Quantitative Cardiovascular Flow Imaging

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Encoding Motion

- **Coherent Motion**
  - Coherent at a scale ≥pixel
  - Spin (tissue) displacement and velocity
  - Example: Phase Contrast MRI (PC-MRI)
- **Incoherent Motion**
  - Incoherent at a scale <pixel
  - Spin perfusion and diffusion
  - Example: Diffusion Weighted MRI (DWI)

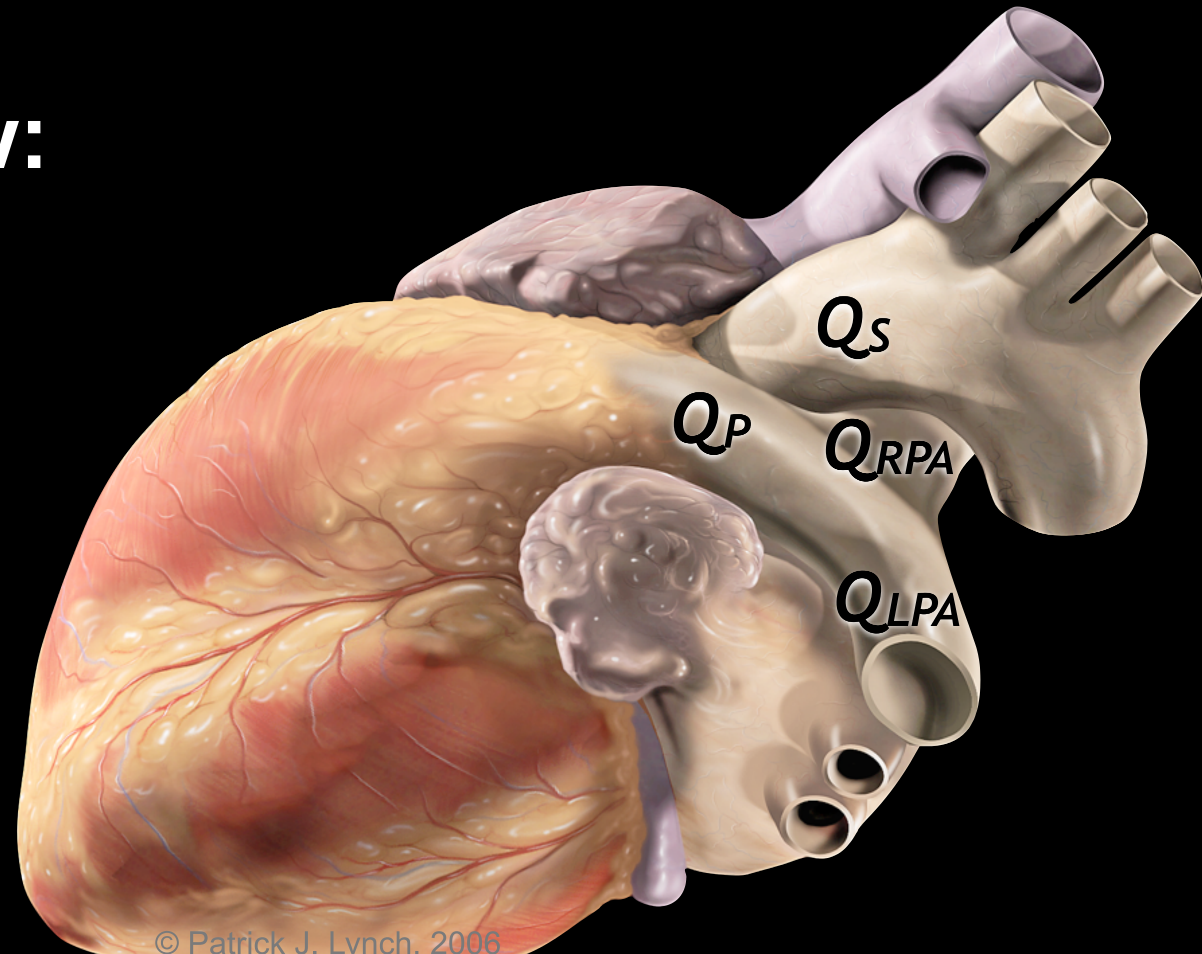
PC-MRI Overview

PC-MRI

Encode velocity into image phase

Phase Contrast MRI

- **PC-MRI can quantify blood flow:**
  - **Peak velocity [cm/s]**
  - **Transvalvular forward flow [mL]**
    - **Regurgitant volumes [mL]**
  - **Pulmonary-Systemic Flow Ratio**
    - **Q_P/Q_S**
  - **Right-Left Lung Flow Ratio**
    - **Q_{RPA}/Q_{LPA}**



What is the peak aortic velocity?

Is the pulmonary to systemic flow ratio (Q_p/Q_s) normal?

What is the right/left lung flow split?

Significance

- The evaluation of CHD patients is enhanced by accurate quantification of blood flow:
  - Peak velocity
  - Transvalvular forward flow
  - Regurgitant volumes
  - Q_p/Q_s and Right/Left lung flow
- CHD patients require frequent monitoring of cardiac functional status
  - Lifetime of radiological exams
  - Elevated cumulative exposure to ionizing radiation

Significance

- Catheterization
  - Disadvantages:
    - Ionizing radiation
    - Invasive
    - Indirect quantification of flow

- Echocardiography
  - Disadvantages:
    - Limited acoustic windows
    - Vessel angulation relative to the transducer
    - Complex cardiovascular anatomy in CHD patients

SIGNIFICANCE

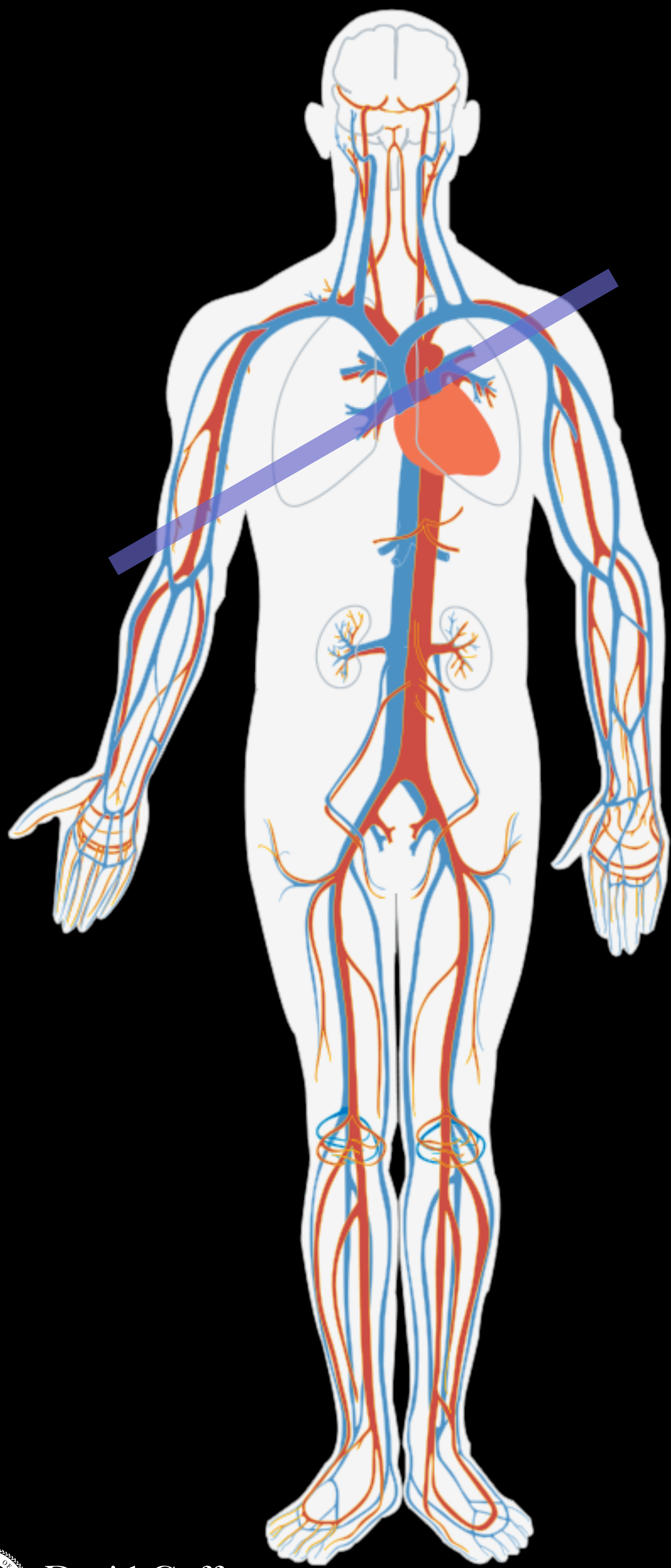
- PC-MRI is useful for measuring flow in CHD patients
  - Non-invasive
  - Direct quantification of velocity & flow
  - Reduced lifetime radiation exposure

- Higher accuracy and clinical confidence in PC-MRI
  - More effective management of patients with CHD

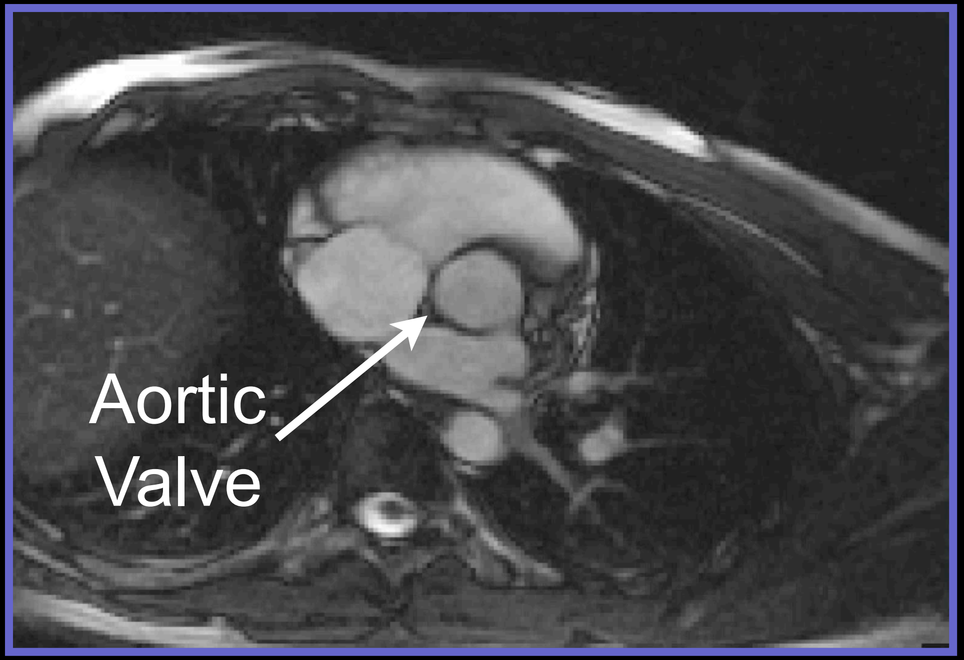
Phase Contrast Applications

- Quantify blood flow
  - Peak velocity & volume of flow,
  - Shear stress
- Measure CSF flow
- Cardiac motion estimation

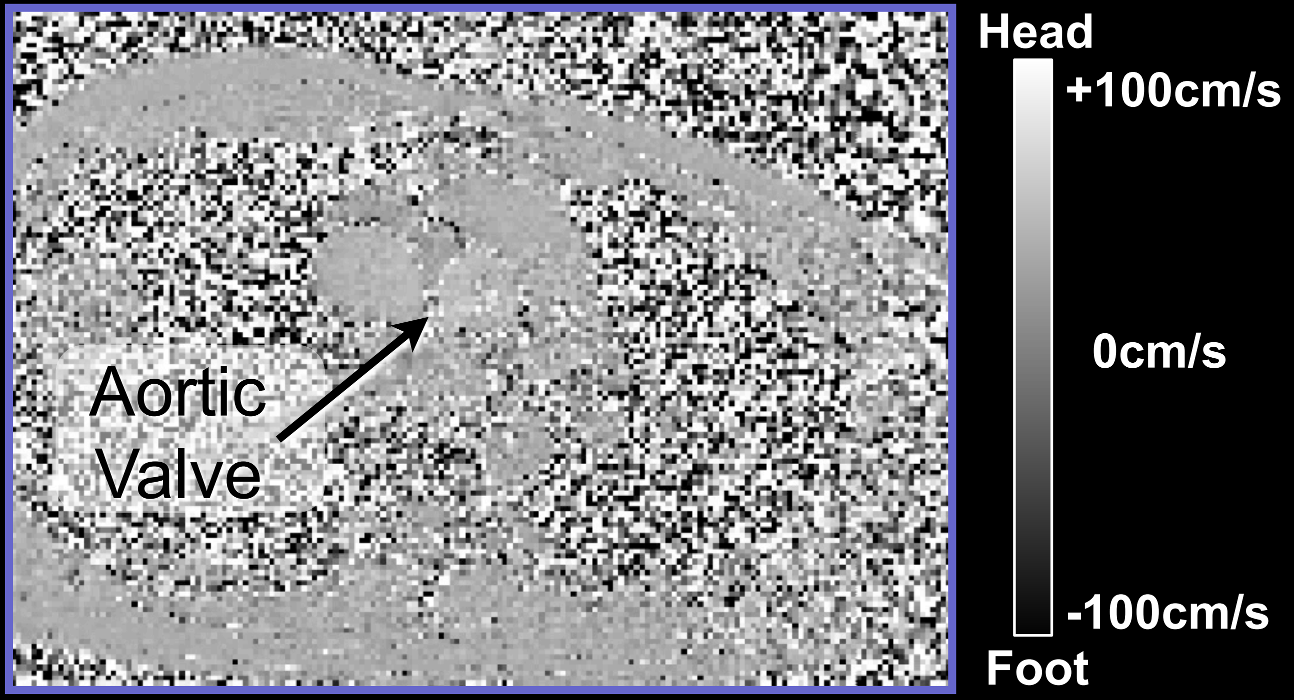
Phase Contrast



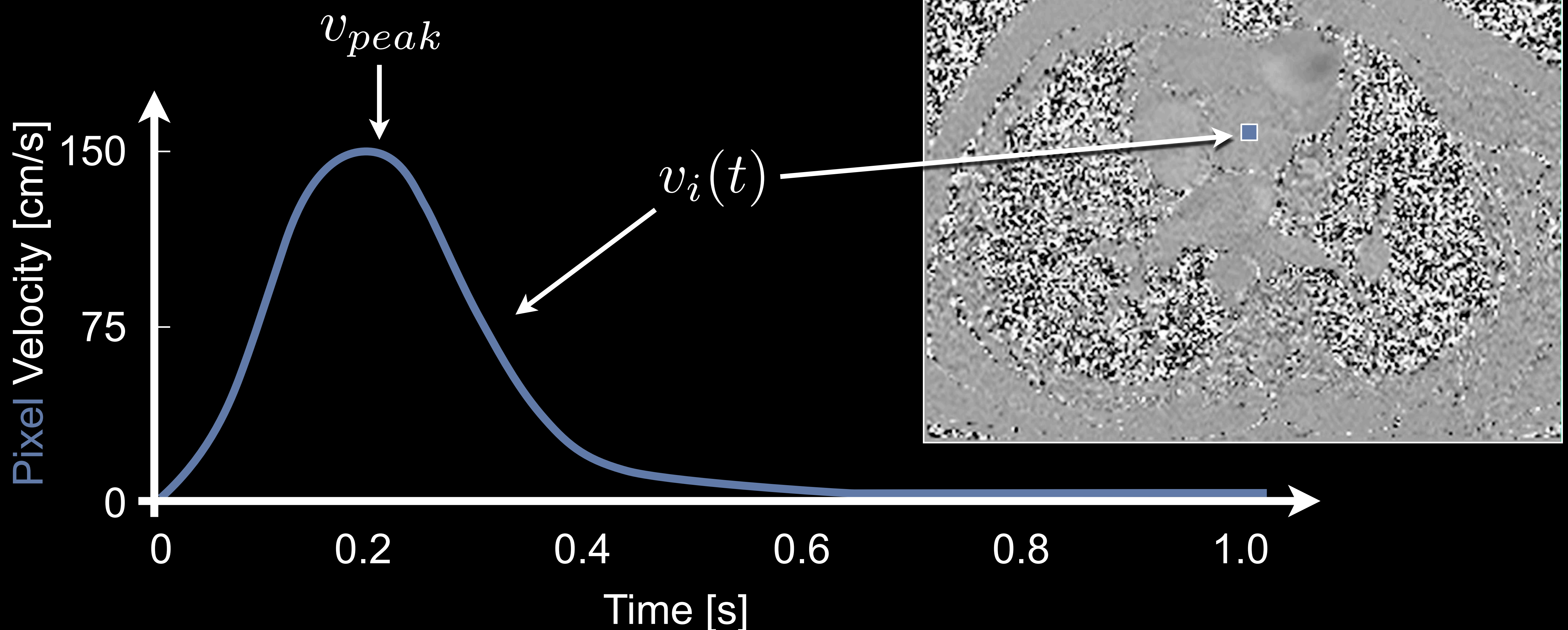
Magnitude Image



Phase Image



Phase Contrast Analysis



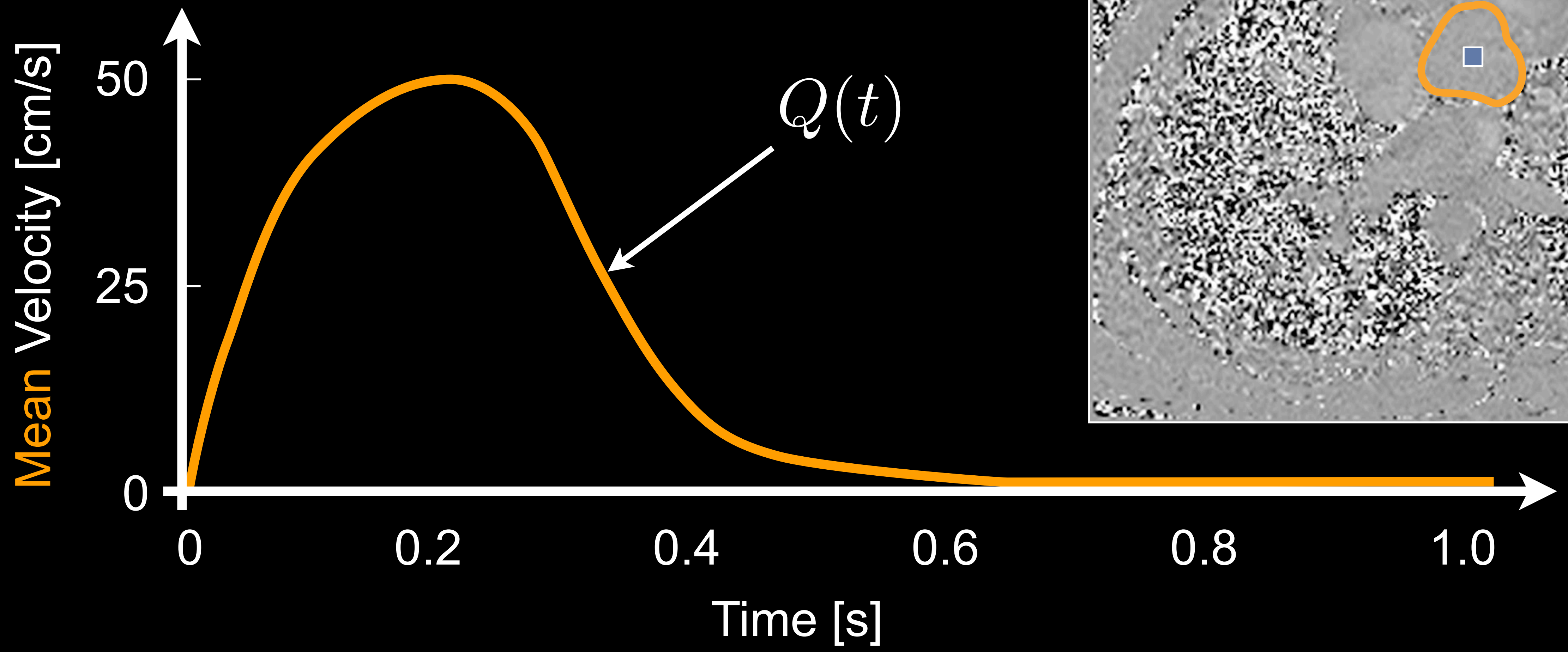
$$\vec{v}_i(t) \cdot \vec{A}_i(t)$$

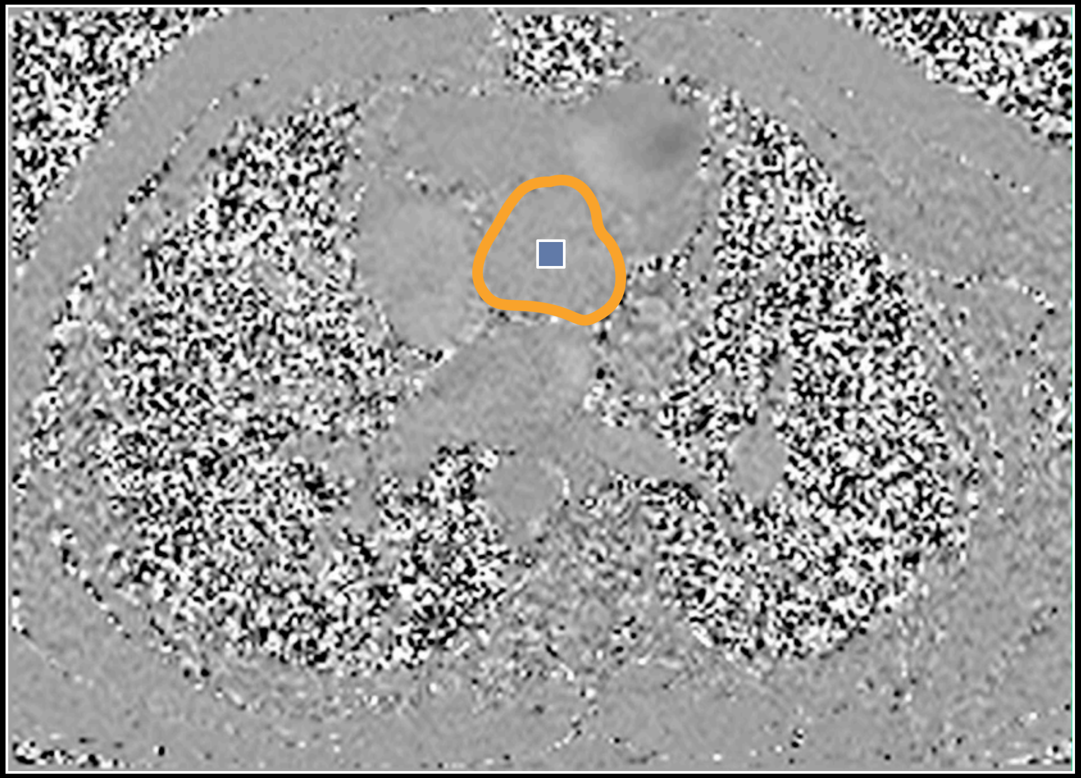
[cm/s] [cm^2]

Pixel Flow Rate

[mL/s]

Phase Contrast Analysis





$$\dot{V}(t) = Q(t) = \sum_{i=1}^{n_{ROI}} \vec{v}_i(t) \cdot \vec{A}_i(t)$$

Volume Flow Rate [mL/s]

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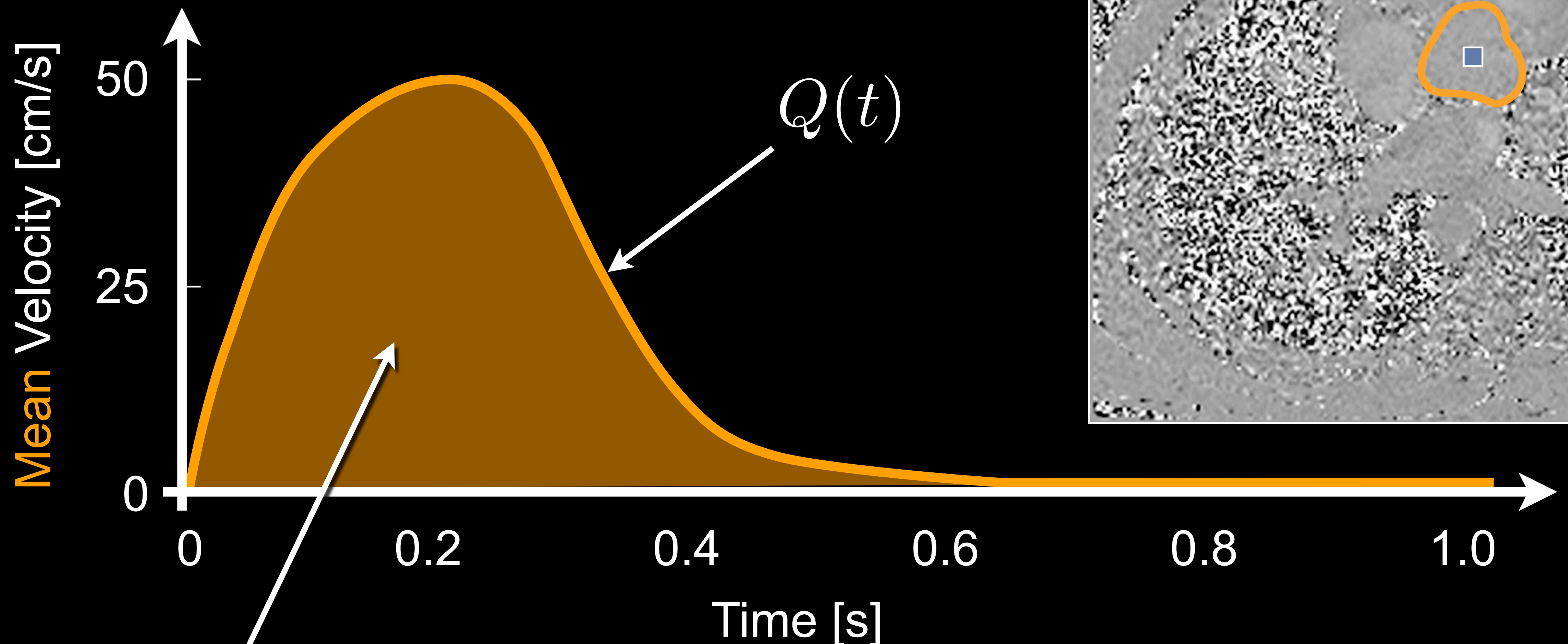
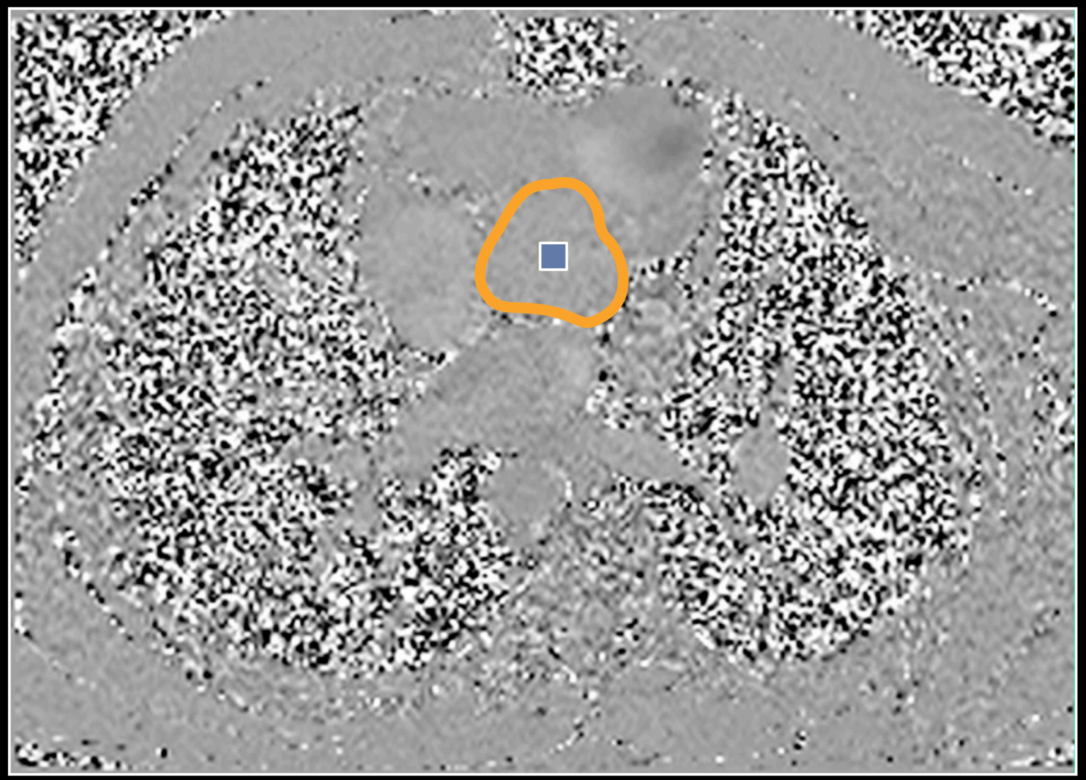
Phase Contrast Analysis



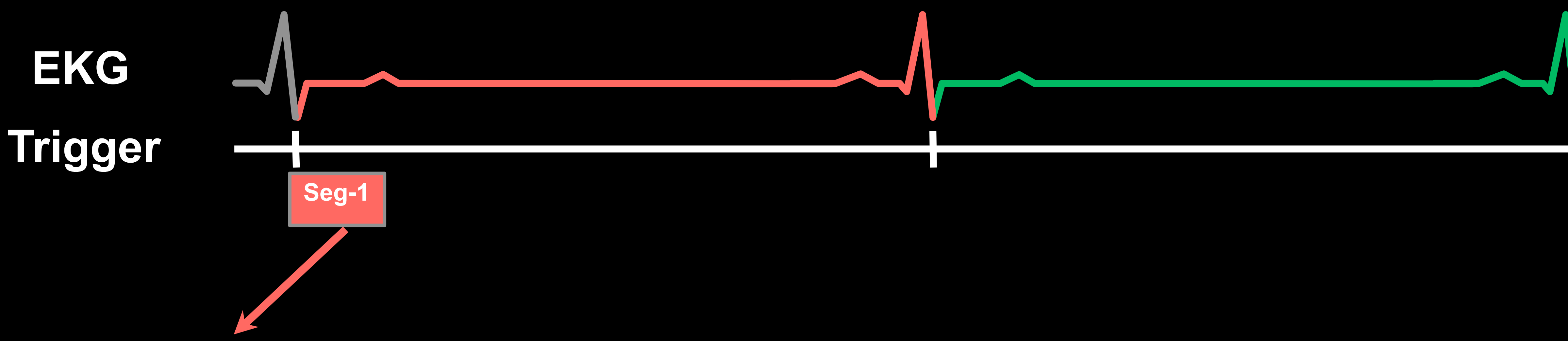


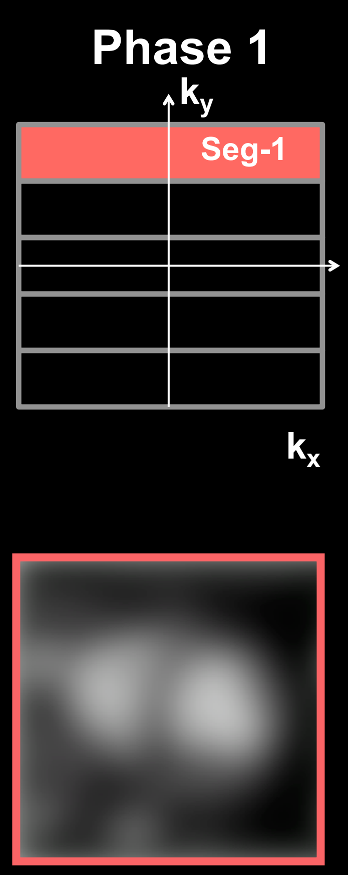
$$Q = \int \left(\sum_{i=1}^{n_{ROI}} \vec{v}_i(t) \cdot \vec{A}_i(t) \right) dt$$

Forward Flow [mL]

How do we acquire cardiac movies?

