MRI:
Fast Imaging & Image Artefacts

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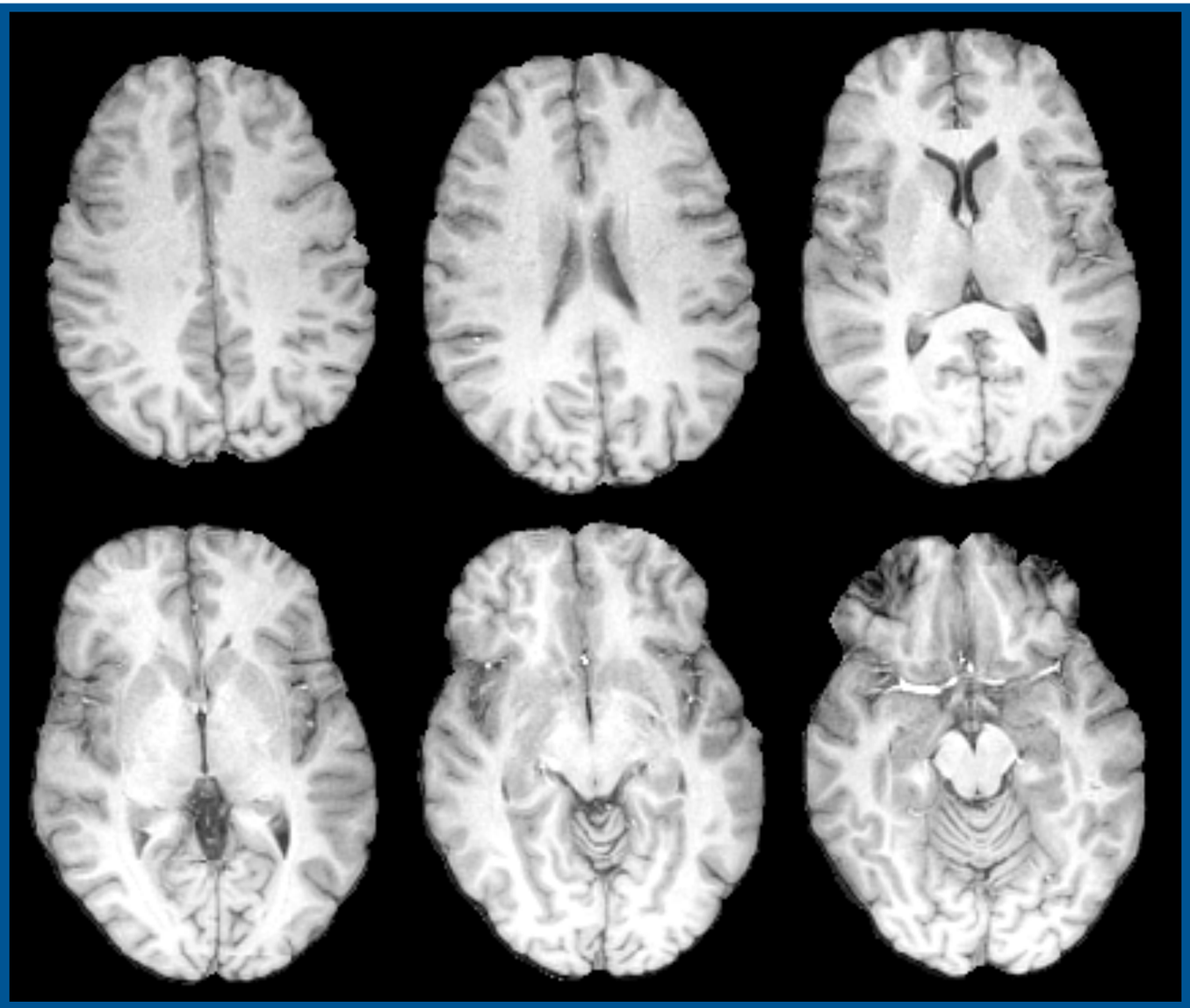
with some materials from K. Miller, P. Koopmans, & T. Okell

Fast Imaging Methods for MRI

or

How to acquire images in *seconds* rather than *minutes*

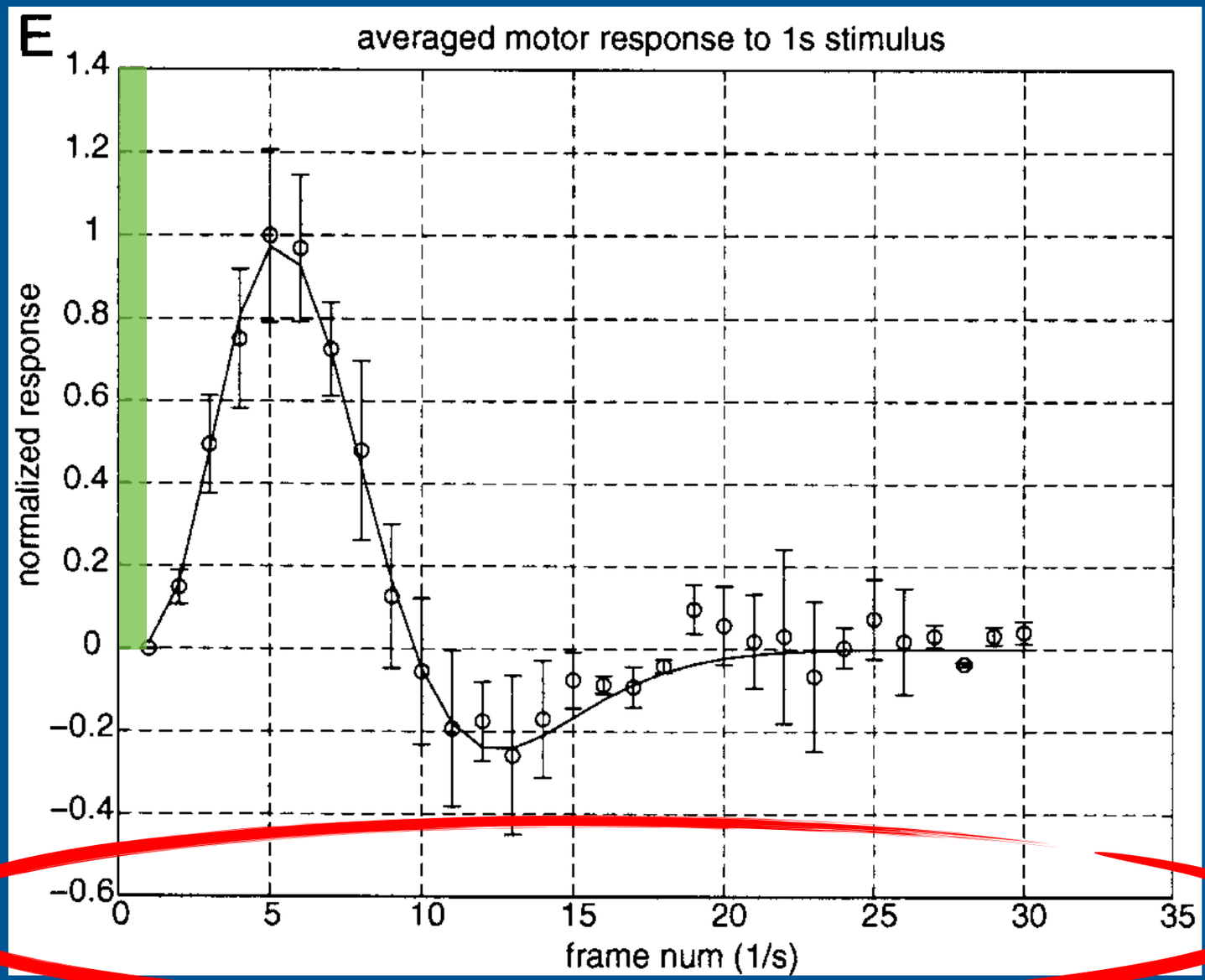
How fast is “fast”?



Typical image of brain structure: ~3–5 minutes

Optimised to balance speed and image quality

How fast is "fast"?



Glover, NeuroImage 1999

Functional changes in response to brain activity: ~seconds!

k-space Review

Image Credit: Google Images

"Pointillism"

In MRI, images are *not* created by directly sensing values associated with "pixel/voxels"

Image Credit: Google Images

k-space Review

Instead, the image is composed by measuring and combining image elements that can span the entire image "canvas"

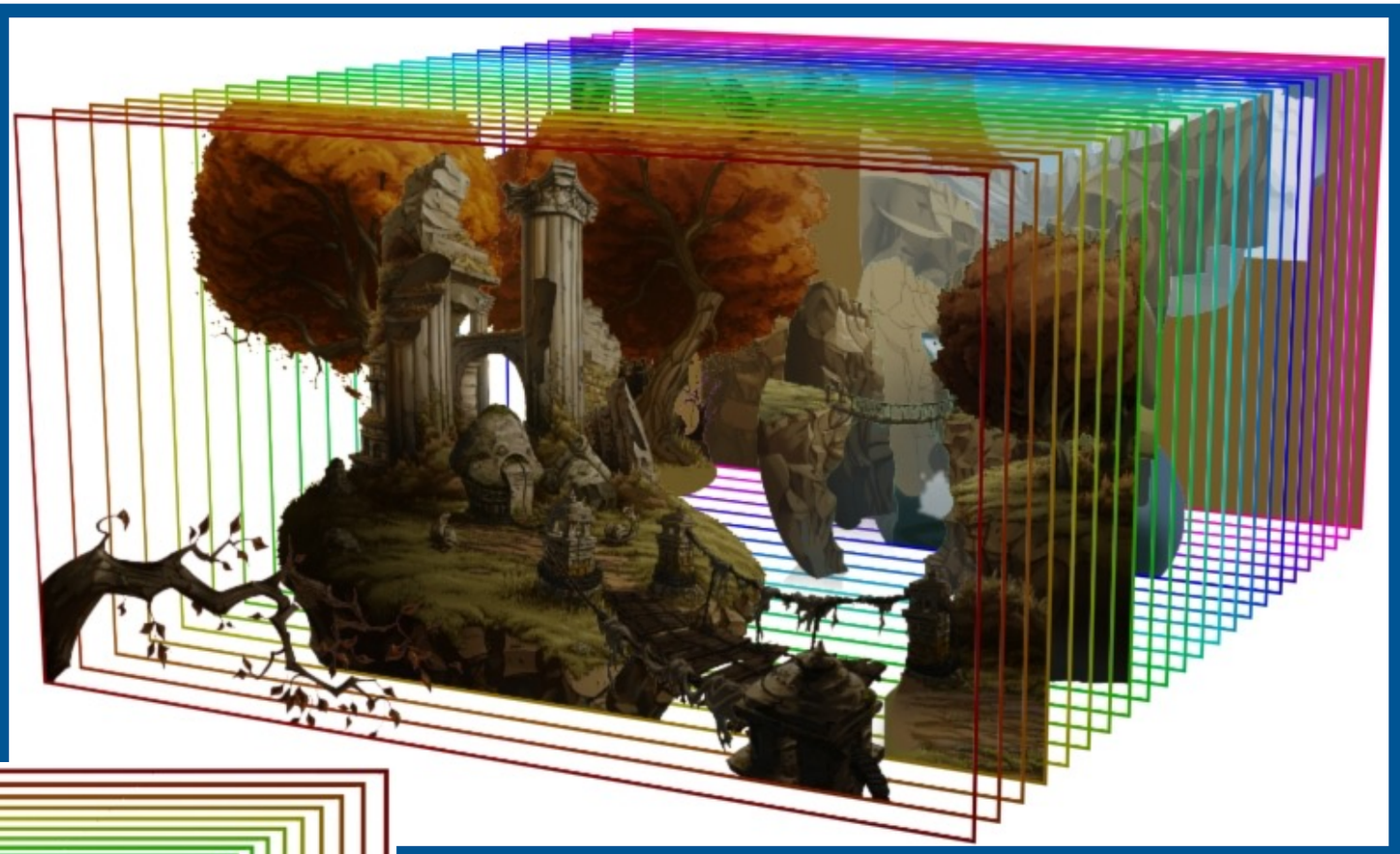


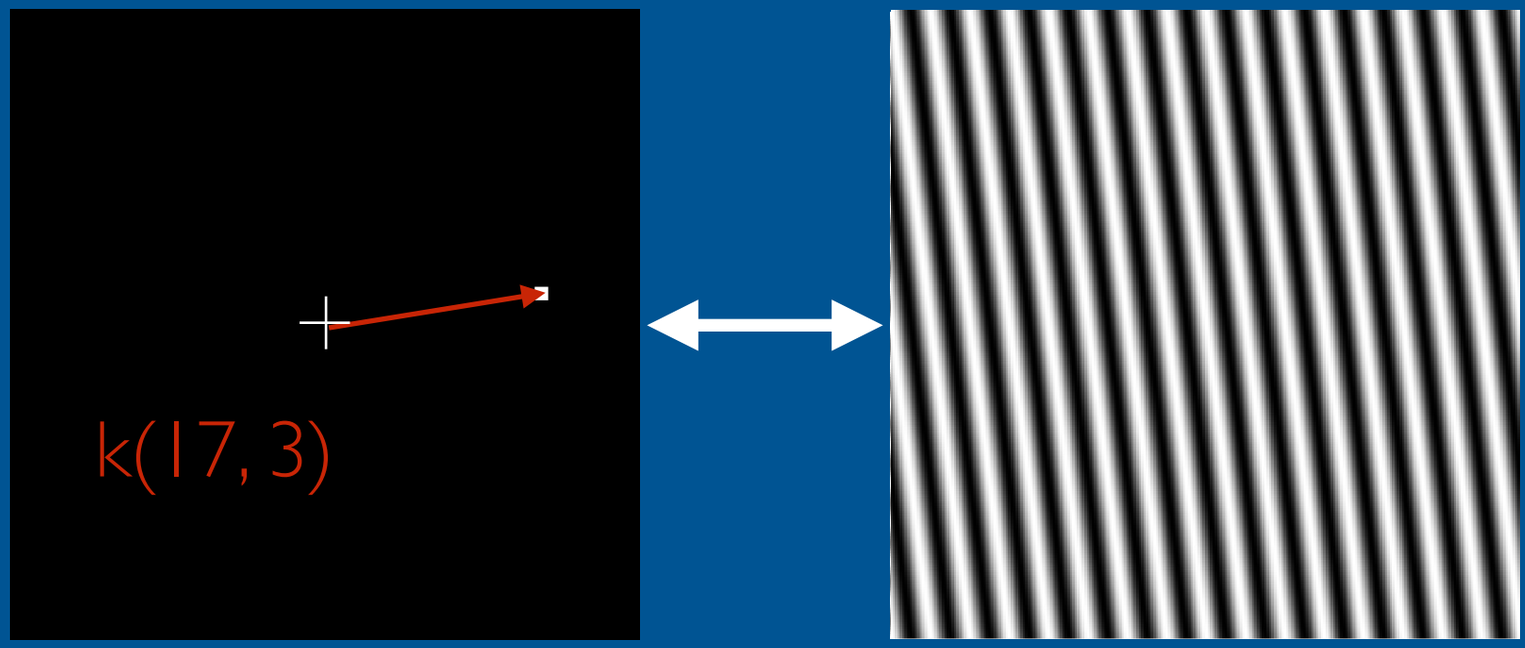
Image Credit: Wikipedia

Image Credit: Wikipedia

The measured contribution of each element to the image is recorded in *k-space*

k-space Review

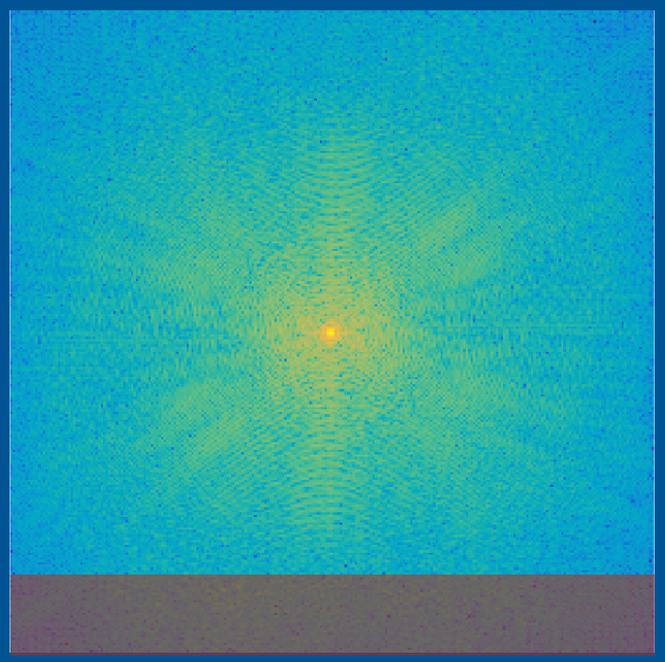
In real k-space, the image elements are more abstract

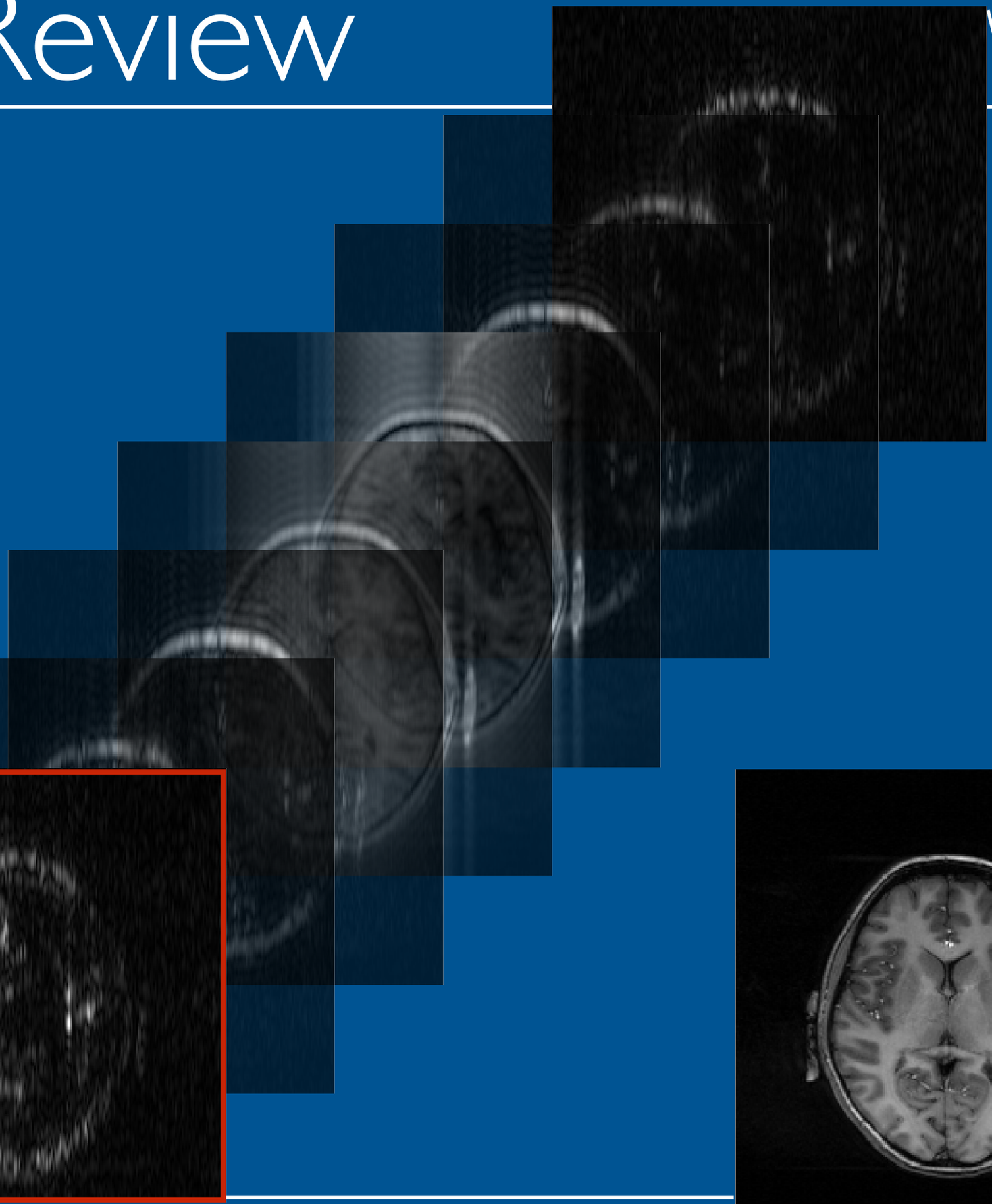


Each k-space location maps to a different image basis element

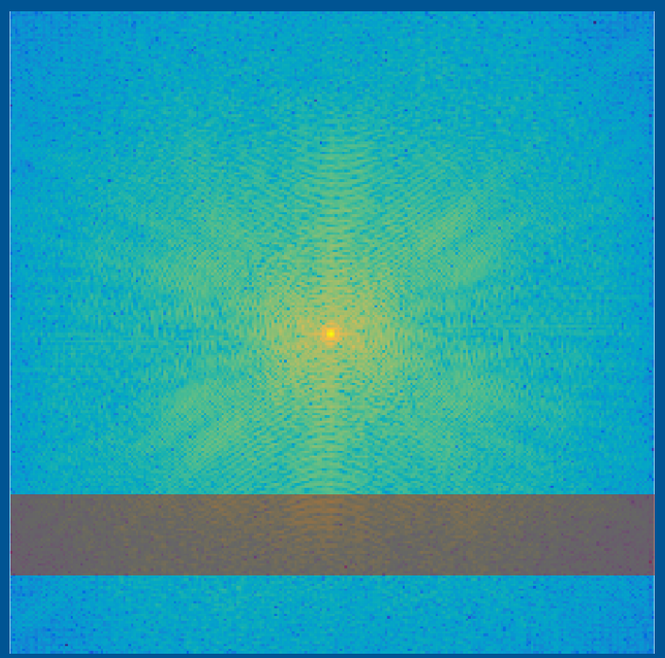
The values recorded in each k-space bin reflect
the strength of each element in the image composition

