Gradient Echoes & *k*-space

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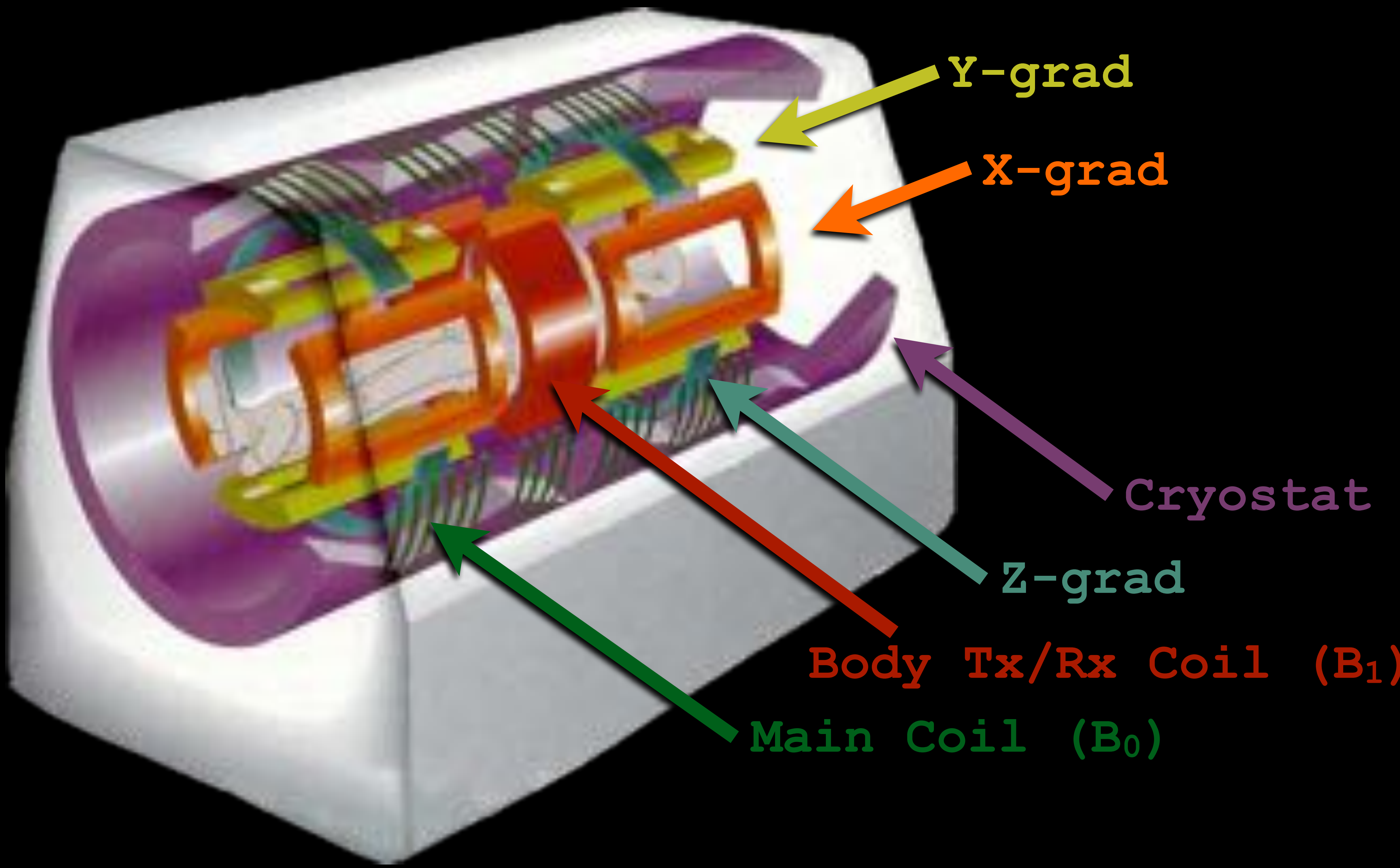
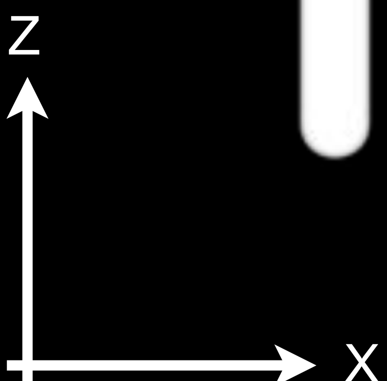
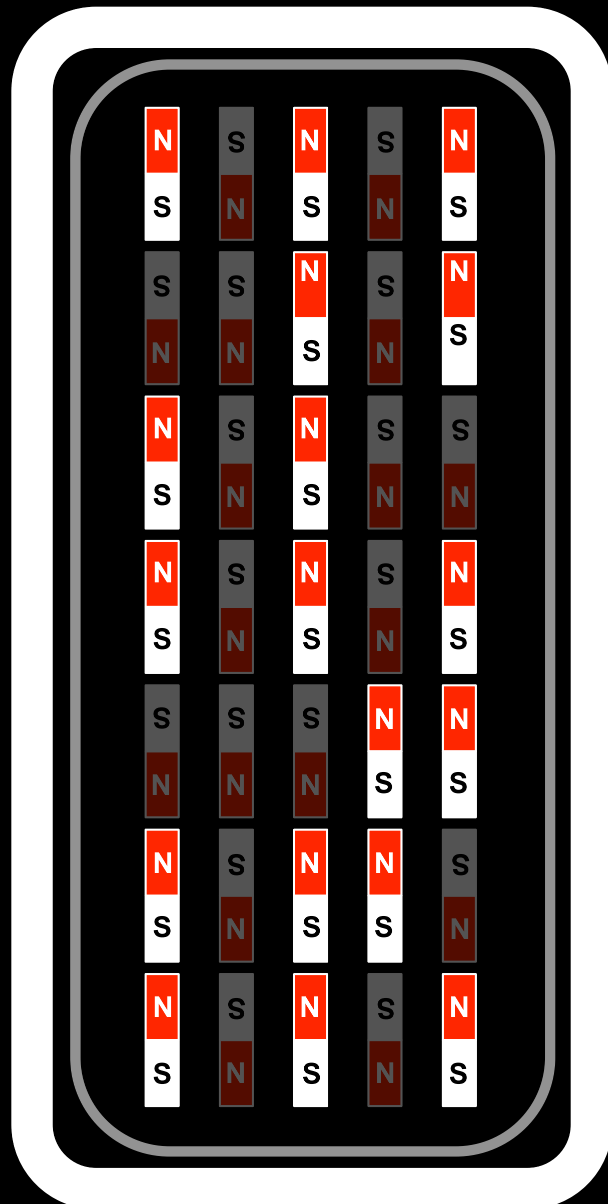
Lightning Review

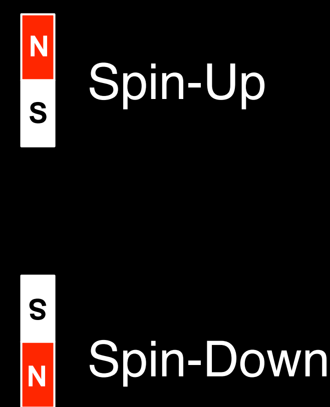
MRI Hardware



B_0 Field ON - Zeeman Splitting

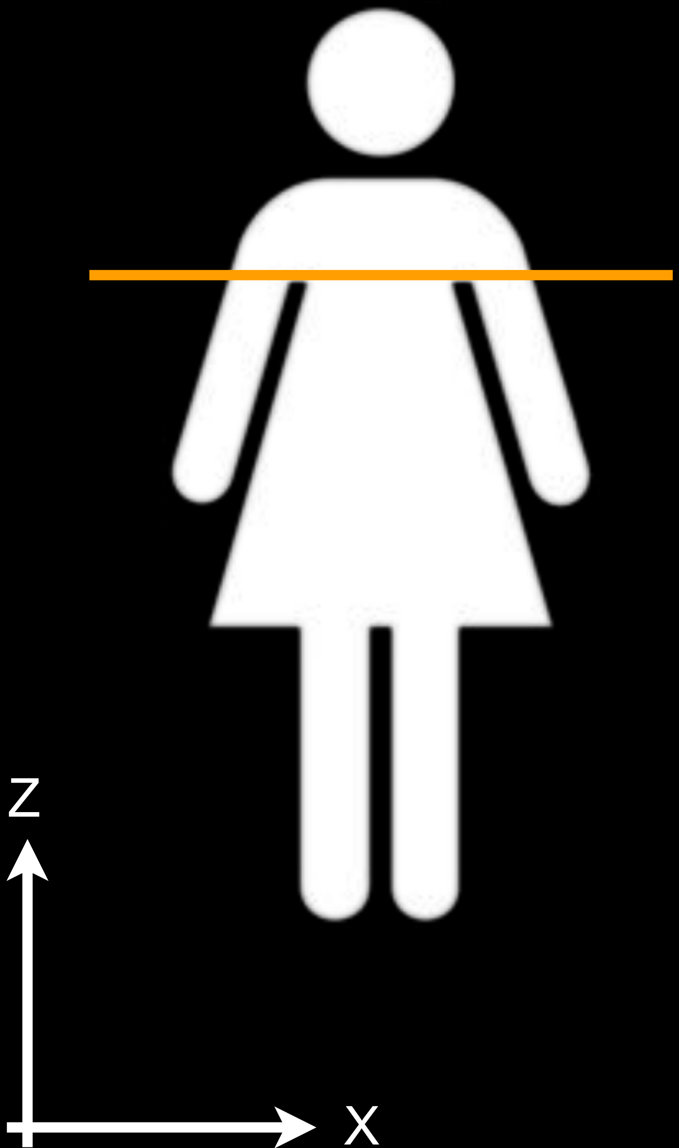


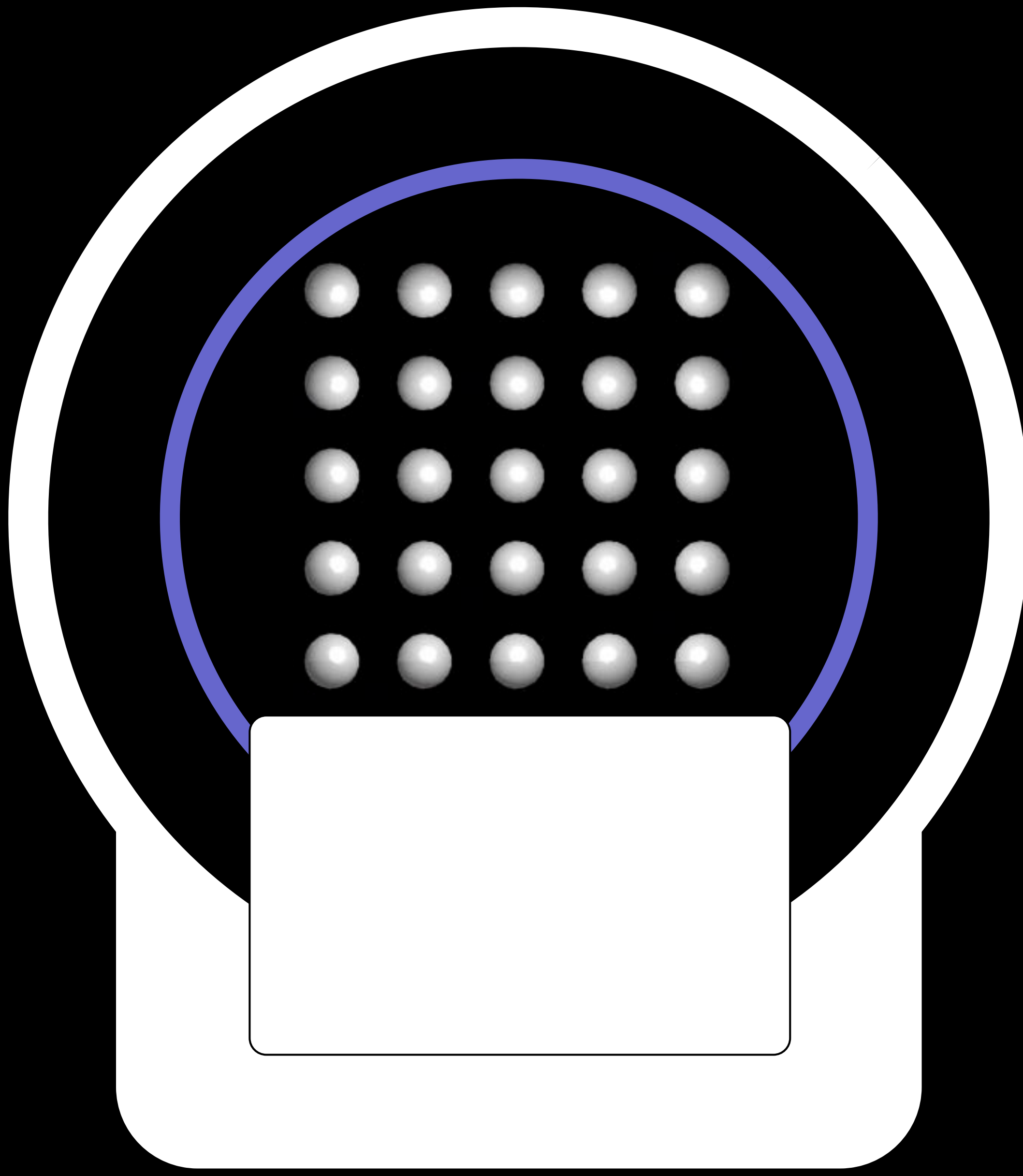




Only a very small number are spin-up relative to spin-down.

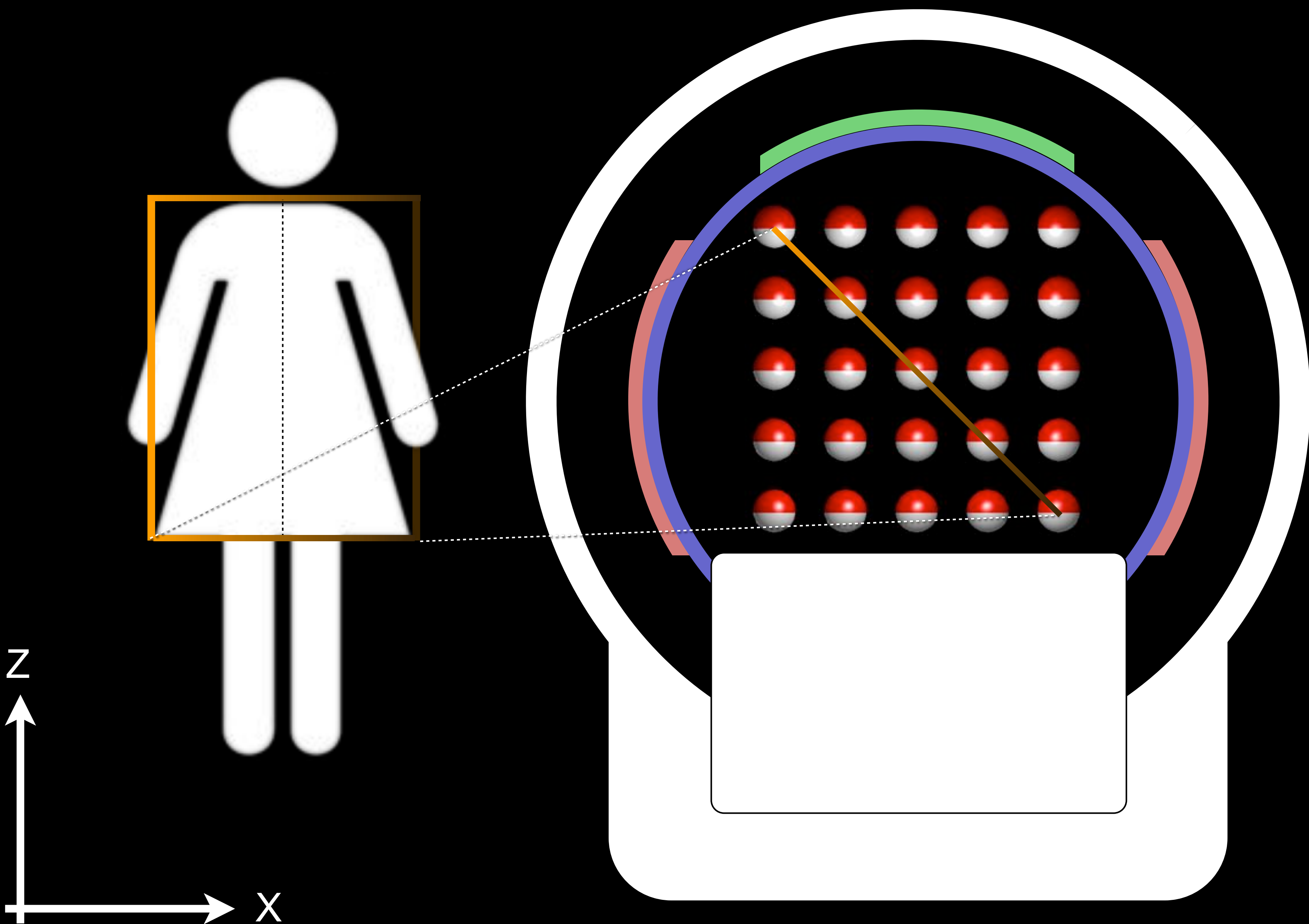
B_1 Excitation and Relaxation





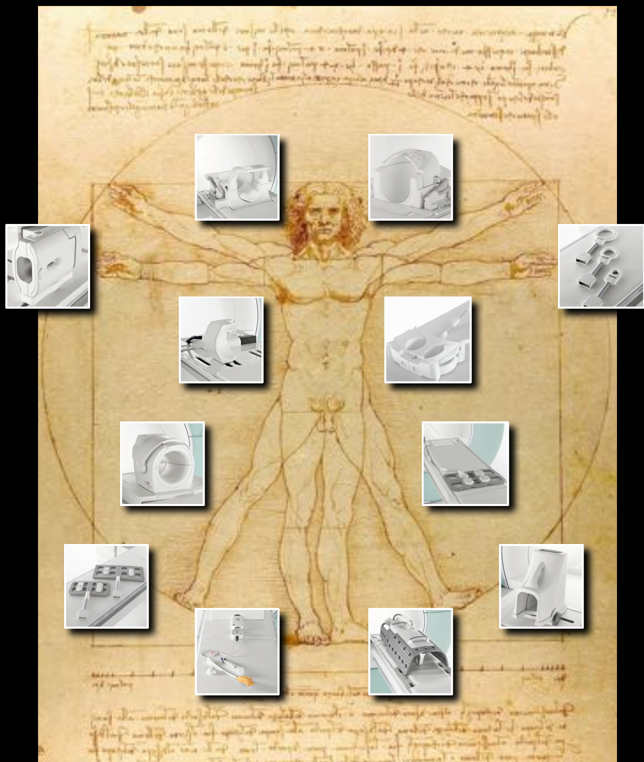
Excitation generates transverse magnetization (Mxy), which subsequently relaxes.

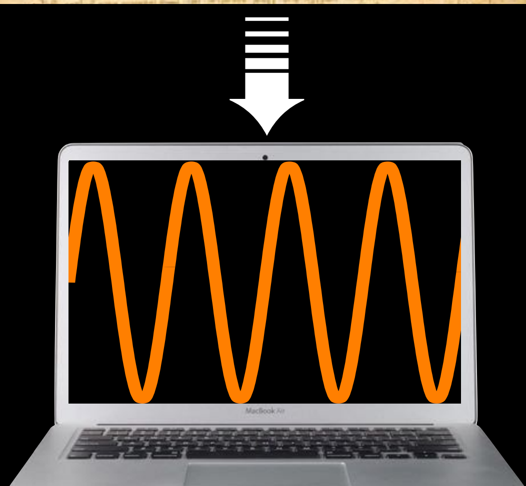
Gradients (G_x, G_y, and G_z)

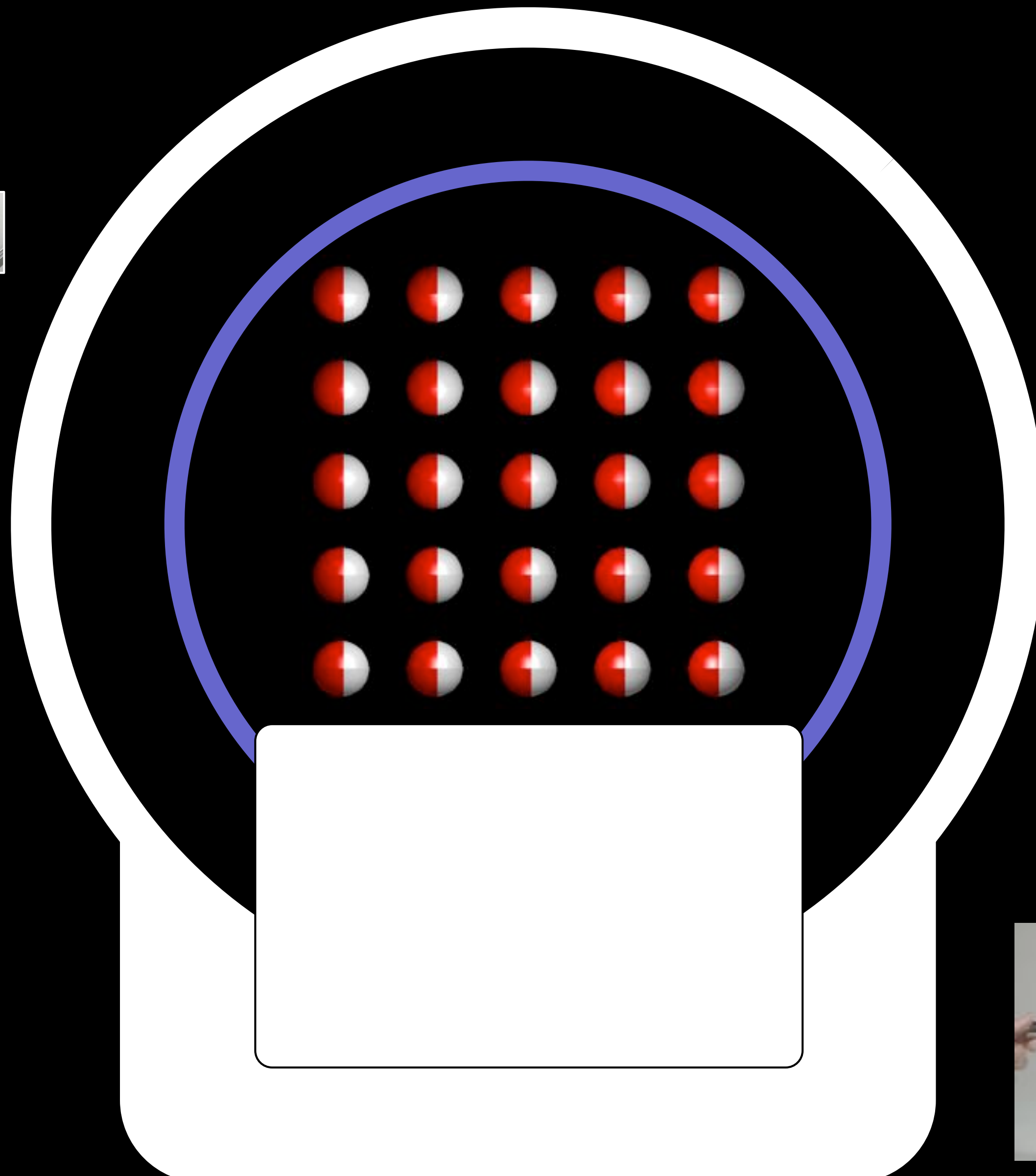


Simultaneous gradients can create an arbitrary isochromat plane.

Faraday’s Law of Induction







The trick is to encode spatial information and image contrast in the echo.

T_1 & T_2 Relaxation

Tissue	T_1 [ms]	T_2 [ms]
gray matter	925	100
white matter	790	92

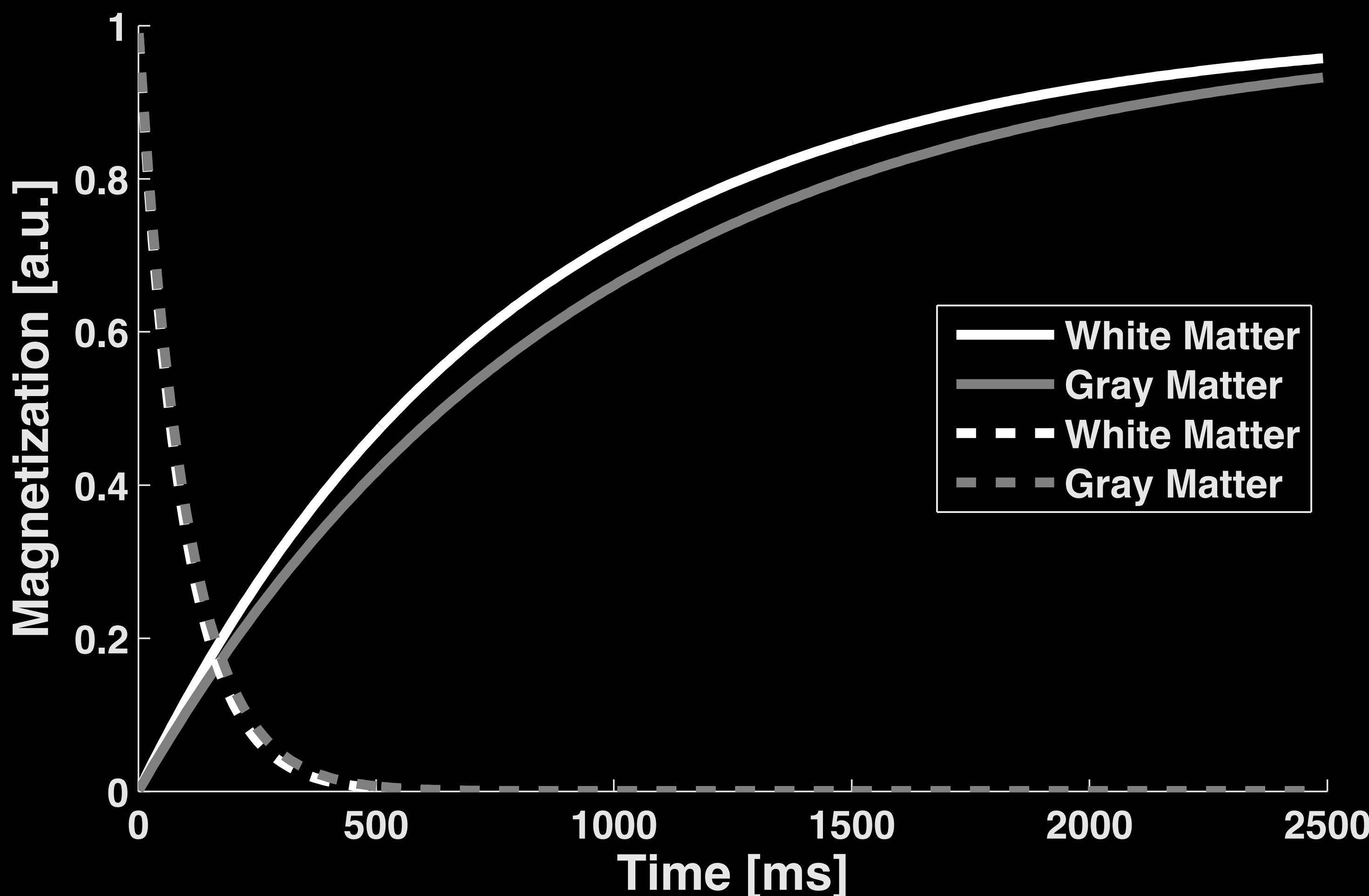
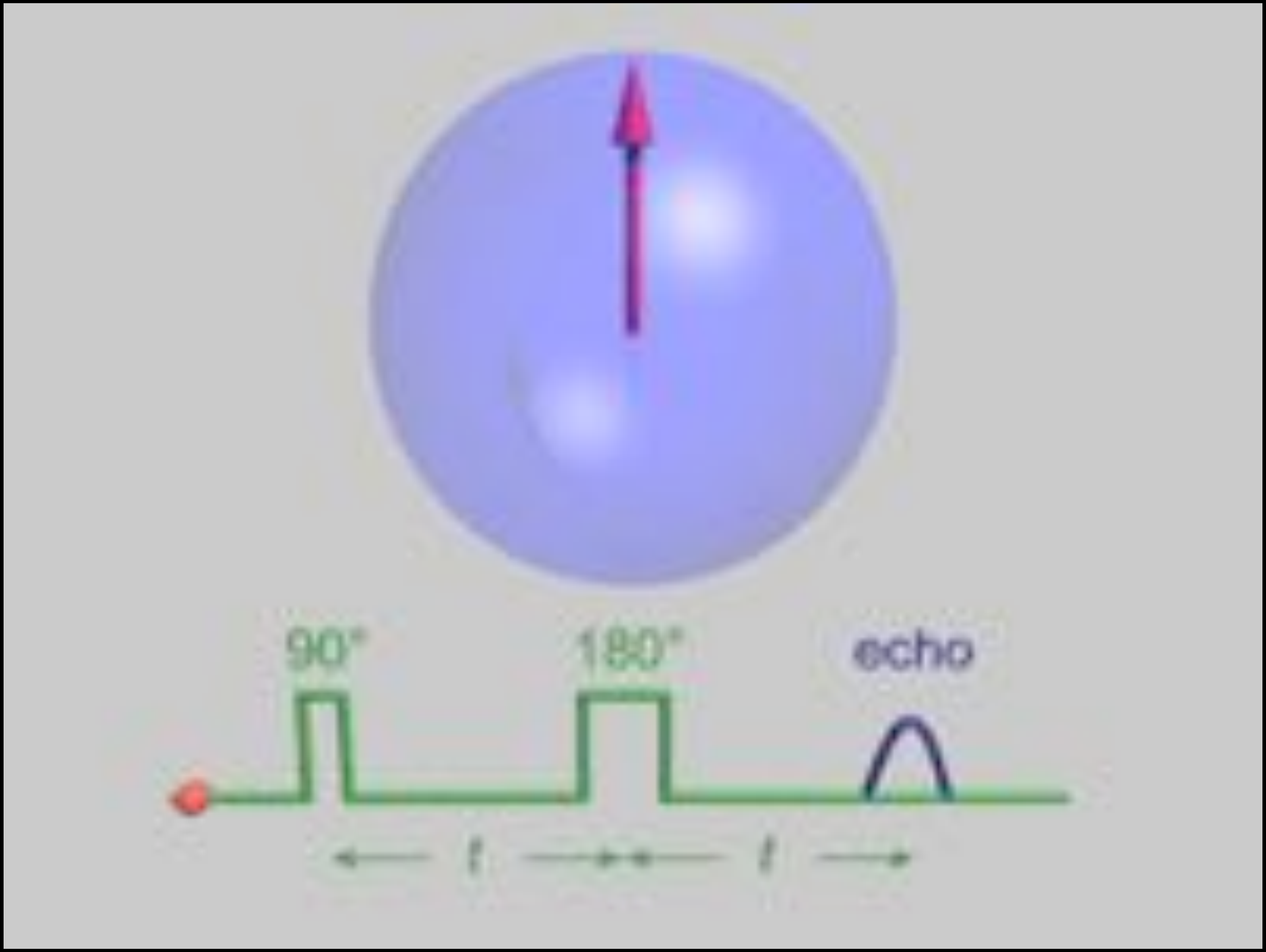


