

Radio spectroscopies, NMR, ESR, MRI

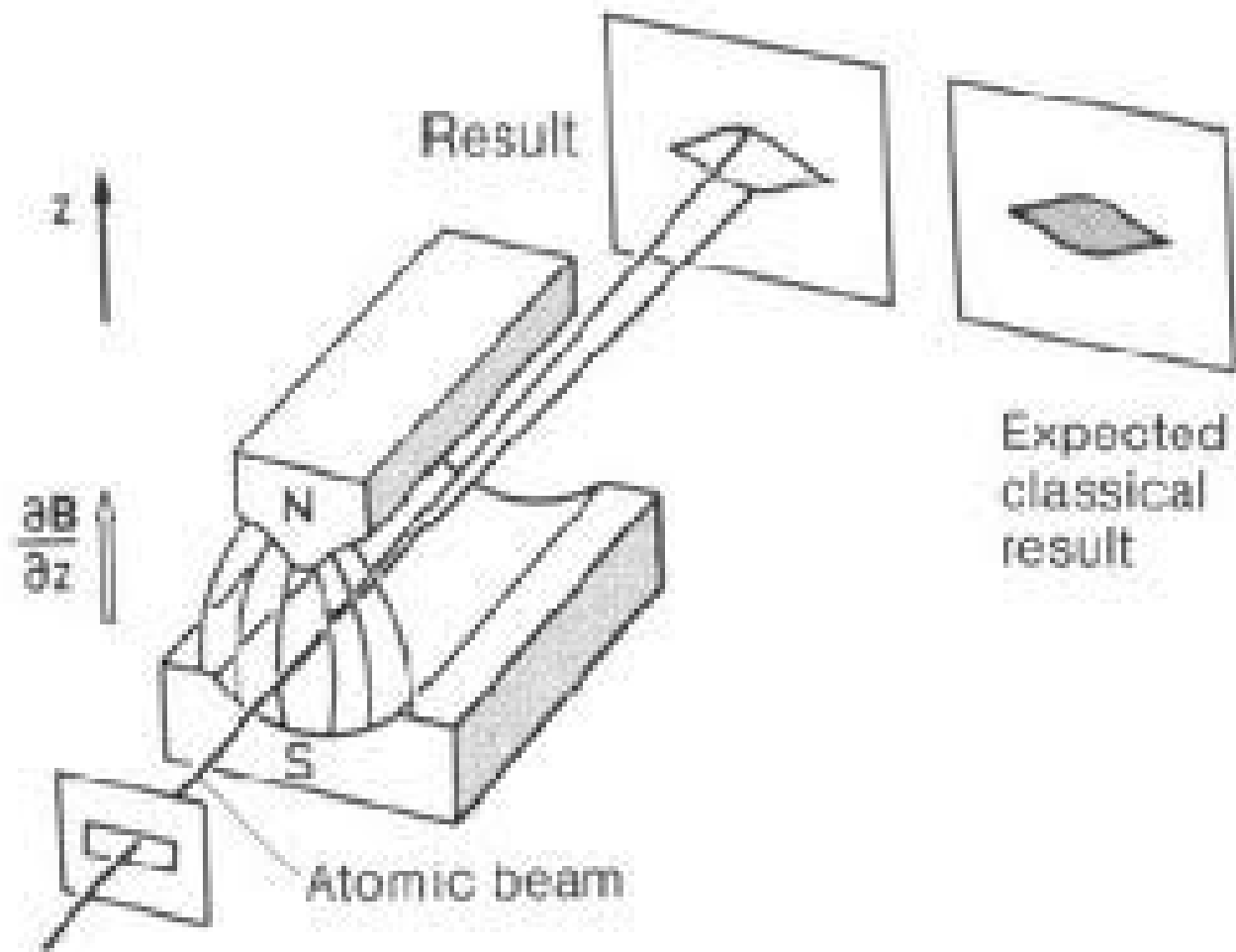
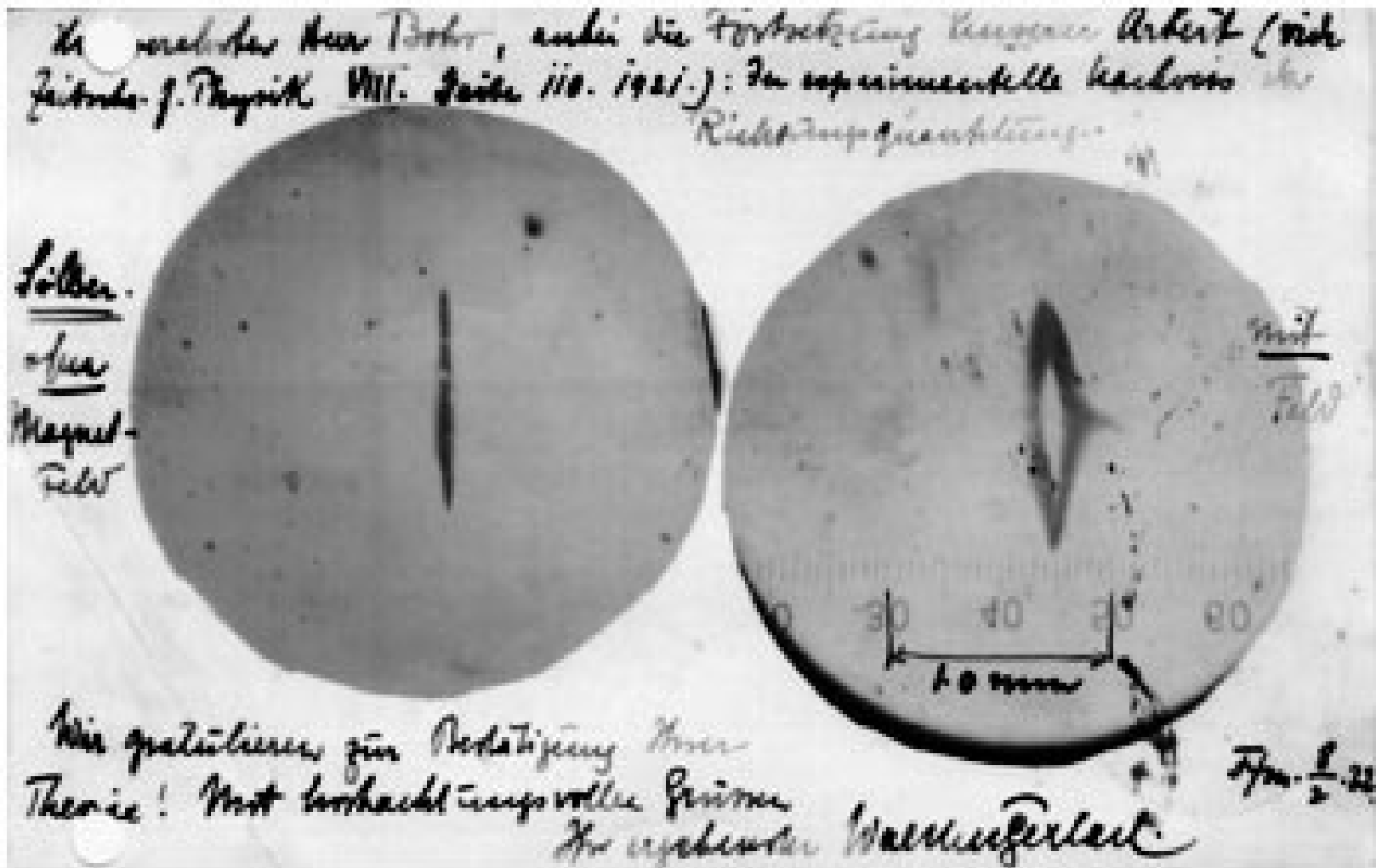
Miklós Kellermayer
(Gusztáv Schay)

Stern-Gerlach experiment (1922)

Walther Gerlach
(1889-1979)

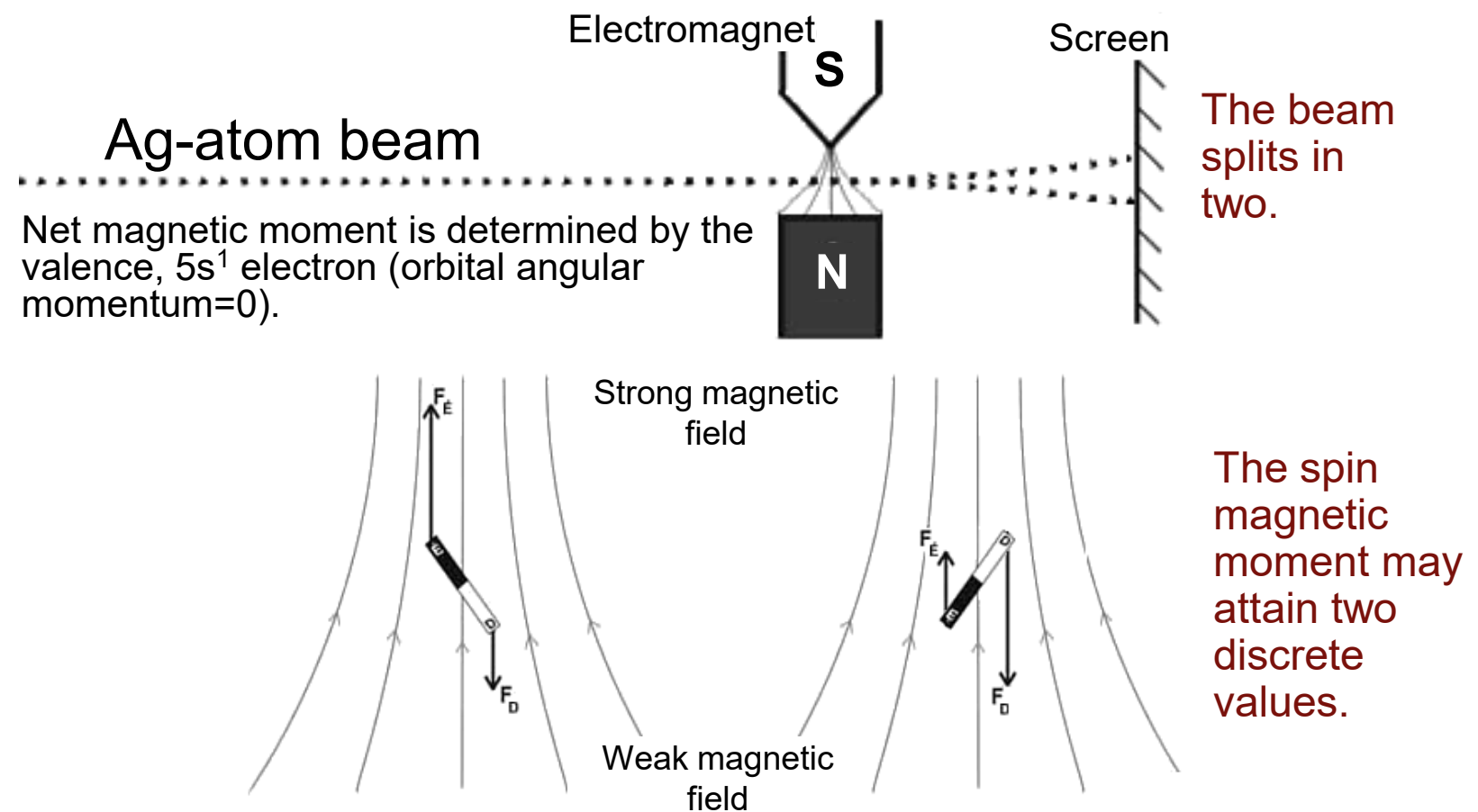
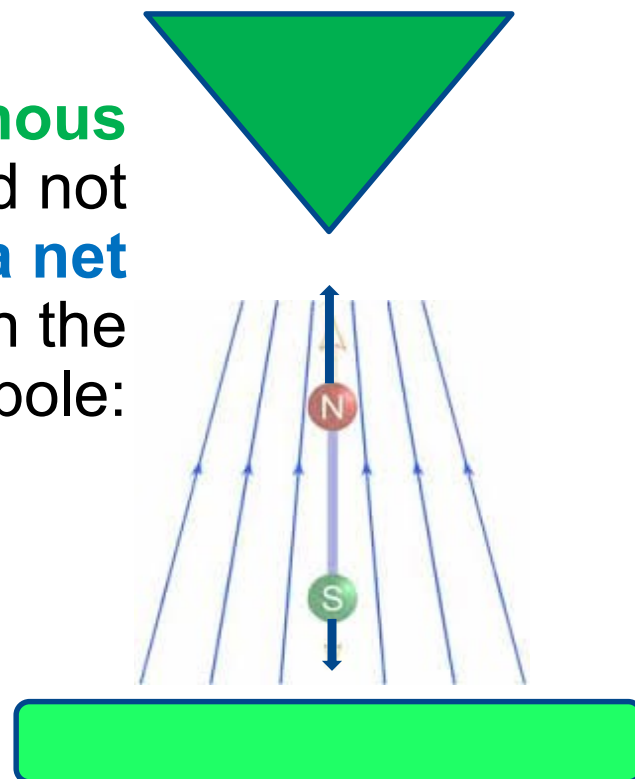


Otto Stern
(1888-1969)



Atomic, molecular systems may behave as elementary magnets

In an **inhomogenous** magnetic field not only torque, but **a net force** also acts on the magnetic dipole:



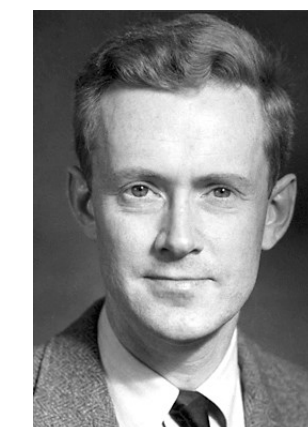
Nuclear magnetic resonance, (NMR)
Nobel-prize, 1952



Isidor Rabi
(1898-1988)



Felix Bloch
(1905-1983)



Edward Mills Purcell
(1912-1997)

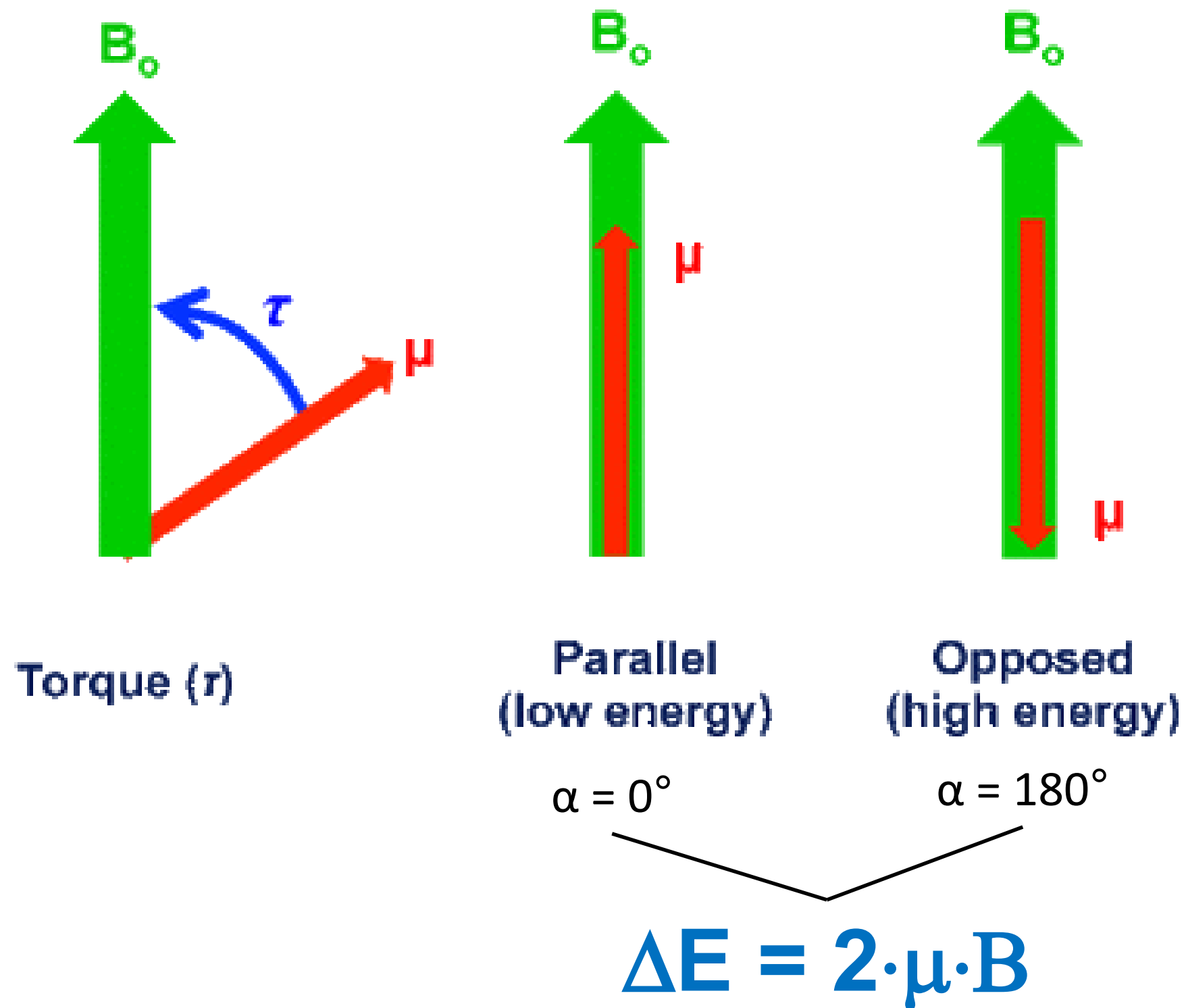
Magnetic resonance: resonance-absorption of electromagnetic energy by a material placed in magnetic field.

Energy of an elementary magnet in an external field

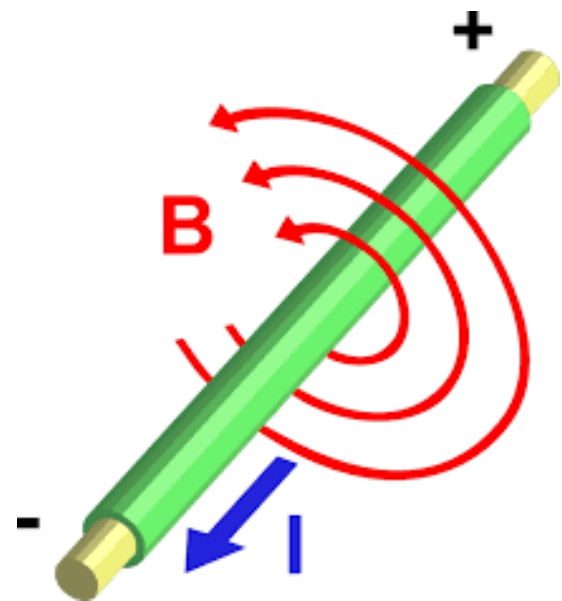
$$E_{\text{pot}} = -\boldsymbol{\mu} \cdot \mathbf{B}$$

vector "dot" product!

$$\boldsymbol{\mu} \cdot \mathbf{B} = |\boldsymbol{\mu}| \cdot |\mathbf{B}| \cdot \cos(\alpha)$$



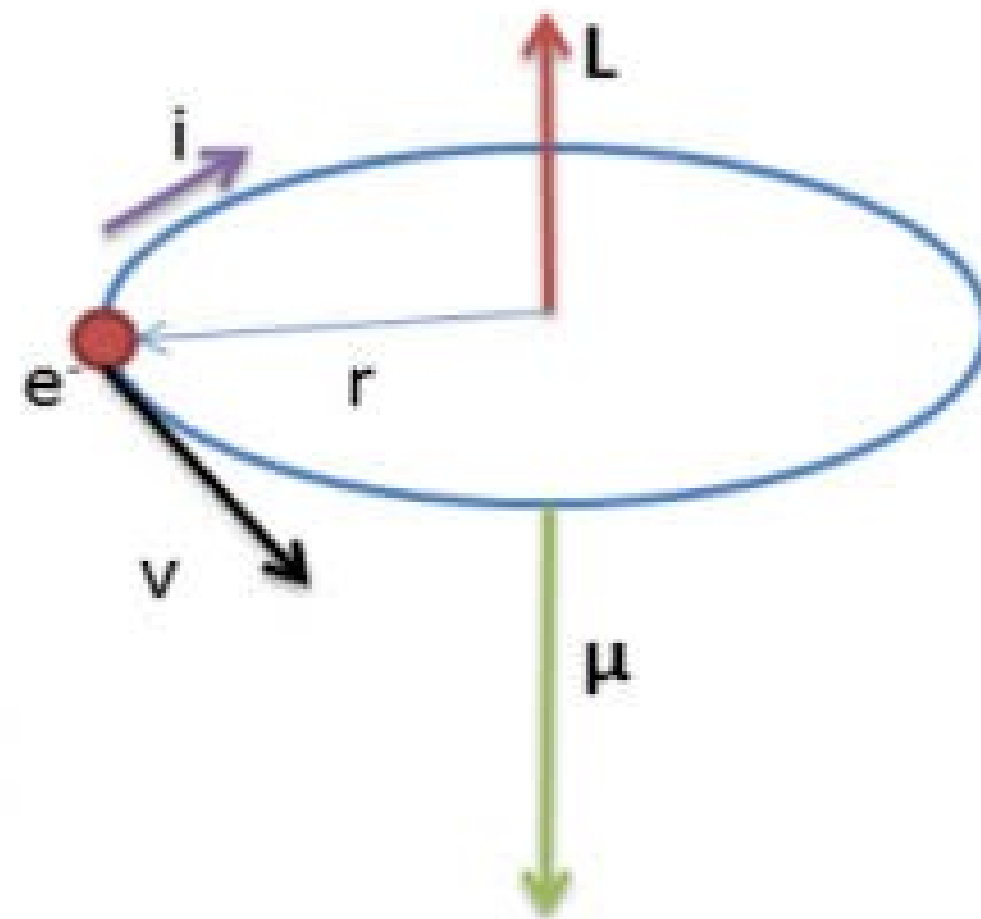
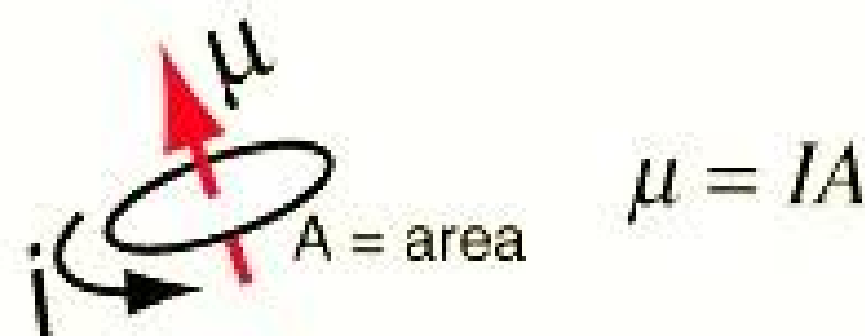
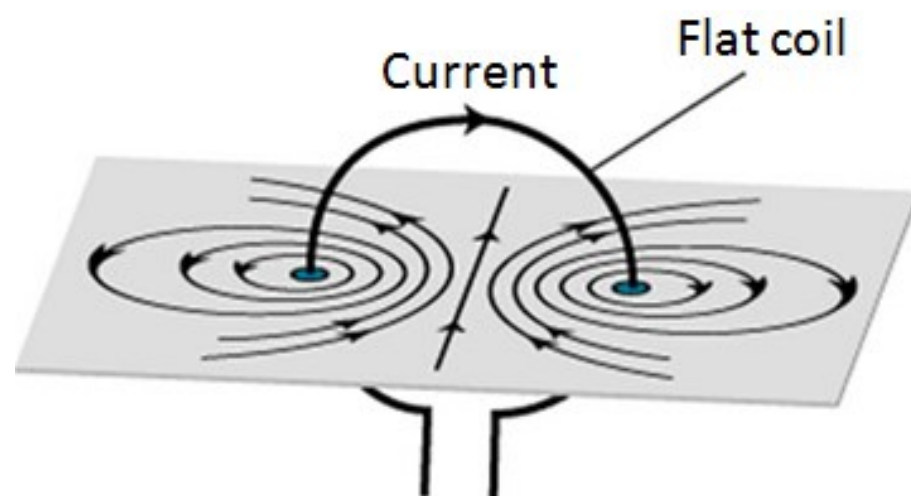
Magnetic fields in atoms



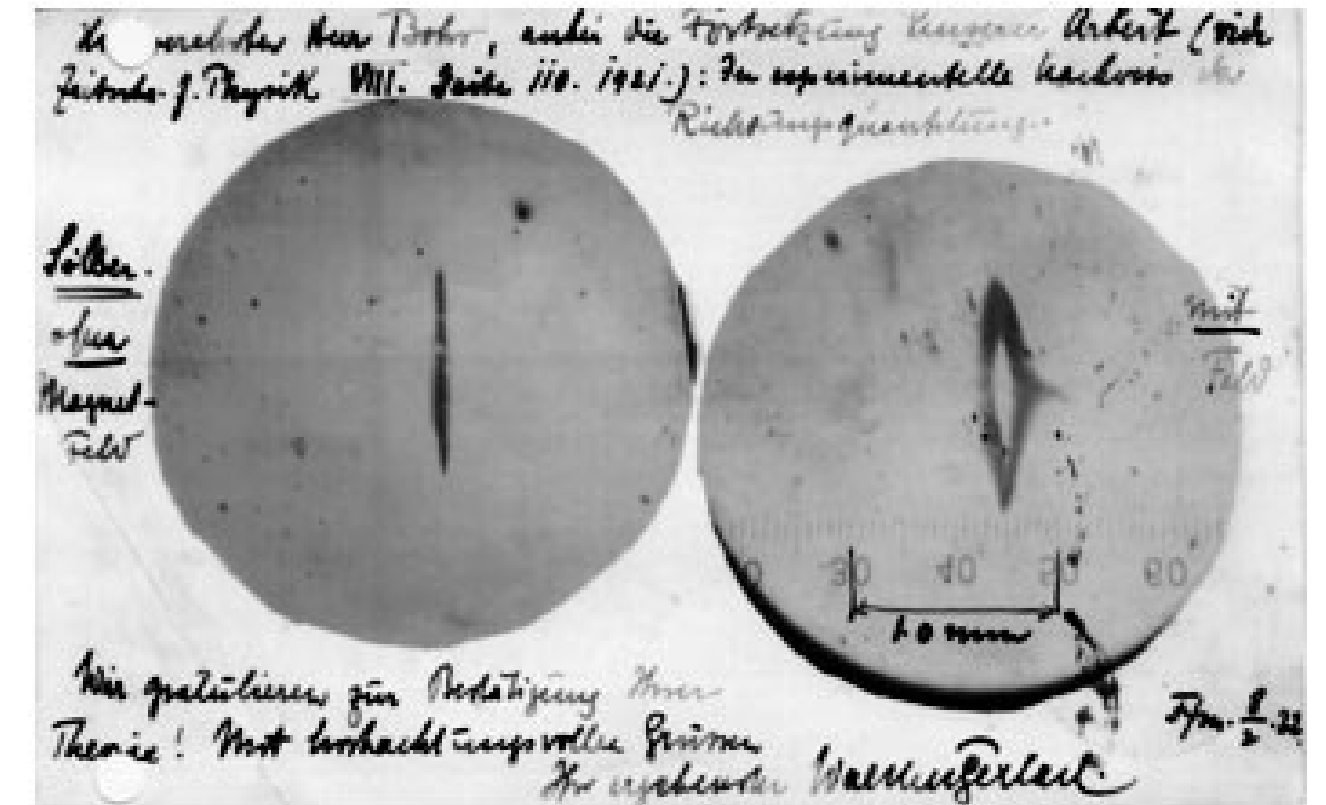
$$\sum_{loop} \mathbf{B} \cdot \Delta \mathbf{l} = \mu_0 I$$

Ampère's law

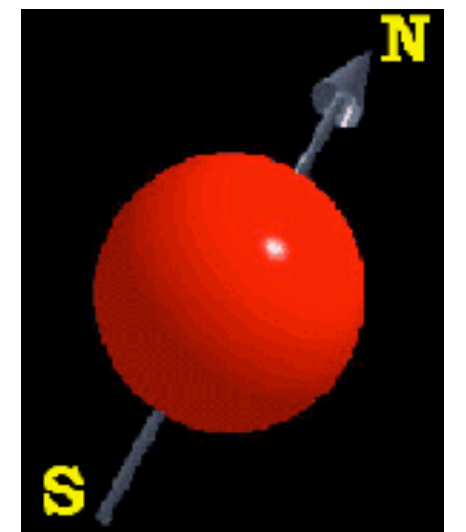
$$\mu_0 = 4\pi \cdot 10^{-7} \text{ N/A}^2 \text{ in vacuum}$$



A single electron has
an orbital-related magnetic moment
magnetic quantum number



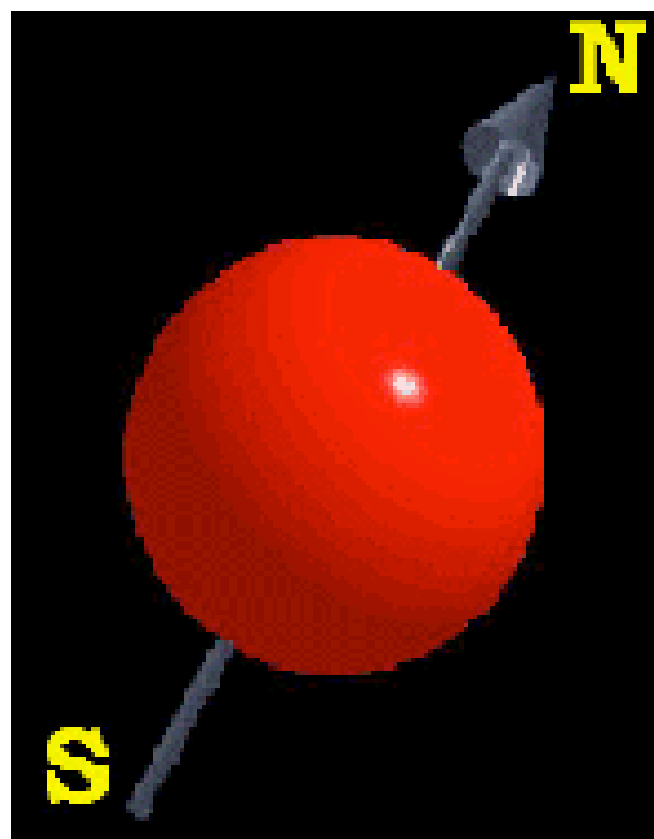
and
something more!
the
SPIN
"embedded"
magnetism
of



elementary particles

Systems with net spin: elementary magnets

- Elementary particles (p, n, e) have their own *spin*.
- Depending on the number of elementary particles and organizational principles (e.g., Pauli principle), *net spin* emerges within the system.
- Atomic nucleus: odd mass number - half nuclear spin (^1H , ^{13}C , ^{15}N , ^{19}F , ^{31}P); even mass number, odd atomic number - whole nuclear spin; even mass and atomic number - zero nuclear spin.
- Electron: net electron spin within a molecular system containing a stable unpaired electron (e.g., free radicals).
- Because of *charge* and *net spin*, *magnetic moment* emerges.