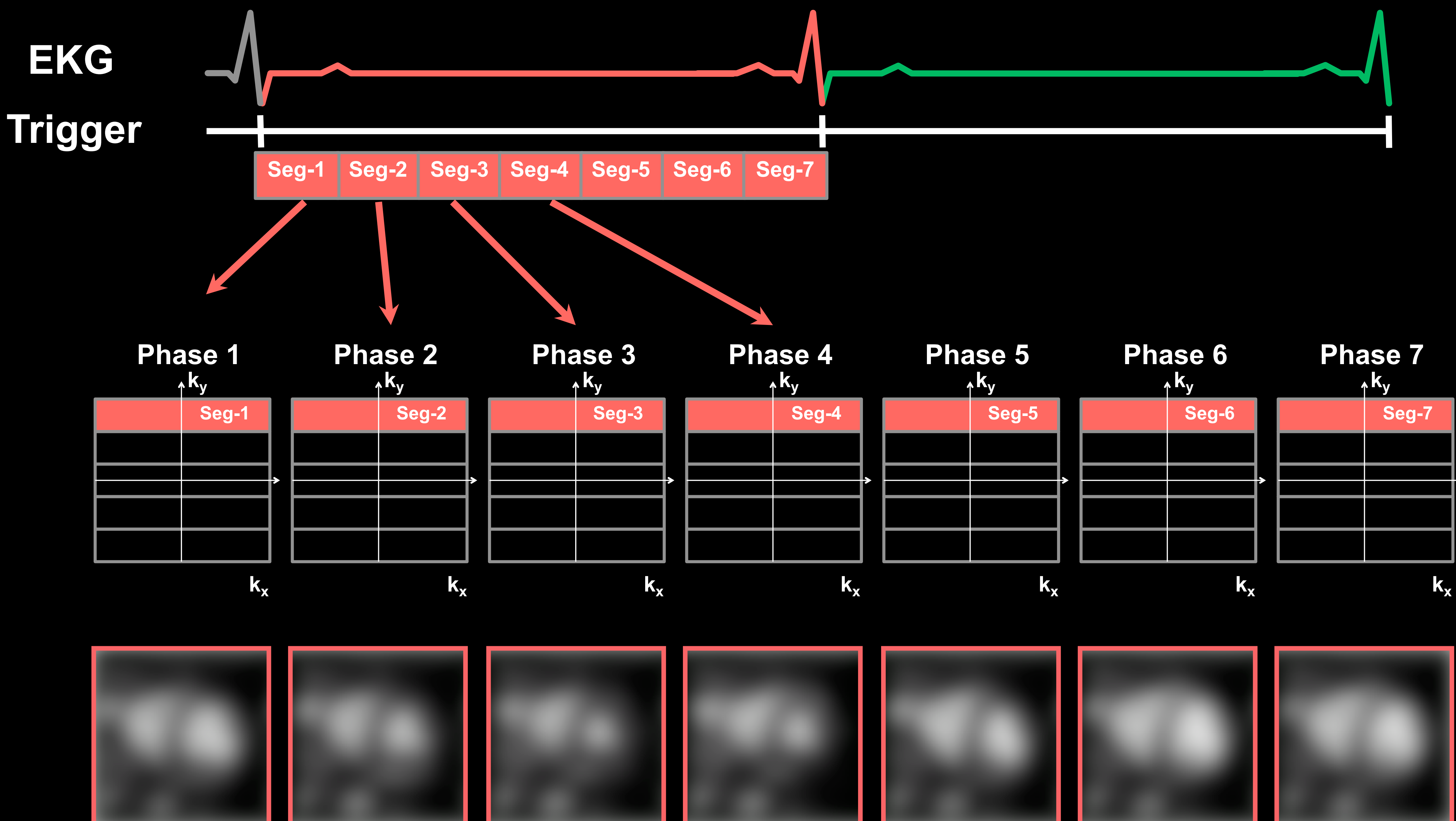
Conventional Segmented Imaging





$$t_{Segment} = TR \cdot N_{ky} = 8ms \cdot 6 = 48ms$$

Conventional Segmented Imaging



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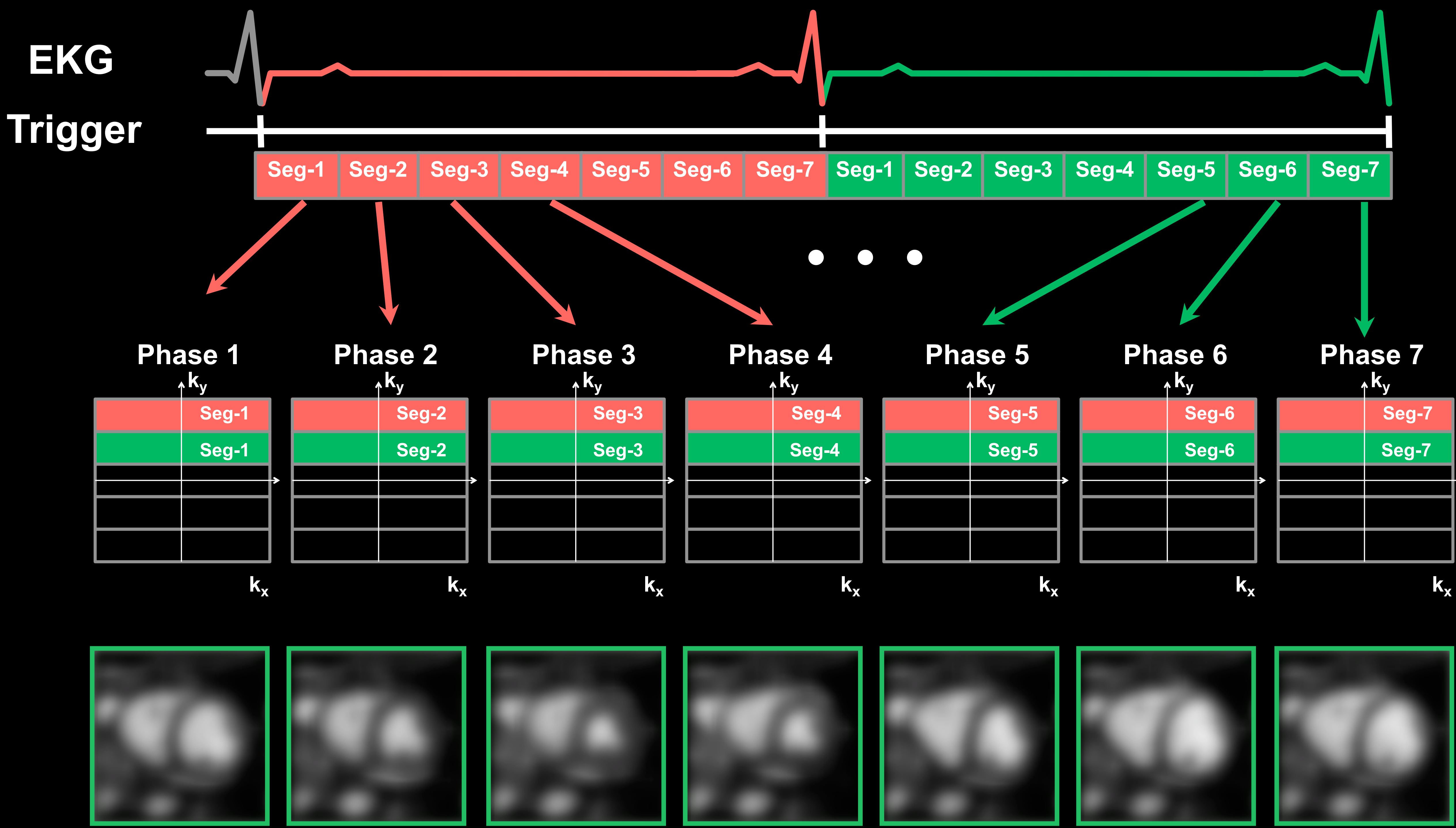
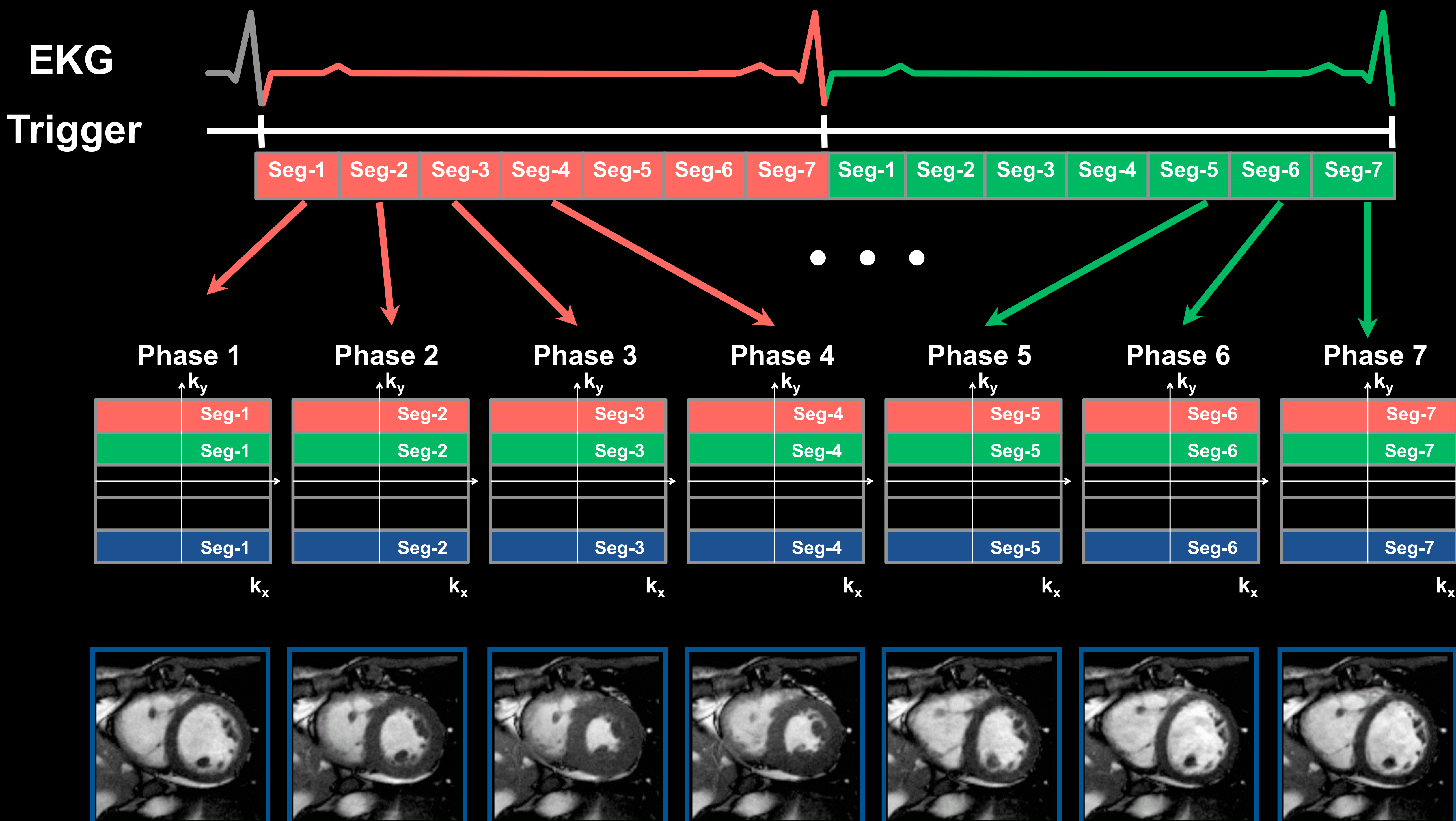
Conventional Segmented Imaging



Conventional Segmented Imaging



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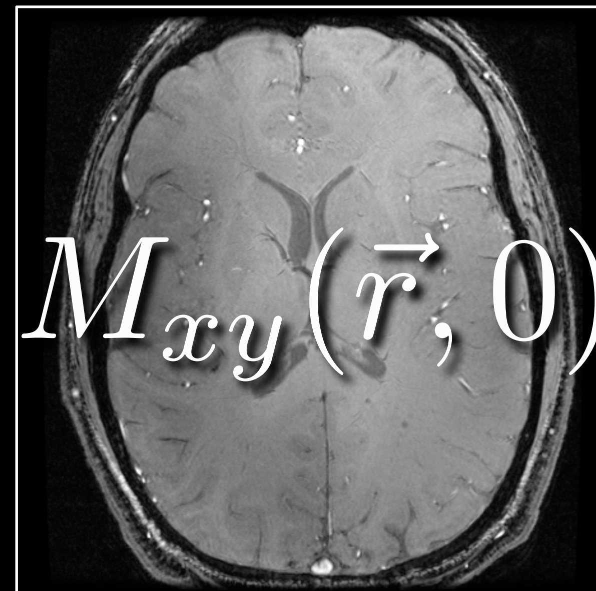
The Principle of Velocity Encoding

k-space Signal

$$S(\vec{k}) = \int M_{xy}(\vec{r},0)\; e^{-i2\pi\vec{k}\cdot\vec{r}}\; d\vec{r}$$



$object$

fourier sample

$$\Downarrow$$

$$I(x) = \Delta k \sum_{n=-\infty}^{\infty} S[n] e^{i2\pi n \Delta k x},\; |x| < \frac{1}{\Delta k}$$

M_{xy} and Images are Complex

$$\mathrm{M}_{xy}\left(\vec{r},\rho,T_1,T_2\right) = \left|\mathrm{M}_{xy}\left(\vec{r},\rho,T_1,T_2\right)\right| e^{i\phi}$$

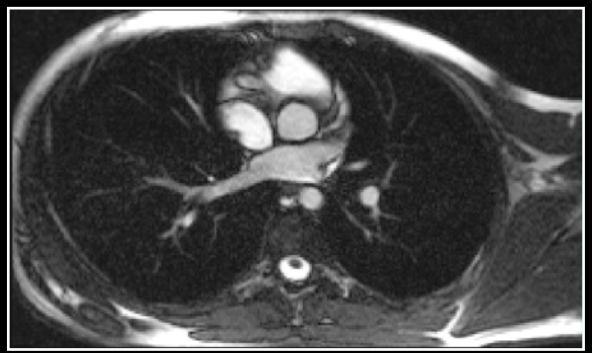
Transverse Magnetization **Magnitude** **Phase**

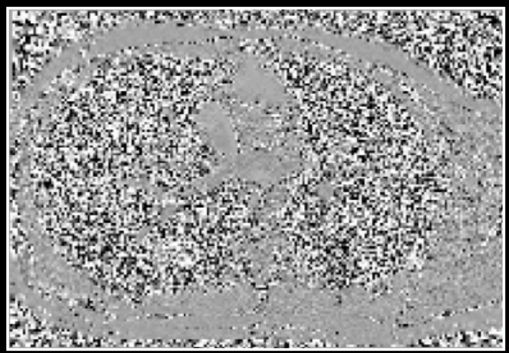
$$\Downarrow$$

Fourier Sampling
-and-
Signal Equation

$$I\left(\vec{r},\rho,T_1,T_2\right) = \left|I\left(\vec{r},\rho,T_1,T_2\right)\right| e^{i\phi}$$

Complex Image **Magnitude Image** **Phase Image**





Phase from many things...

ϕ_{CS}	Chemical Shift [1]	Can be minimized.
ϕ_{Sus}	Susceptibility [2]	Can be corrected.
$\phi_{\delta B_0}$	Inhomogeneity [2]	Can be corrected.
$\phi_{Maxwell}$	Maxwell terms [3]	Can be corrected.
ϕ_{Eddy}	Eddy currents [4]	Can be minimized.
$\phi_{velocity}$	Applied gradients [5]	Encode velocity!

(ϕ_{Sus} and $\phi_{\delta B_0}$ grouped as ϕ_{off})

$$\phi = \phi_{off} + \phi_{velocity}$$

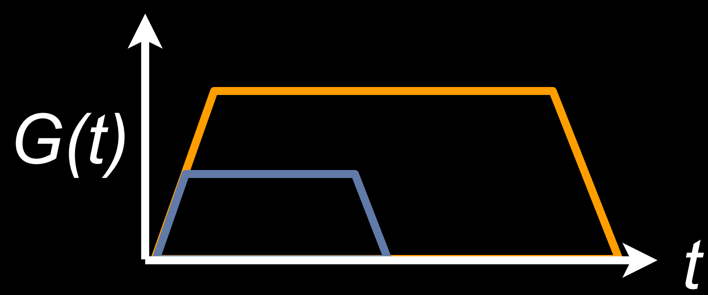
[1] Middione MRM 2013 [2] Bernstein JMRI 1991
[3] Bernstein MRM 1998 [4] Chernobelsky JCMR 2007 [5] Pelc Mag. Res. Qtr. 1991

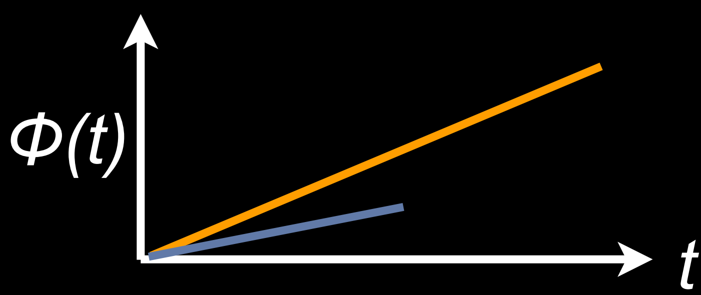
How do gradients encode velocity?

- **Phase arises from a gradient according to:**

$$\phi_{\vec{G}}(\vec{r}, t) = \gamma \int \vec{G}(t) \cdot \vec{r}(t) dt$$

  - **Stronger and longer gradients produce more phase**





- **Spin's position history**

$$\vec{r}(t) = \vec{r}_0 + \vec{v}_0 t + \frac{1}{2}\vec{a}_0 t^2 + \ldots$$

Initial Position — *Initial Velocity* — *Initial Acceleration*

  - **Taylor series expansion...**

To The Board…

Chapter 11

Magnetic Field Gradients

11.1 Phase From A Gradient

Gradients can be functions of time as can the position of a spin. The Larmor frequency for a spin in the presence of superposed B_0 and gradient fields in the Labtoratory frame is:

$$\omega(t) = \gamma[B_0 + \vec{G}(t) \cdot \vec{r}(t)] \tag{11.1.1}$$

Similarly, in the rotating frame we find:

$$\omega(t) = \gamma\vec{G}(t) \cdot \vec{r}(t) \tag{11.1.2}$$

The phase accorded to the bulk magnetization in the presence of a magnetic field gradient is:

$$\phi_G(\vec{r},t)|_{t_0}^{t_1} = \int_{t_0}^{t_1} \omega(t)dt = \gamma \int_{t_0}^{t_1} \vec{G}(t) \cdot \vec{r}(t)dt \tag{11.1.3}$$

In general, the position of a spin as a function of time can be written as a Taylor series expansion where we assume orders of motion higher than acceleration are negligible:

$$\vec{r}(t) = \vec{r}_0 + \vec{v}_0 t + \tfrac{1}{2}\vec{a}_0 t^2 + \ldots \tag{11.1.4}$$

When Eqn. 11.1.4 is substituted into Eqn. 11.1.3 it becomes apparent that the phase imparted on the bulk magnetization by a gradient is:

$$\phi_G(\vec{r},t)|_{t_0}^{t_1} = \gamma \int_{t_0}^{t_1} \vec{G}(t) \cdot (\vec{r}_0 + \vec{v}_0 t + \tfrac{1}{2}\vec{a}_0 t^2)dt \tag{11.1.5}$$

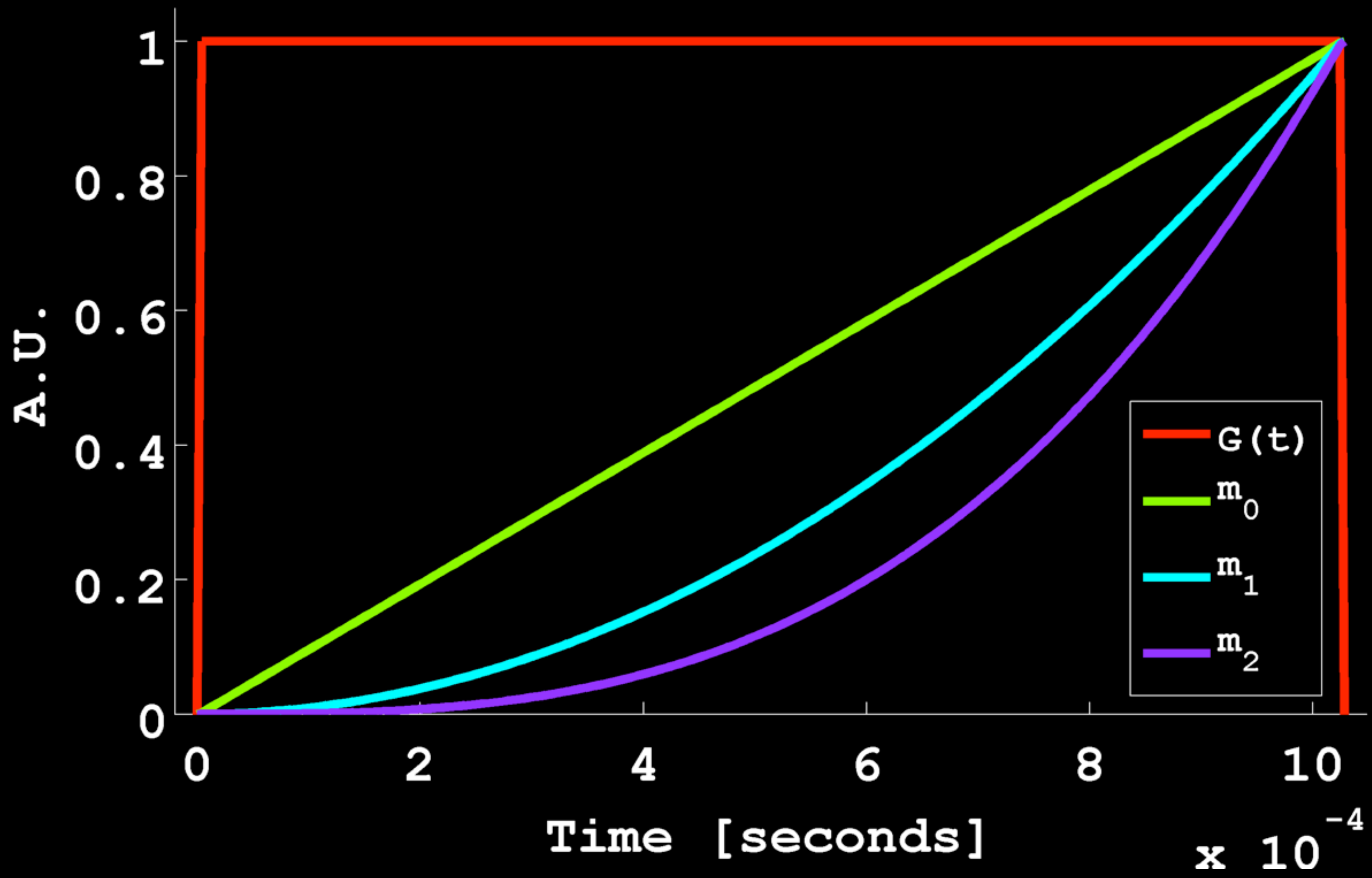
Therein the dependence on terms of an order higher than acceleration ($\vec{a}_0$) have been dropped and it is apparent that there exists a series of terms of the form $\vec{G}(t)t^n$, which accords with the definition of the gradient moments ($\vec{M}_n$):

$$\vec{M}_n = \frac{\gamma}{n!} \int_{t_0}^{t_1} \vec{G}(t)t^n dt \tag{11.1.6}$$

Consequently Eqn. 11.1.5 can be written using Eqn. 11.1.6 as follows:

$$\phi_G(\vec{r},t)|_{t_0}^{t_1} = \sum_{n=0} \vec{M}_n \frac{d^n\vec{r}}{dt^n} \tag{11.1.7}$$

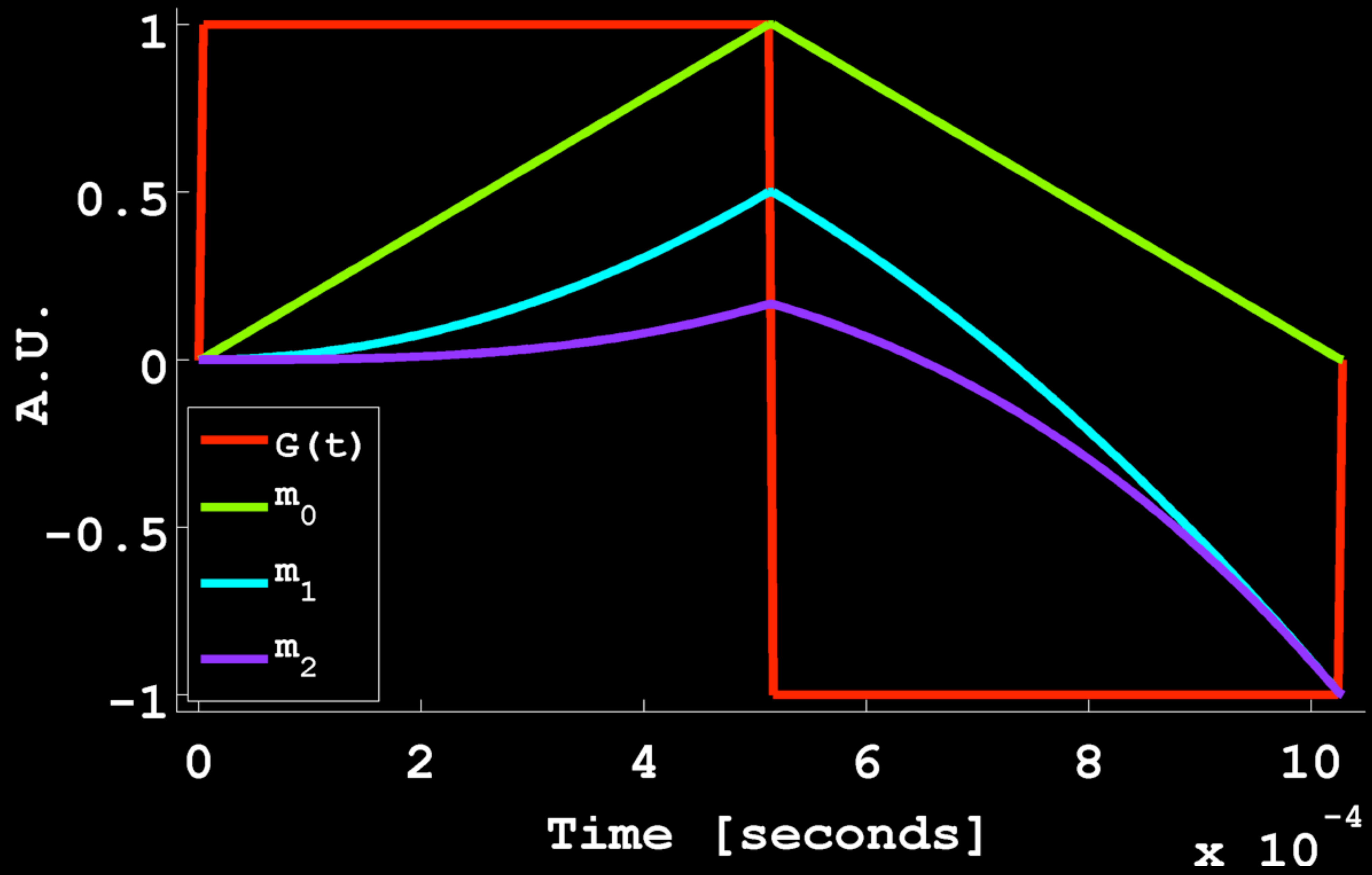
No Compensation



$$\phi_G = \gamma \left[\vec{M}_0 \cdot \vec{r}_0 + \vec{M}_1 \cdot \vec{v}_0 + \frac{1}{2} \vec{M}_2 \cdot \vec{a}_0 \ldots \right]$$

Spin phase (Φ_G) accumulates from position, velocity, and acceleration.

