



BASICS OF NUCLEAR MAGNETIC RESONANCE

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CIBM MRI EPFL

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PHYS-473

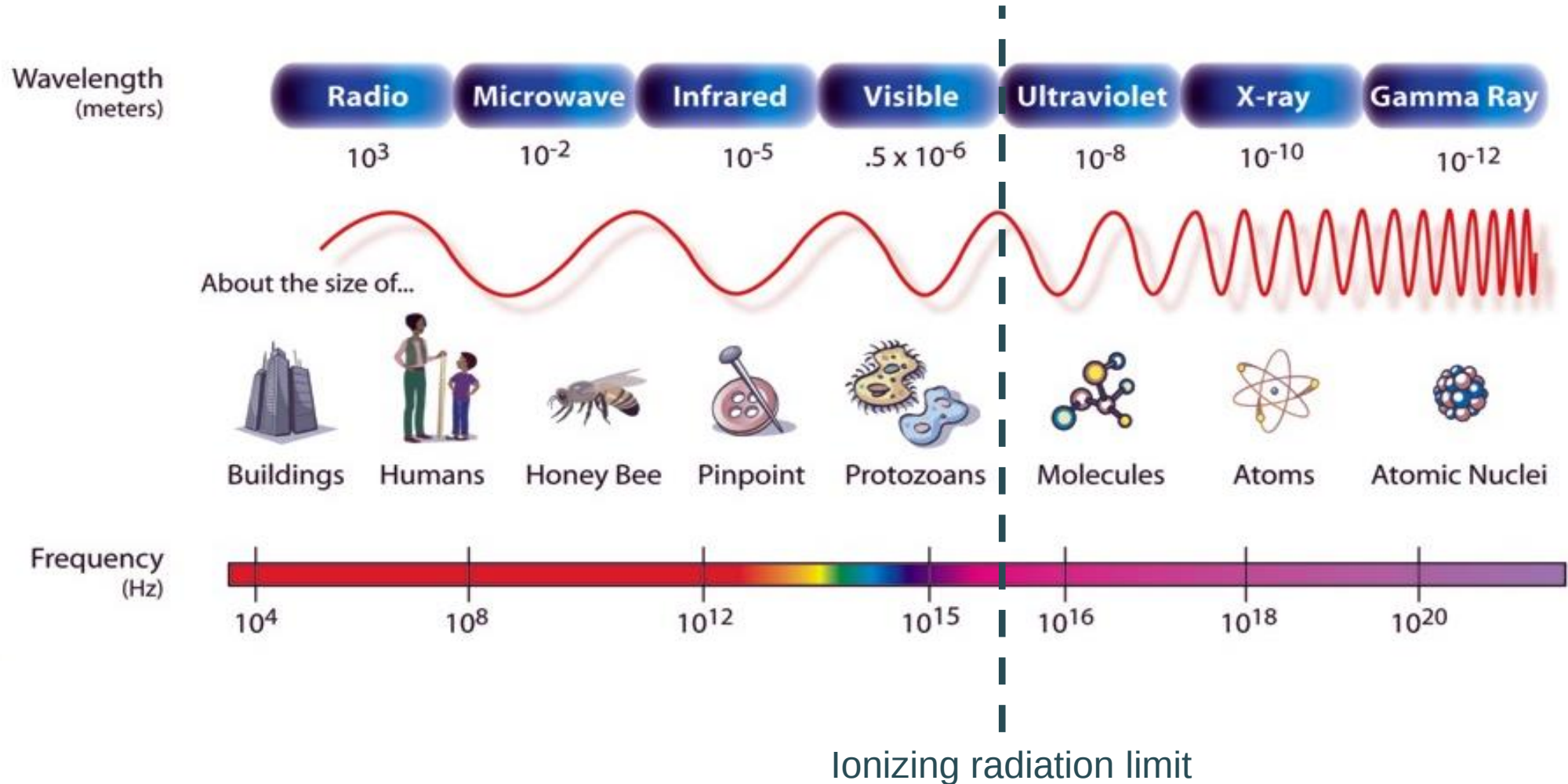
MRI Practicals on CIBM preclinical imaging systems

EPFL

C I B M . C H

THE INTERACTION OF MATTER WITH “RADIATION”

