Biomedical Imaging

Introduction

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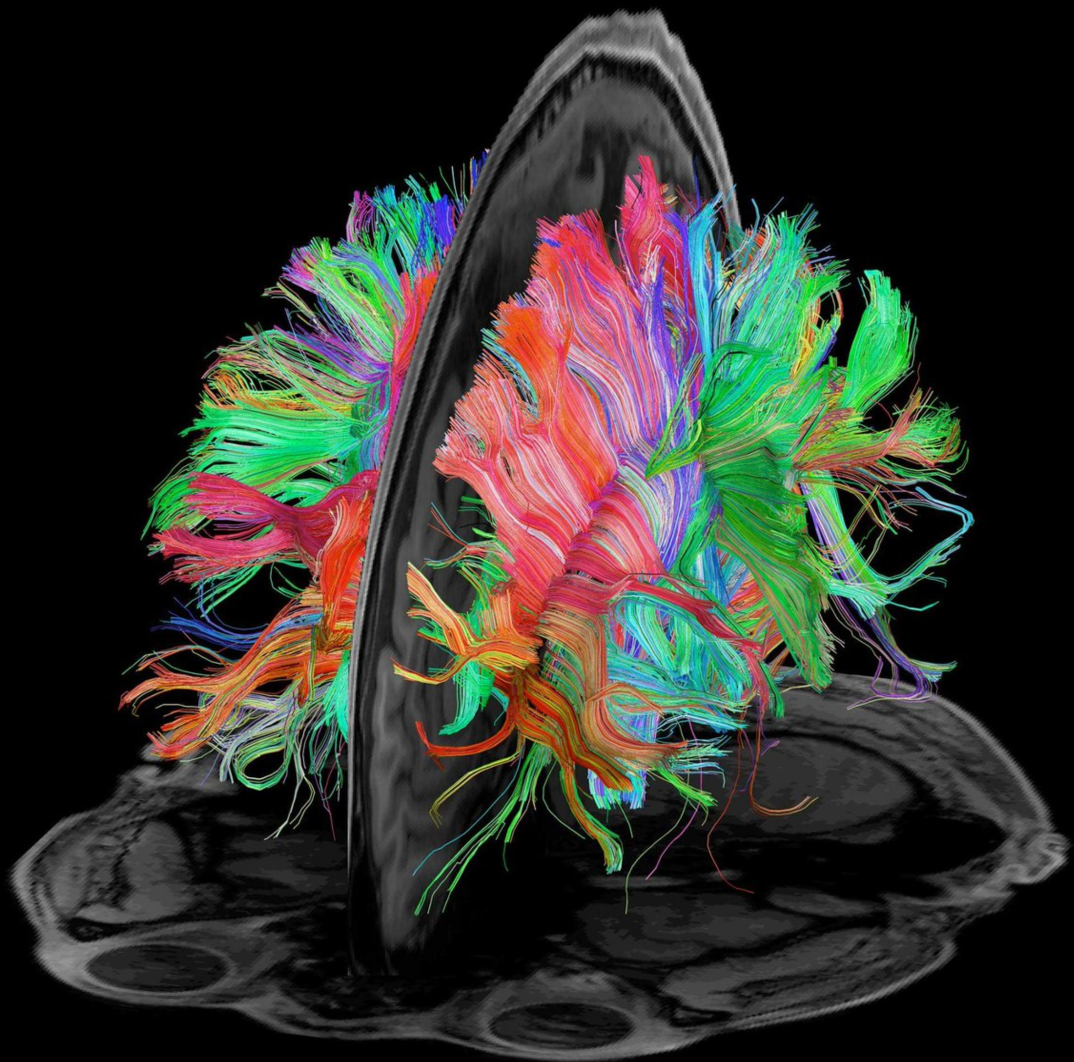
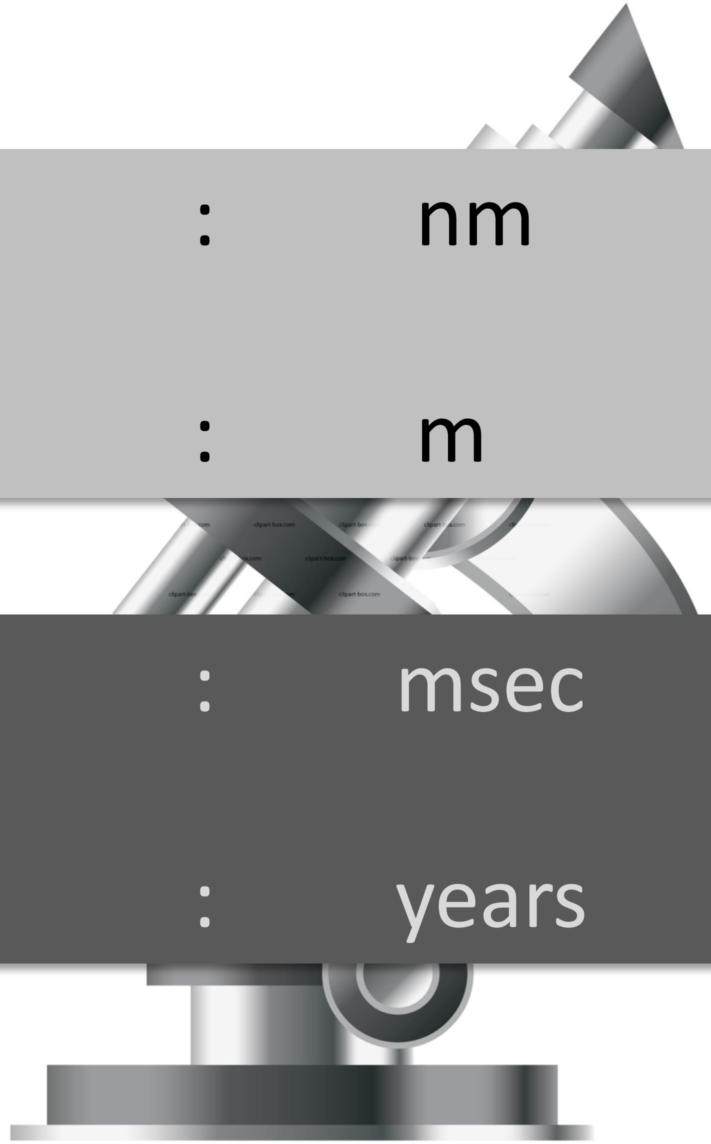


A picture is worth a thousand words

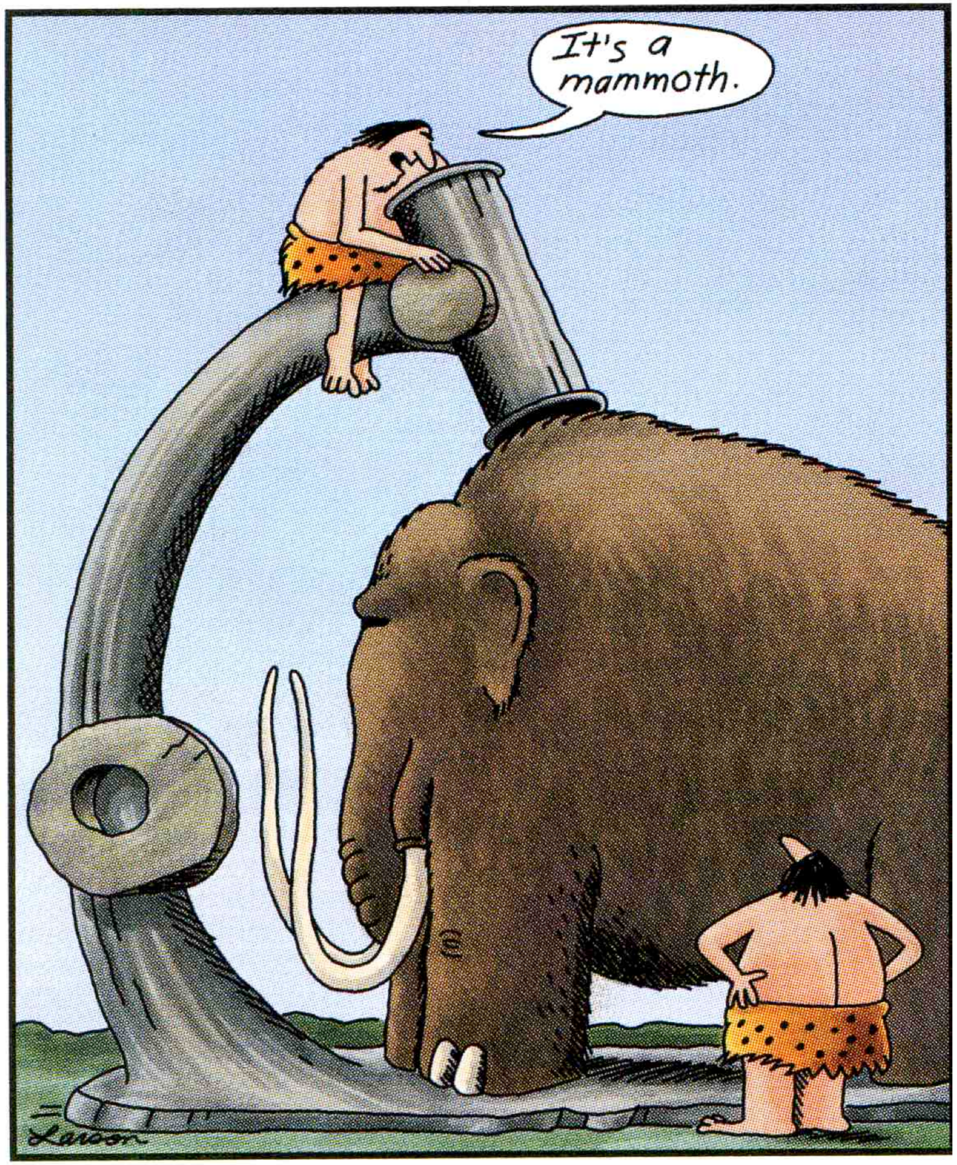
Imaging across scales



Proteins	:	nm	
			1 : 10^9
Body	:	m	

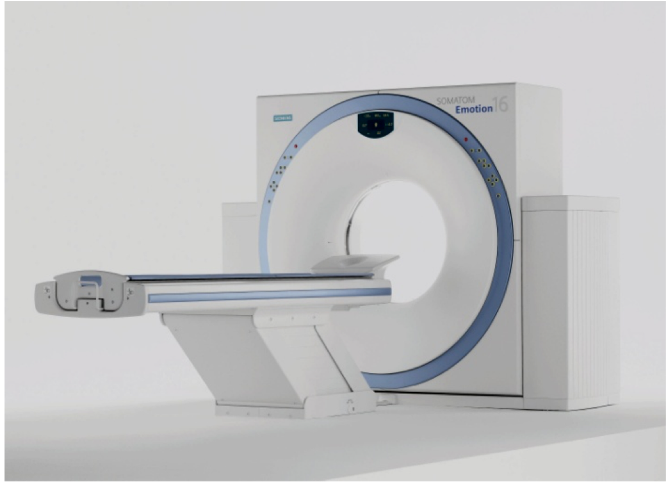
Synapse	:	msec	
			1 : 10^{10}
Life	:	years	

Choosing Instruments



Clinical Biomedical Imaging

X-Ray, Computed Tomography



Magnetic Resonance Imaging

Nuclear Imaging

Ultrasound Imaging

Learning objectives

1	2	3	4
Explain physical and mathematical foundations	Characterize system performance using linear system theory	Define requirements and design basic diagnostic imaging system chain	Identify advantages and limitations of different imaging methods
Signal generation	Transfer function	Data acquisition	Resolution power
Matter interaction	Depiction fidelity	Data pre-processing	Dose, Safety
Signal detection	Noise propagation	Data reconstruction	Experimental use
Image reconstruction	Performance metrics	Data post-processing	Clinical use

Agenda

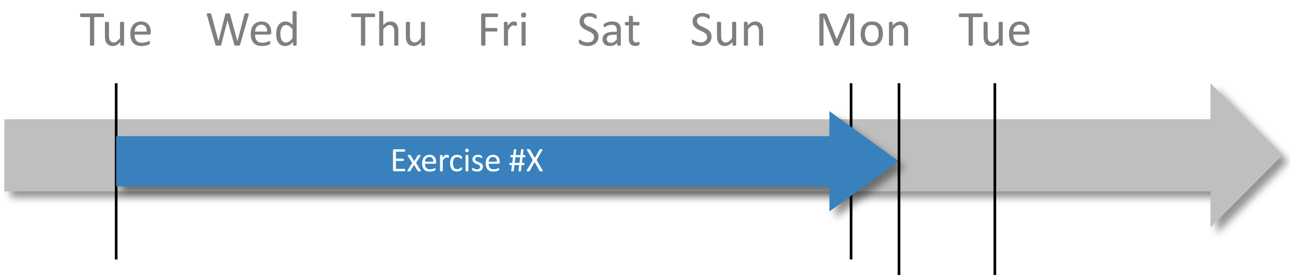
17.09.	**Introduction** (intro, overview, history)	Kozerke
24.09.	**Signal theory and processing** (foundations, transforms, filtering, signal-to-noise ratio)	Pruessmann
01.10.	**Ultrasound** (mechanical wave generation, propagation in tissue, reflection, transmission)	Goeksel
08.10.	**Ultrasound** (spatial and temporal resolution, phased arrays)	Pruessmann
15.10.	**Ultrasound** (Doppler shift, implementations, applications)	Pruessmann
22.10.	**X-rays** (production, tissue interaction, contrast, detection)	Kozerke
29.10.	**X-rays** (resolution, point-spread function, Poisson noise)	Kozerke
05.11.	**X-rays** (Radon transform, filtered back-projection, computed tomography, dosimetry)	Kozerke
12.11.	**Nuclear imaging** (radioactive tracer concept, tracer production, spect/pet)	Kozerke
19.11.	**Nuclear imaging** (detection principles, image reconstruction, resolution limits, kinetic modeling)	Kozerke
26.11.	**Magnetic Resonance** (magnetic moment, spin transitions, excitation, relaxation, detection)	Pruessmann
03.12.	**Magnetic Resonance** (plane wave encoding, Fourier reconstruction, pulse sequences)	Pruessmann
10.12.	**Magnetic Resonance** (contrast mechanisms, gradient- and spin-echo, applications)	Pruessmann
17.12.	**Summary, example exam questions**	Kozerke

Agenda

17.09.	**Introduction** (intro, overview, history)	-
24.09.	**Signal theory and processing** (foundations, transforms, filtering, signal-to-noise ratio)	Exercise #1
01.10.	**Ultrasound** (mechanical wave generation, propagation in tissue, reflection, transmission)	Exercise #2
08.10.	**Ultrasound** (spatial and temporal resolution, phased arrays)	Exercise #3
15.10.	**Ultrasound** (Doppler shift, implementations, applications)	Exercise #4
22.10.	**X-rays** (production, tissue interaction, contrast, detection)	Exercise #5
29.10.	**X-rays** (resolution, point-spread function, Poisson noise)	Exercise #6
05.11.	**X-rays** (Radon transform, filtered back-projection, computed tomography, dosimetry)	Exercise #7
12.11.	**Nuclear imaging** (radioactive tracer concept, tracer production, spect/pet)	Exercise #8
19.11.	**Nuclear imaging** (detection principles, image reconstruction, resolution limits, kinetic modelin	Exercise #9
26.11.	**Magnetic Resonance** (magnetic moment, spin transitions, excitation, relaxation, detection)	Exercise #10
03.12.	**Magnetic Resonance** (plane wave encoding, Fourier reconstruction, pulse sequences)	Exercise #11
10.12.	**Magnetic Resonance** (contrast mechanisms, gradient- and spin-echo, applications)	Exercise #12
17.12.	**Summary, example exam questions**	-

Exercises

- Matlab based (in groups of two); problem solving



13-15 HG E7 Lecture

13-15 HG E19 **Computer room**

15-16 HG E7 **Exercise (preparation)**

15-16 HG E7 **Exercise (solution, discussion)**

Mon <23:59 **Submit Solution in Moodle**

Activity

My expertise in Matlab programming is ...

- Basic
- Intermediate
- Excellent
- What is Matlab?

ETH Edu

Exam

Type	Written, closed-book Personal 2-page formulary
Duration	120 min
Grading	Submitted exercise results are graded. A maximum bonus of 0.25 can be achieved and is added to the exam grade if a minimum of 9 exercises has successfully been accomplished.

Lecture notes

Handouts + Exercises

https://moodle-app2.let.ethz.ch/course/view.php?id=11546

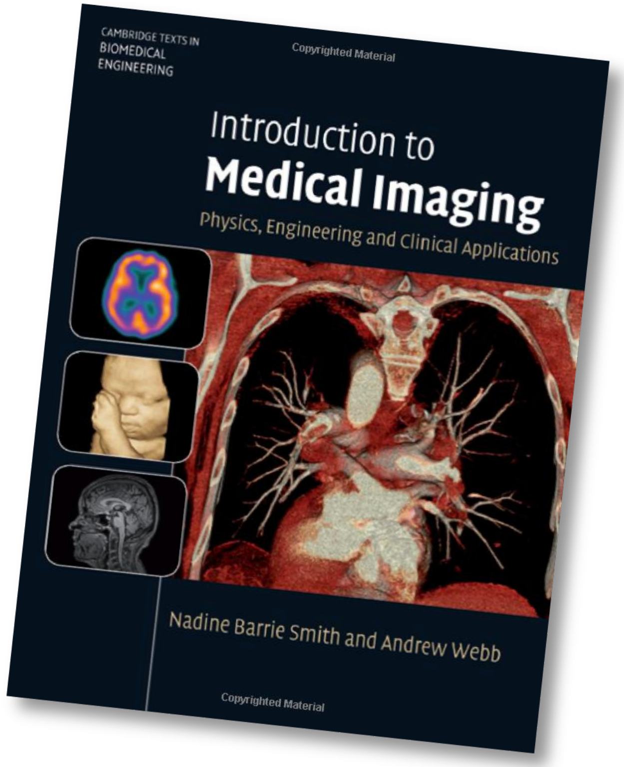
Book

Introduction to Medical Imaging

Cambridge University Press

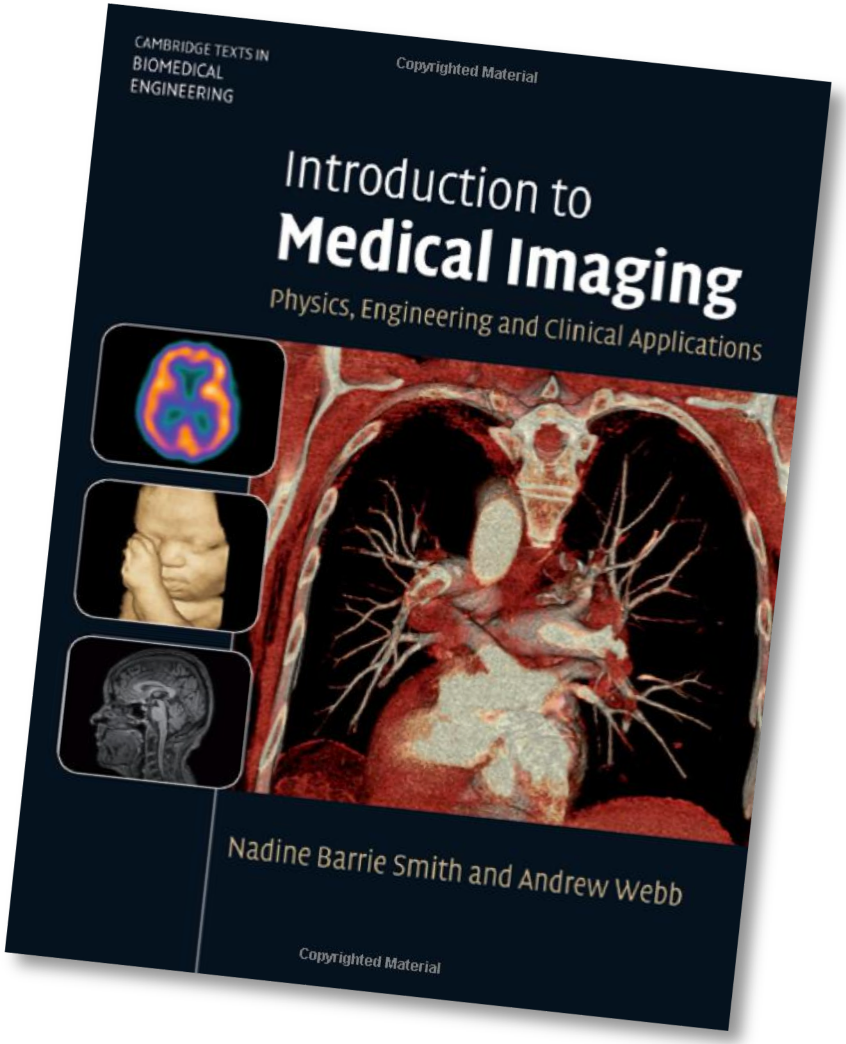
Nadine Barrie Smith, Andrew Webb

www.library.ethz.ch → online access

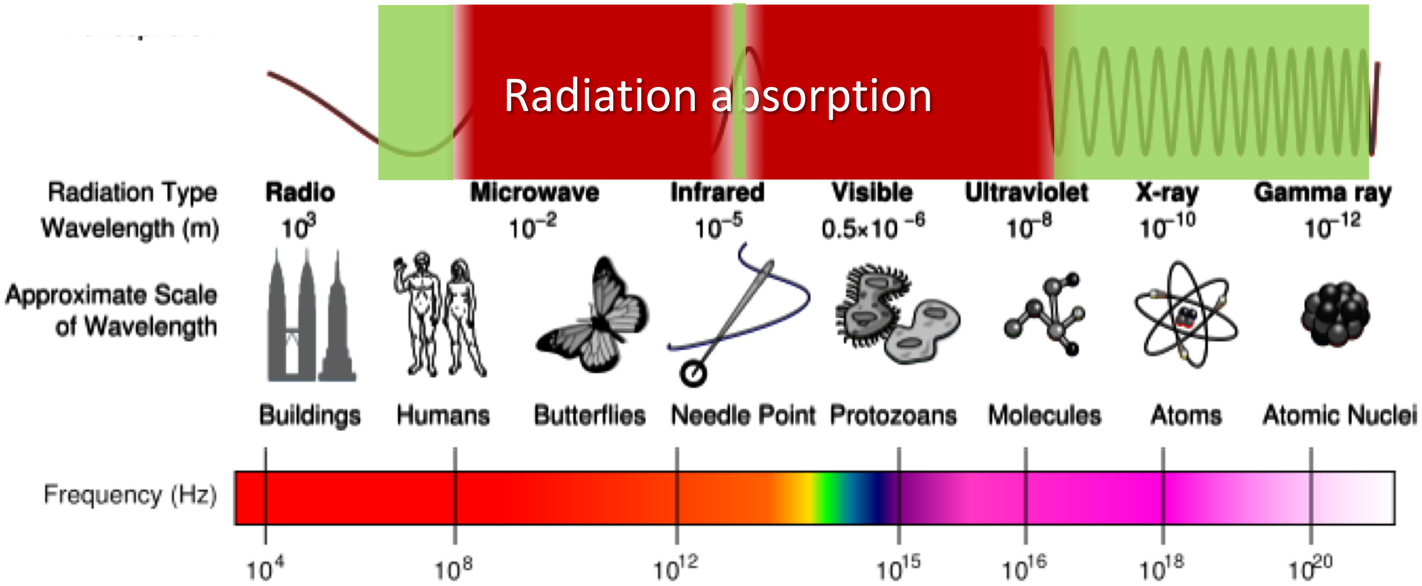


Book

Chapter 2.2-2.3



Electromagnetic radiation



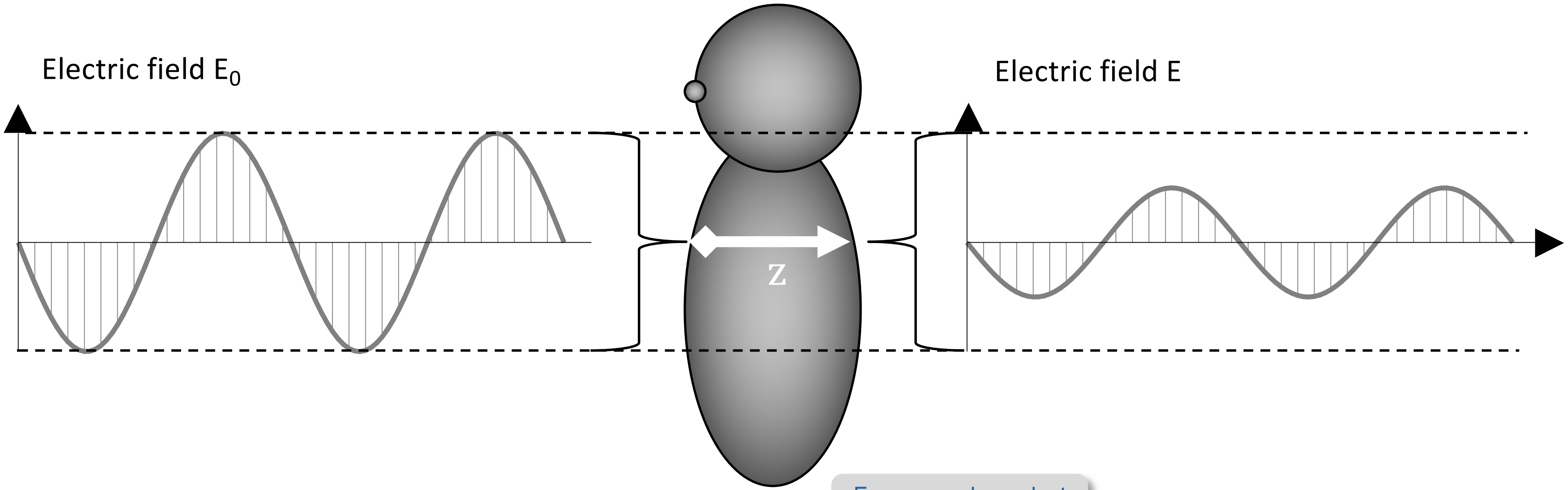
Electric field: $$\frac{\partial^2 \vec{E}}{\partial t^2} - c_0{}^2 \nabla^2 \vec{E} = 0$$

