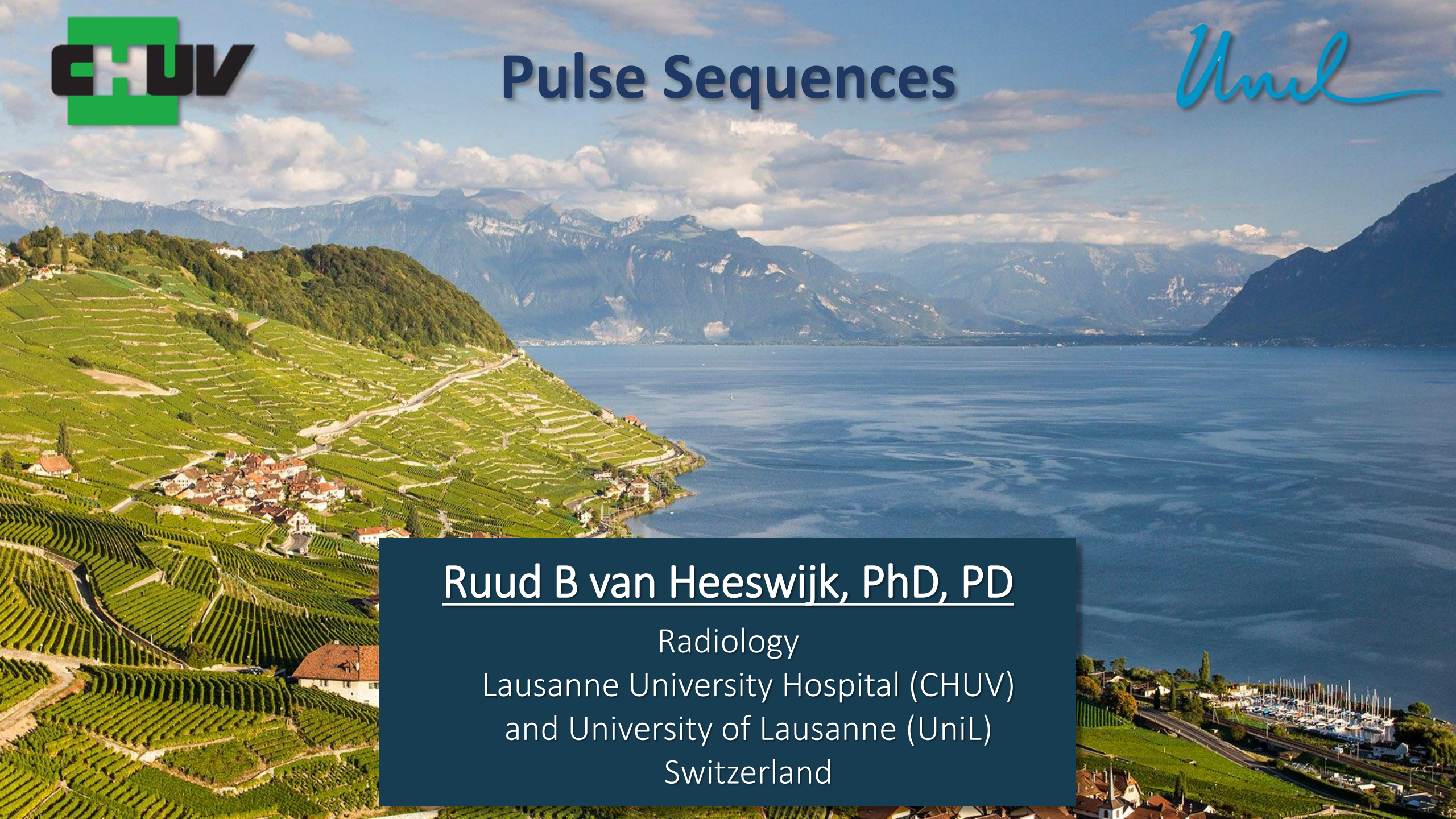
Pulse Sequences



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Radiology

Lausanne University Hospital (CHUV)

and University of Lausanne (UniL)

Switzerland

Overview

- Refresher on k-space encoding
- Spin echo and derivatives
- Gradient echo and derivatives
- Take-home messages

k-Space encoding refresher

k-Space encoding

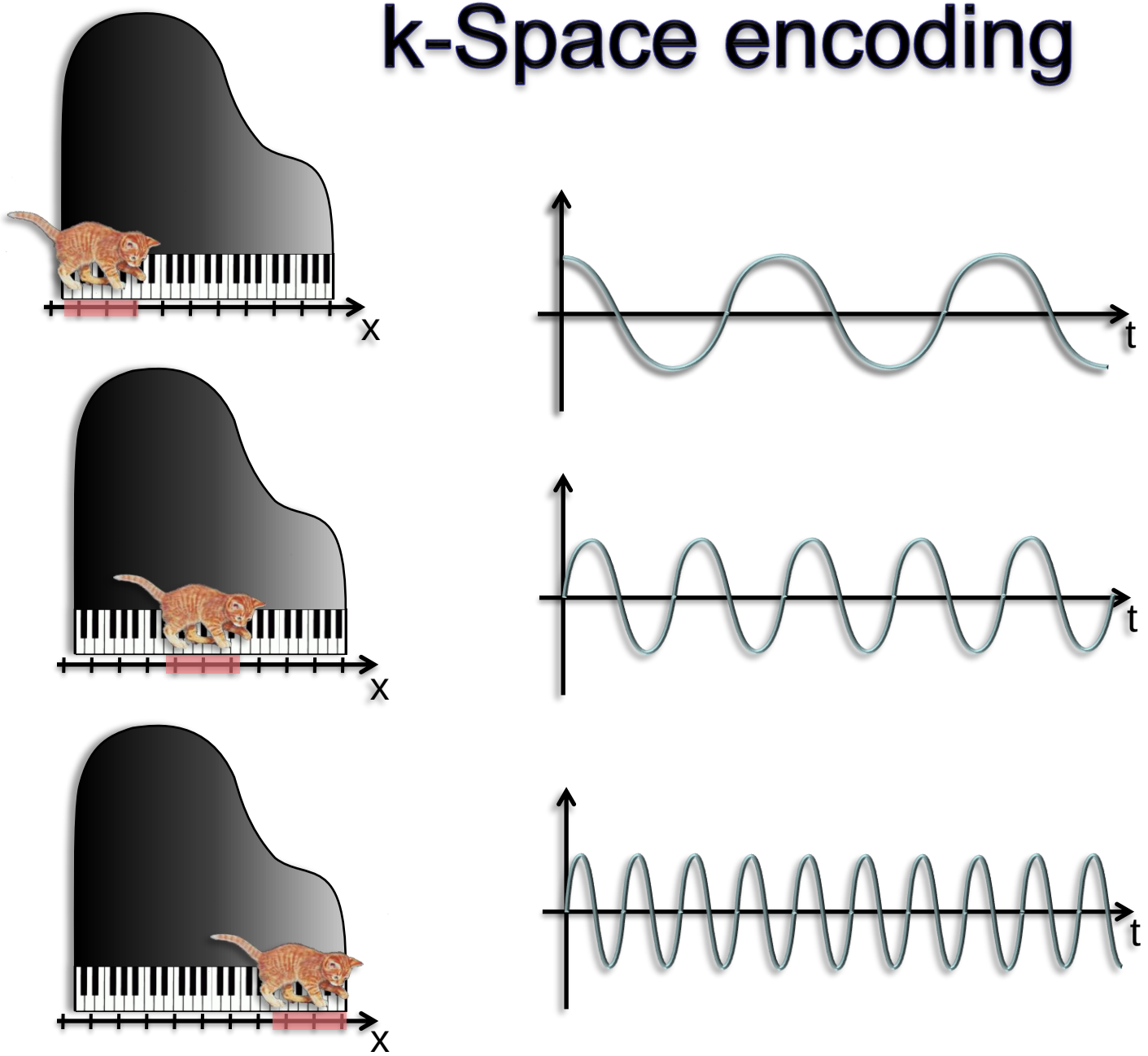
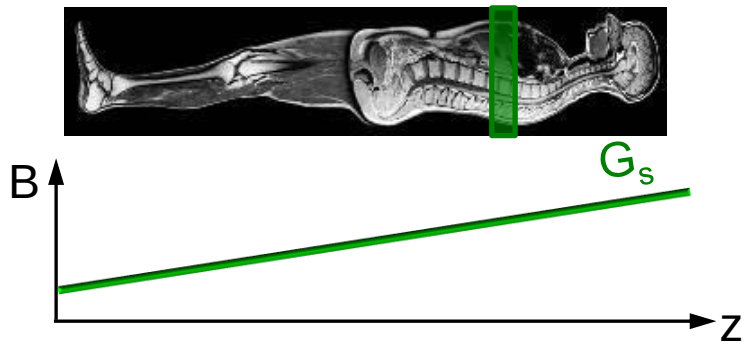
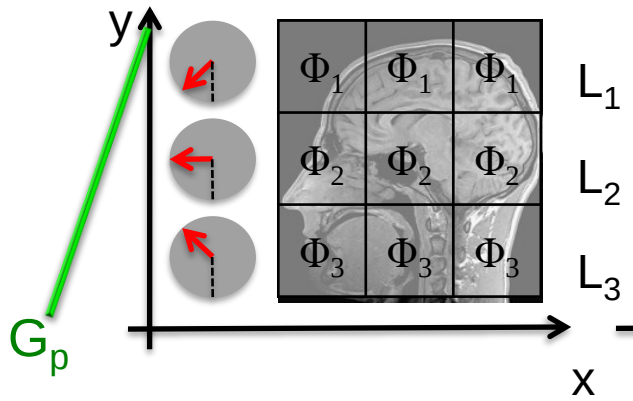


Image Acquisition

- MR signal spatial localization
  1. Selection of an image slice
  2. Phase encoding
  3. Frequency encoding



1.



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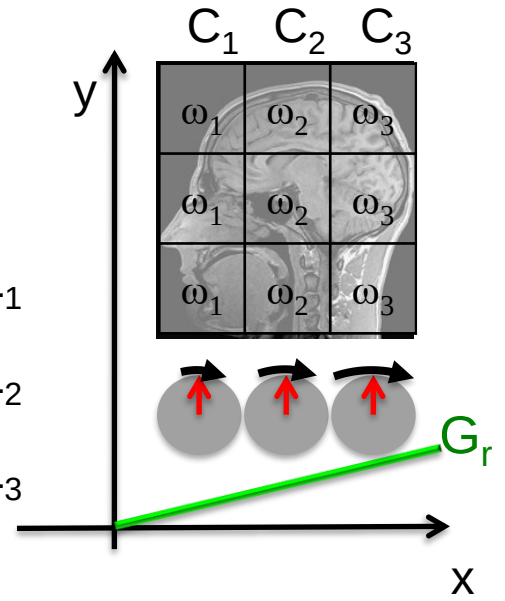
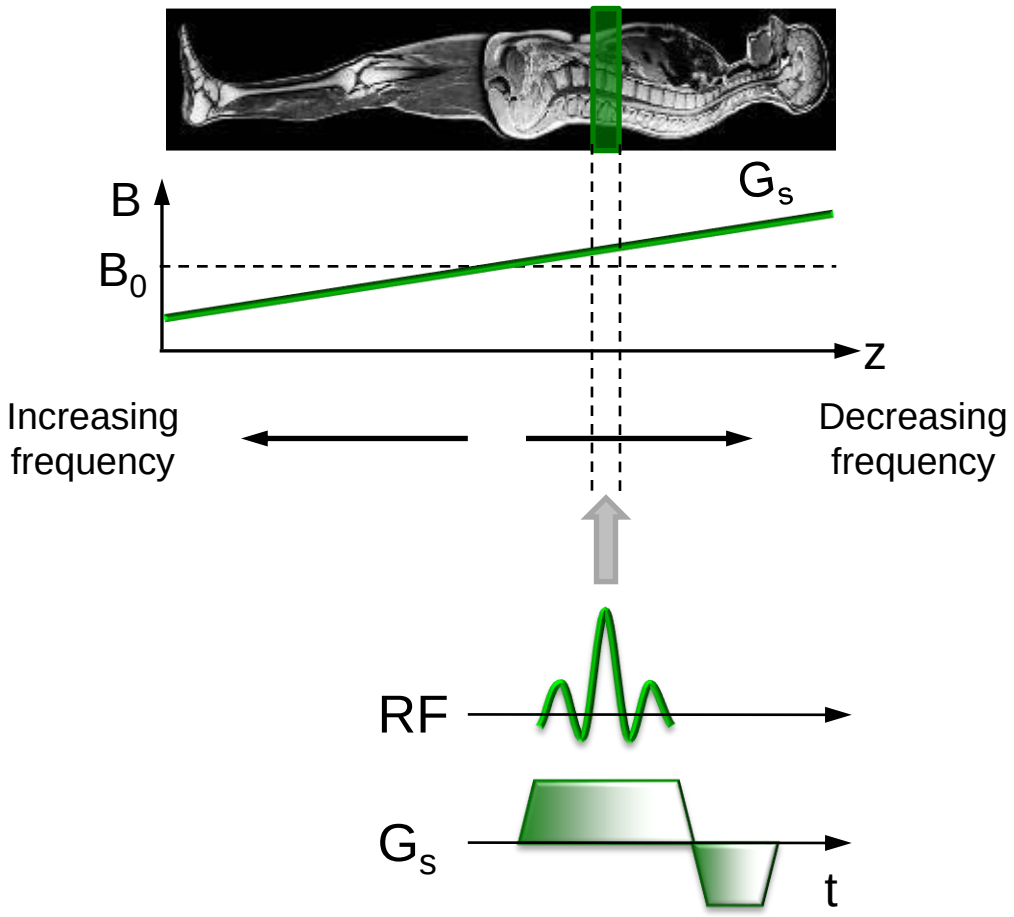


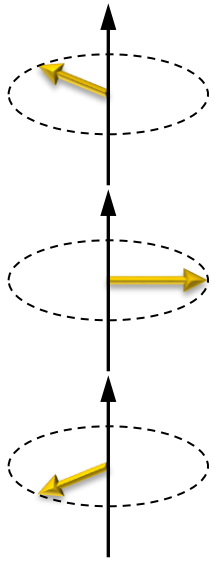
3.

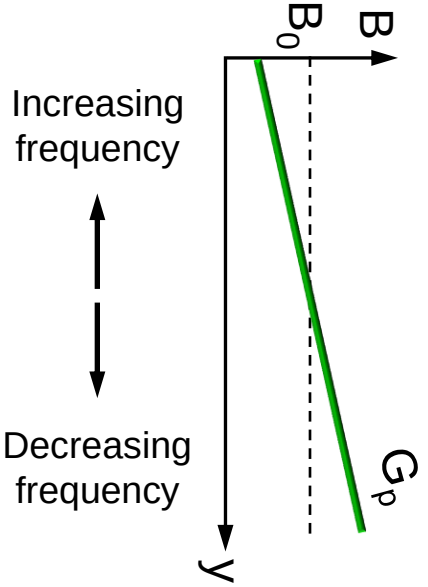
Selection of an Image Slice

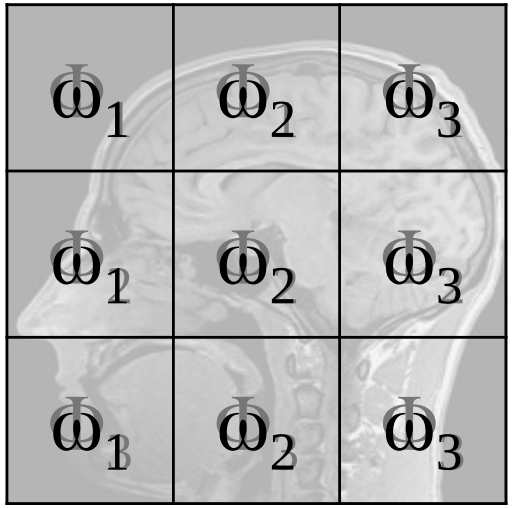
$$\omega_0 = \gamma B_0$$

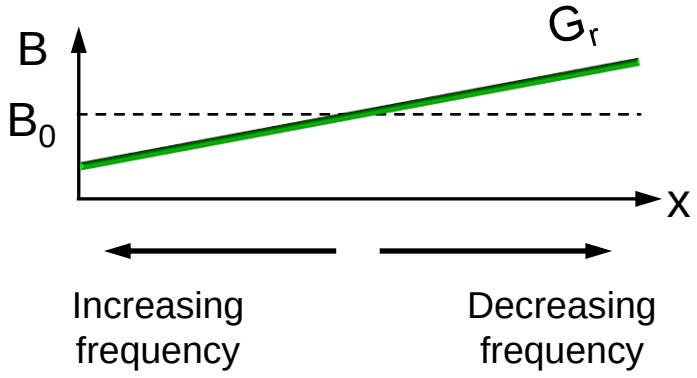


Phase and Frequency Encoding









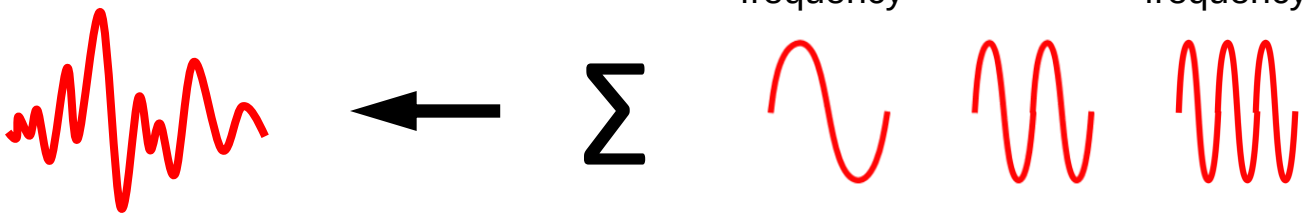
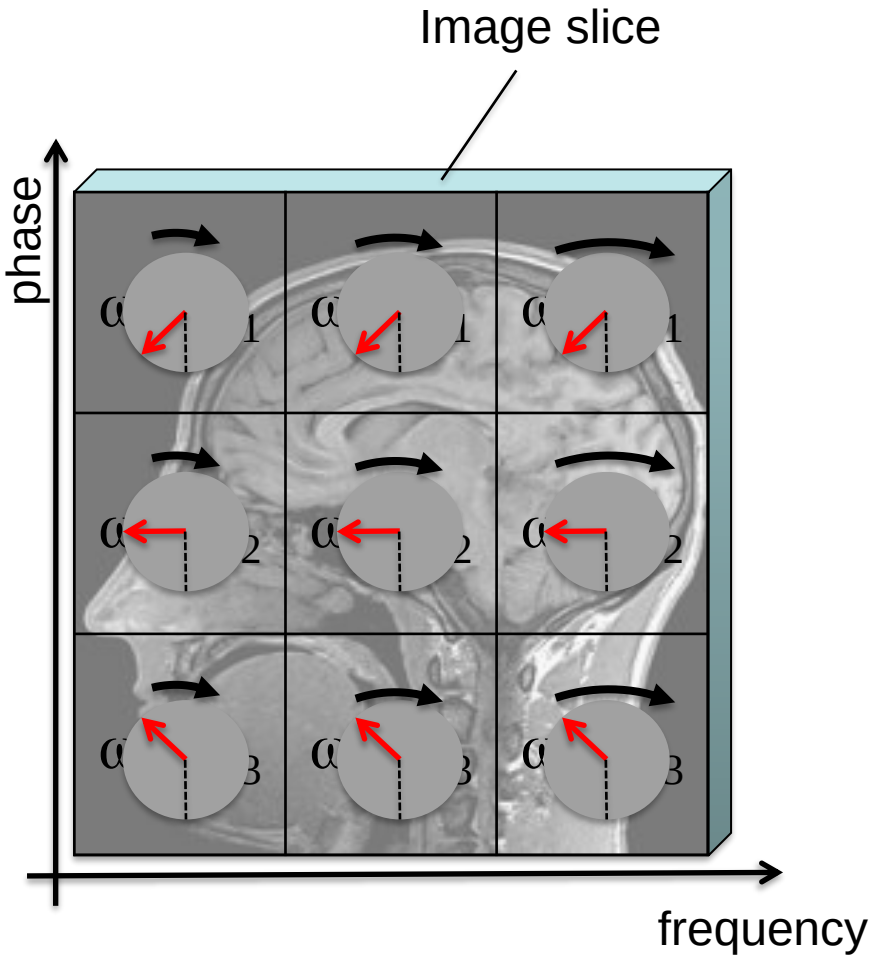


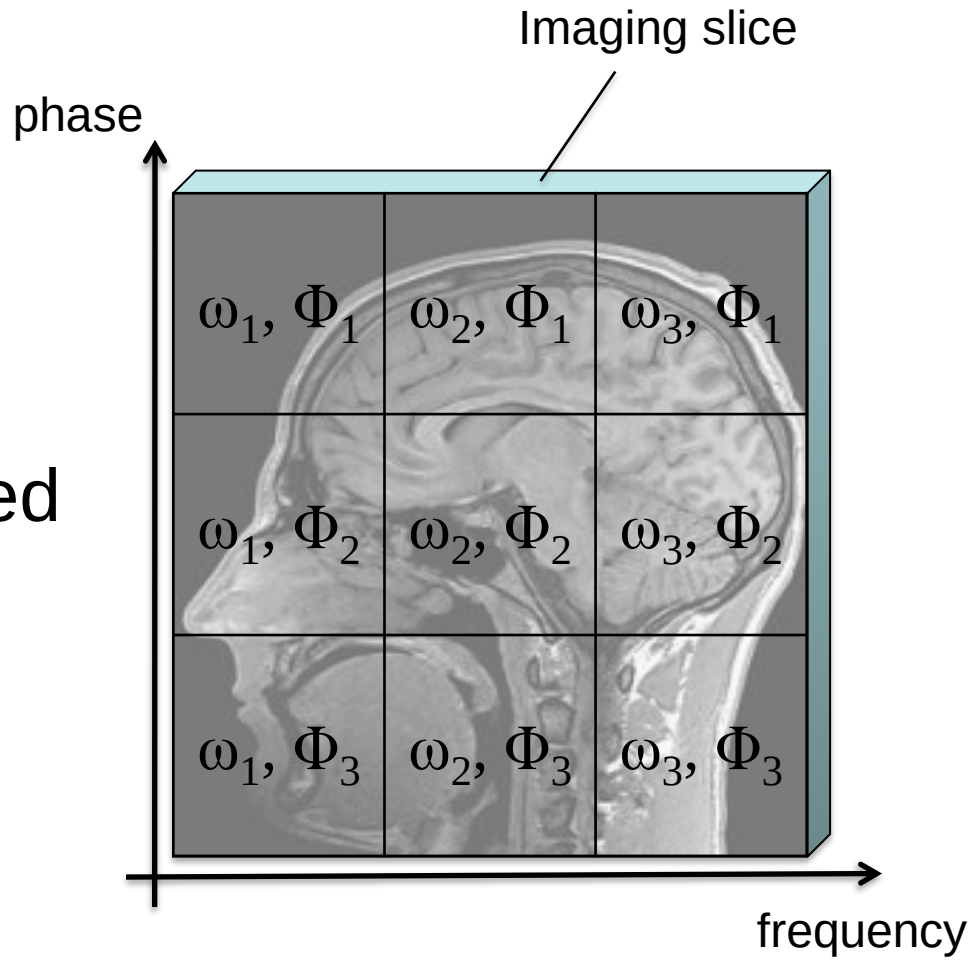
Image Acquisition



Separation of Frequencies (Image Reconstruction)

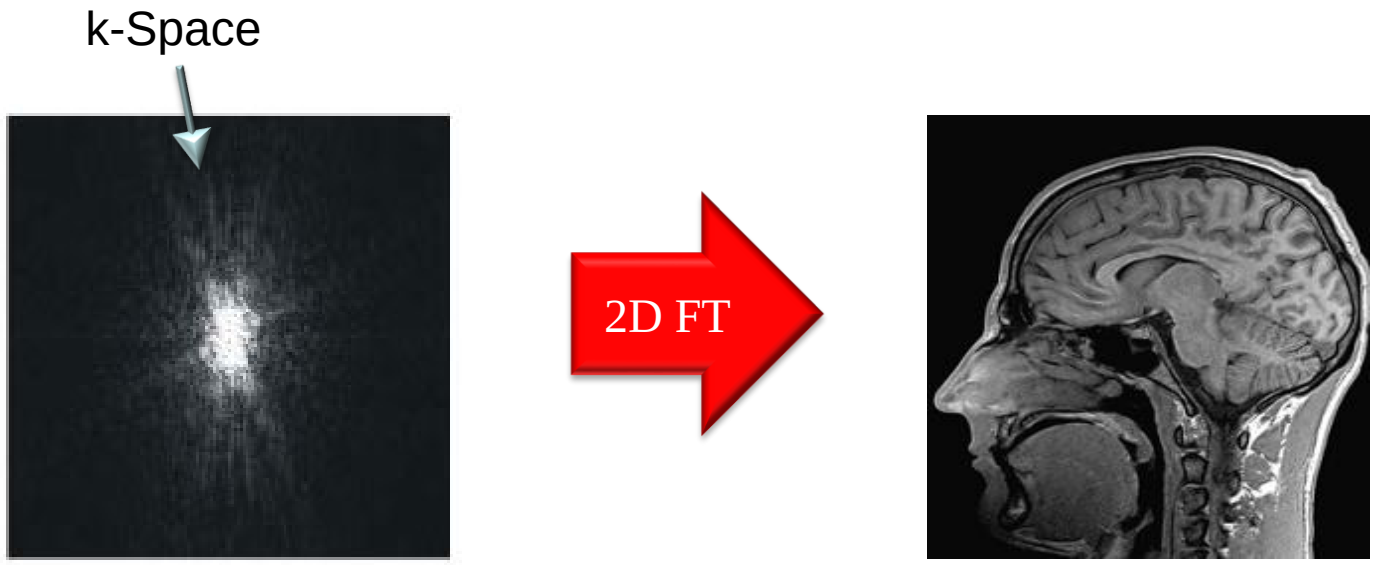
Image Reconstruction

- An image is encoded line by line in k-space.
- At each step, the phase encoding gradient is increased to acquire a new line.
- Typically, images use 2^N different phase shifts (128, 256, etc).



