HST.583 Functional Magnetic Resonance Imaging: Data Acquisition and Analysis
Fall 2008

HST.583: Functional Magnetic Resonance Imaging: Data Acquisition and Analysis, Fall 2008
Harvard-MIT Division of Health Sciences and Technology
Course Director: Dr. Randy Gollub.

MR physics and safety for fMRI

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Outline:

Wed. Sept 24 (LLW):

- MR signal, Gradient and spin echo
- Basic image contrast

Mon. Sept 29 (LLW):

- Encoding the image

Wed Oct 1 (LLW):

- Fast imaging for fMRI, artifacts
- fMRI BOLD

What is NMR?

NUCLEAR

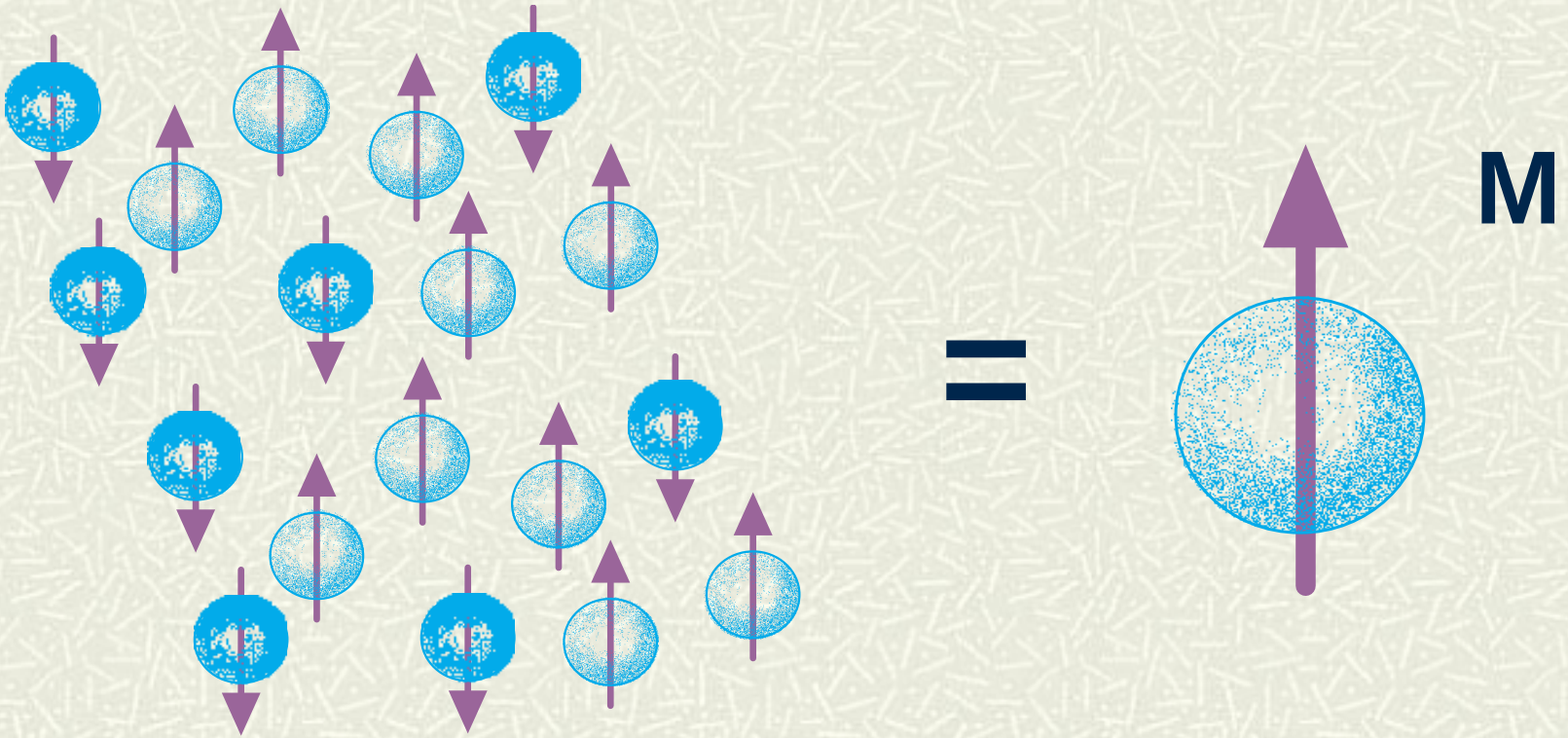
MAGNETIC

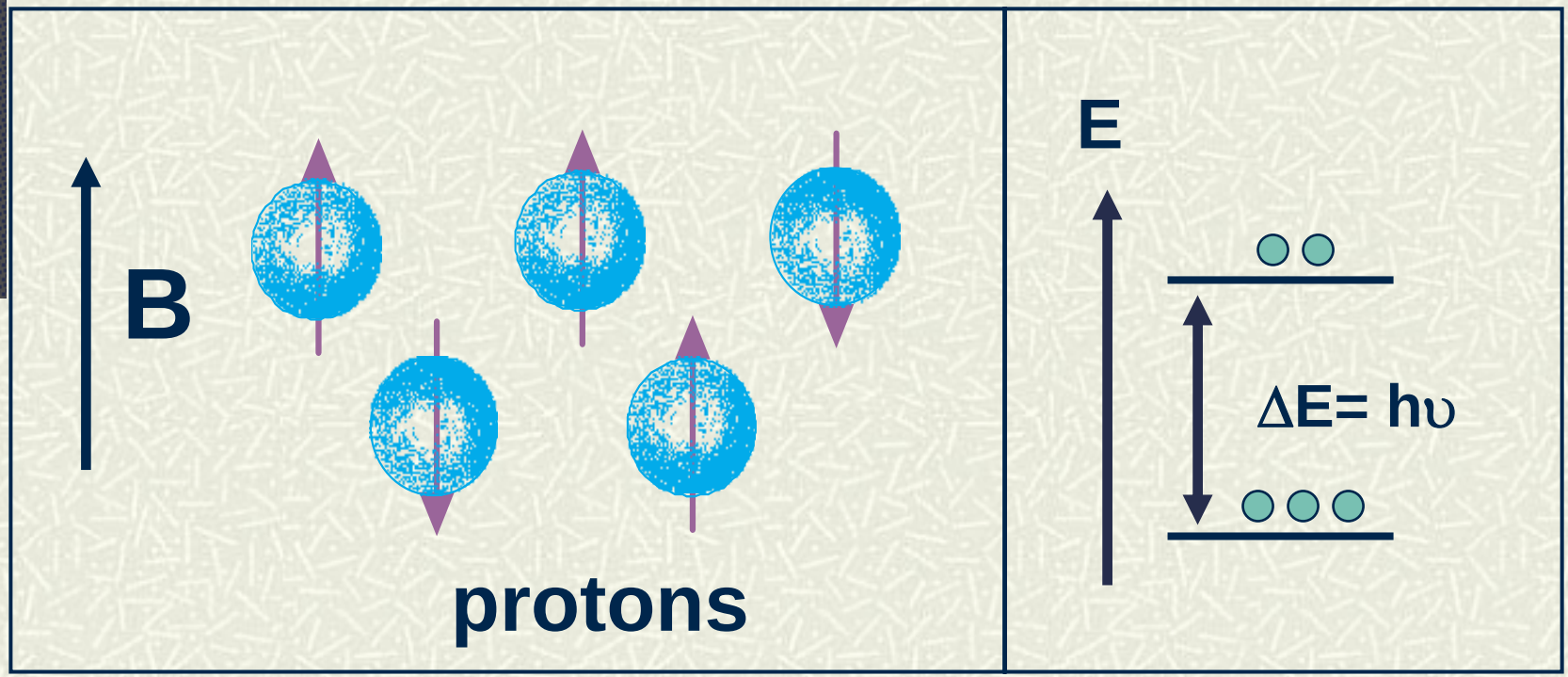
RESONANCE

A magnet, a glass of water,

and a radio wave source and detector….

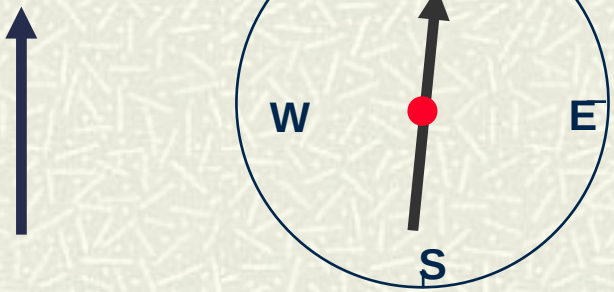
What is NMR?
Nuclear magnetism





$(N\uparrow - N\downarrow)/N_{TOT} = 1 - \exp(-\Delta E/kT)$
$\approx 10^{-4}$

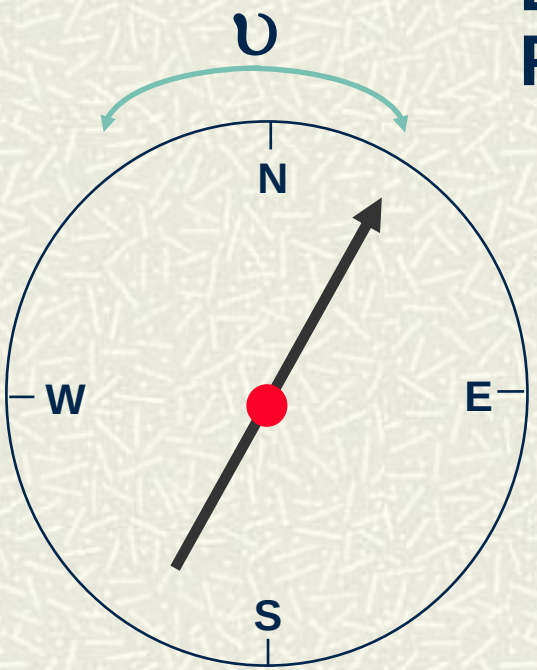
Earth's Field



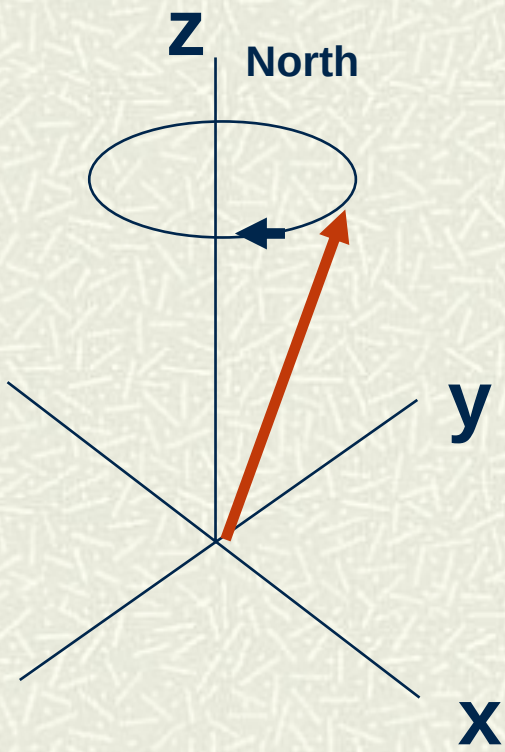
compass

Wald, fMRI MR Physics

Compass needles



Earth's Field

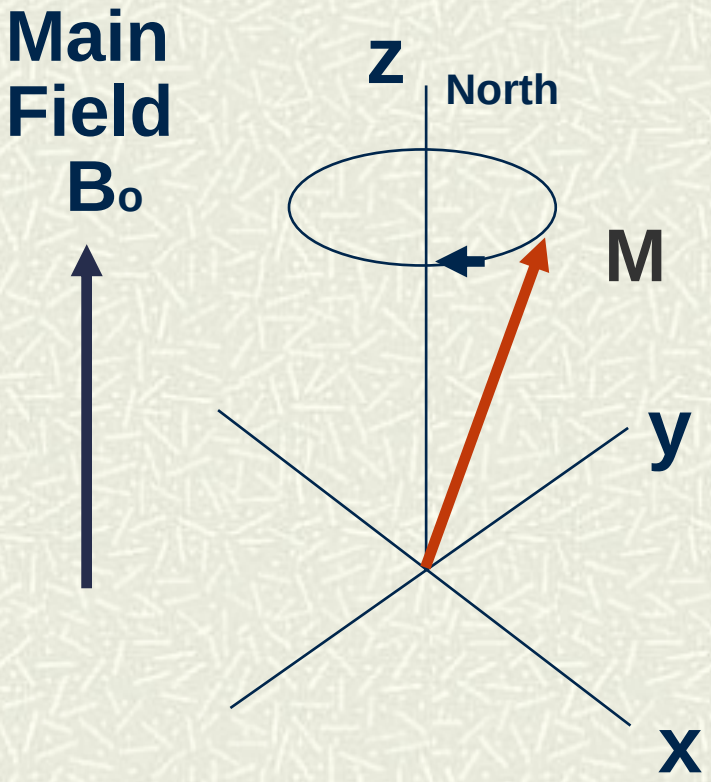


Main Field B_o

Freq = γ B

42.58 MHz/T

Gyroscopic motion



- **Proton has magnetic moment**
- **Proton has spin (angular momentum)**

>>gyroscopic precession

$$\upsilon = \gamma B_o$$

Larmor precession freq. = 42.58 MHz/T

EXCITATION **:** Displacing the spins from Equilibrium (North)

Problem: It must be moving for us to detect it.