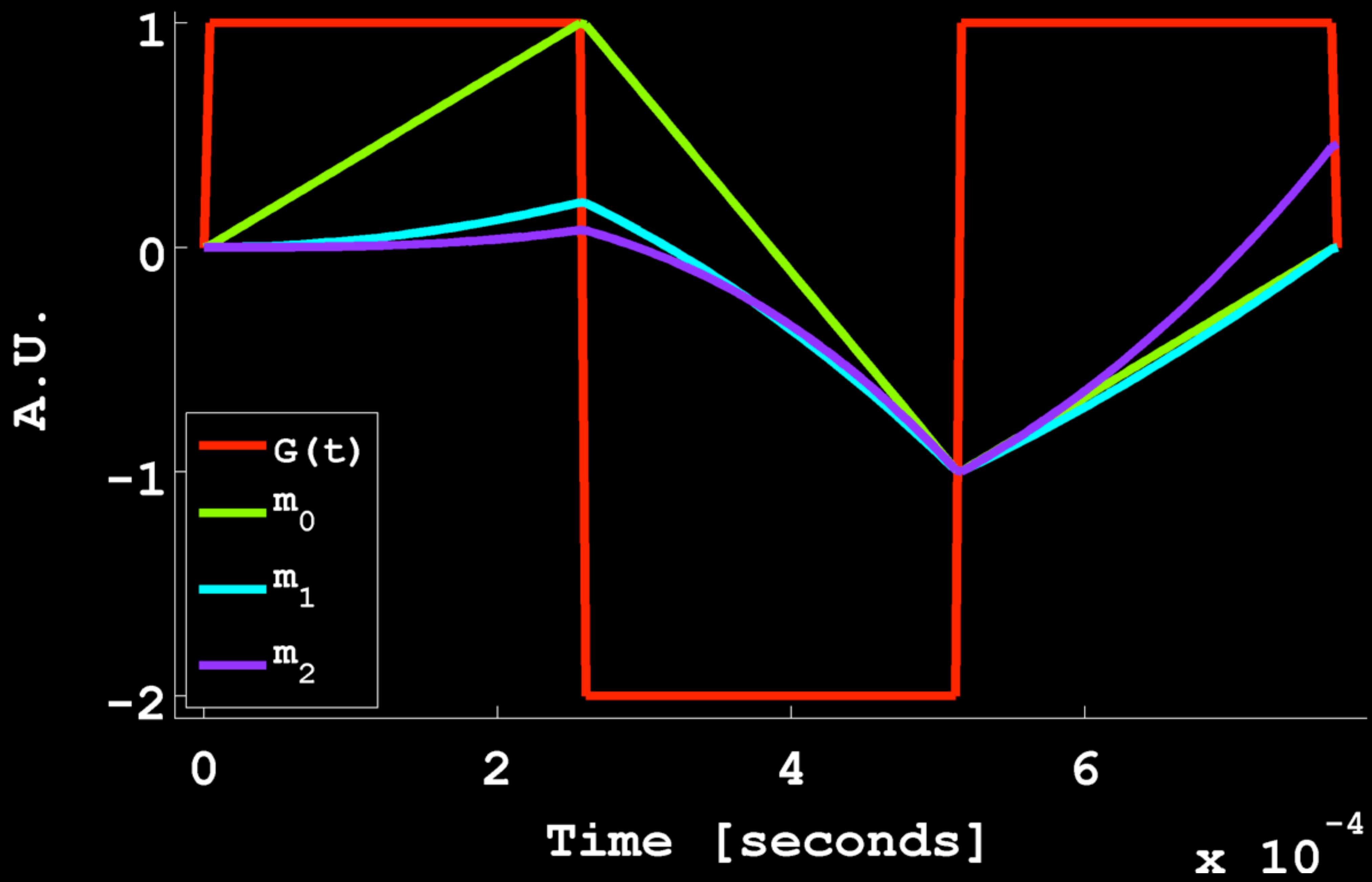
Position Compensation



$$\phi_G = \gamma \left[\vec{M}_1 \cdot \vec{v}_0 + \frac{1}{2} \vec{M}_2 \cdot \vec{a}_0 \ldots \right]$$

Spin phase (Φ_G) accumulates from velocity and acceleration.

Velocity Compensation



$$\phi_G = \gamma \left[\frac{1}{2} \vec{M}_2 \cdot \vec{a}_0 \ldots \right]$$

Spin phase (Φ_G) accumulates from acceleration.

How do gradients encode velocity?

- **Taken together**

$$\phi_G(\vec{r},t) = \gamma \int \vec{G}(t) \cdot \left[\vec{r}_0 + \vec{v}_0 t + \tfrac{1}{2}\vec{a}_0 t^2\right] dt$$

- **For 2D through-plane velocity measurements:**

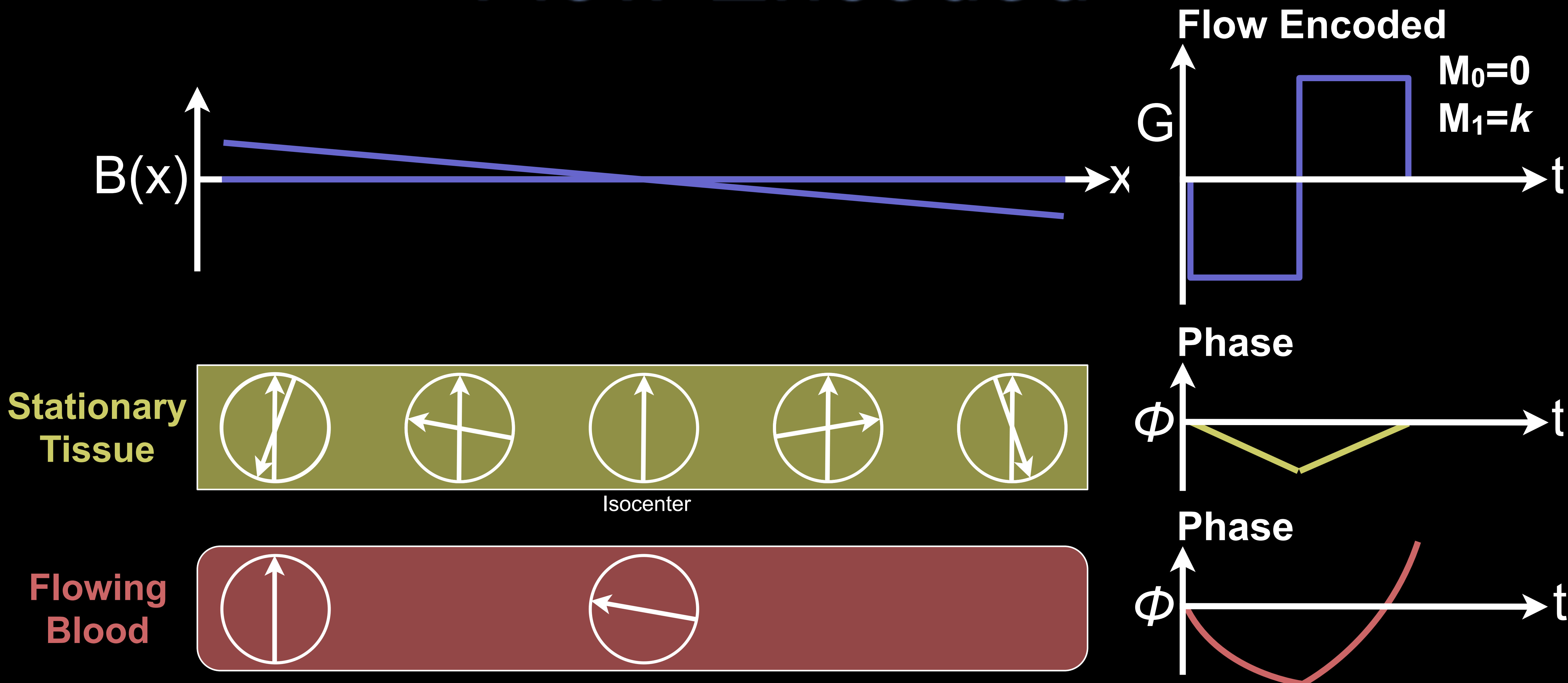
$$\phi = \underbrace{\phi_{off}}_{\text{Off-resonance}} + \underbrace{\gamma M_{0,z} \cdot r_{0,z}}_{\text{Position Encoding}} + \underbrace{\gamma M_{1,z} \cdot v_{0,z}}_{\text{Velocity Encoding}}$$

$$M_{0,z} = \int_0^{\tau} G_z(t)dt \qquad M_{1,z} = \int_0^{\tau} G_z(t)tdt$$

Design M_0 to be zero.

Design M_1 to control velocity sensitivity.

Flow Encoded

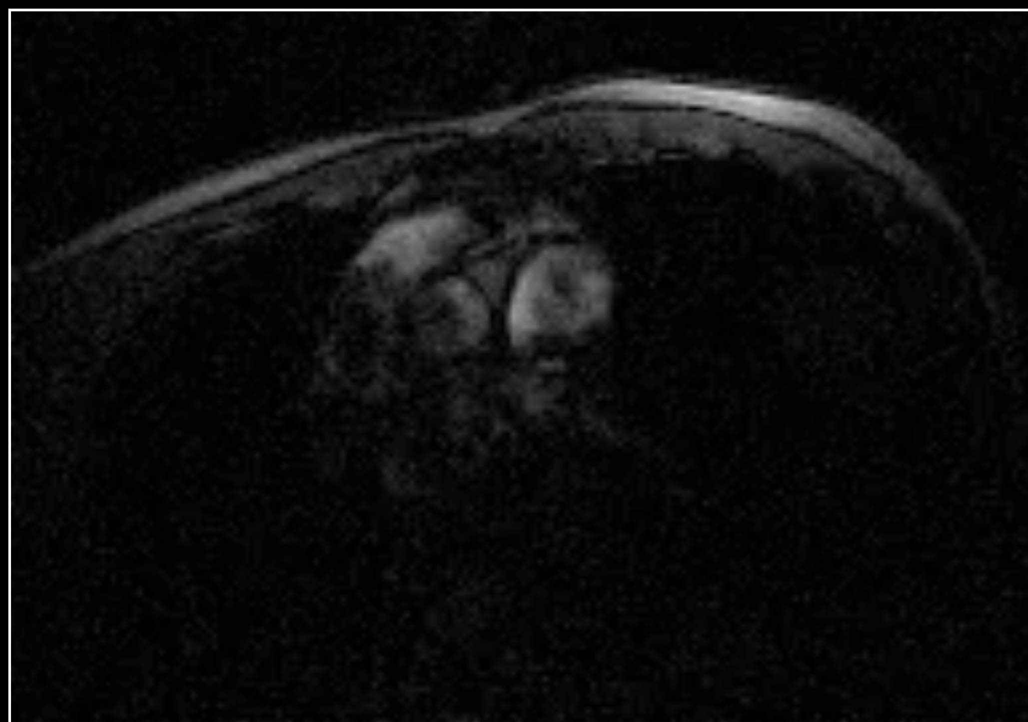


$$\phi_{FE} = \phi_{off} + \gamma \left[\vec{M}_1 \cdot \vec{v}_0 \right]$$

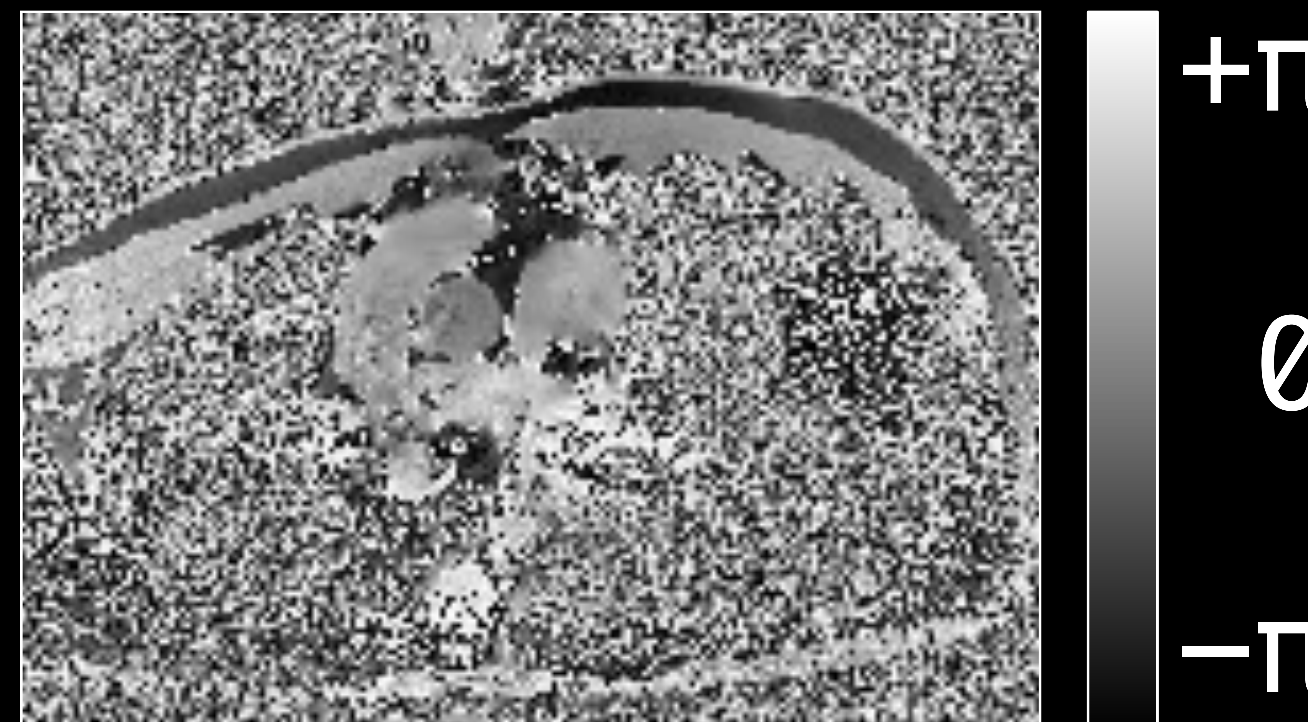
Spin phase (Φ_{FE}) accumulates from off-resonance ***and*** velocity.

Theory – Flow Encoding

Magnitude

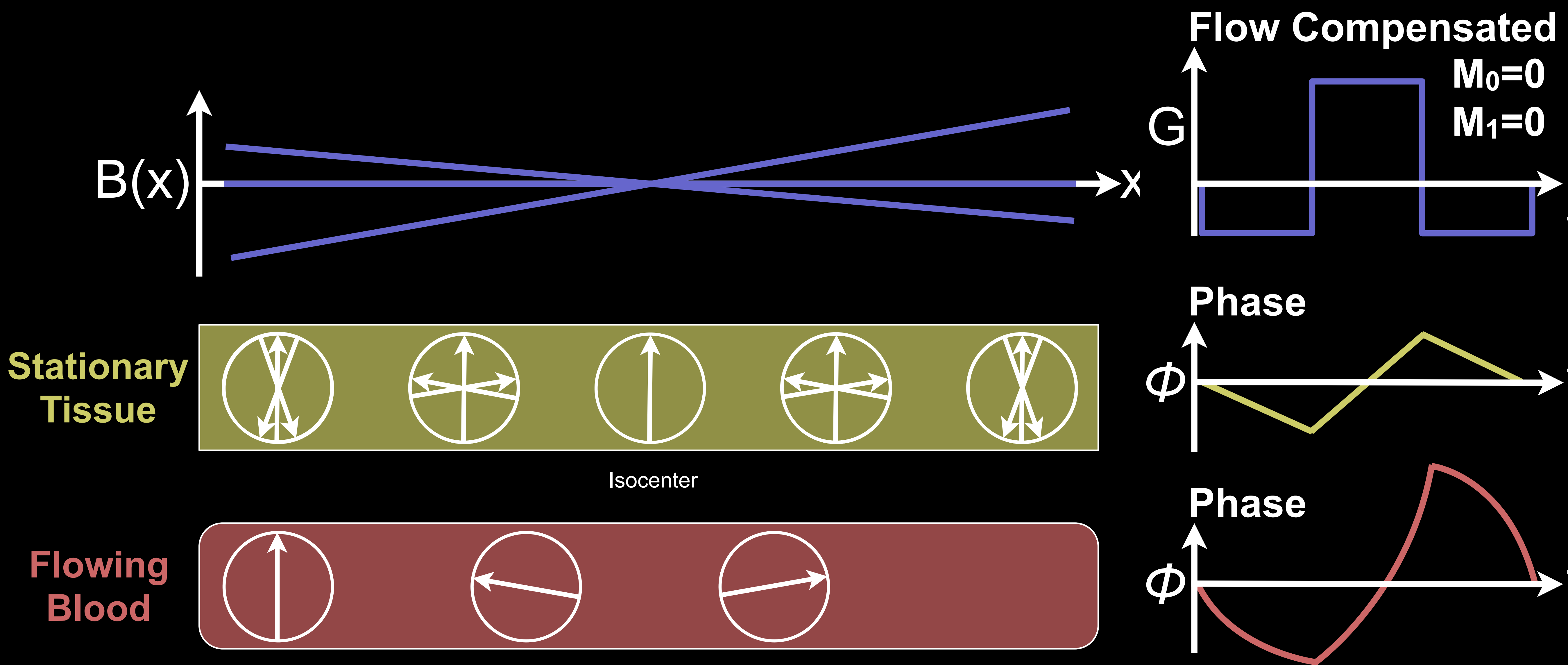


Phase



$$\phi_{FE} = \phi_{off} + \gamma M_{1,z} \cdot v_z$$

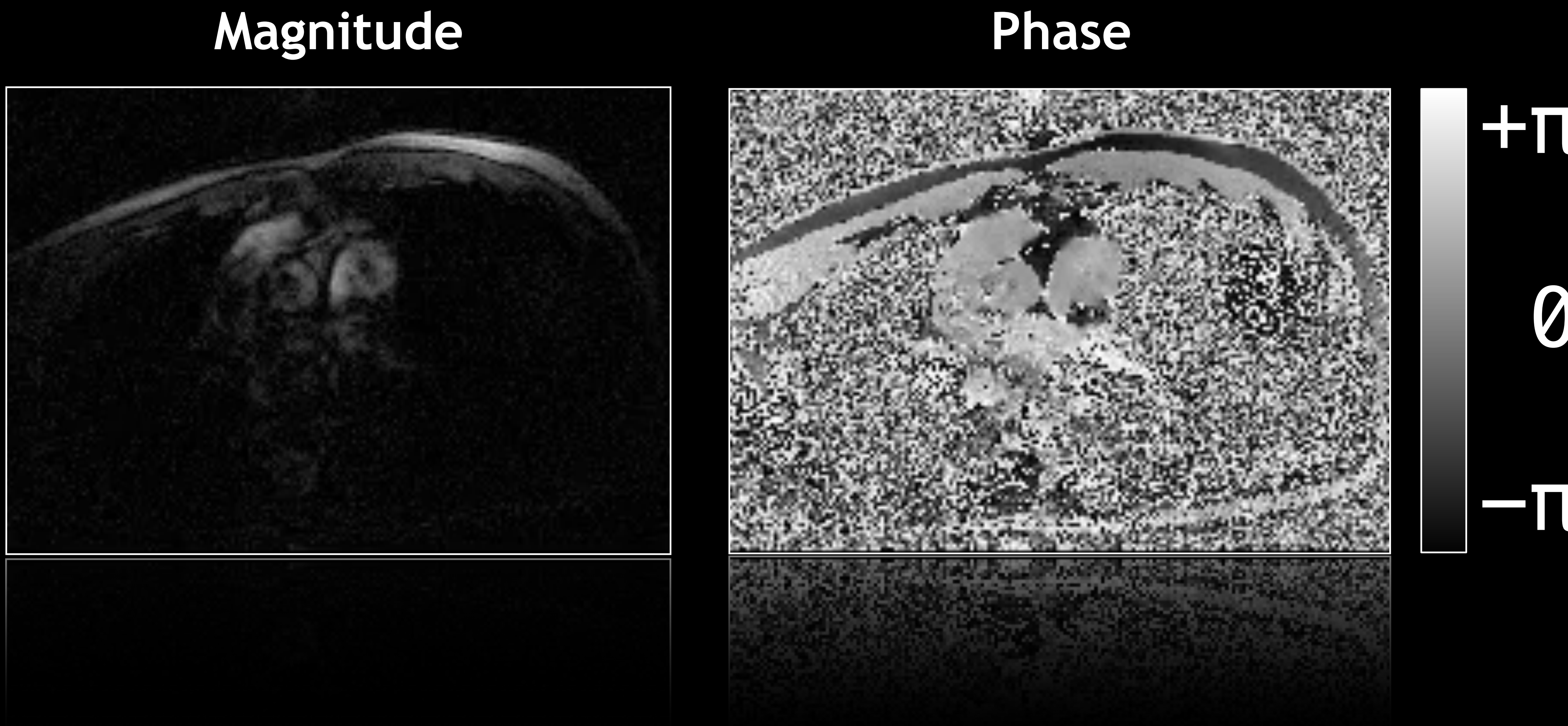
Flow Compensation



$$\phi_{FC} = \phi_{off}$$

Spin phase (Φ_{FC}) ***only*** accumulates from ***off resonance.***

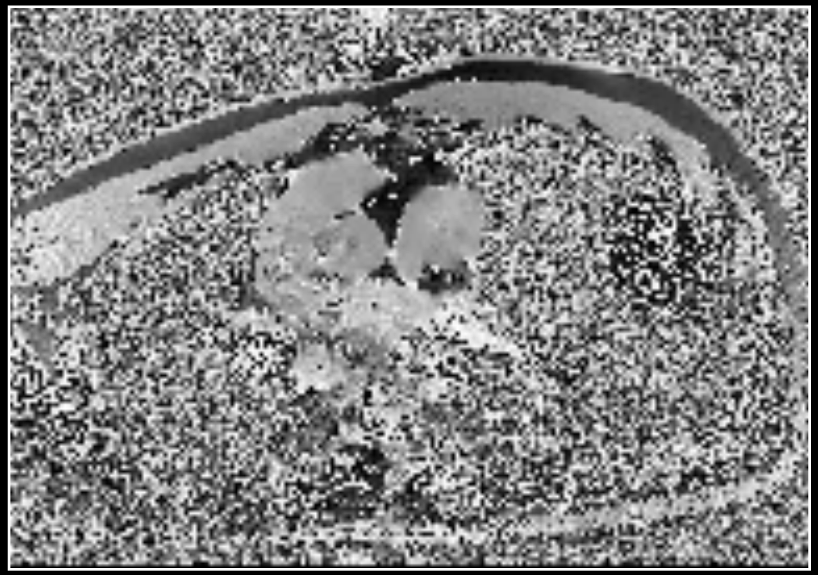
Theory – Flow Compensation



$$\phi_{FC} = \phi_{off}$$

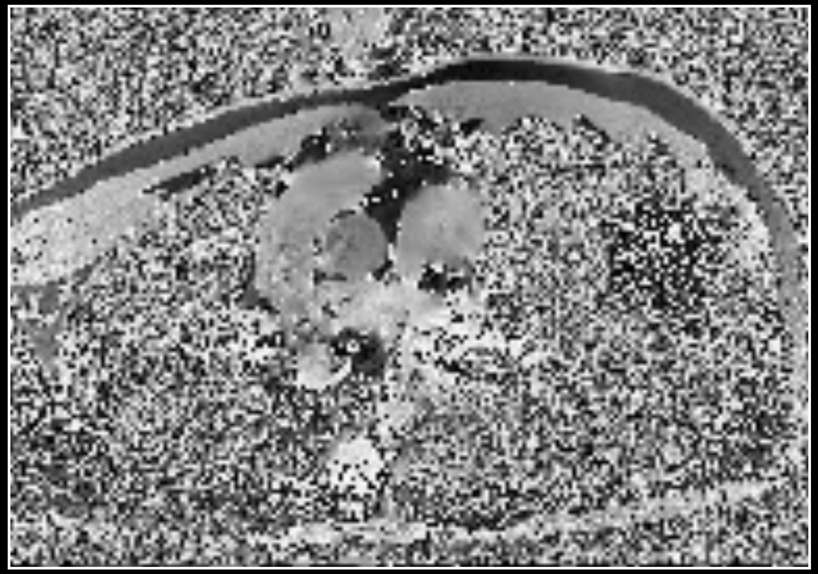
Theory - Echo Combining

FC



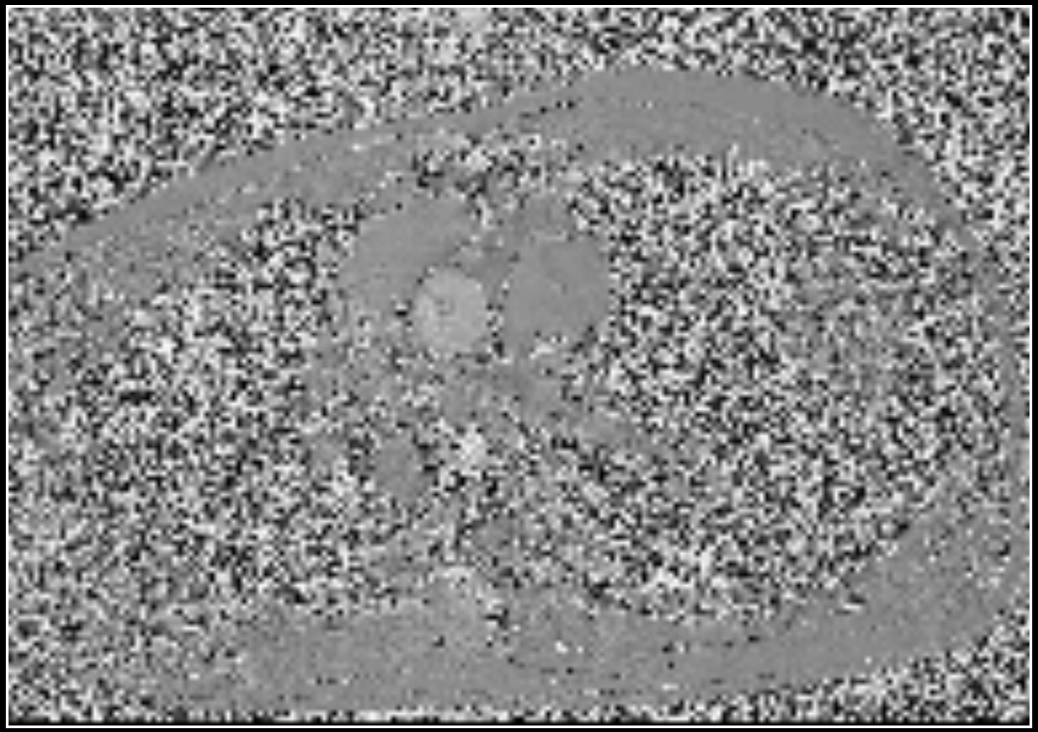
$$\phi_{FC} = \phi_{off}$$

FE



$$\phi_{FE} = \phi_{off} + \gamma M_{1,z} \cdot v_z$$

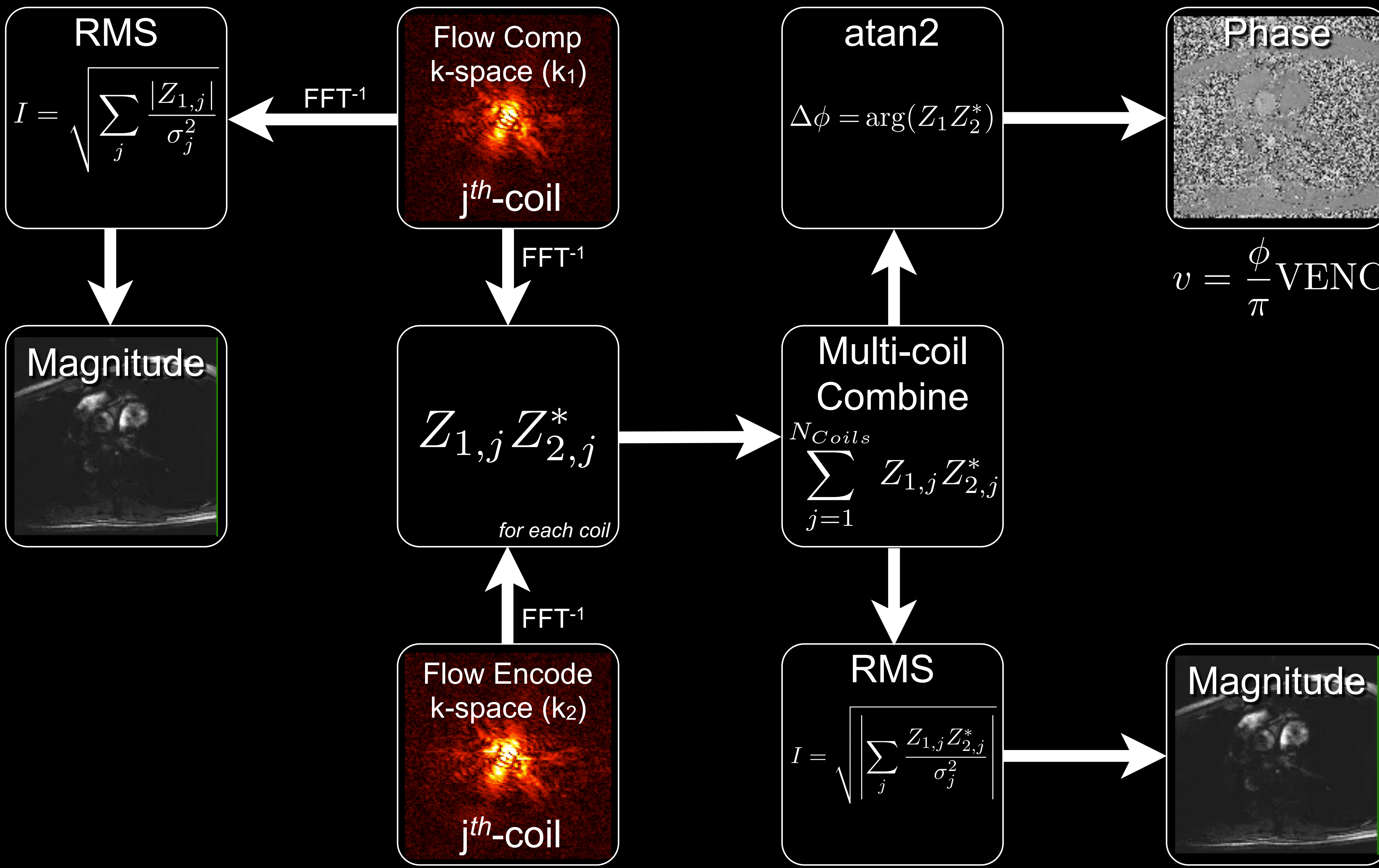
Velocity Map



$$\Delta\phi = \gamma v_z \Delta M_{1,z}$$

Bi-polar Encoding
Uses Two Non-Zero M_1s

Do we phase difference the data? Not exactly....



