



MRC Cognition  
and Brain  
Sciences Unit



UNIVERSITY OF  
CAMBRIDGE

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# Introduction to MRI Physics

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MRC Cognition and Brain Sciences Unit

26<sup>th</sup> of January 2026

# Overview

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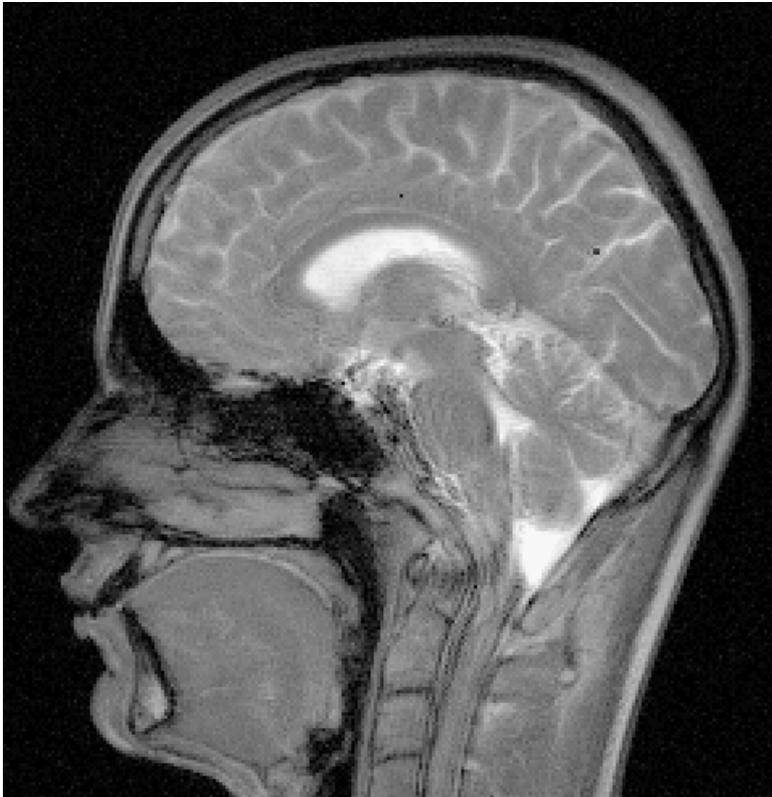
- Nuclear Magnetic Resonance Imaging (NMR)
  - Basic Principles
  - Excitation, Relaxation and Signal
- Magnetic Resonance Imaging (MRI)
  - Spatial Encoding in MRI
  - Image formation and k-space
  - Image contrast
- Magnetic Resonance Spectroscopy (MRS)

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# Part I: Nuclear Magnetic Resonance (NMR)

# MR images: What do we see ?

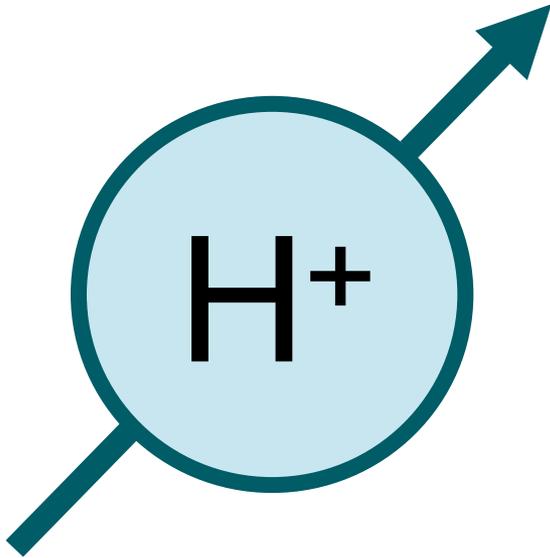
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- MRI images are usually based on the signal from protons
- A proton is the nucleus of the hydrogen atom
- Hydrogen is the most common element in tissue
- The signal from protons is due to their *spin*

# The Nuclear spin

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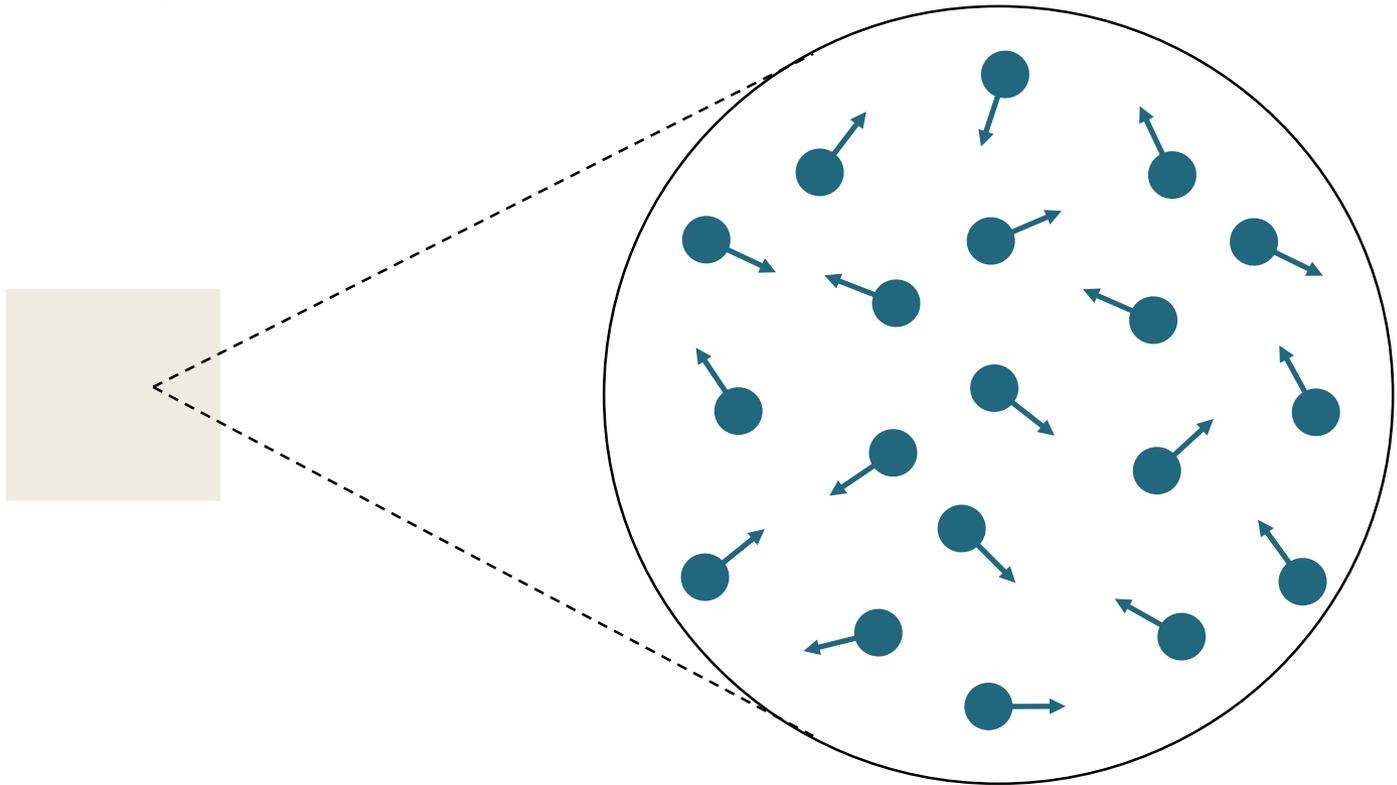


- Elementary property of an atomic nucleus
- Each spin carries an elementary magnetization
- Spins align in an external magnetic field (like a compass needle)

# Macroscopic sample

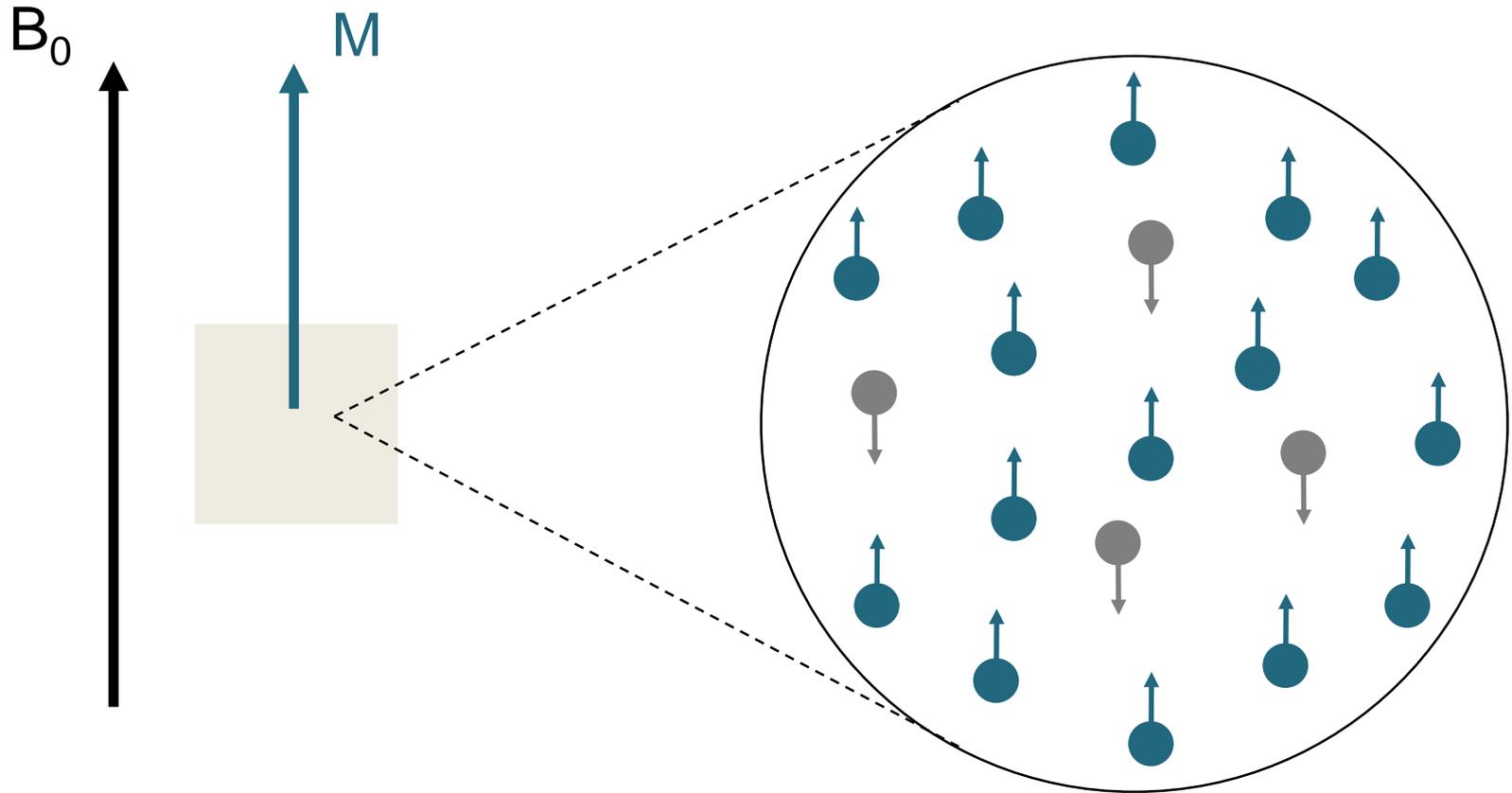
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$M=0$

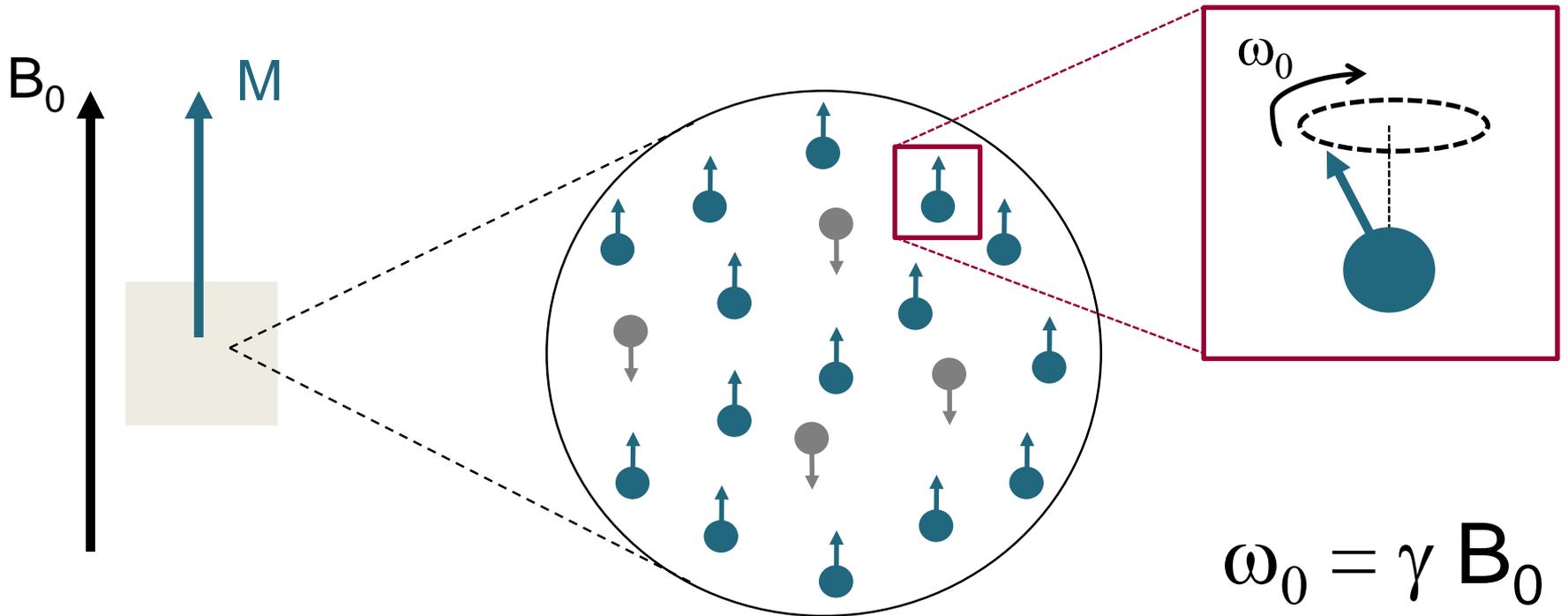


# Macroscopic sample

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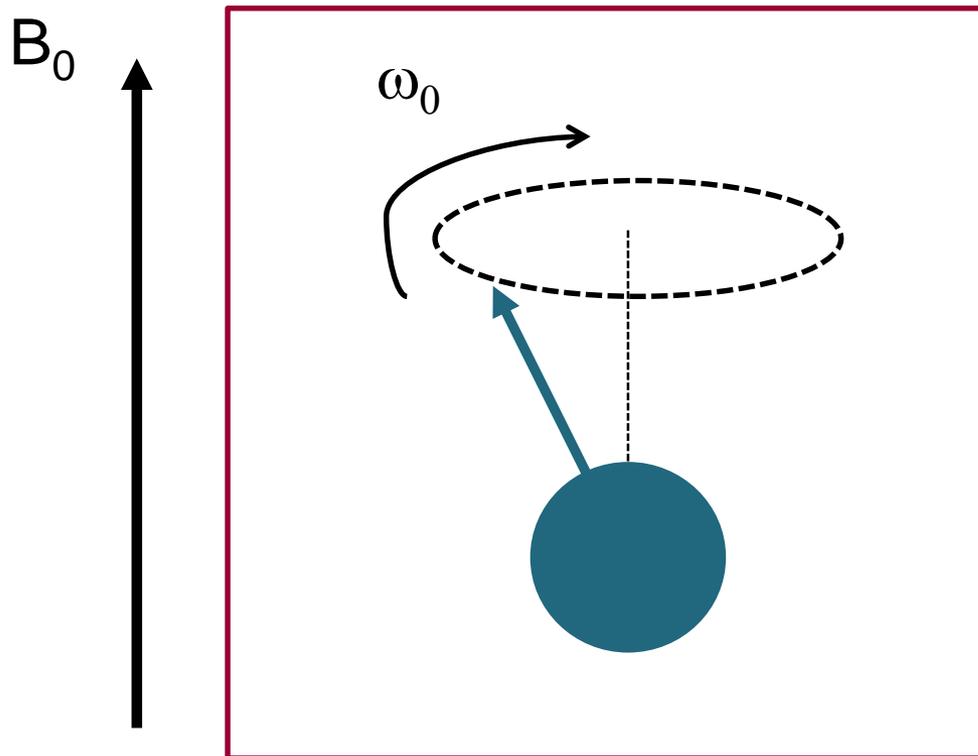


# Precession and Larmor Frequency



# Precession and Larmor Frequency

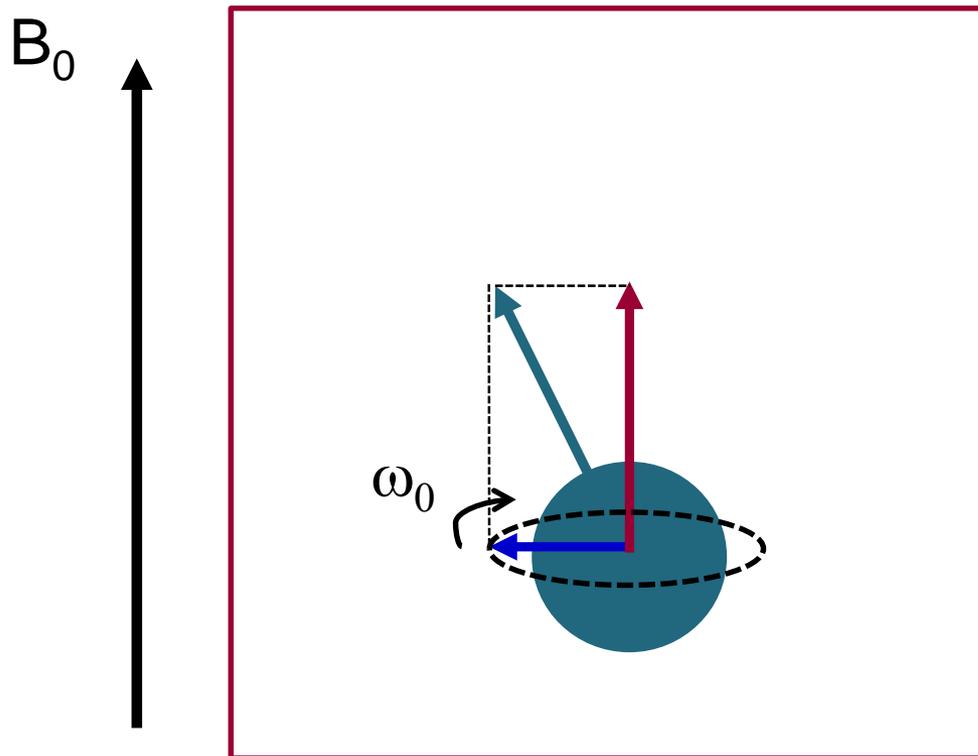
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$$\omega_0 = \gamma B_0$$

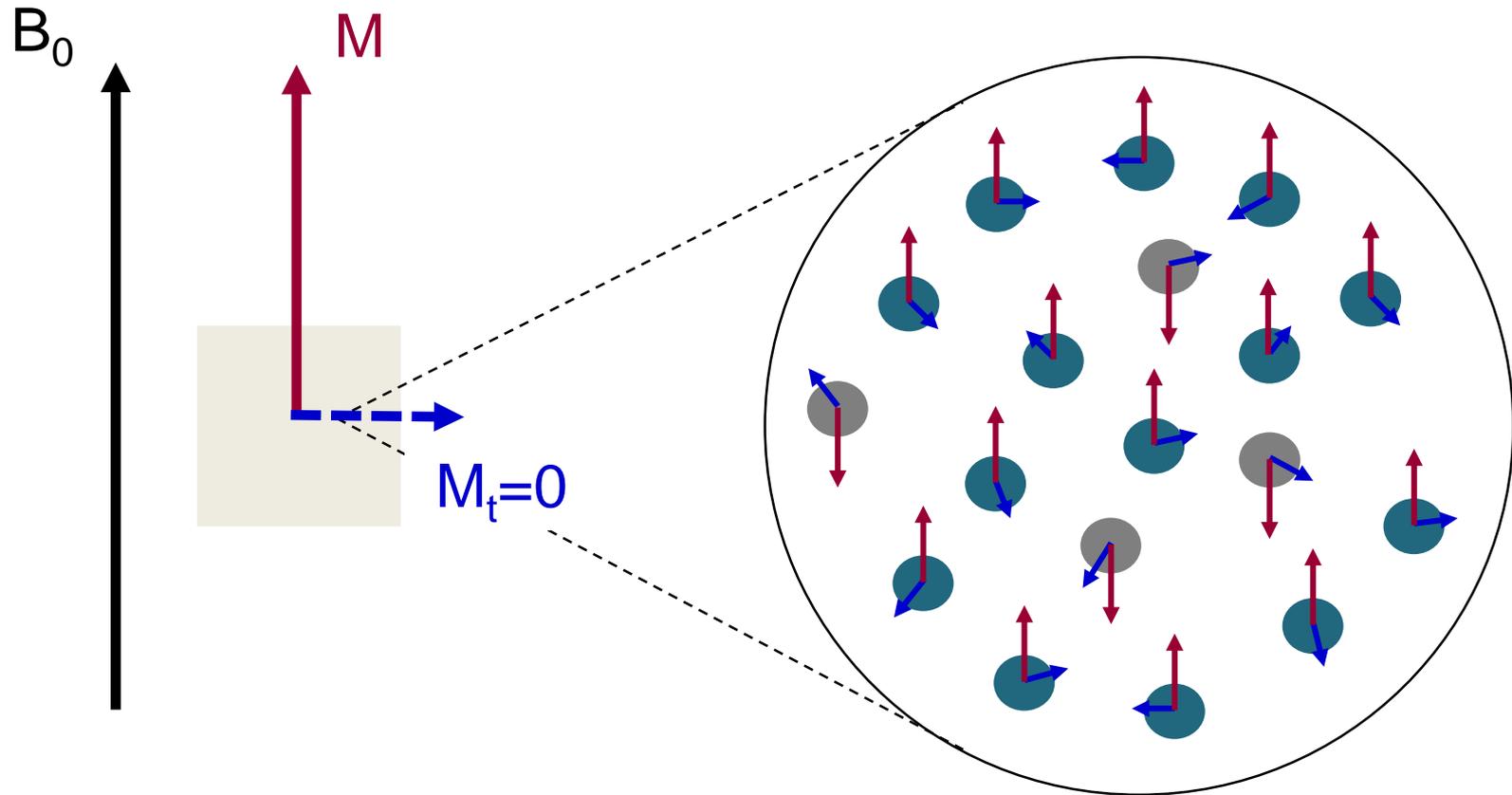
# Precession and Larmor Frequency

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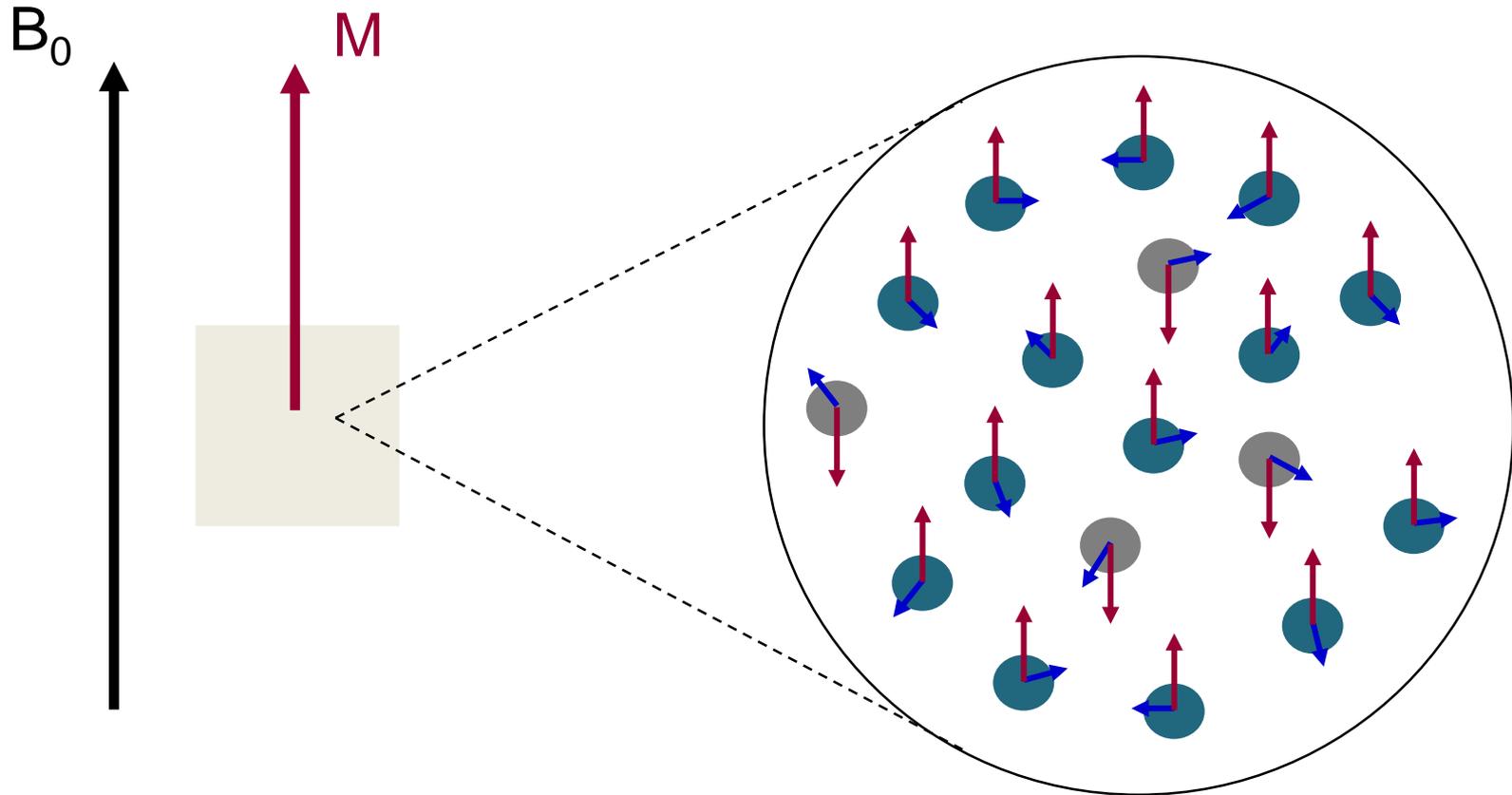
$$\omega_0 = \gamma B_0$$

