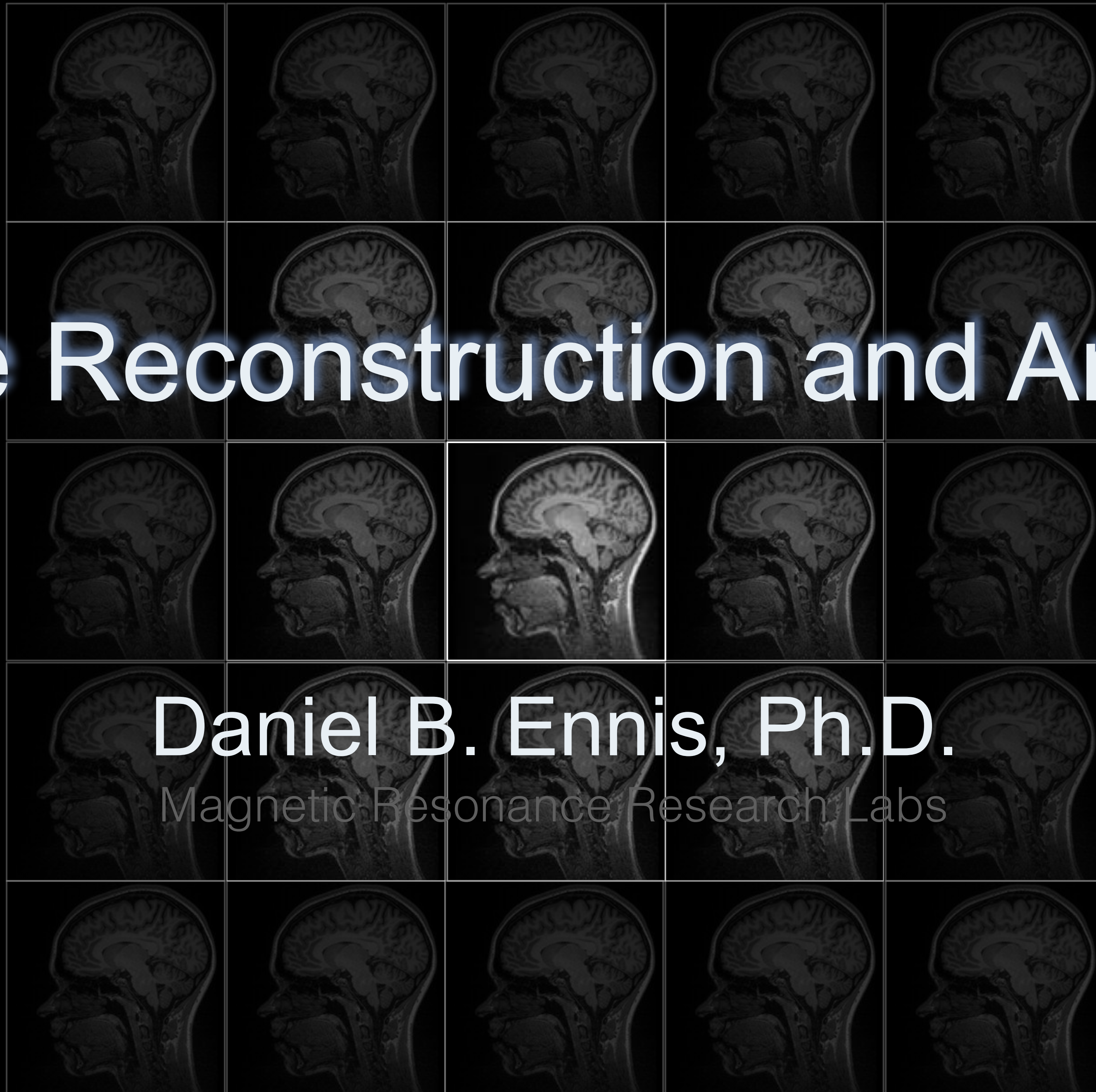
Image Reconstruction and Artifacts



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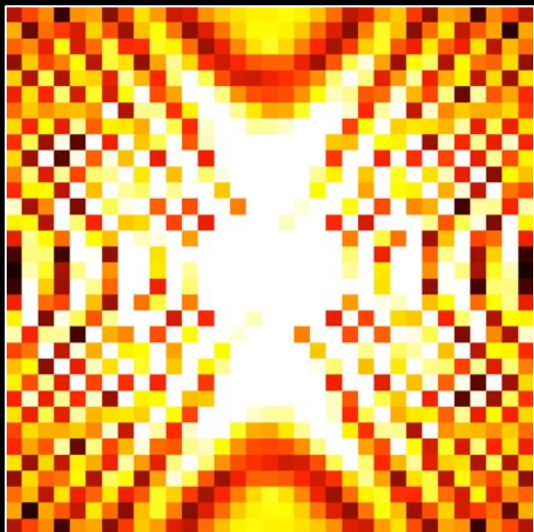
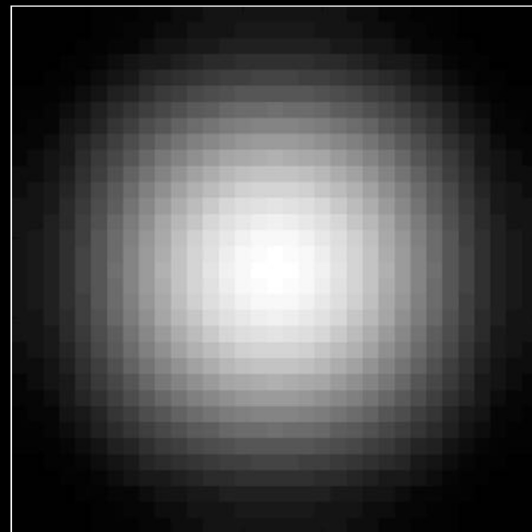
Lecture #13 - Learning Objectives

- **Understand how to combine data from several receiver channels.**
- **Appreciate how the final image is obtained from the sum over all sampled spatial frequency (Fourier) patterns.**
- **Define how the field-of-view and the number of acquired data points impacts spatial resolution.**
- **Describe the parameters that control the field of view.**
- **Understand the applications of zero padding and windowed reconstructions.**
- **Identify sources of Gibb's ringing and ways to mitigate it.**

Lecture #13 Summary



Dot Multiply



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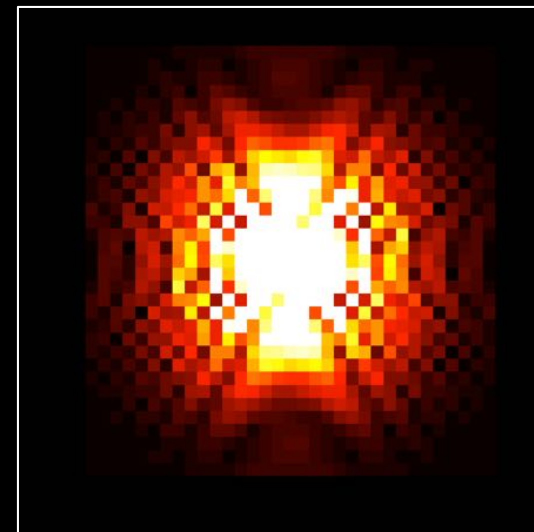


FFT

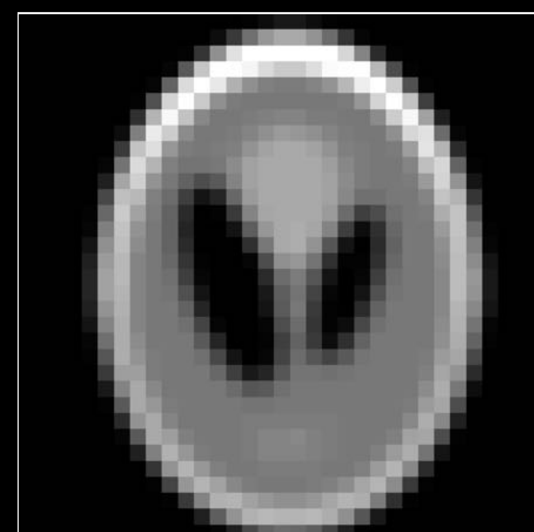
FFT

$$\hat{I}(x) = \Delta k \sum_{n=-N/2}^{N/2-1} S\left(n\Delta k\right) w_n e^{i2\pi n \Delta k x}$$

- $S\left(n\Delta k\right)$: Series Coefficient
- Δk: Fourier Step-size
- w_n: Window Weight
- $e^{i2\pi n \Delta k x}$: Spatial Frequency Encoding

On…

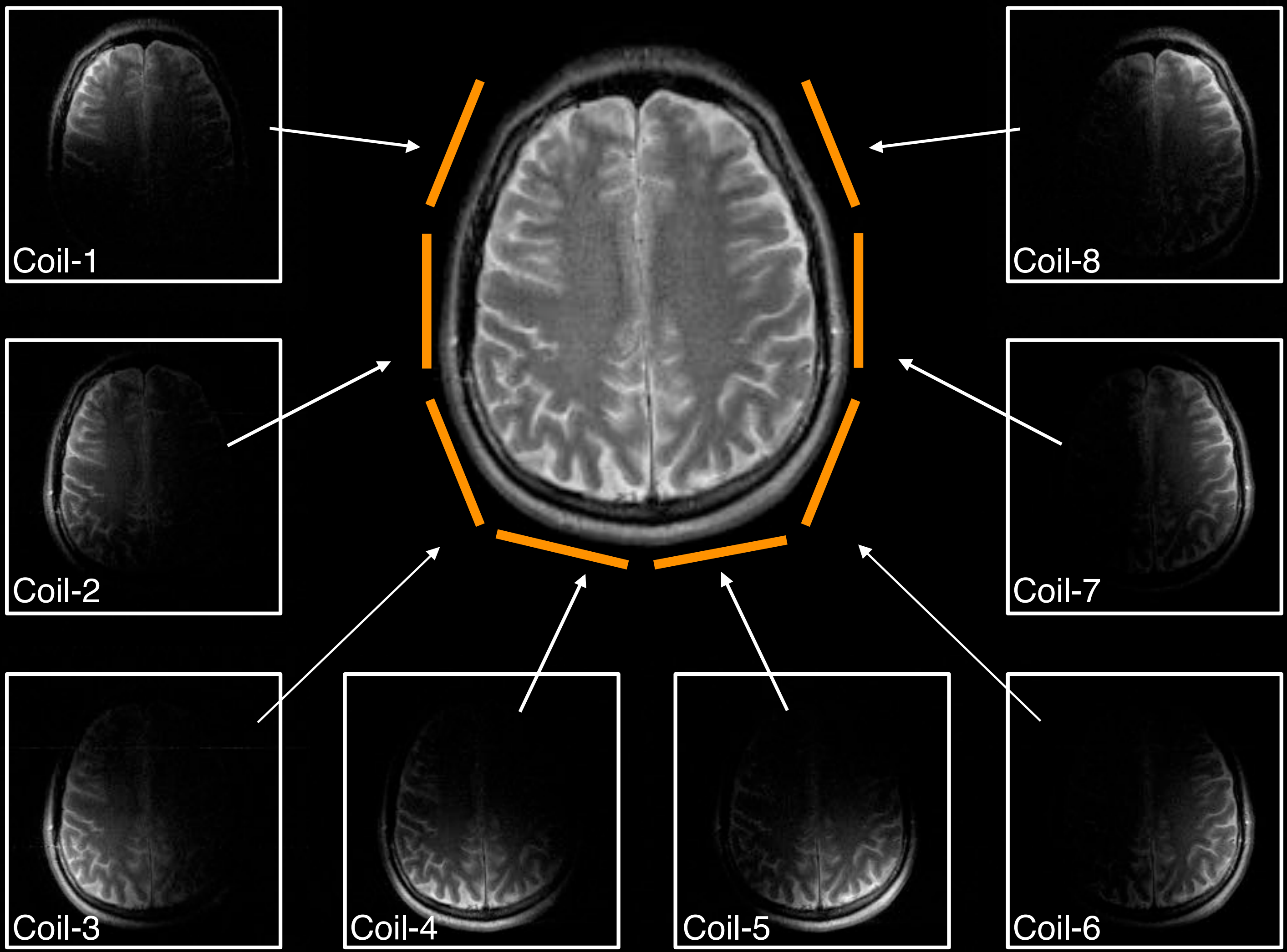
$$|x| < \frac{1}{\Delta k}$$



Fourier Reconstruction Formula (Eqn. 6.20)

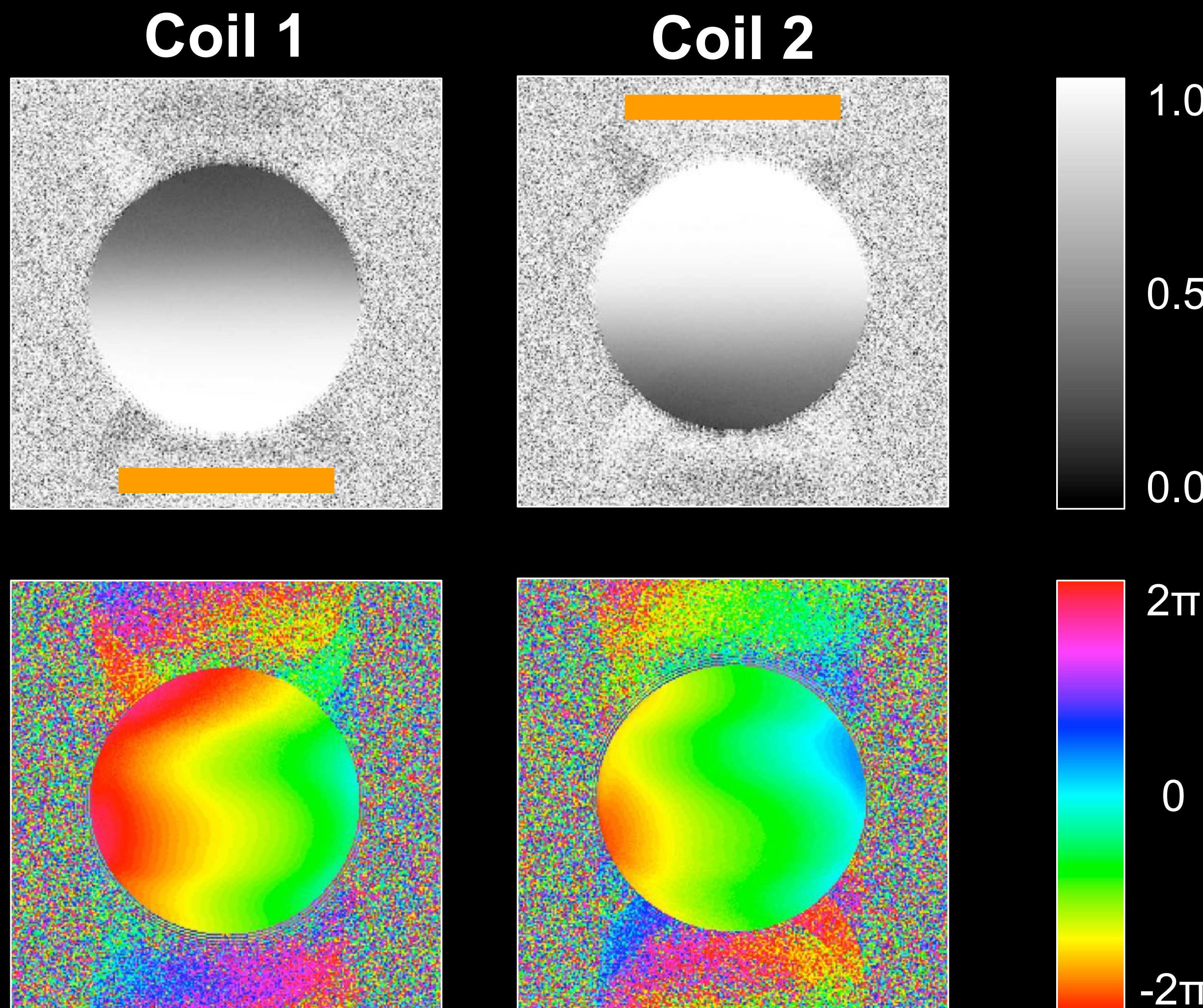
Multi-Channel Reconstruction

8-Channel Head Coil



Each coil element (channel) has a unique sensitivity profile – $\vec{B}_r\left(\vec{r}\right)$

Multi-coil Magnitude & Phase



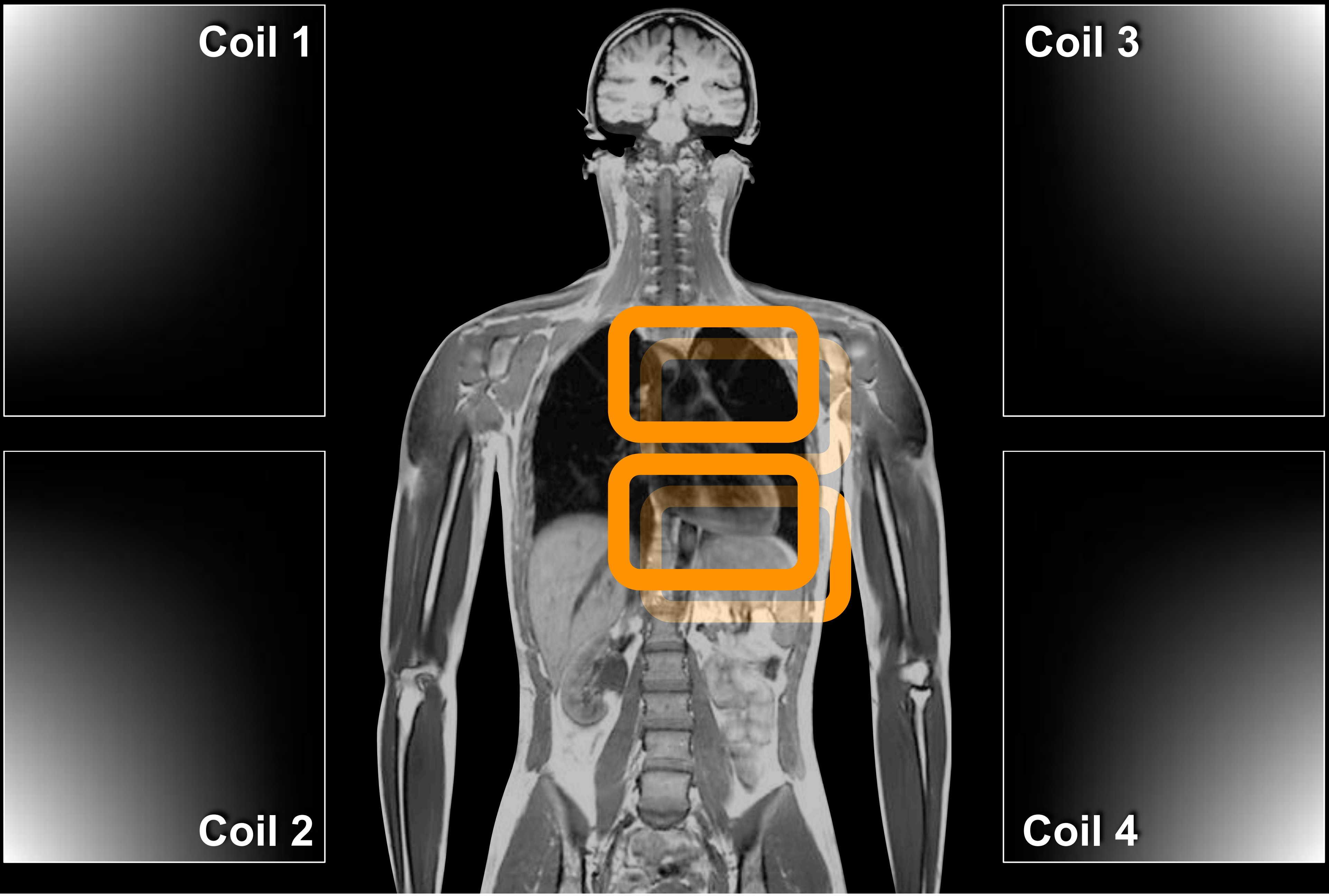
$$\|\vec{B}(\vec{r})\|$$

$$\angle\vec{B}(\vec{r})$$

Coils “color” the magnitude and phase of the received signal.

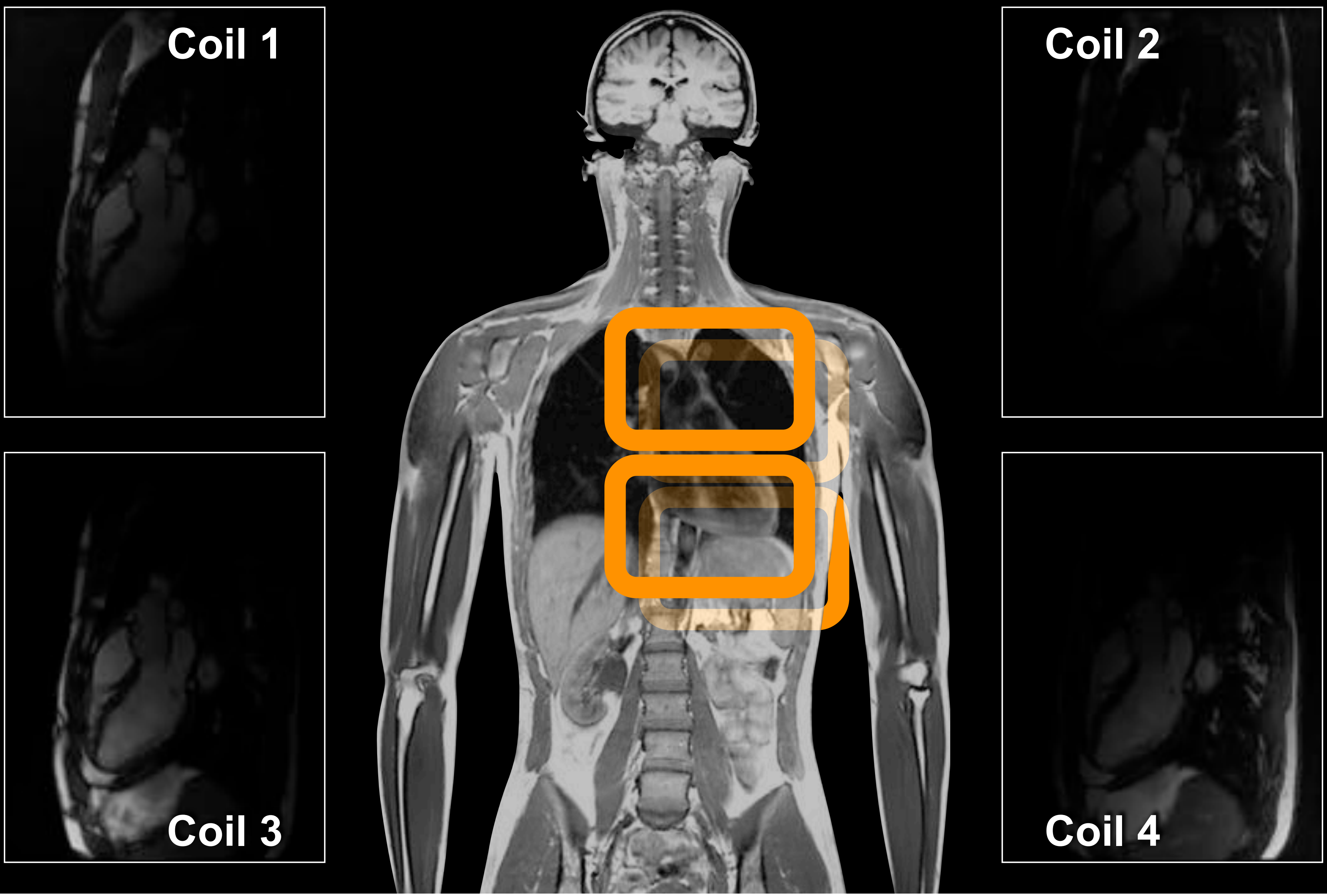
4-Channel Cardiac Coil

Each coil element has a unique sensitivity profile.