Solution: knock out of equilibrium so it oscillates

How? 1) Tilt the magnet or compass suddenly

2) Drive the magnetization (compass needle) with a periodic magnetic field

Excitation: Resonance

Why does only one frequency efficiently tip protons?

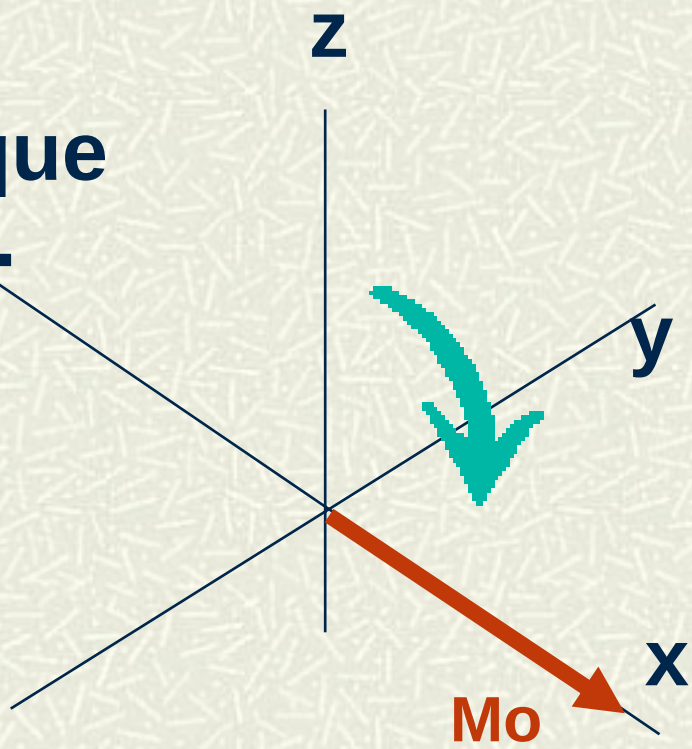
Resonant driving force.

It's like pushing a child on a swing in time with the natural oscillating frequency.

z is "longitudinal" direction
x-y is "transverse" plane

Static Field, B0

RF Field (B_1) applies a torque to the spins…

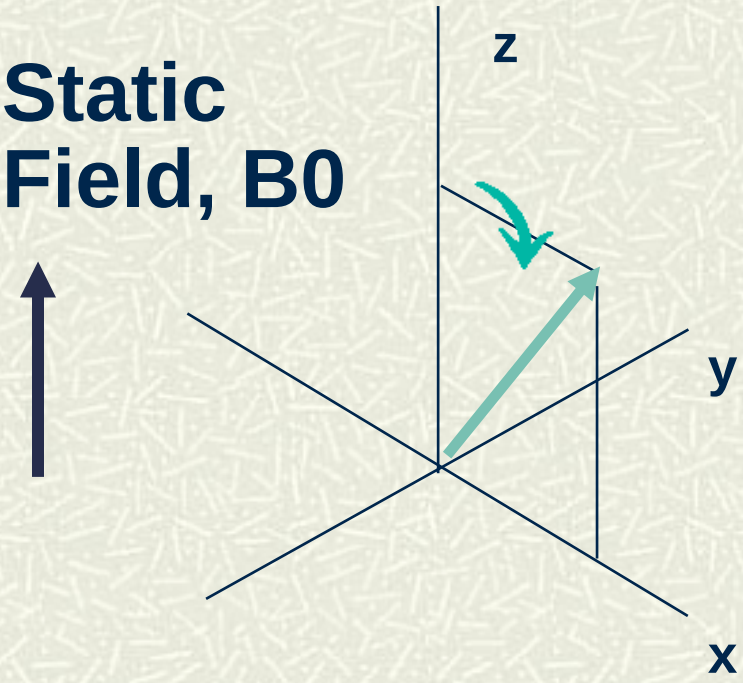


Applied RF Field (B_1)

The RF pulse rotates Mo the about applied field

"Exciting" the Magnetization: tip angle

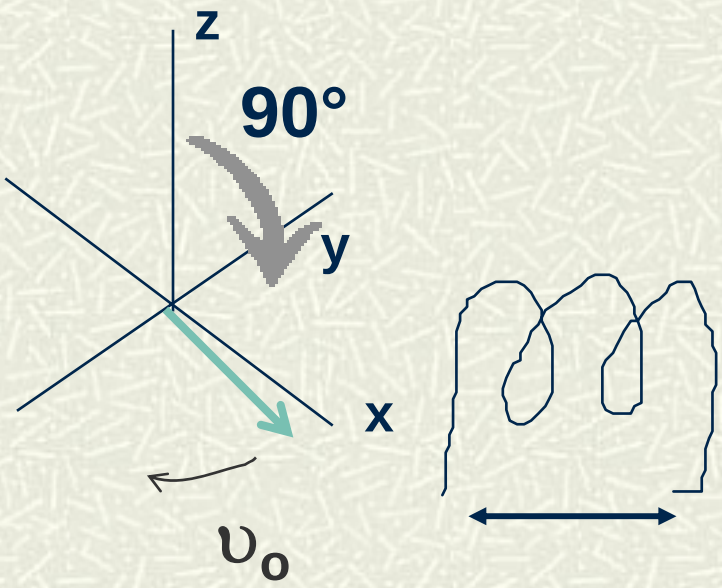
Static Field, B0



45°

90°

Detecting the Magnetization: Faraday's Law



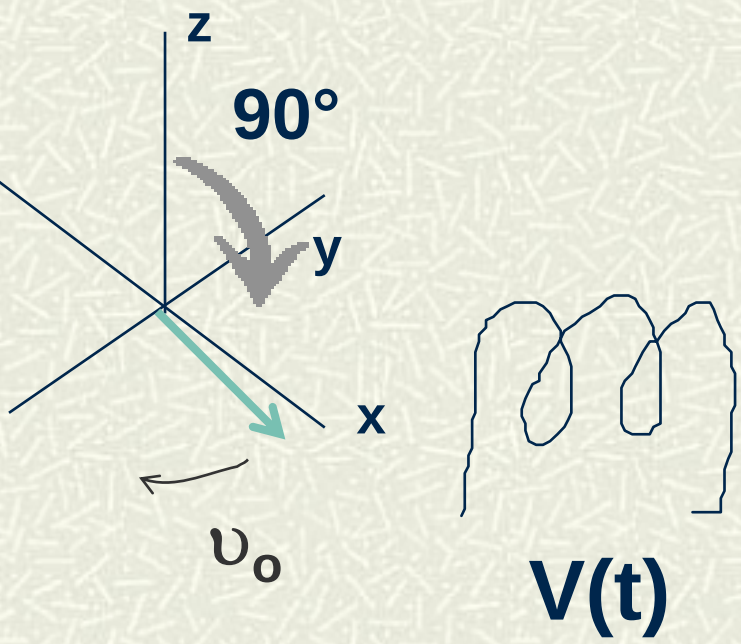
A moving bar magnet induces a Voltage in a coil of wire. (a generator…)

The RF coil design is the #1 determinant of the system SNR

$$V(t) = -d\Phi/dt$$

$$\Phi = n\, B_{spins}\, A$$

Detecting the NMR: the noise

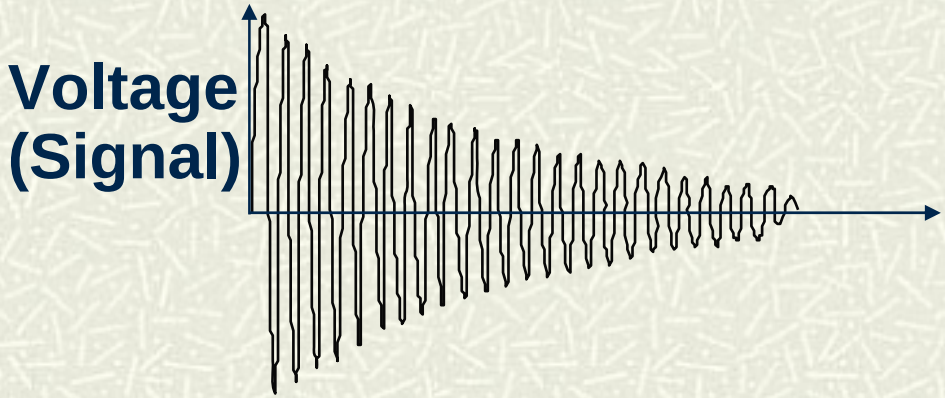


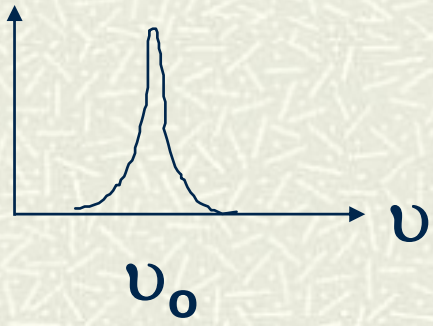
Noise comes from electrical losses in the resistance of the coil or electrical losses in the tissue.

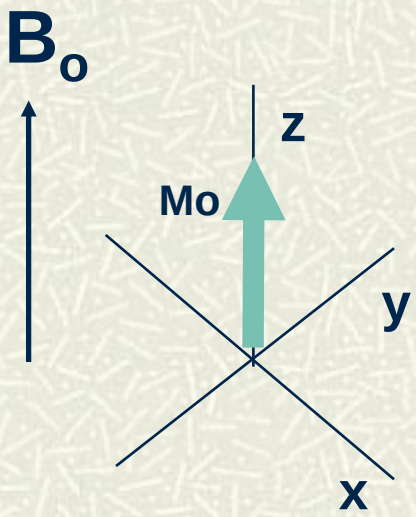
For a resistor:
$P_{noise} = 4kTRB$

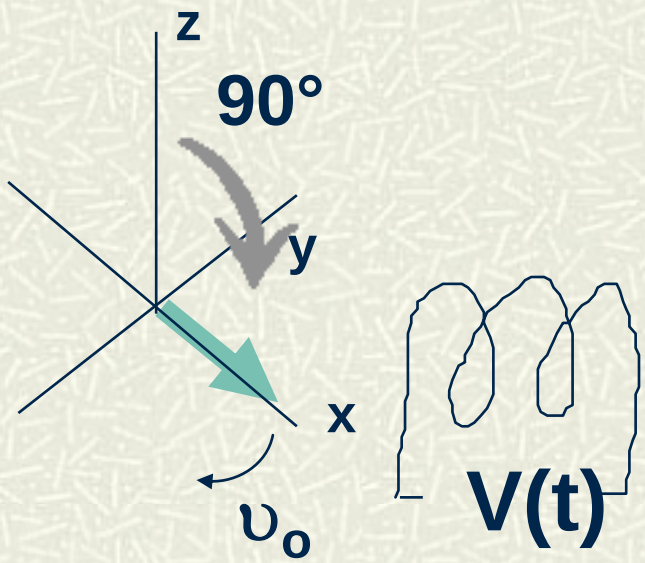
- Noise is white.
  >>Noise power α bandwidth
- Noise is spatially uniform.
- R is dominated by the tissue. >> big coil is bad.

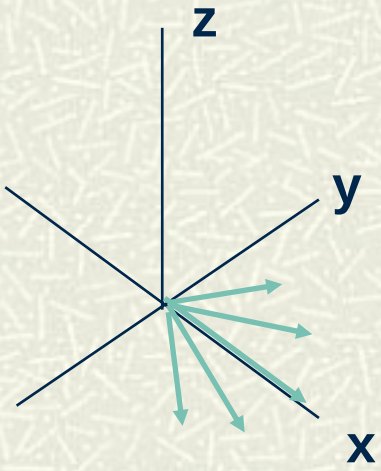
The NMR Signal











Wald, fMRI MR Physics

Signal to Noise Ratio in MRI

- Most important piece of hardware is the RF coil.
- SNR α voxel volume (# of spins)
- SNR α SQRT(total time of data collection)
- SNR depends on the amount of signal you **throw away** to better visualize the brain (gain image contrast)

Physical Foundations of MRI

NMR: 60 year old phenomena that generates the signal from water that we detect.

