Lecture 12

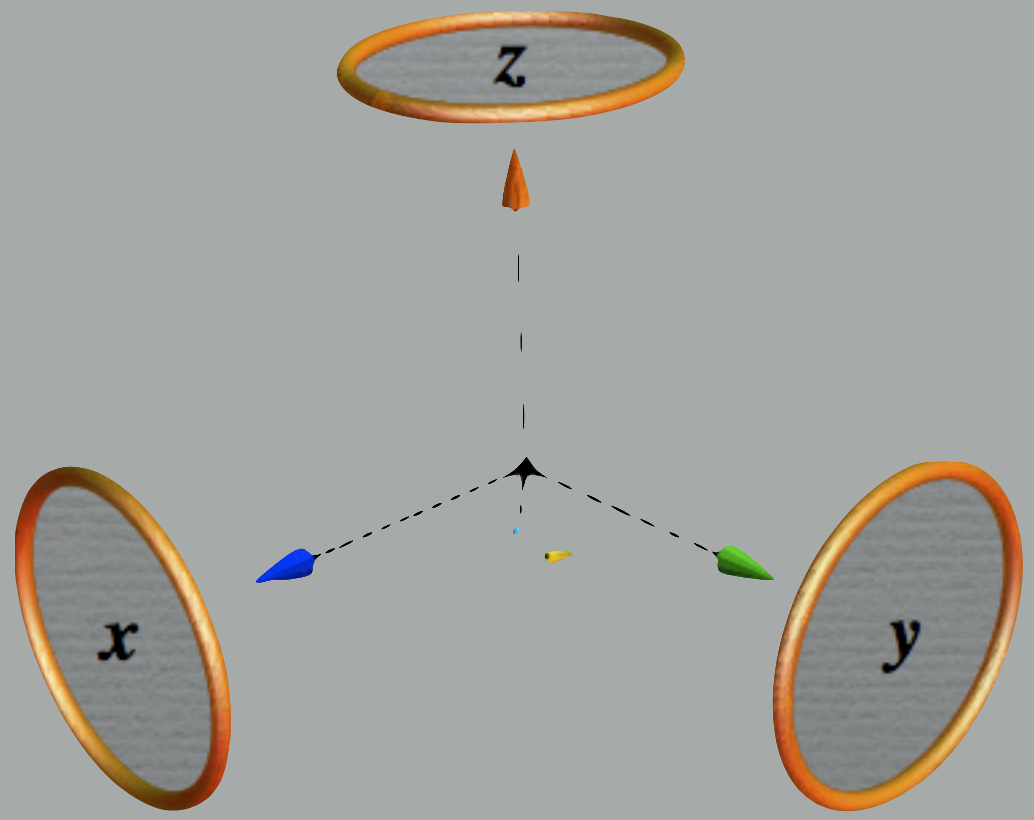
DTI Artifacts and Corrections

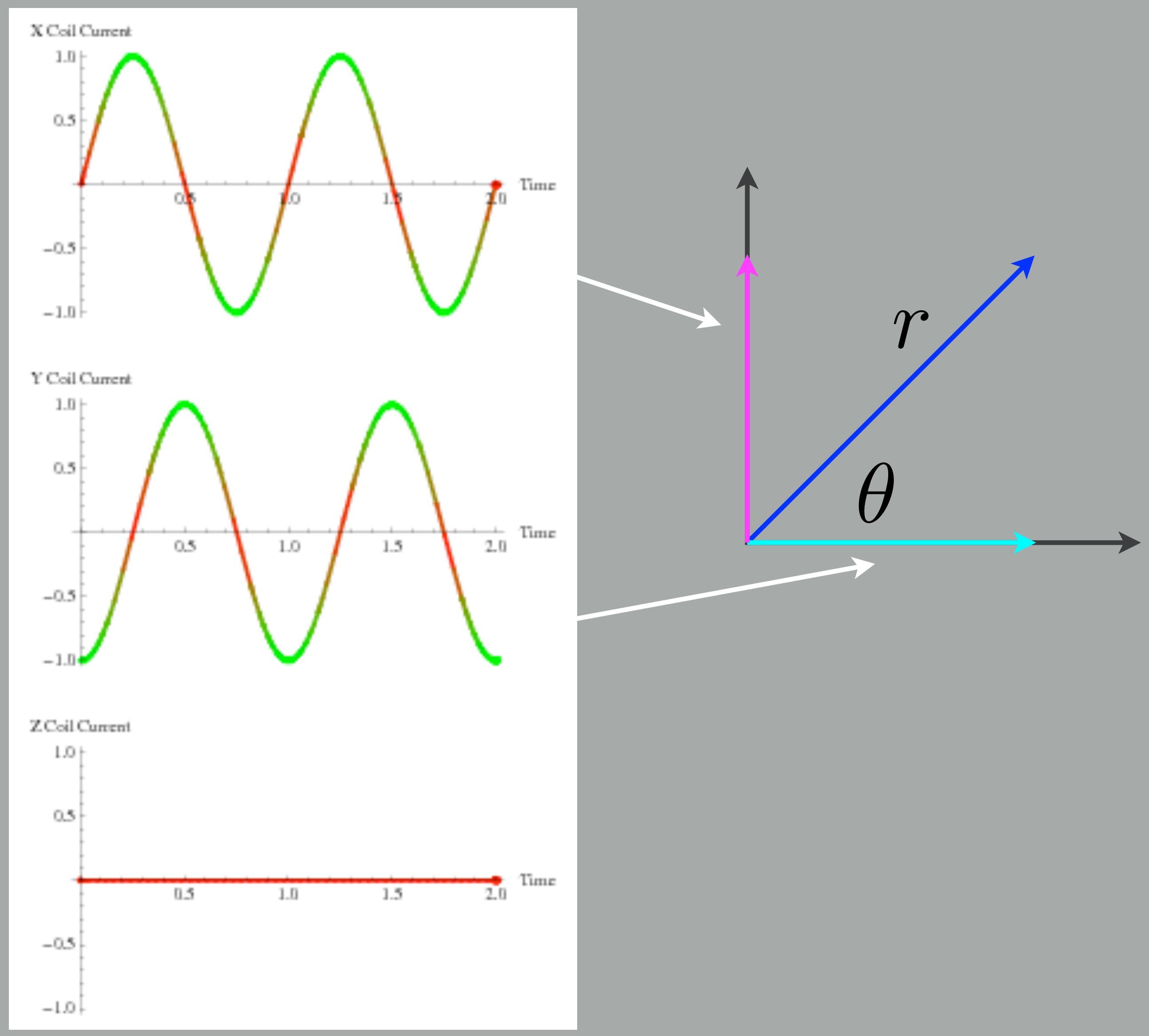
Lecture Summary

1. EPI specific artifacts
2. Static field inhomogeneity
   a. TOPUP
3. Eddy Current
   a. Dual spin echo
   b. EDDY (mutual info)
4. Motion artifacts
   a. self-navigated spirals

First few slides are from
Week 3 Lecture 6 and so there
are redunancies

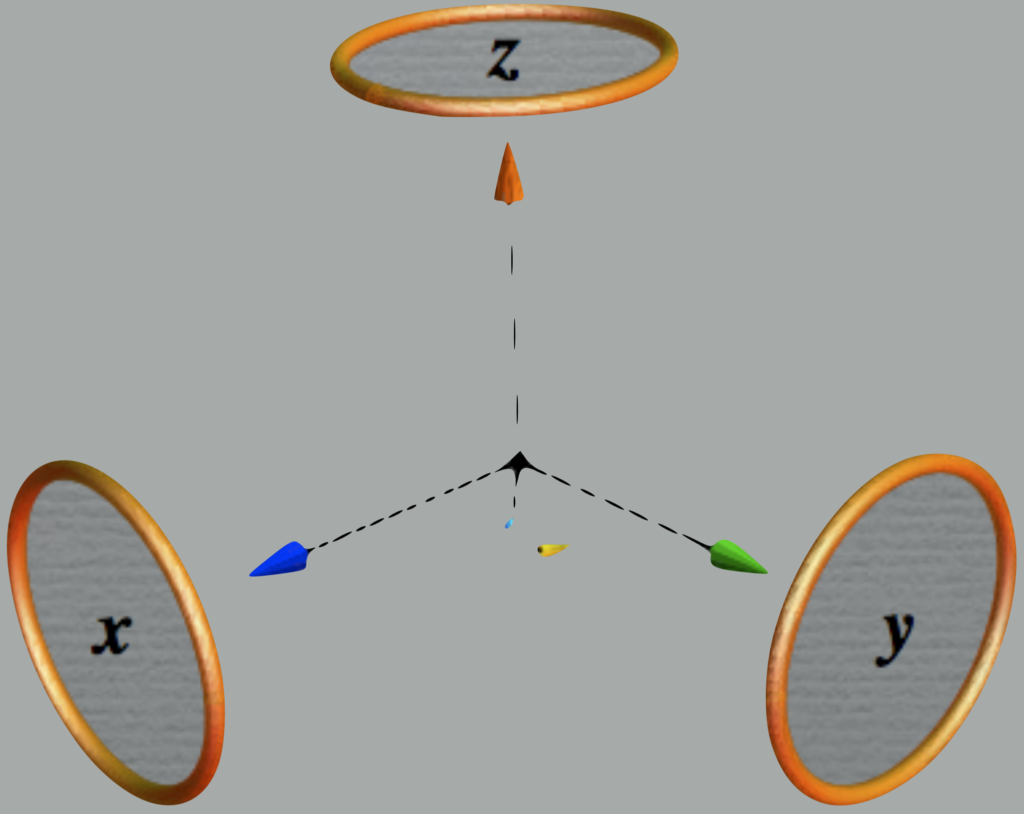
Signal detection





Therefore, we measure m_{xy} only (not m_z)

Signal detection



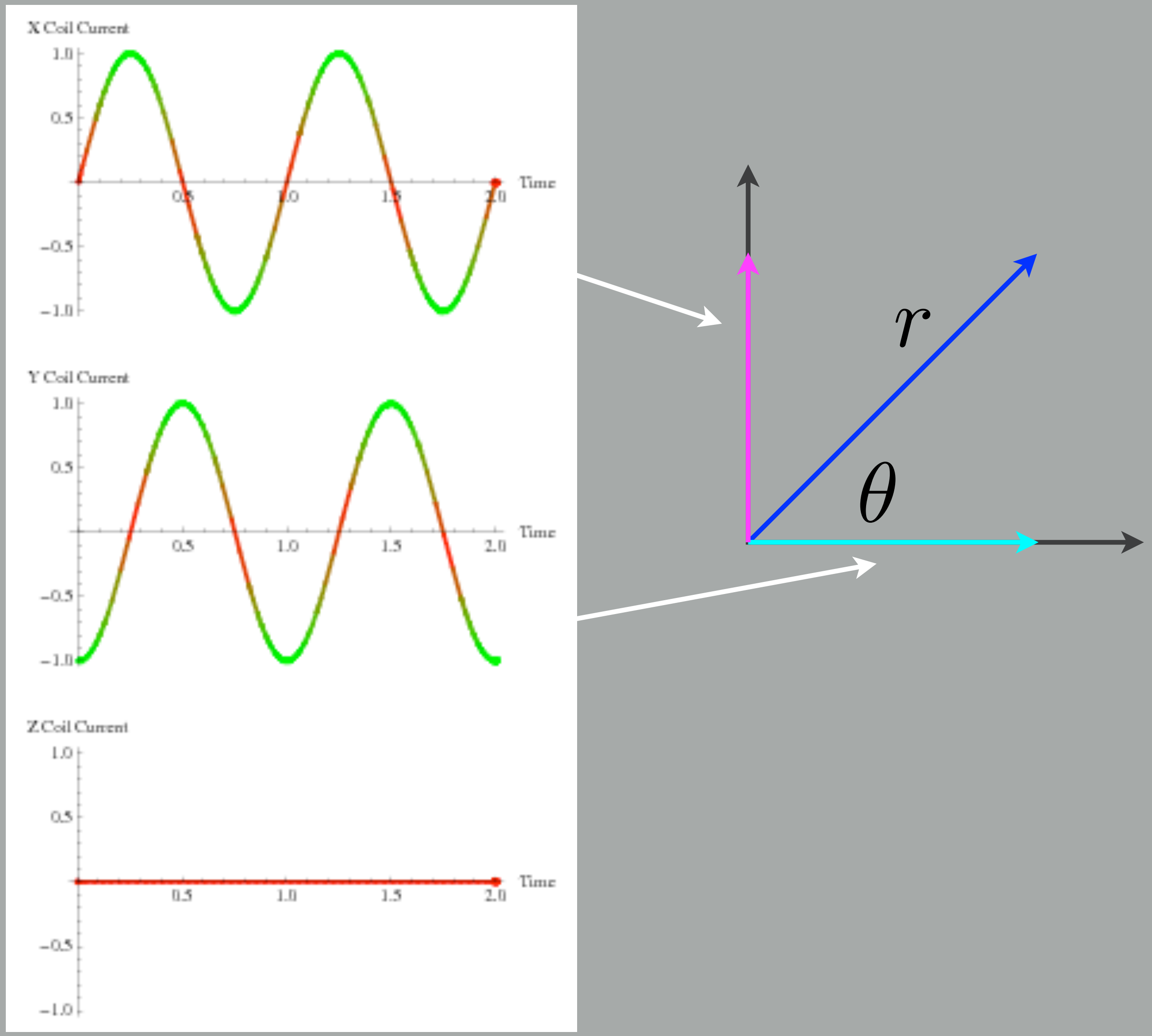
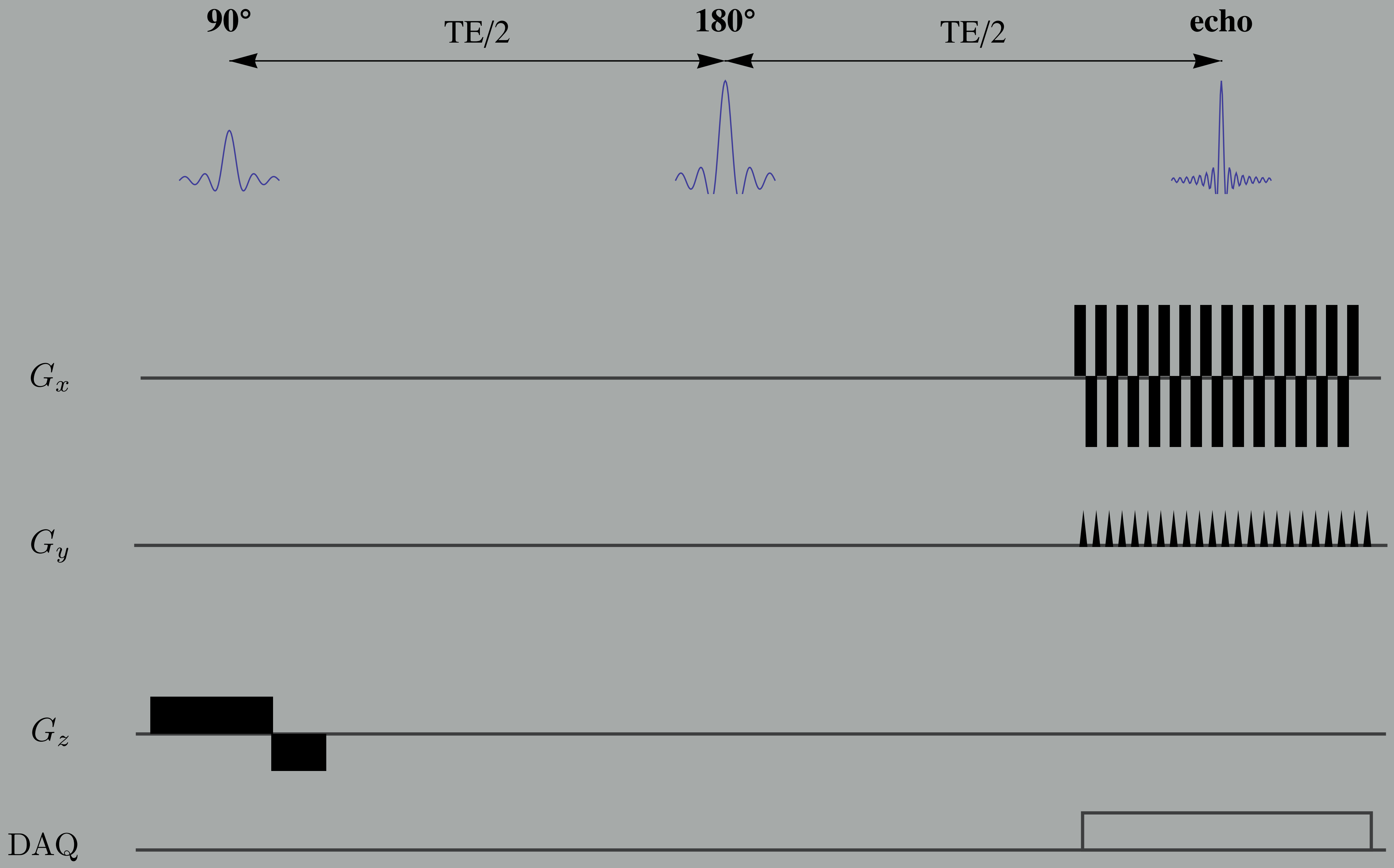


Image data collected in two "channels"
real and *imaginary*

Basic Spin Echo EPI acquisition



Receiver bandwidth

time between data samples:

$$\Delta t = 8\mu s$$

sampling rate:

$$\frac{1}{\Delta t} = \frac{1}{8\mu s} \approx 128kHz$$

This is the *receiver bandwidth*

If 256 points are collected
total acquisition time is 512 x 8*us* = 4*ms*

Image bandwidth

For a read gradient $G_x = .3G/cm$
creates a modulate across the image of

$$\gamma G_x FOV = 4258Hz/G \times .3G/cm \times 24cm \approx 32kHz$$

This is the *image bandwidth*

Bandwidth-per-pixel

Two spins on opposite sides of the image have precessional rates that differ by $32kHz$

Each of the 256 voxels differ in precessional rate from its neighbor by 32kHz/256 = 125Hz

This is the *bandwidth-per-pixel*

Chemical Shift Artifact

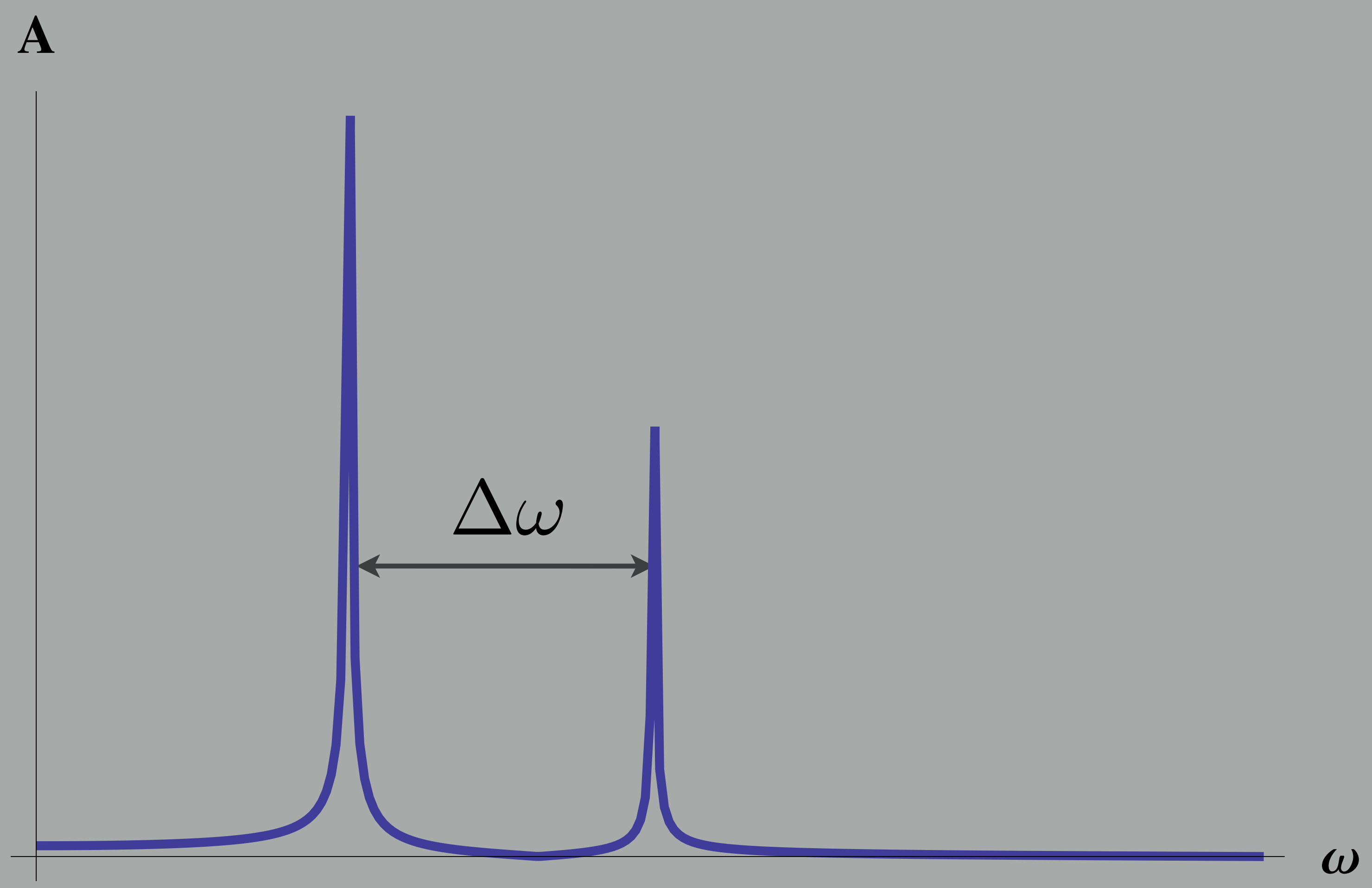
Fat and water have different resonance (Larmor) frequencies by approximately 3.5ppm (parts-per-million)

$$3.5 \times 10^6 \times 42.6MHz/T \approx 150Hz/T$$

So at 3T:

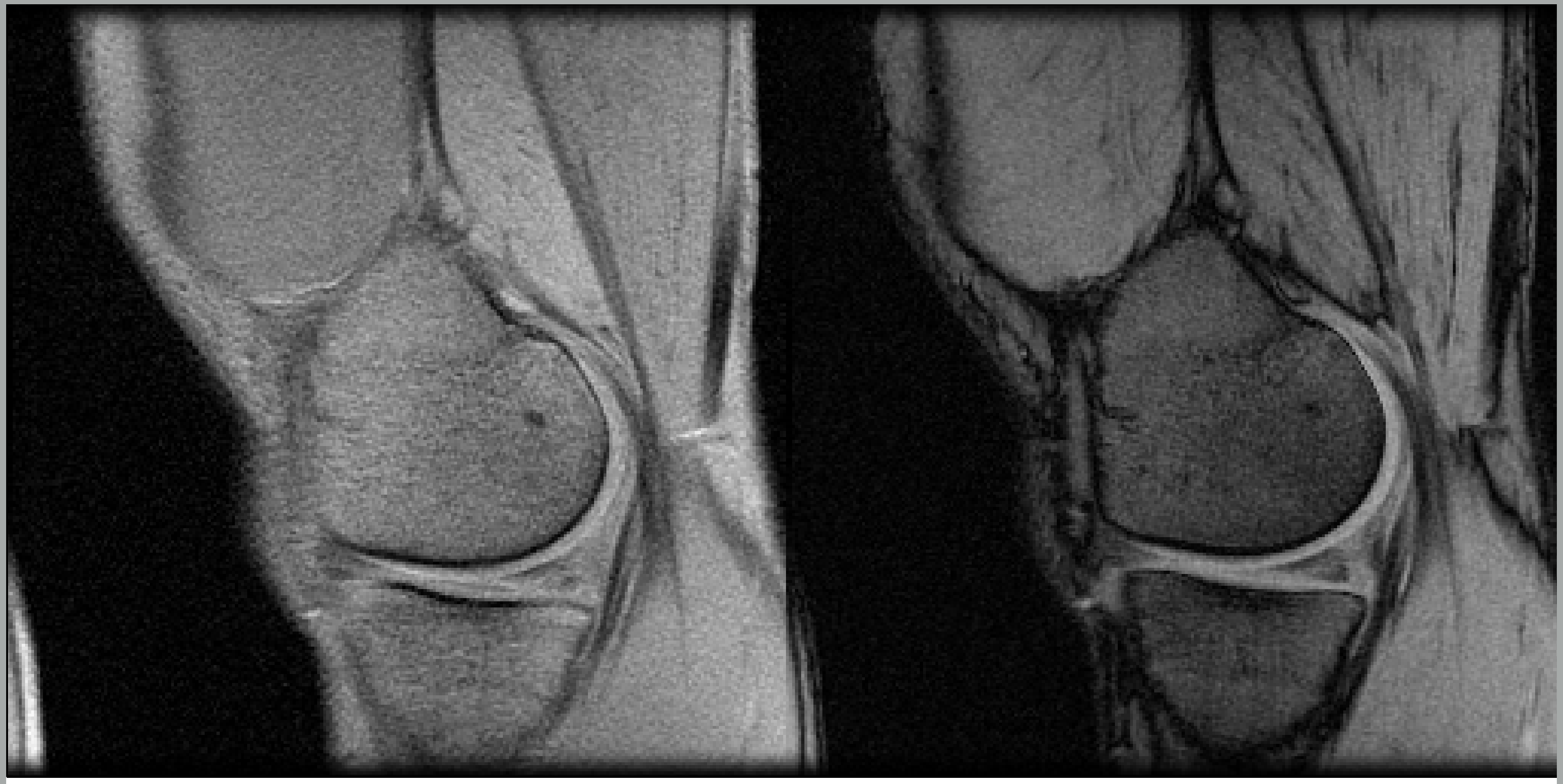
$$3T \times 150Hz/T = 450Hz$$

Chemical Shift Artifact



$$\Delta\omega \approx 440Hz \text{ @ } 3T$$

The uses of chemical shift



In phase
(TE = 3.9 ms)

Out of phase
(TE = 7.0 ms)

Chemical Shift Artifact

Fat is shifted relative to water in the read direction

$$\frac{\text{frequency difference}}{\text{bandwidth-per-pixel}}$$

at 3T for 24cm FOV and 256 pixels:

$$\Delta x = \frac{450 \text{ Hz}}{125 \text{ Hz}} = 3.6 \text{ pixels}$$

Chemical Shift Artifact

Particular bad in EPI which has a very low bandwidth-per-pixel in the phase encoding direction since time between samples is much longer in that direction

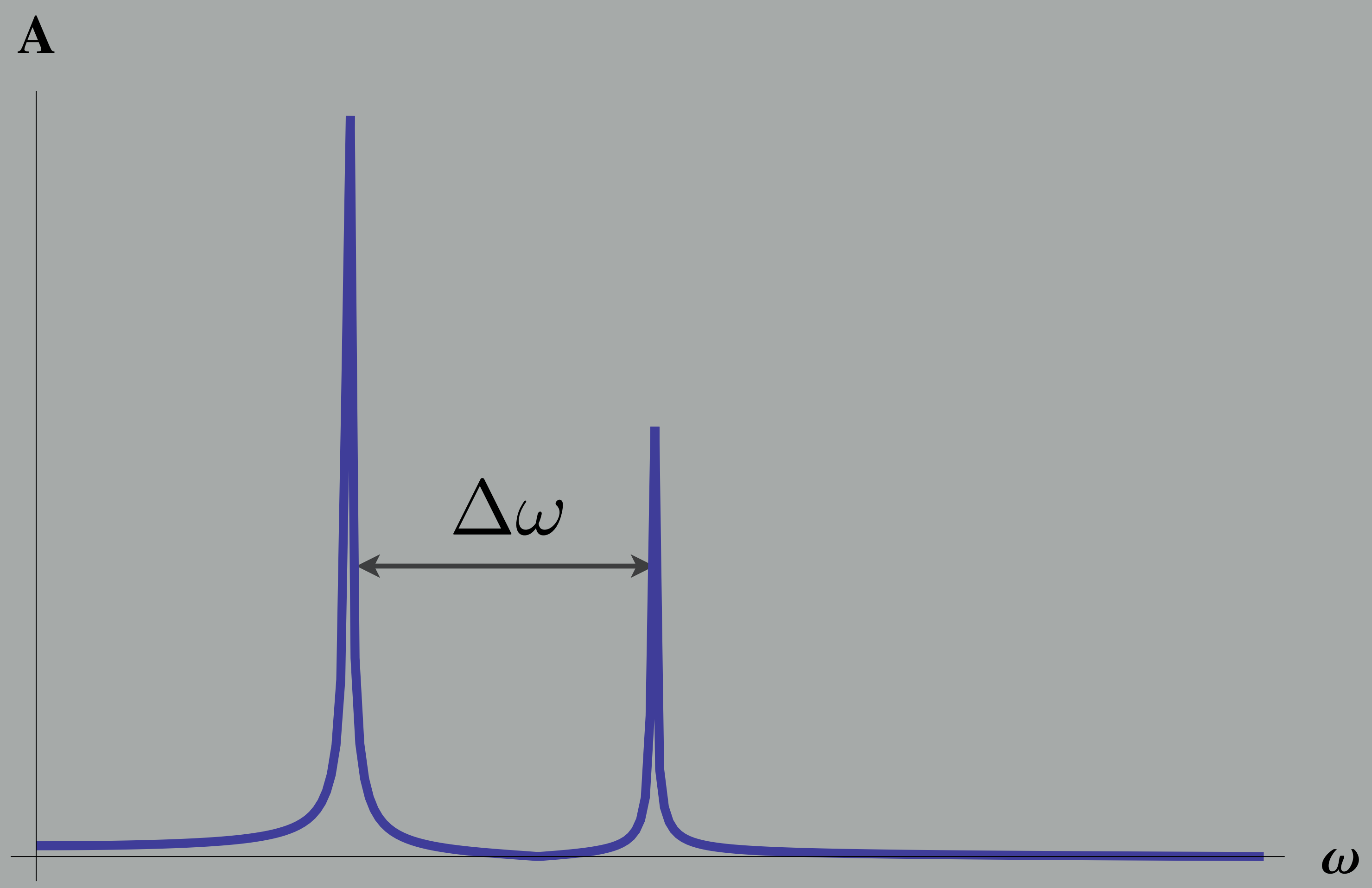
Typically around

15 Hz/pixel

So shift is

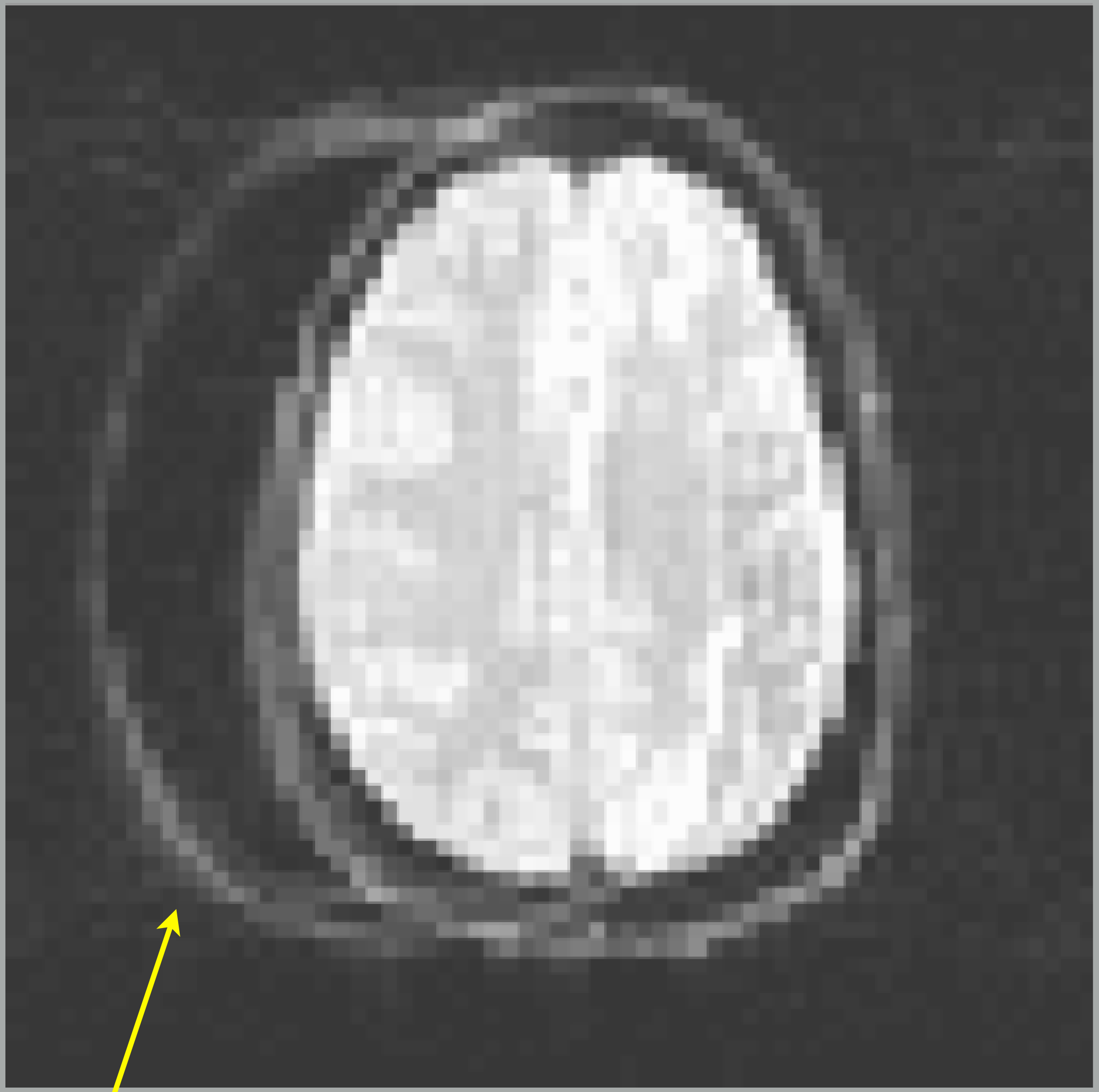
$$450Hz/(15Hz/\text{pixel}) = 30 \text{ pixels}$$

Chemical Shift Artifact



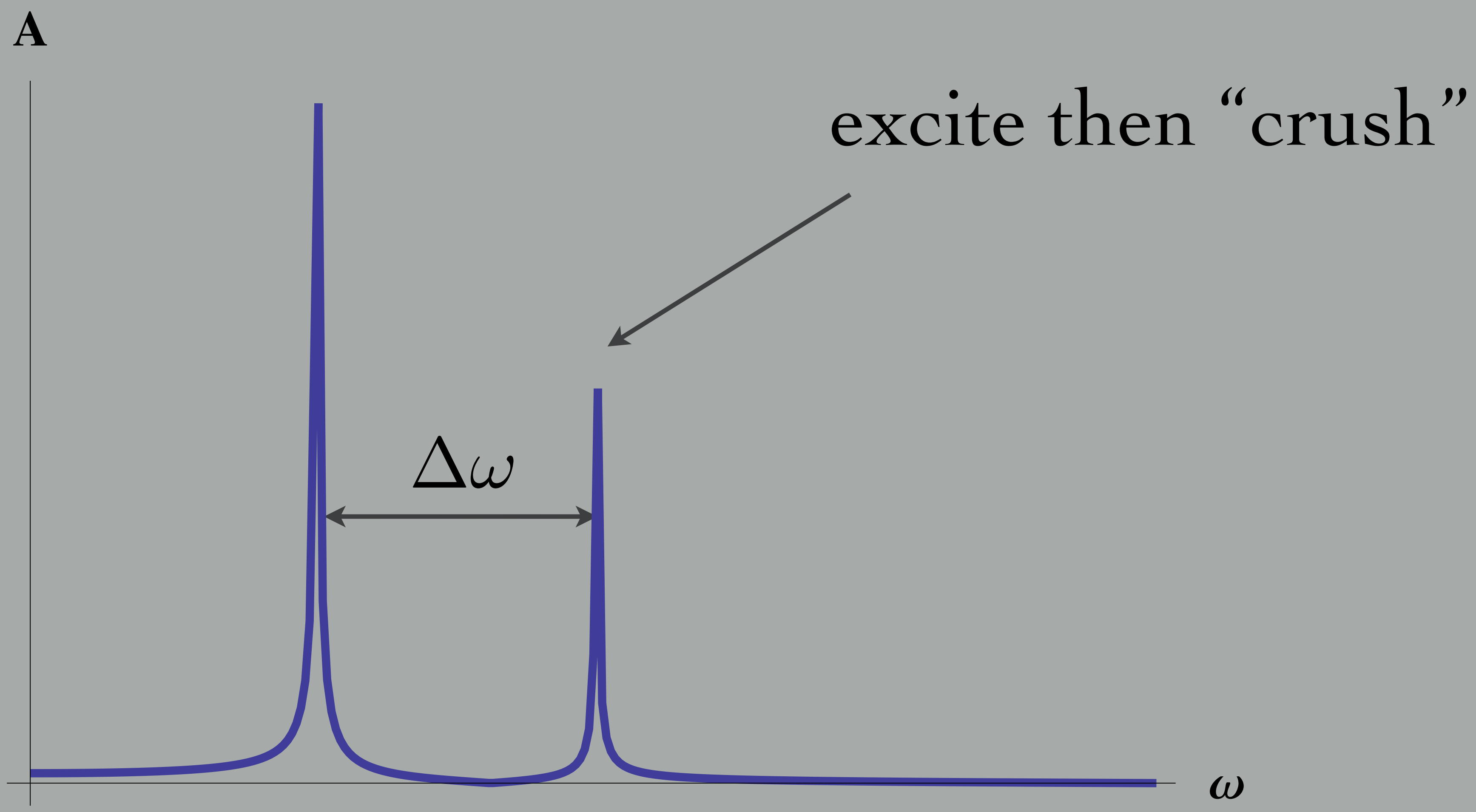
$$\Delta\omega \approx 440Hz \; @ \; 3T$$