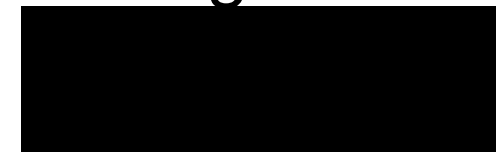


$$M_e = -9.28 \cdot 10^{-24} \text{ J/T}$$

$$M_N = 1.41 \cdot 10^{-26} \text{ J/T}$$

$$M_e/M_N > 600$$

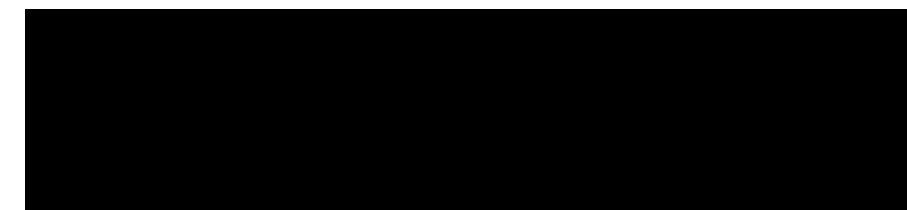
Nuclear magnetic moment:



$$\gamma_N = g \frac{q}{2m}$$

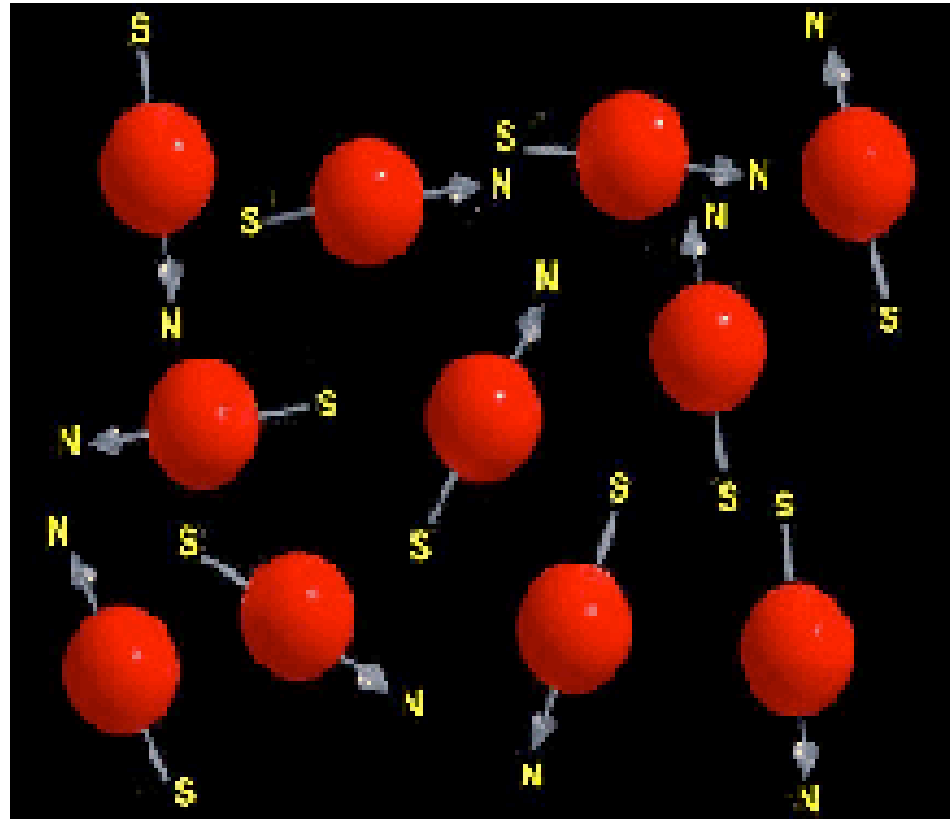
γ_N = gyromagnetic ratio (ratio of magnetic moment and angular momentum.)
 L = nuclear spin (), l = spin quantum number.

Magnetic moment of the electron:



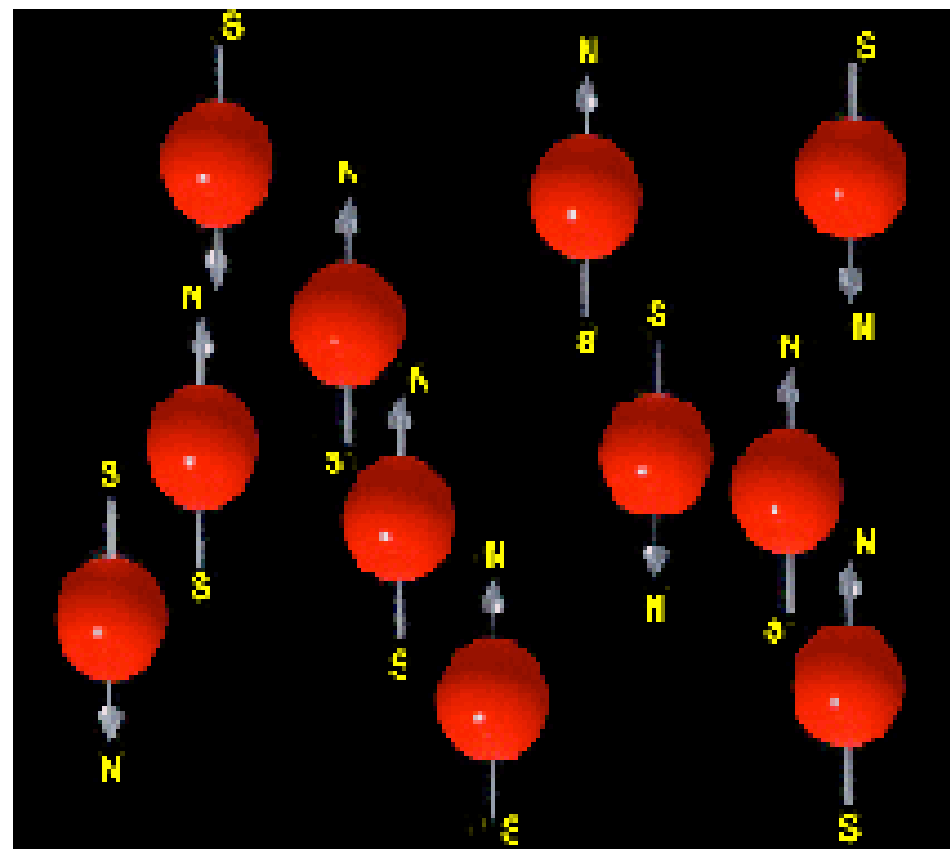
g = electron's g-factor (dimensionless number that describes the relationship between magnetic moment and gyromagnetic ratio), $g=2.00232$
 μ_B = Bohr's magneton (unit of the electron's magnetic moment) $\mu_B = \frac{e\hbar}{2m_e}$
 S = spin quantum number

In external magnetic field the elementary magnets orient



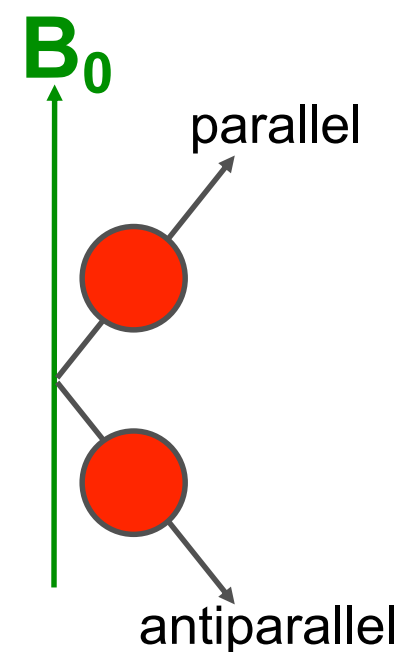
In absence of magnetic field:
random orientation of elementary magnets

Paramagnetism: magnetism emerging in external magnetic field (caused by the orientation of magnetic dipoles).

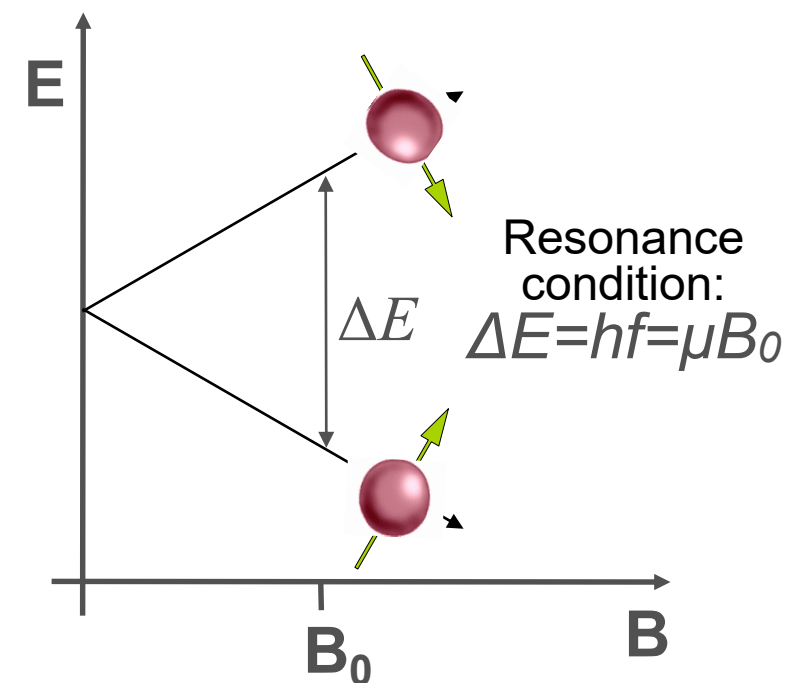


In magnetic field:

elementary
magnets orient

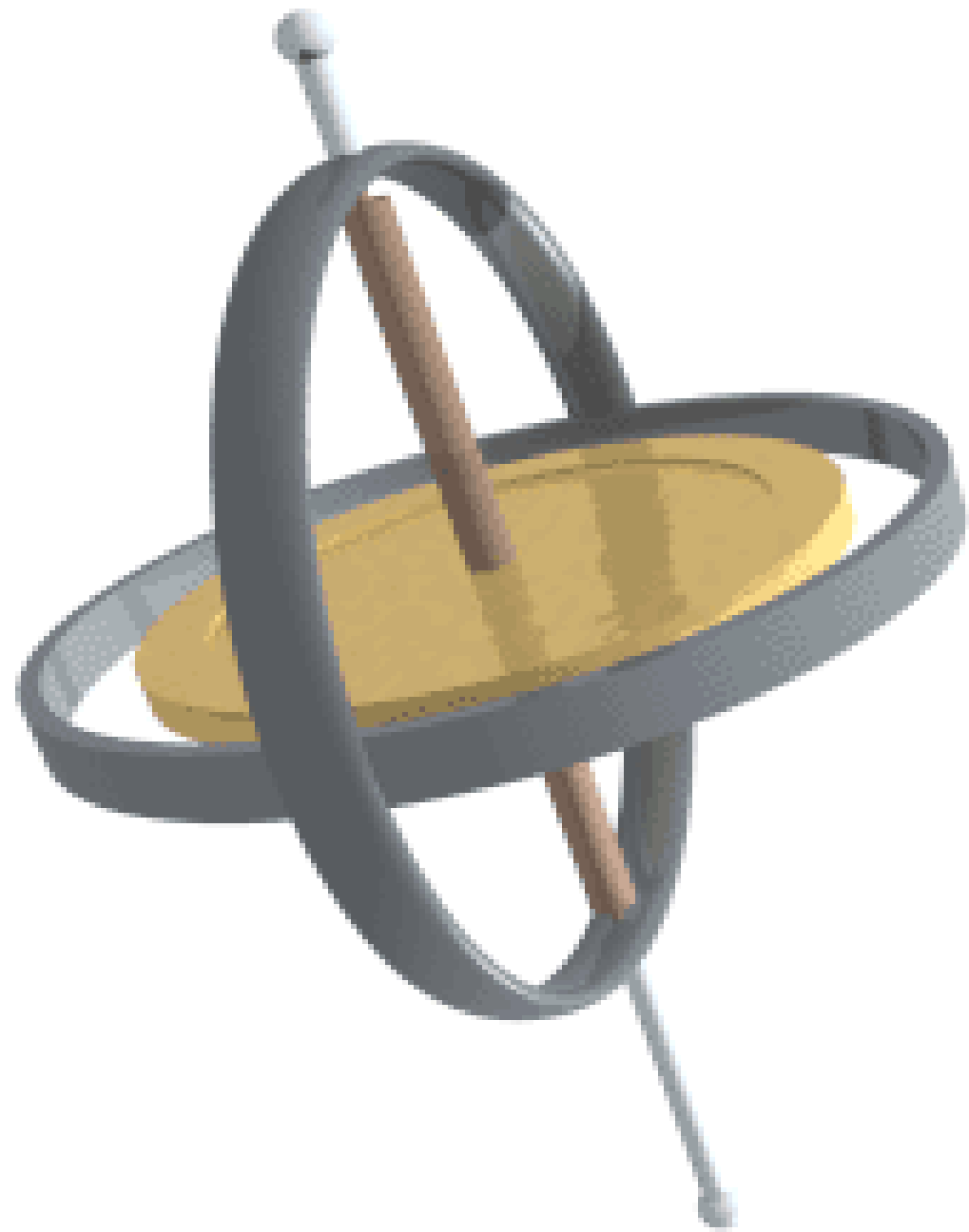


energy
levels split

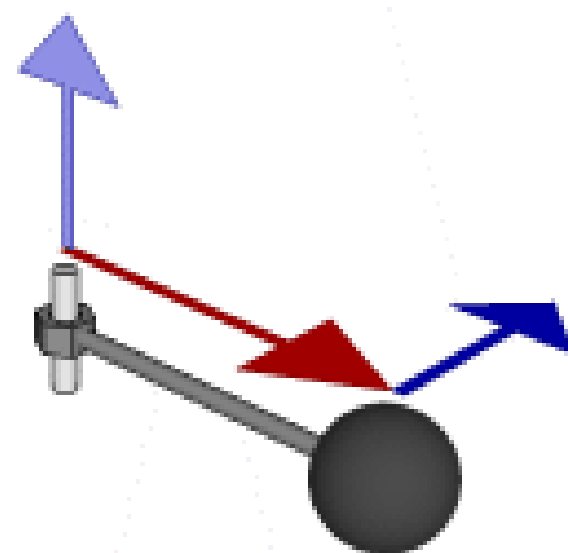


Edward Purcell,
1946

Classical mechanics: a top will precess in an external force field



$$\begin{aligned}\boldsymbol{\tau} &= \mathbf{r} \times \mathbf{F} \\ \mathbf{L} &= \mathbf{r} \times \mathbf{p}\end{aligned}$$

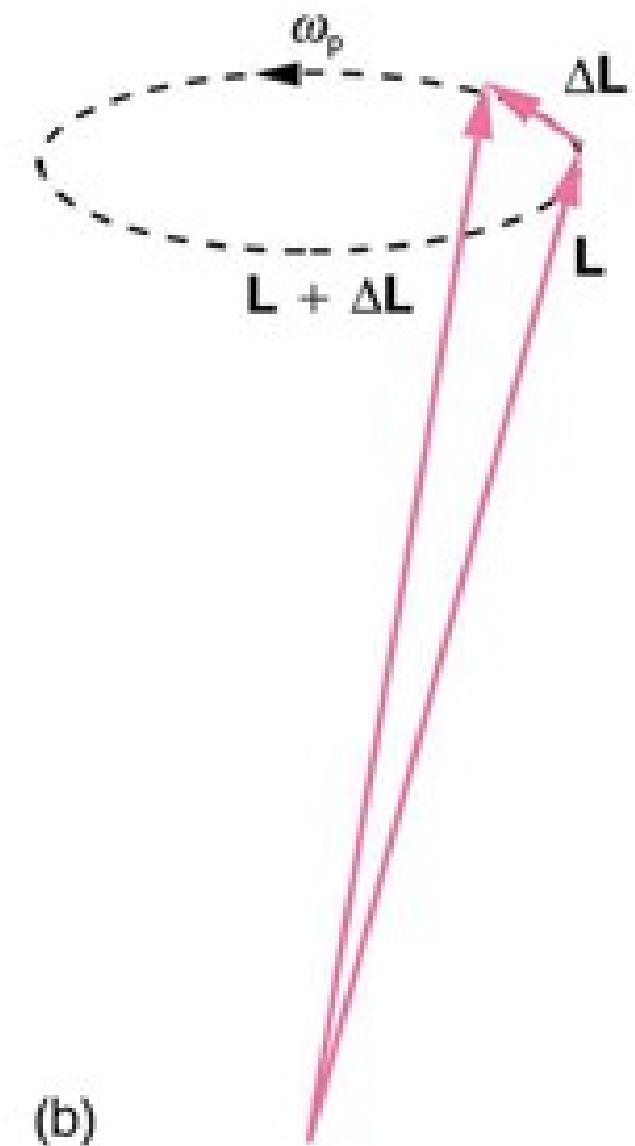
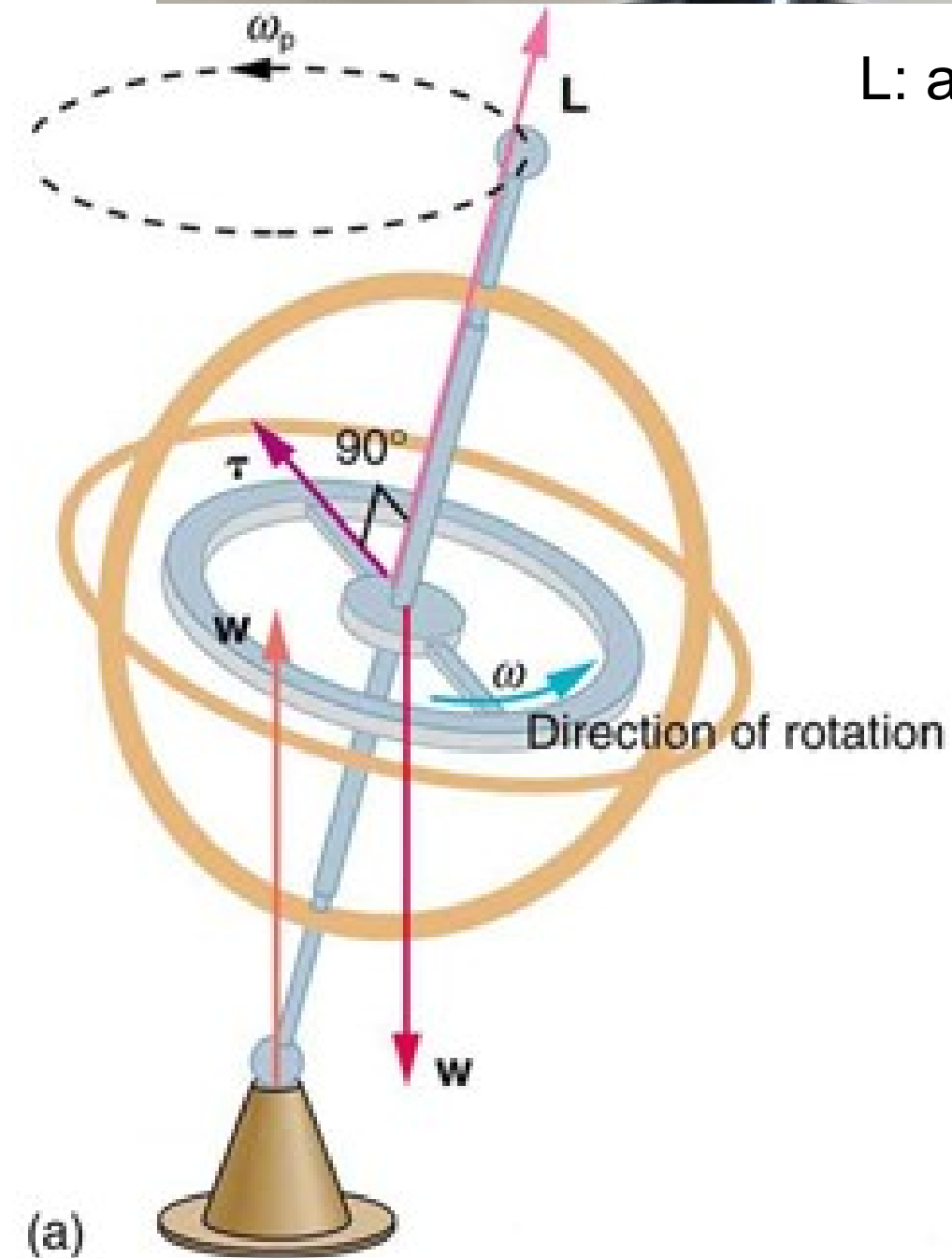


$$\frac{\Delta L}{\Delta t} = \tau$$

τ : torque



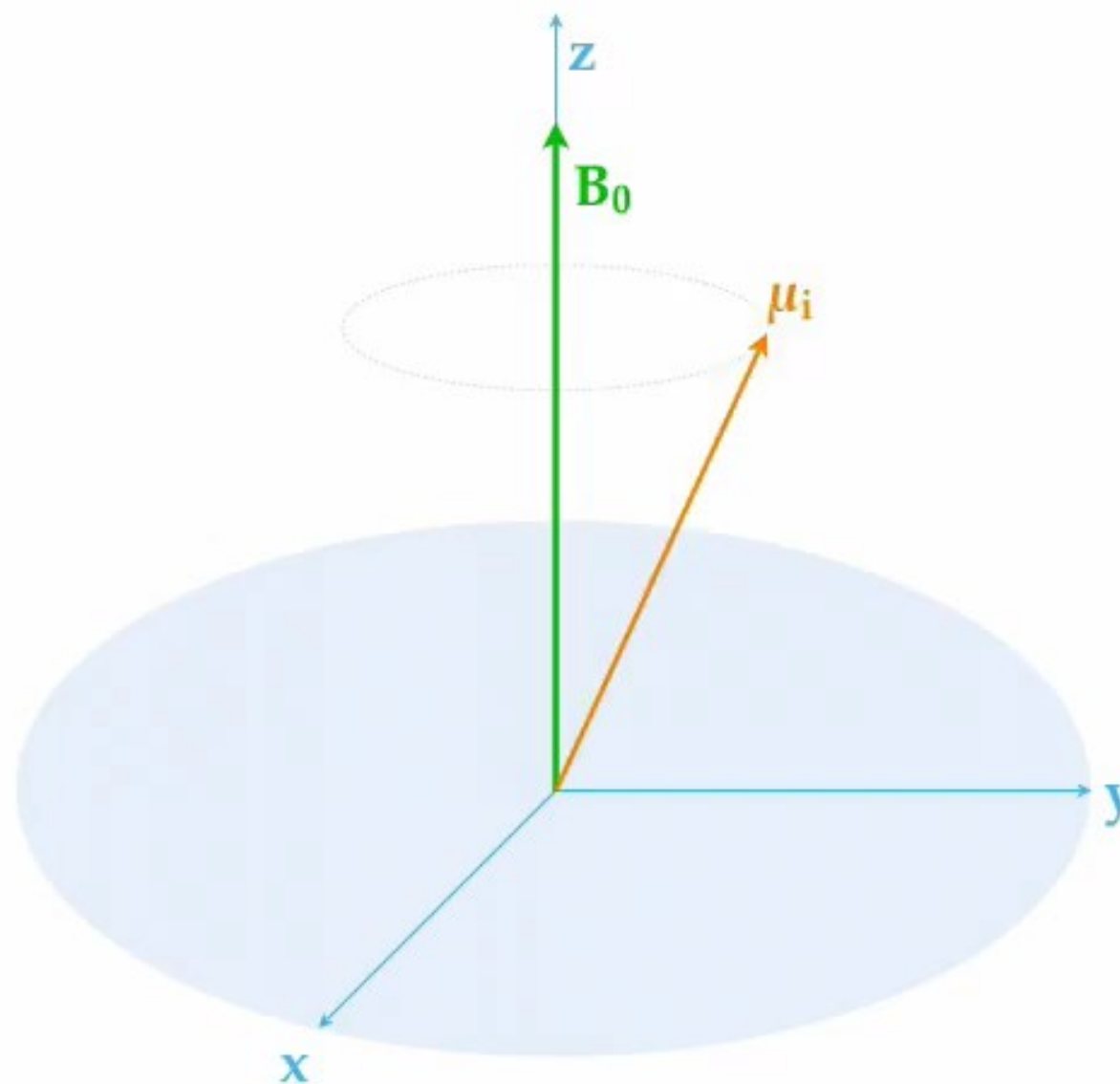
L : angular momentum



Oriented elementary magnets do precessional motion



Precession of a top



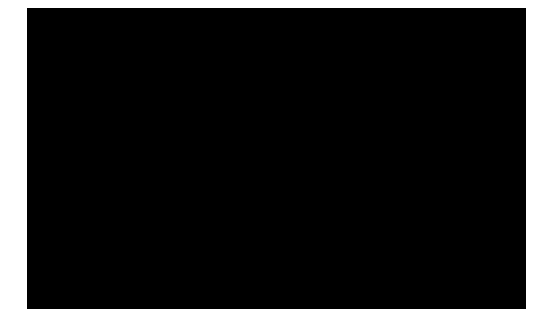
Precession of an elementary magnetic moment (μ_i) in magnetic field (B_0) within a reference xyz space

The mathematics is very similar to the top, hence the name "spin"

Precession or Larmor frequency:

$$\omega_0 = \gamma B_0$$
$$f_{Larmor} = \frac{\gamma}{2\pi} B_0$$

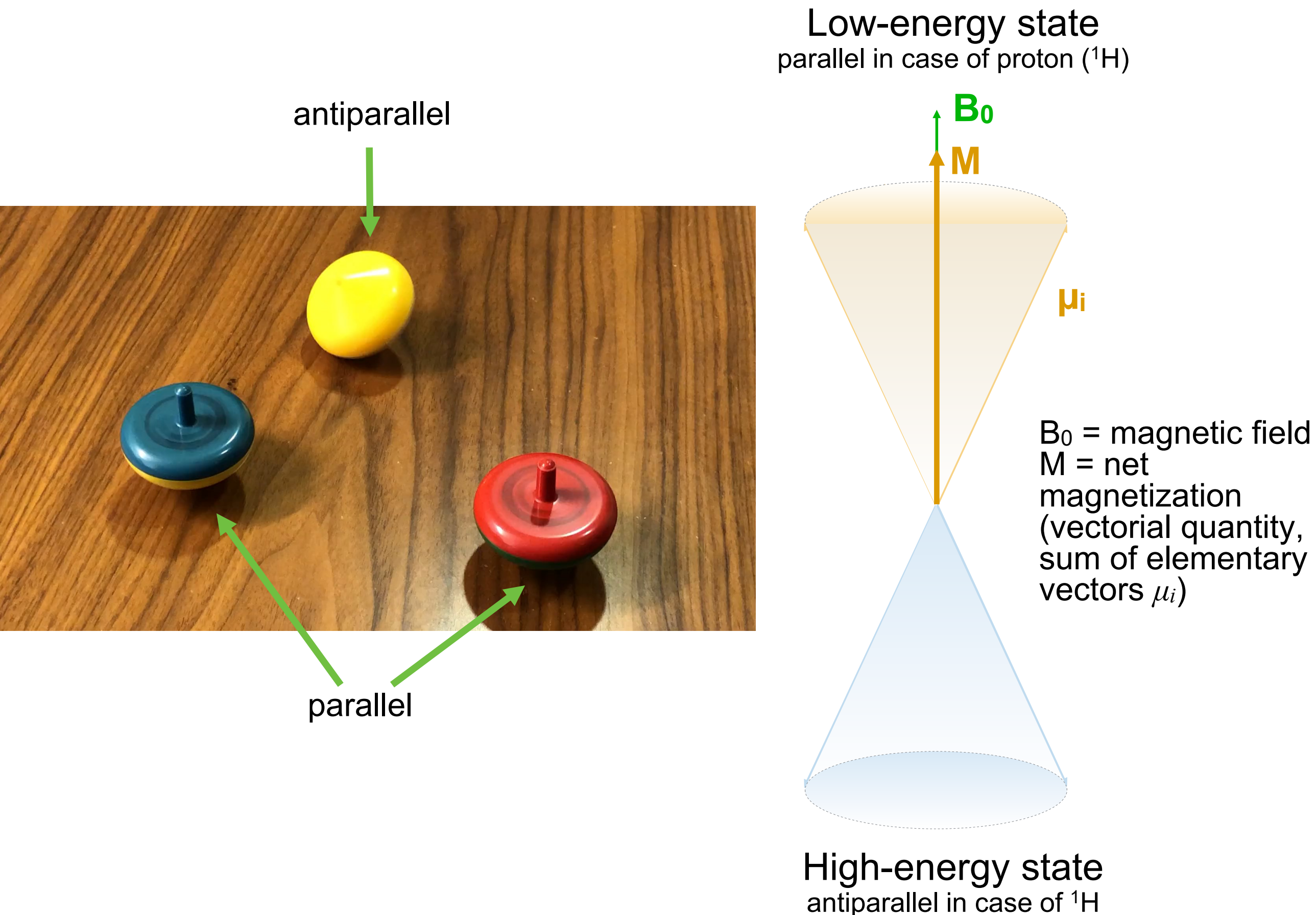
Resonance condition:



Felix Bloch, 1946

Net (macroscopic) magnetization

Due to spin access in different energy states



Ratio of low- and high-energy spin populations is determined by the Boltzmann distribution:

$$\frac{N_{\text{antiparallel}}}{N_{\text{parallel}}} = e^{-\frac{\Delta E}{k_B T}}$$

N.B.: magnetic field in MRI is 20-50-thousand times as strong as the earth's magnetic field.

