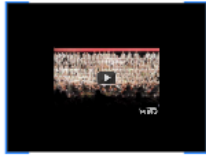


# MRI – Basic principles of medical imaging

Krisztián Szigeti

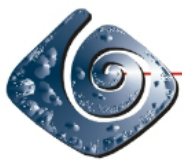


1947 Nobel prize in physics  
 • Felix Bloch  
 • Edward M. Purcell  
 1977 Nobel prize in physics  
 • Paul Lauterbur  
 • Peter Mansfield  
 • Raymond Damadian



# MRI – Basic principles of medical imaging

Krisztián Szigeti

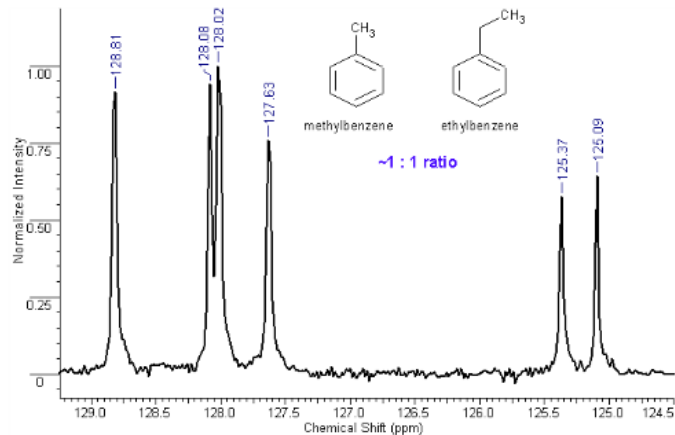


Nanobiotechnológiai és In Vivo Képzési Központ  
**Semmelweis**  
**NIVIC**  
Nanobiotechnology and In Vivo Imaging Center

Biophysics and  
Radiation Biology

## 1947 NMR material science (1952 - Nobel prize):

- Felix Block
- Edward M. Purcell



## 1977 Clinical MRI (2003):

- Paul Lauretbur
- Peter Mansfield
- Raymond Damadian



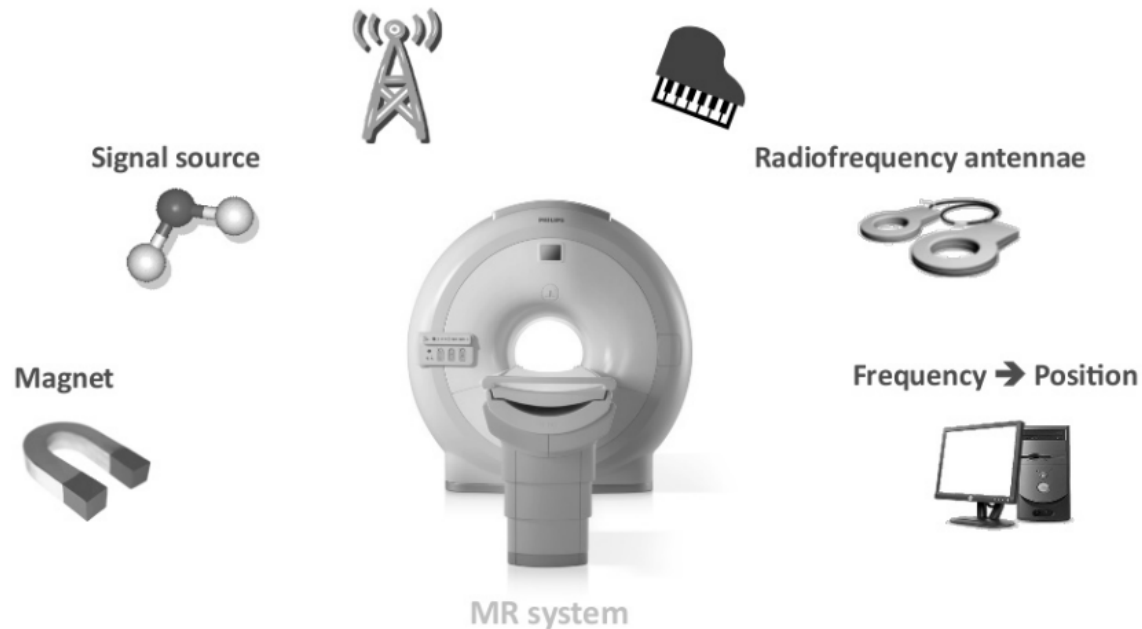


You Tube



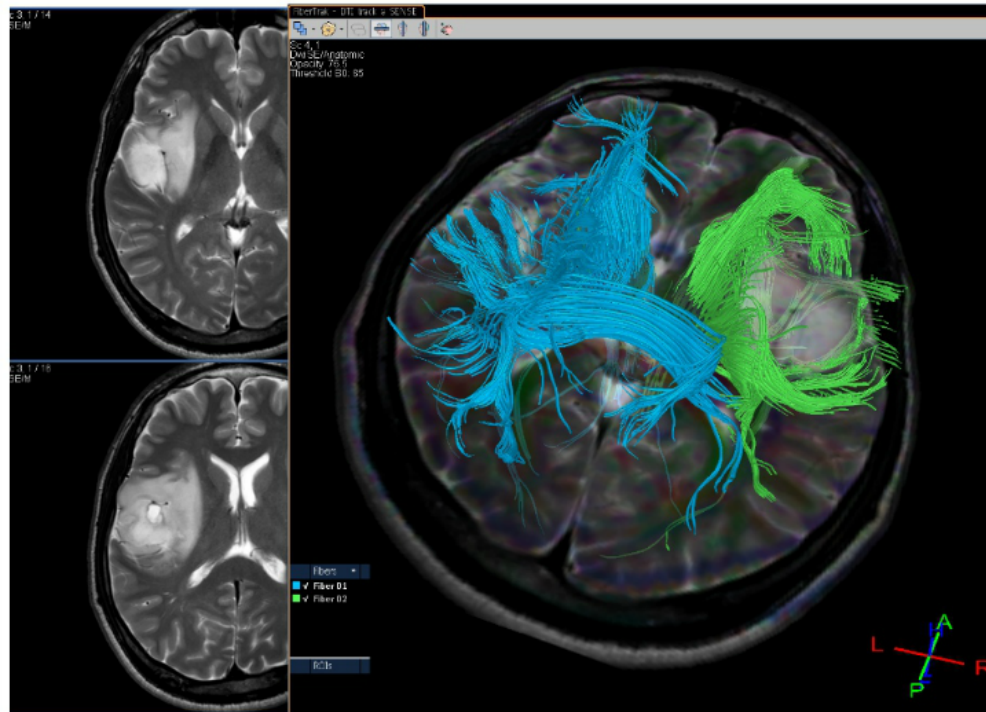
## How does MRI work?

Radiofrequency transmitter    Position → Frequency



- Patient in a strong homogeneous magnetic field
- Excitation of a part of patient tissue by radiofrequency pulses
- Receive emitted radiofrequency signal from the patient
- Repeat the former two steps voxel by voxel in a plane

How could be produce these kind of images?



## What is the connection between choir and MRI?



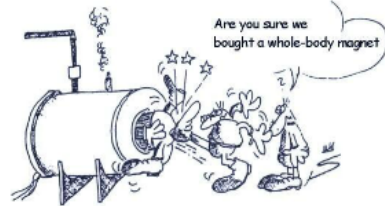
- Orchestra
- Singers
- Floors
- Pitch (frequency)
- Duration (canon)



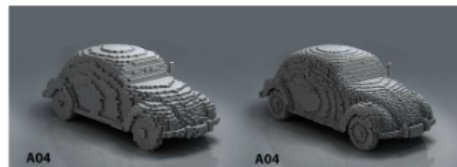
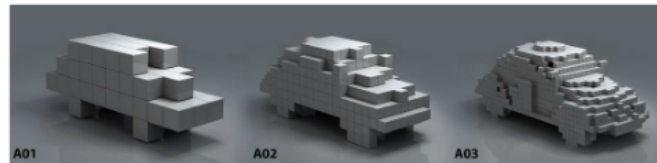
- Magnet (pl: 3T, He)
- Voxel (spins)
- Encoding (3D)

# Magnet and voxel

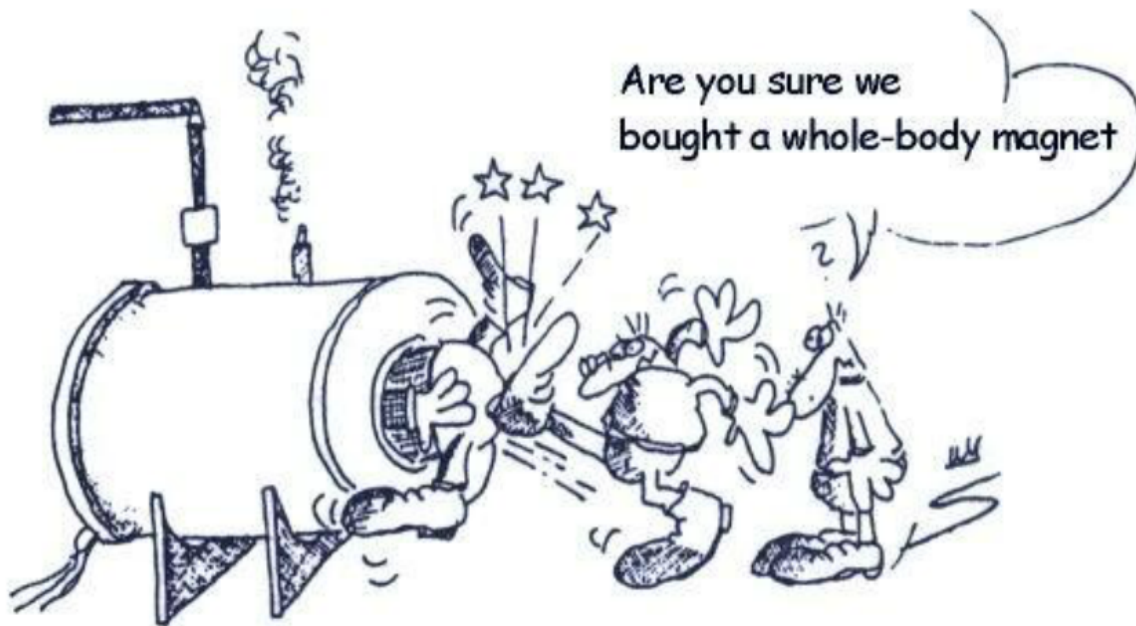
- Earth: 30uT
- MRI: 0.3-12T  
(100,000x )