# Macroscopic sample

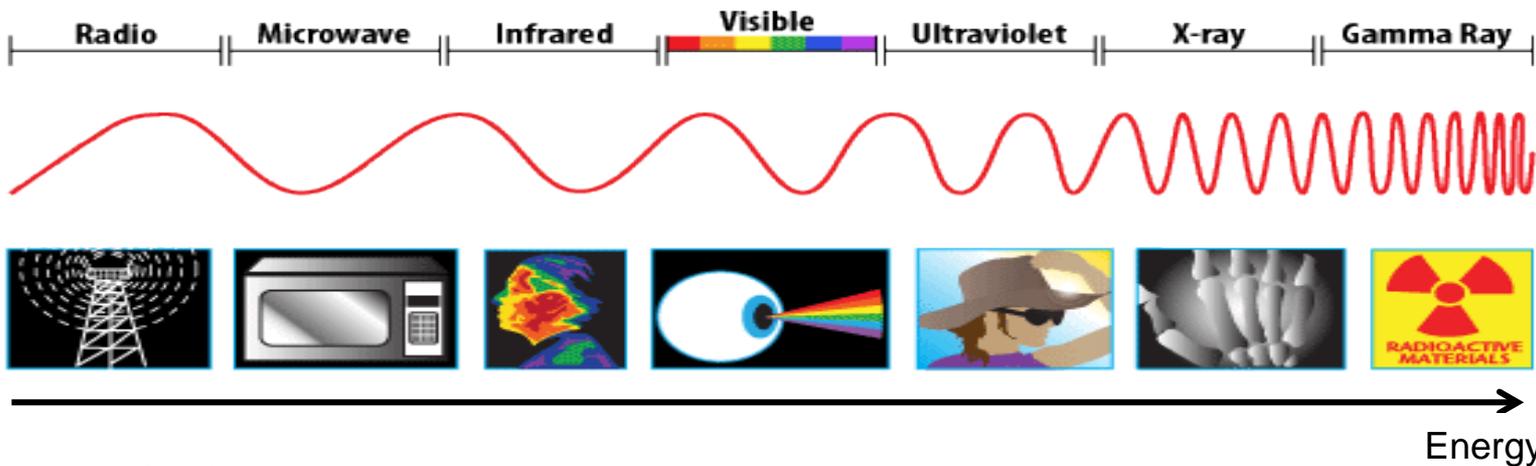
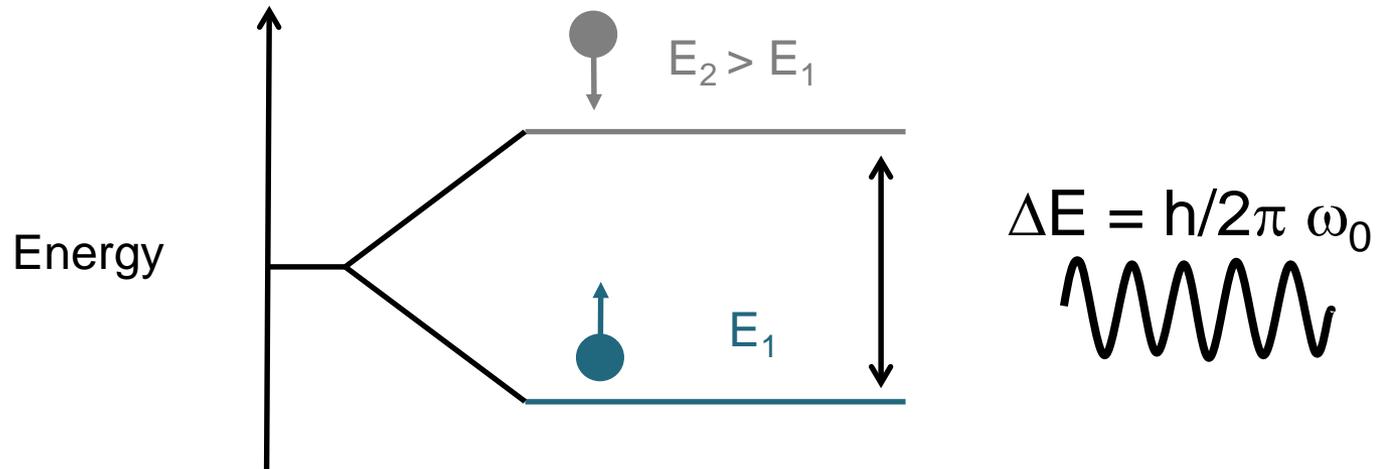


# Macroscopic sample

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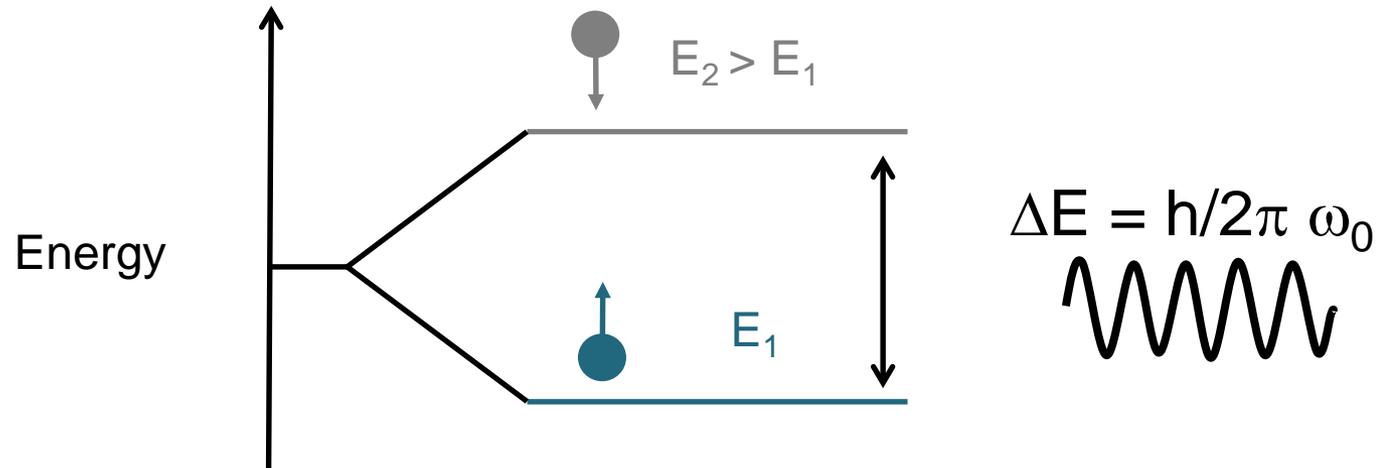


# Magnetic Resonance



# Magnetic Resonance

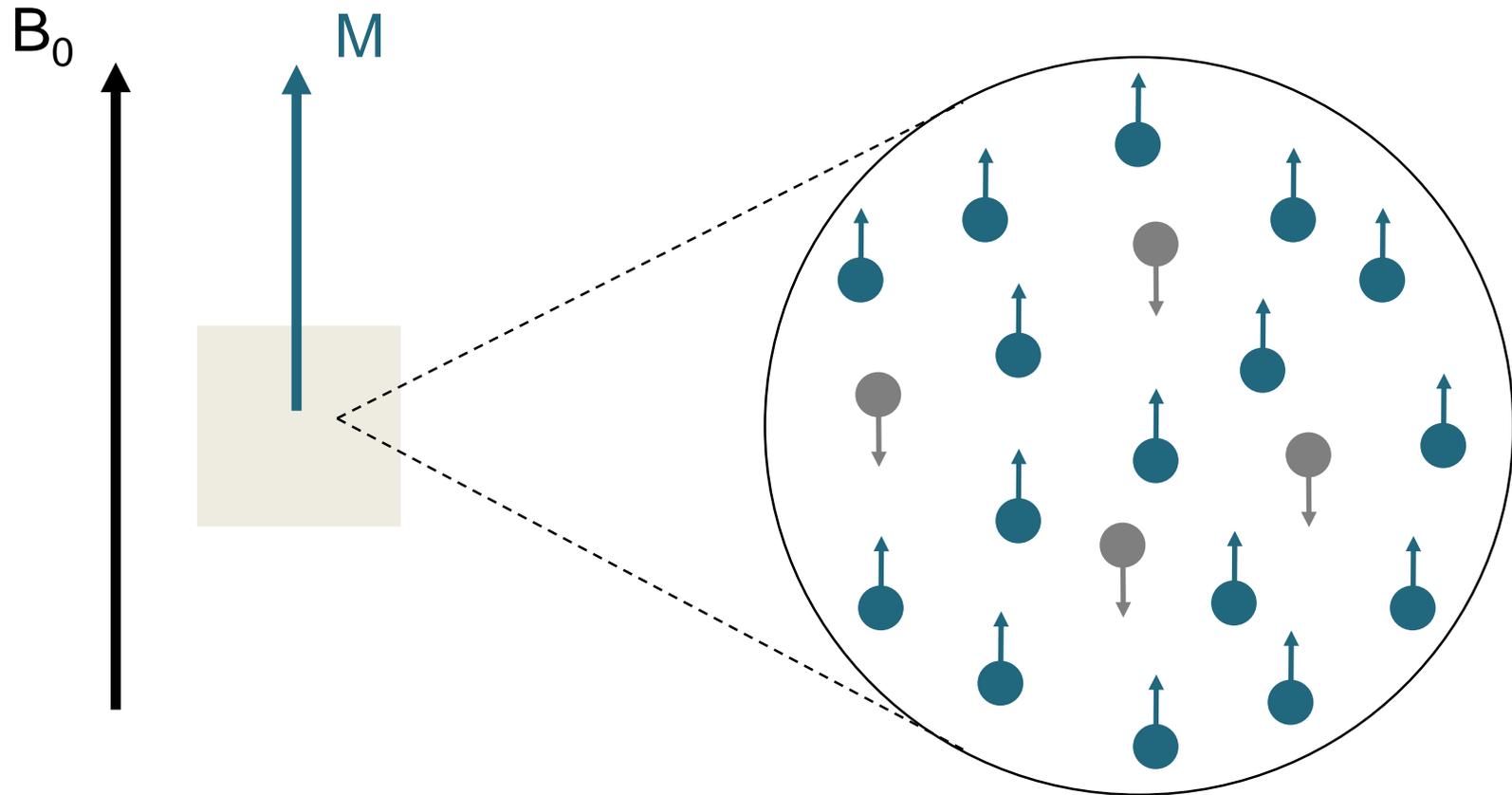
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- Exchange of energy between two systems at a specific energy is called **resonance**.
- **Magnetic resonance** corresponds to the energetic interaction between **spins** and **electromagnetic radiofrequency** (RF).
- Only protons that spin with the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

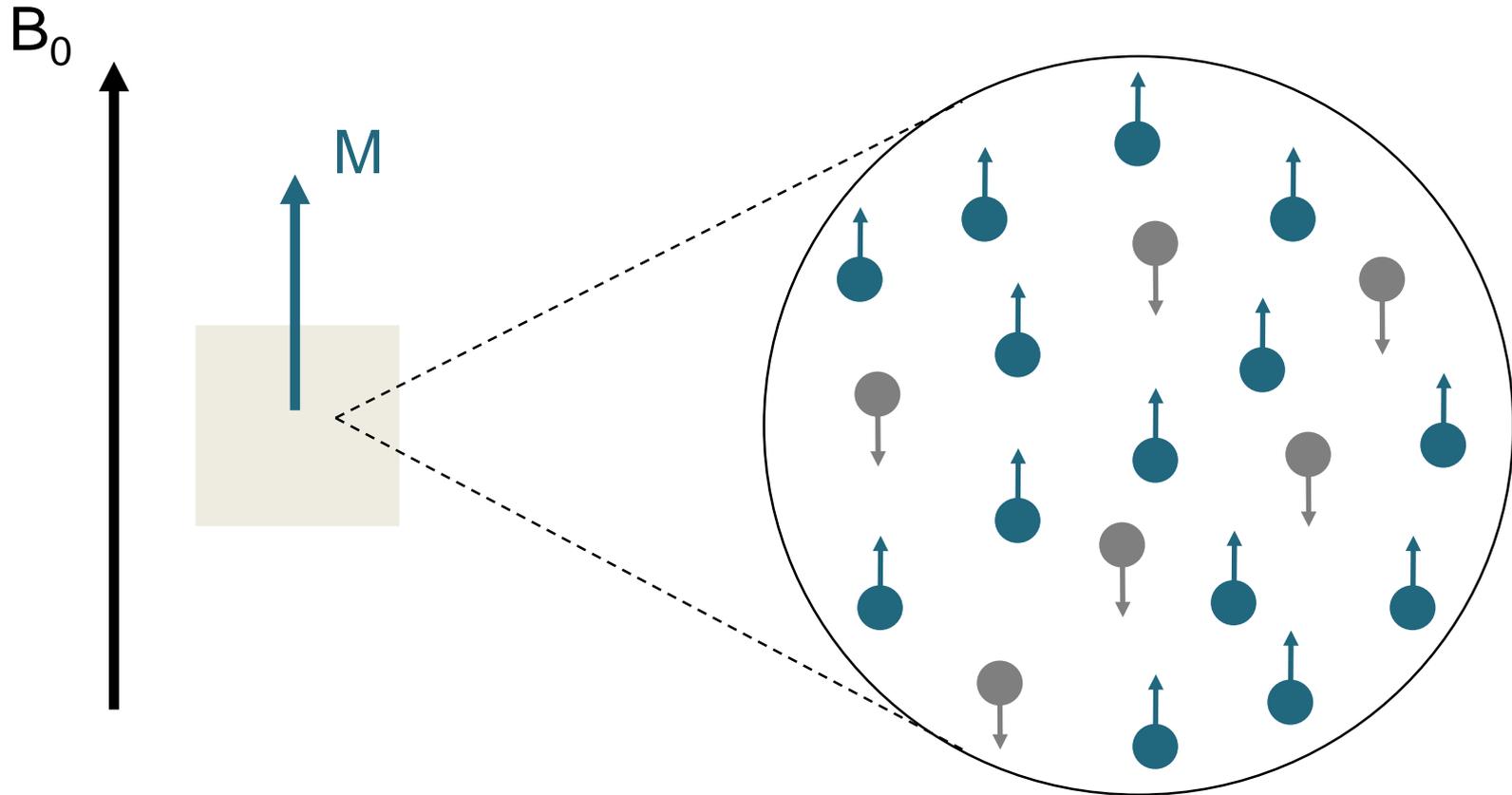
# Macroscopic sample + RF pulse (Energy)

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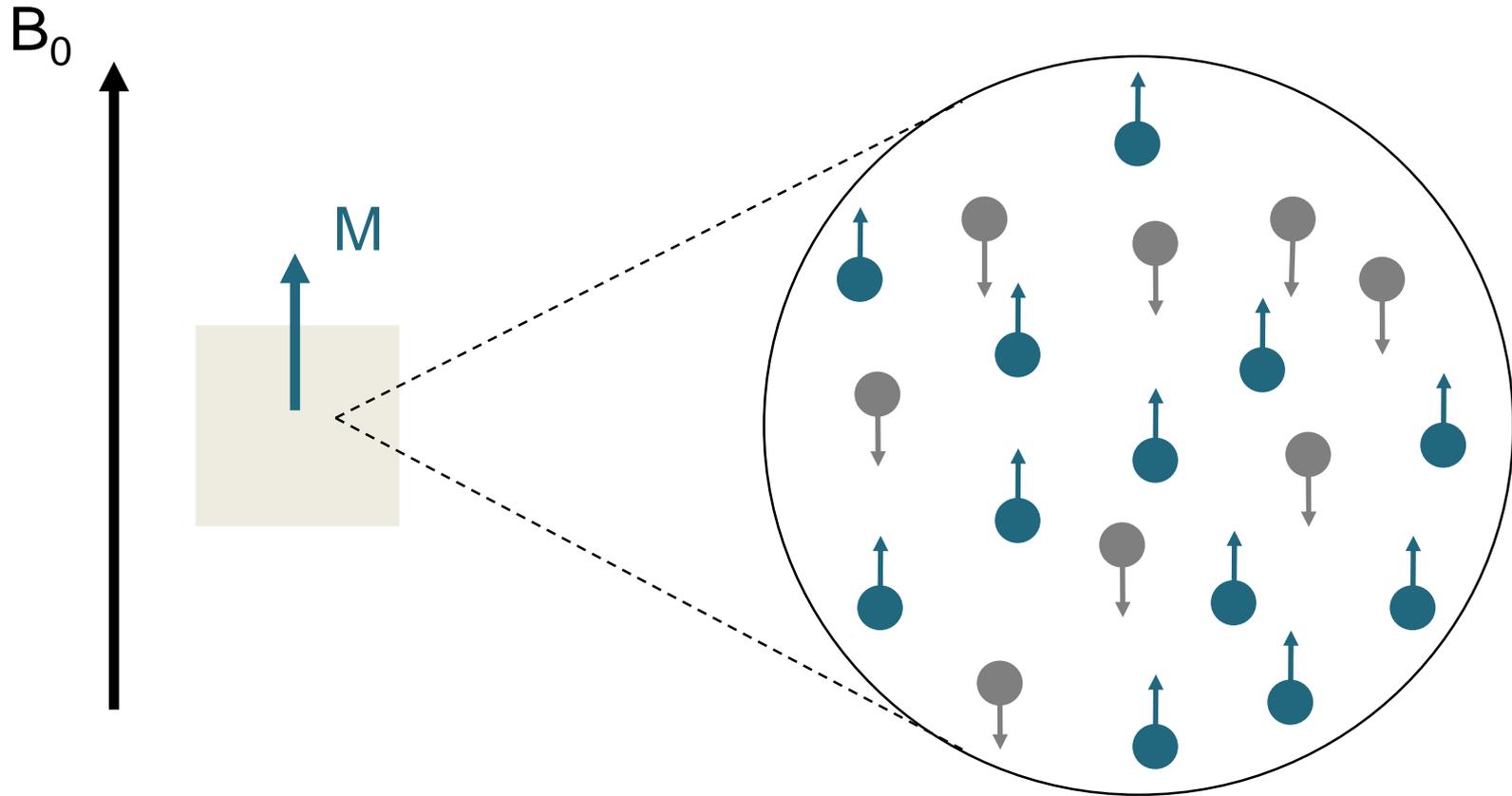
# Macroscopic sample + RF pulse (Energy)

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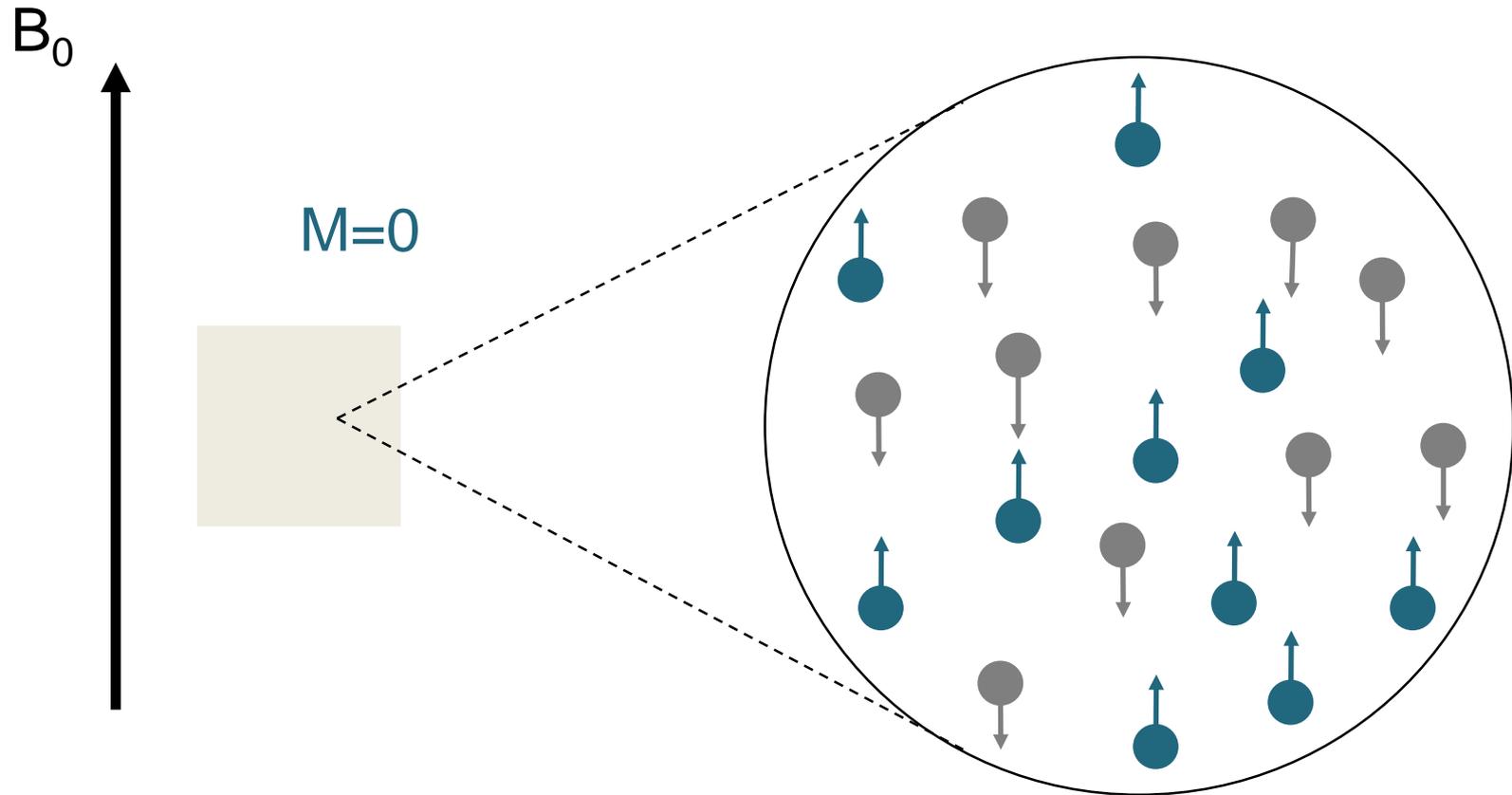
# Macroscopic sample + RF pulse (Energy)