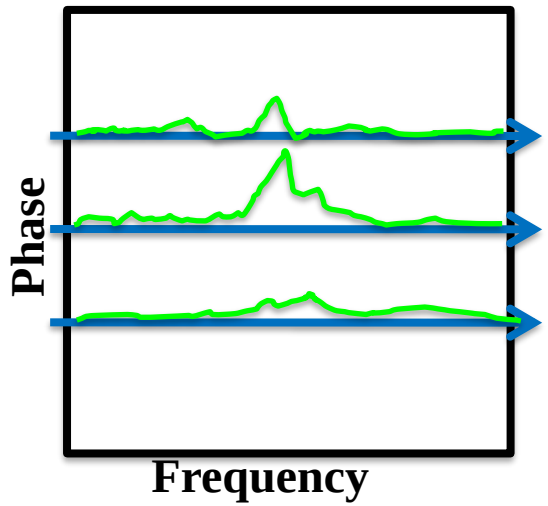
k-Space & Image Reconstruction

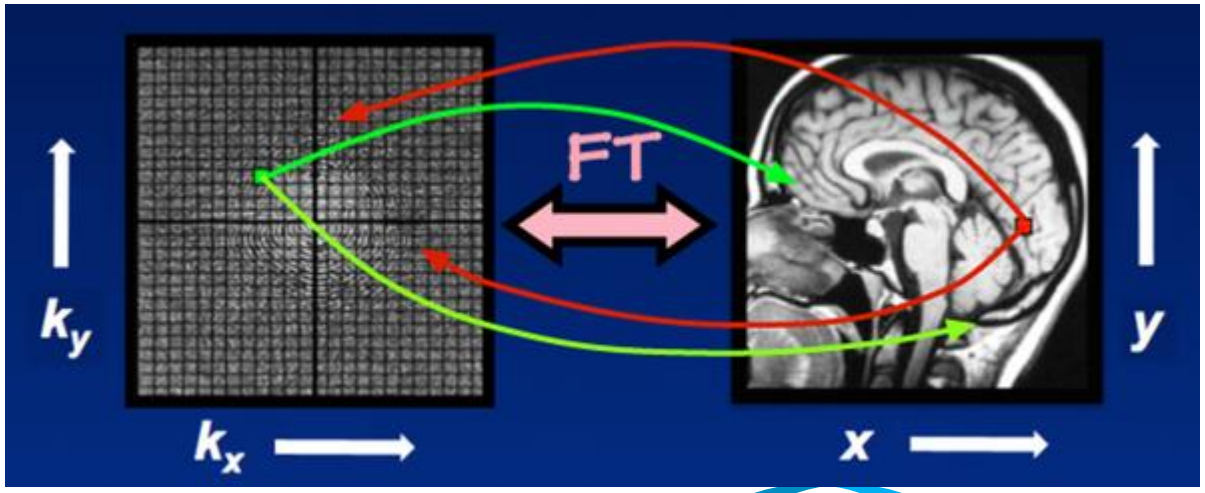
- A two-dimensional Fourier transformation of this matrix results in the reconstruction of the image.

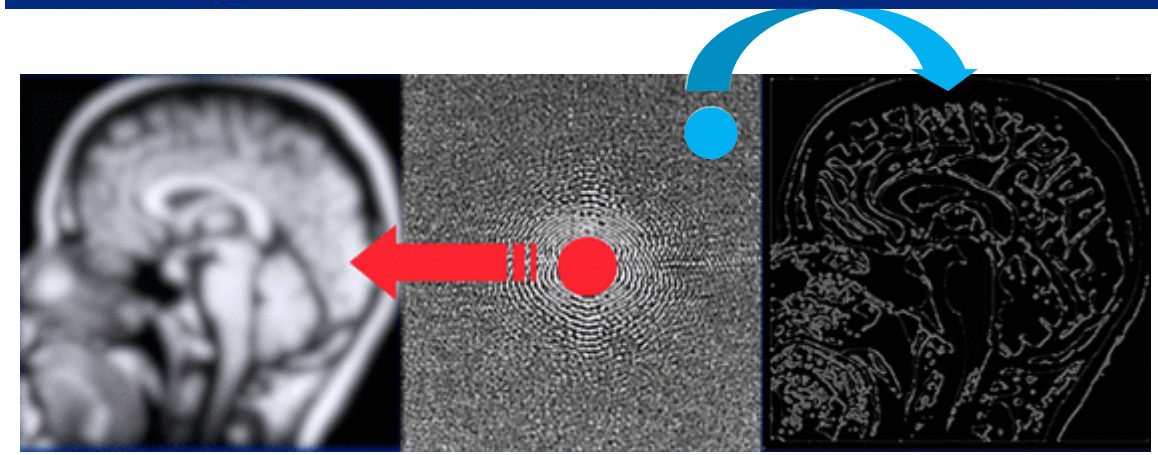


k-Space versus image space

- Each point in k-space has information on the entire image and vice versa





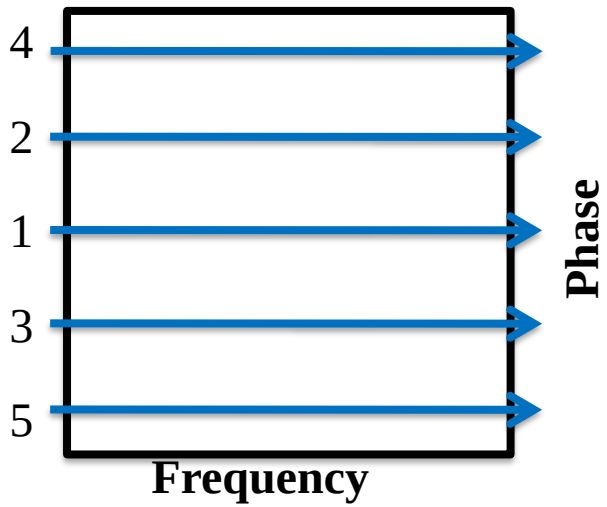


To play with this yourself:
Apple Store: k-Space Odyssey (Haselhoff)
Play Store: k-Spapp (Springorum)

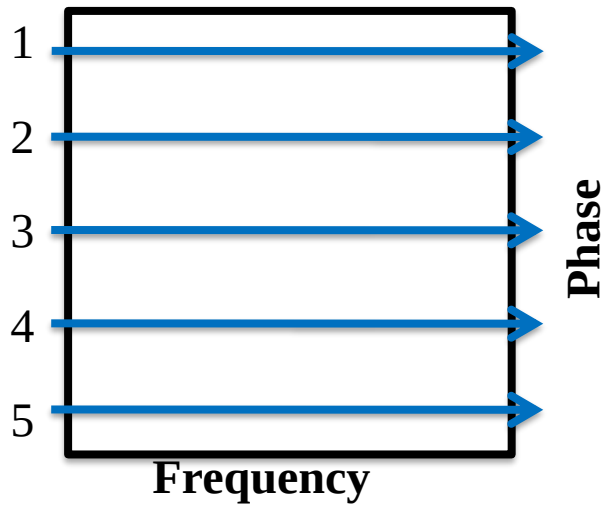
mriquestions.com

Centric versus Linear Sampling

- What line to sample first?
- Influences contrast and eddy currents

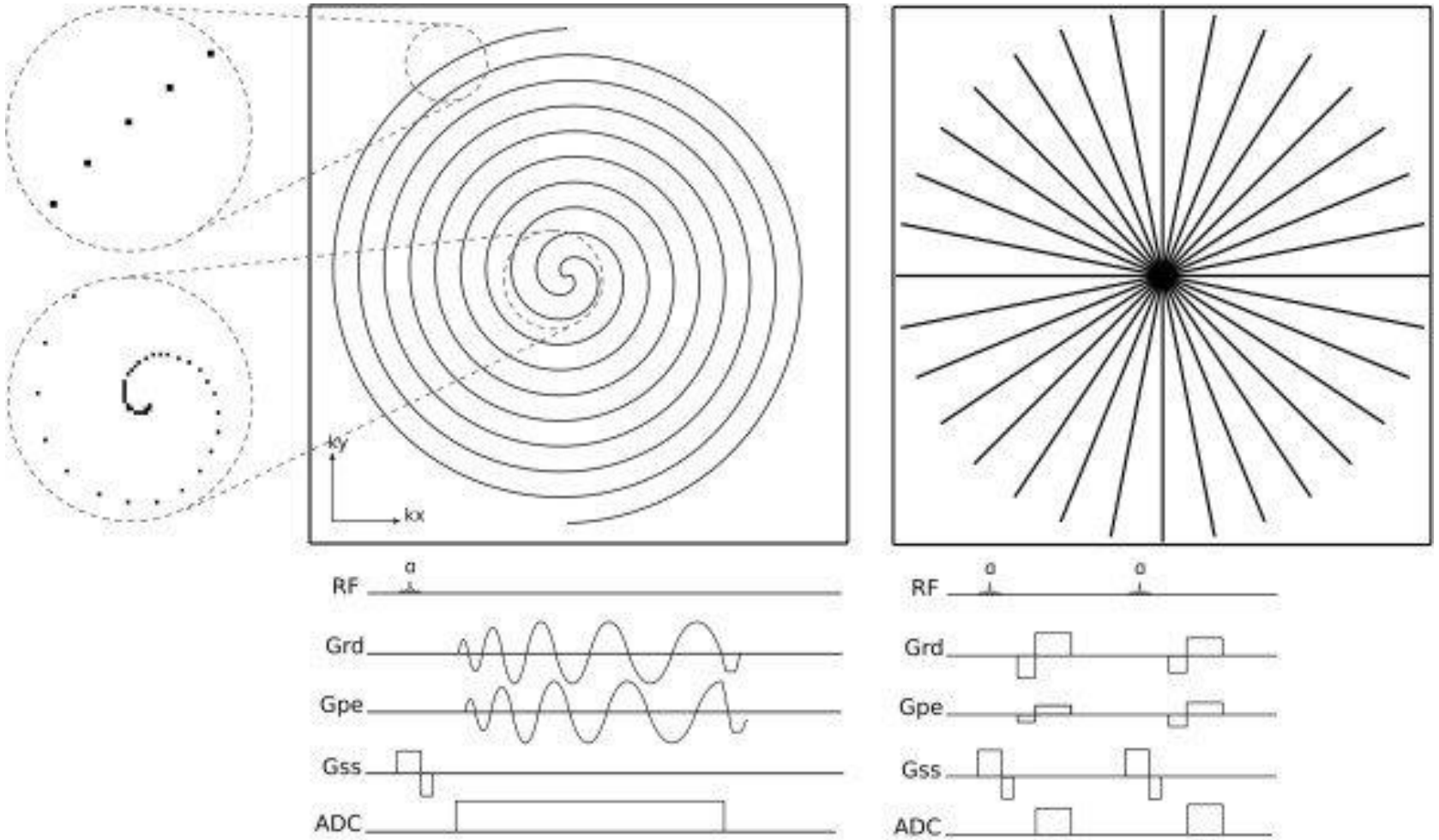


Centric



Linear

Non-Cartesian Sampling: 2D

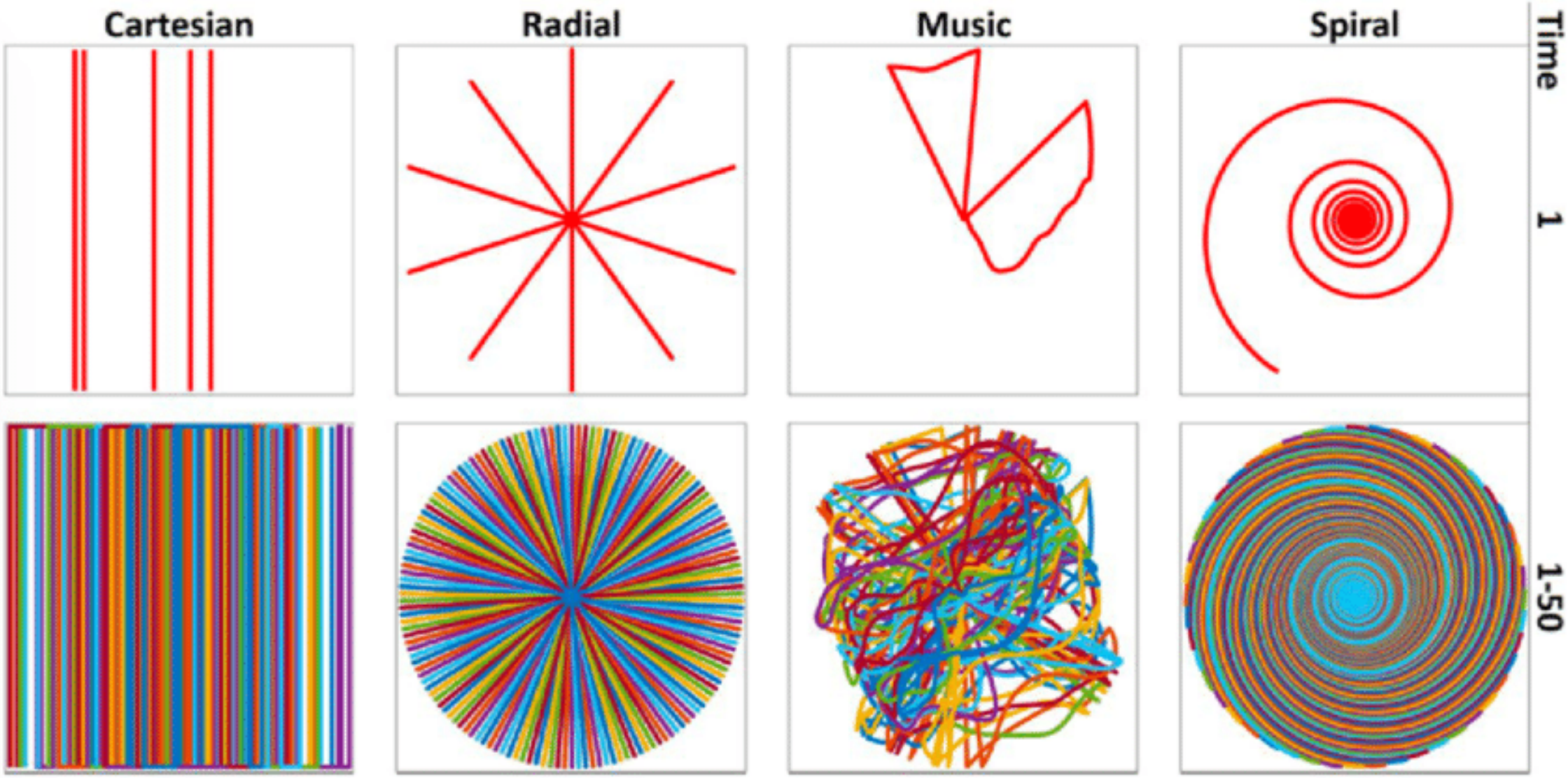


Spiral

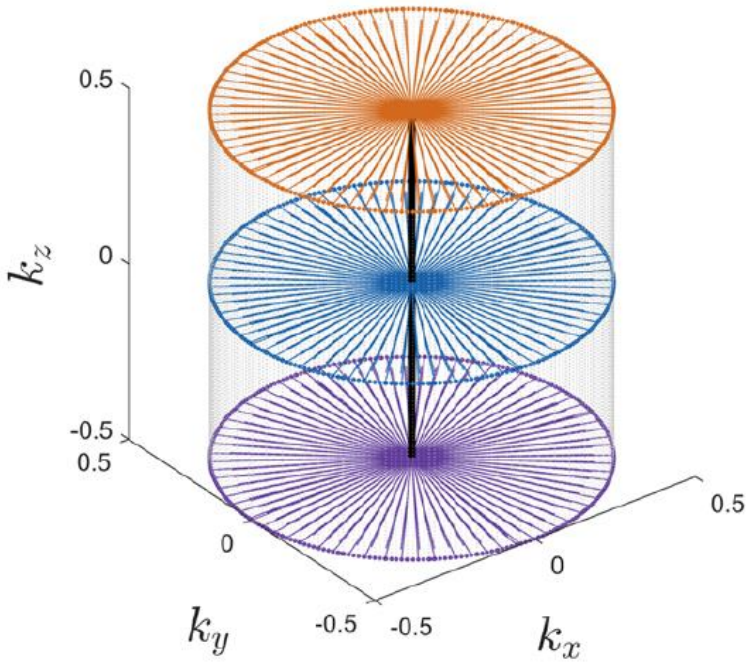
Radial

Ferreira et al. J Cardiov Magn Res (2013)

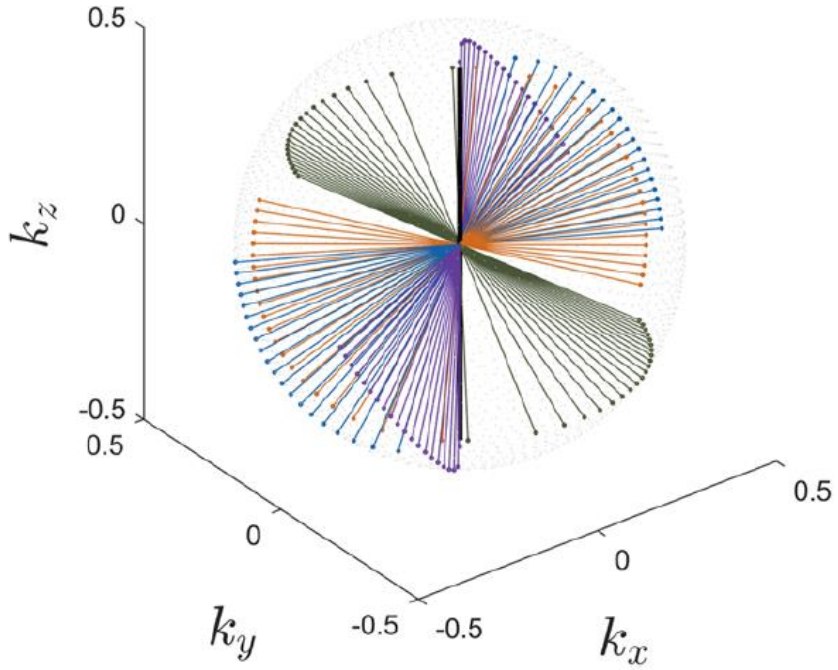
Randomized 2D k-Space Sampling



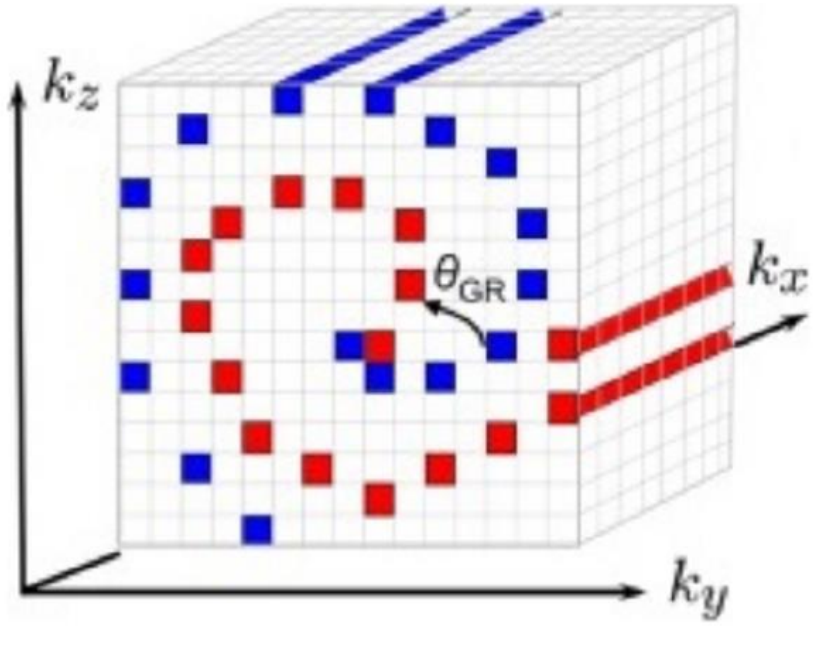
Non-Cartesian Sampling: 3D



3D Radial-Cartesian hybrid



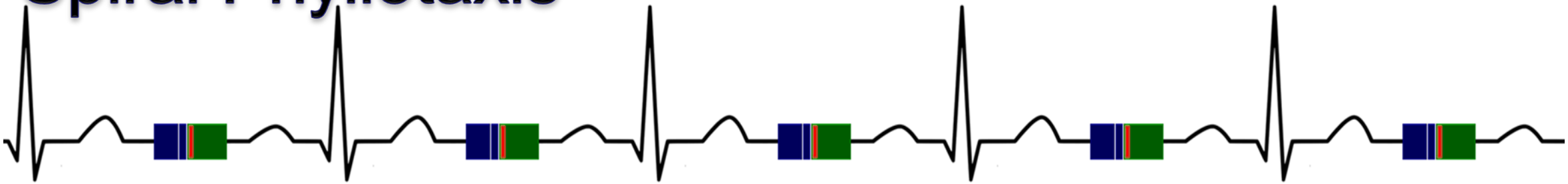
3D radial (spiral phyllotaxis)

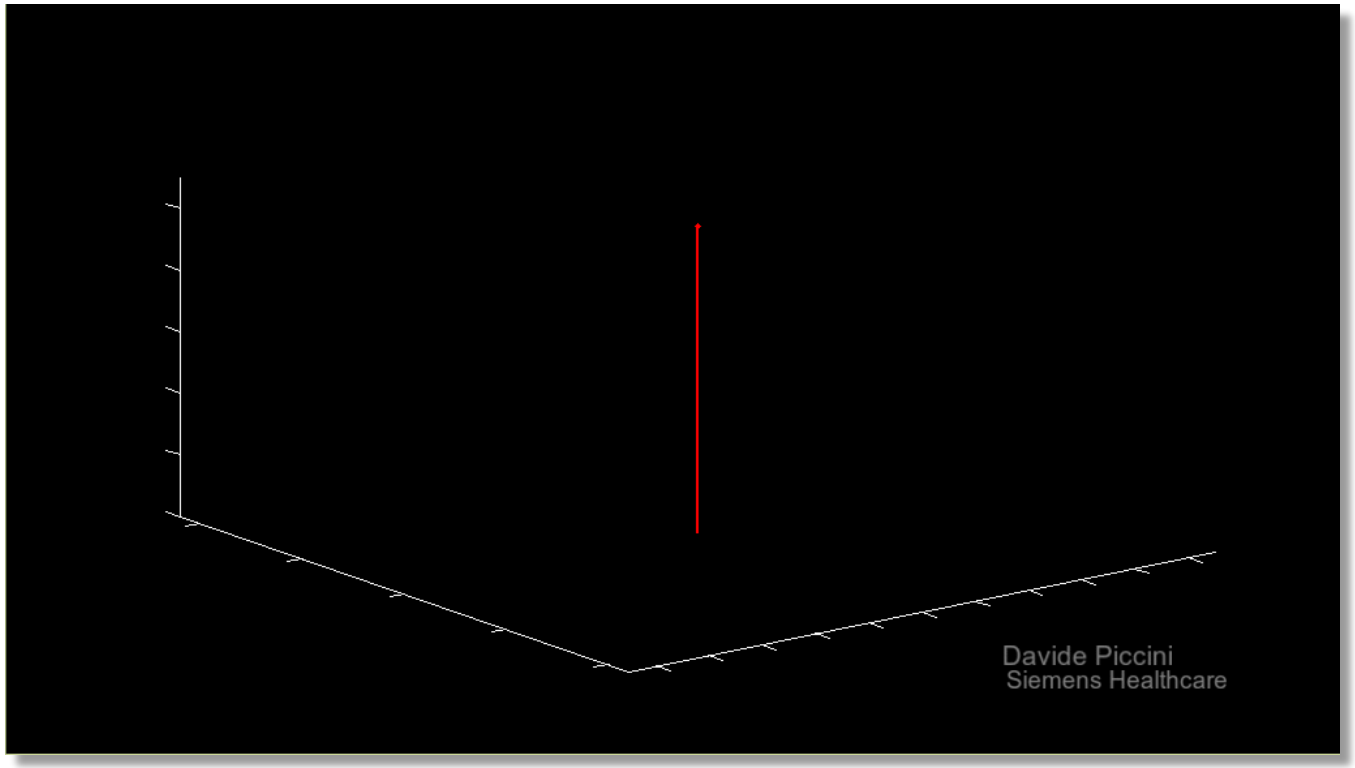


3D Cartesian (pseudo-spiral)