## Voxel

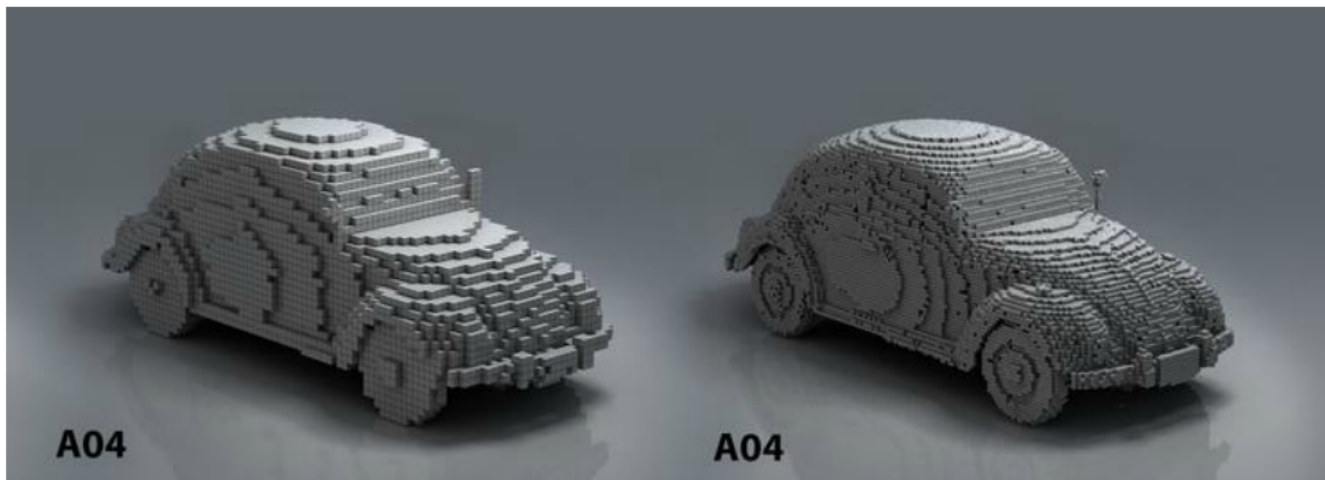
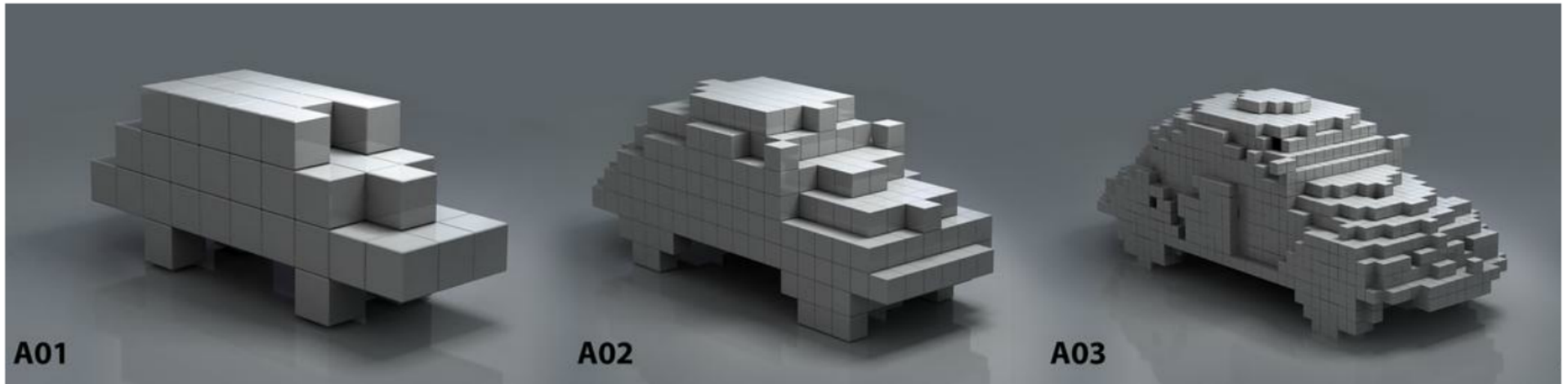


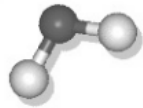
- Earth: 30uT
- MRI: 0.3-12T  
(100,000x )





# Voxel





What is signal source in a voxel?

**WITHOUT EXTERNAL MAGNETIC FIELD**

due to its spin  
a proton  
acts like  
a little  
magnet



spin

magnetic  
vector  
of a single  
spinning  
proton

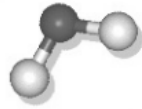


spins are  
not ordered



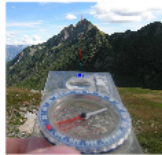
Spins in the selected voxel





What is signal source in a voxel?

A compass is a navigational instrument that shows directions (North - South)



The magnetic compass contains a magnet that interacts with the earth's magnetic field and aligns itself to point to the magnetic poles (N-S)



Spin = atomic level compass

What does the spin in the magnetic field?

A compass is a navigational instrument that shows directions (North - South)



The magnetic compass contains a magnet that interacts with the earth's magnetic field and aligns itself to point to the magnetic poles (N-S)

Spin = atomic level compass



What does the  
spin in the  
magnetic  
field?

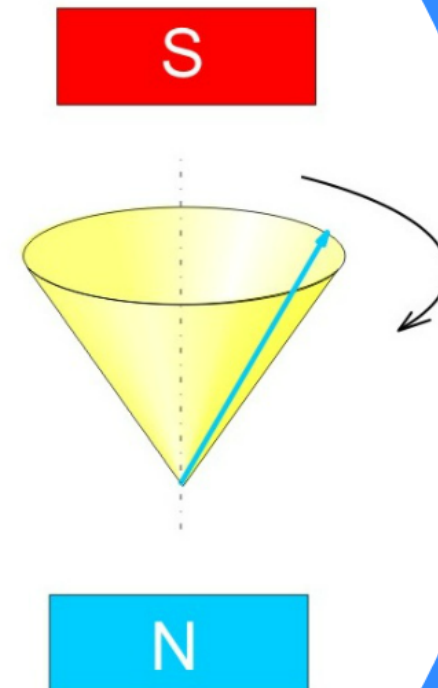


What is the role of magnetic field?

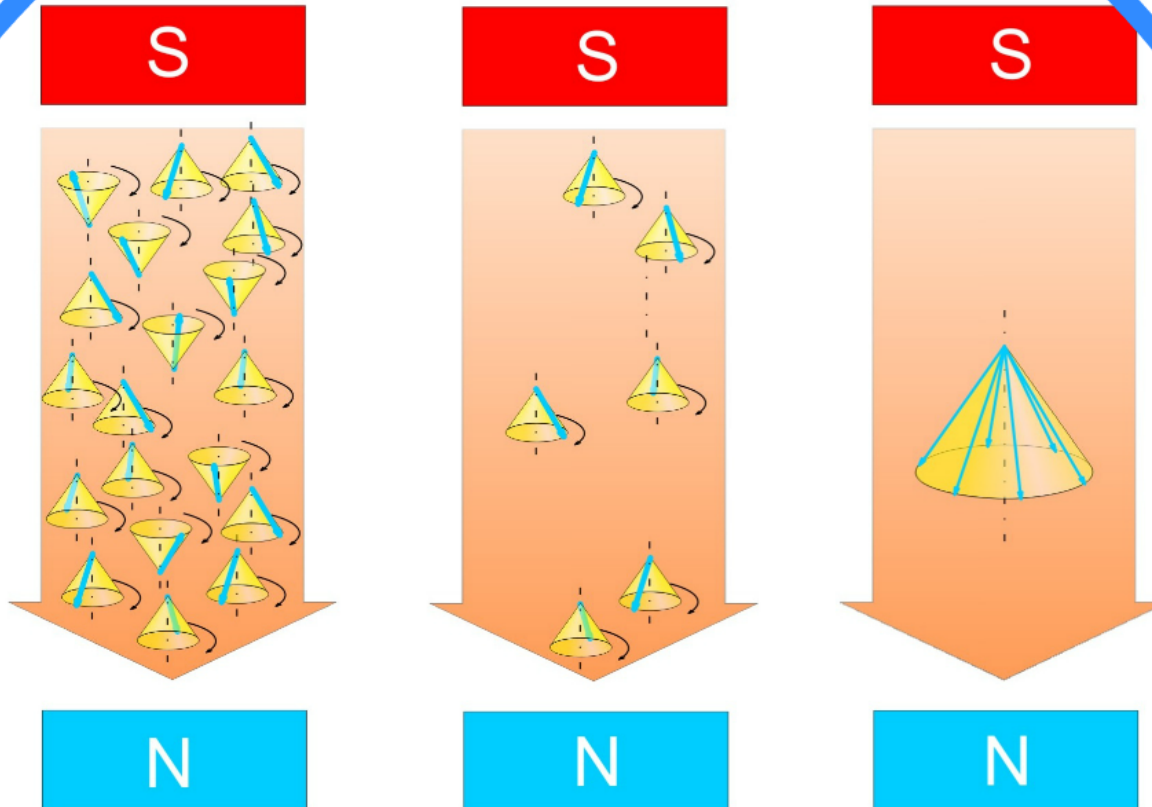
## IN EXTERNAL MAGNETIC FIELD

### PRECESSION:

The spin vector will rotate like a **top (gyroscope)** around a cone with a certain frequency. It aligns to the magnetic field.



## IN A STRONG EXTERNAL MAGNETIC FIELD



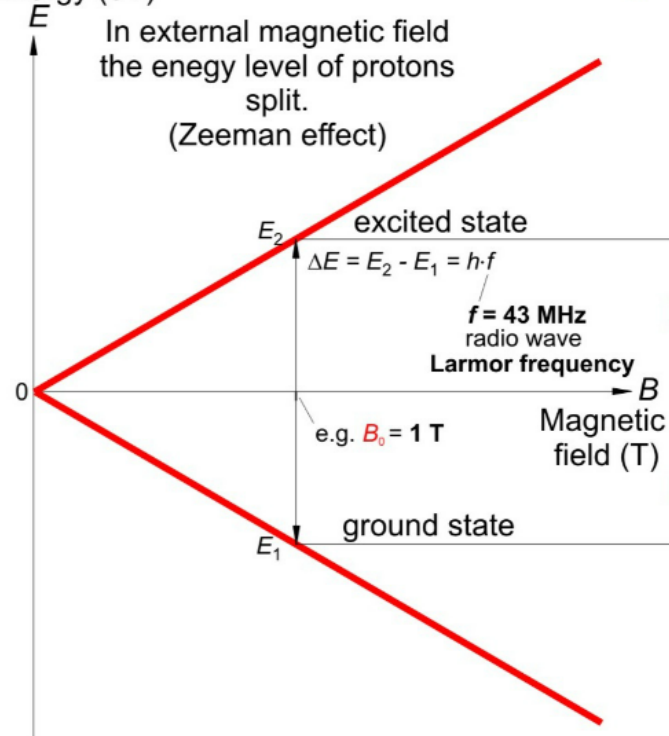
The spins precess aligning in the external magnetic field directed up or down.  
At room temperature  
and in thermal equilibrium  
a little more spins turn downwards.

