Magical Magnetic Resonance Imaging

(Actually not magic but Physics)

Magic?

Of course not, but as Arthur C. Clarke said:

“Any sufficiently advanced technology is indistinguishable from magic. “

MRI uses

- Nuclear spins
- Very Strong Superconducting Magnets
- Fourier Transforms
- Gradient Magnetic Fields (Loud Banging Noise)
- Uses Powerful RF fields
- Detects tiny RF signals
- Clever Software

How to see inside your body

- Use a knife
- Use Light
- Use X-rays
- Use X-ray Tomography (CT)
- Use Injected Radioactive Tracers (SPECT and PET)
- Use Ultrasound
- Use Magnets and Radio Waves (MRI !)

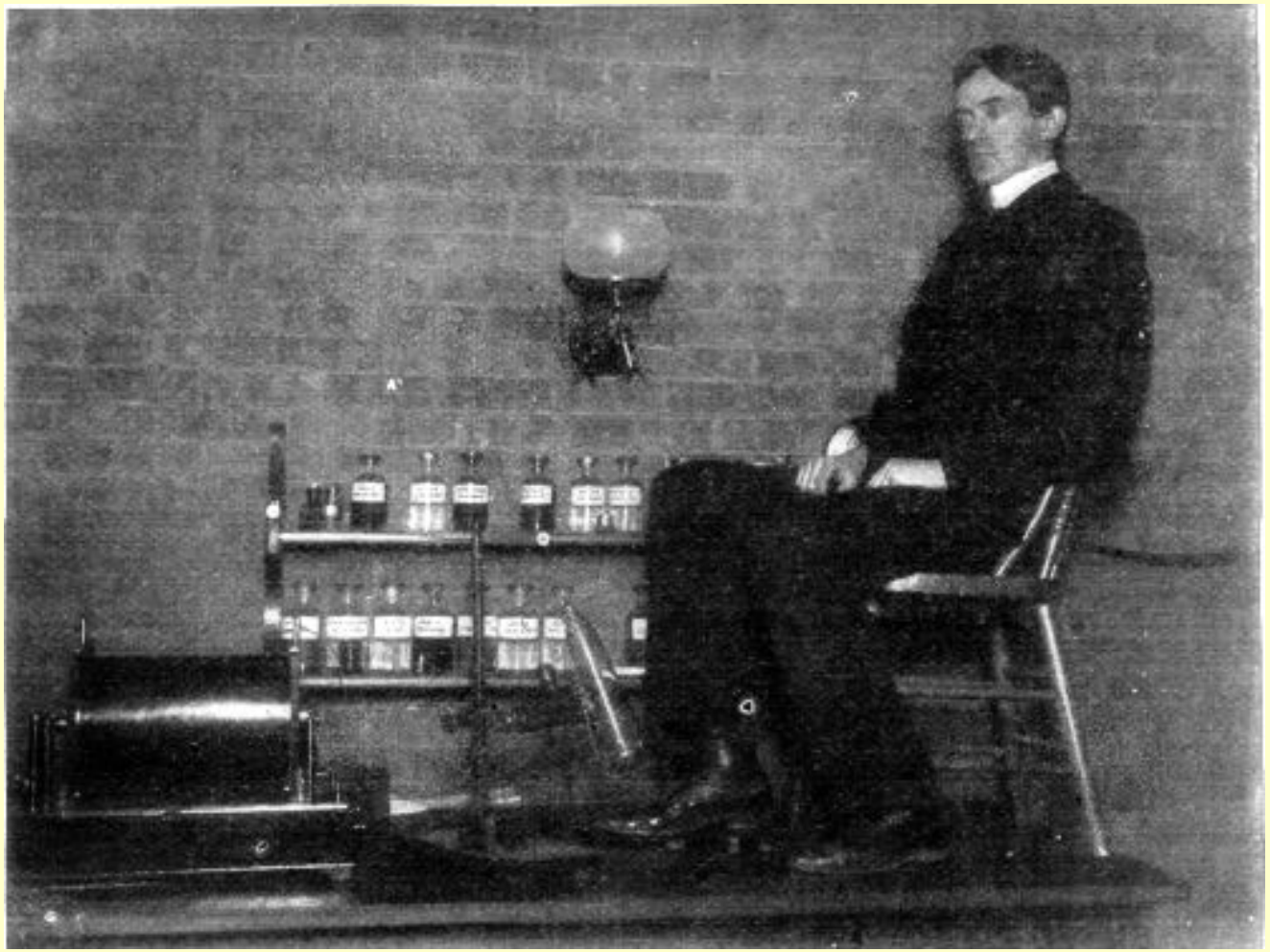
X-rays are well known

The famous radiograph made by Roentgen on 22 December 1895.

This is traditionally known as “the first X-ray picture” and “the radiograph of Mrs. Roentgen's hand”.

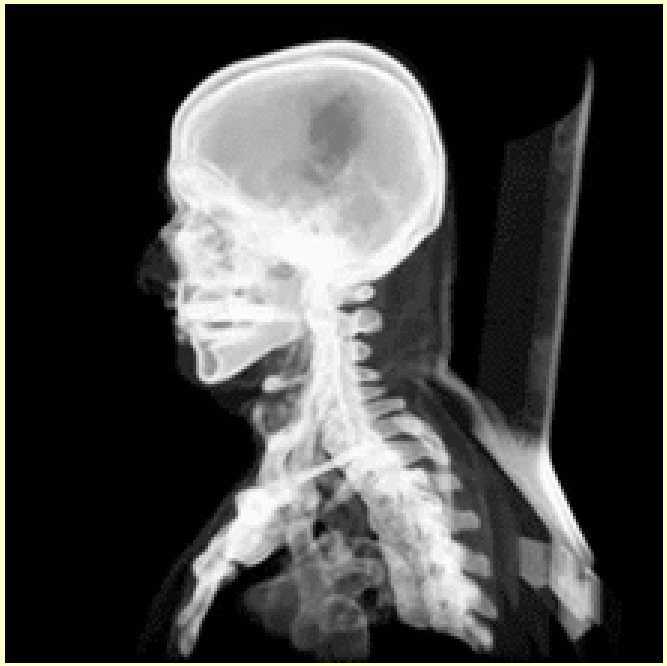
Poor for Soft Tissue!

X-rays in 1896



Victorian Gentleman having foot X-ray

CT Scan - Rotate X-ray source around subject

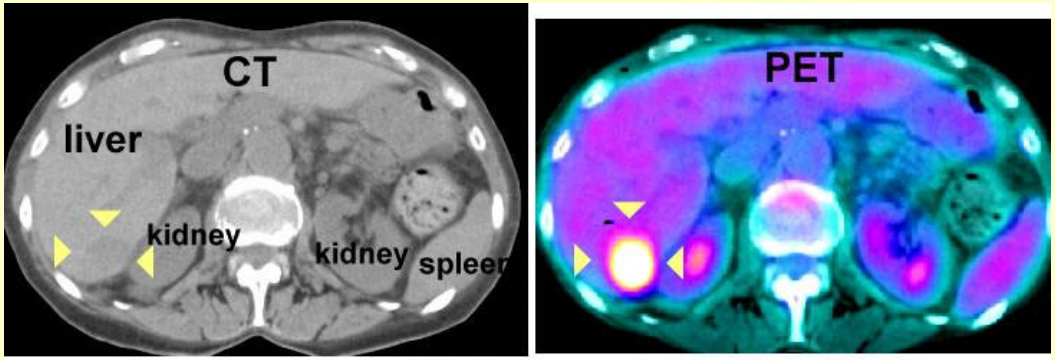


Significant X-ray dose, good for bones but poor soft tissue contrast.

Ultrasound – use echoes from internal structures

Cheap and quick, no harmful radiation, limited resolution.

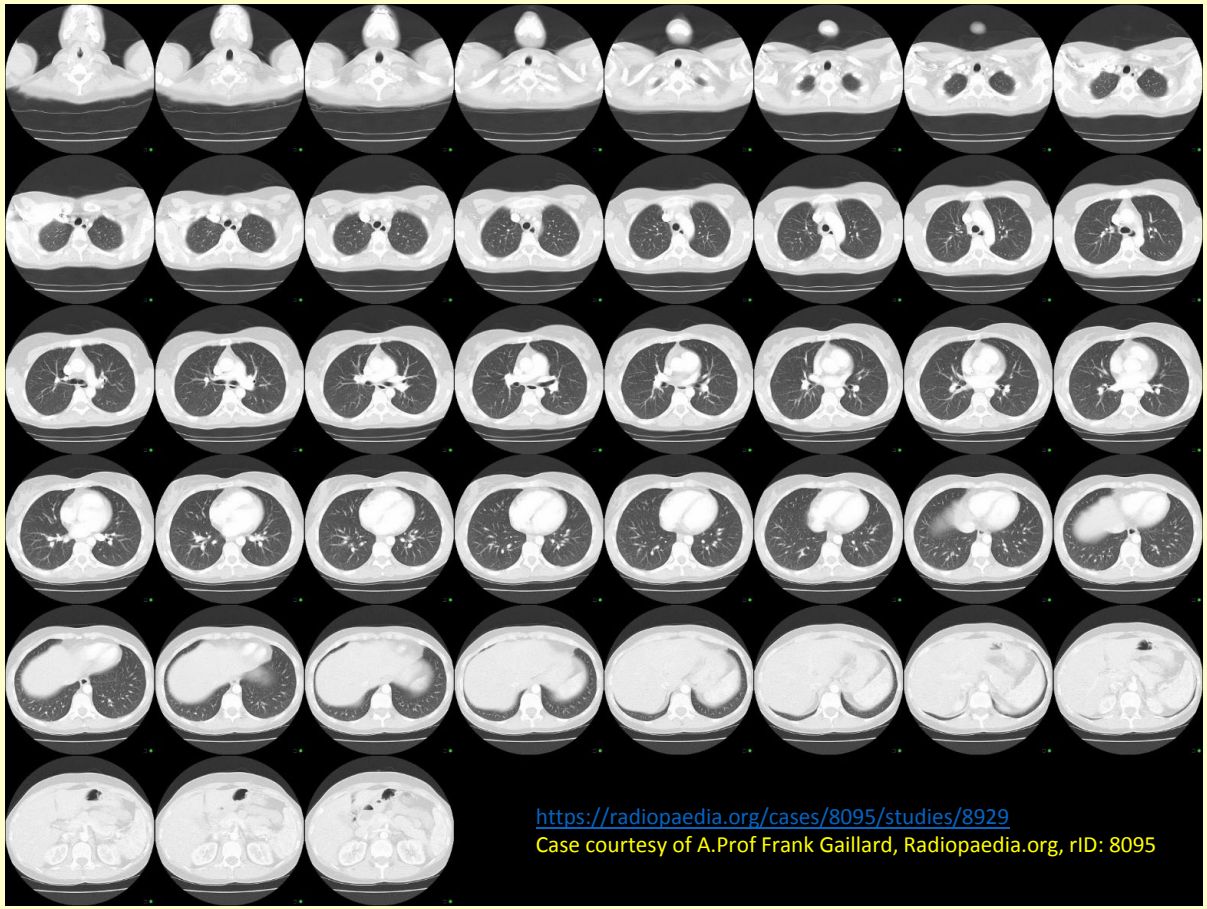
SPECT and PET – inject radioactive tracer

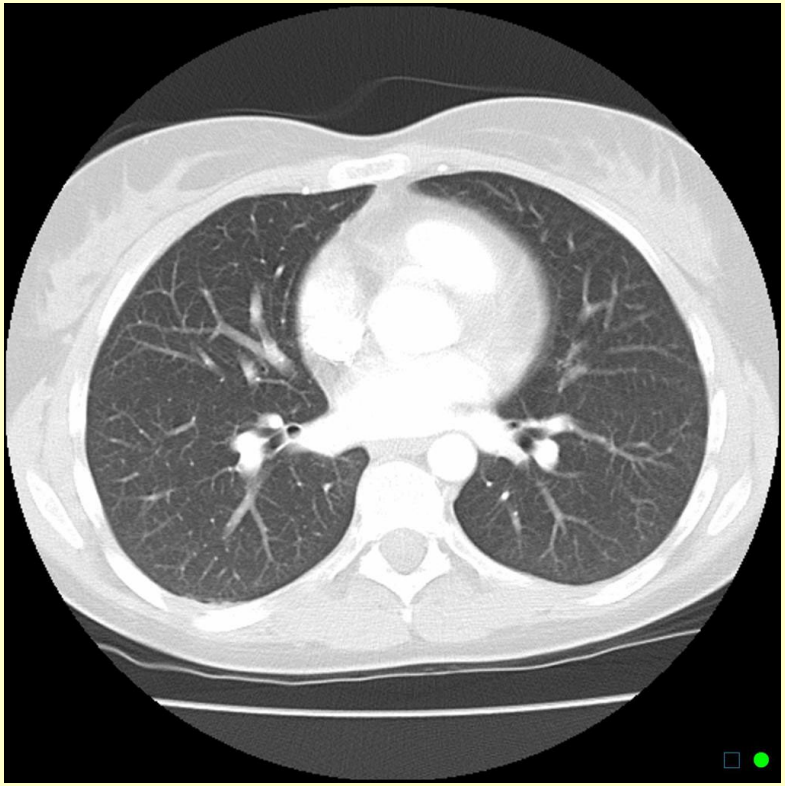


lung cancer with liver metastases, hard to see on CT but easy on PET scan

Tracer accumulates in regions of interest and decay products (photons) detected outside body. Mostly combined with CT in modern scanners.

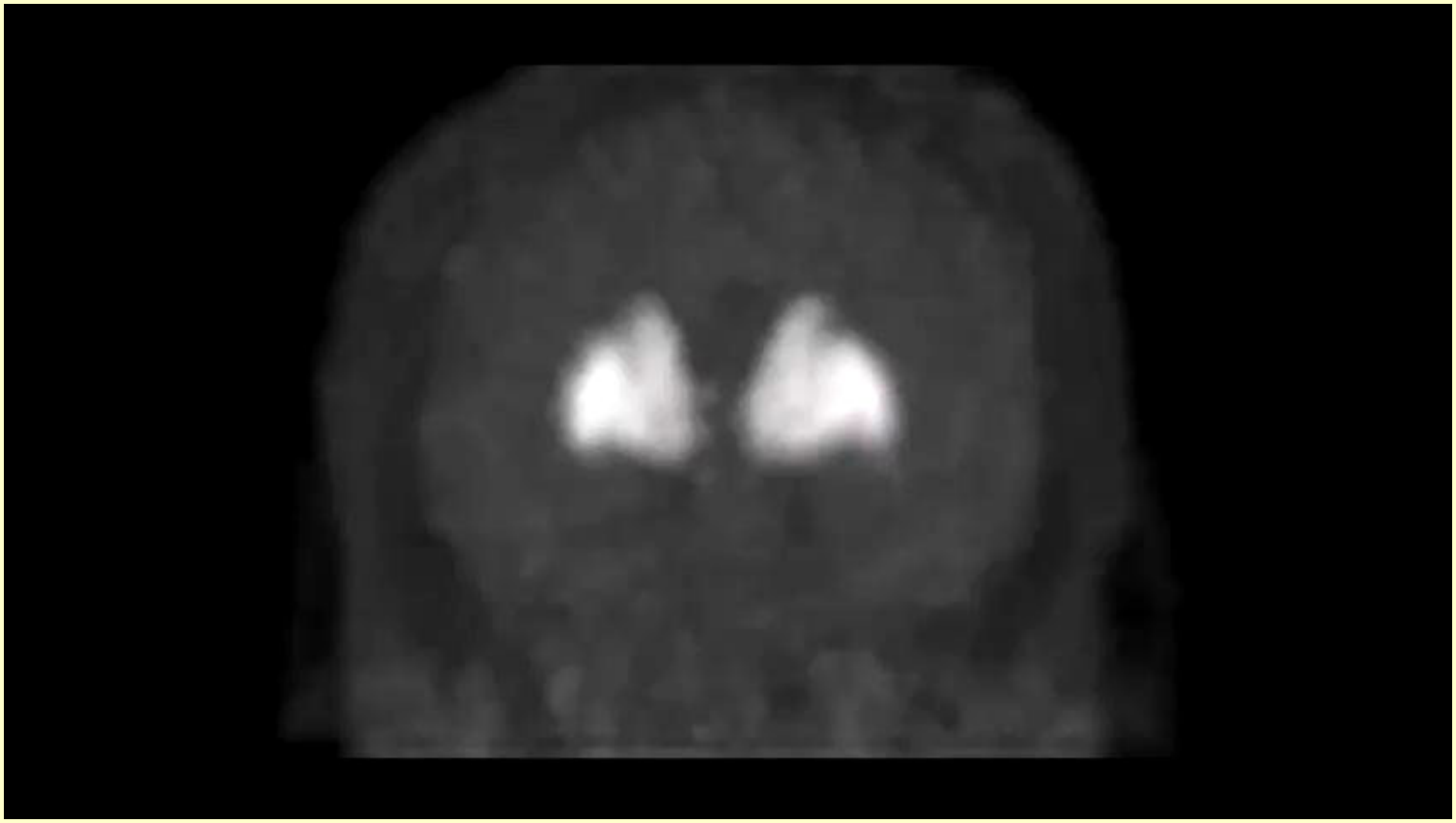
3D Imaging Modalities – Stack of 2D Slices





3D Imaging Modalities – 3D Rendering

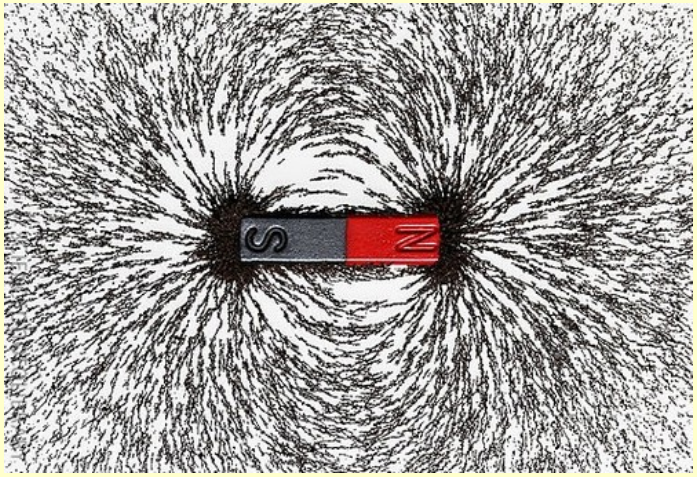
3D Imaging Modalities – 3D Rendering

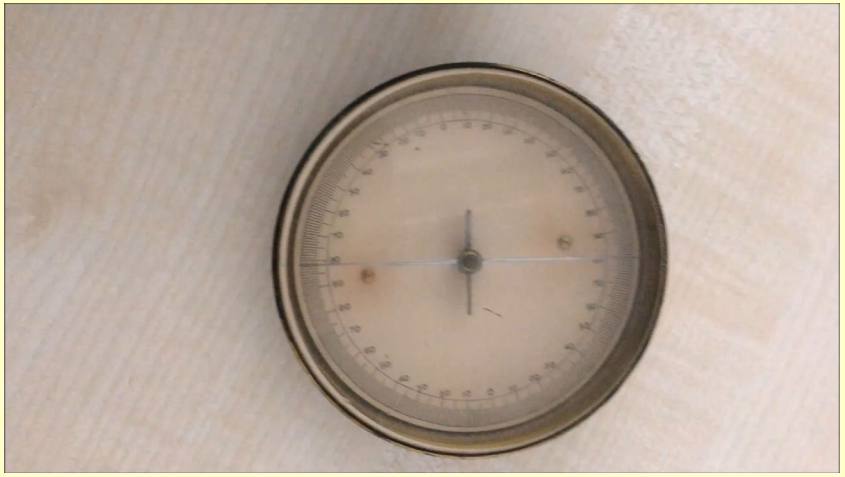


Wolfson Brain Imaging Centre and MRC Cambridge Centre for Behavioural and Clinical Neuroscience

Magnetic Resonance Imaging (MRI)

- Use naturally occurring bar magnets already inside your body
- These magnets are first aligned using a strong constant magnetic field.
- The magnets are then perturbed using radio waves
- This causes the magnets themselves to emit radio waves which are detected outside your body and used to create 3D images.

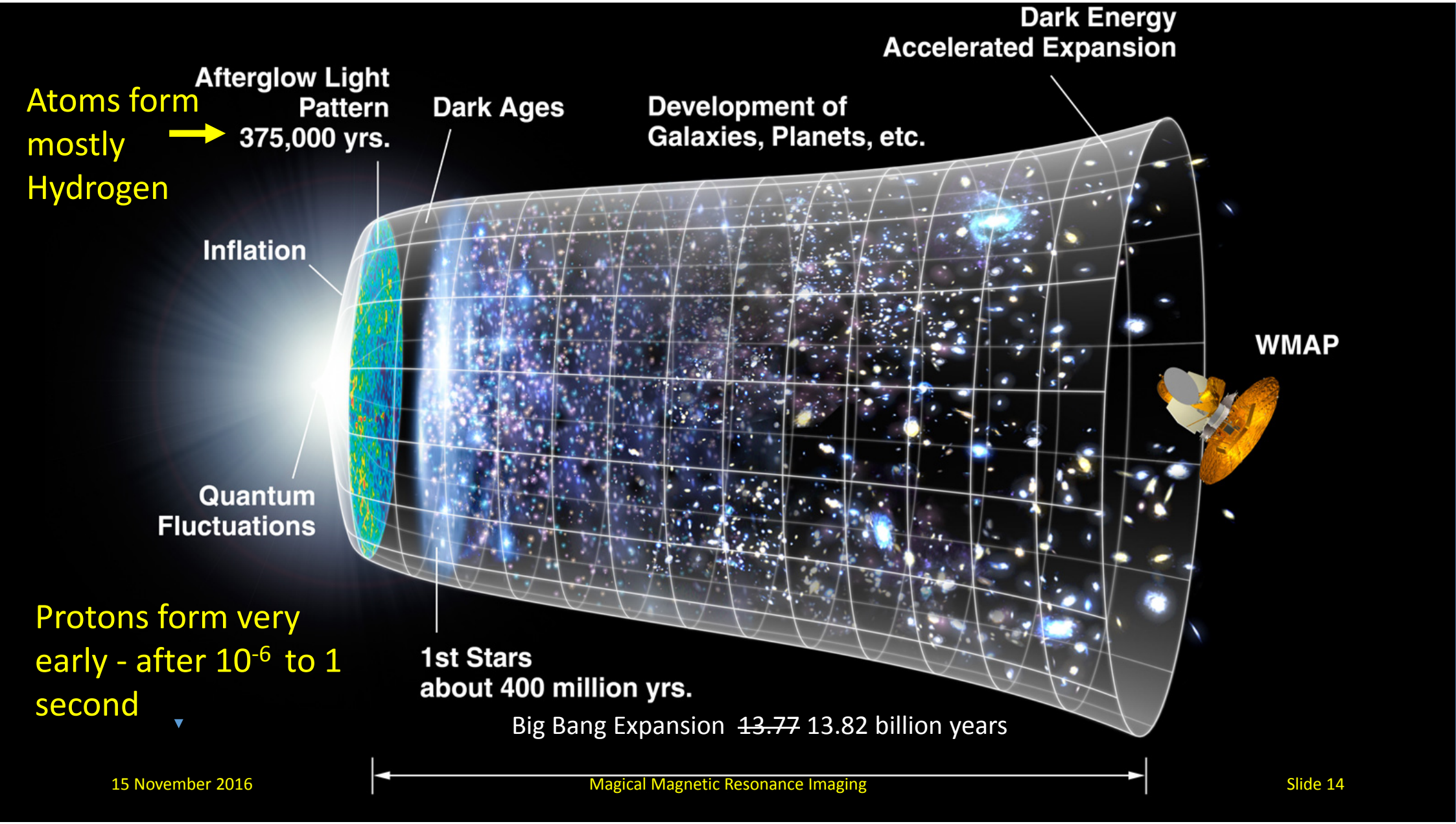




Protons are the Bar Magnets!

The proton is an elementary particle. The proton is the nucleus of the Hydrogen atom which is lightest of all elements. About 75% of all the matter in the universe is Hydrogen. Water molecules H_2O contain two hydrogen atoms. Your body is about 70% water. Most other organic molecules, e.g. fat, are also rich in hydrogen atoms.

Property	Symbol	Value
Mass	m_p	1.673×10^{-27} kg
Size	-	10^{-15} m
Electric charge	e	1.602×10^{-19} C
Spin (intrinsic angular momentum)	$\mathbf{s}$	$\frac{1}{2}\hbar \quad \left(\hbar = 1.054\times10^{-34}\ \text{Js}\right)$
Magnetic Moment	$\boldsymbol{\mu}_p$	1.041×10^{-26} JT^{-1} $= 2.79 e\mathbf{s}/m_p$
Gyromagnetic ratio	γ_p	42.58 MHz T^{-1}



Atoms form mostly Hydrogen

Protons form very early - after 10^{-6} to 1 second

Protons are the Key to MRI

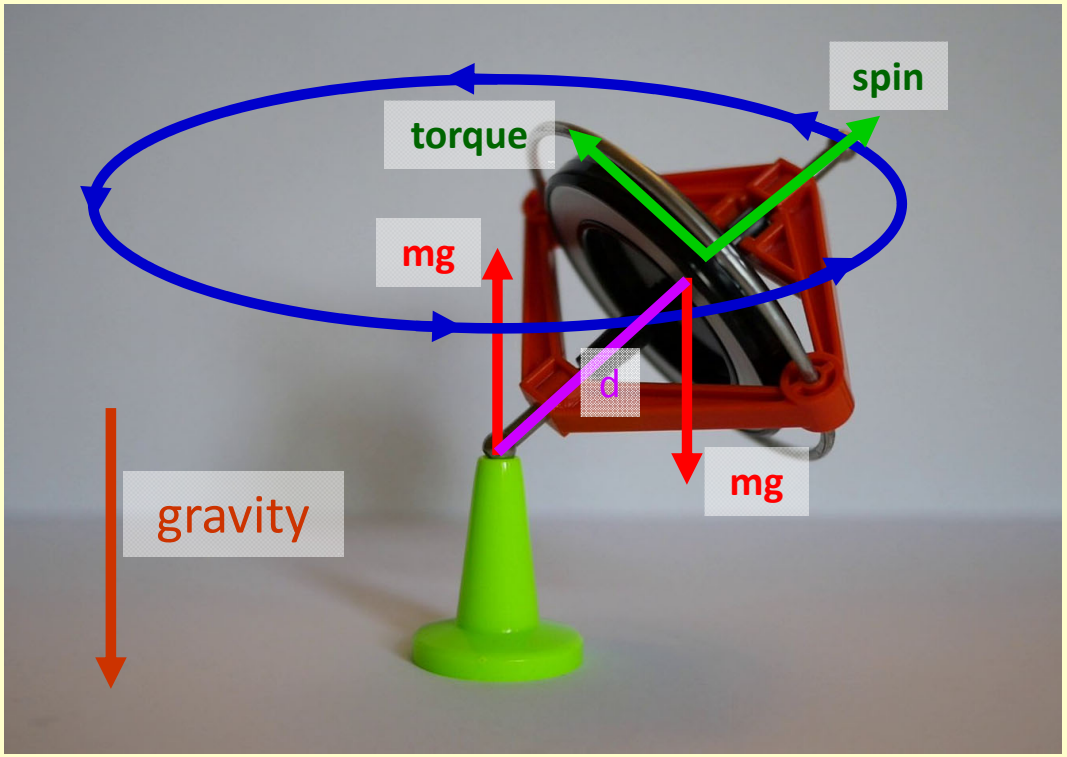
- 1 cc of water contains about 6.7 10^{22} protons
- in a 3T magnetic field approximately 1 in 10^{-5} line up along the field
- these act as a bar magnet ~10^{-7} times weaker than typical toy
- if tip these aligned spins away from external field direction they precess just like the gyroscope.
- the precession frequency is 128 MHz at 3T.
- a small coil placed nearby will detect a signal of microvolts at this frequency, induced by Faraday's law of induction.

