Day 2 - Volume Localization and Image Contrast

CBIC MRI Bootcamp 2025

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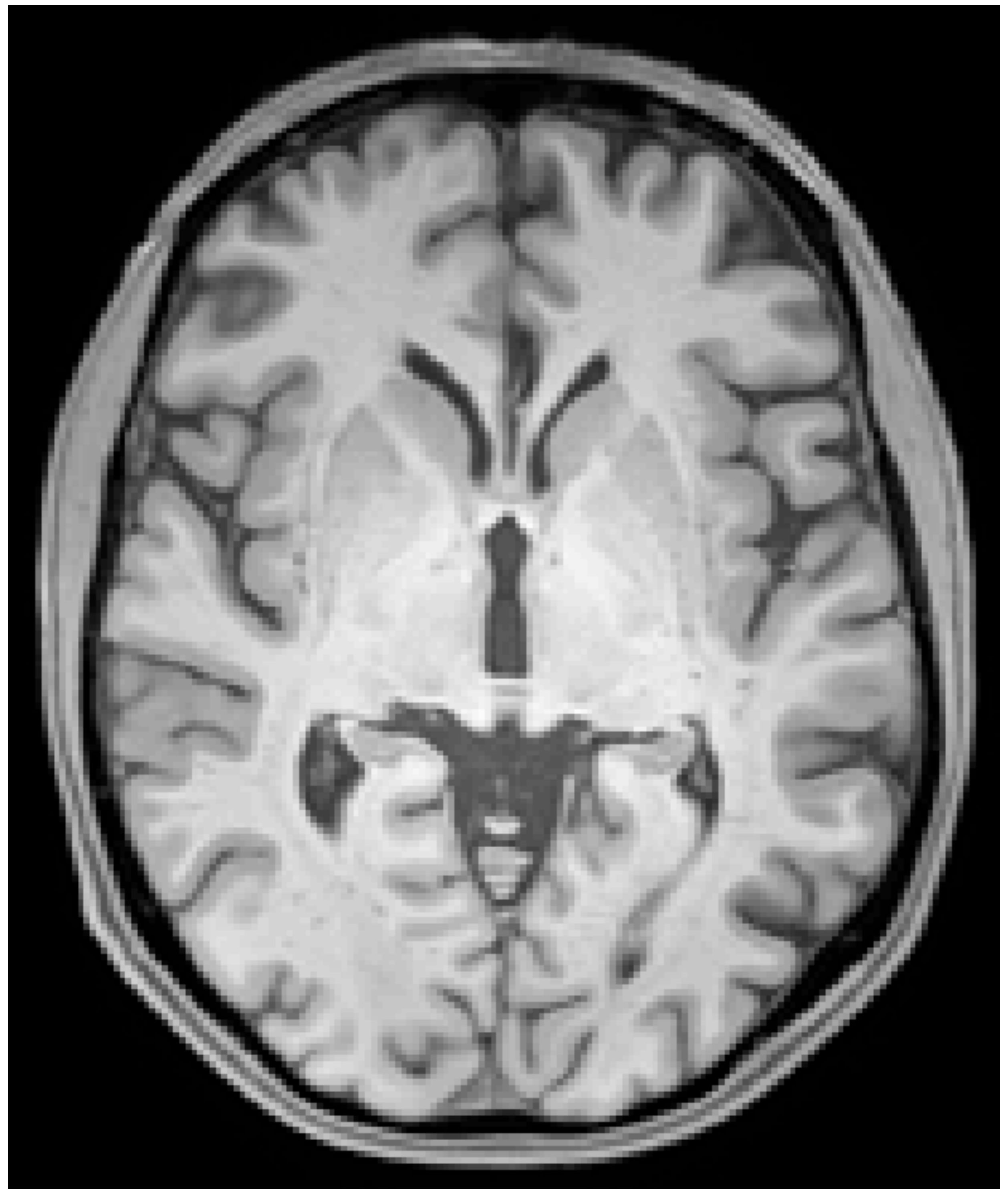
Review

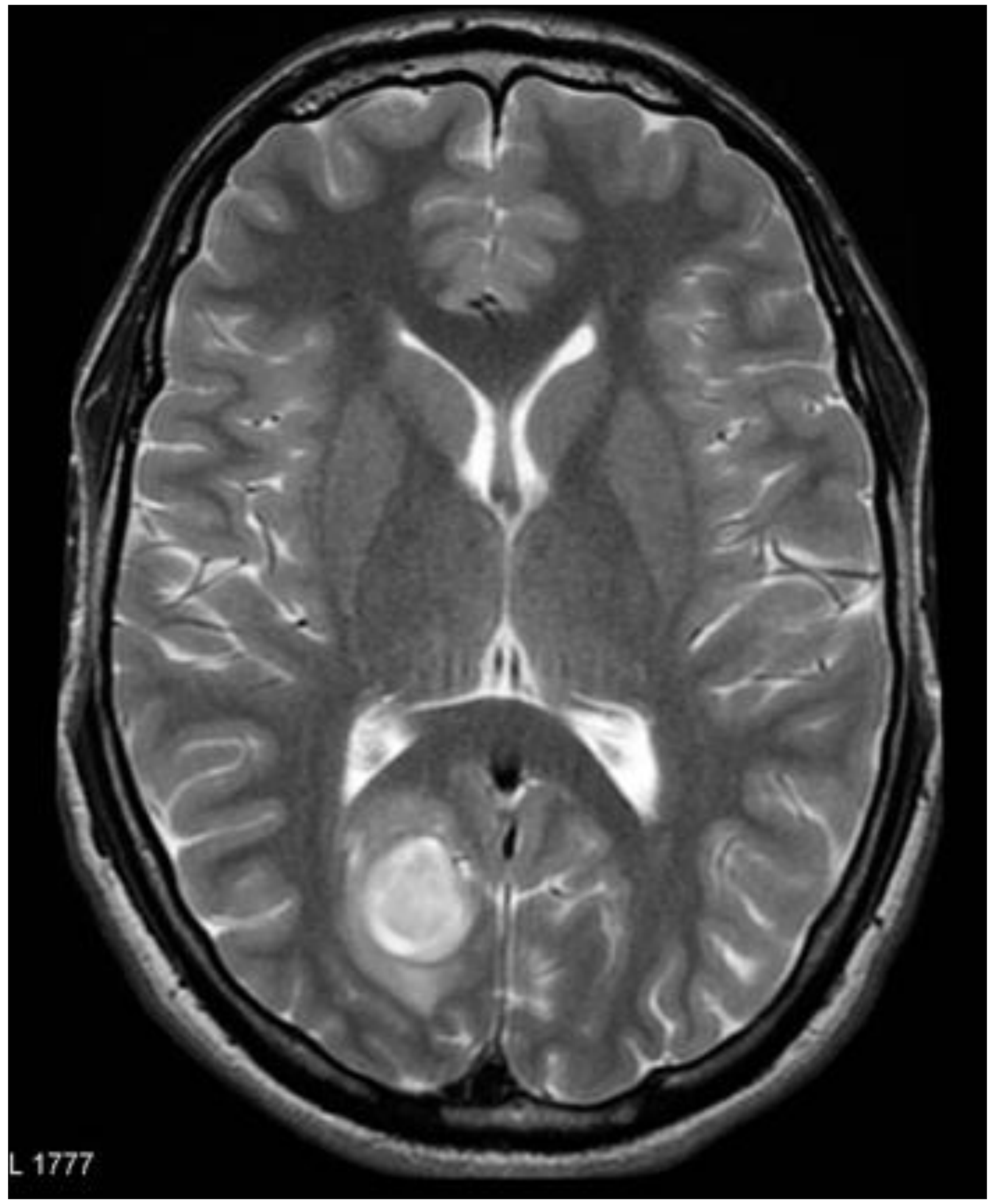
- **How is a magnetic resonance image created?**
- **Excitation** - use RF pulses to create detectable signal from the nuclear paramagnetism of hydrogen atoms
- **Acquire signal in k-space** - complex-valued data, use magnetic field gradient pulses to “scan” k-space
- **Transform to physical space** - use a Fourier transform to create a human-readable image. Still complex-valued, so typically look at the complex magnitude.

Image Contrast

MRI Tissue Contrast

- How do we introduce intensity differences or contrast between different brain structures?





MRI Tissue Contrasts

- **Proton Density**
  - Base contrast for MRI
- **Relaxation Time**
  - How quickly excited magnetism returns to equilibrium
  - Two main mechanisms: spin-lattice (**T1**) and spin-spin (**T2**)
  - Additional relaxation from microscopic field inhomogeneities (**T2***) [**BOLD!**]
- **Motion**
  - Fluid flow, gross motion, molecular diffusion
- **Others**
  - Magnetic susceptibility, exogenous contrast agents, …

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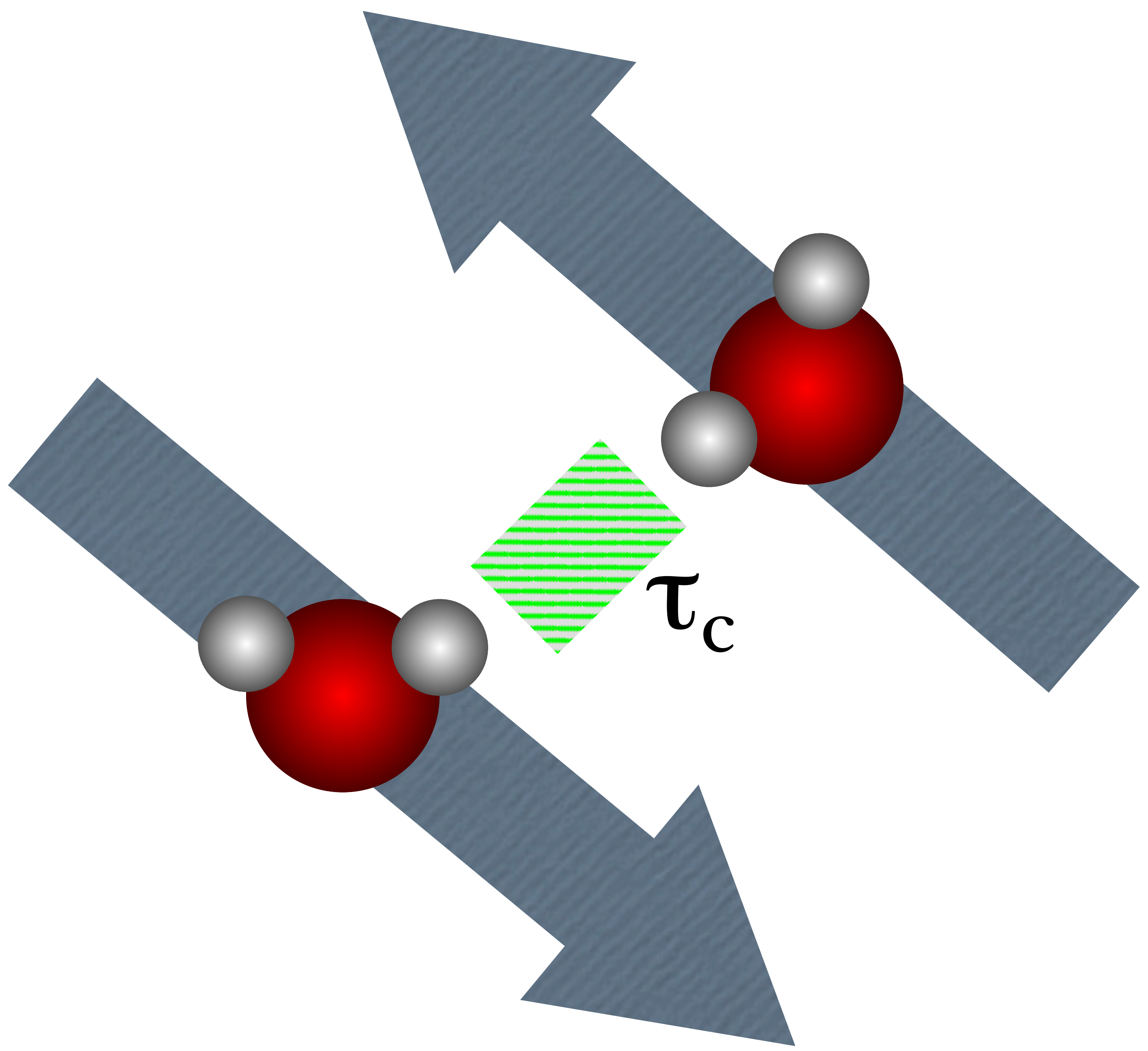
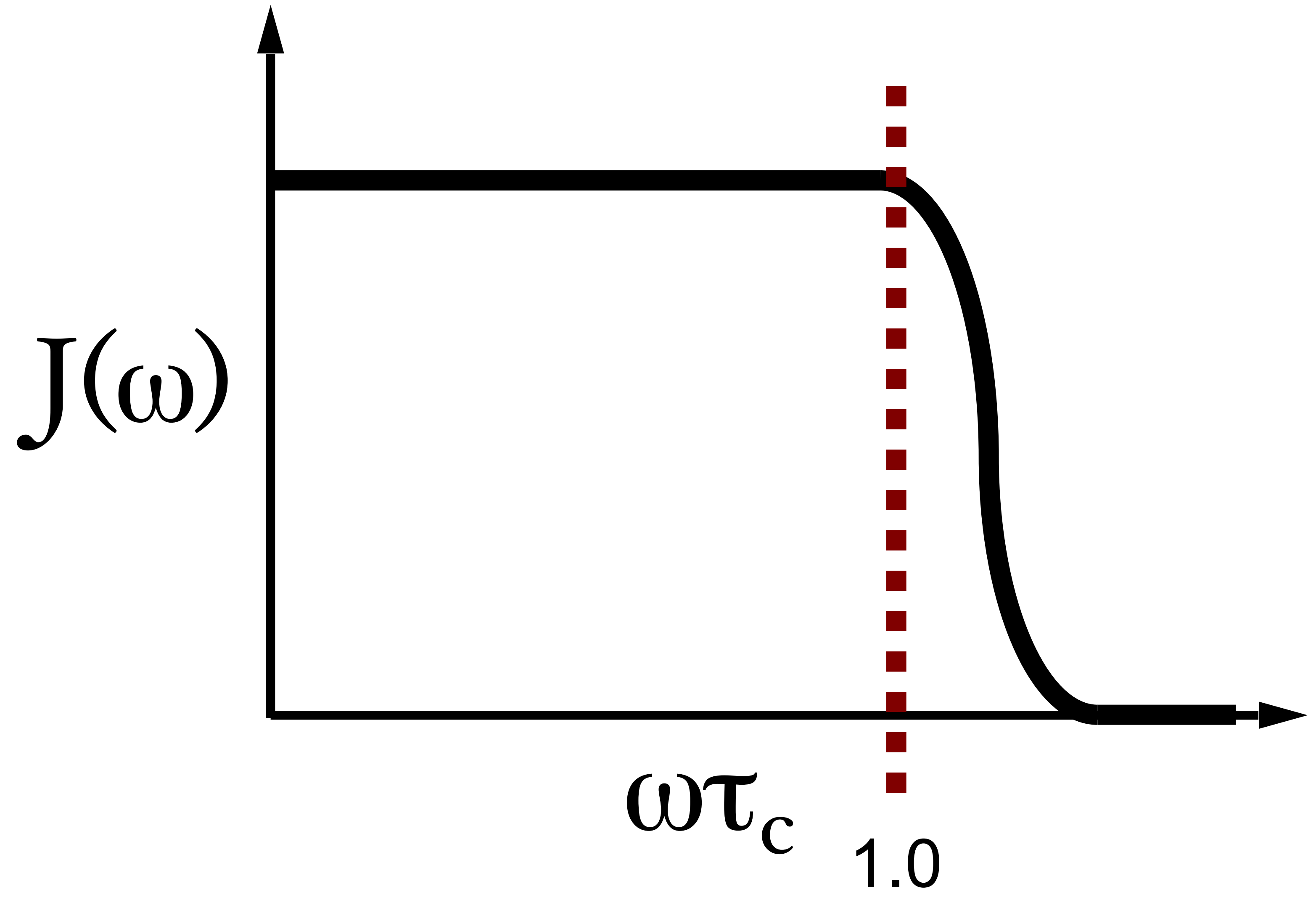
Correlation Time and the Spectral Density Function



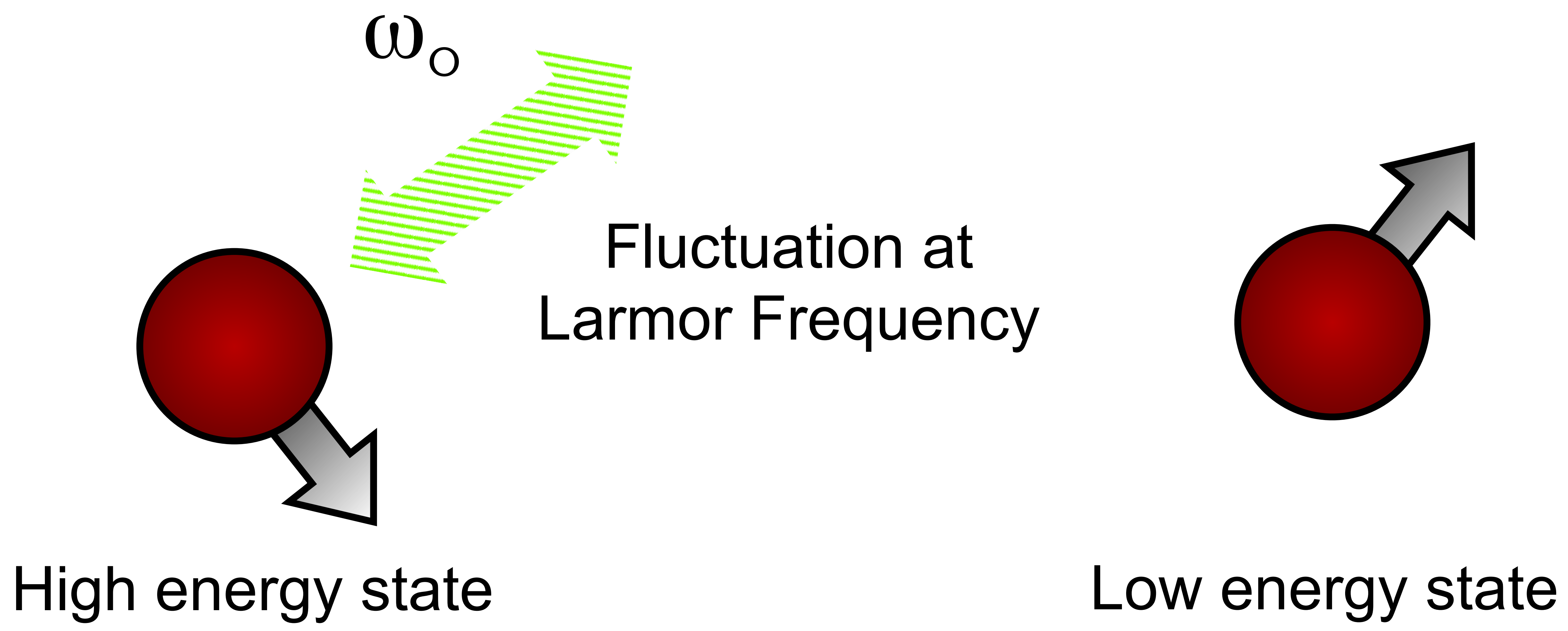
Basis of Bloebergen-Percell-Pound (BPP) relaxation theory

Nuclear spins experience short duration (τ_c) dipole-dipole interactions giving rise to a spectrum of magnetic field fluctuation frequencies (spectral density function)

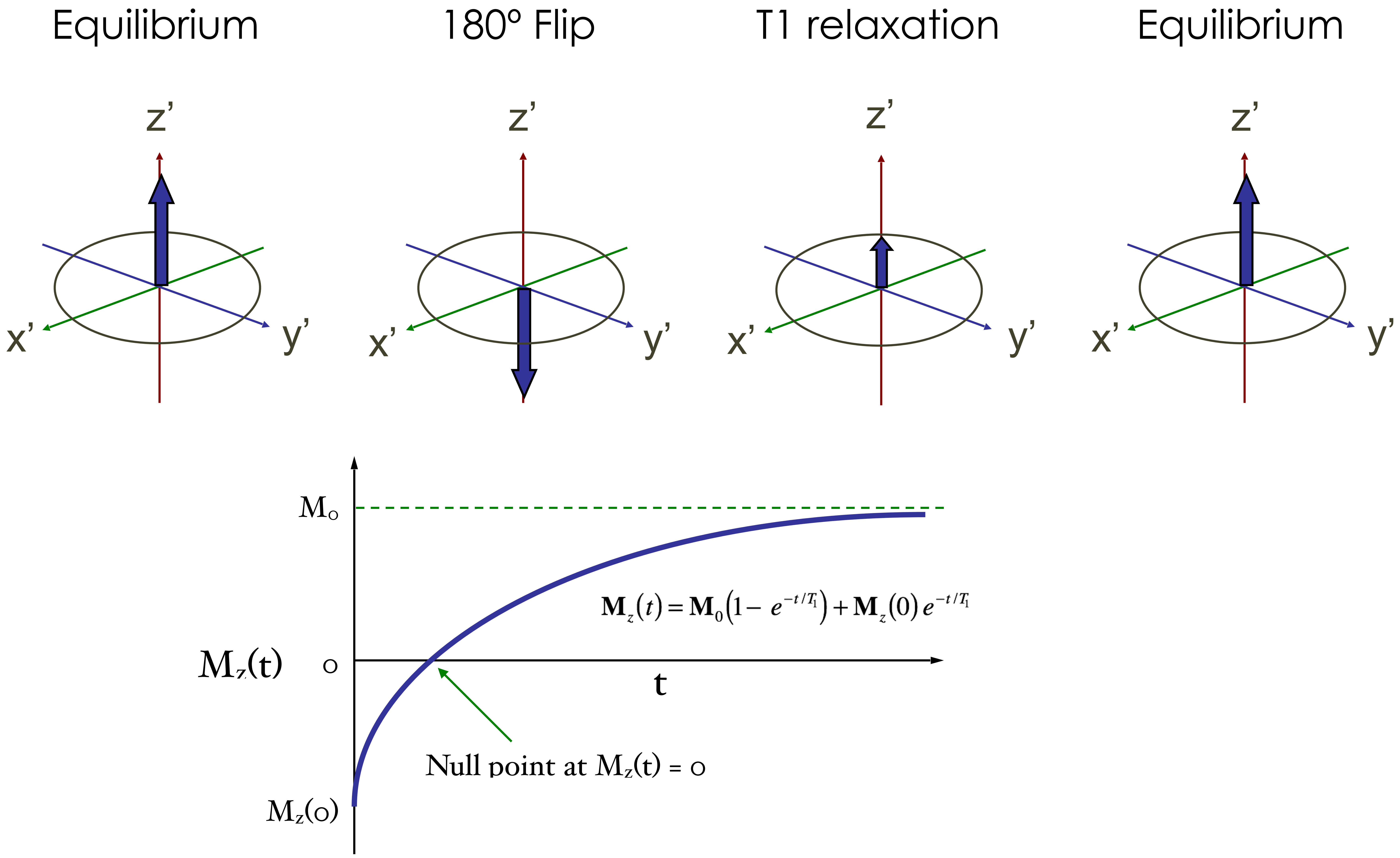


T1 (Spin-Lattice) Relaxation

- Spins do not spontaneously decay from higher to lower energy states because the resonant frequency is very low (MHz).
- T1 relaxation is driven ONLY by field fluctuations at the Larmor frequency.
- The longitudinal magnetization decays exponentially to equilibrium
- Typical T1 for liquid water in tissues ranges from ms to seconds.

