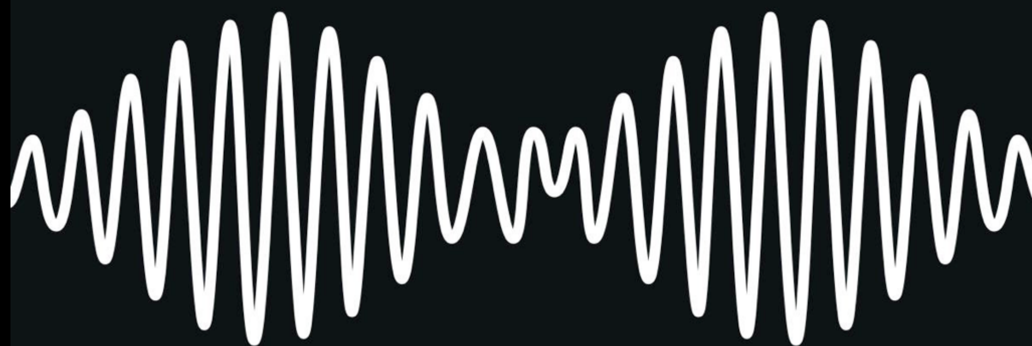
Basic Pulse Sequences III
Gradient Echoes



Daniel B. Ennis, Ph.D.

Magnetic Resonance Research Labs

David Geffen School of Medicine

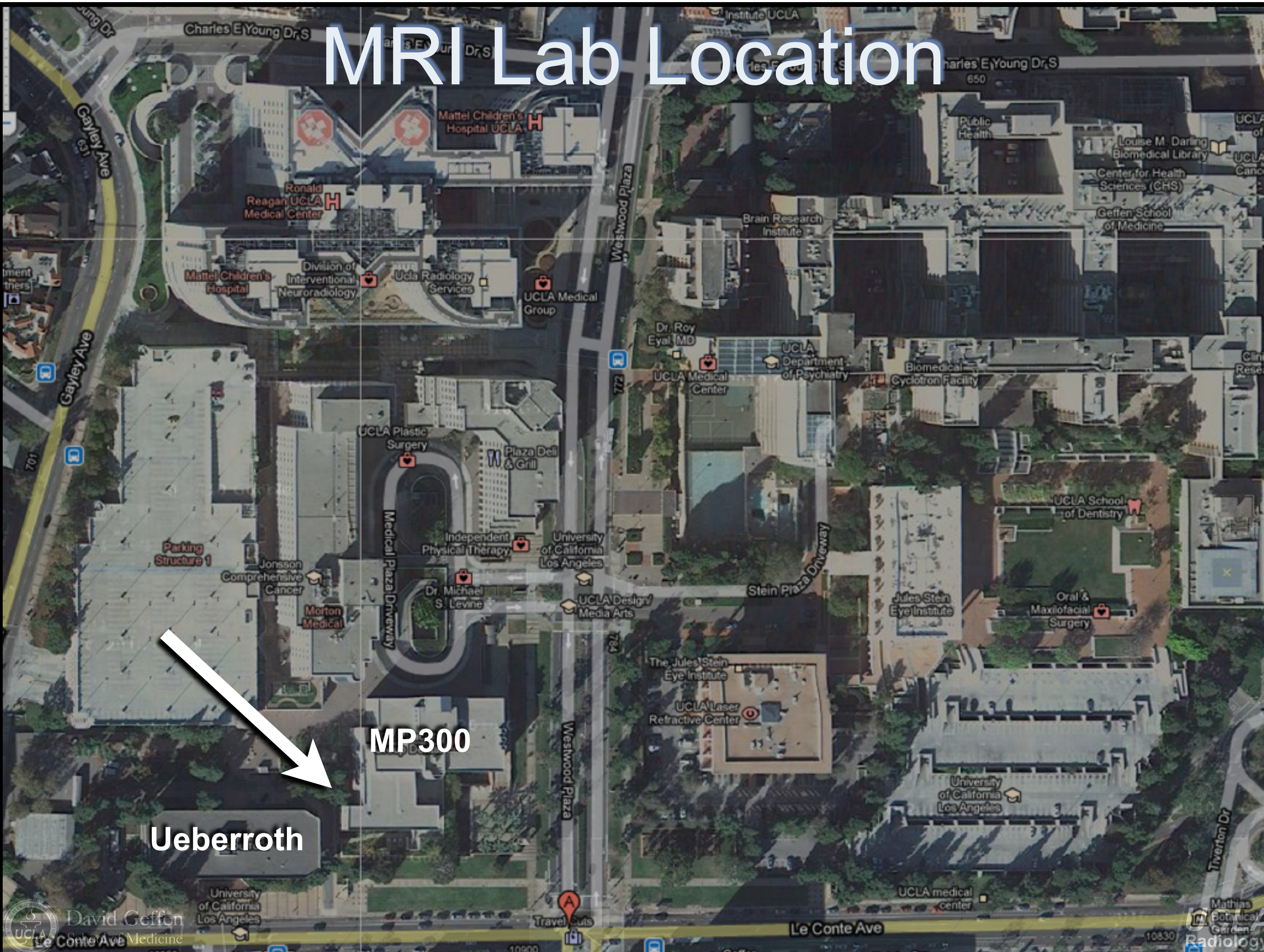
UCLA Radiology

Class Business

Class Business

- **TONIGHT from 6-9pm**
  - **6:00-7:30pm Groups**
    - **Avanto**
      - John Ginn, Geraldine Chee, Ryan Neph, Wenbo Gu
    - **Skyra**
      - Nan Wang, Yiwen Meng, Sagari Grandhi
    - **Prisma**
      - Sen Ma, Ning Wang, Avinash Chinchali, Eric Johnson
  - **7:30-9:00pm Groups**
    - **Avanto**
      - Alborz Feizi, Paranaz Abiri, Nastaran Emaminejad, Kamal Singhrao
    - **Skyra**
      - Zinzhou Li, Jiahao Lin, Jessica Martinez, Kanav Sarnaf
    - **Prisma**
      - ???
  - **MRI Screening Form & Lab in DropBox**
- **BRING THE COMPLETED SCREENING FORM**

MRI Lab Location



Assignments

- **Homework #1**
  - Graded nearly done. Returned by Wednesday.
- **Lab #1**
  - Lab is tonight
  - Write-up due on Friday 2/5 (2 weeks)
- **Homework #2**
  - Available today
  - Due on Wednesday 2/3 (10 days)

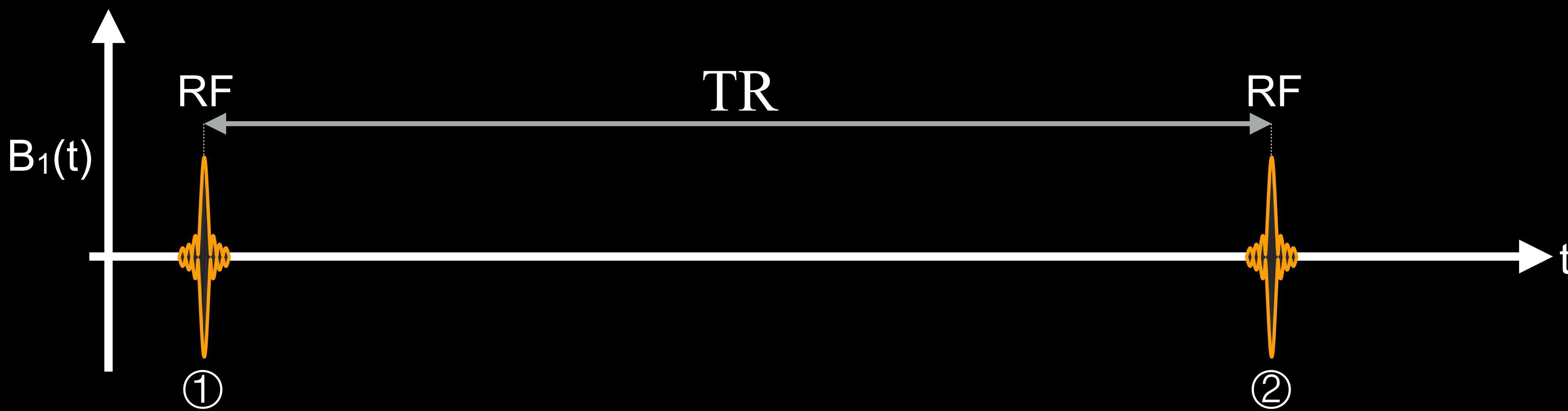
Upcoming Lectures

- **Mathematical Fundamentals**
  - **Dr. Holden Wu**
  - **Wednesday (1/27)**
- **Signal Localization I & II**
  - **Dr. Kyung Sung**
  - **Monday (2/1) and Wednesday (2/3)**

Holden Wu, Ph.D.

Kyung Sung, Ph.D.

Lecture #7 Summary



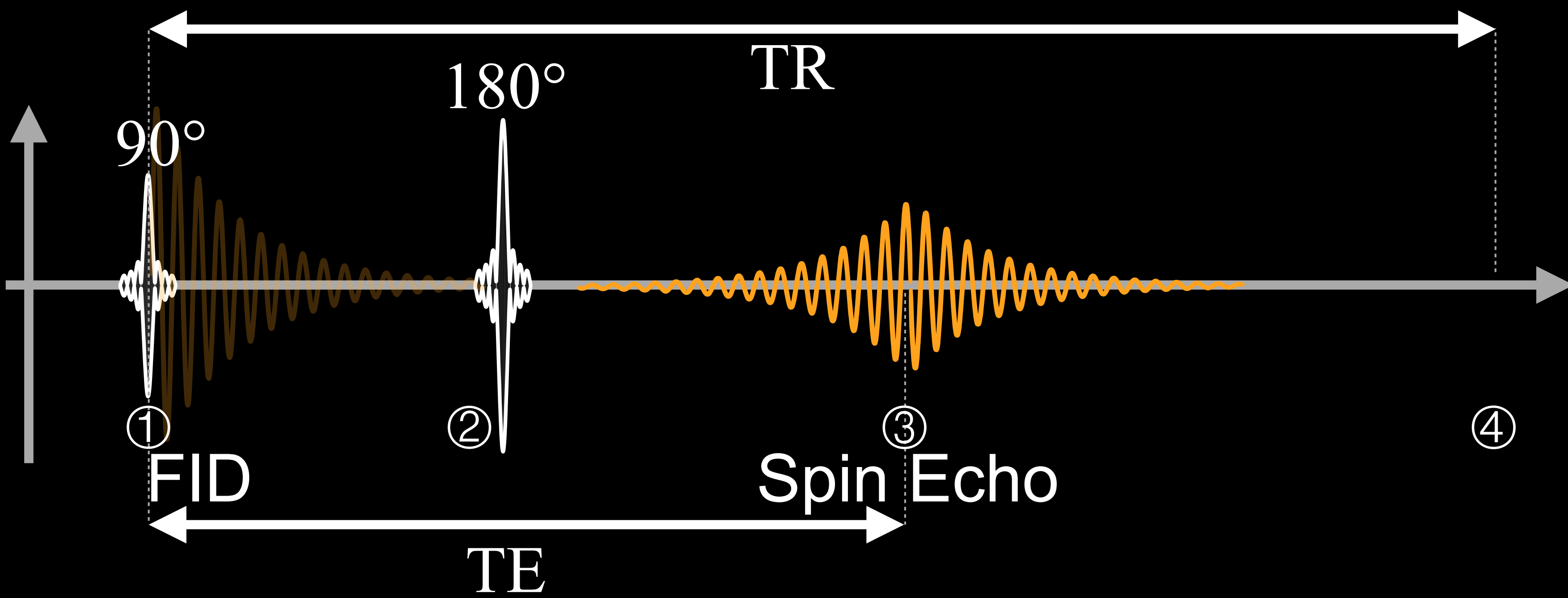
$$\vec{M}^{(1)}(0_-) = \vec{M}_0 = \begin{bmatrix} 0 \\ 0 \\ M_0 \end{bmatrix}$$ Initial Condition

$$\vec{M}^{(1)}(0_+) = RF_\theta^\alpha \vec{M}^{(1)}(0_-)$$ Forced Precession

$$\vec{M}^{(2)}(0_-) = \mathrm{E}(T_1, T_2, TR)\vec{M}^{(1)}(0_+)$$ Free Precession

$$\vec{M}^{(2)}(0_+) = RF_\theta^\alpha \vec{M}^{(2)}(0_-)$$

Spin Echo



$$M_{z'}^{(4)}(0_-) = M_z^0 \left(1 - 2e^{-(TR-TE/2)/T_1} + e^{-TR/T_1}\right)$$

The I.C. for the subsequent TR.

$$A_{Echo} \propto \rho \left(1 - 2e^{-(TR-TE/2)/T_1} + e^{-TR/T_1}\right) e^{-TE/T_2}$$

Signal @ ③ for the second TR.

$$A_{Echo} \propto \rho \left(1 - e^{-TR/T_1}\right) e^{-TE/T_2}$$

Signal at "③" for the second TR when TE<<TR.

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Spin Echo Contrast

$$\mathrm{M}_{z'}^{(4)}\left(0_-\right) = \mathrm{M}_z^0\left(1 - 2e^{-(TR-TE/2)/T_1} + e^{-TR/T_1}\right)$$

This becomes the initial condition for the subsequent TR.

$$A_{Echo} \propto \rho\left(1 - 2e^{-(TR-TE/2)/T_1} + e^{-TR/T_1}\right)e^{-TE/T_2}$$

This the signal at time-point “#3” for the second TR.

$$\text{If } TE \ll TR, \text{ then}$$

$$A_{Echo} \propto \rho\left(1 - e^{-TR/T_1}\right)e^{-TE/T_2}$$

This the signal at time-point “#3” for the second TR when TE<<TR.

Basic Principles of Gradient Echoes

Principal GRE Advantages

- **Fast Imaging Applications**
  - **Why?** *Can use a shorter TE/TR than spin echo.*
  - **When?** Breath-held, realtime, & 3D volume imaging
- **Bright blood signal**
  - **Why?** Inflowing spins haven't "seen" numerous RF pulses.
  - **When?** Cardiovascular & angiographic applications.
- **Low SAR**
  - **Why?** Imaging flip angles are small.
  - **When?** When heating risks are a concern (devices, high field)

Principal GRE Advantages

- **Quantitative**
  - **Why?** Multi-echo acquisition are practical.
  - **When?** Flow quantification & Fat/Water mapping
- **Susceptibility Weighted Imaging**
  - **Why?** No refocusing pulse.
  - **When?** T_2^*-weighted & imaging hemorrhage
- **Reduced Cross-talk**
  - **Why?** SE hard to match slice profile of 90° & 180°
  - **When?** Little or no slice gap for 2D multi-slice

Principal GRE Disadvantages

- **Off-resonance sensitivity**
  - **Why?** Field inhomogeneity, Susceptibility, & Chemical shift
- **T_2^*-weighted rather than T_2-weighted**
  - **Why?** No re-focusing pulse
- **Larger metal artifacts than SE**
  - **Why?** No refocusing pulse.

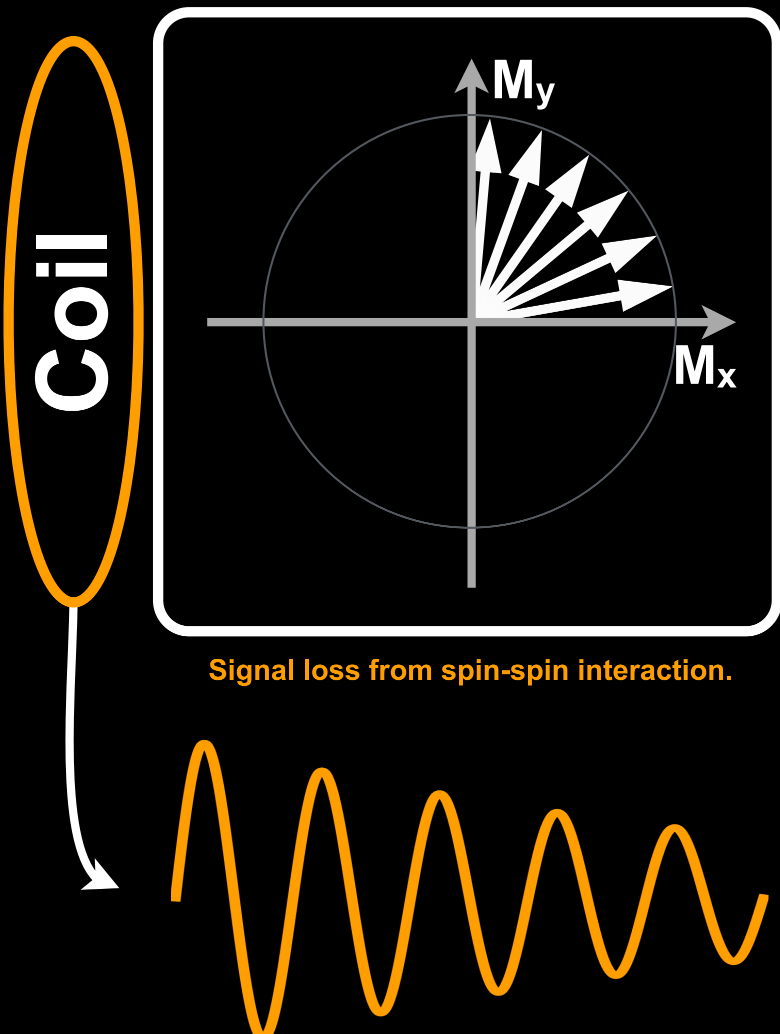
GRE Applications

- **Primarily used for fast scanning**
  - **Flip angle typically <90°**
    - **Only short time needed for T_1 recovery**
    - **Short TRs (2-50ms)**
    - **Short TEs (2-10ms)**
      - **Therefore, weights T1 differences**
- **Varying TE can provide T2* contrast**
  - **Combines field heterogeneity and susceptibility weighting**
- **3D volume imaging**
- **Cardiac/Cardiovascular imaging**
- **Time-of-flight and phase contrast MRA**
- **Sequence names**
  - **FLASH, FISP/true-FISP, GRASS**

T_2 versus T_2^*

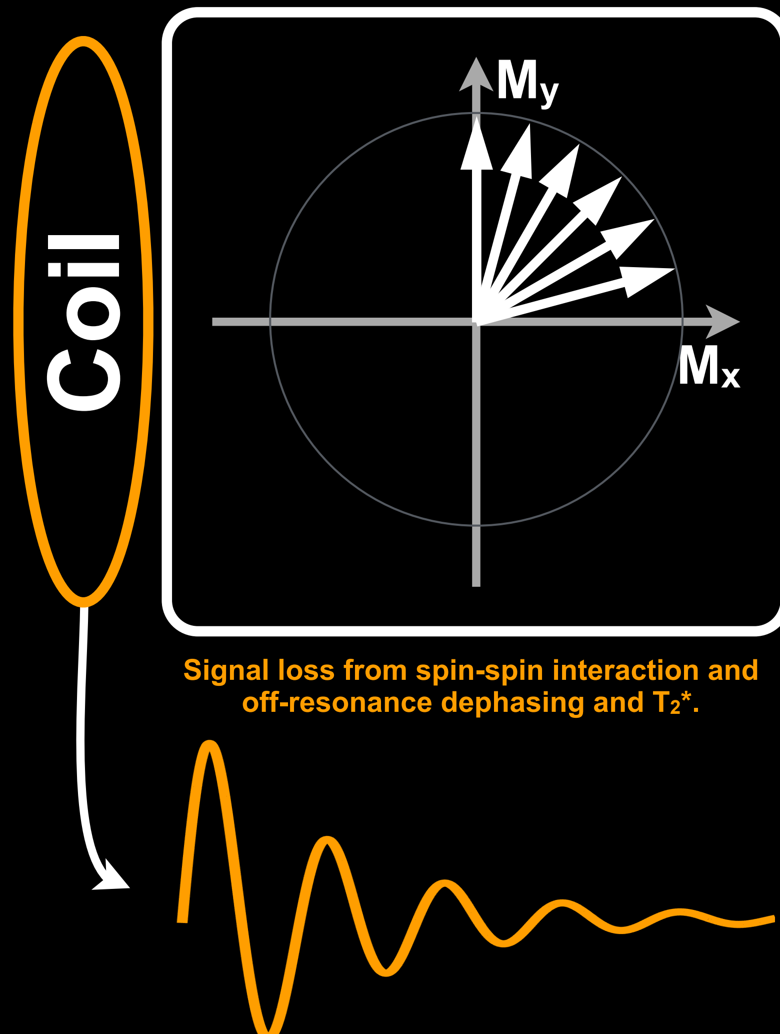
I want to update this slide to include T2 decay of Mxy and show the difference between the two. Need to update the signals too.