Magnetic field: $$\frac{\partial^2 \vec{B}}{\partial t^2} - c_0{}^2 \nabla^2 \vec{B} = 0$$

Wave speed: $$c_0 = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = \lambda \cdot f$$

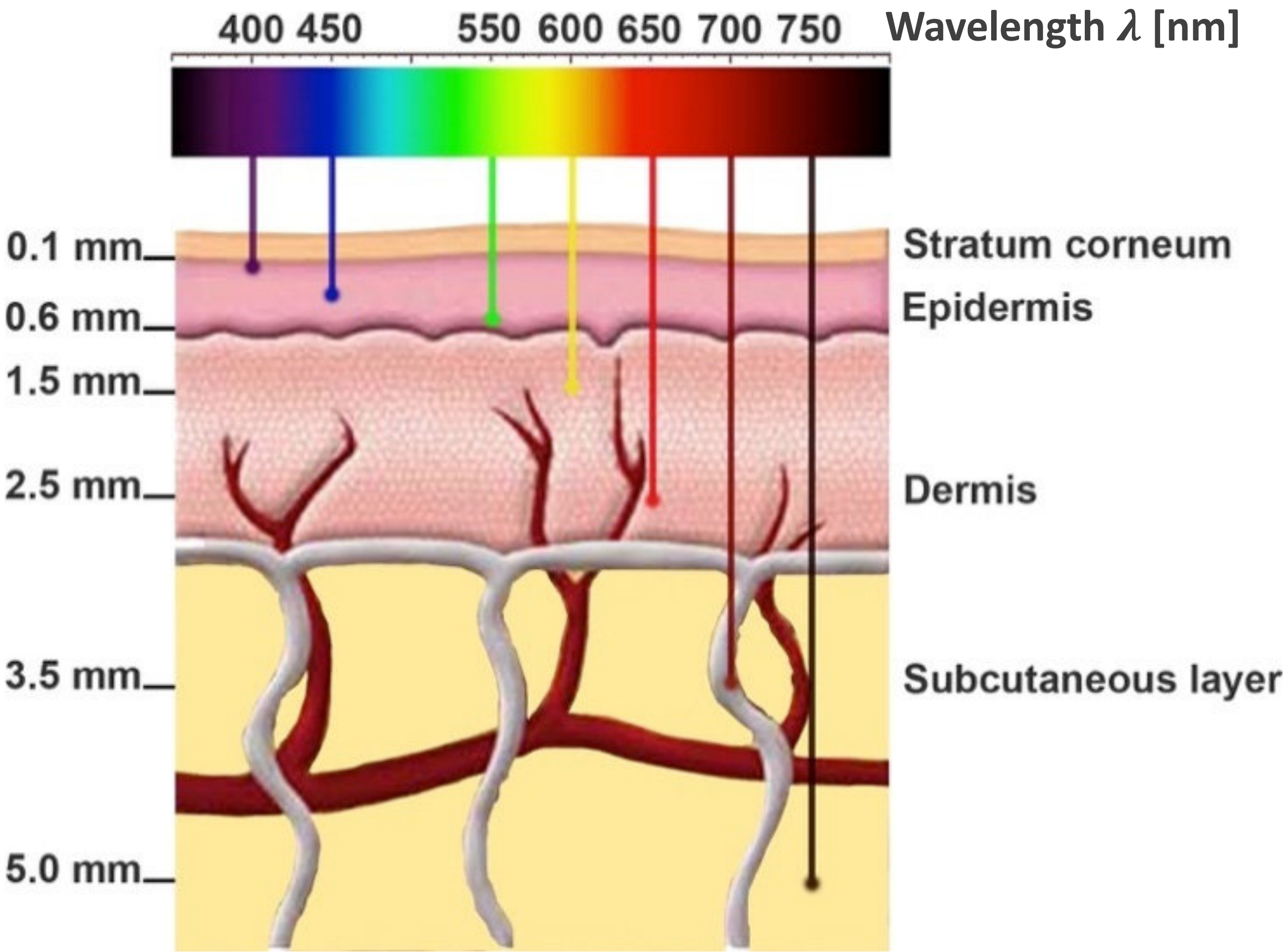
Energy: $$E = h \cdot f = h \cdot \frac{c_0}{\lambda}$$

Electromagnetic wave attenuation

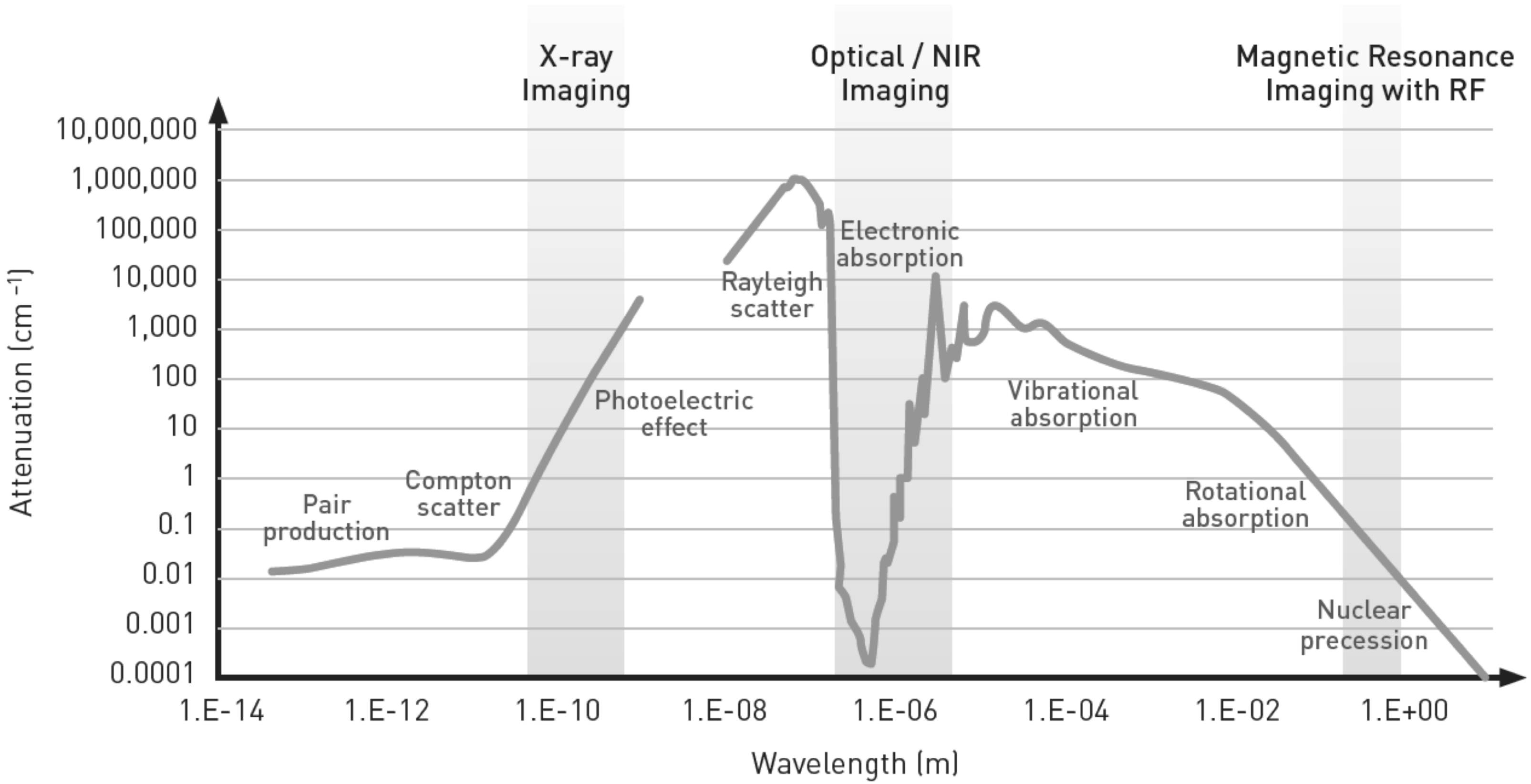


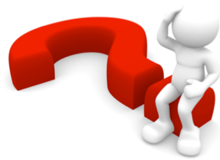
Wave attenuation $E = E_0 e^{-\mu(f)z}$

Attenuation



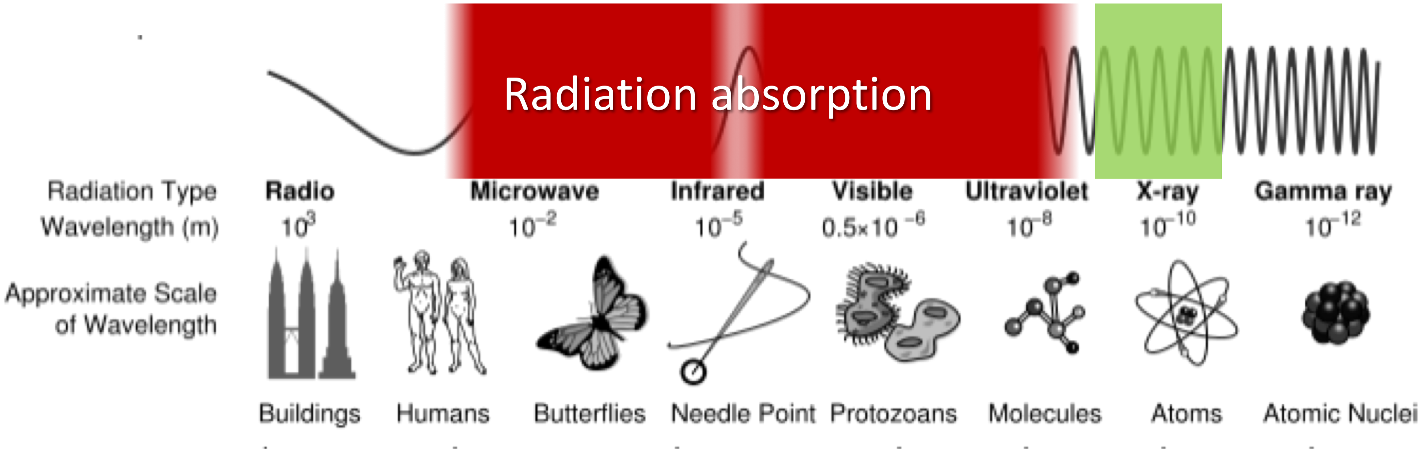
Attenuation



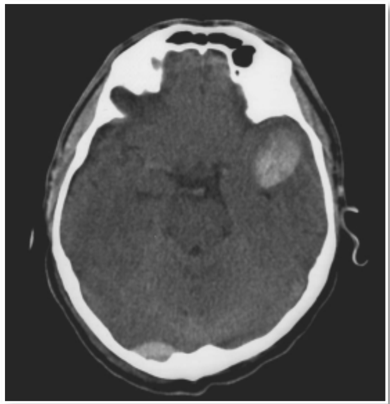


https://www.osa-opn.org/home/articles/volume_26

Biomedical Imaging



X-ray Imaging



Biomedical Imaging

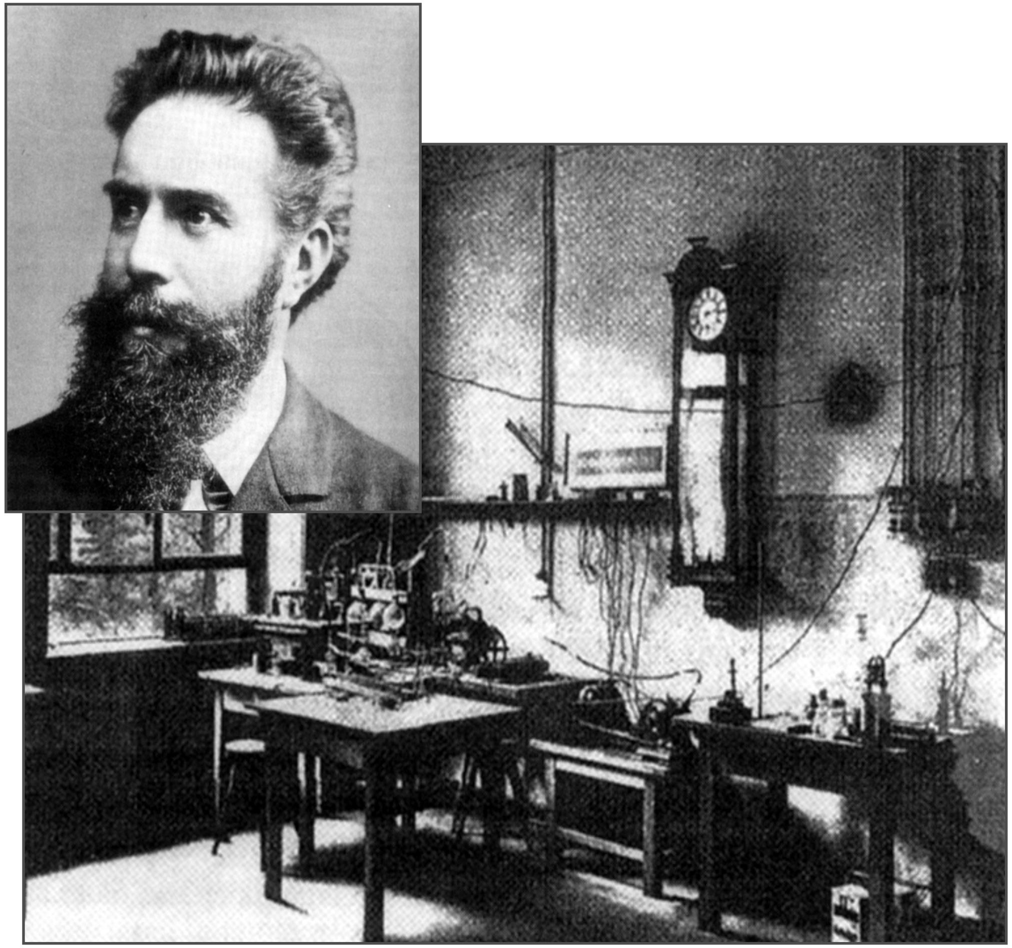
Imaging Mode: X-ray Imaging

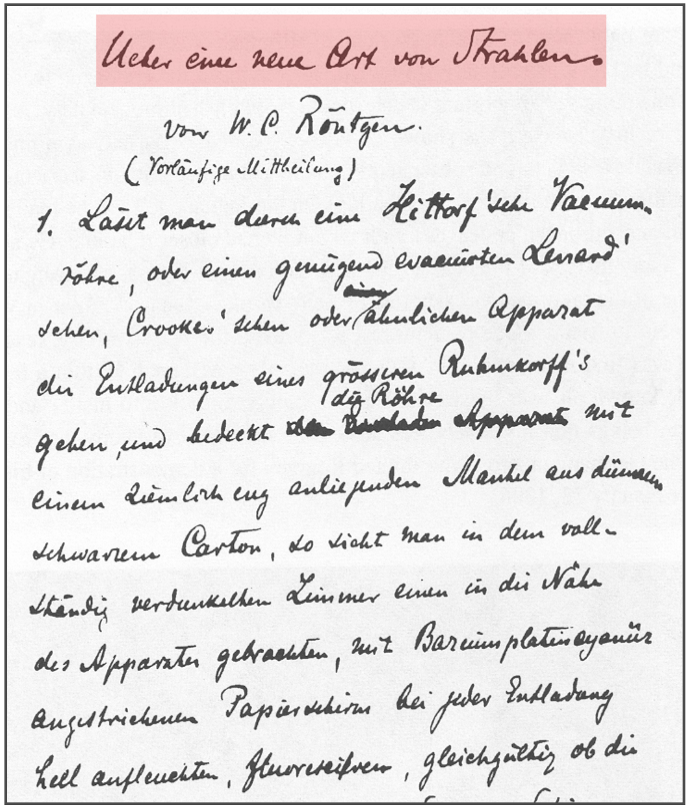
- Probe: X-ray photons
- Wavelength: 10 pm – 10 nm
- Matter interaction: absorption, scatter
- Modalities: Projection imaging

  Digital Subtraction Angiography (DSA)

  Computed tomography

Wilhelm Conrad Röntgen, 1845-1923





Ueber eine neue Art von Strahlen.

von W. C. Röntgen.

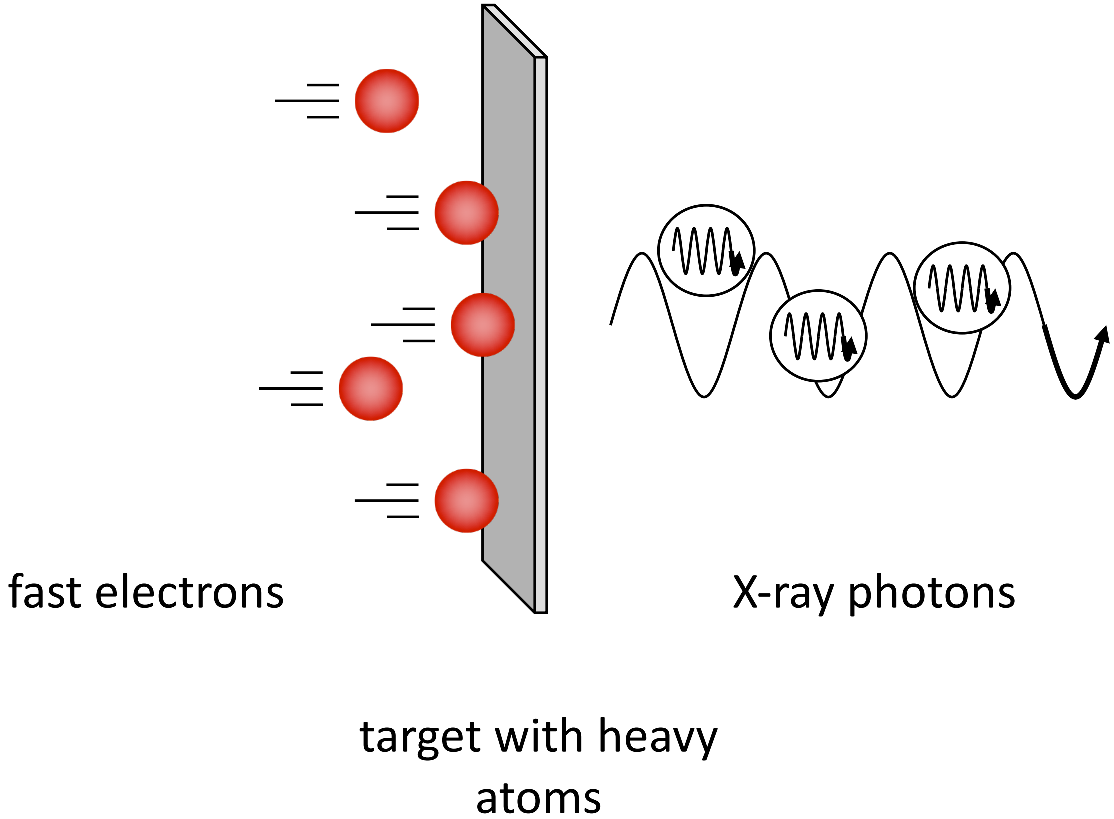
(Vorläufige Mittheilung)

1. Lässt man durch eine Hittorf'sche Vacuum-
röhre, oder einen genügend evacuirten Lenard'-
schen, Crookes'schen oder einen ähnlichen Apparat
die Entladungen eines grösseren Ruhmkorff's
gehen und bedeckt ~~den [illegible] Apparat~~ die Röhre mit
einem ziemlich eng anliegenden Mantel aus dünnem
schwarzem Carton, so sieht man in dem voll-
ständig verdunkelten Zimmer einen in die Nähe
des Apparates gebrachten, mit Bariumplatincyanür
angestrichenen Papierschirm bei jeder Entladung
hell aufleuchten, fluoresciren, gleichgültig ob die

Generation of X-rays

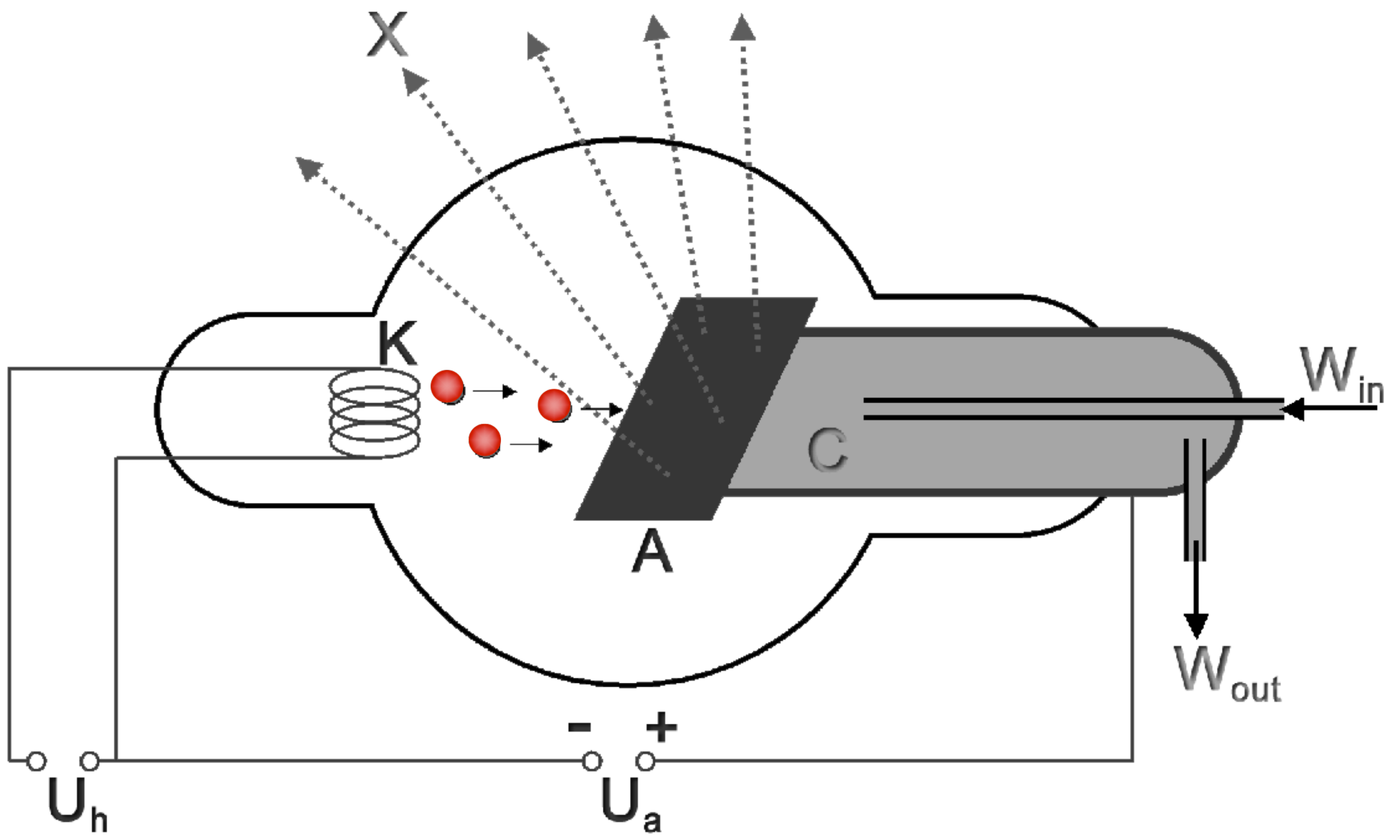
Probe → Matter interaction → Detection → Image production