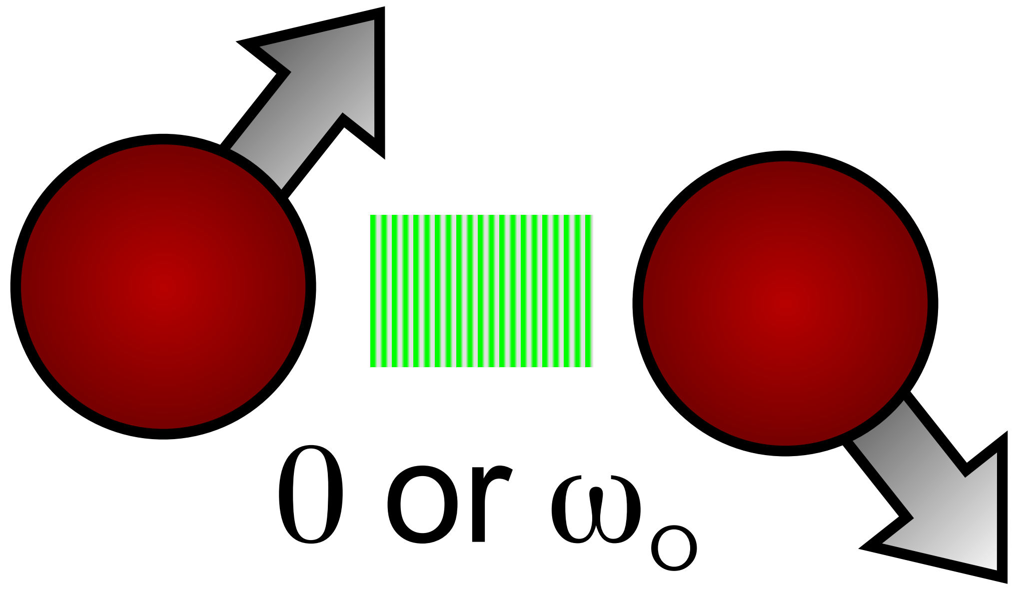


T_1 (Spin-Lattice or Longitudinal) Relaxation

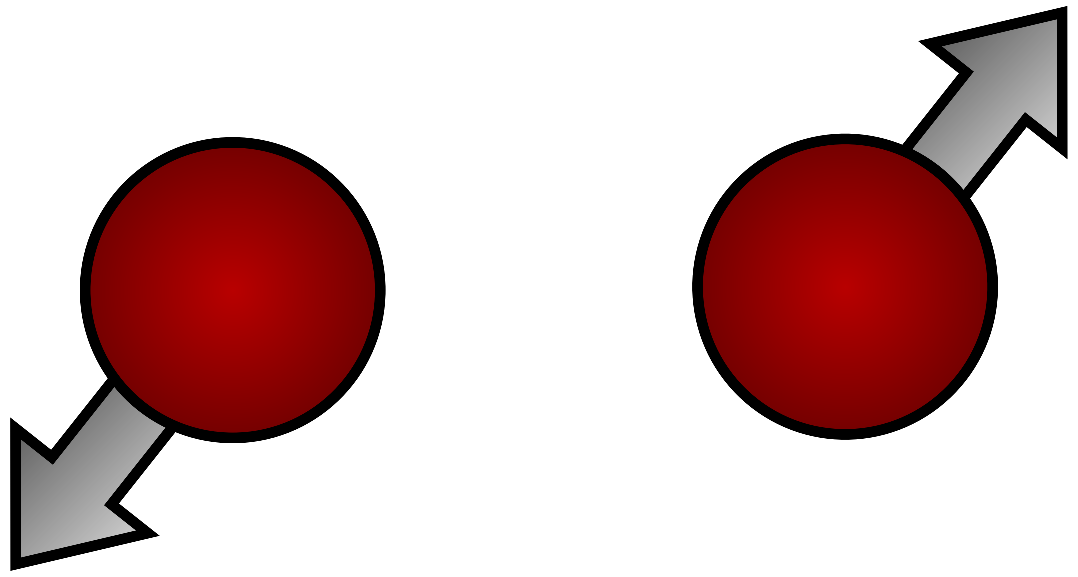


T2 (Spin-Spin or Transverse) Relaxation

- T2 relaxation is driven by field fluctuations at both zero frequency AND the Larmor frequency.
- Spins are in phase following an RF pulse.
- The transverse magnetization decays exponentially to zero due to cumulative dephasing.
- Typical T2 for liquid water in tissues ranges from ms to seconds.

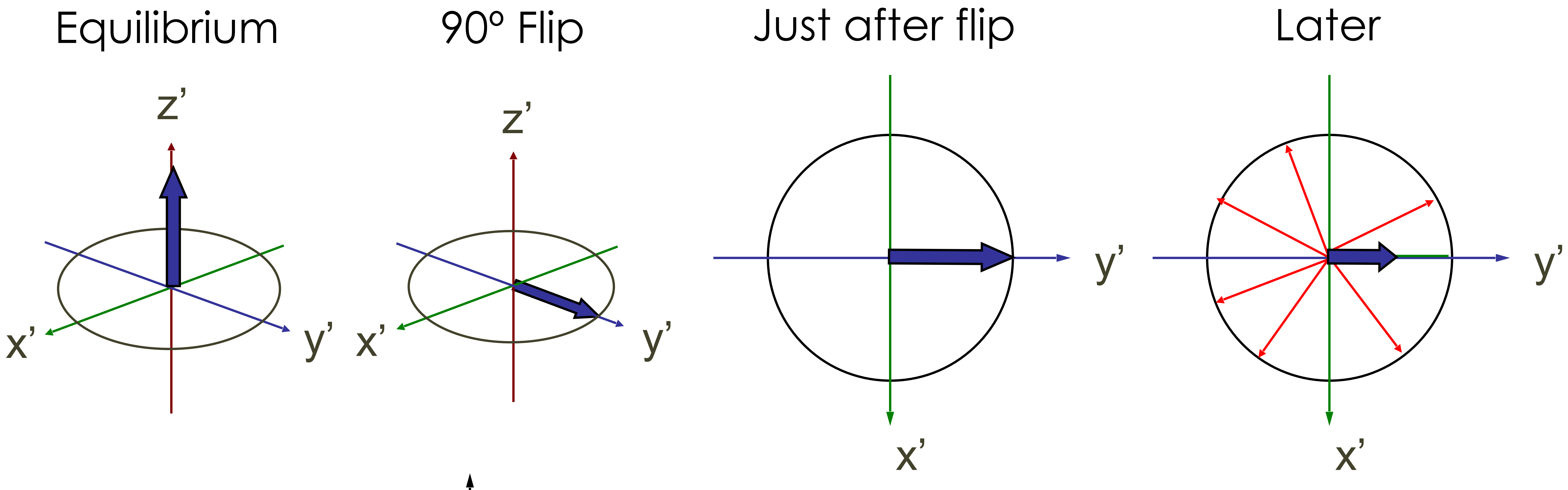


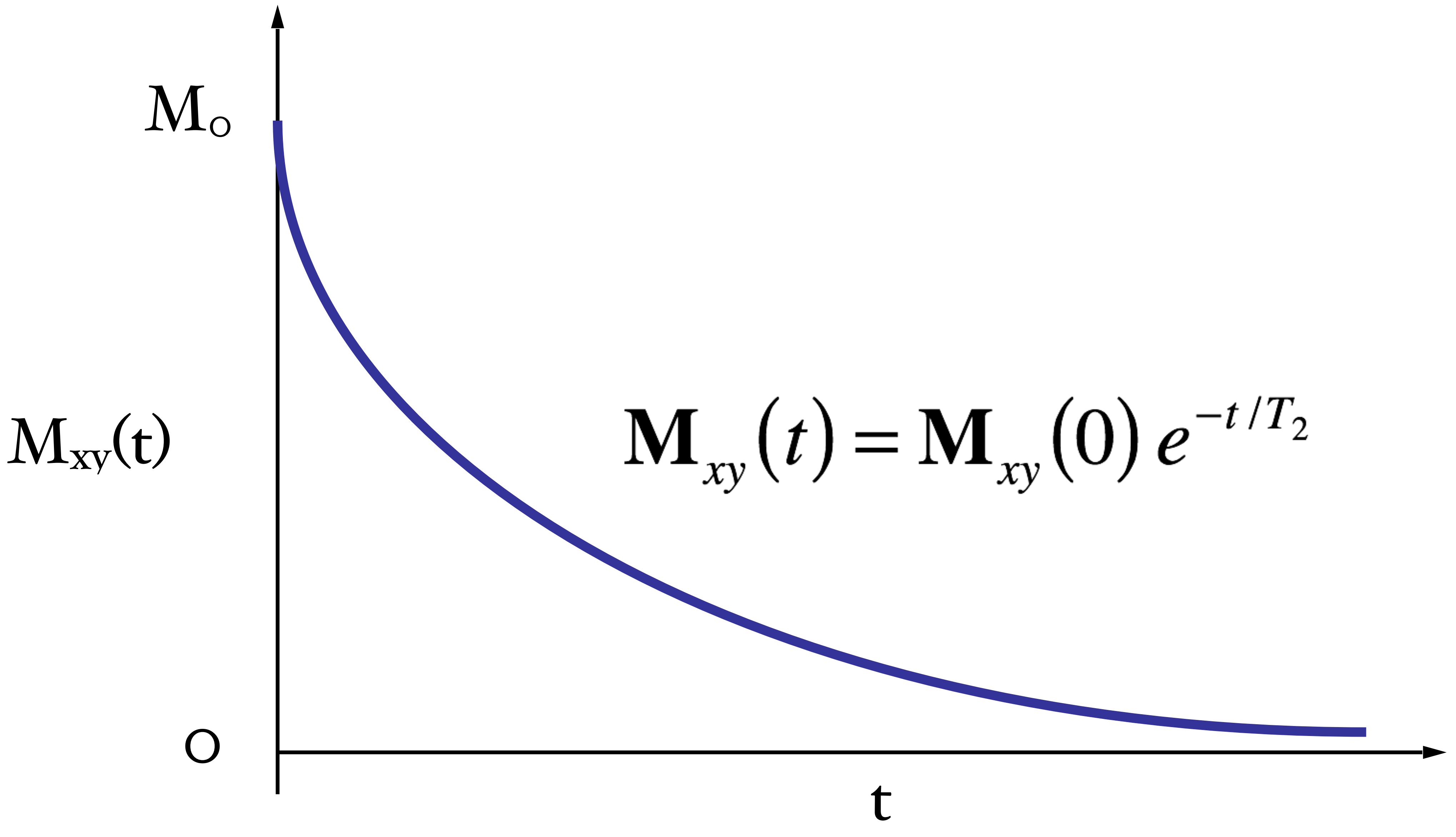
Fluctuation at either zero frequency or the Larmor Frequency causes spin-spin energy exchange.



Total energy preserved. Phase randomized.

T_2 (Spin-Spin) Relaxation





$$\mathbf{M}_{xy}(t) = \mathbf{M}_{xy}(0)\, e^{-t/T_2}$$

Typical Tissue Relaxation Times

Relaxation times are field dependent

Generally, tissue T1s increase and converge at higher field strengths

Tissue T2s decrease at higher field strengths

Tissue	T1 (ms)	T2 (ms)
Cortical GM	1400	90
Subcortical GM	1200	90
White Matter	900	80
Ventricular CSF	4500	2400

Jiang, D., Gou, Y., Wei, Z., Hou, X., Yedavalli, V., & Lu, H. (2023). Quantification of T1 and T2 of subarachnoid CSF: Implications for water exchange between CSF and brain tissues. *Magnetic Resonance in Medicine*, *90*(6), 2411–2419. https://doi.org/10.1002/mrm.29829

Romascano, D., Piredda, G. F., Caneschi, S., Hilbert, T., Corredor, R., Maréchal, B., Kober, T., Ledoux, J.-B., Fornari, E., Hagmann, P., & Denervaud, S. (2024). Normative volumes and relaxation times at 3T during brain development. *Scientific Data*, *11*(1), 429. https://doi.org/10.1038/s41597-024-03267-3

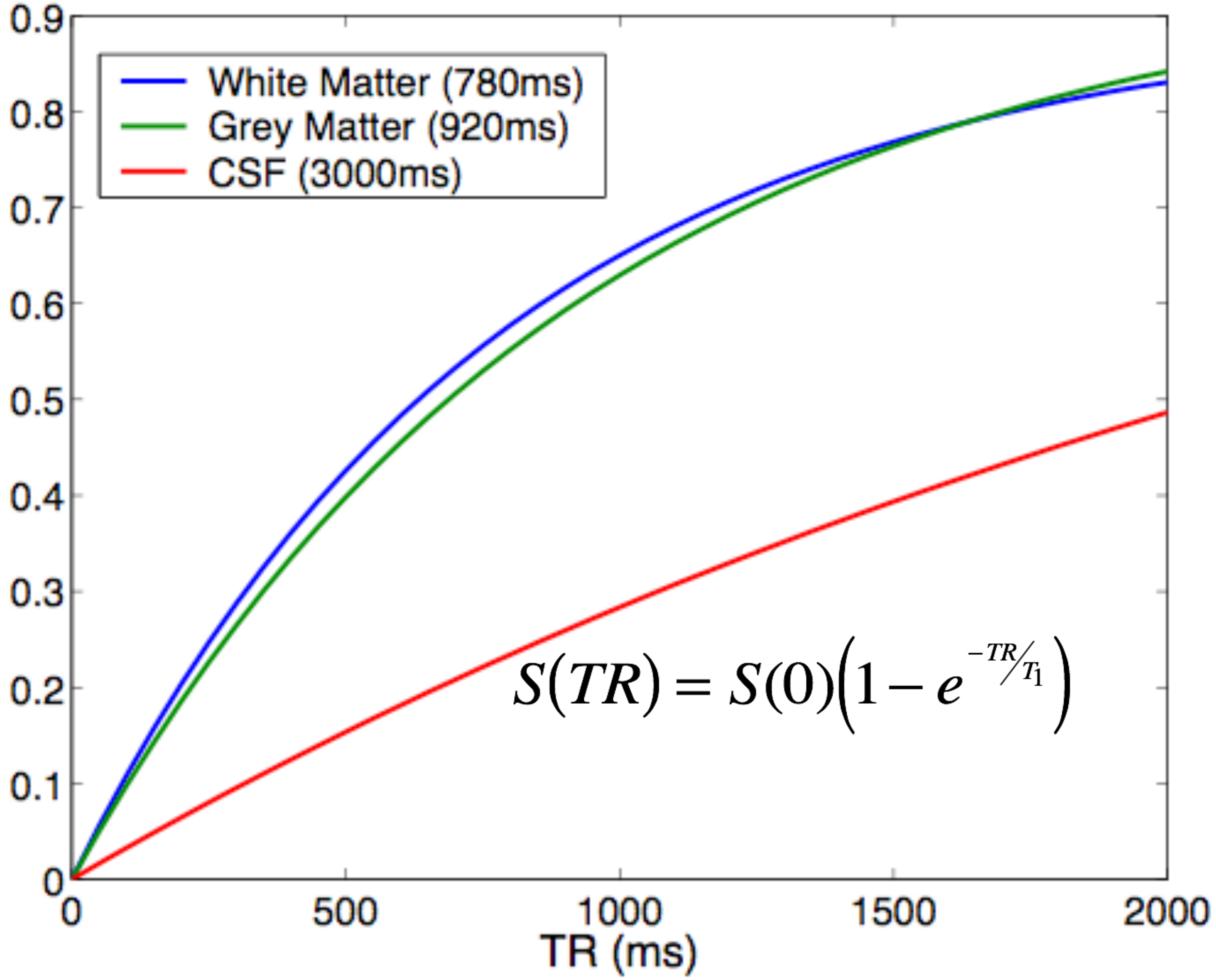
T1-weighted Imaging - Saturation Recovery

Fast repetition of RF excitation ***saturates*** the nuclear magnetization

Use RF pulse repetition times shorter than about 5 x T1

Magnetization does not have time to fully re-equilibrate

Lower Mz and excited Mxy than from full equilibrium

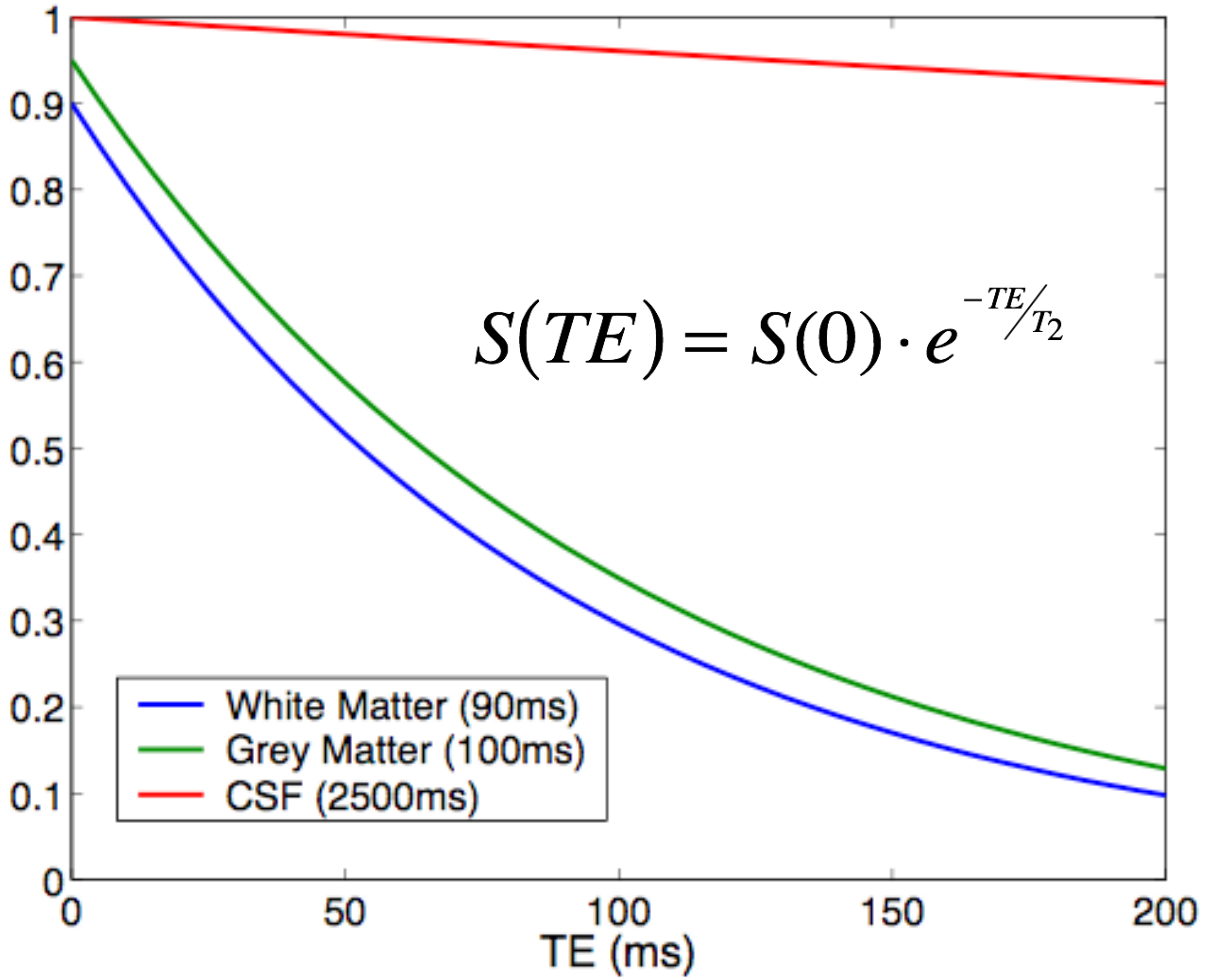


T2-weighted Imaging - Echo Time

Excitated transverse magnetization decays over time

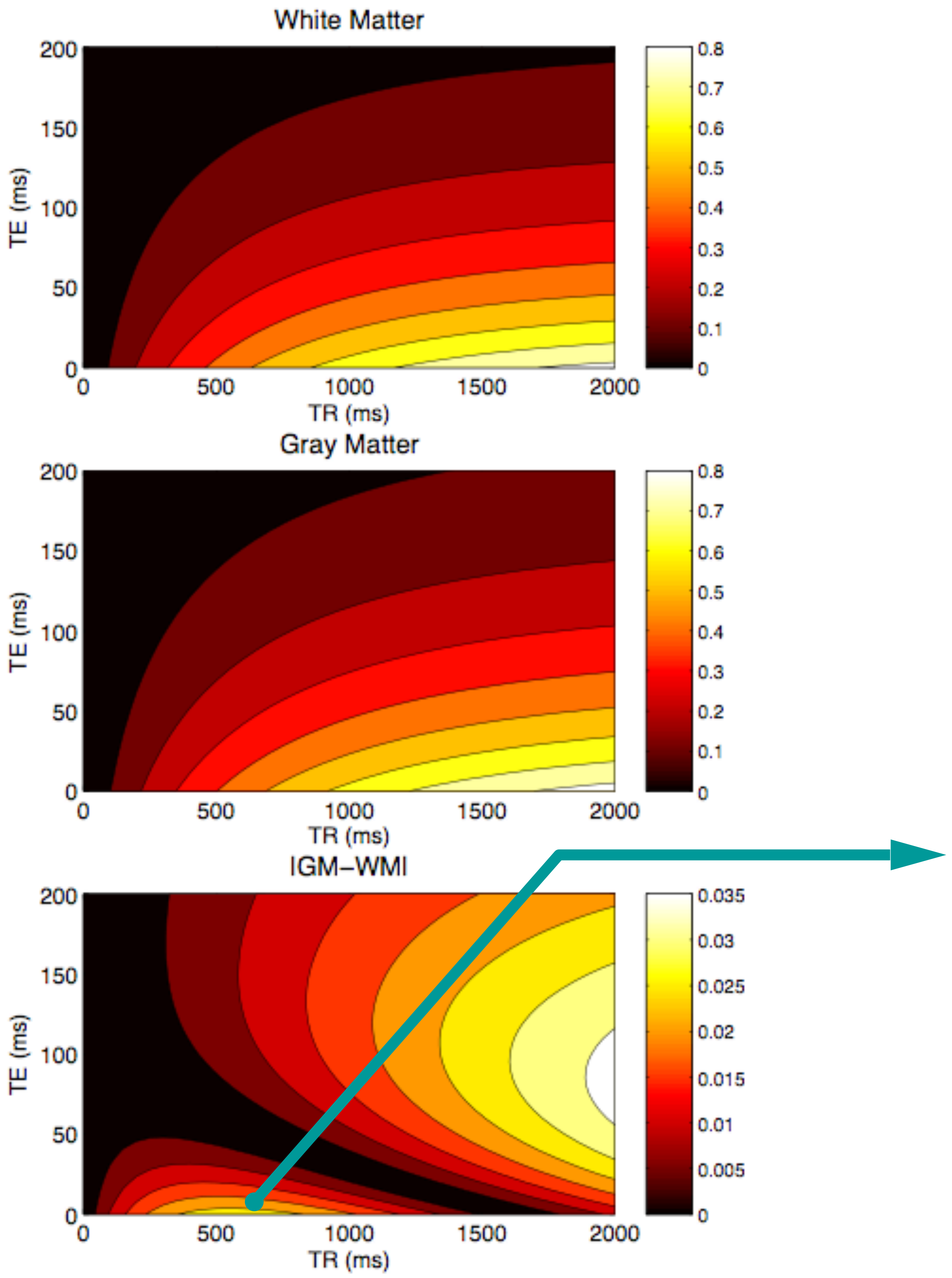
T2 varies between tissues

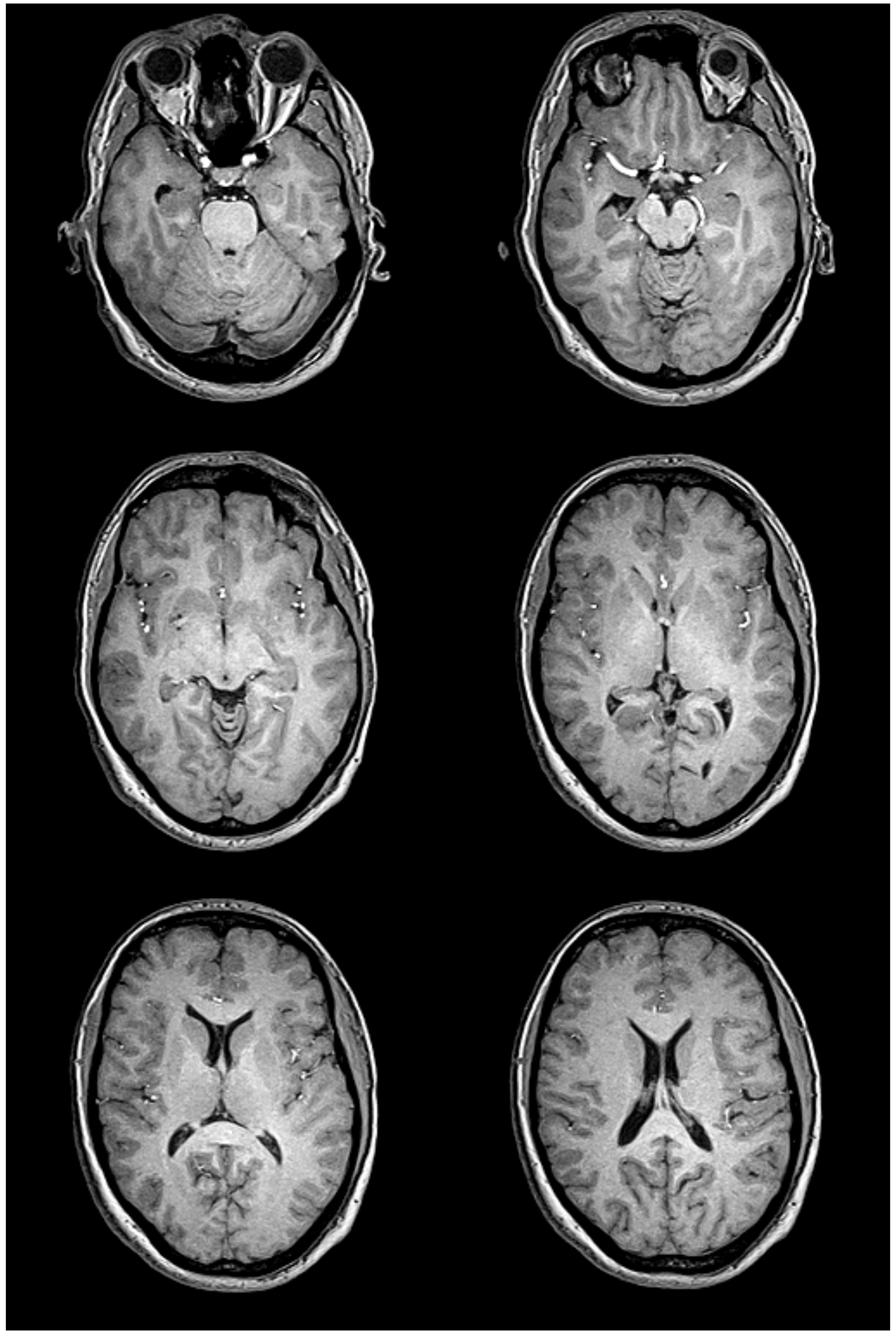
Alter image contrast by altering the time between excitation and echo (TE)