MRI: using NMR signal to generate an image

Three magnetic fields (generated by 3 coils)

1) static magnetic field Bo
2) RF field that excites the spins B1
3) gradient fields that encode spatial info G_x, G_y, G_z

Three Steps in MR:

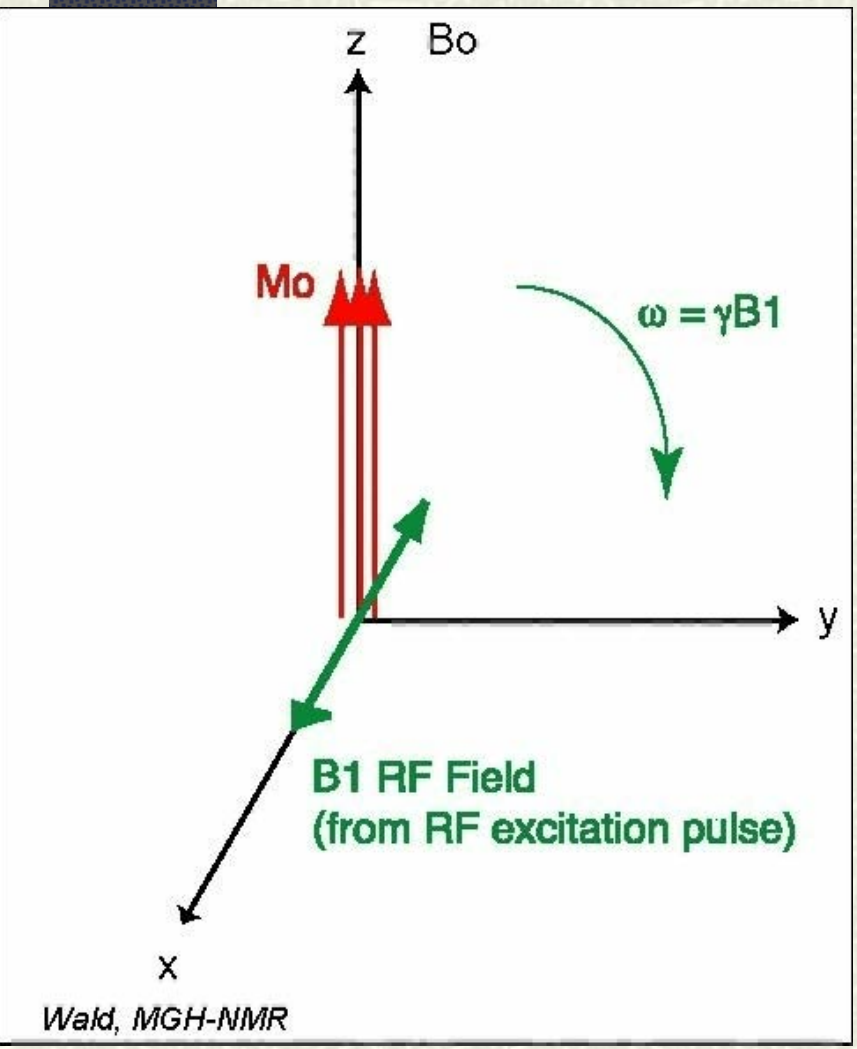
0) Equilibrium (magnetization points along Bo)

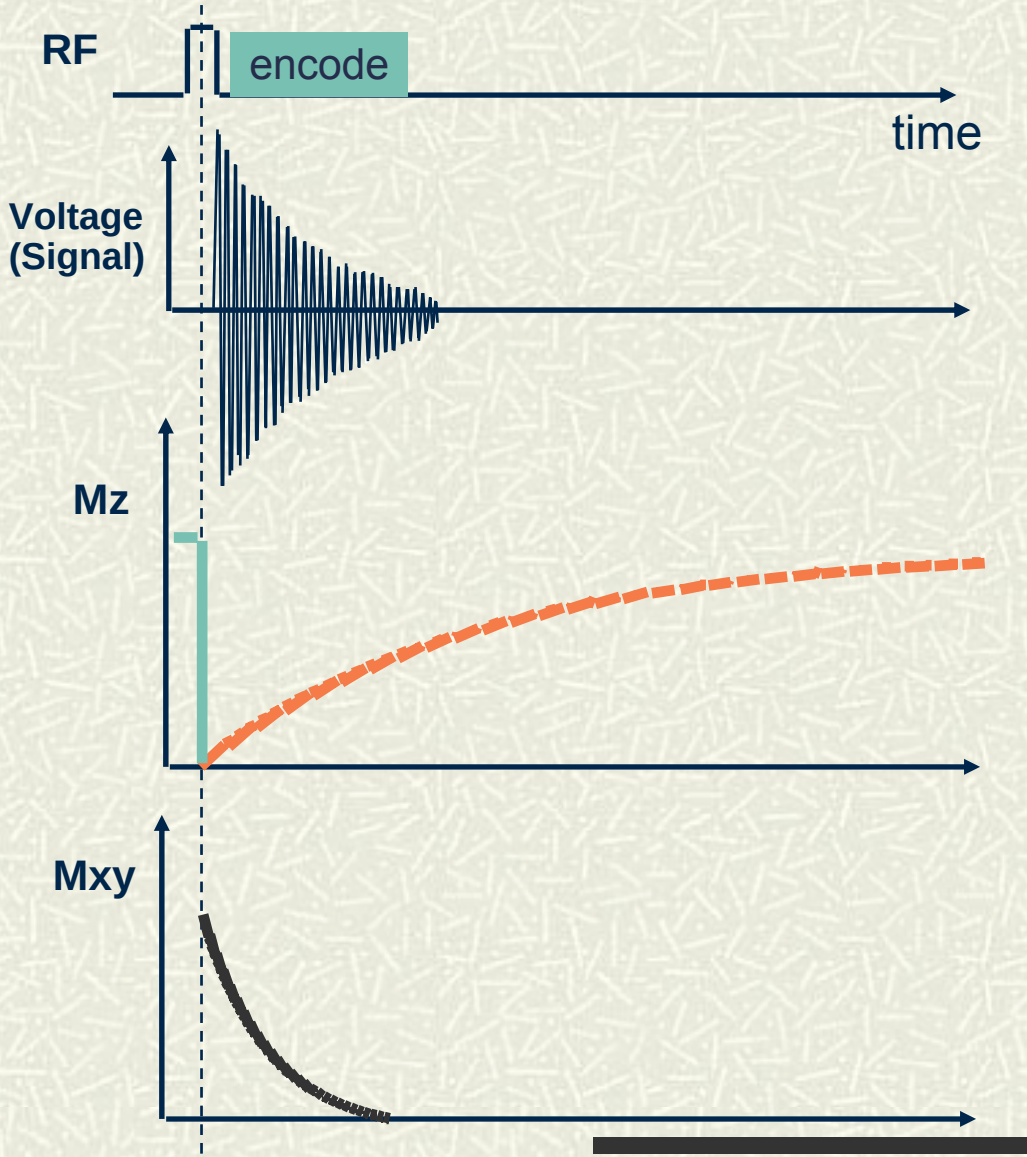
1) RF Excitation (tip magn. away from equil.)

2) Precession induces signal,
dephasing (timescale = T2, T2*).

3) Return to equilibrium (timescale = T1).

Magnetization vector during MR





Wald, fMRI MR Physics

Three places in process to make a measurement (image)

0) Equilibrium (magnetization points along Bo)

1) RF Excitation (tip magn. away from equil.)

proton density weighting

2) Precession induces signal, allow to dephase for time TE.

T2 or T2* weighting

3) Return to equilibrium (timescale =T1).

T1 Weighting

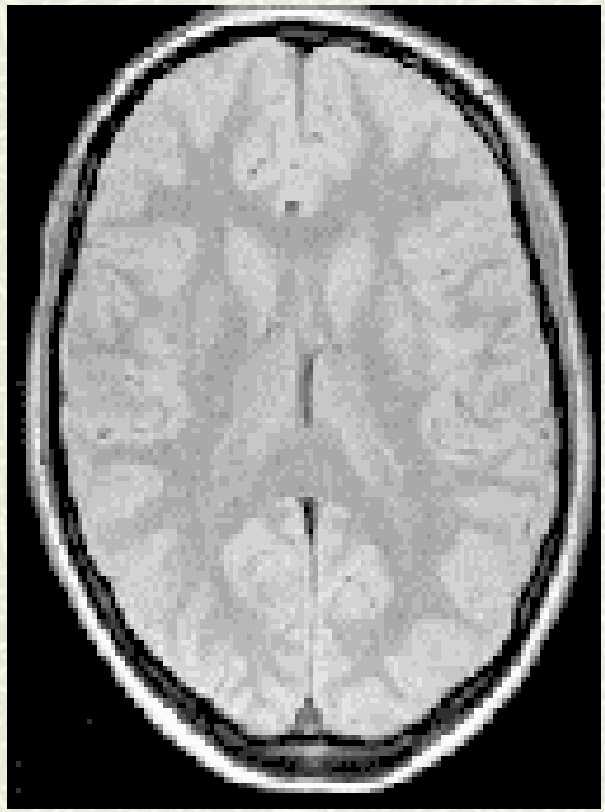
Contrast in MRI: proton density

Form image immediately after excitation (creation of signal).

Tissue with more protons per cc give more signal and is thus brighter on the image.

No chance to dephase, thus no differences due to different tissue T2 values.

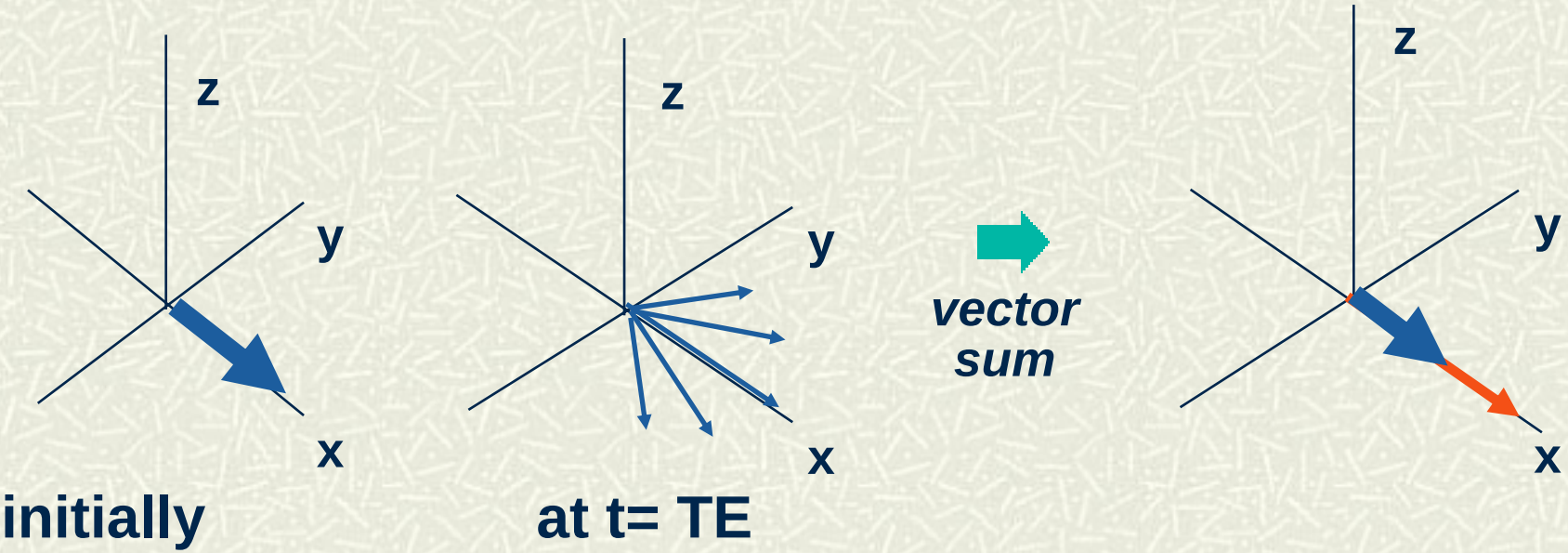
Magnetization starts fully relaxed (full Mz), thus no T1 weighting.



T2*-Dephasing

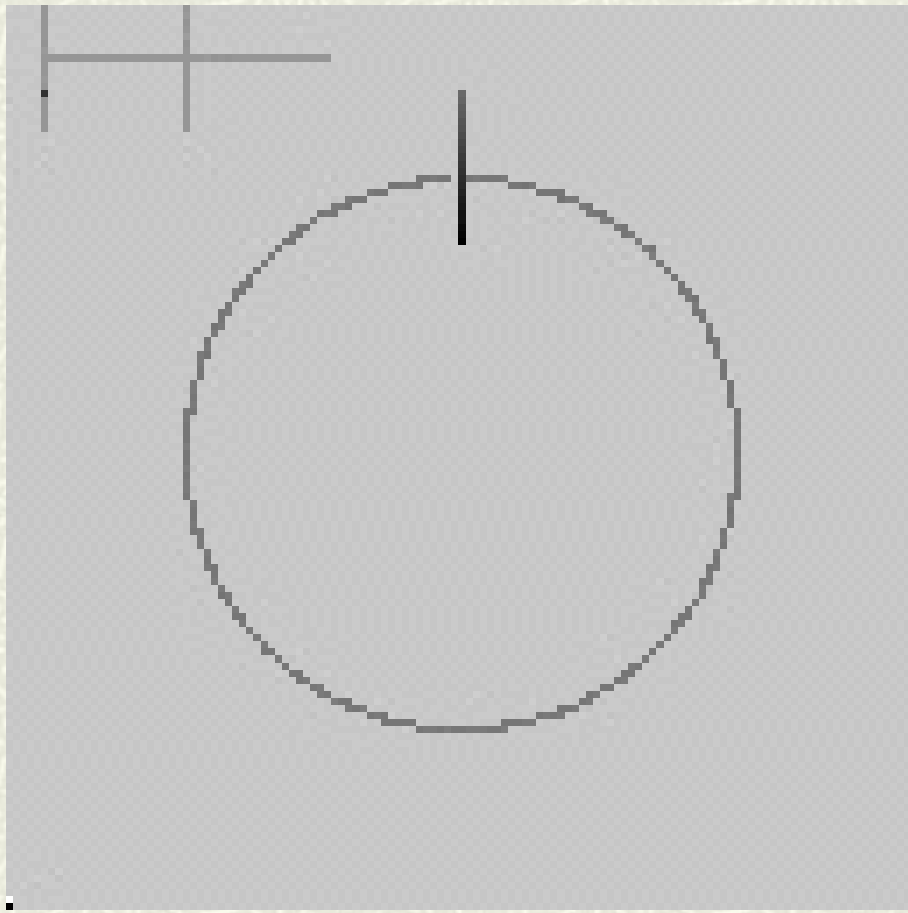
Wait time TE after excitation before measuring M.