T_2 Decay



Signal loss from spin-spin interaction.

T_2^* Decay

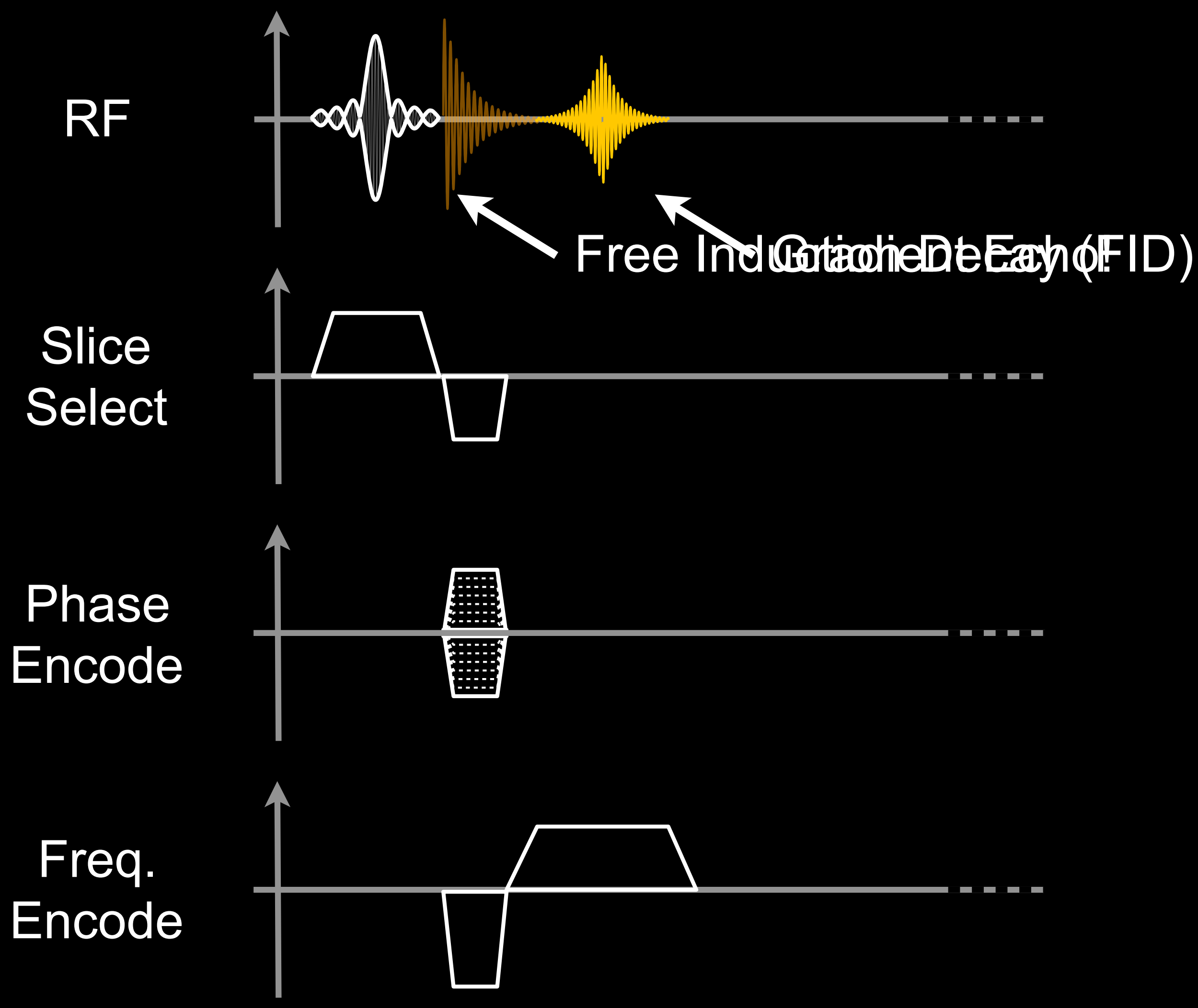


Signal loss from spin-spin interaction and off-resonance dephasing and T_2^*.

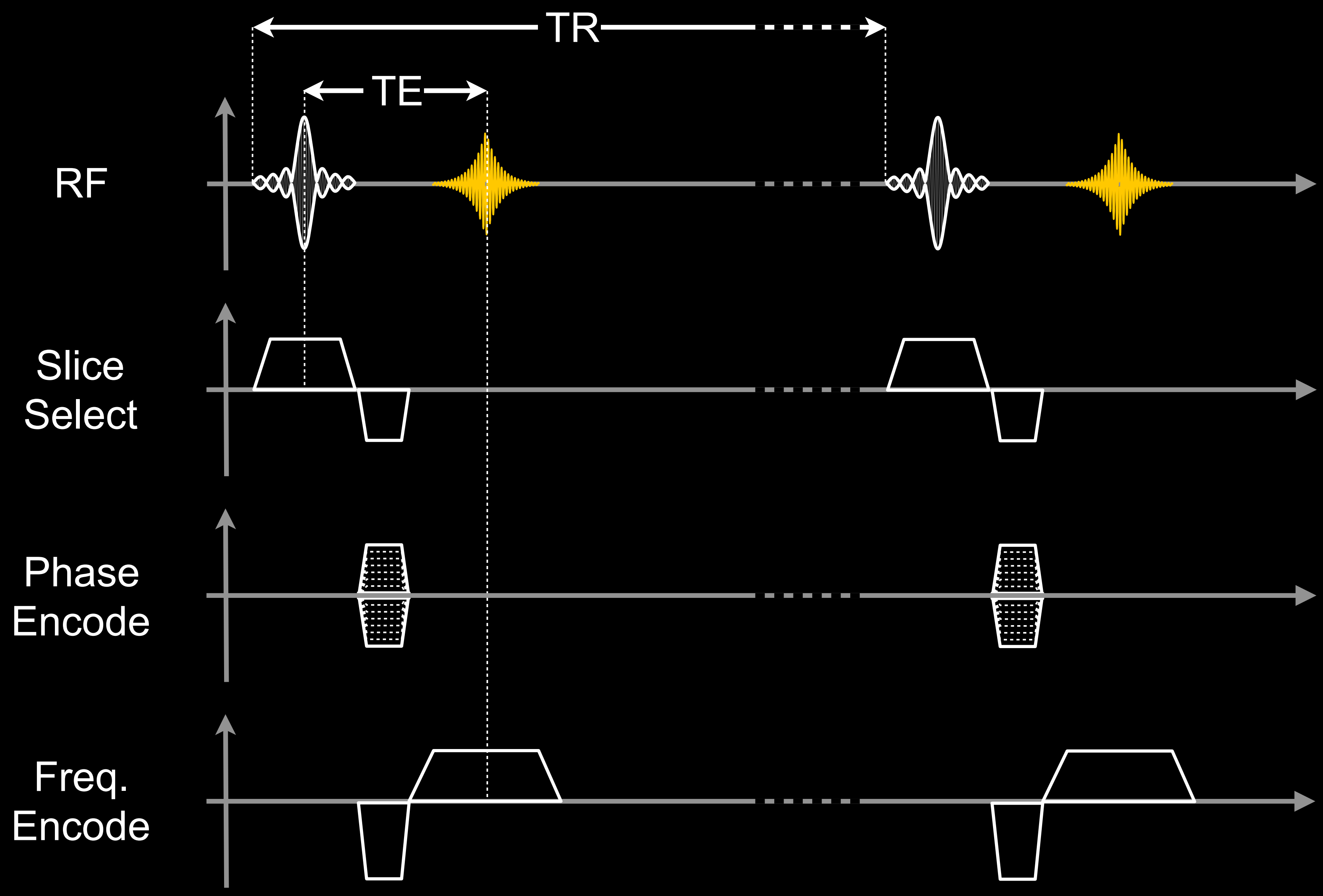
Signal loss from spin dephasing and T_2^*.

Basic Gradient Echo Sequence

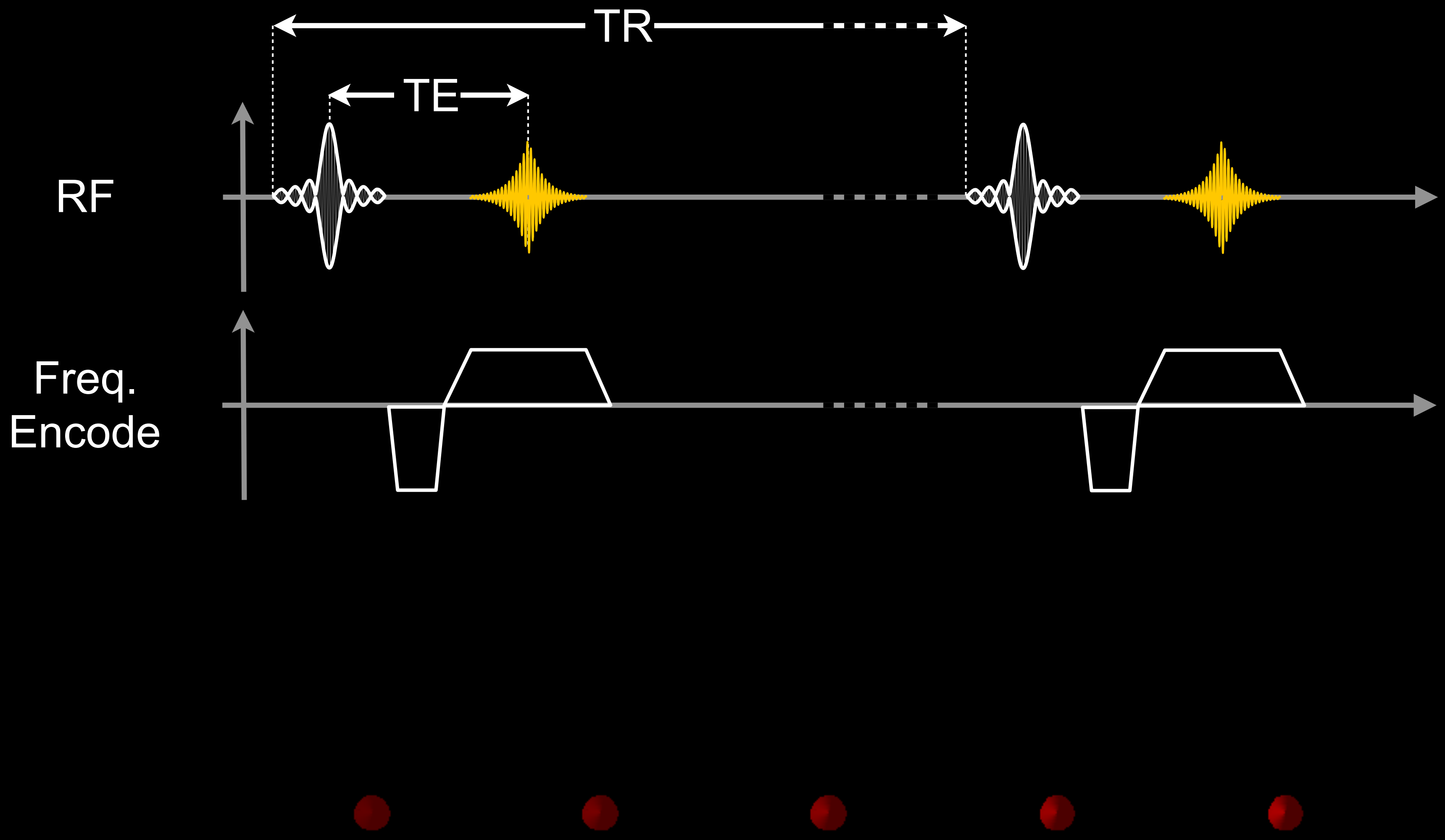
Basic Gradient Echo Sequence



Basic Gradient Echo Sequence



Gradient Echo



To The Board...

Gradient Echoes & Contrast

Spoiled Gradient Echo Contrast

$$M_z^{ss} = \frac{M_0\left(1 - e^{-TR/T_1}\right)}{1 - \cos\alpha e^{-TR/T_1}}$$

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

Contrast adjusted by changing flip angle, TE and TR.

Gradient Echo Contrast

Gradient Echo Parameters

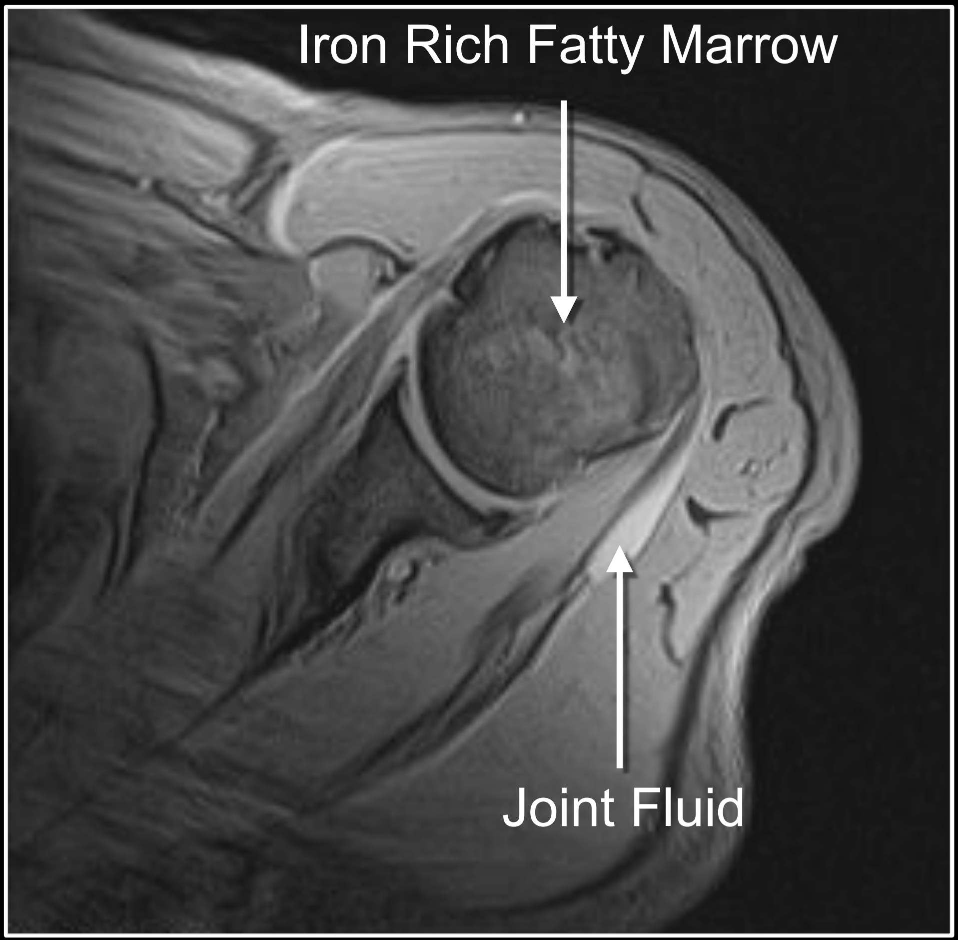
Type of Contrast	TE	TR	Flip Angle
Spin Density	Short	Long	Small
T_1-Weighted	Short	Intermediate	Large
T_2^*-Weighted	Intermediate	Long	Small

Gradient Echo Contrast

Gradient Echo Parameters

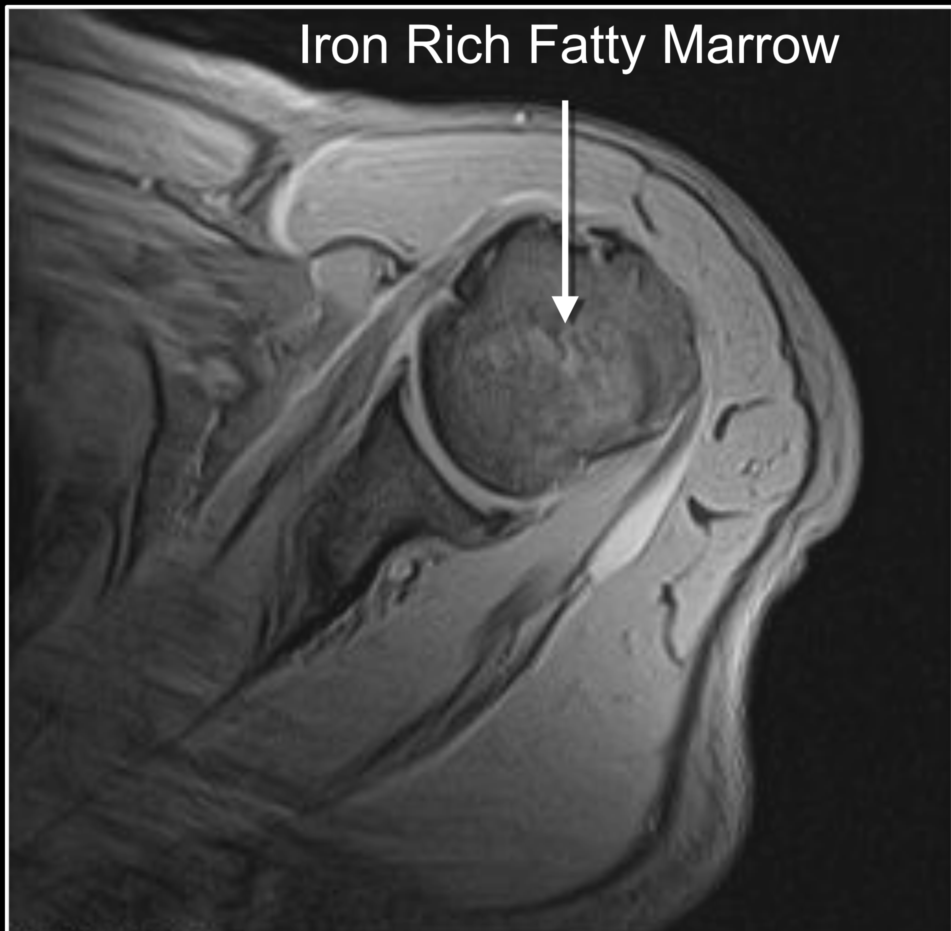
Type of Contrast	TE	TR	Flip Angle
Spin Density	<5ms	>100ms	<10°
T_1-Weighted	<5ms	<50ms	>30°
T_2^*-Weighted	>20ms	>100ms	<10°