Saturation Recovery Contrast (T_1-weighted)

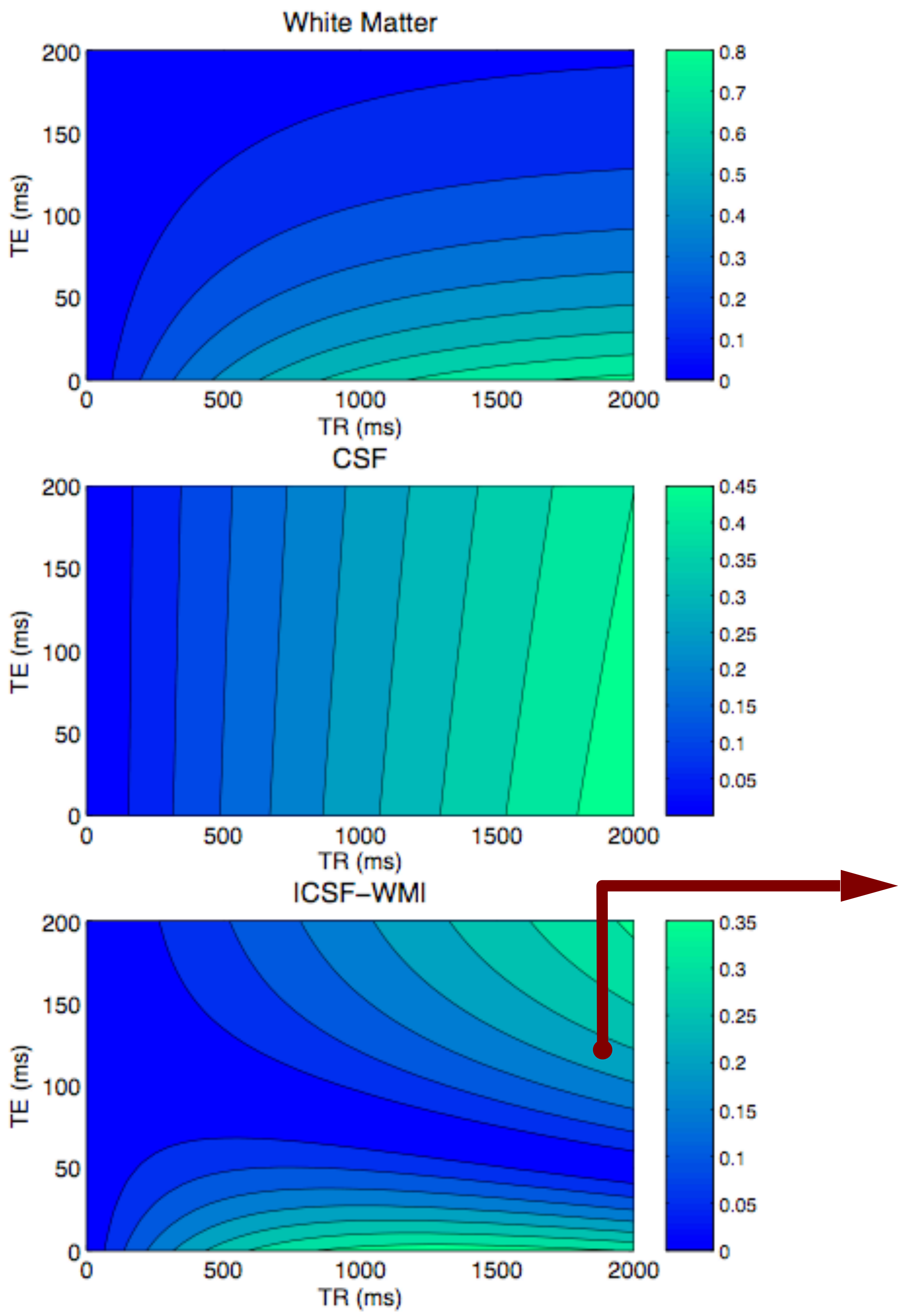
Signal magnitude at echo time

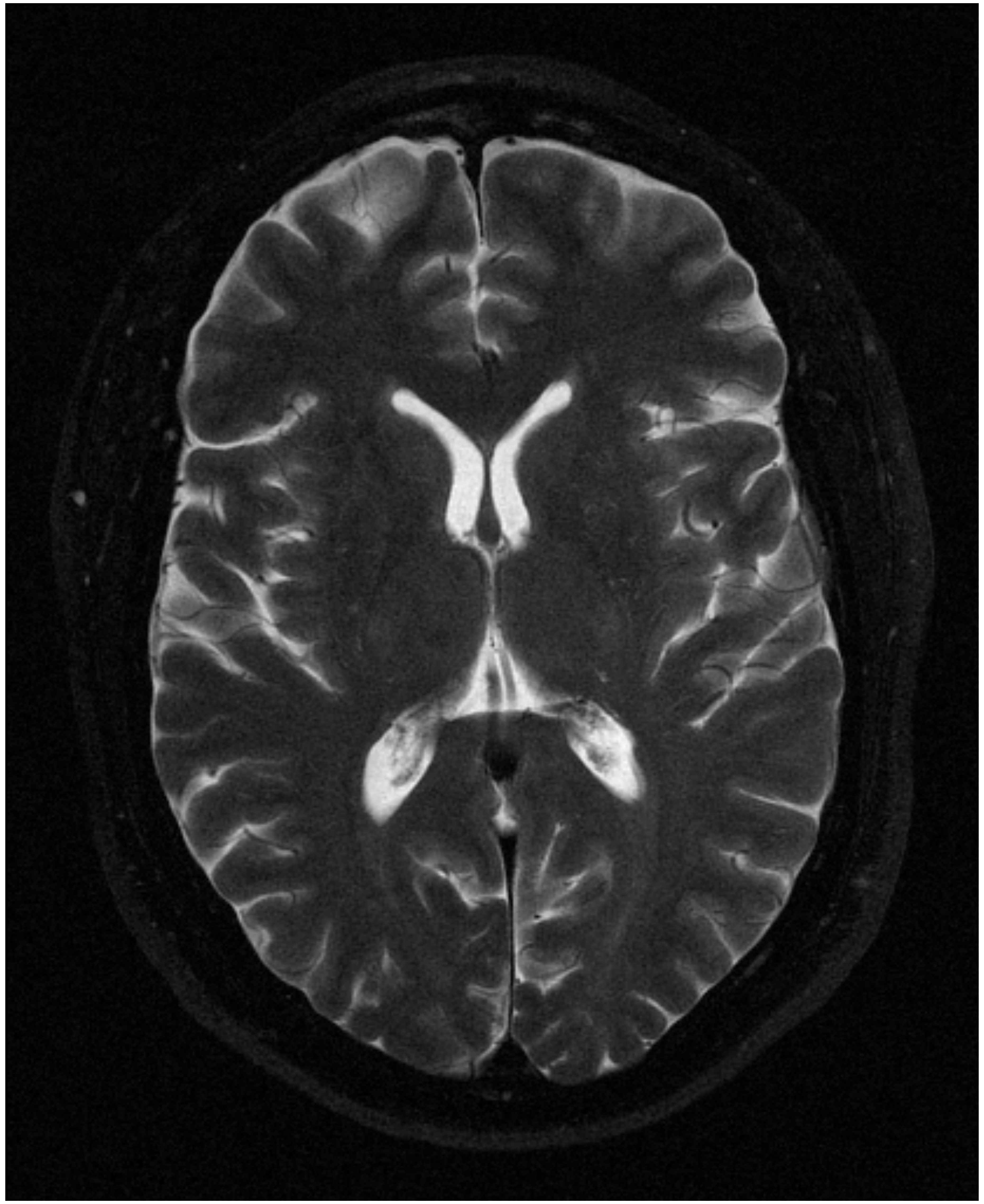




T_2-weighted Contrast

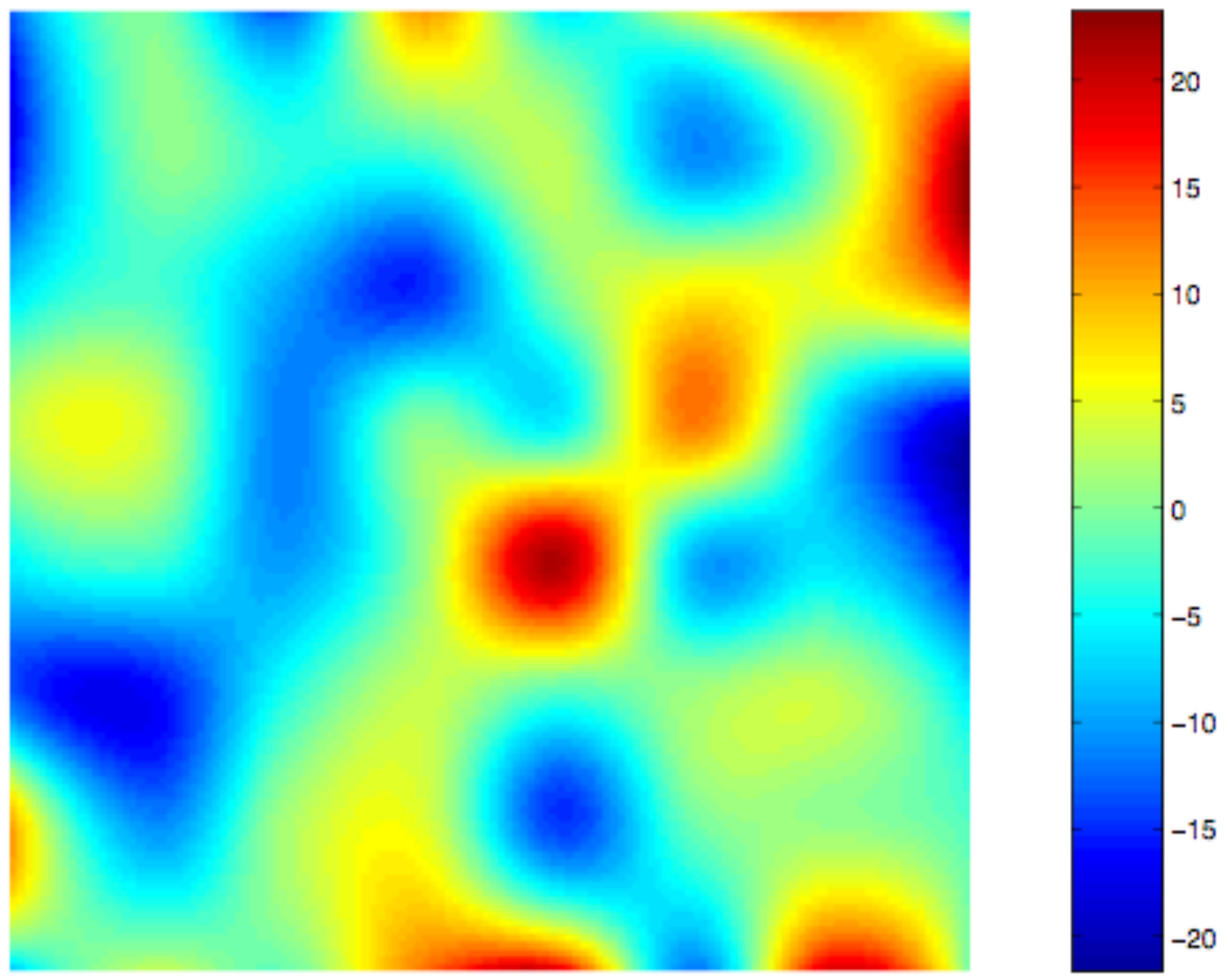
Signal magnitude at echo time

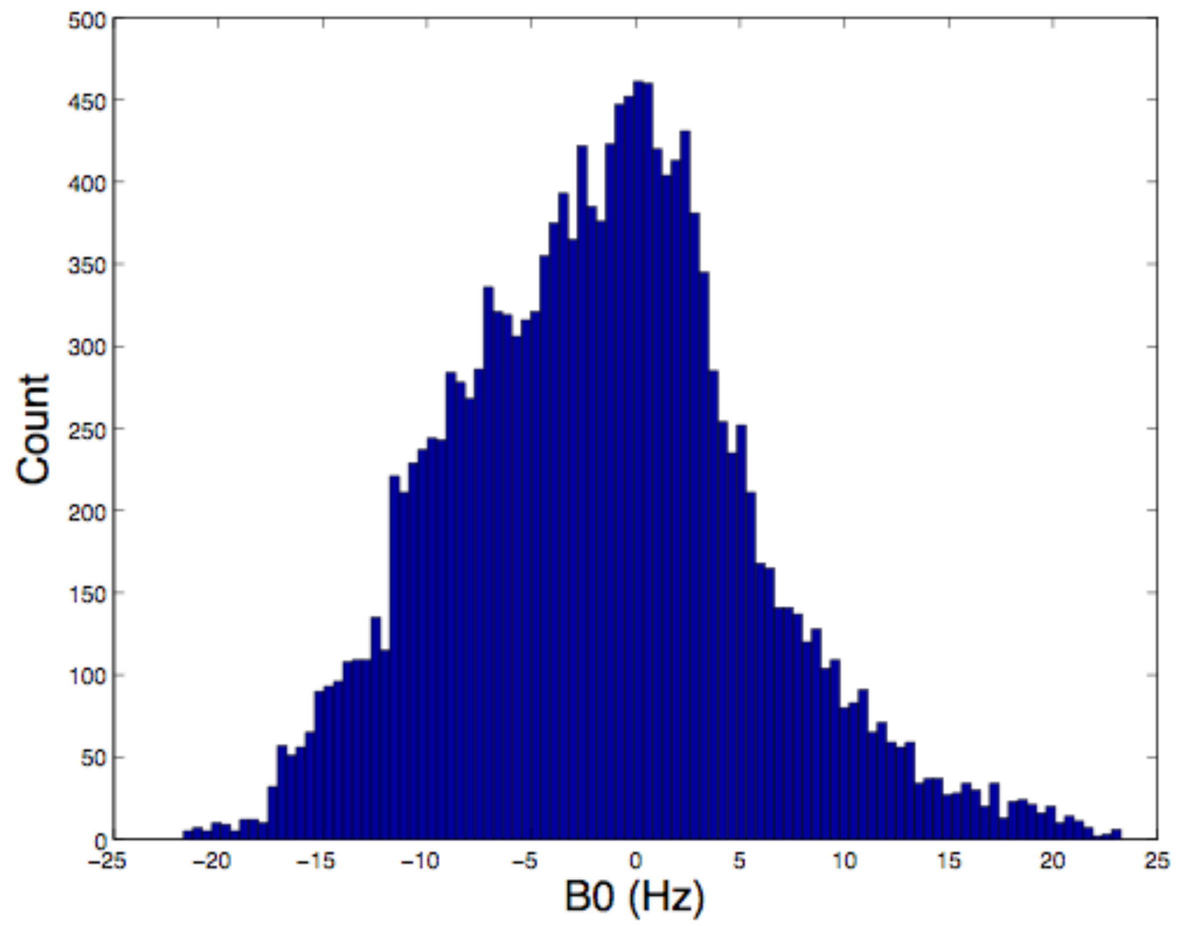




T2* Relaxation

- B_0 inhomogeneities within a volume (right) cause additional dephasing of total Mxy.
- Decreases apparent T2 by providing an additional dephasing mechanism.
- T2* is NOT an exponential process - B_0 distribution (below right) would have to be Lorentzian).
- Basis of **BOLD** and susceptibility sensitive imaging.



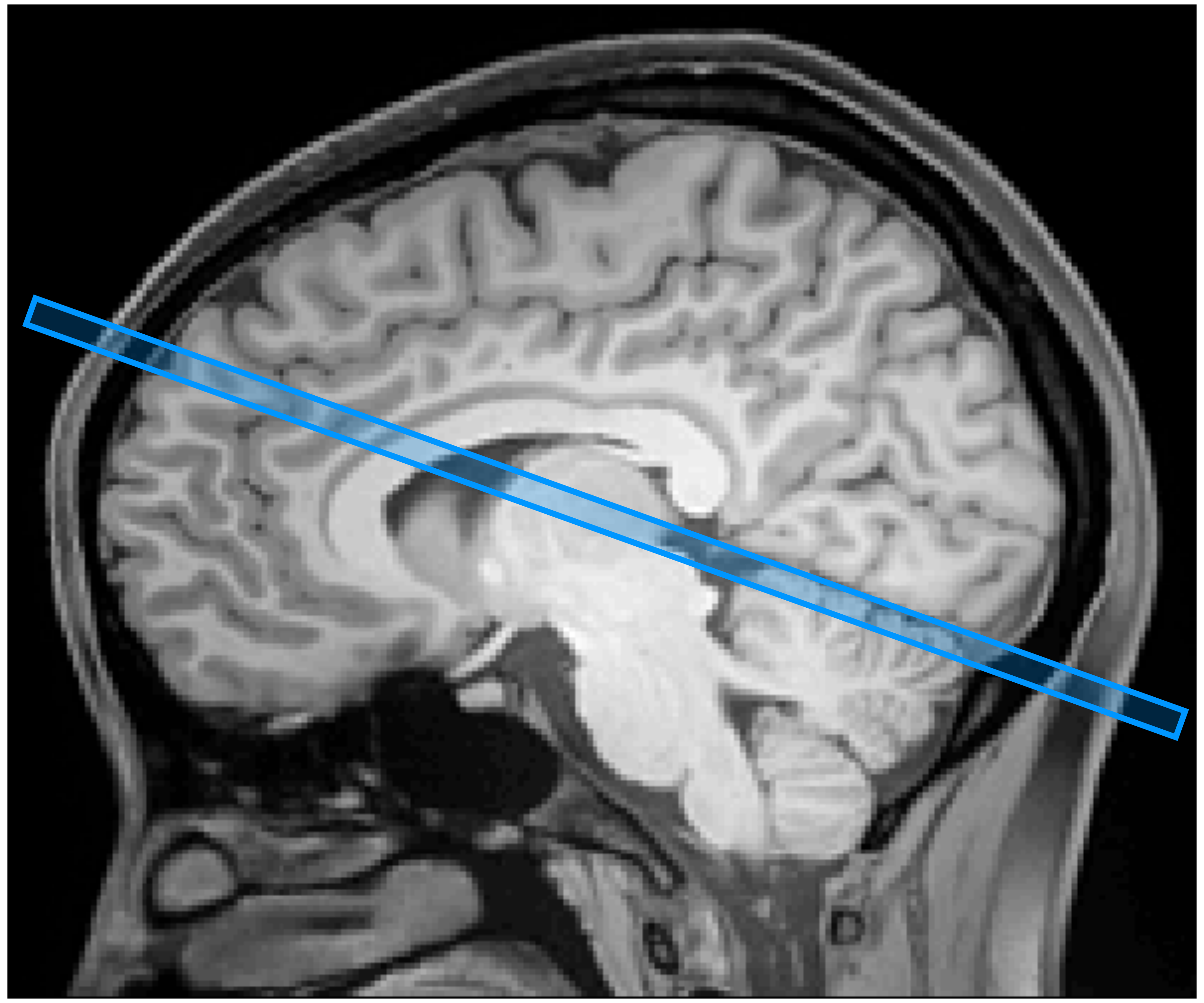


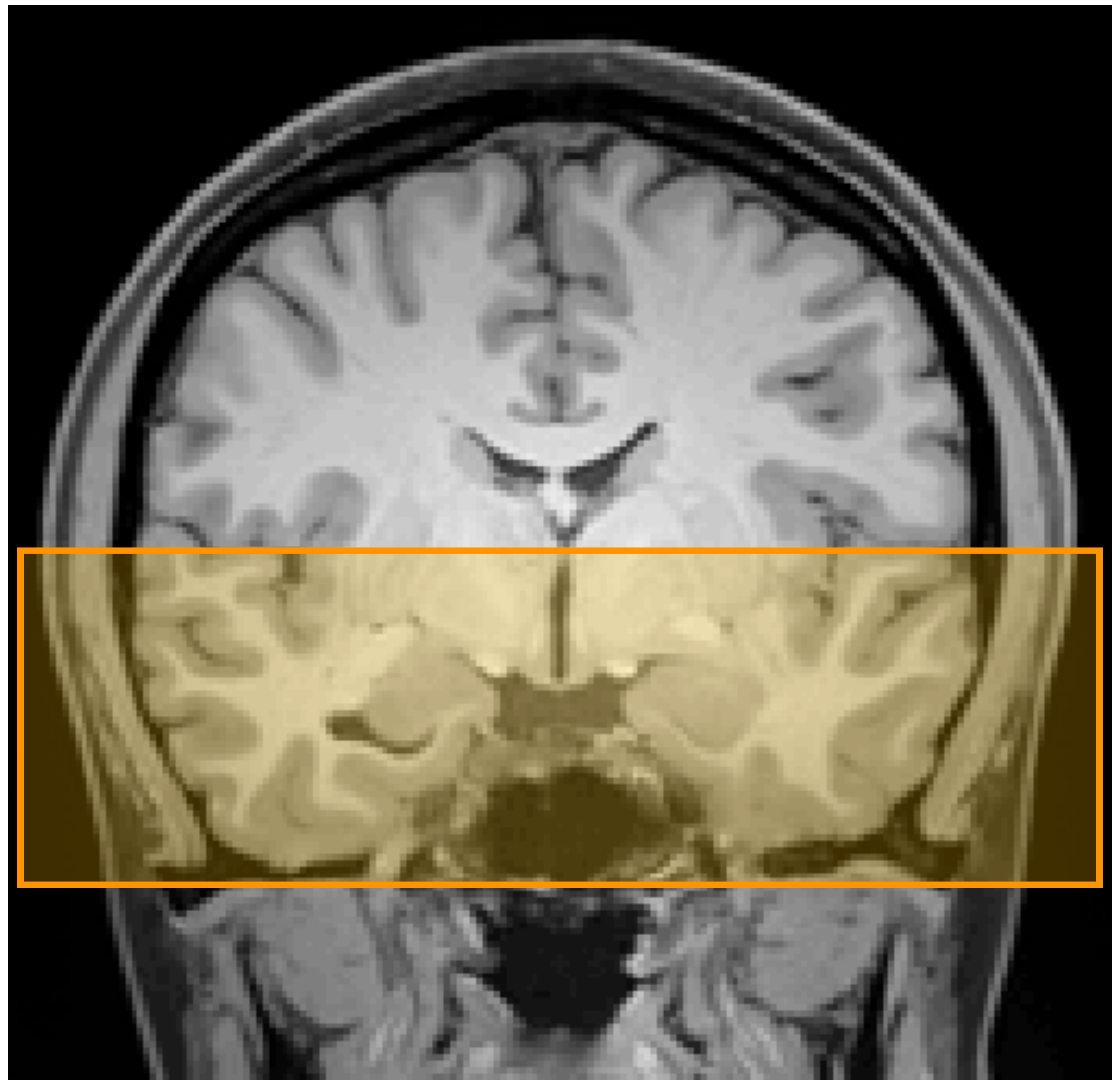
Volume Localization

Volume Localization in MRI

We frequently want to restrict MR signal to only that coming from a sub-volume of tissue

