MRC | Cognition and Brain Sciences Unit

Introduction to MRI Physics

Marta M Correia
MRC Cognition and Brain Sciences Unit, Cambridge, UK

25th January 2017

Overview

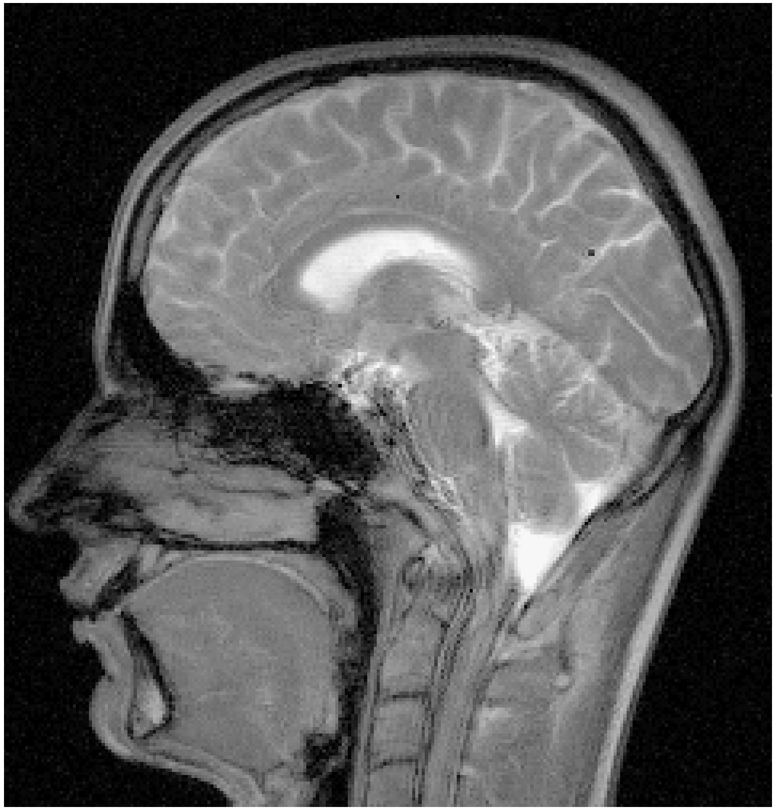
- Basic Principles
  - Nuclear Magnetic Resonance
  - Excitation, Relaxation and Signal
  - Image contrast

- Advanced Concepts
  - Spatial Encoding in MRI
  - Image formation and k-space

Part I
Basic Principles

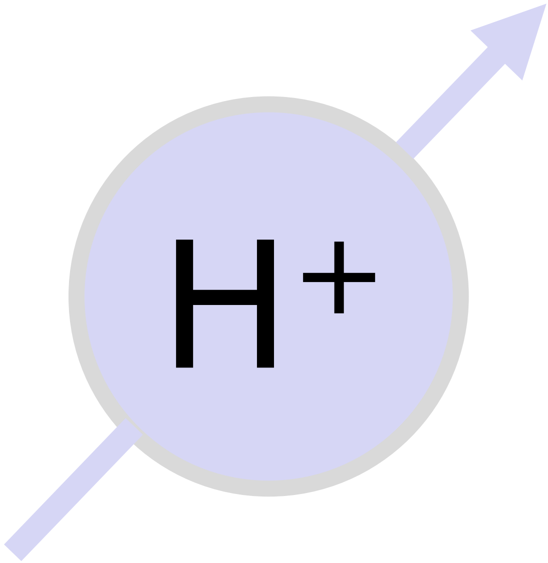
Nuclear Magnetic Resonance

MR images: What do we see ?



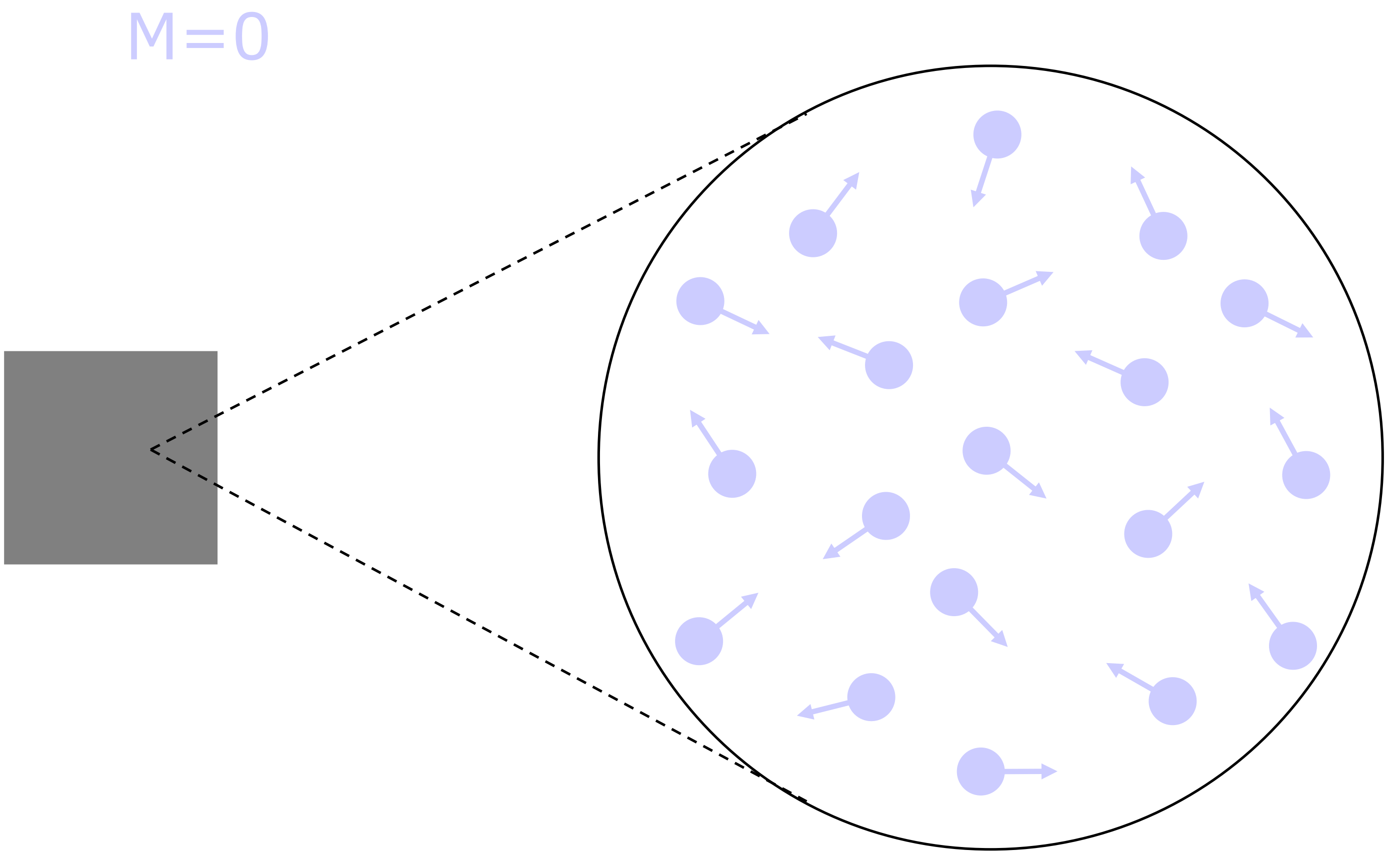
- MRI images are usually based on the signal from protons
- A proton is the nucleus of the hydrogen atom
- Hydrogen is the most common element in tissue
- The signal from protons is due to their *spin*

The Nuclear spin

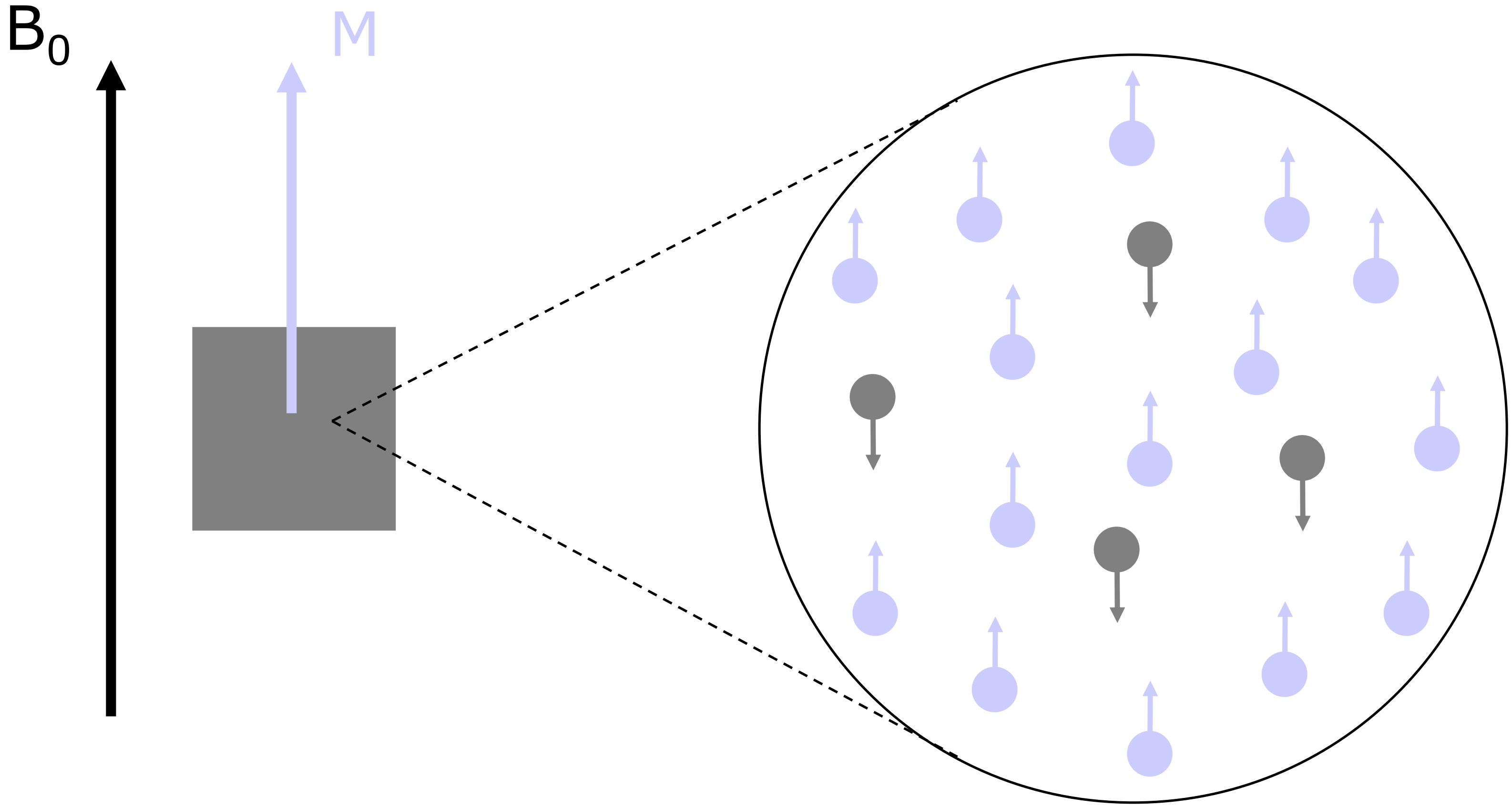


- Elementary property of an atomic nucleus
- Each spin carries an elementary magnetization
- Spins align in an external magnetic field (like a compass needle)

