



MRC Cognition
and Brain
Sciences Unit



UNIVERSITY OF
CAMBRIDGE

Introduction to MRI Physics

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MRC Cognition and Brain Sciences Unit

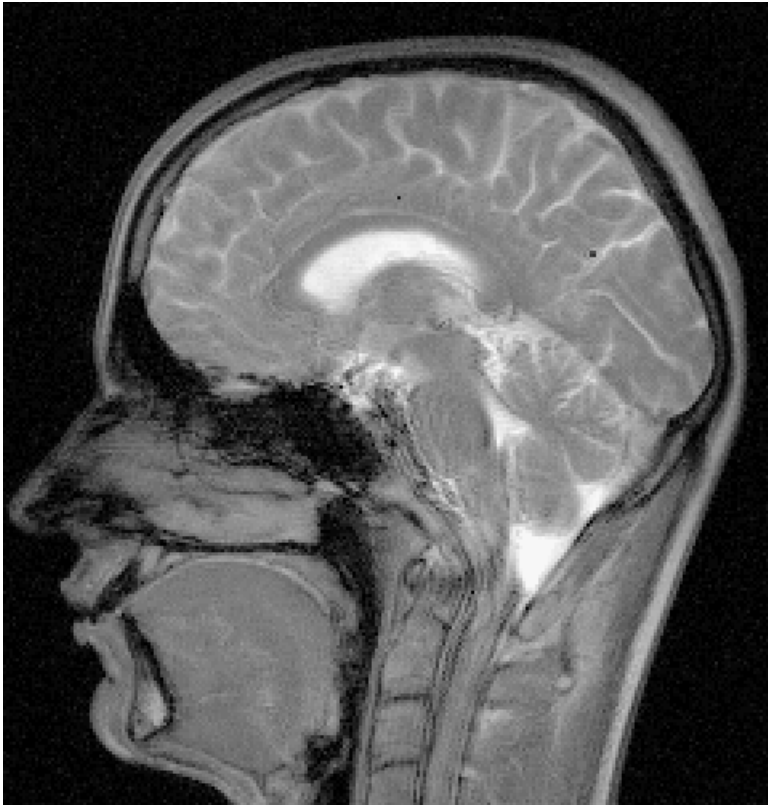
15th January 2024

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)

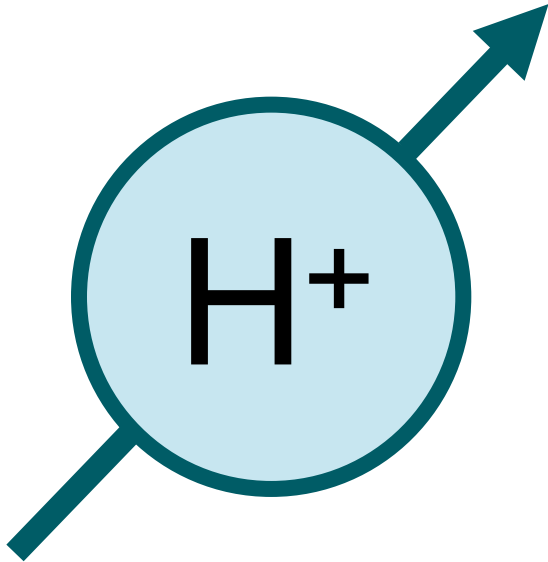
Part I: Nuclear Magnetic Resonance (NMR)

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*

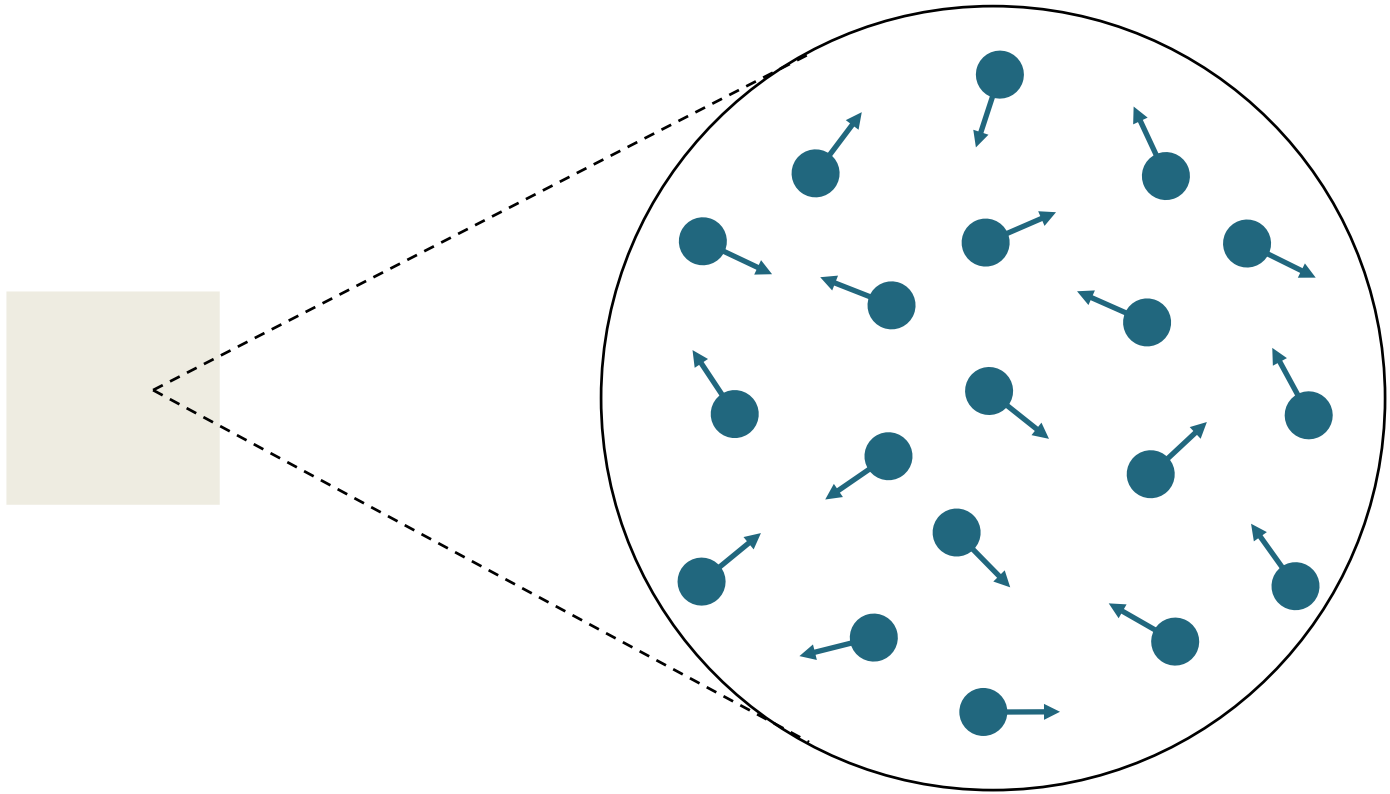
The Nuclear spin



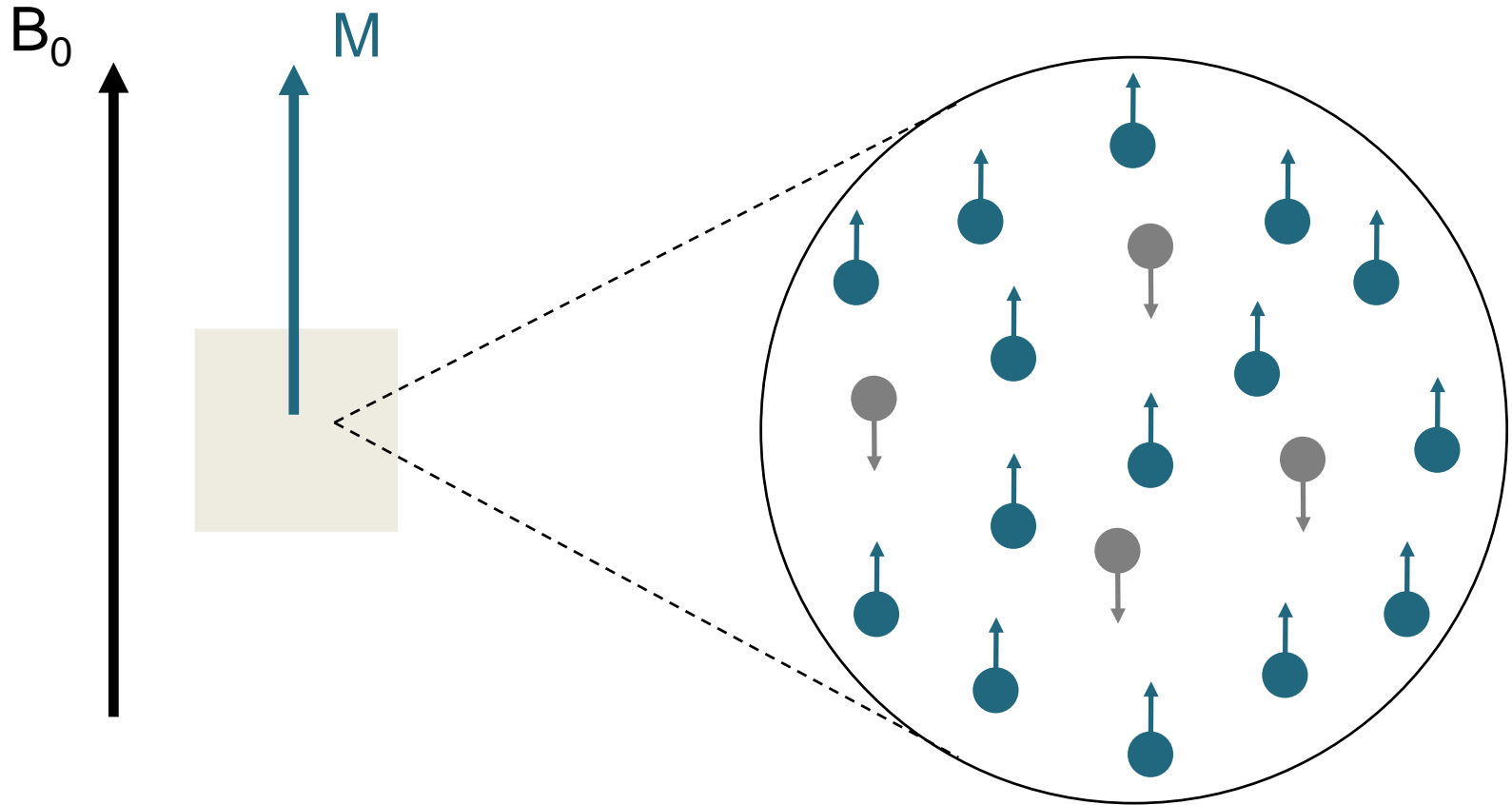
- Elementary property of an atomic nucleus
- Each spin carries an elementary magnetization
- Spins align in an external magnetic field (like a compass needle)

