Introduction to MRI Physics

Marta M Correia

MRC Cognition and Brain Sciences Unit

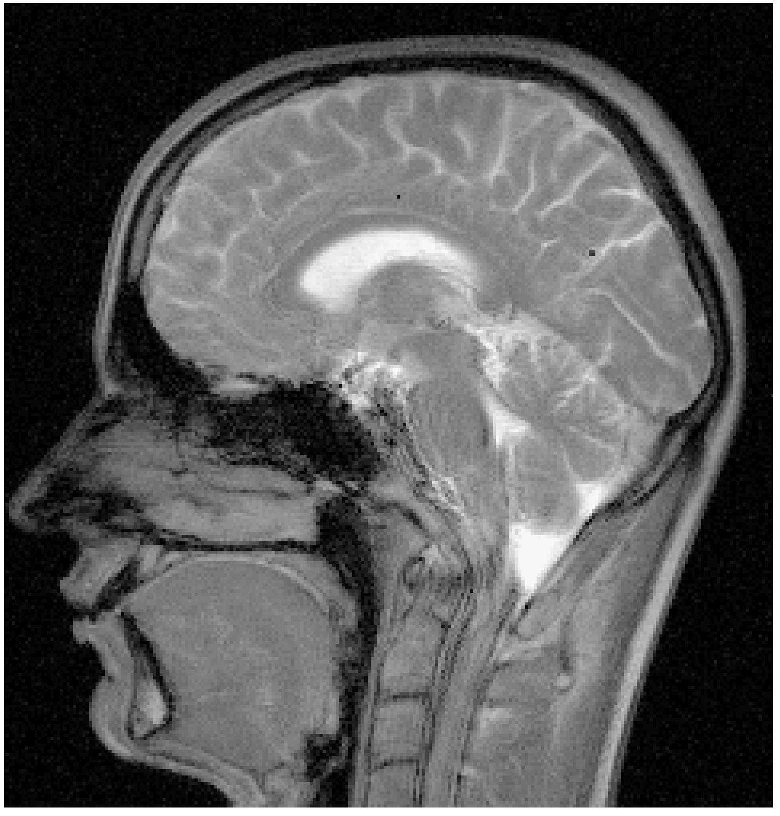
8th April 2019

Overview

- Nuclear Magnetic Resonance Imaging (NMR)
  - Basic Principles
  - Excitation, Relaxation and Signal
- Magnetic Resonance Imaging (MRI)
  - Spatial Encoding in MRI
  - Image formation and k-space
  - Image contrast
- Magnetic Resonance Spectroscopy (MRS)

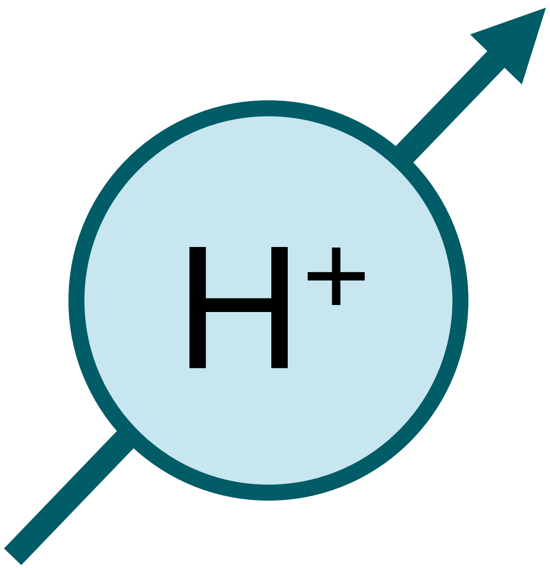
Part I:
Nuclear Magnetic Resonance
(NMR)

MR images: What do we see ?



- MRI images are usually based on the signal from protons
- A proton is the nucleus of the hydrogen atom
- Hydrogen is the most common element in tissue
- The signal from protons is due to their *spin*

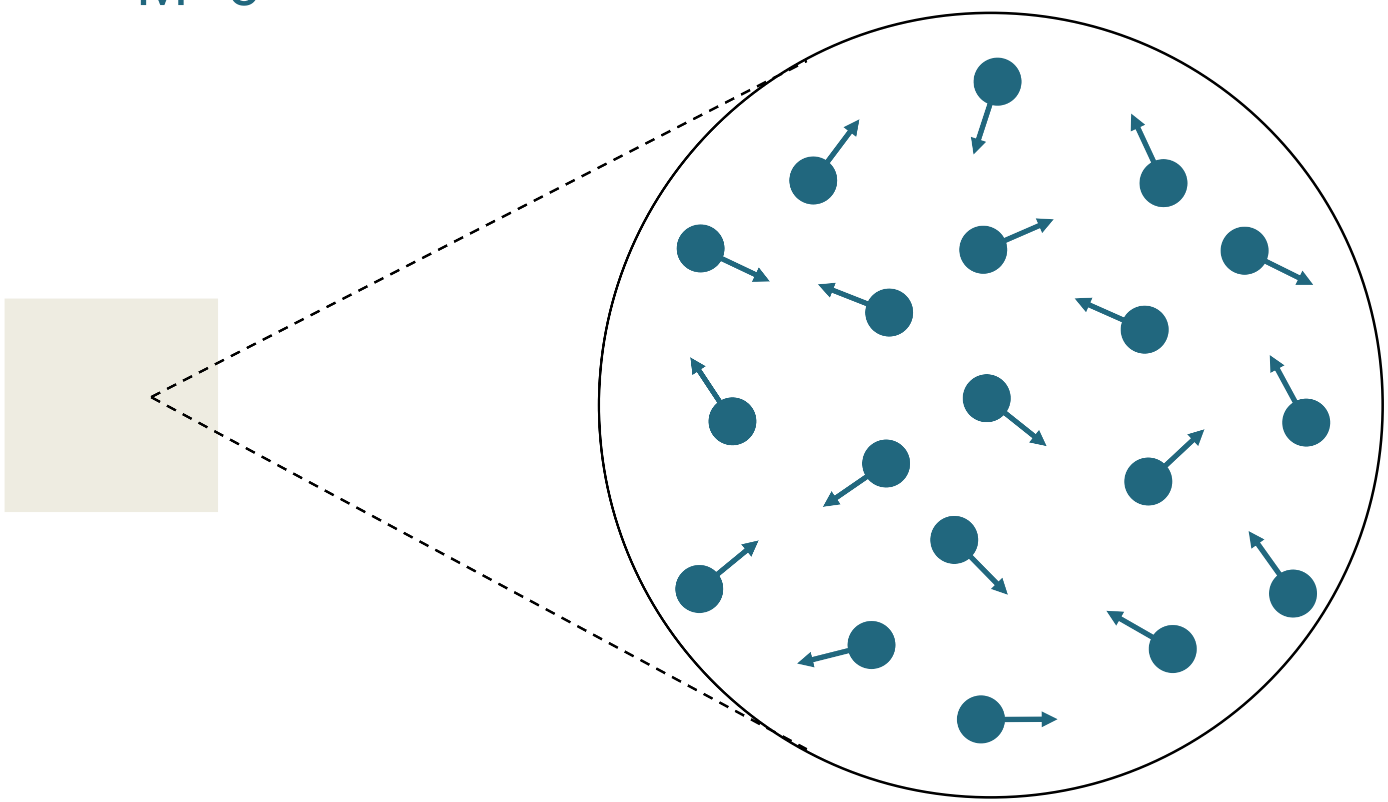
The Nuclear spin



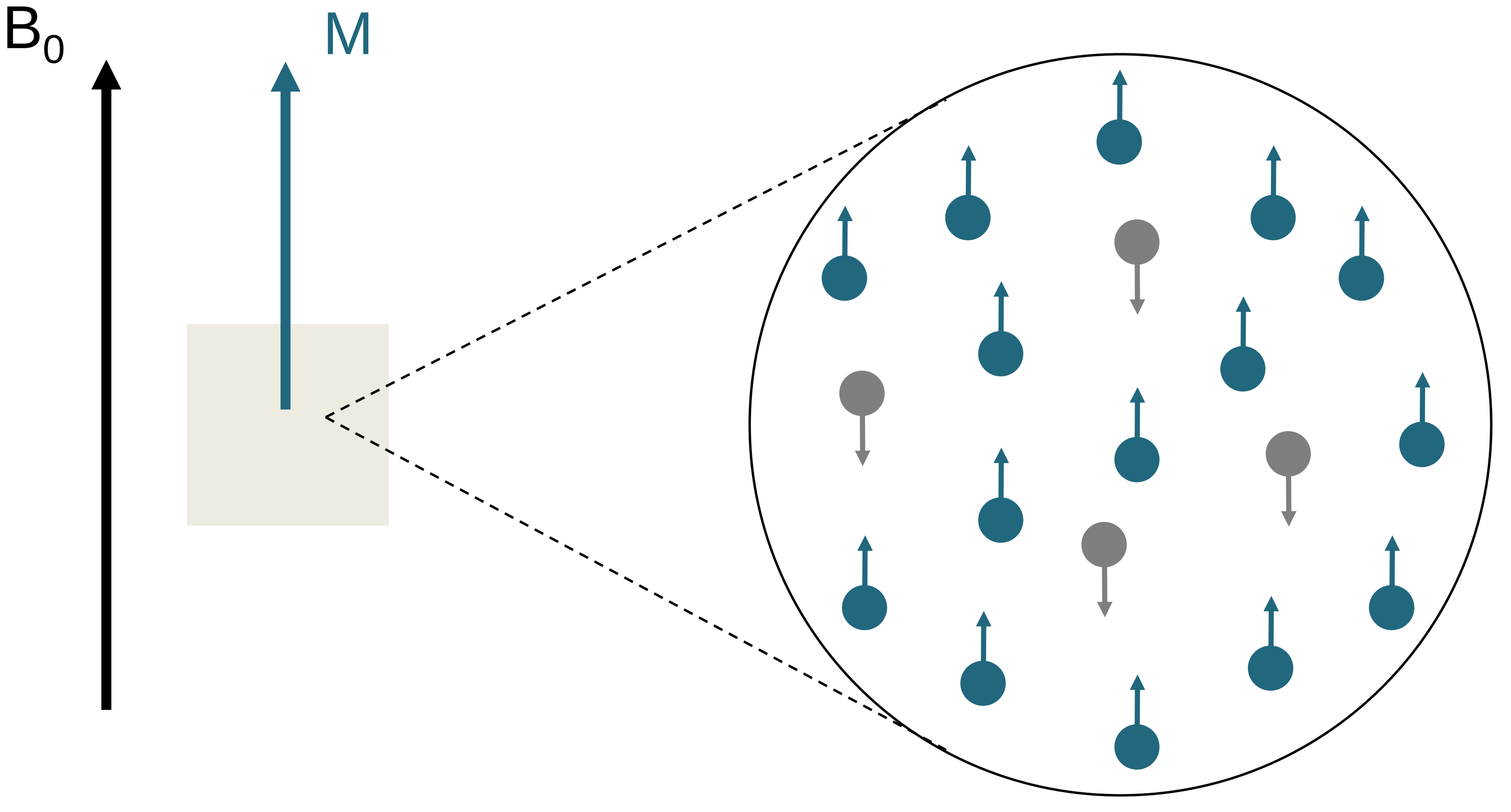
- Elementary property of an atomic nucleus
- Each spin carries an elementary magnetization
- Spins align in an external magnetic field (like a compass needle)