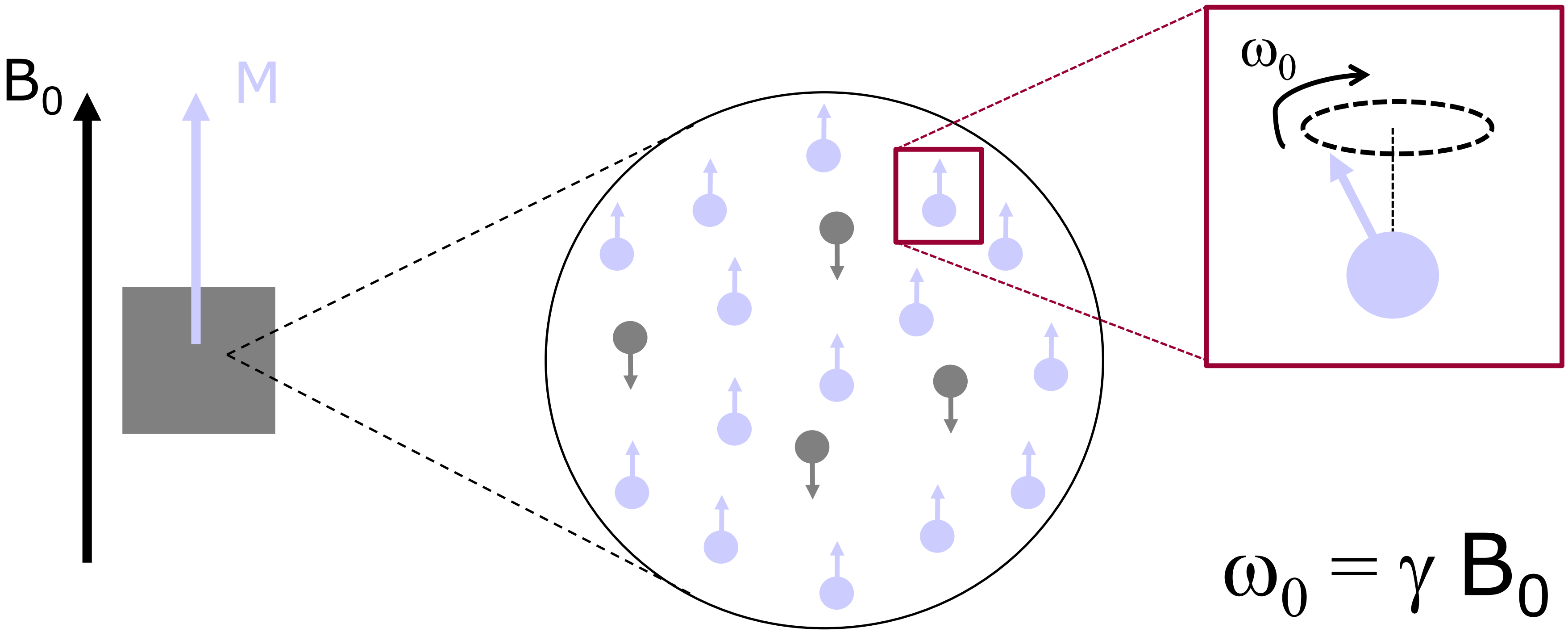
Macroscopic sample



Macroscopic sample

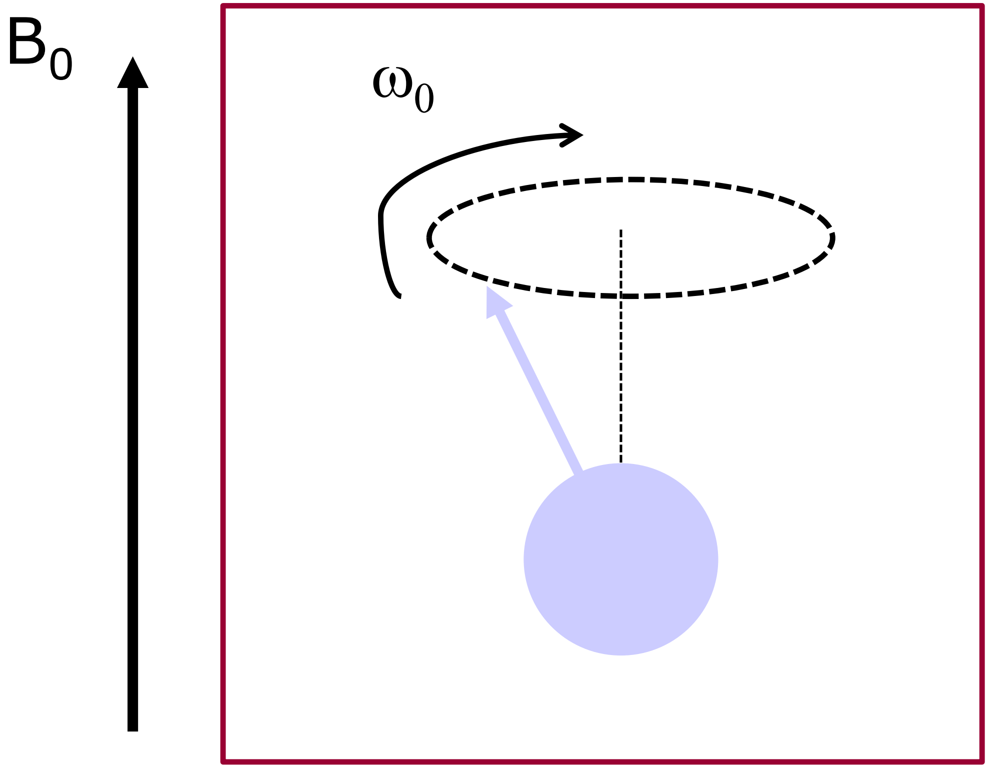


Precession and Larmor Frequency



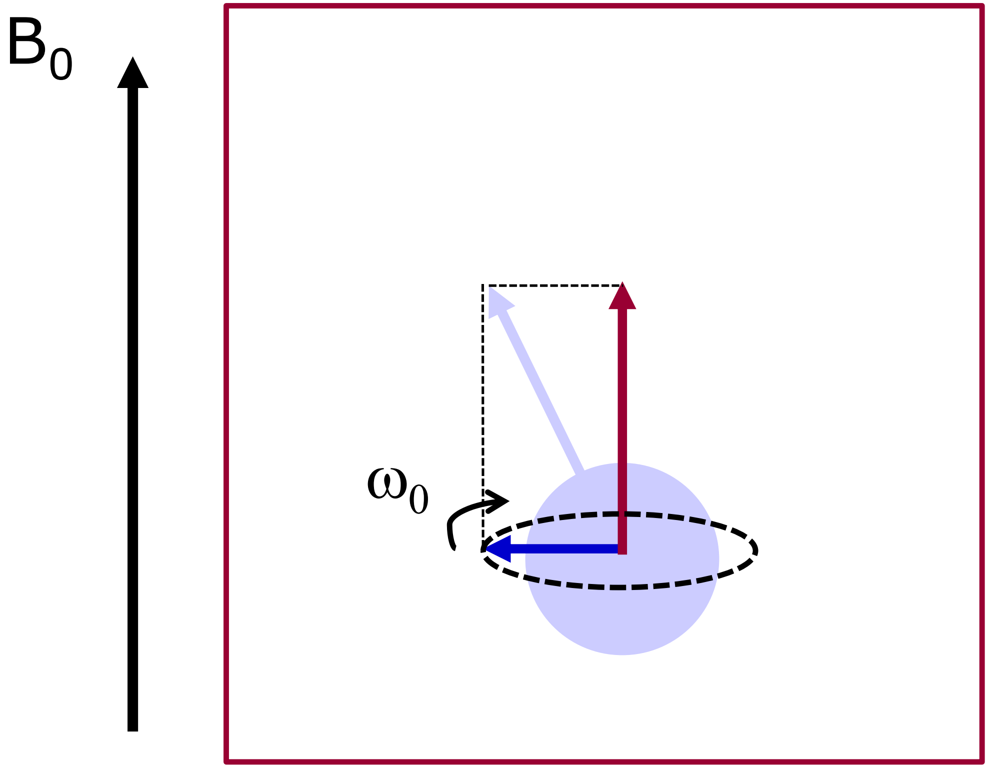
$$\omega_0 = \gamma B_0$$

Precession and Larmor Frequency



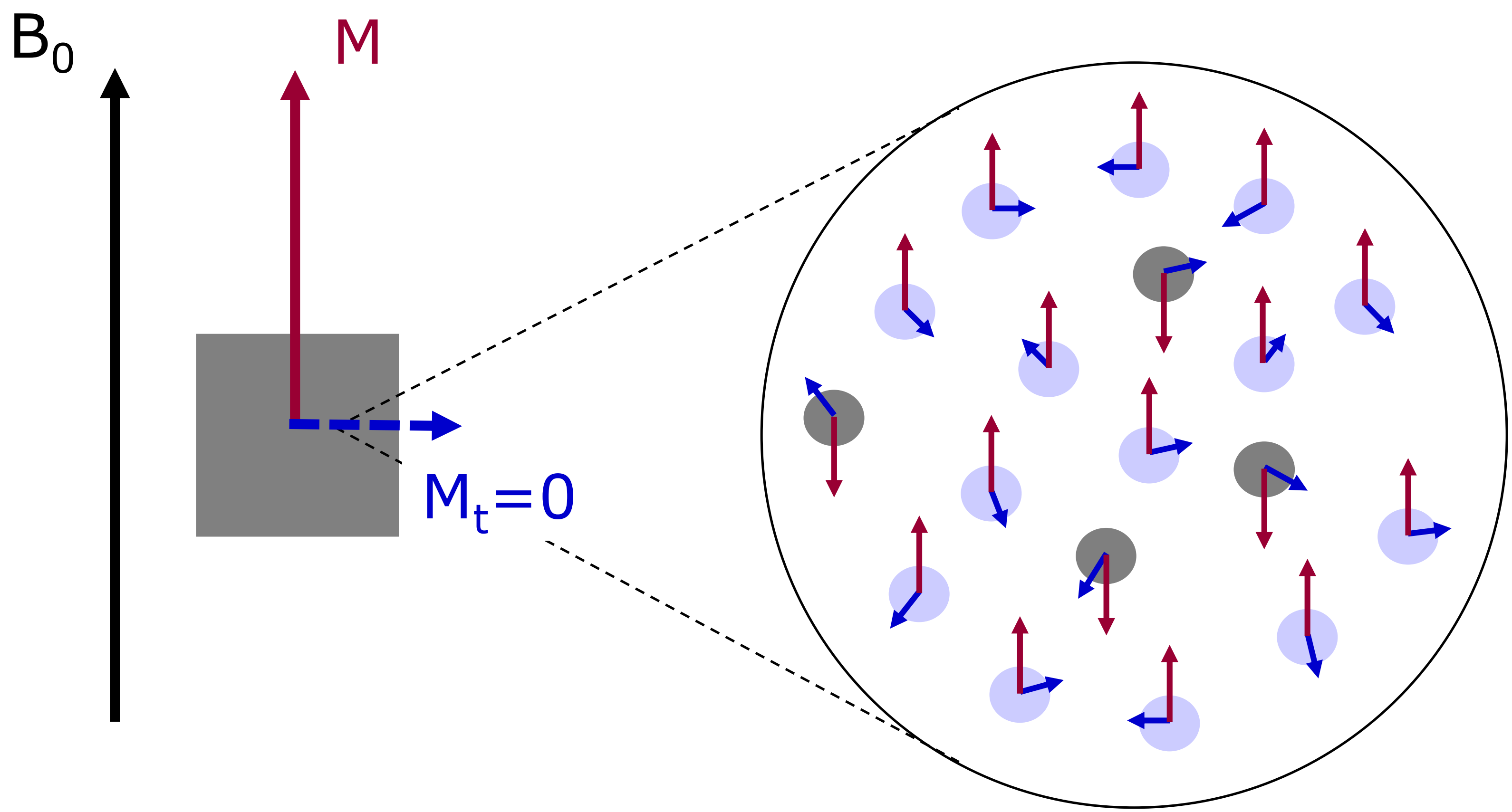
$$\omega_0 = \gamma B_0$$

Precession and Larmor Frequency

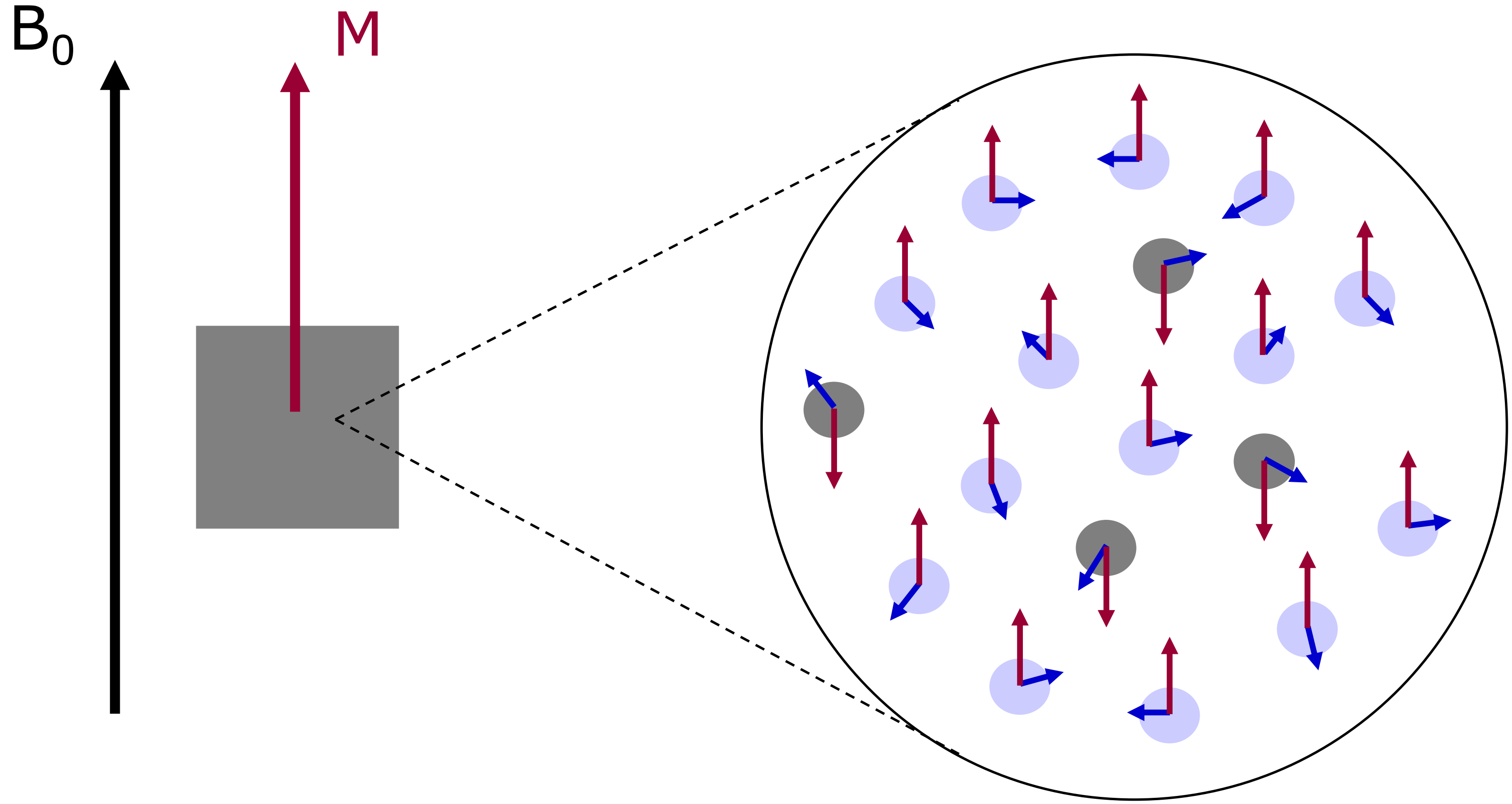


$$\omega_0 = \gamma B_0$$

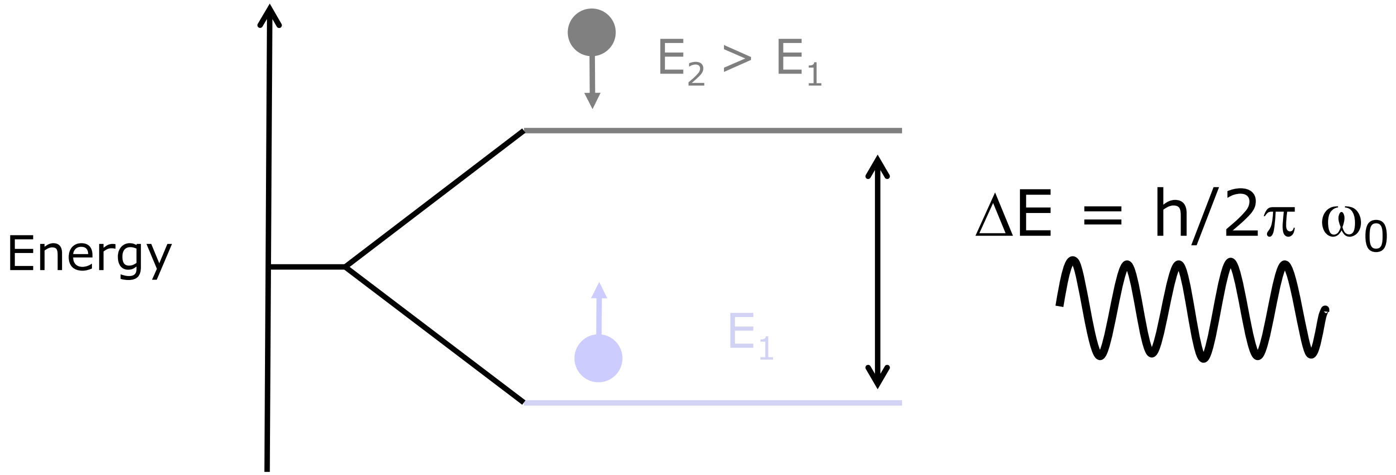
Macroscopic sample



Macroscopic sample

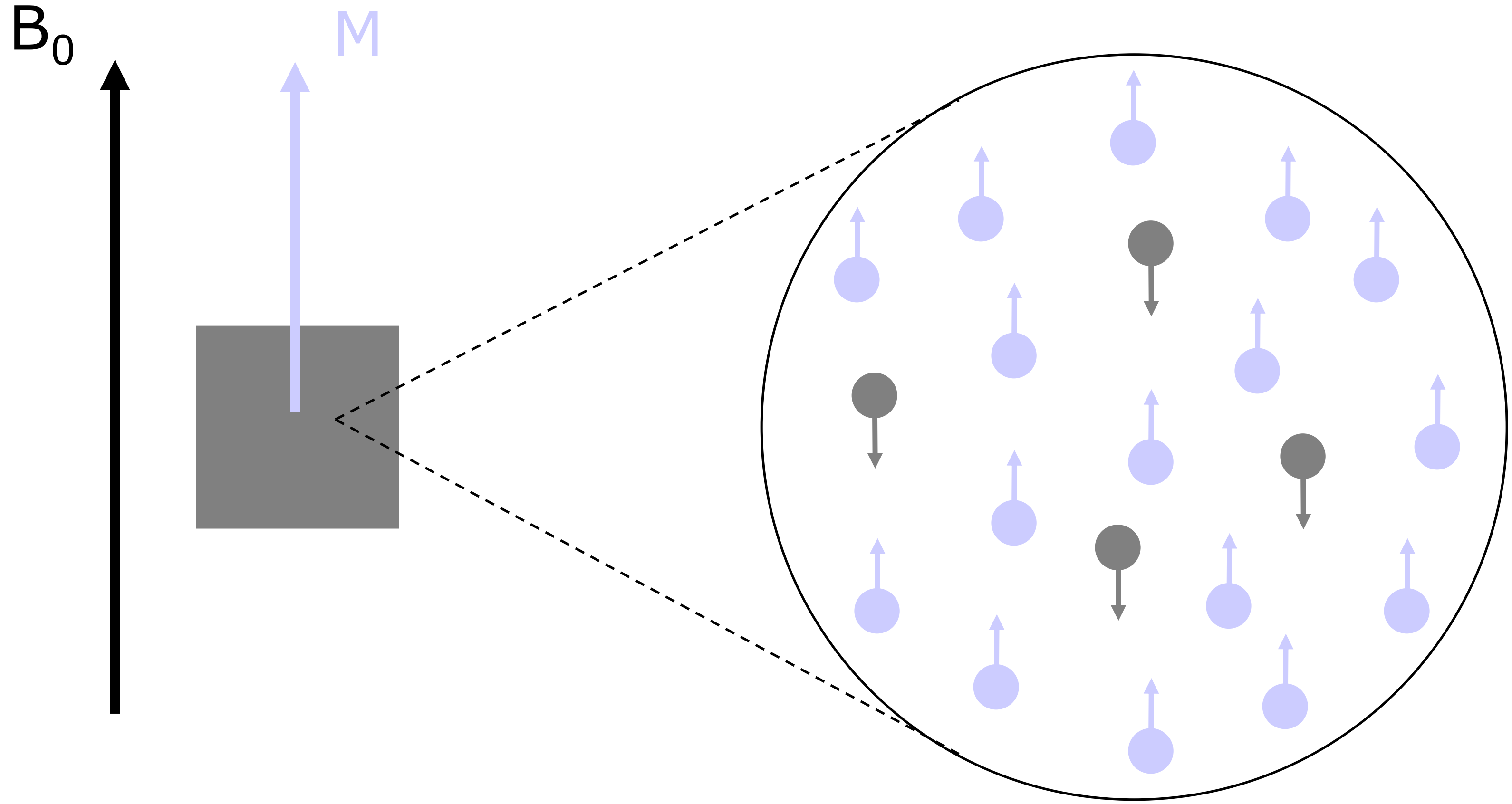


Magnetic Resonance

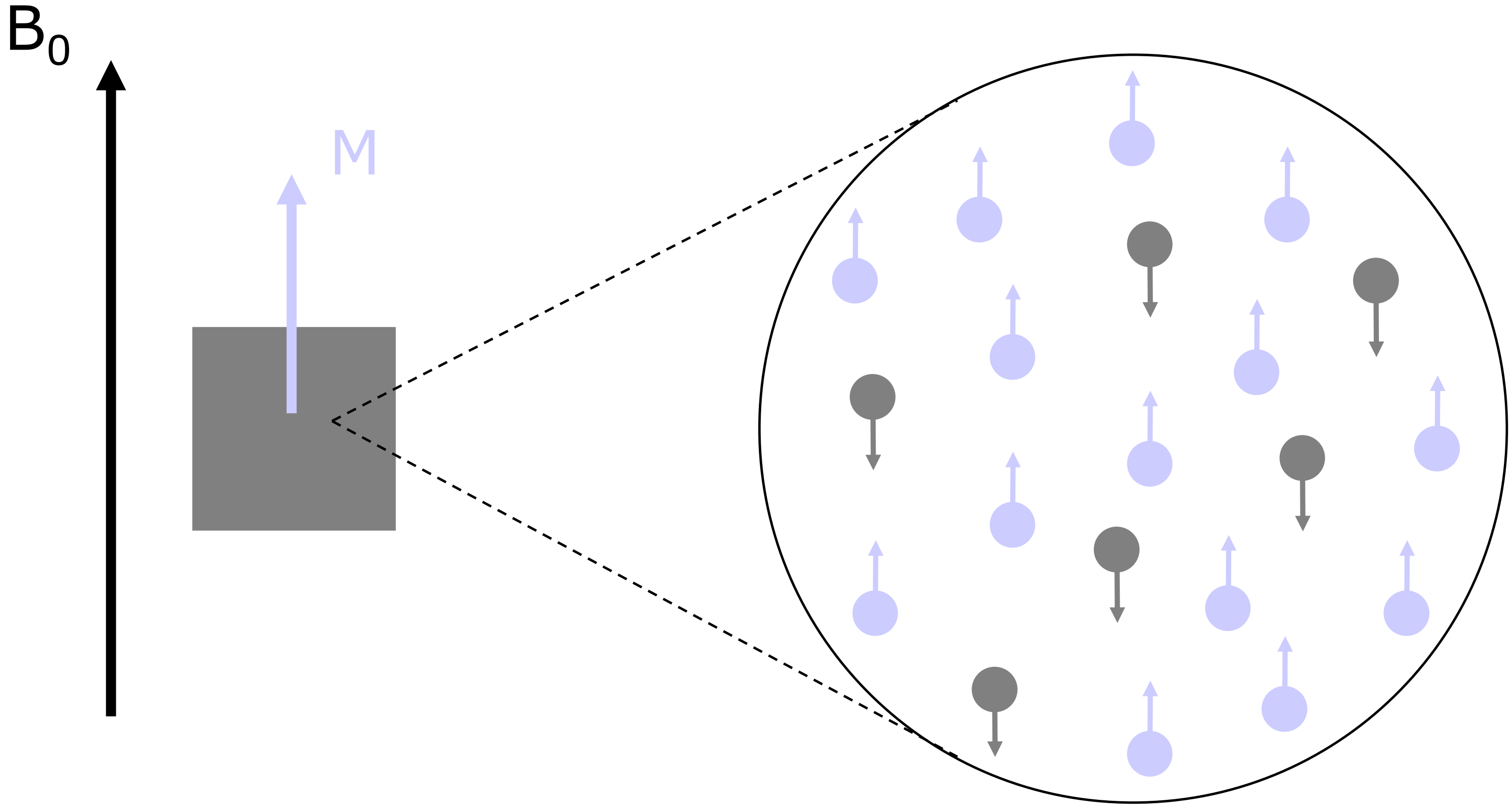


- Exchange of energy between two systems at a specific energy is called **resonance**.
- **Magnetic resonance** corresponds to the energetic interaction between **spins** and **electromagnetic radiofrequency** (RF).
- Only protons that spin with the **same frequency** as the electromagnetic **RF pulse**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

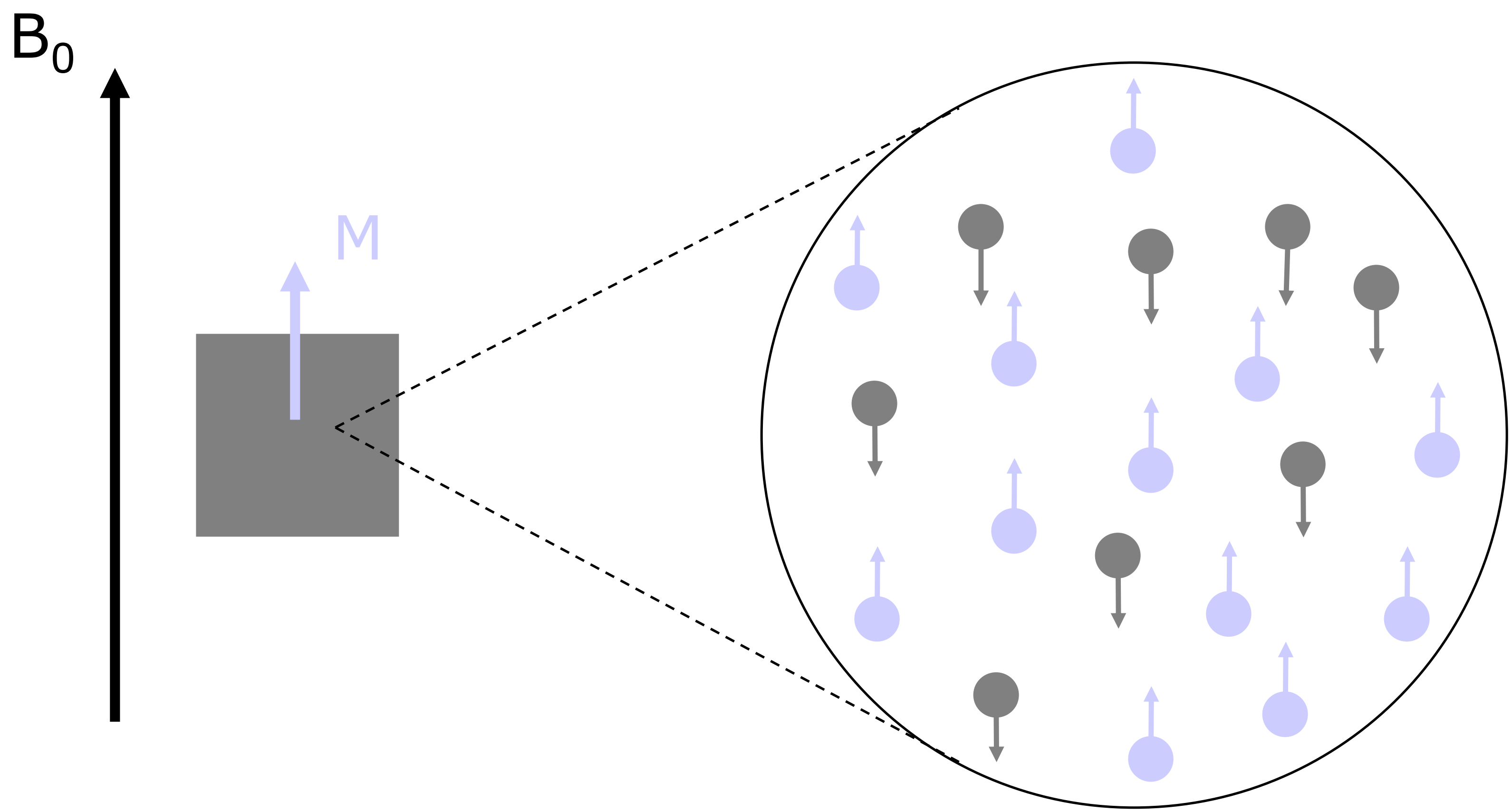
Macroscopic sample + RF pulse (Energy)