The Gyroscope

The Gyroscope

precession rate
= mgd/spin

"spin"
≡ angular momentum
= Iω

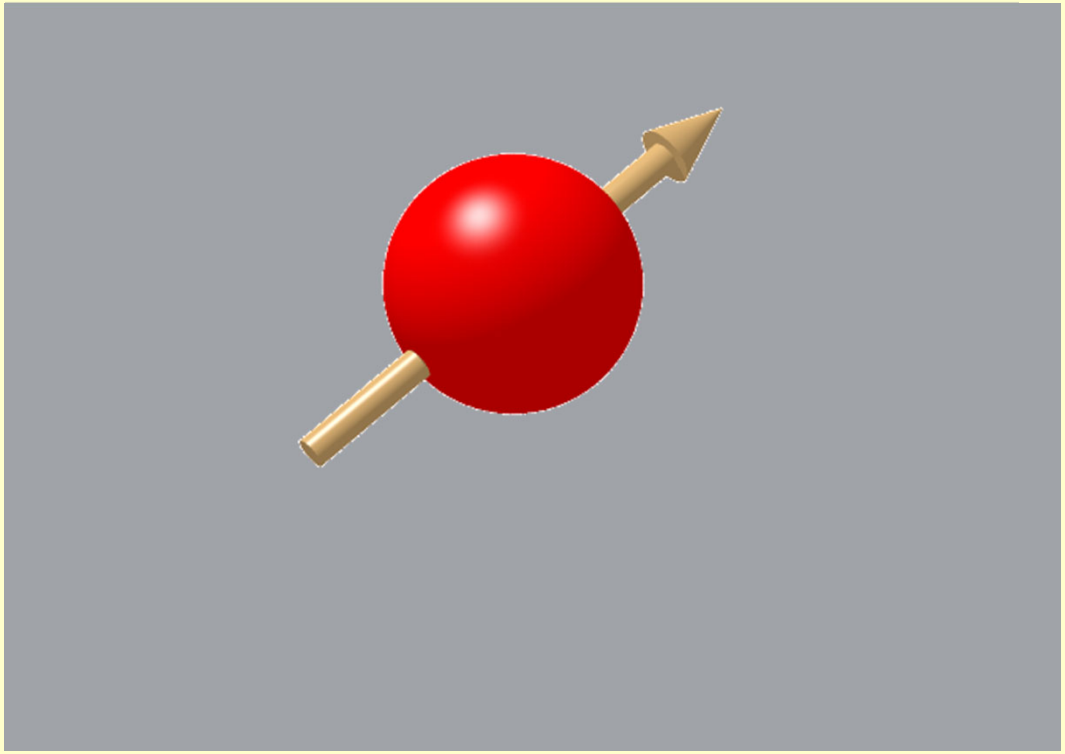


The Proton

The arrow represents both:

spin $s = \frac{1}{2}\hbar$ and

magnetic moment μ_p



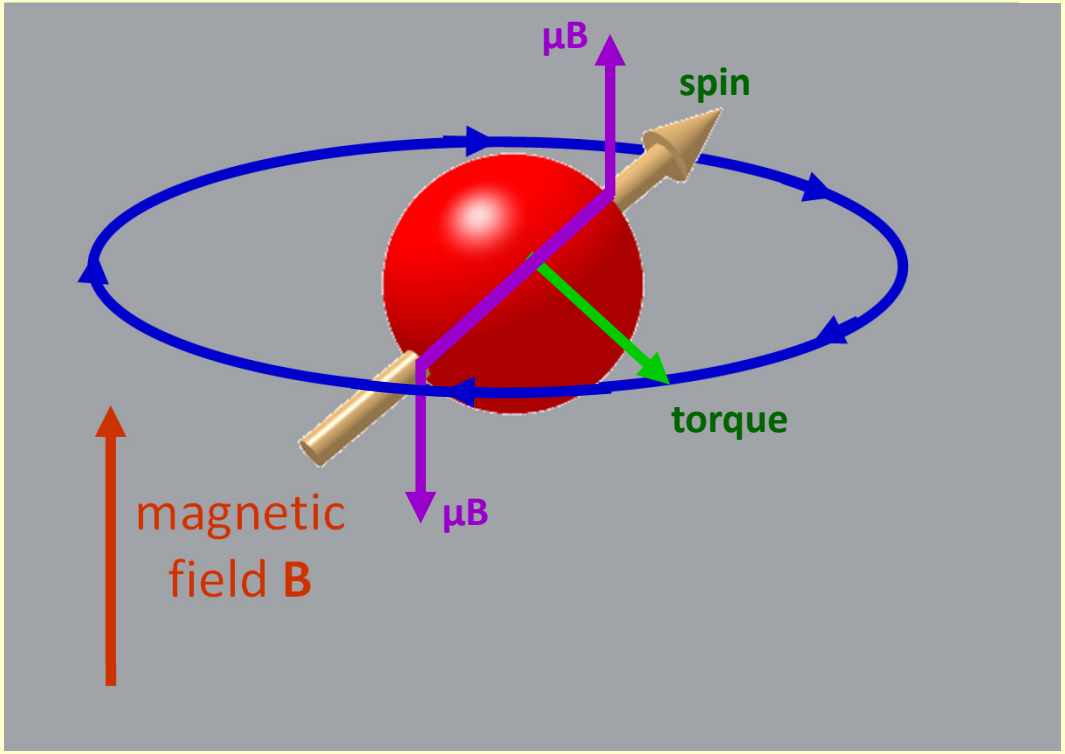
The Proton

Proton precession frequency is:

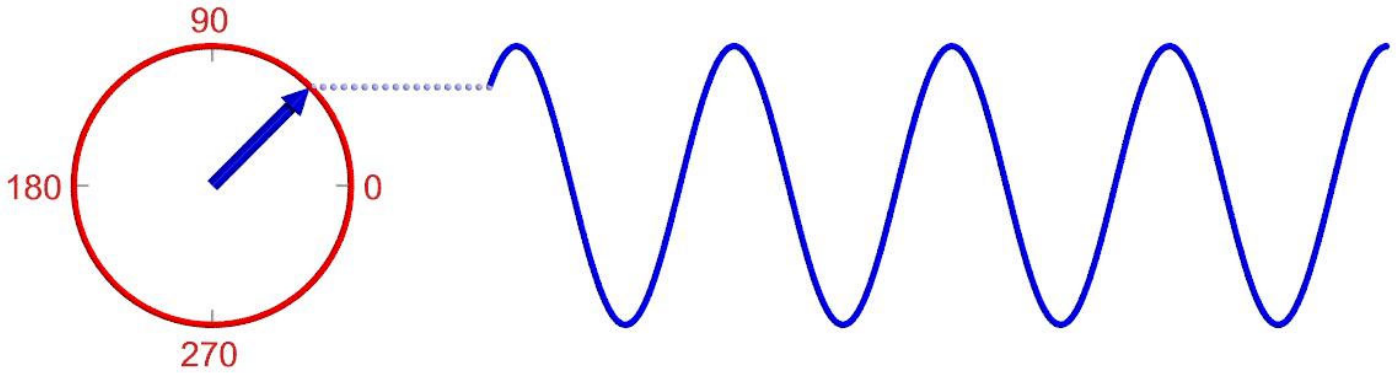
$-\mu_p B \quad =$

$-\gamma_p s B \quad =$

$42.57 \text{ MHz} \times B$

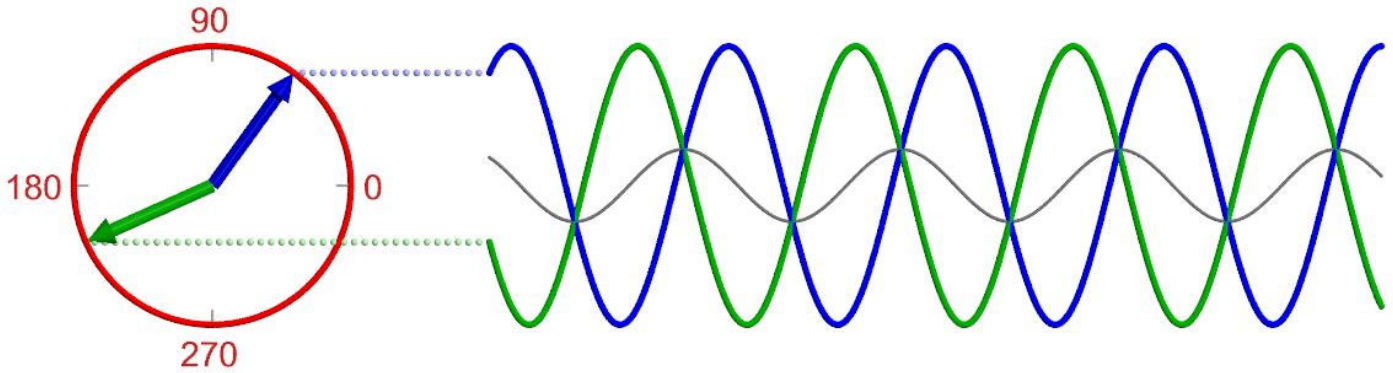


Precession generates sin/cos waves



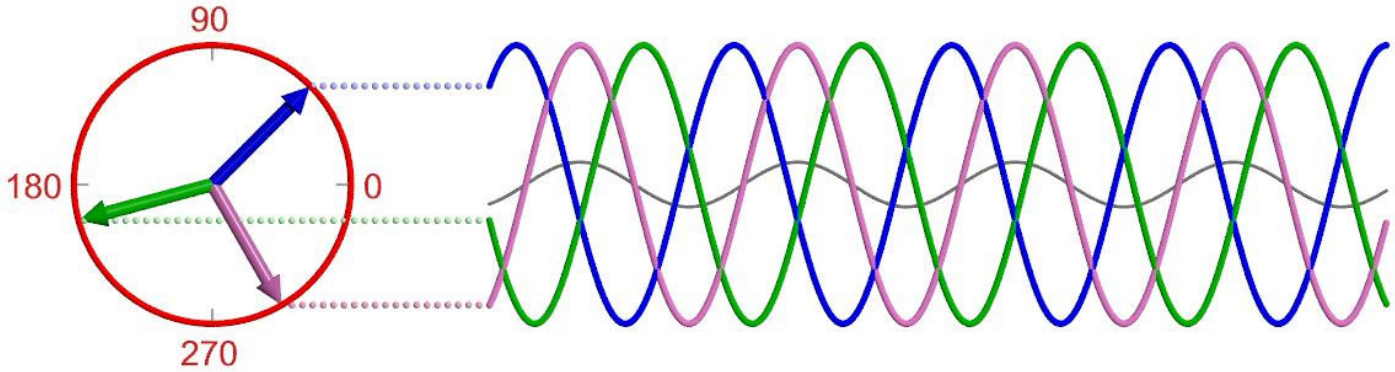
Net Signal Large

Phase differences reduce signal



Net Signal Reduced

Phase differences reduce signal



Net Signal Small

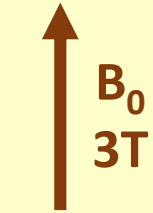
Protons in Magnetic Field

When placed in a strong magnetic field protons:

- Protons gradually align with the magnetic field
- Takes about 1 second
- During alignment the phases are random – no net signal
- After alignment no precession – still no net signal
- Use Radio Frequency pulse to rotate spins into x-y plane
- Coherent precession then generates signal
- But signal rapidly fades due to dephasing