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Adapted from Bernstein's *Handbook of MRI Pulse Sequences (p. 560)*

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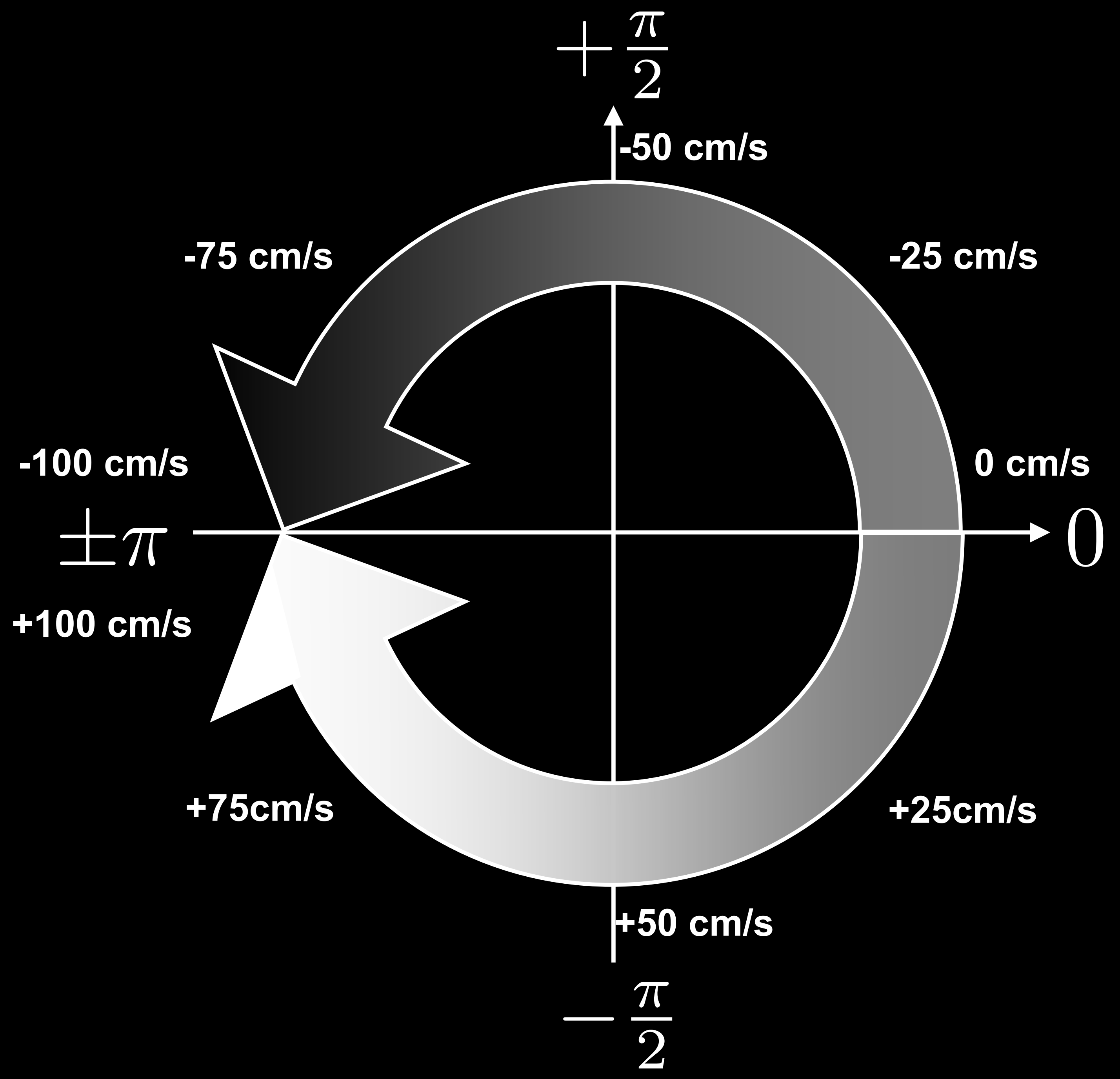
Velocity Sensitivity

$$\Delta\phi = \gamma v_z \Delta M_{1,z}$$

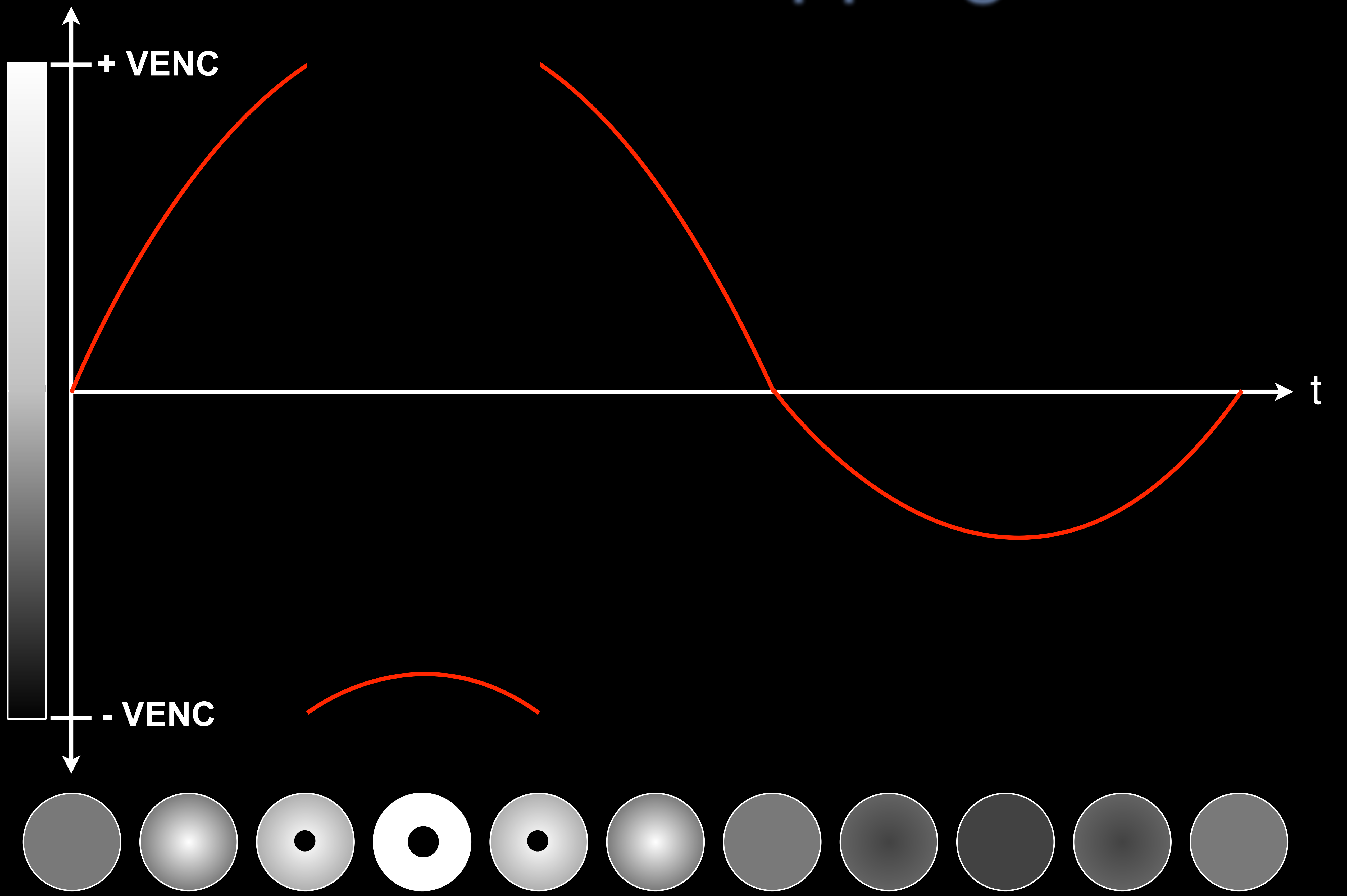
$$\Downarrow$$

$$VENC = \frac{\pi}{\gamma|\Delta M_{1,z}|}$$



- Phase images can be reconstructed on [-π,+π]
  - VENC defines the velocity that produces a phase shift of ±π

Phase Wrapping



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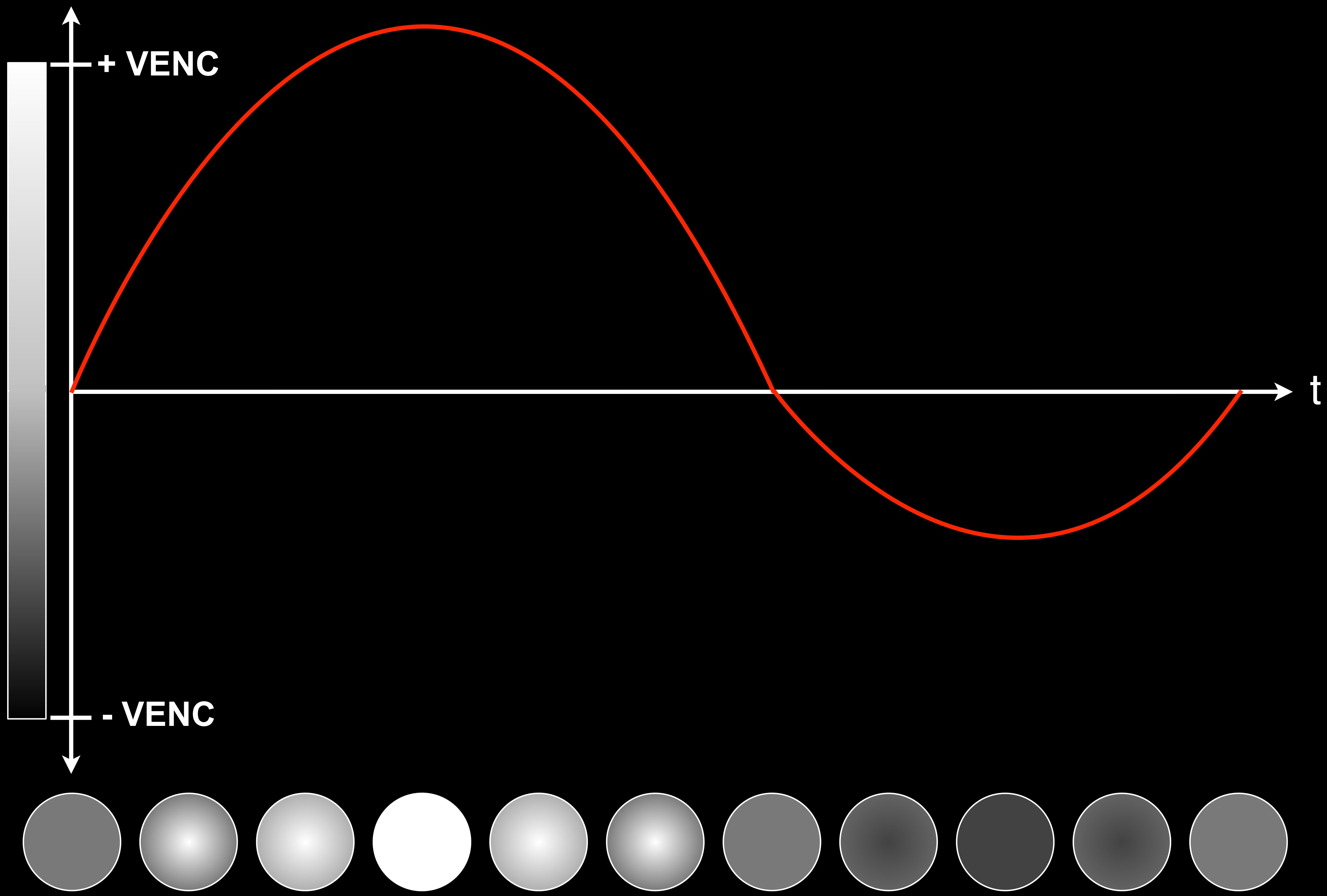
Phase Un-Wrapping

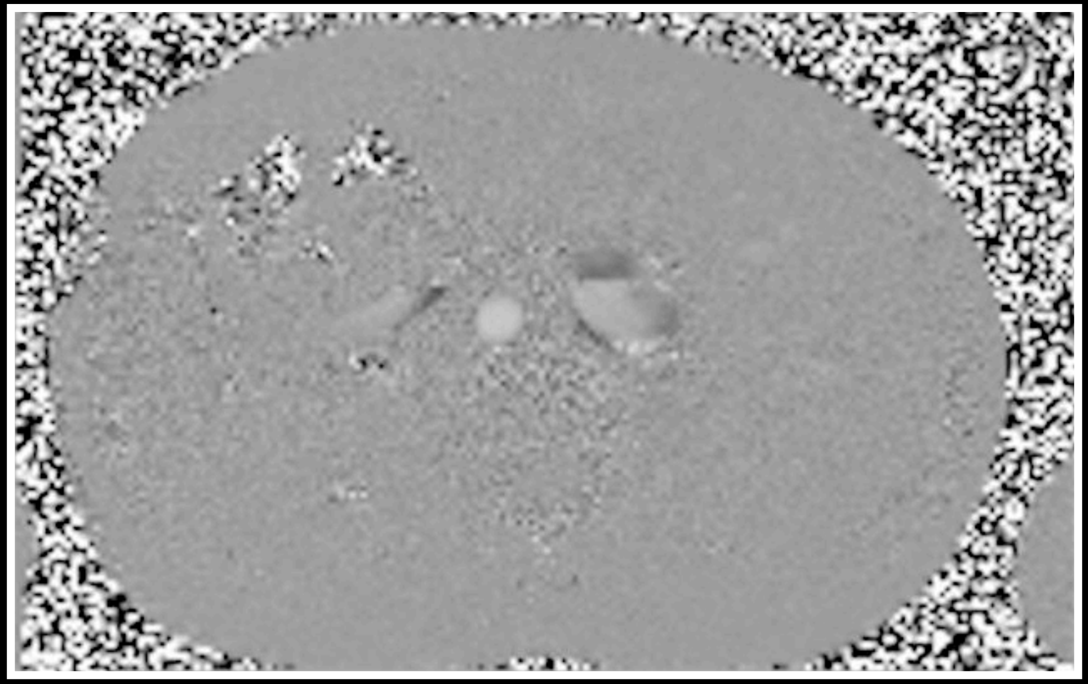


Phase Contrast

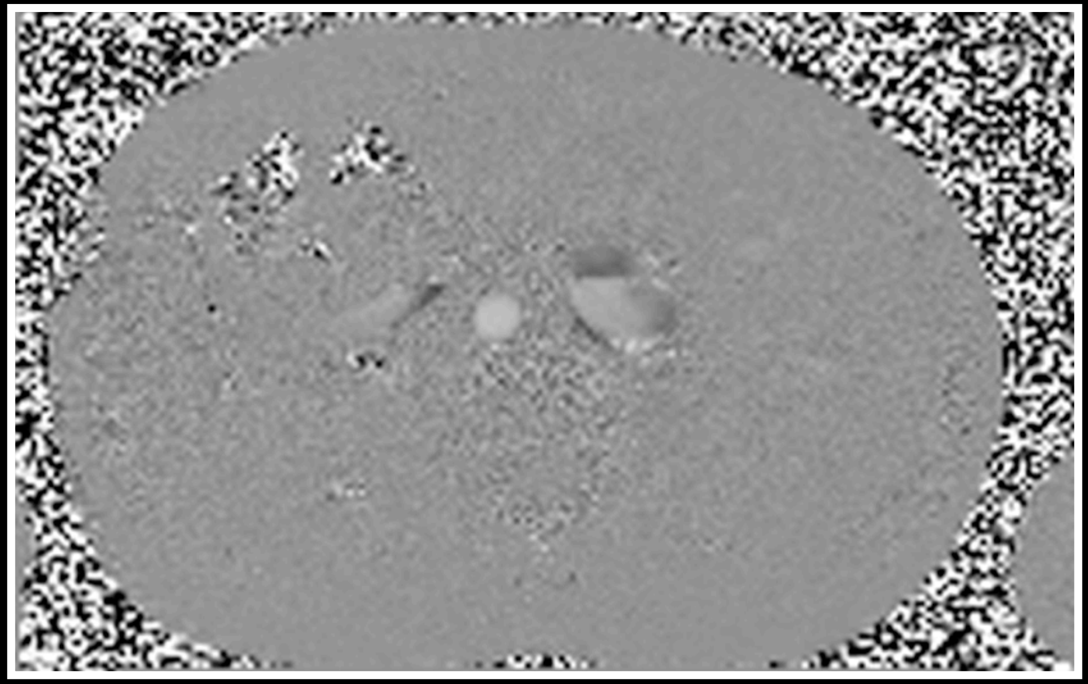
$$\mathrm{VENC} = \frac{\pi}{|\gamma \Delta M_1|}$$

- **VENC typically has units of [cm/s]**
- **HIGH VENC**
  - **Low sensitivity**
  - **Smaller gradient waveform**
  - **"Unlikely" to phase wrap**
- **LOW VENC**
  - **High sensitivity**
  - **Larger gradient waveforms**
  - **"Likely" to phase wrap**

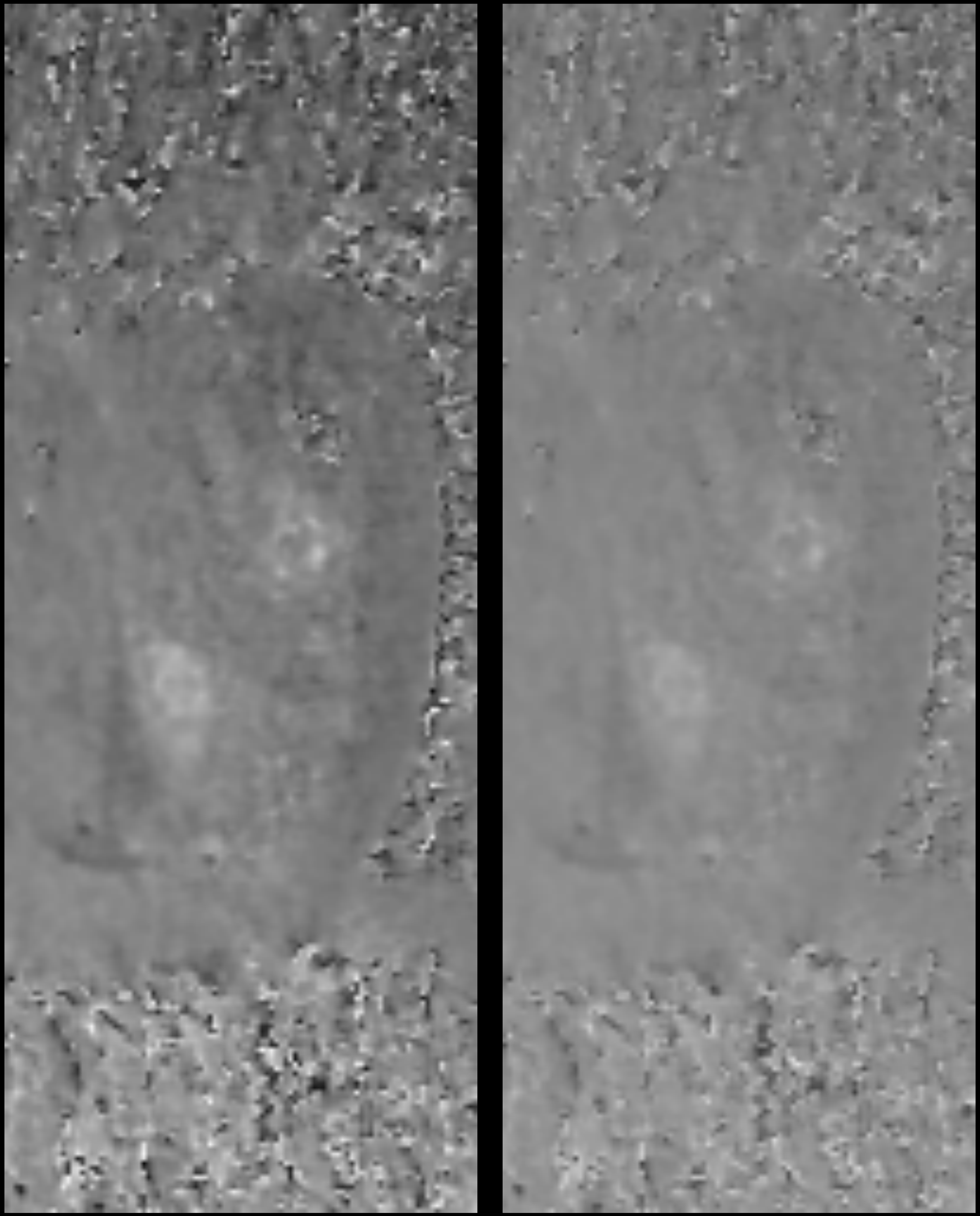
Phase Wrapping



Phase Wrapping - VENC Too Low

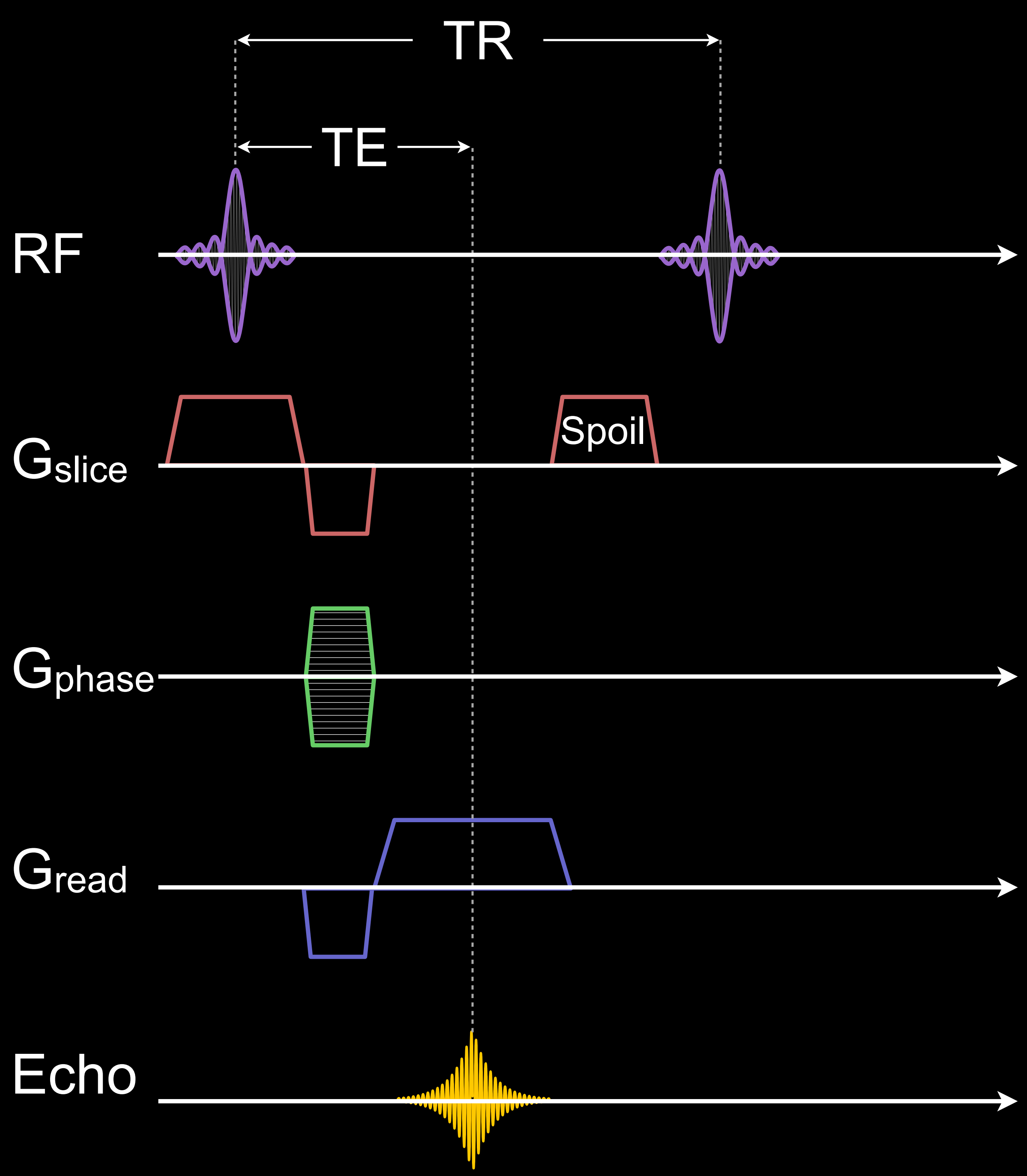


No Phase Wrapping – VENC Just Right

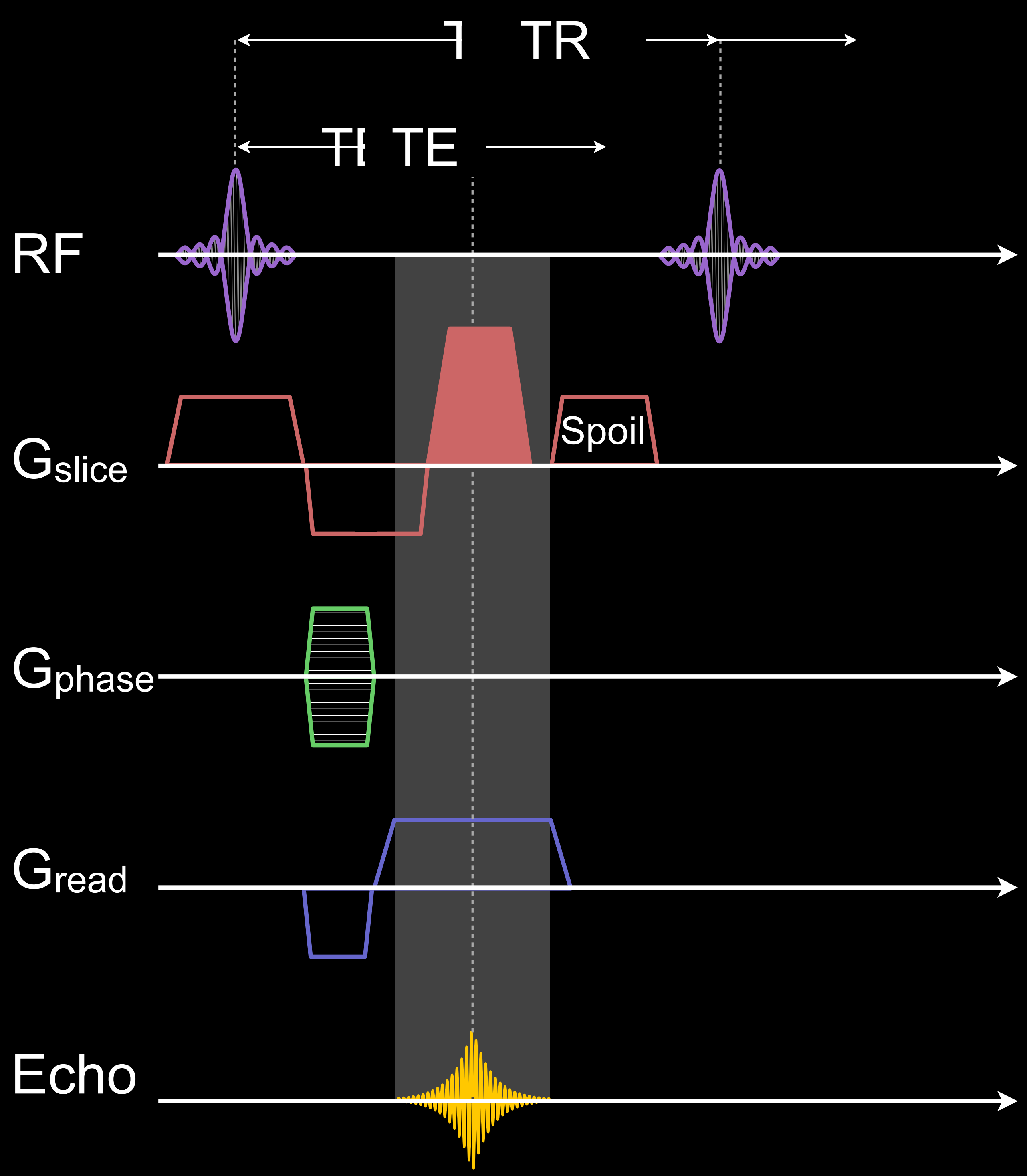


How do we build the sequence?