Electromagnetic waves



MAGNETIC RESONANCE IMAGING

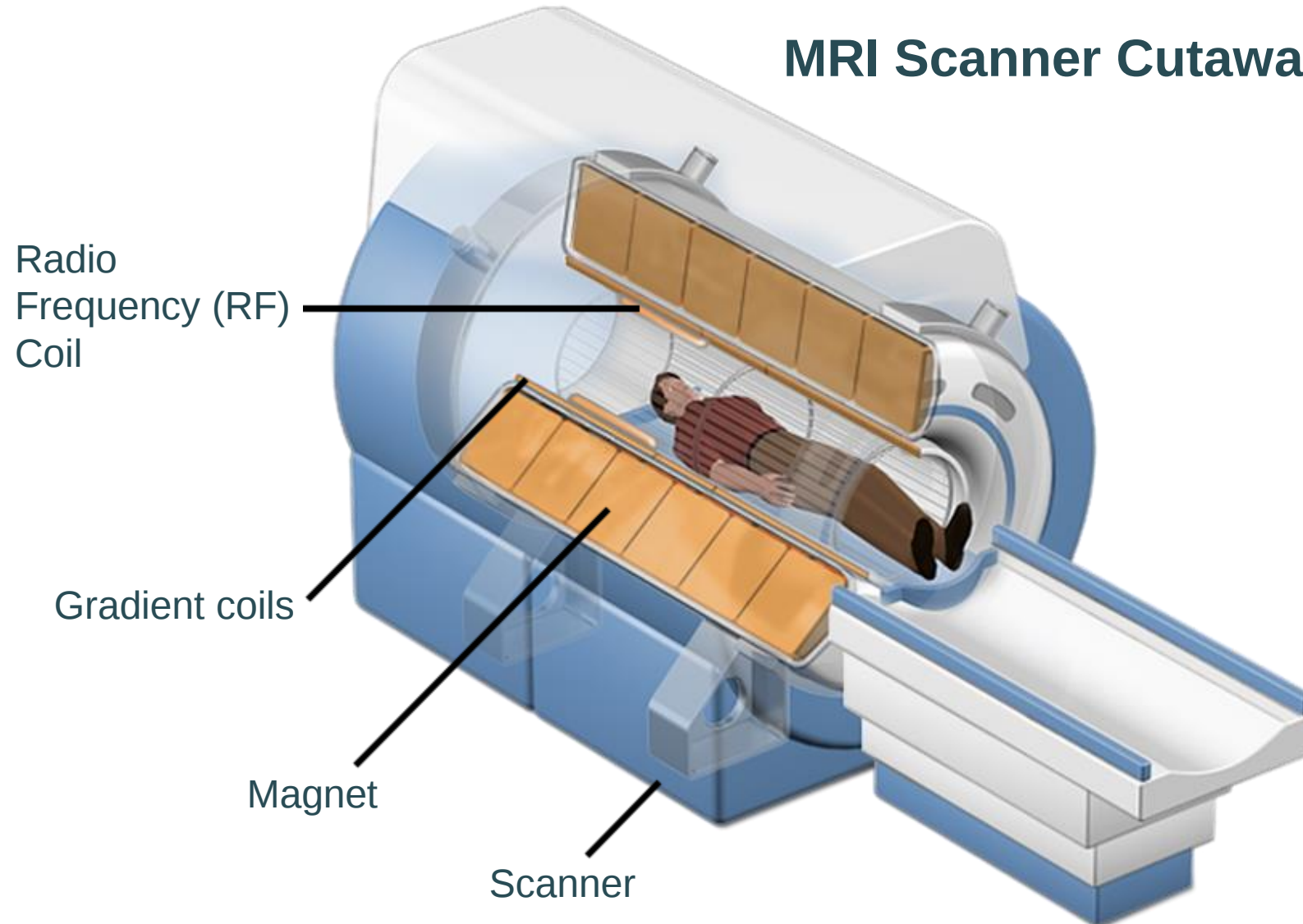


<https://nationalmaglab.org>

MAGNETIC RESONANCE IMAGING

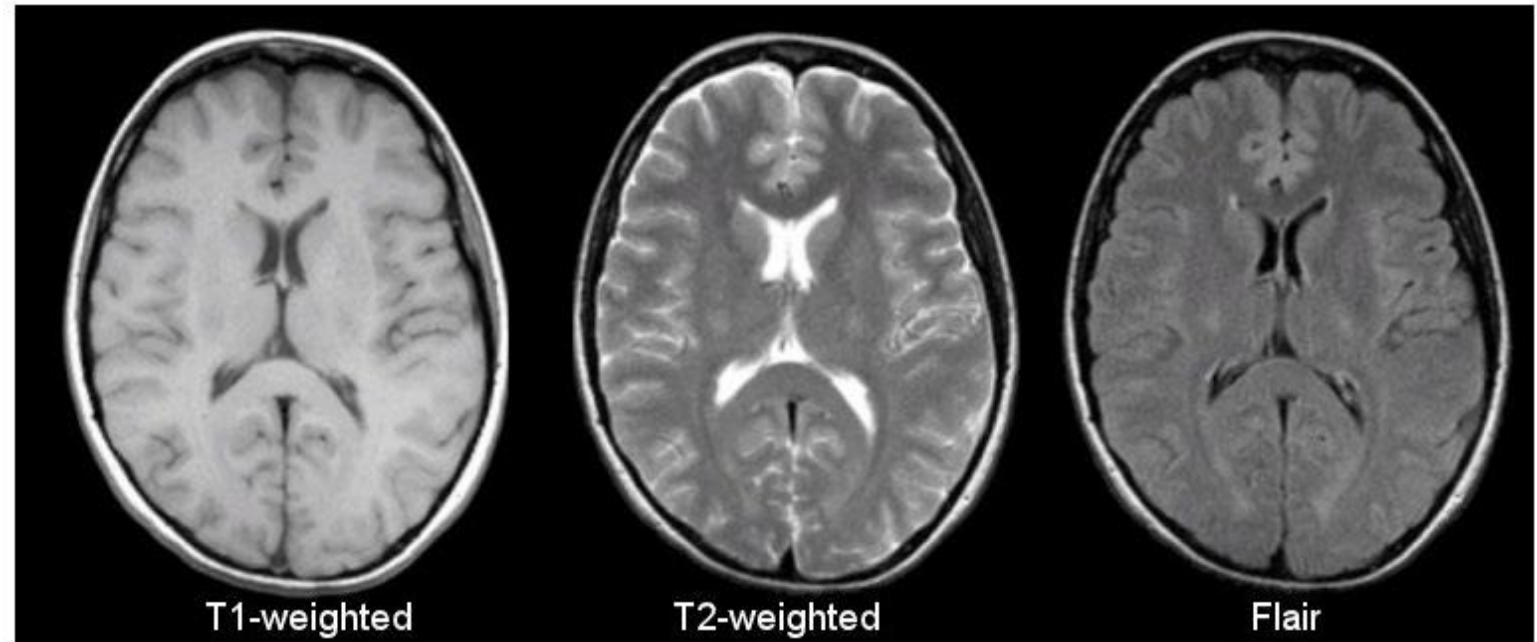
Equipment

MRI Scanner Cutaway



MAGNETIC RESONANCE IMAGING

Applications: soft tissue

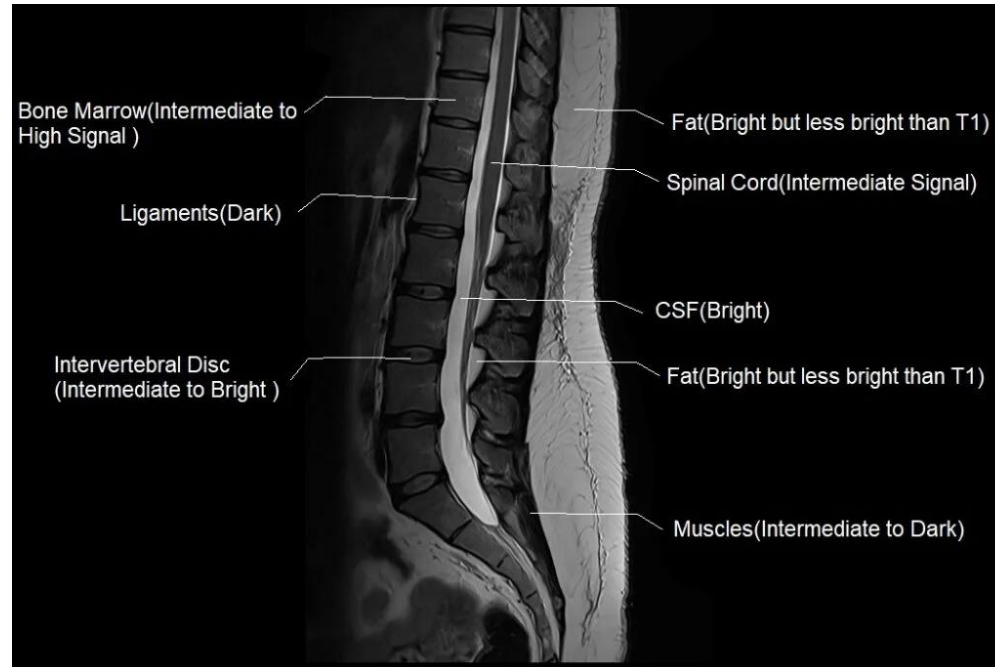


Tissue	T1-Weighted	T2-Weighted	Flair
CSF	Dark	Bright	Dark
White Matter	Light	Dark Gray	Dark Gray
Cortex	Gray	Light Gray	Light Gray
Fat (within bone marrow)	Bright	Light	Light
Inflammation (infection, demyelination)	Dark	Bright	Bright