T_2*-weighted Gradient Echo Imaging

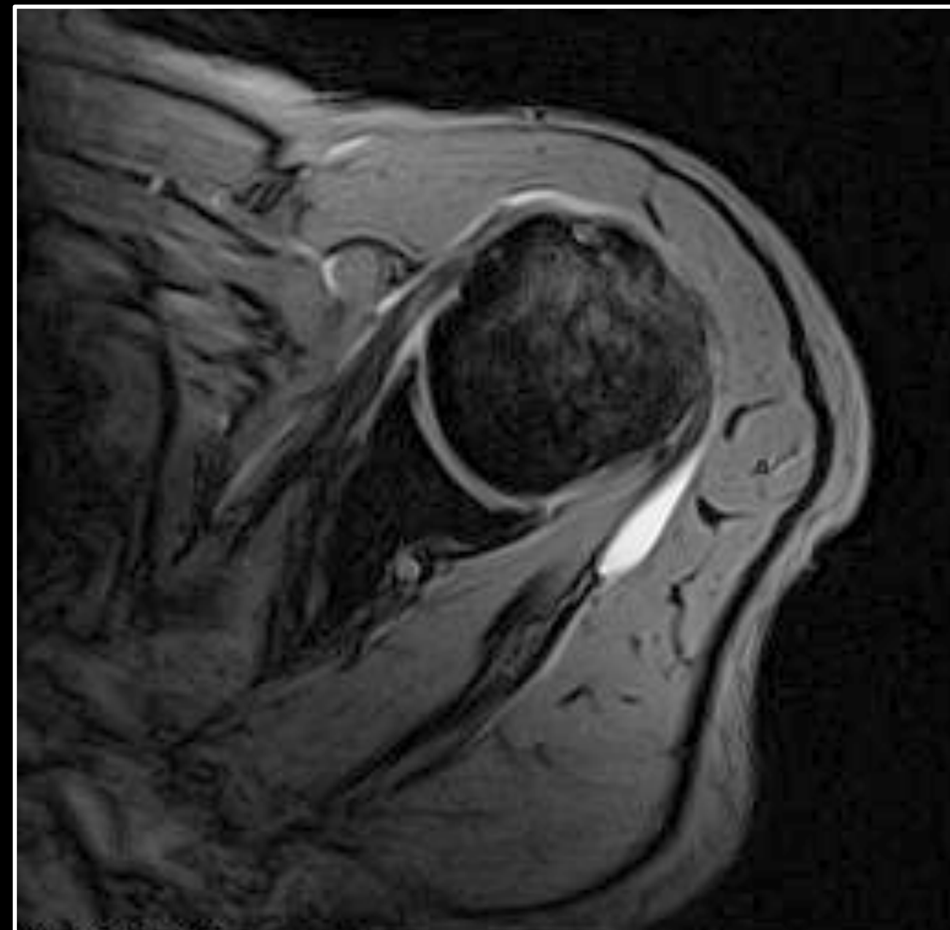


TE=9ms

T_2*-weighted Gradient Echo Imaging

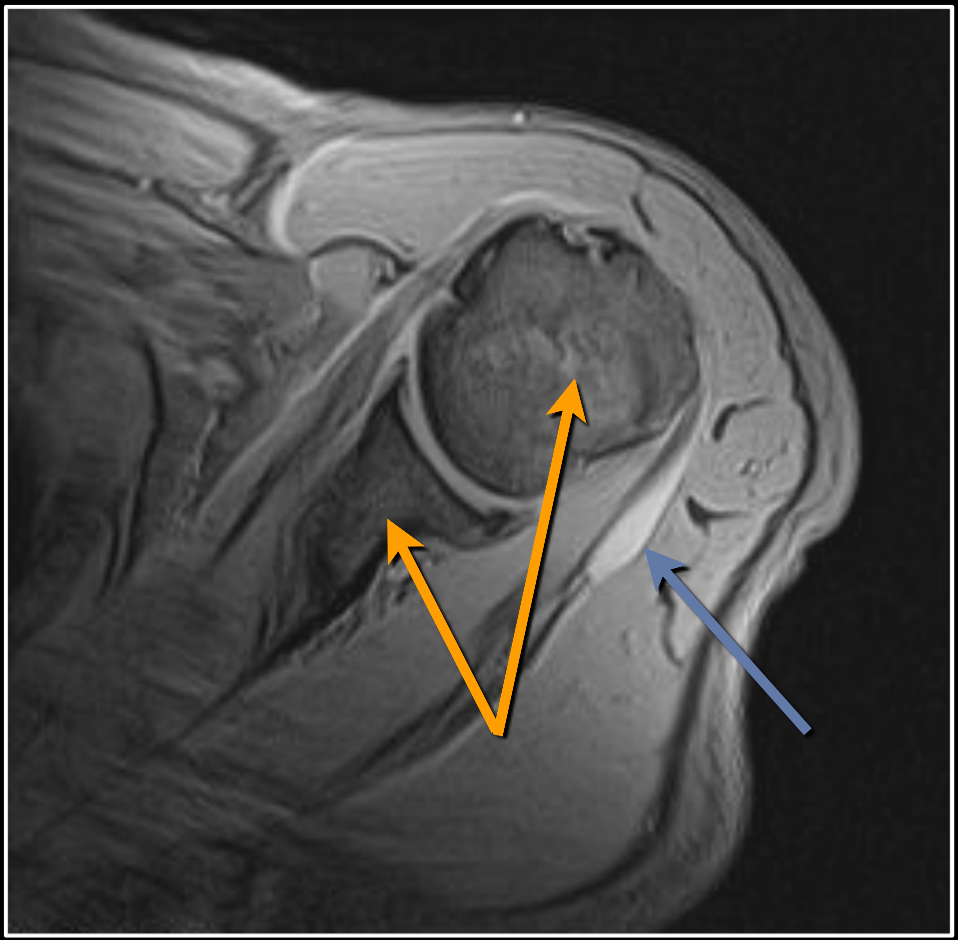


TE=9ms

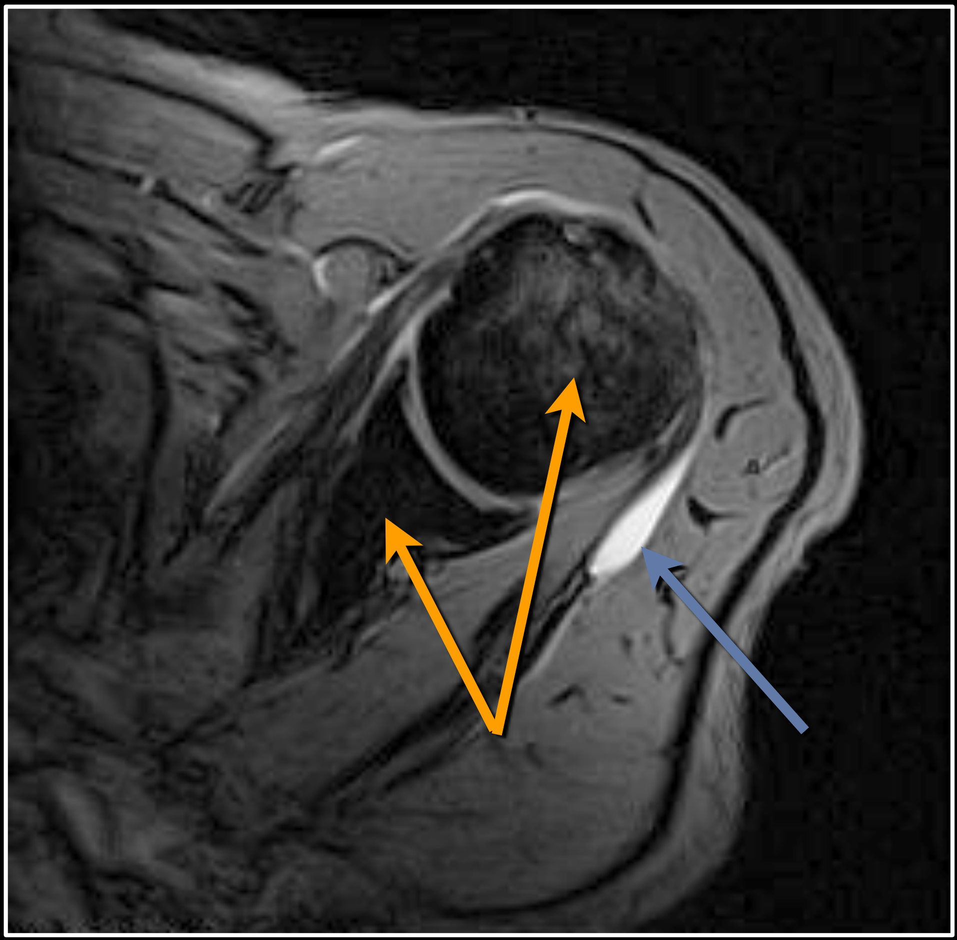


TE=30ms

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 Echoes & Flip Angle

Spoiled GRE & Ernst Angle

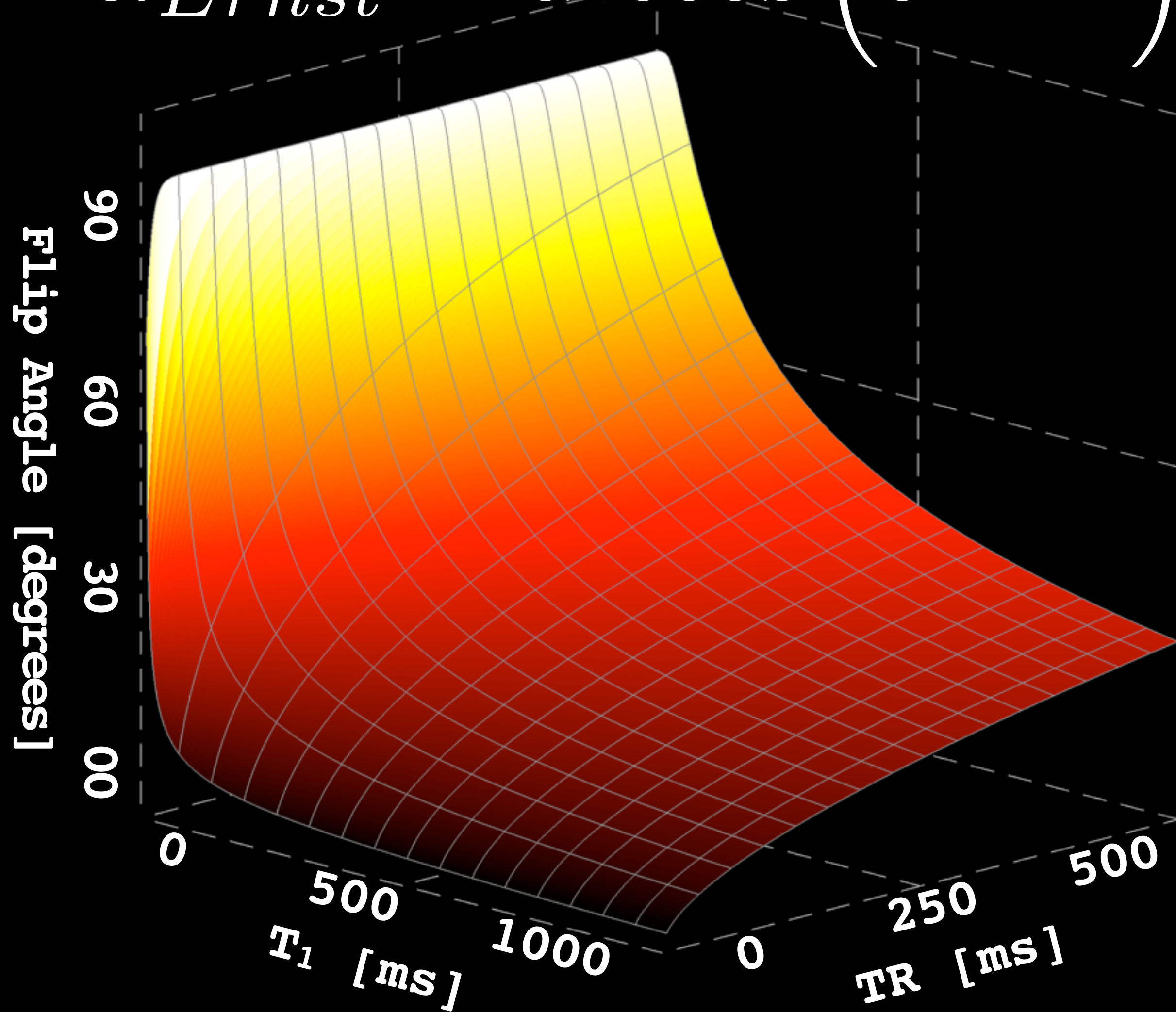
$$\alpha_{Ernst} = \arccos\left(e^{-\frac{TR}{T_1}}\right)$$

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

Ernst Angle

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



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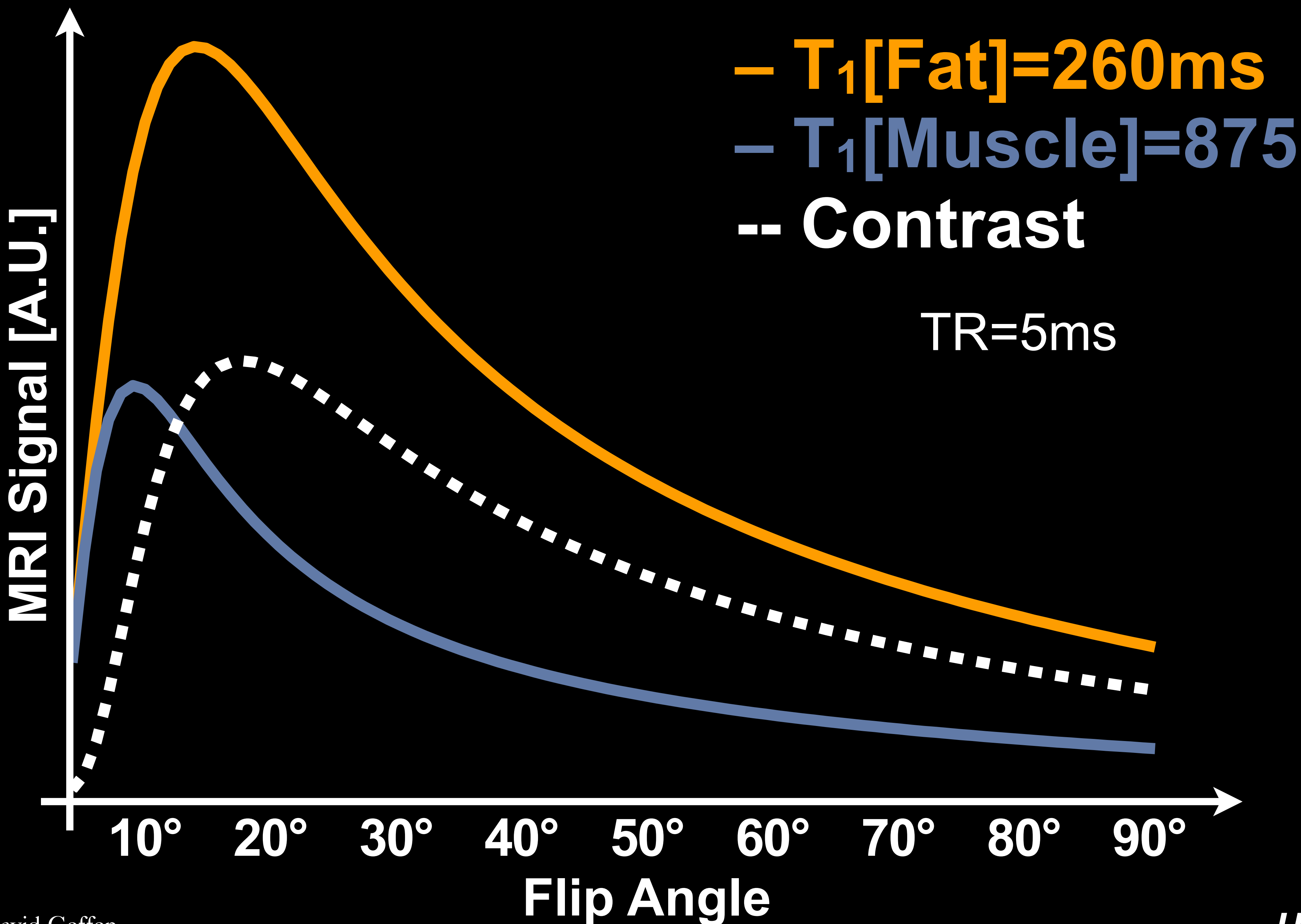
Spoiled GRE & Ernst Angle



Spoiled GRE & Ernst Angle

1°

5°

10°
High Muscle Signal

20°
High Fat Signal

30°
Highest Contrast

45°

60°

90°

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To The Board...

Gradient Echoes & Spoiling

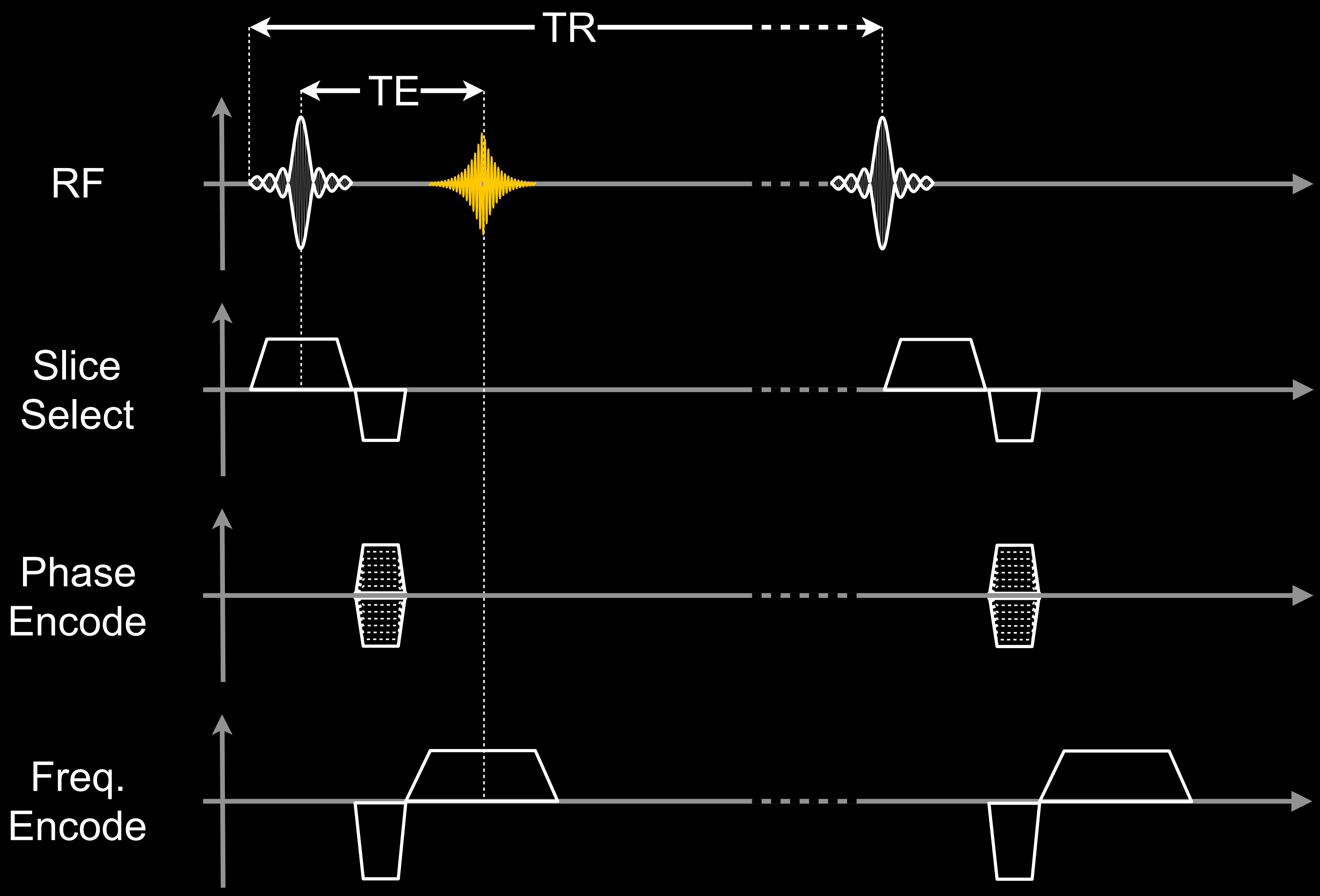
Spoiling - Why?