Chemical shift artifacts in EPI



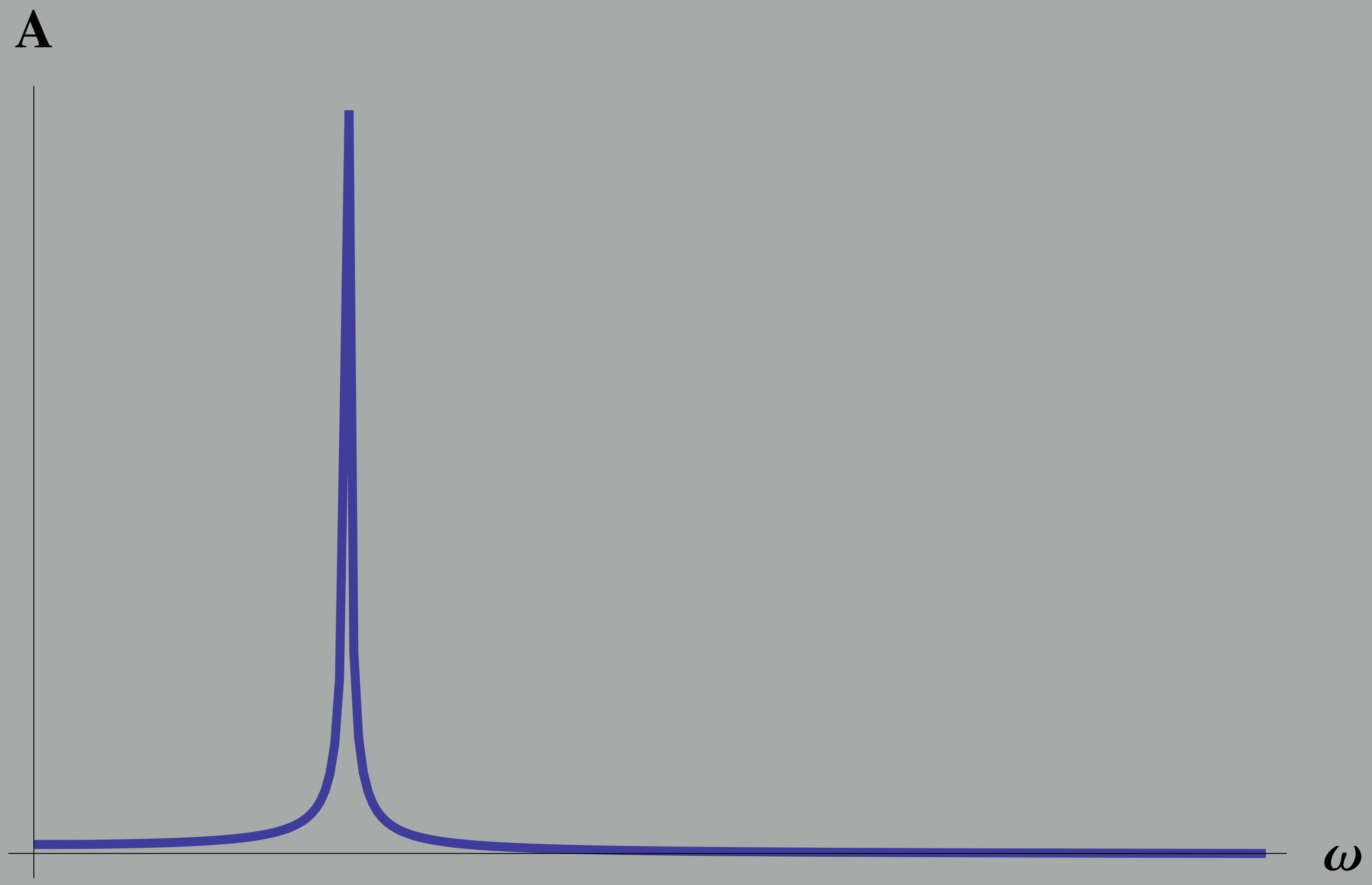
Fat signal

Fat Suppression

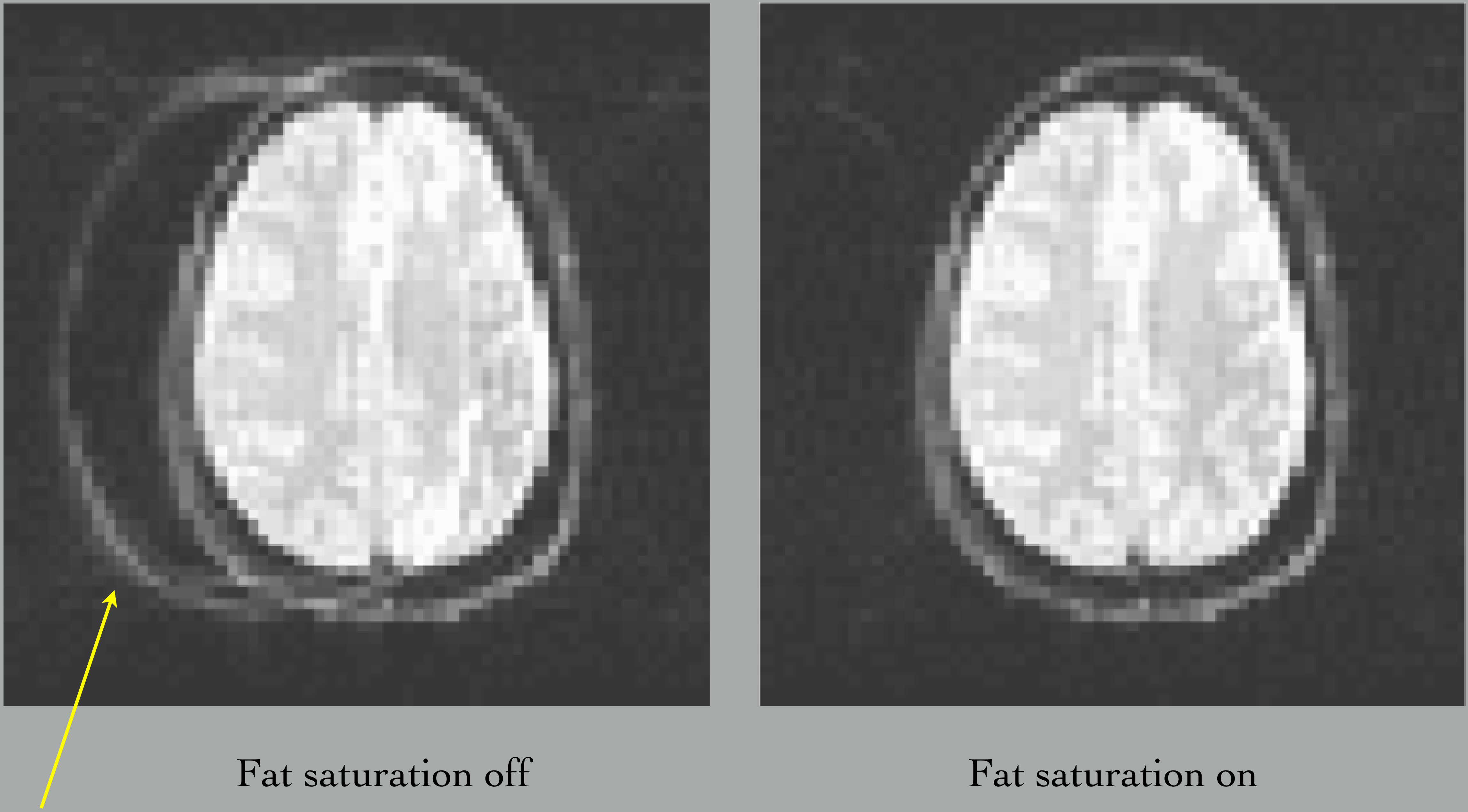


$$\Delta\omega \approx 440Hz \text{ @ } 3T$$

Fat Suppression



Chemical shift artifacts

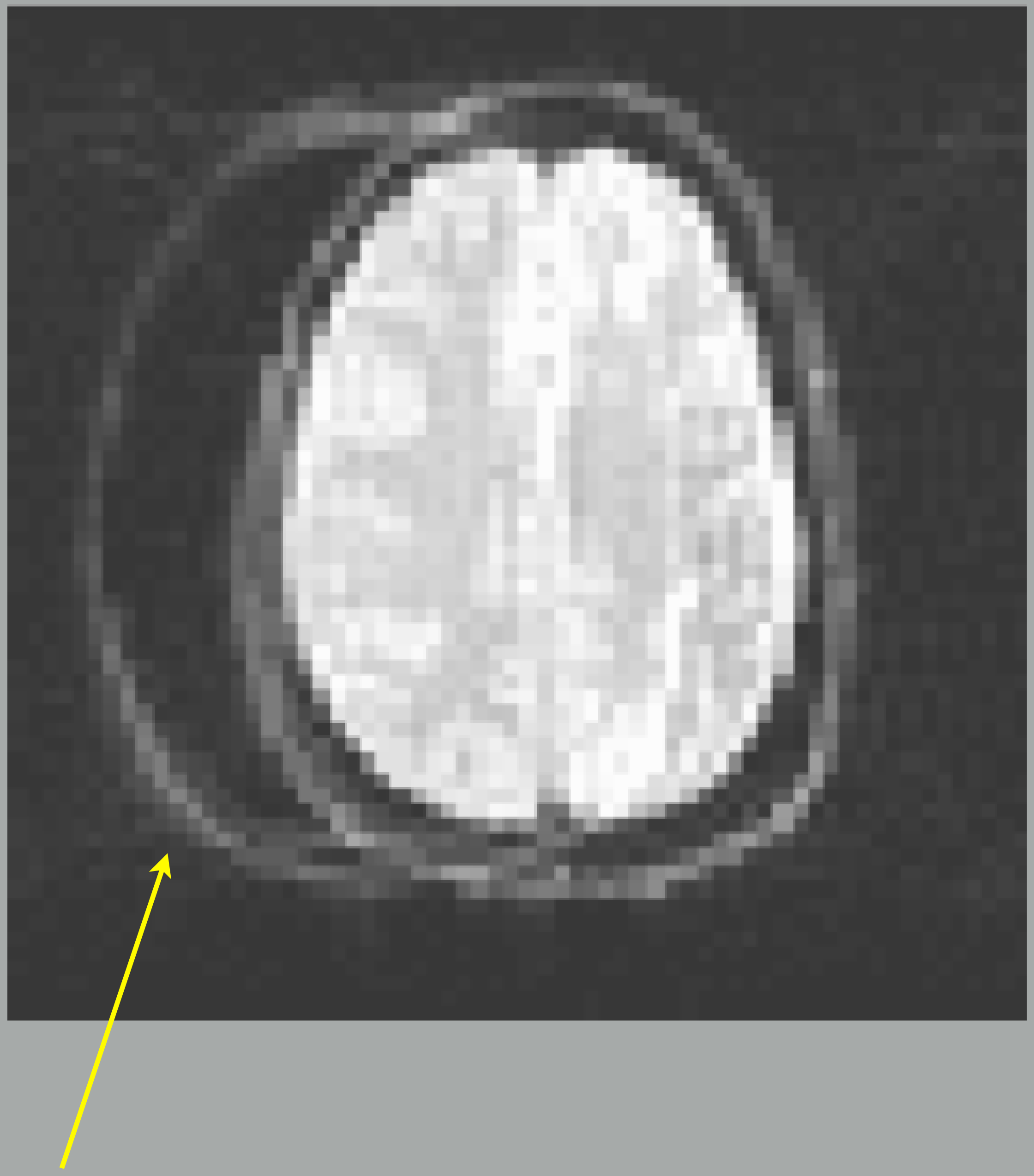


Fat saturation off

Fat saturation on

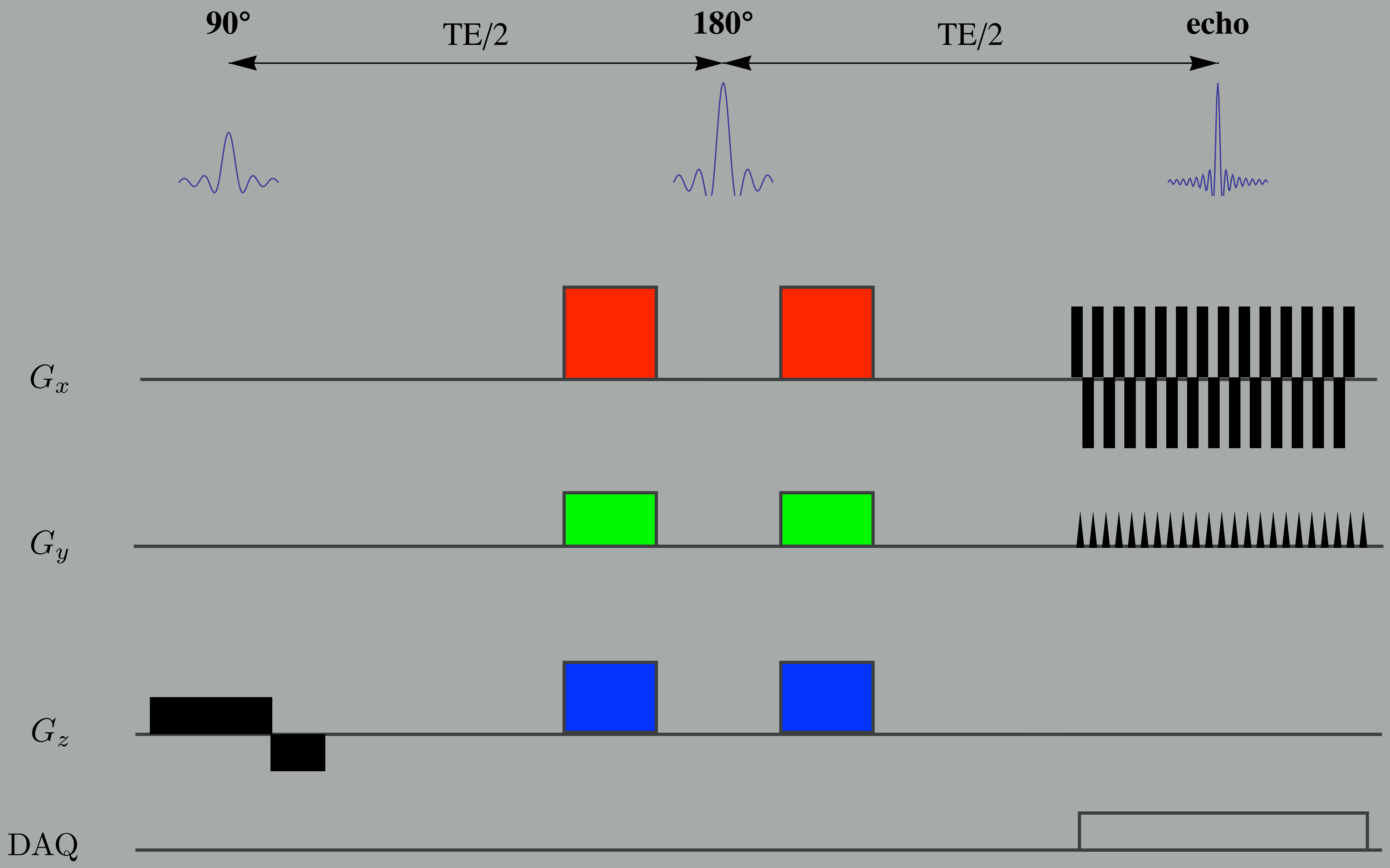
EPI acquisition

Chemical shift artifacts

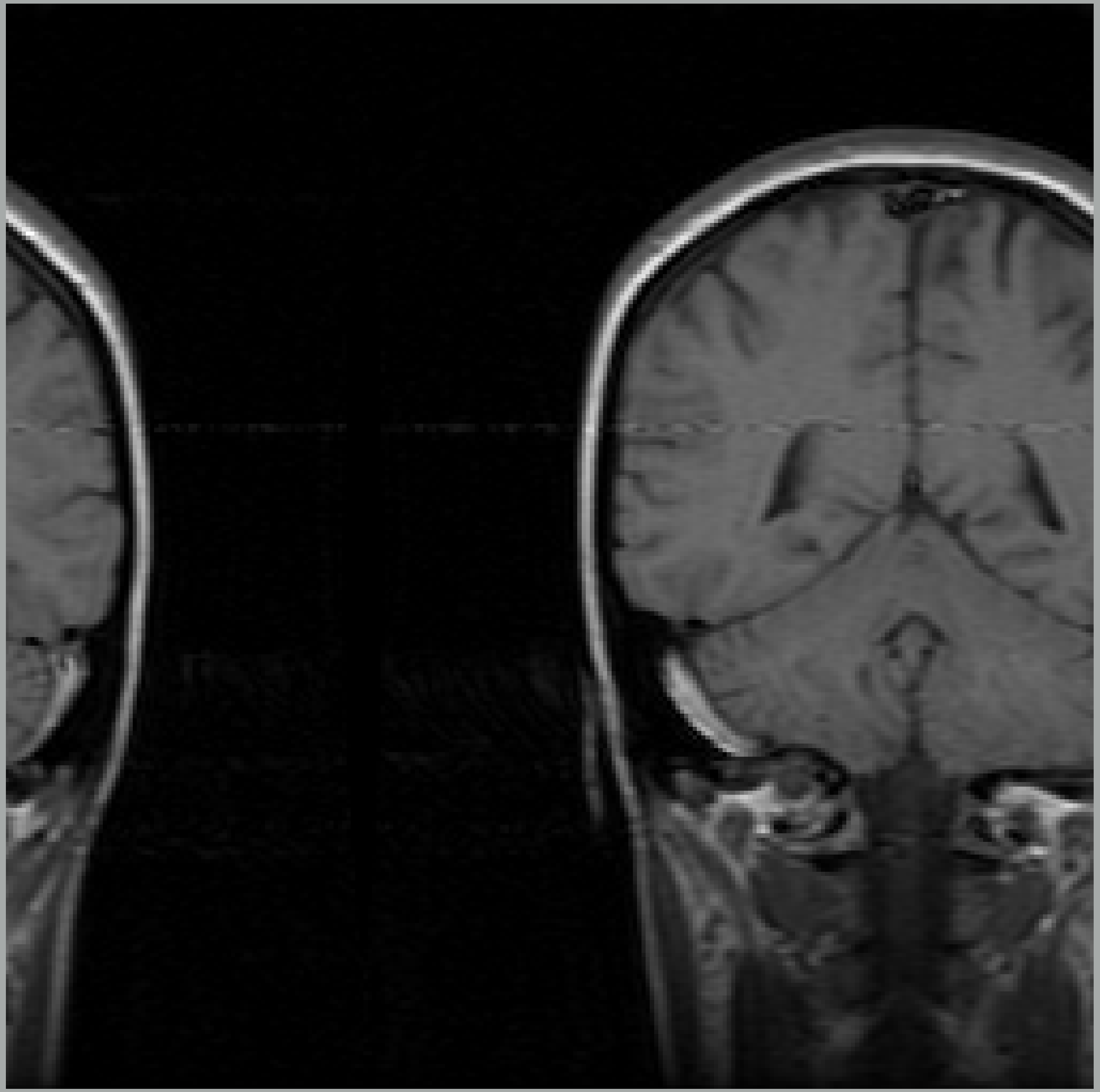


EPI acquisition

Basic Spin Echo EPI DTI acquisition

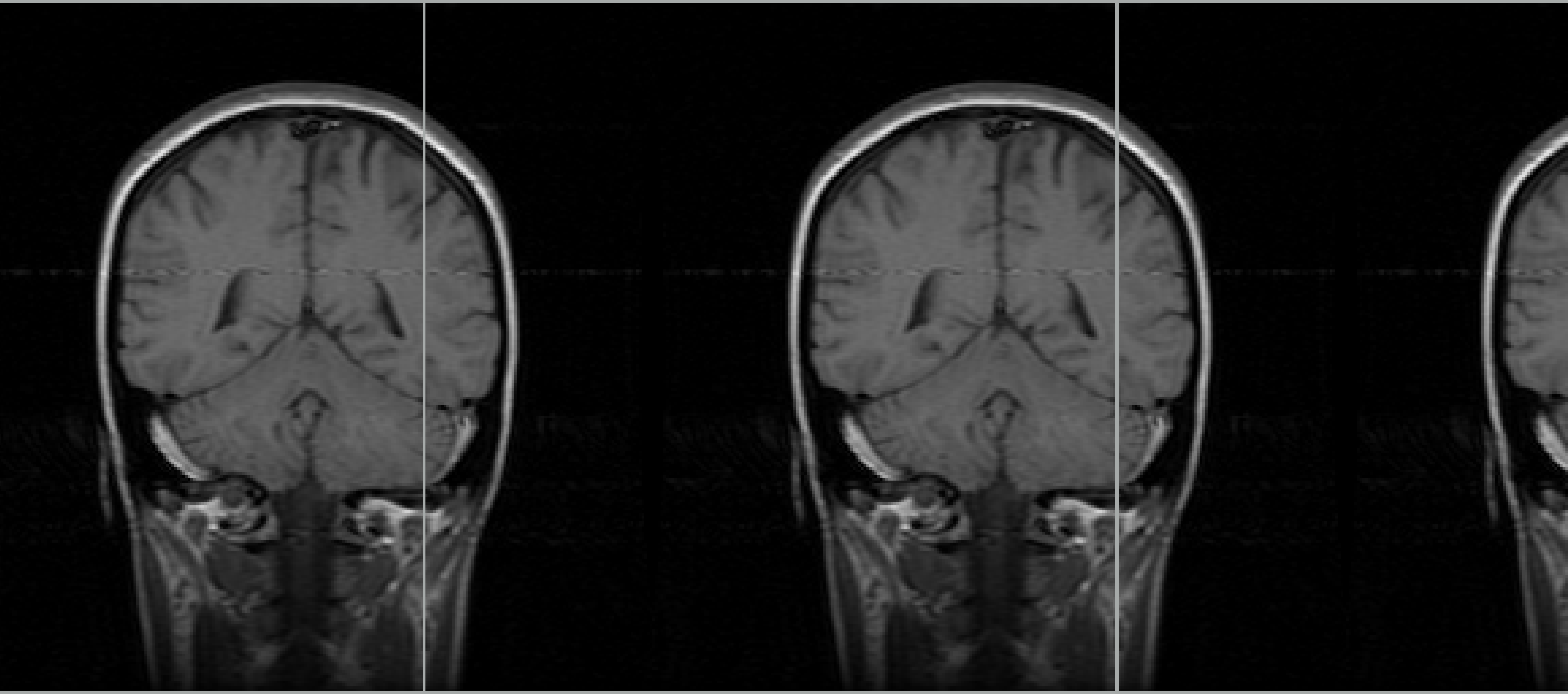


Aliasing



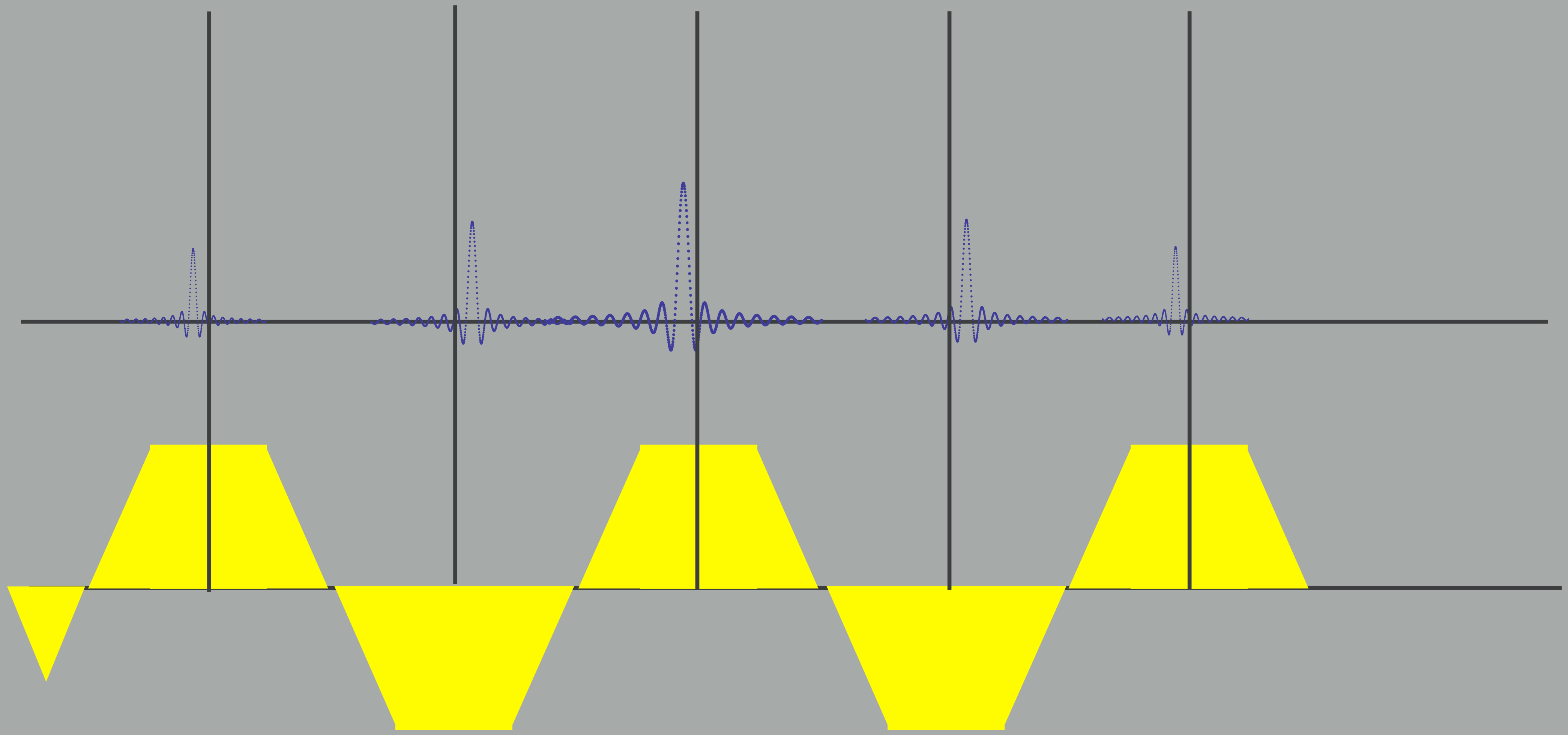
bandwidth of object > receiver bandwidth

Aliasing



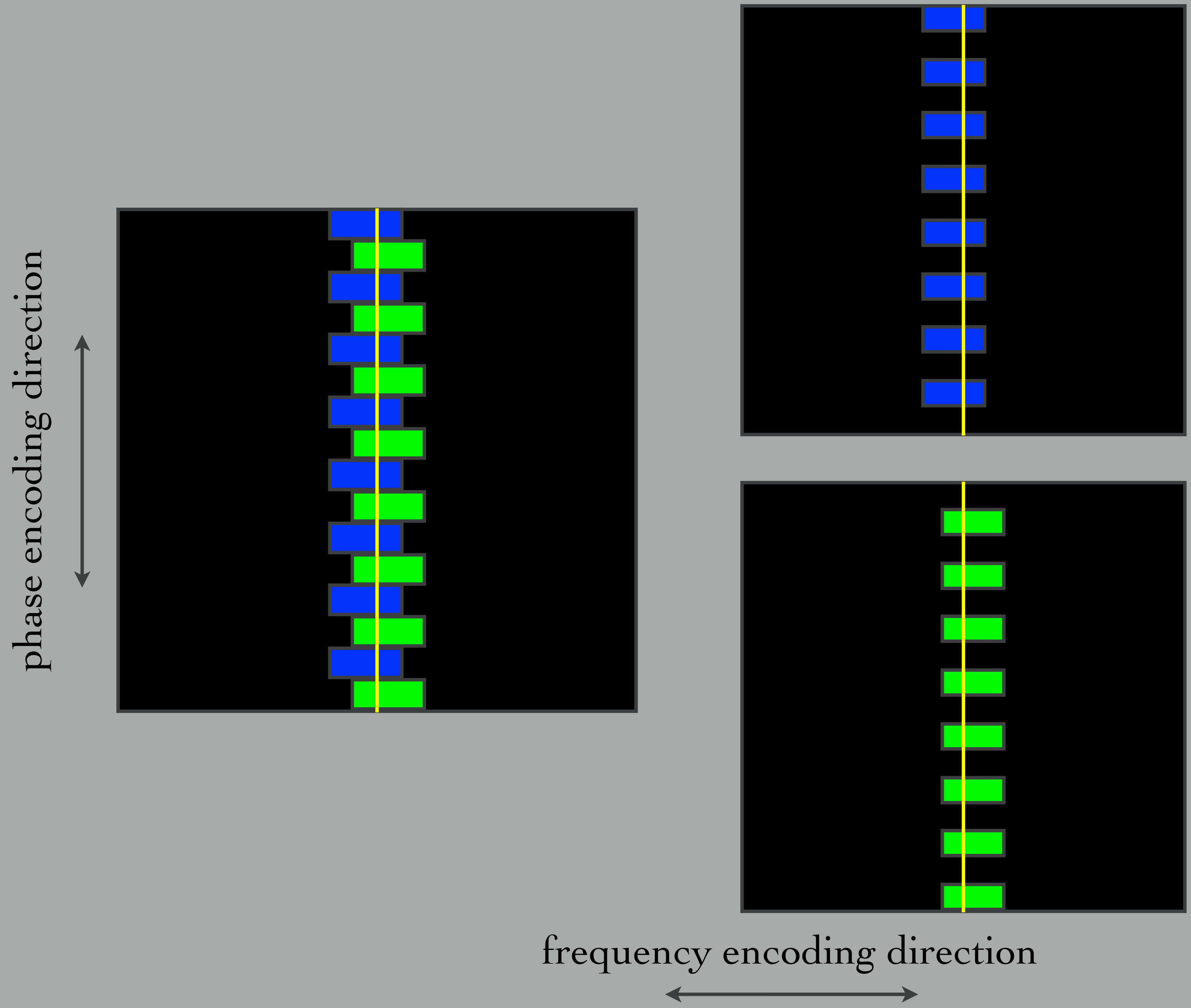
Fourier representation: periodically repeating