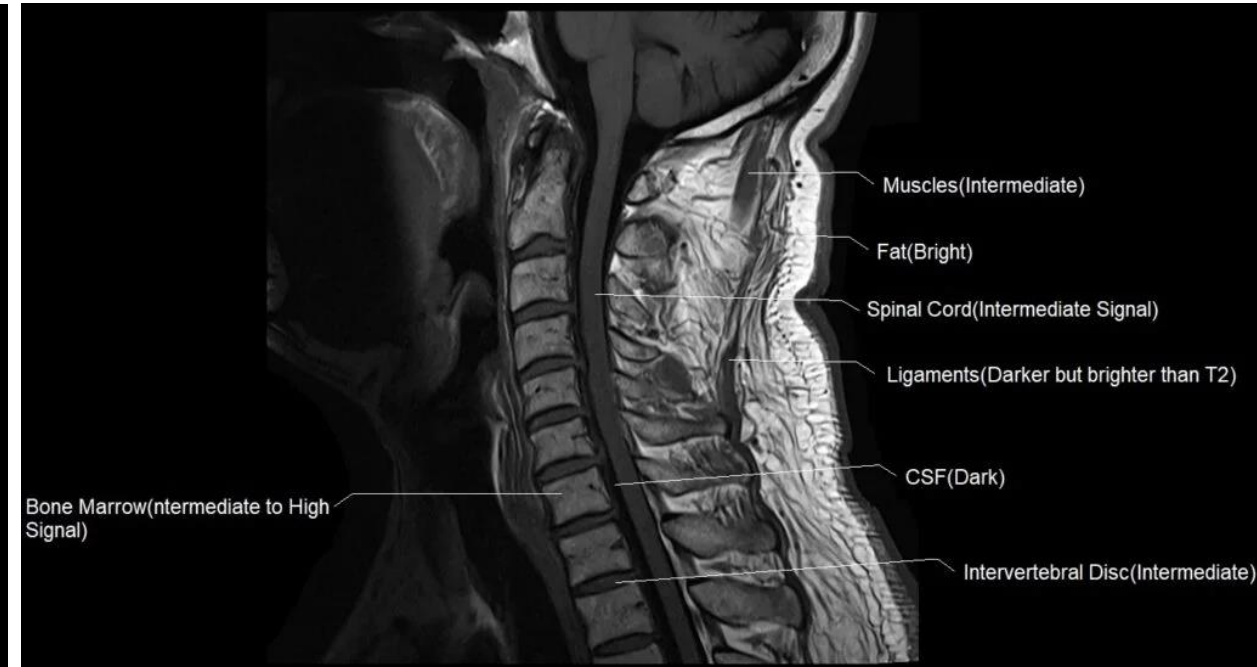
MAGNETIC RESONANCE IMAGING

Applications: anatomy

T2 MRI Image of the the lumbar spine



T1 MRI Image of the Cervical Spine



MAGNETIC RESONANCE IMAGING

Applications: Dynamic imaging



Journal of Cardiovascular Magnetic Resonance

Available online 2 August 2024, 101077

In Press, Journal Pre-proof [What's this?](#)

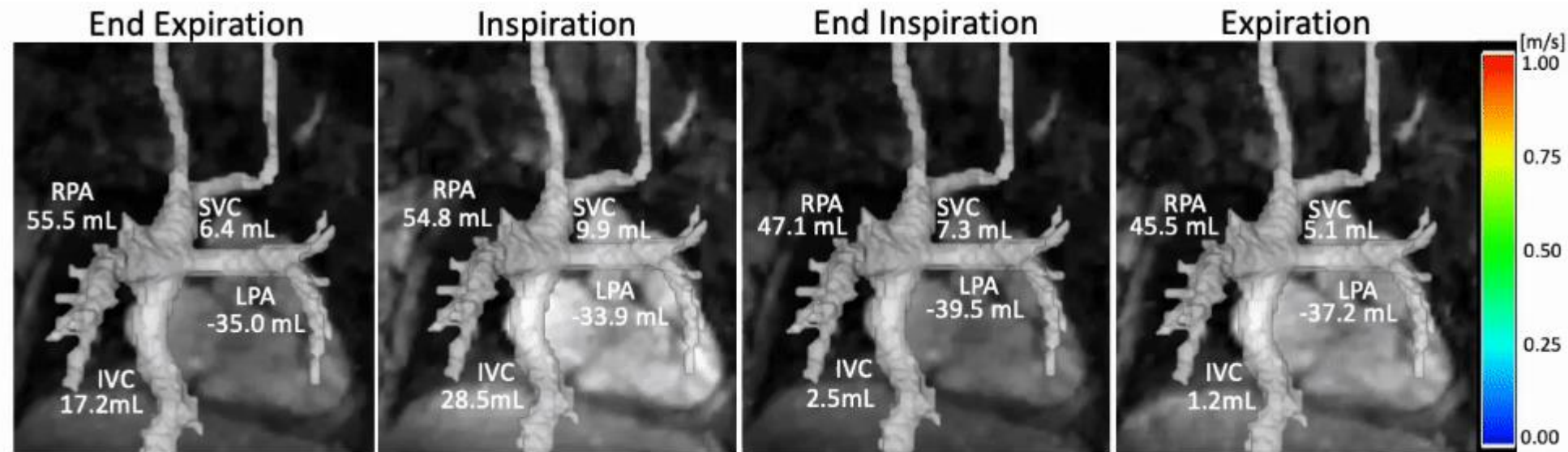


Original research

Respiratory-resolved 5D Flow MRI: *in-vivo* validation and respiratory dependent flow changes in healthy volunteers and patients with congenital heart disease

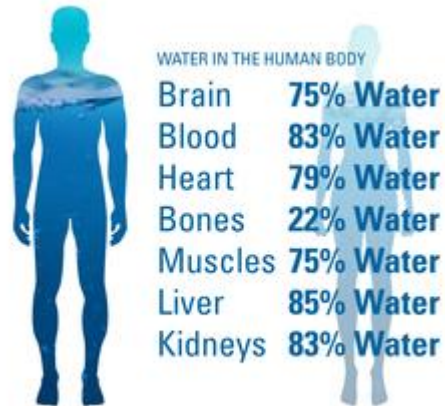
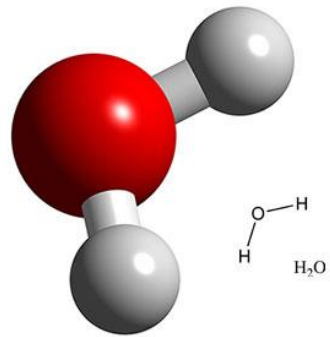
Elizabeth K. Weiss ^{a, b}, Justin Baraboo ^{a, b}, Cynthia K. Rigsby ^{a, c}, Joshua D. Robinson ^d, Liliana Ma ^a, Mariana B.L. Falcão ^e, Christopher W. Roy ^e, Matthias Stuber ^e, Michael Markl ^{a, b}