The un-excited ratio

$$\Delta E = g \cdot \mu_N \cdot B_0 = g_P \cdot \mu_N \cdot H$$

for a single proton $g_P = 5.59$; $\mu_N = 5.05 \cdot 10^{-27} \frac{J}{T}$

$$\Delta E = 5.59 \cdot 5.05 \cdot 10^{-27} \frac{J}{T} \cdot 3T = 8.469 \cdot 10^{-26} J = 5.29 \cdot 10^{-7} eV$$

The excitation energy is very low even at very high magnetic field strength

$$\frac{N_{antiparallel}}{N_{parallel}} = e^{-\frac{\Delta E}{k_B T}} = 0.9999794002$$

i.e. out of 5M protons only 102 pieces excess is in the ground state at 25 °C
(the rest cancel each others magnetic field)

Excitation with a photon

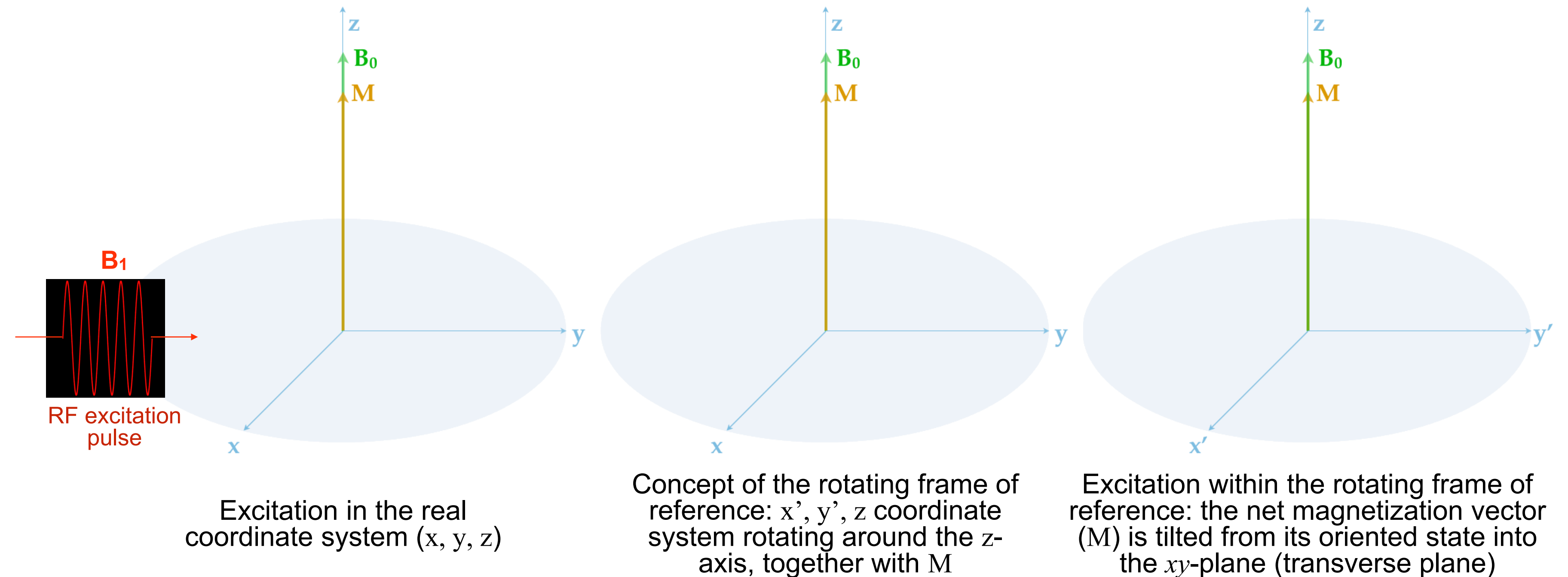
$$f = \frac{\Delta E}{h} = \frac{8.469 \cdot 10^{-26} J}{6.63 \cdot 10^{-34} Js} = 1.27 \cdot 10^8 \frac{1}{s} = 127 MHz$$

Radio wave excitation and emission

Excitation

Resonance condition, Larmor frequency

Employed electromagnetic radiation: radiowaves (NMR, MRI), microwaves (ESR)

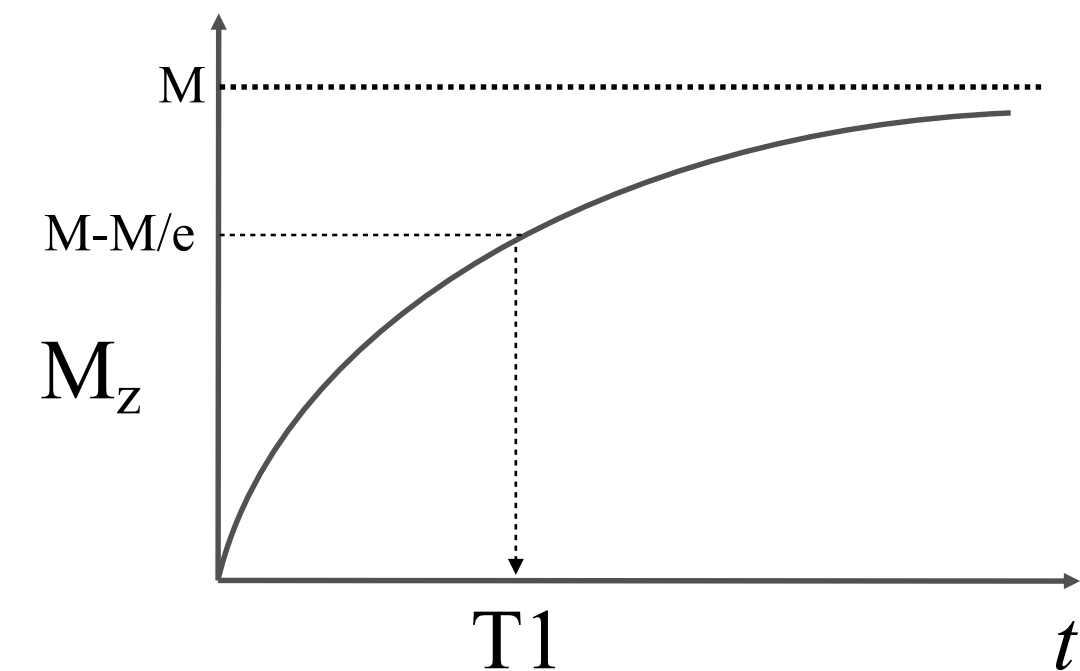
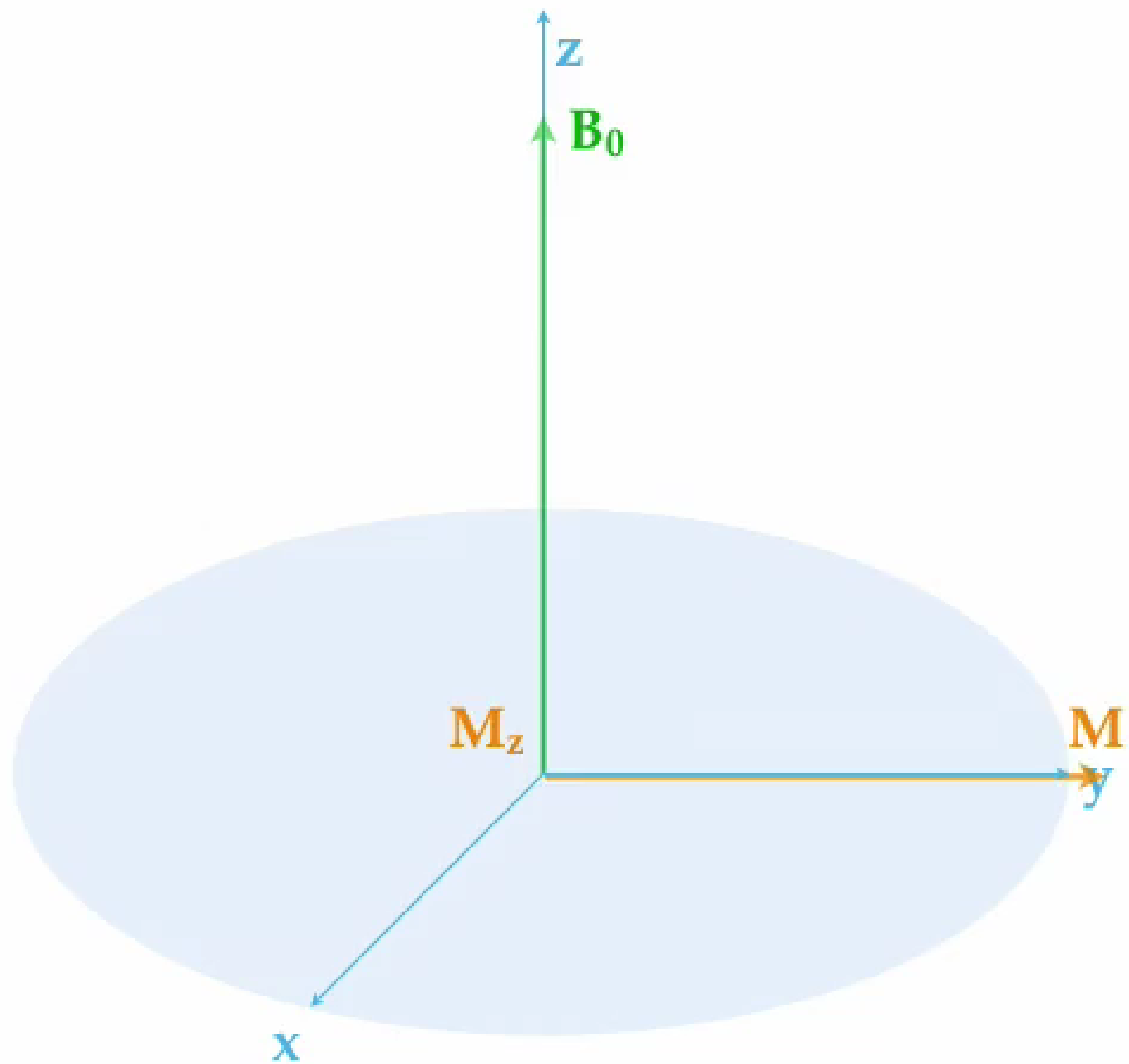


B_0 = magnetic field
 M = net magnetization
 B_1 = irradiated radio frequency wave

Spin-lattice relaxation

T1 or longitudinal relaxation

T1 relaxation process: return (relaxation) of the z -axis vectorial component of M (M_z) towards the direction of the external magnetic field



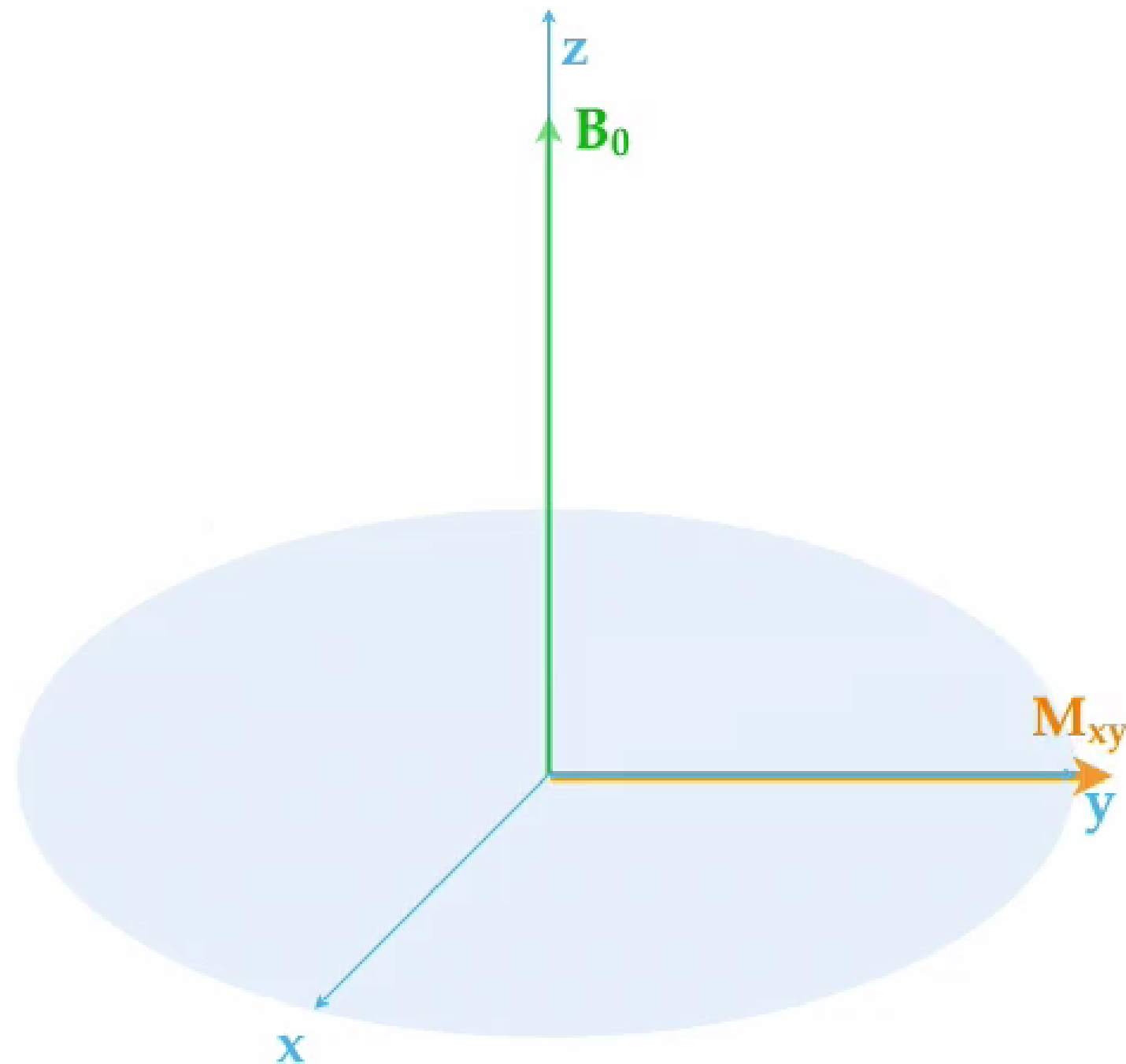
T1 relaxation time:
depends on interaction
between elementary magnet (proton)
and its environment (lattice)

M_z : z -axis vectorial component of M

Spin-spin relaxation

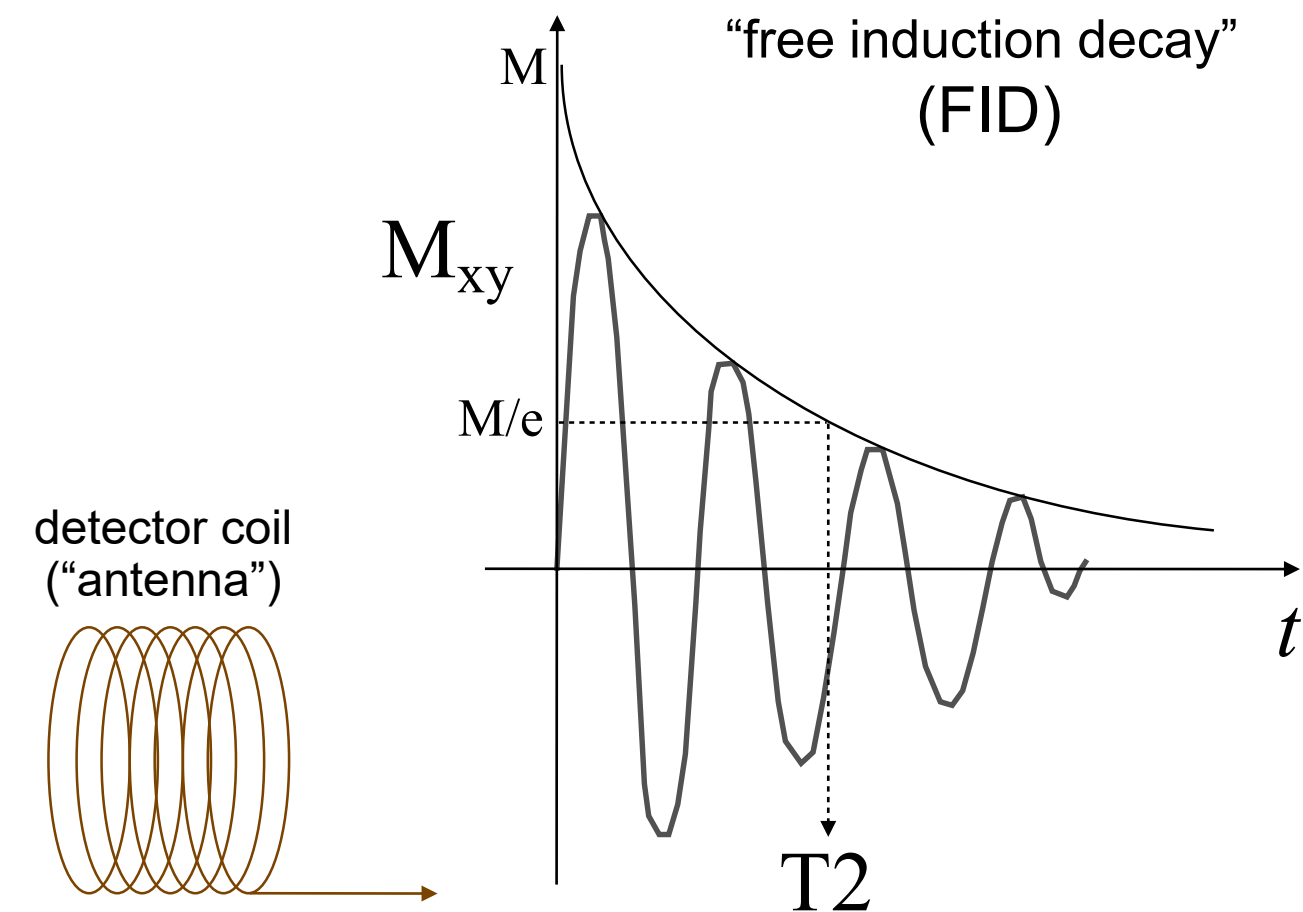
T2 or transverse relaxation

T2 relaxation process: diffusion (spreading) of the elementary magnetic moments (μ_i) resulting in the decay of the transverse(xy)-plane vectorial component of M (M_{xy})



N.B.: because the magnetic field has no xy component, the elementary spins lose their orientation and diffuse apart

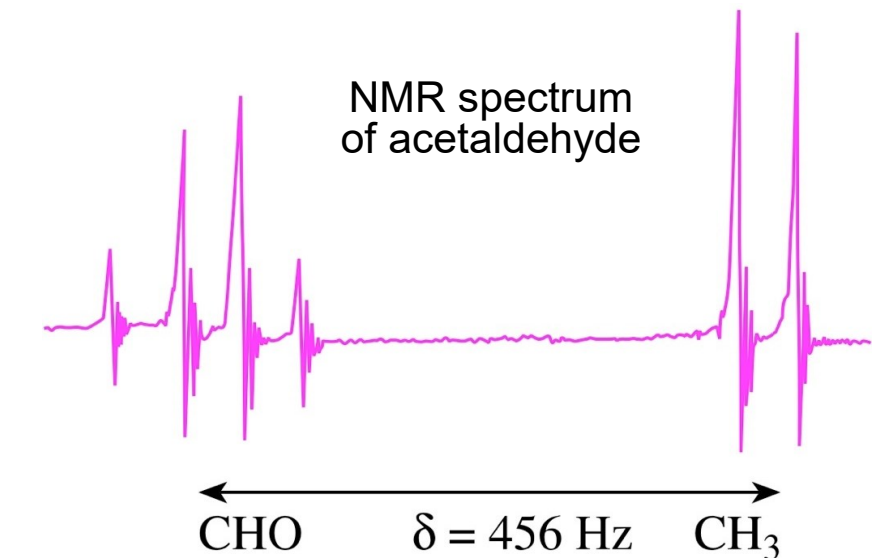
M_{xy} : xy -plane vectorial component of M



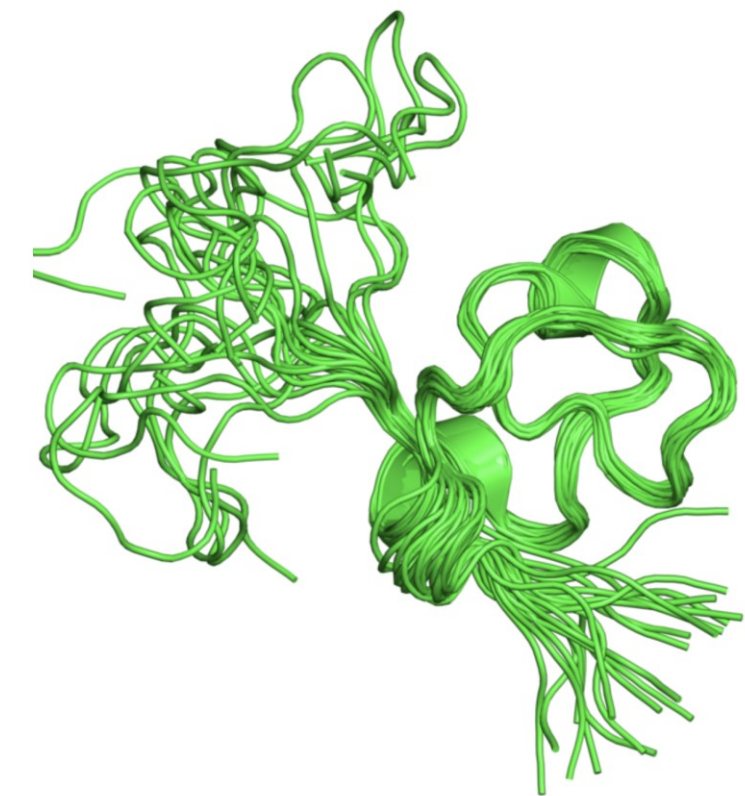
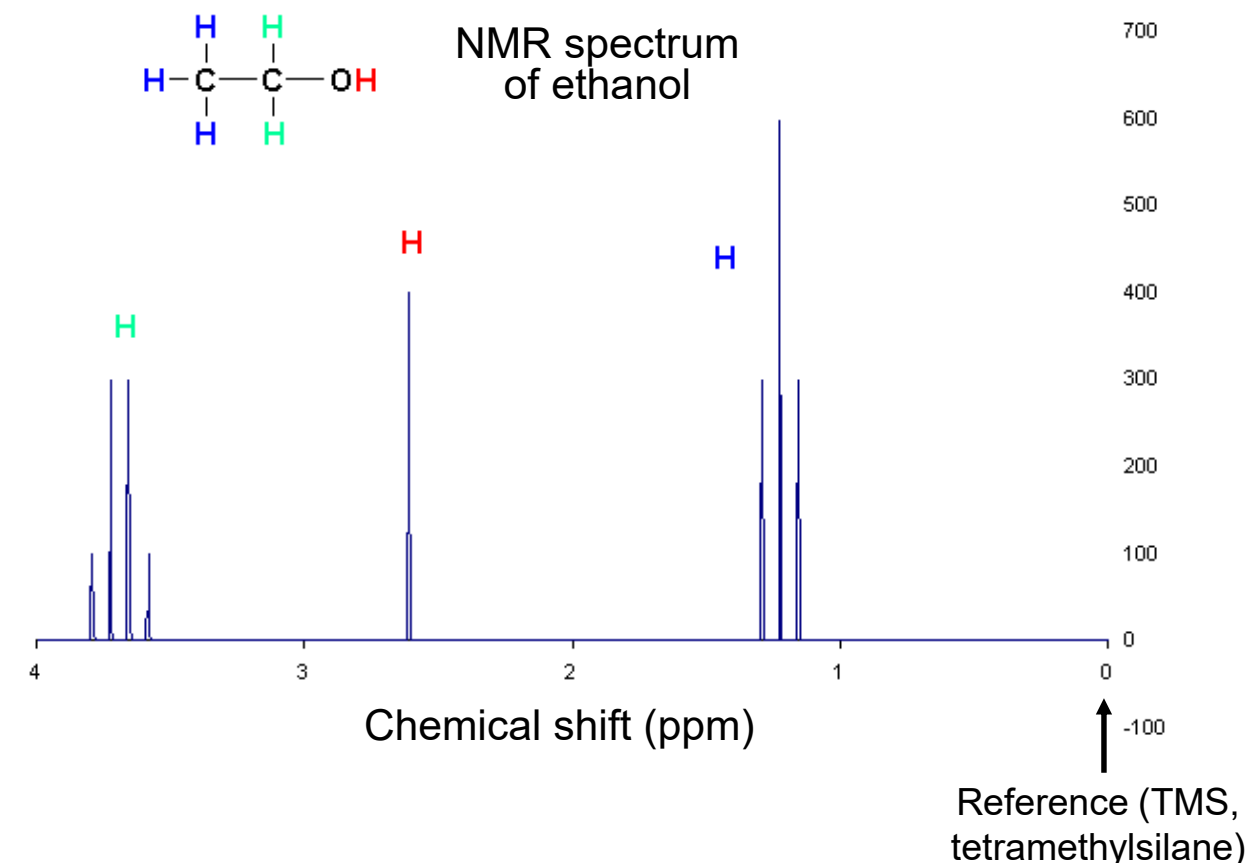
T2 relaxation time:
depends on interaction between elementary magnets (spins, protons);
process occurs in the transverse (xy) plane

NMR spectroscopy

- NMR spectroscopy or Magnetic Resonance Spectroscopy (MRS)
- Spectroscopic method for measuring the local magnetic field around atomic nuclei. We measure the resonance frequencies of the nuclei positioned in the magnetic field.
- NMR spectrometer: superconducting magnet (cooled with liquid He), large magnetic field (spectral resolution is proportional to field strength).
- NMR spectrum: intensity of absorbed electromagnetic radiation as a function of frequency.
- The area under the “NMR-line” is proportional to the number of absorbing atomic nuclei.
- The electron cloud distorts the local magnetic field, therefore the frequency condition is shifted: “chemical shift”. Chemical structure determination is possible.
- Protein NMR: possibility of measuring dynamics and the detection of disordered protein elements



900 MHz NMR, 21.1 T magnet



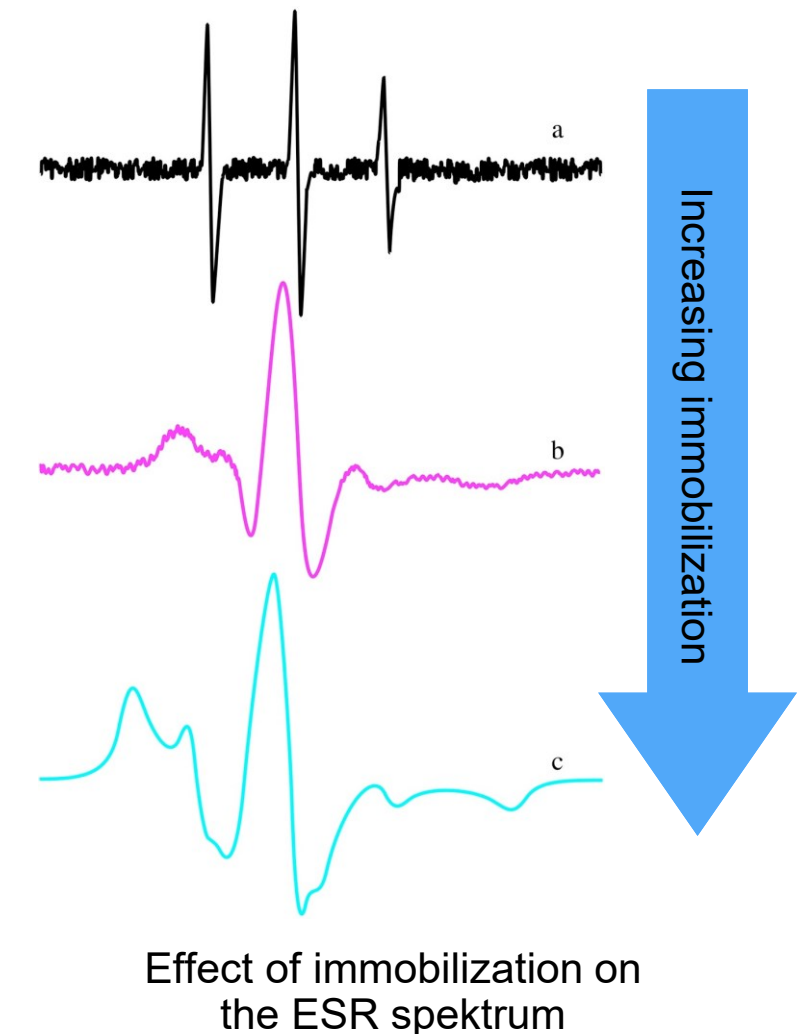
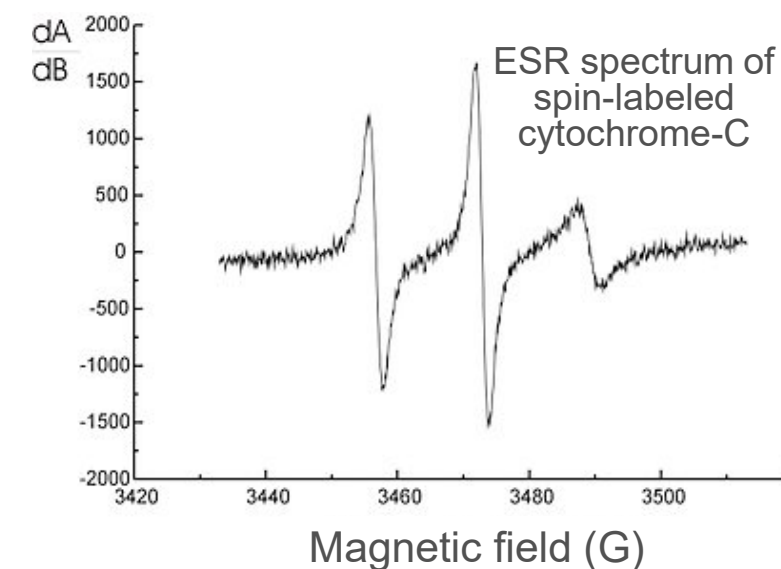
Somatomedin B domain
(superimposed structures)

ESR spectroscopy

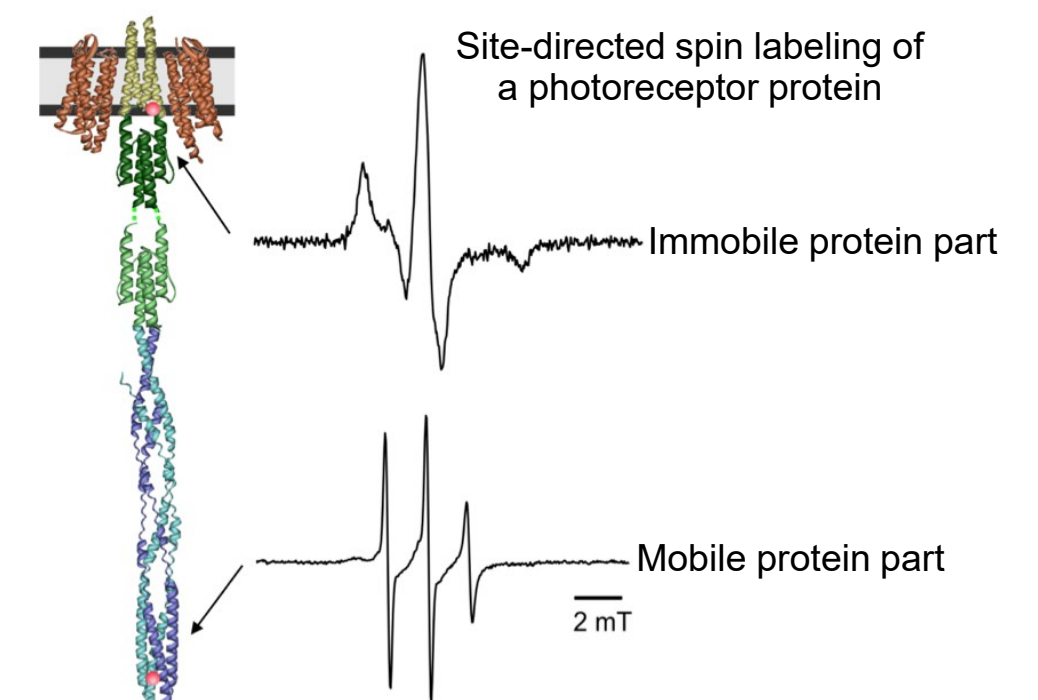
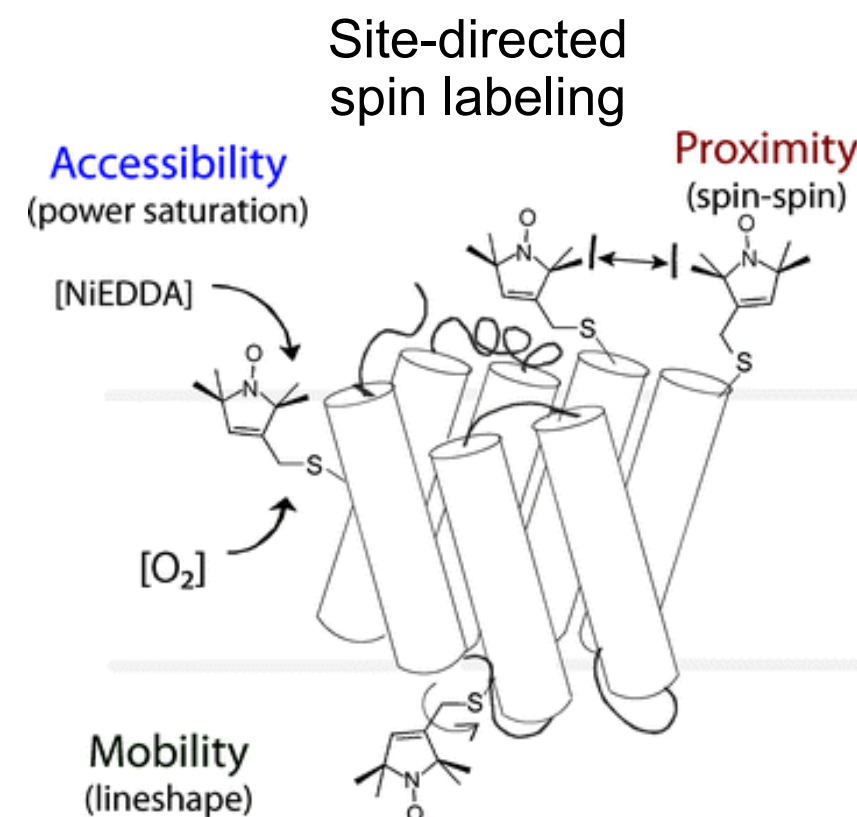
- Electron spin resonance (ESR) or electron paramagnetic resonance (EPR) spectroscopy.
- Spectroscopic method for investigating materials containing unpaired electron.
- EPR spectrum: intensity of electromagnetic radiation as a function of magnetic field.
- Magnetic field is lower, but radiation frequencies are greater (microwave) than in NMR: GHz at <1T field.
- Spin-labeling: attachment of a chemical containing a stable unpaired electron. Site-directed spin labeling: spin labeling of reactive (mostly -SH) residues introduced into the targeted protein by molecular biological tools (point mutation).
- Dynamics of rotational motion can be measured up the 10^{-4} - 10^{-2} s time range.