Generation



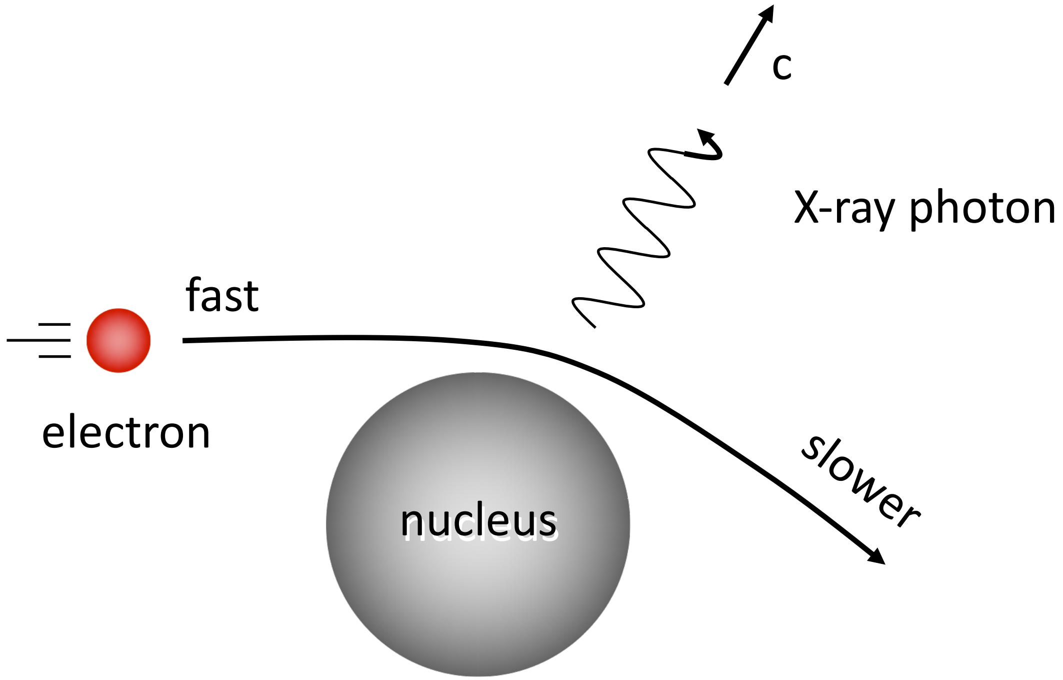
Electrons interact with inner e- shells of target (X-rays are not radioactive!)

Generation – X-ray tube



Acceleration of electron in vacuum tube (U_A = 30-200 kV, I_A = 50-100 mA)

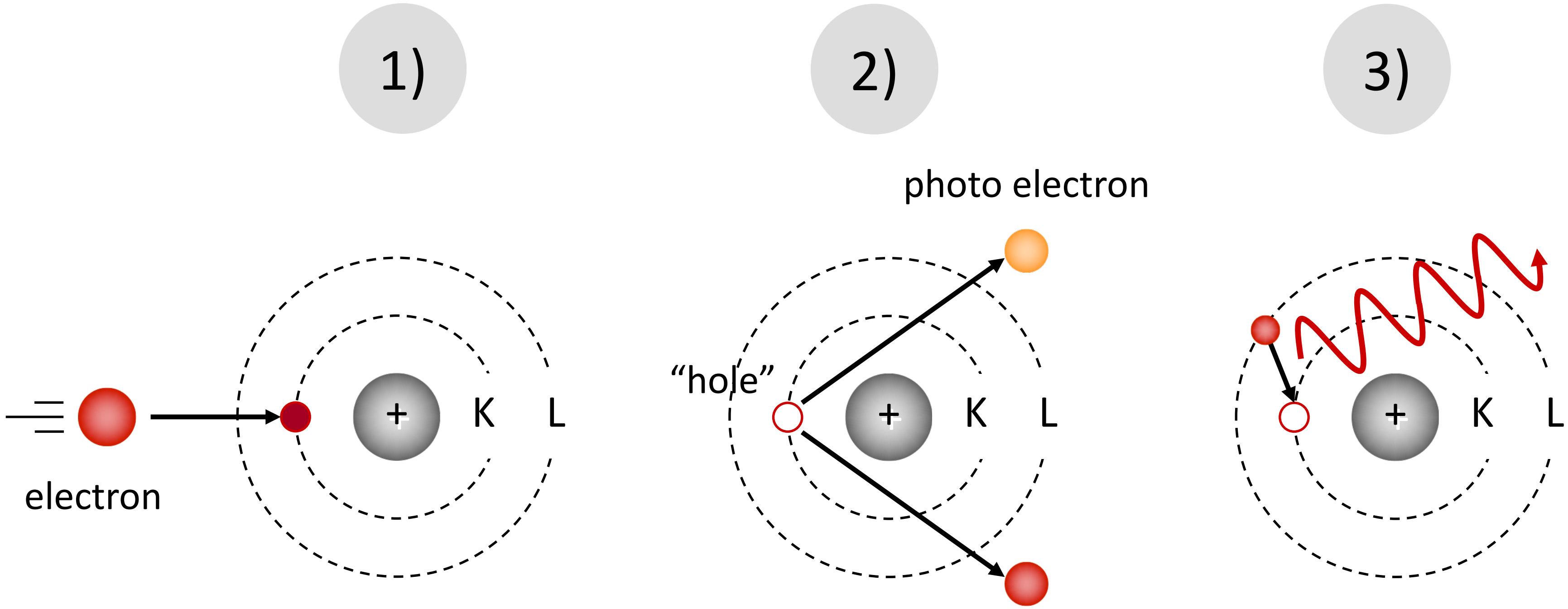
Generation – Bremsstrahlung



Fast-moving electron decelerates when it swings around a heavy nucleus:

- electron interacts with electrons in outer shells
- energy depends on distance at which electron passes nuclei
- spectrum continuous 0 -> E_{max}
- interaction depends on Z value and E of electrons

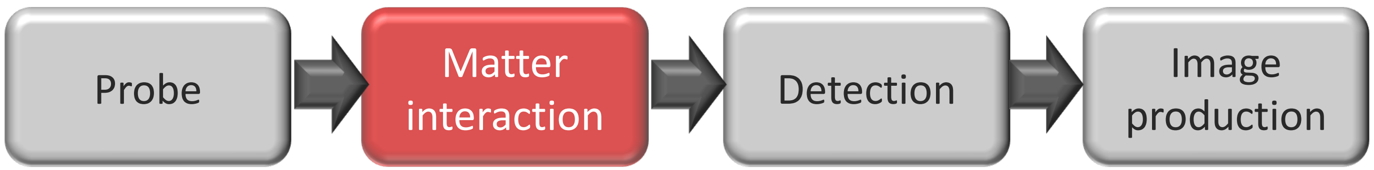
Generation – Characteristic radiation



Fast-moving electron interacts tightly with bound electrons in target:

- K-shell electron is ejected
- Electron energy $E_{electron} > E_{binding,\ K}$
- Discrete energy of emitted radiation $E = E_{binding,K} - E_{binding,L}$

Interaction of X-rays



Attenuation – Photo effect

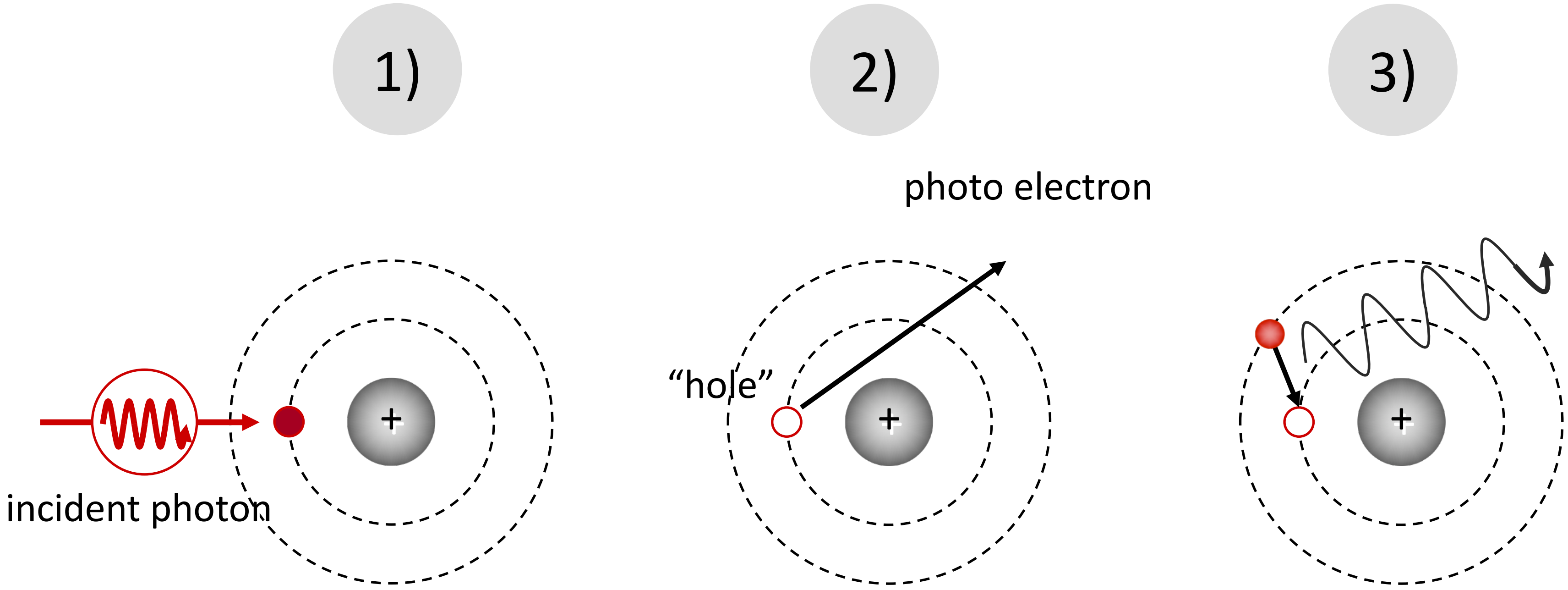
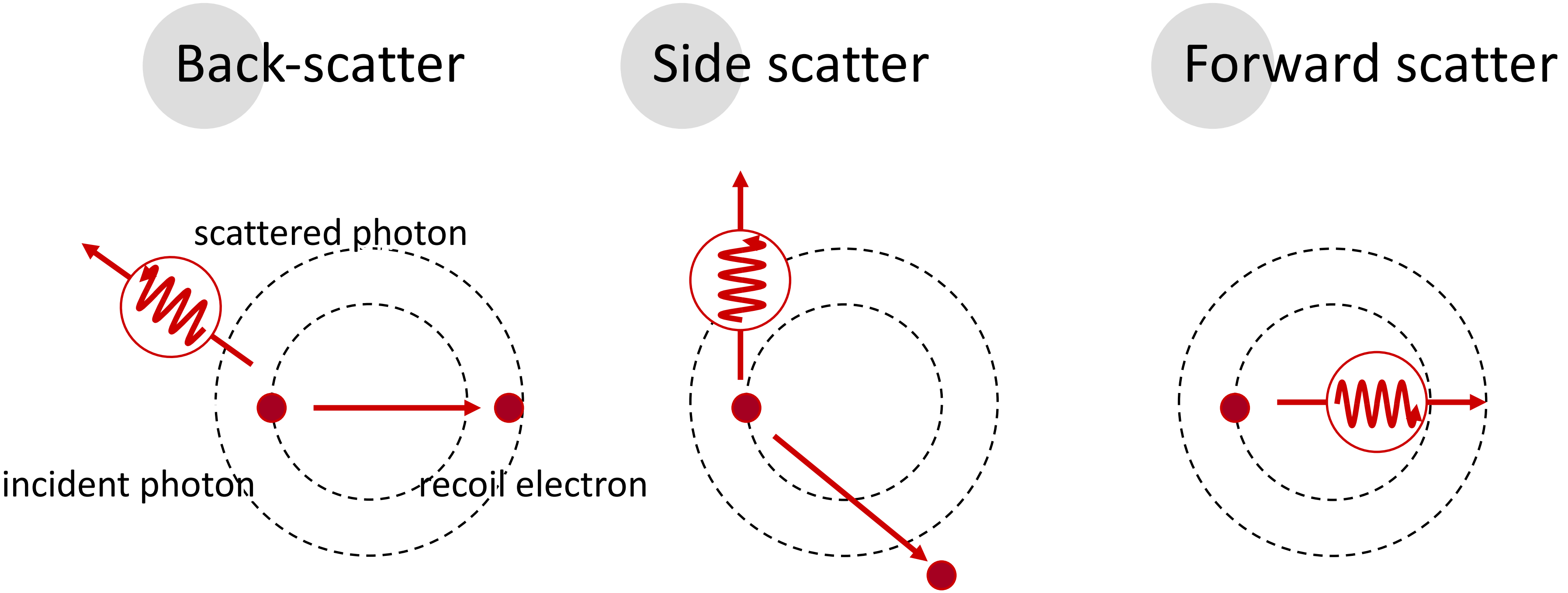


Photo effect leads to total absorption of photon:

- Generation of characteristic x-ray radiation with low energy
- Photo electrons cause biological "damage" → "ionizing radiation"
- Probability ~ $\rho \cdot Z^3/E^3$

Attenuation – Compton effect



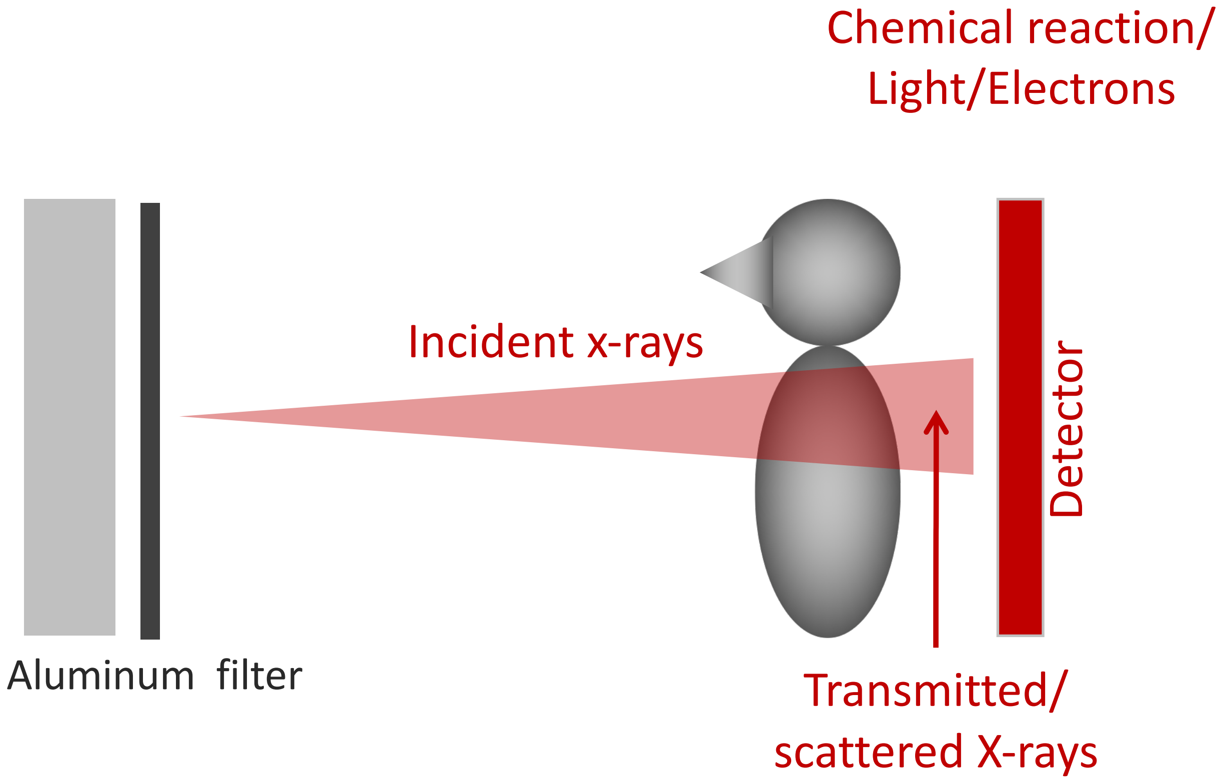
Compton effect leads to photon “bouncing”:

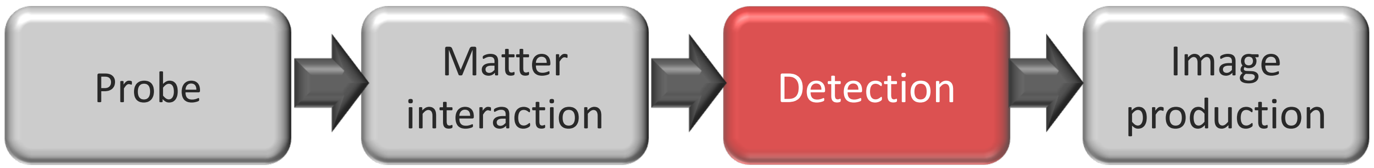
- Photon loses (part of) its energy to kinetic energy of electron
- Detection of photon changes
- Recoil electron responsible for “biological” damage
- Probability ~ ρ/E

Detection of X-rays

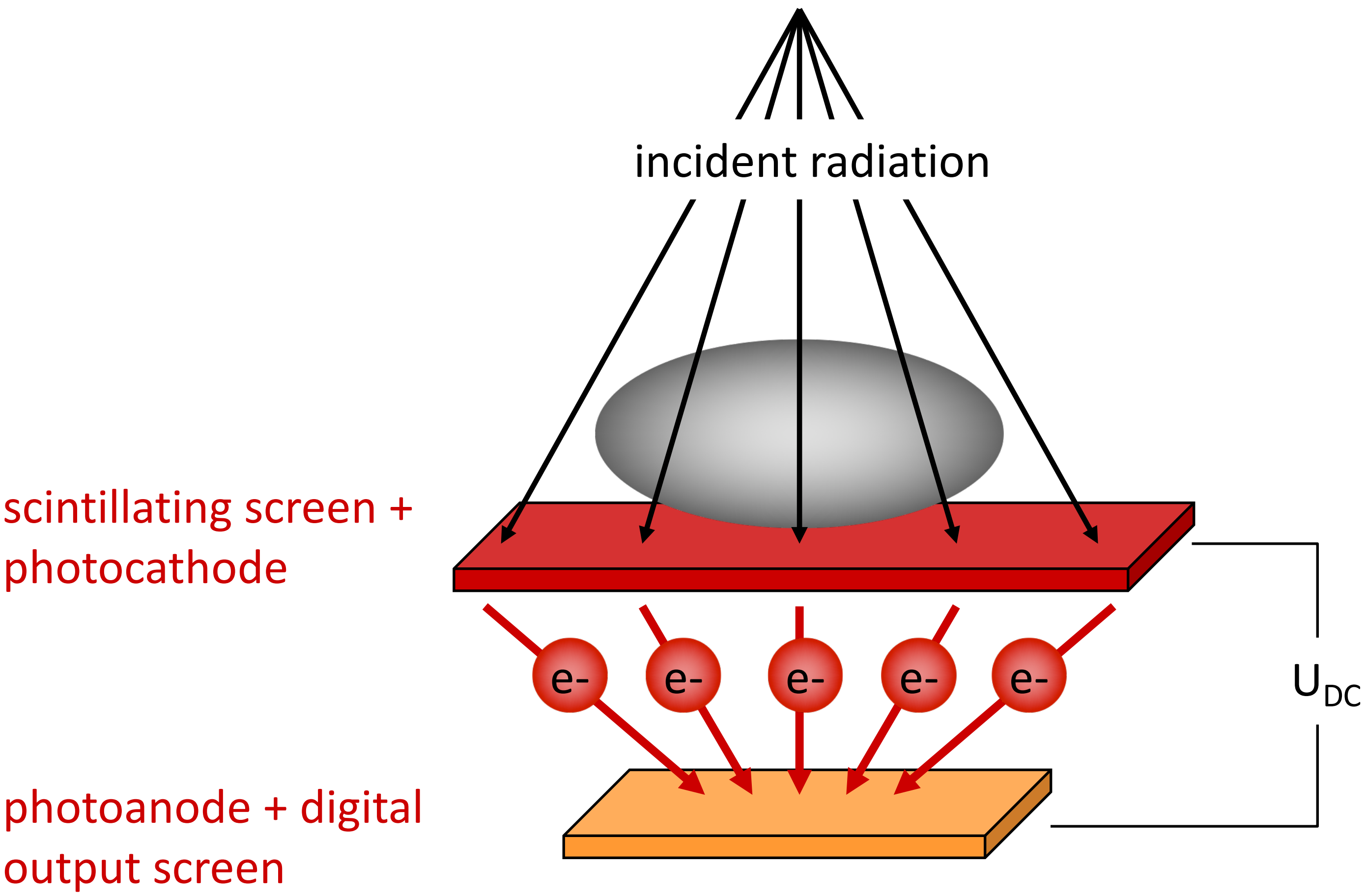
Probe → Matter interaction → Detection → Image production