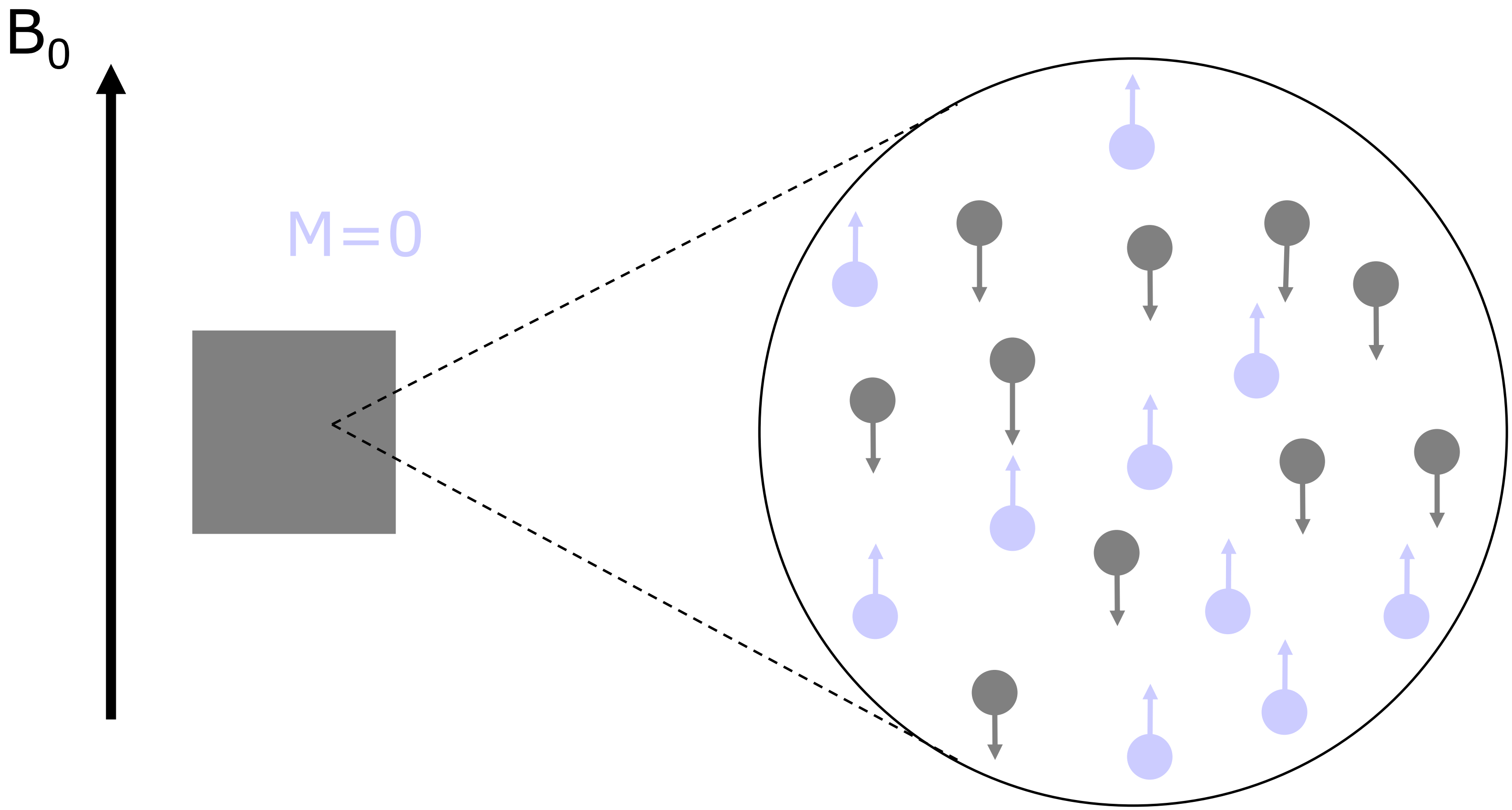
Macroscopic sample + RF pulse (Energy)



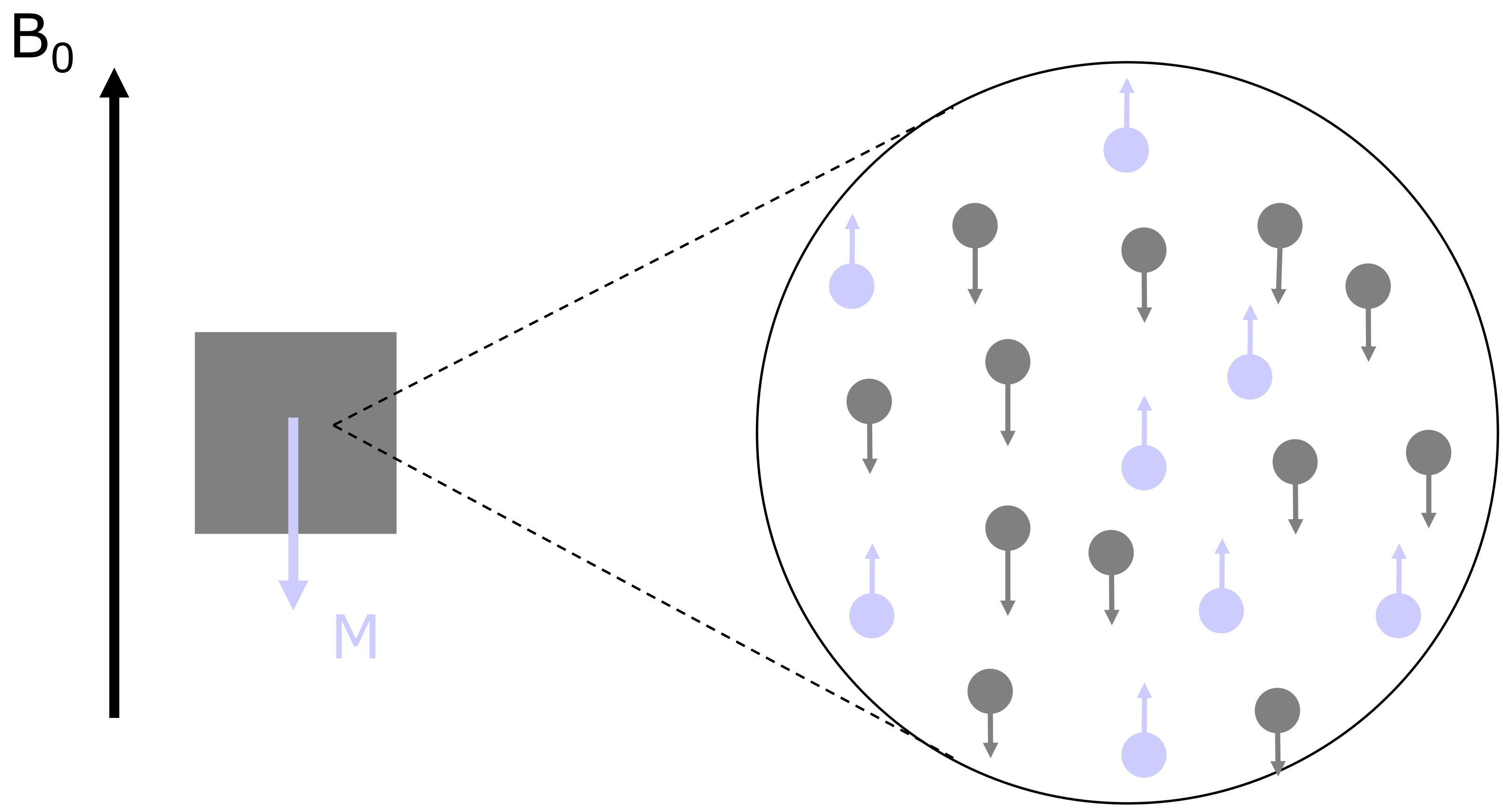
Macroscopic sample + RF pulse (Energy)



Macroscopic sample + RF pulse (Energy)

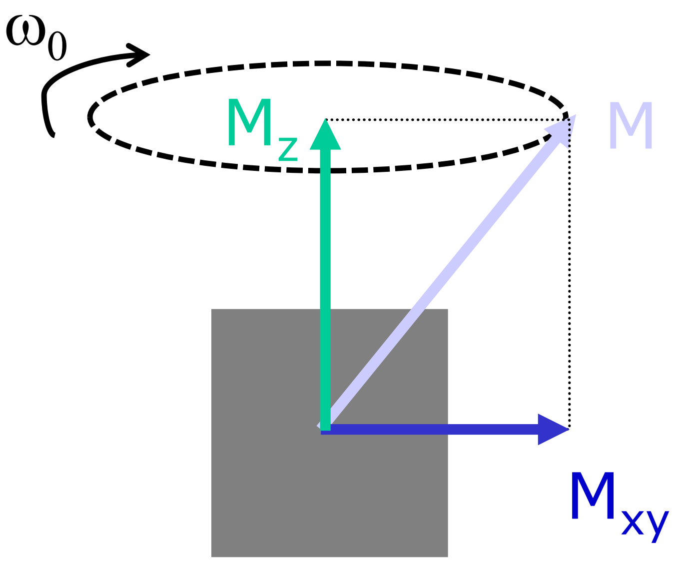


Macroscopic sample + RF pulse (Energy)

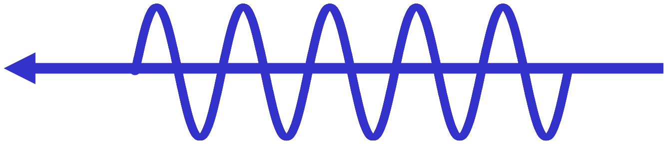


Excitation, Relaxation and Signal Formation

Excitation



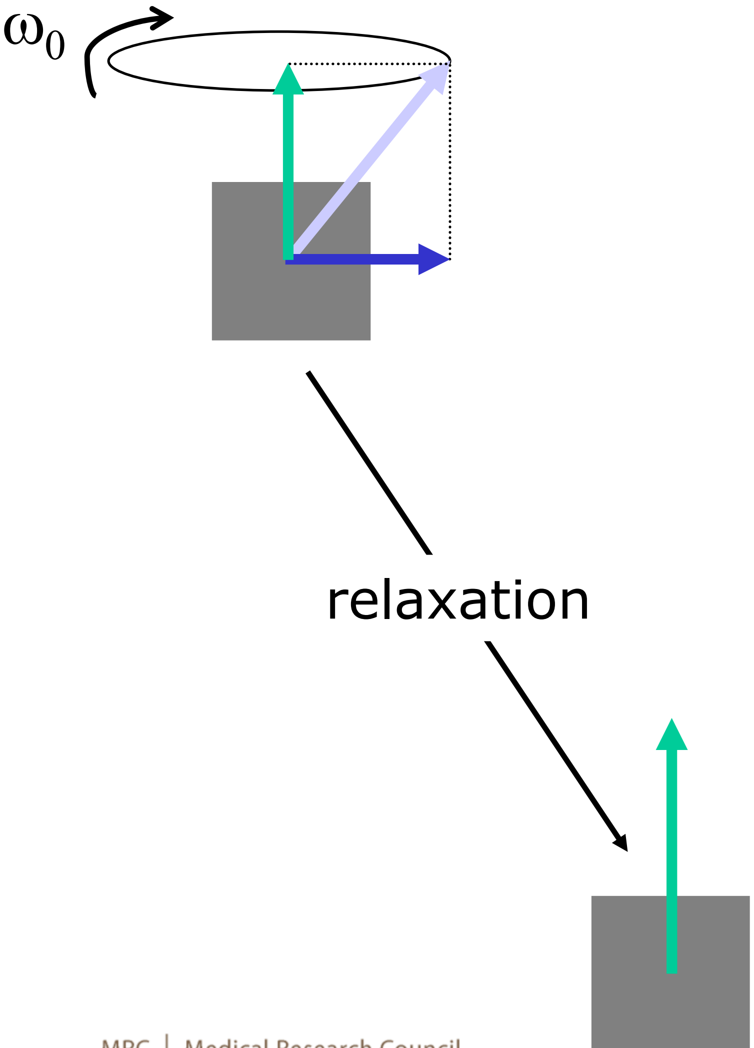
- During excitation, longitudinal magnetization decreases and a transverse magnetization appears.



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

- Longitudinal magnetization 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.

Relaxation



Two independent relaxation processes:

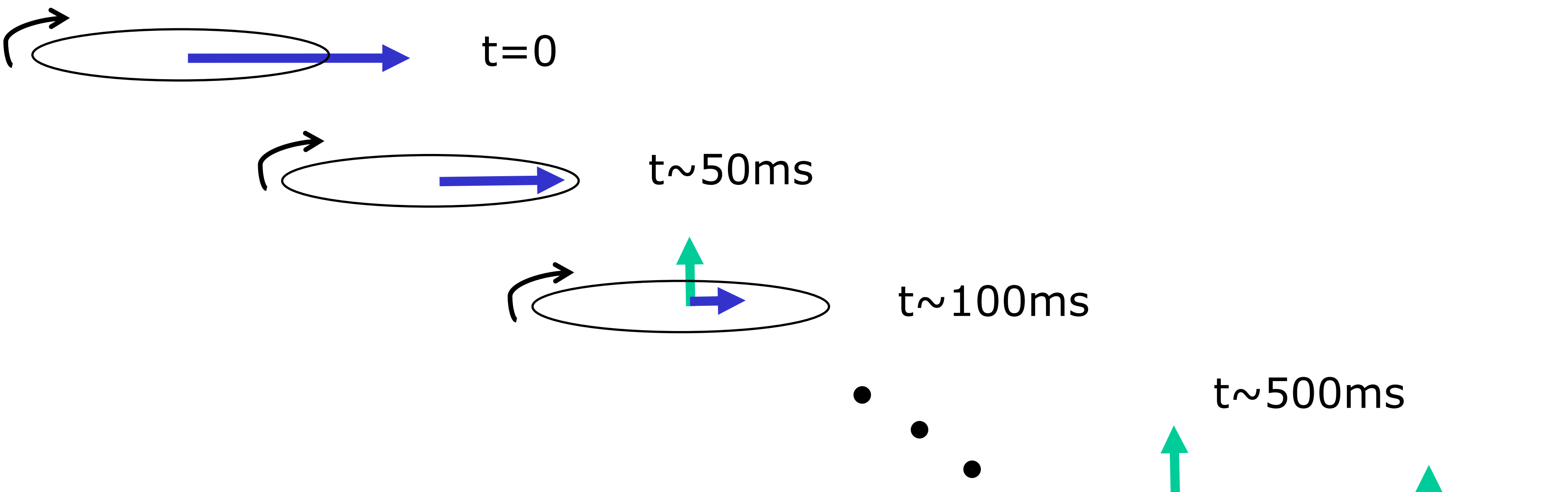
1. $M_l \xrightarrow{T_1} M_0$

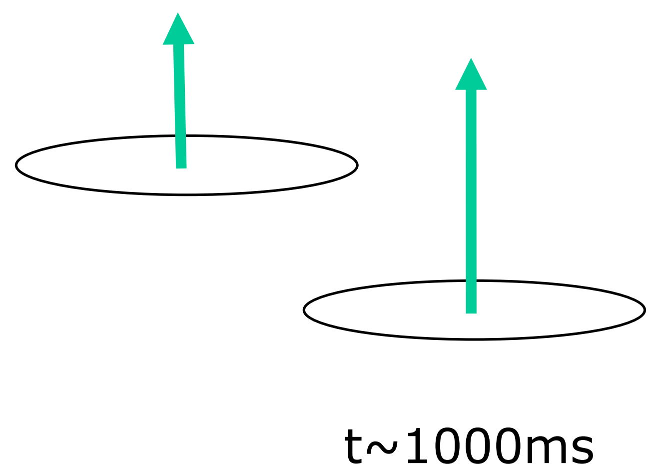
2. $M_t \xrightarrow{T_2} 0$

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

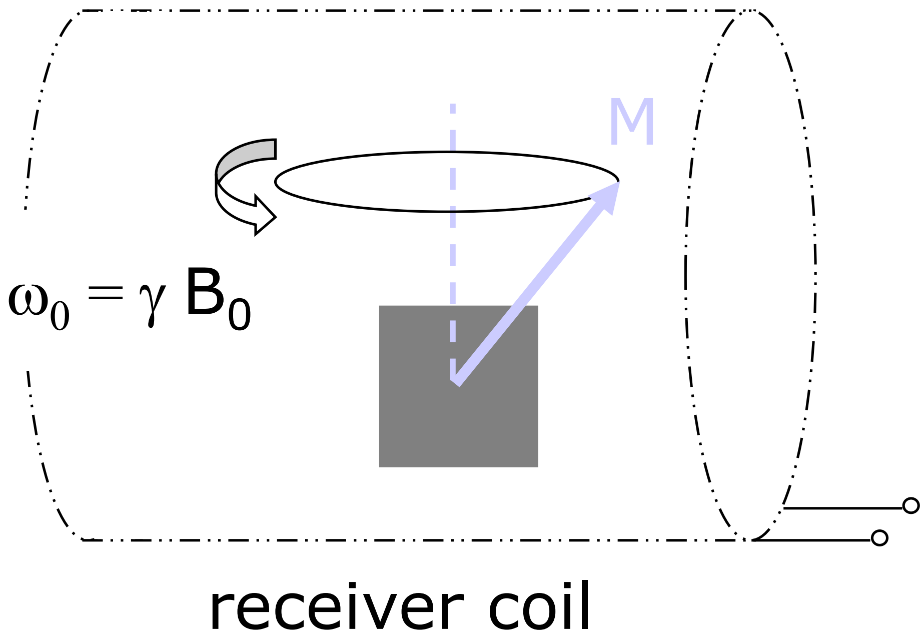
Relaxation





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

Precession and signal induction



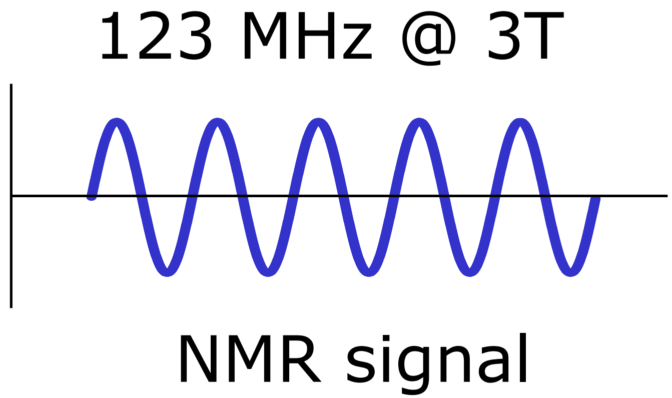
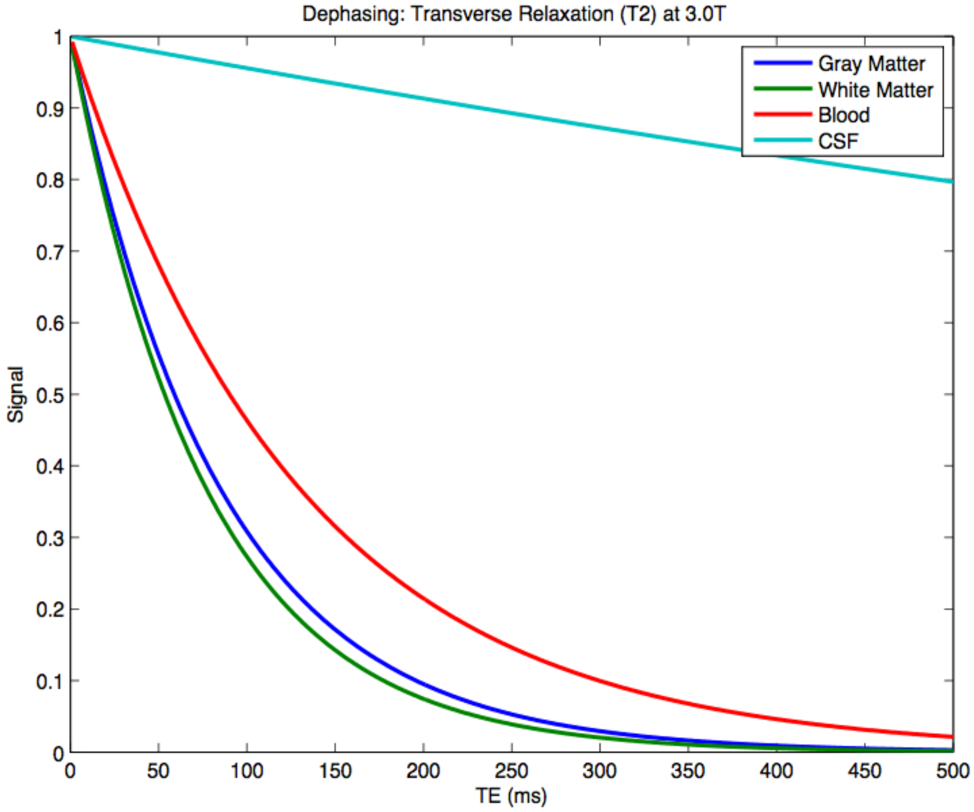
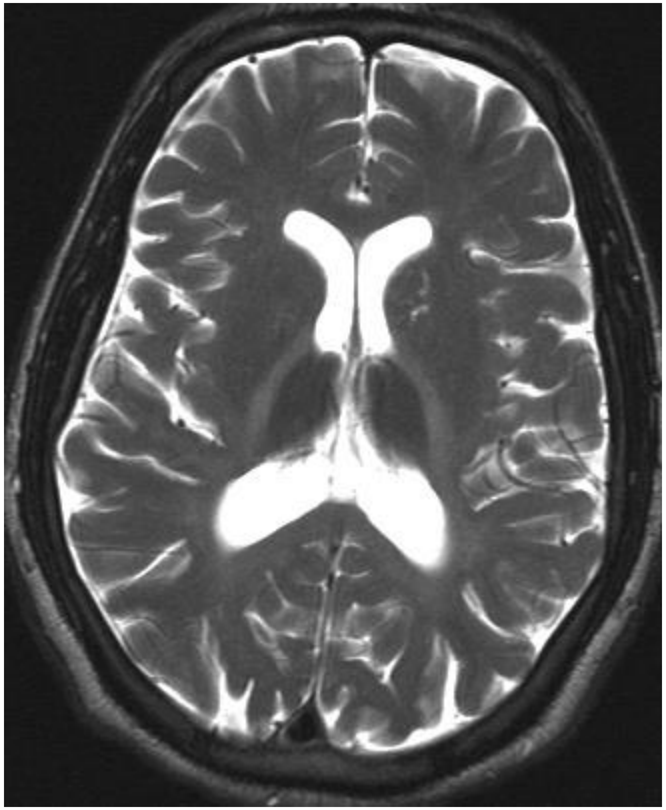


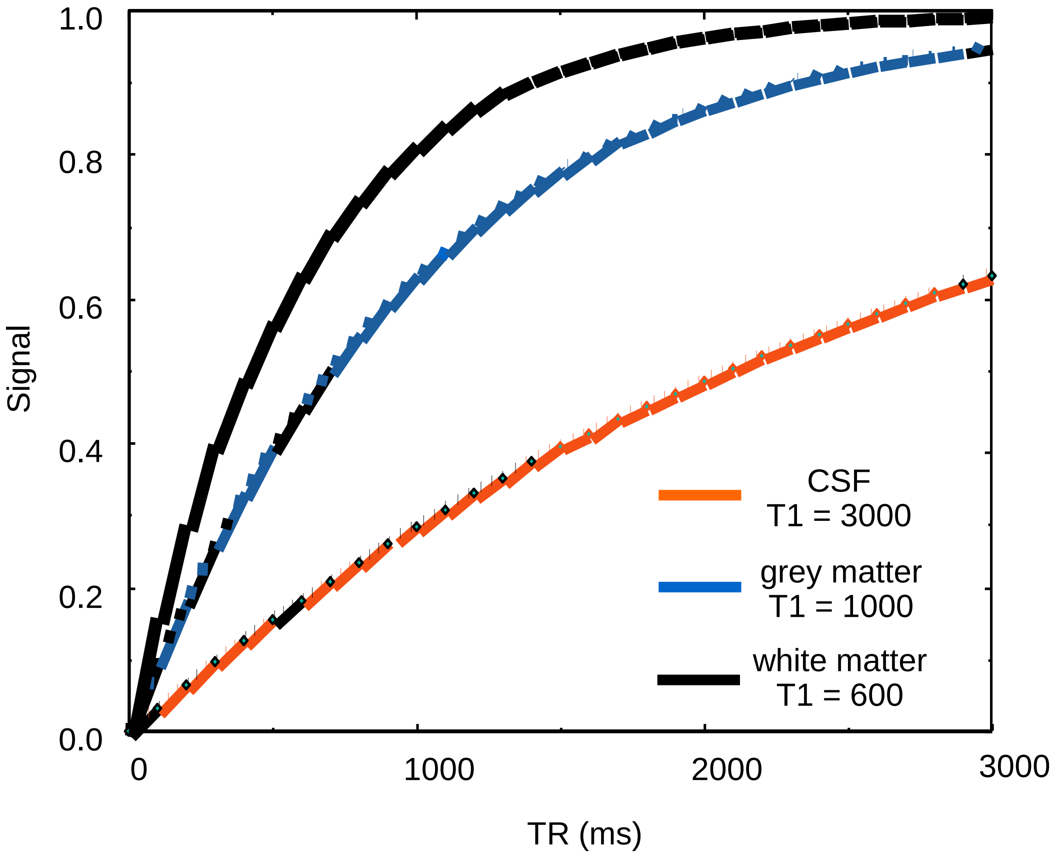
Image Contrast

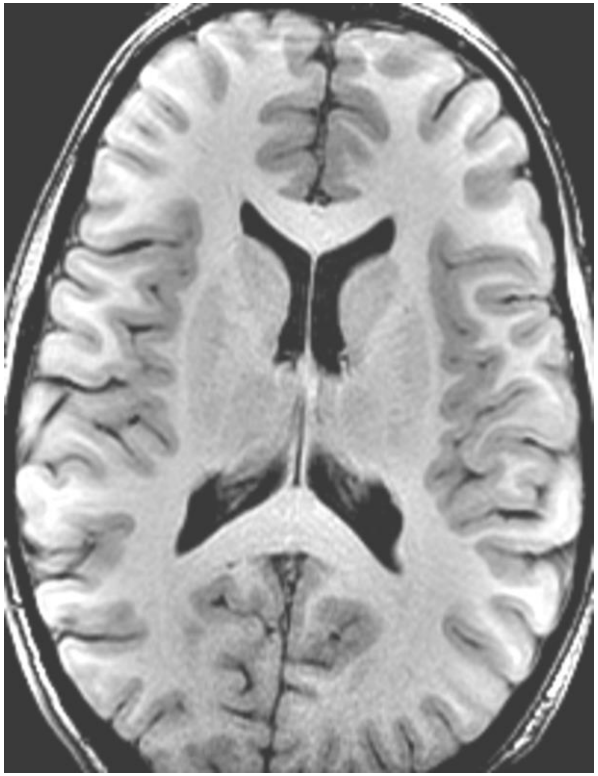
T2-weighted contrast



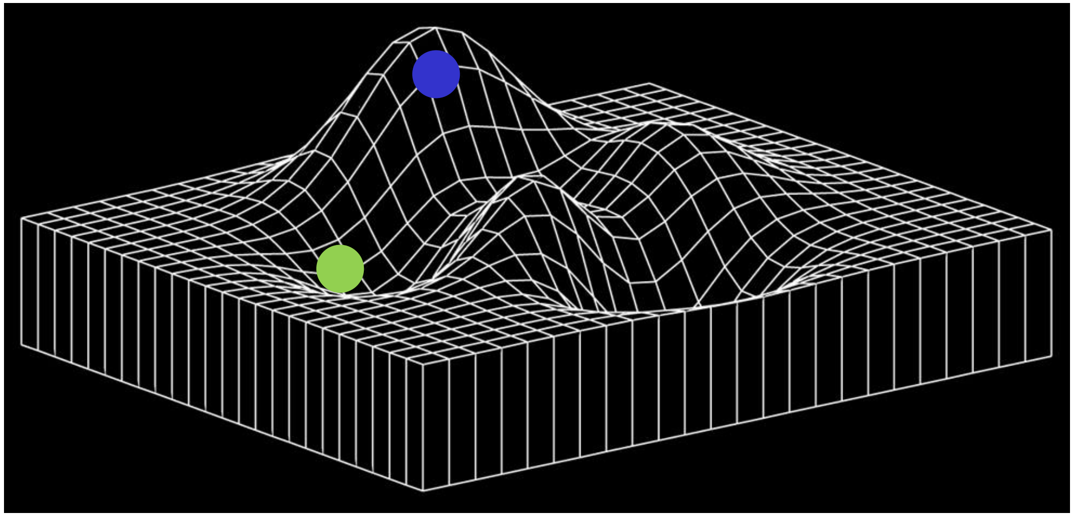


T1-weighted contrast



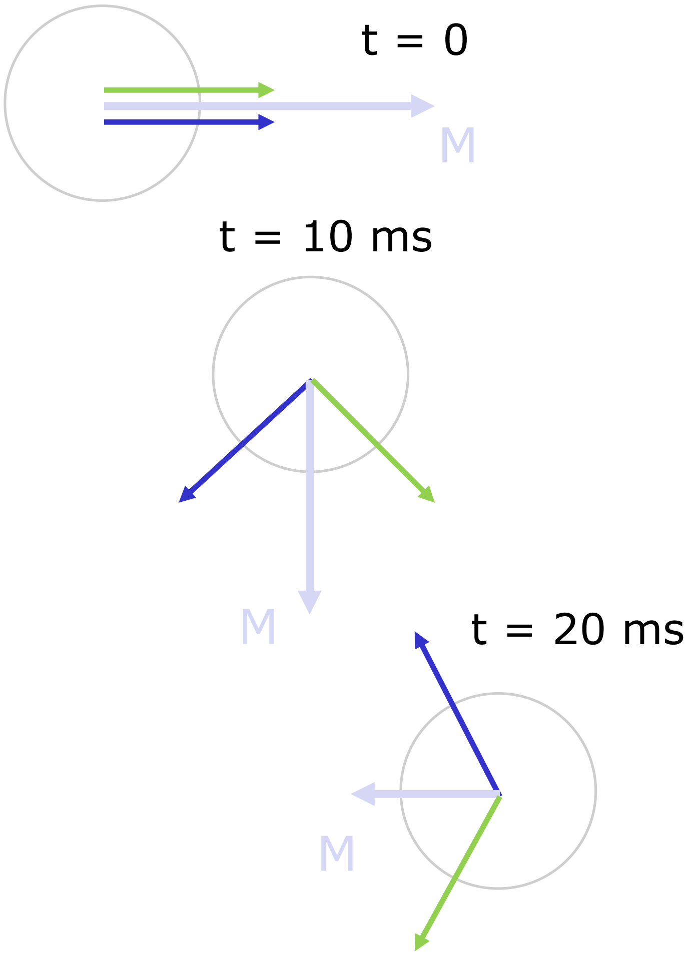


Signal loss due to B_0 inhomogeneity

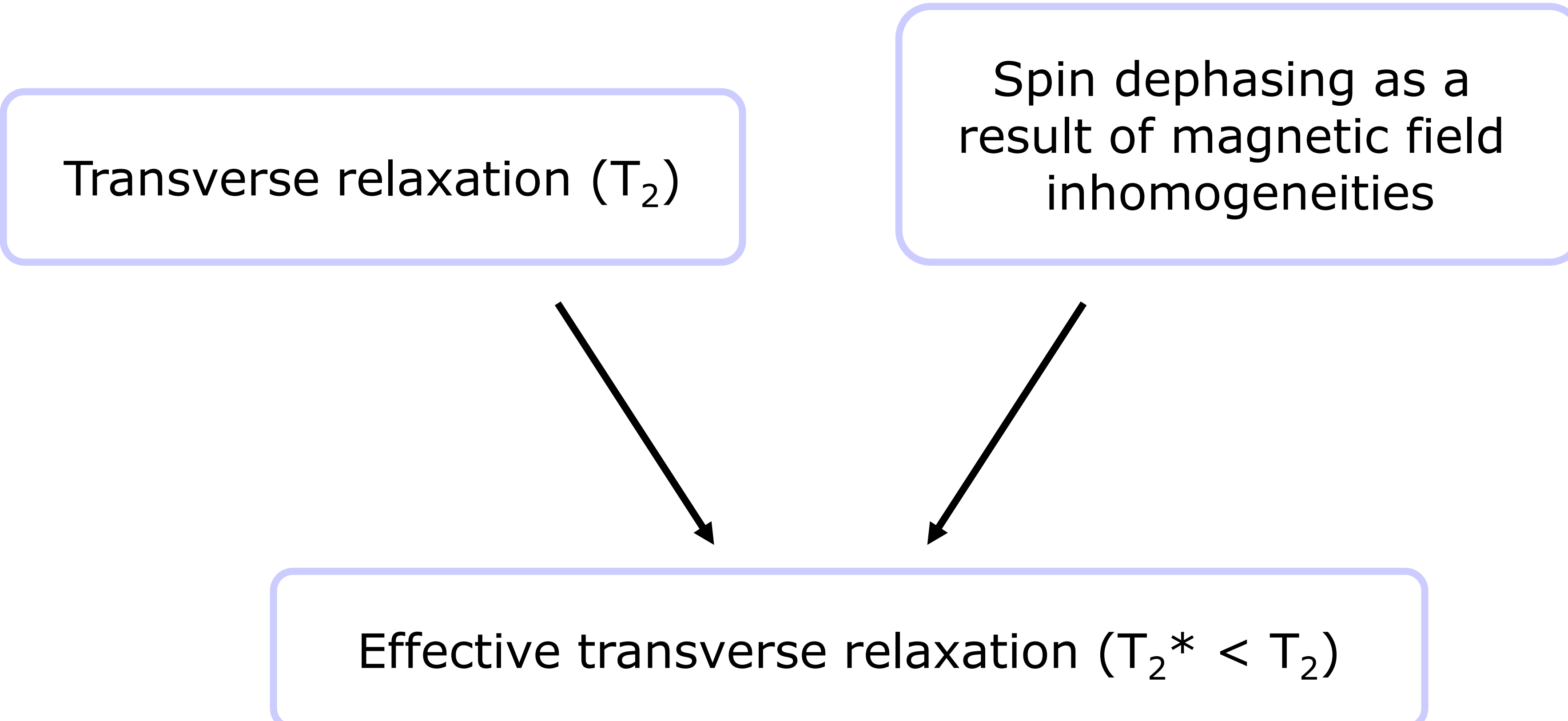


$$\omega_0 = \gamma B_0$$

● has higher frequency than ●



Effective transverse relaxation (T_2*)

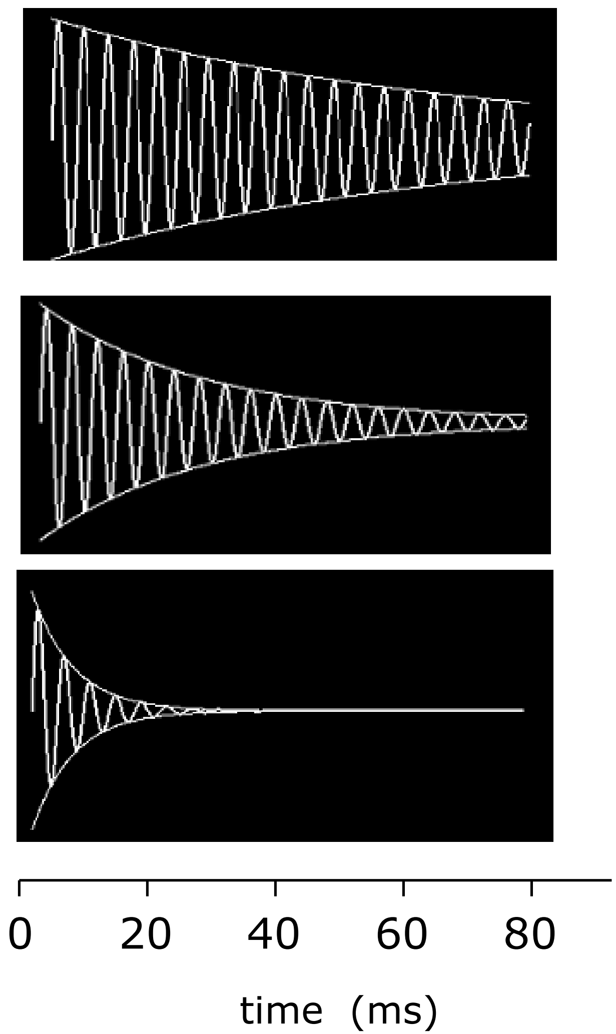


Effective transverse relaxation (T_2*)

No inhomogeneities
(T_2*= T_2 = 100 ms)

Moderate inhomogeneities
(T_2* = 40 ms)

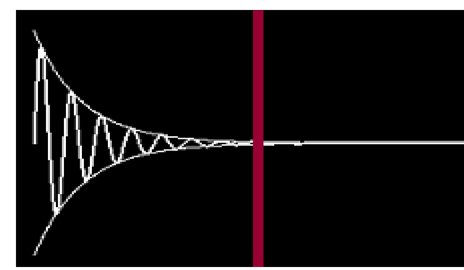
Strong inhomogeneities
(T_2* = 10 ms)



T_2^* related signal dropouts

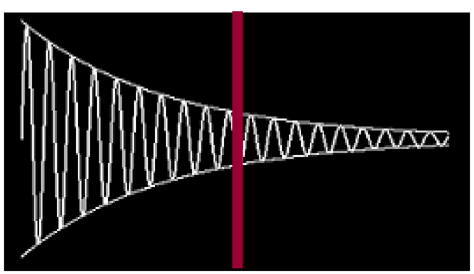
T_2^* reduction due to local field inhomogeneities
$\Rightarrow$ signal dropouts

reduced T_2^*

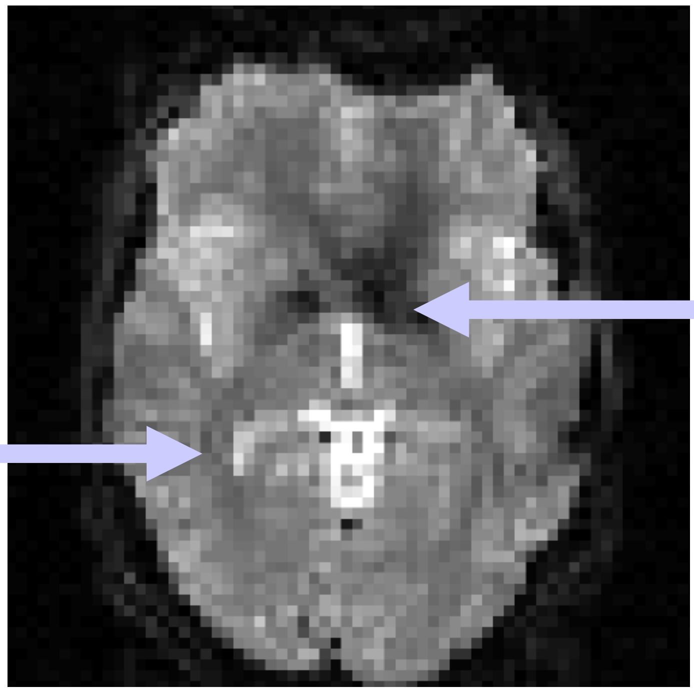


TE

normal T_2^*
(about 40 ms)