Hemodynamics measurements



MAGNETIC RESONANCE IMAGING -> SPECTROSCOPY

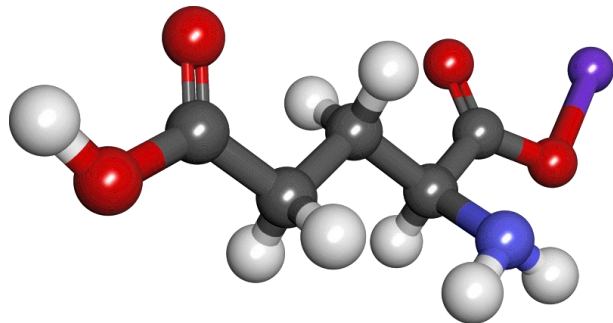
MRI:
Imaging ^1H of water



usgs.gov

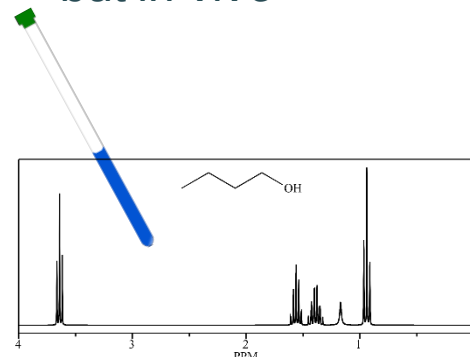
~ 55 M

MRS:
Measuring ^1H of biomolecules

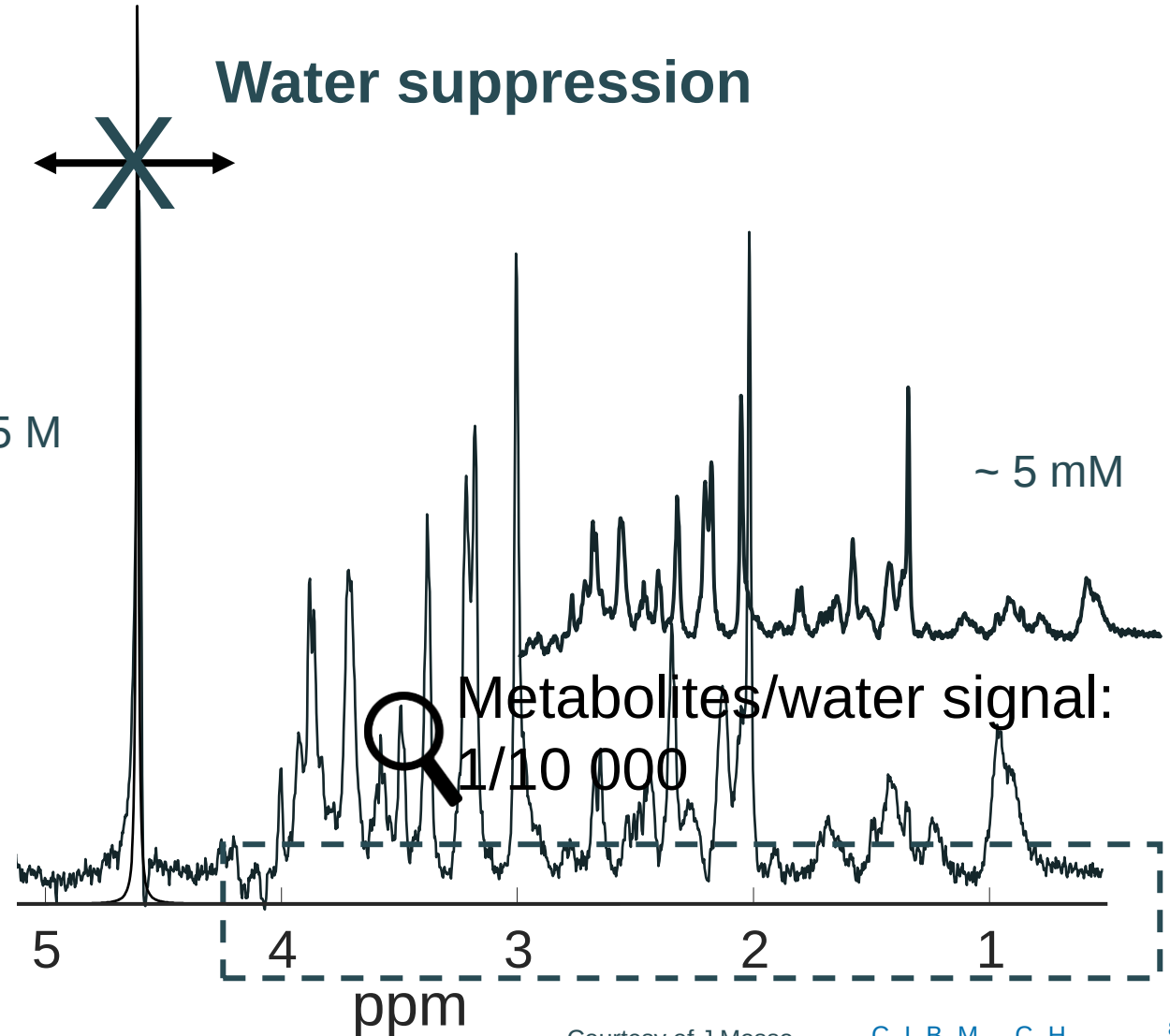


glutamate

As chemical NMR...
but *in vivo*



Water suppression



~ 5 mM

MAGNETIC RESONANCE IMAGING -> SPECTROSCOPY

Applications: biochemical analysis

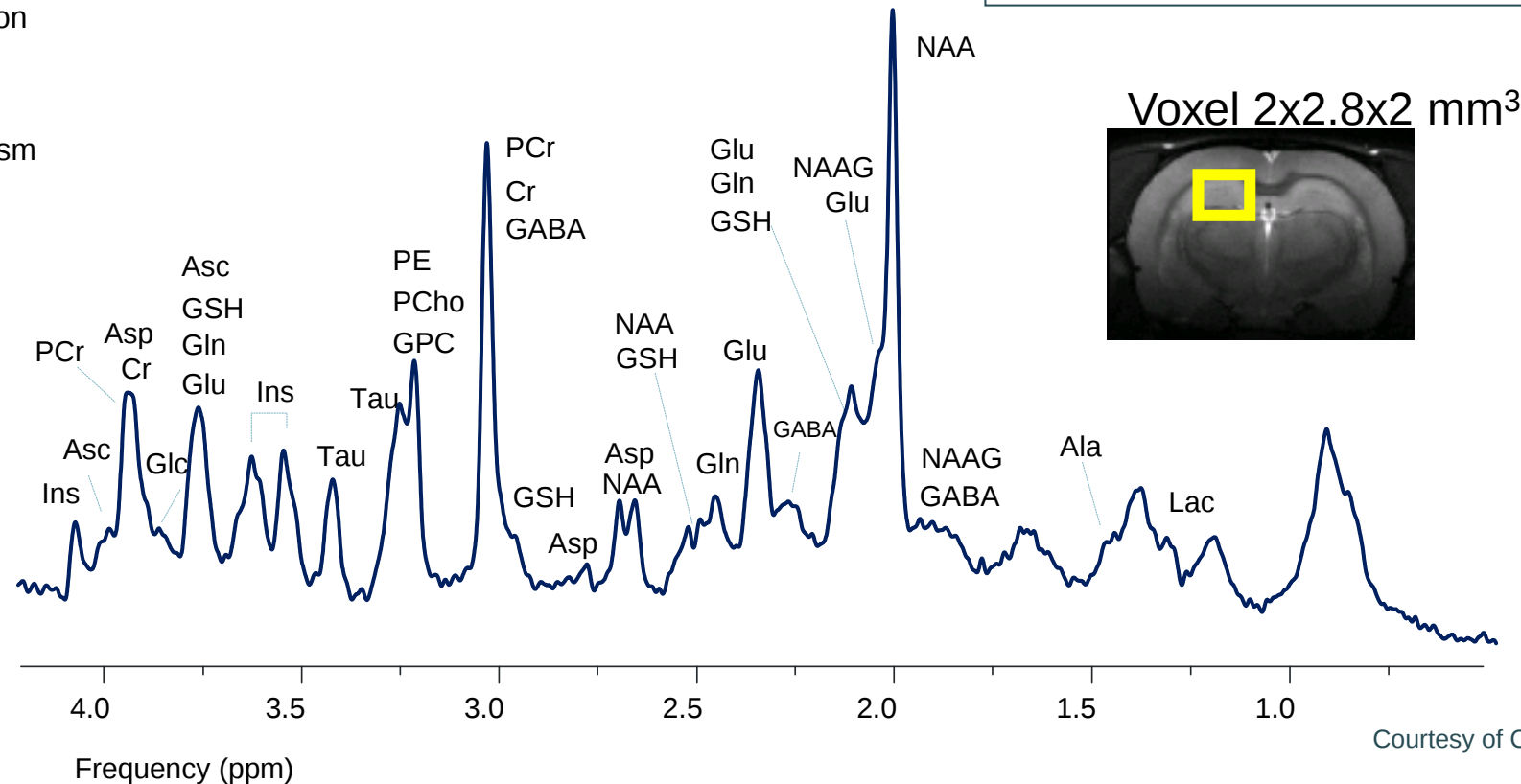
Neurochemical Profile at 9.4T (SPECIAL)

>18 Markers of :

Myelination/Cell proliferation
Energy metabolism
Osmoregulation
Neurotransmitter metabolism
Antioxidants

- at high magnetic field (9.4T)
- ultra short TE (2.8ms)

- *in vivo*
- non invasively
- localized in hippocampus



PRECLINICAL MRI AND MRS: WHY?