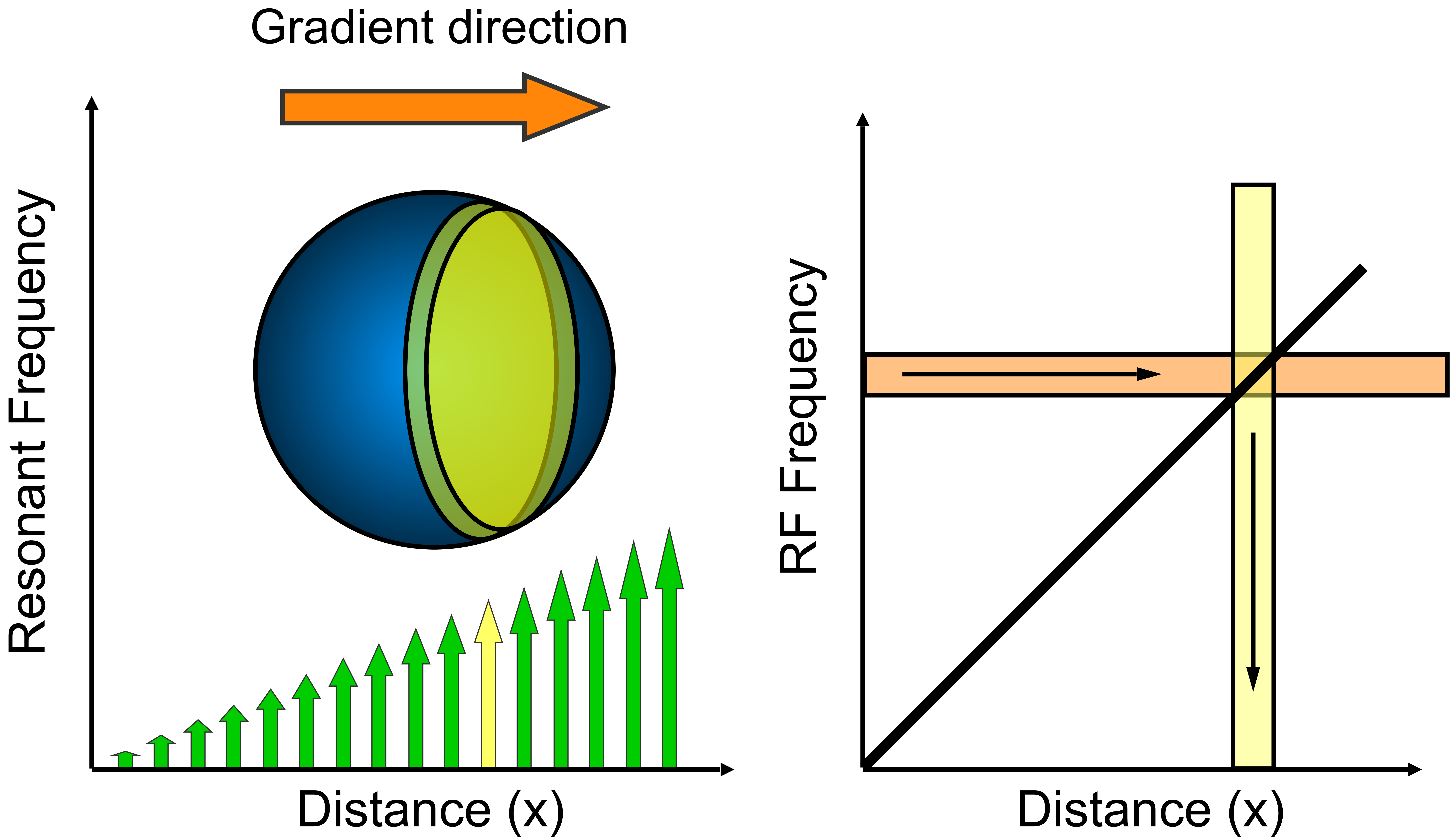
For example a thin slice, thick slab, **narrow pencil** or **cube** of tissue.





Can we achieve this by frequency encoding space?