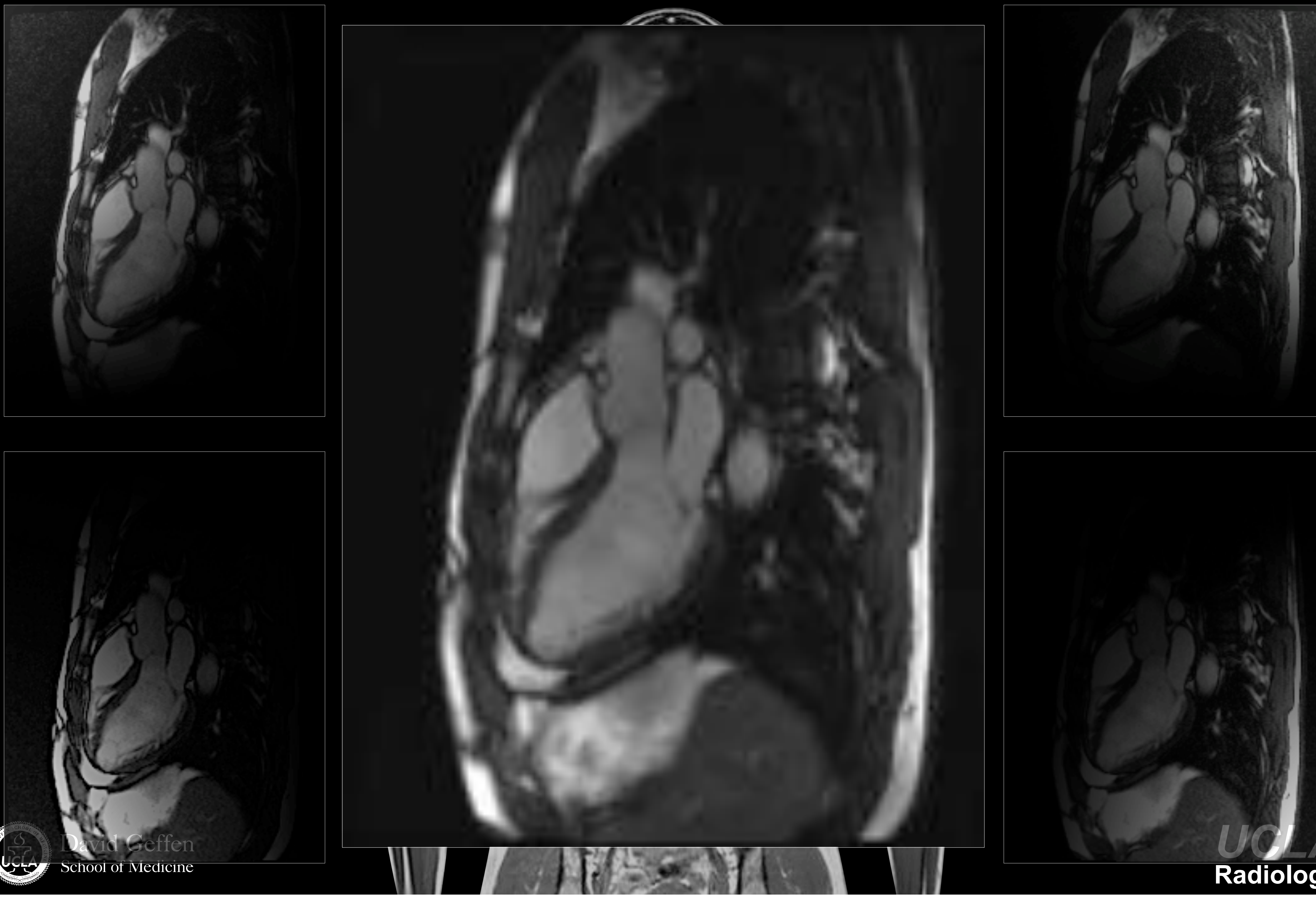
4-Channel Cardiac Coil

Each coil element has a unique sensitivity profile.

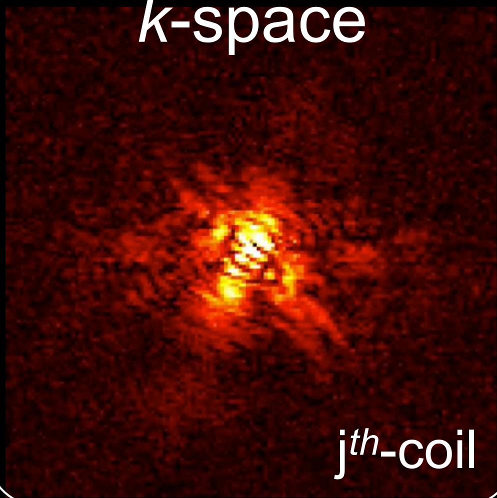


4-Channel Cardiac Coil

Coils are combined to form a single image.



Multiple Coil Reconstruction

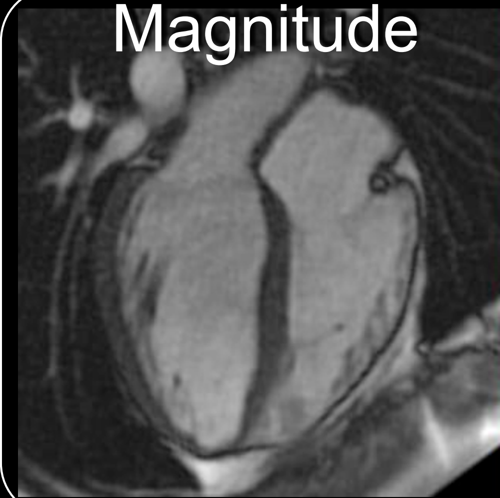


FFT^{-1} →

RMS

$$I(\vec{r}) = \sqrt{\sum_j \left(\frac{|I_j(\vec{r})|^2}{\sigma_j^2} \right)}$$

→



$I(\vec{r}) \longrightarrow$ Final ***magnitude*** image

$I_j(\vec{r}) \longrightarrow$ Image from jth coil

$\sigma_j^2 \longrightarrow$ Noise variance

- Depends on coil loading
- Proximity to patient
- Measured with “noise scan”
- Weights each coil’s contribution

Image Reconstruction

Image Reconstruction

$$S = \mathcal{T}\left\{I\right\}$$

Data Consistency Constraint

Measured Signal

Spatial Information Encoding Scheme (Fourier Transform)

Image Function

$$I = \mathcal{T}^{-1}\left\{S\right\}$$

Our task is to recover *I* from the measured signals.

MR Signal Equation

$$s\left(t\right) = \int\int_{x,y} \vec{M}^0_{xy}\left(\vec{r}\right) \cdot e^{-i\Delta\omega(\vec{r})t} \mathrm{d}\vec{r}$$

The MRI Signal Equation is the…

$$s\left(t\right) = \int\int_{x,y} \vec{M}^0_{xy}\left(x,y\right) \cdot e^{-i\Delta\omega(x,y)t} \mathrm{d}x\mathrm{d}y$$

…2D Fourier Transform!

$$\Delta\omega(x,y) = \gamma G_x \cdot x + \gamma G_y \cdot y$$

Gradients define Δw
(spatial frequencies)

$$k_x(t) = \frac{\gamma}{2\pi} G_x t \qquad k_y(t) = \frac{\gamma}{2\pi} G_y t$$

k-space is convenient…

$$s\left(k_x(t), k_y(t)\right) = \int\int_{x,y} \underbrace{\vec{M}^0_{xy}\left(x,y\right)}_{I\left(\vec{r}\right)} \cdot e^{-i2\pi[k_x(t)x + k_y(t)y]} \mathrm{d}x\mathrm{d}y$$

The acquired signal *is* the FT of the objects transverse magnetization.

Image Reconstruction

$$S[n] = \underbrace{S(n\Delta k_x)}_{\text{This is what we measure!}} = \int_{-\infty}^{+\infty} \underbrace{I(x)}_{\text{This is what we want!}} e^{-i2\pi n\Delta k_x \cdot x} dx$$

This is what we measure!

This is what we want!

Image Reconstruction

$$S[n] = \underbrace{S(n\Delta k_x)} = \int_{-\infty}^{+\infty} \underbrace{I(x)} e^{-i2\pi n\Delta k_x \cdot x} dx$$ Eqn. 6.9

This is what we measure!

This is what we want!

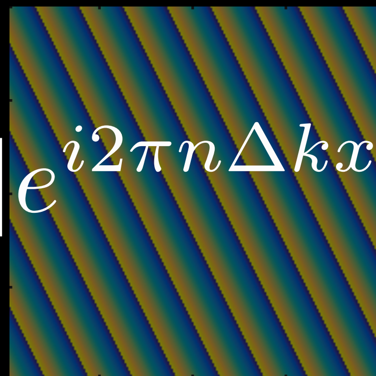
We can show the following...(Page 191 in Lauterbur).

$$\sum_{n=-\infty}^{\infty} S[n] e^{i2\pi n\Delta k x} = \frac{1}{\Delta k} \sum_{n=-\infty}^{\infty} I\left(x - \frac{n}{\Delta k}\right)$$ Eqn. 6.10

Fourier Series

Periodic Extension of I(x)

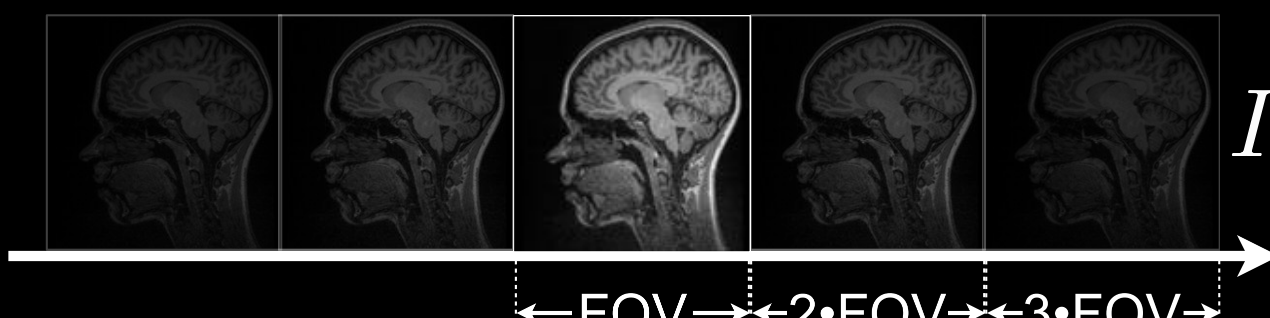
Image Reconstruction



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

- Fourier series
- Δk is the fundamental frequency
- S[n] coefficient of the n^{th} harmonic

- Periodic extension of $I(x)$
- n is an integer
- Period is $1/\Delta k$=FOV



$$I\left(x - \frac{n}{\Delta k}\right)$$

Periodic extensions of a object/function.

Finite Sampling

$S(k)$ is measured at $k \in \mathcal{D}$

$$\mathcal{D} = \{n\Delta k, -N/2 \leq n \leq +N/2\}$$

Fourier Step-size

Number of Sample Points

$$I(x) = \Delta k \sum_{n=-N/2}^{N/2-1} S[n]e^{i2\pi n \Delta k x}, \;\; |x| < \frac{1}{\Delta k}$$ Eqn. 6.20

This is the fundamental image reconstruction equation for MRI.

Spatial Resolution

Spatial Resolution

- **Spatial resolution of an imaging system is the smallest separation δx of two point sources necessary for them to remain resolvable in the resultant image.**

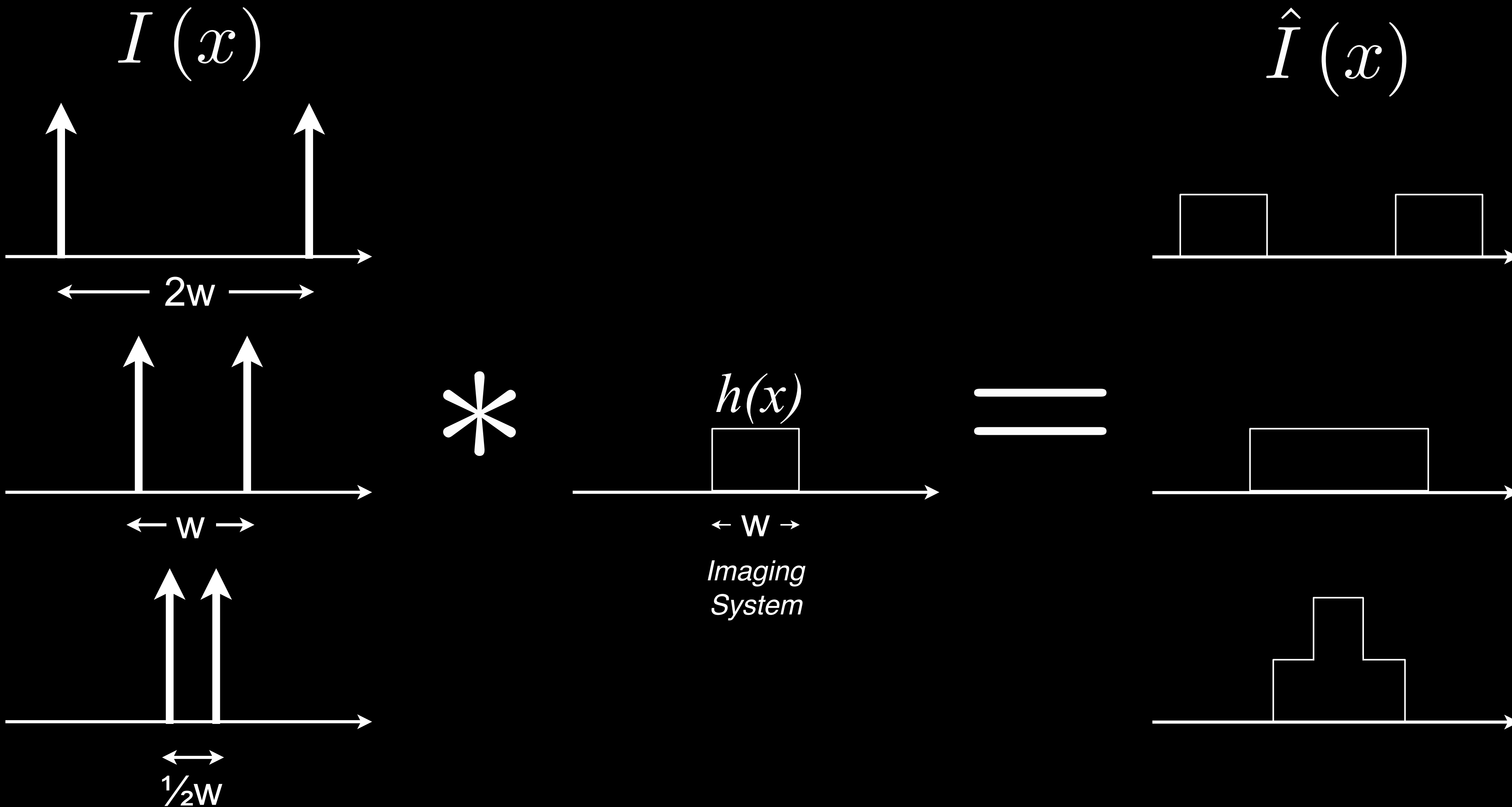
$$\hat{I}\left(x\right) = I\left(x\right) * h\left(x\right)$$

Image

Object

Point Spread Function

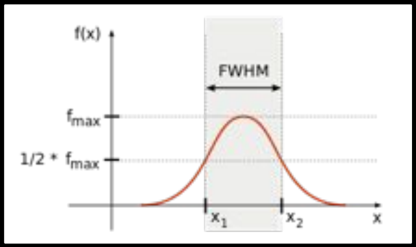
Spatial Resolution



$$\hat{I}(x) = I(x), \text{ if and only if } h(x) = \delta(x)$$

Spatial Resolution

- **The resolution limit of an imaging system is the width (W_h) of its point spread function:**
  - W_h **is the full-width half-max of** $h(x)$



- **Alternately,**
  - W_h **of** $h(x)$ **is the width of an approximating box-function with the same height and area as** $h(x)$**:**

$$W_h = \frac{1}{h_{max}} \int_{-\infty}^{+\infty} h(x)dx$$

Fourier Reconstruction PSF

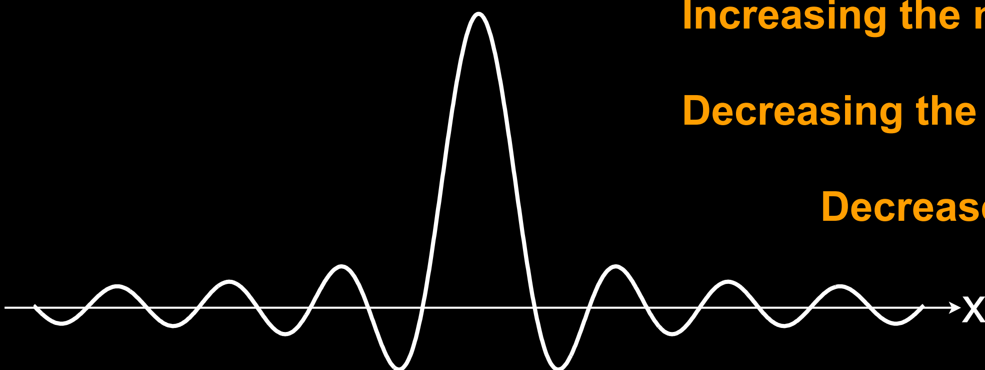
$$h(x) \approx \Delta k \frac{\sin(\pi N \Delta k x)}{\sin(\pi \Delta k x)} = Dir\left(N, \chi\right) \quad \text{Eqn. 8.7}$$

This is the approximate PSF for Fourier sampling.