Projection Imaging

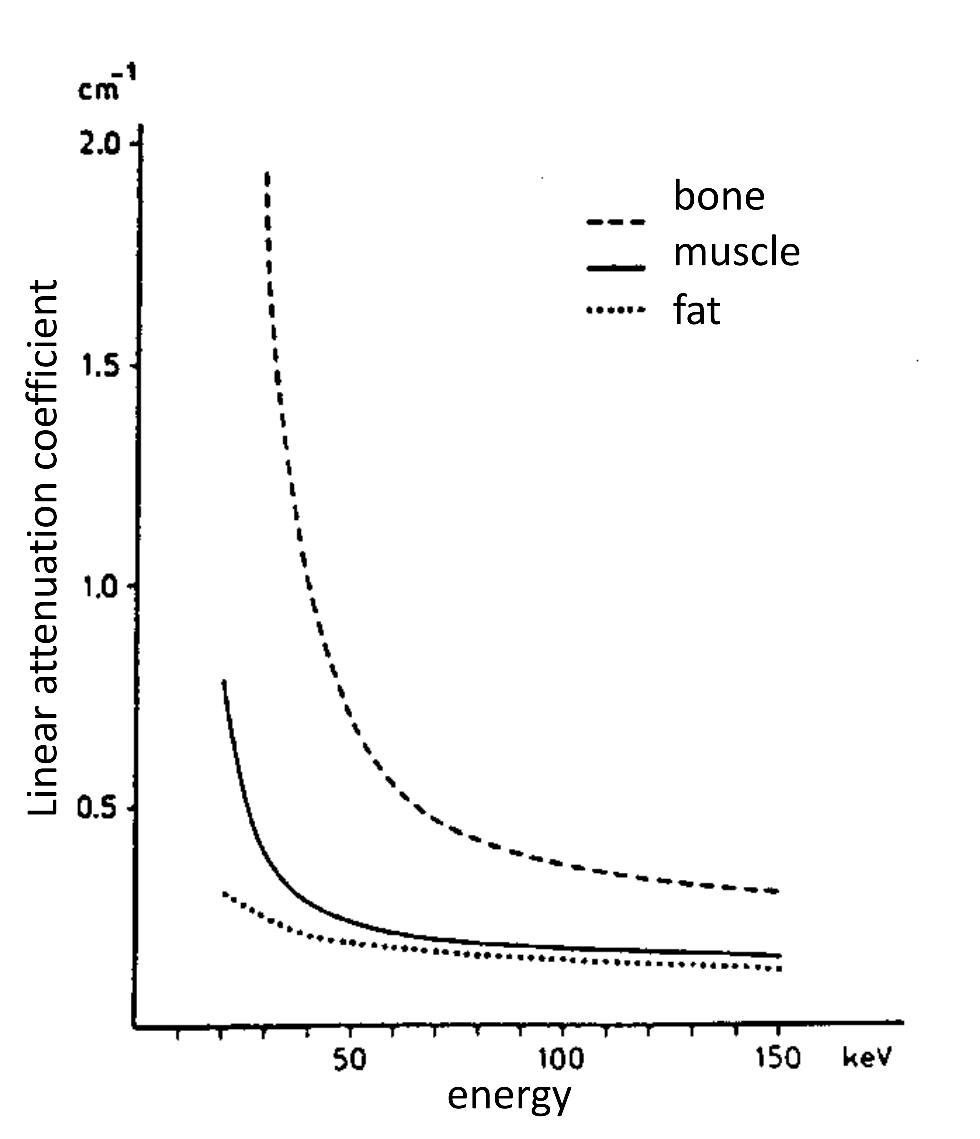




Projection imaging – Image intensifier



Projection Imaging – Contrast



Projection Imaging – Contrast

- Large contrast between bone and tissue/air
- Very little contrast among different tissues

Computed Tomography

Probe → Matter interaction → Detection → Image production

Projection versus Tomographic imaging

Projection imaging

= 3D structures are collapsed onto 2D image:

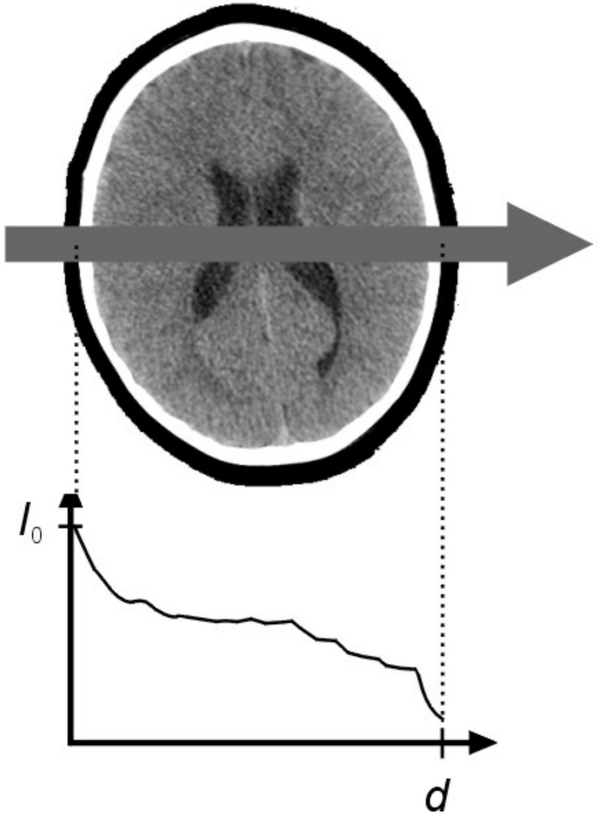
- details are obscured
- low soft-tissue contrast
- not quantitative

Tomographic imaging

= 3D structure is resolved:

- slices ("gr: Tomos = slice")
- Computed image reconstruction
- Projection imaging and CT share same principles of x-ray generation, interaction, detection

CT – Reconstruction problem



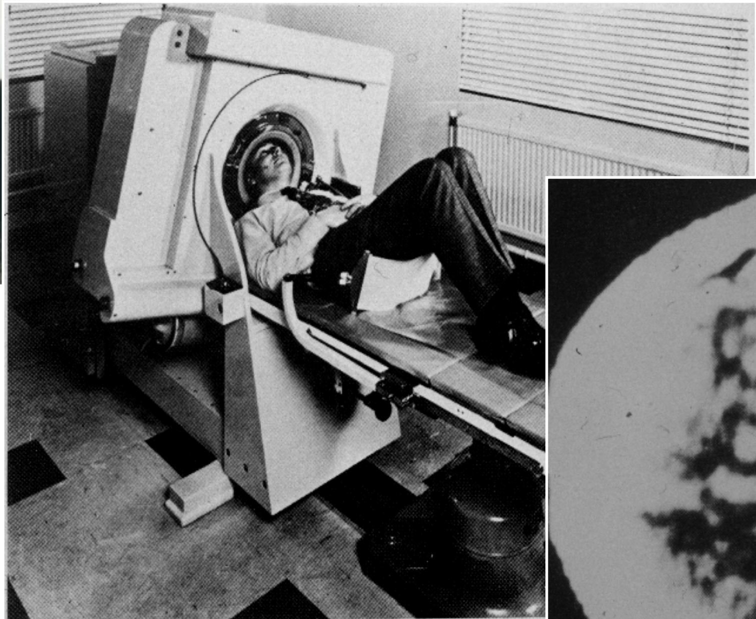
$$I = \int_0^{E_{\max}} I_0(E) \cdot e^{-\int_0^d \mu(E)\, ds}\, dE$$

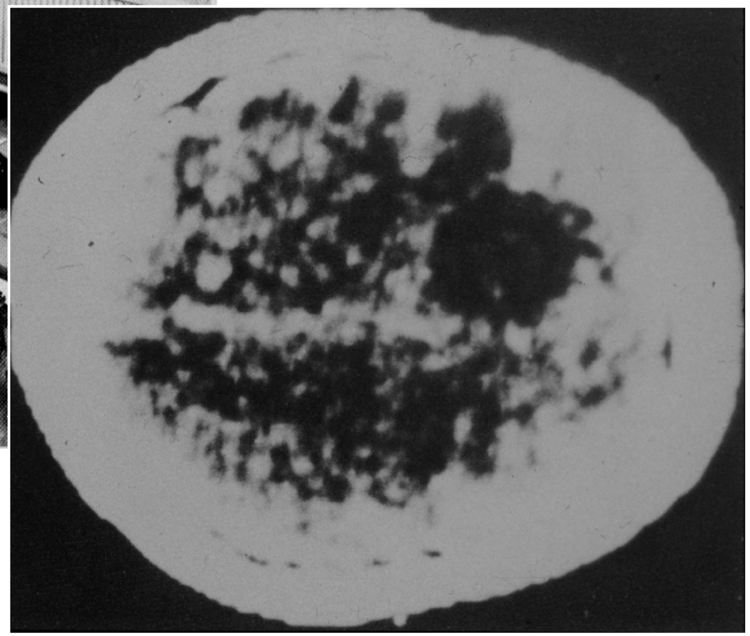
$$P = \ln \frac{I_0}{I}$$

$$\mu(x, y) = ?$$

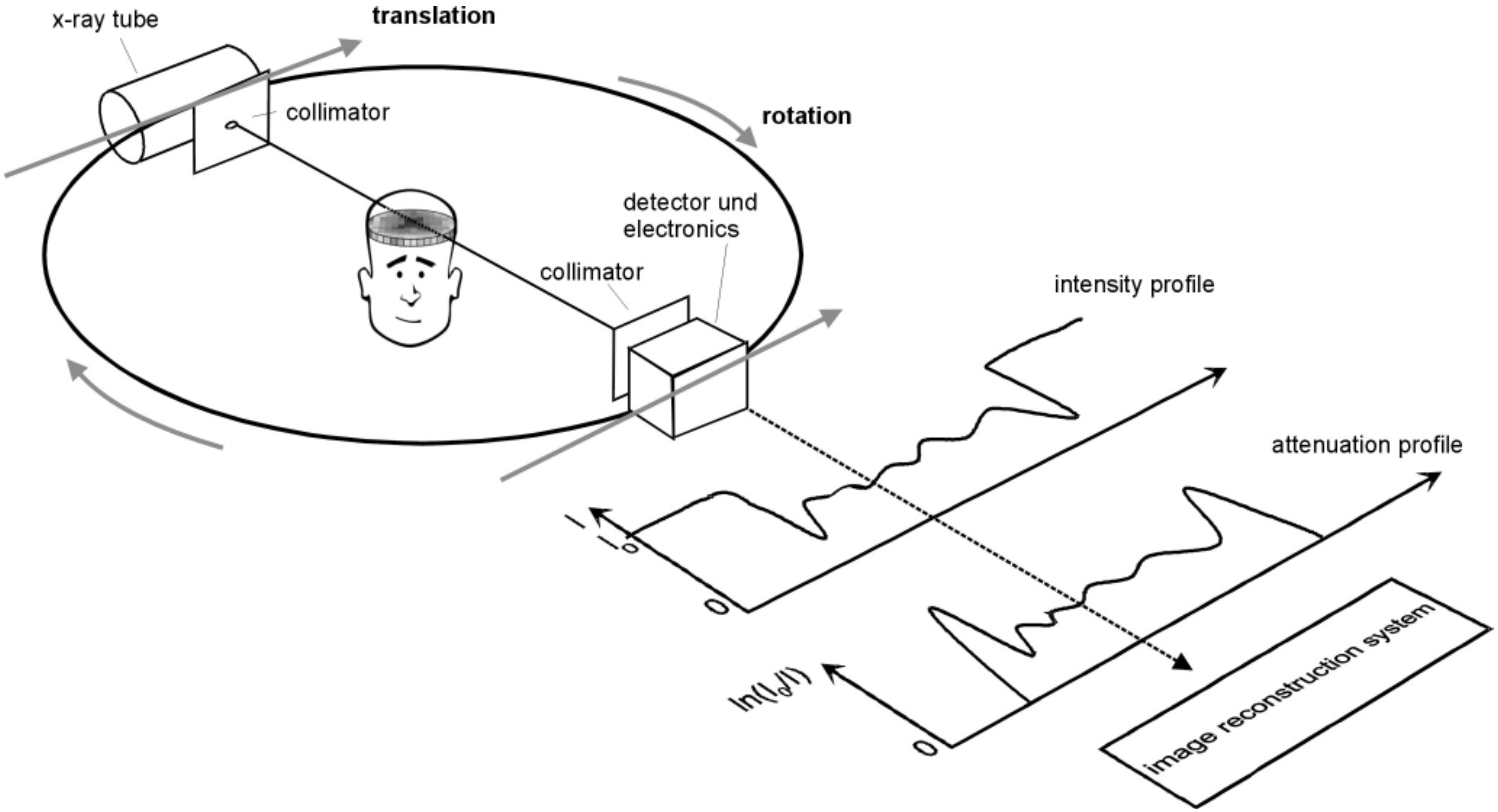
Adapted from Kalender WA, Computed Tomography, ISBN 3-89578-216-5

Godfrey Hounsfield, 1919 – 2004





CT – Principle

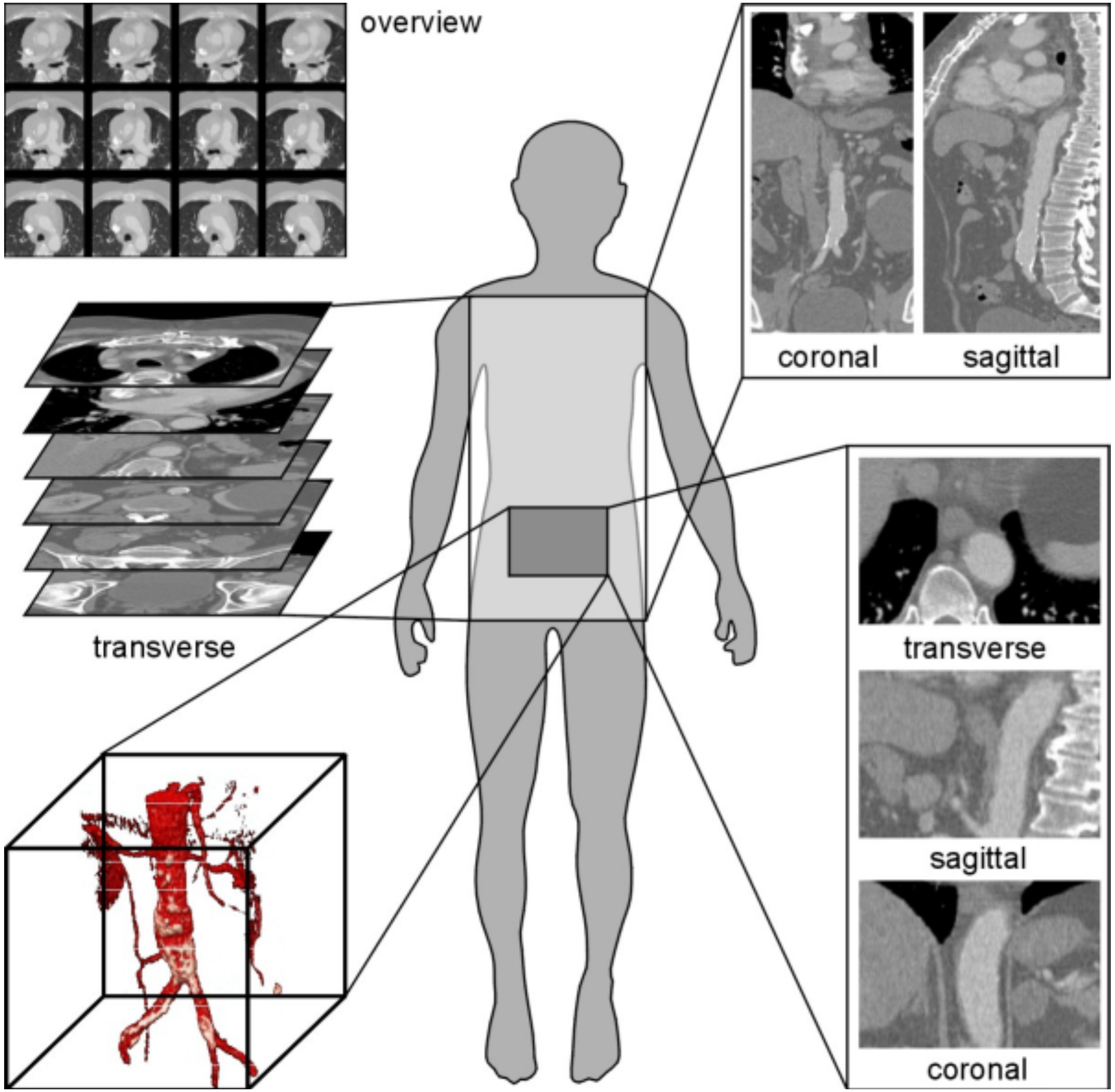


Adapted from Kalender WA, Computed Tomography, ISBN 3-89578-216-5

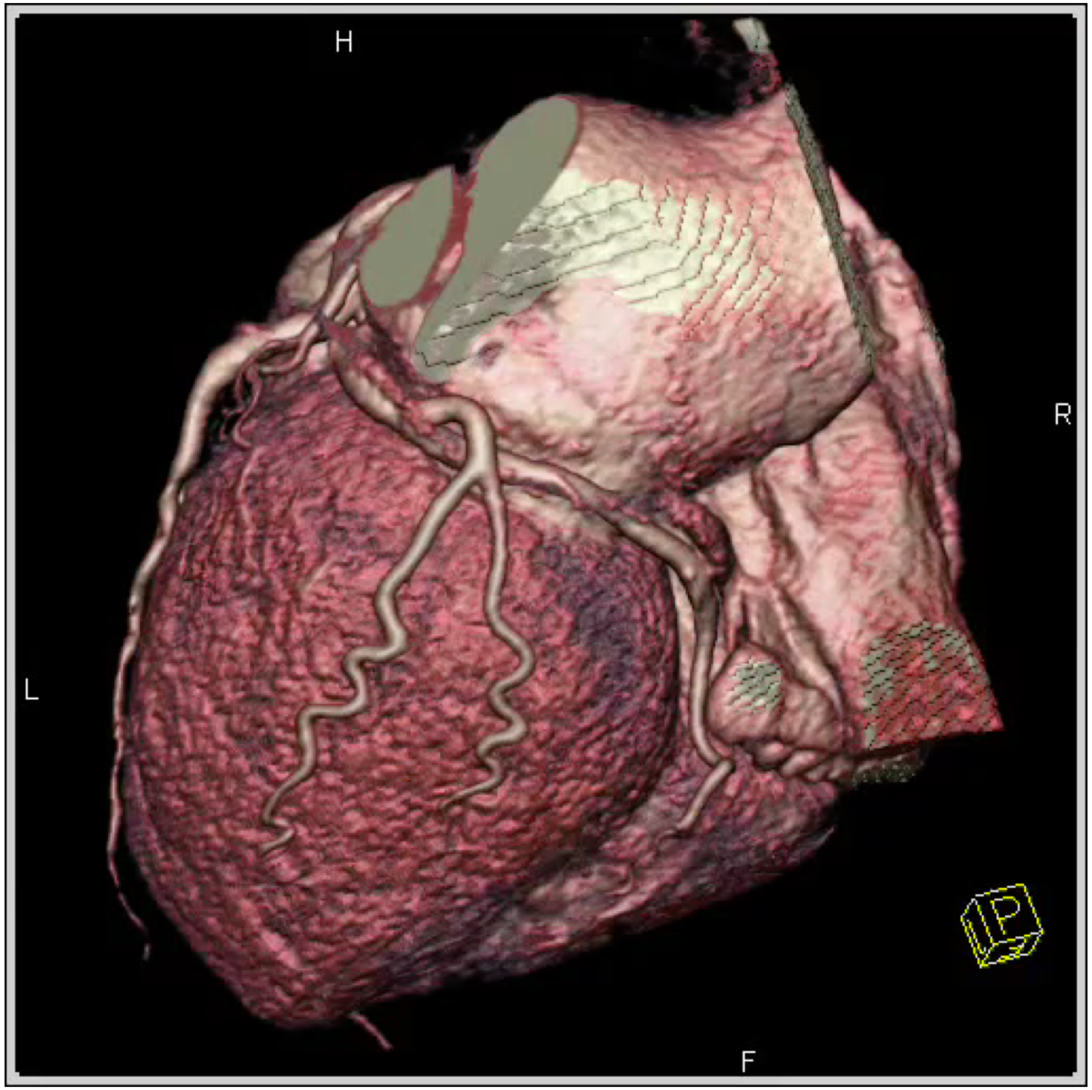
CT – Image reconstruction

Adapted from Kalender WA, Computed Tomography, ISBN 3-89578-216-5

CT – Applications



CT – Applications



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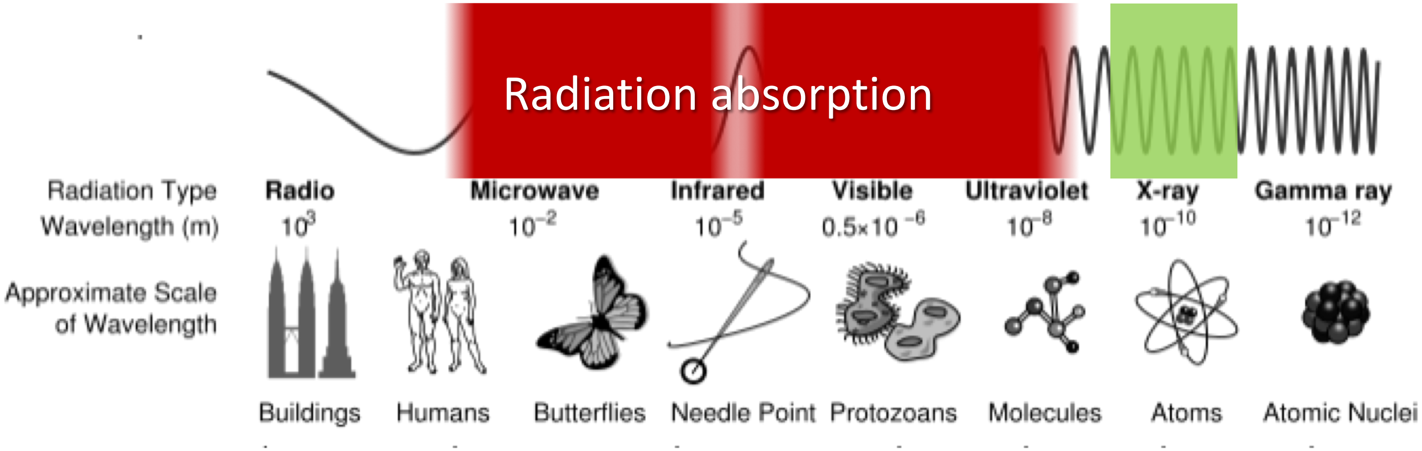
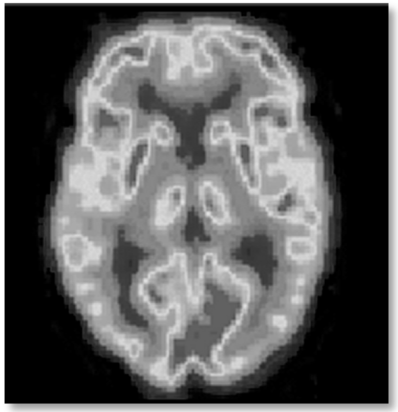
Biomedical Imaging



Nuclear Imaging

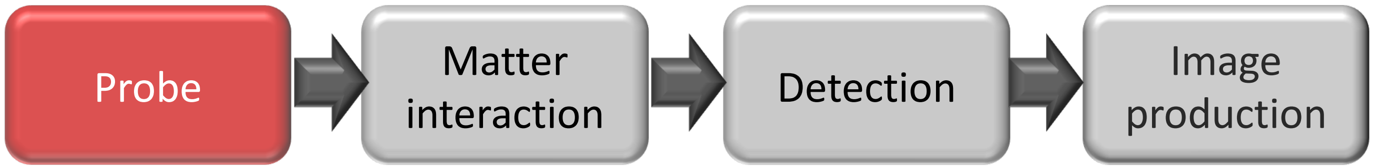


Biomedical Imaging

Imaging Mode: **Nuclear Imaging (SPECT, PET)**

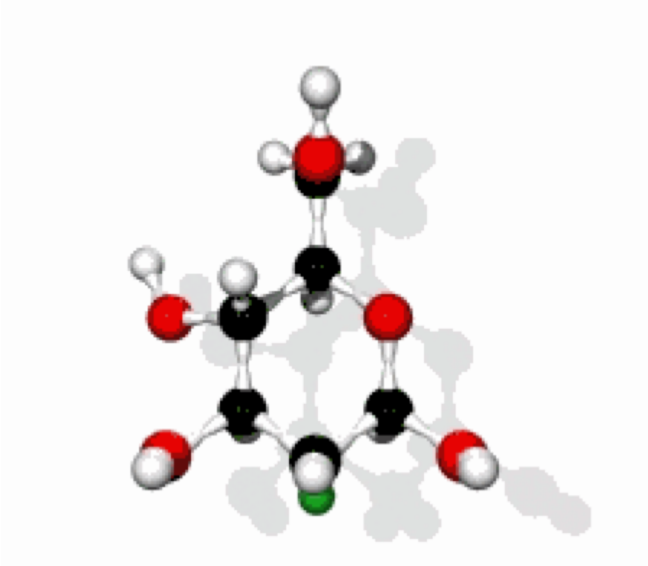
- Probe: γ-ray photon, positron$\rightarrow$ γ-ray photons
- Wavelength: 2 pm – 100 pm
- Matter interaction: absorption, scatter, pair production
- Modalities: SPECT (Single Photon Emission Tomography) PET (Positron Emission Tomography)