Slice Selection with Gradients

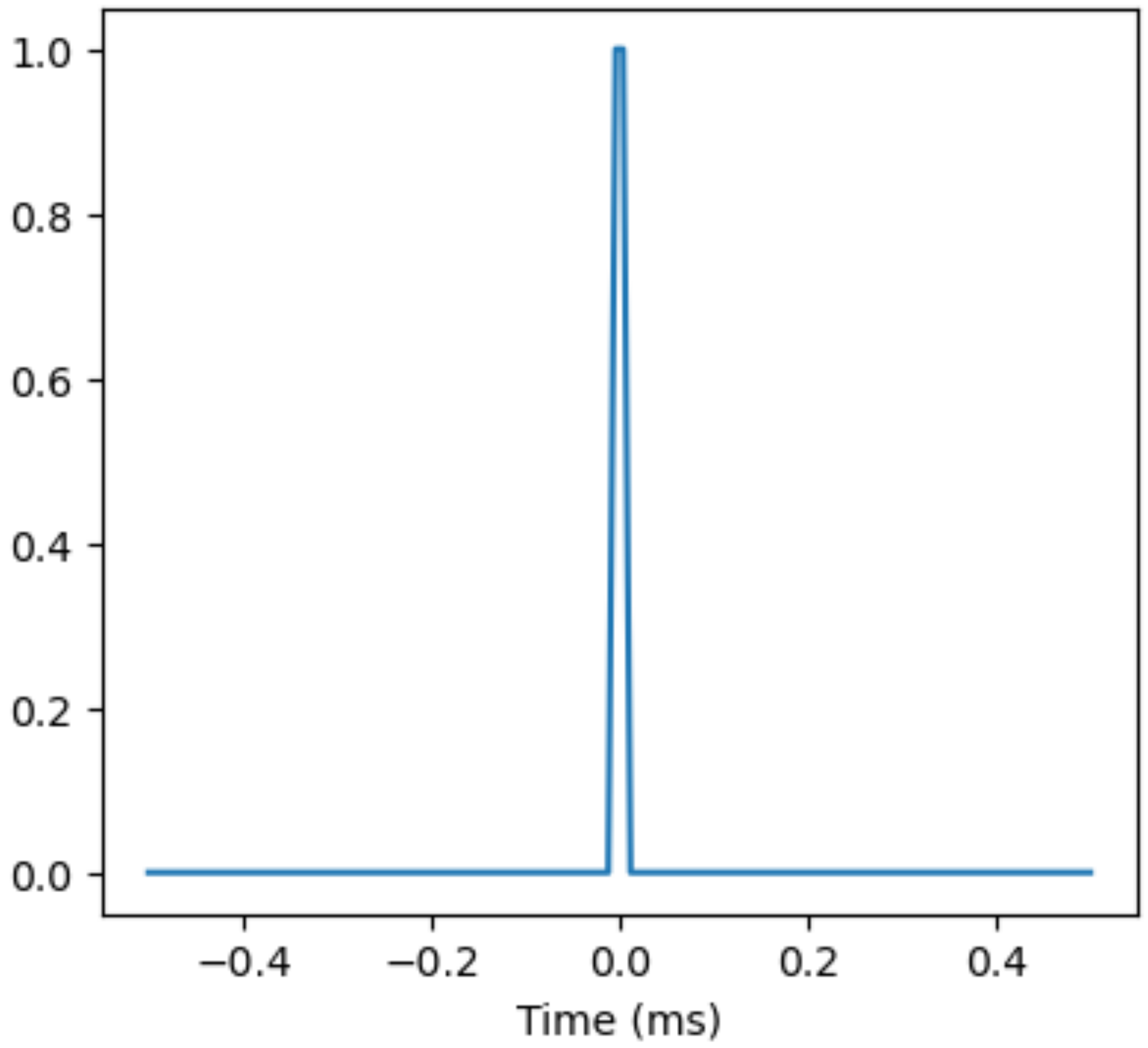


Short Rectangular RF Pulses

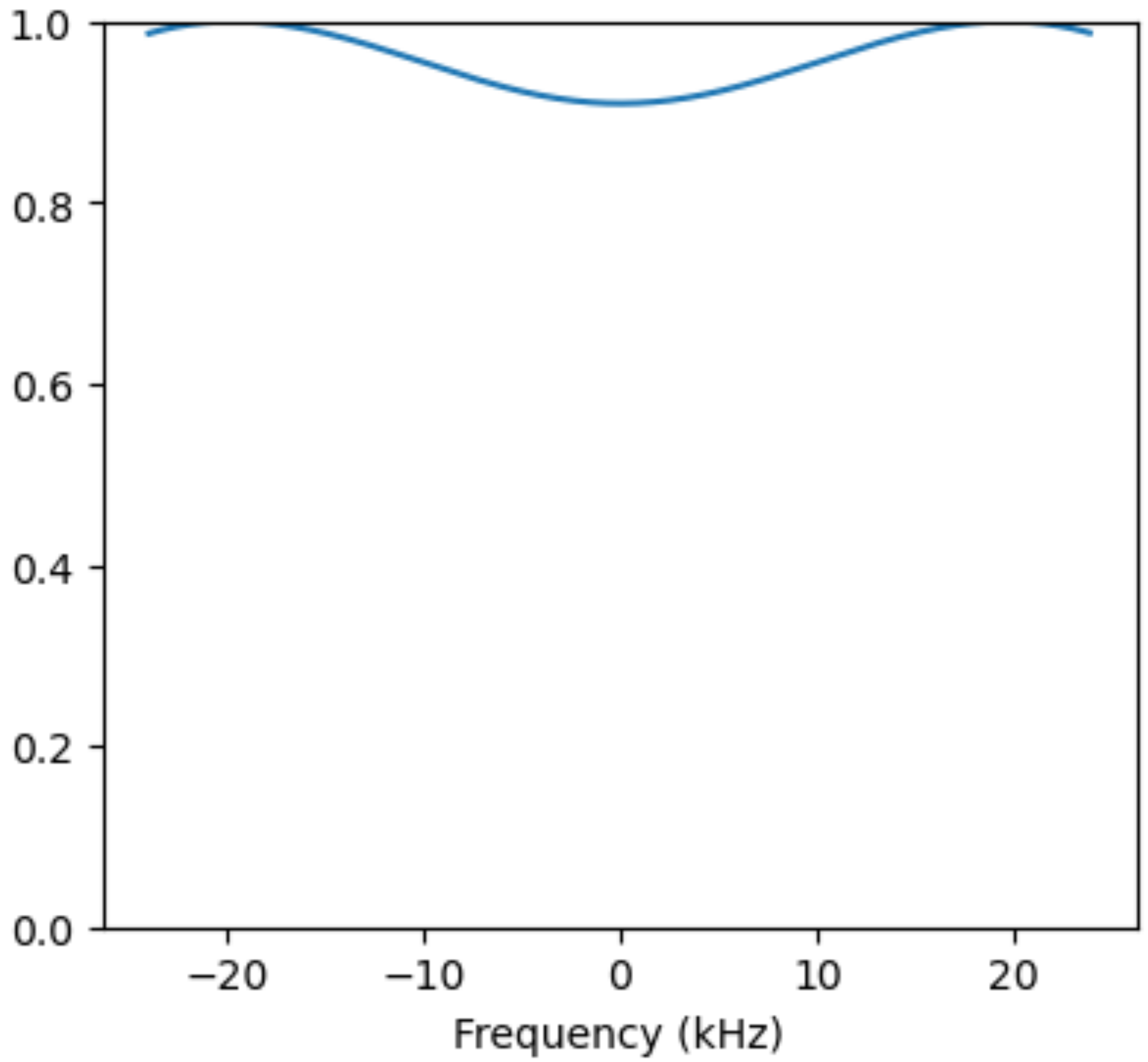
Short, high amplitude RF pulse

Excites a broad range of frequencies/locations

25 μs hard pulse



| Mxy |

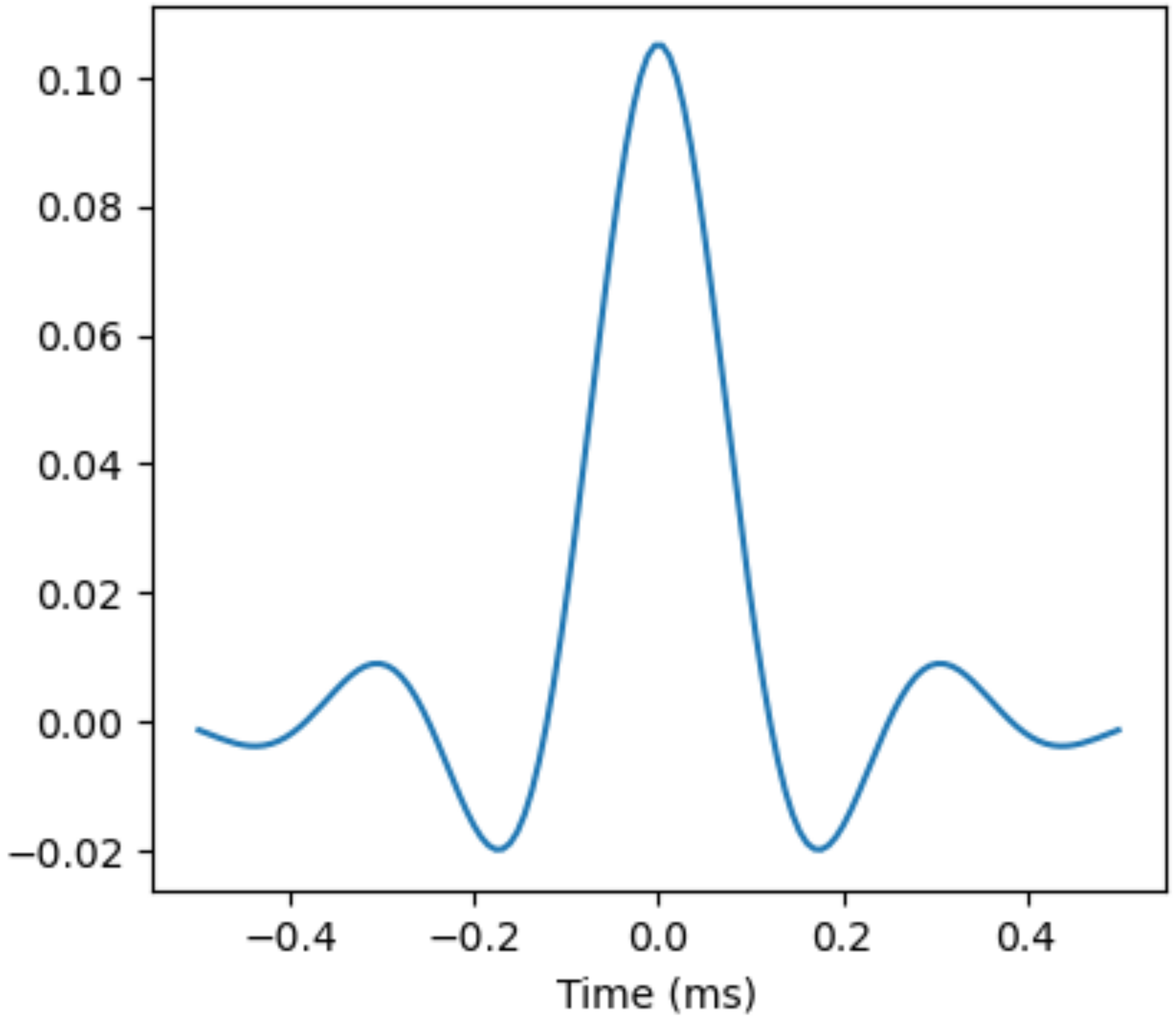


Bandlimited RF Pulses

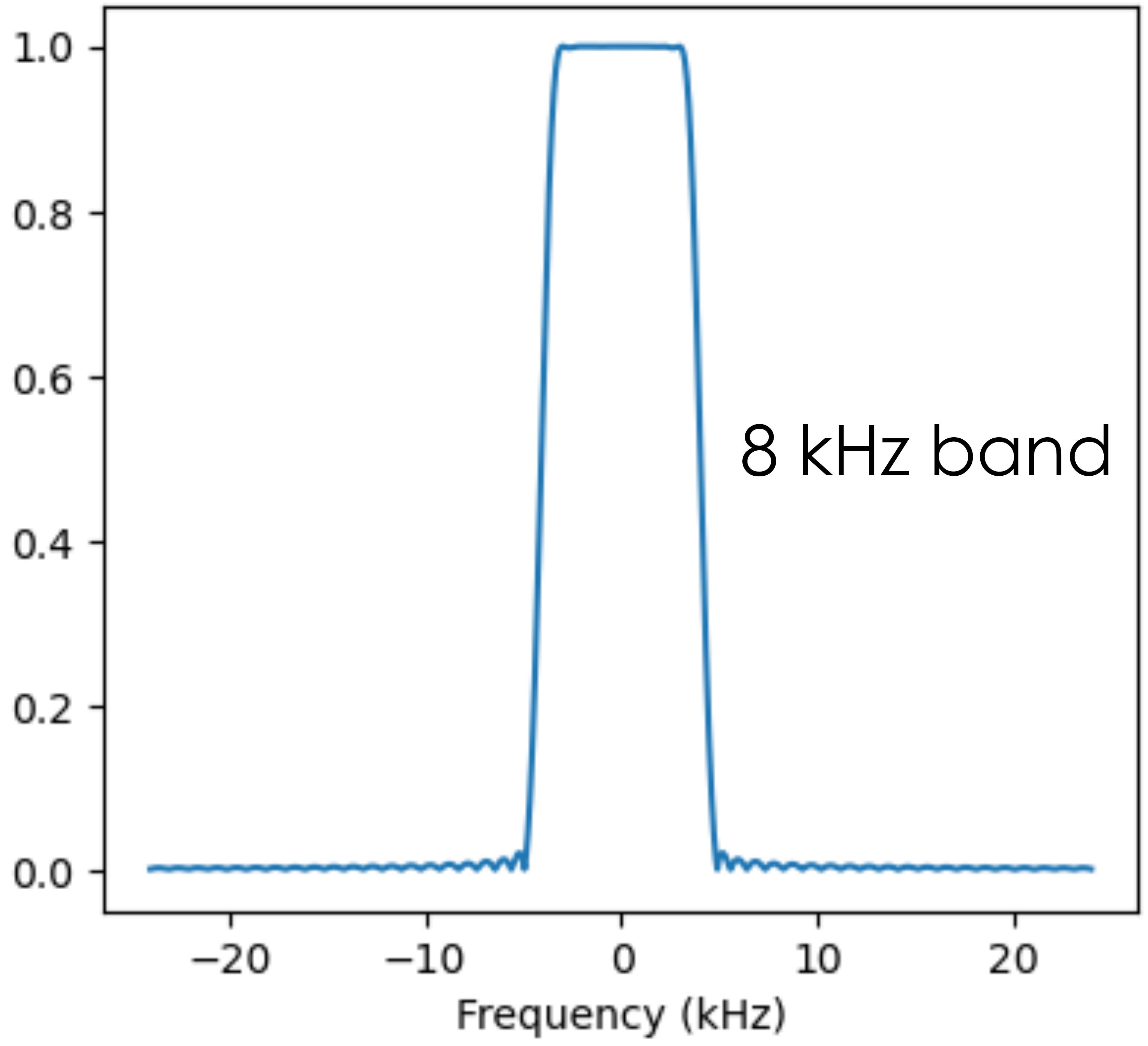
Longer, amplitude modulated pulse

Excites a narrow band of frequencies

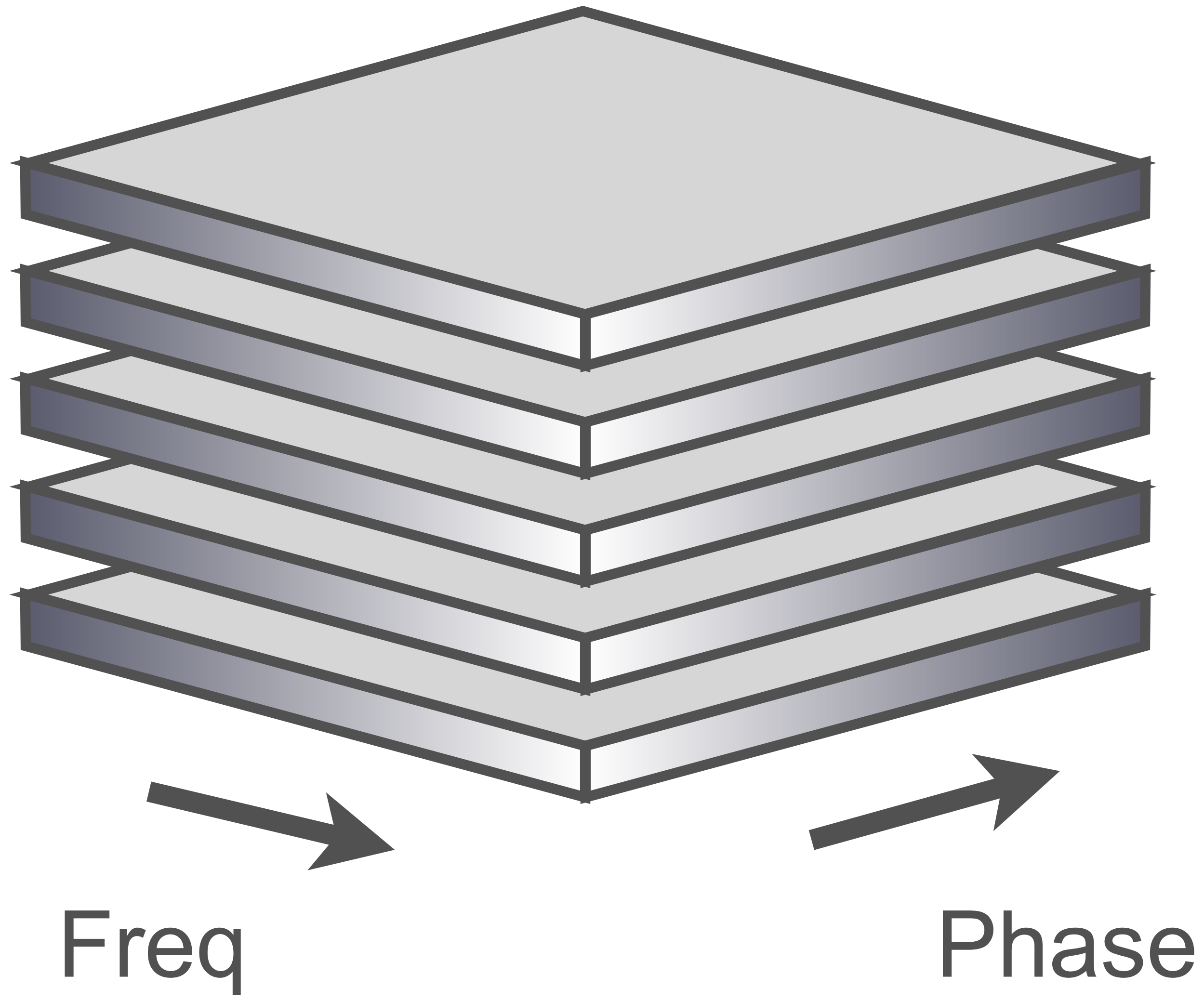
1 ms shape pulse



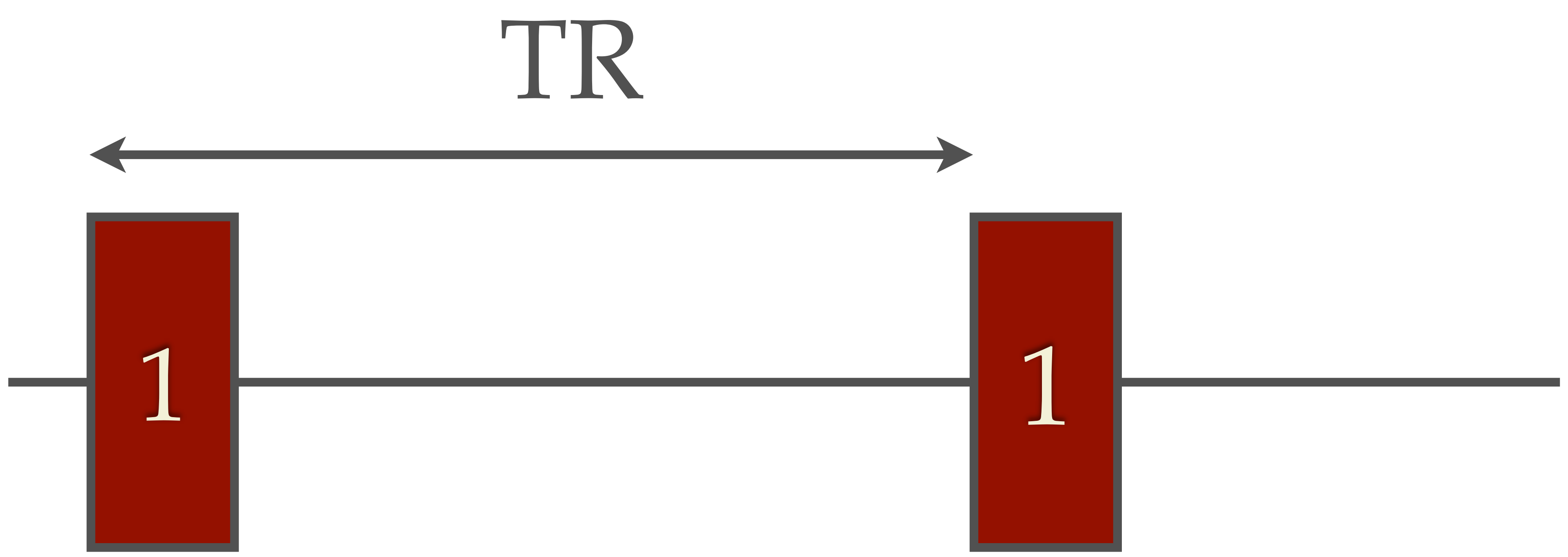
| Mxy |



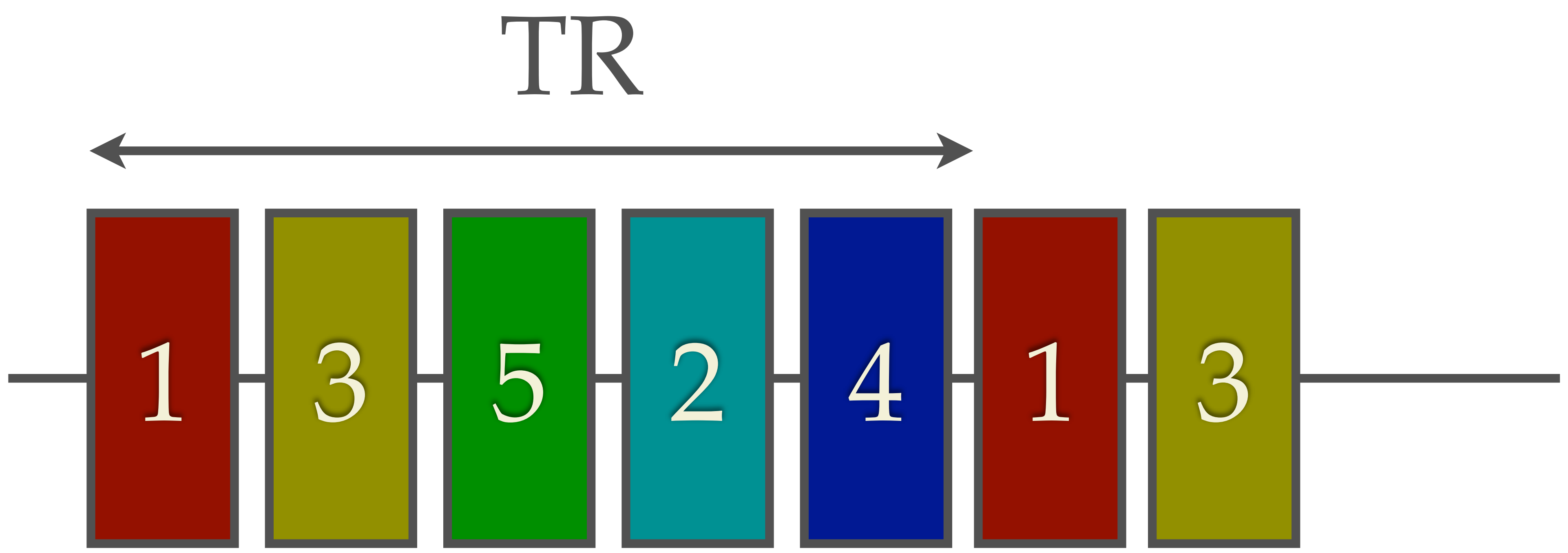
Multislice Imaging



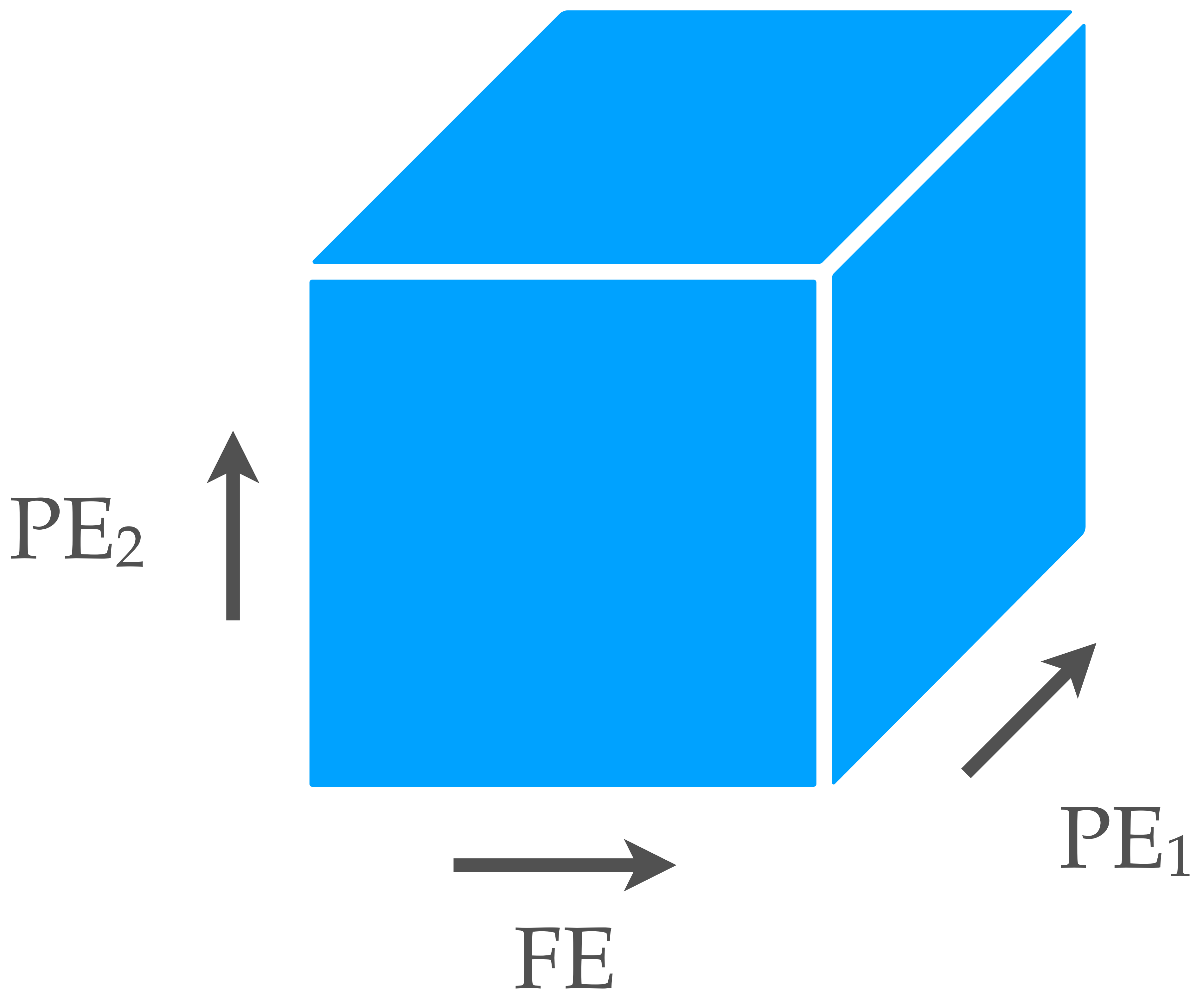
Sequential Slice Acquisition

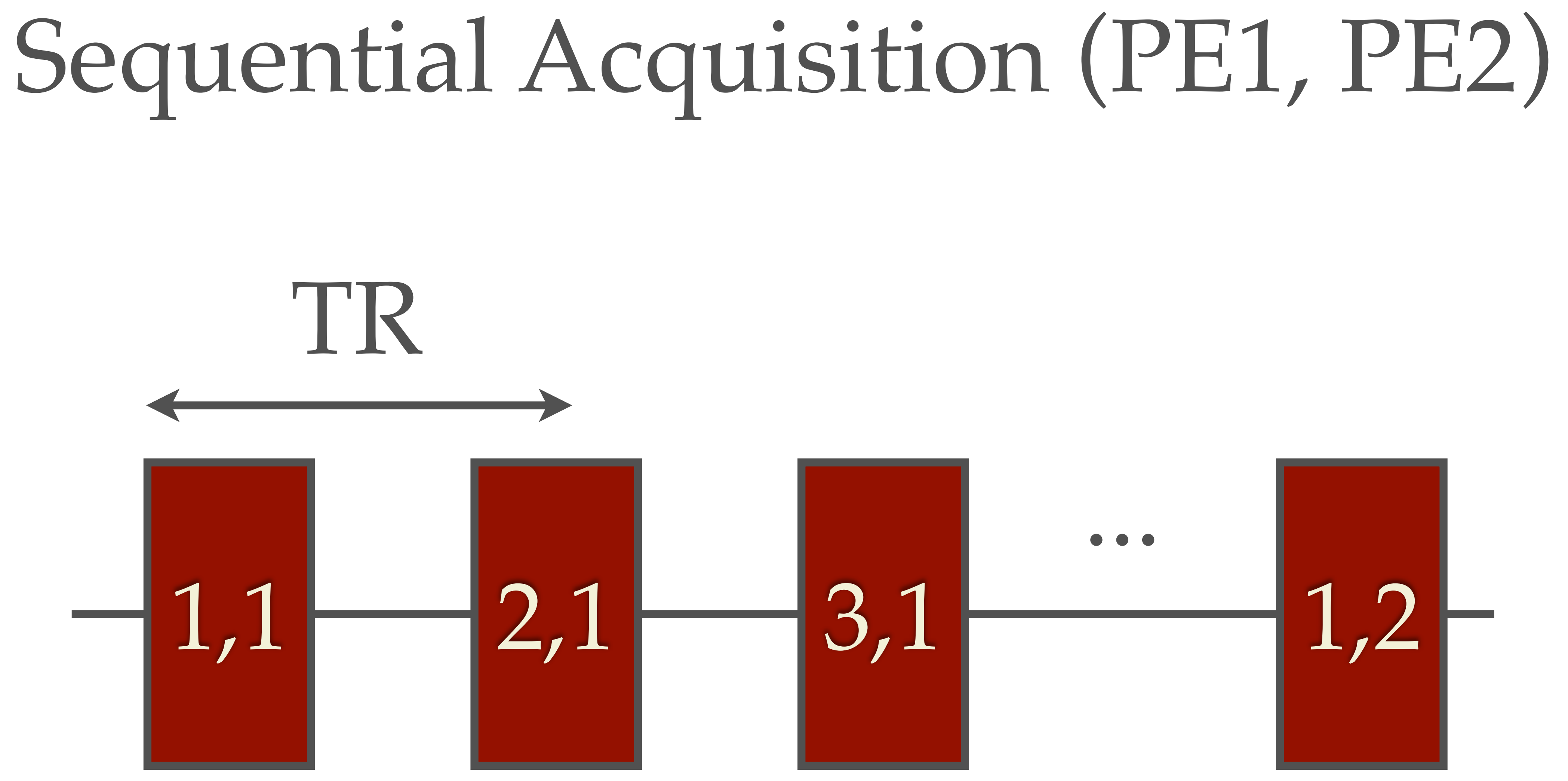


Interleaved Slice Acquisition



3D Volumetric Imaging



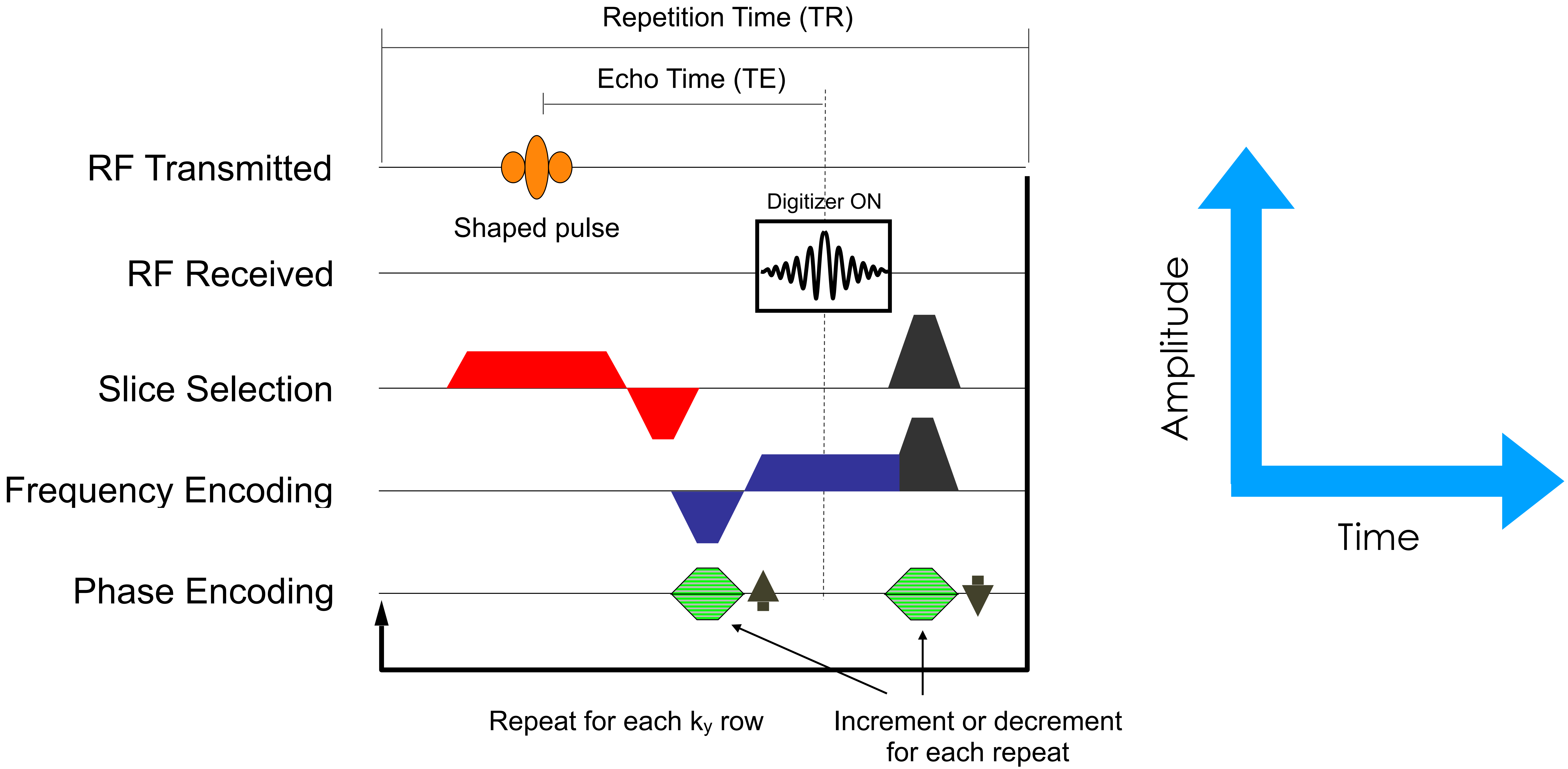


Pulse Sequences

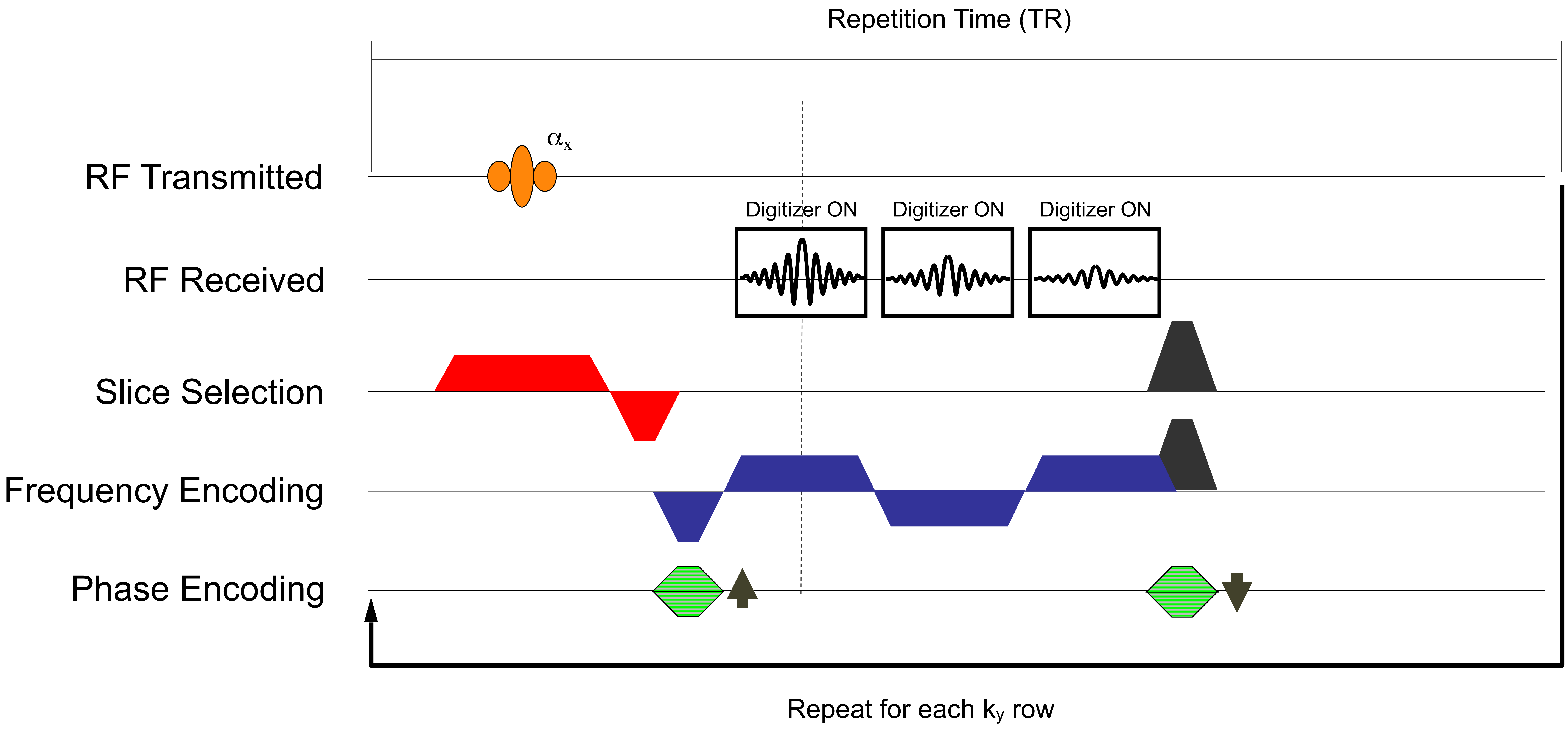
MRI Pulse Sequences

- Combinations of RF and gradient pulses that do the following:
    - **Excite** detectable magnetization
    - **Refocus** magnetization to generate an “echo”
    - **Move** excited magnetization in k-space
    - **Record** detected signal

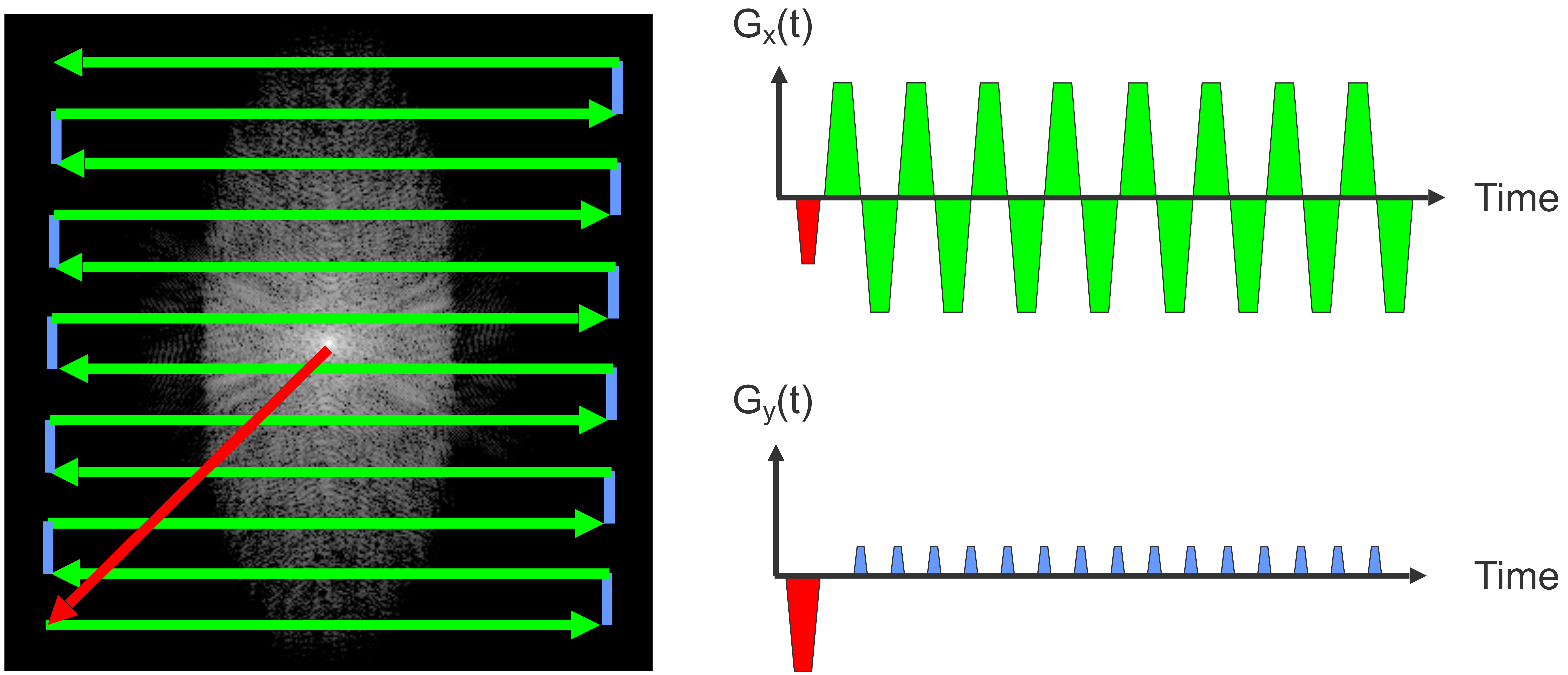
Example Pulse Sequence Diagram : Gradient Echo Imaging



