# MRI – Basic principles of medical imaging

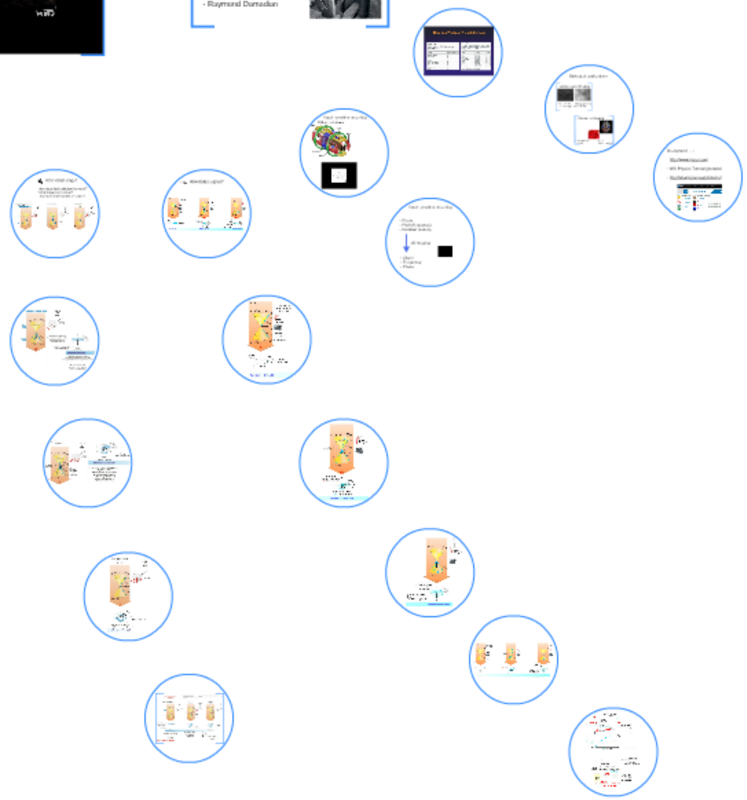

Krisztián Szigeti

Biophysics and Radiation Biology


1947 NMR material science (1952 - Nobel prize):
- Felix Bloch
- Edward M. Purcell

1977 Clinical MRI (2003):
- Paul Lauterbur
- Peter Mansfield

- Raymond Damadian



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Semmelweis NIVIC
Nanobiotechnológiai és In Vivo Képalkotó Központ
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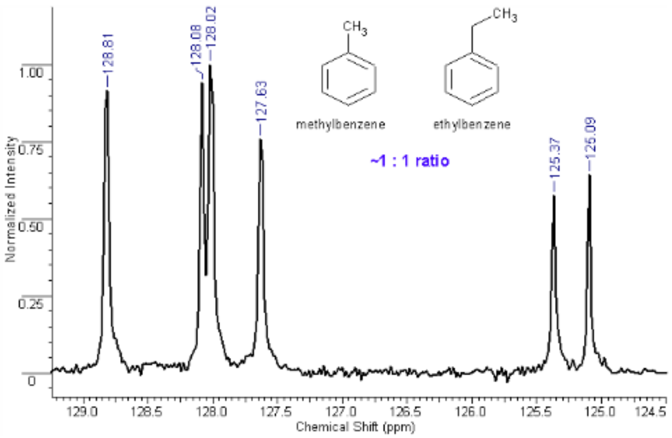


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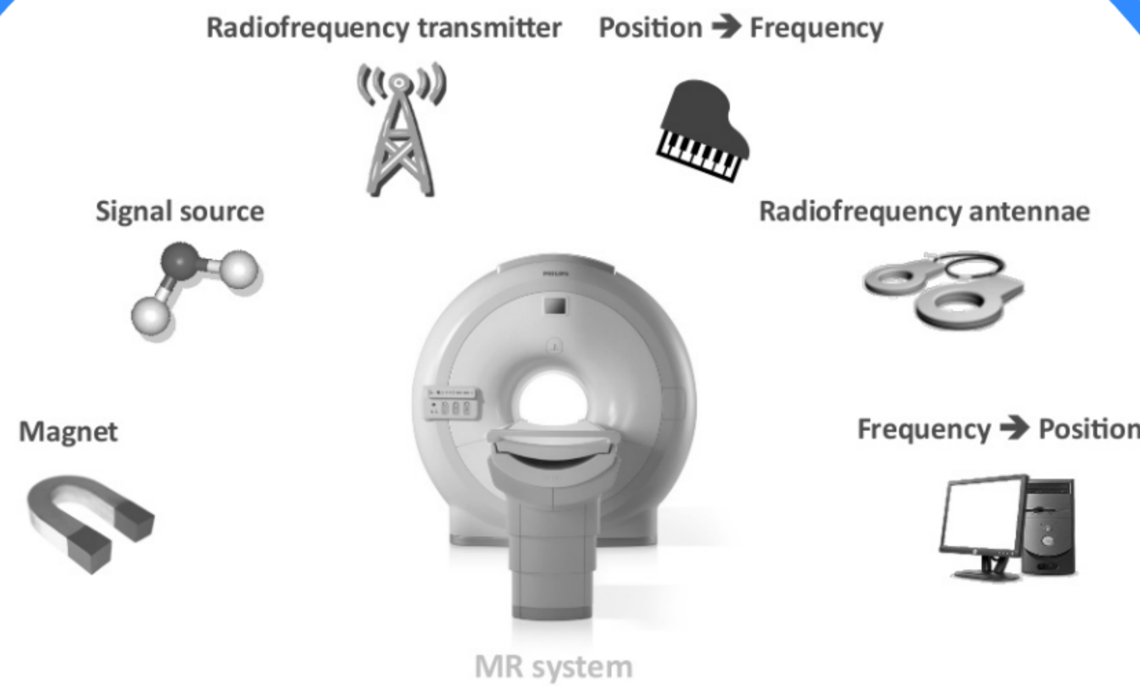
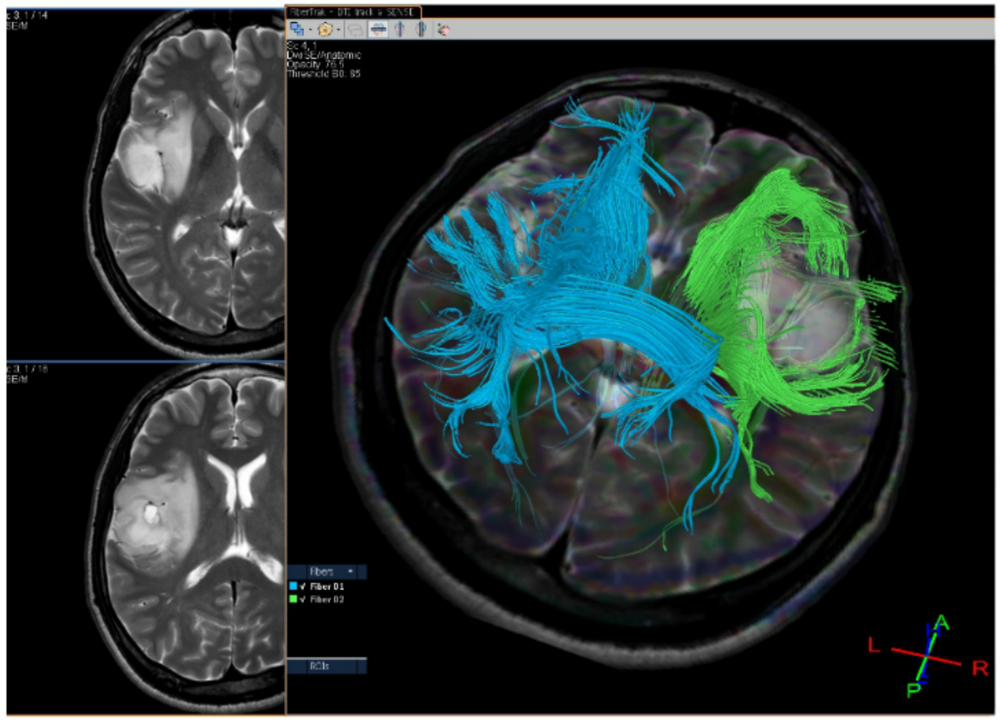
How does MRI work?




- 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

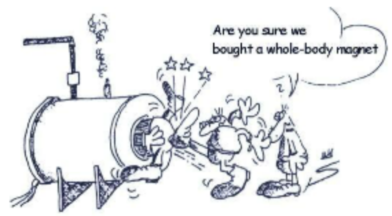
- Floors
- Pitch (frequency)
- Duration (canon)

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

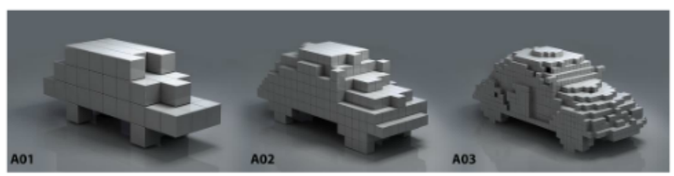
- Encoding (3D)

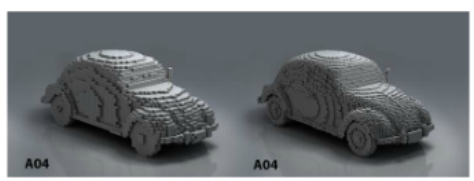
# Magnet and voxel

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




## Voxel



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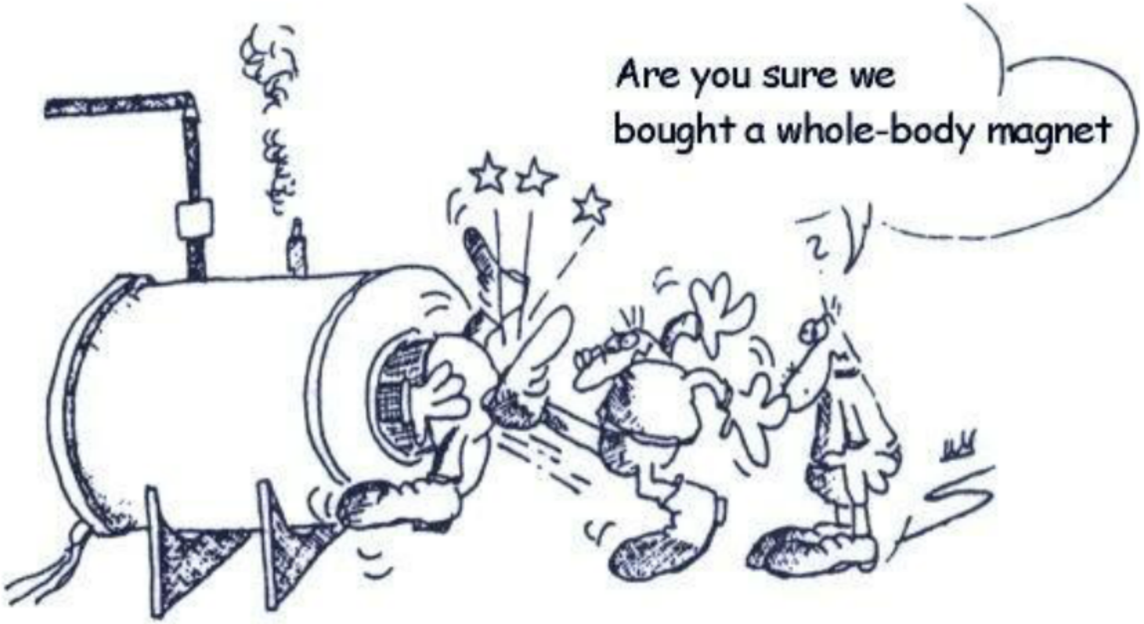
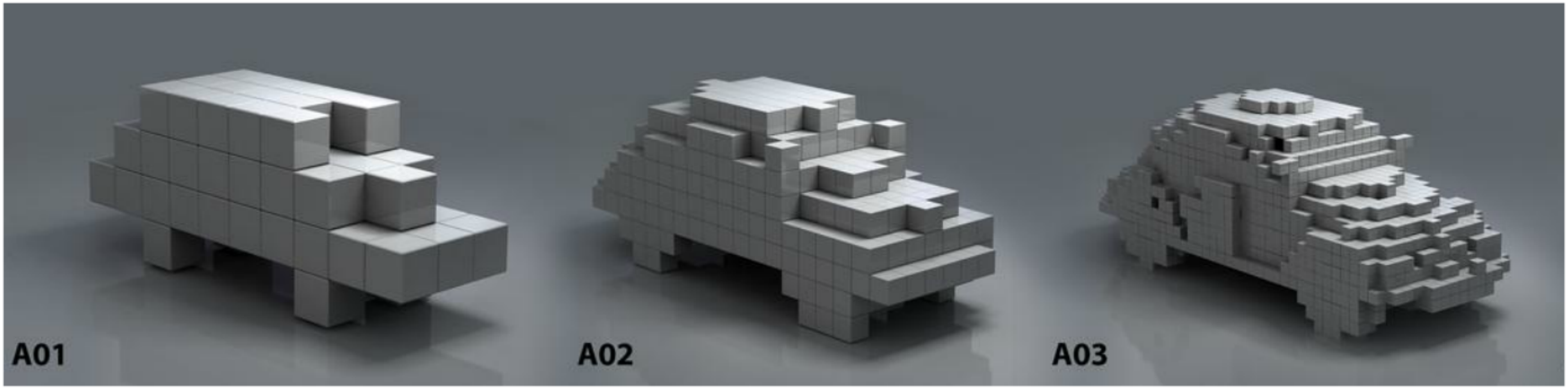
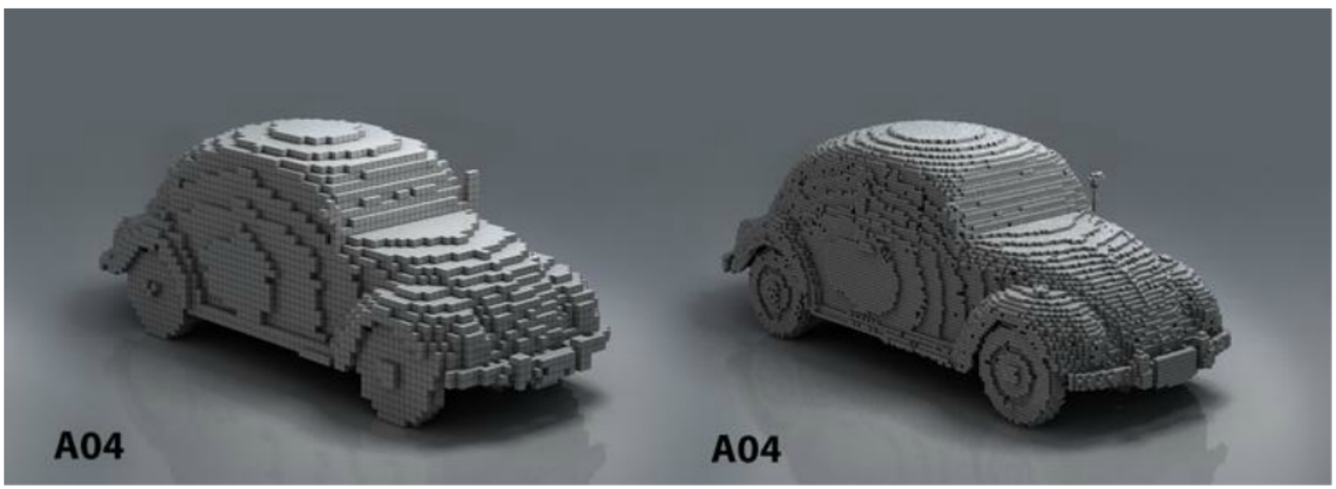
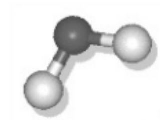