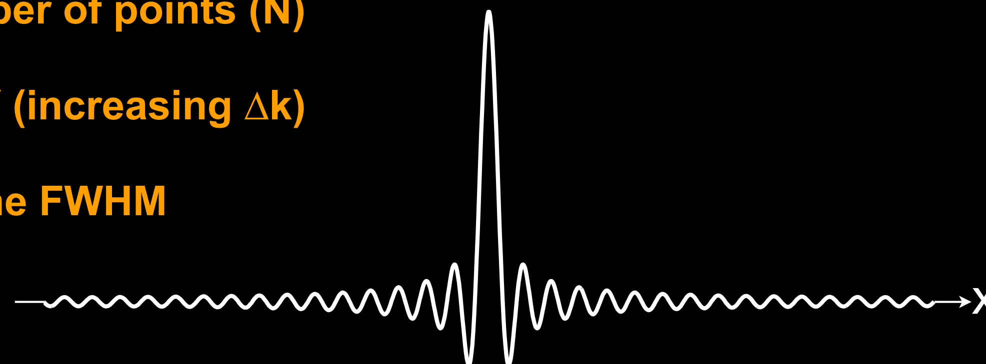
Dirichlet Function

Increasing the number of points (N)
-or-
Decreasing the FOV (increasing Δk)

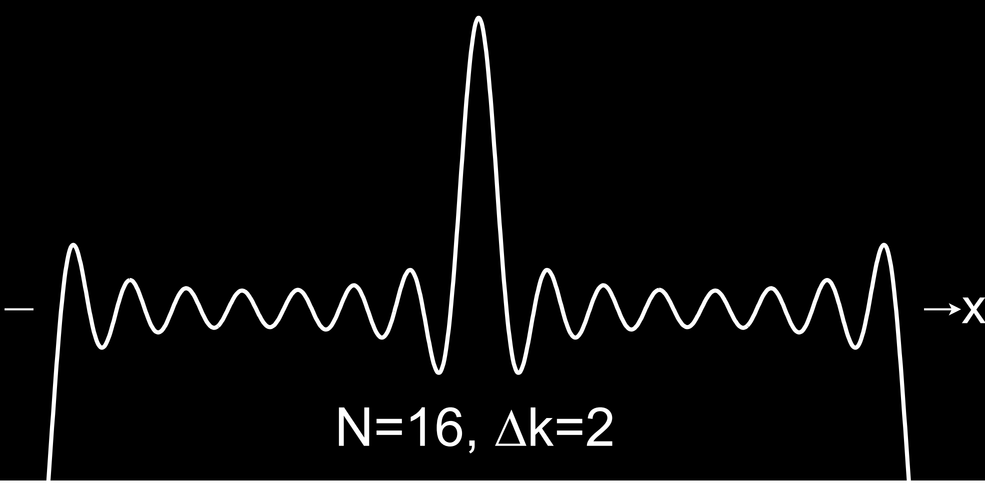
Decreases the FWHM



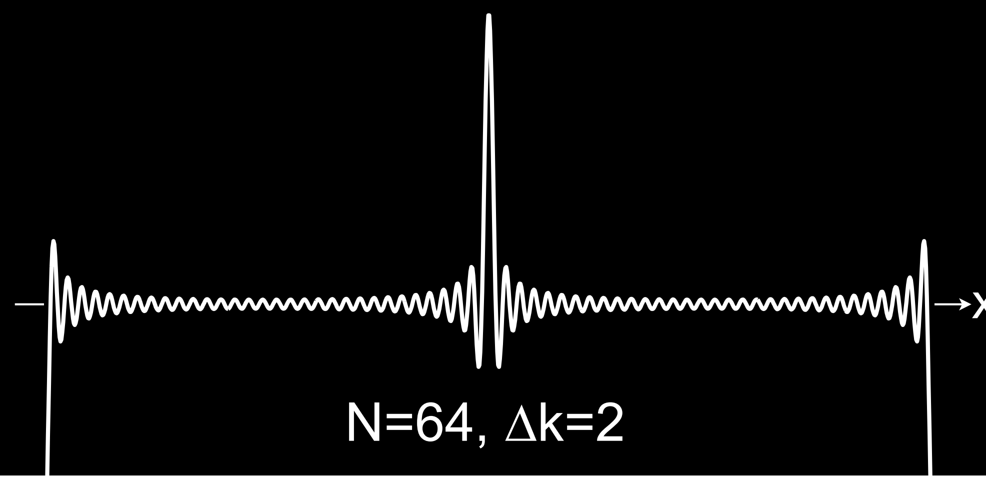
N=16, Δk=1



N=64,Δk=1



N=16, Δk=2



N=64, Δk=2

Fourier Reconstruction PSF

$$W_h = \frac{1}{h_{max}} \int_{-\frac{1}{2\Delta k}}^{\frac{1}{2\Delta k}} h(x)dx = \frac{1}{N\Delta k}$$

Limits over a single period

Fourier Pixel Size (Δx_F)

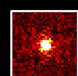
$$W_h = \frac{1}{N\Delta k} = \frac{FOV}{N}$$

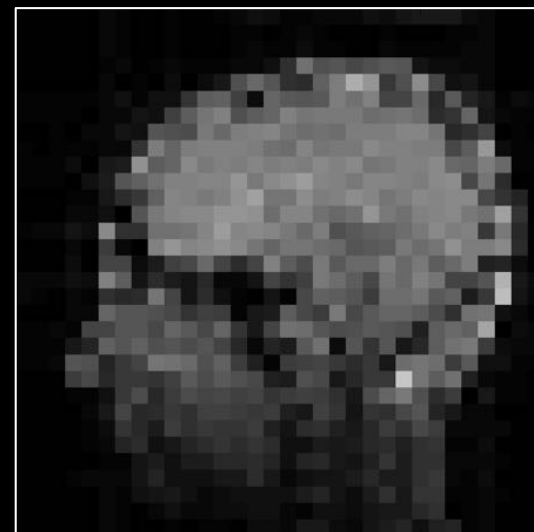
Note, we can't reduce W_h and N simultaneously, therefore

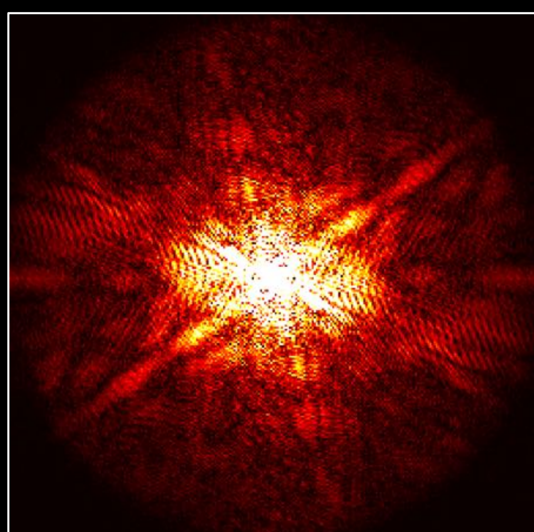
- An increase in spatial resolution (decrease in W_h) requires an increase in N or Δk (decrease in FOV)
- A decrease in spatial resolution (increase in W_h) requires a decrease in N or Δk (increase in FOV)

Finite Sampling

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

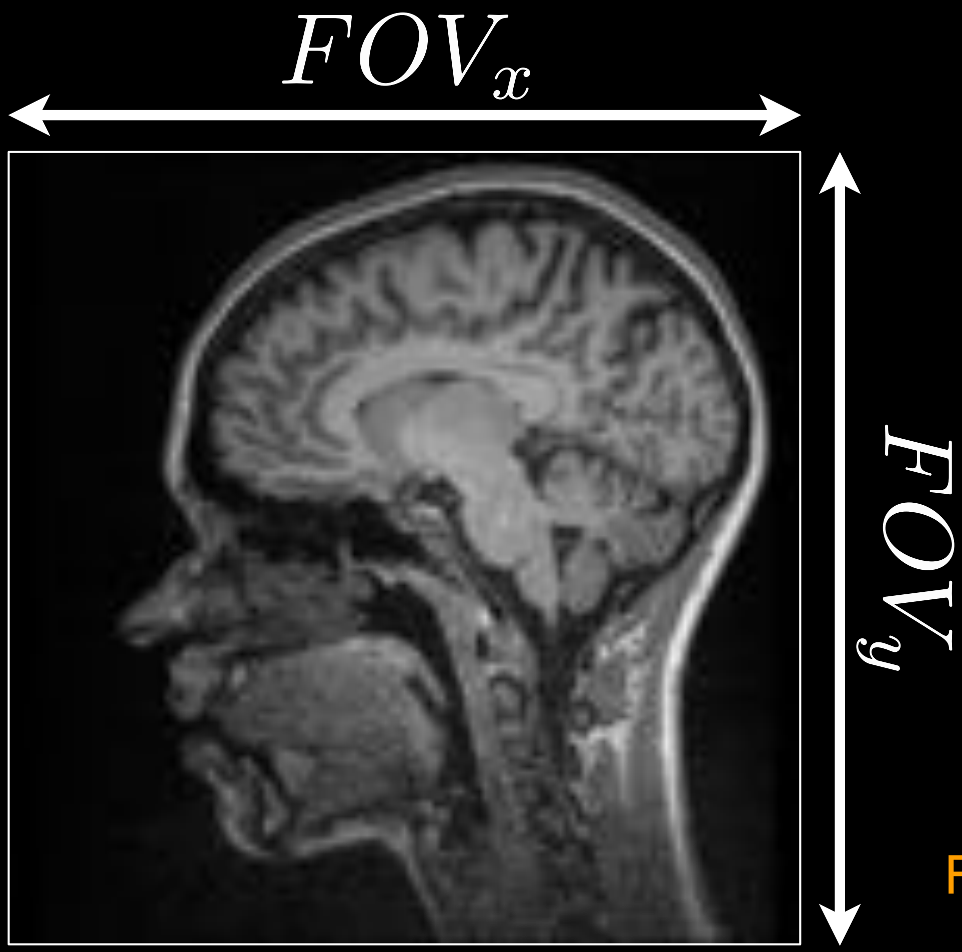






What is the same between the two acquisitions? Different?

Field of View



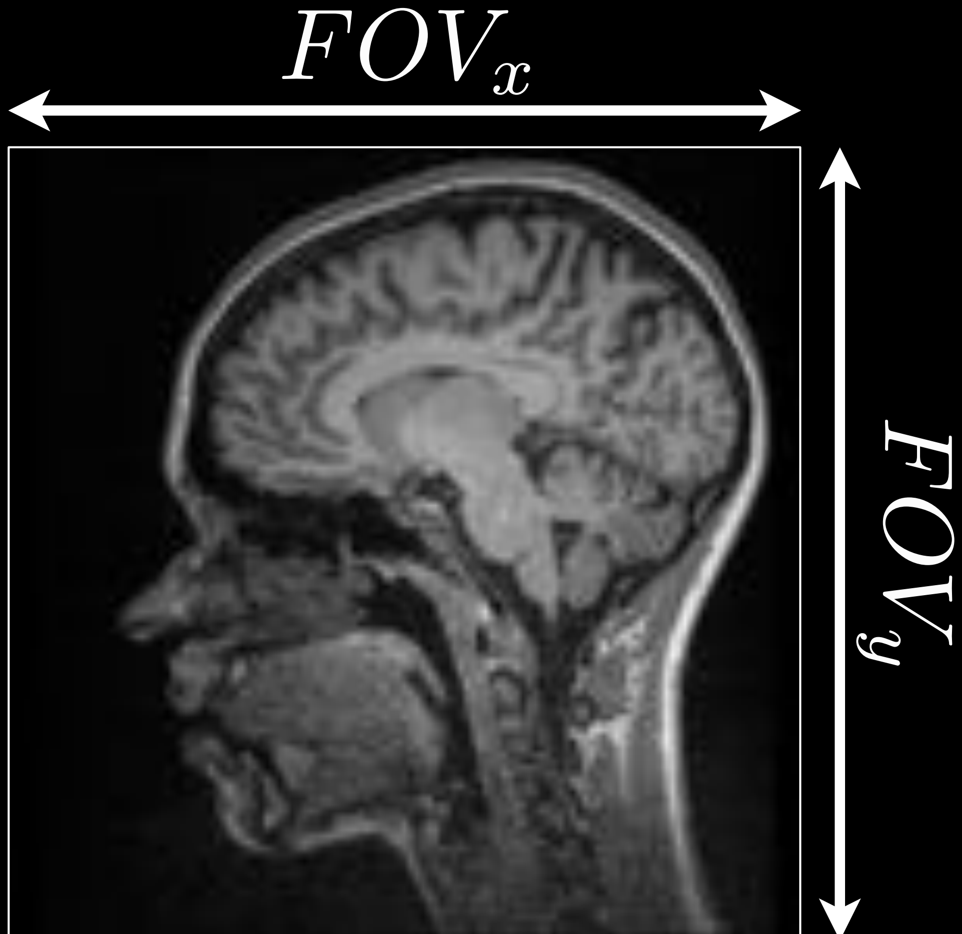
$$\Delta k_x = \frac{1}{\mathrm{FOV}_x} = \gamma |\mathbf{G}_x| \Delta t$$ Eqn. 5.123

FOV constraints during readout.

$$\Delta k_y = \frac{1}{\mathrm{FOV}_y} = \gamma \Delta \mathbf{G}_y T_{pe}$$ Eqn. 5.123

FOV constraints during phase encoding.

Field of View



$$\Delta k_x = \frac{1}{\text{FOV}_x} = \gamma |\mathbf{G}_x| \Delta t$$

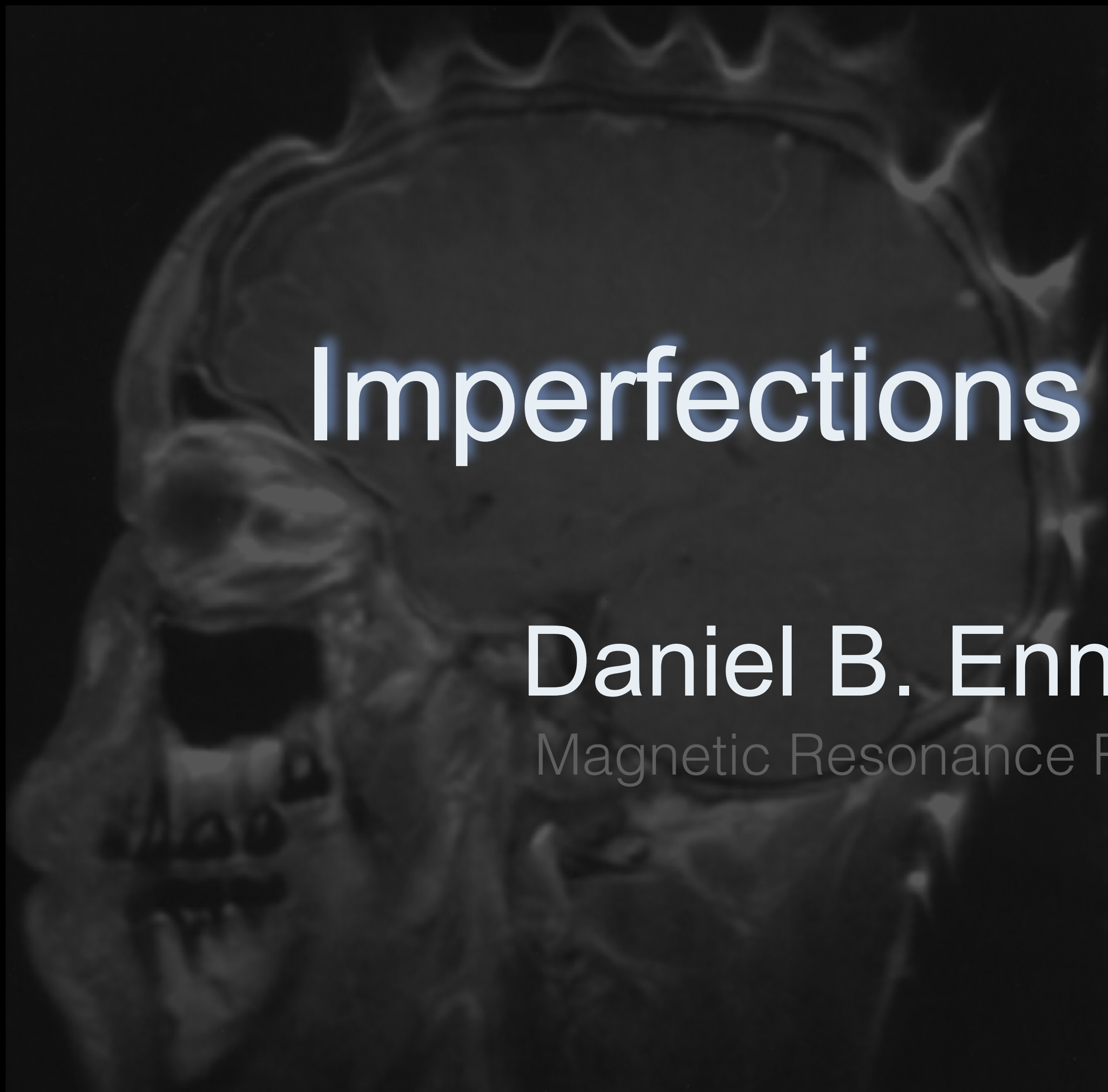
Eqn. 5.123

$$\Delta k_y = \frac{1}{\text{FOV}_y} = \gamma \mathbf{\Delta G}_y T_{pe}$$

$$\Delta t = \frac{1}{\gamma |\mathbf{G}_x| \text{FOV}_x}$$

Eqn. 5.124

$$\Delta \mathbf{G}_y = \frac{1}{\gamma T_{pe} \text{FOV}_y}$$



Imperfections & Artifacts

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http://www.ajronline.org/doi/pdf/10.2214/ajr.182.2.1820532

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Lecture #14 - Learning Objectives

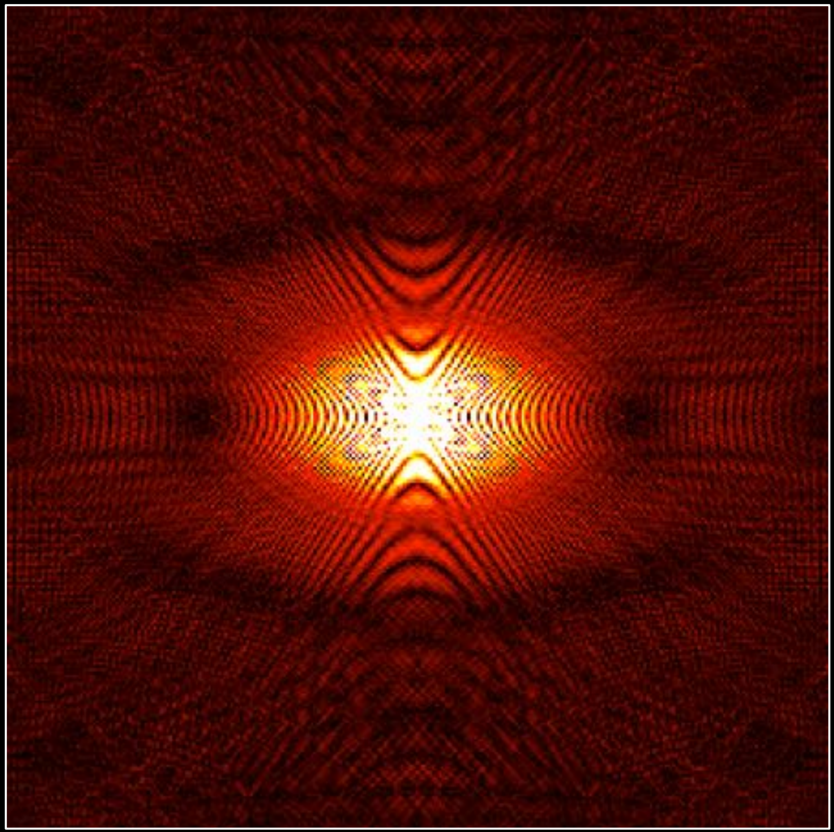
- Describe the origin and correction for several artifacts.
- Understand the impact of spatial resolution and scan time on signal-to-noise ratio.
- Explain the importance of readout bandwidth and the +/- of high (or low) readout bandwidth.
- Define the origin, artifact, and possible correction for chemical shift artifacts.
- Appreciate why motion causes image artifacts in MRI
- Be able to identify several artifacts in an MR image.

Gibb’s Ringing

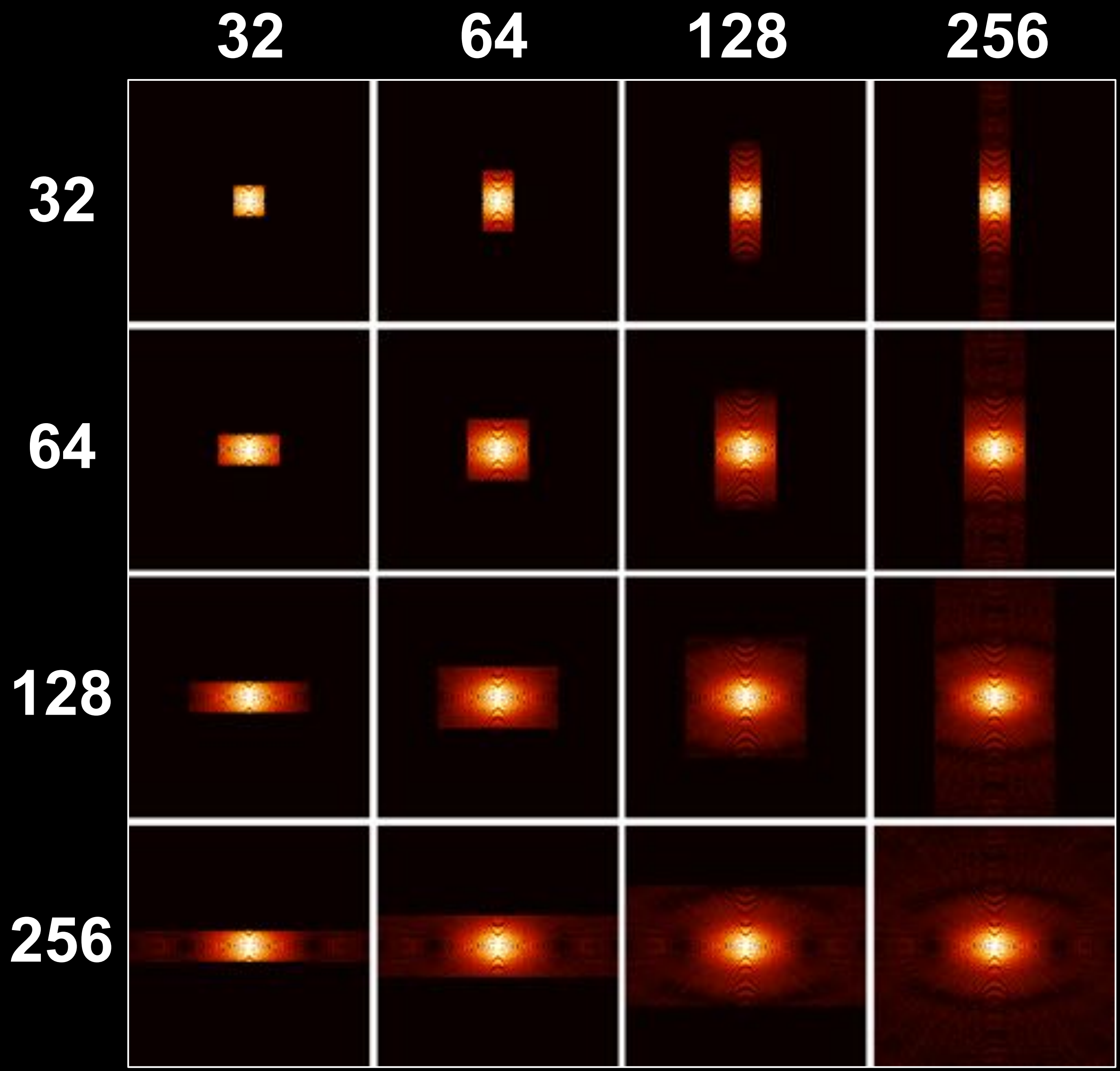
Gibb's Ringing

- Spurious ringing around sharp edges
- Max/Min overshoot is ~9% of the intensity discontinuity
  - Independent of the # of recon points
  - Frequency of ringing increases as # of recon points increases
    - Ringing becomes less apparent
- Result of truncating the Fourier series model as a consequence of finite sampling
- Can reduce by:
  - Acquiring more data
  - Filtering the data which reduces oscillations in the PSF