Jevgenyij Zavoisky, 1944



ESR spectroscopy workstation

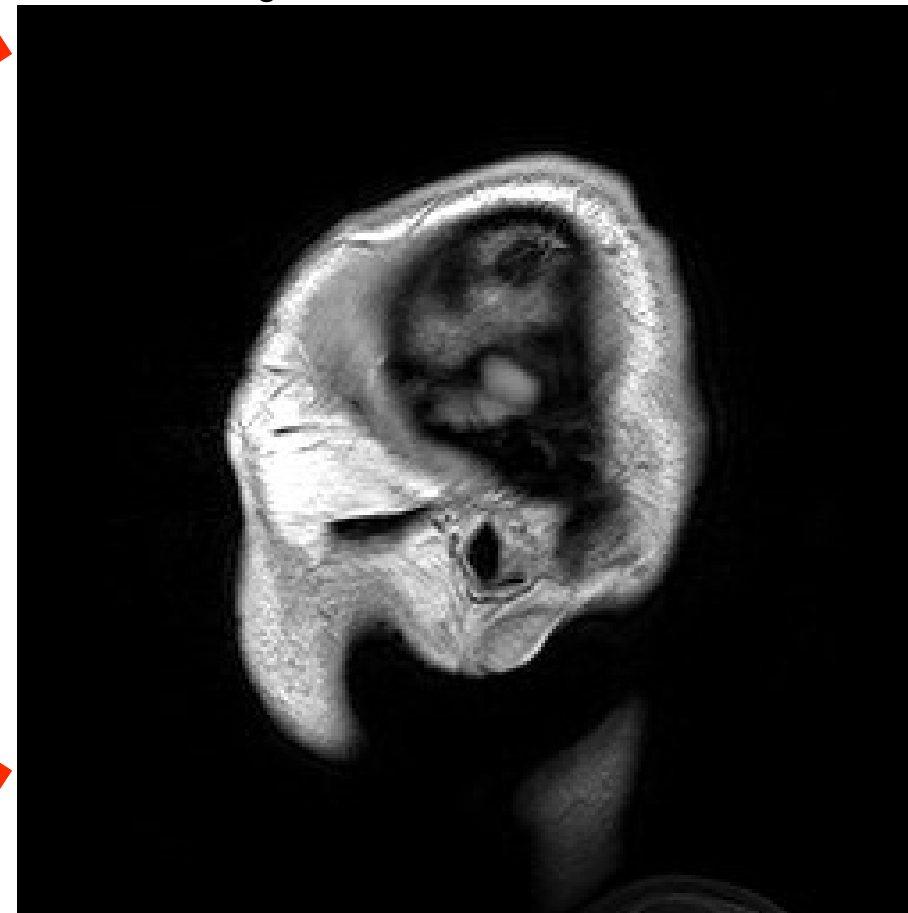


MRI: revolutionary device

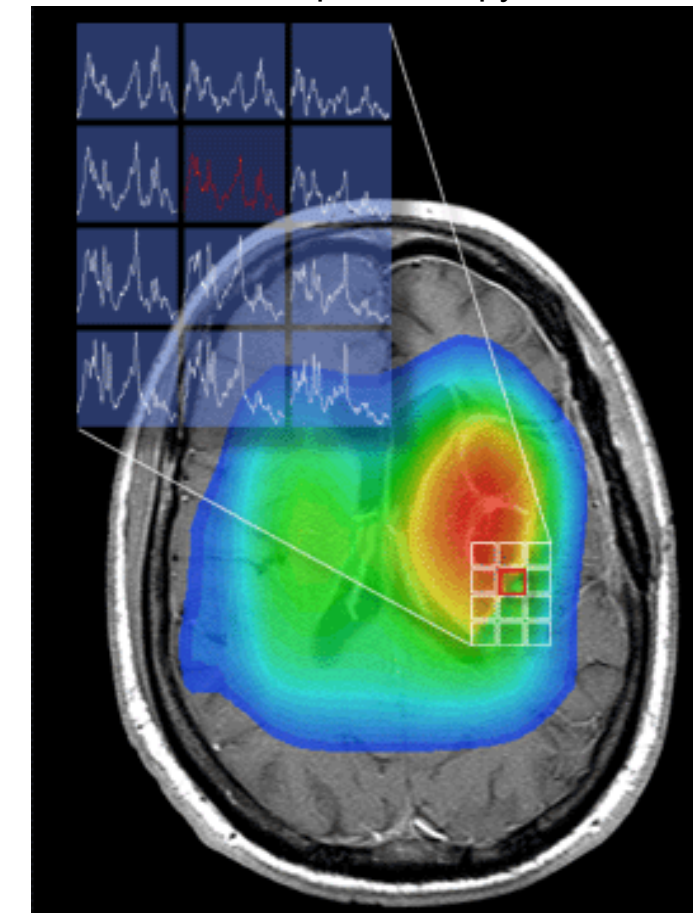


Non-invasive

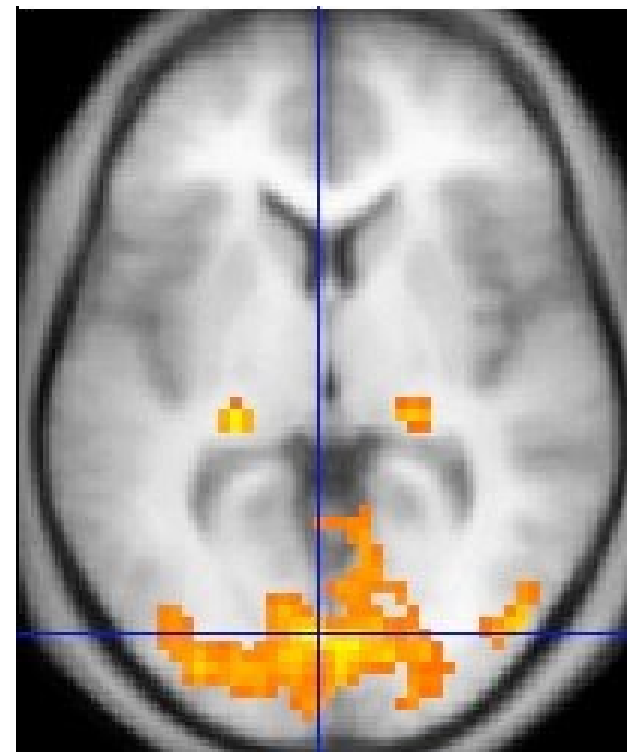
High-resolution, anatomical MRI



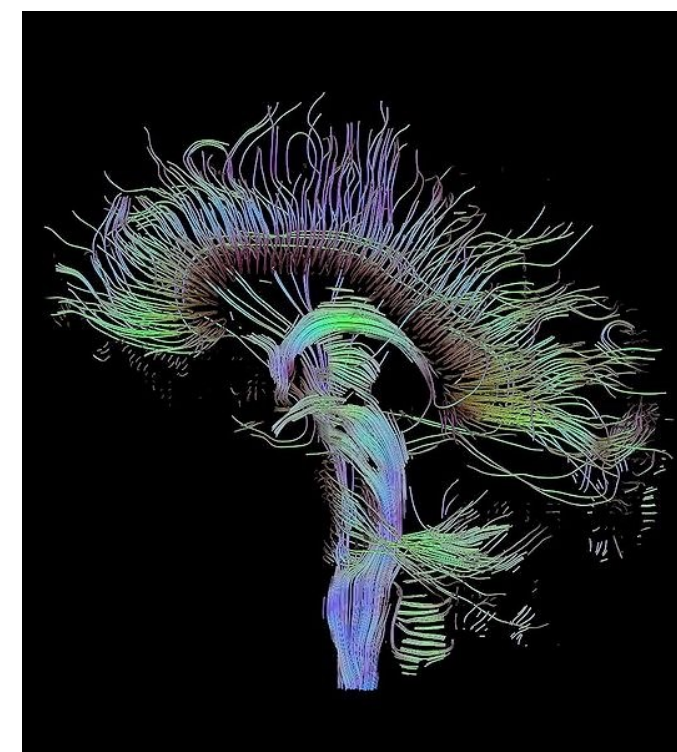
MRI spectroscopy



MRI angiography



Functional MRI (fMRI)

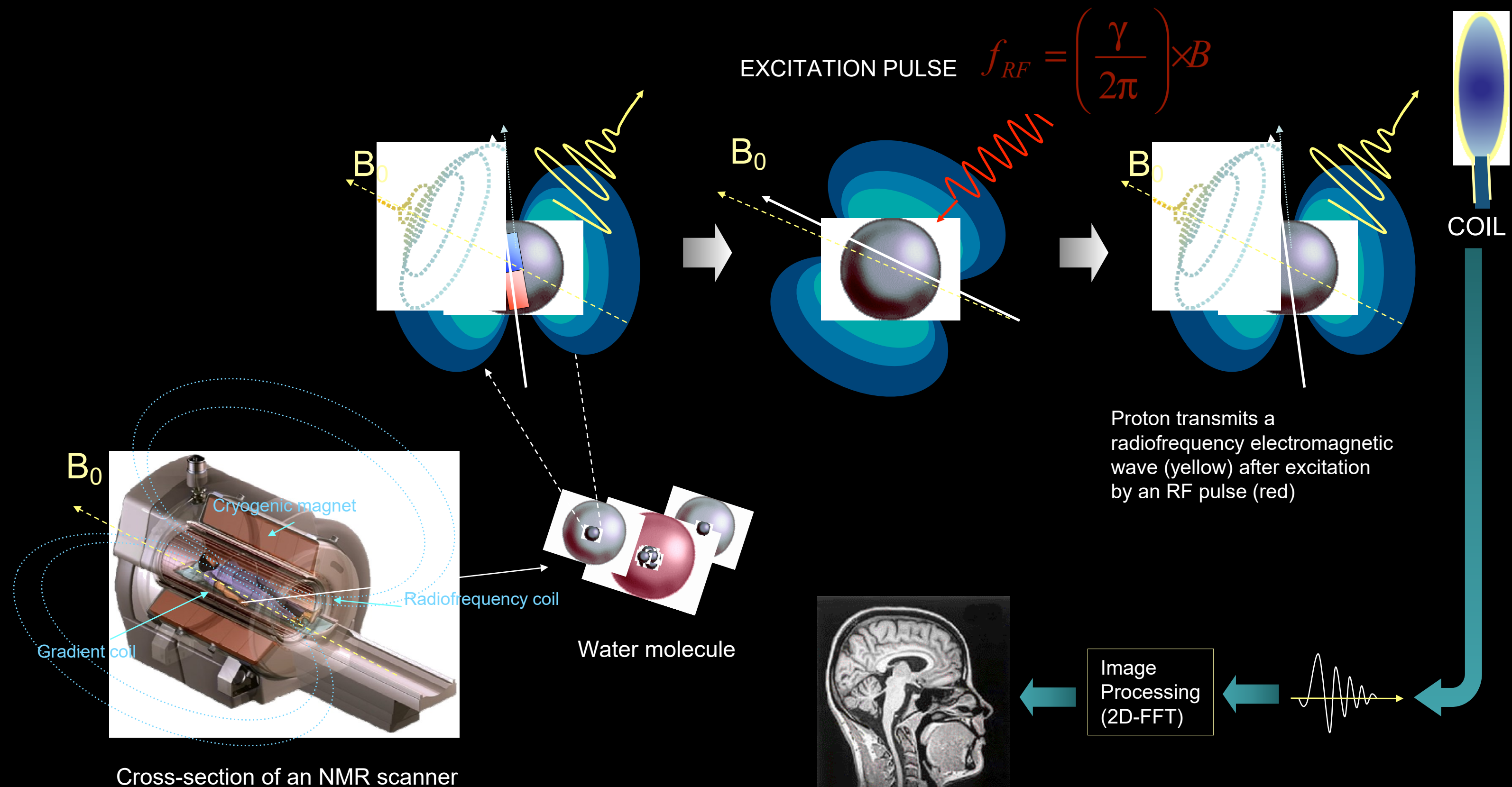


Diffusion MRI (tractography)



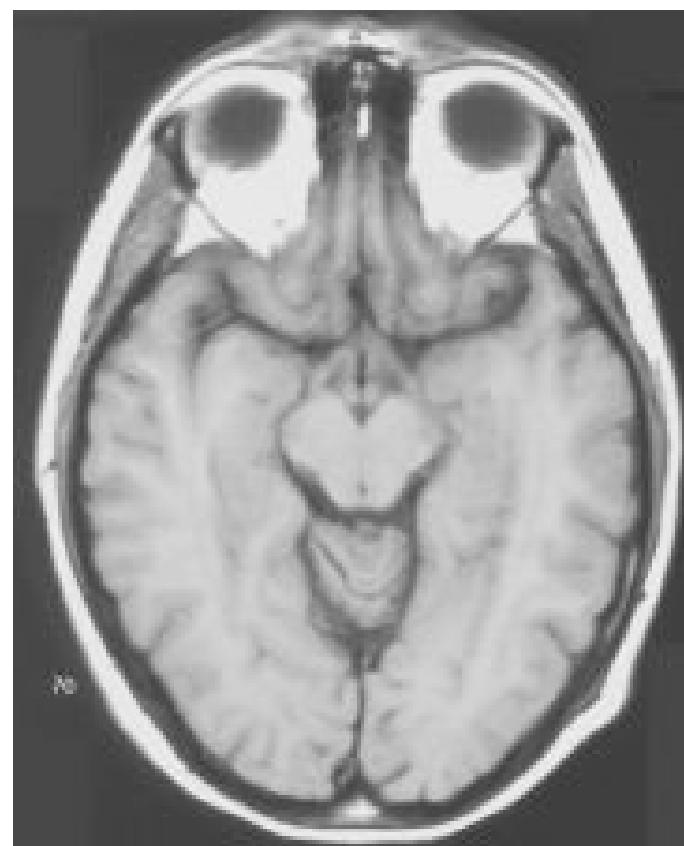
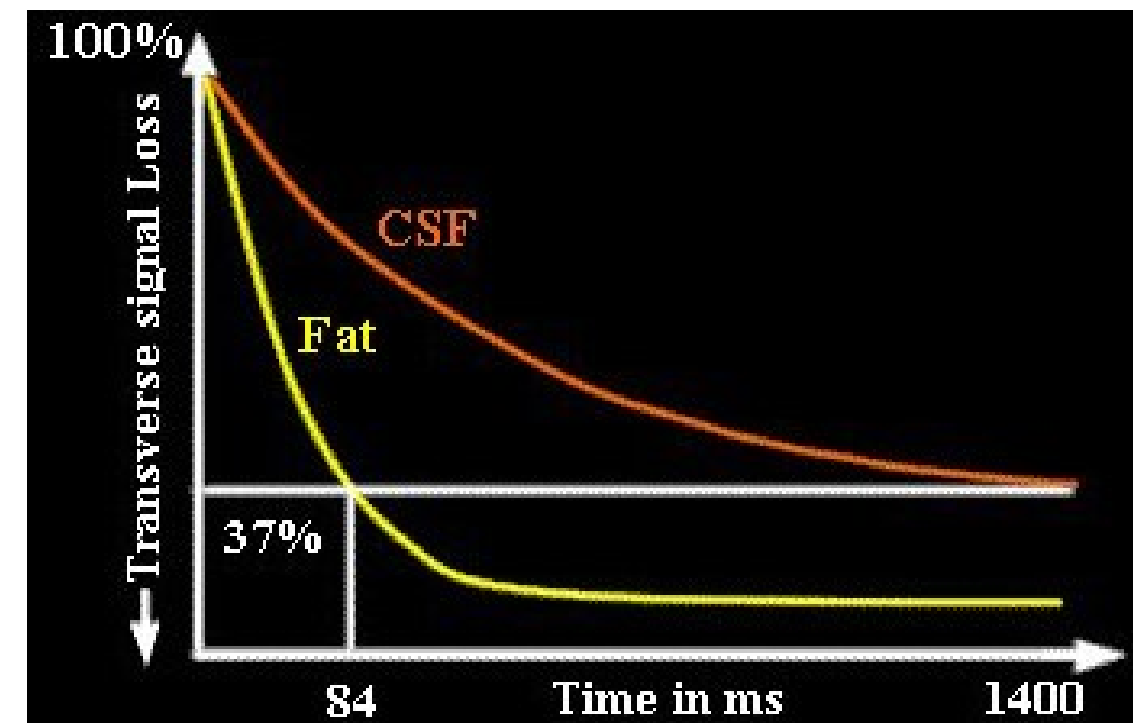
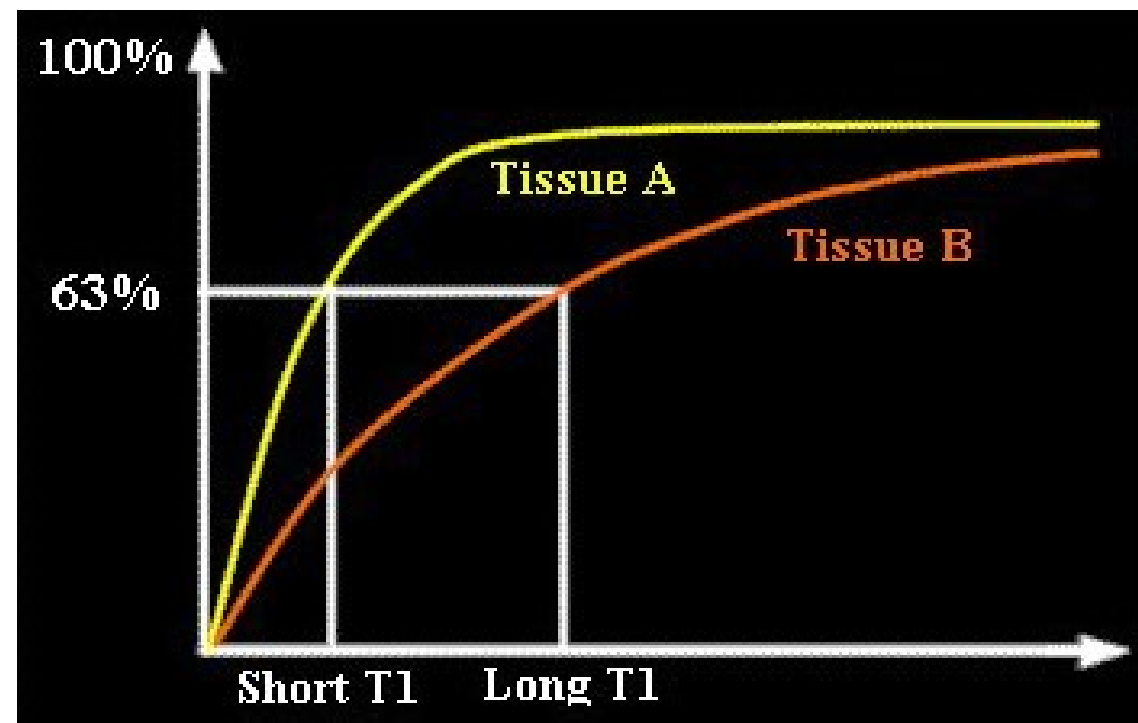
Musculoskeletal MRI

MRI: the human body is macroscopically magnetized

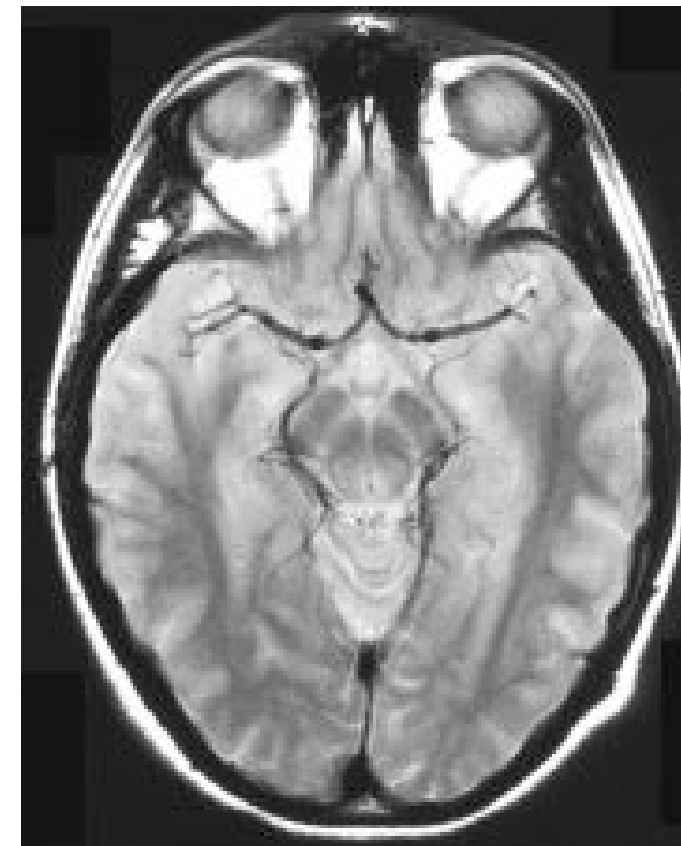


MRI 1: contrast

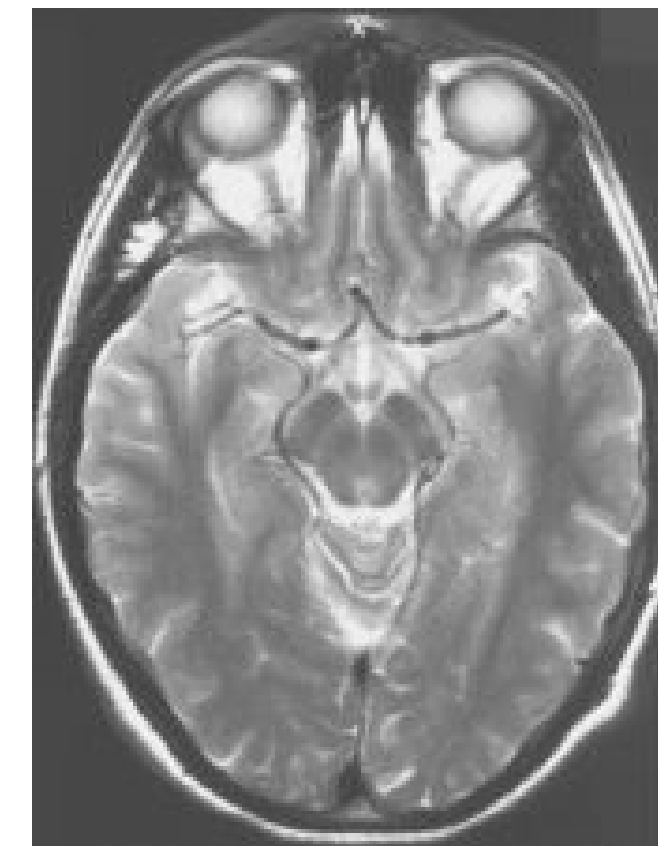
Color contrast based on spin density (proton density, PD)
and relaxation times (T1, T2)



T1-weighting



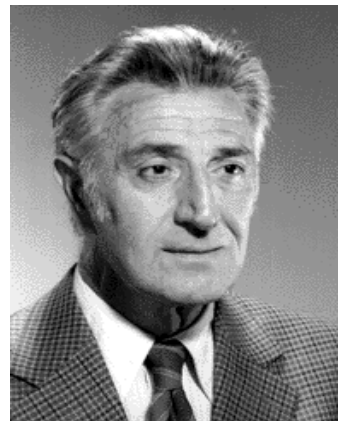
proton density-weighting



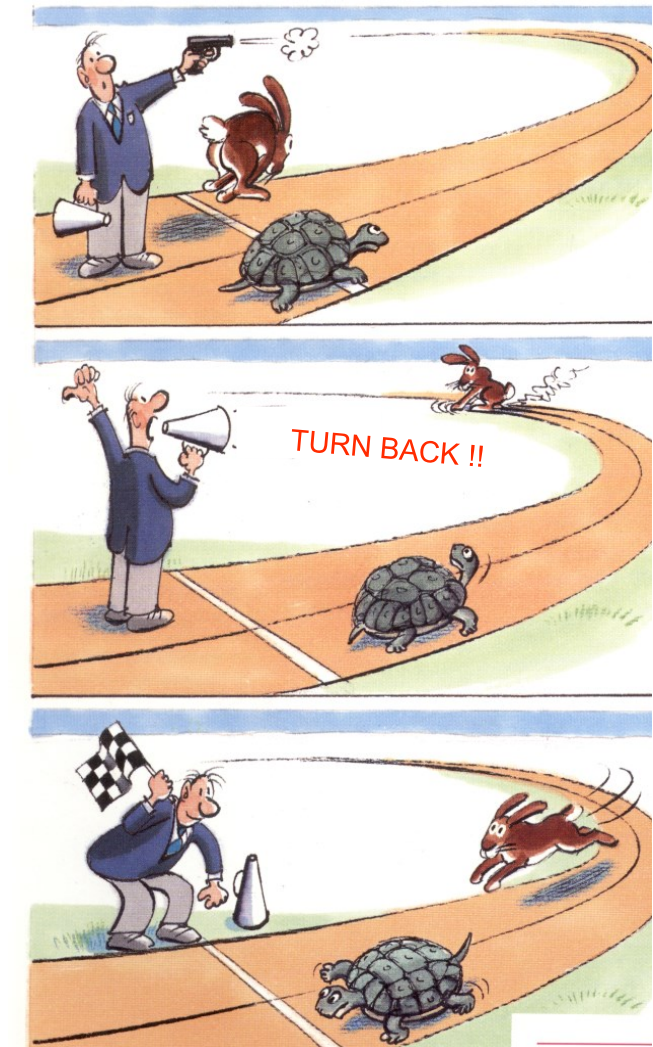
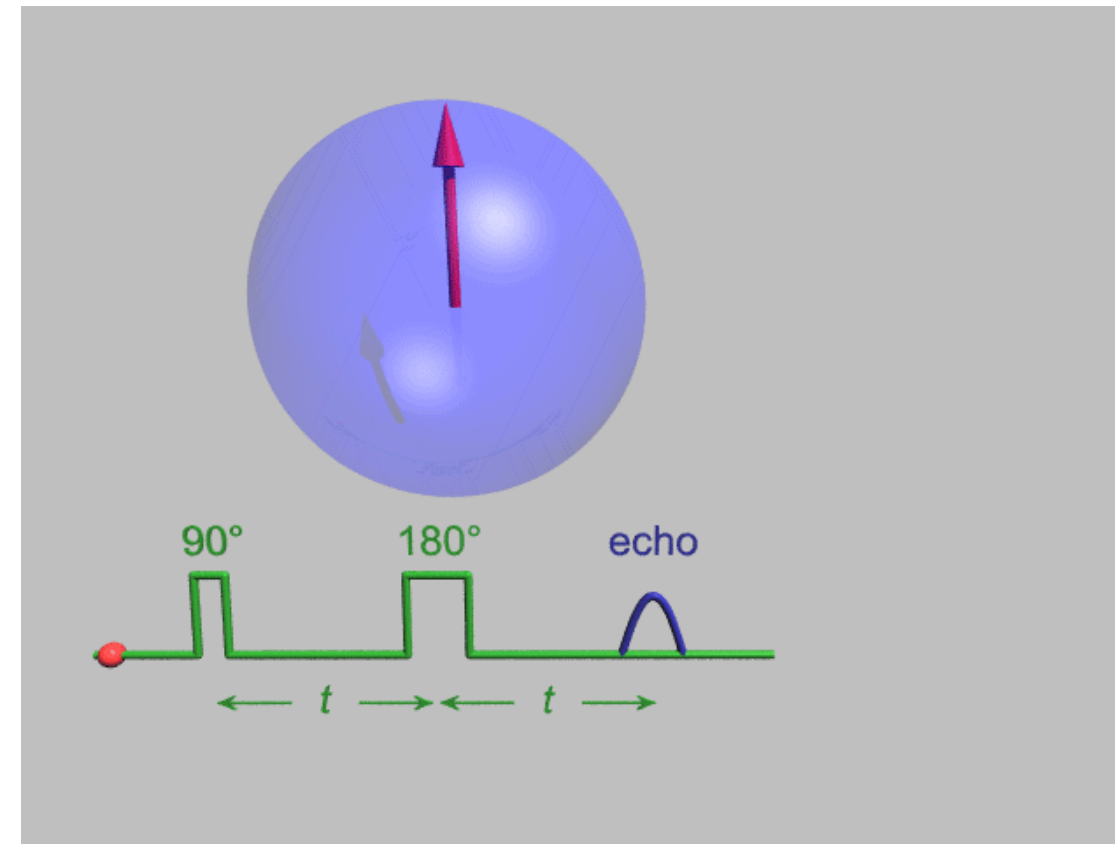
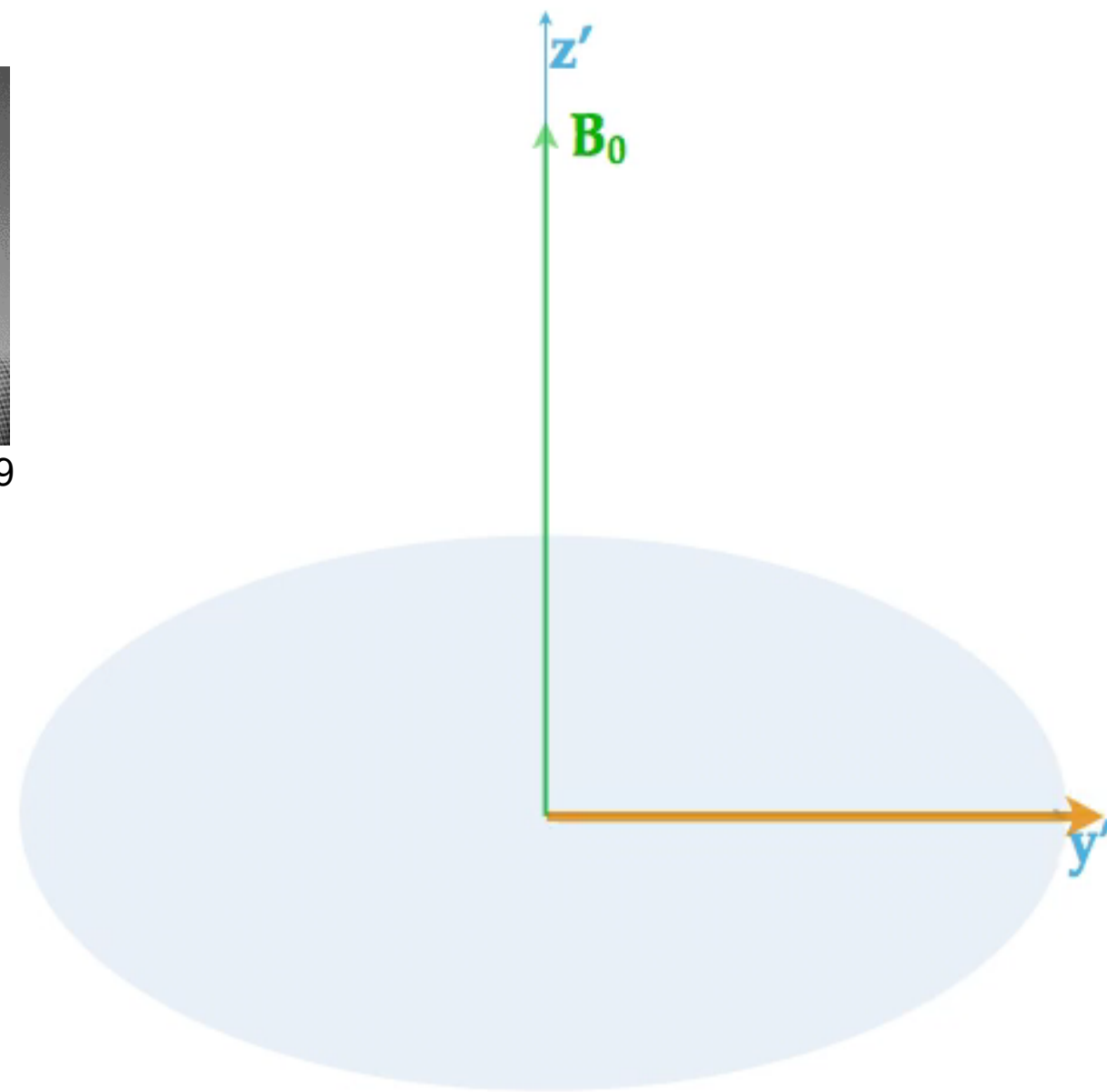
T2-weighting