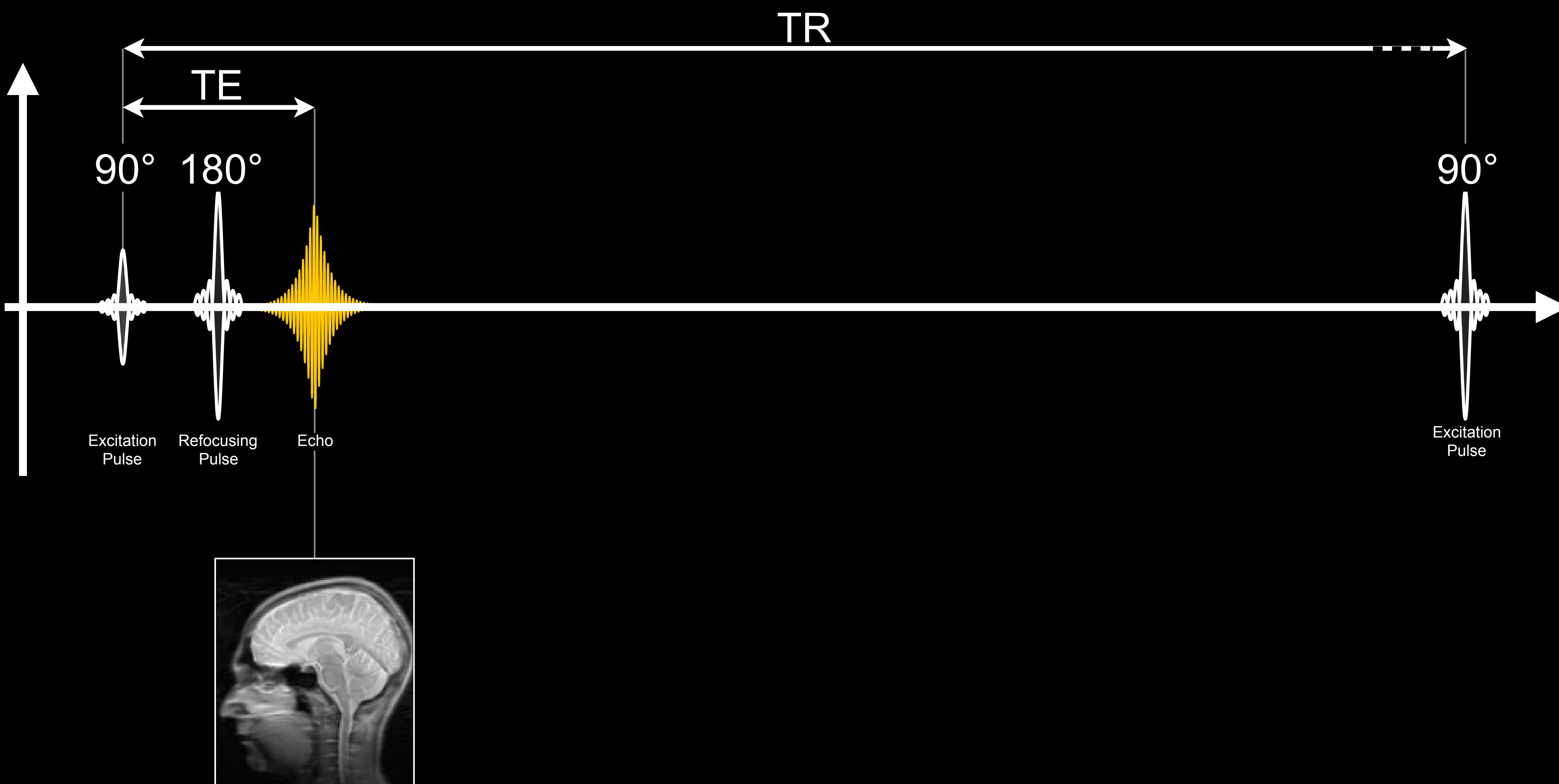
Image contrast is all about taking a “snapshot” at the right time.

Spin Echo - Refocusing



http://en.wikipedia.org/wiki/File:HahnEcho_GWM.gif

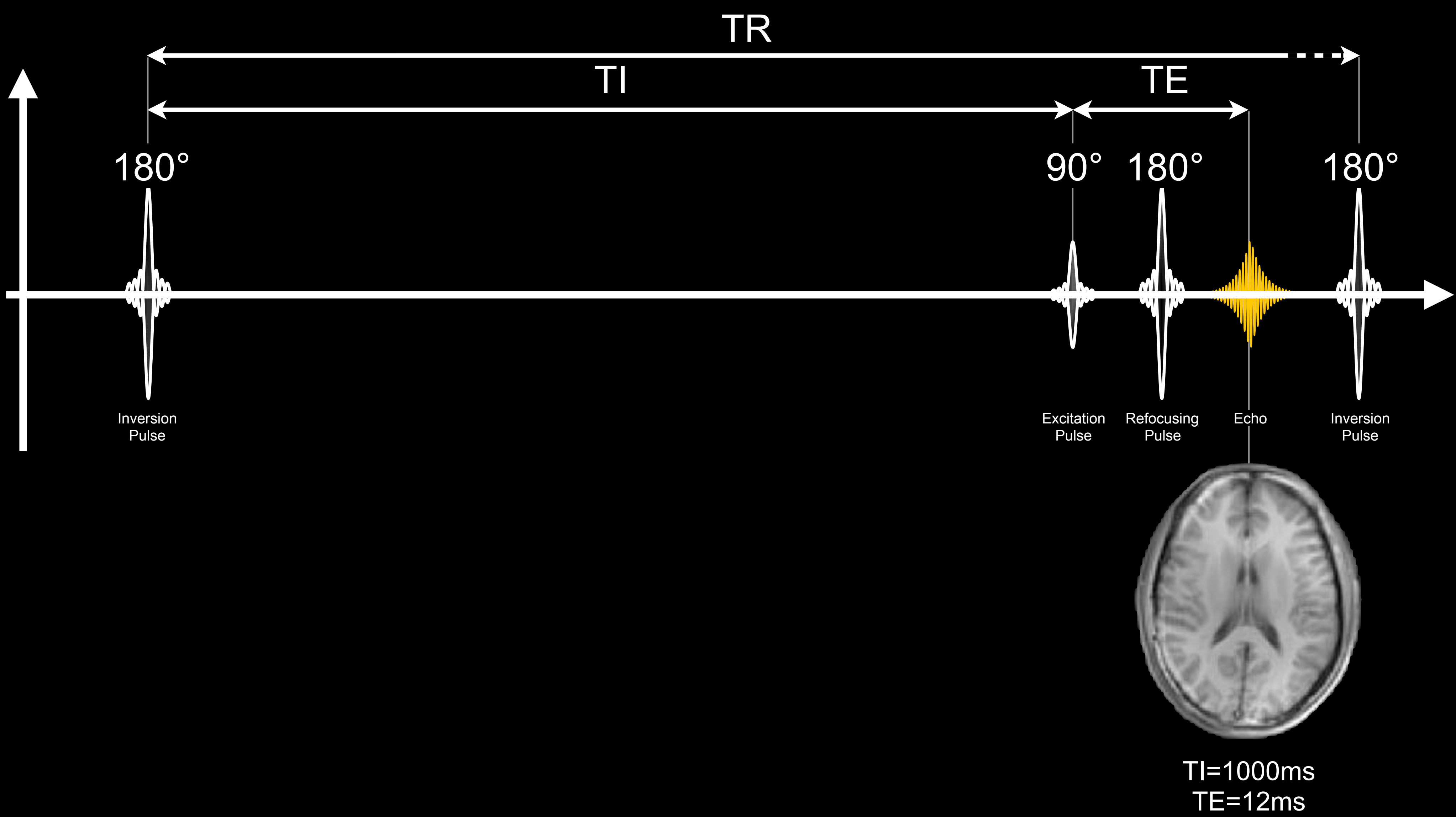
Spin Echo



TE=12ms

Short TE and Long TR is proton density weighted (limited contrast).

Inversion Recovery + Spin Echo



Really long TIs can null CSF (FLAIR).

Basic Principles of Gradient Echoes

Main Gradient Echo Sequences

- **Spoiled Gradient Echo**
  - SPGR, FLASH, T1-FFE
- **Balanced Steady-State Free Precession**
  - TrueFISP, FIESTA, Balanced FFE

Principal GRE Advantages

- **Fast Imaging Applications**
  - **Why?** *Can use a shorter TE/TR than spin echo.*
  - **When?** Breath-held, realtime, & 3D volume imaging

- **Flexible image contrast**
  - **Why?** Adjusting TE/TR/FA controls the signal.
  - **When?** Tissue conspicuity for diagnosis.

- **Bright blood signal** (i.e. in-flow enhancement)
  - **Why?** Inflowing spins haven't "seen" numerous RF pulses.
  - **When?** Cardiovascular & angiographic applications.

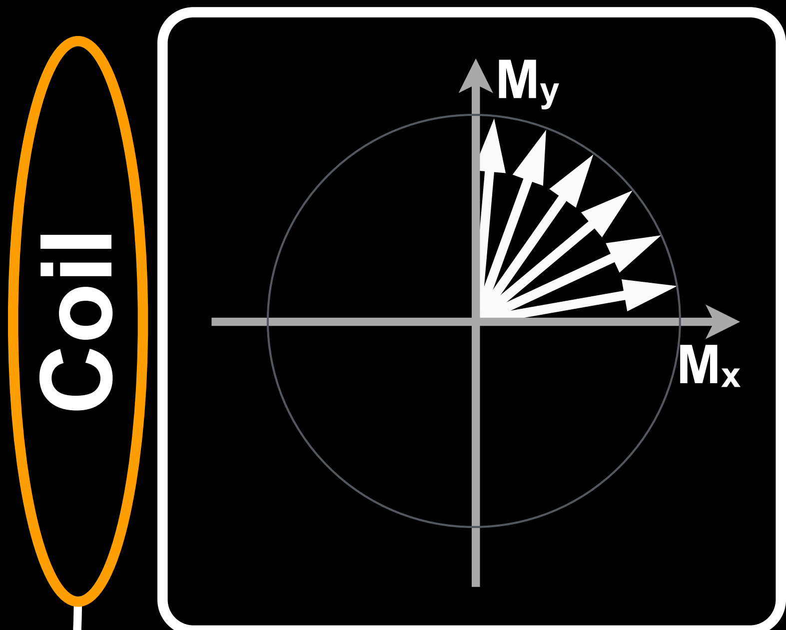
- **Low SAR**
  - **Why?** Imaging flip angles are (typically) small.
  - **When?** When heating risks are a concern (devices, high field)

Principal GRE Disadvantages

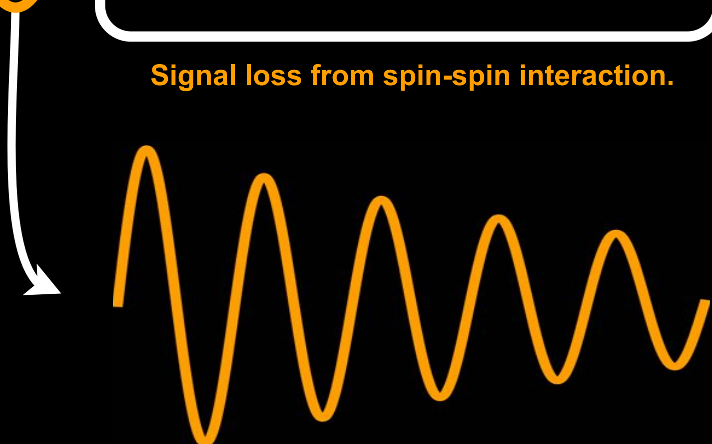
- **Off-resonance sensitivity**
  - **Why?** No refocusing pulse.
    - Field inhomogeneity, Susceptibility, & Chemical shift
- **T_2^*-weighted rather than T_2-weighted**
  - **Why?** No re-focusing pulse
    - Spin-spin dephasing is not reversible with GRE
- **Larger metal artifacts than SE**
  - **Why?** No refocusing pulse.
    - Large field inhomogeneities aren't corrected with GRE

T_2 versus T_2^*

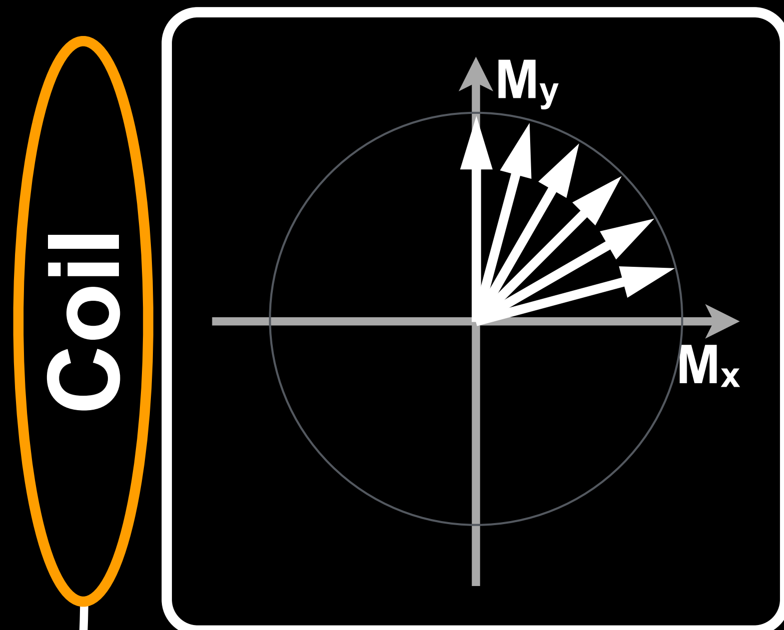
T_2 Decay



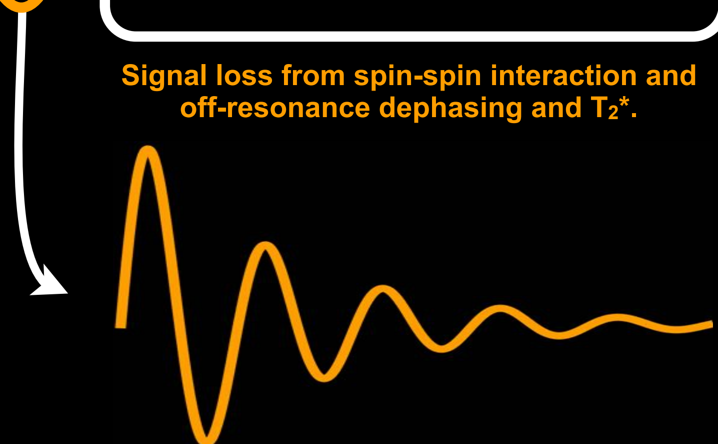
Signal loss from spin-spin interaction.



T_2^* Decay



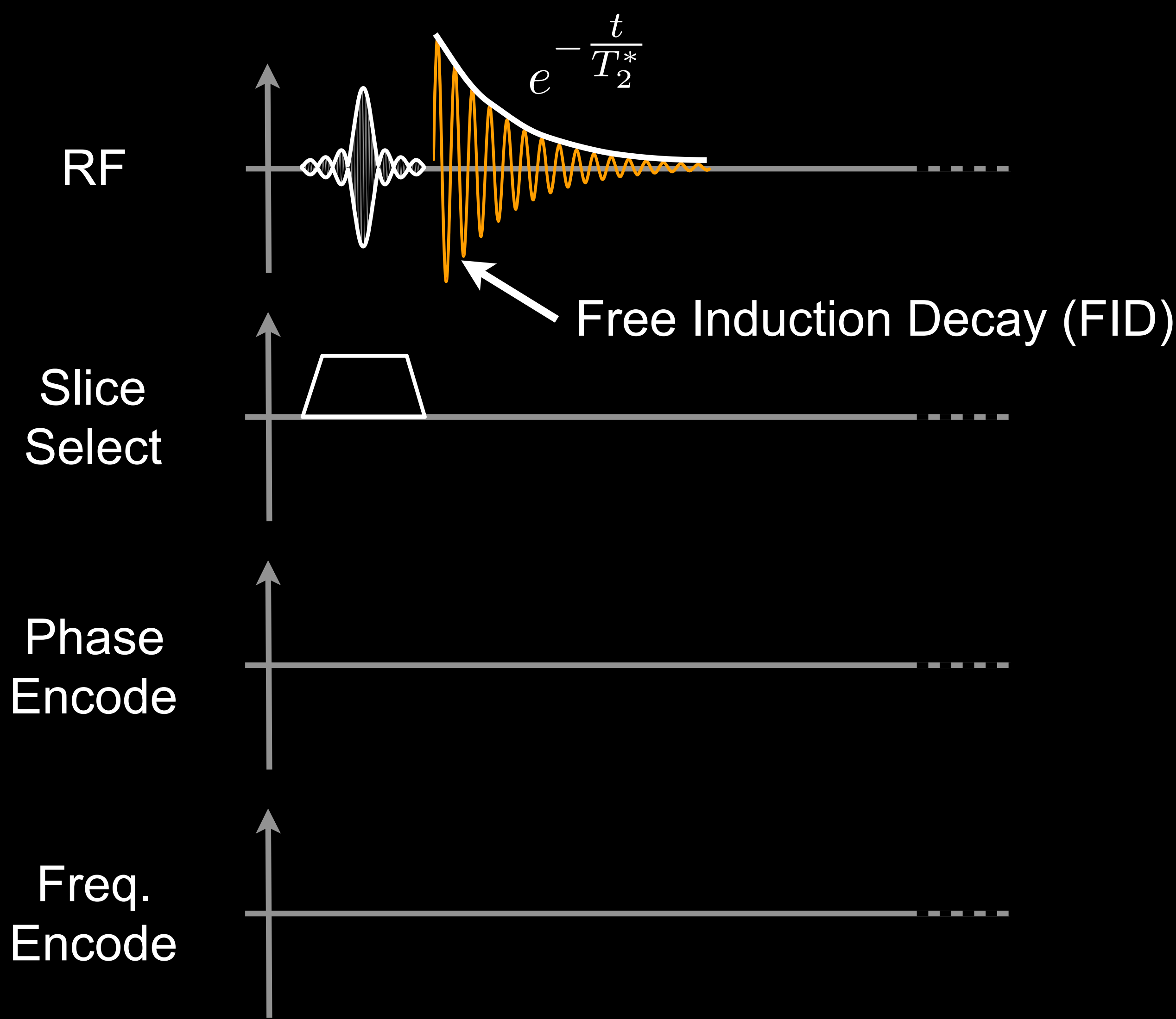
Signal loss from spin-spin interaction and off-resonance dephasing and T_2^*.



T_2^* is signal loss from spin dephasing and T_2.

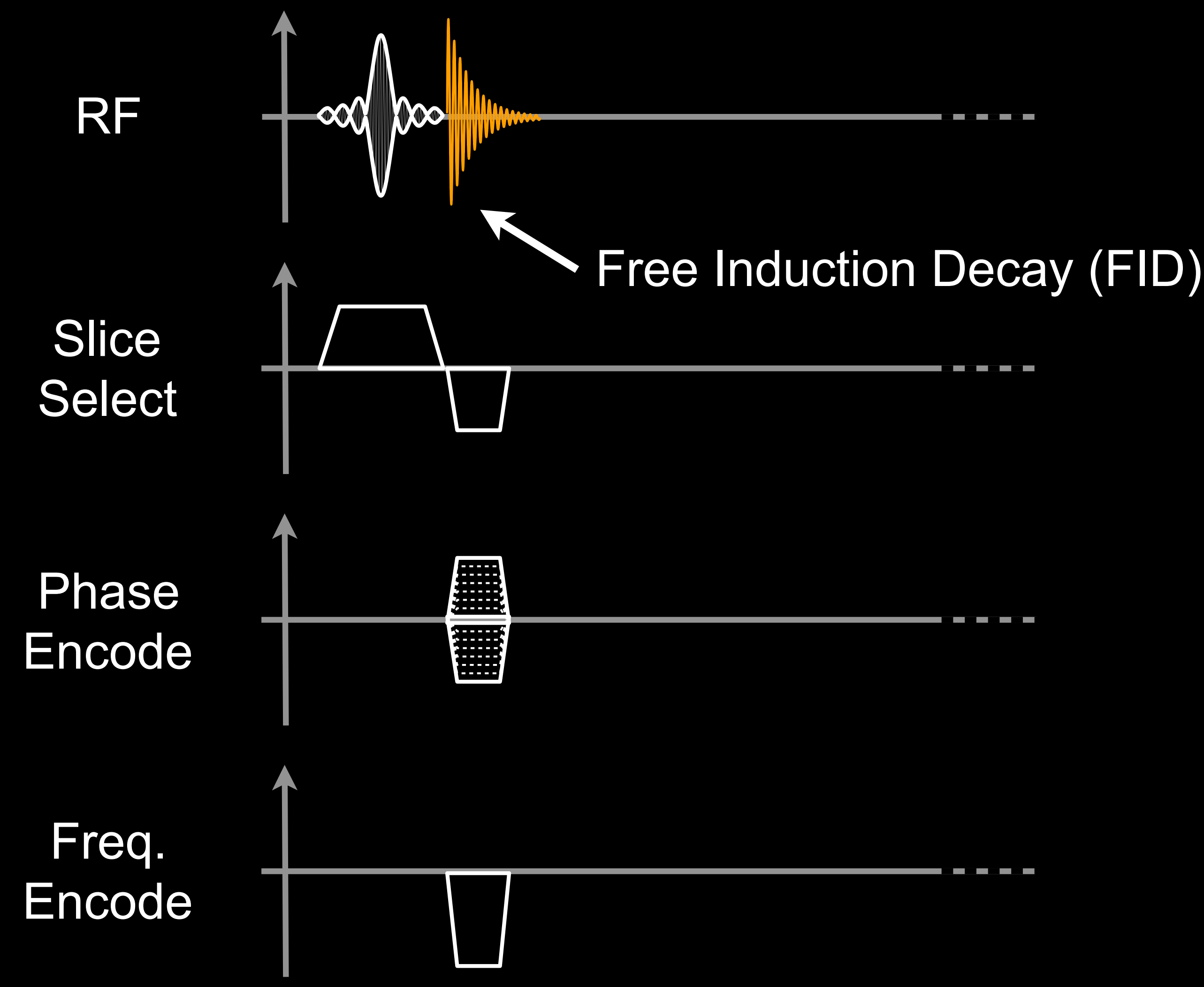
Basic GRE Sequence

Basic Gradient Echo Sequence



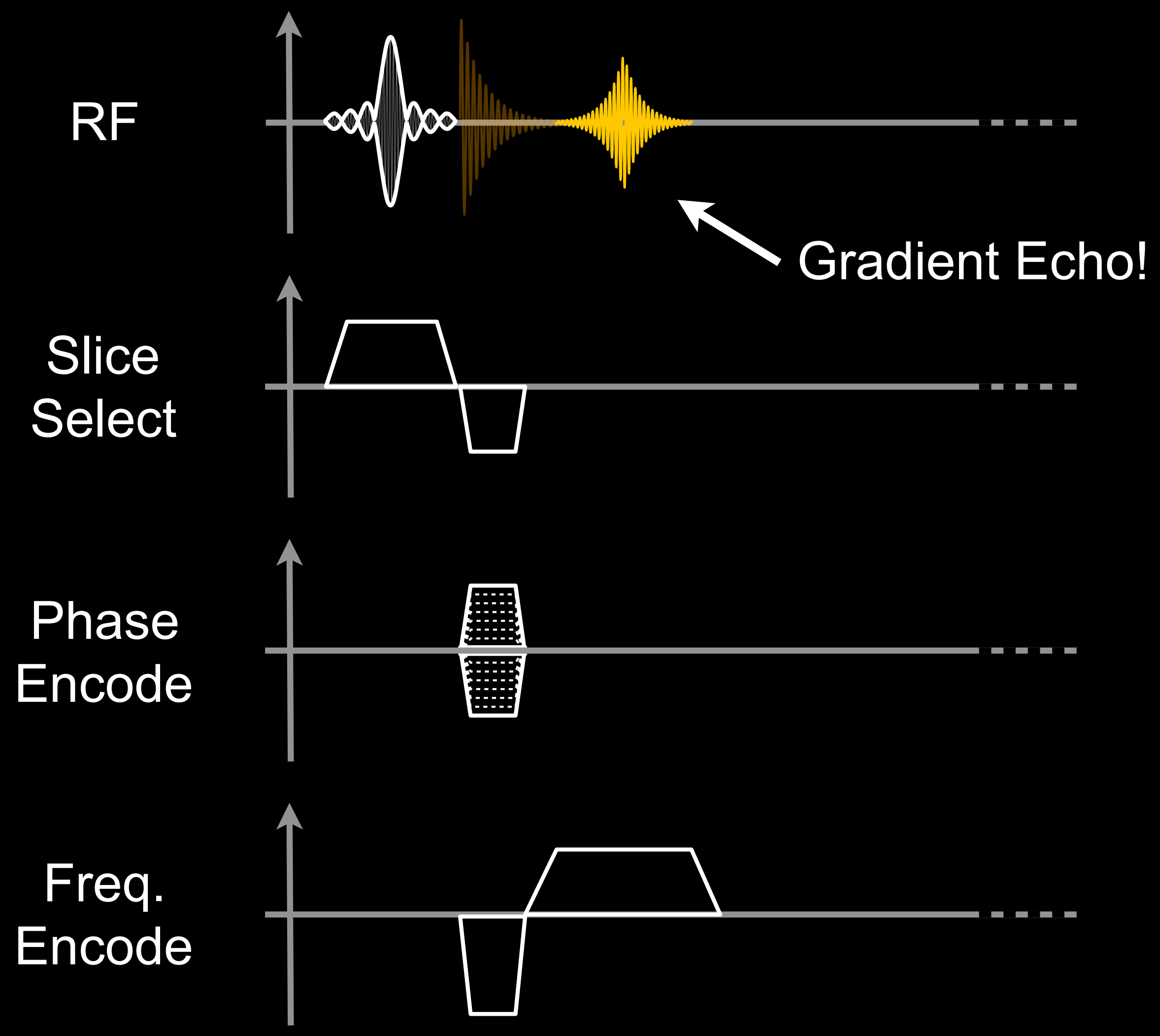
- FID Decay due to
  - T2 decay
  - Spin dephasing

Basic Gradient Echo Sequence



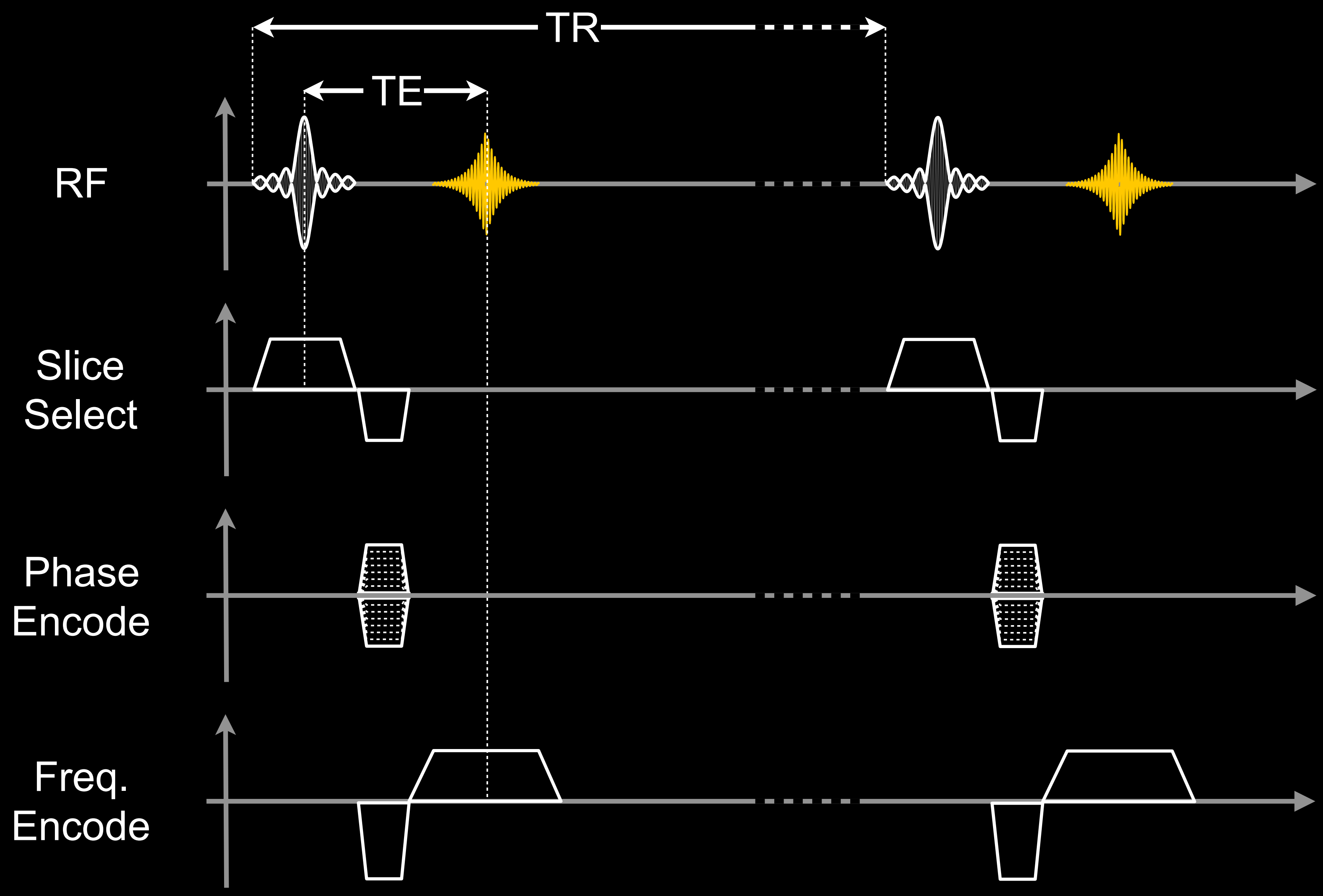
- FID Decay due to
  - T2 decay
  - Spin dephasing
- Gradients accelerate spin dephasing