Shepp-Logan

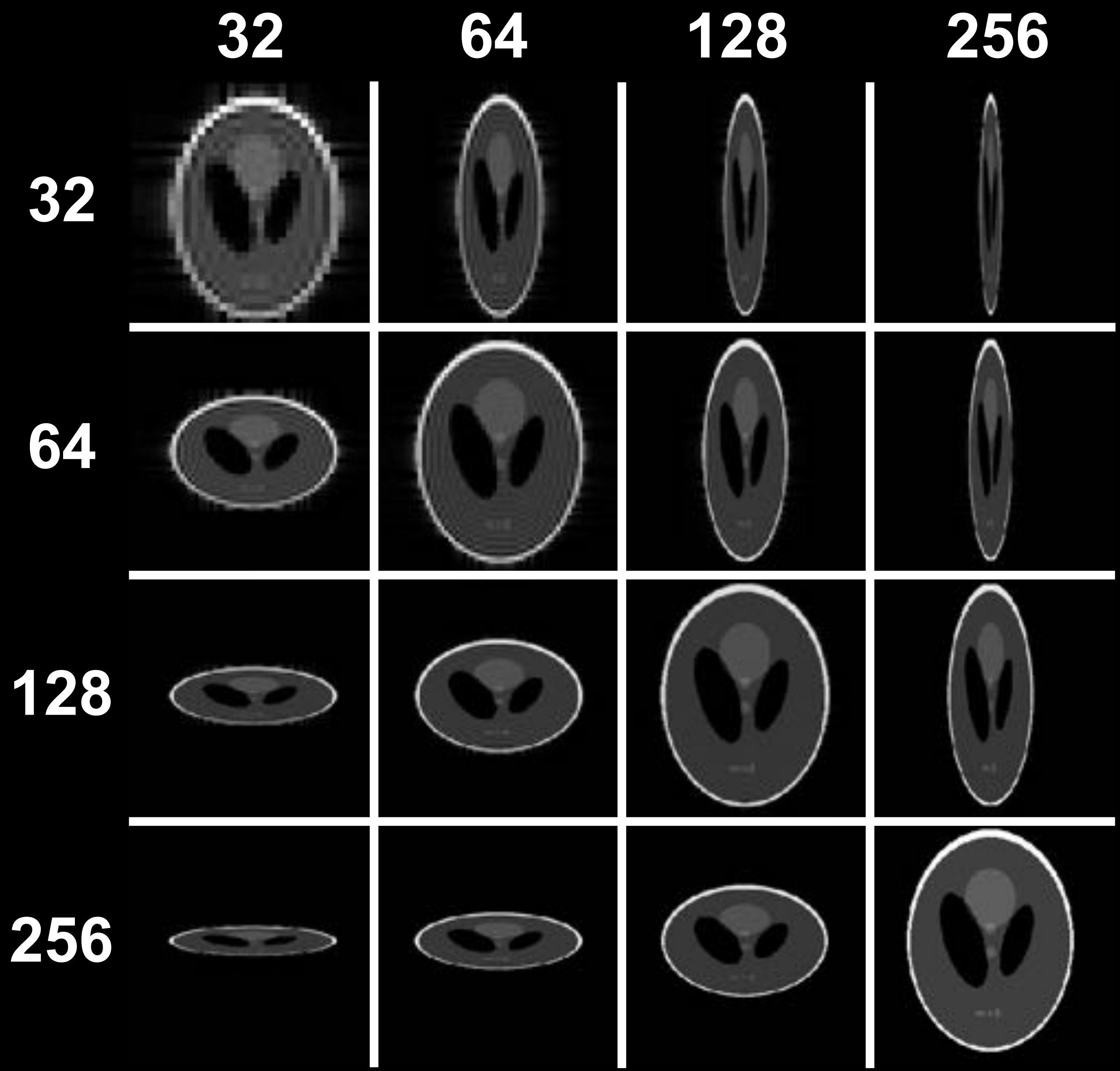


Gibb's Ringing



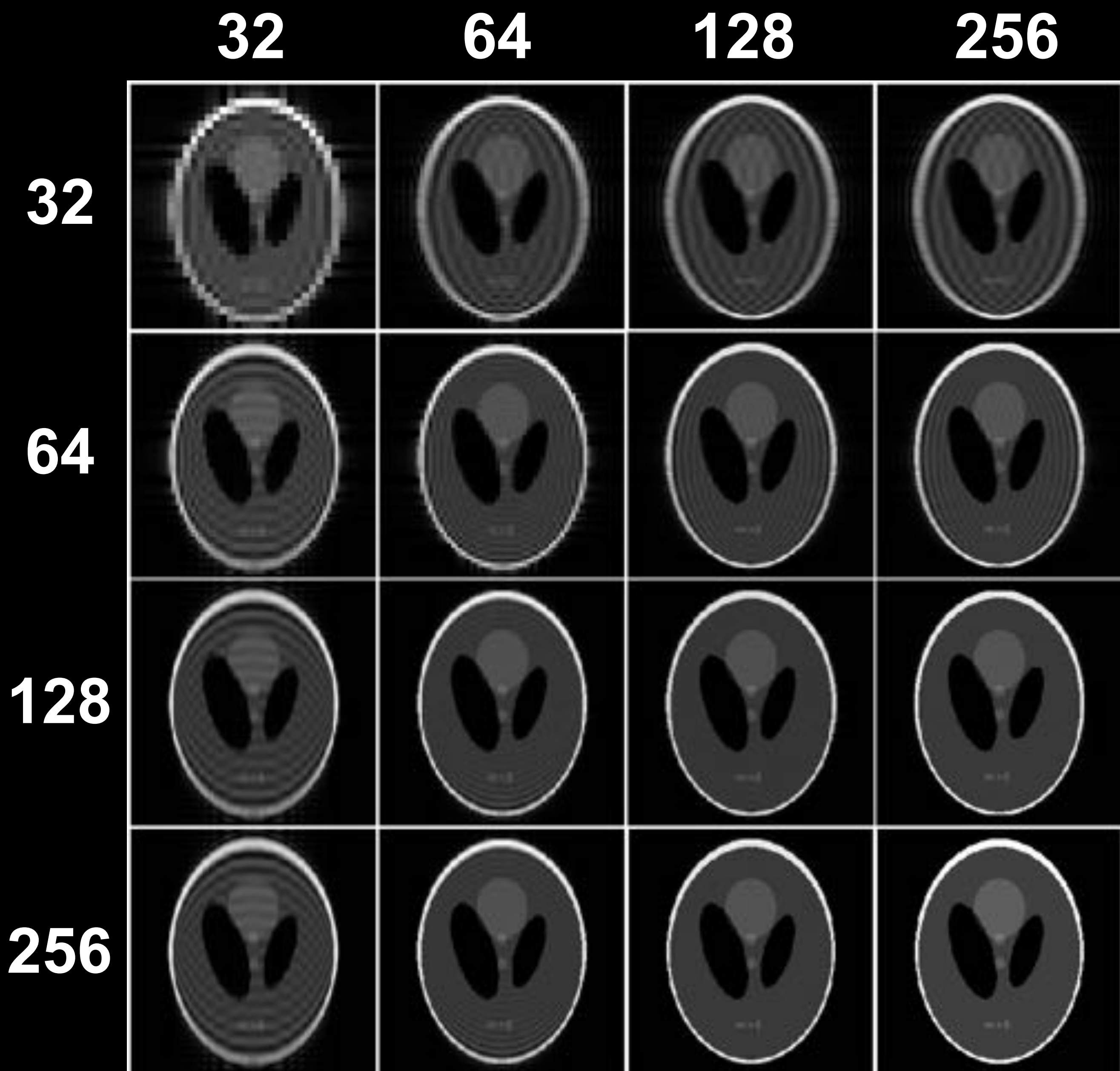
What is the difference between these acquisitions?

Gibb's Ringing



Why do the images look like this?

Zero-Pad



Windowed Reconstruction

Windowed Reconstruction

$$\hat{I}(x) = \Delta k \sum_{n=-N/2}^{N/2-1} S\left(n\Delta k\right) e^{i2\pi n\Delta kx}$$

Fourier reconstruction

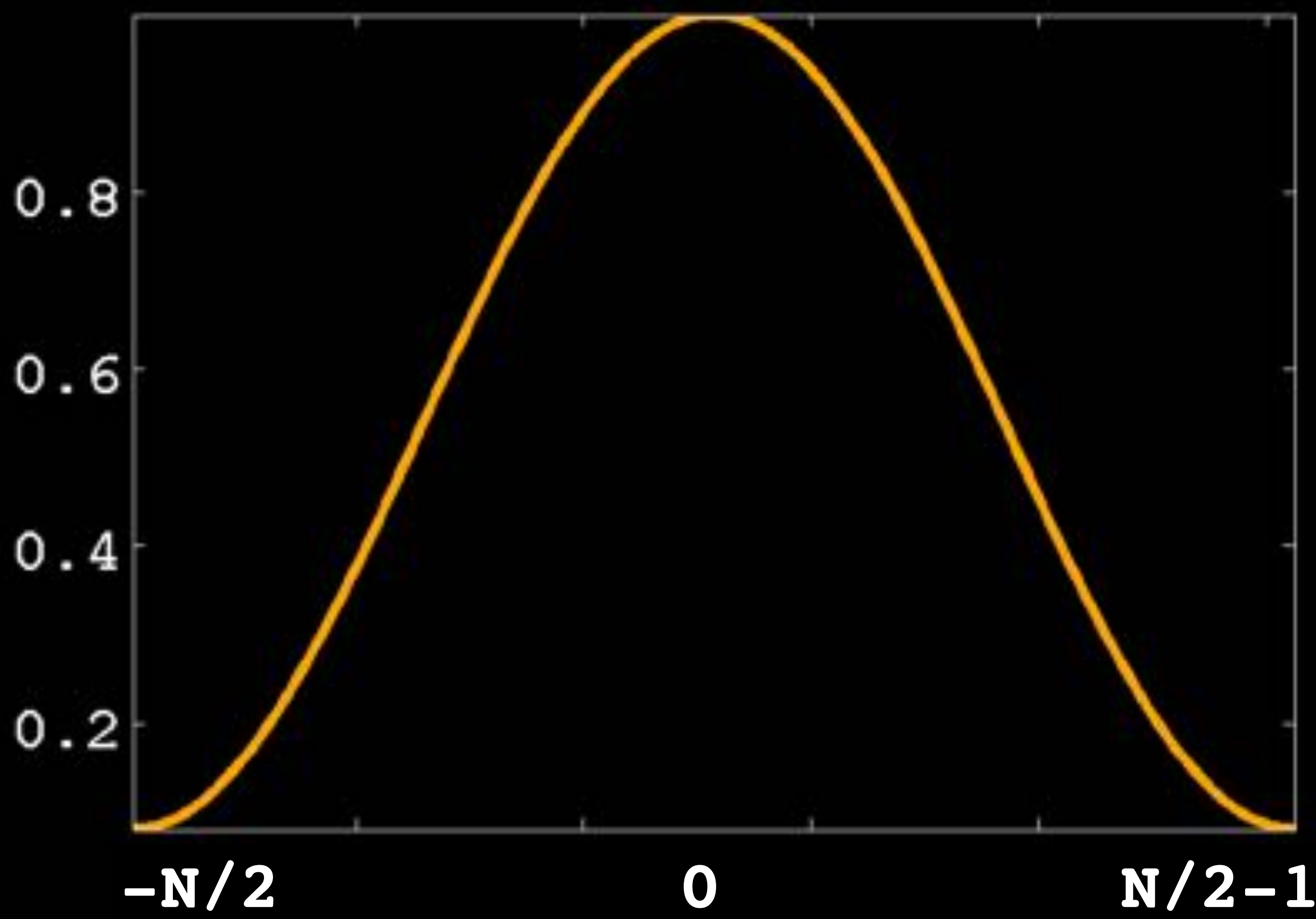
$$\hat{I}(x) = \Delta k \sum_{n=-N/2}^{N/2-1} S\left(n\Delta k\right) w_n e^{i2\pi n\Delta kx}$$ Eqn. 6.21

Windowed Fourier reconstruction

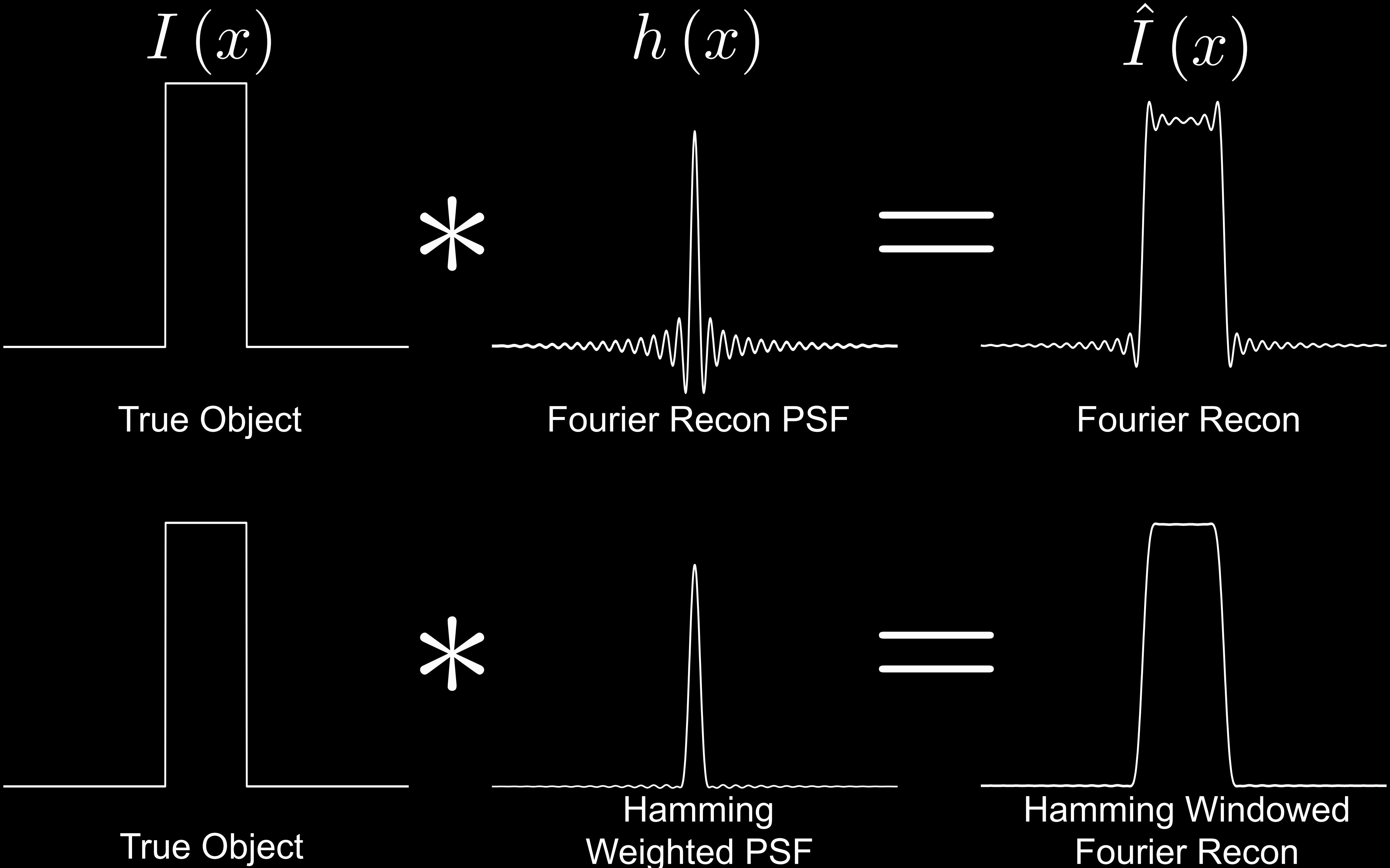
k-space filter/window function

Hamming Filter - 1D

$$w(n) \triangleq \begin{cases} 0.54 + 0.46\cos(2\pi \frac{n}{N}) & -N/2 \le n \le N/2 - 1 \\ 0 & \text{otherwise} \end{cases}$$



Windowed Reconstruction



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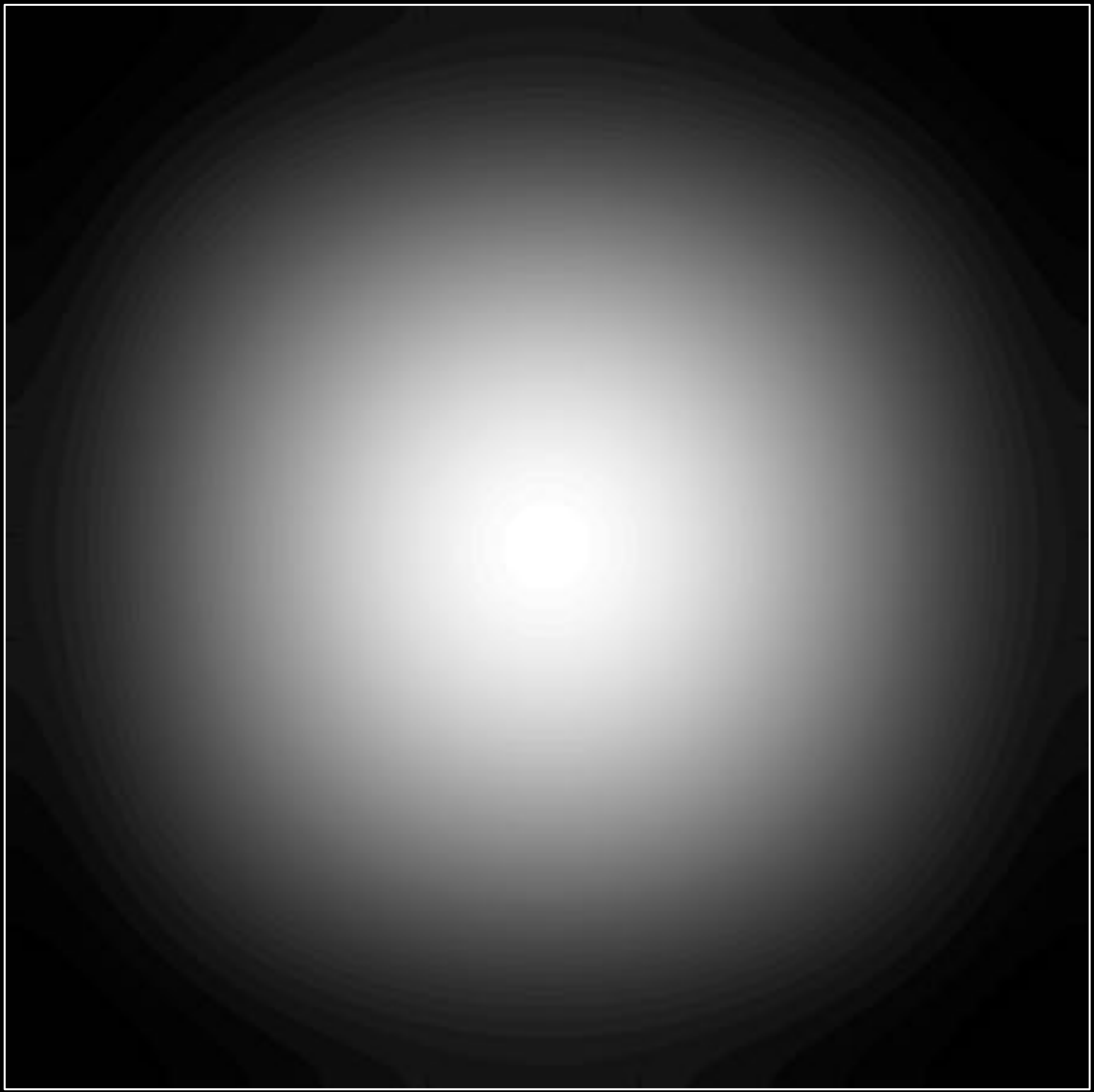
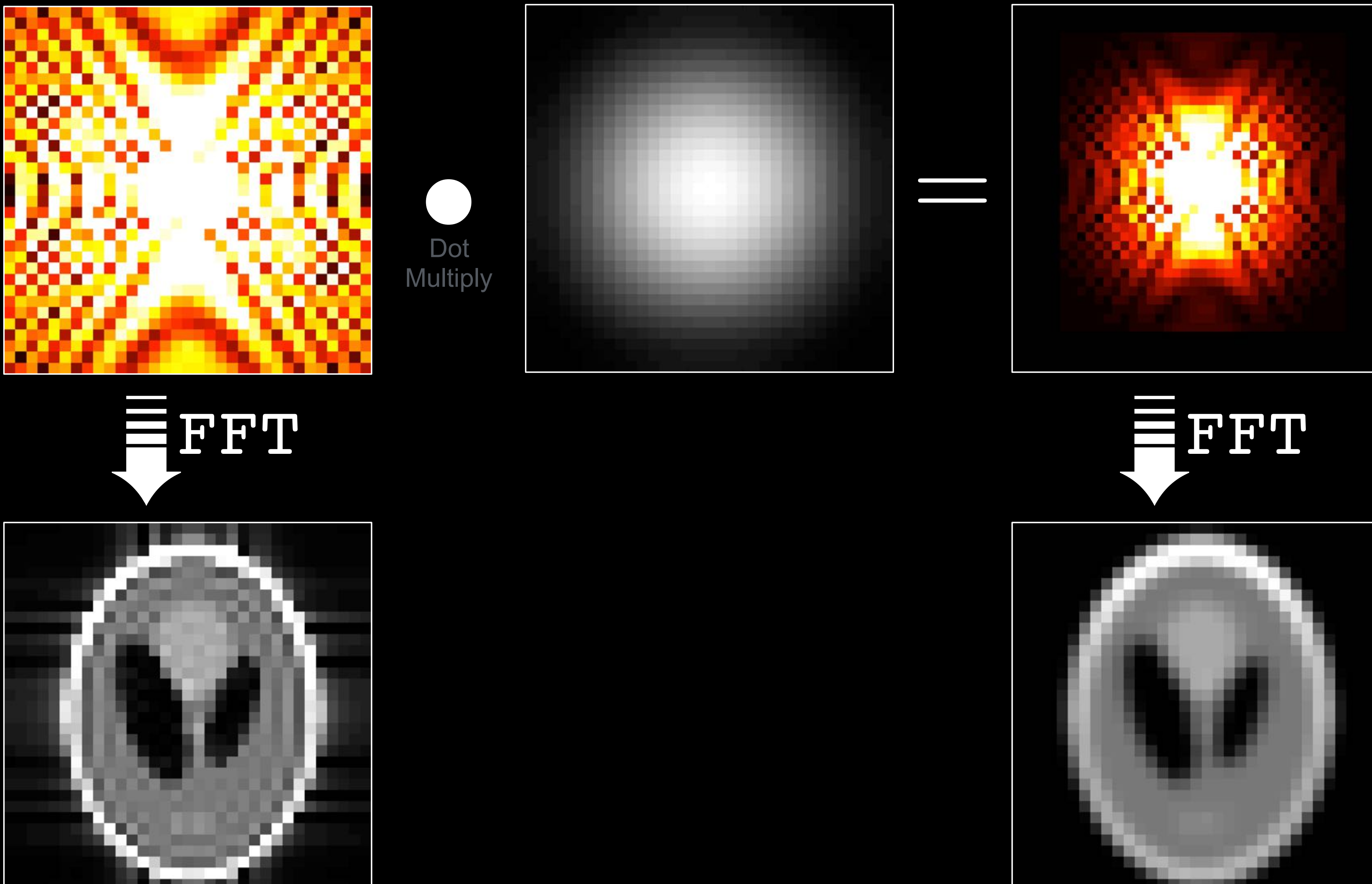
Hamming Filter - 2D