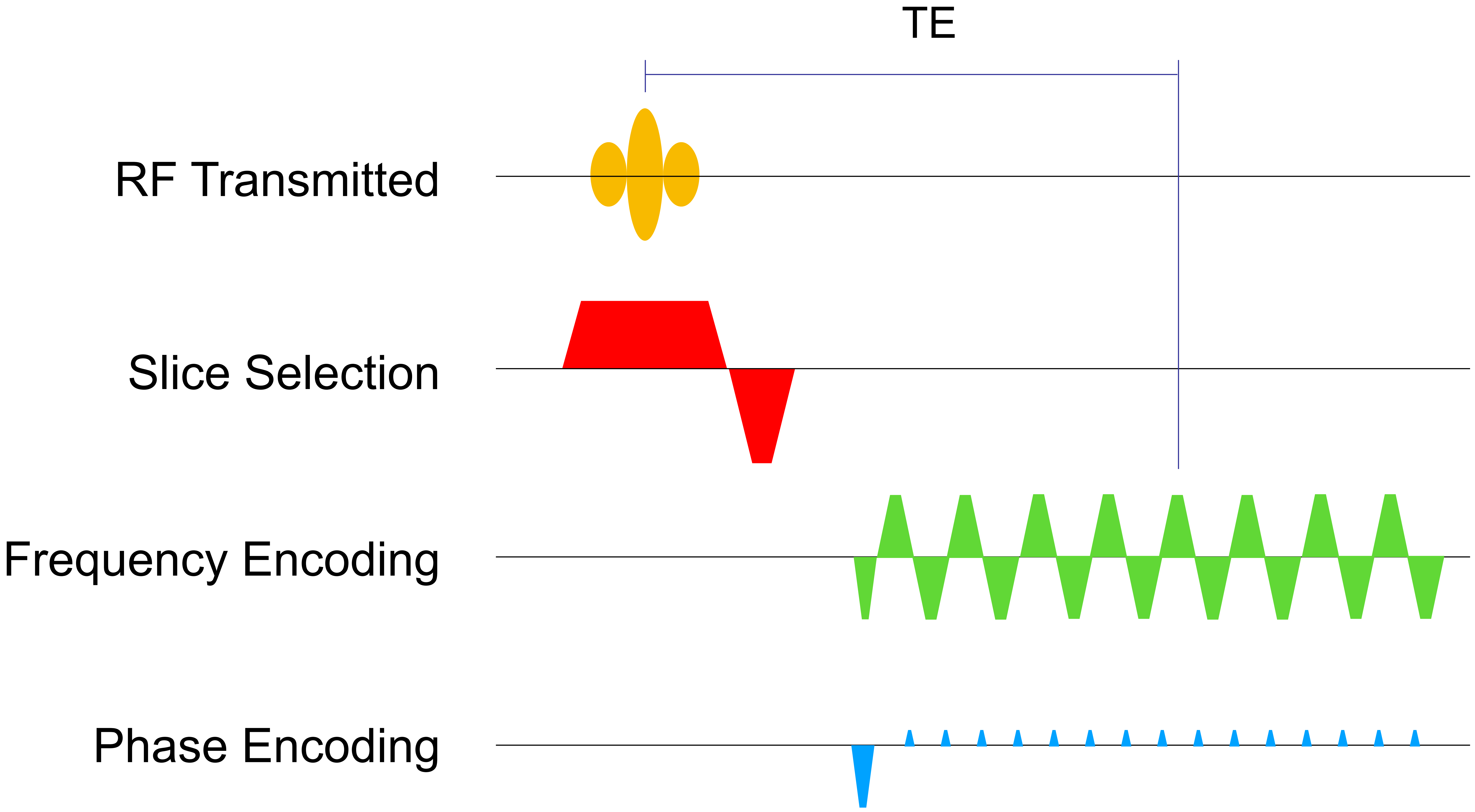
Multiple Gradient Echoes



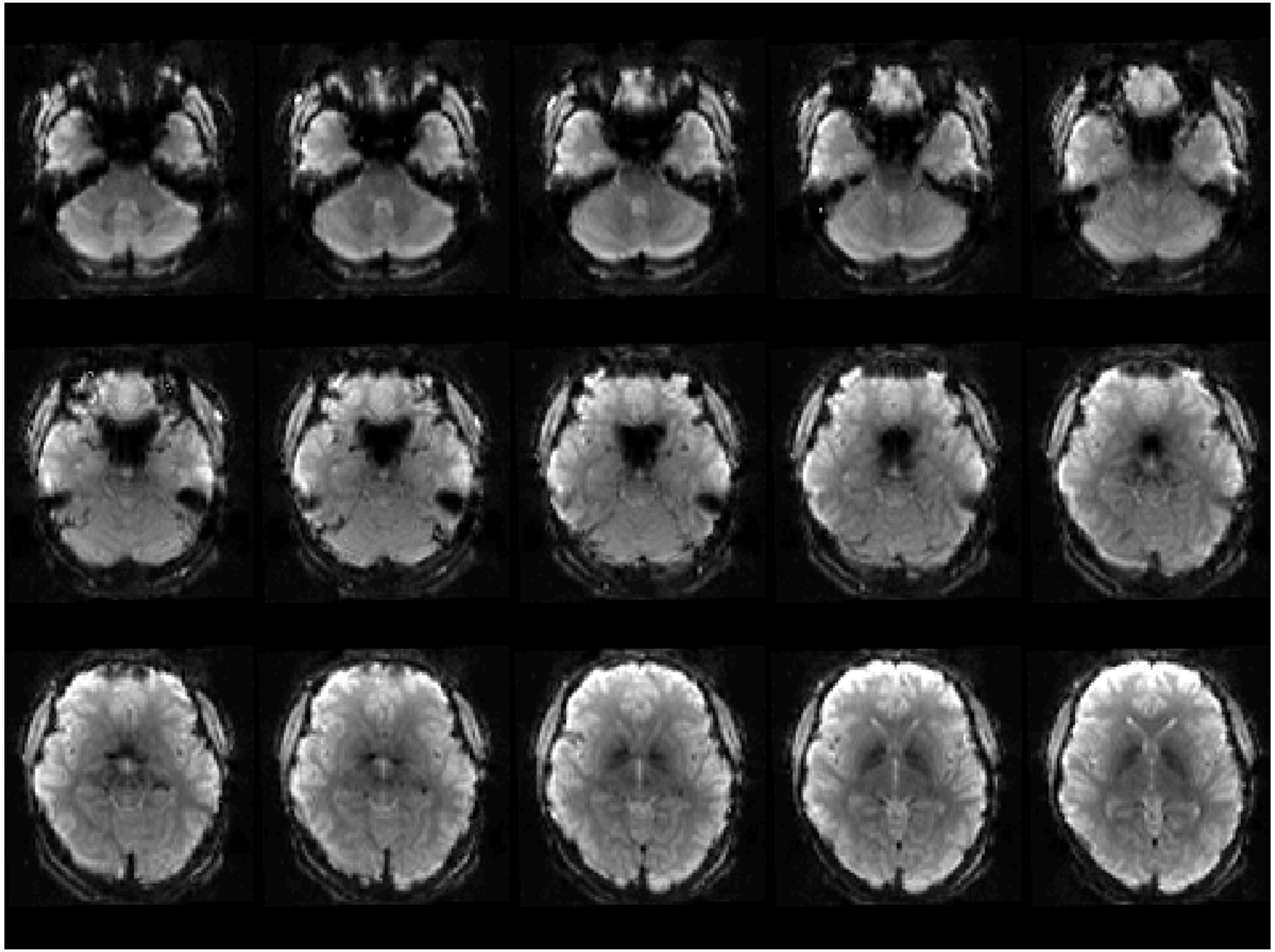
Gradient Echo EPI



Gradient Echo EPI



Gradient Echo EPI Images

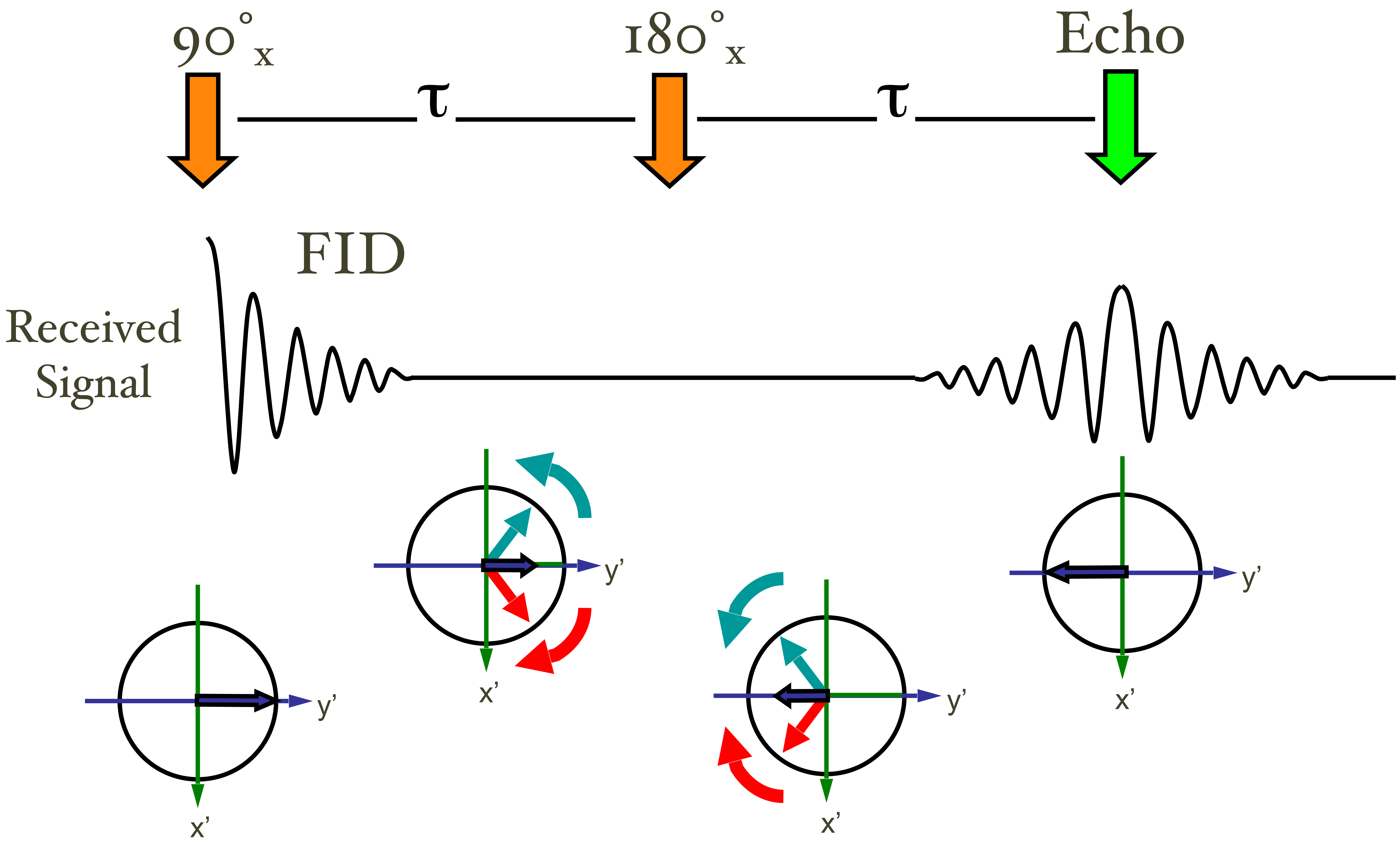


TR	380 ms
TE	30 ms
Slices	2.25 mm x 60
Voxel Size	2.25 mm x 2.25 mm
Matrix Size	80 x 80
Flip Angle	45°

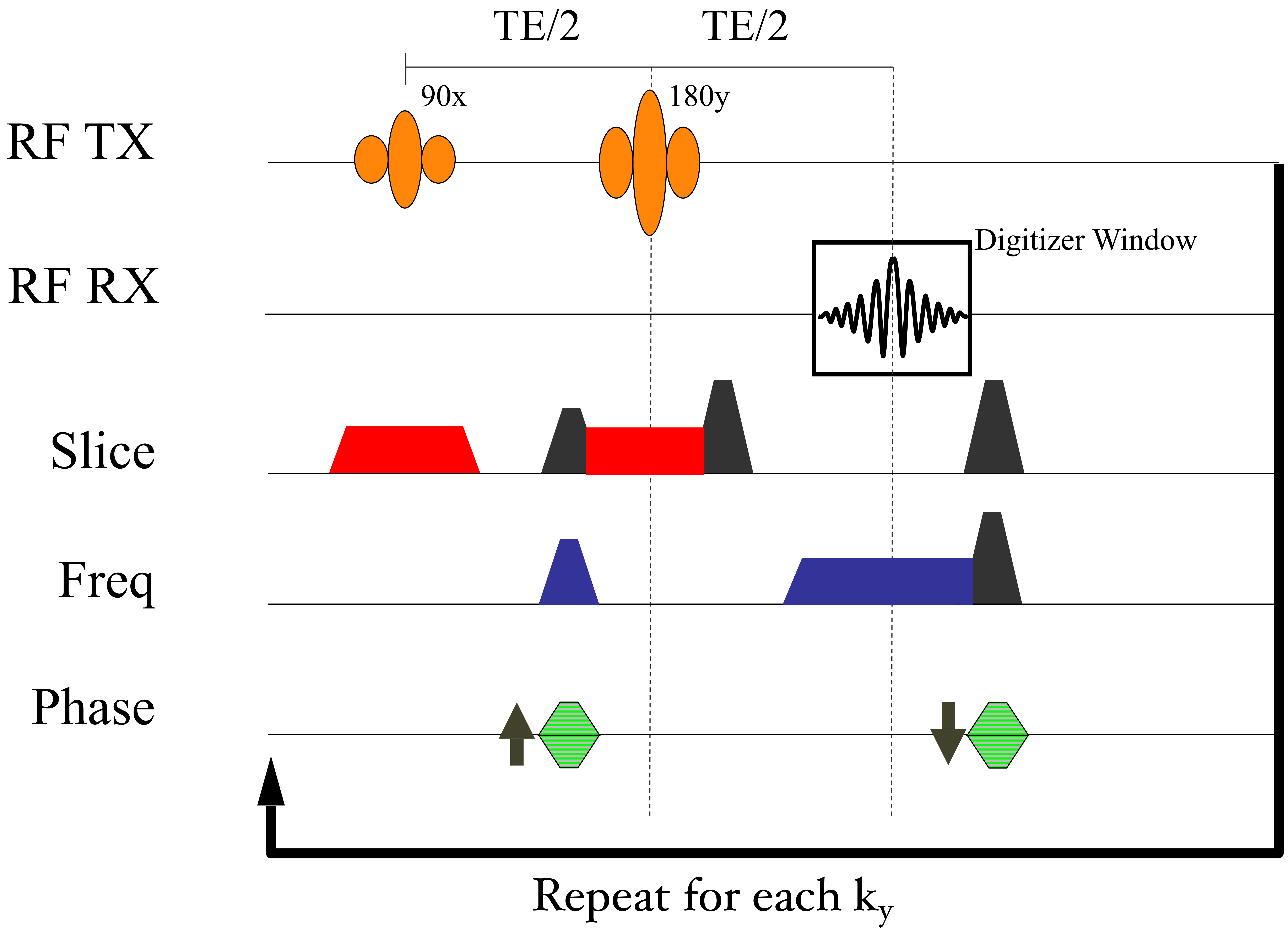
Spin Echo Pulse Sequence

- Predates gradient echo sequences
- Creates an echo with two RF pulses (Hahn Echo)
- Robust to magnetic field inhomogeneities (off-resonance effects)
- Typically used for T2-weighted MRI

