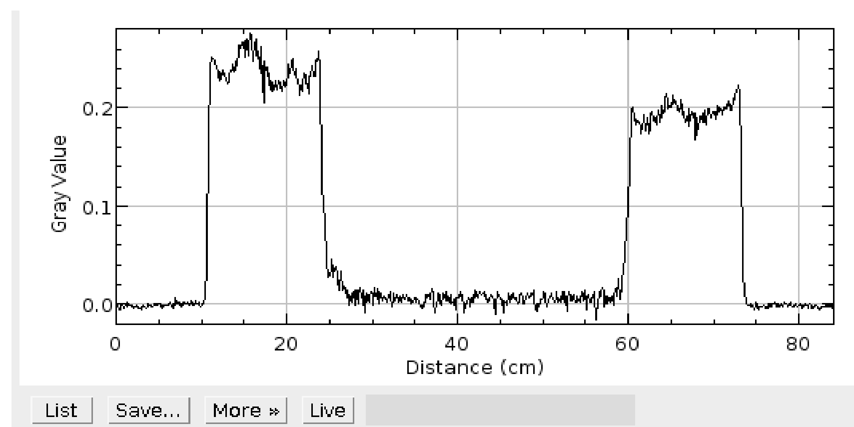
Without BB correction





With BB correction





Neutron imaging methods @ PSI

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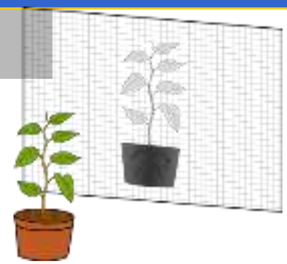
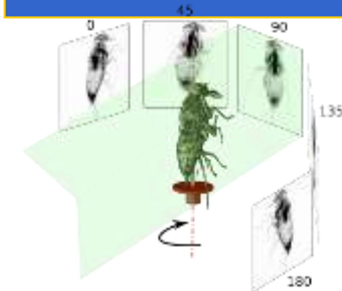
Classic neutron imaging methods