Menchón-Lara et al. Insights into Imaging (2019)

Spiral Phyllotaxis



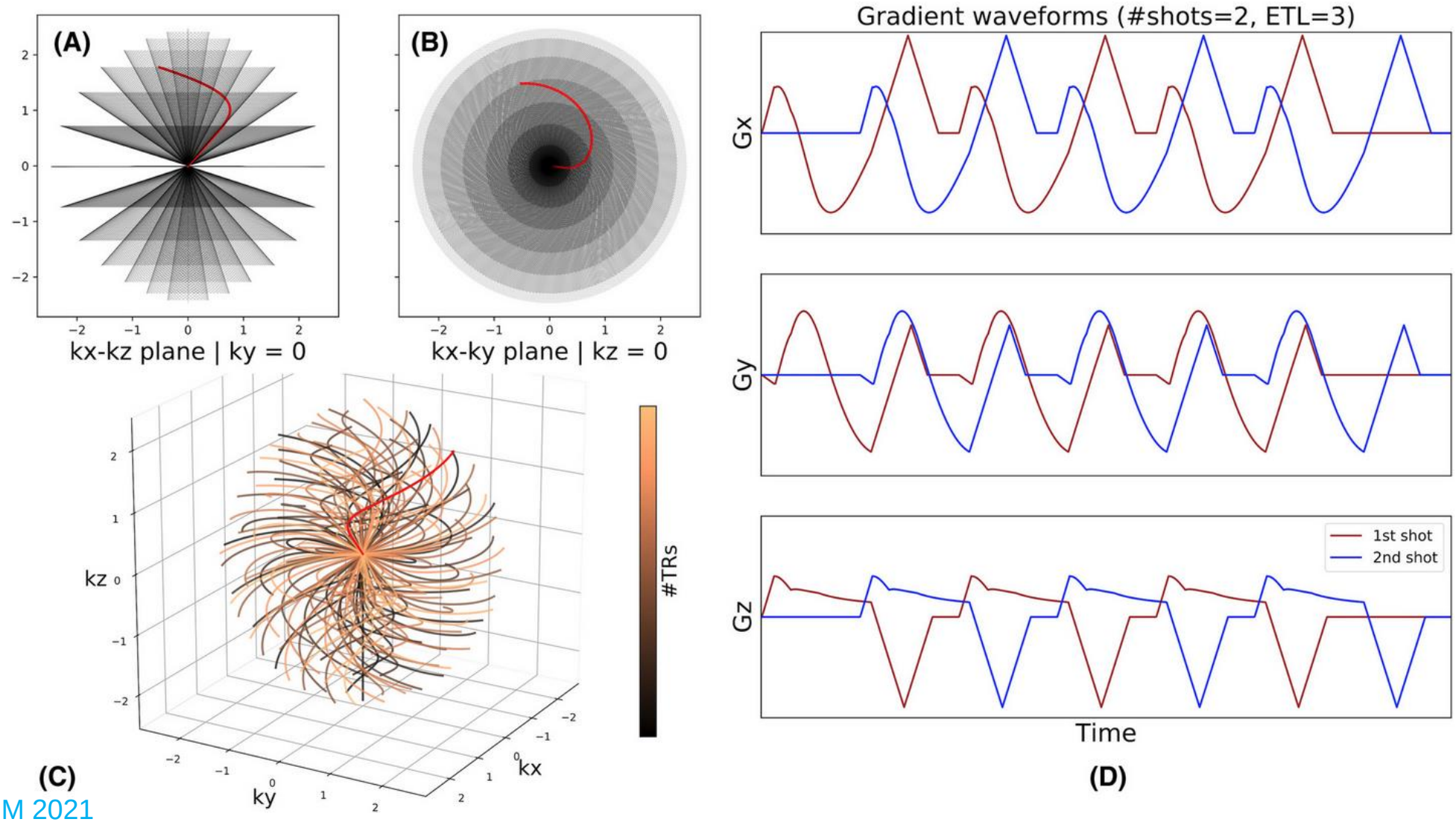


3D radial trajectory with a segmented spiral phyllotaxis pattern

Slide courtesy of Davide Piccini, Siemens Healthcare and CHUV

Piccini et al, Magn Reson Med 66 (2011)

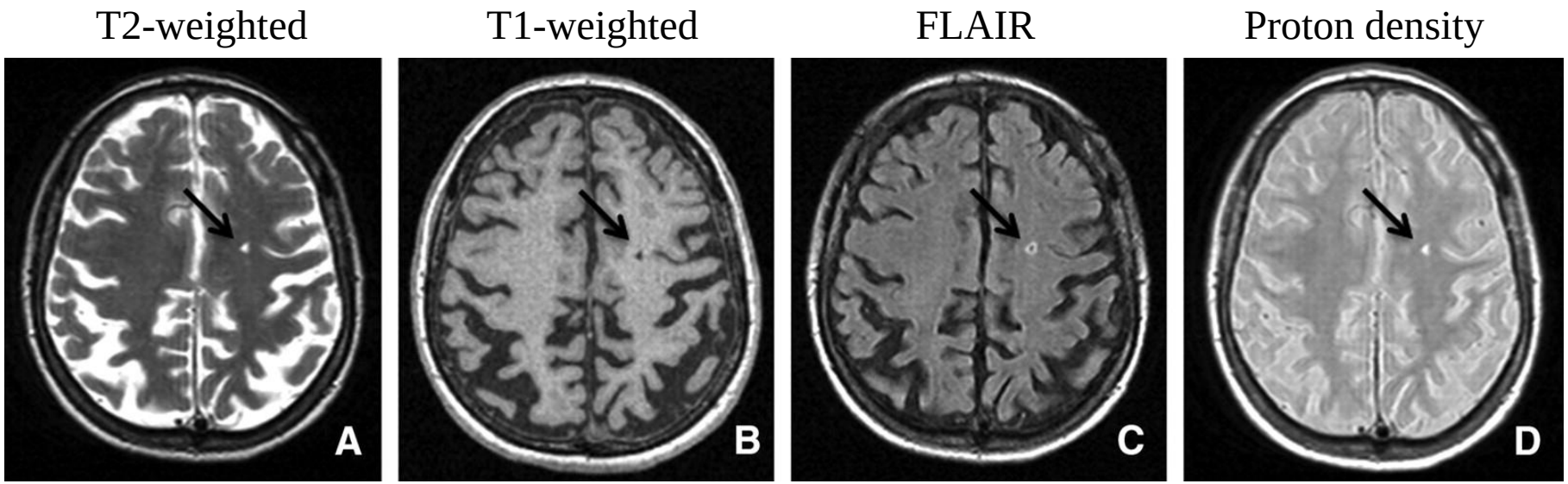
Non-Cartesian Sampling: 3D Cones



Kee et al. MRM 2021

Spin echoes

MR pulse sequences

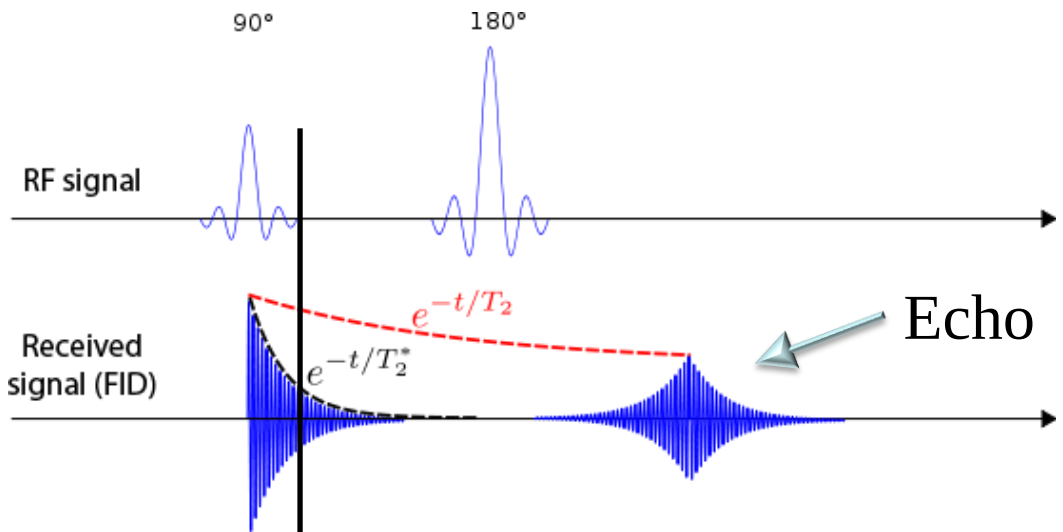


This example shows four images of the same subject anatomy that were acquired with different MR pulse sequences. As a result, the images have different image contrasts

Zhu et al. Stroke. 2011;42:1140-1145

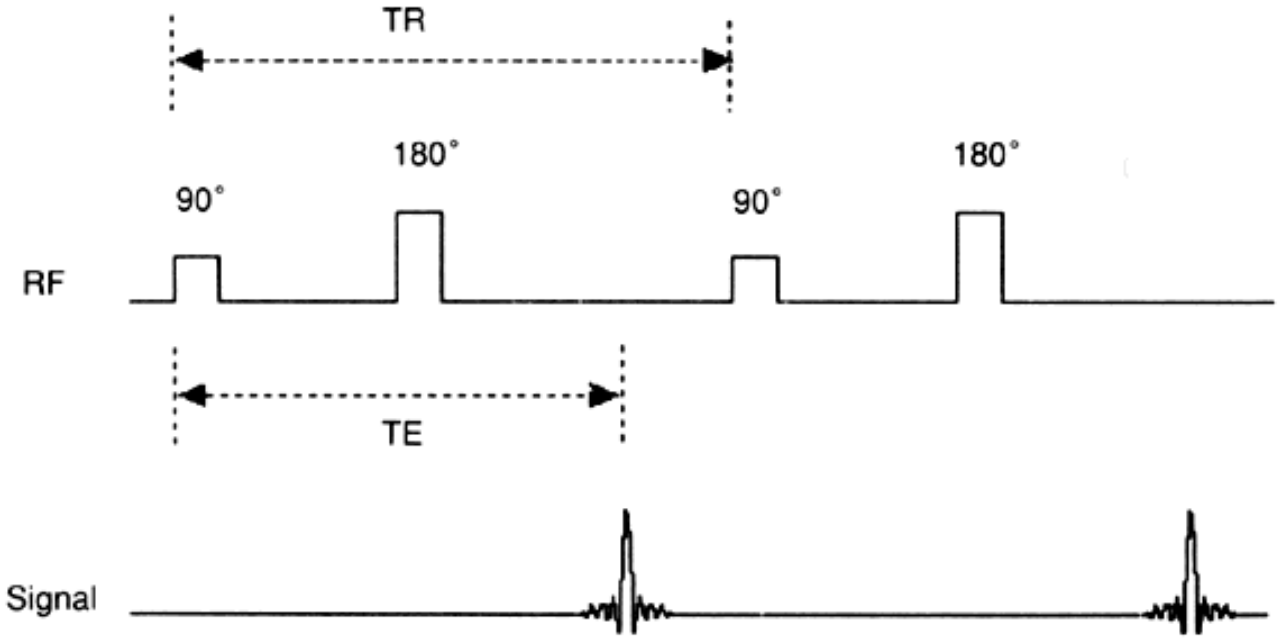
Echoes

- For MR imaging, it is more common to generate and measure the MR signal in the form of an **echo**
- Pulse sequences used to generate echoes: **spin echo** and **gradient echo**



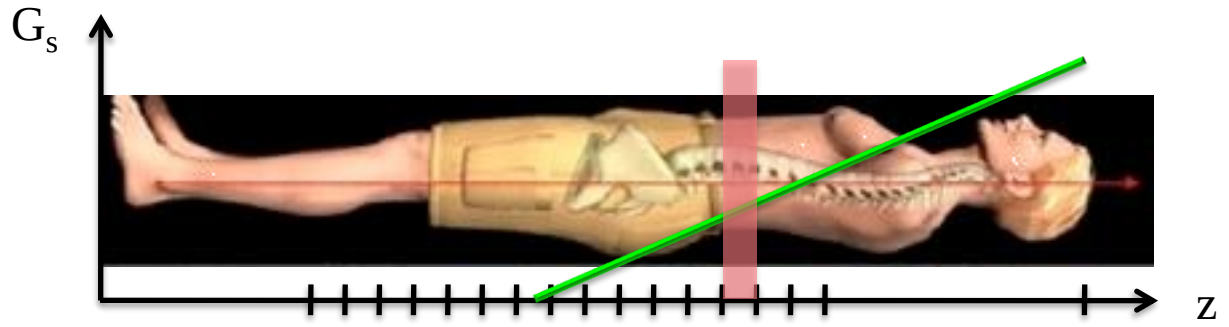
Spin Echo Sequence

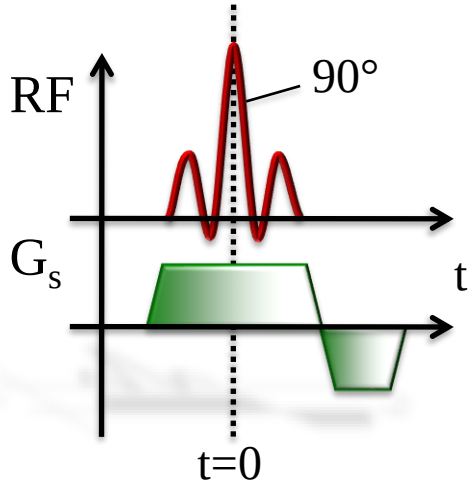
- After the 90° excitation pulse, a 180° refocusing RF pulse is played out
- The 180° pulse must be applied at time TE/2 for the echo to occur at time TE.

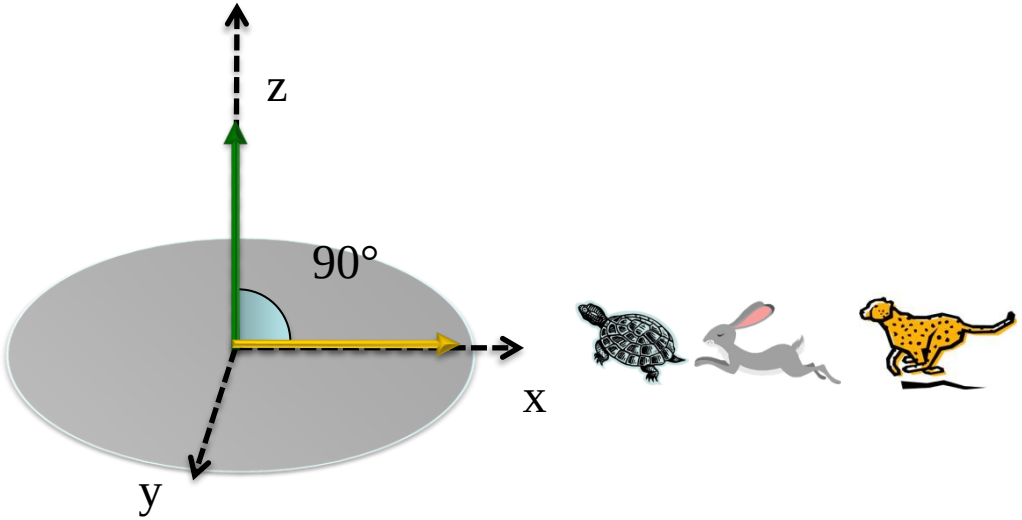


Spin Echo Sequence

1) Slice selection at t=0 (RF excitation pulse 90°).



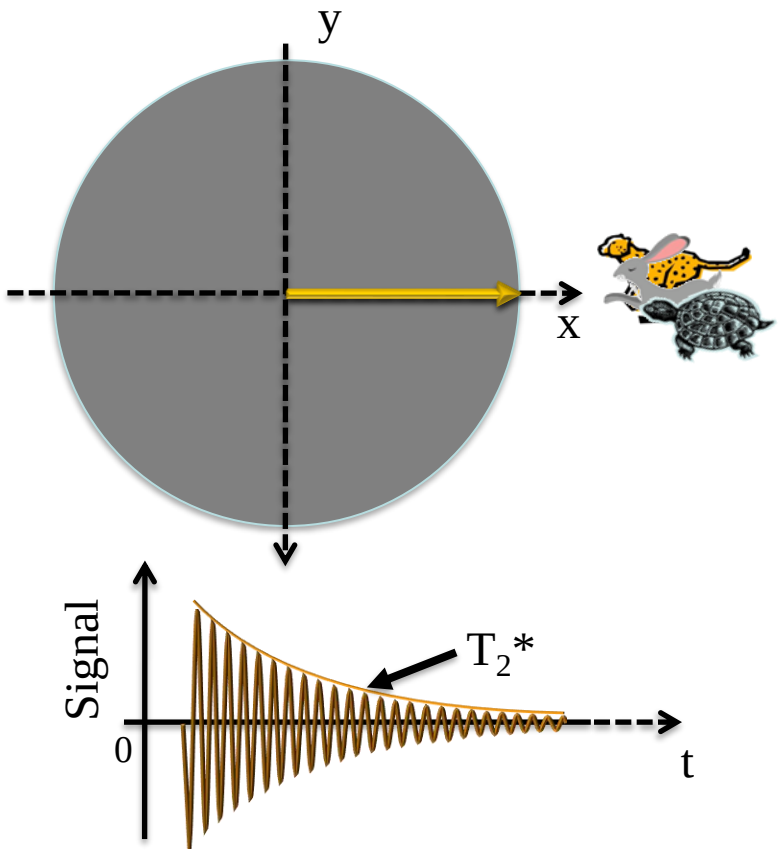


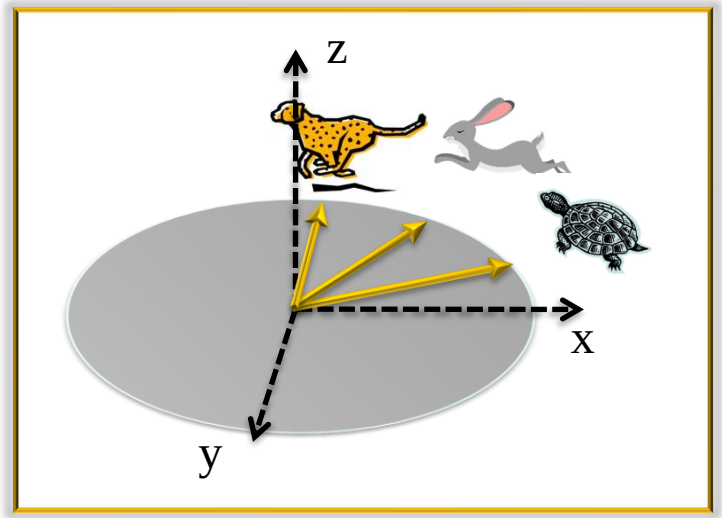


Spin Echo Sequence

2) Spin de-phasing

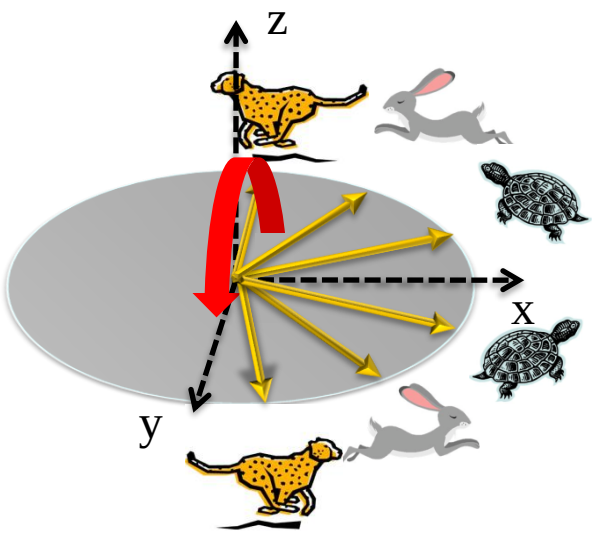
– transverse relaxation: T_2* decay during TE/2.

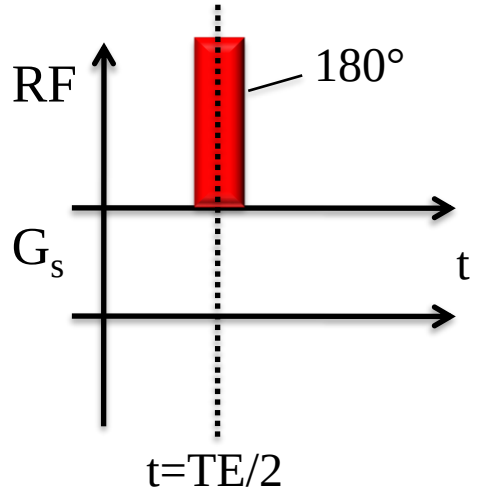




Spin Echo Sequence

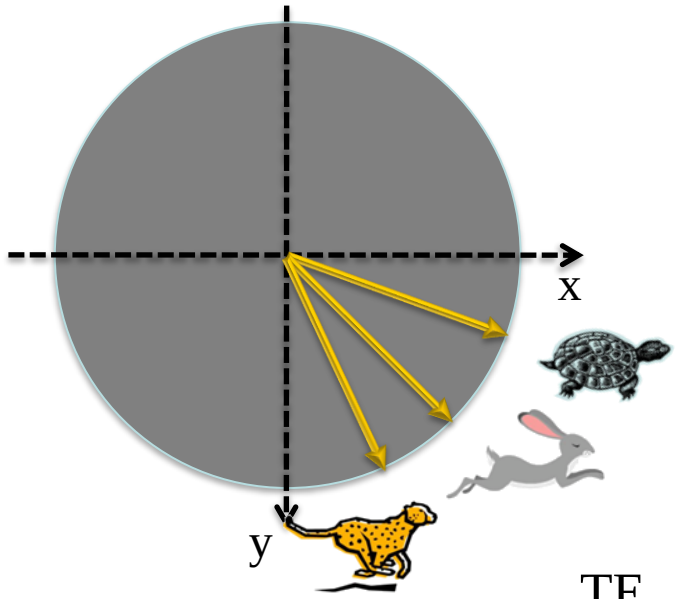
3) 180° refocusing RF pulse at t=TE/2.