Nyquist ghosts



frequency encoding
gradient

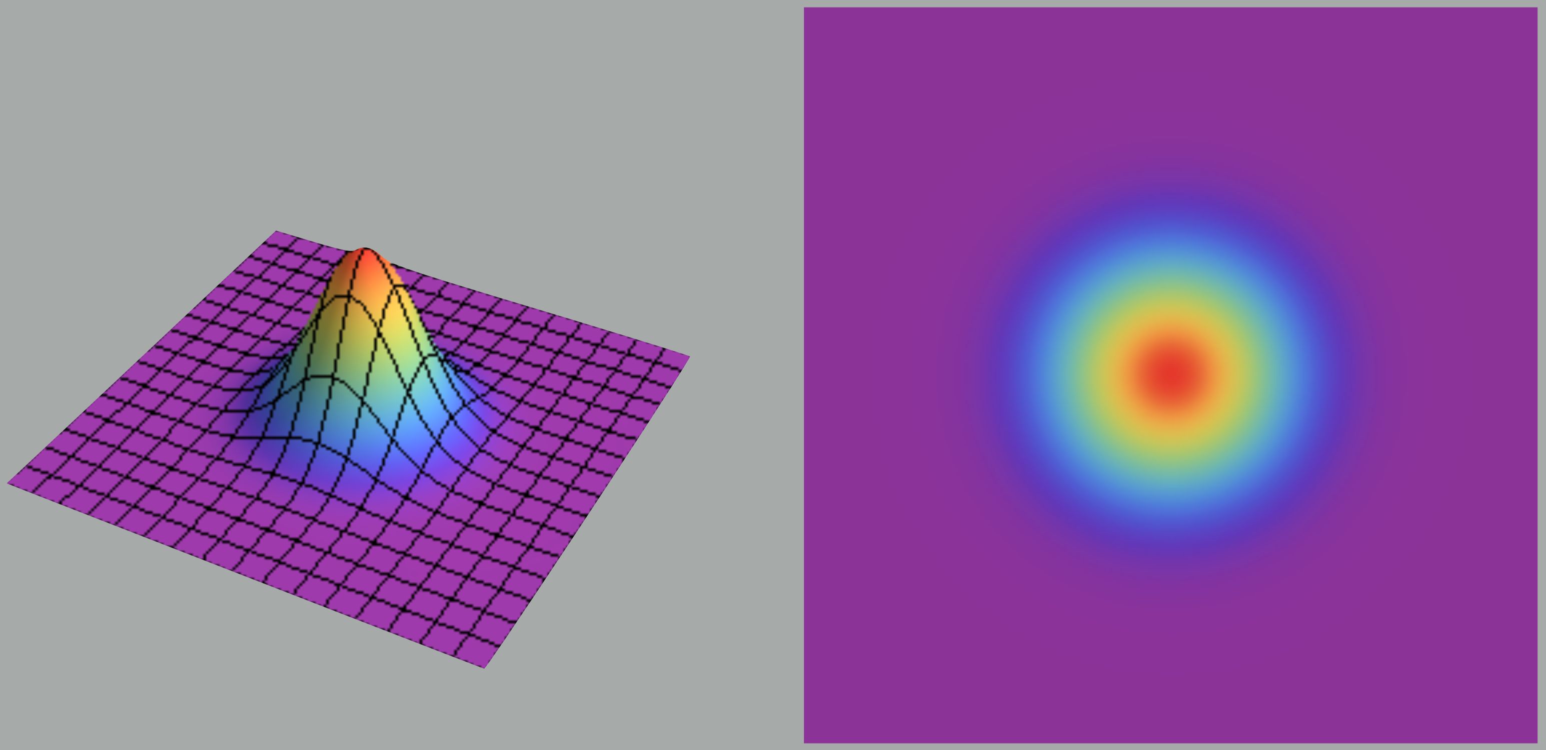
Nyquist ghosts



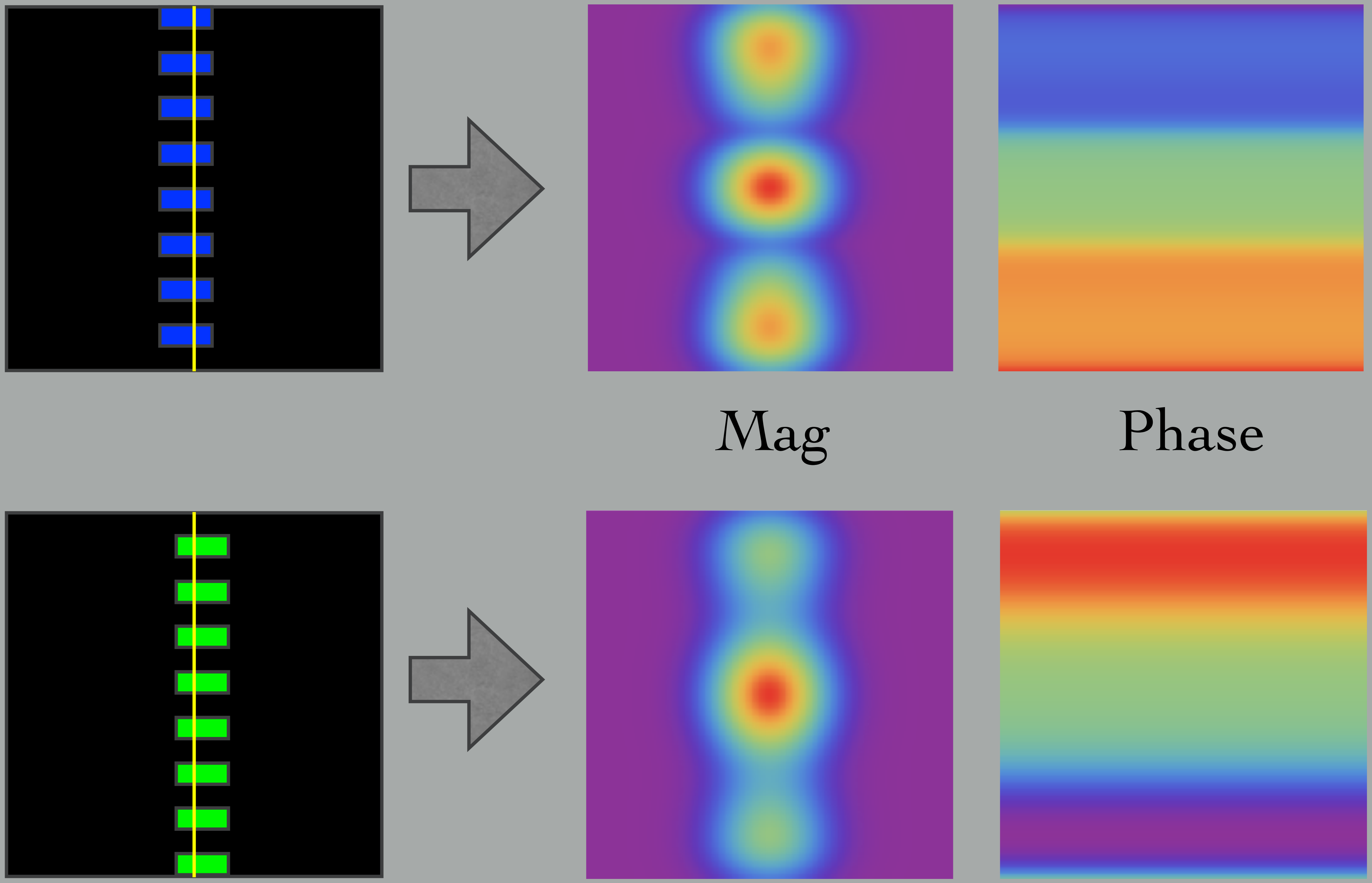
$$FOV_{even} = \frac{2\pi}{2\Delta k}$$

$$FOV_{odd} = \frac{2\pi}{2\Delta k}$$

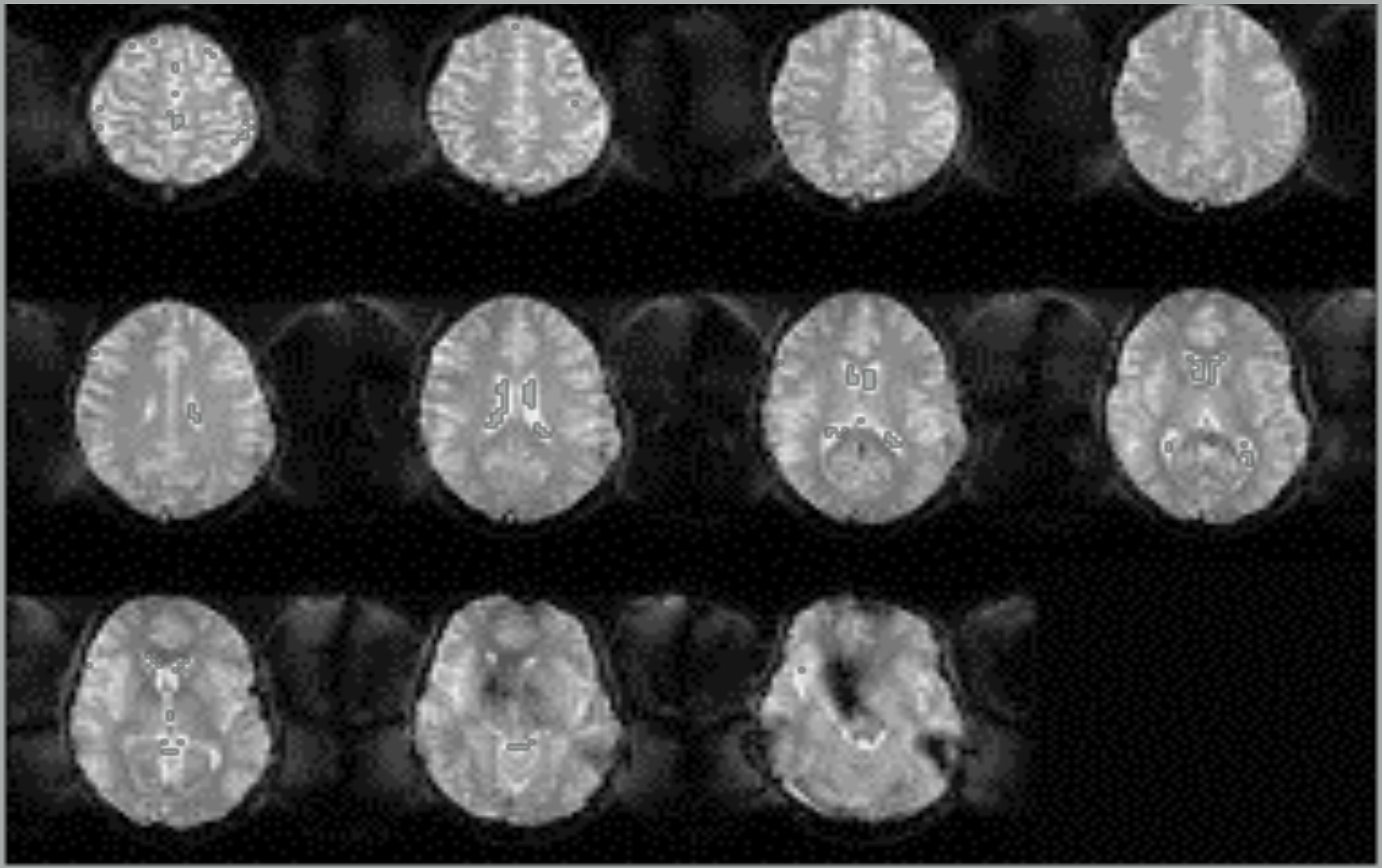
Nyquist ghosts



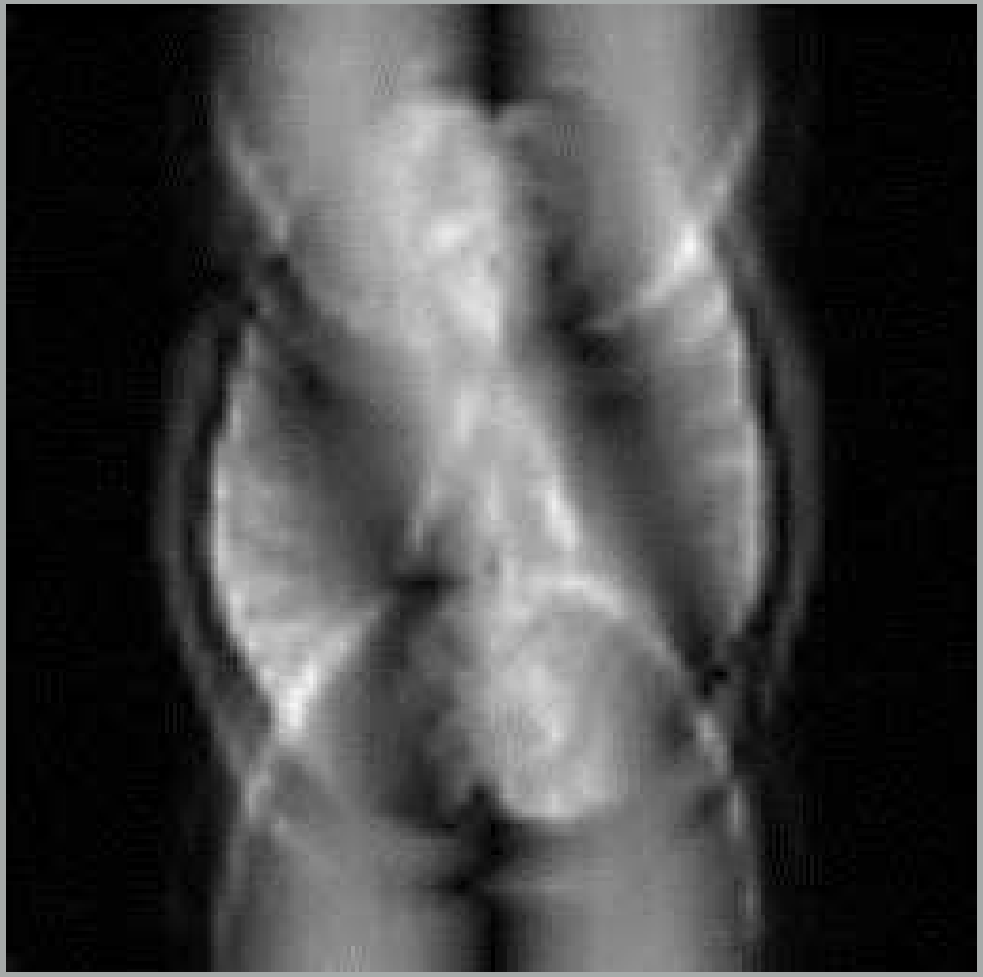
Nyquist ghosts



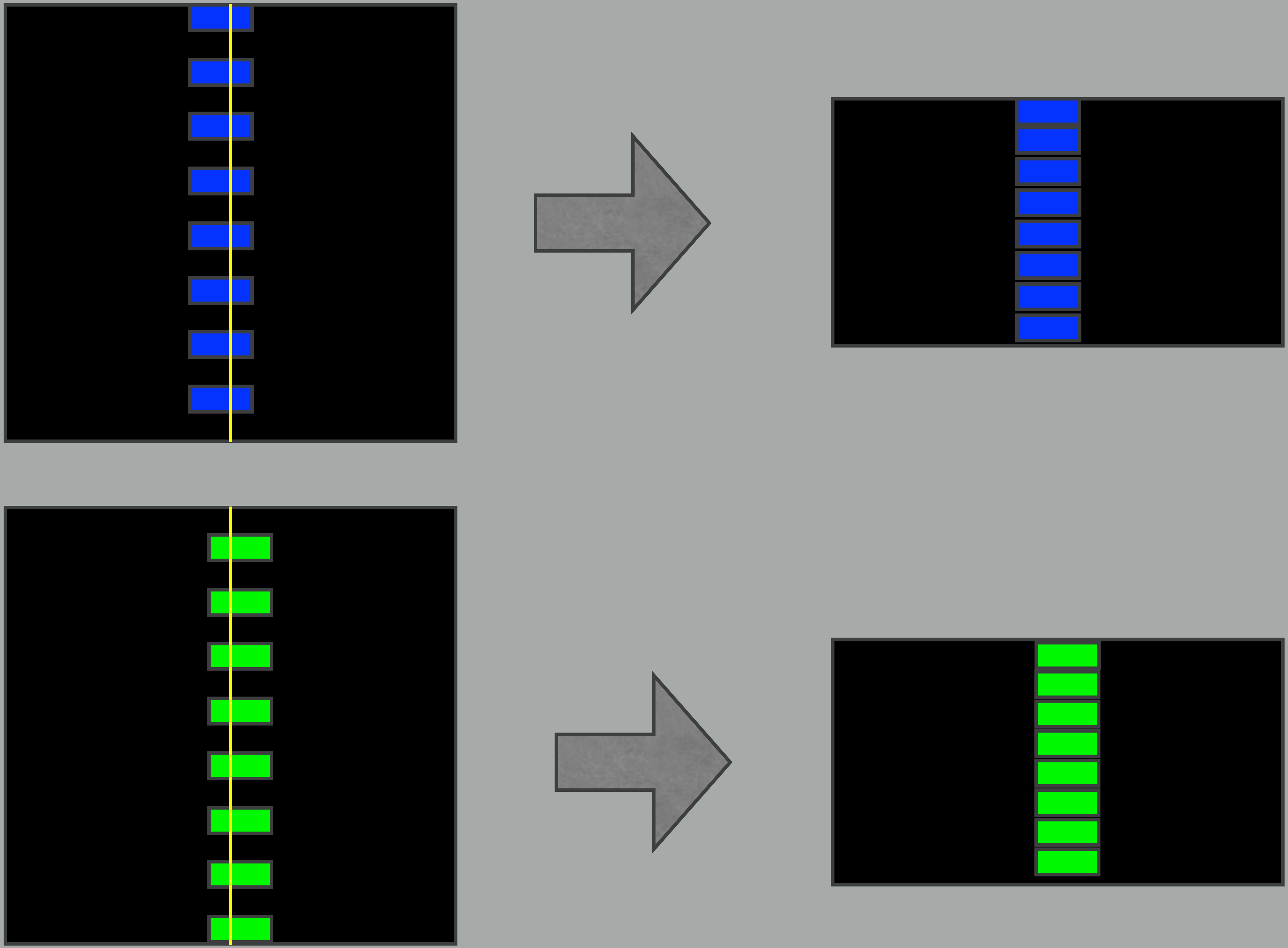
EPI signal dropout



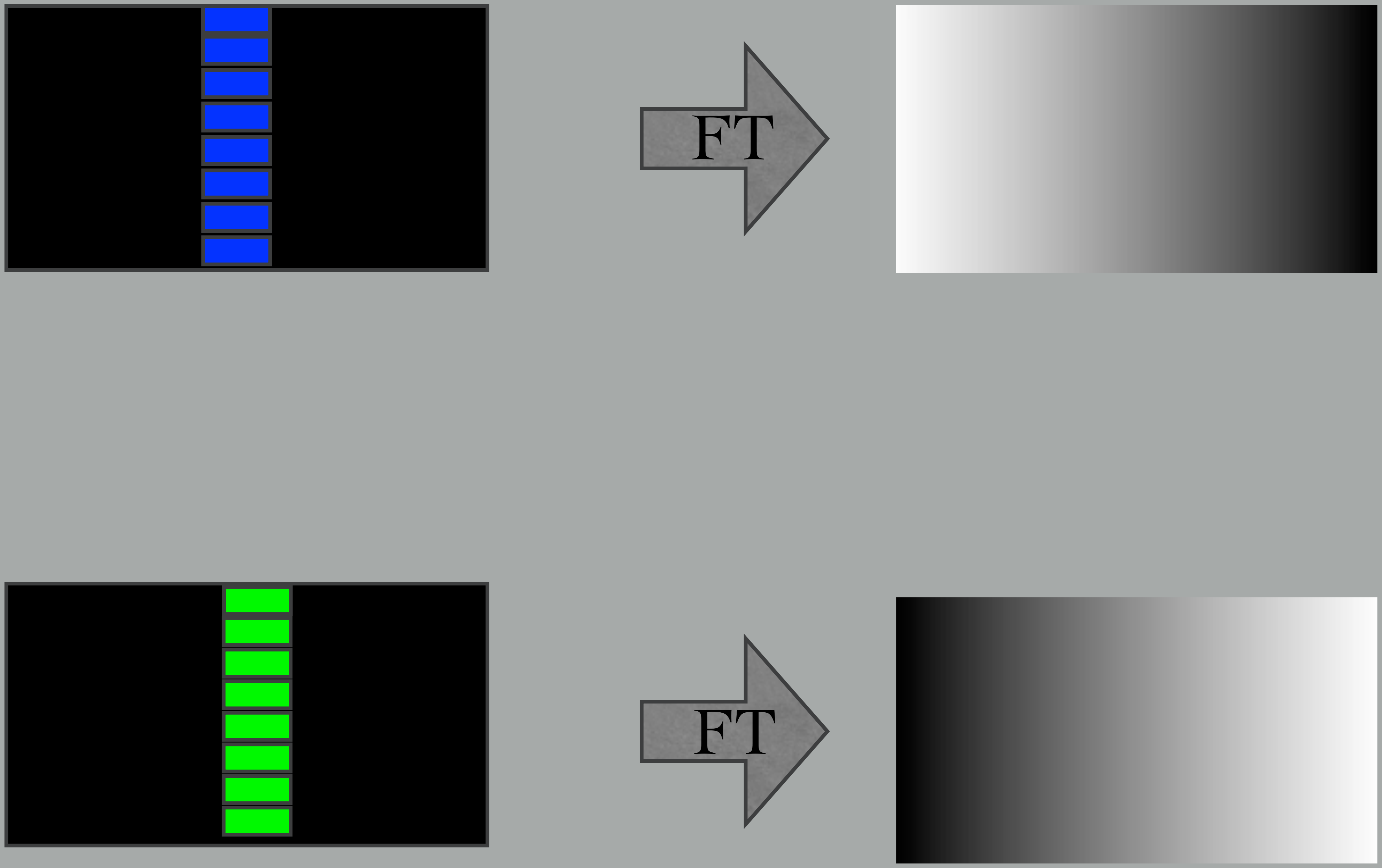
EPI N/2 ghost



Nyquist ghost correction



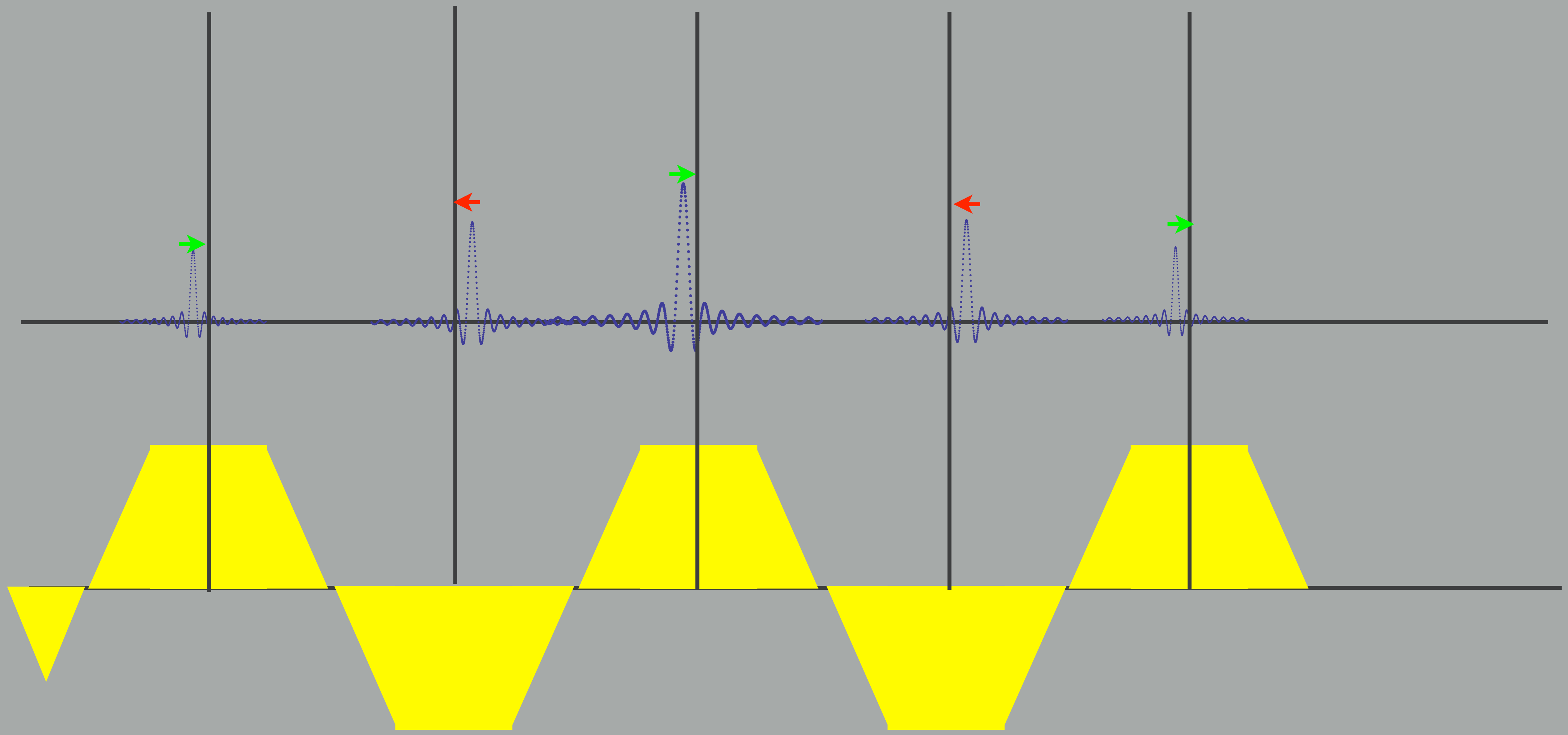
Nyquist ghost correction



FT

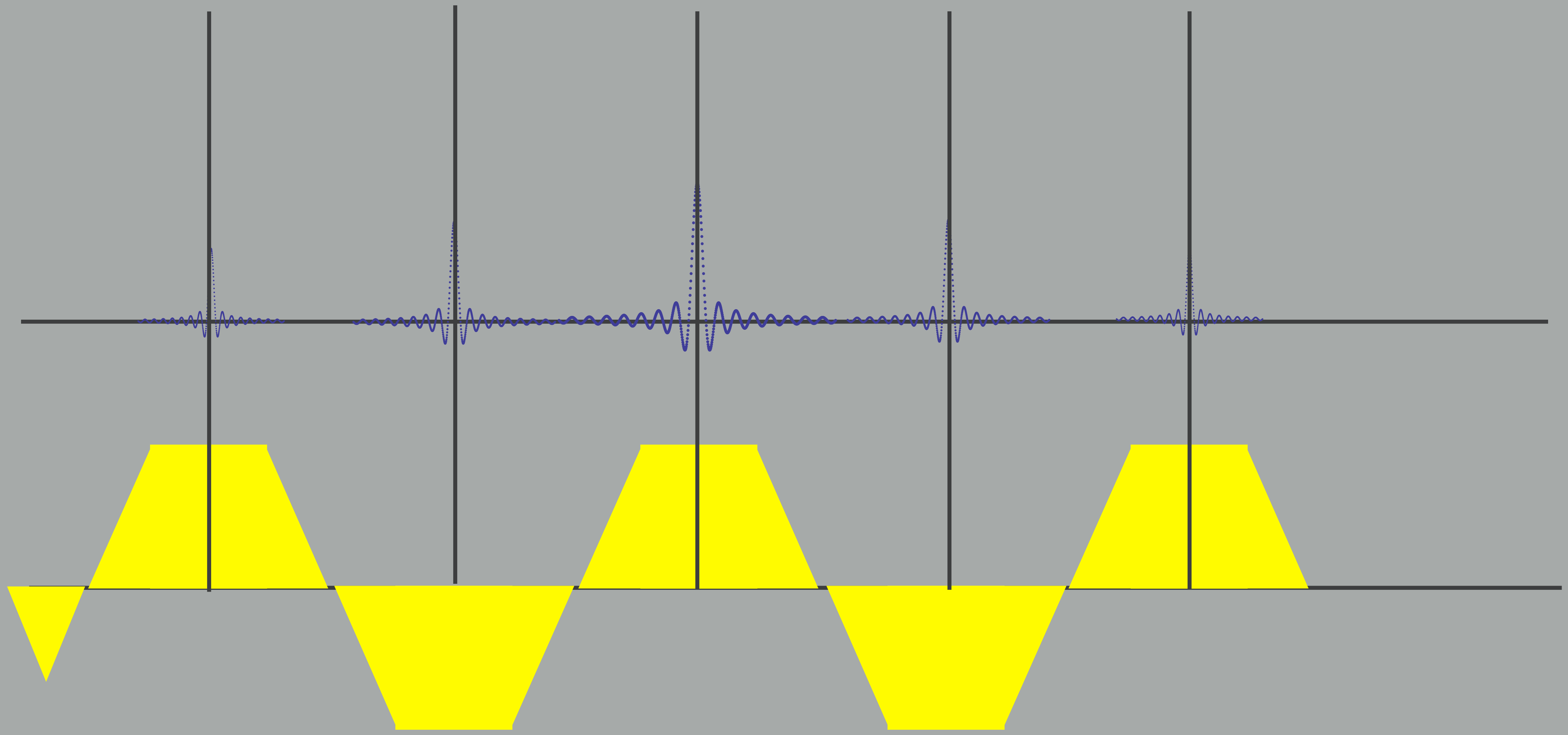
FT

Nyquist ghosts



shift is easily measured:
time shift = phase in FT

Nyquist ghost correction



Field distortions

Pixel shift in *r*

$$\Delta r = \left(\frac{\delta B_o}{W_r} \right) F_r$$

ratio of frequency offset to bandwith

$$\begin{aligned} \delta B_o &= \text{field offset} \\ W_r &= \text{bandwidth in r} \\ F_r &= \text{Field-of-view in r} \end{aligned}$$

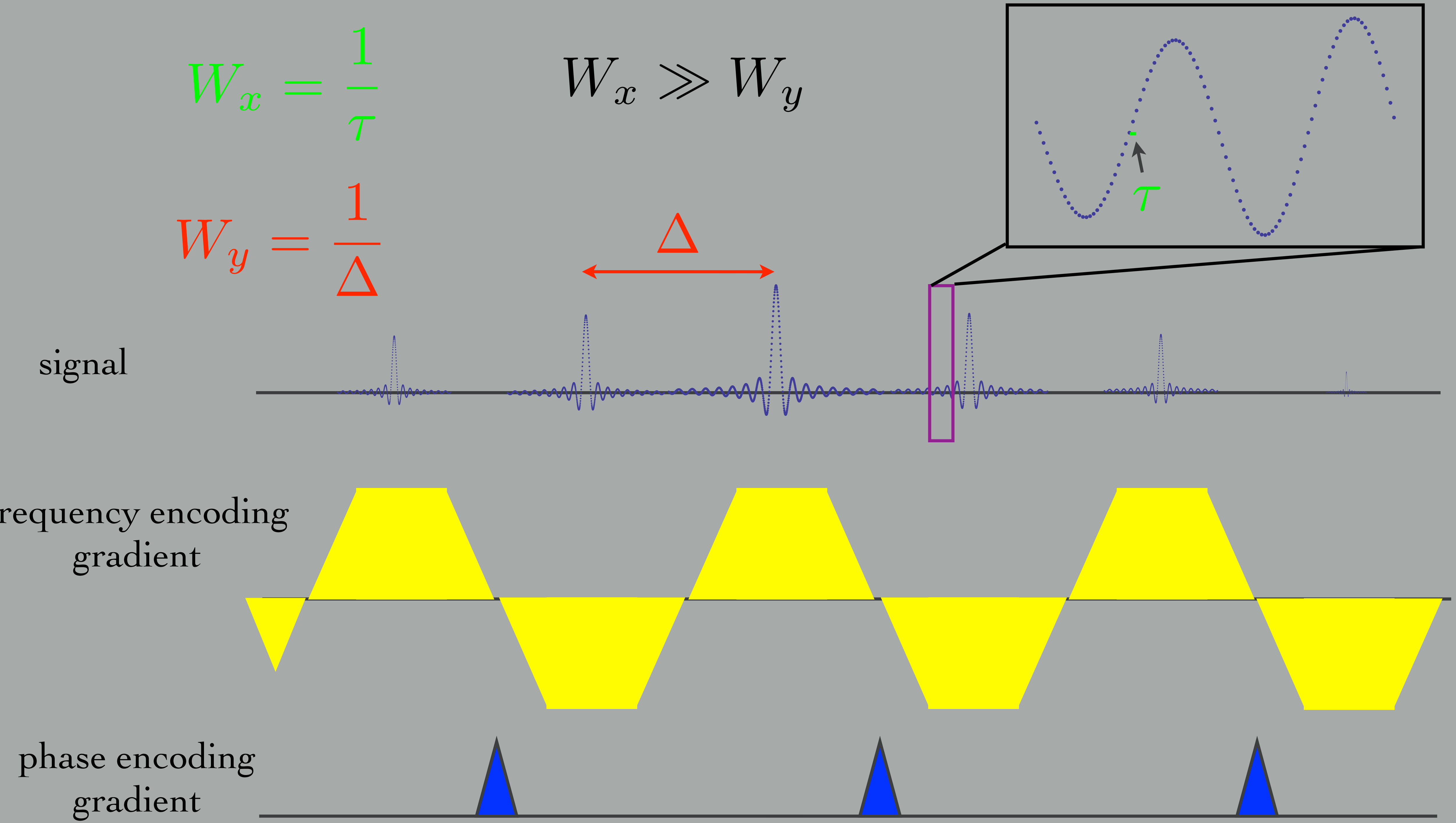
Field distortions:

EPI Bandwidths

$$W_x = \frac{1}{\tau}$$

$$W_y = \frac{1}{\Delta}$$

$$W_x \gg W_y$$



EPI Bandwidths

$$\Delta x = \left(\frac{\delta B_o}{W_x}\right) F_x = \tau \delta B_o F_x$$

$$\Delta \gg \tau \rightarrow \Delta y \gg \Delta x$$

$$\Delta y = \left(\frac{\delta B_o}{W_y}\right) F_y = \Delta \delta B_o F_y$$

(assume $F_x = F_y$)

Field inhomogeneities

Field inhomogeneities cause shift
in the phase encoding direction in EPI

$$x = x_o + \frac{\Delta\nu}{W_{pe}}$$

x_o = true position

$\Delta\nu$ = frequency offset (Hz)

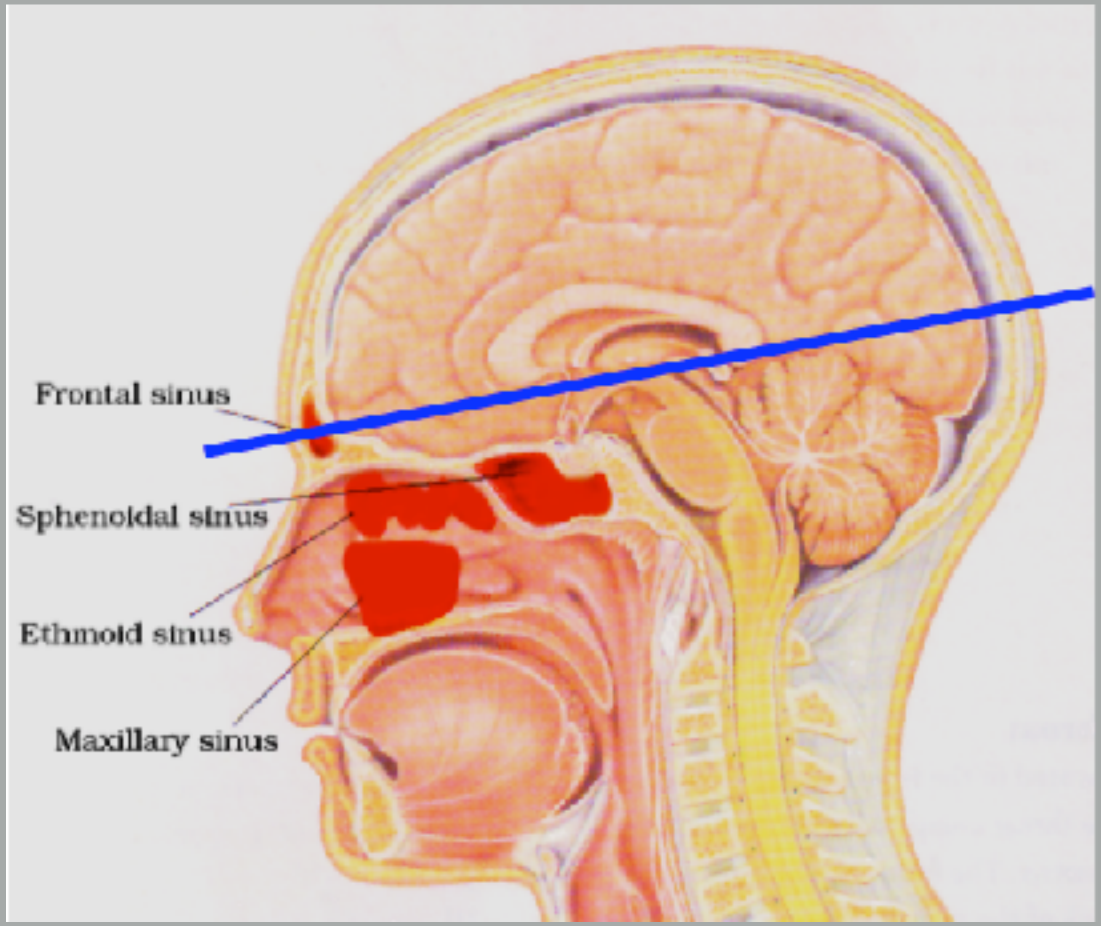
W_{pe} = bandwidth in phase encoding direction (Hz)