Illustrated in following animations

Relax to Equilibrium

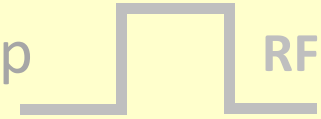


90° Flip

Ideal Precession

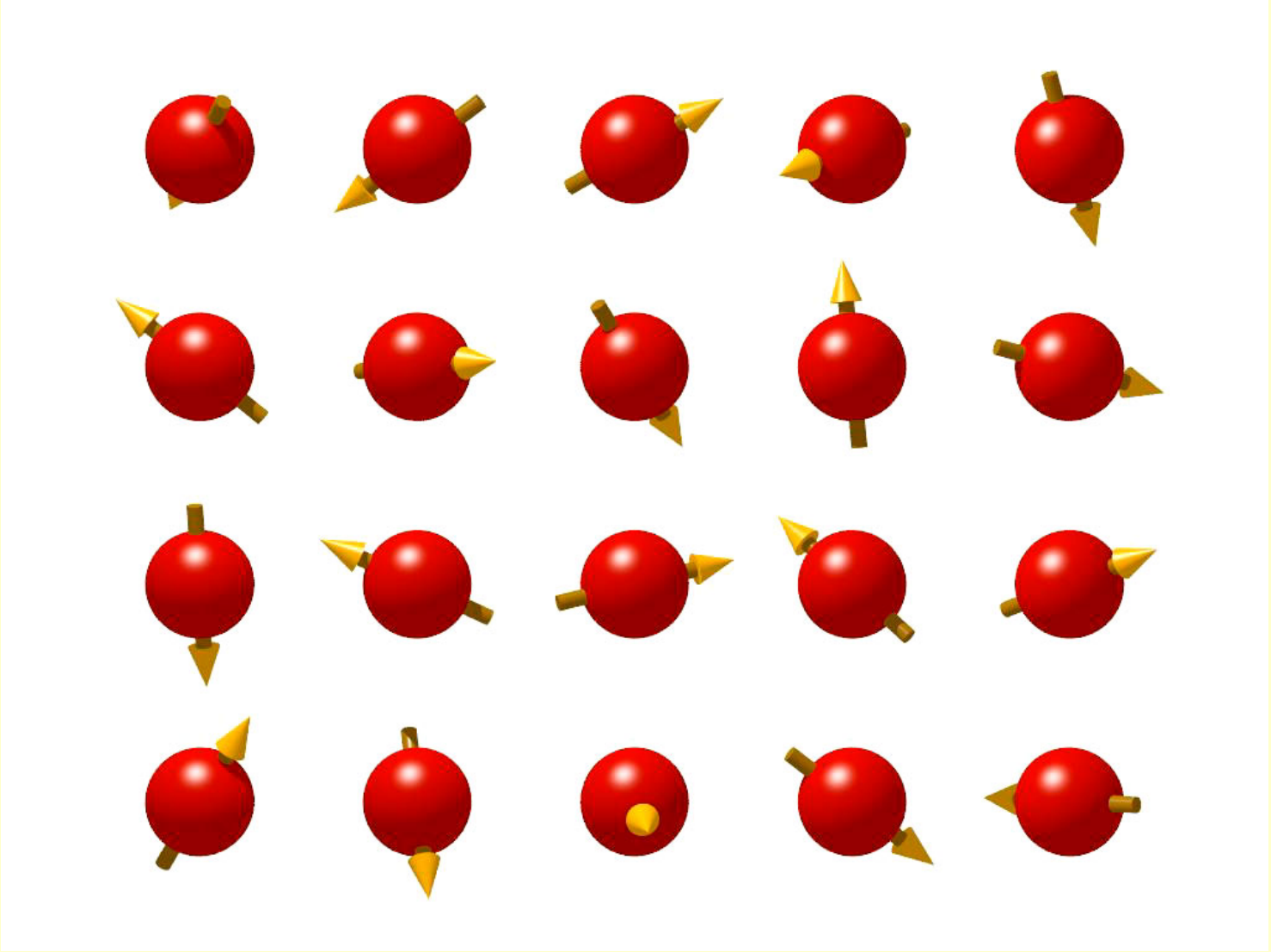
Dephasing

180° Flip



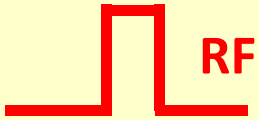
Rephasing

Time T1 100-3000 ms



Relax to Equilibrium

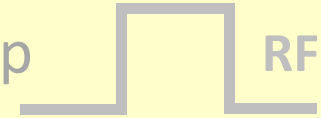
90° Flip



Ideal Precession

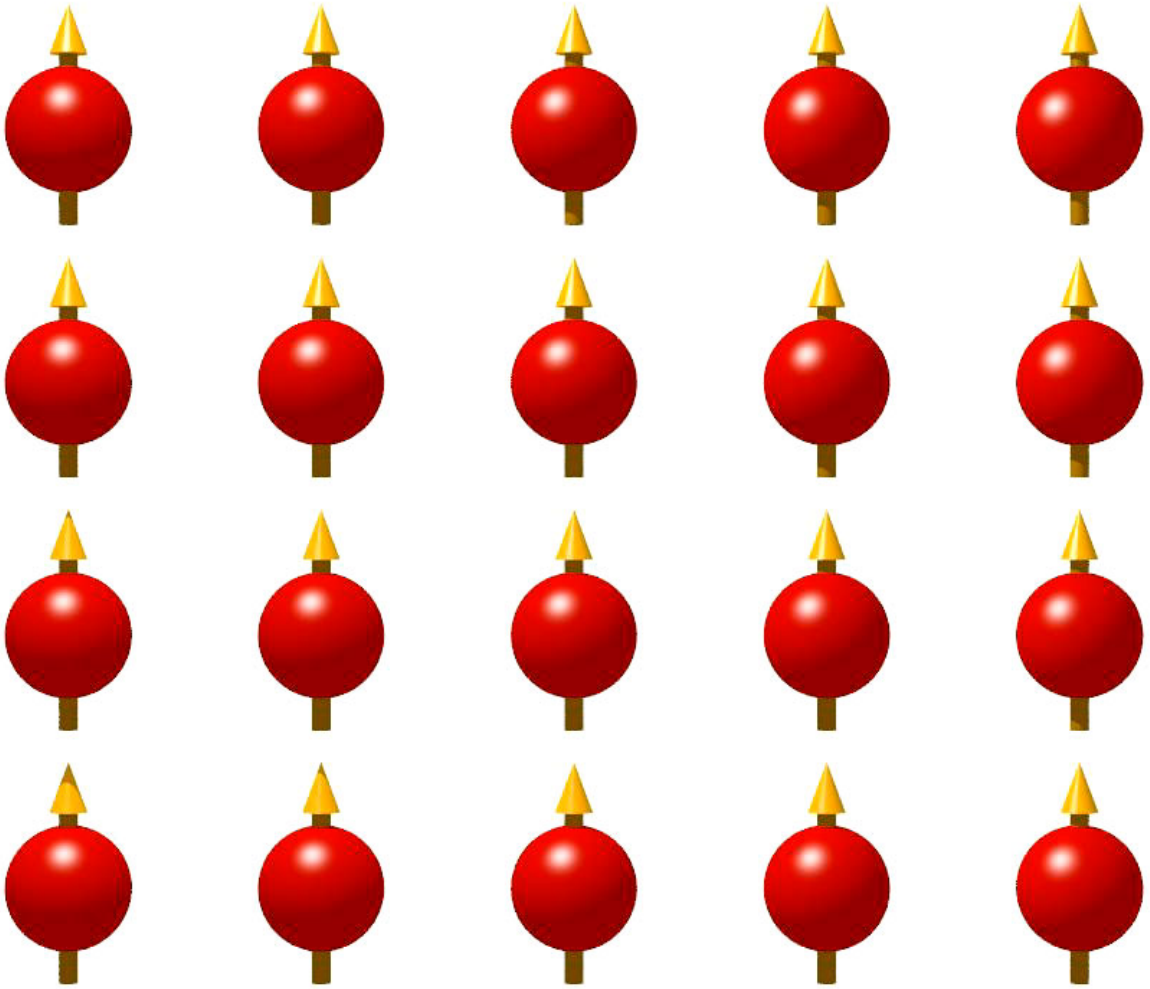
Dephasing

180° Flip



Rephasing

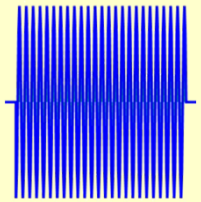
Time 0.1-1 ms



Relax to Equilibrium

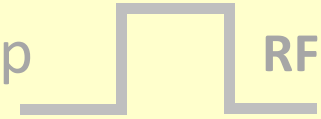
90° Flip

Ideal Precession



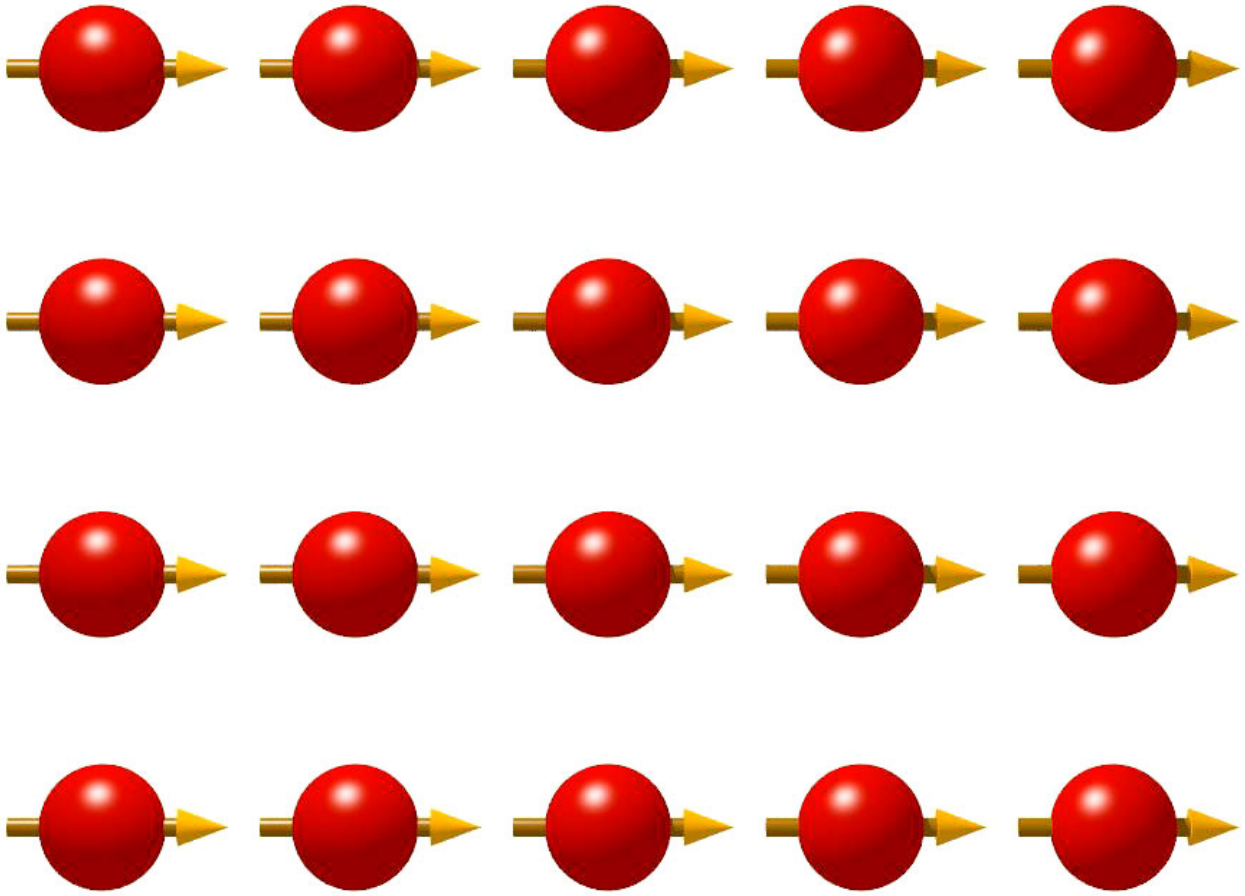
Dephasing

180° Flip



Rephasing

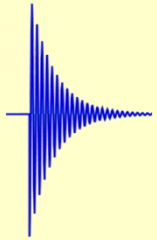
Time T2 100-3000 ms



Relax to Equilibrium

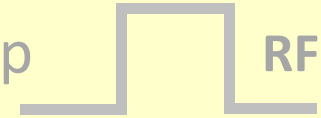
90° Flip

Ideal Precession



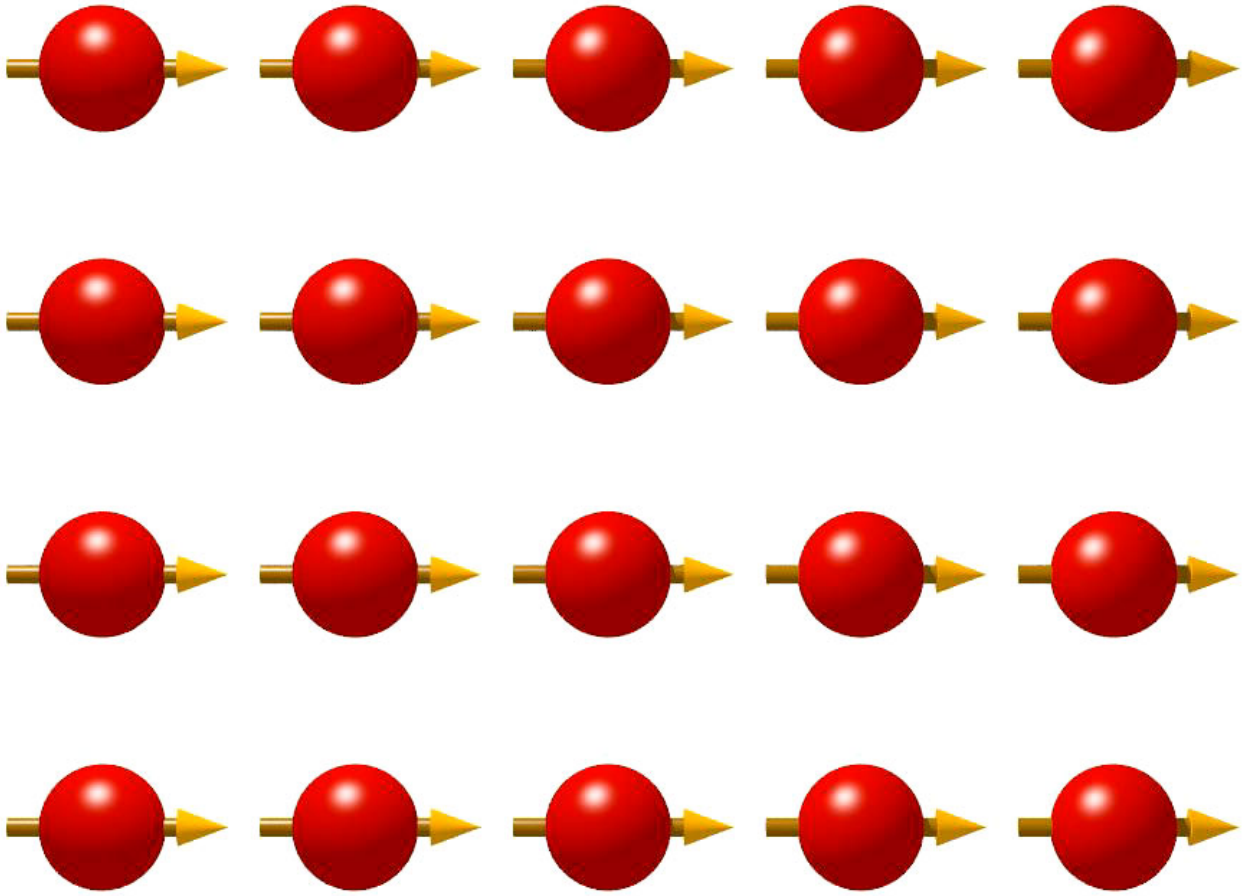
Dephasing

180° Flip



Rephasing

Time T2* 5-50 ms



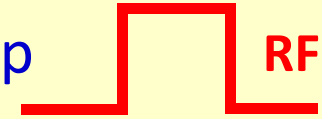
Relax to Equilibrium

90° Flip

Ideal Precession

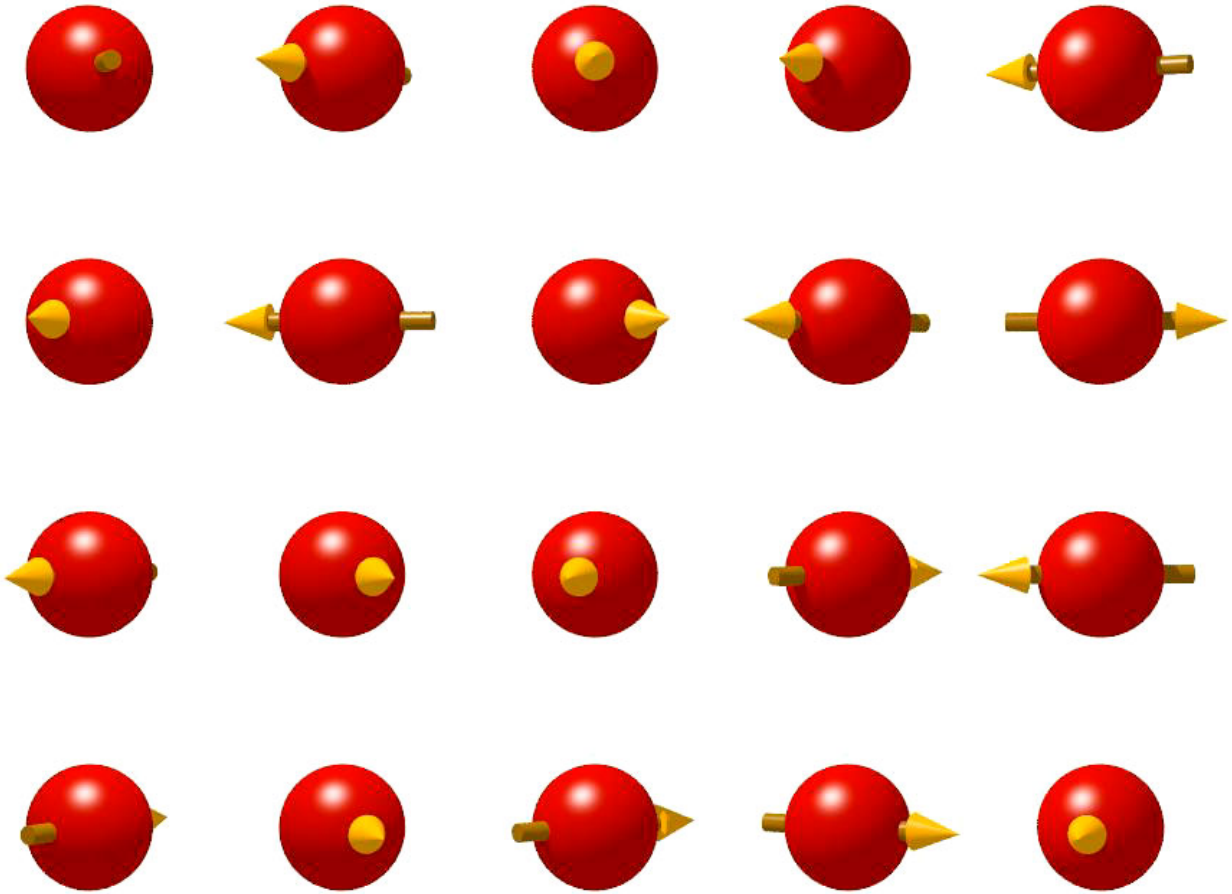
Dephasing

180° Flip



Rephasing

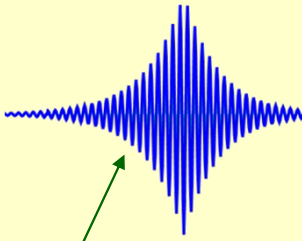
Time 0.1-1 ms



Relax to Equilibrium

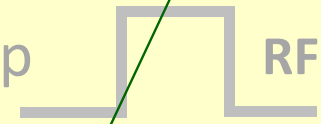
90° Flip

Ideal Precession



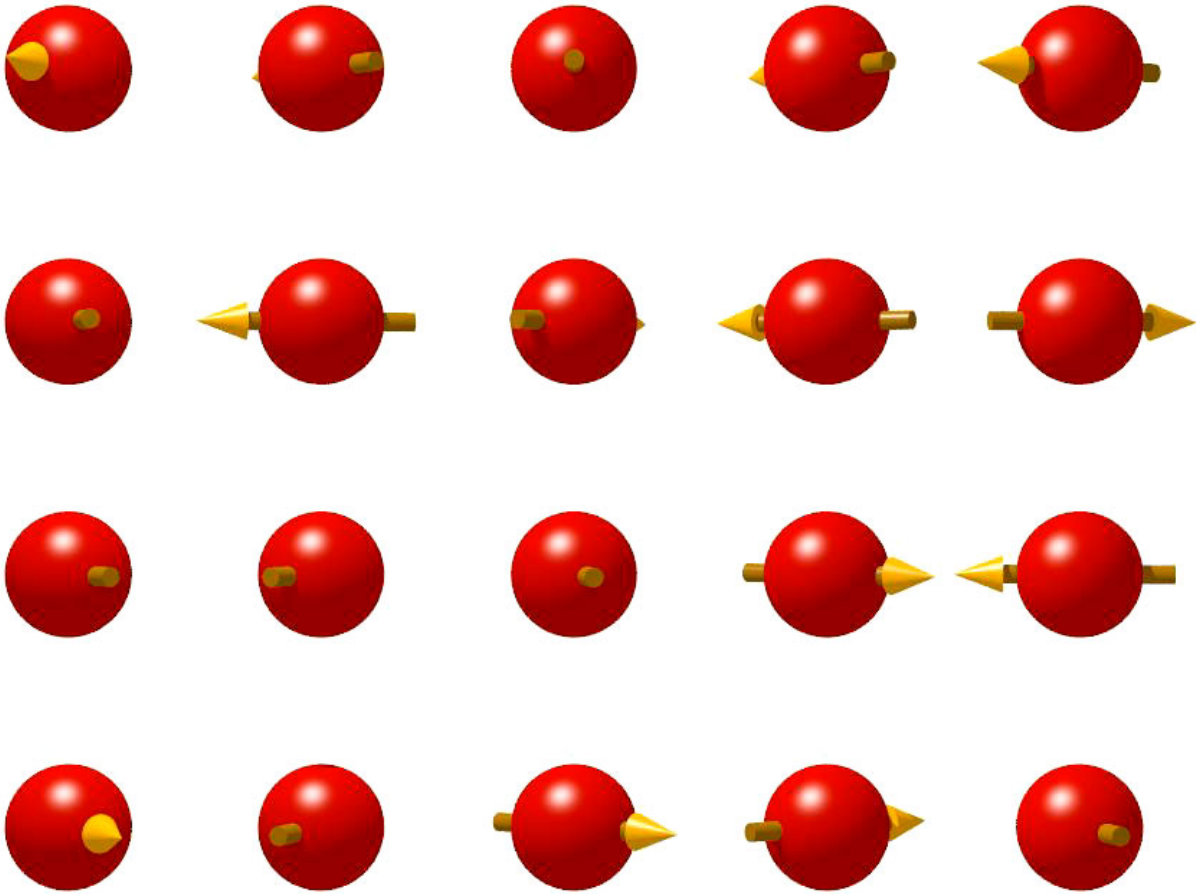
Dephasing

180° Flip



Rephasing

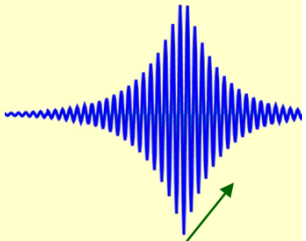
Time T2* 5-50 ms



Relax to Equilibrium

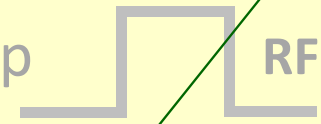
90° Flip

Ideal Precession



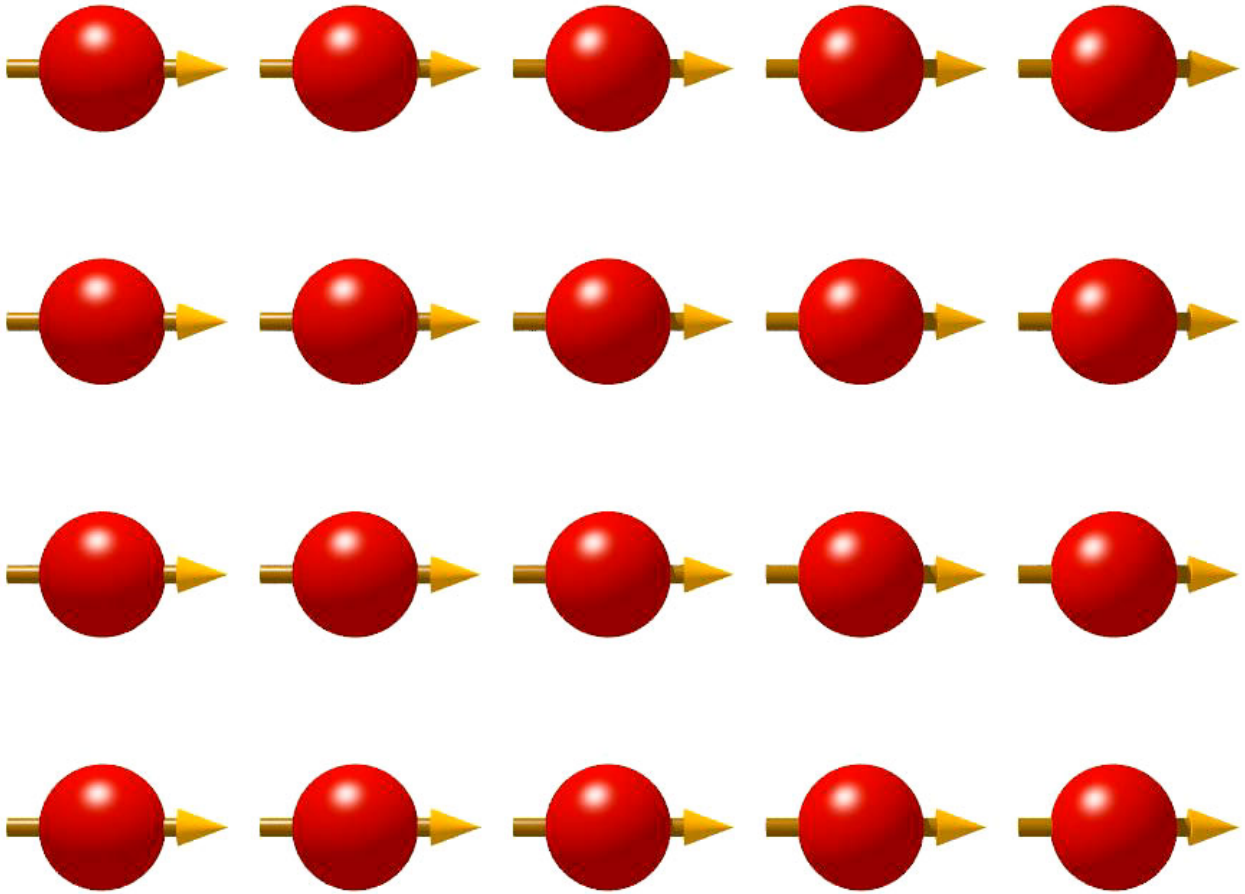
Dephasing

180° Flip

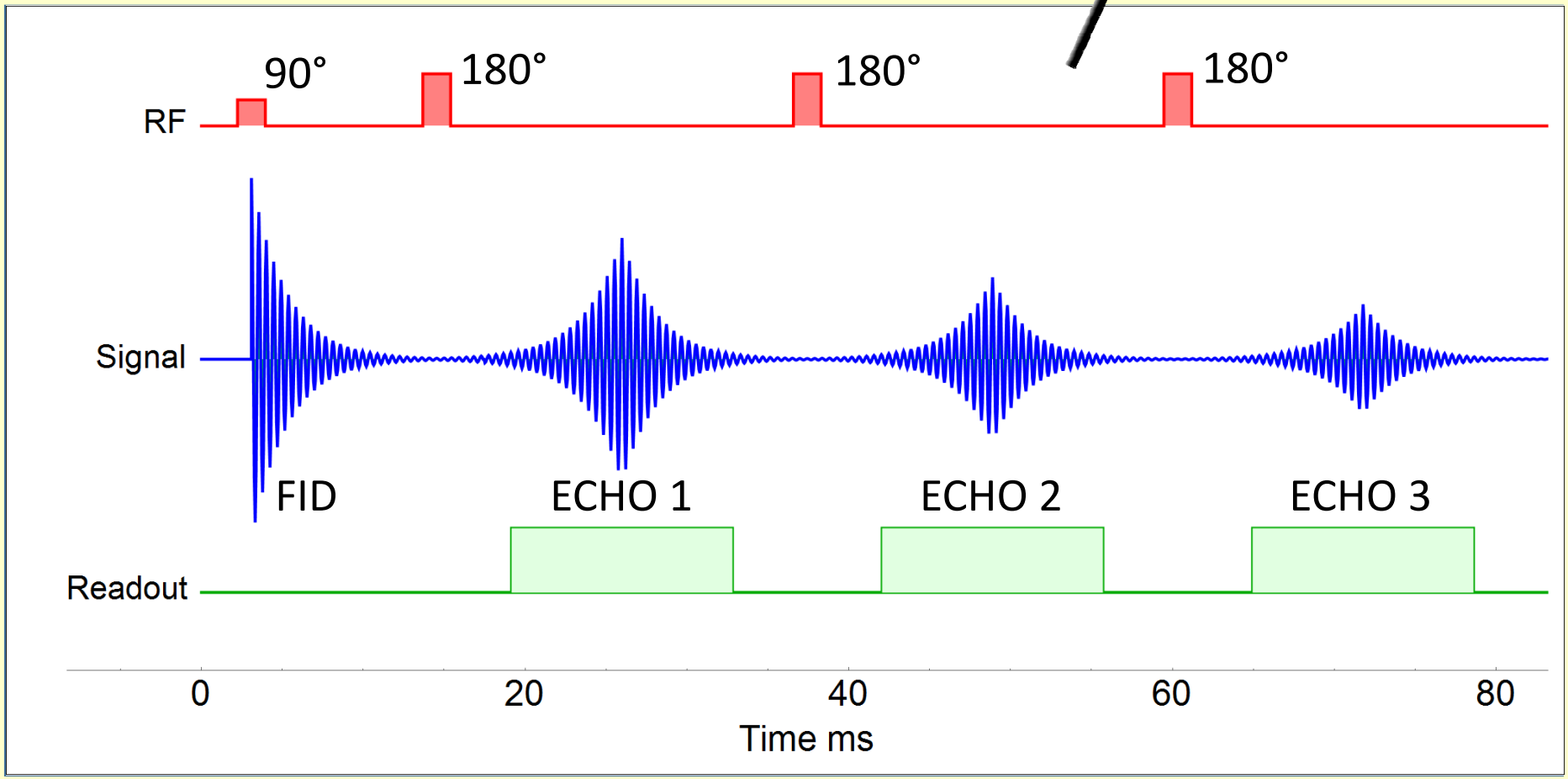


Dephasing

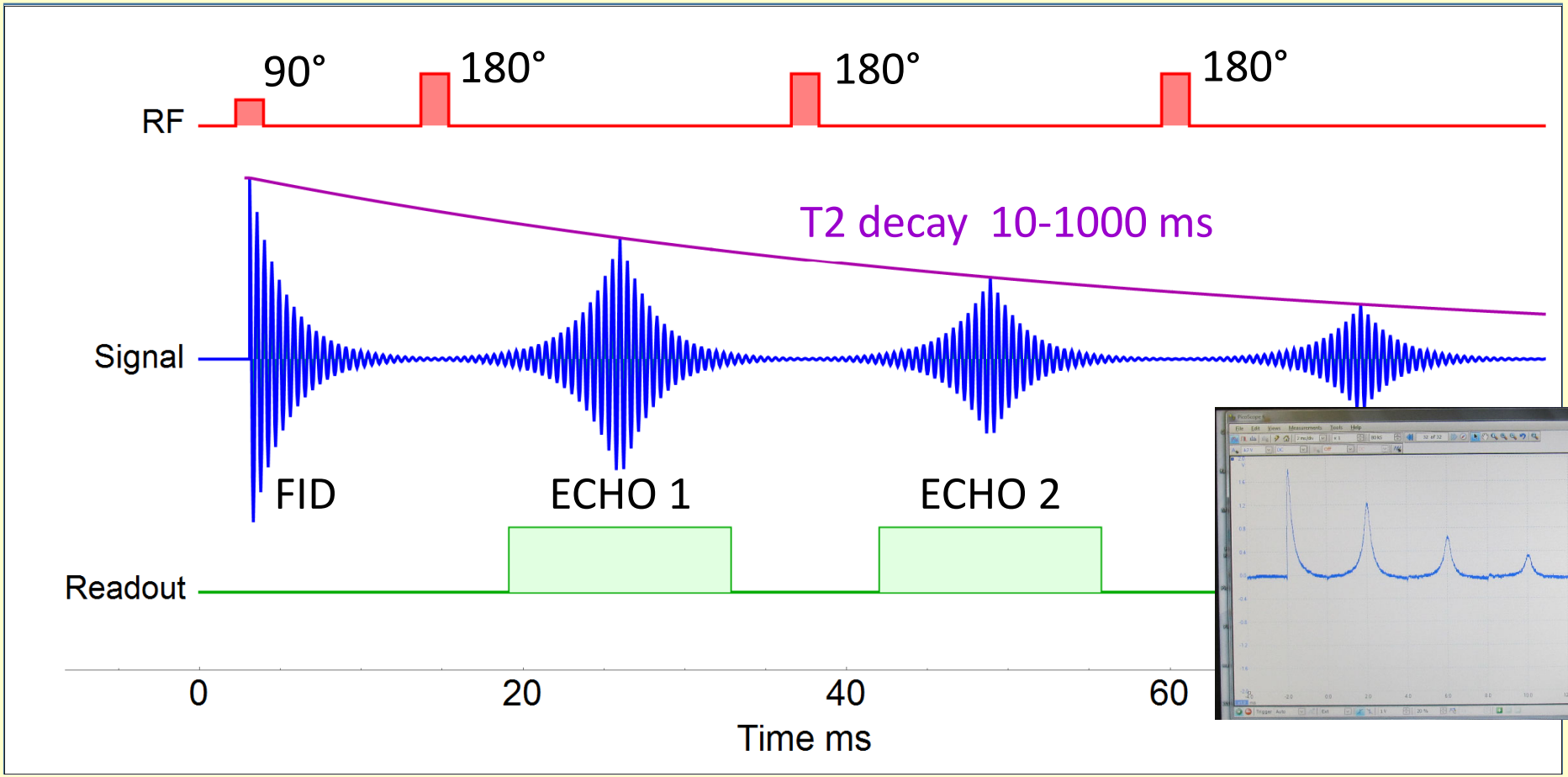
Time T2* 5-50 ms



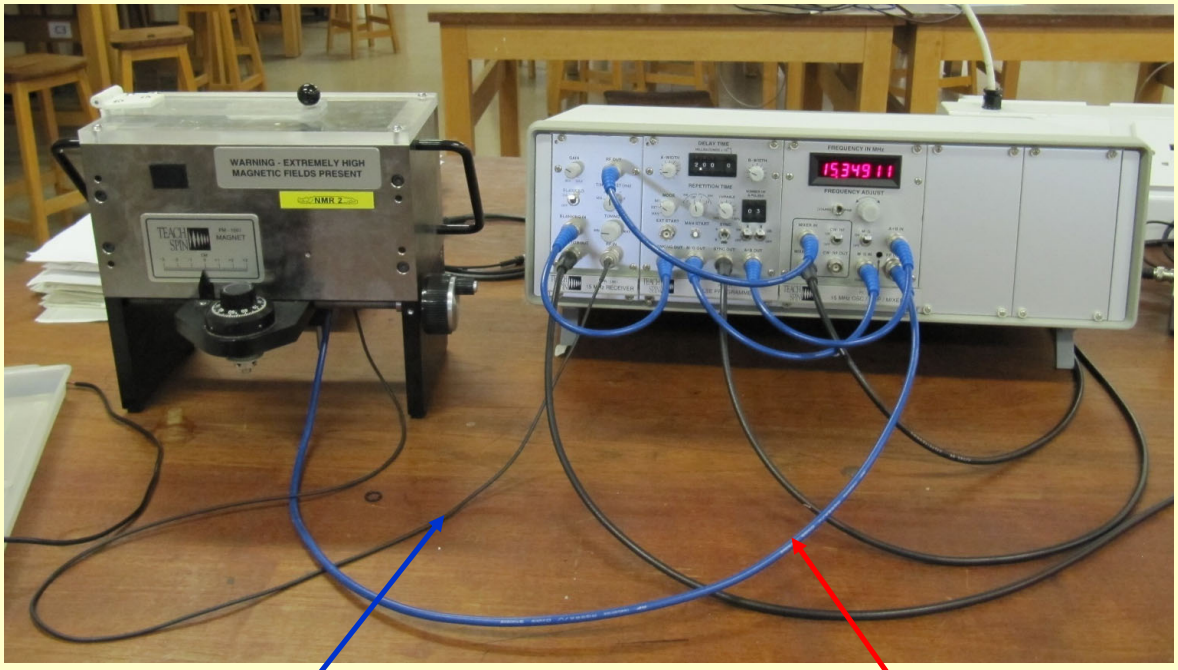
Spin Echo


90°
180°
180°
180°
RF
Signal
FID
ECHO 1
ECHO 2
ECHO 3
Readout
0
20
40
60
80
Time ms

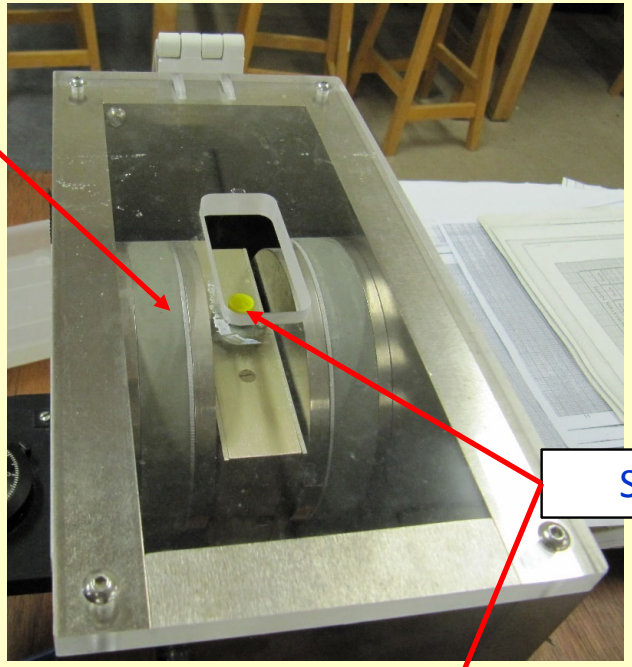
Spin Echo


90°
180°
180°
180°
RF
T2 decay 10-1000 ms
Signal
FID
ECHO 1
ECHO 2
Readout
0
20
40
60
Time ms