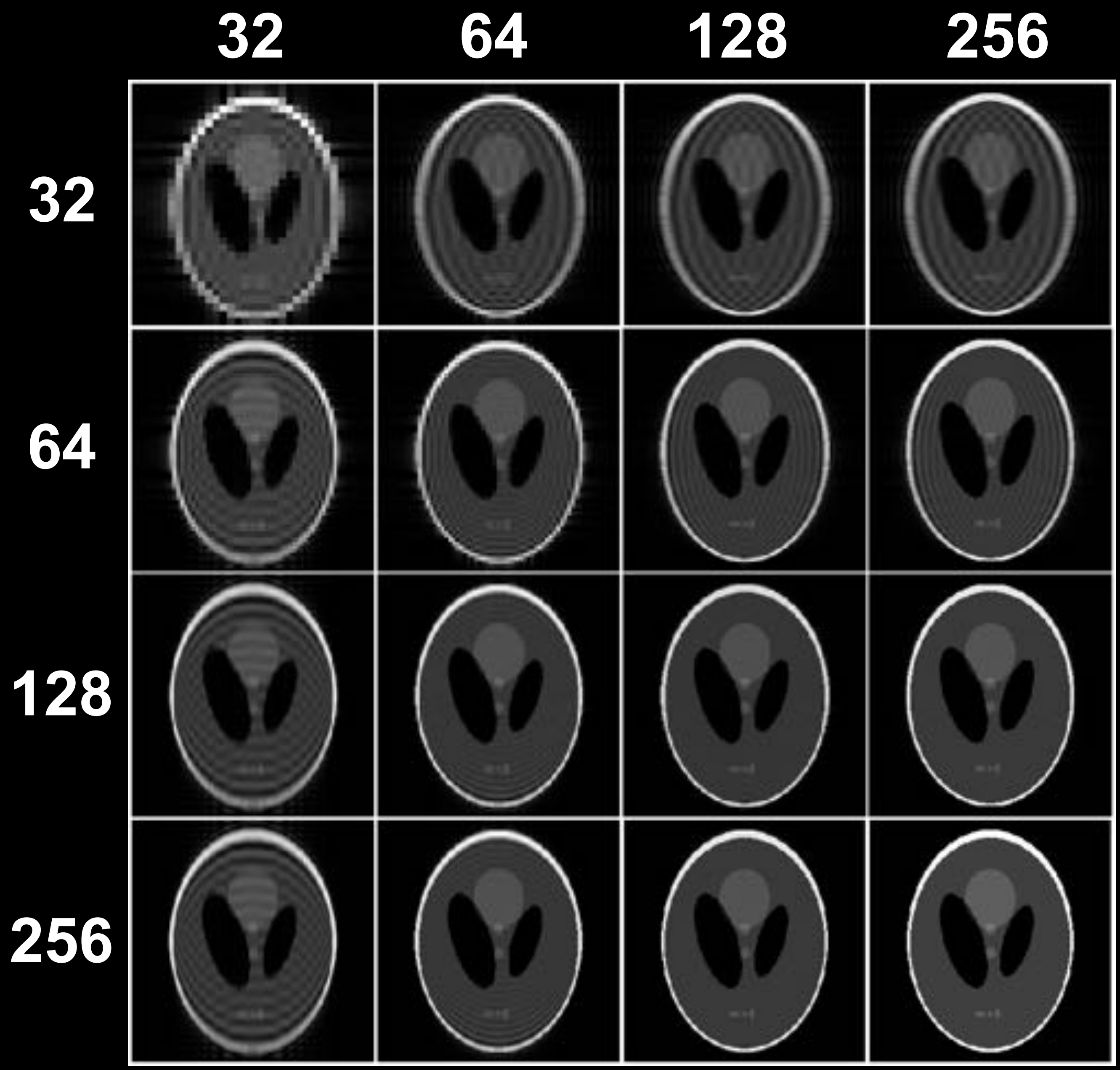
$$W(n) \triangleq w(n) \otimes w(n)$$



Hamming Filter

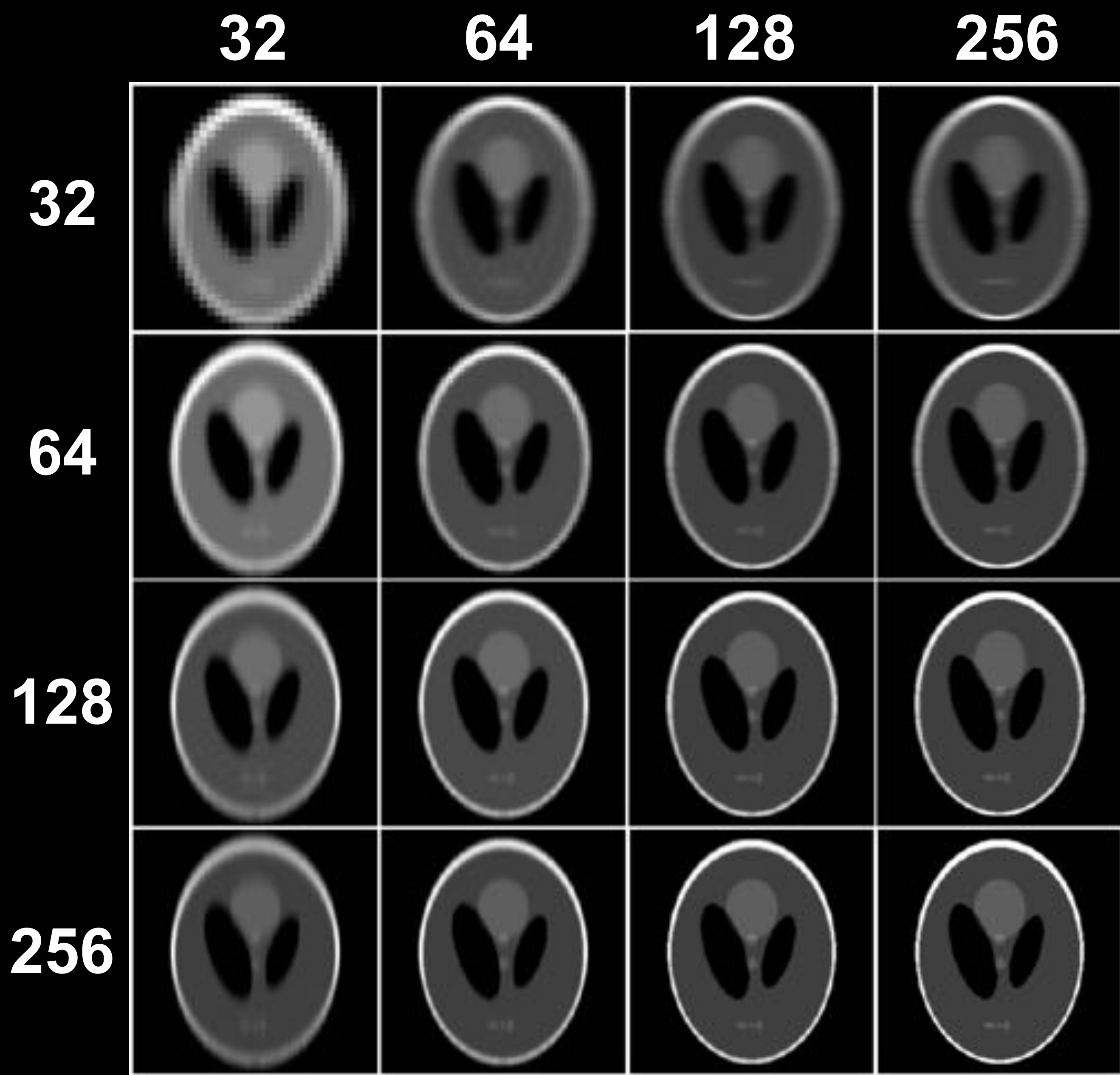


Zero-Pad



With zero padding only, Gibbs ringing is evident.

Hamming Window & Zero-Pad



Windowing *k*-space mitigates Gibb's ringing, but blurs a little.

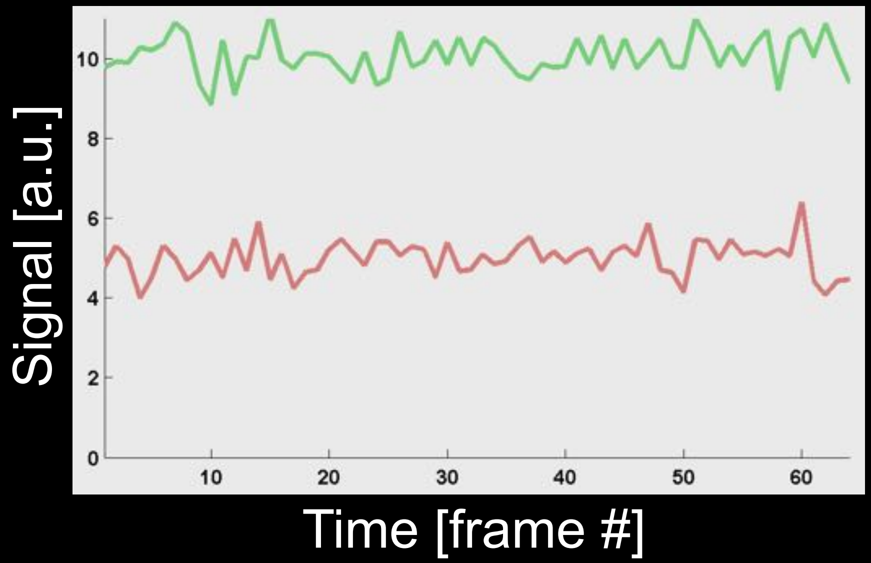
Artifacts

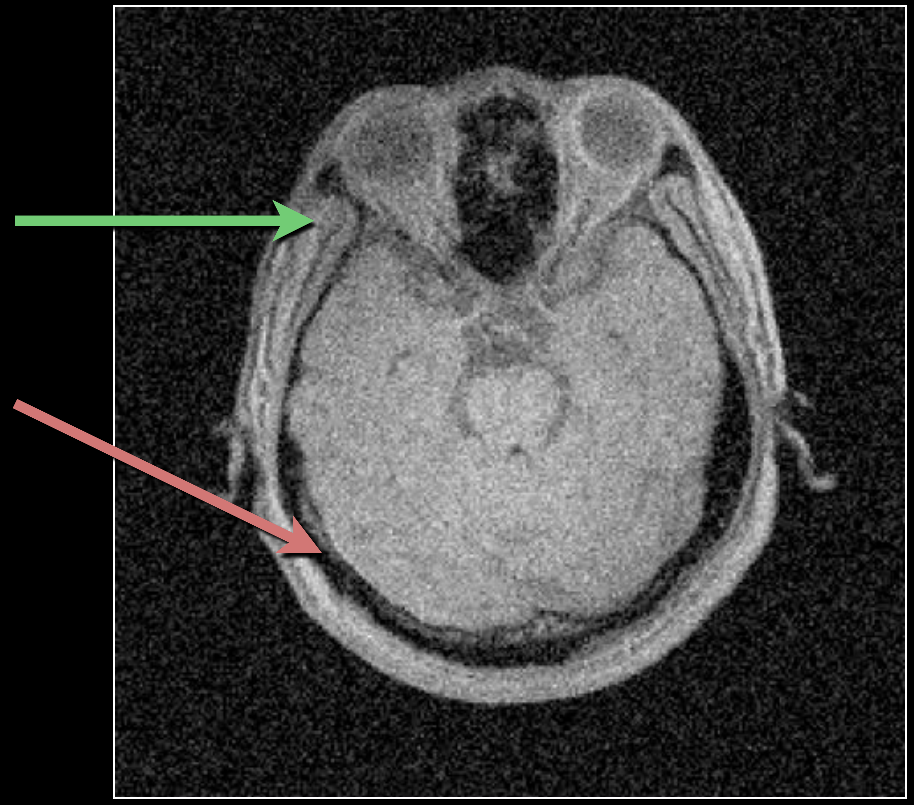
Artifacts

- Aliasing
- Gibb's Ringing
- Noisy spike artifacts
- Noise
- Chemical shift
- Motion Artifacts
- Metal artifacts
- Gradient Non-linearity
- Data clipping
- RF interference
- And more…

Noise

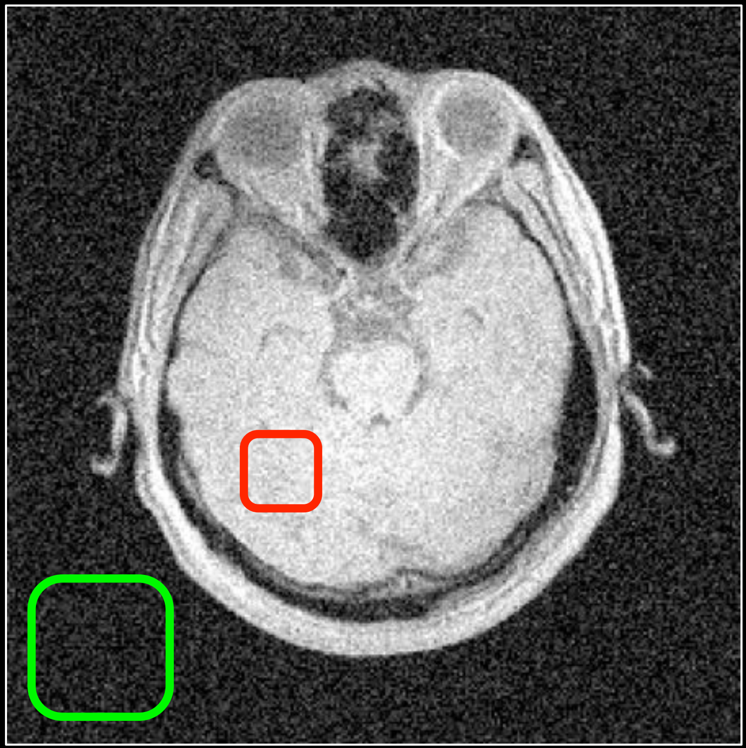
Signal-to-Noise Ratio





Signal-to-Noise Ratio

- **SNR – Signal-to-noise ratio**
  - **Signal – Mean signal intensity in ROI. Assumes:**
    - 1) Tissue homogeneity
    - 2) Noise is only source of variance
  - **Noise – SD of background ROI outside object. Assumes:**
    - 1) Noise is only source of variance



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This method of measuring the SNR is widespread, but imperfect.

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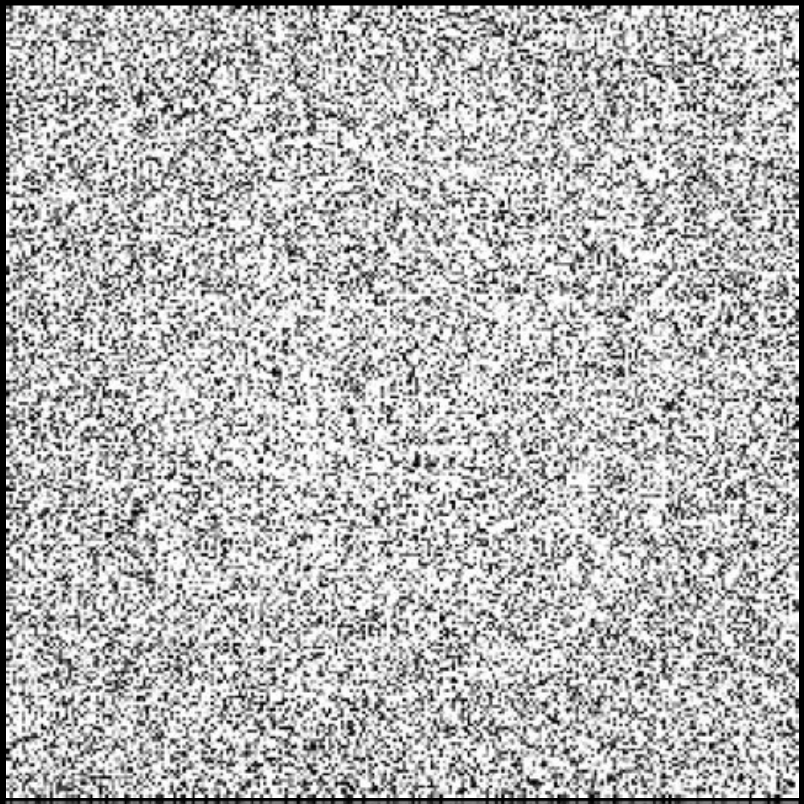
Signal-to-Noise Ratio

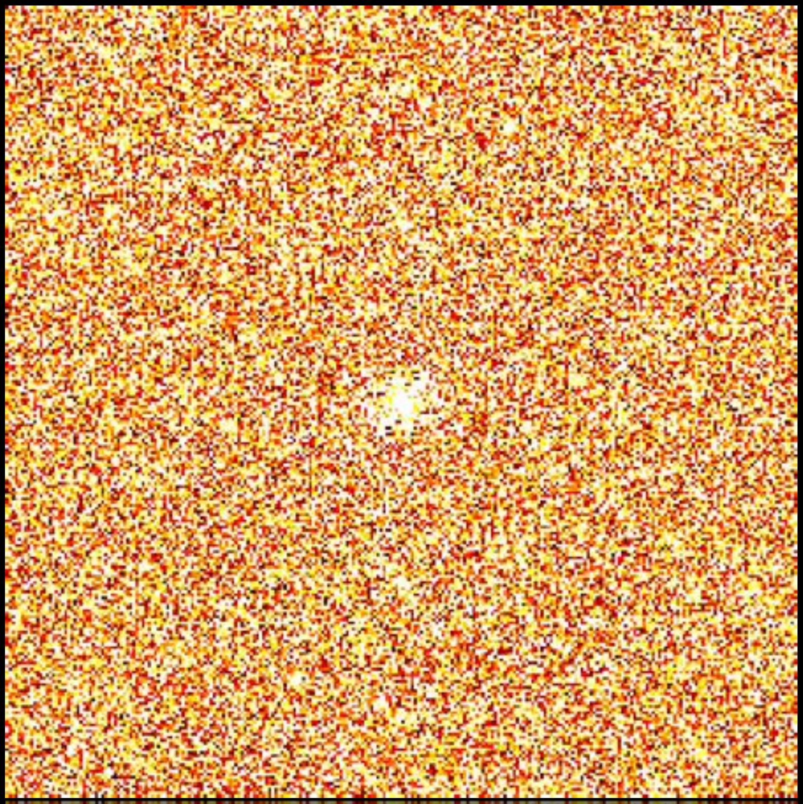
$$SNR \triangleq \frac{\text{signal amplitude}}{\text{standard deviation of noise}}$$

- **SNR – Signal-to-noise ratio**
  - **Signal – Mean signal intensity in ROI**
  - **Noise – Standard deviation of noise**
- **CNR - Contrast-to-noise ratio**
  - **Signal Difference**
    - **Difference between mean signal intensity in two ROIs**
  - **Noise - Standard deviation of noise**

$$CNR \triangleq \frac{\text{signal difference}}{\text{standard deviation of noise}}$$

What is the FT of noise? Noise.





To The Board…

SNR & Imaging Parameters

- Gradient Echo vs. Spin Echo
- TR, TE, TI
- Flip Angle (Gradient Echos)
- Field of View (FOV)
  - Square or Rectangular
- Slice Thickness (h)
- Matrix Size
  - Number of readout points (x)
  - Number of phase encodes (y)
- Bandwidth (Hz)
  - AKA Pixel Bandwidth (Hz/pixel)

Signal-to-noise Ratio

$$SNR \propto V\sqrt{t}$$

Large Voxels (Low Resolution)⇔High SNR

Long Scan Time⇔High SNR

High Resolution + Fast Imaging Severely Compromises SNR

Signal-to-noise Ratio

$$SNR \propto V\sqrt{t}$$

- **V – Voxel Volume**
  - **Slice-thickness (h) x X-res x Y-res**
    - **X-res = FOV_x/N_{kx}**
    - **Y-res = FOV_y/N_{ky}**
- **t – Data acquisition time**
  - **$(N_{kx} \times N_{ky} \times N_{averages})$/bandwidth**

$$SNR \propto \frac{FOV_x}{N_{k_x}}\frac{FOV_y}{N_{k_y}}h\sqrt{\frac{N_{k_x}N_{k_y}N_{avg}}{BW}}$$

Signal-to-noise Ratio

$$SNR \propto V\sqrt{t}$$

- **Example #1**
  - Halving slice thickness requires 4x averages to maintain SNR
- **Example #2**
  - Doubling slice thickness requires 25% time to maintain SNR
- **Example #3**
  - FOV is, in general, fixed.
  - To increase resolution we increase N_{kx} or N_{ky}.
  - This results in increased scan time, but
  - The SNR decreases.

$$SNR \propto \frac{FOV_x}{N_{k_x}} \frac{FOV_y}{N_{k_y}} h \sqrt{\frac{N_{k_x} N_{k_y} N_{avg}}{BW}}$$

Parallel Imaging and SNR

$$SNR_{P.I.} = \frac{SNR}{g\sqrt{R}}$$

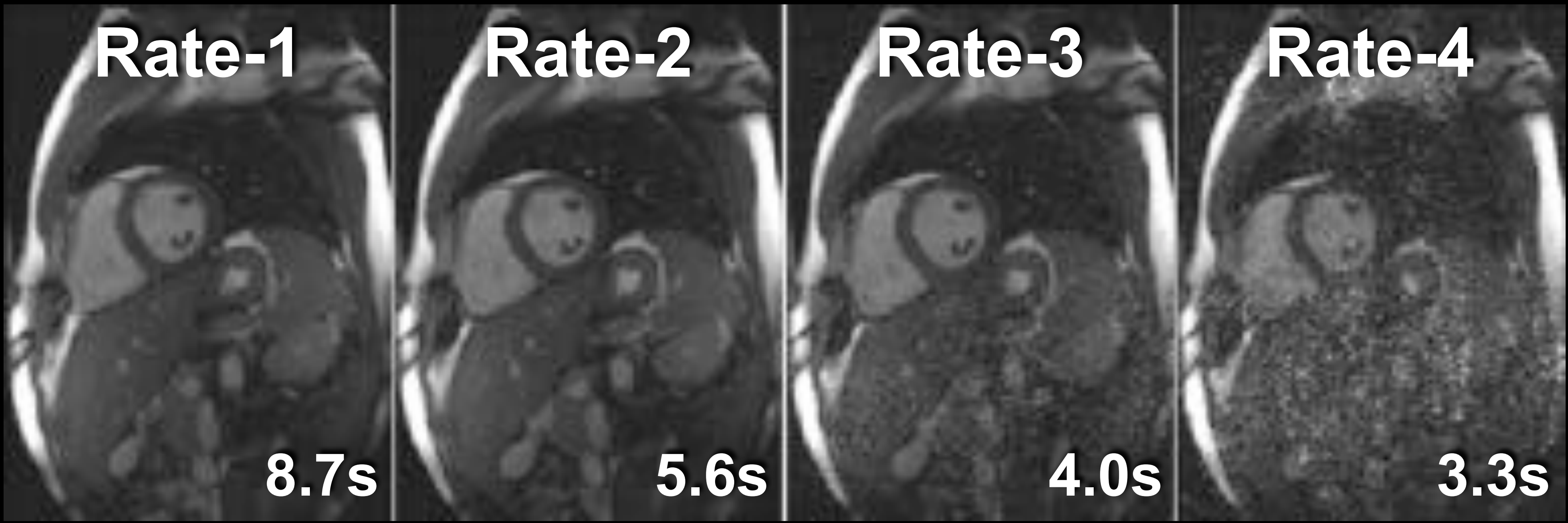
- **g - geometry factor**
  - **Loss associated with coil noise-correlation**
  - **For R=1, g=1**
  - **For R=2, g=~1.1-1.5**
- **R - reduction or acceleration factor**
  - **Loss associated with scan time reduction**
  - **Typically ~1/2 N-coils**
- **SNR for P.I. is spatially dependent**
  - **Higher in areas of aliasing**

Parallel imaging has additional SNR penalties, but decreases scan time.