Preclinical vs clinical

- Framework of preclinical MRI / MRS (rats and mice in most cases)
 - Ethical considerations (ultimately, the goal is not to find ways to cure rodents...)
- Usefulness in terms of biological aspects
 - Animal models
 - Deeper understanding of diseases and healthy mechanisms
 - Follow-up of disease progression stages and treatments
- Usefulness in terms of MR physical aspects
 - New MR acquisition approaches
 - Can be developed on cutting-edge MR systems with less time constraints

THE ORIGIN OF MAGNETIC RESONANCE

- MRI/MRS are powerful imaging techniques for their flexibility and sensitivity to a wide range of tissue properties
- MRI/MRS are popular for their relative safety, their non-invasive nature, the use of no ionizing radiation.
- MRI/MRS are applications of NMR (nuclear magnetic resonance) to radiology.

(N) Nuclear (we play with the atom nucleus)
M Magnetic (we interact with it with magnetic fields)
R Resonance (we need to match the RF field to the natural precession of the nucleus)
I/S Imaging or Spectroscopy (the outcome measurements)

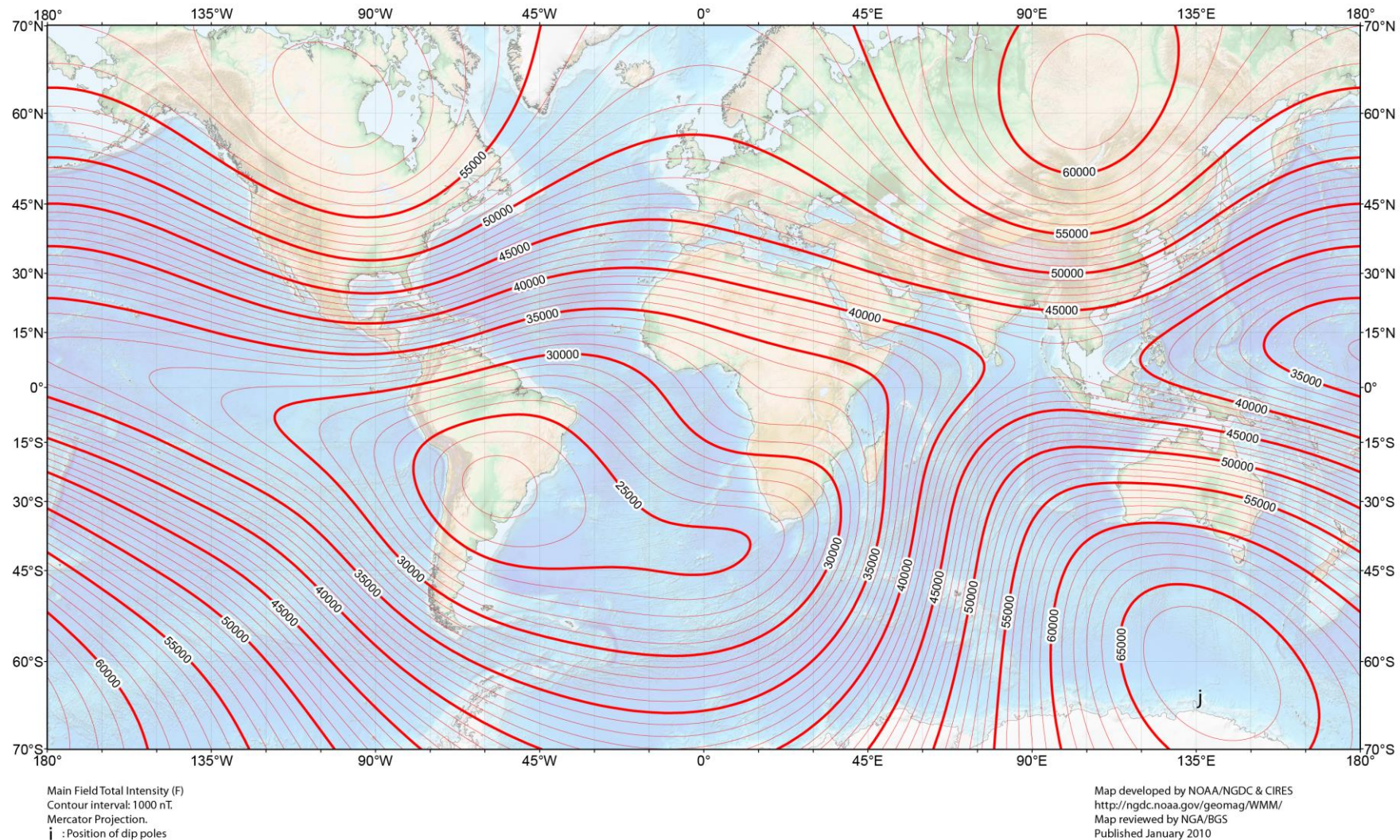
NUCLEAR MAGNETIC RESONANCE

Magnetic fields in the game:

- Main magnetic field B_0 : on the order of 1 T
- Gradient fields G_x, G_y, G_z : on the order of 100 mT/m
- Radio frequency (resonant) field B_1 : on the order of 10 μ T
 - Very low amplitude (earth magnetic field $\approx$ 25-65 μ T)
 - Very high frequency (on the order of 100 MHz)
 - Depends linearly on the applied B_0 field and Nucleus of interest

COMPARISON WITH EARTH MAGNETIC FIELD

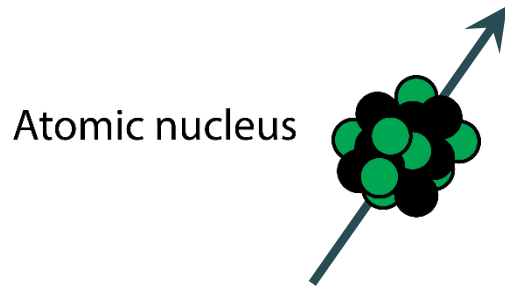
US/UK World Magnetic Model -- Epoch 2010.0
Main Field Total Intensity (F)



THE ORIGIN OF MAGNETIC RESONANCE

The dual nature of the MR phenomenon

Interaction of magnetic moments of nuclei with the magnetic field:



- proton (spin 1/2)
- neutron (spin 1/2)

- Atomic nuclei possess an intrinsic angular momentum (spin) L , as a composition of the spin of their composing protons and neutrons
- According to quantum mechanics, L is quantized: $|\vec{L}| = \left(\frac{h}{2\pi}\right) \sqrt{I(I+1)}$
 $I = 0, 1/2, 1, 3/2, \dots$

Depending on their composition:

- even number of protons and neutrons
- odd number of protons and neutrons
- odd number of protons and even number of neutrons
- odd number of neutrons and even number of protons

$I=0$

$I=\text{integer}$

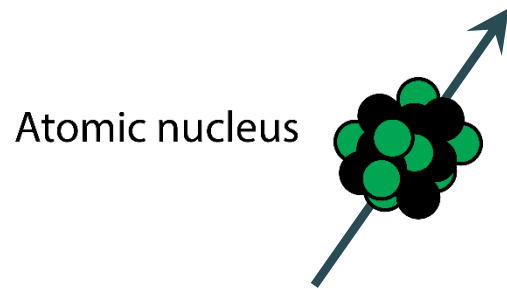
$I=\text{half-integer}$

$I=\text{half-integer}$

NUCLEAR SPIN AND MAGNETIC MOMENT

The dual nature of the MR phenomenon

Interaction of magnetic moments of nuclei with the magnetic field:



Atomic nucleus

- proton (spin 1/2)
- neutron (spin 1/2)

- The intrinsic angular momentum L is associated to a magnetic moment μ :

$$\vec{\mu} = \gamma \vec{L}$$

with γ the gyromagnetic ratio, specific for each nucleus, specifying the strength of coupling between the magnetic field and the angular momentum.