Macroscopic sample

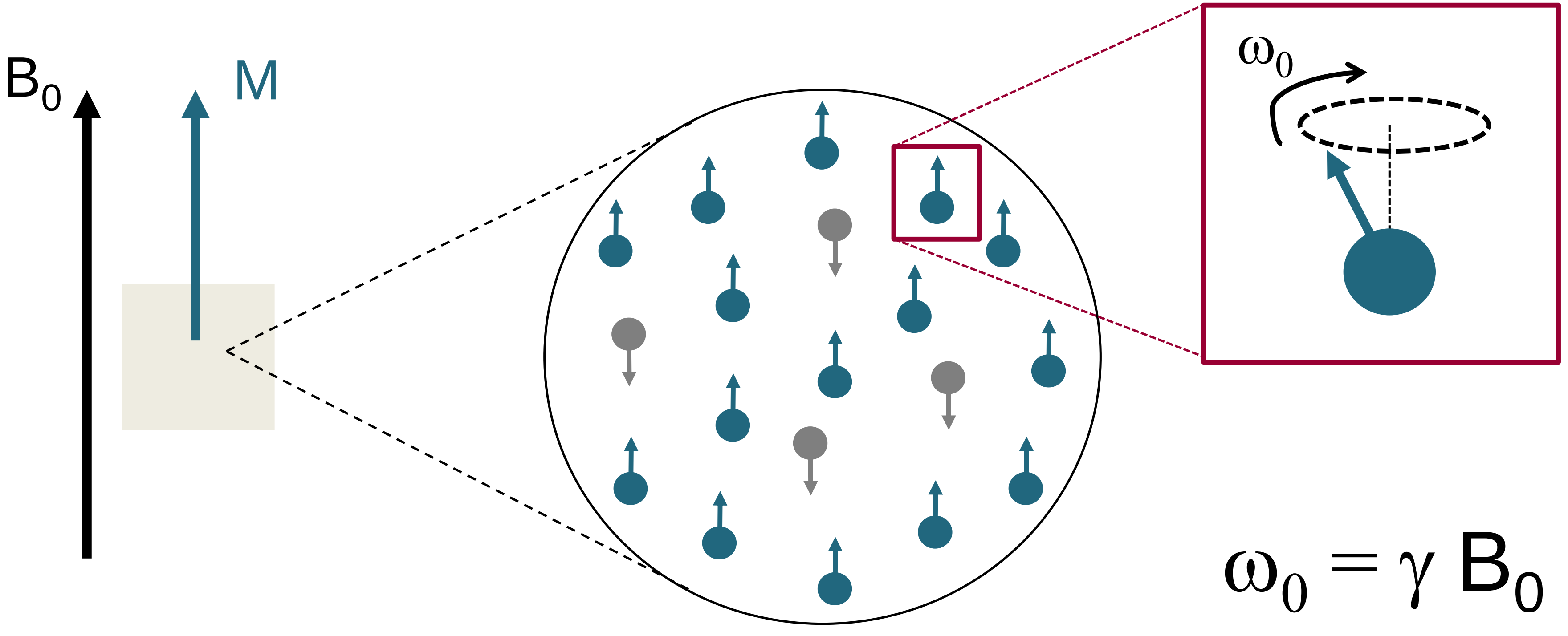
M=0



Macroscopic sample

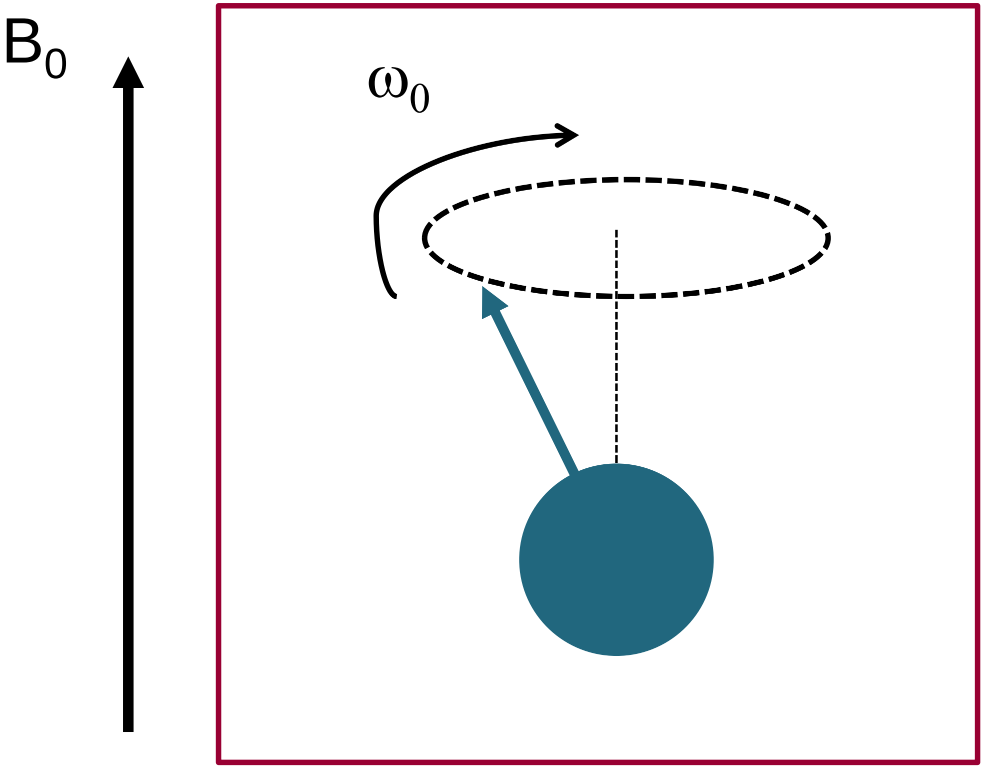


Precession and Larmor Frequency



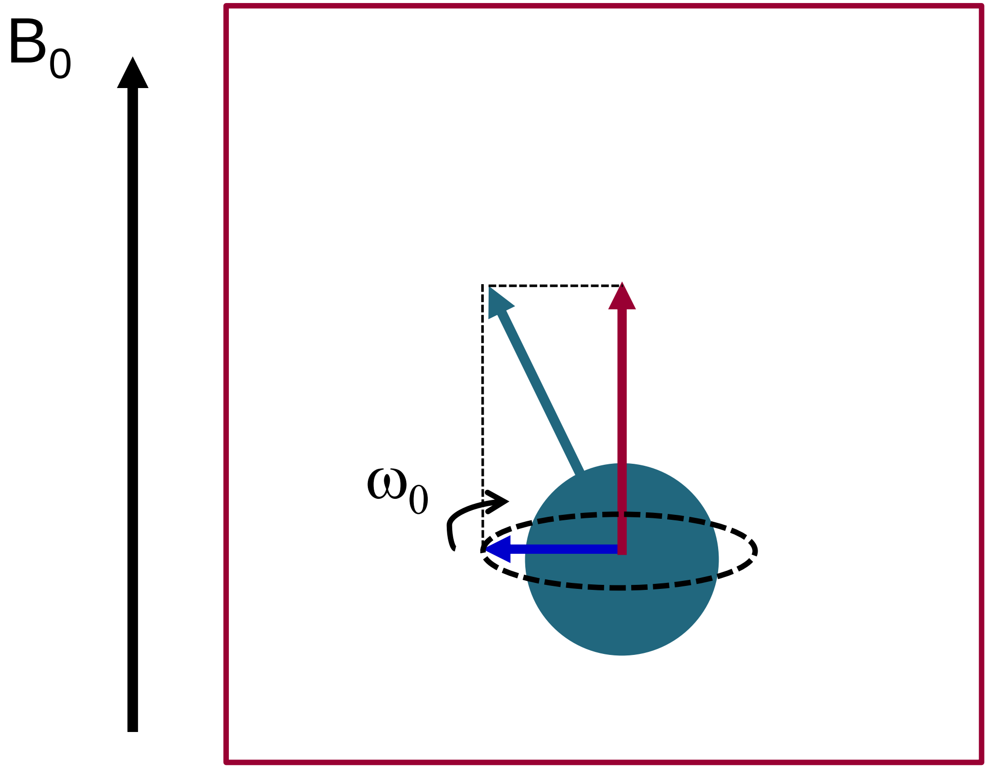
$$\omega_0 = \gamma B_0$$

Precession and Larmor Frequency



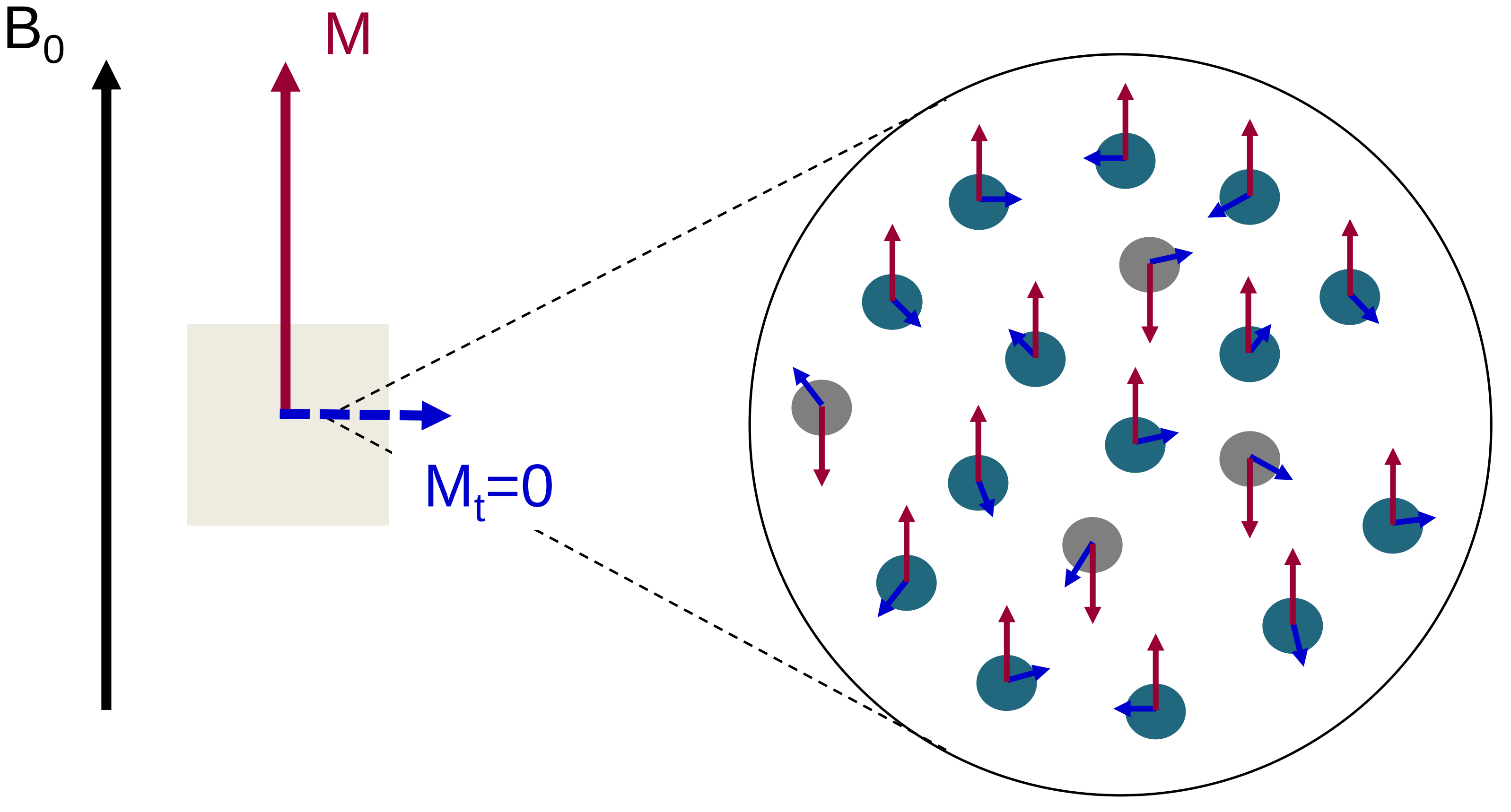
$$\omega_0 = \gamma B_0$$

Precession and Larmor Frequency

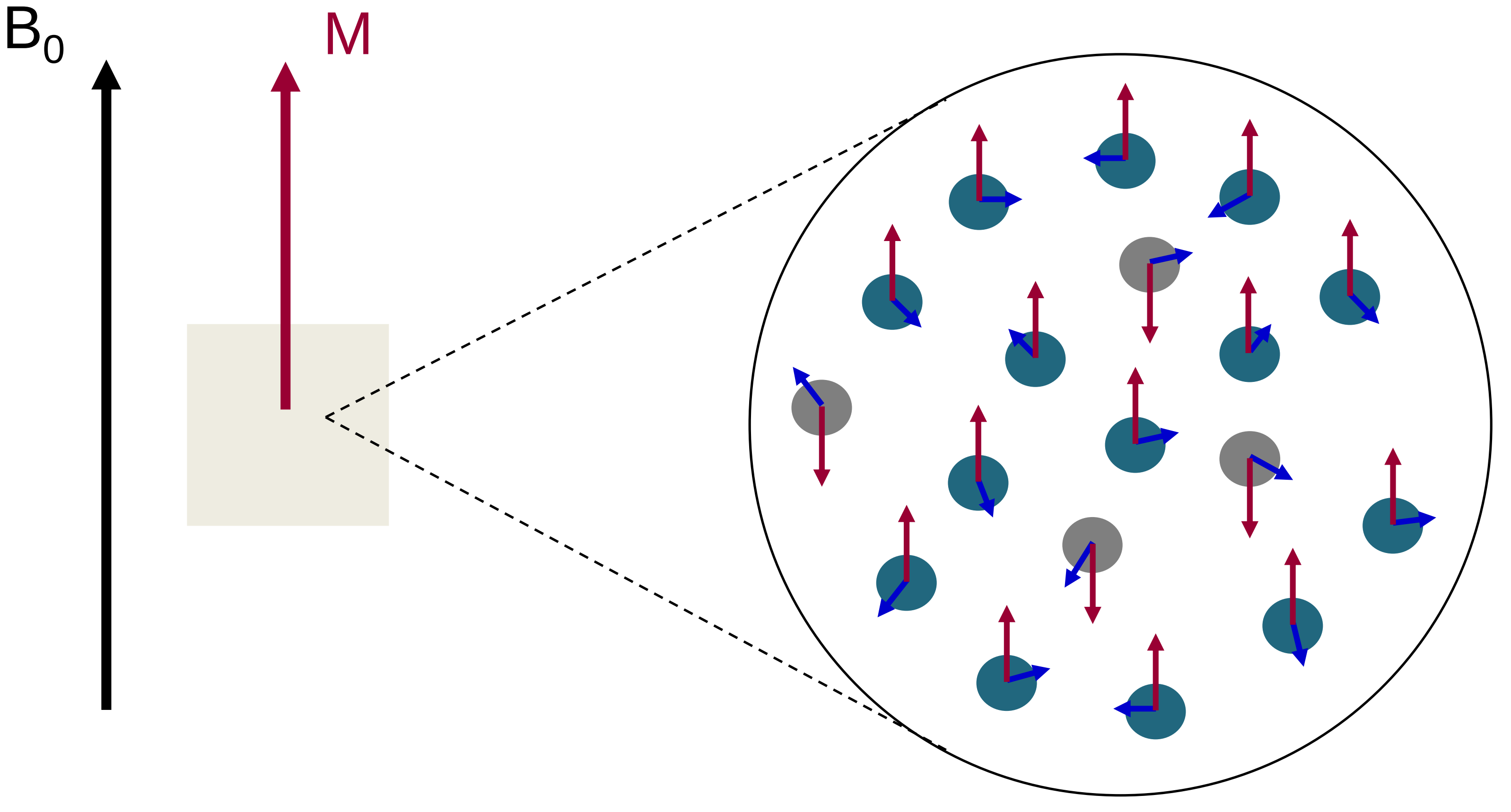


$$\omega_0 = \gamma \, B_0$$

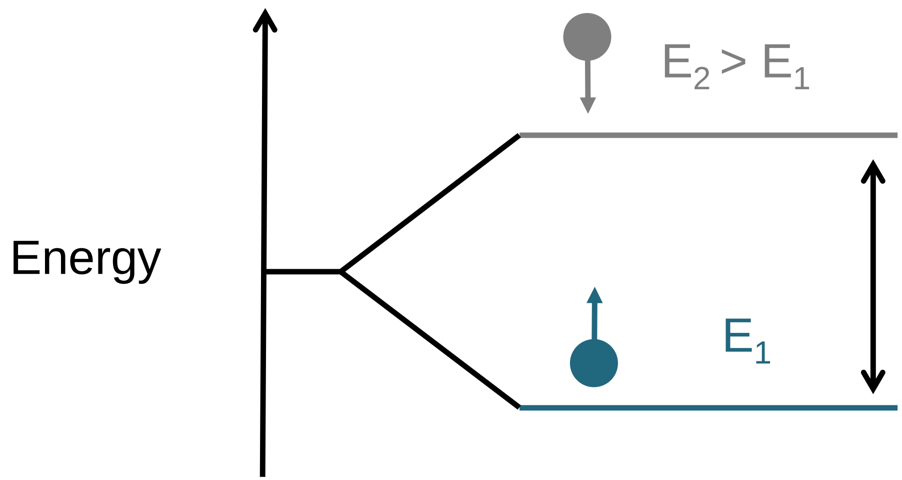
Macroscopic sample



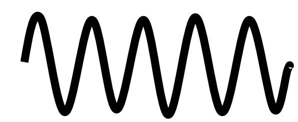
Macroscopic sample

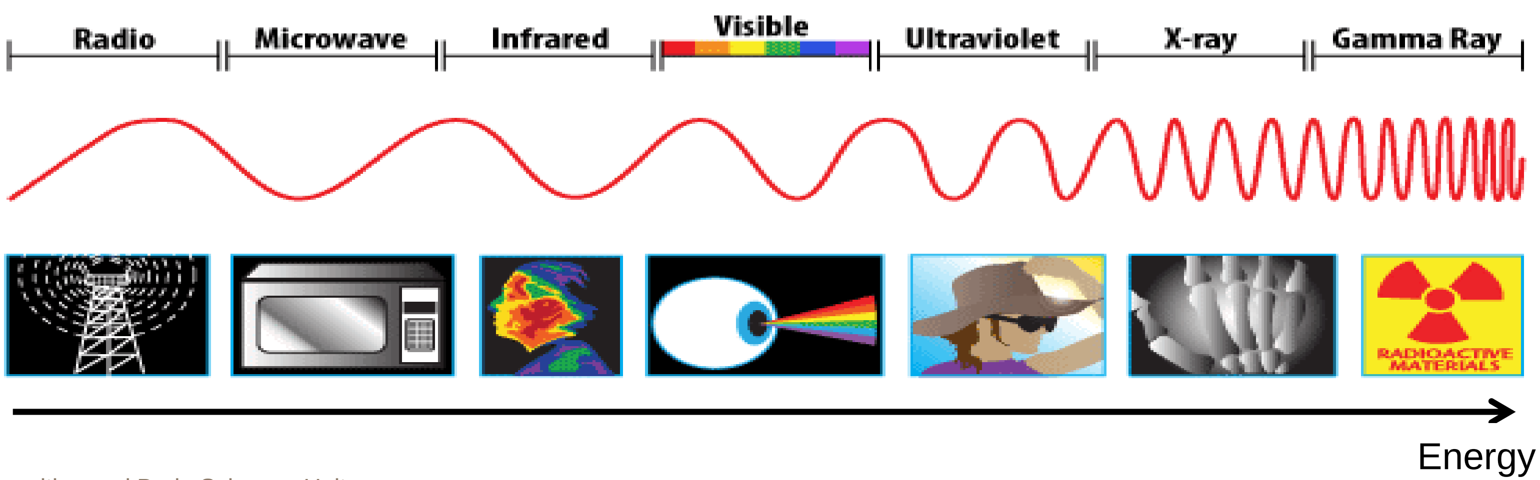


Magnetic Resonance

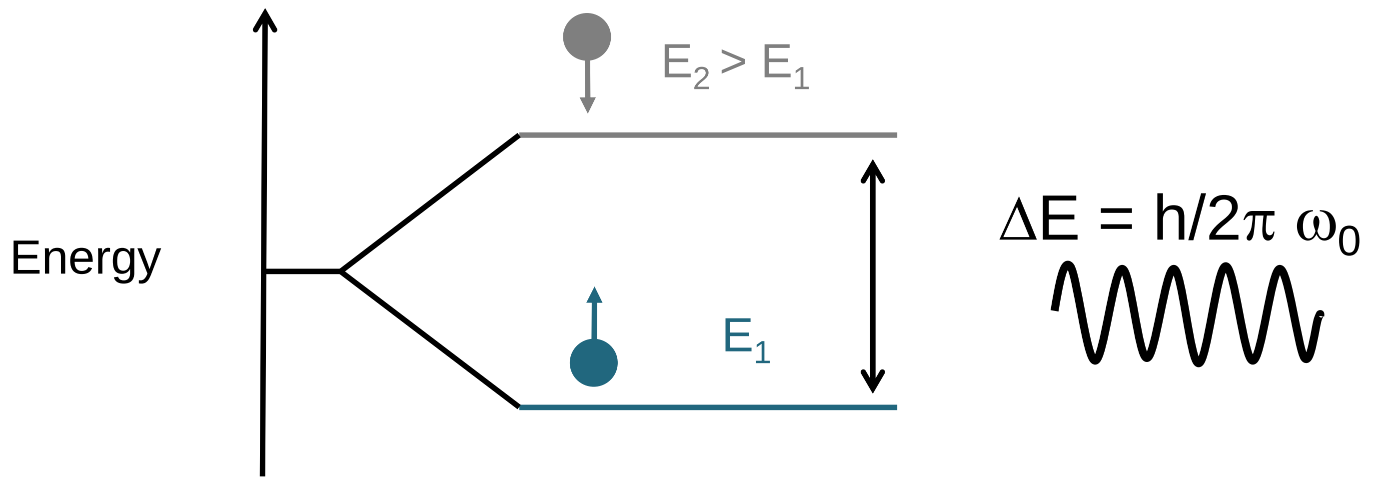


$$\Delta E = h/2\pi\ \omega_0$$



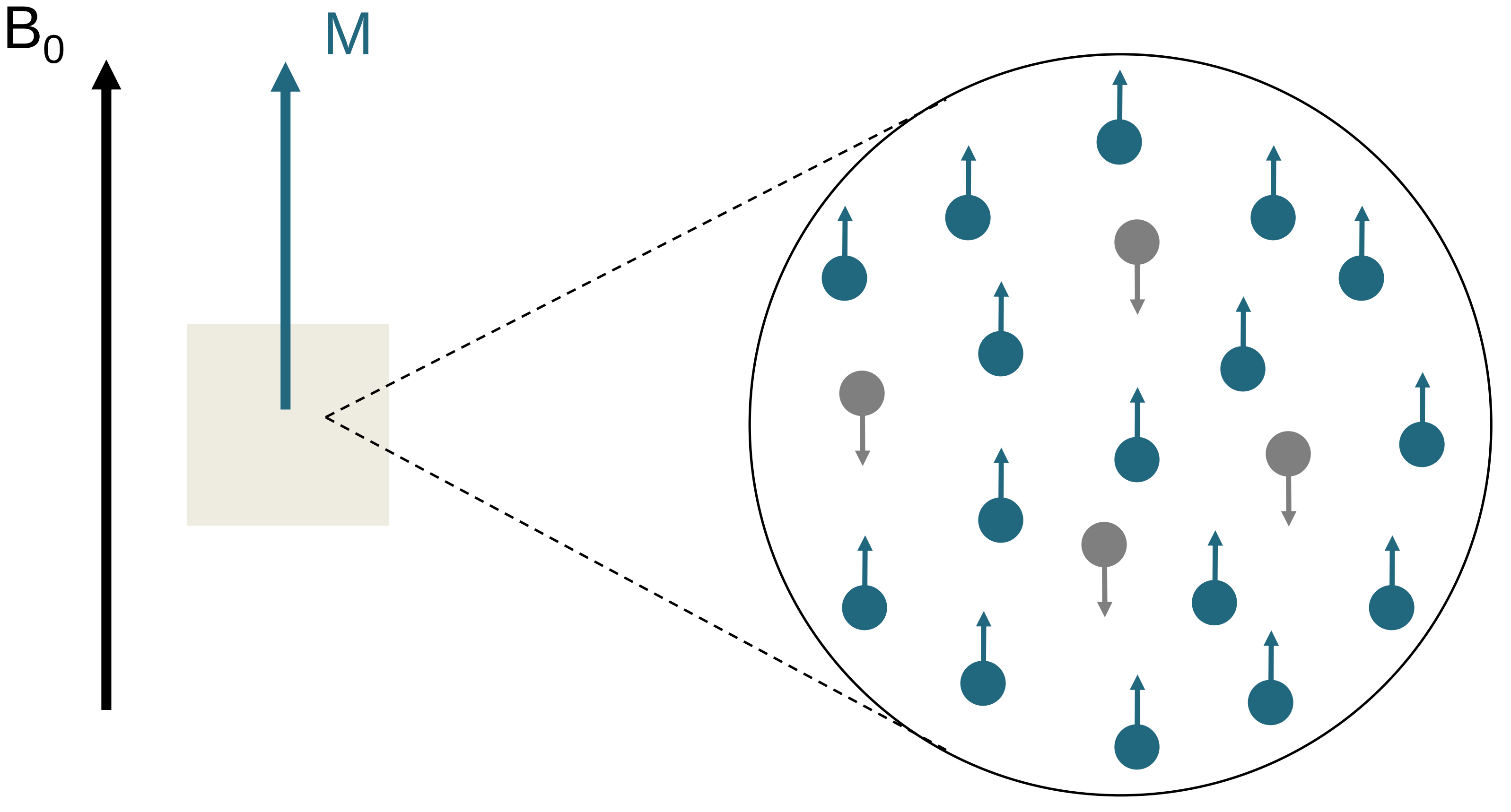


Magnetic Resonance

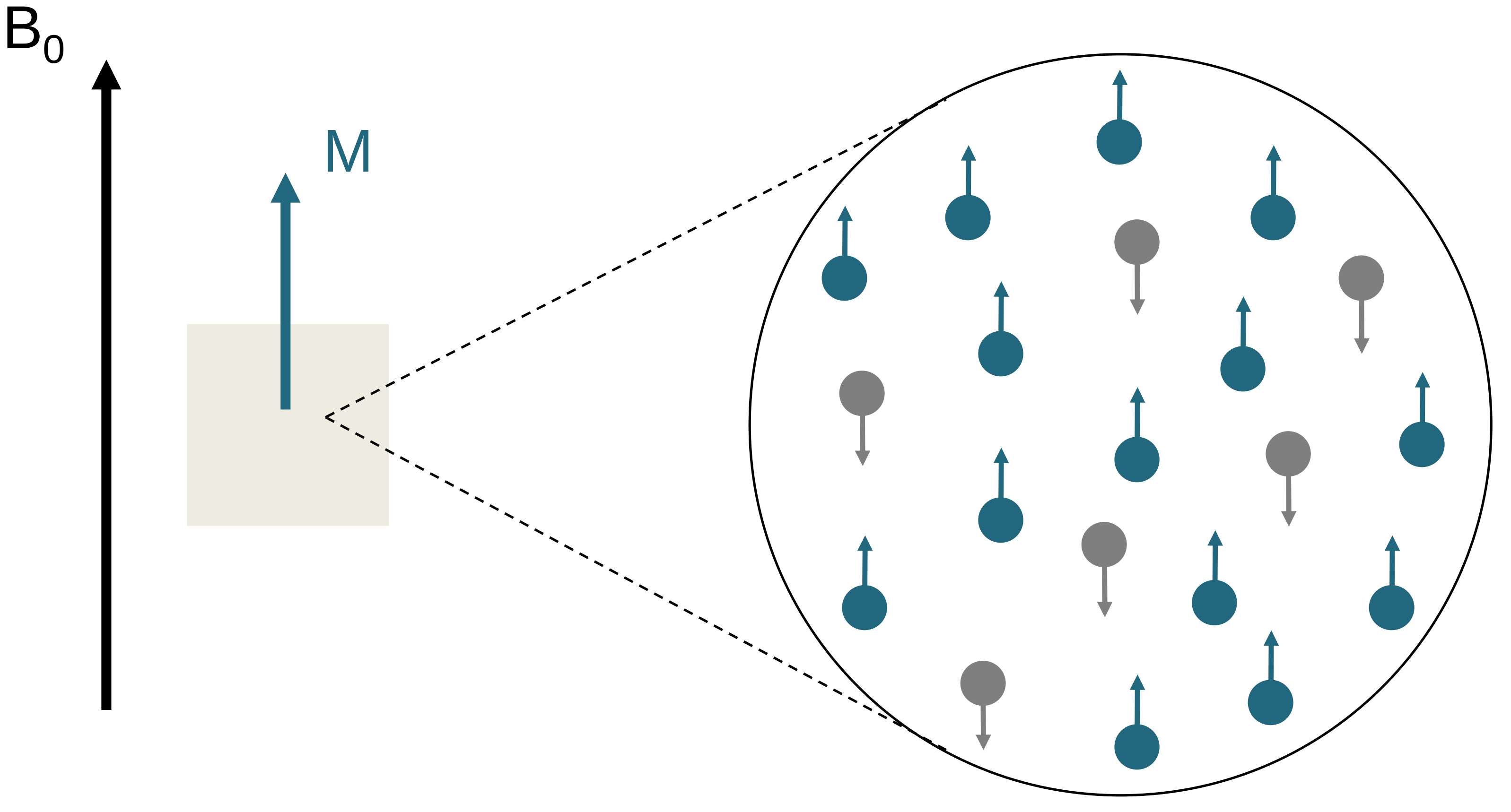


- Exchange of energy between two systems at a specific energy is called **resonance**.
- **Magnetic resonance** corresponds to the energetic interaction between **spins** and **electromagnetic radiofrequency** (RF).
- Only protons that spin with the **same frequency** as the electromagnetic **RF pulse** will respond to that RF pulse.

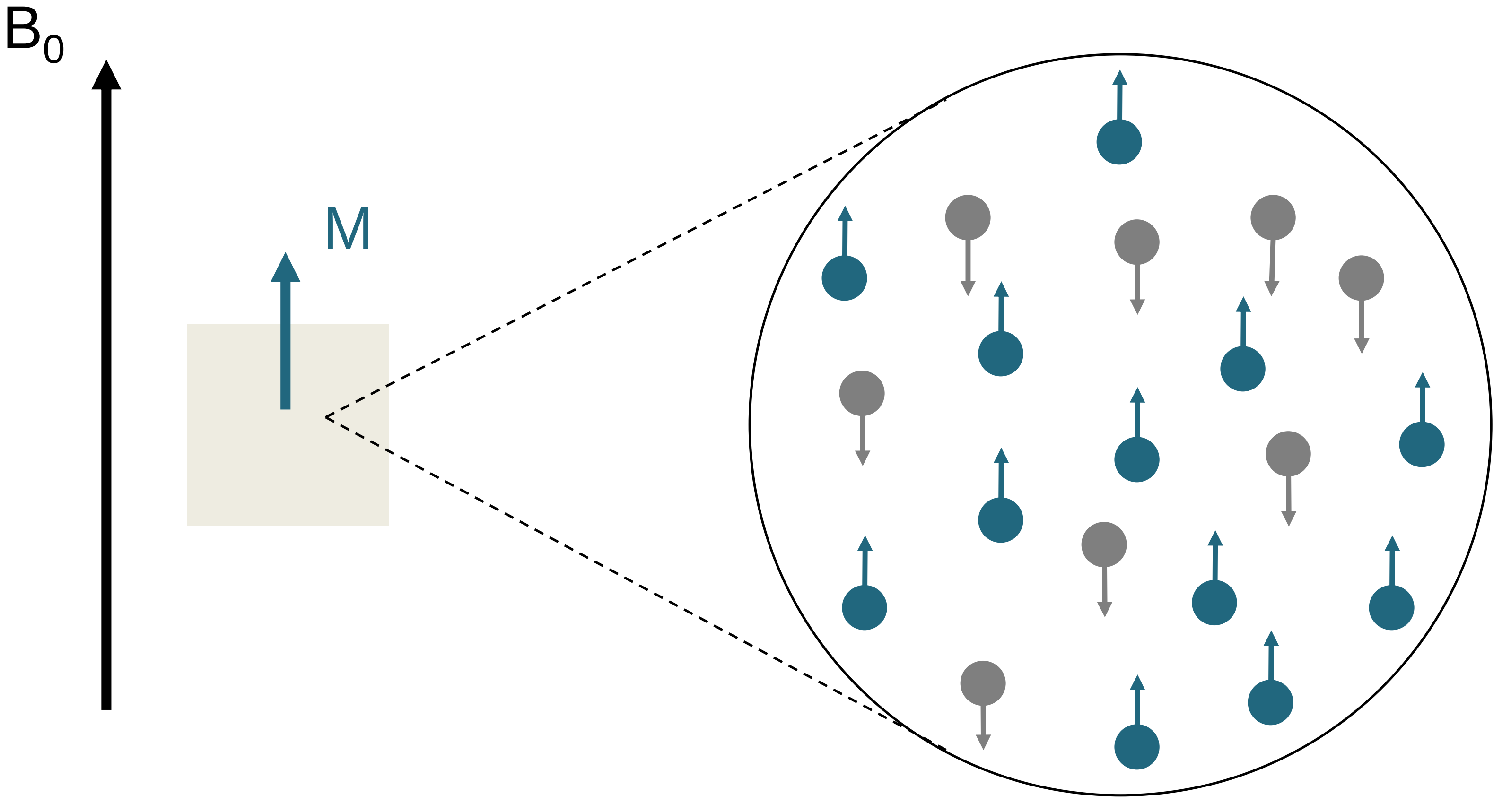
Macroscopic sample + RF pulse (Energy)



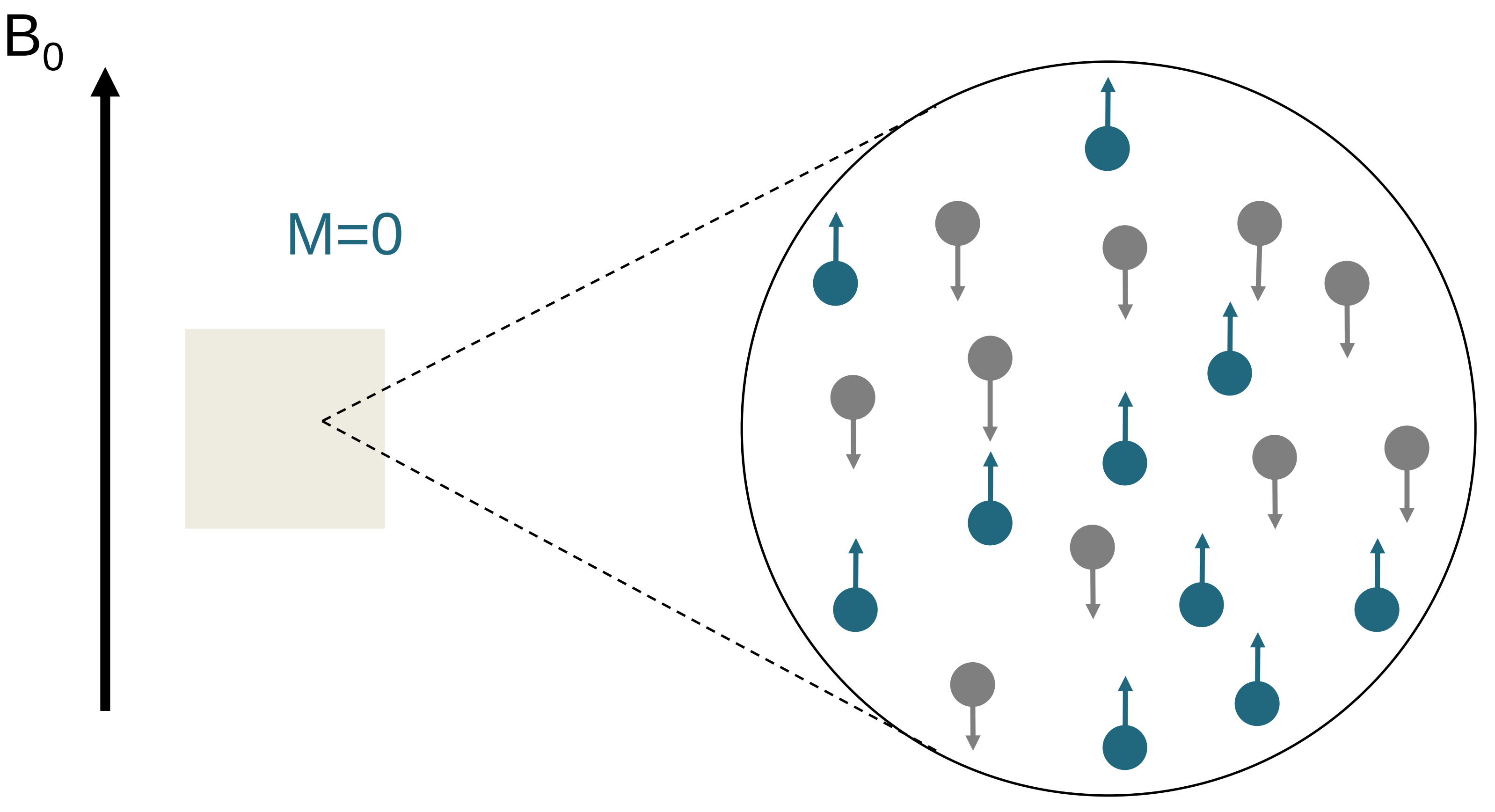
Macroscopic sample + RF pulse (Energy)



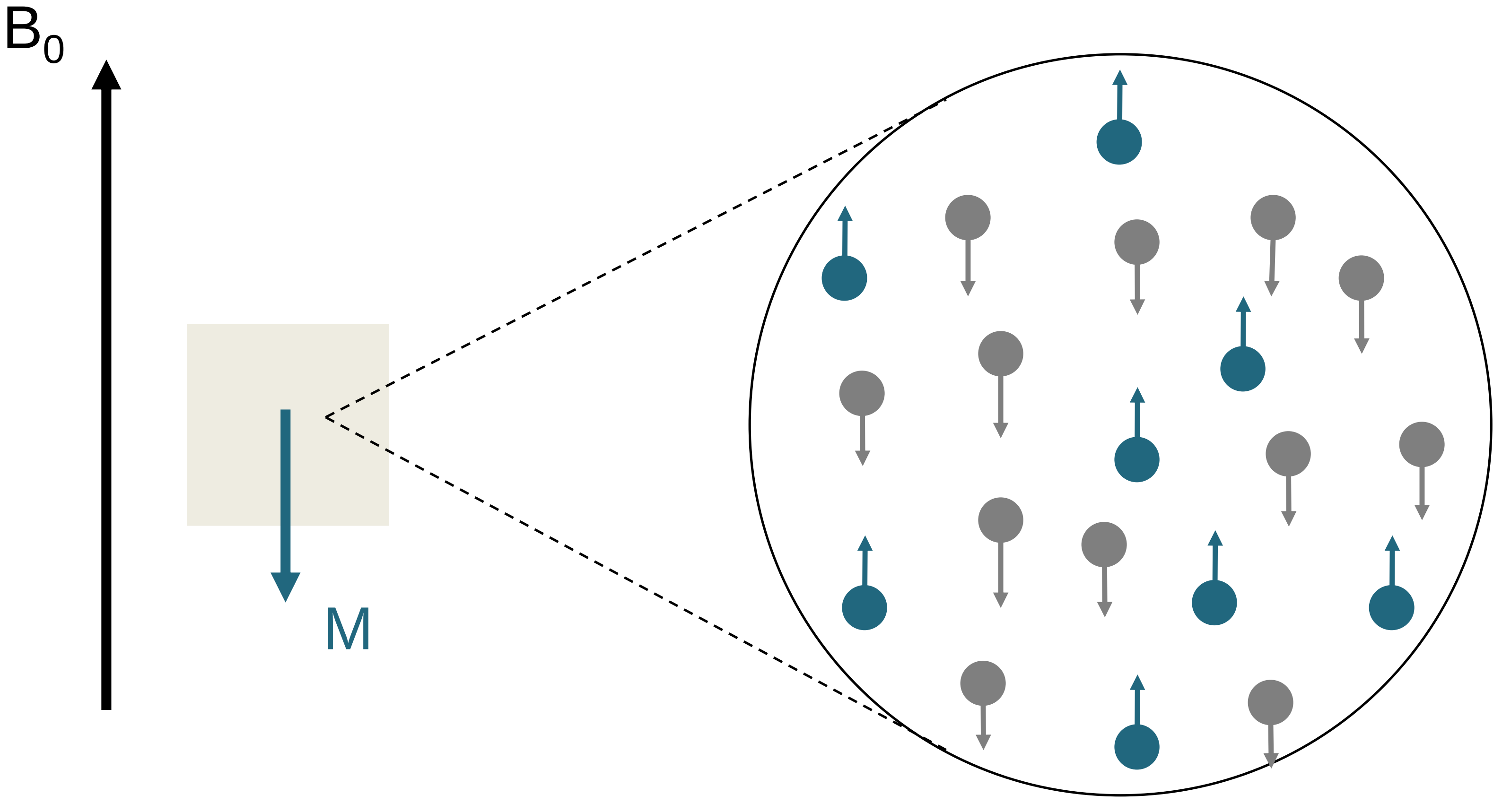
Macroscopic sample + RF pulse (Energy)