# Voxel



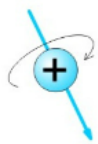





# What is signal source in a voxel?

**WITHOUT EXTERNAL MAGNETIC FIELD**

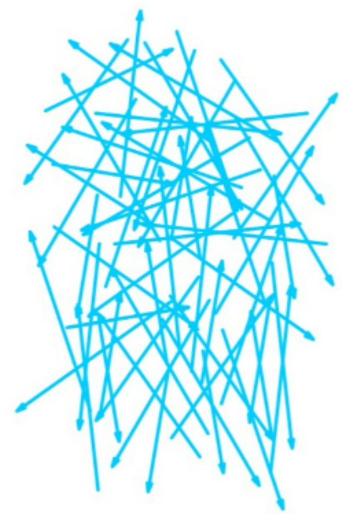
due to its spin a proton acts like a little magnet



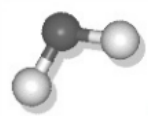
spin

magnetic vector of a single spinning proton

spins are not ordered

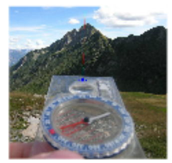


Spins in the selected voxel



# 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

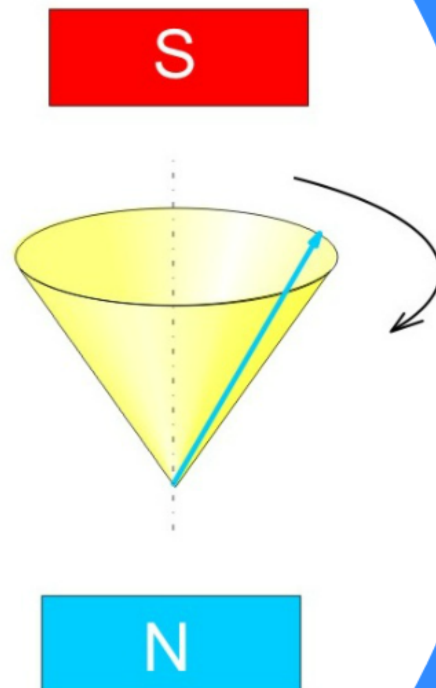

What does the spin in the magnetic field?

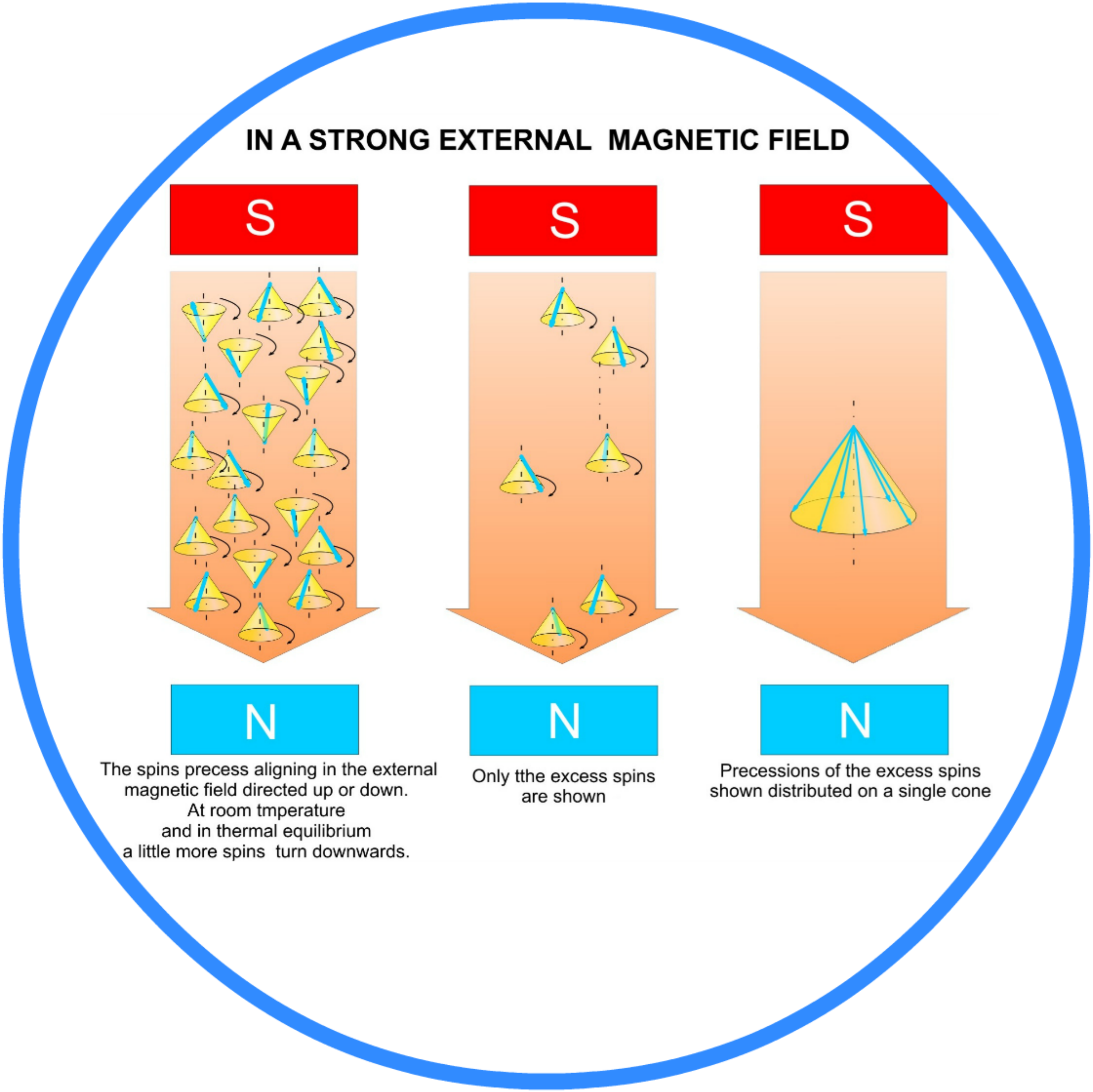
What is the role of magnetic field?

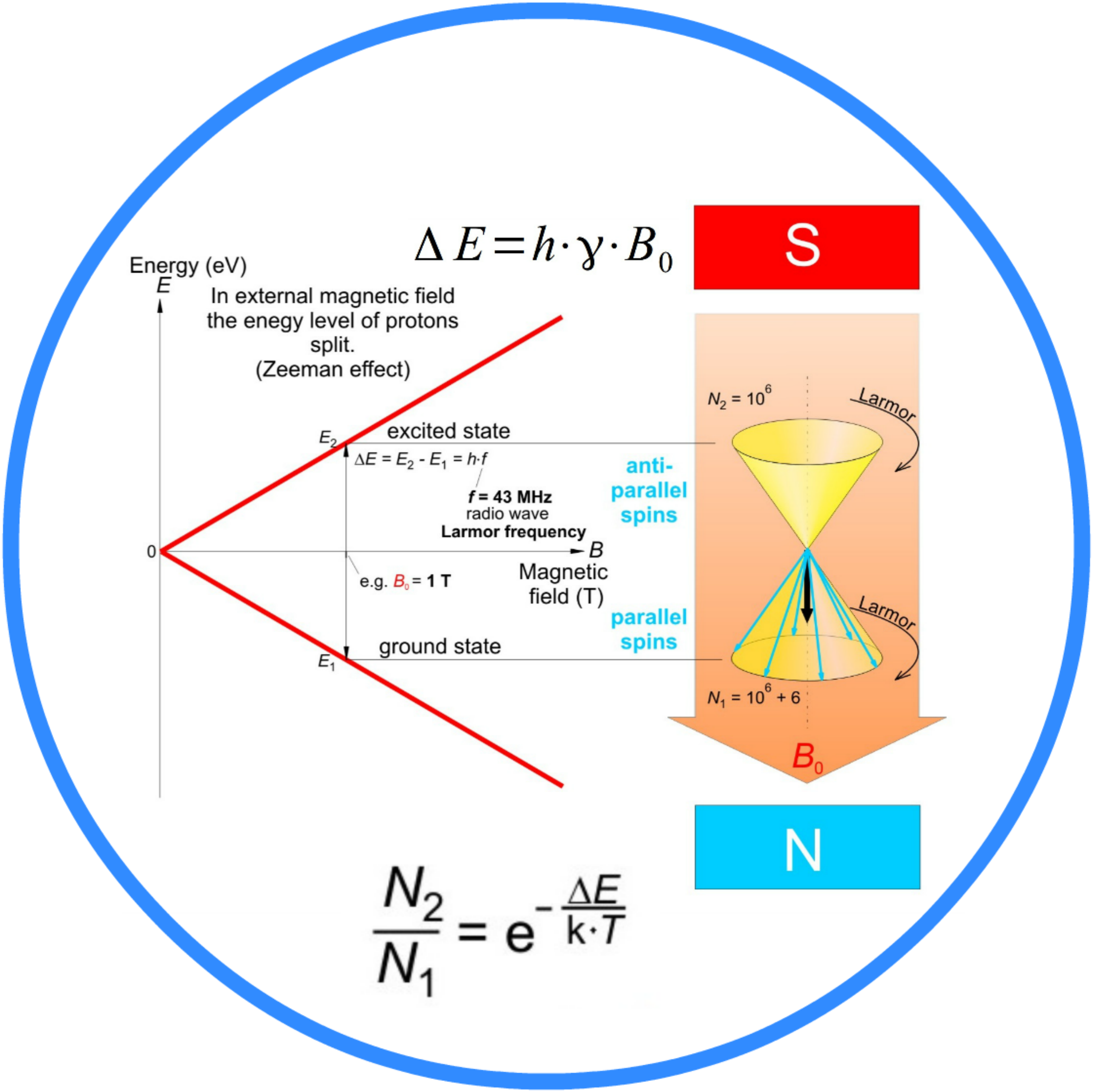
**IN EXTERNAL MAGNETIC FIELD**

PRECESSION:

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

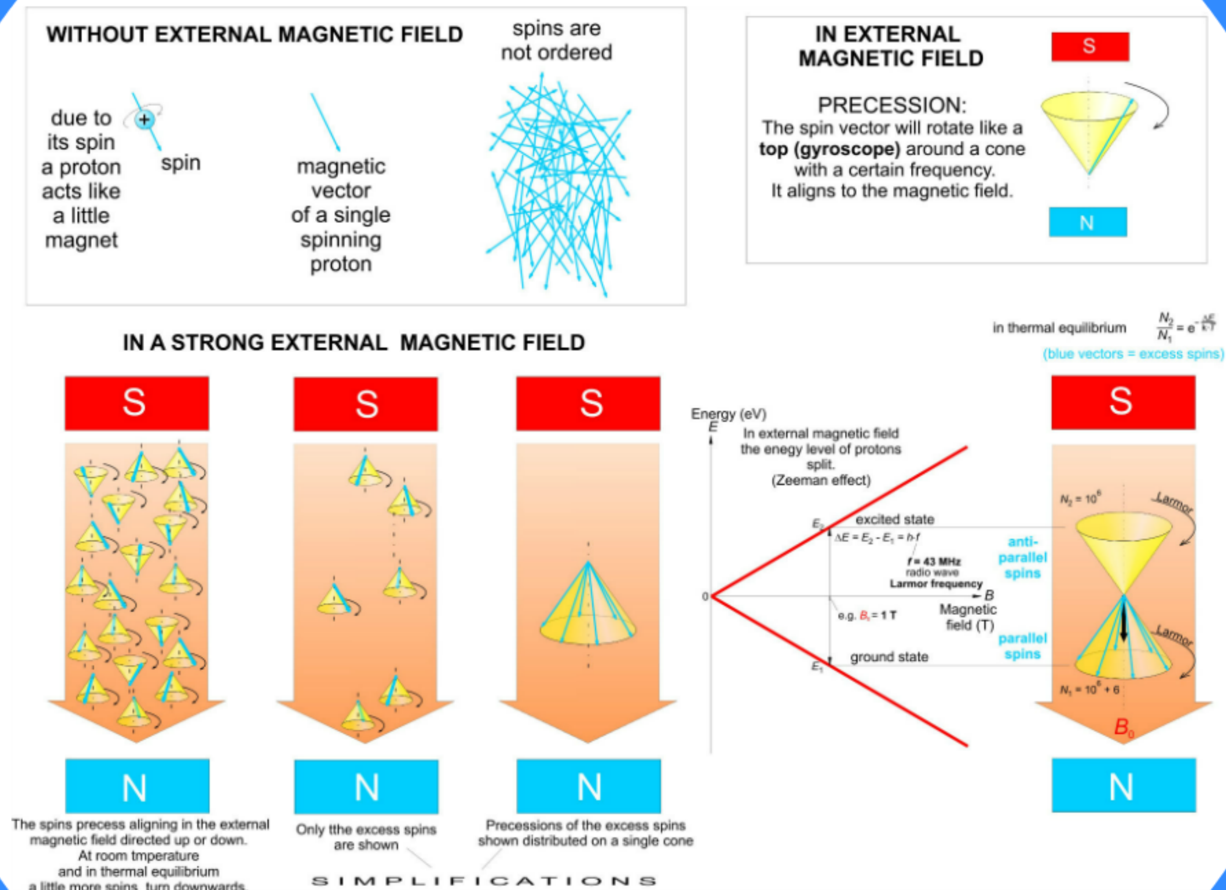



IN A STRONG EXTERNAL MAGNETIC FIELD
S
S
S
N
N
N
The spins precess aligning in the external magnetic field directed up or down. At room tmperature and in thermal equilibrium a little more spins turn downwards.
Only tthe excess spins are shown
Precessions of the excess spins shown distributed on a single cone



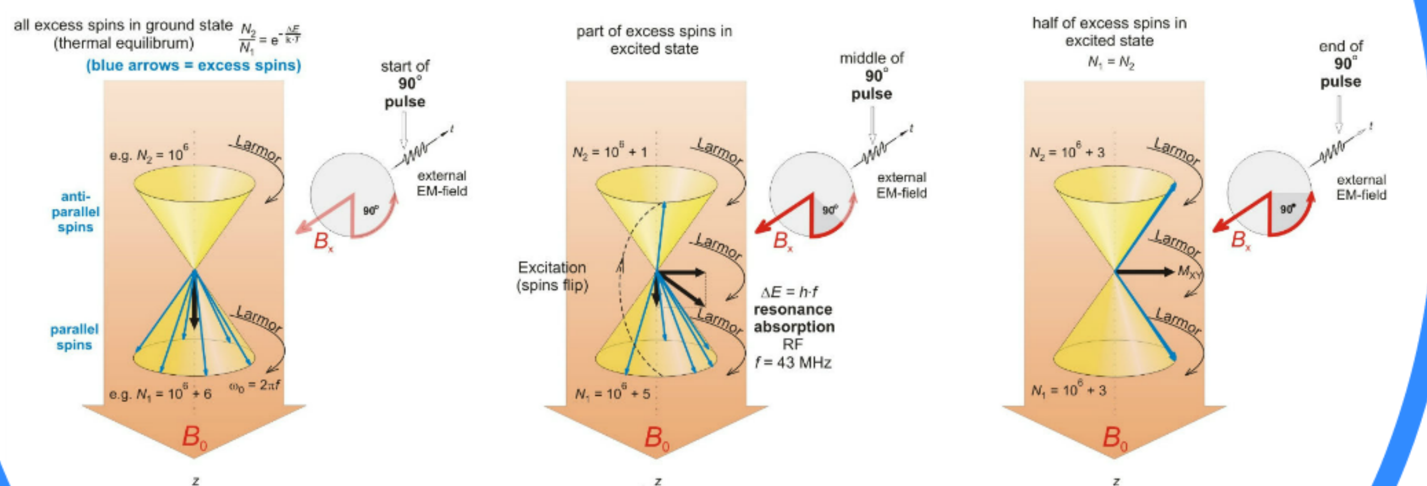
$\Delta E = h \cdot \gamma \cdot B_0$
S
Energy (eV)
E
In external magnetic field the enegy level of protons split.
(Zeeman effect)
$N_2 = 10^6$
Larmor
$E_2$
excited state
$\Delta E = E_2 - E_1 = h \cdot f$
anti-parallel spins
f = 43 MHz
radio wave
Larmor frequency
0
B
e.g. $B_0$ = 1 T
Magnetic field (T)
parallel spins
Larmor
ground state
$E_1$
$N_1 = 10^6 + 6$
$B_0$
N
$\frac{N_2}{N_1} = e^{-\frac{\Delta E}{k \cdot T}}$

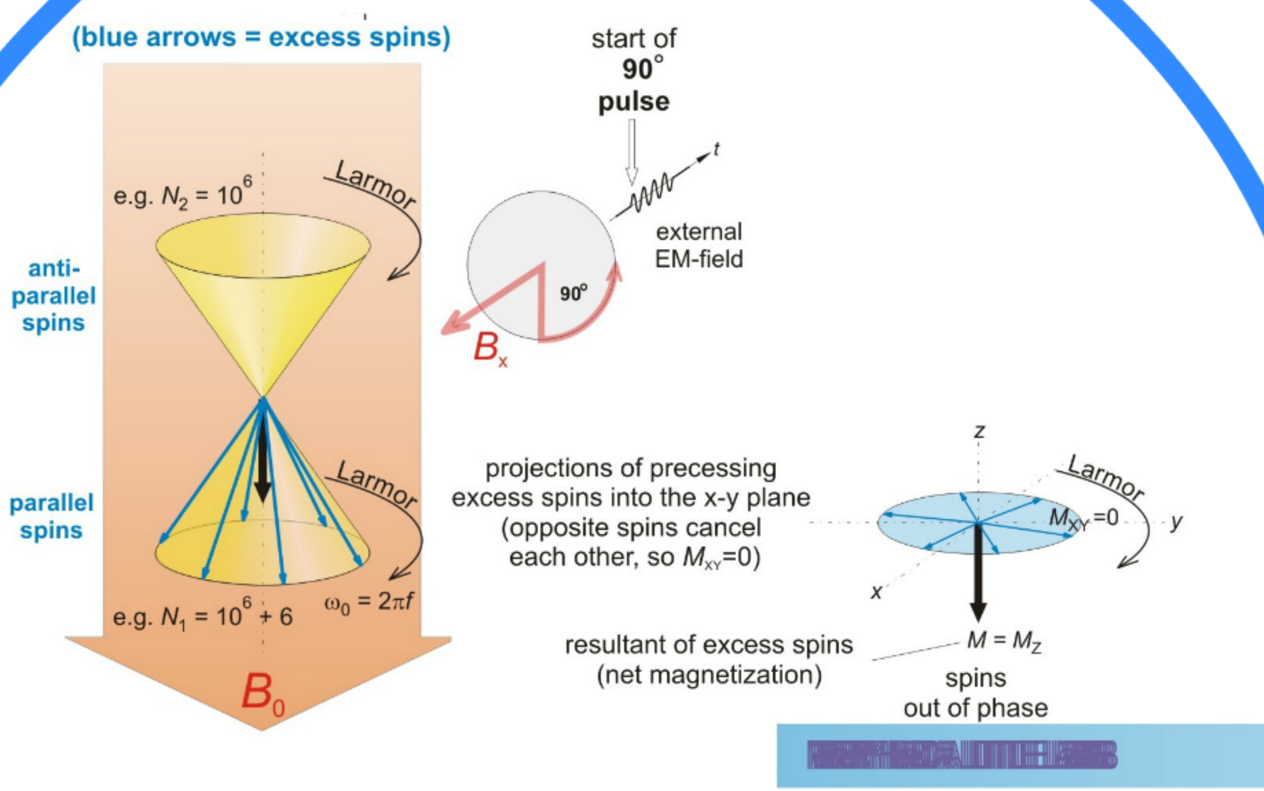
# Source of signal



# How voxel sings?

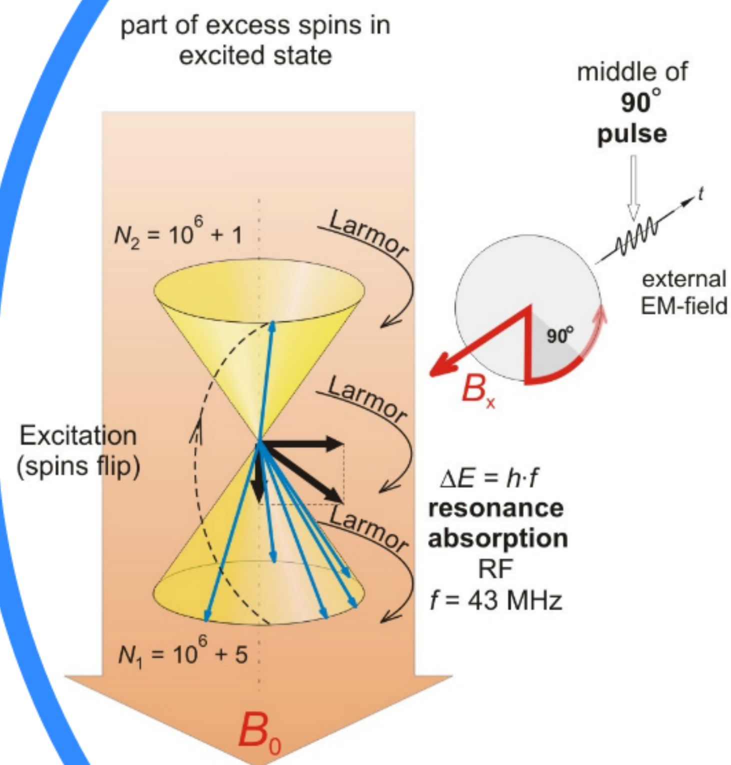
- How absorbed radiation by voxel?
- What happens in voxel?
- How does voxel produce signal?