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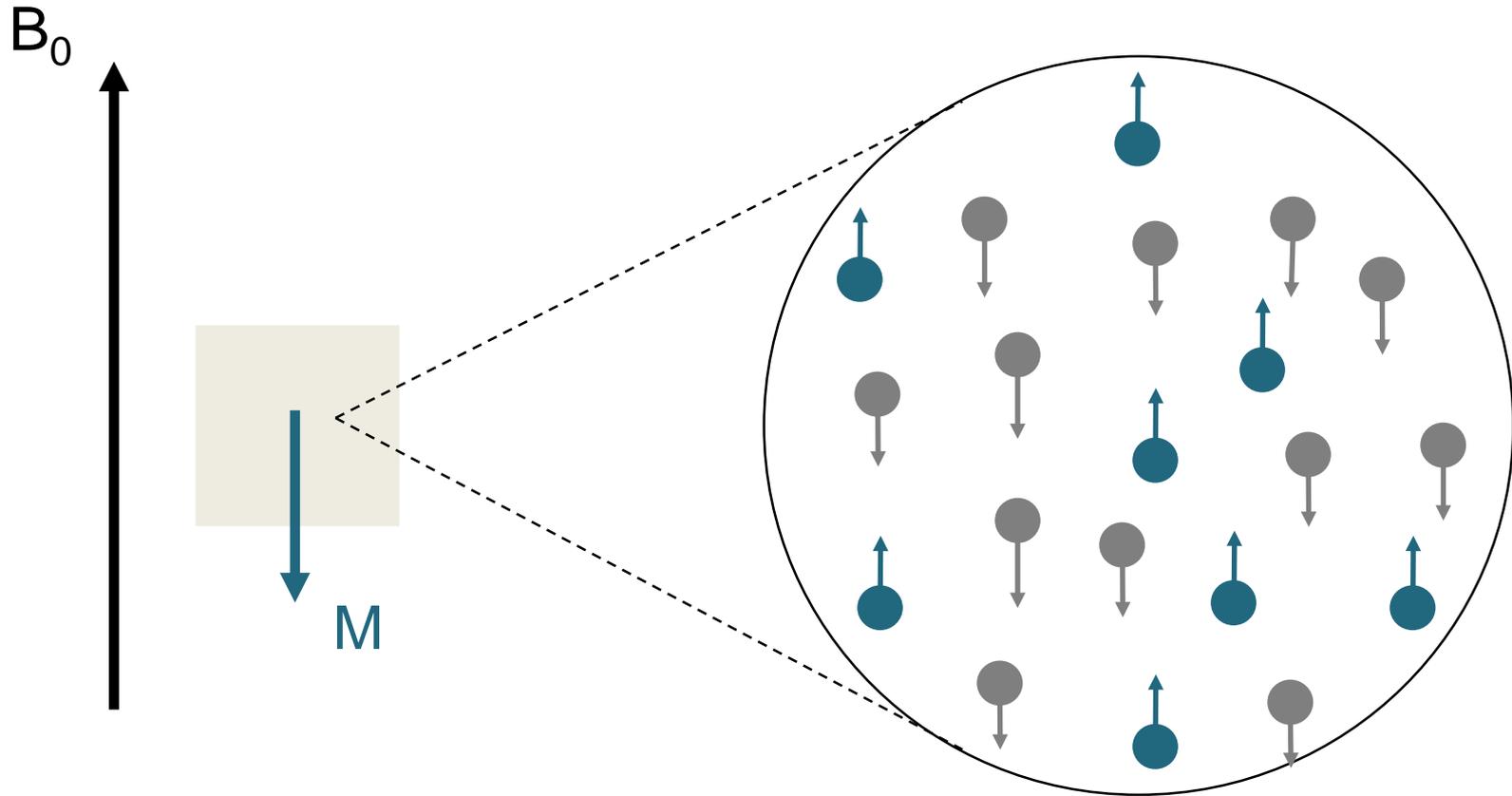
# Macroscopic sample + RF pulse (Energy)

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# Macroscopic sample + RF pulse (Energy)

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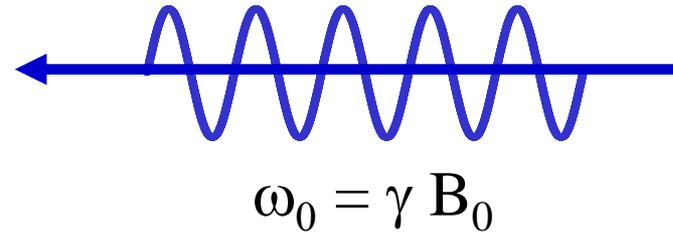
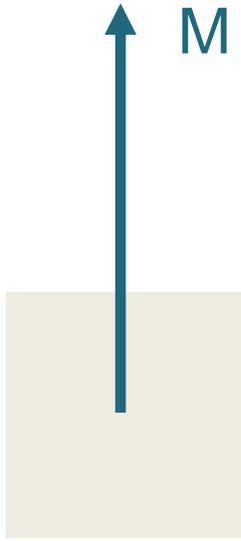


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# Excitation, Relaxation and Signal Formation

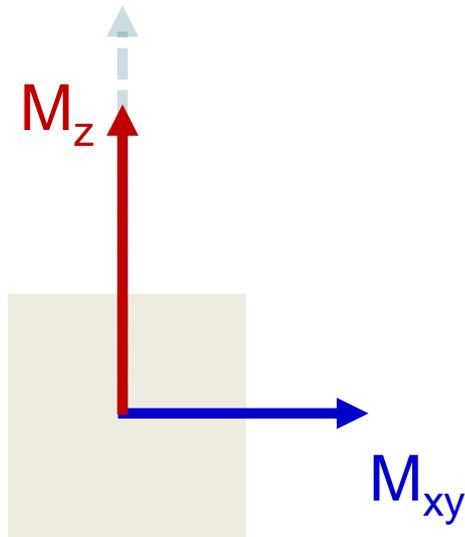
# Excitation

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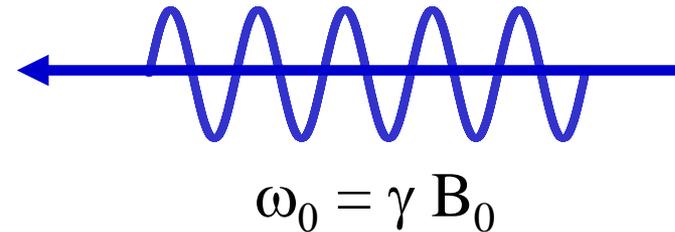


# Excitation

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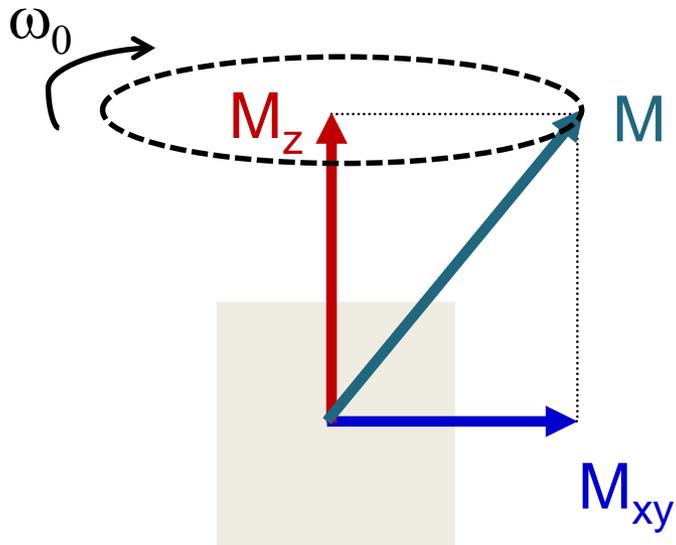


- During excitation, longitudinal magnetization decreases and a transverse magnetization appears.

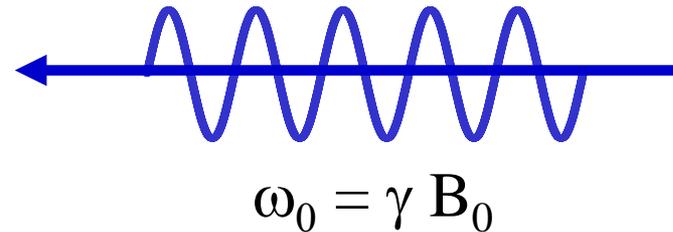


- Longitudinal magnetization decrease is due to a difference in the number of spins in parallel and anti-parallel state.
- Transverse magnetization is due to spins getting into phase coherence.

# Excitation



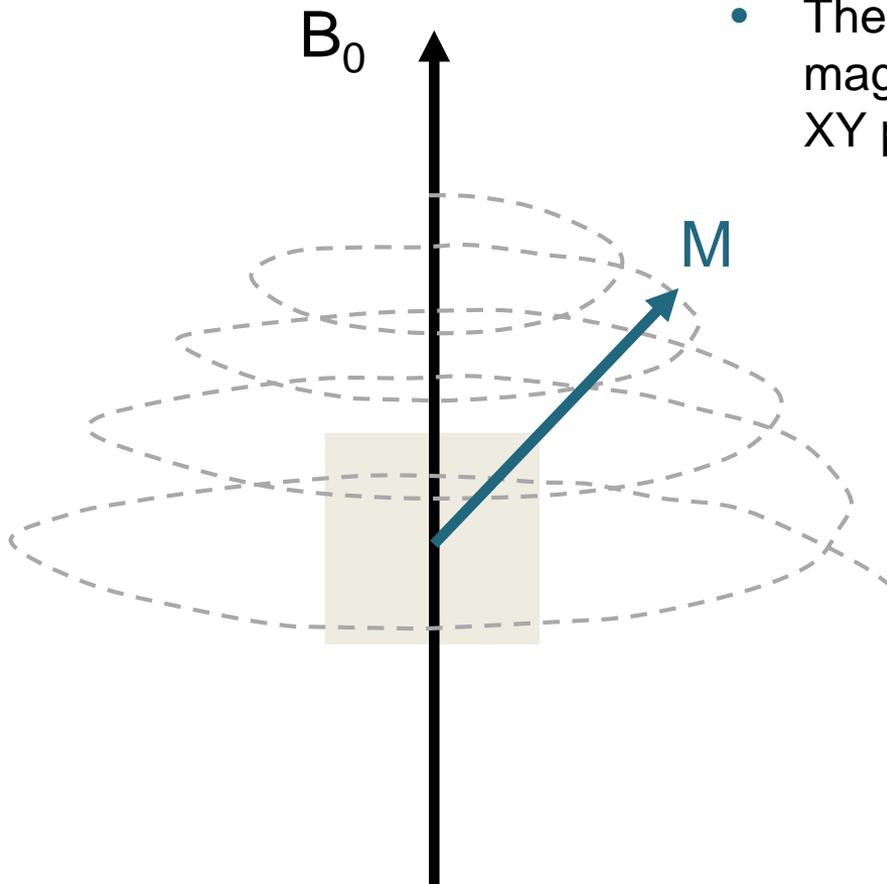
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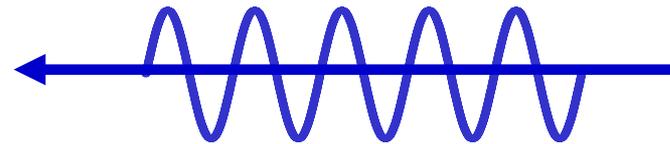
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# Excitation

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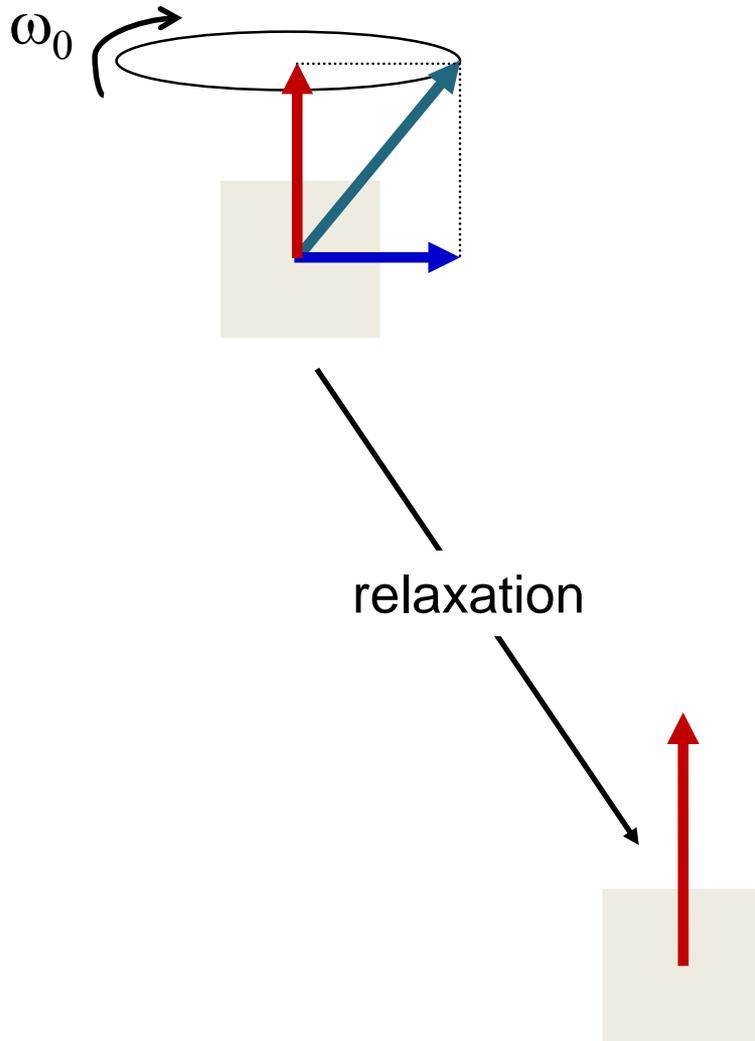


- The consequence on the macroscopic net magnetization is a spiral movement down to the XY plane.



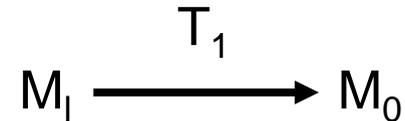
$$\omega_0 = \gamma B_0$$

# Relaxation

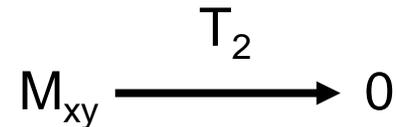


Two independent relaxation processes:

①



②

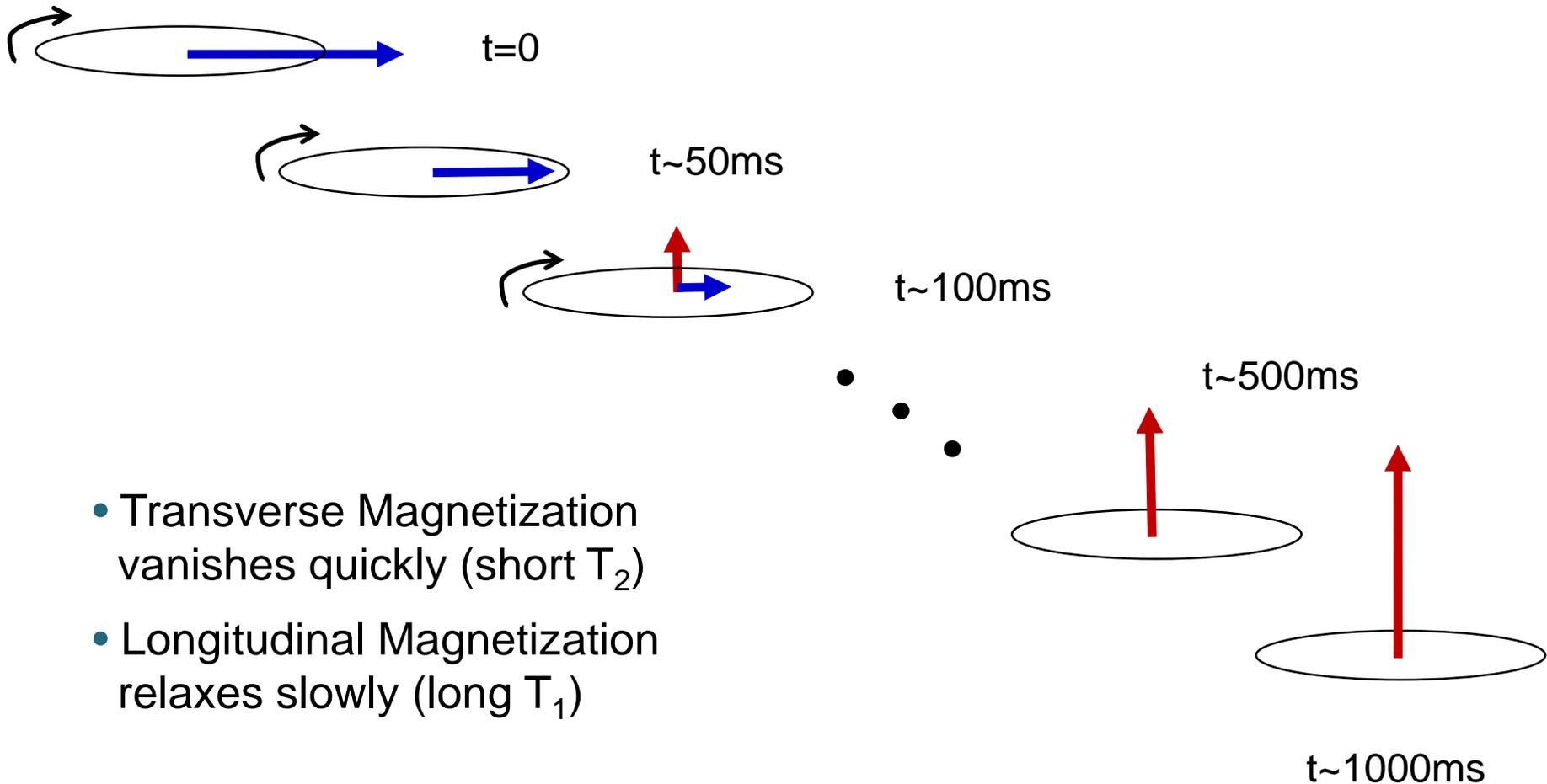


$T_1$ : “*longitudinal relaxation time*”  
( $\approx 1$  s) - energy exchange between  
spins and their surroundings

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

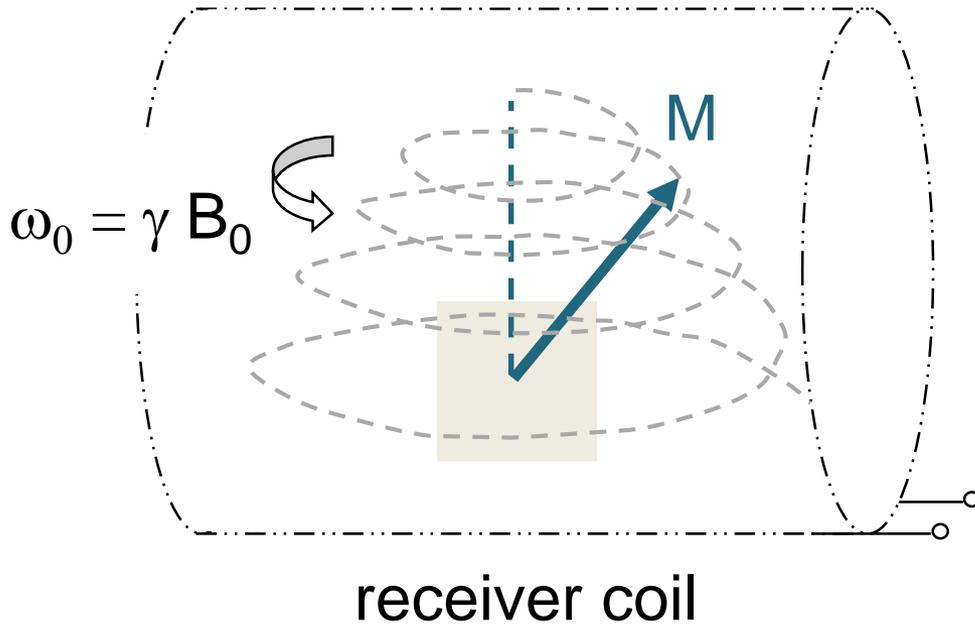
# Relaxation

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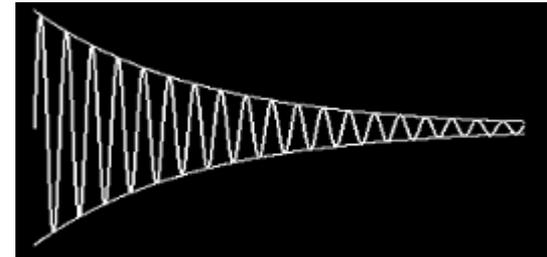


# Precession and signal induction

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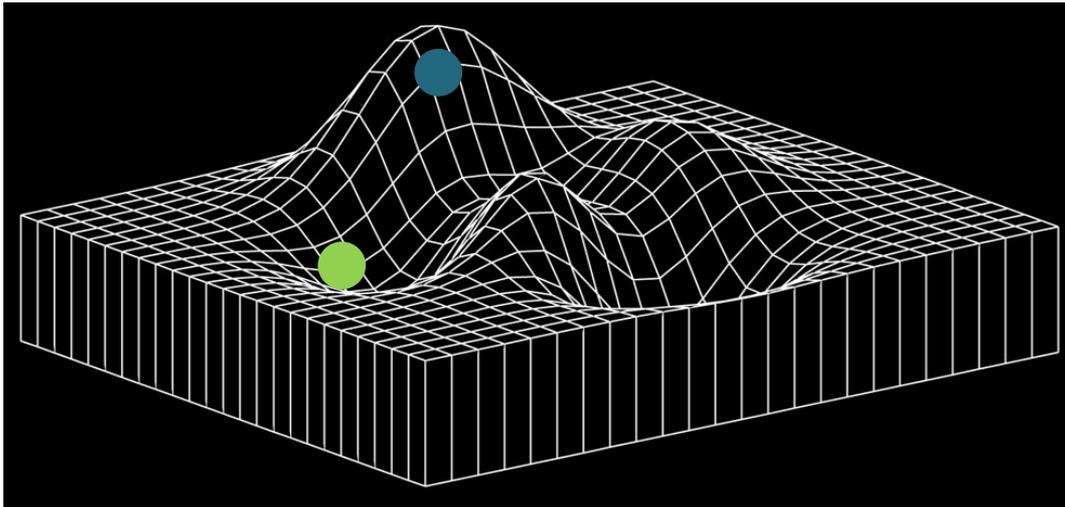