- **Eliminates M_{xy} at end of each TR**
  - Prevents cumulative errors/artifacts
- **Shortens the TR**
  - Faster imaging
- **Enhances T_1 contrast**
  - T_2-dependent signal (M_{xy}) is eliminated

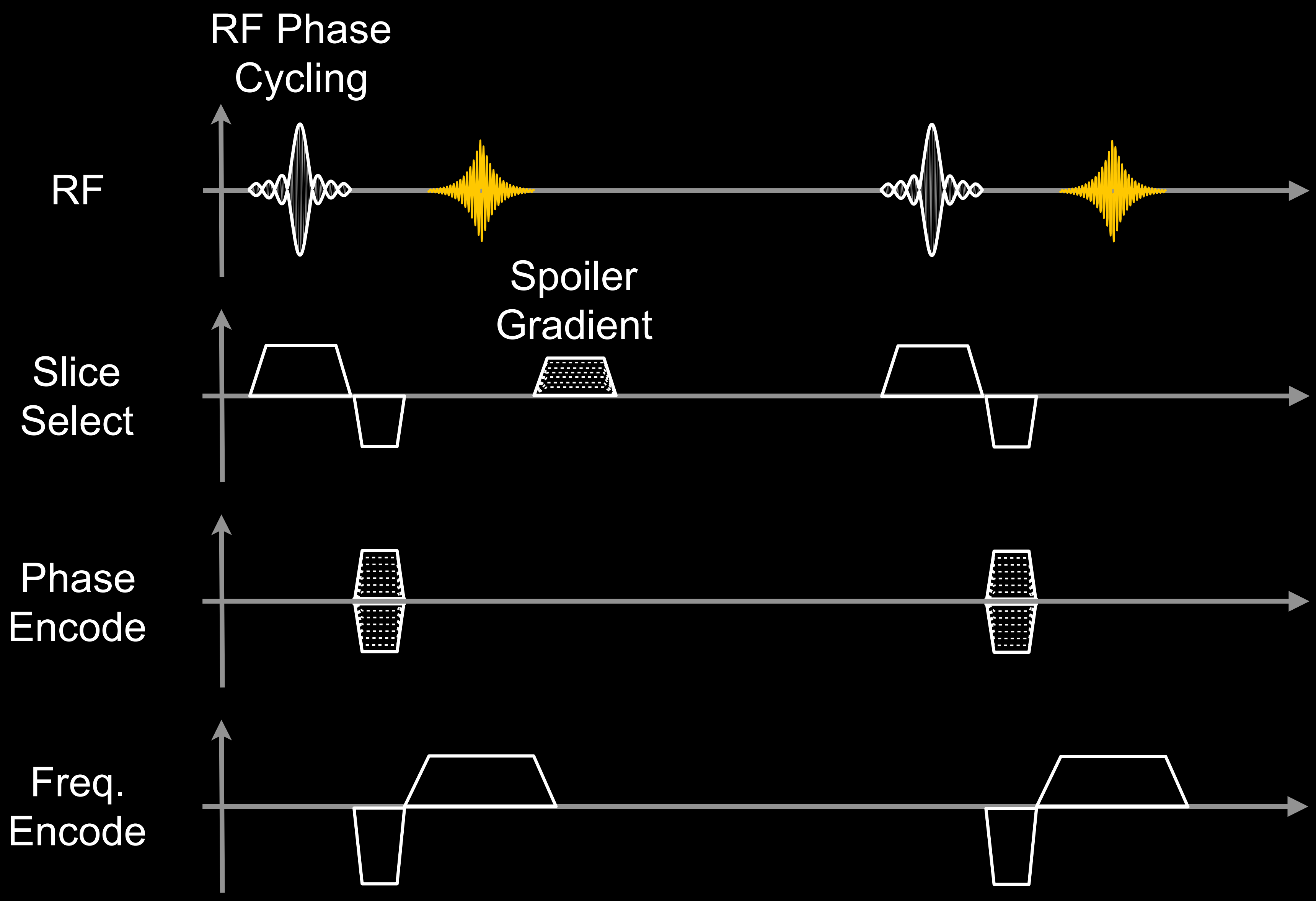
Spoiling - How?

- **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

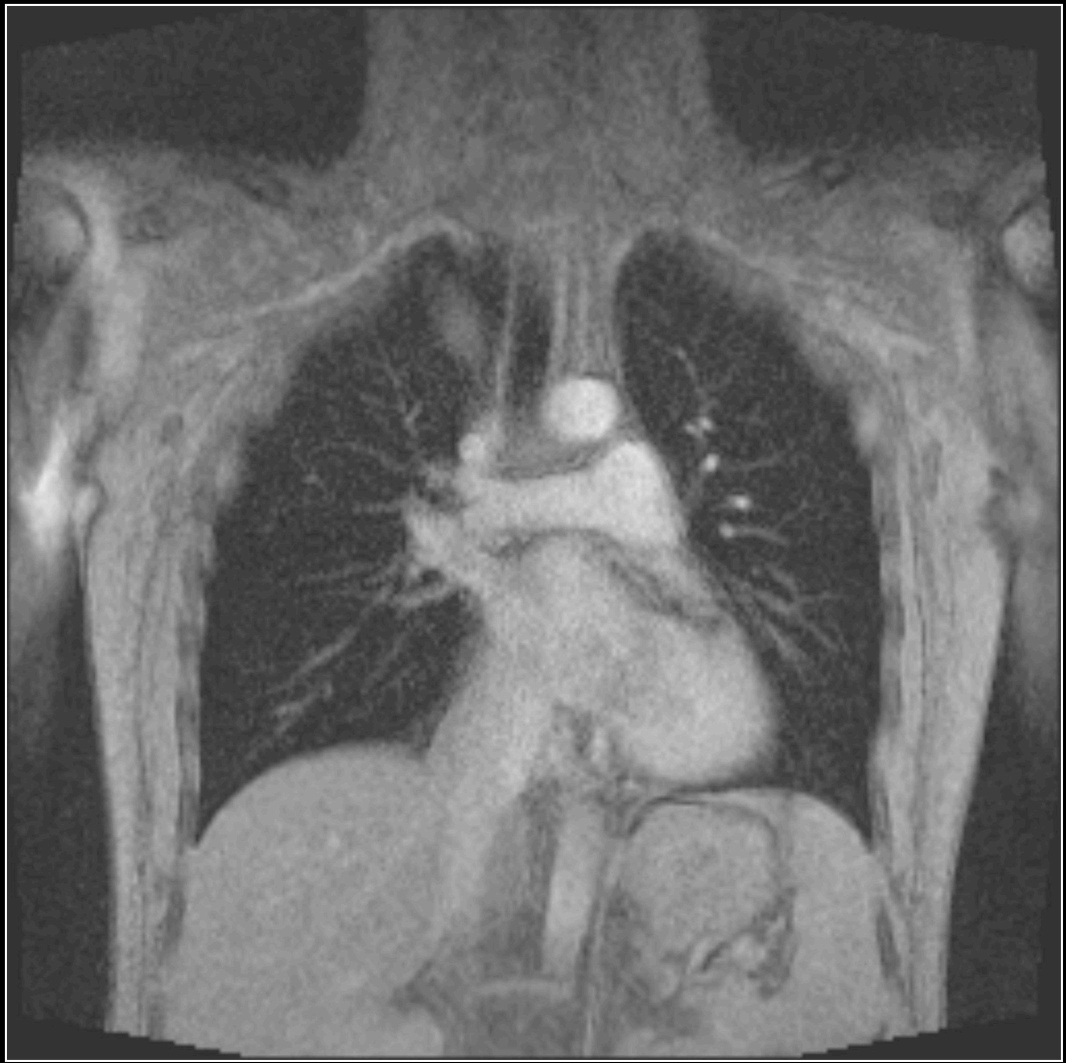
Basic Gradient Echo Sequence



Gradient Echo + Spoiling



Realtime Imaging with Gradient Echoes



Realtime imaging requires very short TE/TRs for rapid image acquisition.

Realtime Imaging with Gradient Echoes

Realtime imaging requires very short TE/TRs for rapid image acquisition.

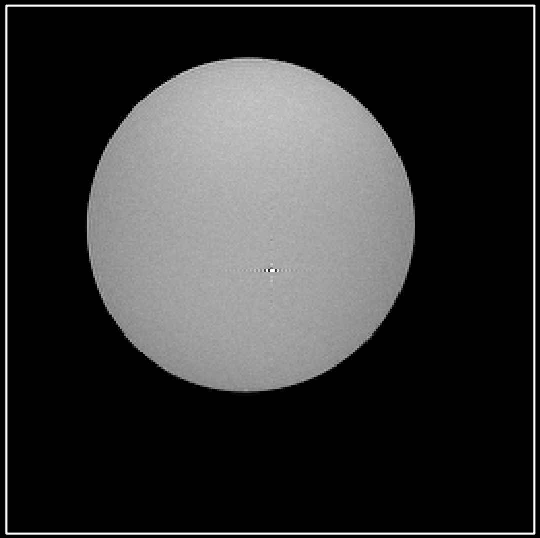
Gradient vs. Spin Echo

Gradient vs. Spin Echo

- **Gradient Echo**
  - Fast Imaging
  - Lower SAR
  - More sensitive to field inhomogeneity
  - Reduced slice cross-talk
    - Little or no slice gap needed
  - Good for 3D volume imaging
- **Spin Echo**
  - Higher intrinsic SNR
  - True T_2 weighted image contrast
  - Long TRs facilitate slice interleaving

B_0 Inhomogeneity

- **Images acquired with a bad shim.**



Spin Echo

Gradient Echo

Images Courtesy of http://chickscope.beckman.uiuc.edu/roosts/carl/artifacts.html

Spin vs. Gradient Echo Contrast

Gradient Echo Parameters

Type of Contrast	TE	TR	Flip Angle
Spin Density	Short	Long	Small
T_1-Weighted	Short	Intermediate	Large
T_2^*-Weighted	Intermediate	Long	Small

Spin Echo Parameters

Spin Density	Short	Long
T_1-Weighted	Short	Intermediate
T_2-Weighted	Intermediate	Long

Spin vs. Gradient Echo Contrast

Gradient Echo Parameters

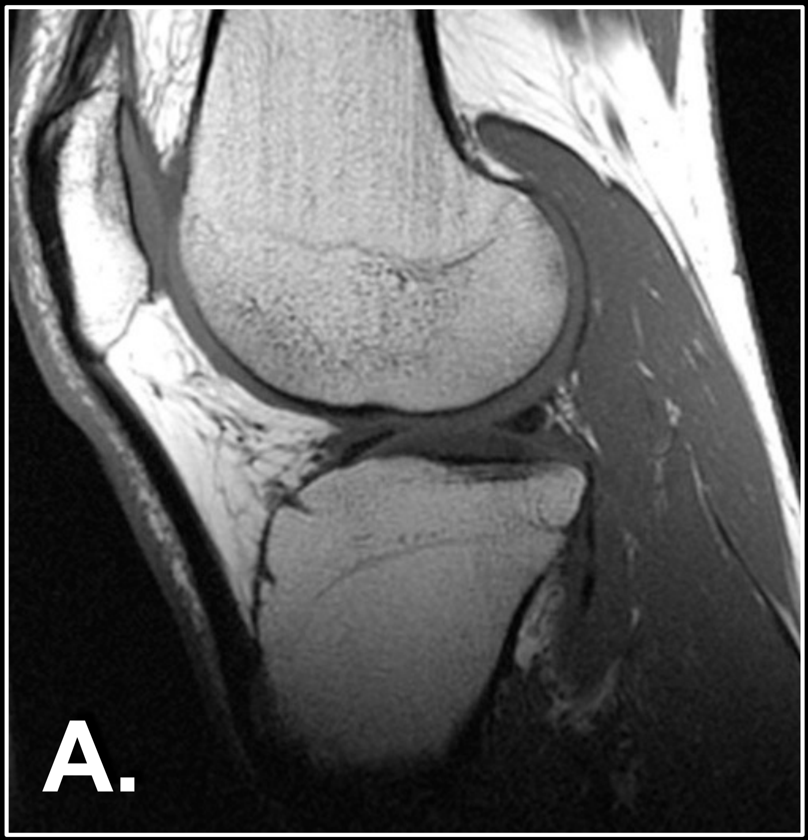
Type of Contrast	TE	TR	Flip Angle
Spin Density	<5ms	>100ms	<10°
T_1-Weighted	<5ms	<50ms	>30°
T_2^*-Weighted	>20ms	>100ms	<10°

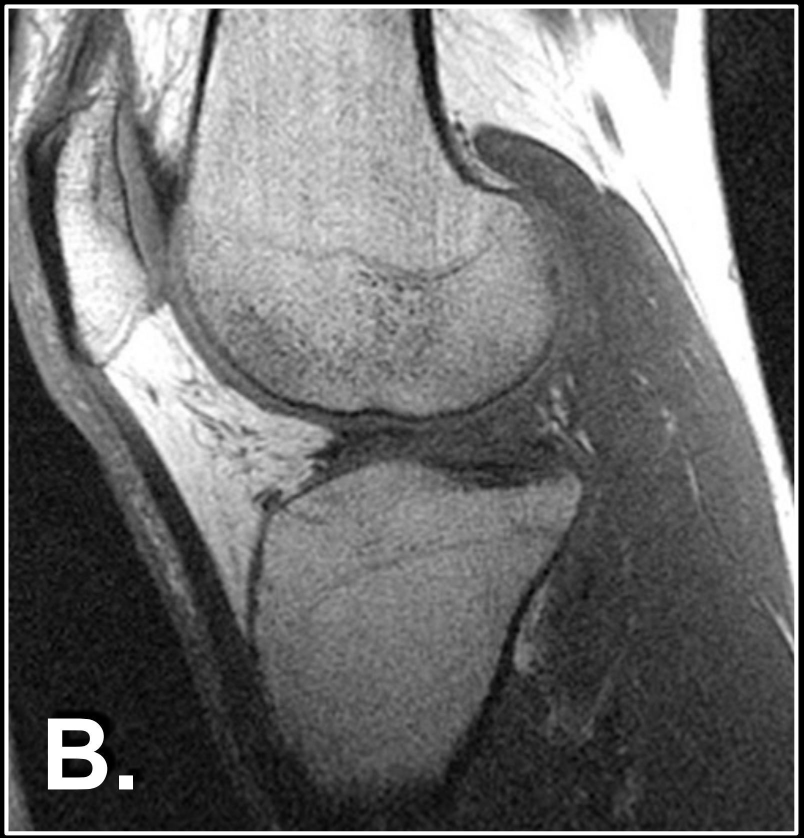
Spin Echo Parameters

Spin Density	10-30ms	>2000ms
T_1-Weighted	10-30ms	450-850ms
T_2-Weighted	>60ms	>2000ms

Gradient vs. Spin Echo

Which image is a gradient echo image?

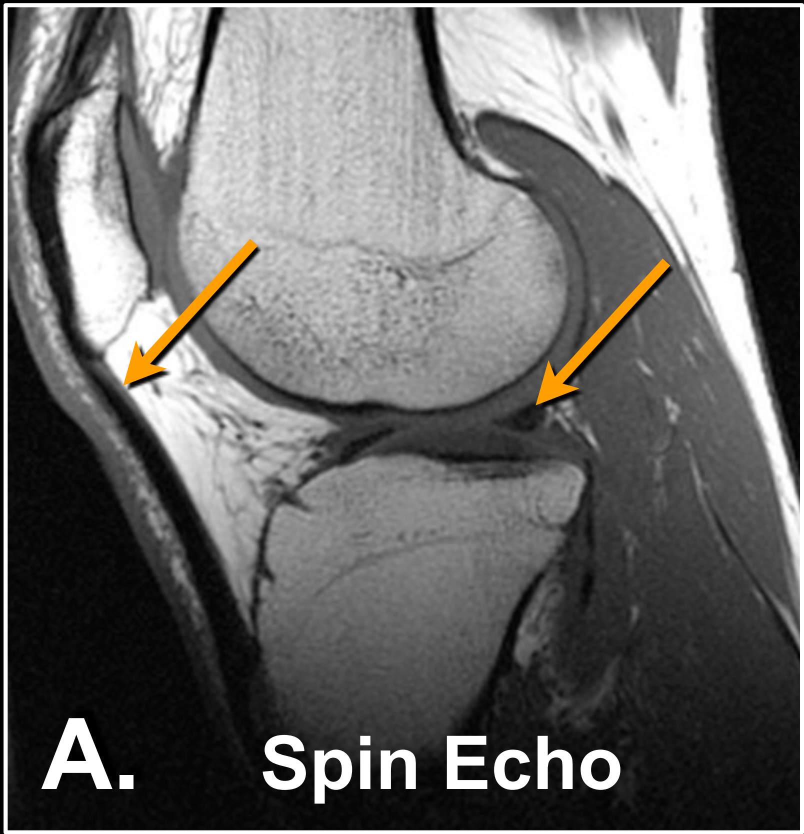


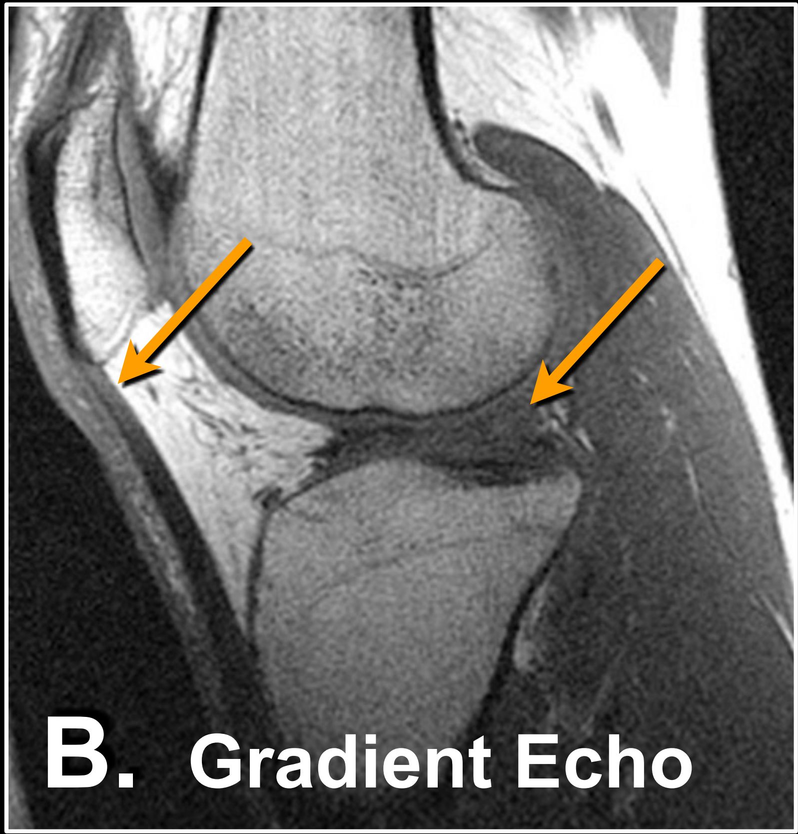


Images Courtesy of Brian Hargreaves

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)

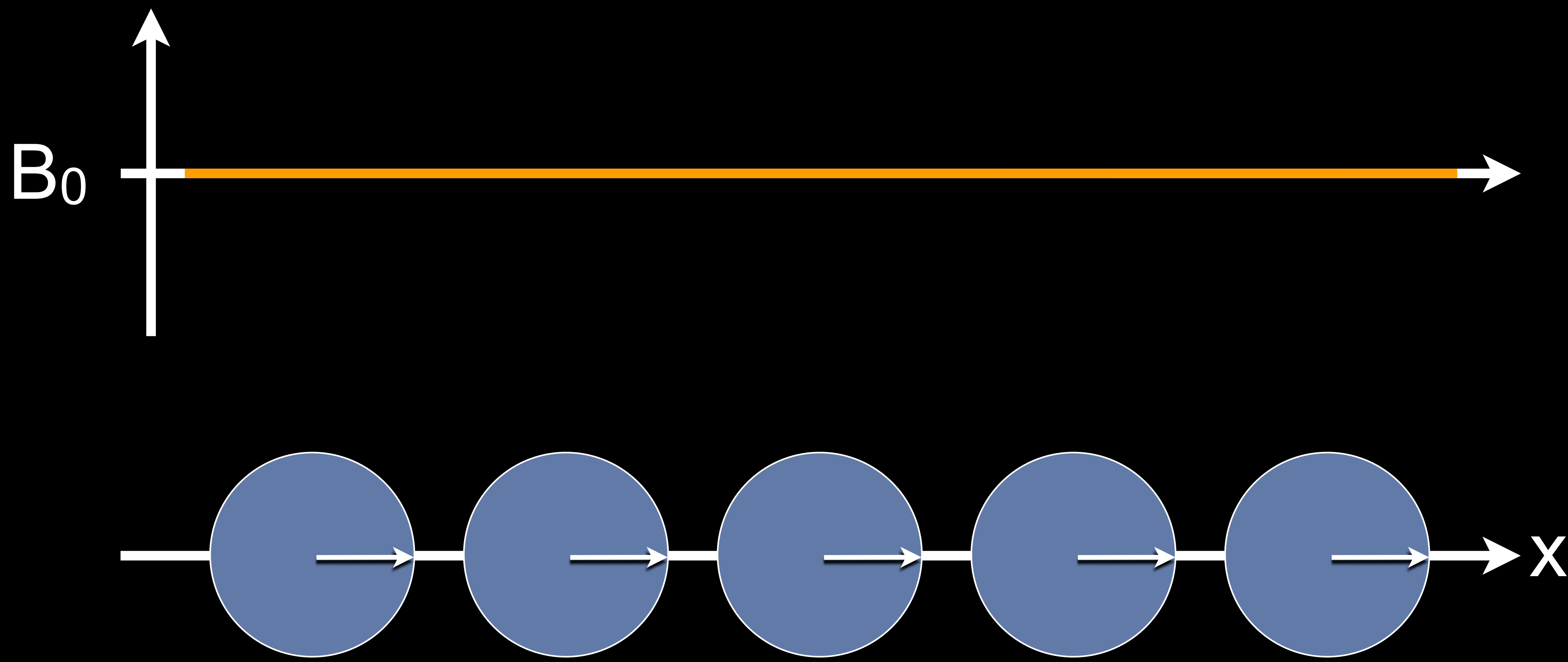
Acquisition Time

- Acquisition time (T_{acq}) can be calculated from the TR and the total number of repetitions.
- $T_{acq}=TR \bullet N_{ky} \bullet N_{kz} \bullet N_{avg}$
- Examples:
  - Spin Echo
    - TR=500ms
    - Matrix is 256x256, No Averages
    - ANSWER - 2 min 8s
  - Gradient Echo
    - TR=10ms
    - Matrix is 256 x 256, No Averages
    - ANSWER - 25.6 seconds