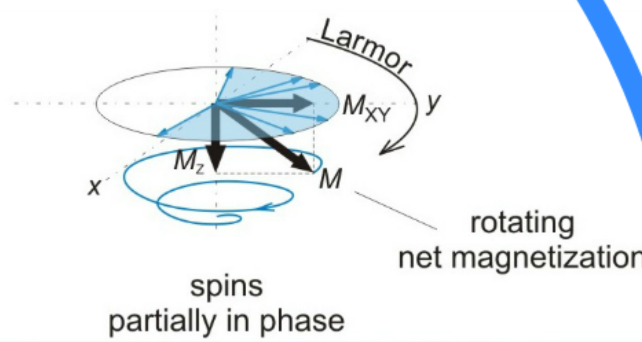





Horizontal component of spins
with random phase cancel each other,
the x-y projection of the magnetization is zero

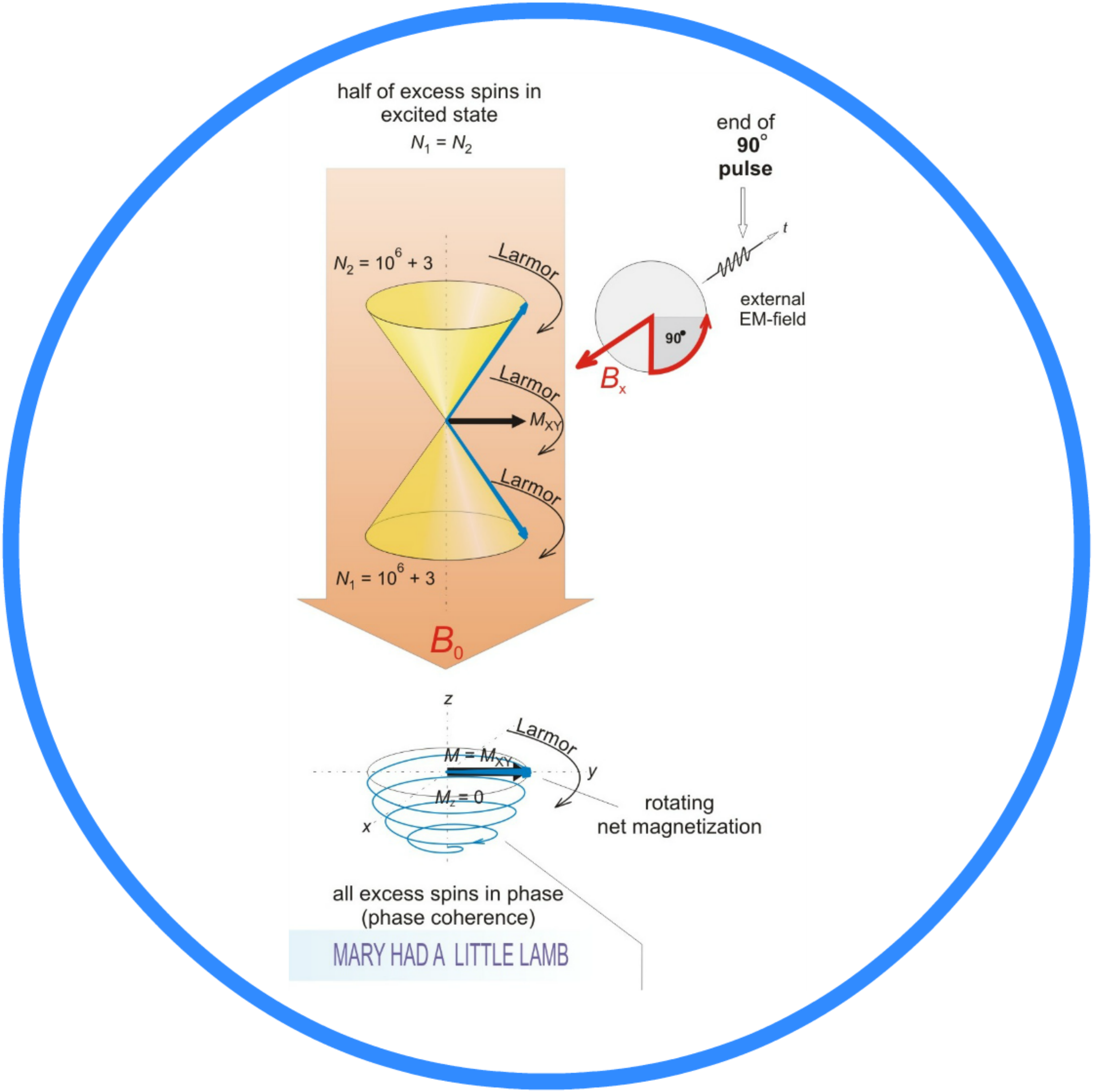
$M_Z$ spins around itself
and aligns to the huge $B_0$
so it is not detectable!



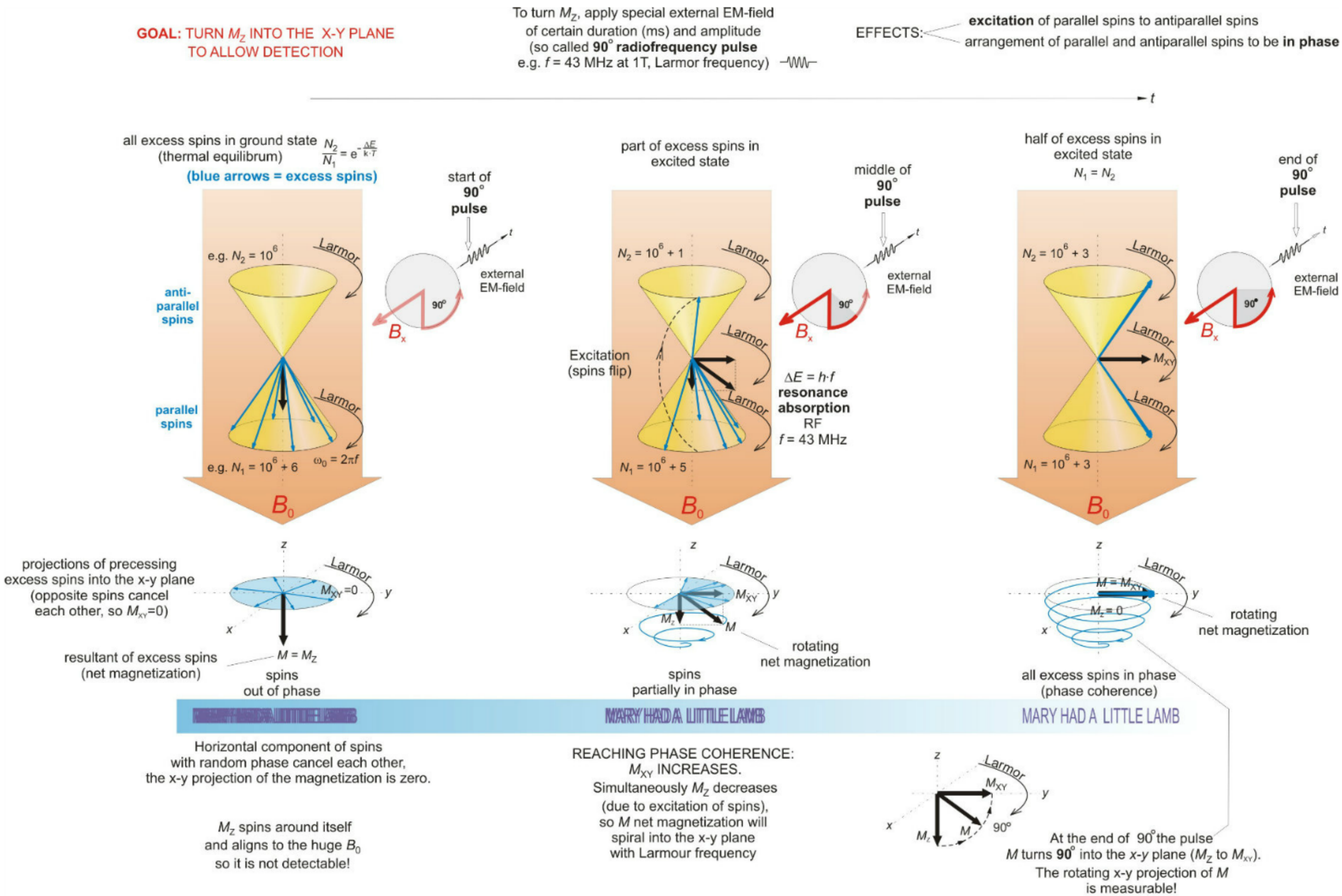




MARY HAD A LITTLE LAMB

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

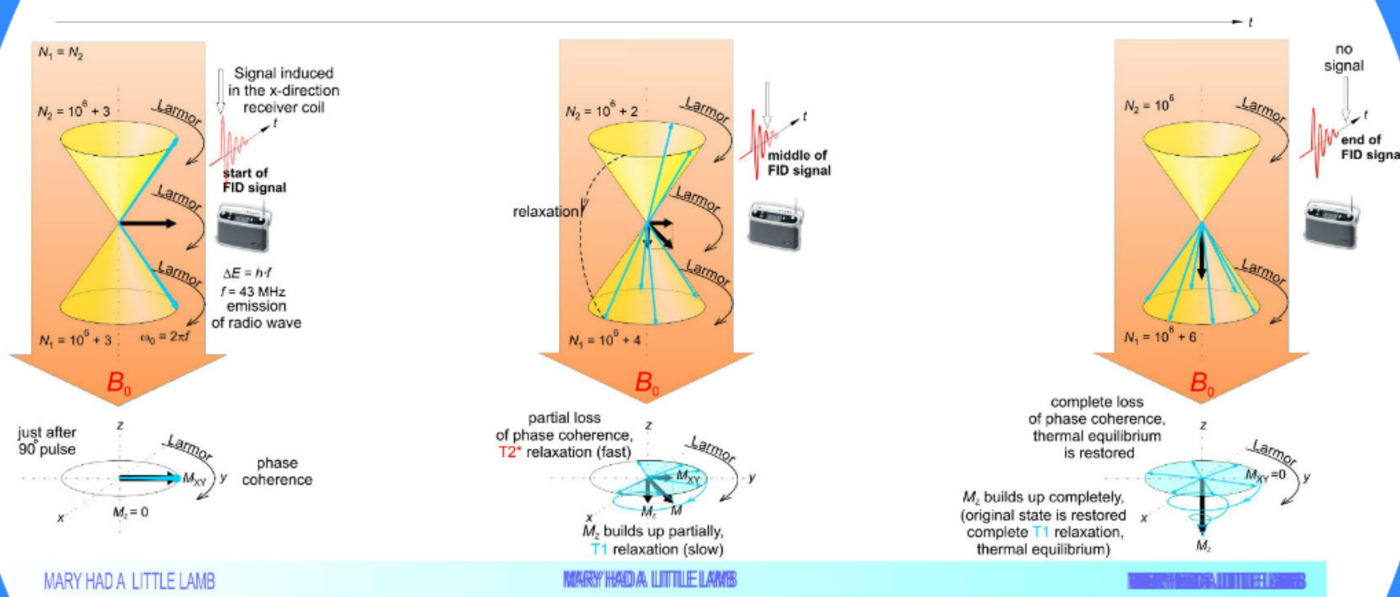


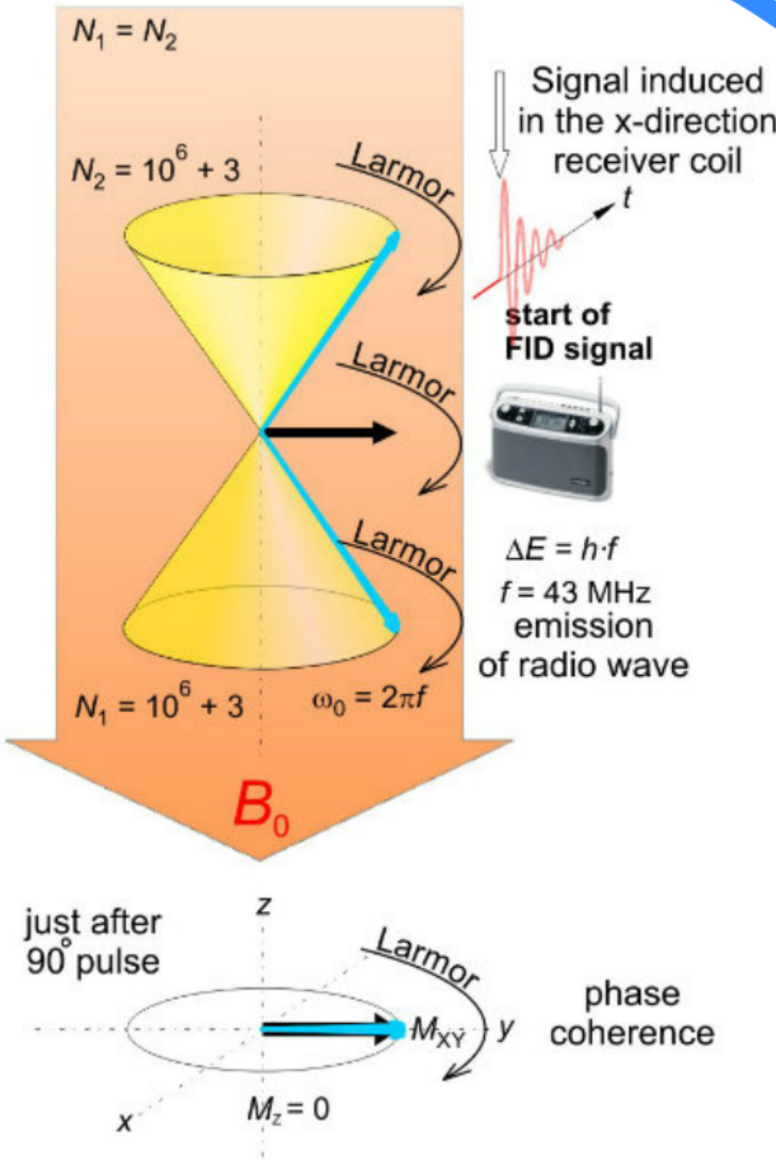
half of excess spins in
excited state
N1 = N2
end of
90°
pulse
t
N2 = 10^6 + 3
Larmor
external
EM-field
90°
Bx
Larmor
MXY
Larmor
N1 = 10^6 + 3
B0
z
Larmor
M = MXY
y
Mz = 0
x
rotating
net magnetization
all excess spins in phase
(phase coherence)
MARY HAD A LITTLE LAMB