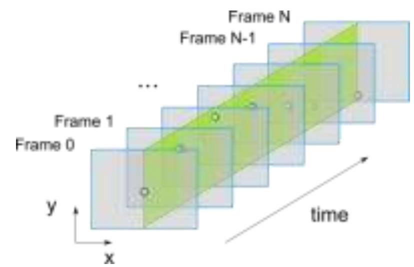
Radiography



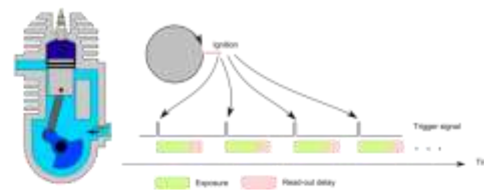
Tomography



Real-time imaging

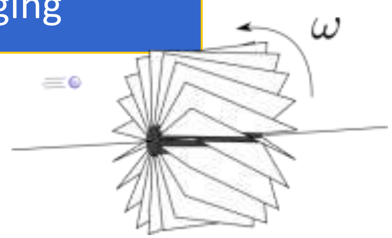


Stroboscopic imaging

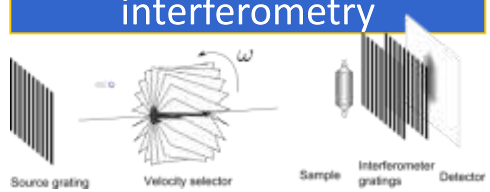


Advanced neutron imaging methods

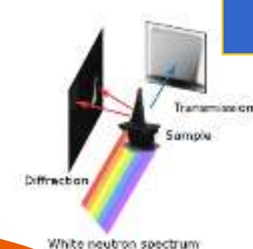
Energy selective imaging



Neutron grating interferometry



Diffraction imaging



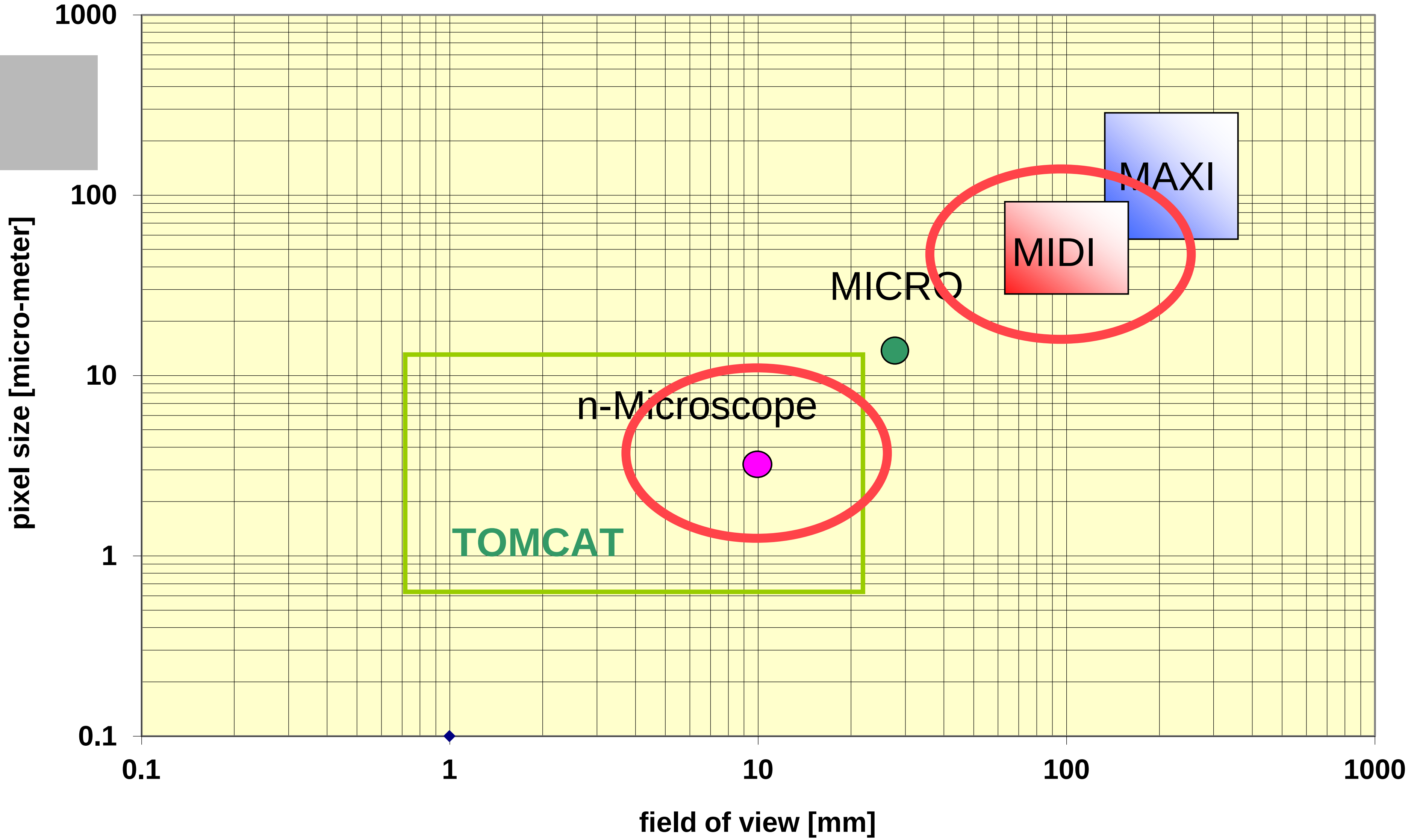
Under preparation:

Imaging with polarized neutrons (BOA)