Macroscopic sample + RF pulse (Energy)

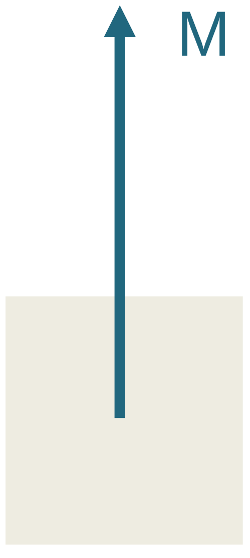


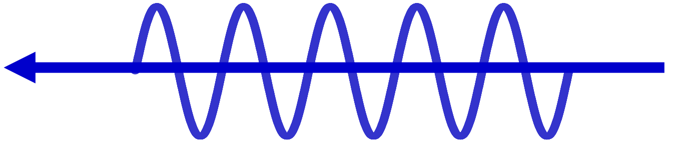
Macroscopic sample + RF pulse (Energy)



Excitation, Relaxation and Signal Formation

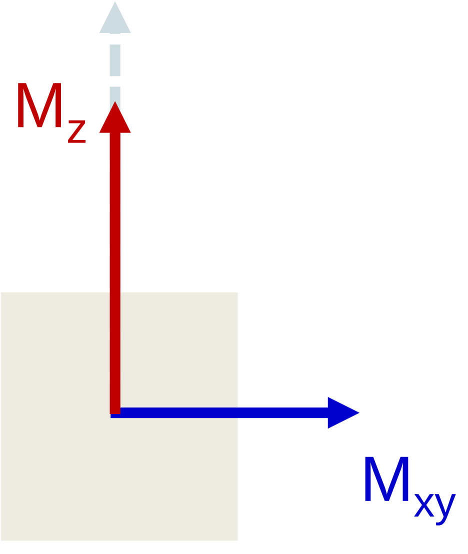
Excitation



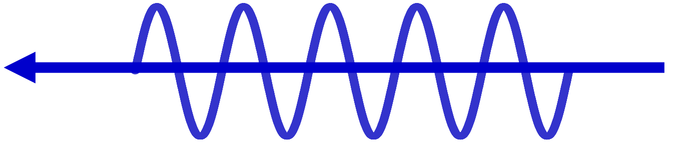


$$\omega_0 = \gamma B_0$$

Excitation



- During excitation, longitudinal magnetization decreases and a transverse magnetization appears.

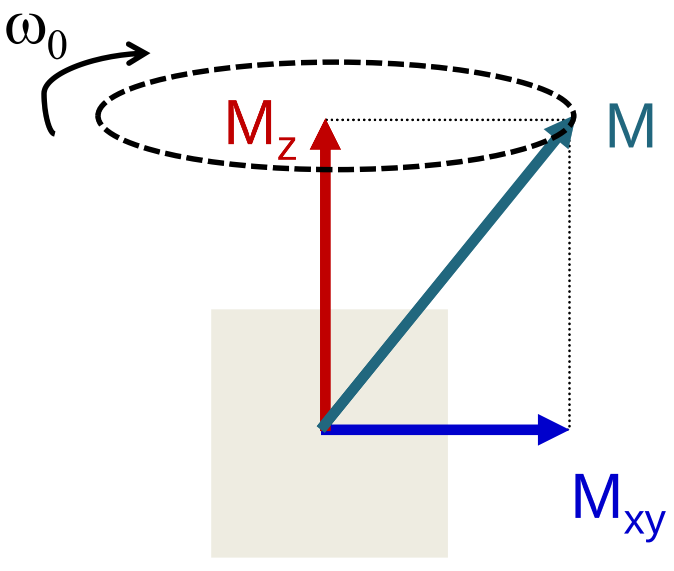


$$\omega_0 = \gamma\, B_0$$

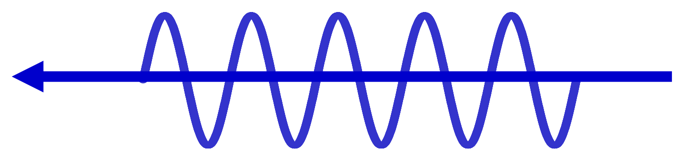
- Longitudinal magnetization decrease is due to a difference in the number of spins in parallel and anti-parallel state.

- Transverse magnetization is due to spins getting into phase coherence.

Excitation



- During excitation, longitudinal magnetization decreases and a transverse magnetization appears.

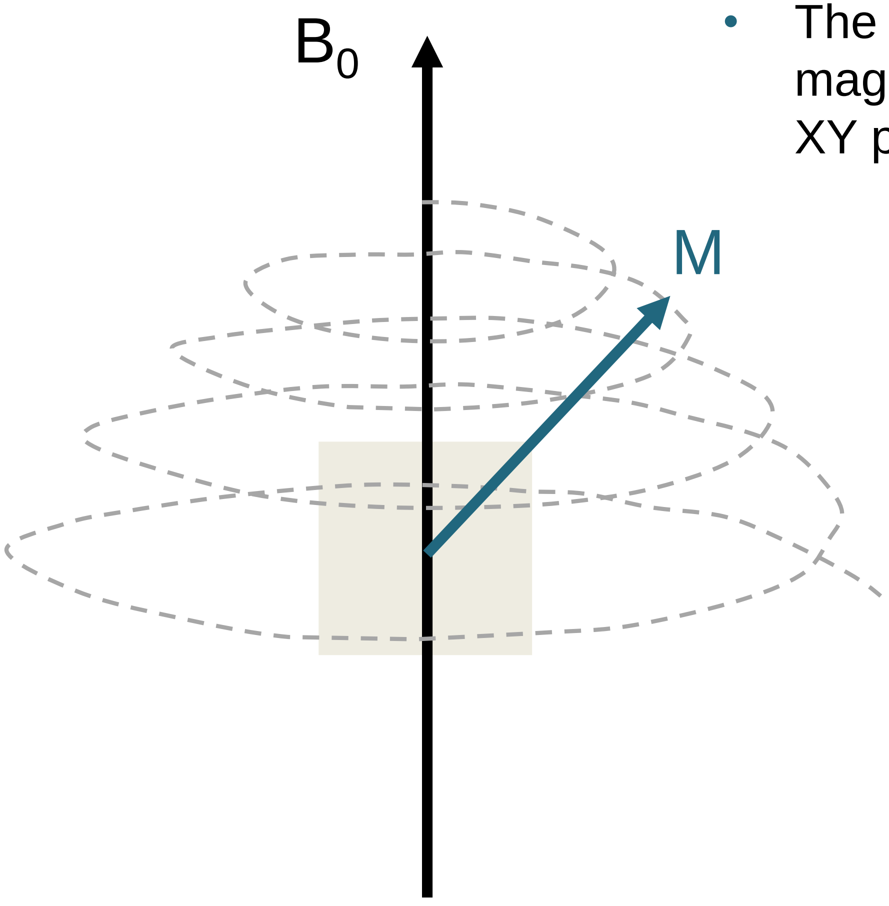


$$\omega_0 = \gamma B_0$$

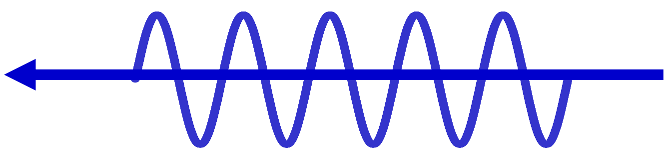
- Longitudinal magnetization decrease is due to a difference in the number of spins in parallel and anti-parallel state.

- Transverse magnetization is due to spins getting into phase coherence.

Excitation

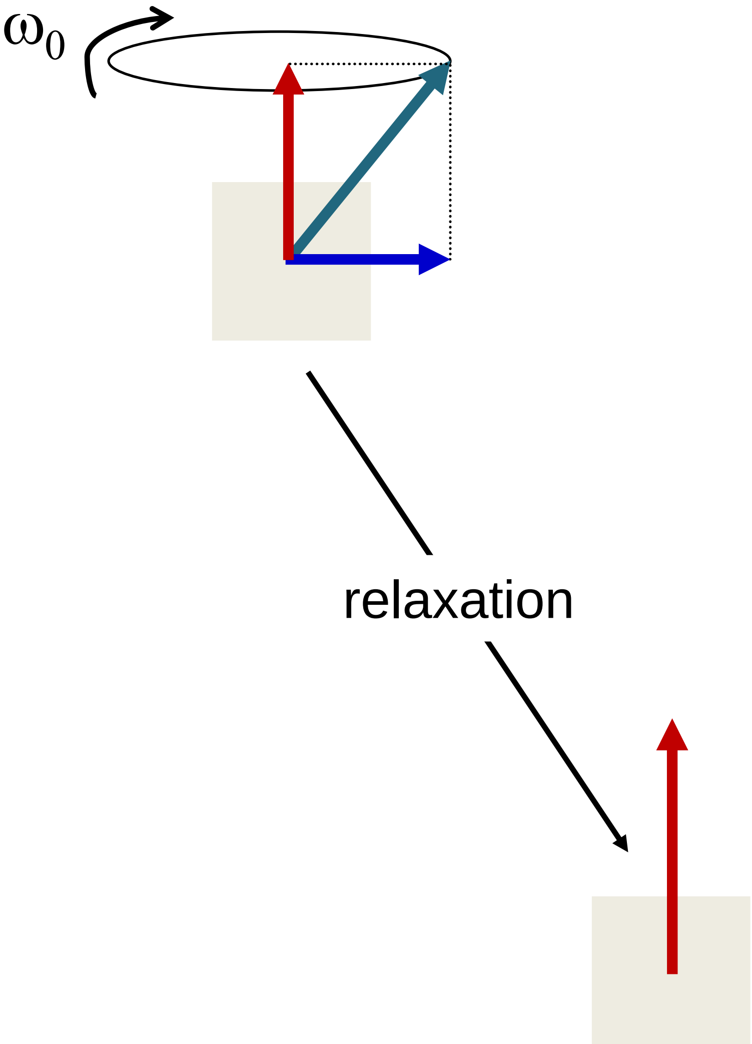


- The consequence on the macroscopic net magnetization is a spiral movement down to the XY plane.



$$\omega_0 = \gamma B_0$$

Relaxation



Two independent relaxation processes:

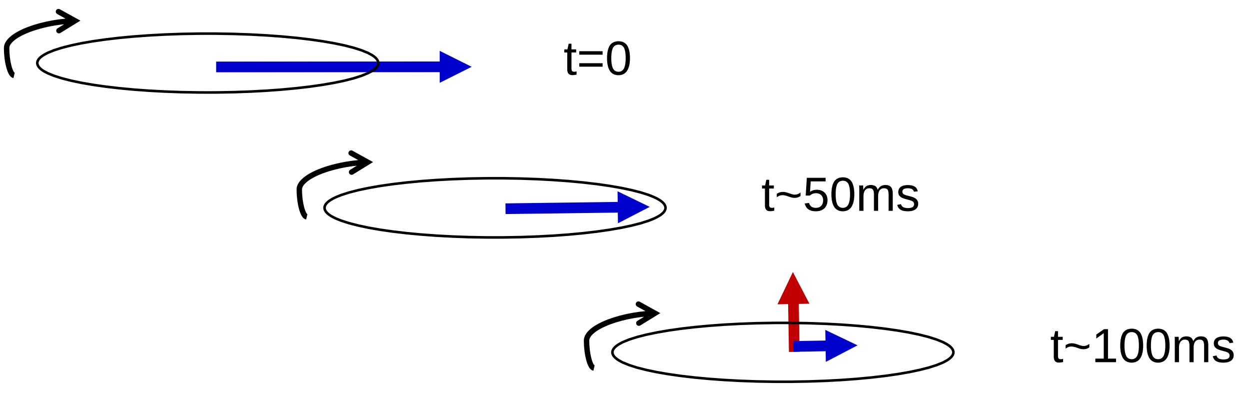
(1) $M_l \xrightarrow{T_1} M_0$

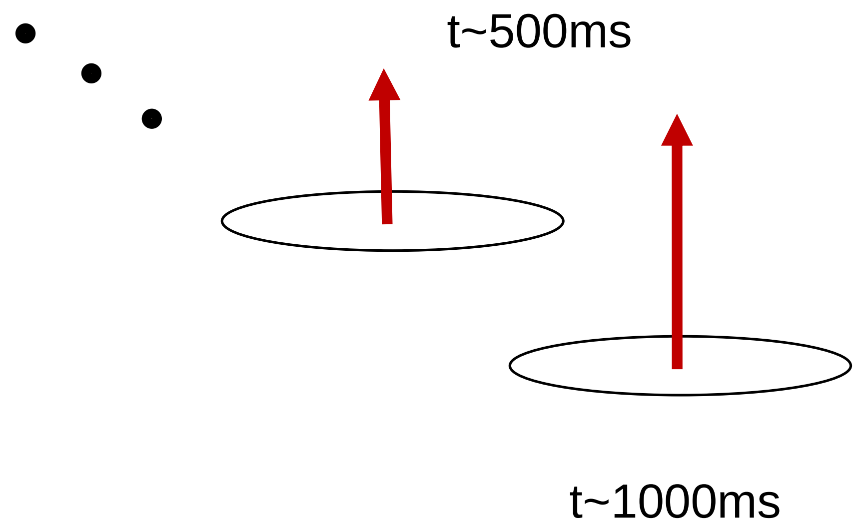
(2) $M_{xy} \xrightarrow{T_2} 0$

T_1: "*longitudinal relaxation time*"
(≈ 1 s) - energy exchange between spins and their surroundings

T_2: "*transverse relaxation time*"
(≈ 100 ms) – dephasing due to spin/spin interactions

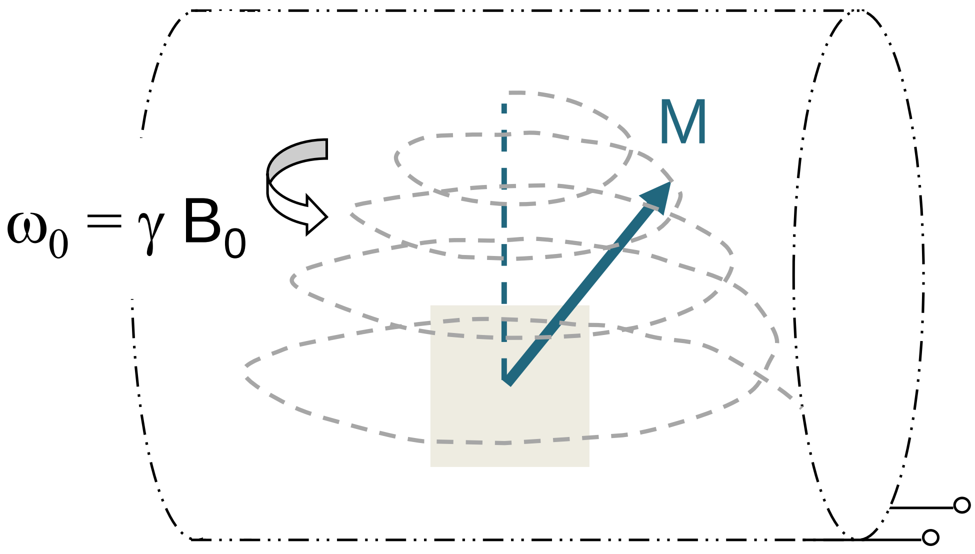
Relaxation





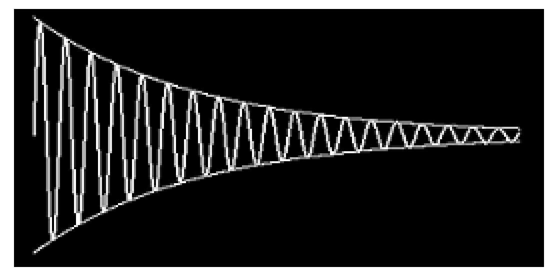
- Transverse Magnetization vanishes quickly (short T_2)
- Longitudinal Magnetization relaxes slowly (long T_1)

Precession and signal induction



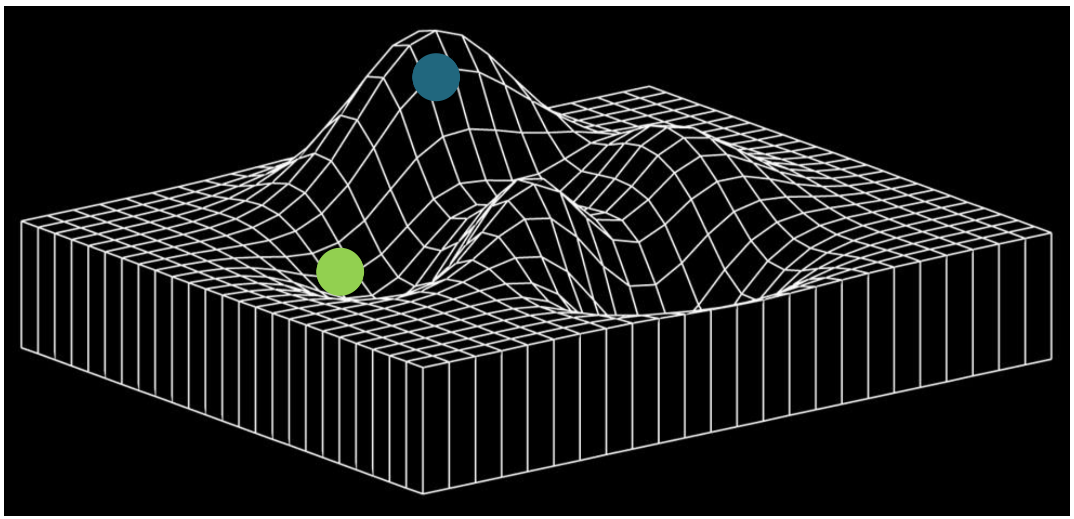
receiver coil

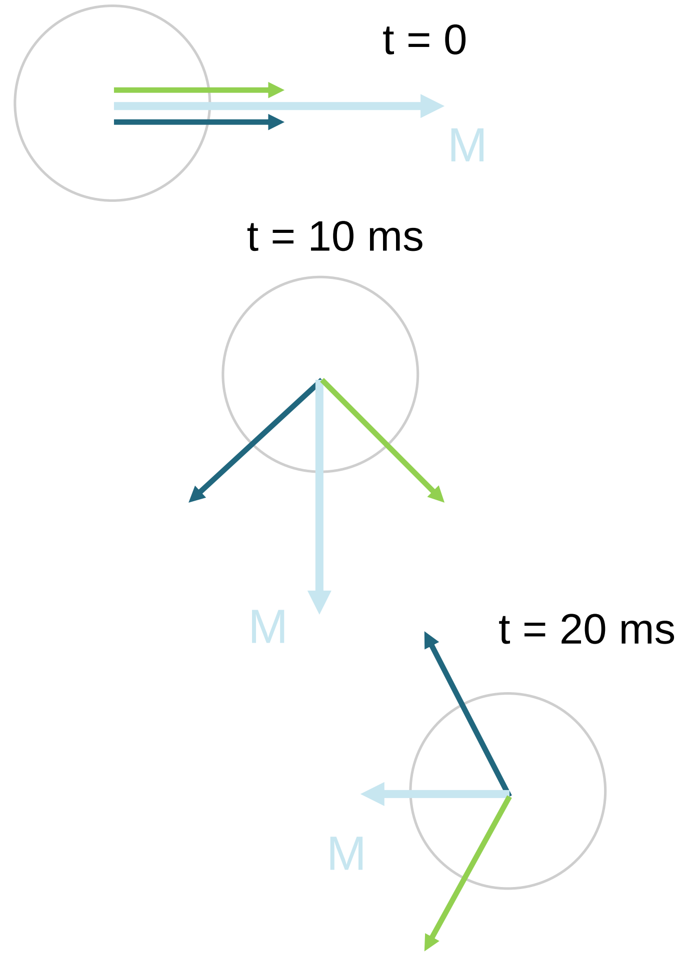
123 MHz @ 3T



NMR signal

Signal loss due to B_0 inhomogeneity

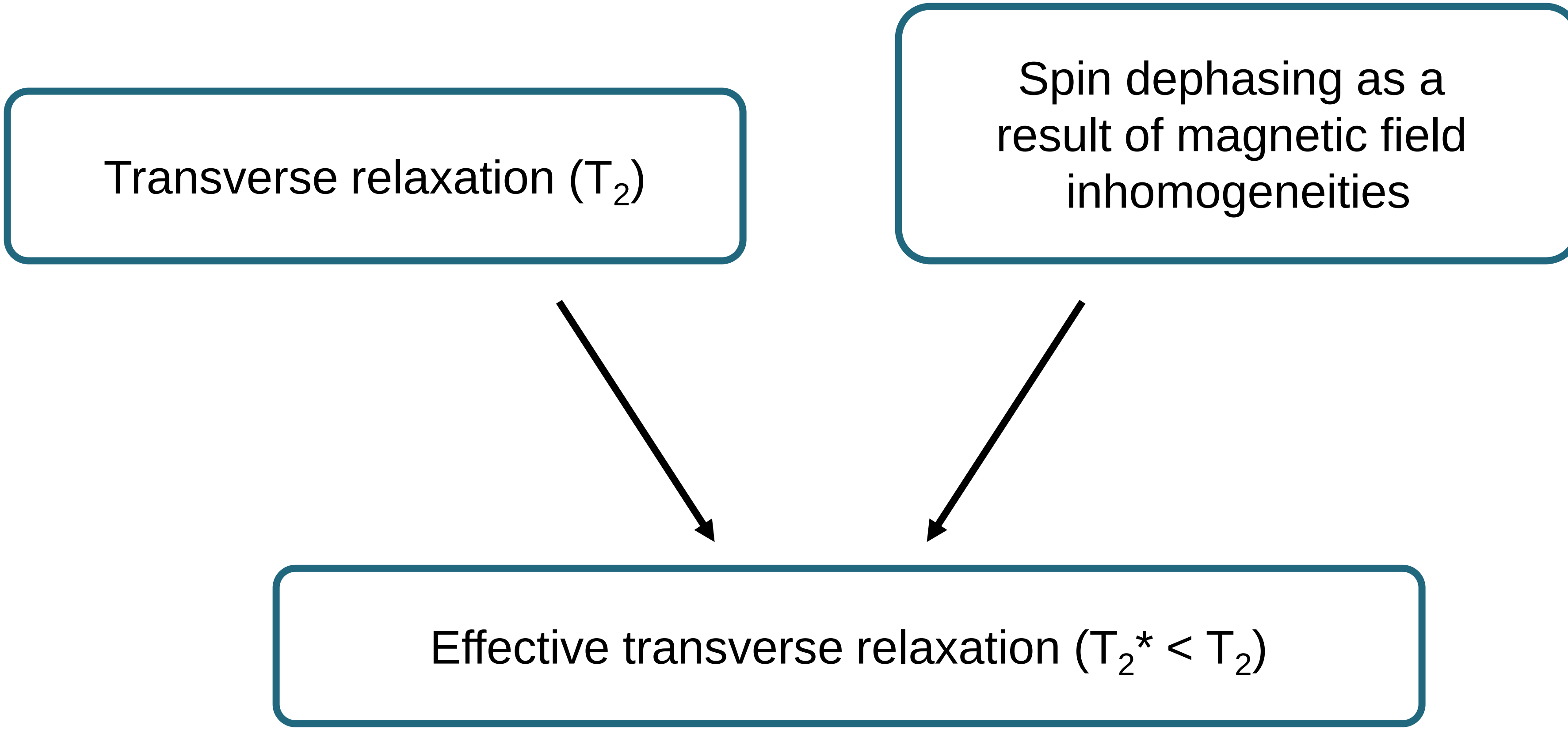




$$\omega_0 = \gamma B_0$$

has higher frequency than

Effective transverse relaxation (T_2*)