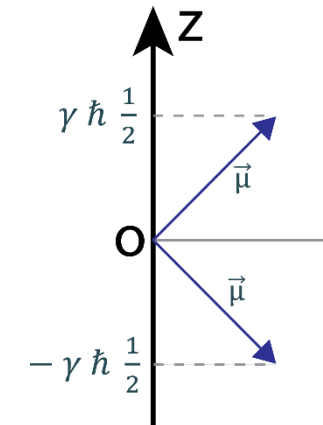
- In the magnetic field $\vec{B}_0$ defined as $\vec{B}_0 = B_0 \hat{e}_z$, the measured projection of the nuclear magnetic moment $\vec{\mu}$ are quantized:

$$\mu_z = \gamma \hbar m$$

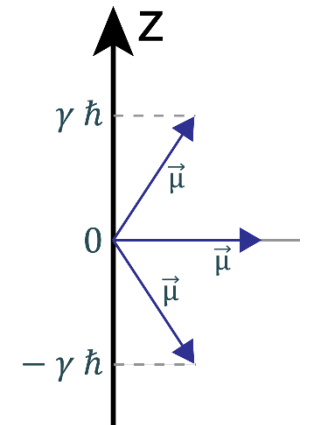
with $m = -l, -l+1, \dots, l-1, l$

($2l+1$ values)

spin 1/2



spin 1



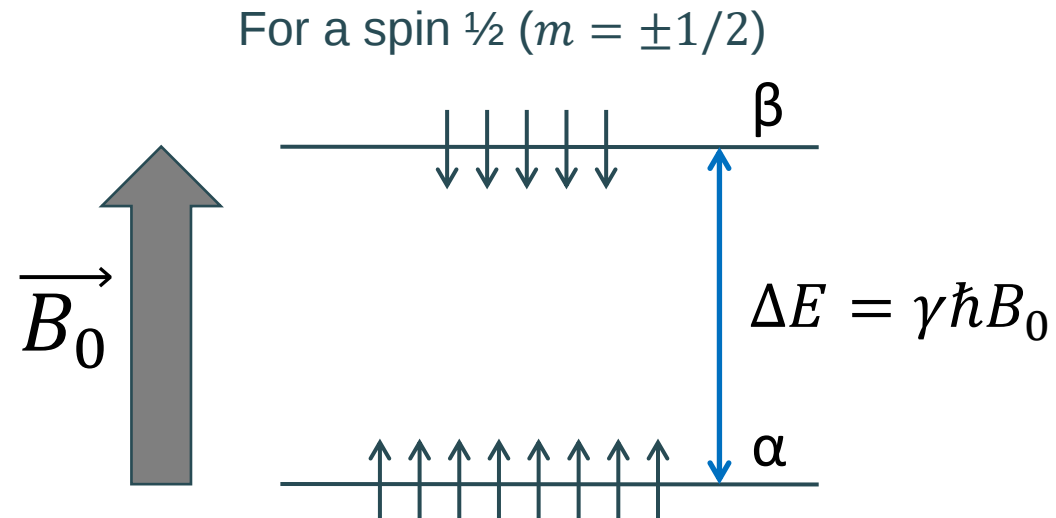
ZEEMAN ENERGY LEVELS

- Zeeman energy:

Potential energy of a magnetized nucleus in an external magnetic field

$$E = -\vec{\mu} \cdot \vec{B}_0$$

$$E = -\mu_z B_0 = -\gamma \hbar m B_0$$

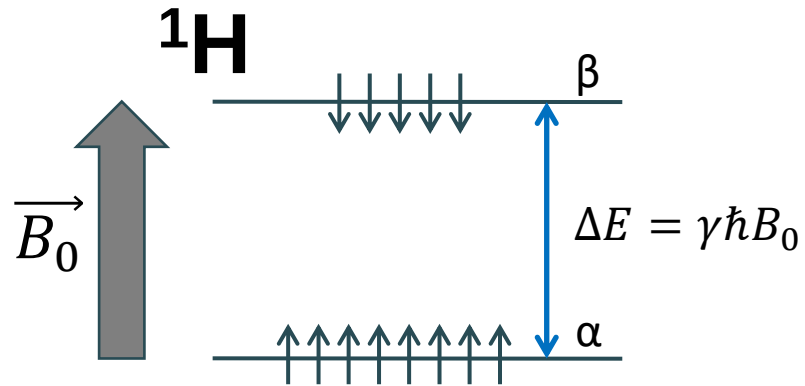


There is no spontaneous transition between energy levels
(no emission of energy)

All changes in the energy of nuclei are through stimulated transitions

ZEEMAN ENERGY LEVELS: SPIN DISTRIBUTION

- Zeeman energy:



Boltzmann distribution:

$$\left(\frac{n_{\alpha}}{n_{\beta}}\right) = e^{\frac{\gamma B_0 \hbar}{kT}}$$

Linearized Boltzmann distribution: $(n_{\alpha} - n_{\beta}) \approx \left(\frac{n h \gamma B_0}{2kT}\right)$

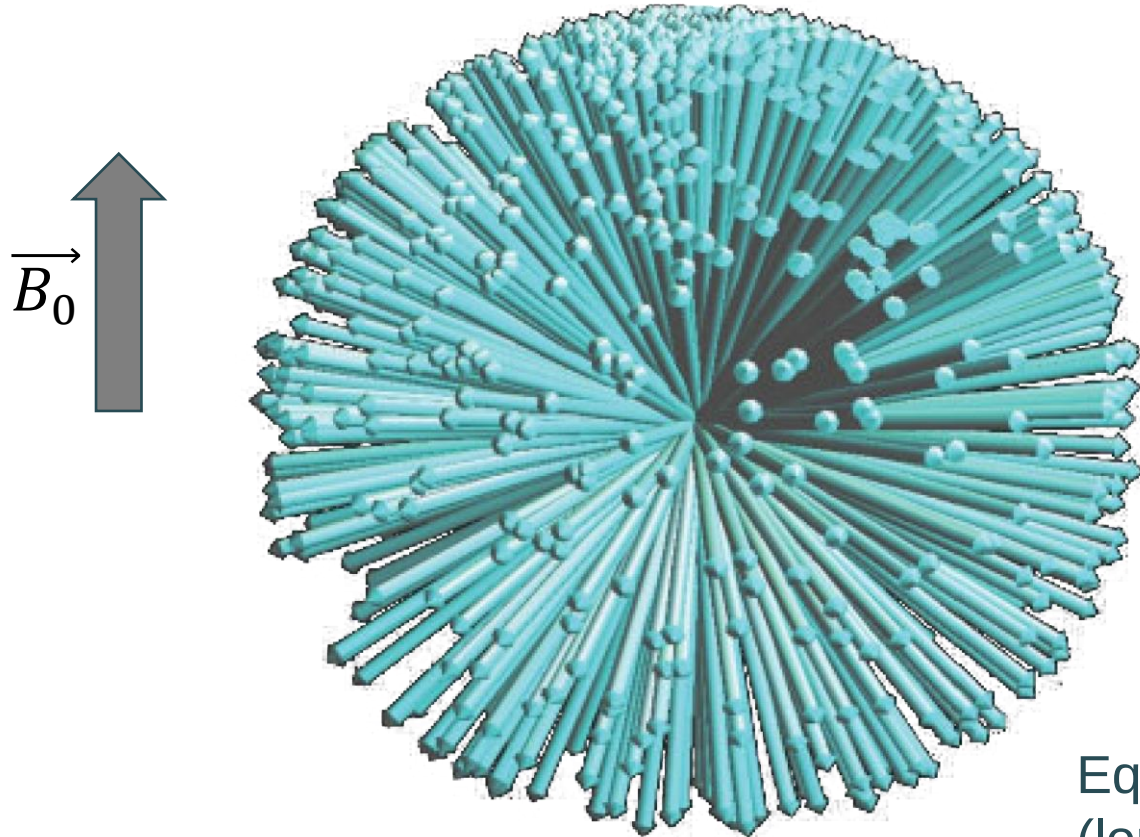
- Amplitude of the magnetization: $M_0 = (n_{\alpha} - n_{\beta}) \mu_z = (n_{\alpha} - n_{\beta}) \gamma \frac{\hbar}{2}$
- Total magnetization: $M_0 = n \frac{1}{2} (\gamma \hbar)^2 \left(\frac{B_0}{2kT}\right) \propto \gamma^2$