Macroscopic sample

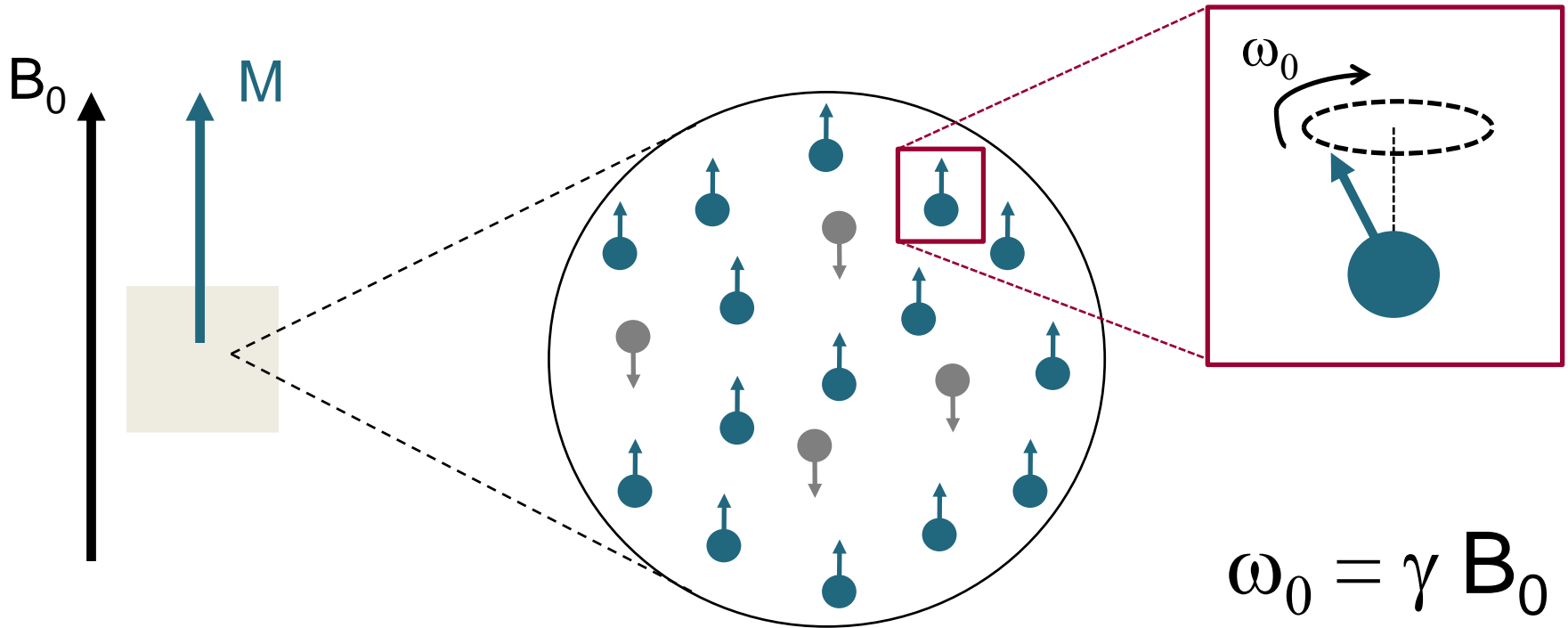
$M=0$



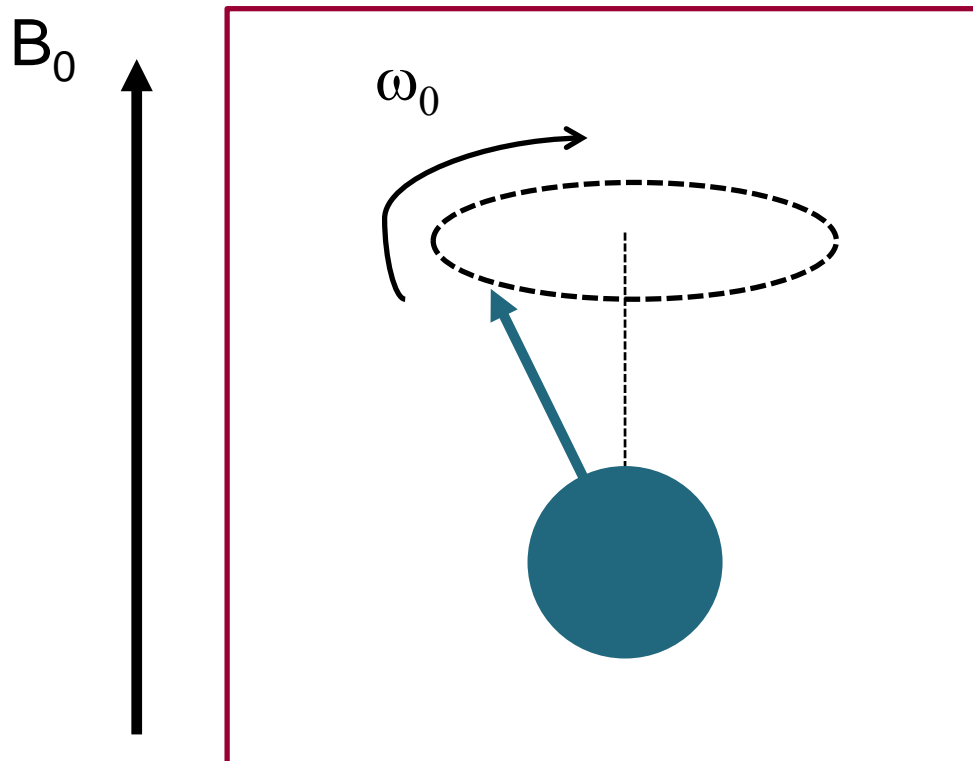
Macroscopic sample



Precession and Larmor Frequency

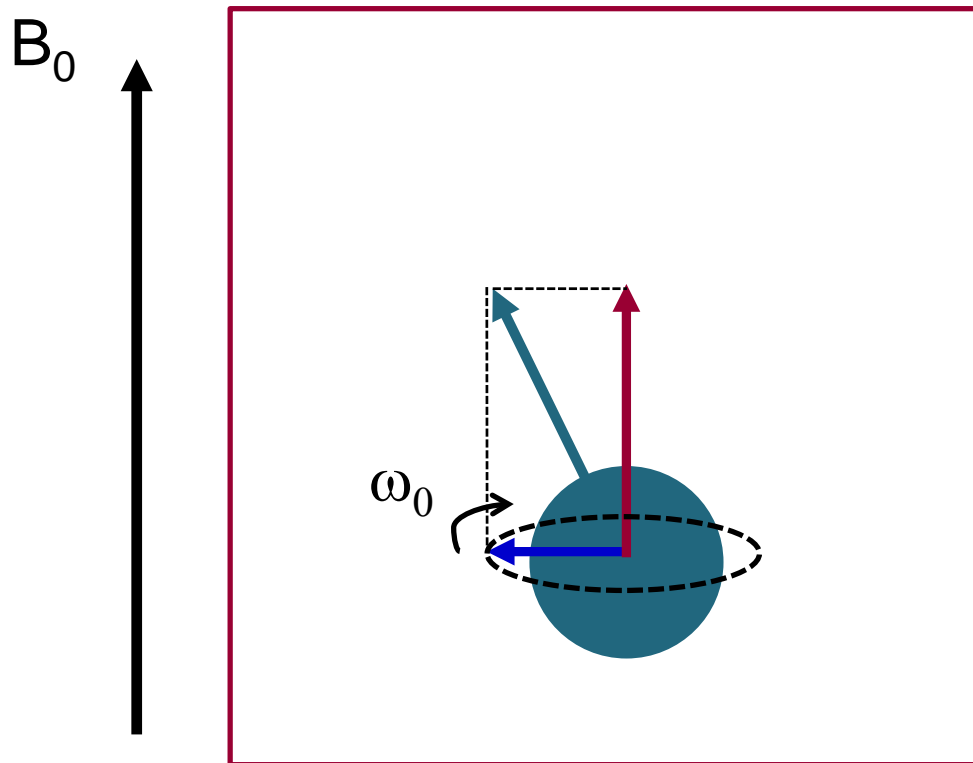


Precession and Larmor Frequency



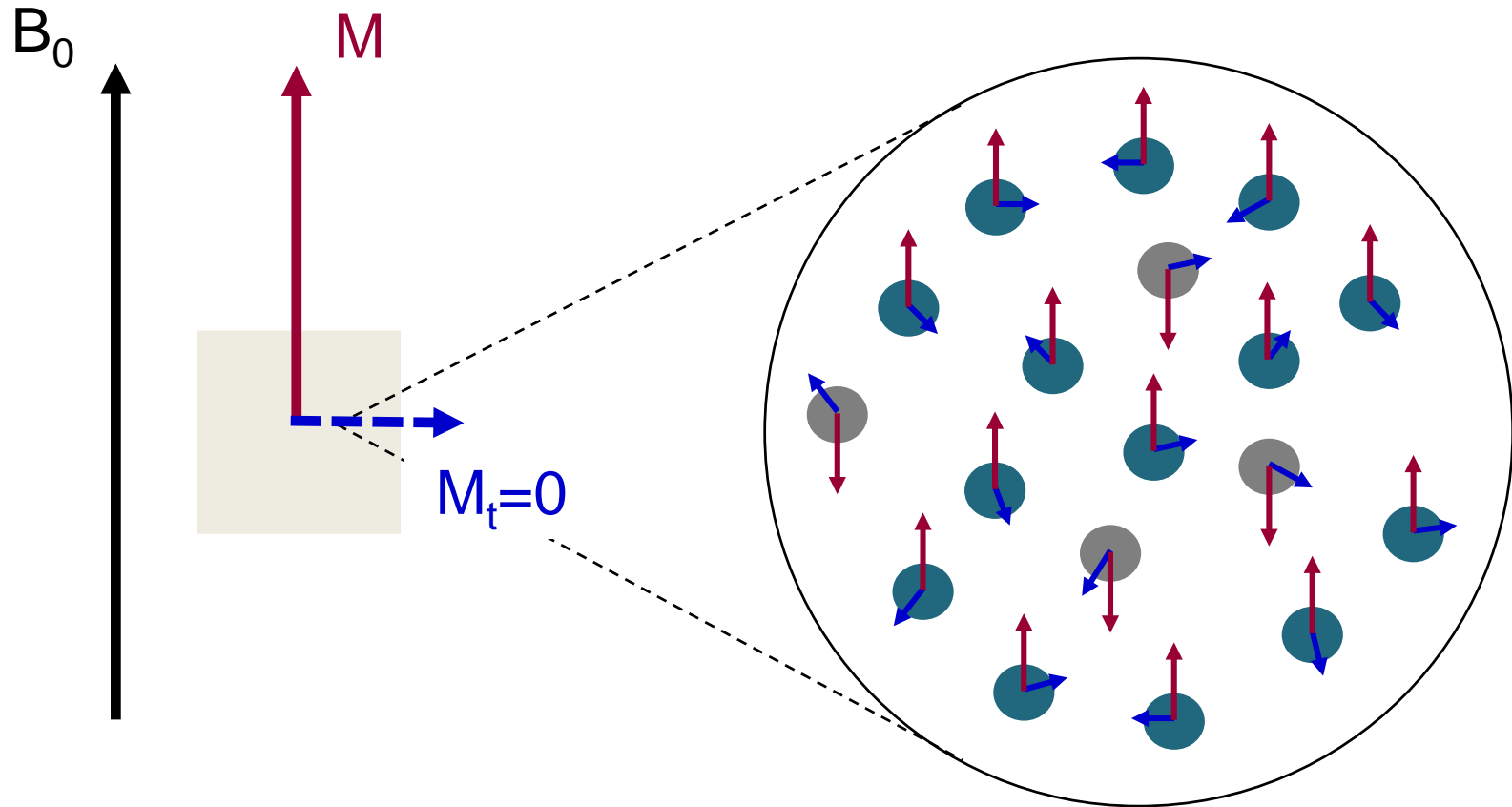
$$\omega_0 = \gamma B_0$$

Precession and Larmor Frequency

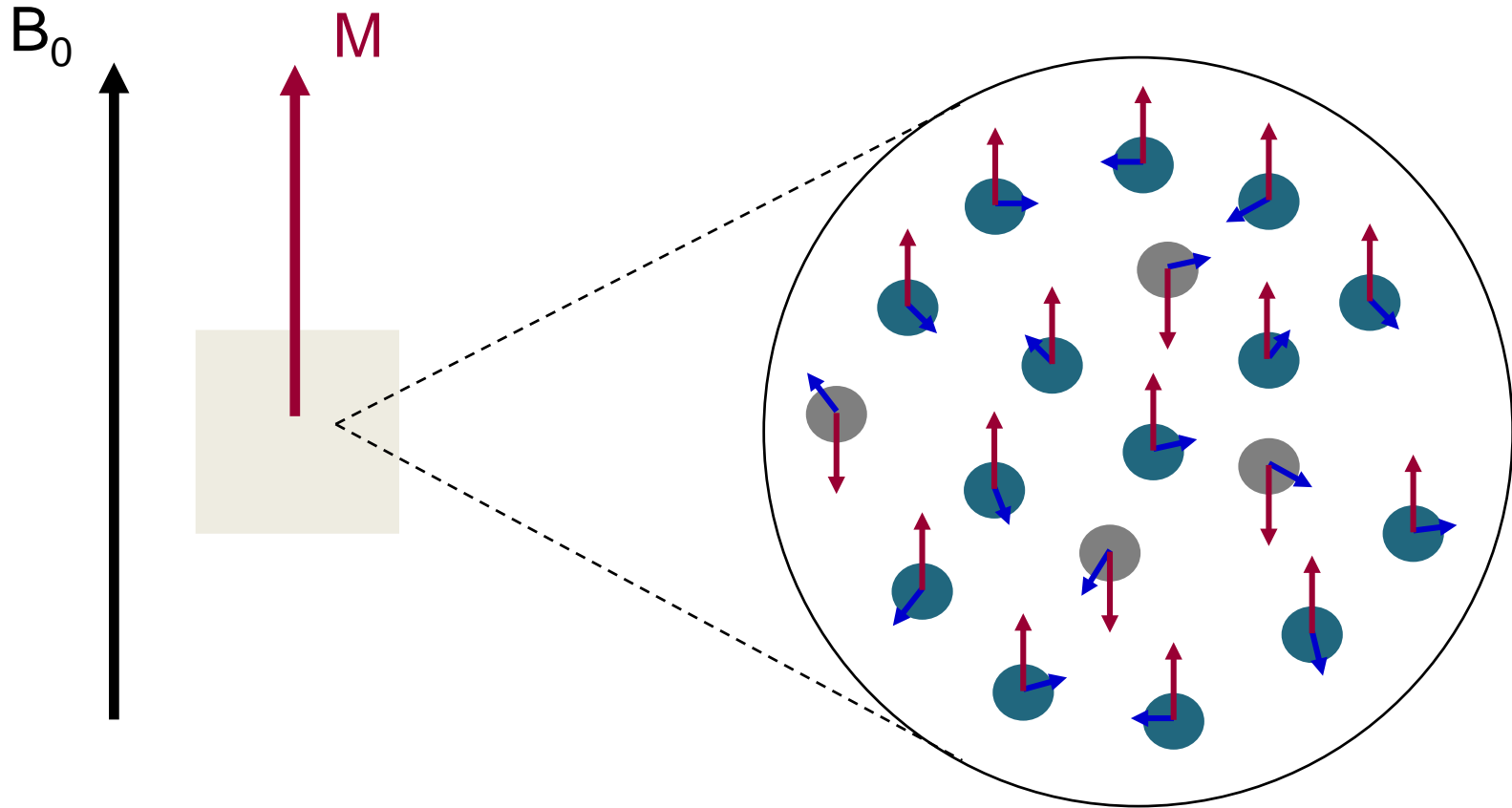


$$\omega_0 = \gamma B_0$$

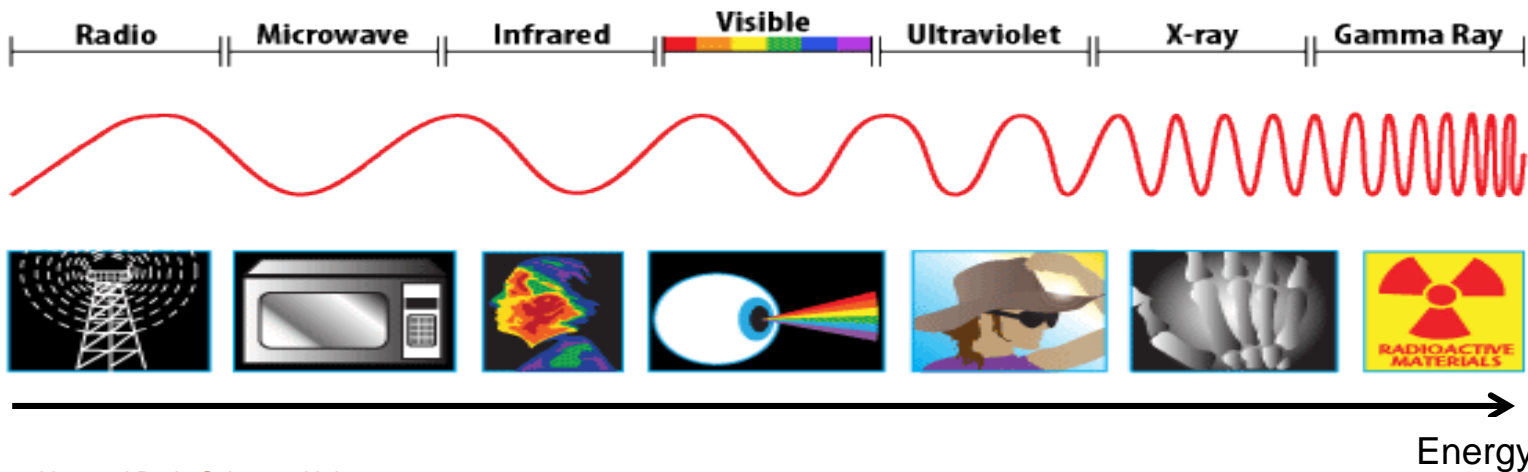
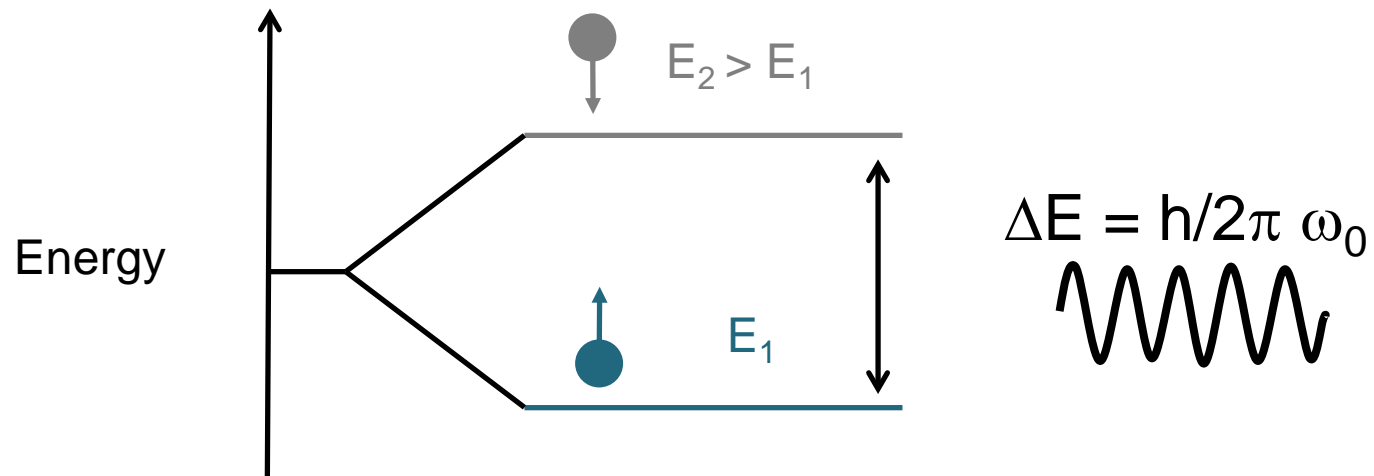
Macroscopic sample



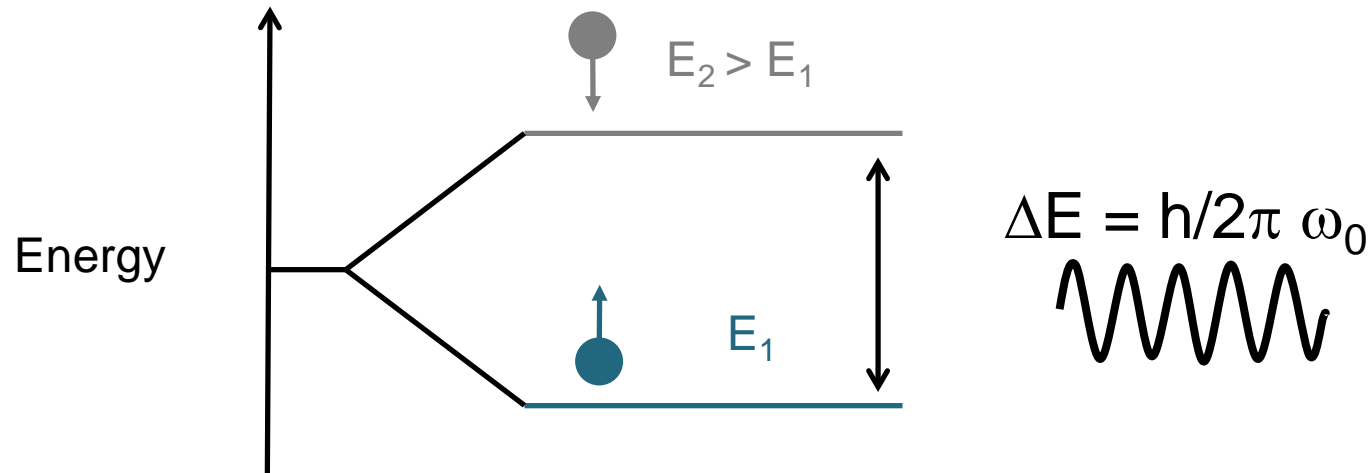
Macroscopic sample



Magnetic Resonance

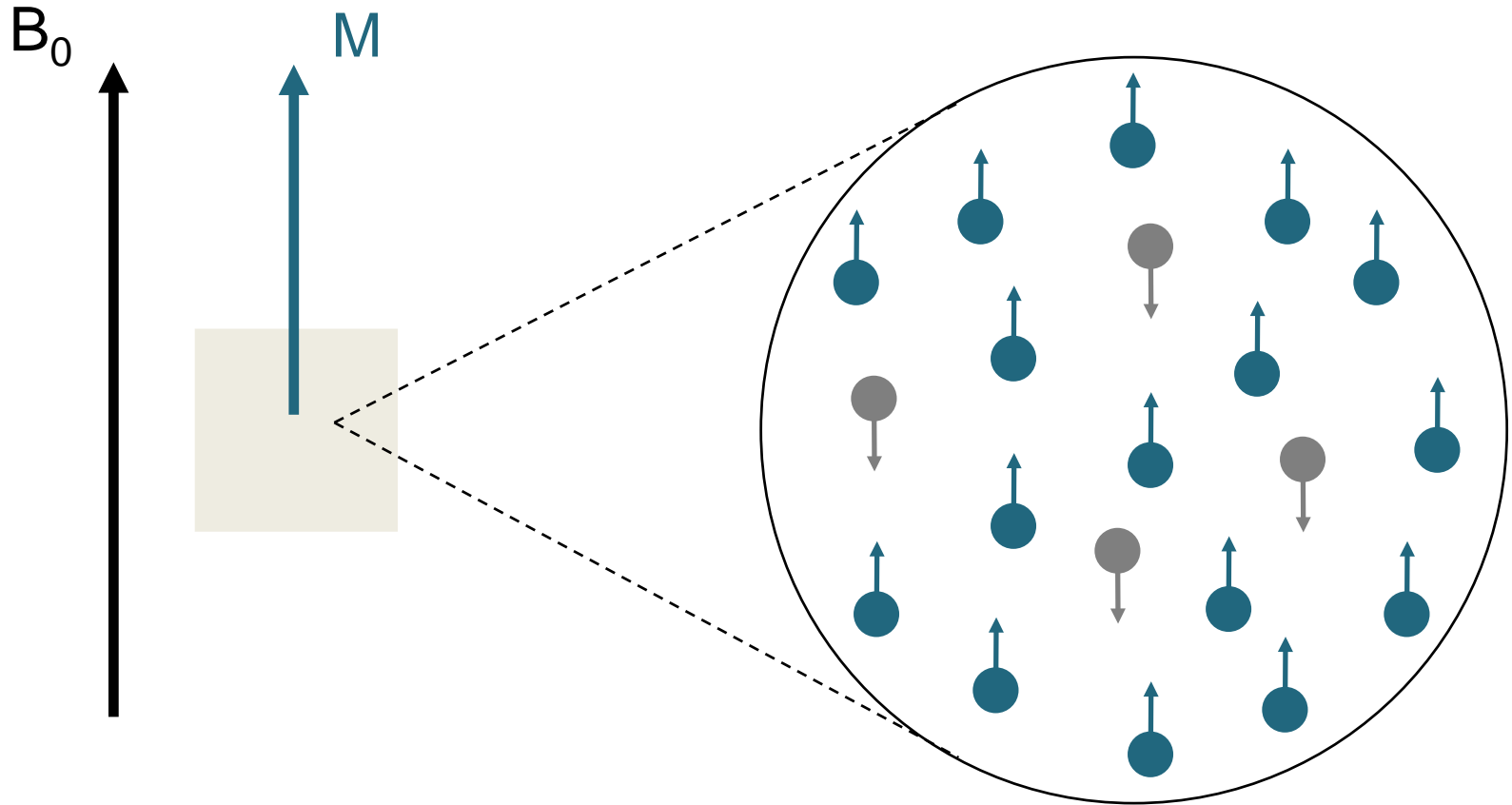


Magnetic Resonance

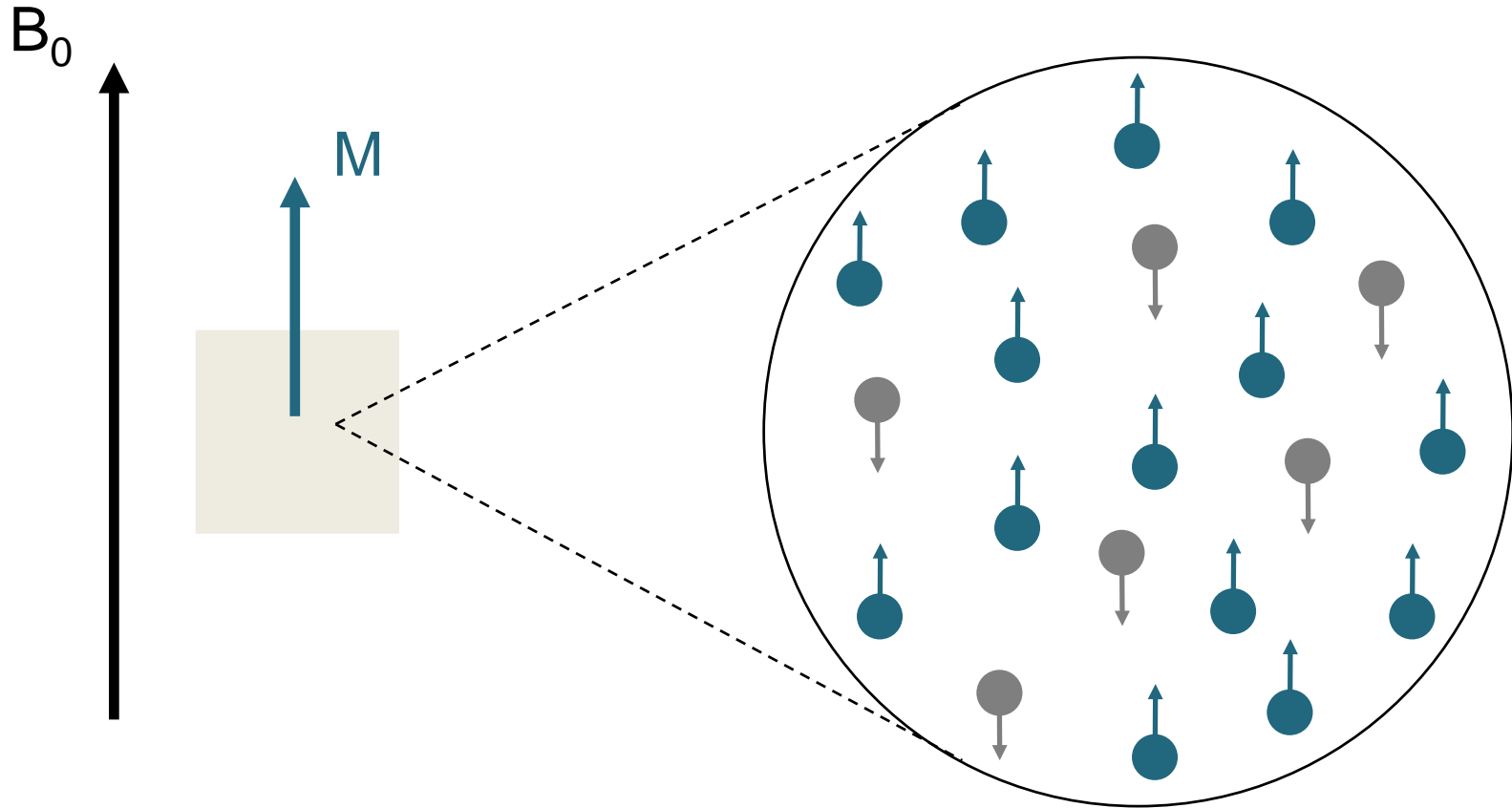


- Exchange of energy between two systems at a specific energy is called **resonance**.
- **Magnetic resonance** corresponds to the energetic interaction between **spins** and **electromagnetic radiofrequency** (RF).
- Only protons that spin with the **same frequency** as the electromagnetic **RF pulse**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

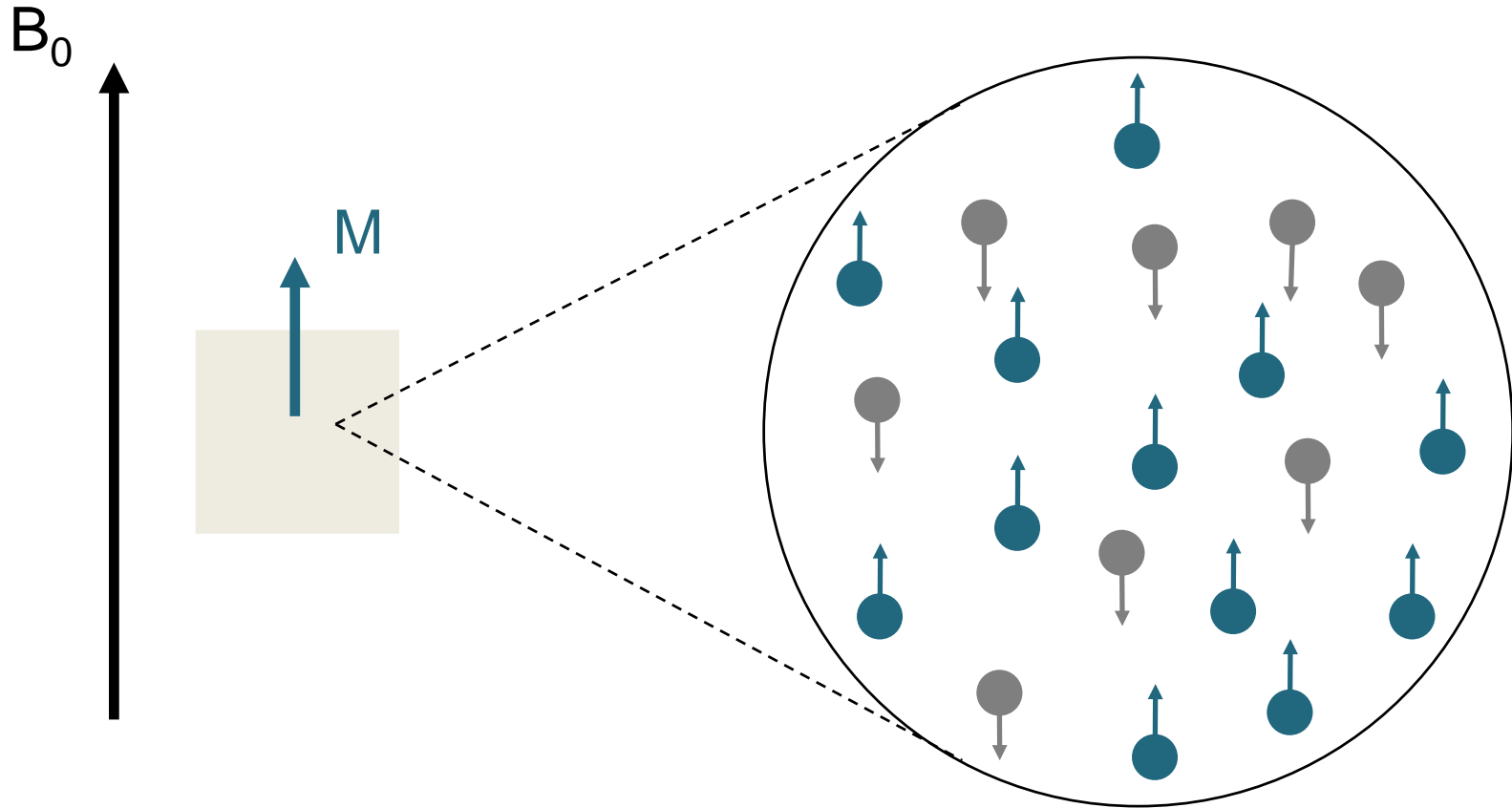
Macroscopic sample + RF pulse (Energy)



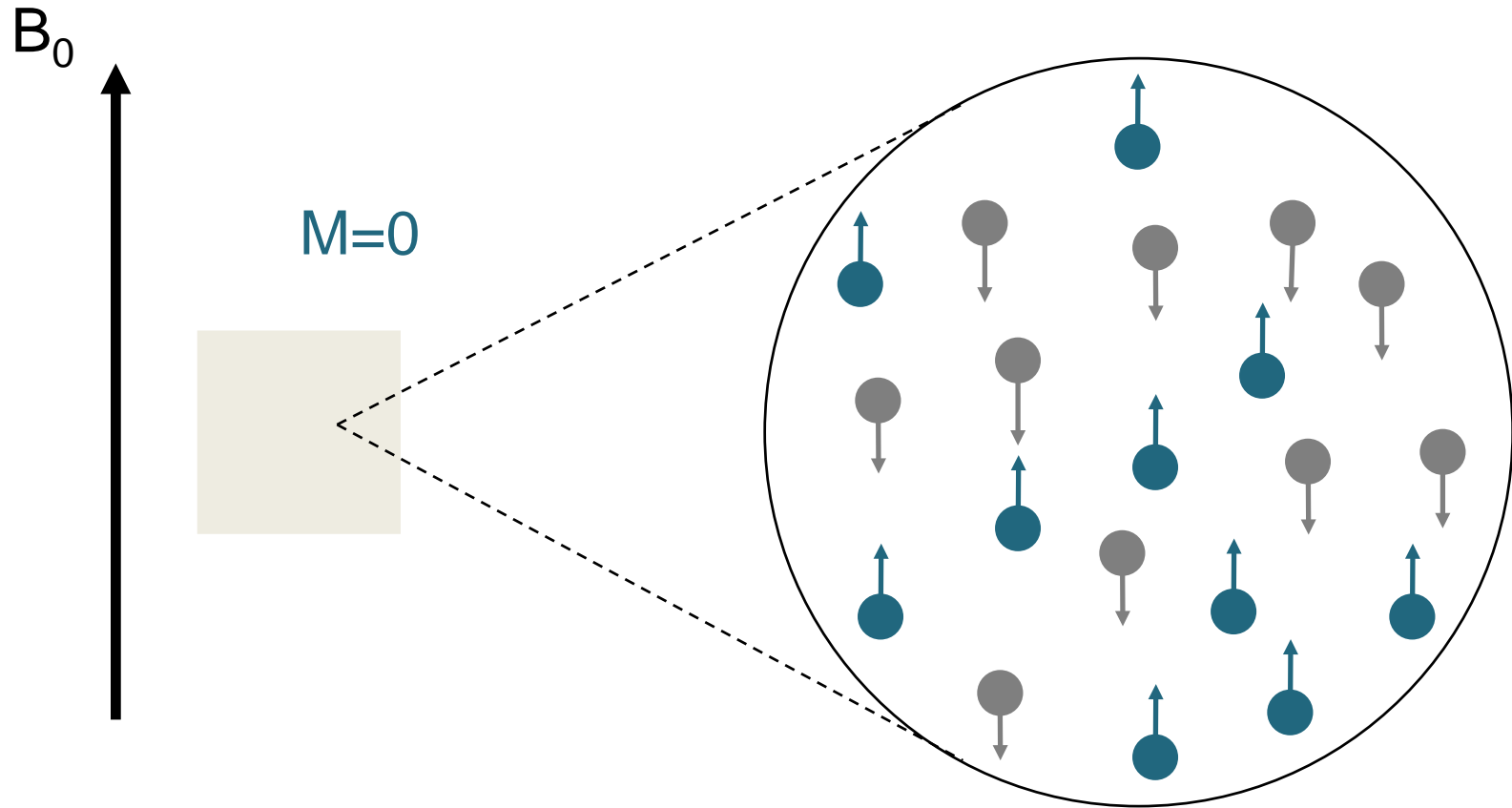
Macroscopic sample + RF pulse (Energy)