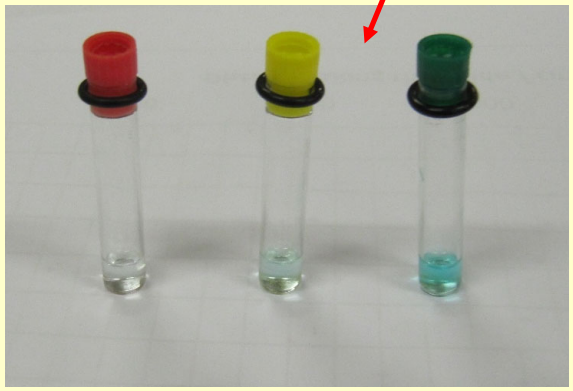
NMR Demo



Permanent magnet



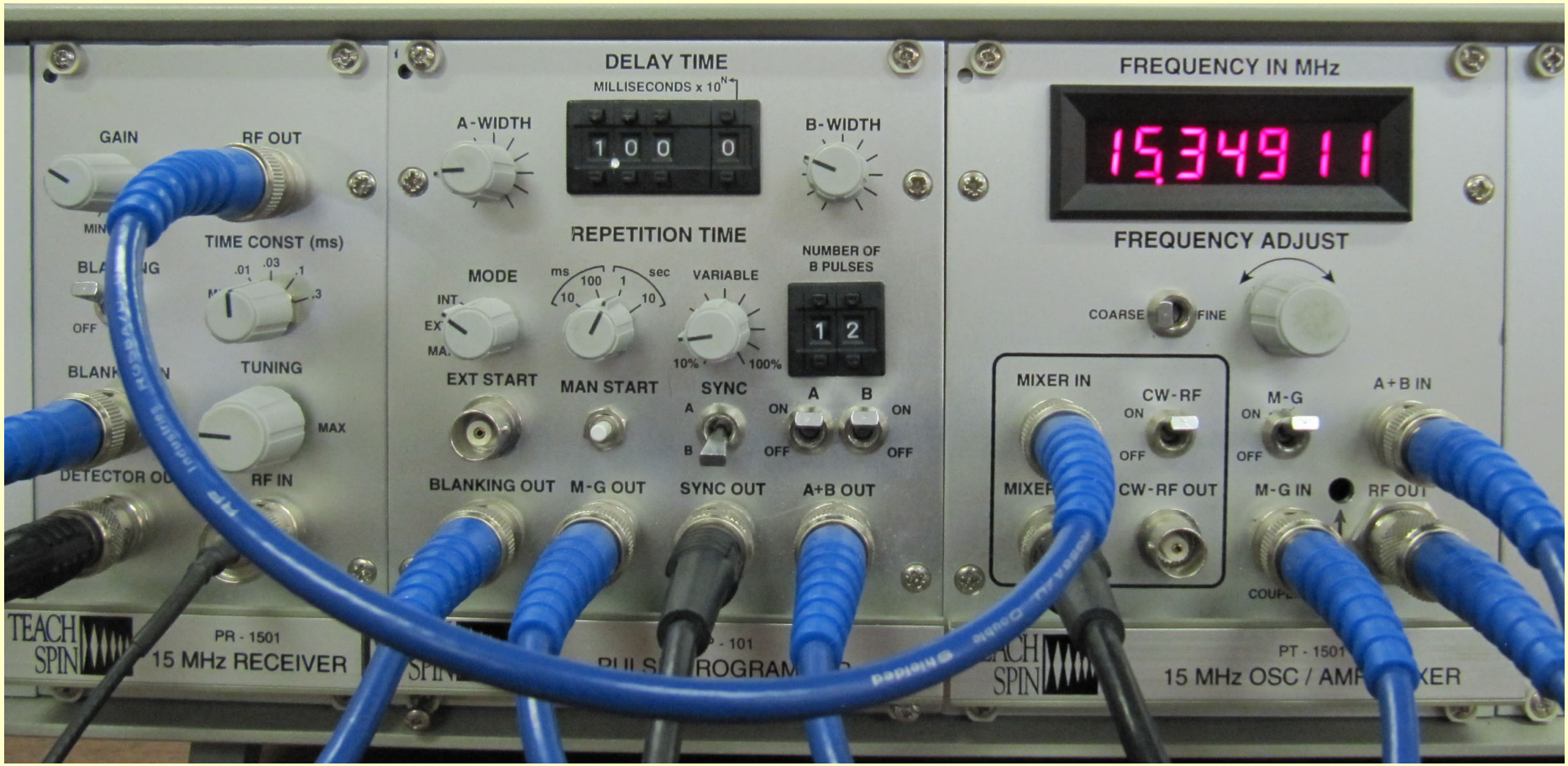
Sample



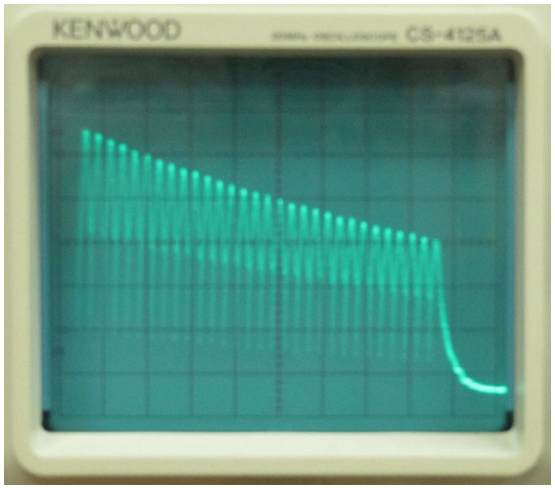
RF signal from to sample holder

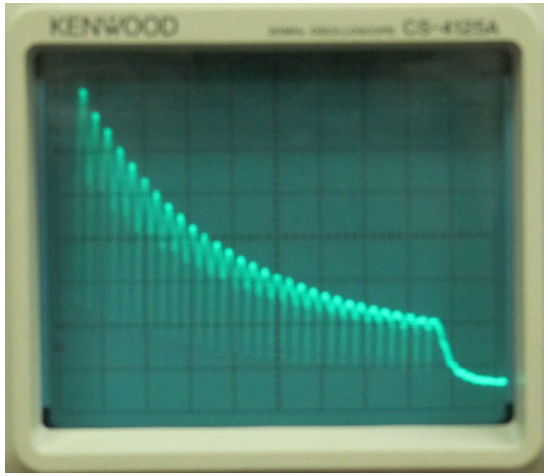
RF power to sample holder

NMR Demo


DELAY TIME
MILLISECONDS x 10^N
A-WIDTH
B-WIDTH
100 0
REPETITION TIME
NUMBER OF B PULSES
MODE
INT
EXT
MAN
VARIABLE
ms
sec
100
1
10
10%
100%
1 2
EXT START
MAN START
SYNC
A
B
ON
OFF
BLANKING OUT
M-G OUT
SYNC OUT
A+B OUT
GAIN
RF OUT
TIME CONST (ms)
TUNING
MAX
RF IN
FREQUENCY IN MHz
15.34911
FREQUENCY ADJUST
COARSE
FINE
MIXER IN
CW-RF
CW-RF OUT
M-G
M-G IN
A+B IN
RF OUT
TEACH SPIN
PR - 1501
15 MHz RECEIVER
PT - 1501
15 MHz OSC / AMP

NMR Demo





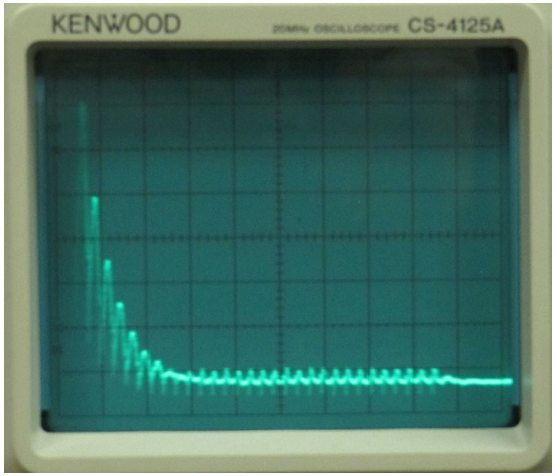
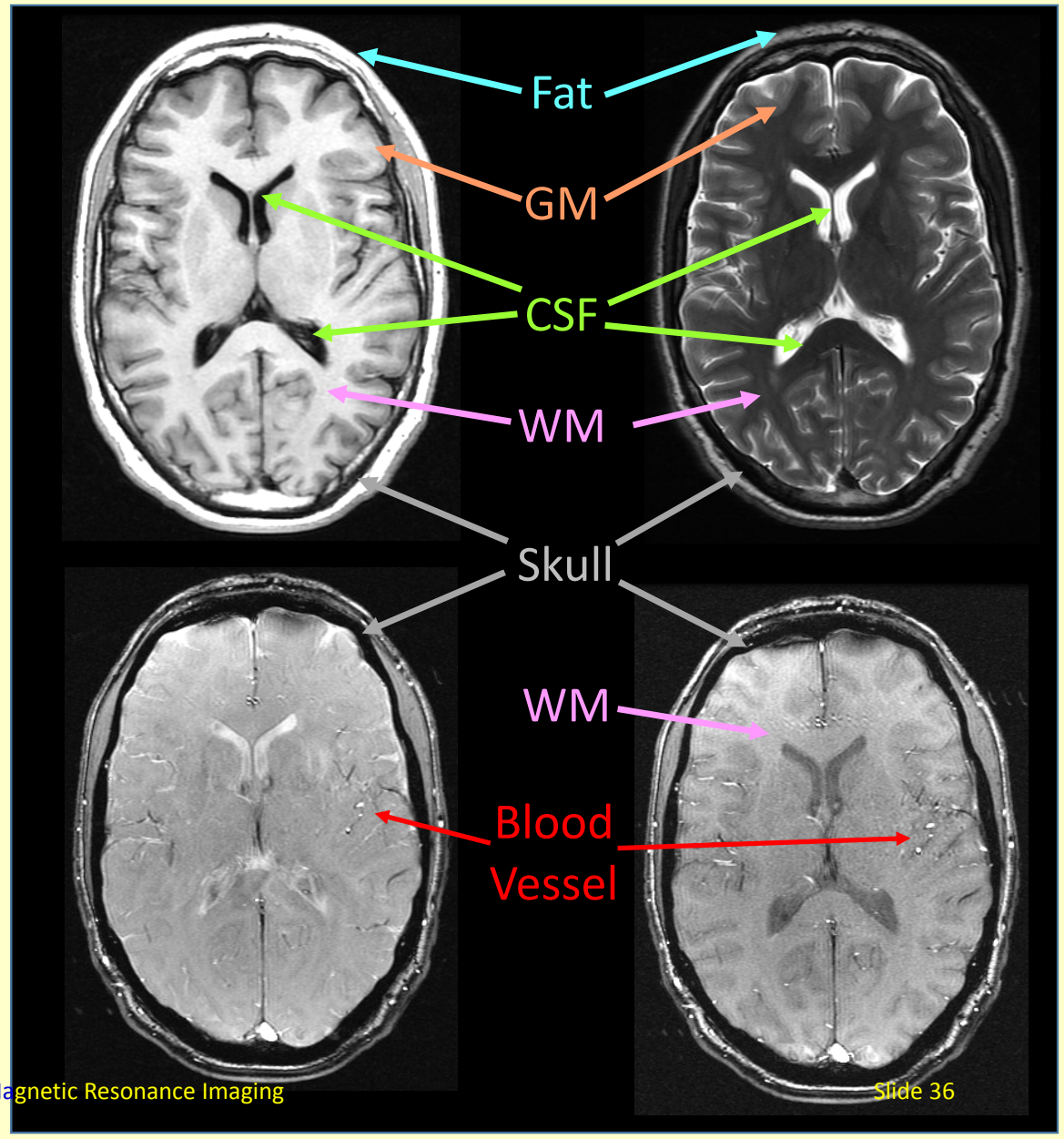


Image Contrast from T1 and T2

Tissue	**T1** ms	**T2** ms
White Matter	1080	69
Grey Matter	1820	99
CSF	3700	1500
Blood	1930	275
Fat	380	68
Muscle	1410	50



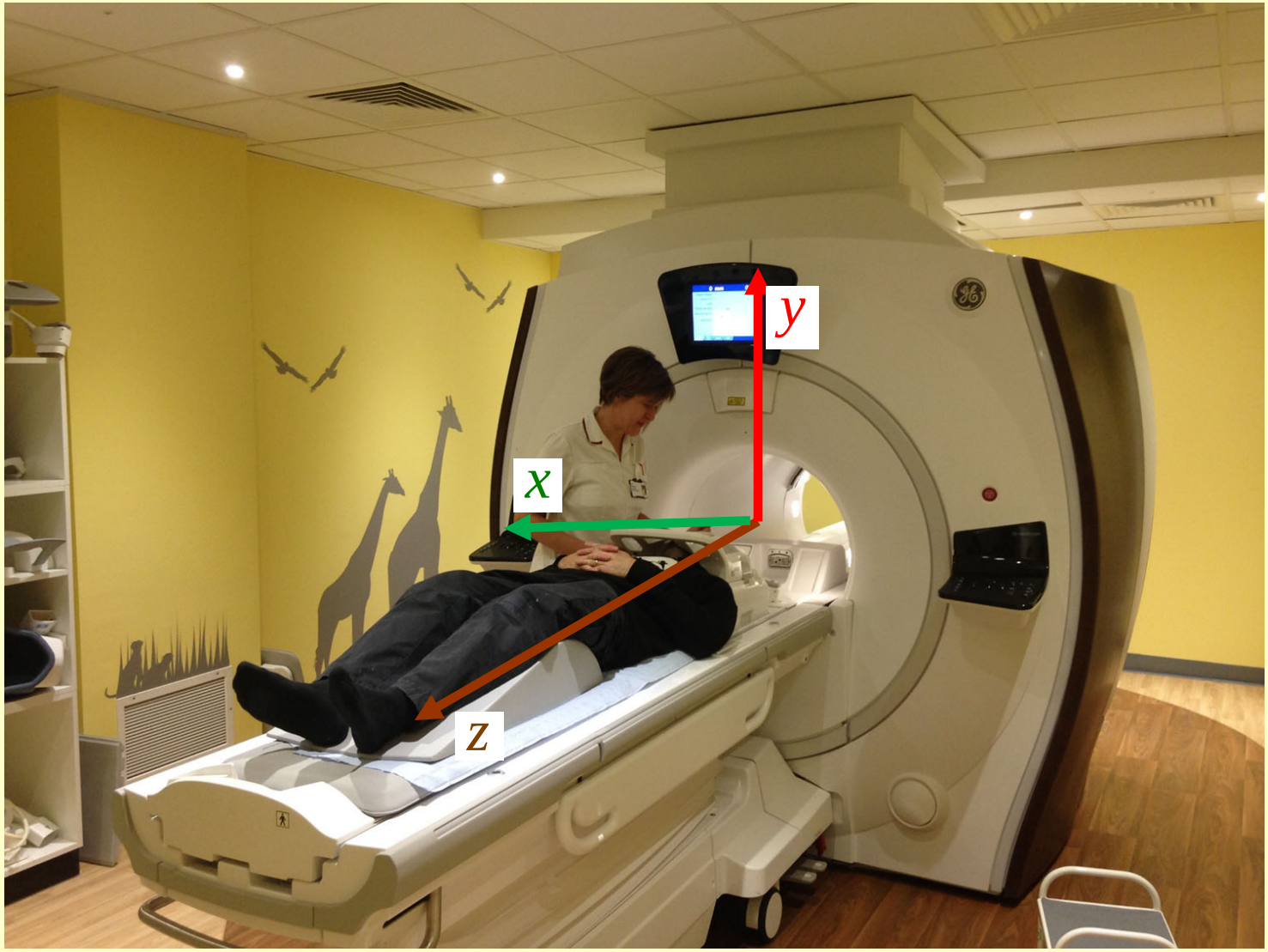
Position

Identify which instrument is playing from the pitch and tone of its sound – hence know where the sound is coming from. (Assumes identical instruments play differently).

Position

In MRI we use frequency and phase to obtain signal positions. This is implemented by using switched gradient fields.

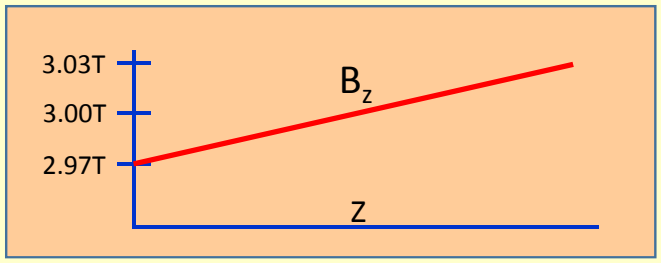
$$B = B_0 + G_x x + G_y y + G_z z$$

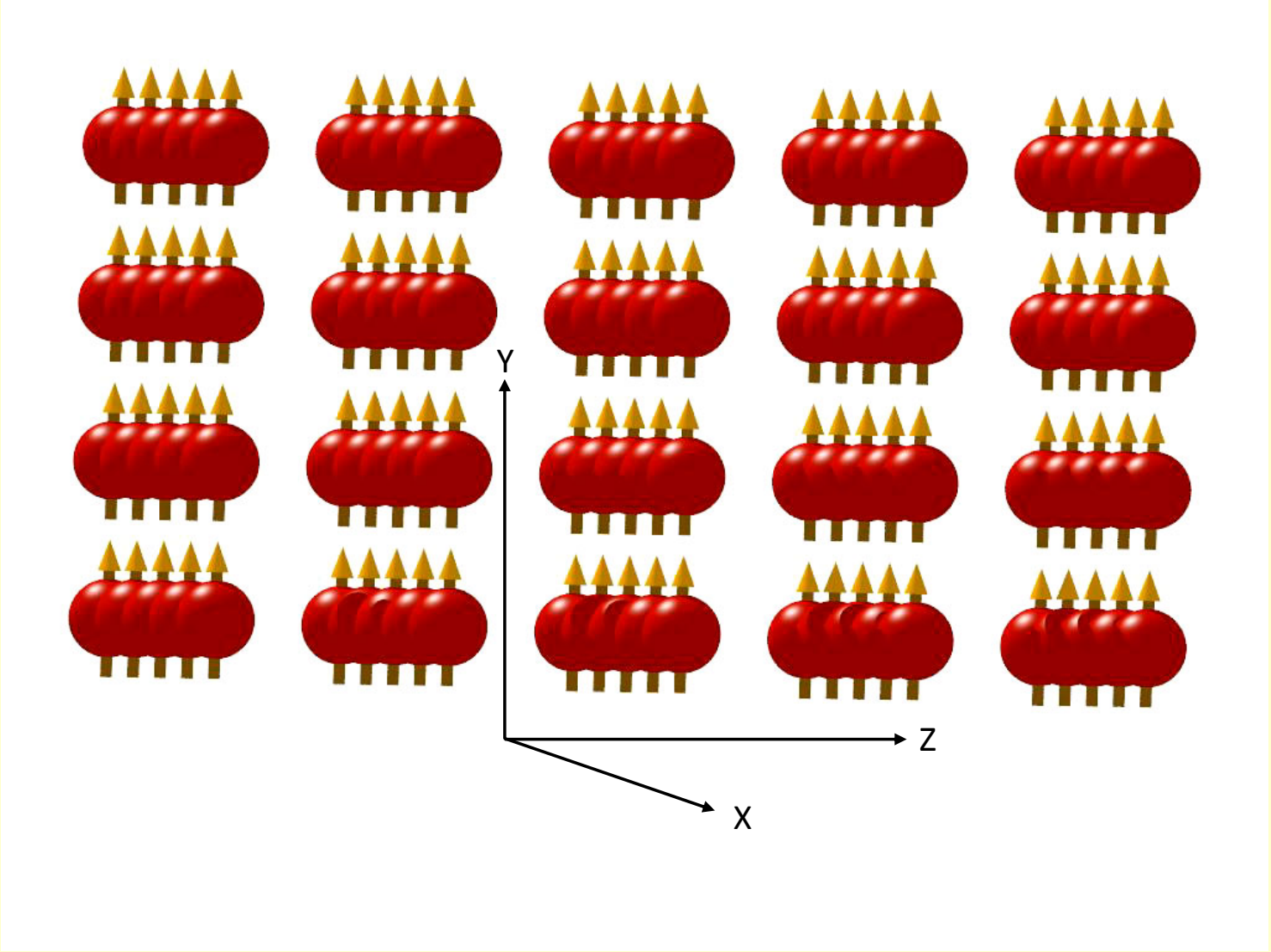


Slice Select using 90° RF pulse and Z gradient field.

Precession Frequency depends on Z

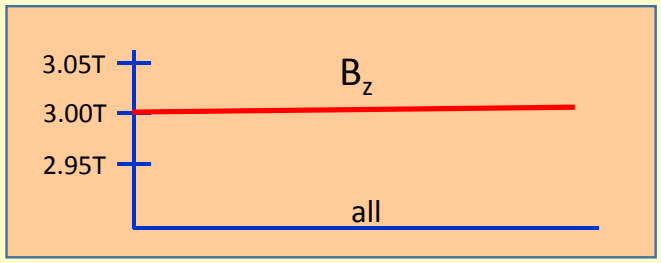
Only spins with same frequency as RF pulse rotate