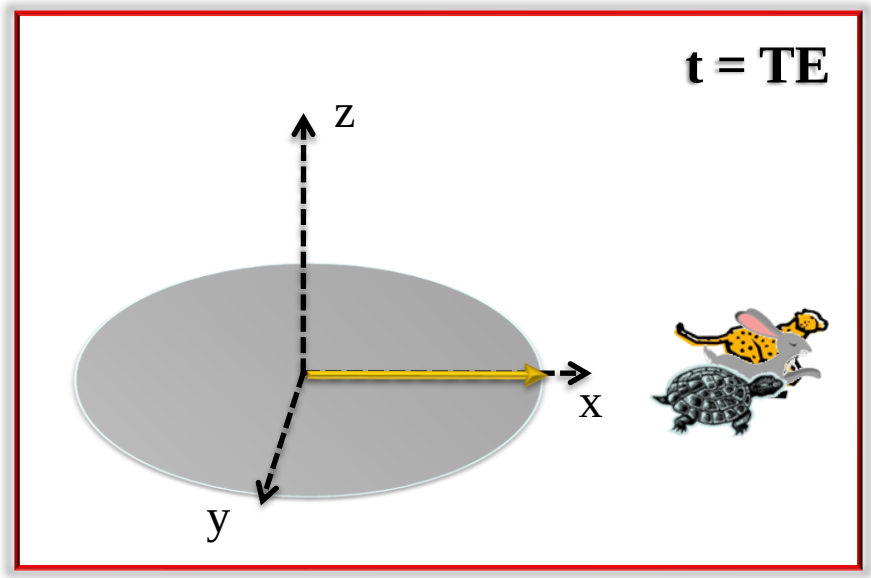


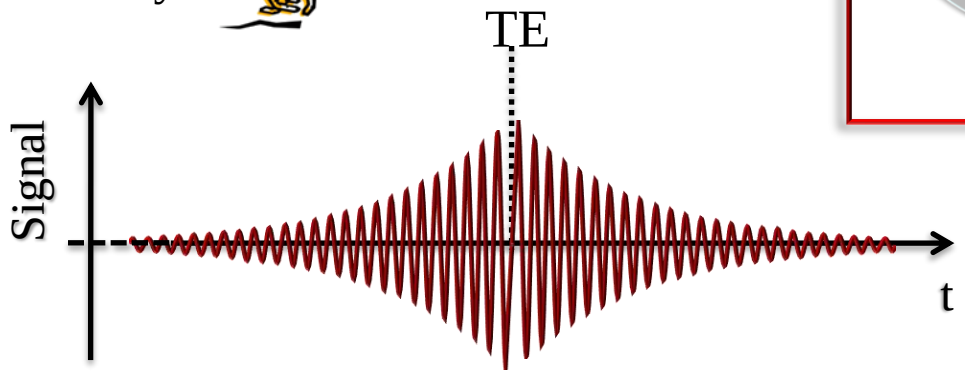


Spin Echo Sequence

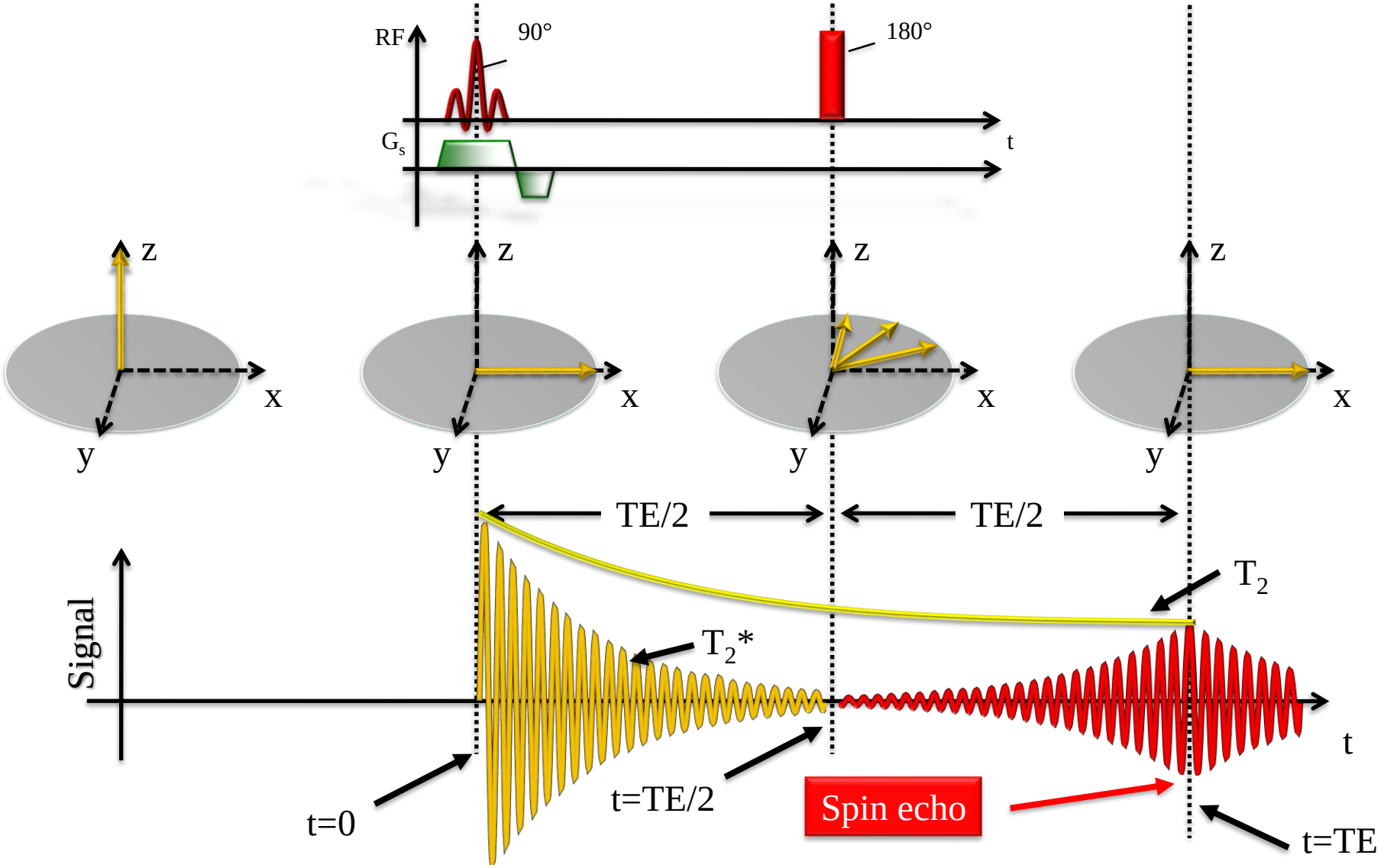
4) Spin echo at t=TE.



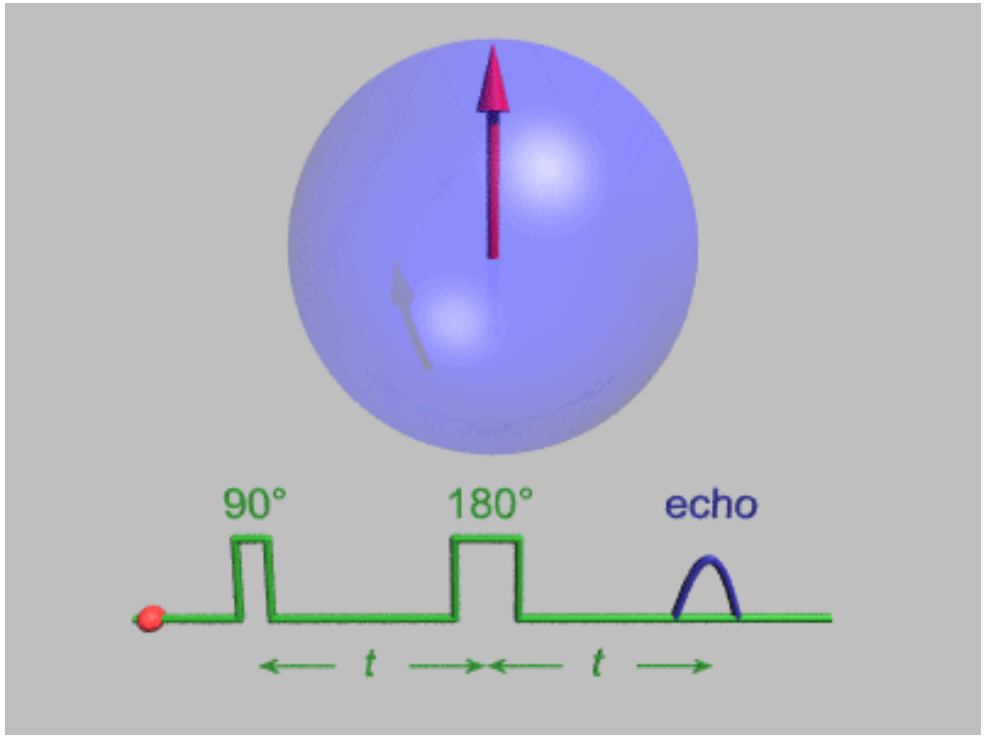




Spin Echo Sequence

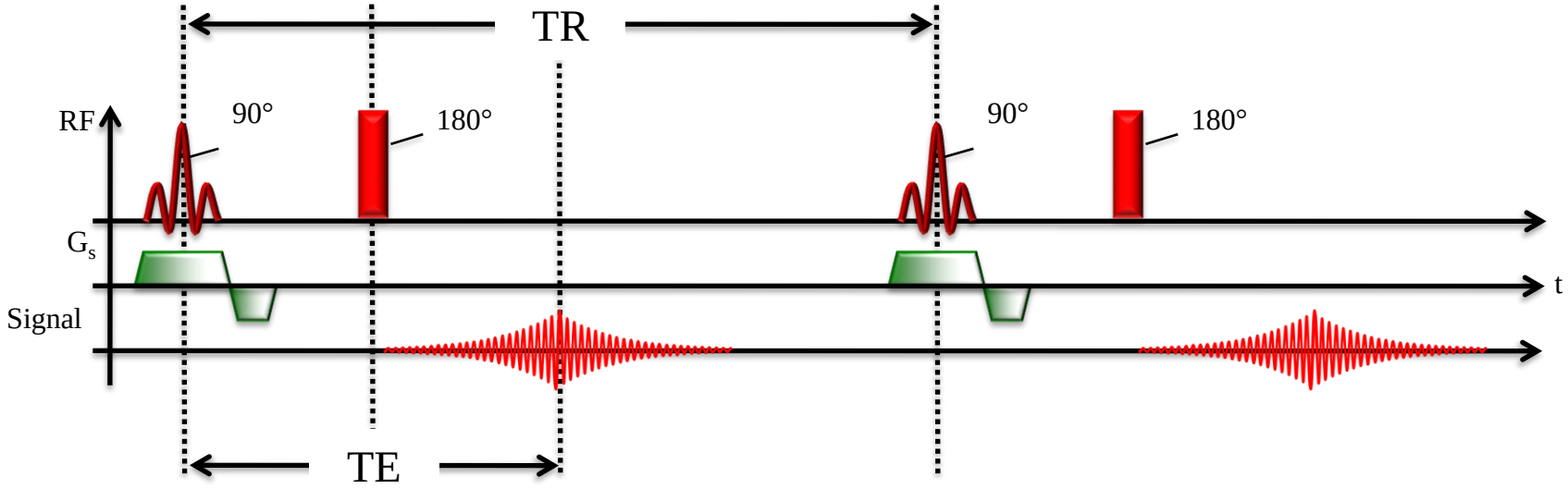


Spin Echo Sequence

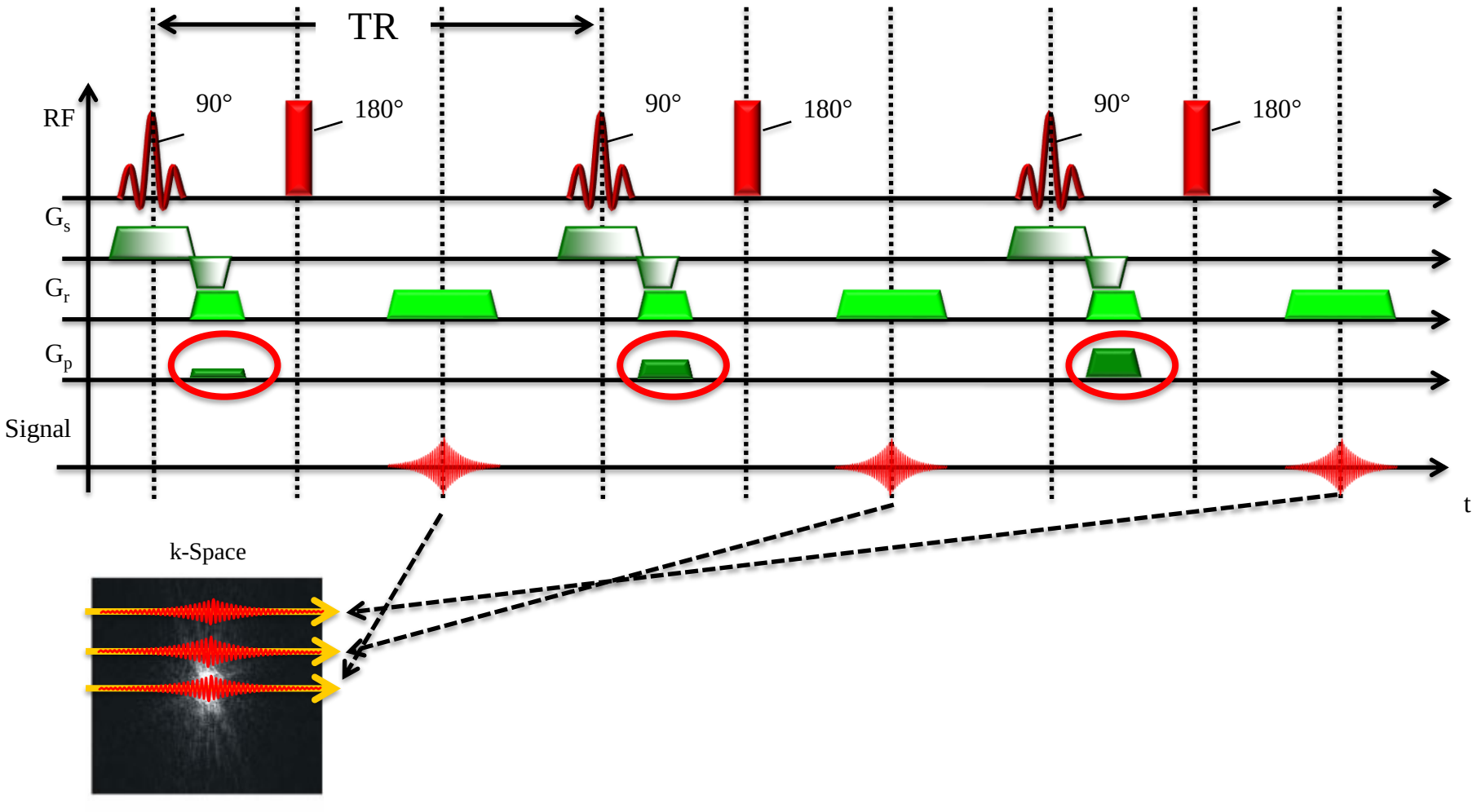


Spin Echo Sequence

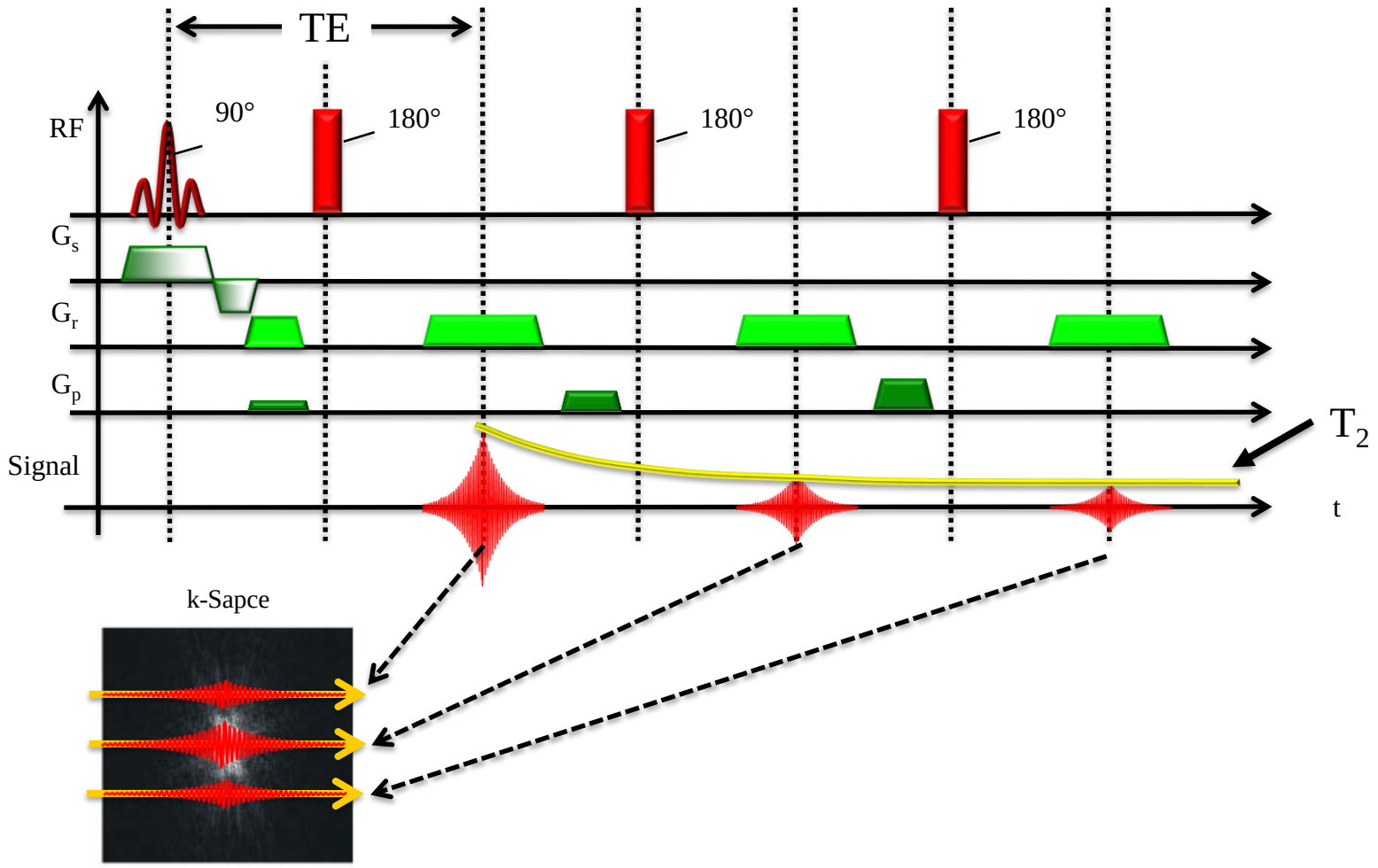
- Repetition time TR and echo time TE



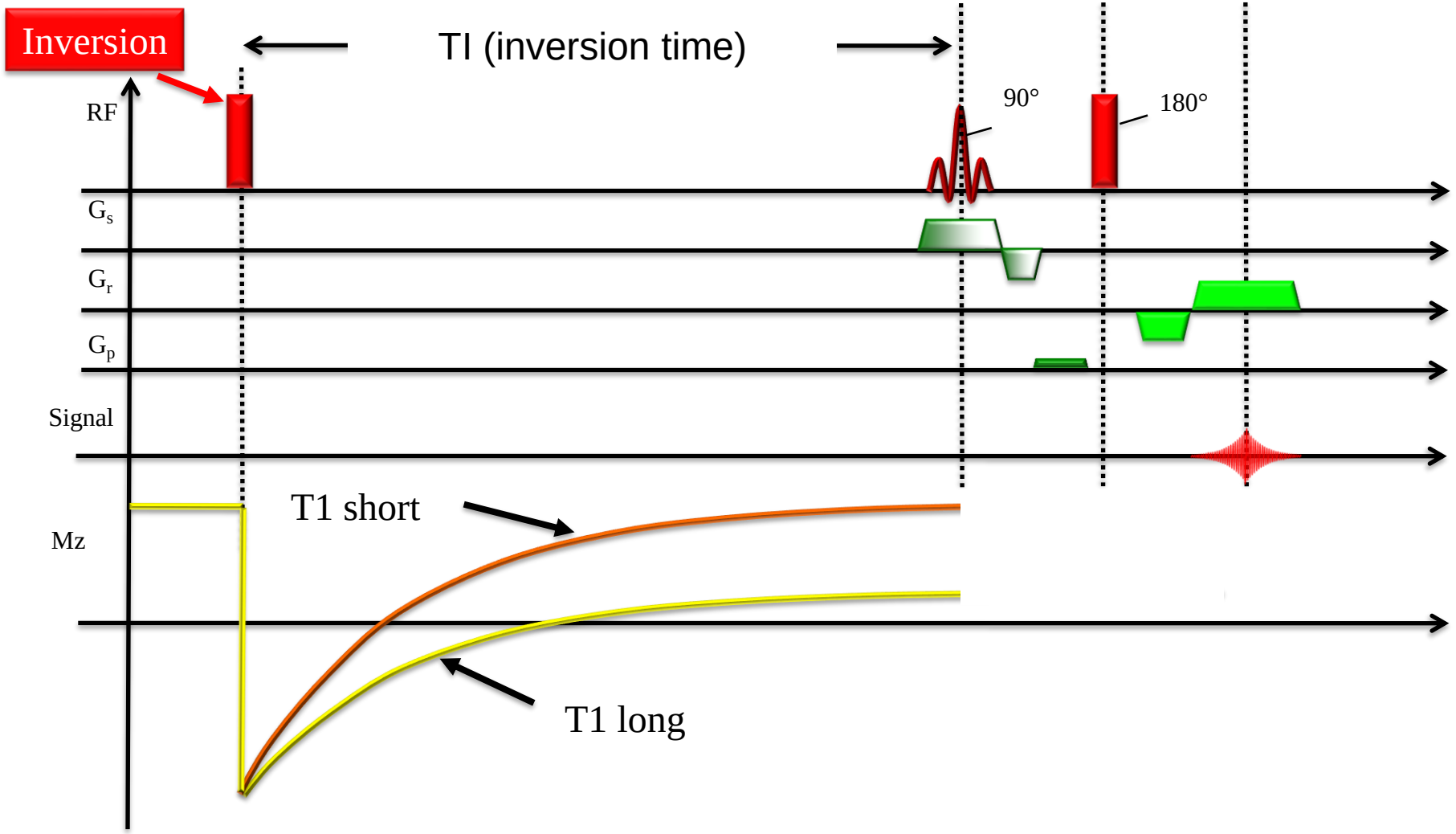
k-Space Filling with SE



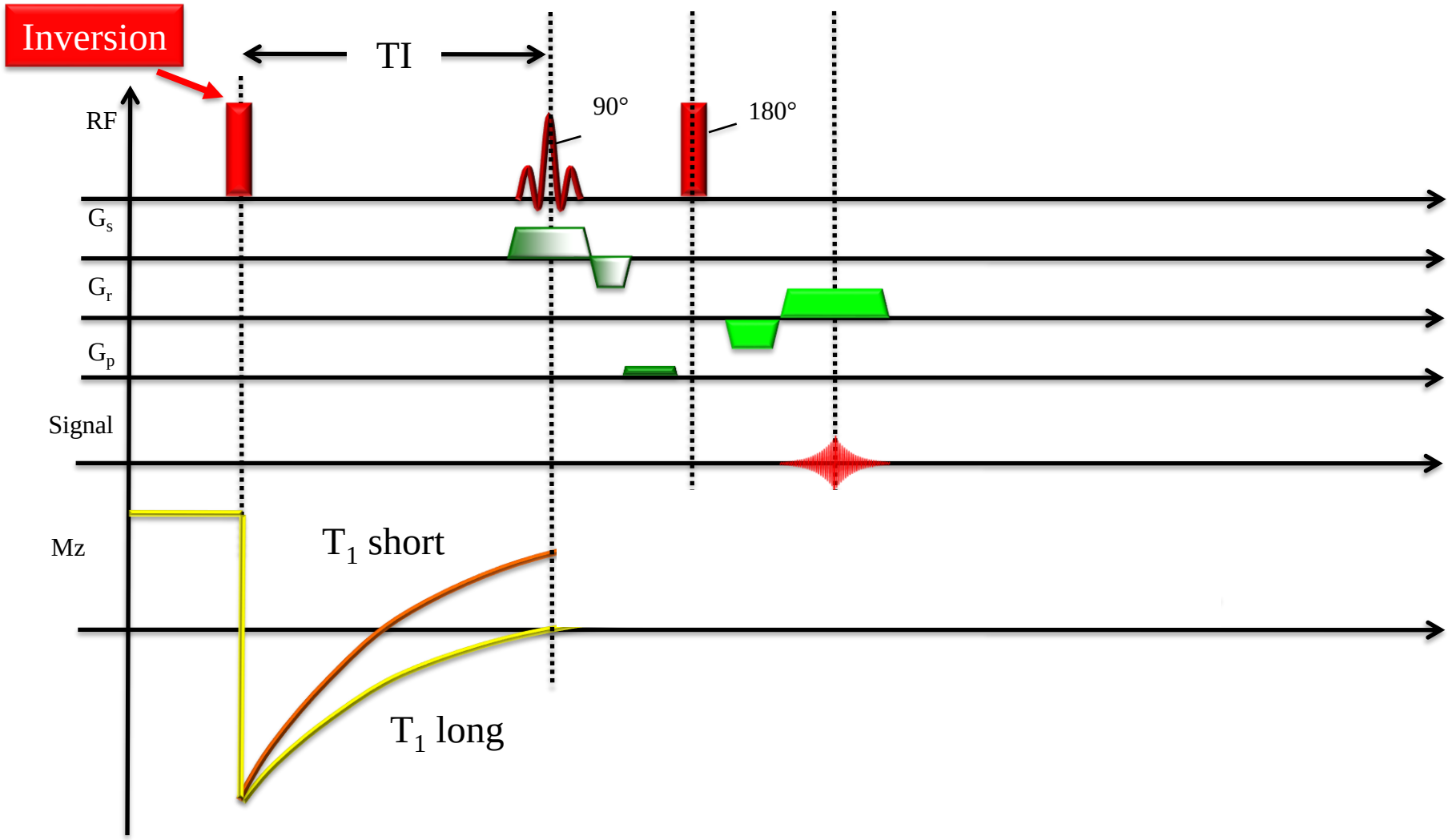
k-Space Filling with **Turbo** Spin Echo