Spoiled GRE Sequence



Flow Compensated Echo

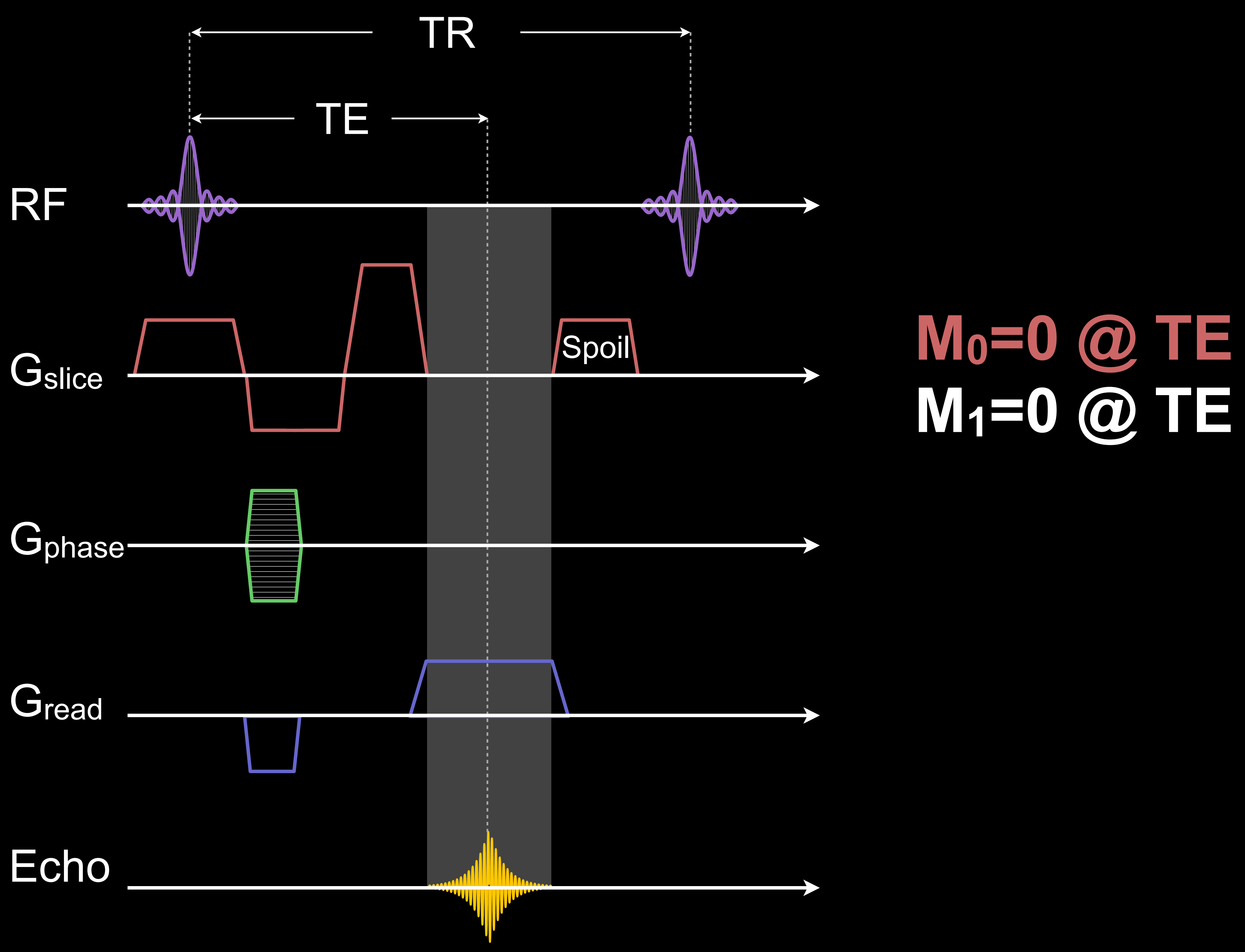


$M_0=0$ @ TE

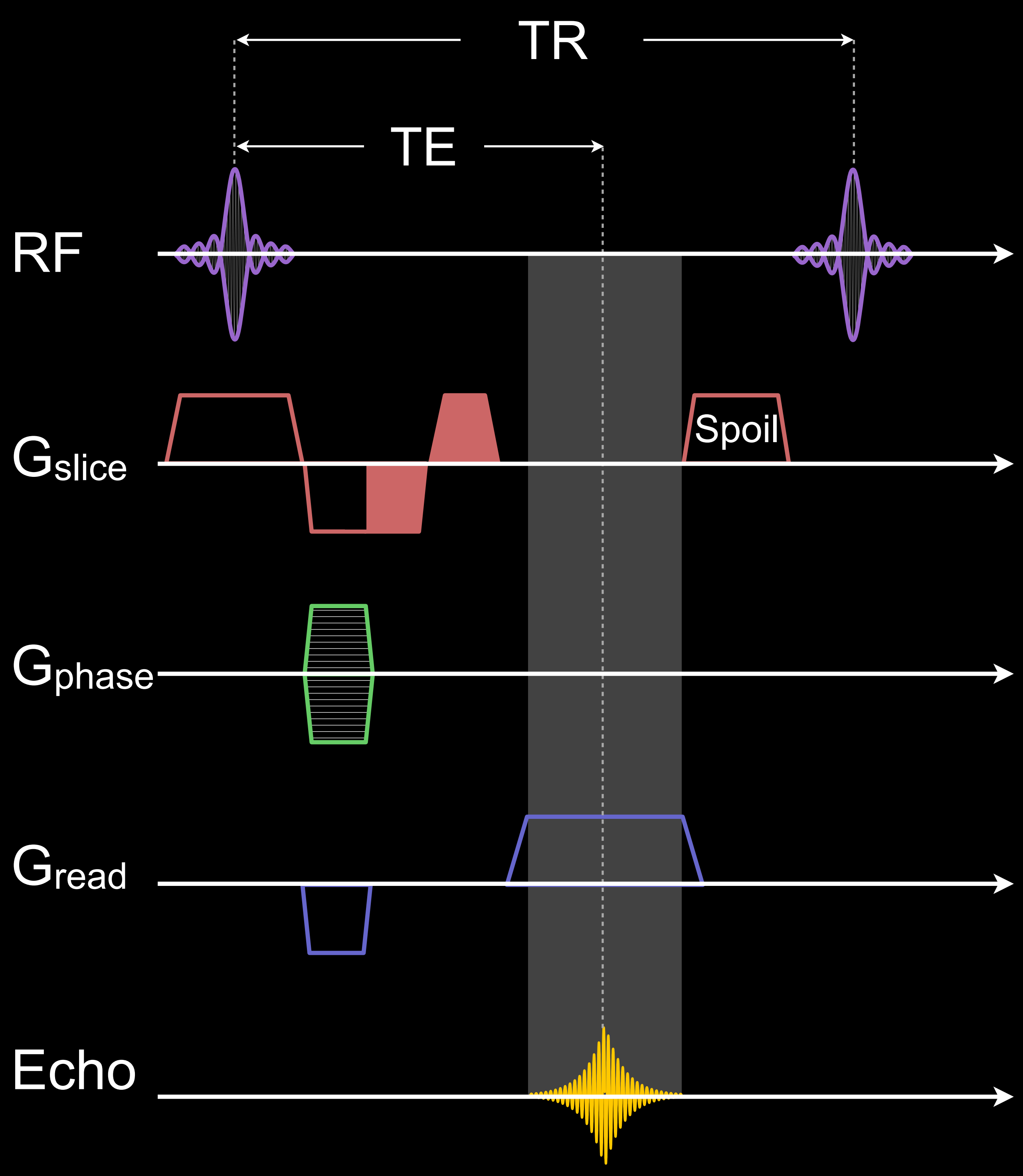
$M_1=0$ @ TE

The TR in PCMRI is 5-15% longer.

Flow Compensated Echo



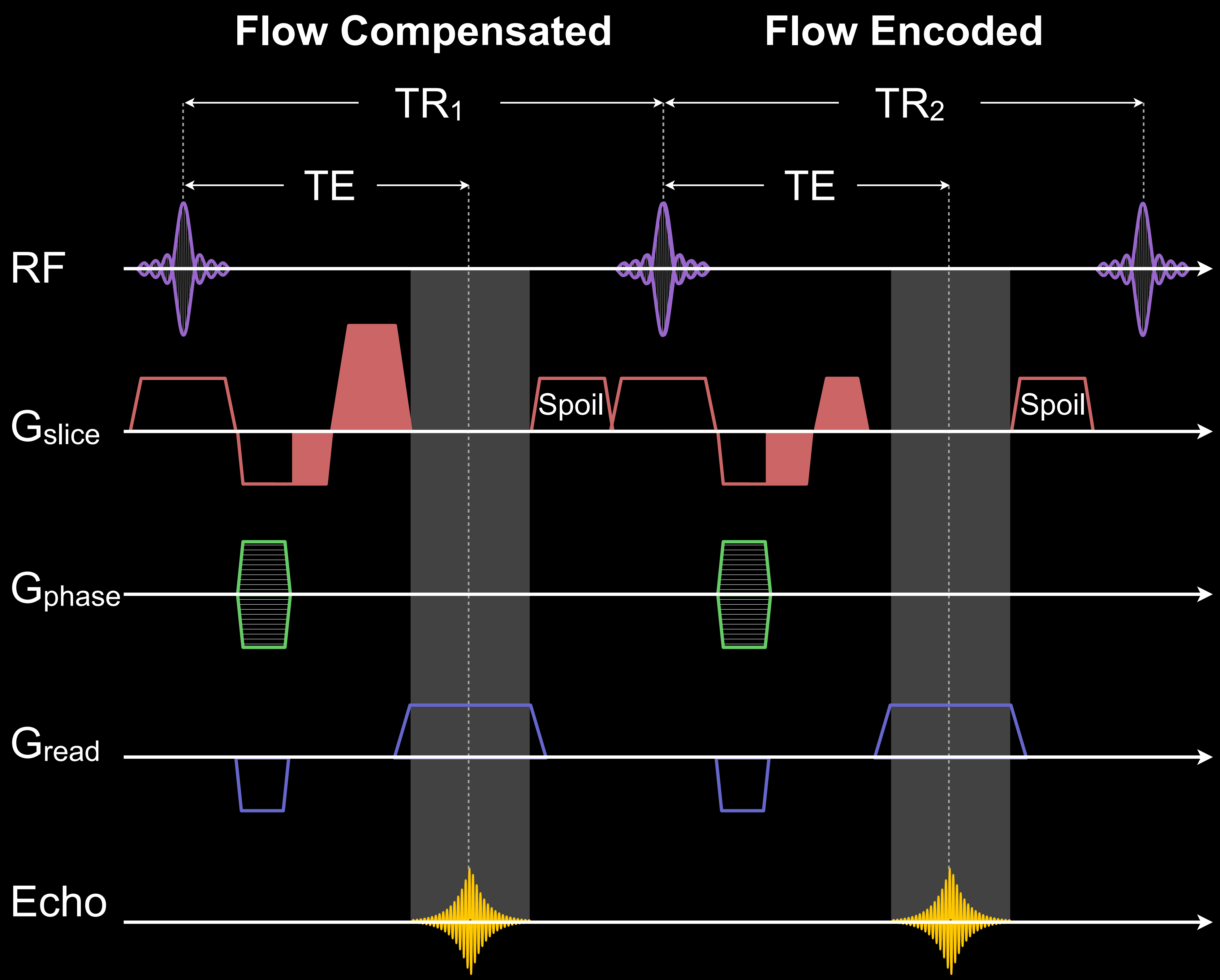
Flow Encoded Echo



$M_0 = 0$ @ TE

$M_1 \propto 1/VENC$ @ TE

PC-MRI Sequence



Need to acquire two echoes, therefore temporal resolution decreased.

PC-MRI Sequence

- The TE & TR are extended to accommodate:
  - Flow compensation
  - Flow encoding
- Two TRs are needed to measure phase
  - Corrects for background off-resonance
  - Requires twice as much scan time

Eddy Currents

Phase from many things...

ϕ_{CS}	Chemical Shift [1]	Can be minimized.
ϕ_{Sus}	Susceptibility [2]	Can be corrected.
$\phi_{\delta B_0}$	Inhomogeneity [2]	Can be corrected.
$\phi_{Maxwell}$	Maxwell terms [3]	Can be corrected.
ϕ_{Eddy}	Eddy currents [4]	Can be minimized.
$\phi_{velocity}$	Applied gradients [5]	Encode velocity!

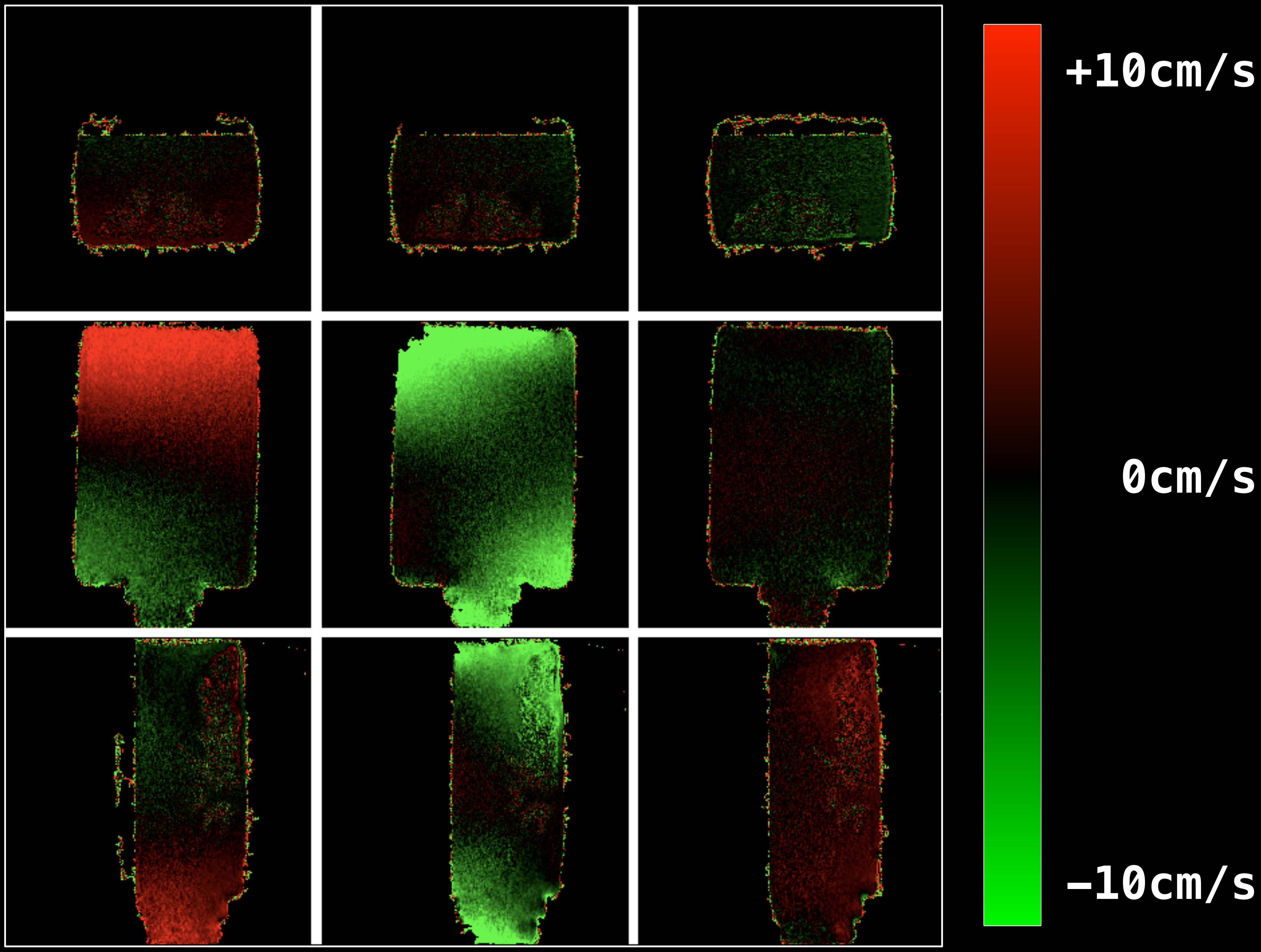
(ϕ_{Sus} and $\phi_{\delta B_0}$ together: ϕ_{off})

$$\phi = \phi_{off} + \phi_{velocity}$$

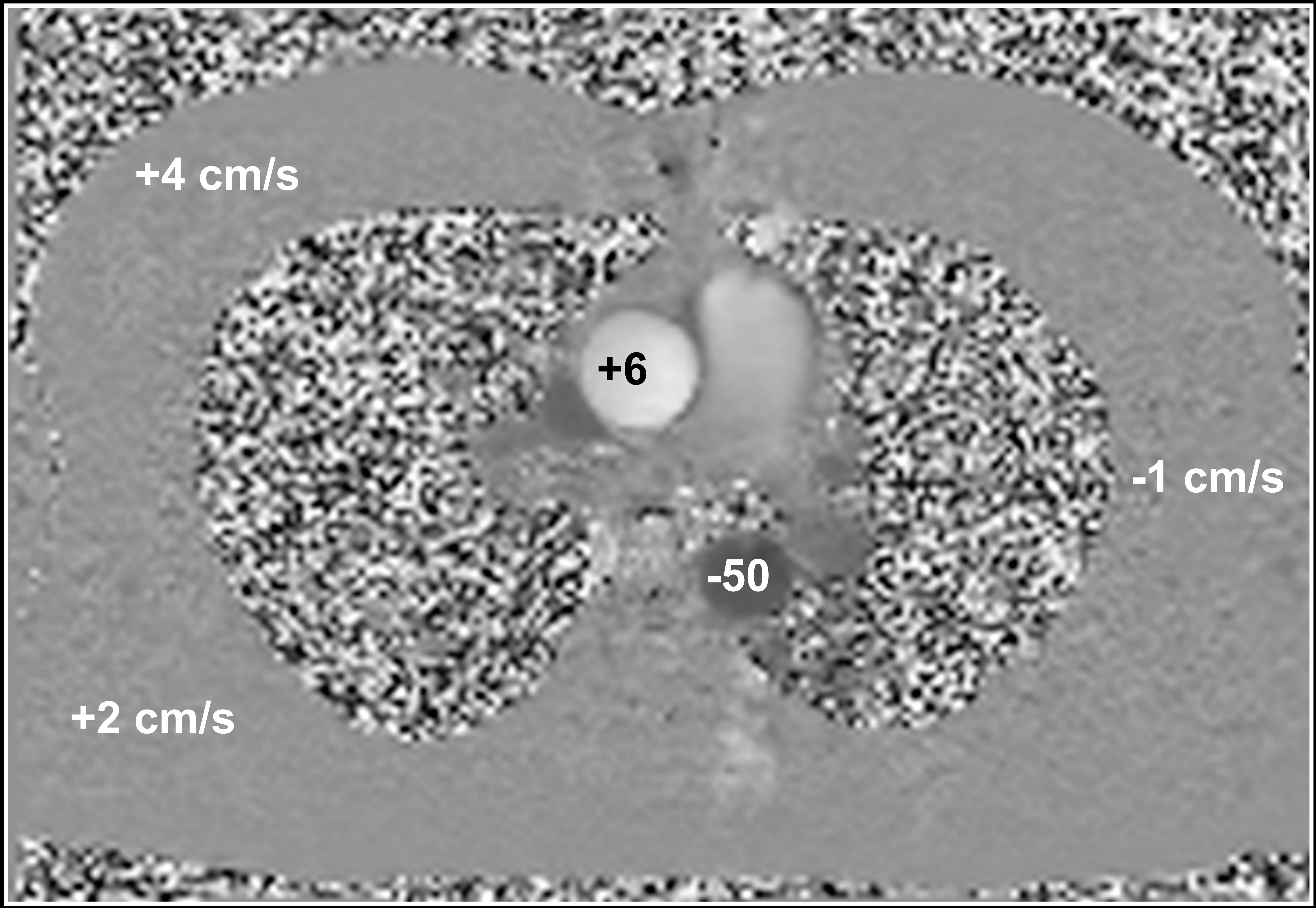
[1] Middione MRM 2013 [2] Bernstein JMRI 1991
[3] Bernstein MRM 1998 [4] Chernobelsky JCMR 2007 [5] Pelc Mag. Res. Qtr. 1991

What velocity should I measure in a stationary phantom?

1.5T Avanto - VENC=100cm/s

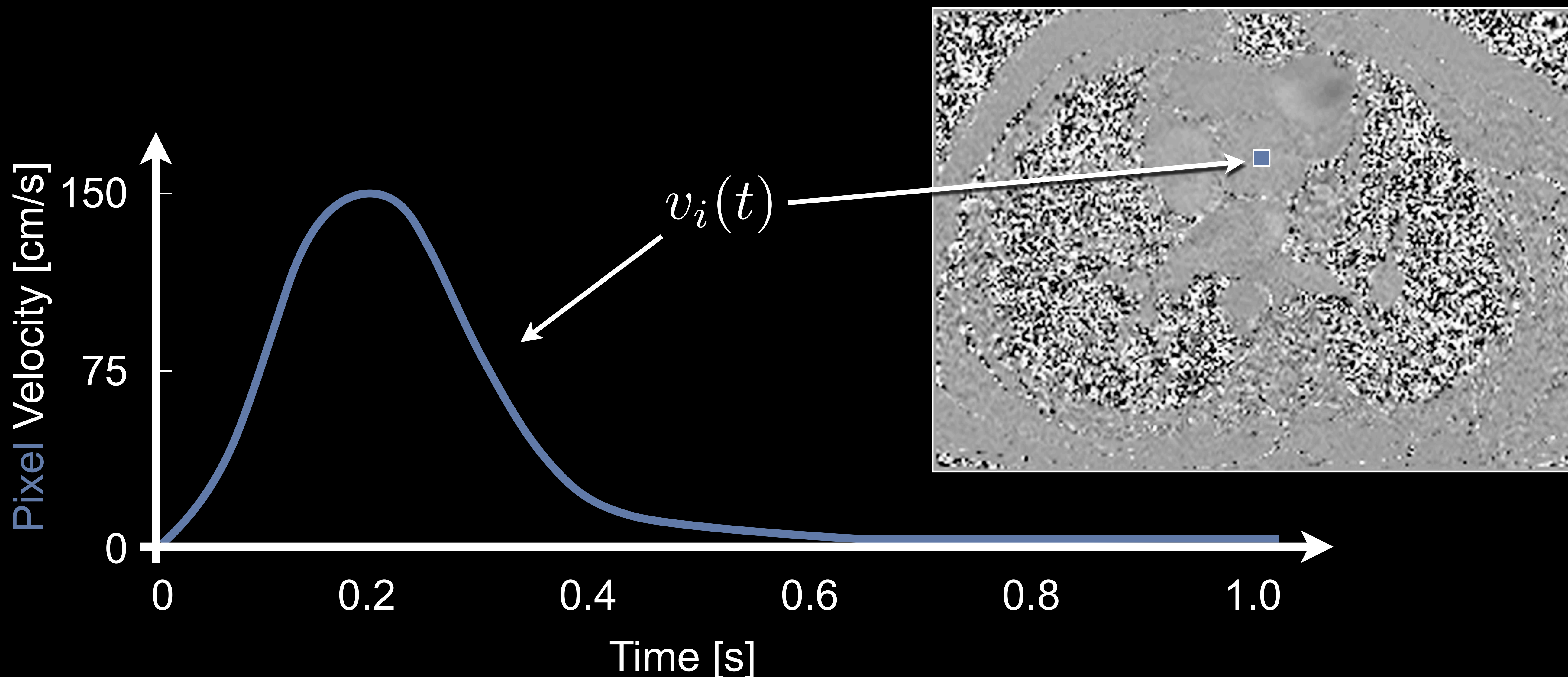


1.5T Avanto - VENC=150cm/s

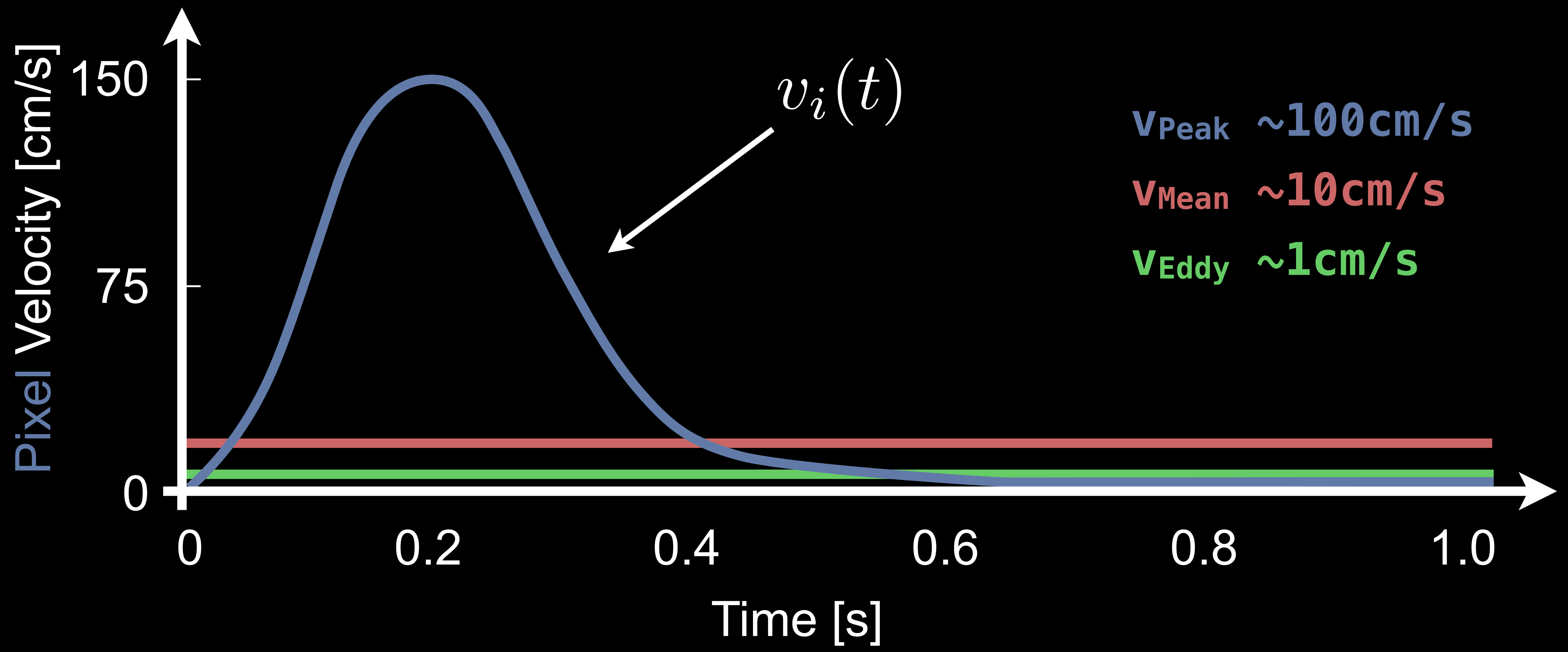


What is the problem?