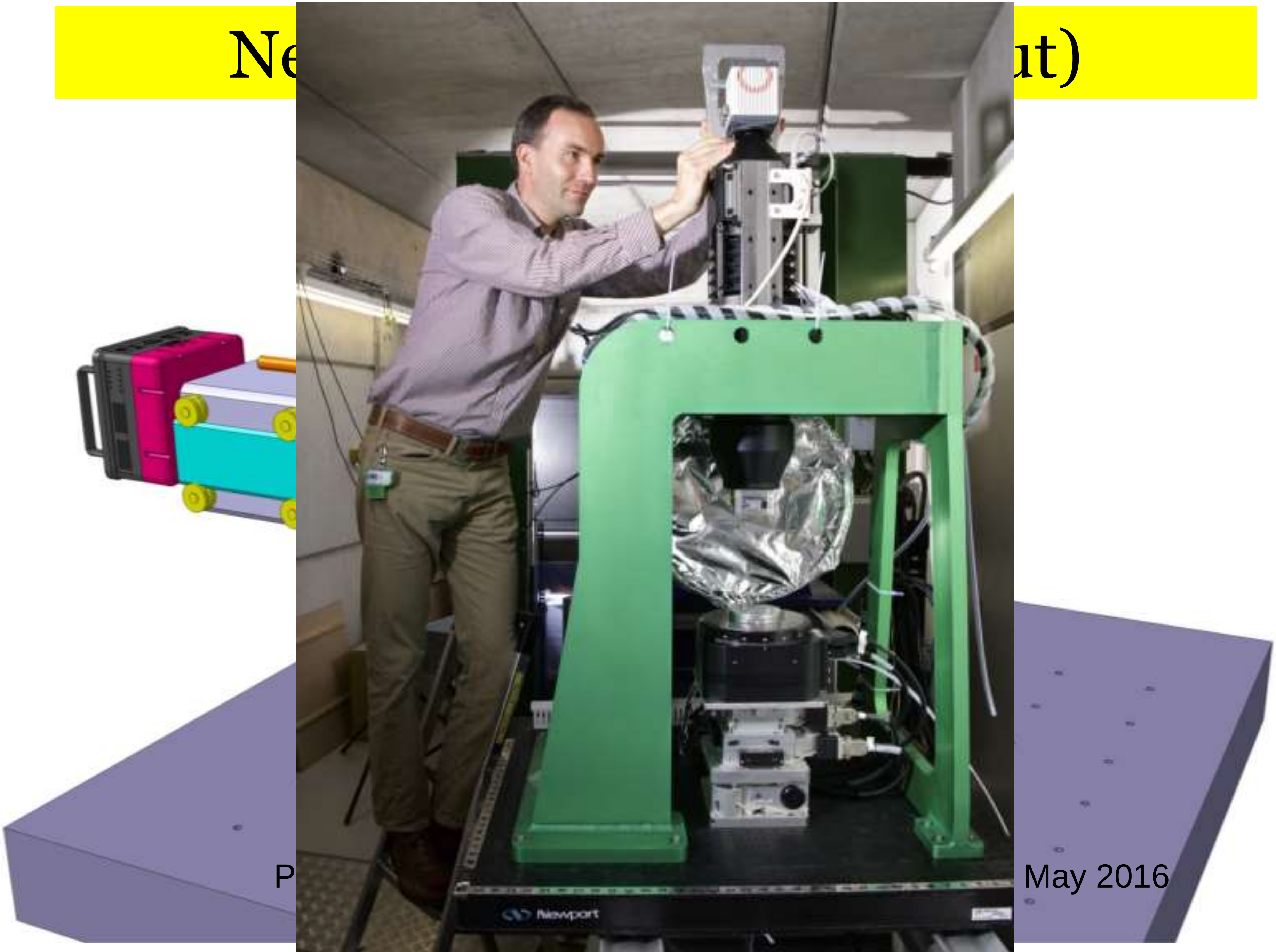
Project neutron microscope

N/X data fusion

Neutron Imaging: Improvement in spatial resolution



Ne ut)