Only the excess spins  
are shown

Precessions of the excess spins  
shown distributed on a single cone

Energy (eV)

In external magnetic field  
the energy level of protons  
split.  
(Zeeman effect)

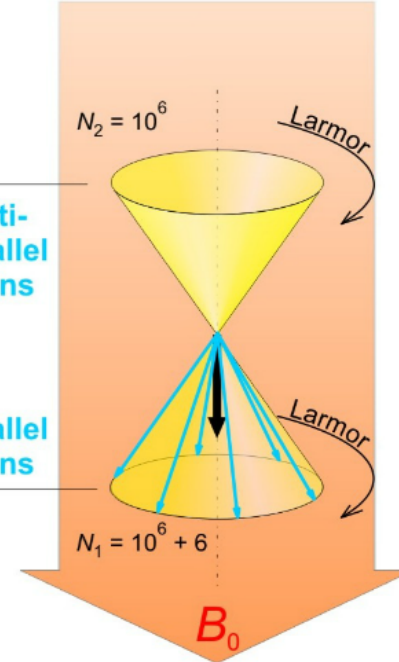


$$\Delta E = h \cdot \gamma \cdot B_0$$

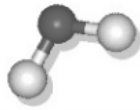
S

anti-  
parallel  
spins

parallel  
spins



$$\frac{N_2}{N_1} = e^{-\frac{\Delta E}{k \cdot T}}$$



# Source of signal

## WITHOUT EXTERNAL MAGNETIC FIELD

due to its spin a proton acts like a little magnet



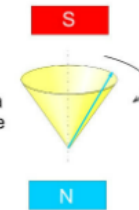
magnetic vector of a single spinning proton

spins are not ordered

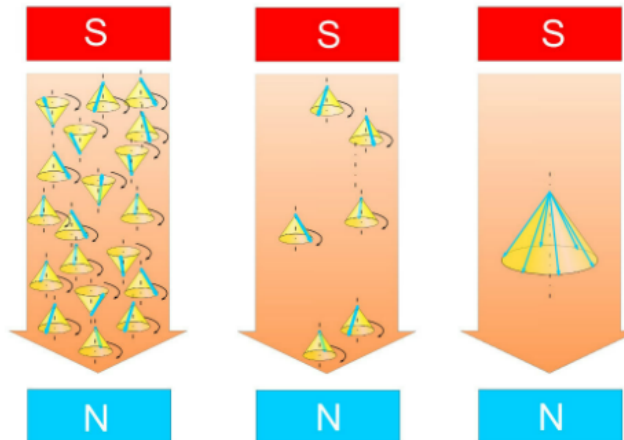


## IN EXTERNAL MAGNETIC FIELD

**PRECESSION:**  
The spin vector will rotate like a top (gyroscope) around a cone with a certain frequency. It aligns to the magnetic field.



## IN A STRONG EXTERNAL MAGNETIC FIELD

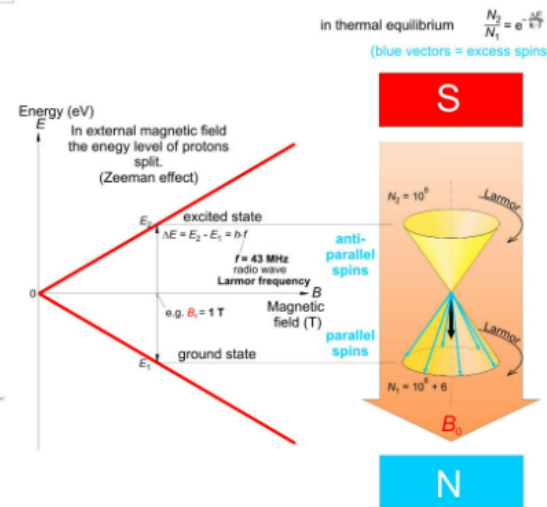


The spins precess aligning in the external magnetic field directed up or down. At room temperature and in thermal equilibrium a little more spins turn downwards.

Only the excess spins are shown

Precessions of the excess spins shown distributed on a single cone

**SIMPLIFICATIONS**

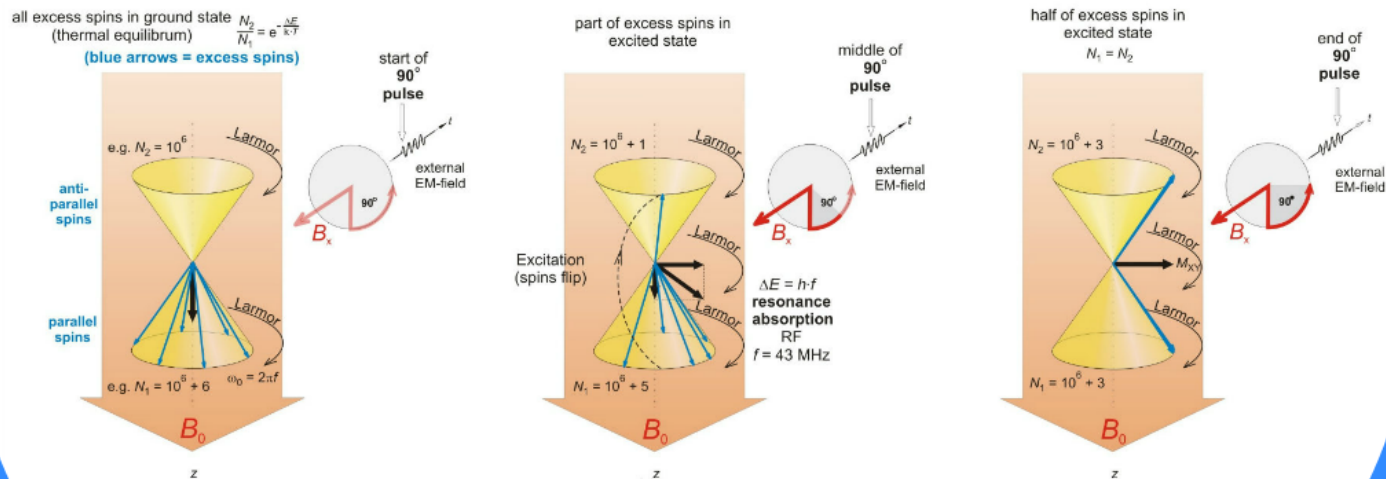




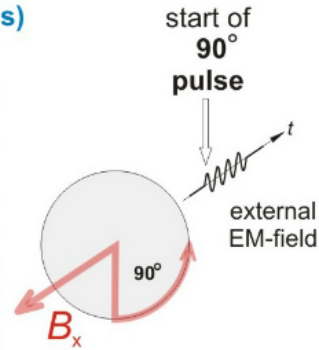
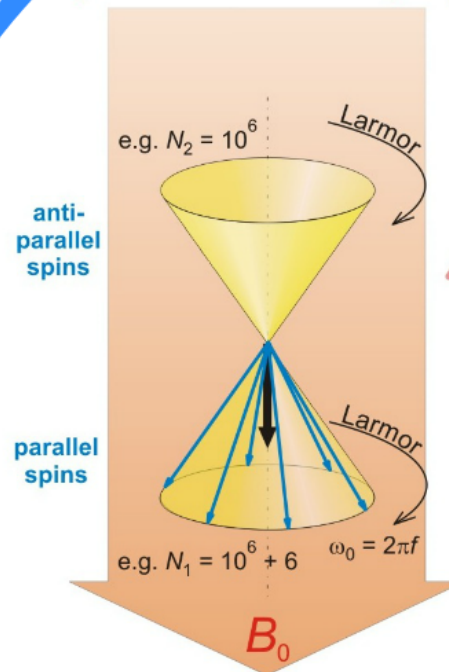


## How voxel sings?

- How absorbed radiation by voxel?
- What happens in voxel?
- How does voxel produce signal?

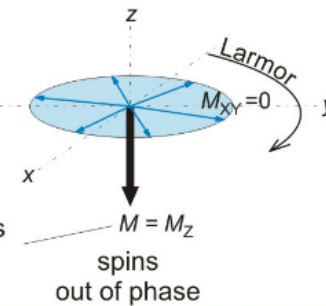


(blue arrows = excess spins)



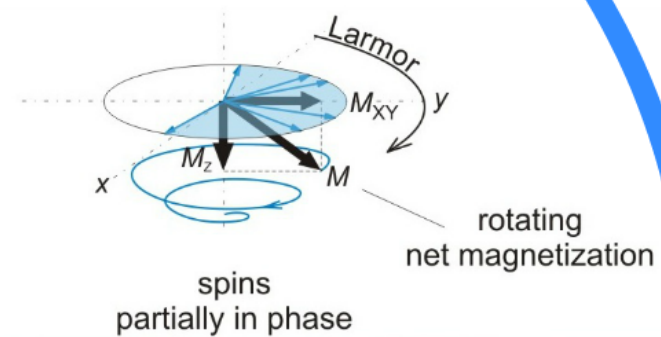
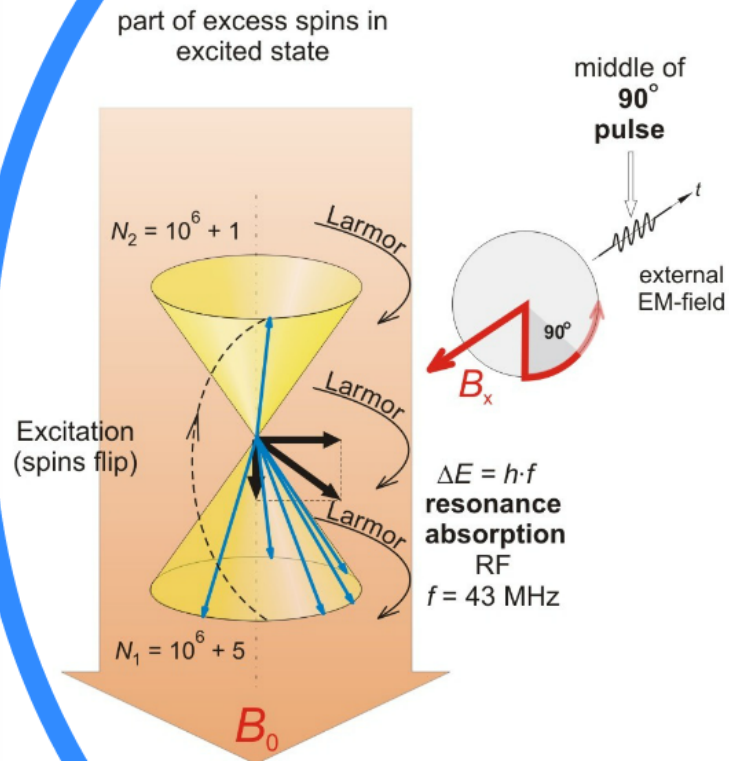
projections of precessing excess spins into the x-y plane (opposite spins cancel each other, so  $M_{xy}=0$ )

resultant of excess spins (net magnetization)



Horizontal component of spins with random phase cancel each other, the x-y projection of the magnetization is zero

$M_z$  spins around itself and aligns to the huge  $B_0$  so it is not detectable!

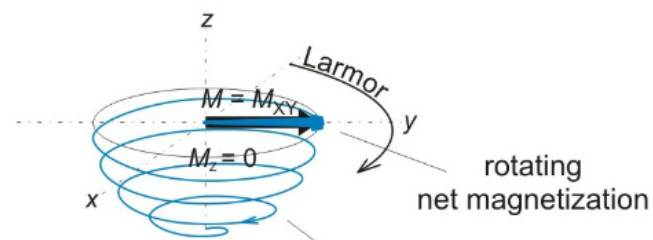
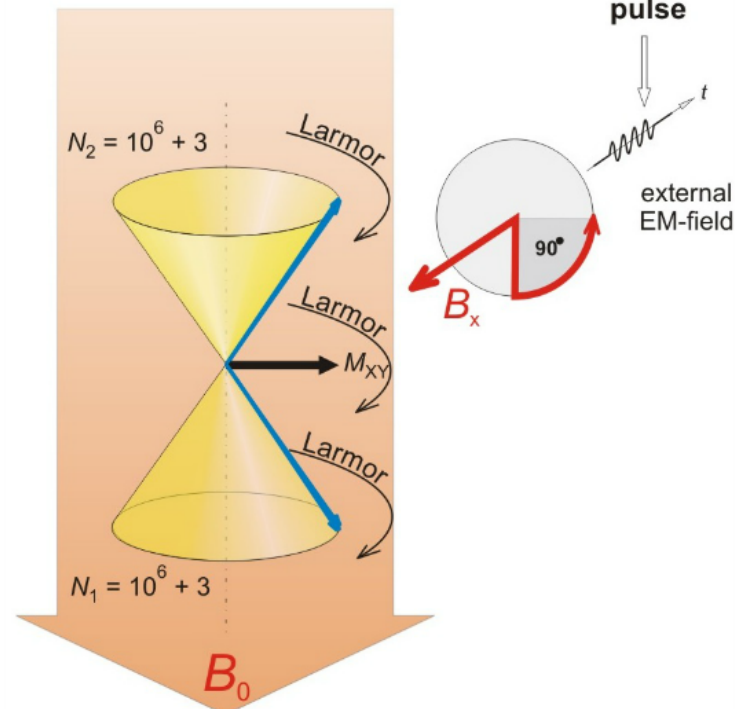


MARY HADA LITTLE LAMB

REACHING PHASE COHERENCE:  
 $M_{xy}$  INCREASES.