123 MHz @ 3T



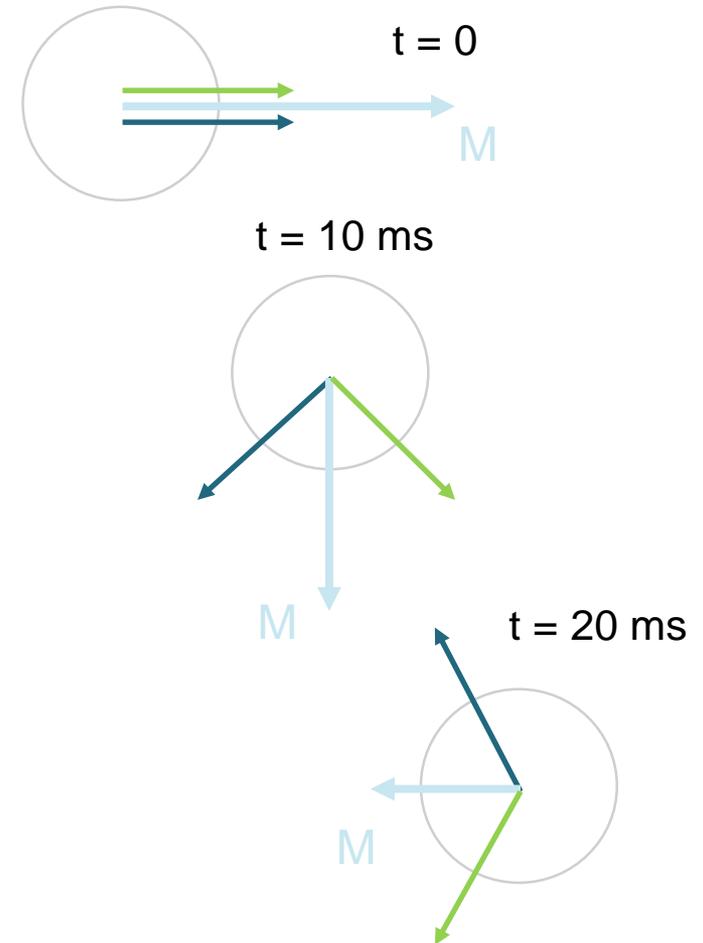
NMR signal

# Signal loss due to $B_0$ inhomogeneity



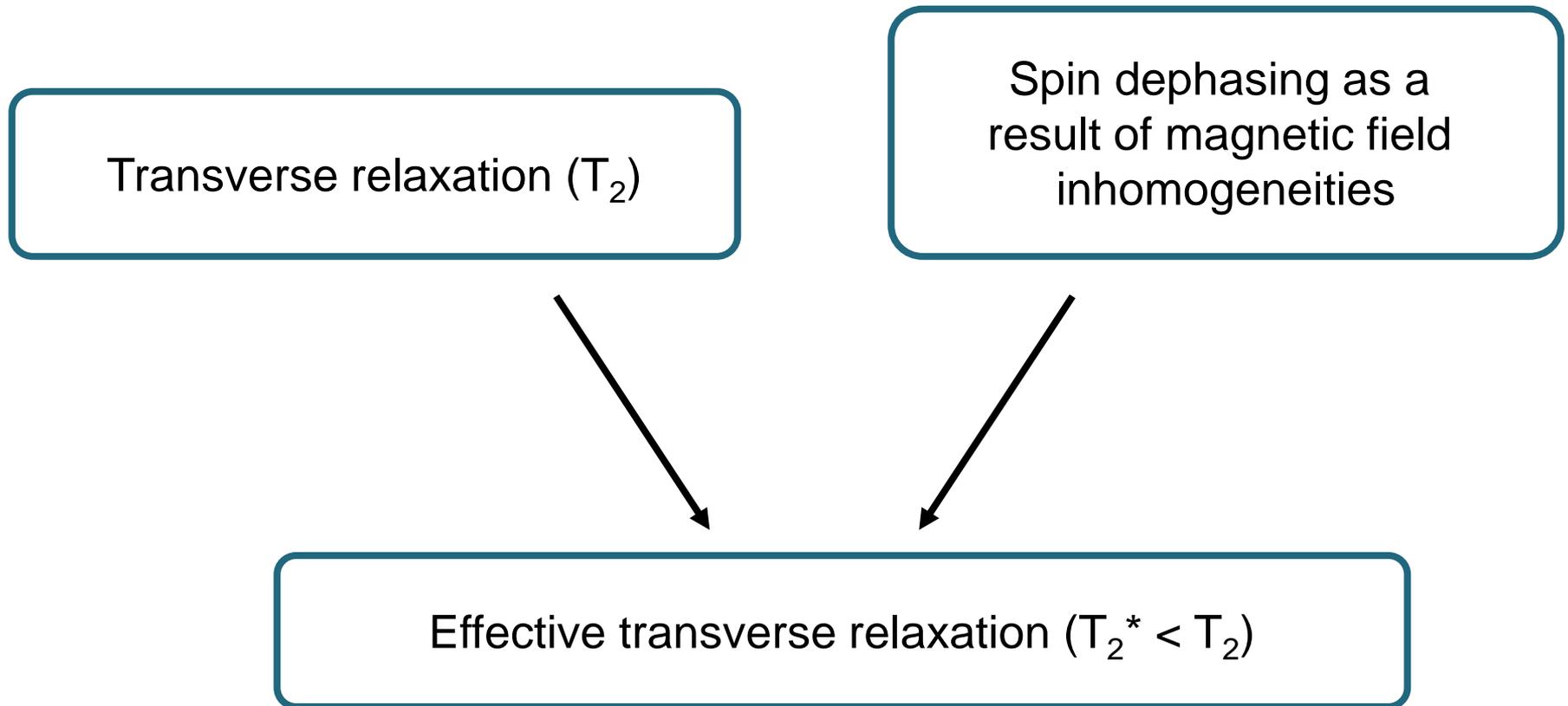
$$\omega_0 = \gamma B_0$$

● has higher frequency than ●



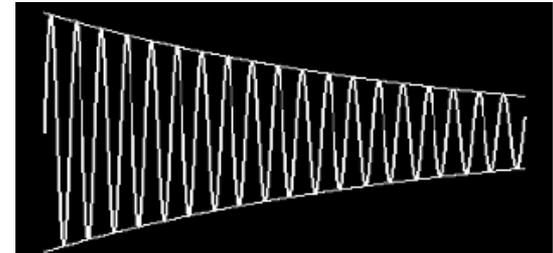
# Effective transverse relaxation ( $T_2^*$ )

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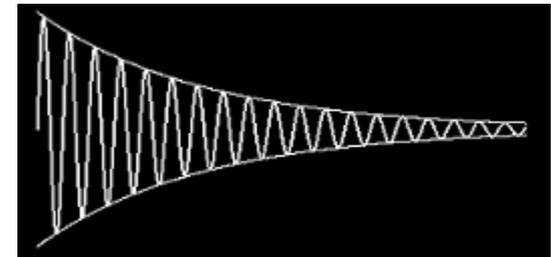


# Effective transverse relaxation ( $T_2^*$ )

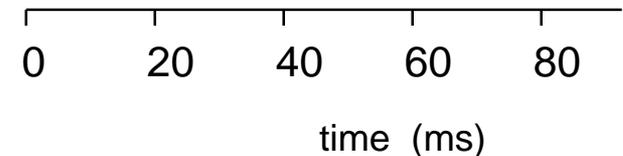
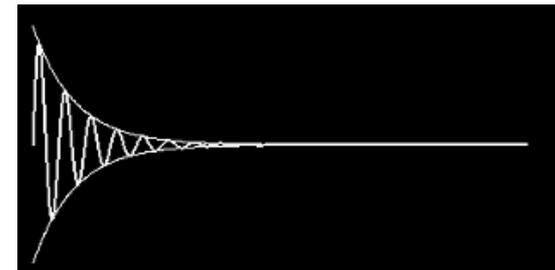
No inhomogeneities  
( $T_2^* = T_2 = 100$  ms)



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

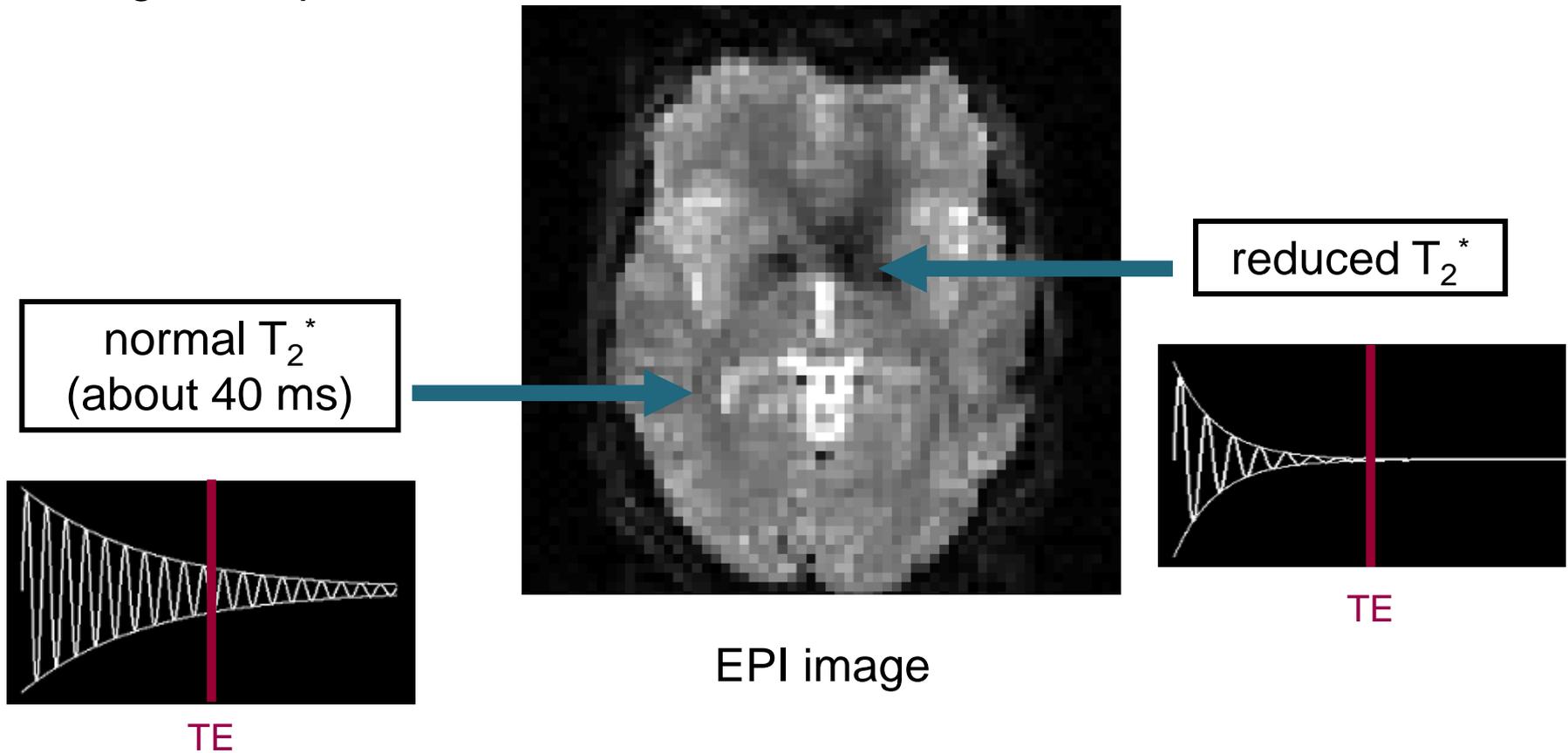


Strong inhomogeneities  
( $T_2^* = 10$  ms)



# $T_2^*$ related signal dropouts

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



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# Part II: Magnetic Resonance Imaging (MRI)

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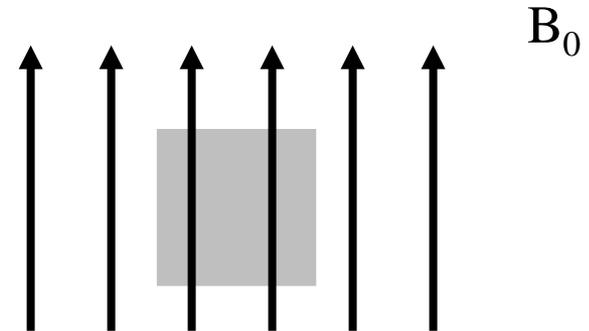
# Spatial Encoding in MRI

# The principles of MRI

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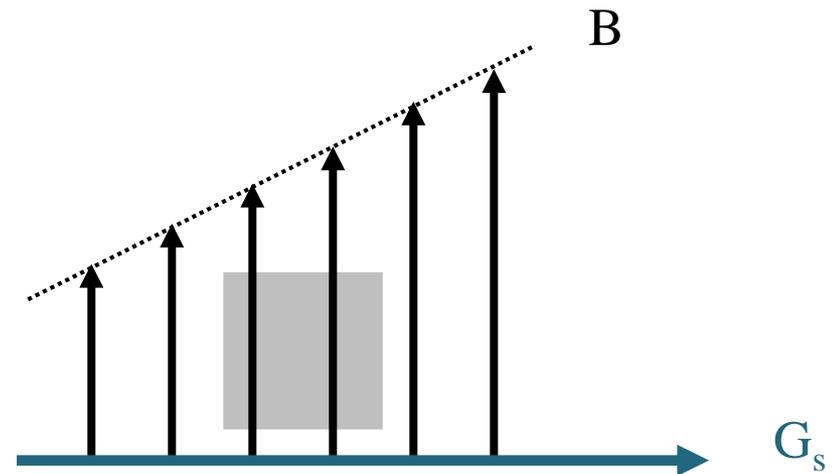
Homogeneous magnetic field

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

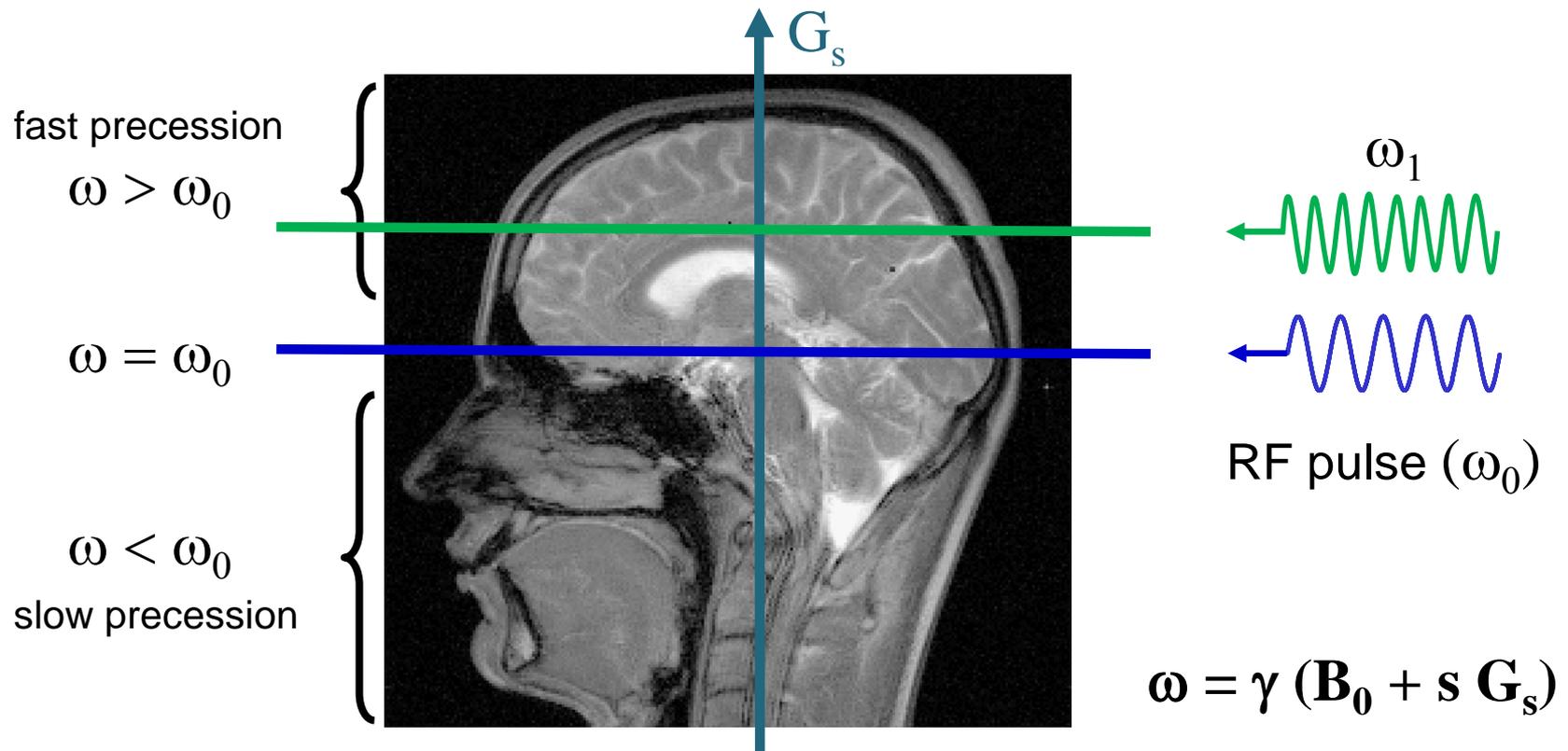


Add magnetic field gradient

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



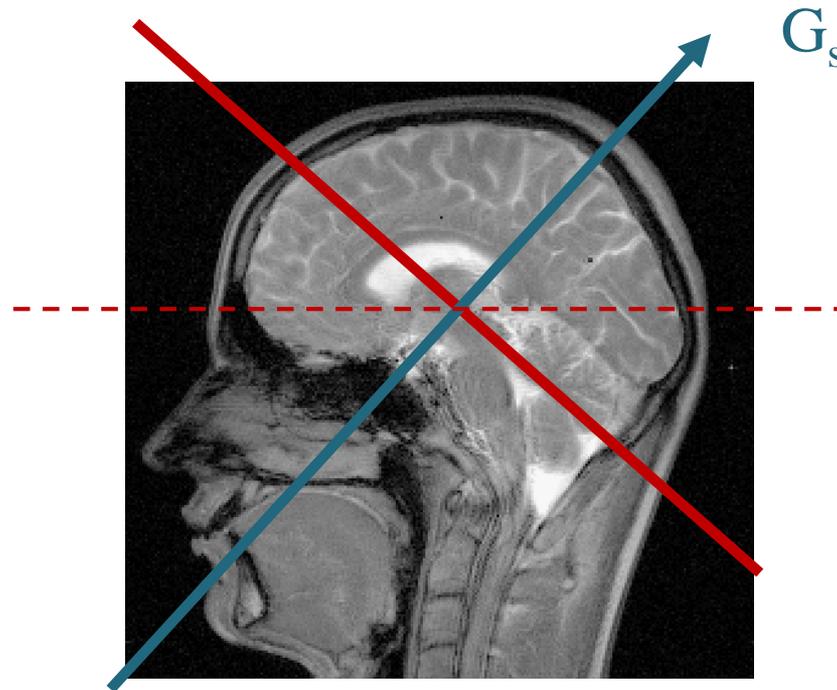
# Slice selective excitation



- Only spins in slice of interest have frequency  $\omega_0$
- RF pulse with frequency  $\omega_0$  excites only spins in slice of interest

# Slice orientation

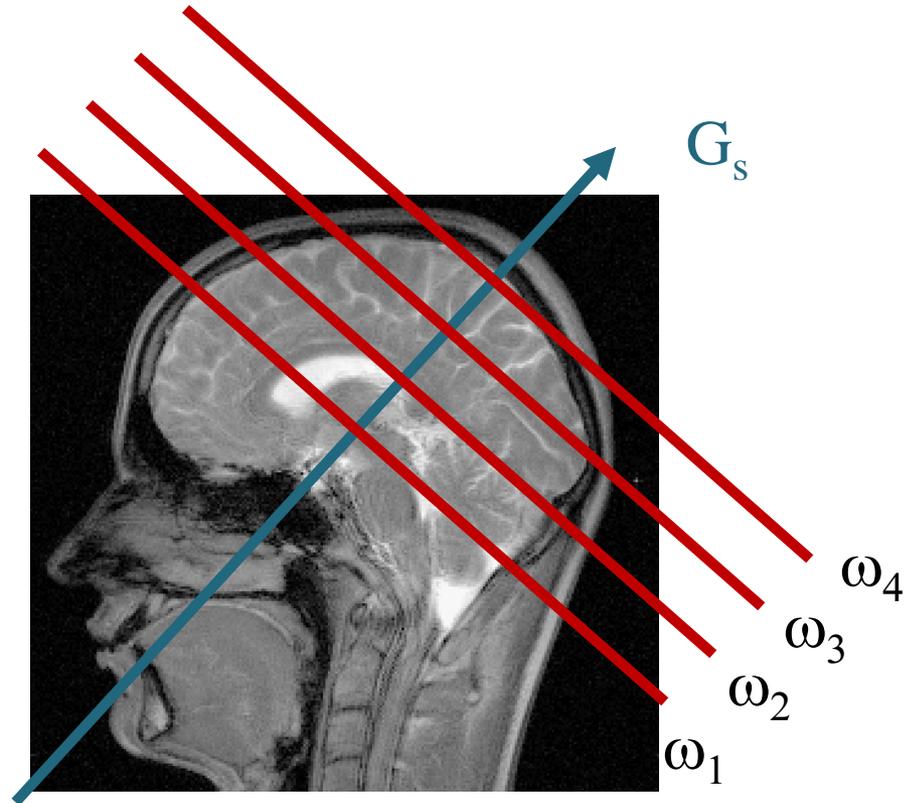
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$$\omega = \gamma (\mathbf{B}_0 + s \mathbf{G}_s)$$

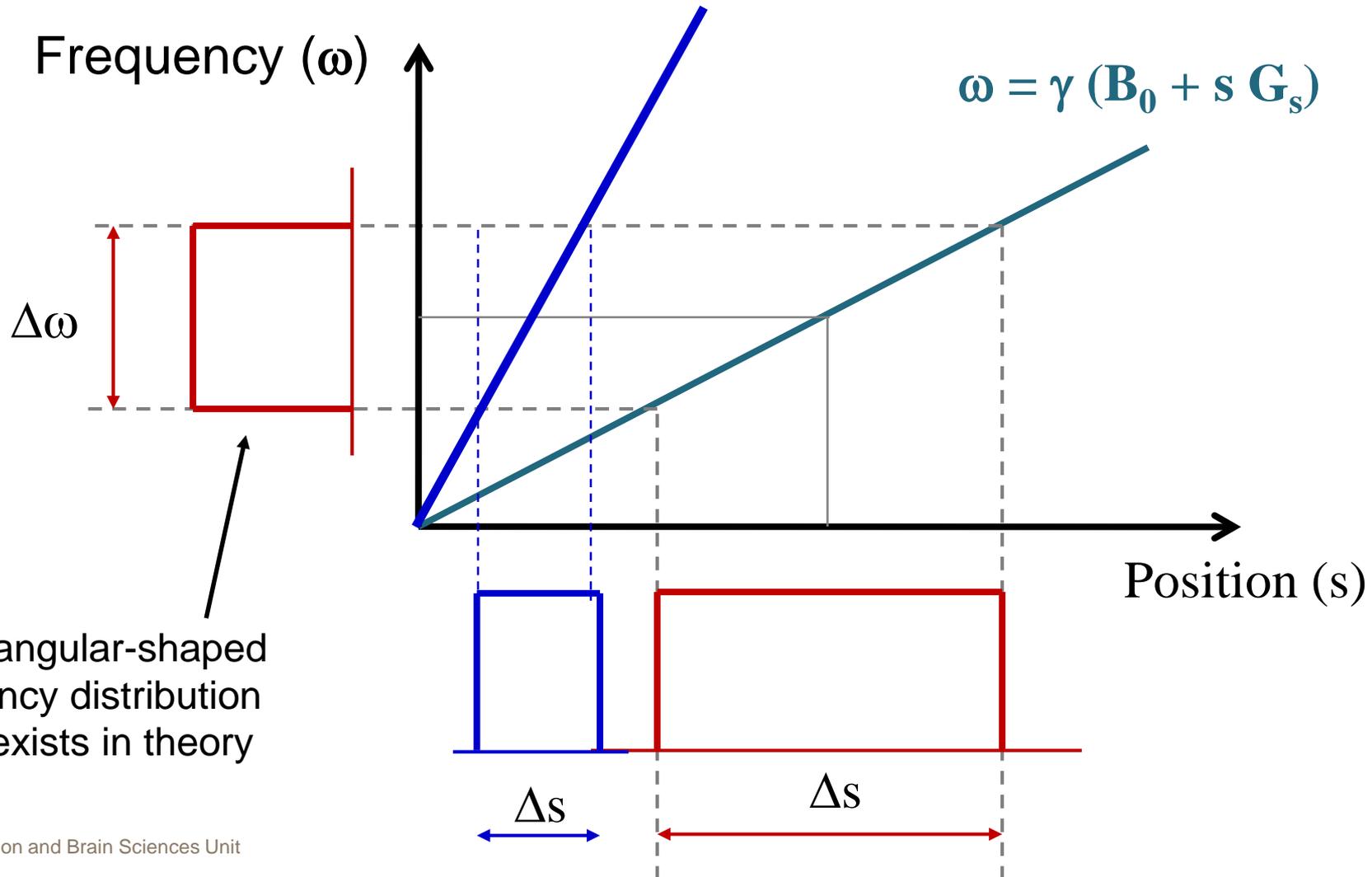
# Multi-slice MRI

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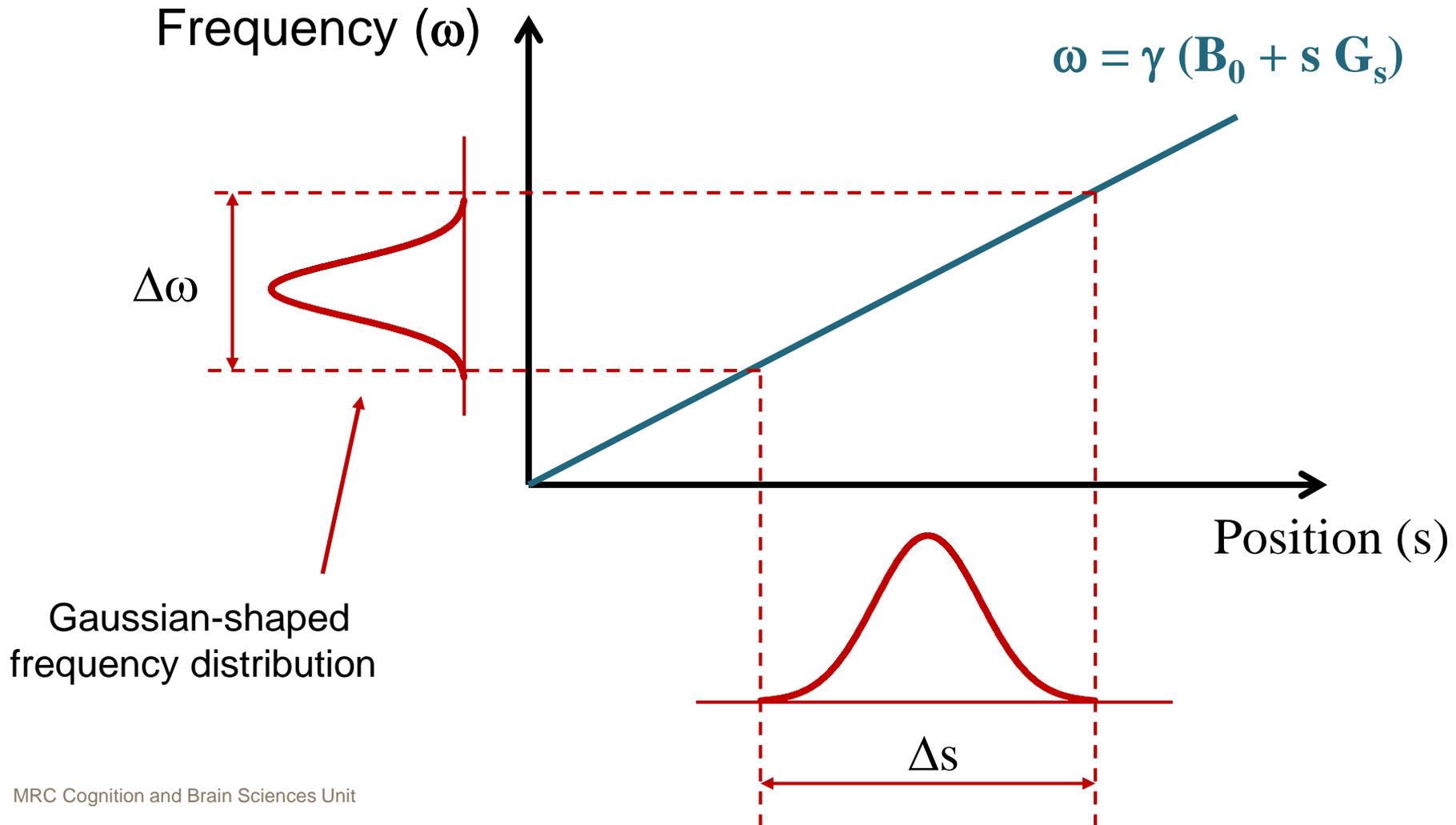
$$\omega = \gamma (\mathbf{B}_0 + s \mathbf{G}_s)$$