Measuring relaxation time: the spin-echo experiment

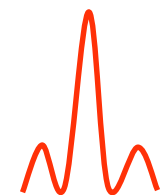
Repeating excitation, refocusing and “echo” pulses: spin-echo sequence



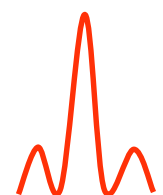
Erwin Hahn, 1949



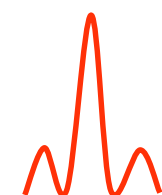
Excitation
pulse (90°)



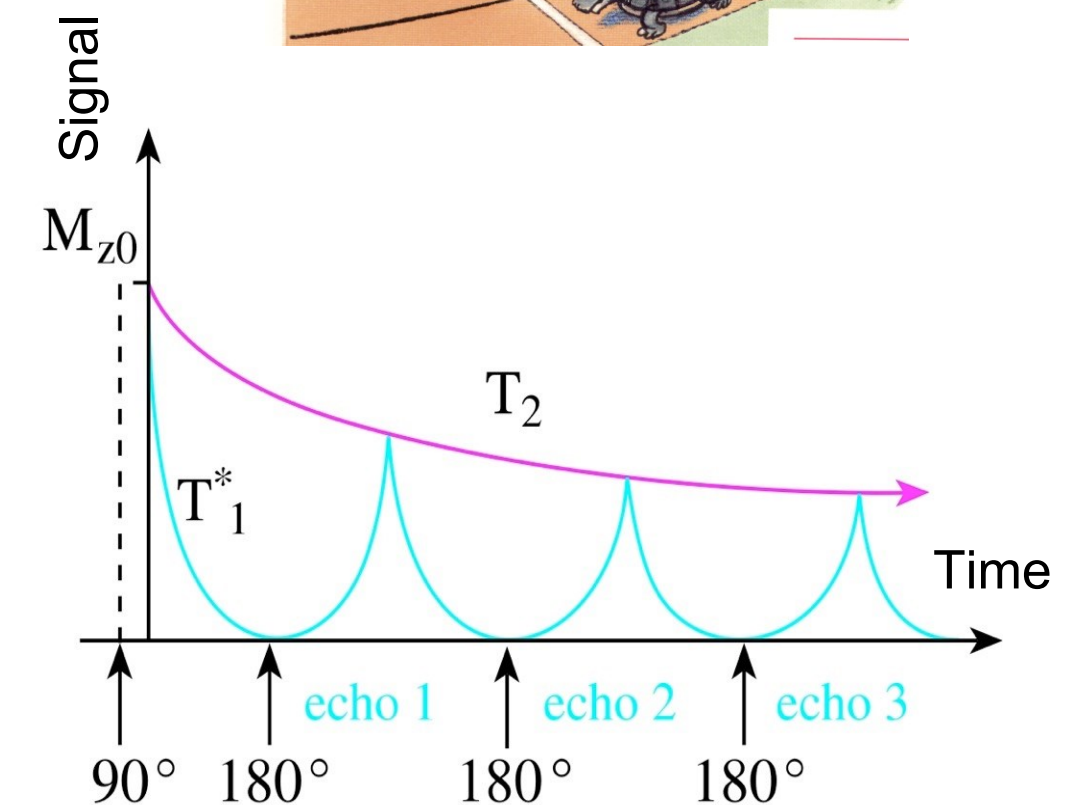
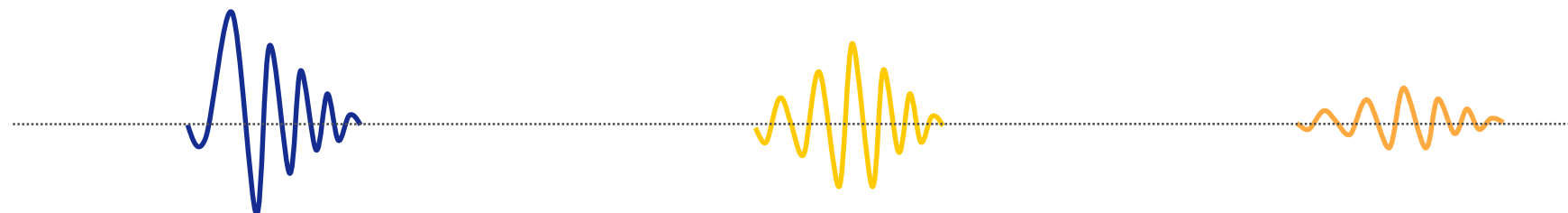
Refocusing
pulse (180°)



Refocusing
pulse (180°)



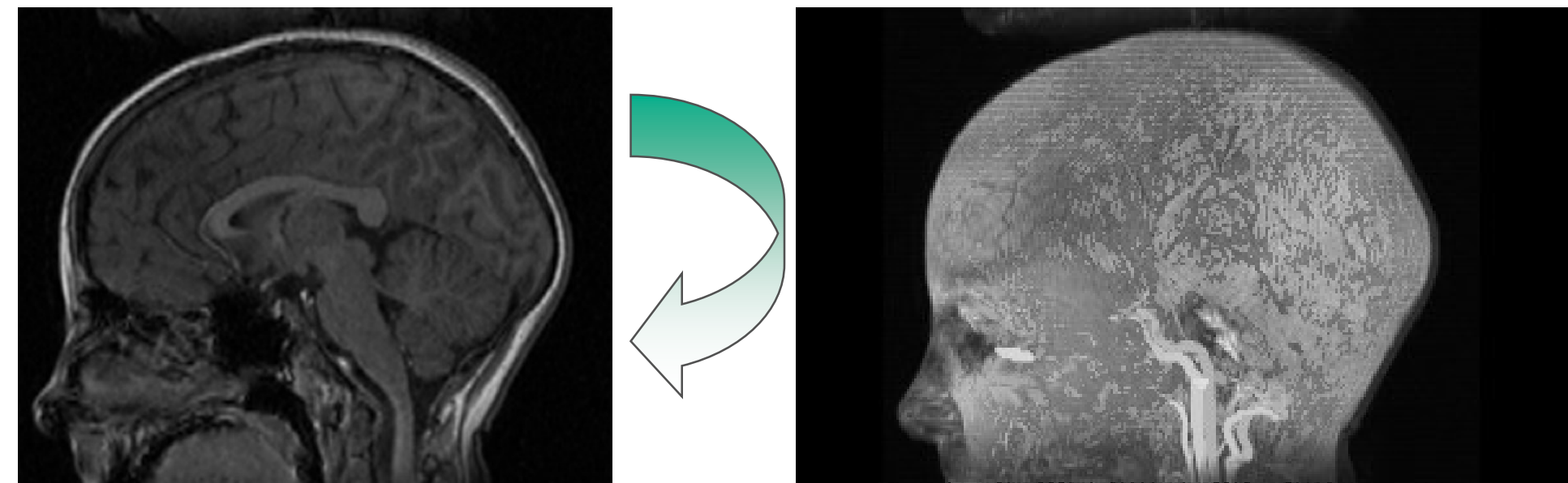
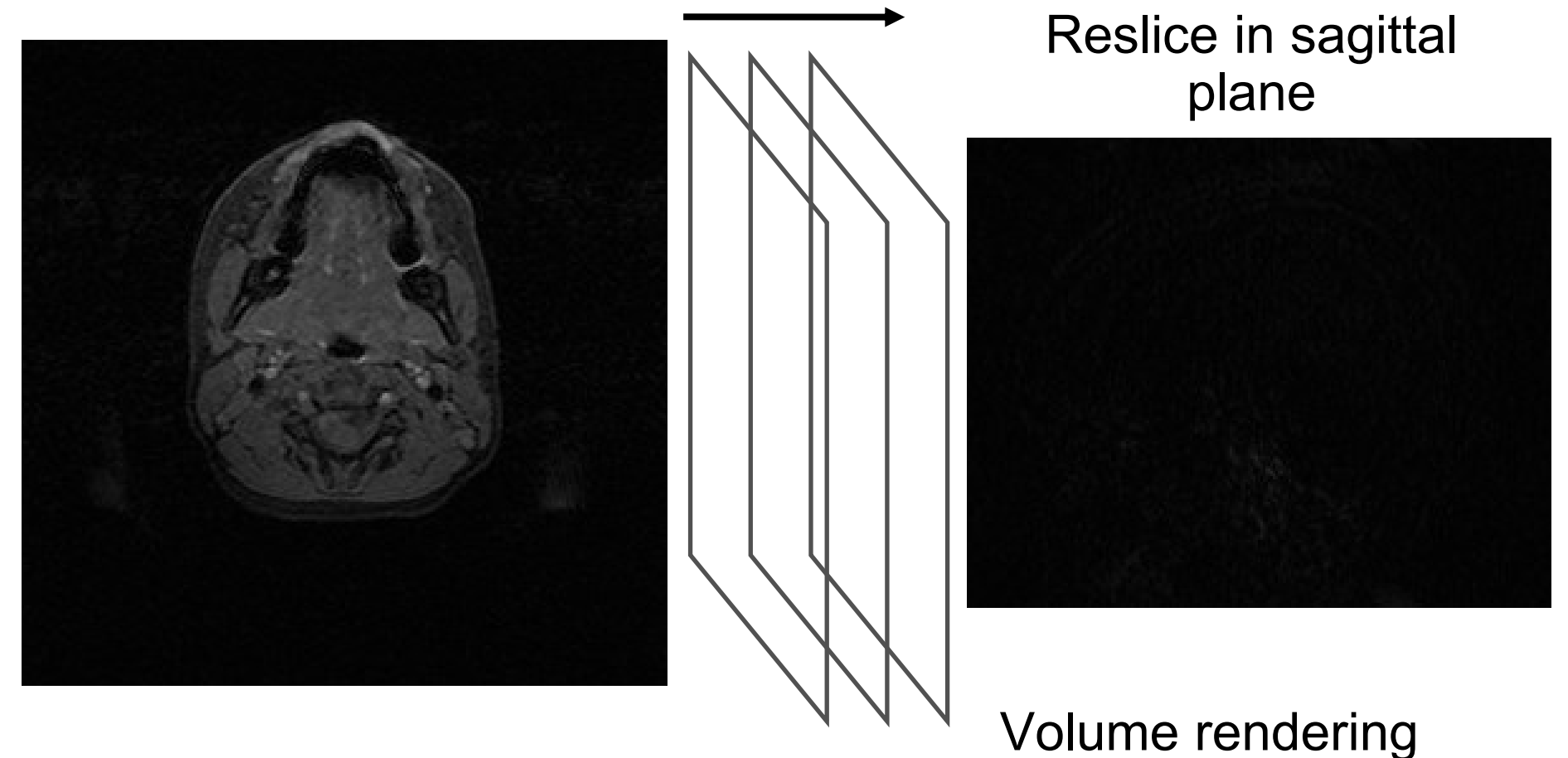
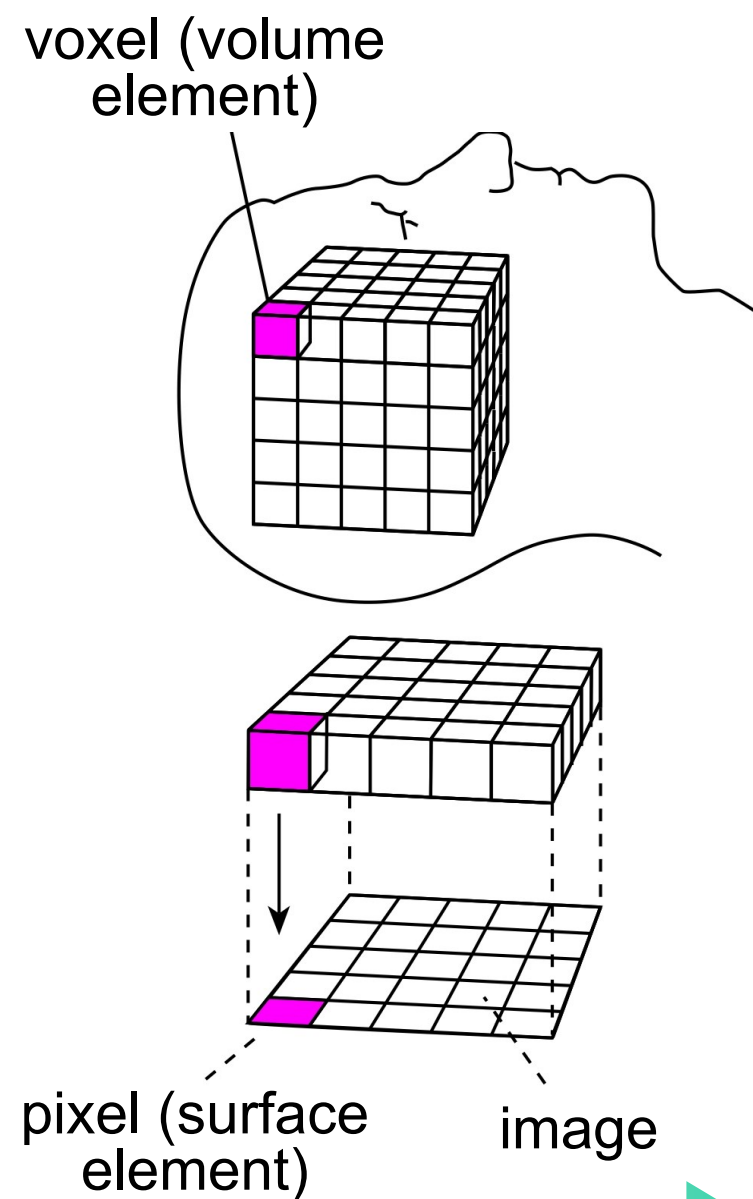
Knocking sounds in MRI:
pulse generation



MRI 2: spatial encoding

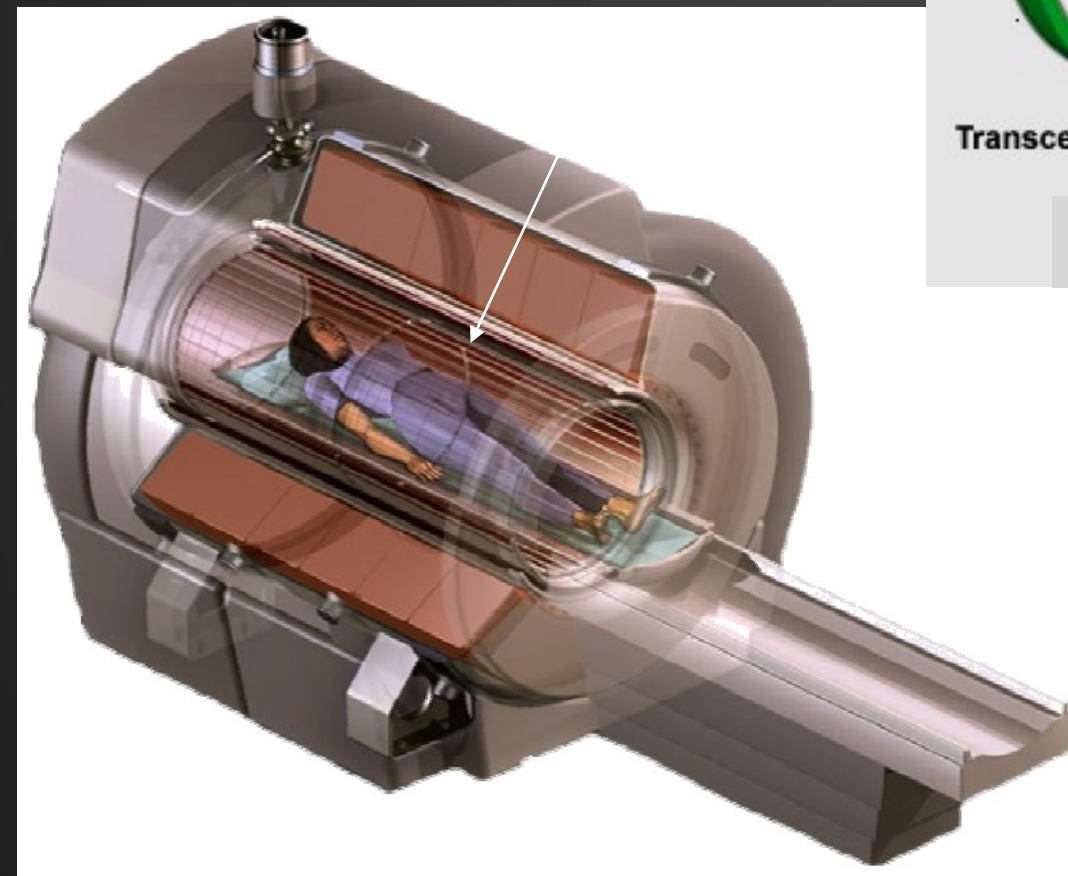


Paul C. Lauterbur
(1929-)

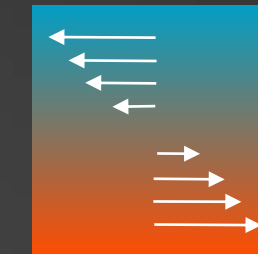
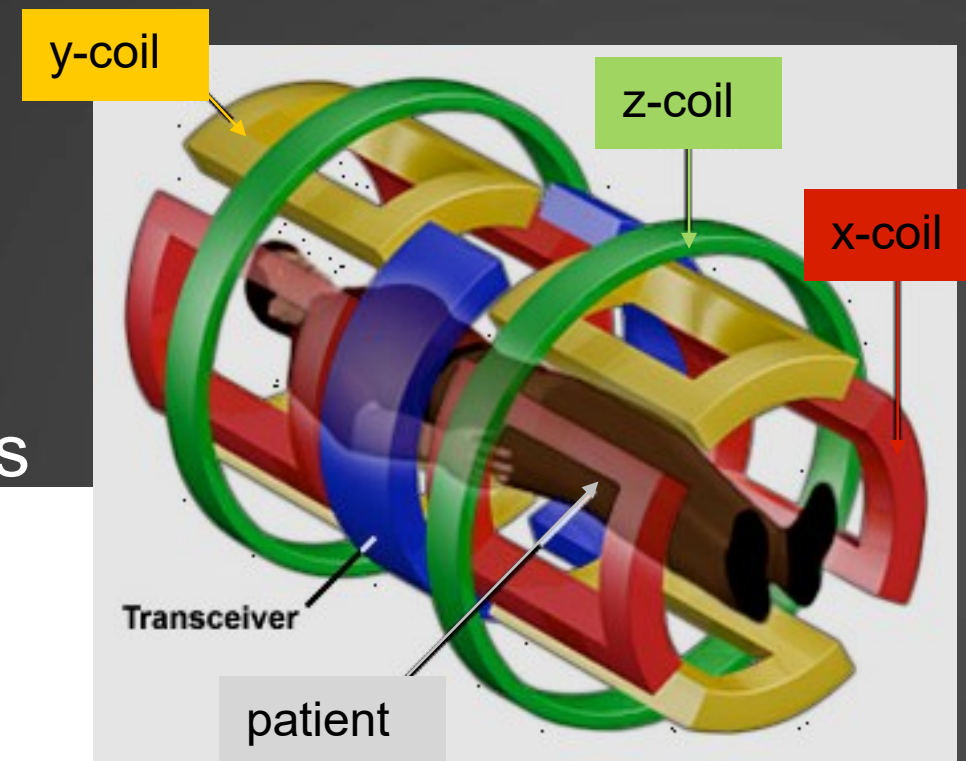


- Defining and addressing elementary 3D points (voxel): by using gradient magnetic field
- Foundations: resonance condition

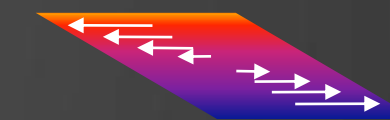
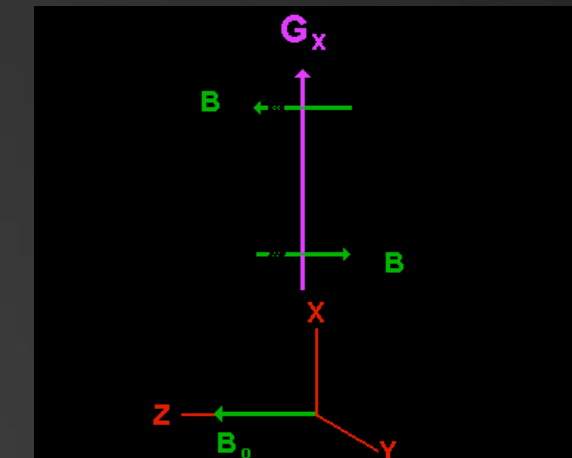
Generation of gradient fields: with gradient coils



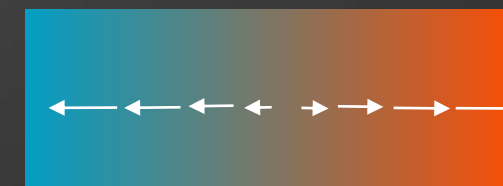
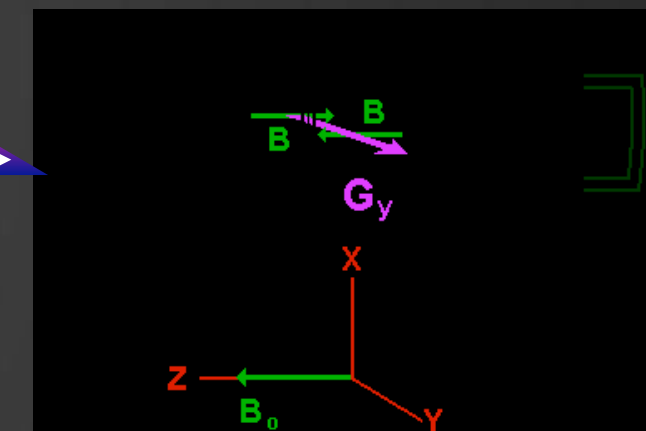
Gradient coils



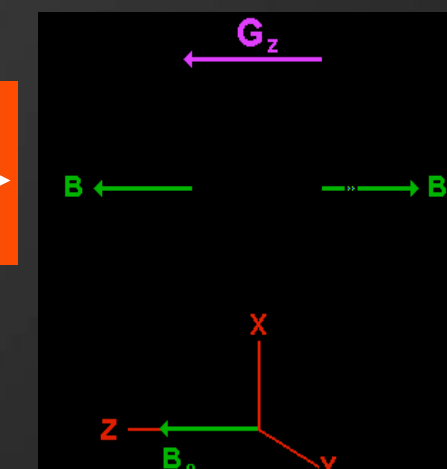
X-gradient coil



Y-gradient coil



Z-gradient coil



IMPORTANT NOTE:
The magnetic field is always in the Z-direction

MRI 3: image reconstruction

1. Back projection

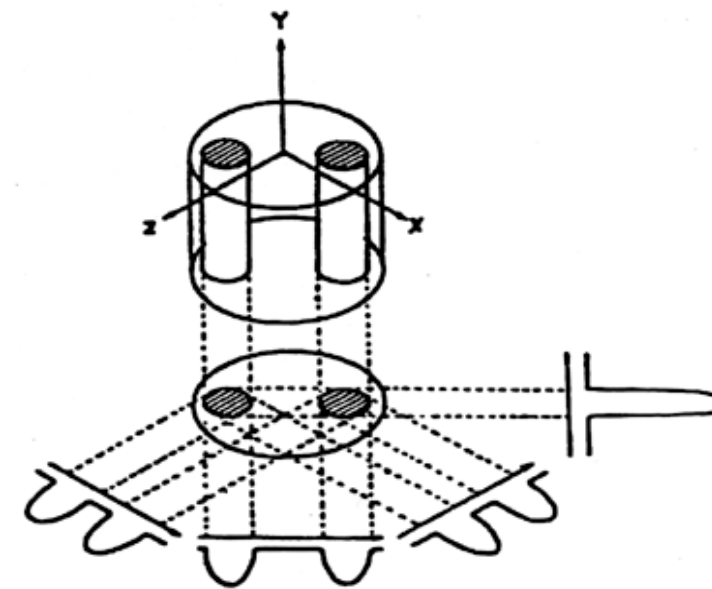
- as in CT scanning superseded by FT-method



Paul Lauterbur,
1973, Illinois



Peter Mansfield,
1973, Nottingham



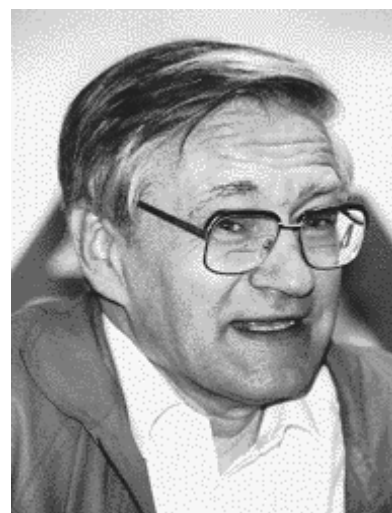
Principle of back
projection



Reconstructed image (cross
section of two test tubes)

2. 2D Fourier transformation

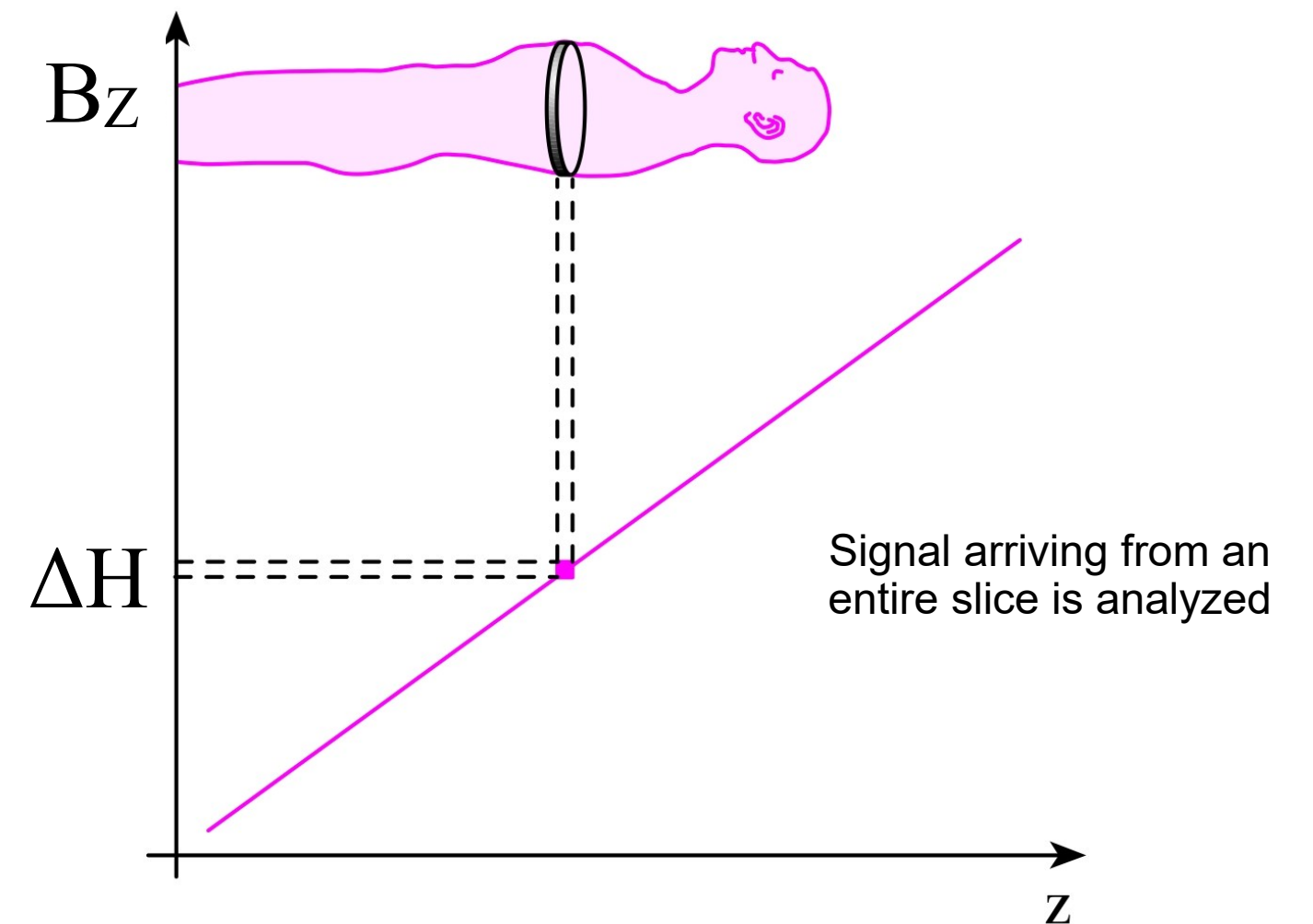
- currently used method
- „NMR Fourier Zeugmatography“