Static Field Inhomogeneity and EPI

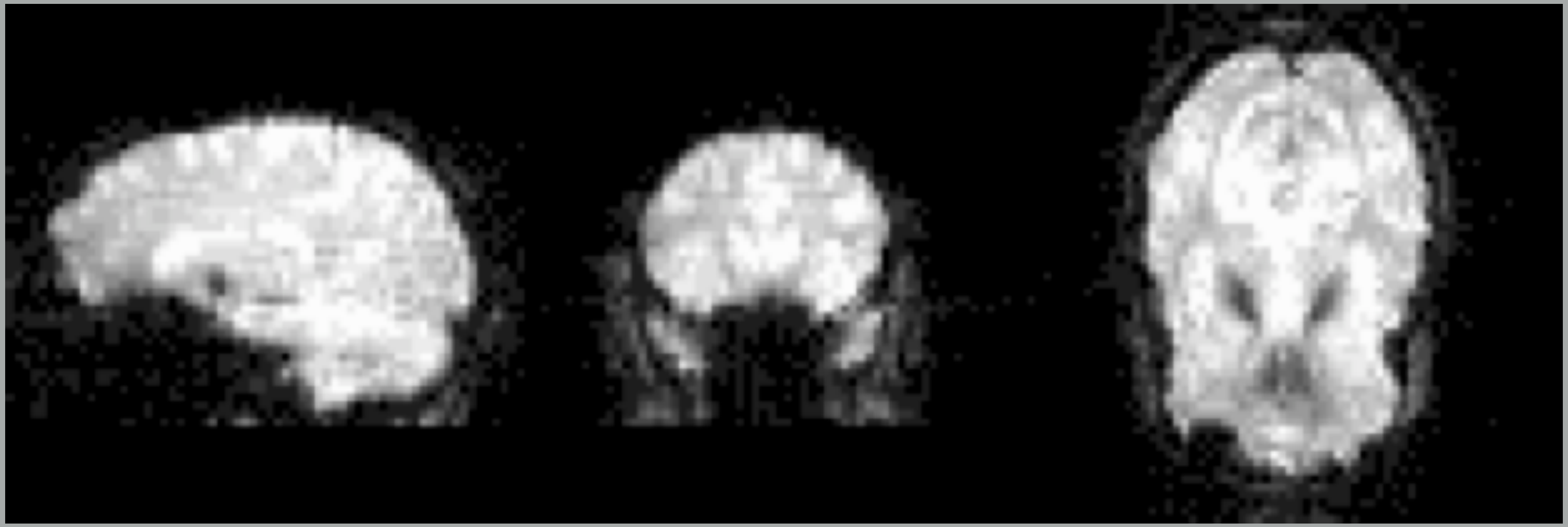
Frequency encoding direction

Phase encoding direction

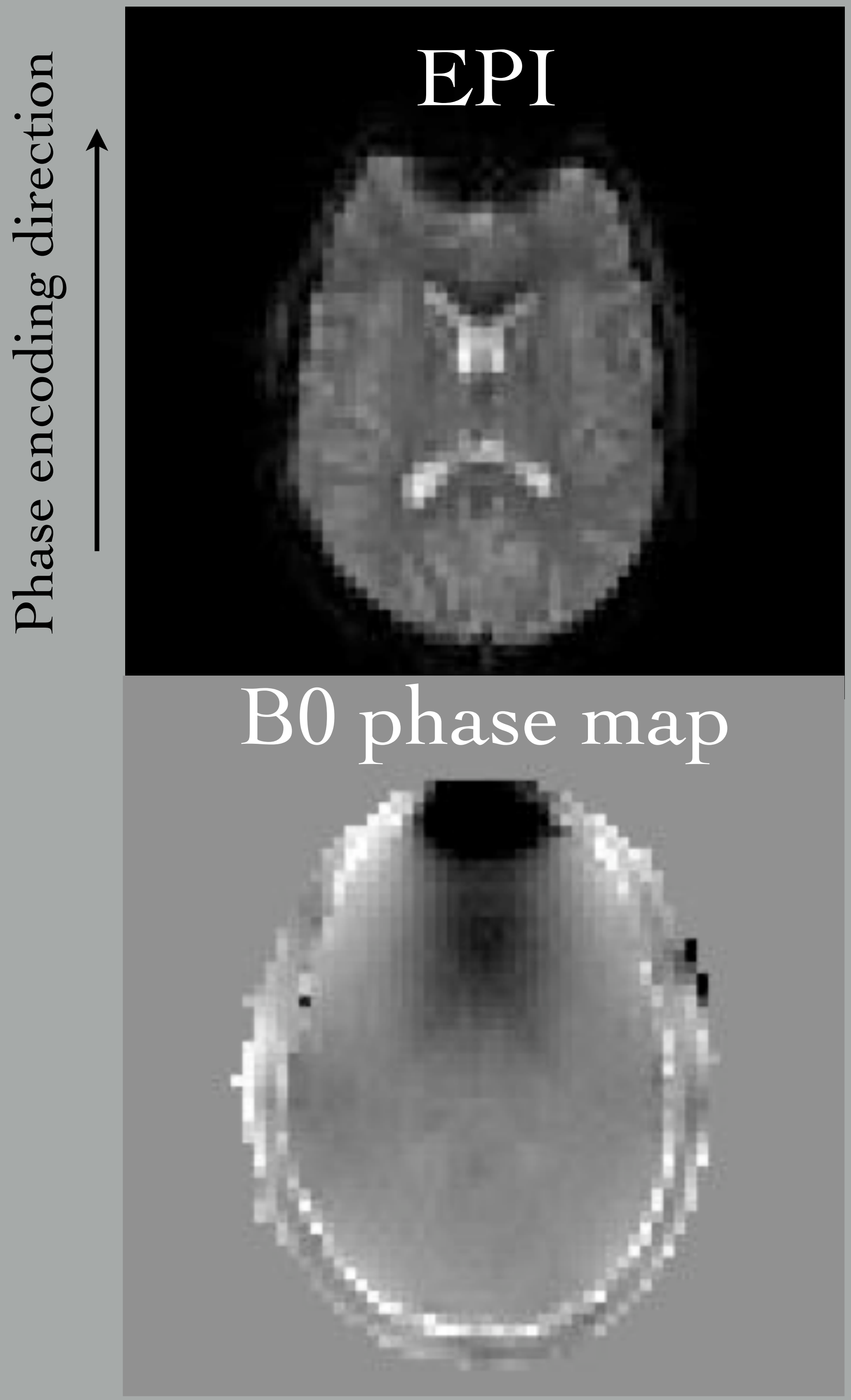
Static Field Inhomogeneity and EPI

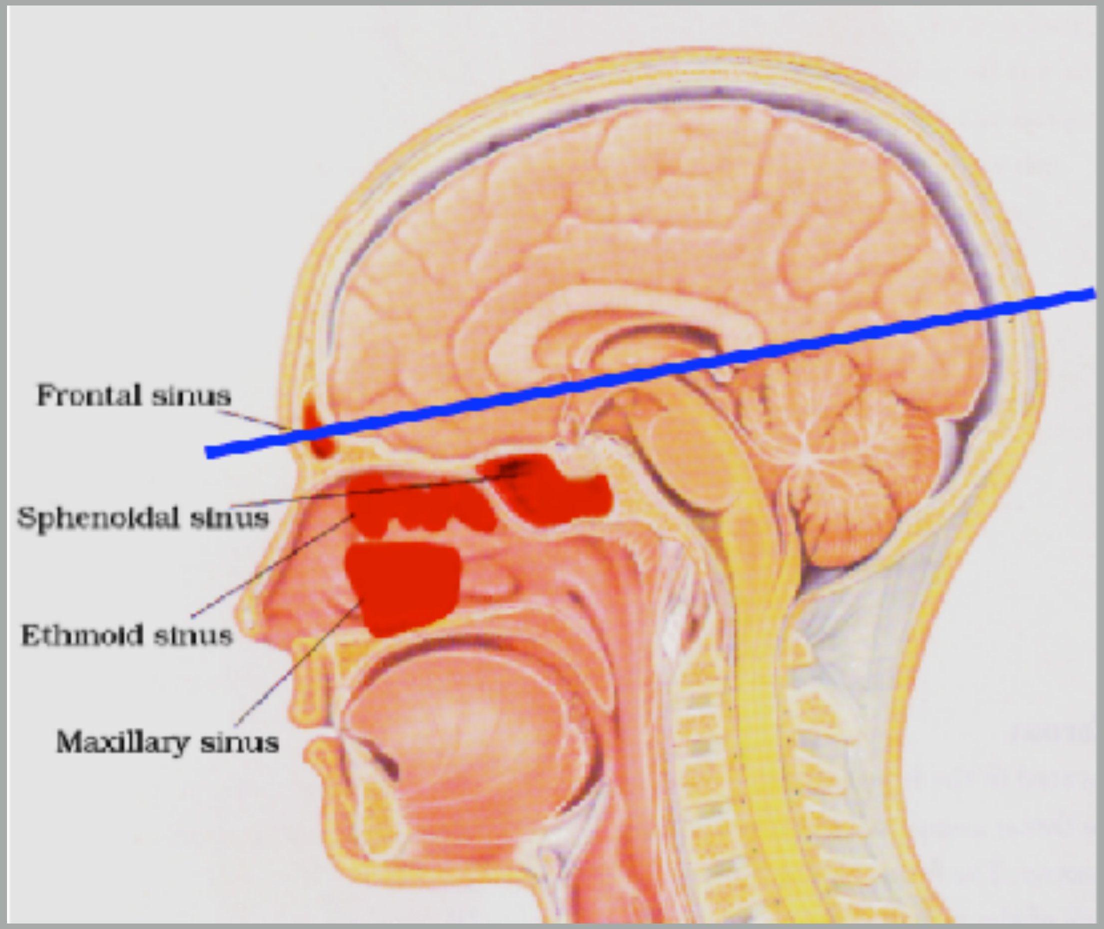


courtesy
D. Greve, MGH



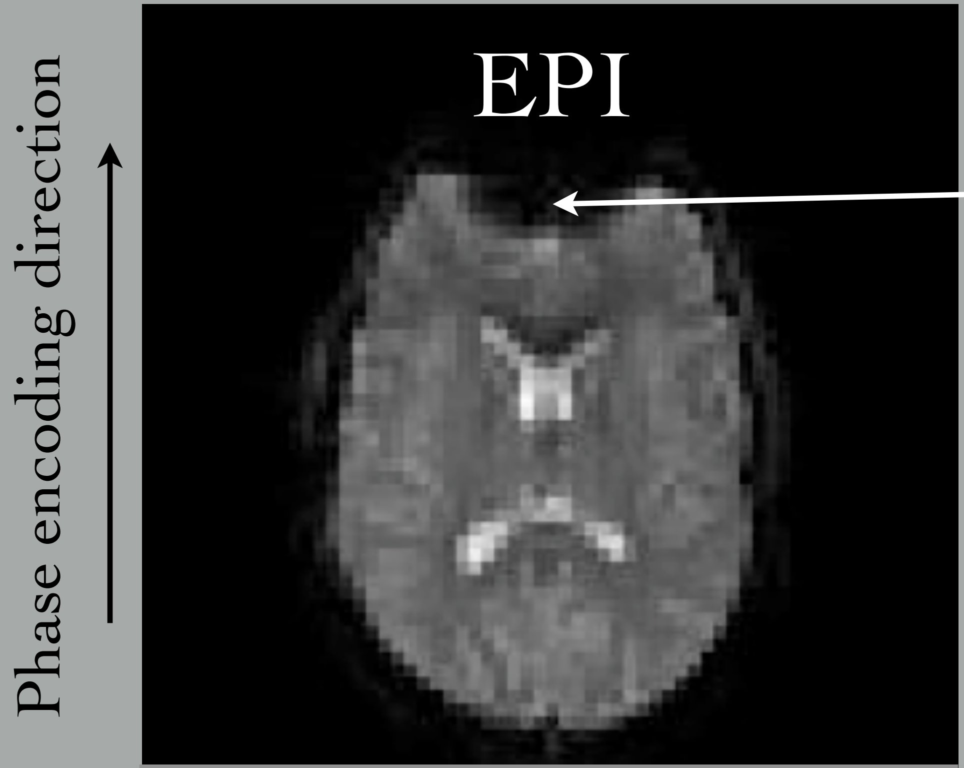
Static Field Inhomogeneity and EPI



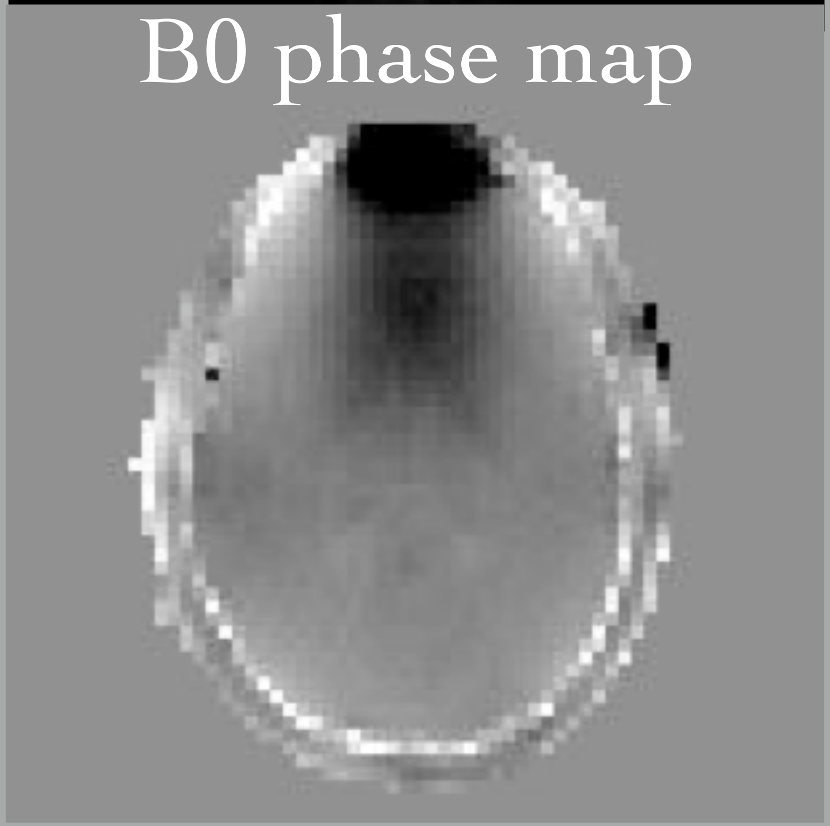


courtesy
D. Greve, MGH

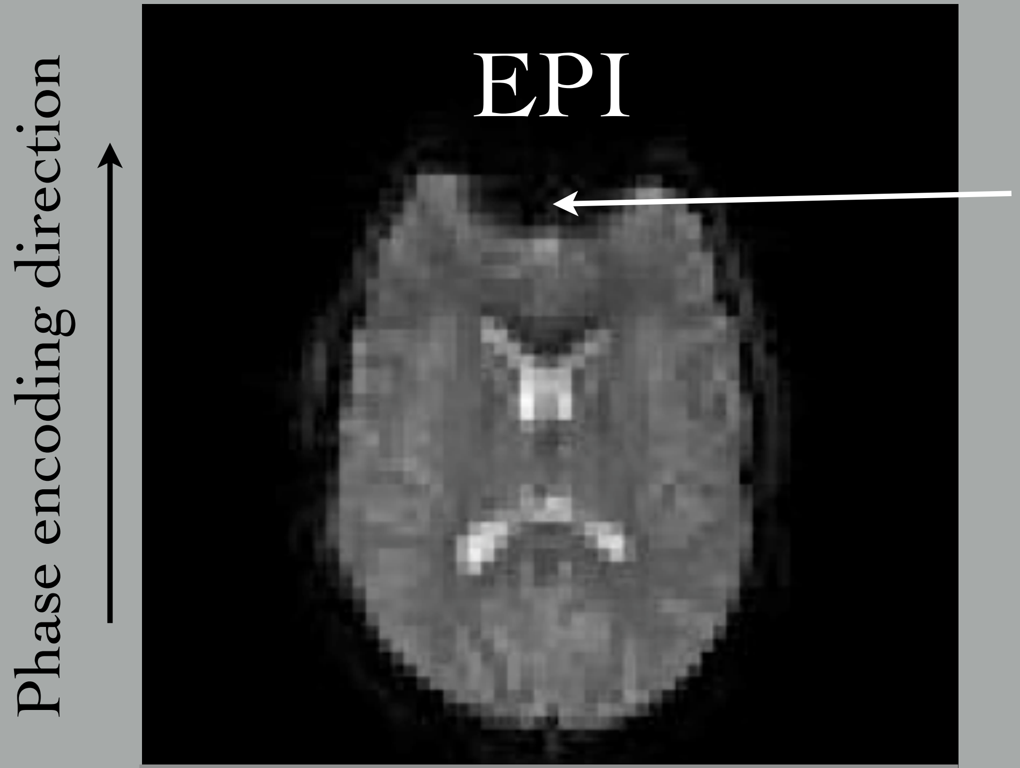
Static Field Inhomogeneity and EPI

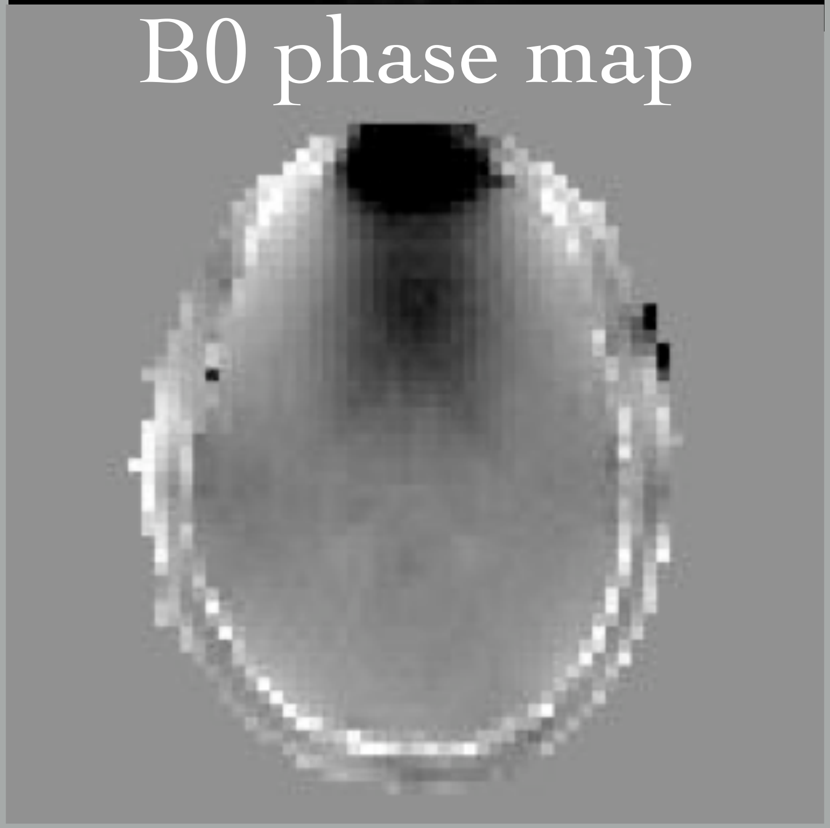

EPI

spatial distortions and signal dropout


B0 phase map

Static Field Inhomogeneity and EPI



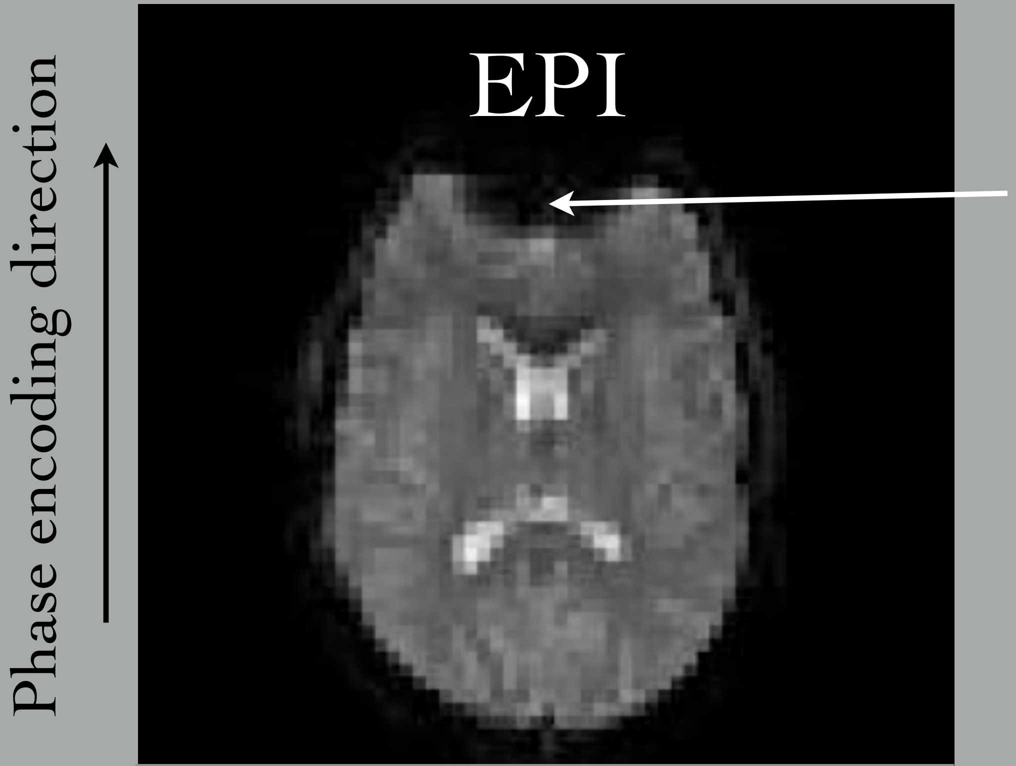


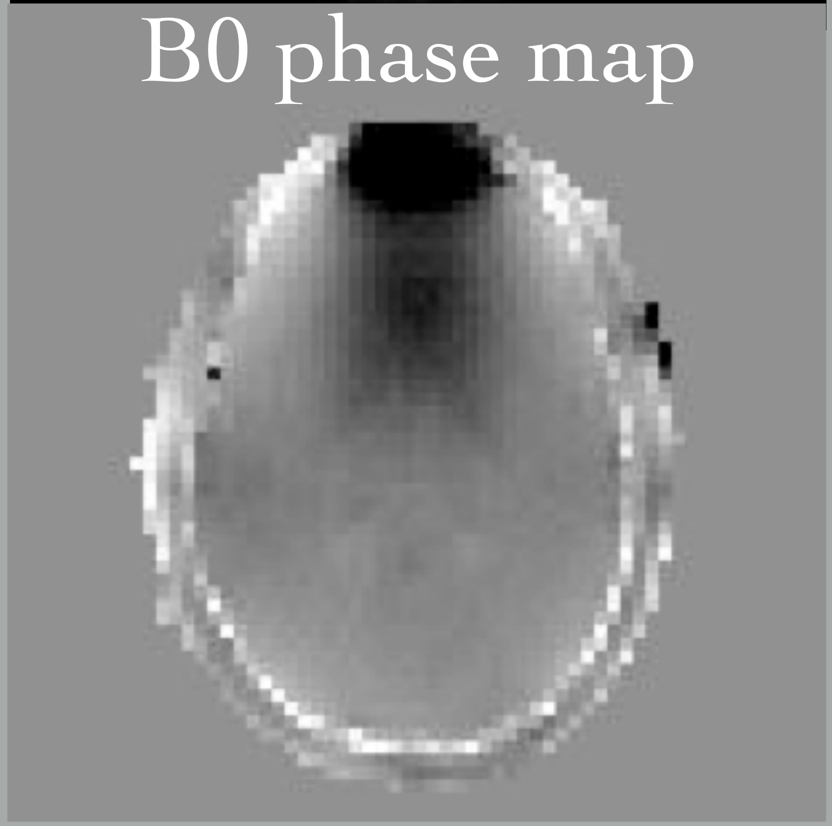
spatial distortions

$$\Delta\phi = \Delta\omega t = \gamma\Delta B_o$$

$$\Delta y = \frac{\gamma\Delta B_o N_y t_{dwell}}{2\pi}$$

Static Field Inhomogeneity and EPI



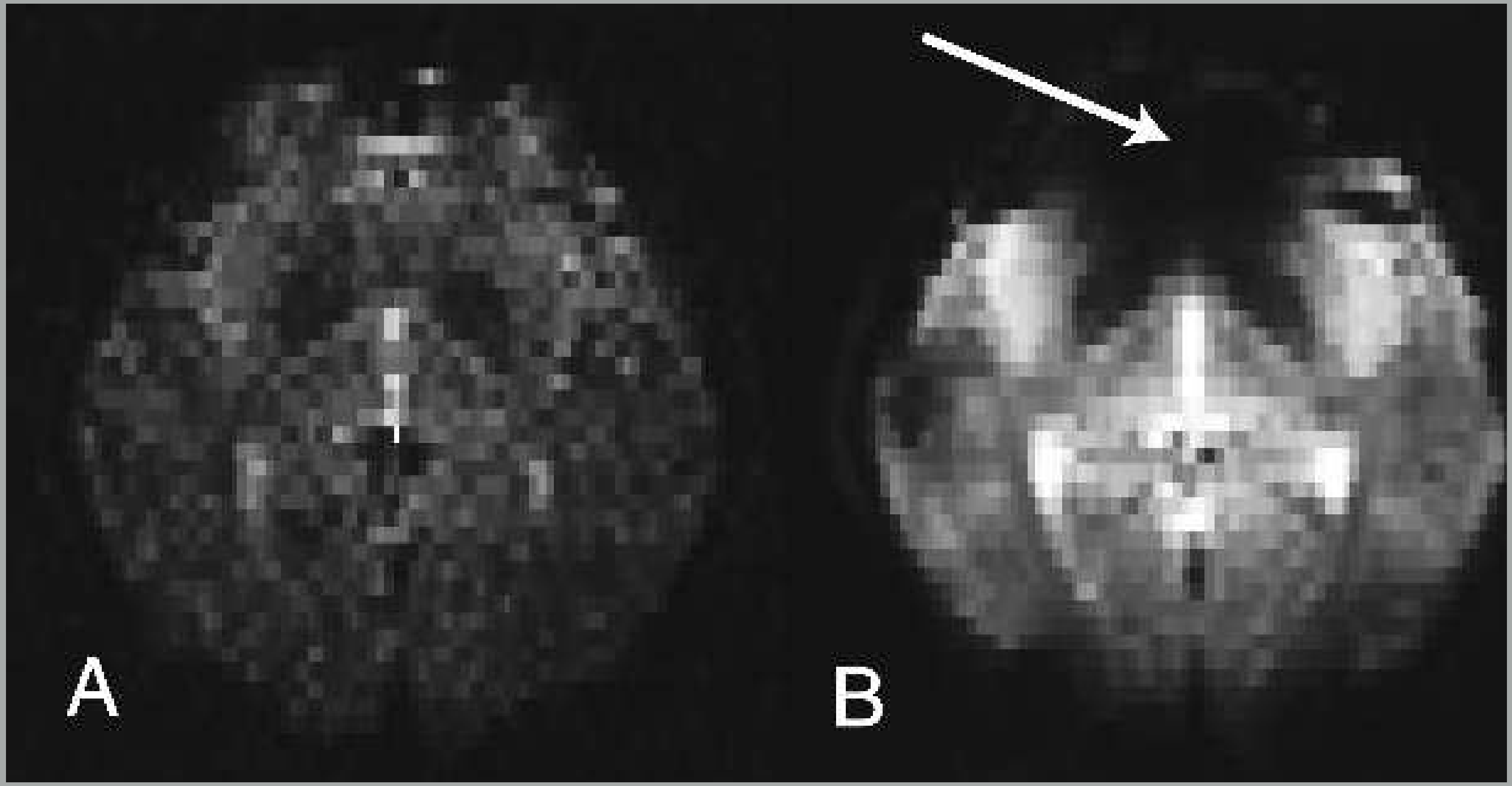


signal dropout

signal dropout over slice direction z

$$s = \int m_{xy}(z) e^{i\gamma \Delta B_o(z) T_e} \, dz$$

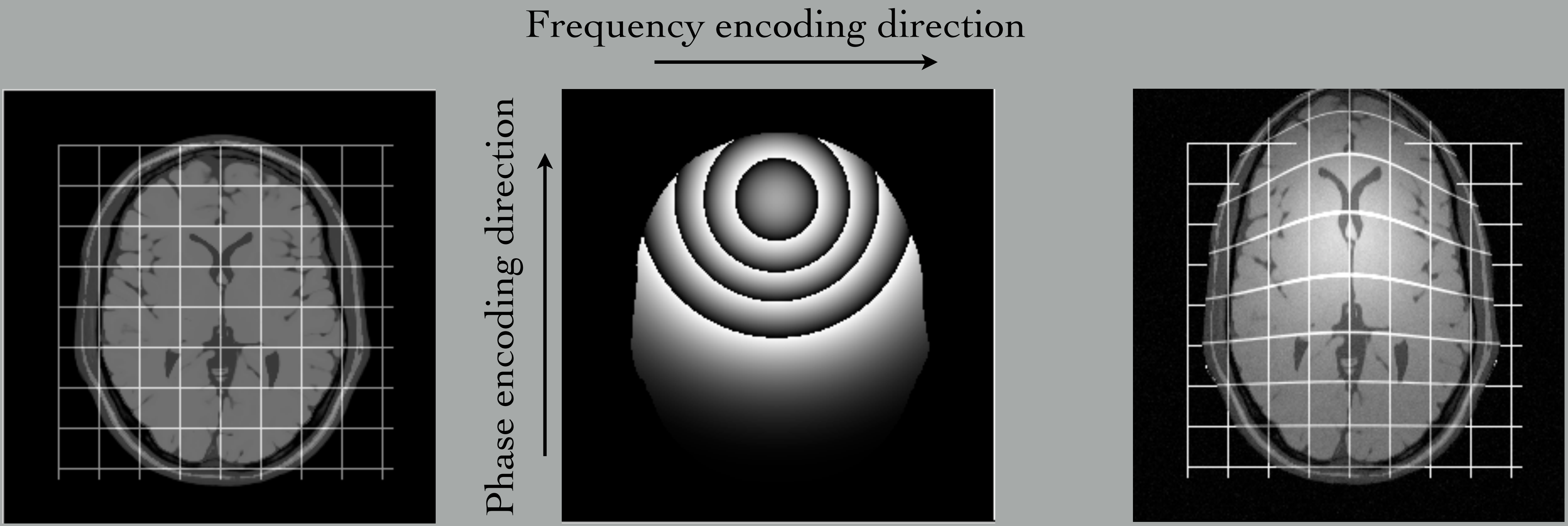
Signal dropout



volume acquisition

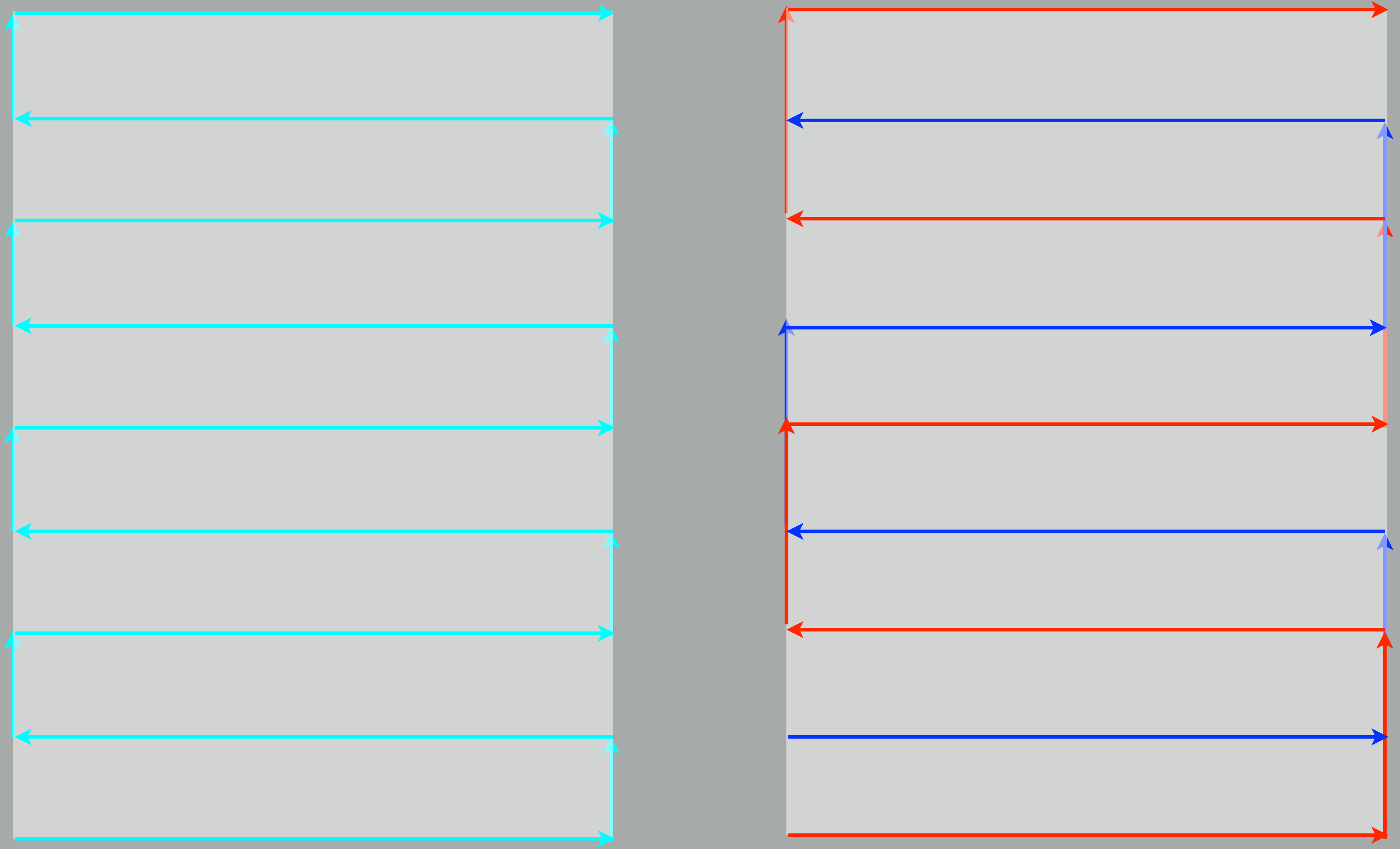
EPI acquisition

Static Field Inhomogeneity and EPI



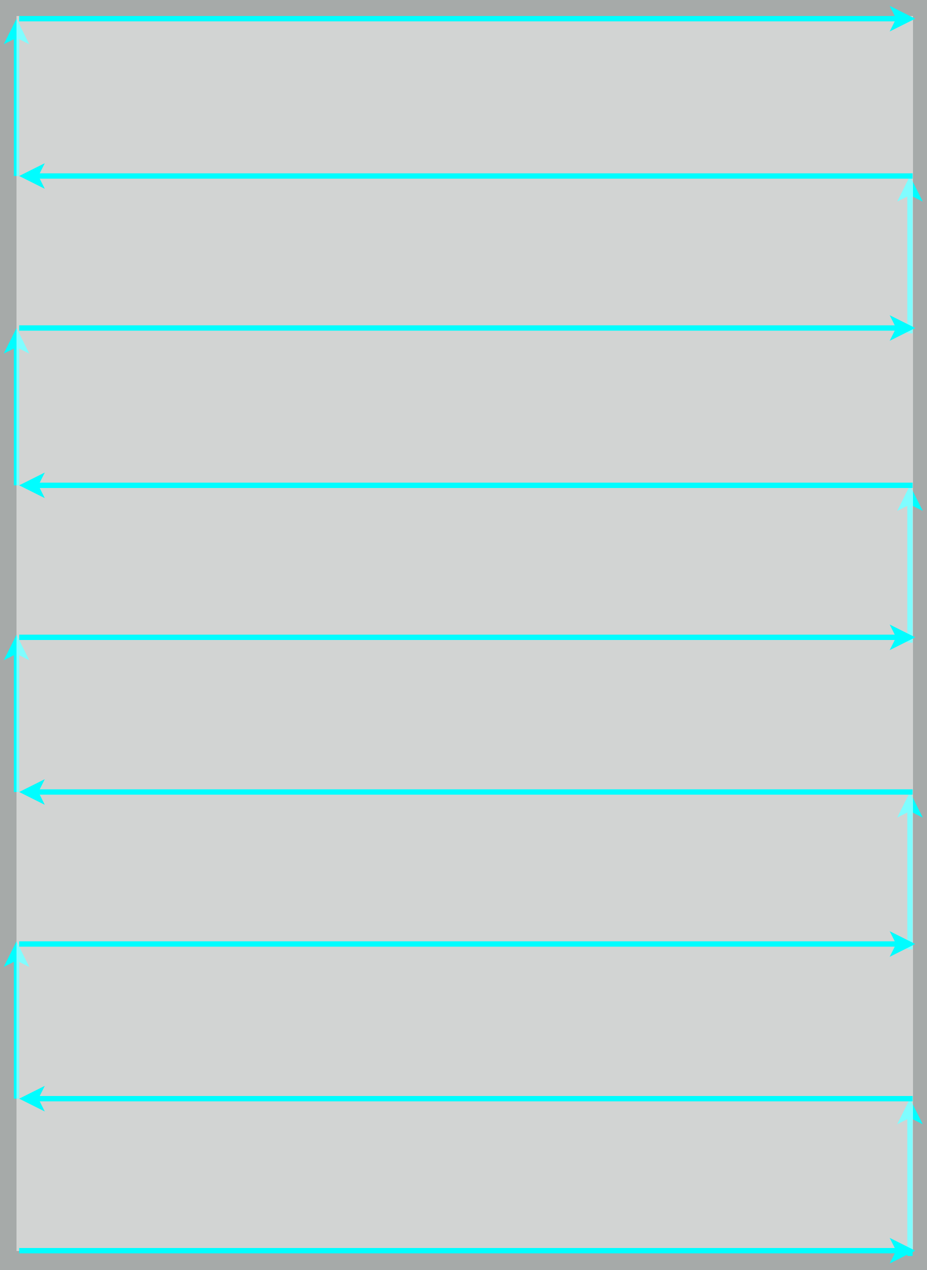
(Simulation program by E. Ghobrial)

Multi-shot acquisition



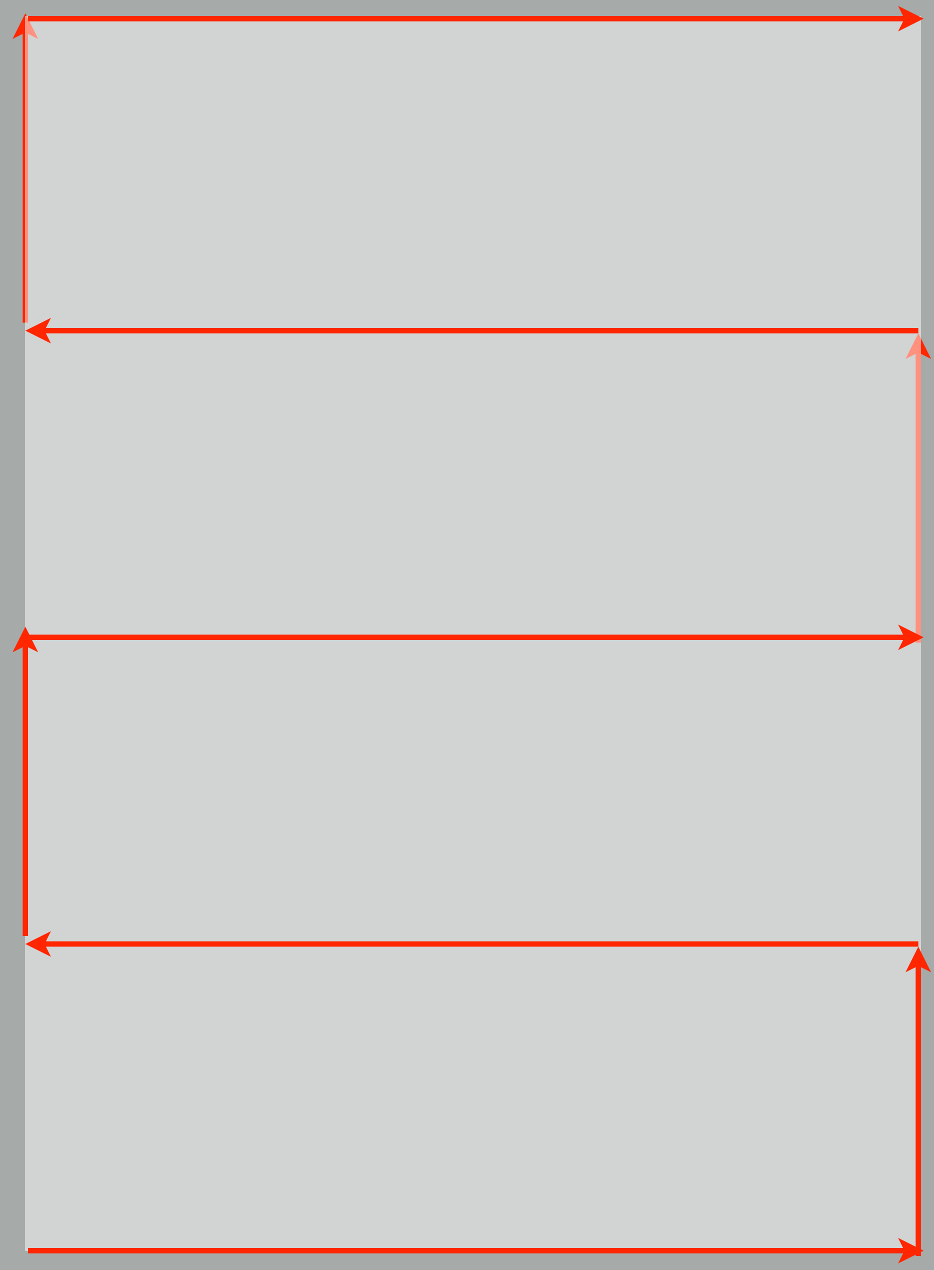
Multi-shot acquisition

F_y



Δy

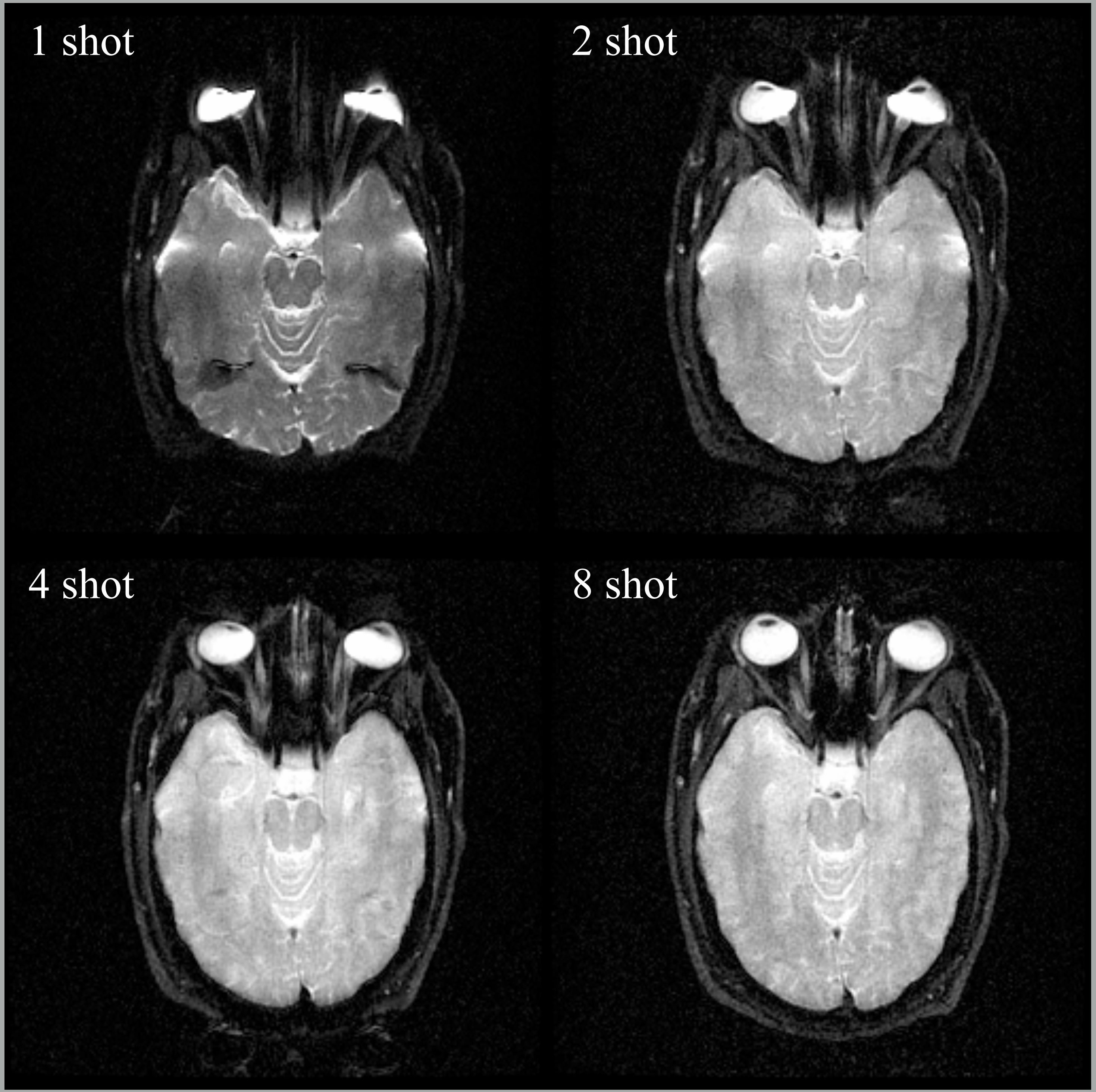
$F_y/2$



$\Delta y/2$

$$\Delta r = \left(\frac{\delta B_o}{W_r} \right) F_r$$

Multi-shot acquisition



Increasing the number of shots per image decreases the EPI echo-train length per shot.

<u>SE-EPI</u>

Shots	: 1-8
TR	: 3000ms
TE	: 60ms
Slice	: 5mm/2.5mm (18)
Matrix	: 256 x 256
FOV	: 24cm x 24cm
Time	: 12s-27s
NEX	: 1

Field inhomogeneities

Field inhomogeneities show up in the phase of gradient echo images

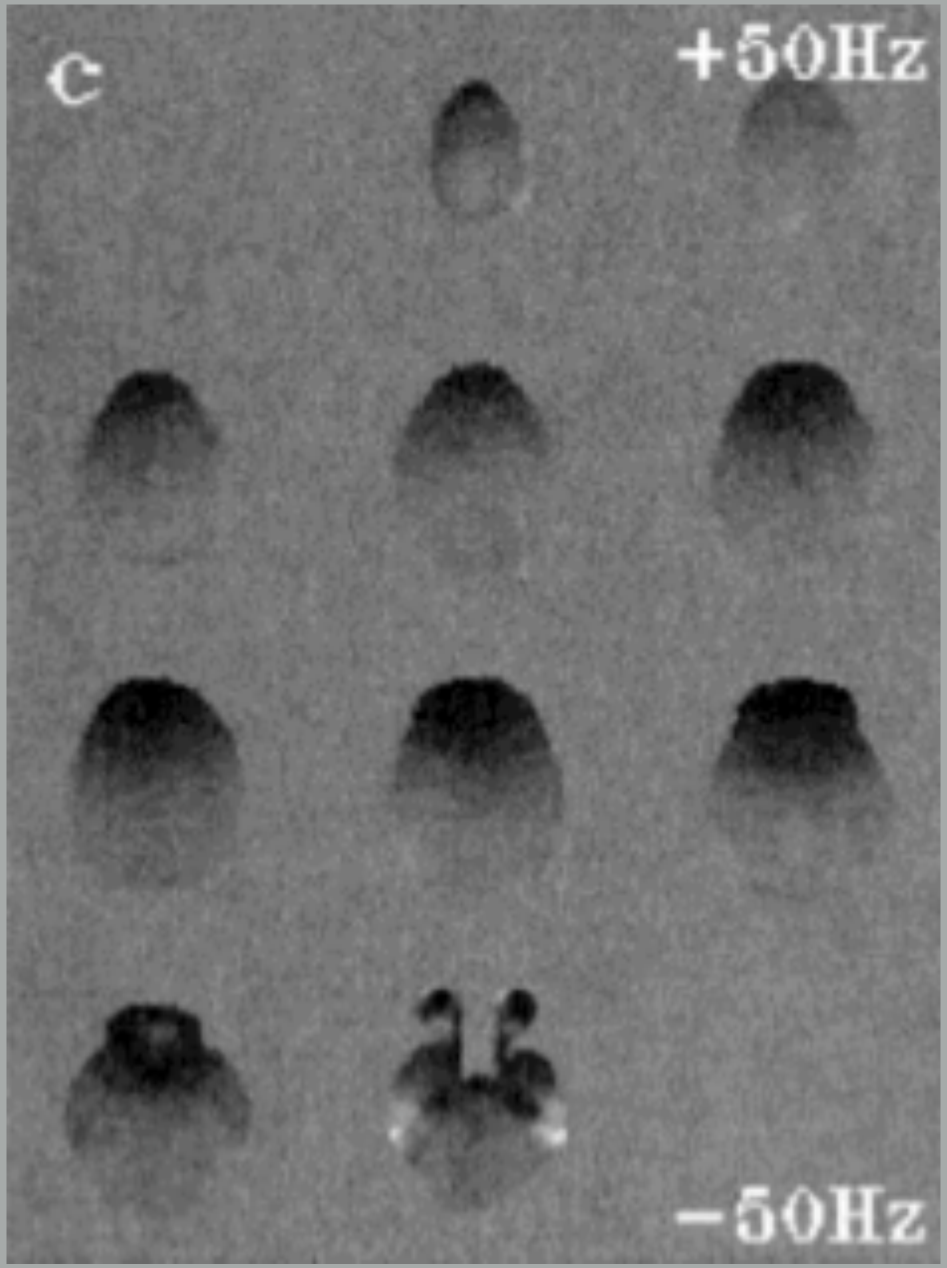
$$x = x_o + \frac{\Delta\nu}{W_{pe}}$$

$$s = e^{i\phi} s_o$$

$s_o =$ Image with no field offsets

$$\phi = \gamma \Delta B_o TE$$

Field inhomogeneities



Jezzard, et. al,
HBM99: 8:80 (1999)

Field inhomogeneities

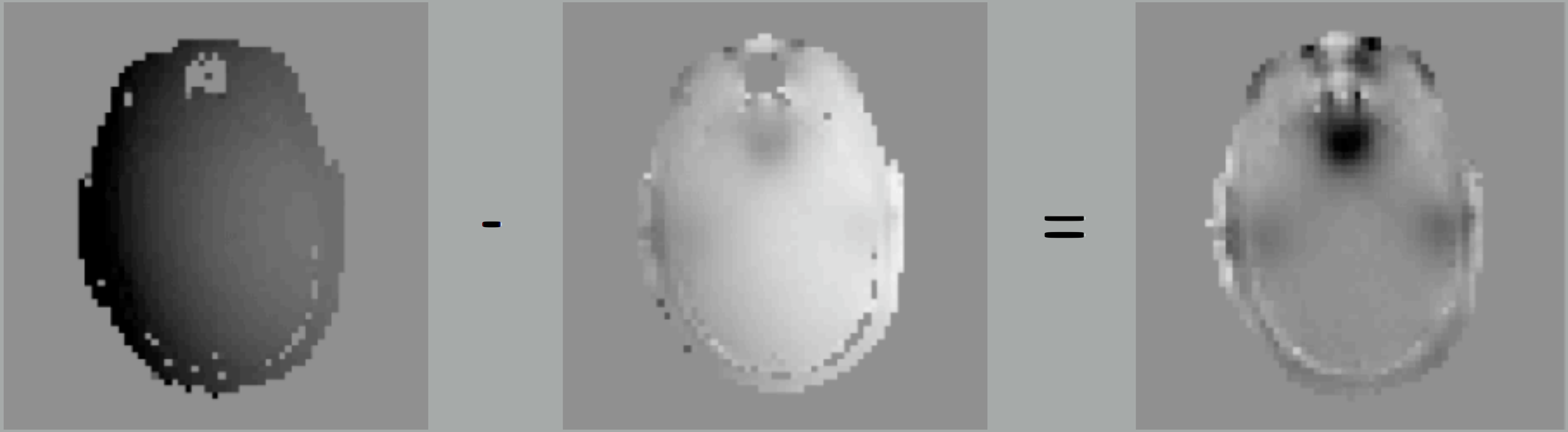
Measure phase *∂ifference* with two gradient echo images at different echo times

$$\Delta\nu(x,y) = \frac{\Delta\phi(x,y)}{2\pi\Delta TE}$$

$$\Delta TE = TE_2 - TE_1$$

Field inhomogeneities

Measure phase *difference* with two gradient echo images at different echo times



$$\phi(TE_2) \quad - \quad \phi(TE_1) \quad = \quad \Delta\phi$$

Field inhomogeneities

Compute displacement and make corrections along the phase encoding direction

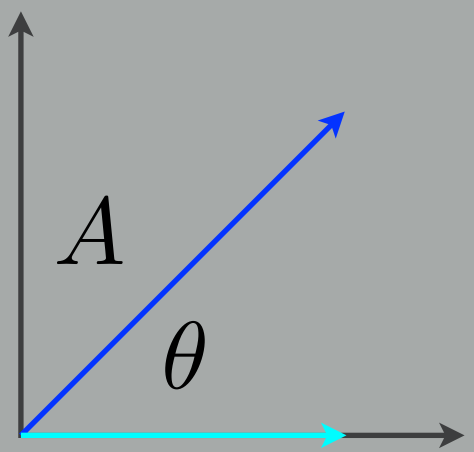
$$x = x_o + \frac{\Delta\nu}{W_{pe}}$$

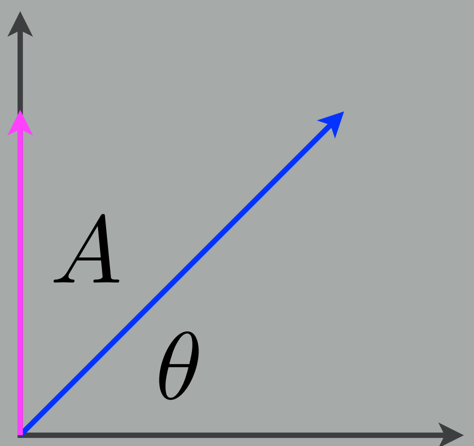
$$\Delta\nu(x,y) = \frac{\Delta\phi(x,y)}{2\pi\Delta TE}$$

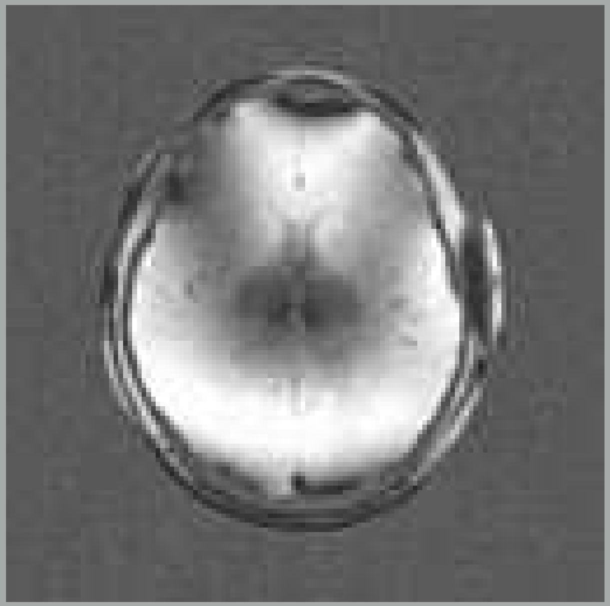
$$\Delta TE = TE_2 - TE_1$$

Gradient echo phase maps

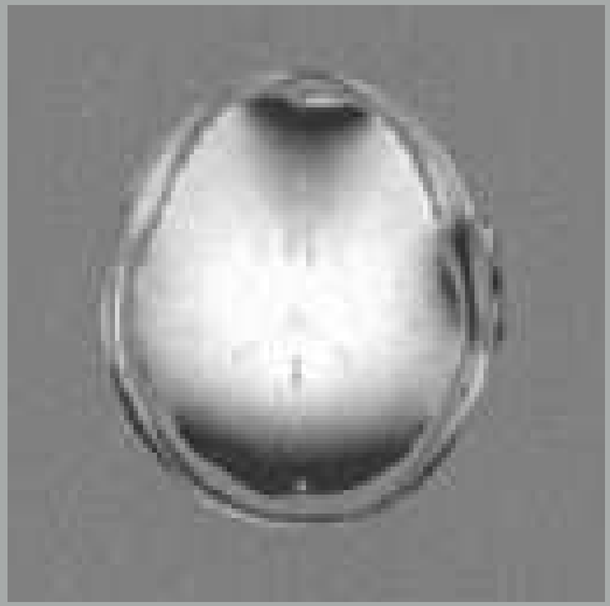
Image data collected in two "channels"
real and *imaginary*