INTERESTING NUCLEI / ISOTOPES

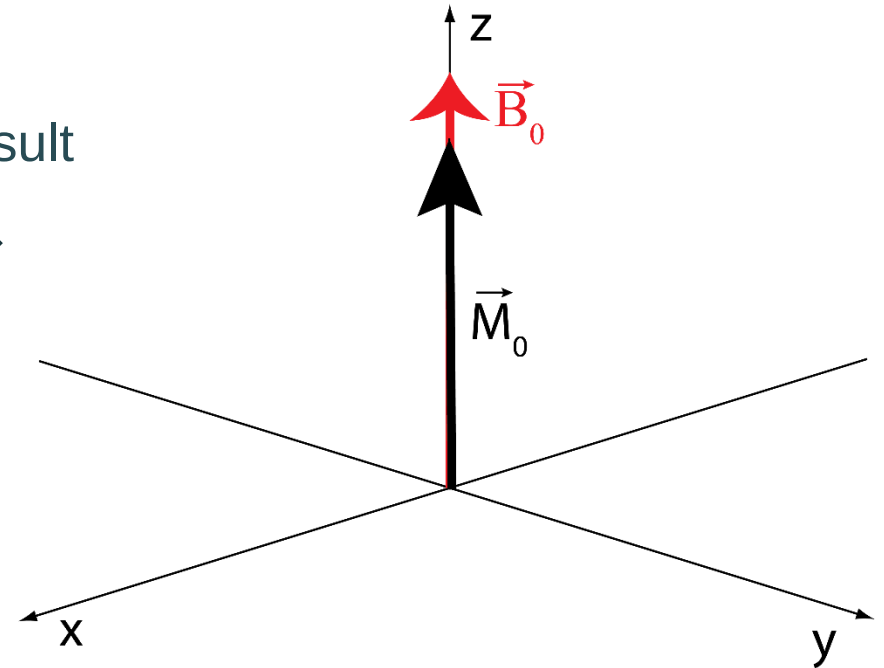
Nucleus	Magnetic moment	Gyromagnetic ratio (rad·MHz T ⁻¹)	Relative sensitivity	Natural abundance (%)
¹H	1/2	267.522	1.0	99.98
² H	1	41.066	0.00965	0.015
¹³ C	1/2	67.283	0.0159	1.108
¹⁴ N	1	19.338	0.0101	99.63
¹⁵ N	1/2	-27.126	0.0104	0.37
¹⁹ F	1/2	251.815	0.83	100
²³ Na	3/2	70.808	0.0925	100
²⁹ Si	1/2	-53.190	0.00784	4.7
³¹ P	1/2	108.394	0.0663	100

MACROSCOPIC MAGNETIZATION

Large spin ensemble



Magnetization



Equilibrium magnetization M_0 is parallel with B_0 (longitudinal magnetization), its status can be changed by a radiofrequency magnetic field

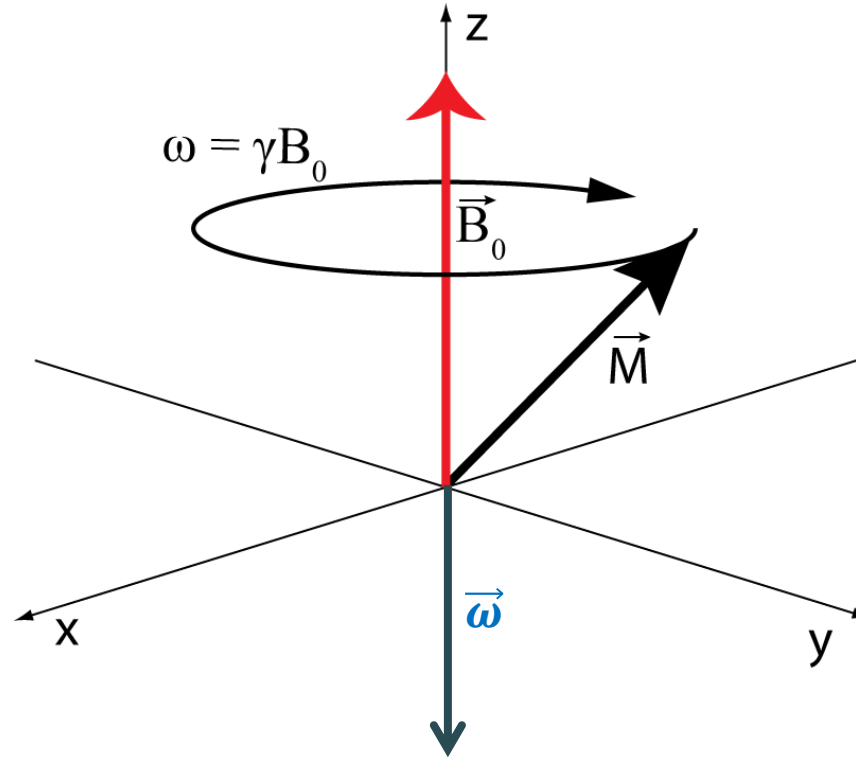
PRECESSION

Equation of precession:

$$\frac{d\vec{M}}{dt} = \gamma \vec{M} \times \vec{B}_0$$

For positive γ (^1H , ^{13}C , ^{31}P)

($\vec{\omega} // \vec{B}_0$ for negative γ , ^{15}N , ^{17}O)

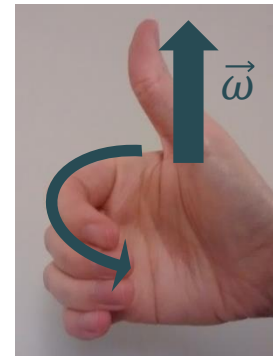


Rotation defined with an angular speed vector:

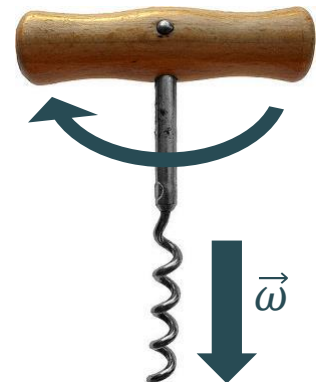
$$\frac{d\vec{M}}{dt} = \vec{\omega} \times \vec{M}$$

With

$\omega = \gamma B_0 \equiv \omega_0$ The Larmor frequency



Or corkscrew rule...