# Slice profile



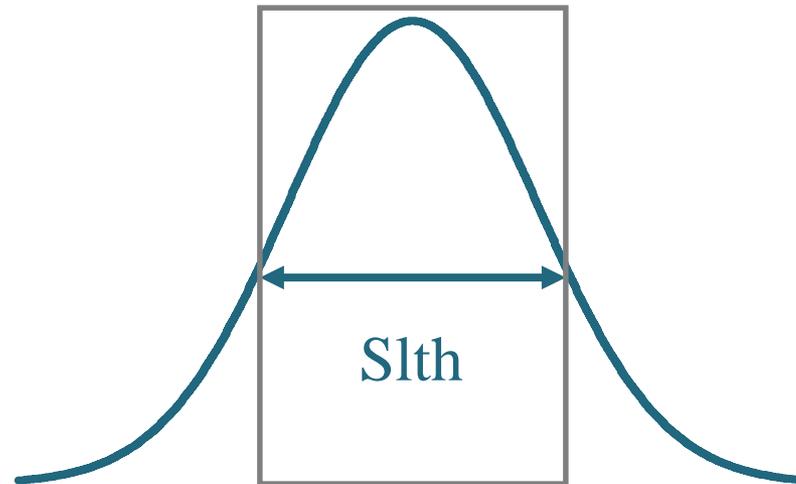
A rectangular-shaped frequency distribution only exists in theory

# Slice profile



# Slice thickness

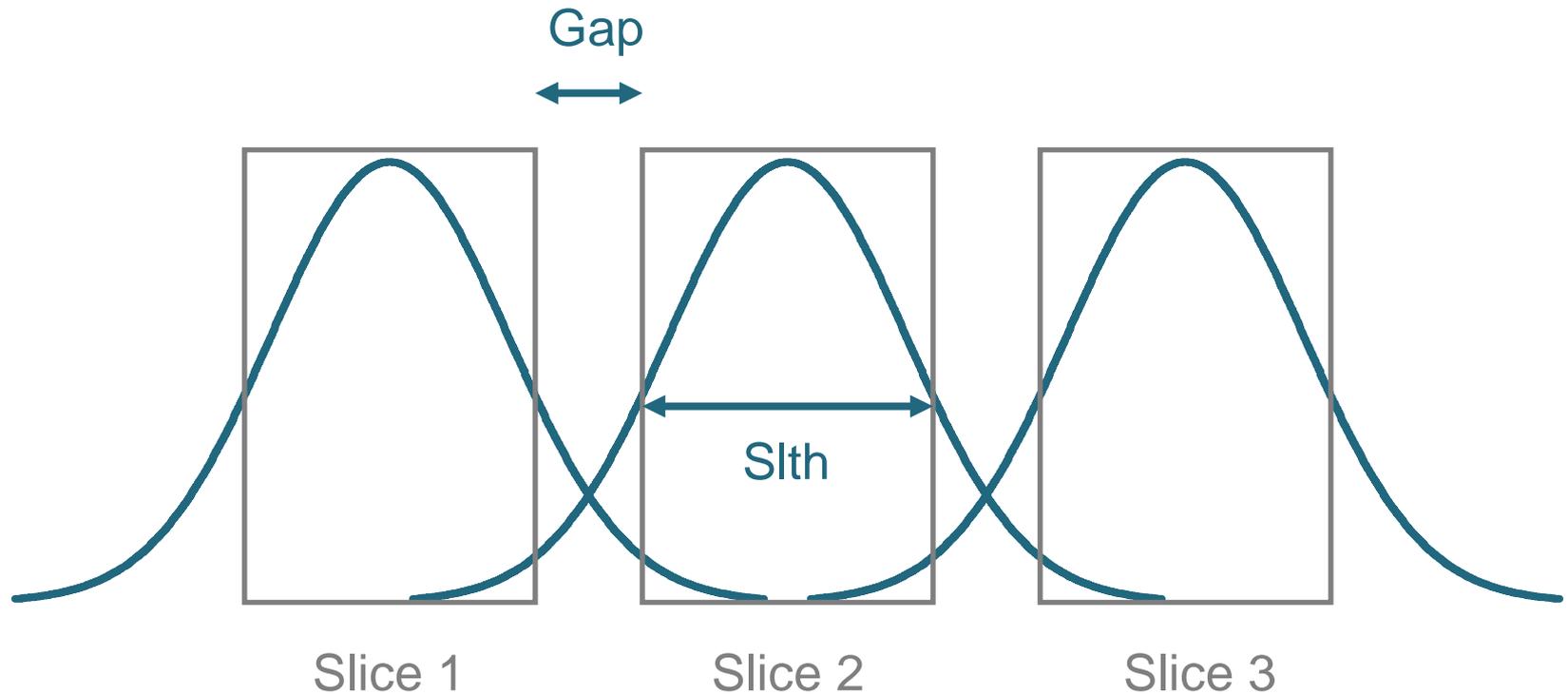
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$Slth =$  Full width at half maximum of the slice profile

# Multi-slice MRI

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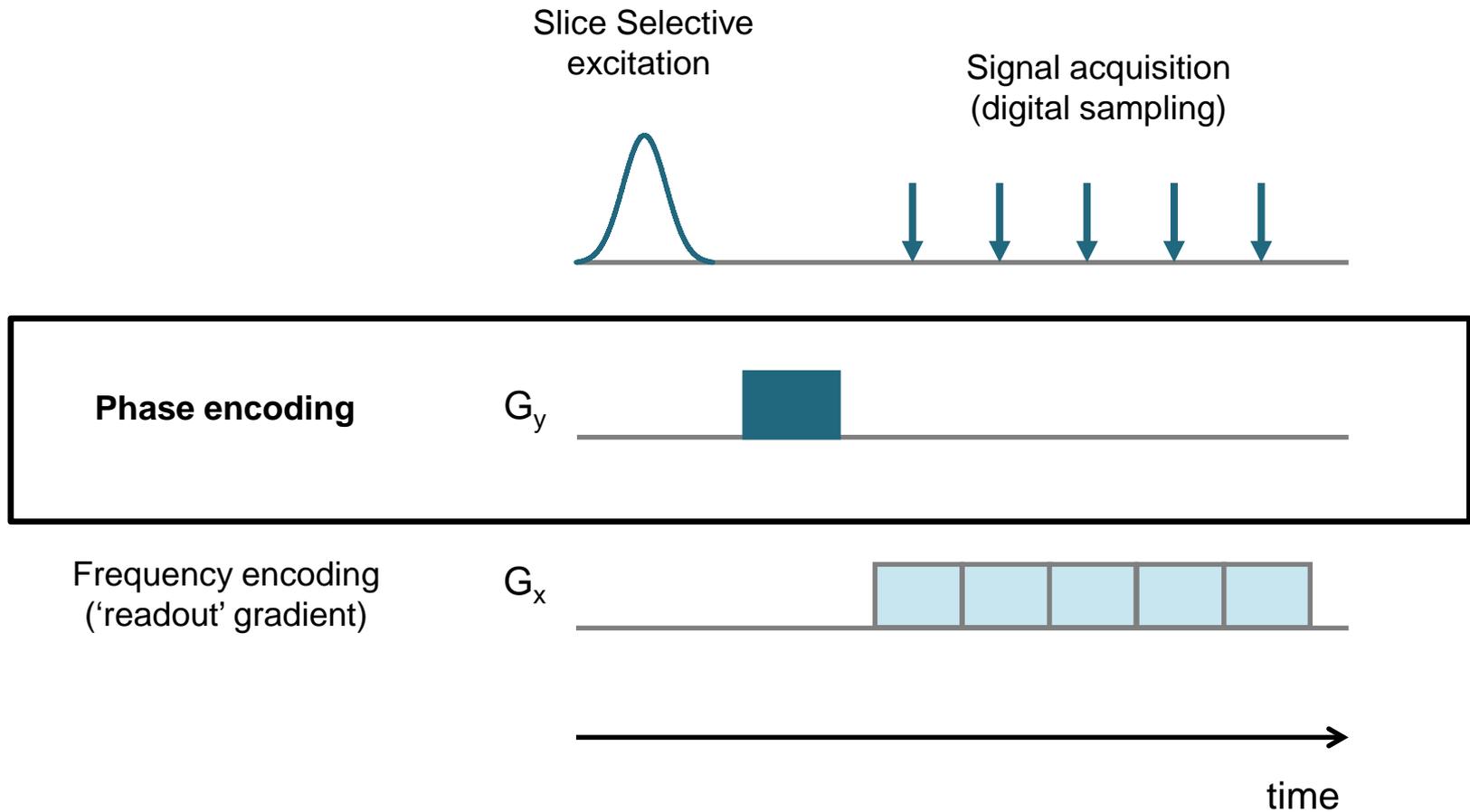


Tissue in the inter-slice gap contributes to the signal of the adjacent slices

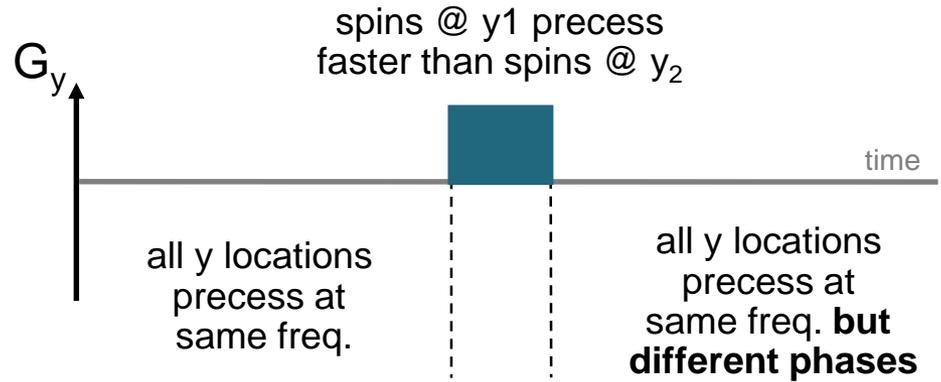
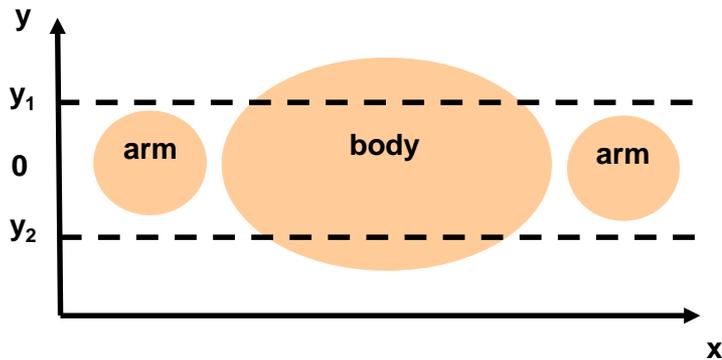
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# Frequency and phase encoding

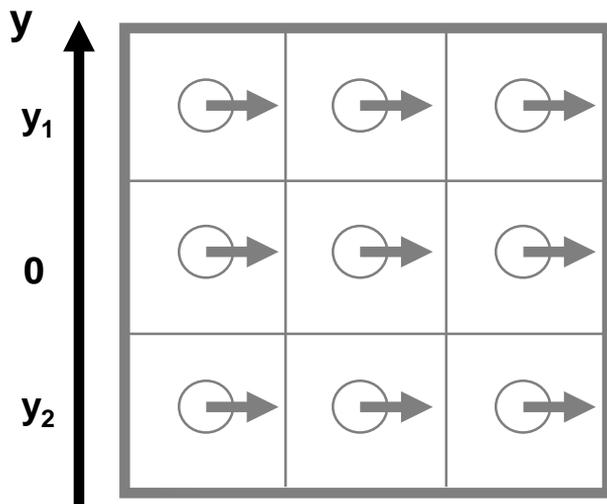
# Phase encoding



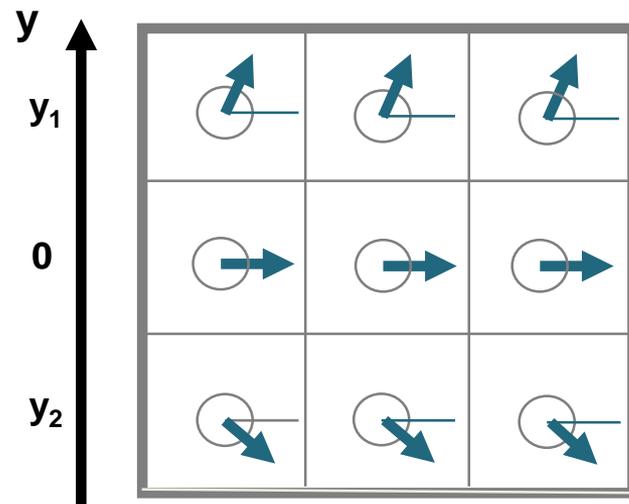
# Phase encoding and spatial information



After RF



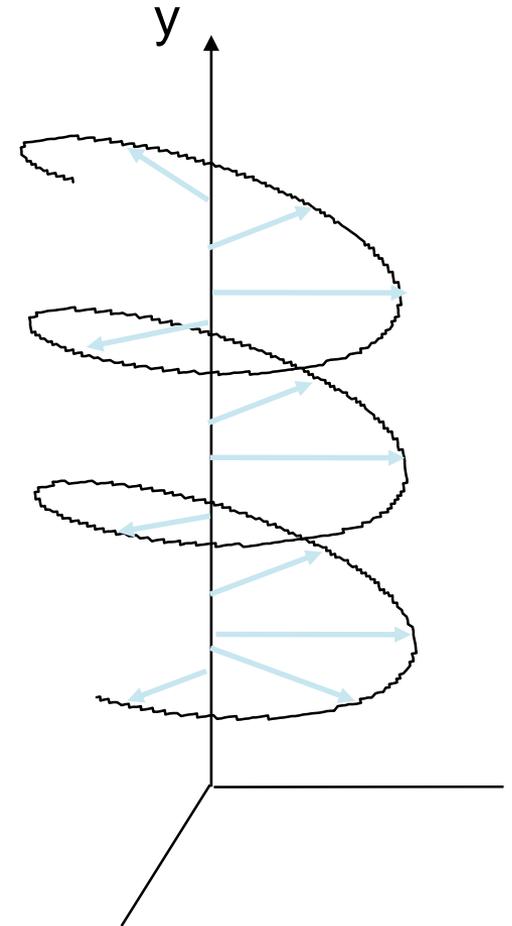
After the phase encoding gradient



# How does phase encoding translate into spatial information?

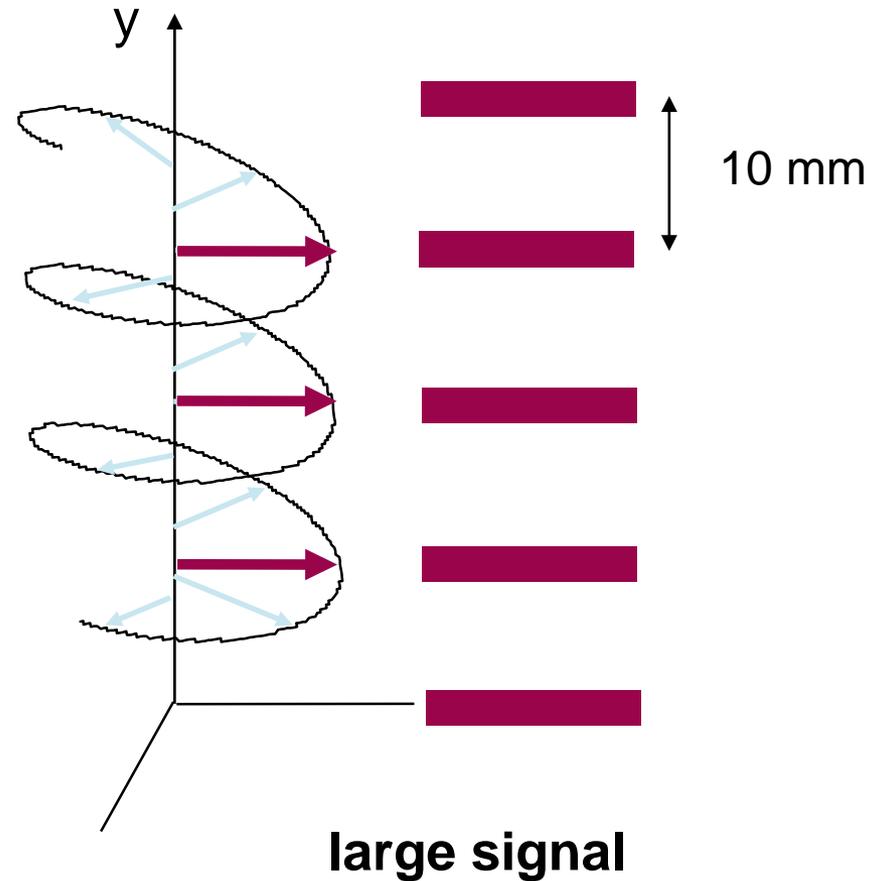
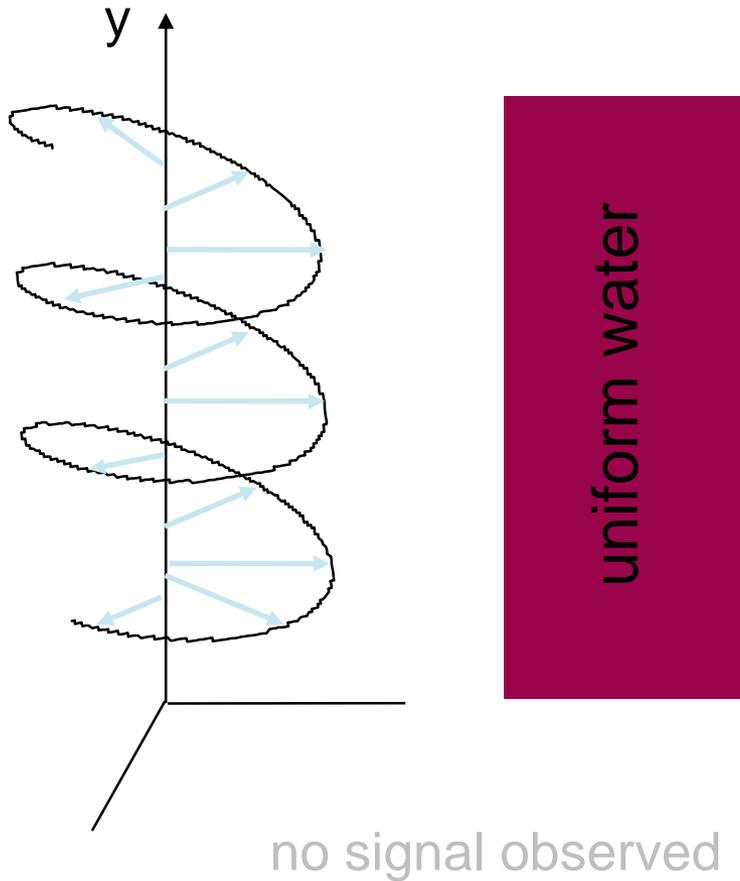
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- The magnetization in the xy plane is wound into a helix directed along y axis.
- Phases are 'locked in' once the phase encode gradient is switched off.



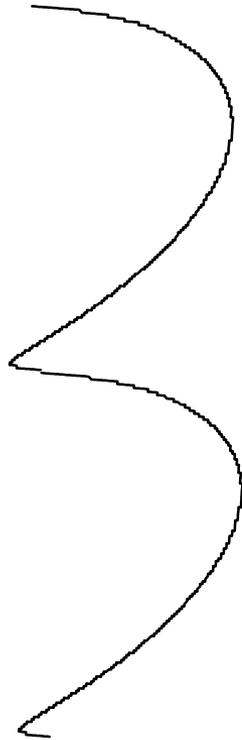
From Larry Wald

# Signal after phase encoding

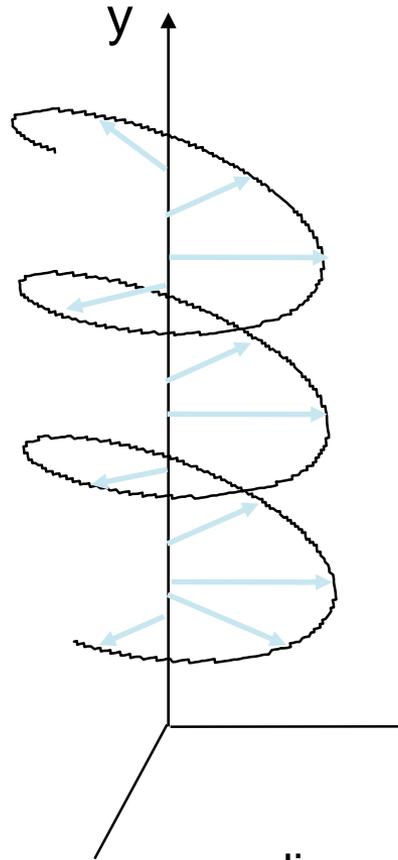


# Gradient area and helix shape

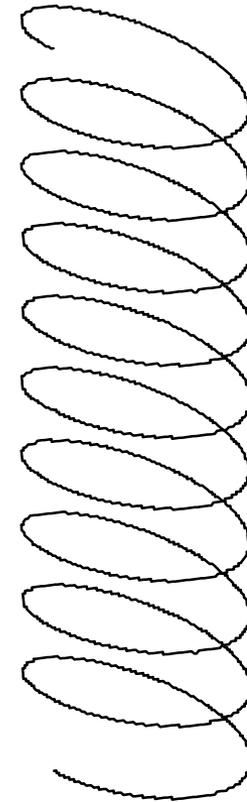
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small area