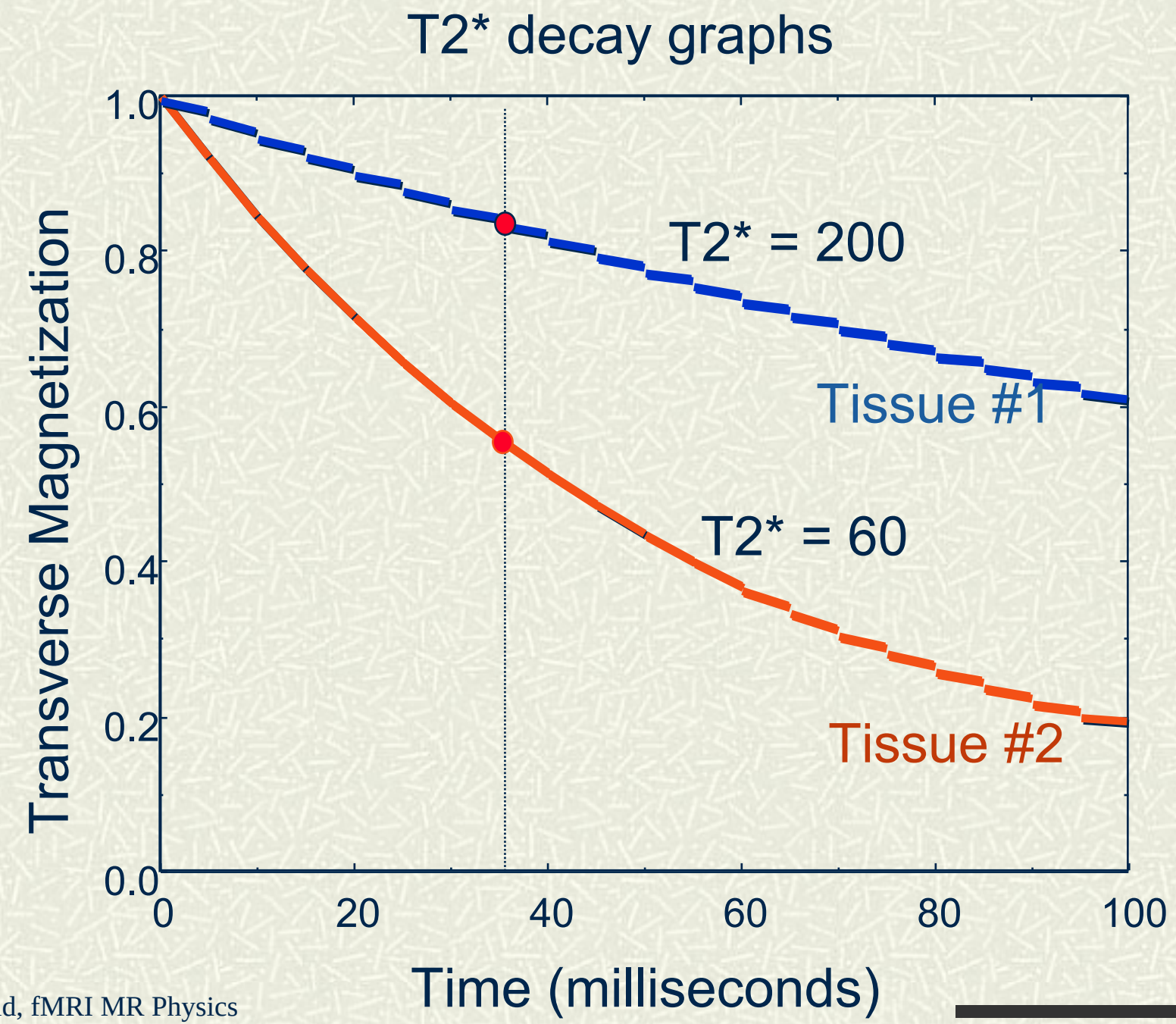
Shorter T2* spins have dephased



T2* Dephasing

Just the tips of the vectors…



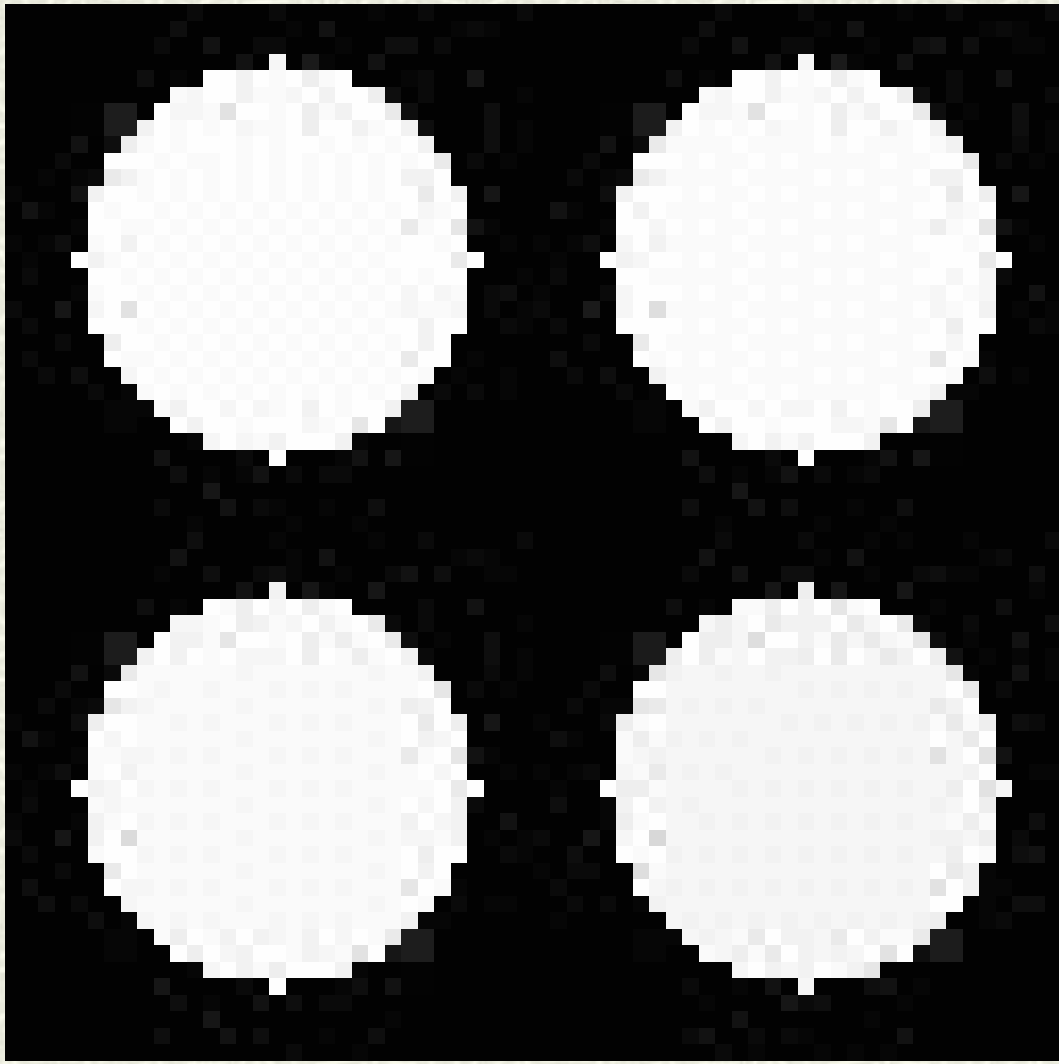

T2* decay graphs
Transverse Magnetization
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
Time (milliseconds)
T2* = 200
Tissue #1
T2* = 60
Tissue #2

T2* Weighting

Phantoms with four different T2* decay rates...

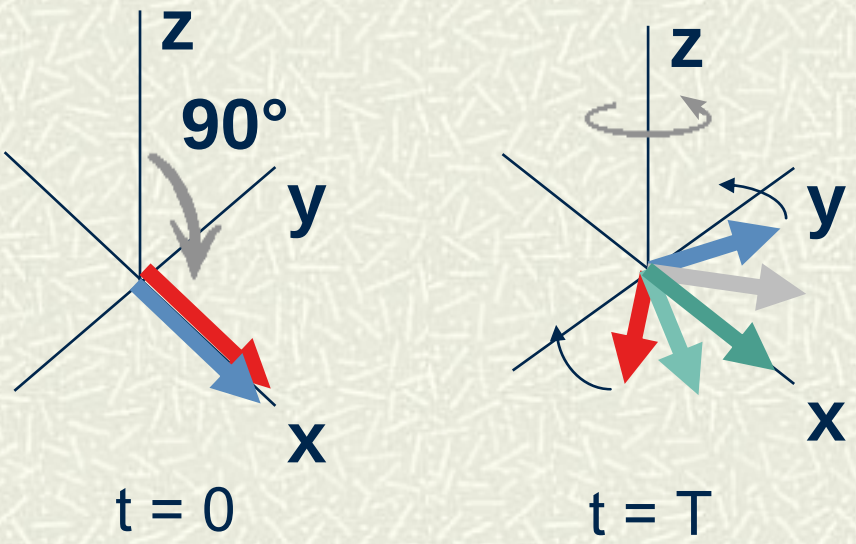
There is no contrast difference immediately after excitation, must wait (but not too long!).

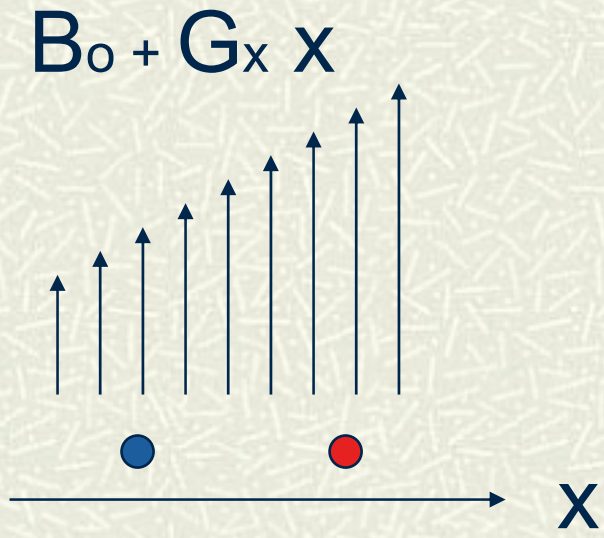
Choose TE for max. inten. difference.



Gradient Echo (T2* contrast)

Dephasing is entirely from a spatial difference in the applied static fields.

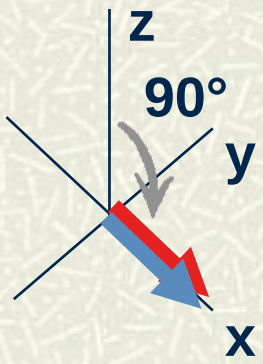




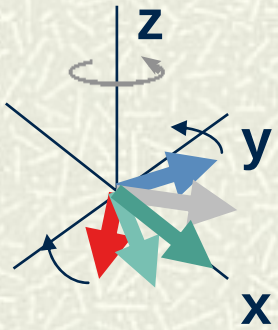
Red arrows processes faster due to its higher local field

Gradient Echo (T2* contrast)

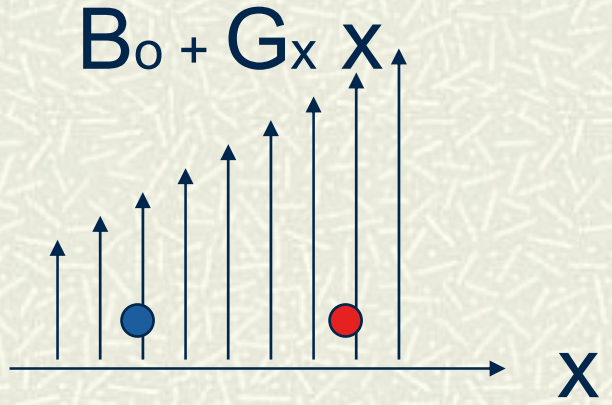
Dephasing is entirely from a spatial difference in the applied static fields.