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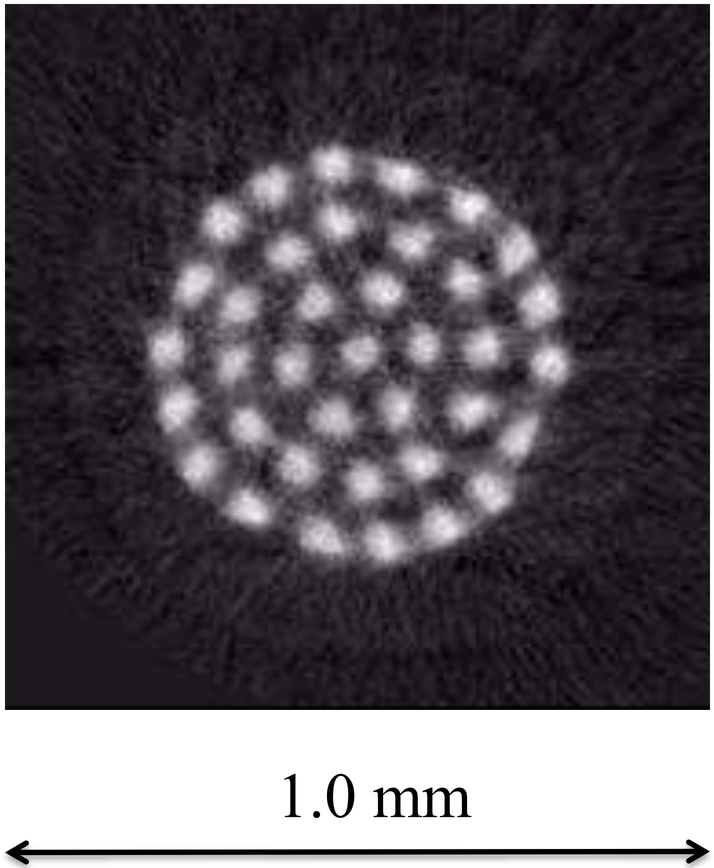
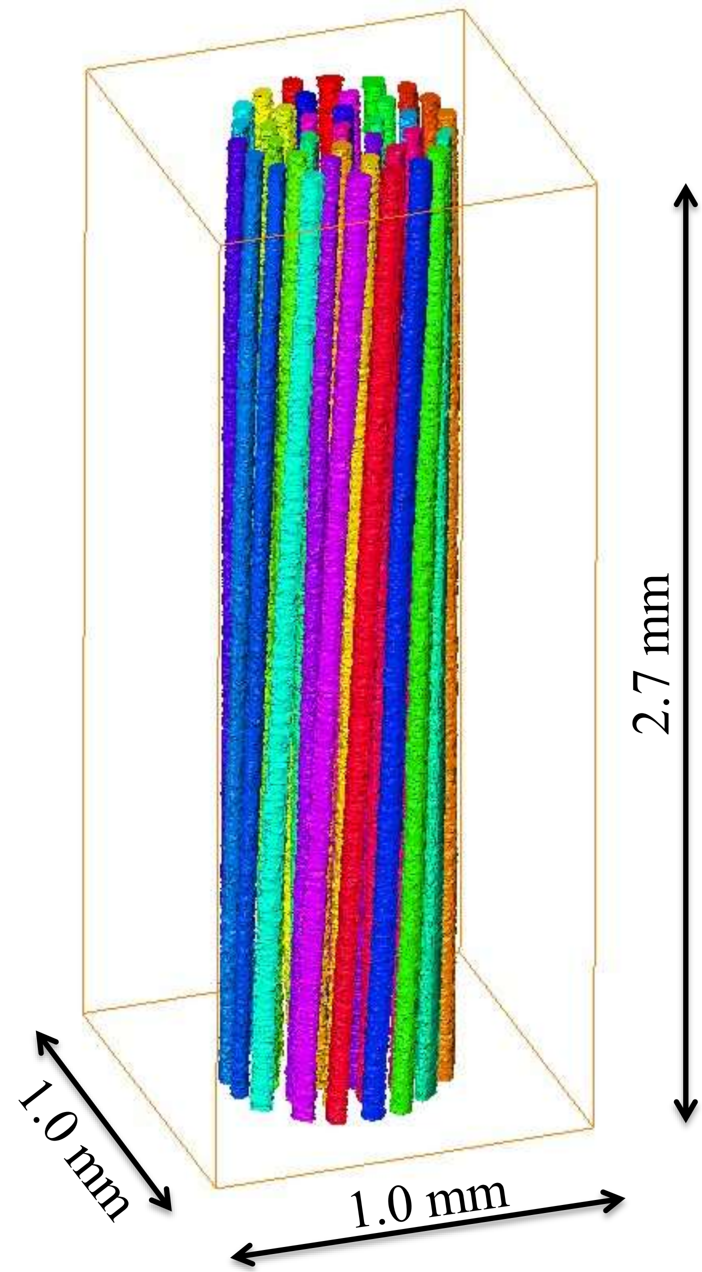
MgB_2 multifilament wire in Ni casing





- 4-binned, 5.2 um pixel size,
- 180 projections
- about 4.5 hours acquisition time

Sample courtesy of Ch. Scheuerlein (CERN)

The Future of Neutron Imaging

- More access to prominent and useful neutron sources (ILL?)
- New installations with high performance
- Further methodical progress, oriented to the user profile
- Qualification of new and young operators of the facilities with respect to image processing and quantification
- Standardization of the processes to attract more industrial customers

New imaging facilities under development (or upgrade)

- **Argentina:** new reactor Buenos Aires
- **Czech Republic:** beam line in Rez
- **China:** CARR reactor with 2 beam lines
- **France:** IMAGINE at Saclay reactor
- **Europe (ILL):** D50 cold guide shared with reflectometer
- **Norway:** beam line upgrade at Halden reactor
- **Netherlands:** project FISH
- **Jordan:** new reactor under construction – with NI facility
- **South Africa:** upgrade to SANRAD-2
- **Russia:** improvements at Dubna pulsed reactor
- **South Korea:** upgrades
- **Hungary:** improvements and upgrades → «club members»

Neutron Imaging @ Spallation Sources

• SINQ: NEUTRA, ICON, *BOA*	operational
• JPARC: RADEN	2015
• ISIS: *IMAT*	2016
• SNS: *VENUS*	2018 ?
• *ESS*: *ODIN*	2019 ?