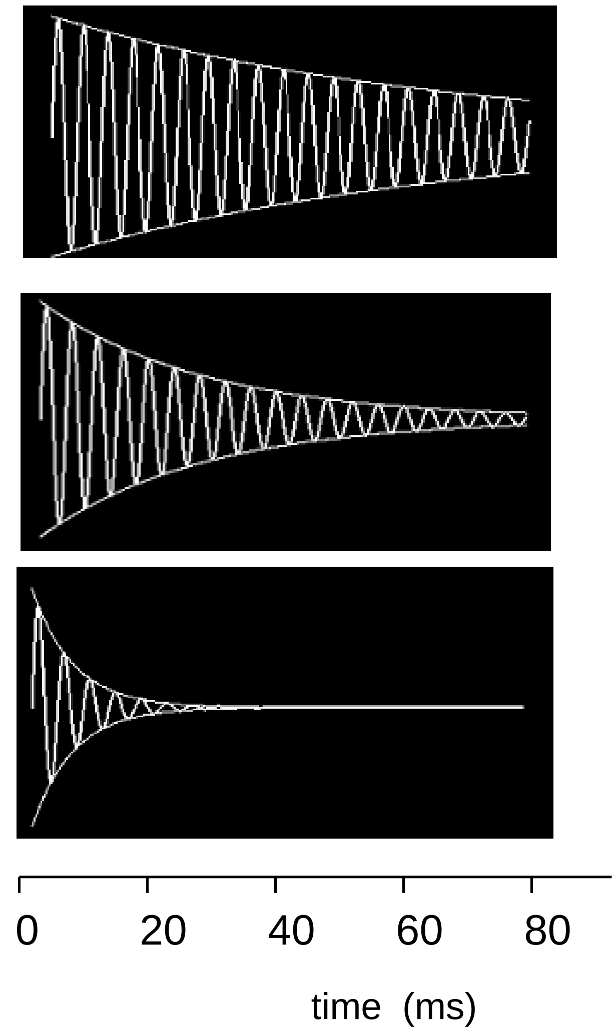


Effective transverse relaxation (T_2*)

No inhomogeneities
(T_2*= T_2 = 100 ms)

Moderate inhomogeneities
(T_2* = 40 ms)

Strong inhomogeneities
(T_2* = 10 ms)

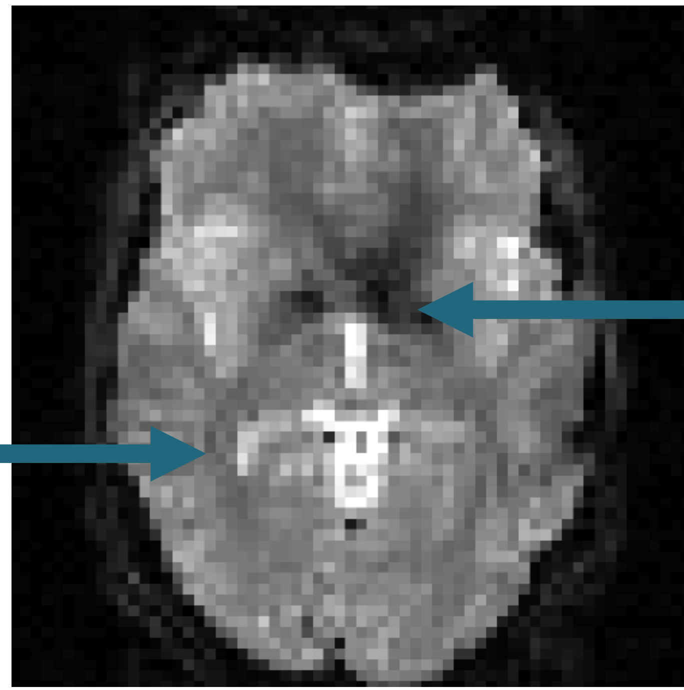


T_2^* related signal dropouts

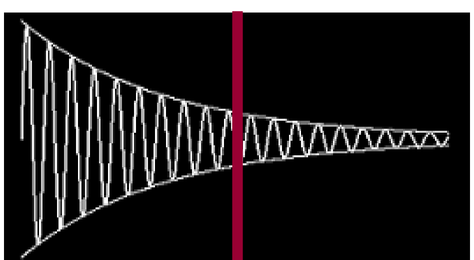
T_2^* reduction due to local field inhomogeneities
$\Rightarrow$ signal dropouts

reduced T_2^*

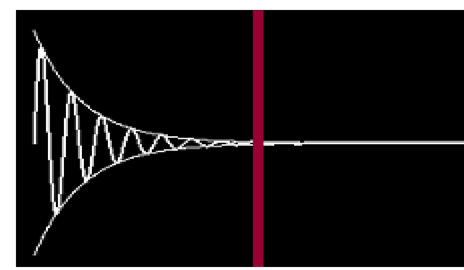
normal T_2^*
(about 40 ms)



EPI image



TE



TE

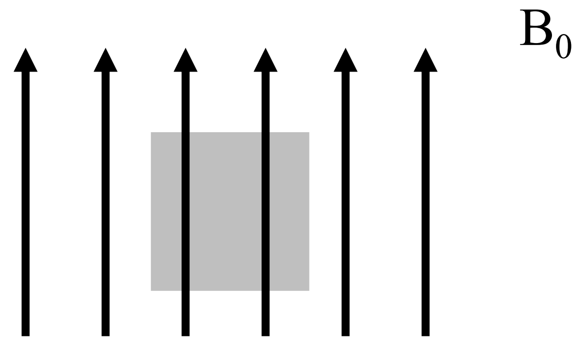
Part II:
Magnetic Resonance Imaging (MRI)

Spatial Encoding in MRI

The principles of MRI

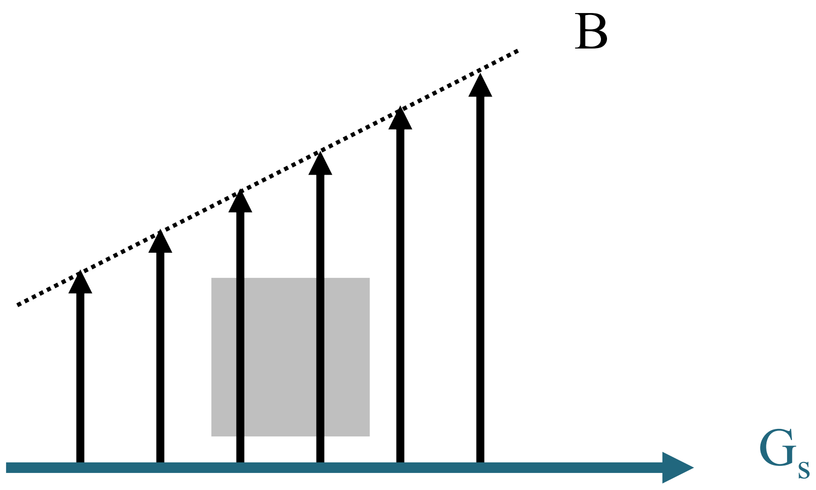
Homogeneous magnetic field

$$\omega_0 = \gamma B_0$$

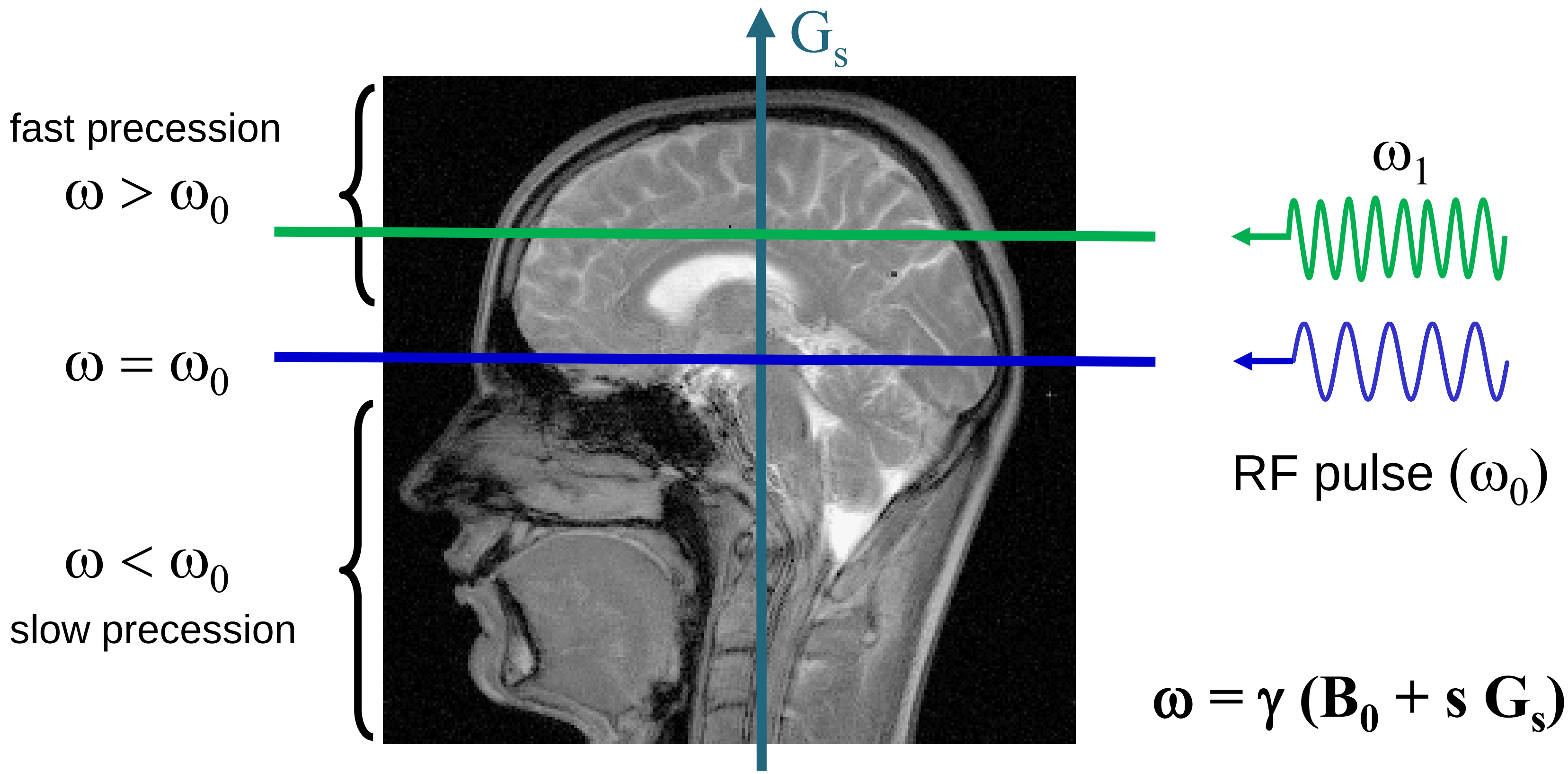


Add magnetic field gradient

$$\omega = \gamma (B_0 + s\, G_s)$$

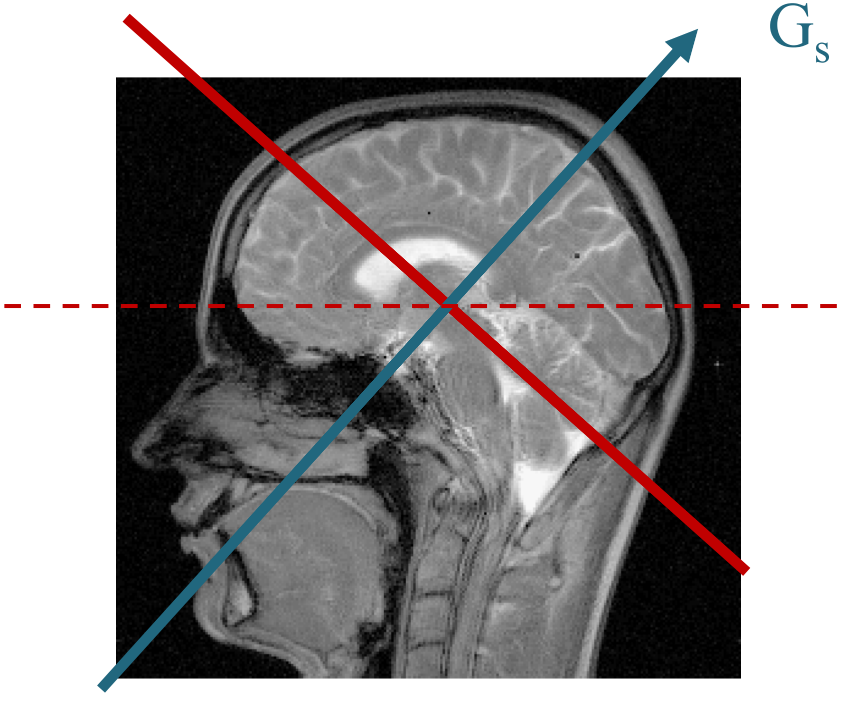


Slice selective excitation



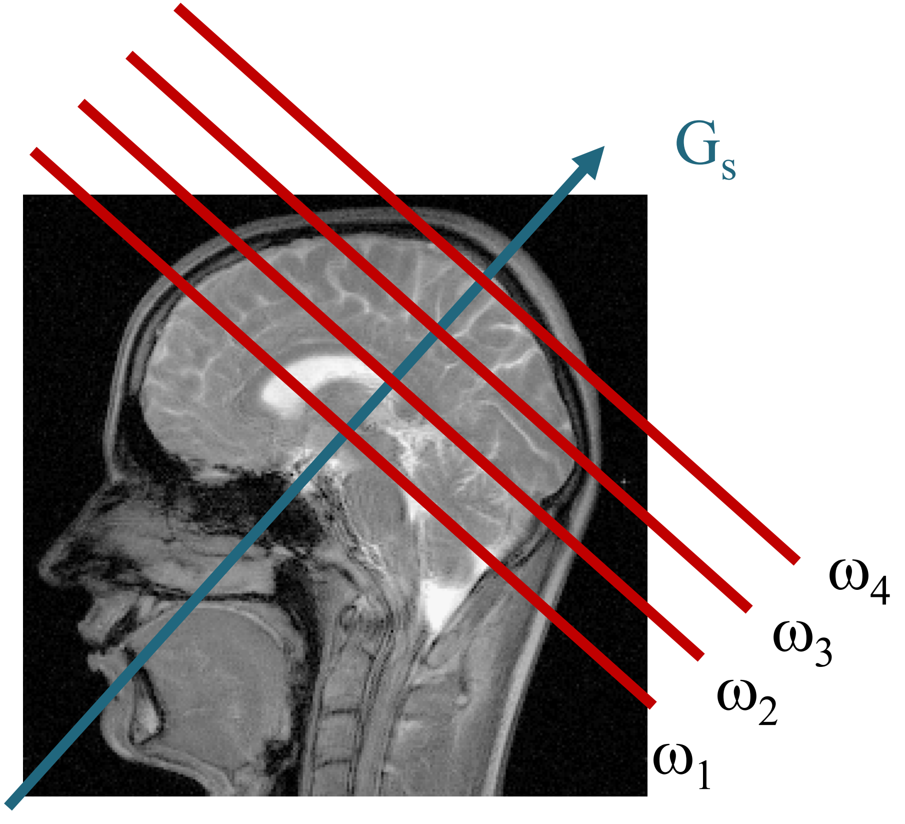
- Only spins in slice of interest have frequency ω_0
- RF pulse with frequency ω_0 excites only spins in slice of interest

Slice orientation



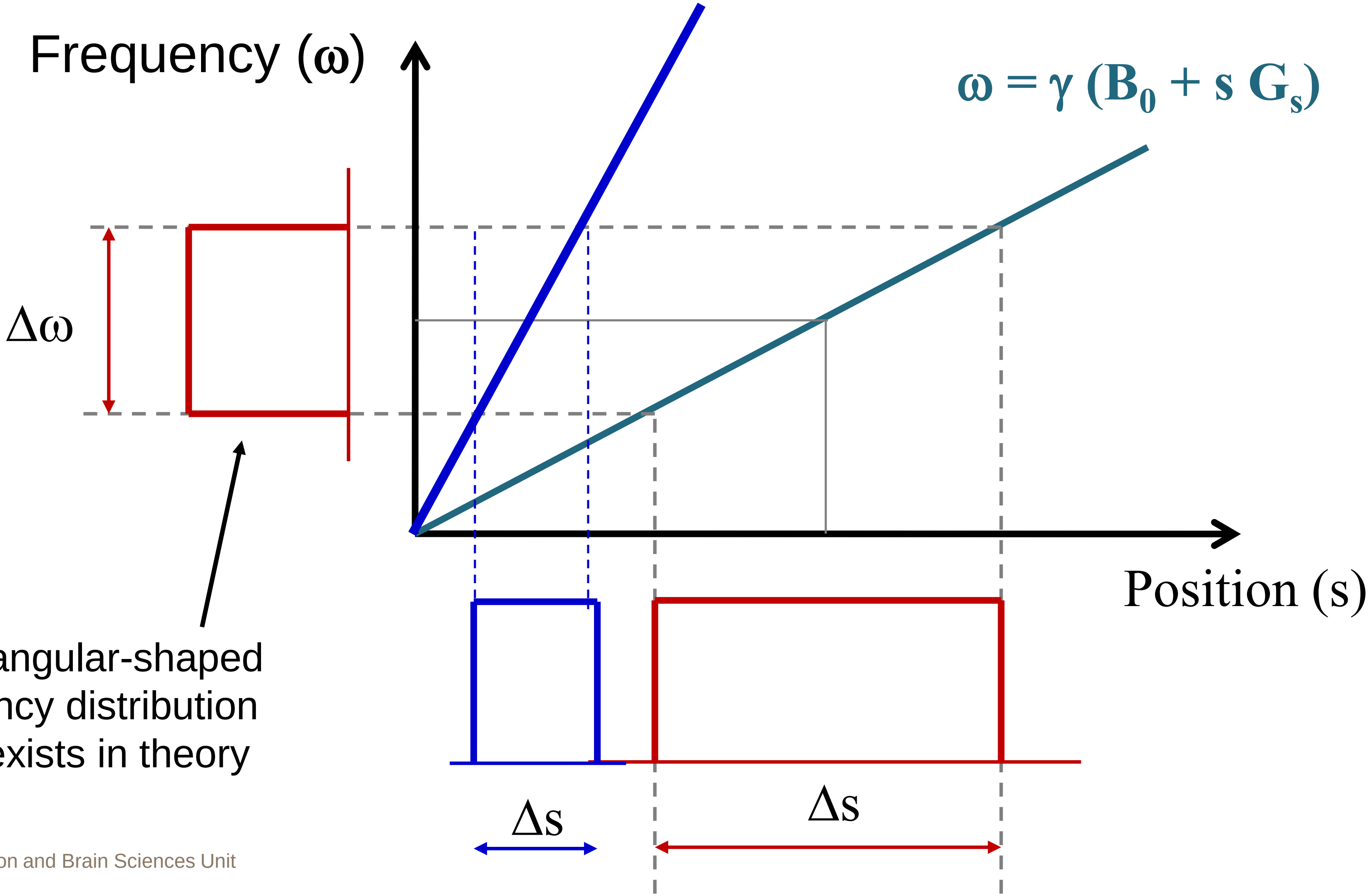
$$\omega = \gamma\,(B_0 + s\ G_s)$$

Multi-slice MRI



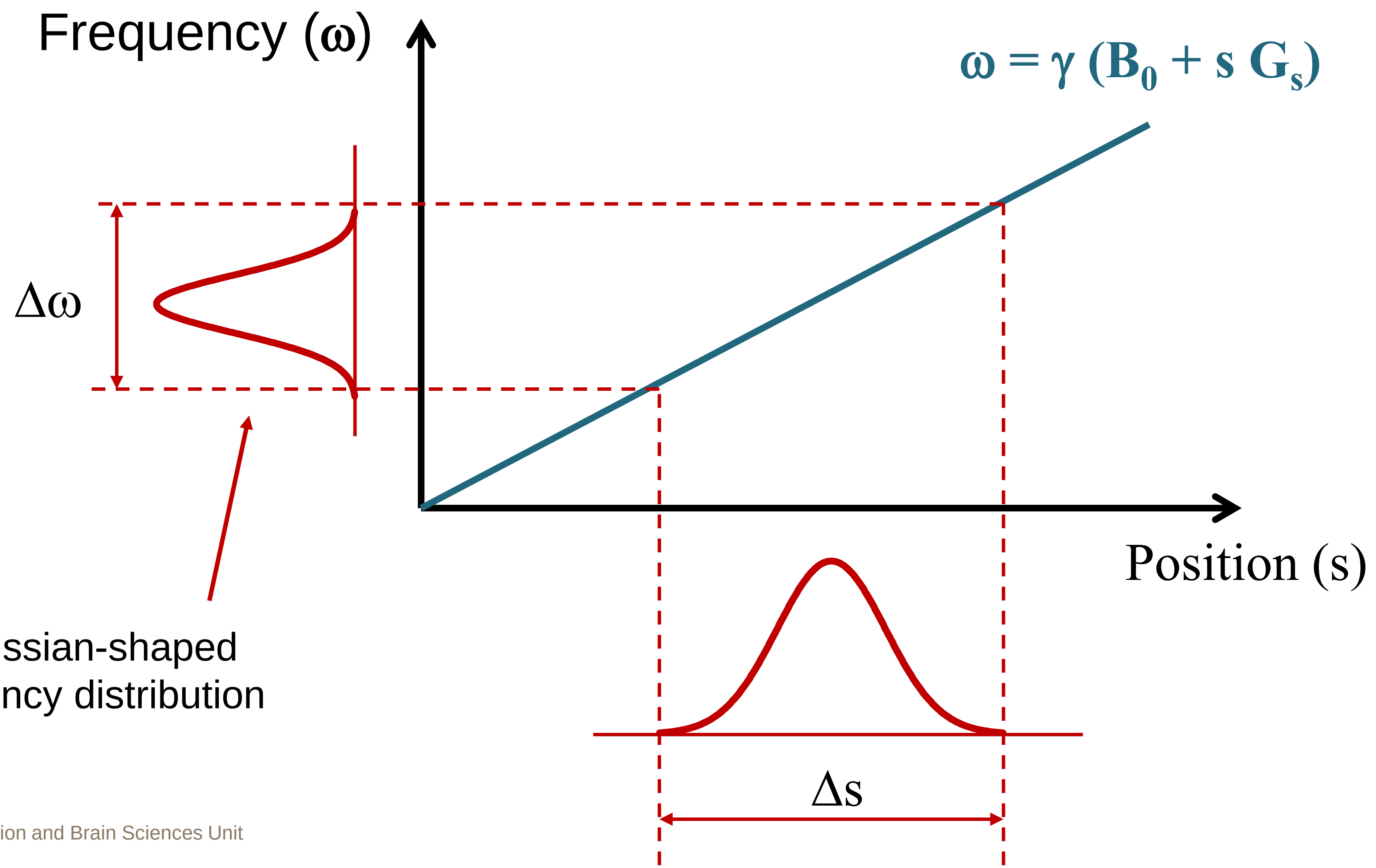
$$\omega = \gamma\,(B_0 + s\,G_s)$$

Slice profile



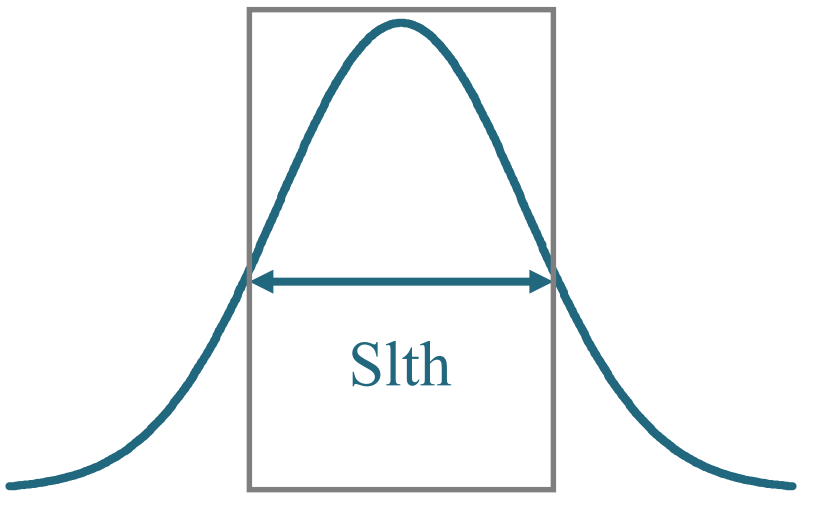
A rectangular-shaped frequency distribution only exists in theory