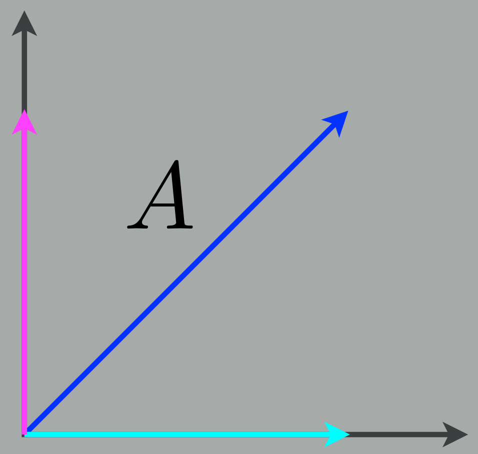
$A\cos\theta$



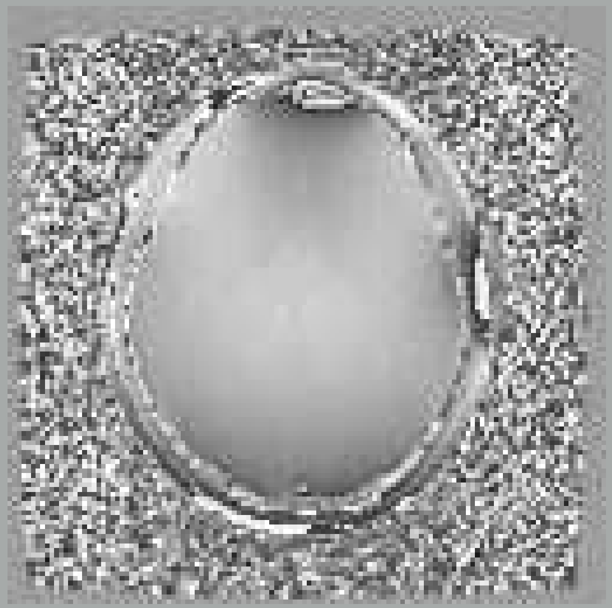
$A\sin\theta$

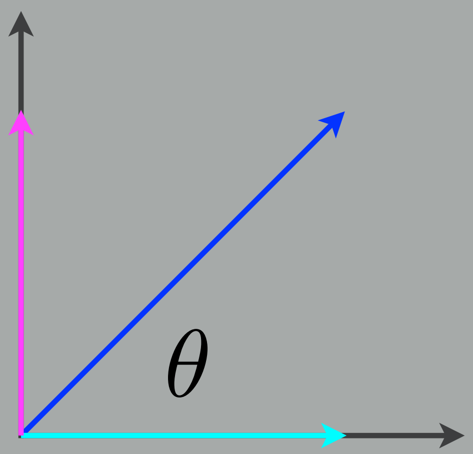
Gradient echo phase maps

amplitude A

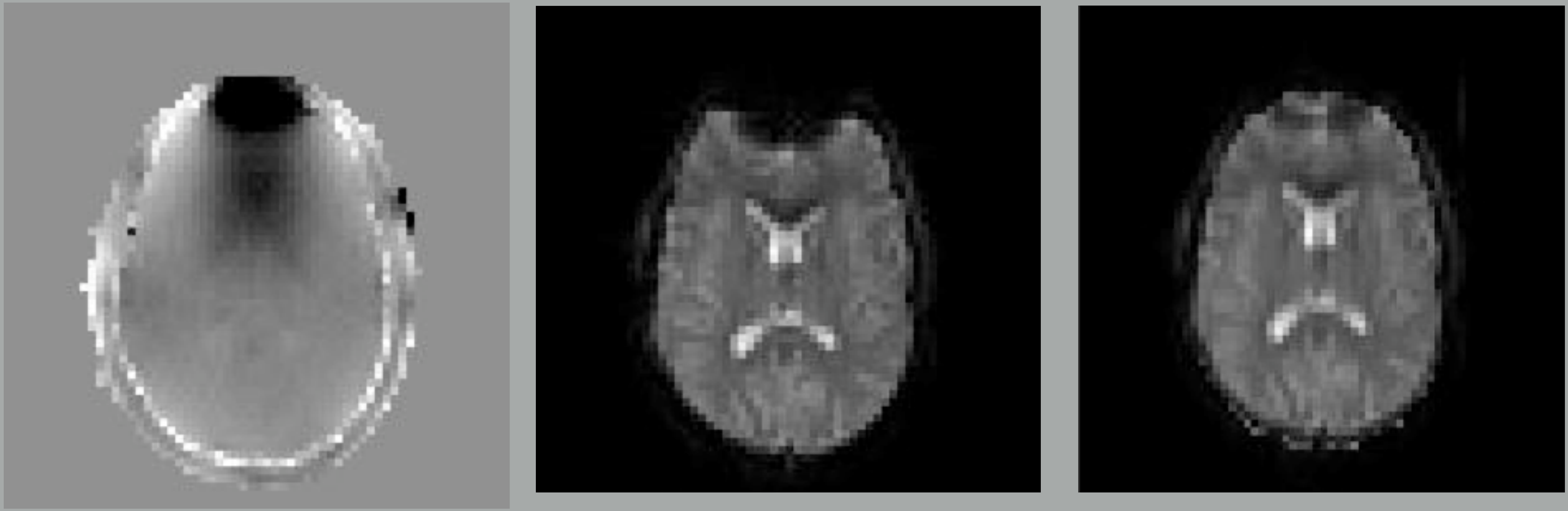


phase θ



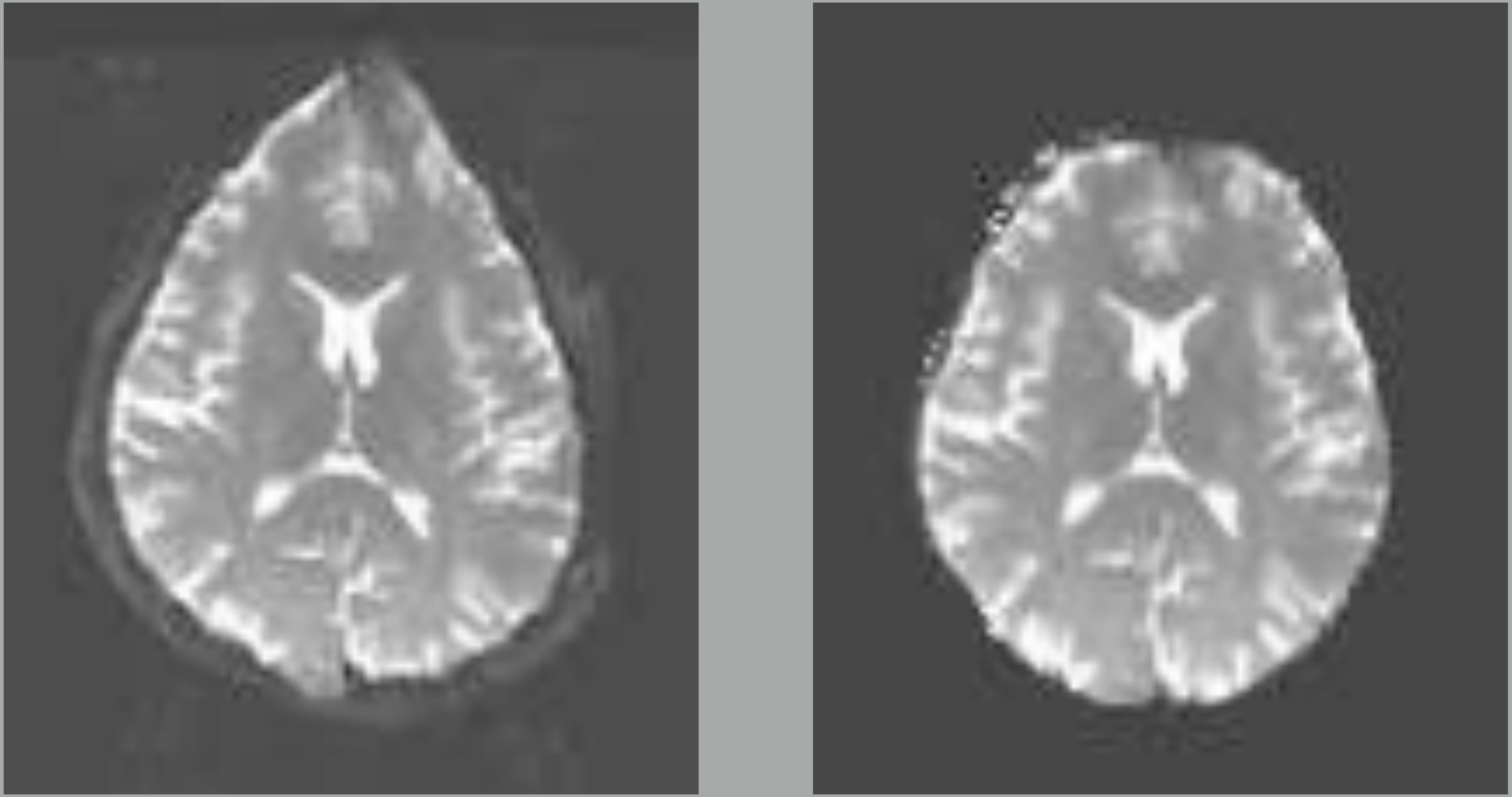


Static Field Inhomogeneity and EPI

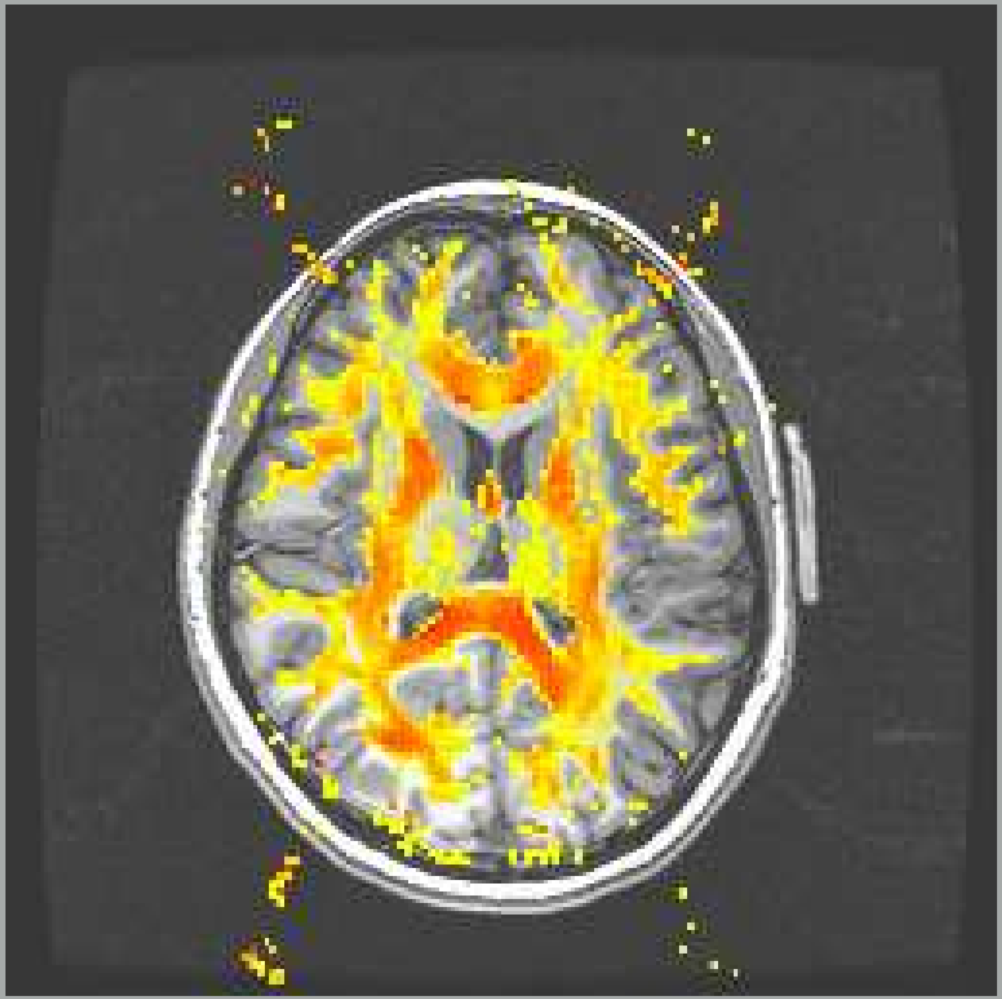


FSL's FUGUE

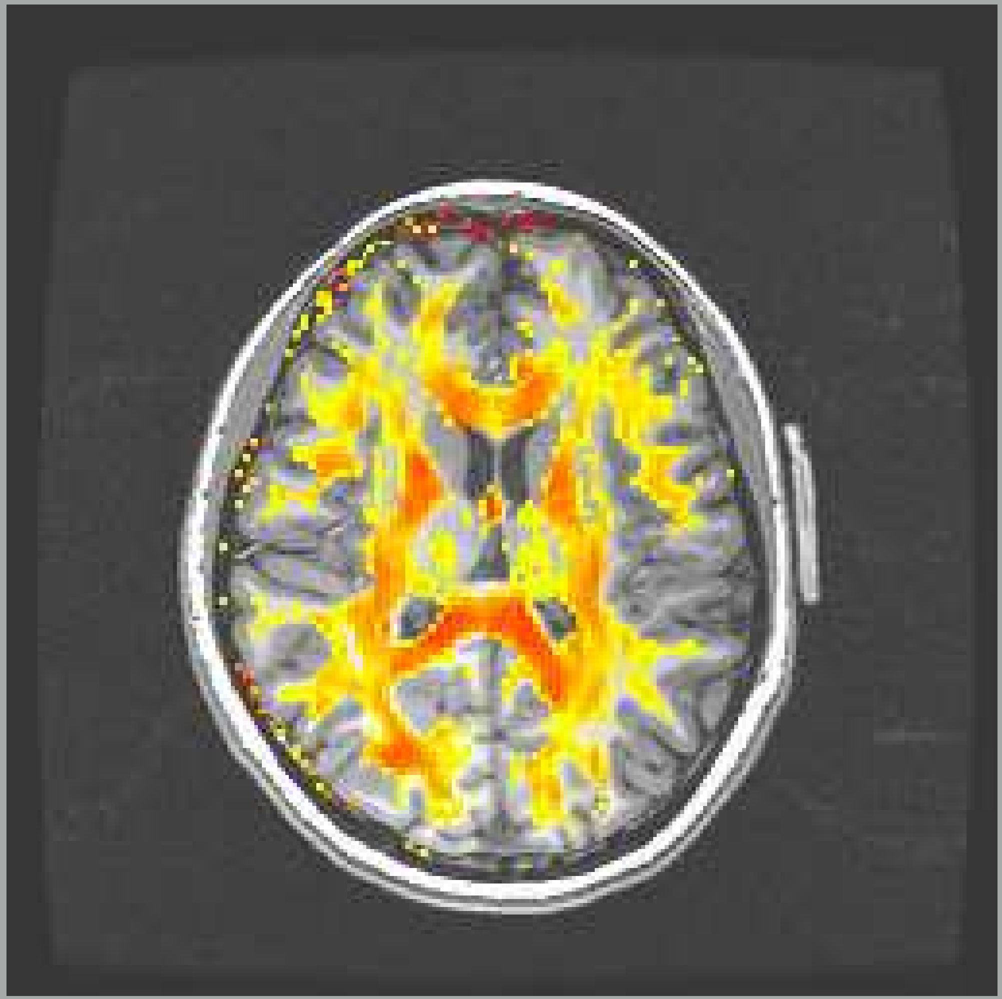
Static Field Inhomogeneity Correction



Unwarping

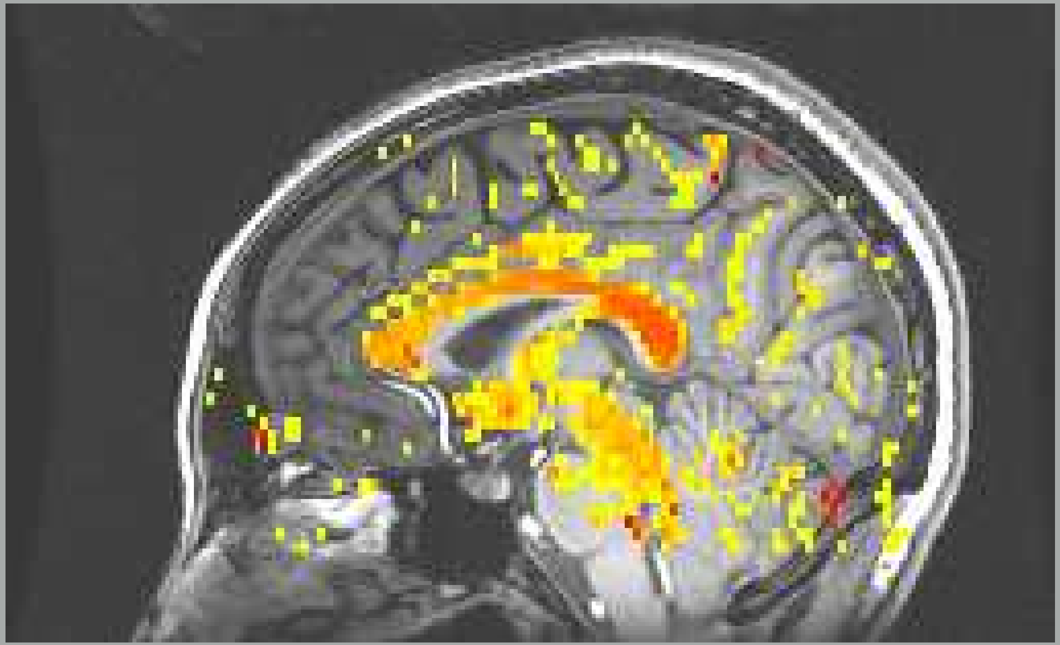


uncorrected

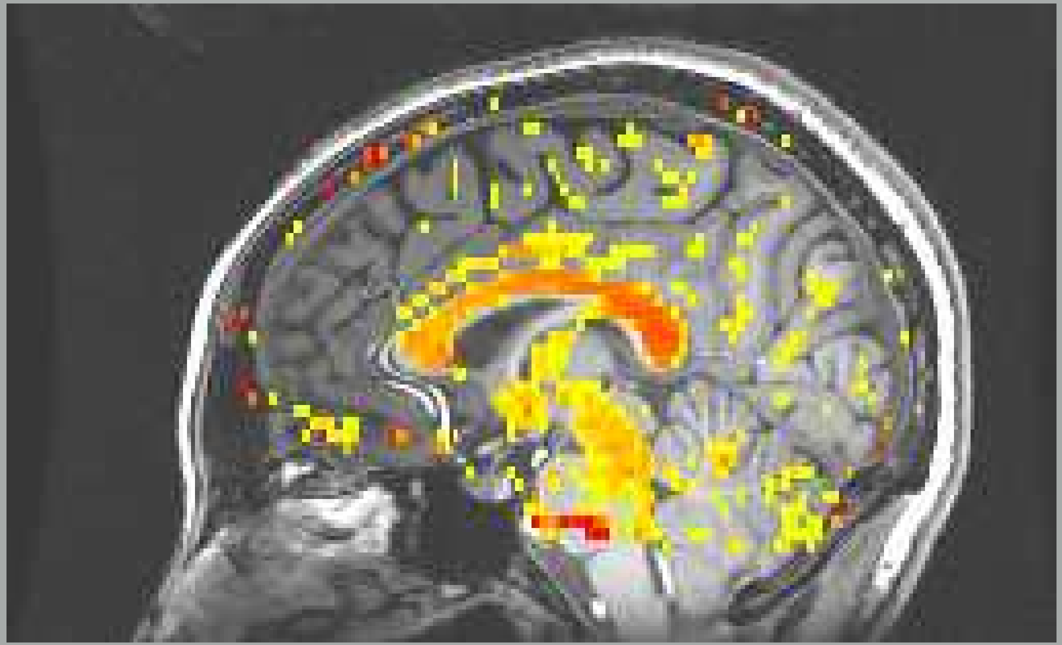


corrected

Unwarping



uncorrected

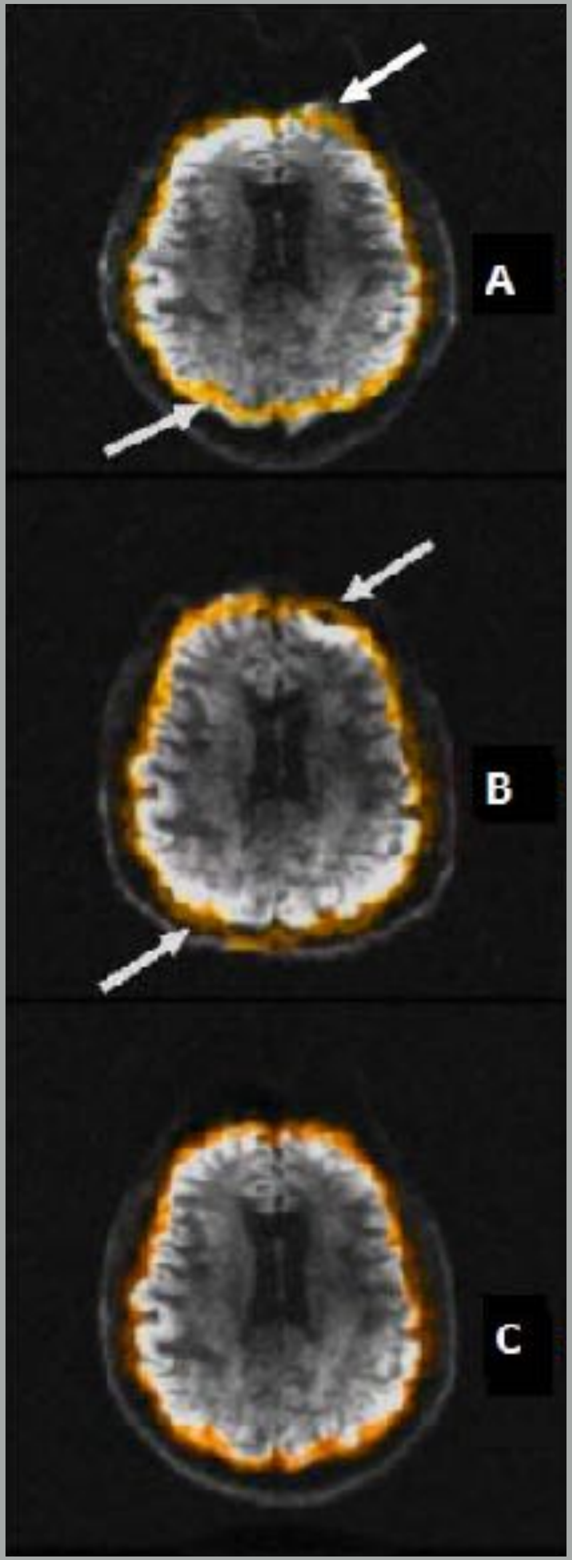


corrected

TOPUP

J.L.R. Andersson, S. Skare, J. Ashburner How to correct susceptibility distortions in spin-echo echo-planar images: Application to diffusion tensor imaging. NeuroImage, 20(2): 870-888, 2003.

TOPUP

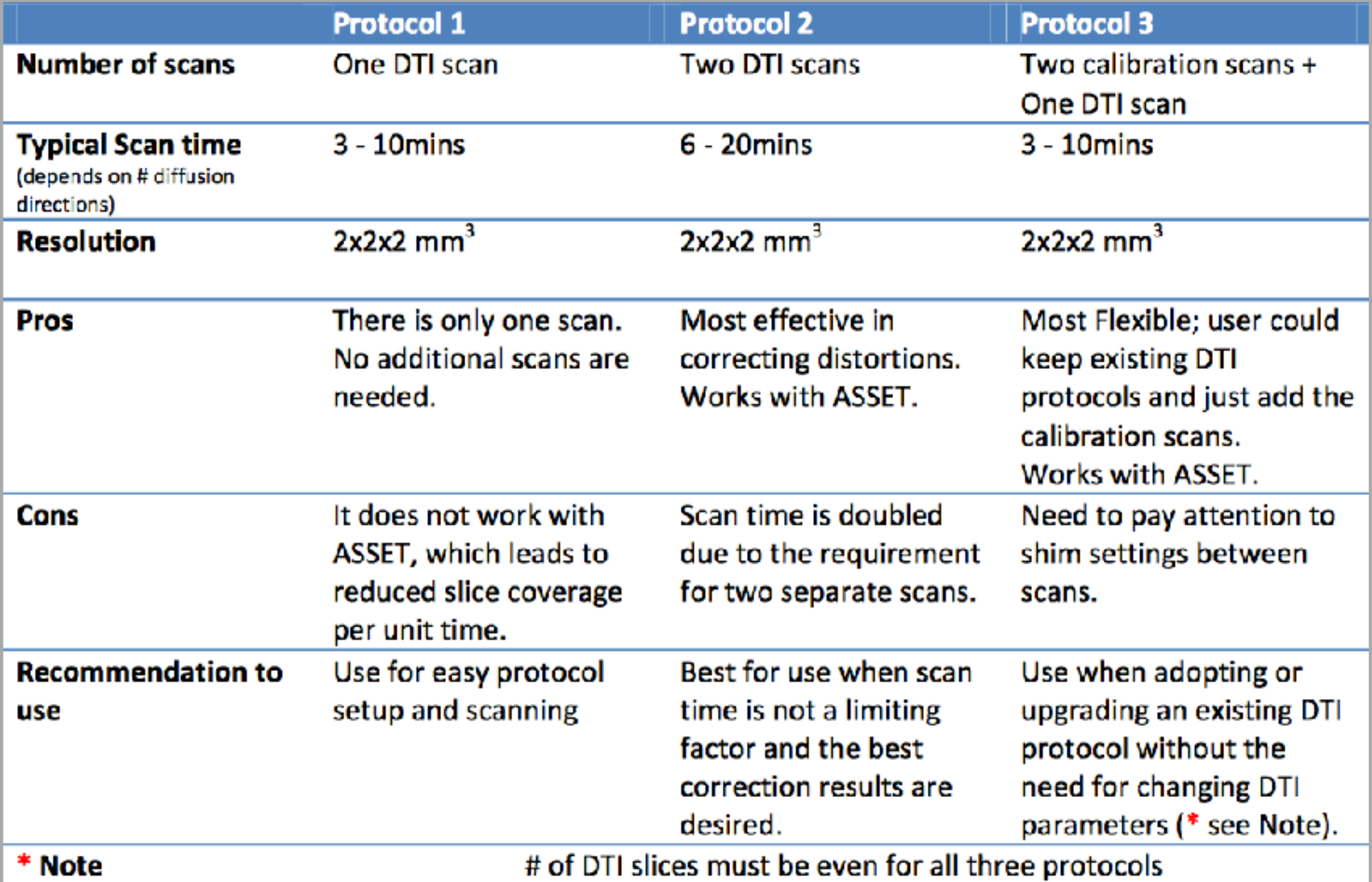


Positive phase encoding

Negative phase encoding

After TOPUP correction

TOPUP

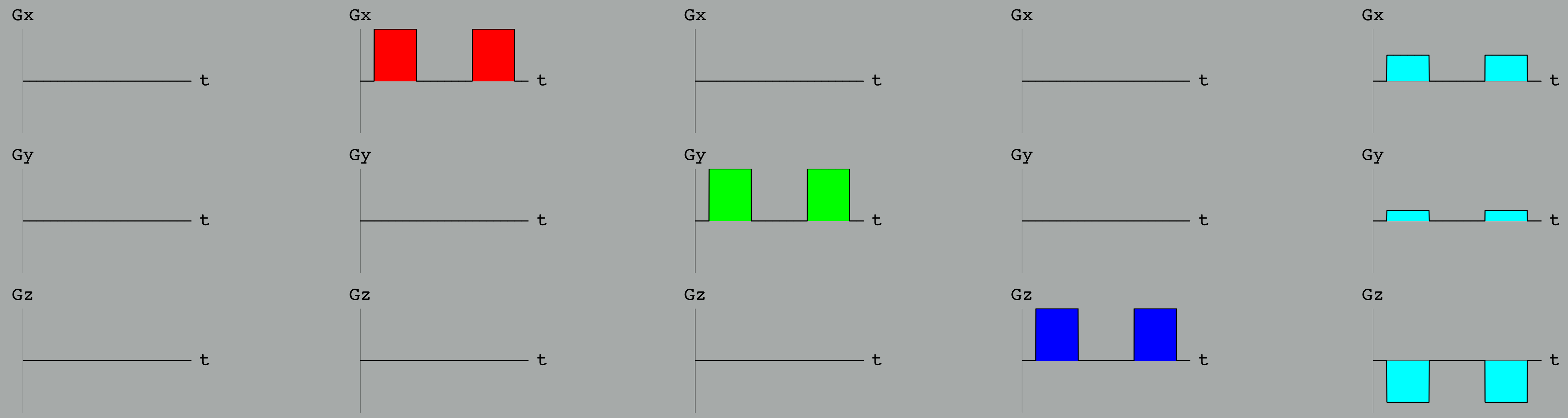


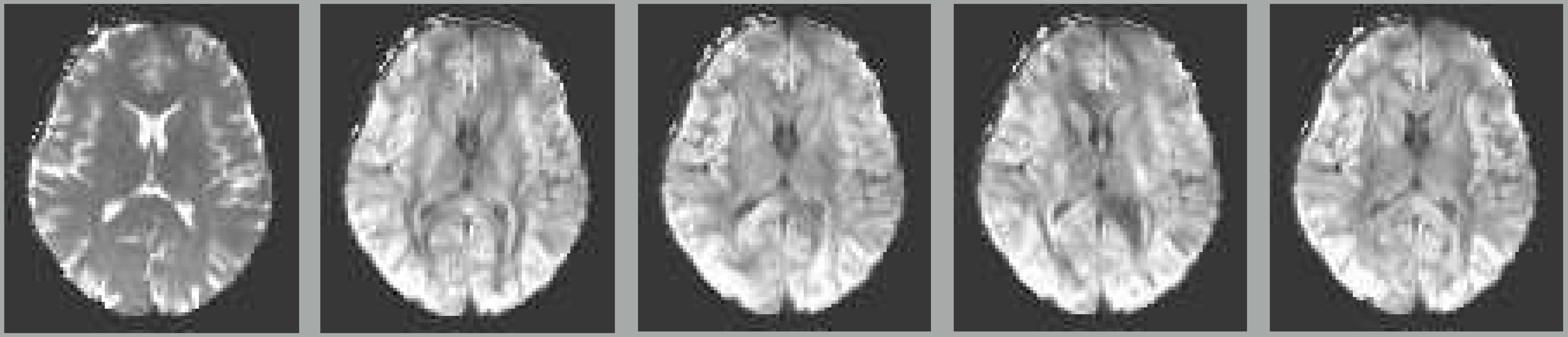
	Protocol 1	Protocol 2	Protocol 3
Number of scans	One DTI scan	Two DTI scans	Two calibration scans + One DTI scan
Typical Scan time (depends on # diffusion directions)	3 - 10mins	6 - 20mins	3 - 10mins
Resolution	2x2x2 mm^3	2x2x2 mm^3	2x2x2 mm^3
Pros	There is only one scan. No additional scans are needed.	Most effective in correcting distortions. Works with ASSET.	Most Flexible; user could keep existing DTI protocols and just add the calibration scans. Works with ASSET.
Cons	It does not work with ASSET, which leads to reduced slice coverage per unit time.	Scan time is doubled due to the requirement for two separate scans.	Need to pay attention to shim settings between scans.
Recommendation to use	Use for easy protocol setup and scanning	Best for use when scan time is not a limiting factor and the best correction results are desired.	Use when adopting or upgrading an existing DTI protocol without the need for changing DTI parameters (* see Note).
* **Note**	# of DTI slices must be even for all three protocols		

Processtopup (http://fmri.ucsd.edu/download/processtopup)

FSL version 5.0 or above (http://fsl.fmrib.ox.ac.uk/fsl/fslwiki/)

Directional diffusion encoding

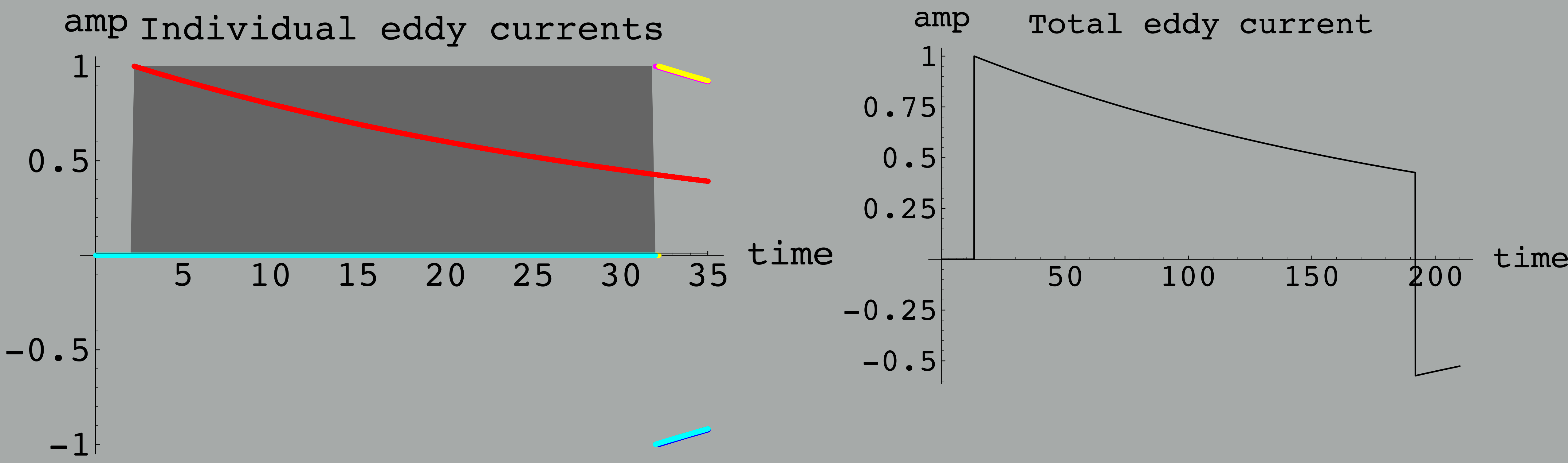




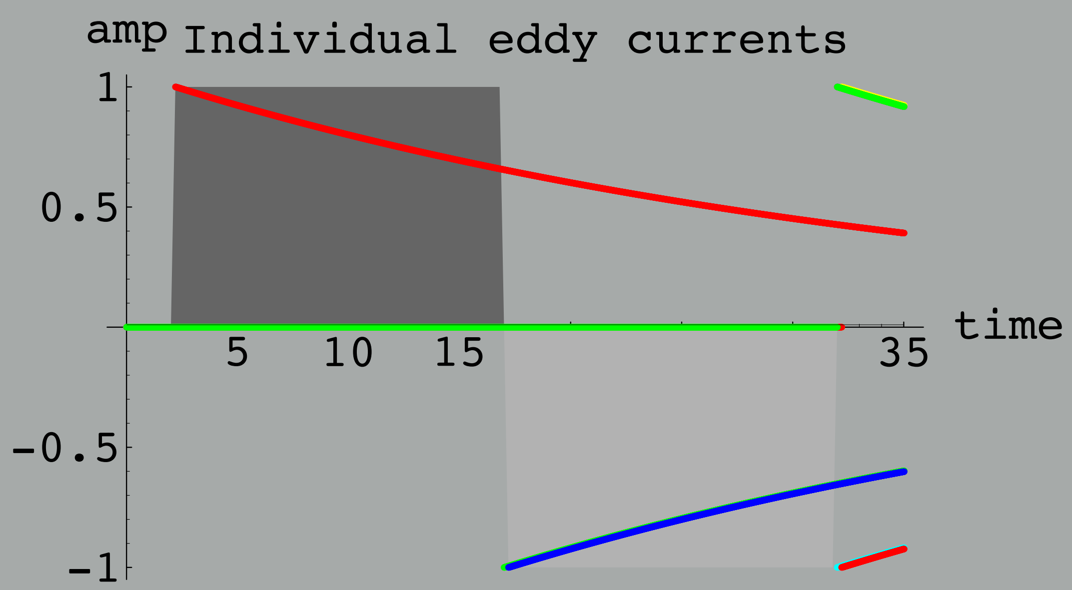
Eddy currents

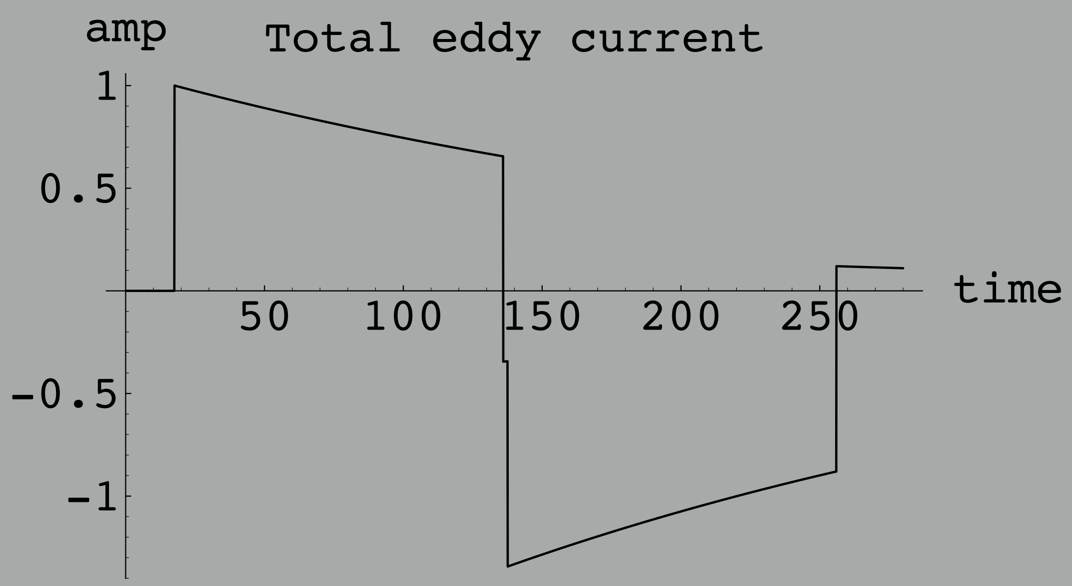
Rapidly changing magnetic fields generate
currents in magnet bore,
which generates magnetic fields