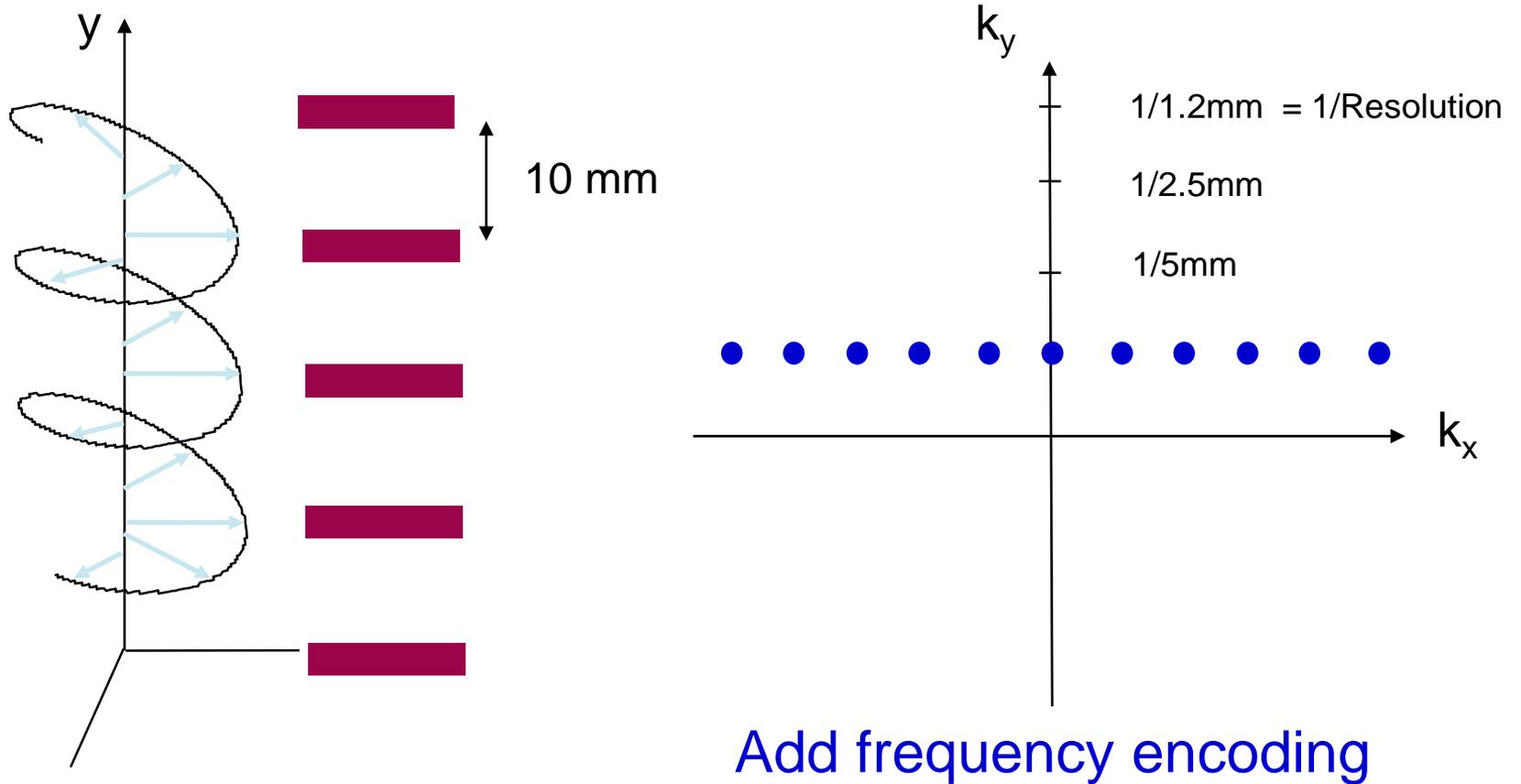


medium area

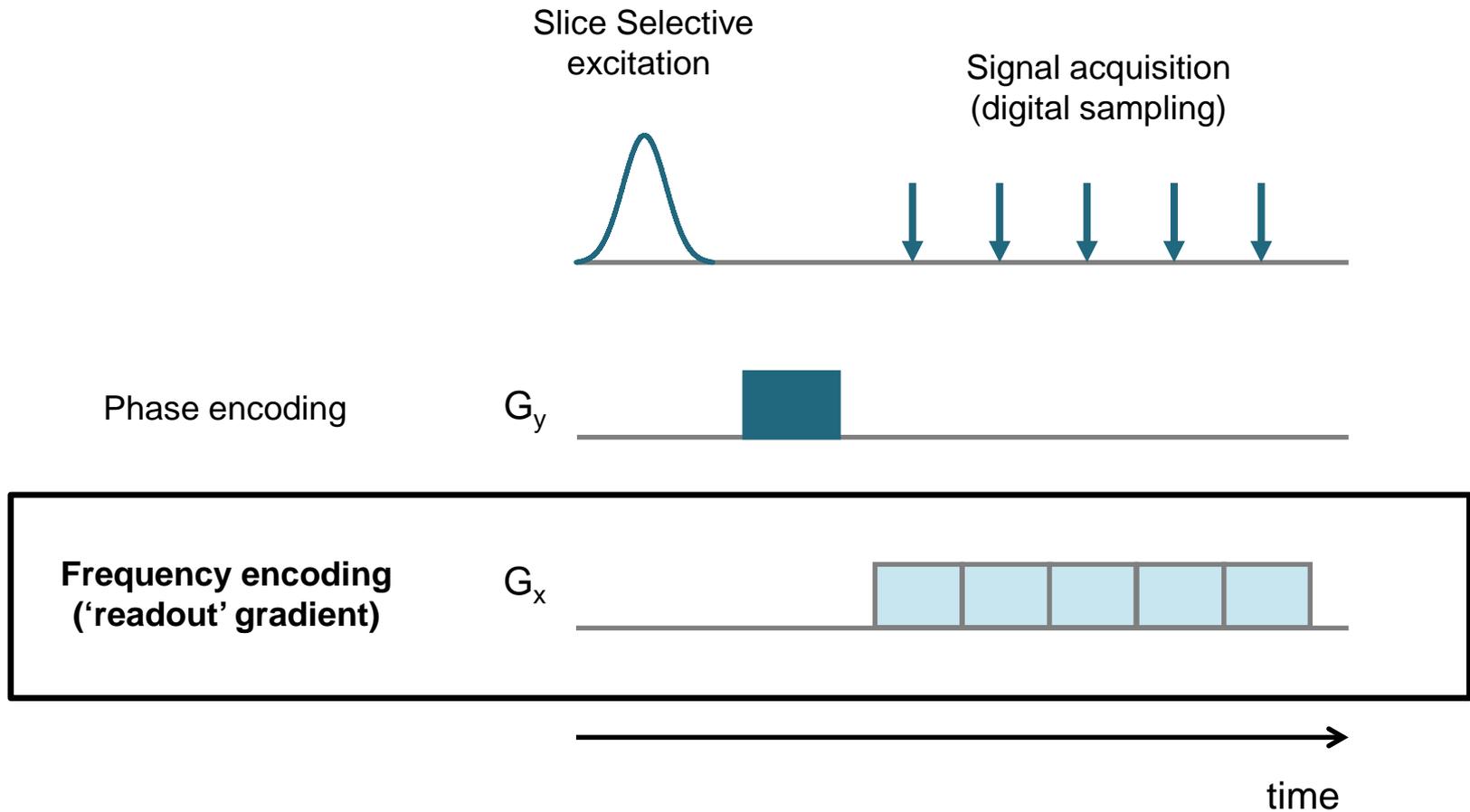


large area

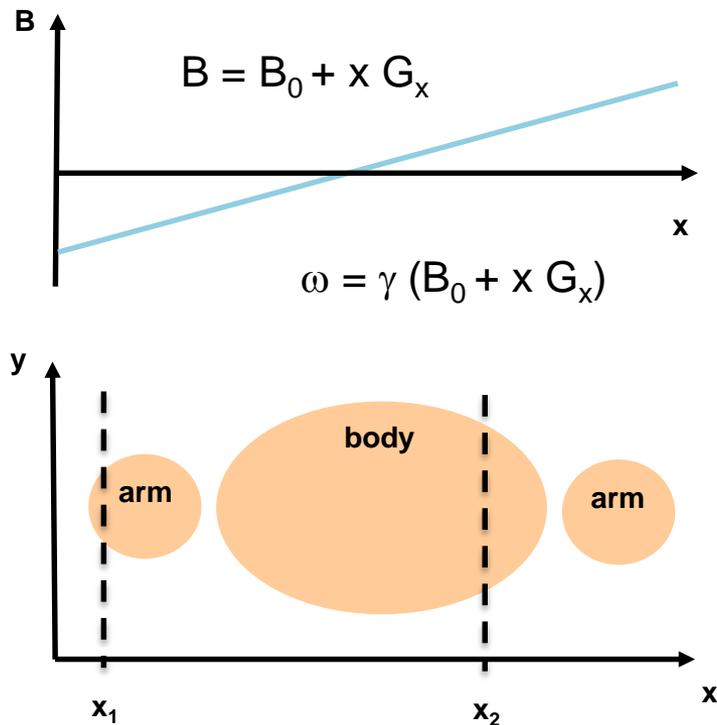
# Signal intensity measured at a spatial frequency



# Frequency encoding

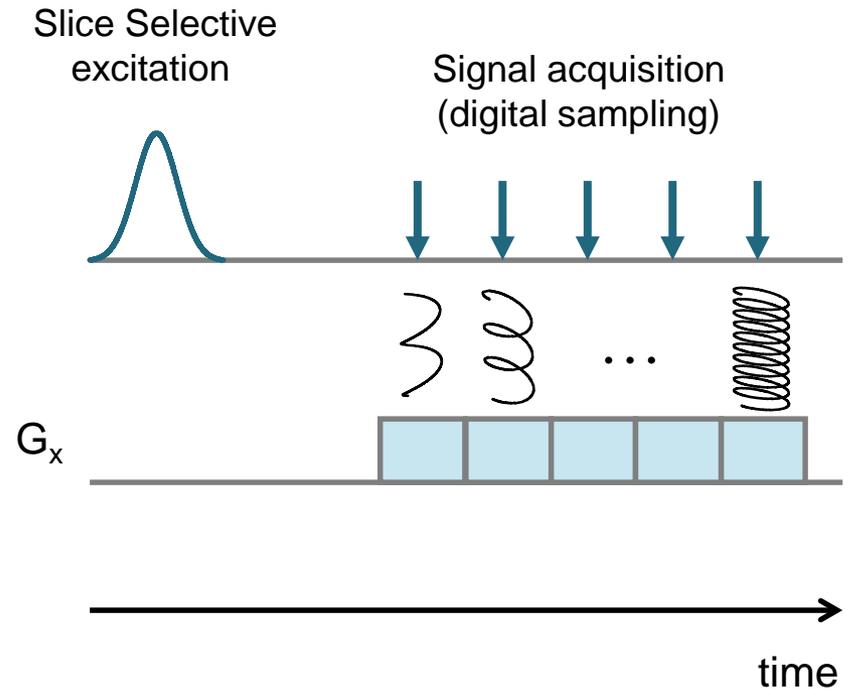


# Frequency encoding



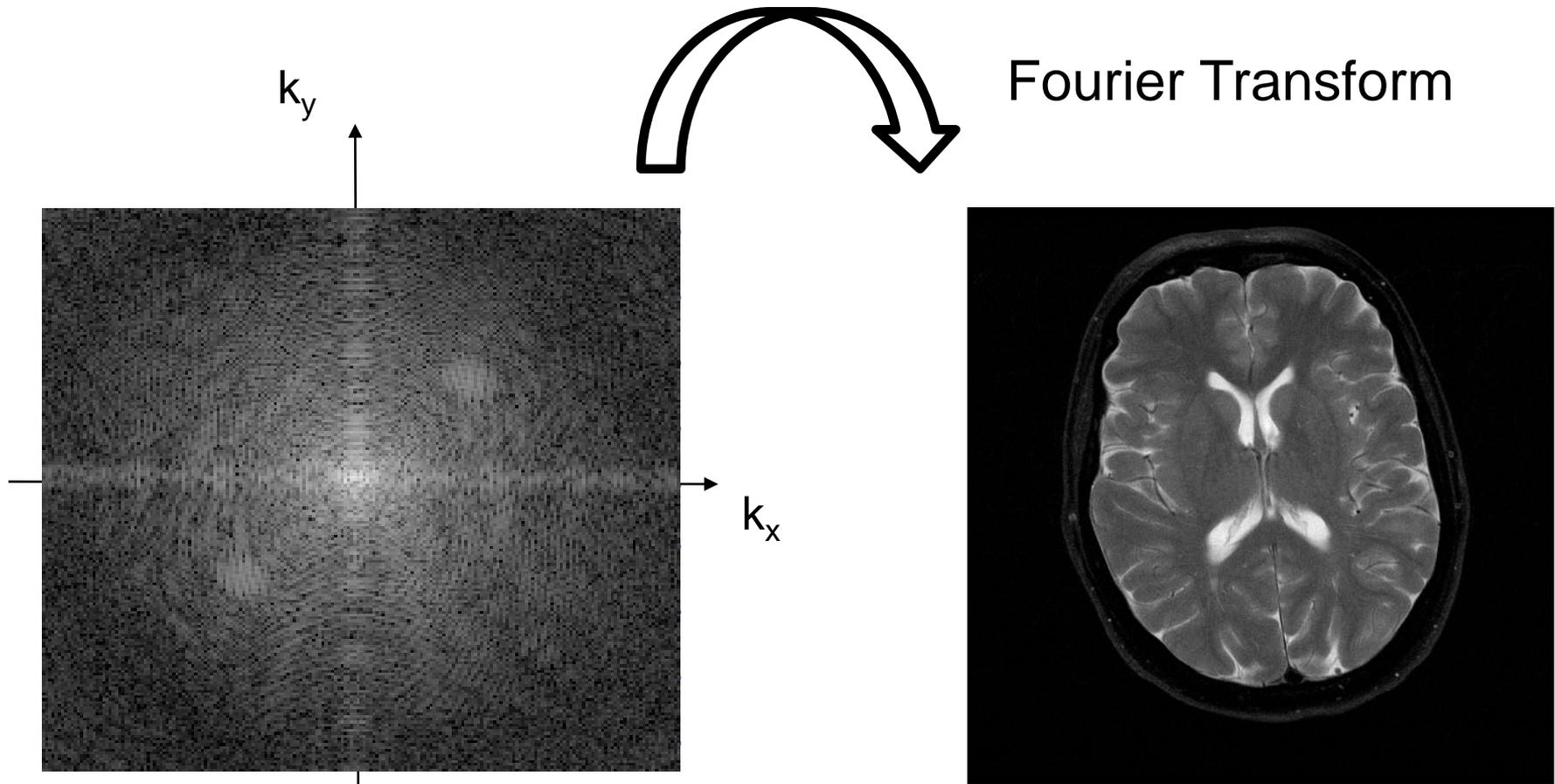
- Spins in position  $x_1$  and  $x_2$  experience different B field and will get out of phase.
- The longer the gradient is applied for, the larger the phase difference.

## Pulse sequence

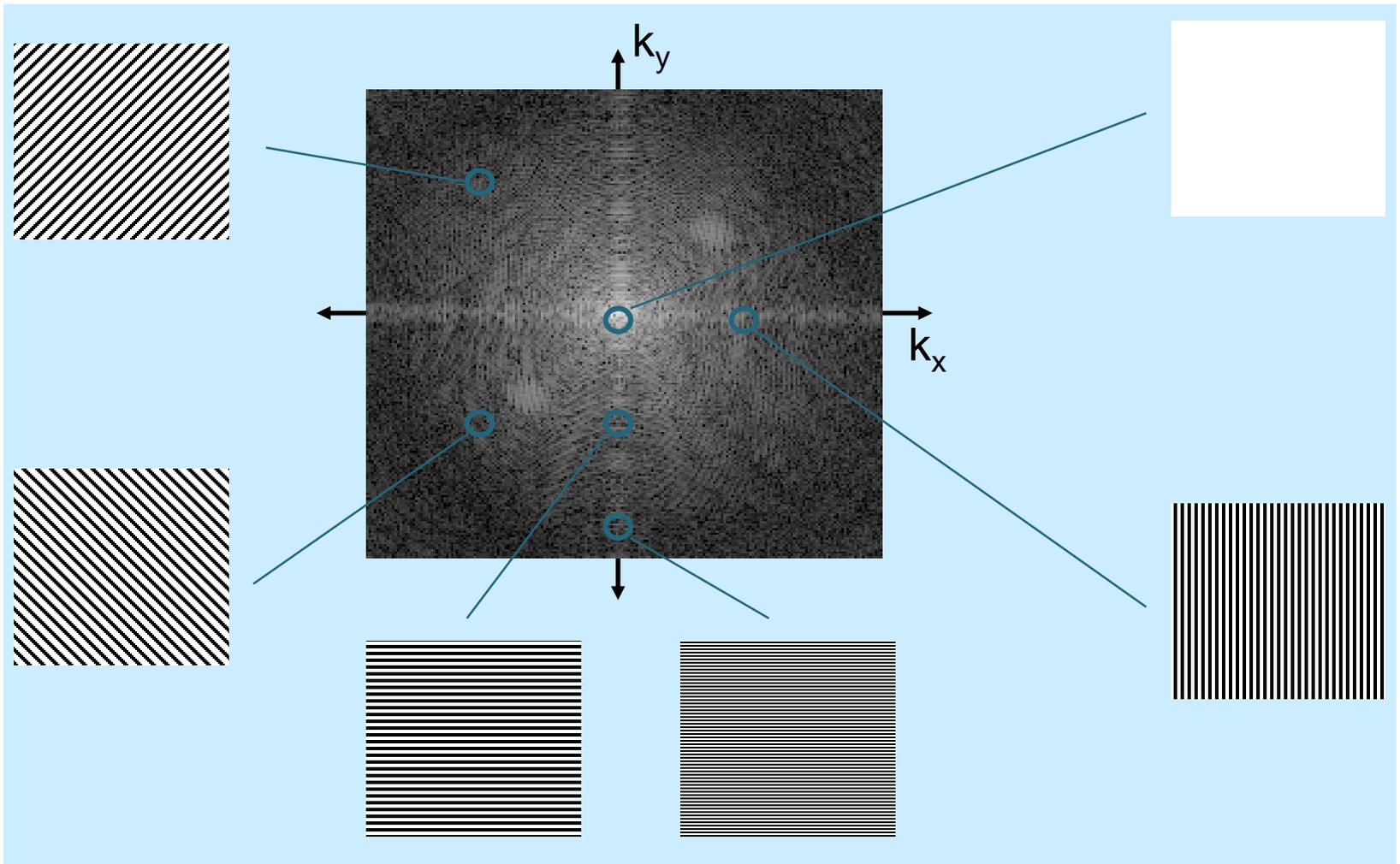


# Image reconstruction and k-space

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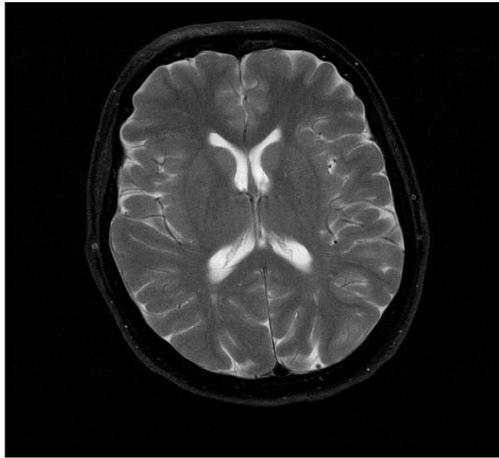


# k-space

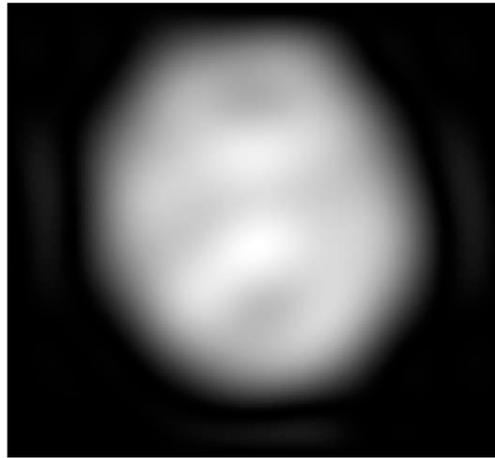


# Spatial frequency and contrast

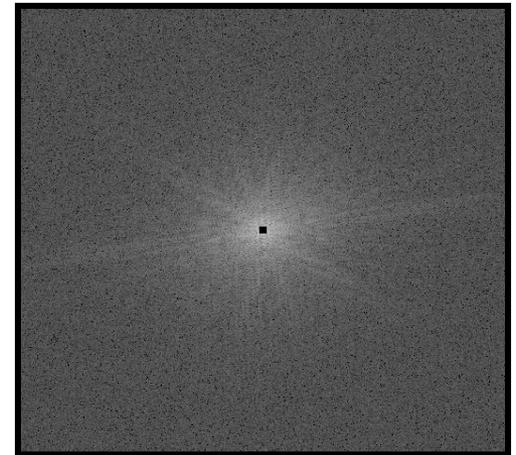
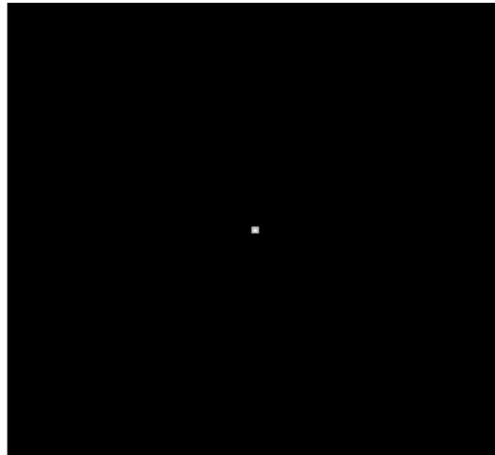
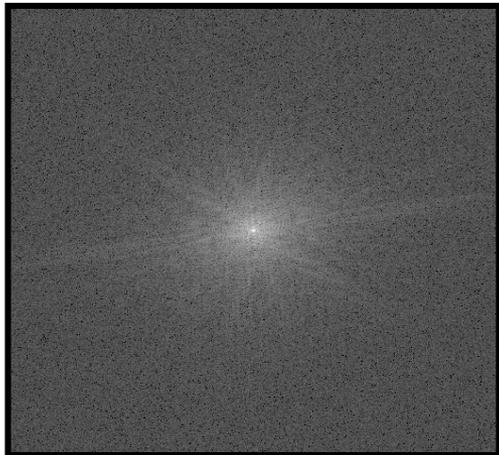
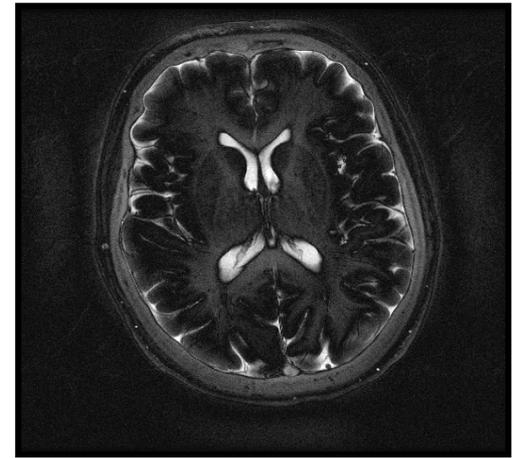
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512 x 512

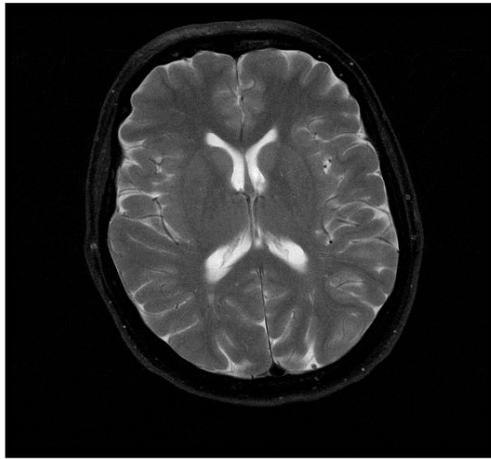


8 x 8

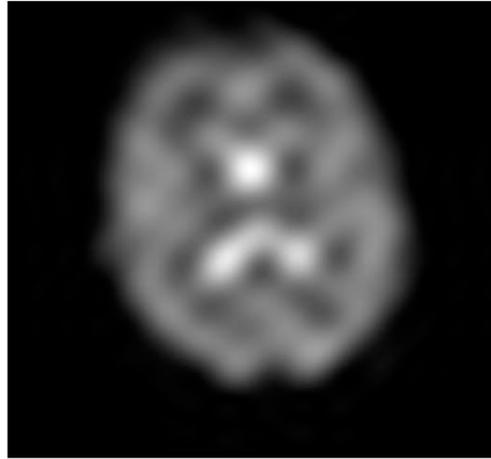


# Spatial frequency and contrast

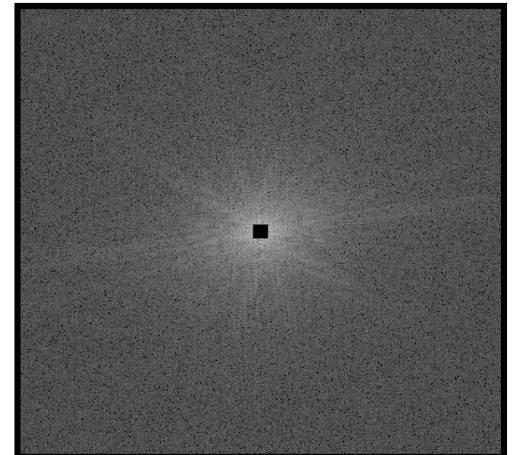
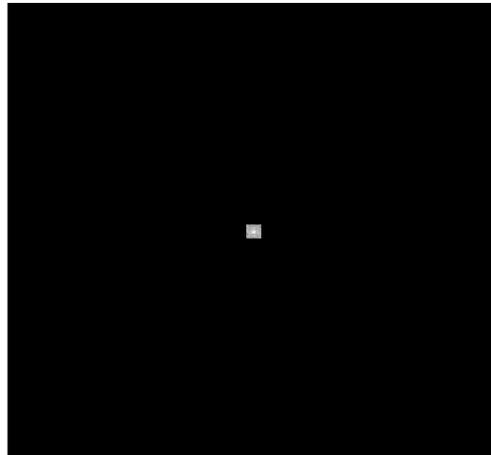
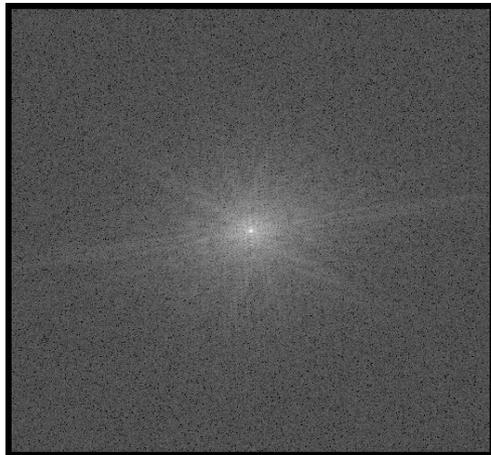
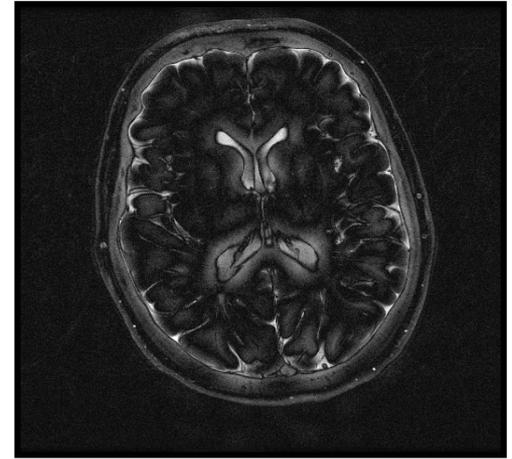
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512 x 512