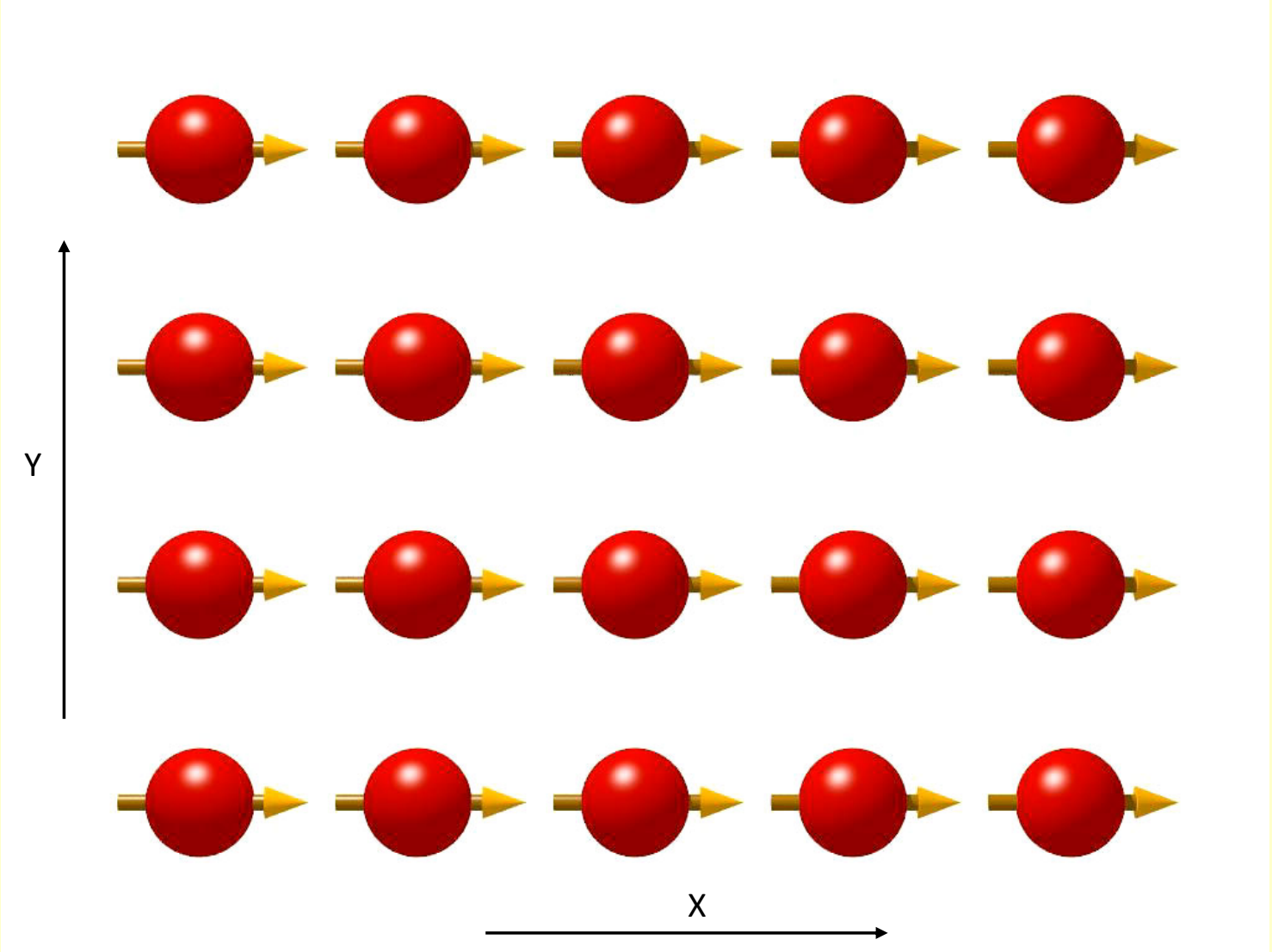




Steady precession in X-Y plane after 90° RF pulse

No spatial Information

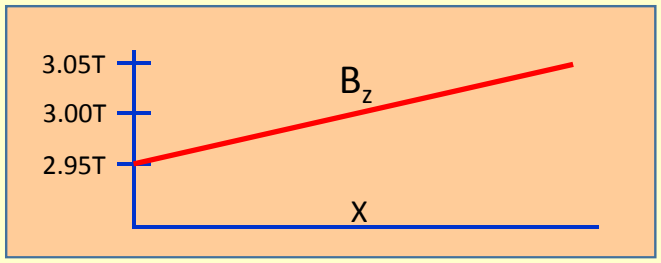


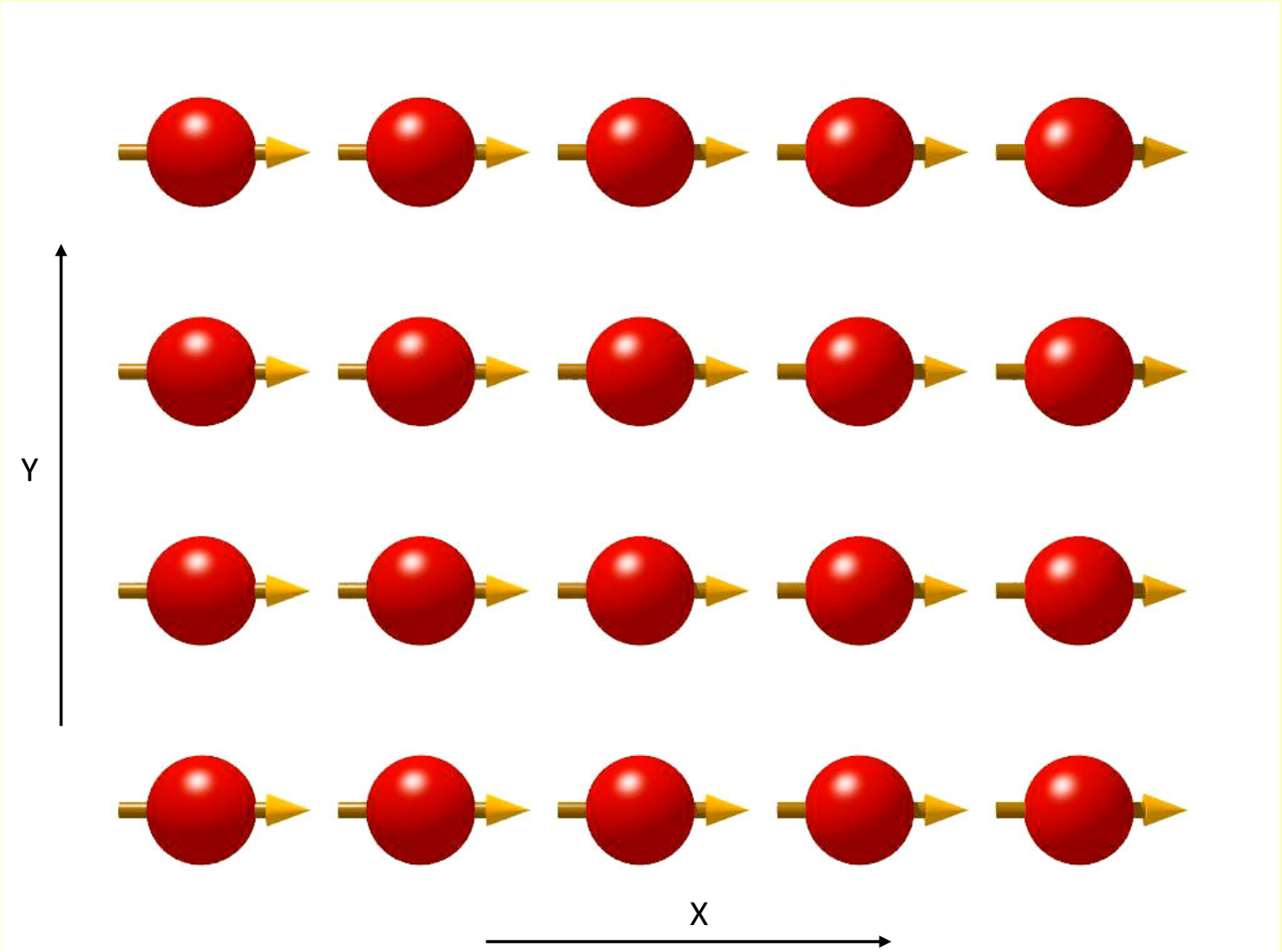


Steady Precession in X-Y plane after 90° RF pulse

Frequency Encode Gradient Present

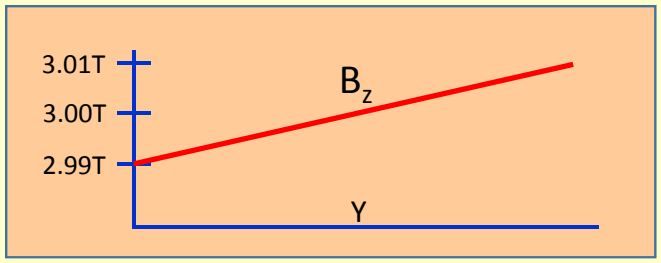
X Position Now Coded by Frequency

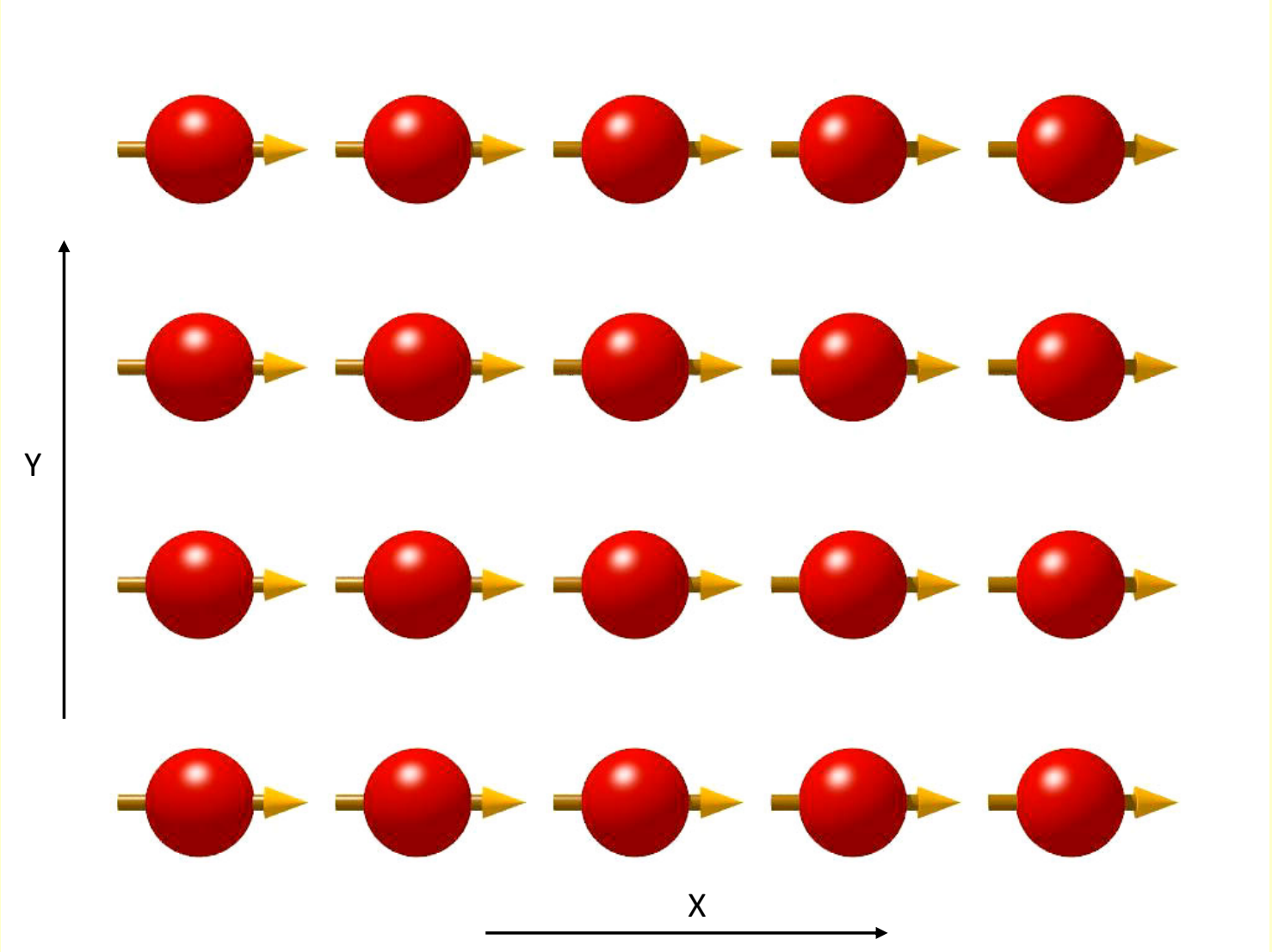




Phase Encode applied in Y direction after 90° RF pulse

Y position now coded by phase

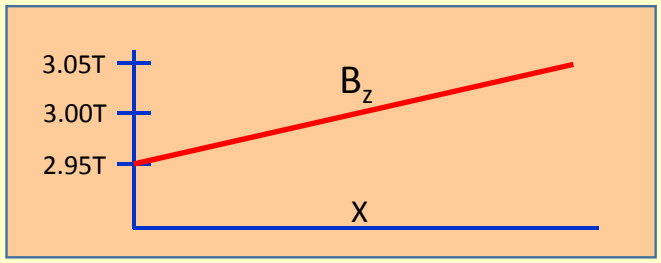


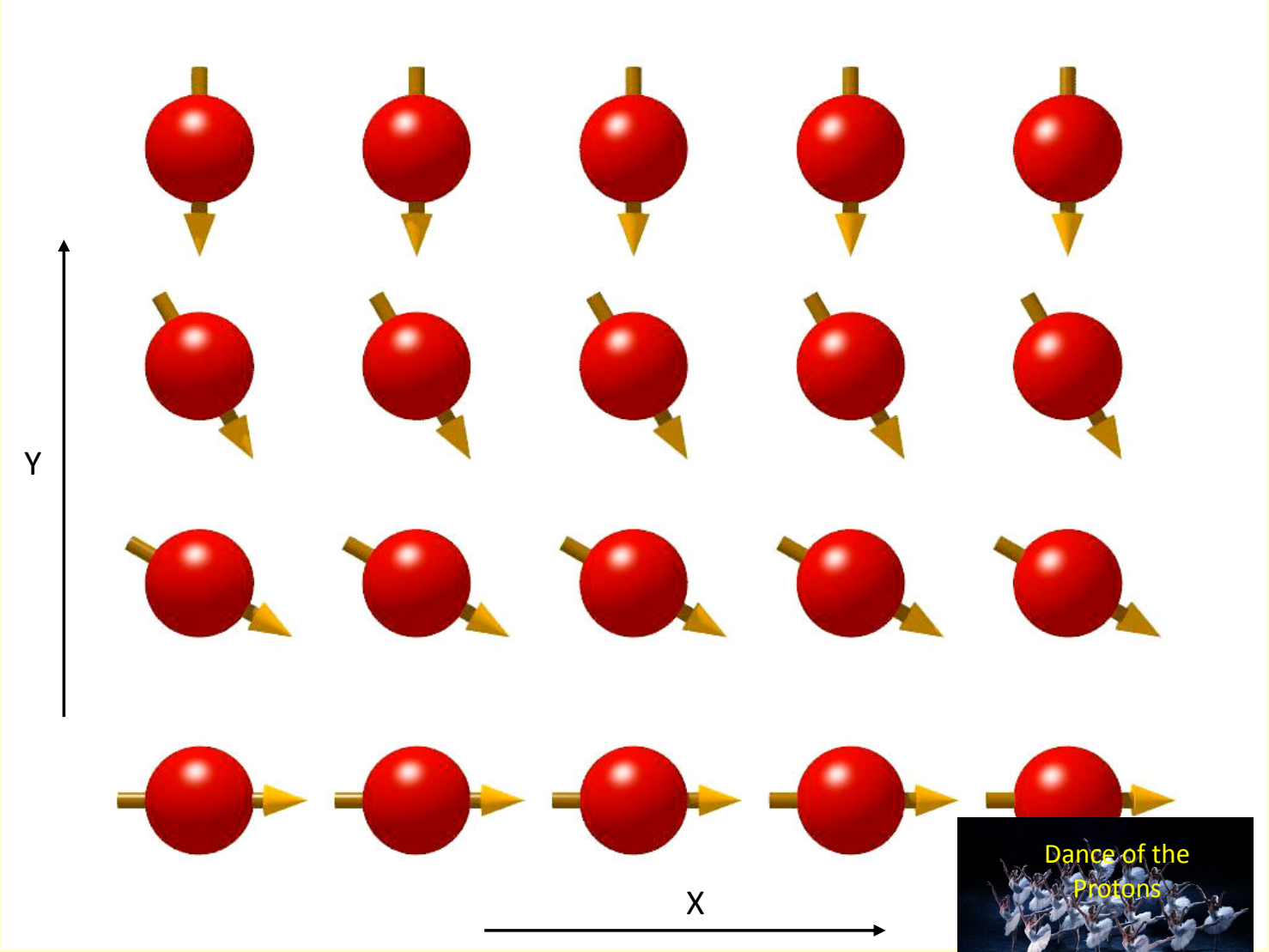


Steady precession in X-Y plane after 90° RF pulse and phase encode Y-gradient

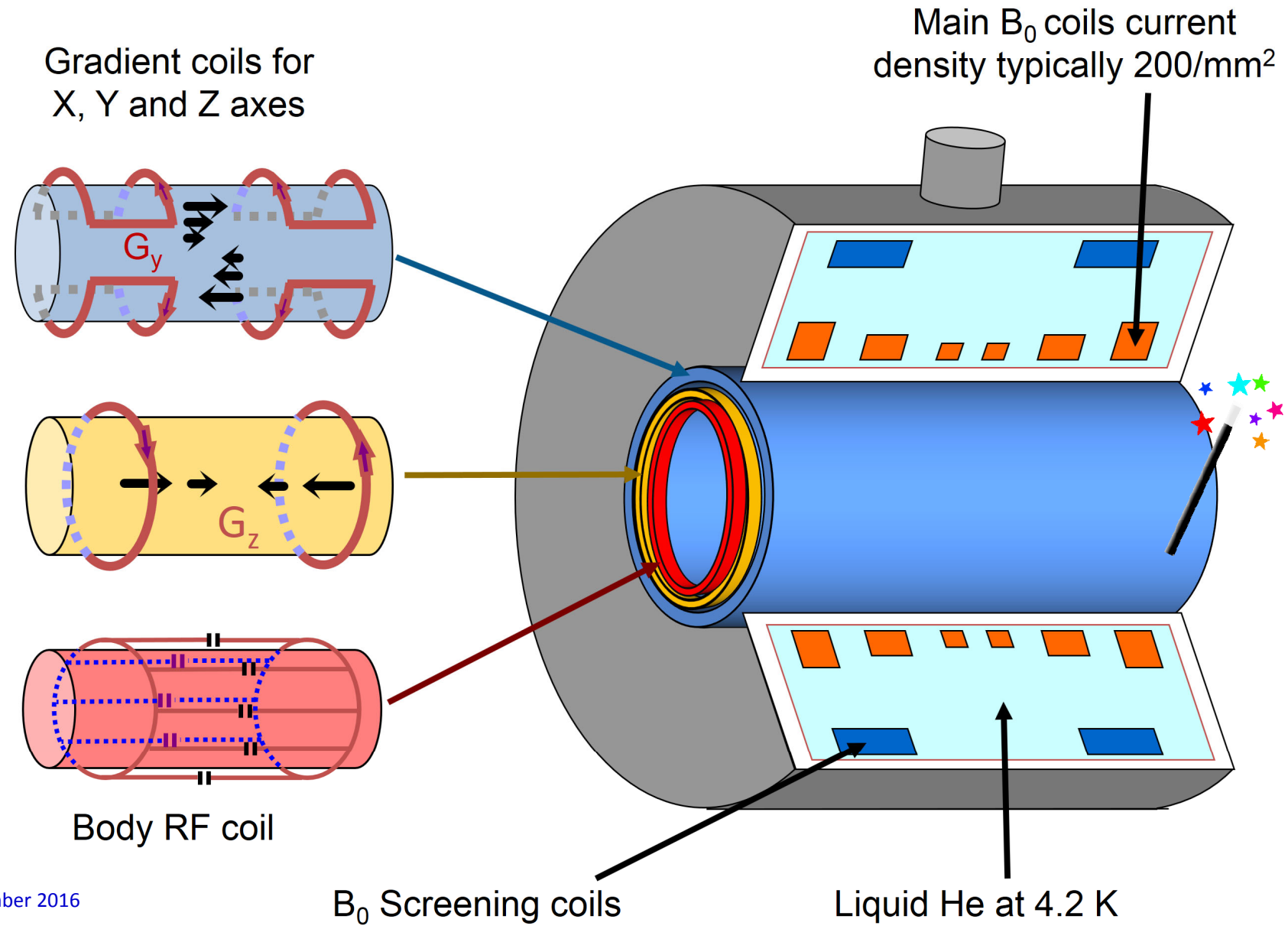
Frequency encode X-gradient present

X position coded by frequency and Y position encoded by phase

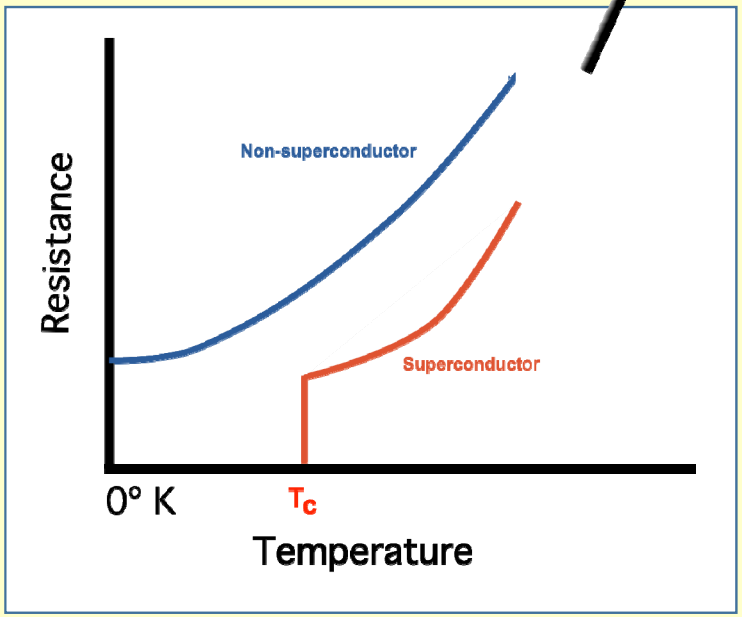




Technology

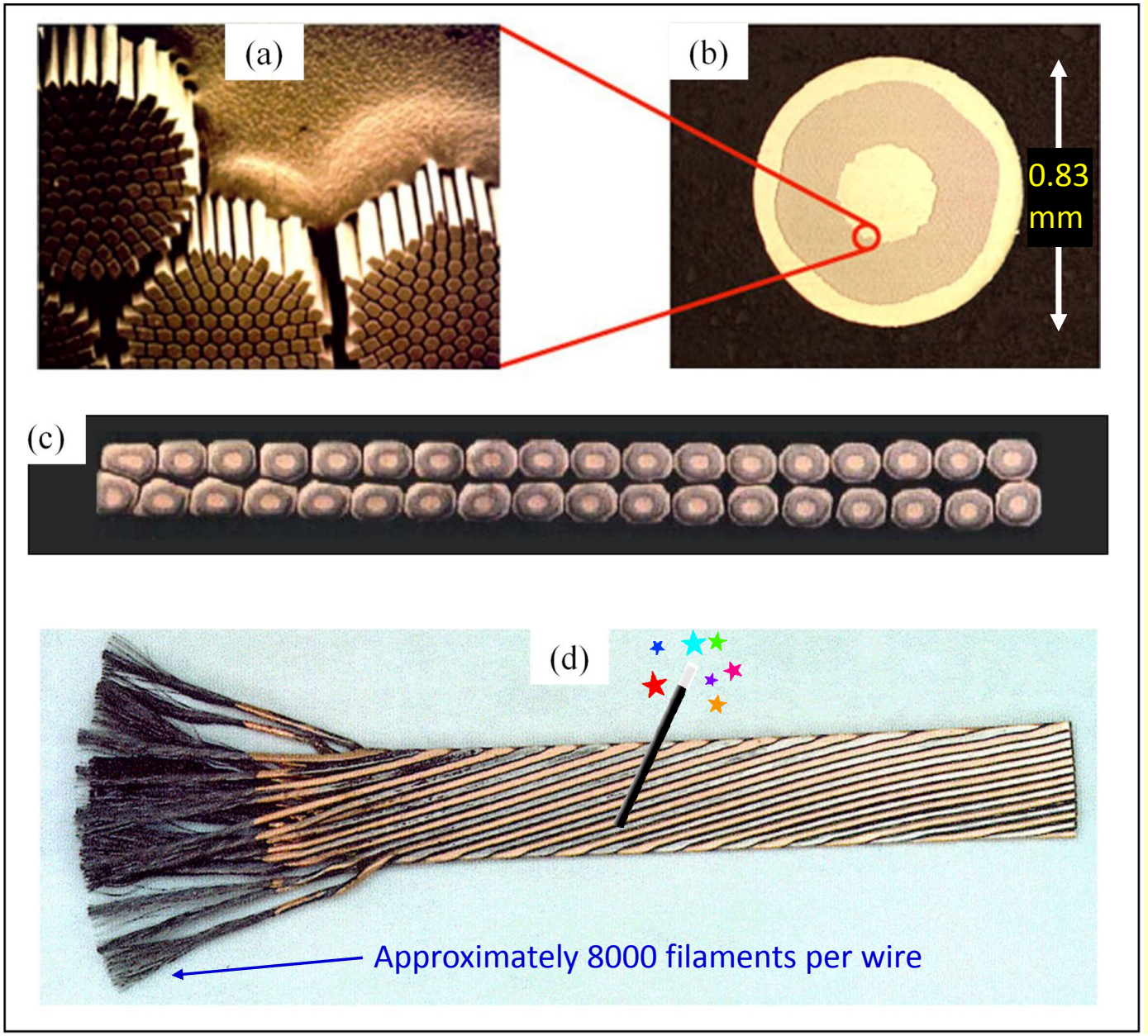

Gradient coils for
X, Y and Z axes
Main B_0 coils current
density typically 200/mm^2
G_y
G_z
Body RF coil
B_0 Screening coils
Liquid He at 4.2 K

Superconducting wire

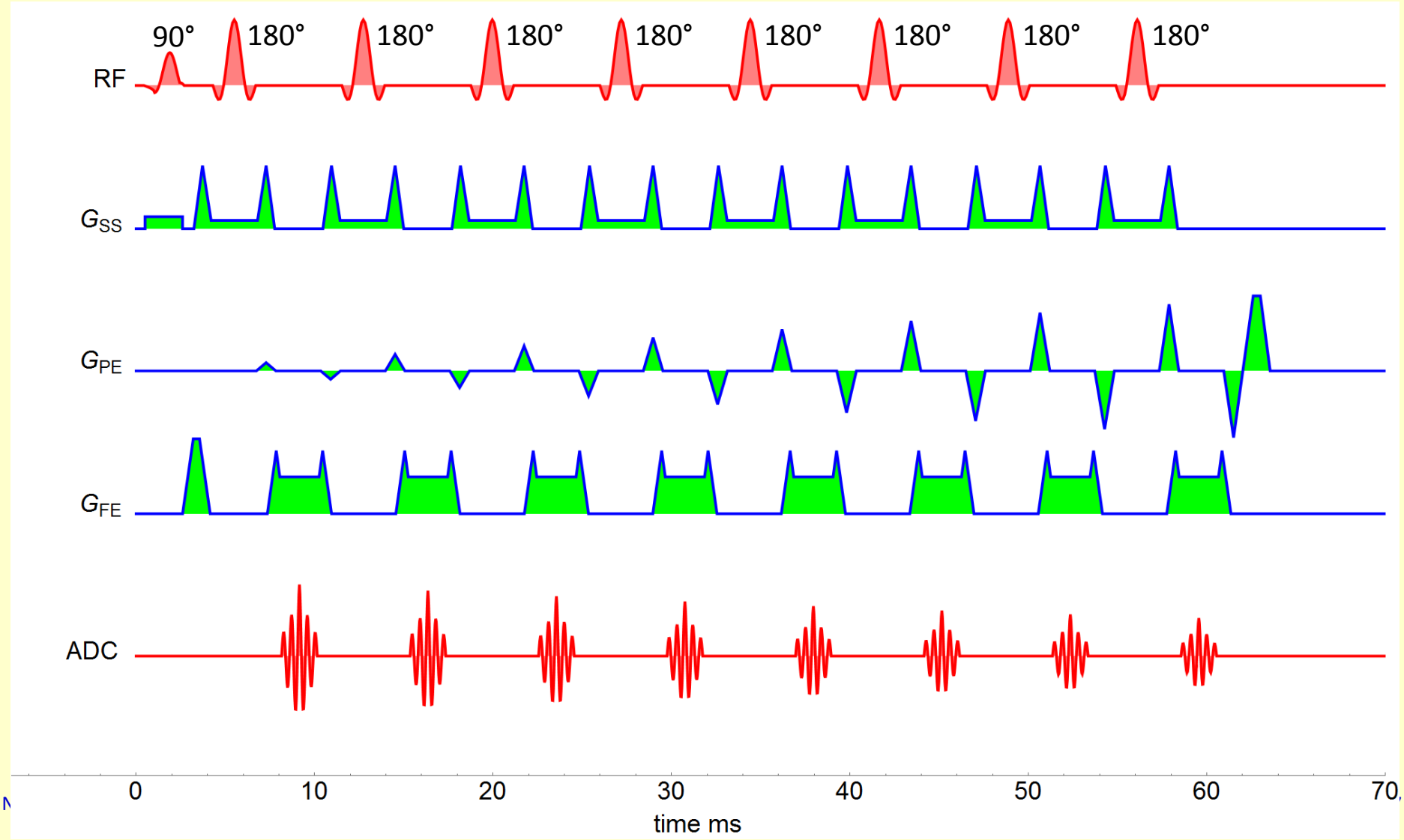


A Gift from CERN and Rutherford Appleton lab

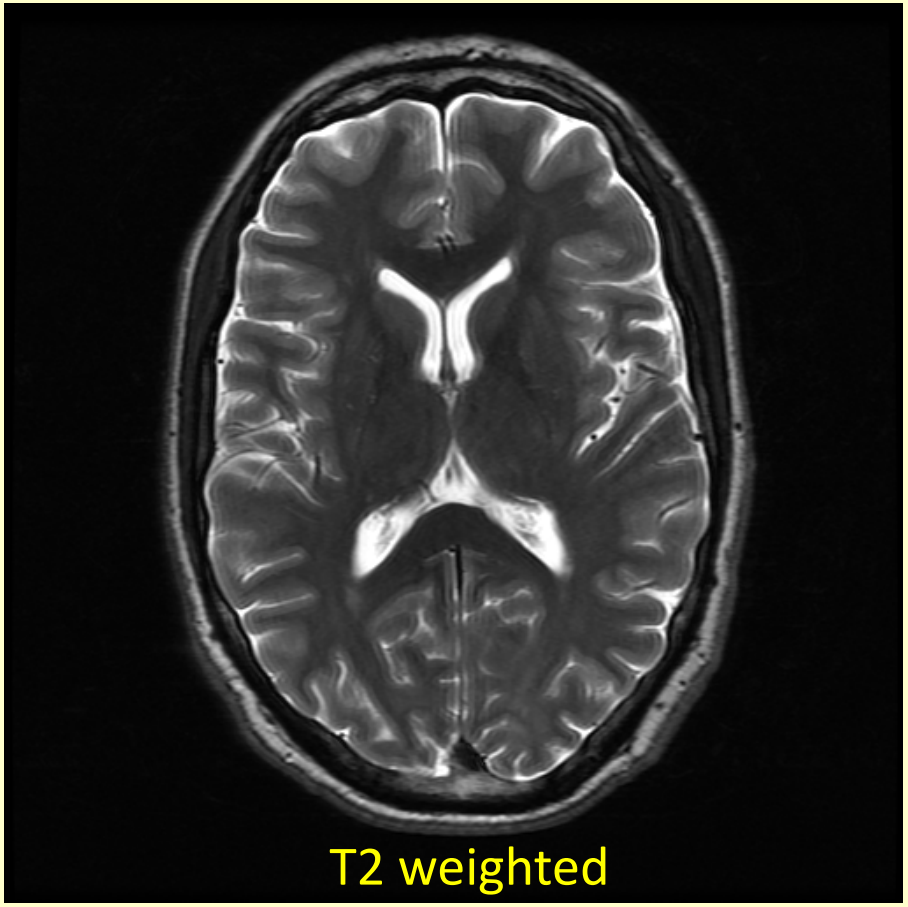
15 November 2016

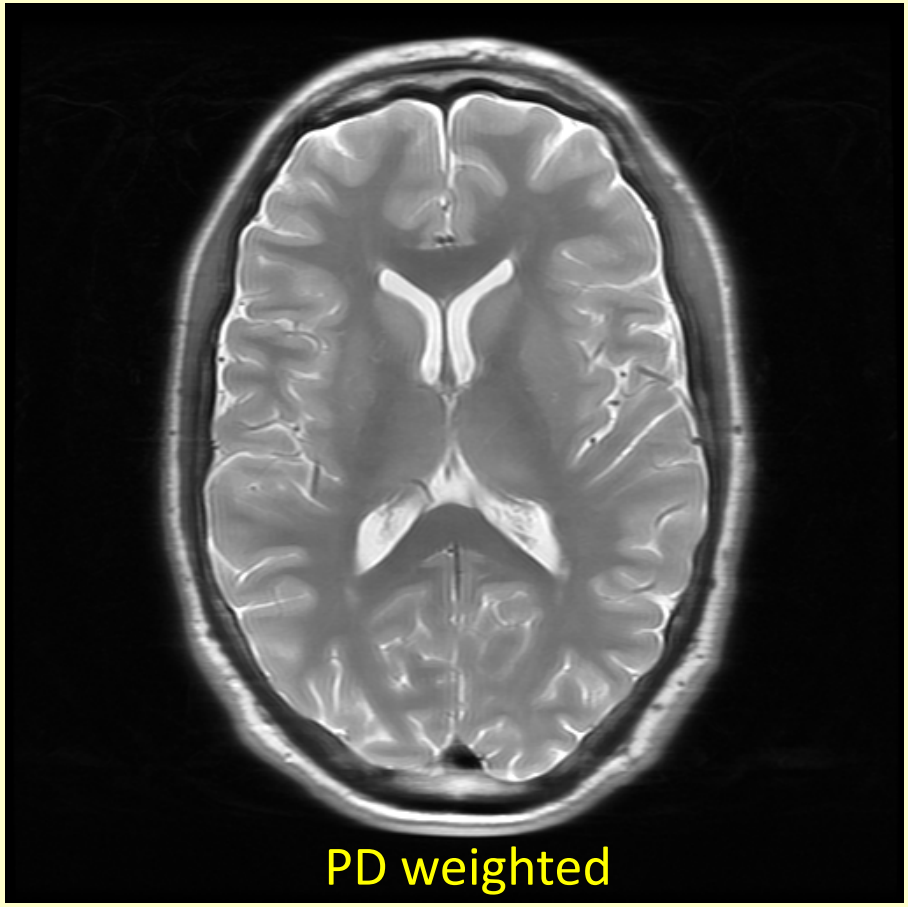


Real Sequence: Spin-Echo (SE)