Slice profile



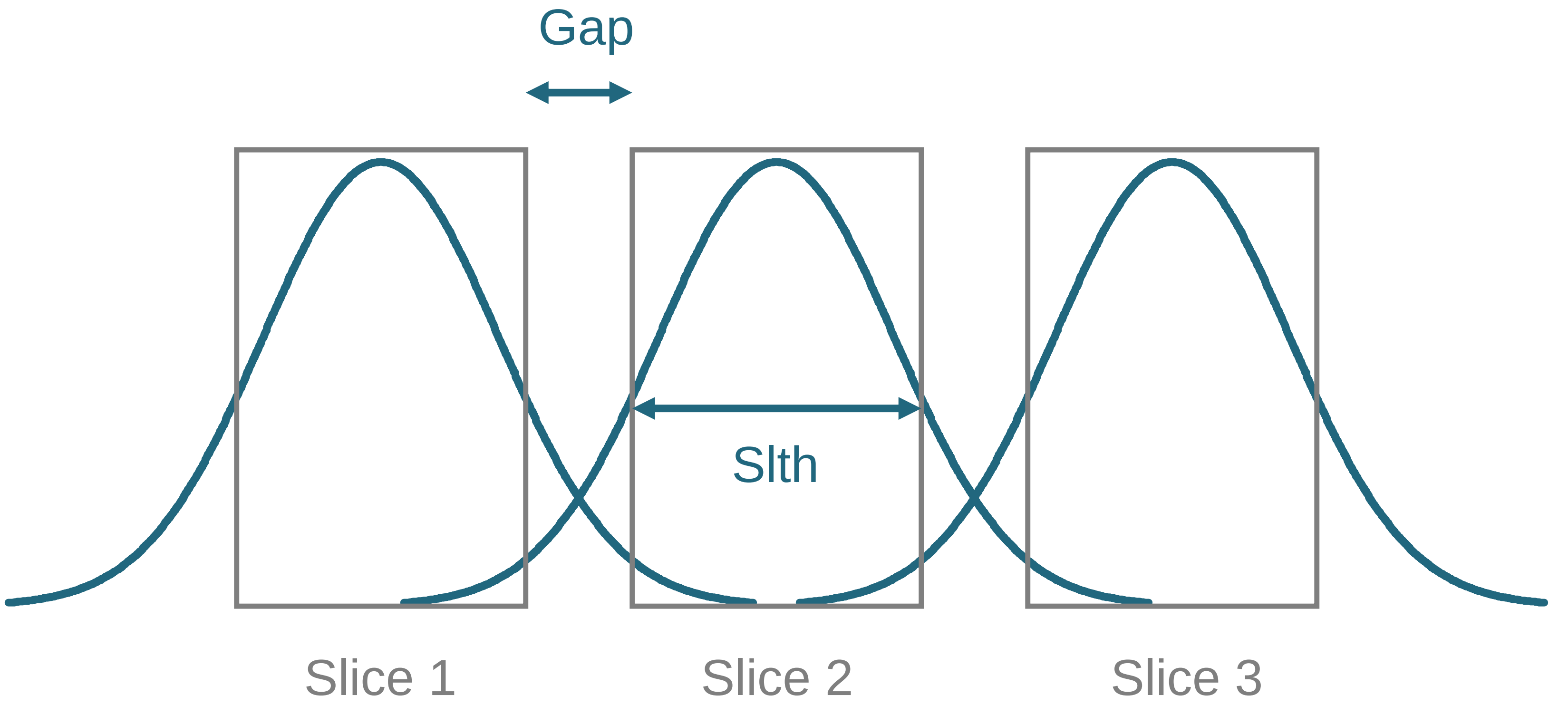
Gaussian-shaped frequency distribution

Slice thickness



Slth= Full width at half maximum of the slice profile

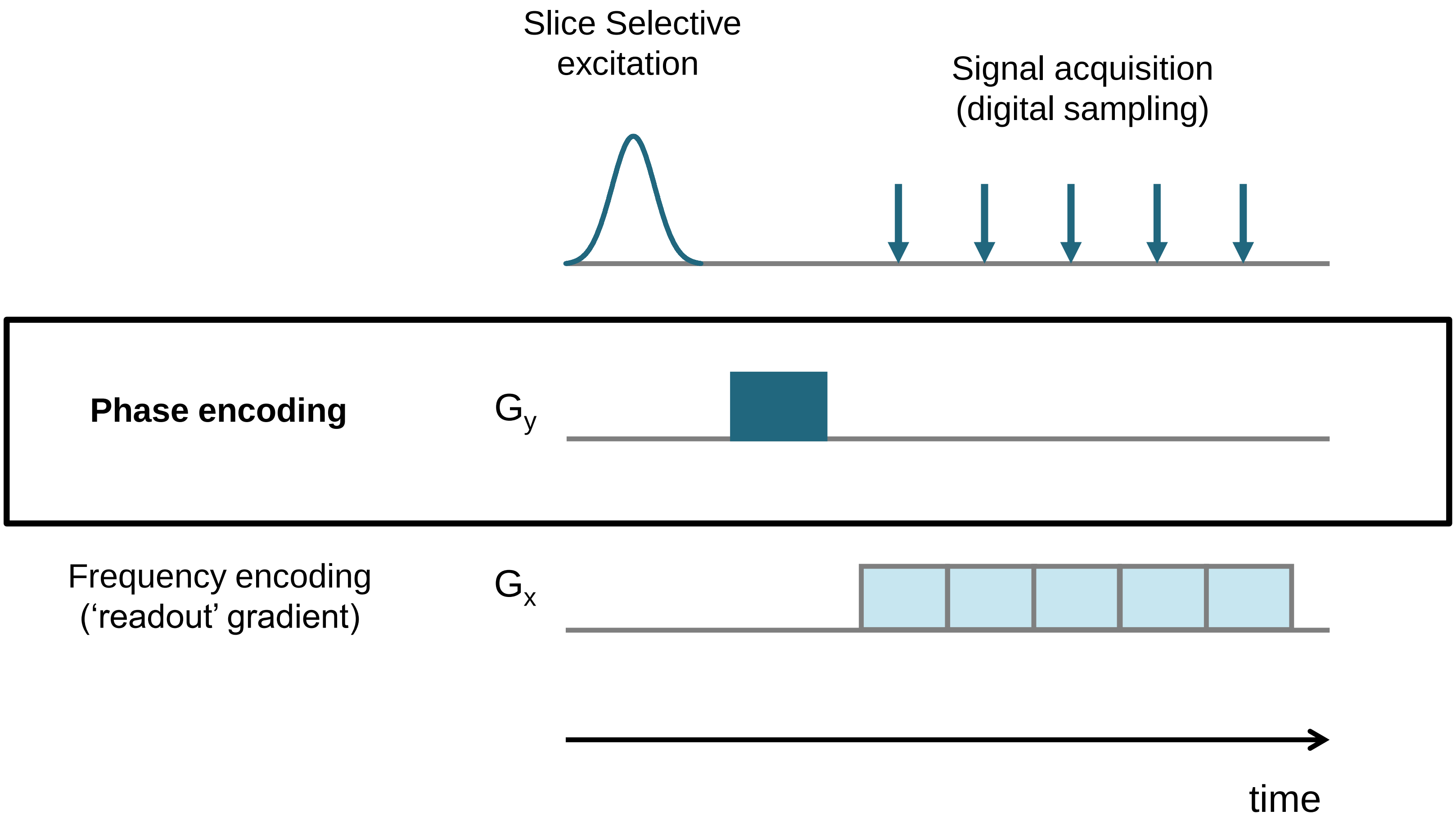
Multi-slice MRI



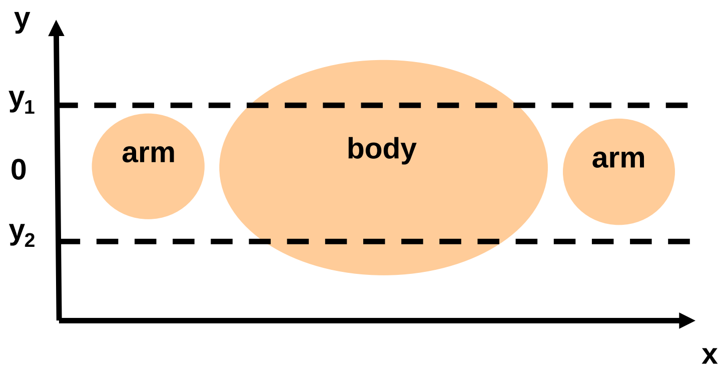
Tissue in the inter-slice gap contributes
to the signal of the adjacent slices

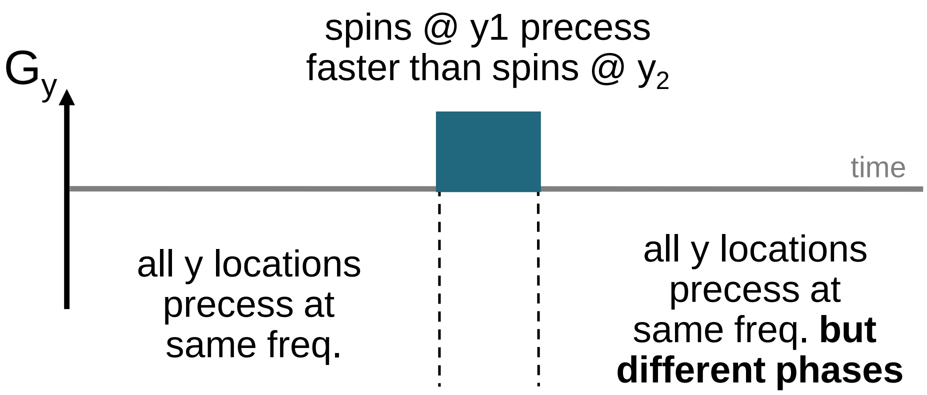
Frequency and phase encoding

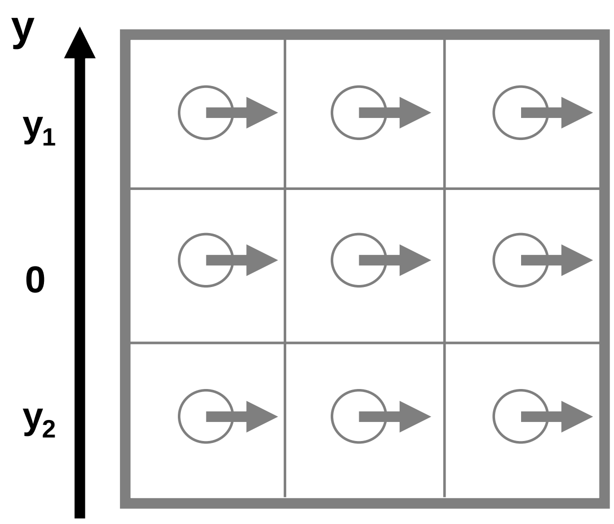
Phase encoding

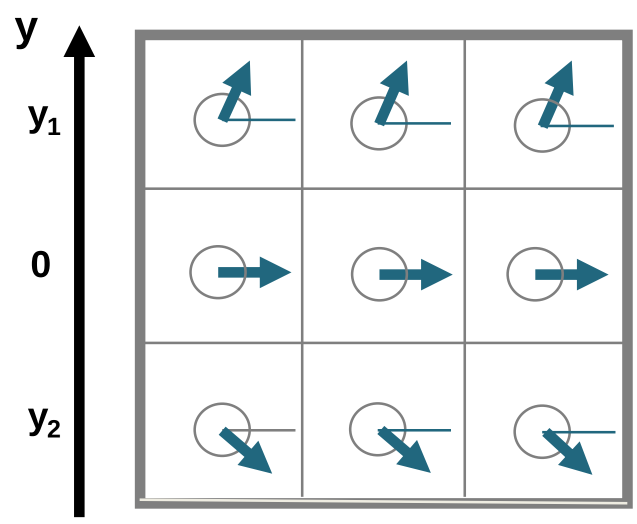


Phase encoding and spatial information



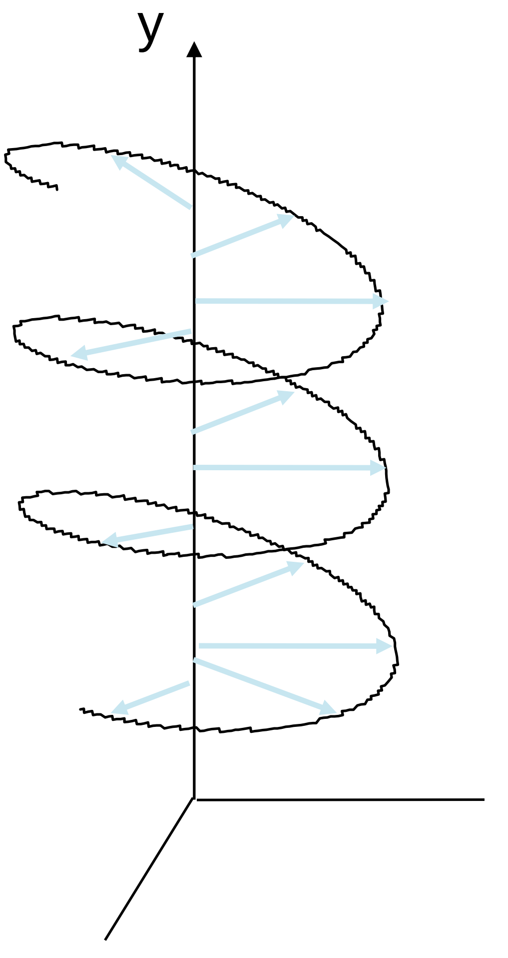






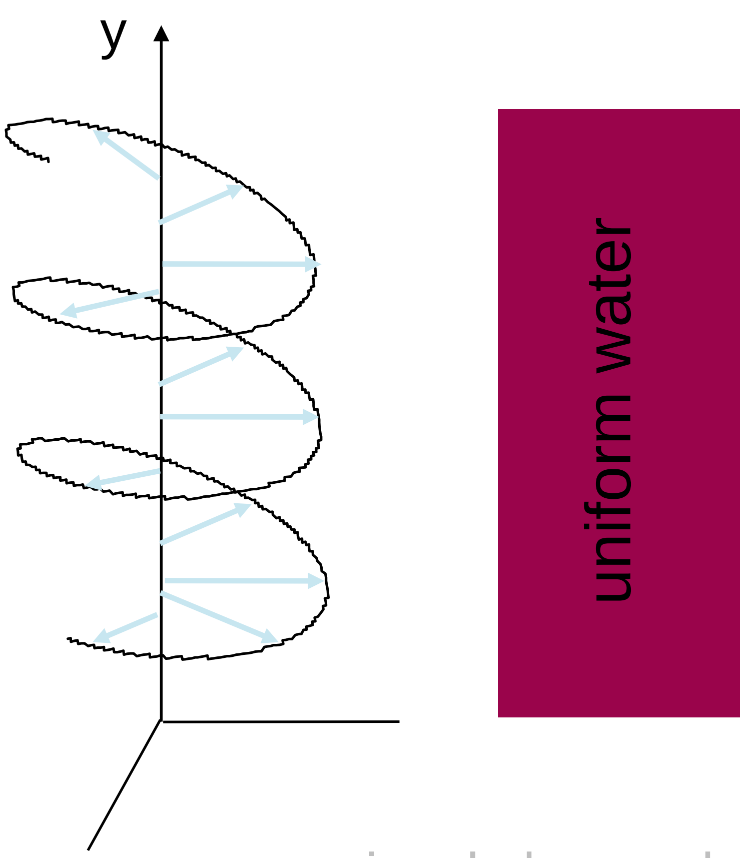
How does phase encoding translate into spatial information?

- The magnetization in the xy plane is wound into a helix directed along y axis.
- Phases are ‘locked in’ once the phase encode gradient is switched off.

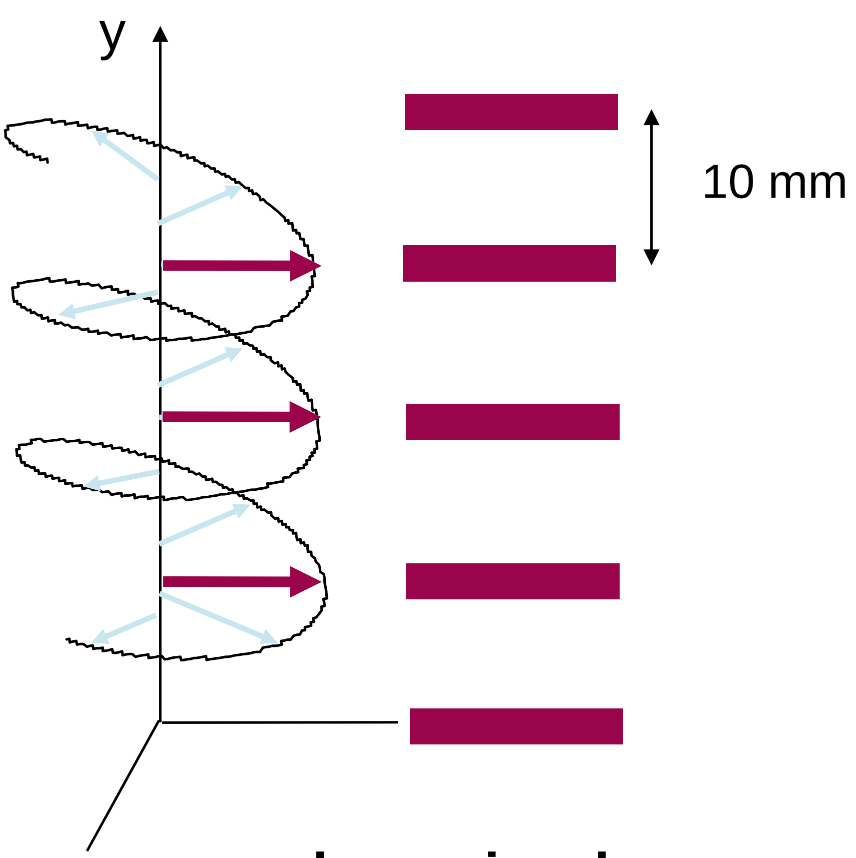


From Larry Wald

Signal after phase encoding



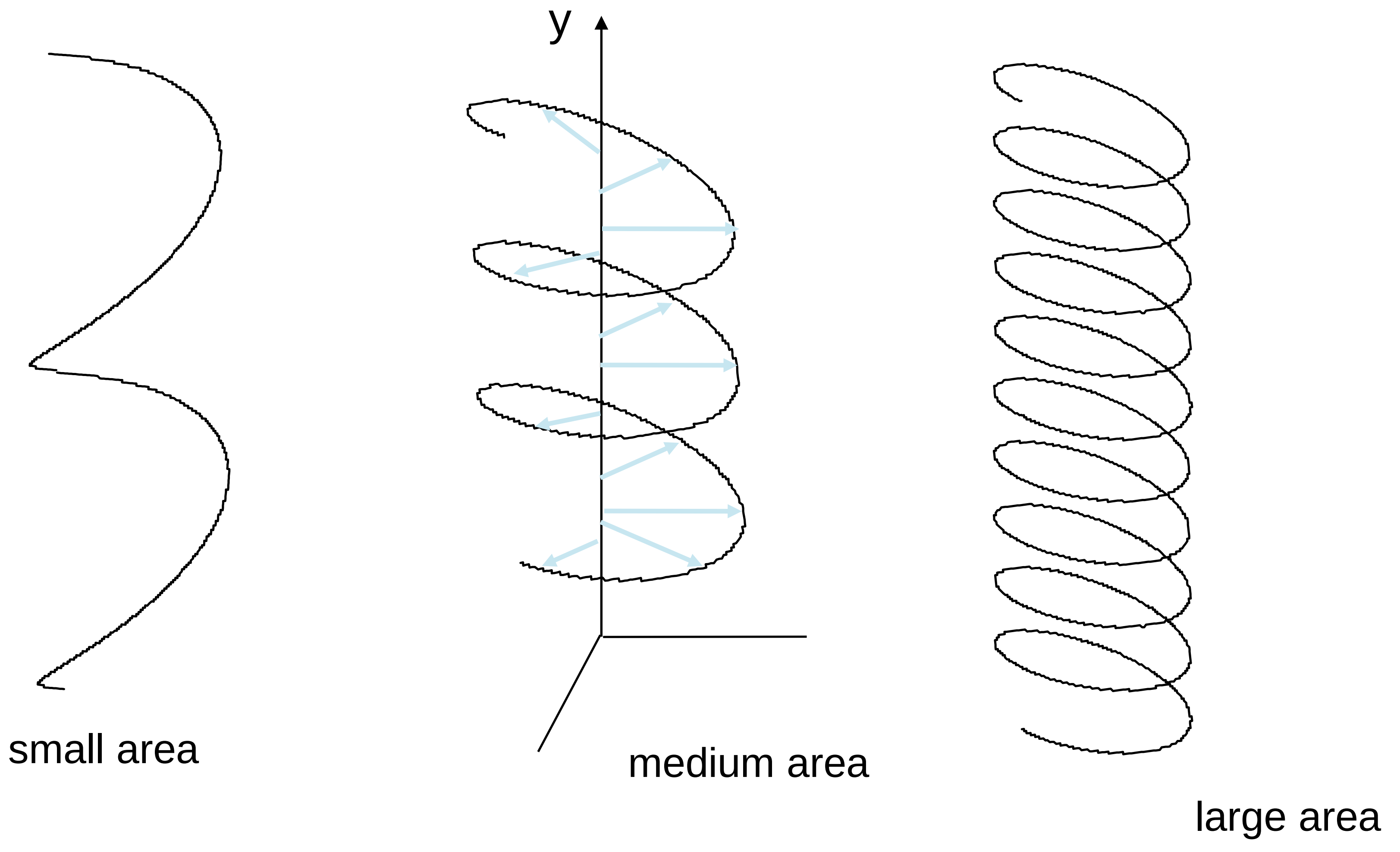
no signal observed



large signal

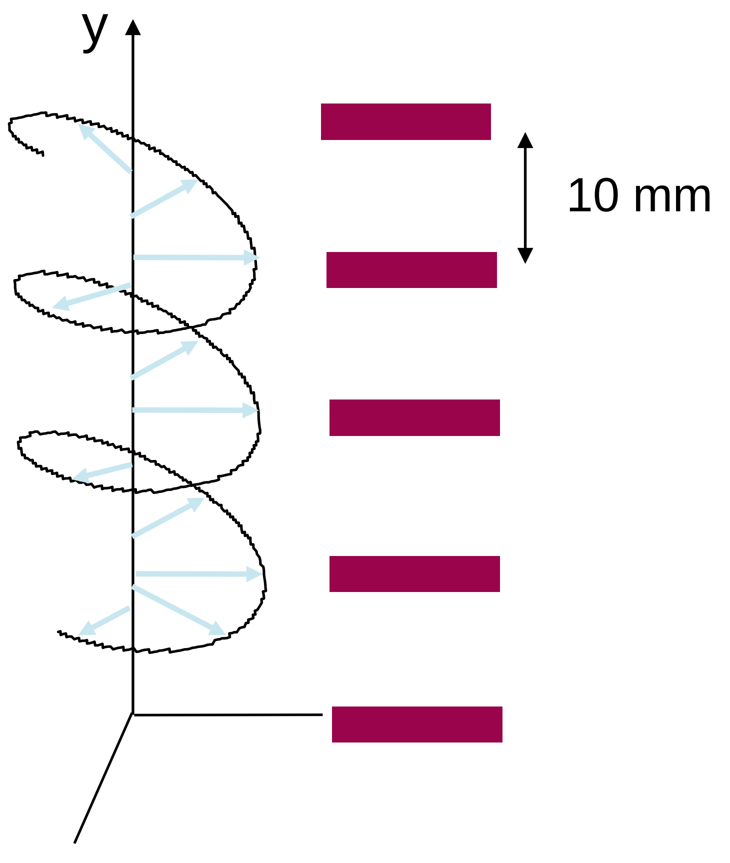
From Larry Wald

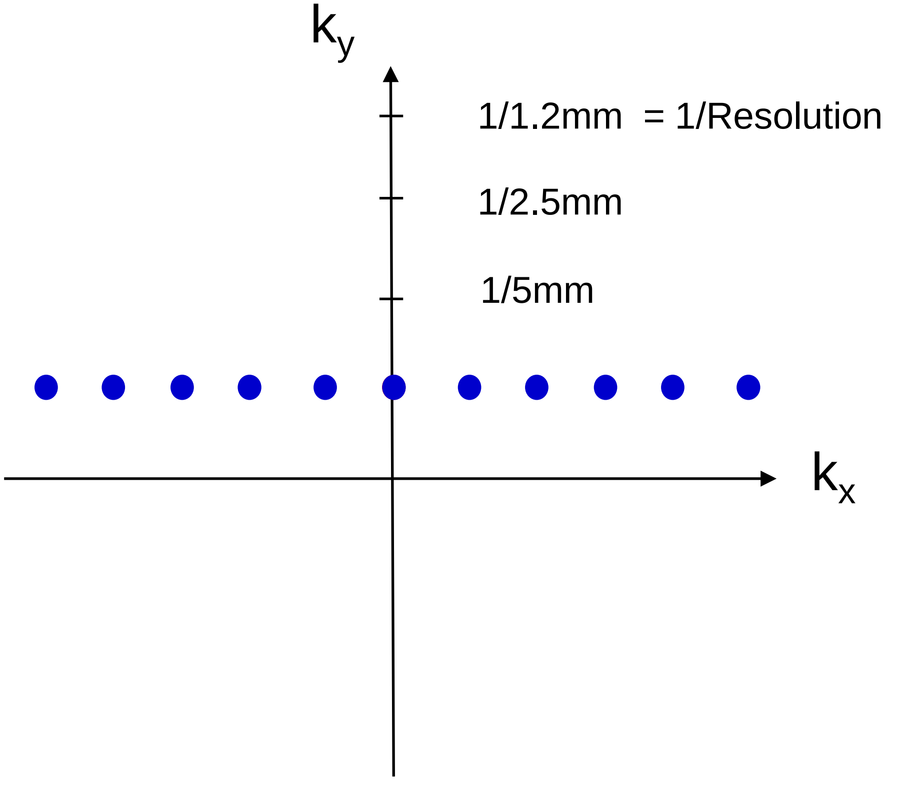
Gradient area and helix shape



From Larry Wald

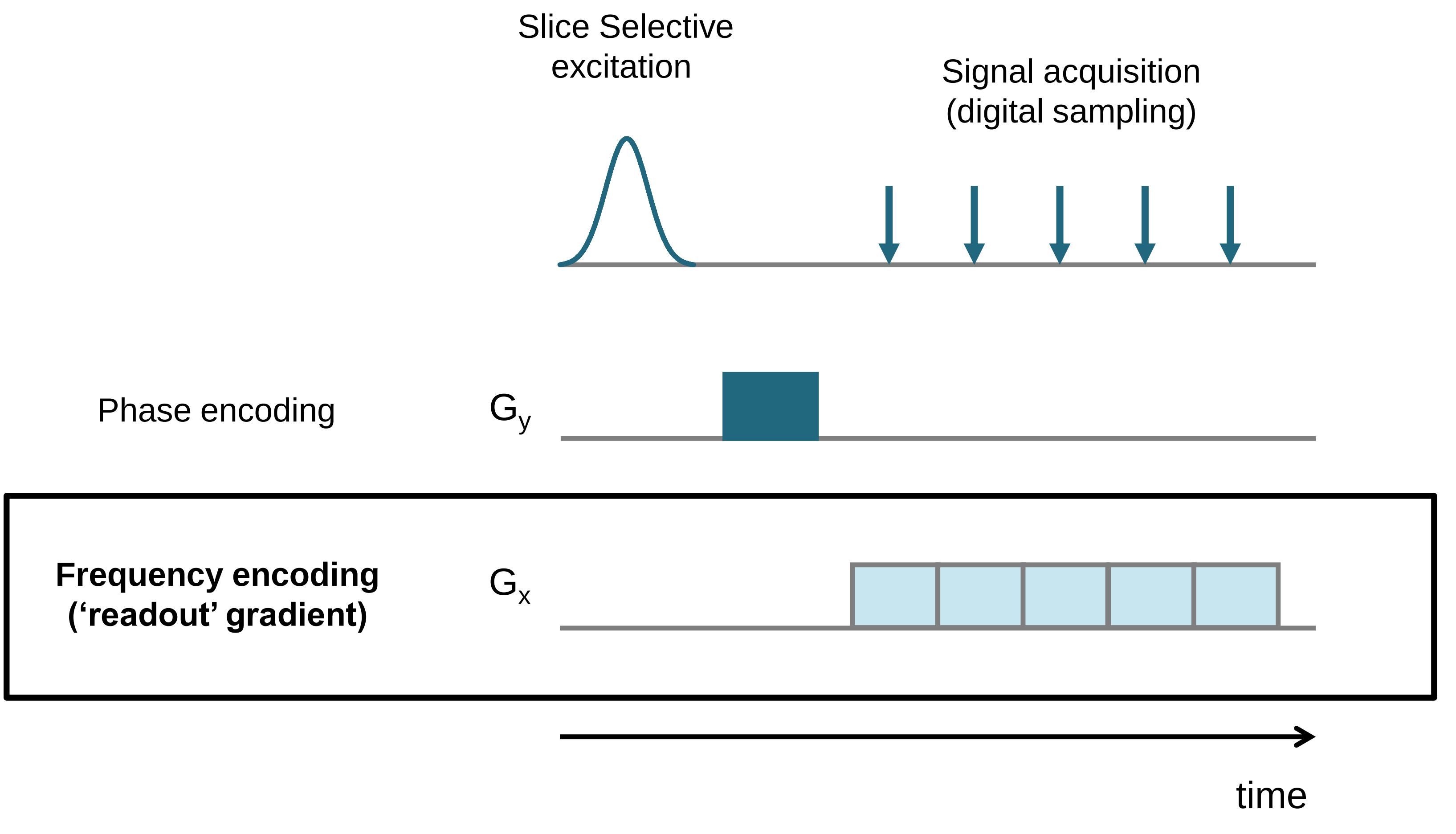
Signal intensity measured at a spatial frequency