Impact of Acceleration

High SNR
"Long" Acq.

Low SNR
Short Acq.



P. Kellman (NIH)

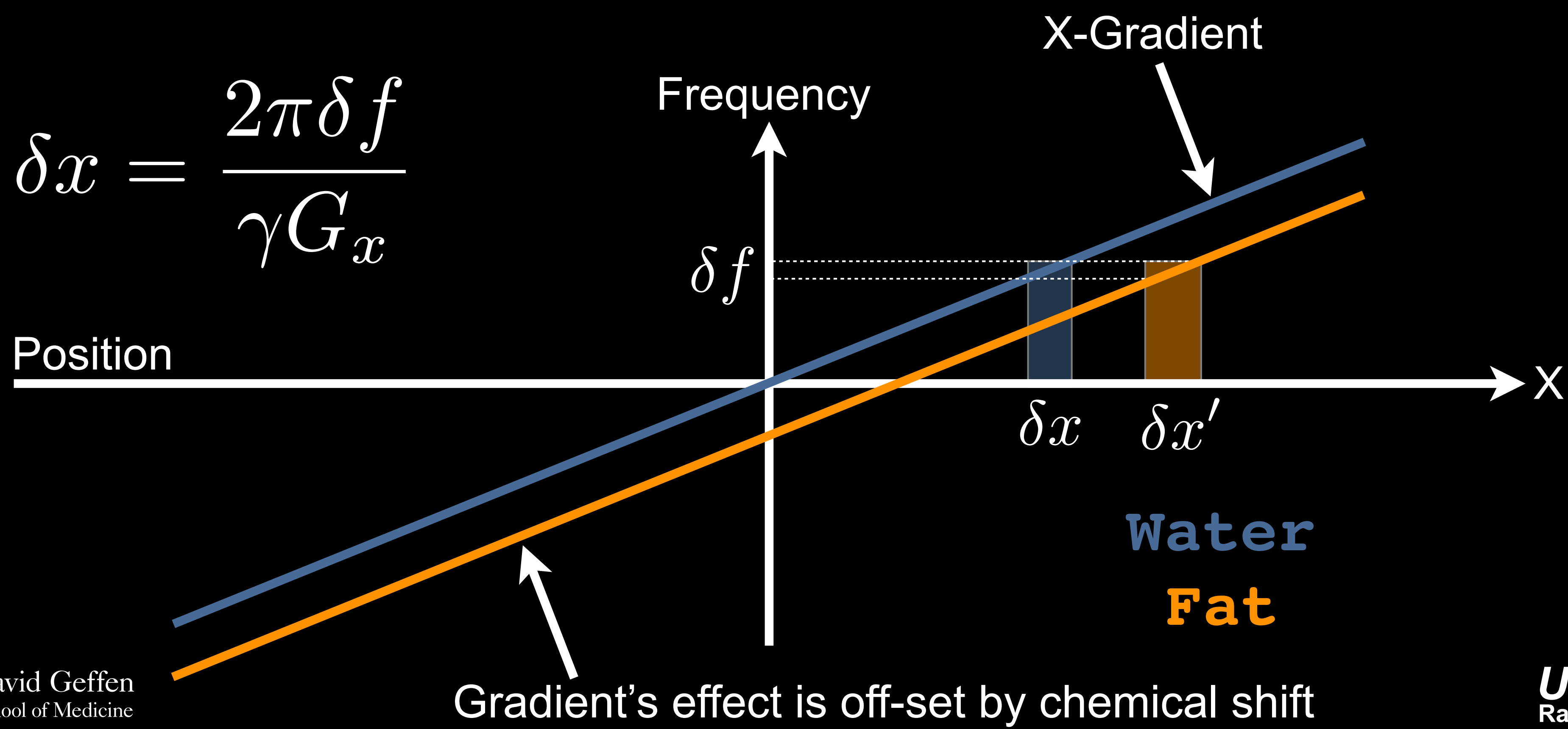
High acceleration rates lead to local noise amplification.

Chemical Shift

Chemical Shift Artifact

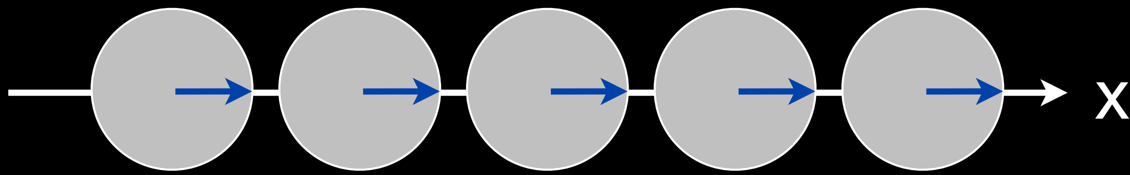
- **Gradients provide linear variation in frequency**
- **Fat has a 3.5ppm lower frequency than water**
  - **-222Hz @ 1.5T and -444Hz @ 3.0T**
- **Scanner detects frequency, then maps to position**
- **Scanner "assumes" everything is water, therefore fat (lower frequency) is interpreted as lower frequency (shifted position) water.**

$$\delta x = \frac{2\pi \delta f}{\gamma G_x}$$

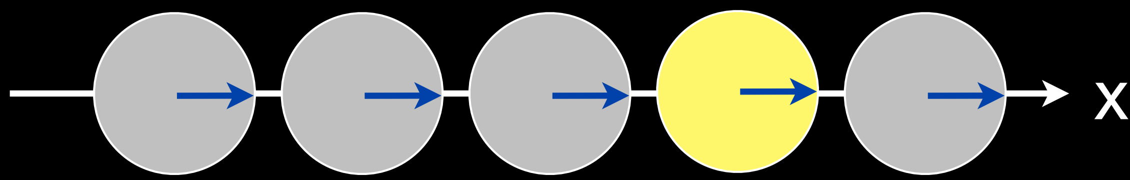


Chemical Shift Artifact

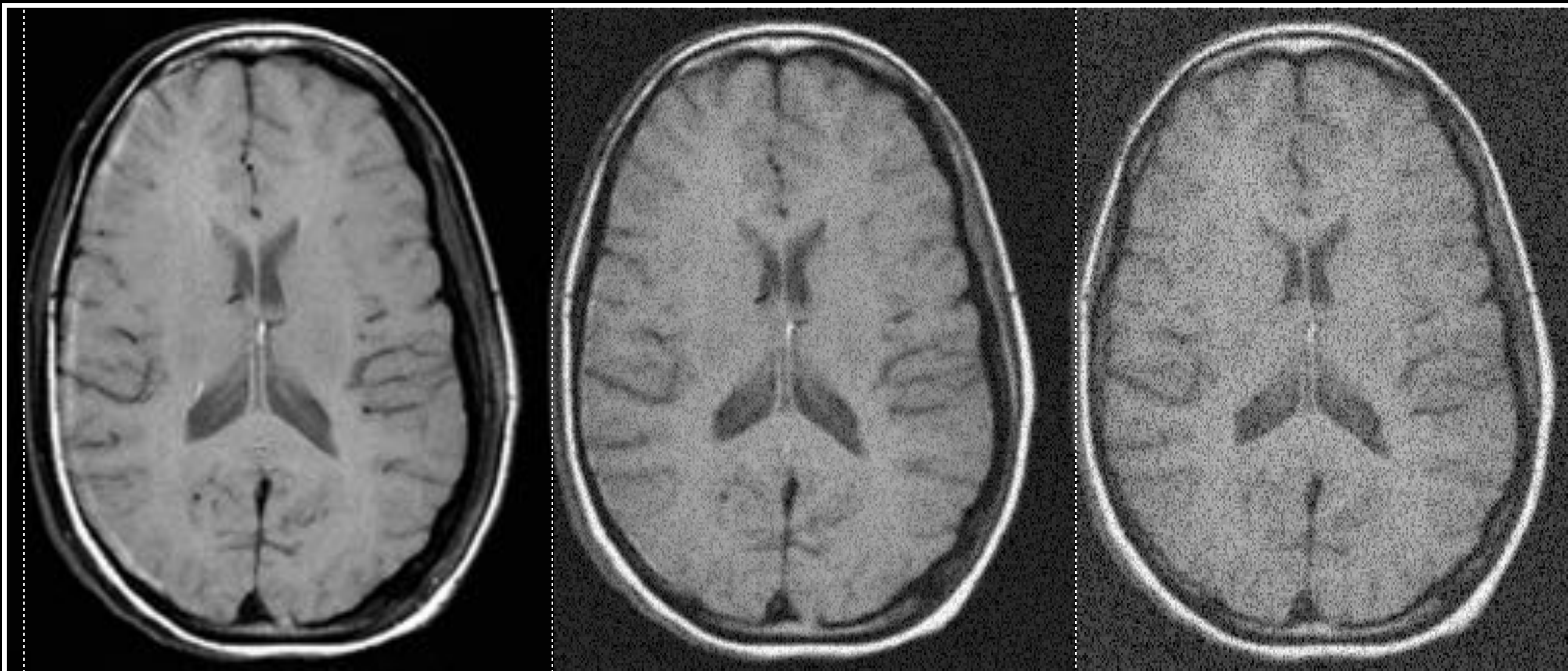
Normal Spins



Off-Resonant Spin



Chemical Shift Artifact



BW = ± 4kHz

Low Bandwidth
Large Fat-Water Shift
High SNR

BW = ± 8kHz

Readout →

BW = ± 16kHz

High Bandwidth
Small Fat-Water Shift
Low SNR

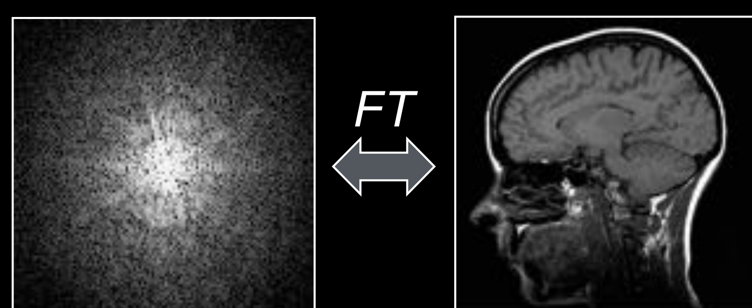
Solution

- **High bandwidth pulse sequences**
  - **Degrades SNR (reduces acquisition time)**
  - **Reduces chemical shift artifact**
- **Fat saturation pulses/techniques**

Motion Artifacts

Motion in MRI

- **Motion is responsible for a corruption in spatial localization in PE direction, resulting in blurring and/or ghosting artifacts.**
- **Typical types of motion in body**
  - **Patient motion**
  - **Respiration**
  - **Cardiac motion and vascular pulsation**
  - **Peristalsis & bowel gas.**
- **Recording signal in *k*-space not image domain!**



Motion Artifacts - Part I

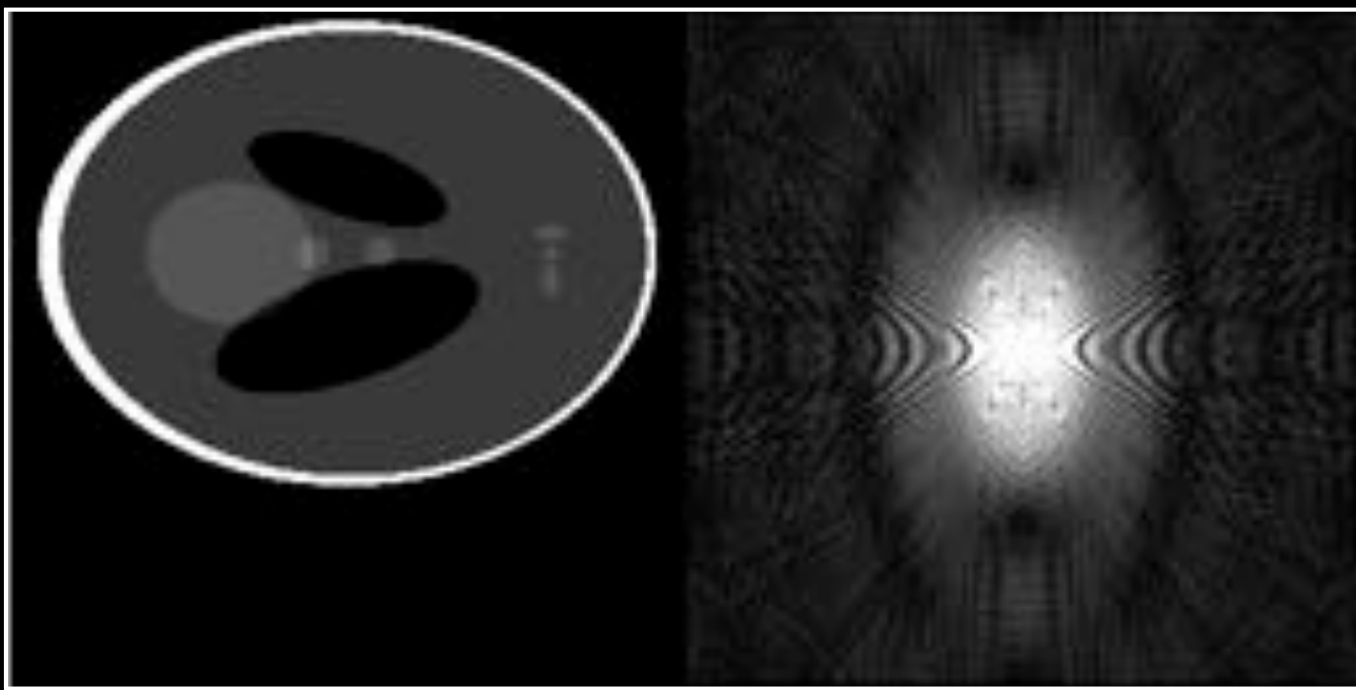
Slow/Bulk Motion

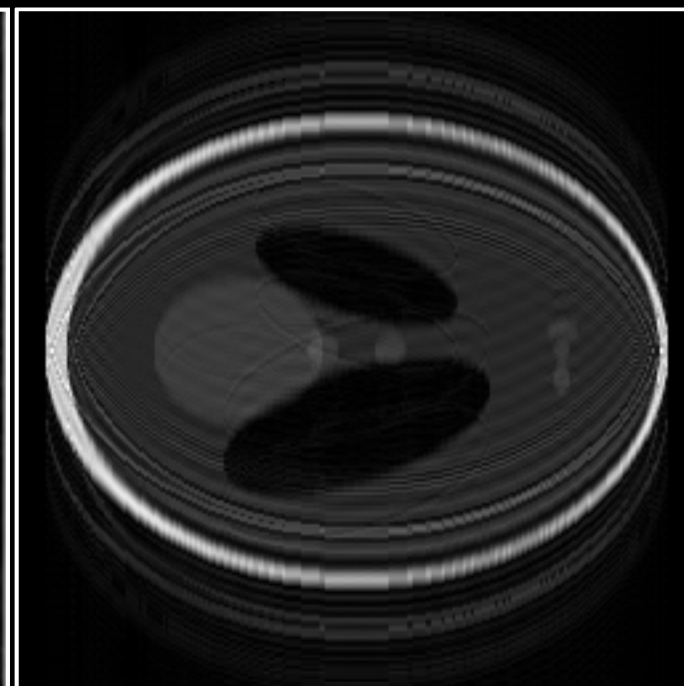
Examples:
- Respiration
- Feet motion
- Swallowing