Positron Emission



PET – Positron Emission

Isotope	Half-life
Carbon-11	**20 min**
Nitrogen-13	10 min
Oxygen-15	2 min
Fluorine-18	**110 min**
Gallium-68	68 min
Rubidium-82	1.25 min



Fluorodeoxyglucose (FDG)

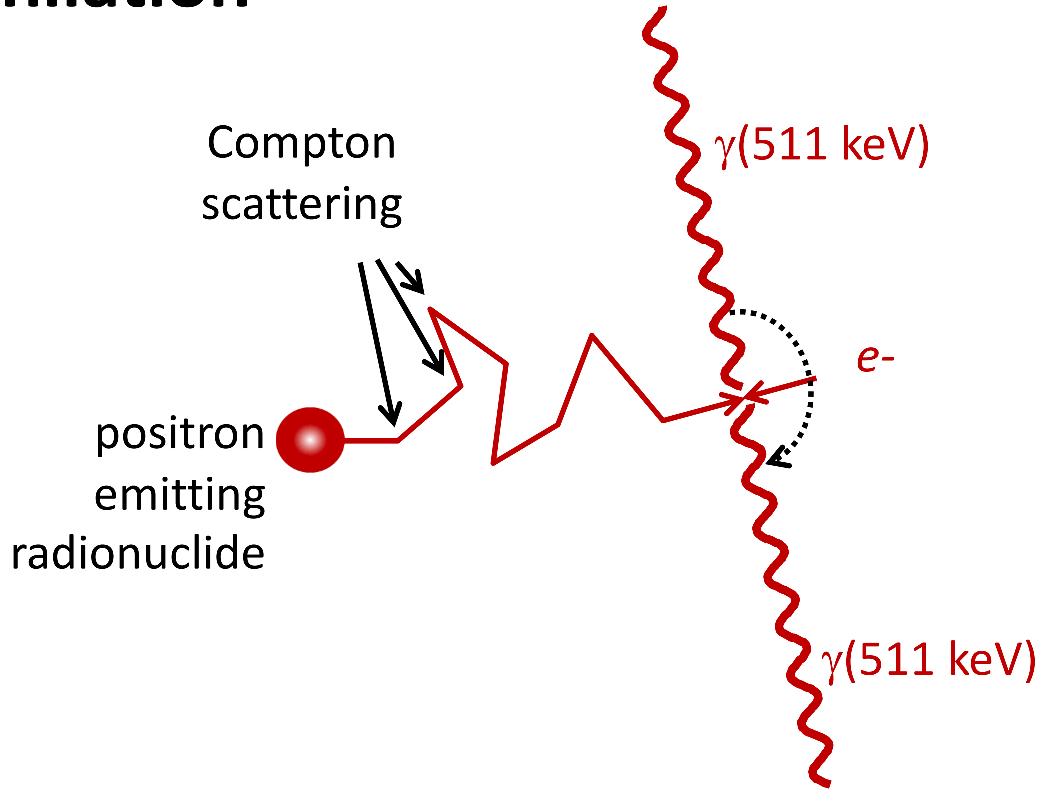
$$\boxed{{}^{A}_{Z}\mathbf{X} \rightarrow {}_{Z-1}^{\;\;A}\mathbf{Y} + \mathbf{e}^{+} + \boldsymbol{\nu}}$$

Positron

Positron Annihilation

Probe → Matter interaction → Detection → Image production

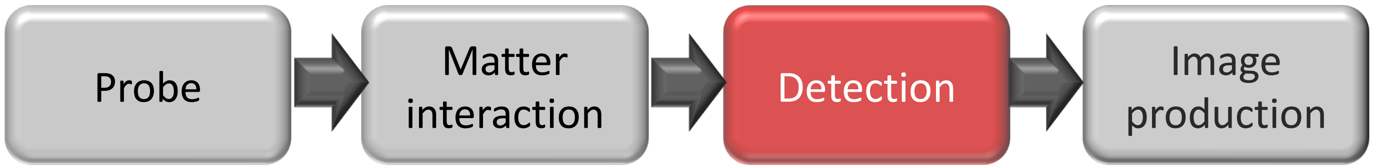
PET – Annihilation



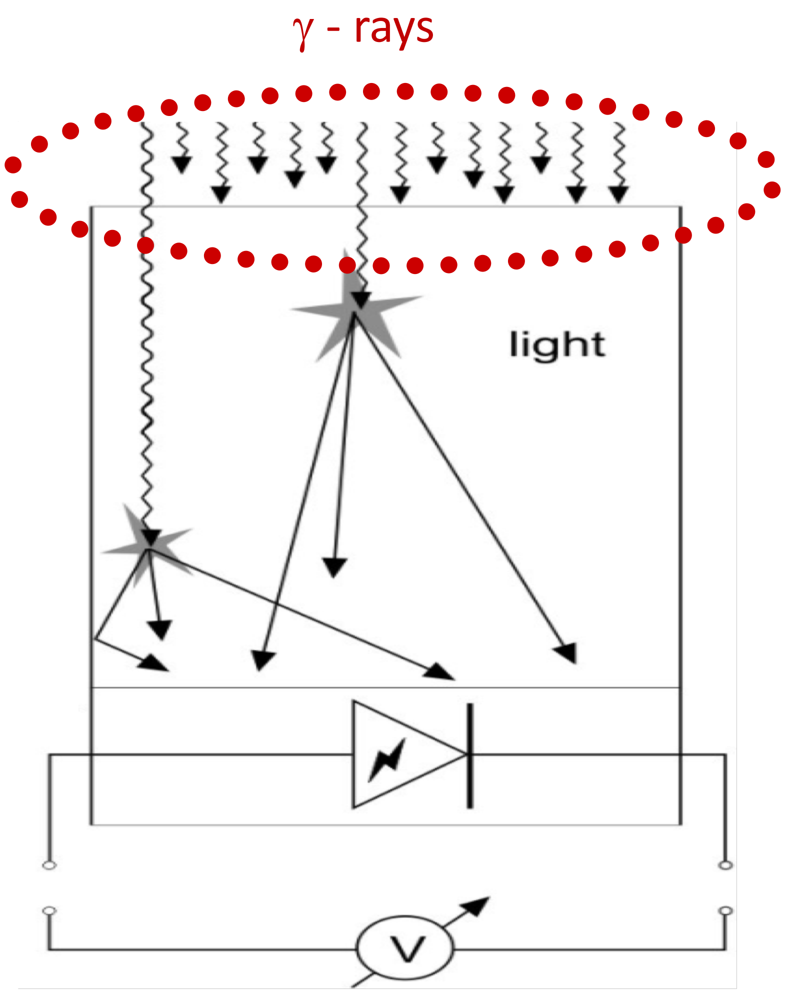
$$e^+ + e^- \rightarrow \gamma + \gamma$$

Coincidence detection of two γ-rays gives information on location of positron-electron anihilation (<u>not</u> on location of radionuclide)

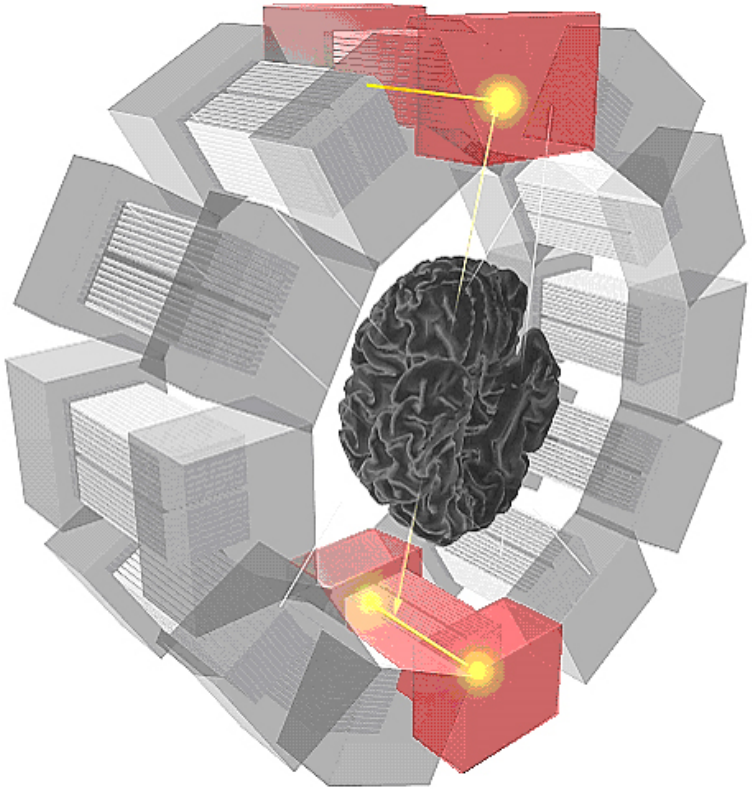
Coincidence Detection



PET – Detector

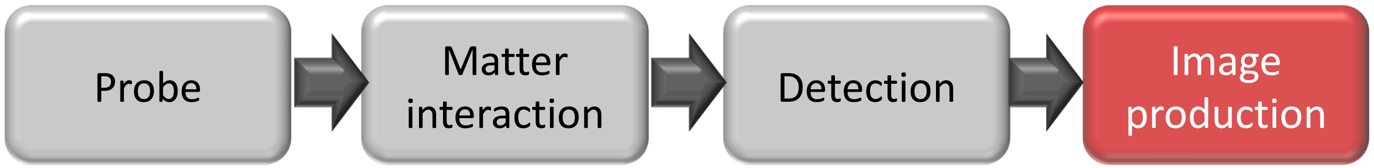


Scintillation Detector

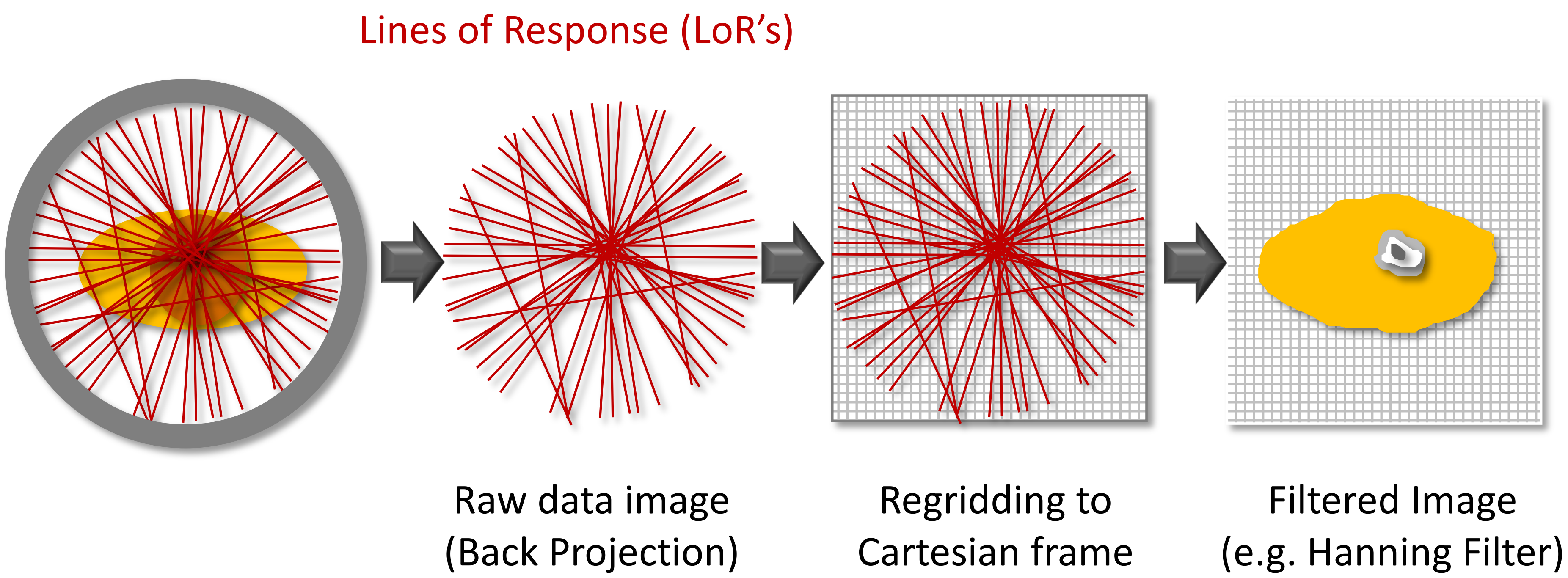


Coincidence Detection

Image Production

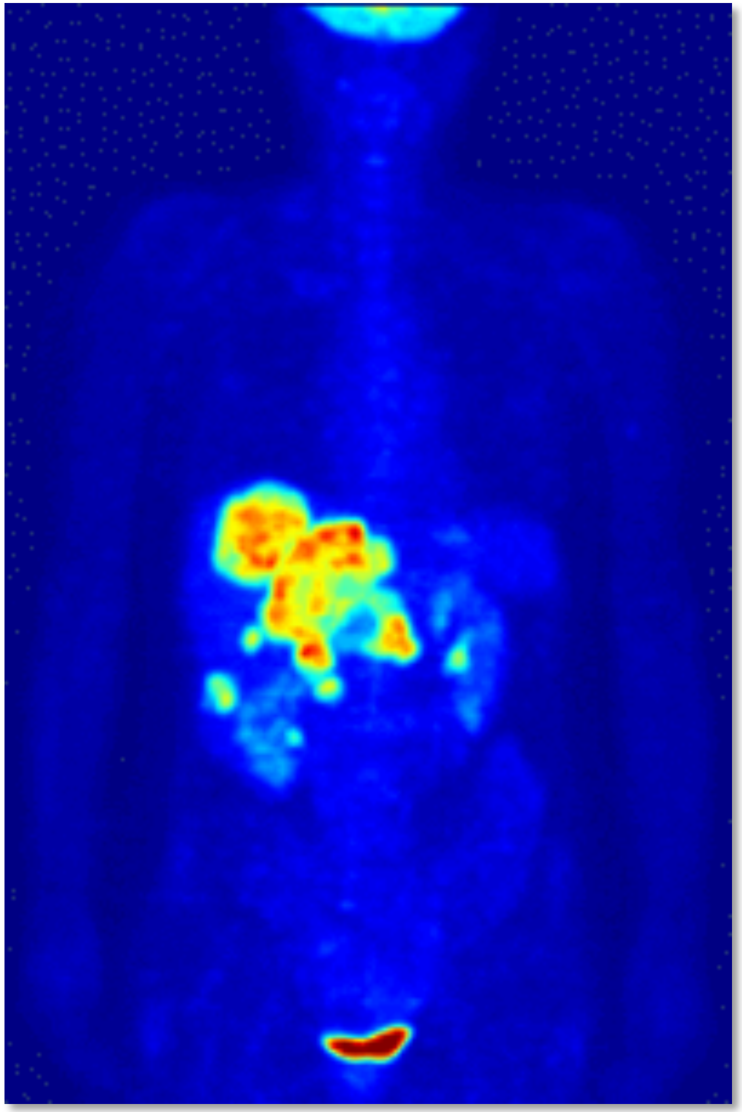


PET – Image Production



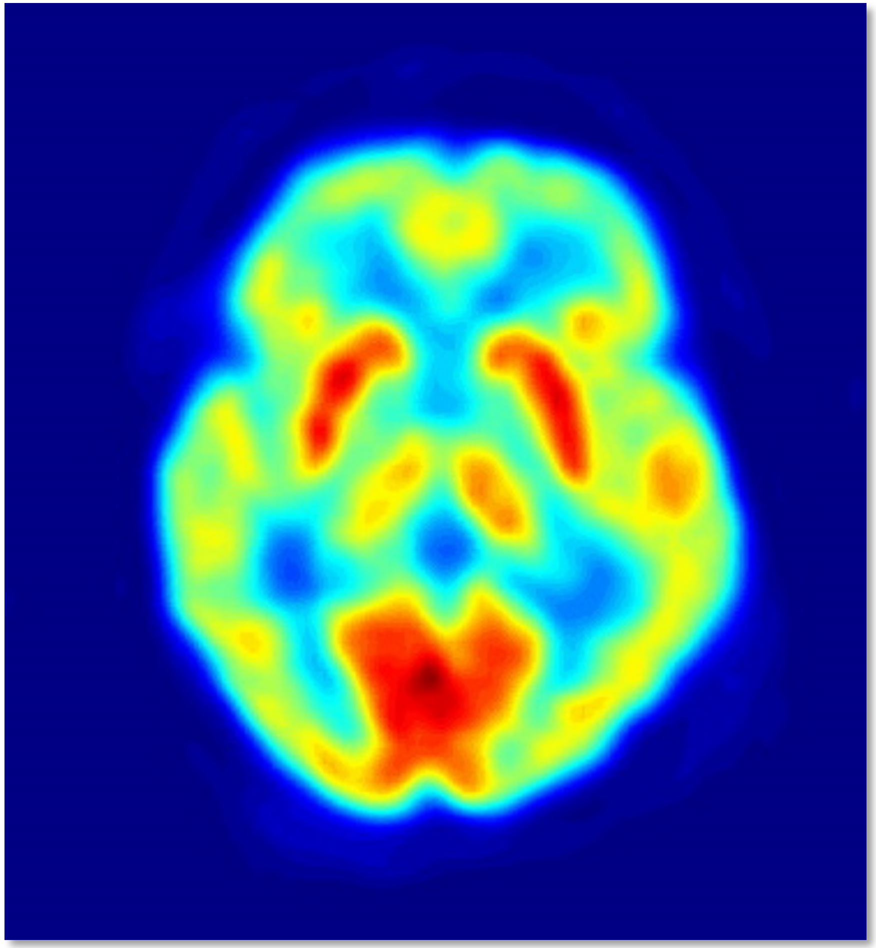
Slide courtesy of Markus Rudin, AIC

FDG – PET



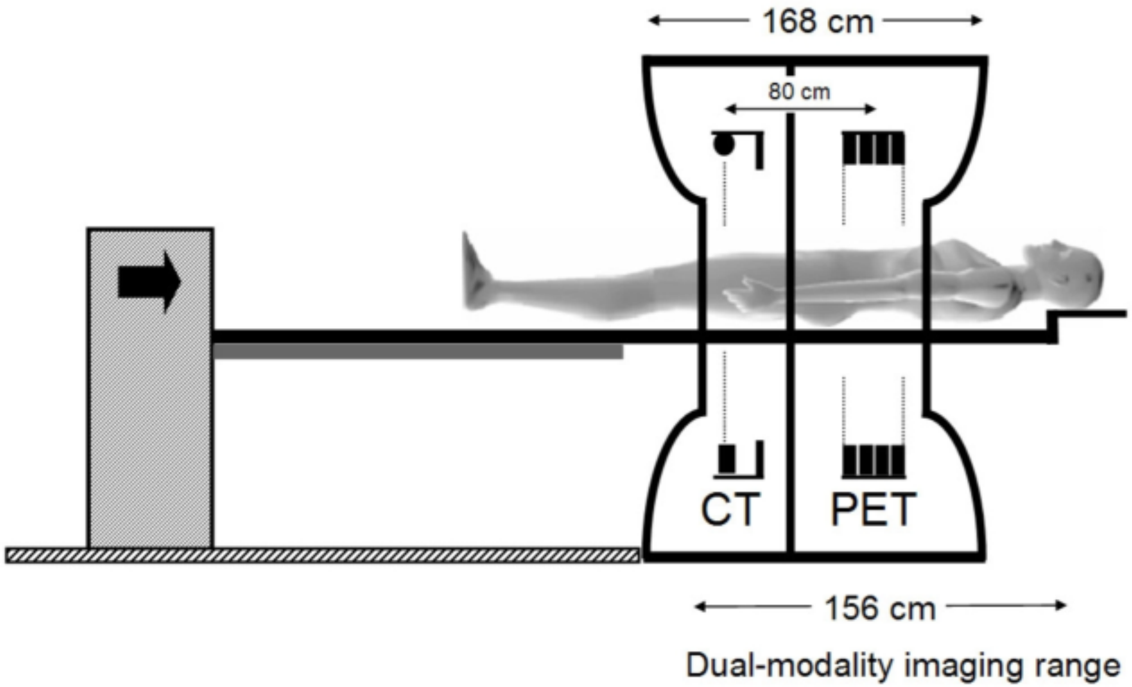
www.wikipedia.com

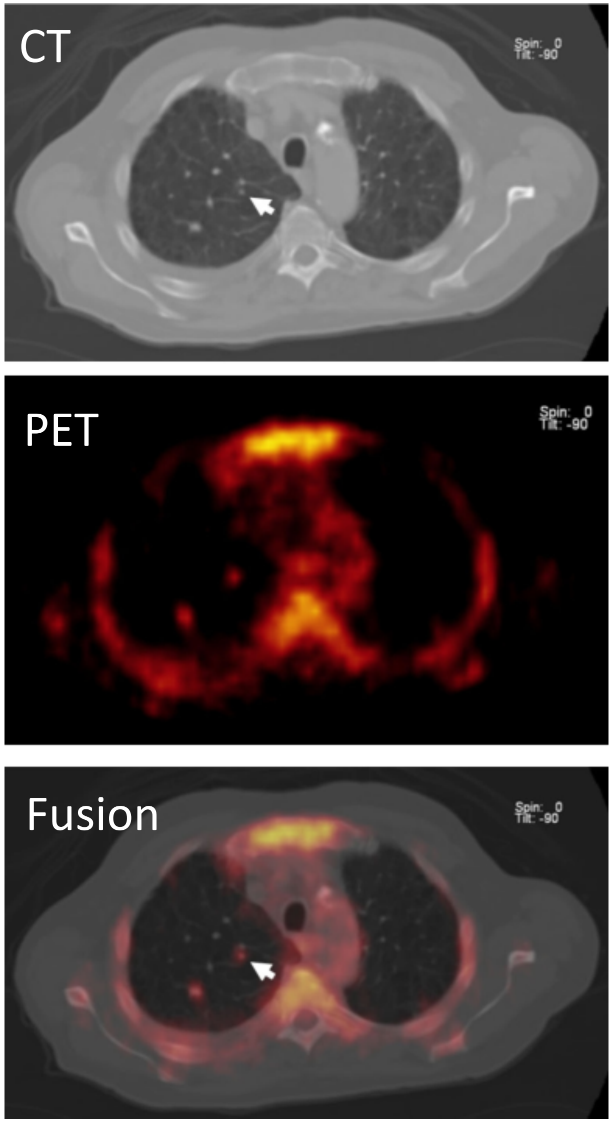
FDG – PET



www.wikipedia.com

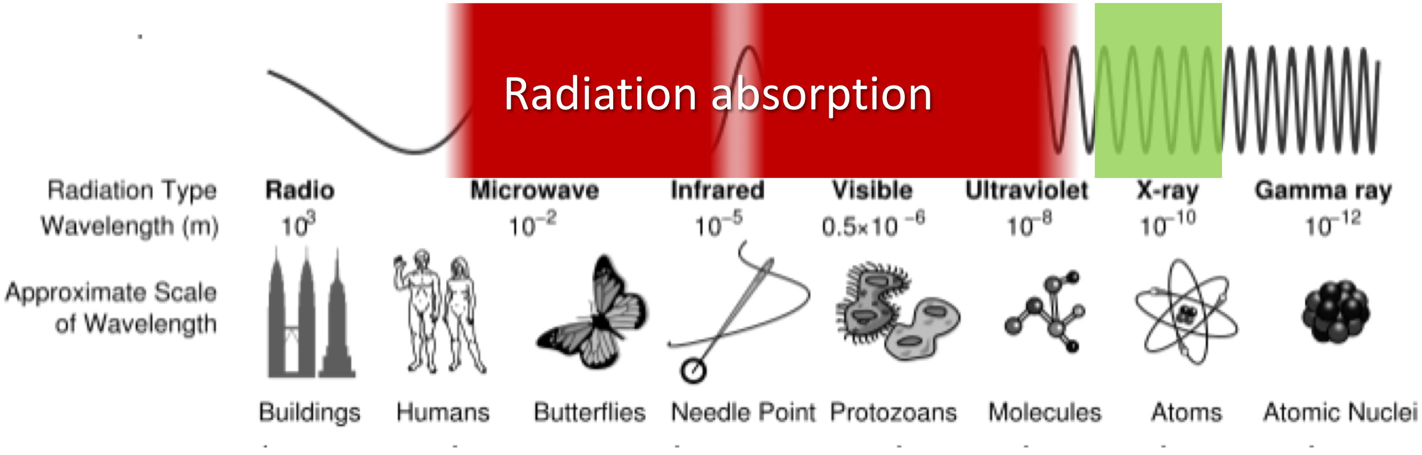
PET – CT



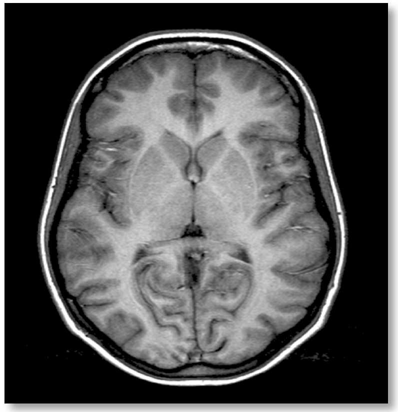


From Kalender WA, Computed Tomography, ISBN 3-89578-216-5

Biomedical Imaging



Magnetic Resonance Imaging



Biomedical Imaging

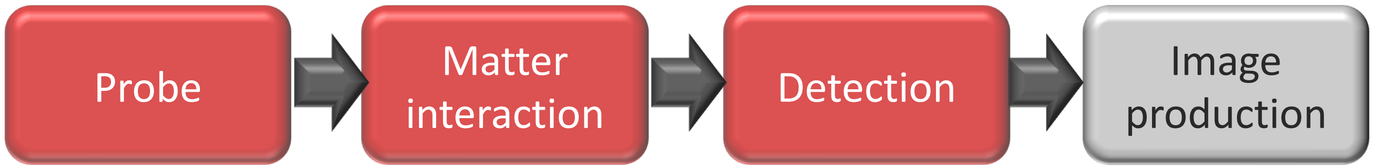
Imaging Mode: Magnetic Resonance (MR)