TE



EPI image

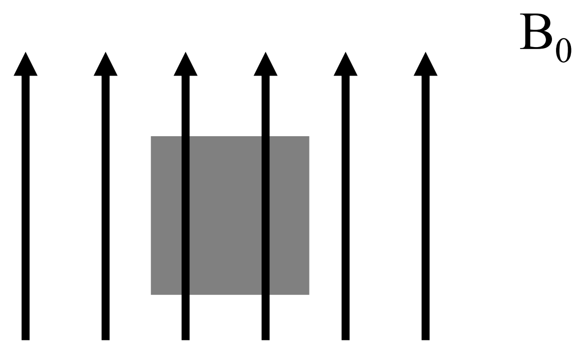
Part II
Advanced Concepts

Spatial Encoding in MRI

The principles of MRI

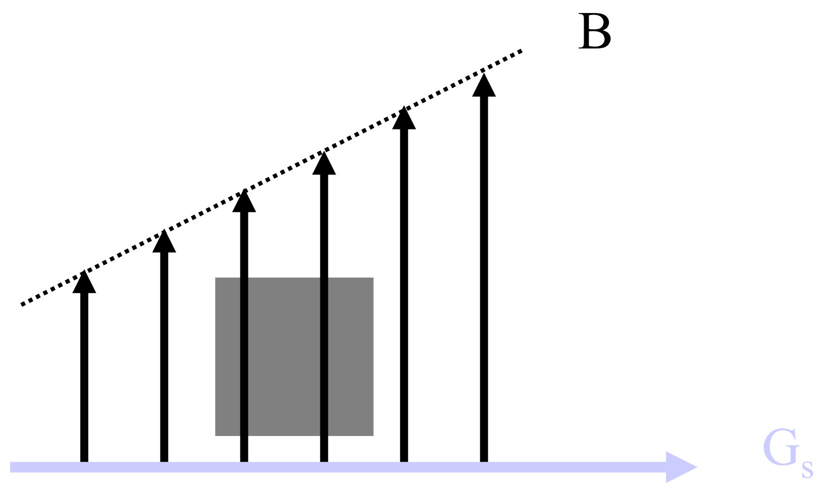
Homogeneous magnetic field

$$\omega_0 = \gamma B_0$$

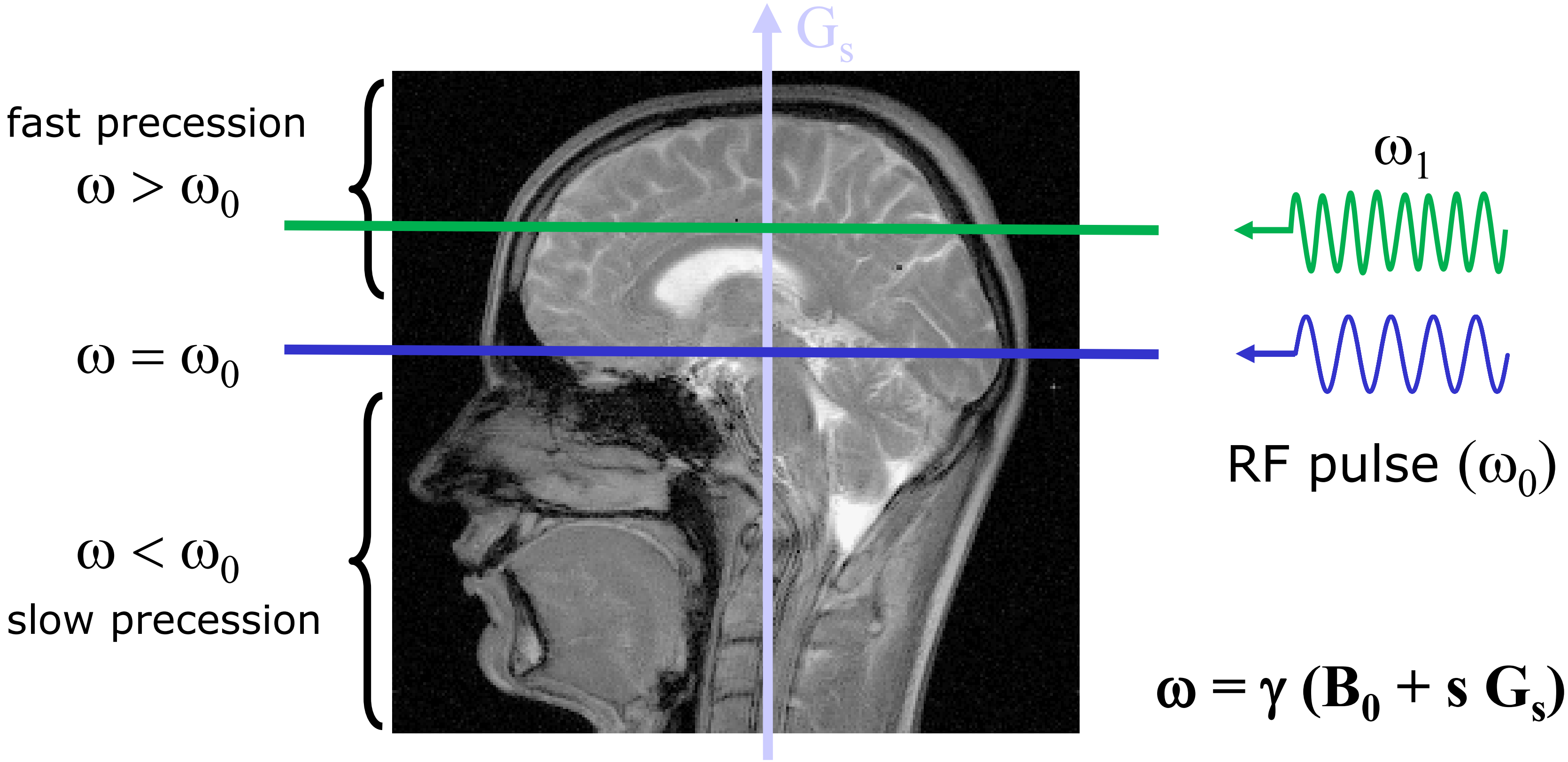


Add magnetic field gradient

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



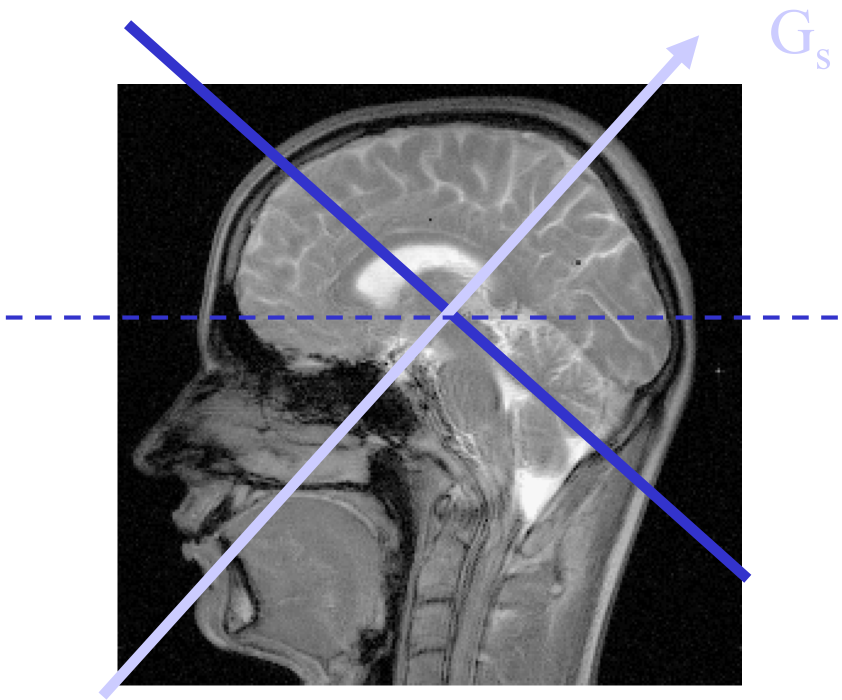
Slice selective excitation



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

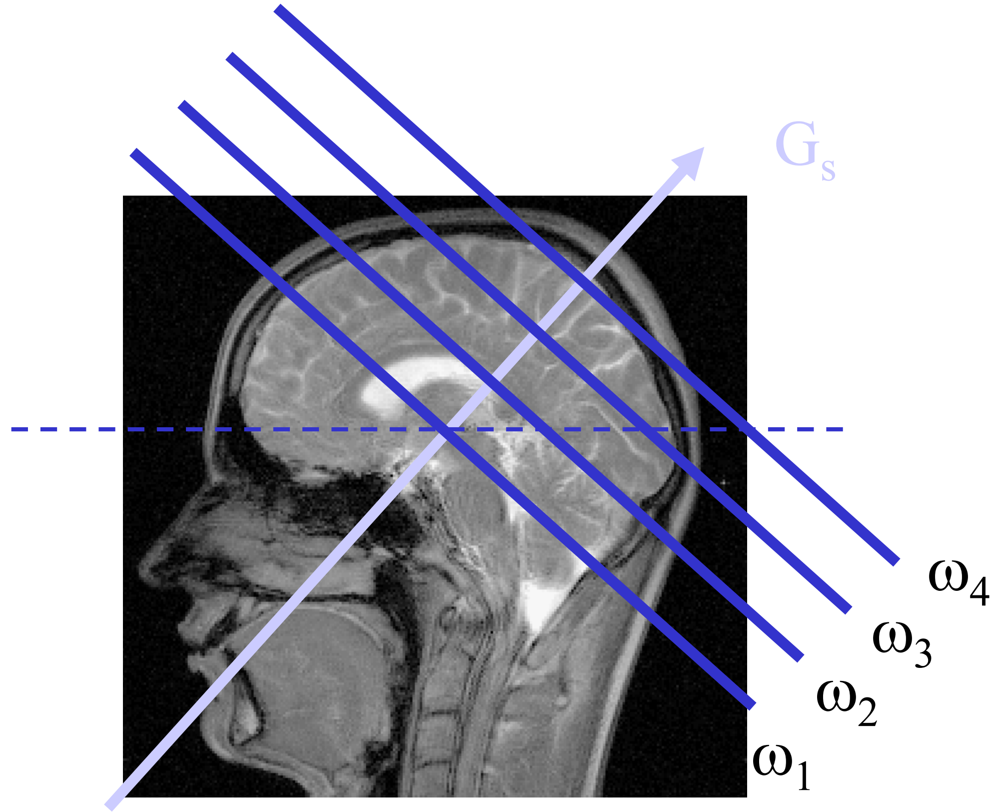
- Only spins in slice of interest have frequency ω_0
- RF pulse with frequency ω_0 excites only spins in slice of interest

Slice orientation



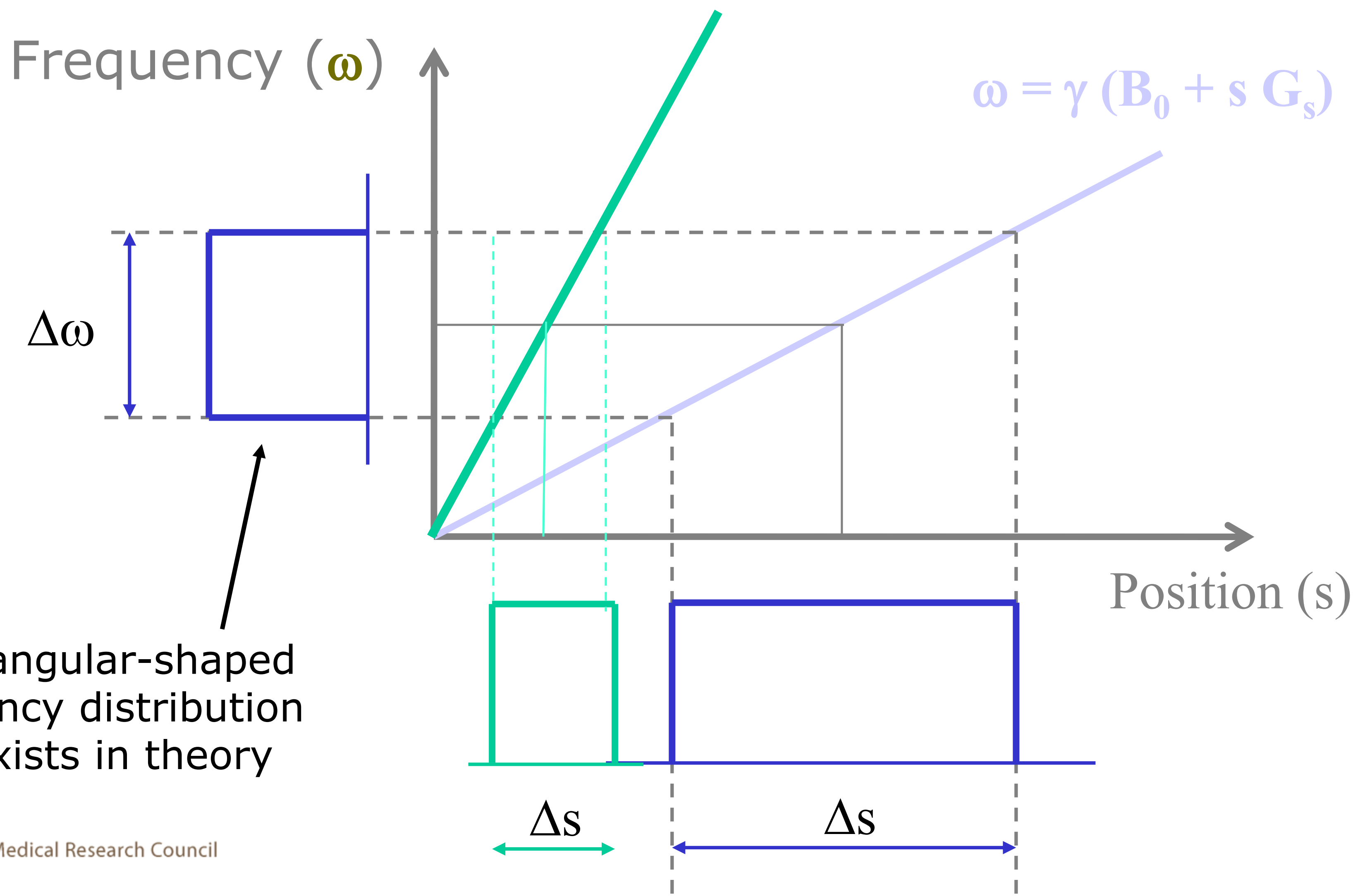
$$\omega = \gamma\,(B_0 + s\,G_s)$$

Multi-slice MRI



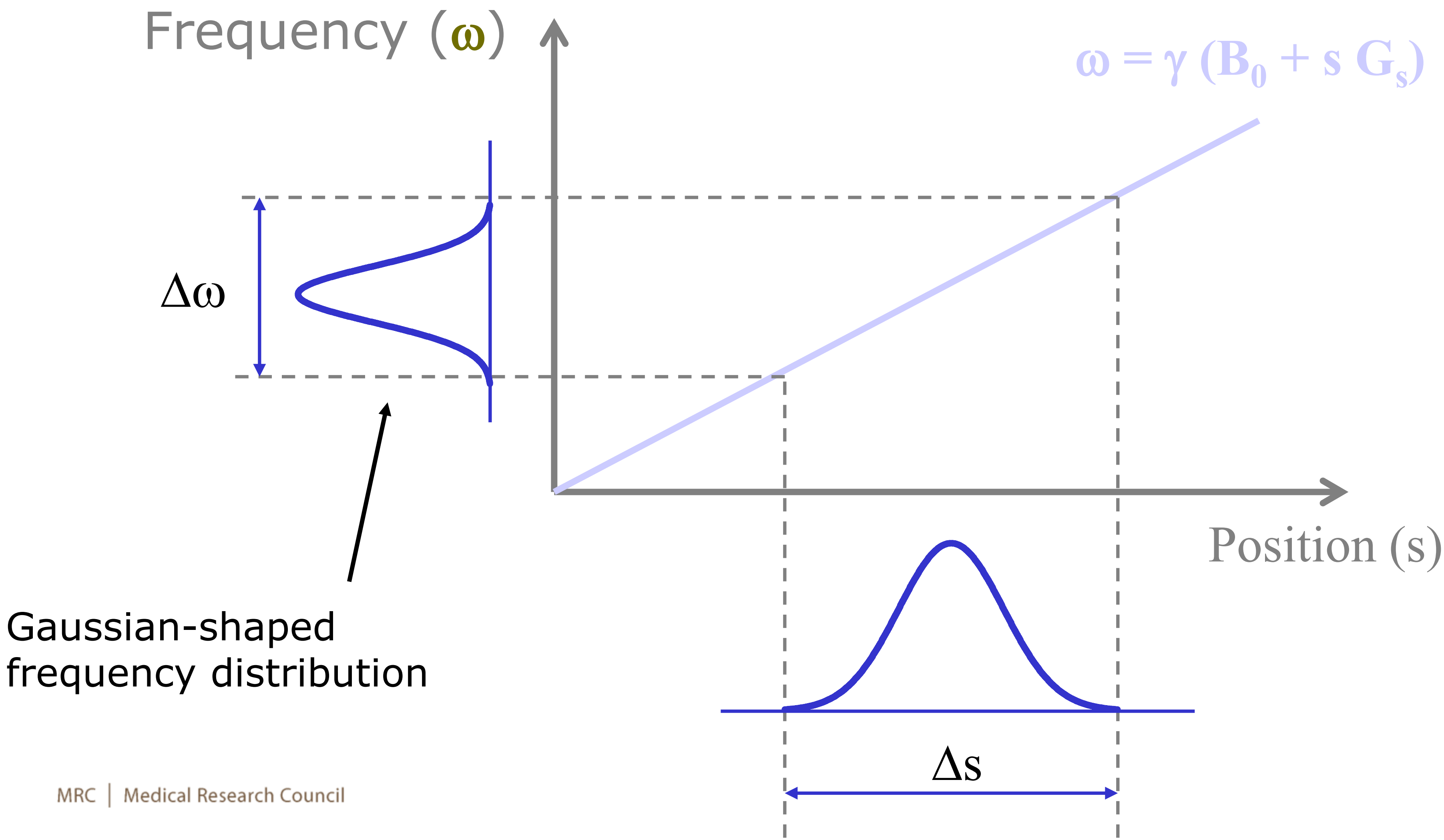
$$\boldsymbol{\omega = \gamma\,(B_0 + s\,G_s)}$$