# EXCITATION BY 90° RF- PULSE

# How detect signal?



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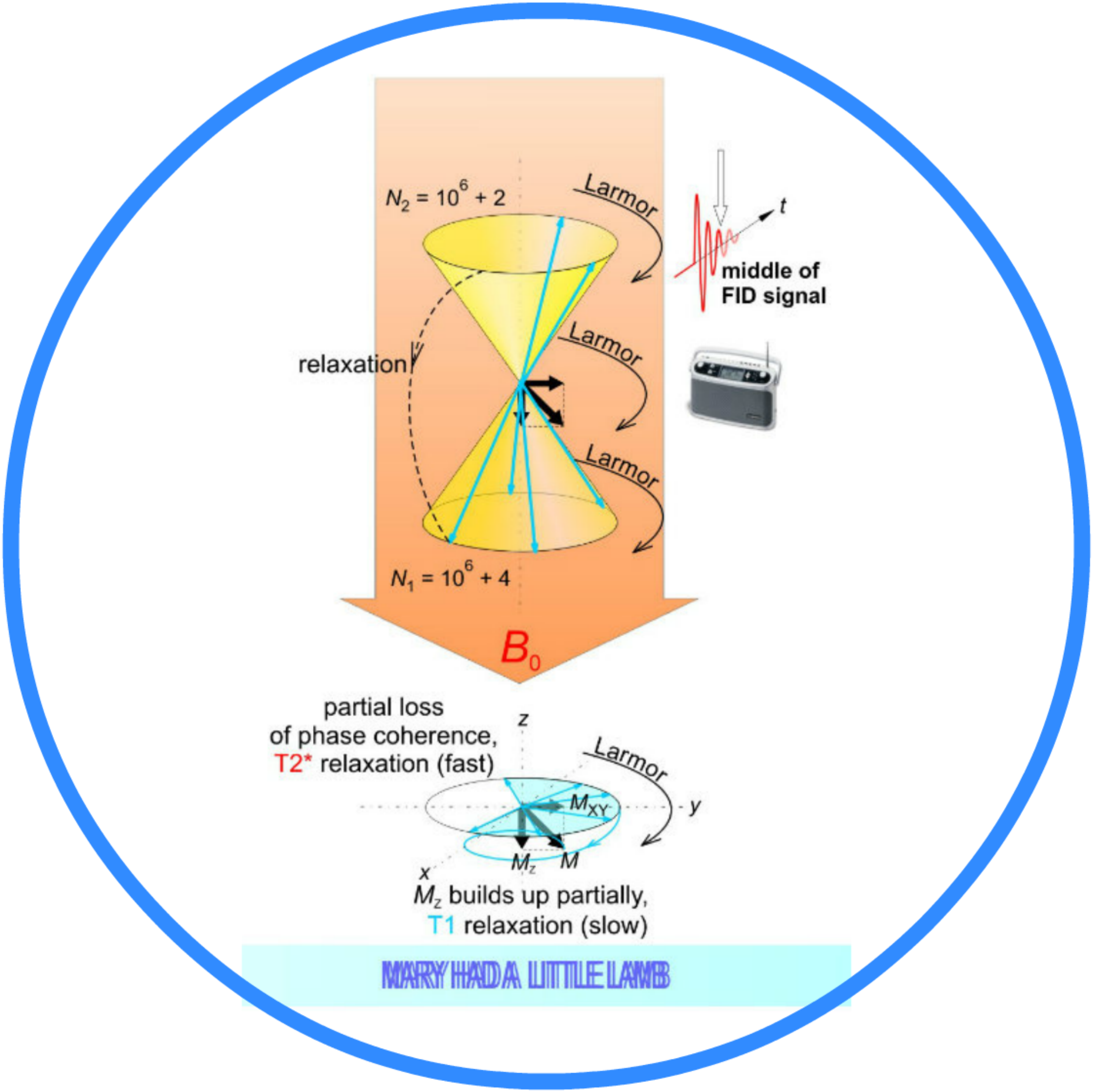
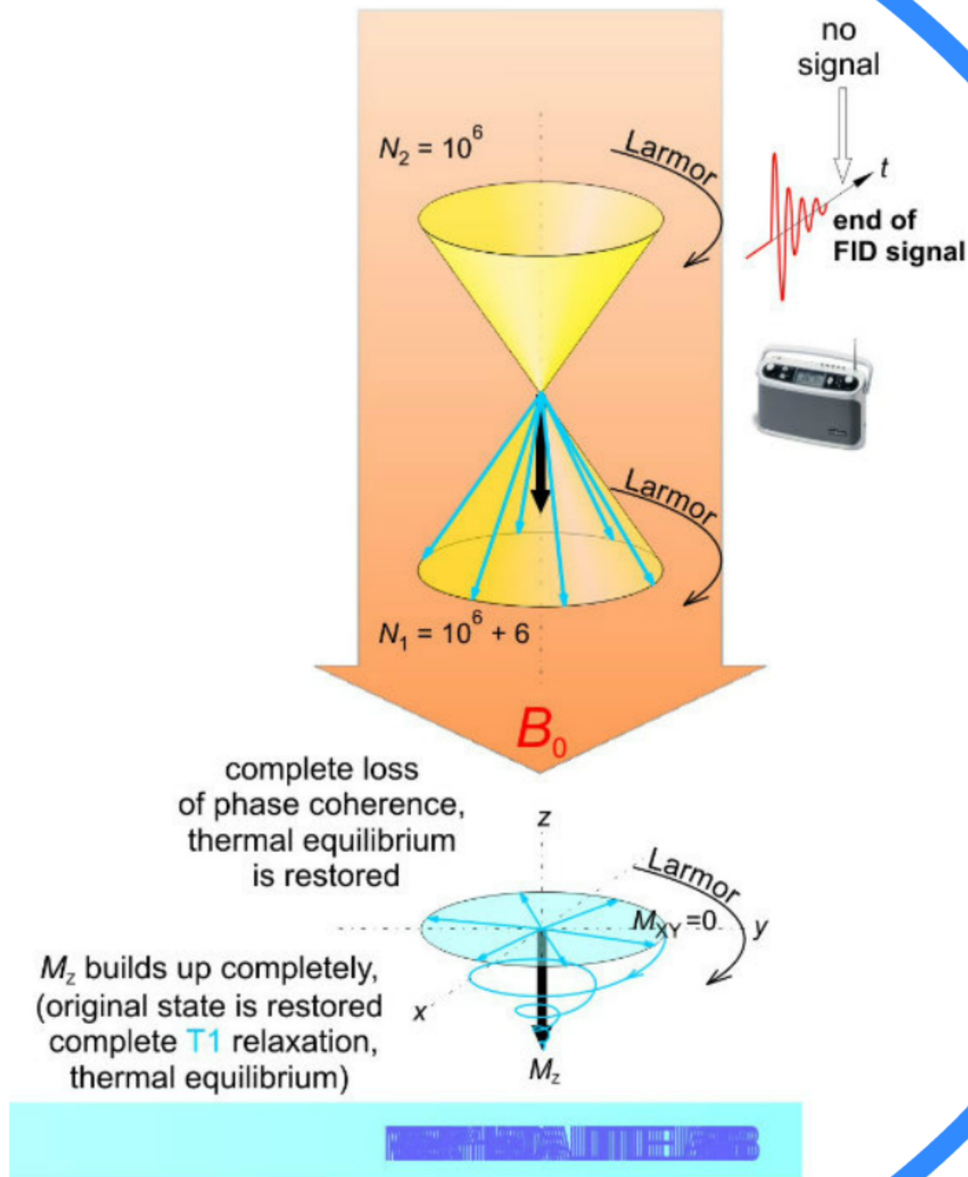
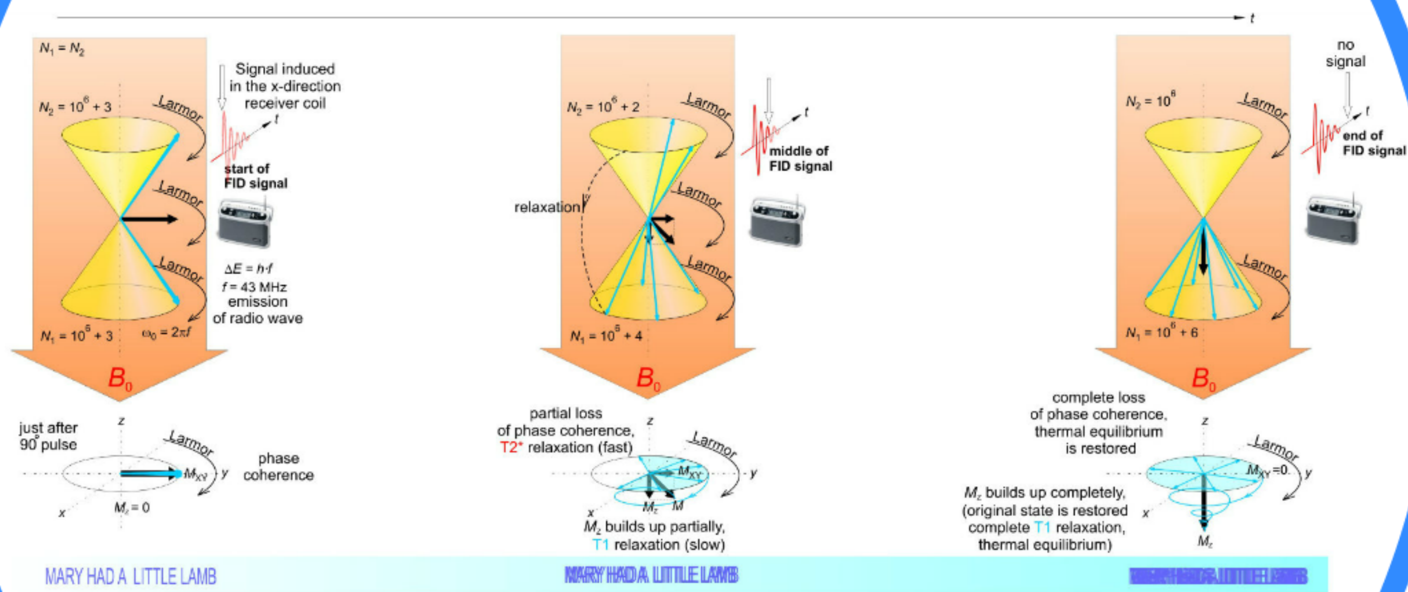