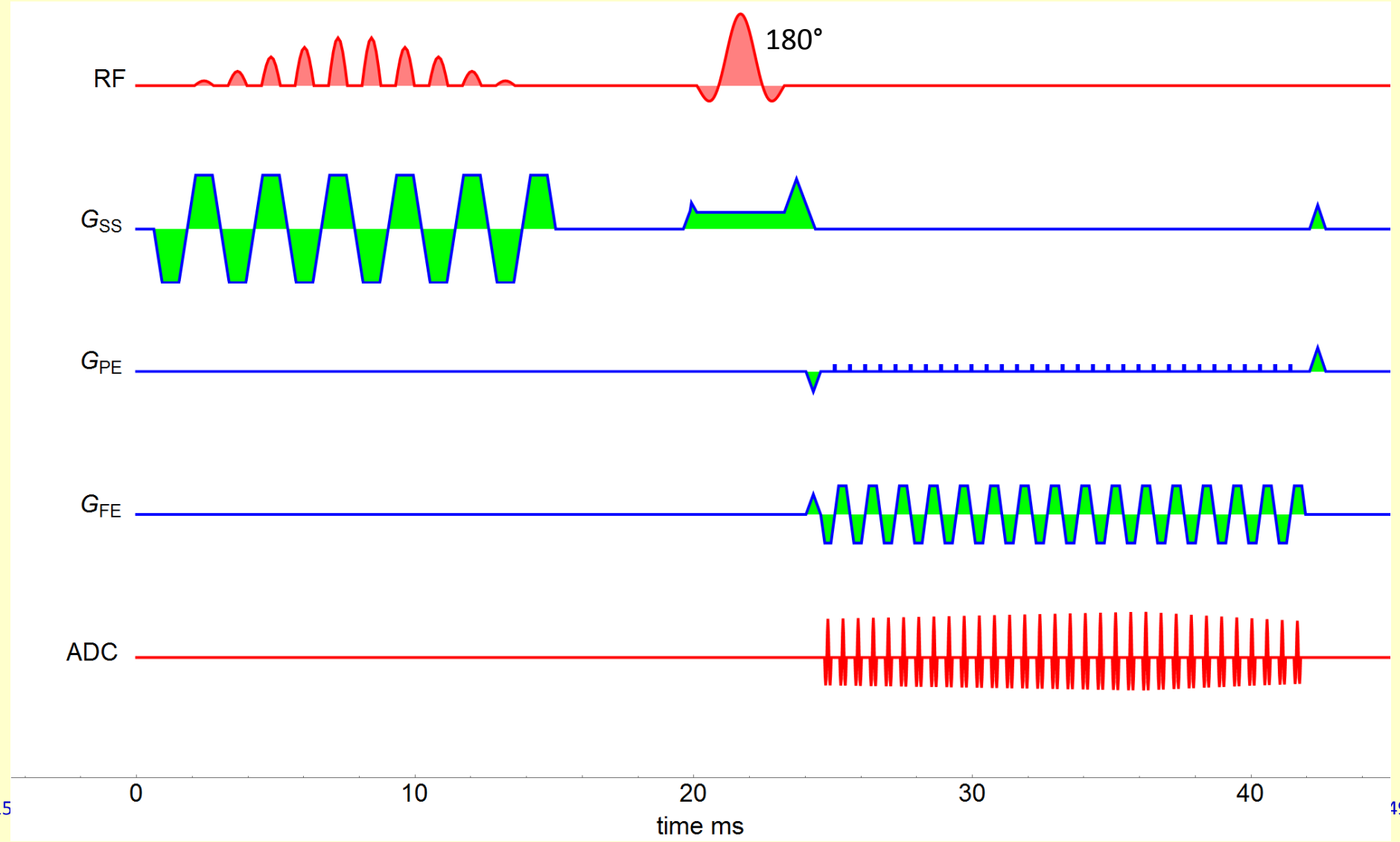


Real Sequence: Spin-Echo (SE)



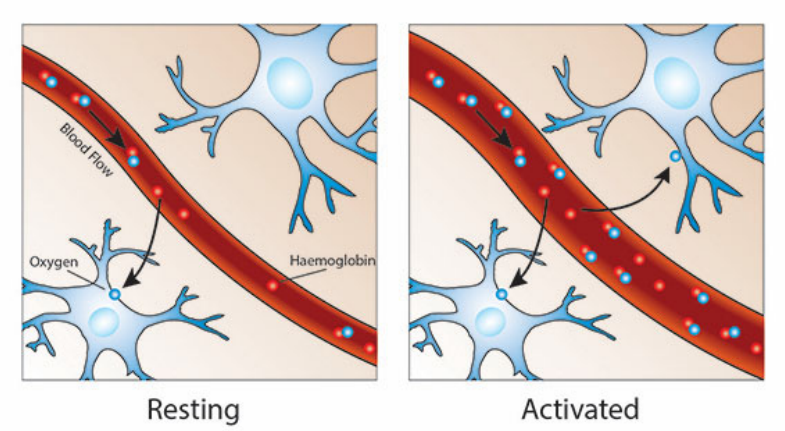


Real Sequence: SE-EPI



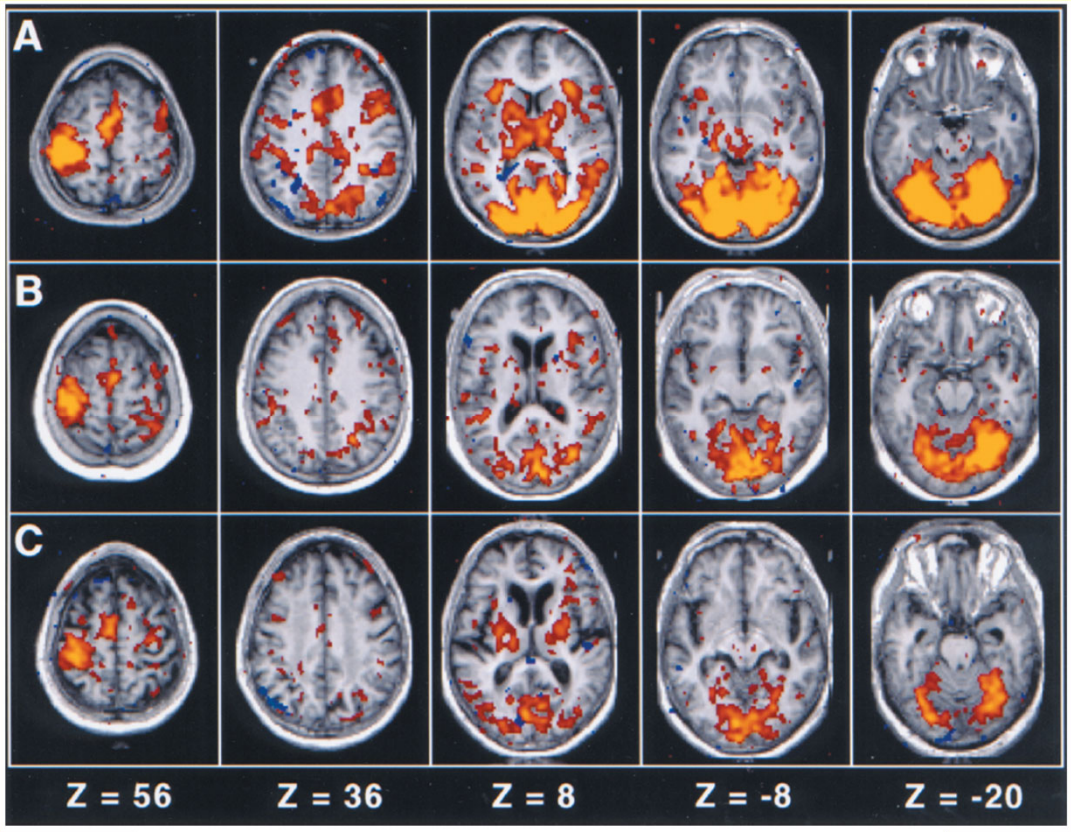
Real Sequence: SE-EPI

Very Fast – Typically used for BOLD Imaging in functional studies - fMRI



Subtract resting and activate images to get map of active regions

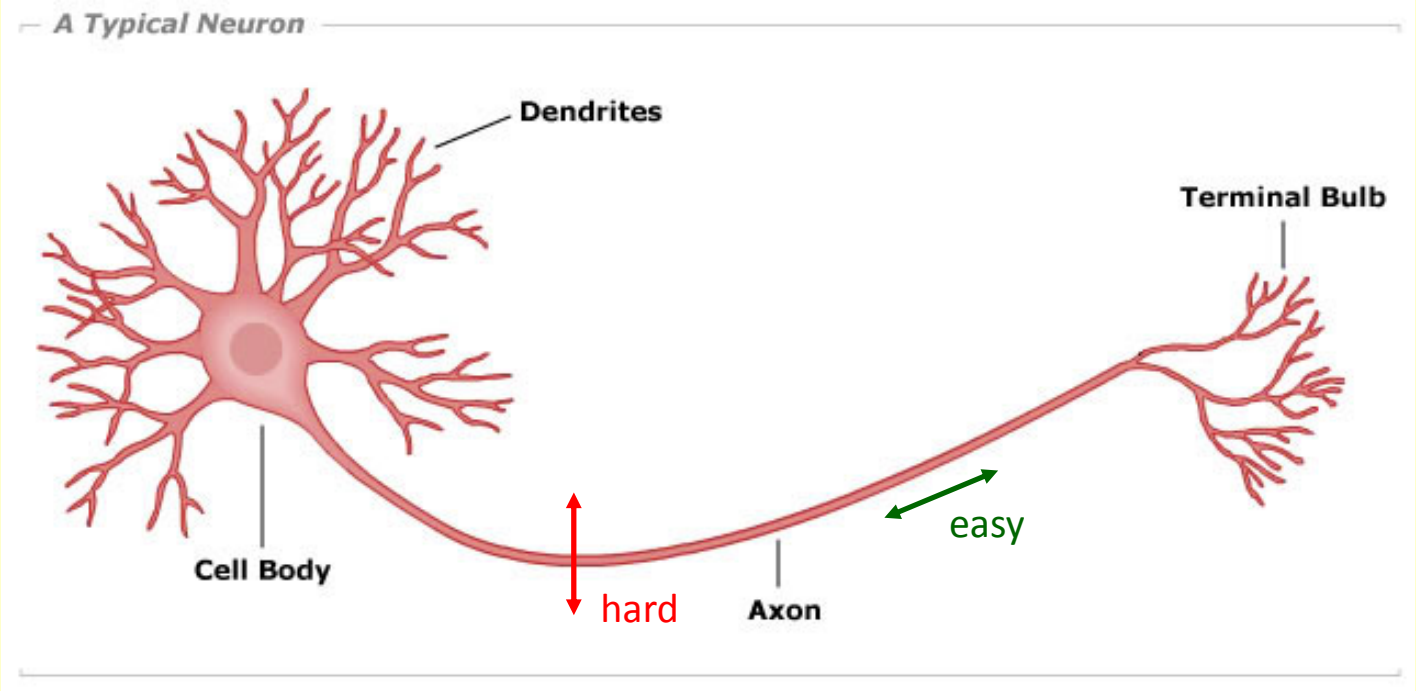
Aging study, visual task:
(a) young, (b) old (c) dementia



Buckner et al. Journal of Cognitive Neuroscience 2000

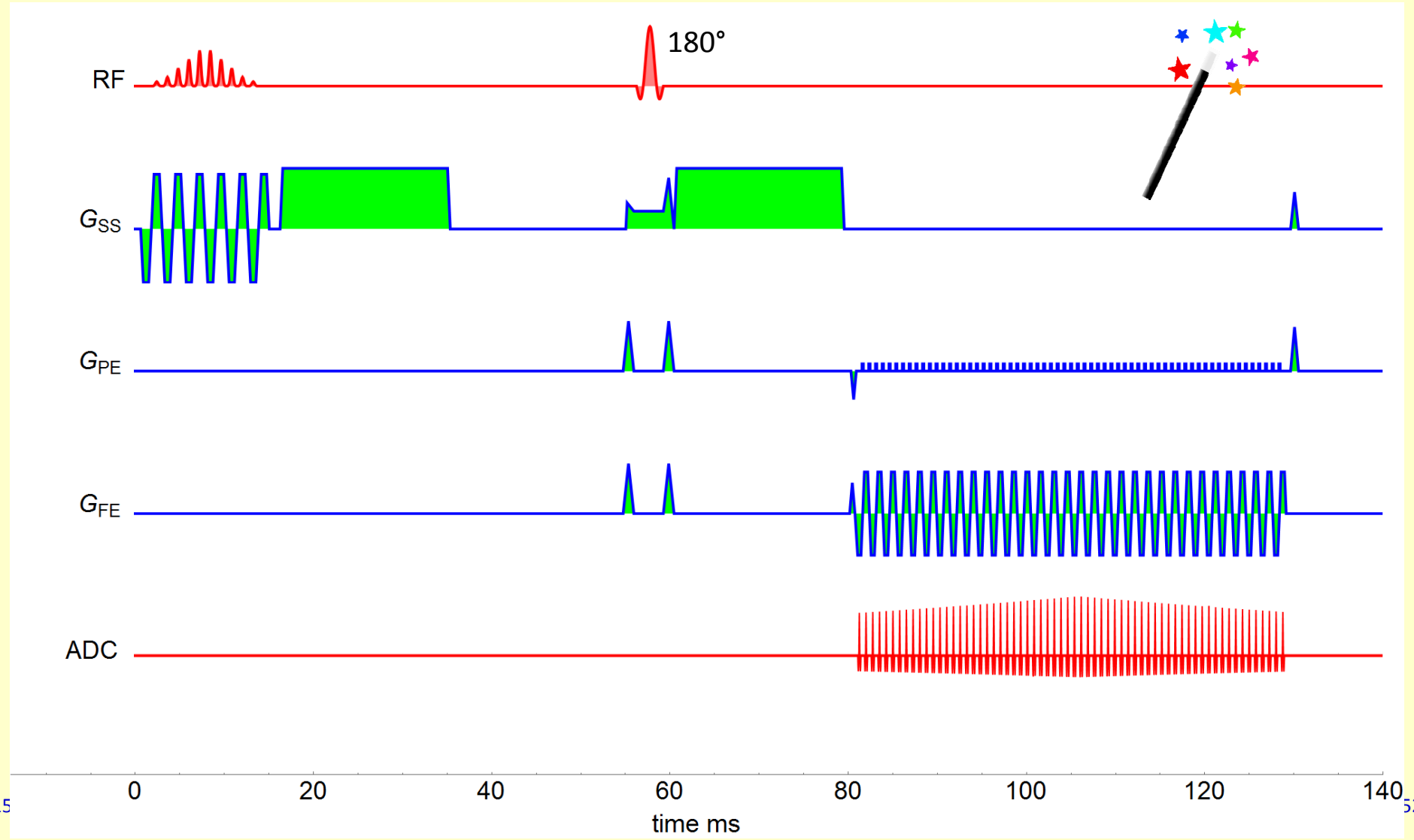
Diffusion Tensor Imaging

Water molecules inside an axon diffuse along the nerve fibre rather than in the perpendicular direction

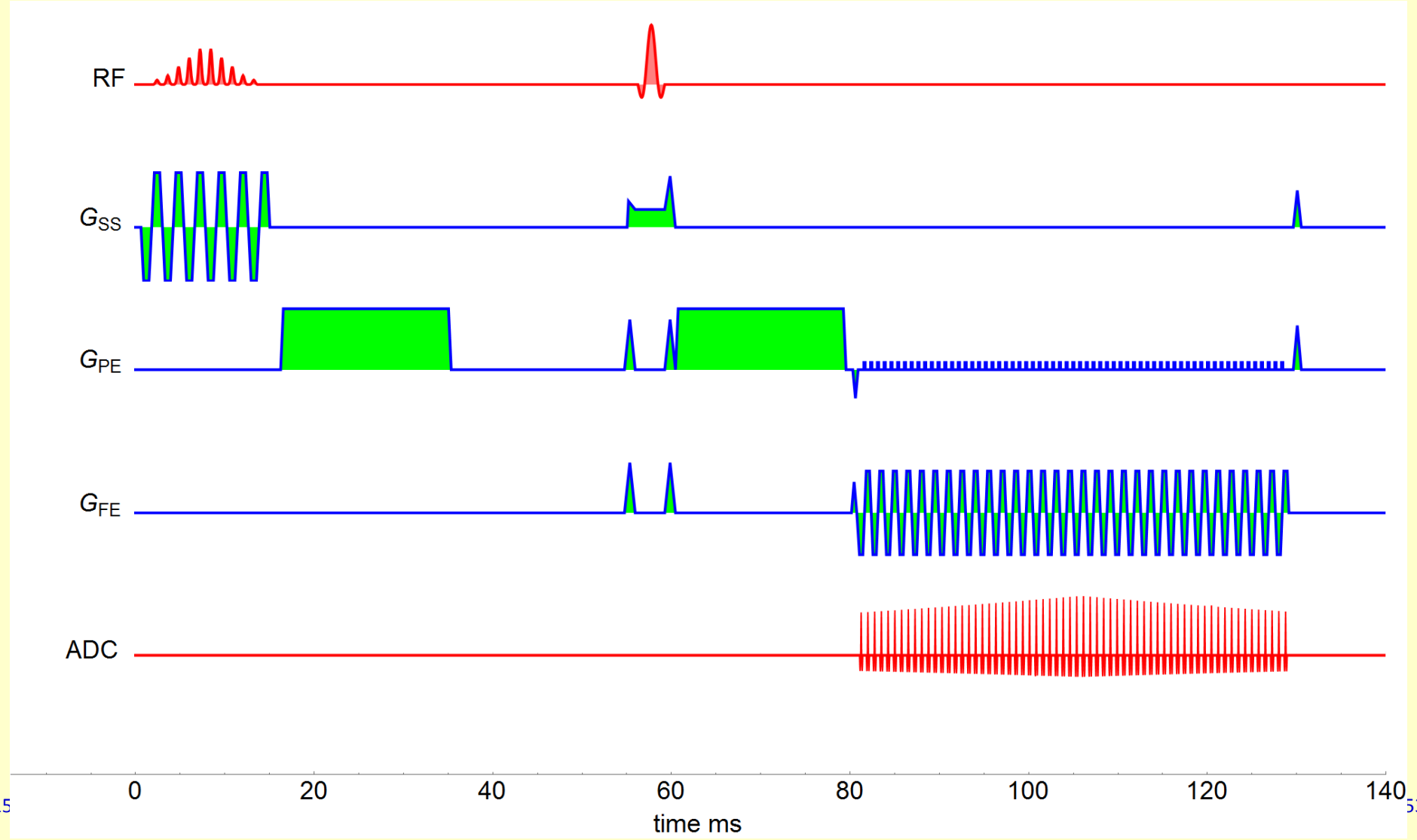


A strong dephasing gradient before the 180° pulses followed by an equal rephasing gradient after the 180° pulse will have no net effect unless a proton moves along the applied gradient between the two pulses