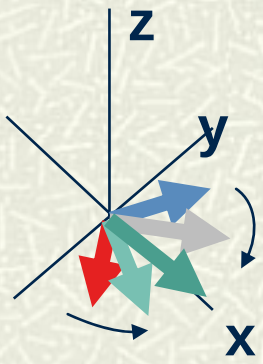


t = 0

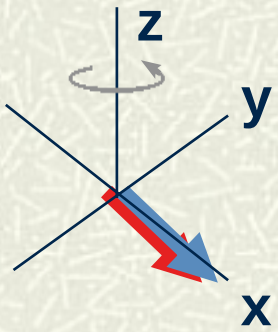


t = T

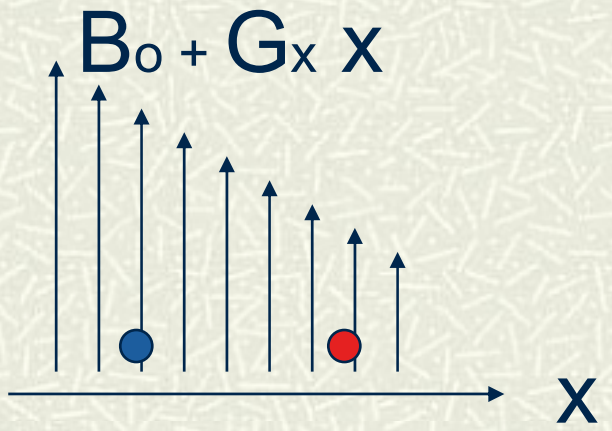




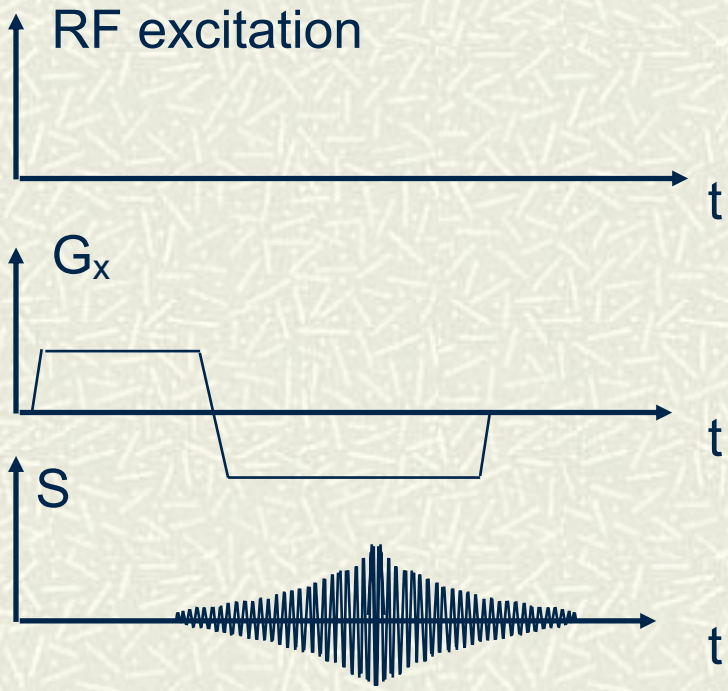
t = T



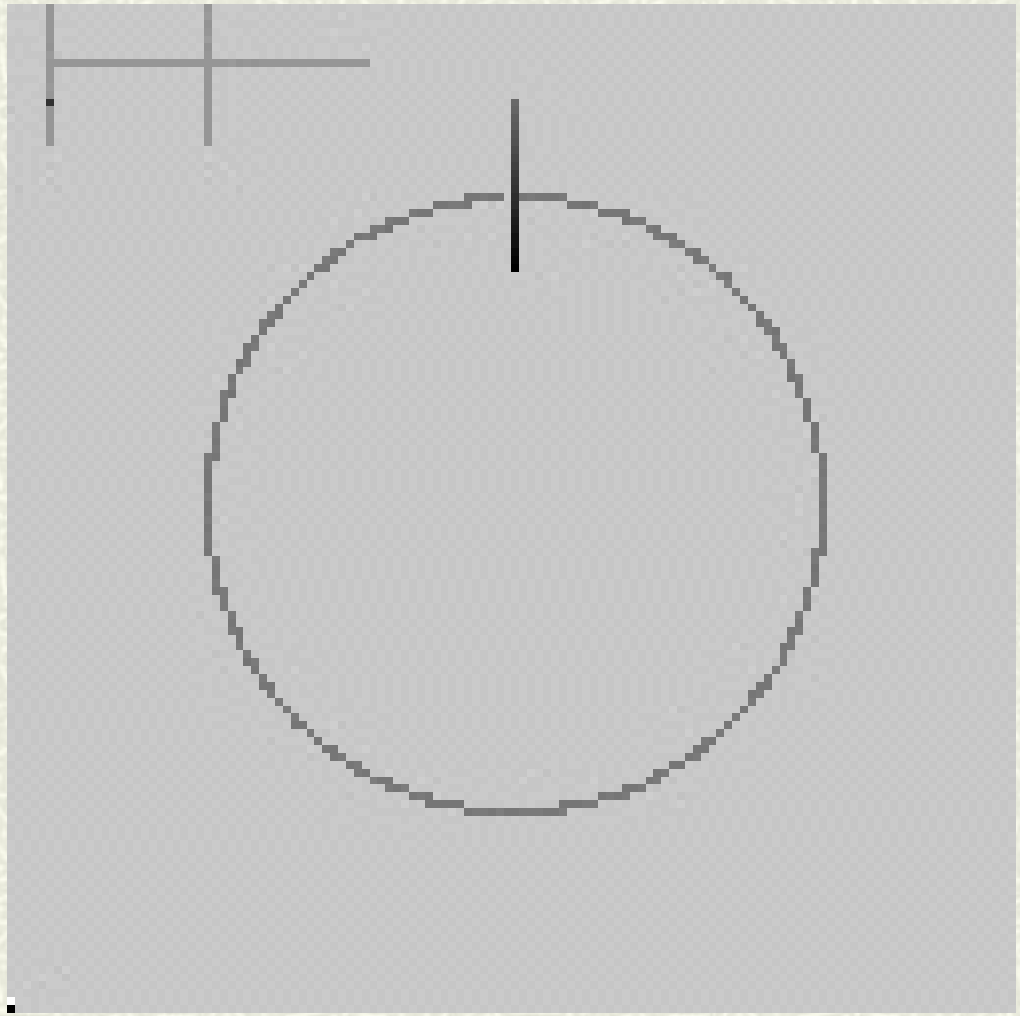
t = 2T



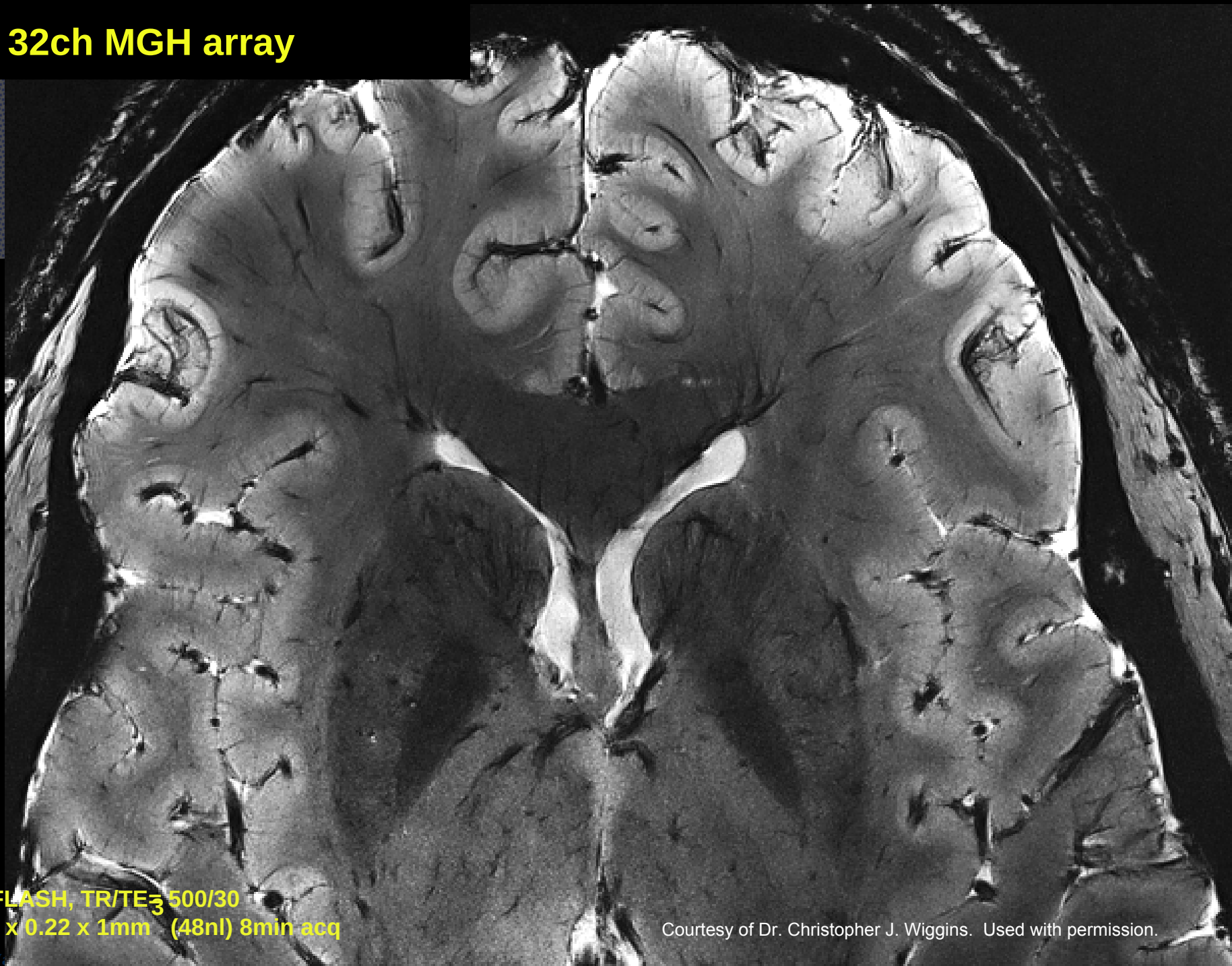
Gradient Echo



Boring!



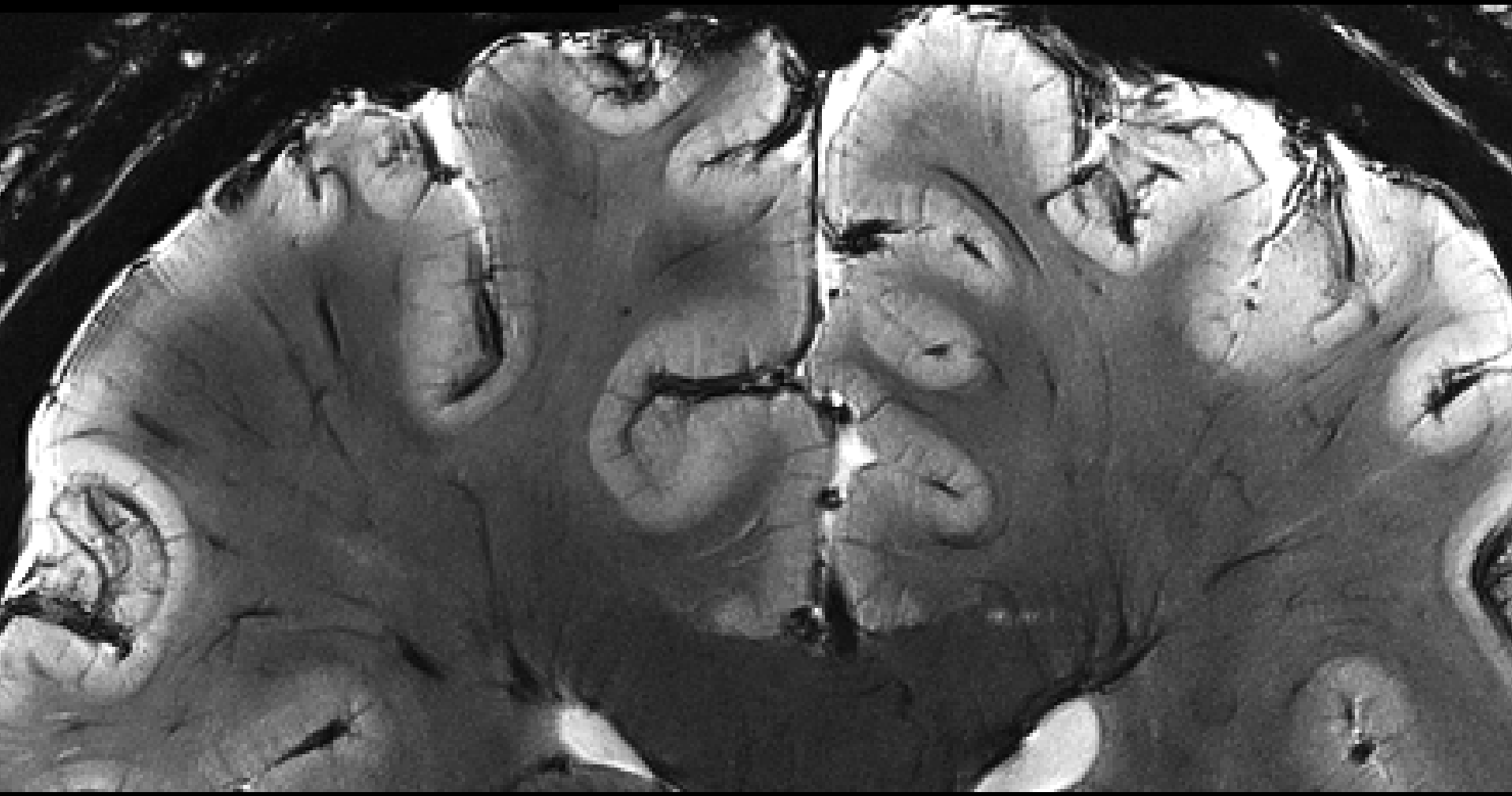
7T 32ch MGH array



2D FLASH, TR/TE=500/30
0.22 x 0.22 x 1mm (48nl) 8min acq

Courtesy of Dr. Christopher J. Wiggins. Used with permission.