$N_2 = 10^6 + 2$
Larmor
t
middle of
FID signal
relaxation
Larmor
Larmor
$N_1 = 10^6 + 4$
$B_0$
partial loss
of phase coherence,
T2* relaxation (fast)
z
Larmor
$M_{XY}$
y
x
$M_z$
M
$M_z$ builds up partially,
T1 relaxation (slow)
MARY HAD A LITTLE LAMB



no
signal
$t$
end of
FID signal
$N_2 = 10^6$
Larmor
Larmor
$N_1 = 10^6 + 6$
$B_0$
complete loss
of phase coherence,
thermal equilibrium
is restored
z
Larmor
$M_{XY} = 0$
y
x
$M_z$ builds up completely,
(original state is restored
complete T1 relaxation,
thermal equilibrium)
$M_z$



t
$N_1 = N_2$
$N_2 = 10^6 + 3$
Larmor
Larmor
Larmor
Signal induced
in the x-direction
receiver coil
t
start of
FID signal
$\Delta E = h \cdot f$
$f$ = 43 MHz
emission
of radio wave
$N_1 = 10^6 + 3$
$\omega_0 = 2\pi f$
$B_0$
just after
90° pulse
z
Larmor
$M_{XY}$
y
x
$M_z = 0$
phase
coherence
$N_2 = 10^6 + 2$
Larmor
Larmor
Larmor
t
middle of
FID signal
relaxation
$N_1 = 10^6 + 4$
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partial loss
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T2* relaxation (fast)
z
Larmor
$M_{XY}$
y
x
$M_z$
M
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$N_2 = 10^6$
Larmor
Larmor
no
signal
t
end of
FID signal
$N_1 = 10^6 + 6$
$B_0$
complete loss
of phase coherence,
thermal equilibrium
is restored
z
Larmor
$M_{XY} = 0$
y
x
$M_z$
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thermal equilibrium)
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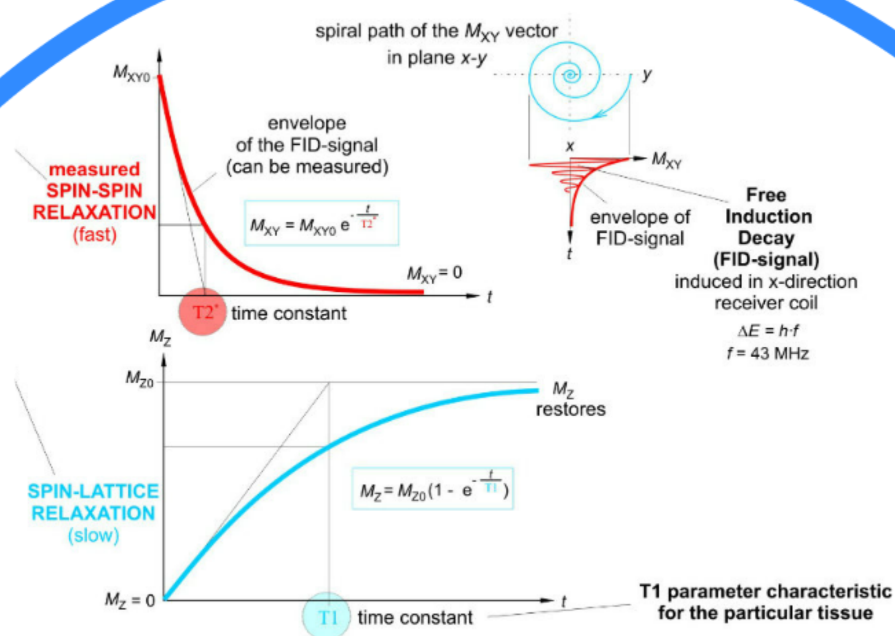



after the 90° pulse

1. Spins **lose their phase coherence** fast — Exponential decay, caracterised by T2* relaxation time
2. Slow relaxation of **antiparallel spins to parallel spins** — Exponential decay, caracterised by T1 relaxation time

reasons of losing phase coherence

- **inhomogenity** of magnetic field $\boldsymbol{B_0}$ ($T2_{rev}$)
- **inhomogenity** of magnetisation **in tissue** (T2)

$$\frac{1}{T2^*} = \frac{1}{T2} + \frac{1}{T2_{rev}}$$

**time constant of measured SPIN-SPIN RELAXATION** and inhomogenity of $B_0$ together

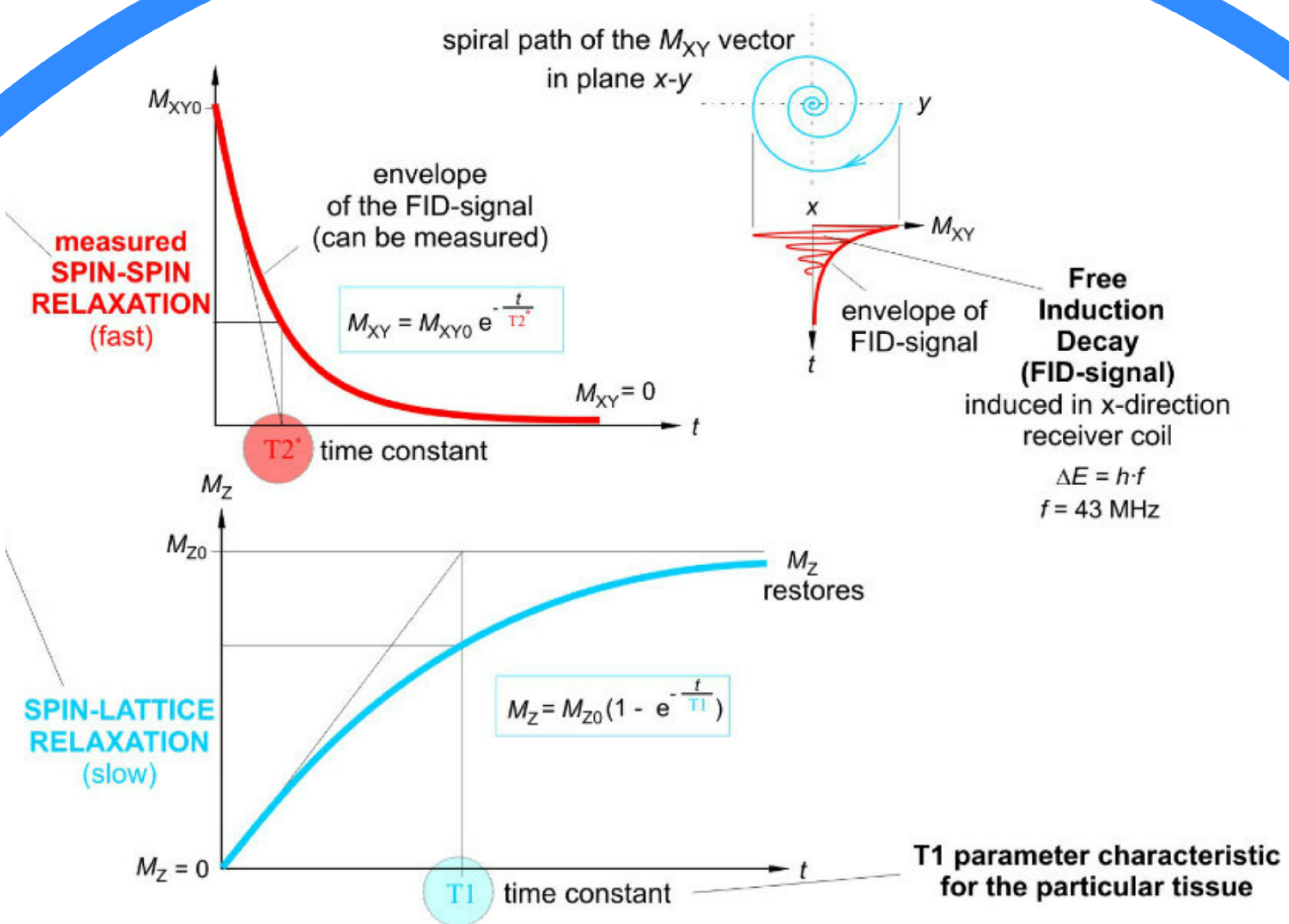
time constant of **SPIN-SPIN RELAXATION** in tissue

time constant caused by inhomogenity of magnetic field $B_0$ (technical inconvinience, constant in time)

**T2 parameter characteristic of the particular tissue**

Only T2* can be measured. Spin-echo technique reveals T2.

# RELAXATION, LOSS OF PHASE COHERENCE, DETECTING MRI SIGNALS



spiral path of the $M_{XY}$ vector in plane $x$-$y$
$y$
$x$
$M_{XY}$
$t$
envelope of FID-signal
Free Induction Decay (FID-signal)
induced in x-direction receiver coil
$\Delta E = h \cdot f$
$f$ = 43 MHz
$M_{XY0}$
envelope of the FID-signal (can be measured)
measured SPIN-SPIN RELAXATION (fast)
$M_{XY} = M_{XY0} e^{-\frac{t}{T2^*}}$
$M_{XY} = 0$
$T2^*$ time constant
$M_Z$
$M_{Z0}$
$M_Z$ restores
SPIN-LATTICE RELAXATION (slow)
$M_Z = M_{Z0}(1 - e^{-\frac{t}{T1}})$
$M_Z = 0$
T1 time constant
T1 parameter characteristic for the particular tissue

after the 90° pulse

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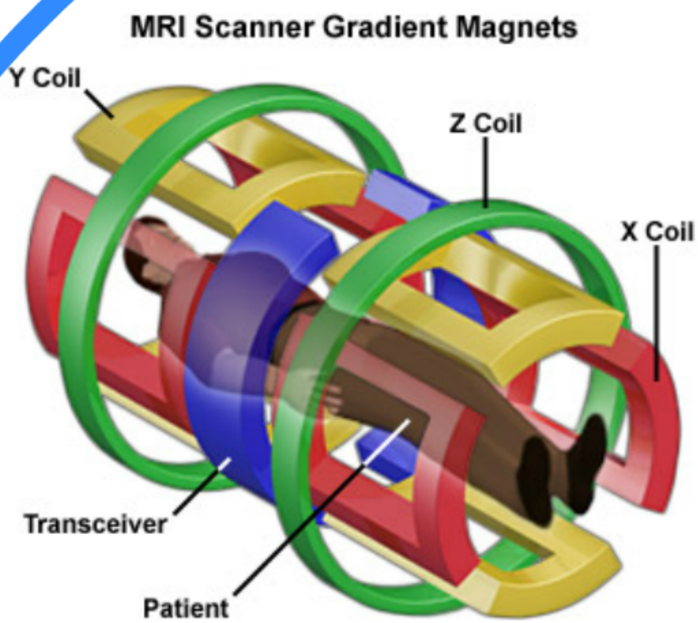
- Orchestra
- Singers

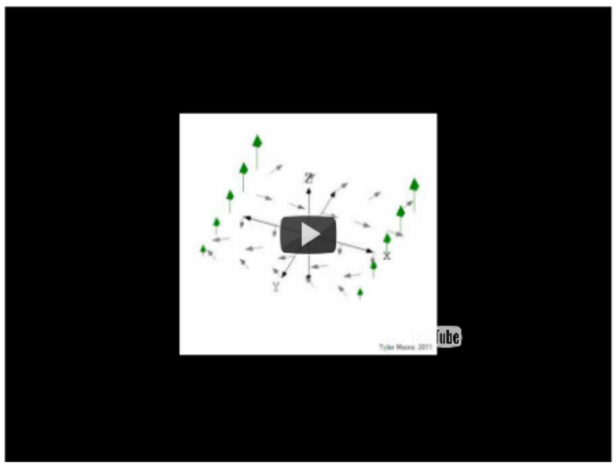
- Floors
- Pitch (frequency)
- Duration (canon)

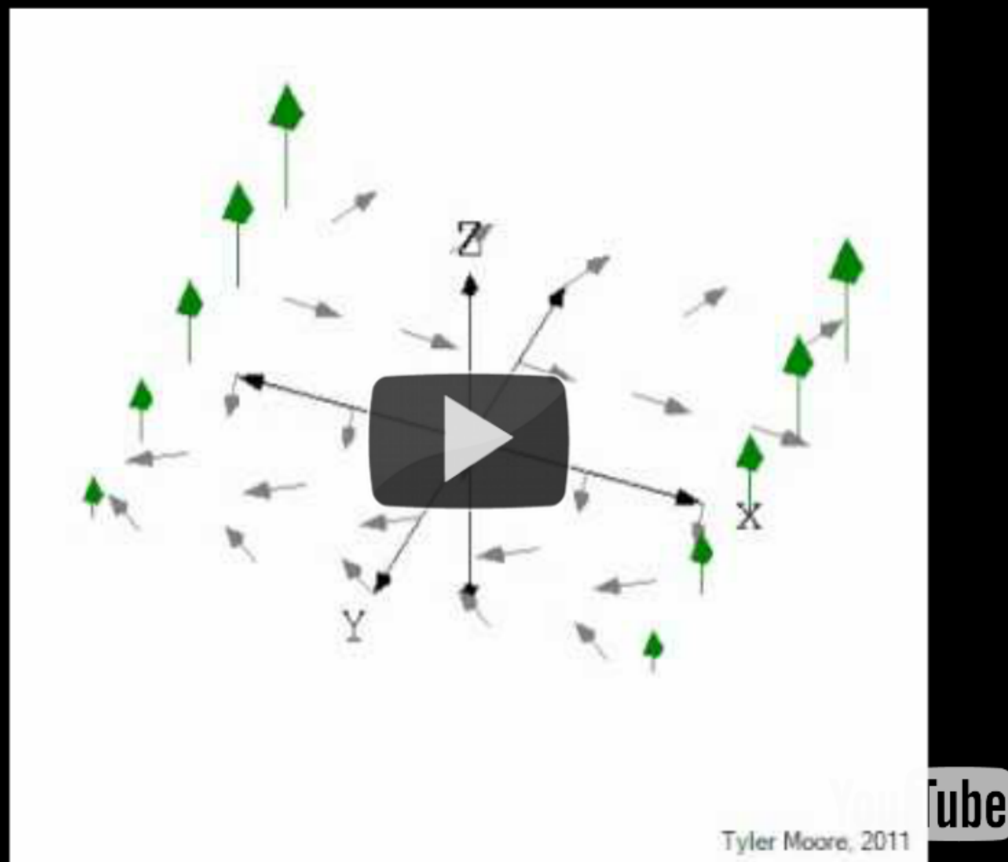
- Magnet (pl: 3T, He)
- Voxel (spins)