Motion Artifacts - Part I

Slow/Bulk Motion

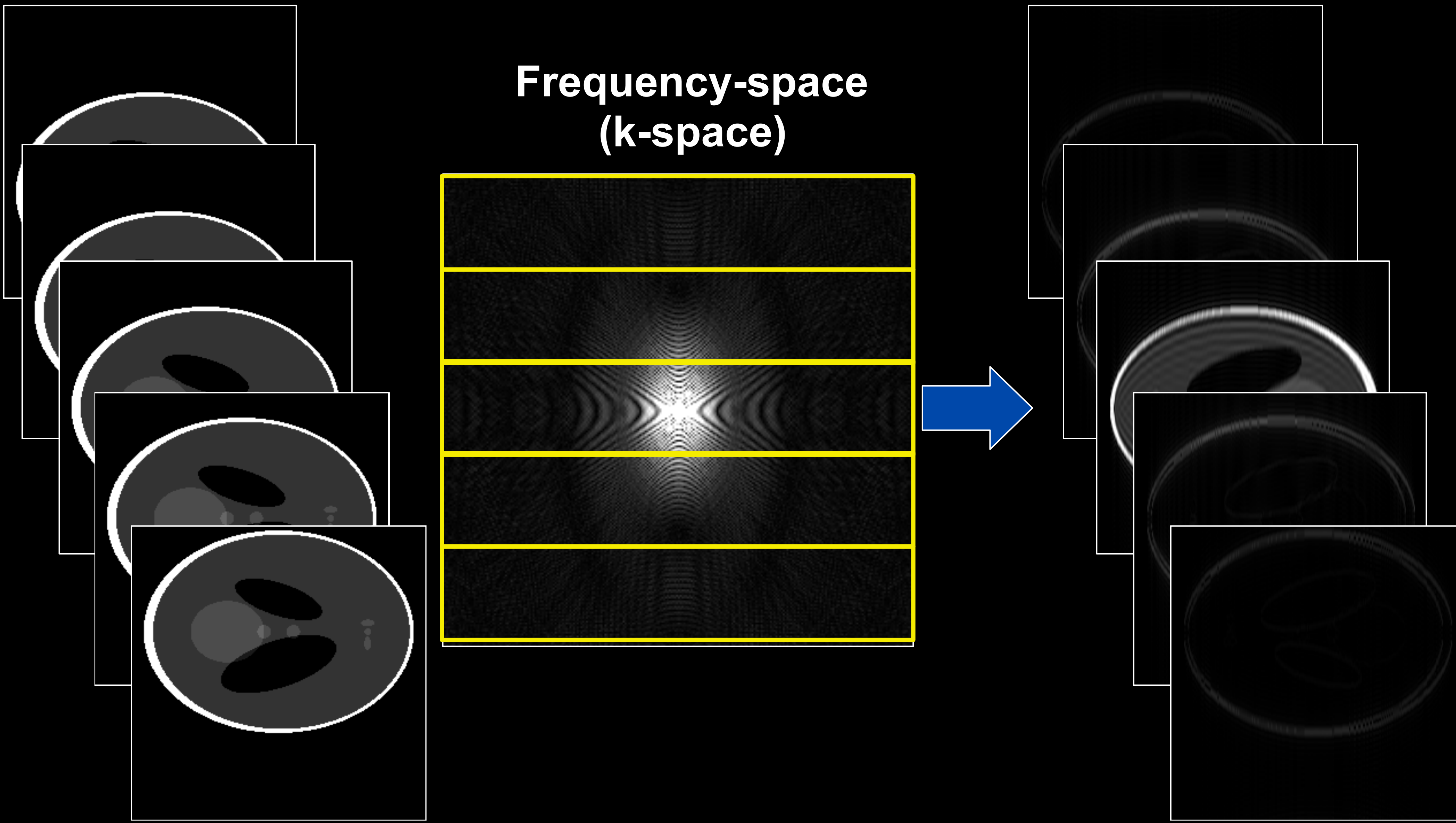
MR Image with
Motion Artifacts



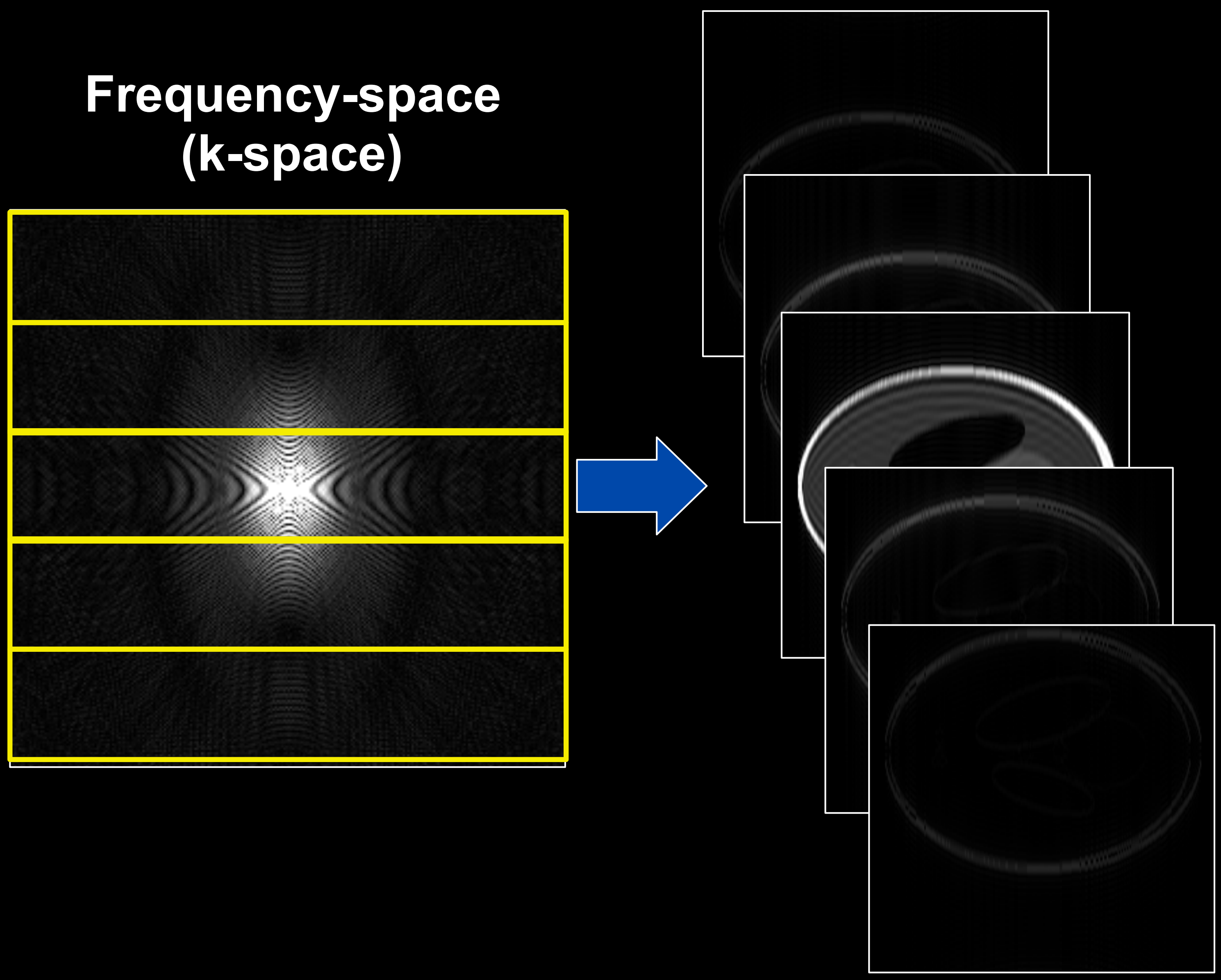


Fourier
Transform

Motion Artifacts - Part I

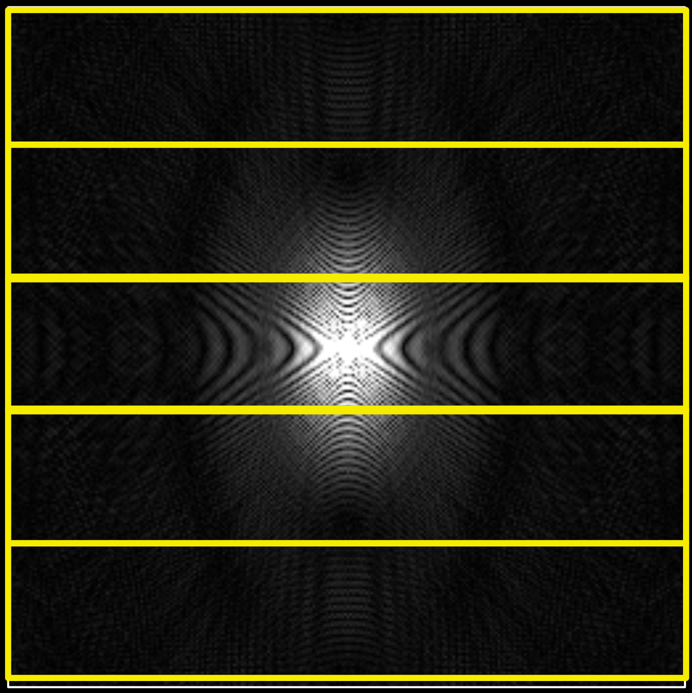


Motion Artifacts - Part I

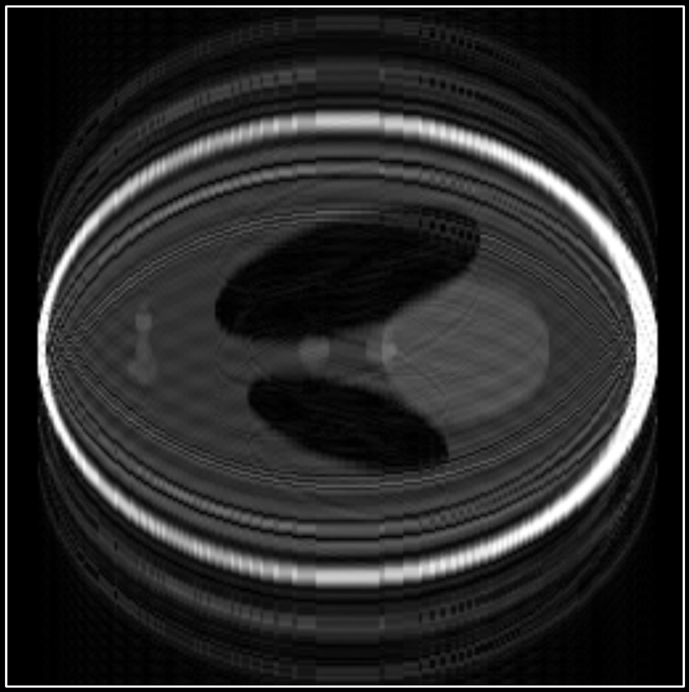


Motion Artifacts - Part I

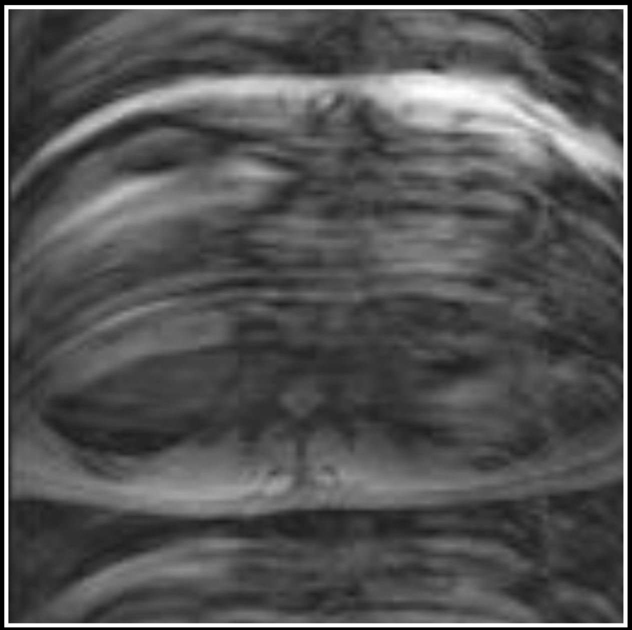
Frequency-space (k-space)



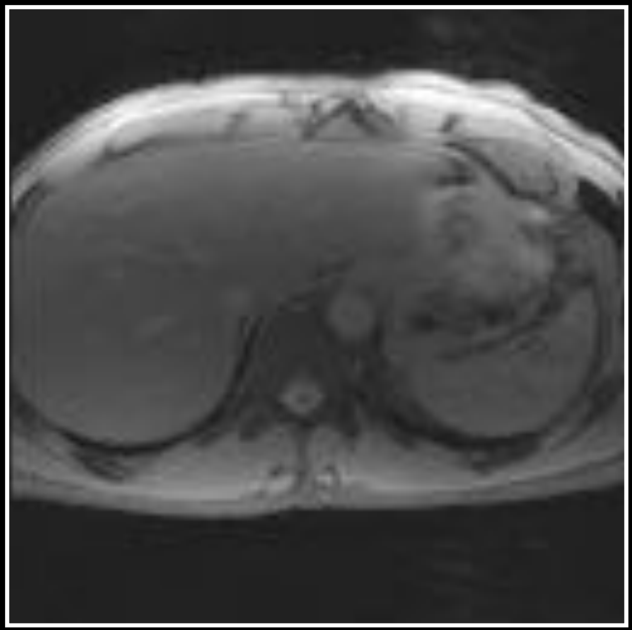
MR Image with Motion Artifacts



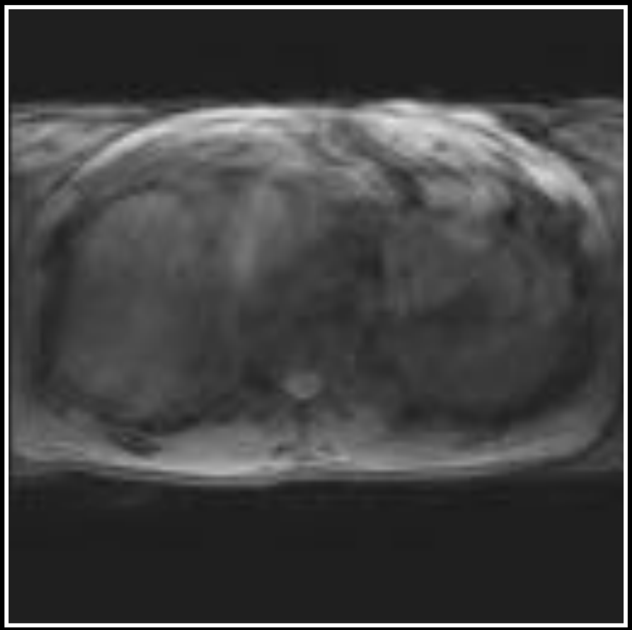
Breathing (Motion) Artifacts



Free Breathing



Breath held



Free Breathing

Motion artifacts appear in the phase encode direction.

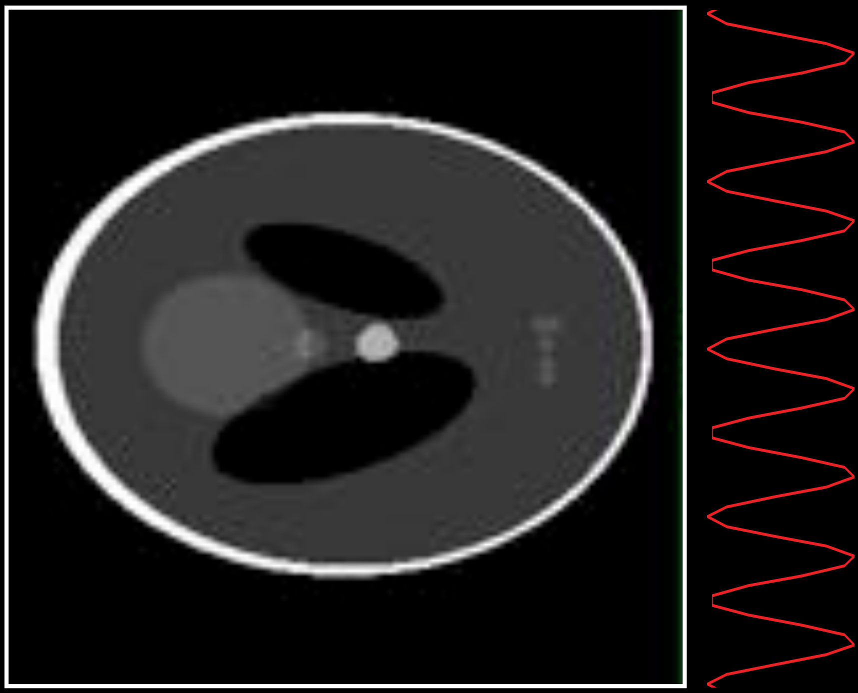
Remedies (and Penalties)

- **Possible solutions?**
  - **Breath-holding**
  - **Respiratory gating**
  - **Reduces body movements**
    - **Patient coaching, physical restraint, sedation**

- **Disadvantages**
  - **Requires fast sequences**
  - **Increases the scan time; restricts the available TRs**
  - **Patients acceptance and discomfort**

Motion Artifacts - Part II

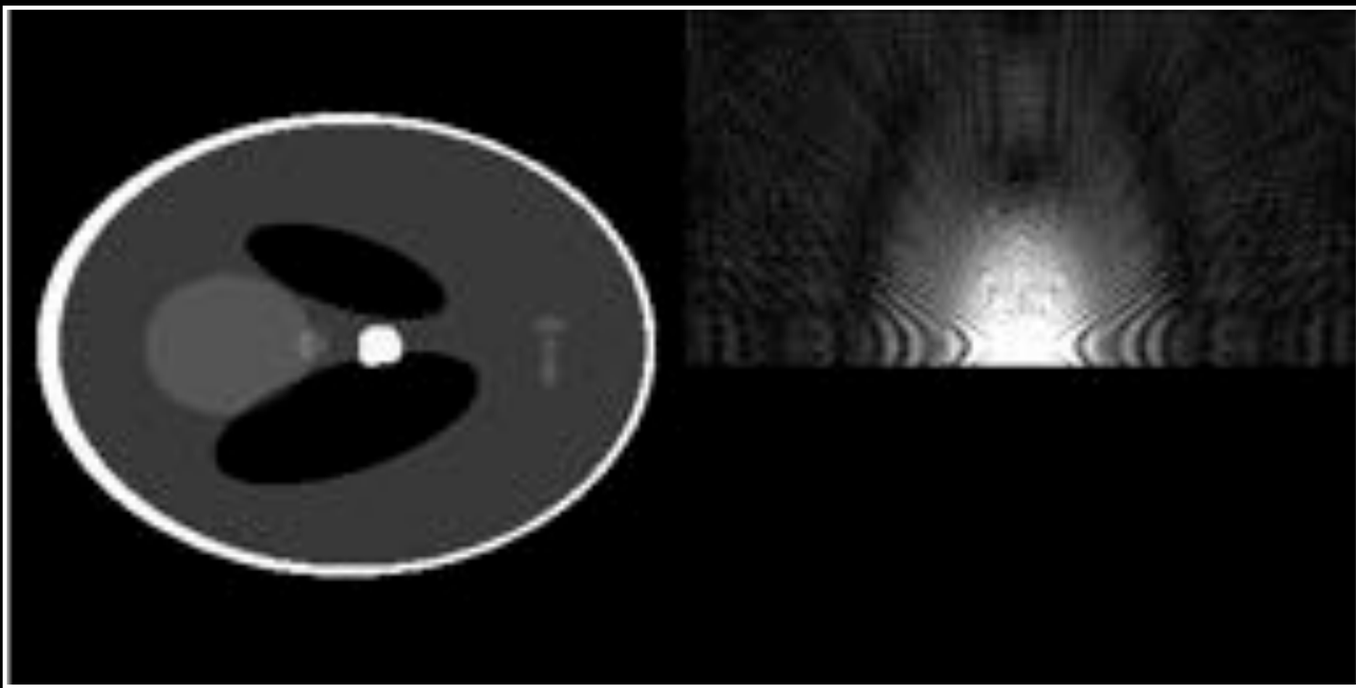
Periodic Motion



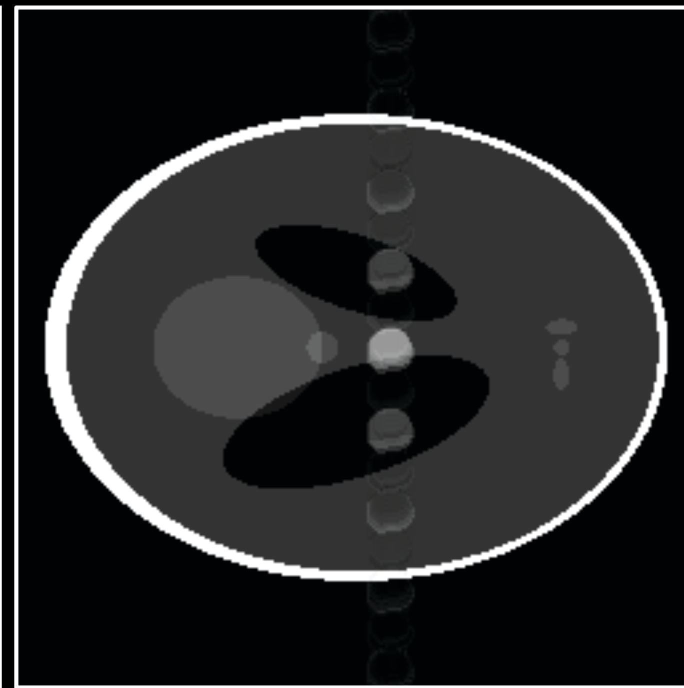
Examples:
- Aortic Pulsation
- Arterial Pulsation