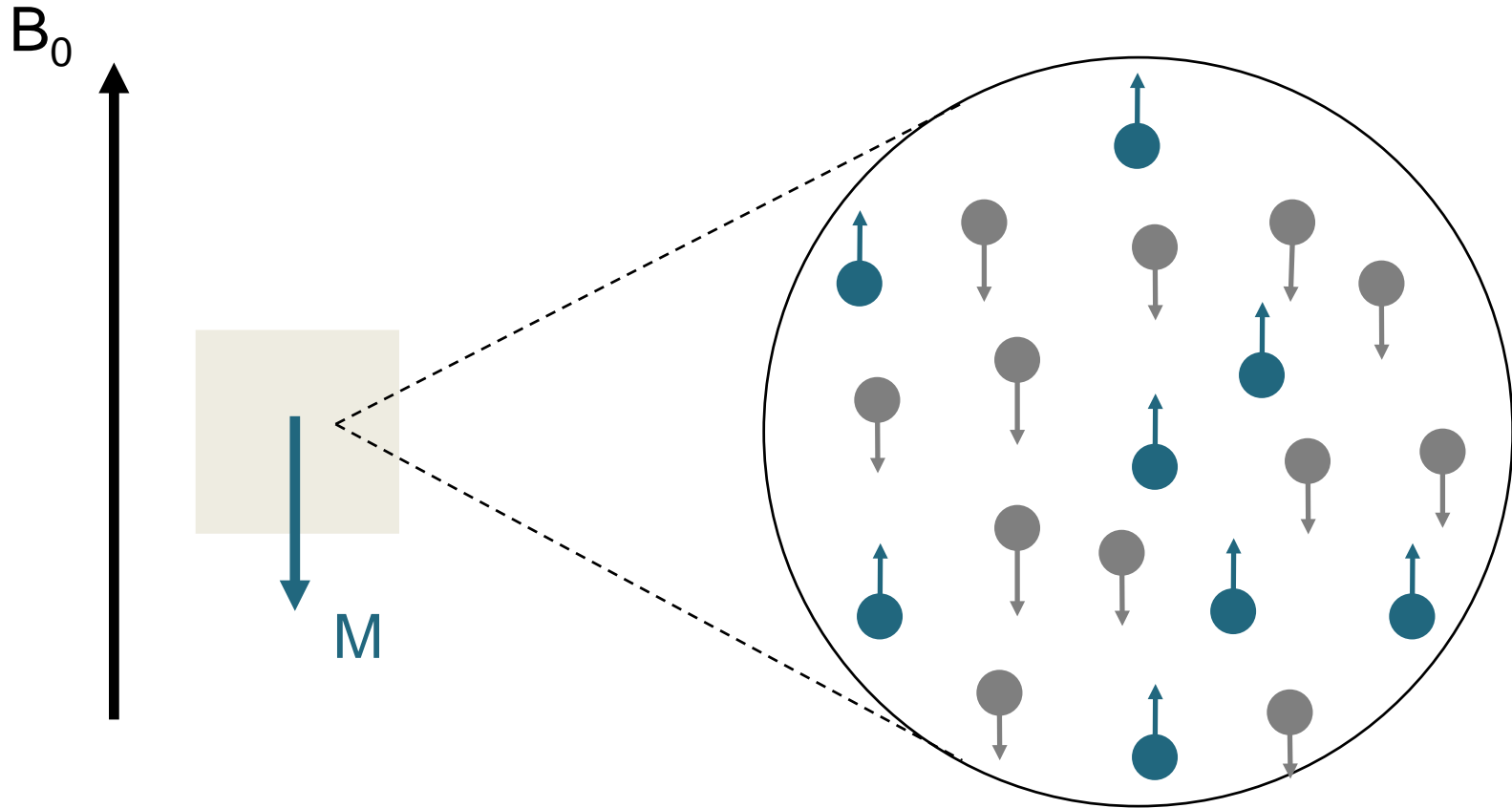
Macroscopic sample + RF pulse (Energy)



Macroscopic sample + RF pulse (Energy)

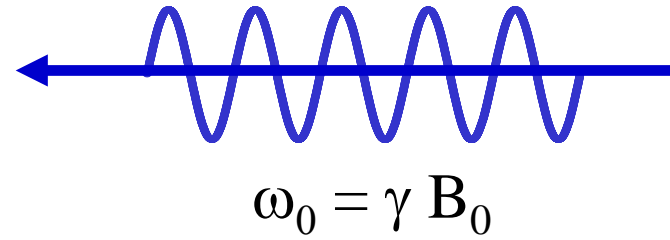
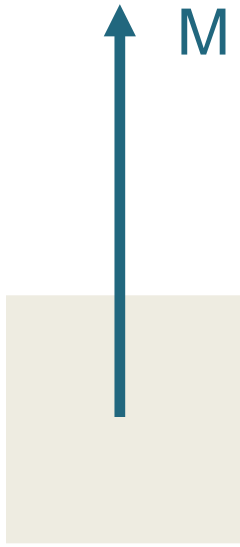


Macroscopic sample + RF pulse (Energy)

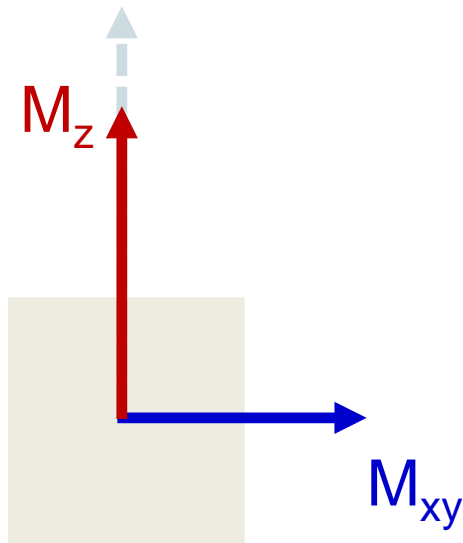


Excitation, Relaxation and Signal Formation

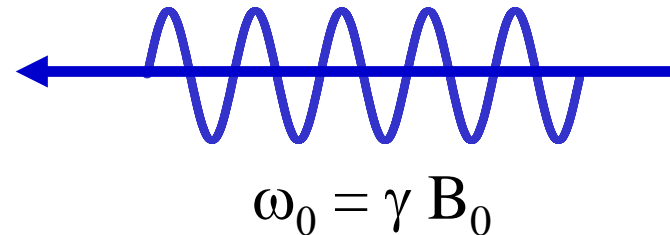
Excitation



Excitation

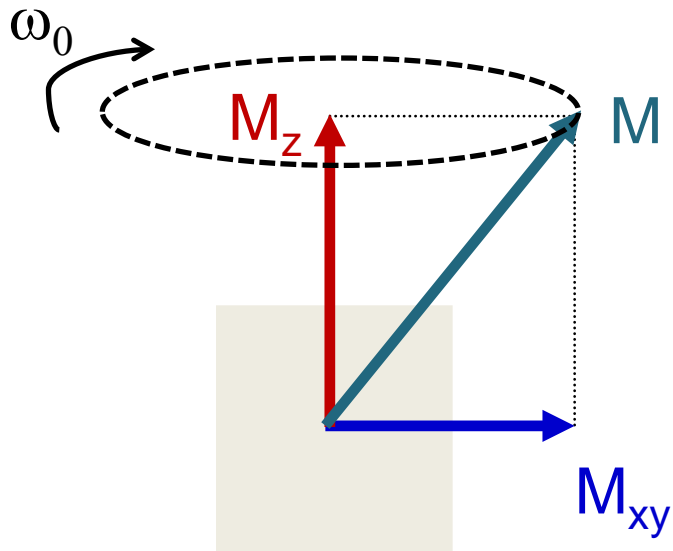


- During excitation, longitudinal magnetization decreases and a transverse magnetization appears.

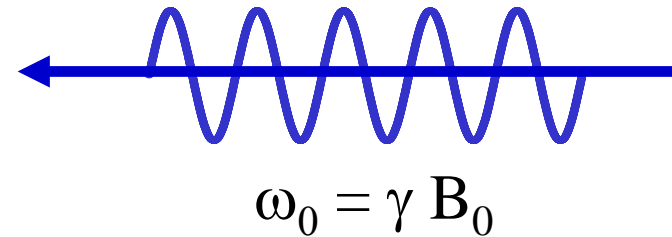


- Longitudinal magnetization decrease is due to a difference in the number of spins in parallel and anti-parallel state.
- Transverse magnetization is due to spins getting into phase coherence.

Excitation

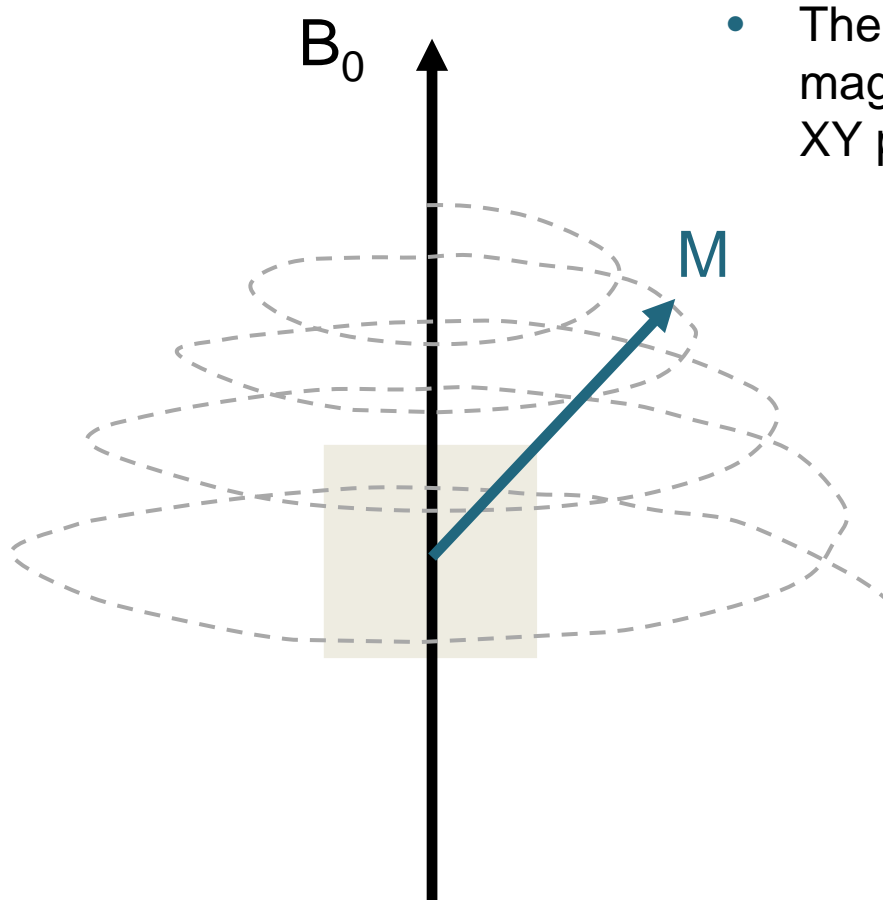


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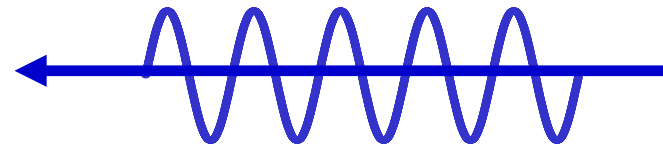


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Excitation

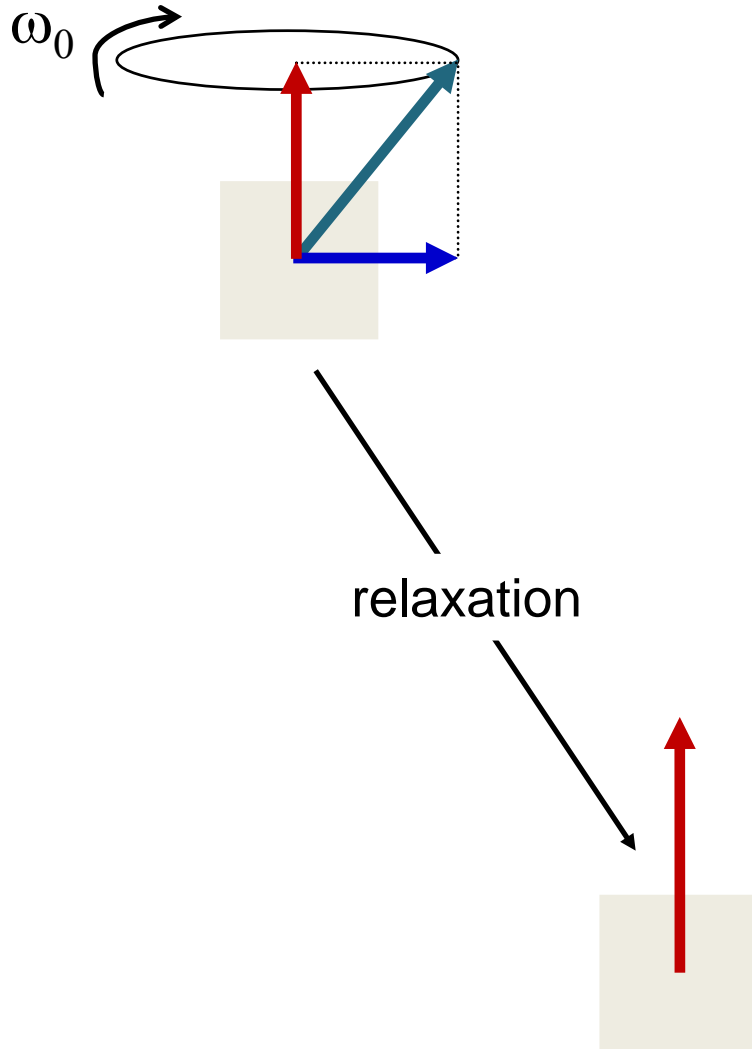


- The consequence on the macroscopic net magnetization is a spiral movement down to the XY plane.



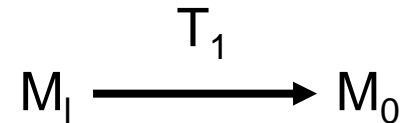
$$\omega_0 = \gamma B_0$$

Relaxation

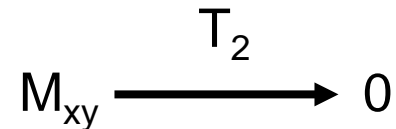


Two independent relaxation processes:

①



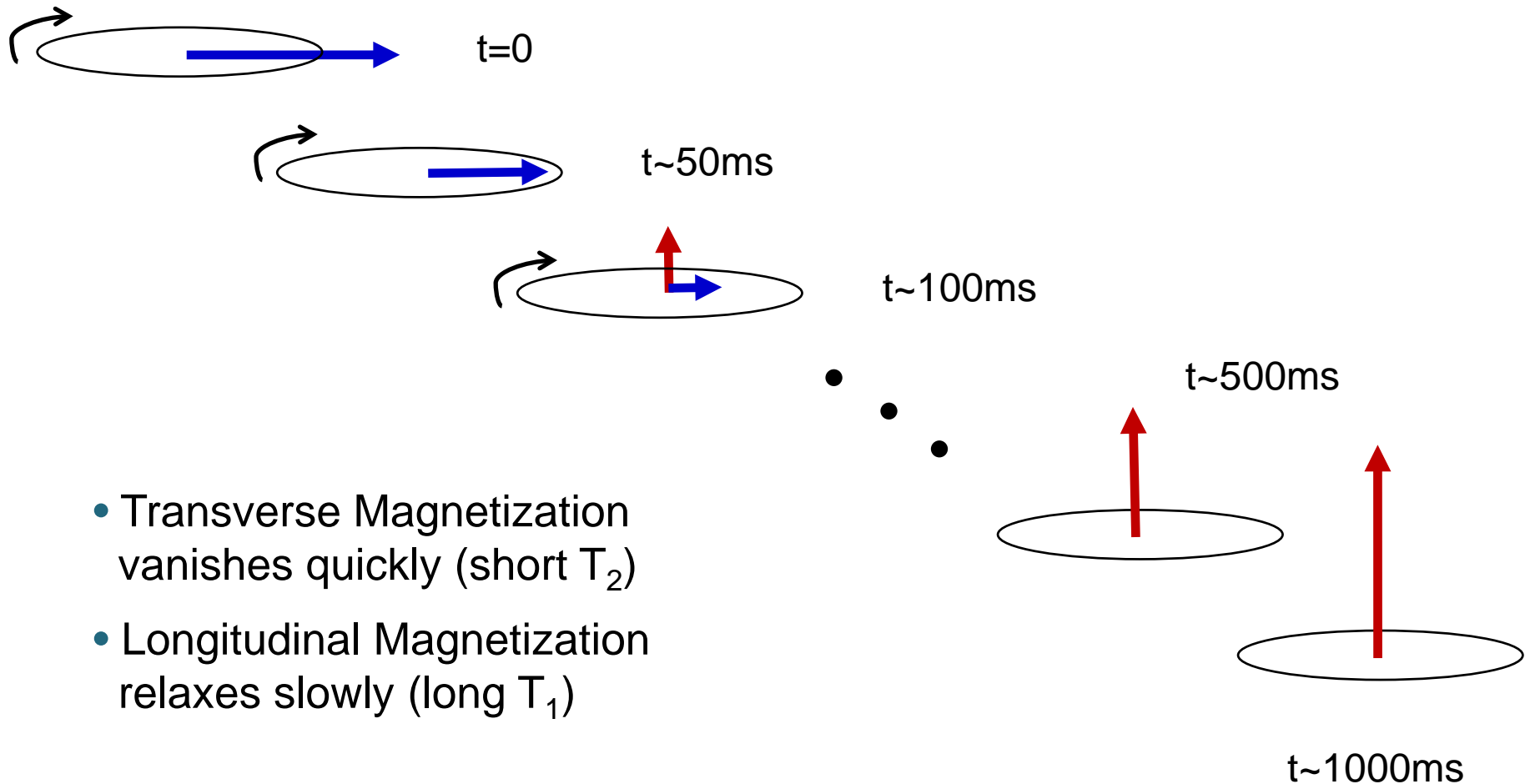
②



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

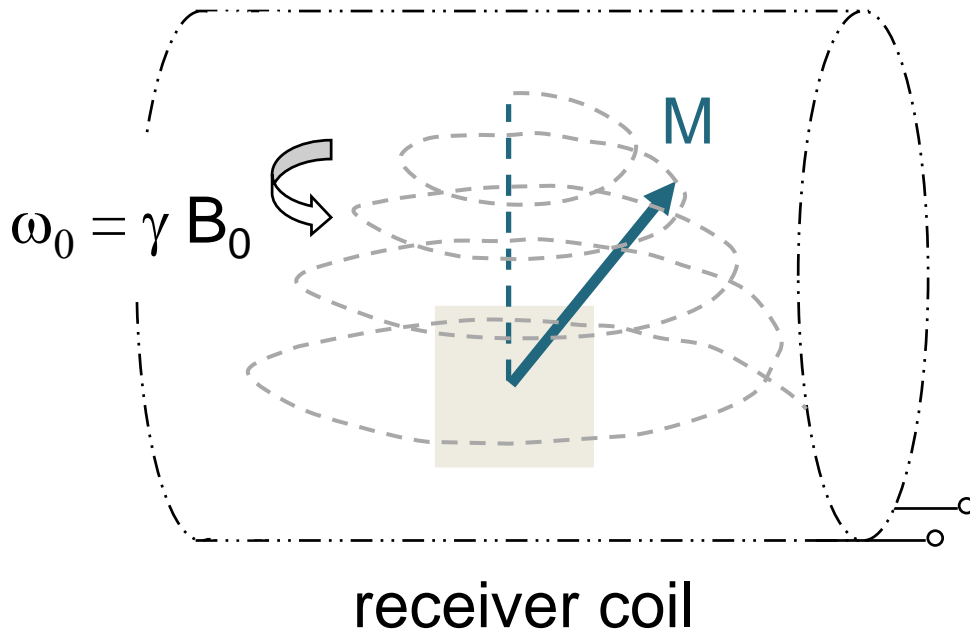
T_2 : “*transverse relaxation time*”
(≈ 100 ms) – dephasing due to spin/spin
interactions

Relaxation

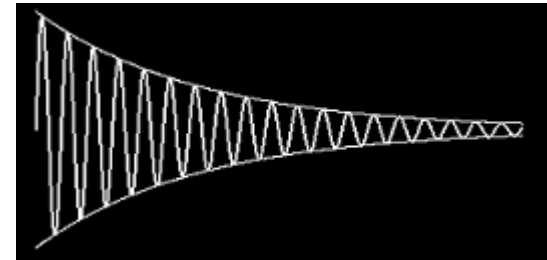


- Transverse Magnetization vanishes quickly (short T_2)
- Longitudinal Magnetization relaxes slowly (long T_1)

Precession and signal induction

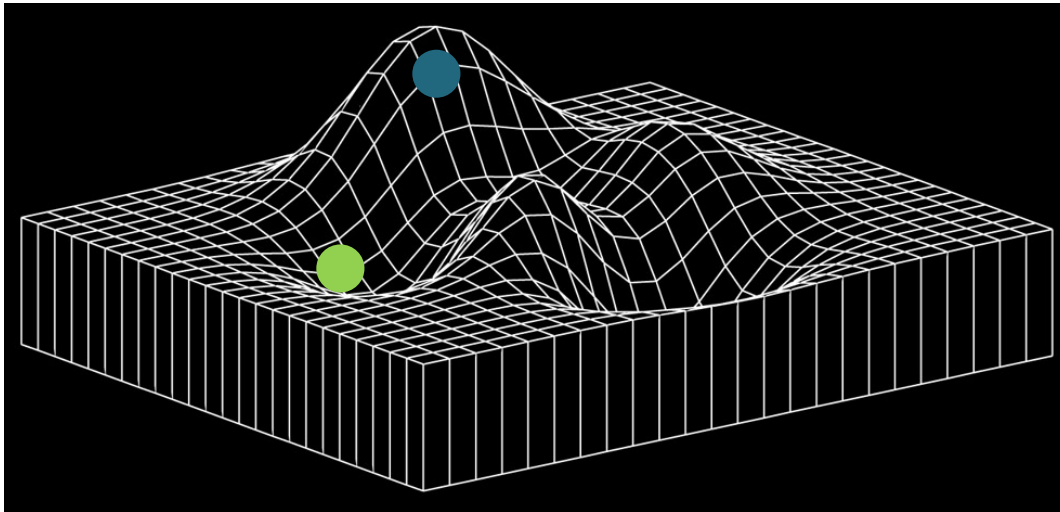


123 MHz @ 3T



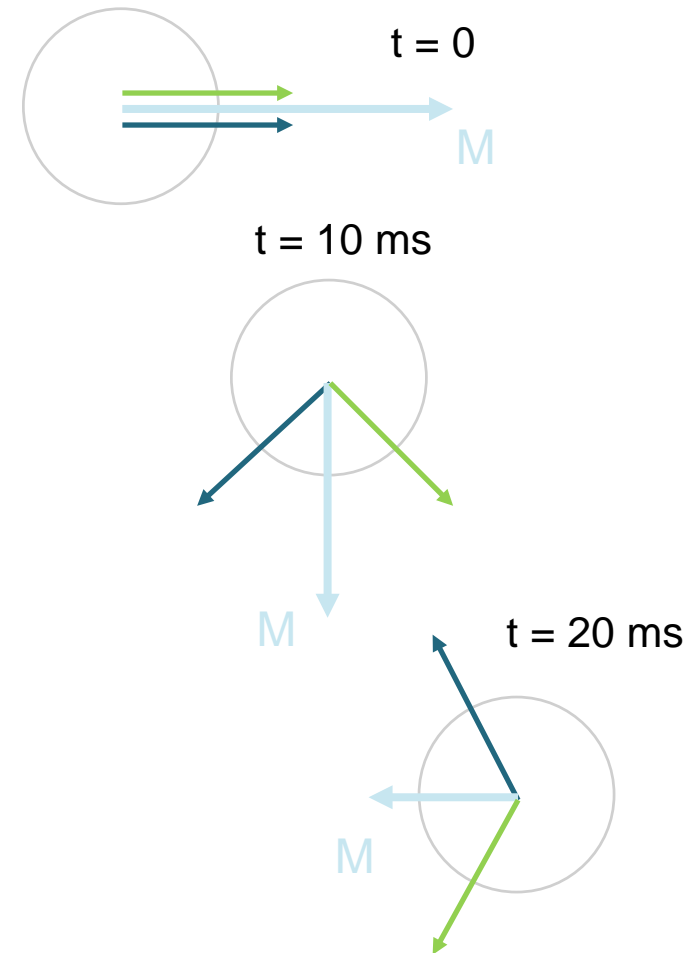
NMR signal

Signal loss due to B_0 inhomogeneity

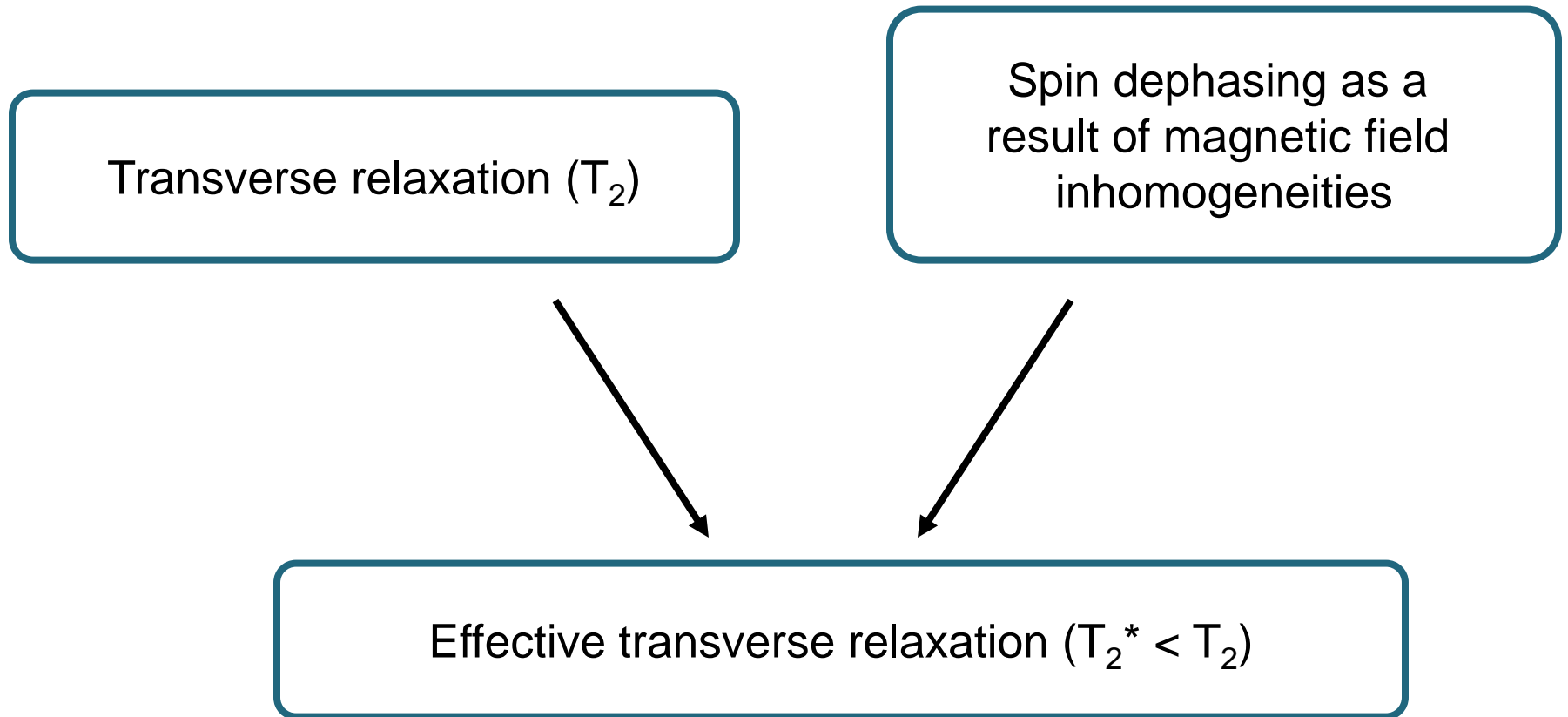


$$\omega_0 = \gamma B_0$$

● has higher frequency than ●

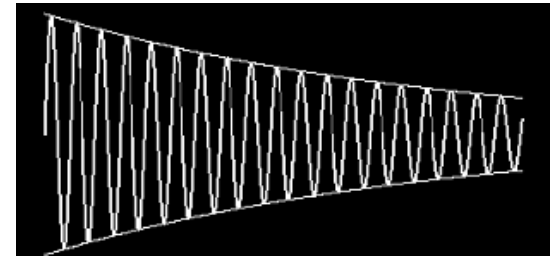


Effective transverse relaxation (T_2^*)