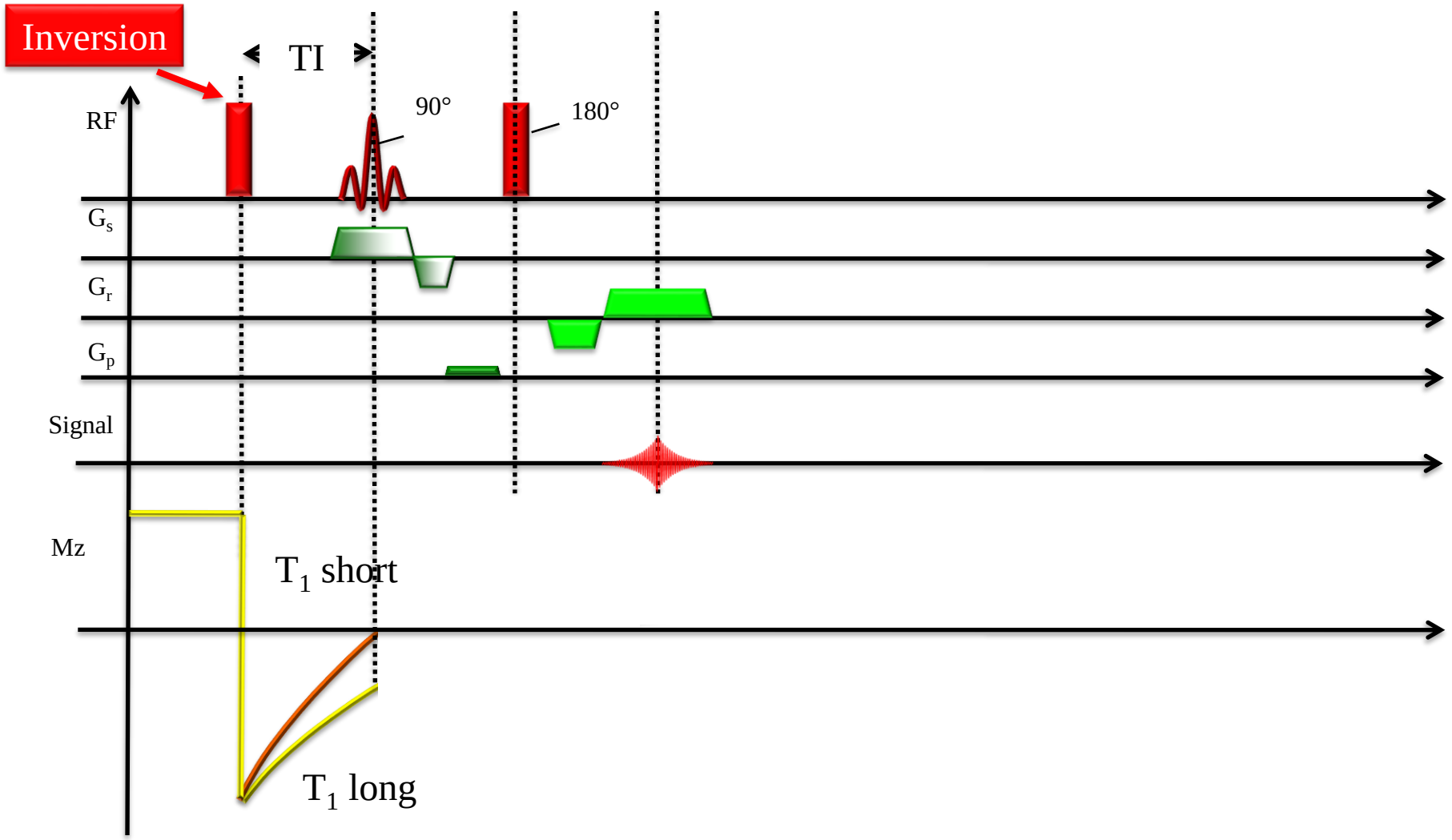
Inversion Recovery Preparation



Inversion Recovery Preparation

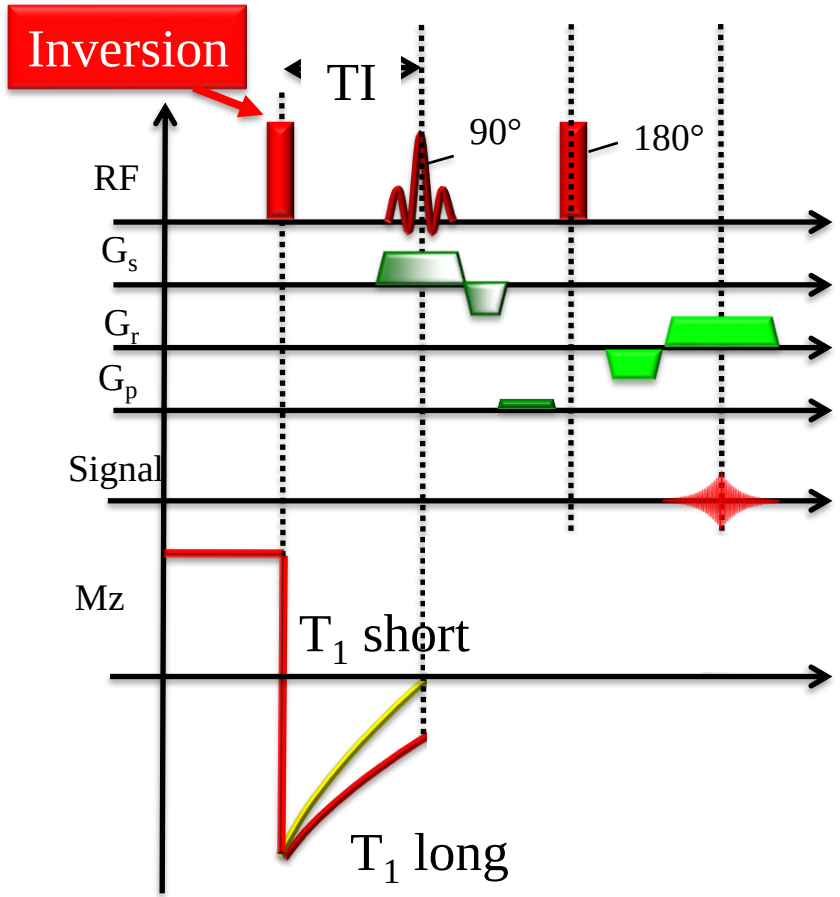


Inversion Recovery Preparation



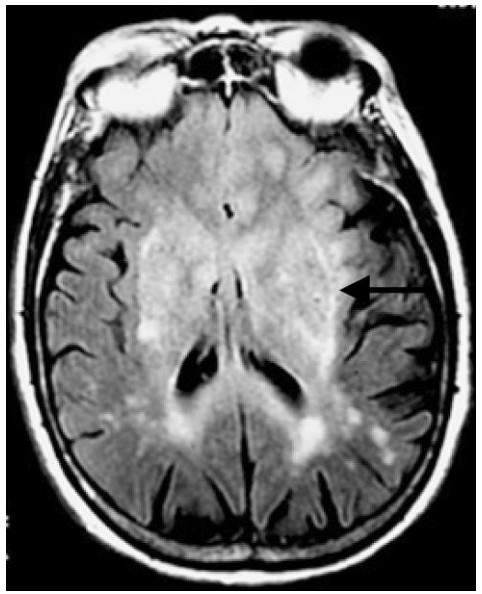
Example - STIR

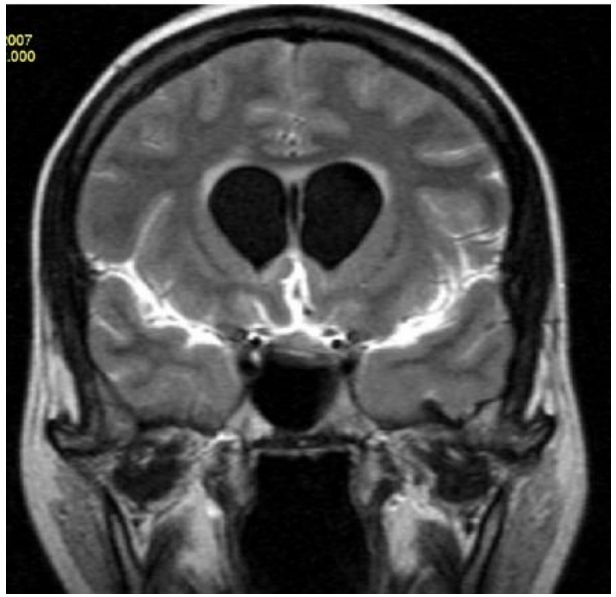
- Short-TI Inversion Recovery
- TSE with non-selective IR
- Short TI (usually 160-180 ms at 1.5T) to suppress fat
- Non-selective IR = robust, but inverts everything (so not post-Gd)



Example - FLAIR

- Fluid-Attenuated Inversion Recovery
- IR-TSE with TI chosen such that liquids (CSF, urine, blood, etc.) signals pass through zero



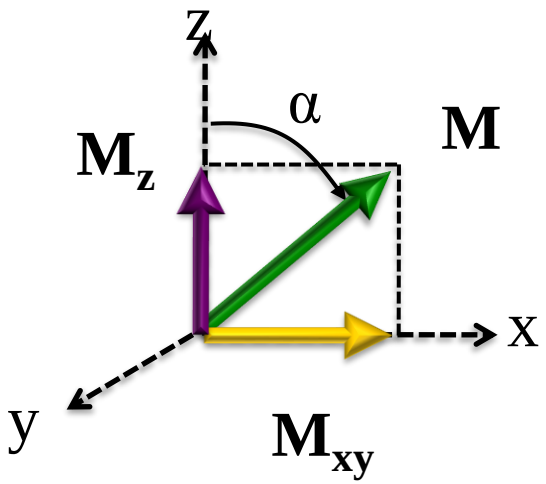


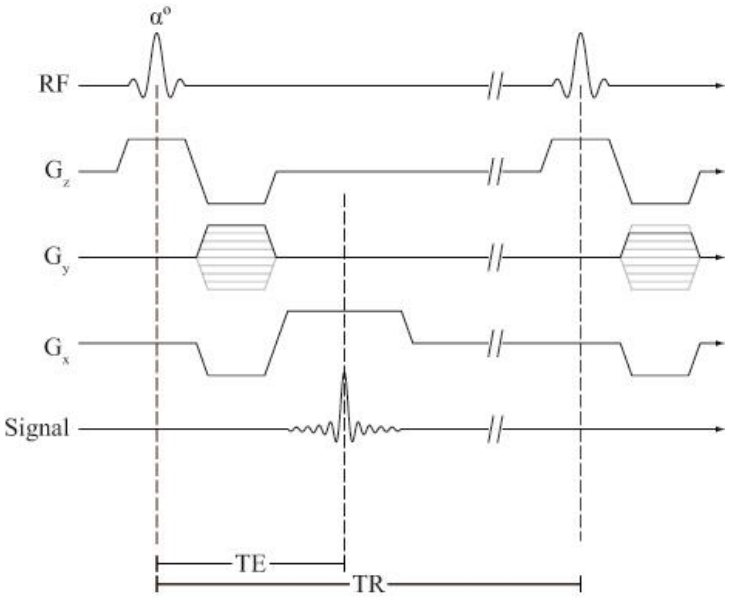
Wikipedia.org

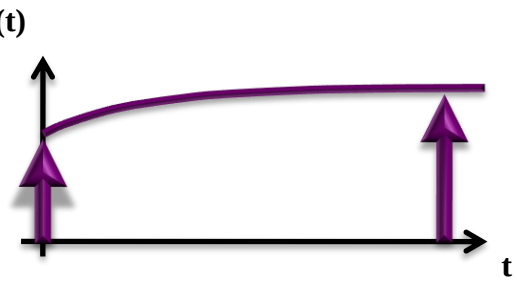
Spin Echo Sequence Summary

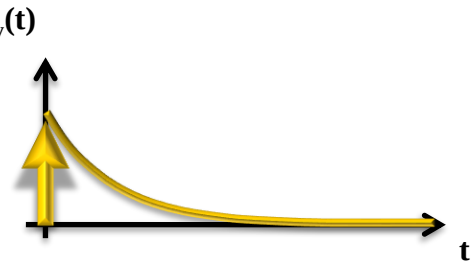
1. **t=0**: Slice selection and excitation with a 90° RF pulse and slice selection gradient G_s.
2. Spatial encoding with phase (G_p) and frequency (G_r) encoding gradients (line selection in k-space matrix).
3. **t=TE/2**: 180° refocusing RF pulse.
4. **t=TE**: refocus the spin with readout gradient to measure the MR signal (spin echo).
5. **t=TR**: repeat sequence to encode another k-space line.

Image Contrast



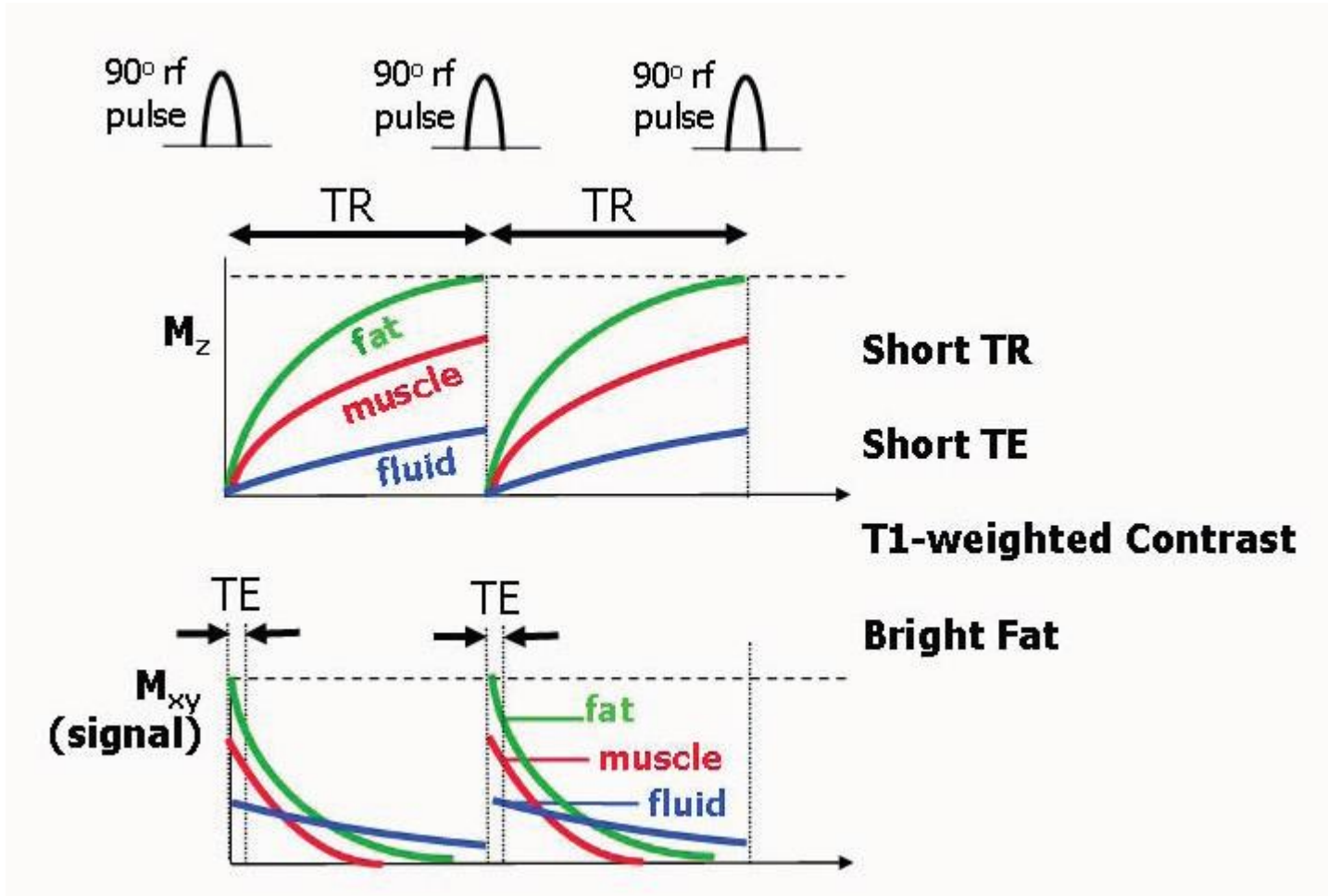




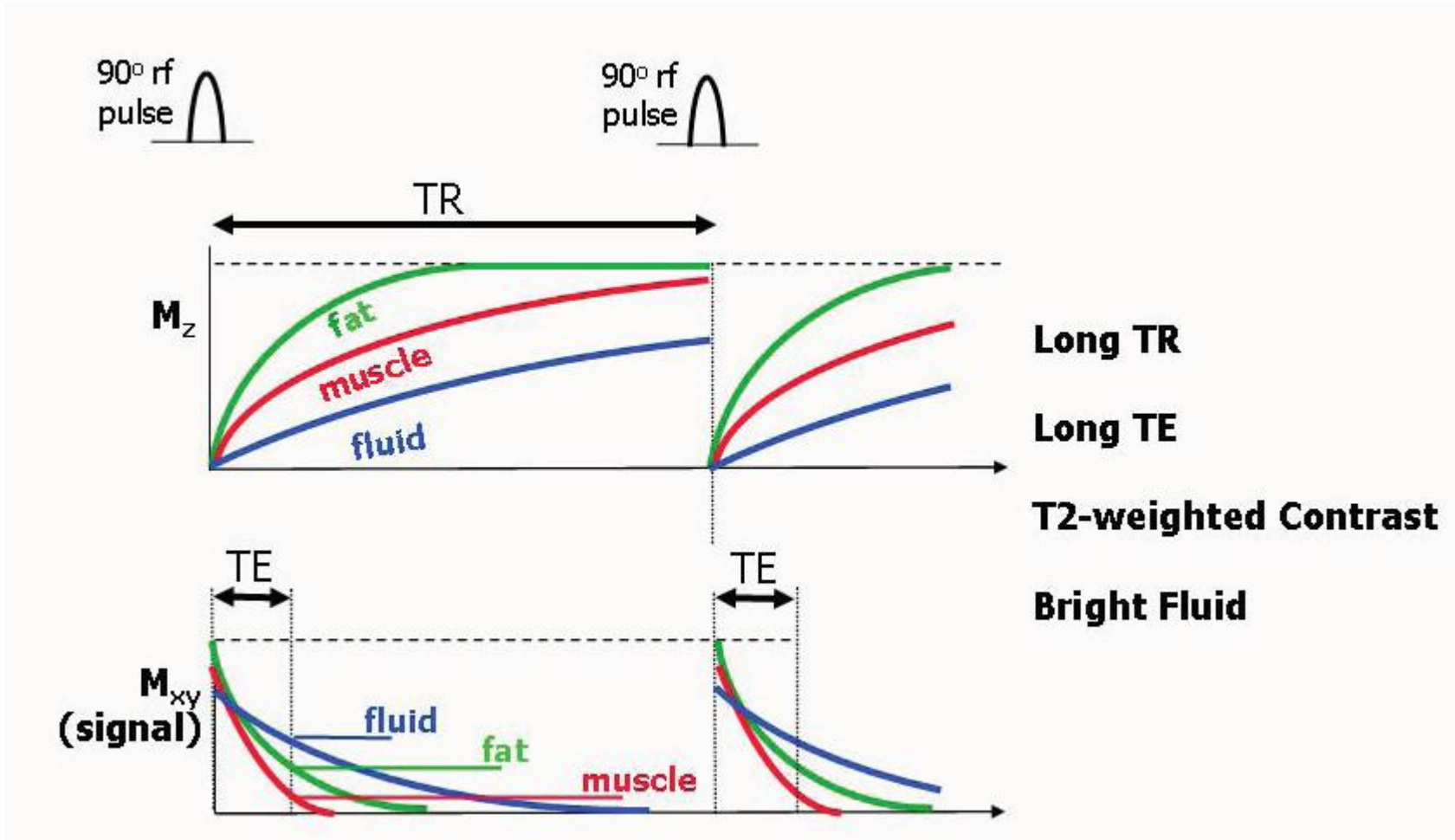


- Long TRs minimize T_1 effects, since all tissues have time to **fully recover** between excitations
- Short TEs minimize T_2 effects, since there is little time for T_2 decay differences **to appear**