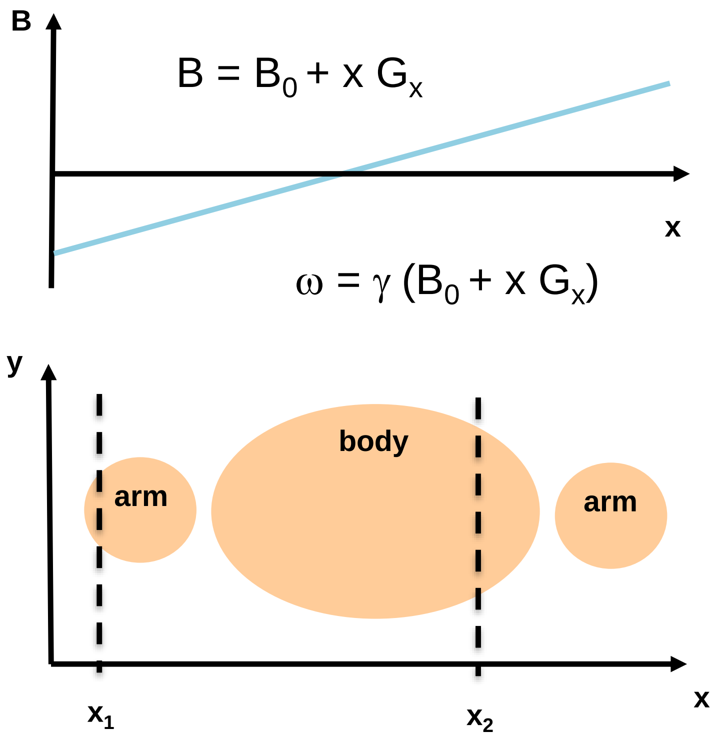


Add frequency encoding

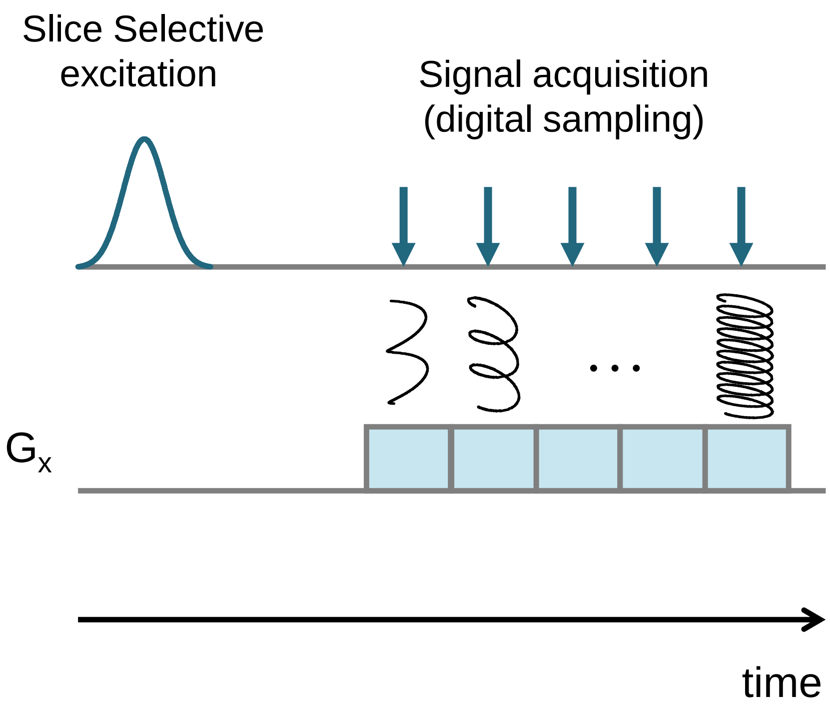
Frequency encoding



Frequency encoding

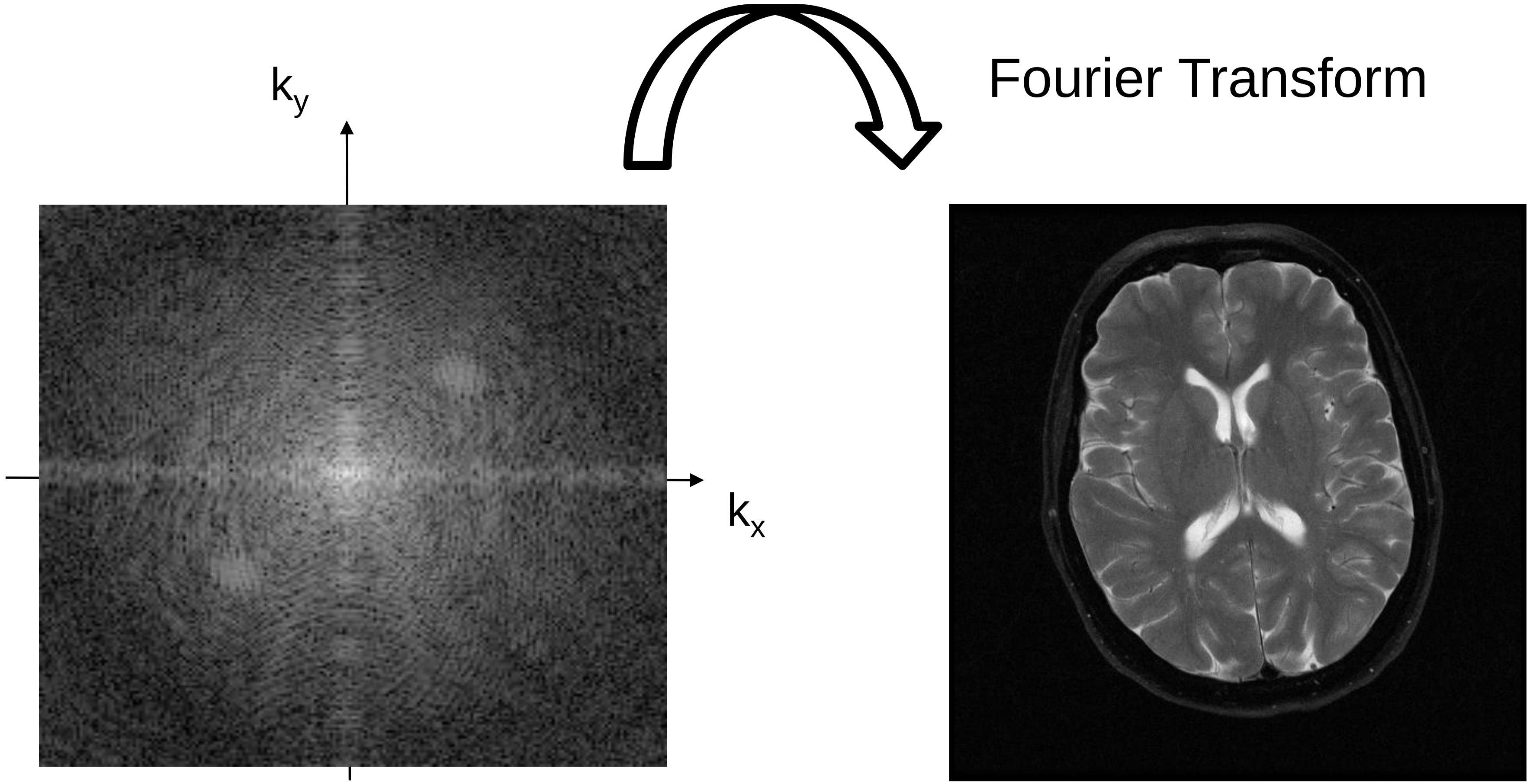


Pulse sequence

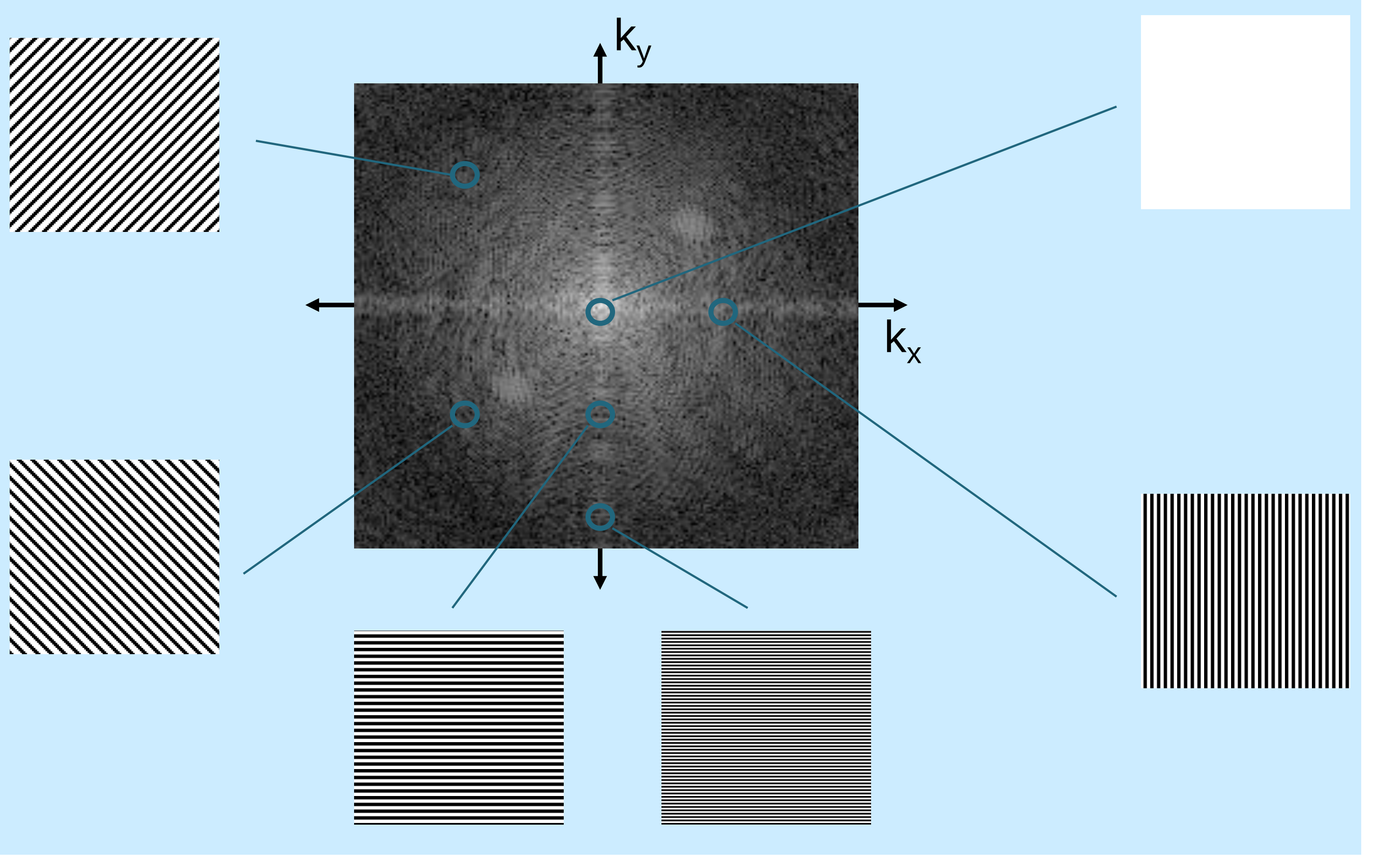


- Spins in position x_1 and x_2 experience different B field and will get out of phase.
- The longer the gradient is applied for, the larger the phase difference.