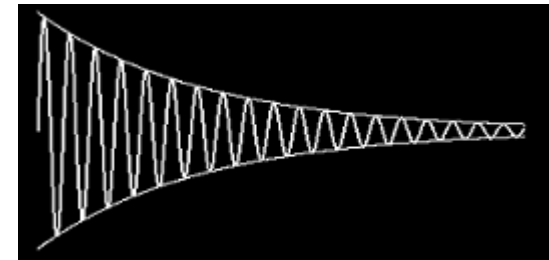


Effective transverse relaxation (T_2^*)

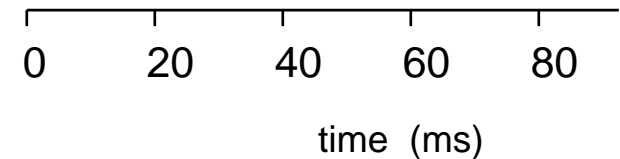
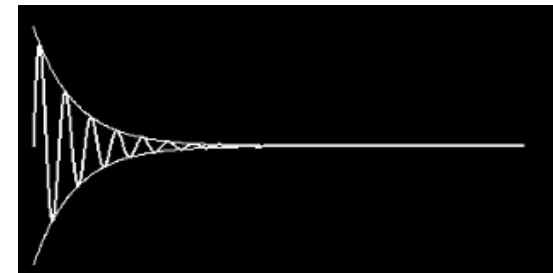
No inhomogeneities
($T_2^* = T_2 = 100$ ms)



Moderate inhomogeneities
($T_2^* = 40$ ms)

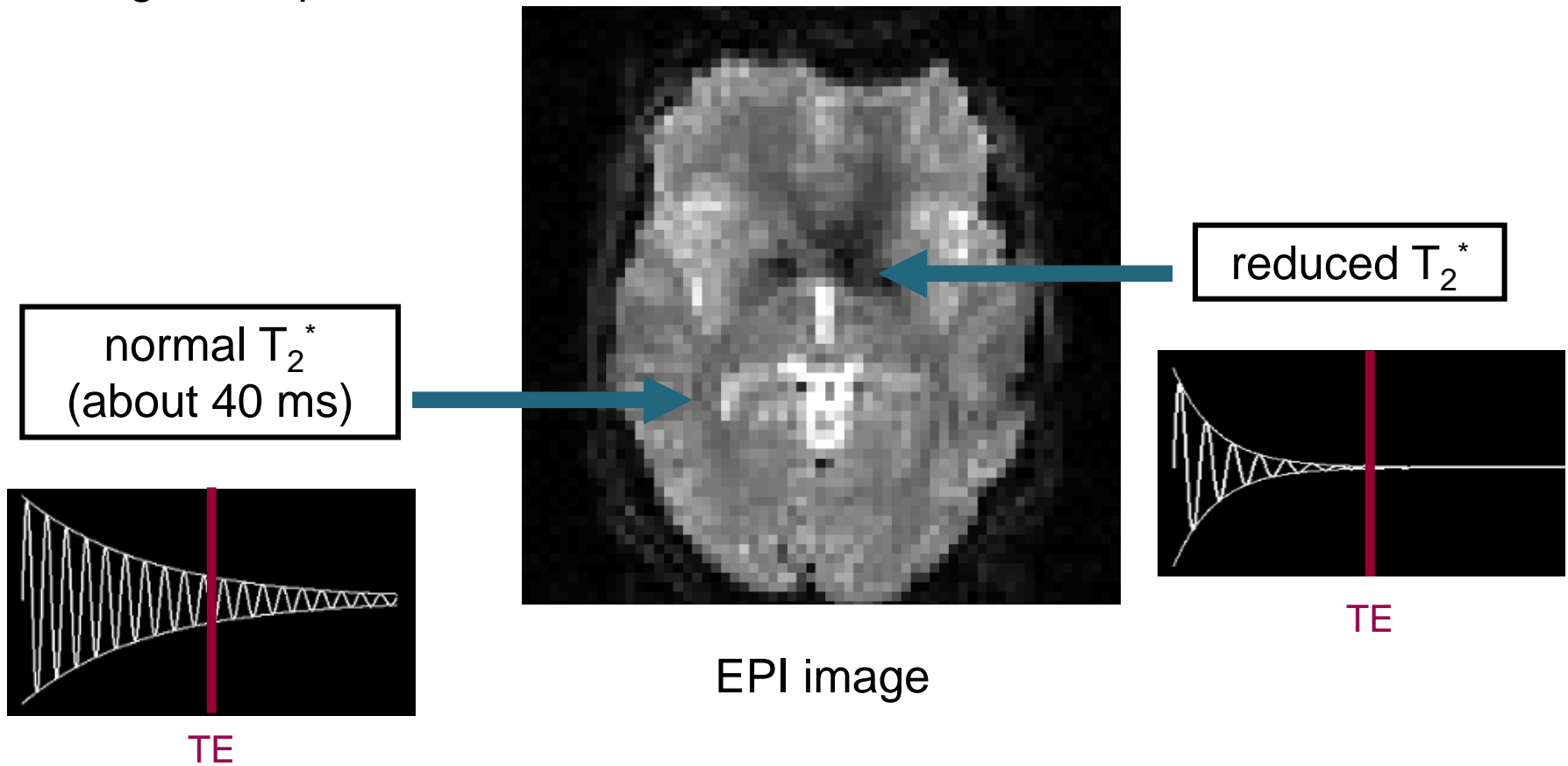


Strong inhomogeneities
($T_2^* = 10$ ms)



T_2^* related signal dropouts

T_2^* reduction due to local field inhomogeneities
⇒ signal dropouts



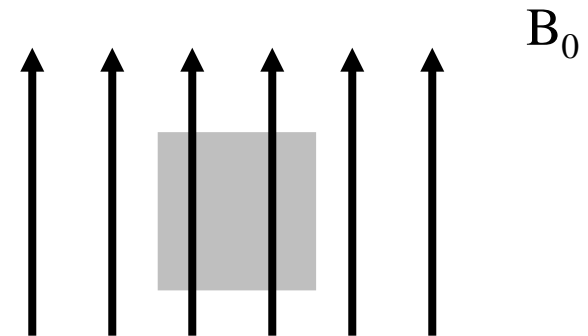
Part II: Magnetic Resonance Imaging (MRI)

Spatial Encoding in MRI

The principles of MRI

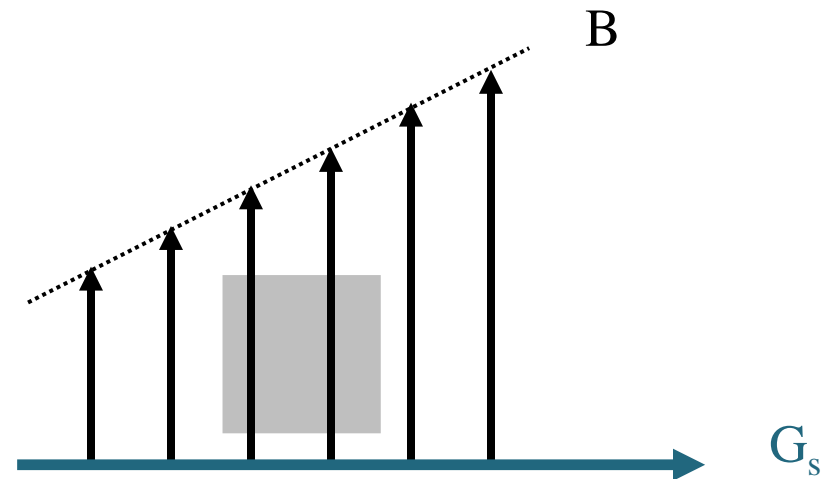
Homogeneous magnetic field

$$\omega_0 = \gamma \mathbf{B}_0$$

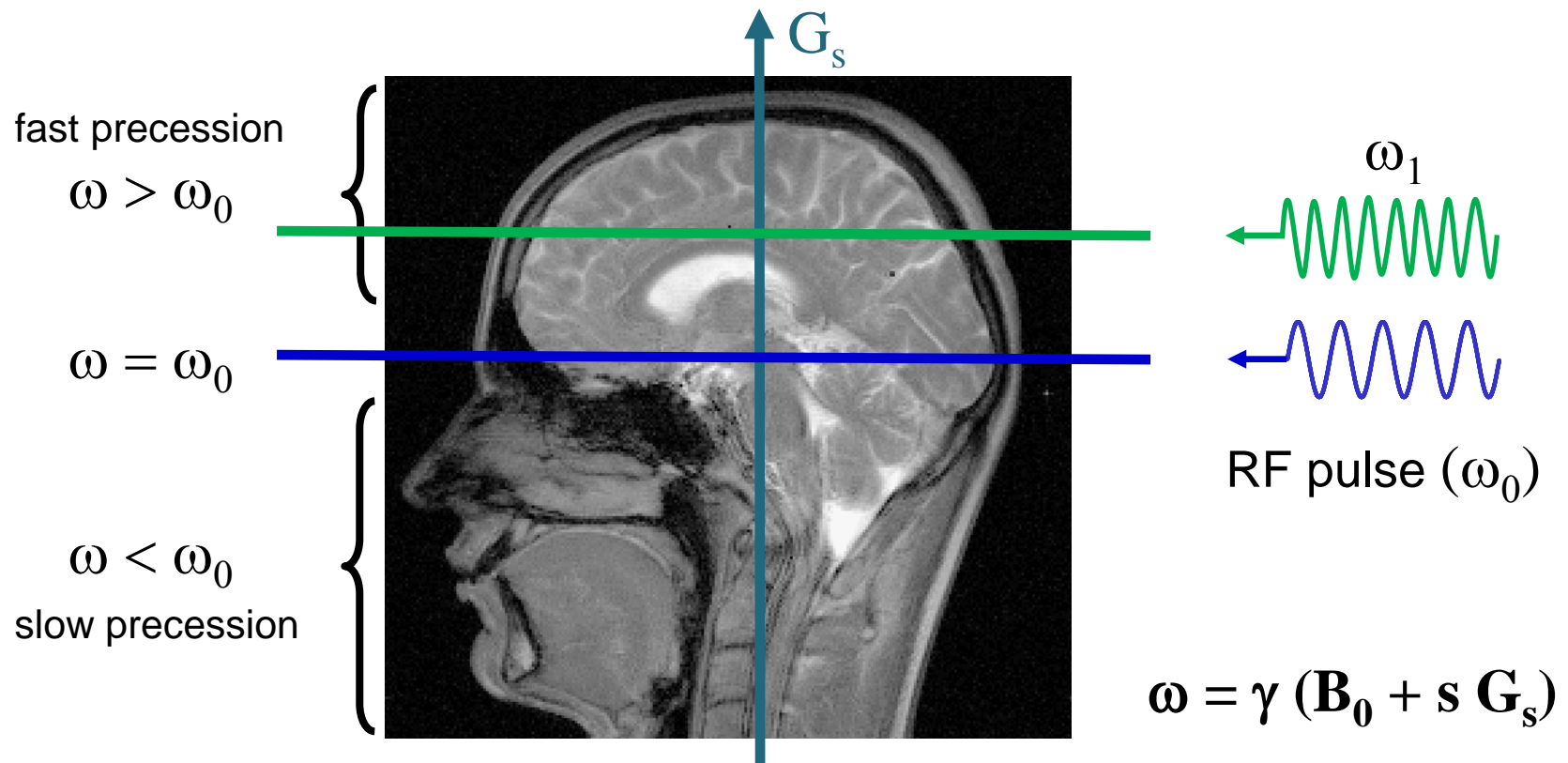


Add magnetic field gradient

$$\omega = \gamma (\mathbf{B}_0 + s \mathbf{G}_s)$$

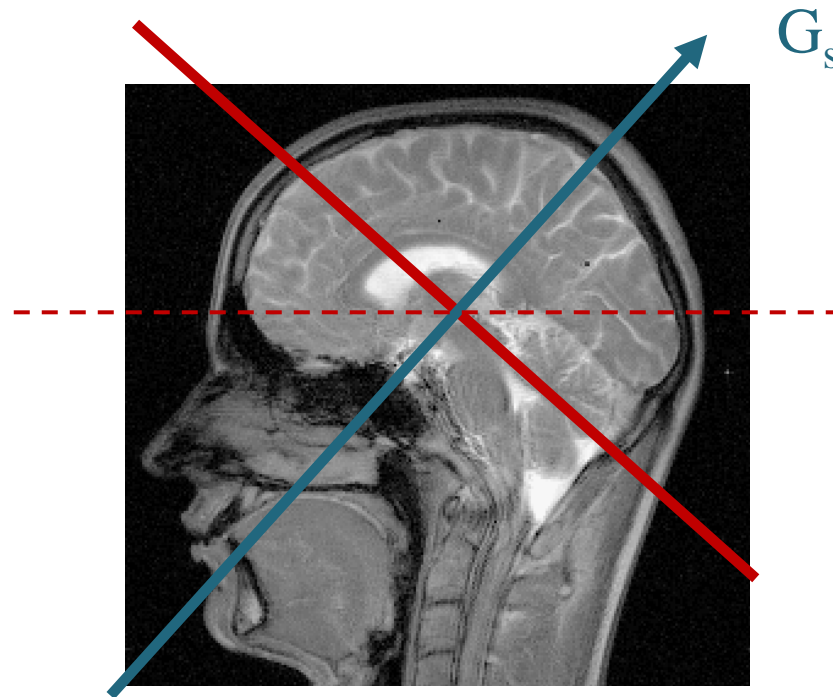


Slice selective excitation



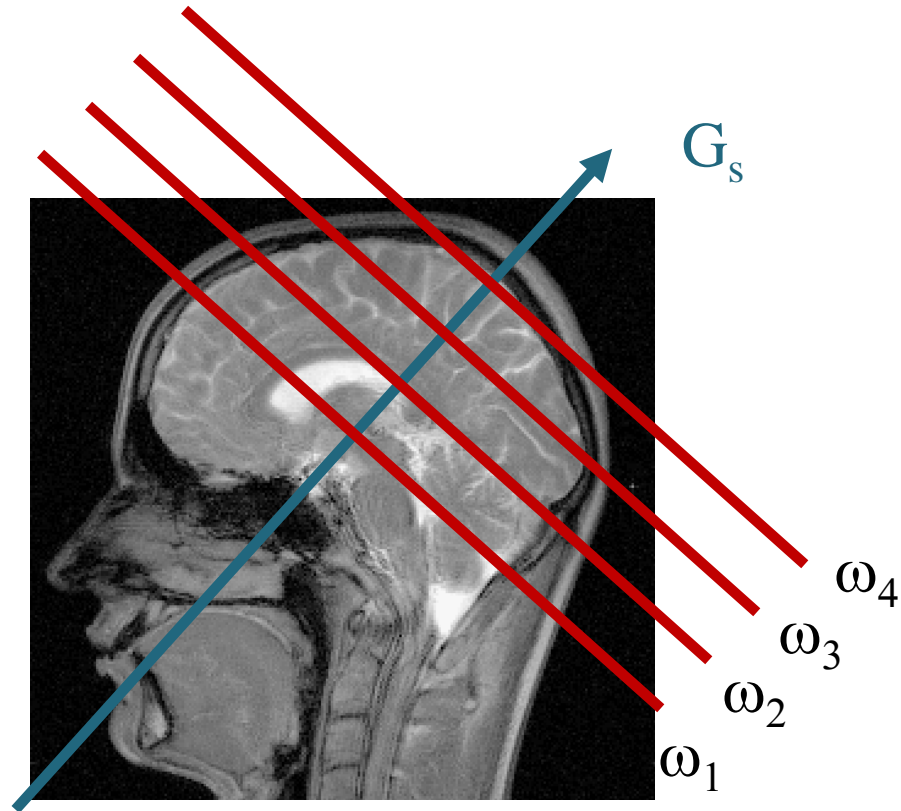
- Only spins in slice of interest have frequency ω_0
- RF pulse with frequency ω_0 excites only spins in slice of interest

Slice orientation



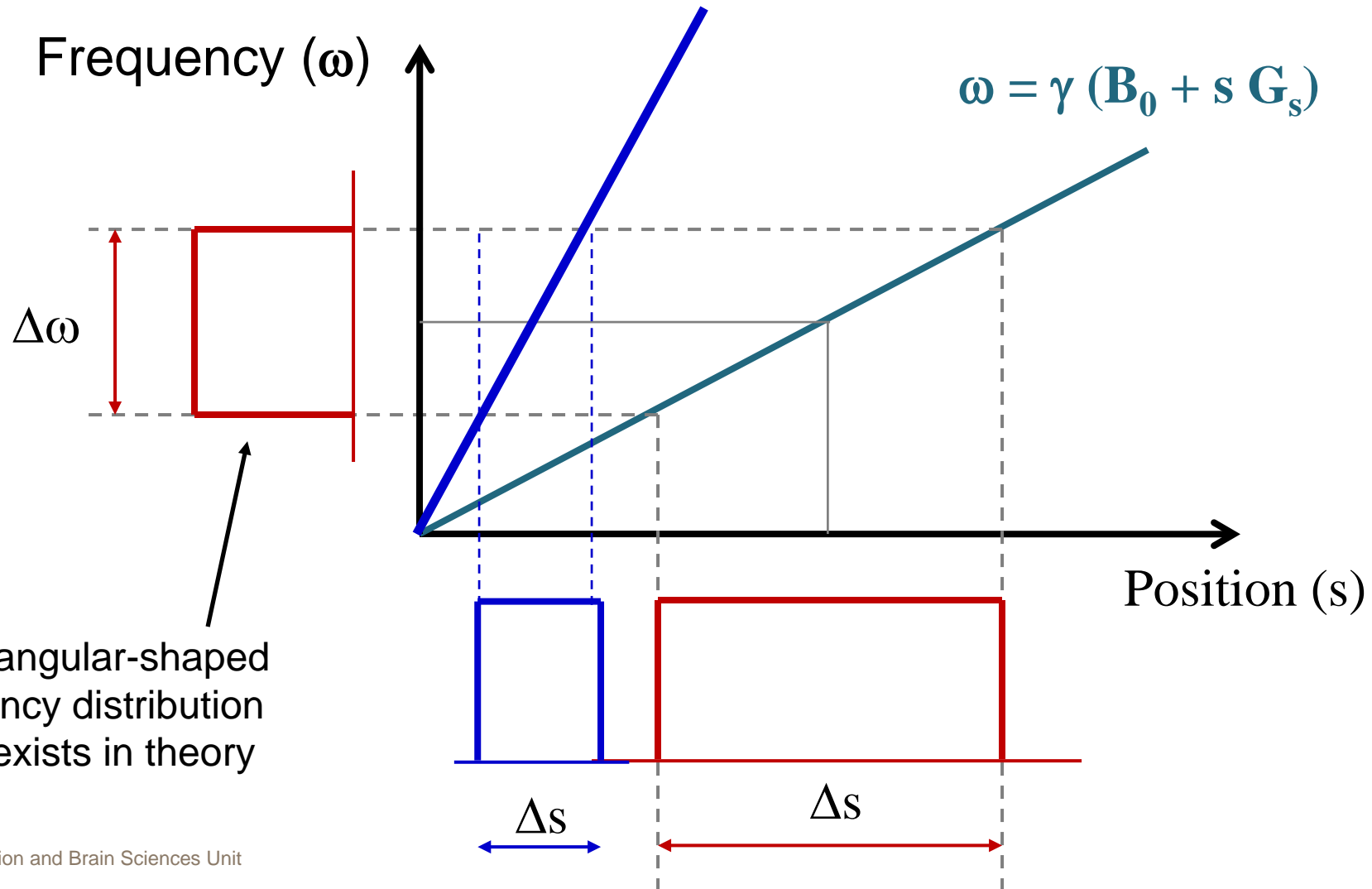
$$\omega = \gamma (\mathbf{B}_0 + s \mathbf{G}_s)$$