Basic Gradient Echo Sequence

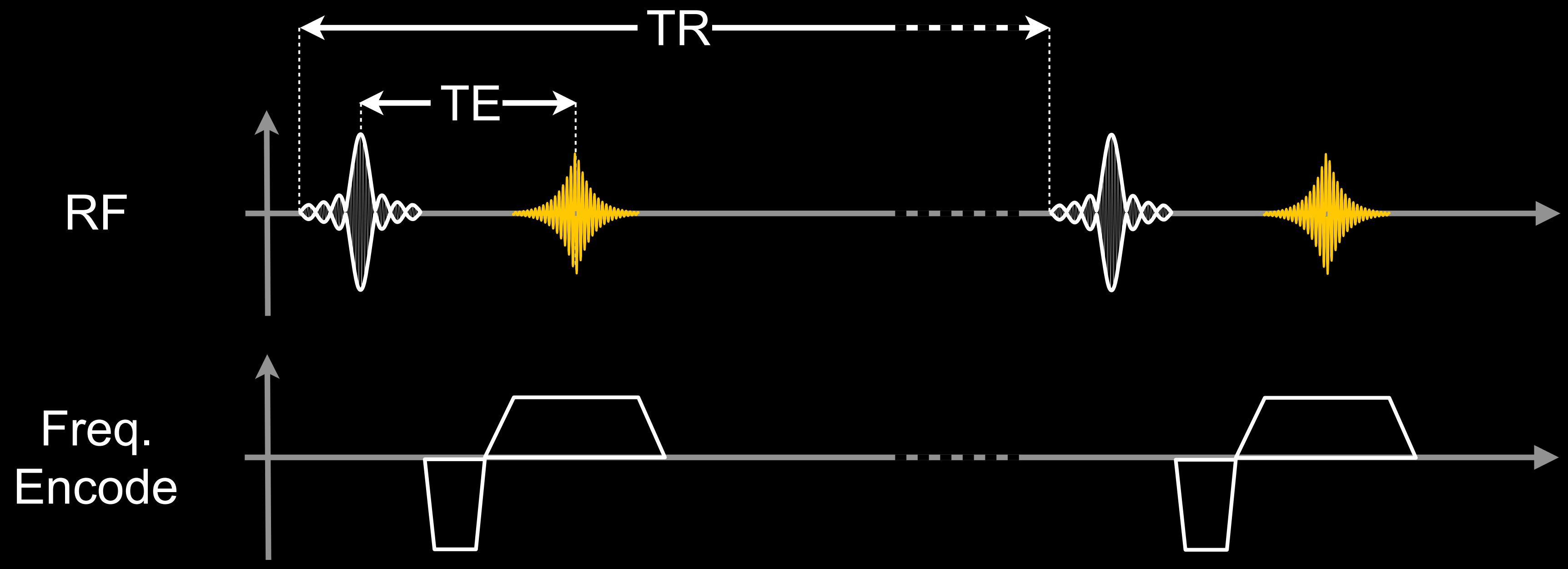


- FID Decay due to
  - T2 decay
  - Spin dephasing
- Gradients accelerate spin dephasing
- Gradients can undo gradient induced spin dephasing

Basic Gradient Echo Sequence



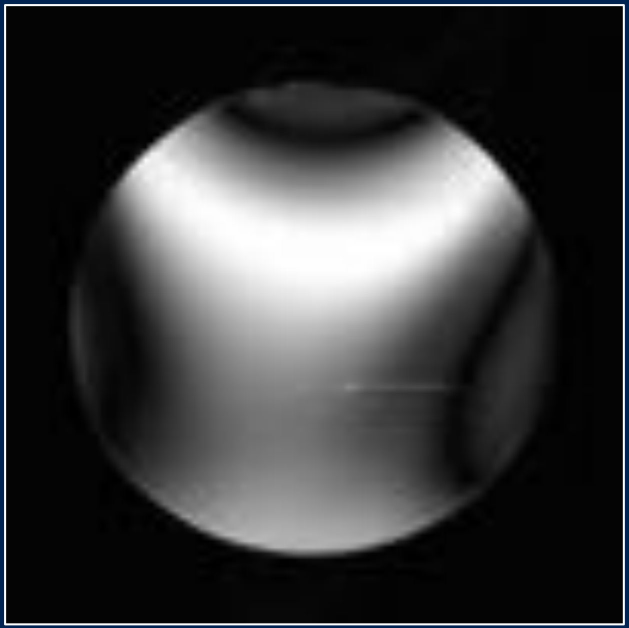
Gradient Echo



SE vs. GRE: B_0 Inhomogeneity

- **Images acquired with a bad shim**
  - Poor B_0 homogeneity (lots of off-resonance)

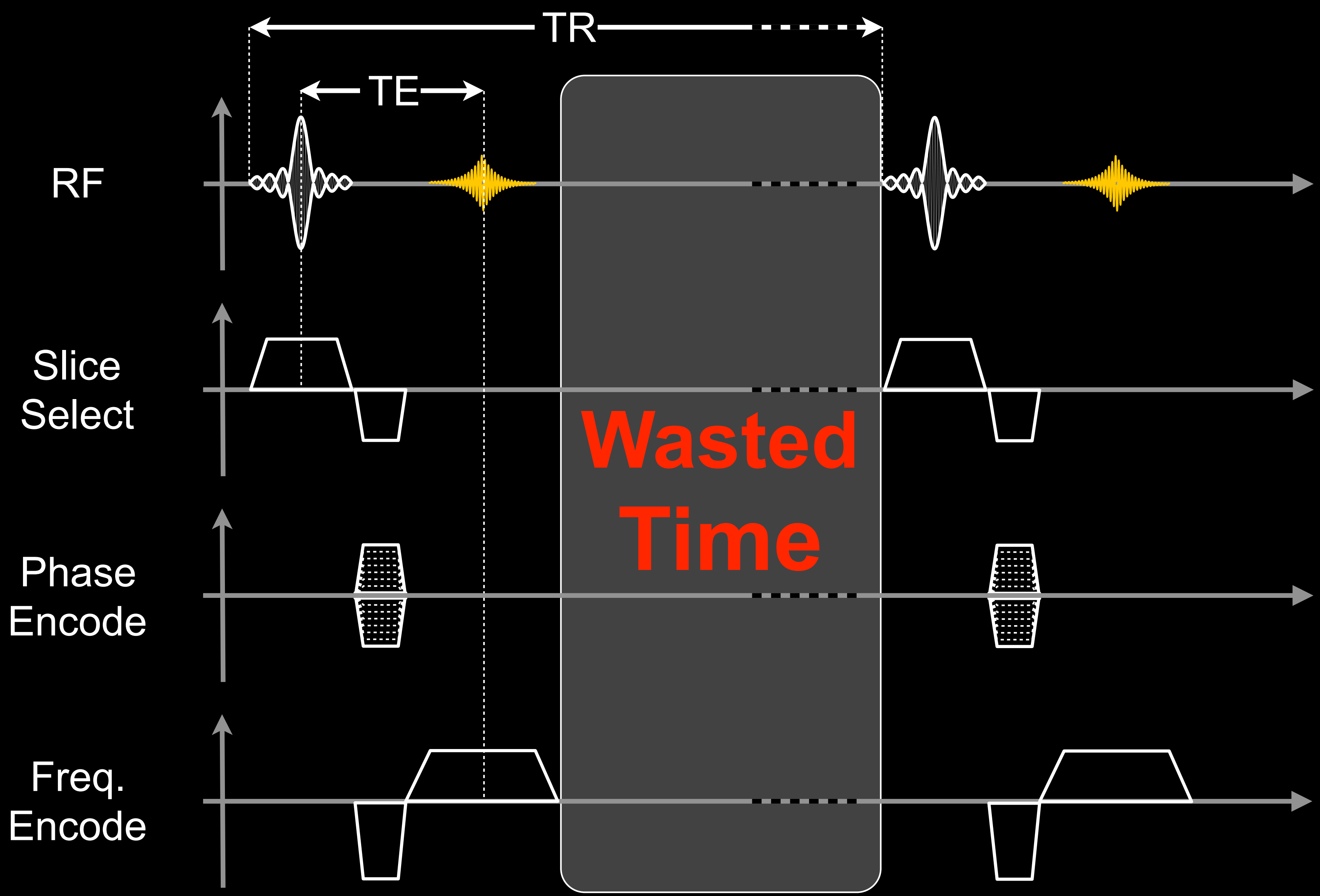
Spin Echo



Gradient Echo

Gradient Echoes & Spoiling

Basic Gradient Echo Sequence



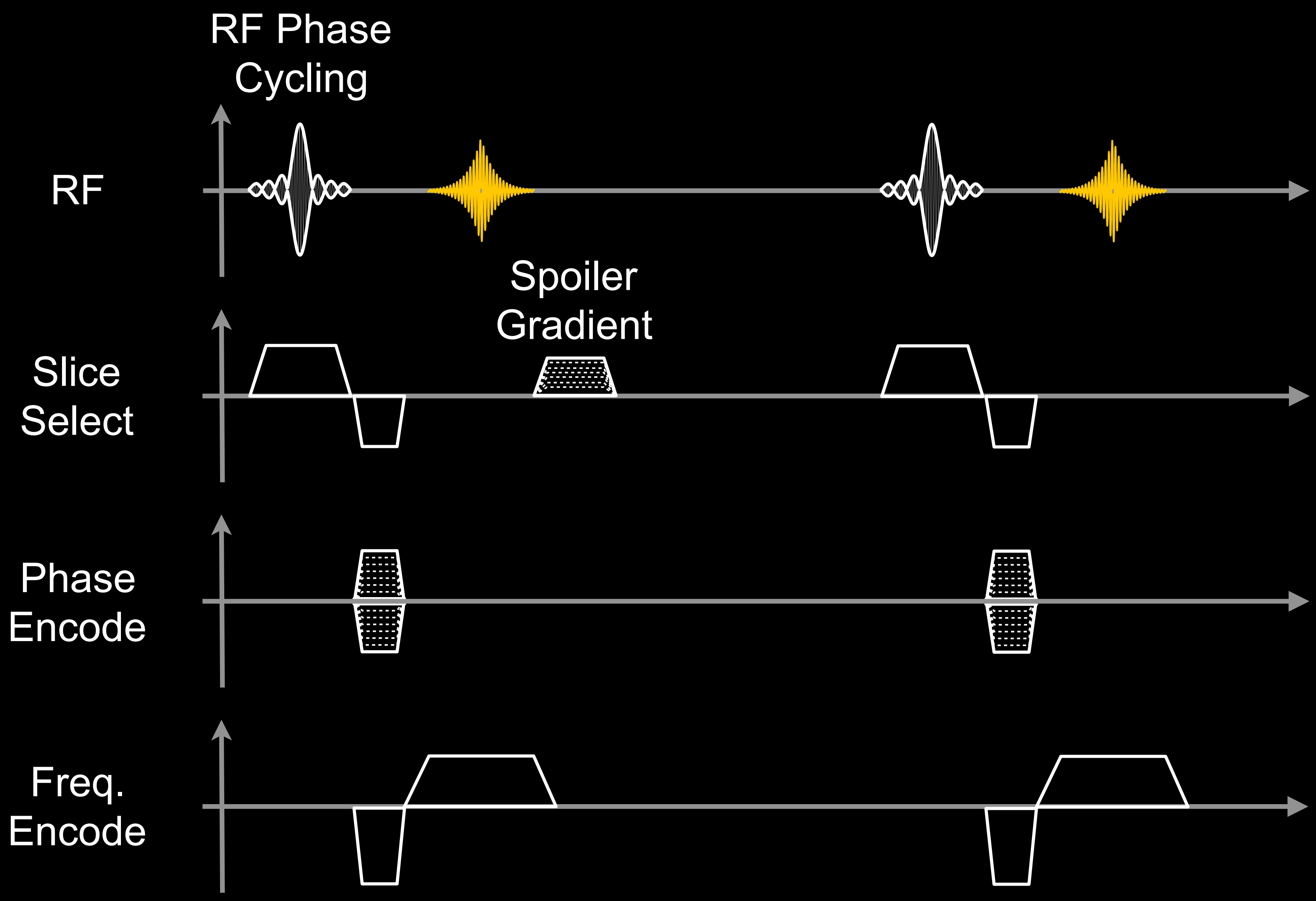
Spoiling - Why?

- **Eliminates M_{xy} at end of each TR**
  - Prevents cumulative errors
- **Shortens the TR**
  - Without spoilers have to wait 5x T_2*
  - Faster imaging
- **Enhances T_1 contrast**

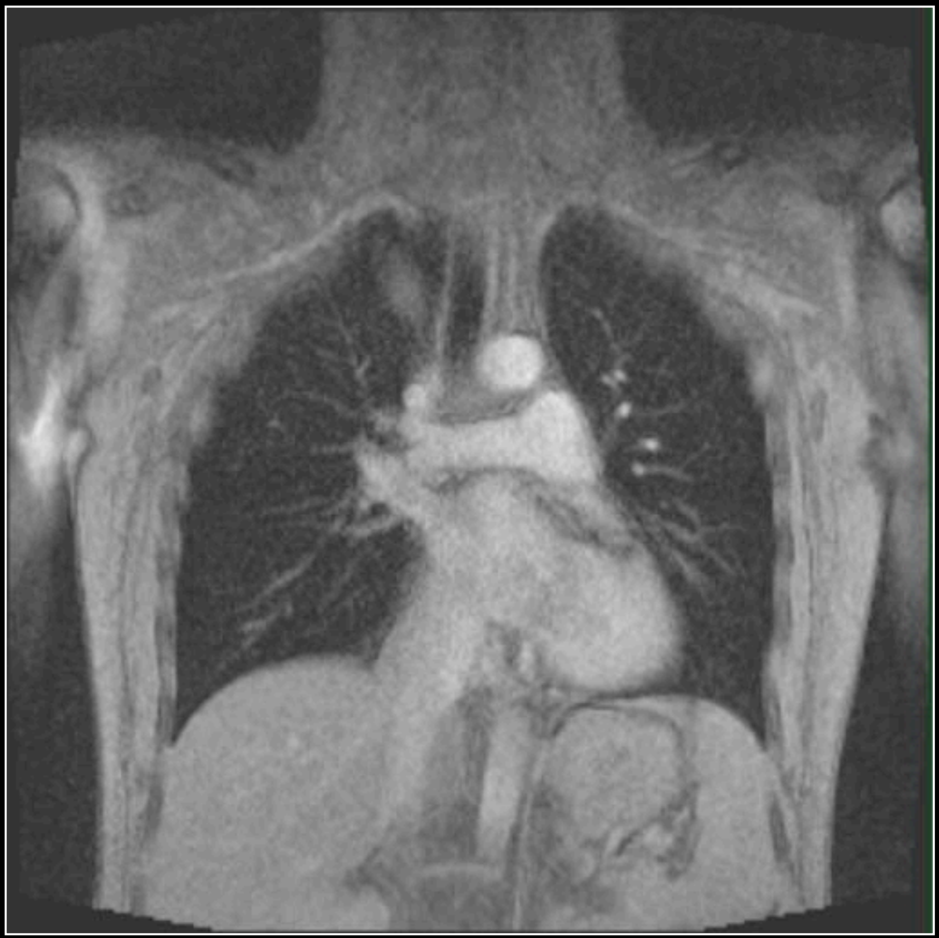
Spoiling - How?

- **Long TR**
  - Choose TR 4-5x T_2*
  - Can work for interleaved multi-slice
- **Gradient spoiling**
  - Applied at end of TR
  - Dephases spins within voxel
  - Variable gradient area from TR to TR
  - Spatially non-uniform
- **RF spoiling**
  - Cycle the phase of the RF pulse
  - Minimizes coherent signal pathways
  - Requires a phase encode rewinder

Gradient Echo + Spoiling



Realtime Imaging with Gradient Echoes



Realtime imaging requires very short TE/TR.

Quiz: Gradient Echoes - True or False?

1. Echoes are needed because the FID disappears too quickly.
2. GRE is less sensitive to off-resonance than spin echo imaging.
3. GRE uses a refocusing pulse to form an echo.
4. Gradient and RF spoiling enable faster imaging.

Gradient Echoes & Contrast

Spoiled Gradient Echo Contrast

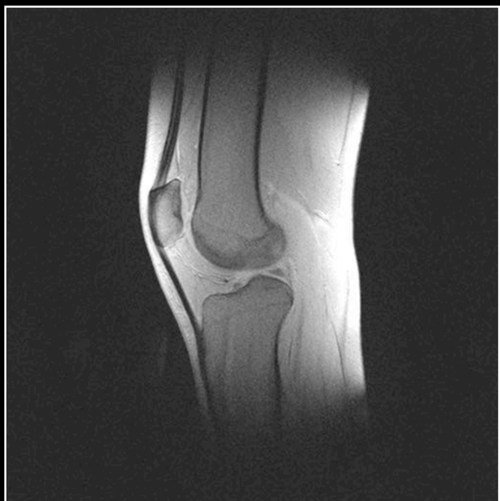
Contrast depends on tissue's ρ, T_1 and T_2*.

$$A_{echo} \propto \frac{\rho\left(1 - e^{-TR/T_1}\right)}{1 - \cos\alpha e^{-TR/T_1}} \sin\alpha e^{-TE/T_2^*}$$

Contrast adjusted by changing TR, flip angle, and TE.

T_2*-weighted Gradient Echo Imaging

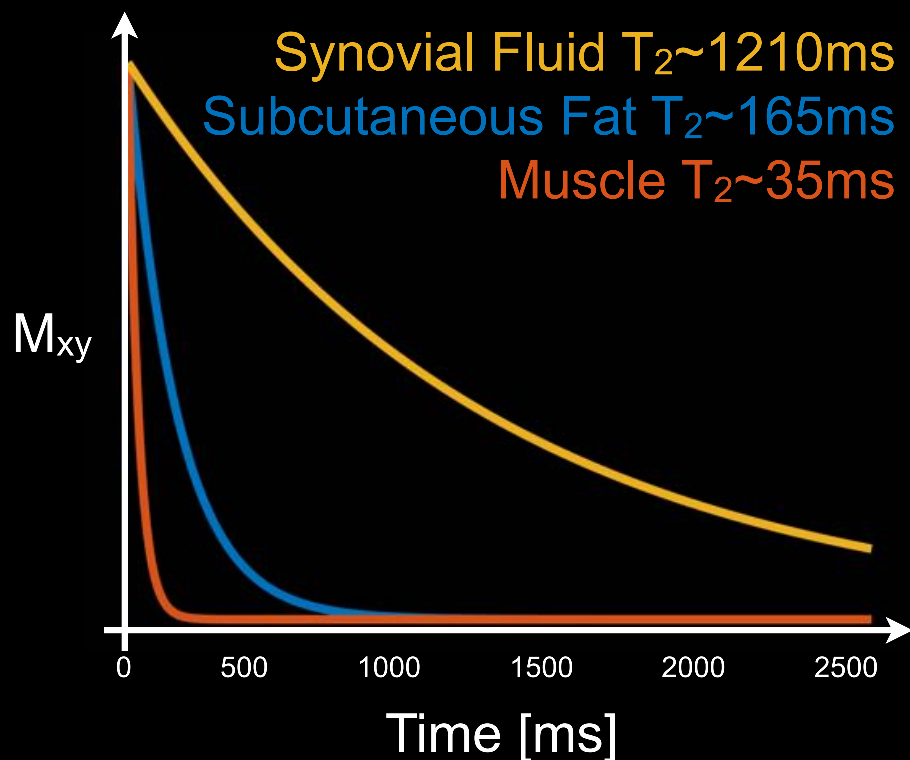
FLASH – TE=4.8ms; TR=200ms



FLASH – TE=14.2ms; TR=200ms

FLASH – TE=24ms; TR=200ms

FLASH – TE=49ms; TR=200ms



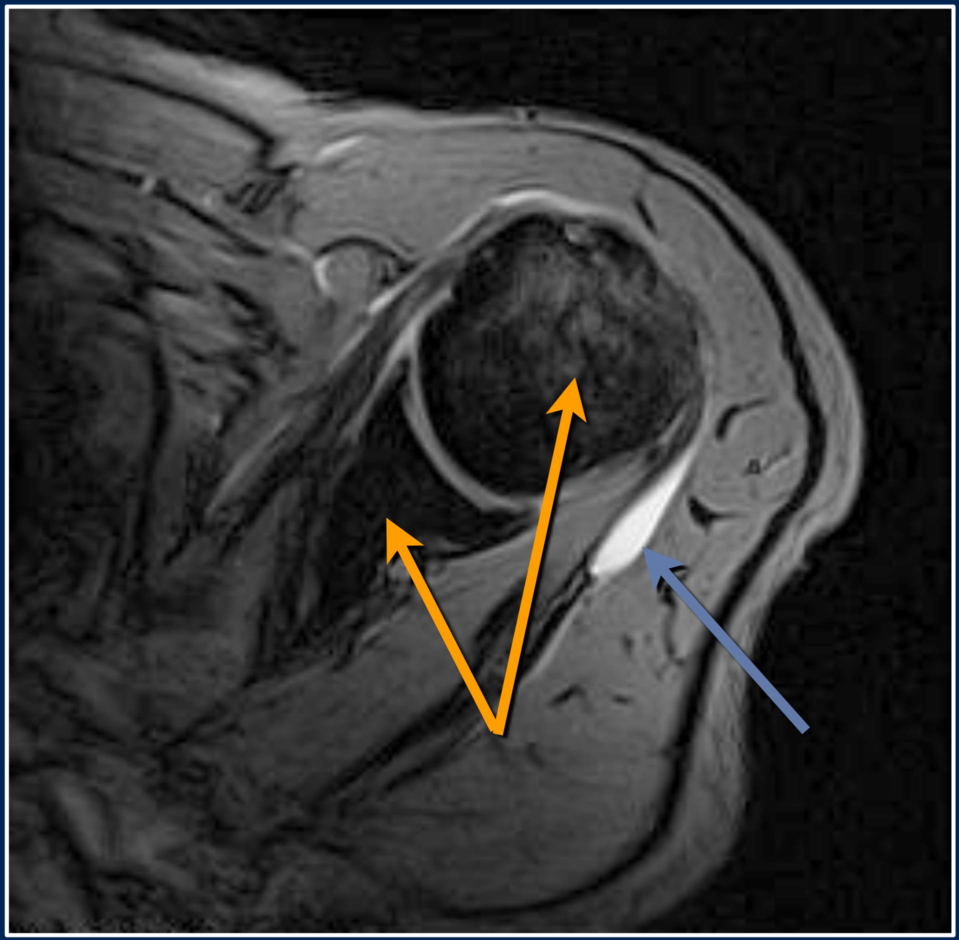
David Geffen School of Medicine

Musculoskeletal MRI at 3.0 T: relaxation times and image contrast. AJR Am J Roentgenol. 2004 Aug;183(2):343-51.

UCLA Radiology

T_2*-weighted Gradient Echo Imaging

TE=9ms



TE=30ms

Susceptibility Weighting (darker with longer TE)

Bright fluid signal (long T_2* is "brighter" with longer TE)

Gradient vs. Spin Echo Contrast

Gradient Echo Parameters

Type of Contrast	TE	TR	Flip Angle
Spin Density	Short	Long	<10°
T_1-Weighted	Short	Intermediate	>30°
T_2^*-Weighted	Intermediate	Long	<10°

Spin Echo Parameters

Type of Contrast	TE	TR	Flip Angle
Spin Density	Short	Long	90+180
T_1-Weighted	Short	Intermediate	90+180
T_2-Weighted	Intermediate	Long	90+180

GRE and SE use the same ***qualitative*** TEs and TRs to produce the same contrast.

Gradient vs. Spin Echo Contrast

Gradient Echo Parameters

Type of Contrast	TE	TR	Flip Angle
Spin Density	<5ms	>100ms	<10°
T_1-Weighted	<5ms	<50ms	>30°
T_2^*-Weighted	>20ms	>100ms	<10°

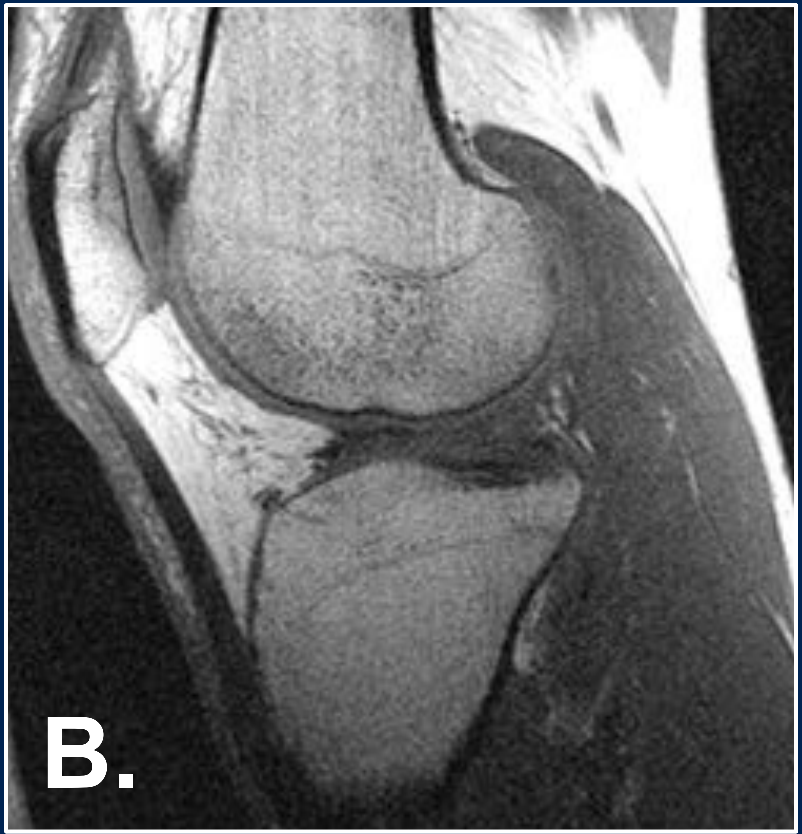
Spin Echo Parameters

Type of Contrast	TE	TR	Flip Angle
Spin Density	10-30ms	>2000ms	90+180
T_1-Weighted	10-30ms	450-850ms	90+180
T_2-Weighted	>60ms	>2000ms	90+180

GRE and SE use different ***quantitative*** TEs and TRs to produce the same contrast.

Gradient vs. Spin Echo

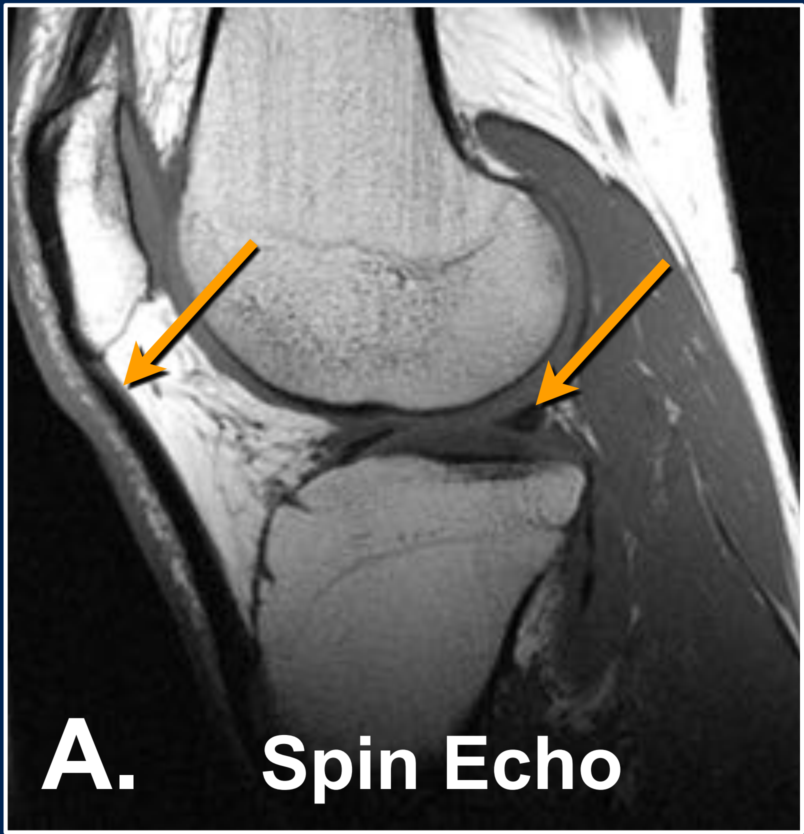
Which image is a gradient echo image?