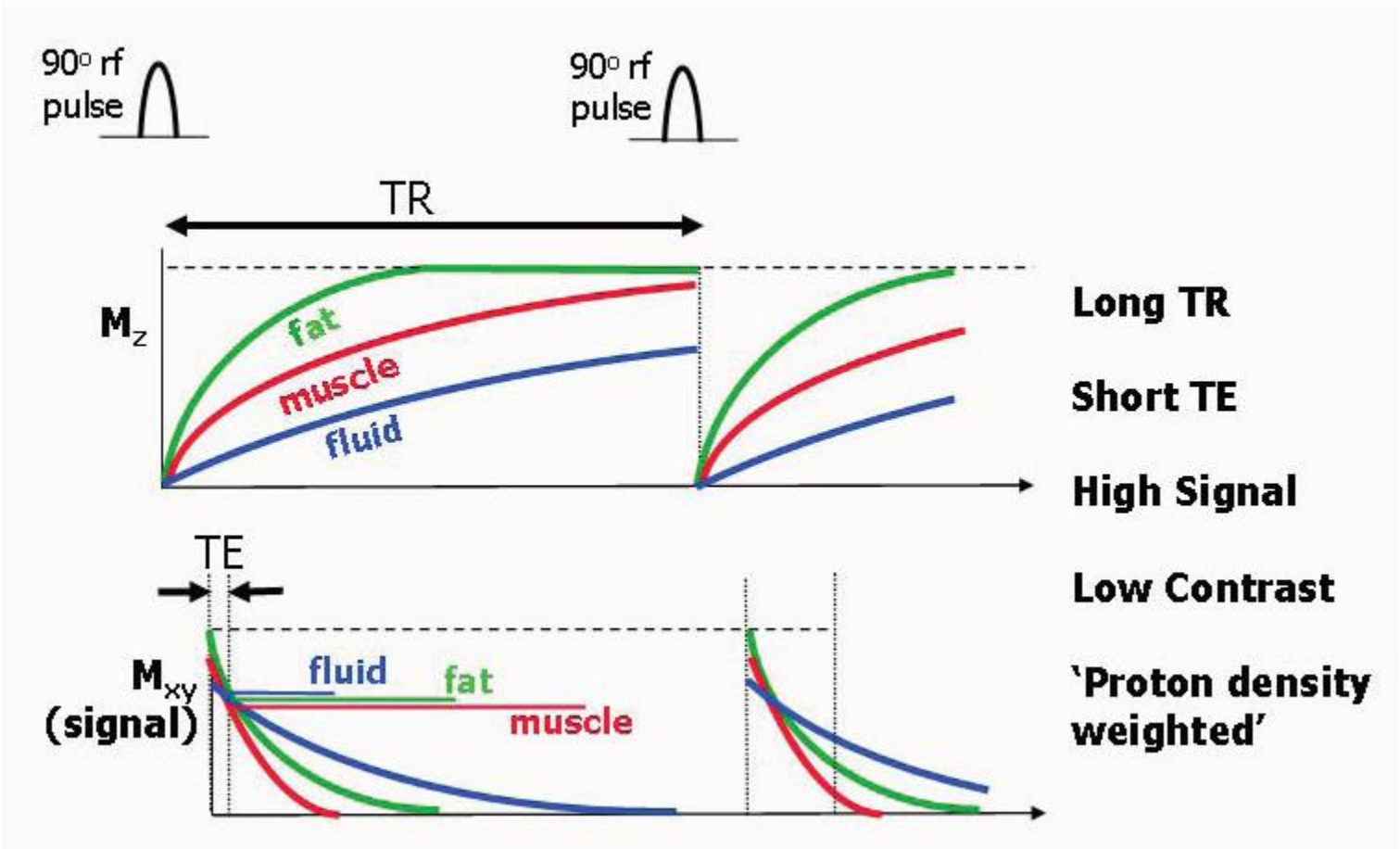
T_1-Weighted Contrast



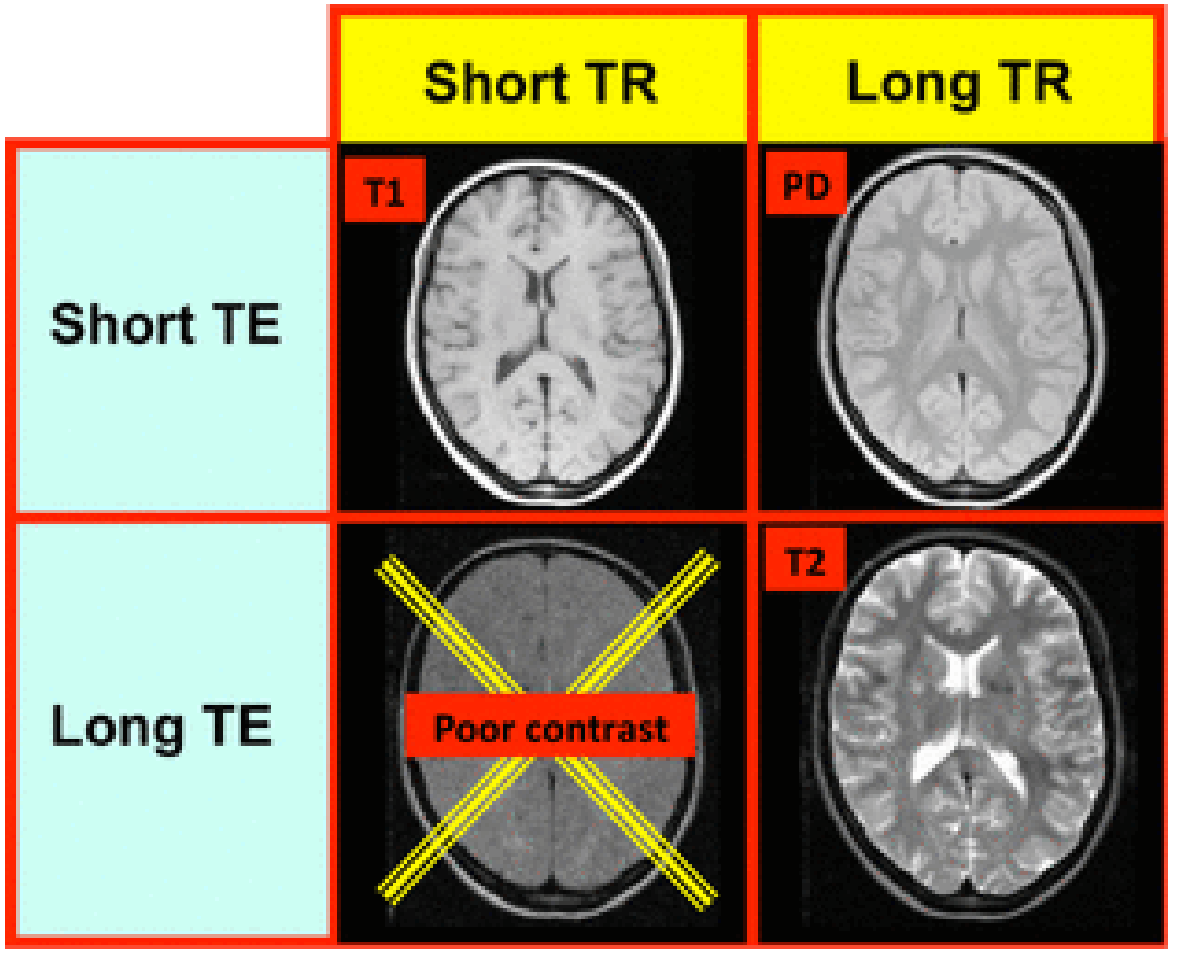
T_2-Weighted Contrast



Proton Density-Weighted Contrast

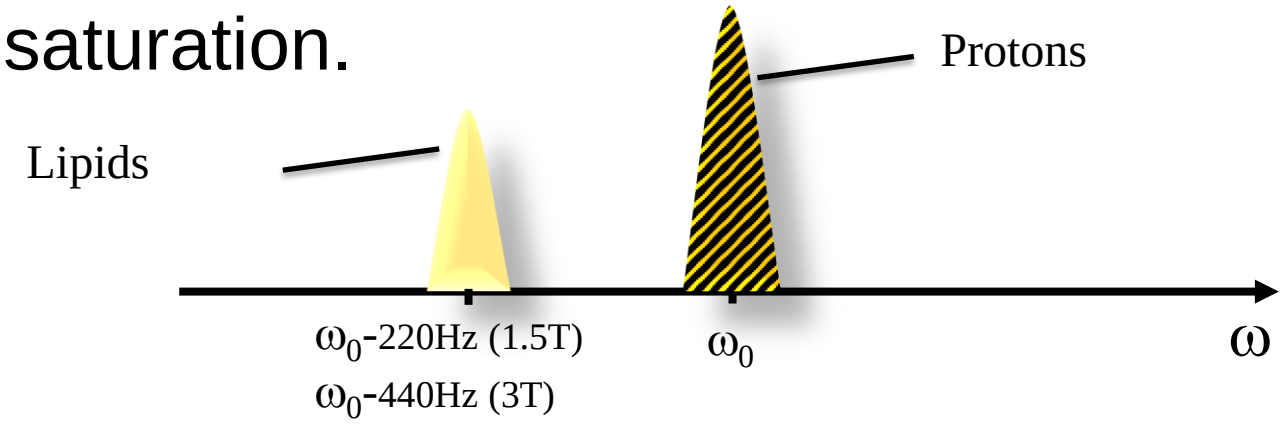


TE vs TR

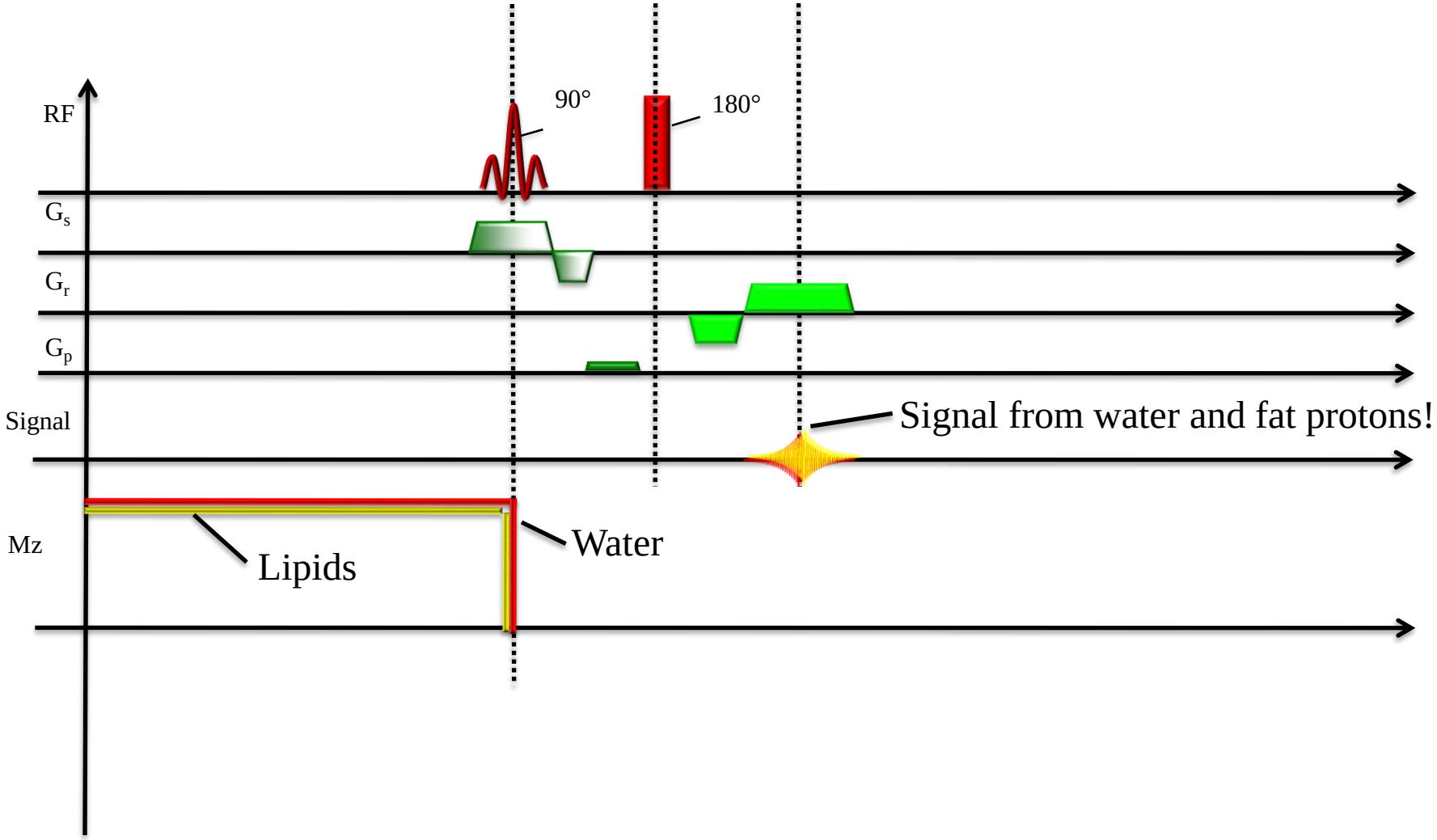


Fat Signal Suppression

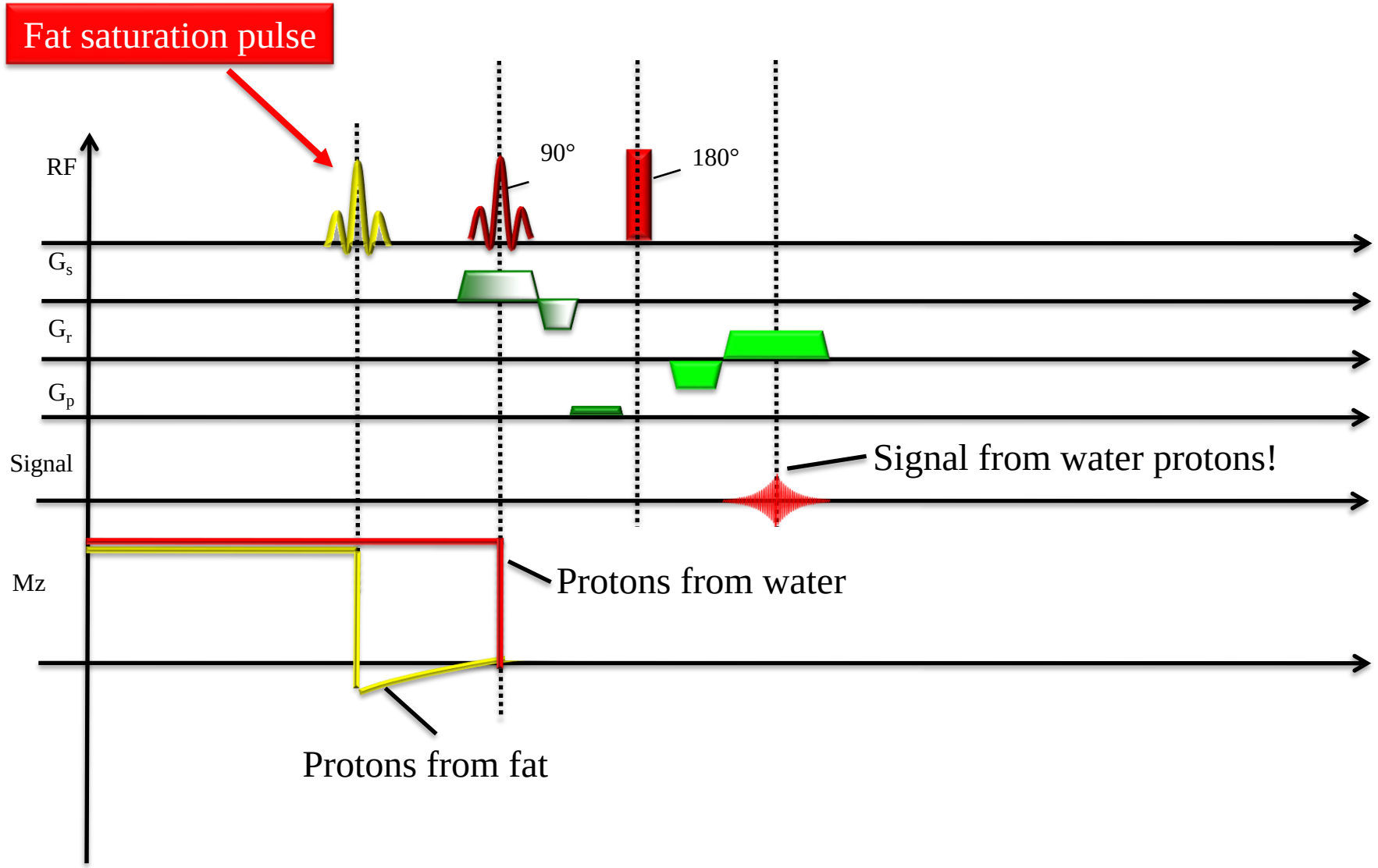
- Fat signal suppression techniques are used to suppress the signal from adipose tissue.
- Lipid protons and hydrogen protons from water have a small difference in resonance frequency , which is related to the different electronic environments.
- This so-called chemical shift allows frequency-selective fat saturation.



Without Fat Saturation Pulse

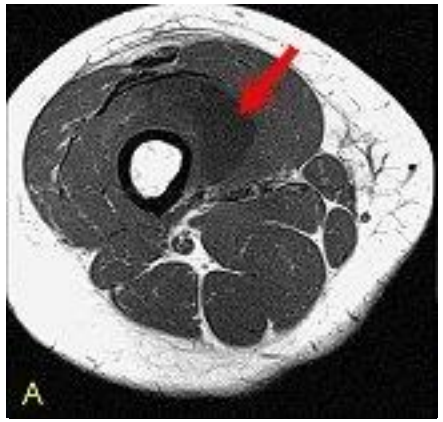


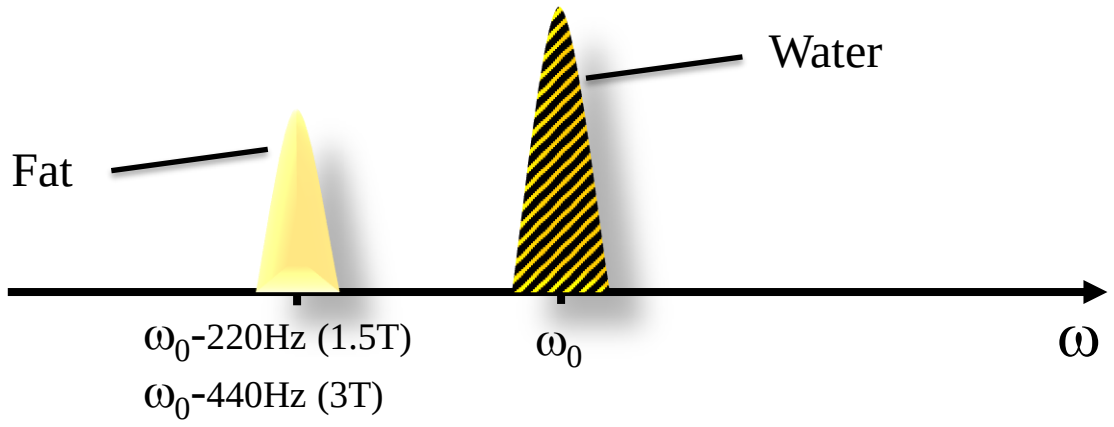
With Fat Saturation Pulse



Fat Saturation

Edema

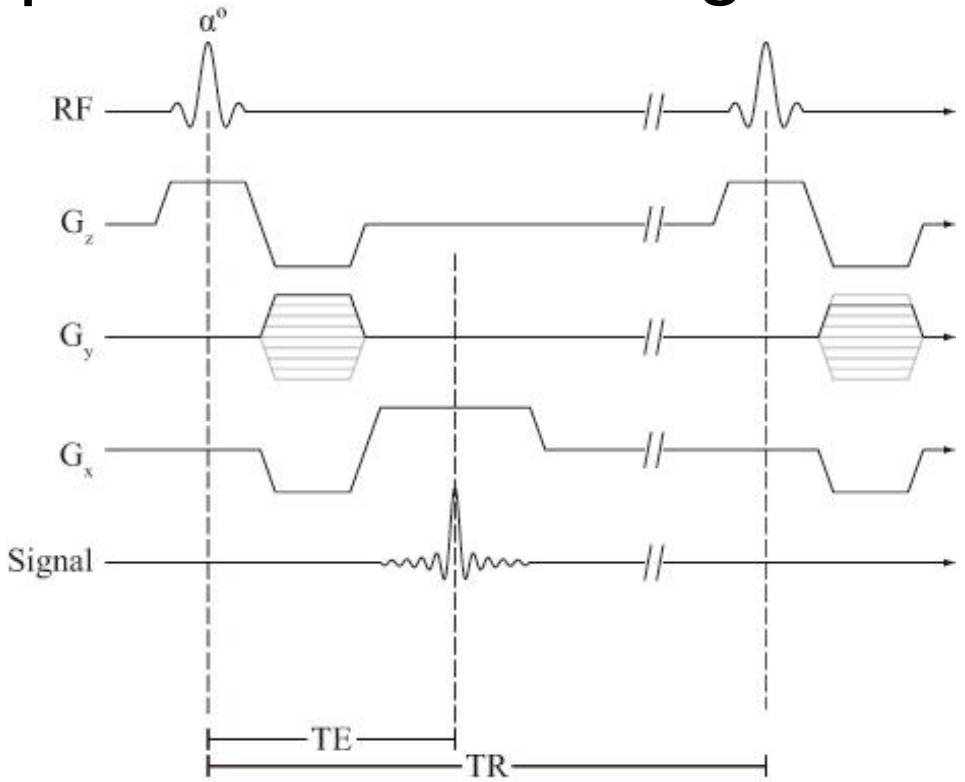




Gradient echoes

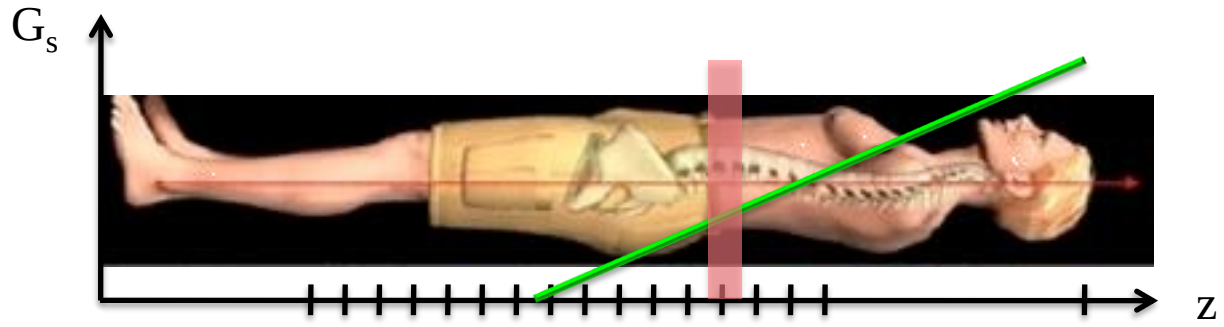
Gradient Echo Sequence

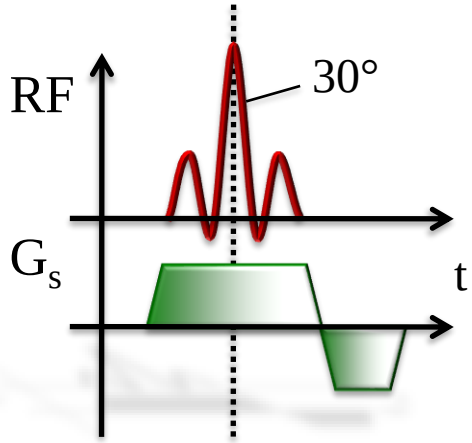
- An RF excitation pulse (less than 90°) is followed by a controlled application of **magnetic field gradients** to de- and refocus the spins and create a gradient echo.

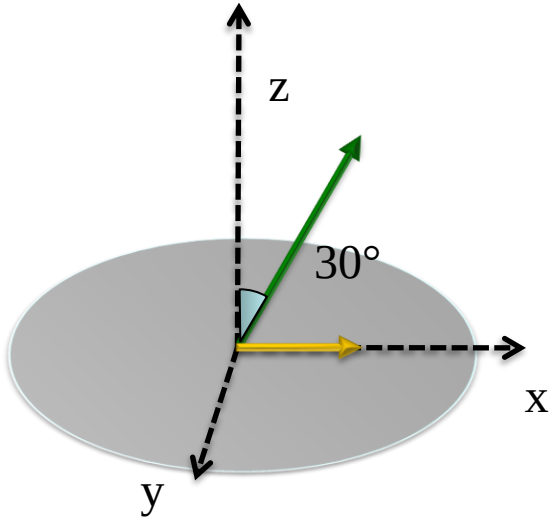


Gradient Echo Sequence

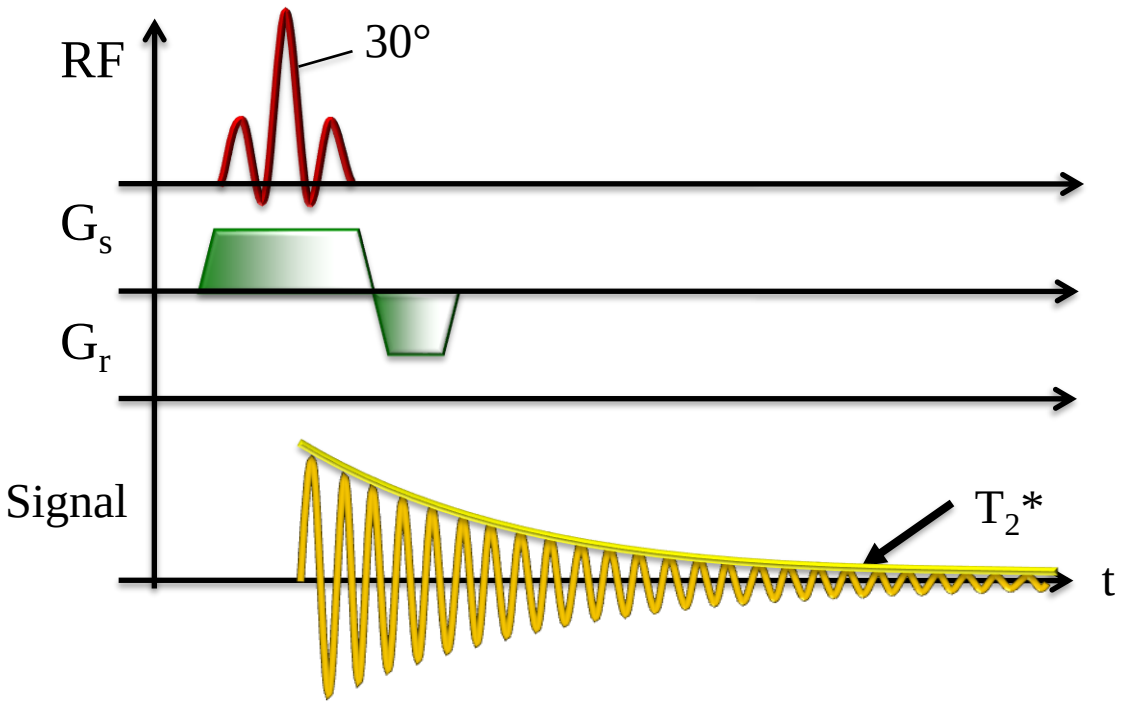
1) Slice selection at t=0 (RF excitation pulse <90°).