SE and GRE Tricks

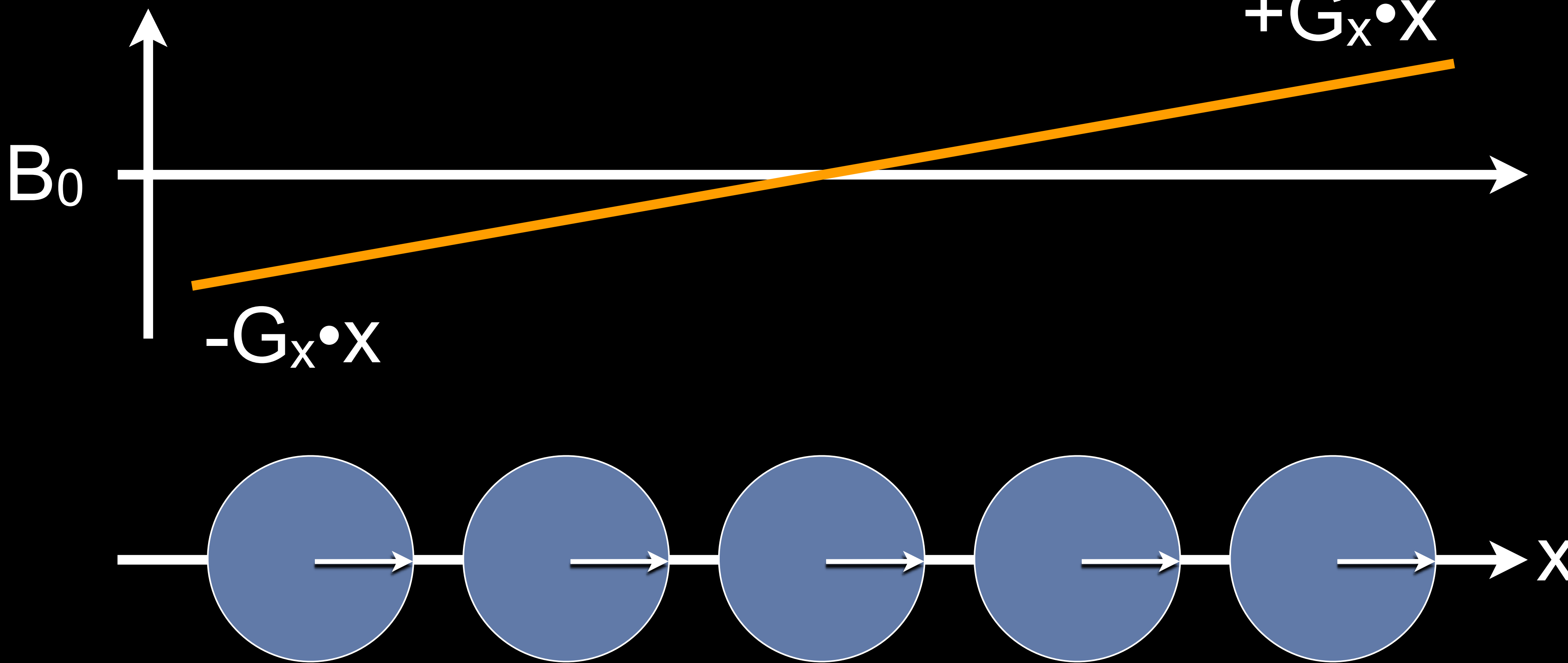
Gradient Echoes & Fat

GRE & Fat/Water Frequency



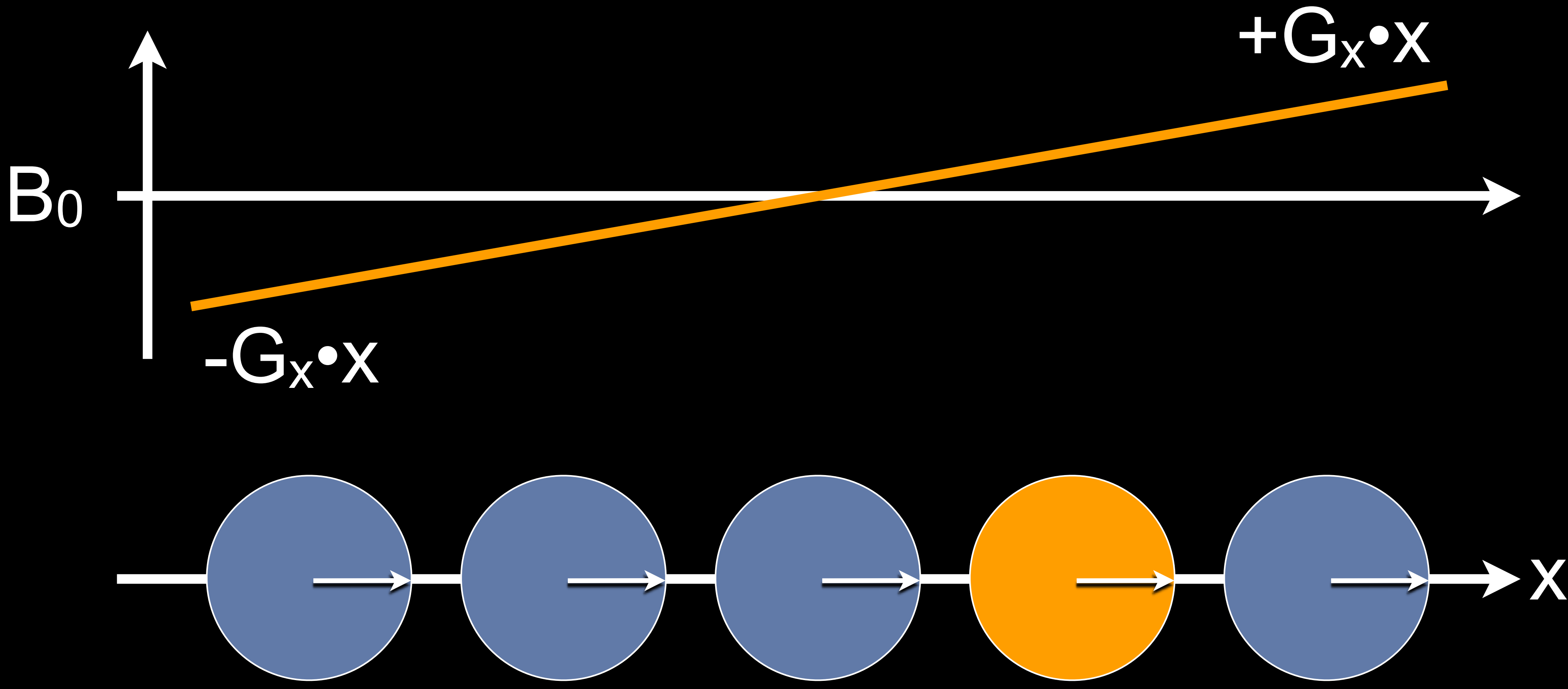
Water Spins in a Uniform Field

GRE & Fat/Water Frequency



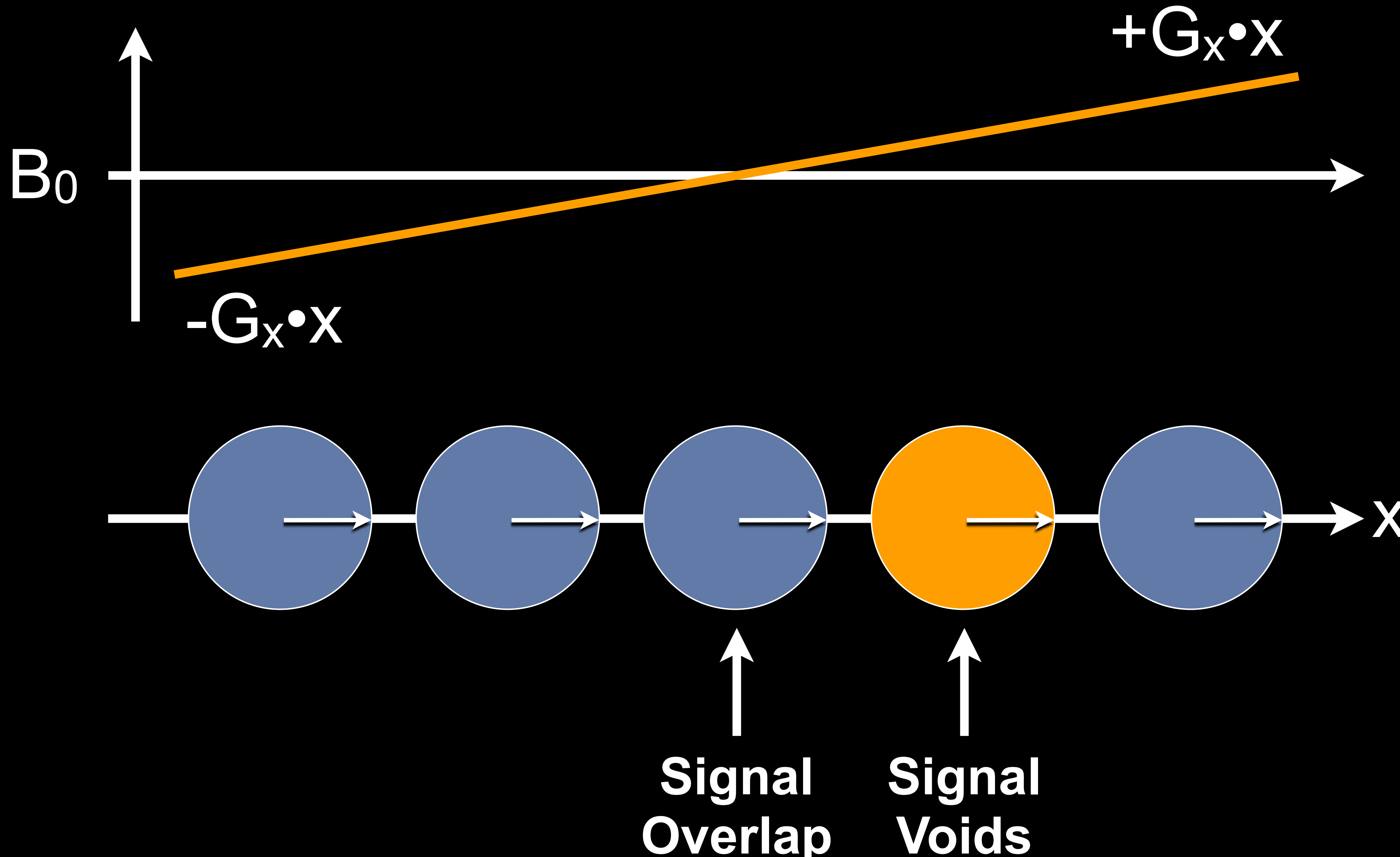
Water Spins in a Gradient Field

GRE & Fat/Water Frequency



Water & Fat Spins in a Gradient Field

GRE & Fat/Water Frequency



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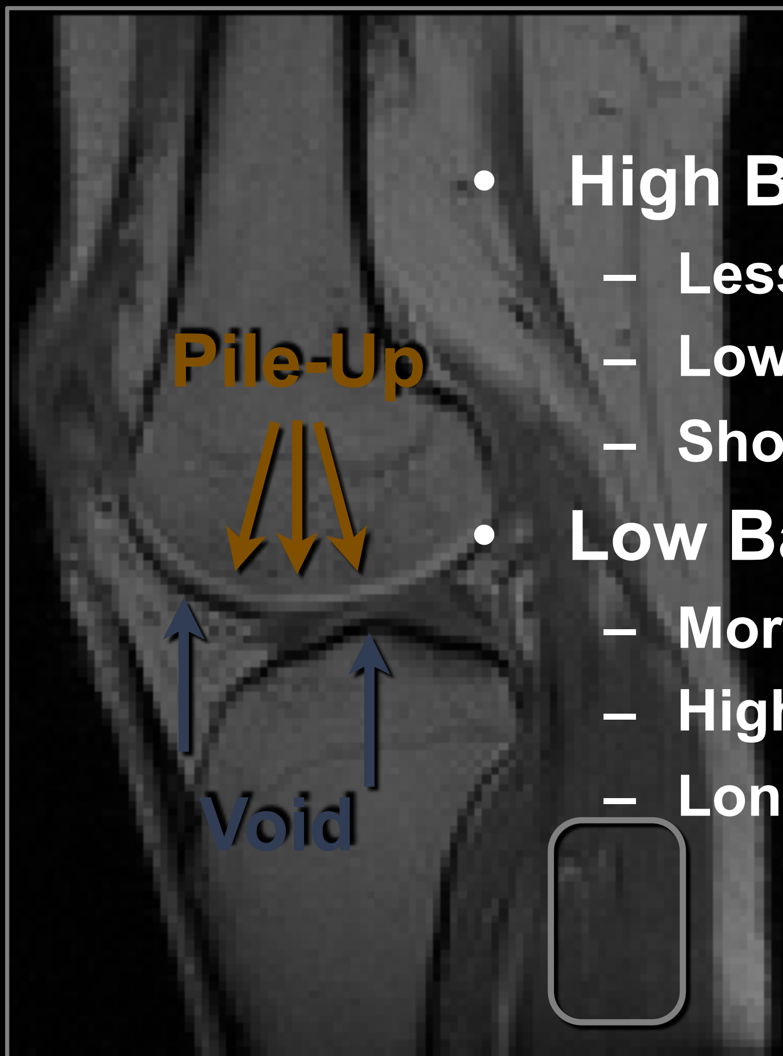
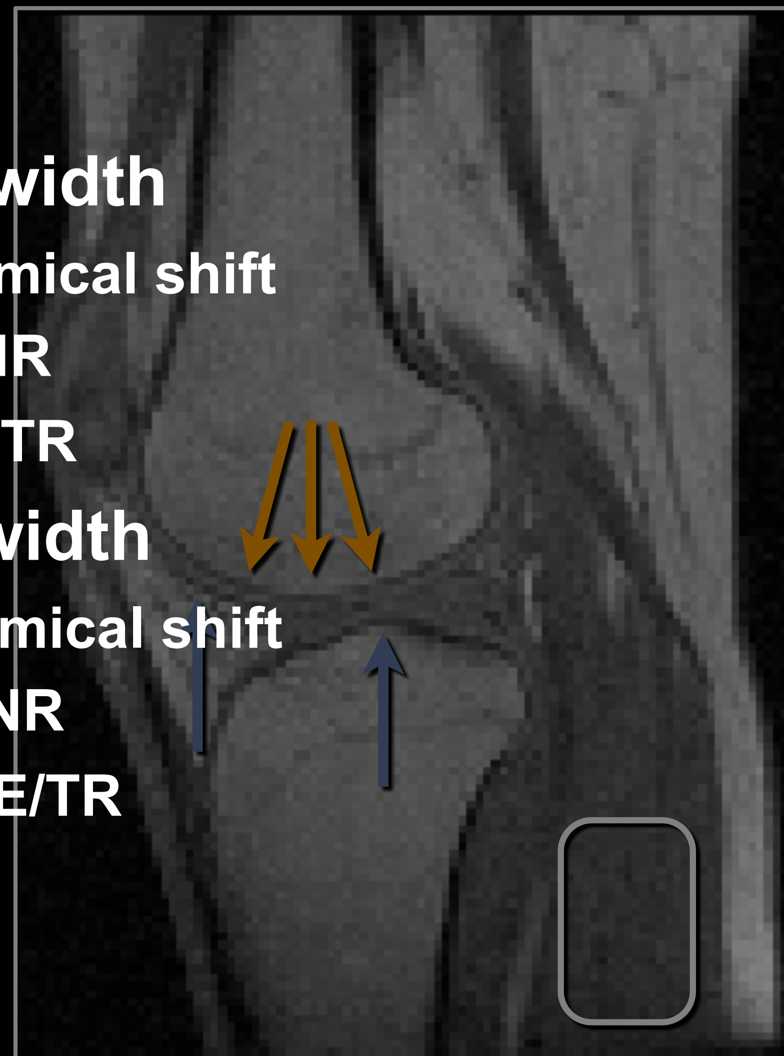
GRE & Fat/Water Frequency