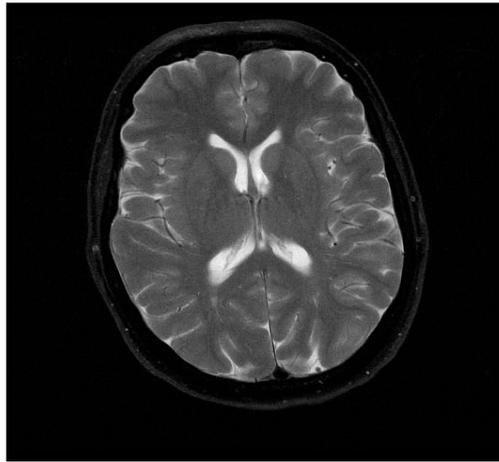


16 x 16

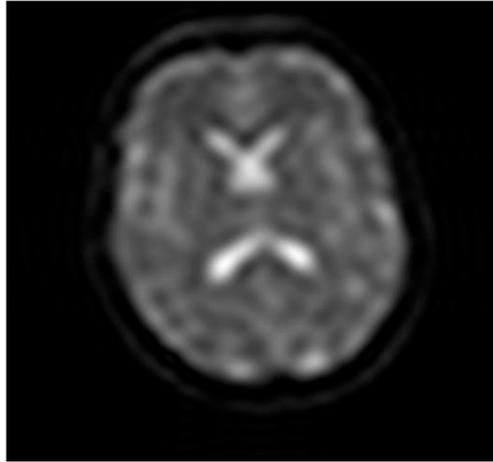


# Spatial frequency and contrast

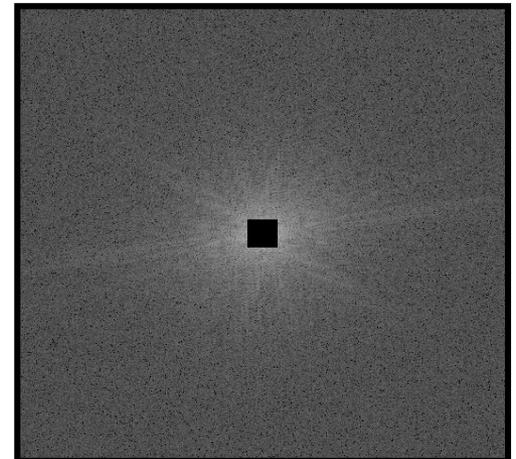
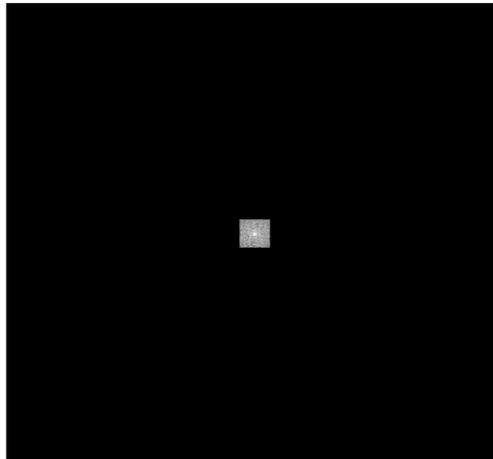
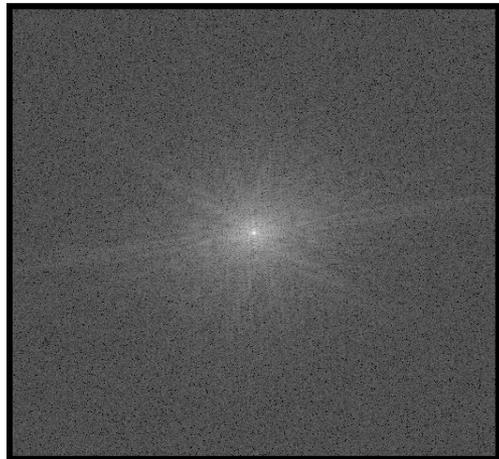
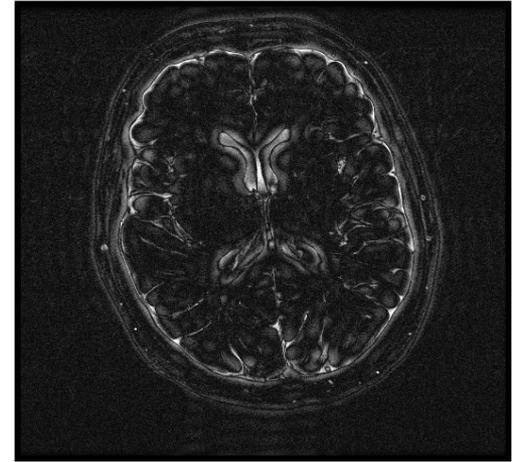
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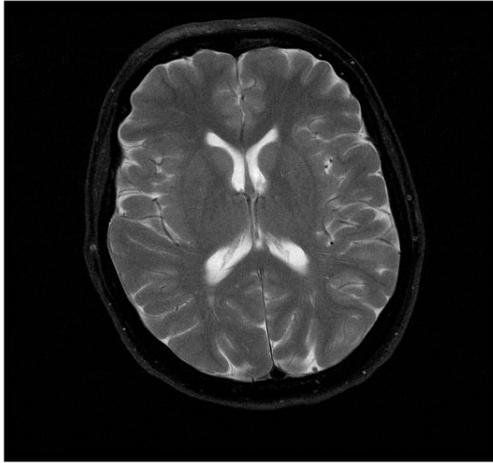
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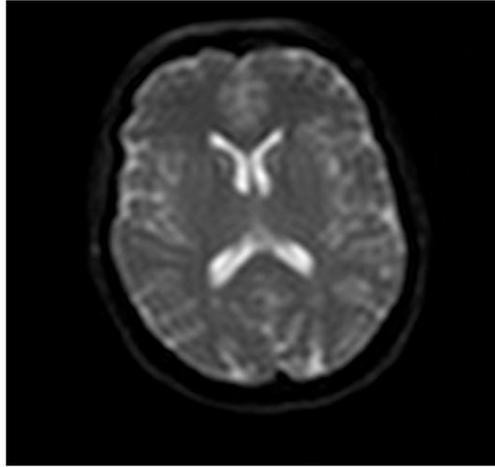
32 x 32



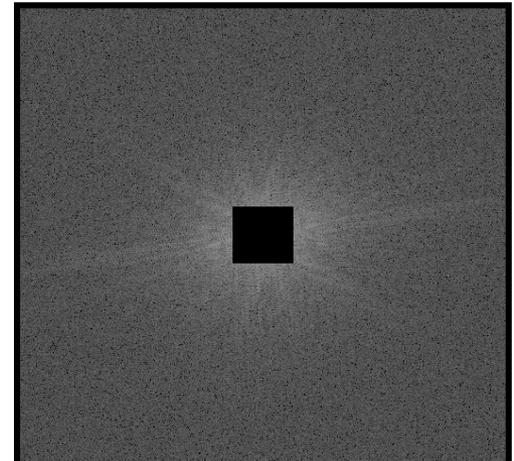
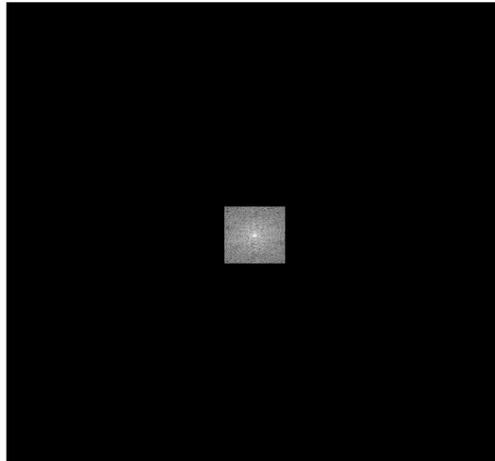
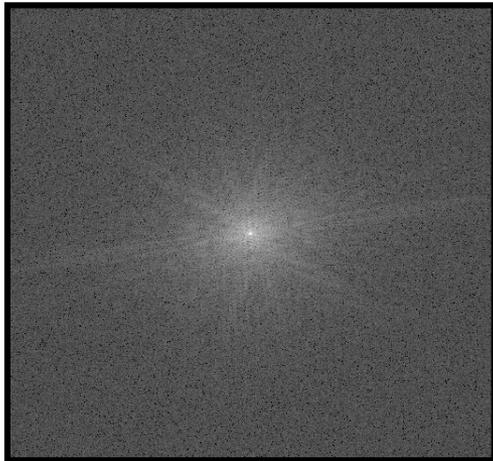
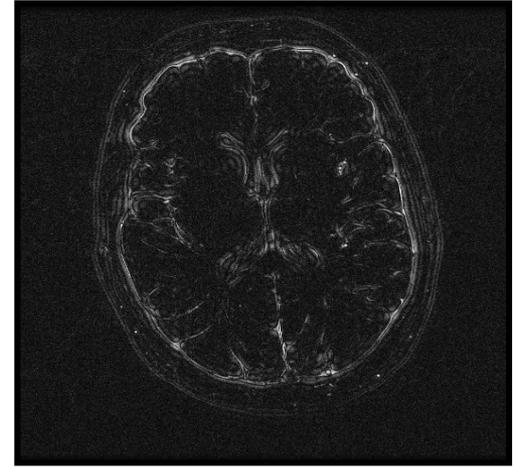
# Spatial frequency and contrast



512 x 512

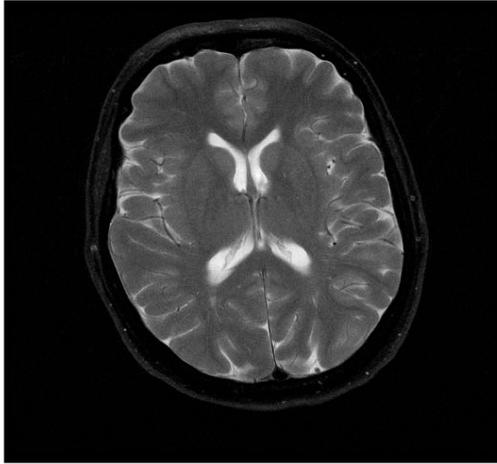


64 x 64

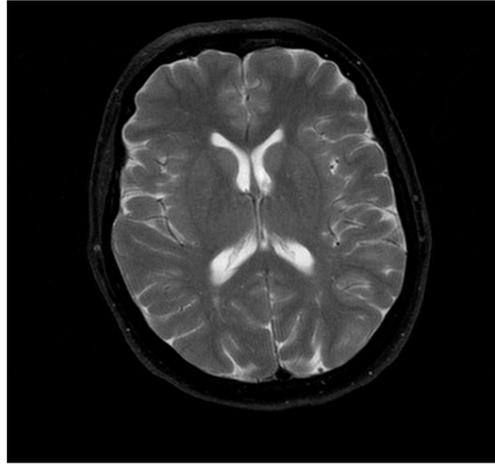


# Spatial frequency and contrast

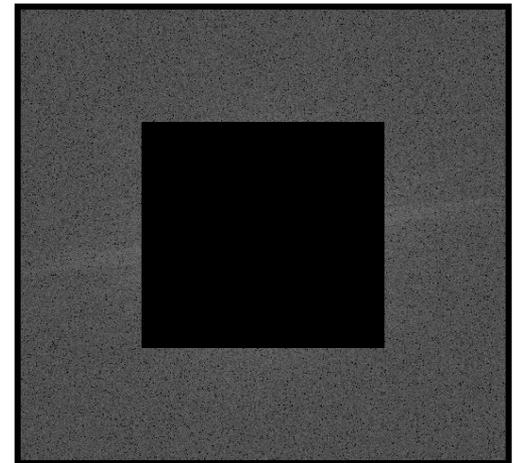
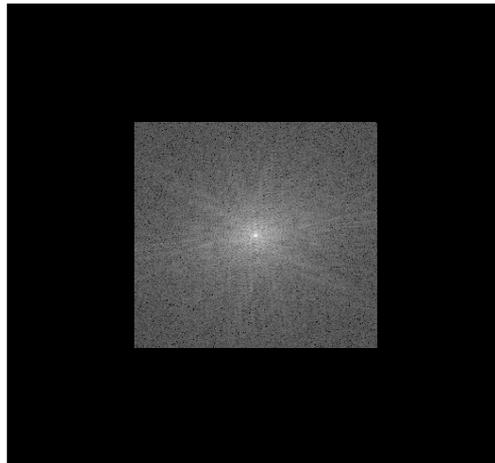
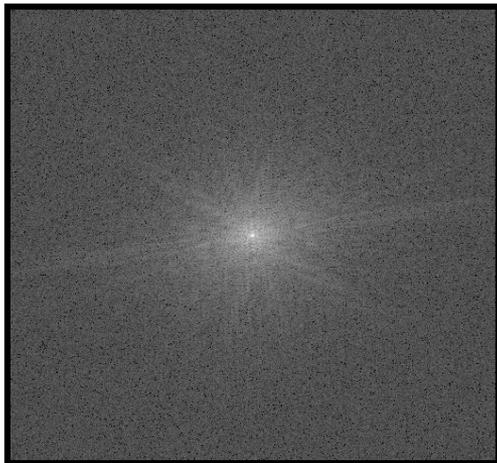
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512 x 512

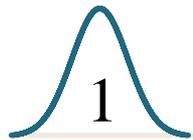


256 x 256

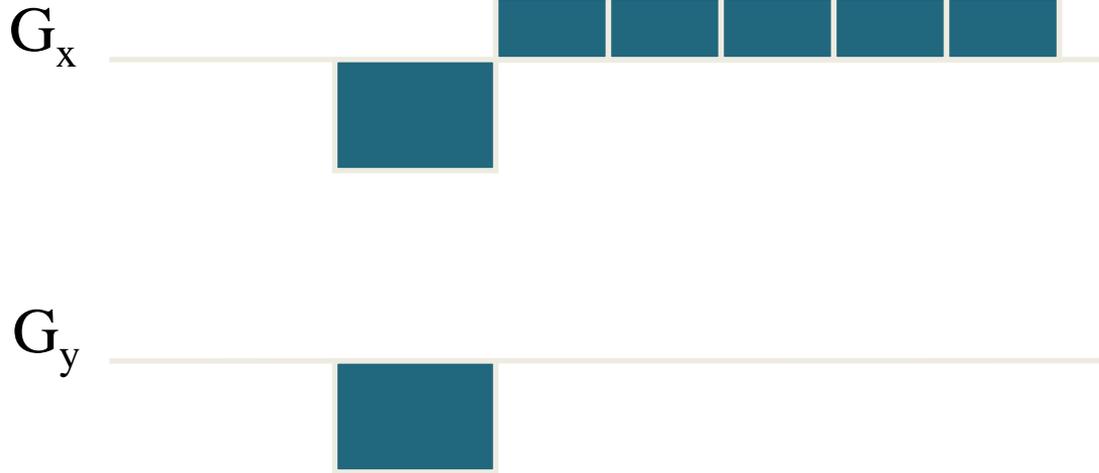


# k-space acquisition – Structural Imaging (FLASH)

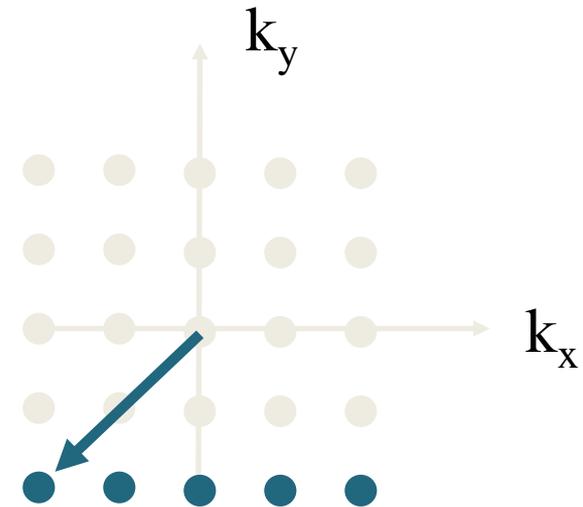
Selective excitation



Signal acquisition  
(digital sampling)



*K* space

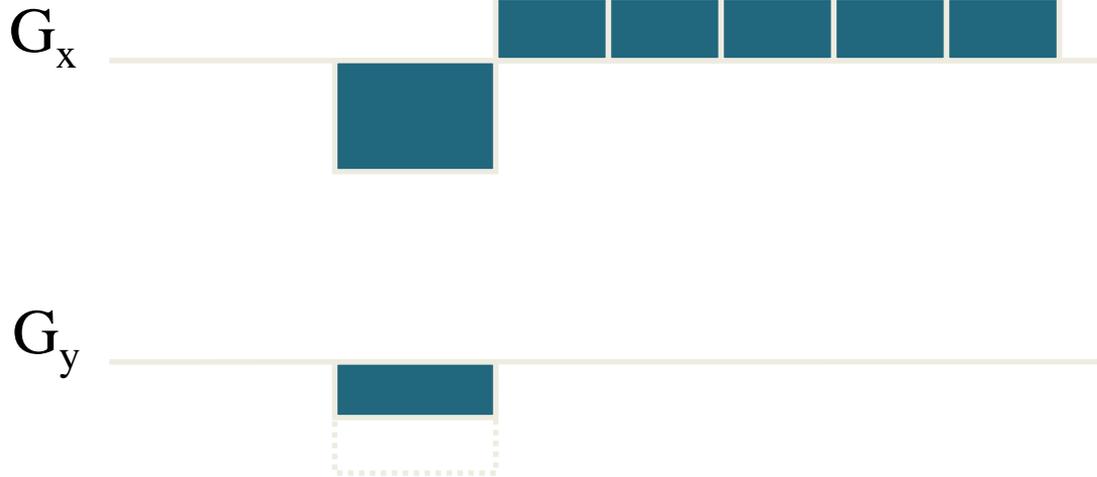


# k-space acquisition – Structural Imaging (FLASH)

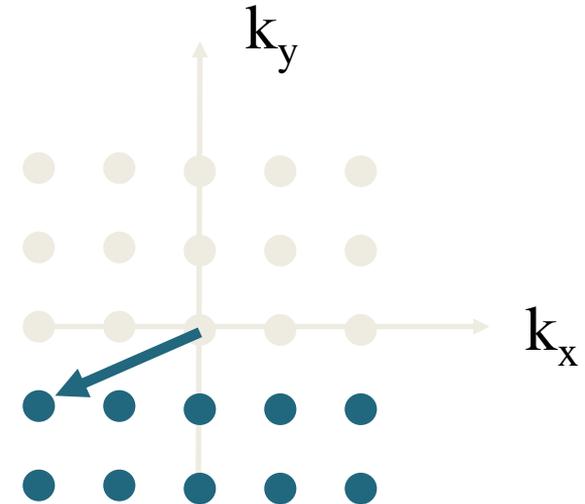
Selective excitation



Signal acquisition  
(digital sampling)



*K* space

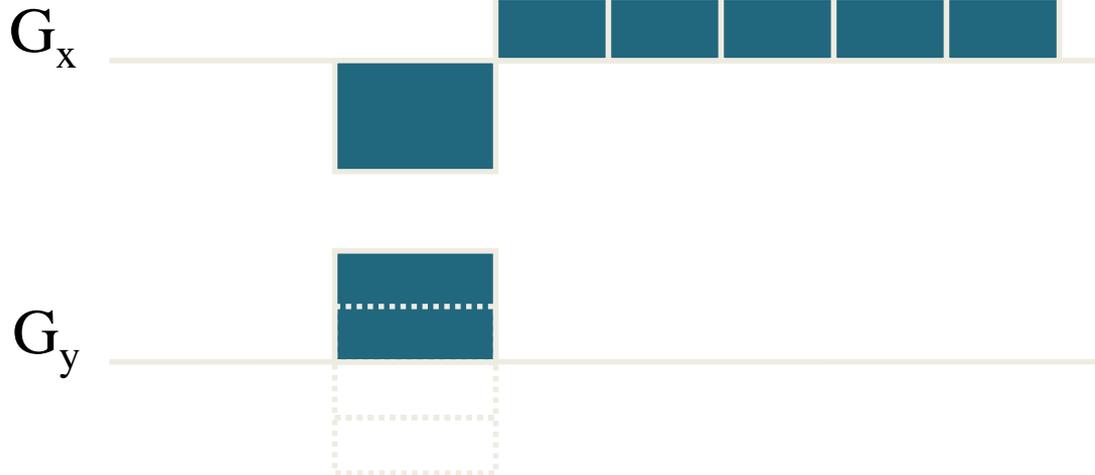


# k-space acquisition – Structural Imaging (FLASH)

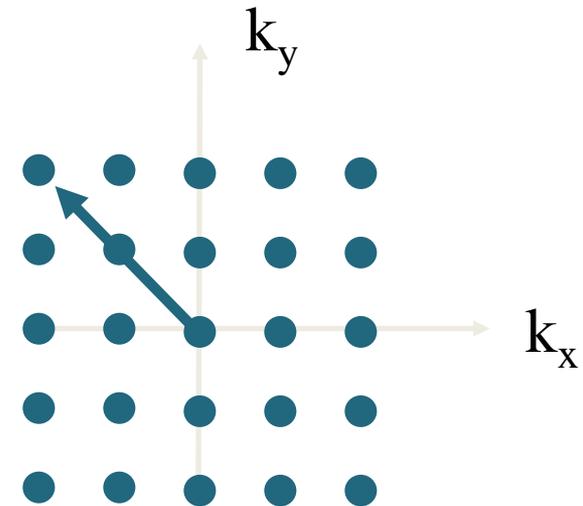
Selective excitation



Signal acquisition  
(digital sampling)

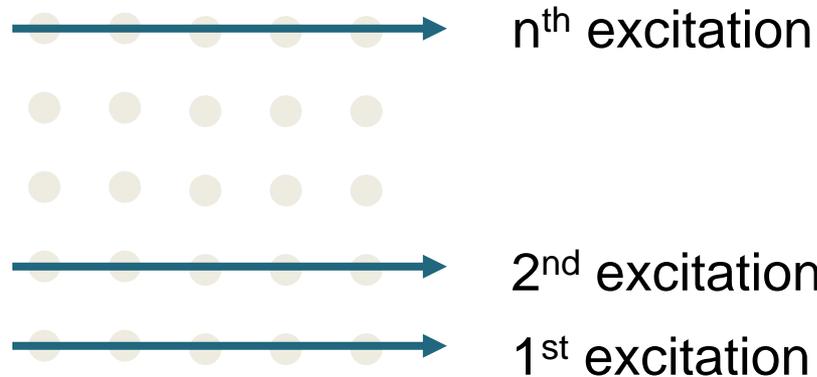


*K* space



# k-space acquisition – Structural Imaging (FLASH)

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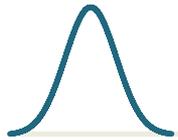
Problem: This sequence is rather slow

- $K$  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)