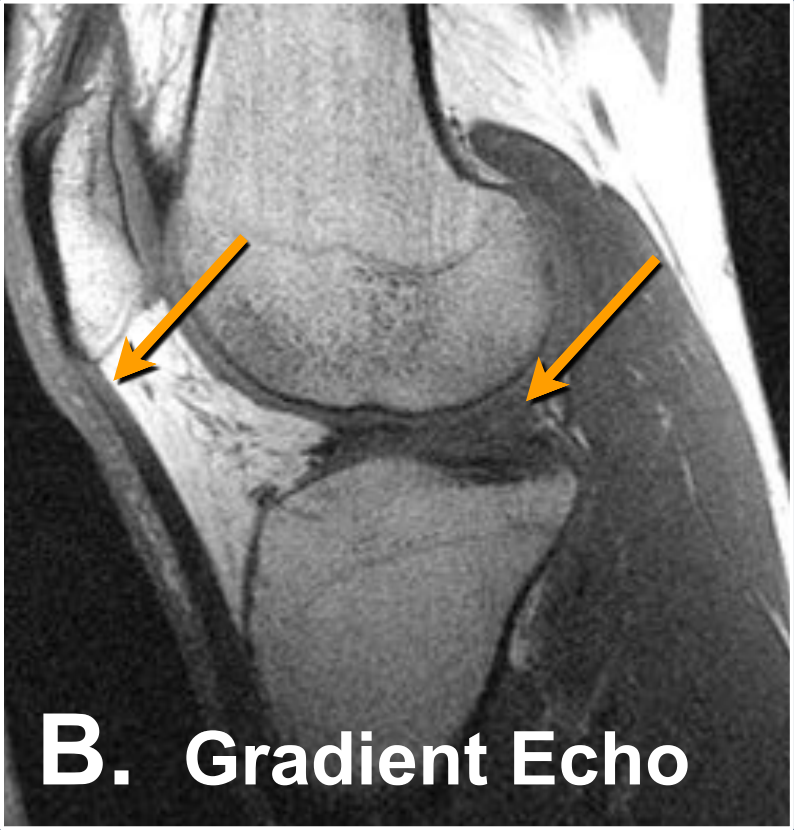


Images Courtesy of Brian Hargreaves

Gradient vs. Spin Echo

Which image is a gradient echo image?





Both are T1-weighted

Spin Echo has higher SNR (longer TR)

GRE has shorter TE (meniscus/tendon is brighter)

Images Courtesy of Brian Hargreaves

Quiz: Gradient Echoes - True or False?

1. GRE sequences have longer TRs than SE sequences.
2. GRE is great for fast T1-weighted imaging.
3. Metal artifacts on GRE are typically small.
4. GRE is great for T2 contrast.

Gradient Echoes & Flip Angle

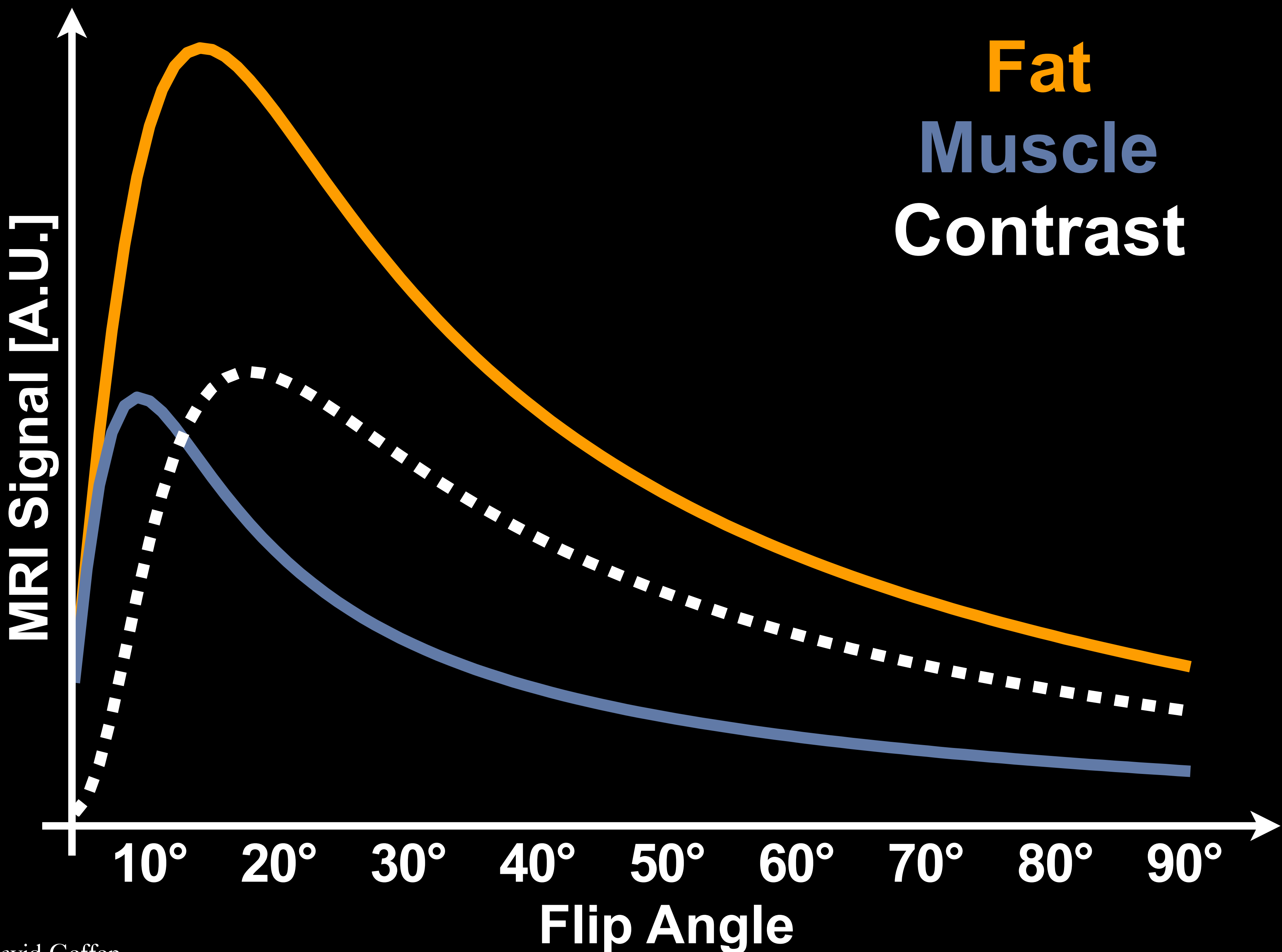
Spoiled GRE & Ernst Angle

$$\alpha_{Ernst} = \arccos\left(e^{-\frac{TR}{T_1}}\right)$$

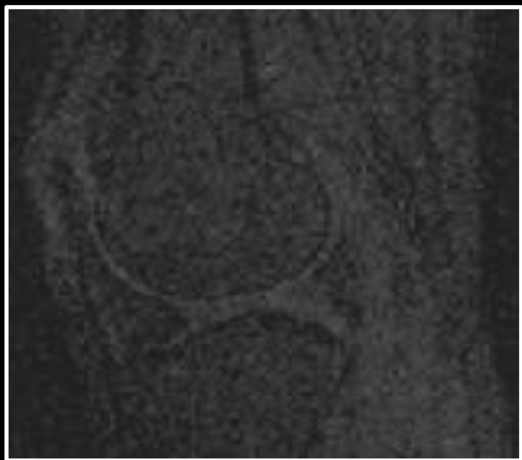
Produces the largest MRI signal for a given TR and T_1.

Tissue	T_1 [ms]	T_2 [ms]
muscle	875	47
fat	260	85

Spoiled GRE & Ernst Angle



Spoiled GRE & Ernst Angle



1°

5°

10°
High Muscle Signal

20°
High Fat Signal

30°
Highest Contrast

45°

60°

90°

Quiz: Gradient Echoes - True or False?

1. GRE and SE can both provide T2* contrast.
2. GRE and SE use the same TE and TR to produce a T1-weighted image.
3. SE is better for visualizing tissues with a very short T2 because of the refocusing pulses.
4. In GRE higher flip angles always produce brighter images.

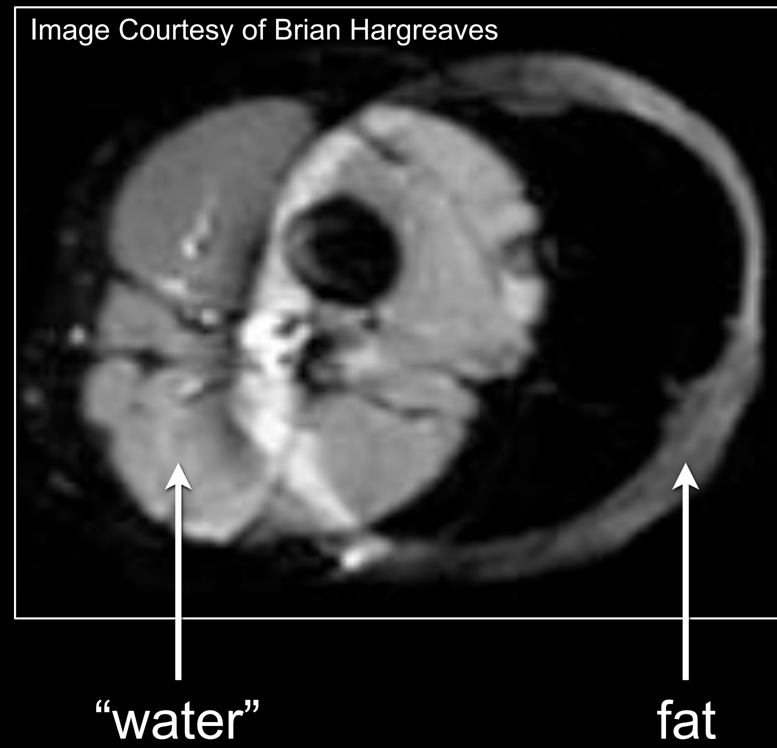
Learning Objectives - Gradient Echoes

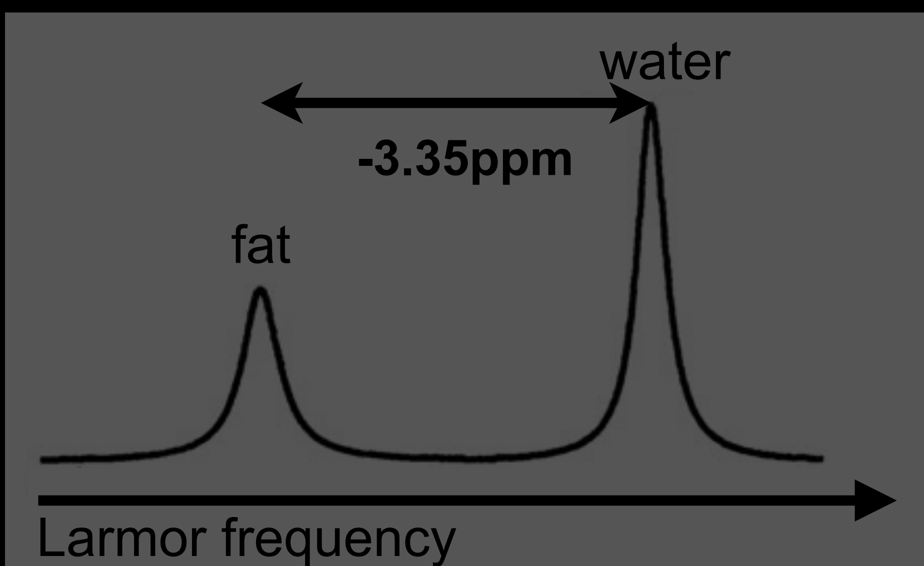
1. Understand three advantages and disadvantages of gradient echoes.
2. Be able to explain why “gradient reversal” helps form a gradient echo.
3. Describe how “spoiling” enables faster imaging.
4. Describe the forms of image contrast available with GRE imaging and how contrast is controlled.

Gradient Echoes & Fat

Chemical Shift - Type 1

- Fat and water have different Larmor frequencies
  - ~220Hz different at 1.5T
  - ~440Hz different at 3.0T
- Spatial position is related to spin frequency in MRI.
  - Fat is *more* spatially mis-registered @ 3T



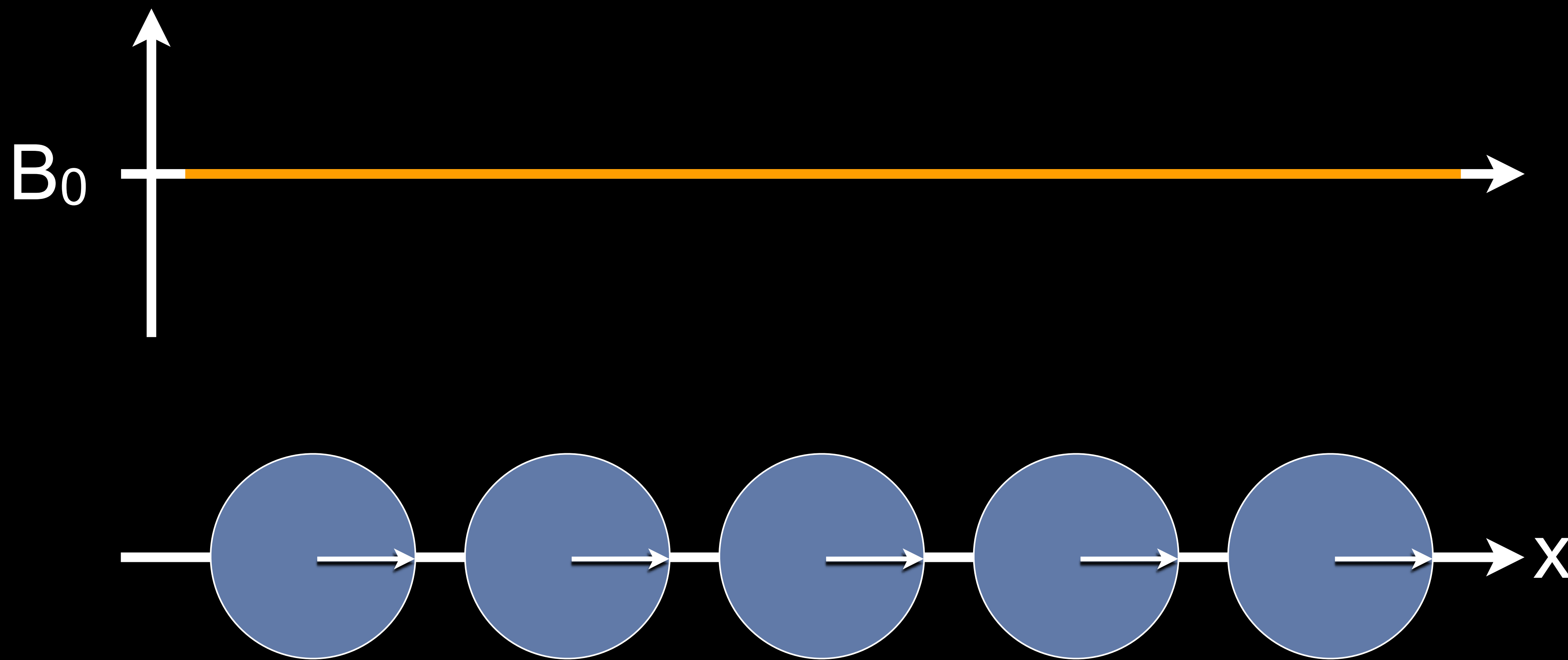


$$B = B_0 (1 - \delta)$$

$$\delta_{-\mathrm{CH}_2} = 3.35ppm$$

$3.35\text{x}10^{-6} \bullet 64\text{MHz} = 214\text{Hz}$

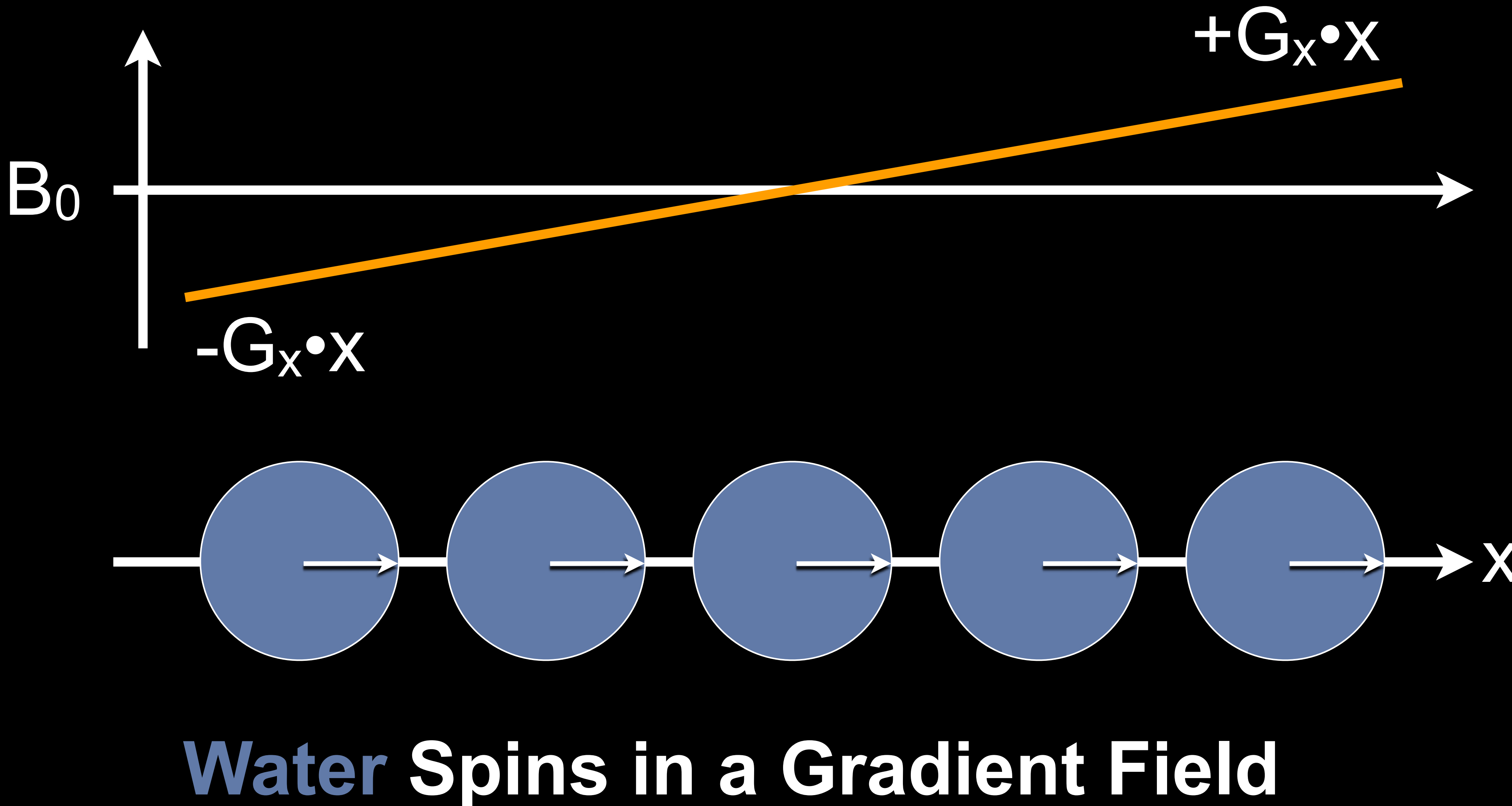
GRE & Fat/Water Frequency



Water Spins in a Uniform Field

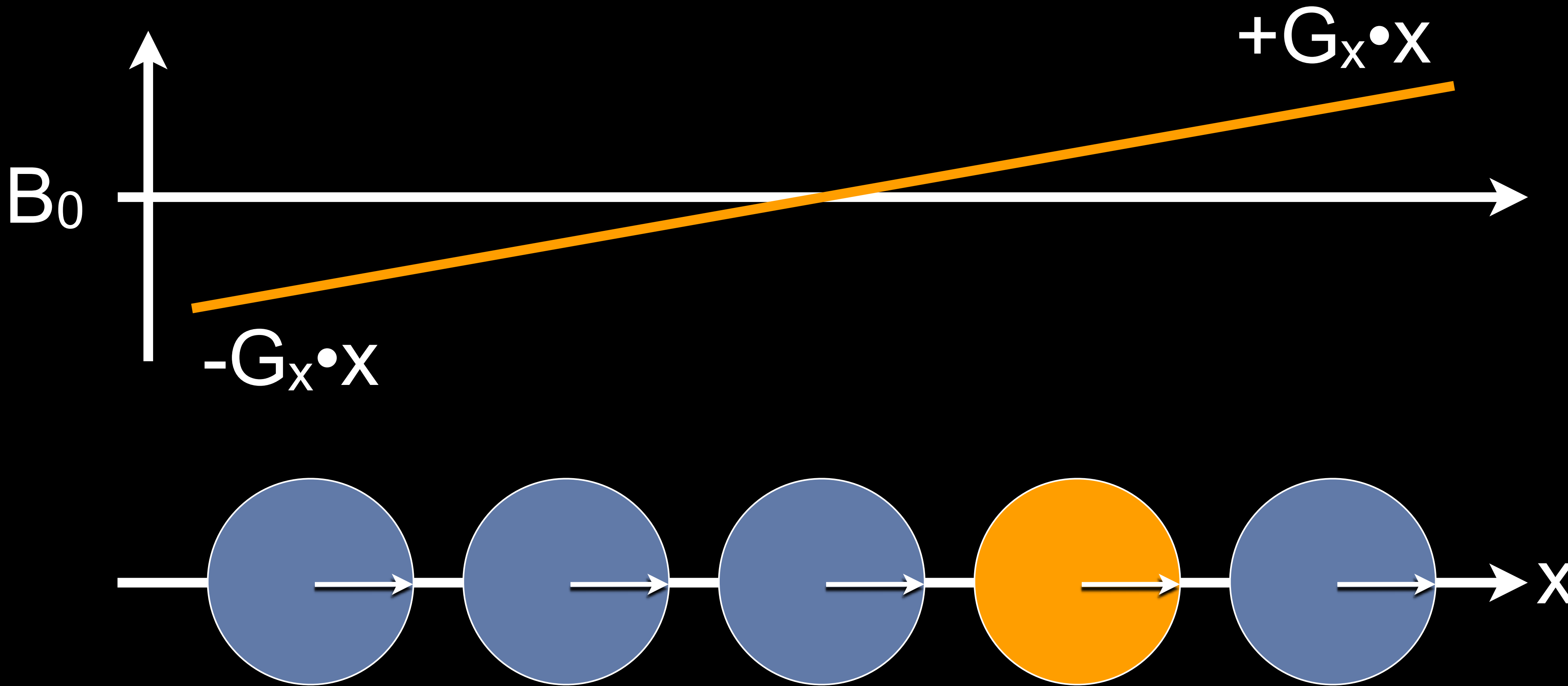
Water spins precess at the same Larmor frequency in a uniform B_0 field.

GRE & Fat/Water Frequency



Water spins precess at ***different*** Larmor frequencies in a non-uniform B_0 field.

GRE & Fat/Water Frequency

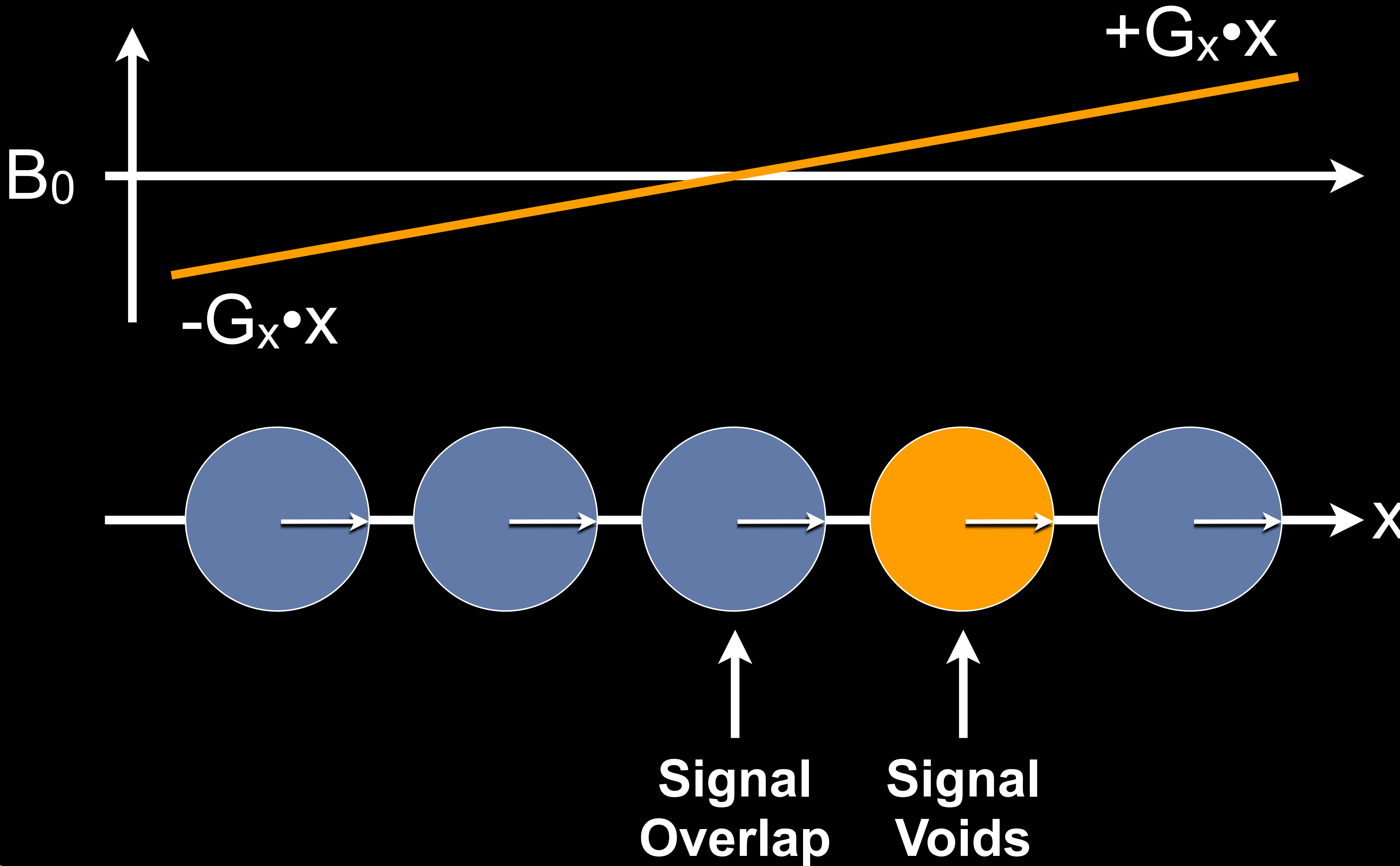


Water & Fat Spins in a Gradient Field

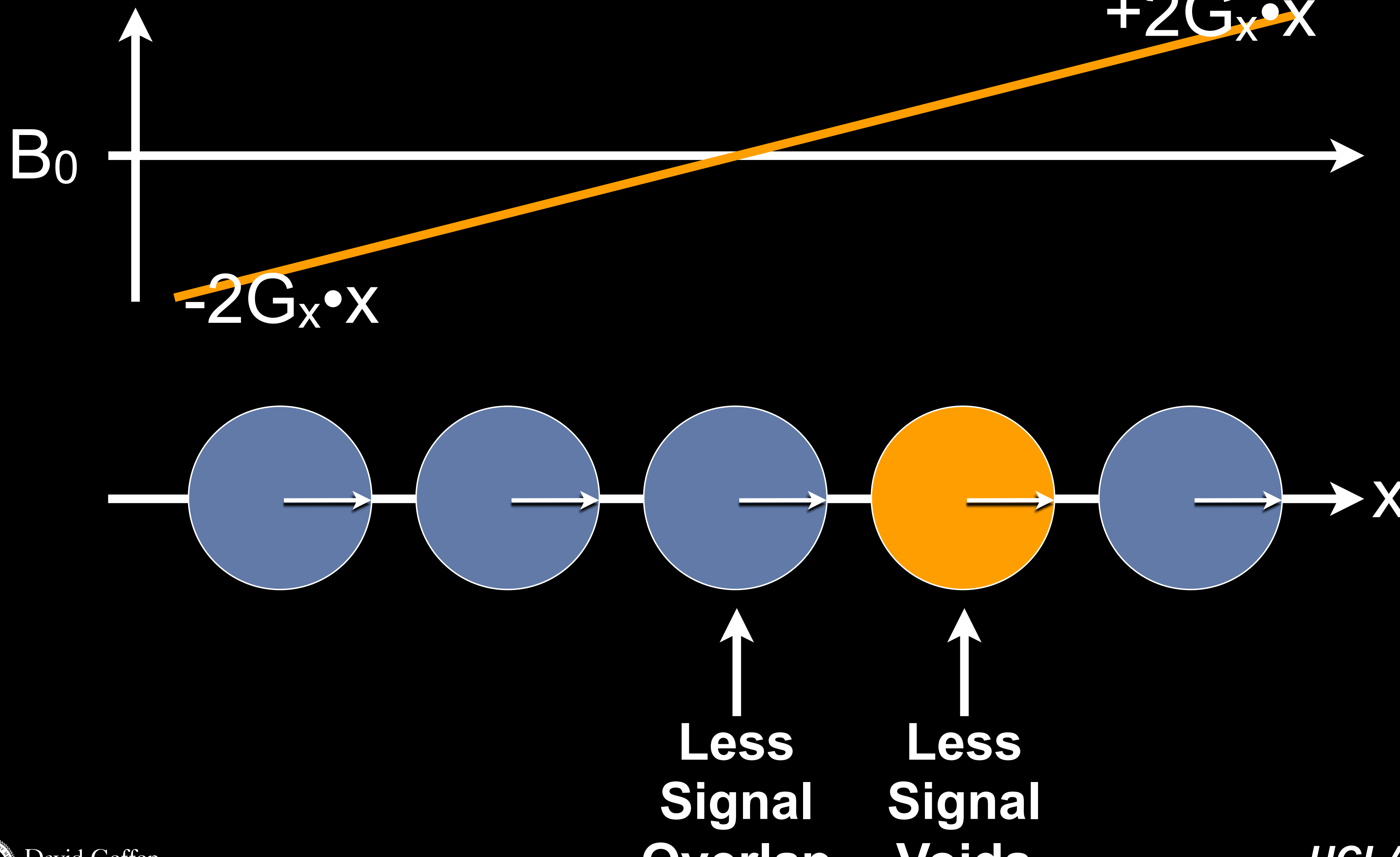
Fat Spins ~220Hz slower than water @ 1.5T

Spatial ***position*** is inferred from Larmor frequency.
Chemical (frequency) shift produces and apparent spatial shift.