- Probe: radiofrequency waves
- Wavelength: 5 – 150 cm
- Matter interaction: nuclear spin transitions
- Modalities: Magnetic Resonance Imaging (MRI)

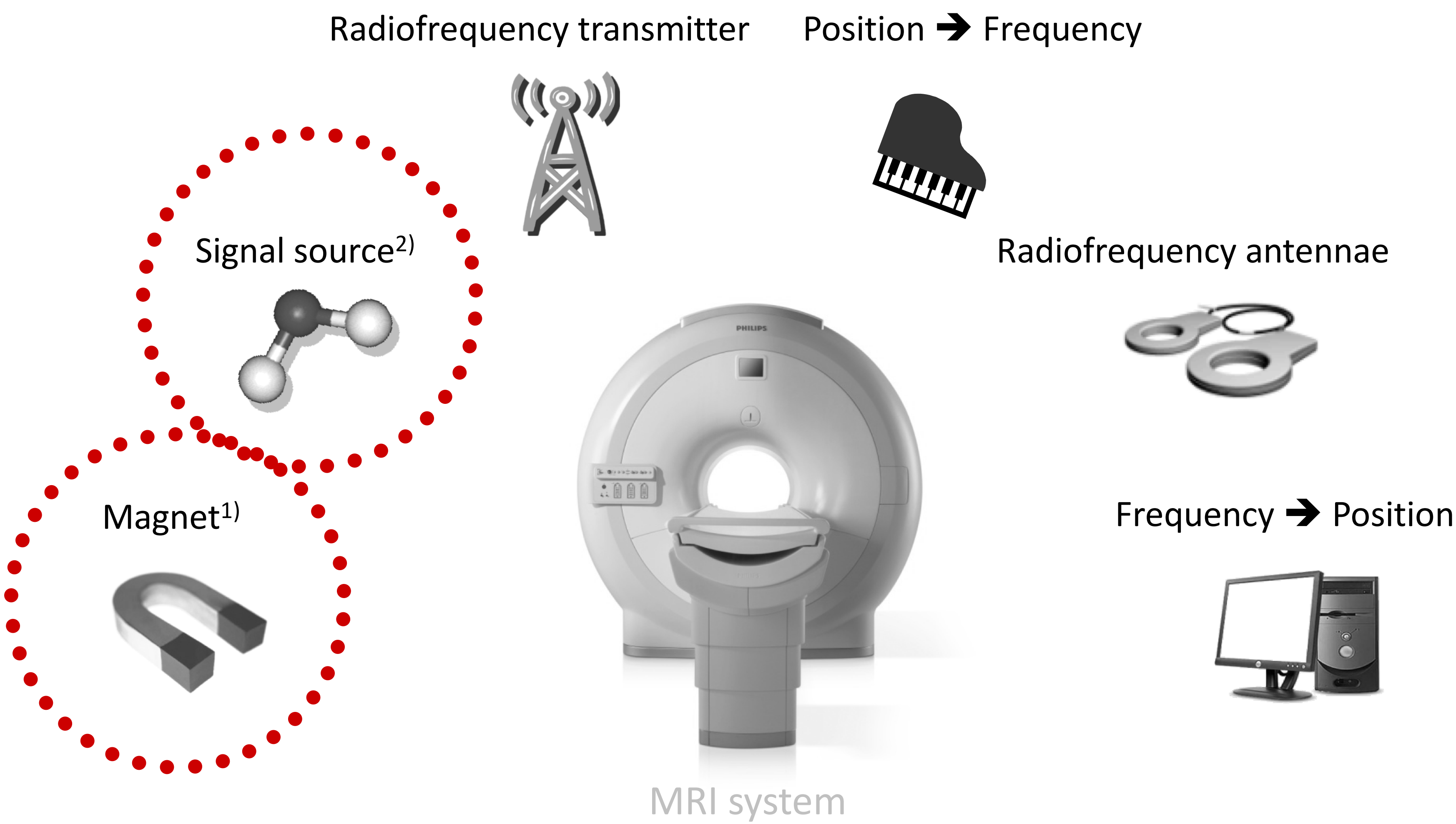
  Magnetic Resonance Spectroscopy (MRS)

  Functional MRI (fMRI)

Magnetic Resonance



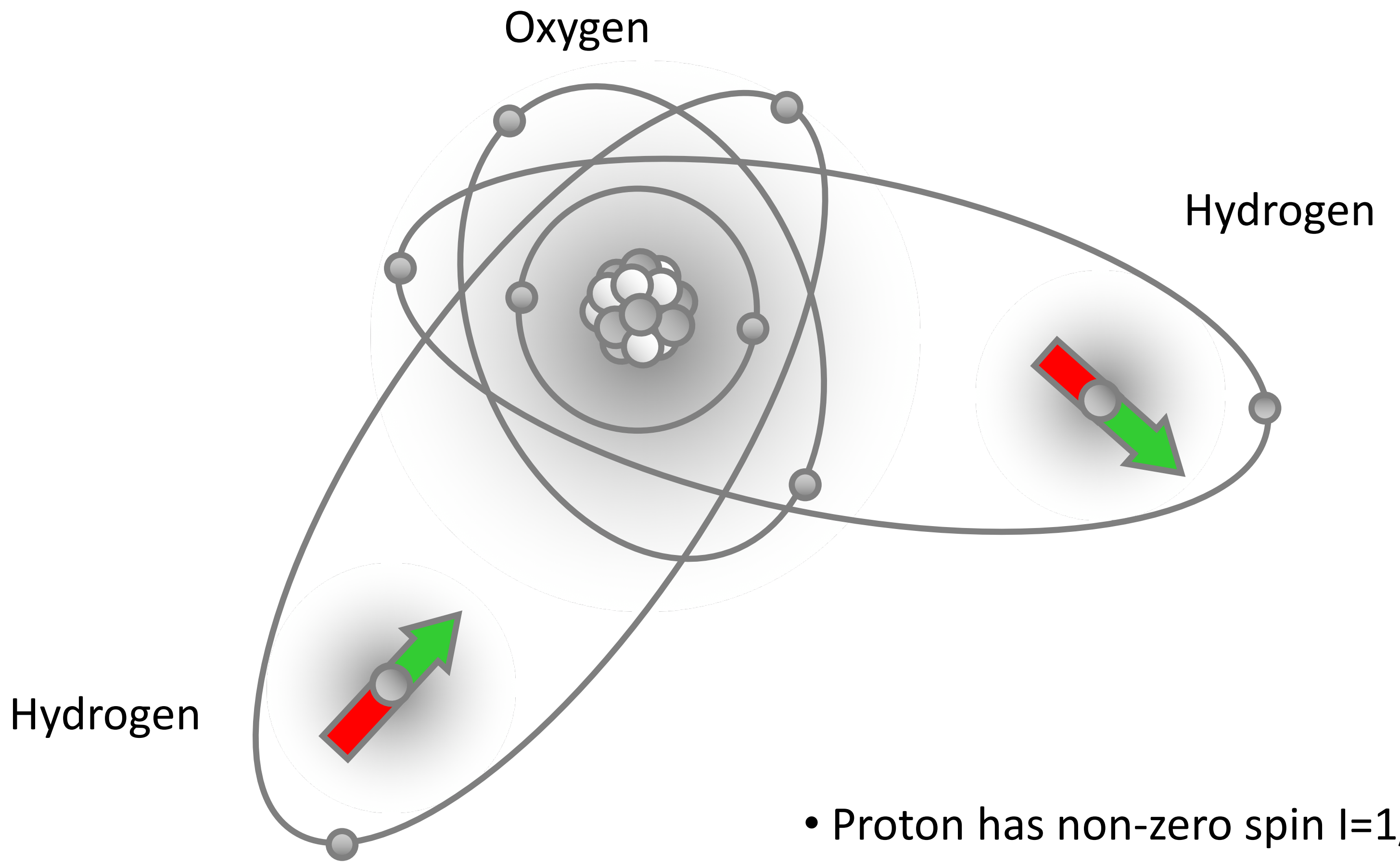
Magnetic Resonance Imaging



1) 0.5-14 Tesla

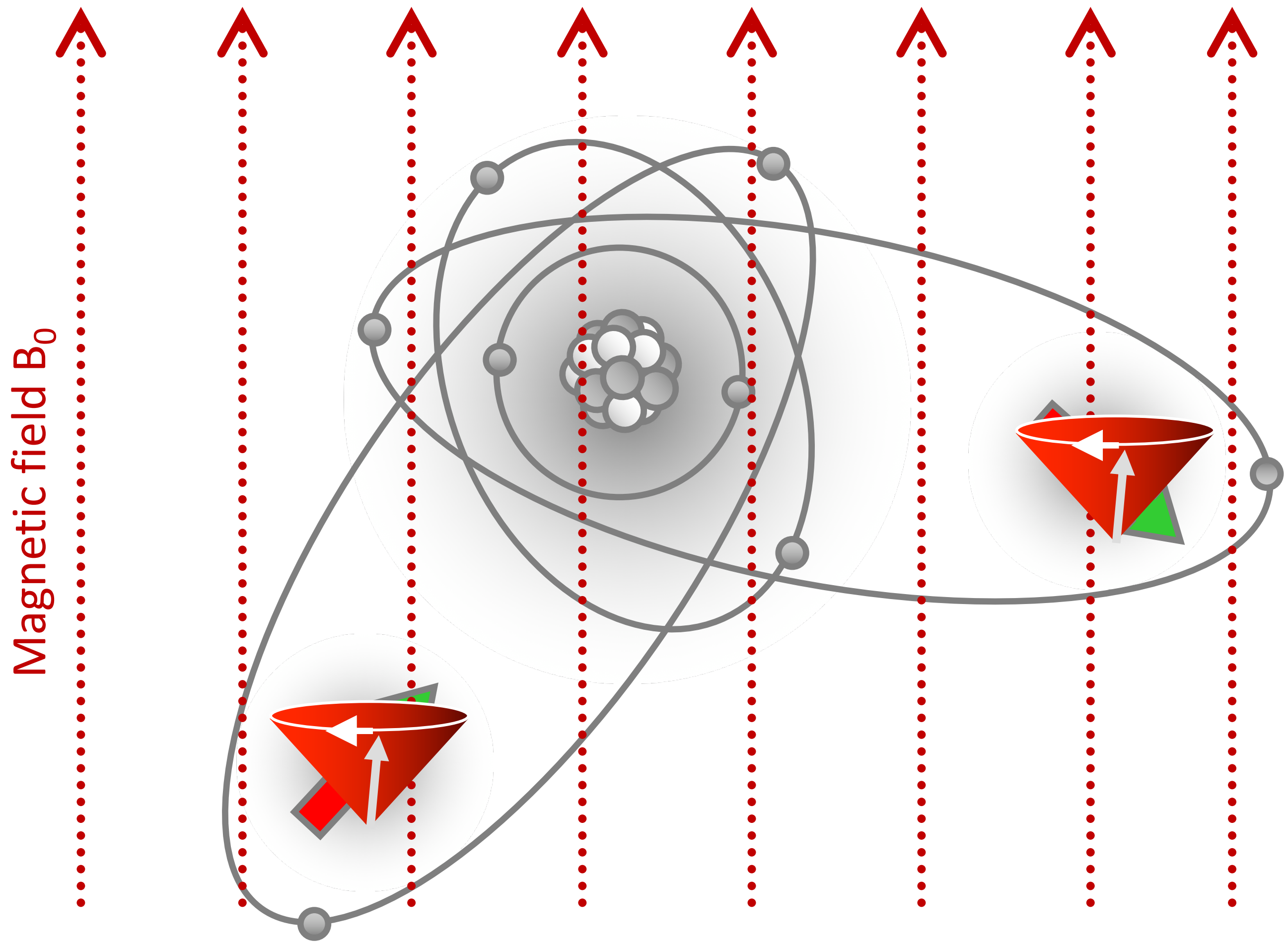
2) 1H, 31P, 13C, 19F

Signal source – Protons



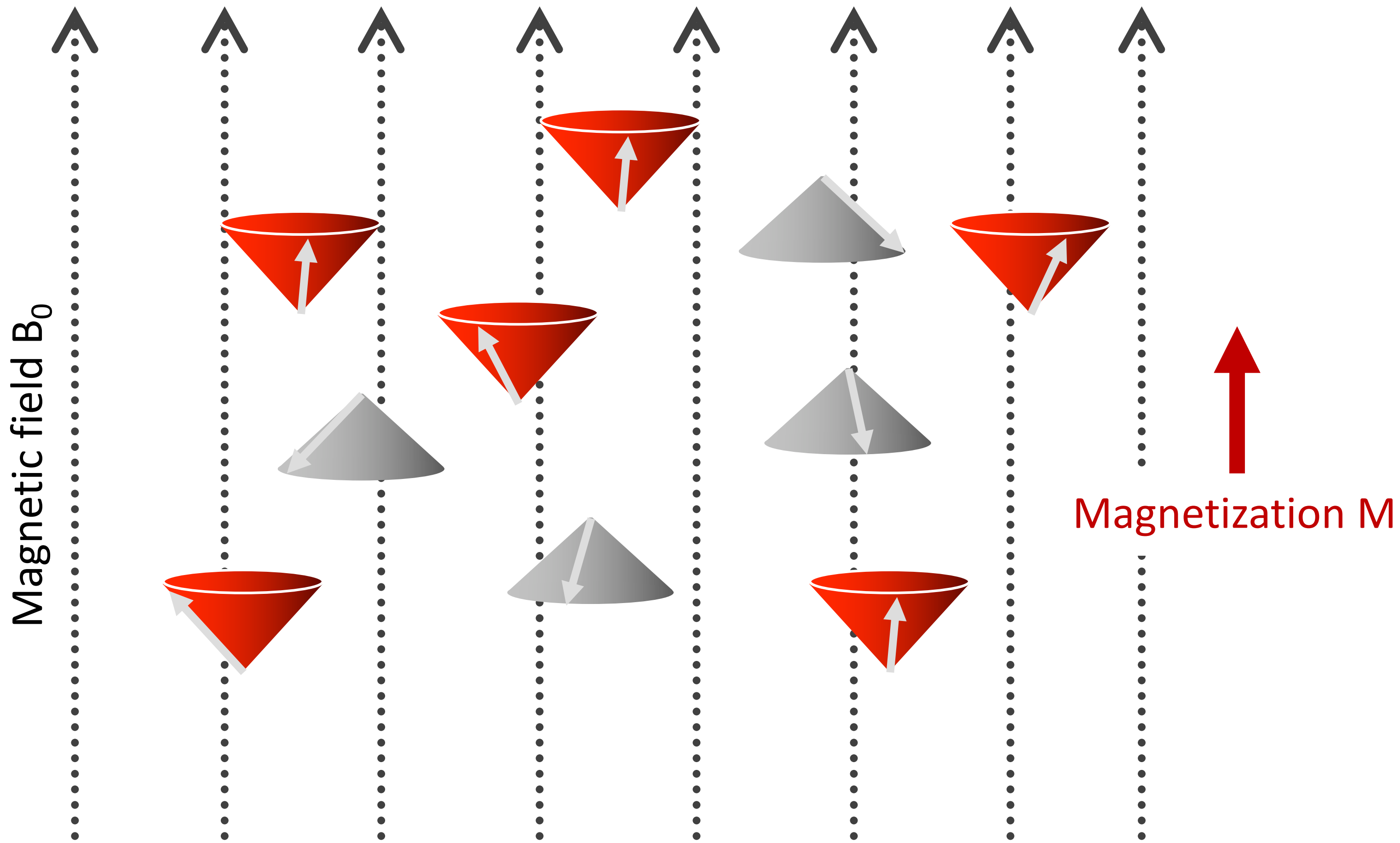
- Proton has non-zero spin I=1/2
- Oxygen has zero spin I=0

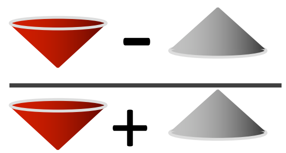
Signal source in external magnetic field



Precession about B_0 with Larmor frequency: $\omega_0 = \gamma B_0$; $\gamma = 42.6$ MHz/T

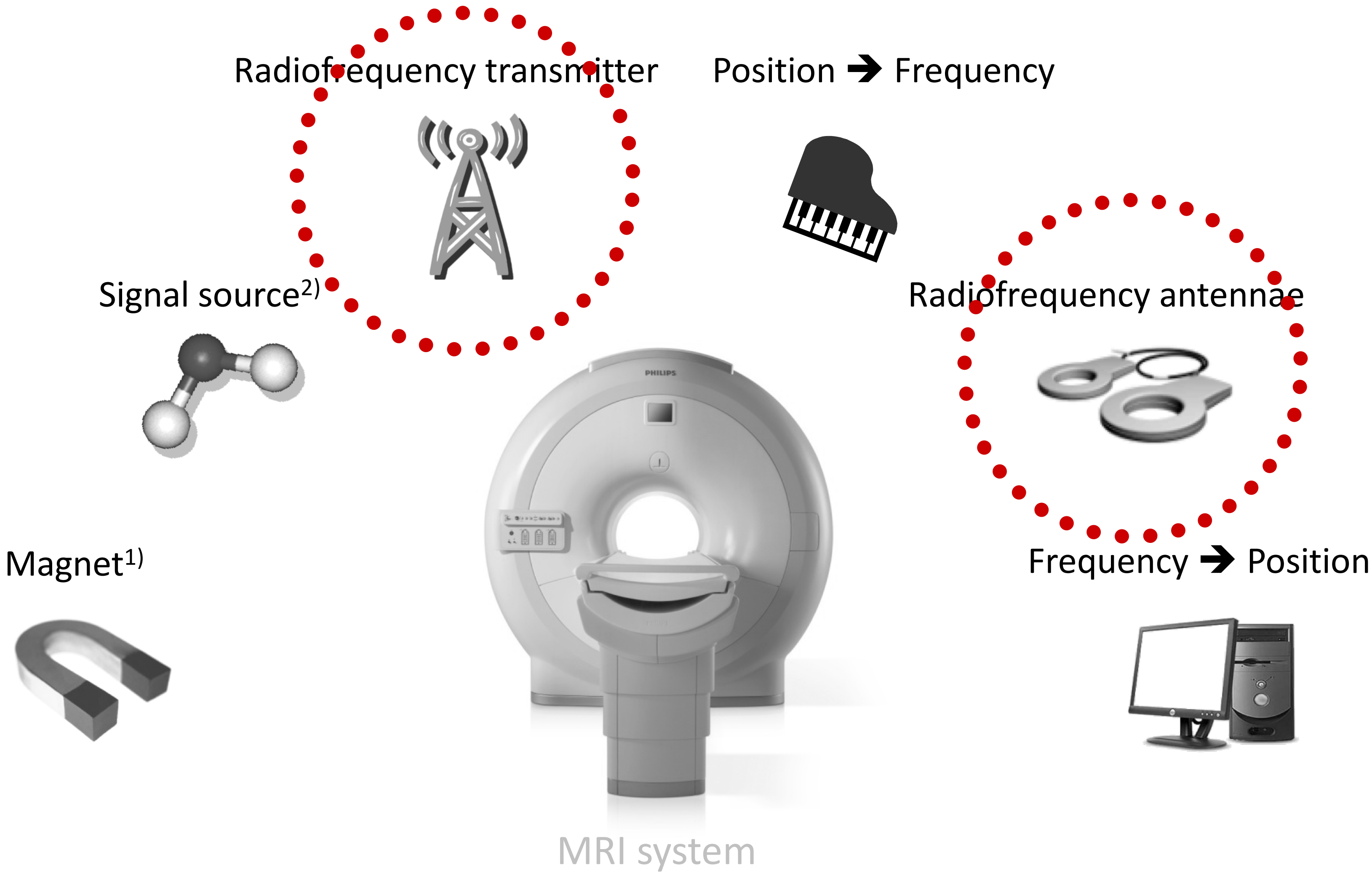
Signal source in external magnetic field