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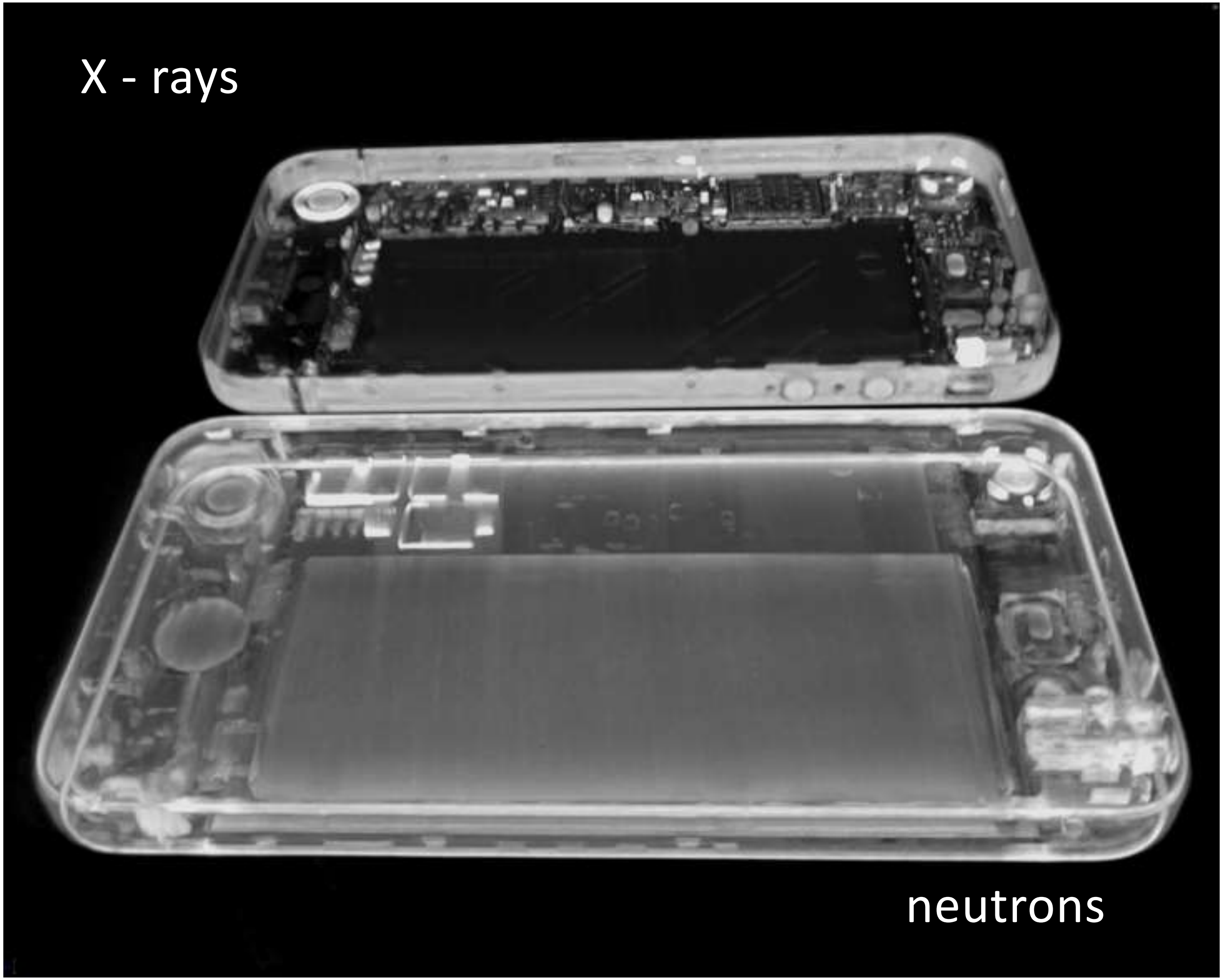
Outlook: Trends in Neutron Imaging

- colder neutrons
- energy selectivity → pulsed sources, higher E - resolution
- polarized neutrons
- combination of imaging with diffraction
- symbiosis of neutron with X-ray imaging
- highest possible intensities → higher temporal and spatial resolution

Smartphone – Tomography mode



Thanks to: NIAG Team (2/2017)

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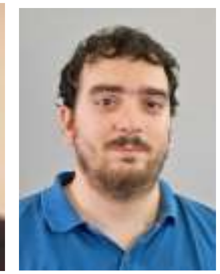
Projects: ESS & CCMX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Visit PSI and Switzerland ...
... for collaboration and utilization