Eddy currents from single pulse

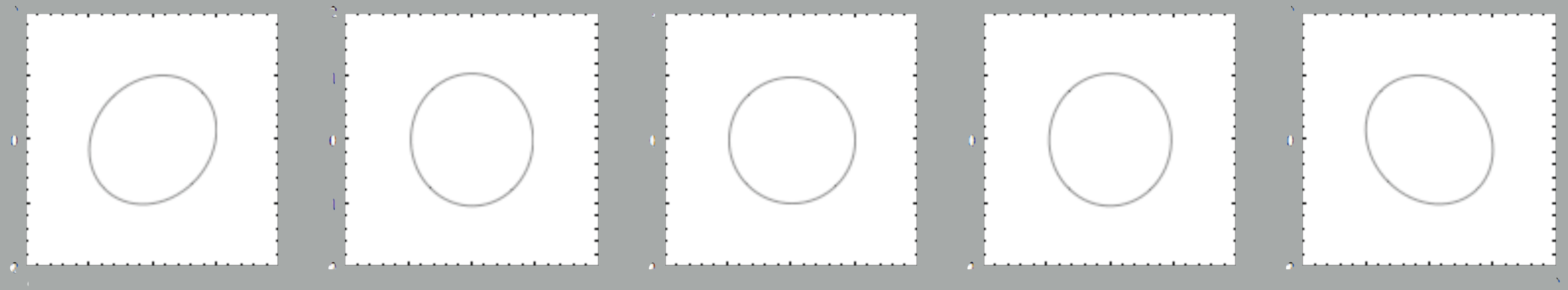


Eddy Currents

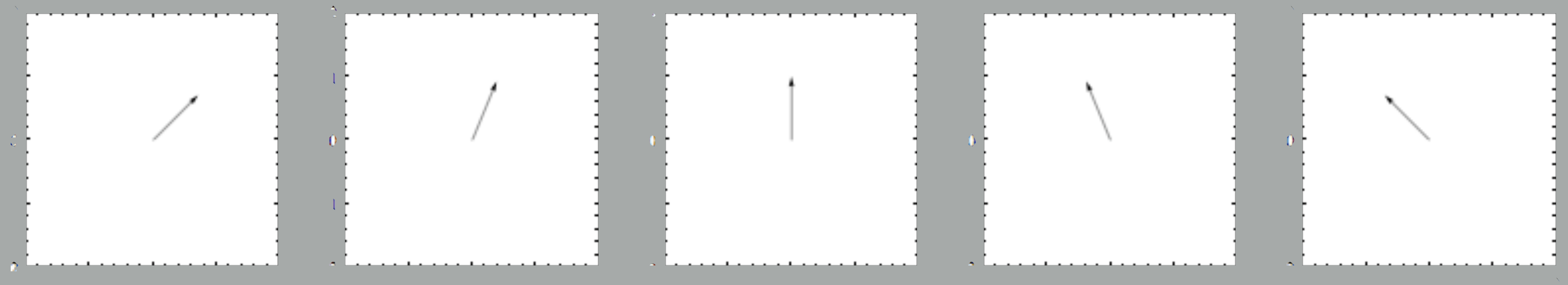




Eddy currents

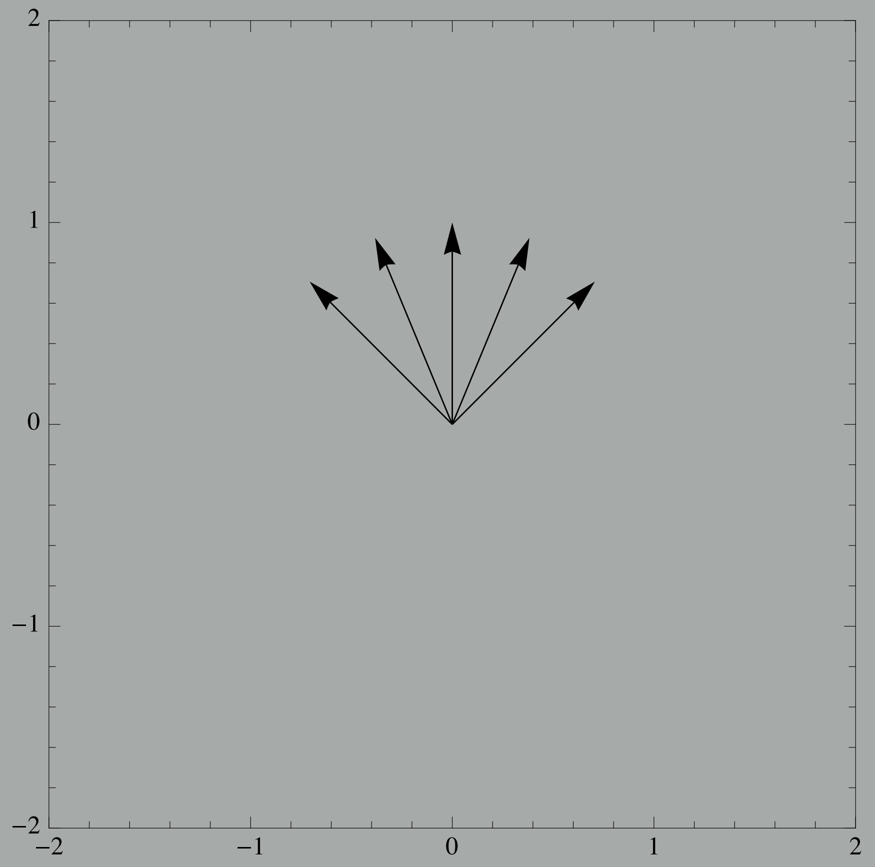


edge of sphere

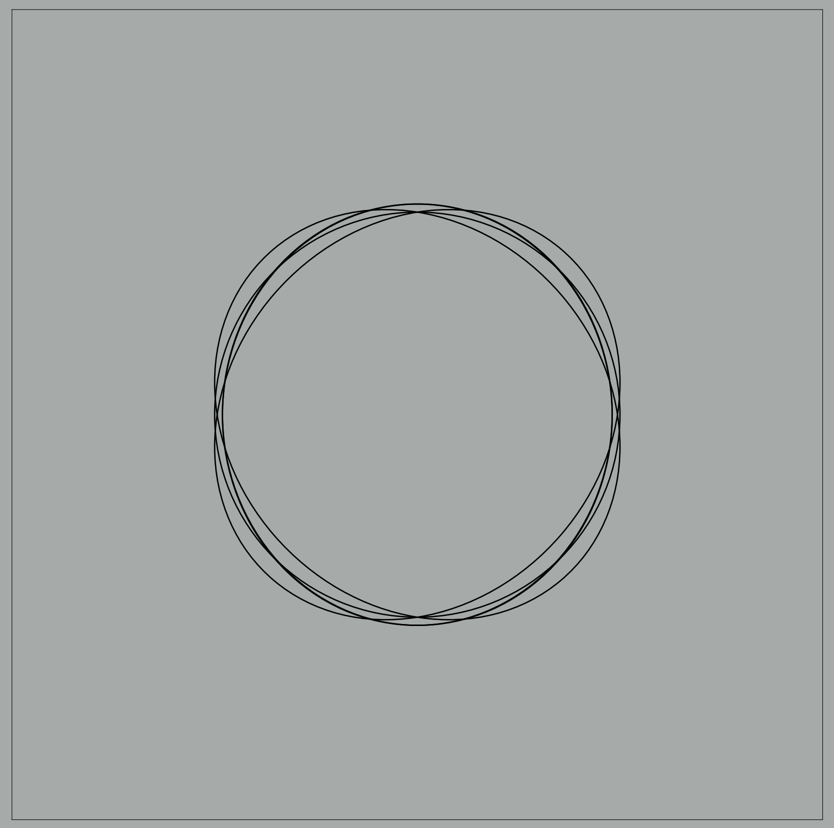


gradient directions

Eddy currents



gradient directions

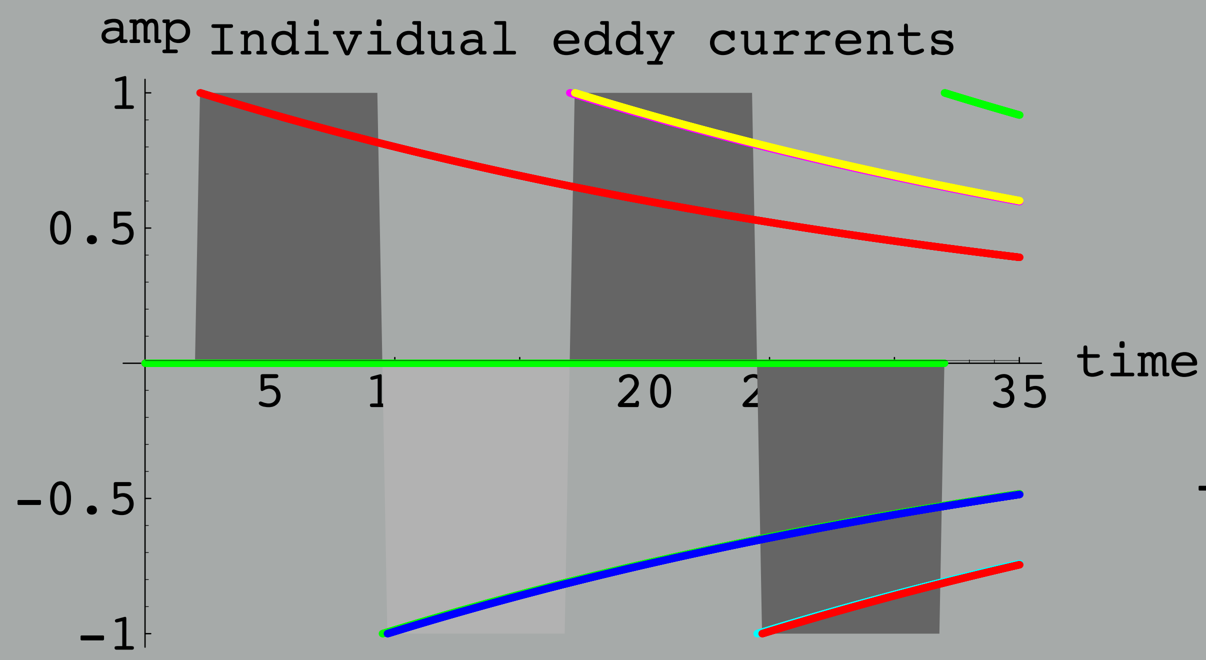


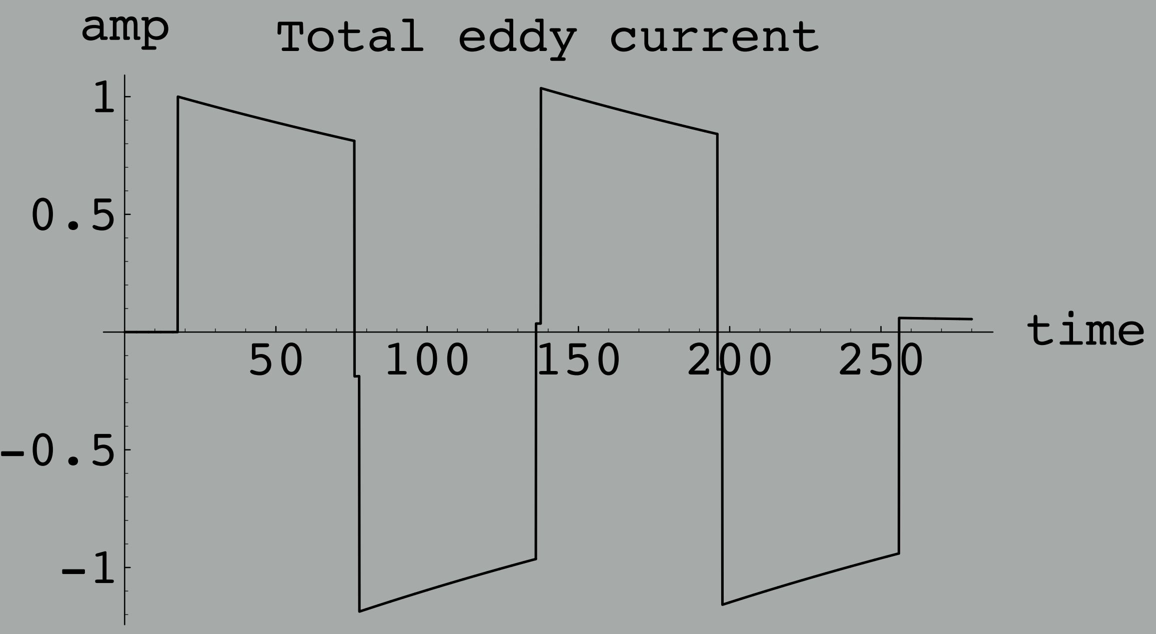
edge of sphere

Eddy currents - uncorrected

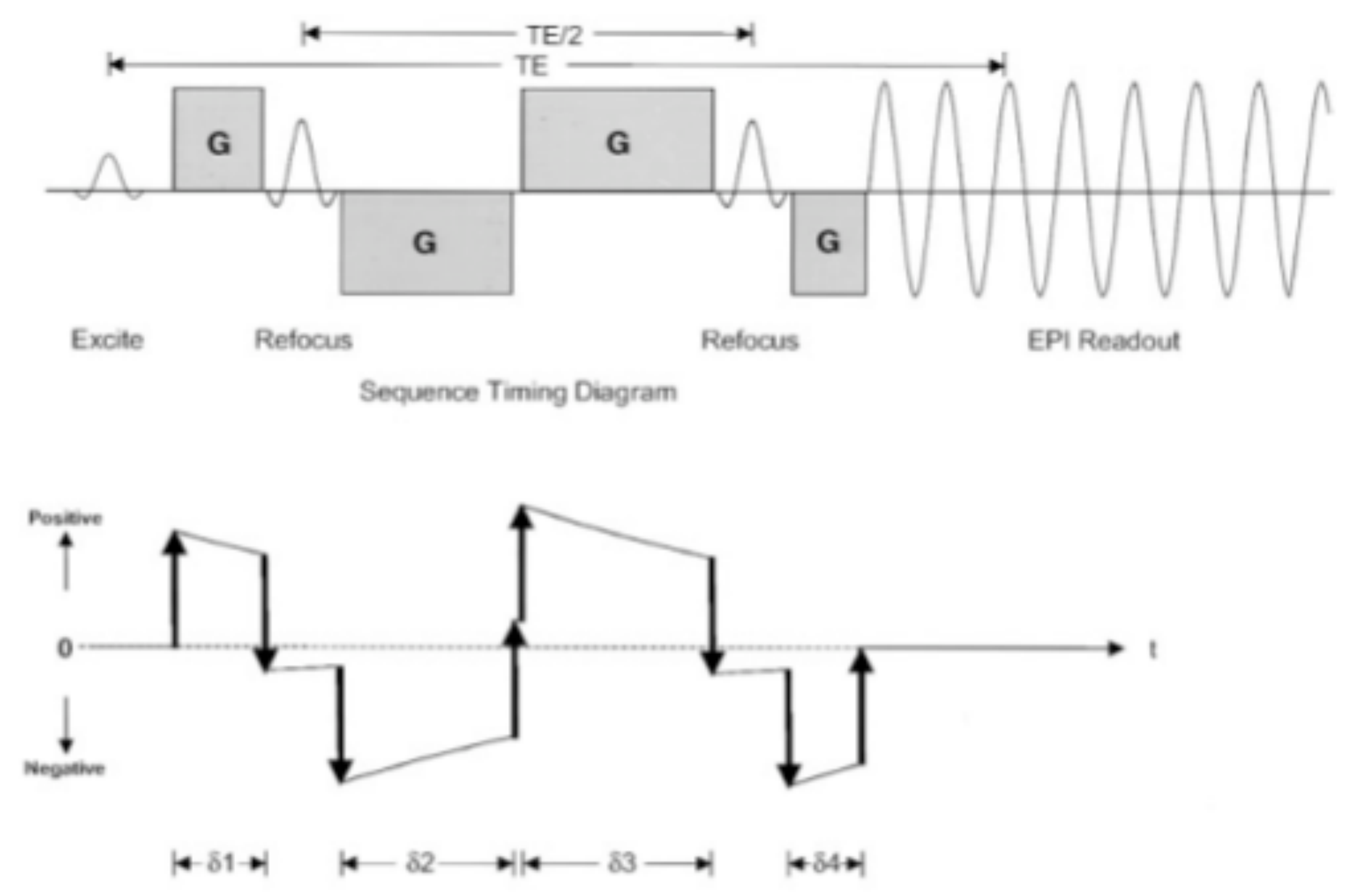
FSL: http://www.fmrib.ox.ac.uk/fsl

Dual Spin Echo

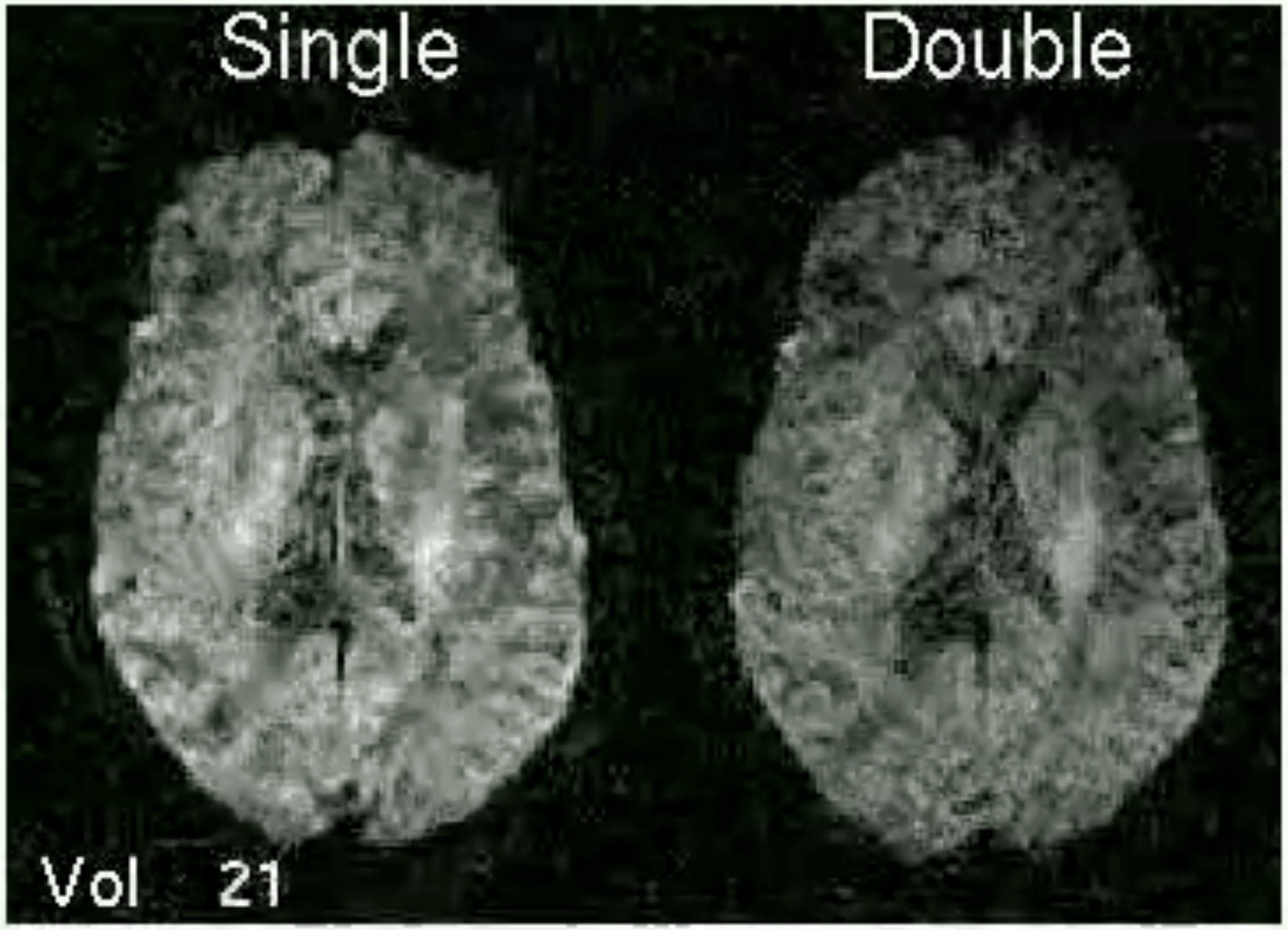

Individual eddy currents


Total eddy current

Dual Spin Echo

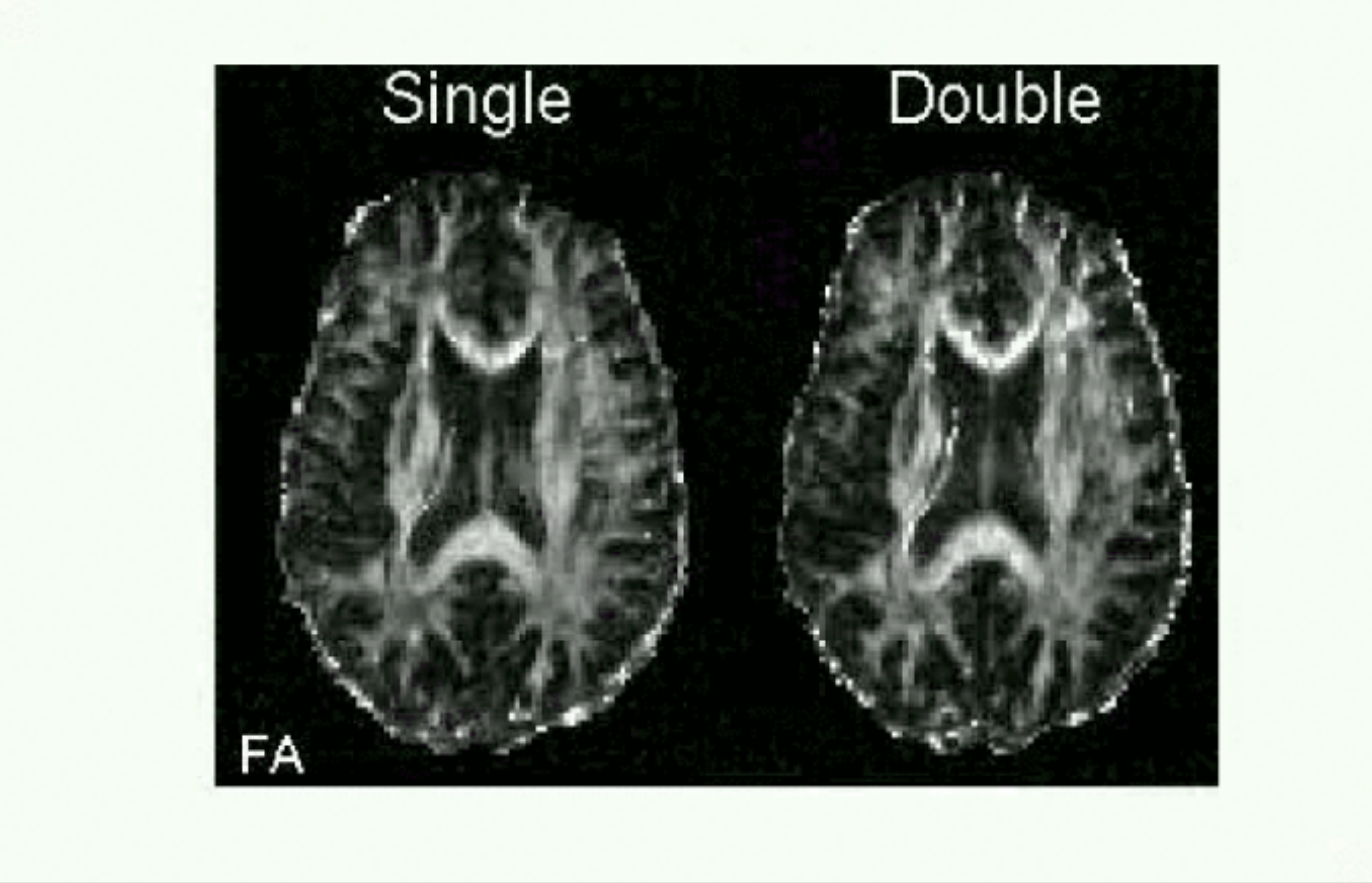


Eddy currents



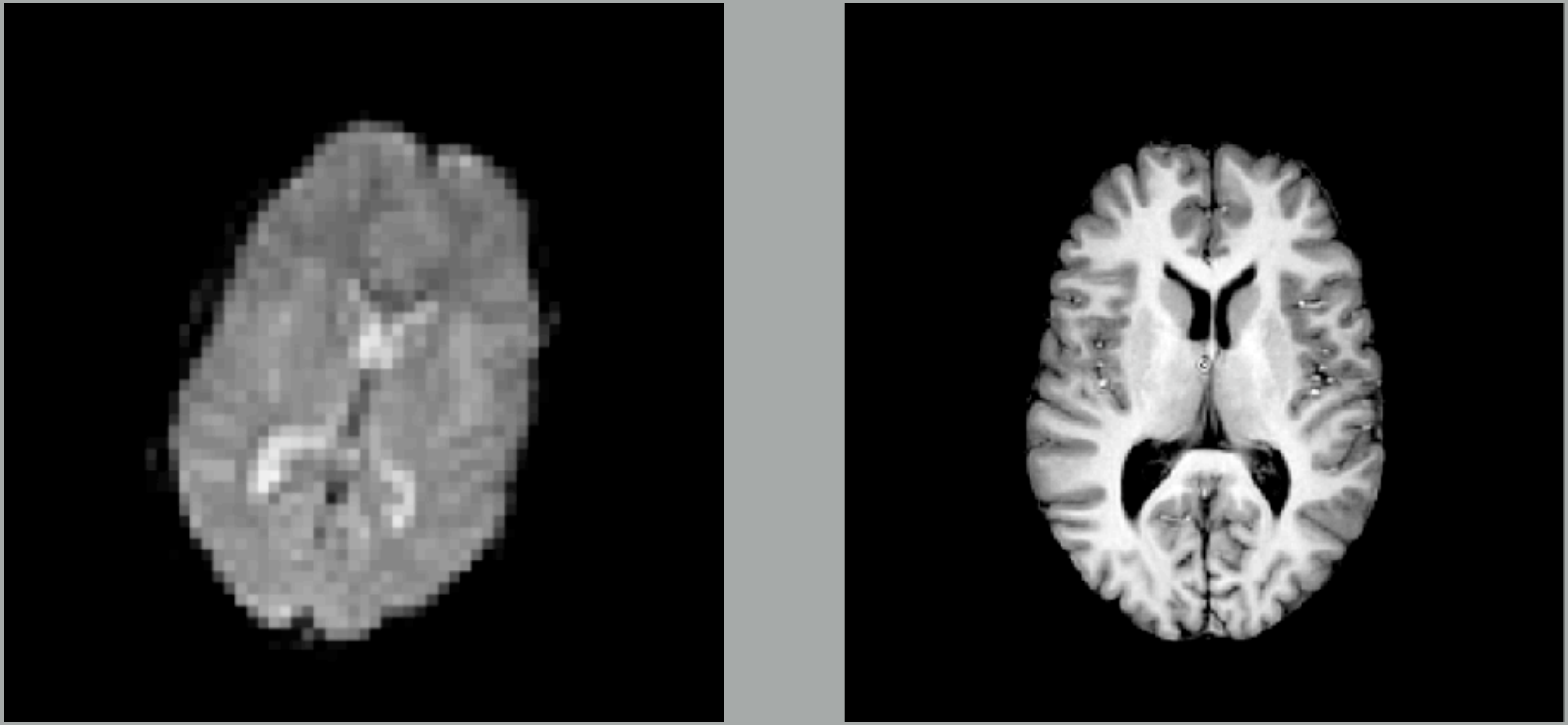
FSL: http://www.fmrib.ox.ac.uk/fsl

Eddy currents - corrected



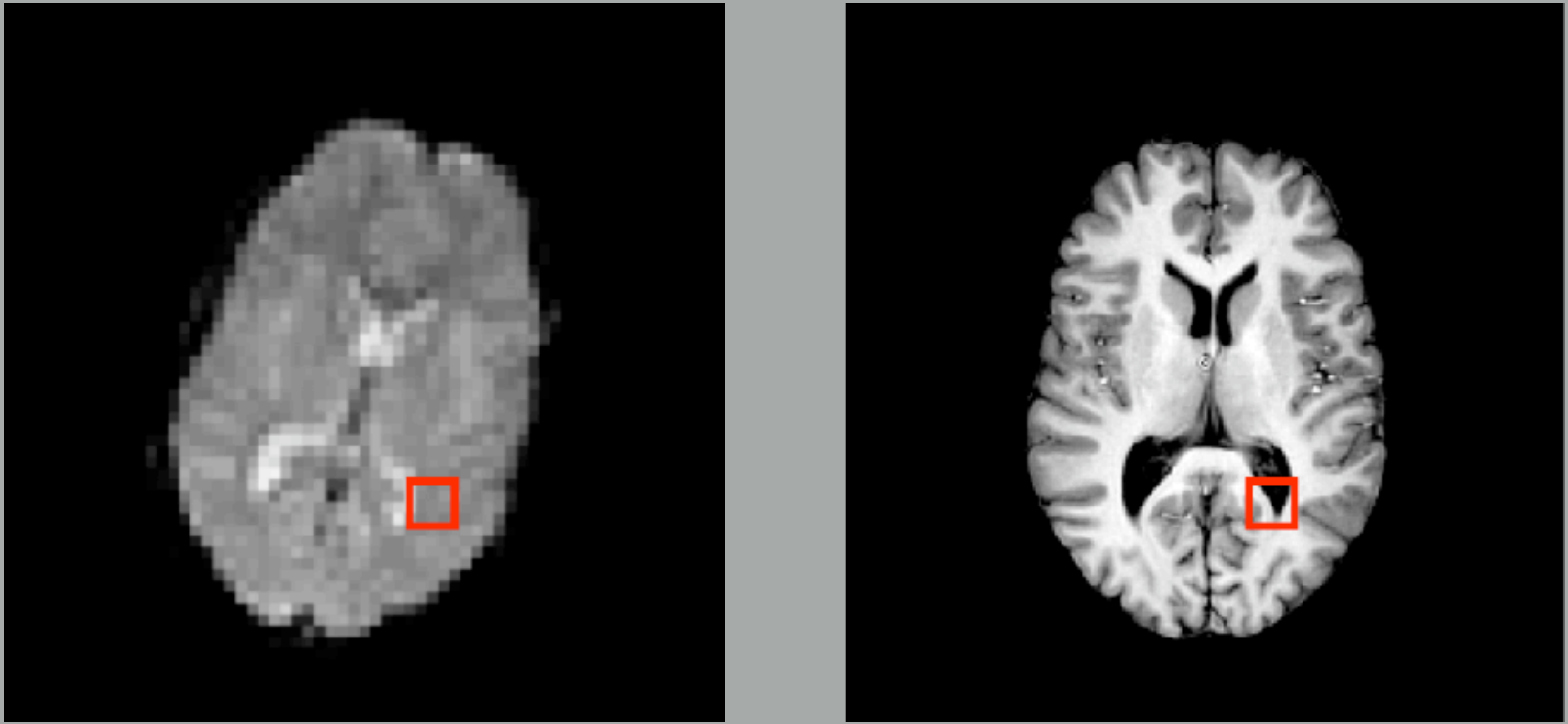
FSL: http://www.fmrib.ox.ac.uk/fsl

Registration



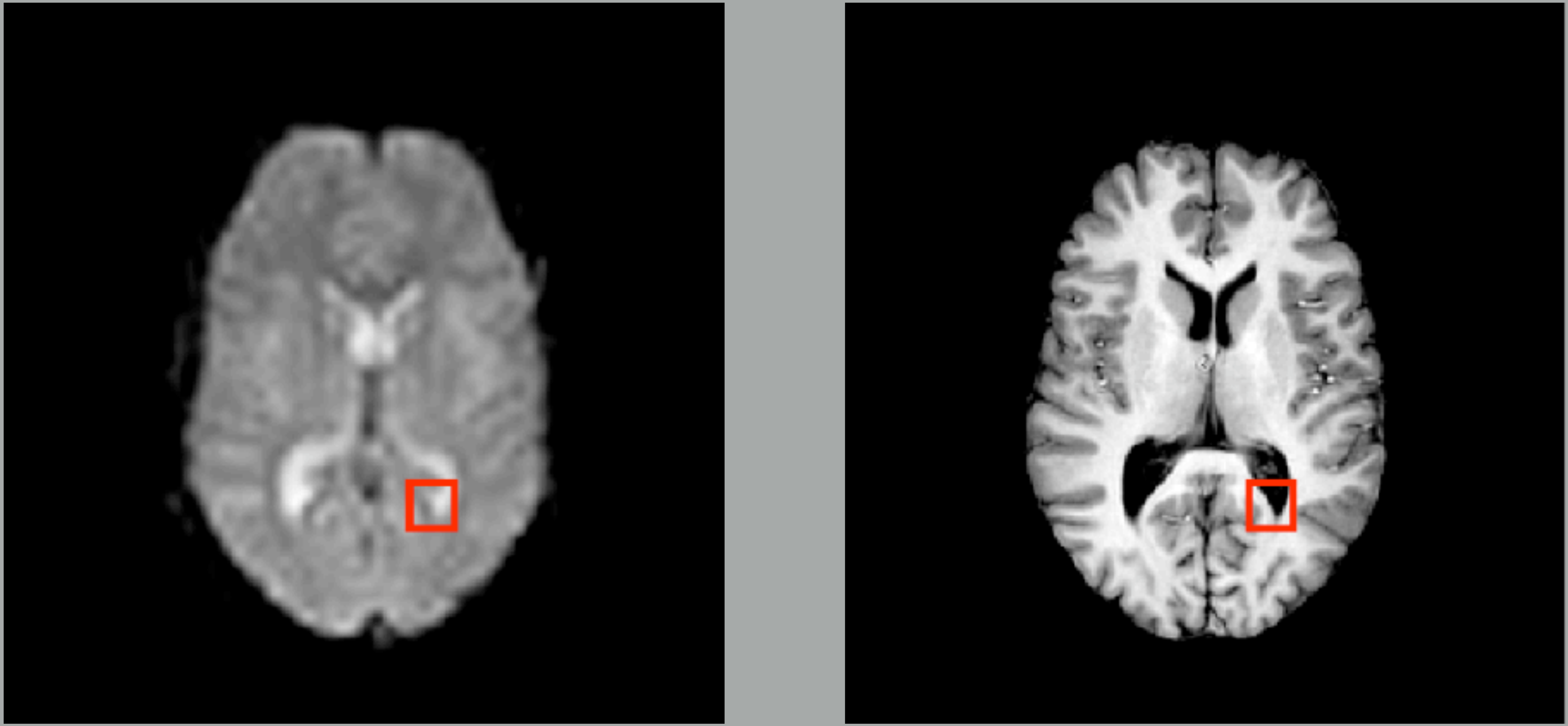
FSL: http://www.fmrib.ox.ac.uk/fsl

Registration



FSL: http://www.fmrib.ox.ac.uk/fsl

Registration



FSL: http://www.fmrib.ox.ac.uk/fsl

Registration

1. Rigid Body registration: 6 DOF
2. Affine registration: 12 DOF
3. Non-linear registration: DOF>12

DOF = “Degrees of Freedom”
The number of independent parameters

Rigid Body Registration

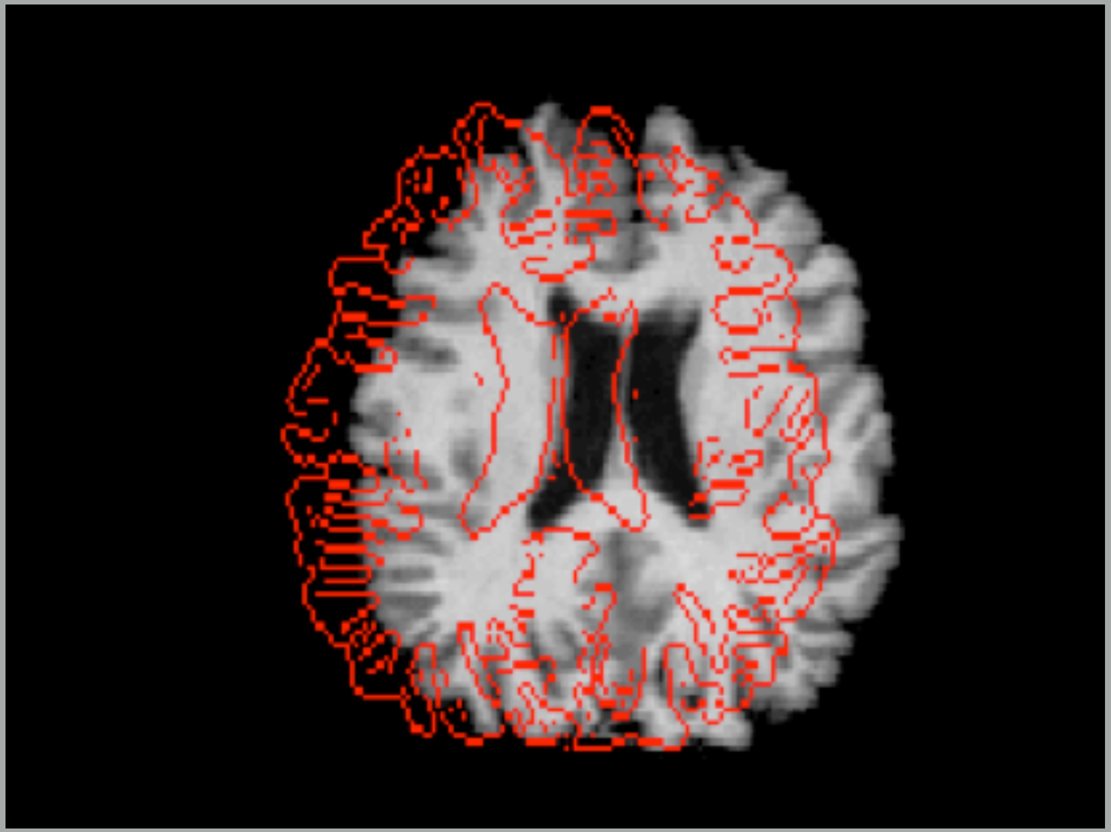
A rigid body in d dimensions has
d(d + 1)/2 degrees of freedom:

d translations
d(d –1)/2 rotations

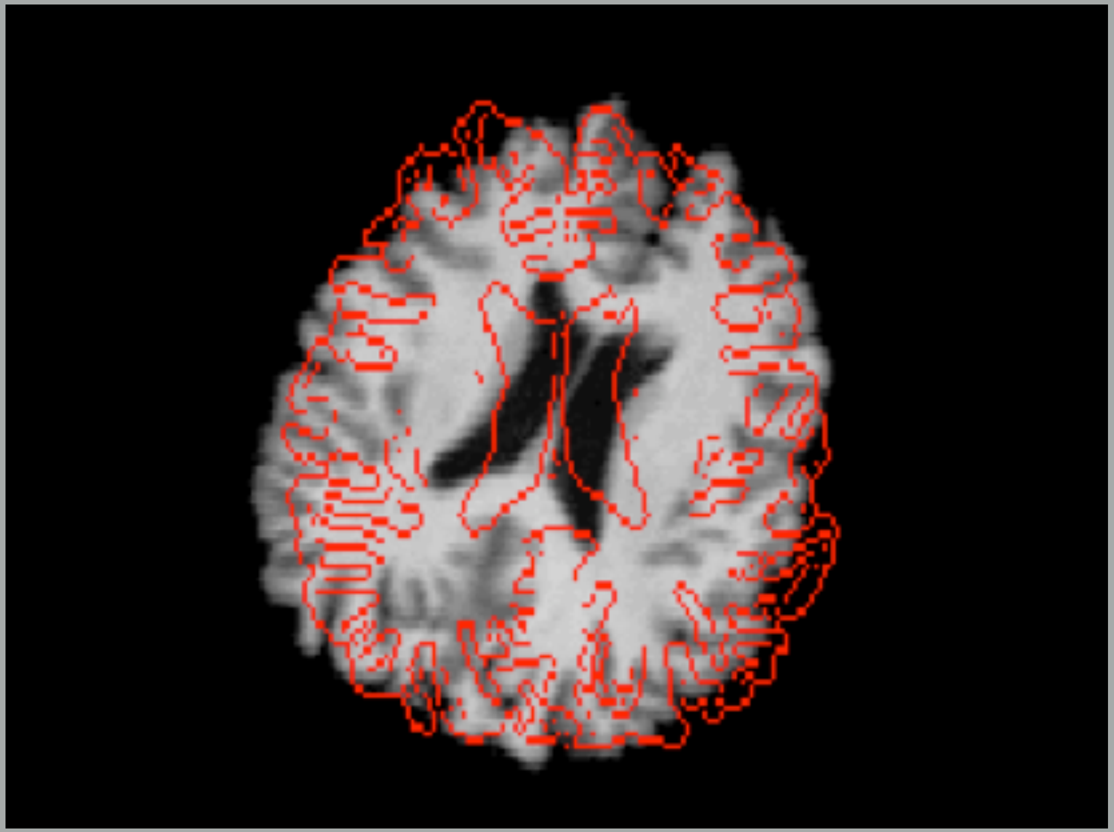
Example:
In 3-dimensions,
3 translations (x,y,z)
3 rotations (Euler angles)

Affine Registration

Rigid Body Registration



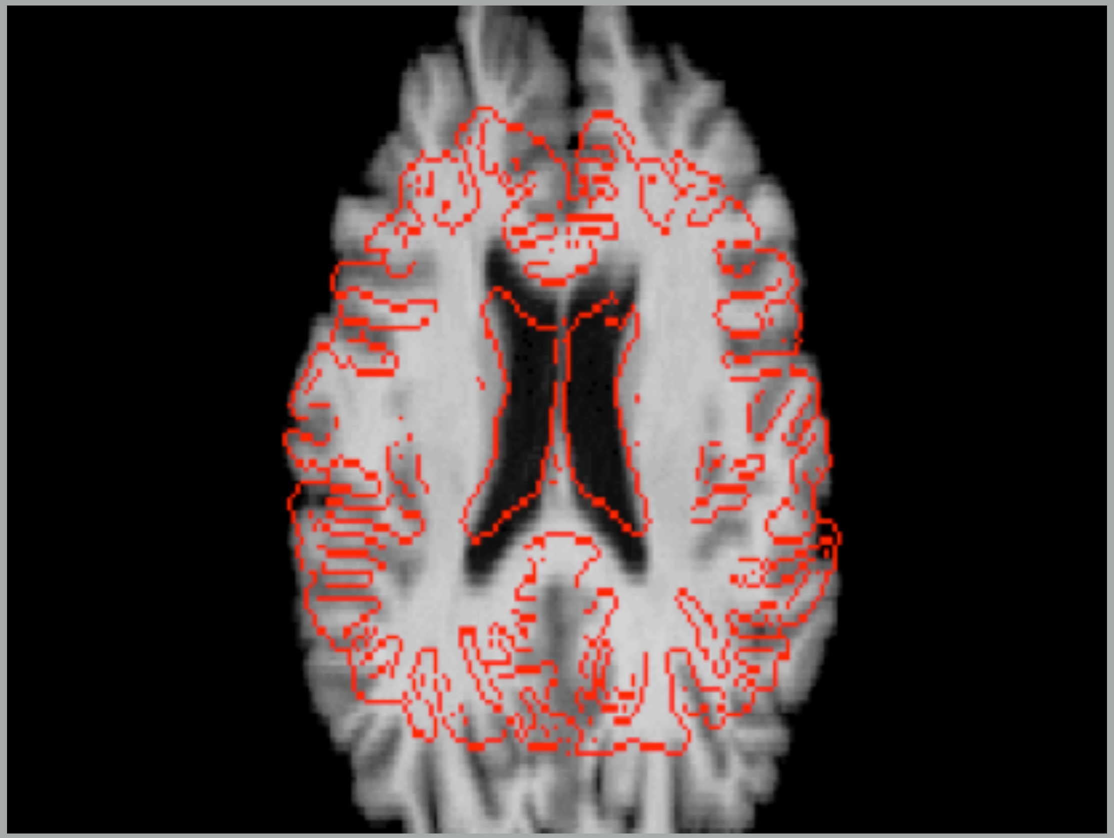
3 translations
(x,y,z)



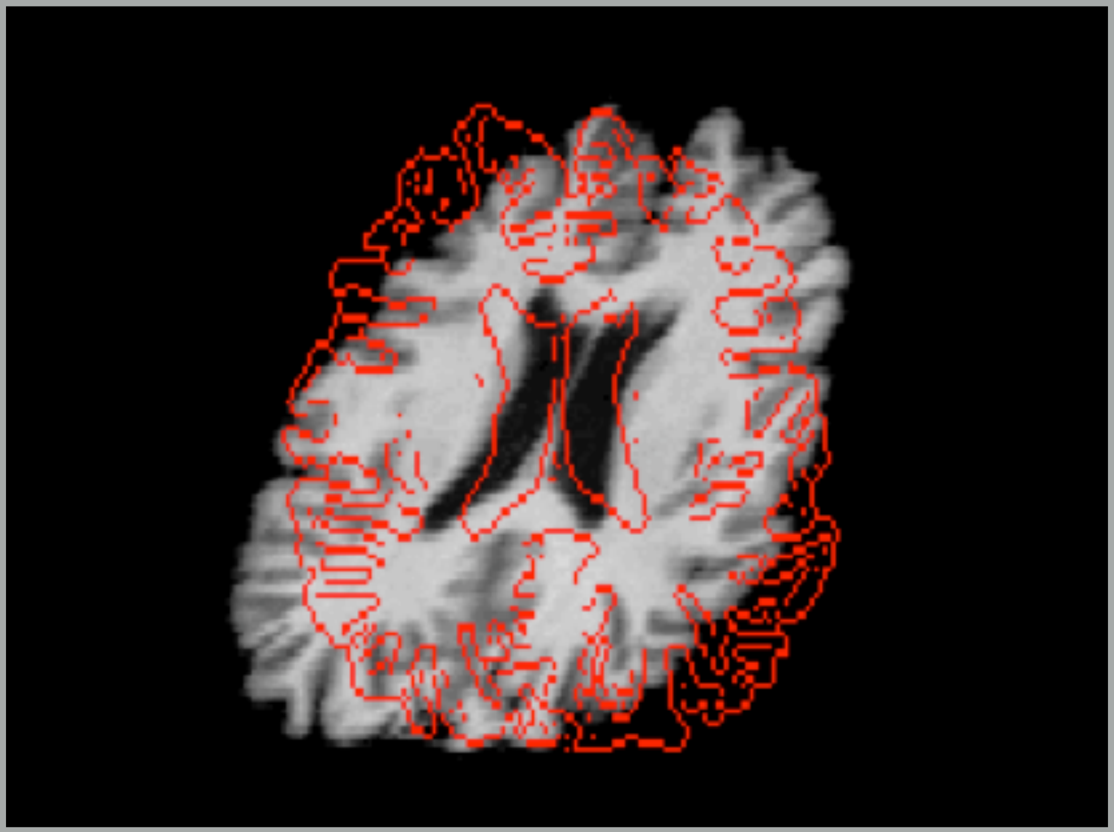
3 rotations
(x,y,z)

FSL: http://www.fmrib.ox.ac.uk/fsl

Affine Registration



3 scalings
(x,y,z)



3 shears
(x,y,z)

FSL: FLIRT (affine registration)

FSL: http://www.fmrib.ox.ac.uk/fsl

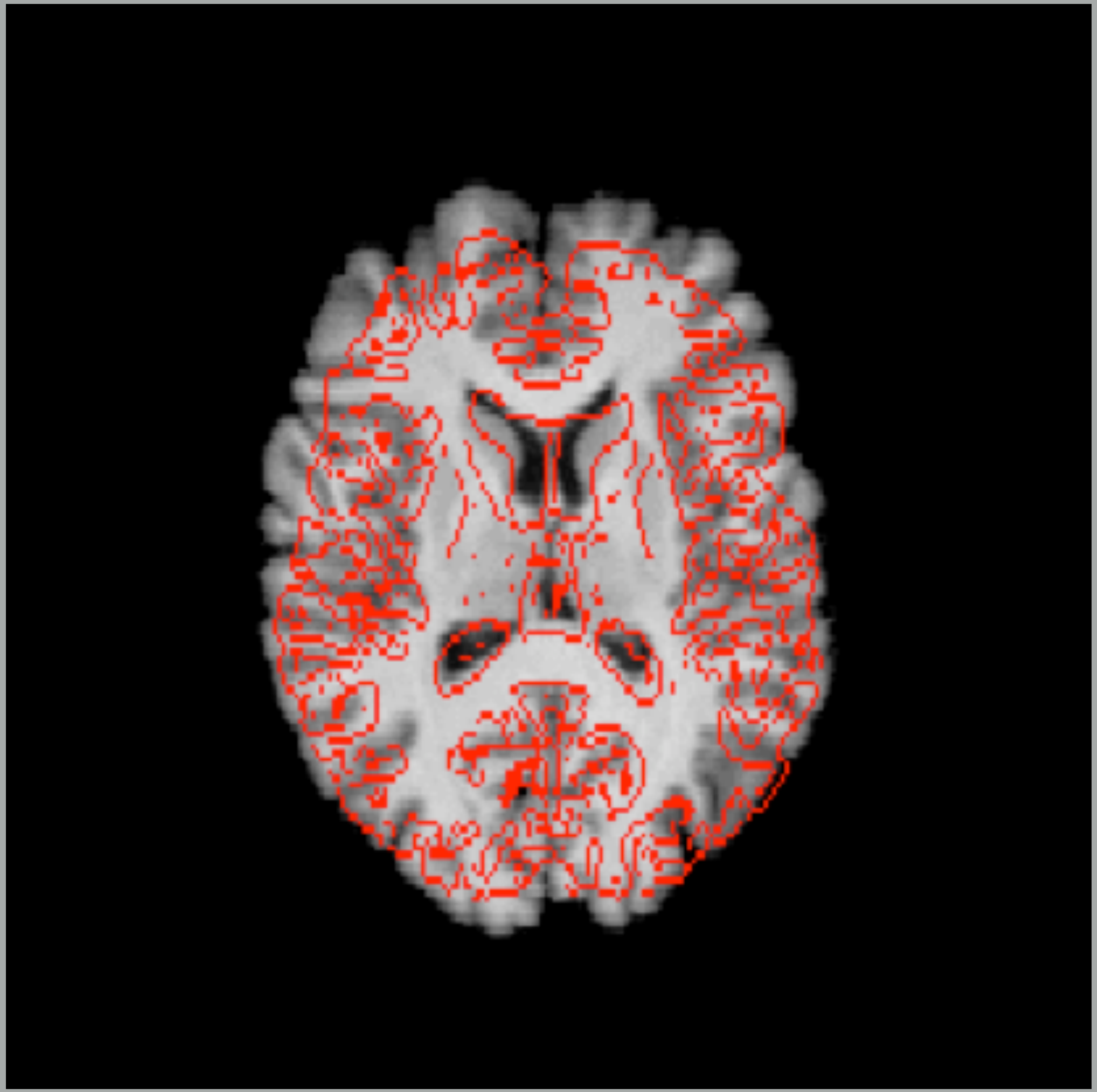
Registration

1. Rigid body transformation used for **intra-subject** registration

2. Affine transformations used for **subject-standard** registration (e.g., Talairach) and for **eddy current correction**

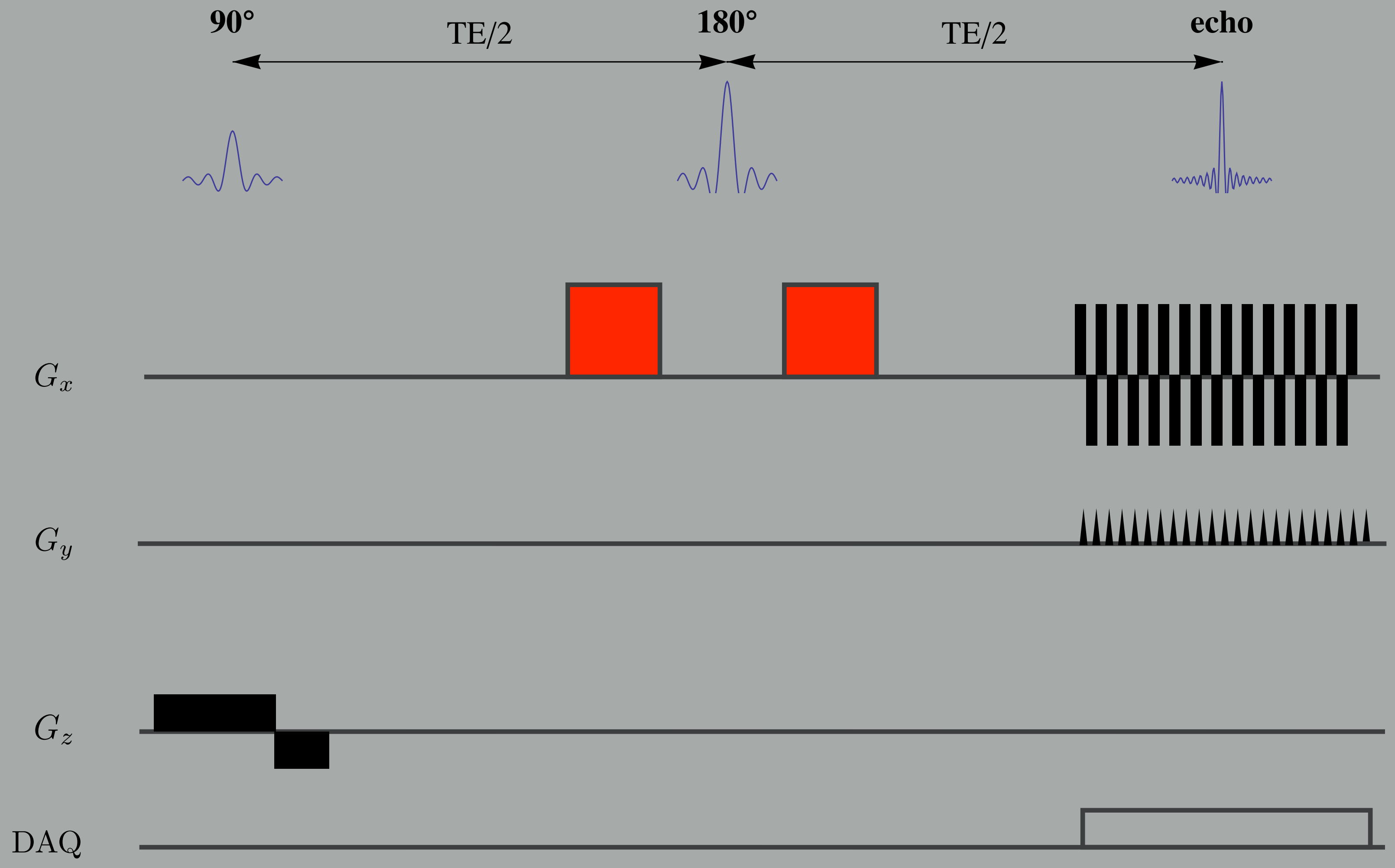
3. Non-linear transformation used for **inter-subject** registration