Simultaneously  $M_z$  decreases  
 (due to excitation of spins),  
 so  $M$  net magnetization will  
 spiral into the x-y plane  
 with Larmour frequency

half of excess spins in  
excited state  
 $N_1 = N_2$



all excess spins in phase  
(phase coherence)

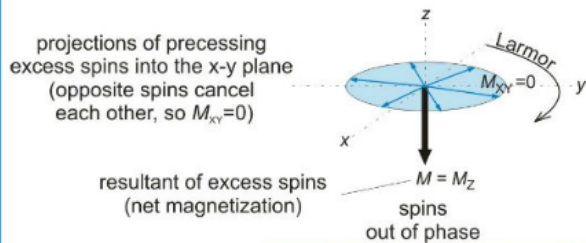
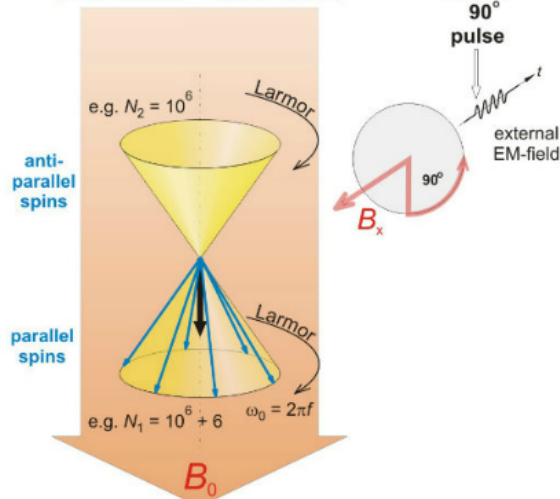
MARY HAD A LITTLE LAMB

**GOAL: TURN  $M_z$  INTO THE X-Y PLANE TO ALLOW DETECTION**

To turn  $M_z$ , apply special external EM-field of certain duration (ms) and amplitude (so called **90° radiofrequency pulse** e.g.  $f = 43$  MHz at 1T, Larmor frequency) —

EFFECTS: **excitation** of parallel spins to antiparallel spins  
arrangement of parallel and antiparallel spins to be **in phase**

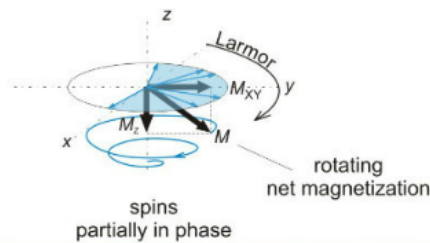
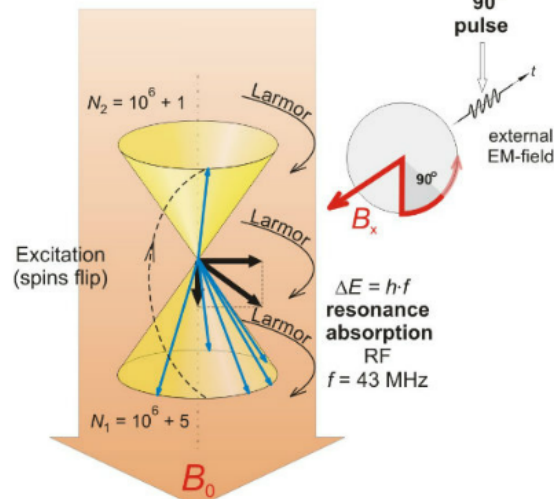
all excess spins in ground state (thermal equilibrium)  $\frac{N_2}{N_1} = e^{-\frac{\Delta E}{k \cdot T}}$   
(blue arrows = excess spins)



Horizontal component of spins with random phase cancel each other, the x-y projection of the magnetization is zero.

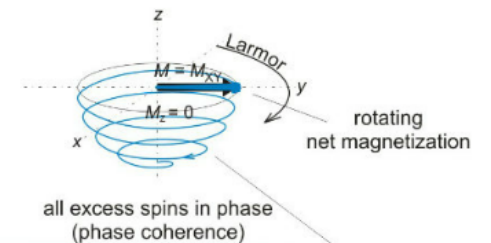
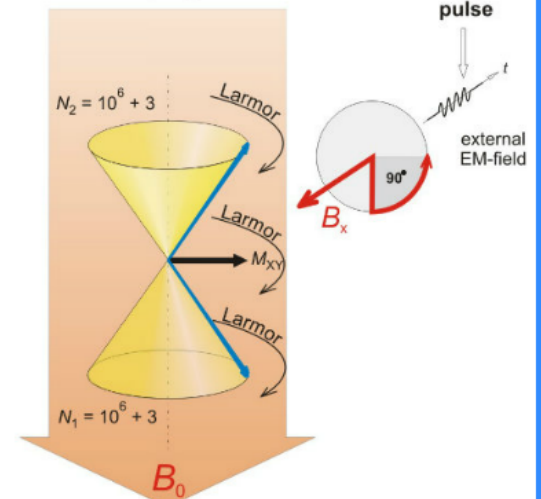
$M_z$  spins around itself and aligns to the huge  $B_0$  so it is not detectable!

part of excess spins in excited state

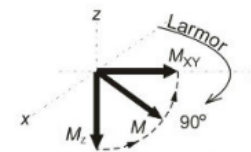


REACHING PHASE COHERENCE:  $M_{xy}$  INCREASES. Simultaneously  $M_z$  decreases (due to excitation of spins), so  $M$  net magnetization will spiral into the x-y plane with Larmour frequency

half of excess spins in excited state  $N_1 = N_2$



MARY HAD A LITTLE LAMB

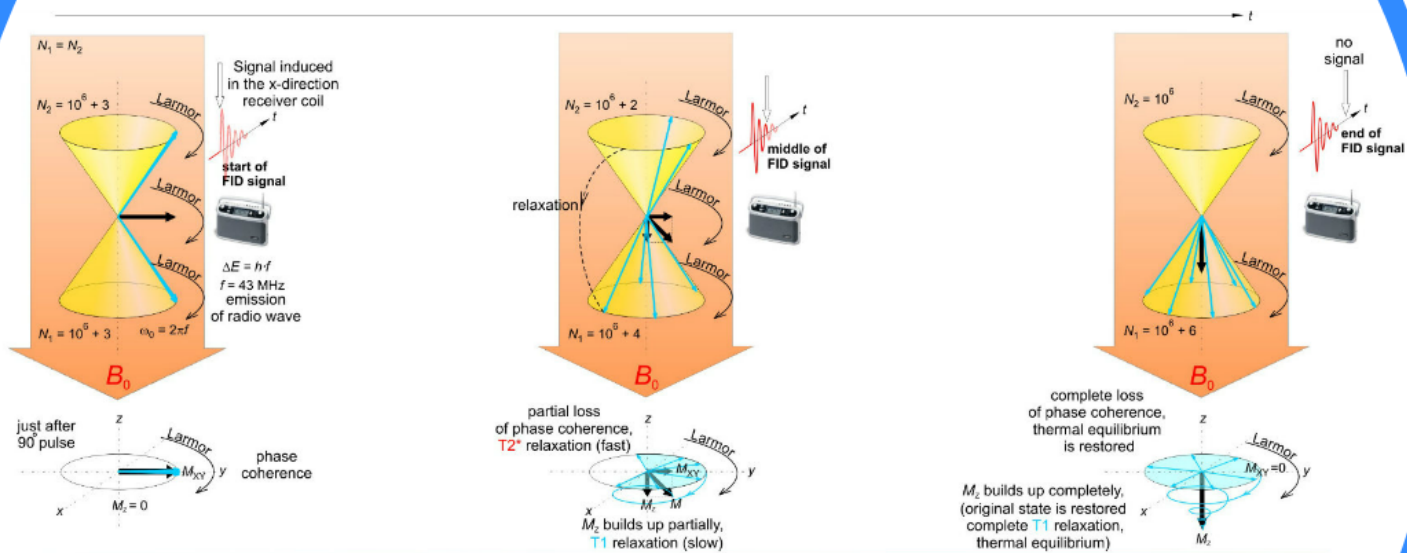


At the end of 90° the pulse  $M$  turns 90° into the x-y plane ( $M_z$  to  $M_{xy}$ ). The rotating x-y projection of  $M$  is measurable!

**EXCITATION BY 90° RF- PULSE**



# How detect signal?

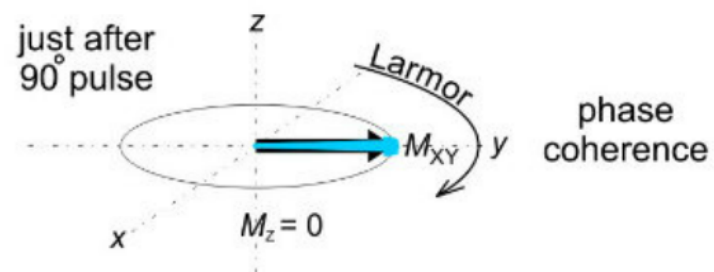
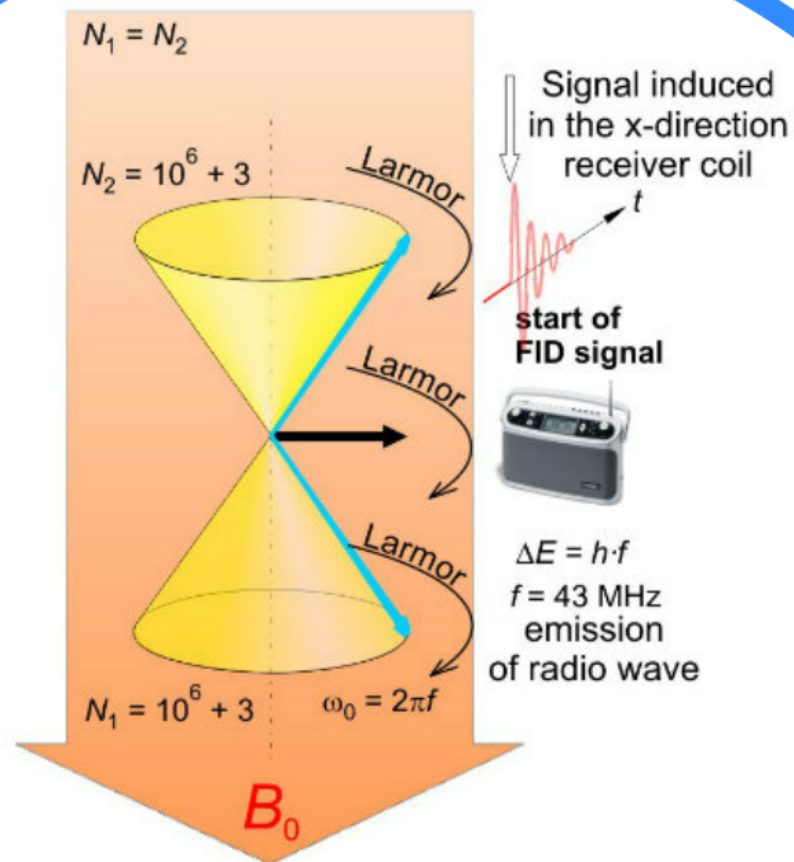