Multi-slice MRI



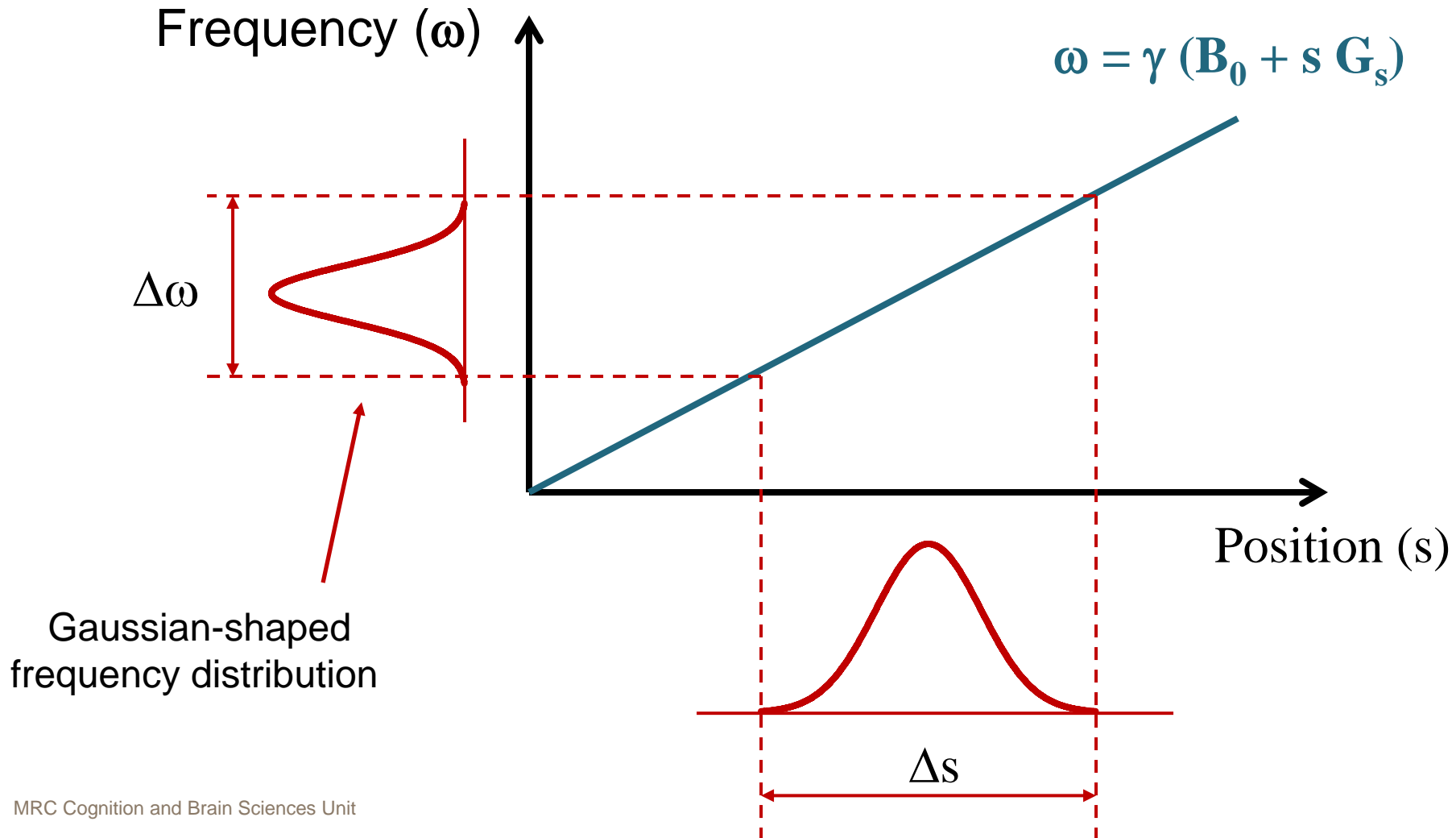
$$\omega = \gamma (\mathbf{B}_0 + s \mathbf{G}_s)$$

Slice profile

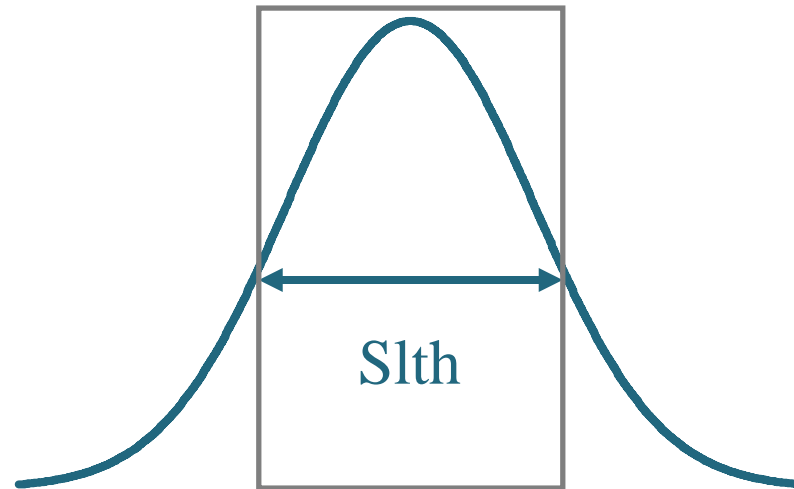


A rectangular-shaped frequency distribution only exists in theory

Slice profile

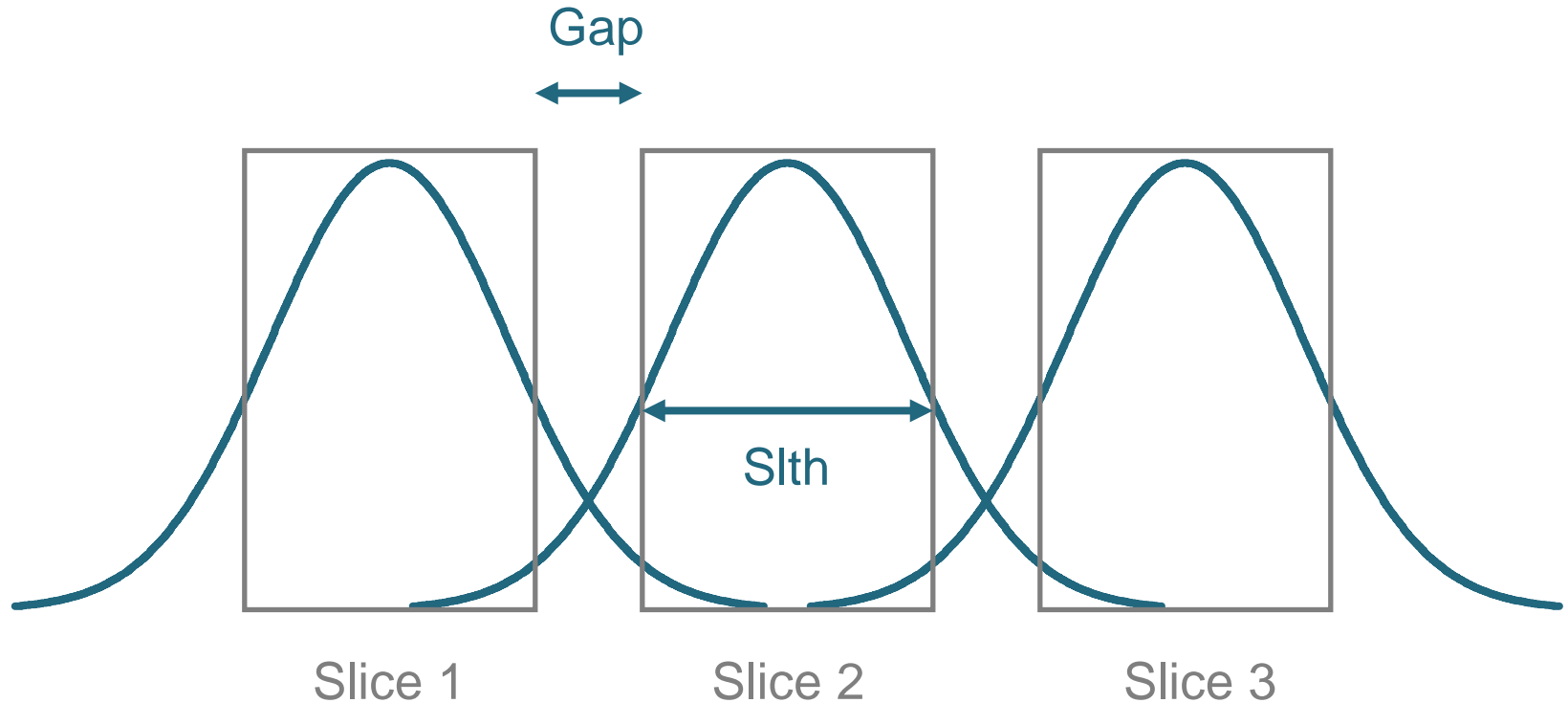


Slice thickness



$Slth =$ Full width at half maximum of the slice profile

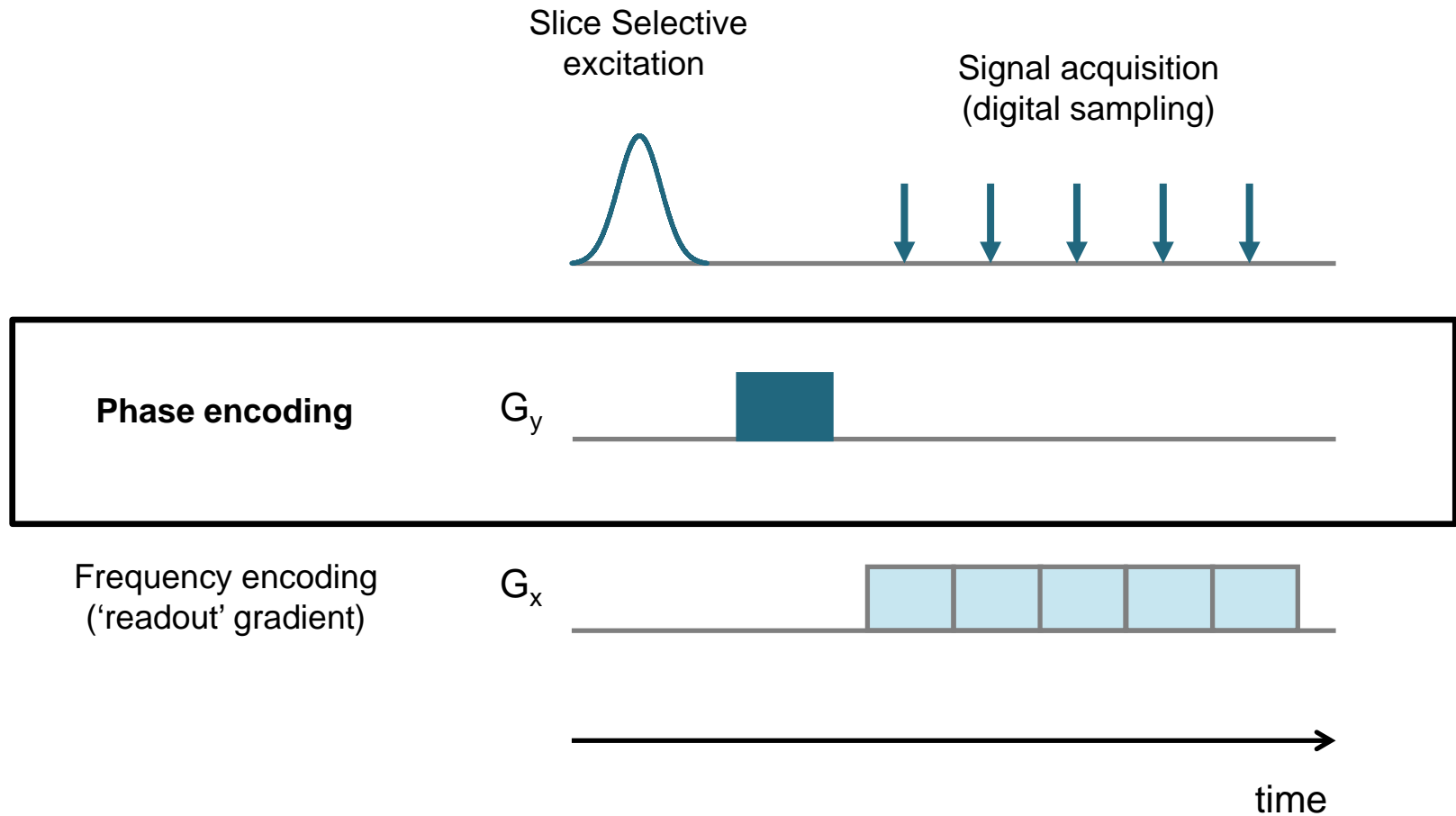
Multi-slice MRI



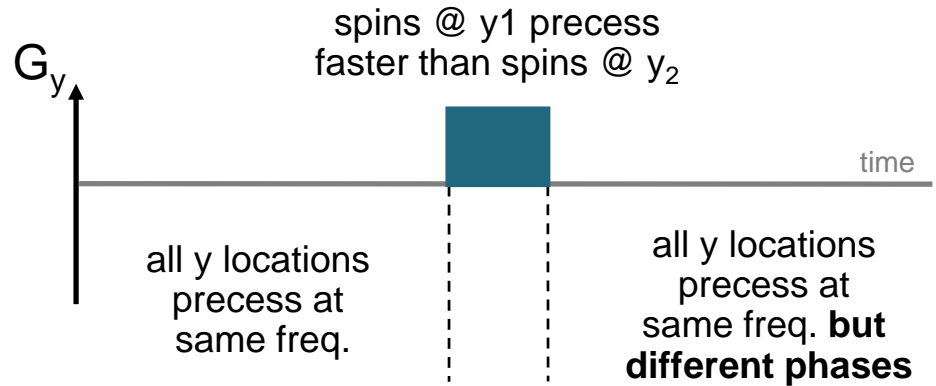
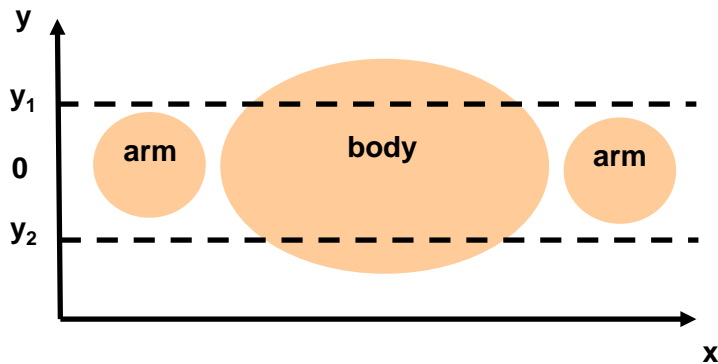
Tissue in the inter-slice gap contributes to the signal of the adjacent slices

Frequency and phase encoding

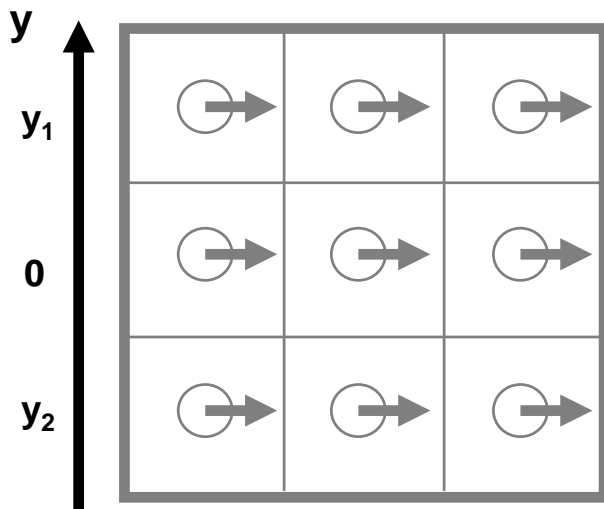
Phase encoding



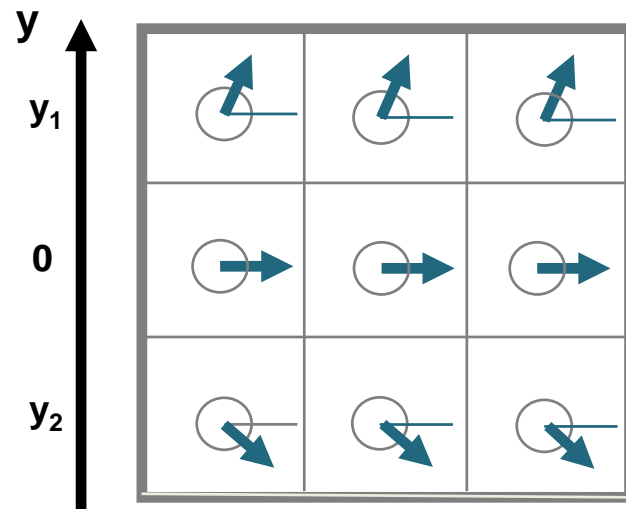
Phase encoding and spatial information



After RF

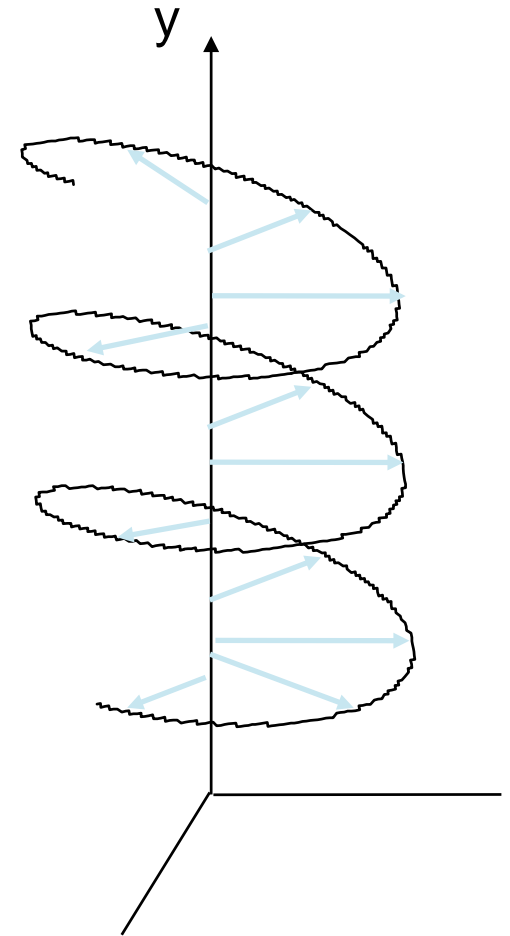


After the phase encoding gradient



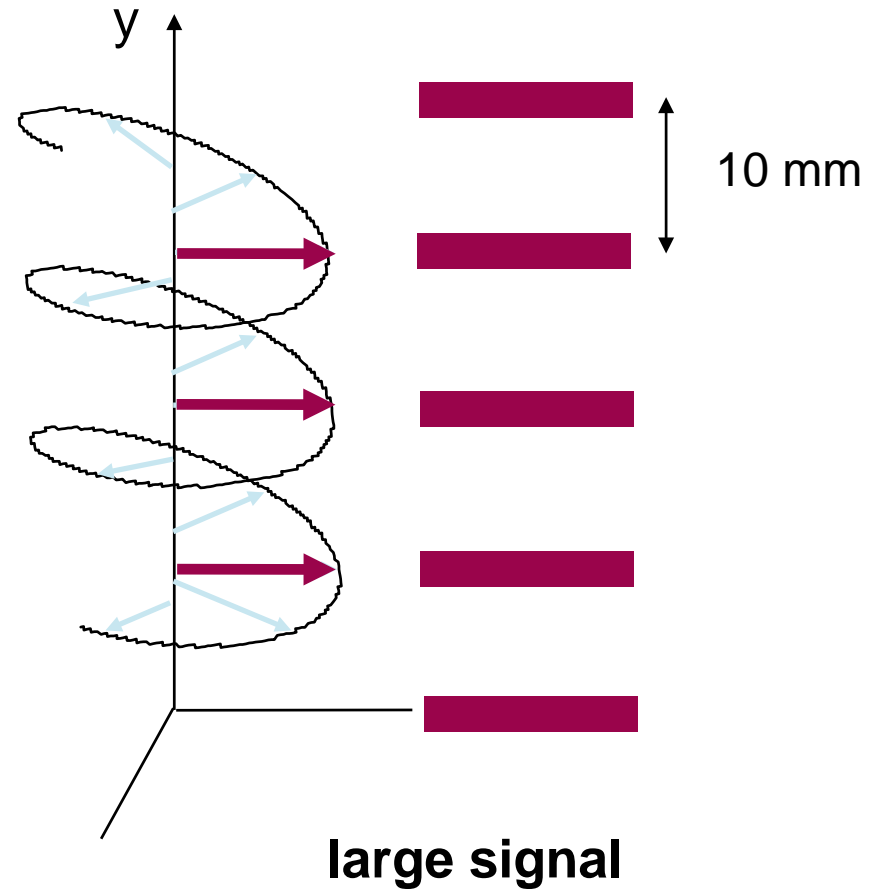
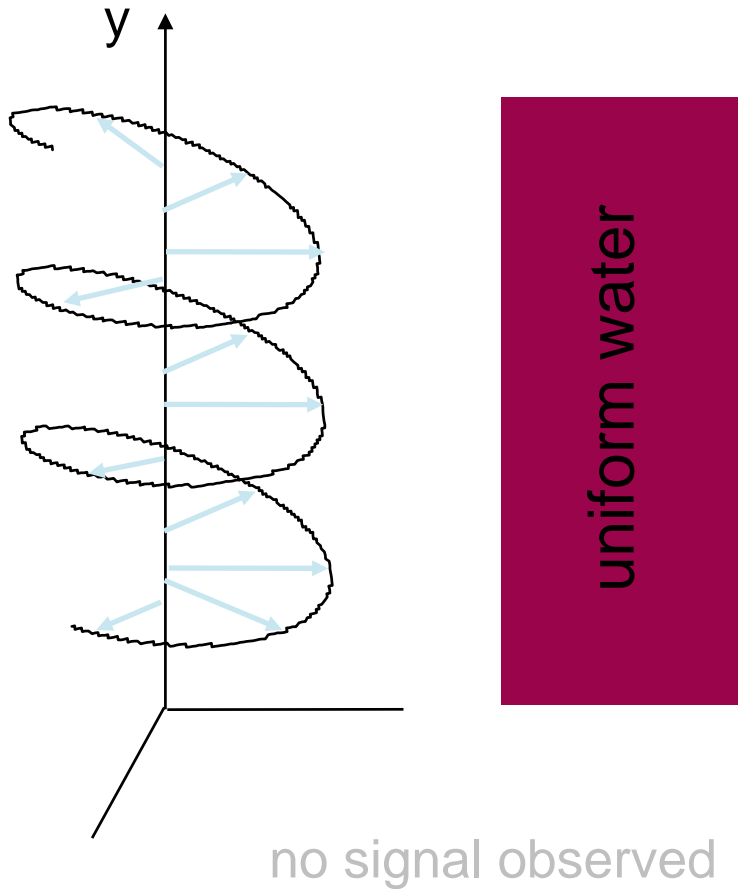
How does phase encoding translate into spatial information?

- 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.