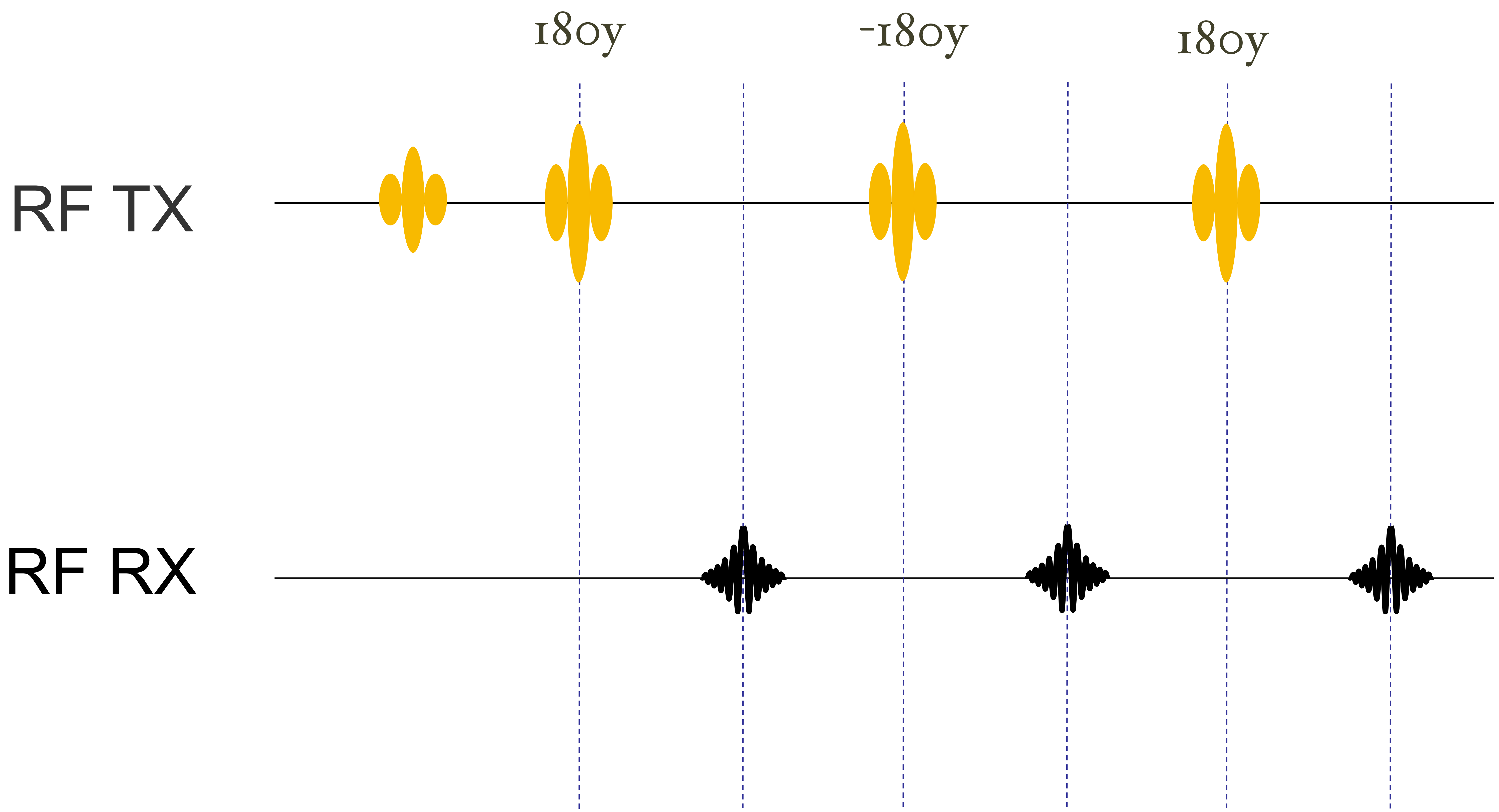
The Hahn Spin Echo Explained



Spin Echo Pulse Sequence

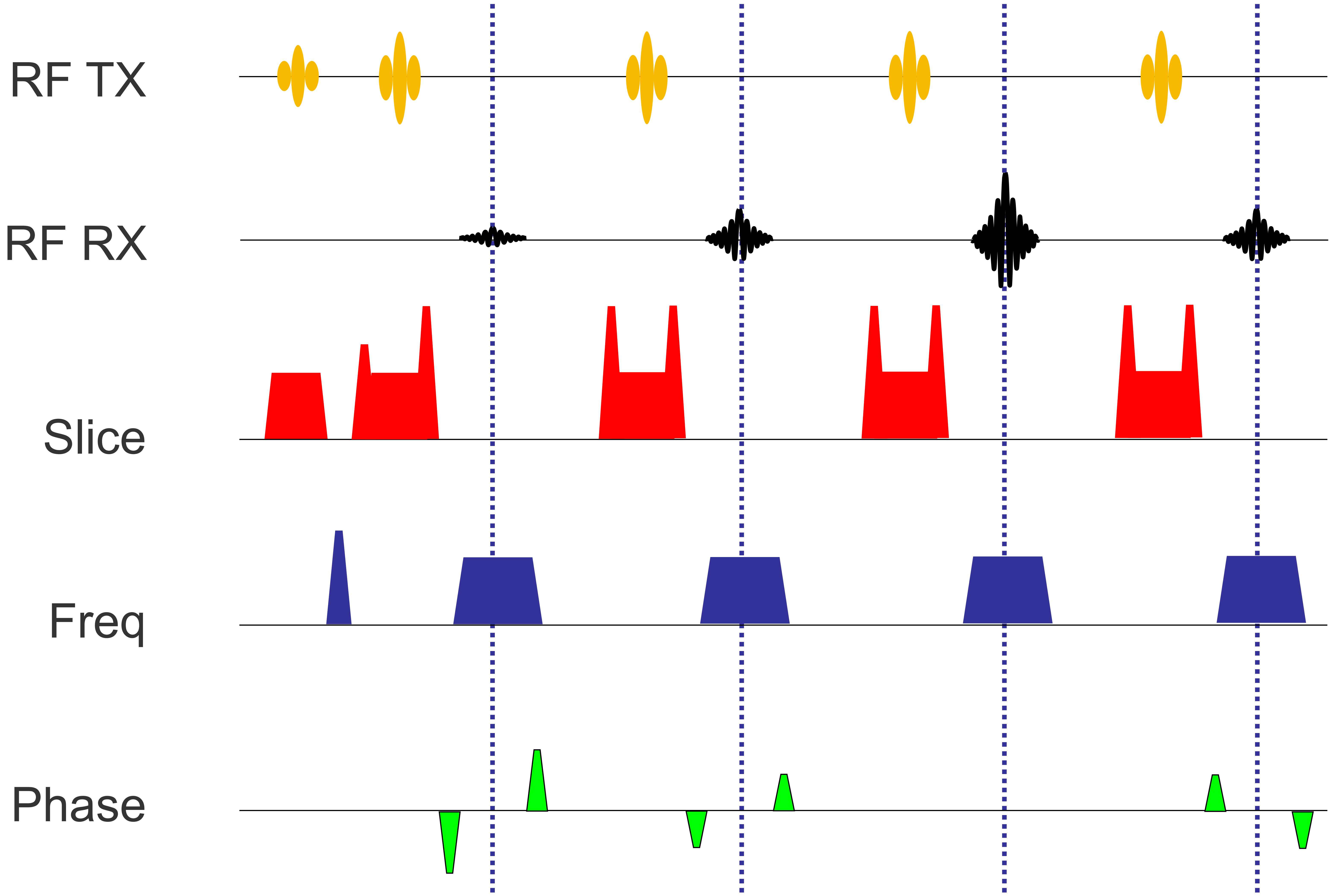


Multiple Spin Echo Sequence

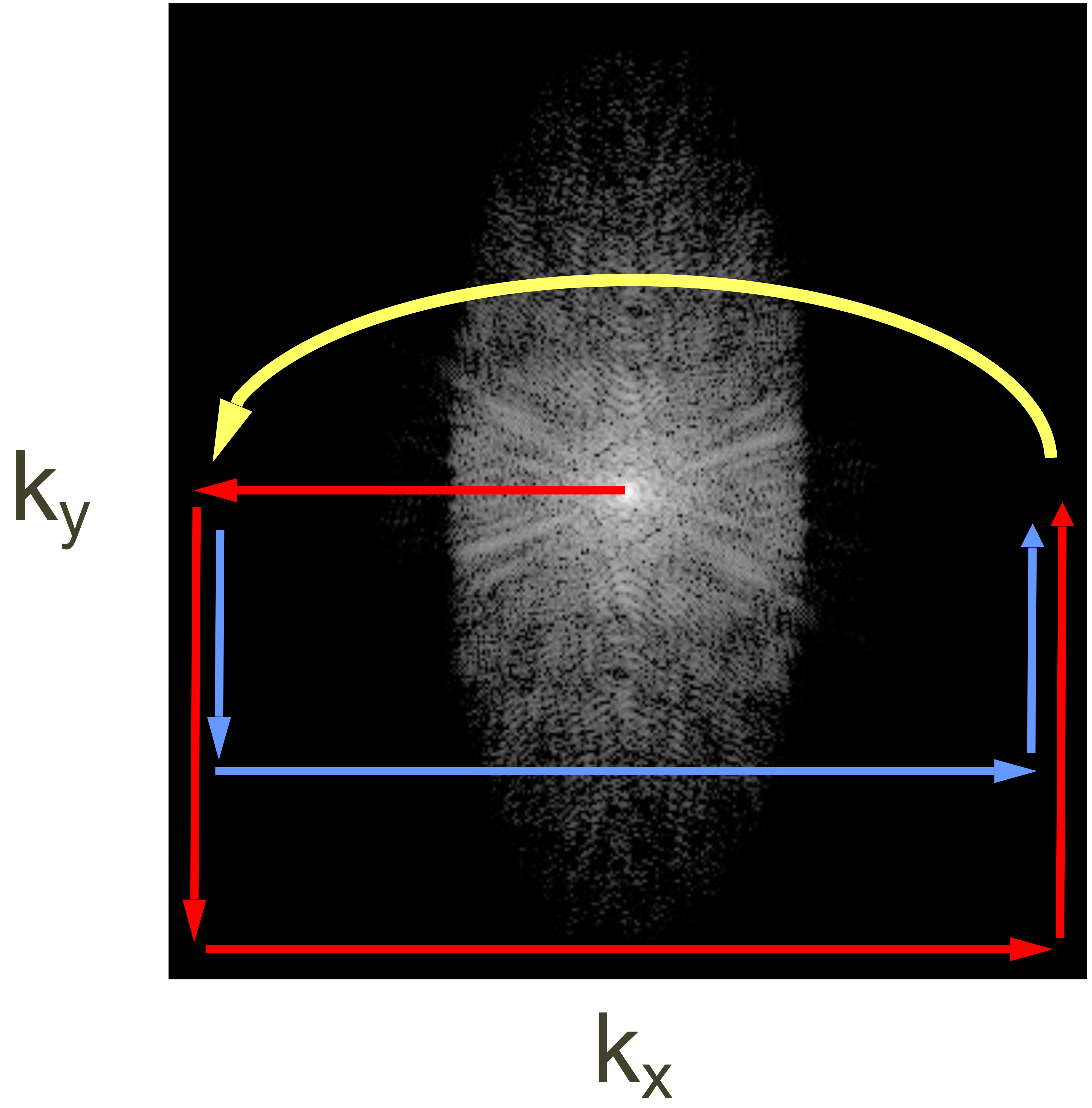


Multiple spin echoes refocused from single excitation

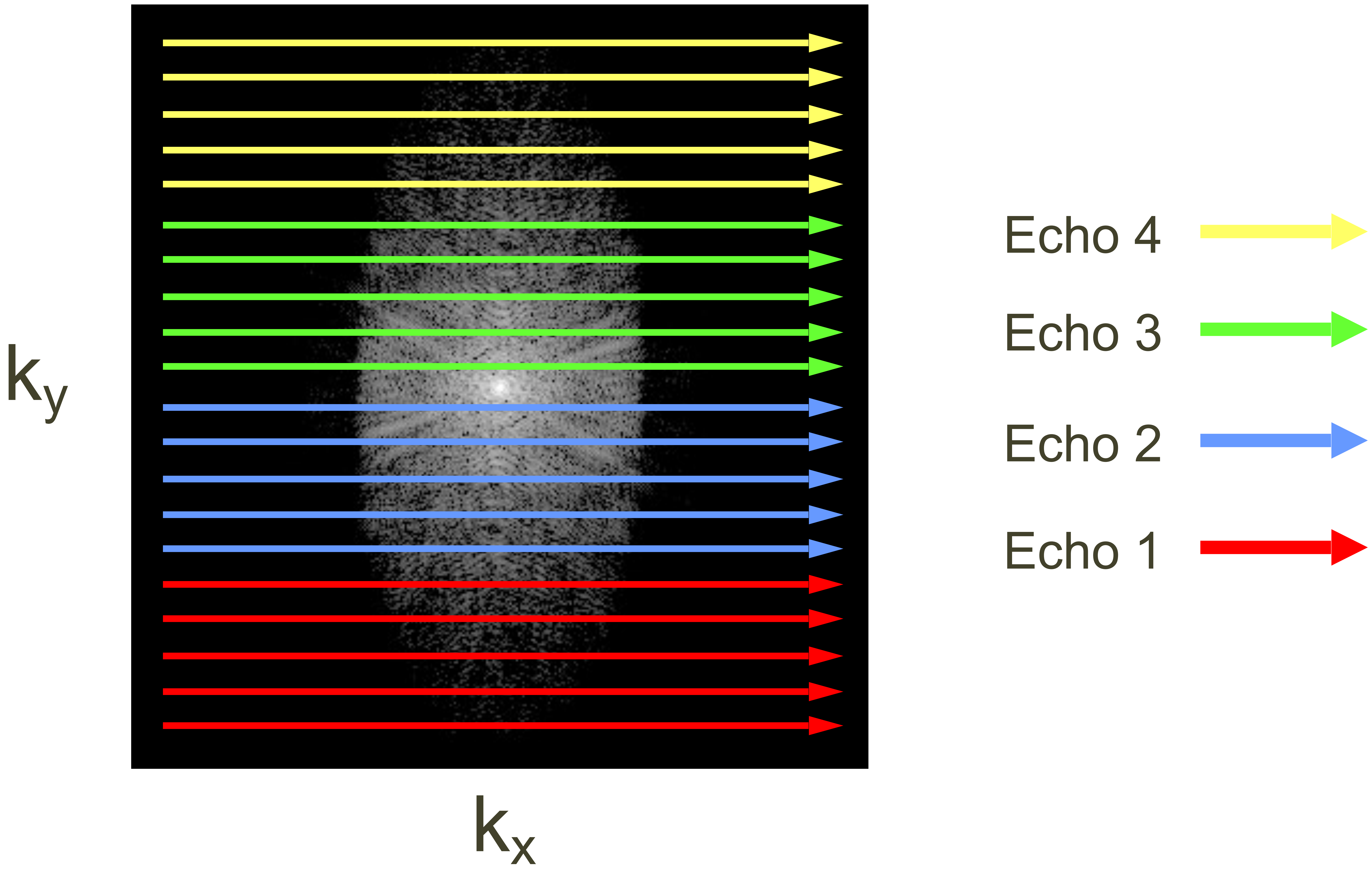
Turbo Spin Echo Imaging Sequence



Turbo Spin Echo k-space trajectory



Turbo Spin Echo k-space trajectory

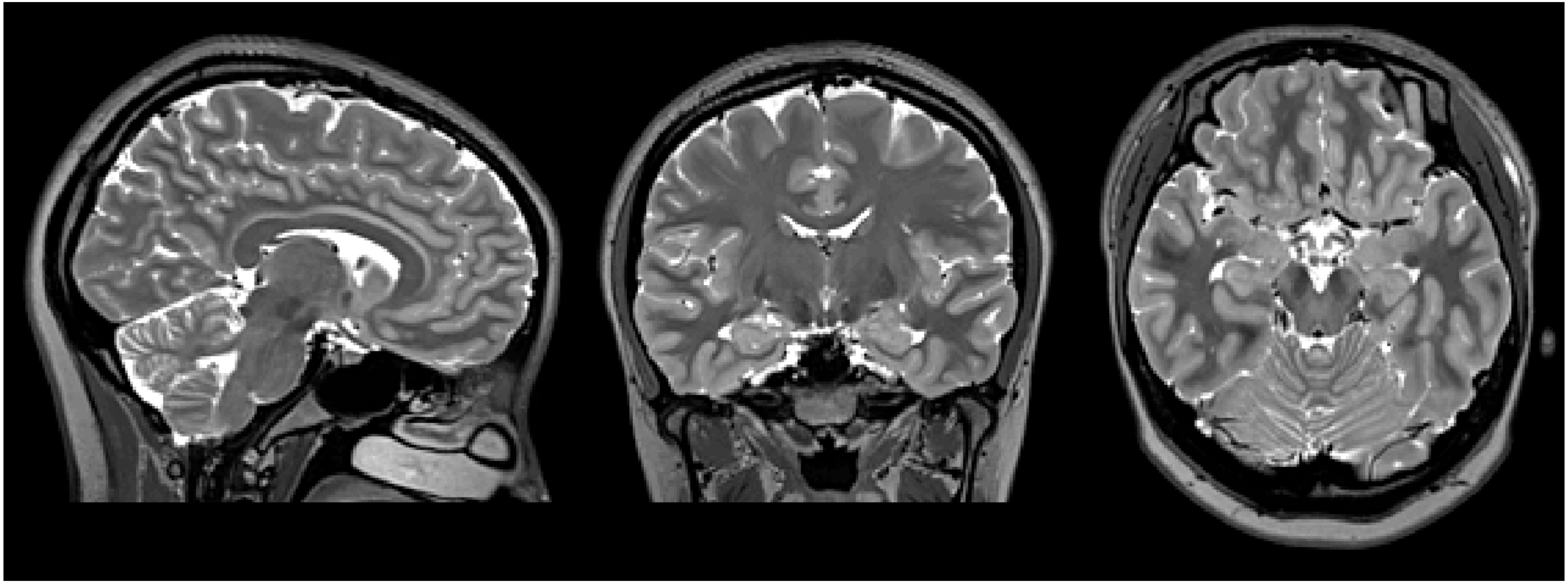


T2w SPACE

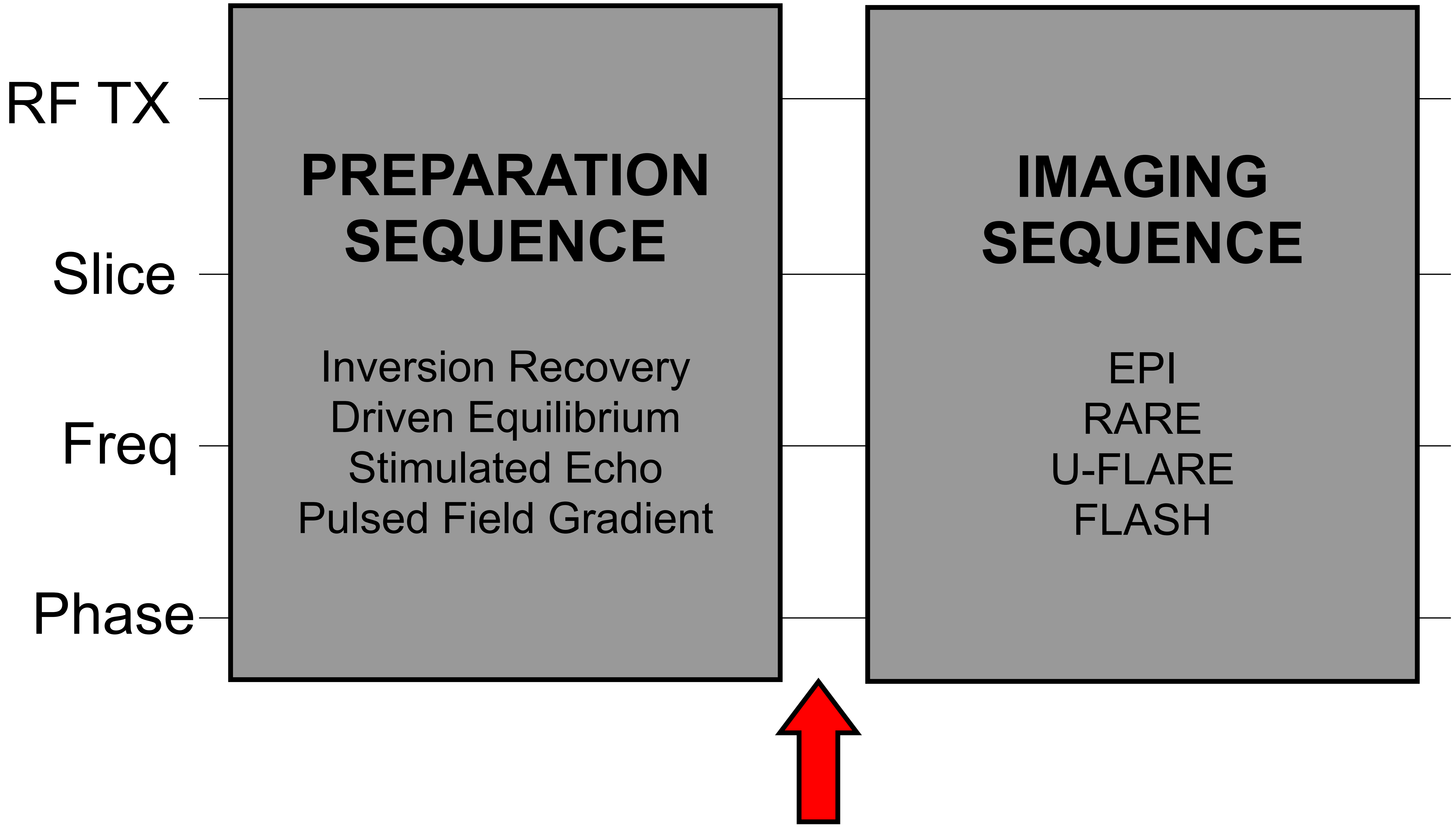
Multi-shot 3D turbo spin echo

Efficient, high-resolution T2w structural imaging

Sampling **P**erfection with **A**pplication optimized **C**ontrast using different flip angle **E**volution

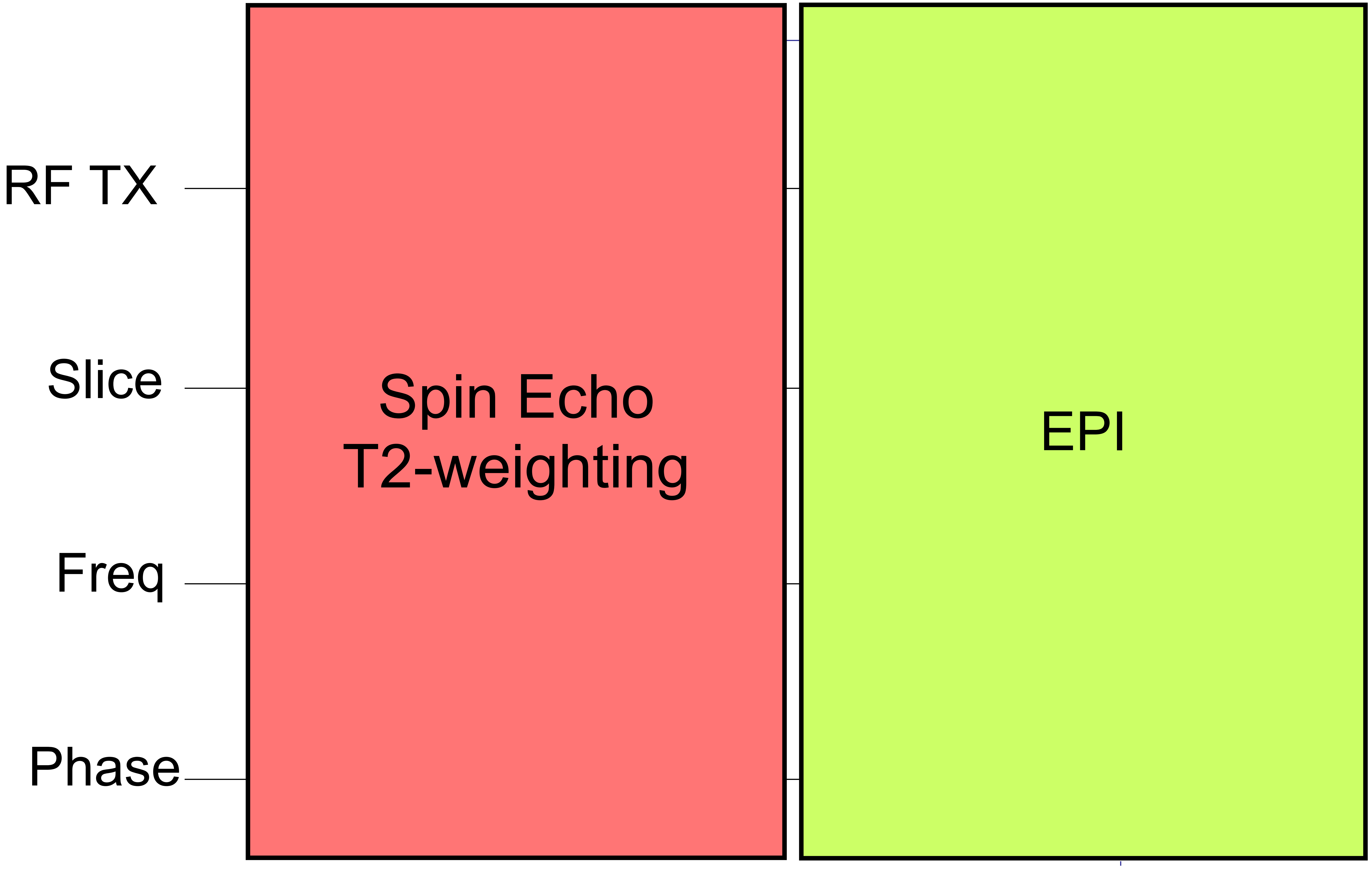


Magnetization Preparation

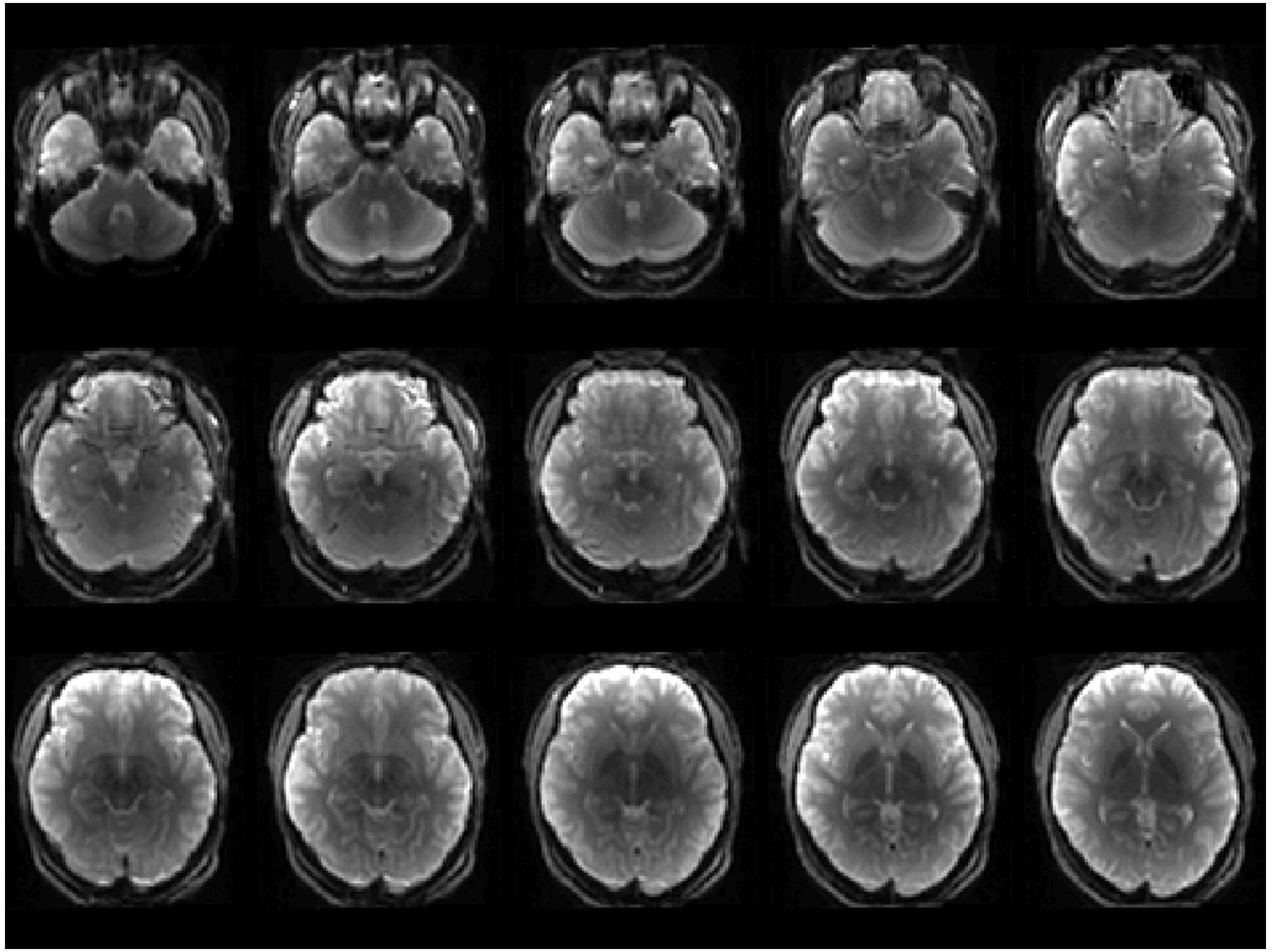


Longitudinal or transverse magnetization carries magnetization contrast prepared by initial pulse sequence

T2w Spin Echo EPI



SE-EPI Images



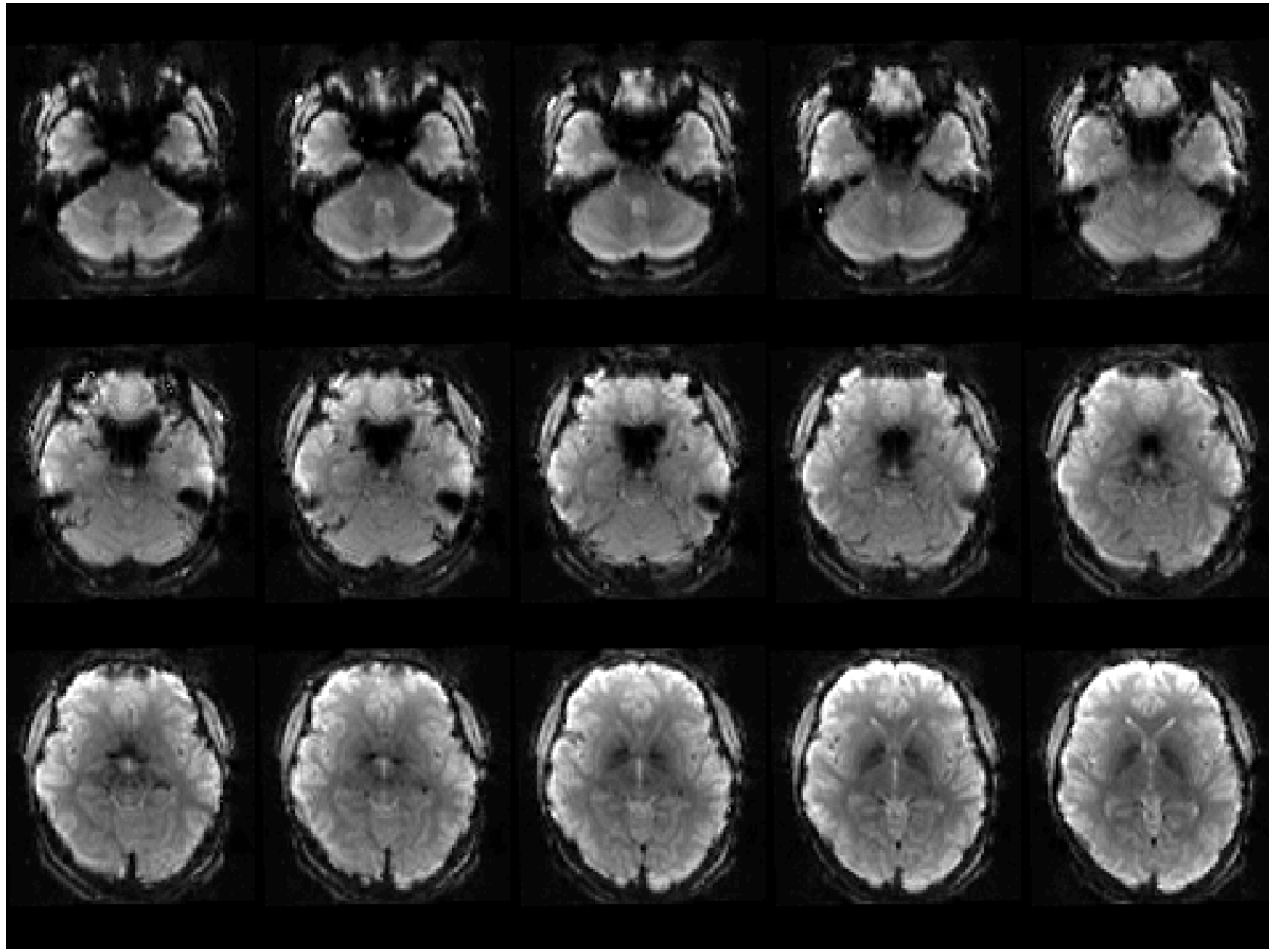
TR	2000 ms
TE	43 ms
Slices	2.25 mm x 20
Voxel Size	2.25 mm x 2.25 mm
Voxel Matrix	84 x 84
Flip Angle	90°