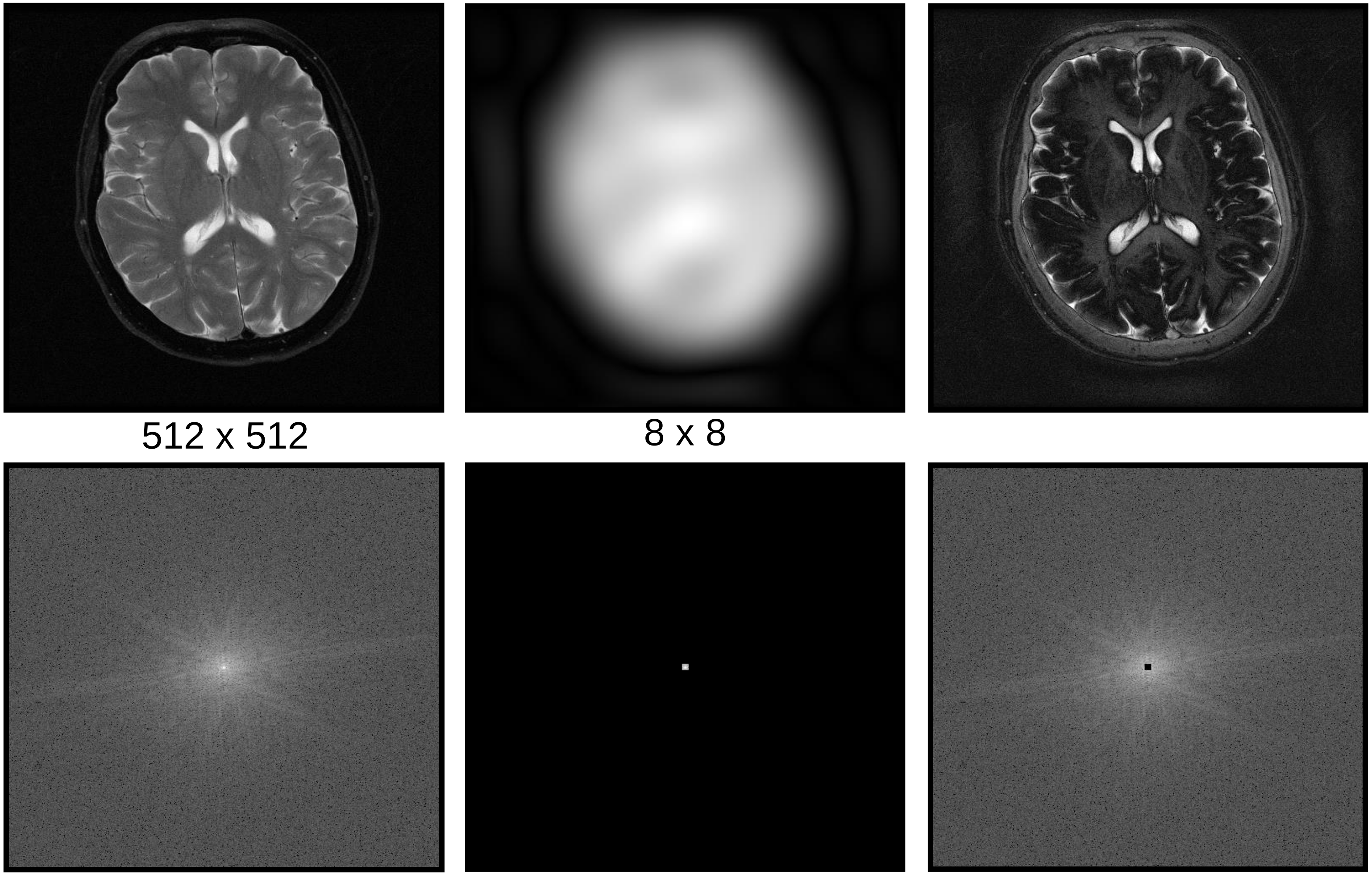
Image reconstruction and k-space



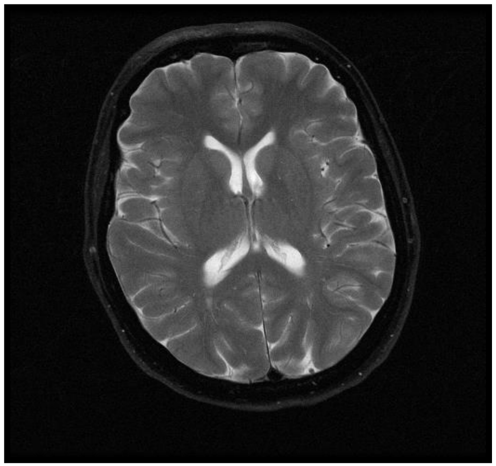
k-space



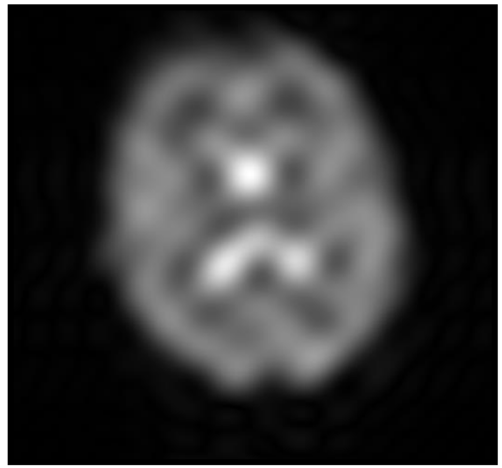
Spatial frequency and contrast



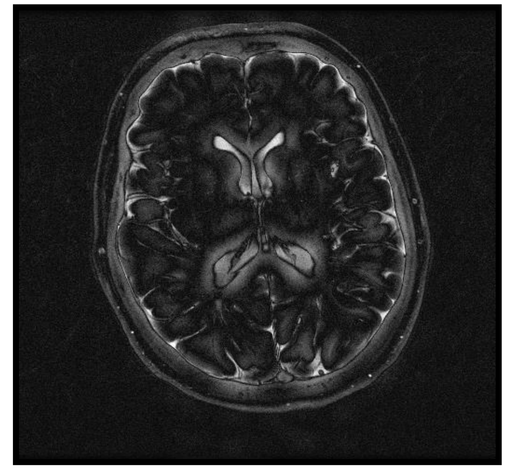
Spatial frequency and contrast

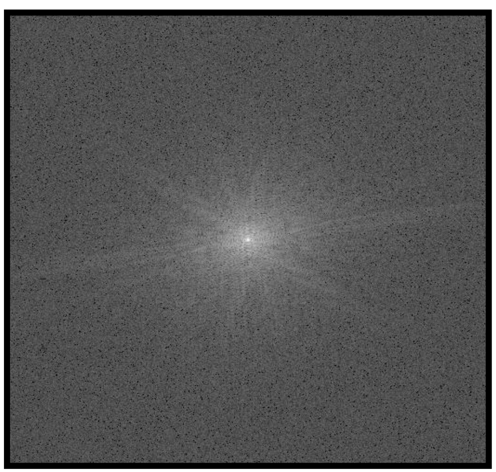


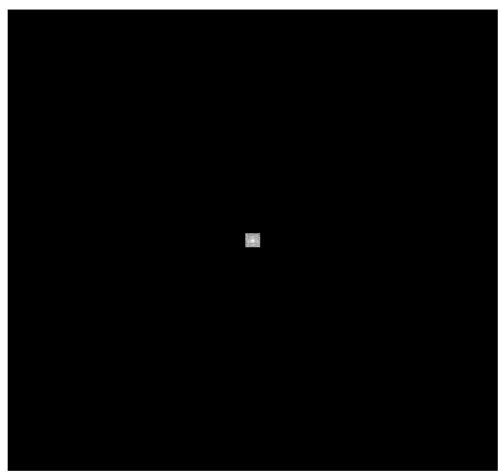
512 x 512

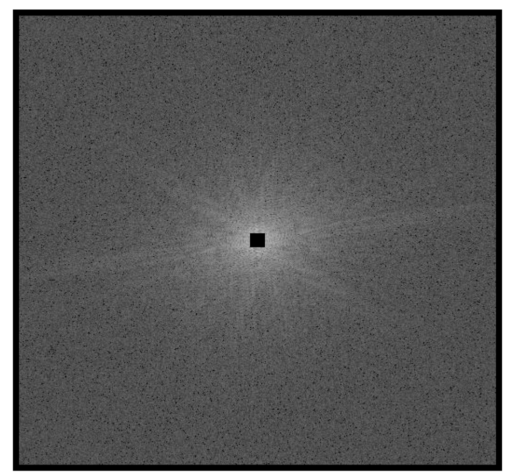


16 x 16

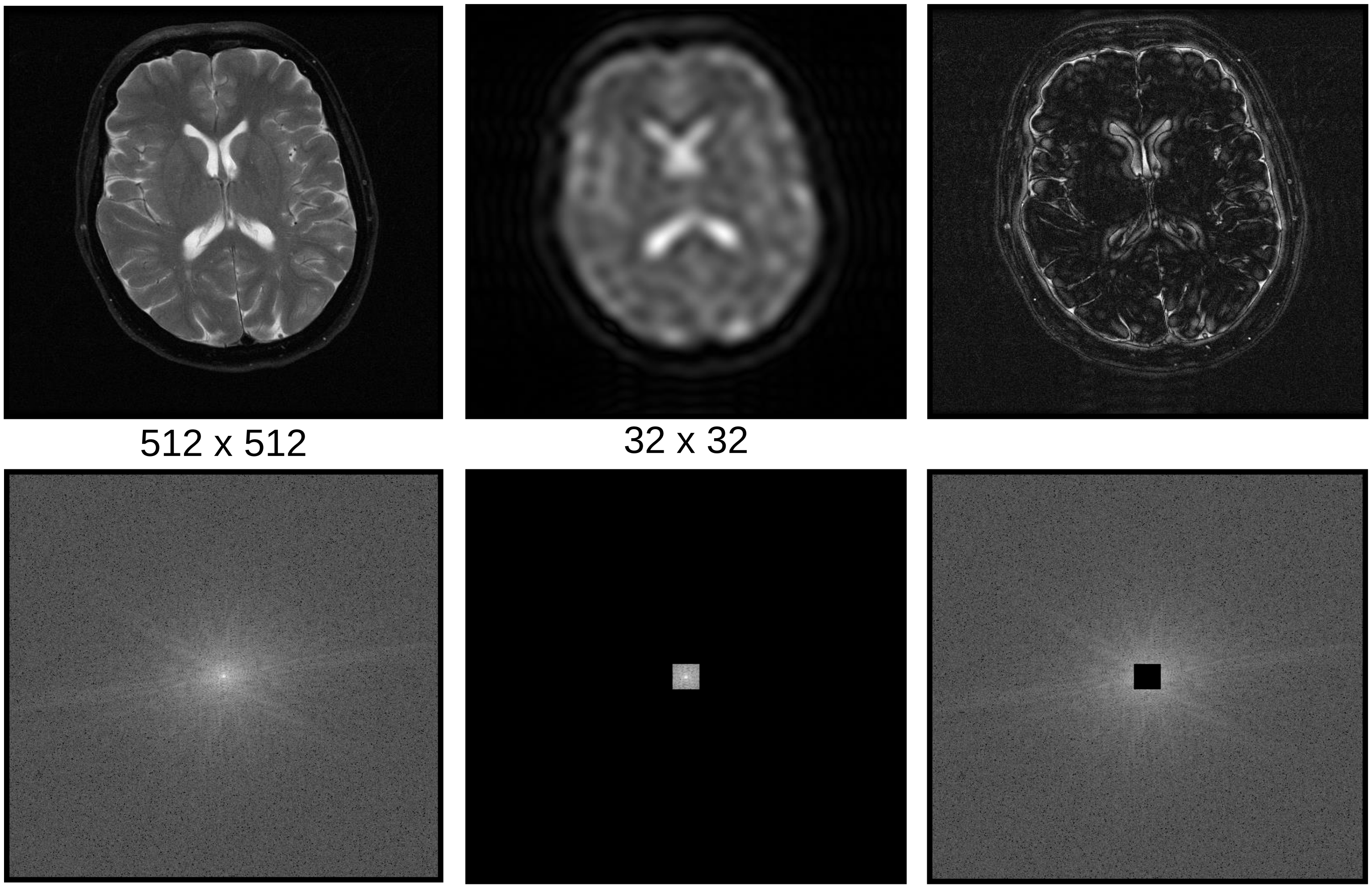




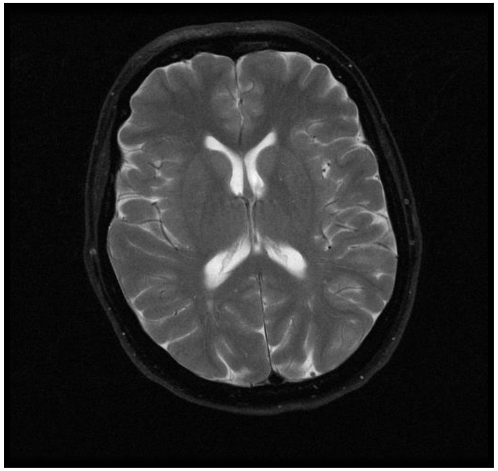


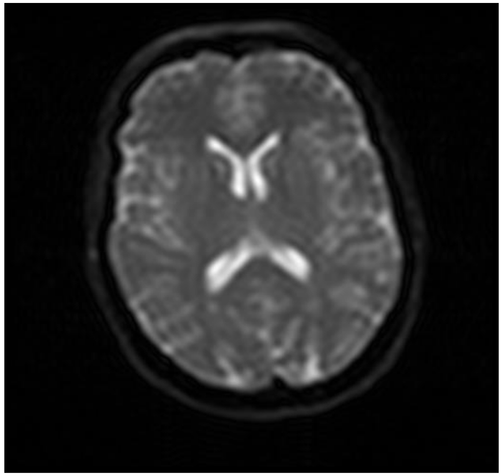


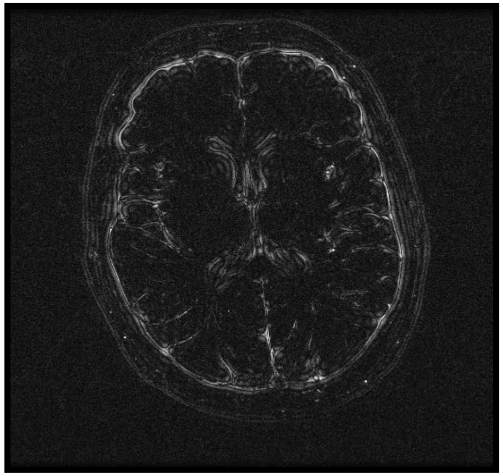
Spatial frequency and contrast

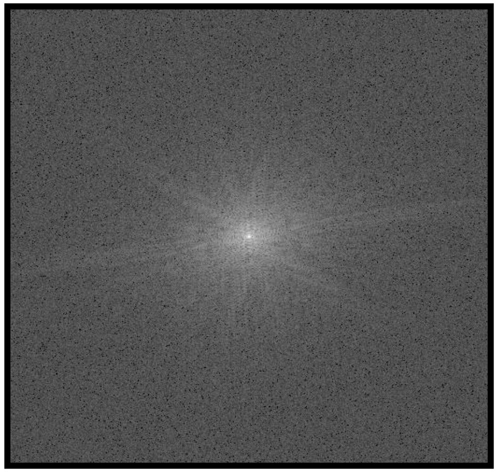


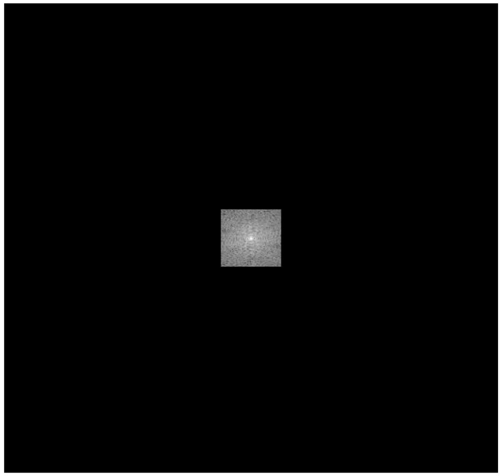
Spatial frequency and contrast

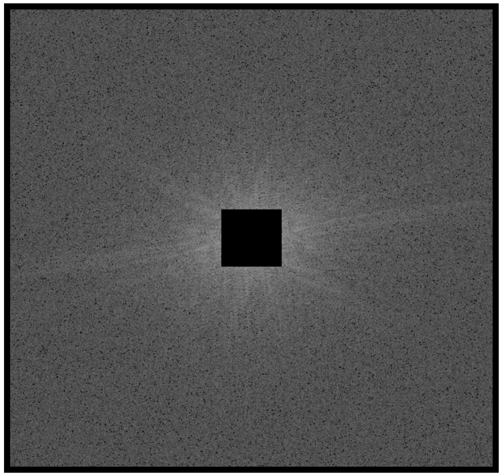

512 x 512


64 x 64

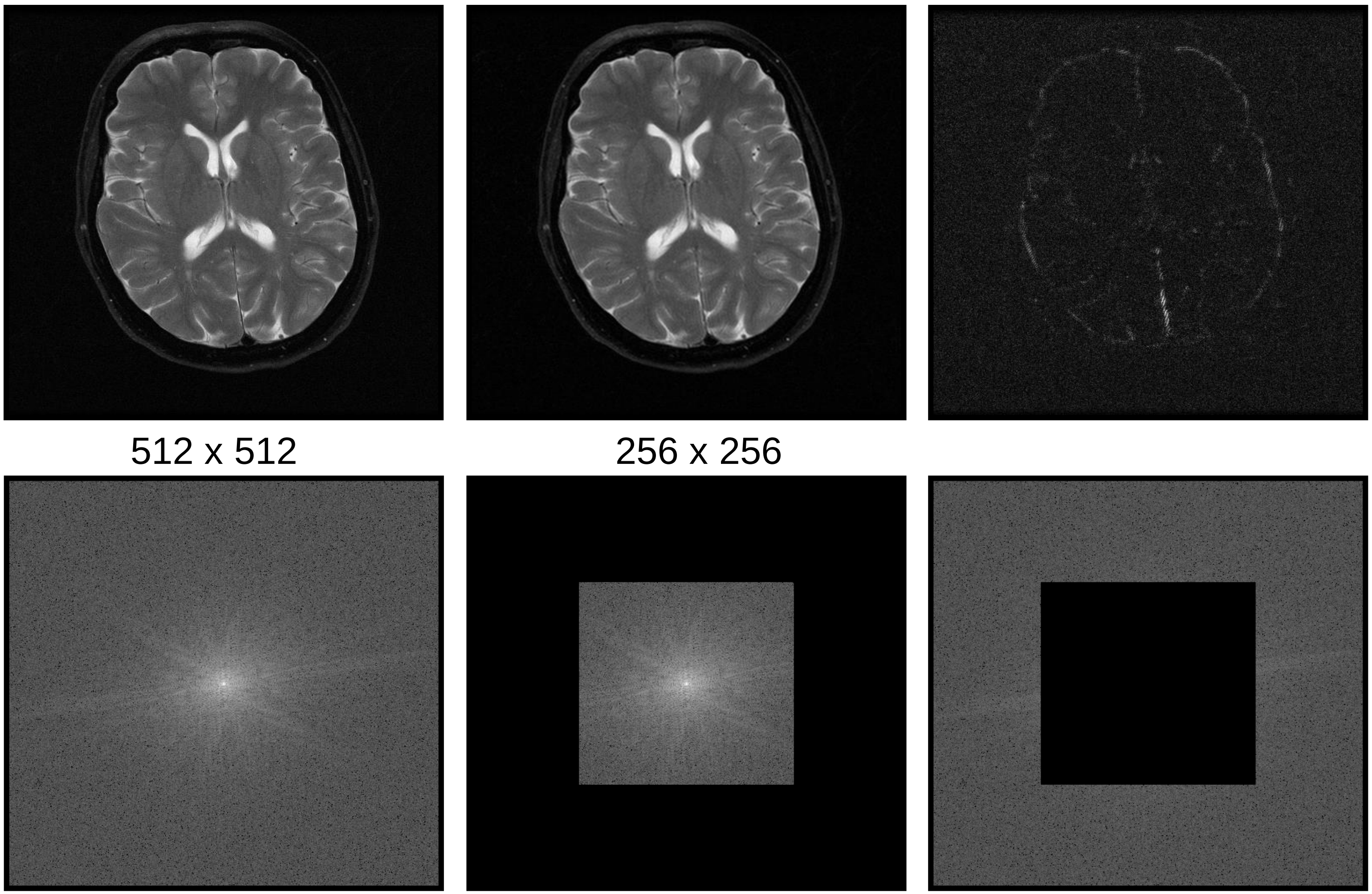




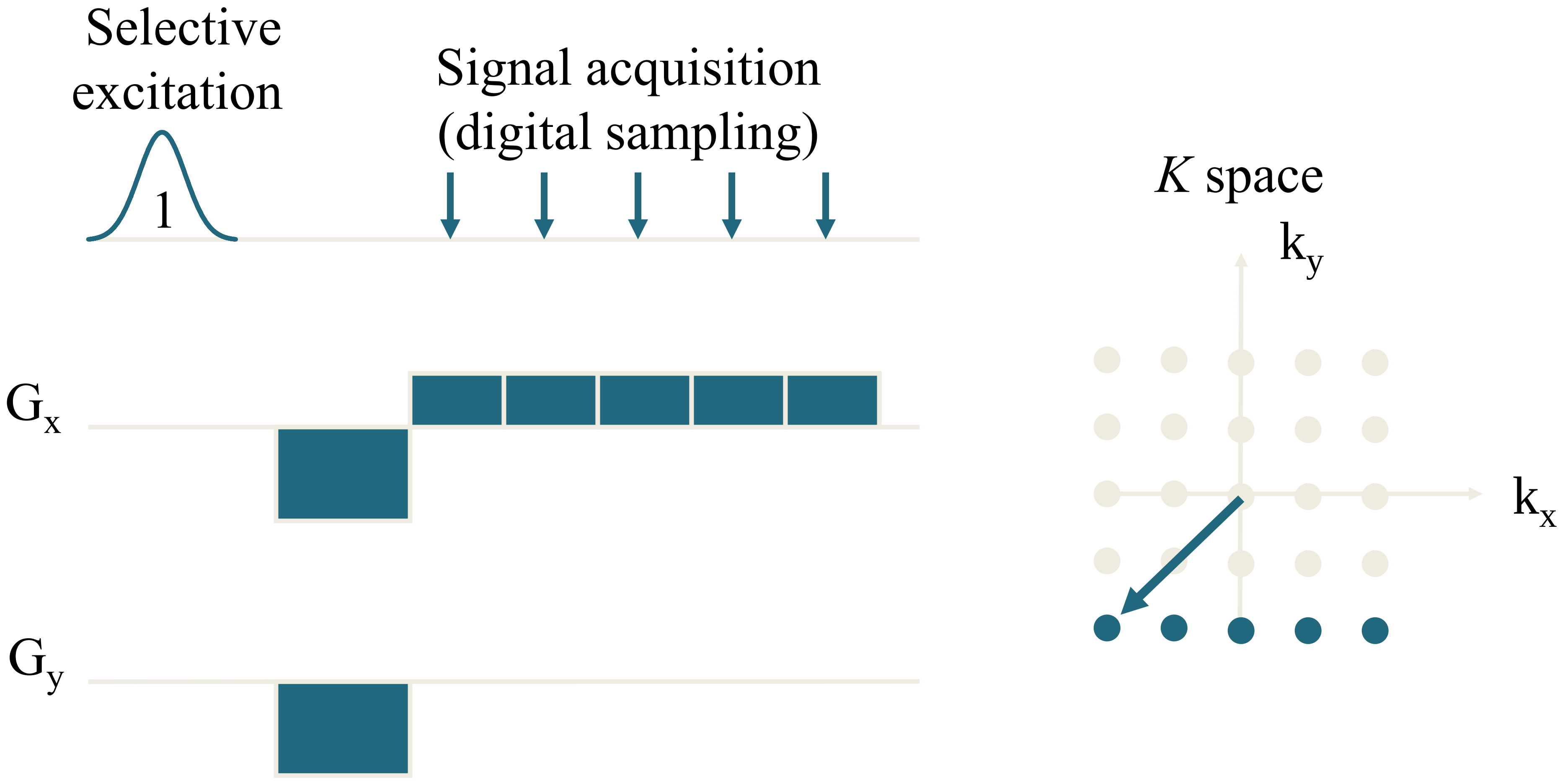




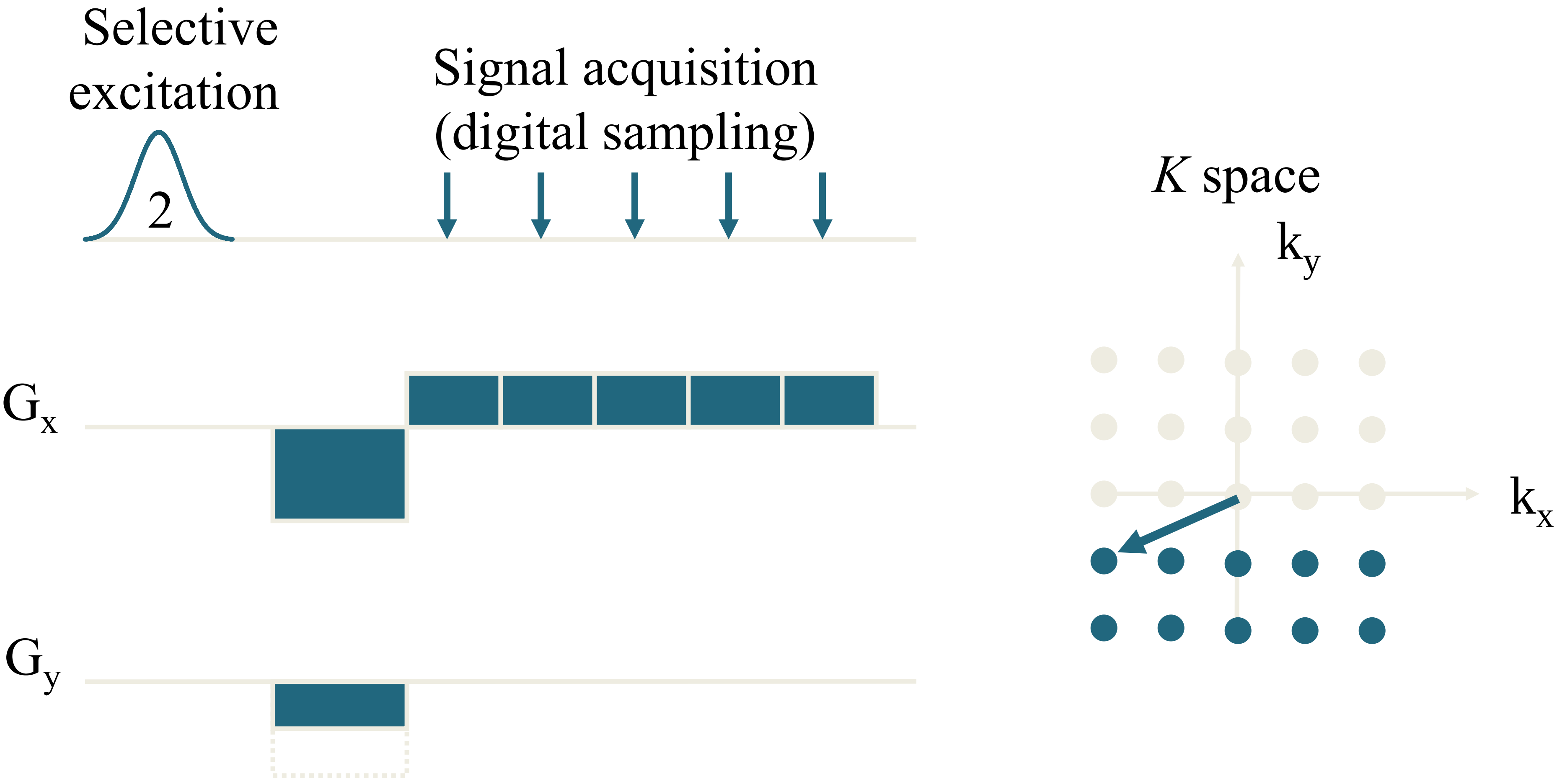
Spatial frequency and contrast



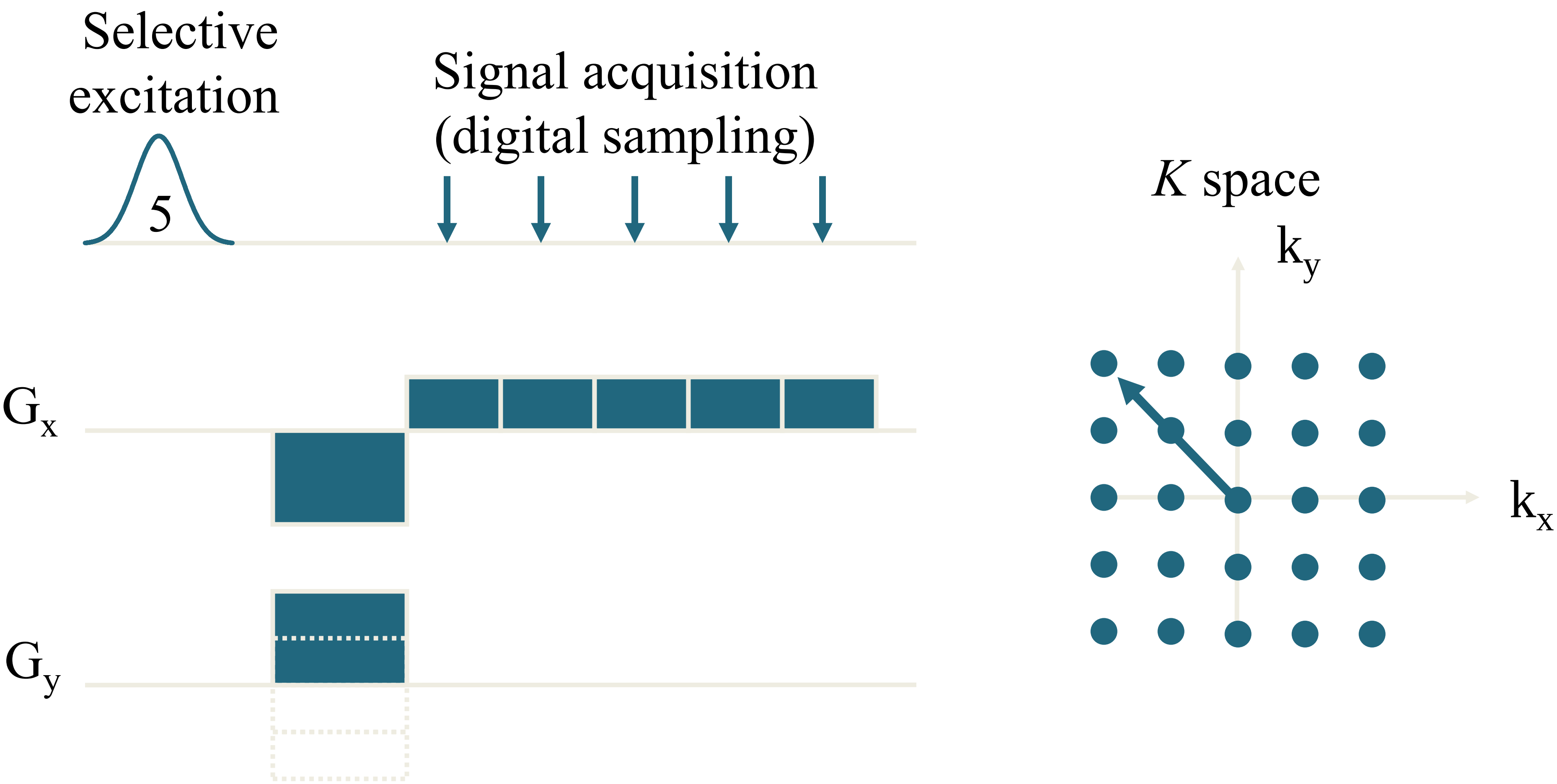
k-space acquisition – Structural Imaging (FLASH)



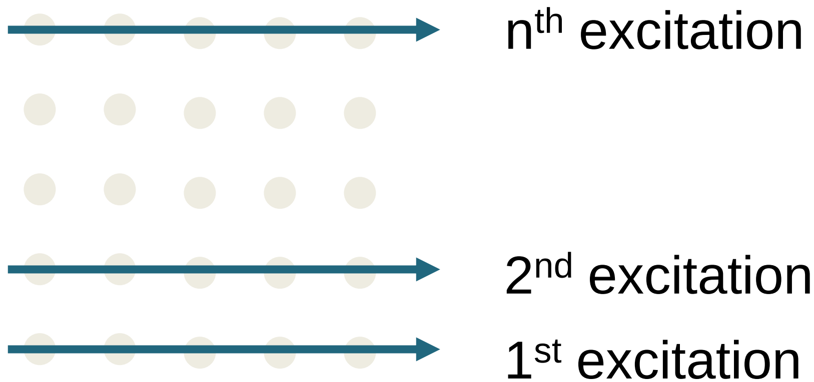
k-space acquisition – Structural Imaging (FLASH)



k-space acquisition – Structural Imaging (FLASH)



k-space acquisition – Structural Imaging (FLASH)



Problem: This sequence is rather slow

- *K* space is sampled line by line
- After each excitation one must wait for the longitudinal magnetization to recover

Example: n = 256, TR = 2s ⇨ T = n TR = 8.5 min

Echo Planar Imaging (EPI)