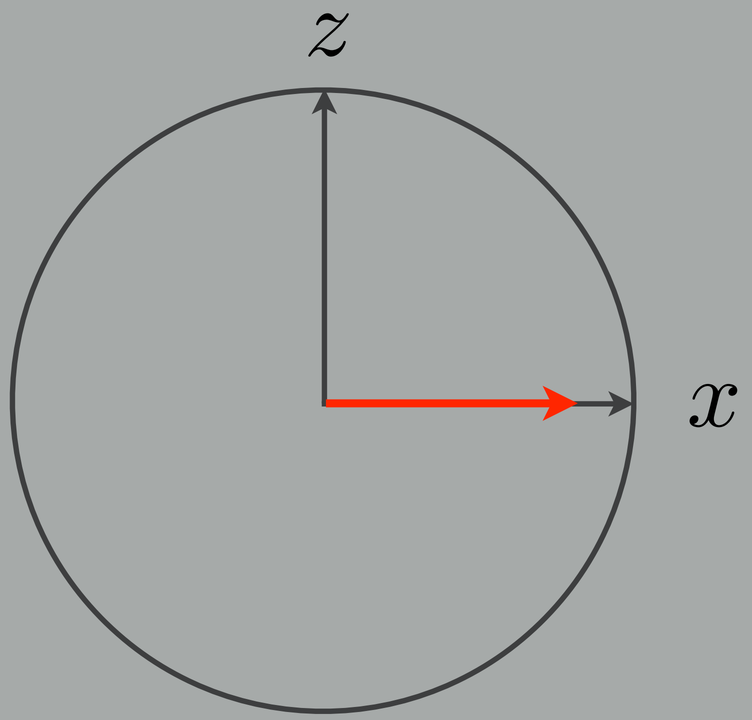
Non-linear Registration



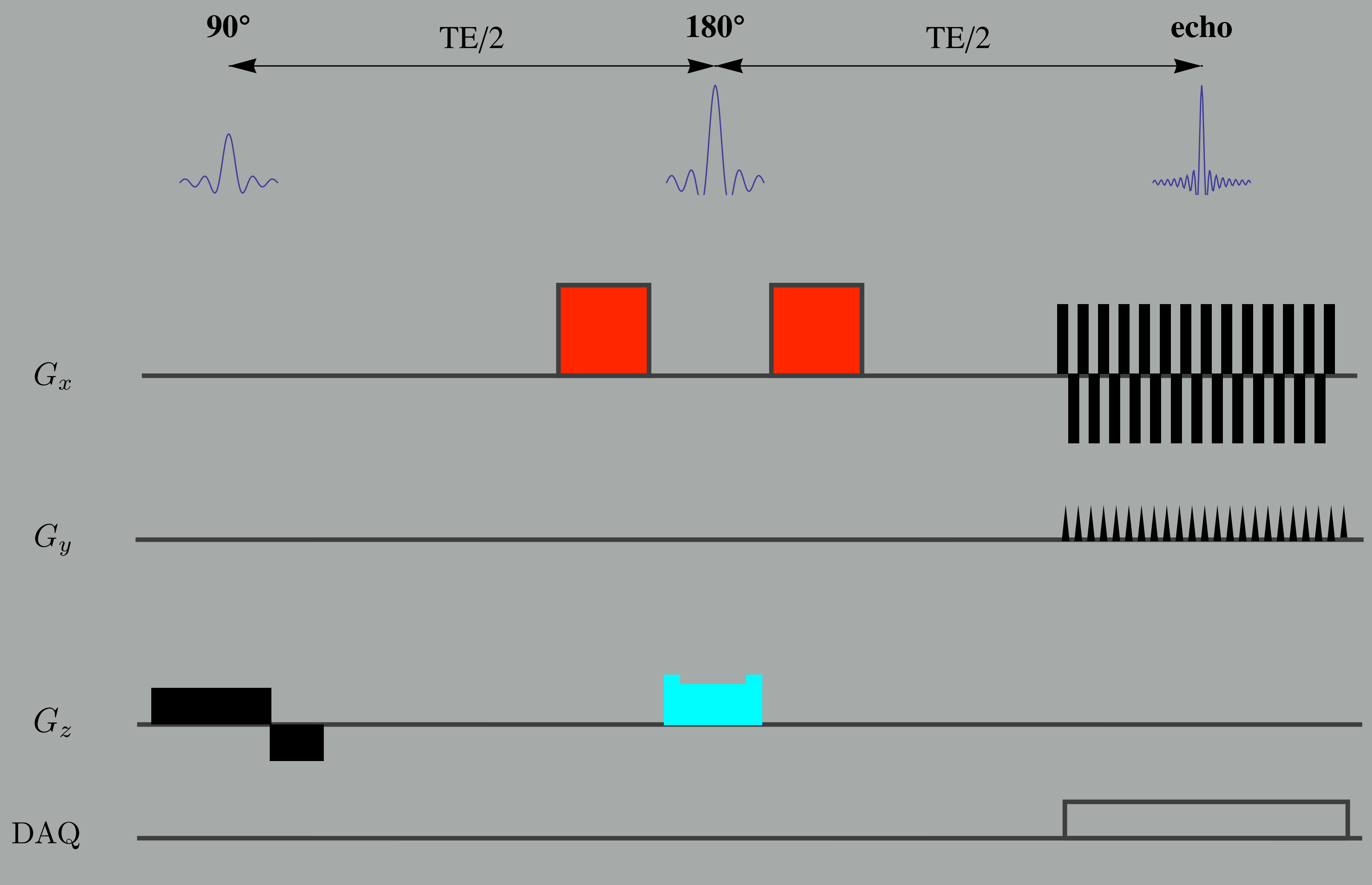
FSL: http://www.fmrib.ox.ac.uk/fsl

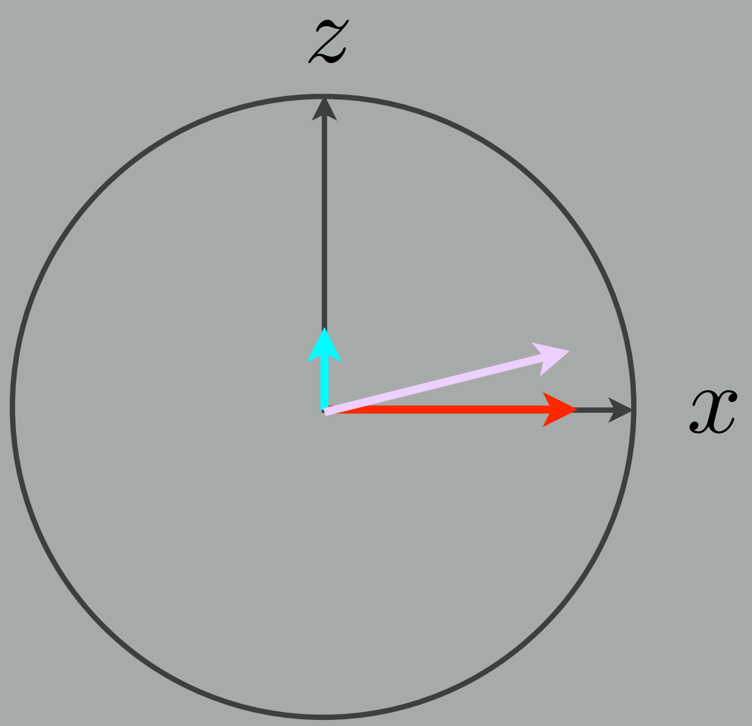
Imaging Gradient Cross Terms





Imaging Gradient Cross Terms

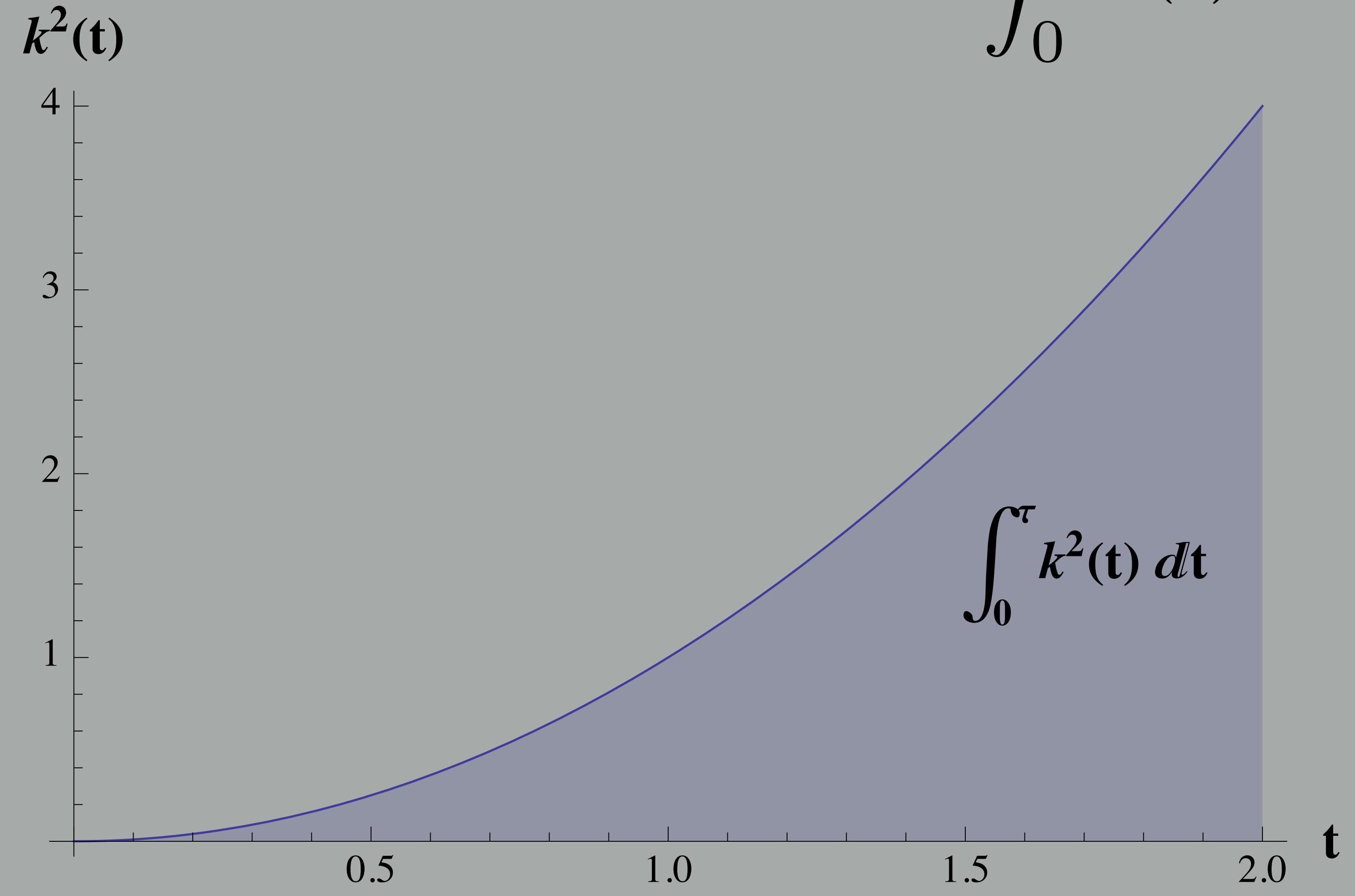




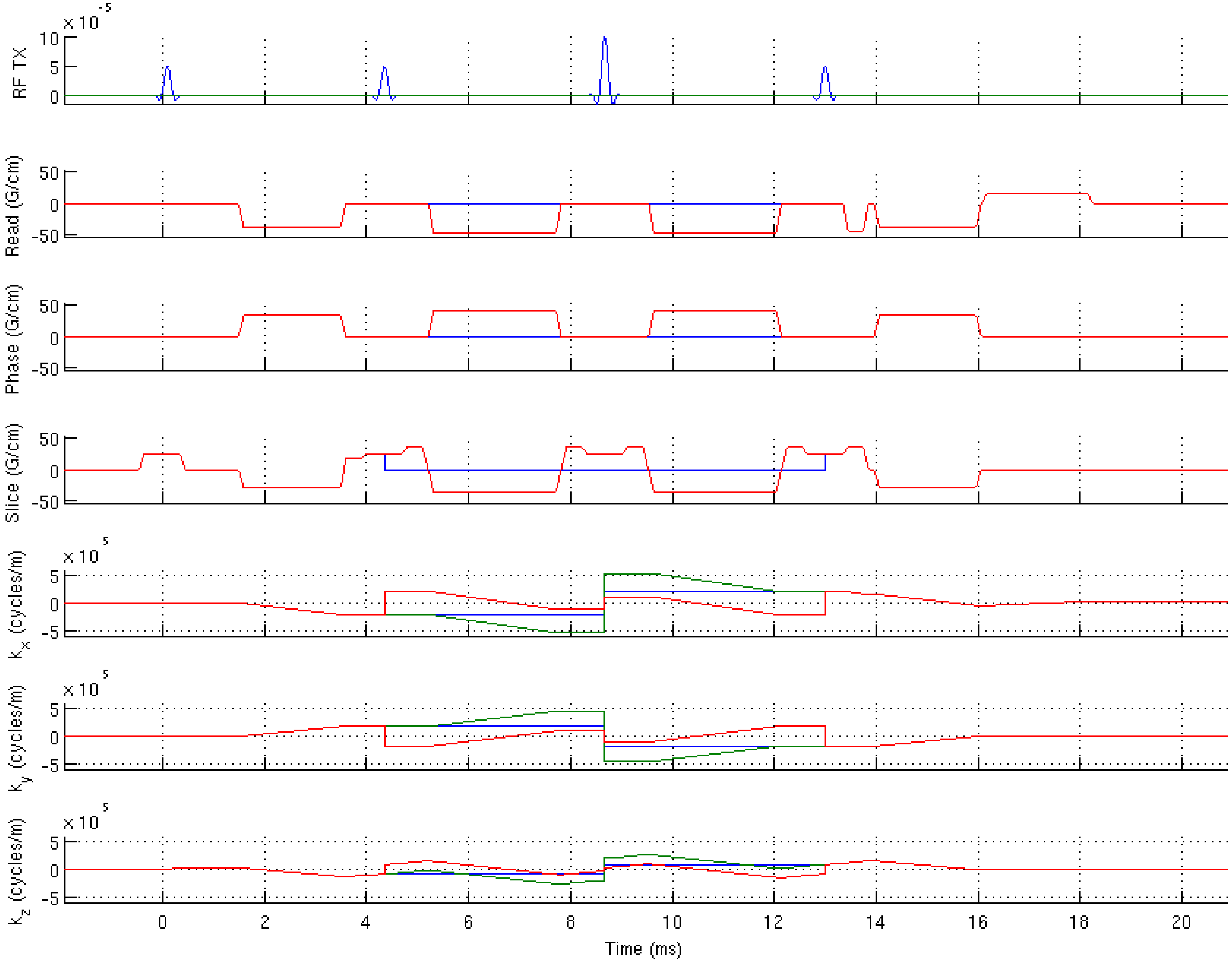
The b-factor

$$b_i(\tau) = \int_0^\tau |k_i(t)|^2 \, dt$$ $i = (x, y, z)$

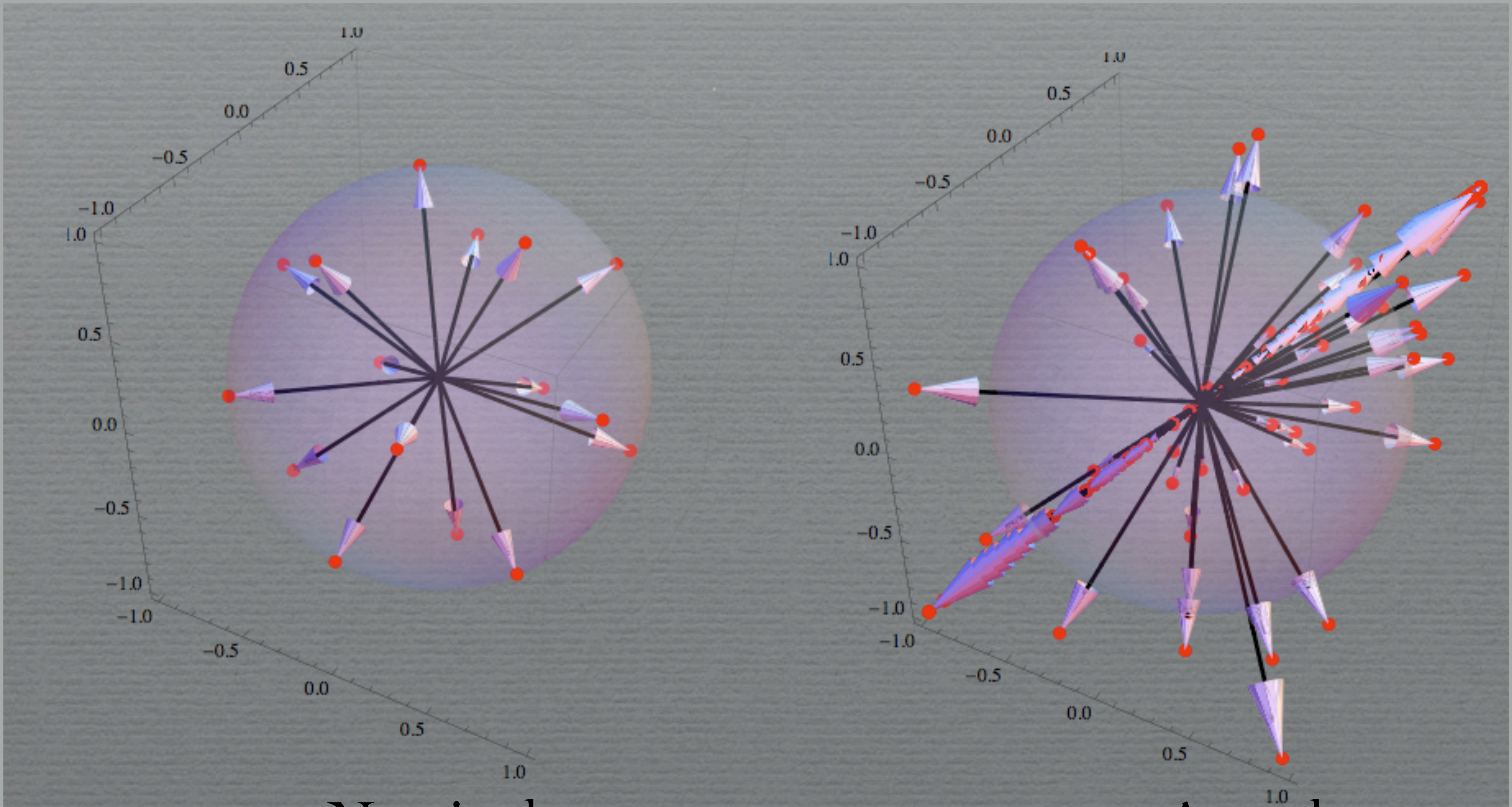
where $$k = \int_0^\tau g(t) dt$$



True B-matrix

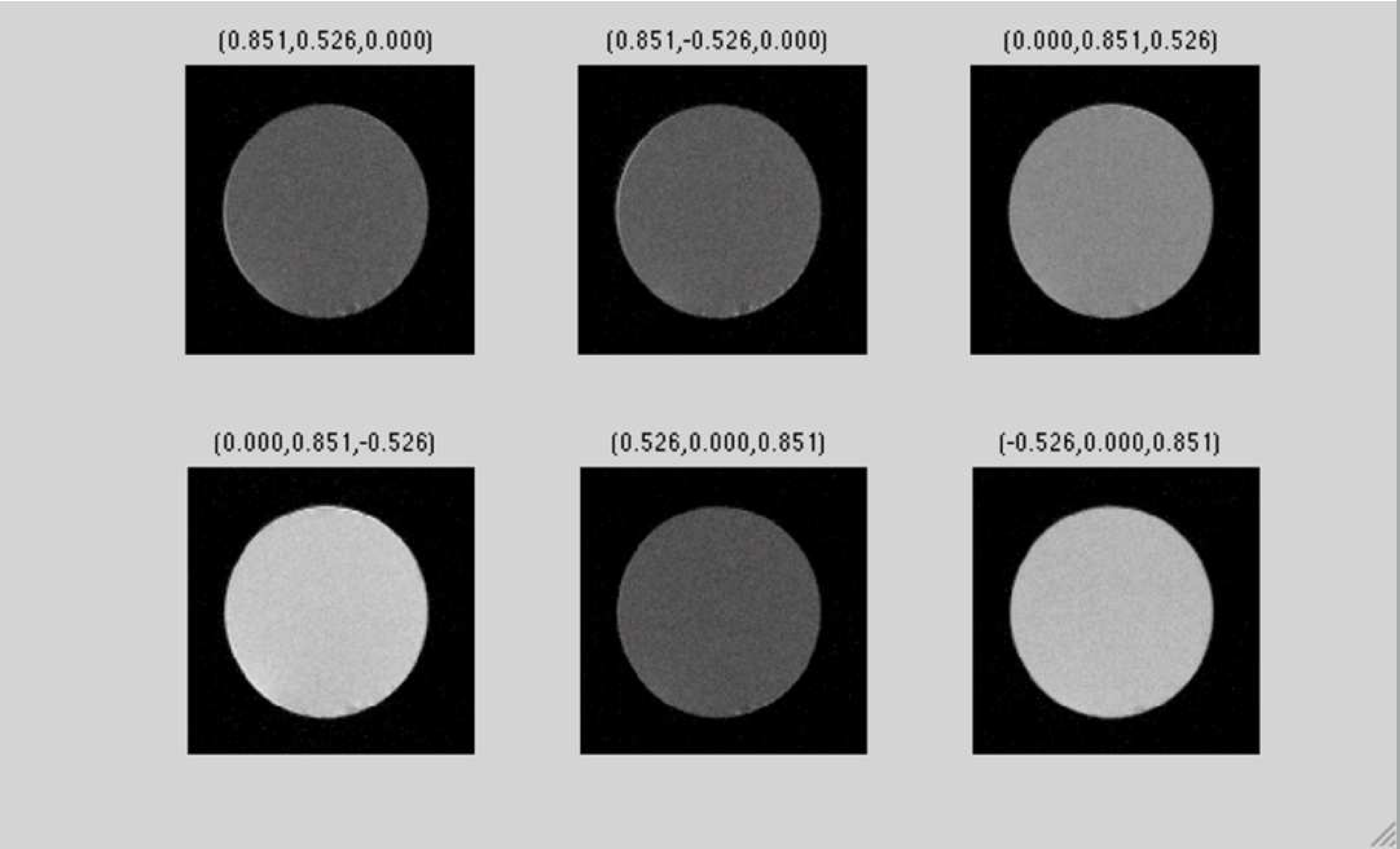


True B-matrix



Nominal Actual

Effect of cross terms



(0.851,0.526,0.000)

(0.851,-0.526,0.000)

(0.000,0.851,0.526)

(0.000,0.851,-0.526)

(0.526,0.000,0.851)

(-0.526,0.000,0.851)

Extra Slides

Motion correction with VDS

3T Fast Spin Echo (FSE) DTI

The Good

1. Better able to resolve different tissues
2. Reduced partial volume effects
3. Reduced susceptibility effects (FSE)

The Bad

1. High resolution requires interleaves
2. Interleaves affected by motion & eddy currents

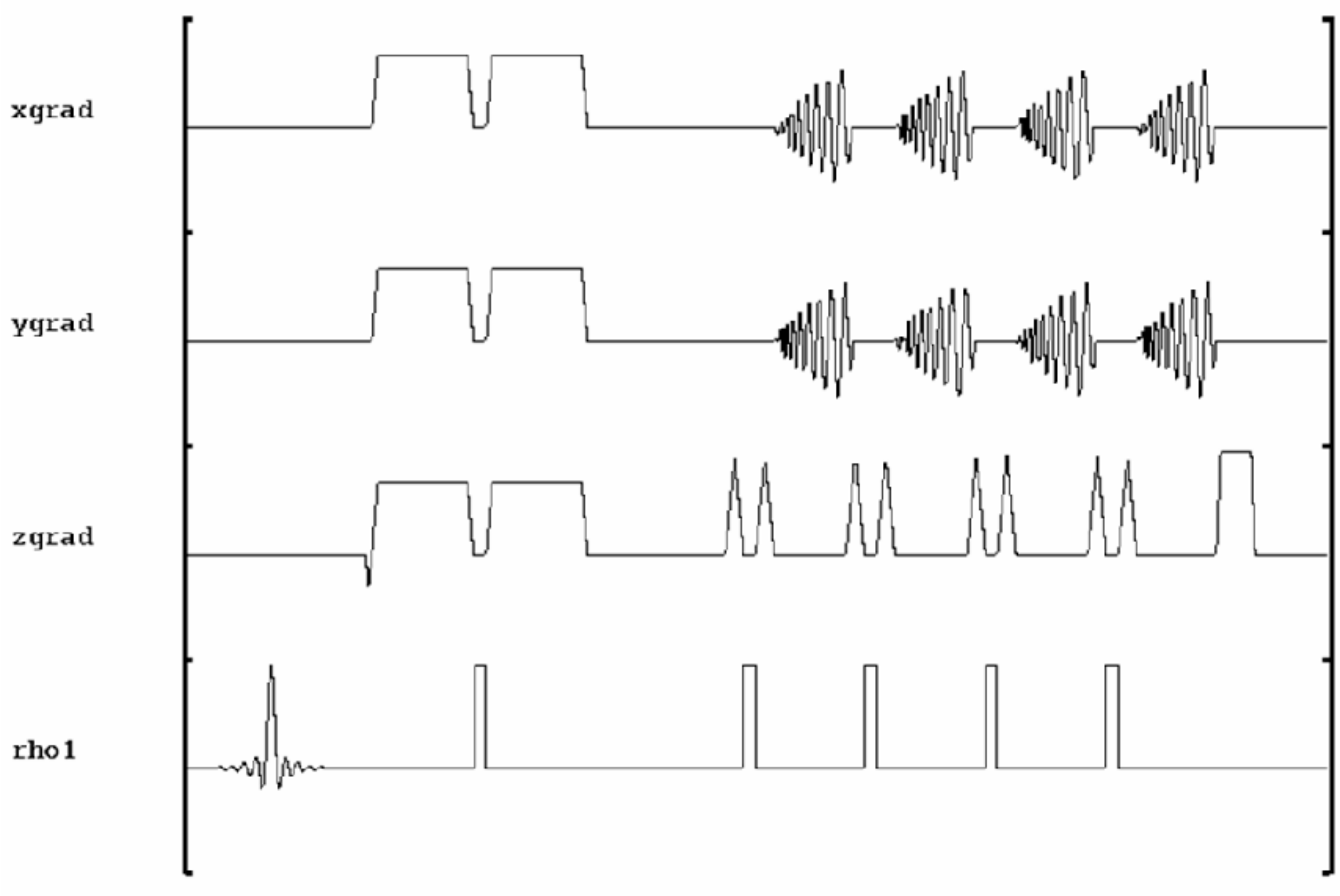
The Ugly

1. Correcting for eddy currents induced phases
2. Correcting for motion induced phases

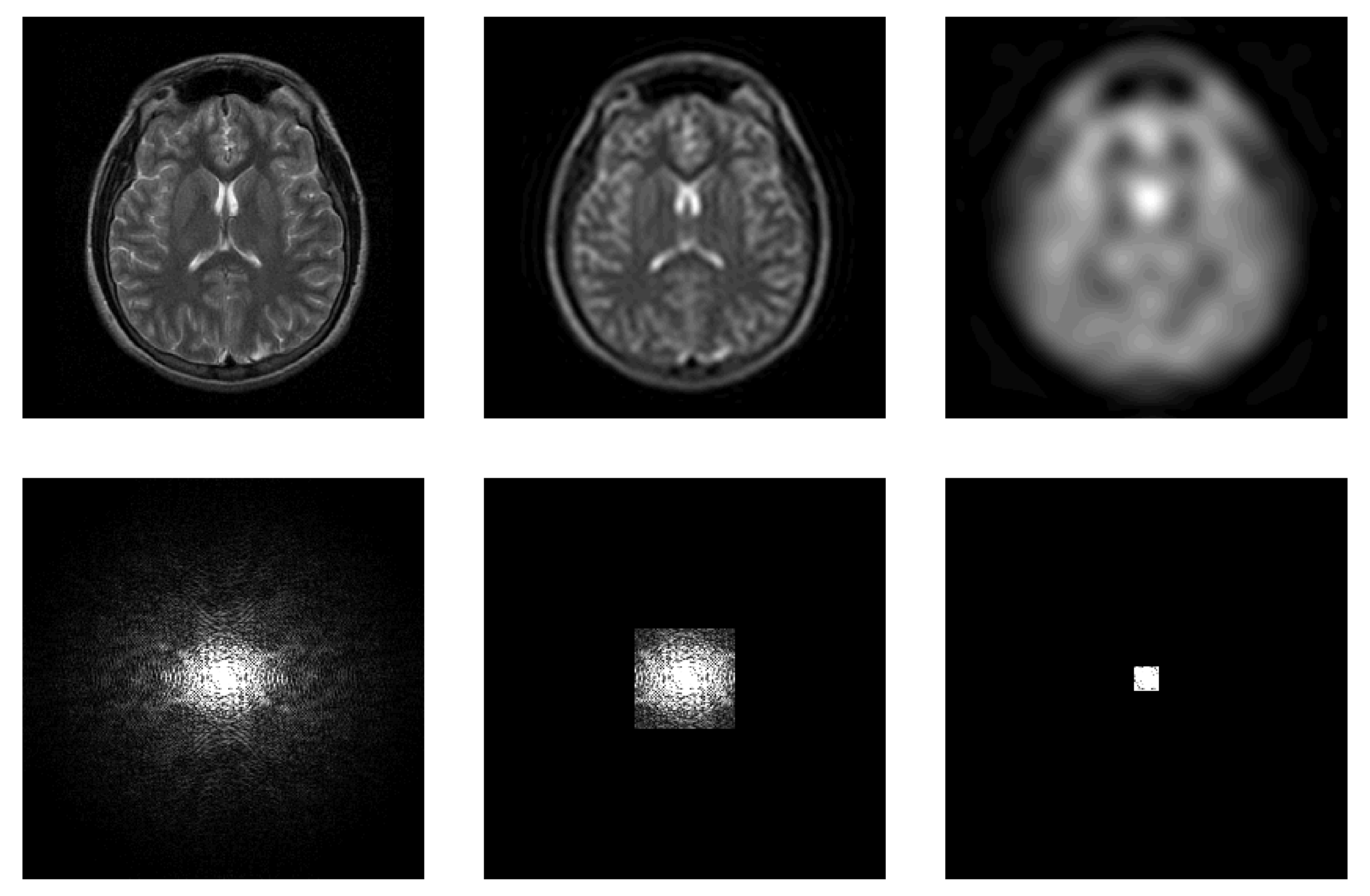
High resolution with motion correction

High resolution requires multiple interleaves,
but then motion and eddy currents make it hard
to put the k-space pieces back together correctly

3T Fast Spin Echo (FSE) DTI

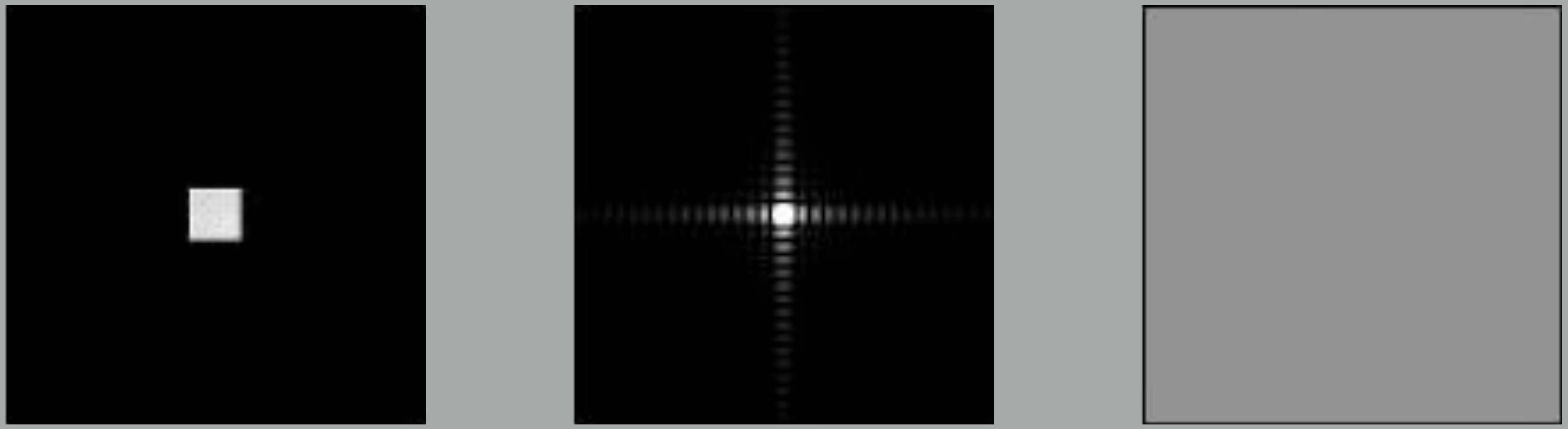


The Anatomy of k-space



low frequencies at center

Motion and k-space



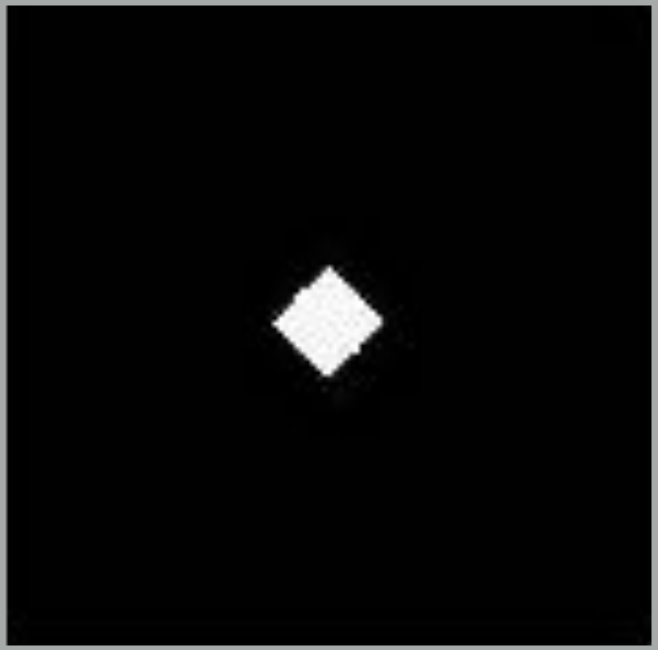
image

k-space mag

k-space phase

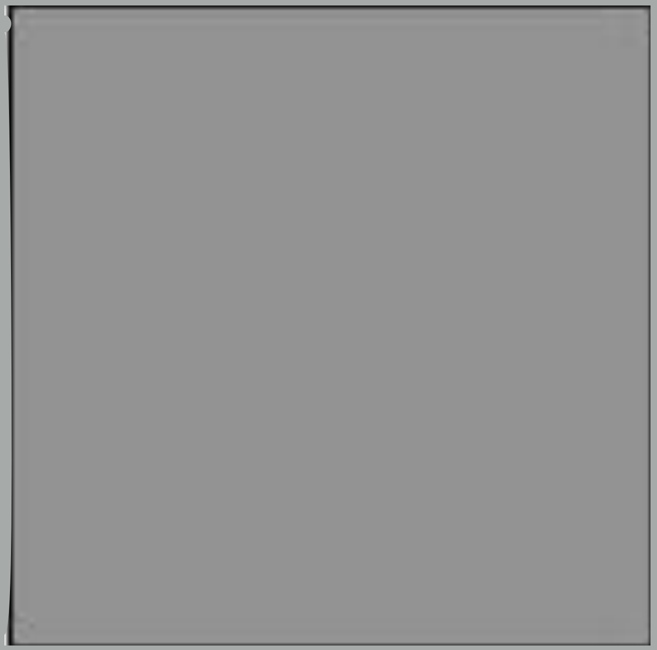
no motion

Motion and k-space



image

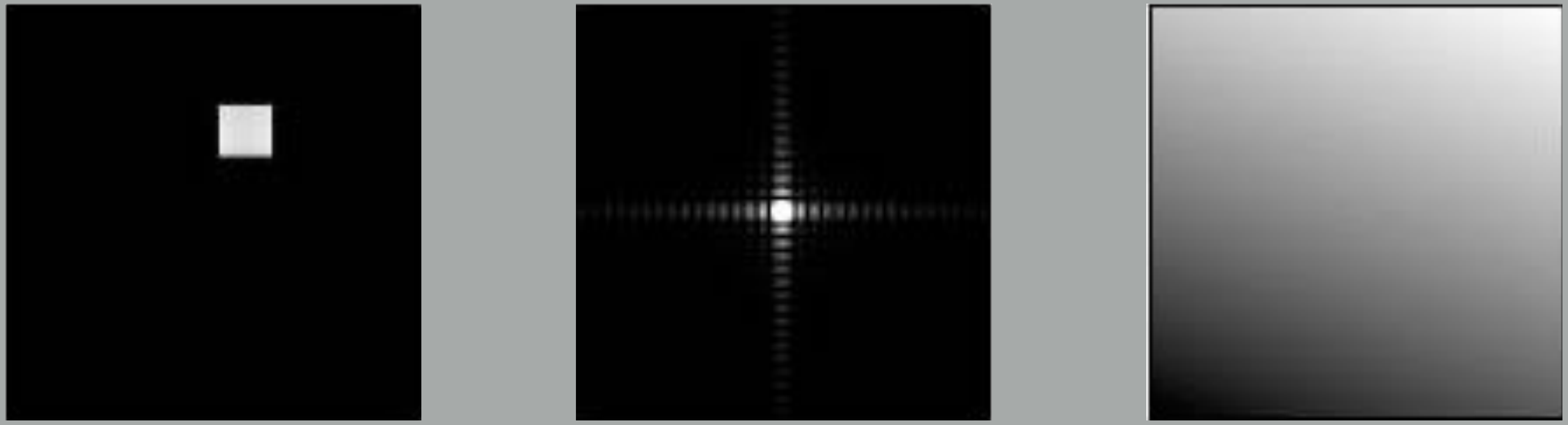
k-space mag



k-space phase

rotation

Motion and k-space



image

k-space mag

k-space phase

translation

Motion and k-space

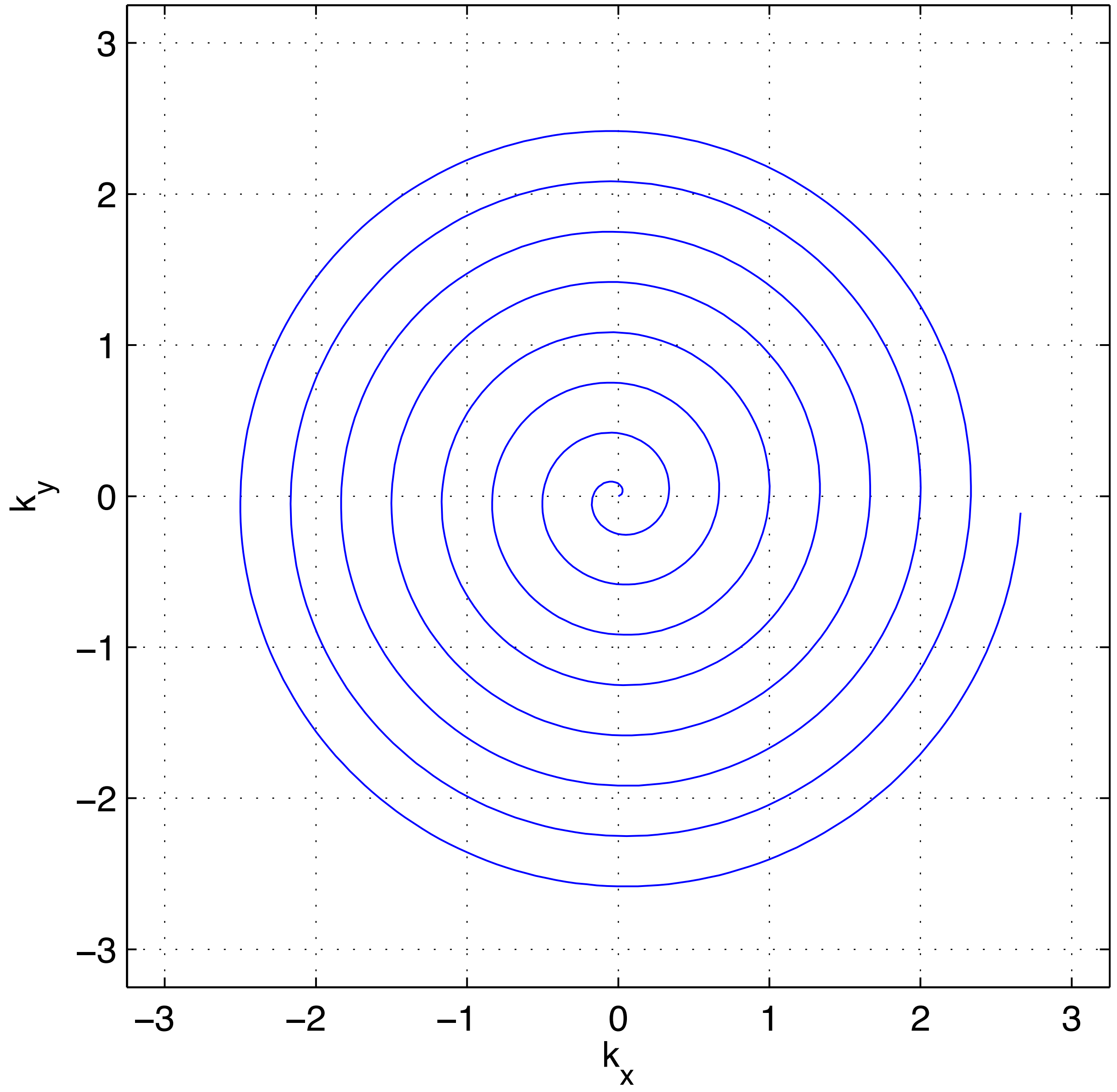
image

k-space mag

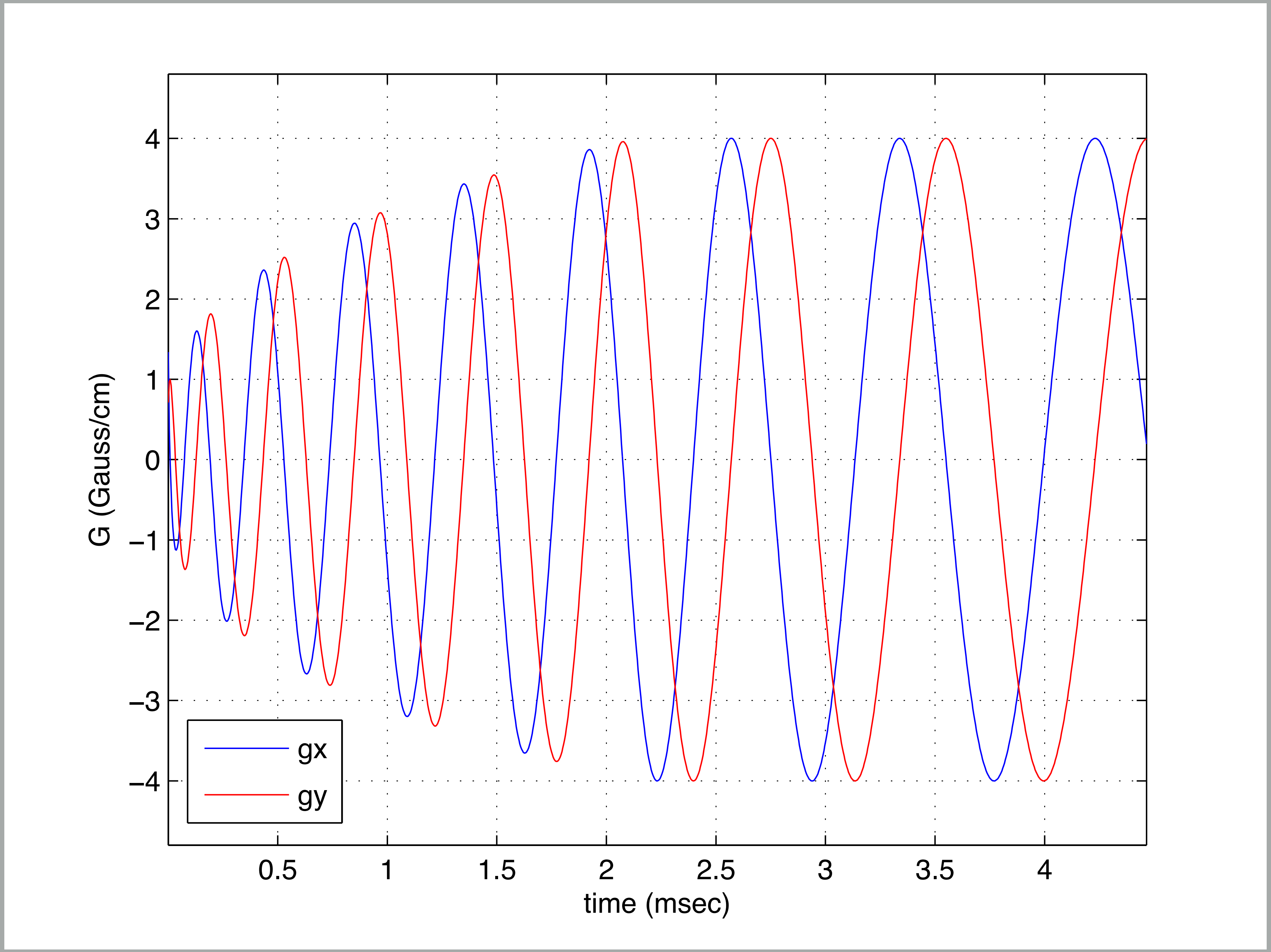
k-space phase

translation and rotation

Spirals



Spirals

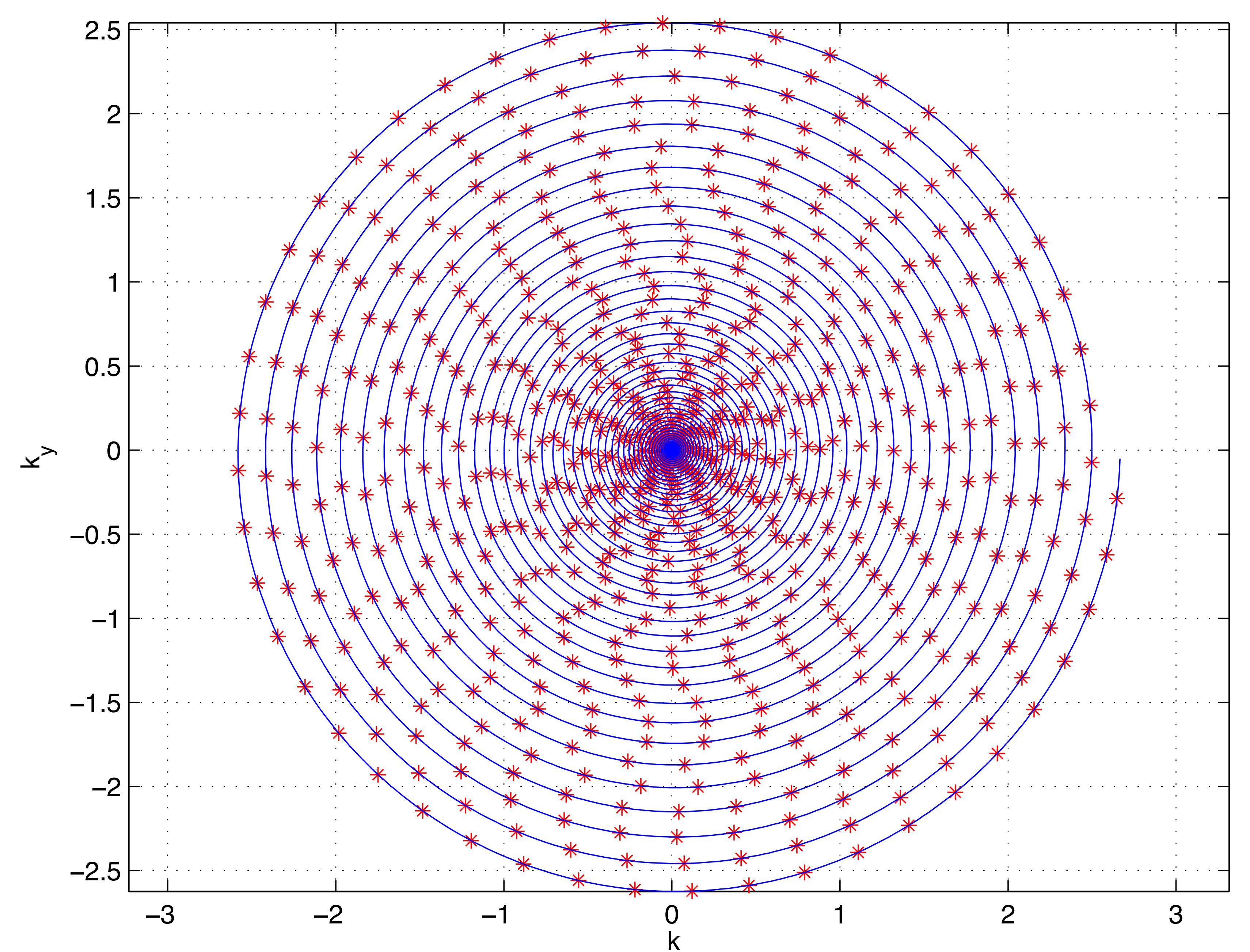


Variable Density Spirals (VDS)

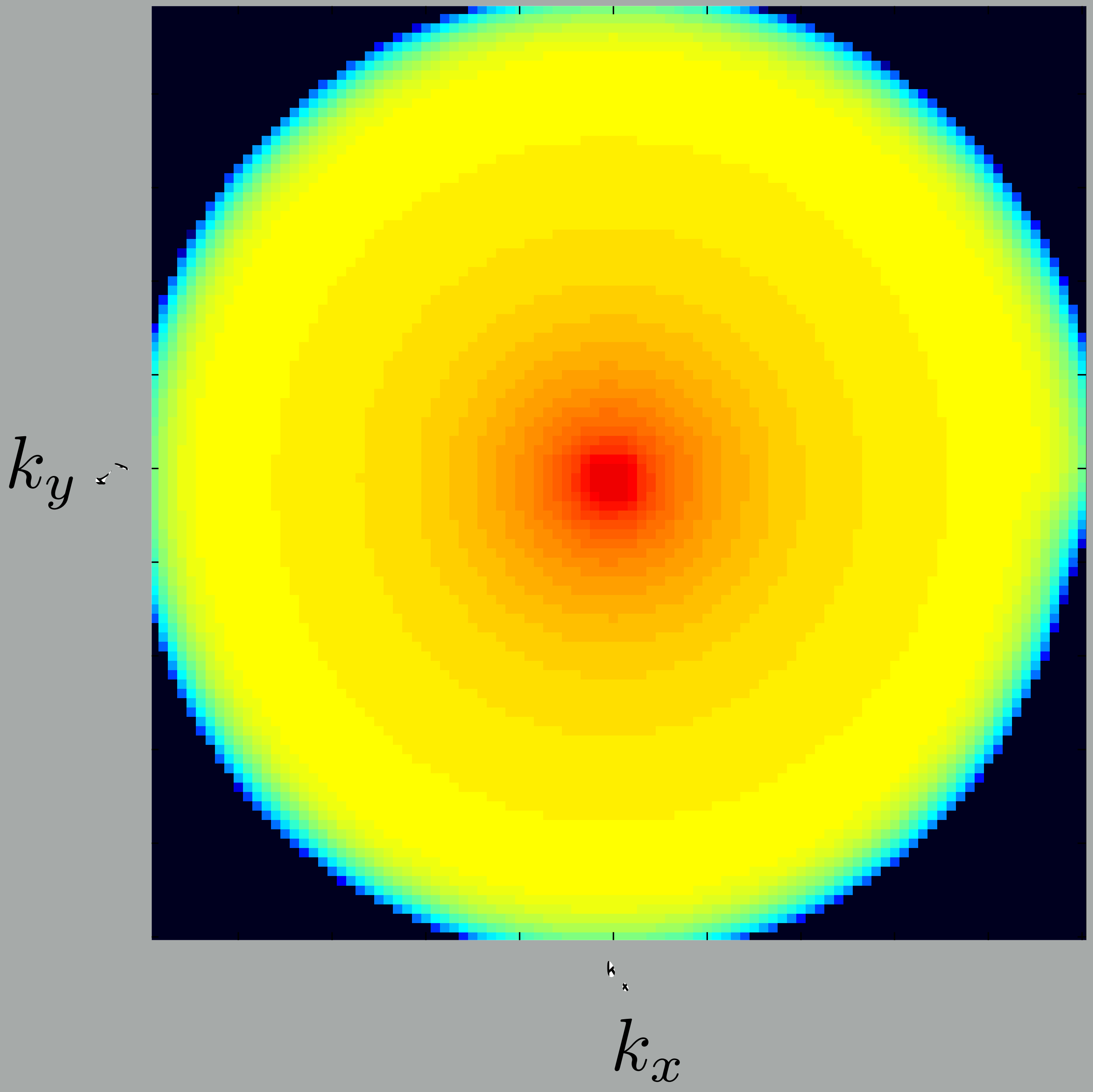
Phase errors generated by eddy currents
and motion are low spatial frequency