GRE & Fat/Water Frequency

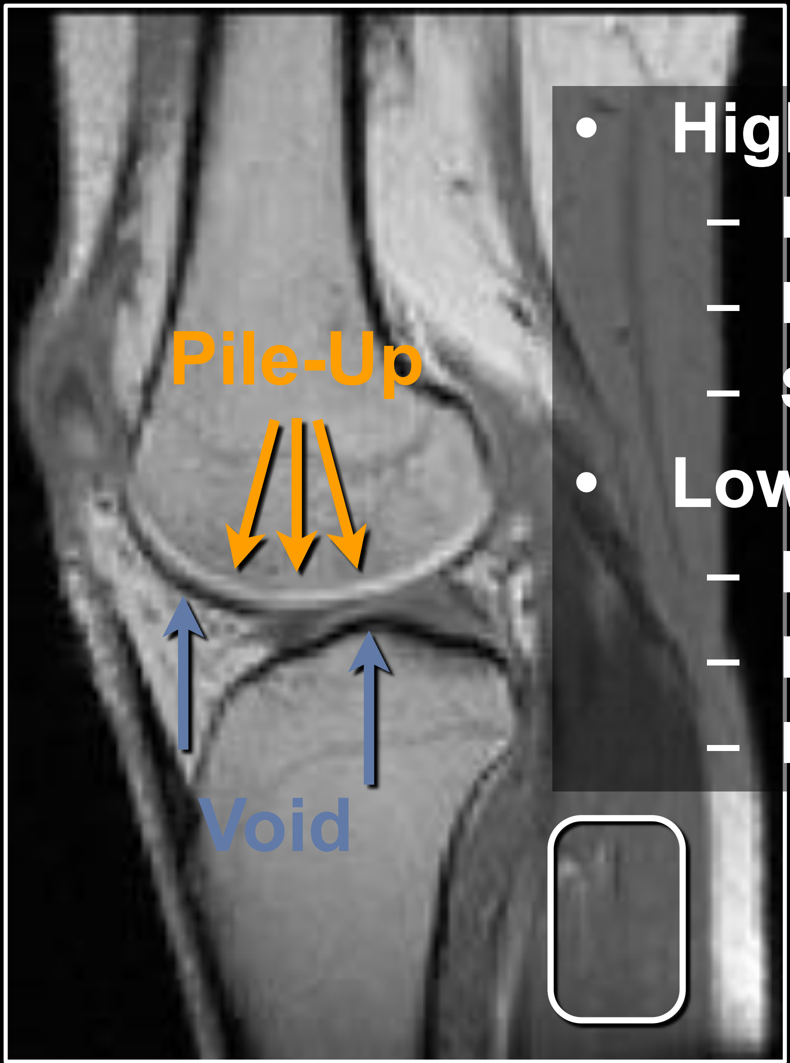


GRE & Higher Bandwidth

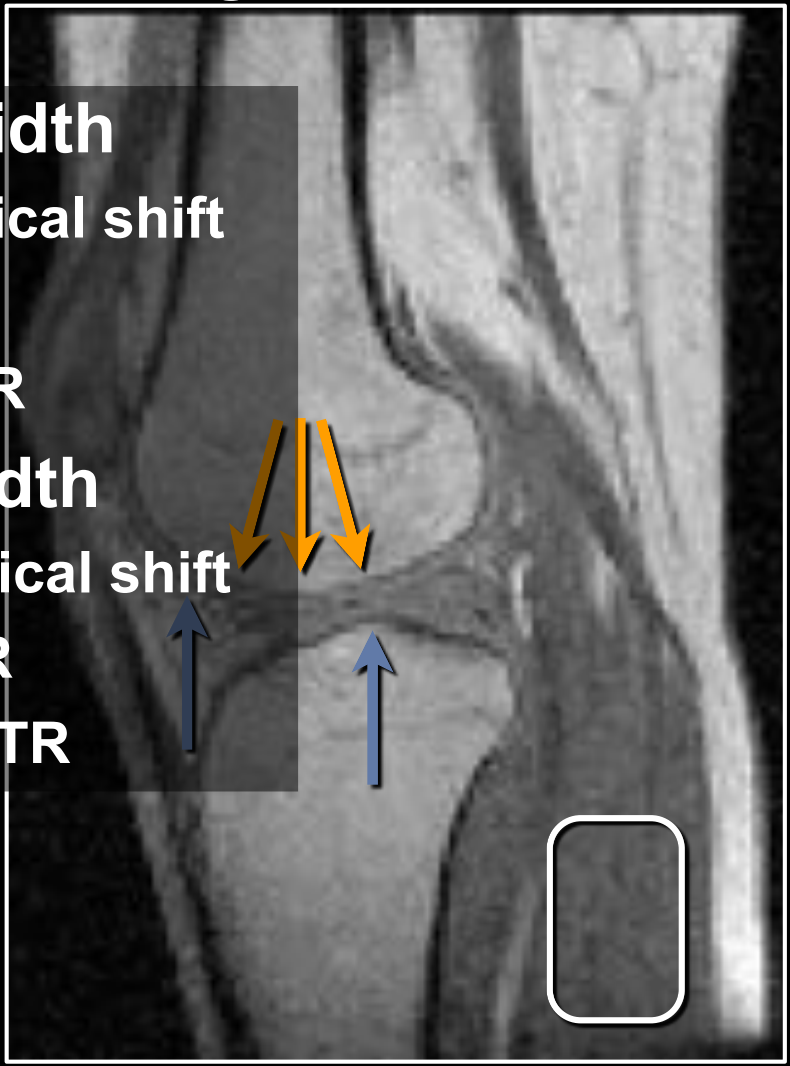


GRE, Fat/Water & Bandwidth

Low Bandwidth



High Bandwidth

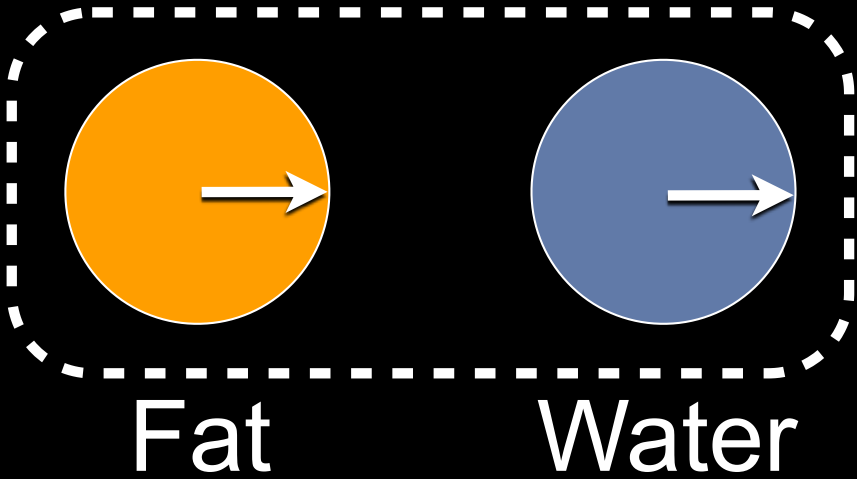


- High Bandwidth
  - Less chemical shift
  - Lower SNR
  - Short TE/TR
- Low Bandwidth
  - More chemical shift
  - Higher SNR
  - Longer TE/TR

Acquisition ***bandwidth*** is related to the ***speed*** with which an echo is acquired.
If the ***bandwidth*** (speed) is high, then there is less time for chemical shift, less time for signal acquisition (lower SNR), and shorter TE/TR.

Chemical Shift - Type 2

- **Pixels are frequently a mixture of fat and water**
- **Pixel intensity is the vector sum of fat and water**



In-Phase

$\rightarrow + \rightarrow\ > 0$

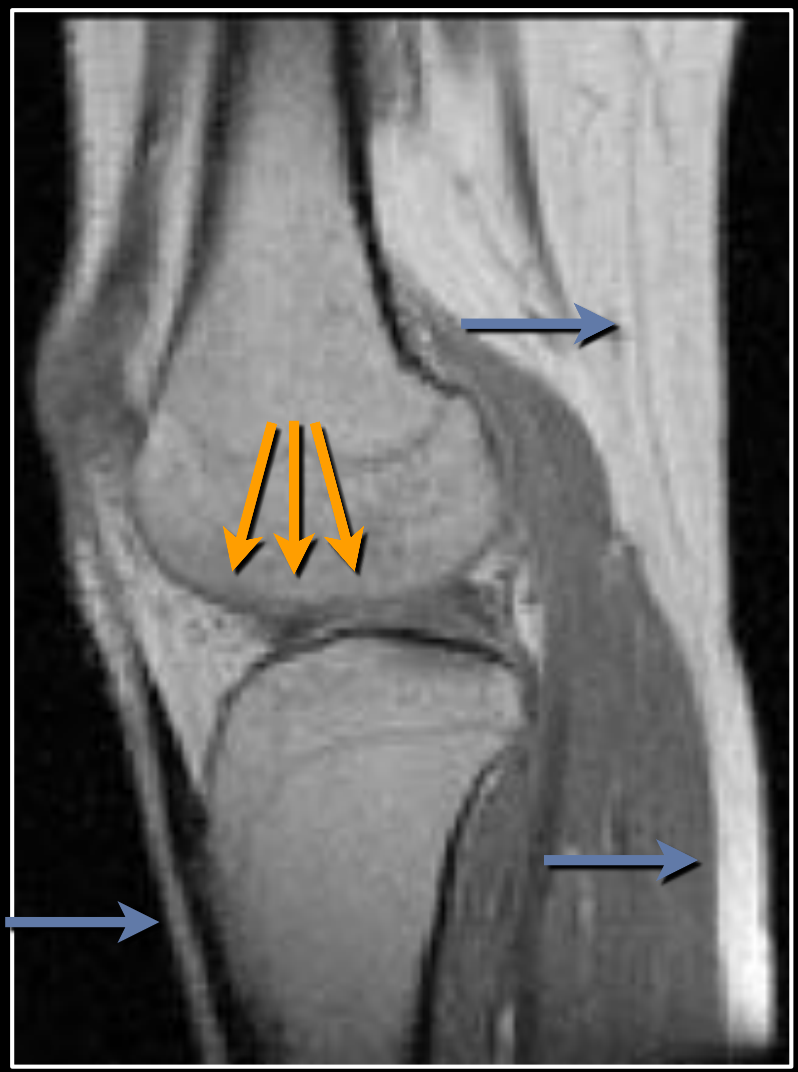
Opposed-Phase

$\leftarrow + \rightarrow\ = 0$

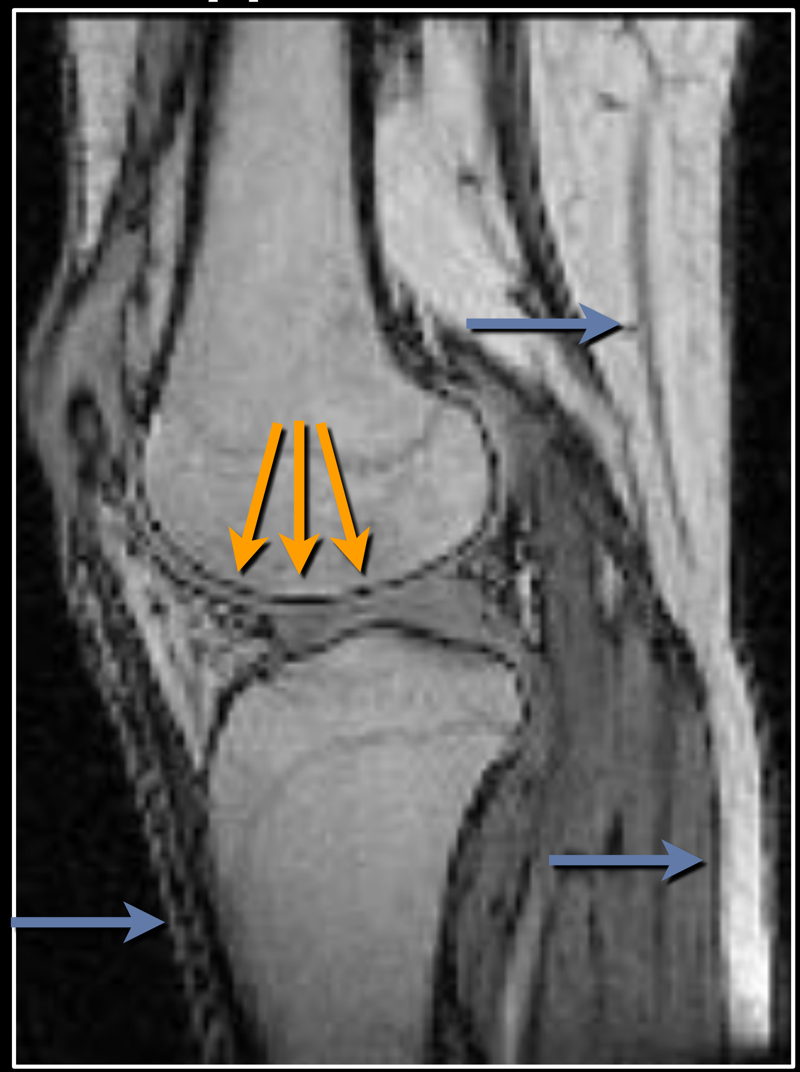
The TE controls the phase between fat and water.

GRE and Fat/Water Phase

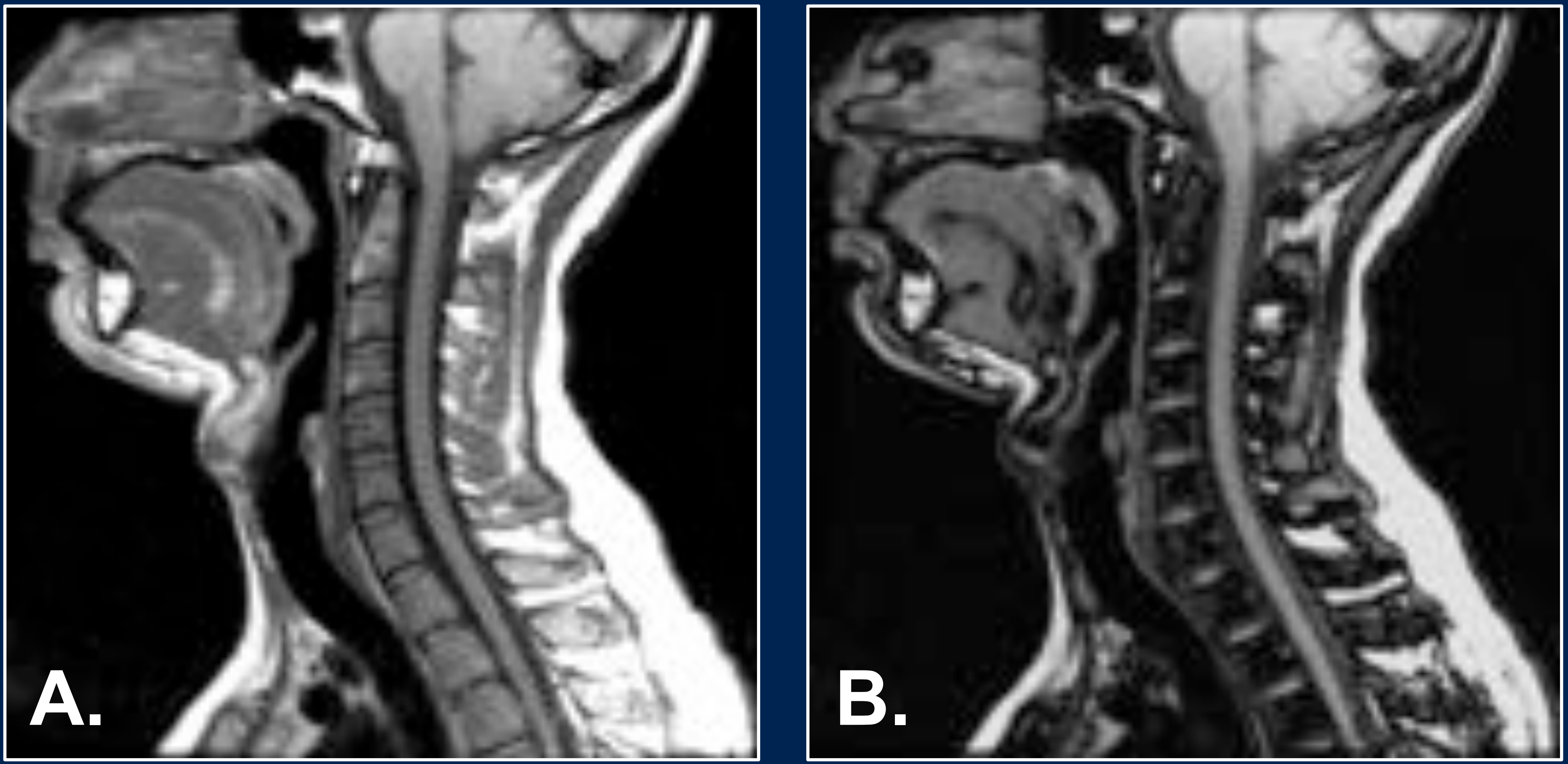
In-Phase



Opposed-Phase

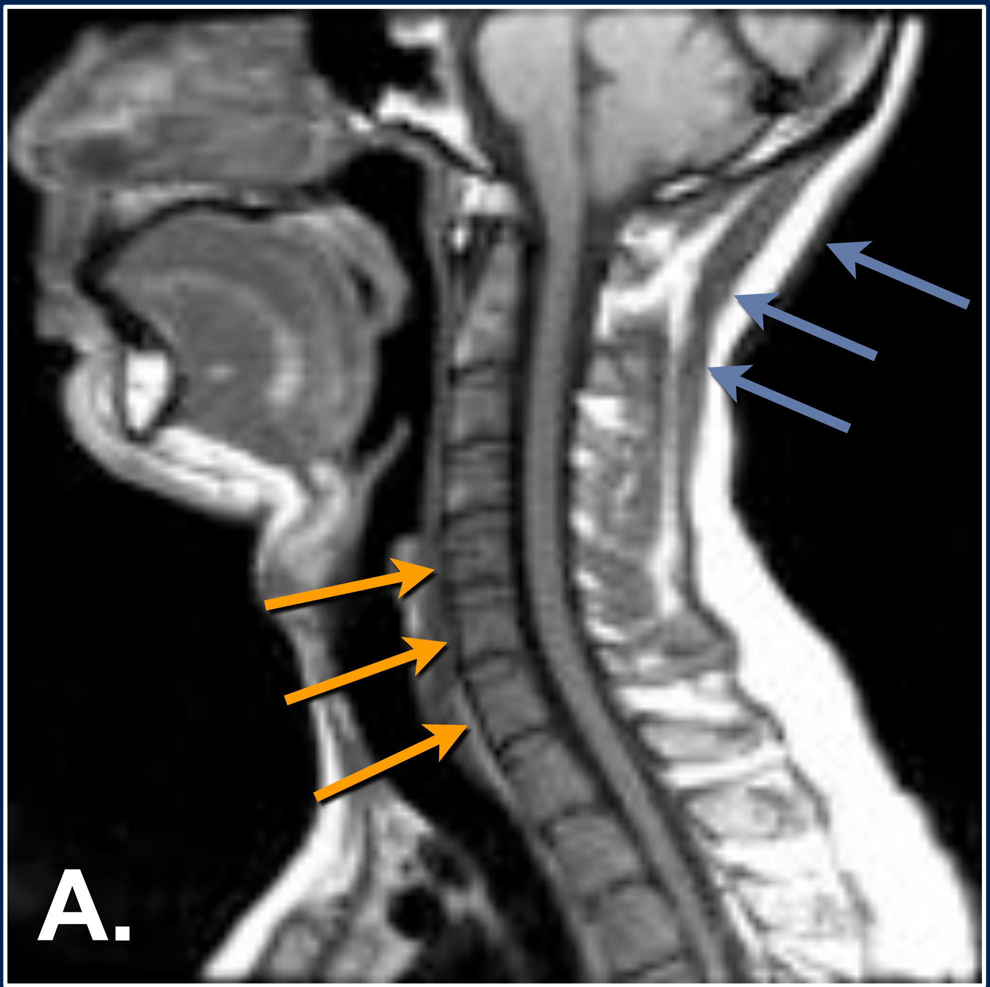


Which image is the in-phase image?

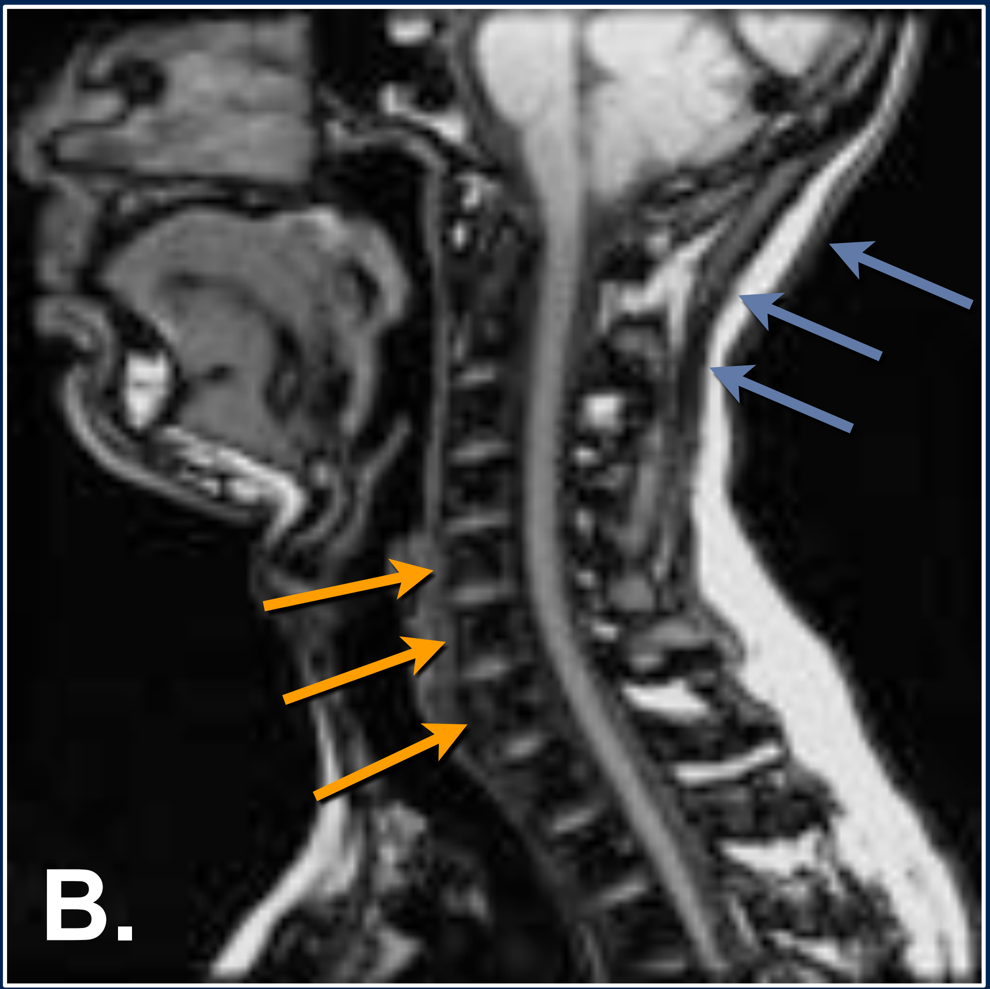


Images Courtesy of Scott Reeder

Which image is the in-phase image?



In-Phase



Opposed-Phase

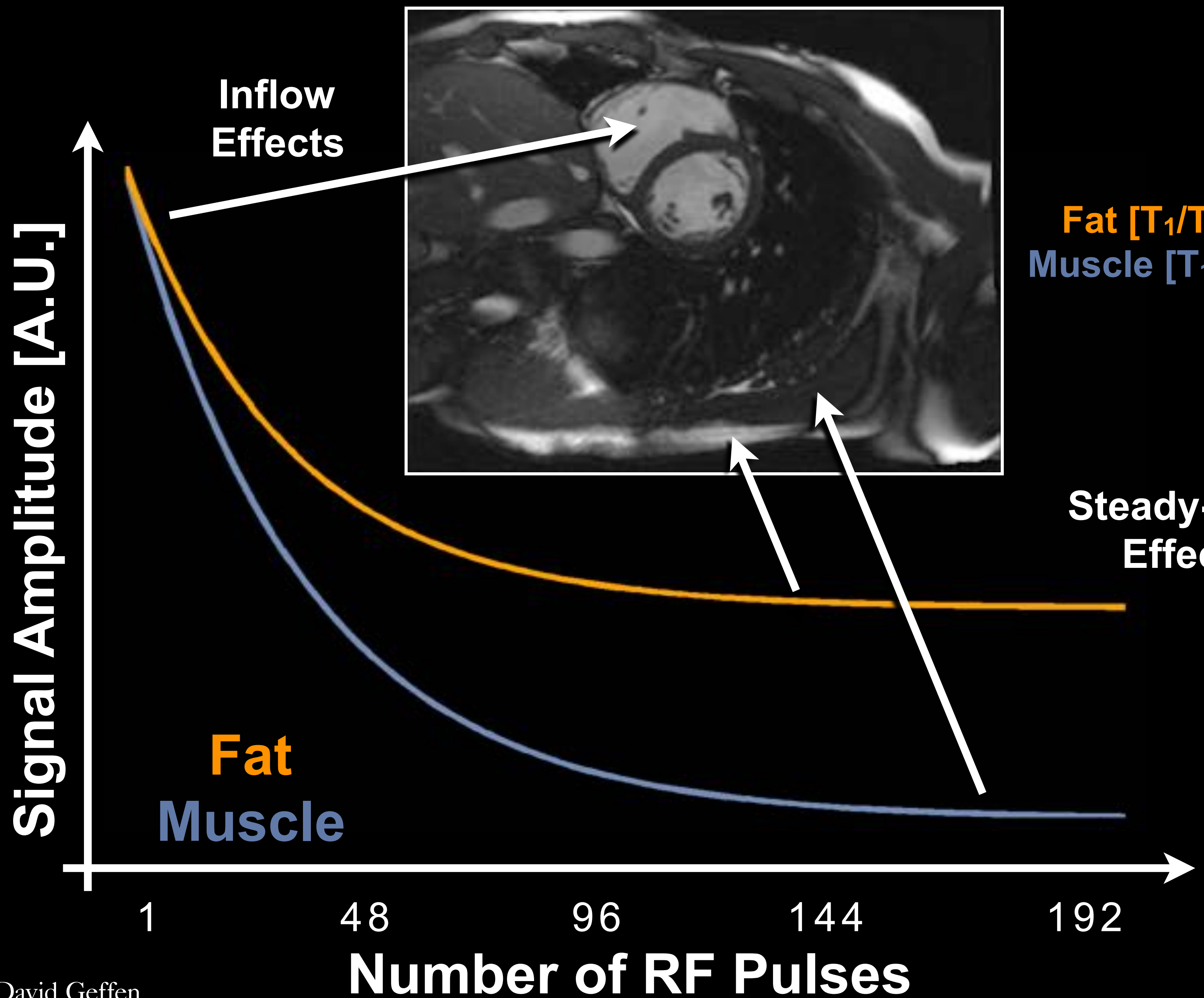
Gradient Echoes & Flow

Principle of In-flow Enhancement

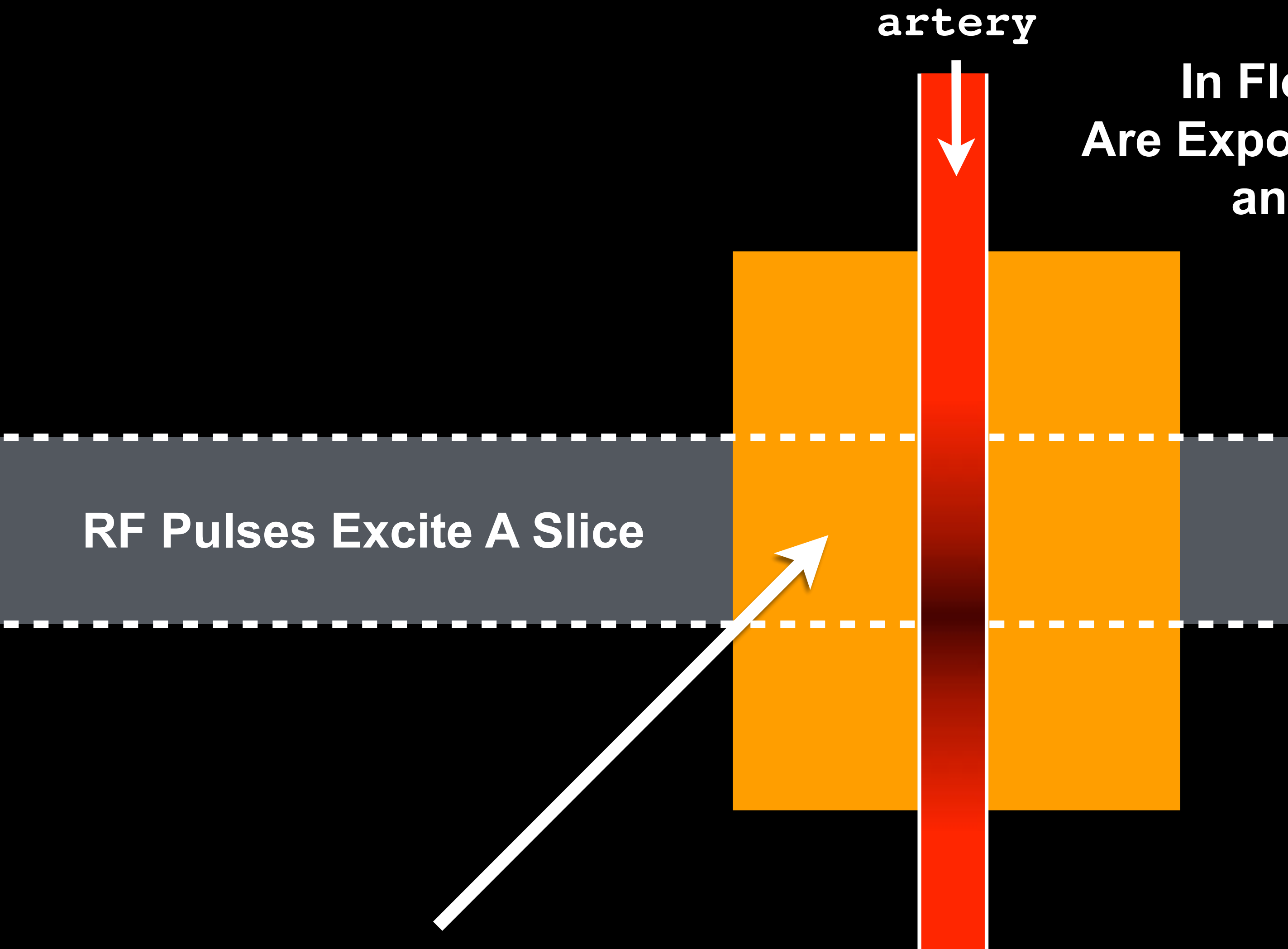
- **Partial saturation of stationary tissue**
  - **If TR<<T1, tissue can't fully relax each TR**
- **Inflow of fully relaxed spins**
  - **These spins haven't seen an RF pulse**
- **In combination high contrast is achieved**

Time-of-flight uses In-flow Enhancement and MIPs to visualize the vasculature.