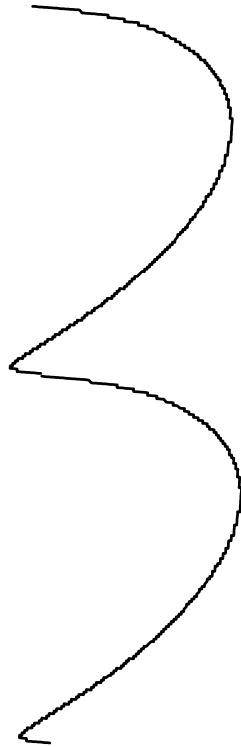


From Larry Wald

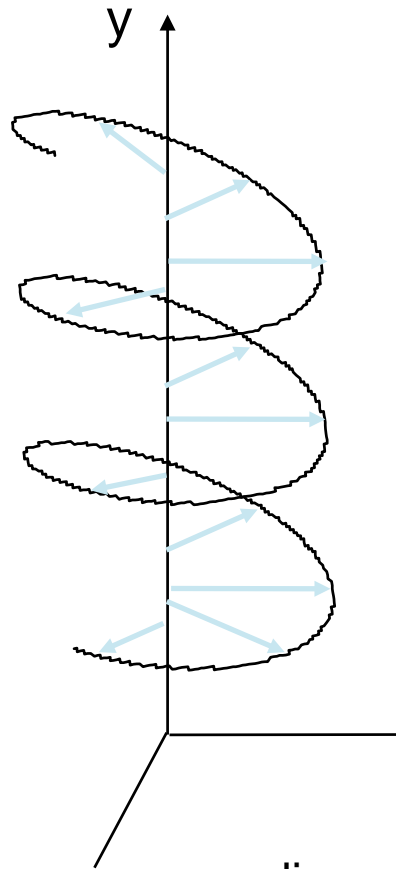
Signal after phase encoding



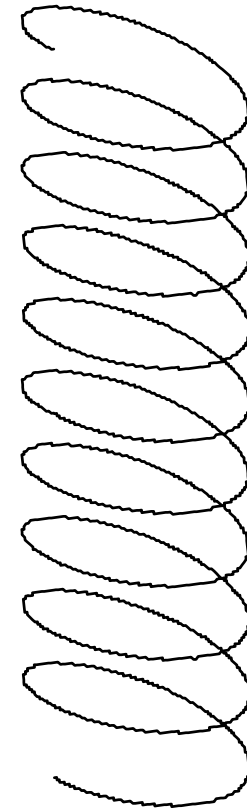
Gradient area and helix shape



small area

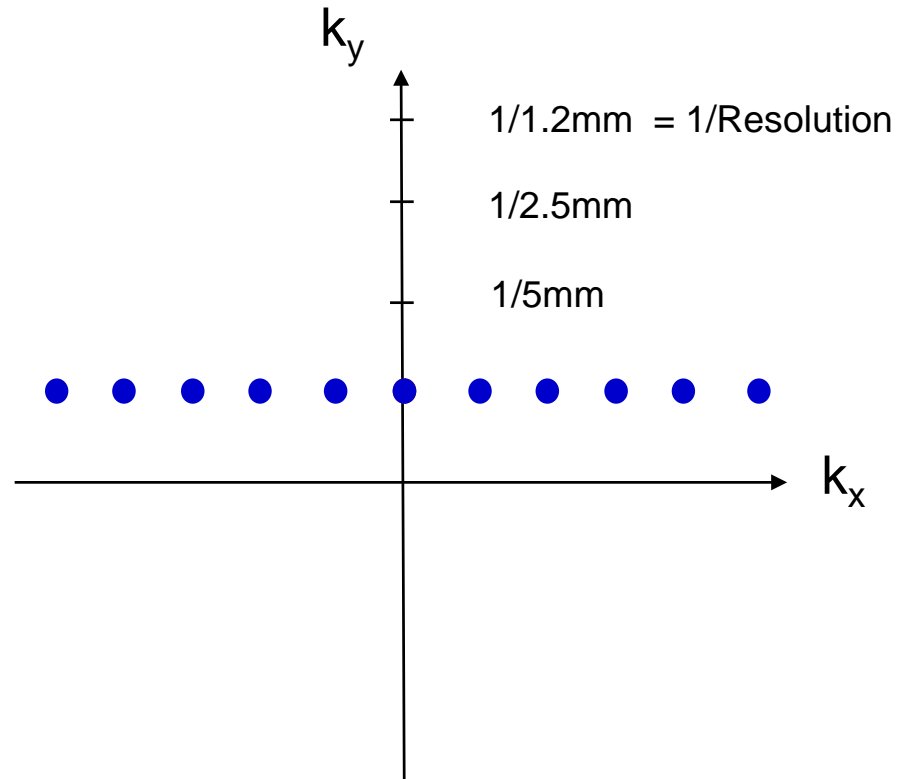
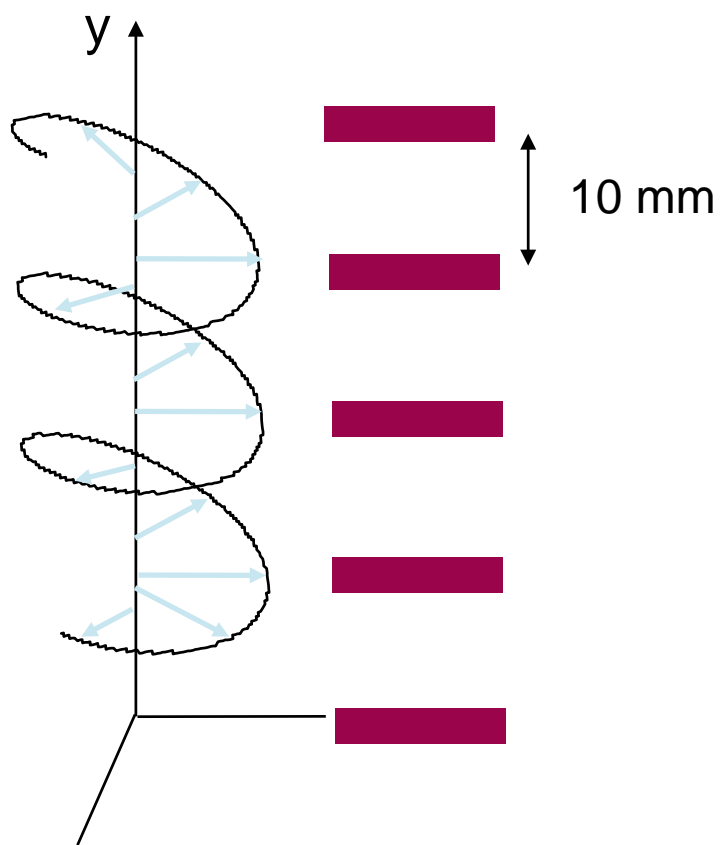


medium area



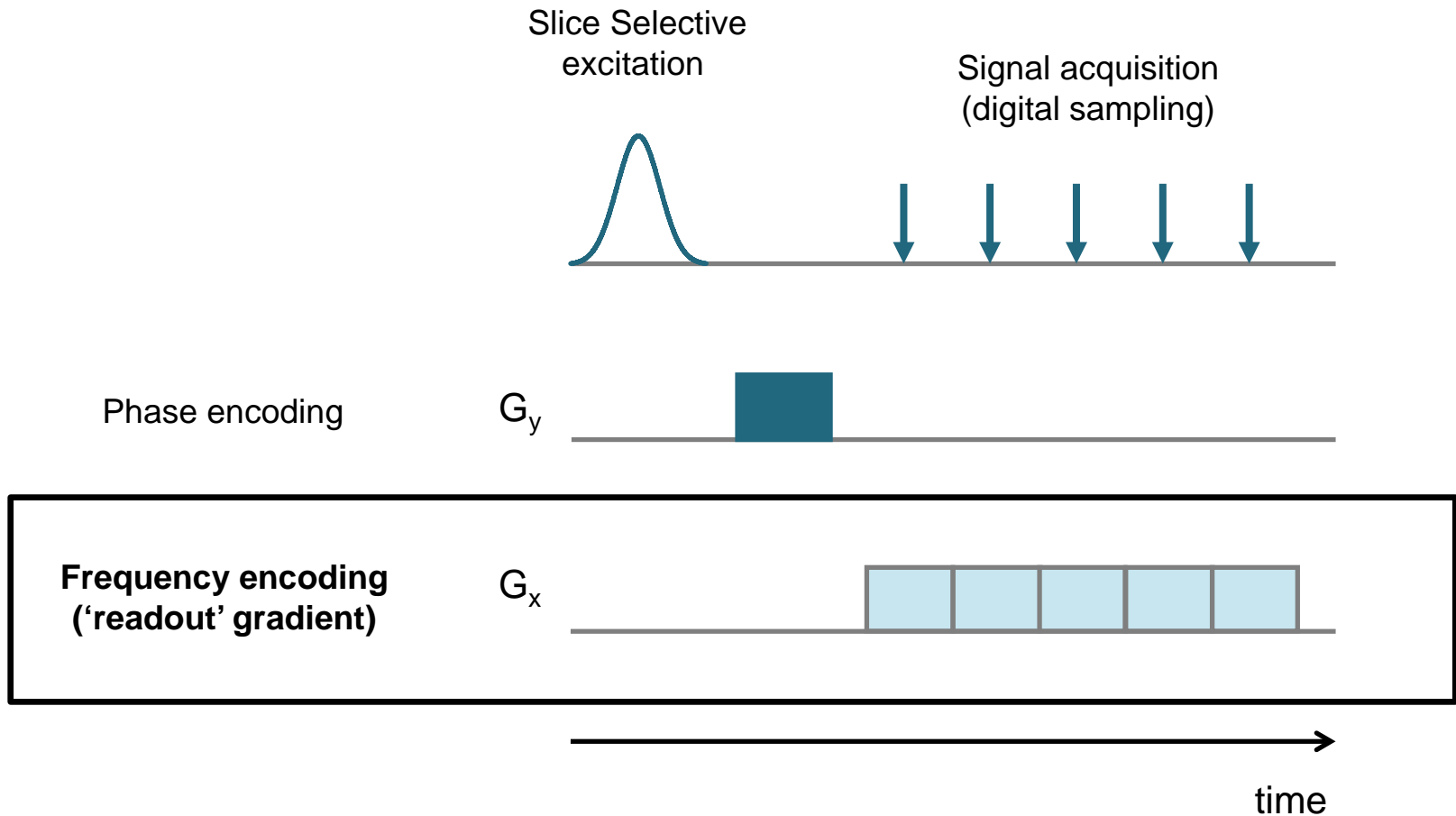
large area

Signal intensity measured at a spatial frequency

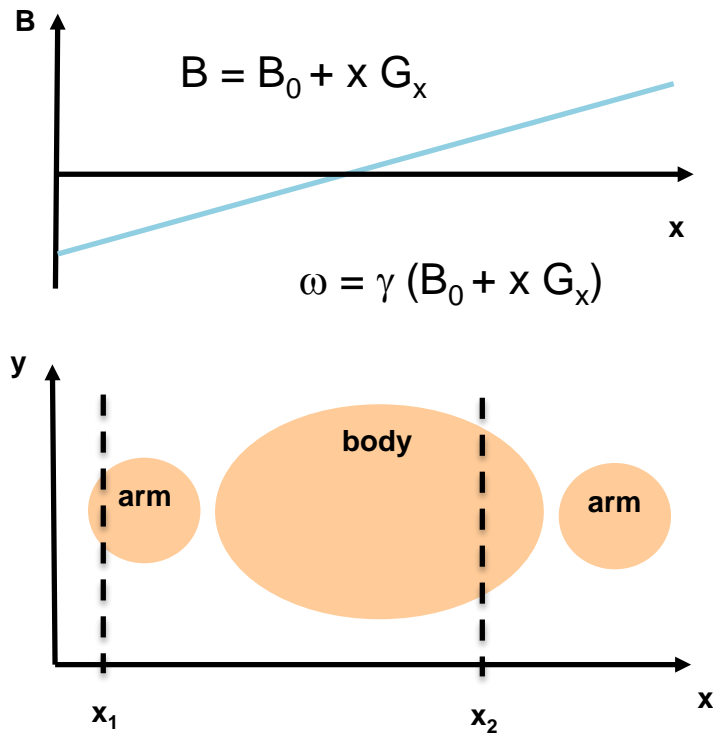


Add frequency encoding

Frequency encoding



Frequency encoding



- 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.

Pulse sequence

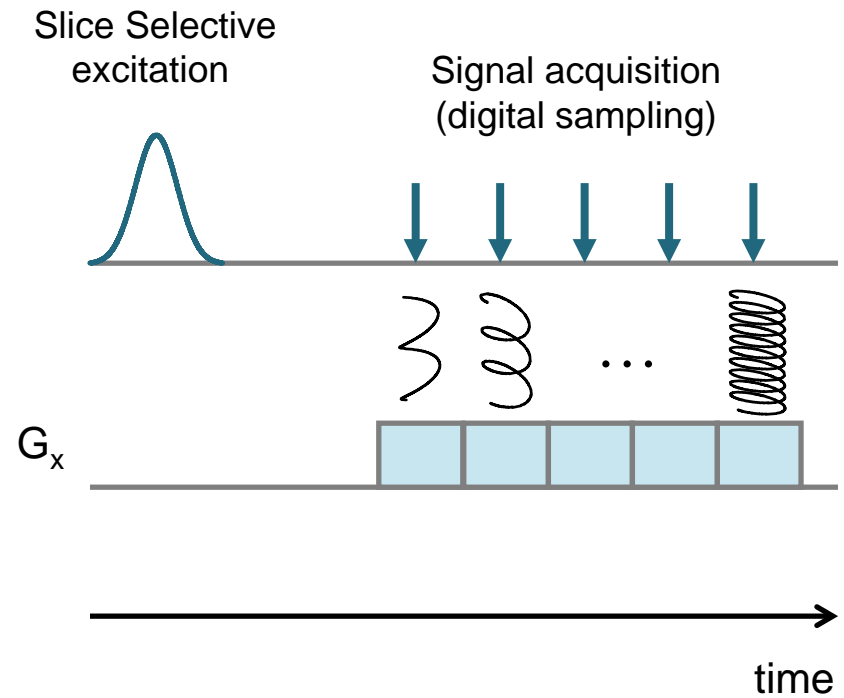
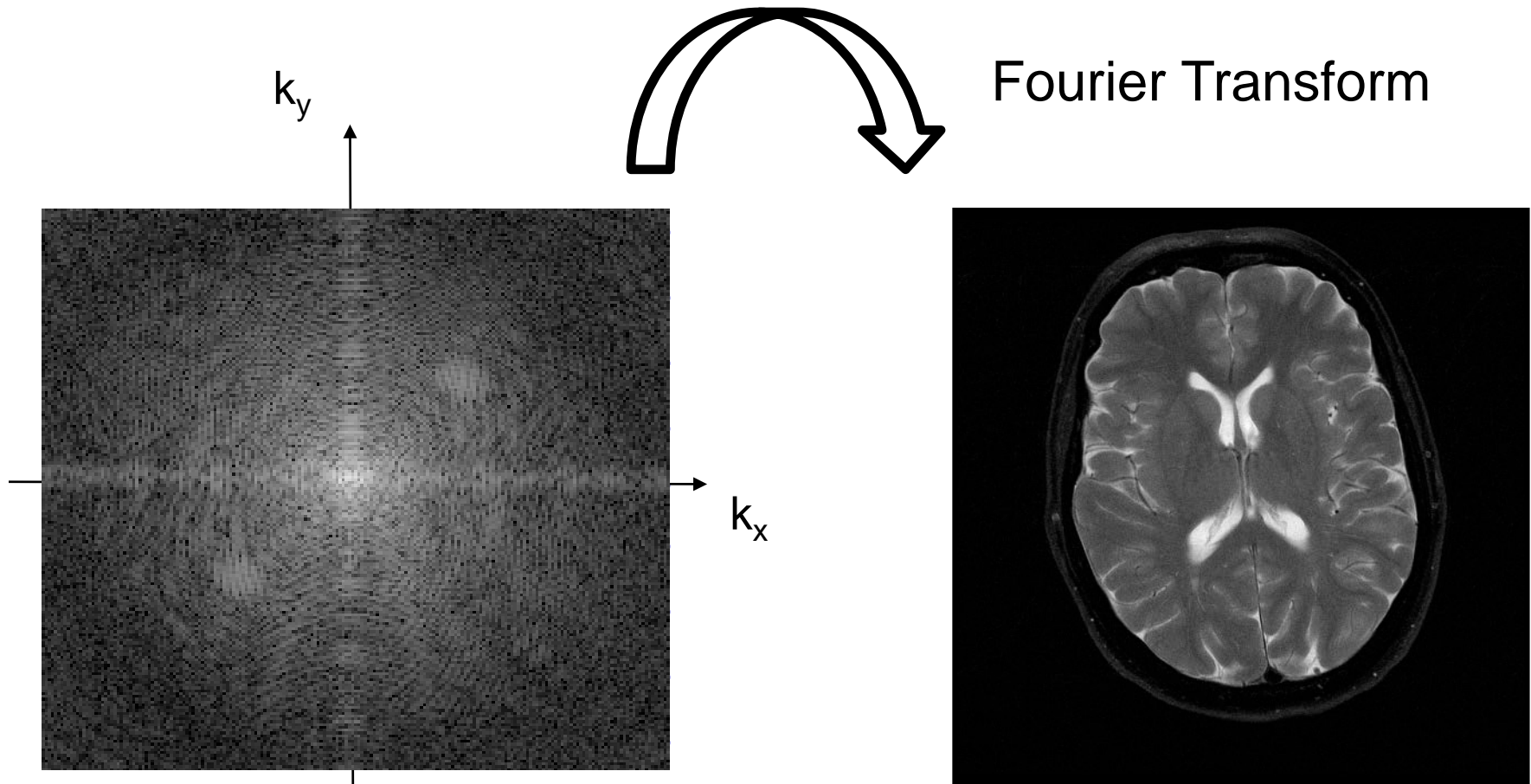
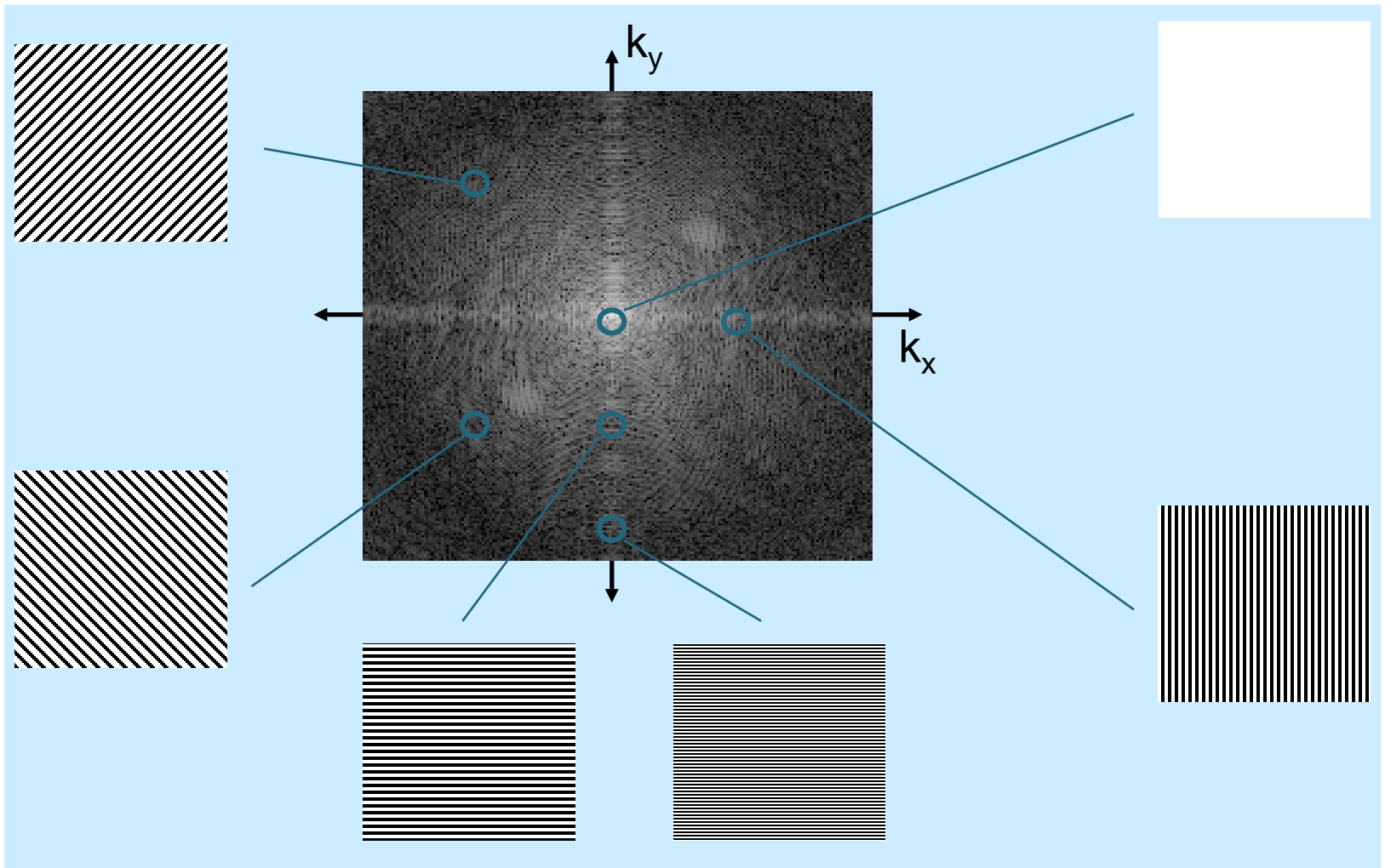


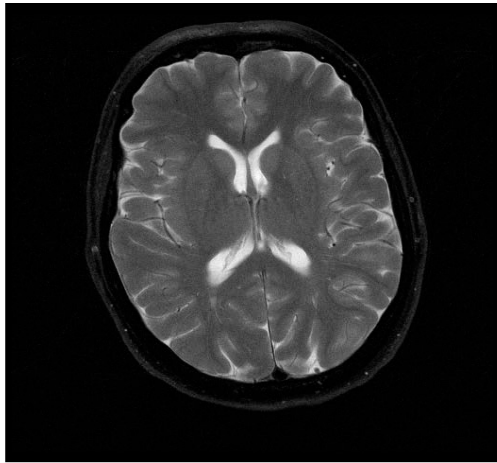
Image reconstruction and k-space



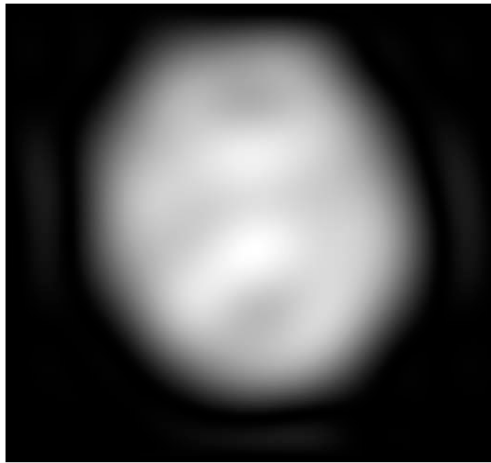
k-space



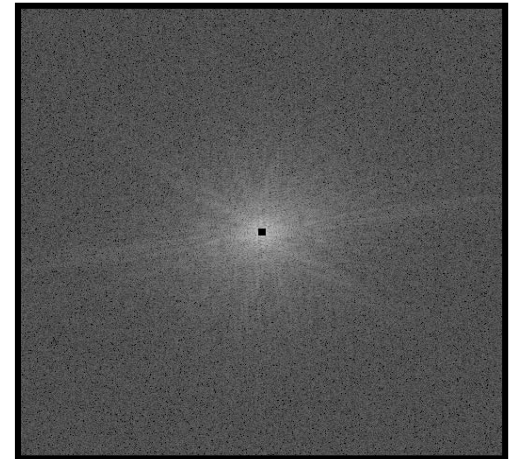
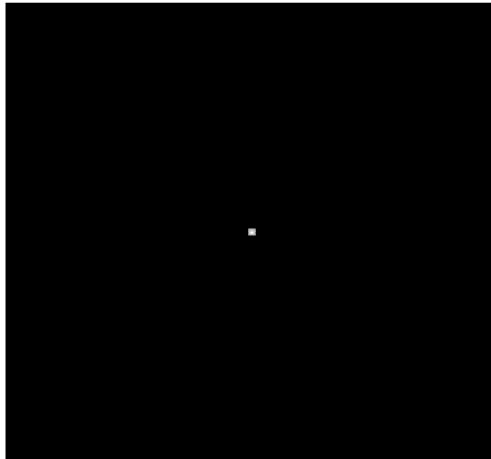
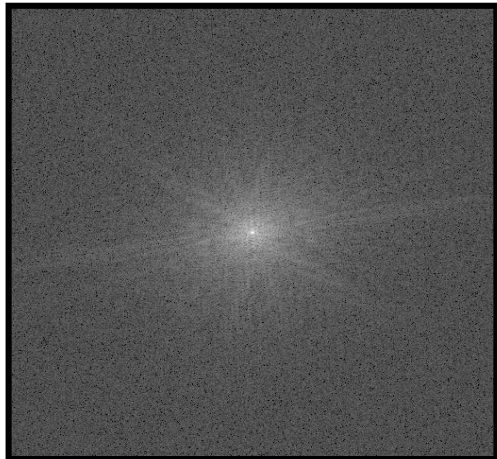
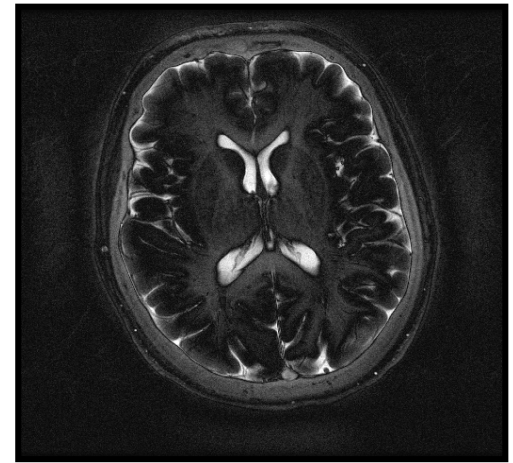
Spatial frequency and contrast