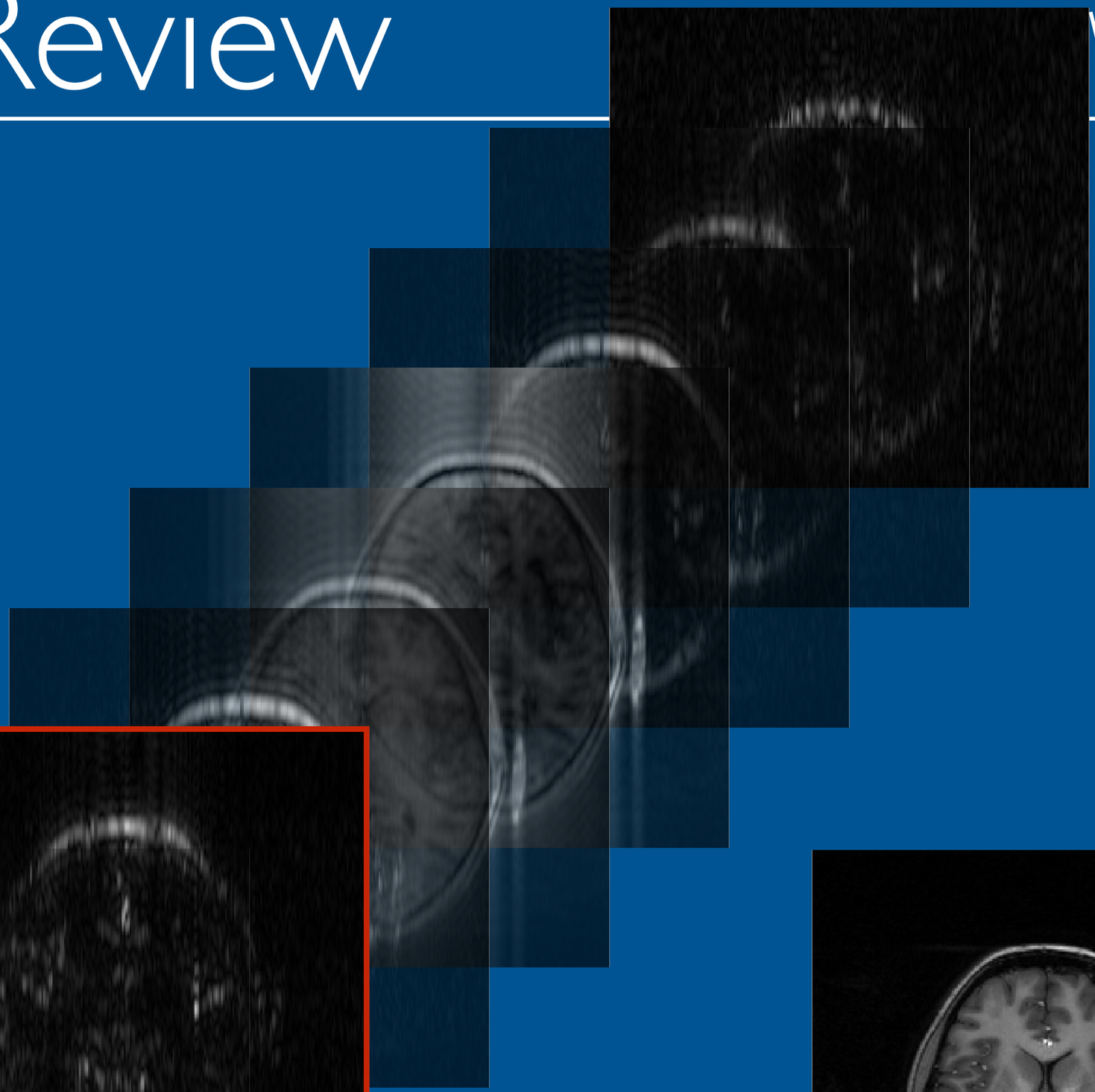
k-space Review

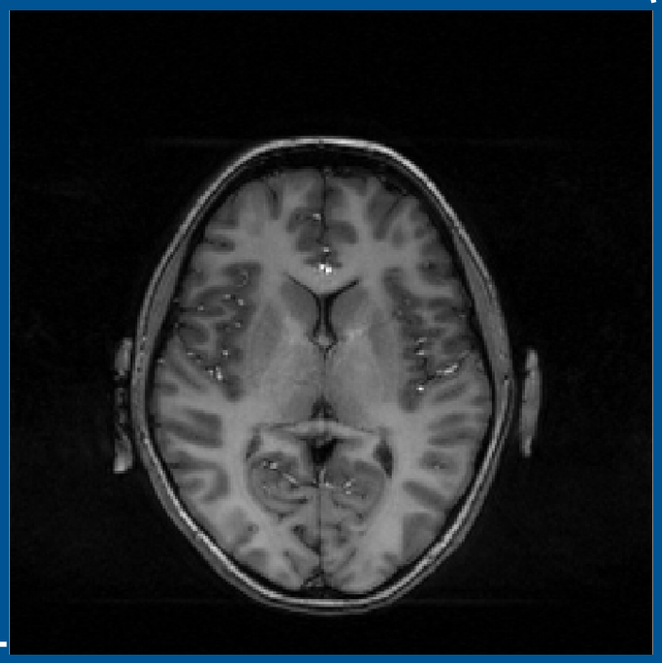




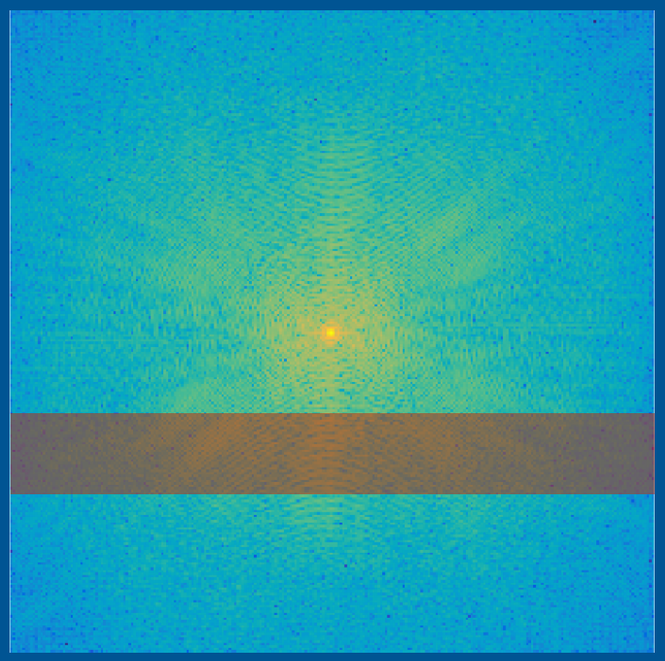
k-space Review

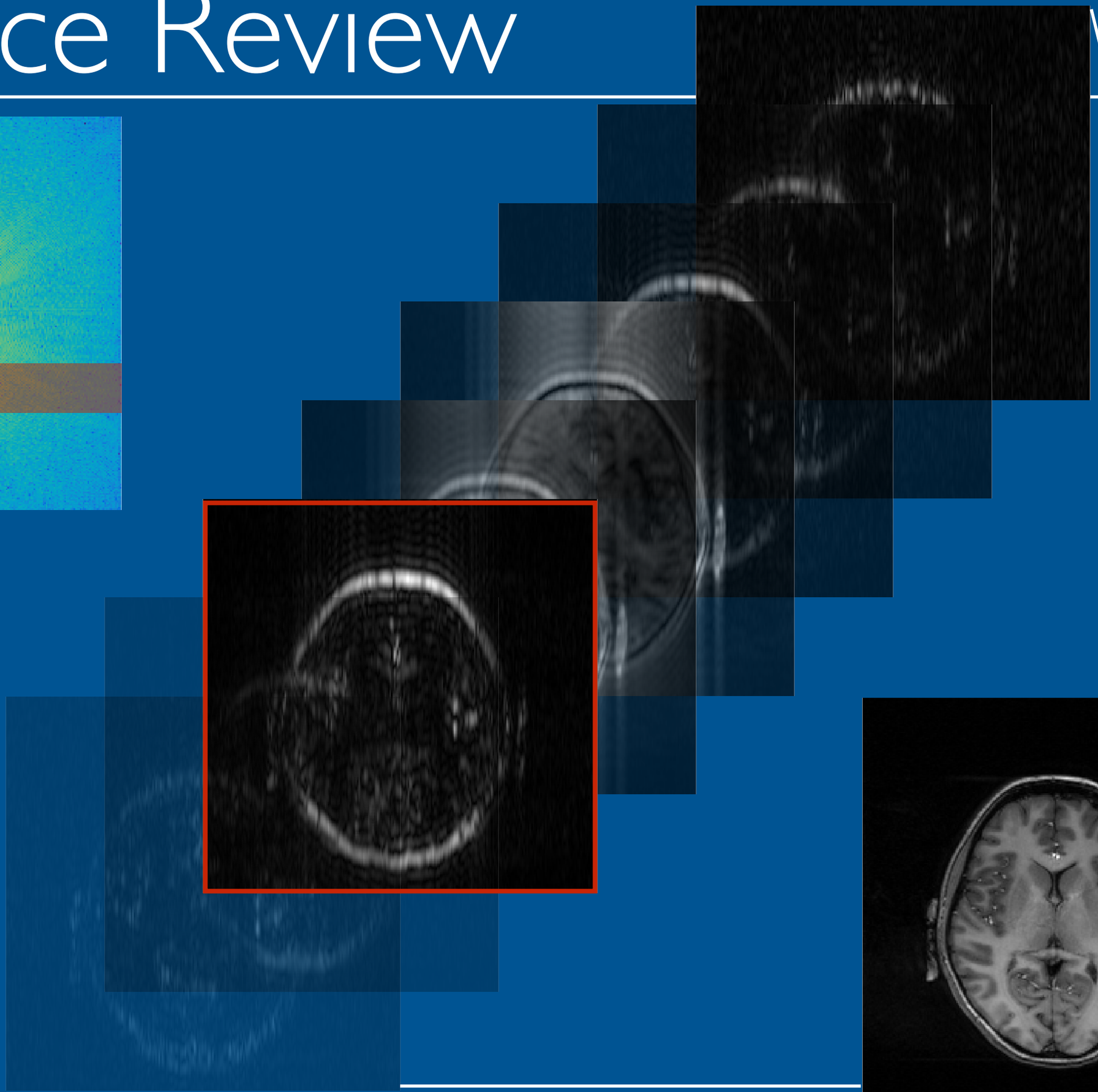




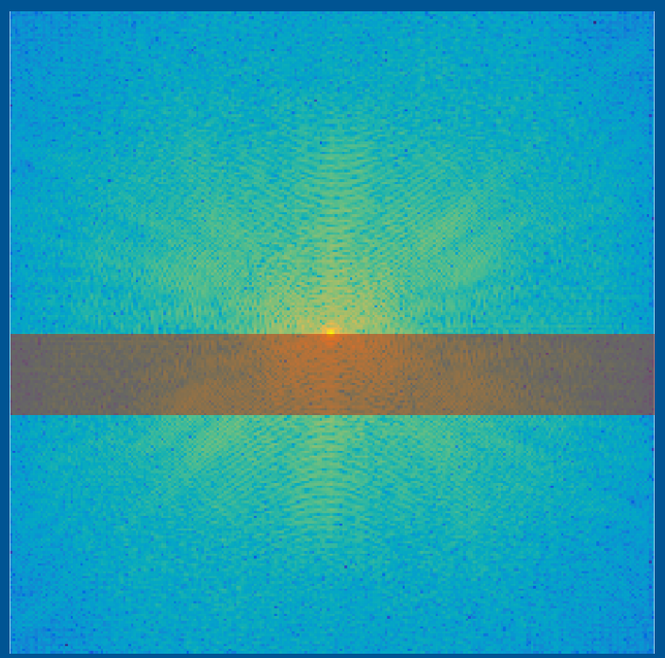


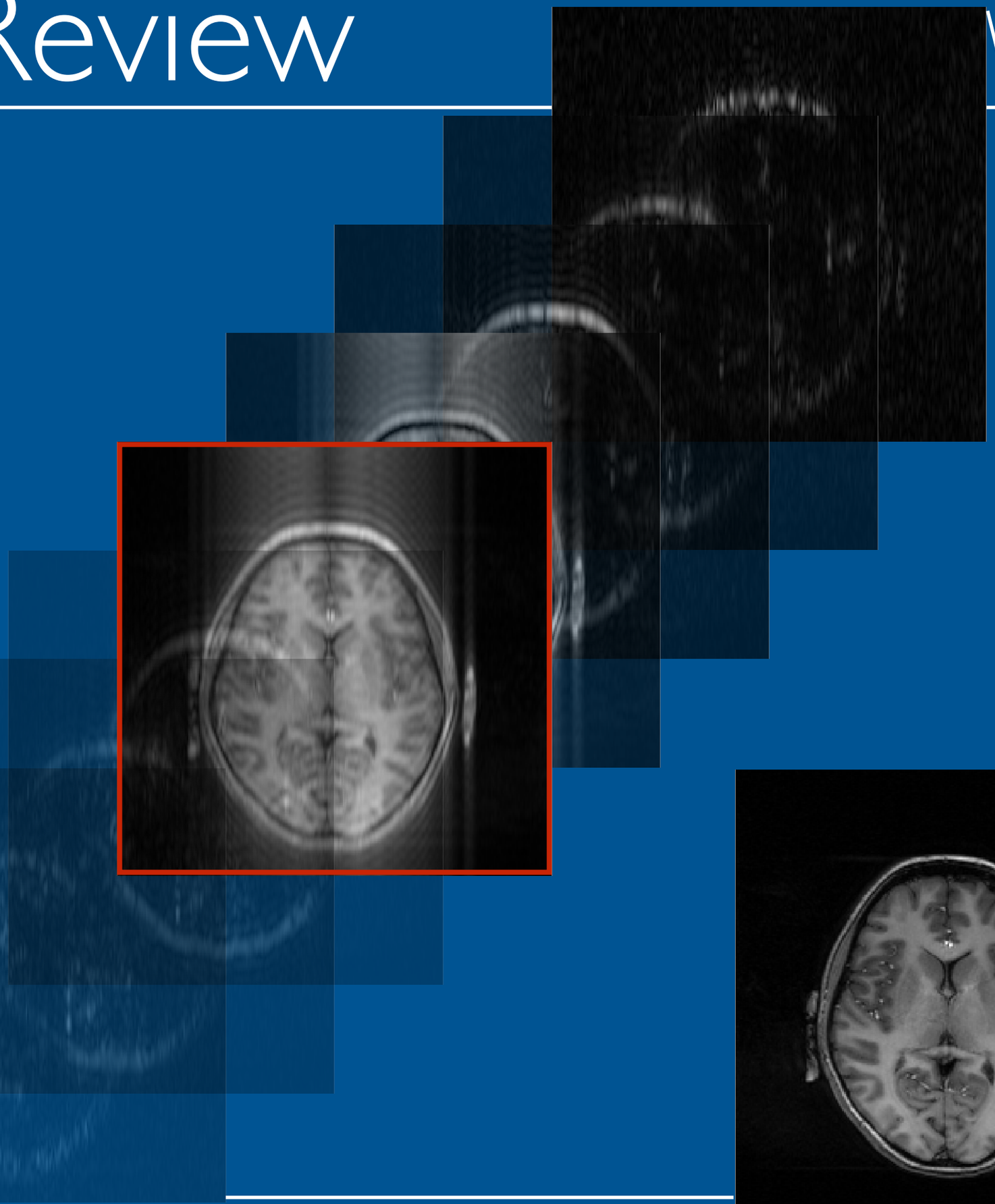
k-space Review



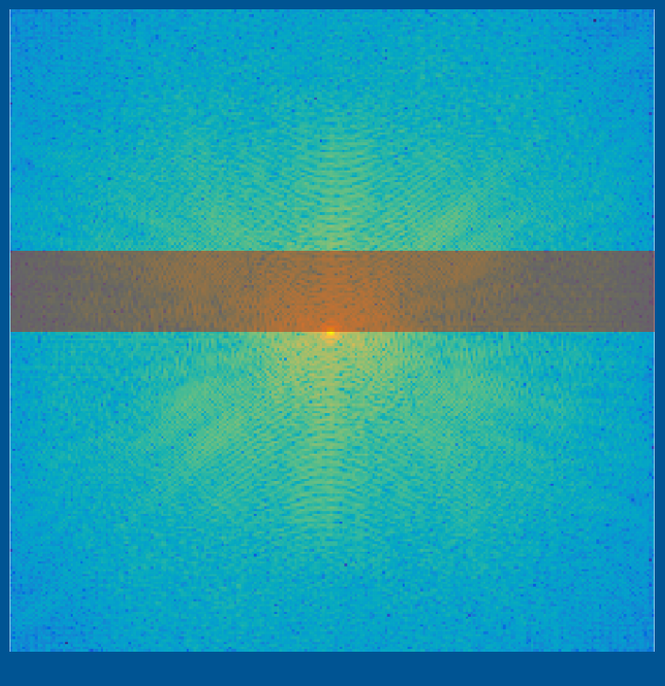


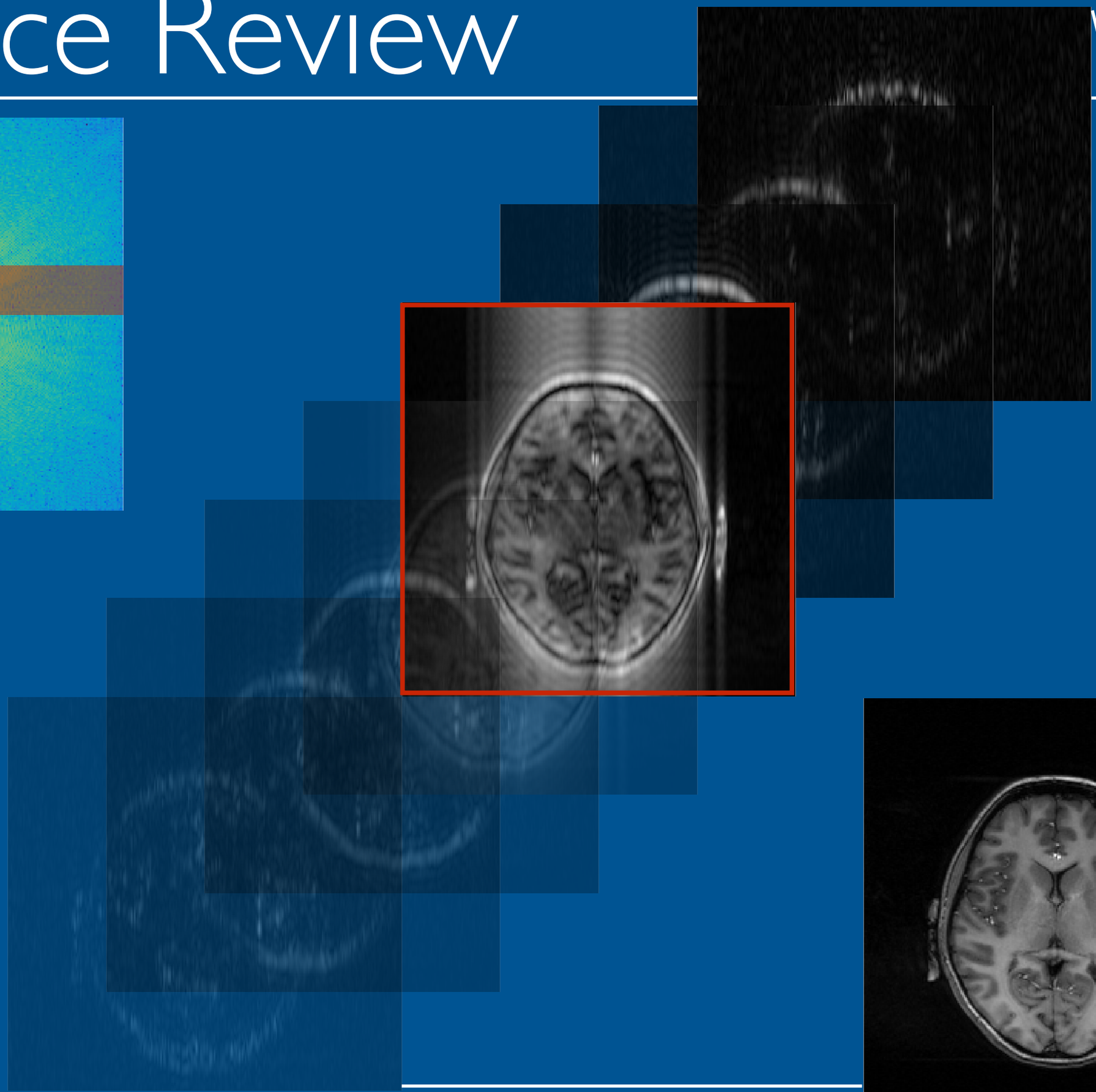
k-space Review



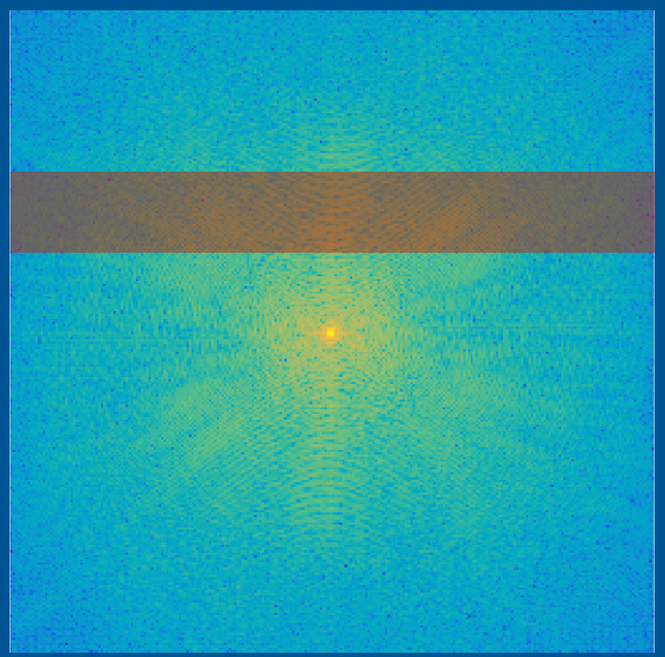


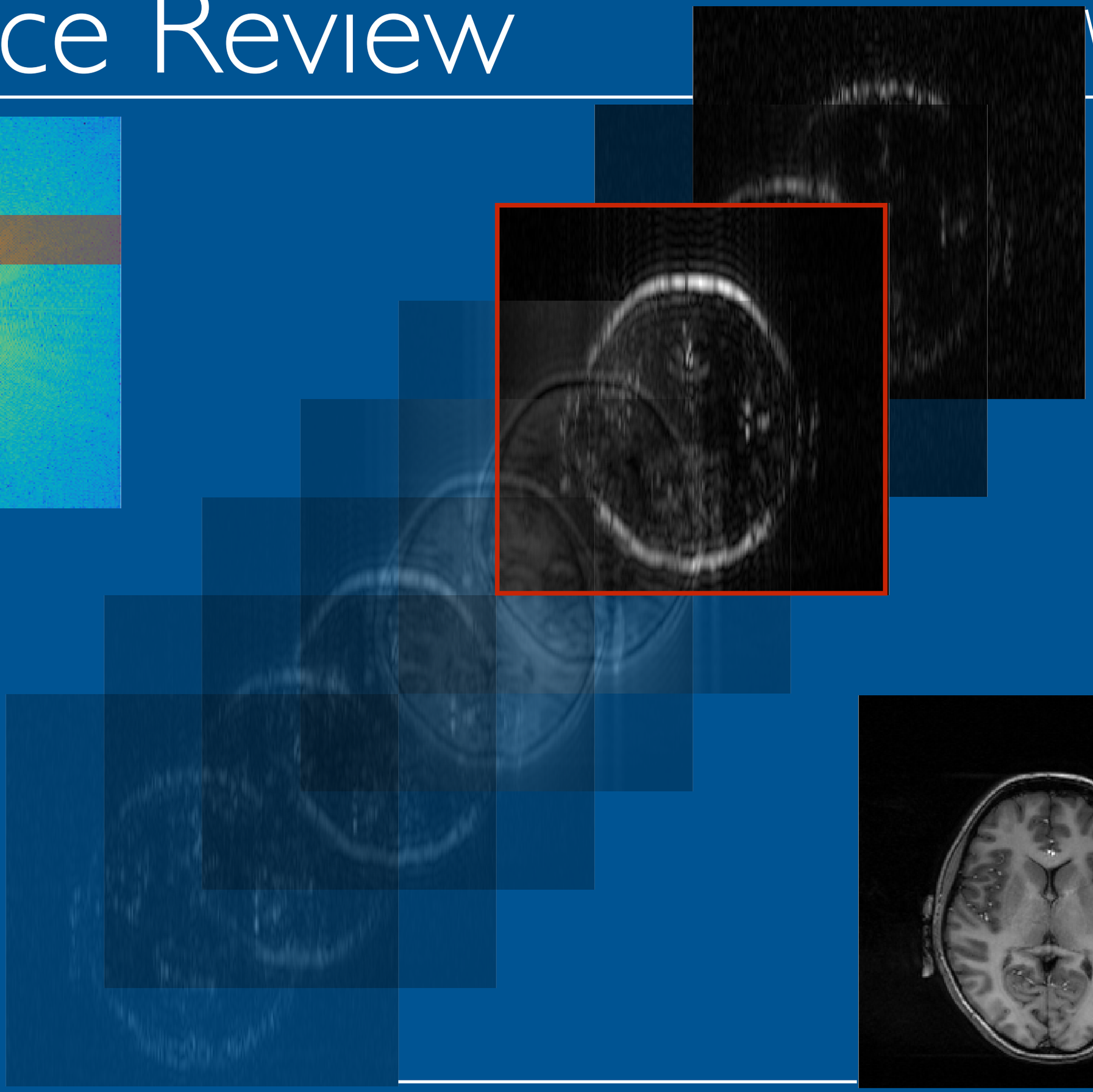
k-space Review



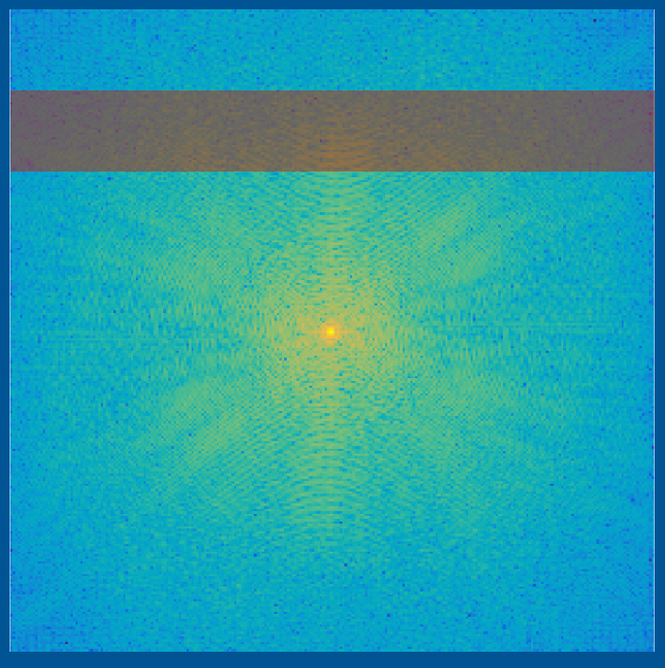


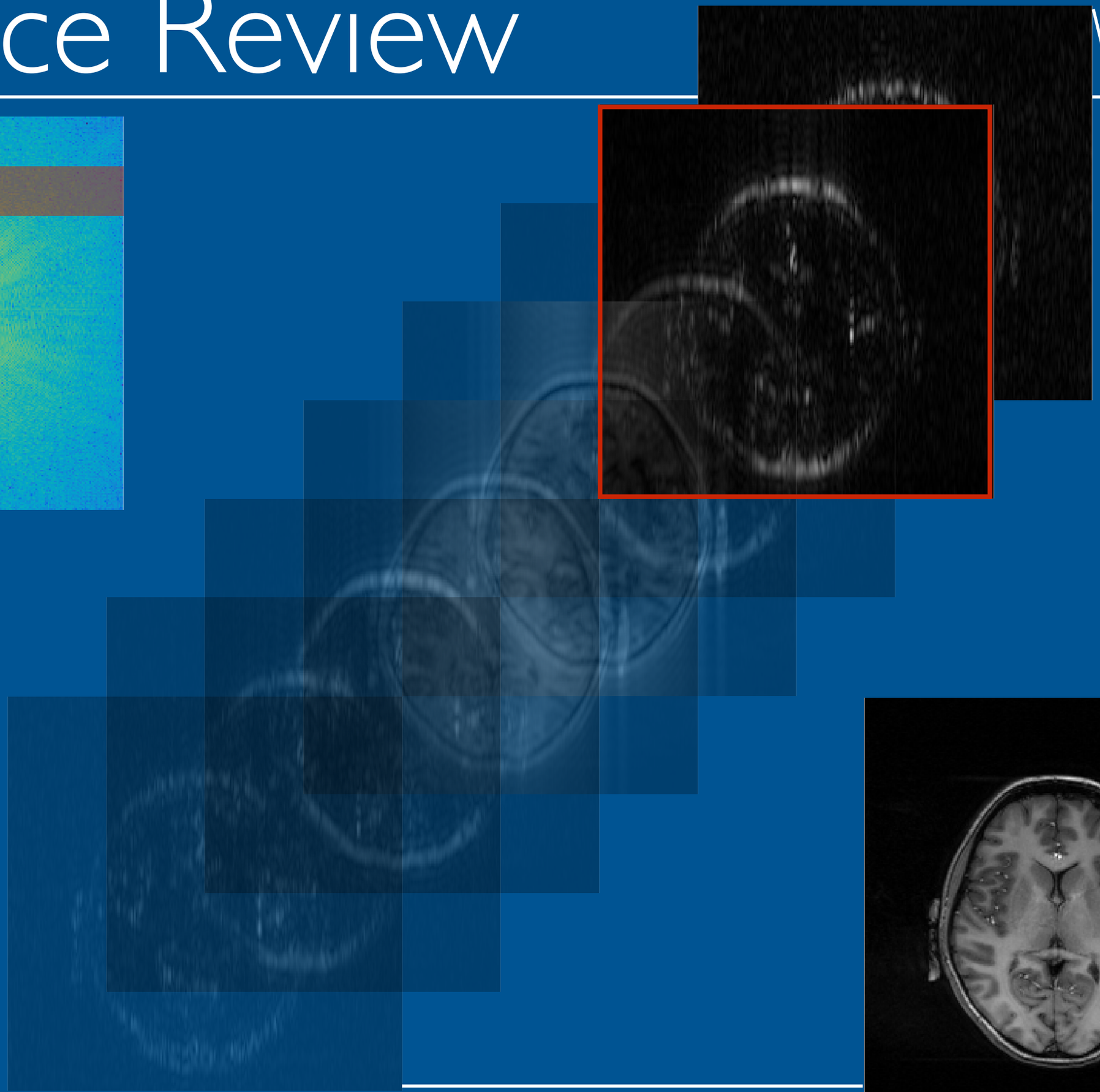
k-space Review



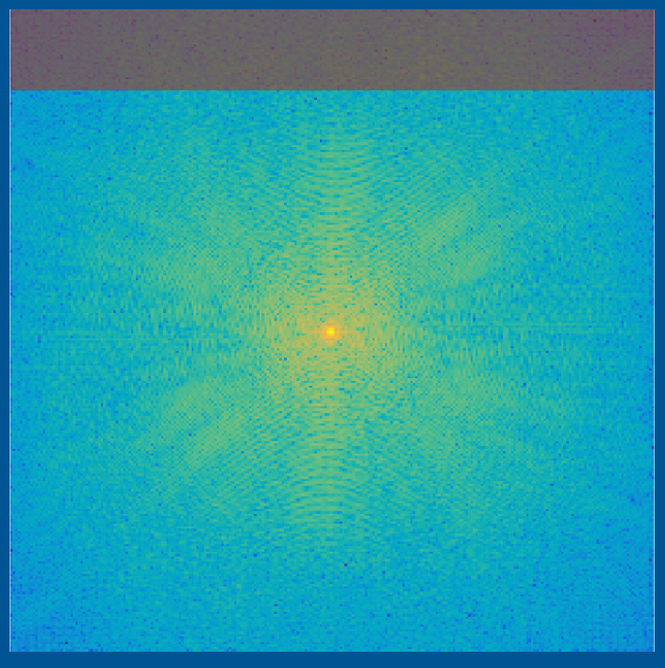


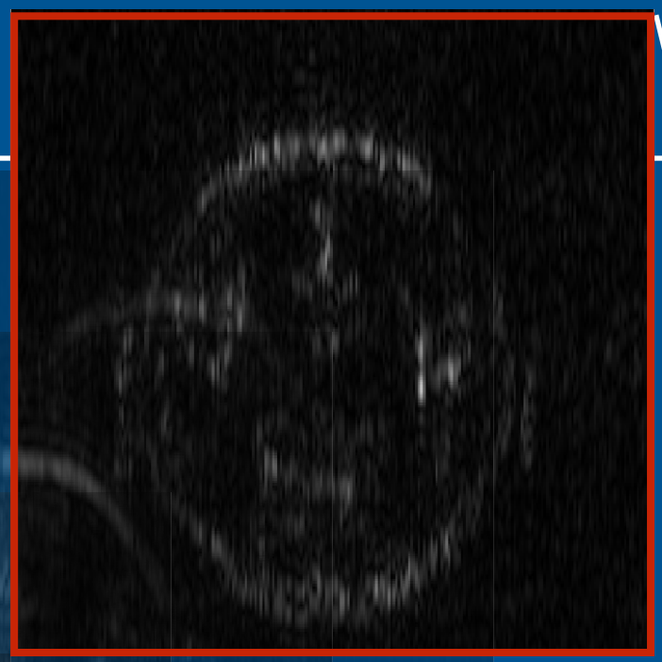
k-space Review

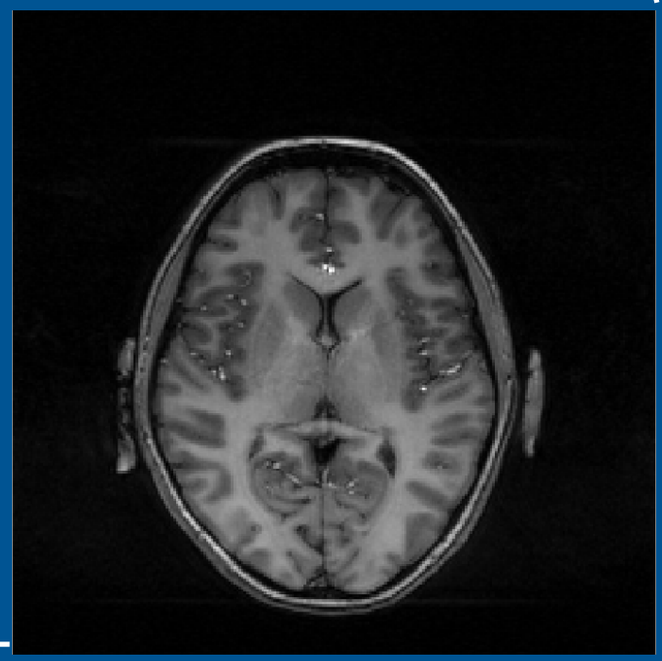




k-space Review



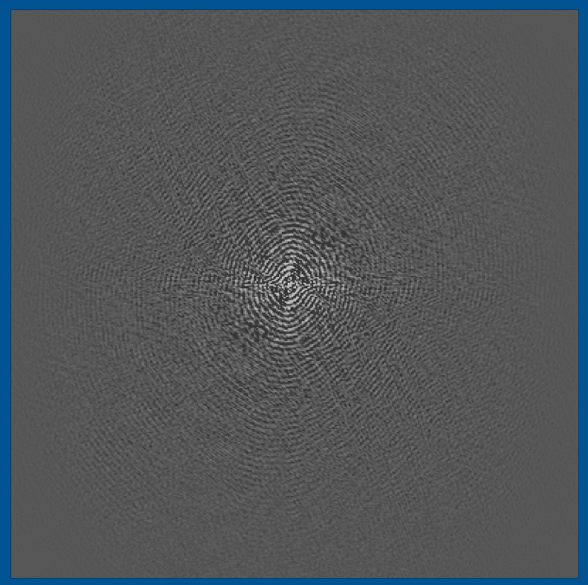




k-Space

The measurement process in MRI determines the values of different points in k-space