Slice profile

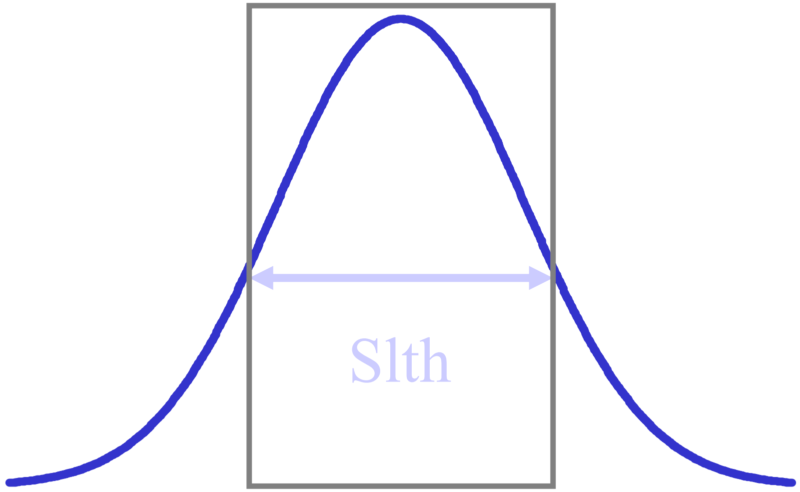


A rectangular-shaped frequency distribution only exists in theory

Slice profile

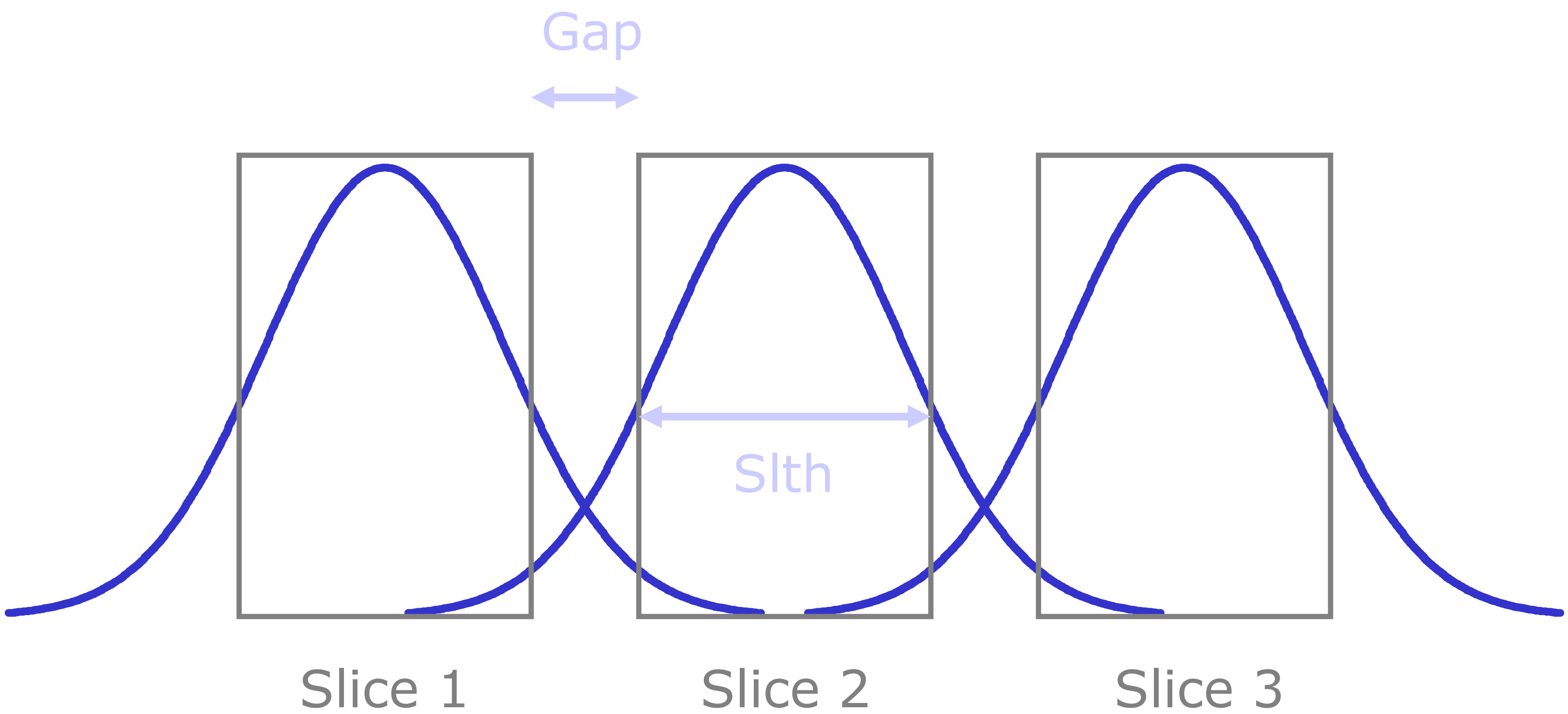


Slice thickness



Slth= Full width at half maximum of the slice profile

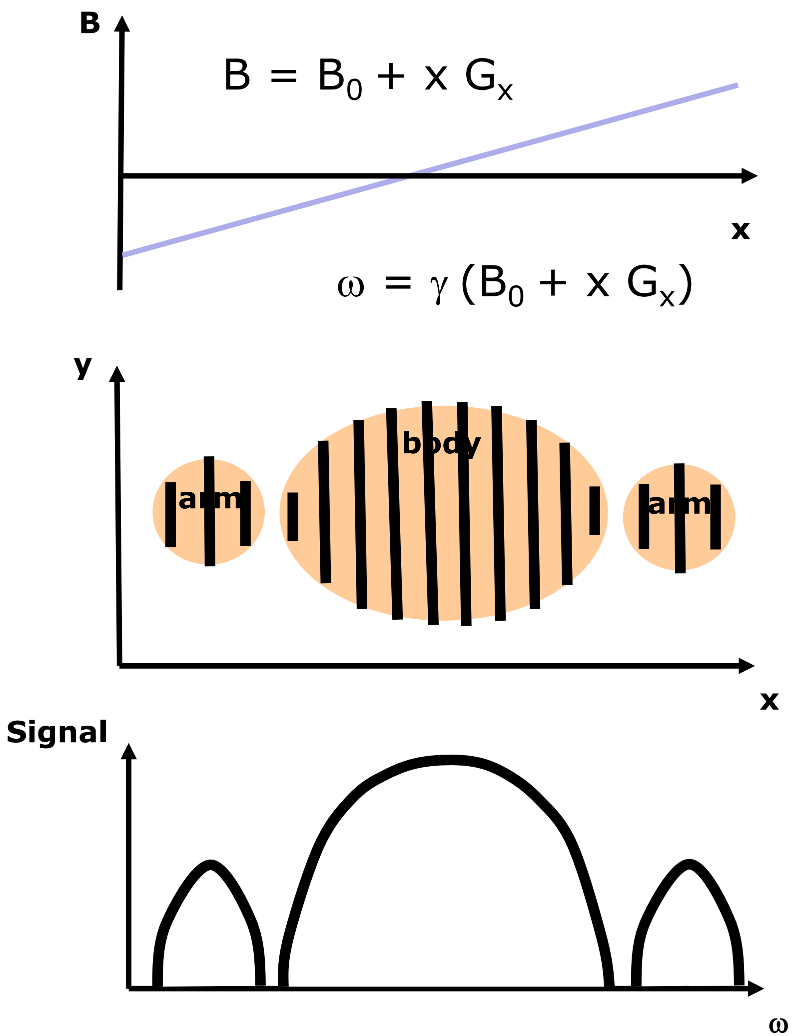
Multi-slice MRI



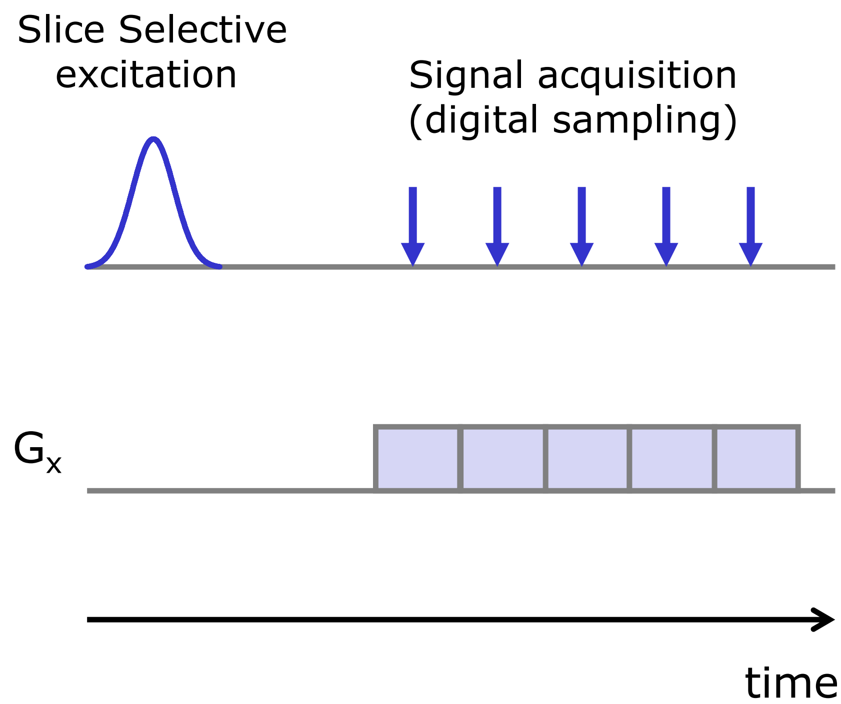
Tissue in the inter-slice gap contributes to the signal of the adjacent slices

Frequency and phase encoding

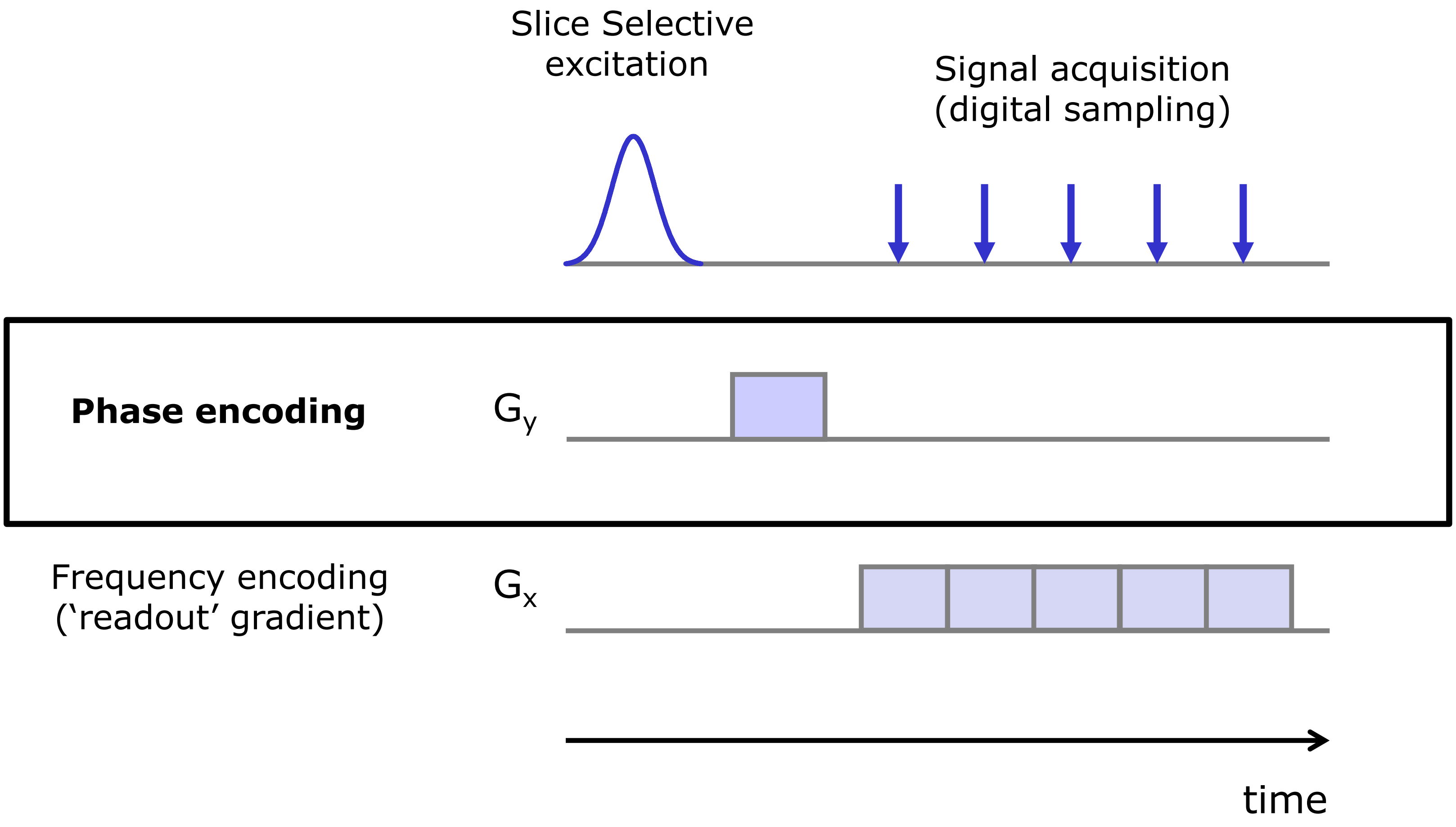
Frequency encoding



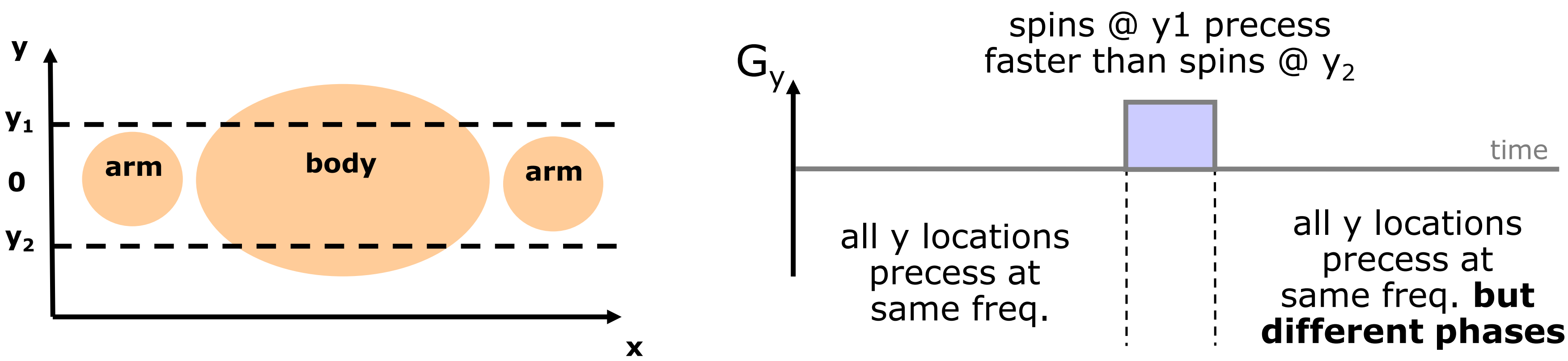
Pulse sequence (so far)

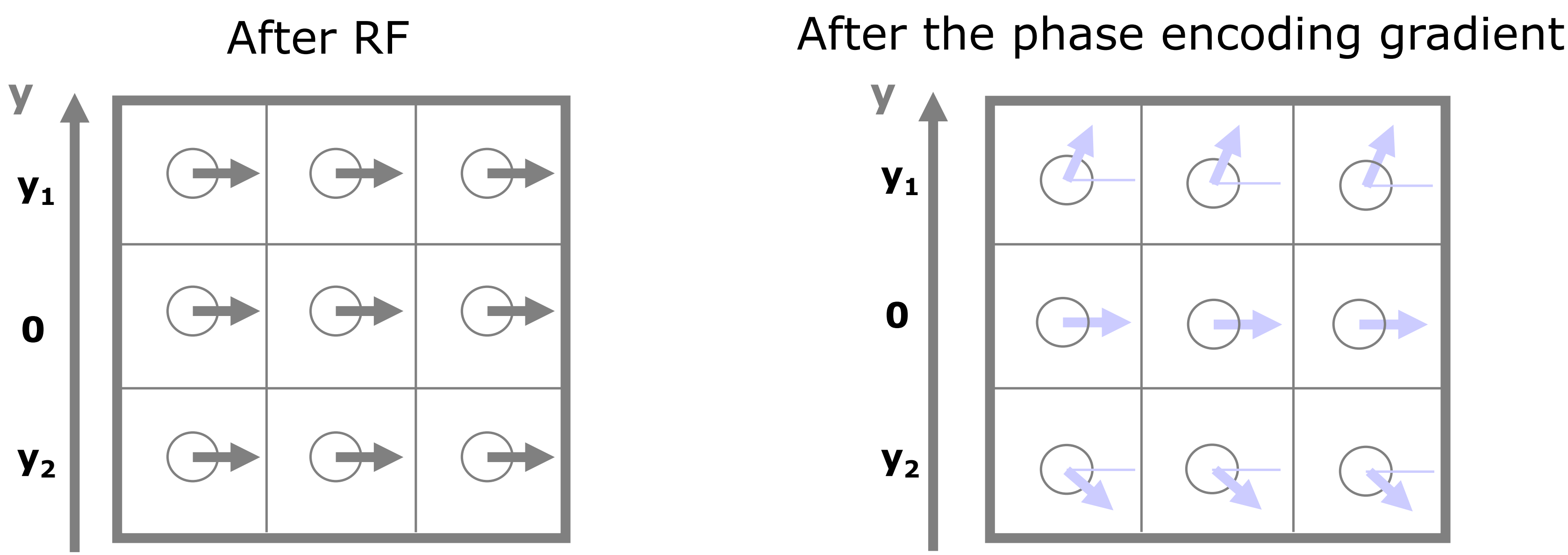


Phase encoding



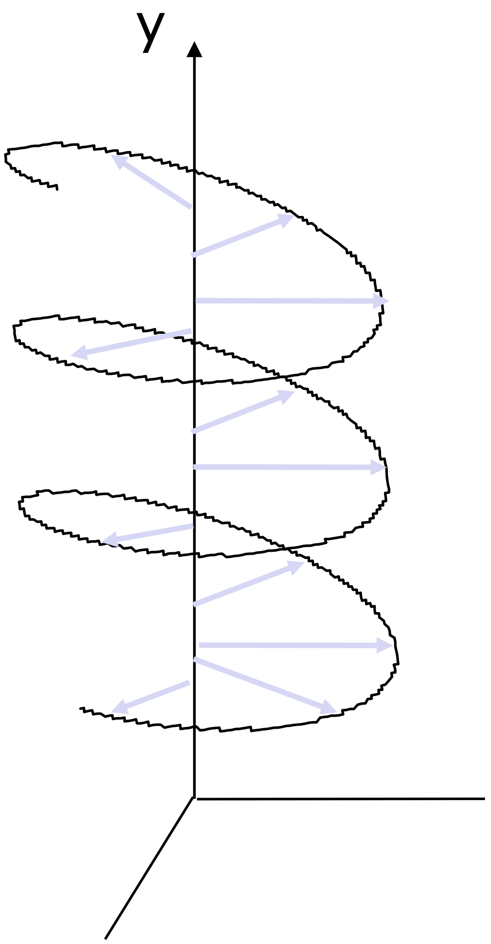
How does phase encoding translate into spatial information?





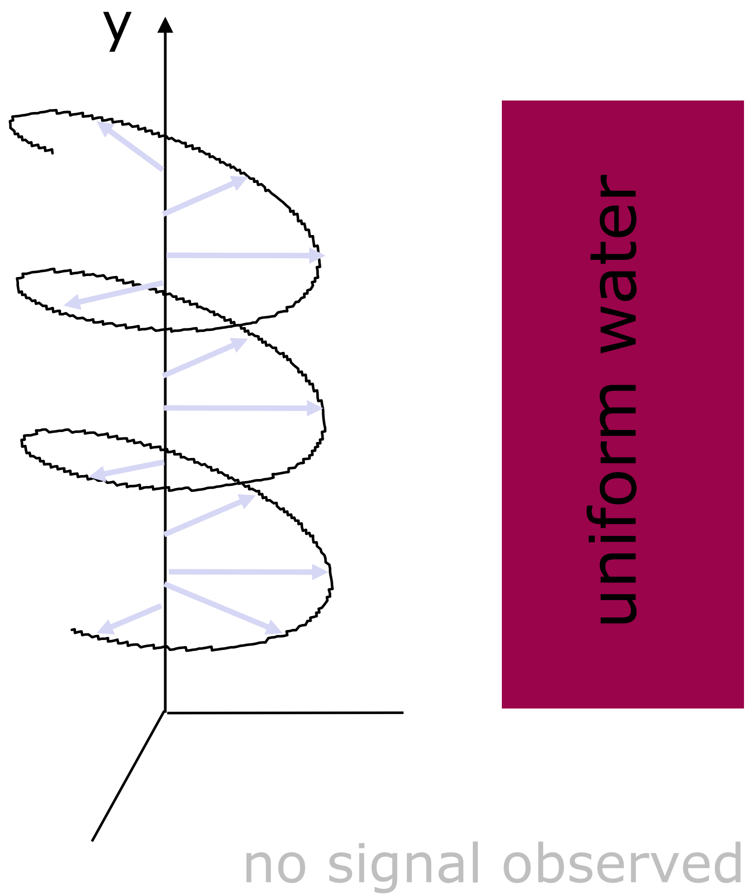
How does phase encoding translate into spatial information?