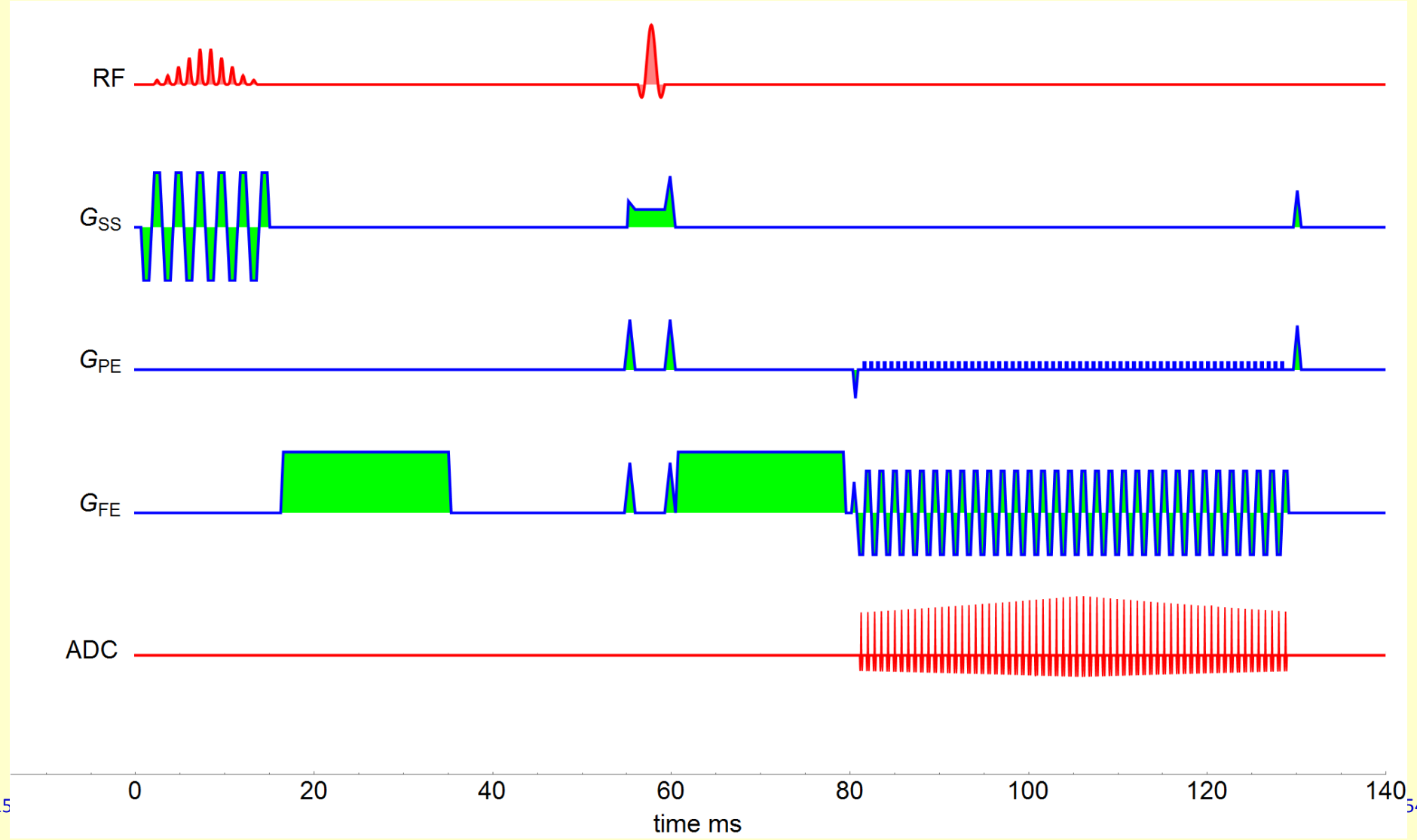
Real Sequence – DW-EPI



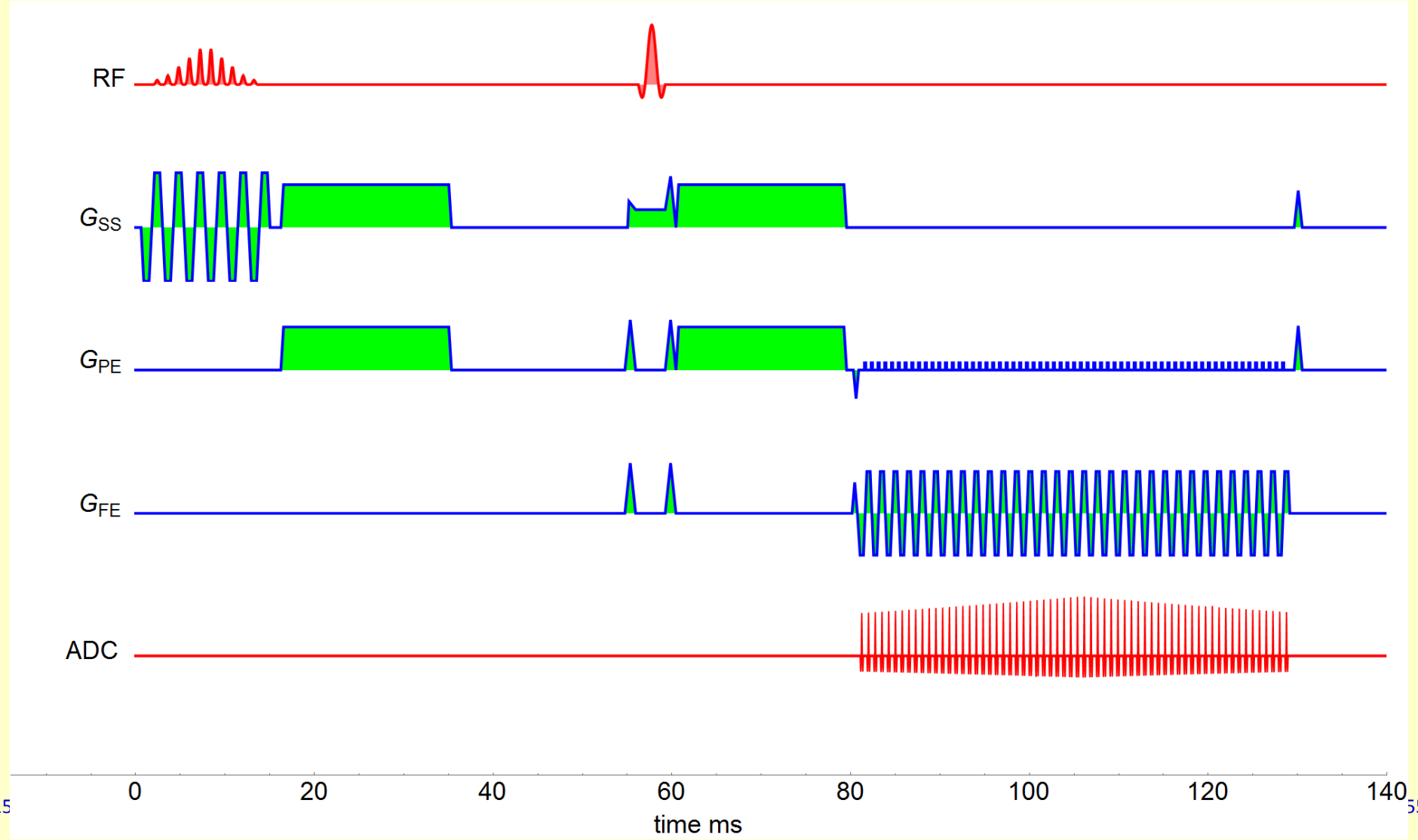
Real Sequence – DW-EPI



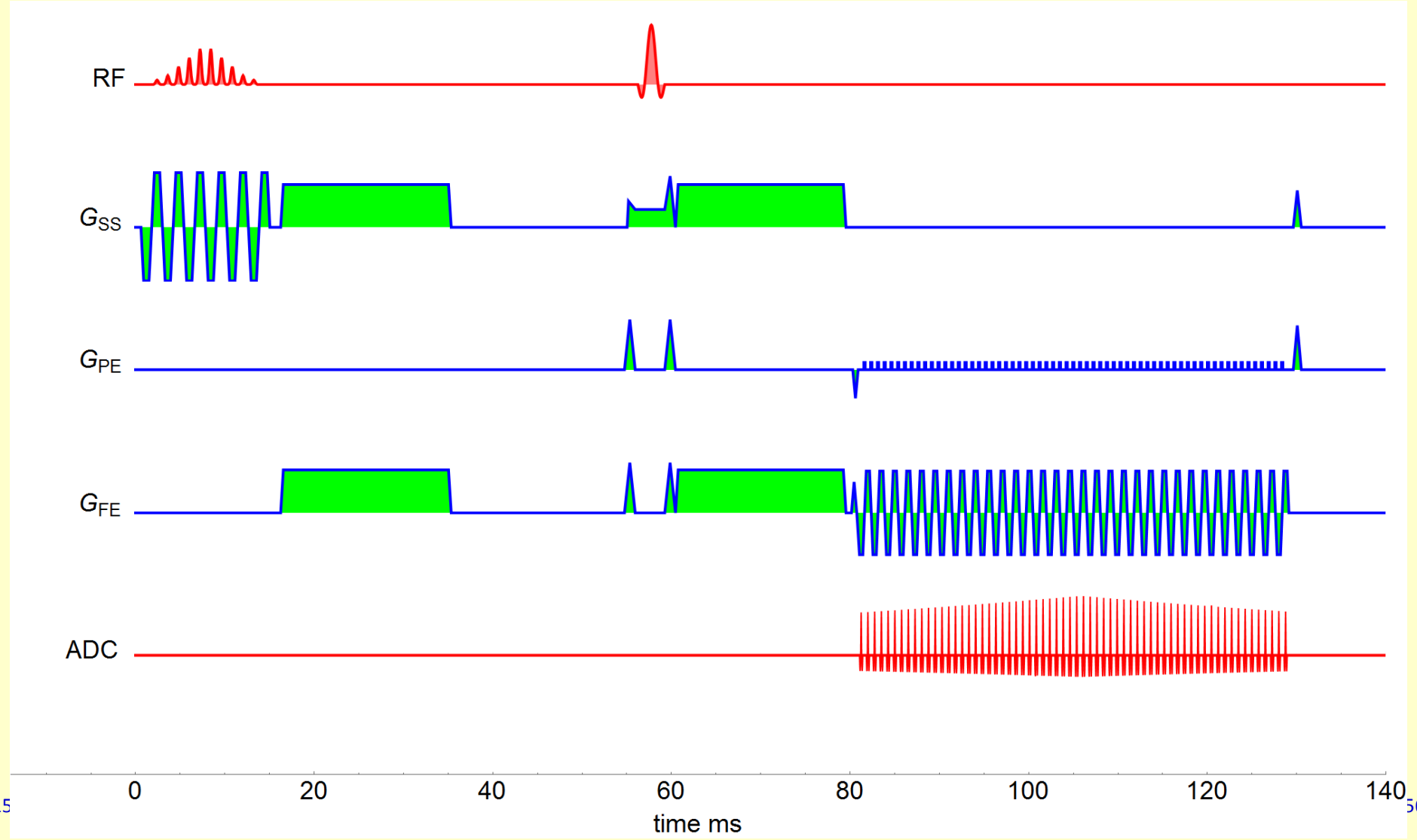
Real Sequence – DW-EPI



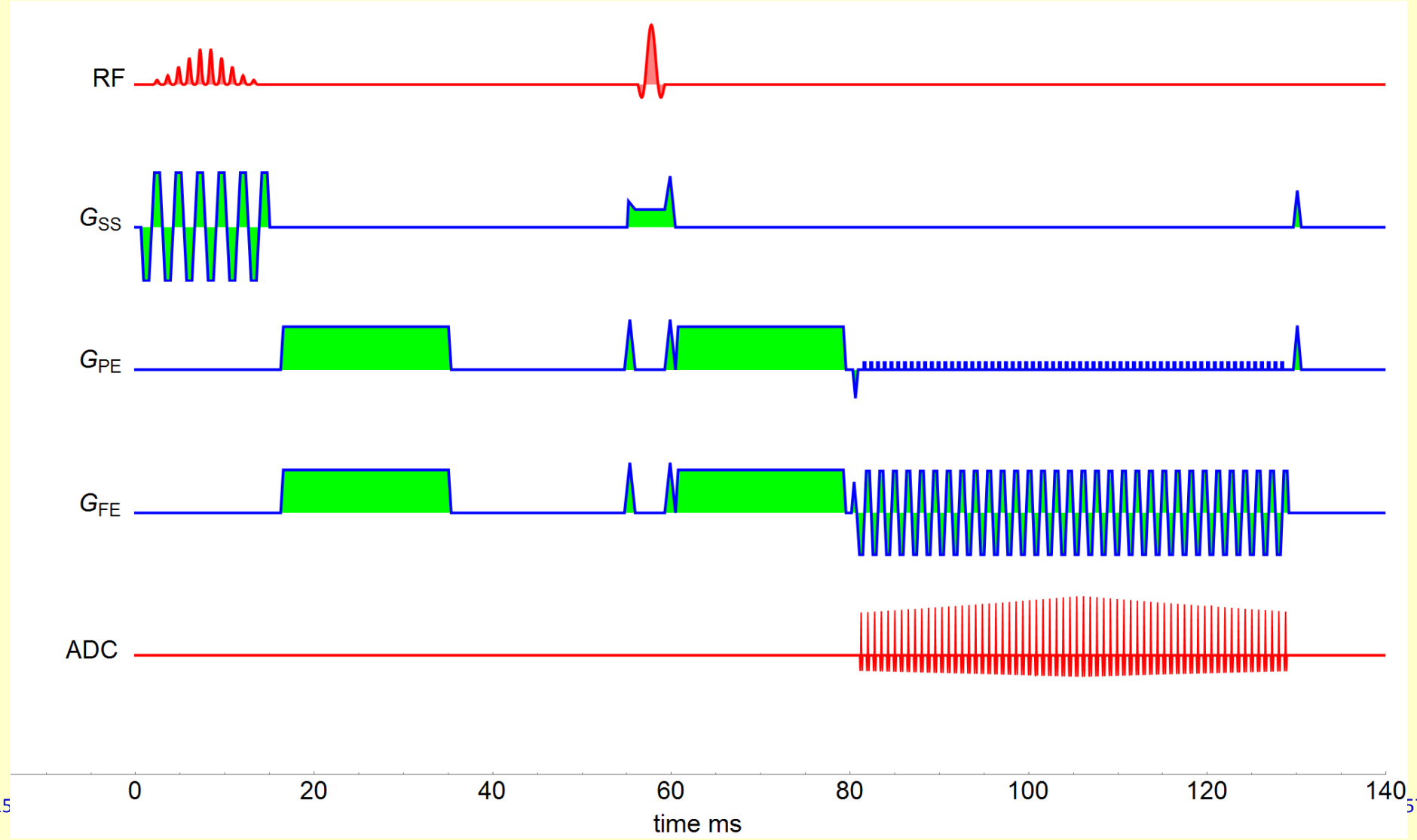
Real Sequence – DW-EPI



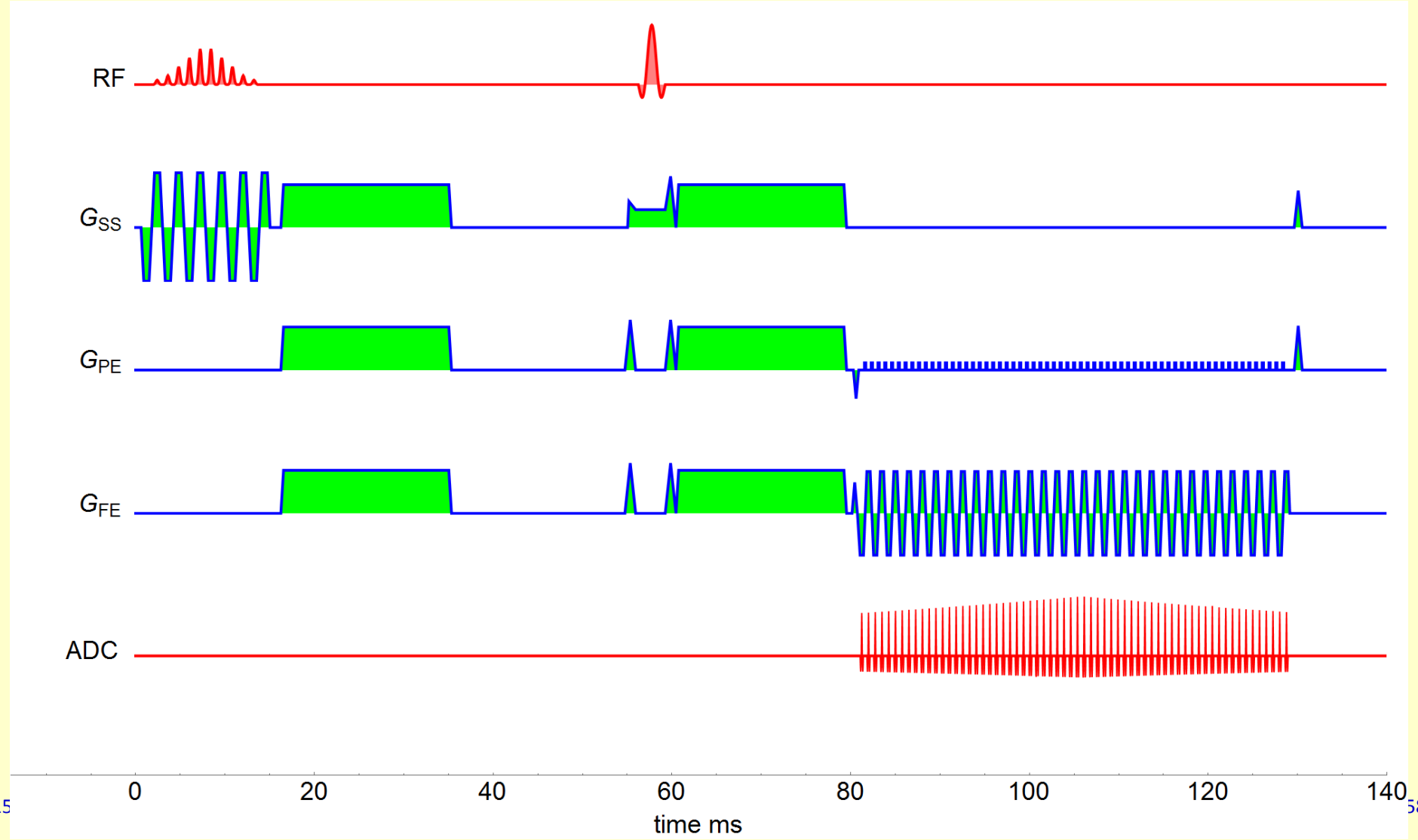
Real Sequence – DW-EPI



Real Sequence – DW-EPI

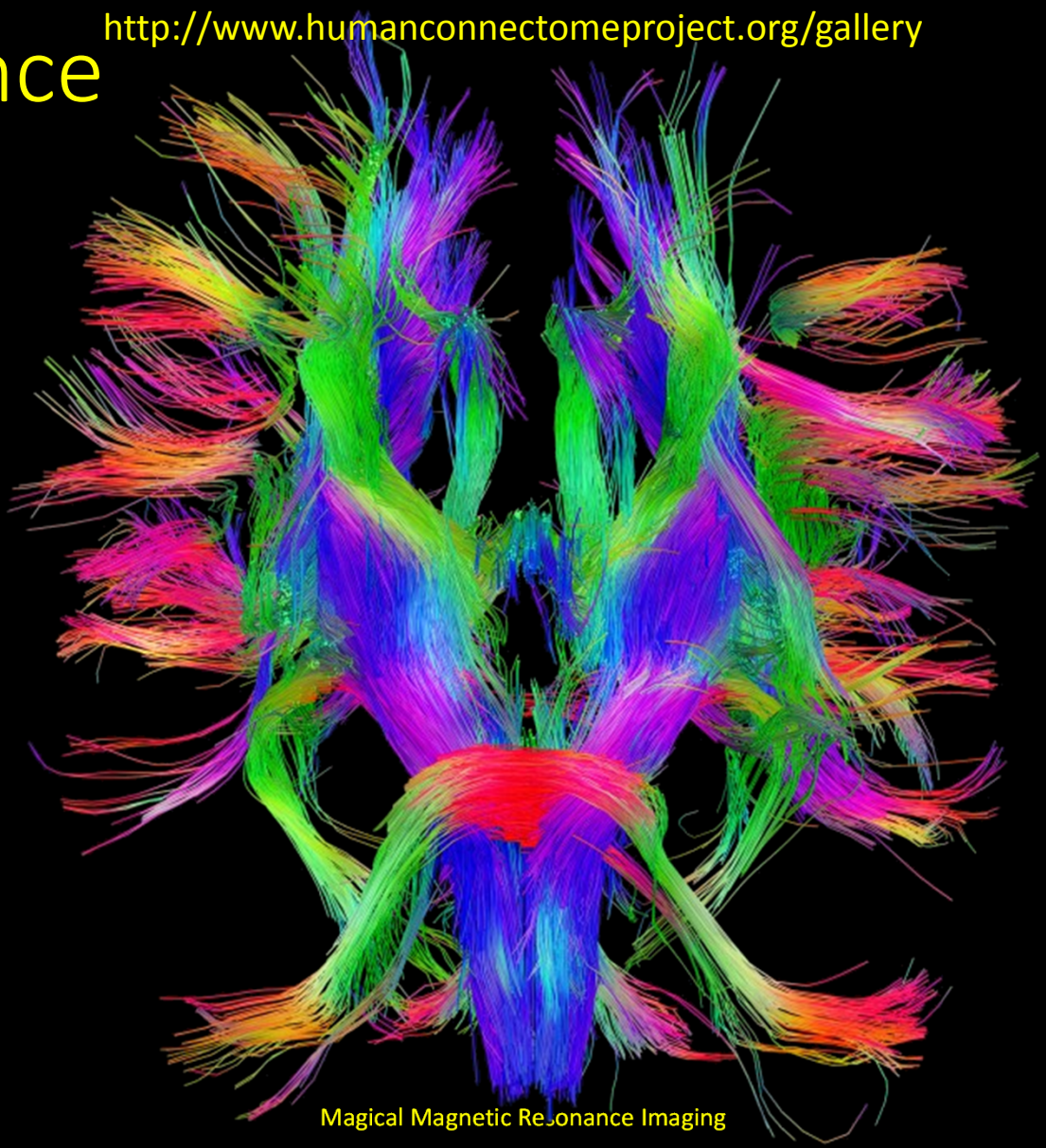


Real Sequence – DW-EPI



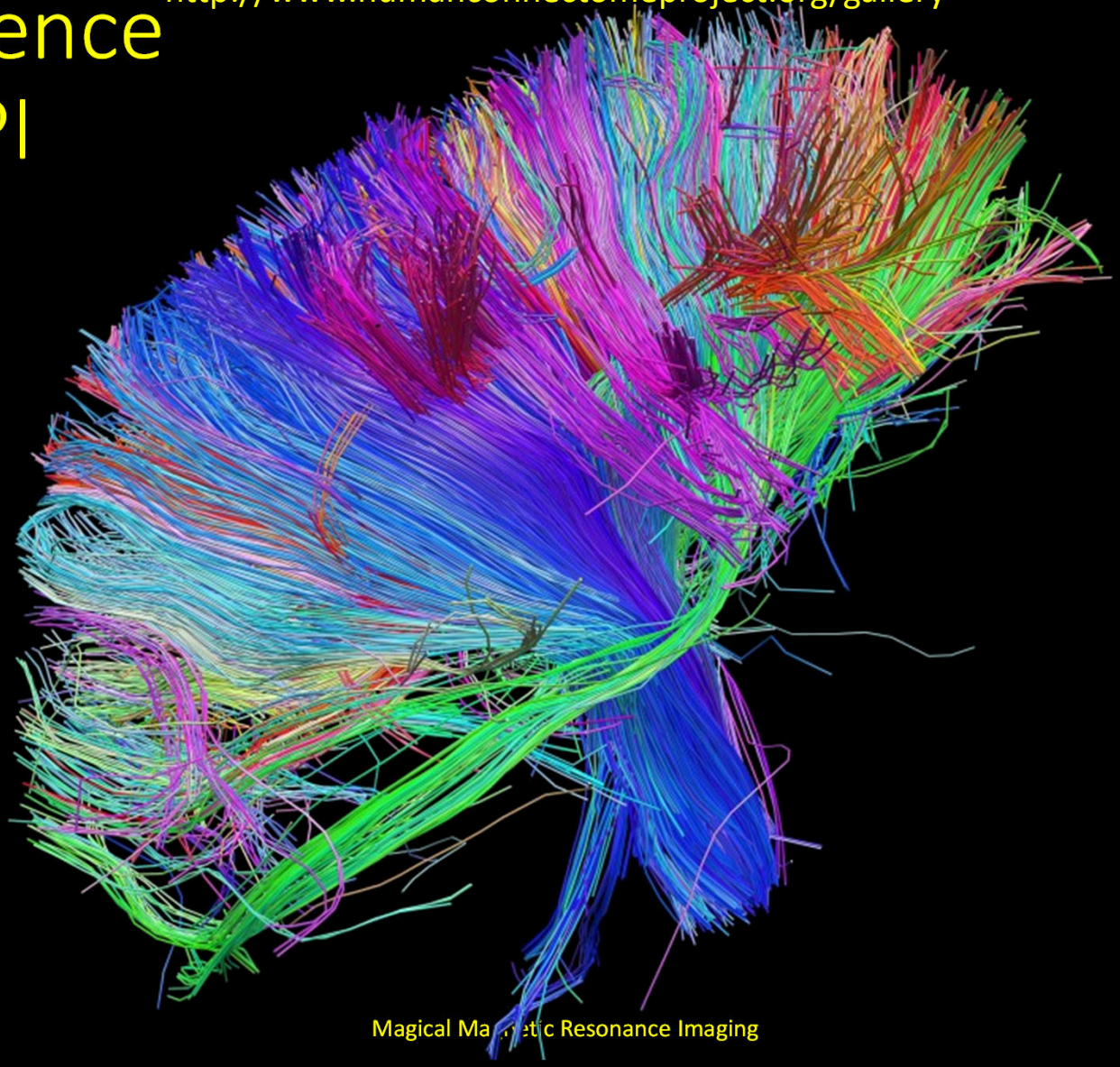
Real Sequence DW-EPI

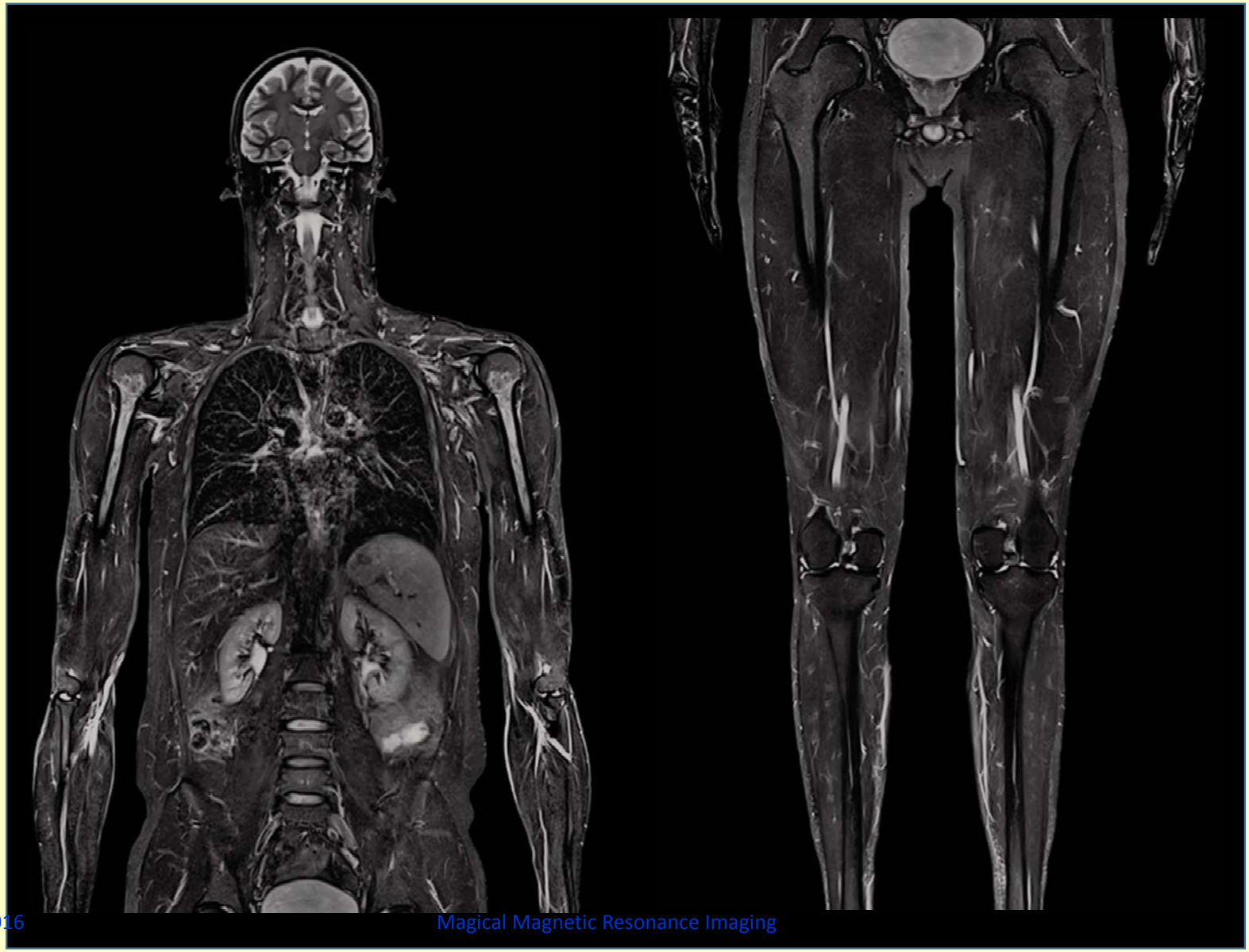
http://www.humanconnectomeproject.org/gallery