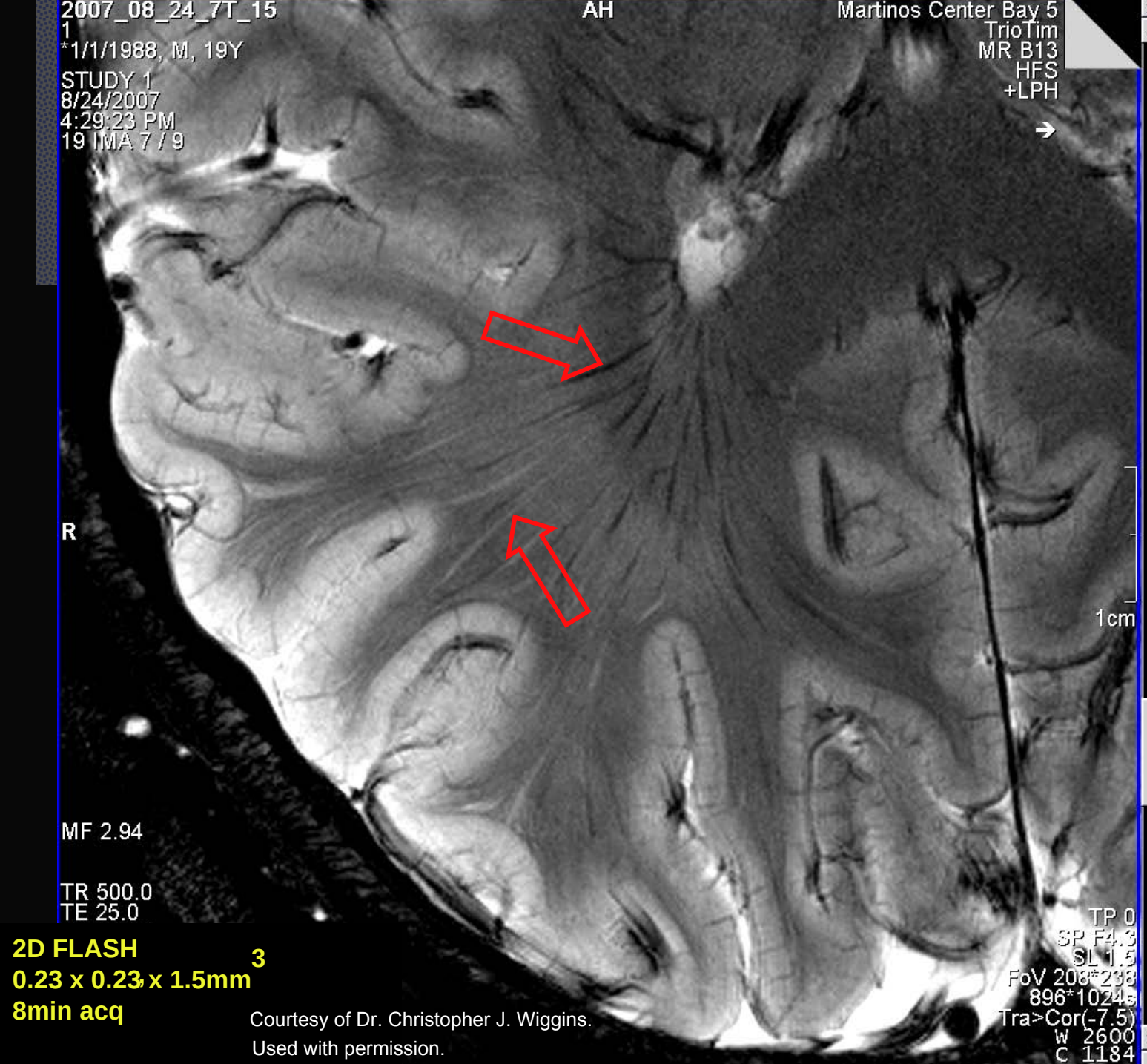
7T 32ch MGH array



Courtesy of Dr. Christopher J. Wiggins. Used with permission.

G. Wiggins,
C. Wiggins,
Martinos Center MGH

2D FLASH, TR/TE= 500/30
0.22 x 0.22 x 1mm^3 (48nl) 8min acq



7 Tesla
230um

2D FLASH
0.23 x 0.23 x 1.5mm^3
8min acq

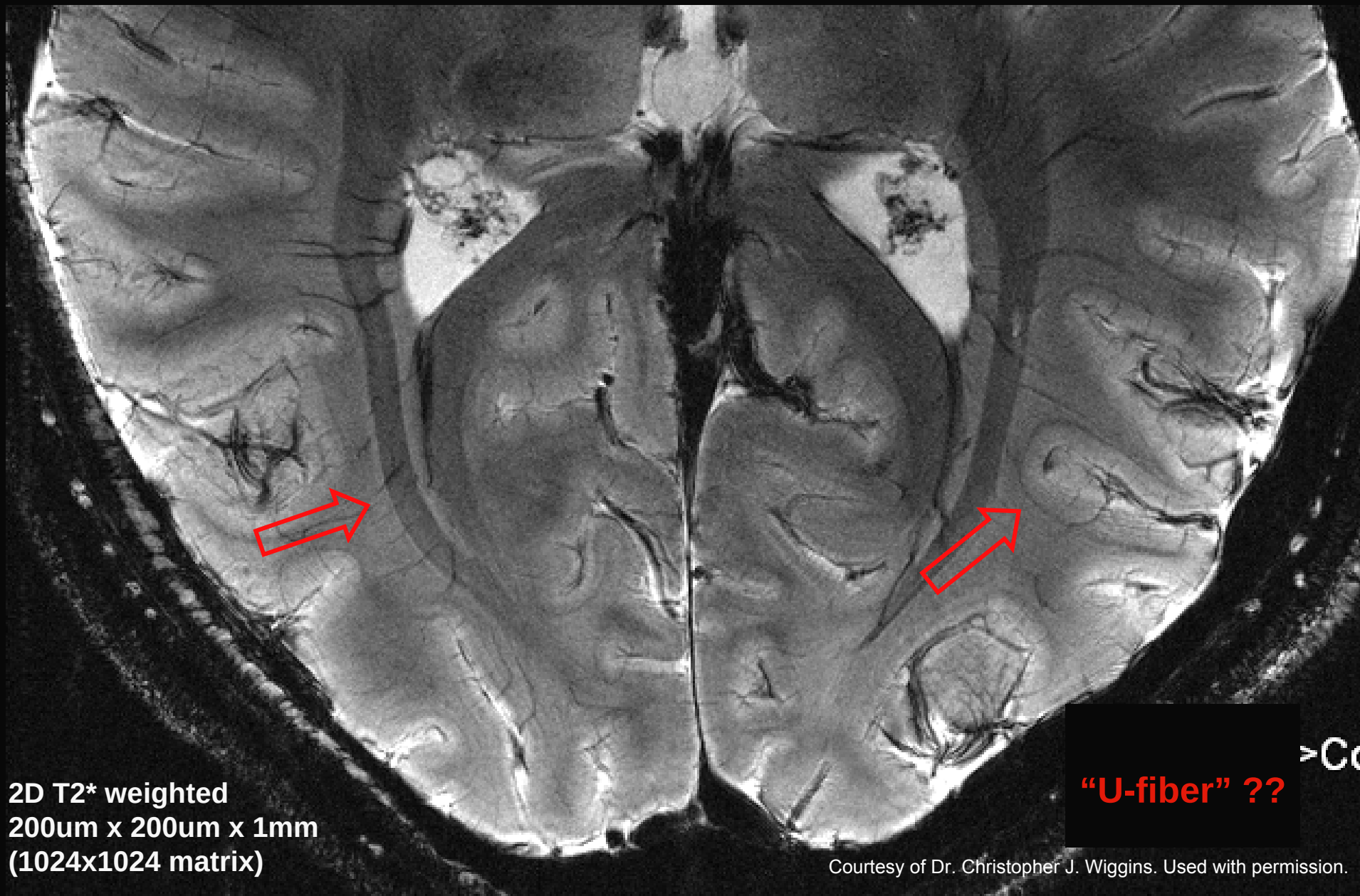
Courtesy of Dr. Christopher J. Wiggins.
Used with permission.

7 Tesla
230um

2D FLASH,
0.23 x 0.23 x 1.5mm^3
8min acq

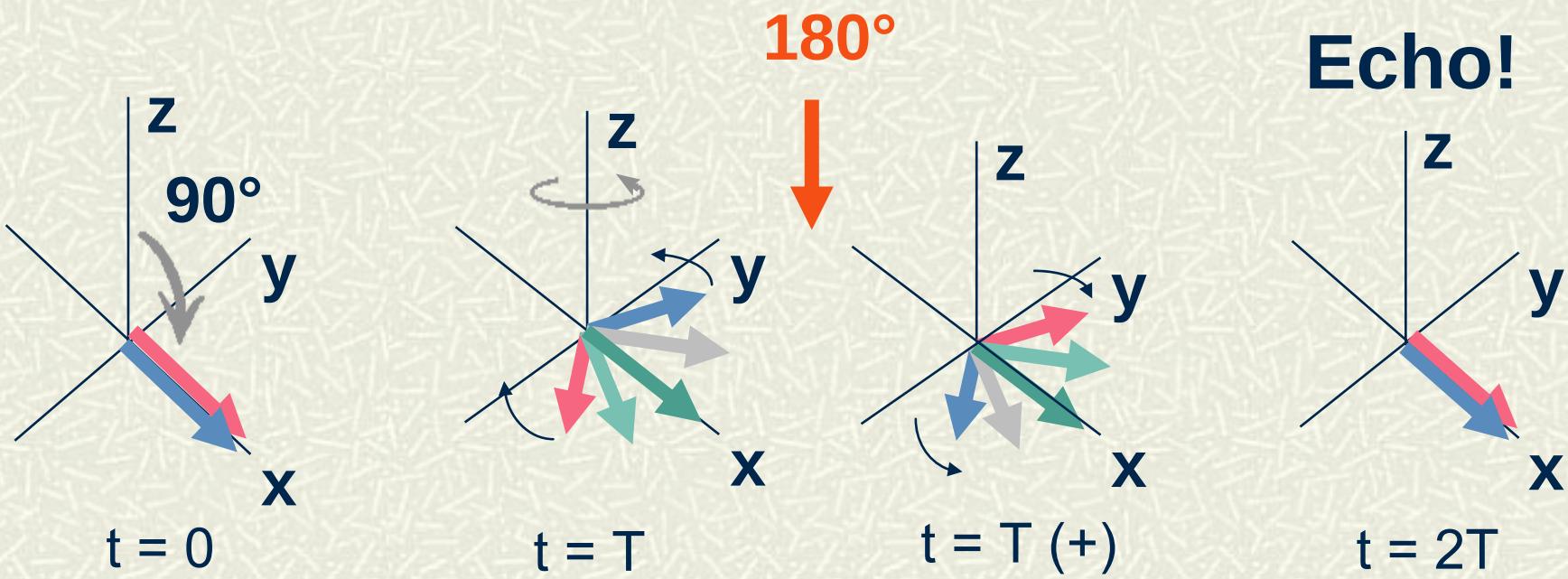
Courtesy of Dr. Christopher J. Wiggins.
Used with permission.

7 T, 32ch 200um x 200um x 1mm



Spin Echo (T2 contrast)

Some dephasing can be refocused because its due to static fields.



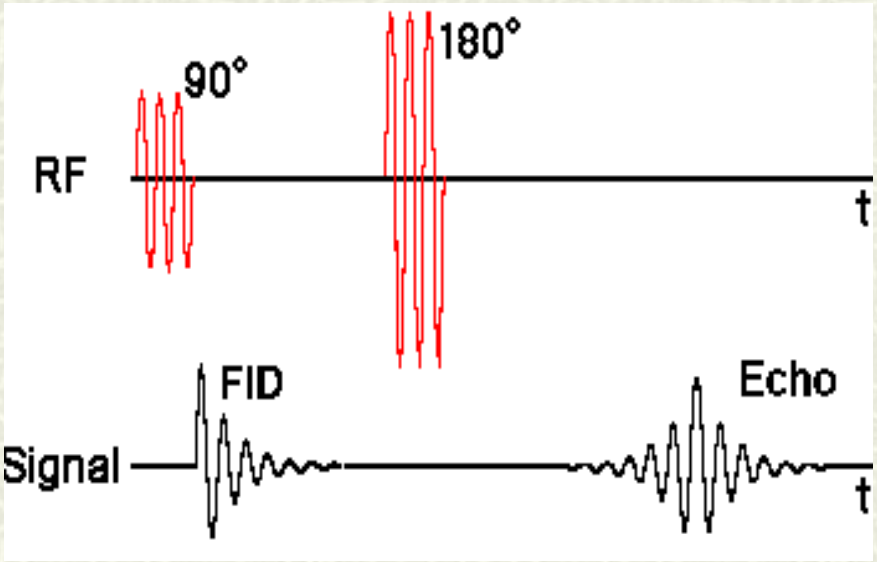
Blue arrows precesses faster due to local field inhomogeneity than red arrow

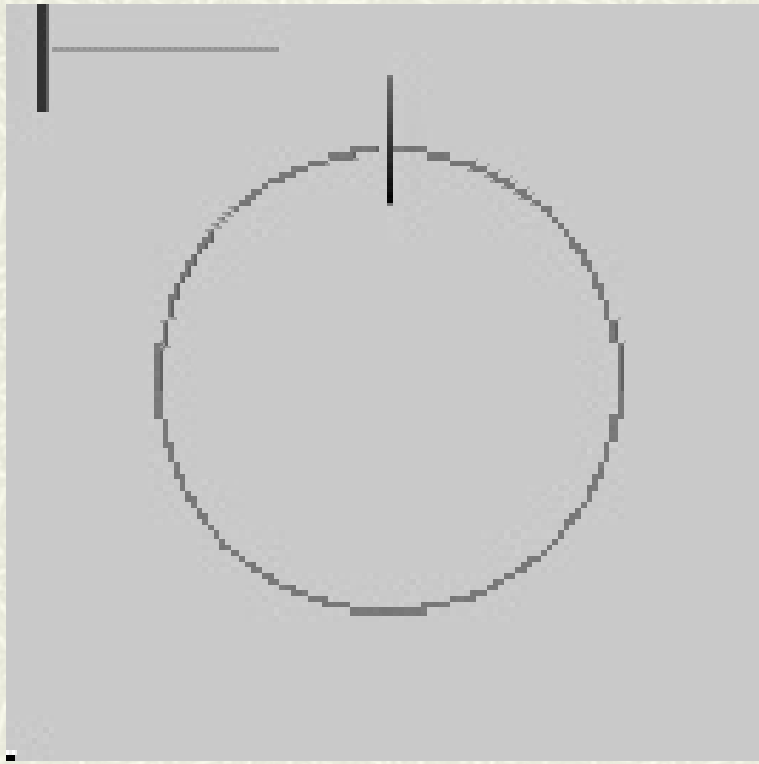
Spin Echo

180° pulse only helps cancel static inhomogeneity

The “runners” can have static speed distribution.