Richard Ernst,
1974, Zürich



“MRI Scanner Mark One”,
Aberdeen, Scotland



Gradient: the magnetic field strength changes by position

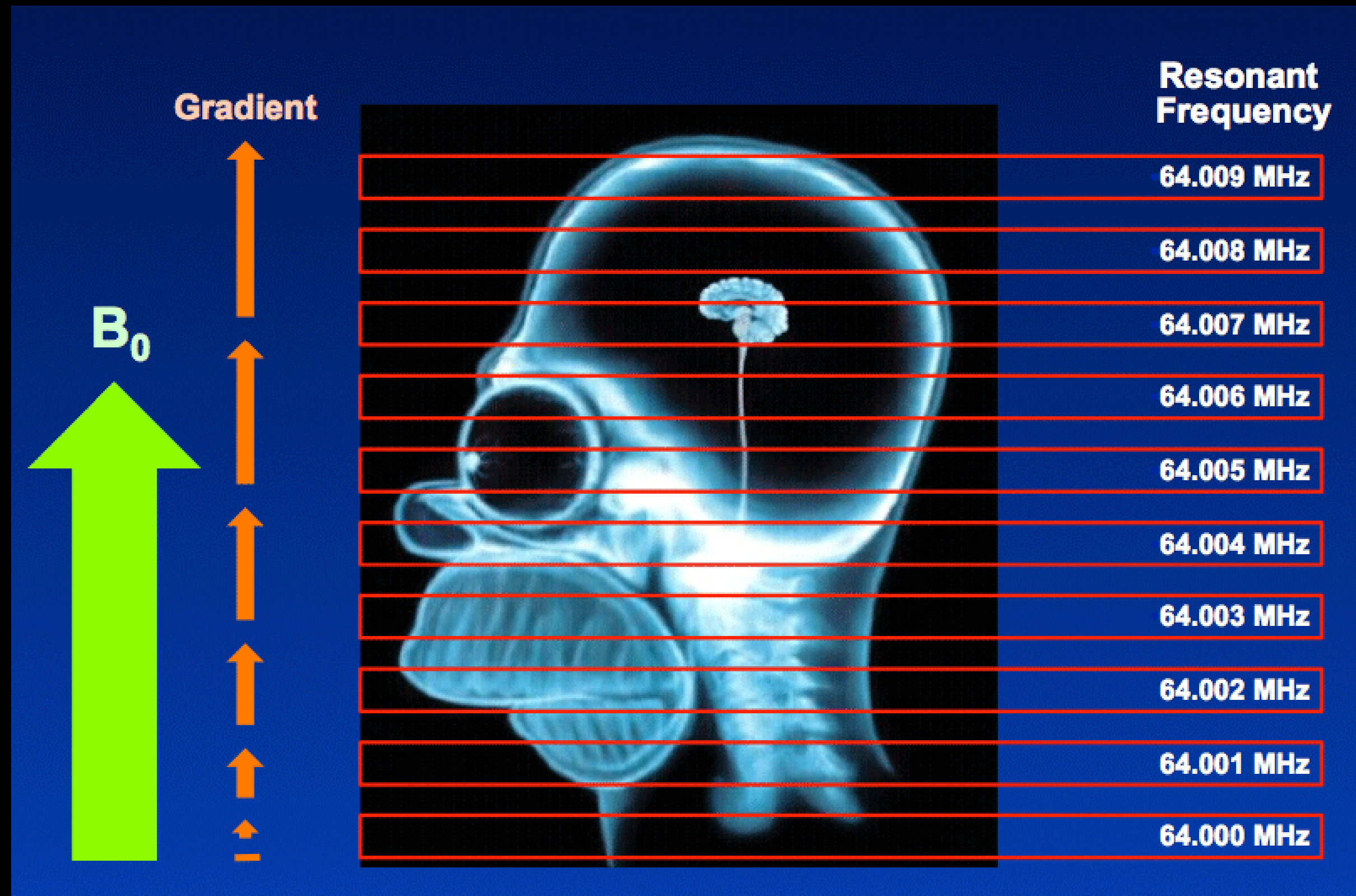
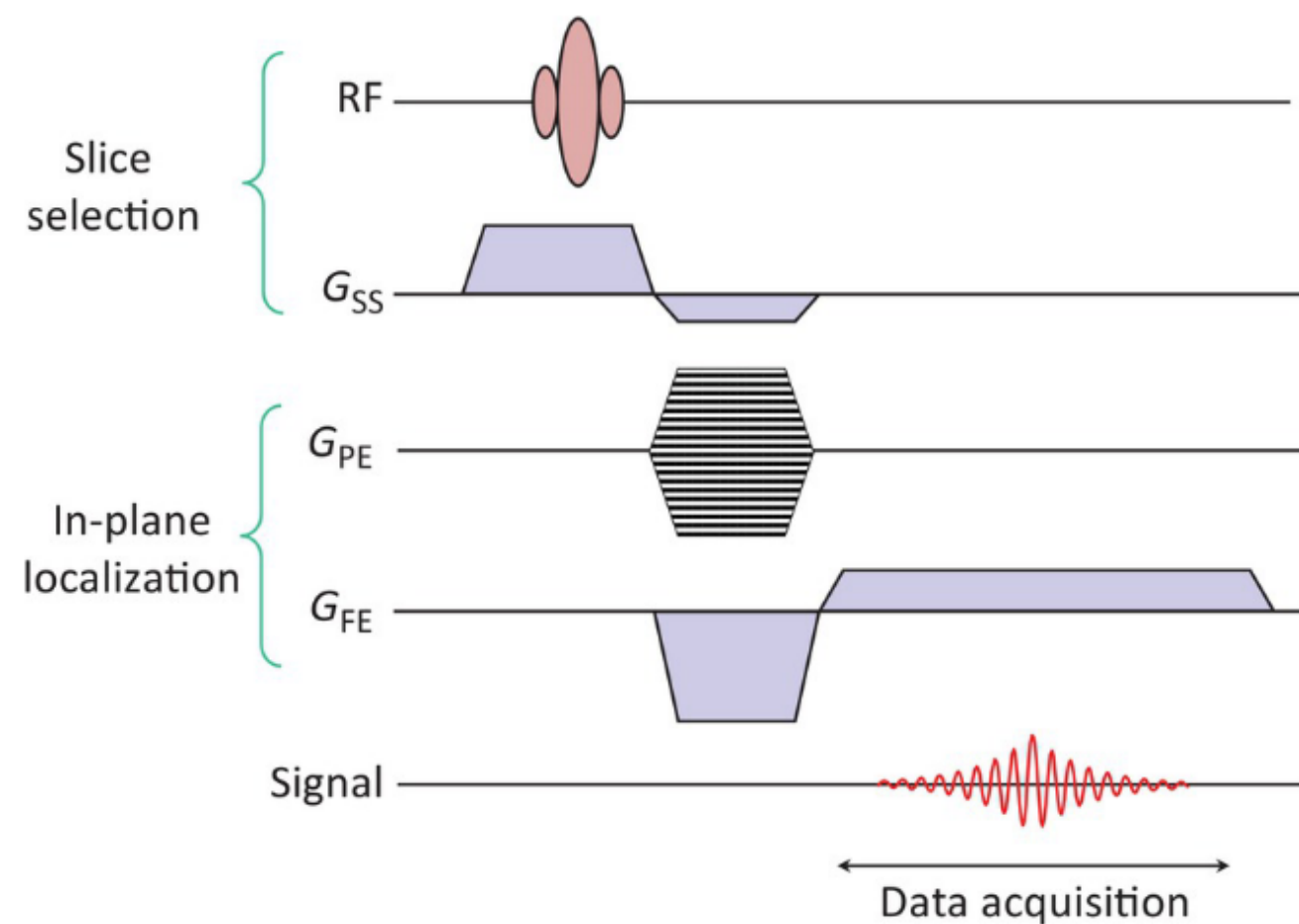
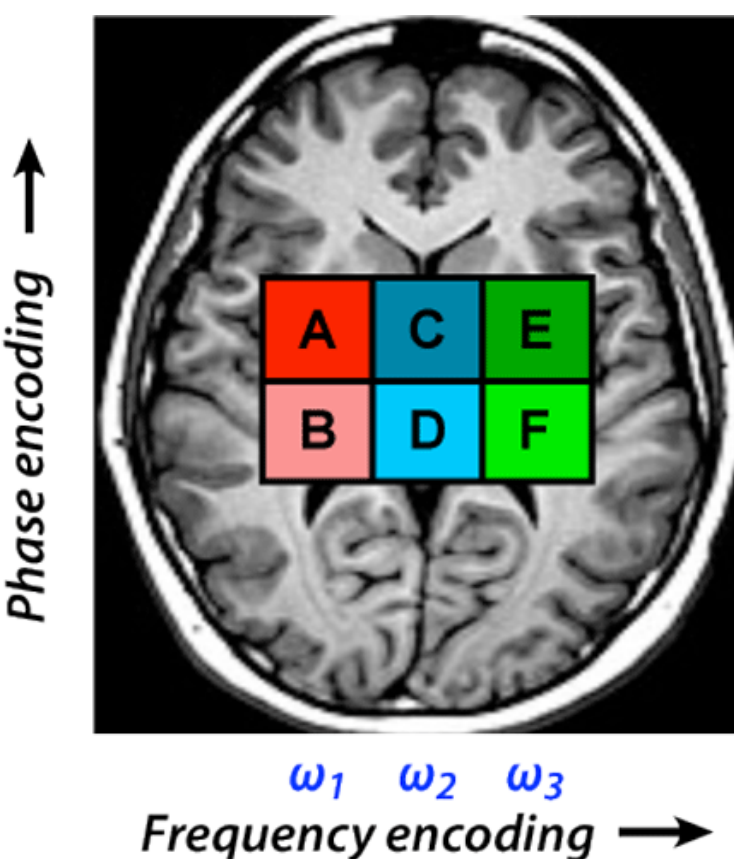
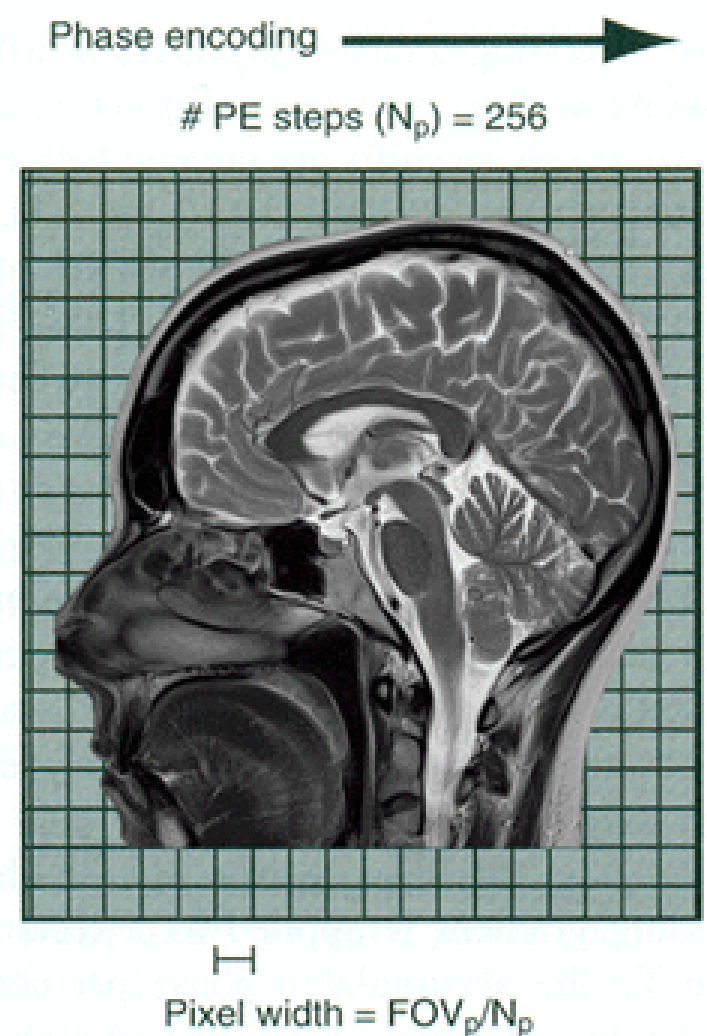


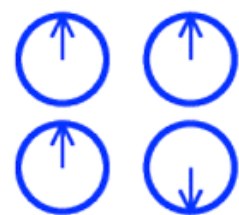
image reconstruction: FT method



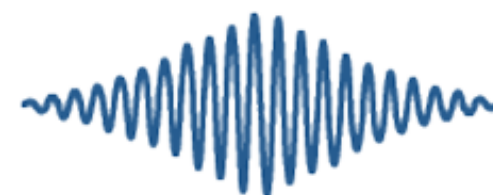
- Slice is selected during the 90° excitation pulse
- In the plane during the echo sequence 180° pulse two additional magnetic field gradients are applied for phase and frequency encoding.
- In each echo signal multiple voxels contribute with distinct frequencies
- The frequency components can be recovered by FT
- The data acquisition has to be repeated multiple times



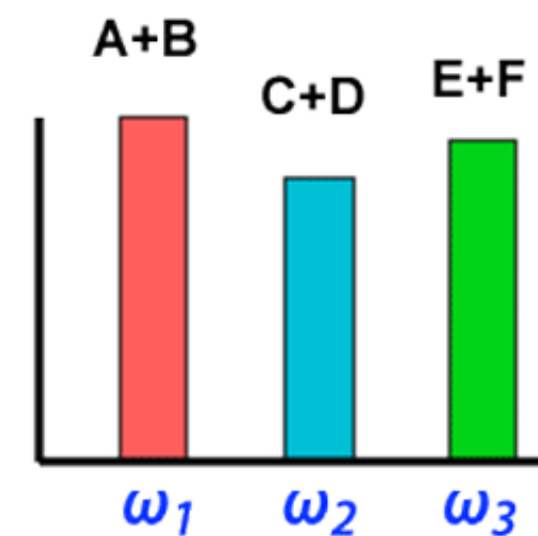
Phase Step 0 Phase Step 1



Phase Step 0

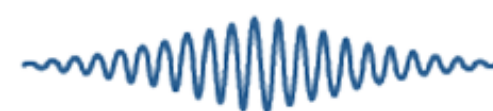


FT

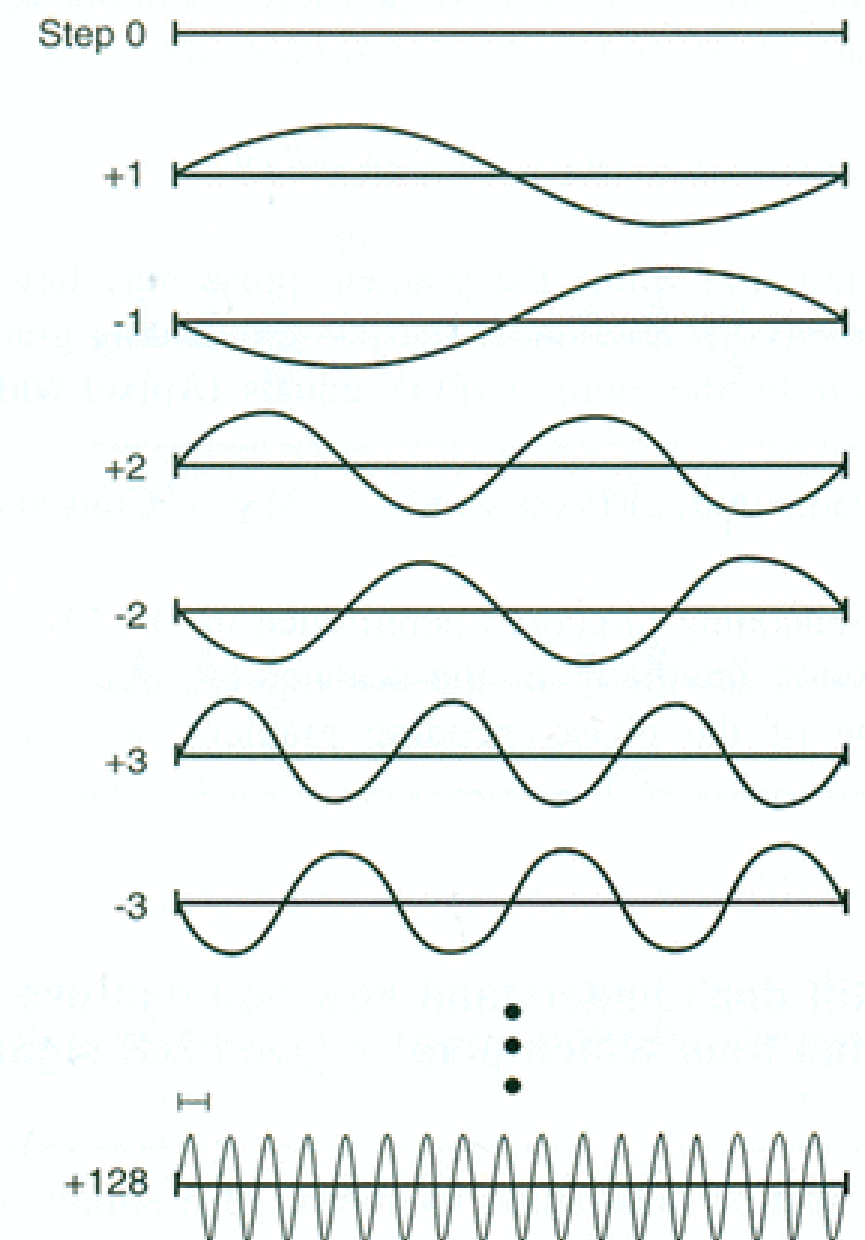
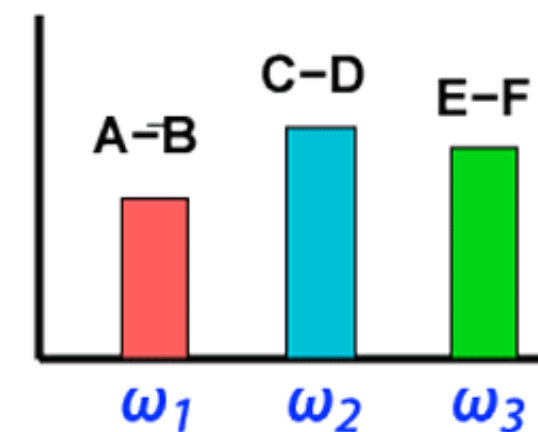


aggregate signal from all 6 pixels recorded at each PE Step

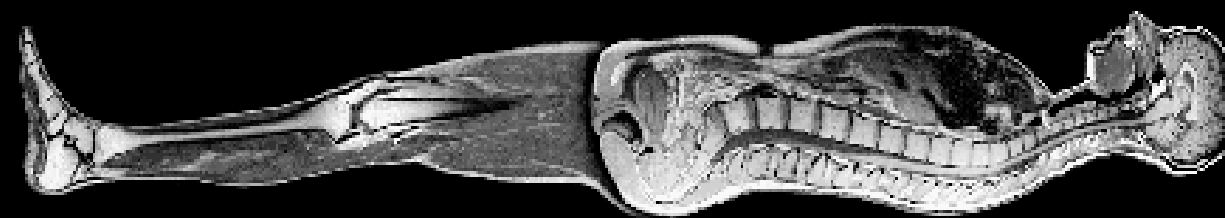
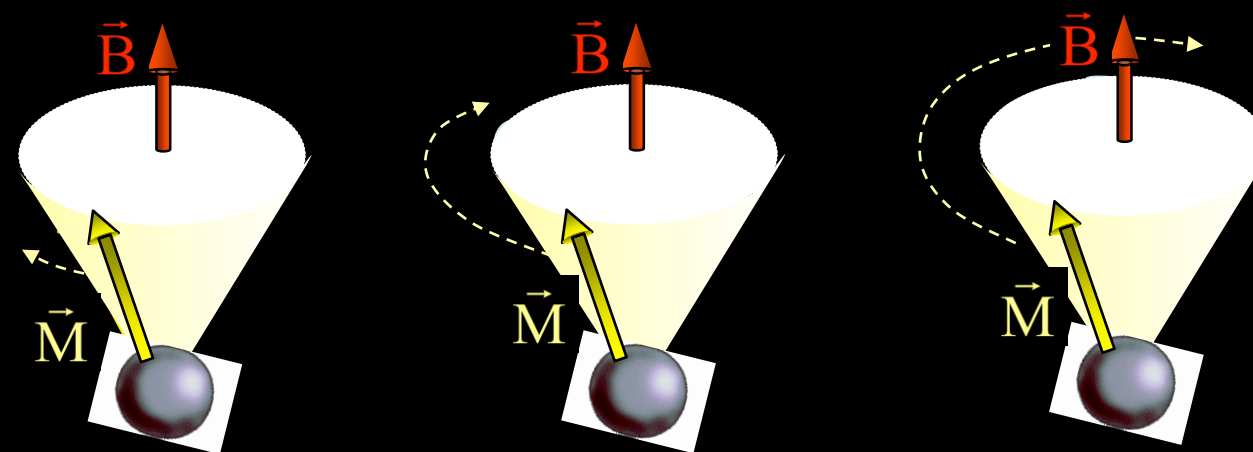
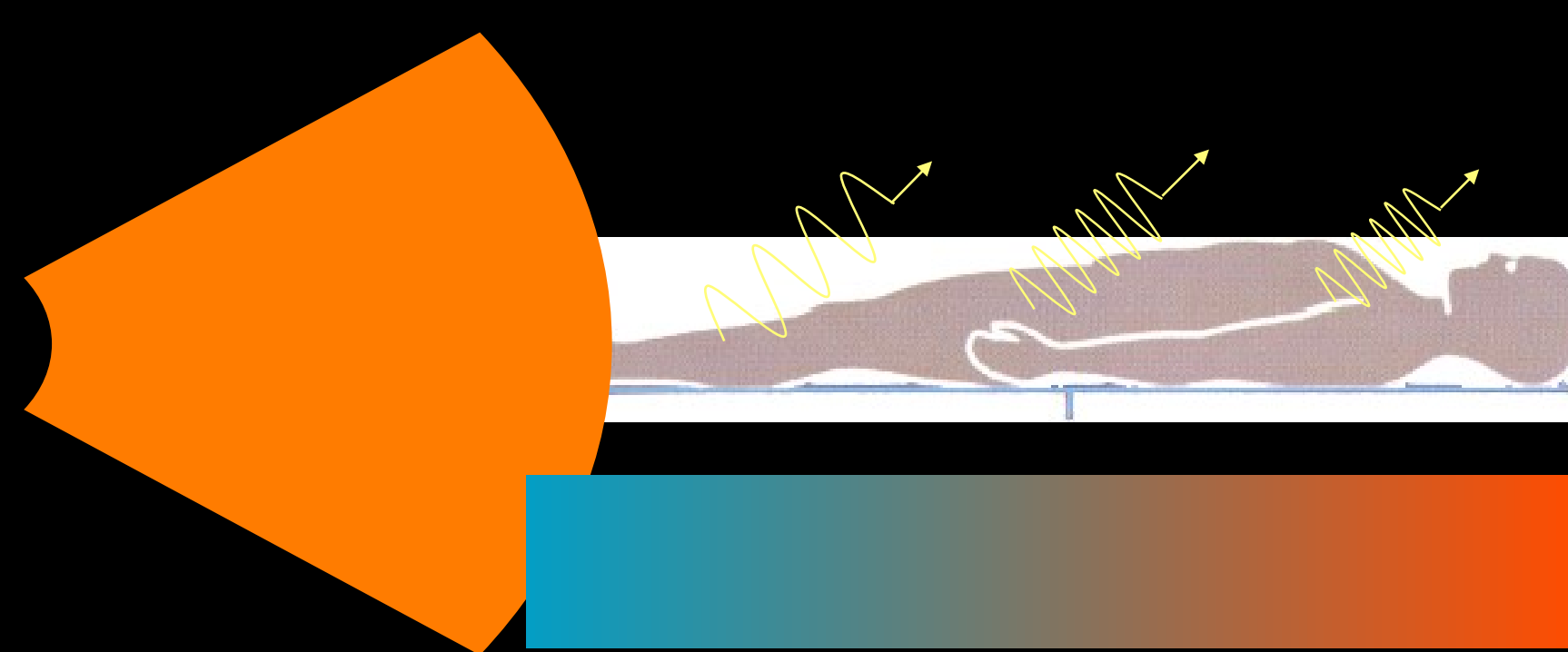
Phase Step 1



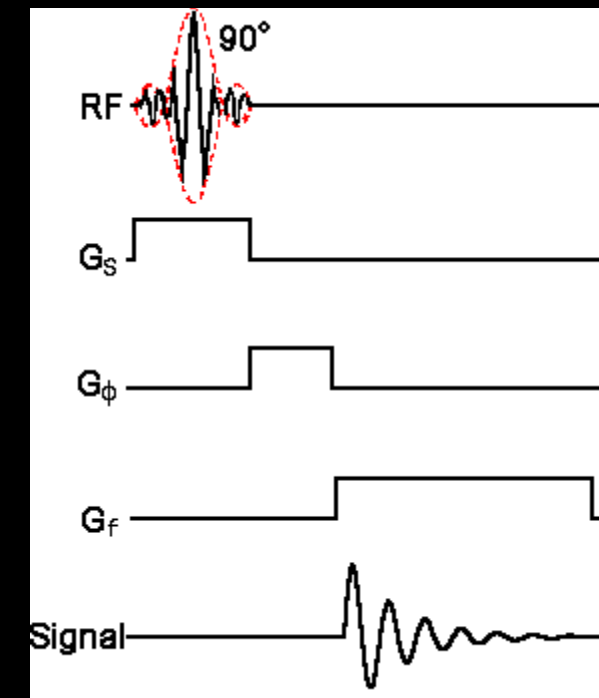
FT



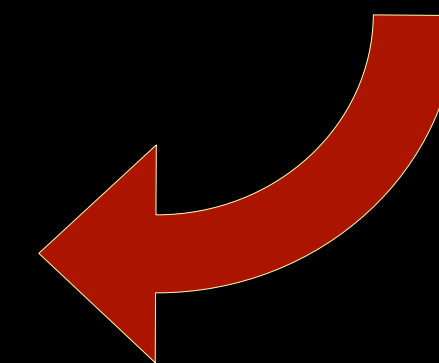
MRI: spatial coding and image reconstruction based on the resonance condition (B_0 -dependent ω)



RF coil



Fourier
transformation

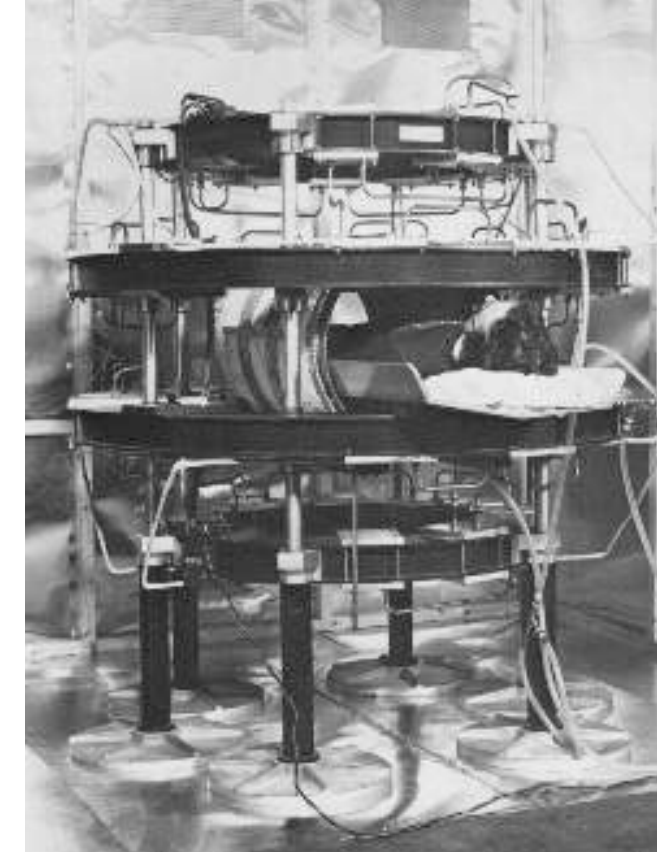


MRI 4: scanners

Early times



Indomitable (Damadian)



MRI Scanner Mark One (Ernst)