Population difference =  $\sim \frac{\gamma h B_0}{2kT}$

Excess of “up” spins at 1.5 Tesla: 5*10-6

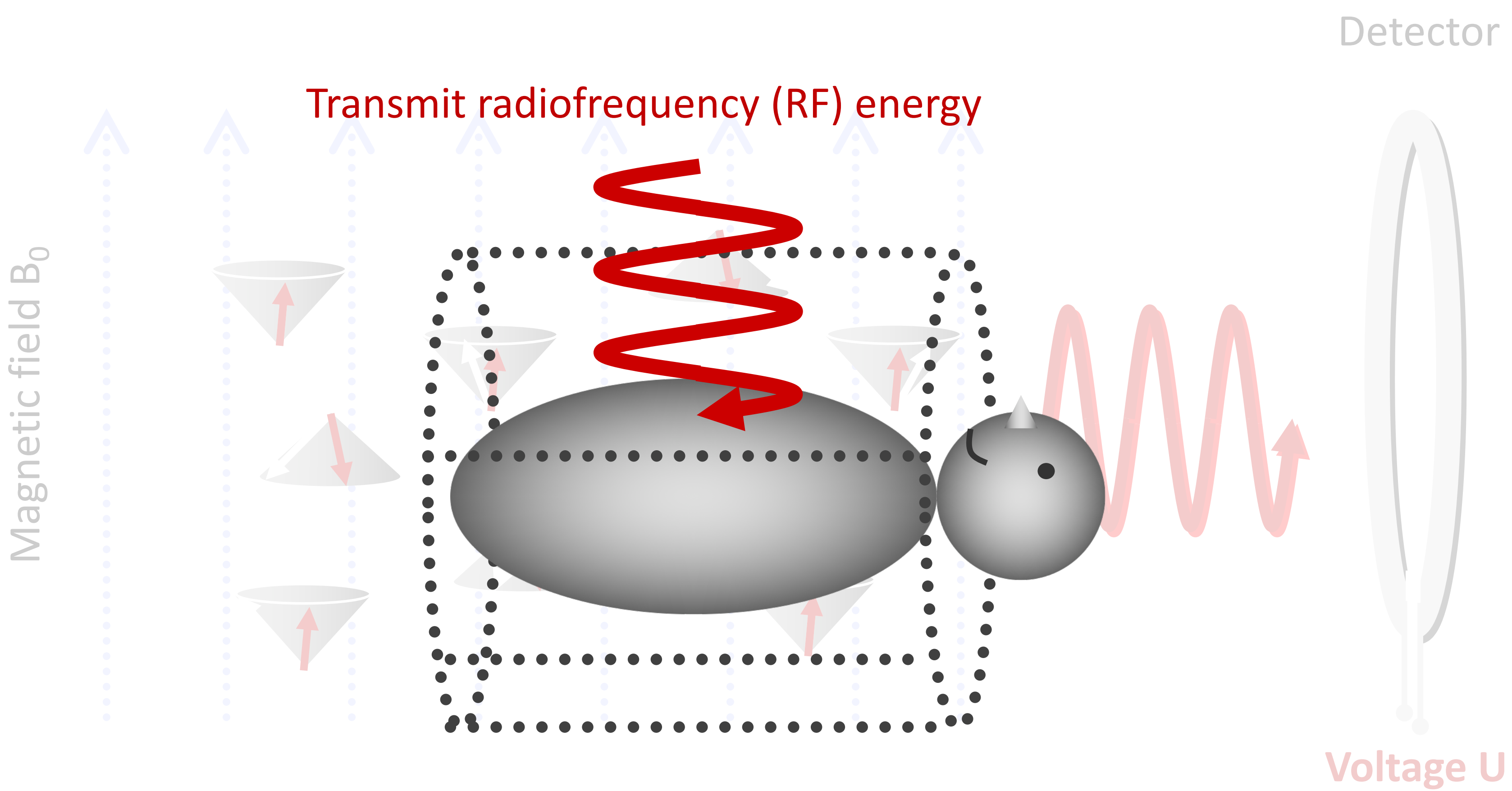
Magnetic Resonance Imaging



1) 0.5-14 Tesla

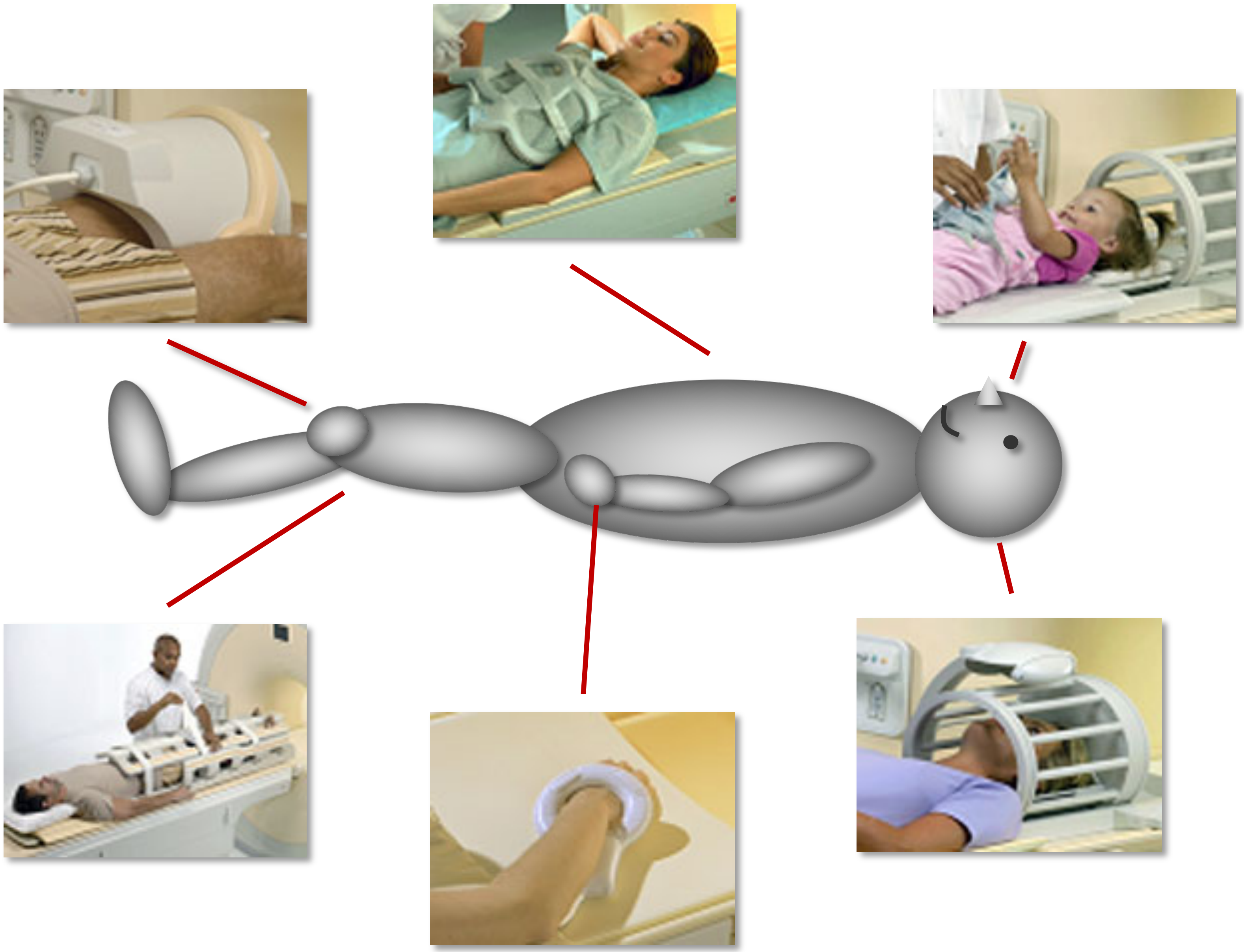
2) 1H, 31P, 13C, 19F

Detection

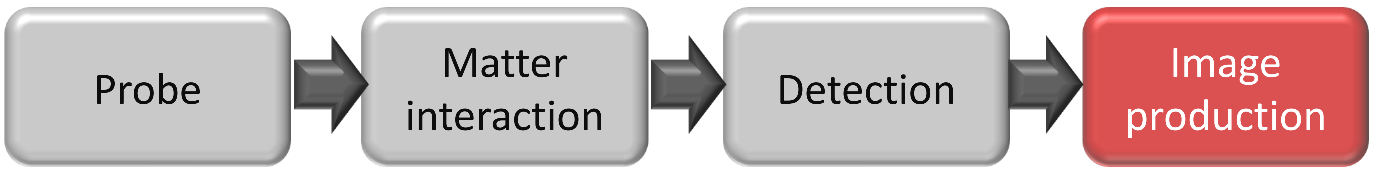


Voltage U = $\delta\Phi/\delta t \sim \omega M$

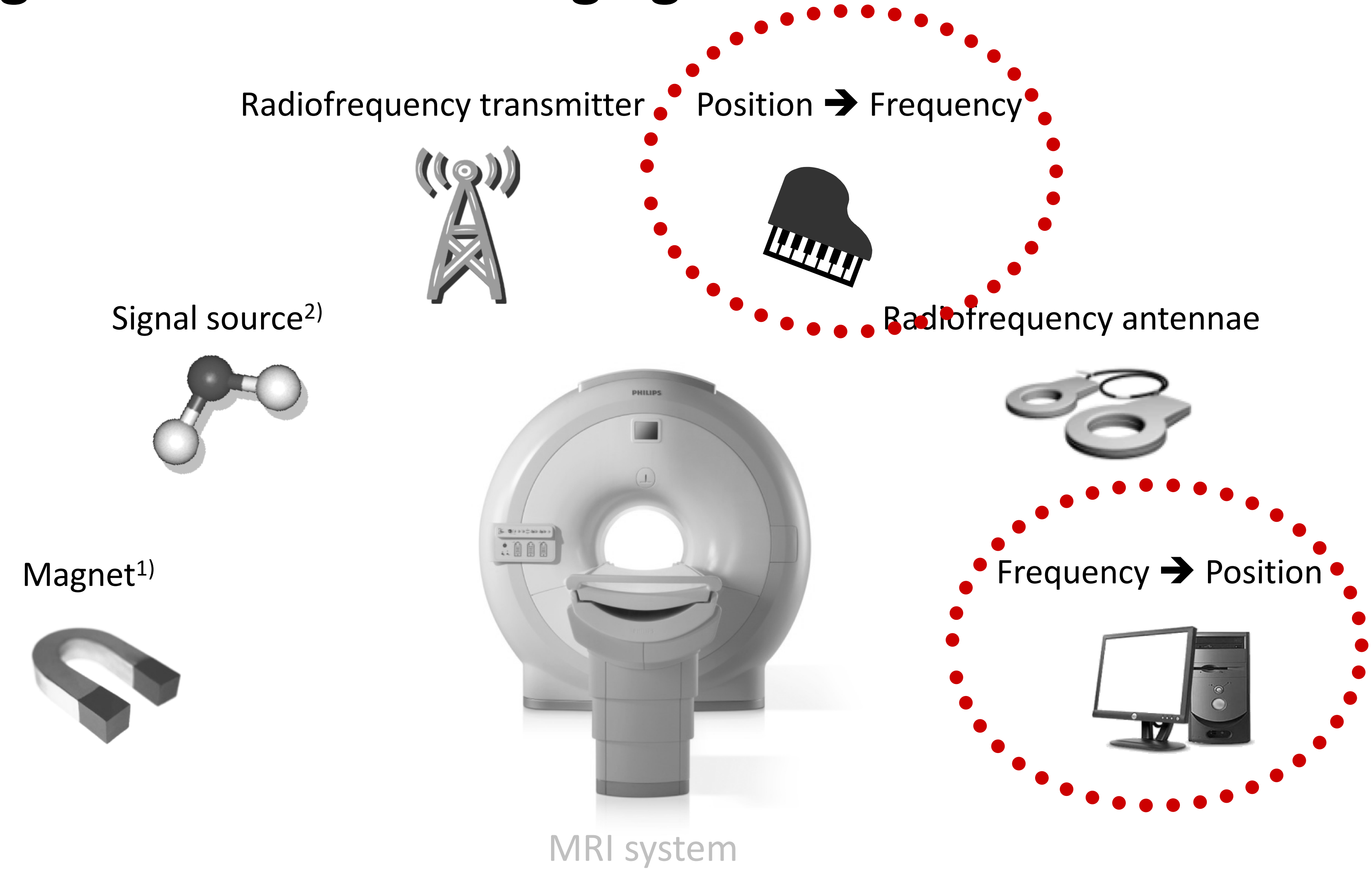
Detectors



MR Imaging



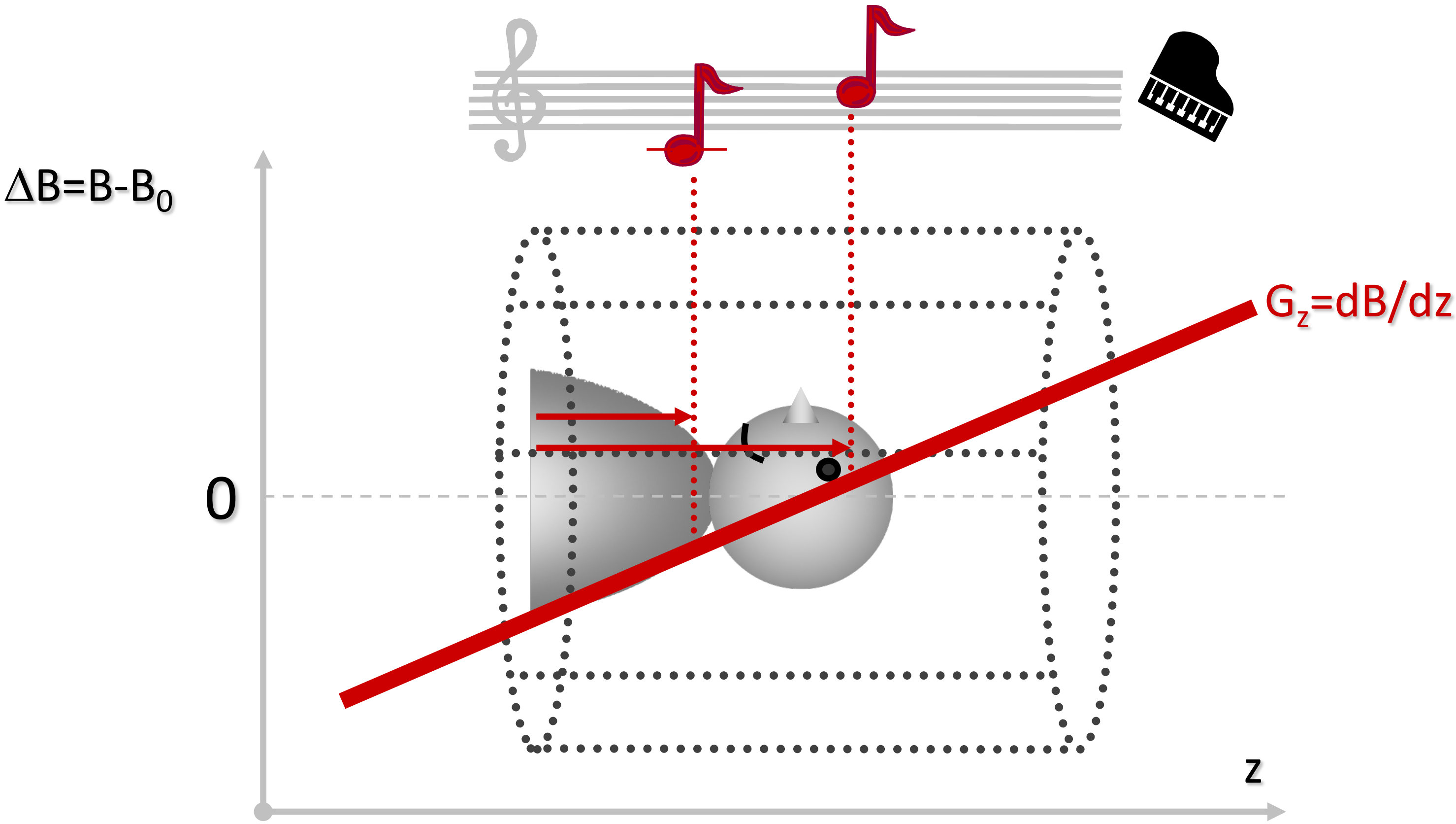
Magnetic Resonance Imaging



[1)] 0.5-14 Tesla

[2)] 1H, 31P, 13C, 19F

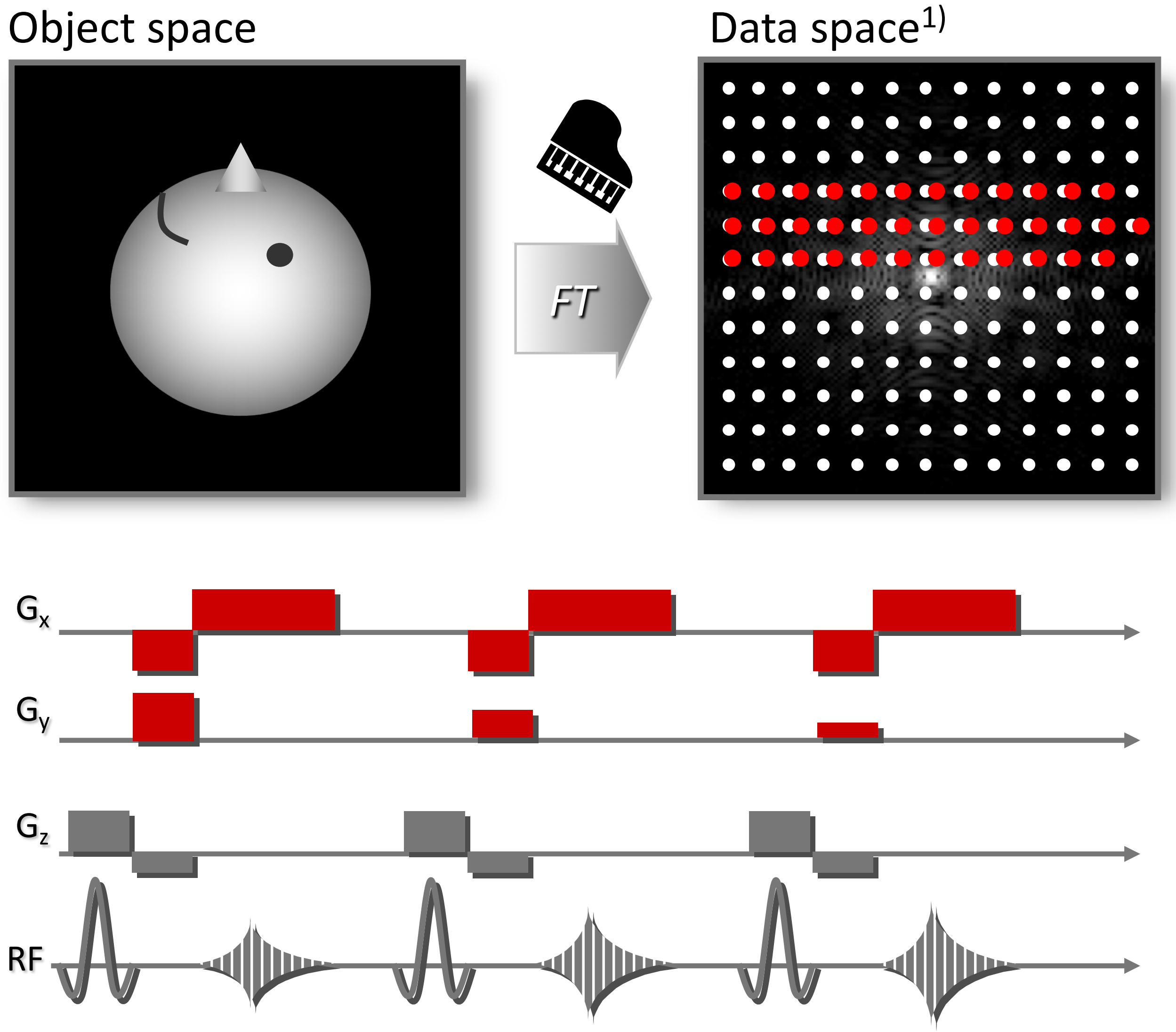
Position → Frequency



$$\omega(z) = \gamma\,(B_0 + \Delta B)$$

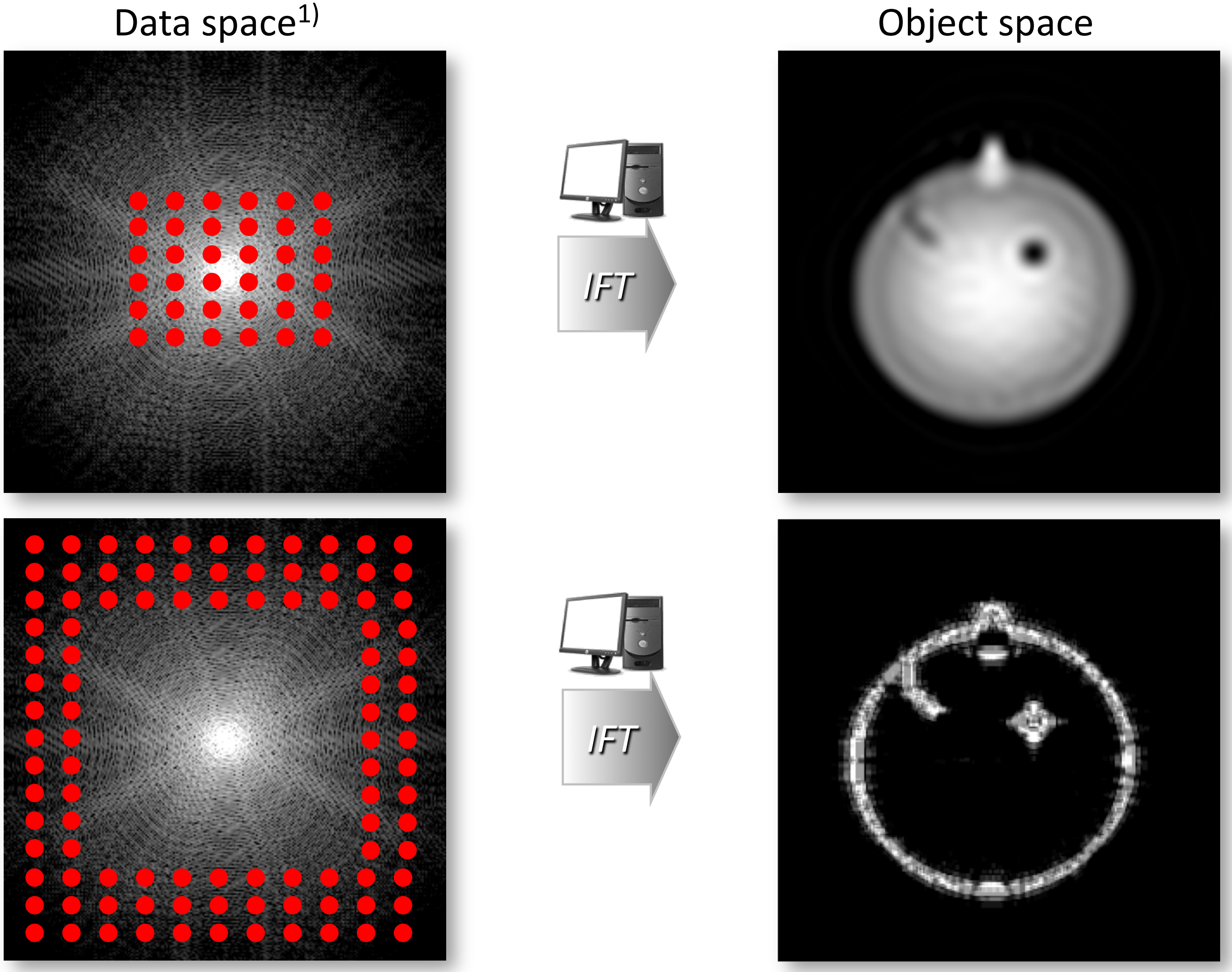
"Lamor frequency"