T2*w GRE-EPI vs T2w SE-EPI Images

GRE-EPI

Sensitive to B0 inhomogeneities

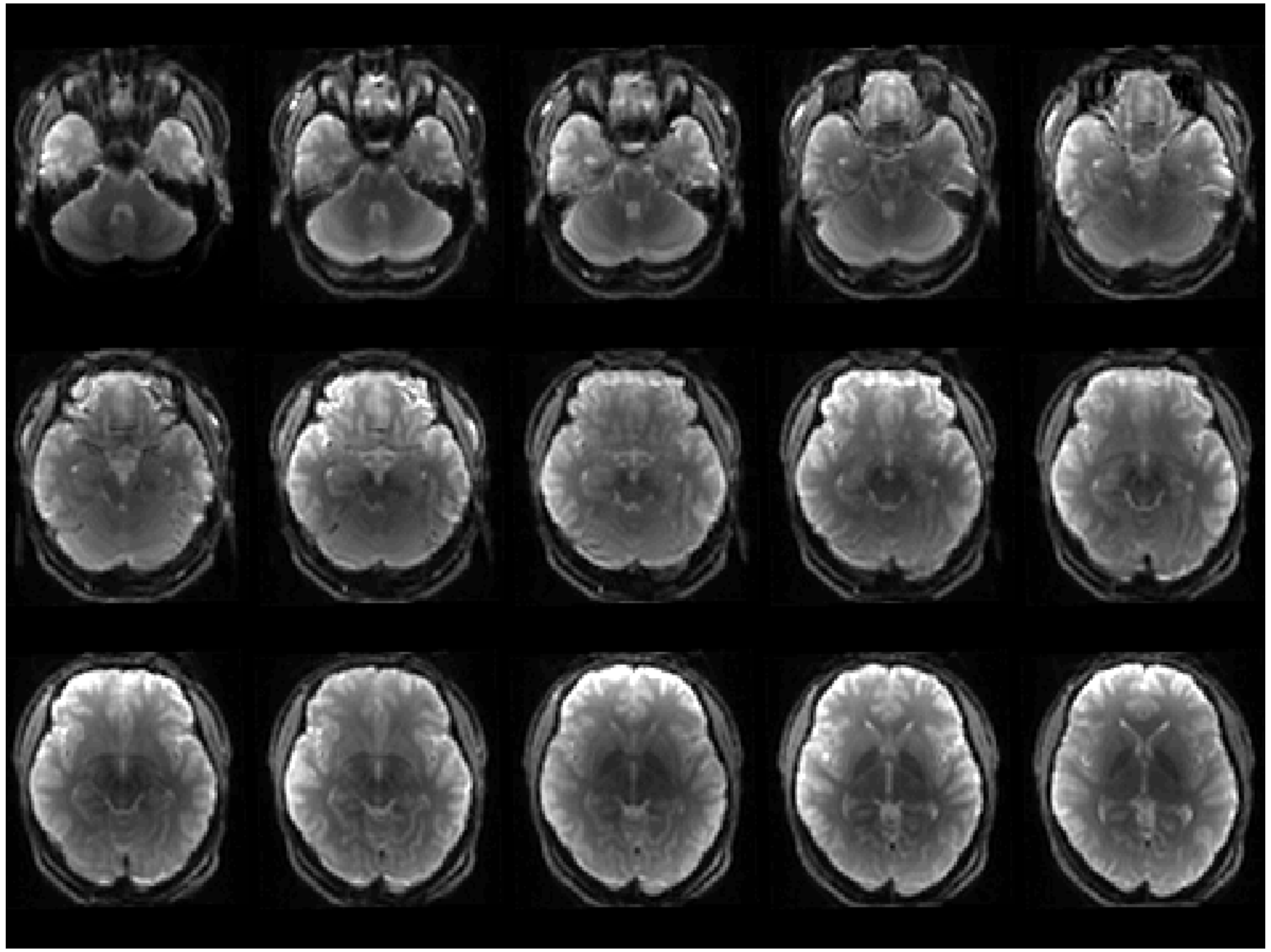
BOLD fMRI workhorse sequence



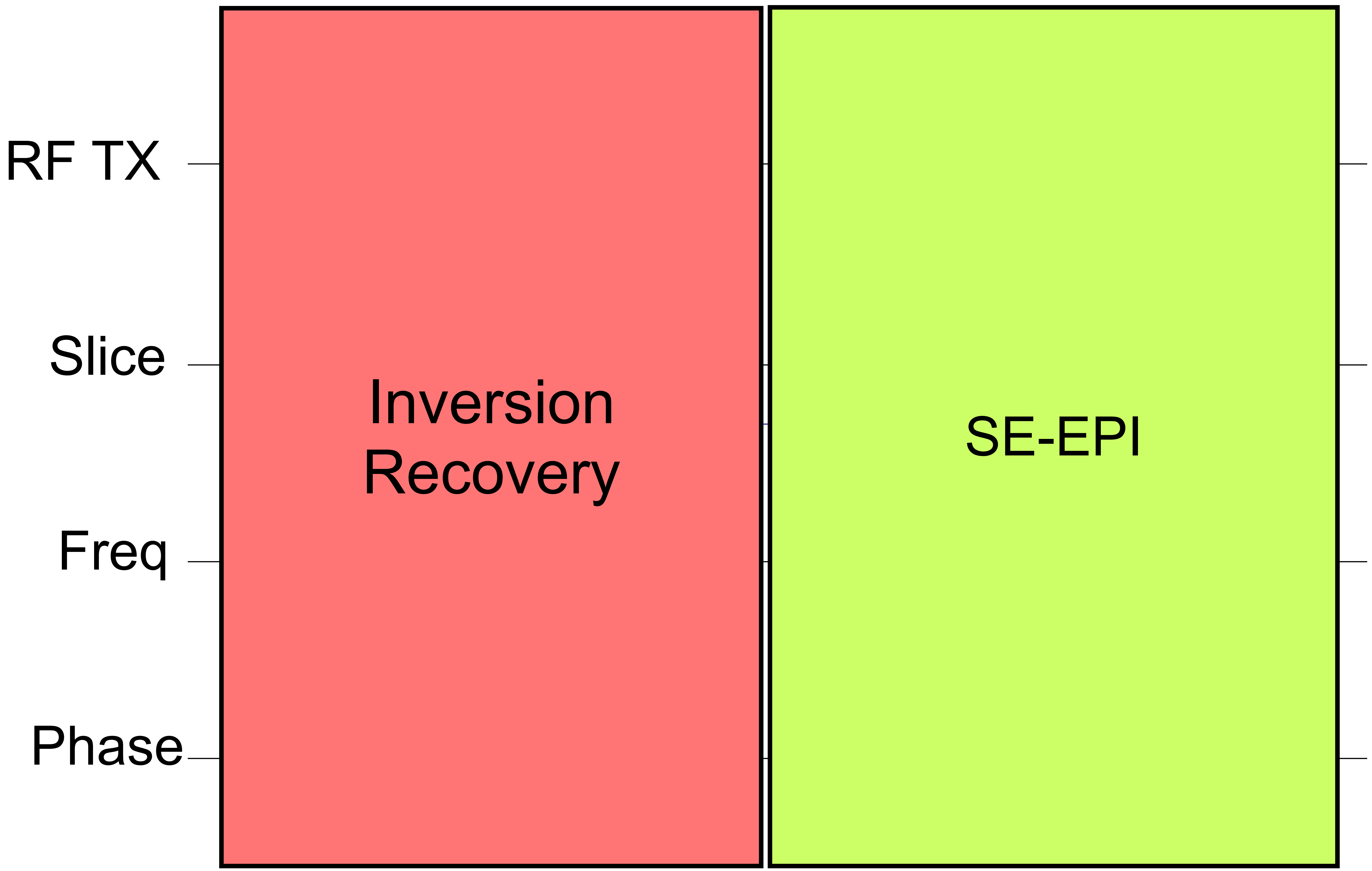
SE-EPI

Insensitive to B0 inhomogeneities

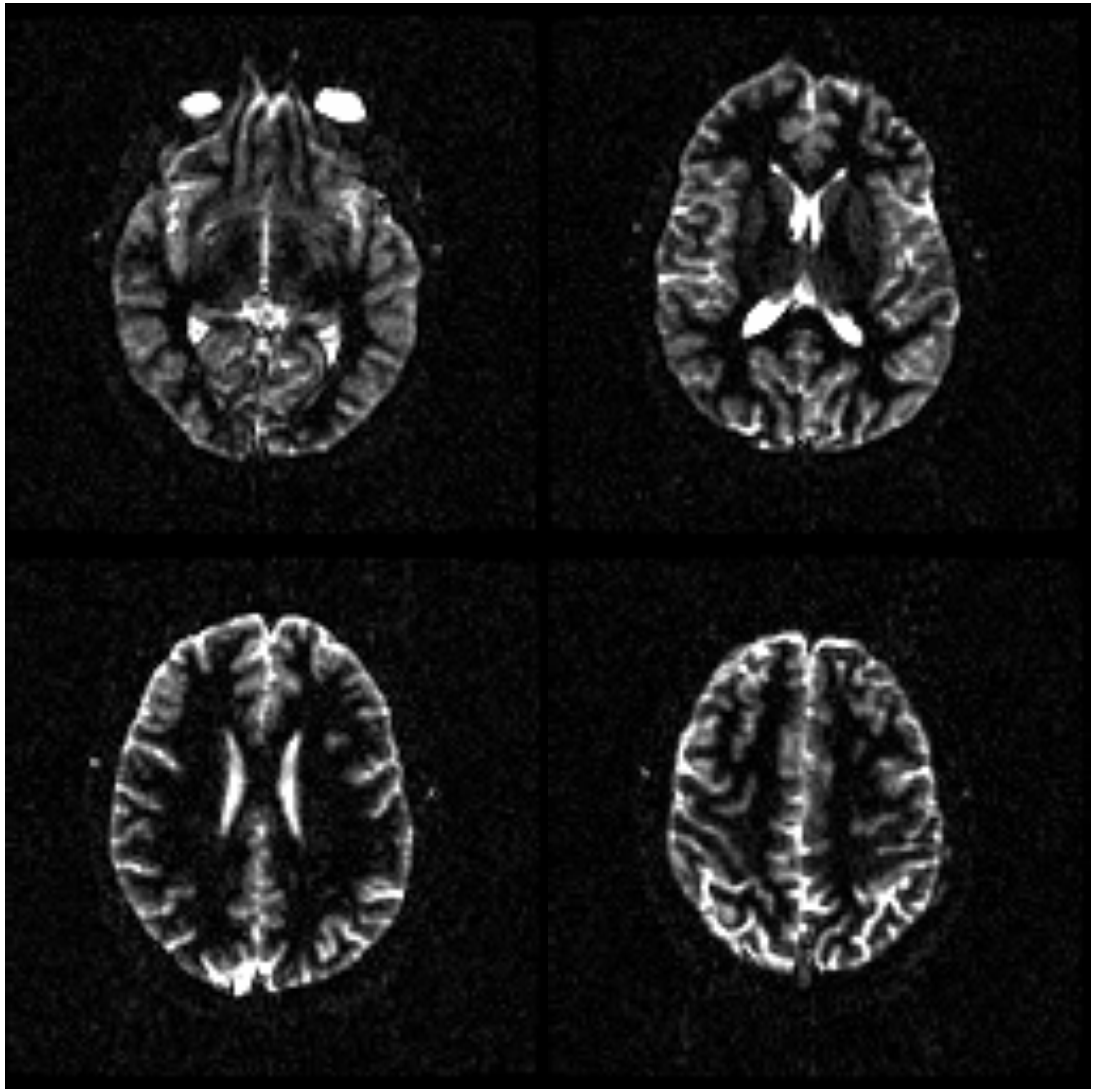
Distortion correction sequence for GRE-EPI



Inversion-Recovery SE-EPI



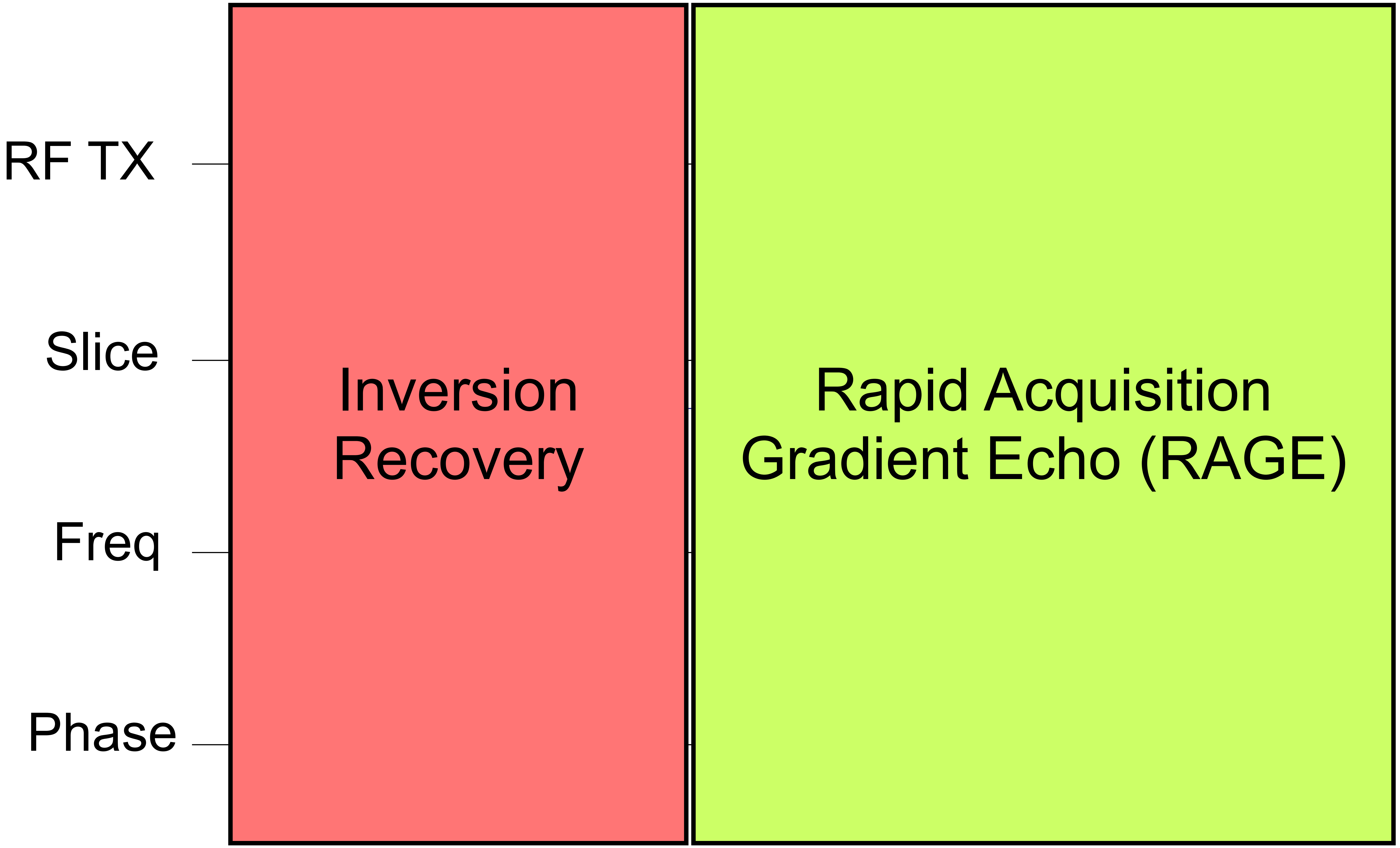
IR-SE-EPI Images



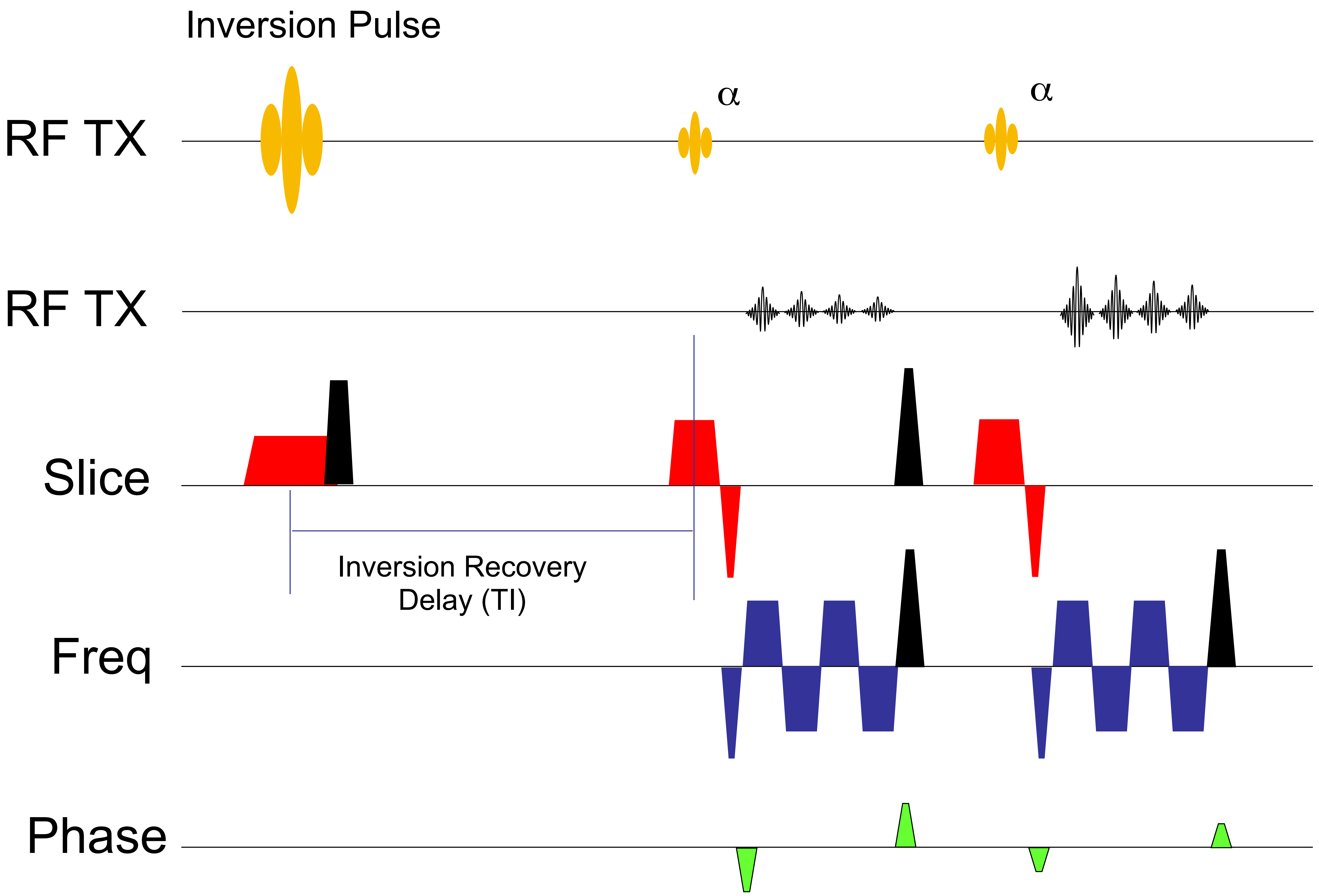
<u>IR-SE-EPI</u>

Shots	: 1
TI	: 400ms
TR	: 3000ms
TE	: 60ms
Slice	: 5mm/2.5mm (18)
Matrix	: 128 x 128
FOV	: 24cm x 24cm
Time	: 12s
NEX	: 1

MP-RAGE Pulse Sequence



Even better - multi echo MP-RAGE!

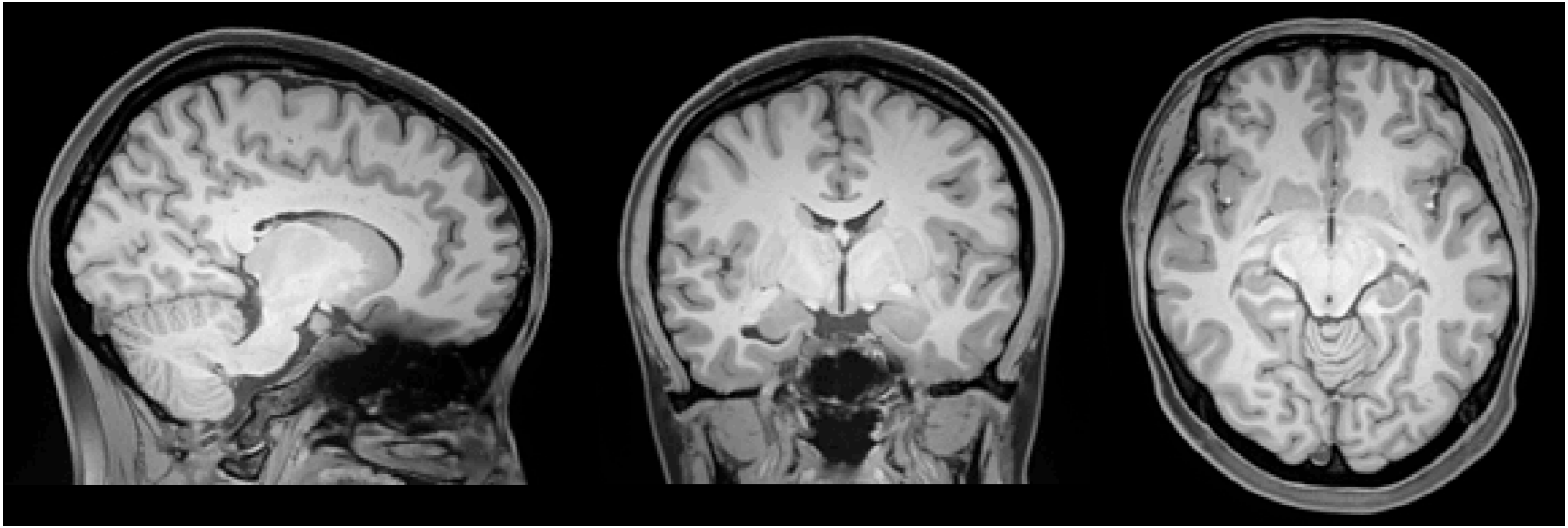


T_1-weighted MEMP-RAGE

Multi-echo Magnetization Prepared Rapid Acquisition Gradient Echo

Inversion recovery magnetization preparation

Take RMS average of all echo images to improve SNR



Next Time

- Accelerated Imaging
- Image Artifacts
- Noise
- Optimization