k-space



Fourier Transform

image space

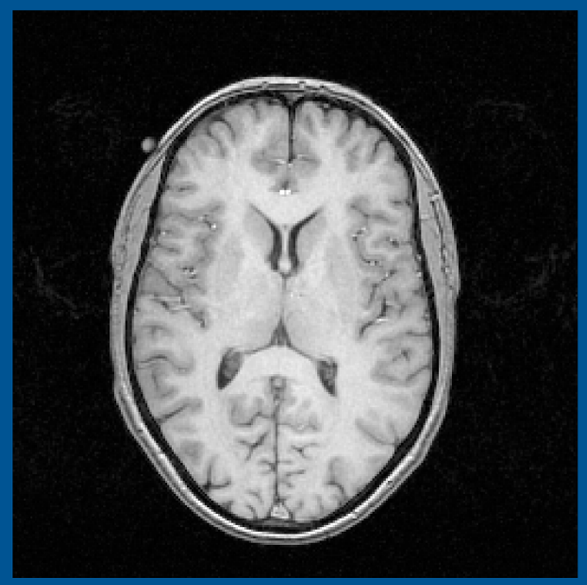


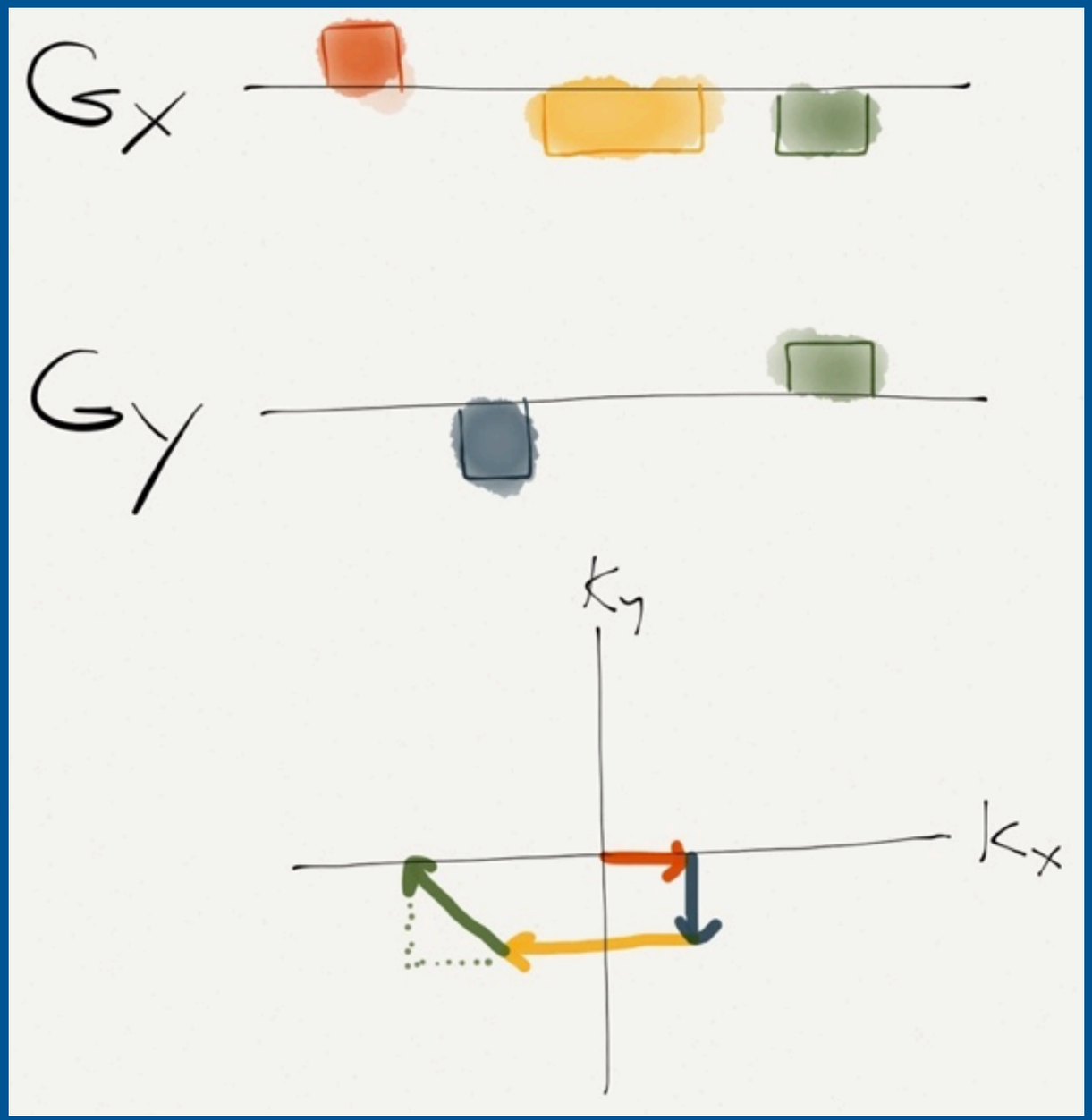
Image properties, like resolution, depend on sampling in k-space

i.e. How many, and which basis elements will be used to create the image?

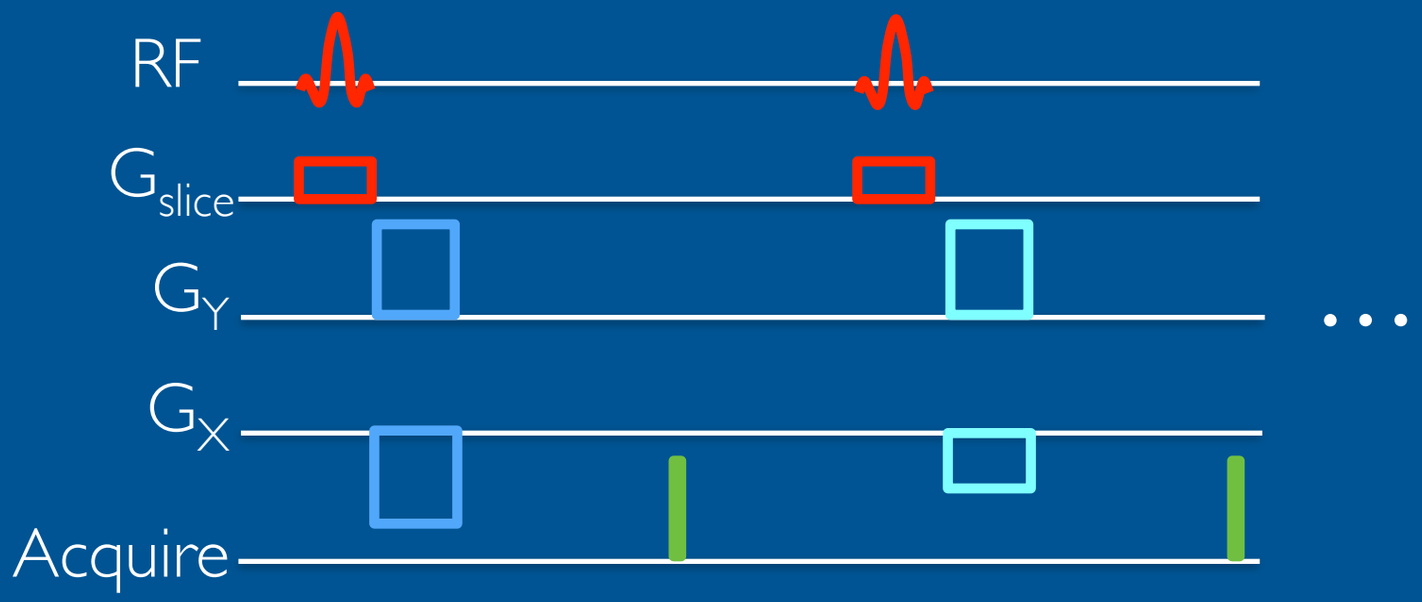
<u>k-space samples, however, must be acquired serially!</u>

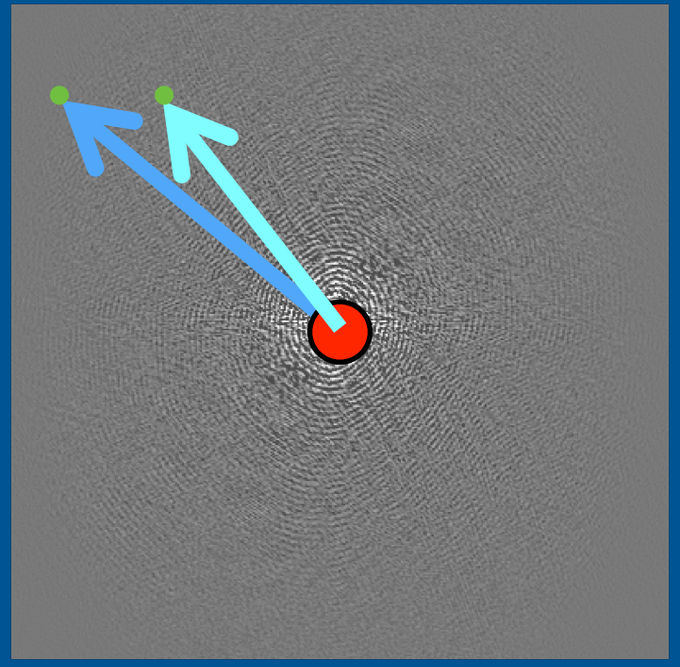
Movement in k-space

Magnetic field gradients control k-space sampling locations



The Most Inefficient Sampling

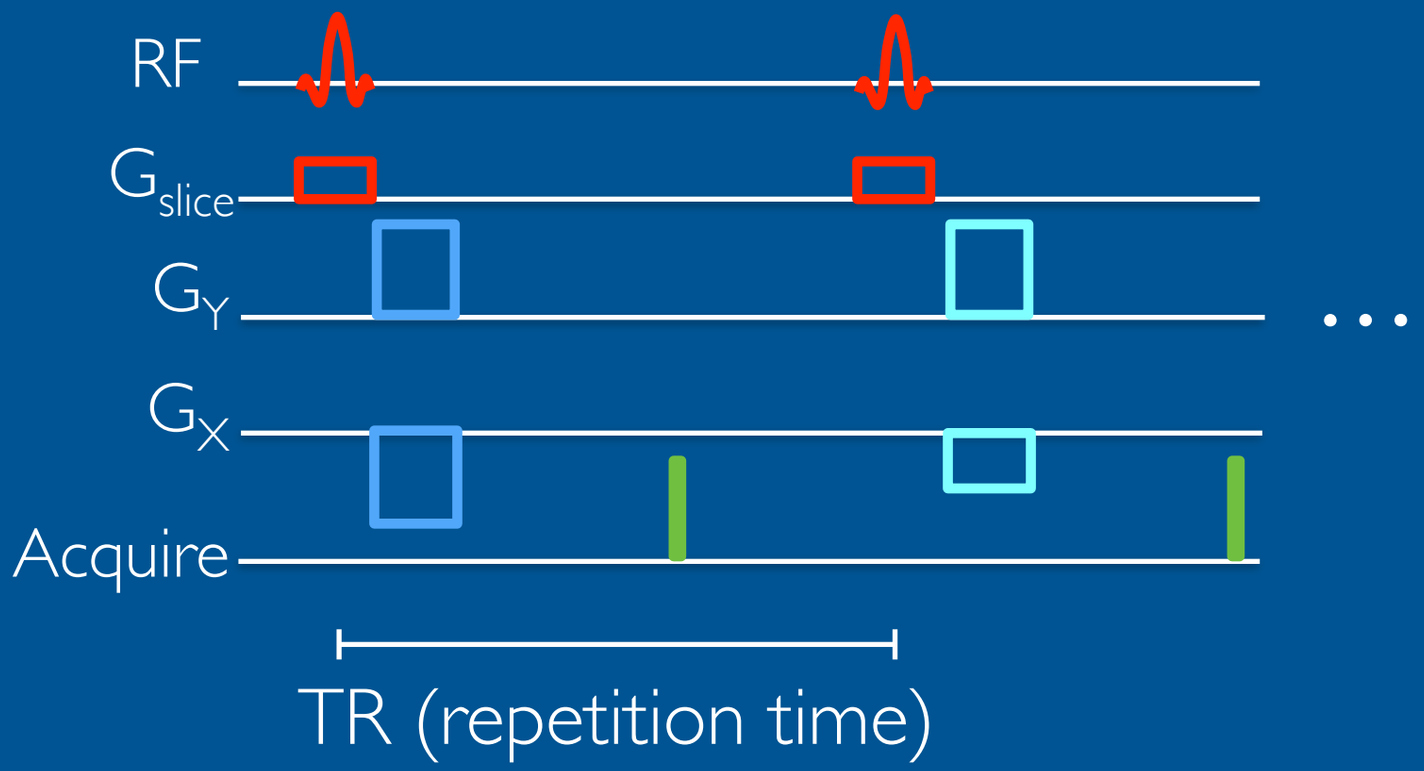




Excite the magnetisation, move to a location in k-space, and record the signal

Repeat for every k-space point you need to measure!

The Most Inefficient Sampling



For a 256x256 k-space corresponding to a 1 mm resolution image:

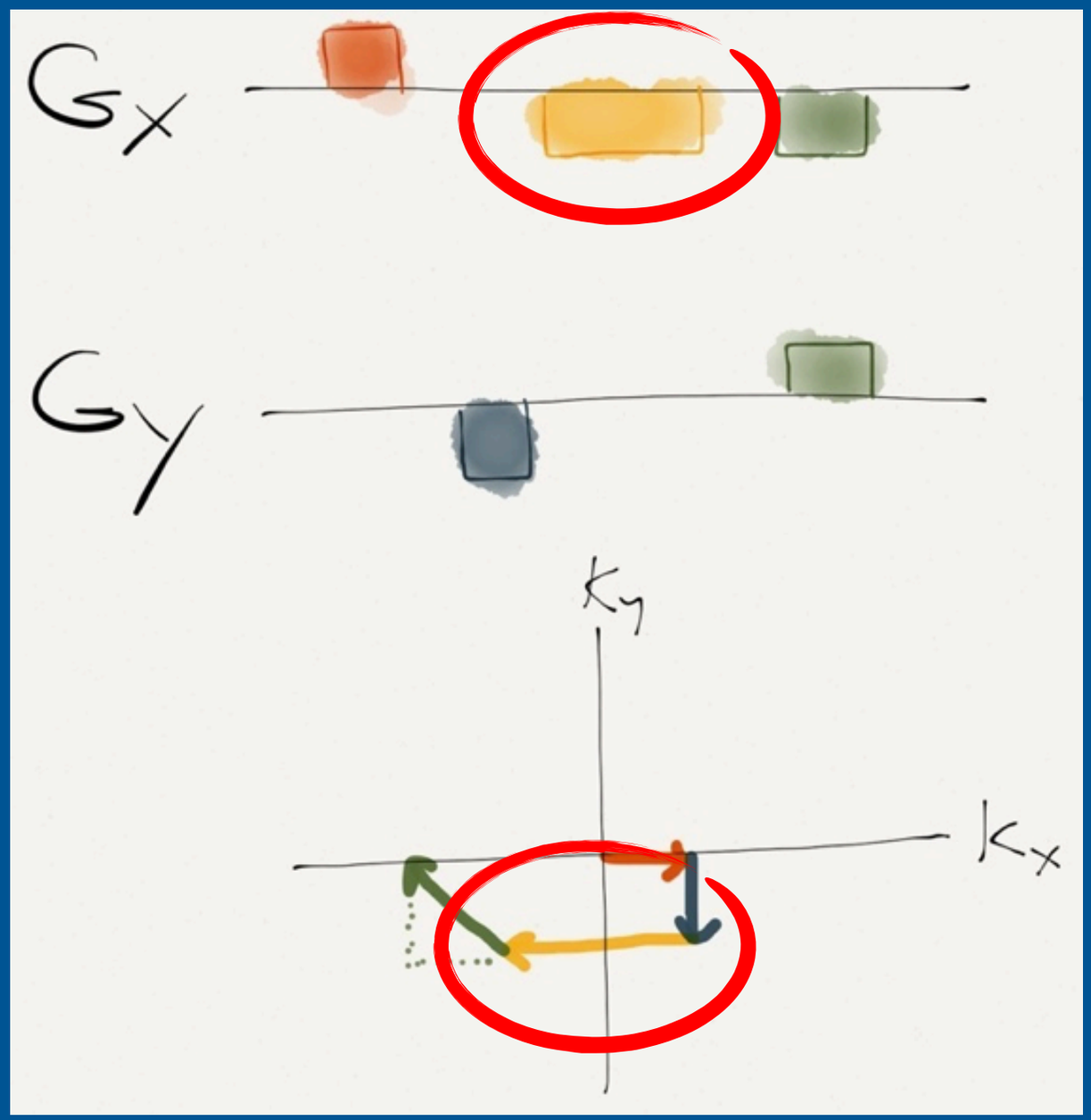
$$\text{Total Imaging Time} = \text{TR} \times \#k_x \text{ points} \times \#k_y \text{ points} \times \#\text{slices}$$

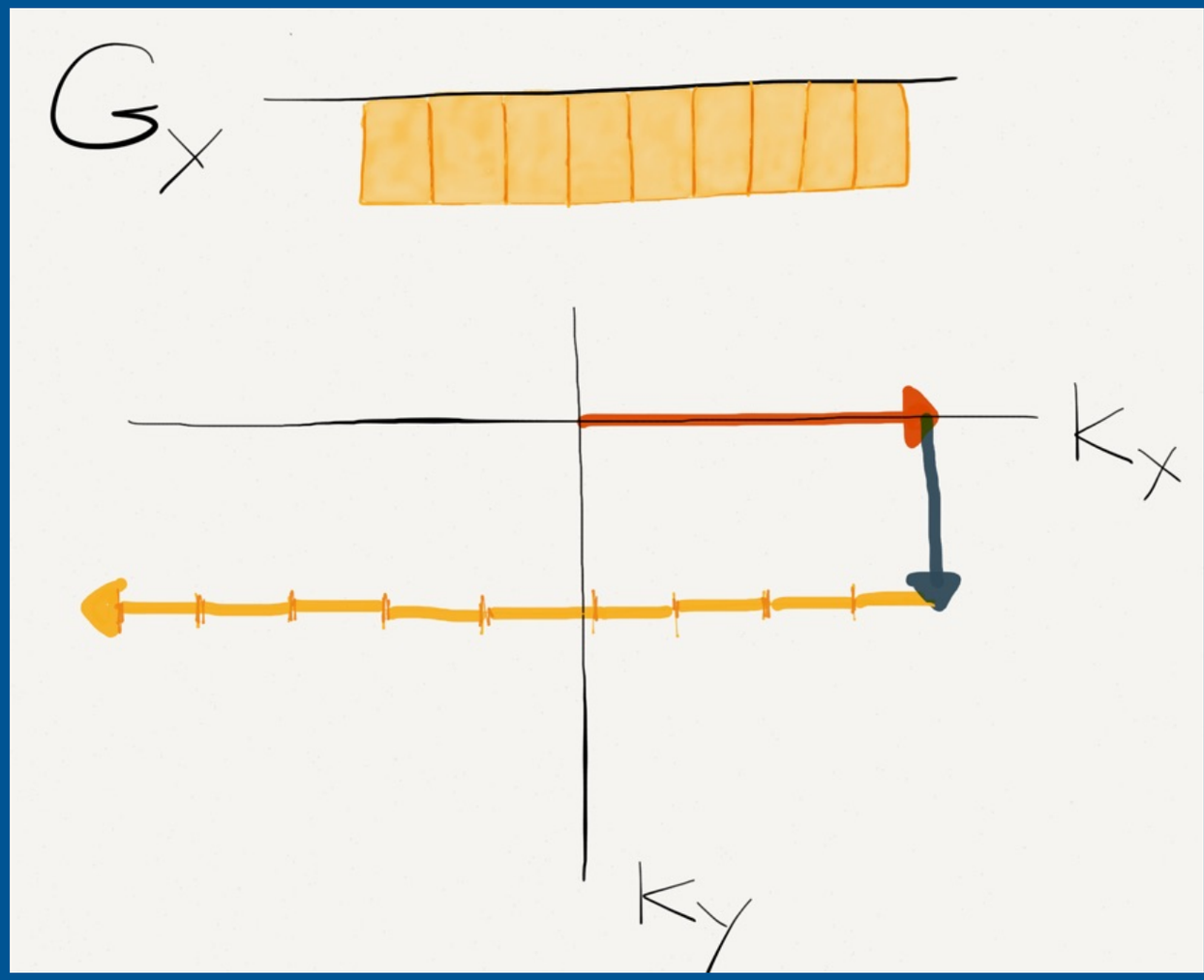
$$= (10 \text{ ms}) \times 256 \times 256 \times 128$$

$$= \sim 23 \text{ hours!}$$

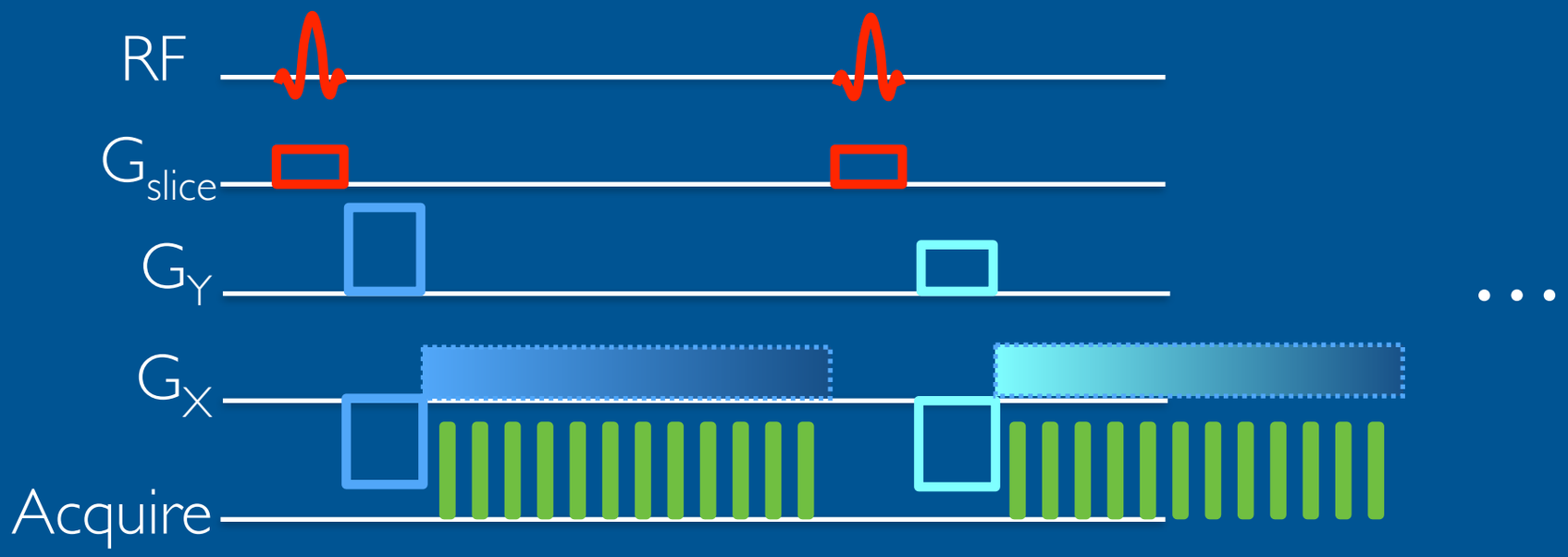
Adjacent k-space positions

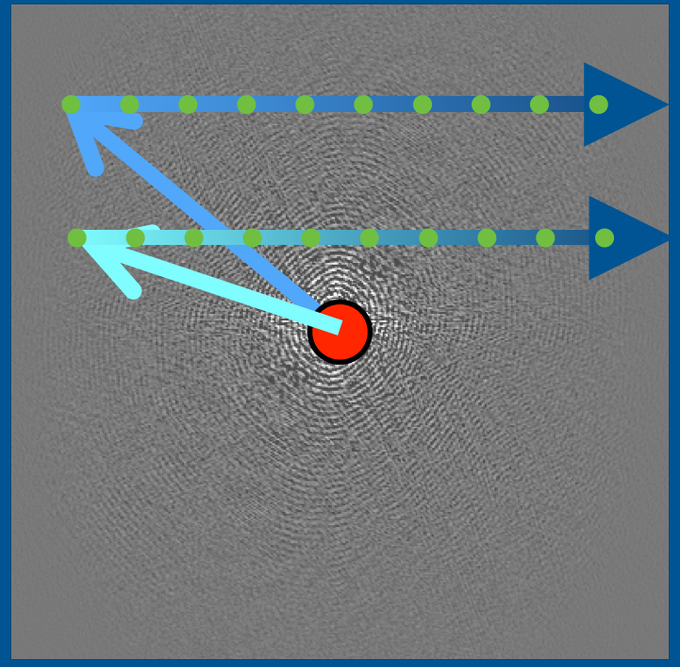
Luckily, adjacent positions in k-space are fast and easy to reach!