MARY HAD A LITTLE LAMB

MARY HAD A LITTLE LAMB

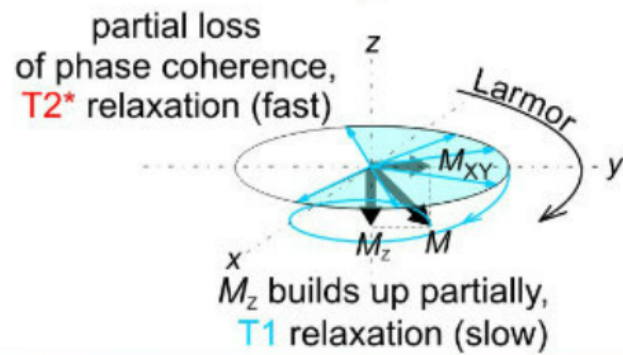
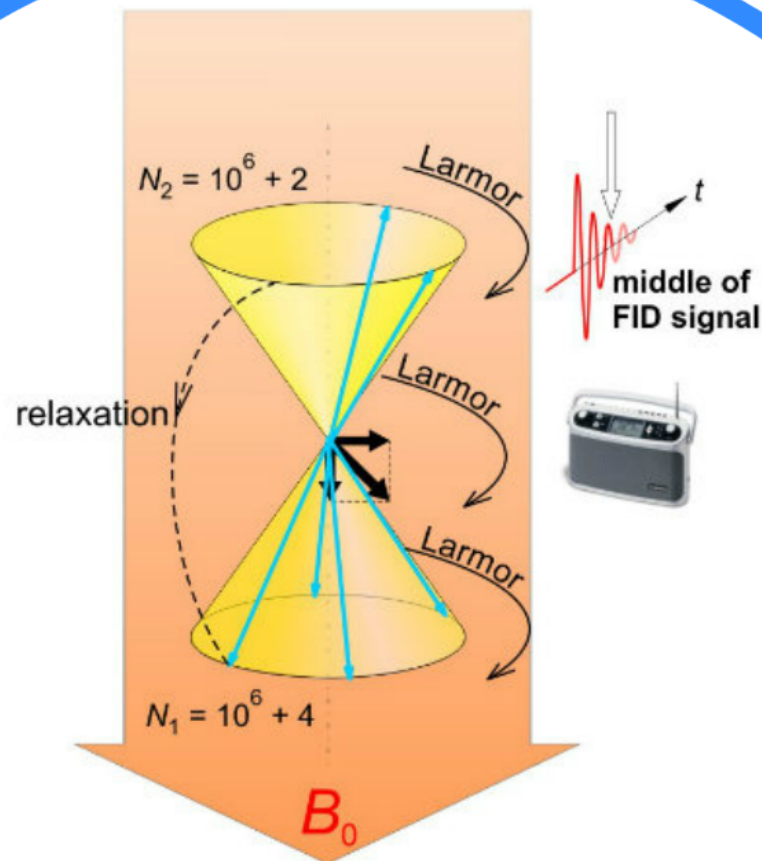
MARY HAD A LITTLE LAMB



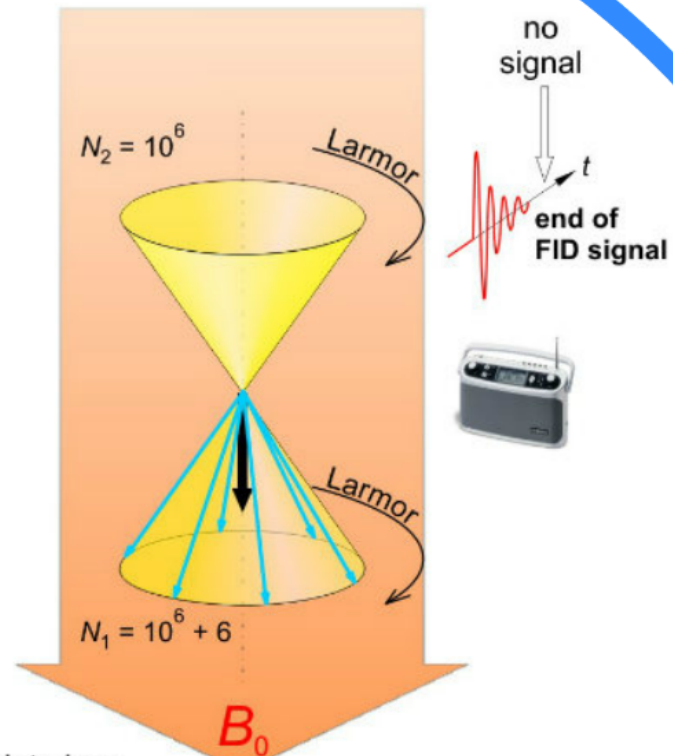


MARY HAD A LITTLE LAMB



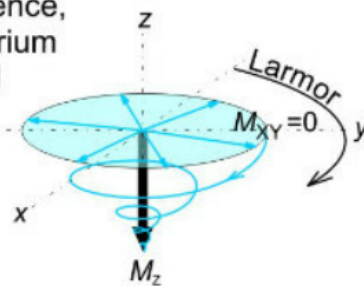


MARY HAD A LITTLE LAMB

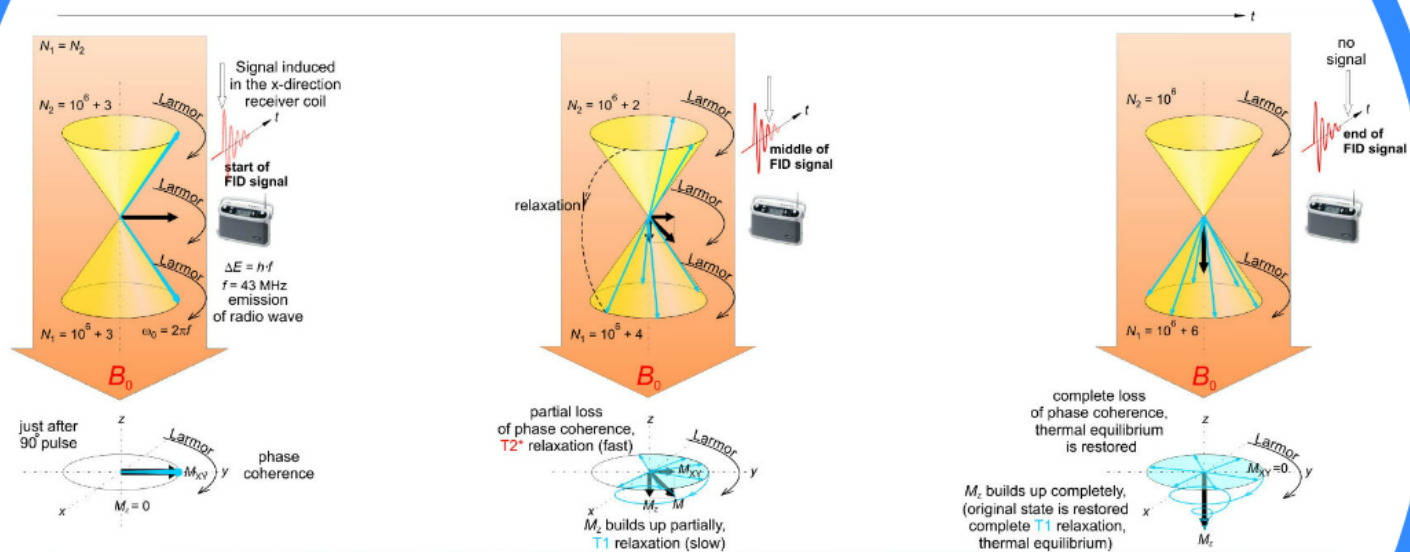


complete loss  
of phase coherence,  
thermal equilibrium  
is restored

$M_z$  builds up completely,  
(original state is restored  
complete **T1** relaxation,  
thermal equilibrium)



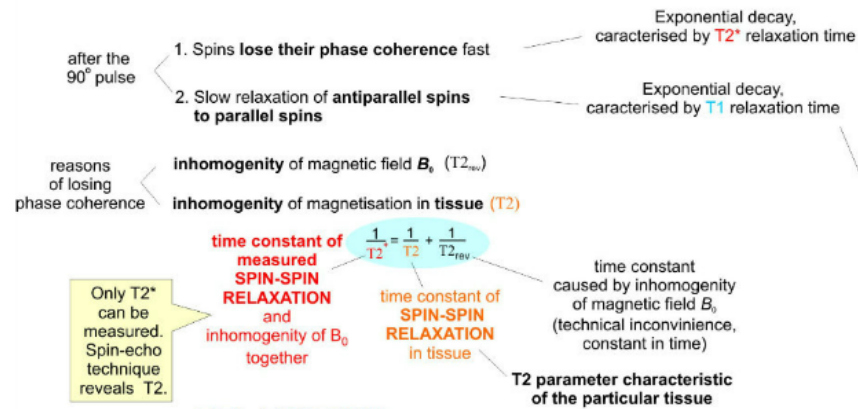
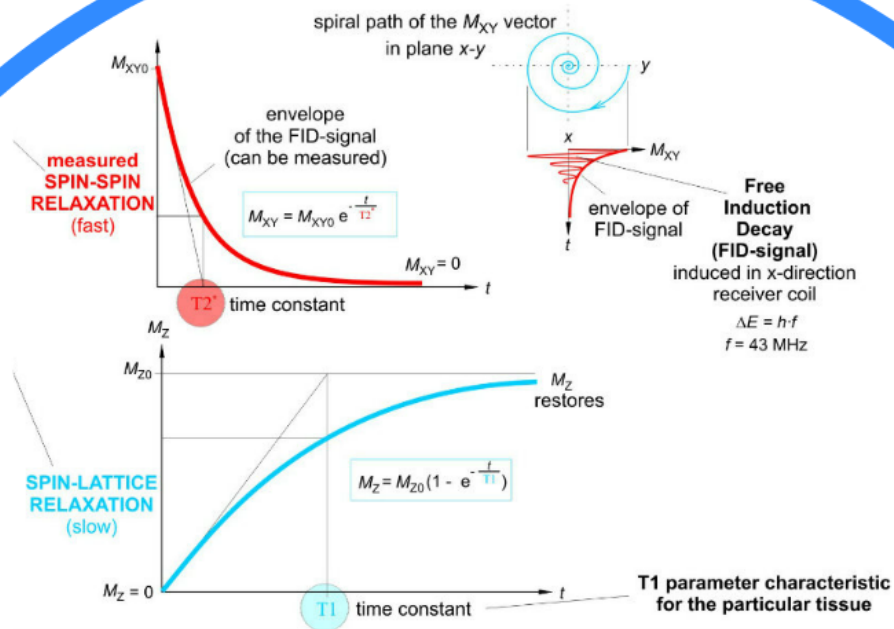
RESTAURATION OF THERMAL EQUILIBRIUM