Low Bandwidth



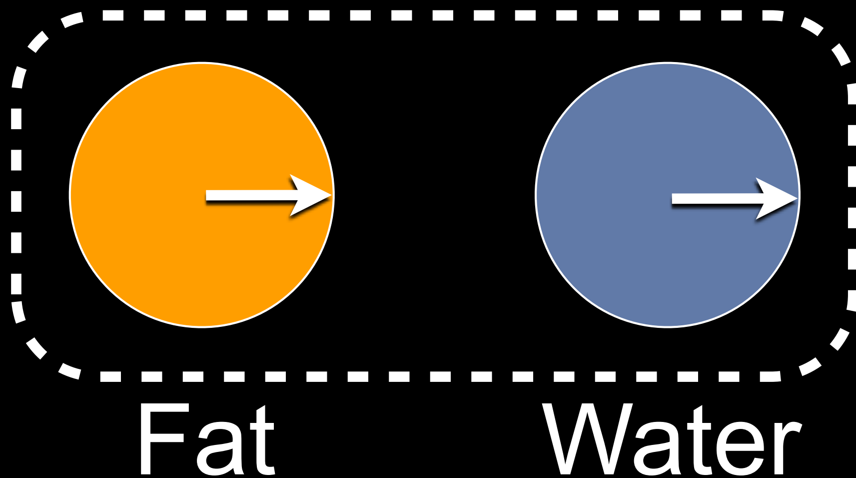
High Bandwidth



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

GRE and Fat/Water Phase

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



In-Phase

→ + → >0

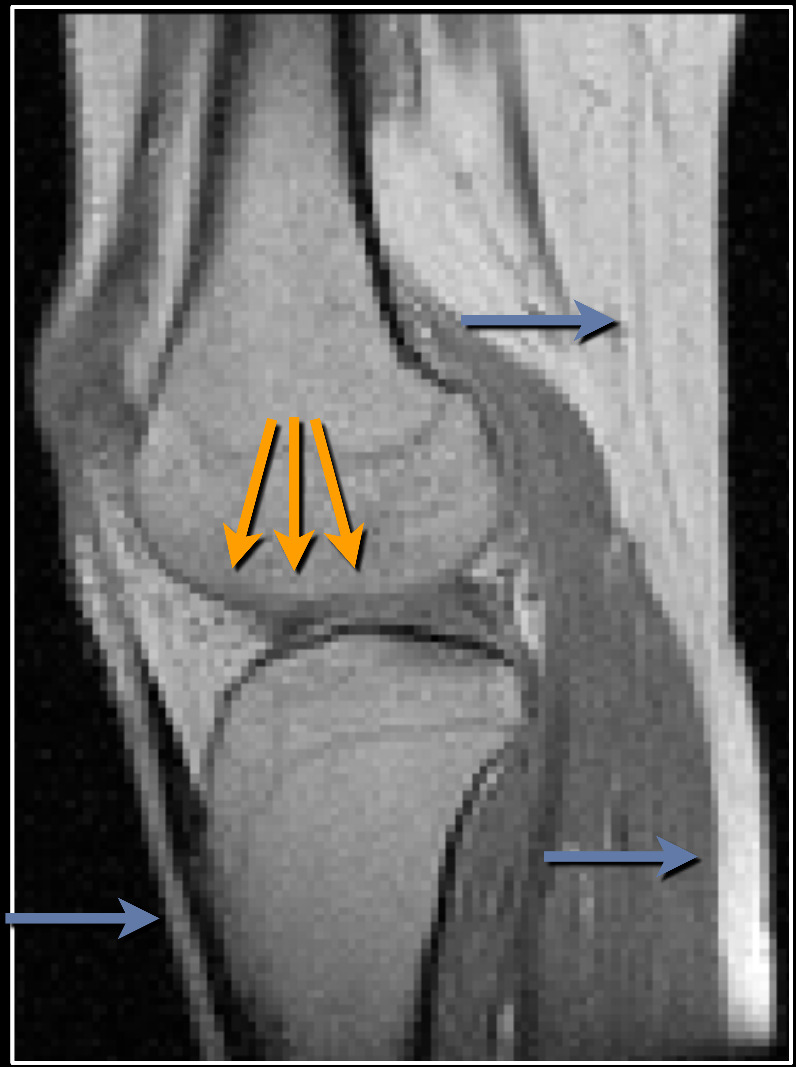
Opposed-Phase

← + → =0

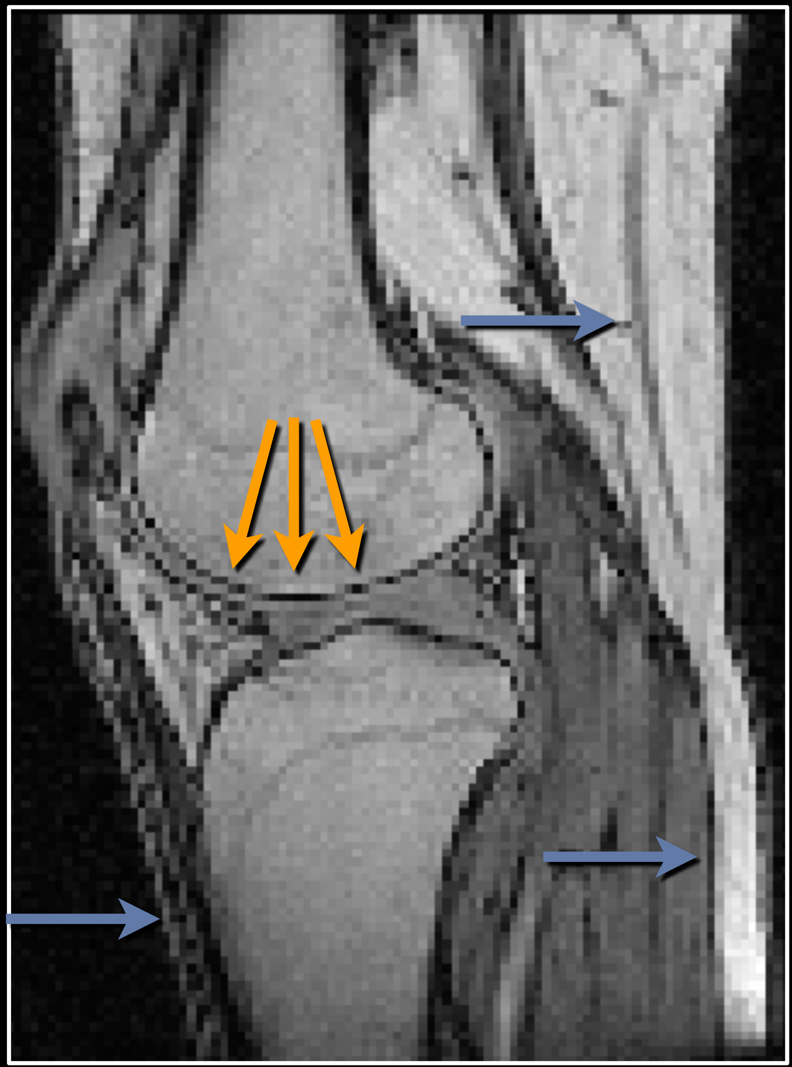
The TE controls the phase between fat and water.

GRE and Fat/Water Phase

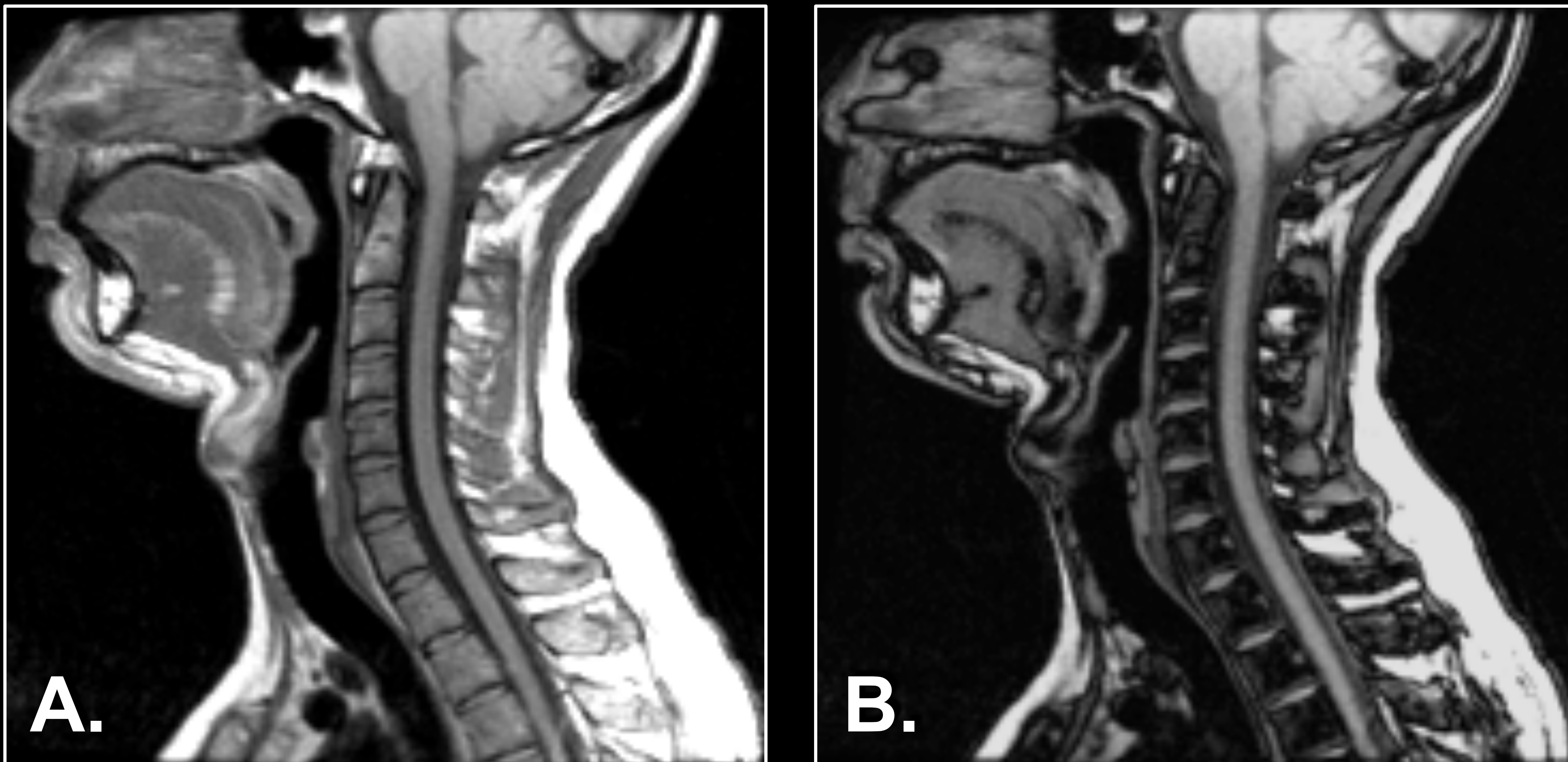
In-Phase



Opposed-Phase

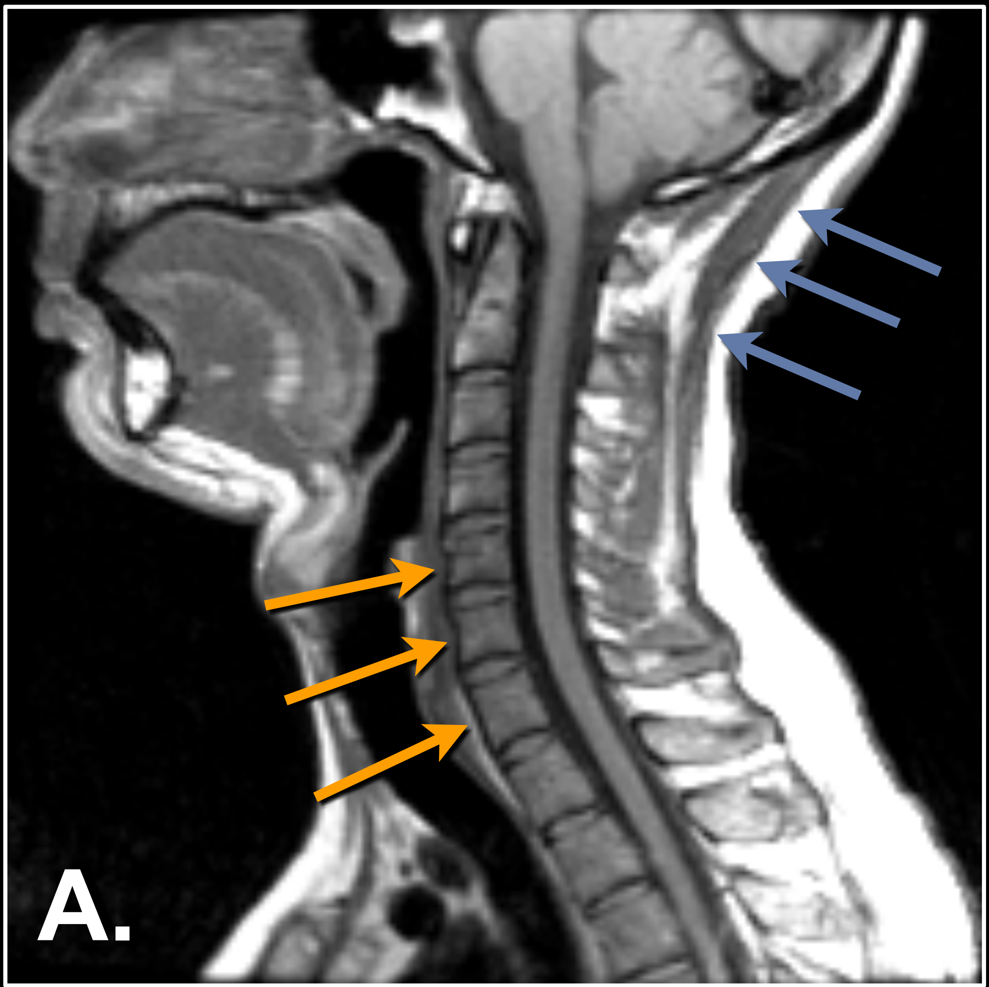


Which image is the in-phase image?

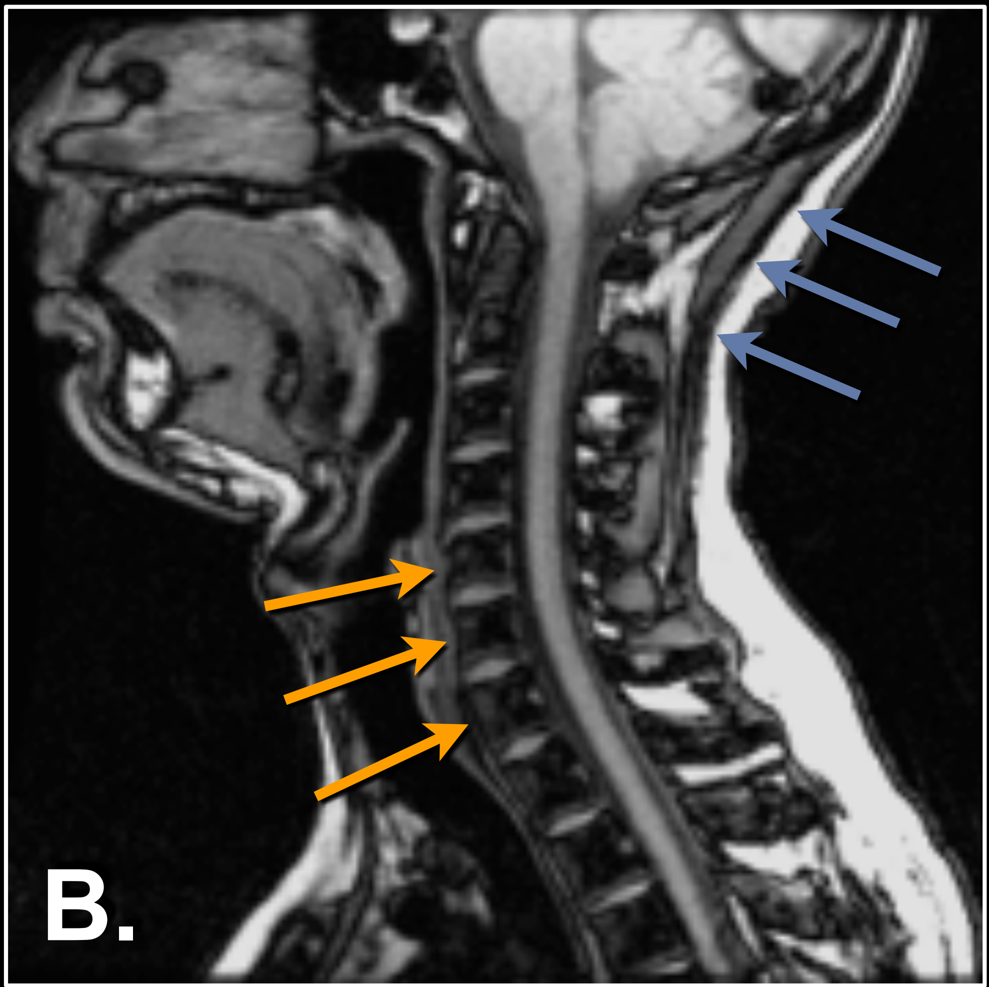


Images Courtesy of Scott Reeder

Which image is the in-phase image?



In-Phase

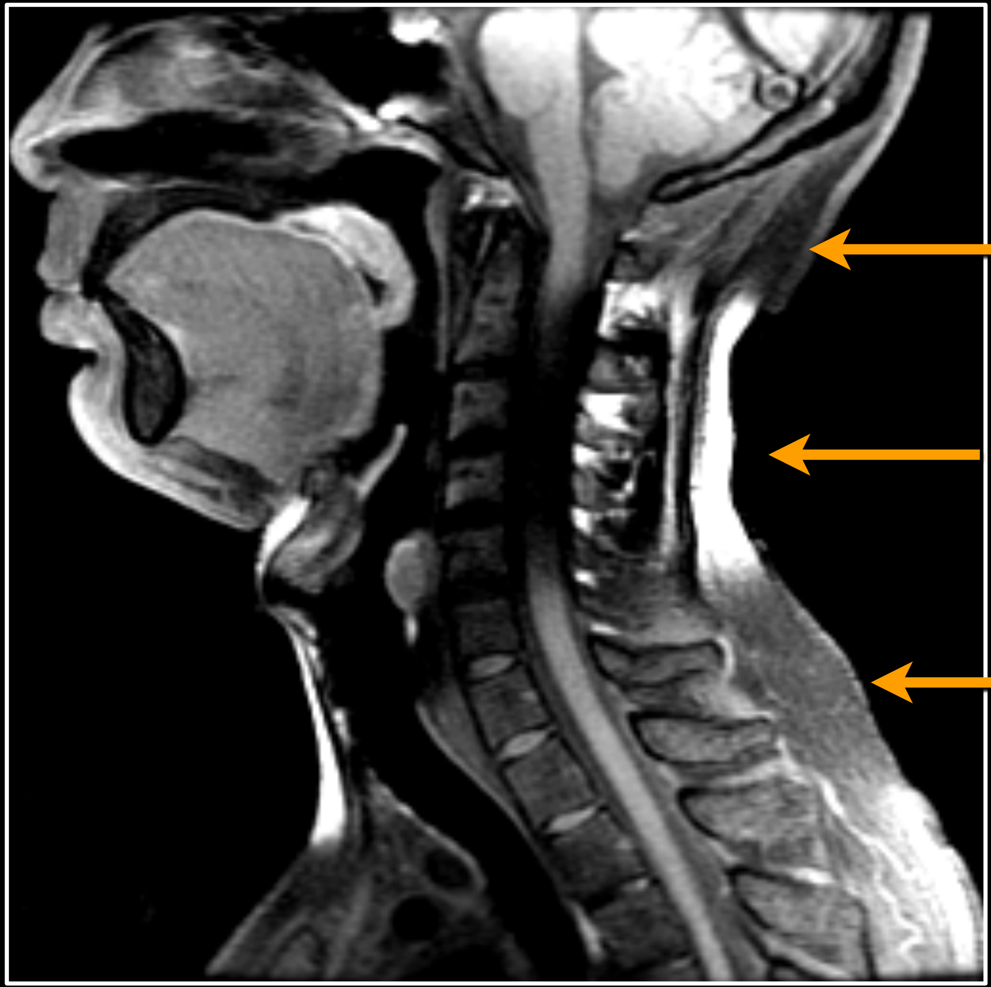


Opposed-Phase

Gradient Echoes & Fat Suppression

- **Why is fat suppression/separation important?**
  - Fat is bright on most pulse sequences.
  - But so are many other things...
    - CSF & edema
    - Flowing blood
    - Contrast enhanced tissues
- **Fat obscures underlying pathology**
  - Edema, neoplasm, inflammation
- **How can fat be eliminated in GRE images?**
  - Fat saturation pulses
  - Multi-echo acquisitions
    - Dixon/IDEAL

Gradient Echoes & Fat/Water Separation



Fat-Sat Image

Fat-Sat Can Be Spatially Non-Uniform

Gradient Echoes & Fat/Water Separation

IDEAL Water Image

IDEAL Fat Image

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Images Courtesy of Scott Reeder