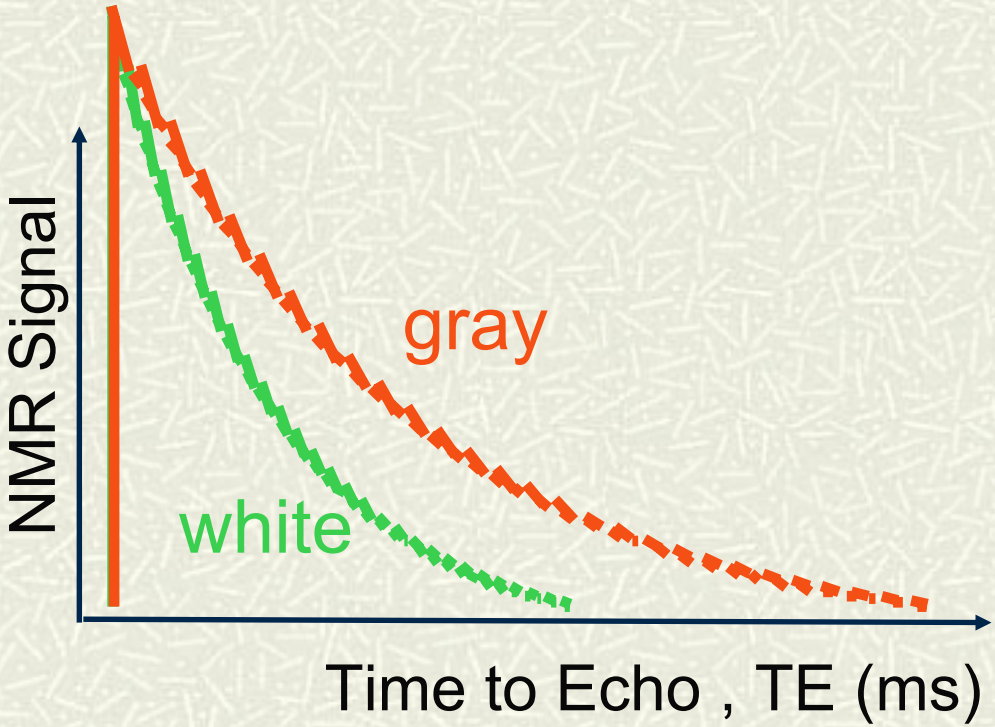
If a runner trips, he will not make it back in phase with the others.





Wald, fMRI MR Physics

T2 weighed spin echo image



Other contrast for MRI

In brain: (gray/white/CSF/fat)

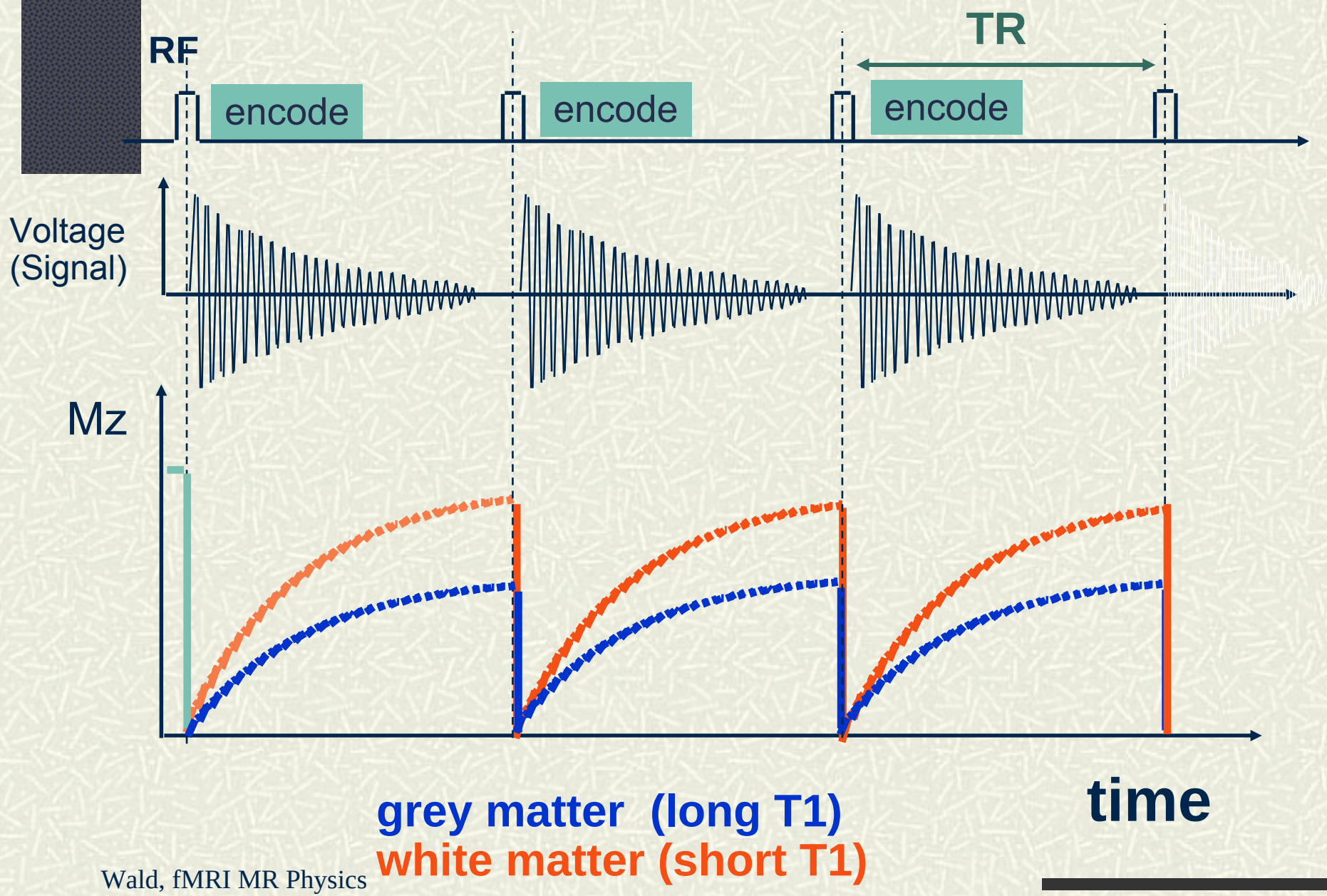
Proton density differ ~ 20%

T1 relaxation differ ~ 2000%

How to exploit for imaging?

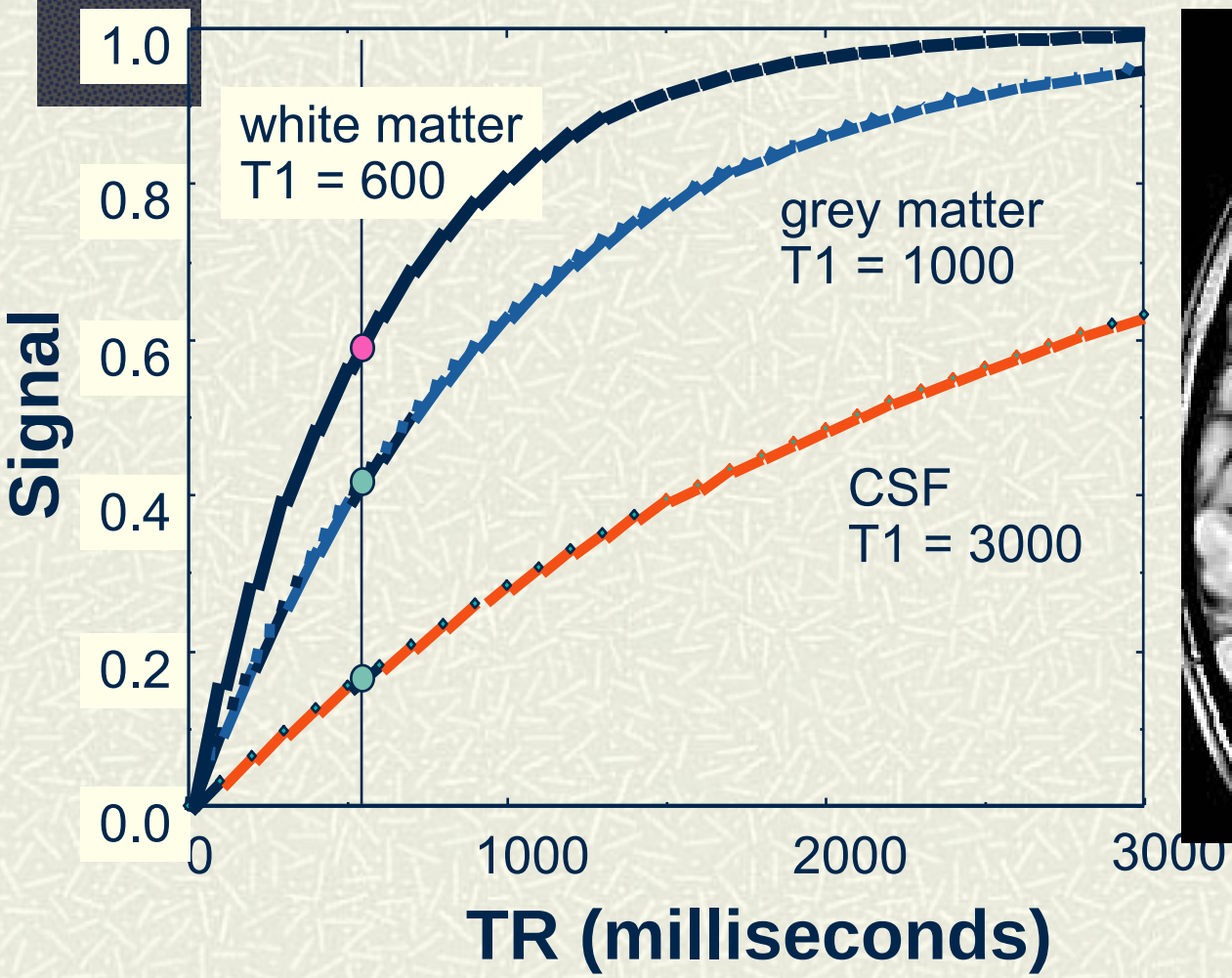
Vary repetition rate - TR

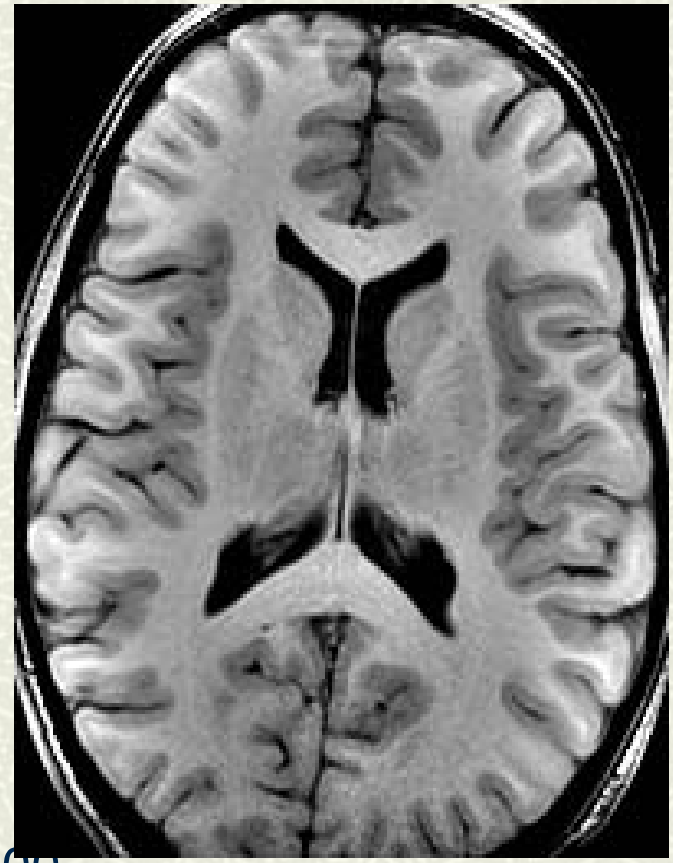
T1 weighting in MRI (w/ 90° excite)