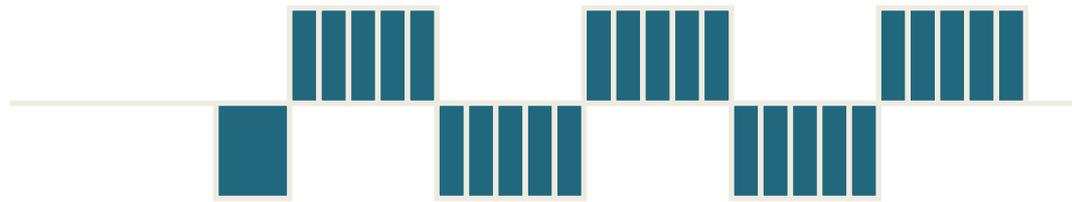
Selective excitation



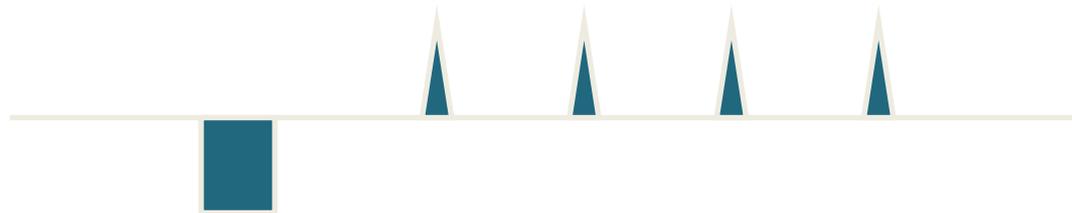
Signal acquisition  
(digital sampling)



$G_x$

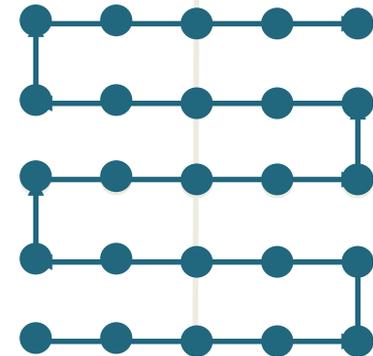


$G_y$



$K$  space

$k_y$

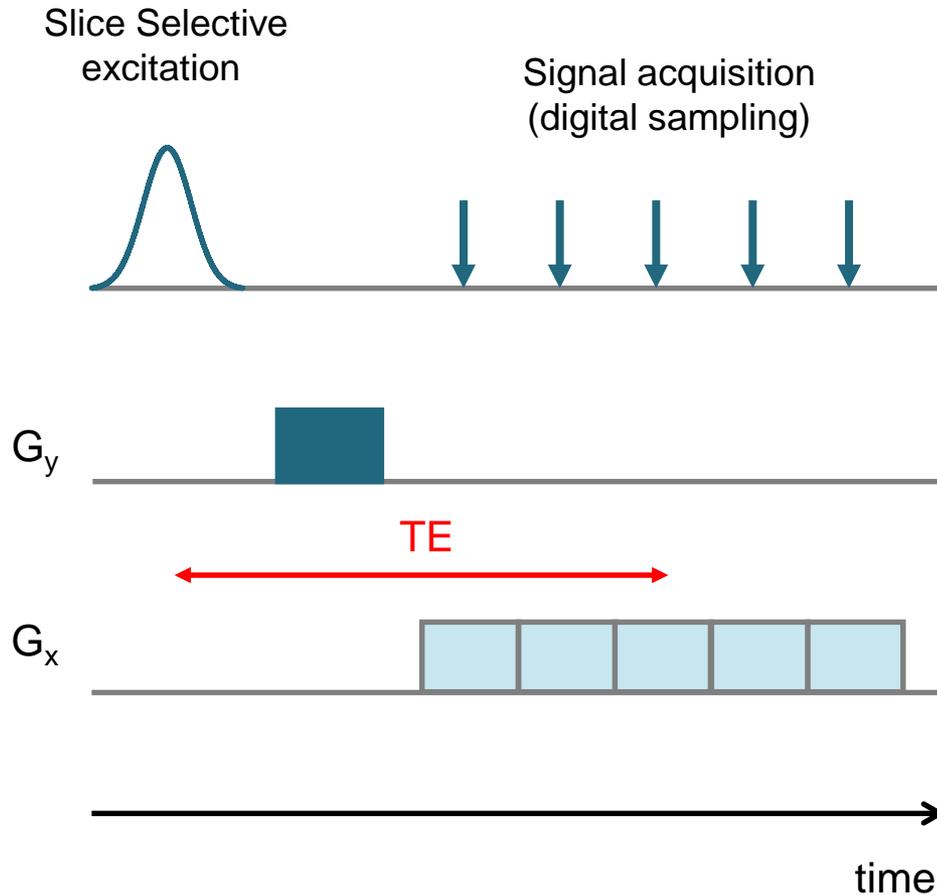


$k_x$

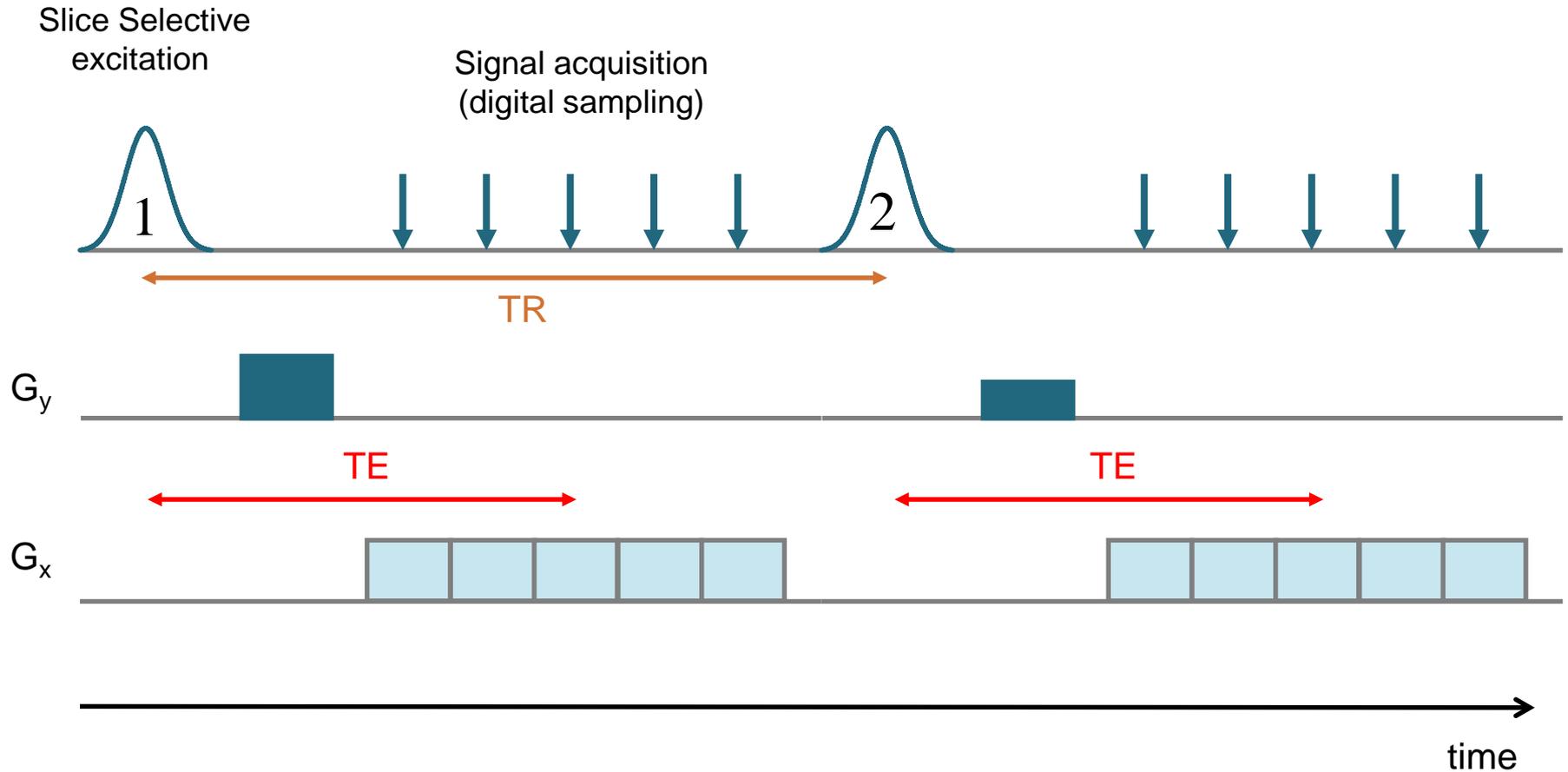
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# Image Contrast

# Echo Time (TE) and Repetition Time (TR)



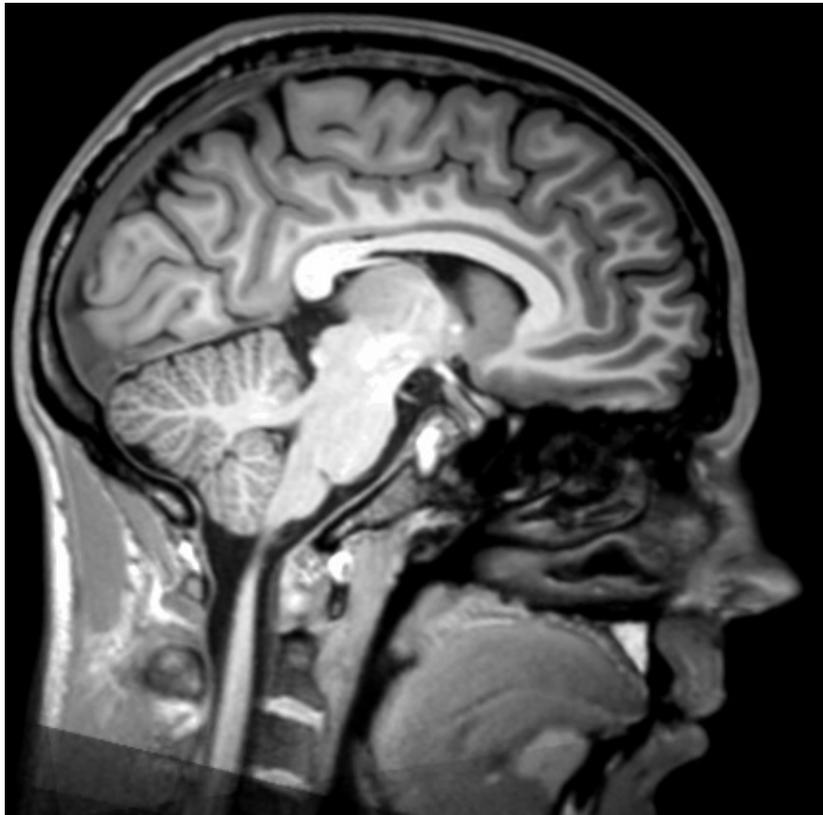
# Echo Time (TE) and Repetition Time (TR)



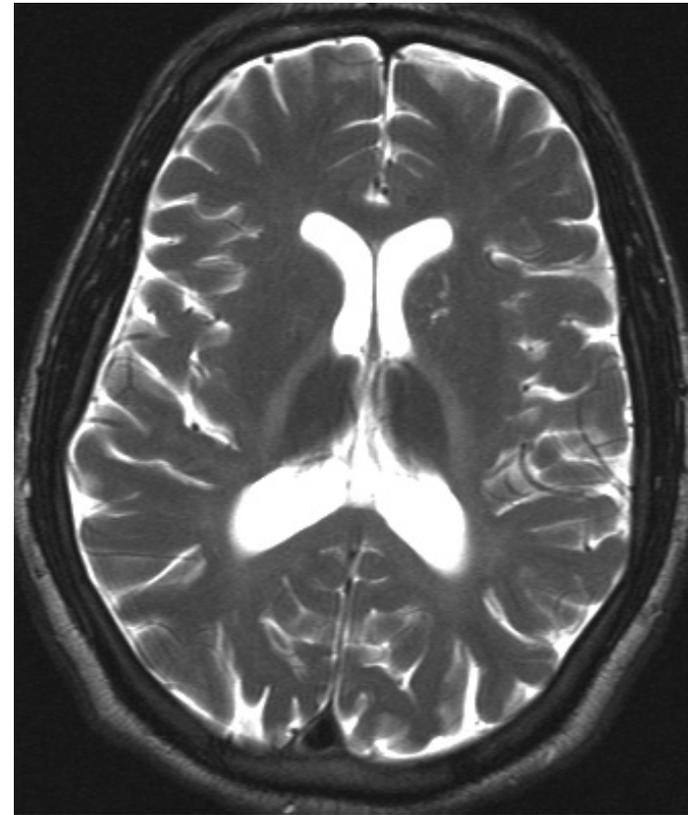
# Tissue Contrast

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



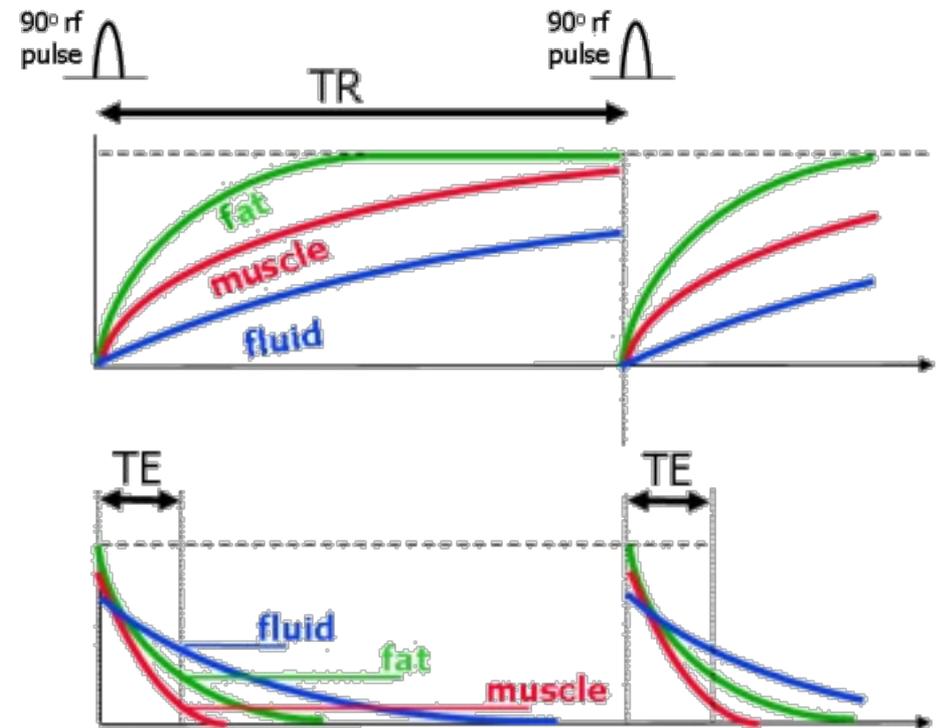
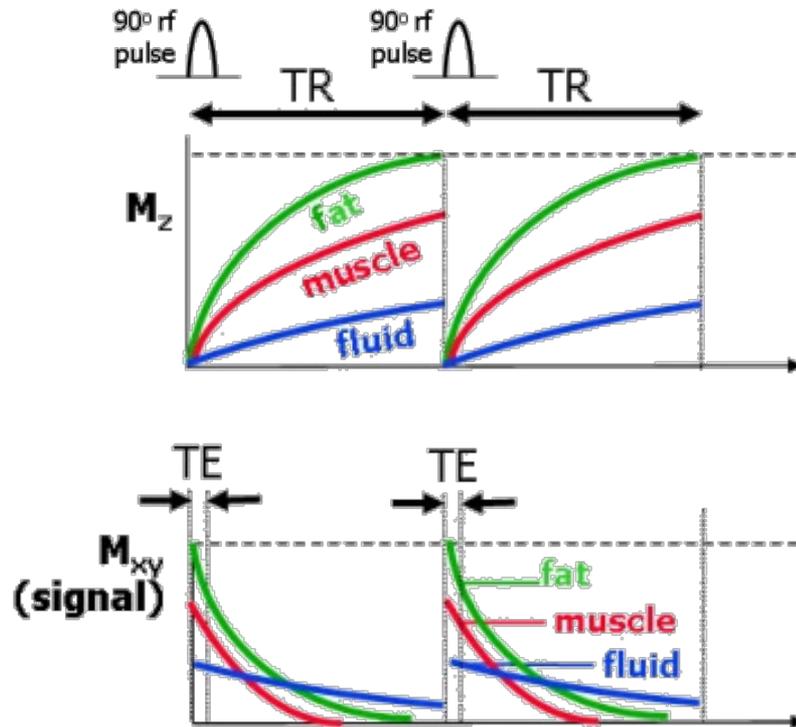
**T2-weighted**  
Bright **fluid**, **Long TR & TE**



# Tissue Contrast

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

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

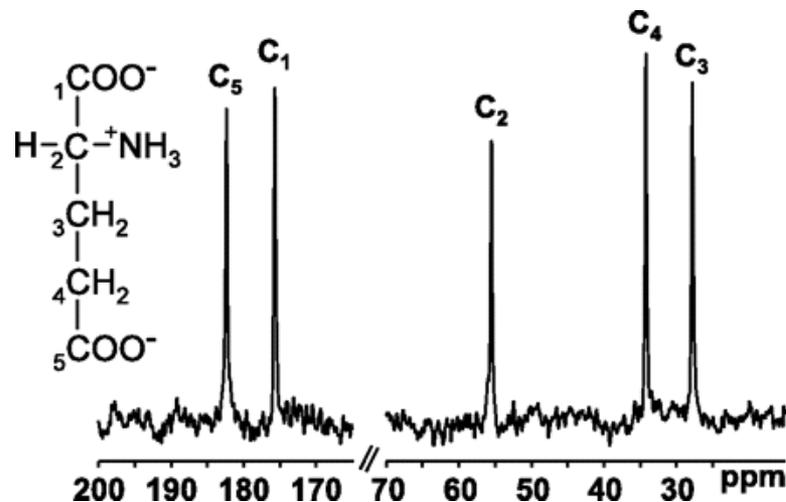


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# Part III: Magnetic Resonance Spectroscopy (MRS)

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



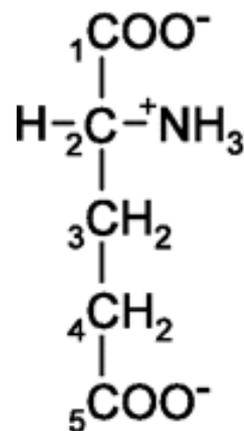
The MRS spectrum of glutamate

Befroy DE and Shulman GI.  
Diabetes 2011

# Basic principles of MRS

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- 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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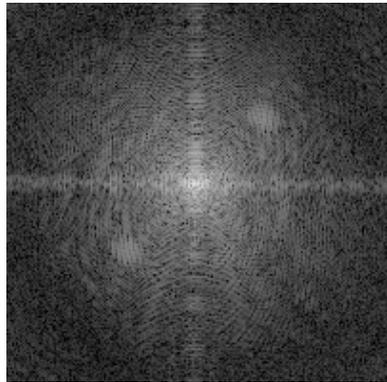
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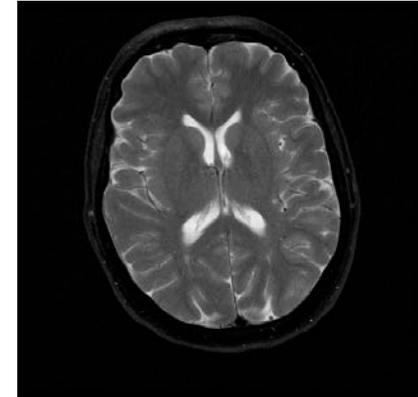
$$\omega_5 = \gamma B_5$$

# Basic principles of MRS

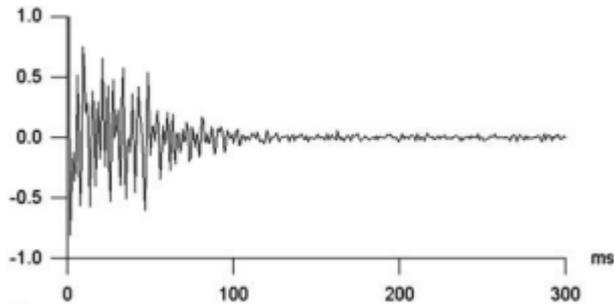
**MRI**



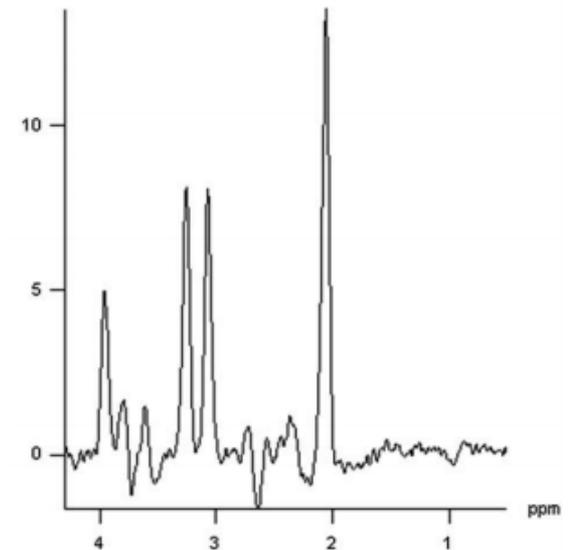
**Fourier Transform**



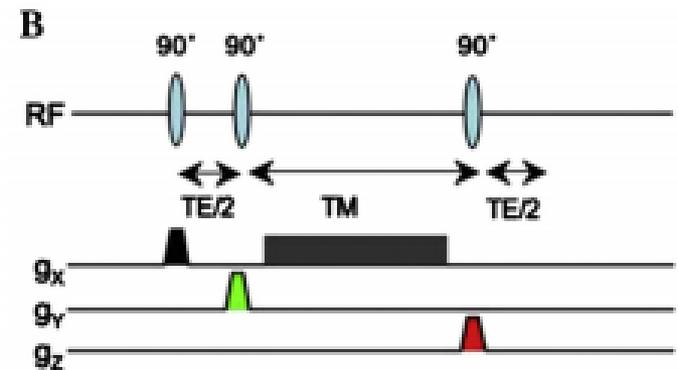
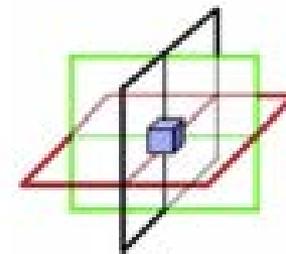
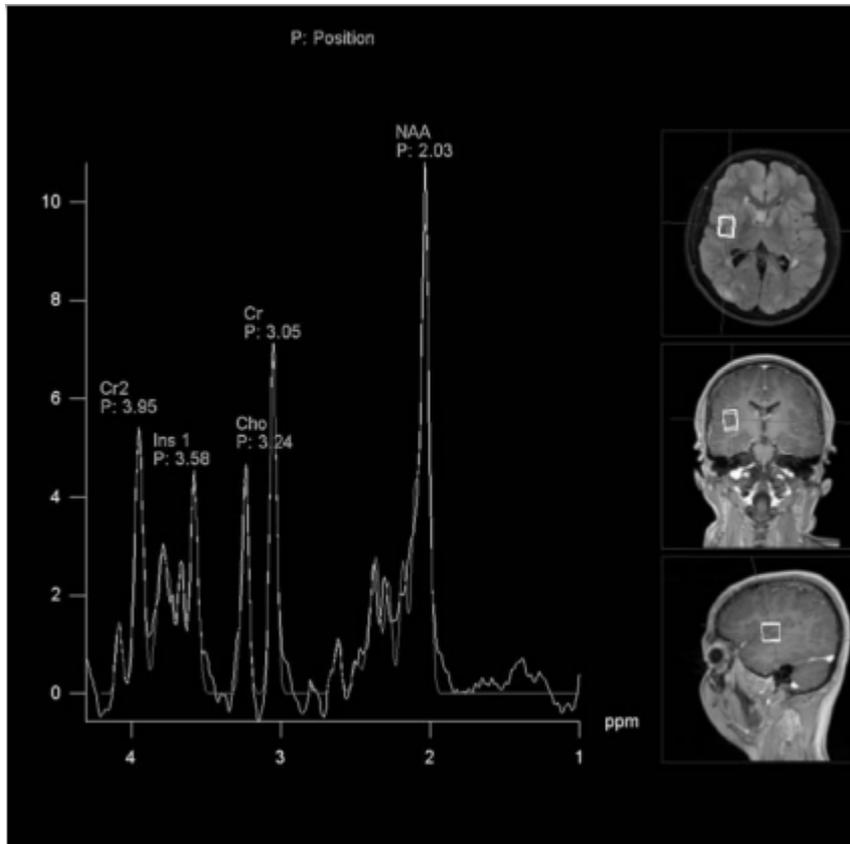
**MRS**



**Fourier Transform**



# MRS and Signal Localisation



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# Questions?

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