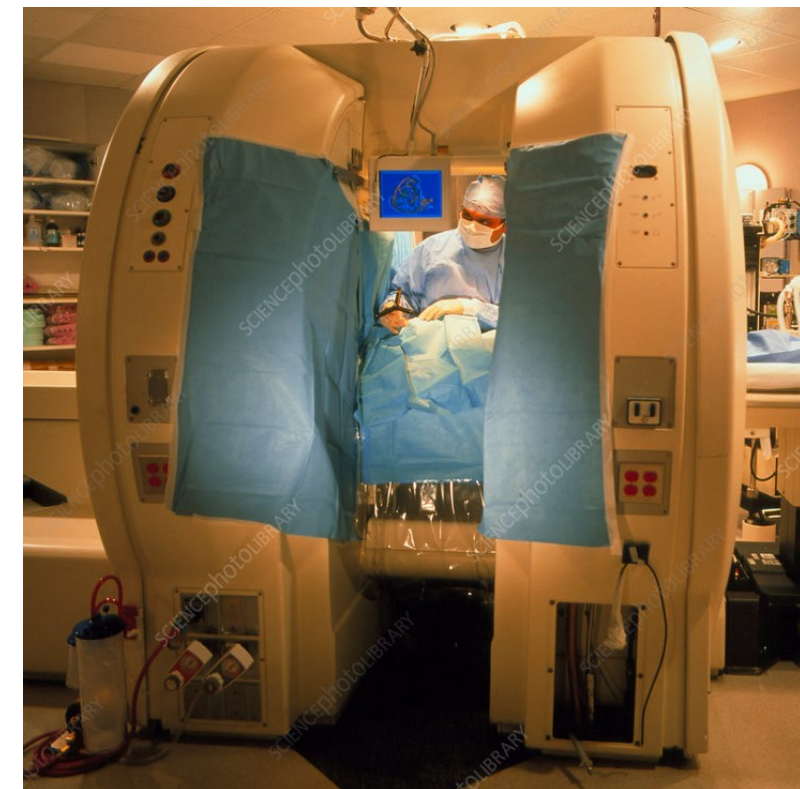
Present



3T MRI



Open MRI unit



Interventional MRI unit

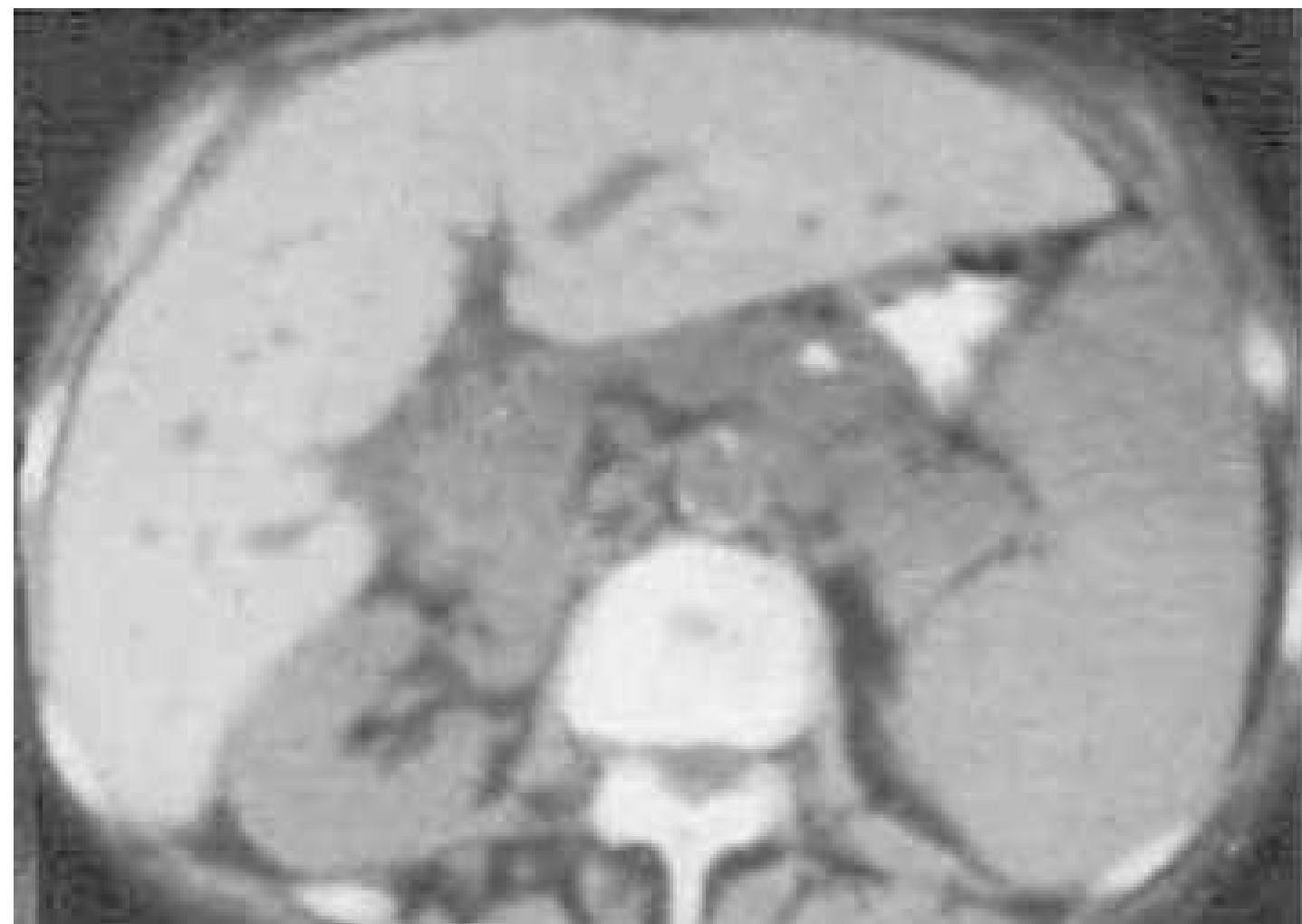


Mobile MRI

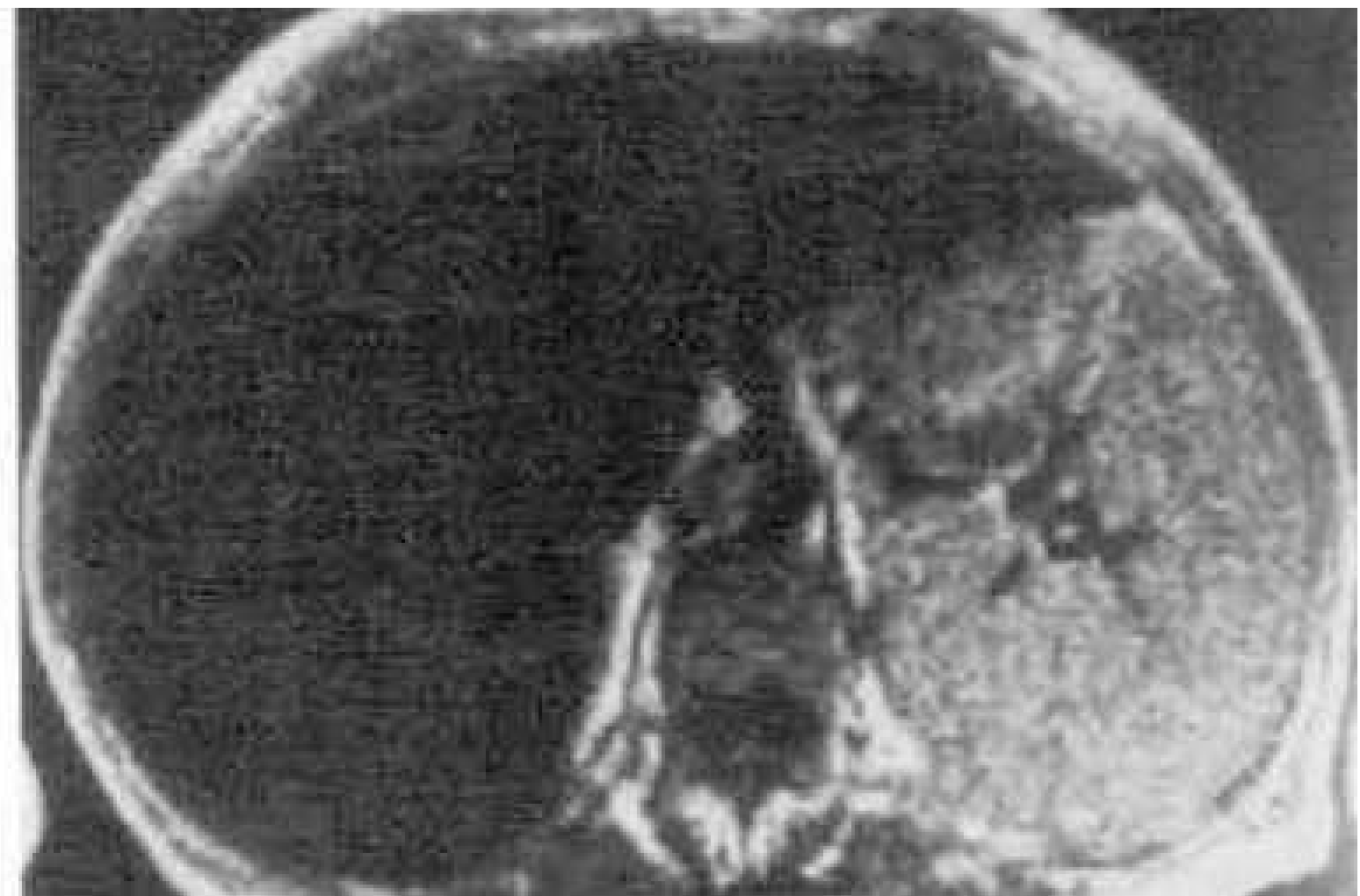
MRI 5: contrast agents

Positive: paramagnetic elements (T1 contrast): Gd, Mn

Negative: superparamagnetic, ferromagnetic (T2 contrast): FeIII, MnII



CT

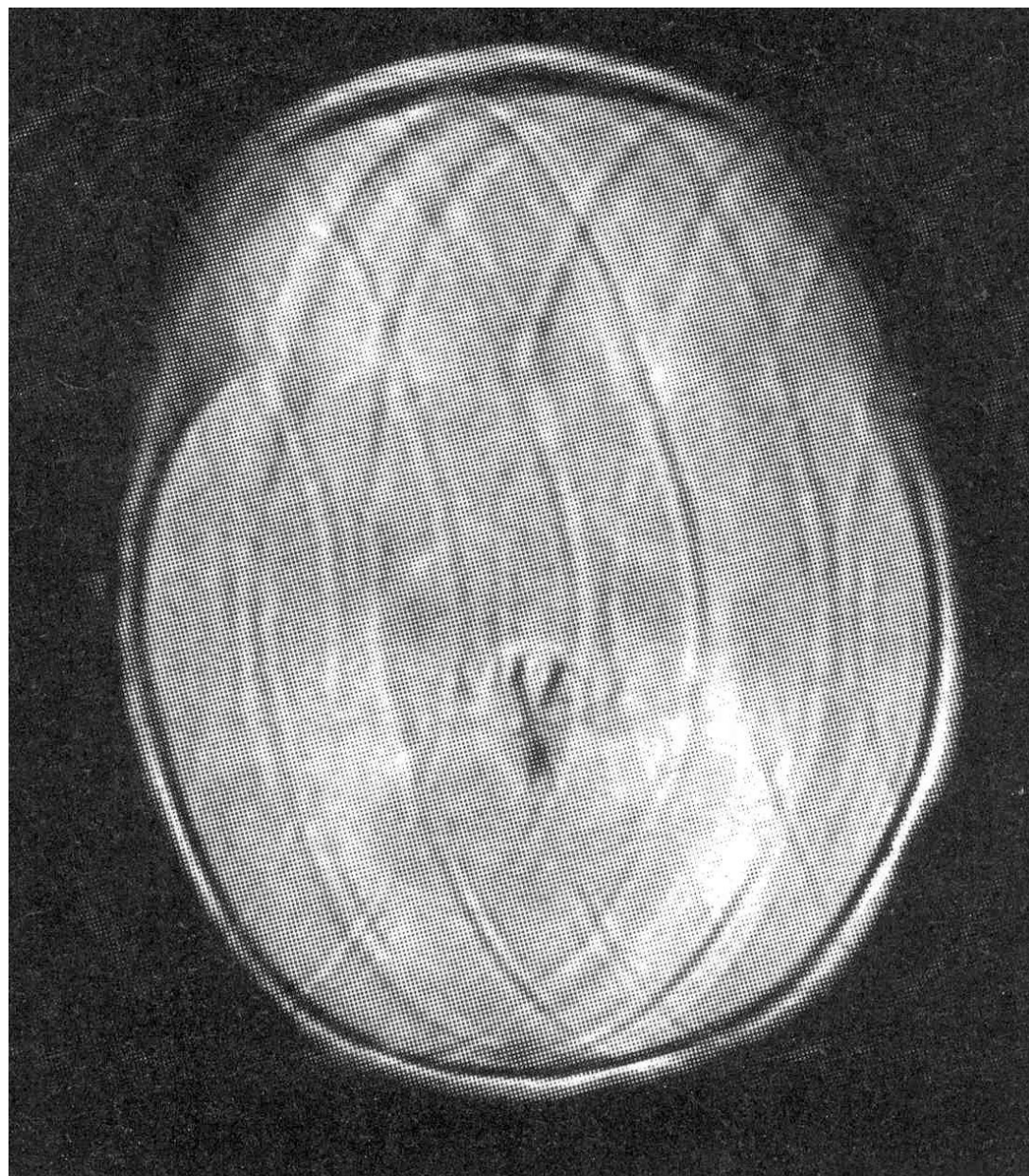


MR T2

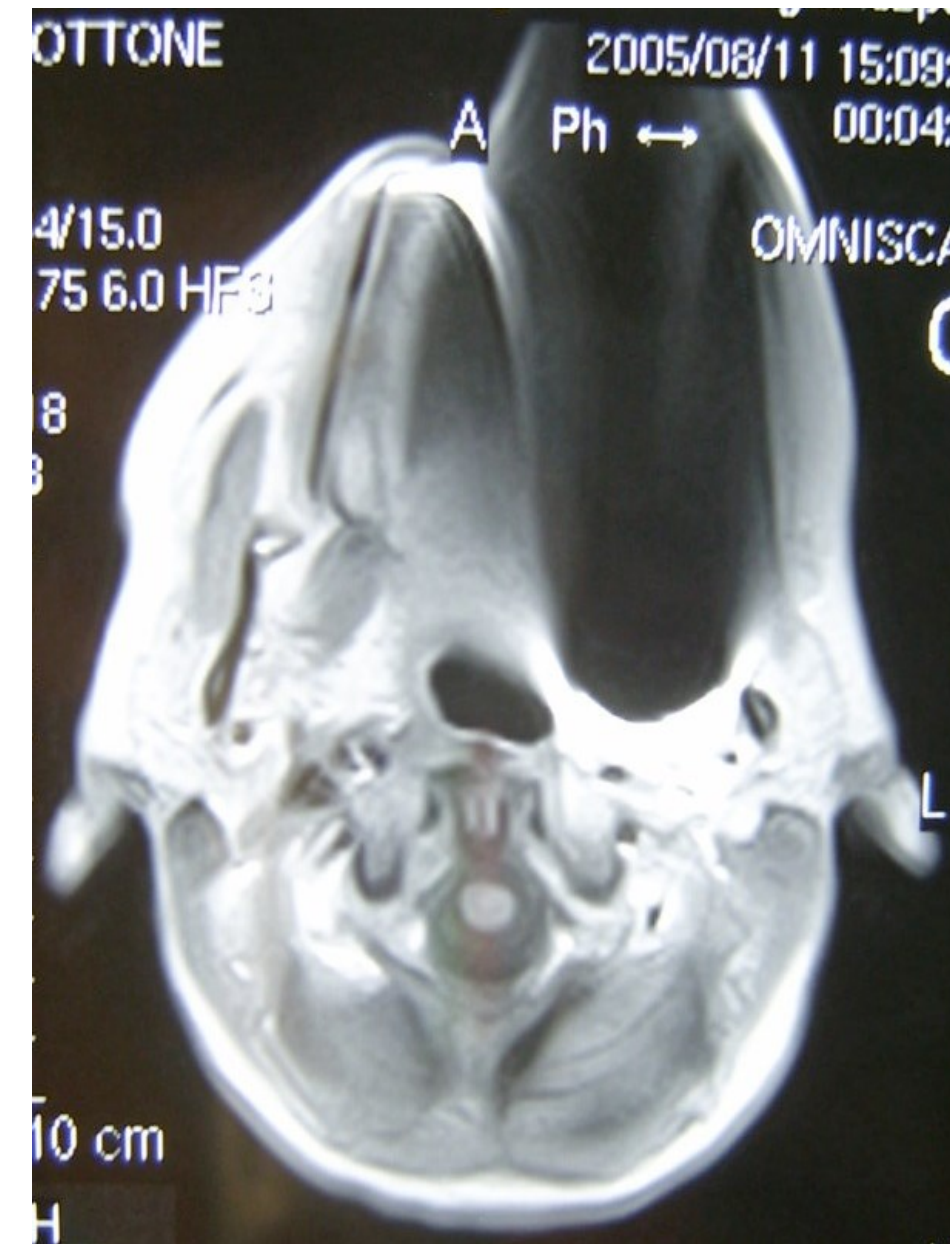
Haemochromatosis hepatis (iron accumulation in liver)

MRI 6:artefacts

- Motion
- Metals (implants, injury)



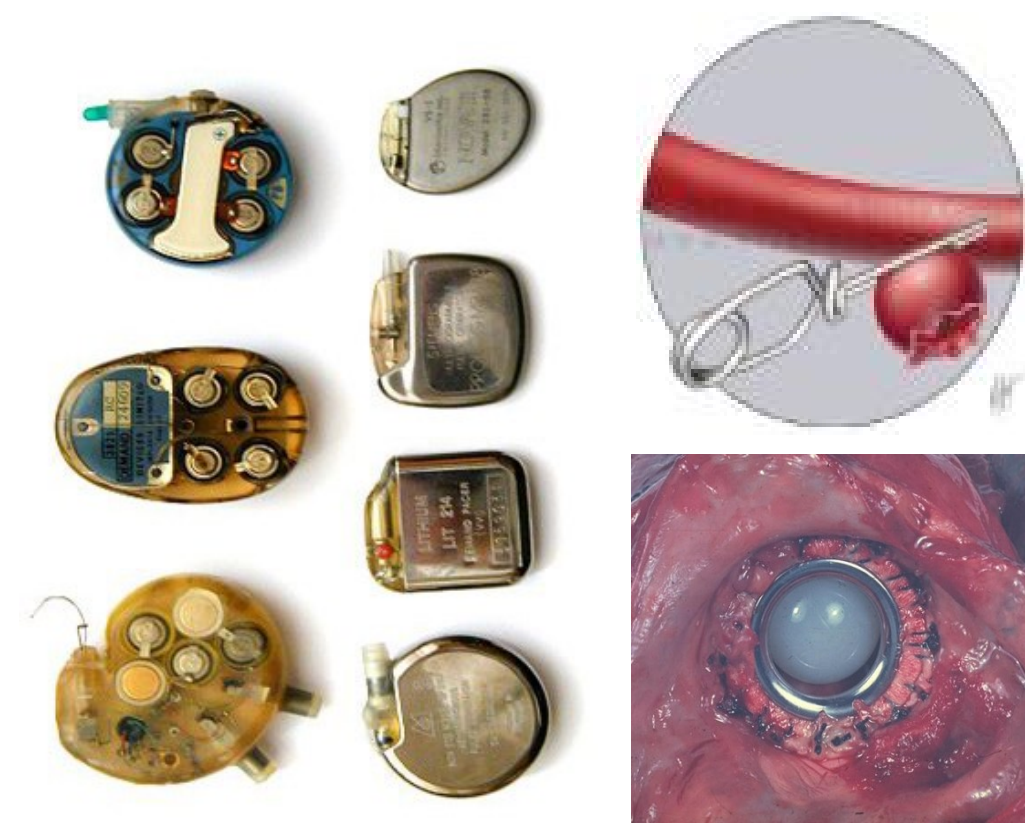
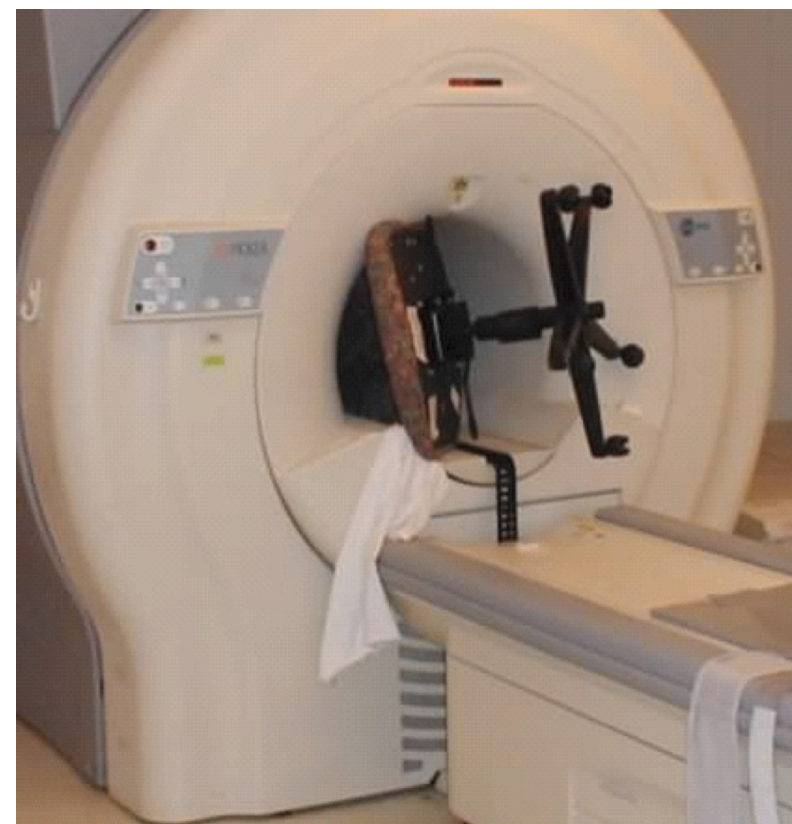
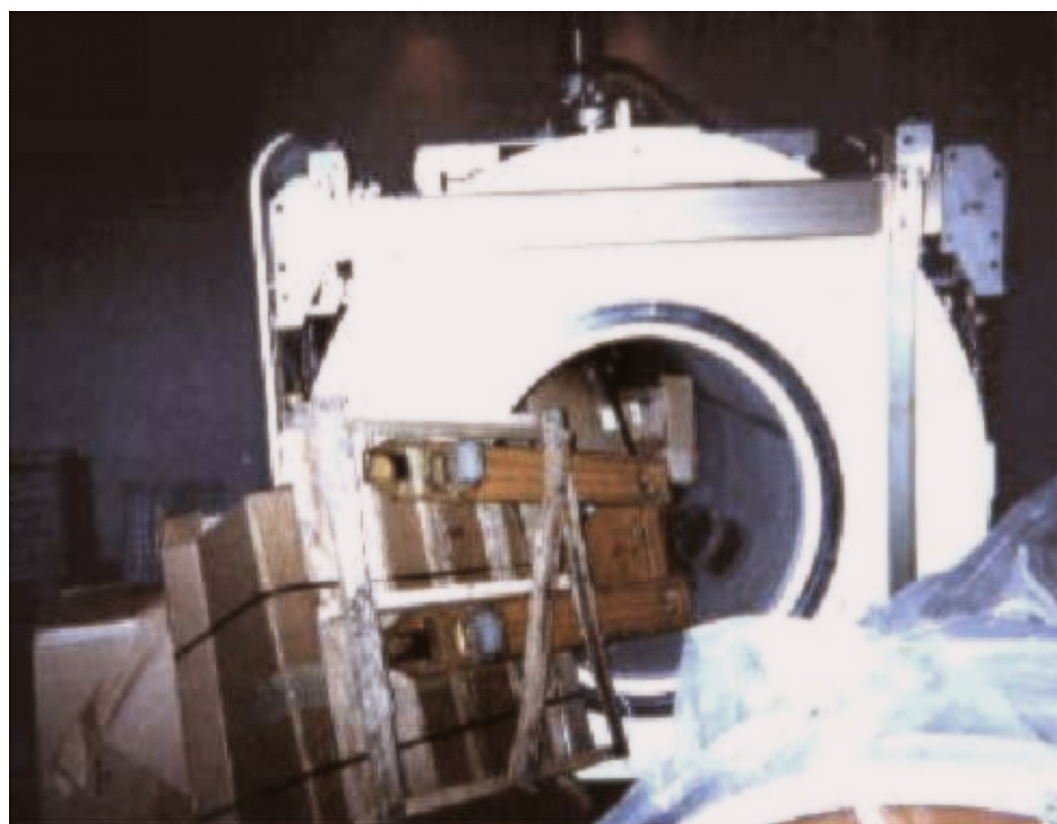
Motion artefact



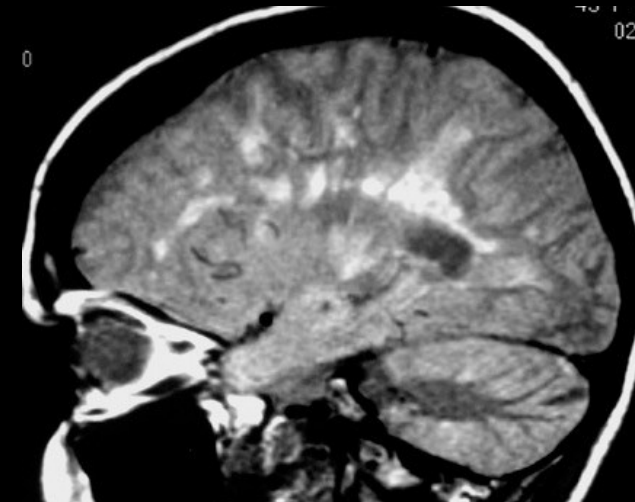
Metal in the orbit of the eye

MRI 7: dangers, contraindications

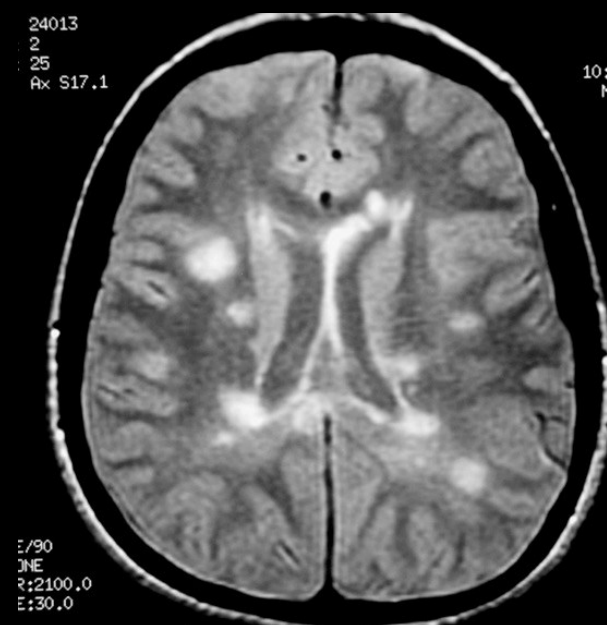
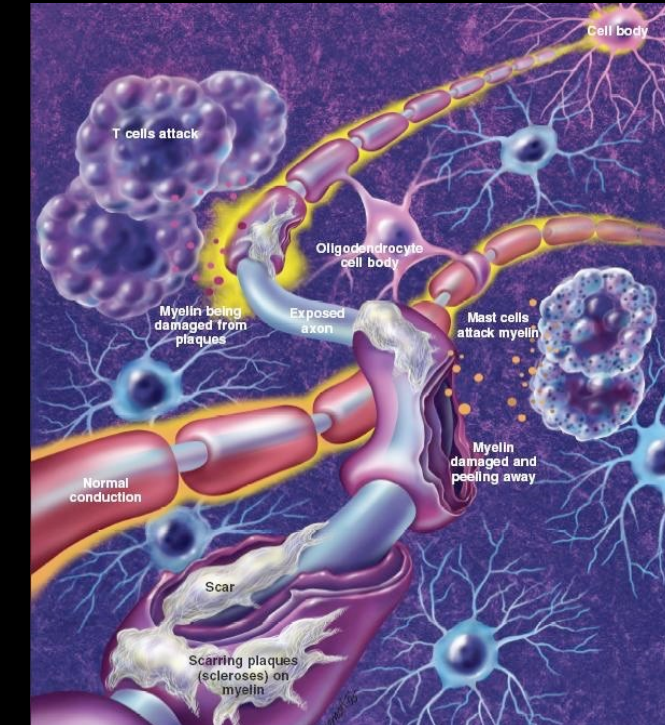
- Static magnetic field - metal objects
Contraindications: implanted devices (pacemaker, defibrillator, hearing aids, drug delivery devices), neurostimulators, brain aneurysm clamps, early cardiac valve implants
- Gradient field - induced current
- Radio frequency field - thermal effects (lens, testis)



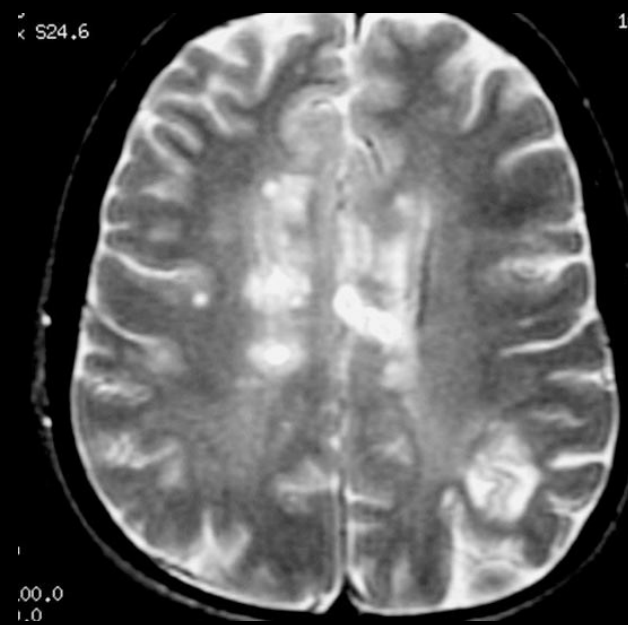
Applications: Anatomical imaging - Multiple sclerosis



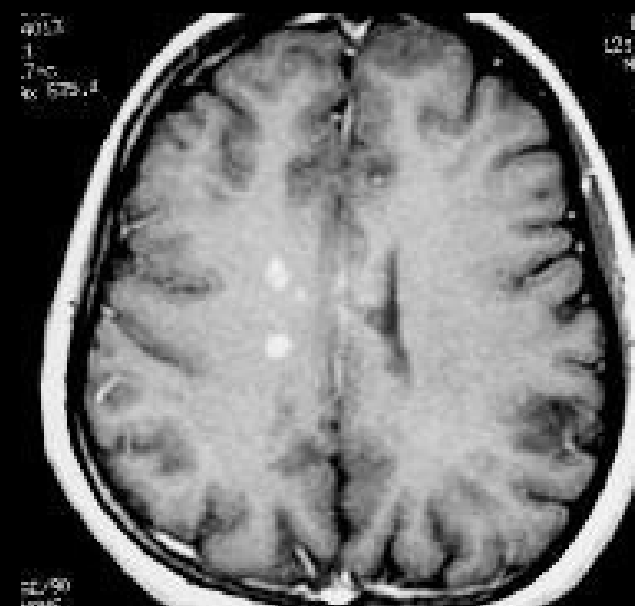
Proton density (sagittal)



Proton density (transverse)



T2 weighted
(transverse)

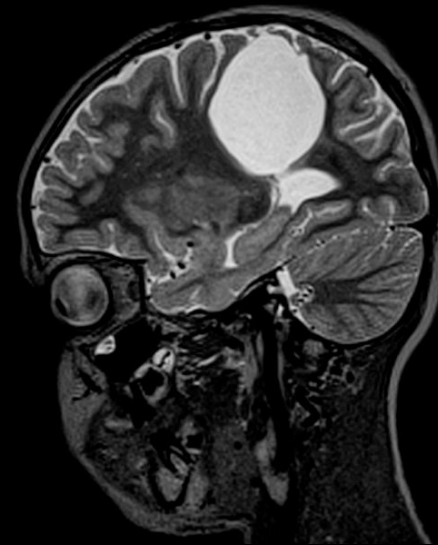


T1 weighted
With contrast agent

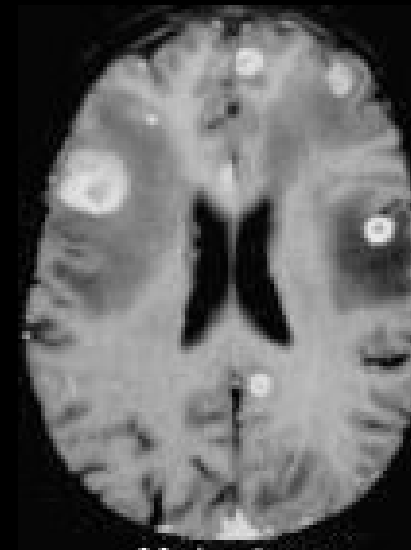
Anatomical imaging: Oncology



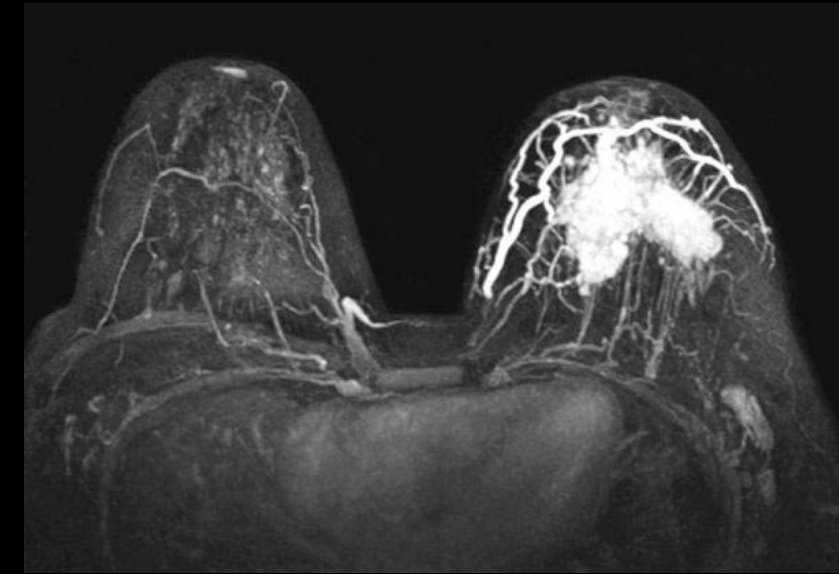
T2 weighted
(chondrosarcoma)



T2 weighted
(cyst)



Proton density
(Brain metastasis)



T1 weighted with contrastagent
(Breast carcinoma)



T2 weighted
(cervix carcinoma)



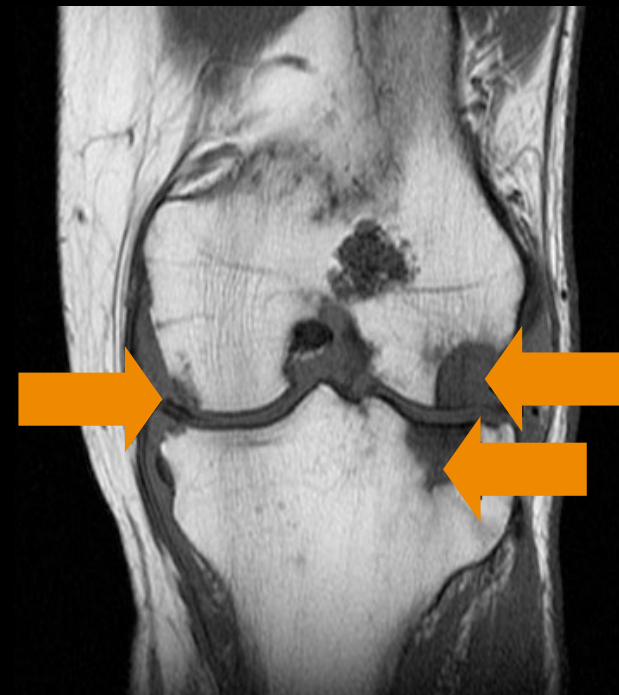
T2 weighted
(prostate tumor)

Anatomical imaging

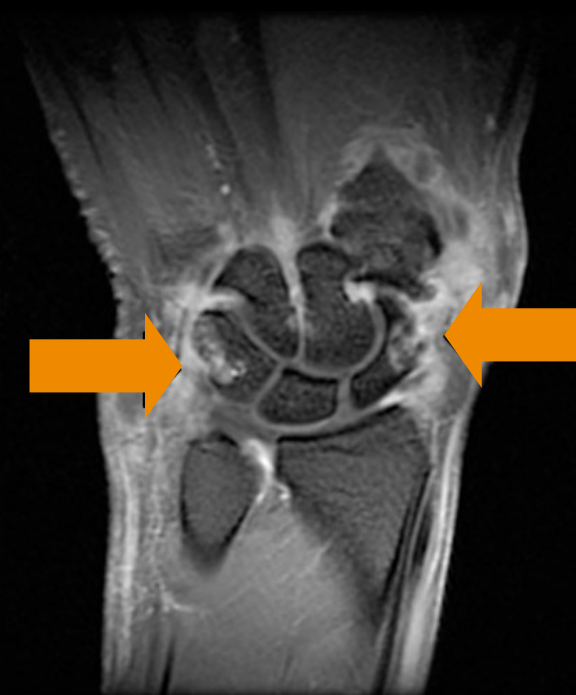
Bone and soft tissue



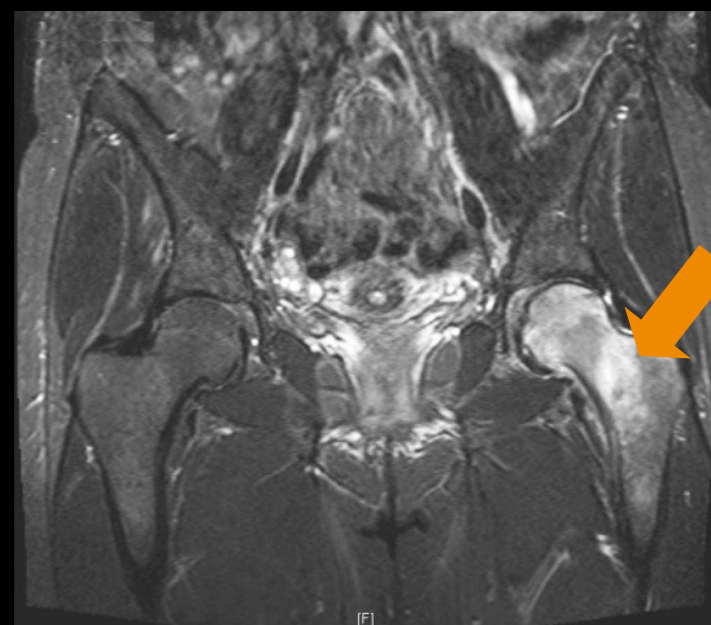
T2 weighted
(torn ligaments)



Rheumatoid arthritis
knee



Rheumatoid arthritis
wrist



Osteoporosis (femur)

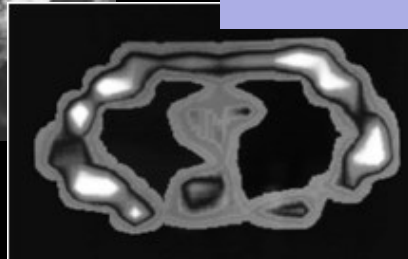


T2 weighted
(hernia)

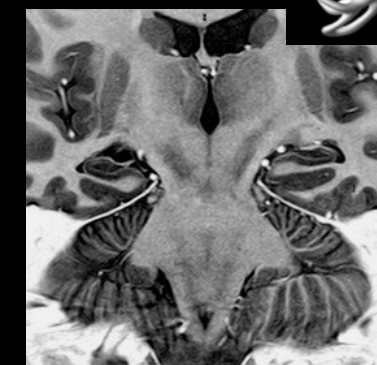
There is more to MRI than anatomical imaging ...