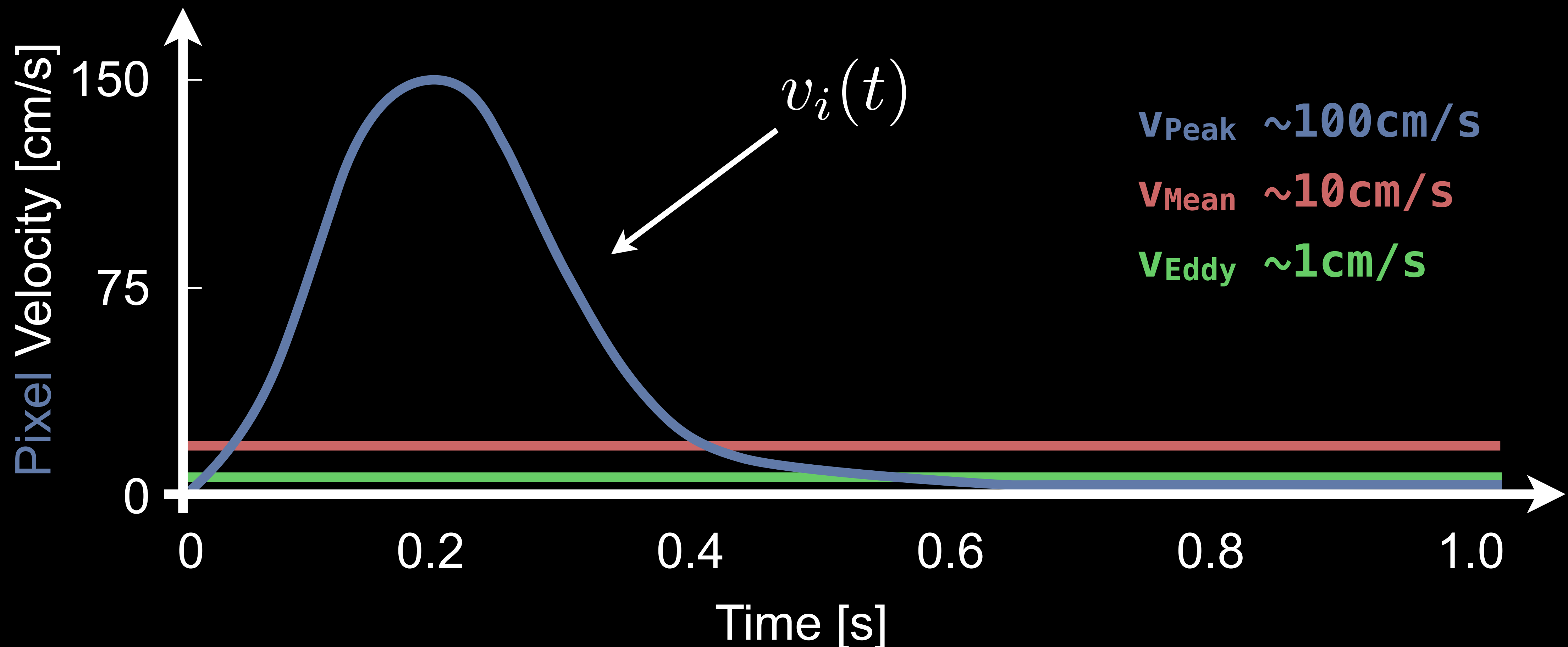
Aortic Velocity



Aortic Velocity



Aortic Velocity



$$Q = \int \left[\sum_{i=1}^{n_{ROI}} \left(\vec{v}_i(t) + v_{eddy} \right) \cdot \vec{A}_i(t) \right] dt$$ Forward Flow [mL]

Adds up over space.

Integrates over time.

Eddy Current Artifacts: Phase Contrast

$$\phi_1 = \phi_{v_1} + \phi_{off_1} + \phi_{e_1}$$

$$\phi_2 = \phi_{v_2} + \phi_{off_2} + \phi_{e_2}$$

$$\phi_{off_1} = \phi_{off_2} \text{ ...but } \phi_{e_1} = -\phi_{e_2}$$

$$\delta\phi = \phi_{v_1} - \phi_{v_2} + 2\phi_e$$

Eddy Current Origins: Hardware

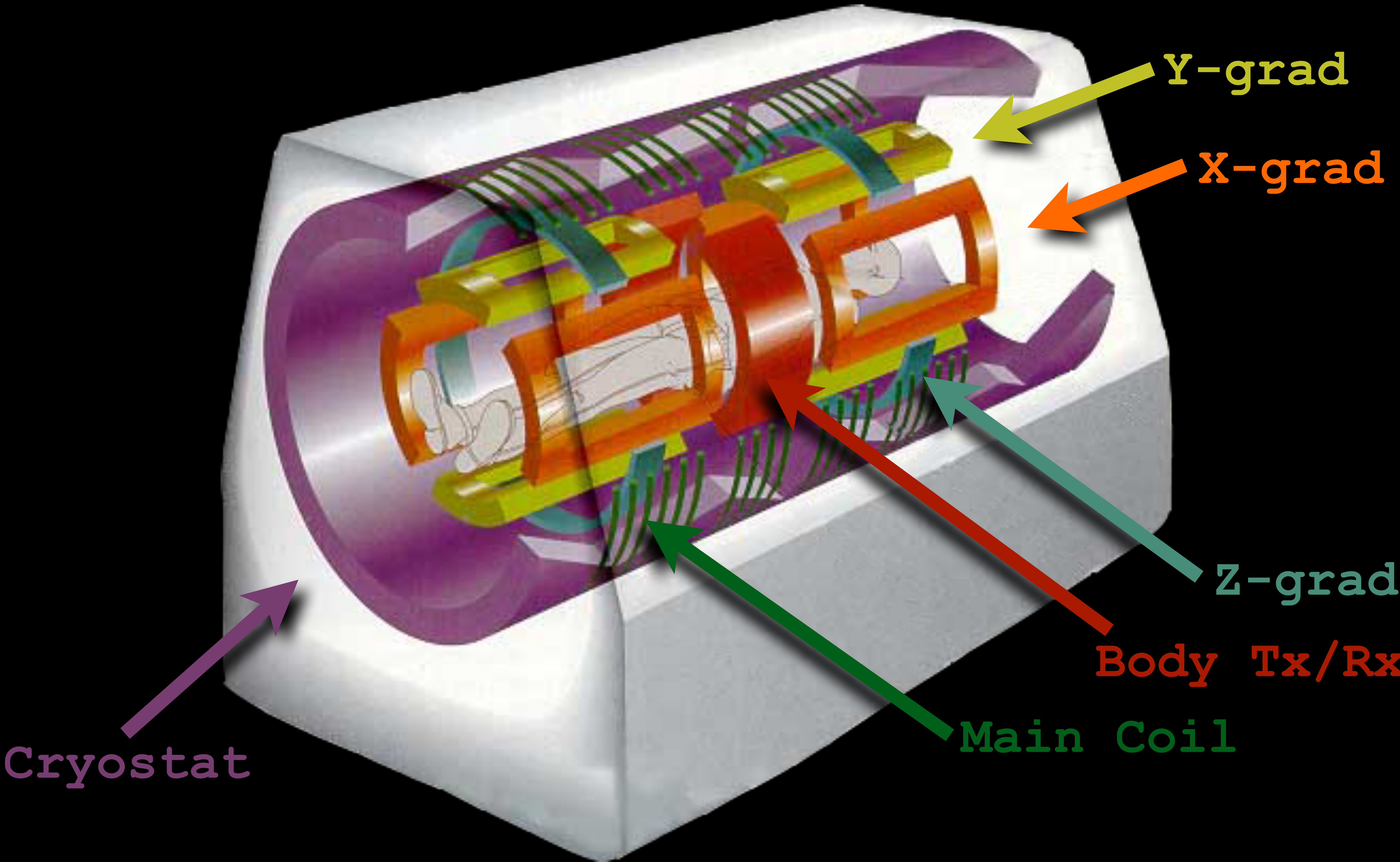
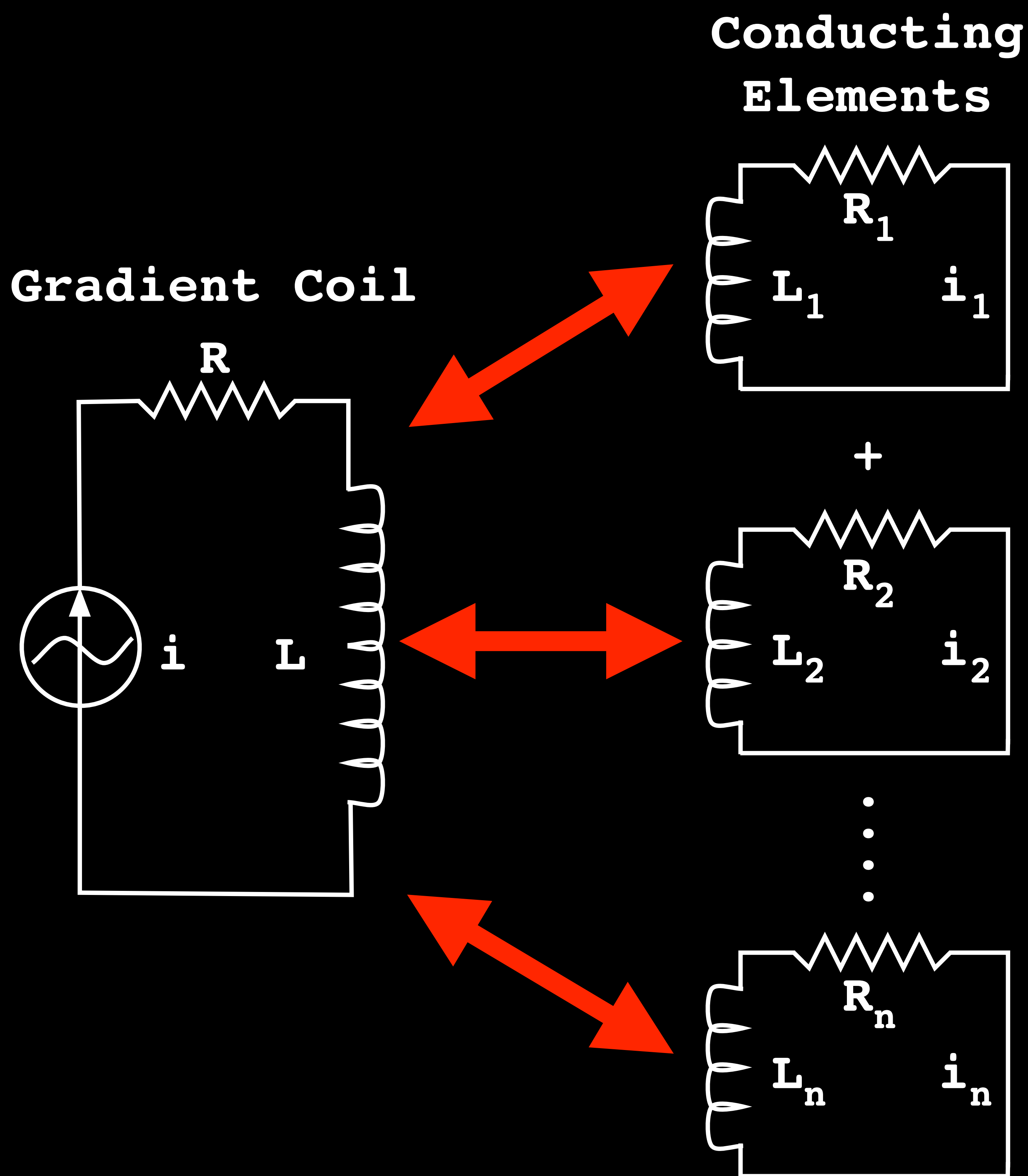


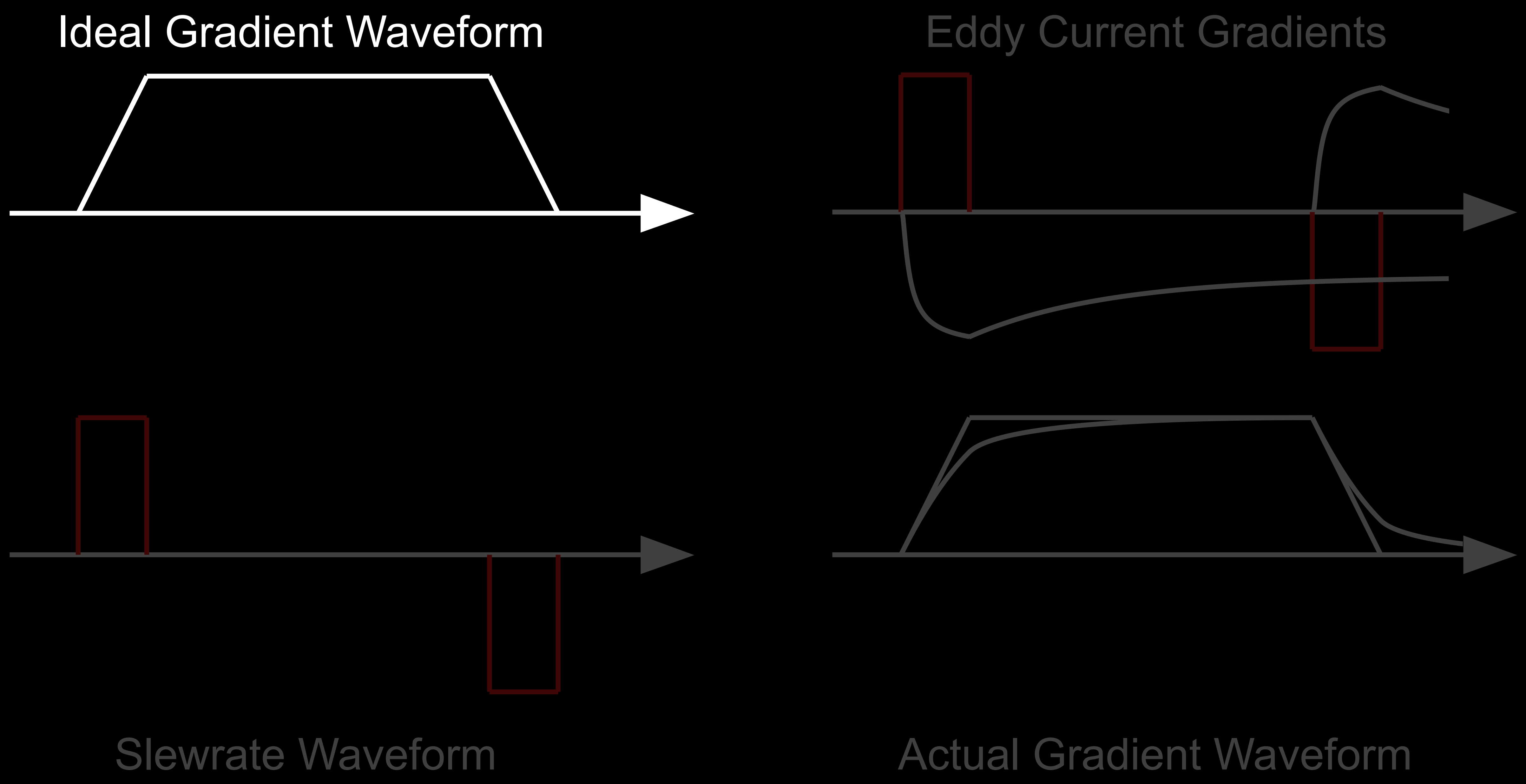
Image Adapted From: http://www.ee.duke.edu/~jshorey

Eddy Current Origins: Diagram



The gradient coil induces currents in nearby structures while *slewing*.

Eddy Current Gradient Distortion

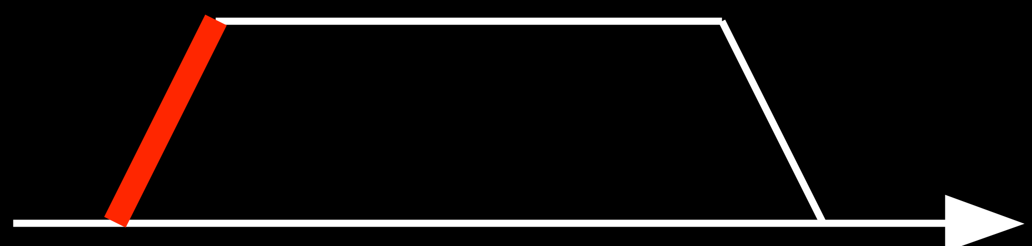


Eddy Current Origins: Mathematics

$$V_e = -\oint_{\vec{A}} \frac{\partial G}{\partial t} \cdot d\vec{A}$$

Faraday's Law

Lenz's Law



$$I_0\left(t\right) = I_f\left(1 - e^{-\frac{Rt}{L}}\right)$$

Ohm's Law

$$I_e\left(t\right) = I_0\left(t_r\right)e^{-Rt/L}$$

Source-Free
***RL* Circuit**

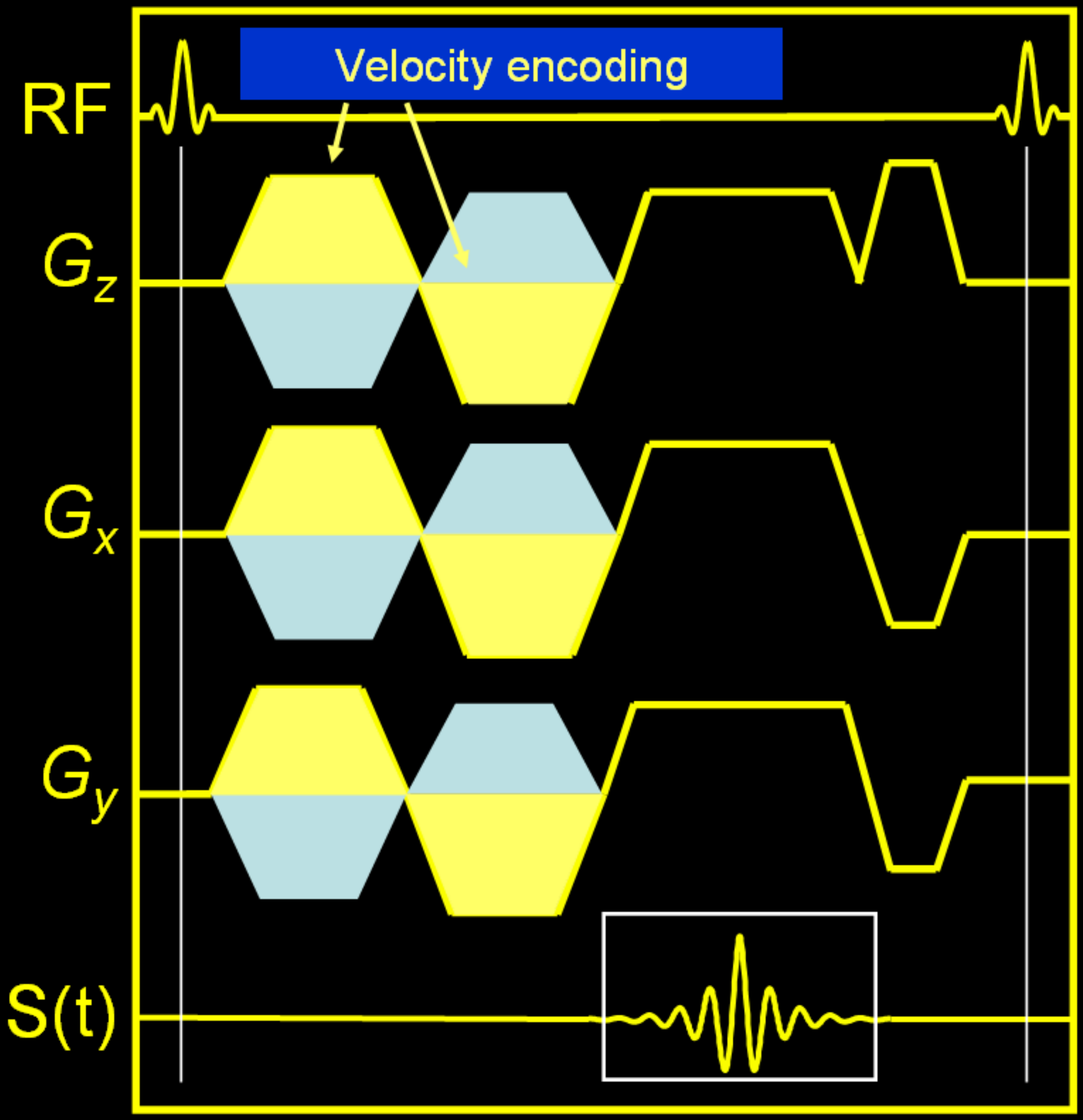
$$B_e\left(t\right) \propto I_e(t)$$

Eddy Current
Induced Field

Eddy Current Compensation

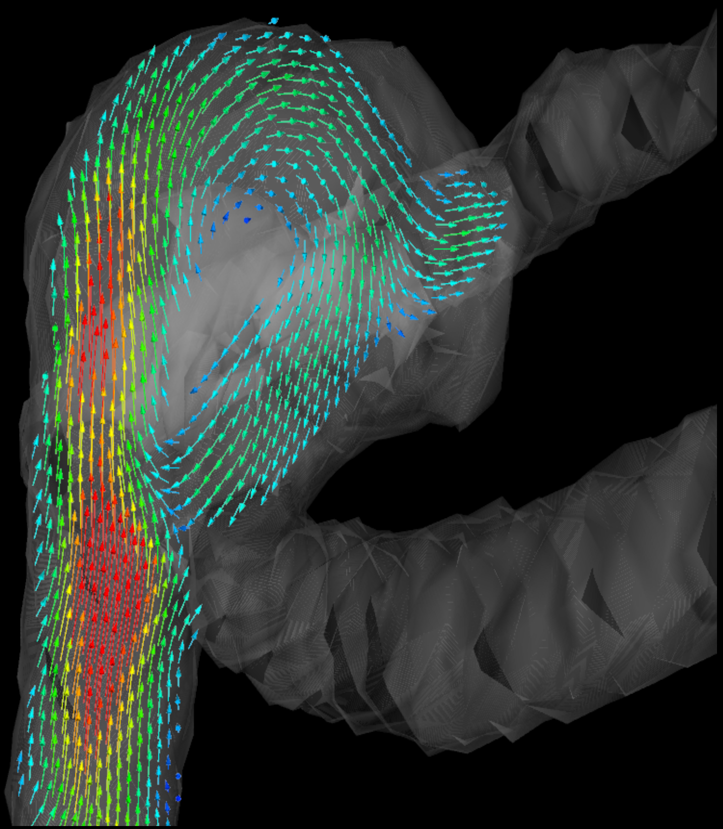
- **Hardware**
  - **Shielded Gradient Coils**
  - **Waveform Pre-emphasis**
- **Pulse Sequence**
  - **Slewrate de-rating**
  - **Twice Re-focused Spin Echo**
- **Reconstruction**
  - **Measure & Subtract (PC)**
  - **Predict & Subtract**

4D Flow

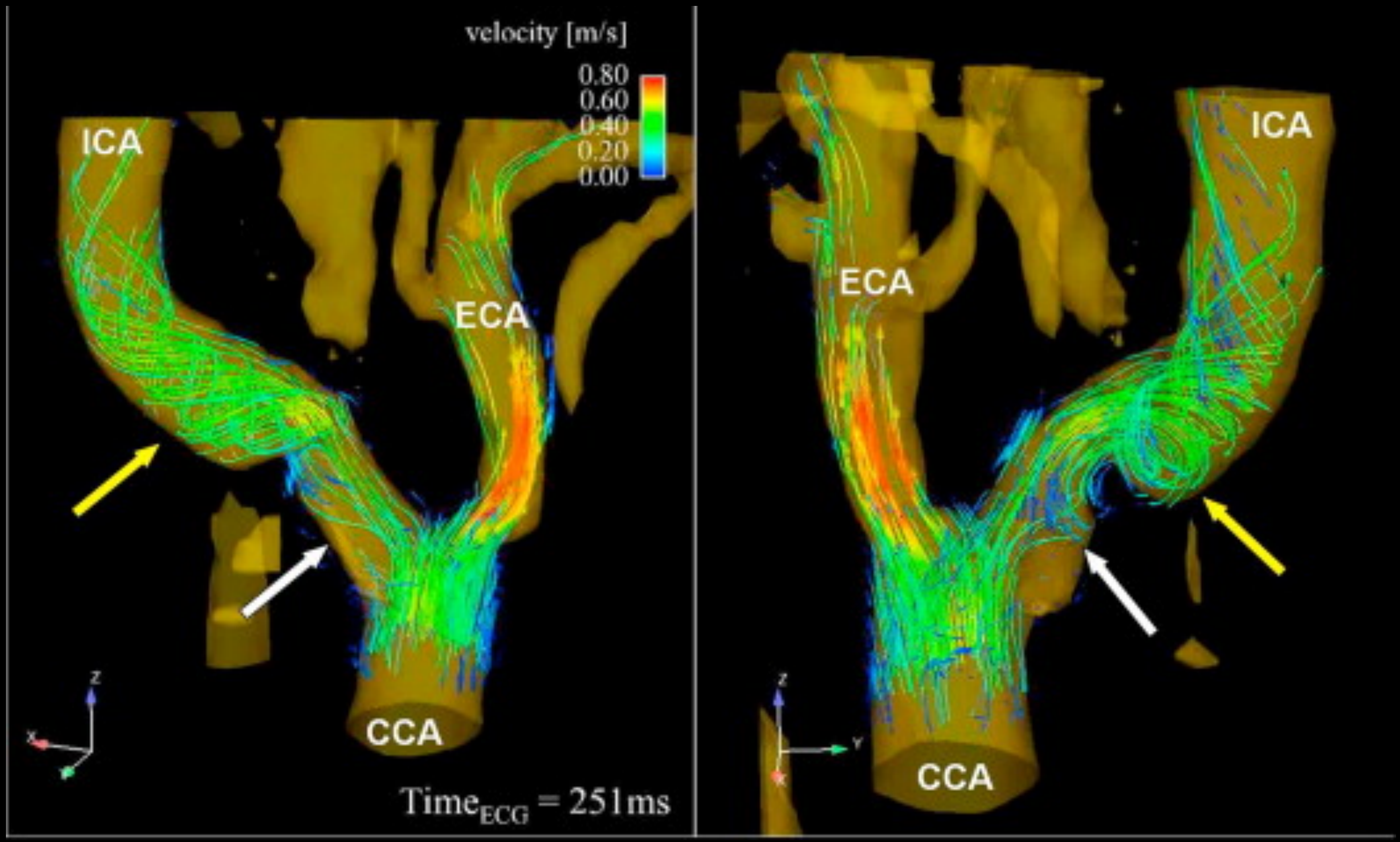


3 Directional encoding
- 4 separate velocity encodes

x
y
z
Velocity (m/s)
0.00
0.38
0.75
0.19
0.56

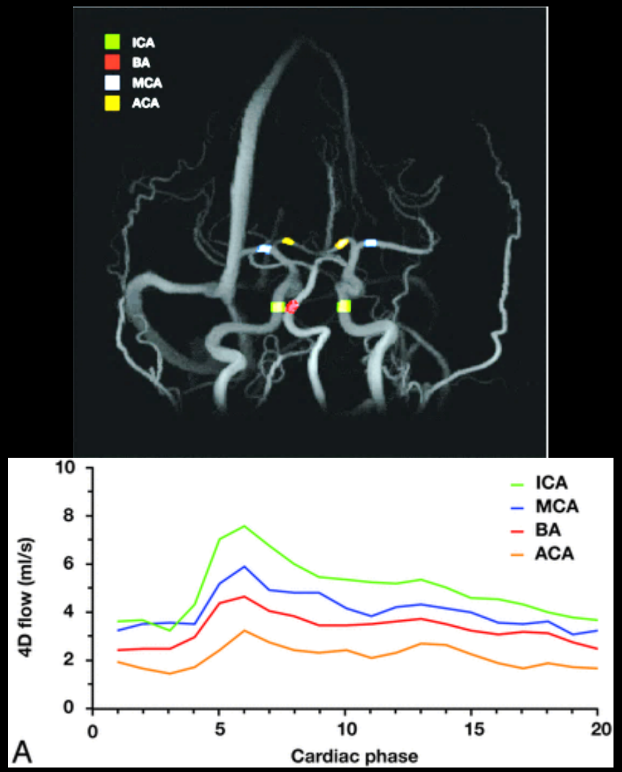


S. Kecskemeti et al., JMRI 2012

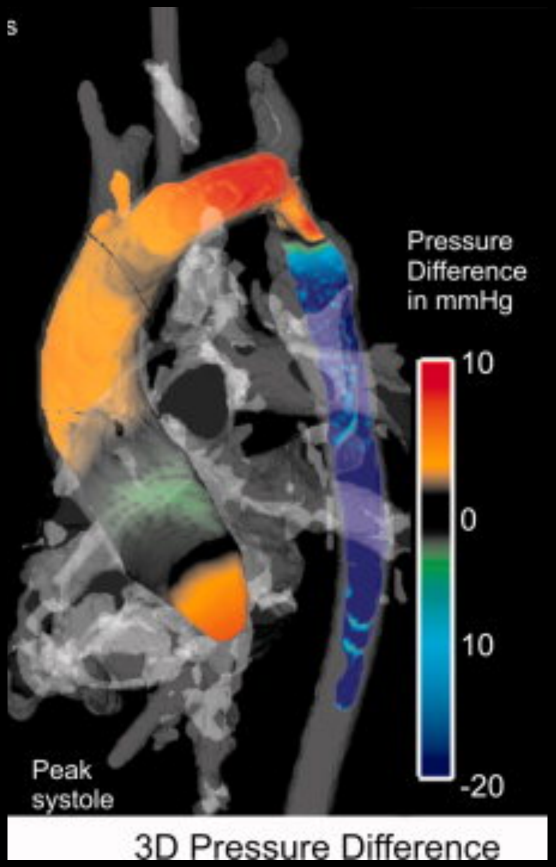


Harloff et al, *Perspectives in Medicine*, 2012

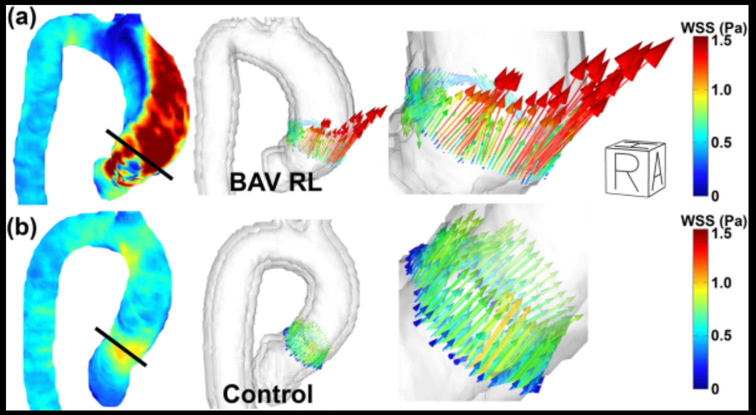
- Potential parameters from 4D flow acquisition
  - Flow
  - Pressure gradients (stenoses)
  - Wall shear stress
  - Pulse wave velocity
  - Turbulent kinetic energy
  - Reflux
  - Resistance Index
  - Vorticity/helicity
  - Pulsatility
  - …