Principle of In-flow Enhancement



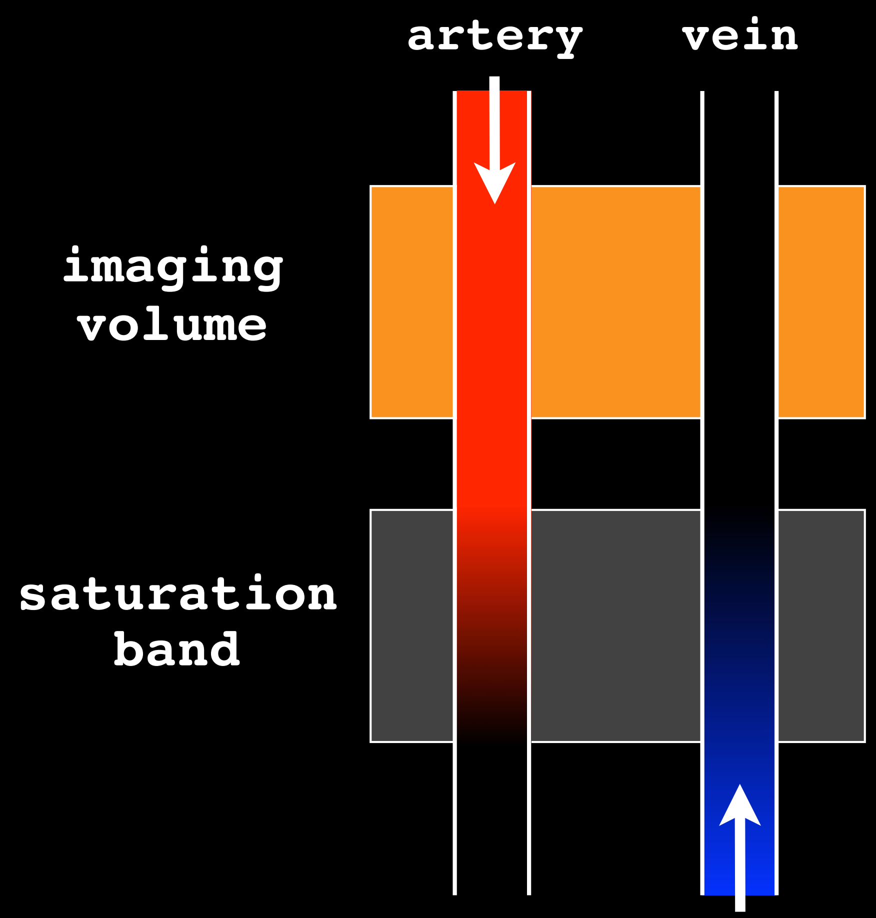
Principle of In-flow Enhancement



This is typical of most tissues in all typical MR images.

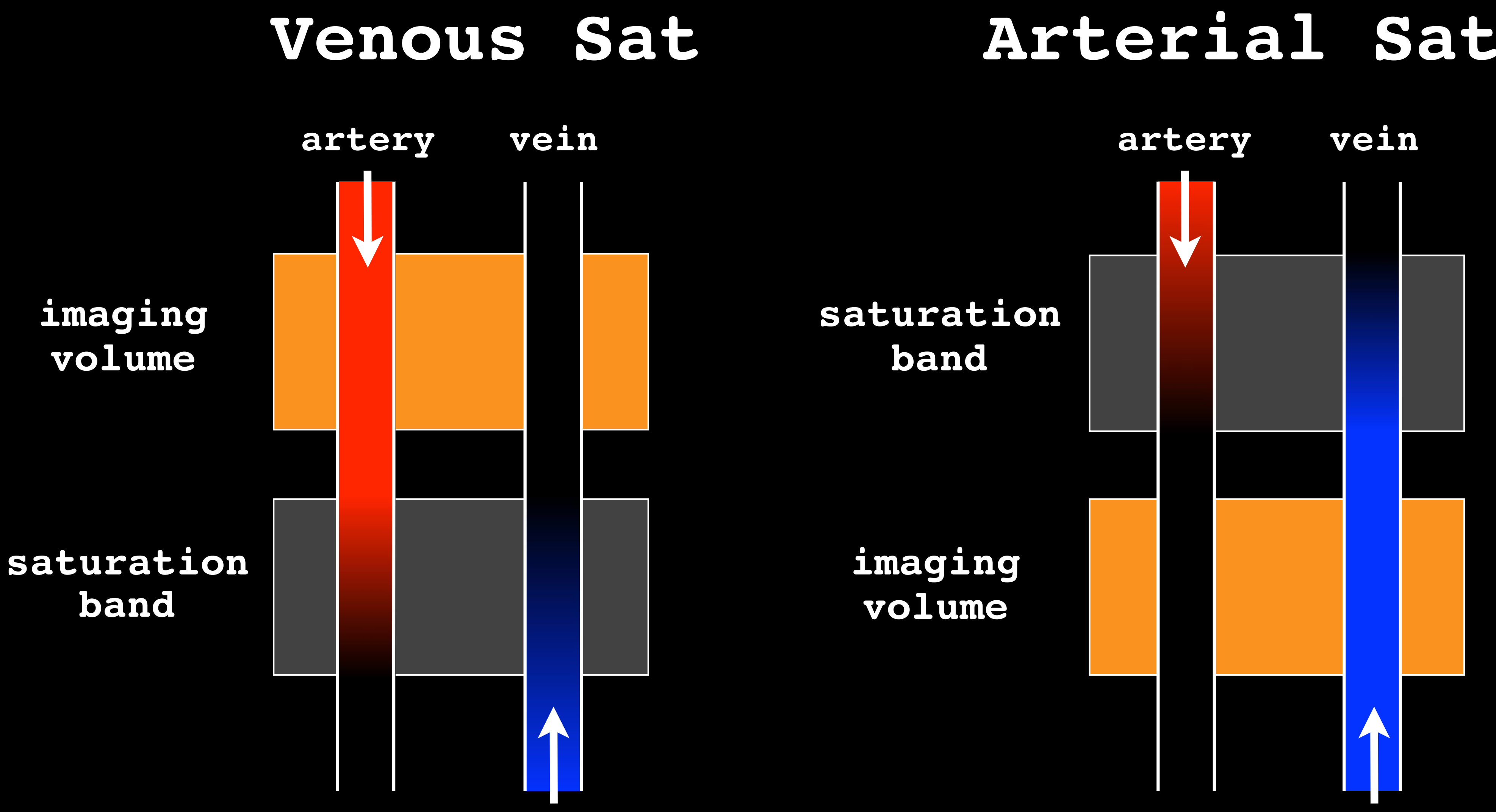
Spatial Pre-saturation

Venous Sat



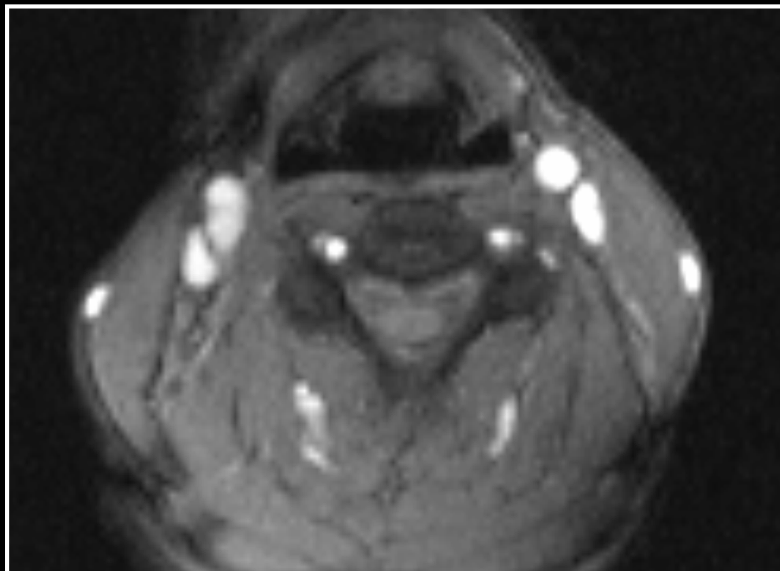
Saturation bands suppress tissue signals.

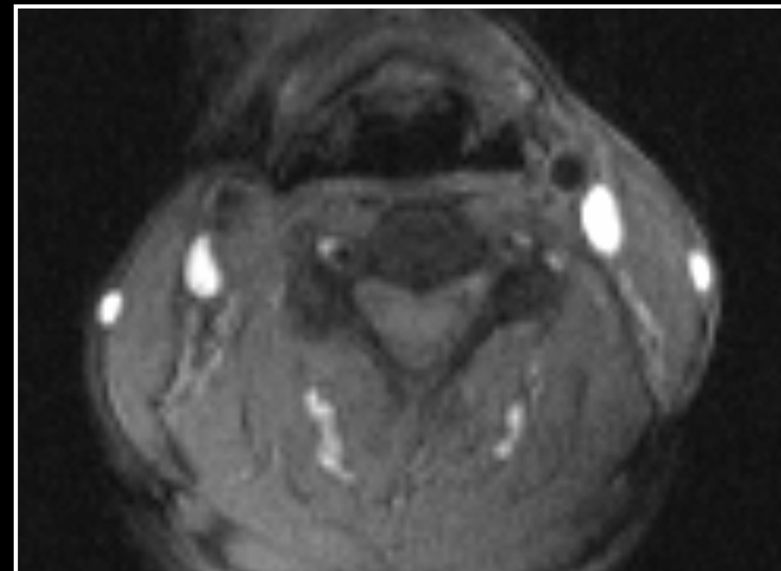
Spatial Pre-saturation

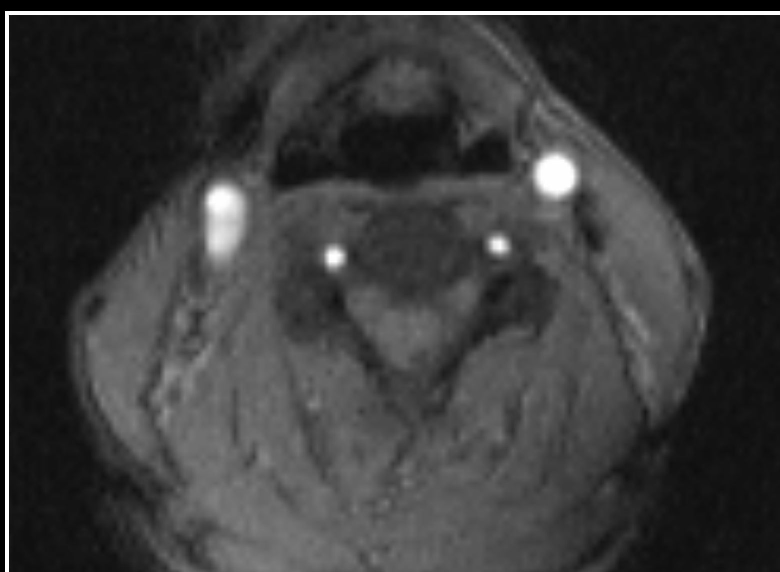


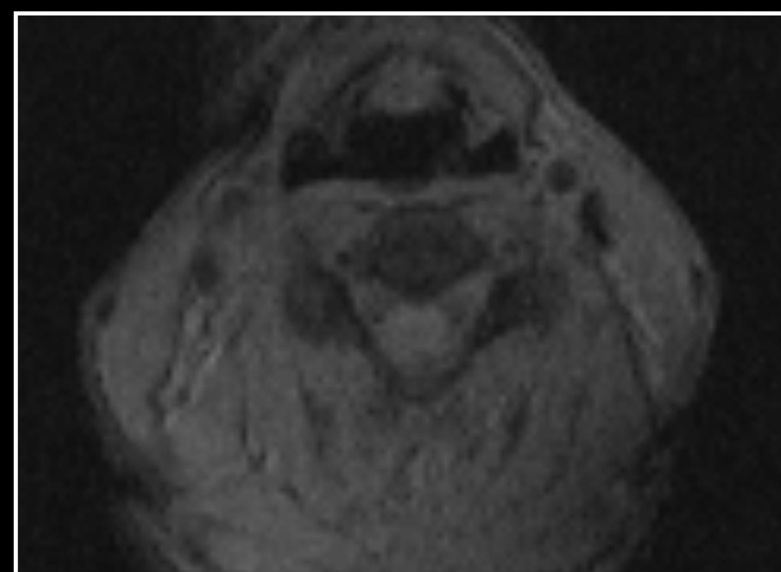
Saturation bands can suppress arterial or venous flow.

Spatial Pre-saturation


no sat


arterial sat


venous sat


parallel sat

Quiz: Gradient Echoes - True or False?

1. Fat and water precess at frequencies that are >1000Hz different.

2. Fat and water are always out of phase.

3. Fat and water destructively interfere when they are in phase.

4. In-flowing spins are bright because they "see" hundreds of excitation pulses.

Spatial Localization

Spatial Encoding

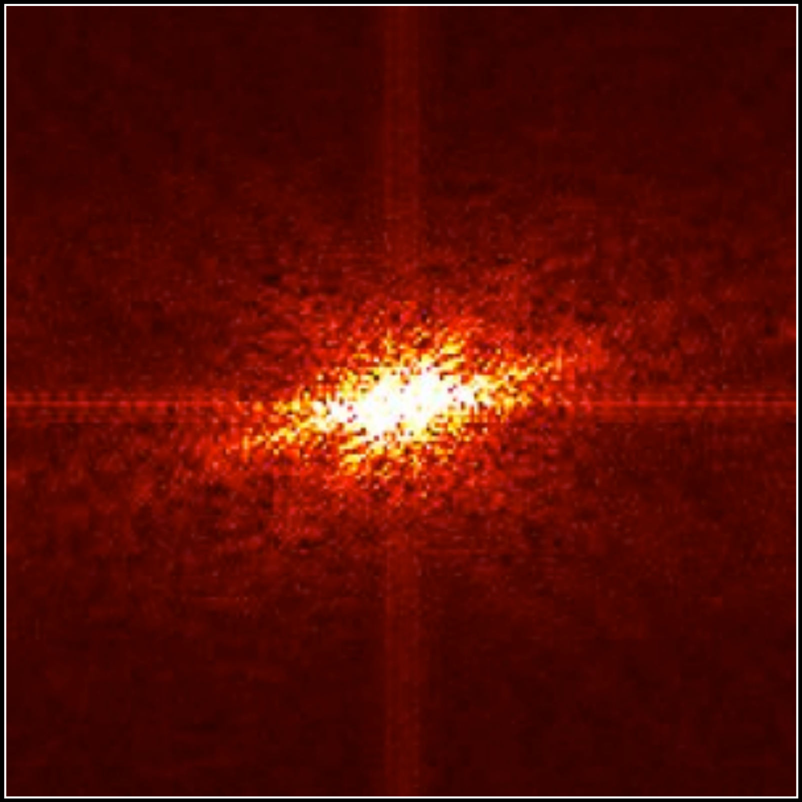
- **Three key steps:**
  - **Slice selection**
    - You have to pick slice!
  - **Phase Encoding**
    - You have to encode 1 of 2 dimensions within the slice.
  - **Frequency Encoding (aka *readout*)**
    - You have to encode the other dimension within the slice.

Steps required to acquire k-space data.

What is *k*-space?

k-space

image space

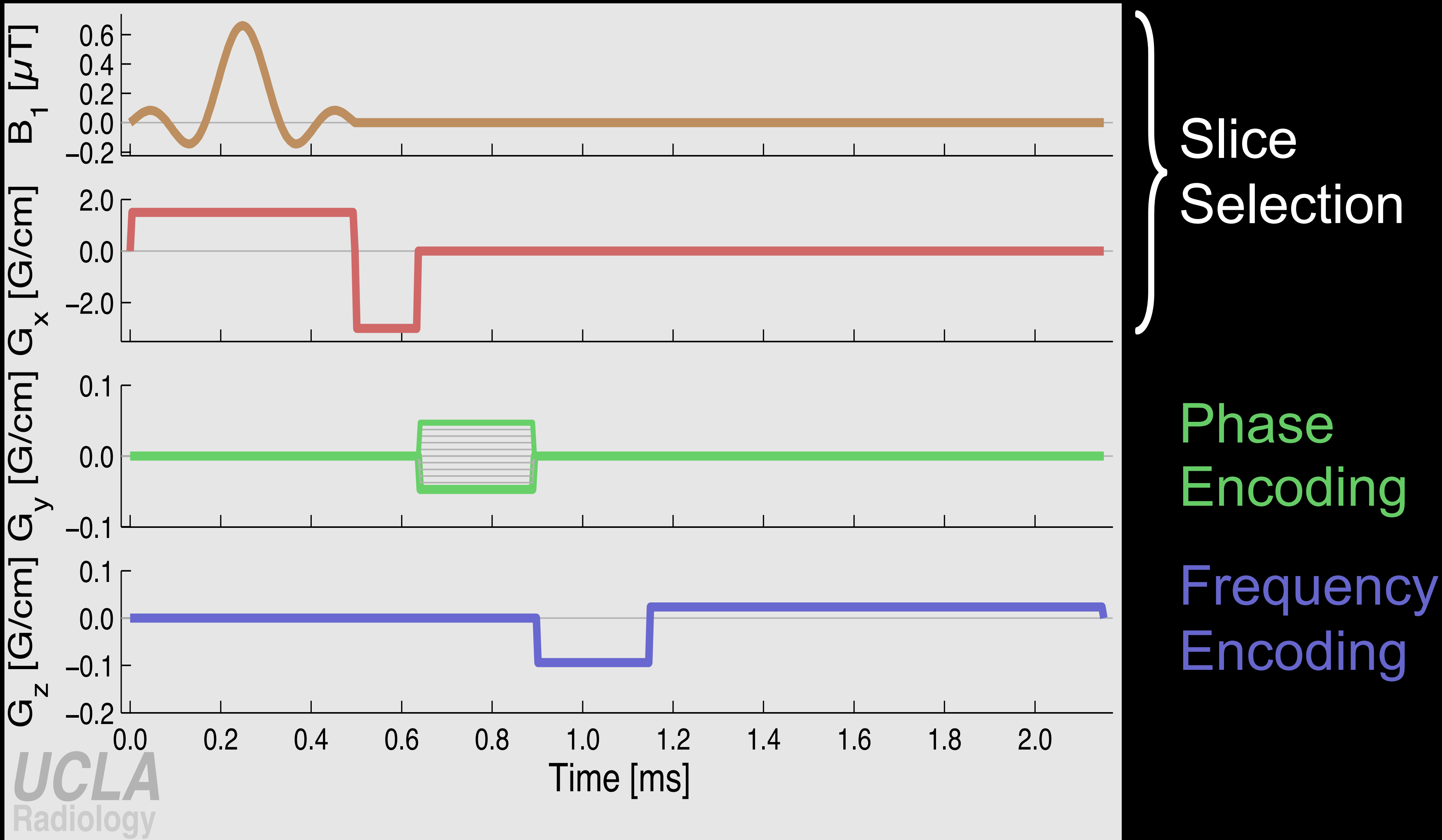


FFT

_k_-space is the raw data collected by the scanner.

A point in _k_-space represents the presence/absence of a particular spatial frequency.

Spatial Localization



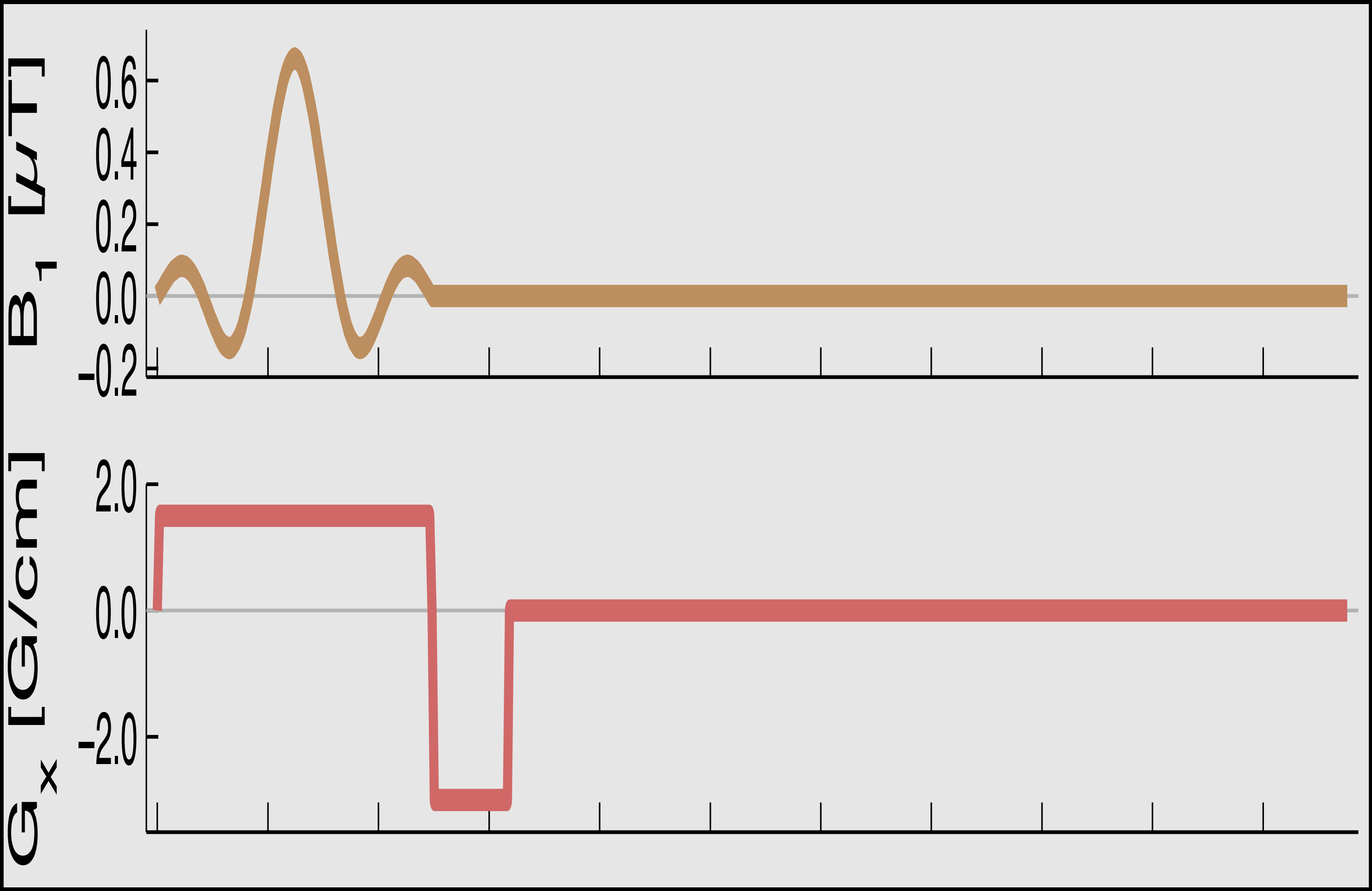
Pulse Sequence Diagram - Timing diagram of the RF and gradient events that comprise an MRI pulse sequence.

David Geffen School of Medicine

Spatial localization requires three key steps.

UCLA Radiology

Slice Selection



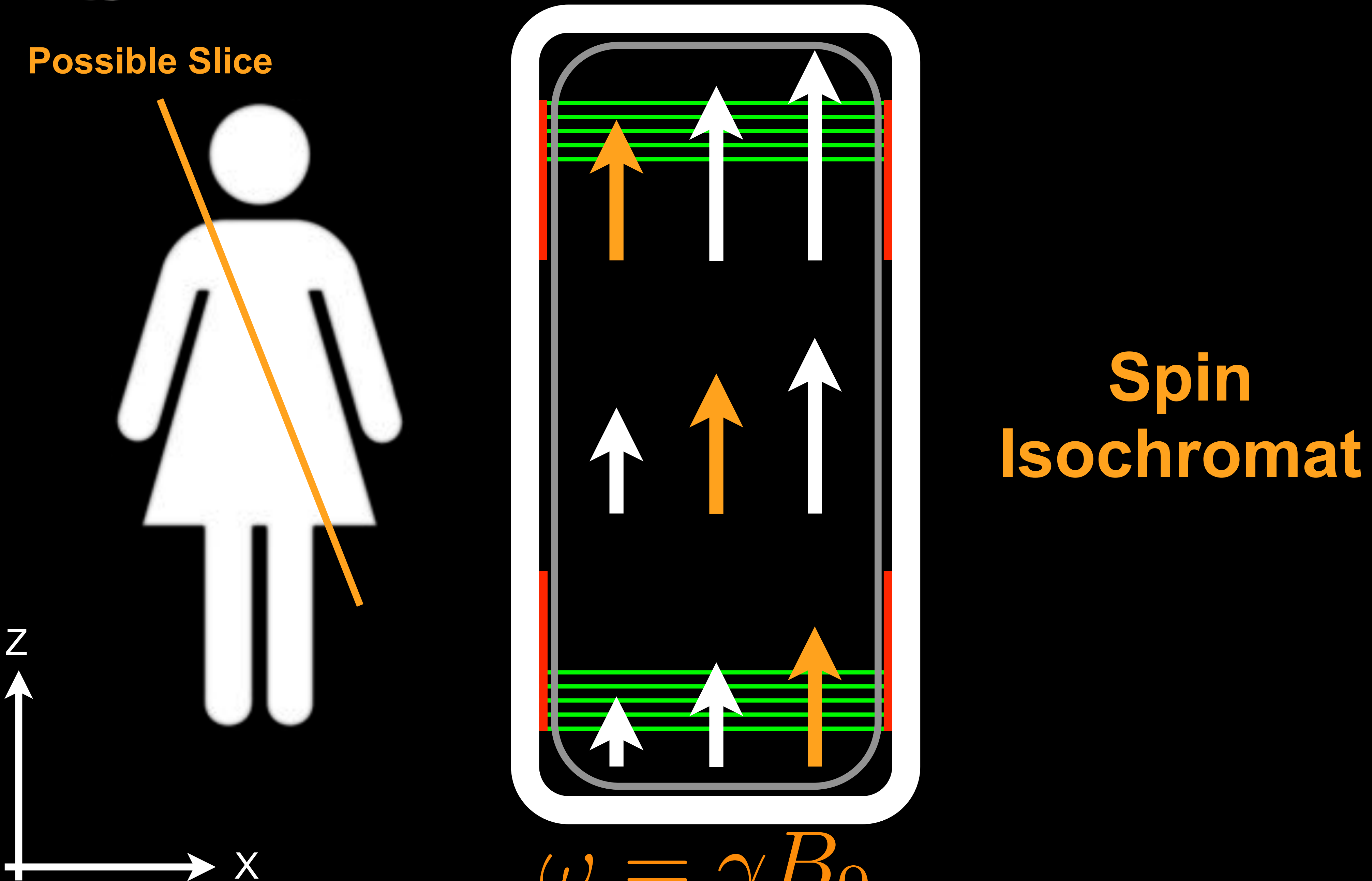
RF pulse tuned to frequencies (slice) of interest.

Create a range of frequencies to distinguish slices.

Re-phase spins in slice to increase signal-to-noise.

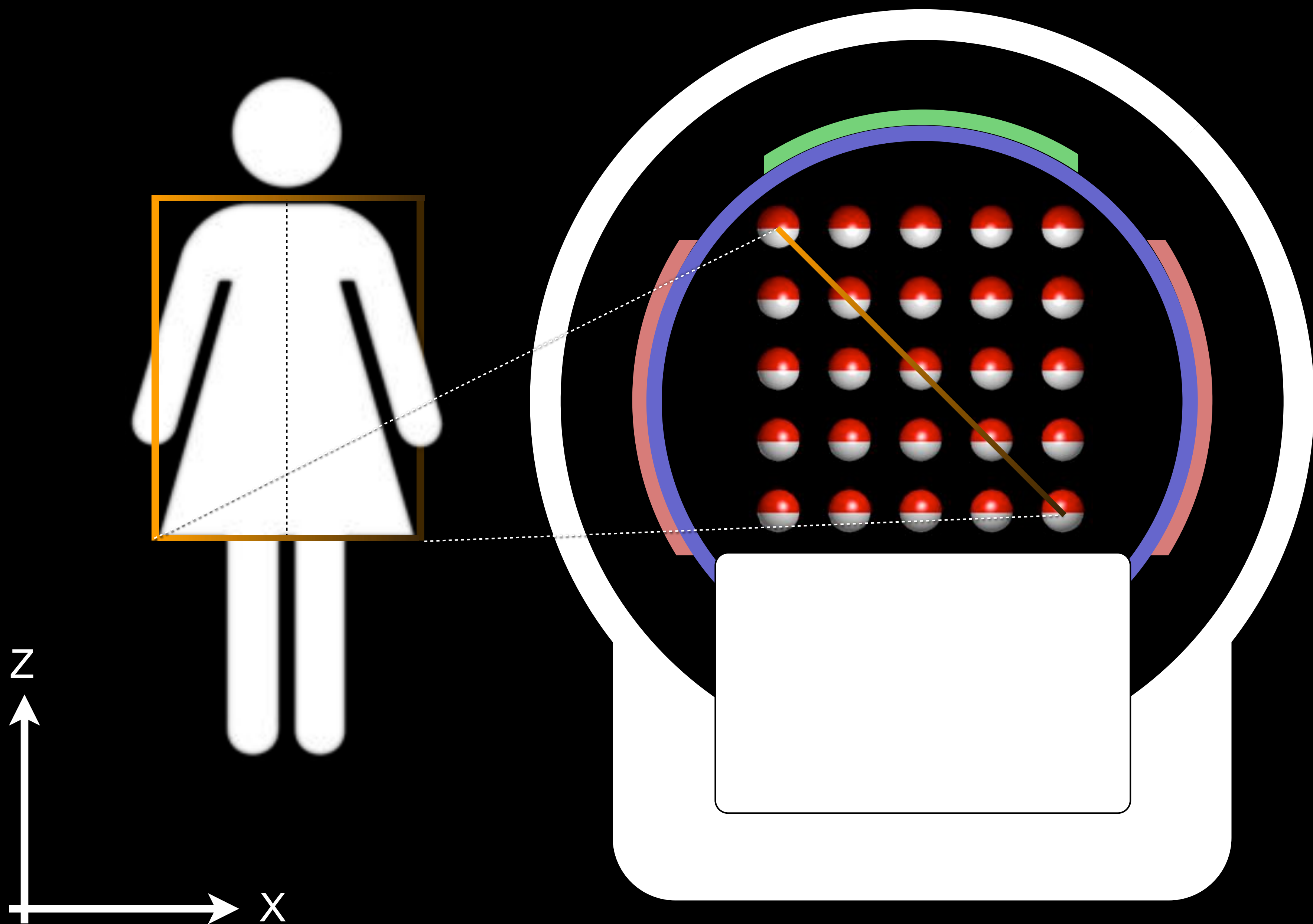
Slice selection requires RF and a gradient.