Fourier imaging



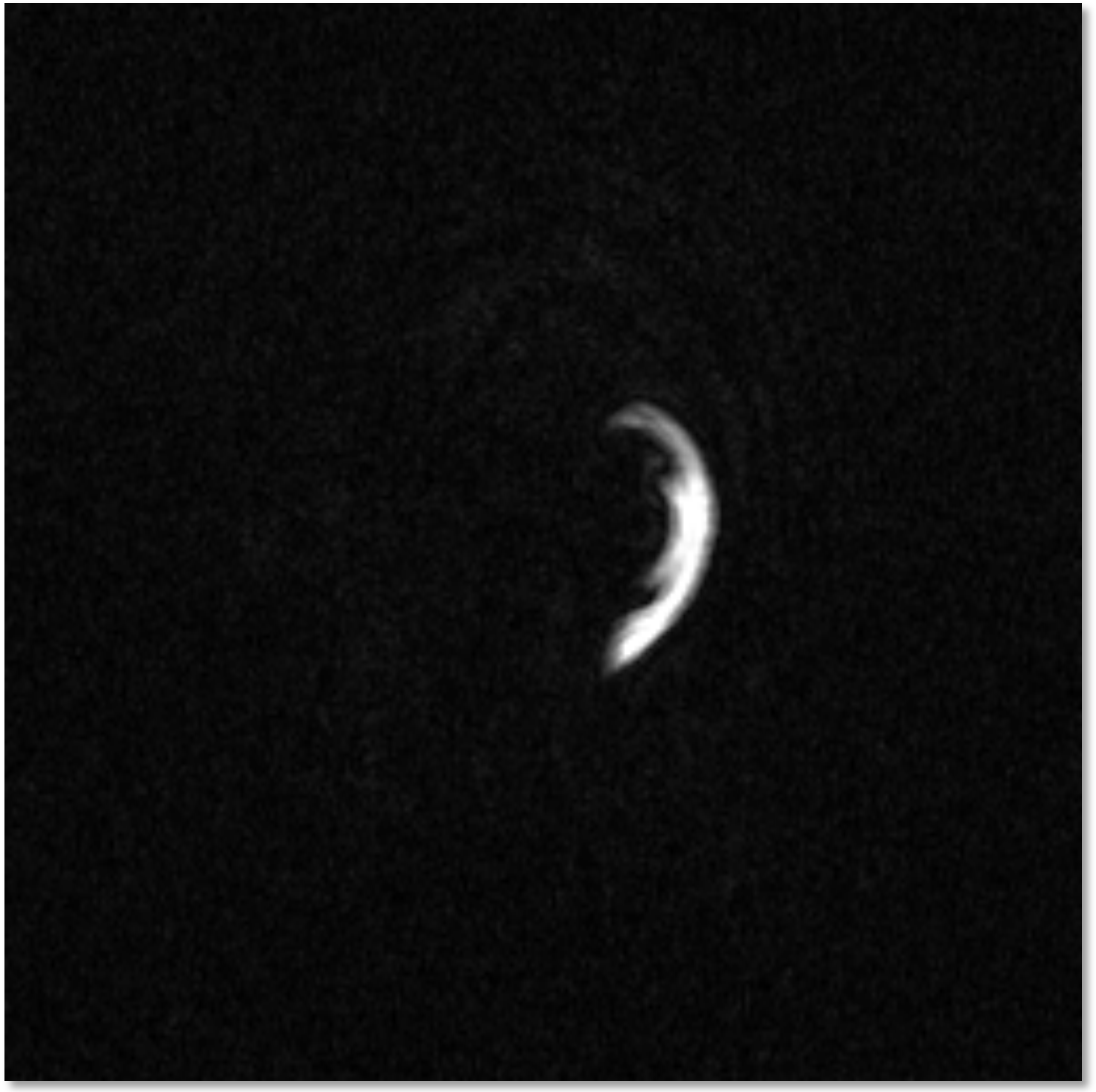
1) also: k-space; k = spatial frequency

Data space ↔ Object space



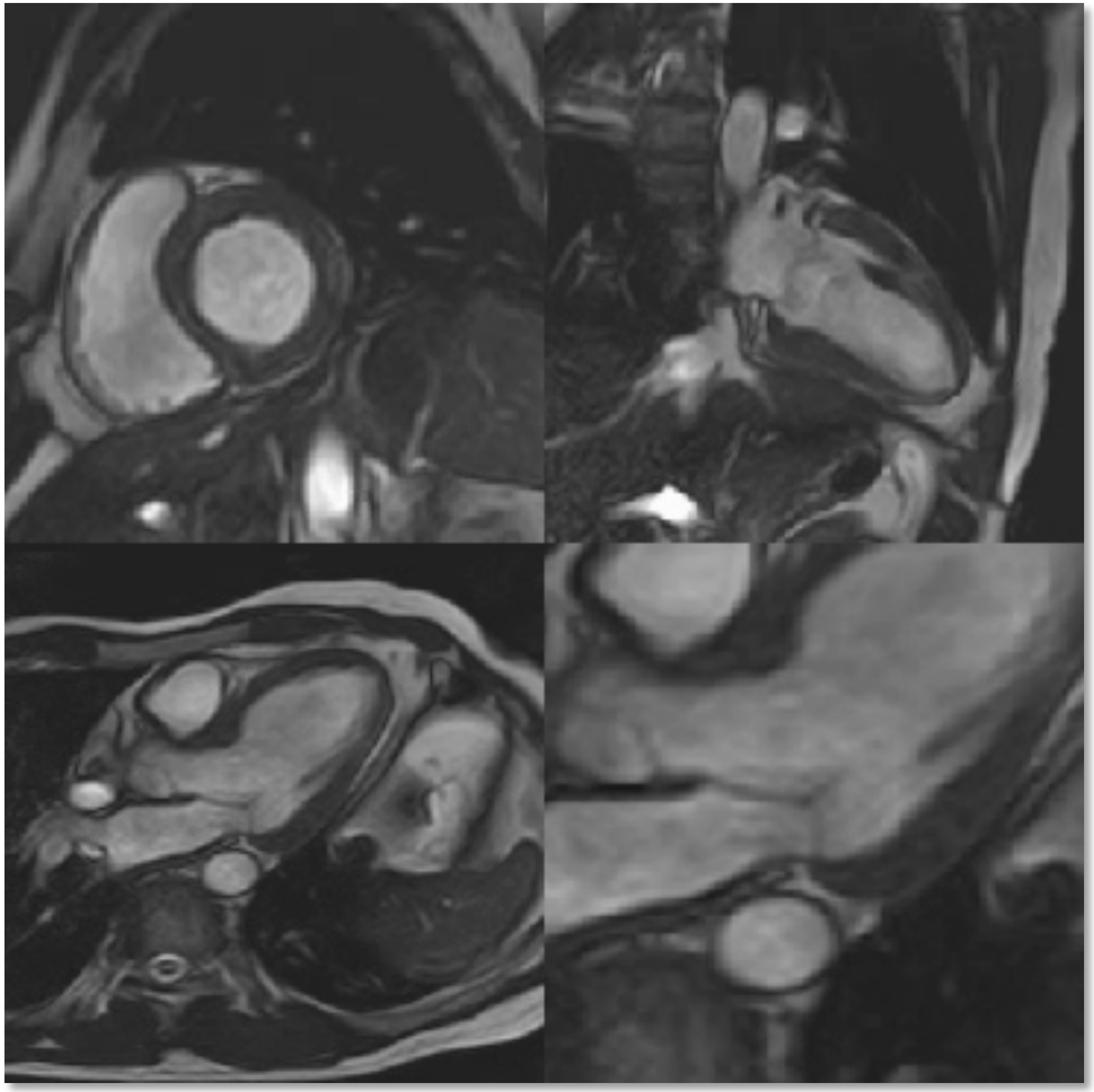
[1)] also: k-space; k = spatial frequency

MRI – Anatomy

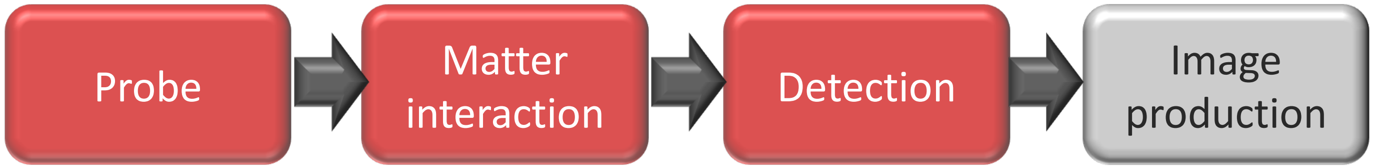


MRI – Angiography

MRI – Heart



Ultrasound Imaging



Biomedical Imaging

Imaging Mode: Ultrasound

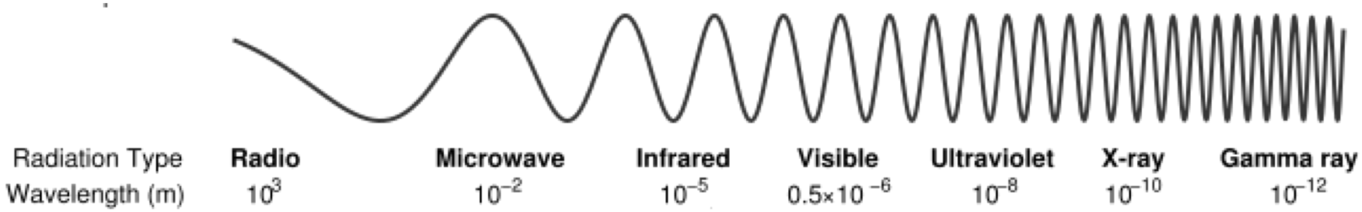
- Probe: acoustic waves
- Wavelength: 0.07 – 1.5 mm
- Matter interaction: scattering, absorption
- Modalities: Echography

  Doppler Imaging

  Thermal Therapy

Biomedical Imaging

Electromagnetic waves



- Do NOT require medium to transmit
- Energy stored in propagating electromagnetic fields
- Wave velocity is constant

Acoustic waves

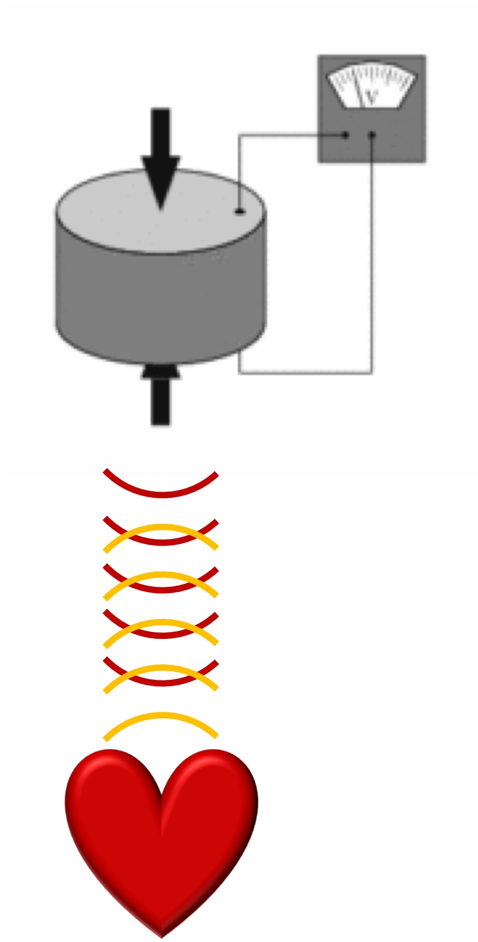
- DO require medium to transmit
- Energy transport by mechanical displacement
- Wave velocity depends on medium properties

Ultrasound Imaging

Piezoelectric transducer

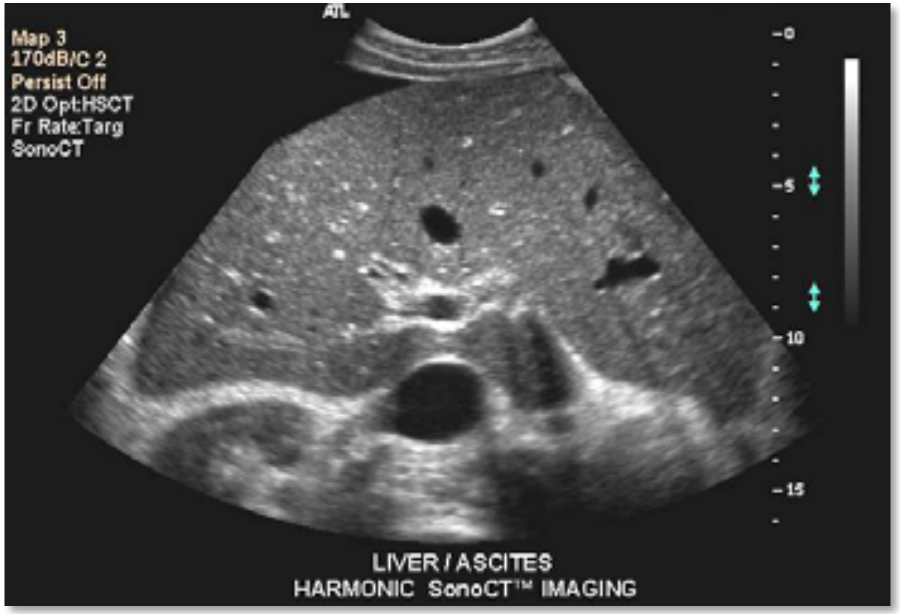
Acoustic wave

Scattering/absorption

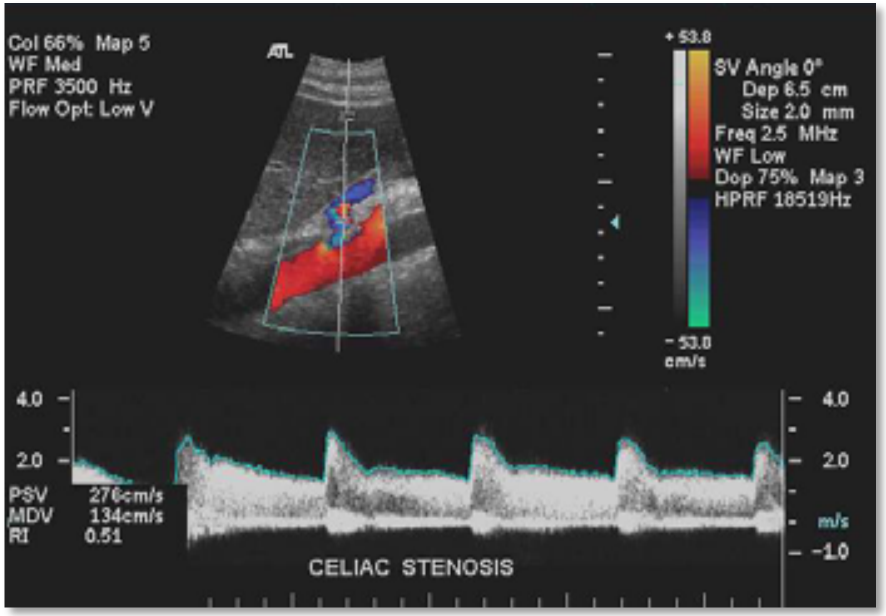


Ultrasound Imaging

High-resolution liver imaging

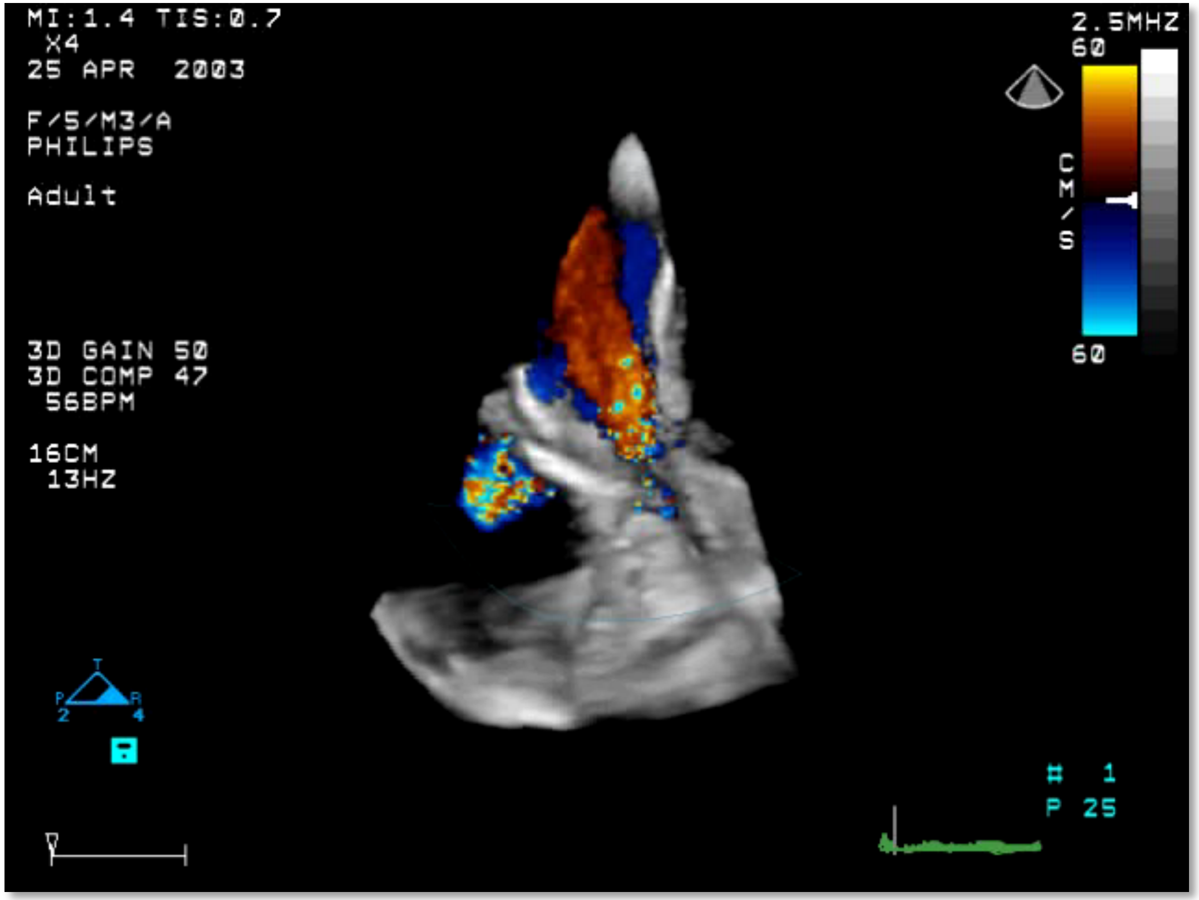


Color-Doppler flow imaging



Ultrasound Imaging

3D Ultrasound – Aortic regurgitation

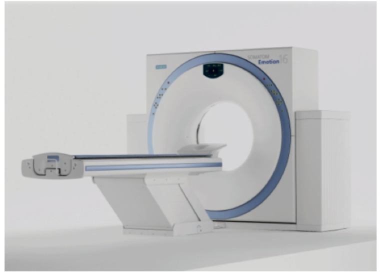


Philips Healthcare

Activity

Arrange imaging methods according to wave frequency involved (high to low) …

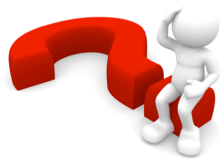
X-Ray, Computed Tomography



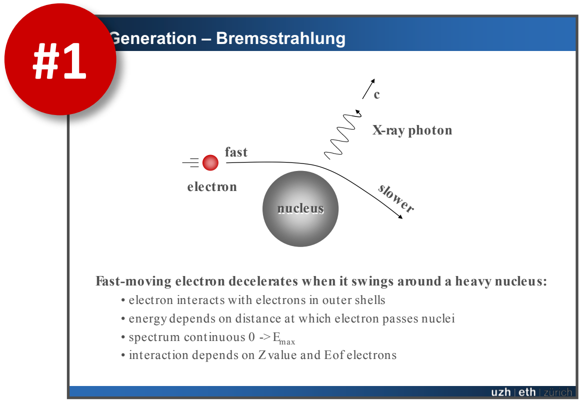
Magnetic Resonance Imaging

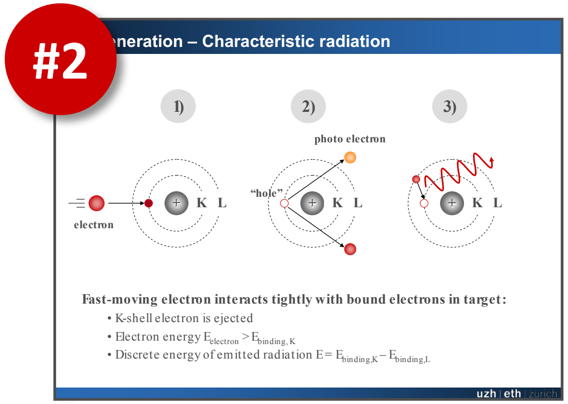
Nuclear Imaging

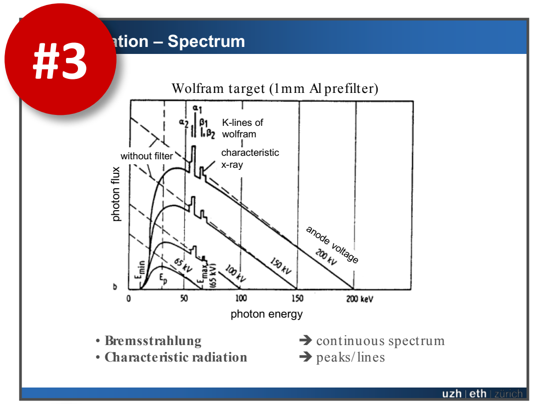
Ultrasound Imaging

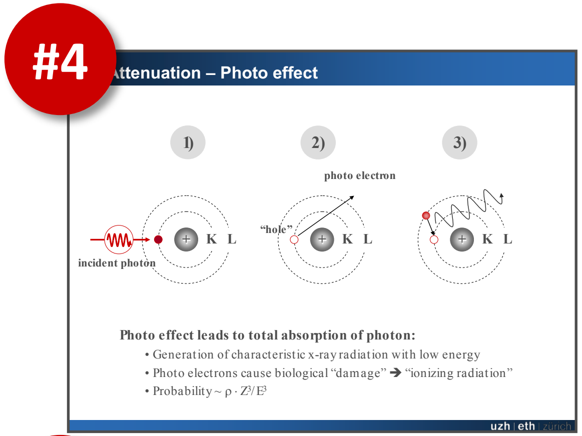


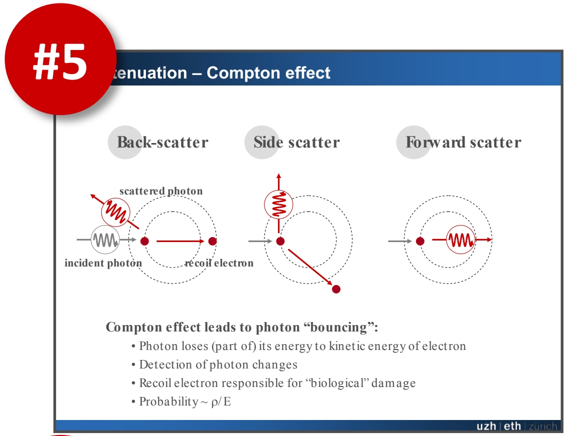
"The most important slides"

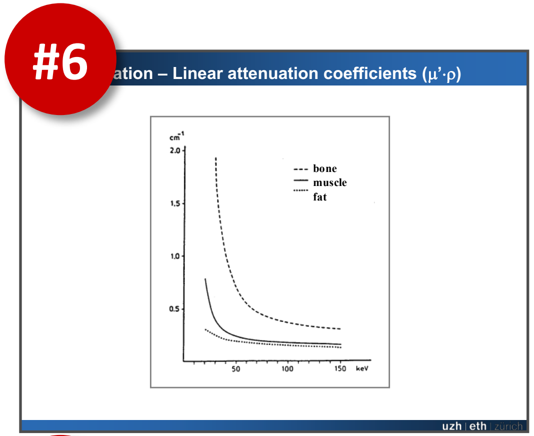


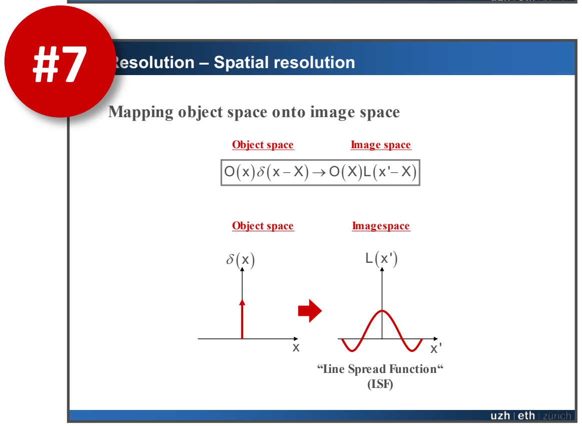


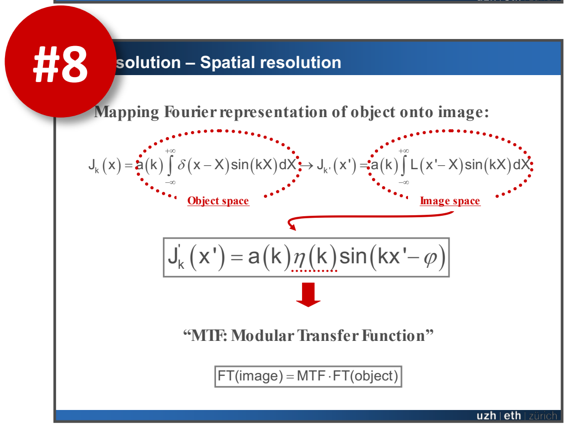


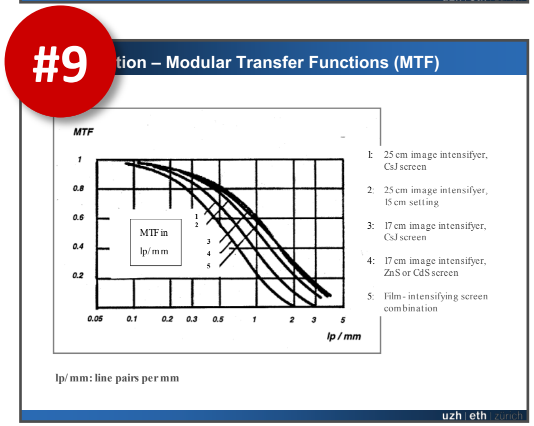












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