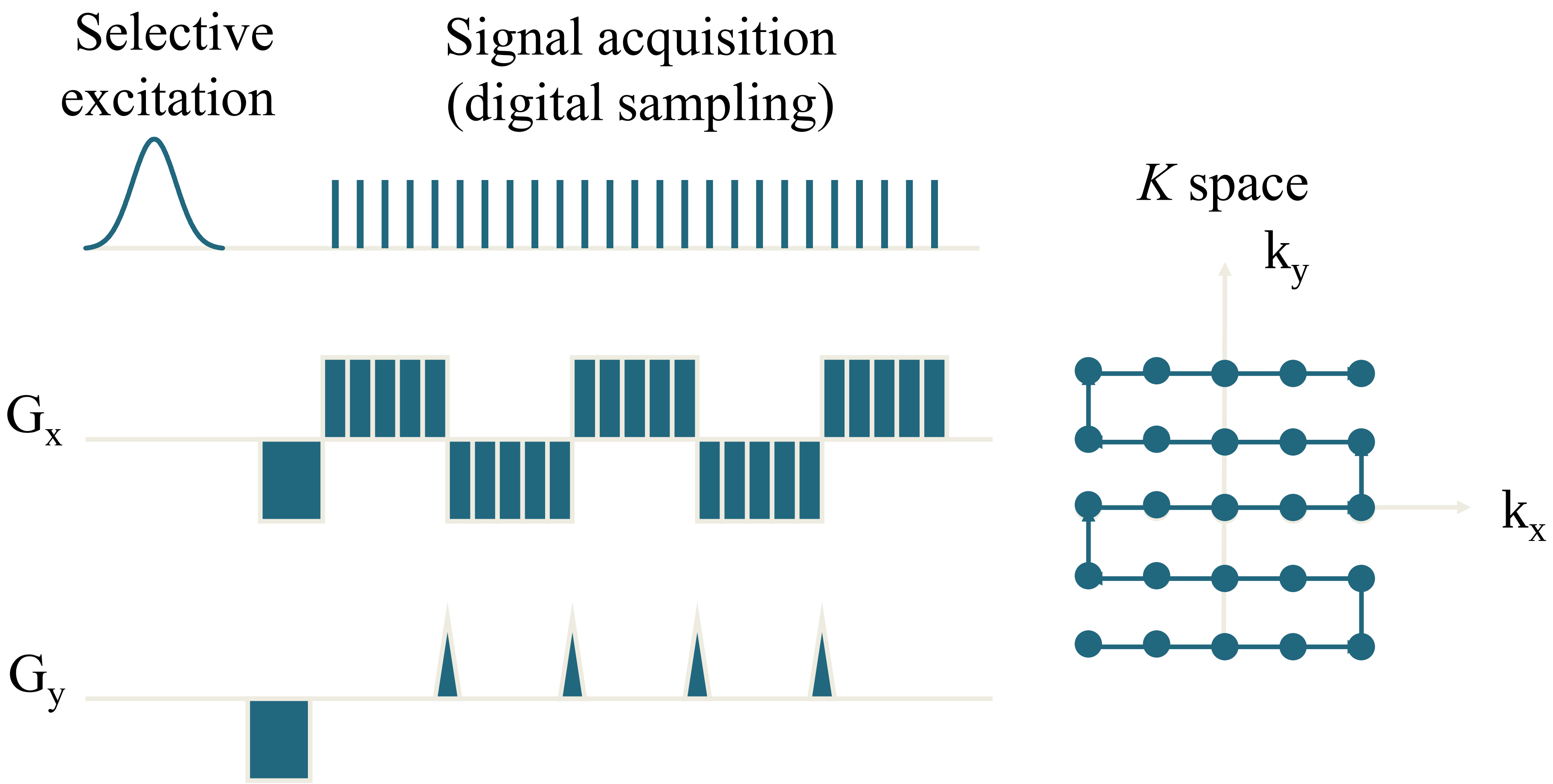
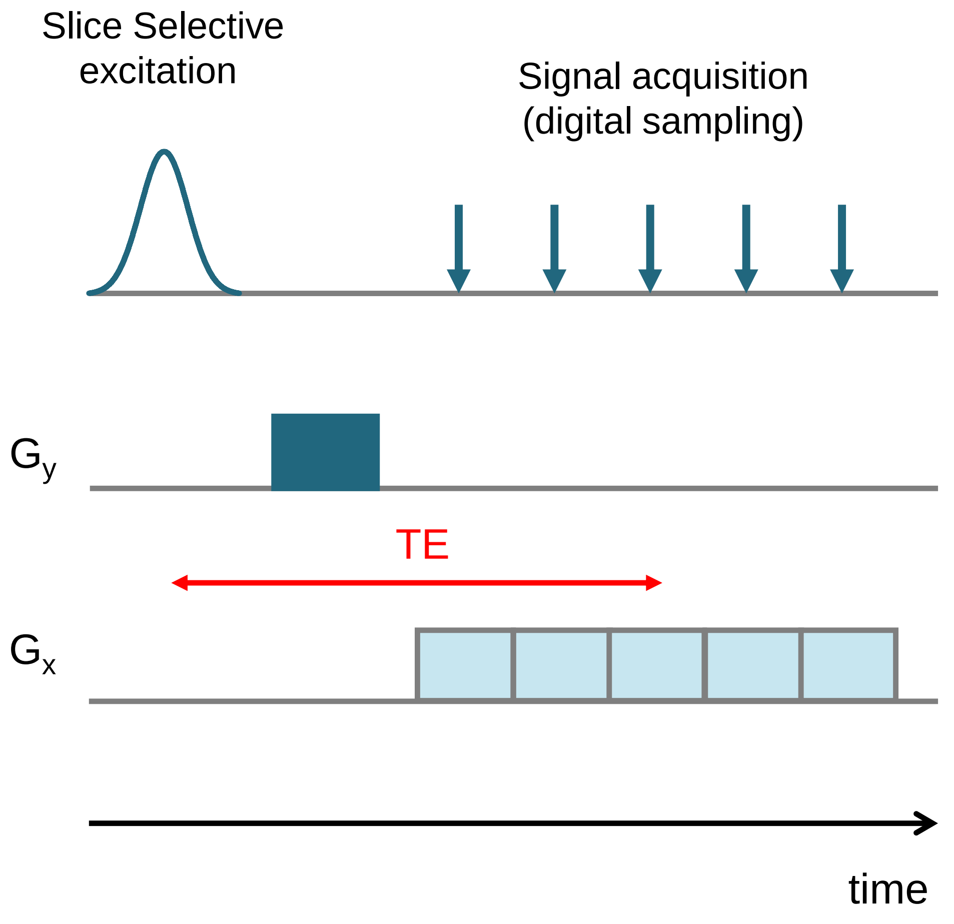
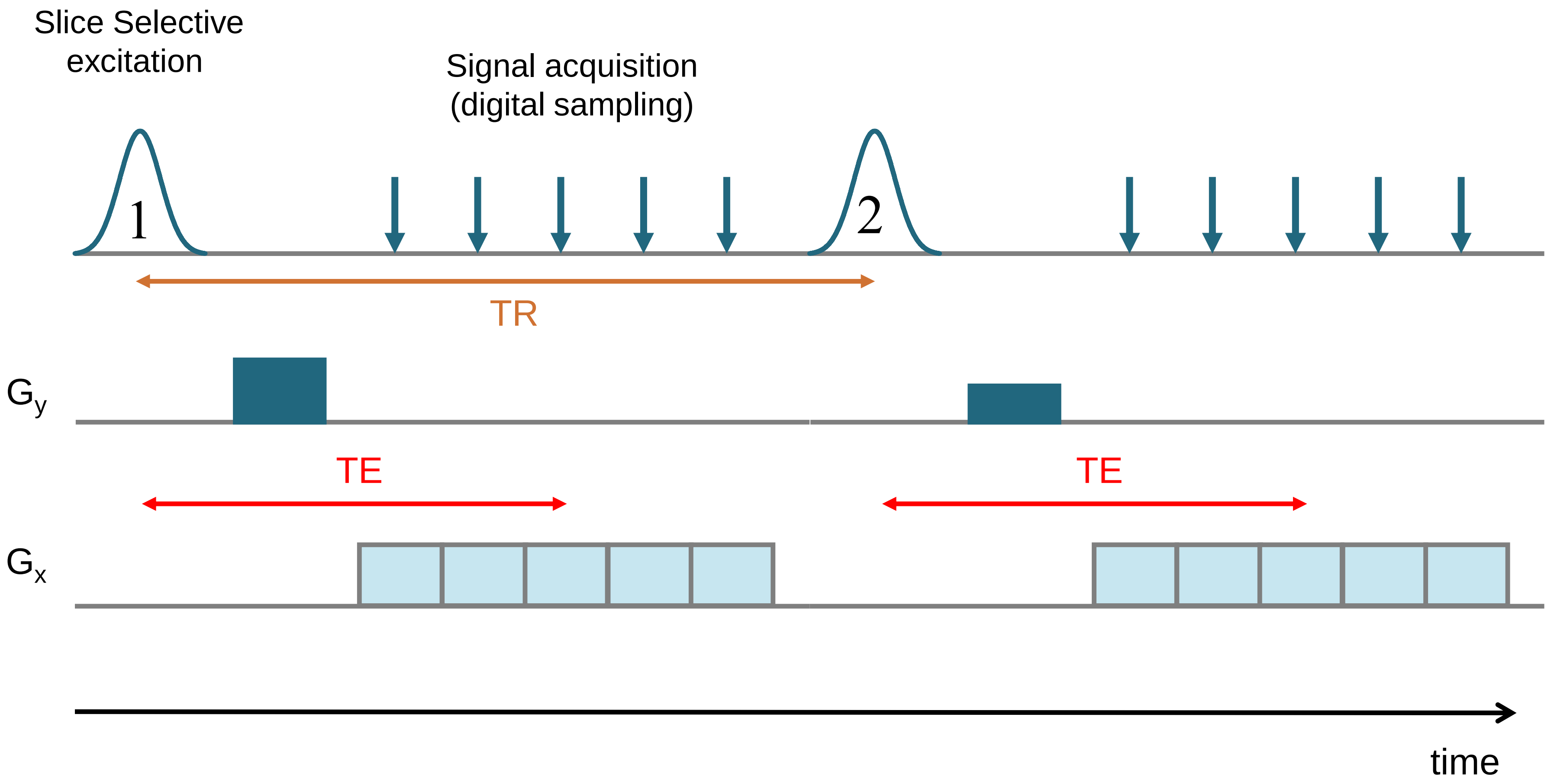


Image Contrast

Echo Time (TE) and Repetition Time (TR)

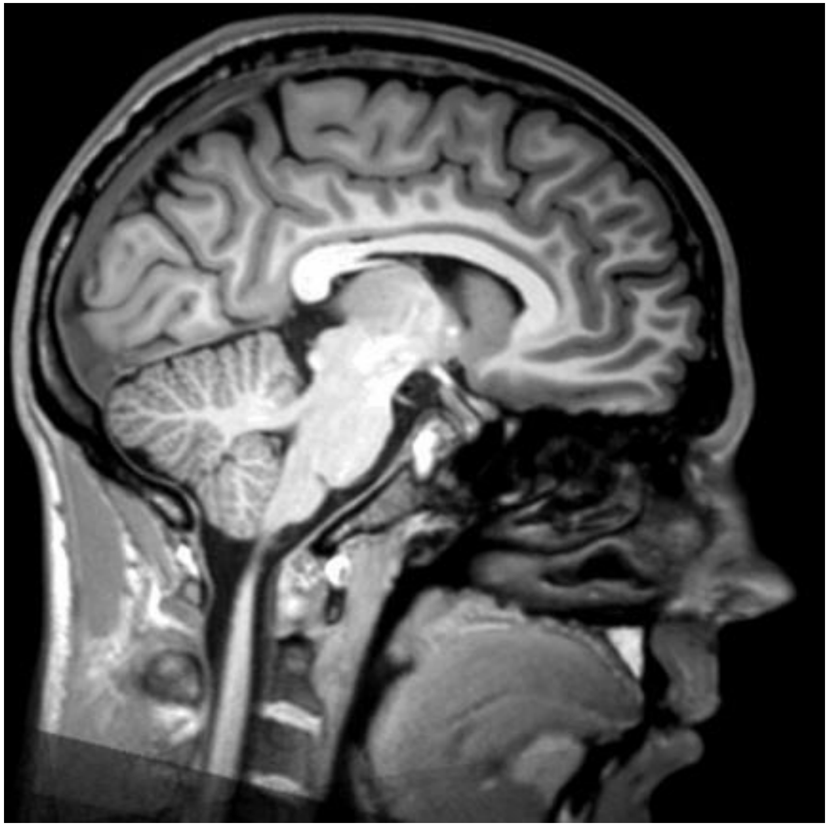


Echo Time (TE) and Repetition Time (TR)

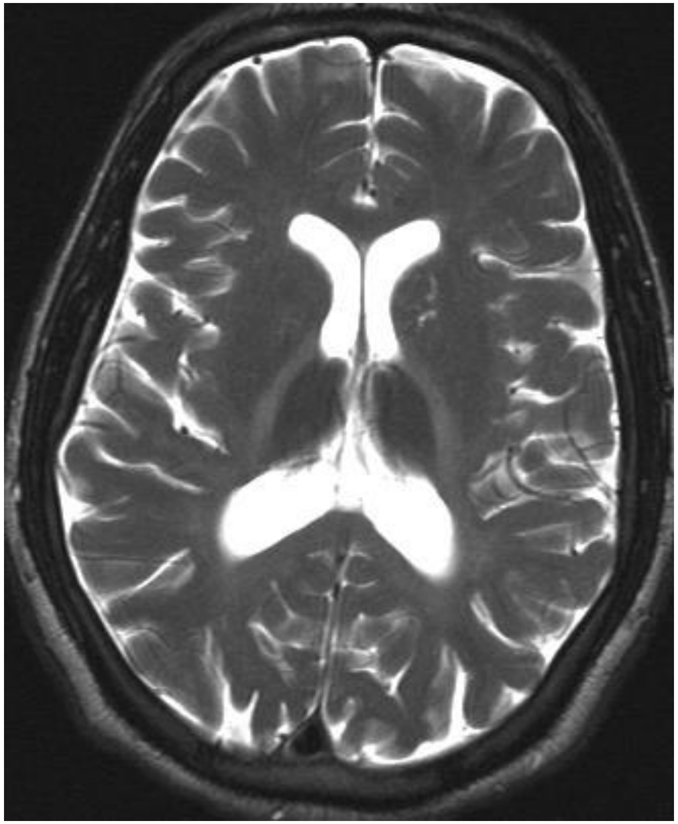


Tissue Contrast

T1-weighted
Bright **fat, Short** TR & TE



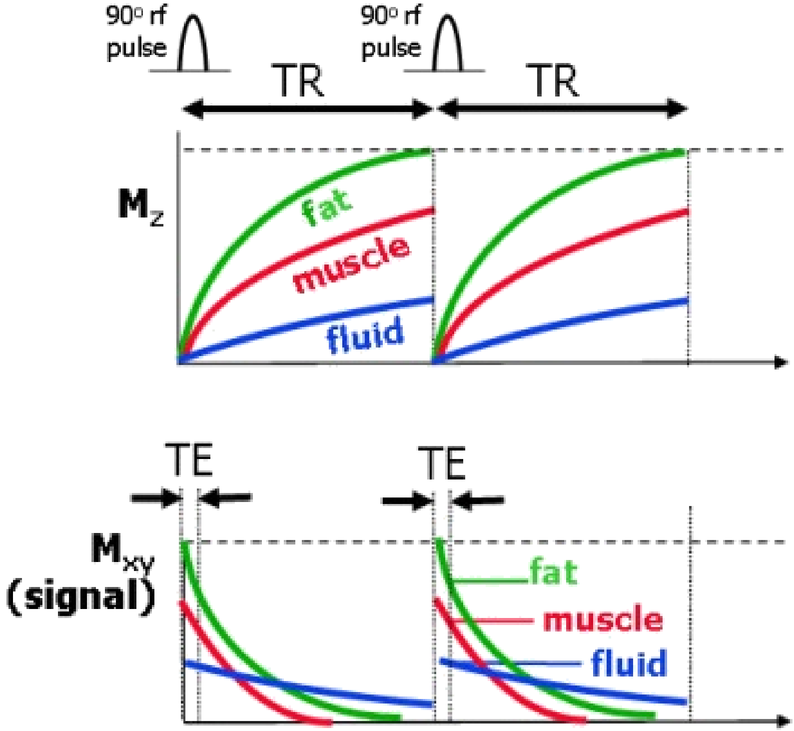
T2-weighted
Bright **fluid, Long** TR & TE



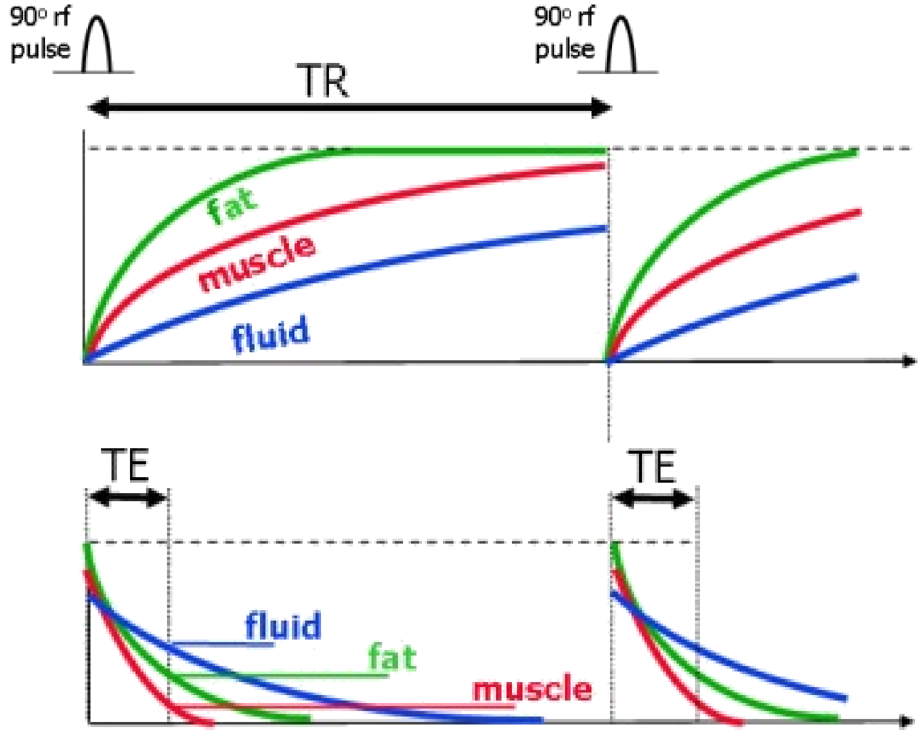
Ridgeway, J. (2010) Cardiovascular magnetic resonance physics for clinicians: Part I

Tissue Contrast

T1-weighted
Bright **fat, Short** TR & TE



T2-weighted
Bright **fluid, Long** TR & TE

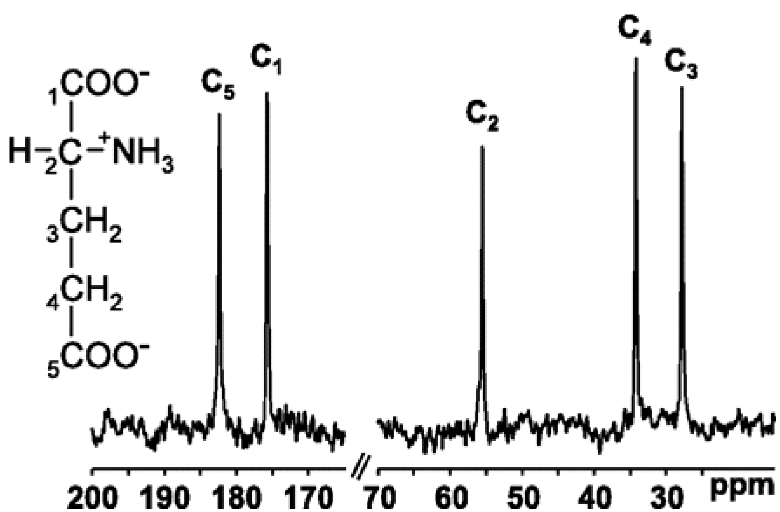


Ridgeway, J. (2010) Cardiovascular magnetic resonance physics for clinicians: Part I

Part III:
Magnetic Resonance Spectroscopy (MRS)

What is MRS?

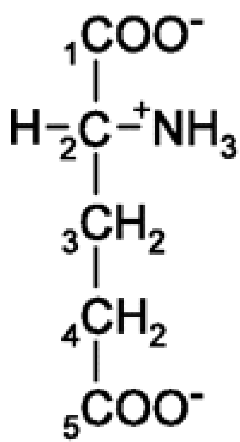
- MRI determines the spatial distribution of water protons across a region of interest.
- MRS measures the chemical content of MR-visible nuclei, including hydrogen (^{1}H), carbon (^{13}C), and phosphorus (^{31}P).
- MRS is sensitive to different chemical environments within a molecule.



Befroy DE and Shulman GI. Diabetes 2011

Basic principles of MRS

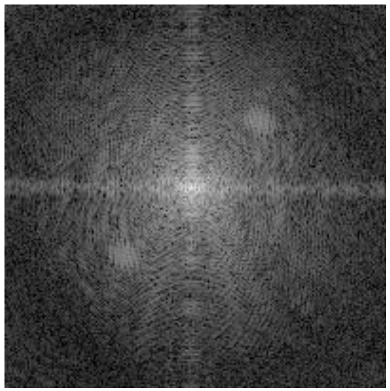
- Unlike MRI, a read-out gradient is not applied in MRS.
- The frequency information is used to identify the different chemical compounds, instead of the spatial distribution of protons.
- Proton spins in different molecules will experience slightly different magnetic fields, which in turn alters their resonance frequency.



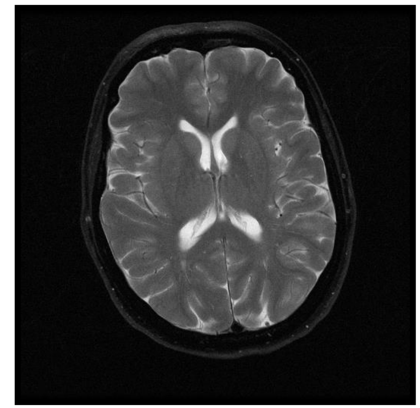
$$\omega_1 = \gamma B_1$$
$$\omega_2 = \gamma B_2$$
$$\vdots$$
$$\omega_5 = \gamma B_5$$

Basic principles of MRS

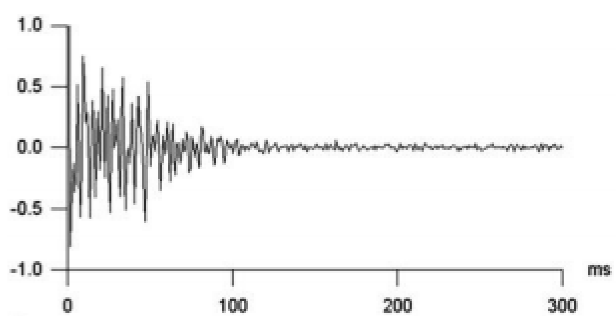
MRI



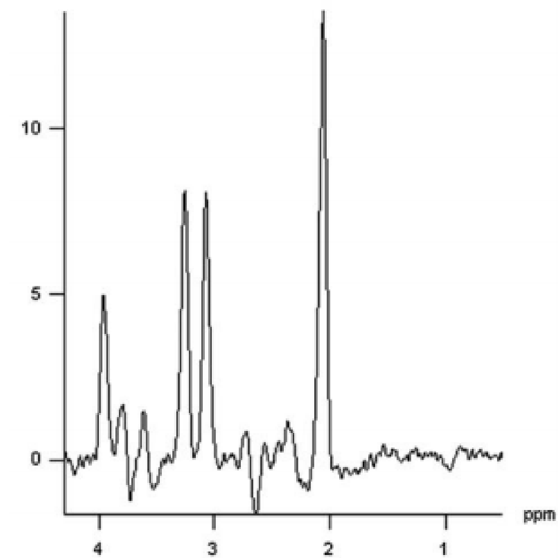
Fourier Transform



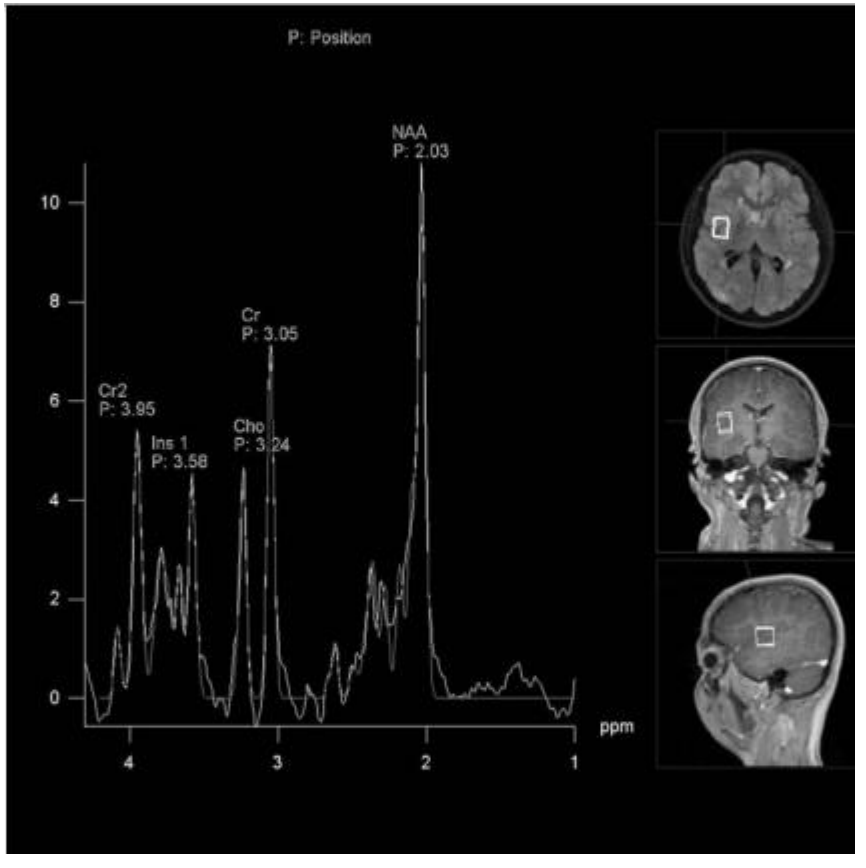
MRS

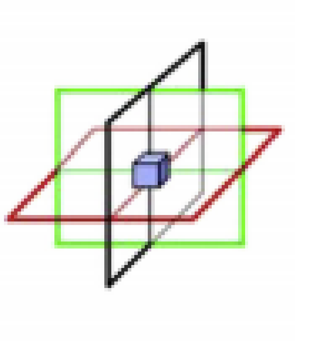


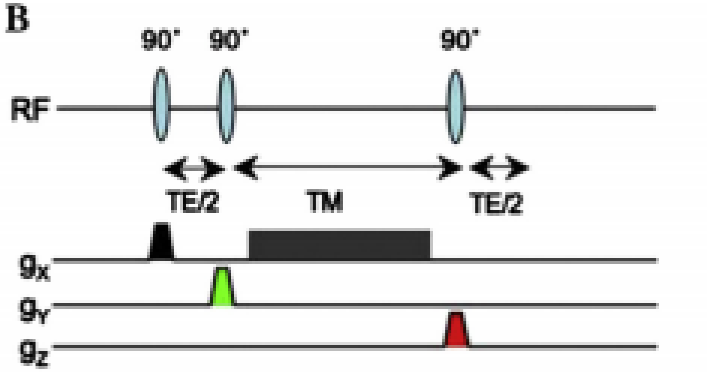
Fourier Transform



MRS and Signal Localisation







Questions?

marta.correia@mrc-cbu.cam.ac.uk