Wald, fMRI MR Physics

T1-Weighting





T1 weighting in MRI (w/ 30° excite)

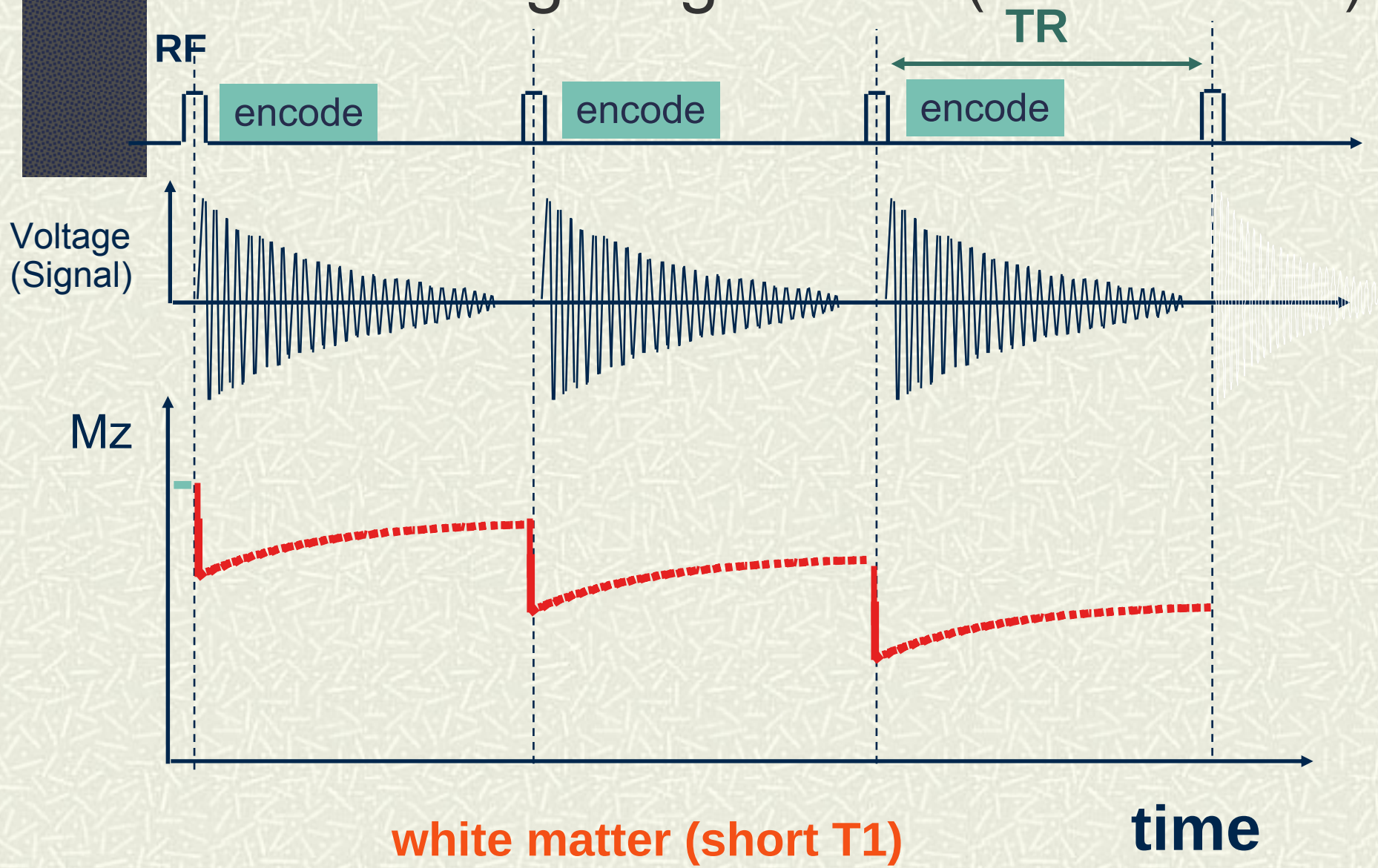
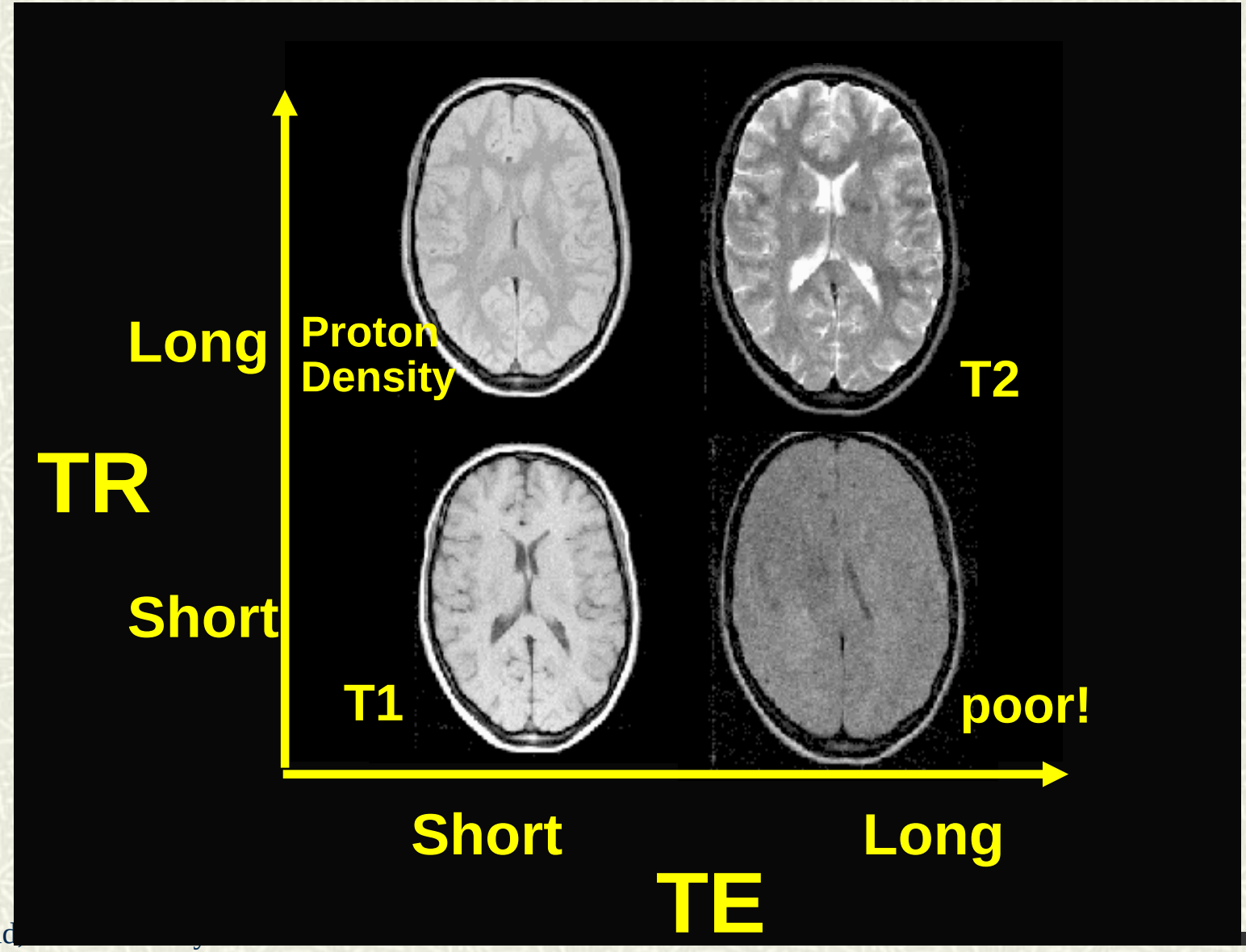


Image contrast summary: TR, TE



Source of T1 and T2 contrast in brain: Myelin content

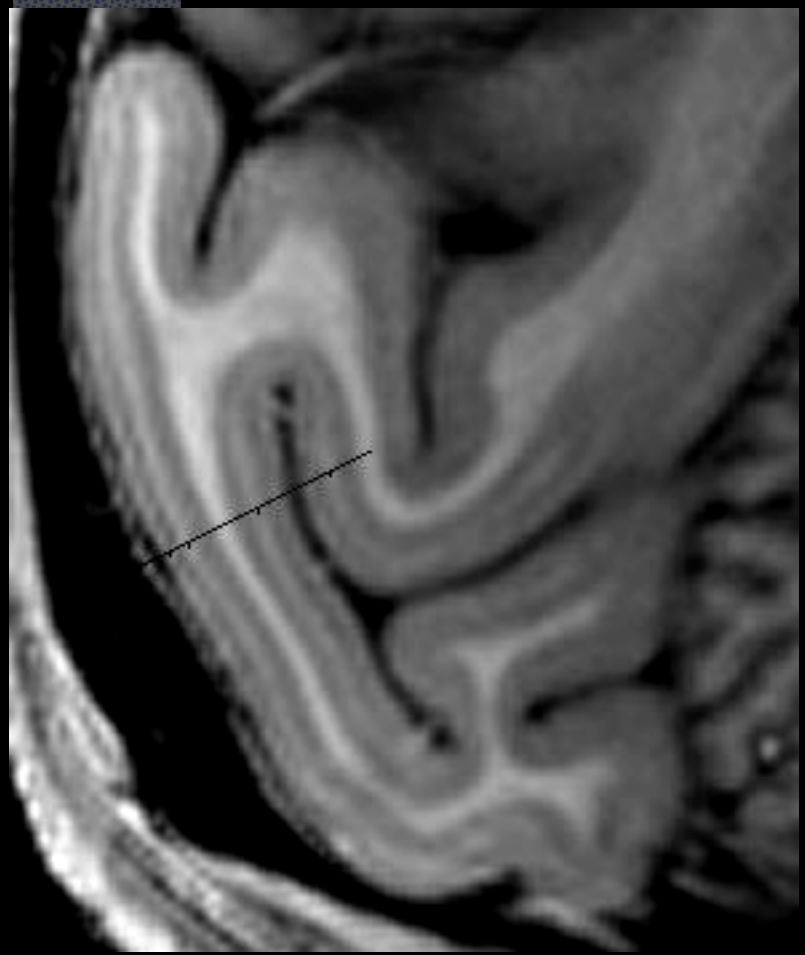
Image removed due to copyright restrictions.
Diagram showing the arrangement of nerve cells and fibers in layers and sublayers parallel to the surface in a vertical section through the human striate area or visual cortical center.

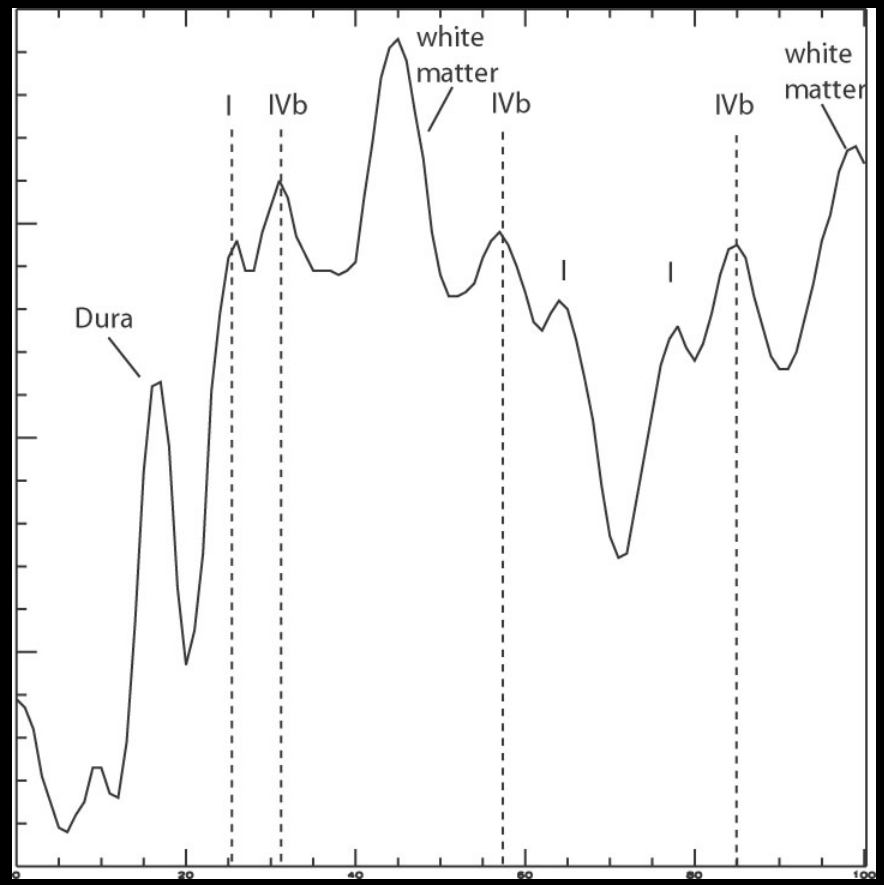
Determine functional boundaries based on MR strucure alone…

Nissel stain: cell bodies

Weigert stain: fibers

Cortical layers in Monkey at 7T





Intensity along line perpendicular To V1

MPRAGE 250um x 250um x 750um (4 hours)