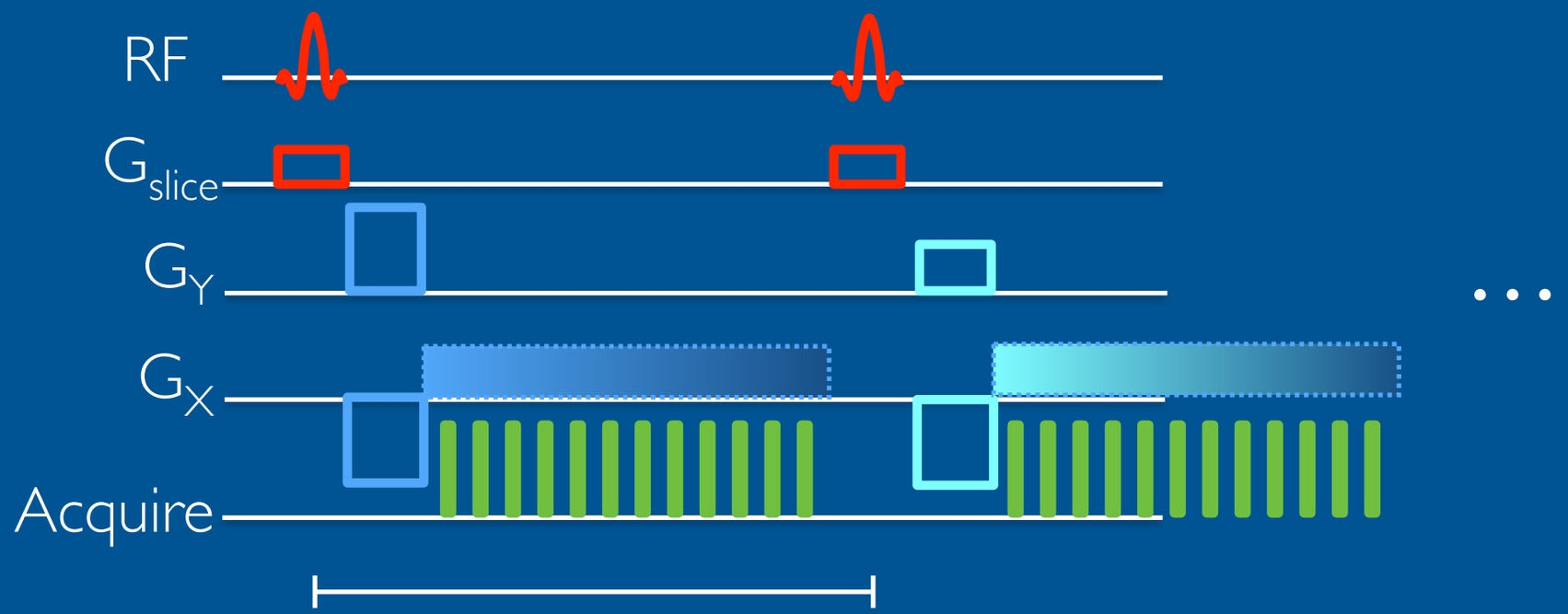
Typical k-space sampling





k-space sampling can be performed sequentially along a line

Typical k-space sampling



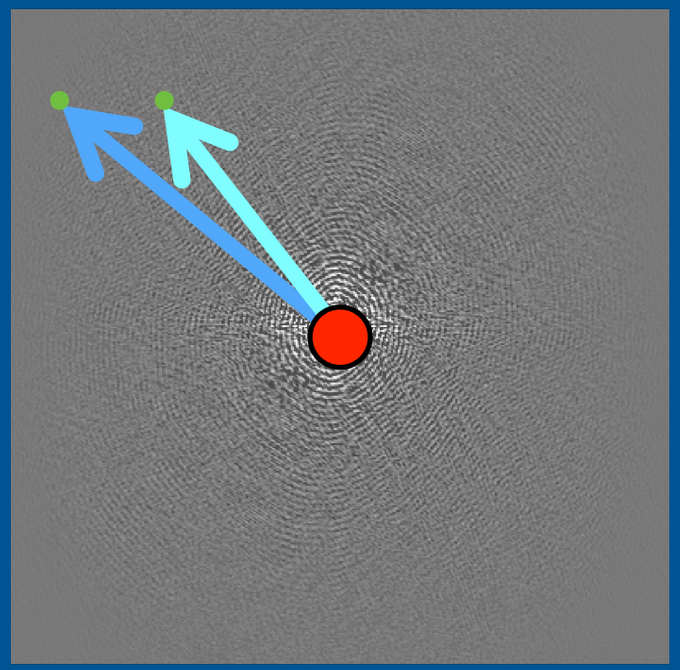
For a 256x256 k-space corresponding to a 1 mm resolution image:

Total Imaging Time = TR × #k_y points × #slices

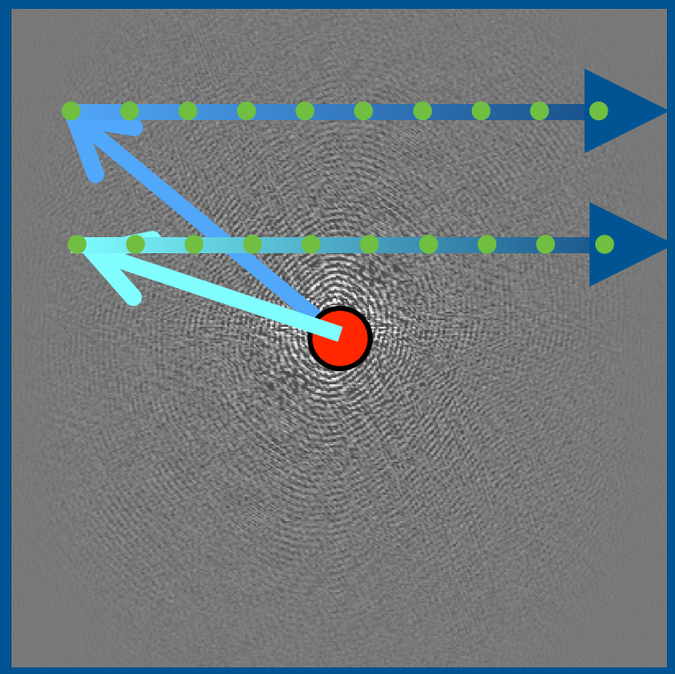
= (12 ms) × 256 × 128

= ~5 min 30 seconds!

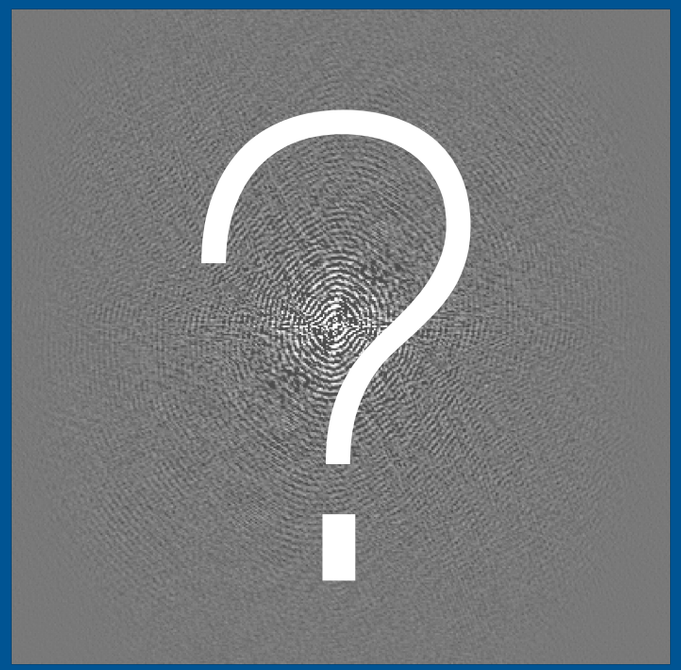
Faster k-space sampling



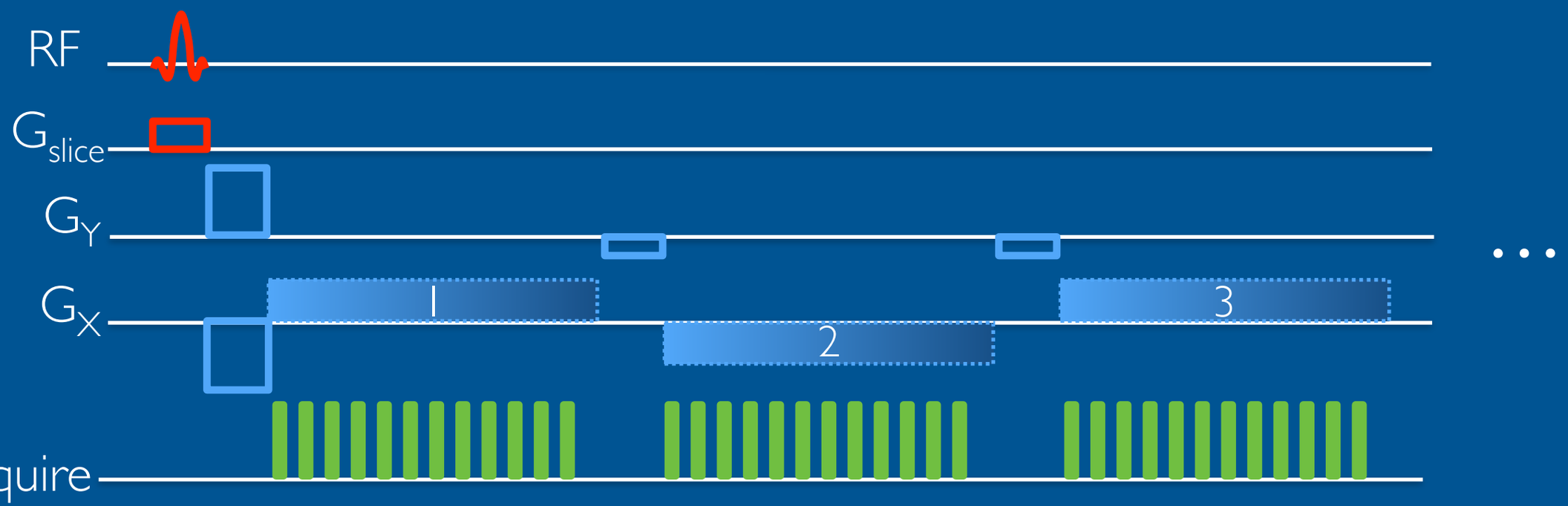
Point-by-point measurement

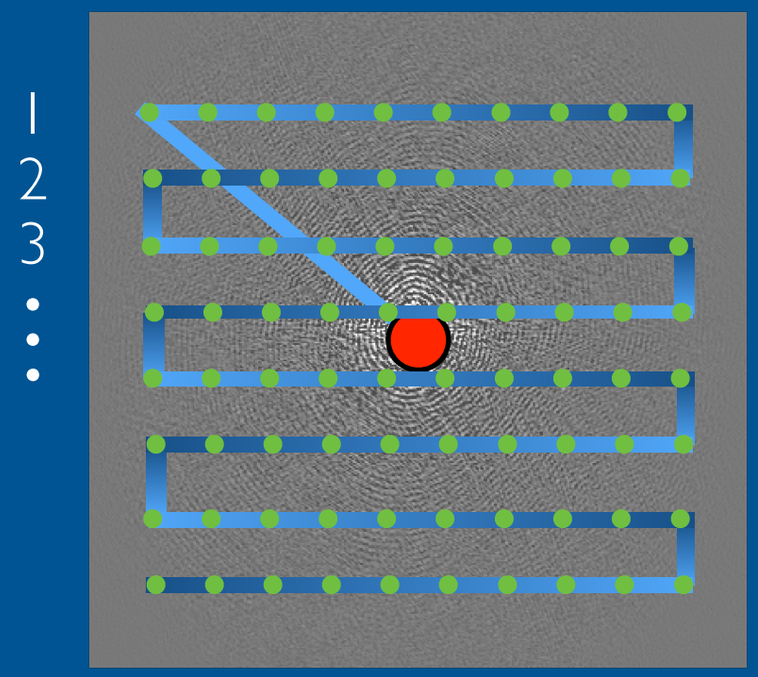


Line-by-line measurement



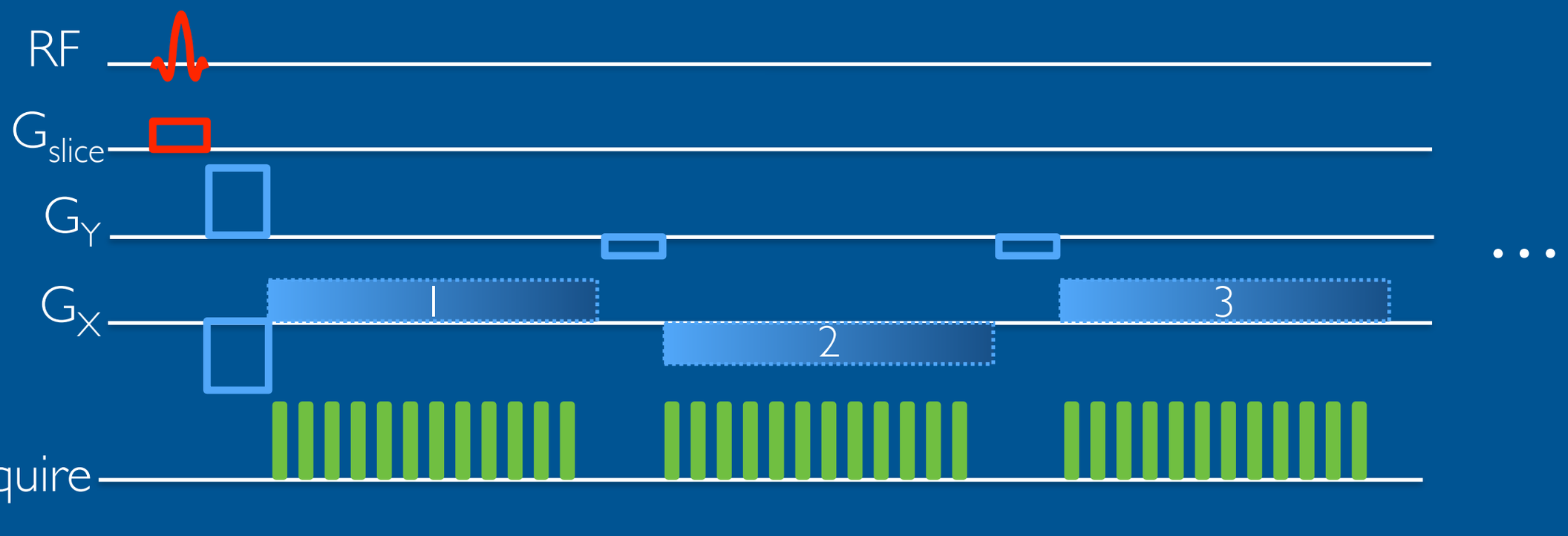
Echo-Planar Imaging (EPI)



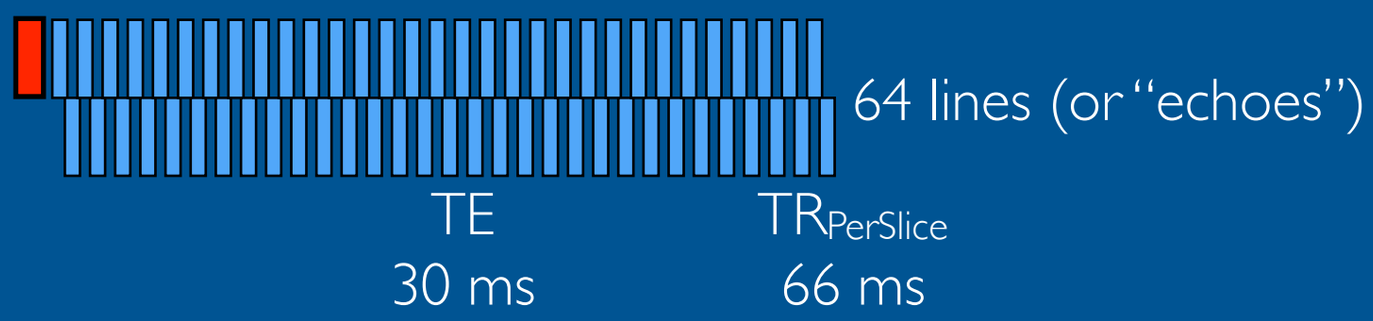


EPI sampling acquires all k-space measurements in a single excitation

Echo-Planar Imaging (EPI)



…



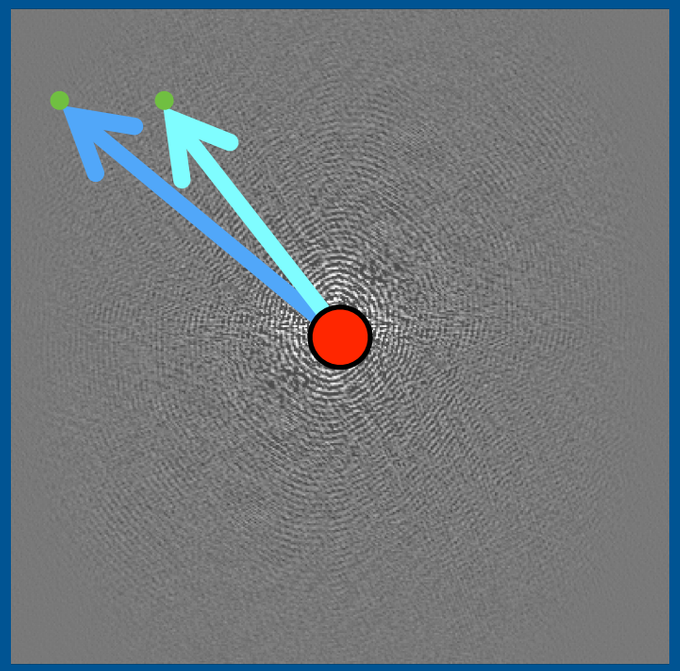
Total Imaging Time = TR × #slices

= (66 ms) × 45

= ~3 seconds

EPI k-space sampling

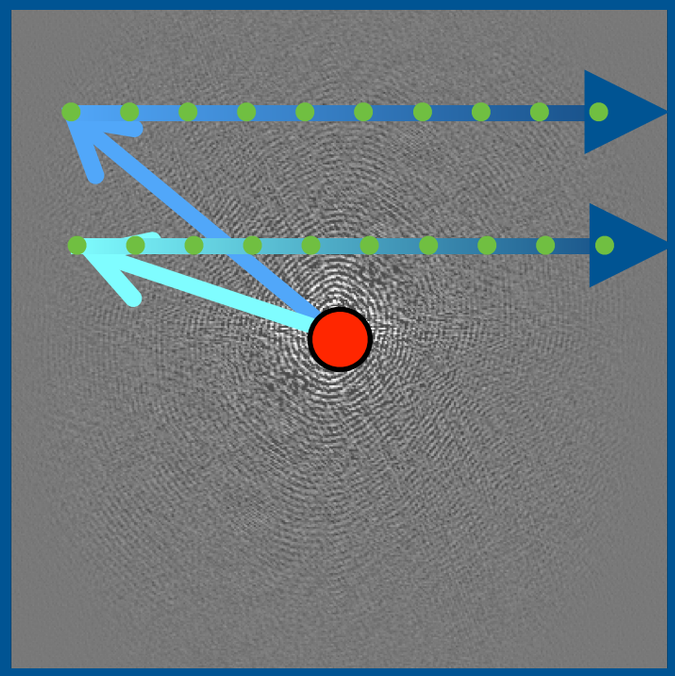
Significantly faster, but at the cost of some resolution loss



Point-by-point measurement

1 mm resolution

~ 23 hours



Line-by-line measurement

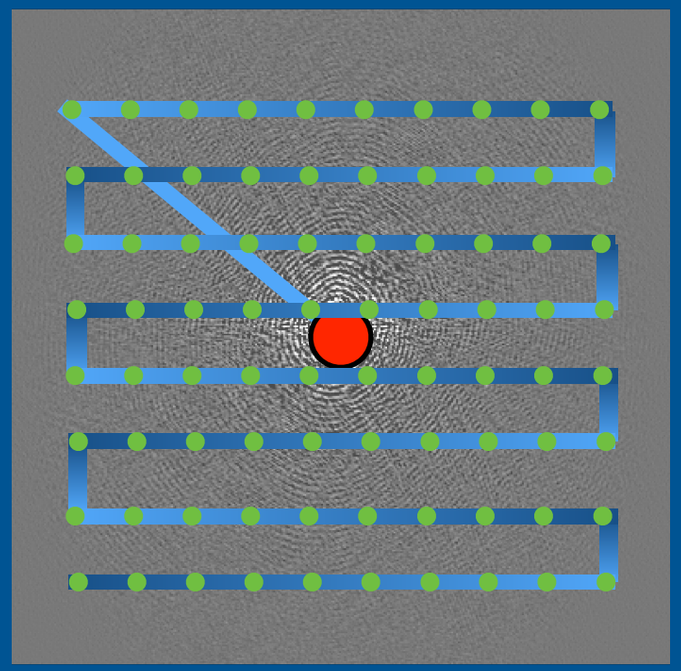
1 mm resolution

~ 5.5 minutes

EPI measurement

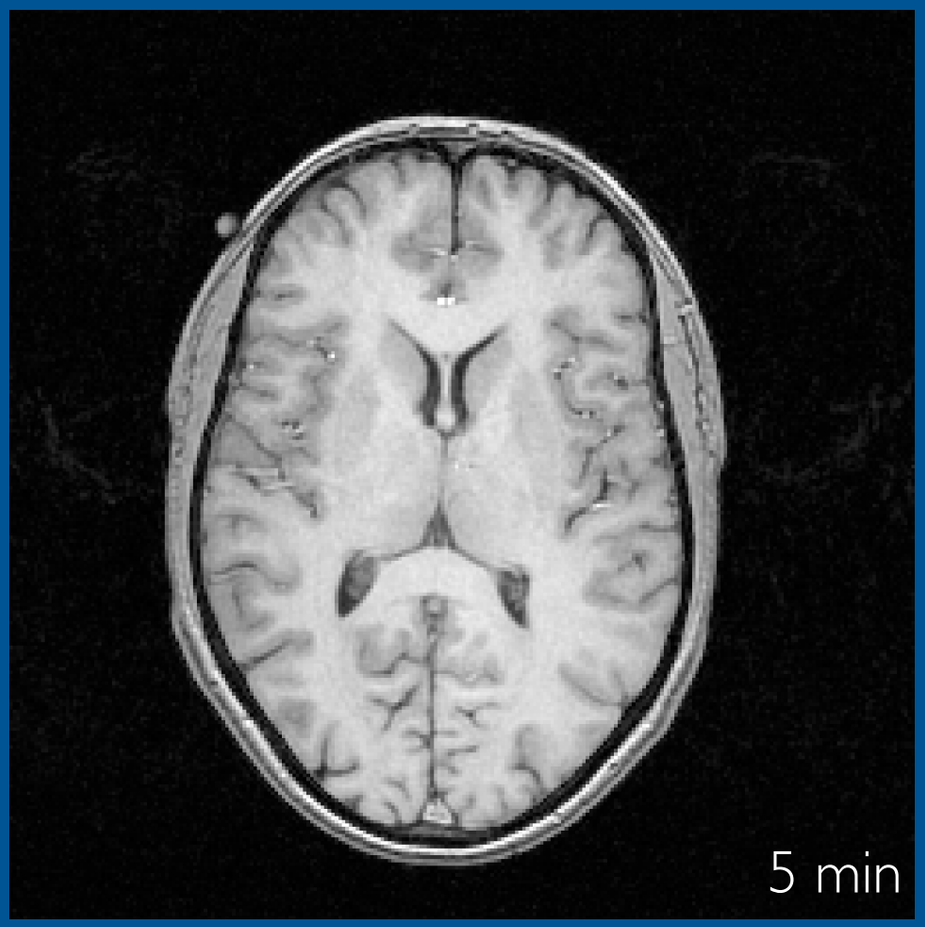
3 mm resolution

~ 3 seconds



Fast Images

There are costs associated with faster imaging



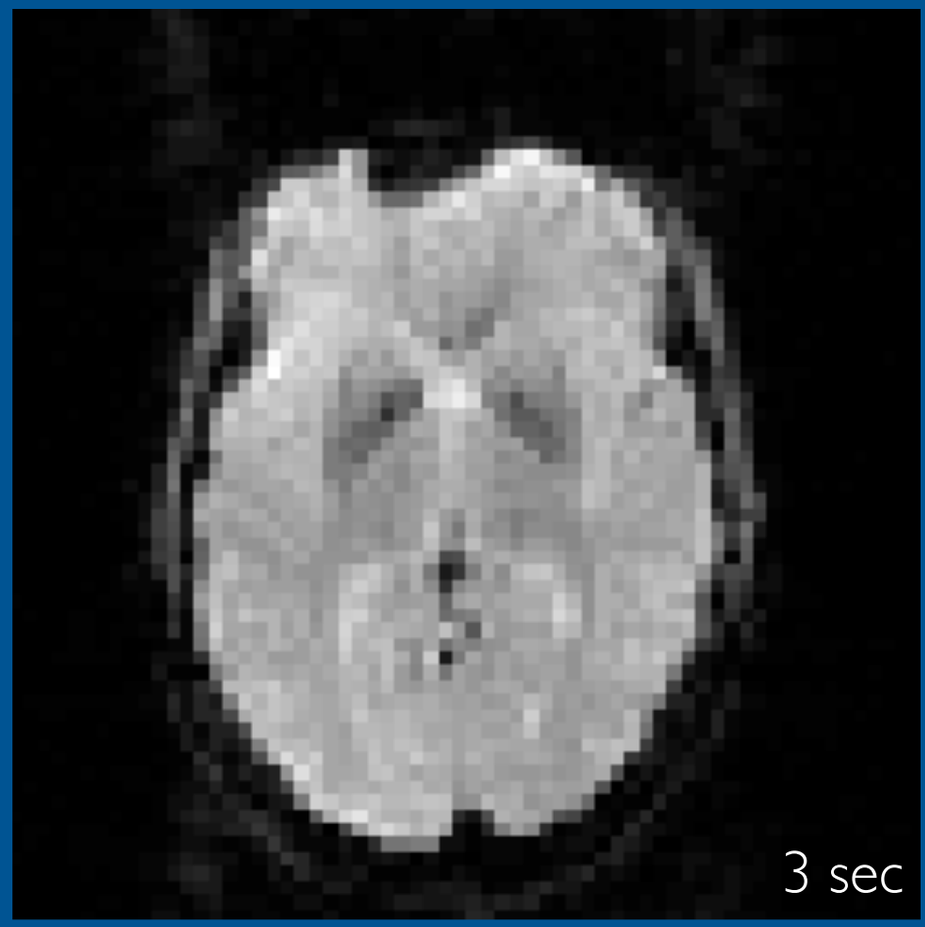
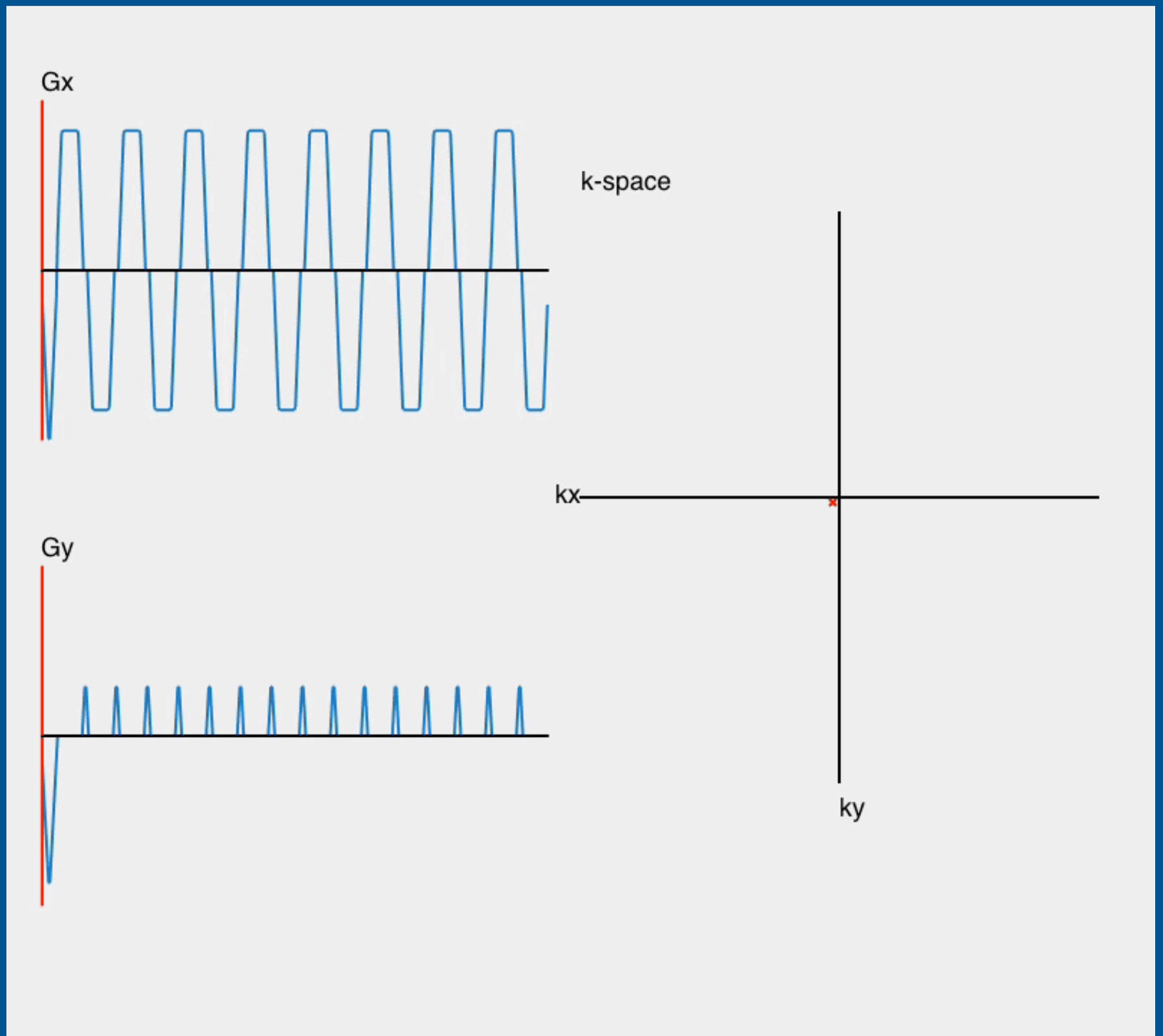


Image quality (signal-to-noise ratio) scales with $\sqrt{}$(acquisition time)