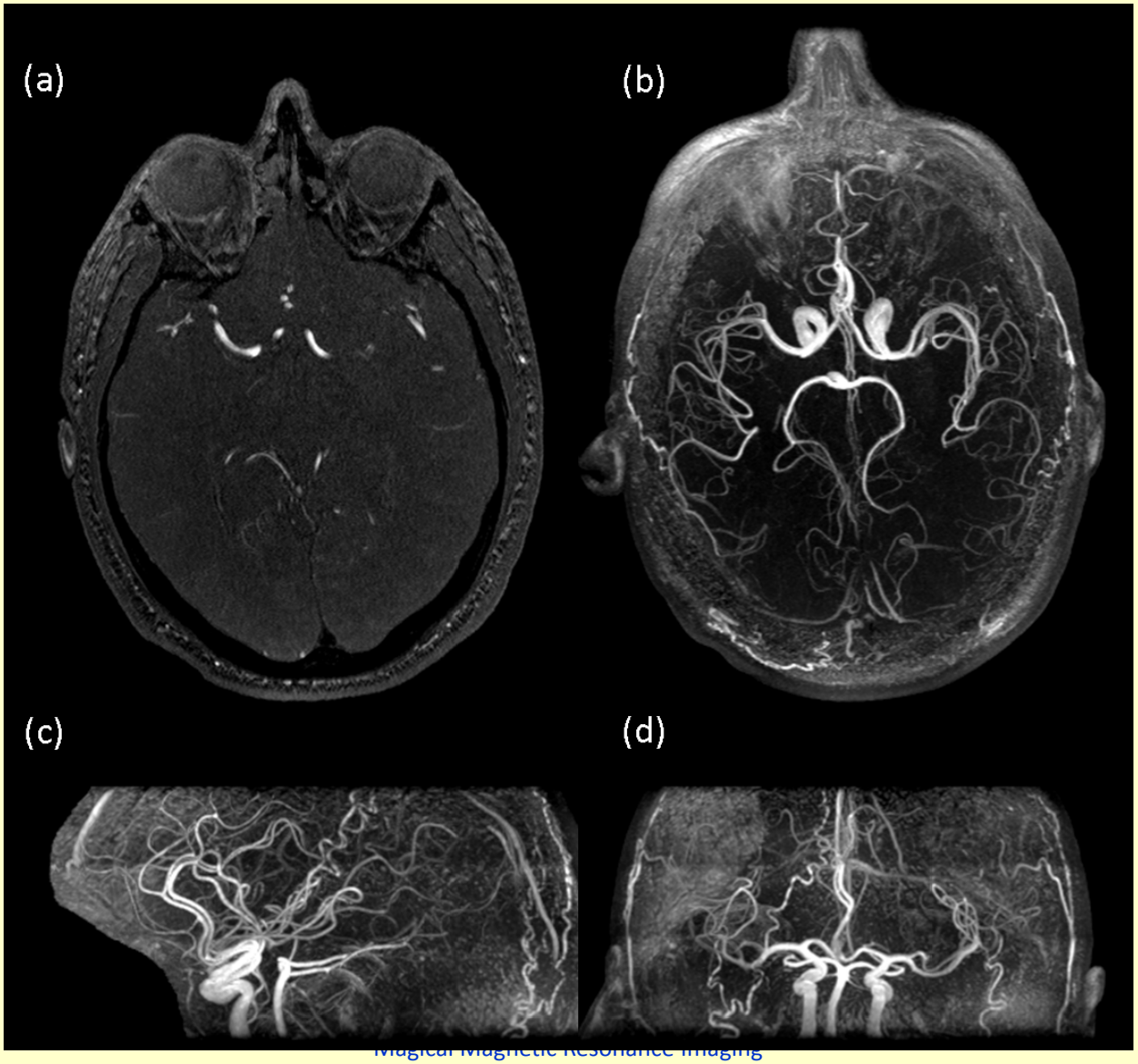


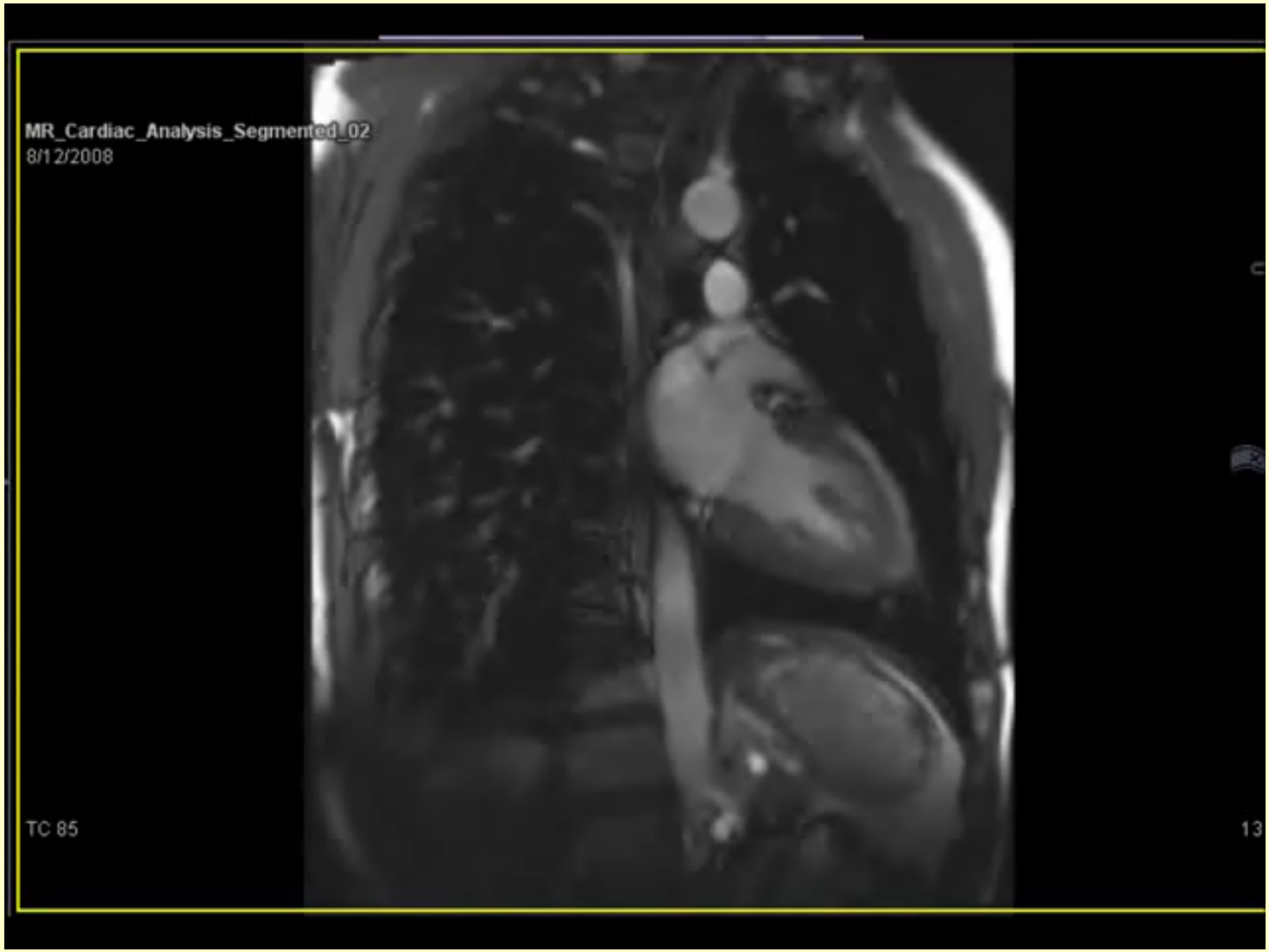
Real Sequence DW-EPI

http://www.humanconnectomeproject.org/gallery

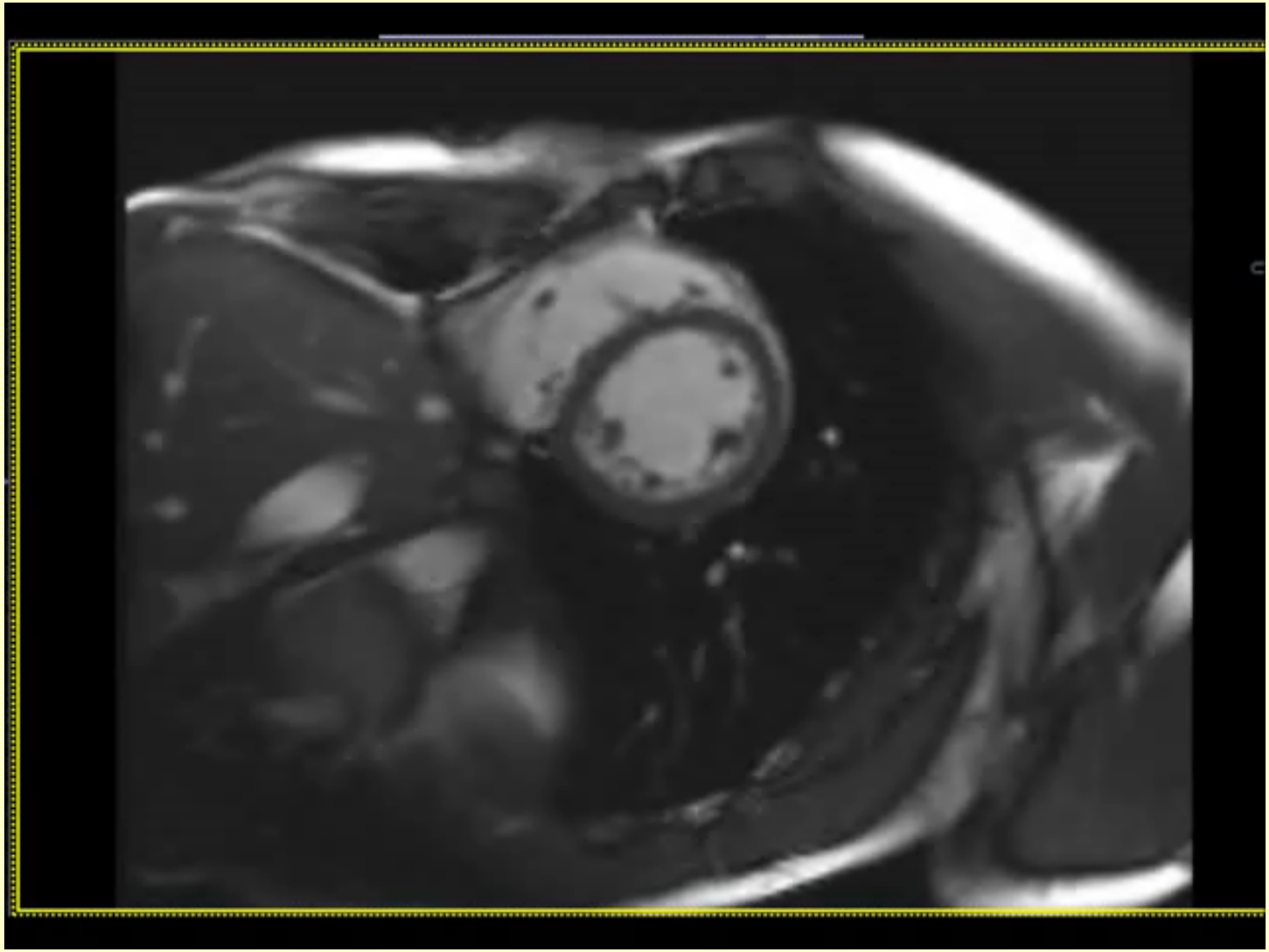


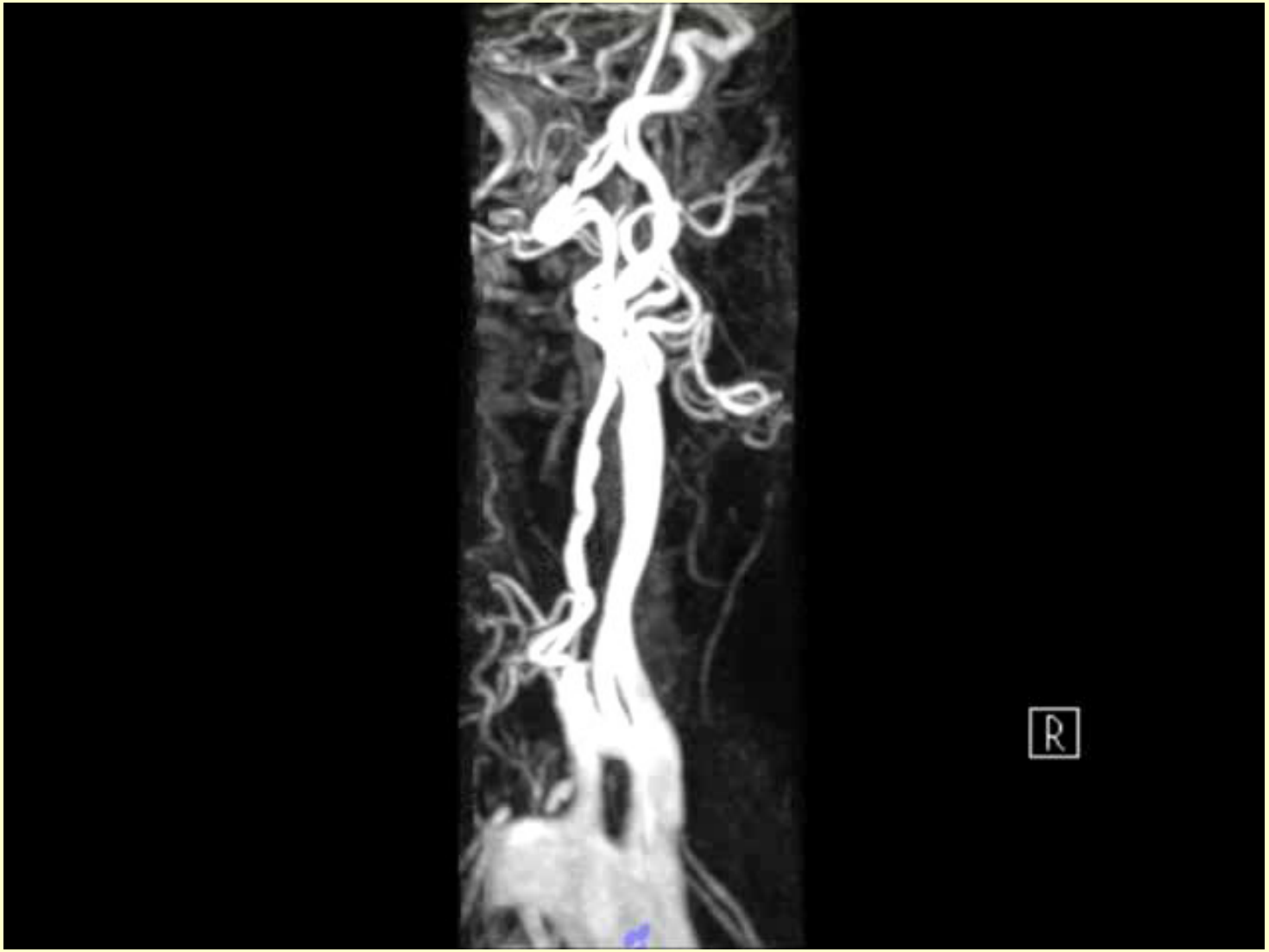



(a)
(b)
(c)
(d)

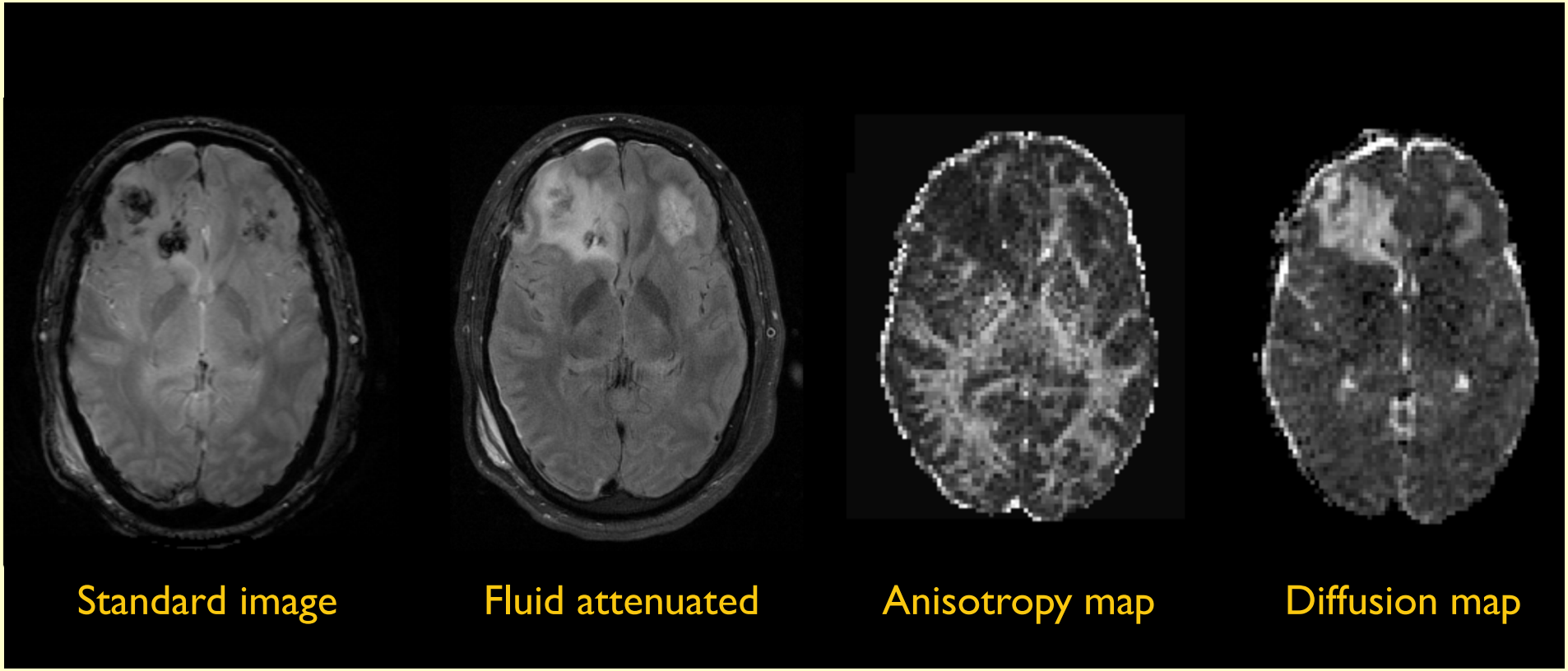

MR_Cardiac_Analysis_Segmented_02
8/12/2008
TC 85
13


MR_Cardiac_Analysis_Segmented_02
8/12/2008
TC 85
23

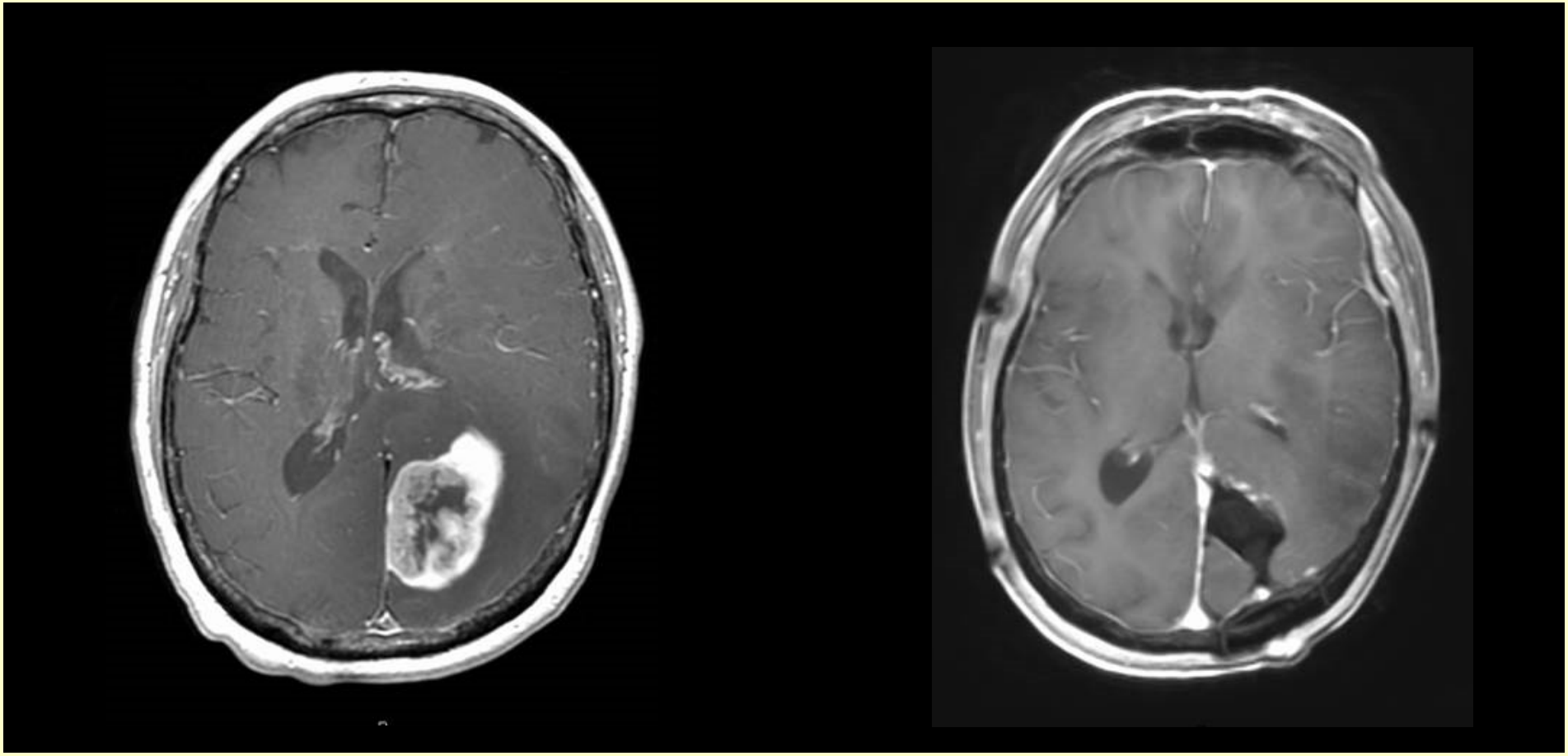



R

Acute Brain Injury



Oncology



Is MRI Safe?

- Static magnetic fields of a few T have no known harmful effects
- However RF and/or pulsed gradients might be harmful
  - Implants / metal fragments
  - Tattoos
  - Conducting wires need to be places with care
  - Peripheral nerve stimulation possible
- The main magnet needs respect
  - Projectiles
  - Quench
  - Explosion

Projectiles

Quench

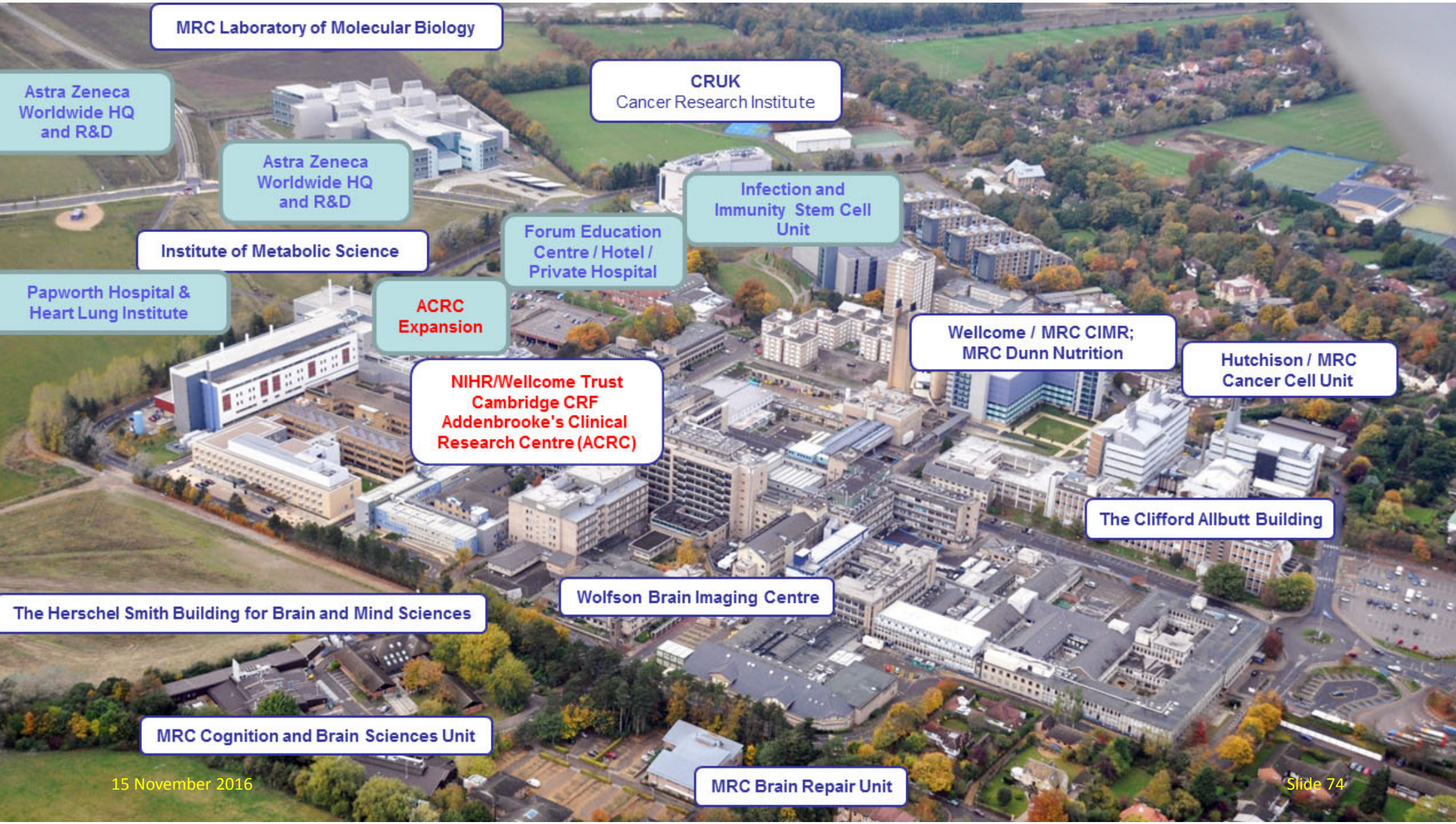
https://www.youtube.com/watch?v=9SOUJP5dFEg

Quench

https://www.youtube.com/watch?v=CXWqIz68eqw

Cryogen Explosion

https://www.youtube.com/watch?v=1R7KsfosV-o


MRC Laboratory of Molecular Biology
Astra Zeneca Worldwide HQ and R&D
CRUK Cancer Research Institute
Astra Zeneca Worldwide HQ and R&D
Infection and Immunity Stem Cell Unit
Institute of Metabolic Science
Forum Education Centre / Hotel / Private Hospital
Papworth Hospital & Heart Lung Institute
ACRC Expansion
Wellcome / MRC CIMR; MRC Dunn Nutrition
Hutchison / MRC Cancer Cell Unit
NIHR/Wellcome Trust Cambridge CRF Addenbrooke's Clinical Research Centre (ACRC)
The Clifford Allbutt Building
Wolfson Brain Imaging Centre
The Herschel Smith Building for Brain and Mind Sciences
MRC Cognition and Brain Sciences Unit
MRC Brain Repair Unit

Thank you – Questions?

Bach's Cello Suite No. 1

Ma, Dan, et al. (2016) "Music-based magnetic resonance fingerprinting to improve patient comfort during MRI examinations." *Magnetic Resonance in Medicine* 75 (6) 2303-2314