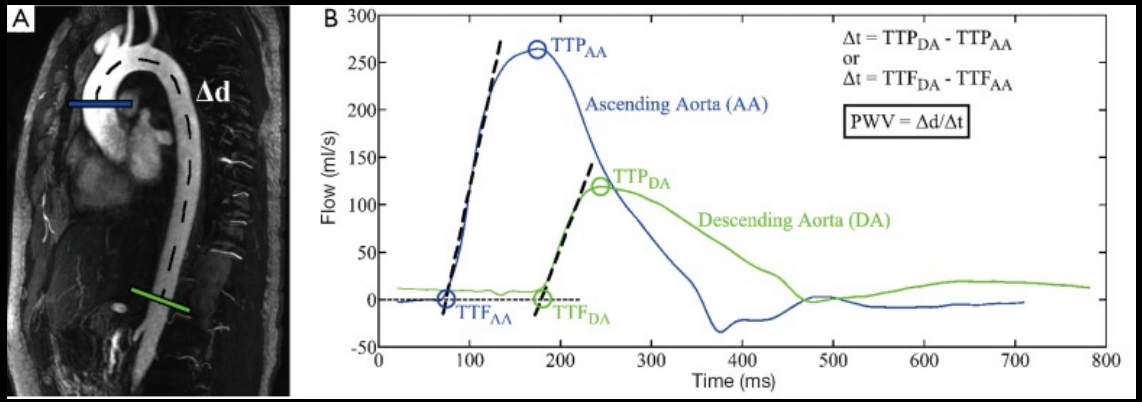
Wåhlin, et al *AJNR* 2013.



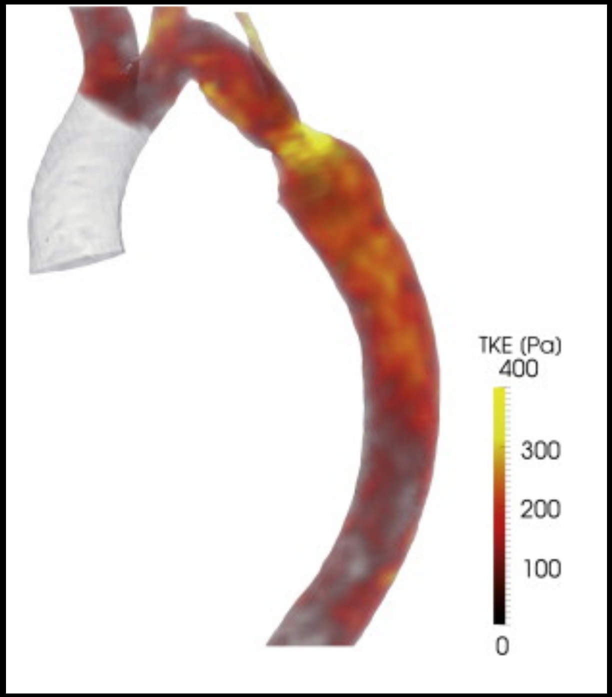
Bock, et al *MRM* 2011



Van Ooij, et al *Annals BioEgr* 2014



Wentland, et al. *Cardiovasc Diagn Ther* 2014



Lantz, et al *J Biomech* 2013

Requirements

4-5 velocity encoding acquisitions

+

20+ timeframes

+

3D acquisition with large FOV

=

long scan times (1 hour +)

or

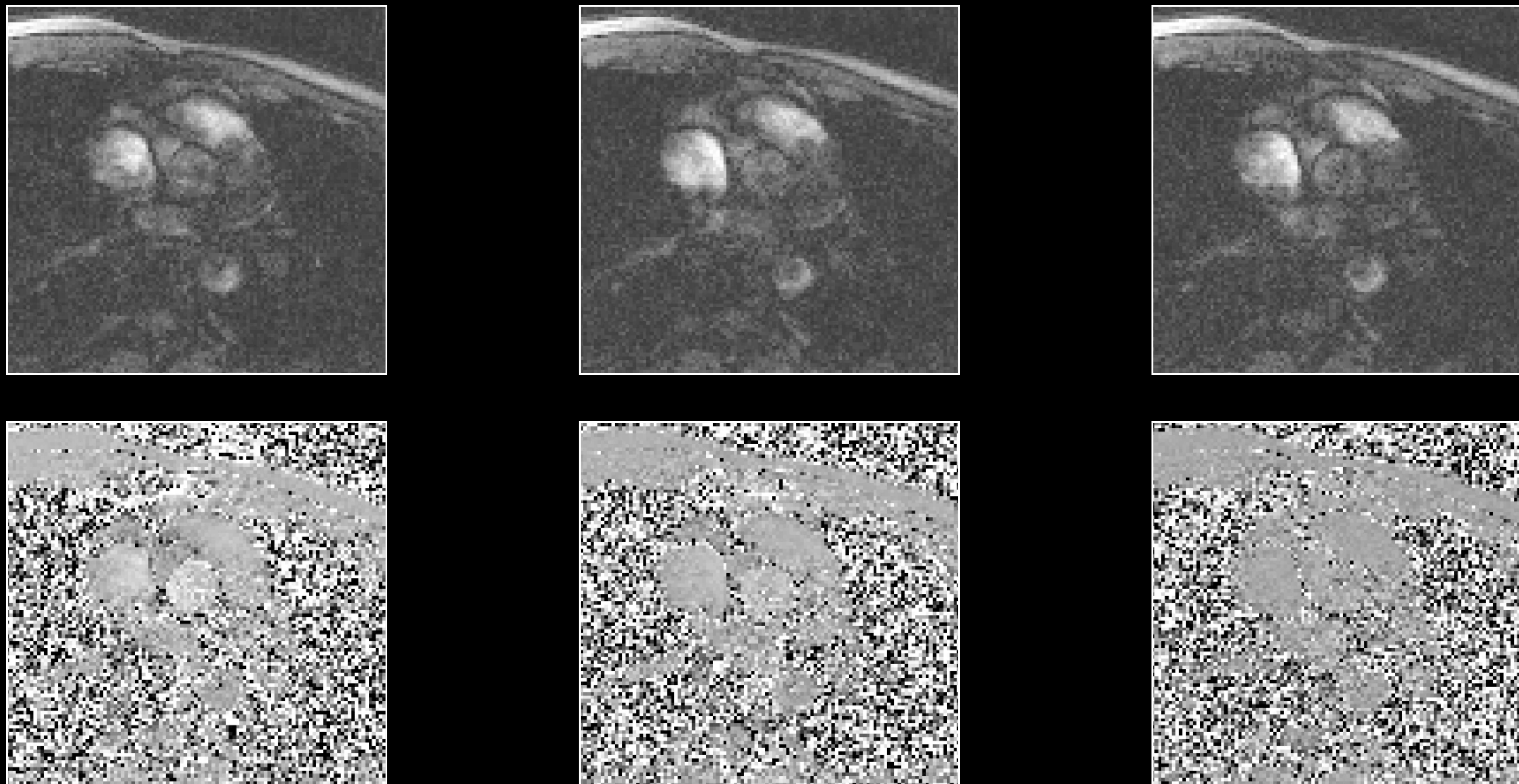
accelerate A LOT

Parameter Selection

For any MRI protocol always ask yourself:

Why is ***that*** value chosen for ***that*** parameter?

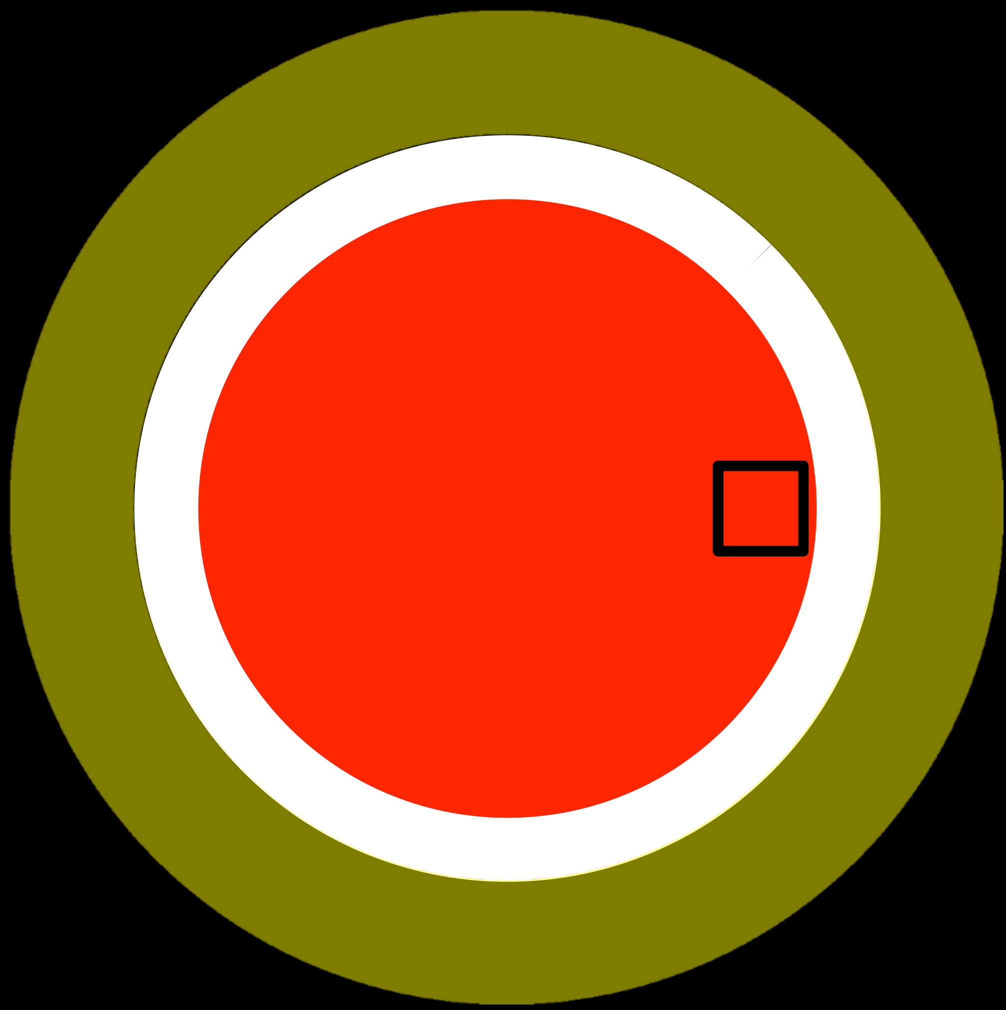
VENC Selection



VENC=75cm/s	**VENC~1.2•v_{Max}=150cm/s**	VENC=900cm/s
Phase Wrapping	No Phase Wrapping	No Phase Wrapping
Larger M_1	Intermediate M_1	Smaller M_1
Longer TE/TR (3.2/5.6ms)	Shorter TE/TR (2.4/4.8ms)	Shorter TE/TR (2.3/4.6)
Higher Sensitivity	Intermediate Sensitivity	**Lower Sensitivity**

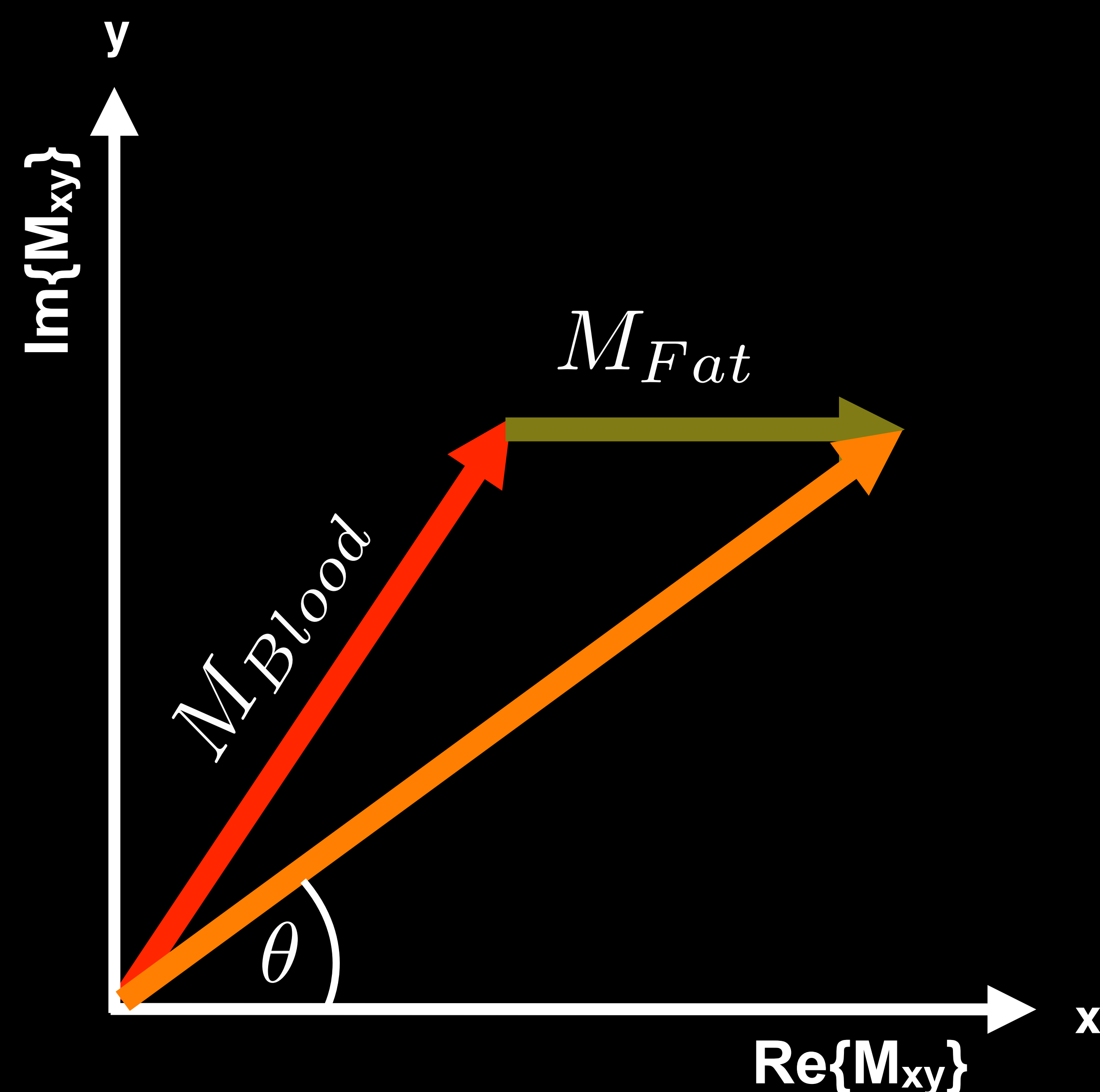
Choose VENC to be ~1.2 the expected maximum velocity.

Chemical Shift Effects

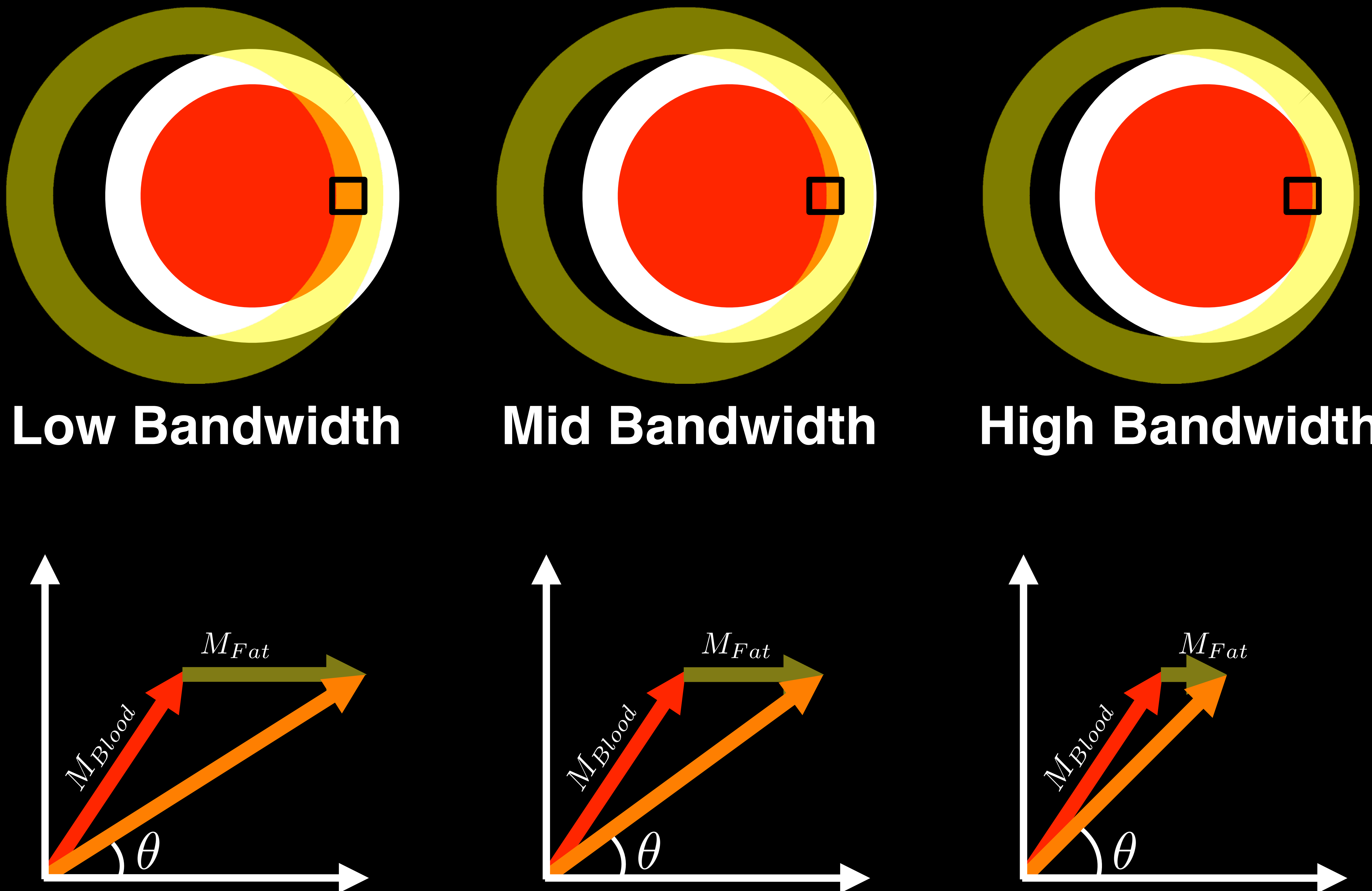


Blood Wall Fat

Blood+Fat Wall+Fat

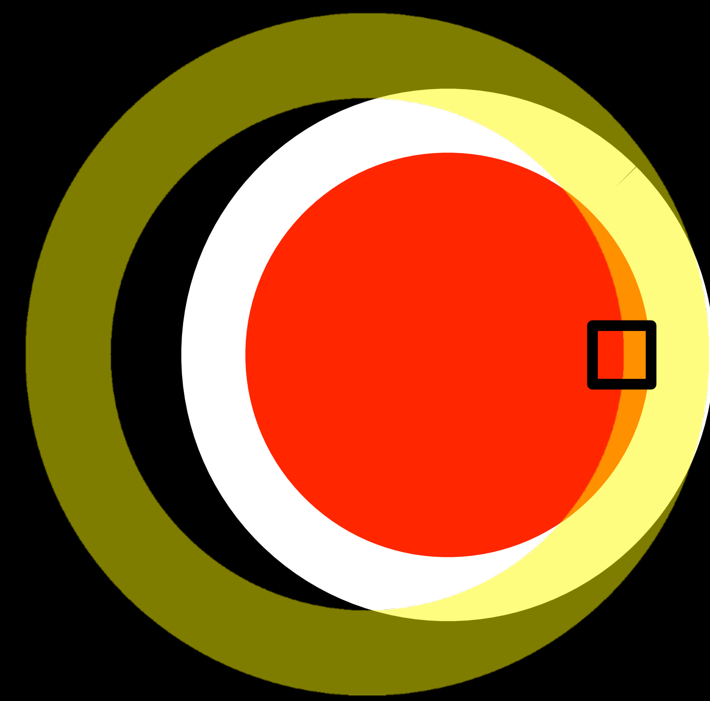


Phase Contrast - Effect of Bandwidth

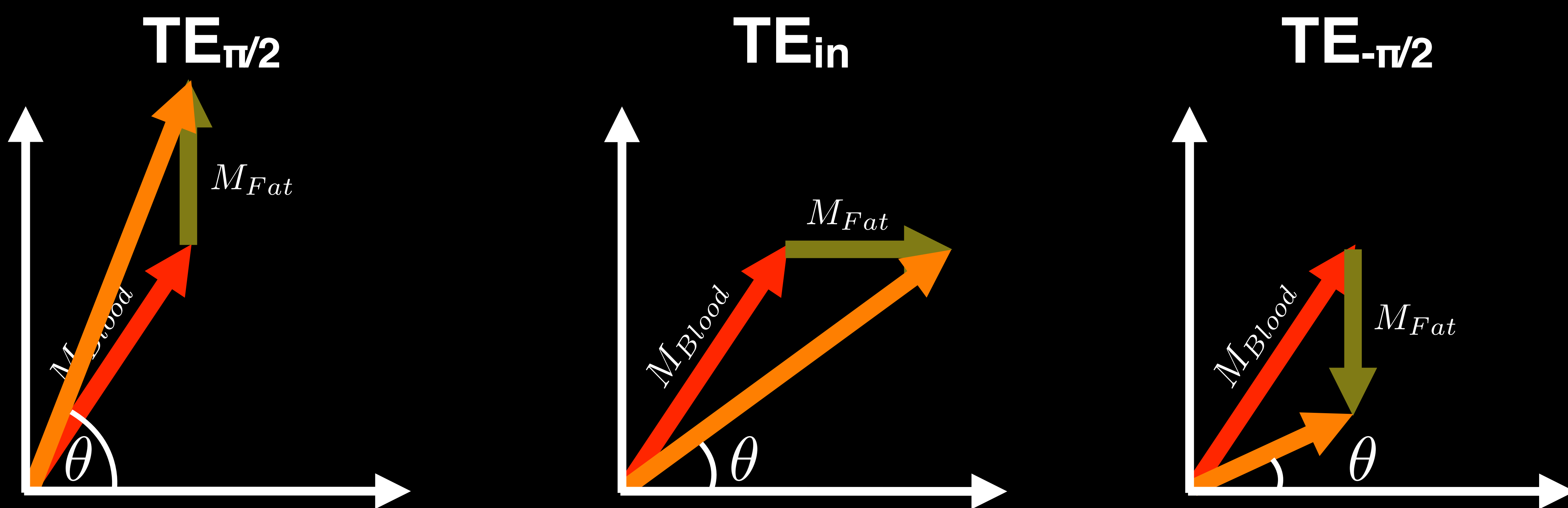


Blood Wall Fat Blood+Fat Wall+Fat

Phase Contrast - Effect of TE



Mid Bandwidth



Blood Wall Fat Blood+Fat Wall+Fat

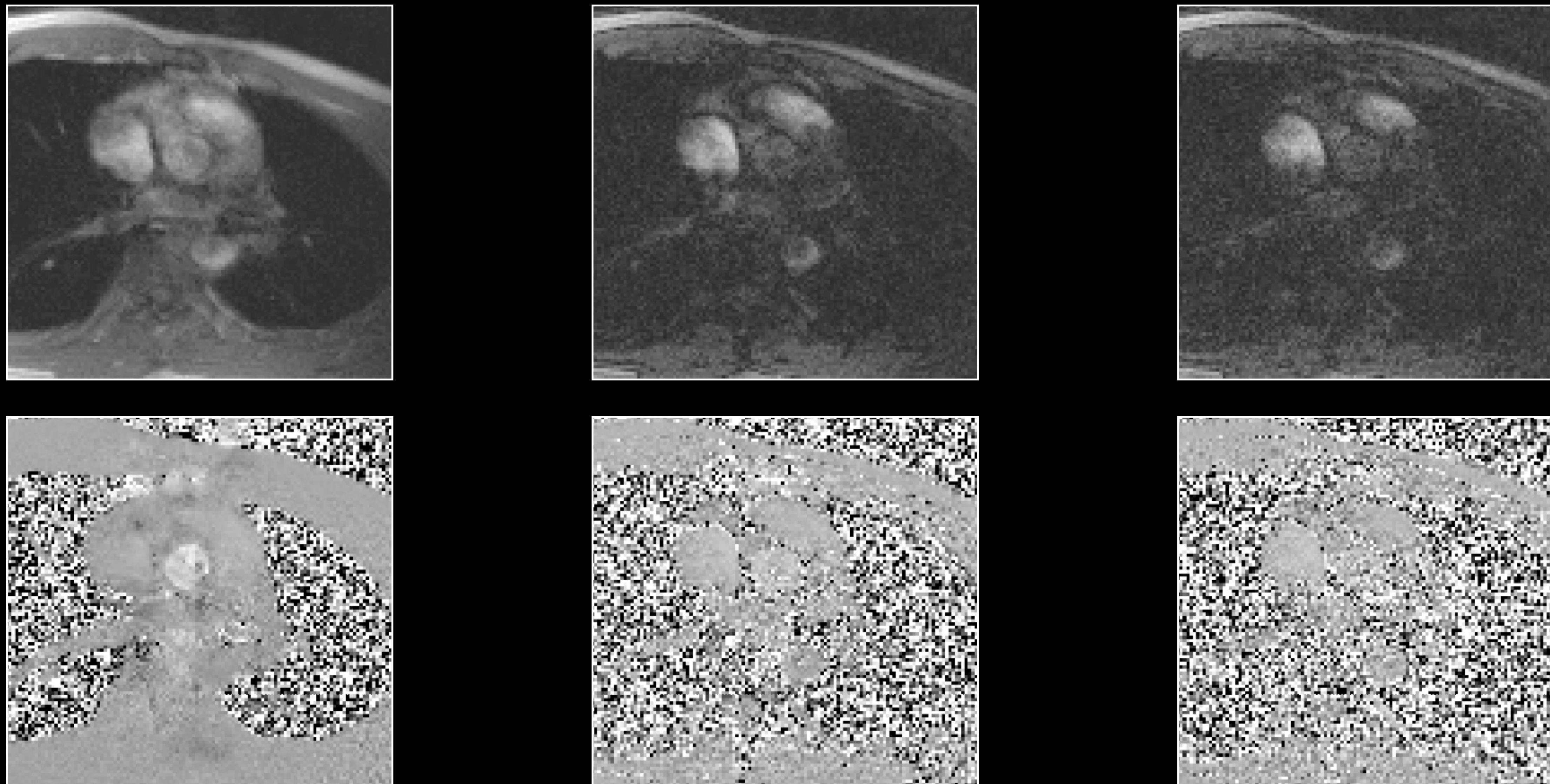
How to pick BW and TE?