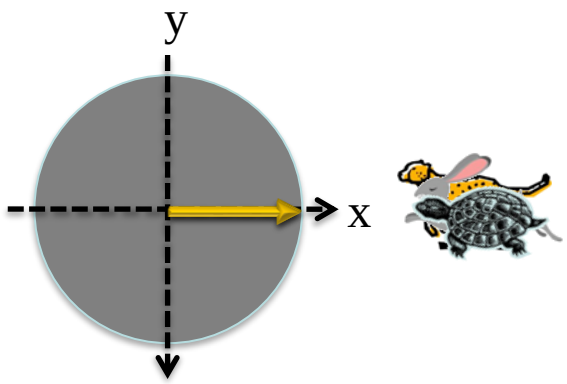




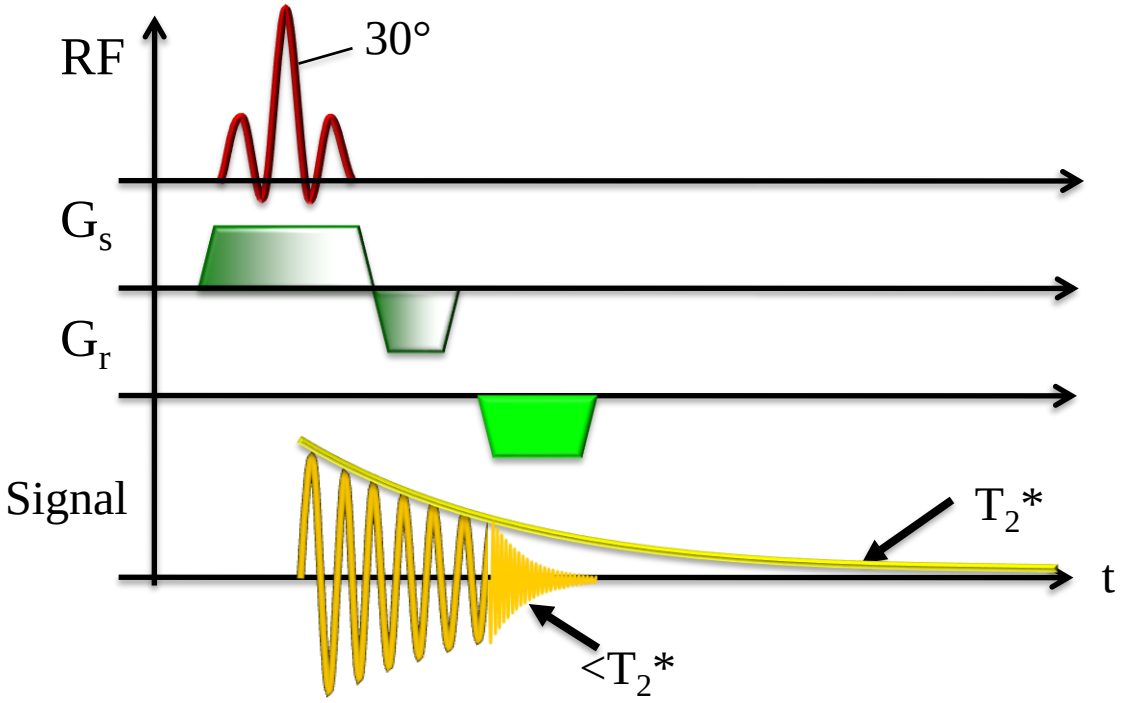


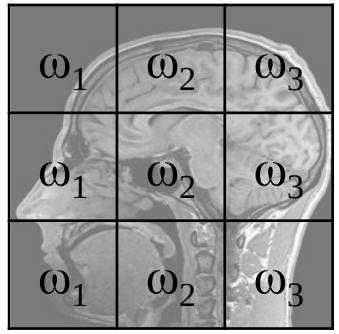
Gradient Echo Sequence

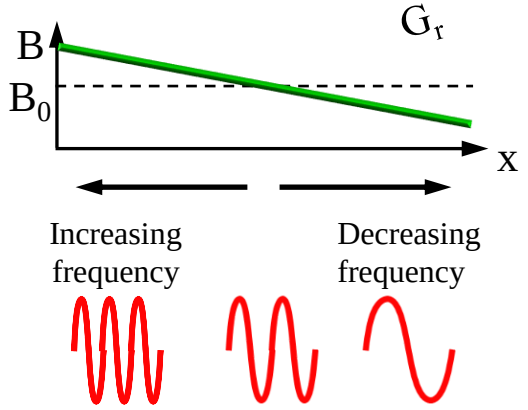




Gradient Echo Sequence

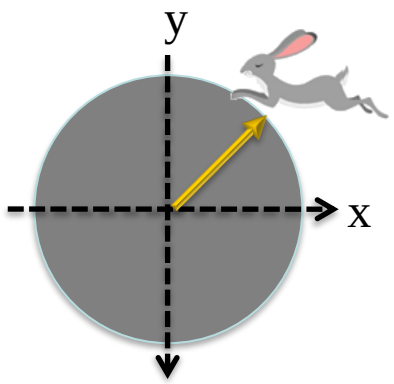




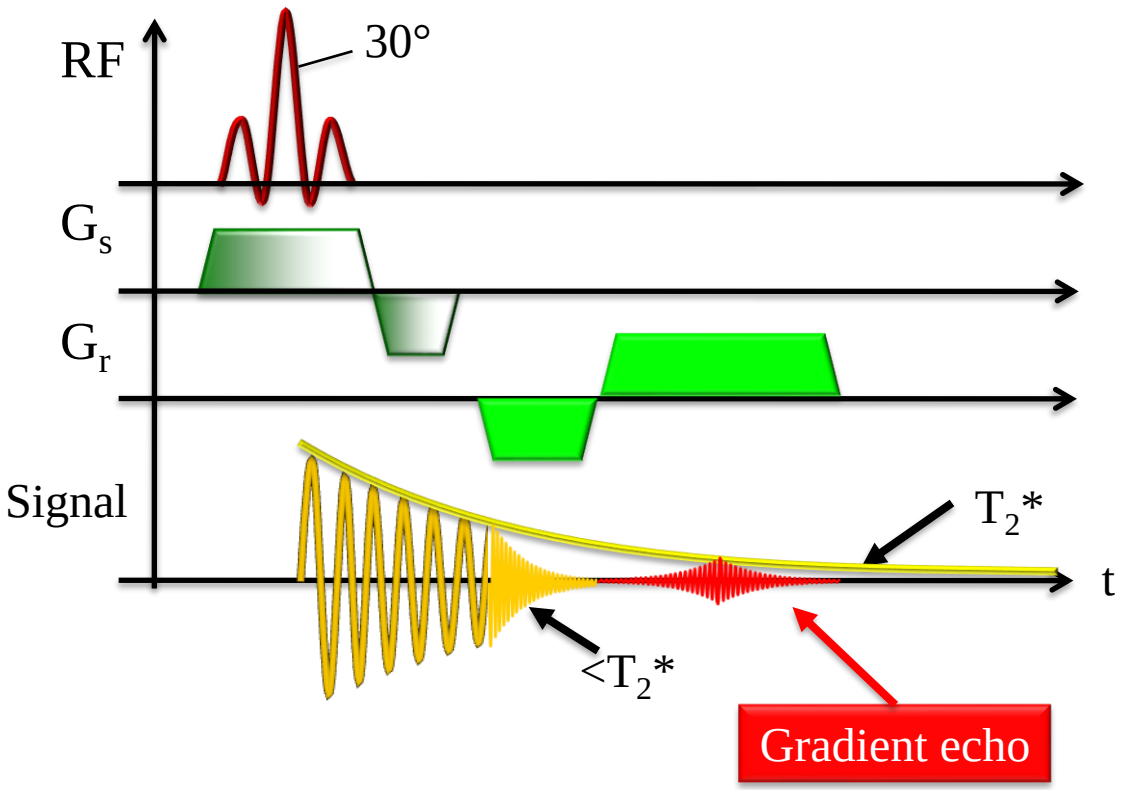


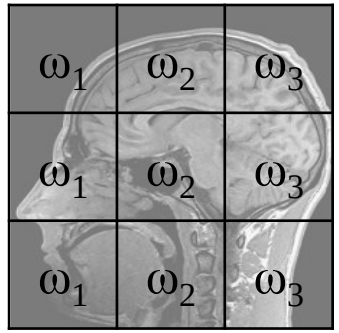
2) Spin de-phasing

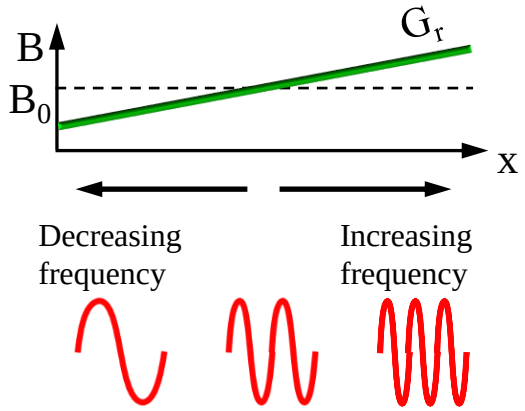
– Transverse relaxation: <<T_2*, accelerated by readout gradient G_r).



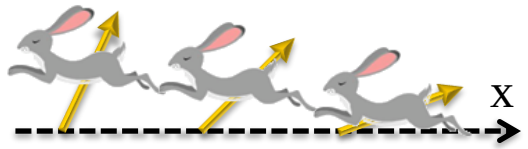
Gradient Echo Sequence





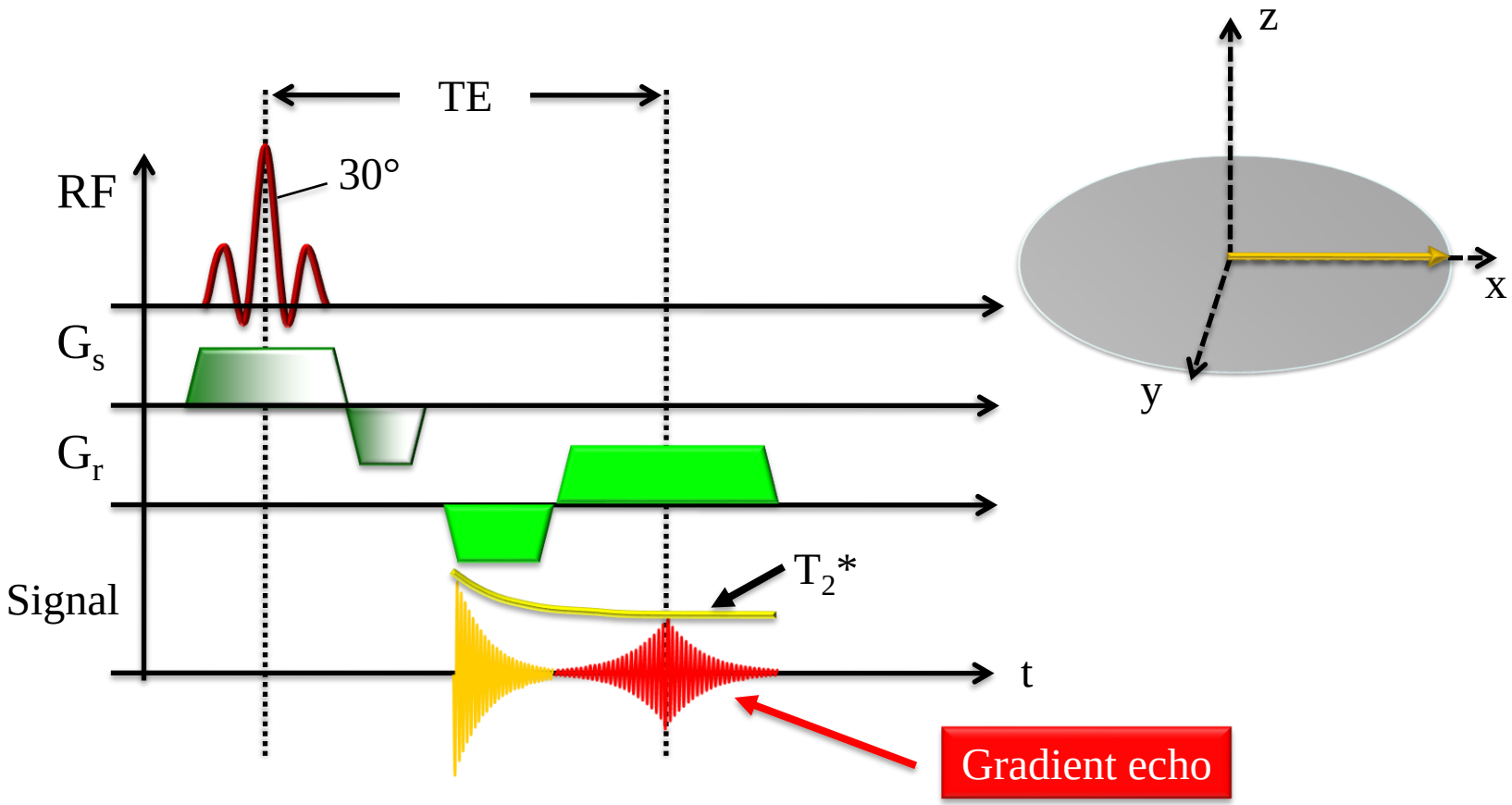


3) Refocusing of the spins with bipolar gradient.



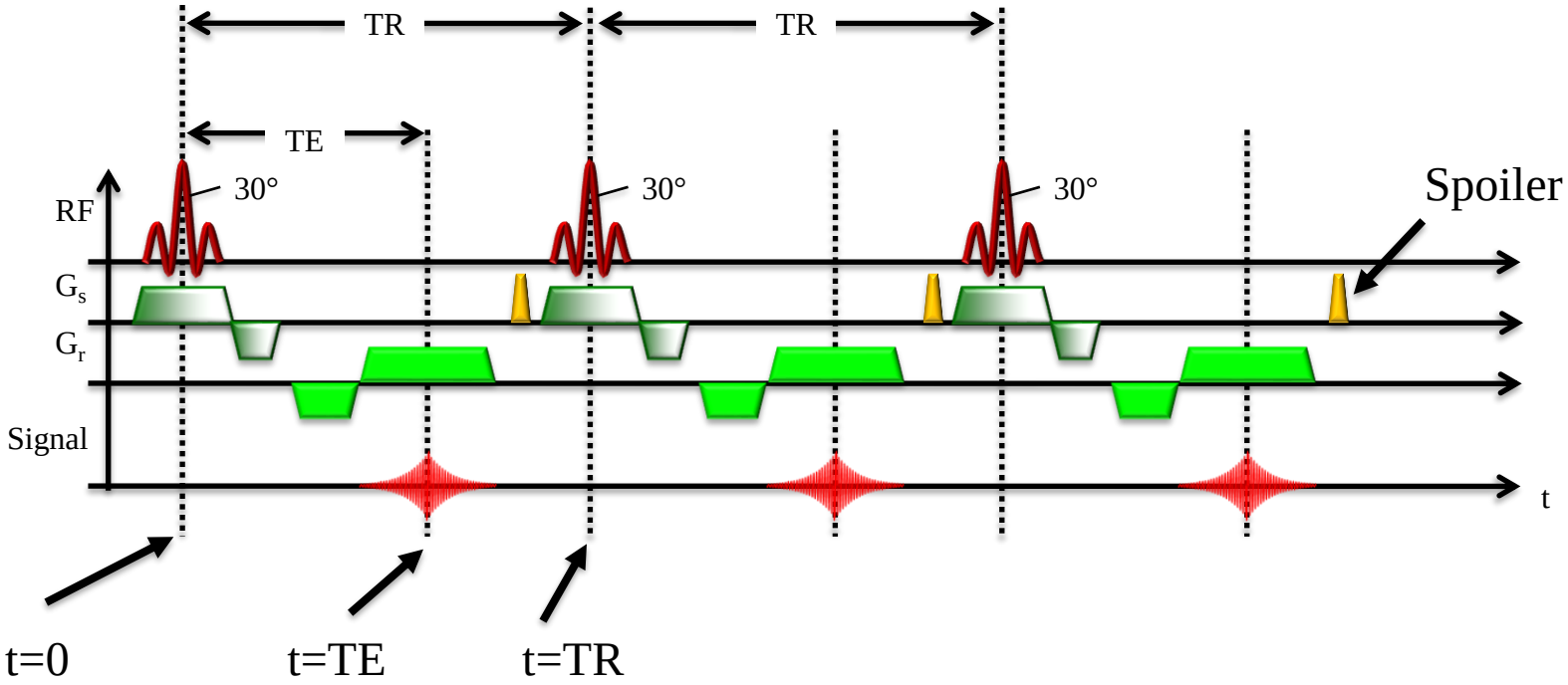
Gradient Echo Sequence

- Gradient echo at time TE

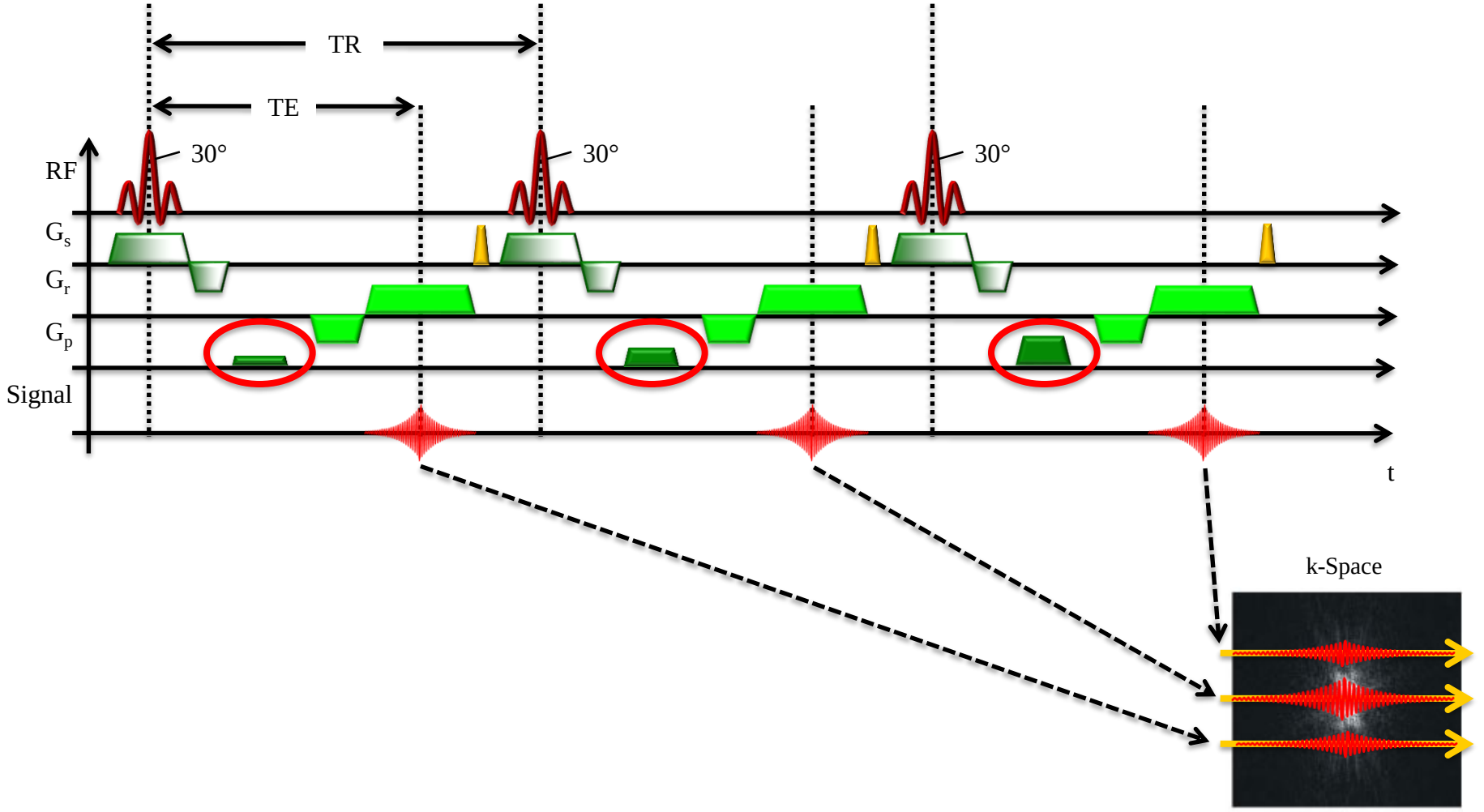


Gradient Echo Sequence

- Repetition time TR



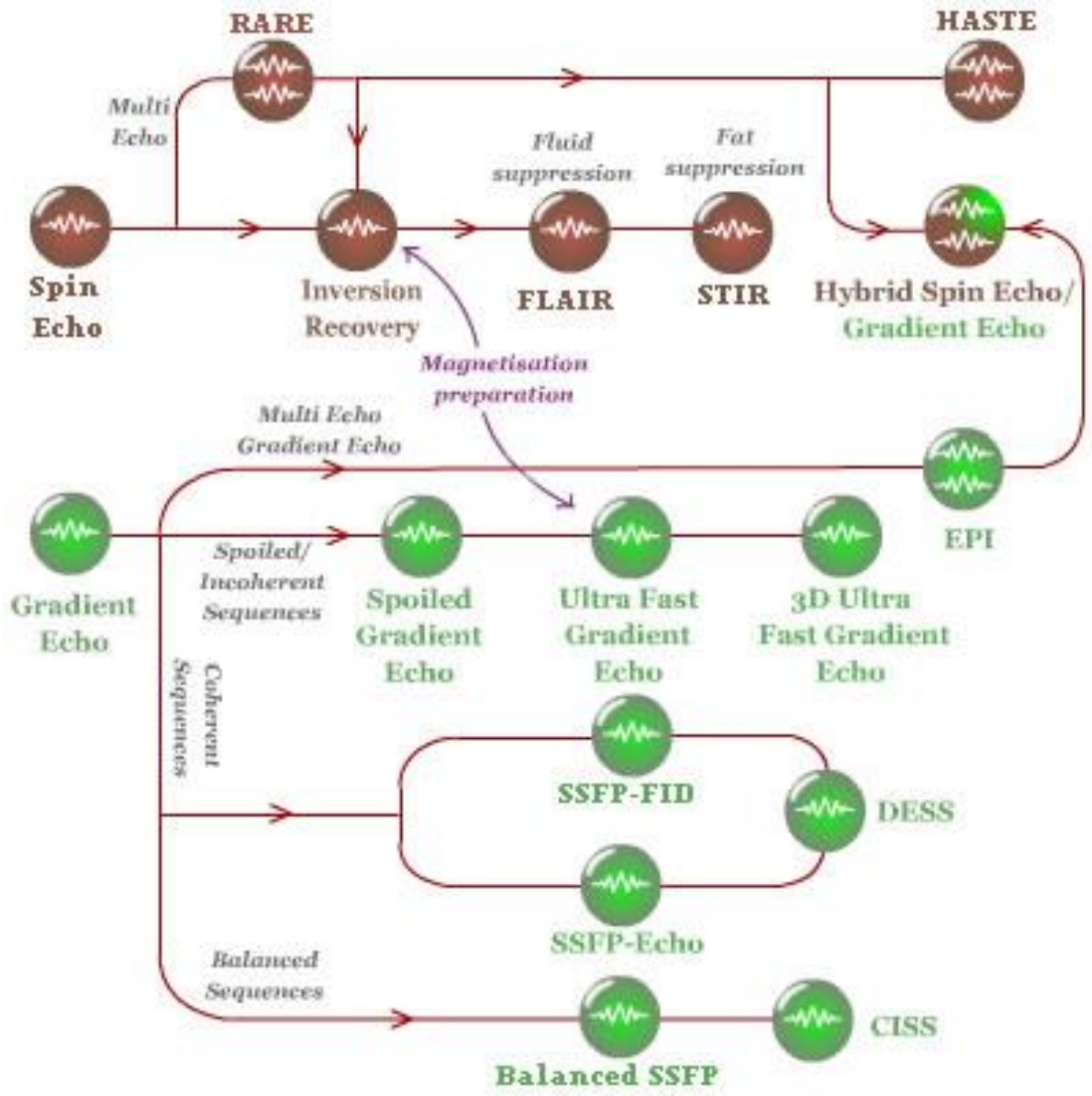
k-Space Filling with GRE Sequence



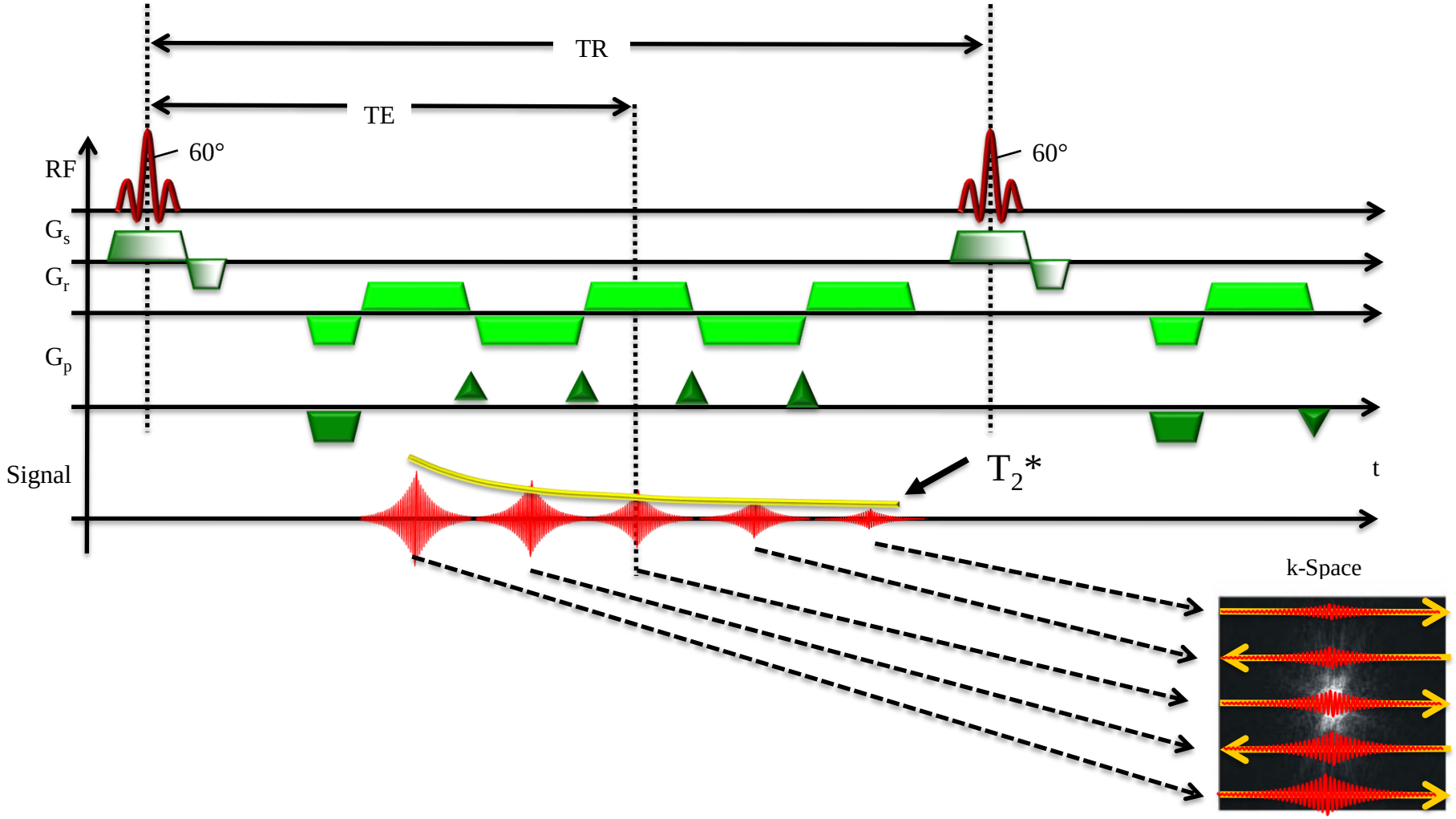
Gradient Echo Sequence Summary

- 1.) t=0: Slice selection and excitation with a <90° RF pulse and slice selection gradient G_s.
- 2.) Spatial encoding with phase (G_p) and frequency (G_r) encoding gradients (line selection of k-space matrix).
- 3.) t=TE: Refocus spins readout gradient to measure the MR signal (gradient echo).
- 4.) t=TR: Repeat sequence to encode another k-space line.