MARY HAD A LITTLE LAMB

MARY HAD A LITTLE LAMB

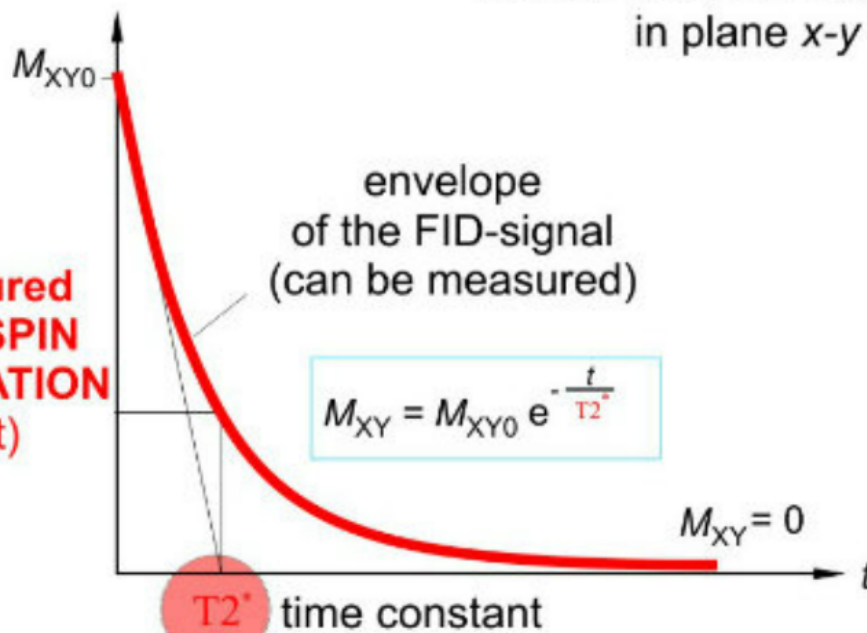
MARY HAD A LITTLE LAMB



**RELAXATION,  
LOSS OF PHASE COHERENCE,  
DETECTING MRI SIGNALS**

spiral path of the  $M_{XY}$  vector  
in plane x-y

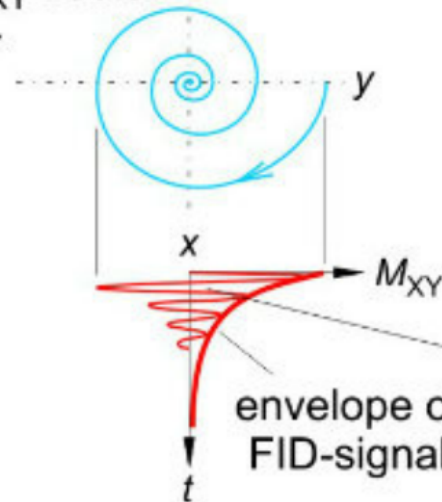
**measured  
SPIN-SPIN  
RELAXATION  
(fast)**



envelope  
of the FID-signal  
(can be measured)

$$M_{XY} = M_{XY0} e^{-\frac{t}{T2^*}}$$

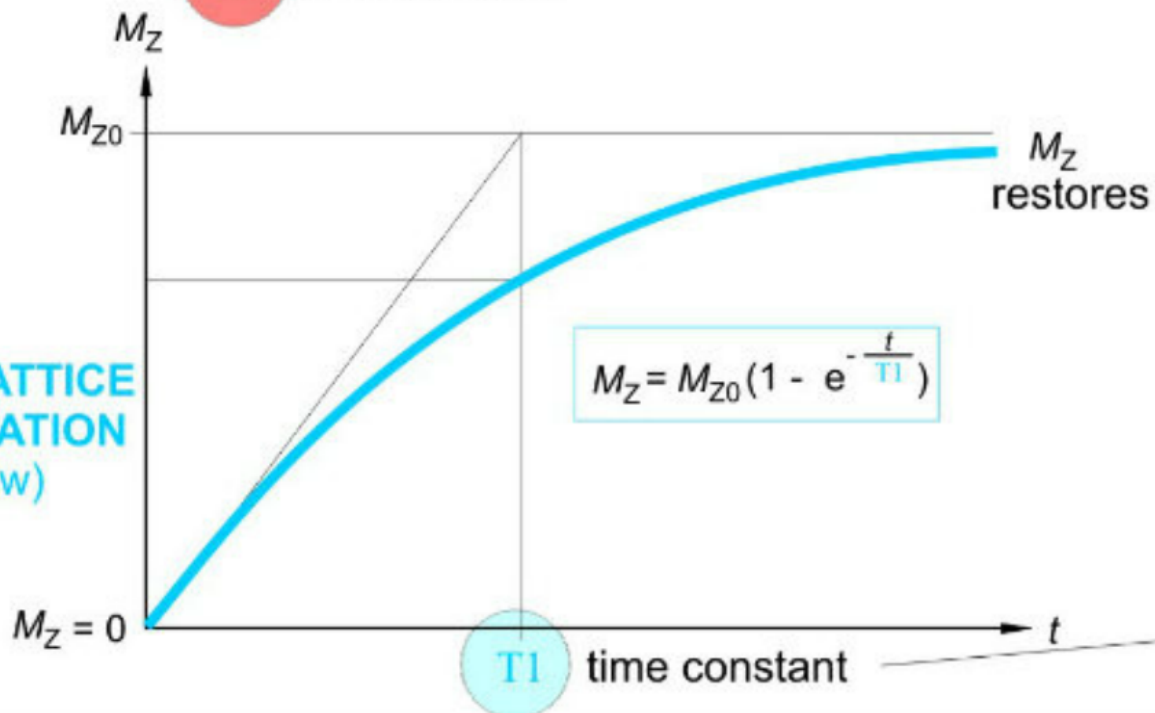
$M_{XY} = 0$



**Free  
Induction  
Decay  
(FID-signal)**  
induced in x-direction  
receiver coil

$$\Delta E = h \cdot f$$
$$f = 43 \text{ MHz}$$

**SPIN-LATTICE  
RELAXATION  
(slow)**

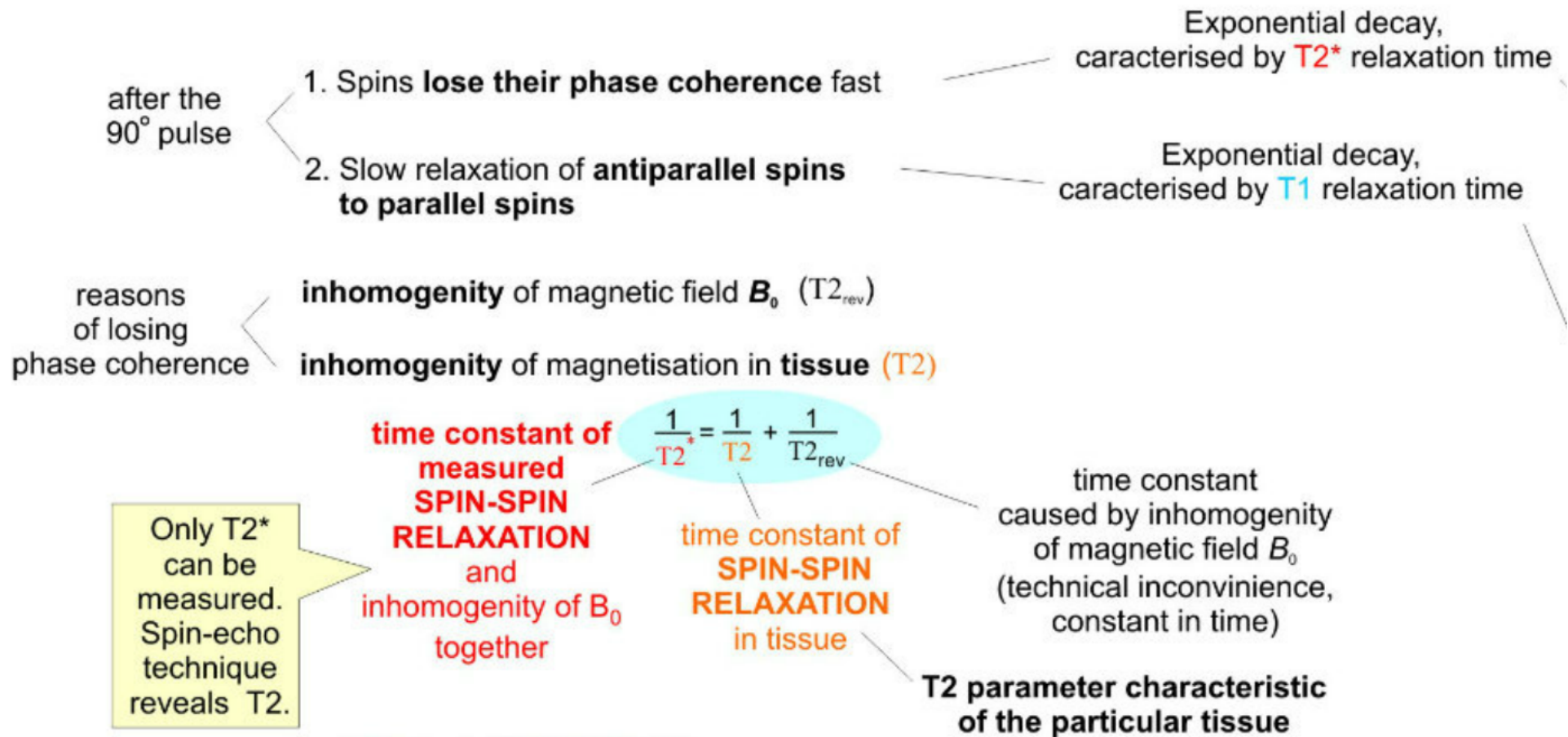


$T1$

time constant

**$T1$  parameter characteristic  
for the particular tissue**





## RELAXATION, LOSS OF PHASE COHERENCE, DETECTING MRI SIGNALS



You Tube



## What is the connection between choir and MRI?

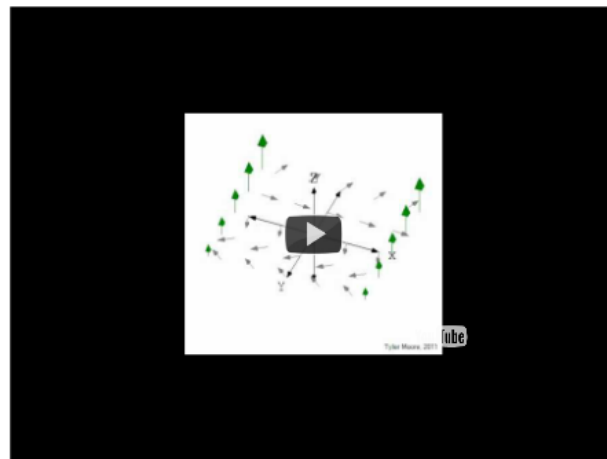
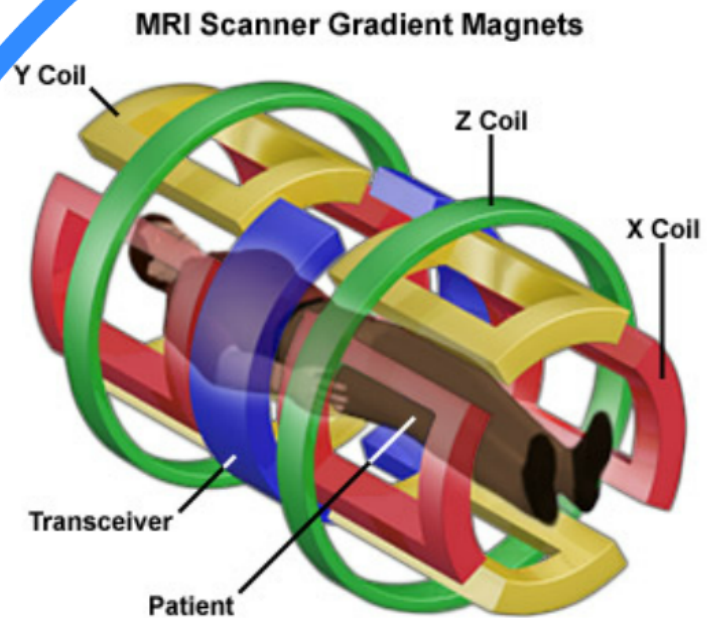