Motion Artifacts - Part II

Periodic Motion



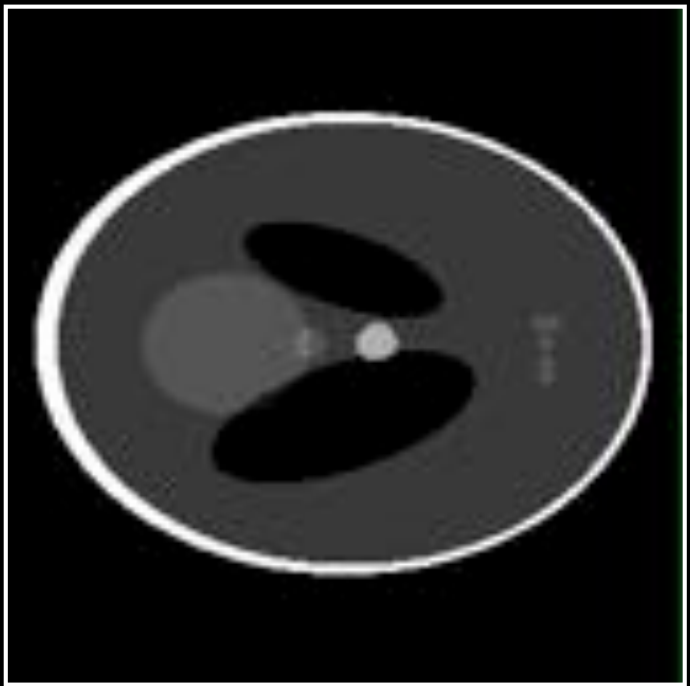
MR Image with
Motion Artifacts



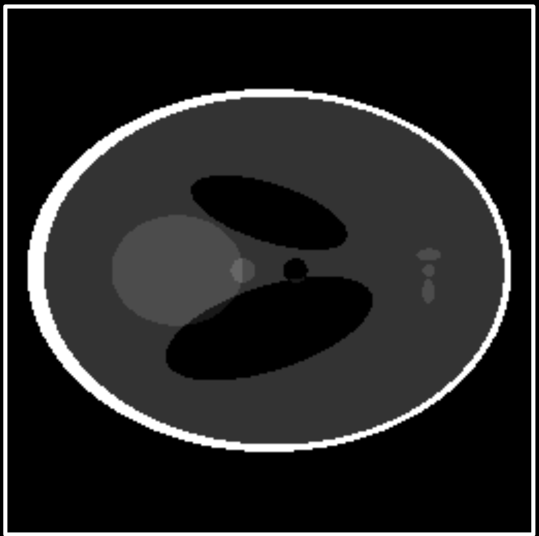
Fourier
Transform

Motion Artifacts - Part II

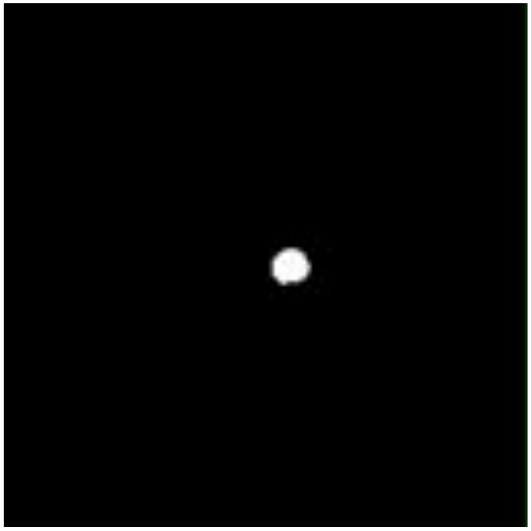
Periodic Motion



Static Part

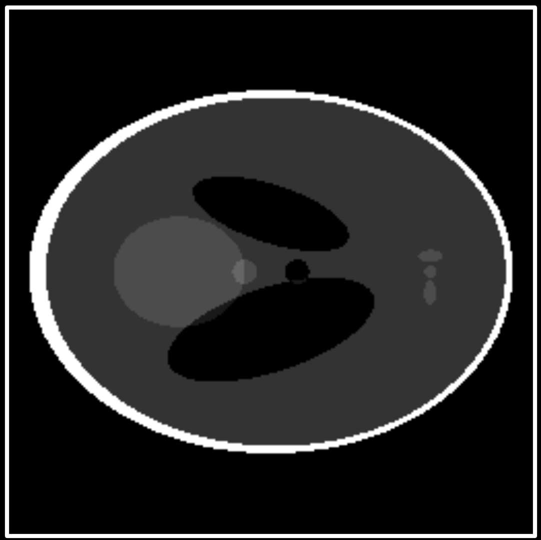


Moving Part

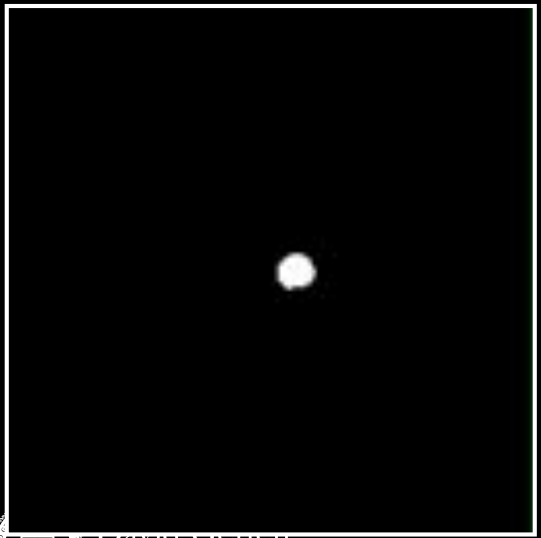


Motion Artifacts - Part II

Static Part

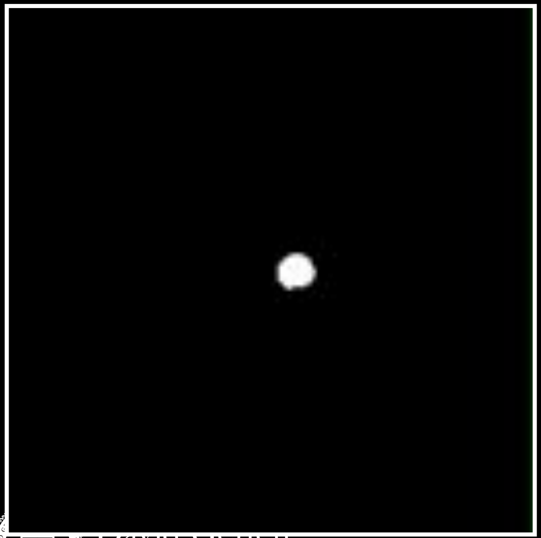


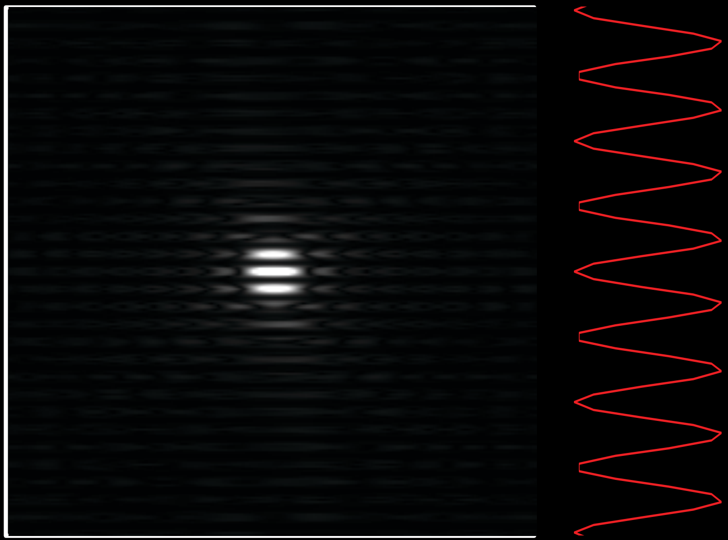
Moving Part



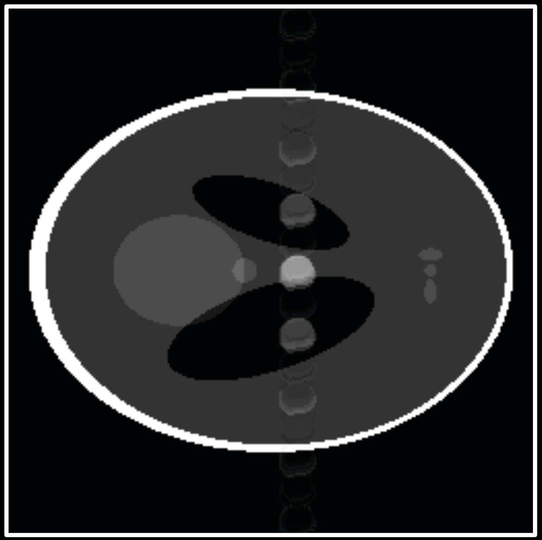
Motion Artifacts - Part II

Moving Part



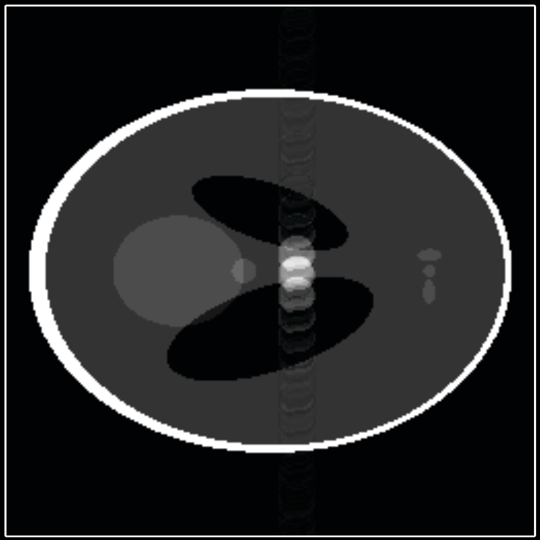


MR Image with
Ghosting Artifacts

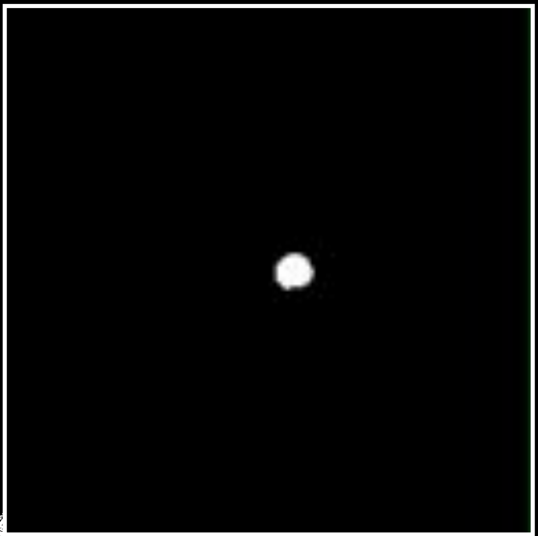


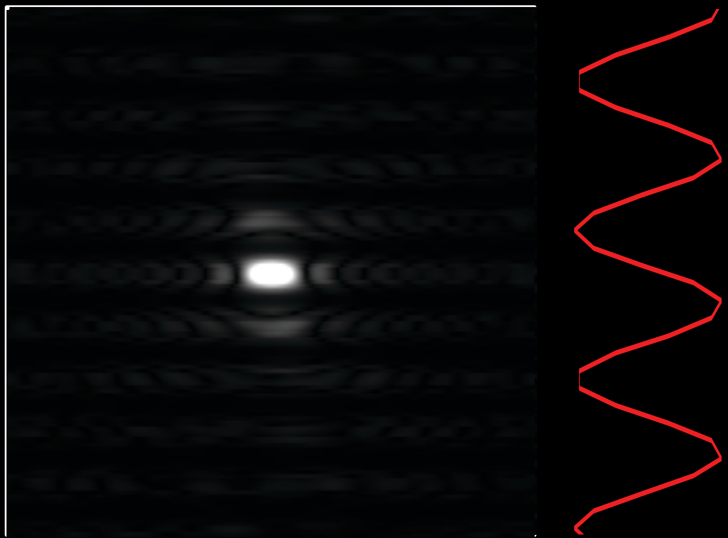
Motion Artifacts - Part II

MR Image with Ghosting Artifacts



Moving Part





Remedies (and Penalties)

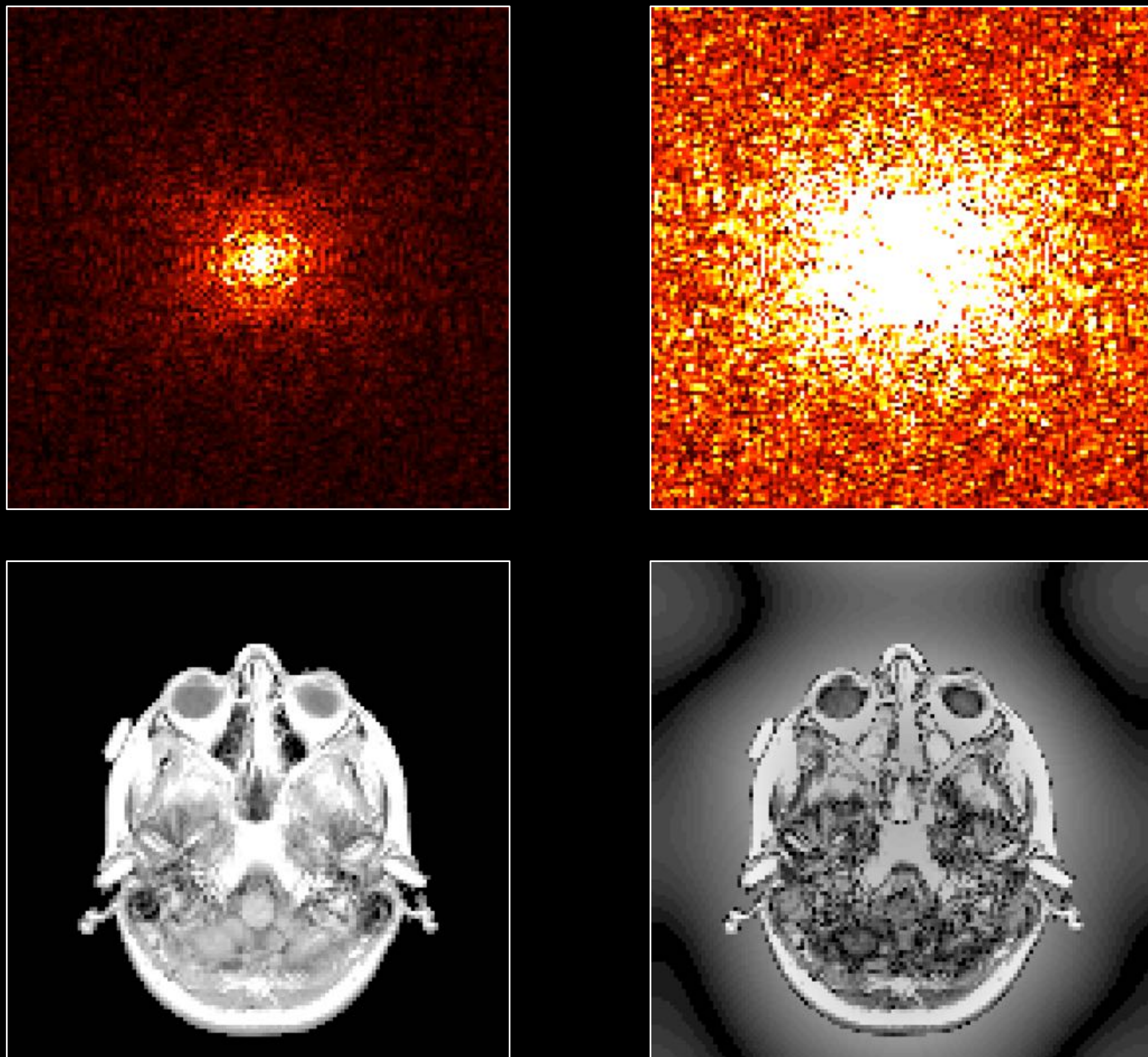
- **Possible solutions?**
  - **Cardiac gating ± segmented imaging.**
  - **Signal suppression of moving tissues.**
  - **Swapping phase-encoding and frequency encoding directions**
- **Disadvantages**
  - **Increases scan time.**
  - **Increases TR (due to preparation pulses).**
  - **Only shifts the artifacts.**

Data Clipping

Data Clipping

- **Received signal saturates the receiver.**
- **Peak signal usually in the middle of *k*-space, therefore lose low spatial frequency information:**
  - **Contrast**
  - **Intensity**
- **Pre-scan procedure usually avoids data clipping by adjusting receiver gains.**

Data Clipping



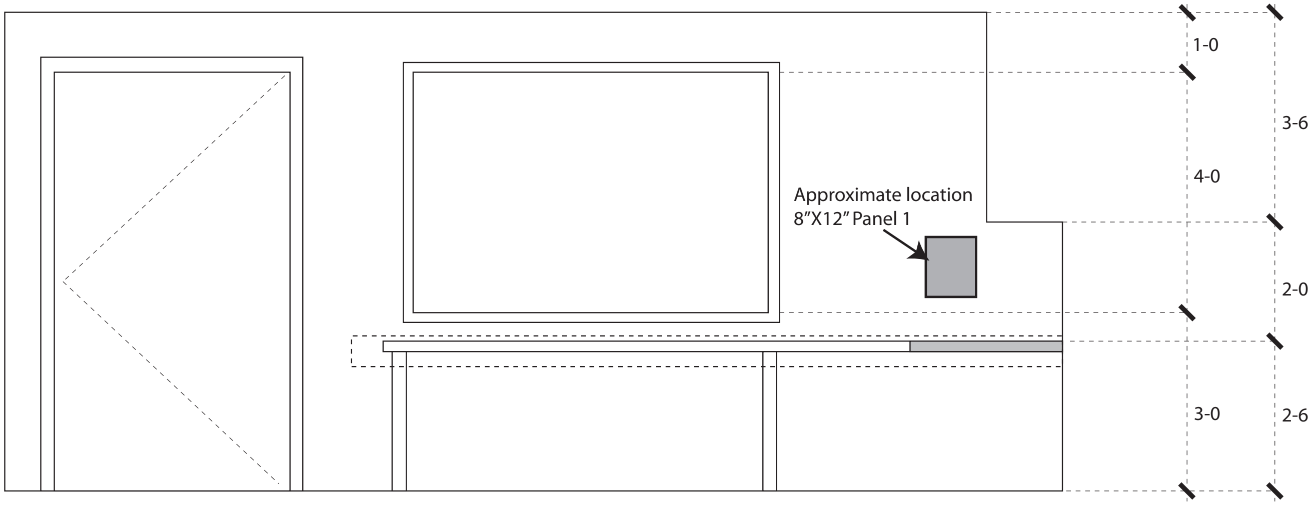
Radio Frequency Interference

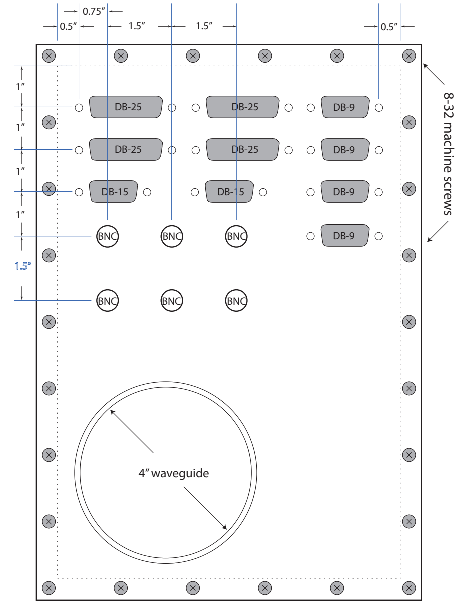
RF Shielding

- **RF fields are close to FM radio**
  - **^1H @ 1.5T ⇒ 63.85 MHz**
  - **^1H @ 3.0T ⇒ 127.71 MHz**
  - **KROQ ⇒ 106.7 MHz**
- **Need to shield local sources from interfering**
- **Copper room shielding required**

Penetration Panel

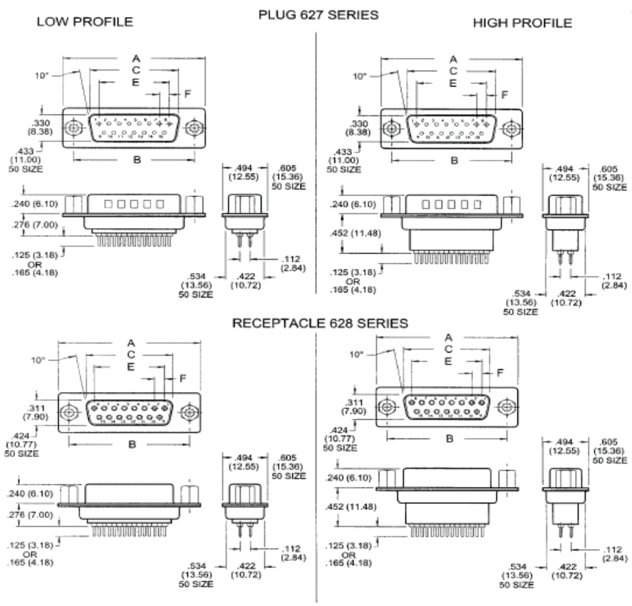
Penetration Panel



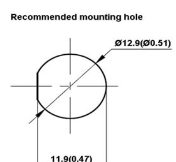


Panel 1 - between scan room and console room

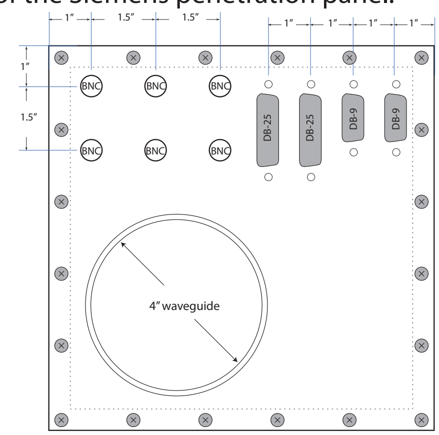
8" X 12" penetration (panel size is 9" X 13")



Location of Panel 2 is to be in the proximity of the Siemens penetration panel.



BNC Hole Dimensions



Penetration panels should be made from 16 ga. steel or aluminum

8" Penetration (panel size is 9")

Panel 2 - between equipment room and scan room

NUMBER OF CONTACTS	A		B		C PLUG		C RECEPTACLE		E		F	
	Inch	(mm)	Inch	(mm)	Inch	(mm)	Inch	(mm)	Inch	(mm)	Inch	(mm)
9	1.214	(30.84)	.984	(24.99)	.667	(16.92)	.640	(16.26)	.432	(10.97)	.108	(2.74)
15	1.545	(39.24)	1.312	(33.32)	.994	(25.25)	.967	(24.56)	.756	(19.20)	.108	(2.74)
25	2.088	(53.04)	1.852	(47.04)	1.534	(38.96)	1.508	(38.30)	1.304	(33.12)	.109	(2.76)
37	2.730	(69.34)	2.500	(63.50)	2.182	(53.08)	2.156	(54.76)	1.956	(49.68)	.109	(2.76)
50	2.640	(67.05)	2.406	(61.11)	2.080	(52.83)	2.054	(52.17)	1.740	(44.20)	.109	(2.76)

DB cutout dimensions

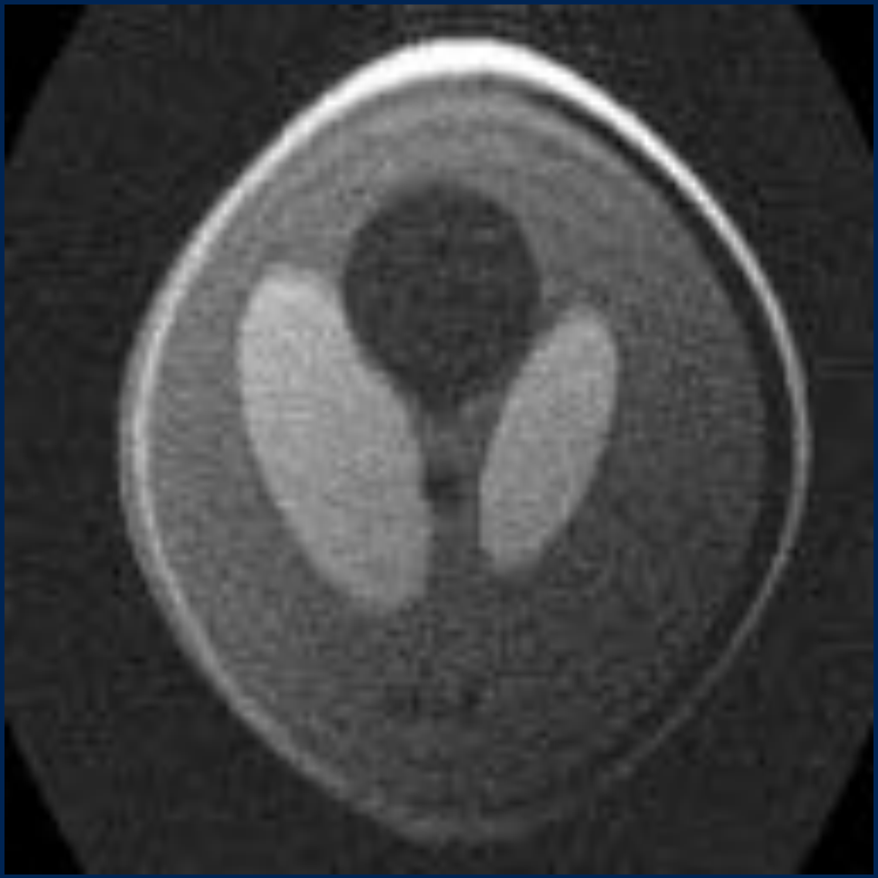
Cables must be filtered before entering the MRI suit.

Radiofrequency Interference

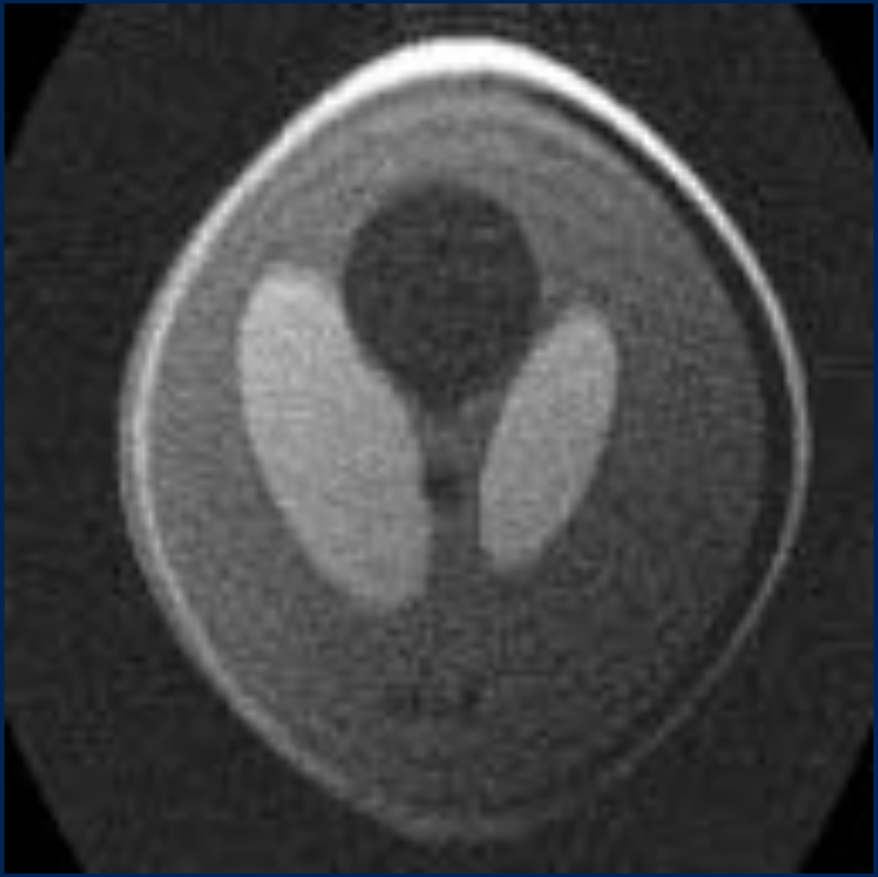
- Caused by RF leak
  - Scanner Door is Open
  - Wires running in/out of scan room
  - Faulty Room Shielding

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

How many artifacts can you see?



How many artifacts can you see?



Noise
Gradient Distortion
Gibb's Ringing
Chemical Shift
Coil shading

Thanks

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