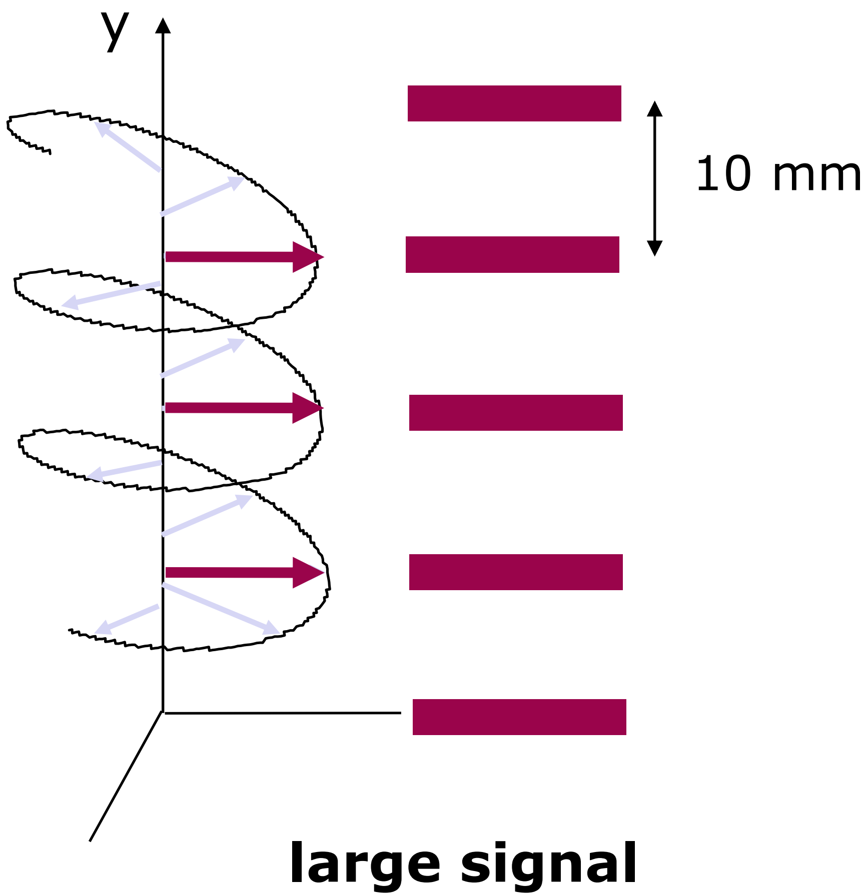
- The magnetization in the xy plane is wound into a helix directed along y axis.
- Phases are 'locked in' once the phase encode gradient is switched off.



From L. Wald

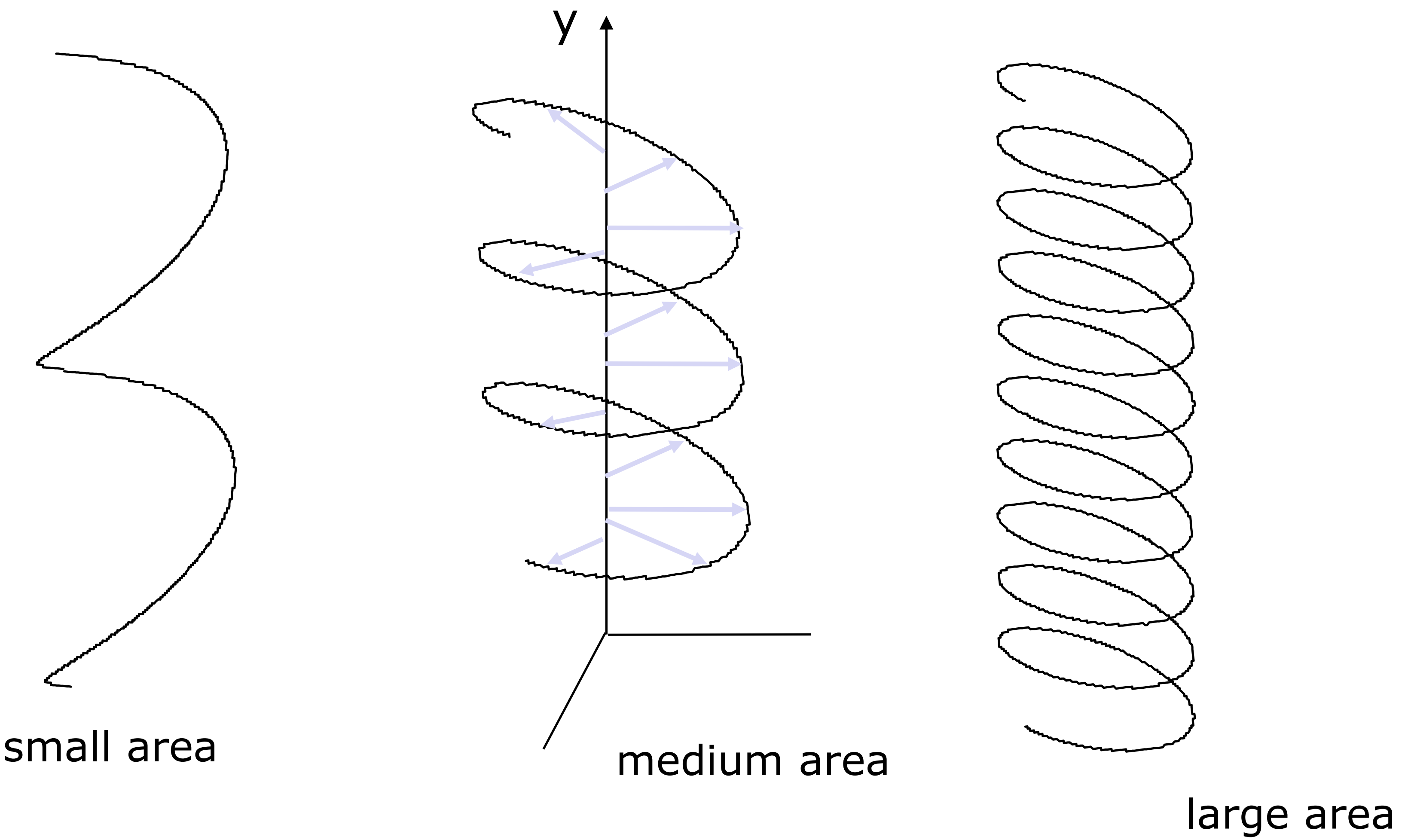
Signal after phase encoding





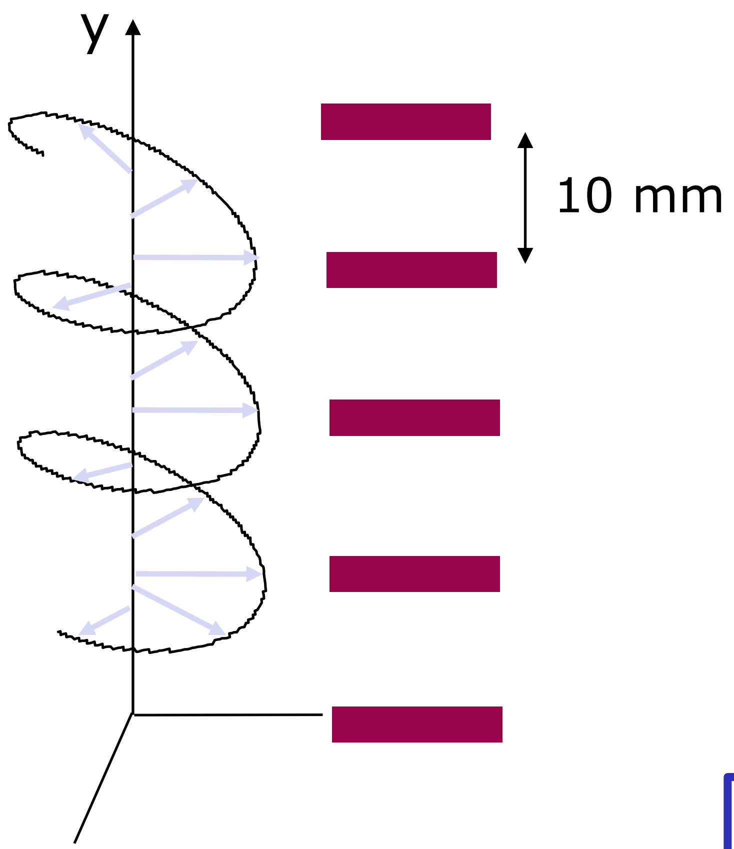
From L. Wald

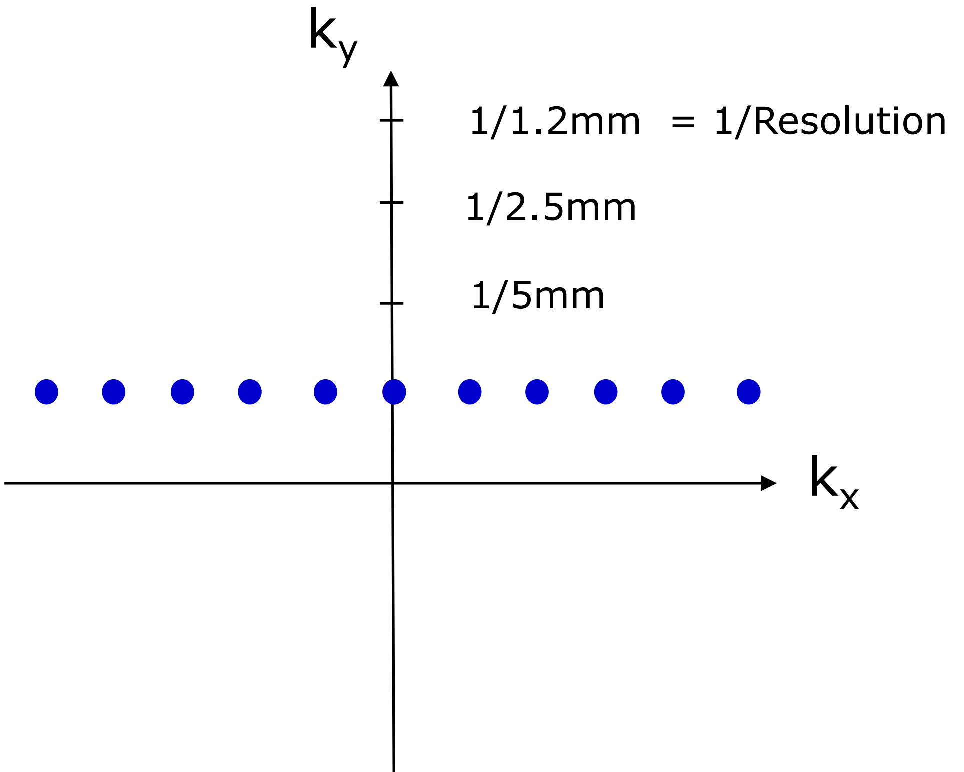
Gradient area and helix shape



From L. Wald

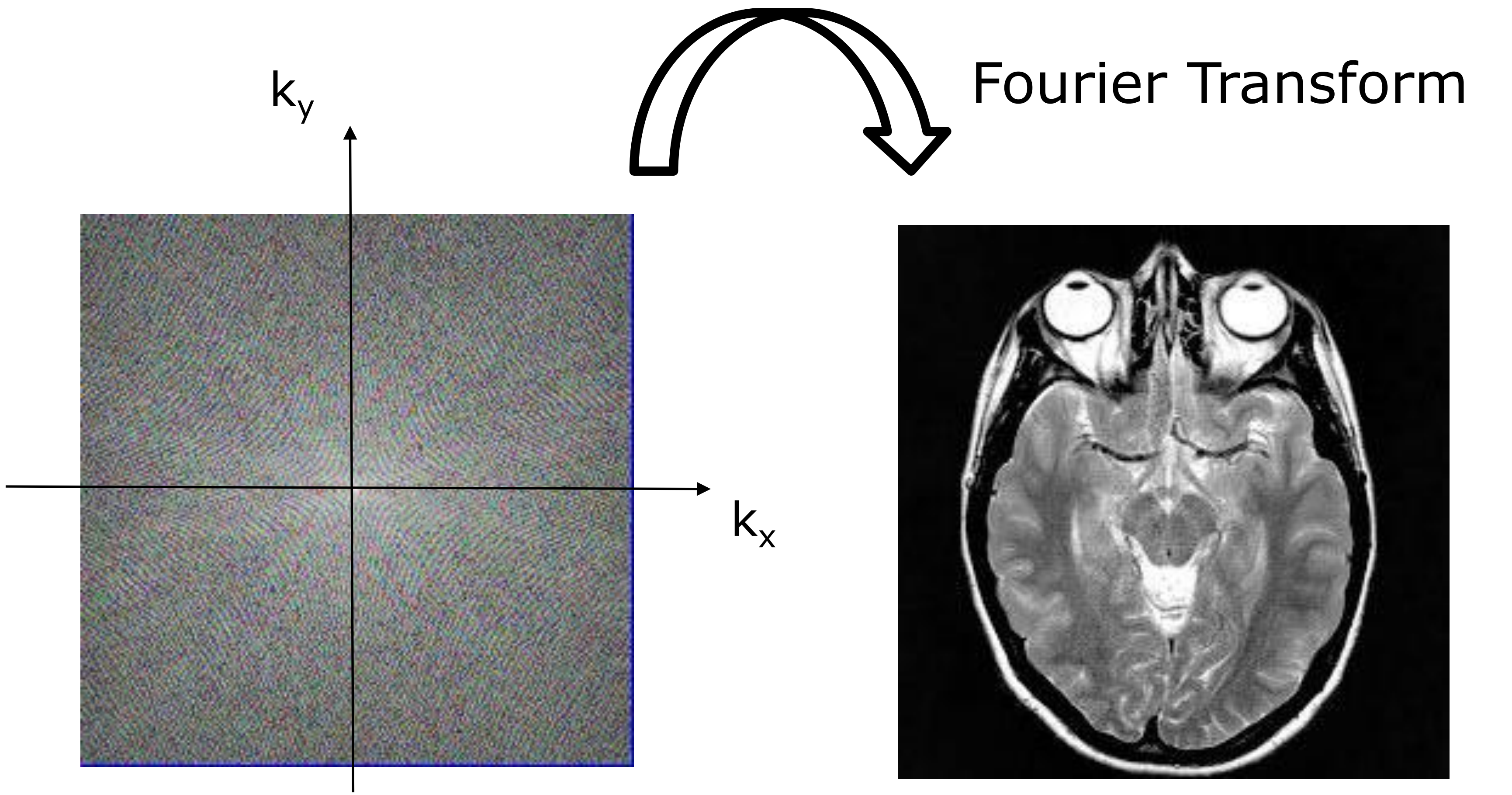
Signal intensity measured at a spatial frequency





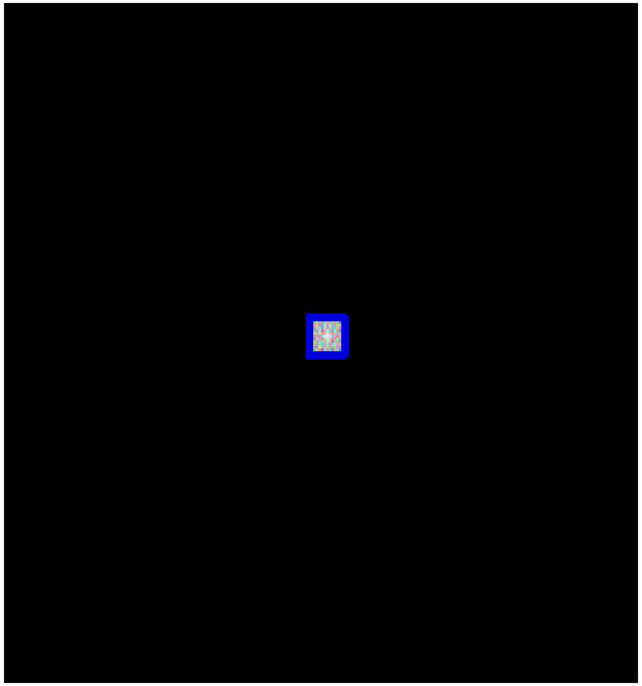
Add frequency encoding

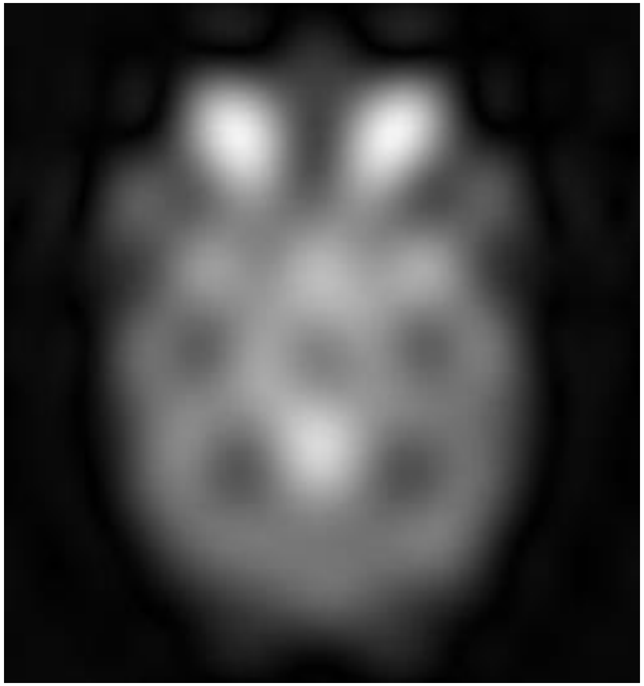
Image reconstruction and k-space



Spatial frequency and contrast

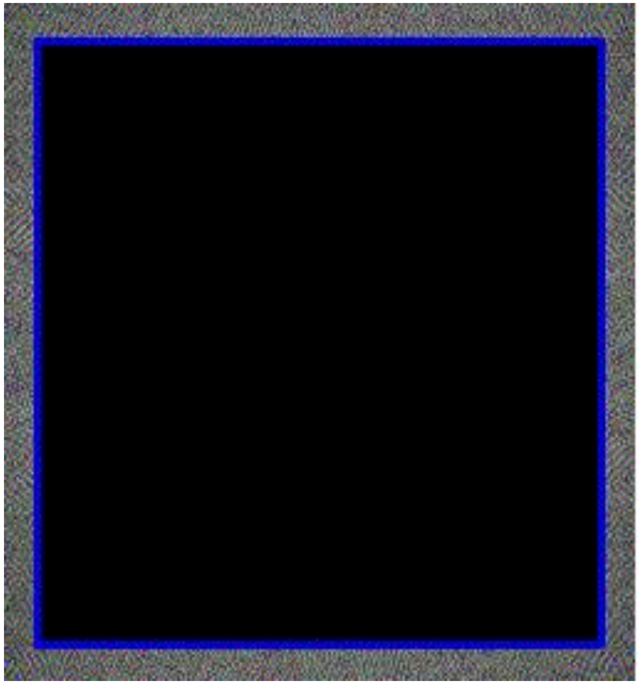
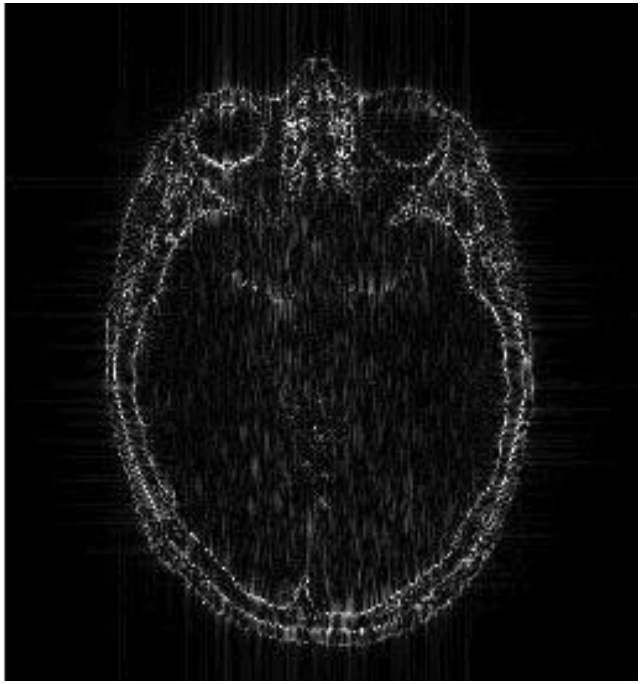
Centre of k-space: low spatial frequency data have the highest amplitude, giving the greatest changes in grey levels (contrast).