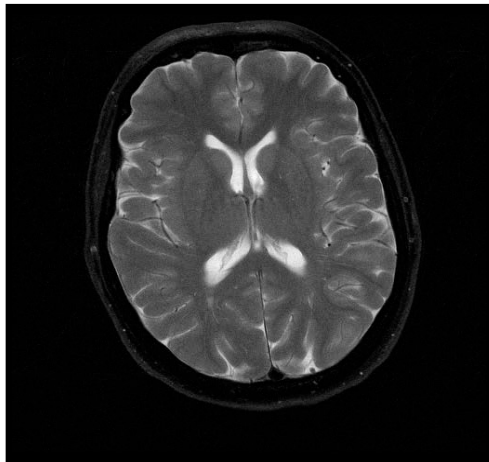
512 x 512



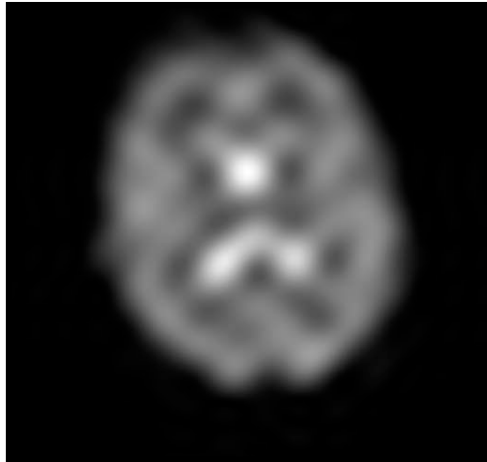
8 x 8



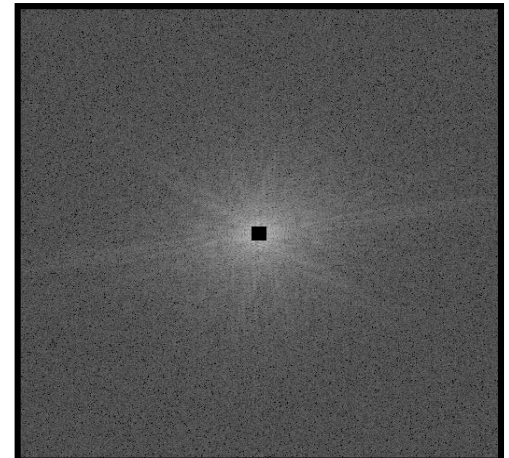
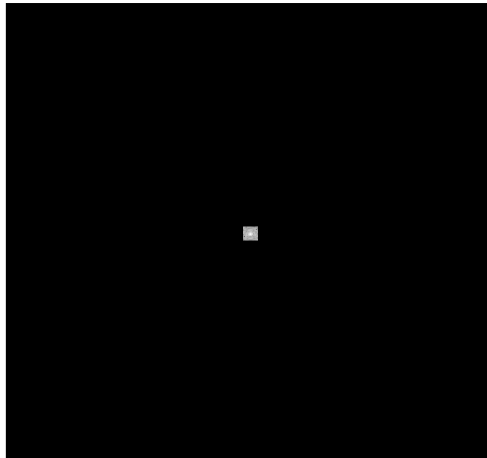
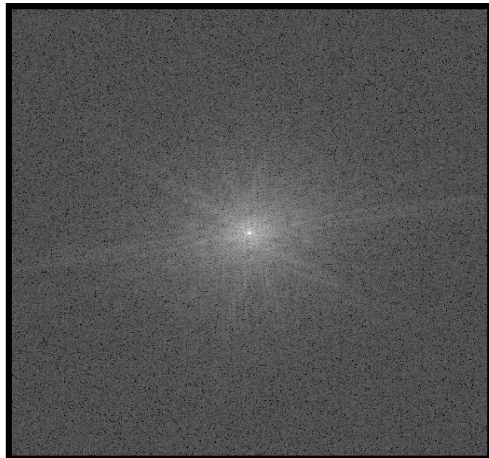
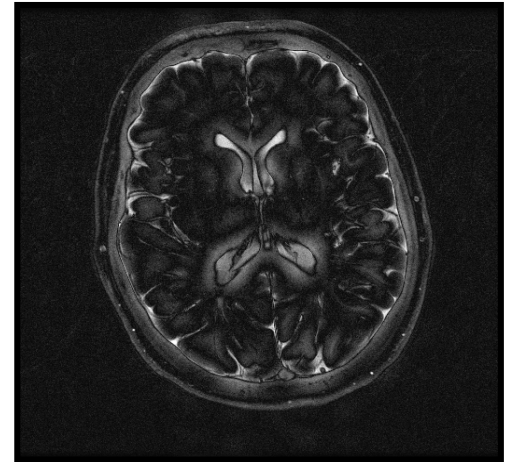
Spatial frequency and contrast



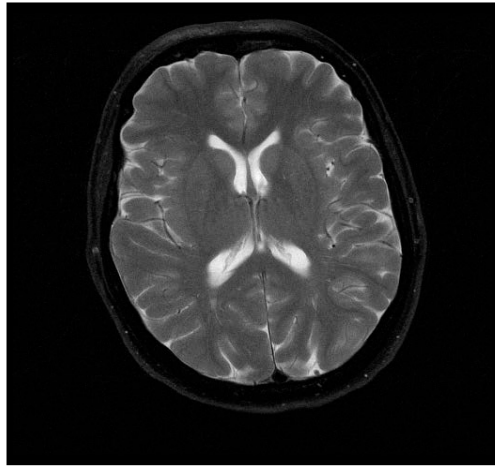
512 x 512



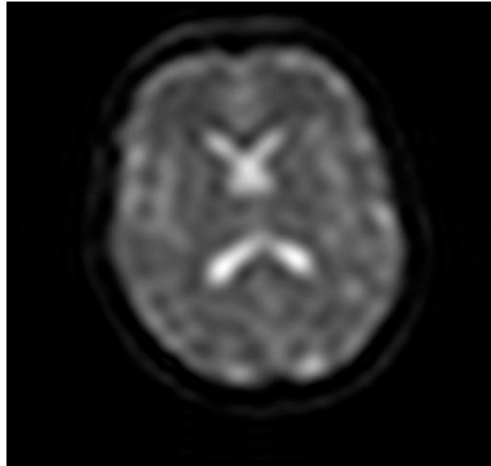
16 x 16



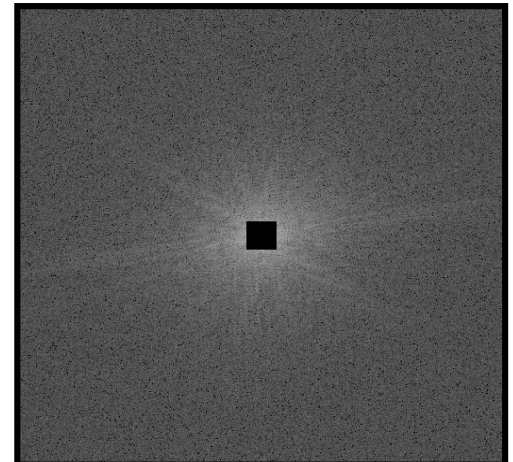
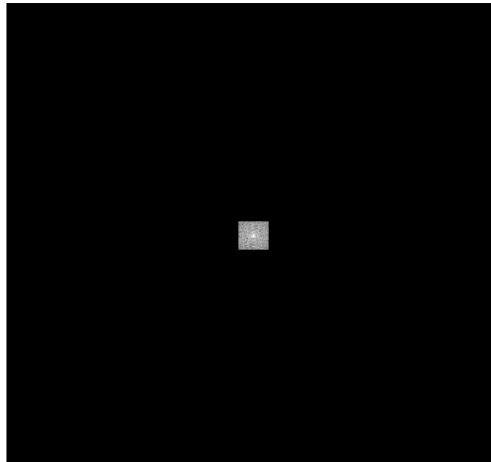
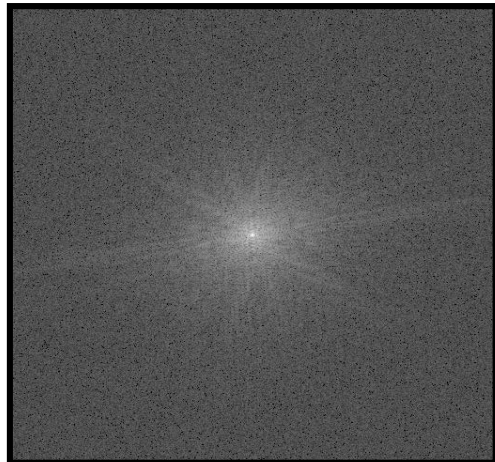
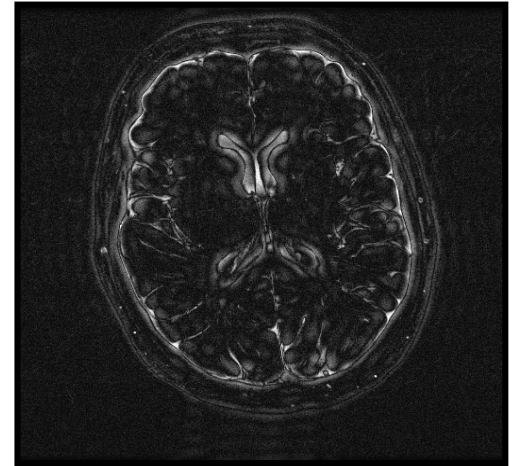
Spatial frequency and contrast



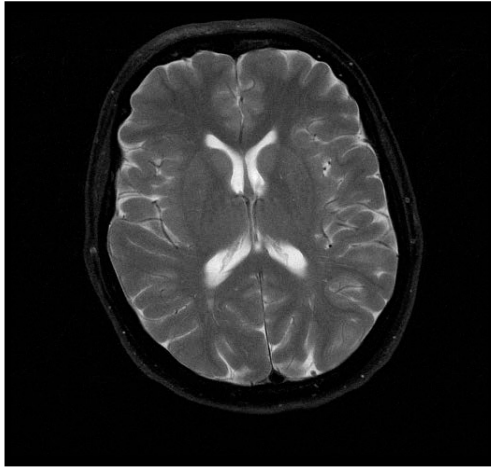
512 x 512



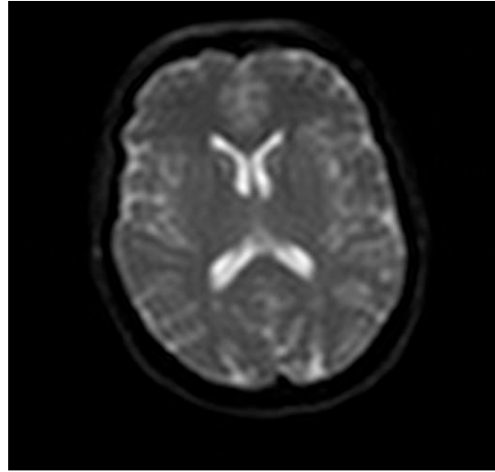
32 x 32



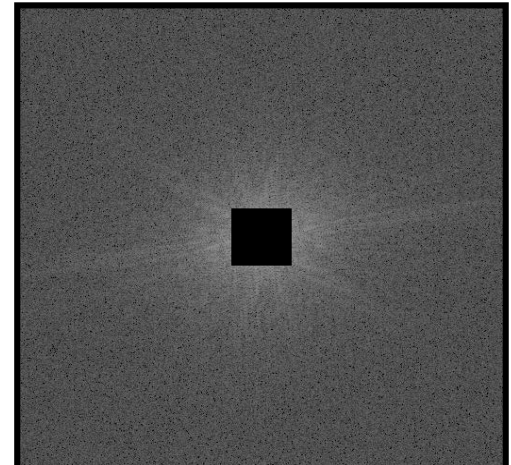
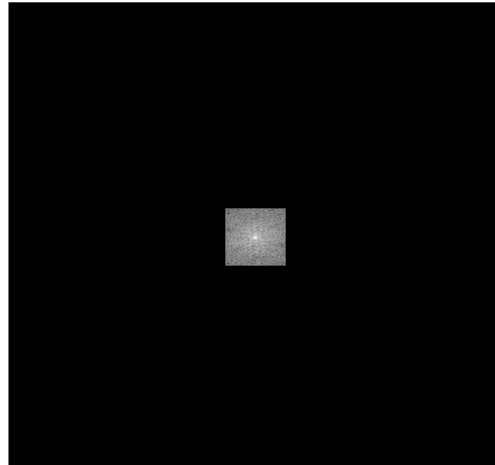
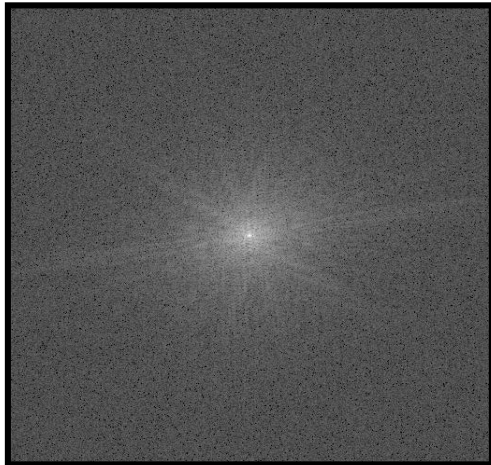
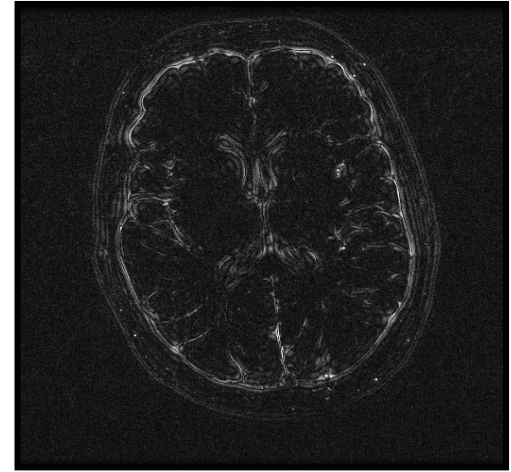
Spatial frequency and contrast



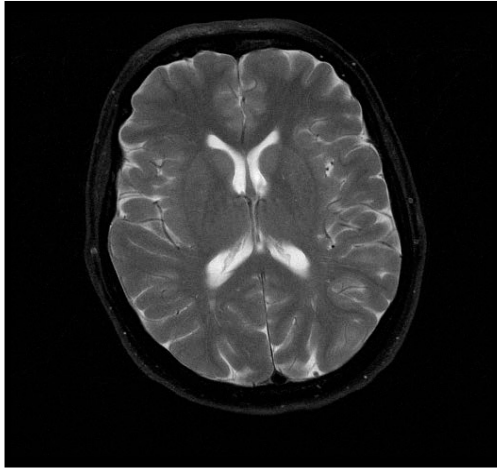
512 x 512



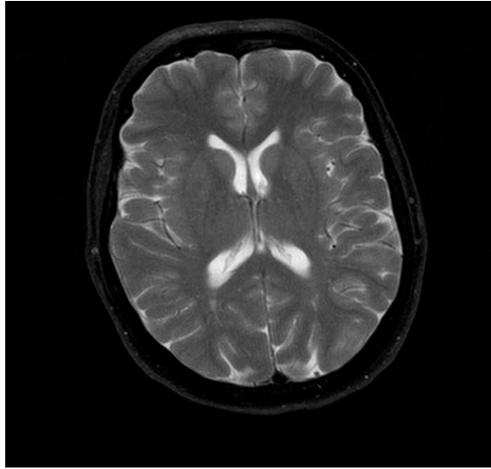
64 x 64



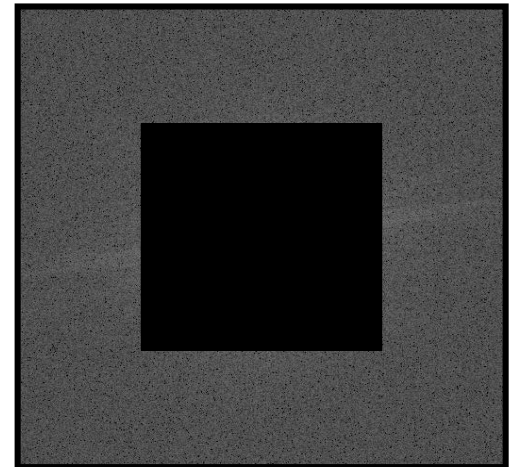
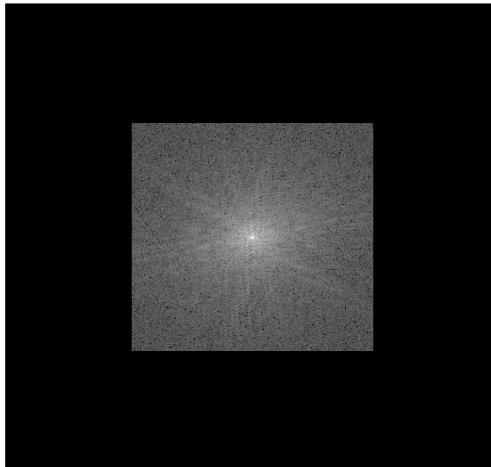
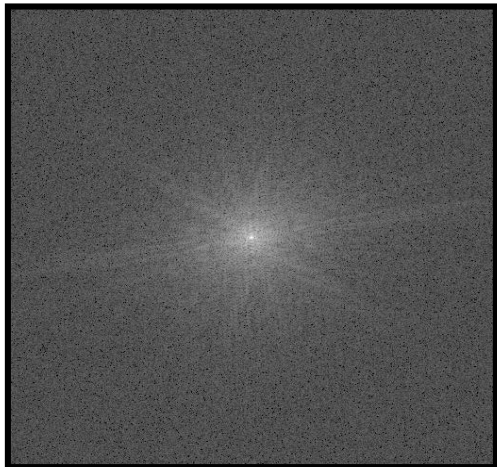
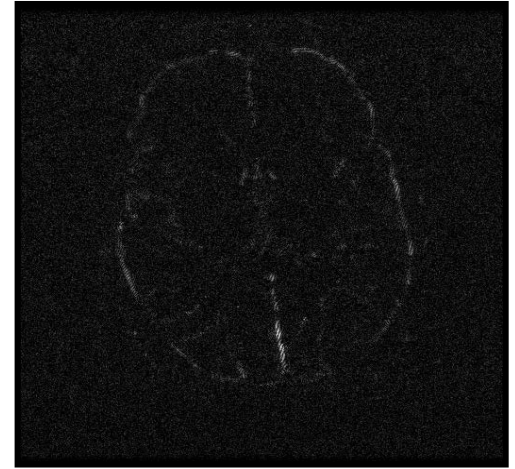
Spatial frequency and contrast



512 x 512

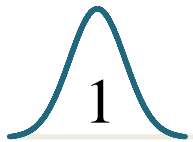


256 x 256



k-space acquisition – Structural Imaging (FLASH)

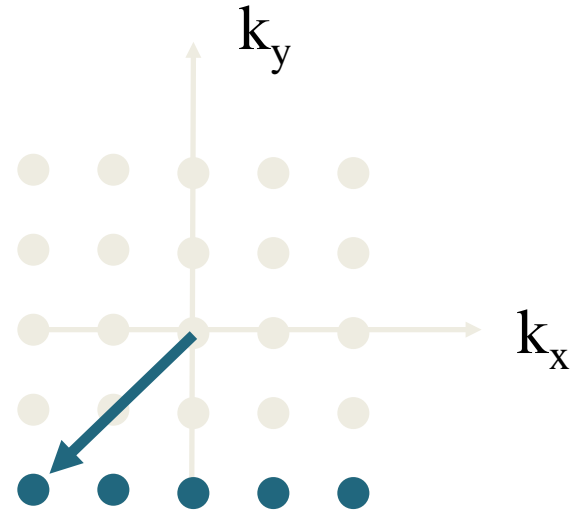
Selective excitation



Signal acquisition
(digital sampling)



K space

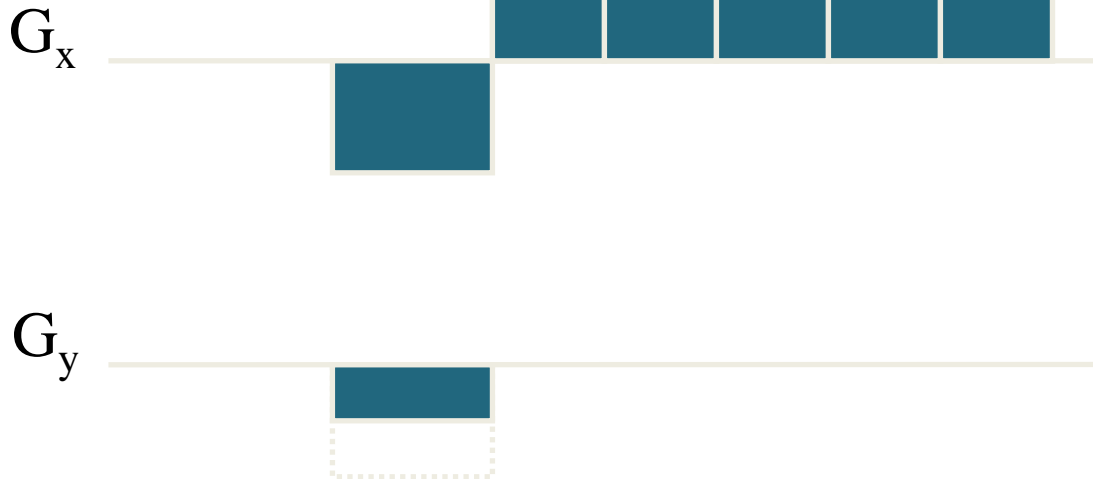


k-space acquisition – Structural Imaging (FLASH)

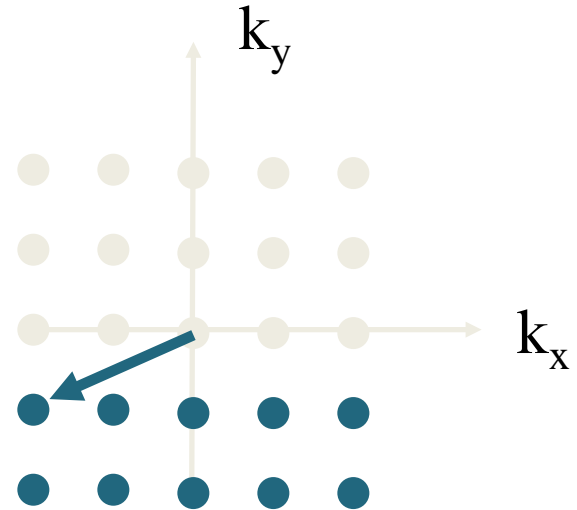
Selective excitation



Signal acquisition
(digital sampling)

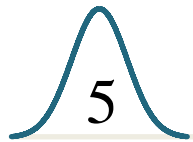


K space

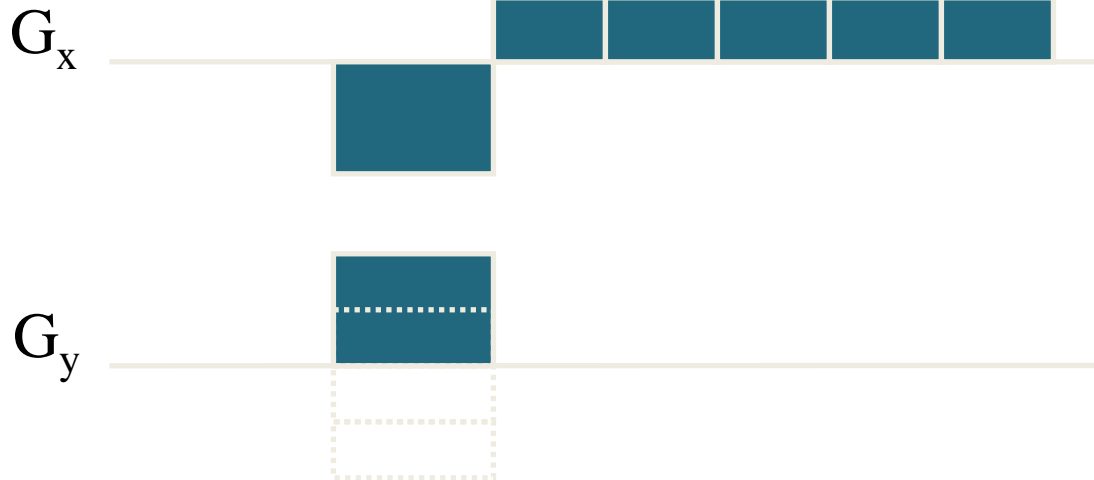


k-space acquisition – Structural Imaging (FLASH)

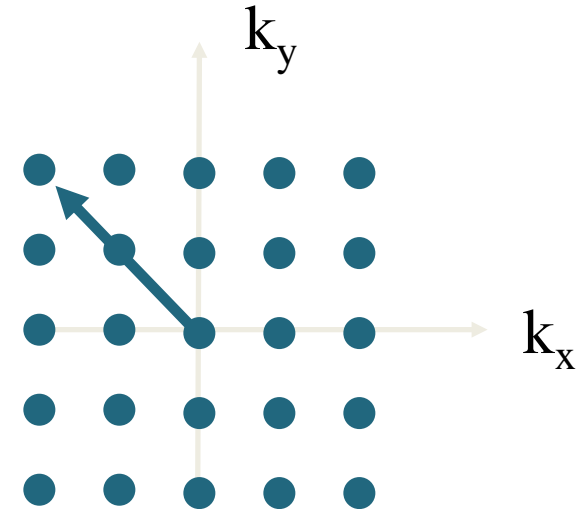
Selective excitation



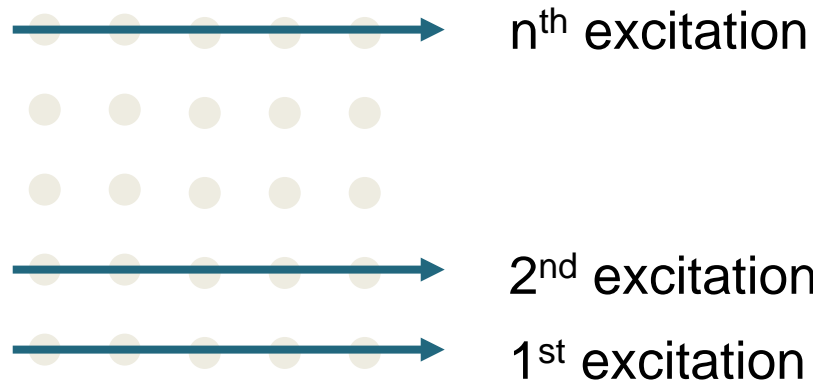
Signal acquisition
(digital sampling)



K space



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: $n = 256$, $TR = 2\text{s}$ $\Rightarrow T = n TR = 8.5 \text{ min}$

Echo Planar Imaging (EPI)