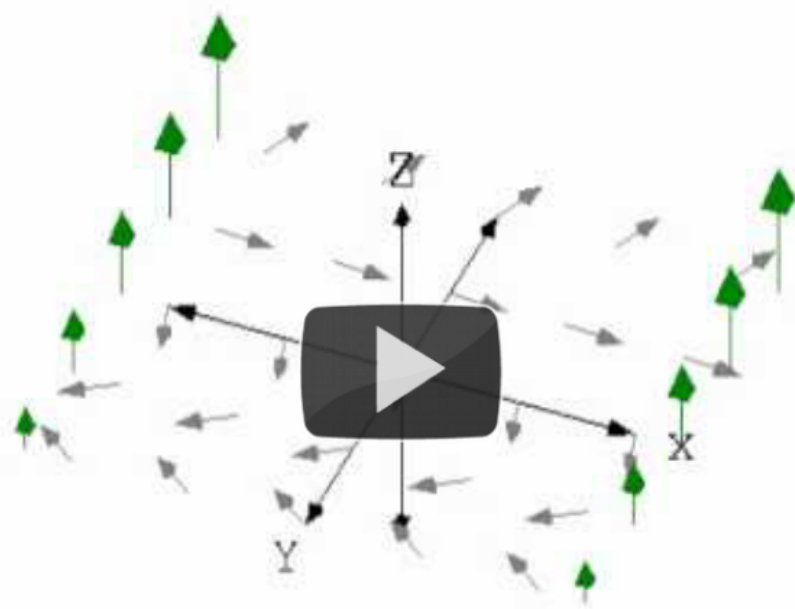
- Orchestra
- Singers
- Floors
- Pitch (frequency)
- Duration (canon)



- Magnet (pl: 3T, He)
- Voxel (spins)
- Encoding (3D)

# Voxel - position encoding

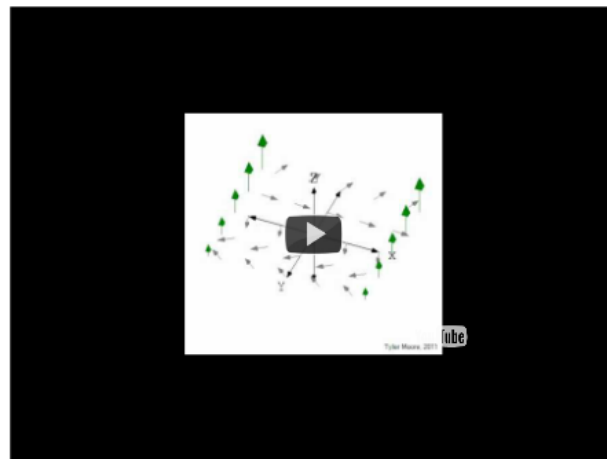
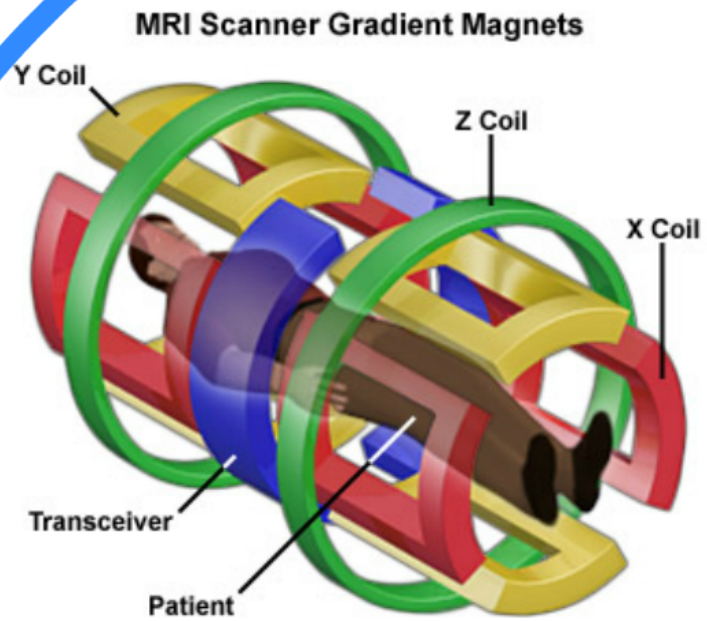




Tyler Moore, 2011

Tube

# Voxel - position encoding



## Voxel - position encoding

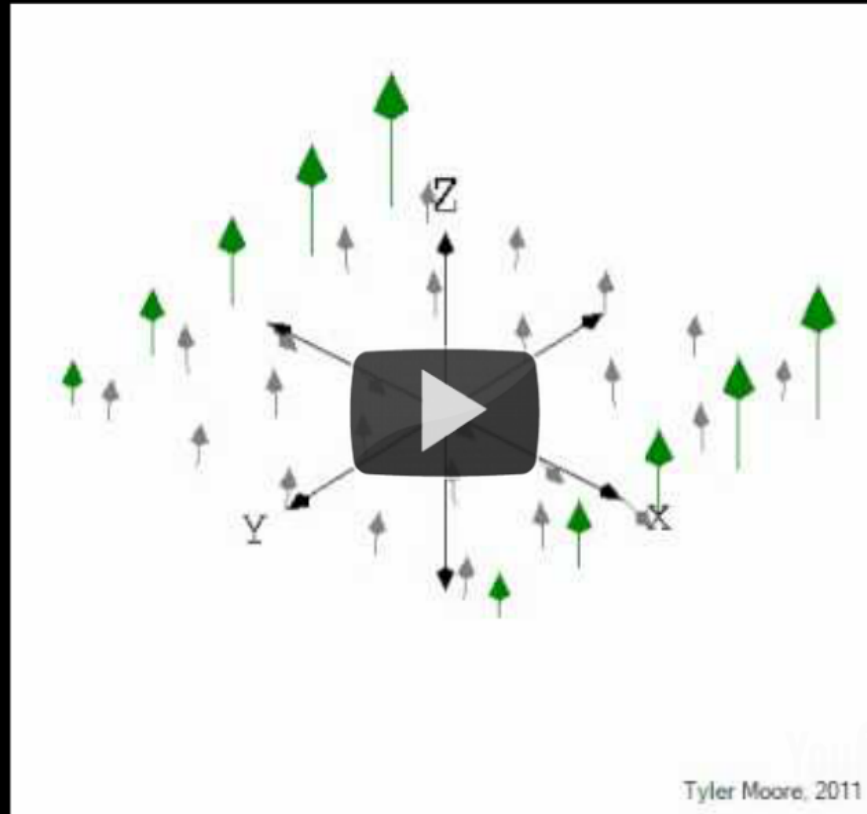
- Floors
- Pitch (frequency)
- Duration (canon)



3D imaging

- Slices
- Frequency
- Phase





Tyler Moore, 2011

YouTube



## Now Can We Make A Useful Image?

**Table XIV**

Water content of fat-free normal human tissue

Tissue	Water content (%)
Skeletal muscle	79
Myocardium	80
Liver	71
Kidney	81
Brain white matter	84
Brain gray matter	72
Nerve	56
Femur cortex	12
Teeth	10

**Table XV**

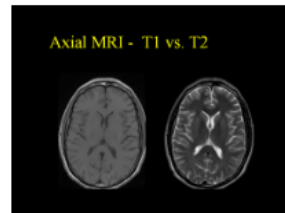
The spin-lattice relaxation time ( $T_1$ ) and spin-spin relaxation time ( $T_2$ ) of various biological tissues at 0.2 tesla

Tissue	$T_1$ , msec	$T_2$ , msec
Fat	$240 \pm 20$	$60 \pm 10$
Muscle	$400 \pm 40$	$50 \pm 10$
Gray matter	$495 \pm 85$	$100 \pm 10$
White matter	$390 \pm 70$	$90 \pm 20$
Lung	$460 \pm 90$	$80 \pm 30$
Kidney	$670 \pm 60$	$50 \pm 10$
Liver	$380 \pm 20$	$40 \pm 20$
Liver metastases	$570 \pm 190$	$40 \pm 10$
Lung carcinoma	$940 \pm 460$	$20 \pm 10$

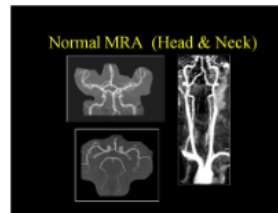
Source: Morgan and Hendee, 1984

# Biological applications

## Morphological imaging

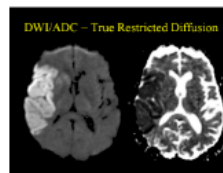


- T1 "anatomy"
- T2 "pathology"

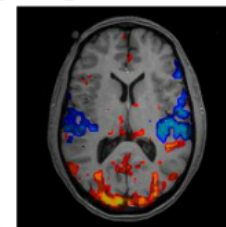
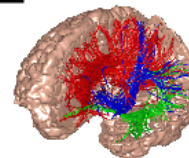


- Angiography (T1)  
(Gd contrast)

## Functional imaging



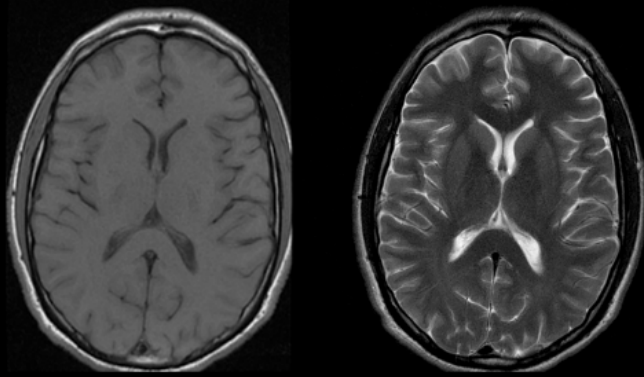
- Diffusion coeff  
(water)



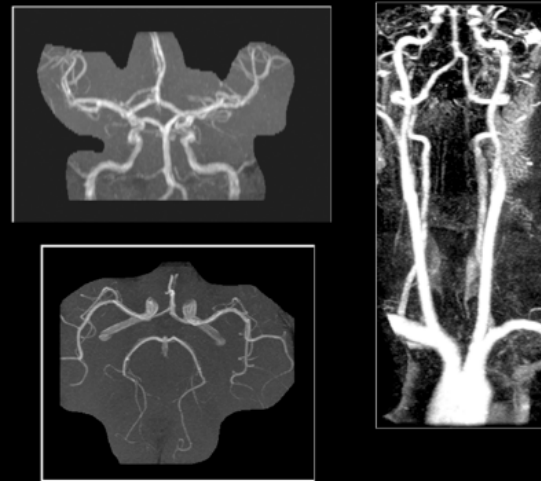
- Blood  
(oxiFe - deoxiFe)