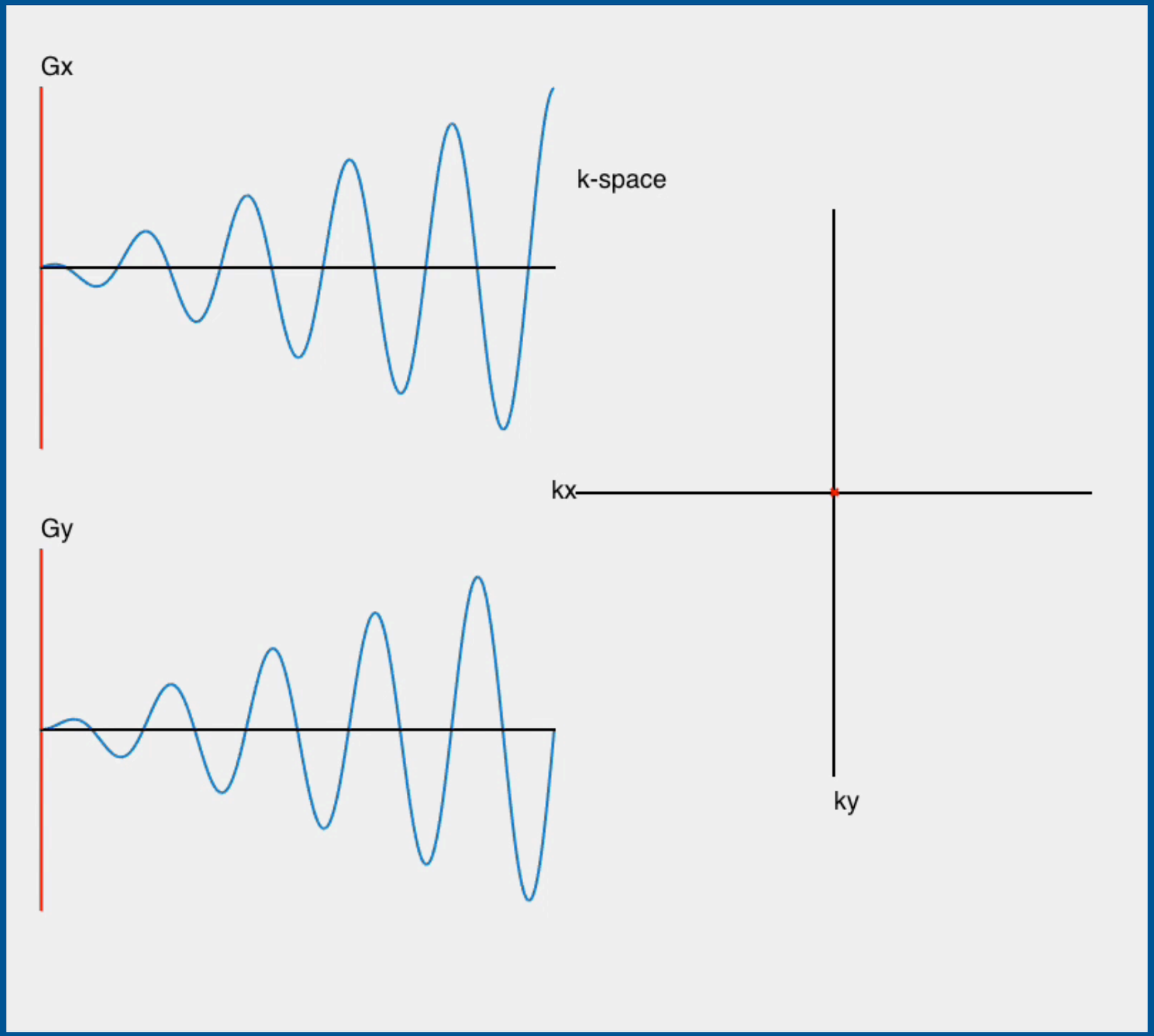
The EPI Trajectory

"Trajectories" describe the pattern of movement across k-space



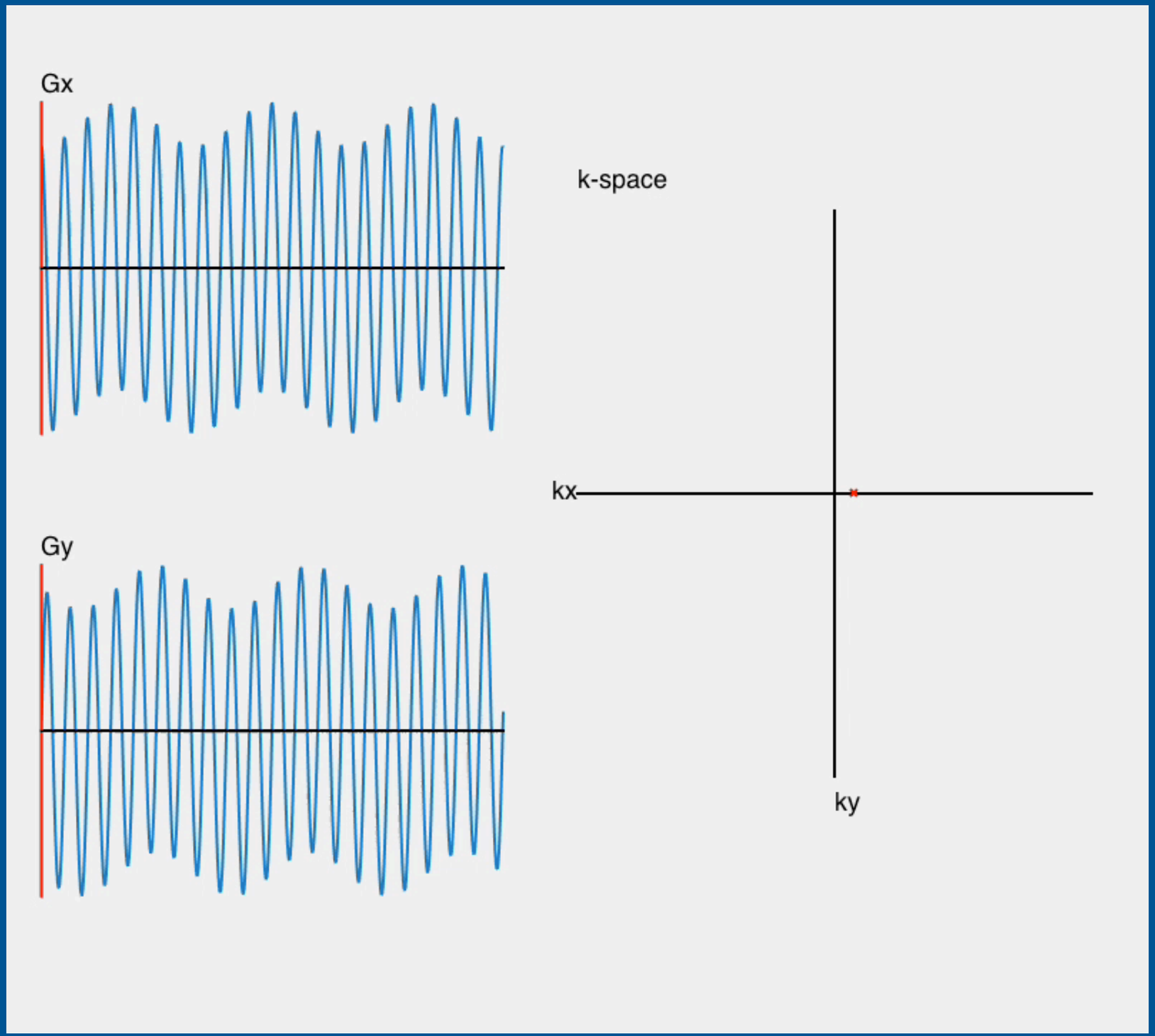
Other Fast, Planar Trajectories

Spiral k-space trajectory



Other Fast, Planar Trajectories

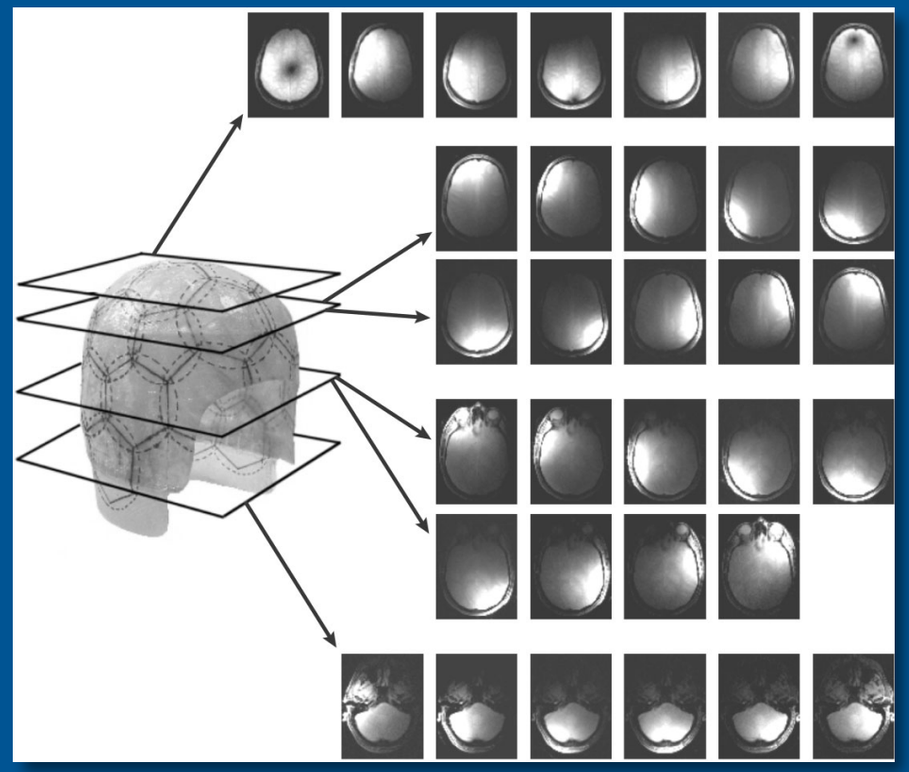
Rosette k-space trajectory



Parallel Imaging

Modern MRI signal receivers are arrays of coils (wire loops) or coil elements

Image Credit: Siemens

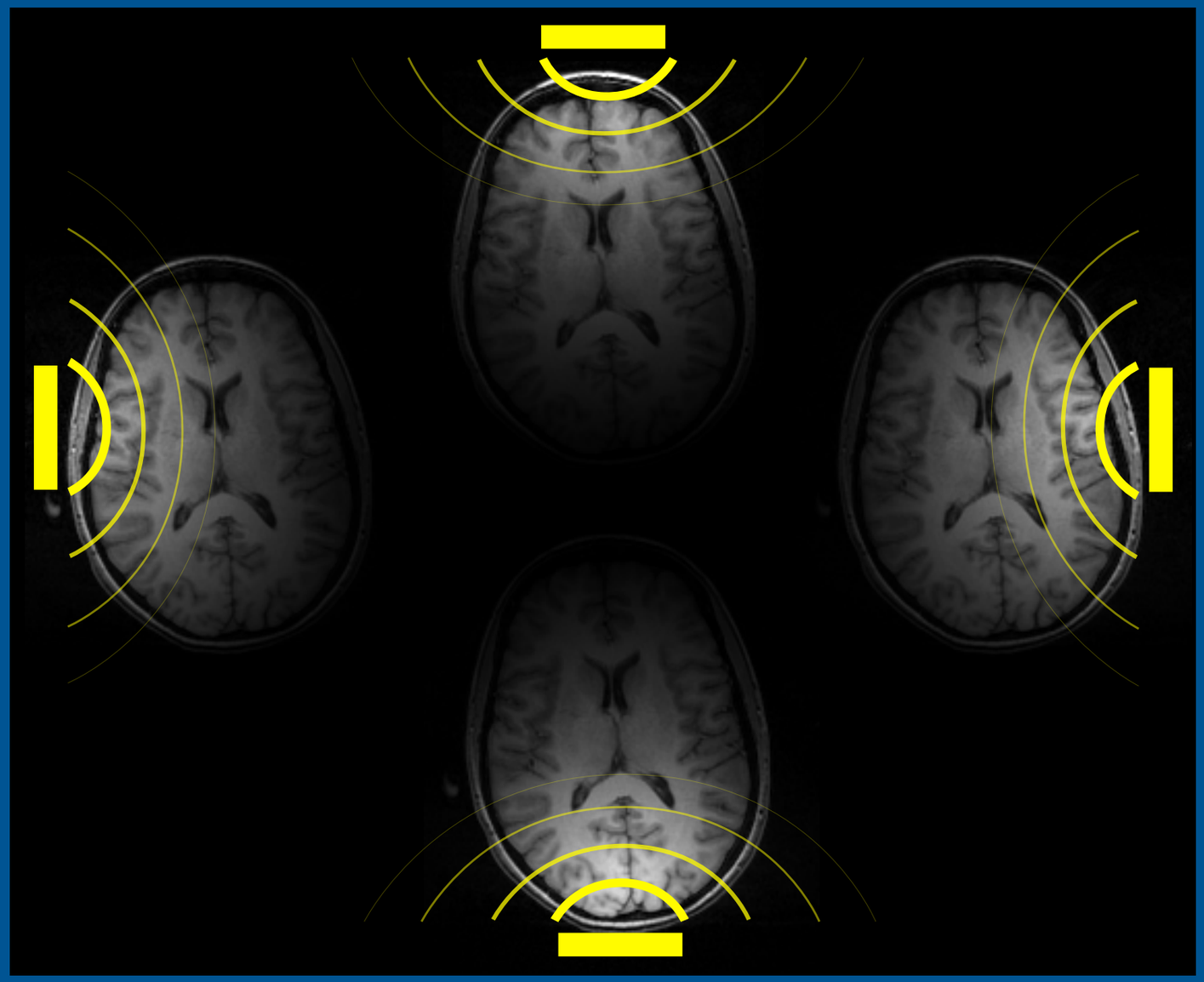


Wiggins et al., MRM 2006

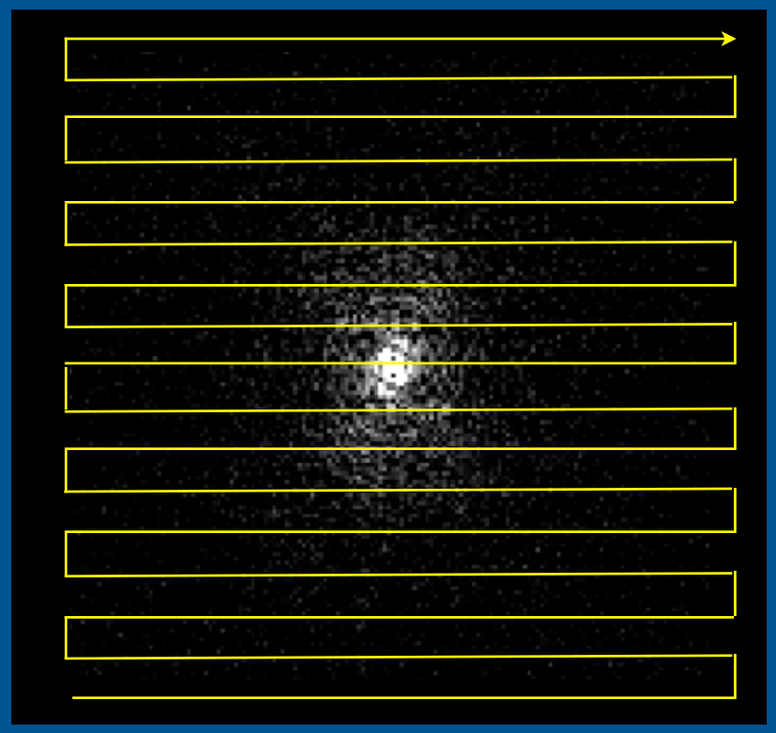
Each coil is an independent sensor,
and produces its own measurement of k-space

Coils Have Different Sensitivities

The sensitivity of each coil depends on coil position and geometry

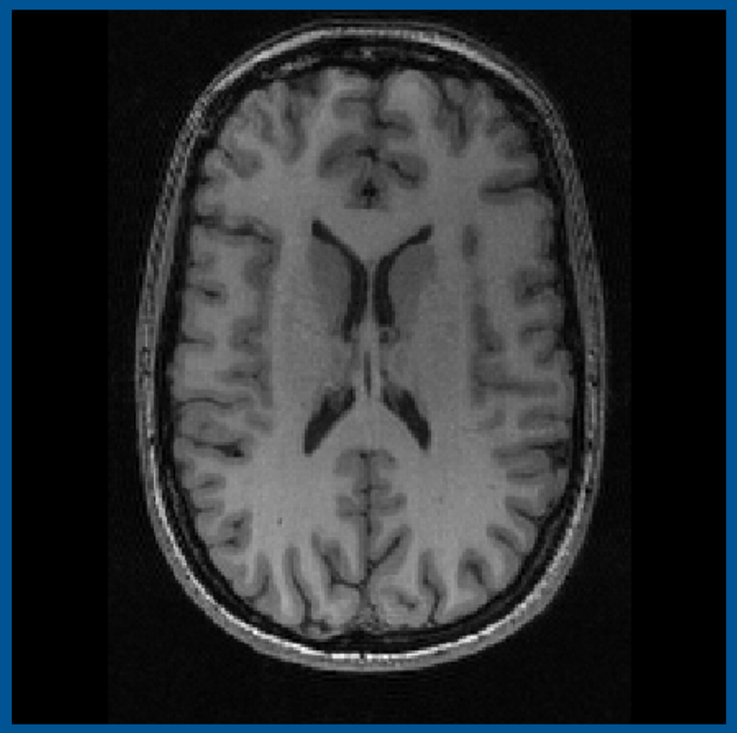


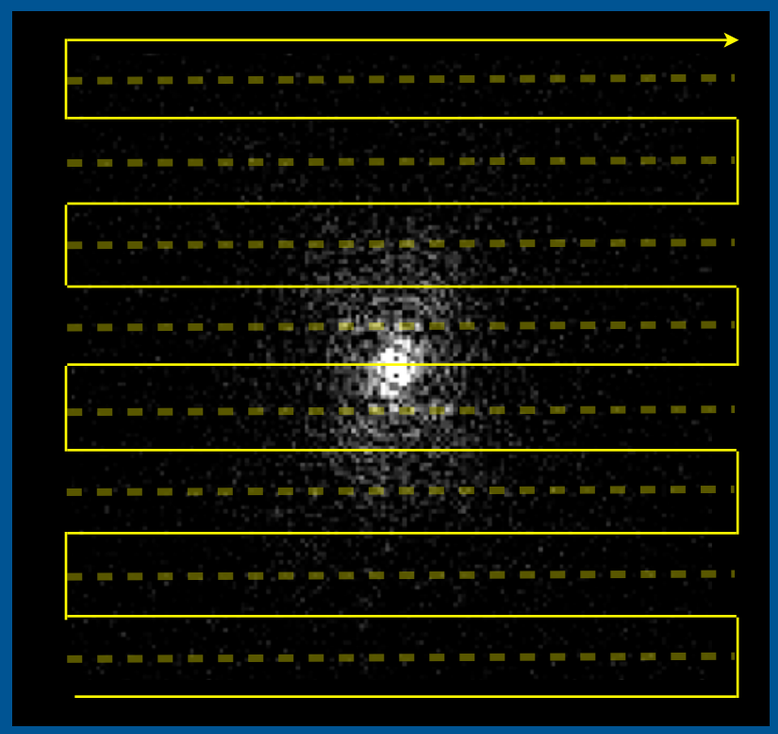
Parallel Imaging Speedup



EPI trajectory

TR = 66 ms

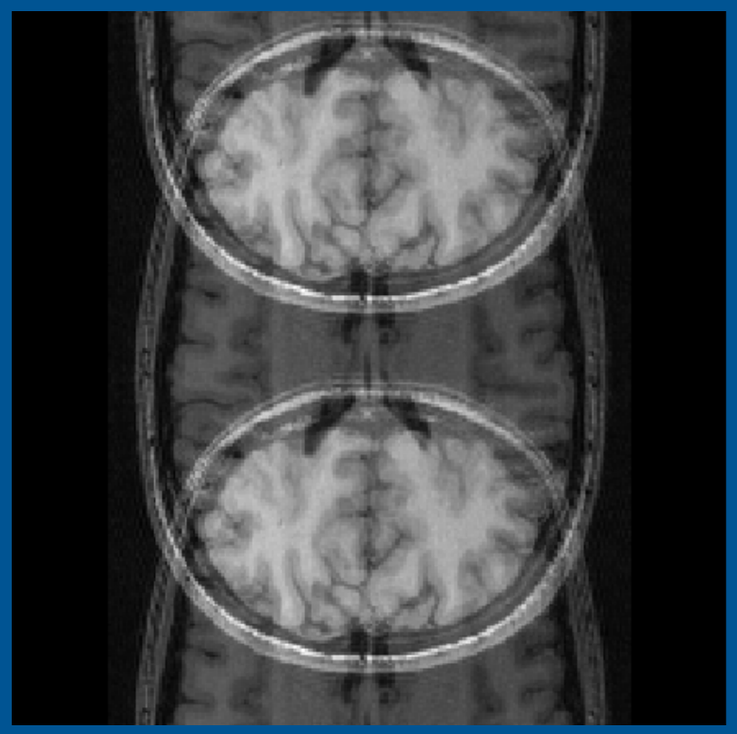




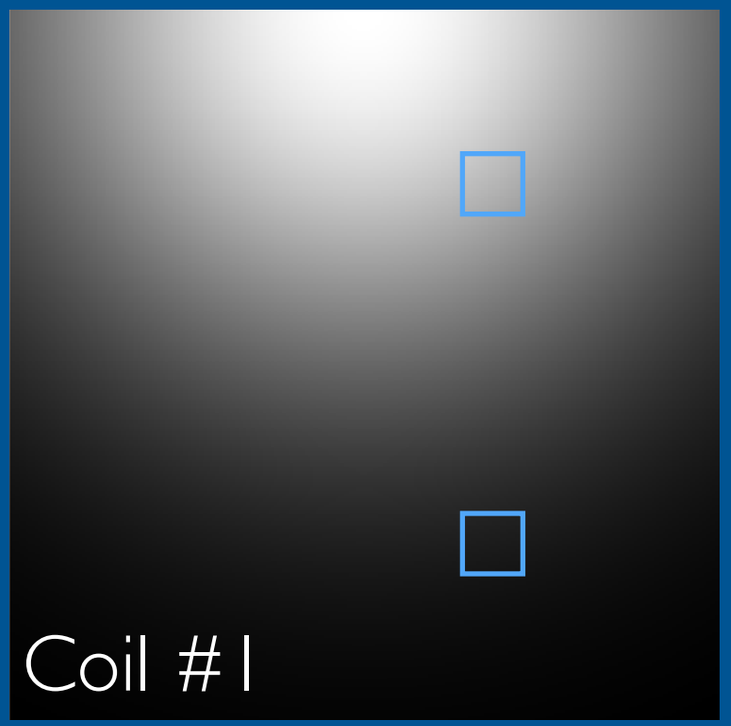
EPI trajectory, R=2

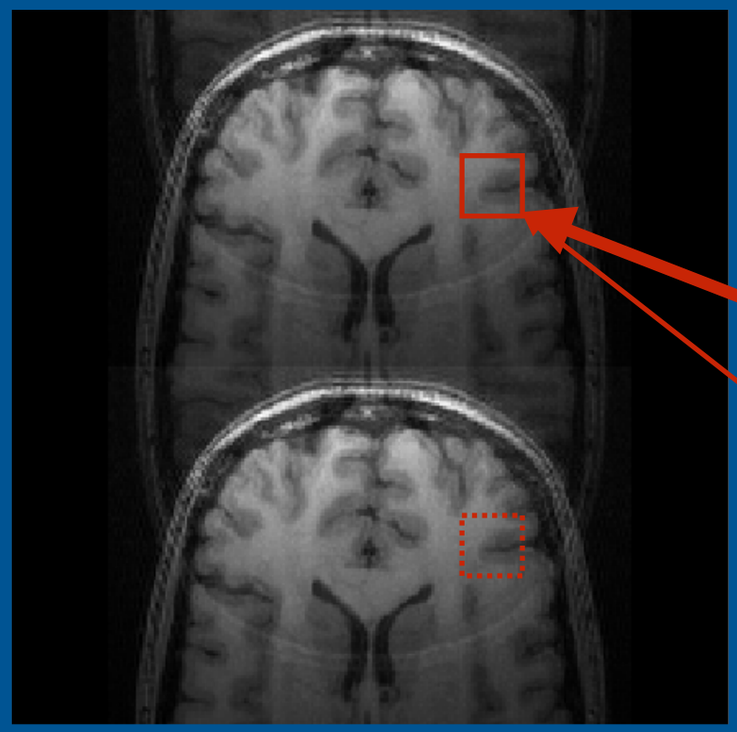
TR = 33 ms

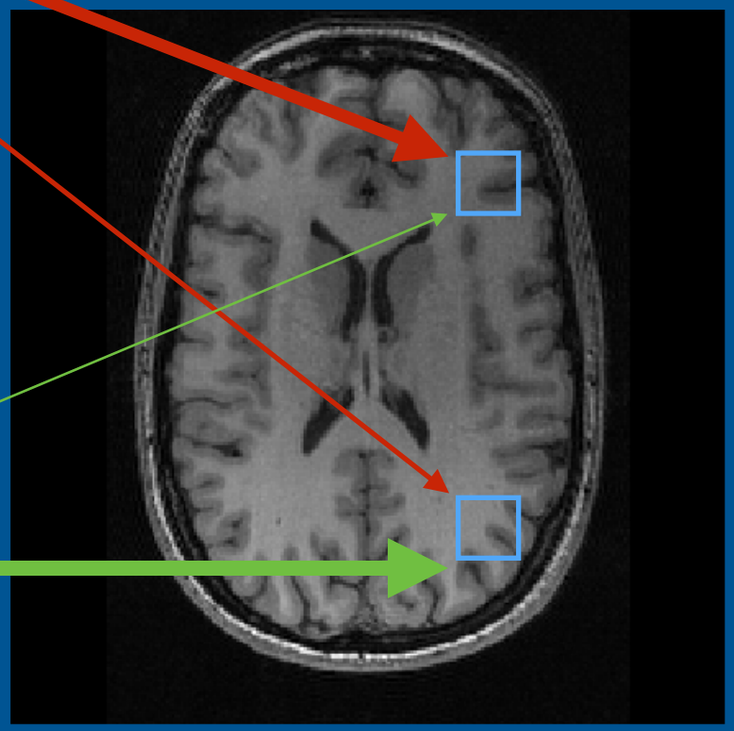
50% time savings!