- Encoding (3D)

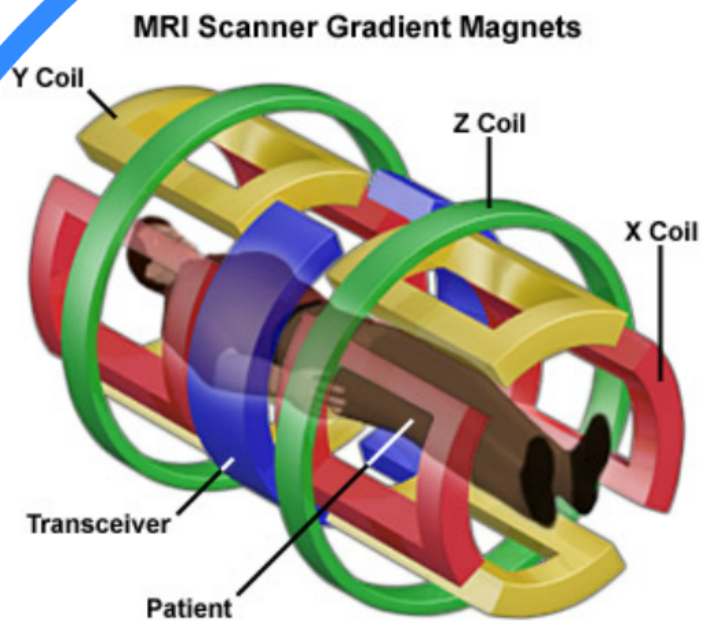
# Voxel - position encoding

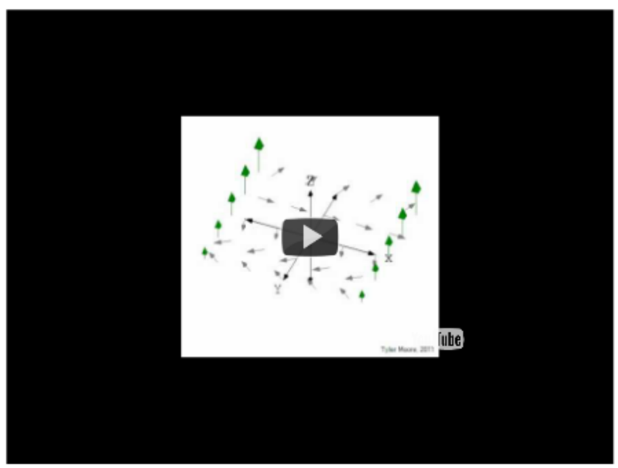



Z
X
Y
Tyler Moore, 2011

# Voxel - position encoding



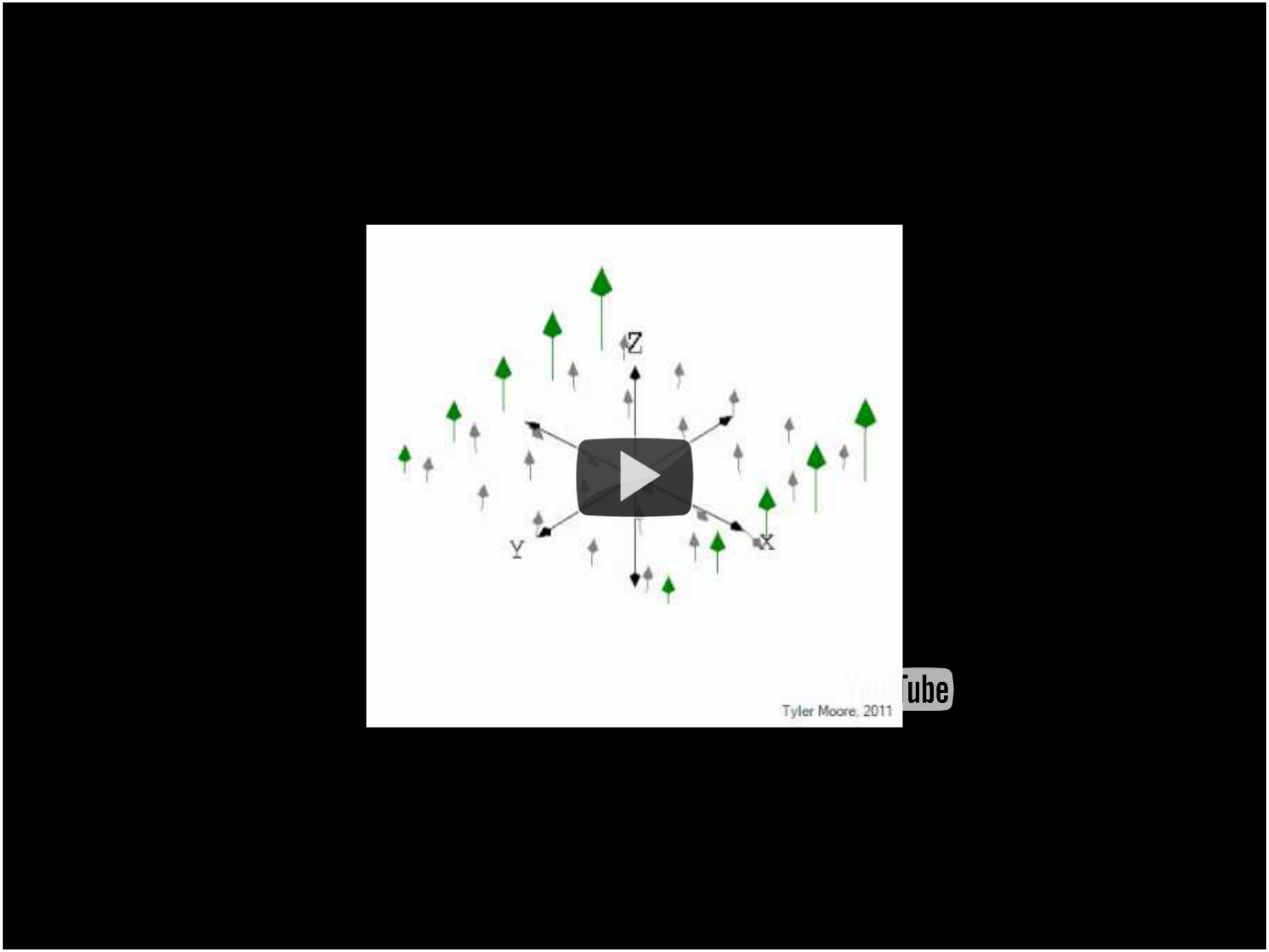



## Voxel - position encoding

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

3D imaging

- Slices
- Frequency
- Phase


Z
Y
X
Tyler Moore, 2011

# 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 |

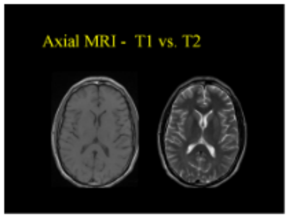
**Table XV**
The spin–lattice relaxation time ($T_1$) and spin–spin relaxation time ($T_2$) of various biological tissues at 0.2 tesla

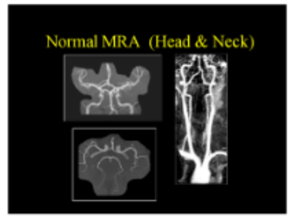
| Tissue | $T_1$, msec | $T_2$, msec |
|---|---|---|
| Fat | 240 ± 20 | 60 ± 10 |
| Muscle | 400 ± 40 | 50 ± 10 |
| Gray matter | 495 ± 85 | 100 ± 10 |
| White matter | 390 ± 70 | 90 ± 20 |
| Lung | 460 ± 90 | 80 ± 30 |
| Kidney | 670 ± 60 | 50 ± 10 |
| Liver | 380 ± 20 | 40 ± 20 |
| Liver metastases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

*Source:* Morgan and Hendee, 1984

# Biological applications

## Morphological imaging

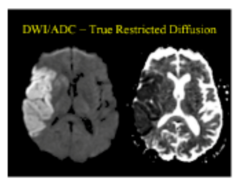


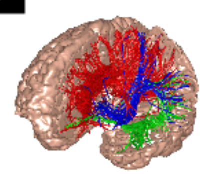



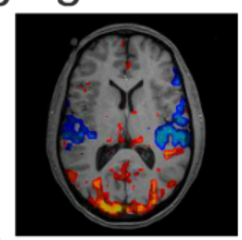

- T1 "anatomy"
- T2 "pathology"

- Angiography (T1)
(Gd contast)

## Functional imaging



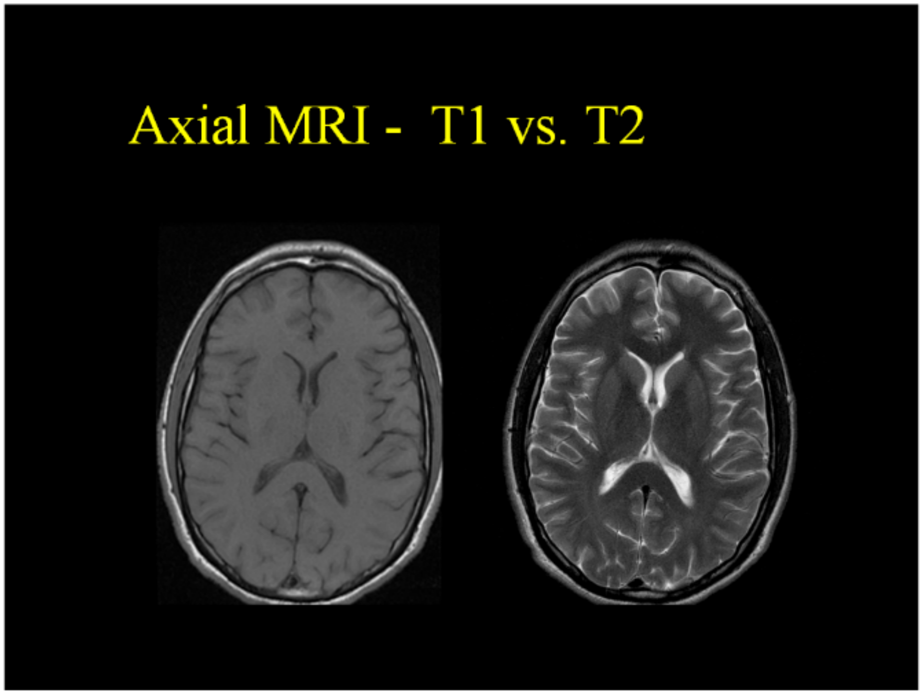



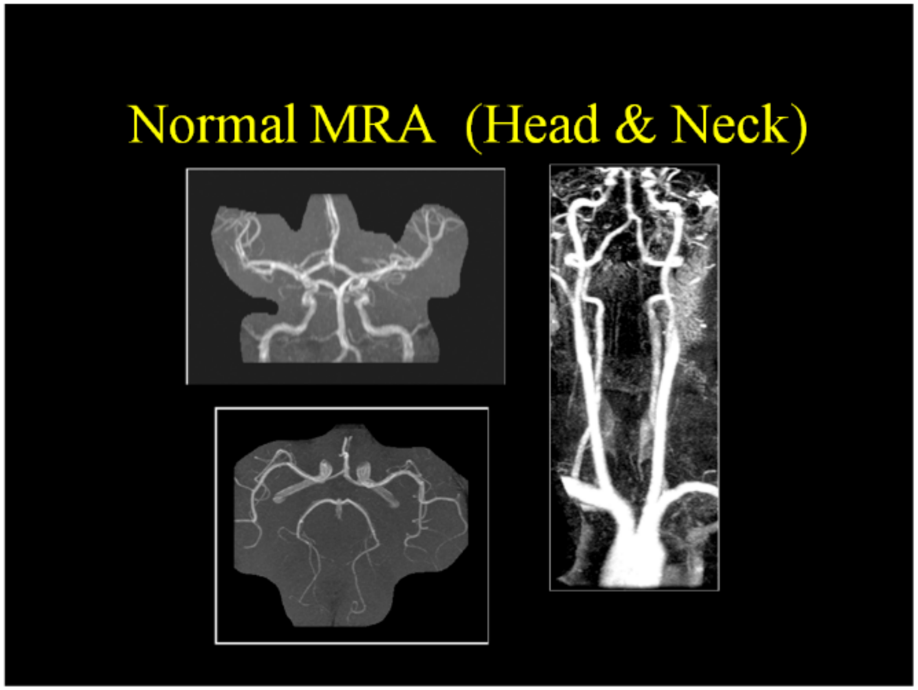


- Diffusion coeff
(water)