THE ROTATING FRAME(S)

LARMOR FRAME

In the laboratory frame:

$$\frac{d\vec{M}}{dt} = \gamma \vec{M} \times \vec{B}_0$$

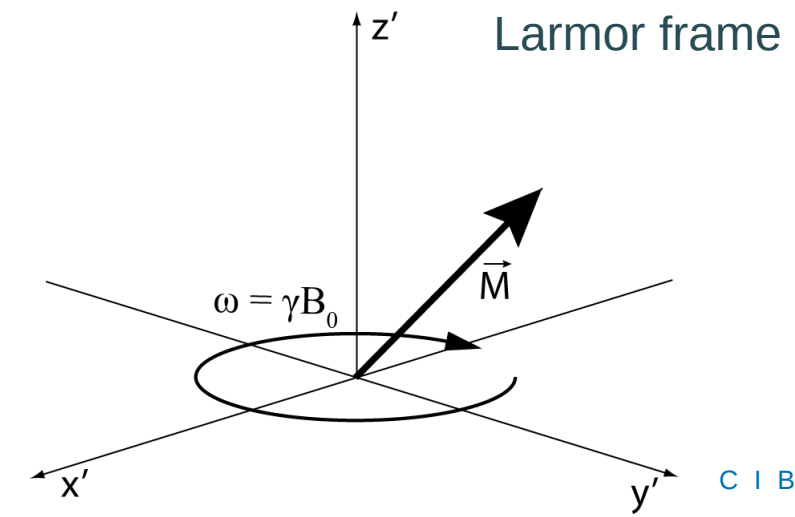
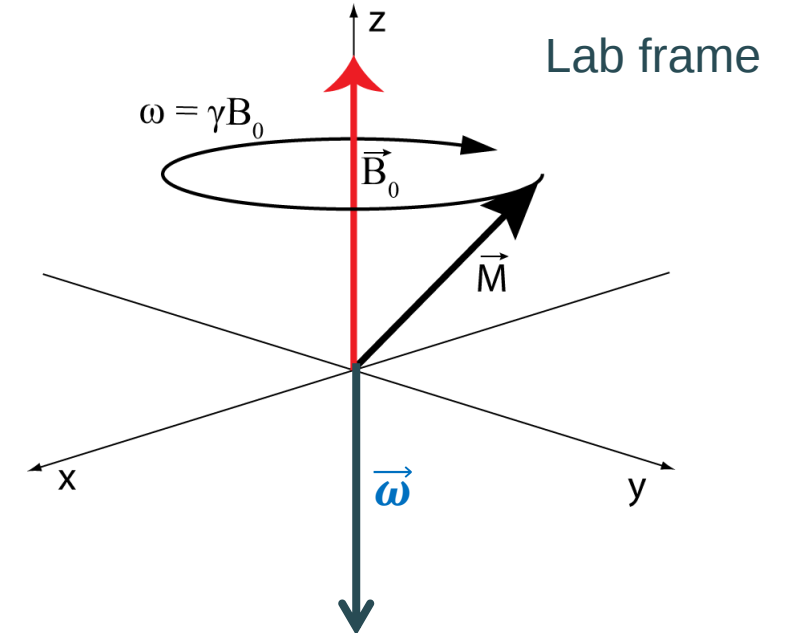
Expression in the rotating frame:

$$\left(\frac{d\vec{M}}{dt}\right)_{lab} = \left(\frac{d\vec{M}}{dt}\right)_{rot} + \vec{\omega} \times \vec{M}$$

In the Larmor rotating frame:

$$\left(\frac{d\vec{M}}{dt}\right)_{rot} = \left(\frac{d\vec{M}}{dt}\right)_{lab} + \gamma \vec{B}_0 \times \vec{M}$$

$$\frac{d\vec{M}}{dt} = 0 \rightarrow \text{No apparent } B_0 \text{ magnetic field}$$



FLIP ANGLE

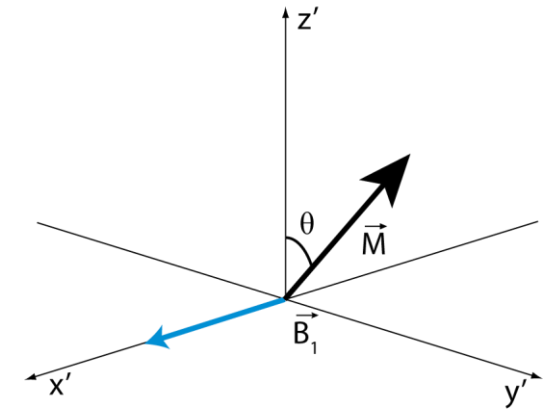
THE RESONANCE CONDITION

If we apply a pulse $B_1(t)$ right at the Larmor frequency of the considered spin system

$$\rightarrow \omega_{RF} = \omega_0$$

The dynamics of the magnetization is very much simplified:

$$\left(\frac{d\vec{M}}{dt}\right)_{rot} = \gamma \vec{M} \times \vec{B}_1(t) \quad \text{with } B_1(t) \text{ the envelope of the pulse}$$

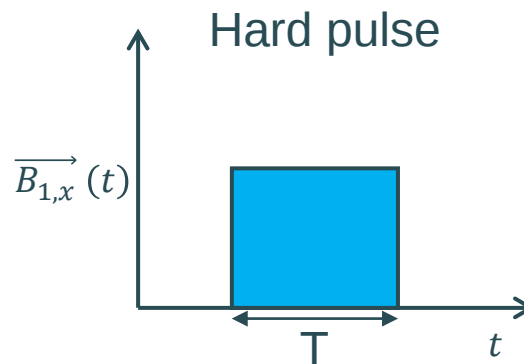


Flip angle (nutation angle)

$$\theta = \gamma \int_t^T B_1(t) dt$$

For a hard pulse

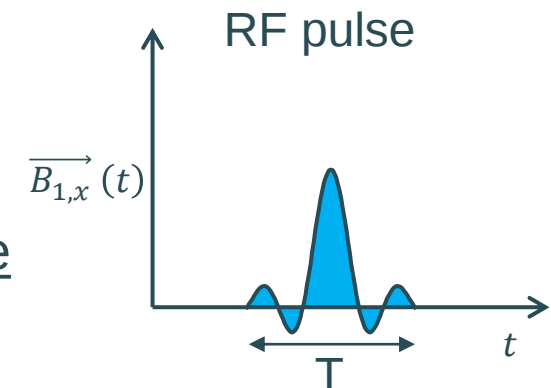
$$\theta = \gamma B_1 T$$



For a general pulse

$$\theta = \gamma B_1 T S_{int}$$

with S_{int} the pulse shape integral

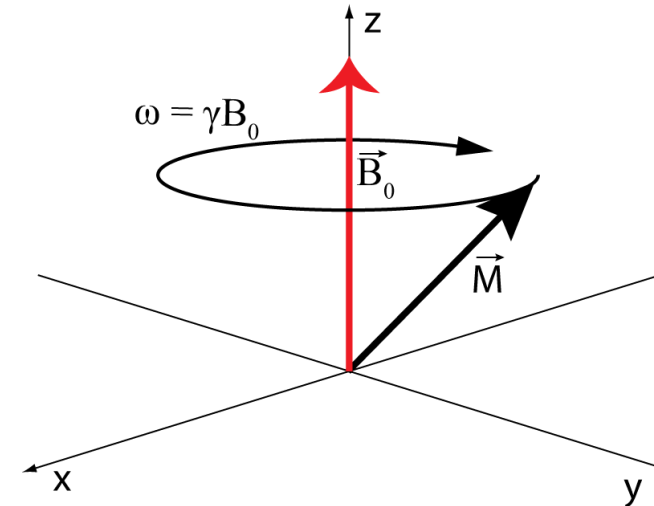


QUANTUM DESCRIPTION

Single spin expectation values

Haake et al., Magnetic Resonance Imaging, Physical principles and sequence design, Wiley 1999

$$\begin{aligned}\langle \mu_x \rangle &= \frac{\gamma \hbar}{2} \sin \theta \cos (\phi_0 - \omega_0 t) \\ \langle \mu_y \rangle &= \frac{\gamma \hbar}{2} \sin \theta \sin (\phi_0 - \omega_0 t) \\ \langle \mu_z \rangle &= \frac{\gamma \hbar}{2} \cos \theta\end{aligned}$$



$$\begin{aligned}\langle \mu_{x'}(t) \rangle &= \langle \mu_{x'}(0) \rangle \\ \langle \mu_{y'}(t) \rangle &= \langle \mu_{y'}(0) \rangle \cos \omega_1 t + \langle \mu_z(0) \rangle \sin \omega_1 t \\ \langle \mu_z(t) \rangle &= -\langle \mu_{y'}(0) \rangle \sin \omega_1 t + \langle \mu_z(0) \rangle \cos \omega_1 t\end{aligned}$$