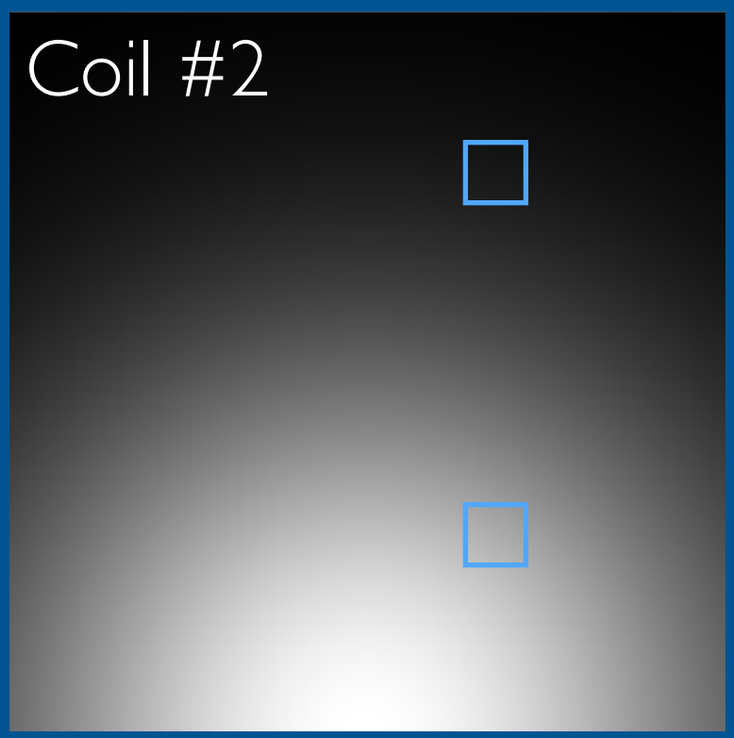


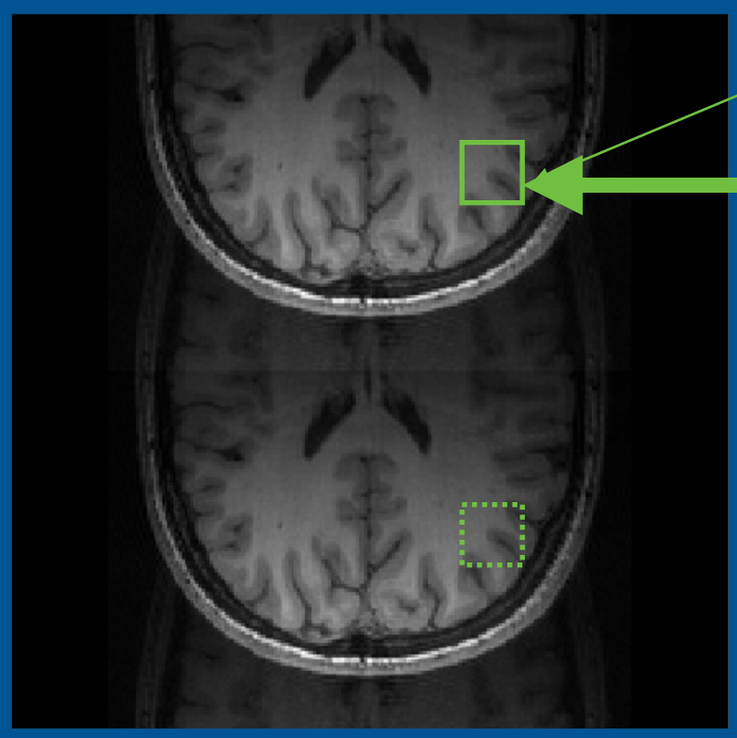
Using The Coil Information





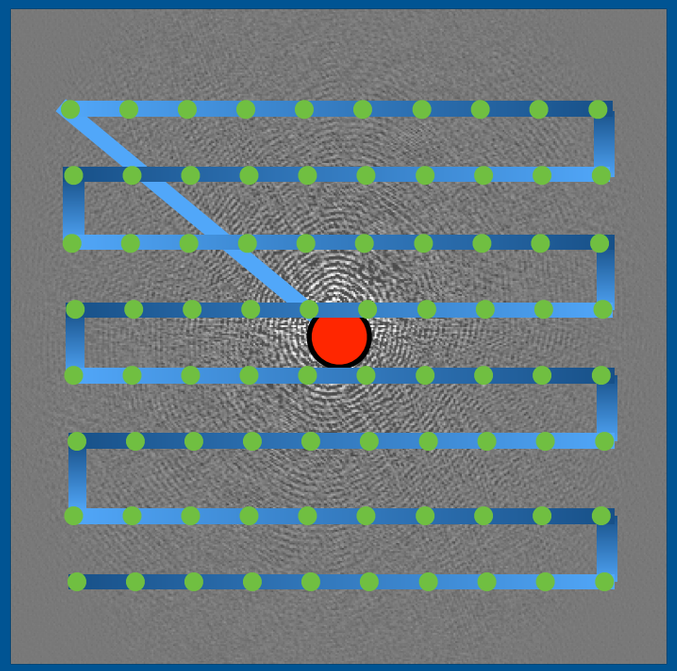






Parallel Imaging Speedup

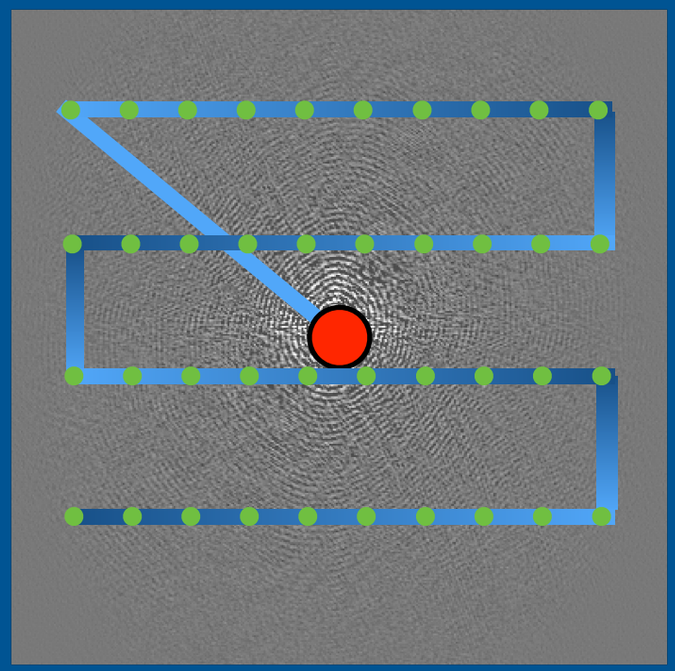
Significantly faster, but at the cost of some increased noise



EPI Trajectory

R=1 (No parallel imaging)

~ 3 seconds



EPI Trajectory

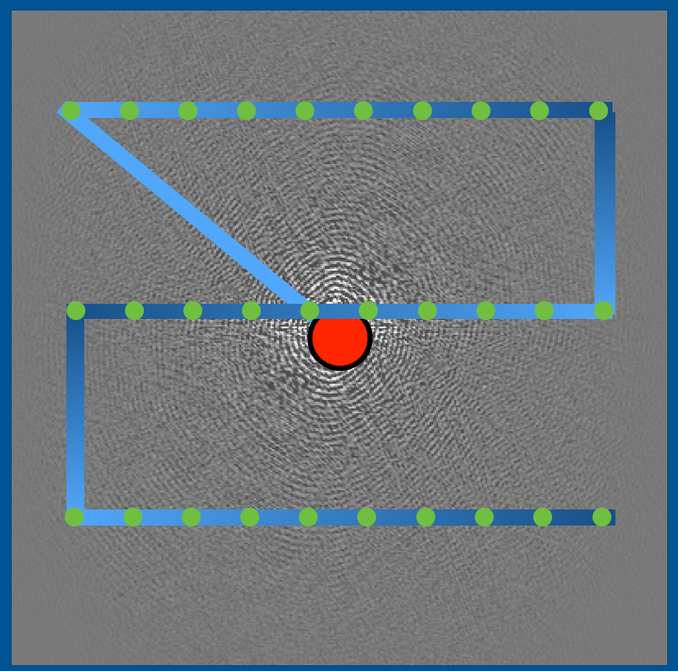
R=2 (Every 2nd line)

~ 1.5 seconds

EPI Trajectory

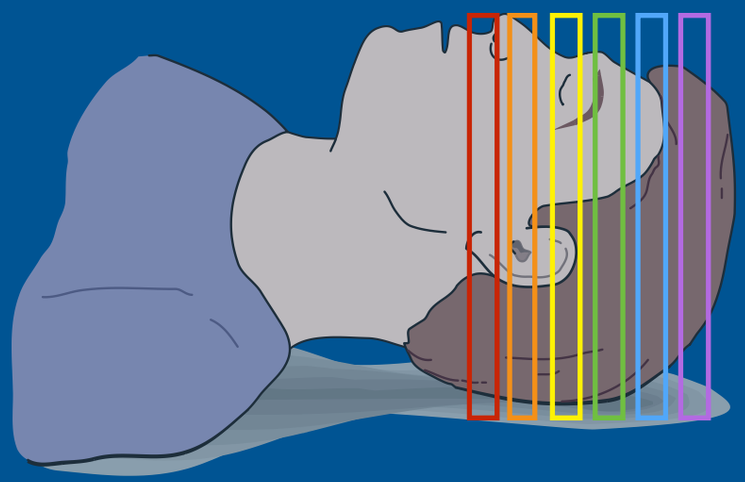
R=3 (Every 3rd line)

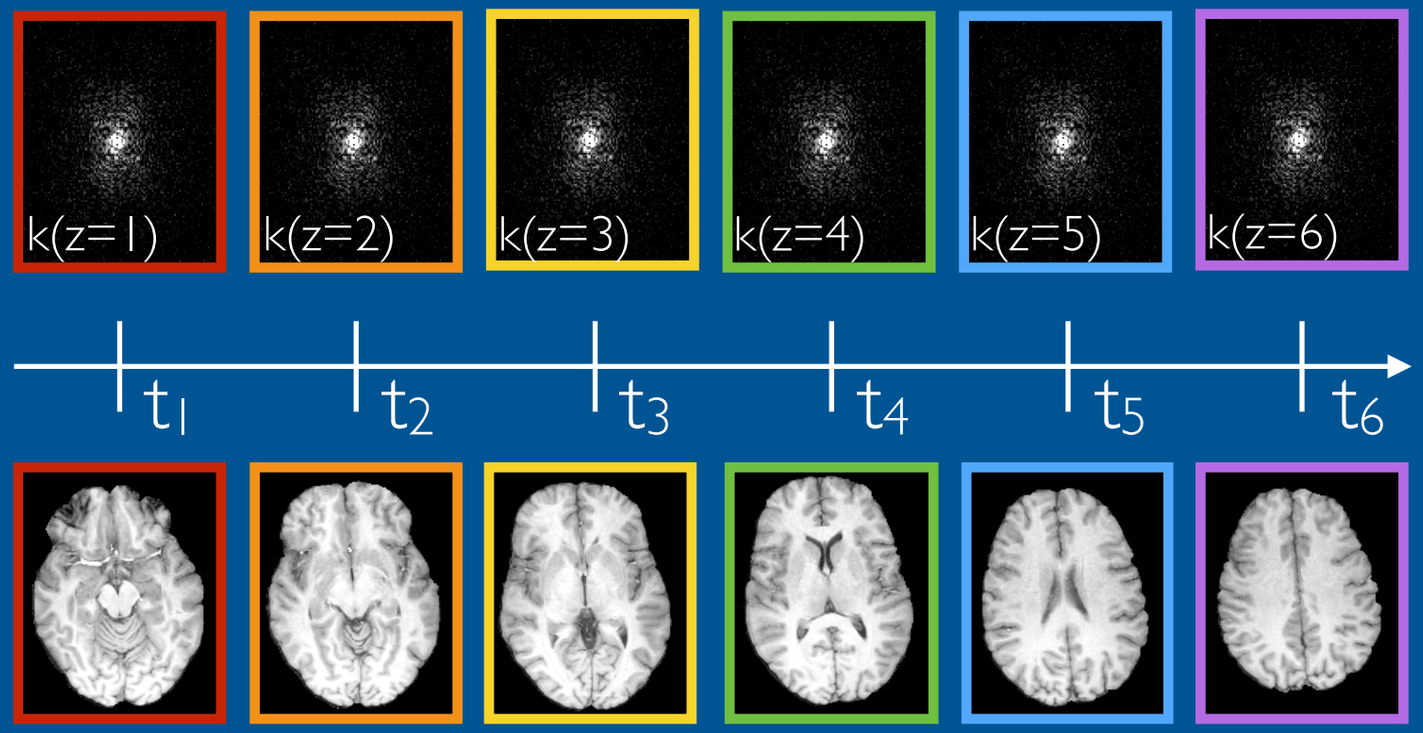
~ 1 second



2D Multislice Imaging

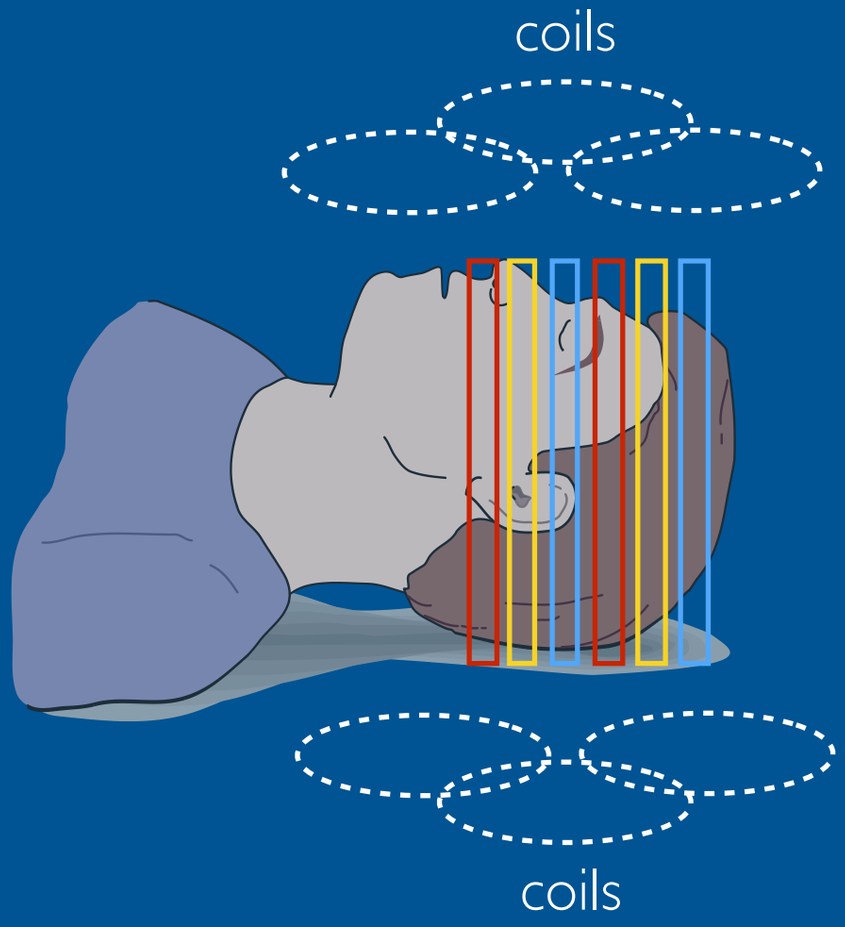
Data from different slices (z-positions) are excited and acquired sequentially

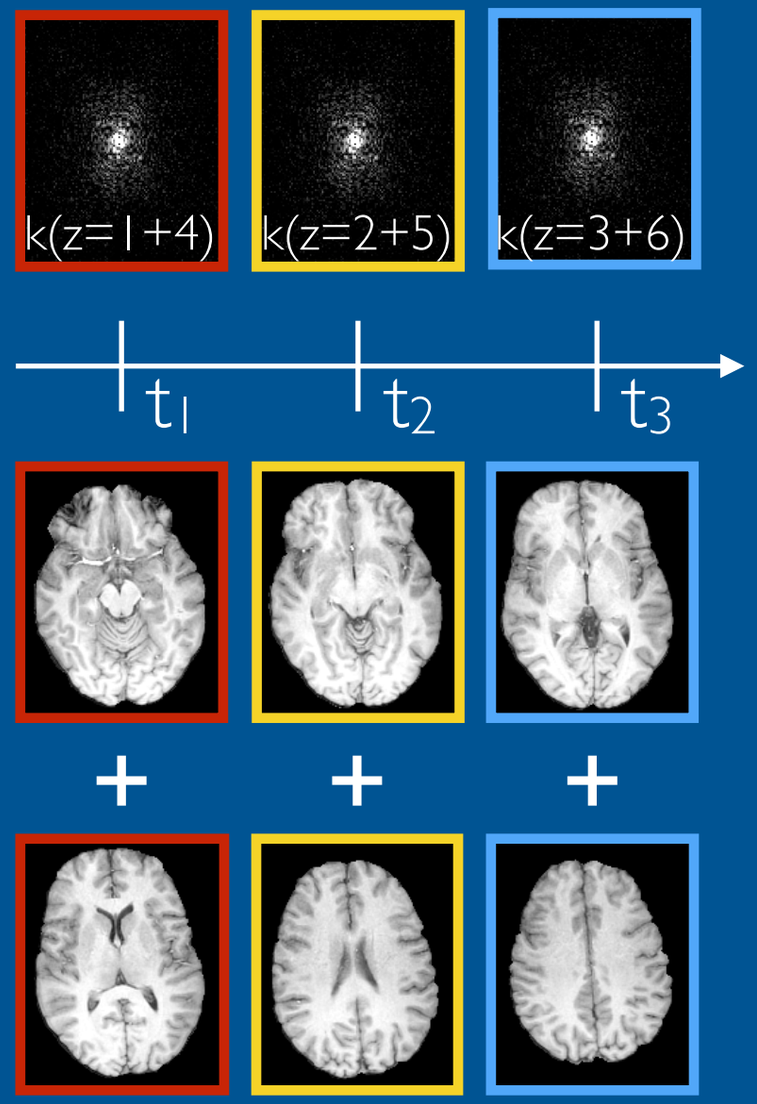




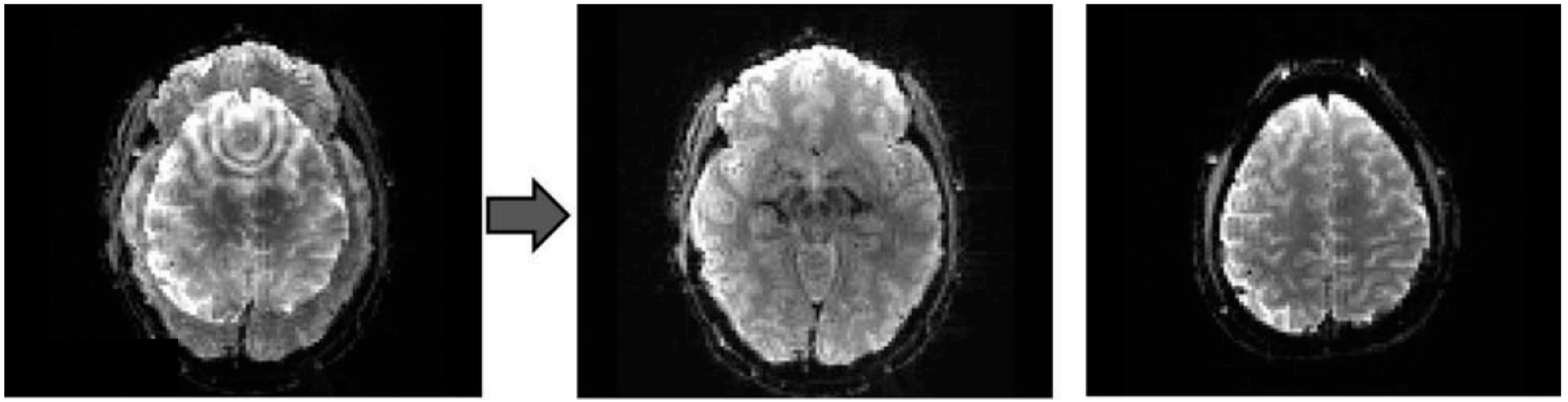
Simultaneous Multi-Slice Imaging

Data from multiple slices (z-positions) are excited and acquired simultaneously



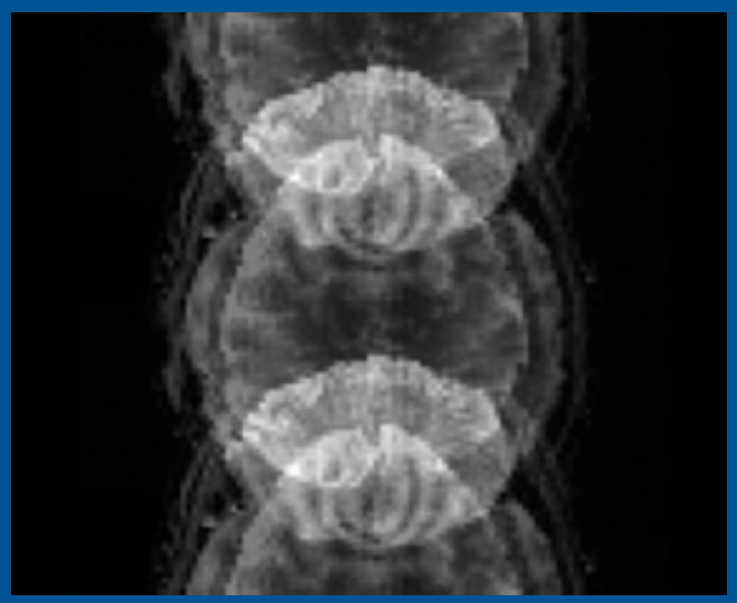


Simultaneous Multi-Slice Imaging



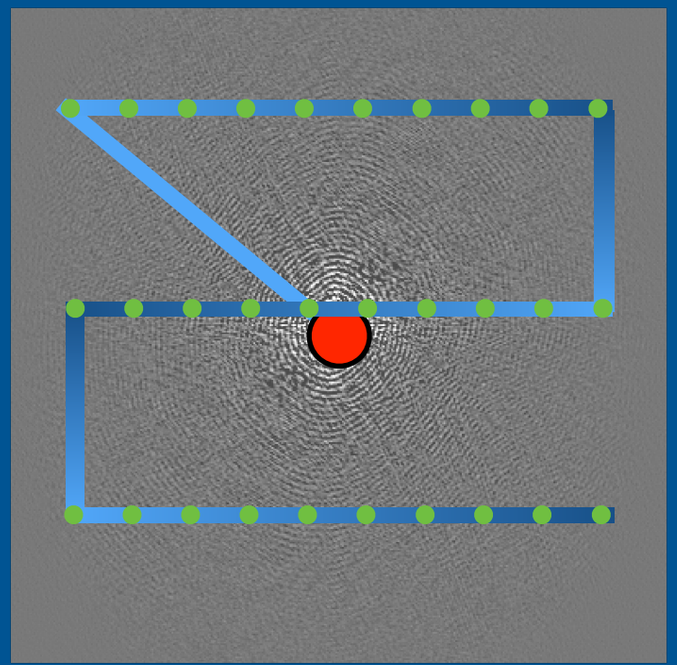
Setsompop et al. MRM 2012

Conceptually similar to parallel imaging



It can be combined with parallel imaging to compound acceleration!

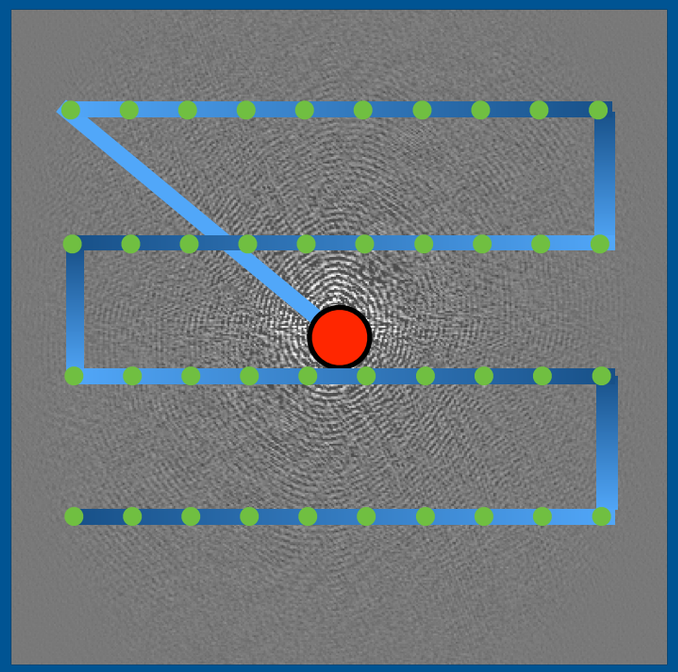
Simultaneous Multi-Slice Speedup



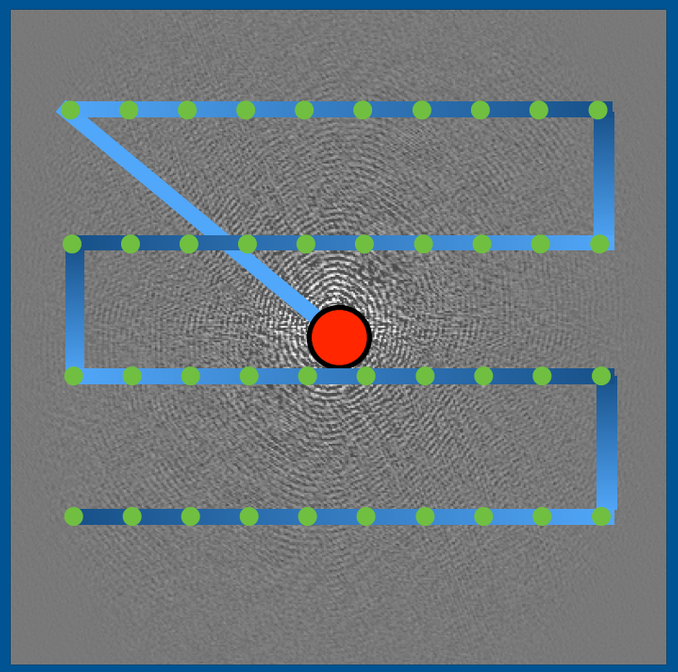
EPI Trajectory
R=3 (Every 3nd line)
1 slice at a time
~ 1 second

Significantly faster, but at the cost of some increased noise

Slice 1

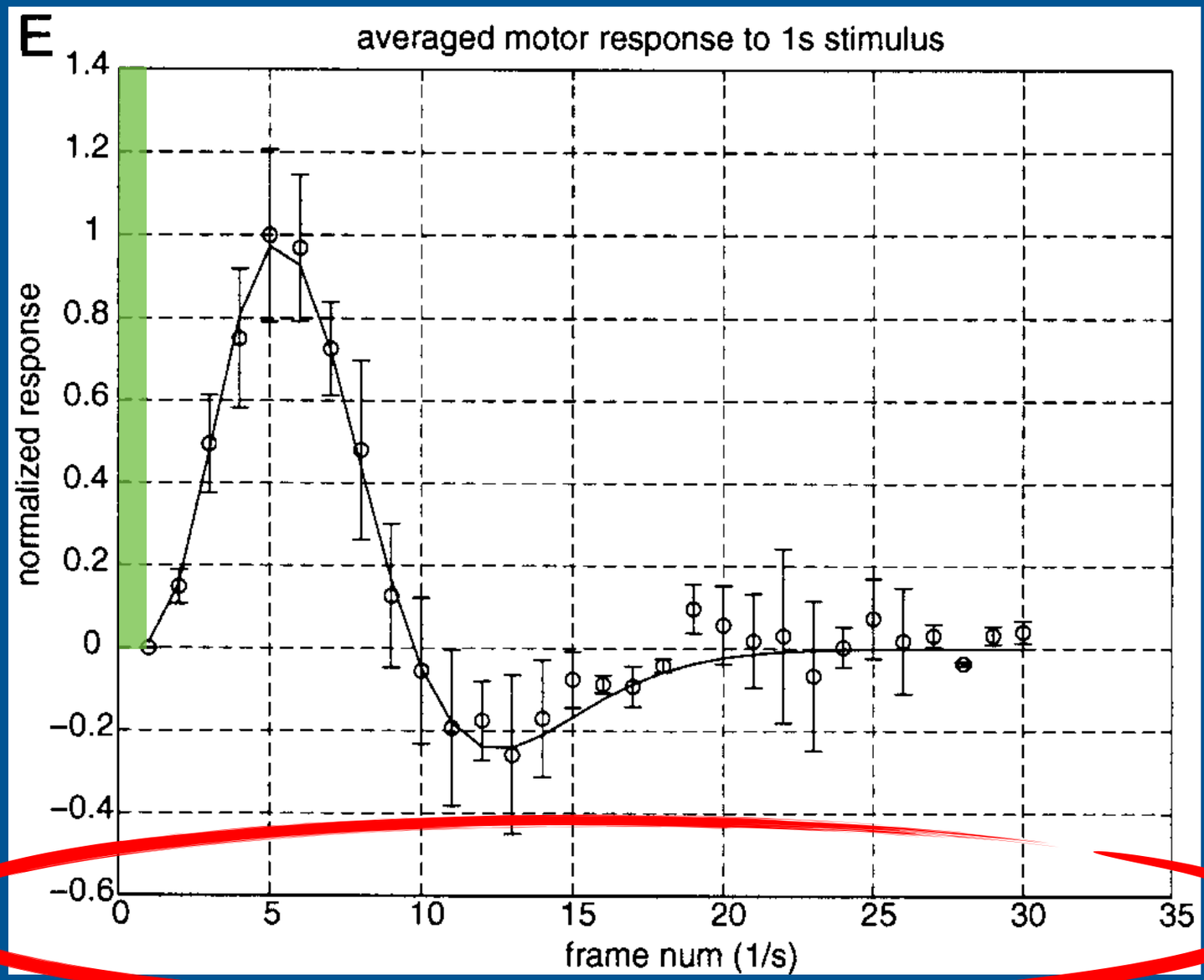


Slice 2



EPI Trajectory
R=3 (Every 3nd line)
2 slices at a time
~ 0.5 second

Fast Imaging Summary



Glover, NeuroImage 1999

From 5 minutes down to 0.5 seconds, at the cost of

- Image resolution
- Increased noise
- Image artefacts

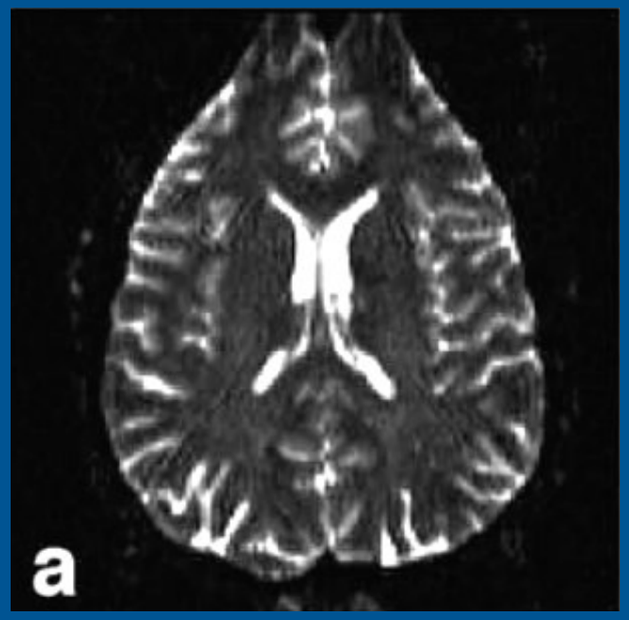
MRI Image Artefacts

or

A brief look at some of the ways MRI images can be corrupted

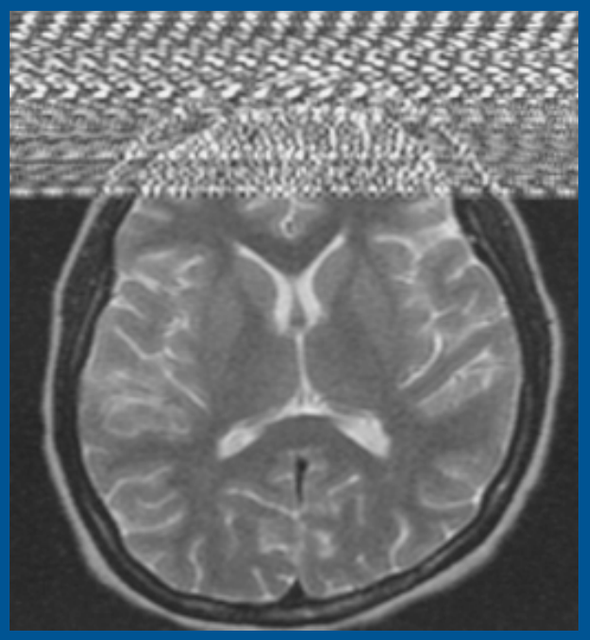
What are Artefacts?