Intermediate/high BW mitigates chemical shift errors.

In-phase TE mitigates chemical shift errors.

More important at 3T where off-resonance of fat is ~440Hz.

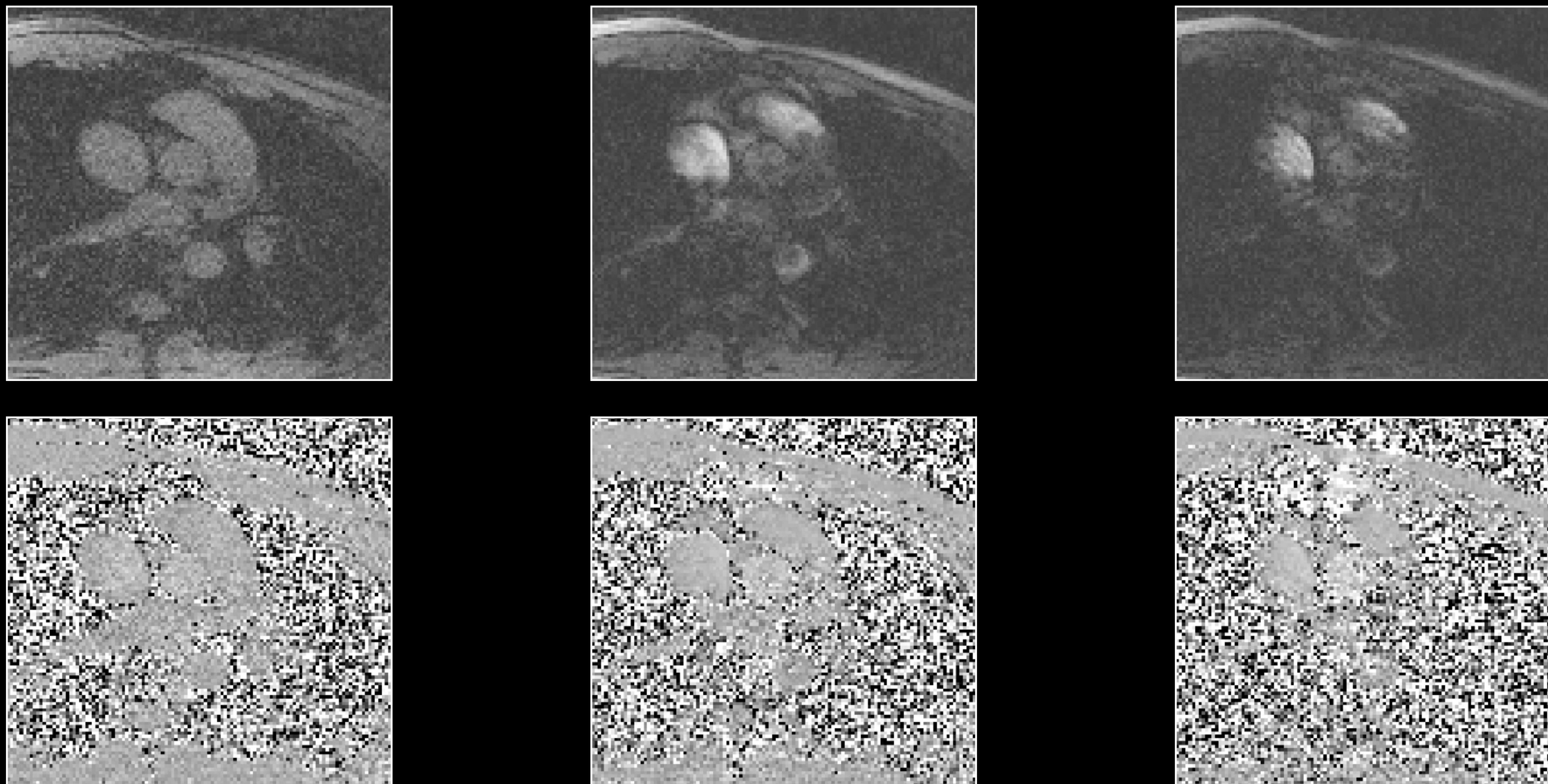
Readout Bandwidth



220Hz/Pixel=±21.1kHz	814Hz/Pixel=±78.1kHz	1532Hz/Pixel=±147.1kHz
~1 Pixel Chemical Shift	~0.25 Pixel Chemical Shift	~0.14 Pixel Chemical Shift
Longer TE/TR (4.2/9.0)	Intermediate TE/TR (2.4/4.8)	Shorter TE/TR (2.3/4.3)
Higher SNR	Intermediate SNR	Lower SNR

Intermediate/high BW mitigates chemical shift errors.
More important at 3T where off-resonance of fat is ~440Hz.

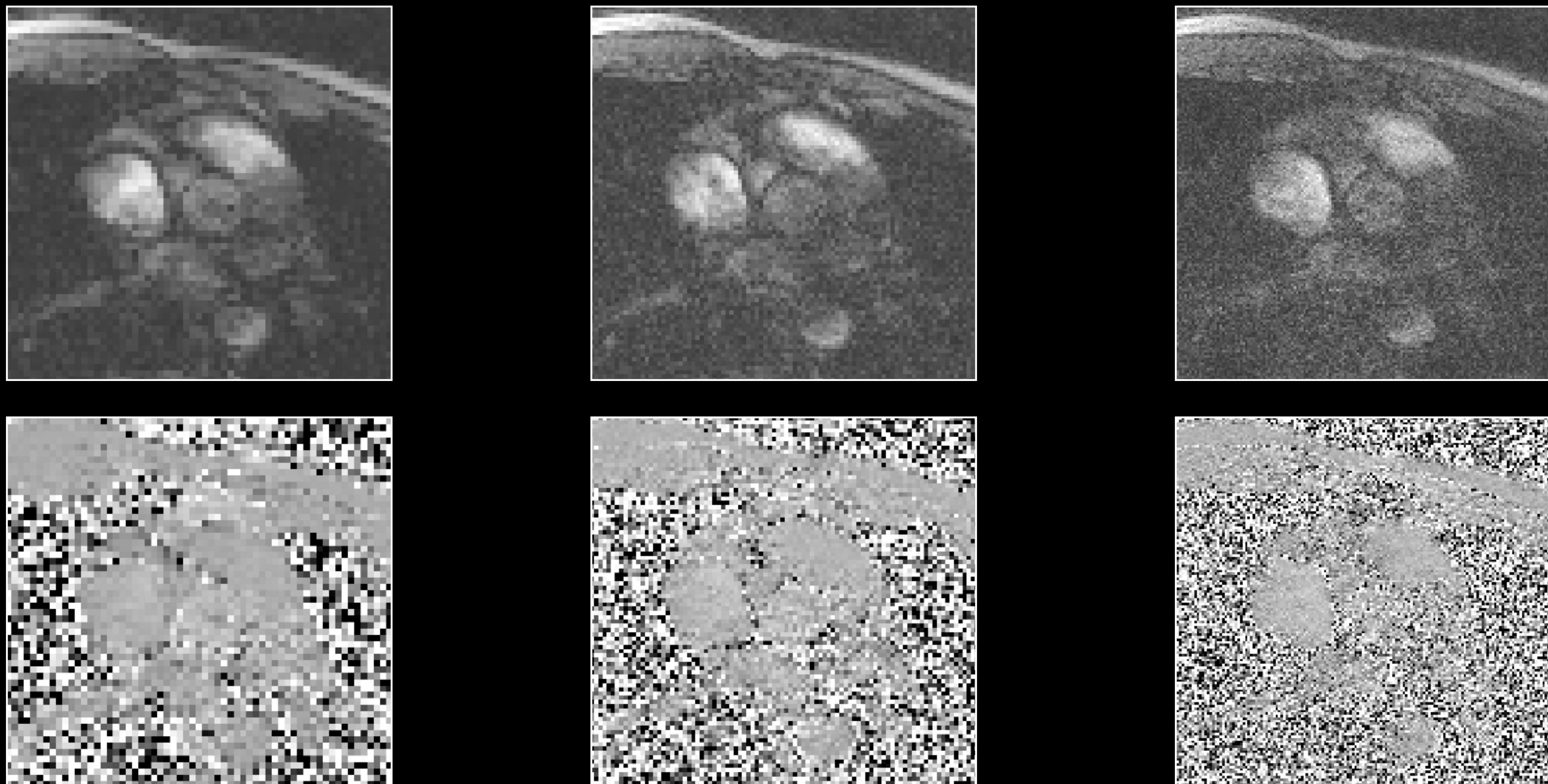
Flip Angle



FA=$\alpha_{Ernst,Blood}$=5°	FA=30°	FA=60°
Poor Blood SNR Low SAR	Excellent Blood SNR Low SAR	Saturated Blood Signal High SAR

Choose a flip angle greater than the Ernst angle due to in-flow effects.

Spatial Resolution

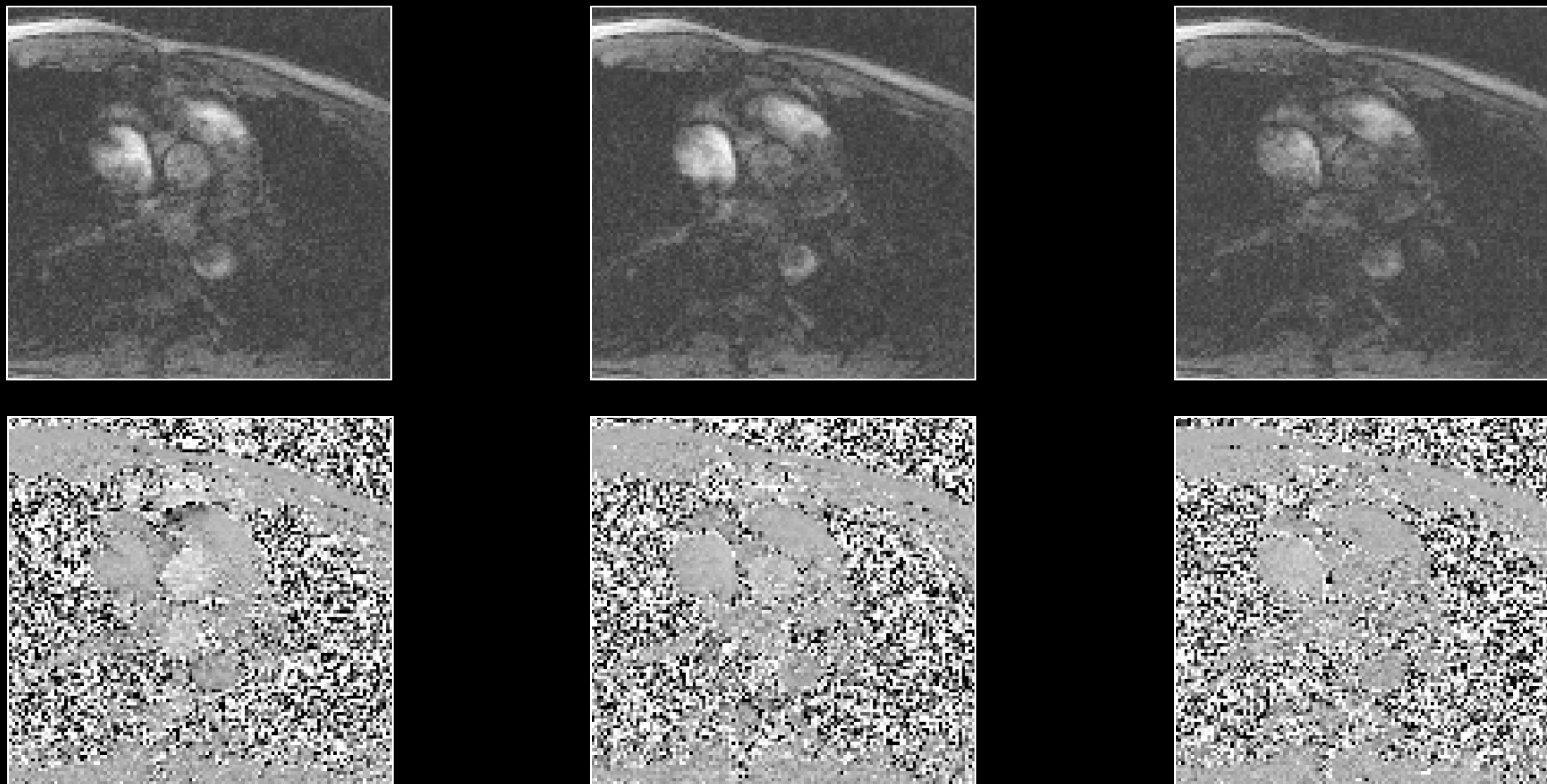


2.5mm x 2.5mm in-plane | 1.7mm x 1.7mm in-plane | 1.0mm x 1.0mm in-plane

2.5mm x 2.5mm in-plane	1.7mm x 1.7mm in-plane	1.0mm x 1.0mm in-plane
Shorter breath holds	Intermediate breath holds	Longer breath holds
Larger voxels	Intermediate voxels	Smaller voxels
Higher SNR	Intermediate SNR	Lower SNR

High spatial resolution needed for volume estimates.

Temporal Resolution



80ms/frame | 40ms/frame | 10ms/frame

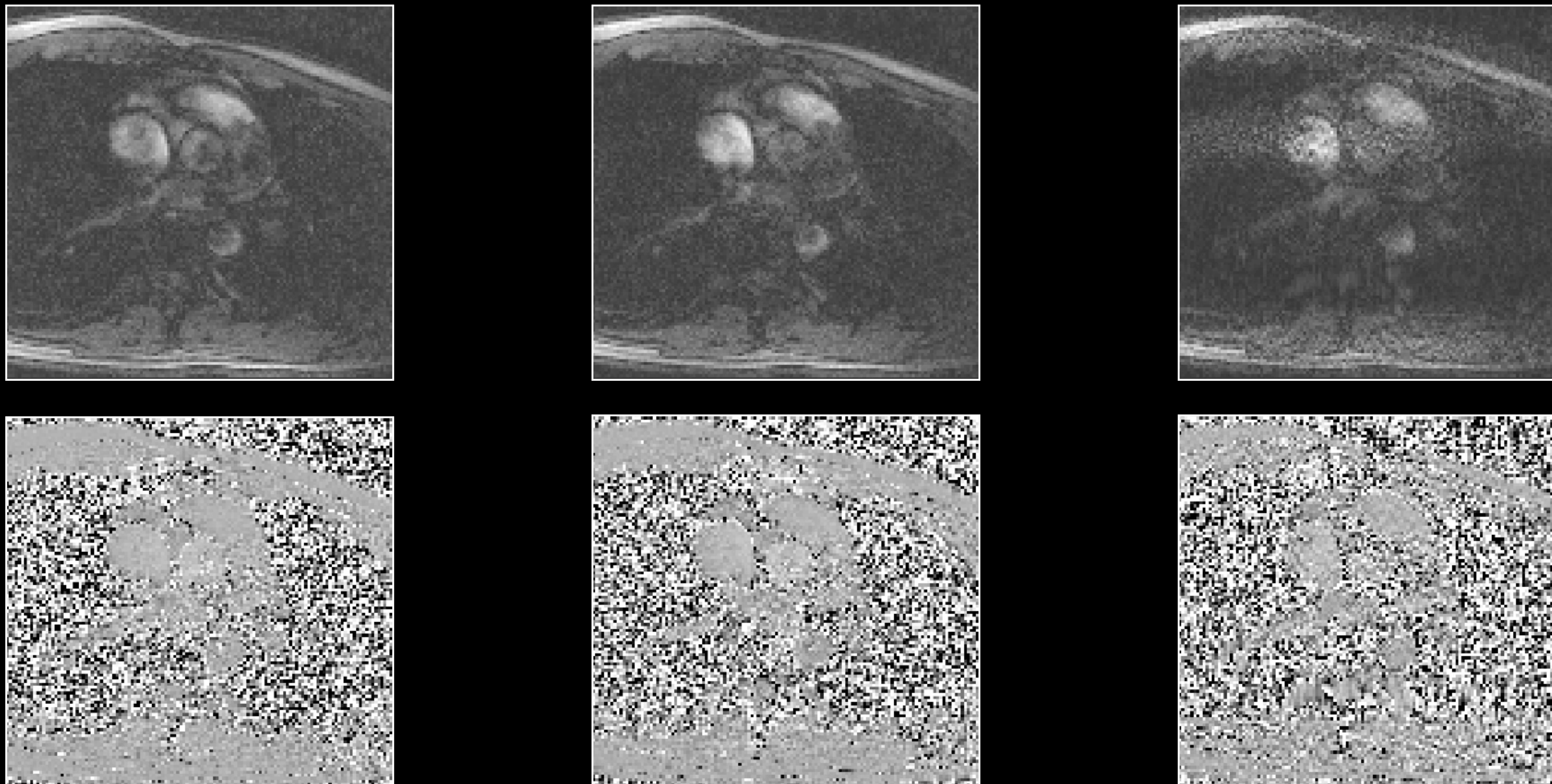
Lower Temporal Resolution
(80ms, VPS=8)
Shorter Breath Holds (7s)

Intermediate Temp. Res.
(40ms, VPS=4)
Intermediate Breath Hold (14s)

High Temporal Resolution
(10ms, VPS=1)
Long Breath Hold (56s)

High temporal resolution needed for v_{Max} estimates.

Parallel Imaging



No Acceleration | ~2x Acceleration | ~8x Acceleration

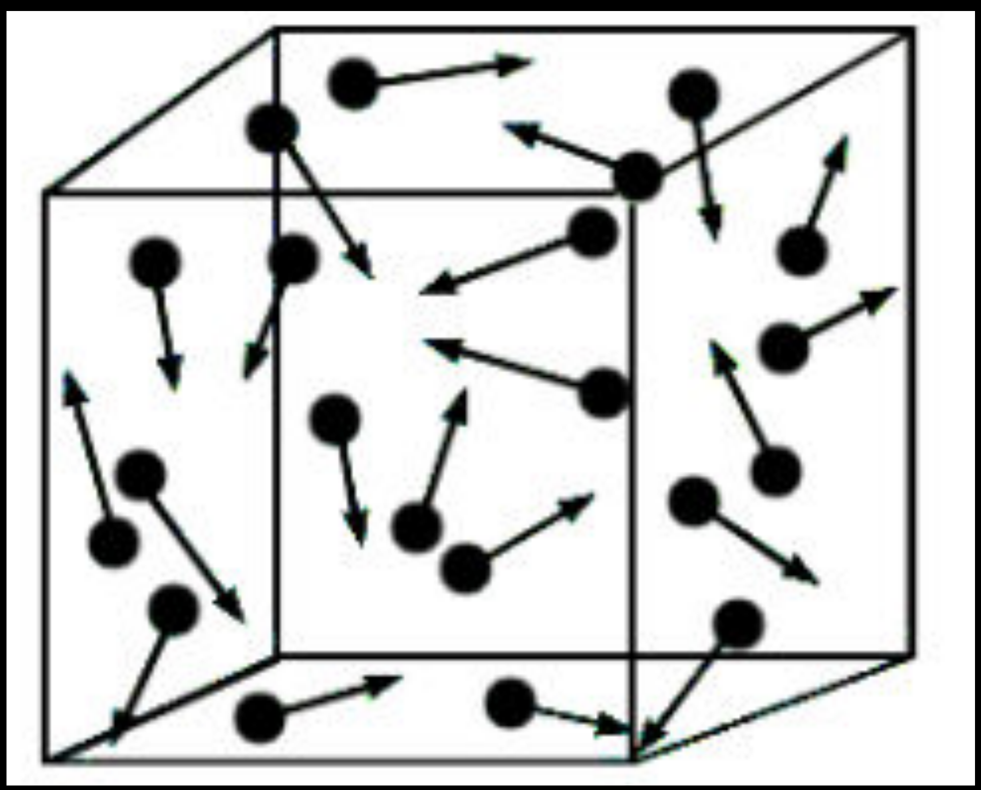
No Acceleration	~2x Acceleration	~8x Acceleration
Lower S/T Resolution	Intermediate S/T Resolution	High S/T Resolution
Long Breath Holds	Intermediate Breath Holds	Short Breath Holds
Higher SNR	Intermediate SNR	Low SNR & Artifacts

2x acceleration widely used for 2D PC-MRI.

PC-MRI Summary

- **PC-MRI useful for estimating:**
  - **Peak velocity**
  - **Volumes of flow**
  - **Myocardial motion**
- **The protocol *must* be optimized for the application.**
- **Routine correction of eddy currents is important.**
- **Without attention to detail quantitative inaccuracies can foment clinical disinterest.**

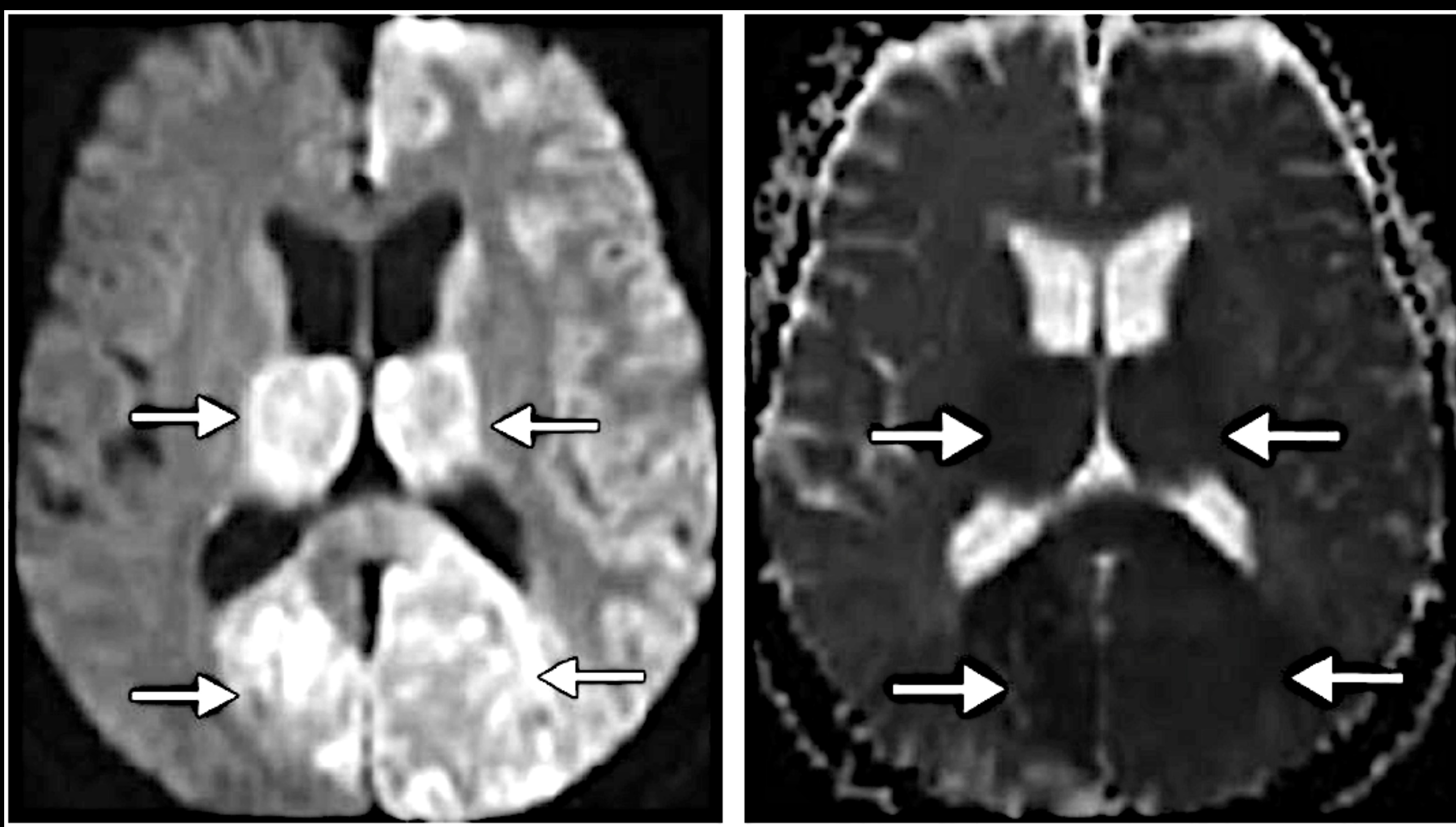
Diffusion Weighted Imaging



Random velocities + big bipolar
= random phase
= dephasing
= signal loss

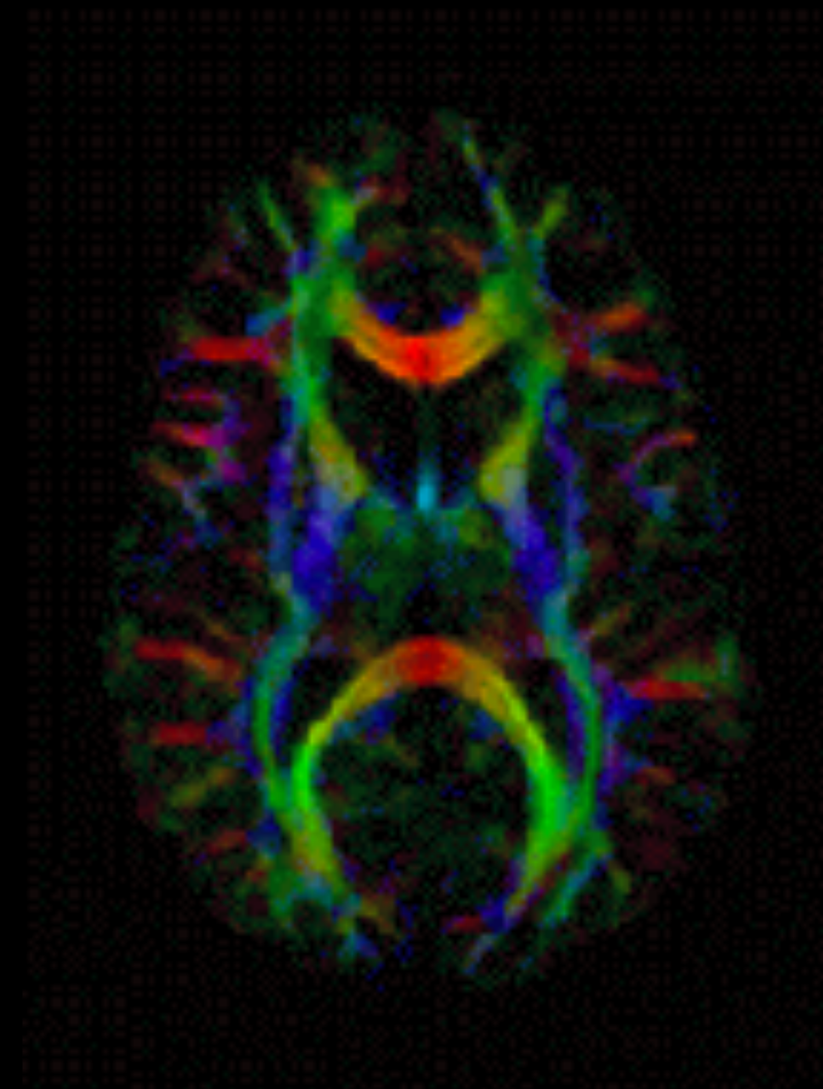
Signal loss is proportional to diffusion
(directional measure like PC-MRI)
so in the simplest terms:
Play a big M1 gradient, signal loss = diffusion

DWI ADC



a. b.

Figure 15. Acute stroke of the posterior circulation in a 77-year-old man. **(a)** Diffusion-weighted MR image ($b = 1000$ sec/mm^2) shows bilateral areas of increased signal intensity (arrows) in the thalami and occipital lobes. **(b)** ADC map shows decreased ADC values in the same areas (arrows). These findings are indicative of acute ischemia.



DTI

Srinivasan A, *et al*. State-of-the-art imaging of acute stroke. Radiographics 2006;26 Suppl 1:S75-95.

Thanks

Thanks

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