# Morphological imaging

Axial MRI - T1 vs. T2



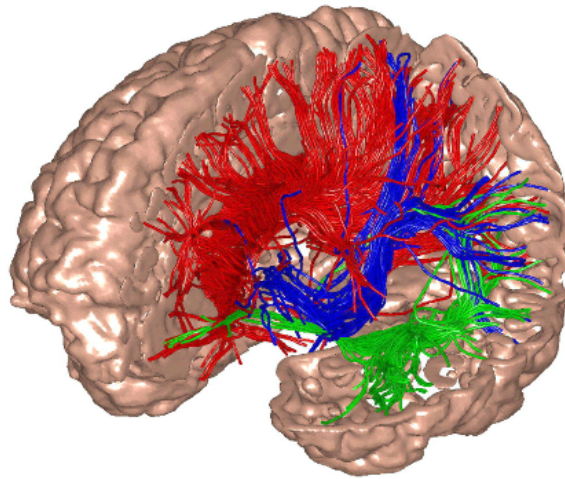
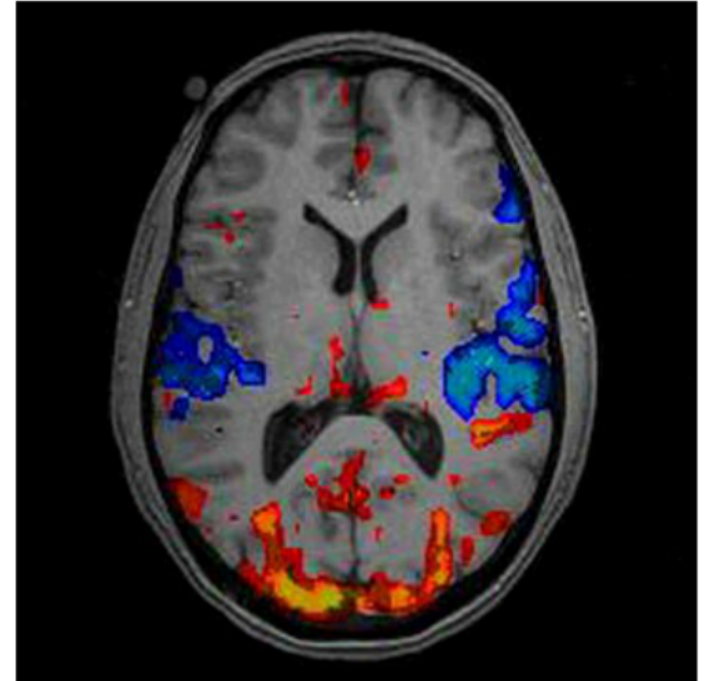
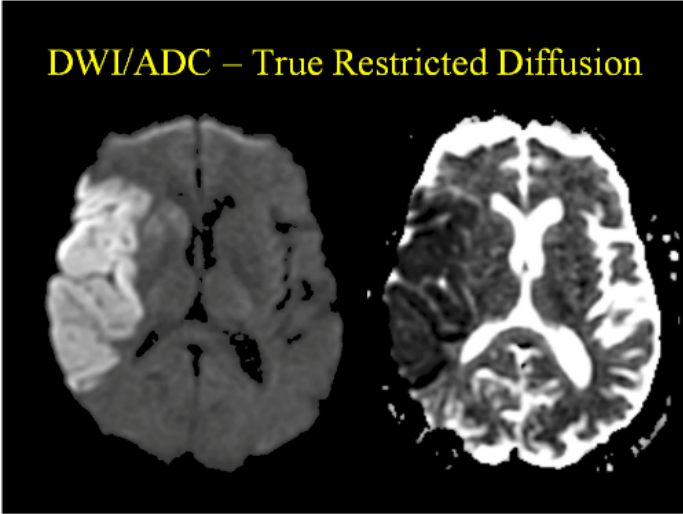
Normal MRA (Head & Neck)



- T1 "anatomy"
- T2 "pathology"
- Angiography (T1) (Gd contrast)

# Functional imaging

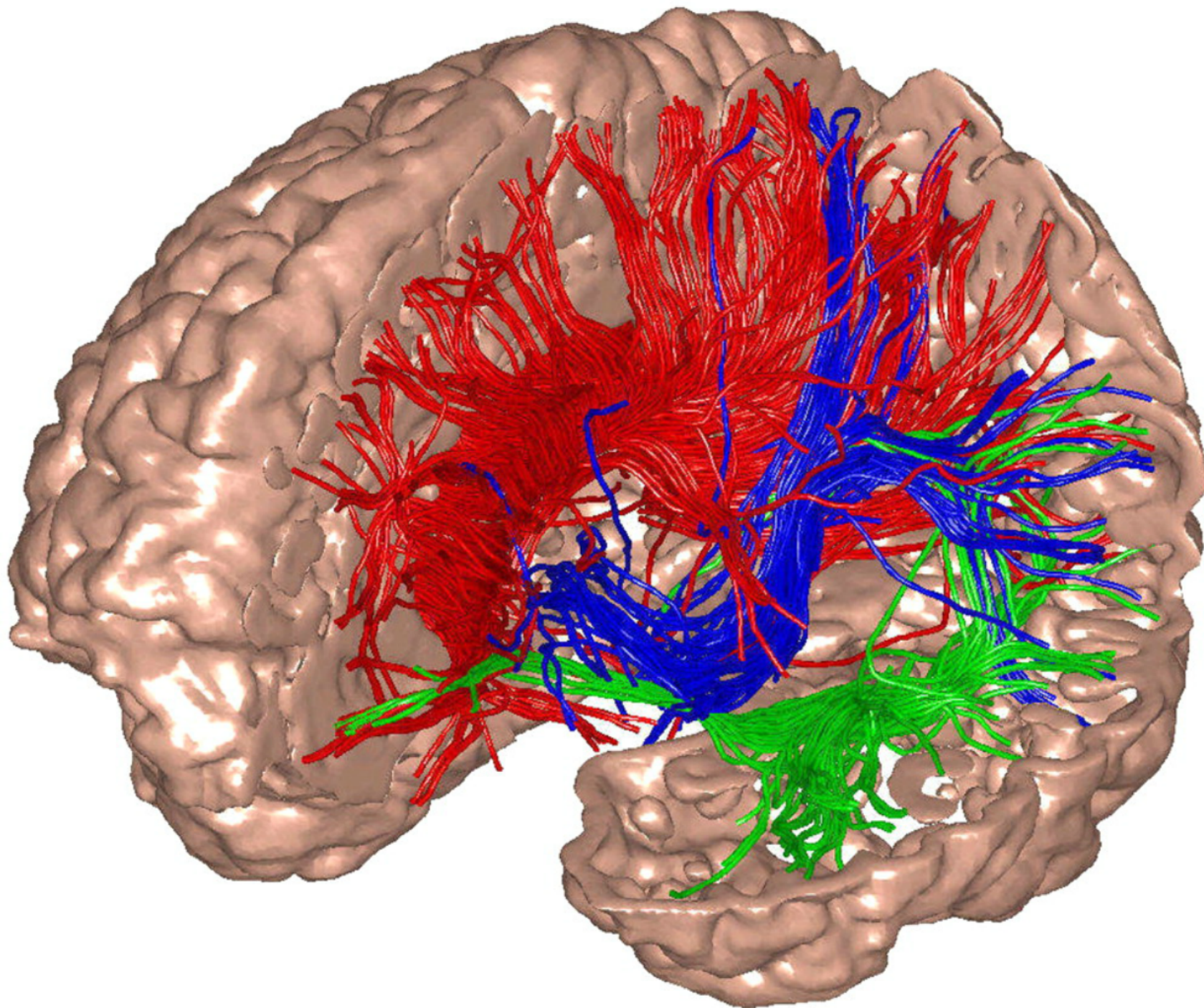
DWI/ADC – True Restricted Diffusion



- Diffusion coeff  
(water)

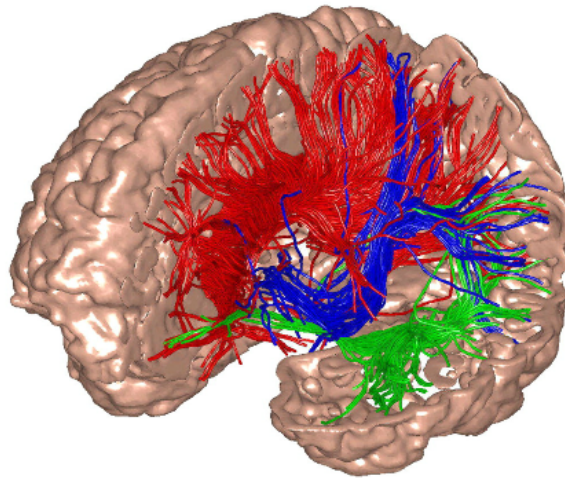
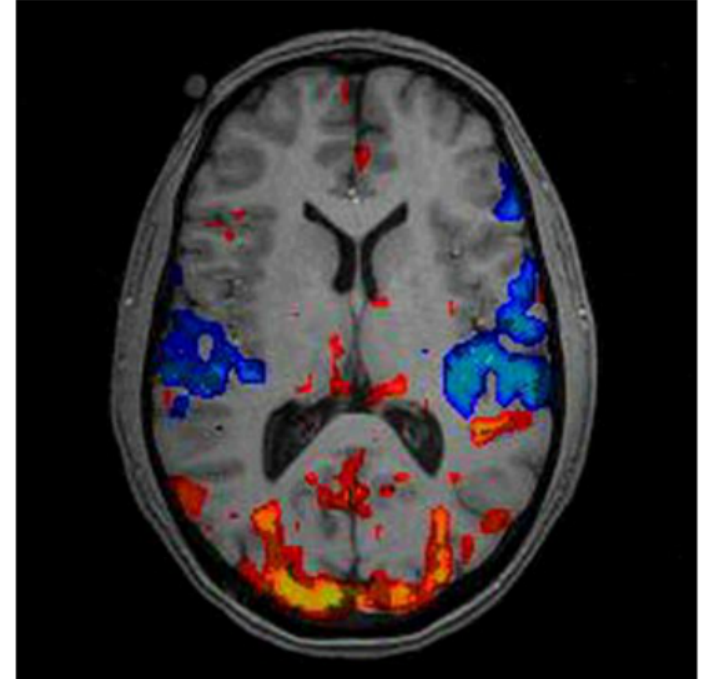
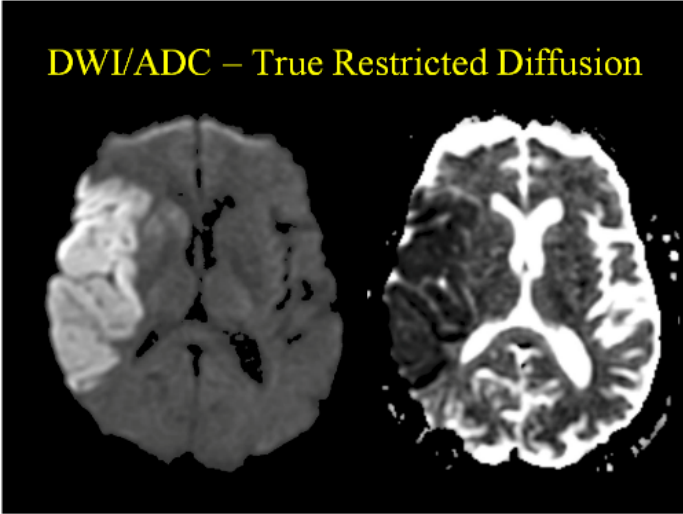
- Blood  
(oxiFe - deoxiFe)





# Functional imaging

DWI/ADC – True Restricted Diffusion



- Diffusion coeff  
(water)

- Blood  
(oxiFe - deoxiFe)



Background ... :

- <http://www.imaios.com>
- MRI Physics Tutorial (youtube)
- <http://oftankonyv.reak.bme.hu/>