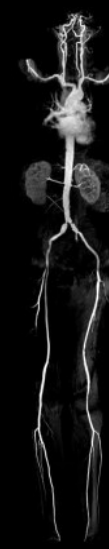
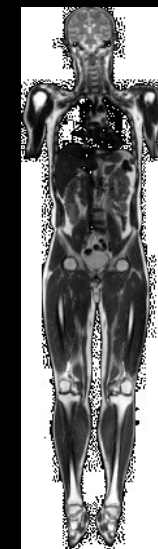
1972



First NMR images



2008

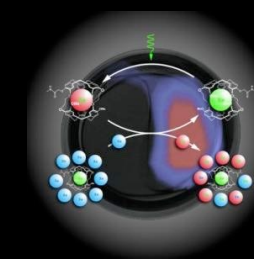
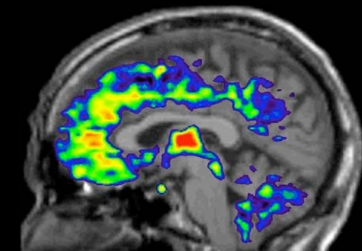
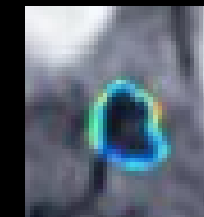
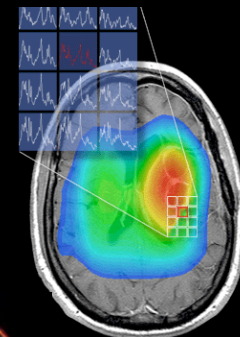


'State of the art'

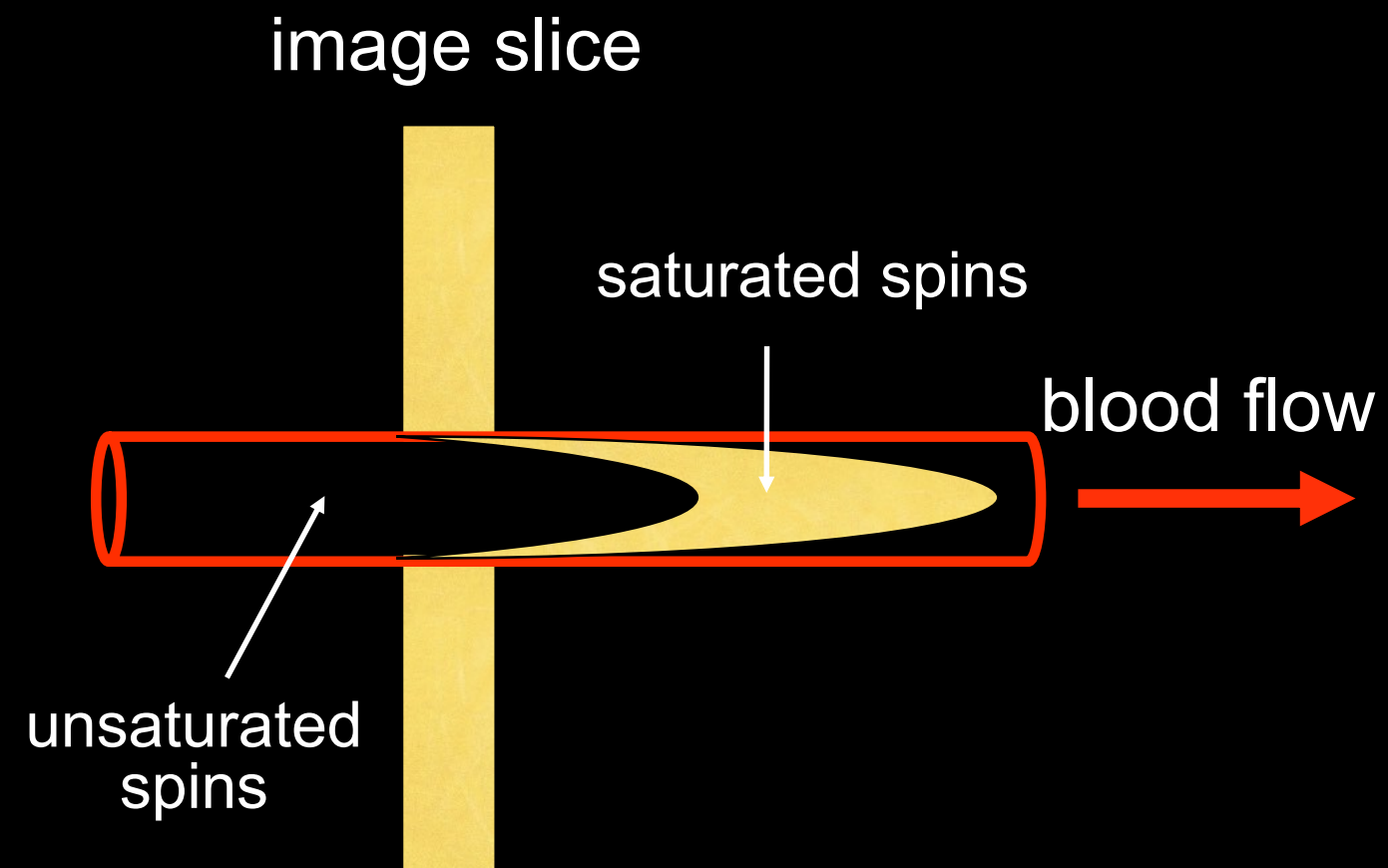
- 3D images
- dynamic images
- sharp image resolution

In research phase

- quantitative imaging
- cell-specific contrast agents
- hyperpolarized MRI
- in vivo spectroscopy
- functional imaging
- 'multimodality' imaging



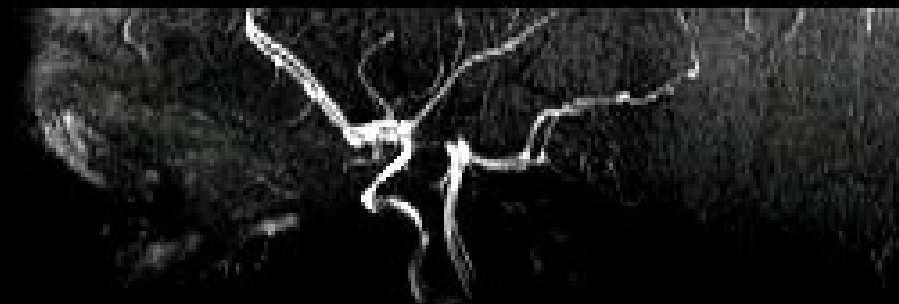
MRI: Non-invasive angiography



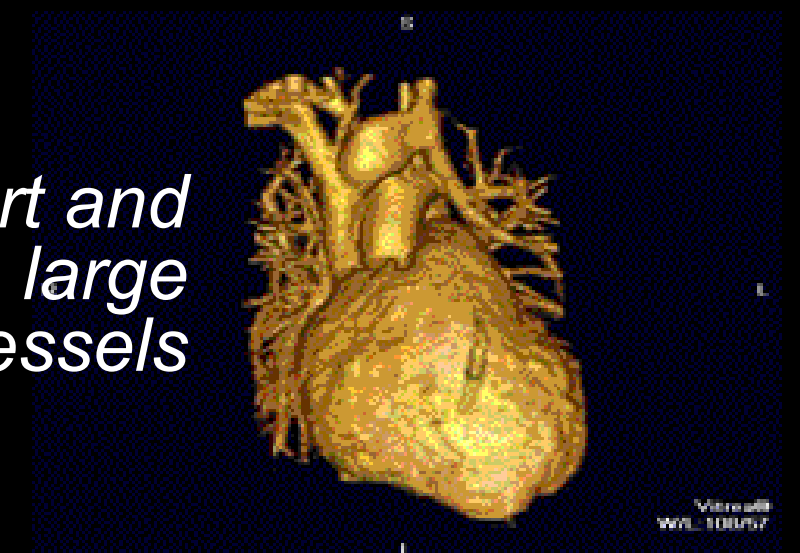
*Arteria
carotis*



*Circulus
arteriosus
Willisii*



*Heart and
large
vessels*



Time-resolved MRI (ECG-gating required)



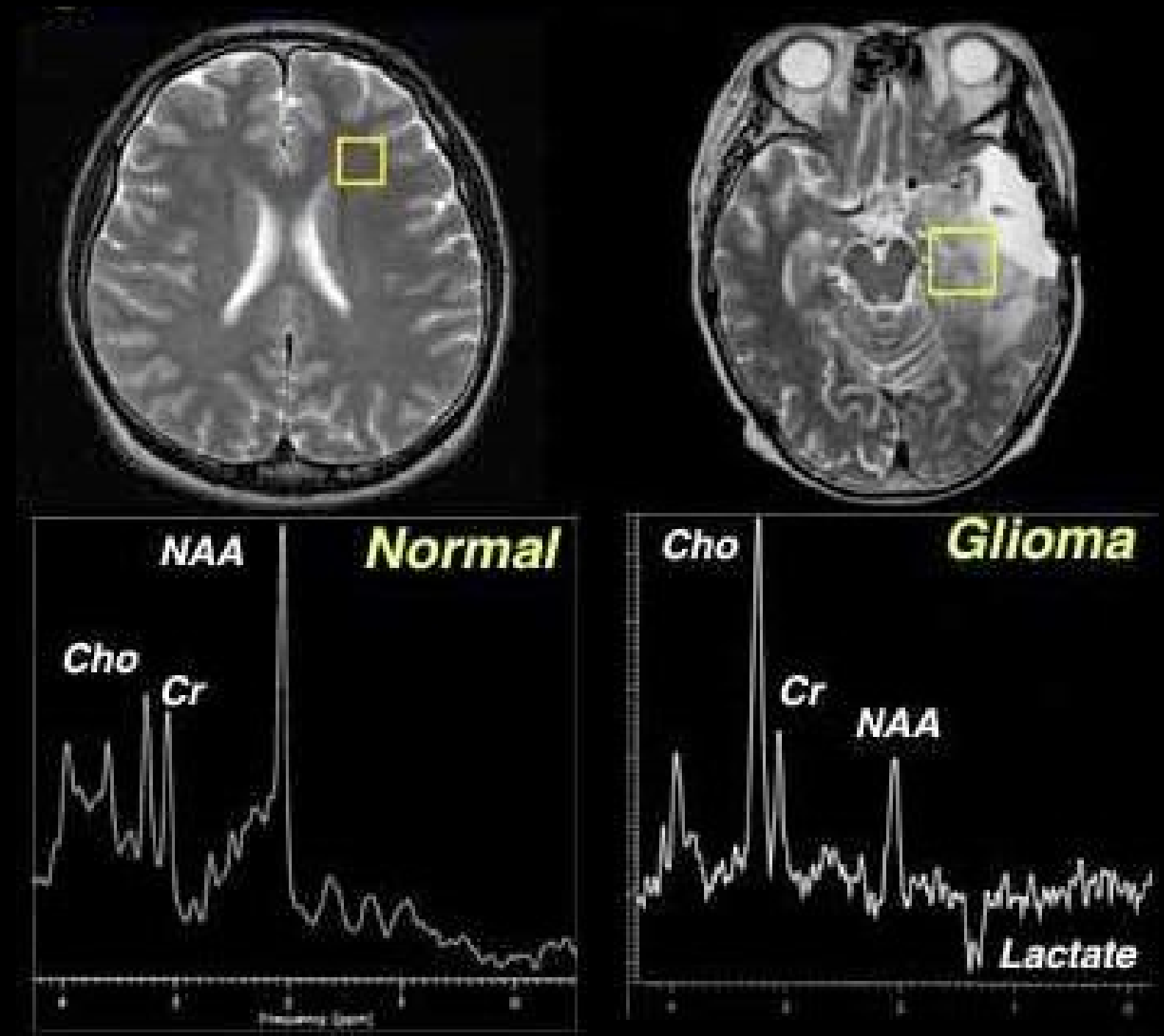
Blood flow across the cardiac chambers



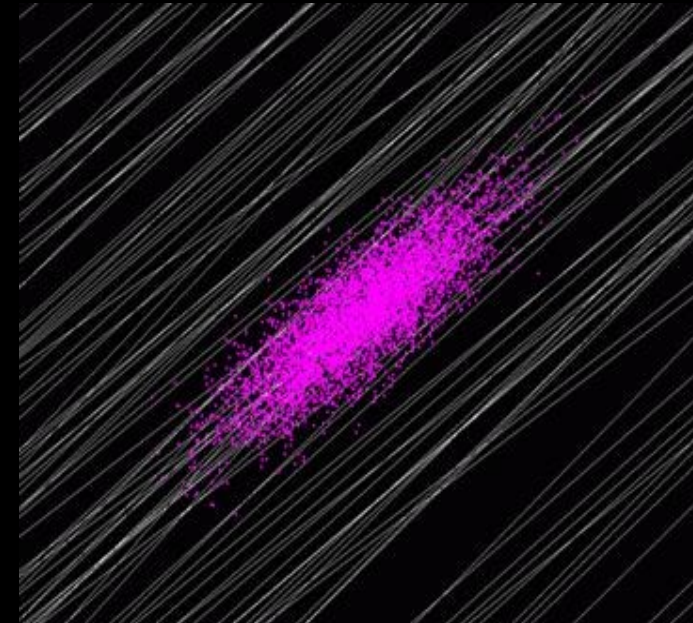
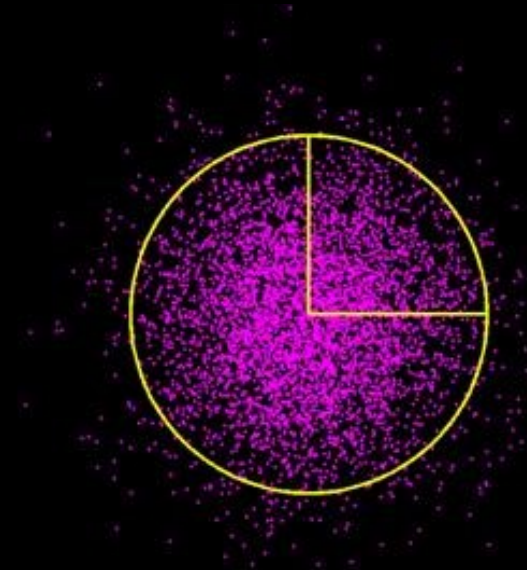
Opening and closing of aorta valve

MR Spectroscopy

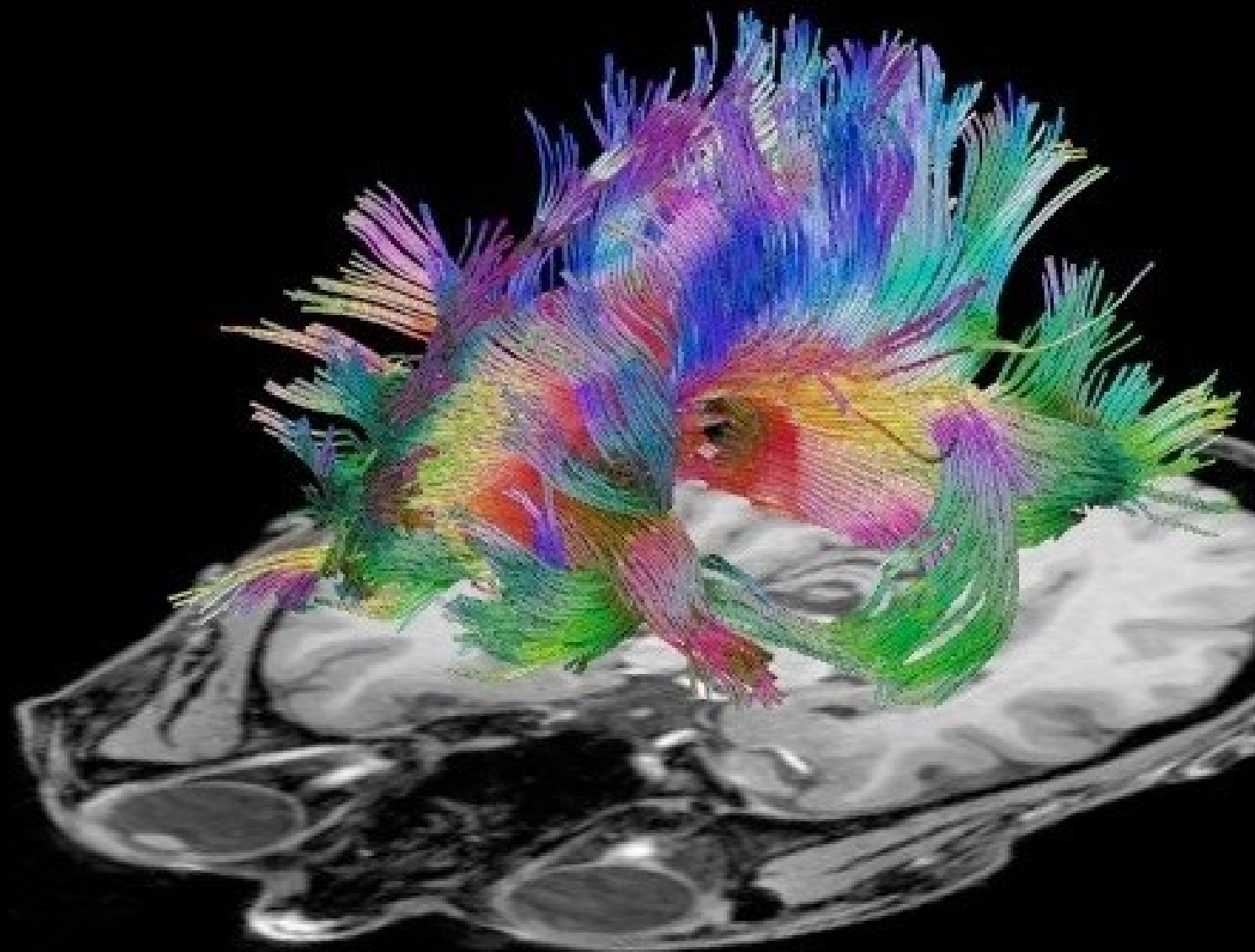
- Chemical shift
- Identification of metabolites
- Tumor diagnostics



Diffusion imaging



Anisotropic water diffusion:
contrast generation

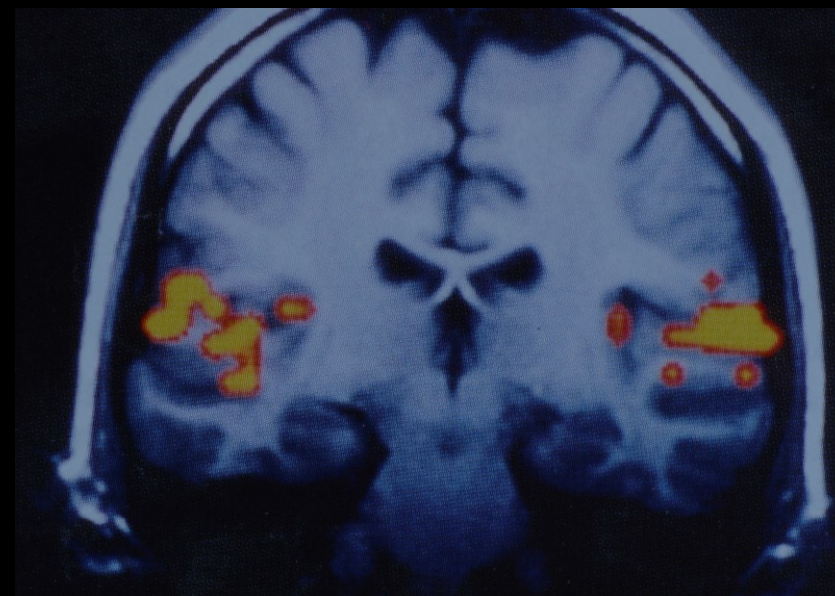
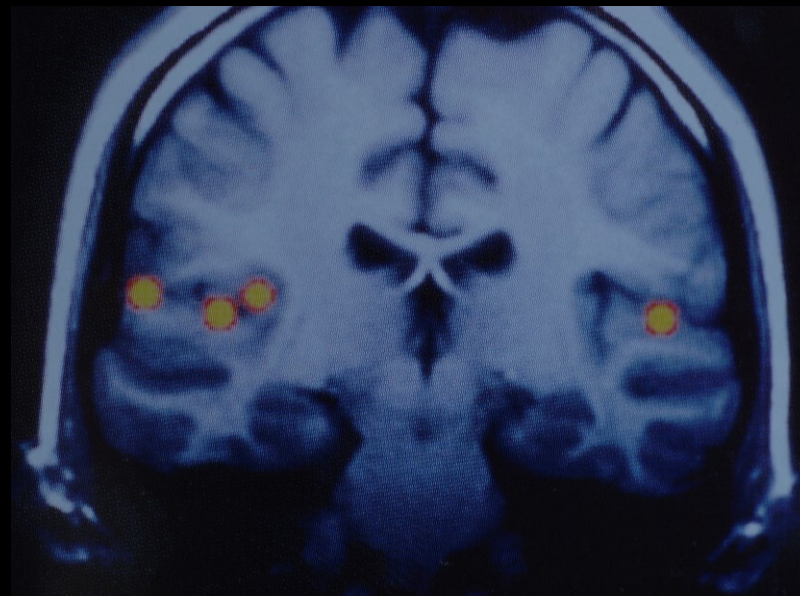


Imaging neural tracts:
tractography

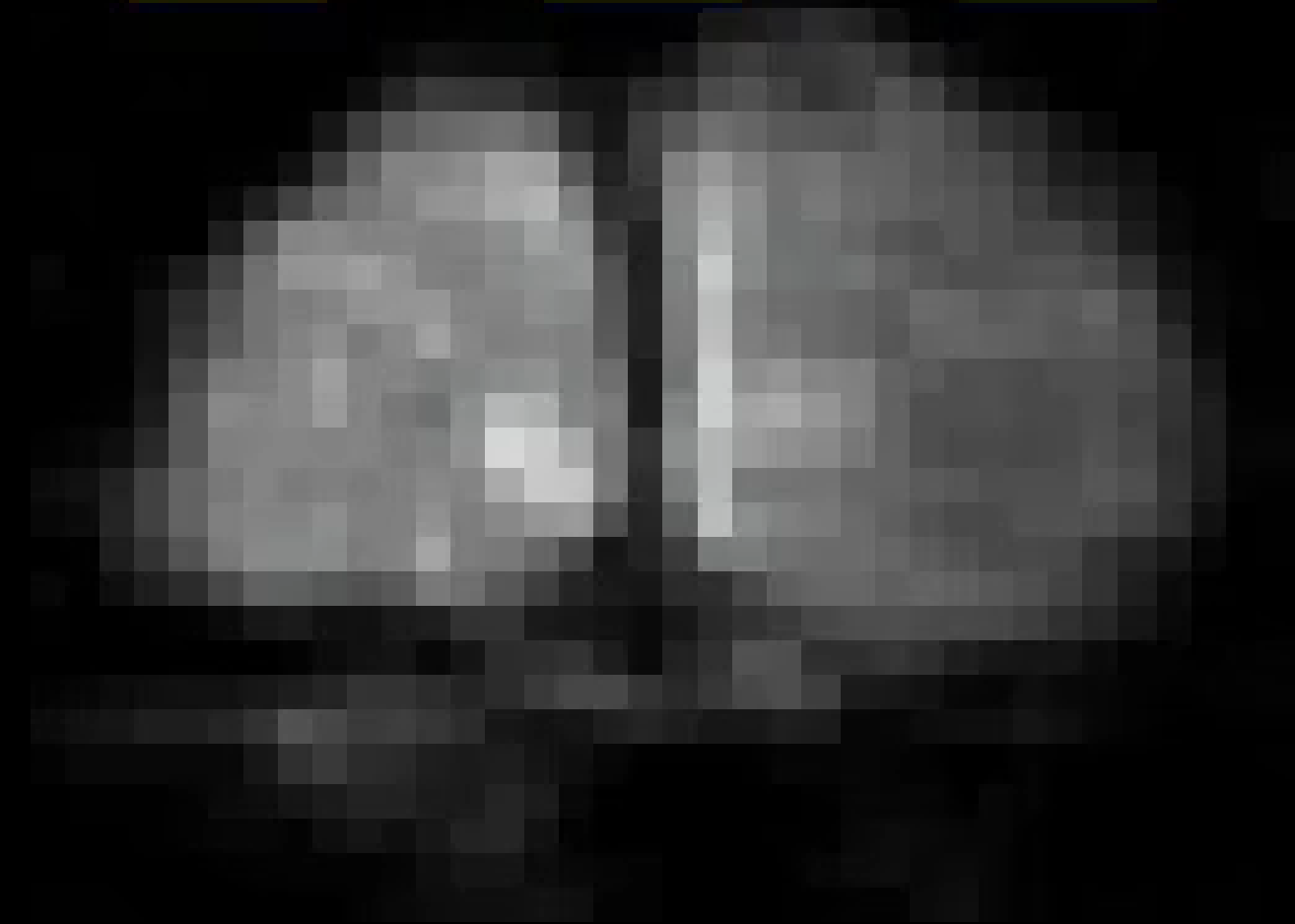
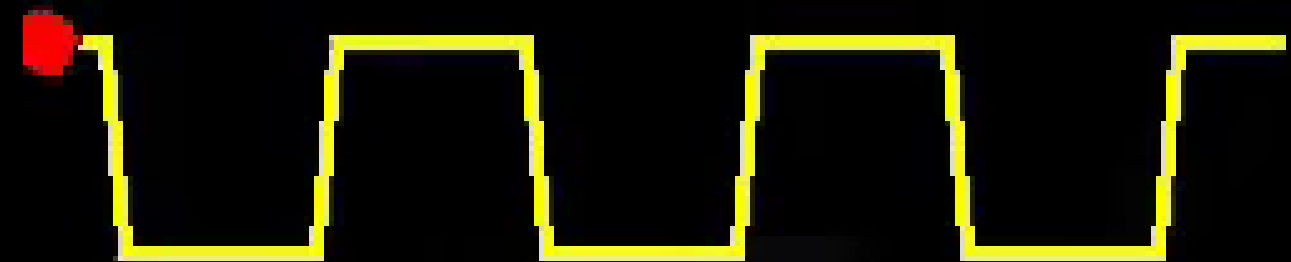
Corpus callosum

Functional MRI (fMRI)

High time resolution images recorded synchronously with physiological processes

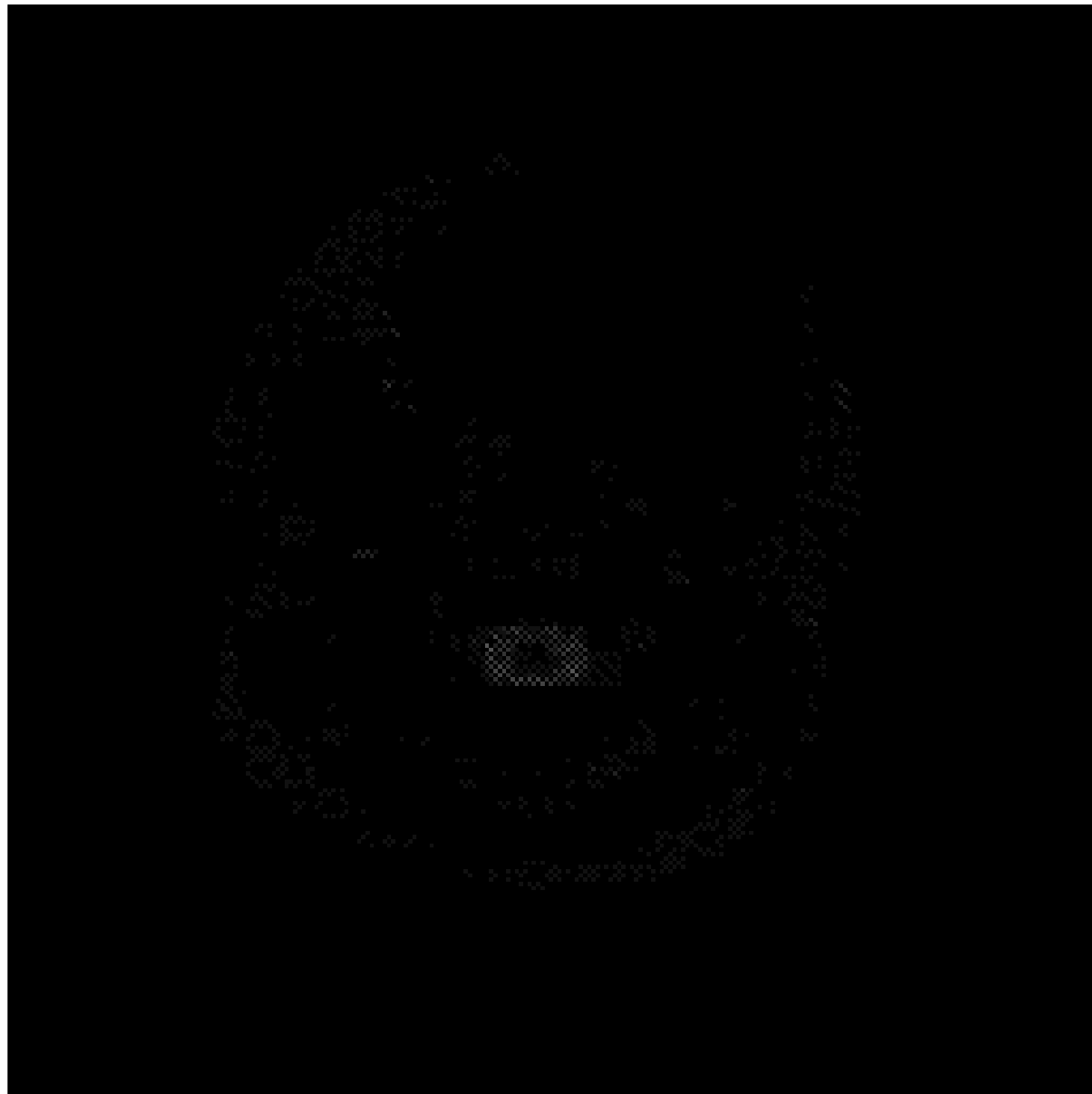


Activation in the
auditory cortex



Effect of light pulses on
the visual cortex

Superposition of MRI and PET



Intracranial tumor



PET signal: cortical areas activated
during eye movement
Volume rendering