Oversample the low spatial frequencies
to estimate these phases *every* interleave

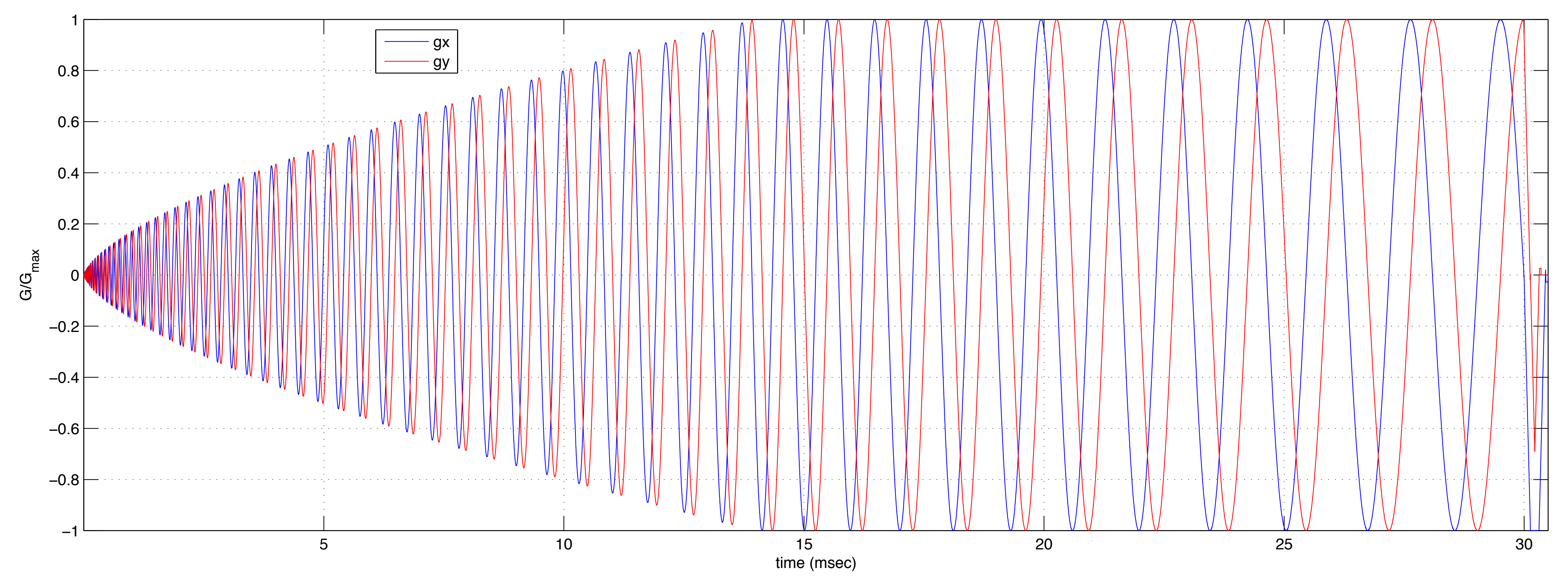
Variable Density Spirals (VDS)



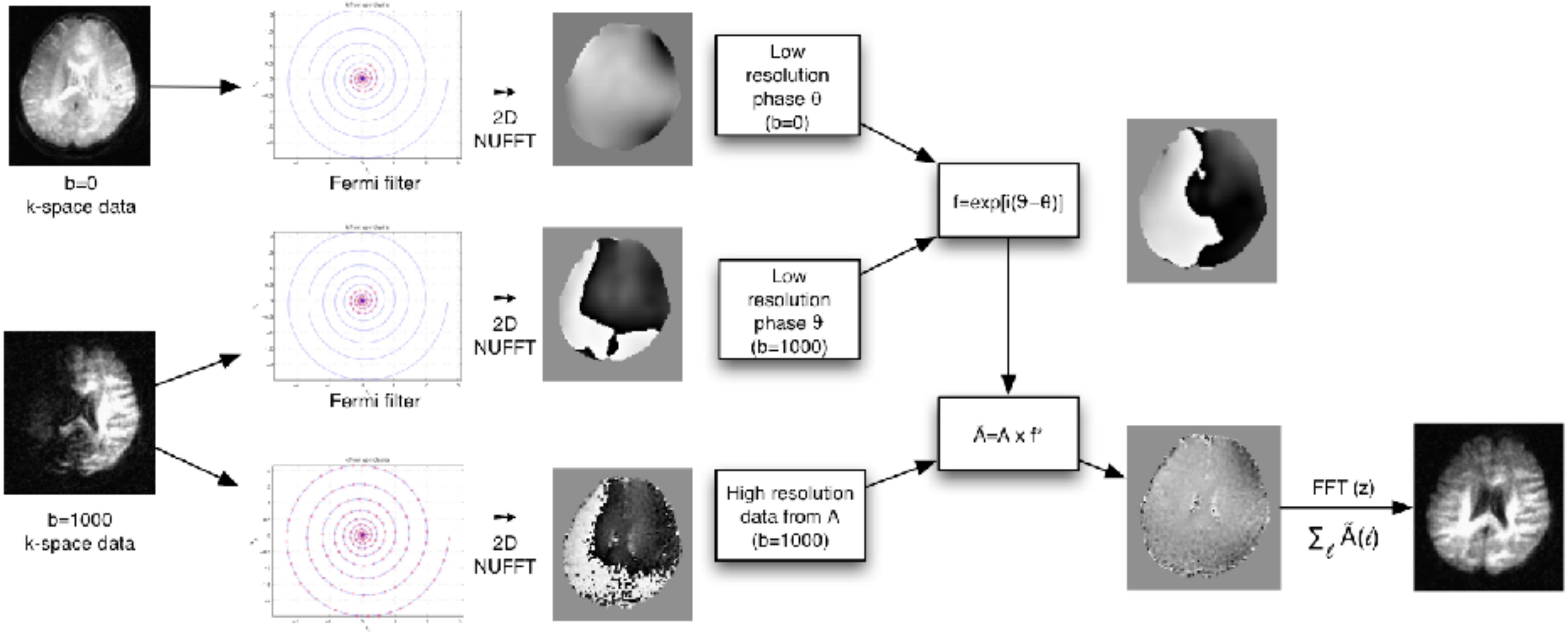
Variable Density Spirals (VDS)



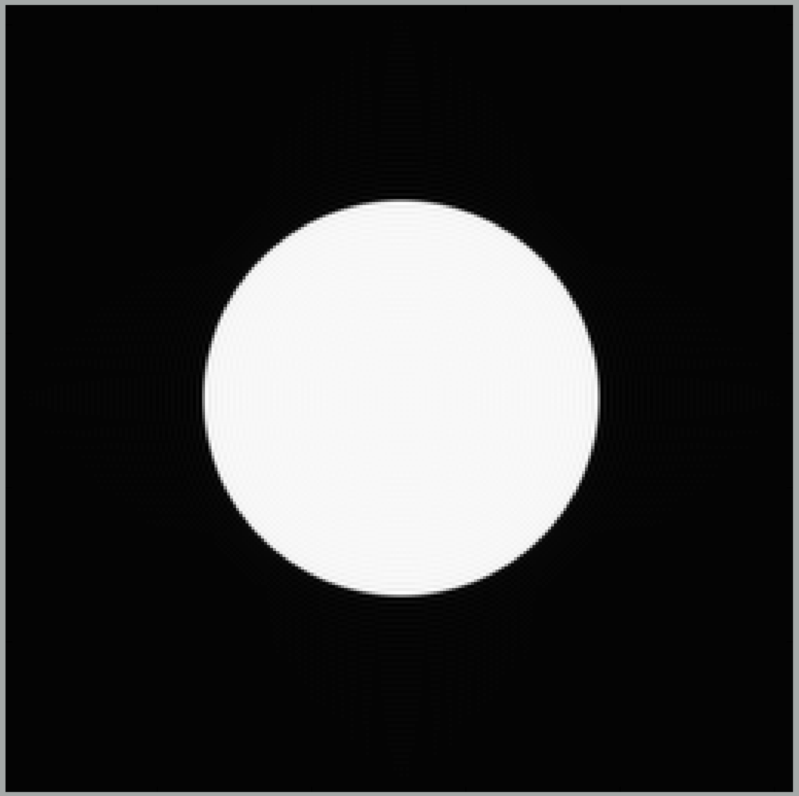
Variable Density Spirals (VDS)



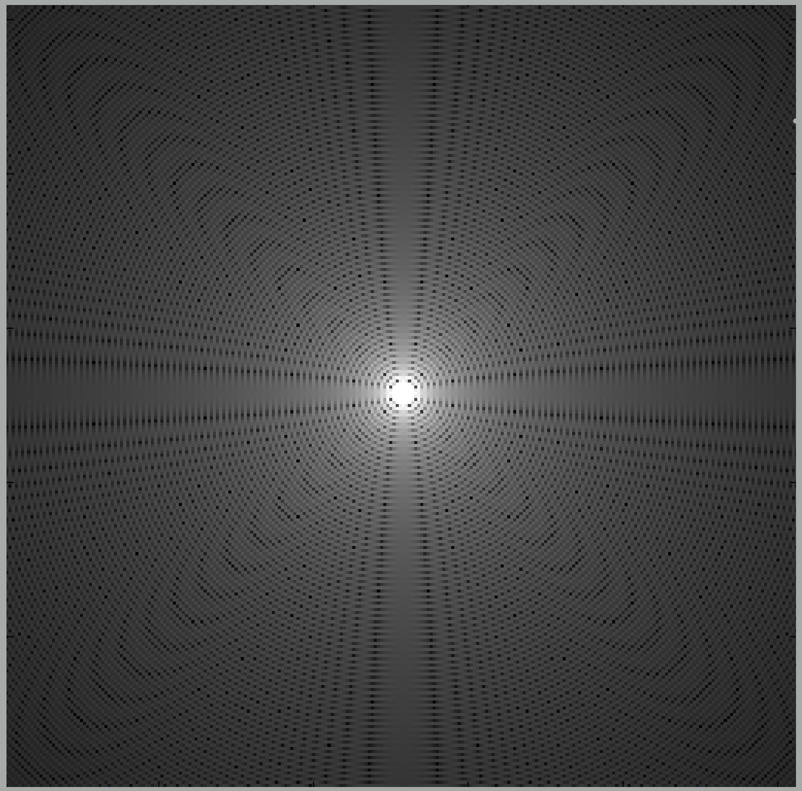
Processing strategy



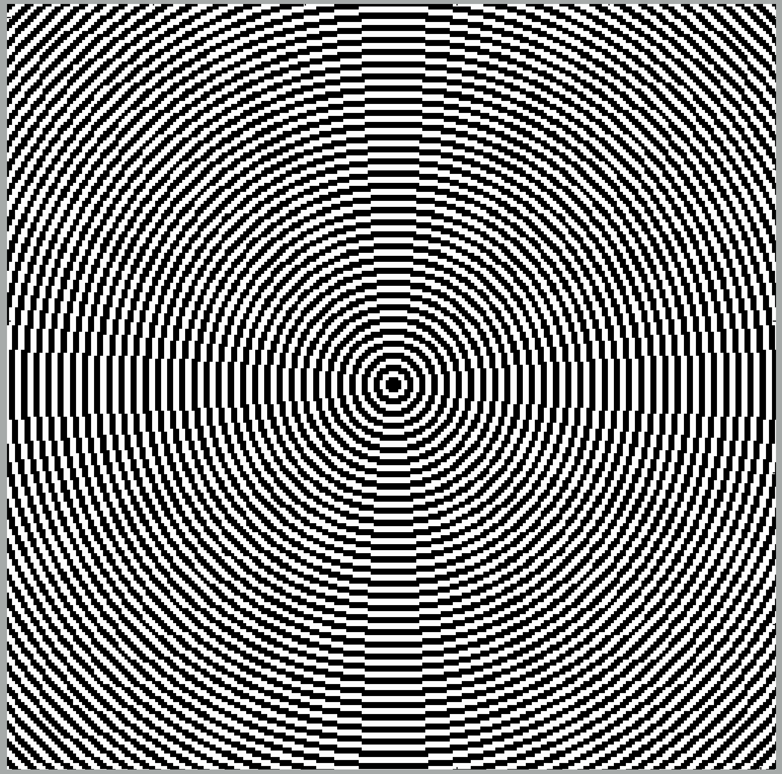
Diffusion induced phase changes



image

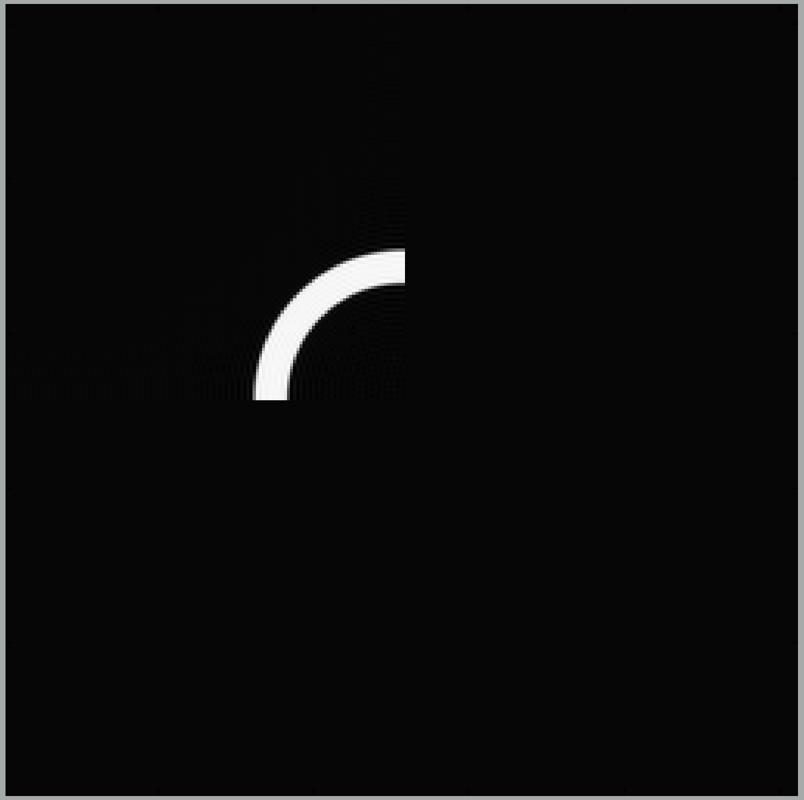


k-space magnitude

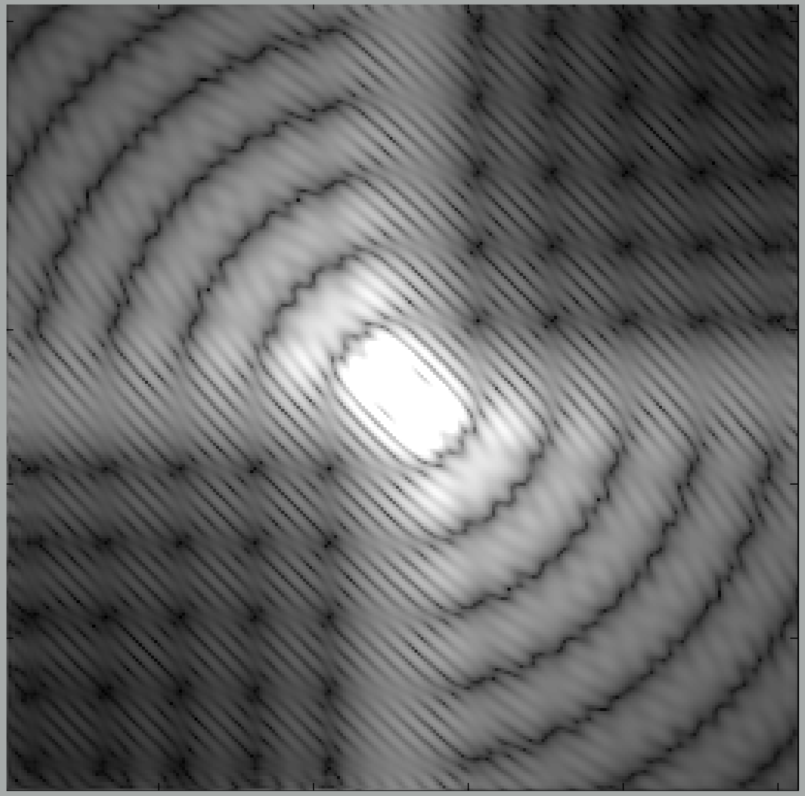


k-space phase

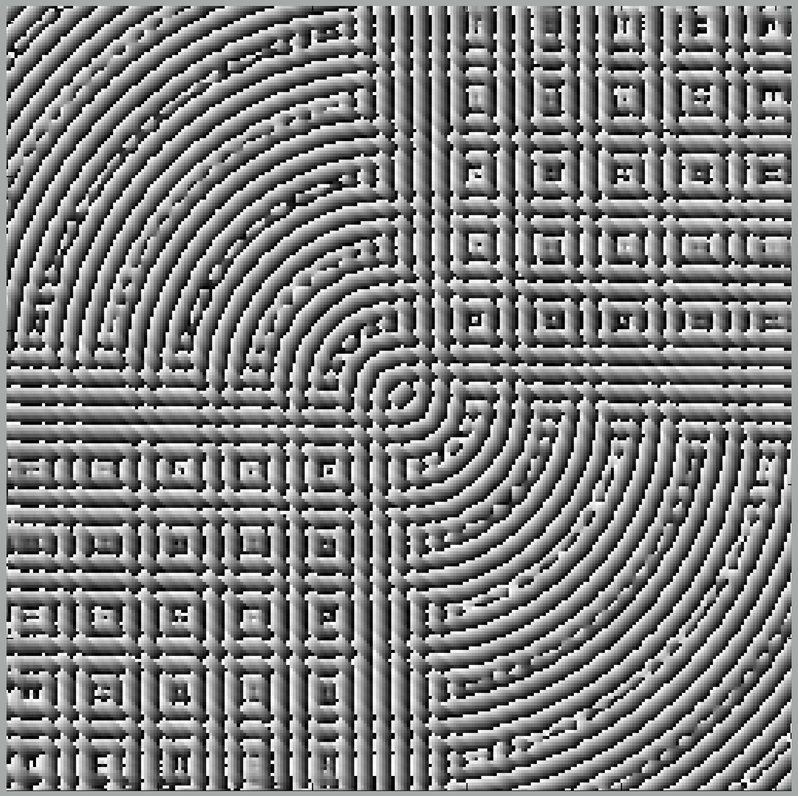
Diffusion induced phase changes



image

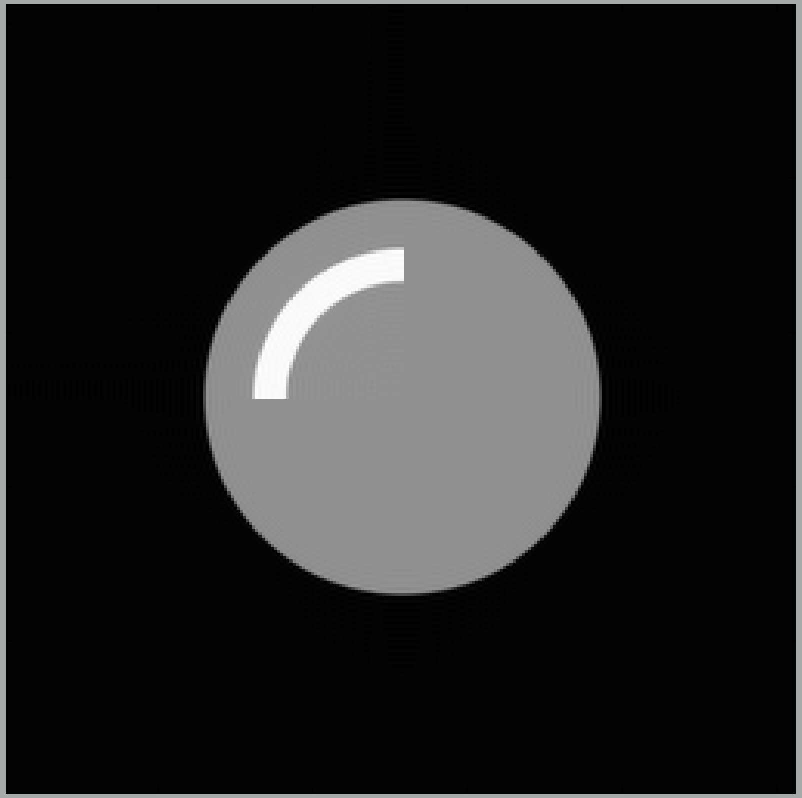


k-space magnitude

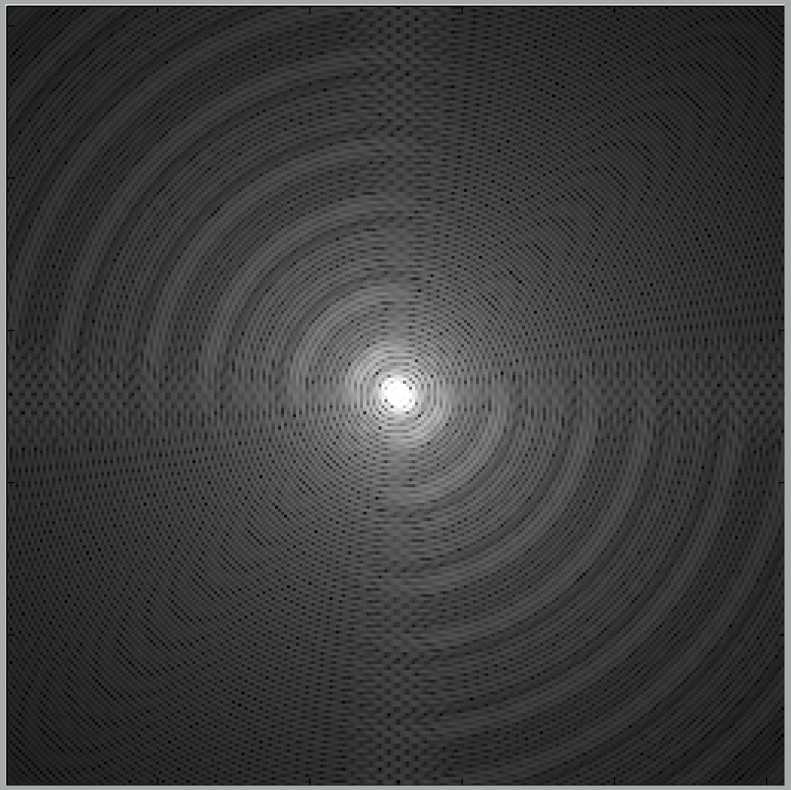


k-space phase

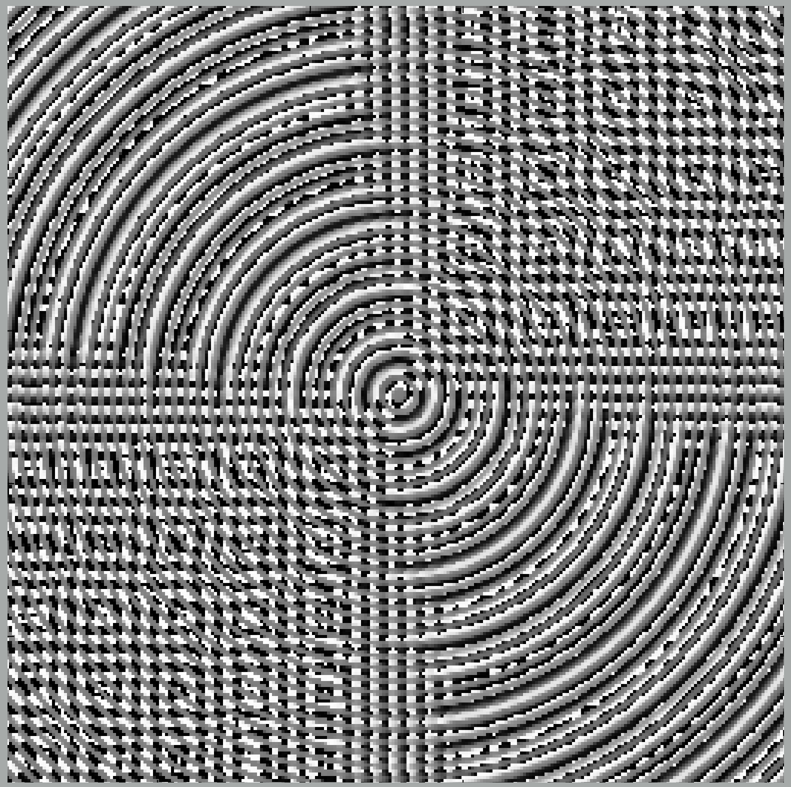
Diffusion induced phase changes



image

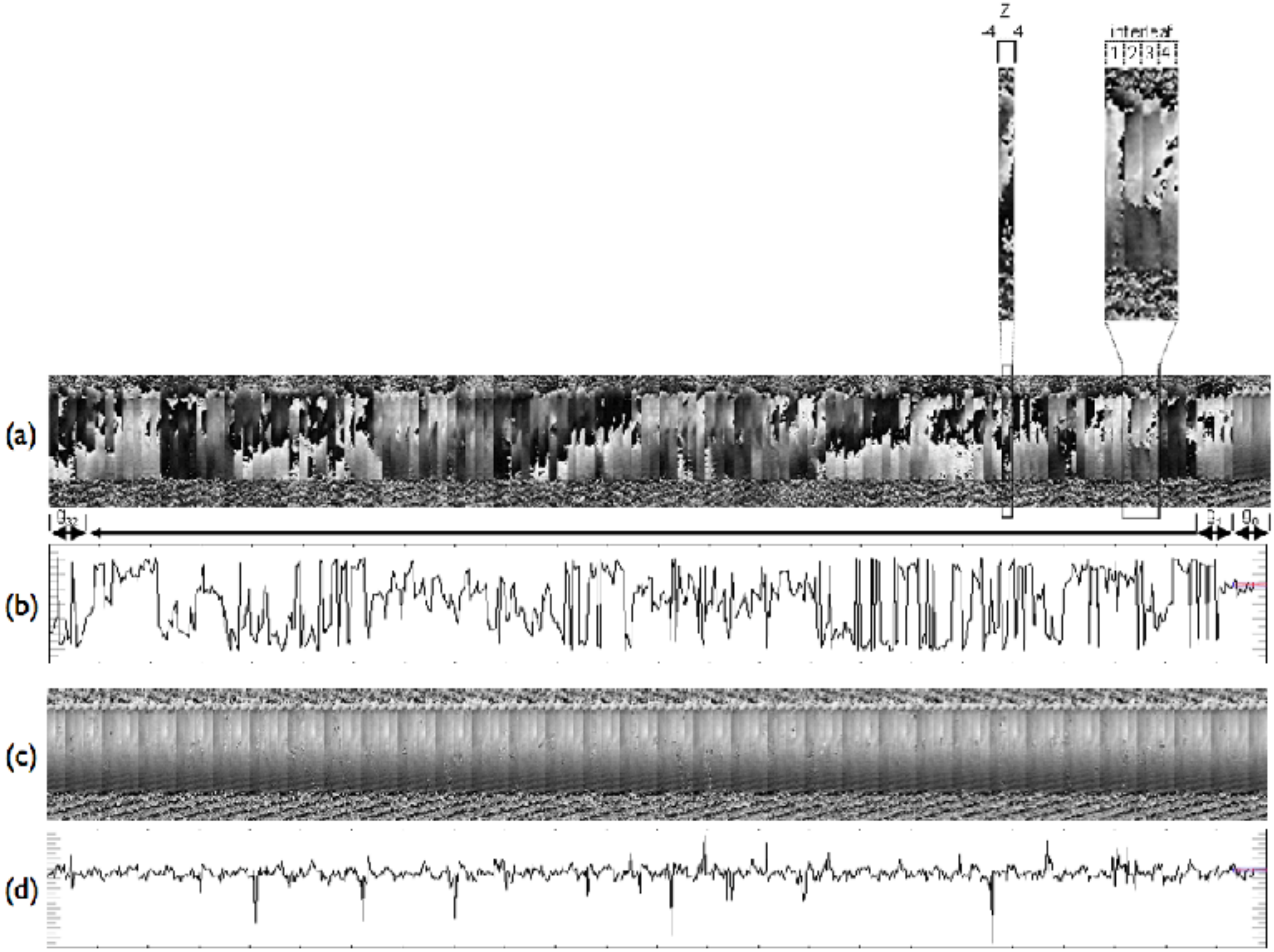


k-space magnitude

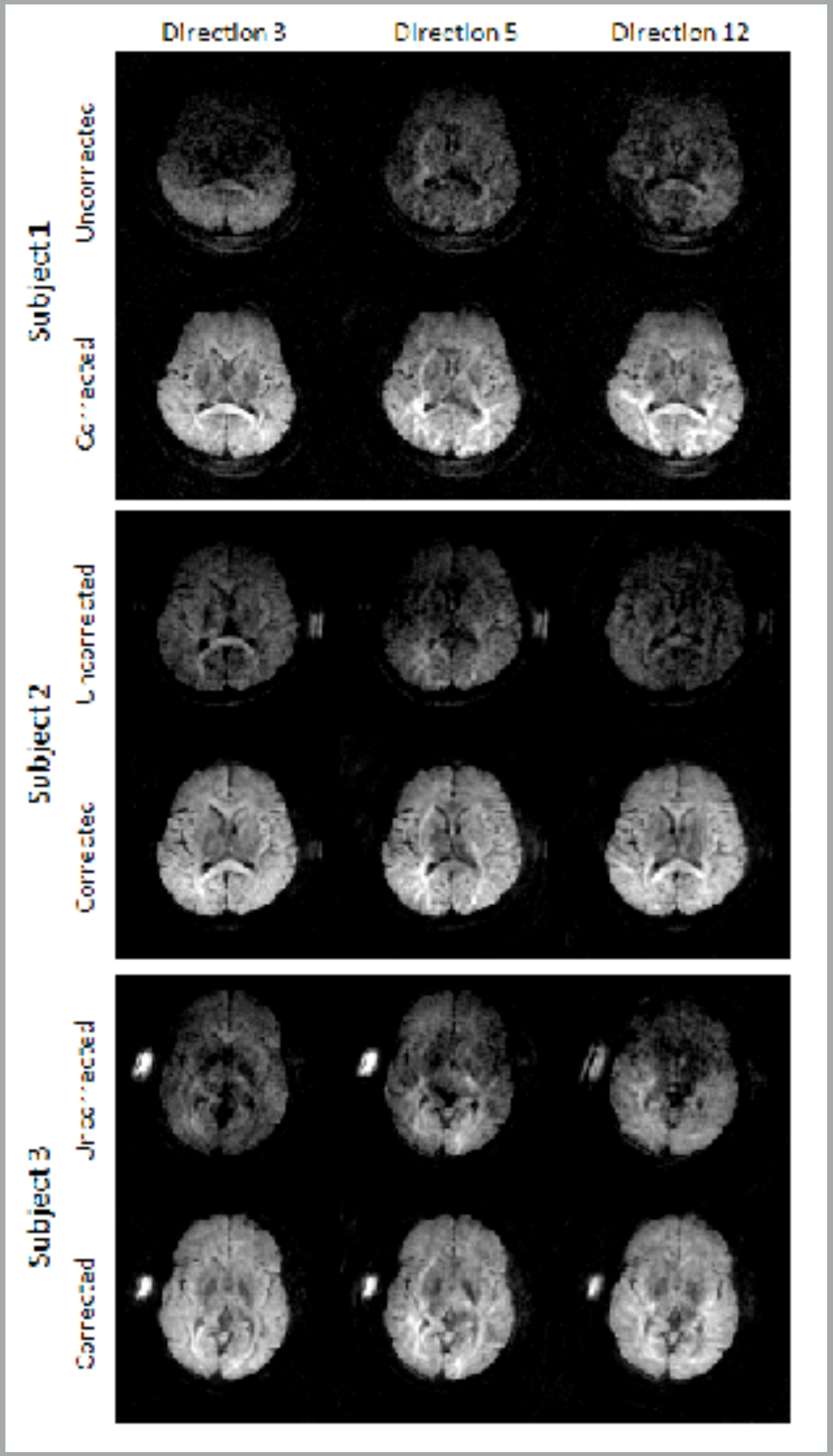


k-space phase

Processing results

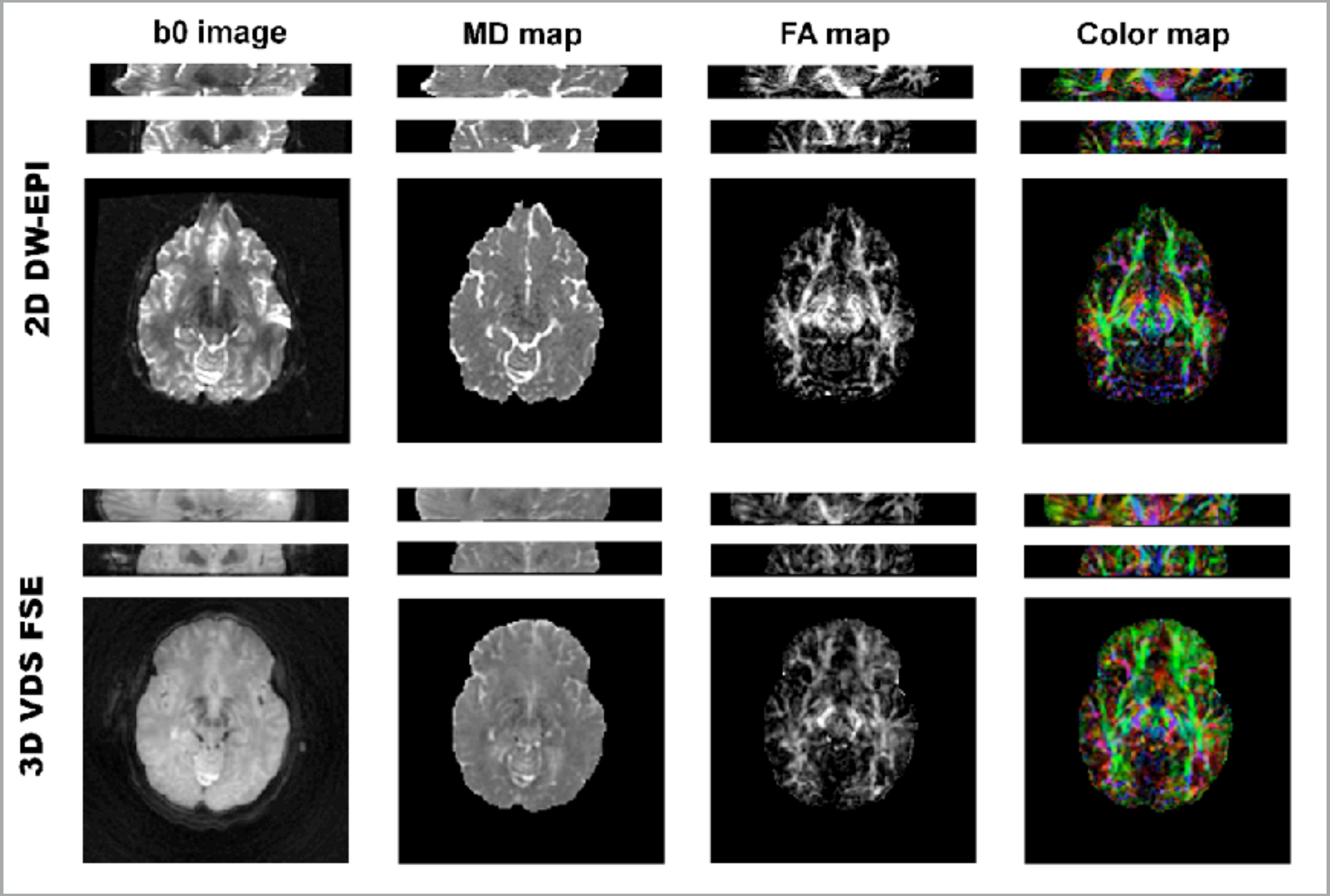


Processing results

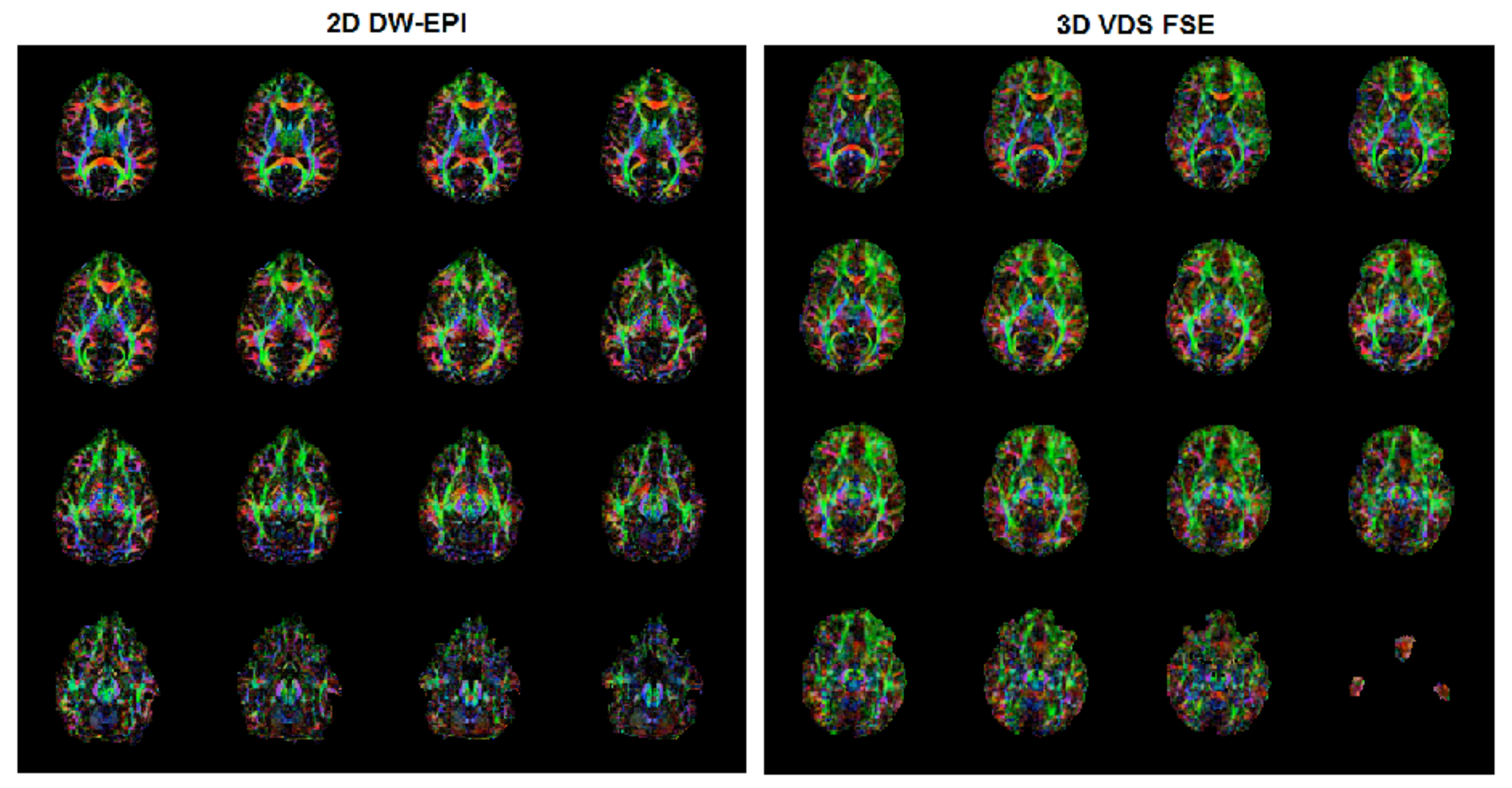


corrected images

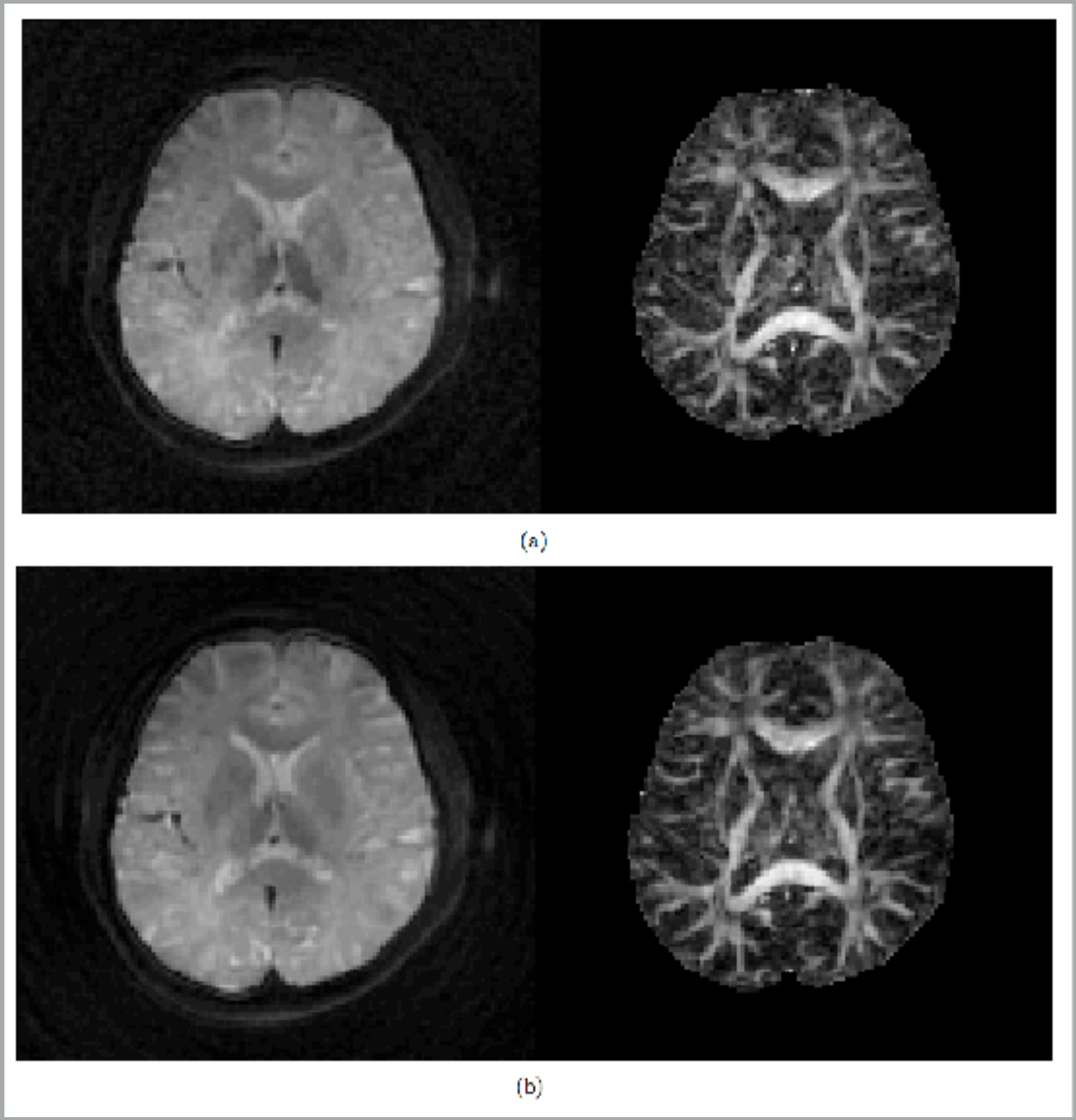
Processing results



Processing results



Efficiency



(a)

(b)

TR=1.0

TR=0.5