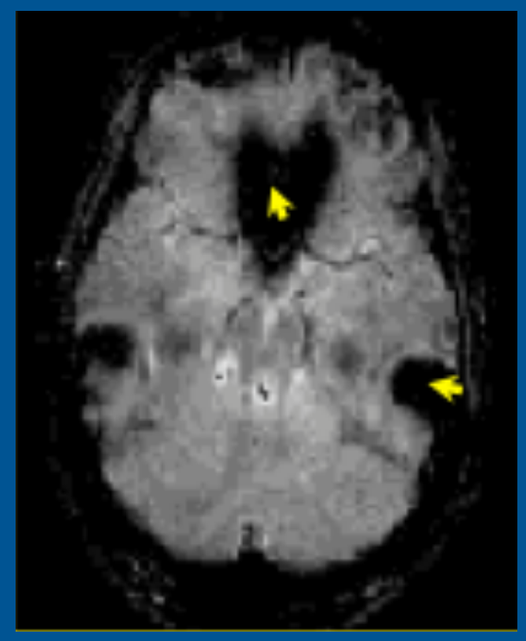
Artefacts are any *errors* in the image



e.g. signal is misplaced

e.g. signal from unwanted source

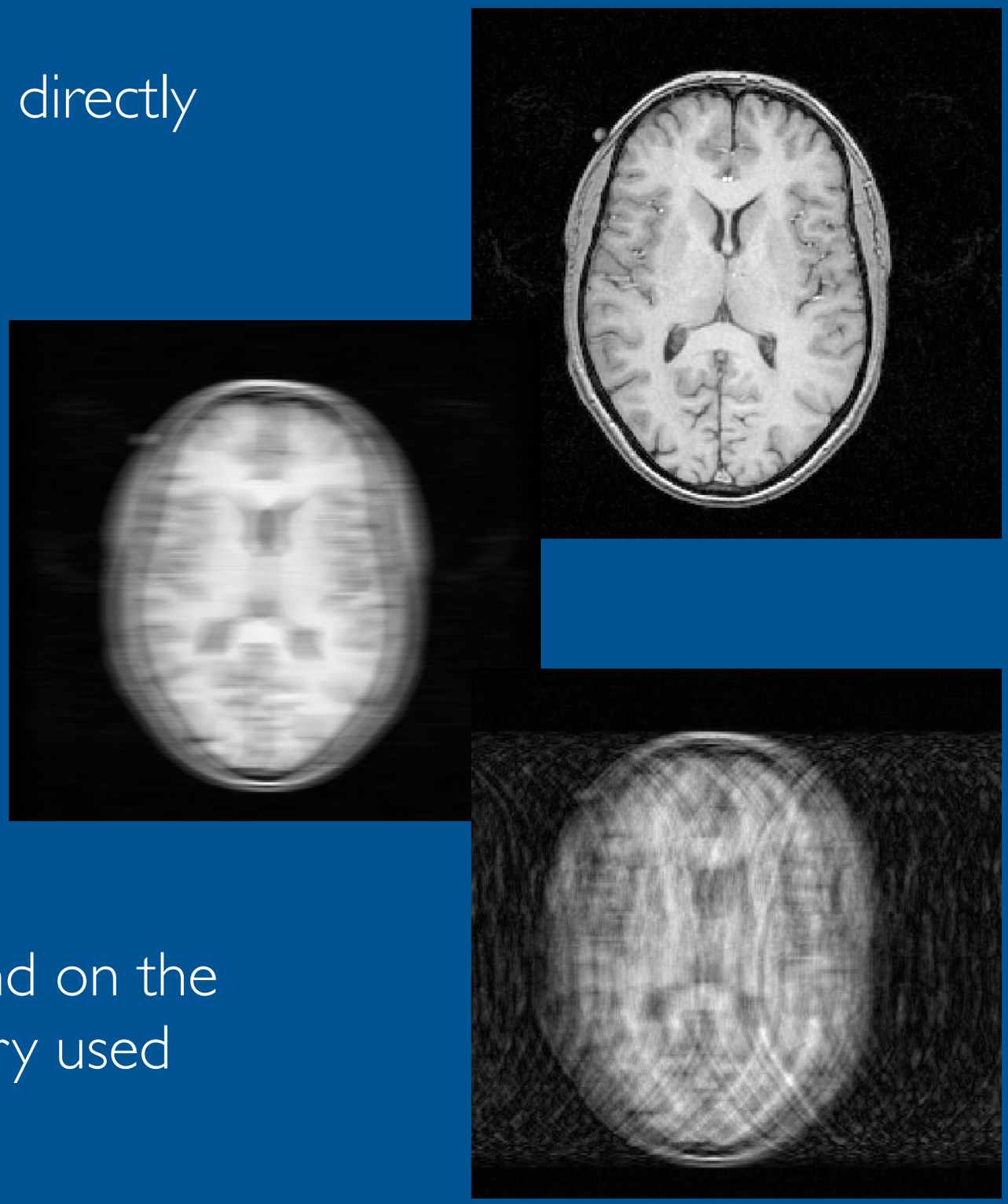




e.g. signal is lost

Artefacts can be Non-Intuitive

Because signals are not measured directly
but rather in k-space

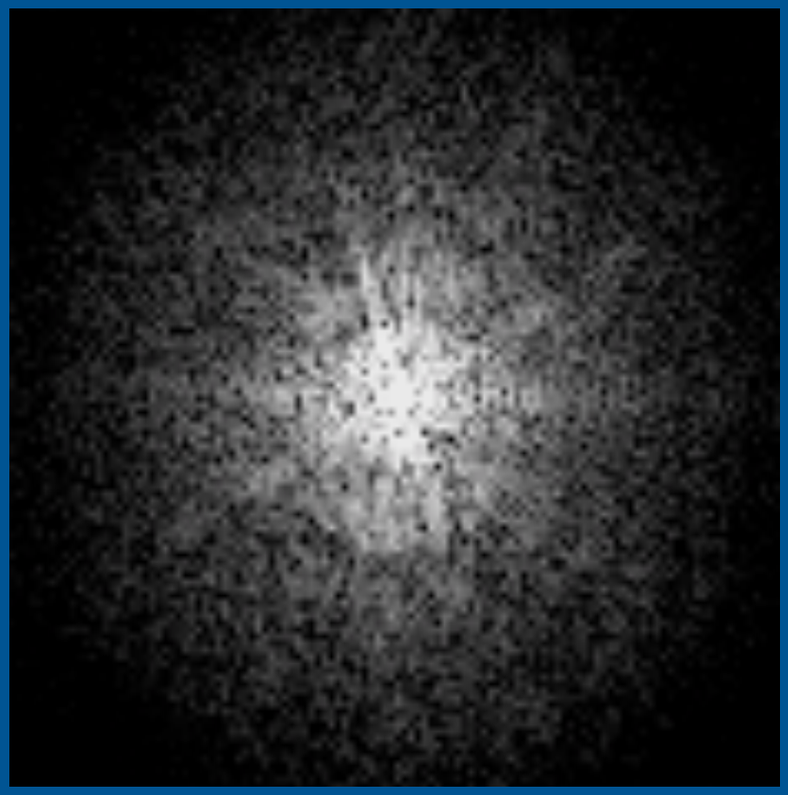


Errors in k-space can cause a wide
variety of different corruptions

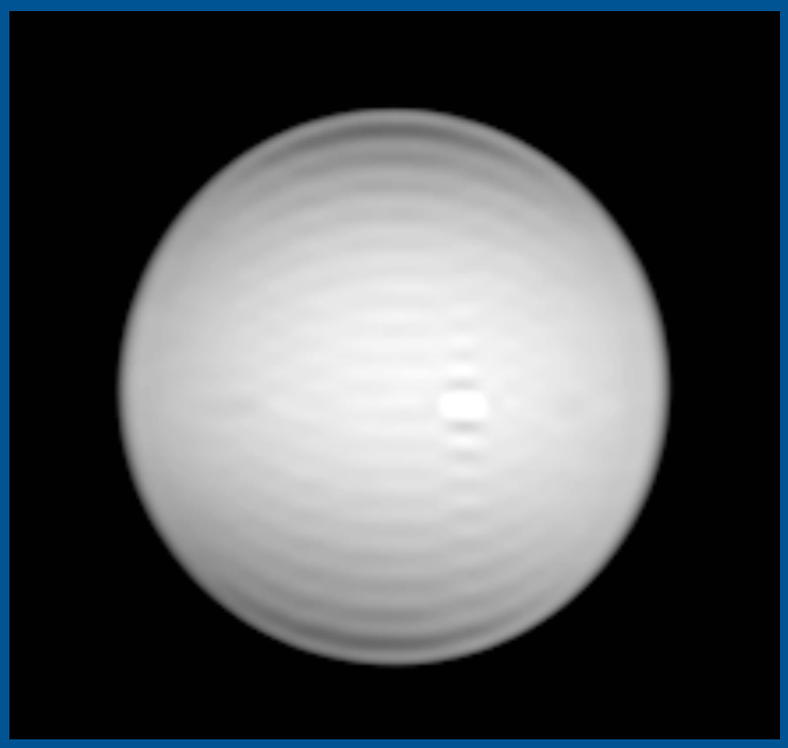
These errors can also depend on the
particular k-space trajectory used

Gibbs Ringing

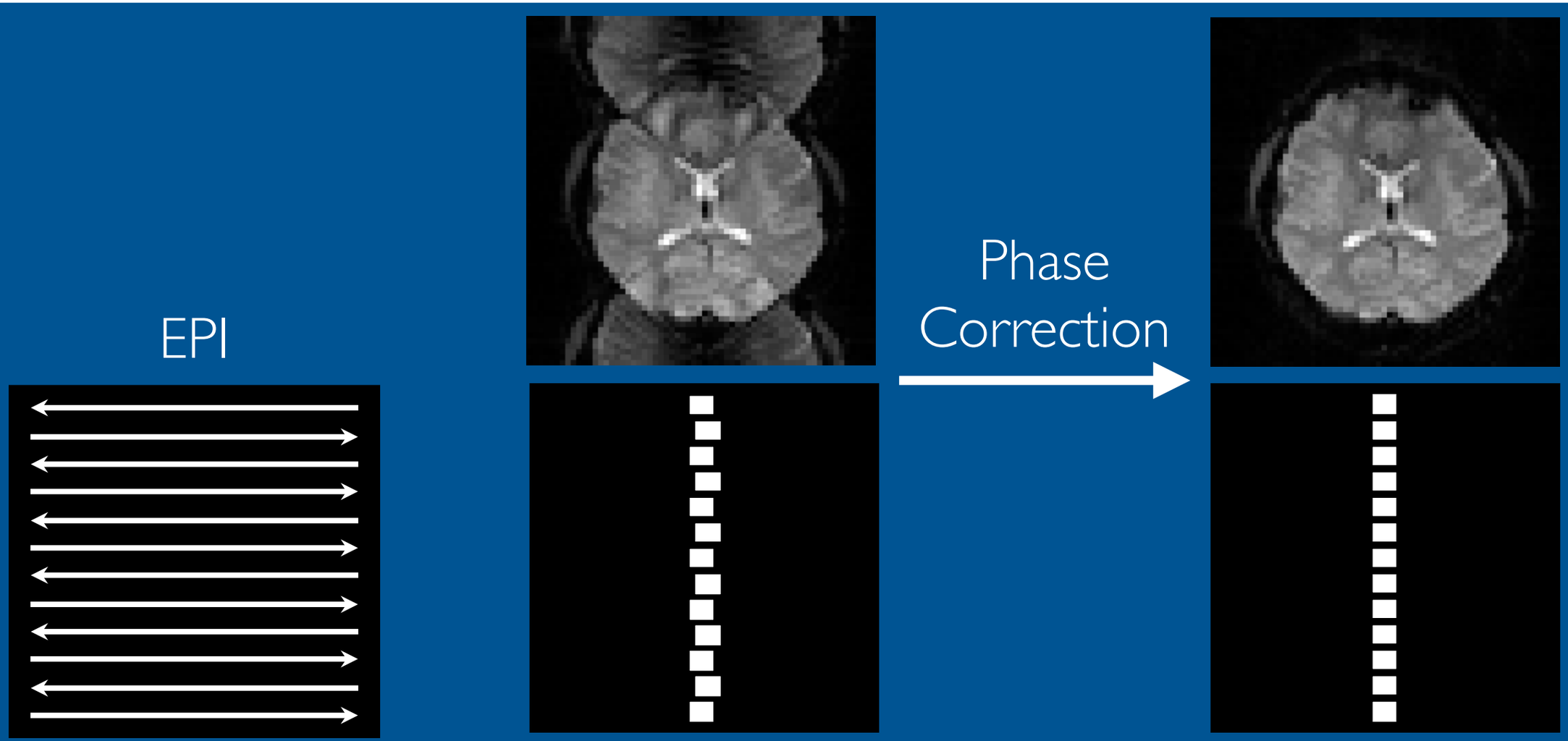
- **Problem:**
  - Maximum spatial frequency sampled (k_{max}) is not sufficient



- **Solutions:**
  - Increase k-space sampling (k_{max})
  - Filter k-space (apodization)

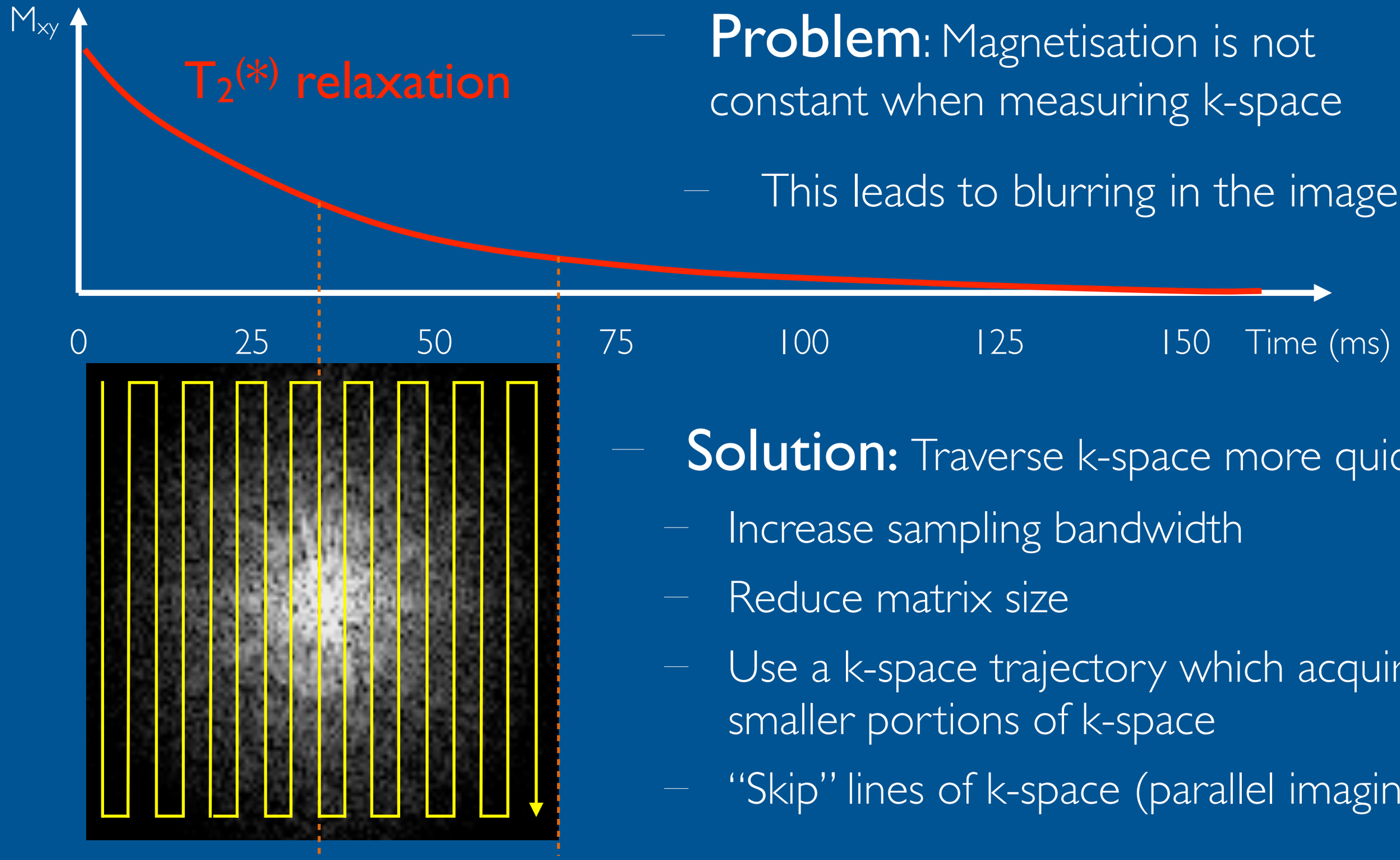


Nyquist (N/2) Ghosting



- **Problem**: Signal misaligned between forward and reverse lines in EPI
- **Solution**: "Phase correction" to realign data

T2* Blurring



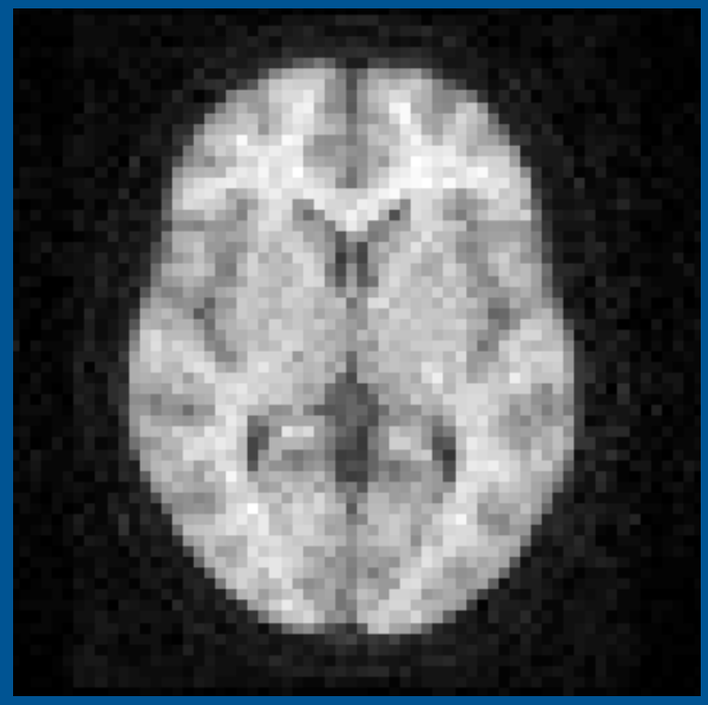
- **Problem**: Magnetisation is not constant when measuring k-space
  - This leads to blurring in the image

- **Solution:** Traverse k-space more quickly
  - Increase sampling bandwidth
  - Reduce matrix size
  - Use a k-space trajectory which acquires smaller portions of k-space
  - "Skip" lines of k-space (parallel imaging)

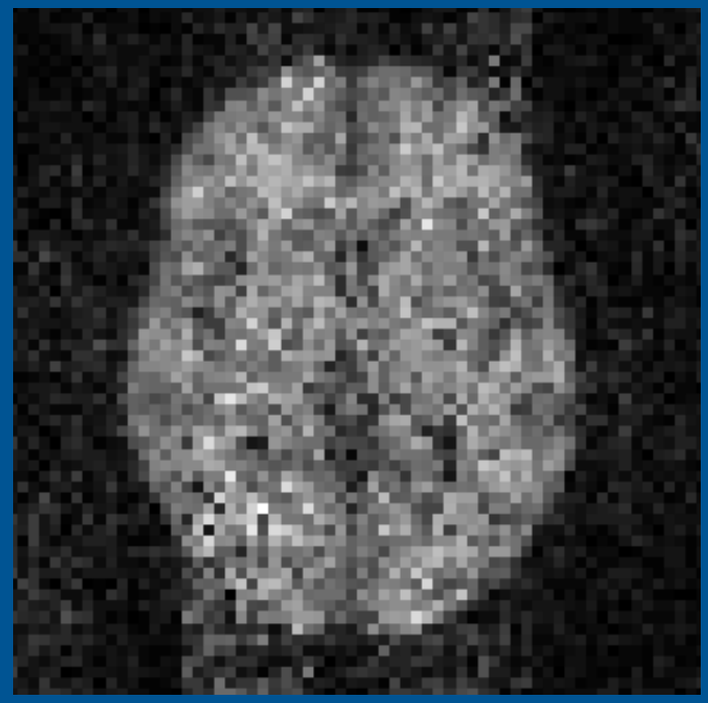
Parallel Imaging Noise Amplification

The signal-to-noise (SNR) ratio drops (*i.e.* noise increases) variably across the image and depends on the coils used and acceleration factor

No acceleration

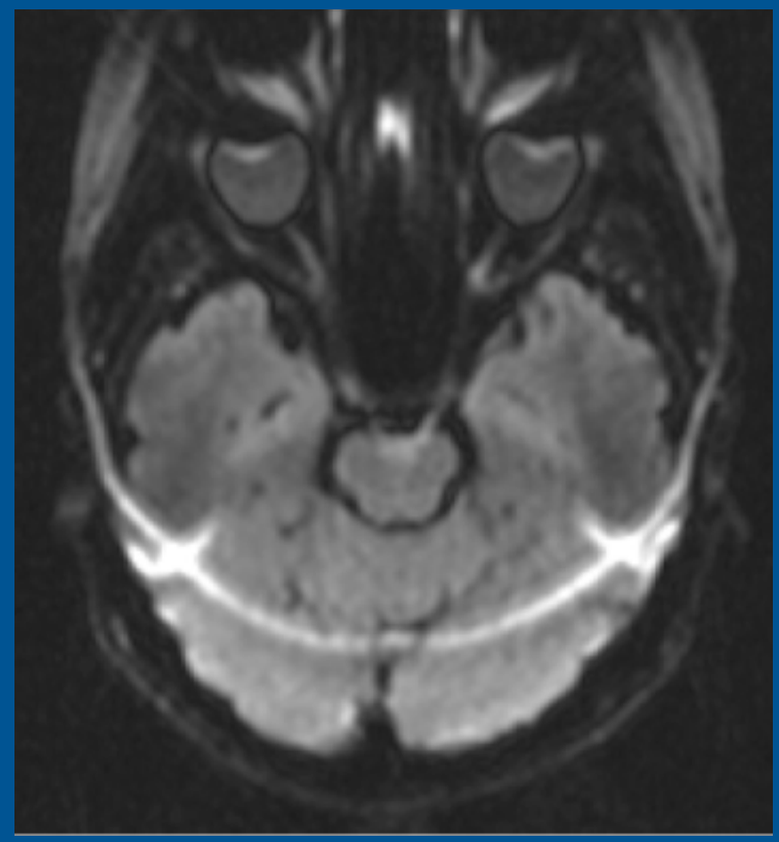


Acceleration (R = 4)



Chemical Shift

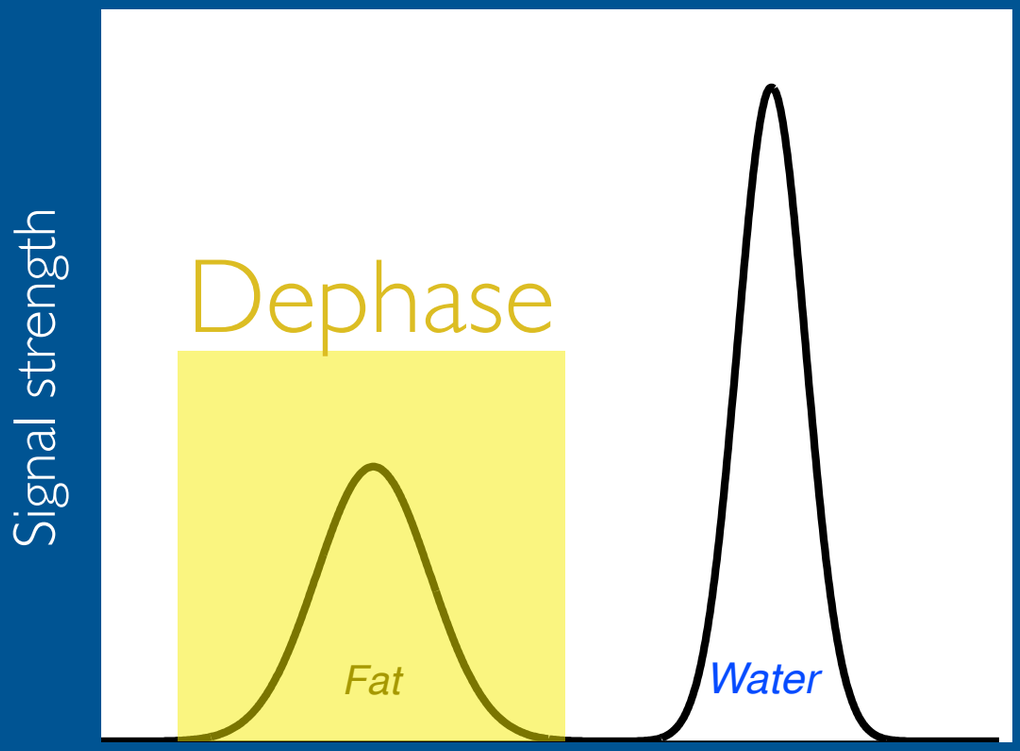
- **Problem:** Protons in fat precess at a different frequency to those in water!
  - We rely on precession frequency to tell us where the signal is coming from
  - Signal is mis-localised



- **Solution 1:** Increase the sampling bandwidth by increasing the gradient strength
  - Fat-water frequency difference becomes small relative to frequency differences induced by the gradient
  - Note, cost of increased sampling bandwidth is reduced SNR (noisier images)

Chemical Shift

- **Solution 2**: "Destroy" the fat signal before acquiring the image
  - Selectively excite the fat signal first
  - "Destroy" it by applying large magnetic field gradients to dephase magnetisation
  - Immediately excite the water signal