X+Z-Gradients are ON



$$\omega = \gamma B_0$$

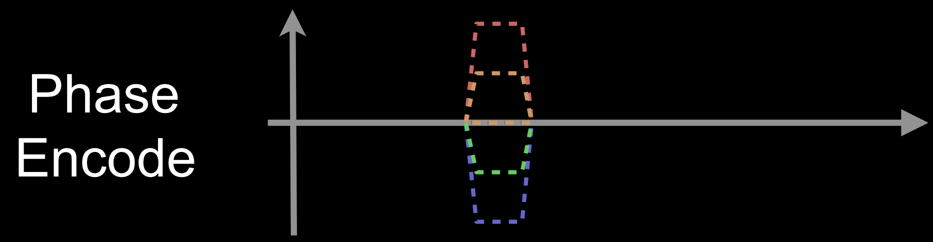
Spins and X- & Y-Gradients



RF pulse frequency is “tuned” to slice of interest.

Phase Encoding

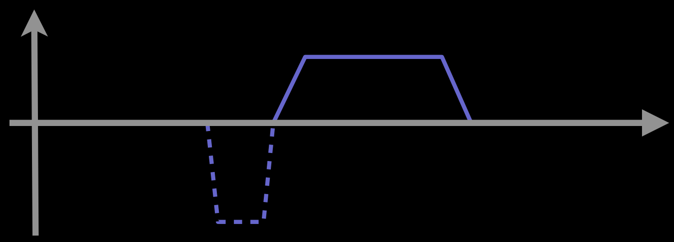
- **Consists of:**
  - **Phase encoding gradient**
    - **Magnitude changes with each TR**
- **After excitation, before readout**
- **Adds linear spatial variation of phase**
- **Phase encode in**
  - **one direction for 2D imaging**
  - **two directions for 3D imaging**
- **Only one PE step per echo**



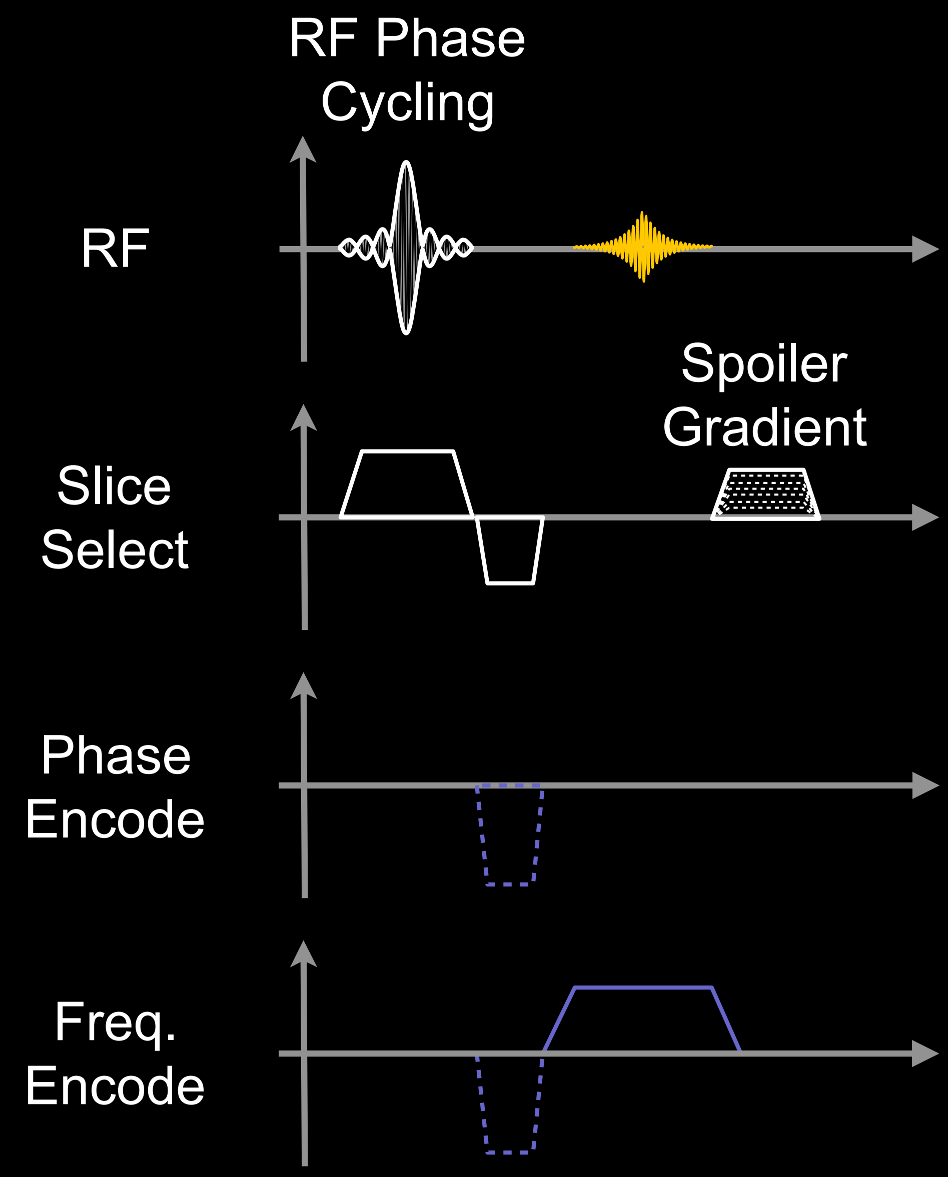
Frequency Encoding

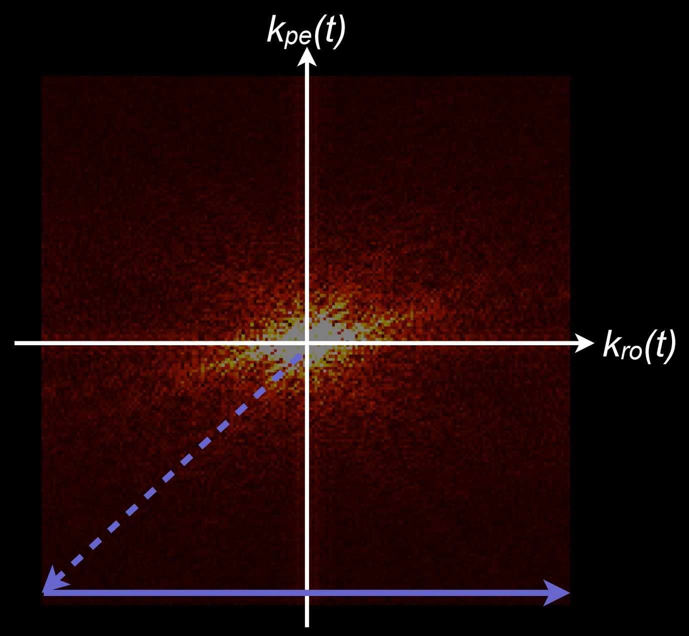
- **Consists of:**
  - **Frequency encoding gradient**
    - **Constant for each TR**
  - **No simultaneous**
    - **RF (B_1)**
    - **Other gradients**
      - **phase encoding, slice encoding, crushers**
  - **Readout pre-phasing gradient**
    - **Prepares spin phase so peak echo amplitude occurs at middle of readout (TE)**
    - **AKA "readout de-phasing gradient"**
- **Adds linear spatial variation of frequency**
- **Helps form an *echo***

Freq. Encode



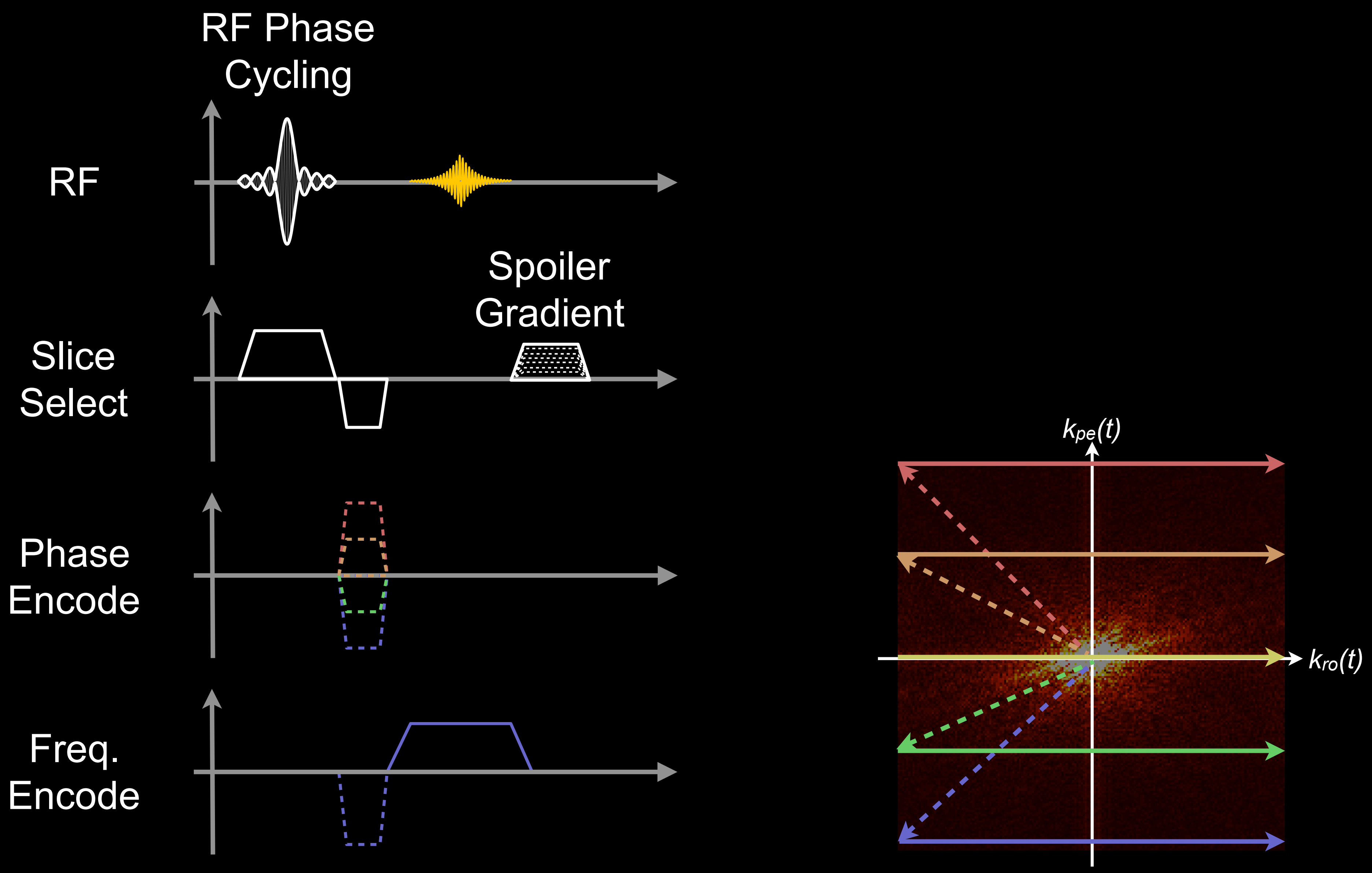
Where am I in *k*-space?





One phase encoded echo is acquired per TR.

Where am I in *k*-space?



Gradients move the acquisition through *k*-space.

How do we calculate scan time?

$$T_{Scan} = TR \cdot PE \cdot N_{avg}$$

- T_{Scan}=1000ms•256•1=4:16 [mm:ss]
- **Assumes one echo per TR.**
- **MRI scanning can be *slow*.**

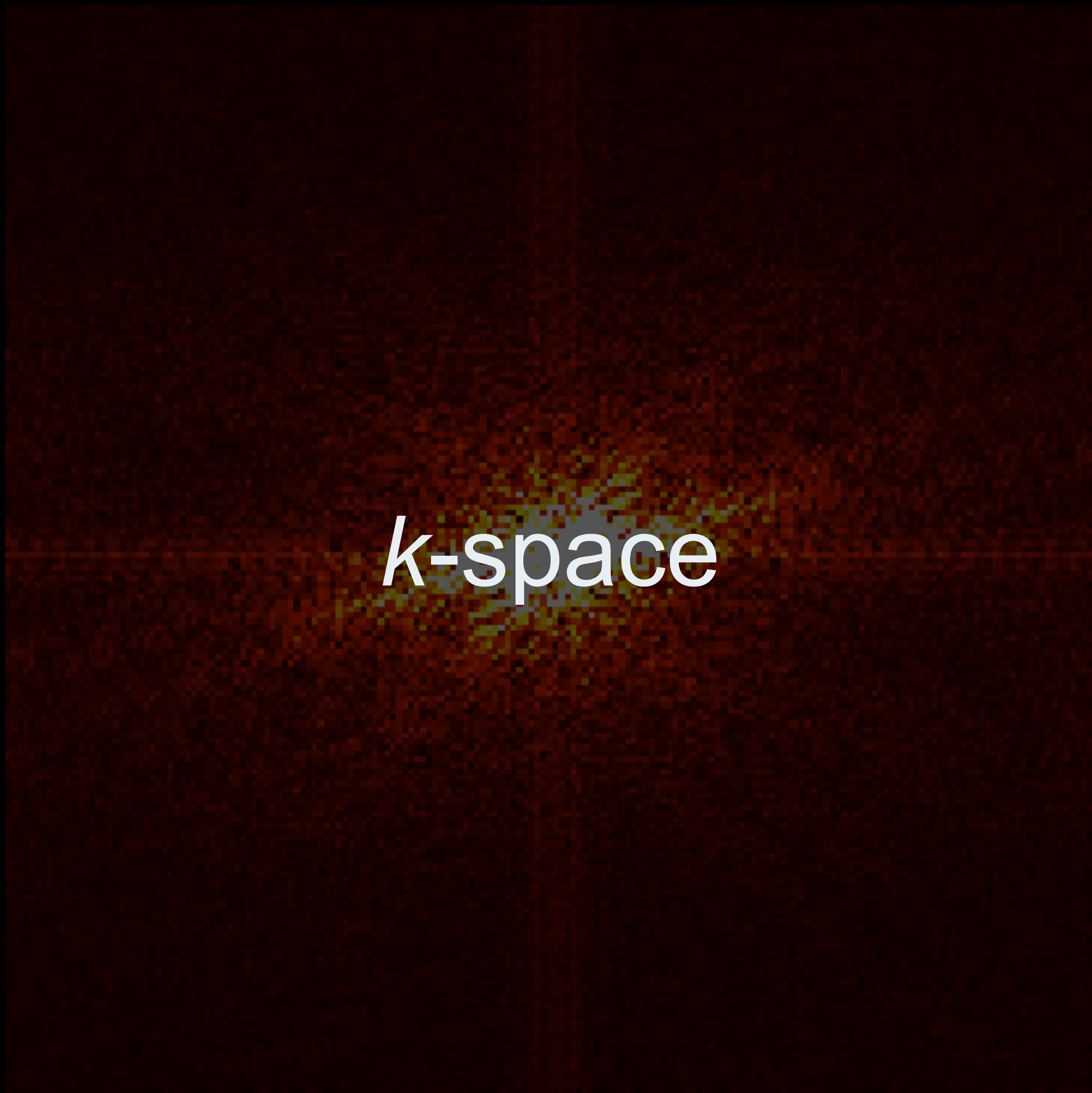
Quiz: Spatial Localization - True or False?

1. Slice selection only requires an RF pulse.

2. Phase and frequency encoding map out the image information within a slice.

3. Slice-select, frequency encode, then phase encode.

4. GRE TRs are ~10ms, therefore MRI scanning is *very* fast.


k-space

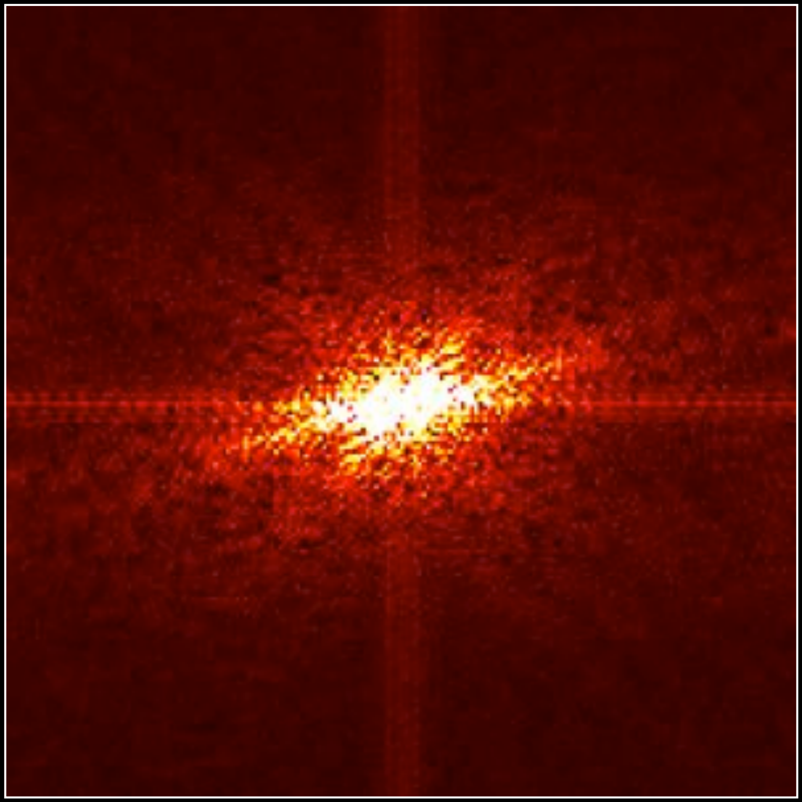
What is *k*-space?

- ***k*-space is the raw data collected by the scanner.**
  - A point in k-space tells us about the presence/absence of a spatial frequency (pattern) in the acquired image.
  - Each echo measures *many* of the spatial frequencies that comprise the object.
  - *k*-space has units of cm^{-1} or mm^{-1}
    - Audio signals have units of Hertz (s^{-1})
- **Gradients**
  - Help extract spatial frequency information
  - Move us around in k-space
- **A line of *k*-space is filled by an echo**
- **2D FT of *k*-space produces the image**

What is *k*-space?

k-space

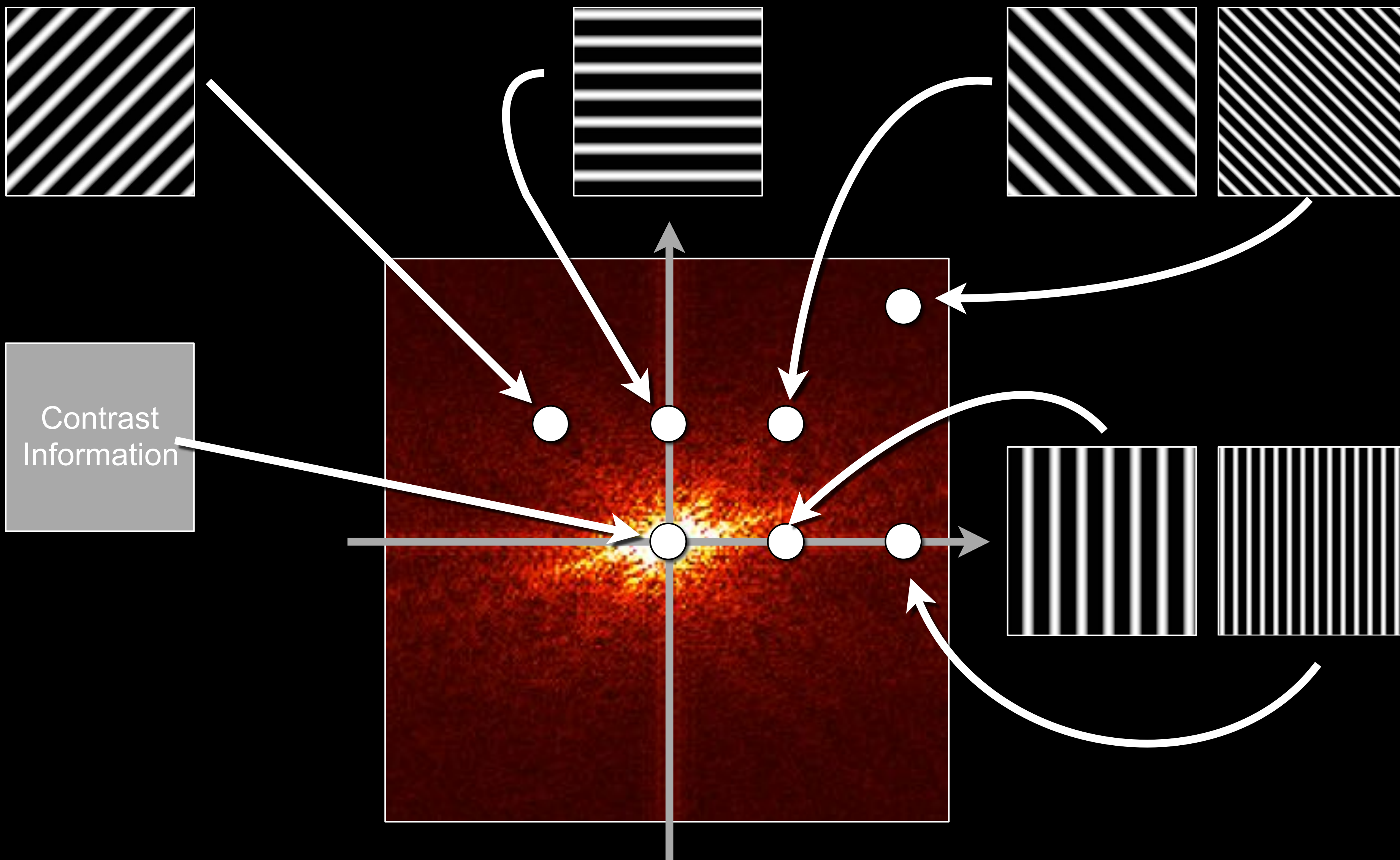
image space



FFT

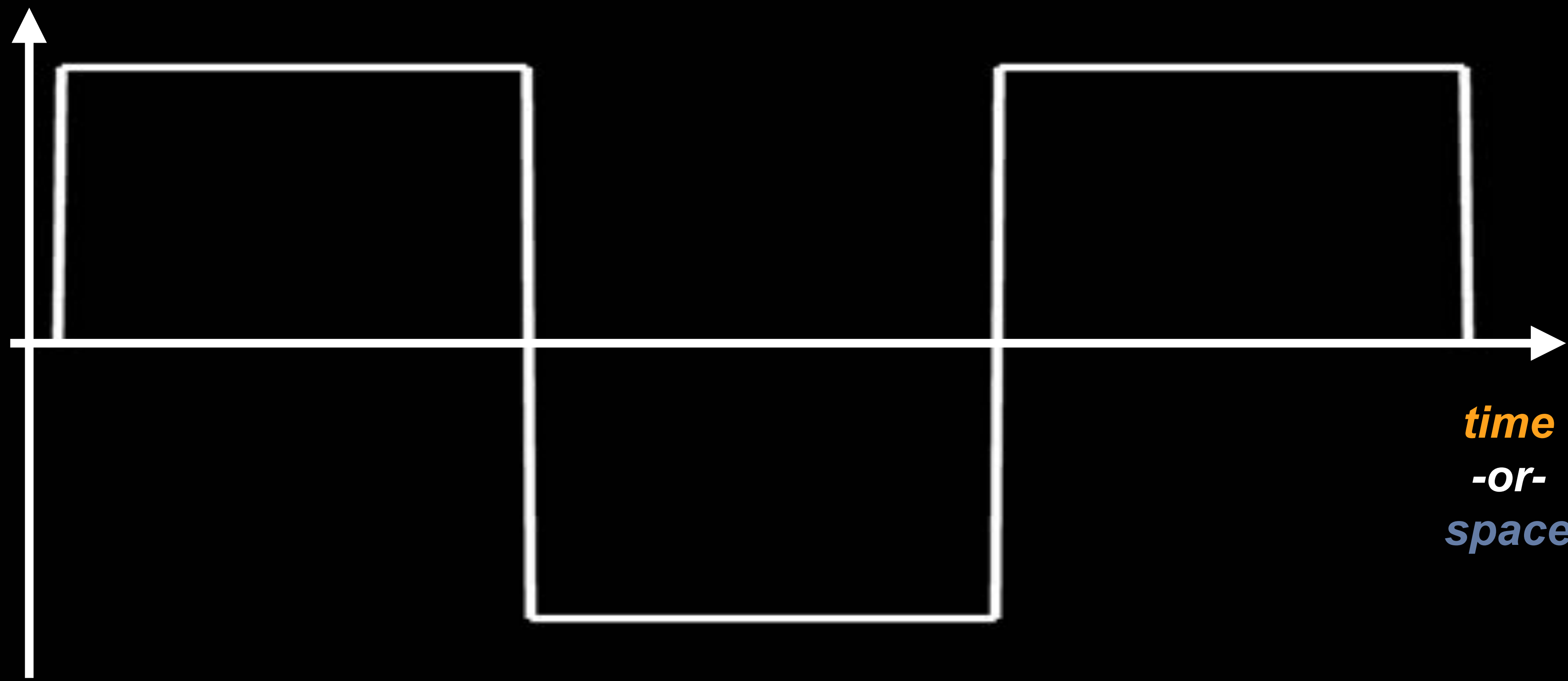
***k*-space is the raw data collected by the scanner.**

What is *k*-space?



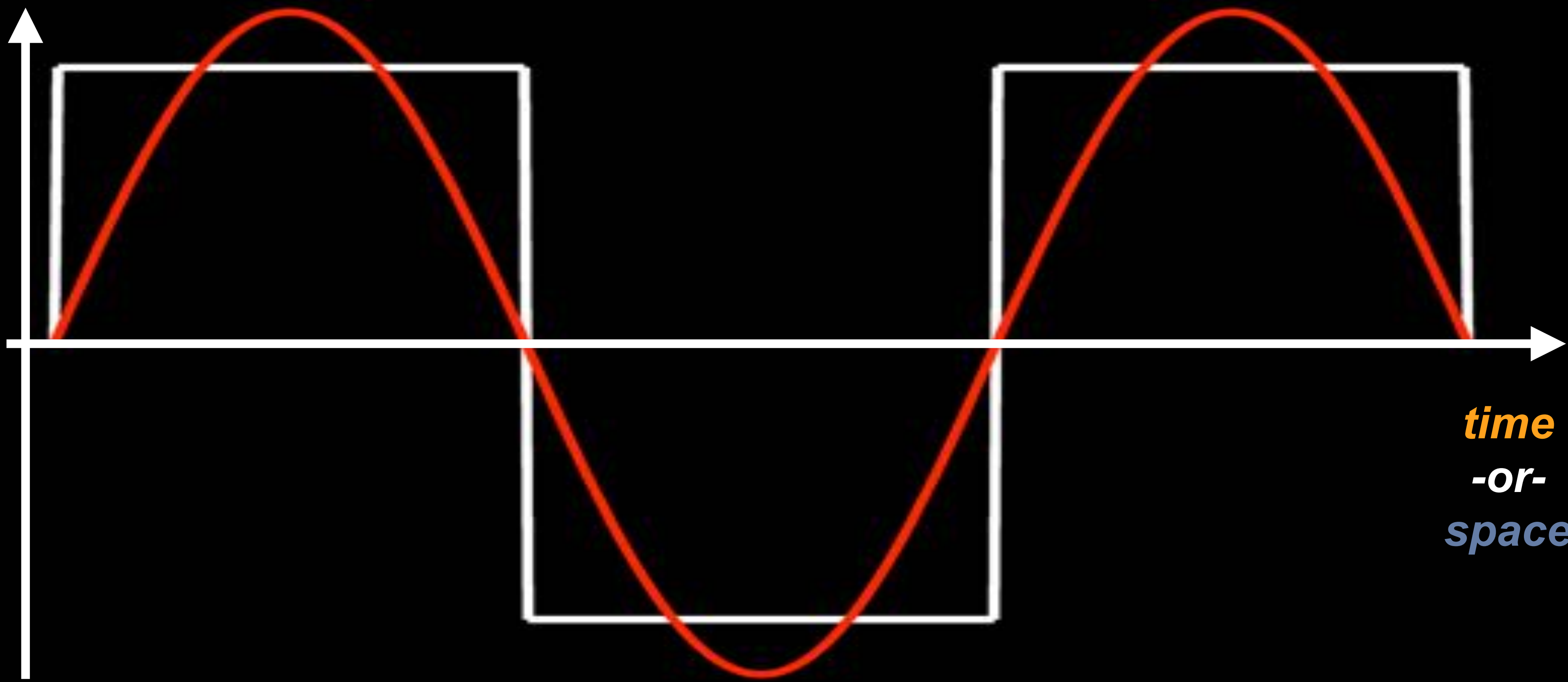
Points in *k*-space represent different patterns in an image.