- Blood
(oxiFe - deoxiFe)

# Morphological imaging

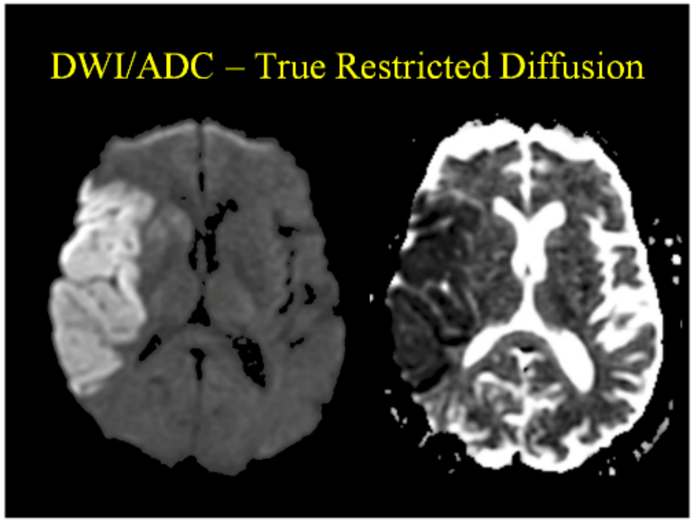


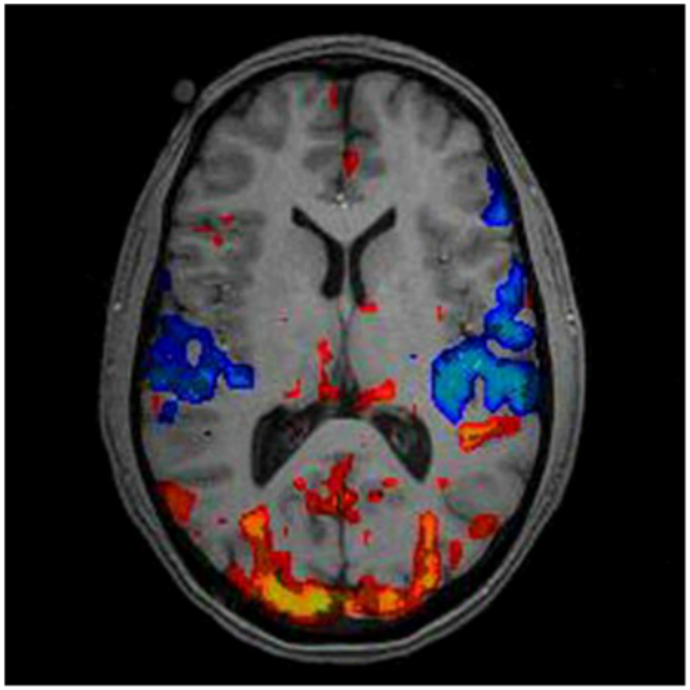



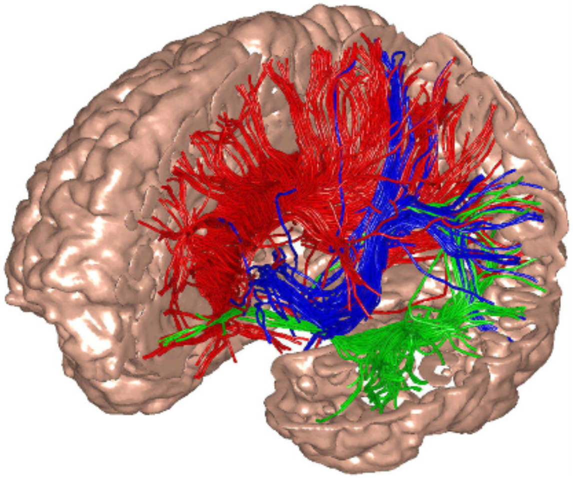

- T1 "anatomy"
- T2 "pathology"

- Angiography (T1) (Gd contast)

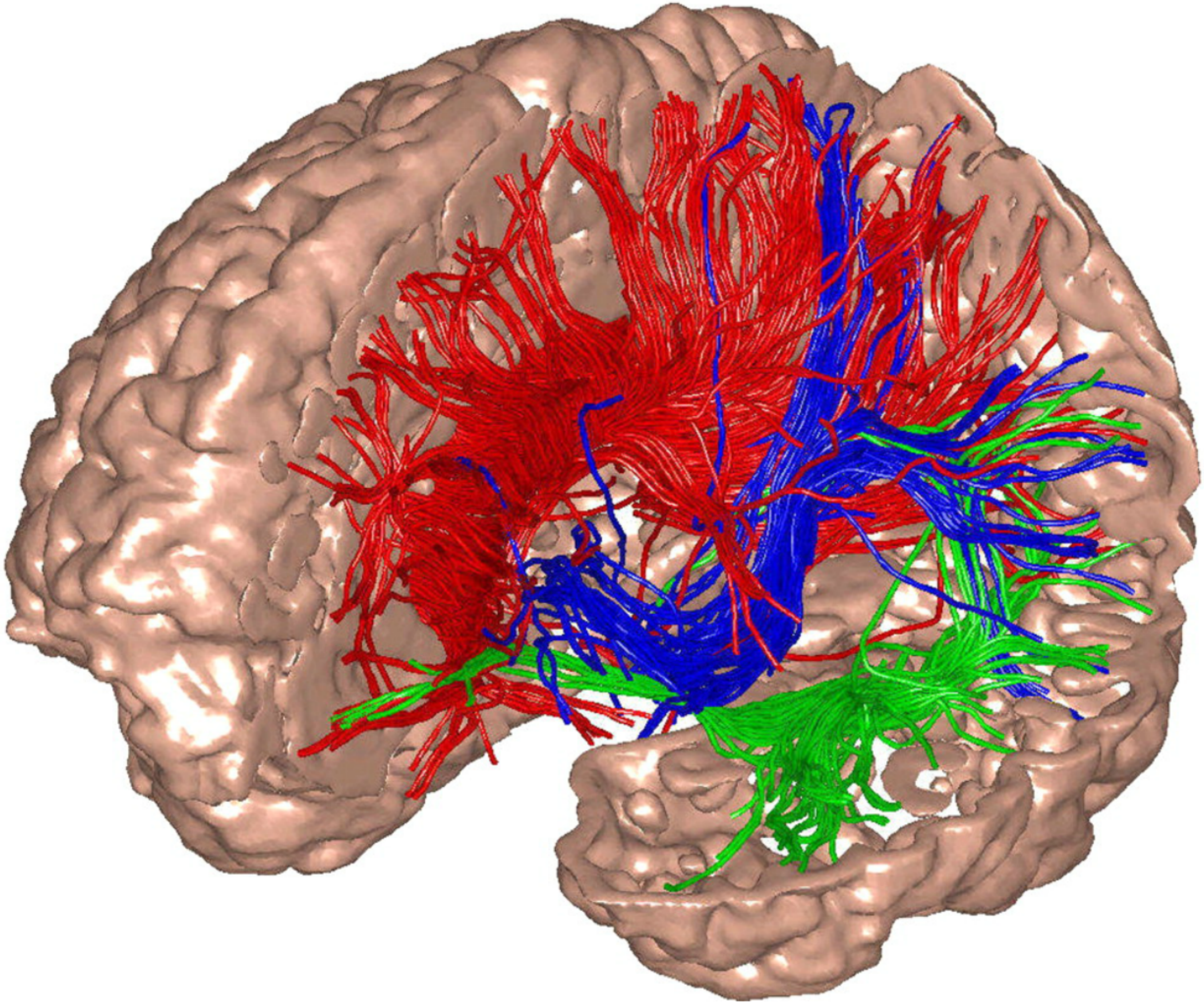
# Functional imaging



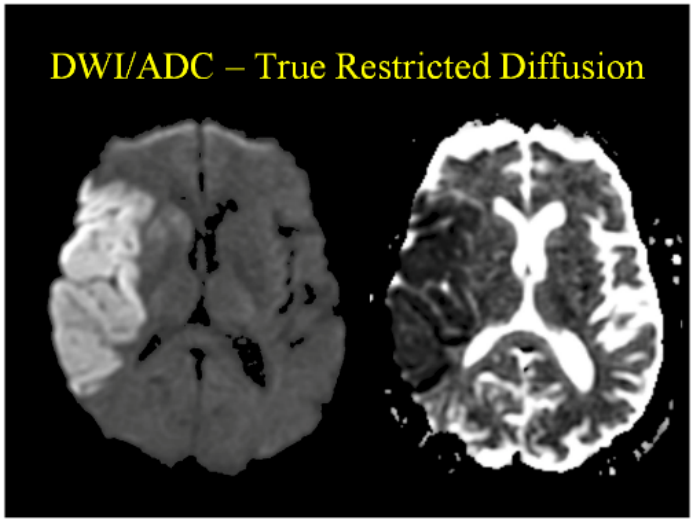



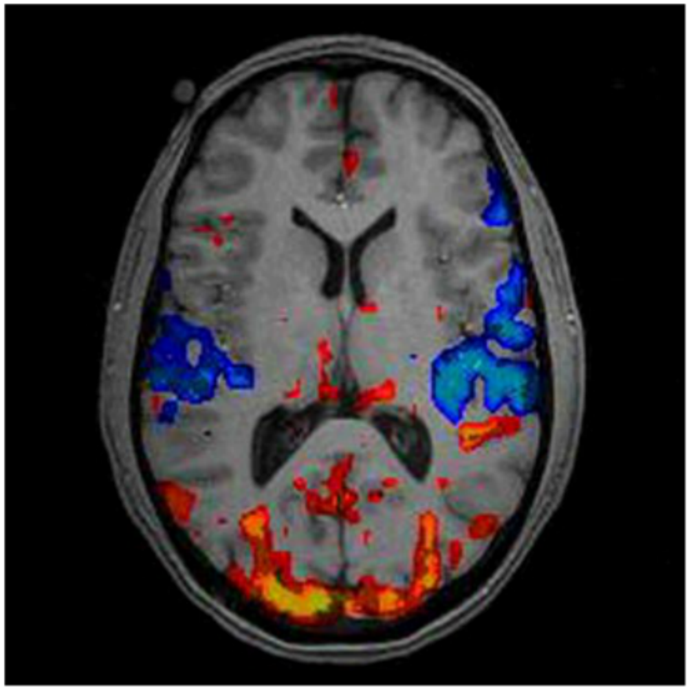


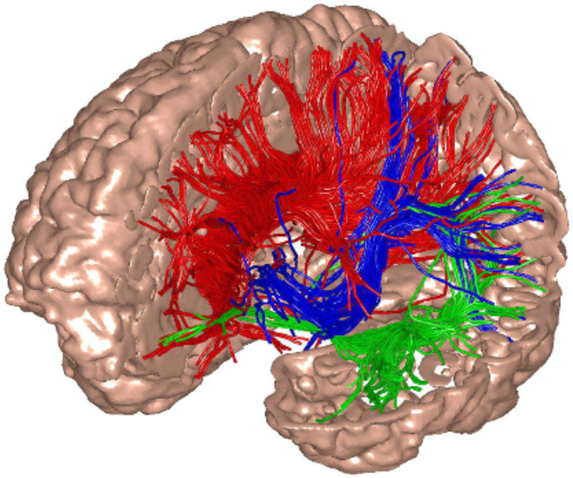
- Diffusion coeff (water)
- Blood (oxiFe - deoxiFe)



# Functional imaging





- Diffusion coeff (water)

- Blood (oxiFe - deoxiFe)

Background ... :

- http://www.imaios.com

- MRI Physics Tutorial (youtube)

- http://oftankonyv.reak.bme.hu/