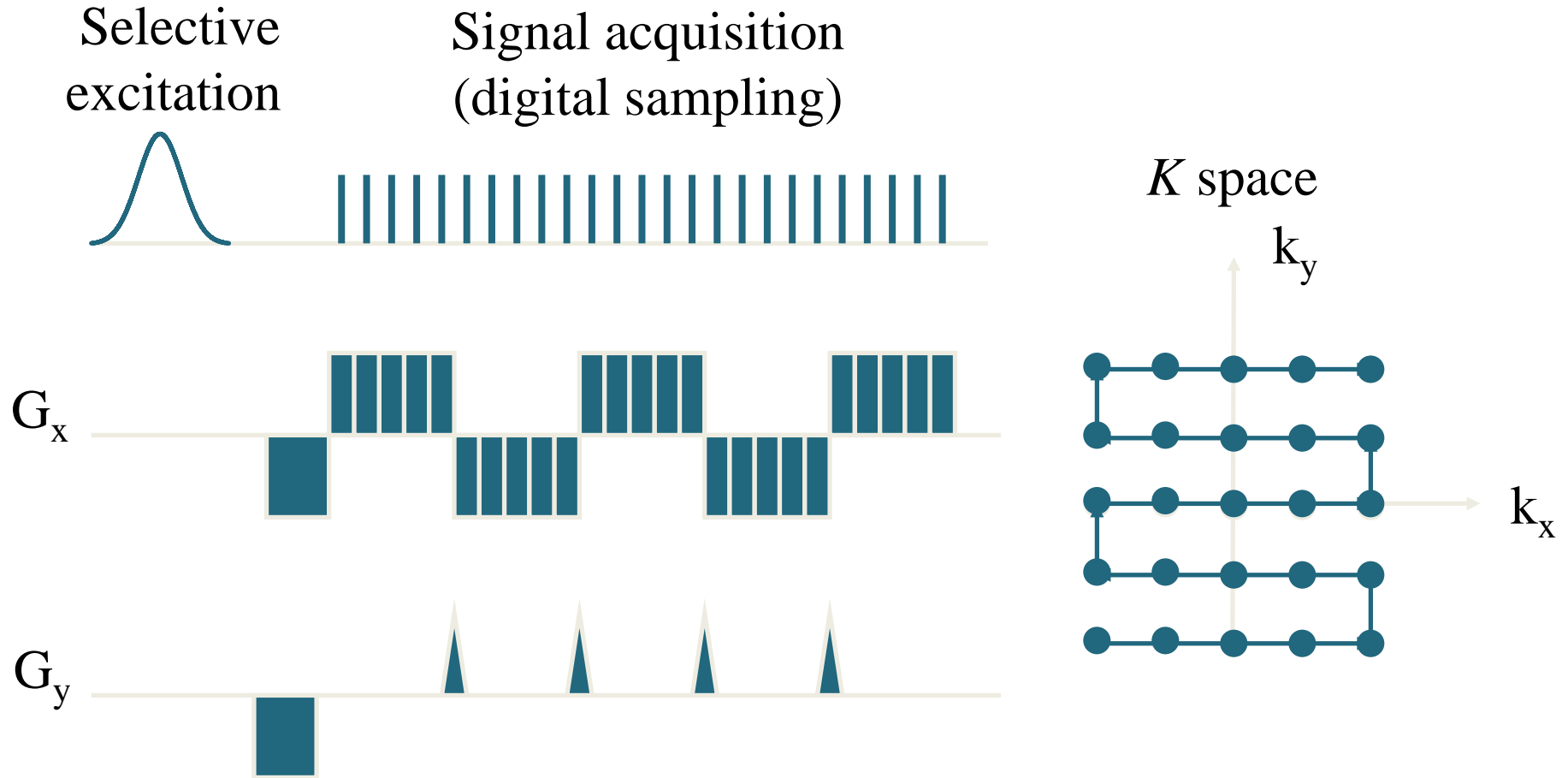
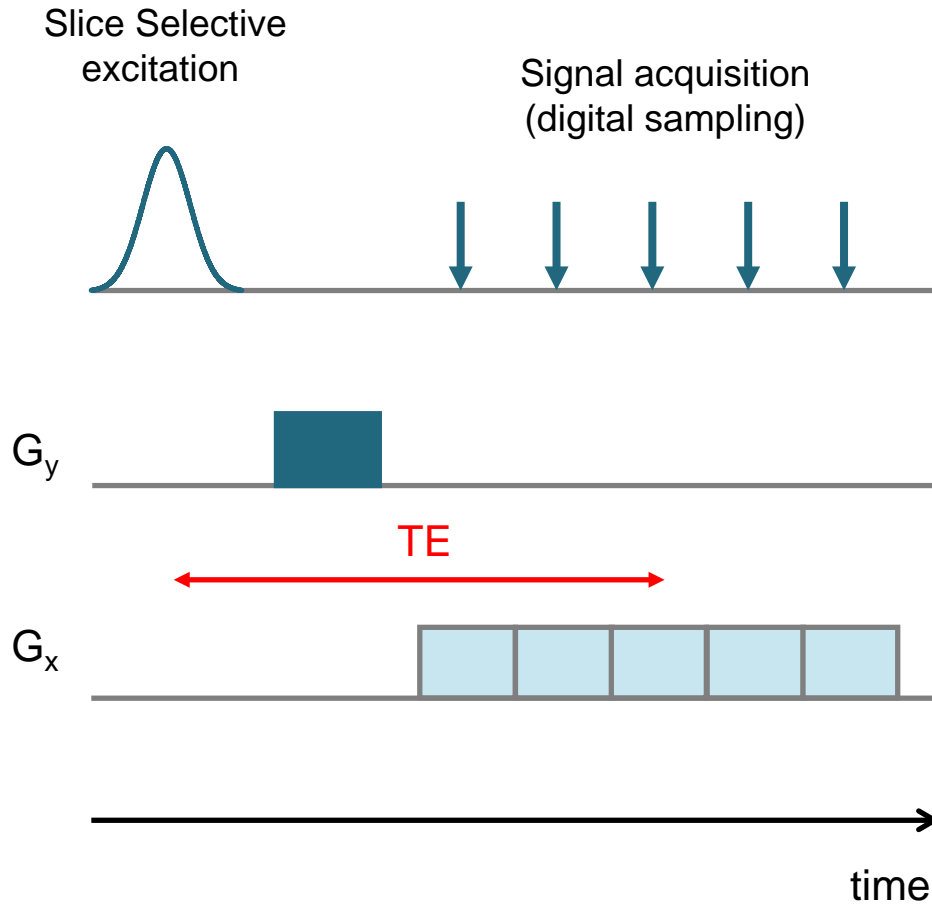
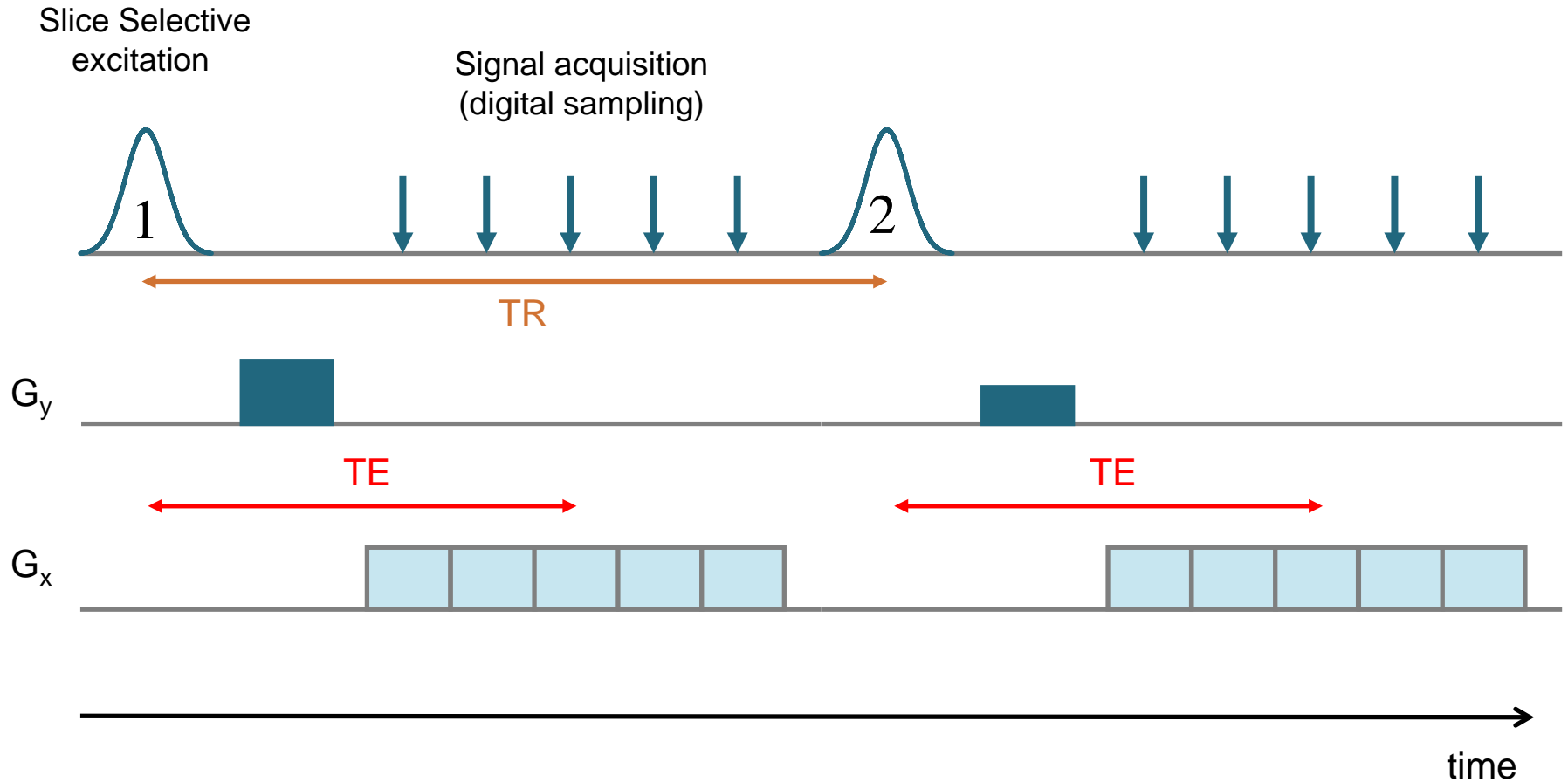


Image Contrast

Echo Time (TE) and Repetition Time (TR)



Echo Time (TE) and Repetition Time (TR)

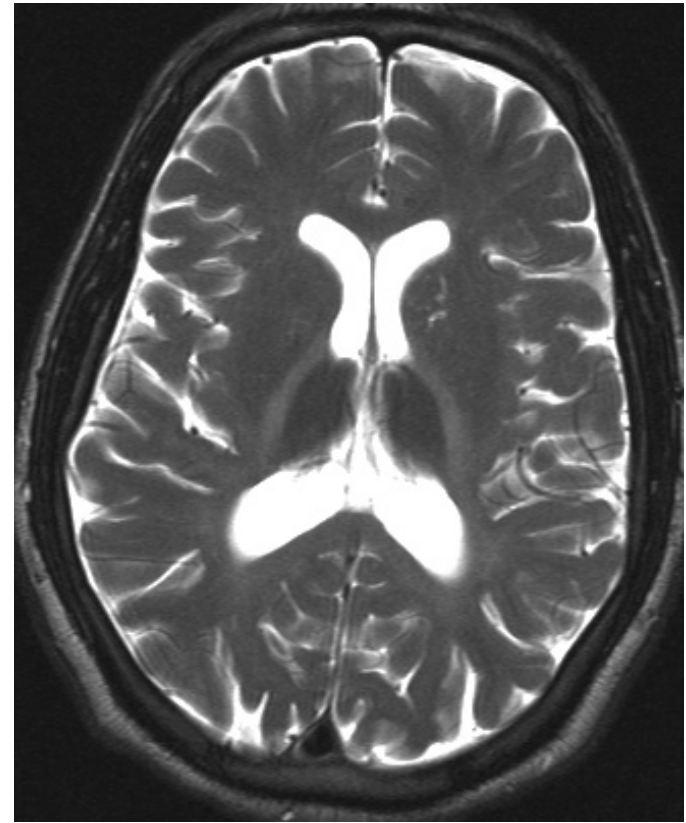


Tissue Contrast

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



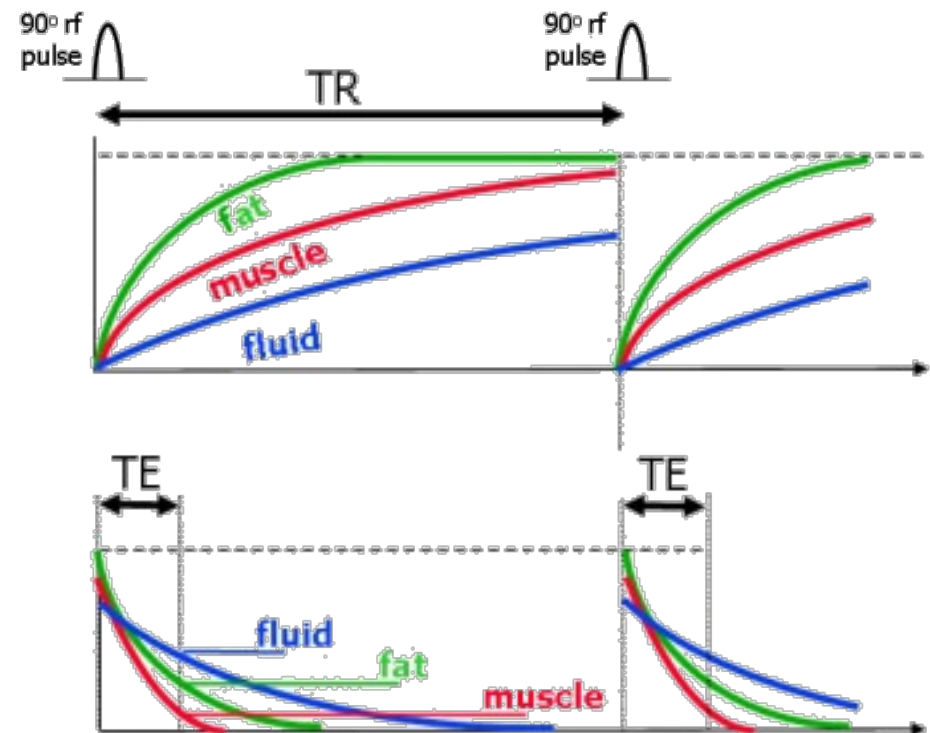
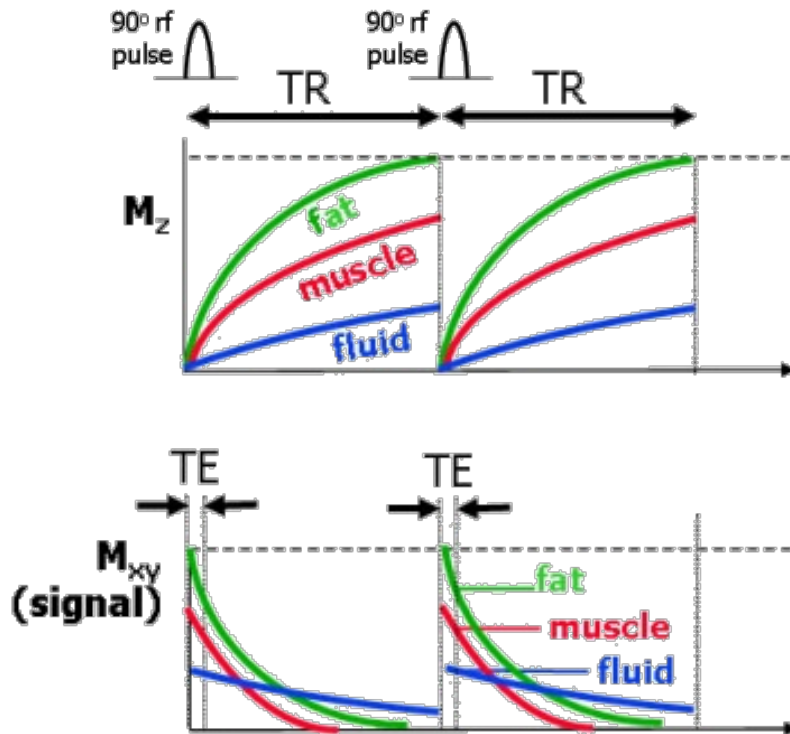
T2-weighted
Bright **fluid**, **Long TR & TE**



Tissue Contrast

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

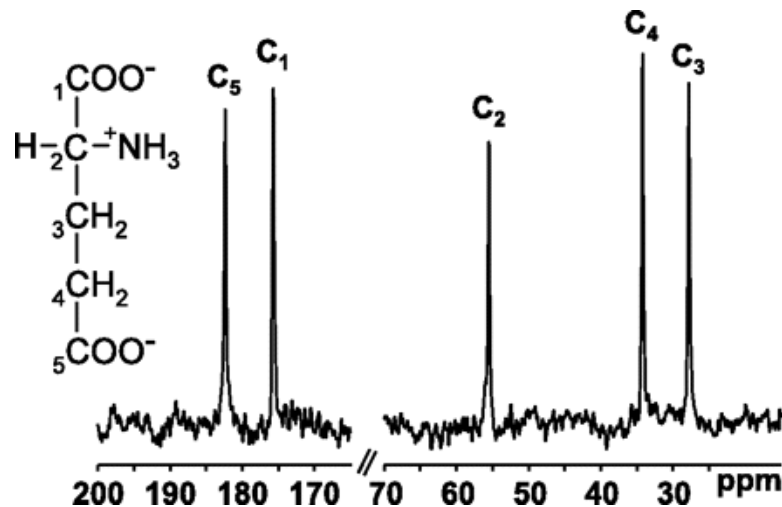
T2-weighted
Bright **fluid**, **Long TR & TE**



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 (^1H), carbon (^{13}C), and phosphorus (^{31}P).
- MRS is sensitive to different chemical environments within a molecule.

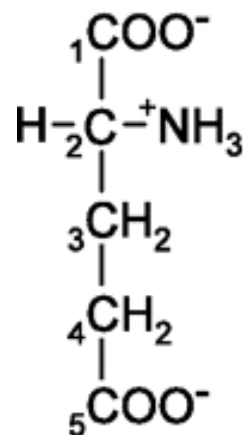


The MRS spectrum of glutamate

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.



$$\omega_1 = \gamma B_1$$

$$\omega_2 = \gamma B_2$$

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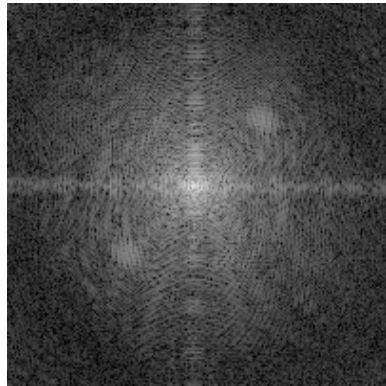
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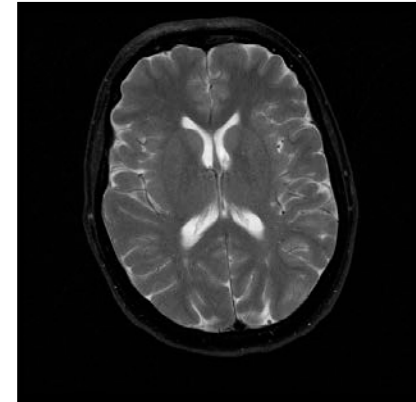
$$\omega_5 = \gamma B_5$$

Basic principles of MRS

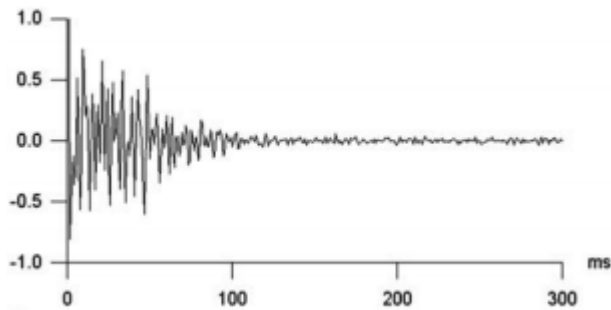
MRI



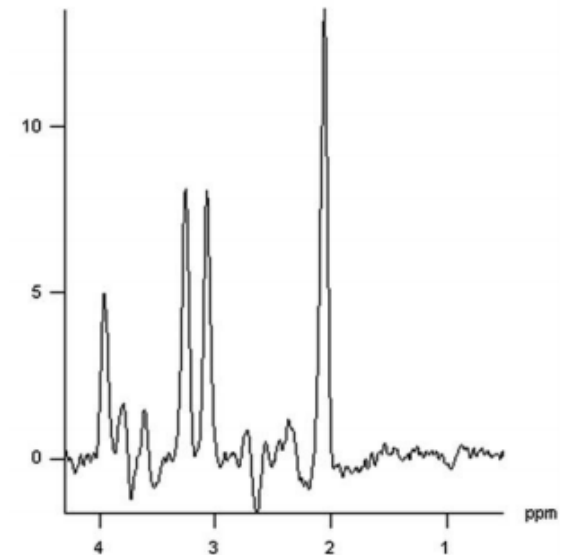
Fourier Transform



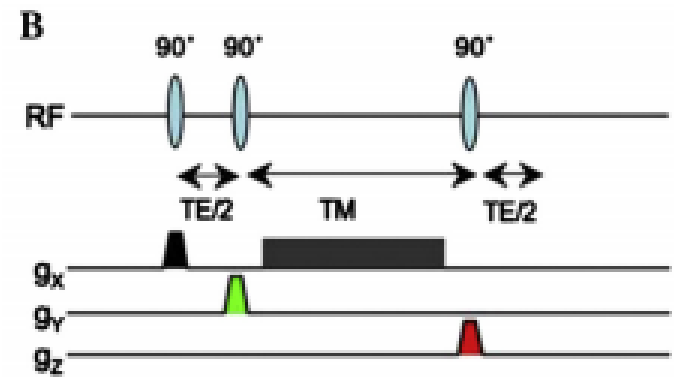
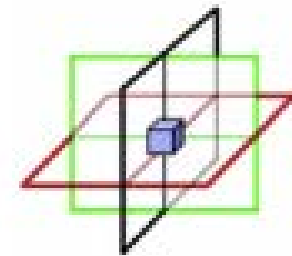
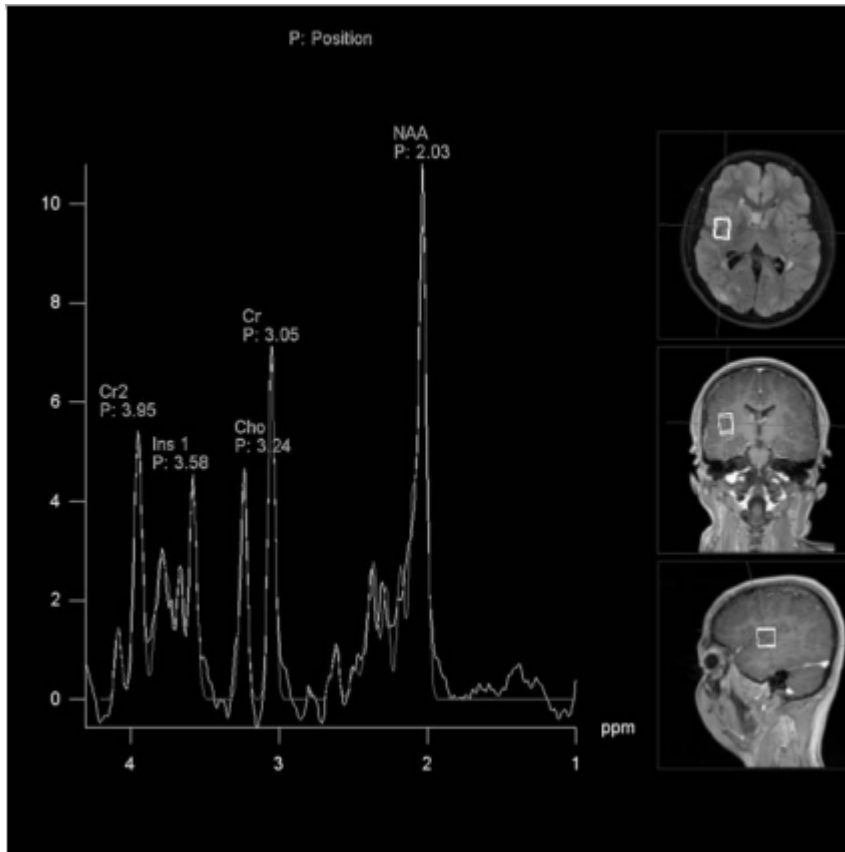
MRS



Fourier Transform



MRS and Signal Localisation



Questions?

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