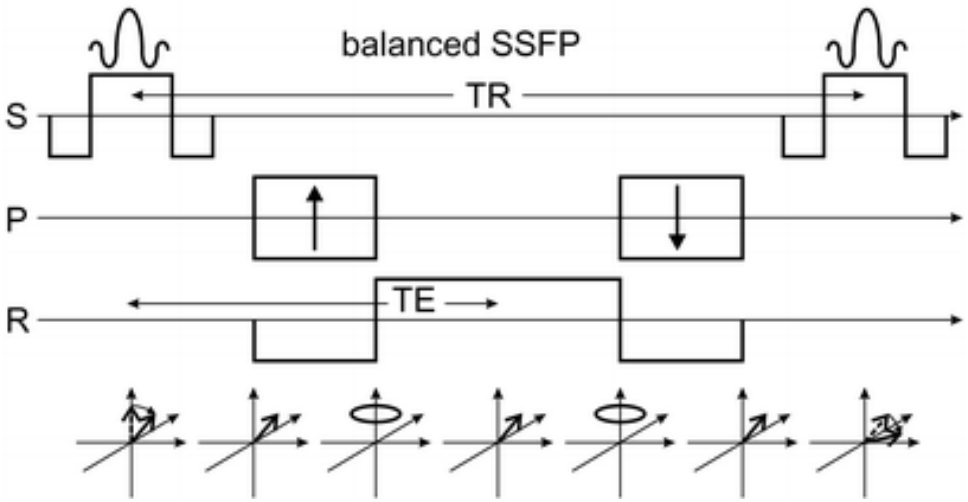
Families of Pulse Sequences

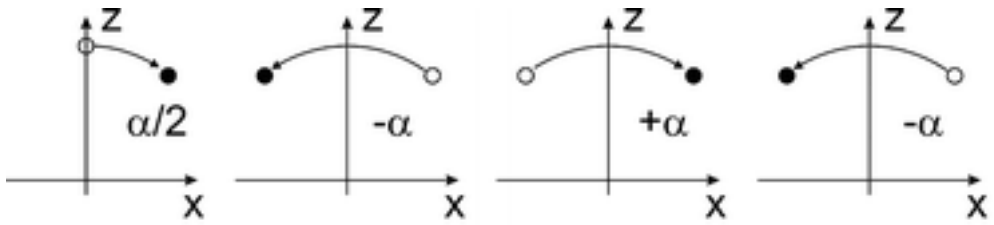


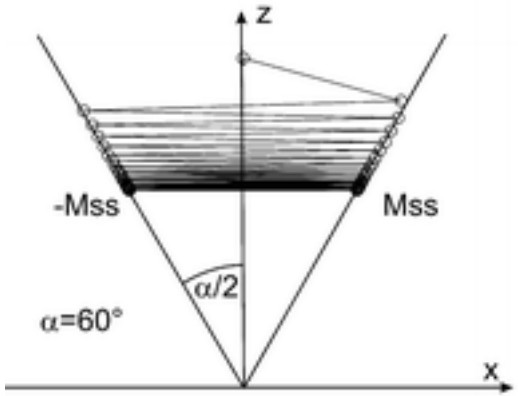
Echoplanar Imaging (EPI)

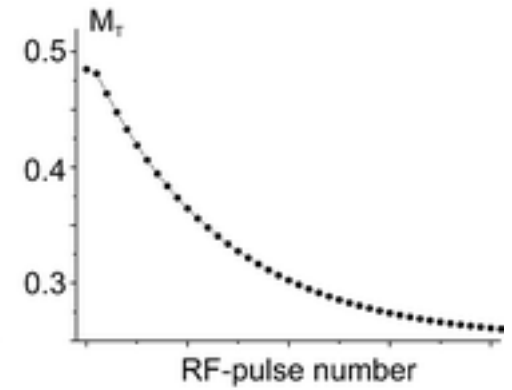


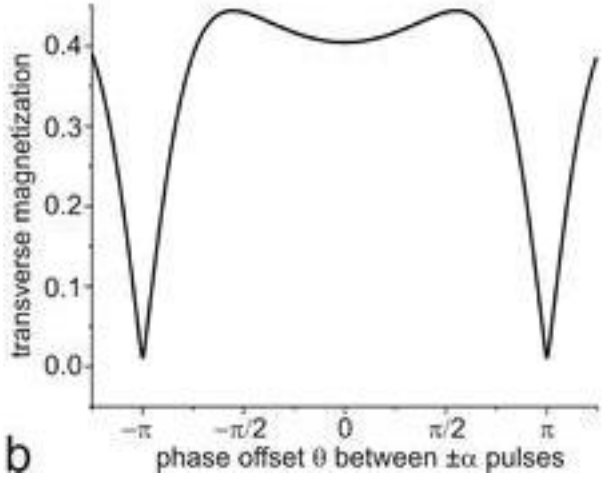
Balanced steady-state free precession (bSSFP)











- Everything balanced – no need to dephase
- Allows for high flip angle
- Dark rim artifacts in inhomogeneities

Scheffler & Lehnhardt. Eur Radiol 2003

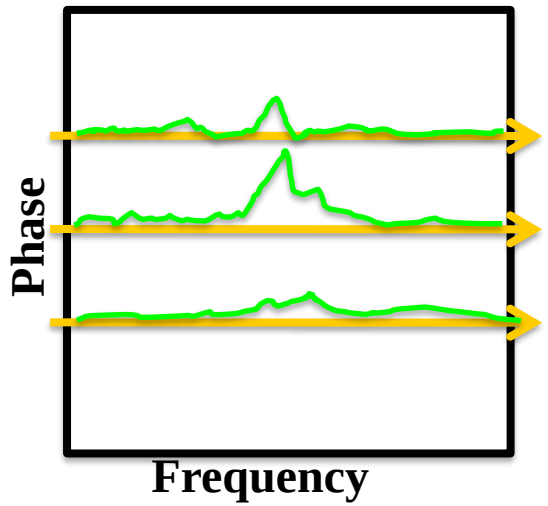
Families of Pulse Sequences

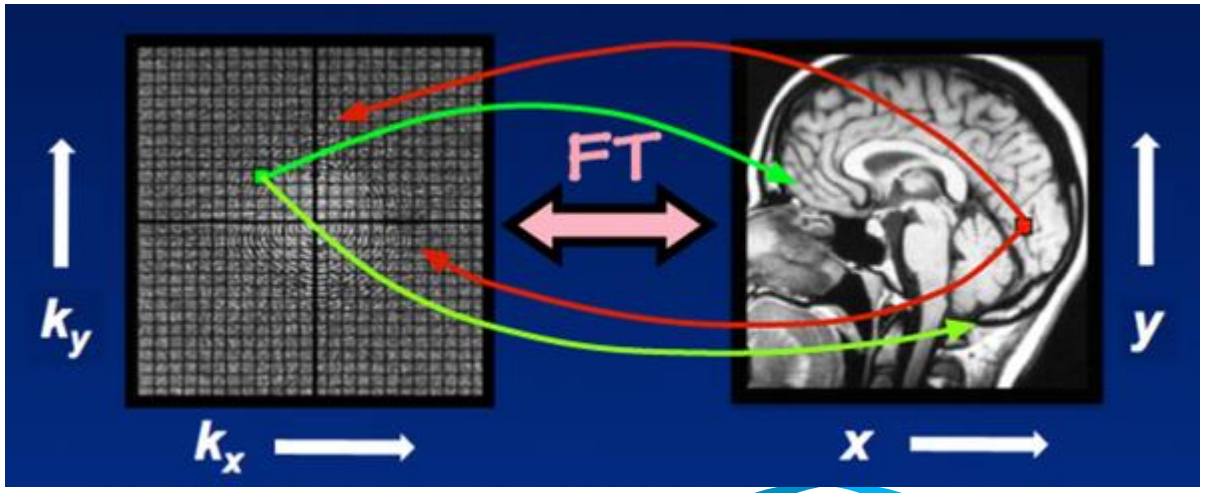
Sequence	Siemens	GE	Philips	Hitachi	Toshiba
Generic Gradient Echo	GRE	GRE	FFE	GE	FE
RF-Spoiled GRE	FLASH	SPGR	T1-FFE	RSSG	T1-FFE
Coherent GRE with "FID" Refocusing	FISP	GRASS	FFE	SARGE (SG)	FE
Coherent GRE with "Echo" Refocusing	PSIF	SSFP	T2-FFE	TRSG	SSFP
Coherent GRE with Balanced "FID/Echo" Refocusing	True FISP	FIESTA	Balanced FFE	BASG	True SSFP
Coherent Balanced GRE using Dual-excitation	CISS	FIESTA-C	---	PBSG	---
Coherent Double GRE using Combined "FIDs" & "Echoes"	DESS	MENSA	---	---	---
Spoiled GRE using Combined Multiple FIDs	MEDIC	MERGE	M-FFE	---	---
Ultrafast GRE	TurboFLASH (2D) MP-RAGE (3D)	Fast GRE BRAVO (3D)	TFE 3D T1-TFE	RGE (2D) 3D-GEIR	Fast FE
Spoiled 3D GRE Variants	VIBE	FAME/LAVA	THRIVE	TIGRE	3D QUICK
GRE Plus SE with Combined Signal	TGSE	---	GRASE	---	Hybrid EPI

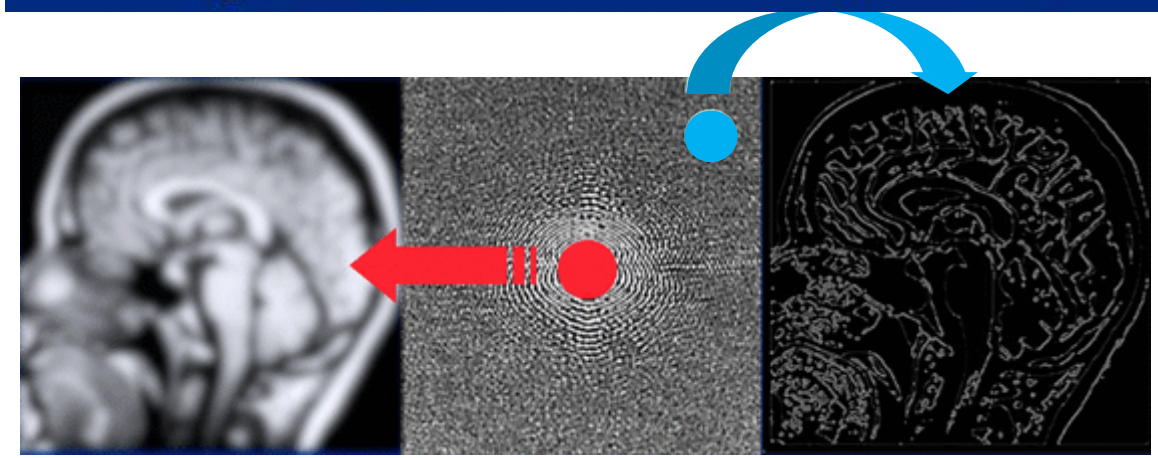
Search online for "Siemens MRI acronyms" for an overview

k-Space versus image space

- Each point in k-space has information on the entire image and vice versa





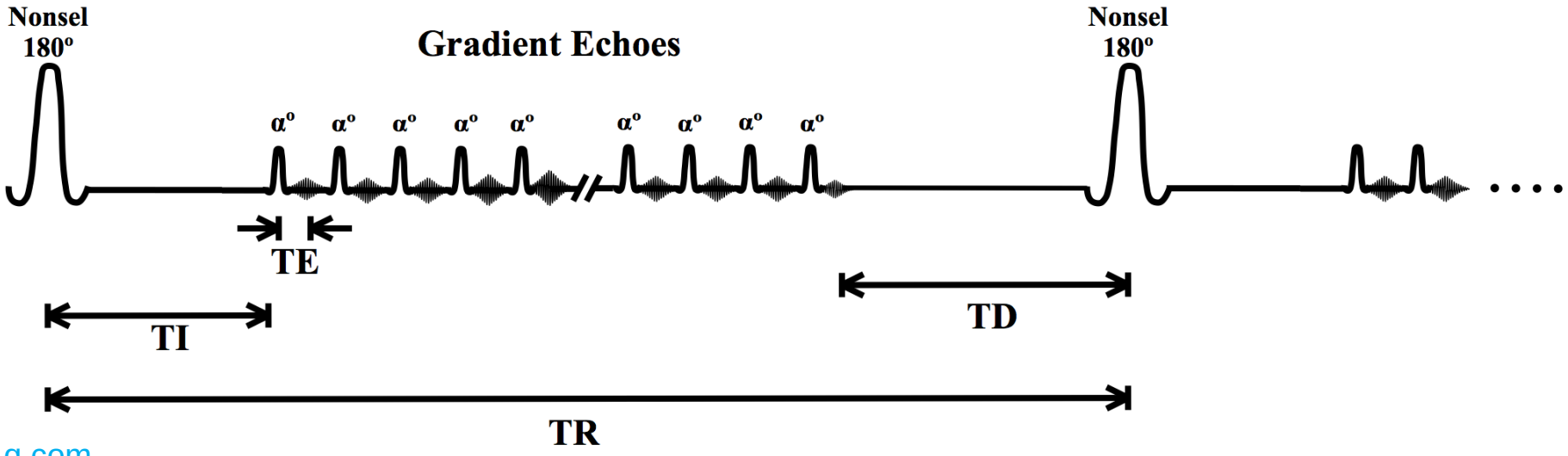


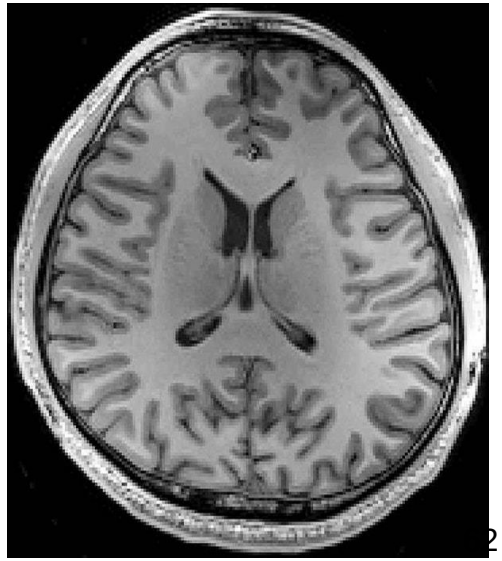
To play with this yourself:
Apple Store: k-Space Odyssey (Haselhoff)
Play Store: k-Spapp (Springorum)

mriquestions.com

MP-RAGE

- Magnetization Prepared - RApid Gradient Echo
- T_1 weighted
- non-selective (180º) inversion pulse (medium *TI* of 600-900 ms)
- Series of GRE readouts at short *TEs* (2-4 ms) and small flip angles (5- 12º)
- Long repetition time (*TR*) of approximately 2000 ms

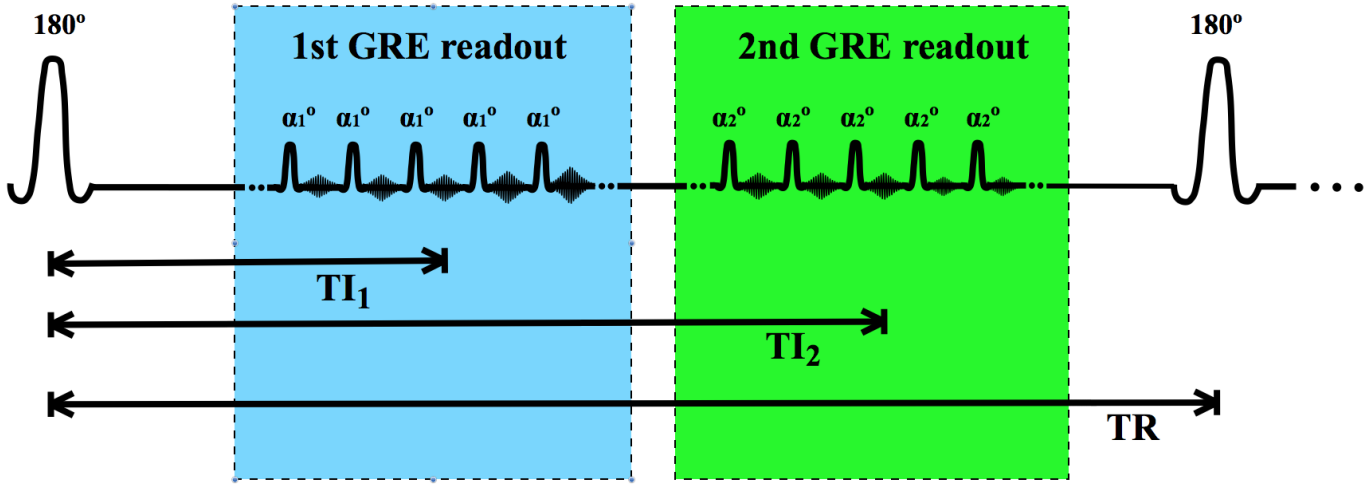




MP2RAGE

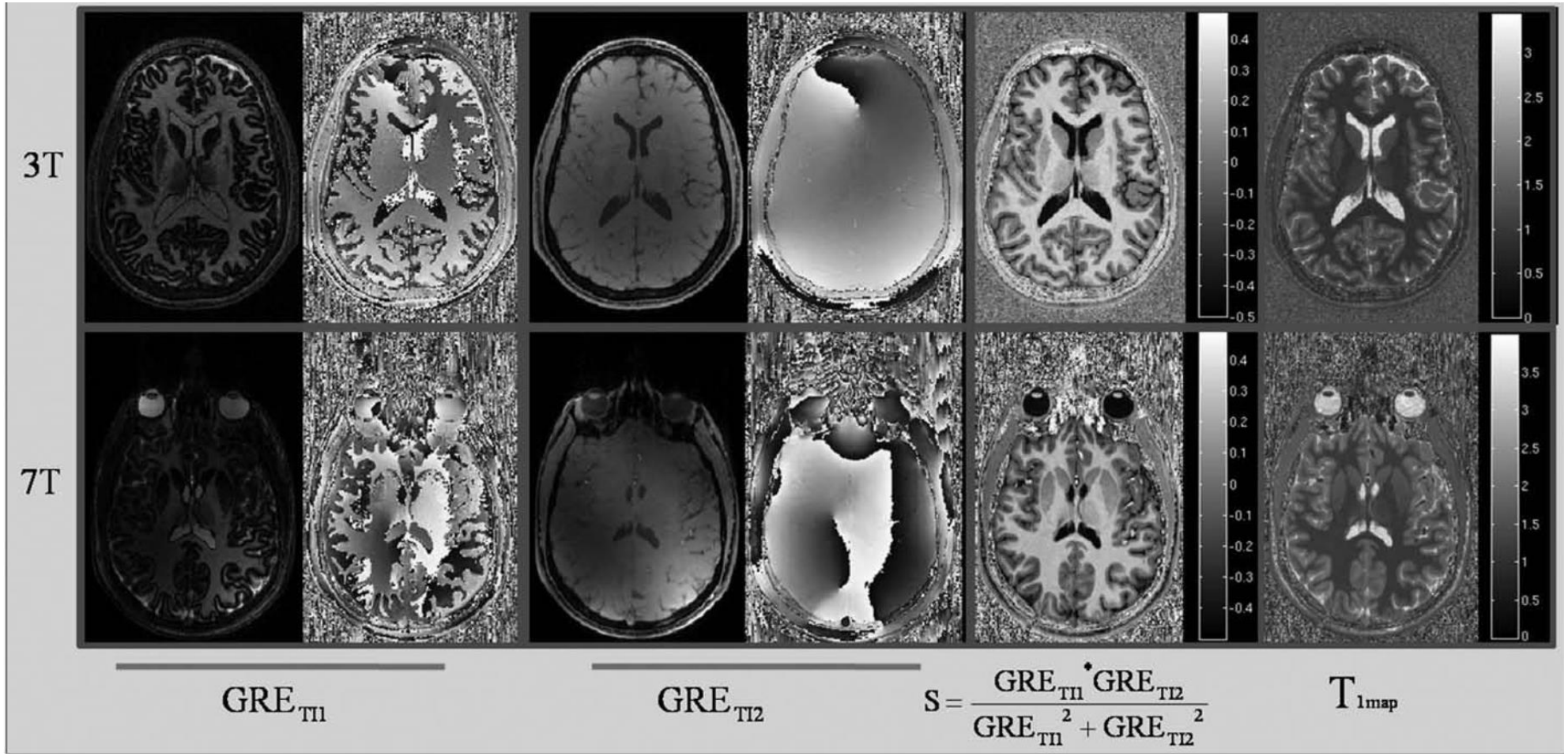
- Two GRE readouts between each inversion pulse
- First inversion time (*TI1*) ~700 ms → T1w image with the gray matter nulled
- Second inversion time (*TI2*) is long (~2500 ms)
- Multiply and normalize both images for unbiased contrast:

$$MP2RAGE = \frac{GRE_{TI1} \cdot GRE_{TI2}}{GRE_{TI1} + GRE_{TI1}}$$



Marques et al. Neuroimage 2010

MP2RAGE



Marques et al. Neuroimage 2010

Take home messages

TL;DR

In general:

- **Spin echo** is robust, slow, and high-SNR
- **Gradient echo** is fast, sensitive and lower-SNR

Also:

- **Contrast** can be tailored to your liking through timing
- **Preparation modules** can be added to your liking
- Just **look up** any new acronym you come across, it will be a GRE or SE variant in the end