1D *k*-space



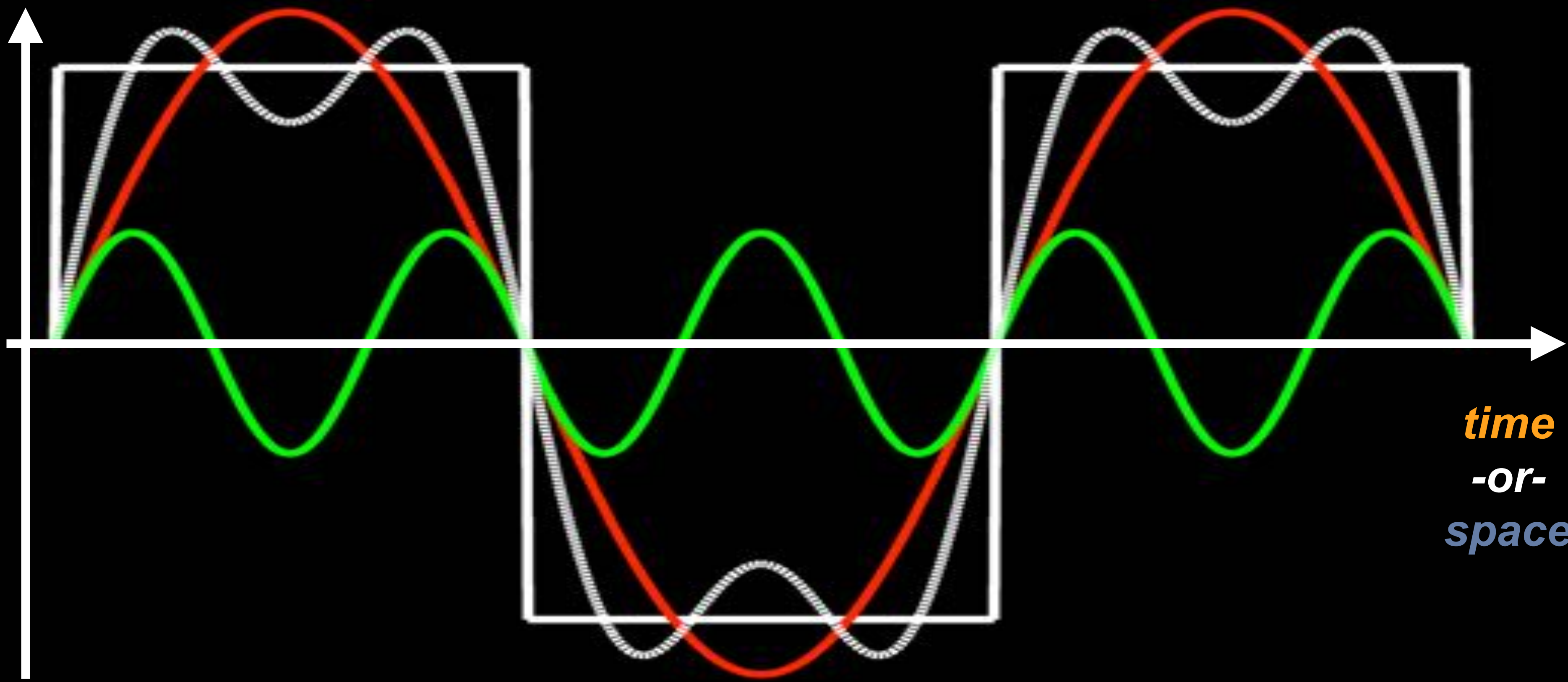
Any signal/image can be decomposed into a summation of sine waves of appropriate amplitude.

1D *k*-space



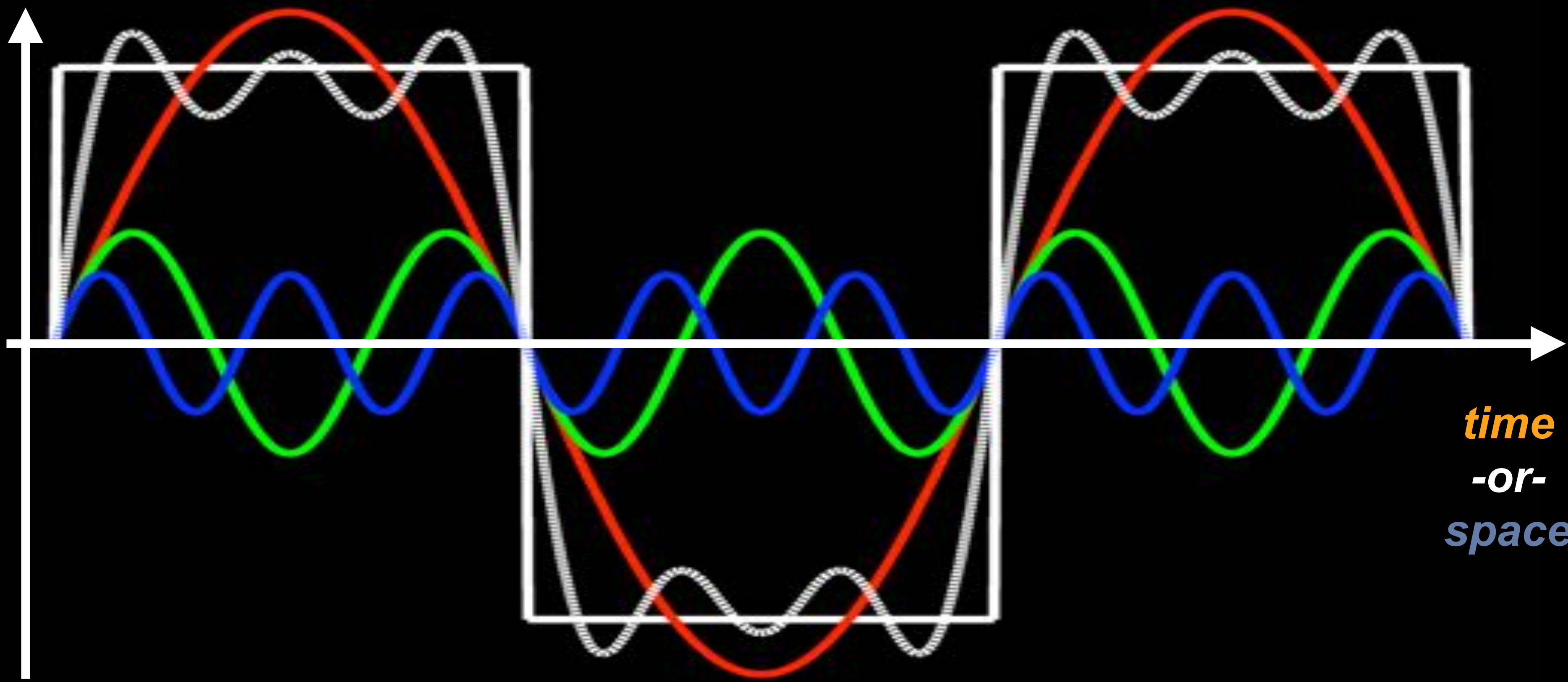
Any signal/image can be decomposed into a summation of sine waves of appropriate amplitude.

1D *k*-space



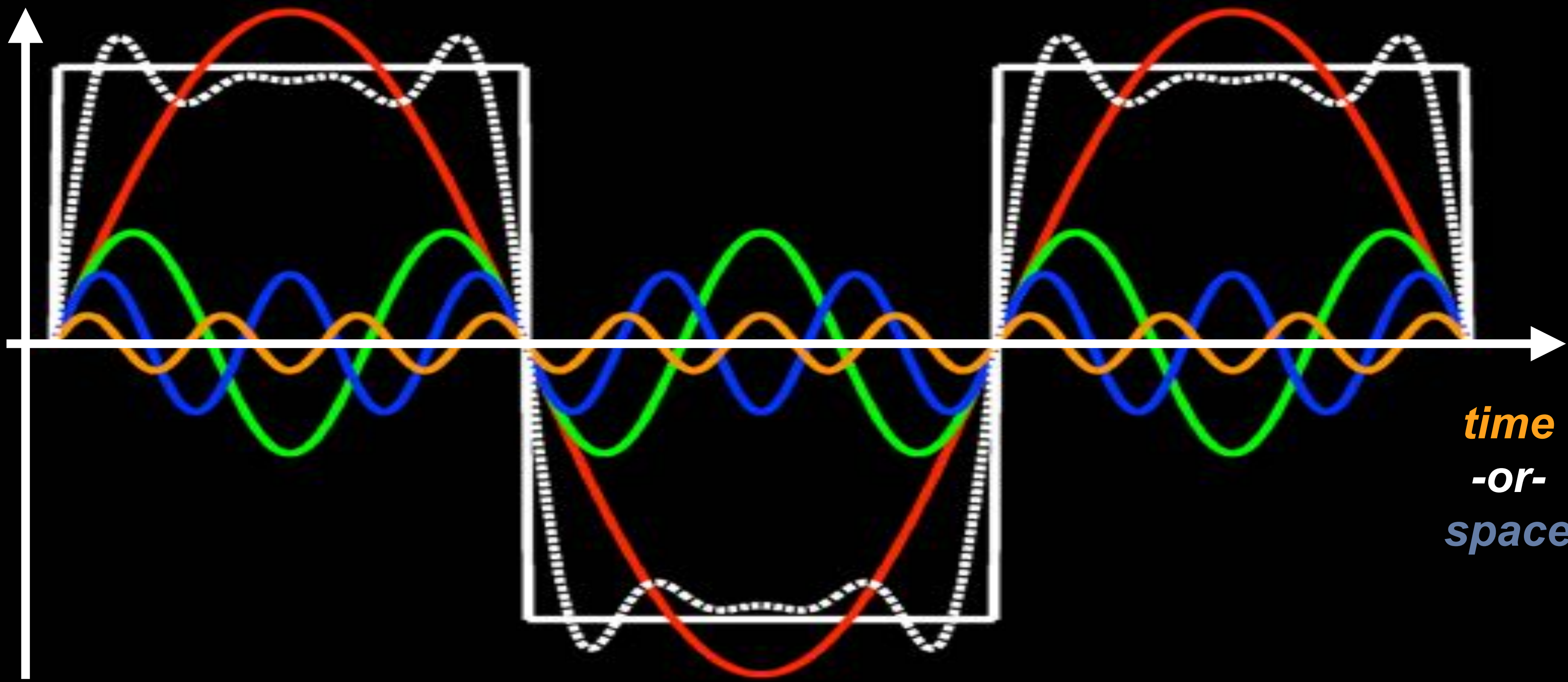
Any signal/image can be decomposed into a summation of sine waves of appropriate amplitude.

1D *k*-space



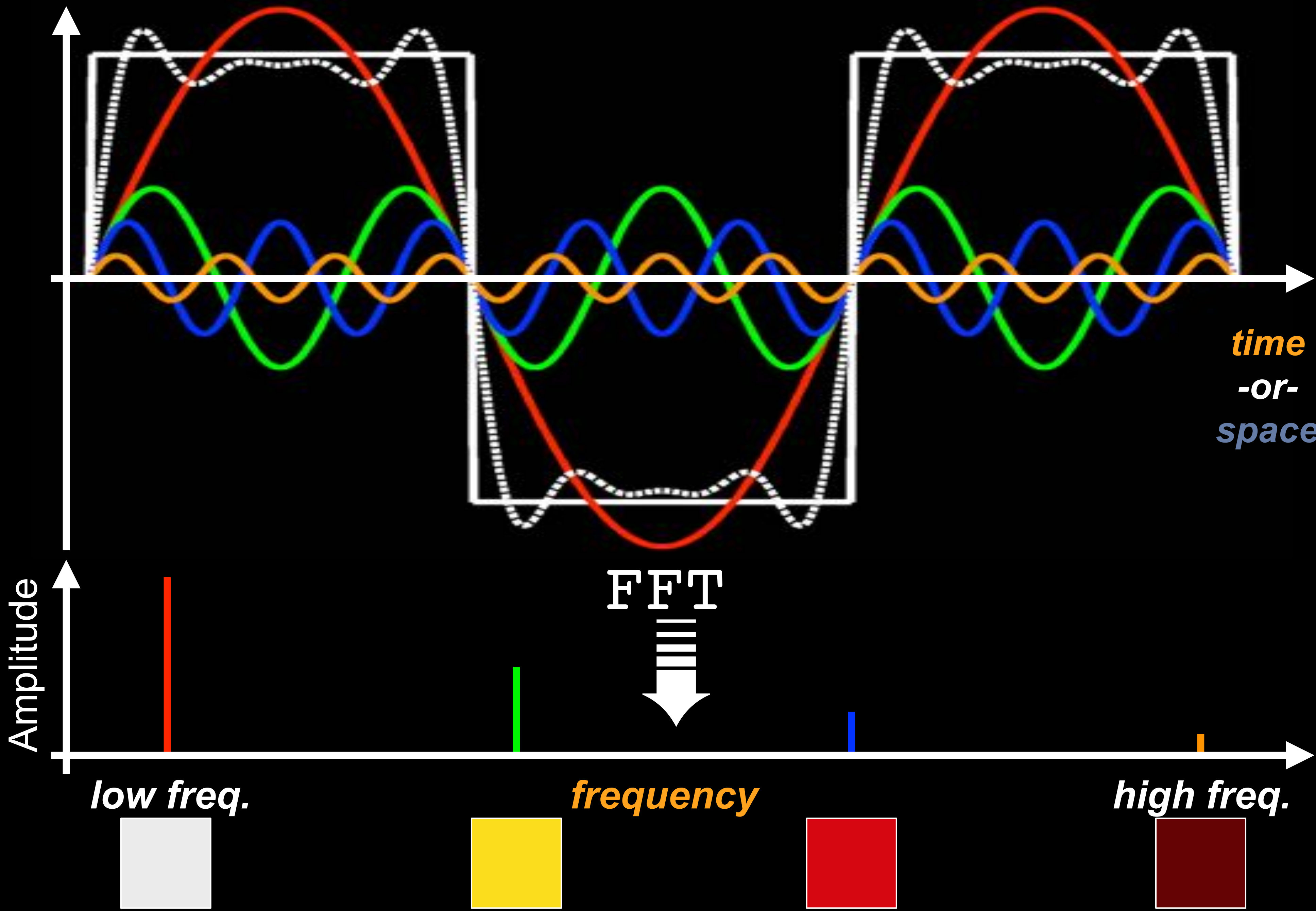
Any signal/image can be decomposed into a summation of sine waves of appropriate amplitude.

1D *k*-space



Any signal/image can be decomposed into a summation of sine waves of appropriate amplitude.

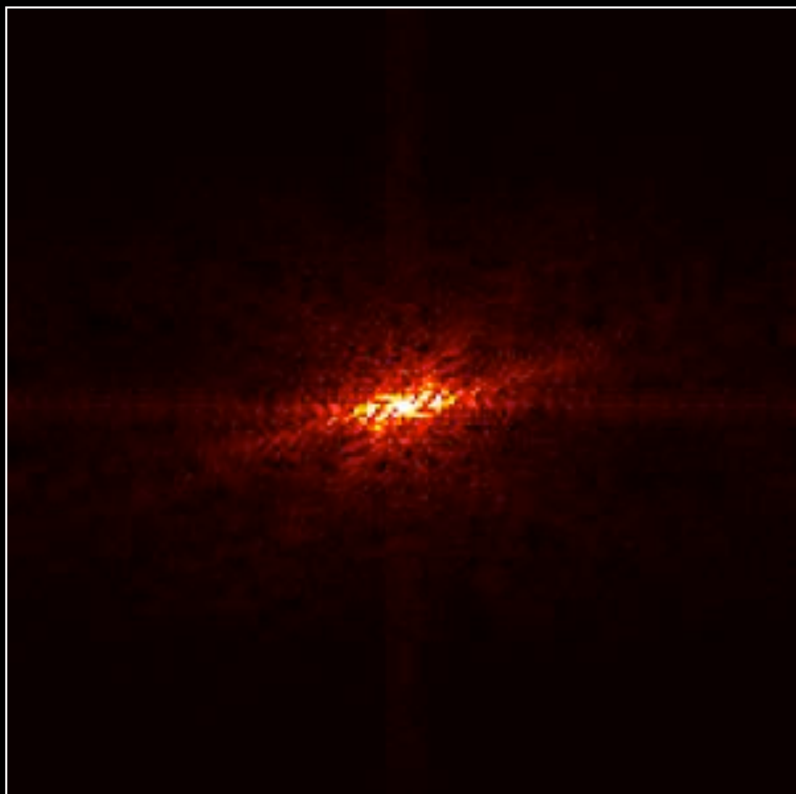
Fourier Representation



k-space spikes

k-space

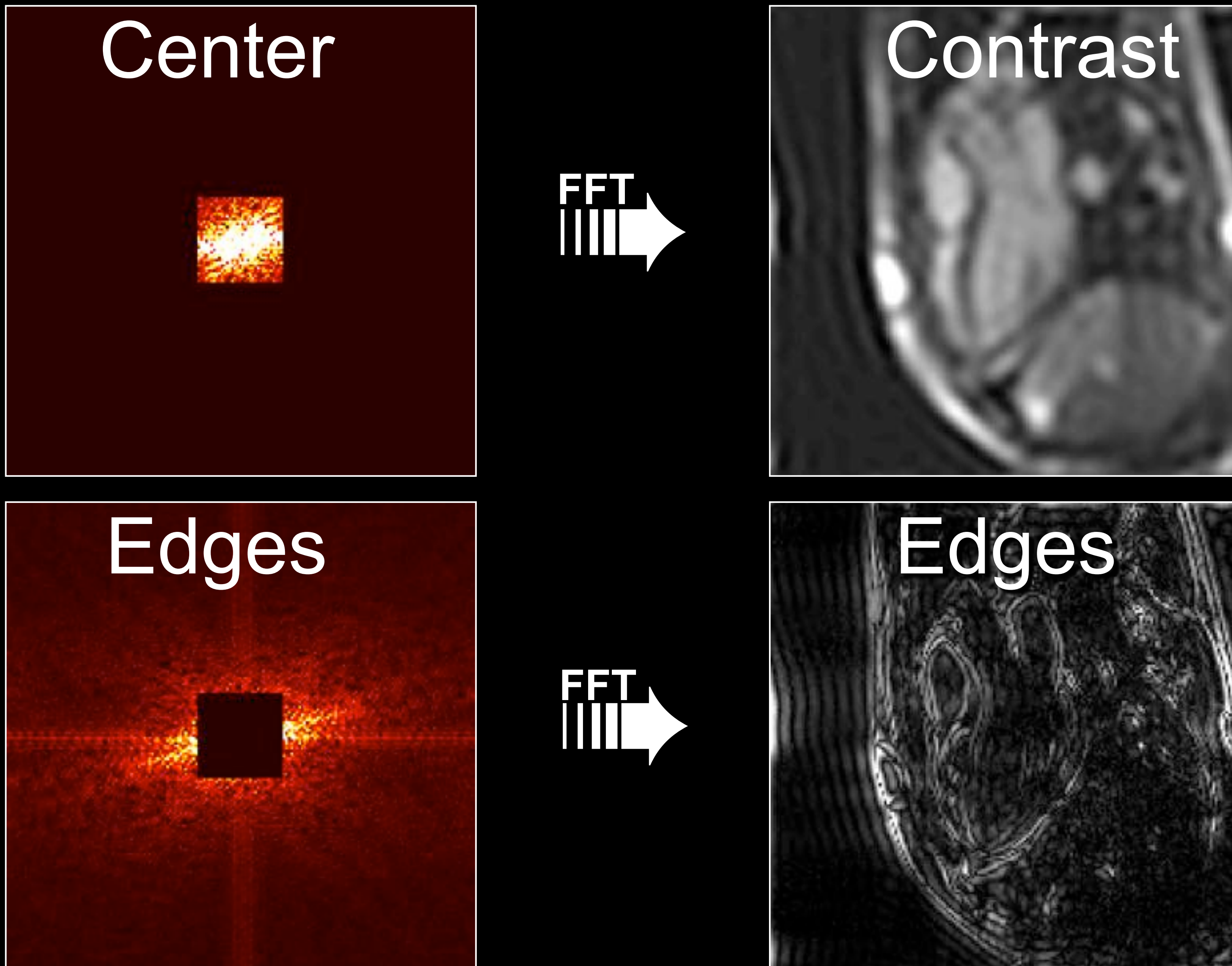
image space



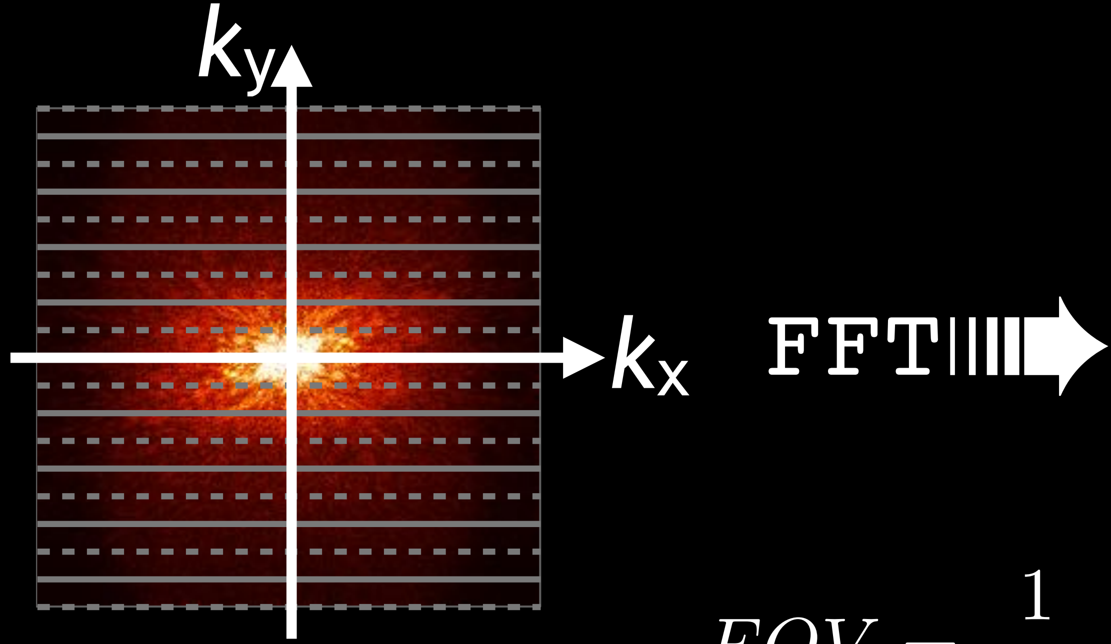
FFT

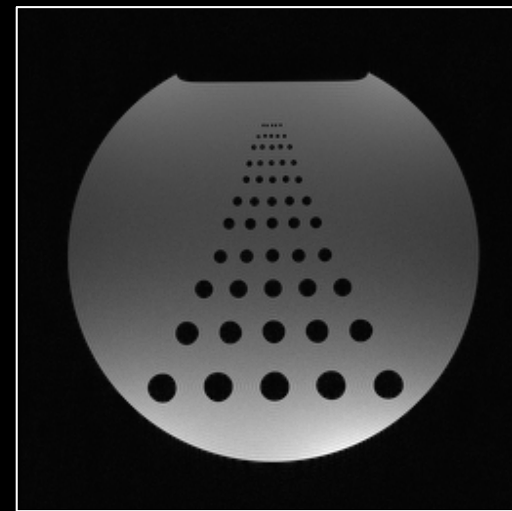
A *k*-space spike creates a banding artifact.

What is *k*-space?

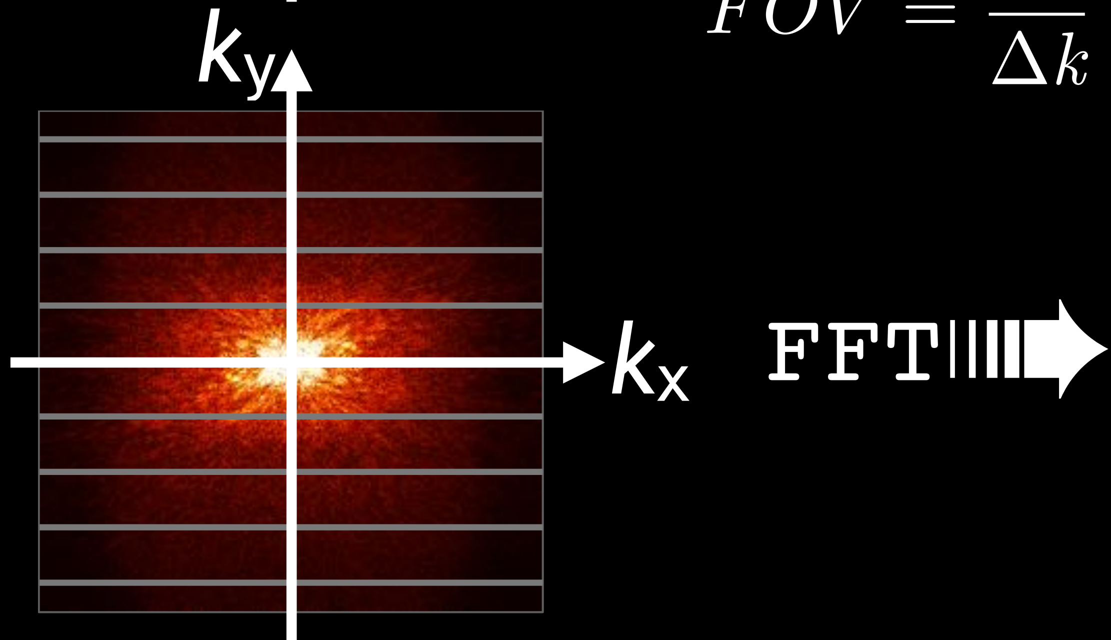


k-space and Field of View



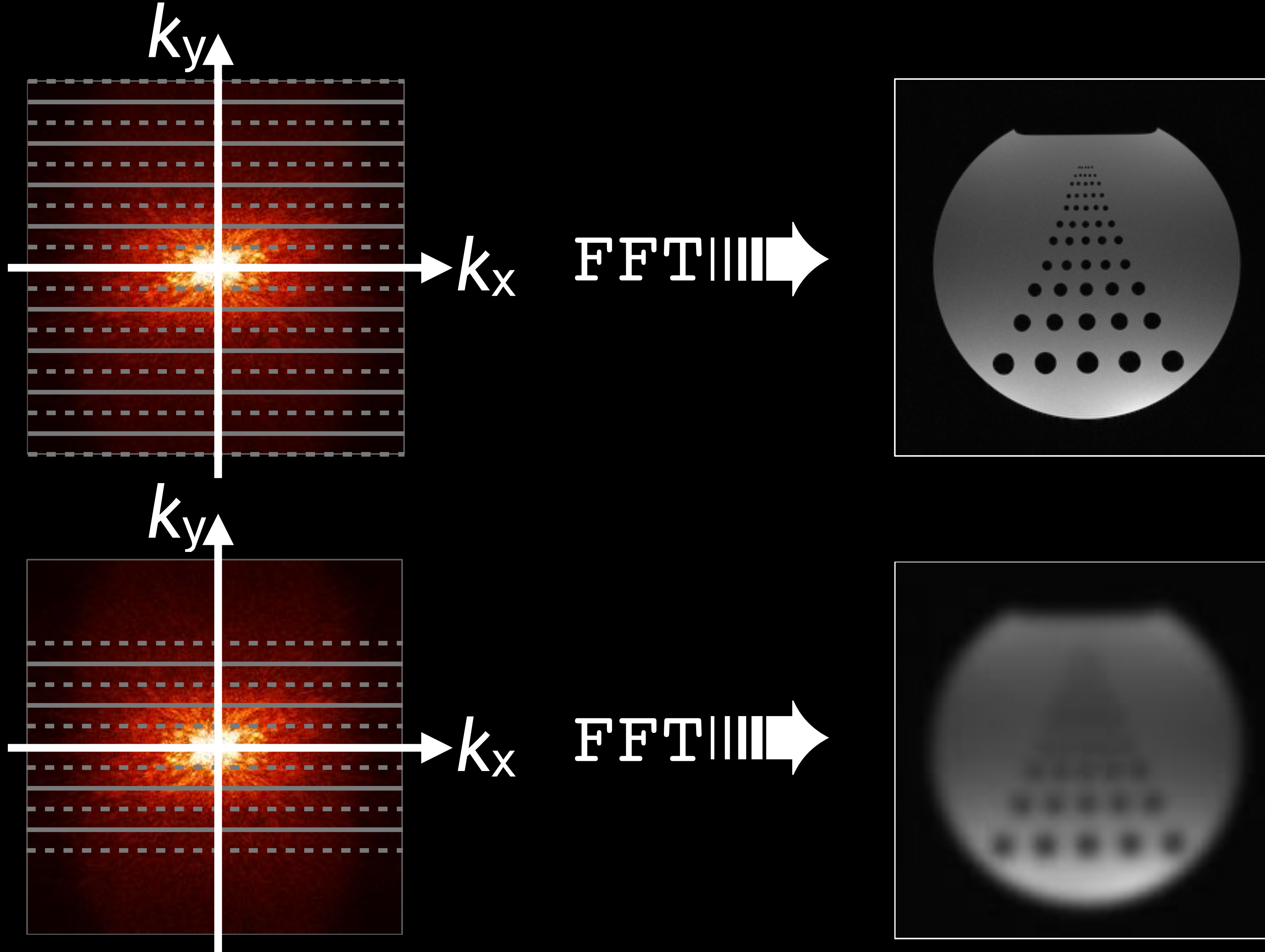


$$FOV = \frac{1}{\Delta k}$$



Uniformly skipping lines in *k*-space causes ***aliasing***.

k-space and Resolution



Acquiring fewer high phase encodes decreases resolution.

Quiz: *k*-space - True or False?

1. *k*-space is the raw data collected by the scanner.
2. A point in *k*-space represents the pixel intensity in the image.
3. An echo corresponds to a single point in *k*-space.
4. The edges of *k*-space relate to image contrast.
5. A single echo fills all of *k*-space.
6. High resolution imaging takes longer because we need to acquire more of *k*-space.

Thanks!

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