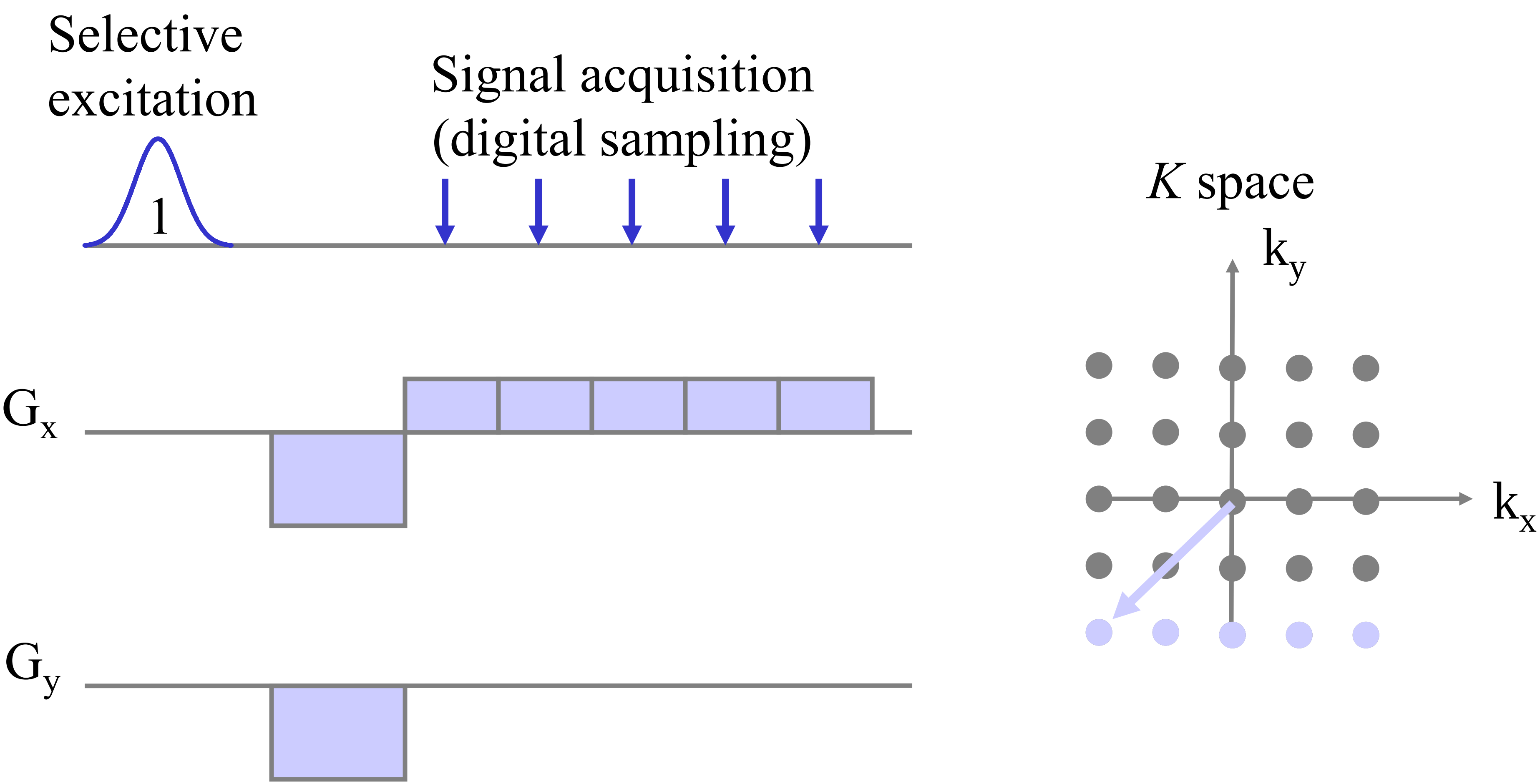


Spatial frequency and contrast

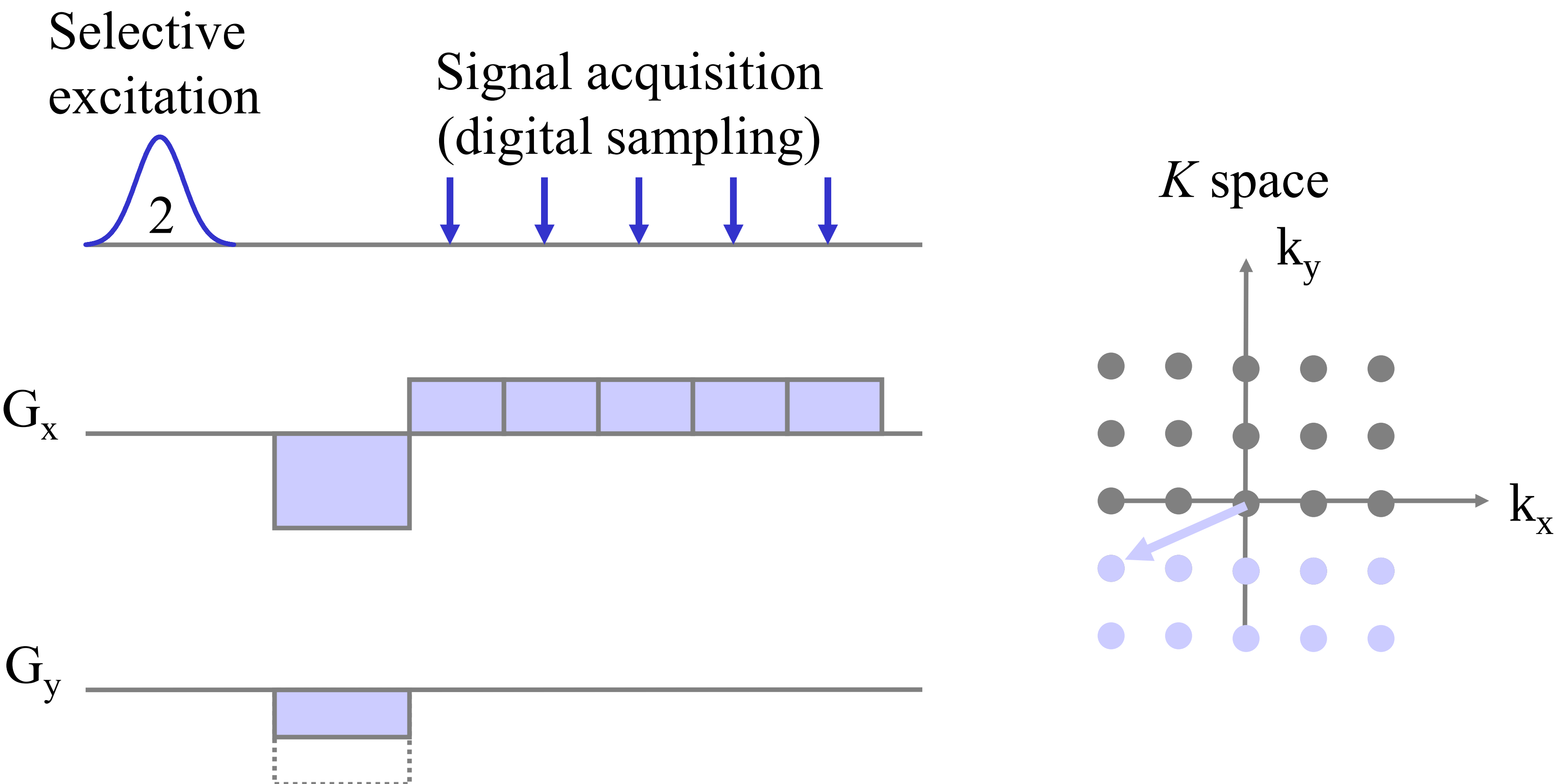
Periphery of k-space: high spatial frequency data sharpens the image as they encode the edges (rapid changes of image signal as a function of position)

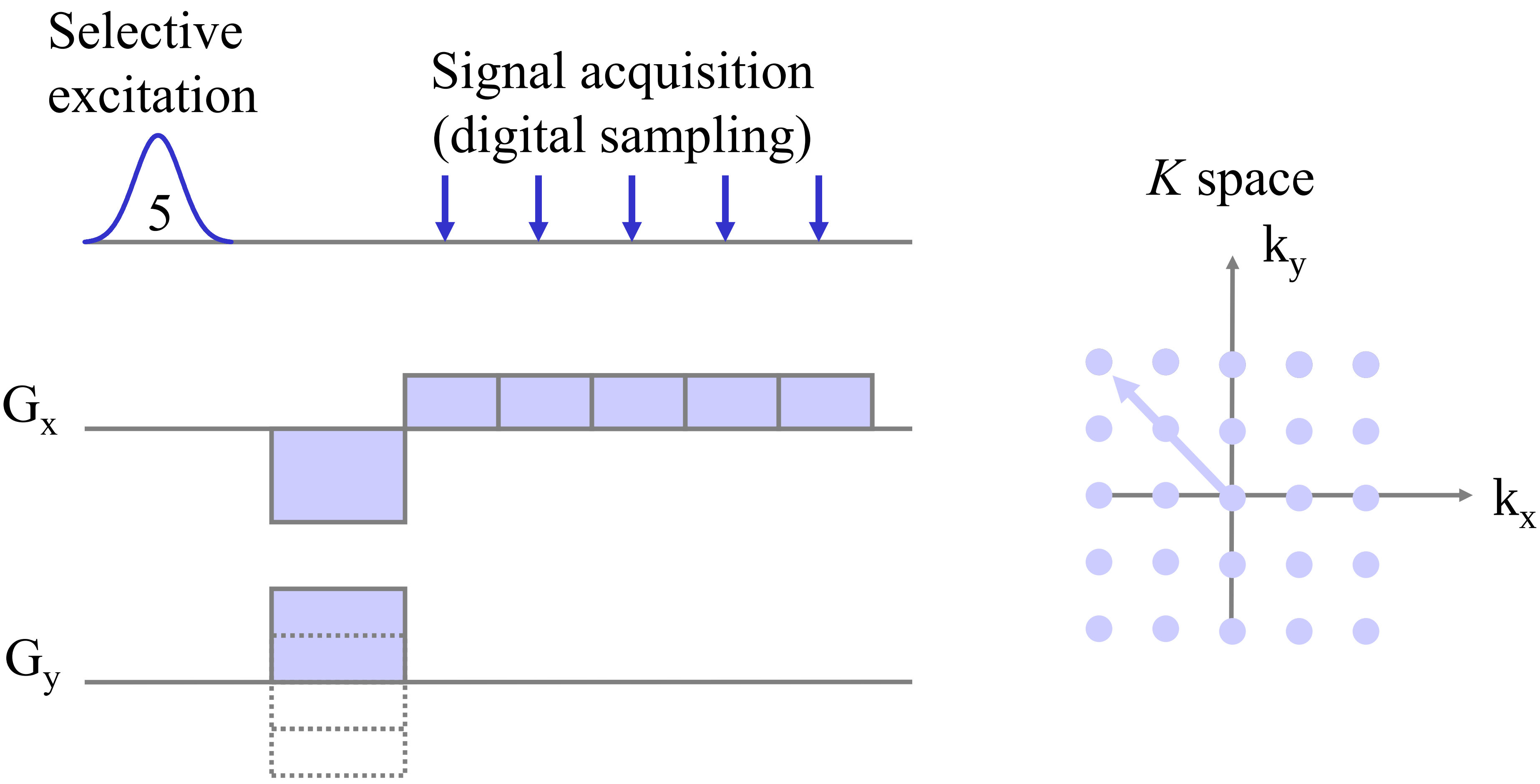
k-space acquisition - FLASH



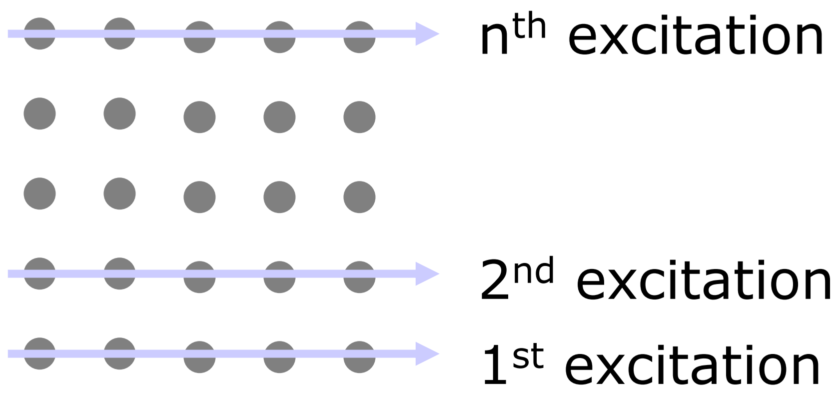
k-space acquisition - FLASH



k-space acquisition - FLASH



k-space acquisition - FLASH

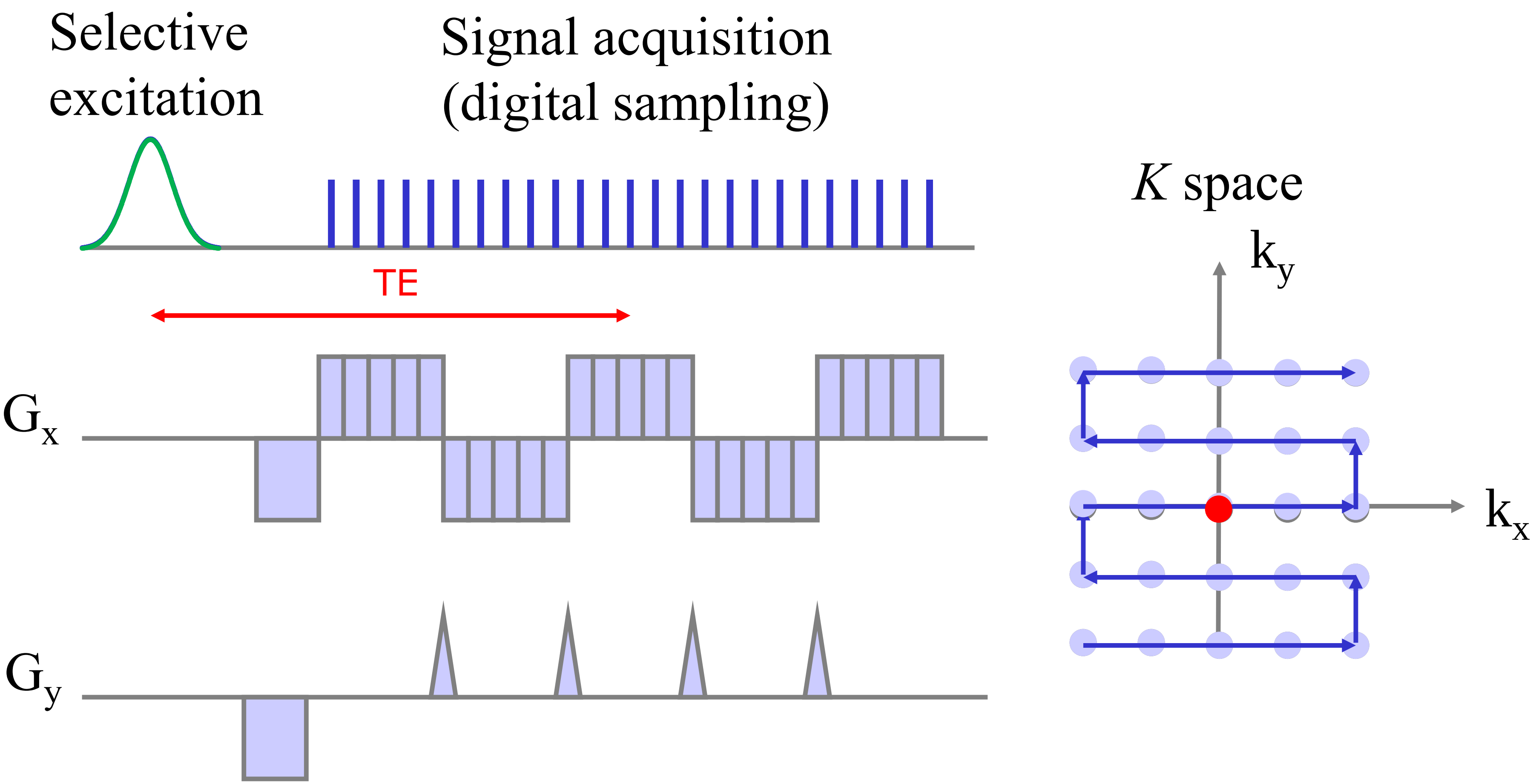


Problem: This sequence is rather slow

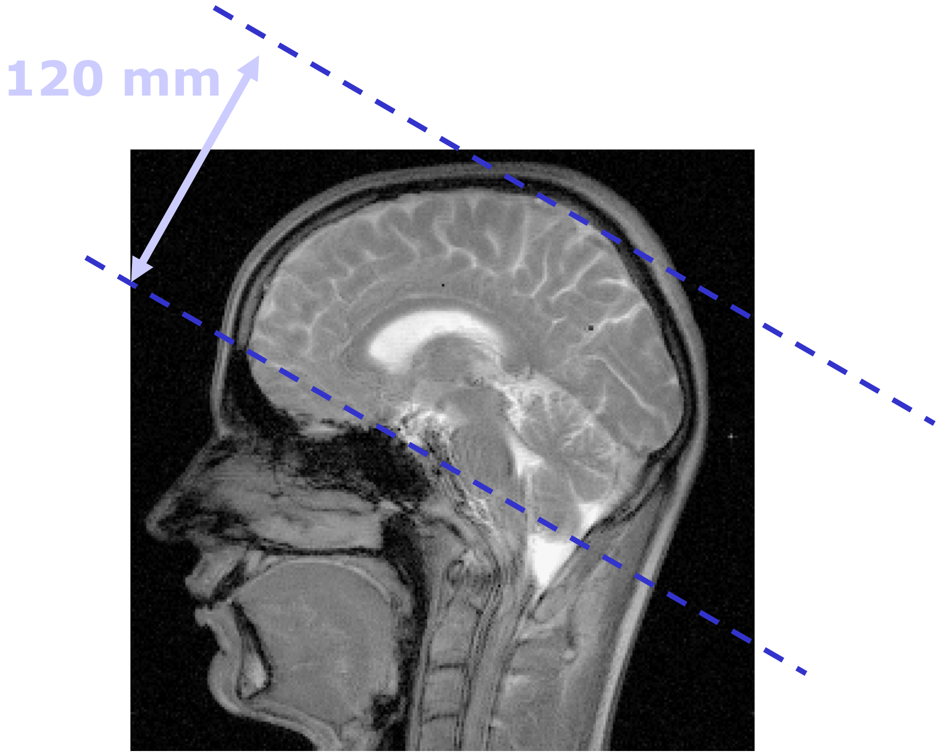
- *K* space is sampled line by line
- After each excitation one must wait for the longitudinal magnetization to recover

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

Echo Planar Imaging (EPI)



EPI at the CBU



How many slices ?

$$\frac{120 \text{ mm}}{3 \text{ mm} + 0.75 \text{ mm}} = 32$$

And the minimum TR ?

32 * 62.5 ms = 2000 ms

Questions?