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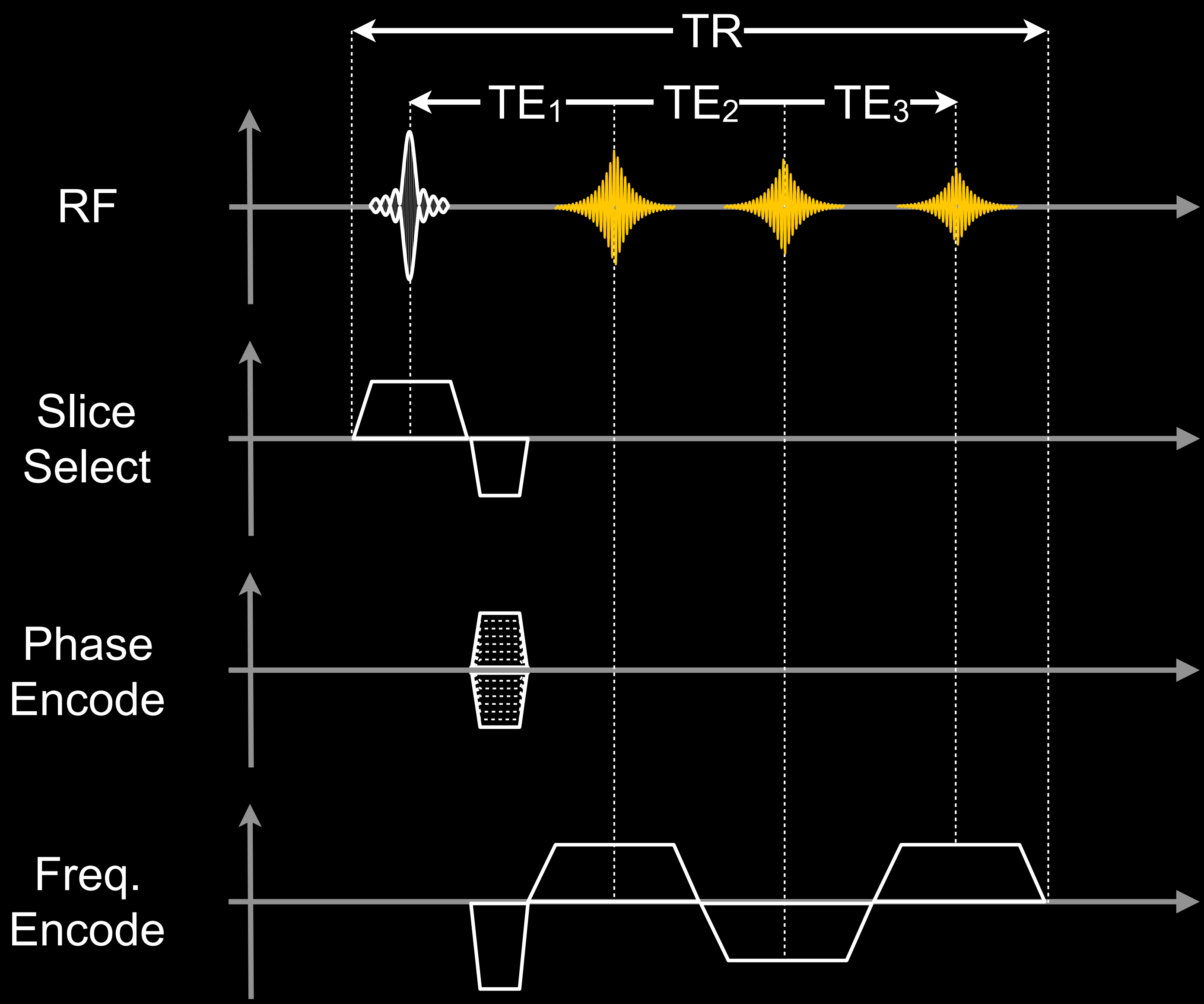
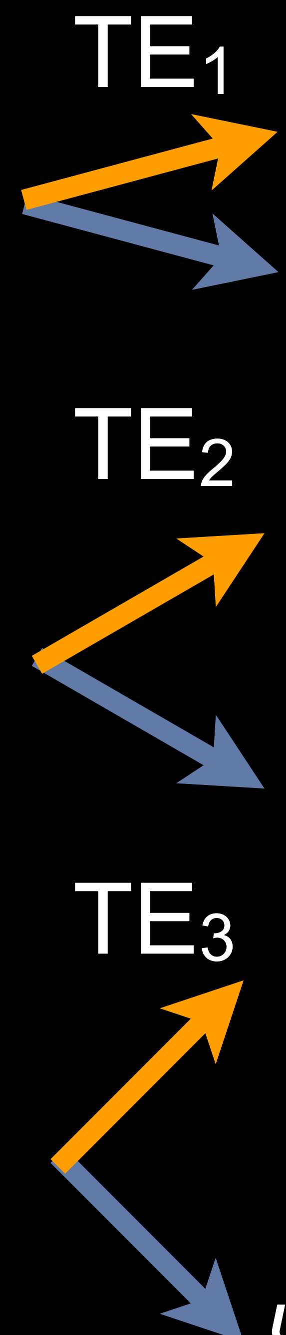
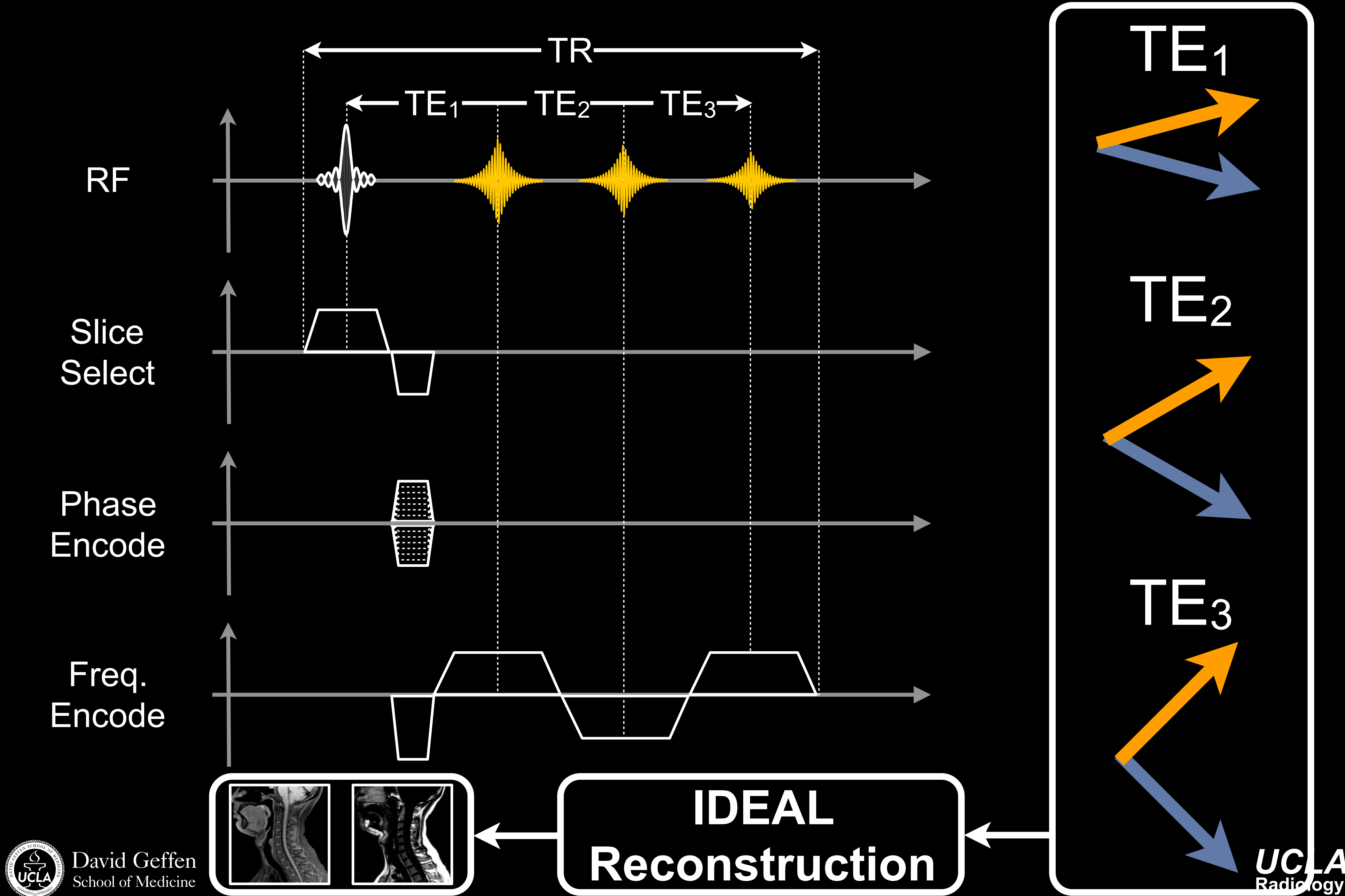
GRE & Fat/Water Separation - How?





GRE & Fat/Water Separation - How?



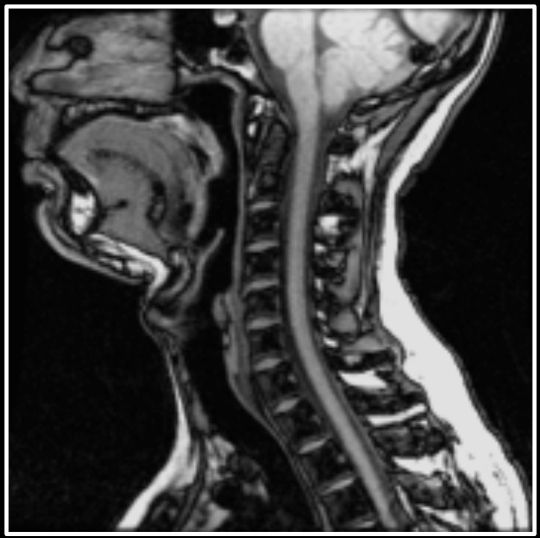
Gradient Echoes & Fat/Water Separation

Imperfect Fat Sat

IDEAL water image

IDEAL fat image

in-phase



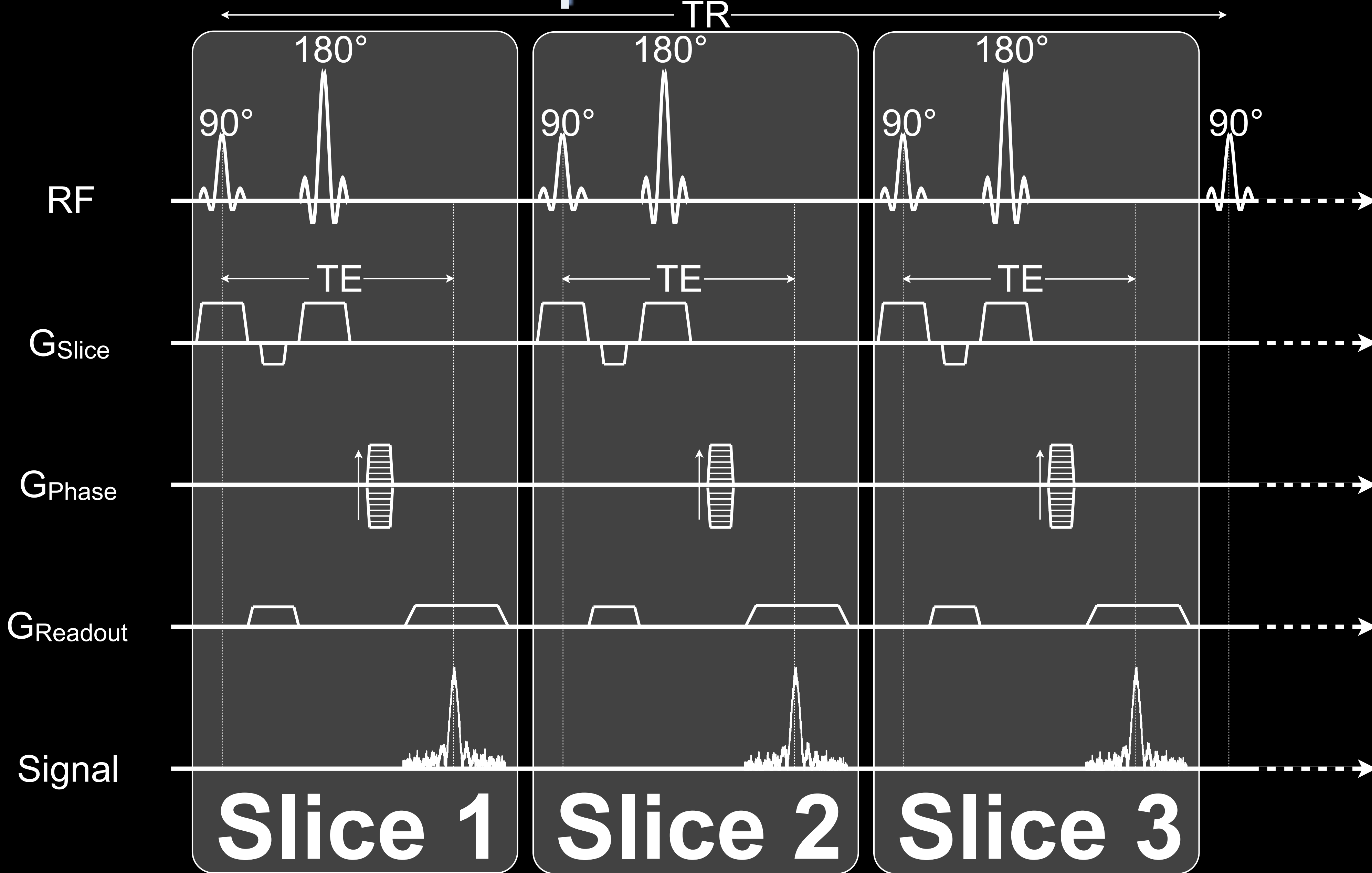
opposed-phase

Images Courtesy of Dr. Scott Reeder

Spin Echo 2D Slice Interleaving

Spin Echo

Spin Echo



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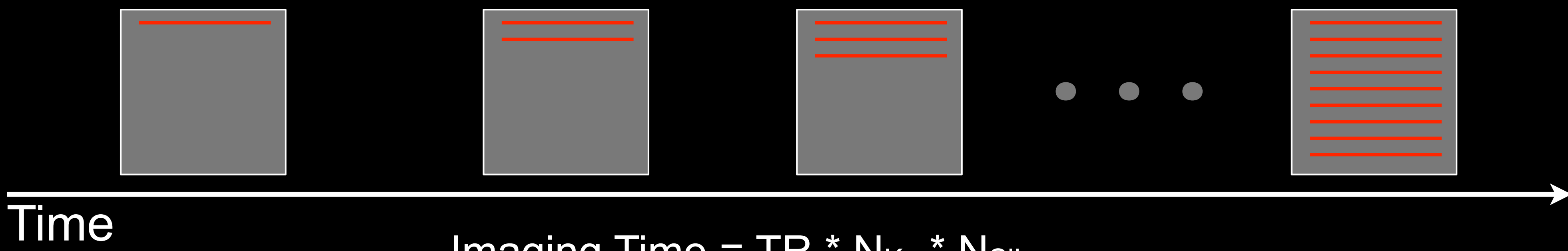
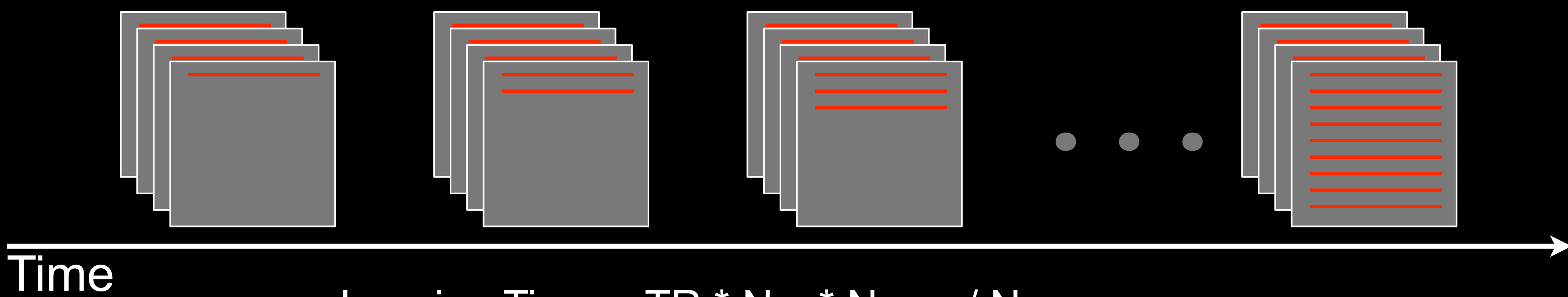
Slice Interleaving

Sequential 2D Imaging



$$\text{Imaging Time} = TR * N_{Ky} * N_{Slices}$$

Slice Interleaved 2D Imaging



$$\text{Imaging Time} = TR * N_{Ky} * N_{Slices} / N_{Interleaves}$$

2D Slice Interleaving

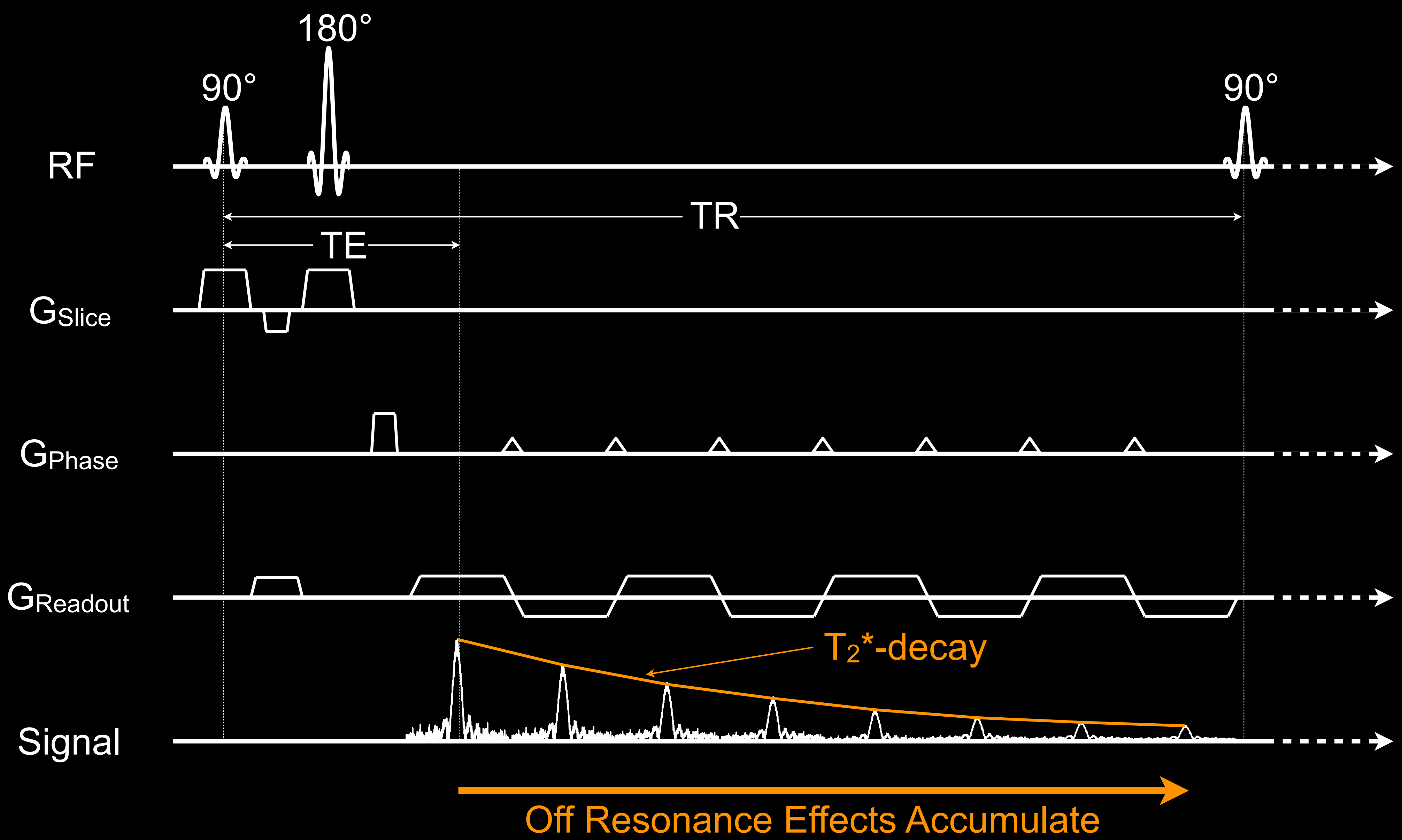
- **Advantages**
  - **Accelerate imaging many times**
- **Disadvantages**
  - **Acceleration limited by**
    - **$N_{Interleaves}$~TR/TE**
    - **SAR**
  - **Difficult to acquire adjacent slices**
    - **Hard to get good 180° slice-profile to match 90° slice-profile for multi-slice imaging**
- **Applications**
  - **T_2 imaging**
    - **TR must be long**
  - **DWI**
    - **TR should be long**

Conclusion

- **Slice interleaving makes sense when TR is really long.**

Spin Echo EPI

Spin Echo EPI



Spin Echo EPI

- Advantages
  - Can acquire data in a "single shot"
  - Can be used with 2D slice interleaving
  - Allows T_2^* weighted imaging in a breath hold
- Disadvantages
  - Single Shot EPI
    - Ghosting
    - Blur images
    - Image distortion
    - Alter image contrast
  - Multi-shot EPI
    - Slower than single shot
      - Faster than SE
- Applications
  - DWI, Perfusion, fMRI

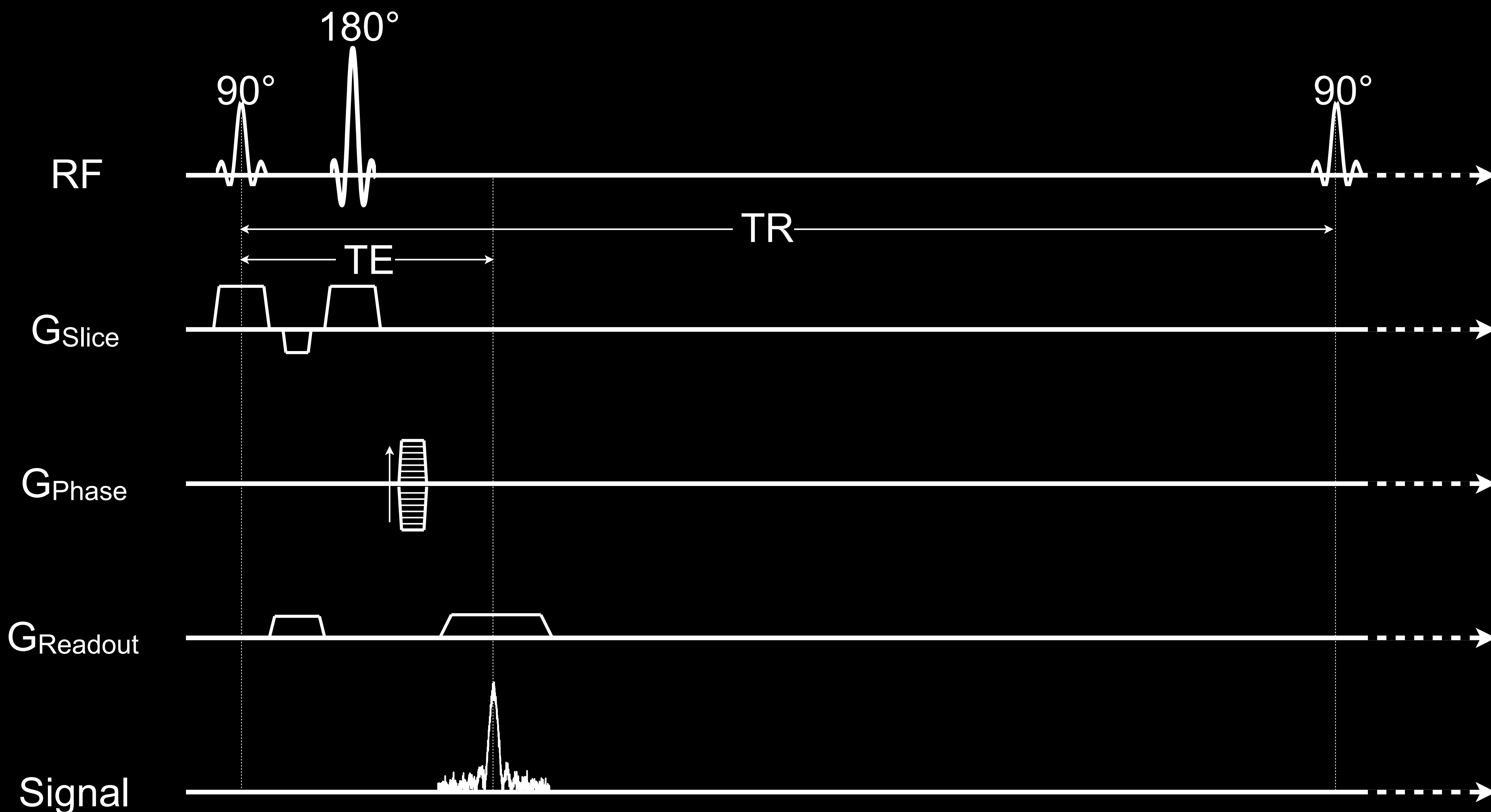
Multi-Echo Spin Echo Imaging

How do we calculate scan time?

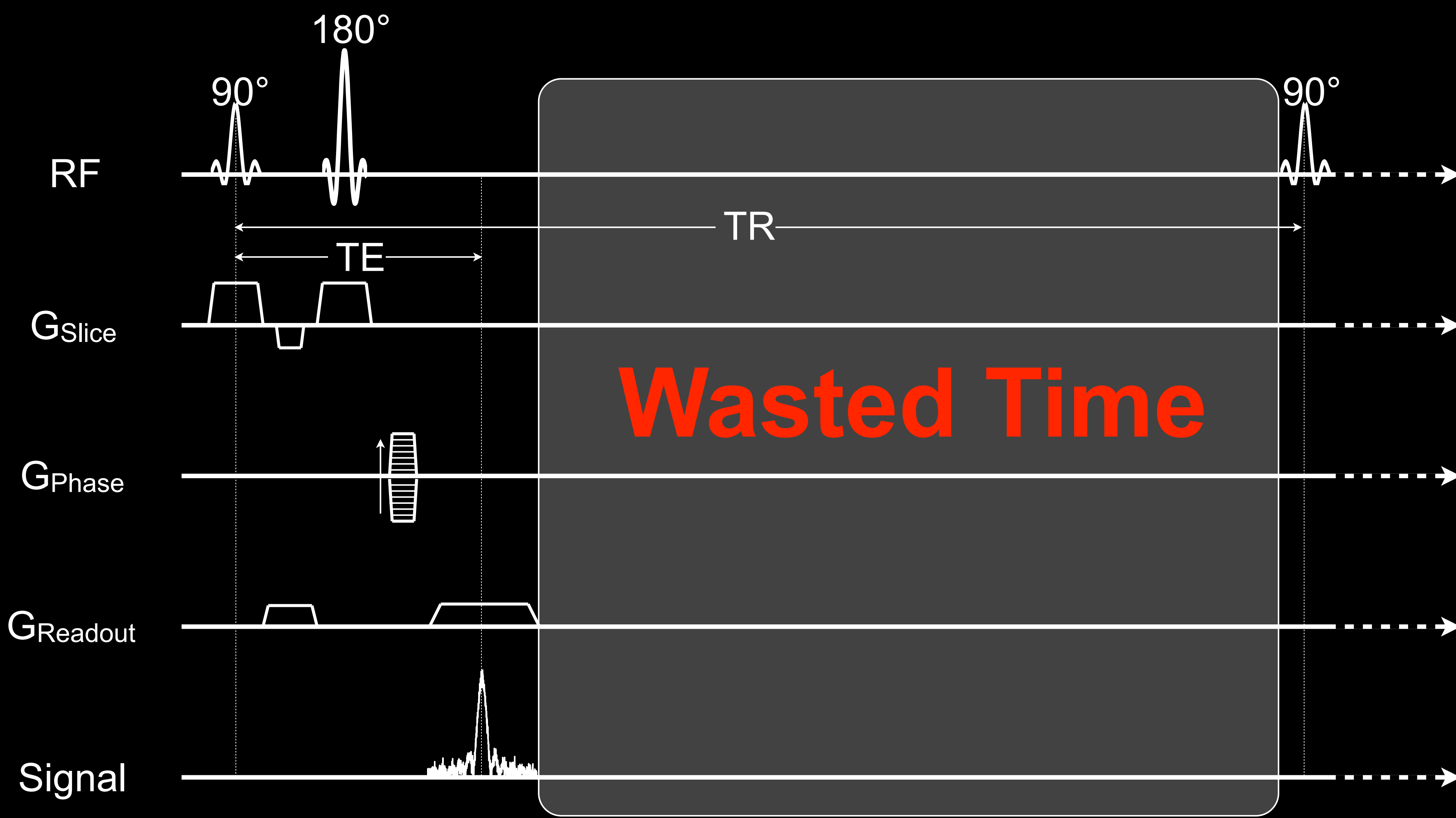
$$T_{Scan} = TR \cdot PE \cdot N_{avg}$$

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

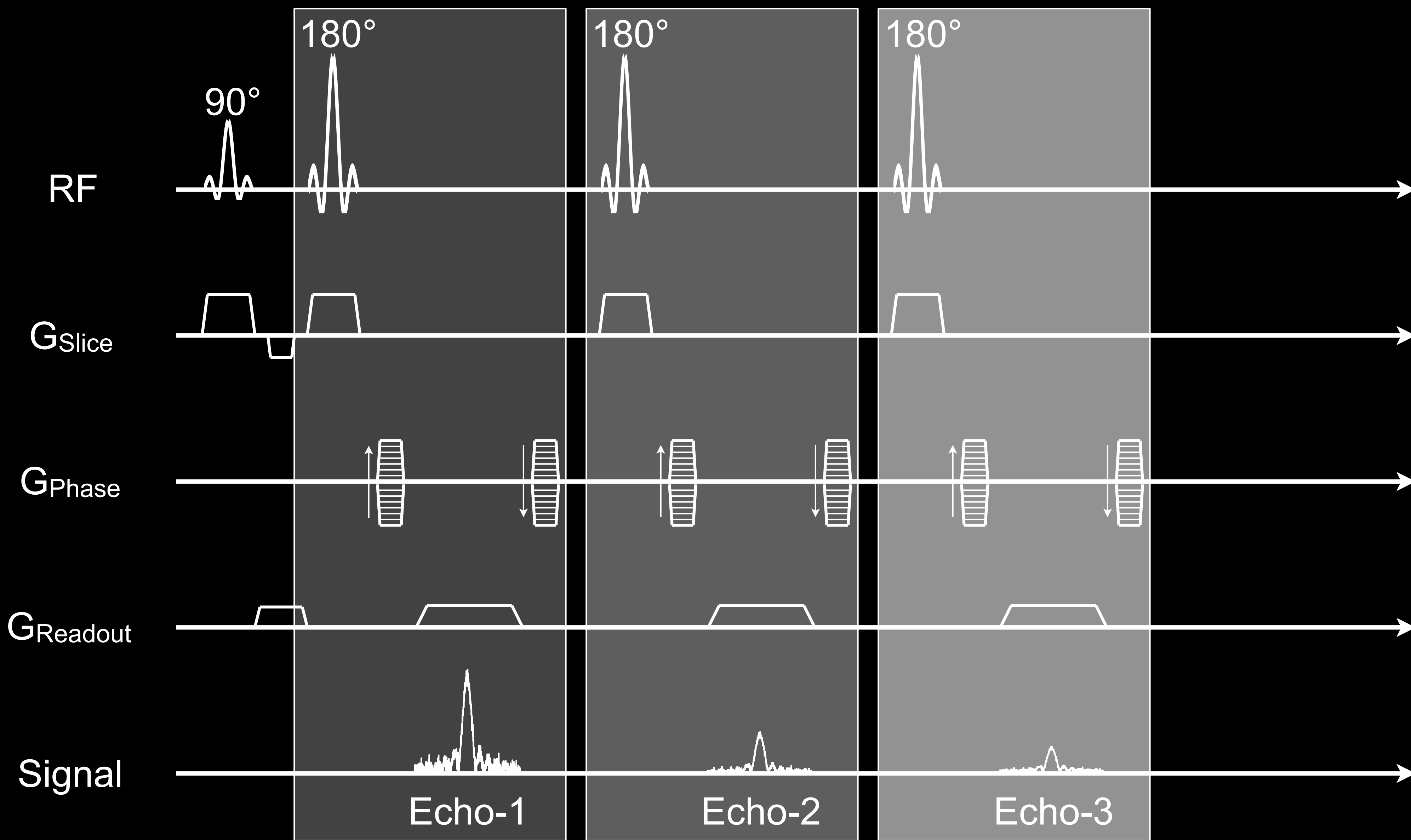
Spin Echo



Spin Echo



Fast Spin Echo



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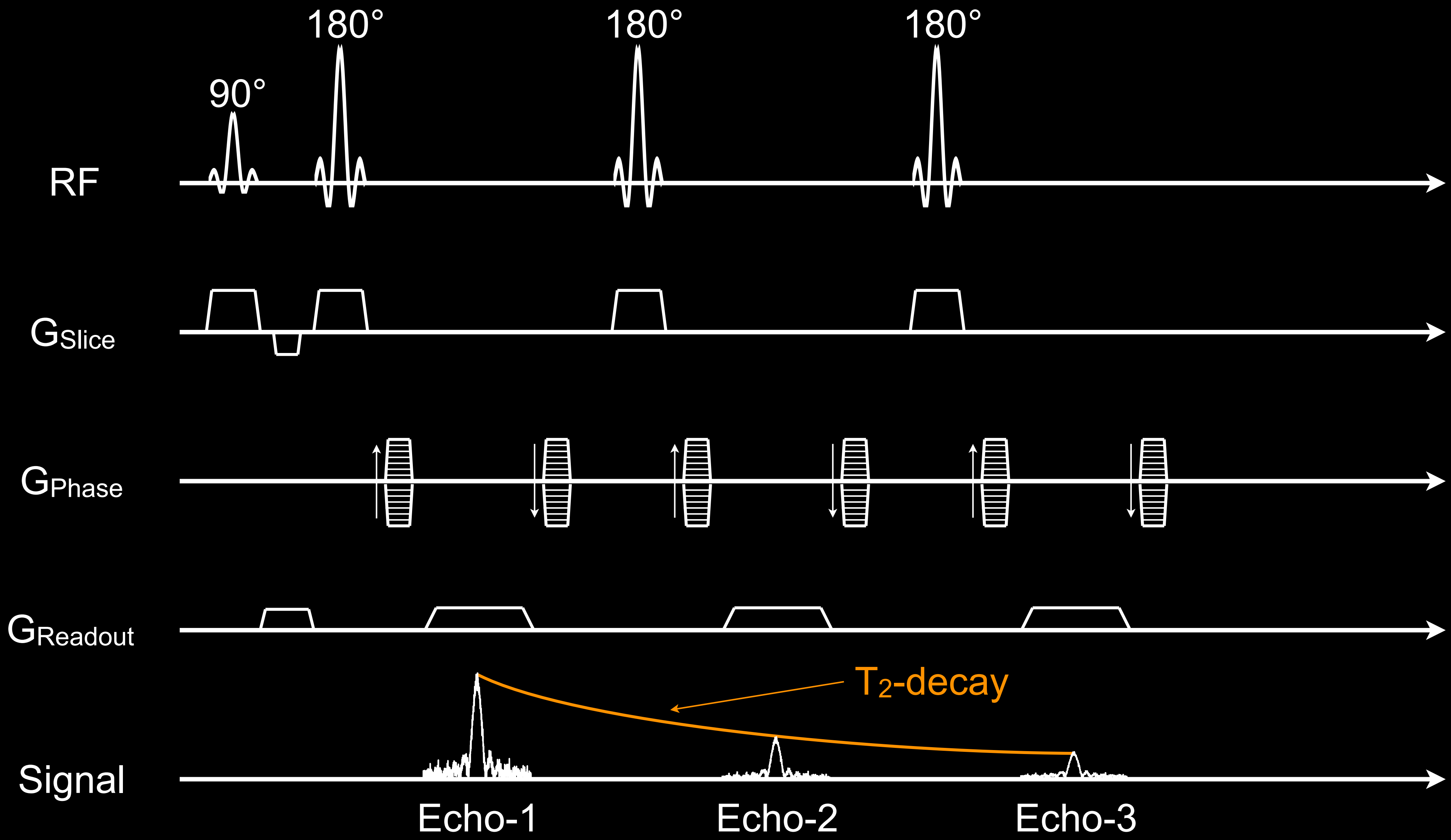
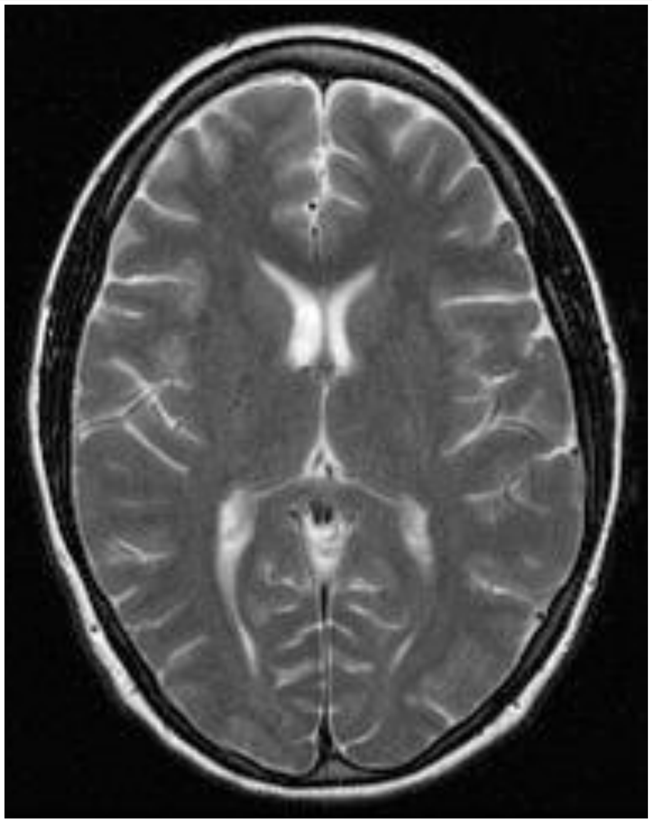
Fast Spin Echo



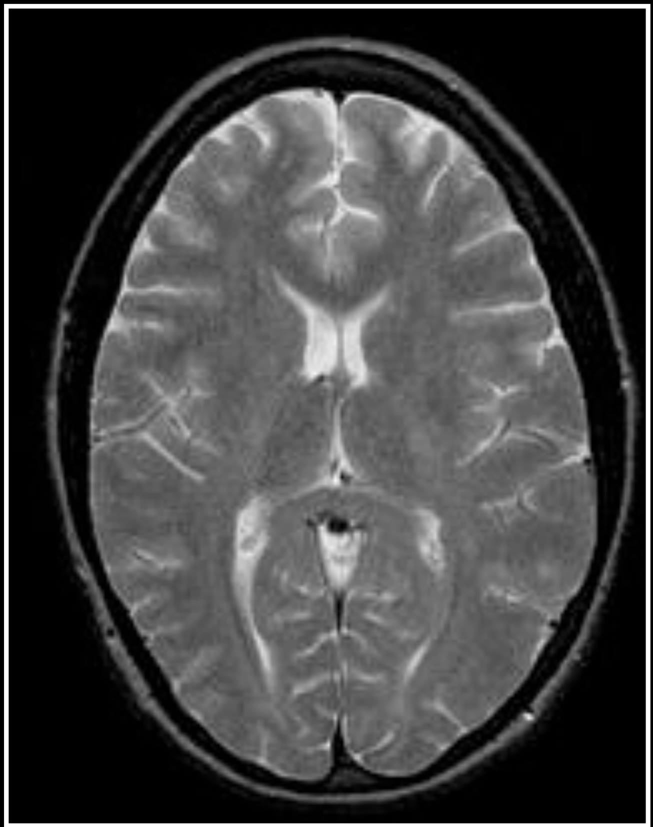
T_2 Weighting (FSE vs. SE)

FSE



TR = 2500
TE = 116
ETL = 16
NEX = 2
24 slices
Time = 2:51

SE



TR = 2500
TE = 112
ETL = N/A
NEX = 1
24 slices
Time = 22:21

Fast Spin Echo

- **Advantages**
  - Turbo factor accelerates imaging
  - Can be used with 2D slice interleaving
  - Allows T_2 weighted imaging in a breath hold
- **Disadvantages**
  - High turbo factors (ETL>4):
    - Blur images
    - Alter image contrast
  - Fat & Water are both bright on T_2-weighted
    - Water/CSF T_2 is long
    - Repeated 180s reduce spin-spin interaction
      - This lengthens the moderate T_2 of fat
  - SAR can be high

Thanks

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