Field Inhomogeneity

- The presence of the subject in the scanner distorts the main magnetic field
- The magnetic field at the interface of air and tissue is distorted
- Metallic implants also strongly distort the magnetic field
- Remember: precession frequency is proportional to local magnetic field strength
- If the magnetisation does not precess at the frequency we expect…

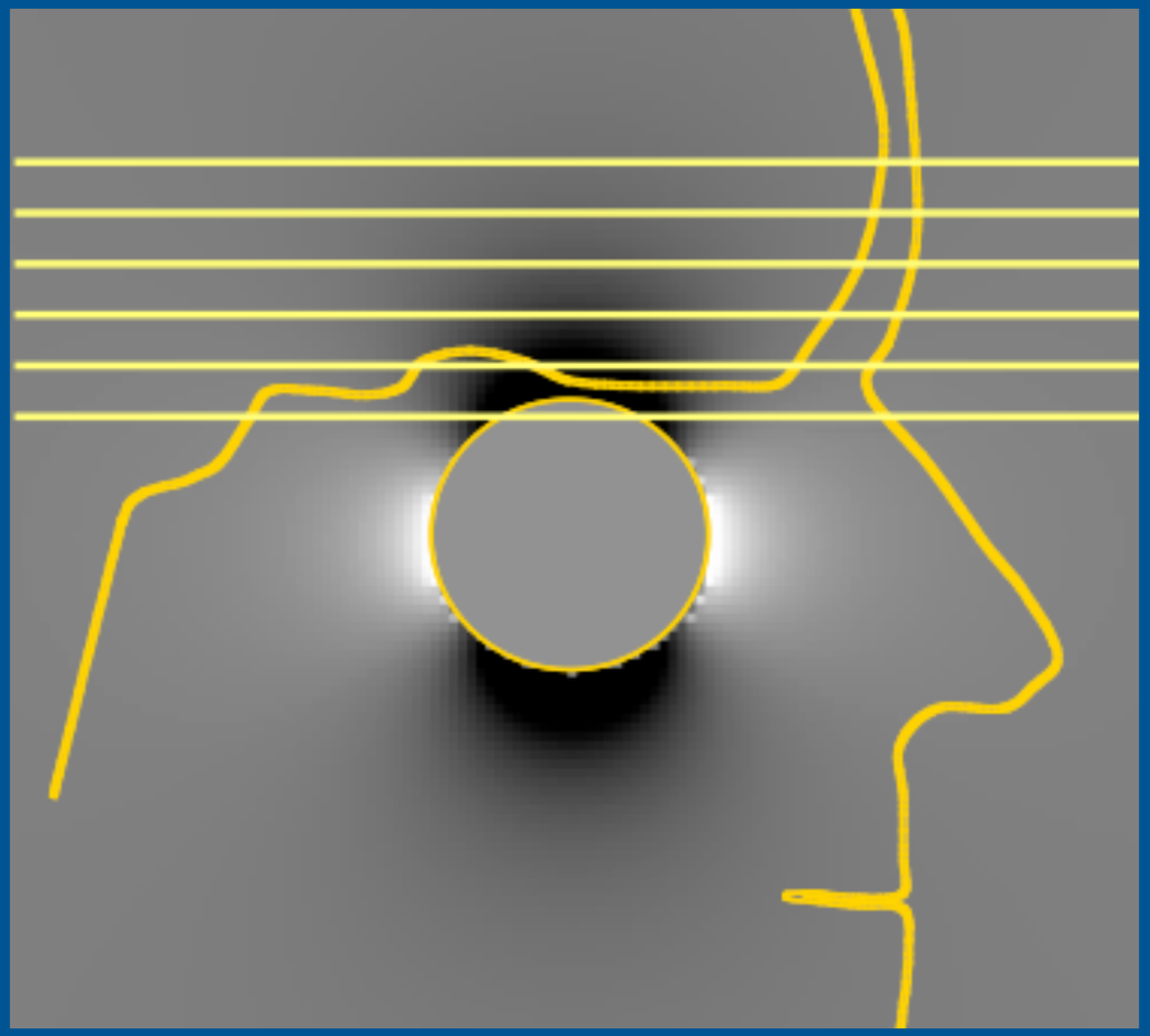
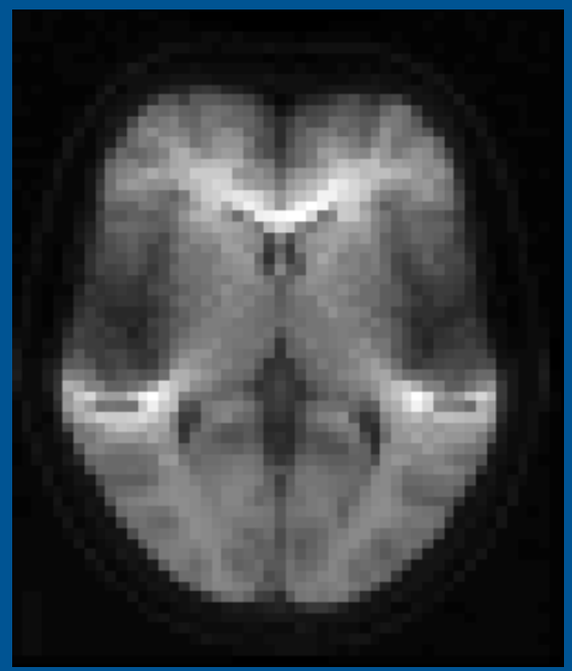


Image Distortion

- **Problem**:
  - We rely on precession frequency to tell us where the signal is coming from
  - Magnetic field inhomogeneity changes the local precession frequency
  - Signal is mis-localised near field inhomogeneities



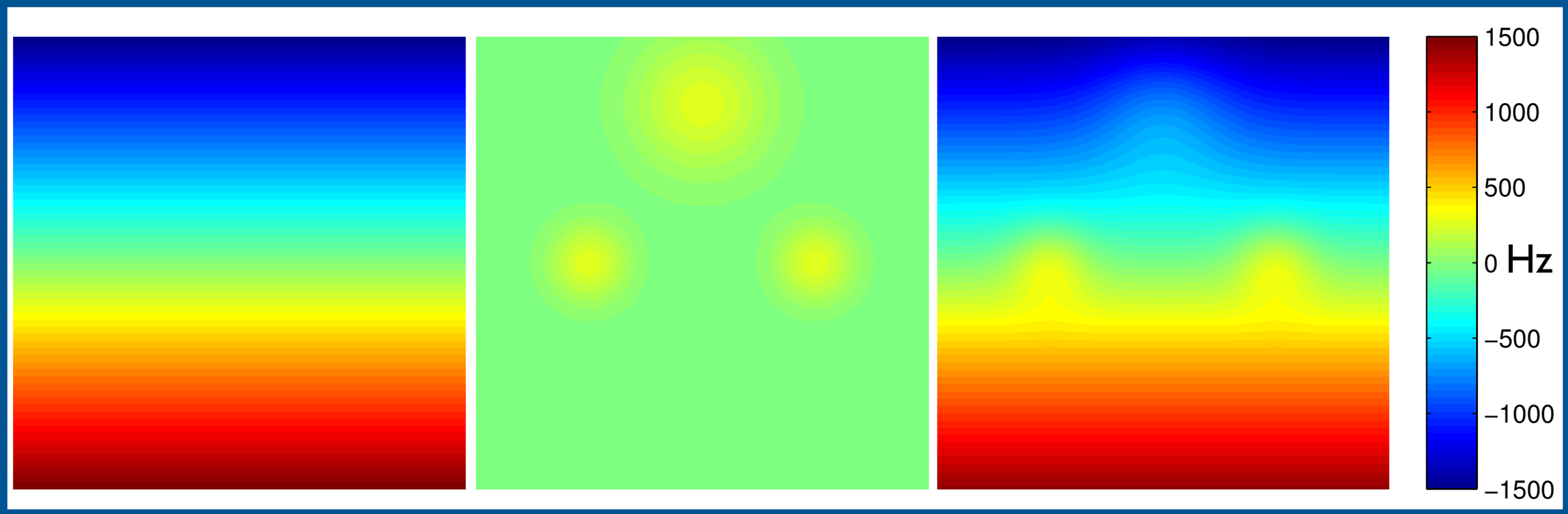
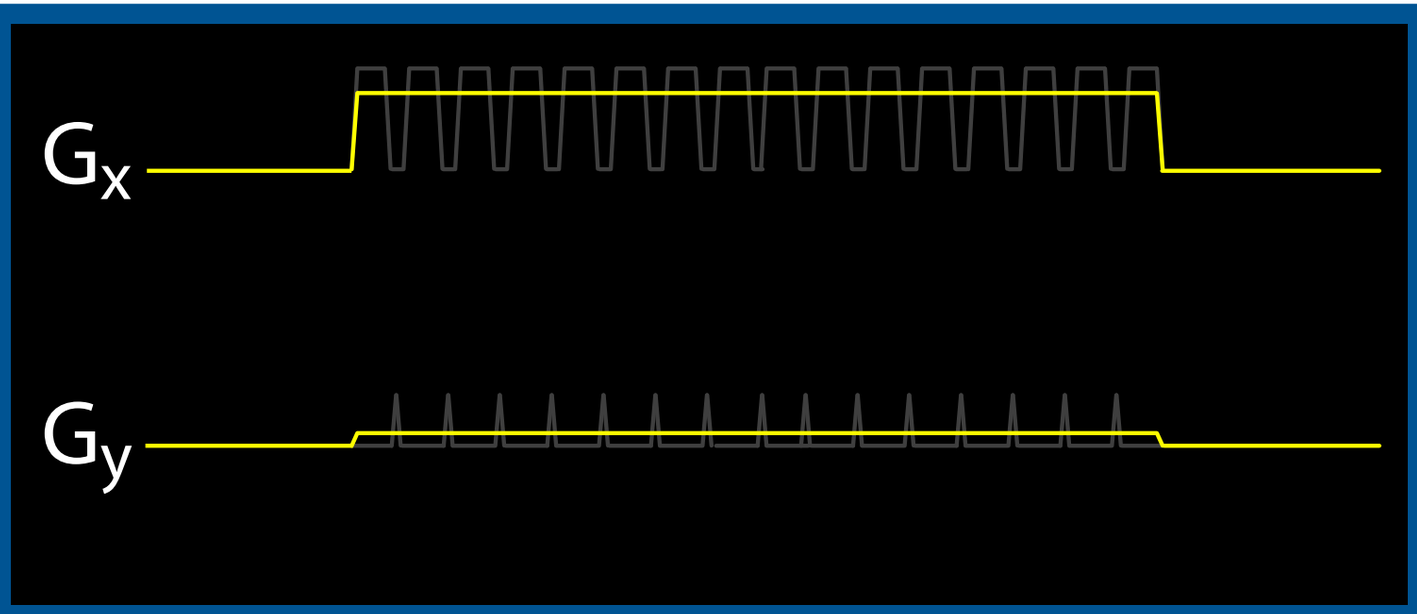
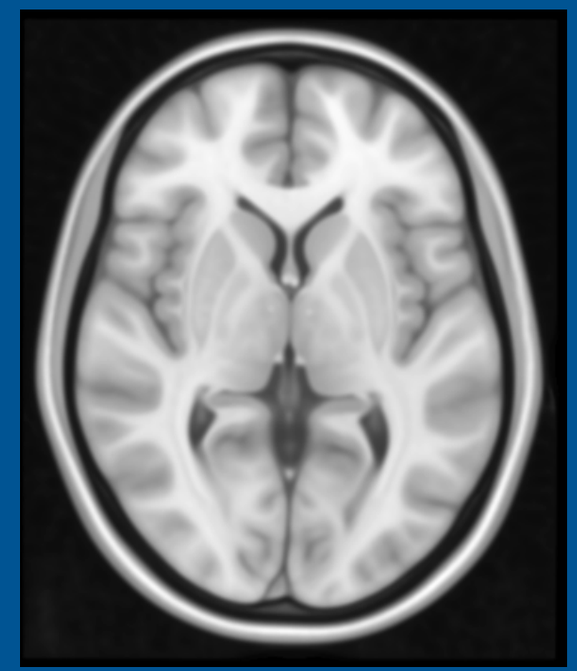


Image Distortion in EPI





In the EPI "frequency encode" or "along line" direction

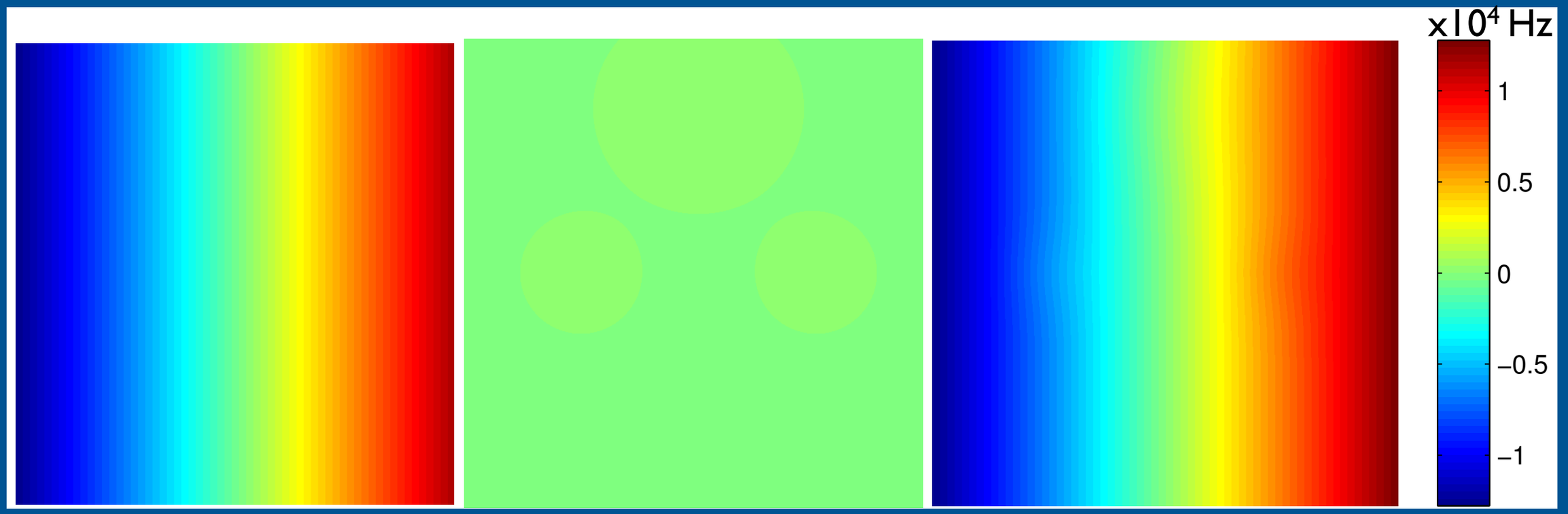
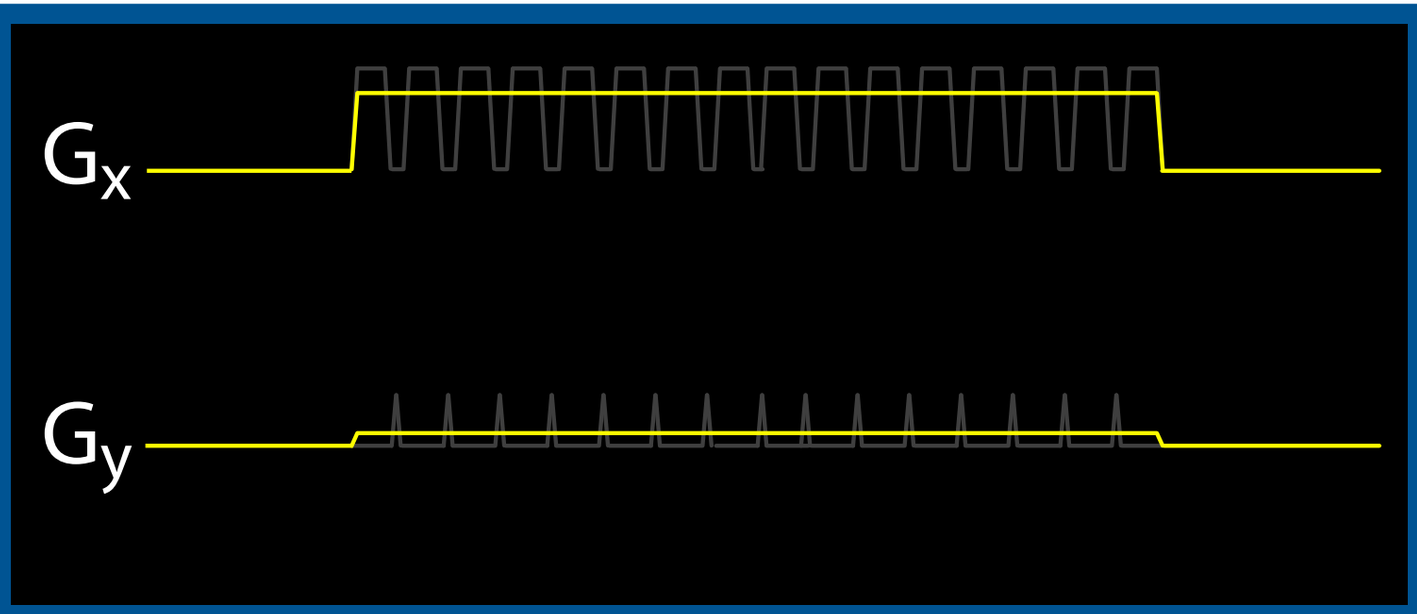
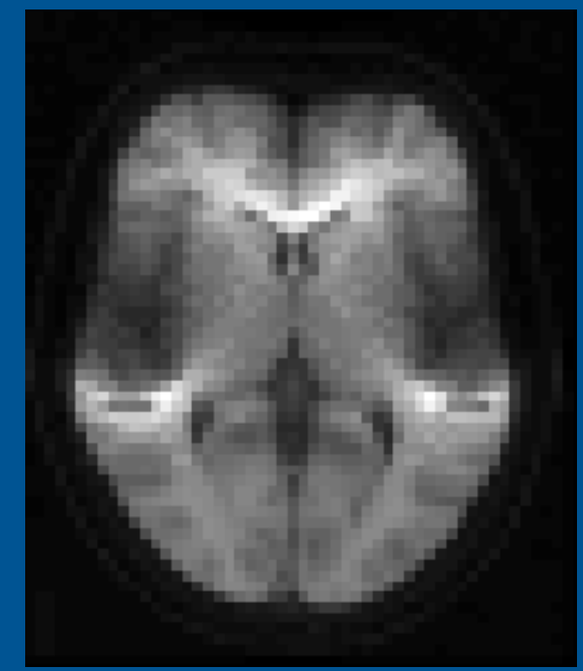


Image Distortion in EPI





In the EPI "phase encode" or "across lines" direction

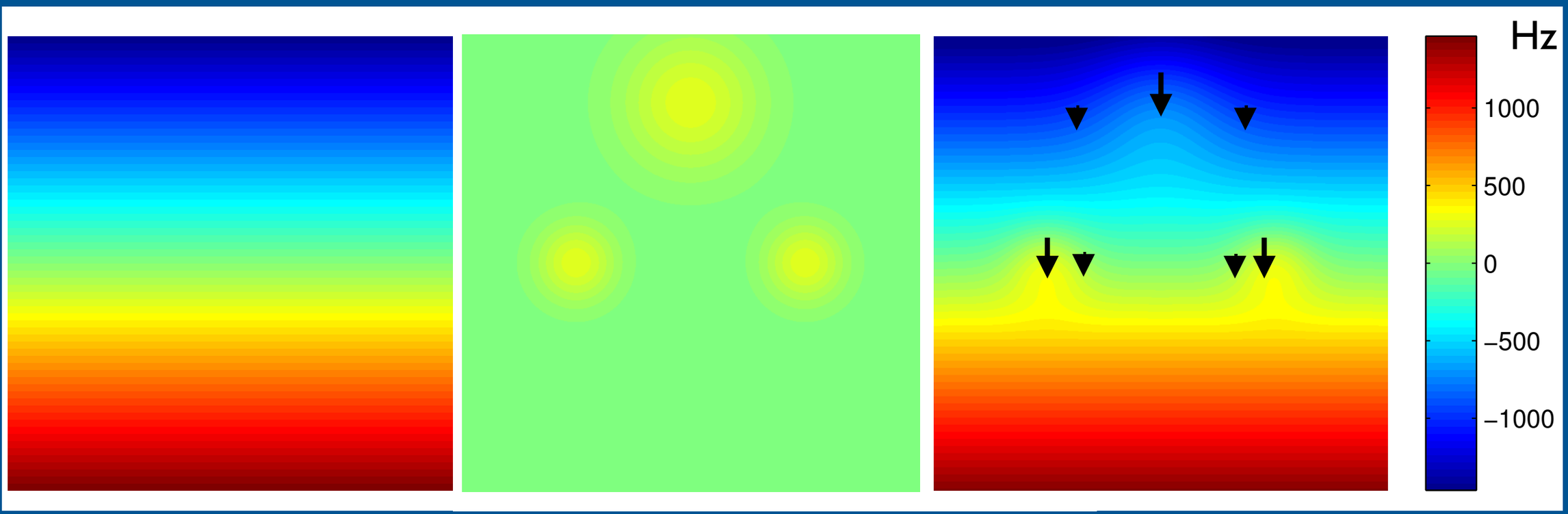
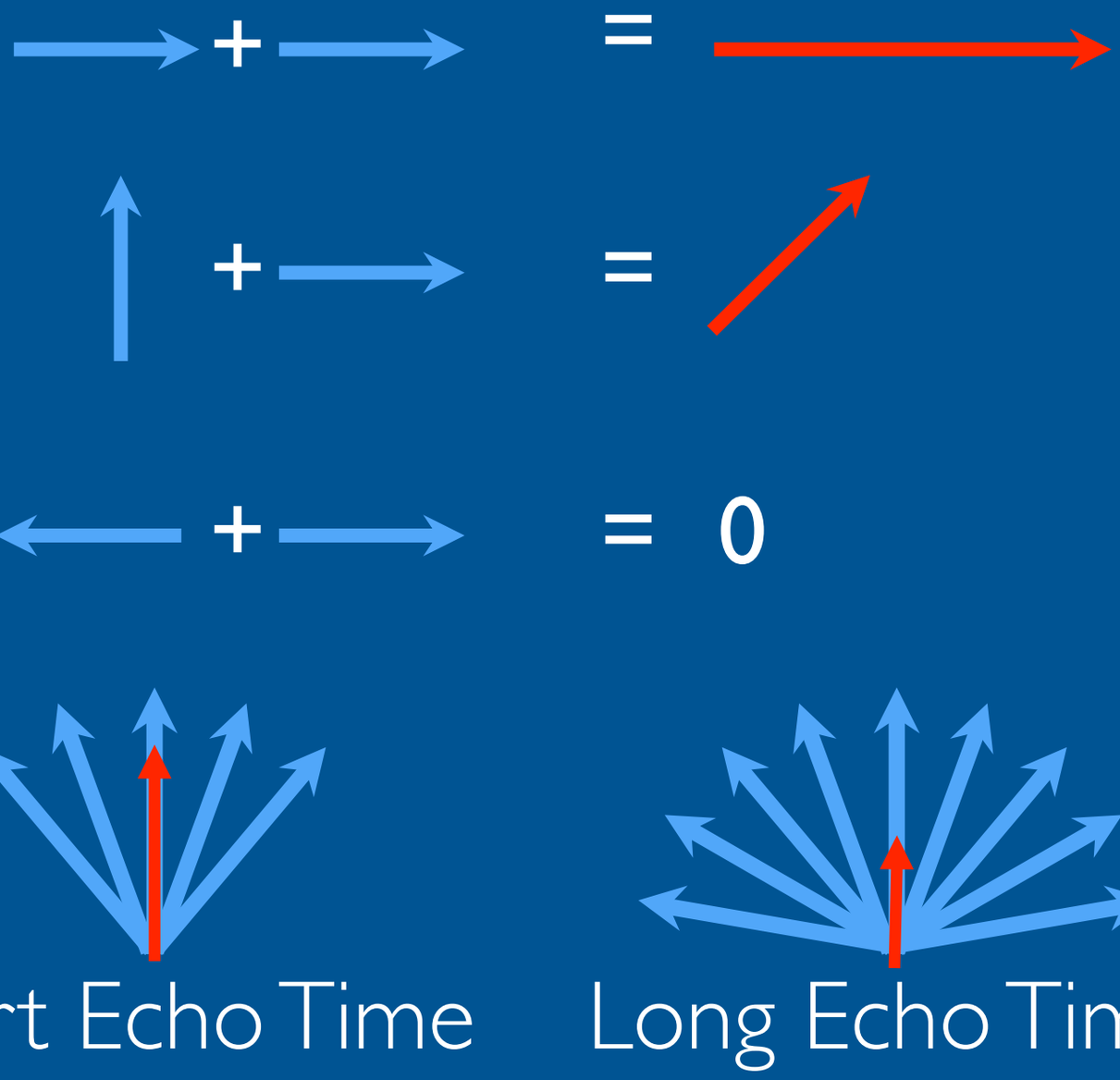


Image Distortion in EPI

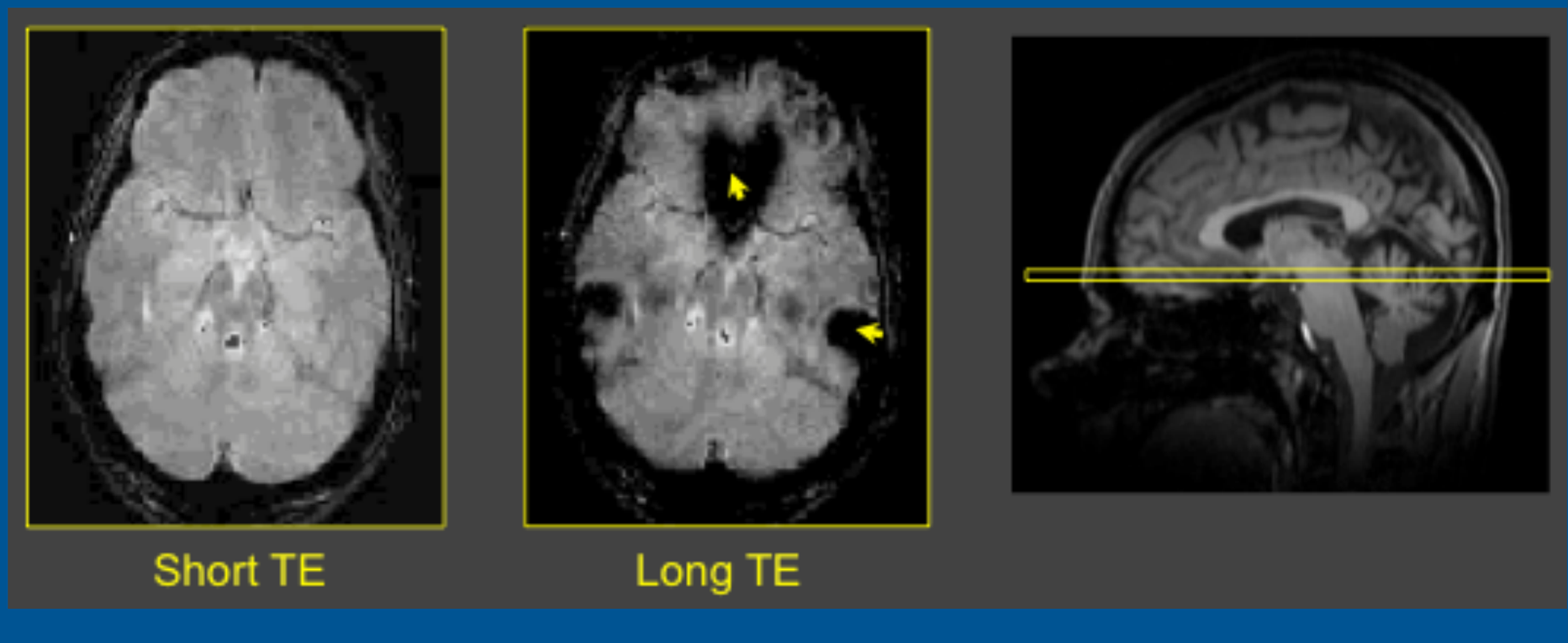
- Solutions:
  - Increase average gradient strength (increase sampling bandwidth)
  - Use parallel imaging (effective increase in sampling bandwidth)
  - Correct distortions in post-processing using a magnetic field map

Signal Dropout

- **Problem**: If magnetisation within a voxel is precessing at different frequencies, it will start to partially cancel out or "dephase", giving lower signal



Signal Dropout



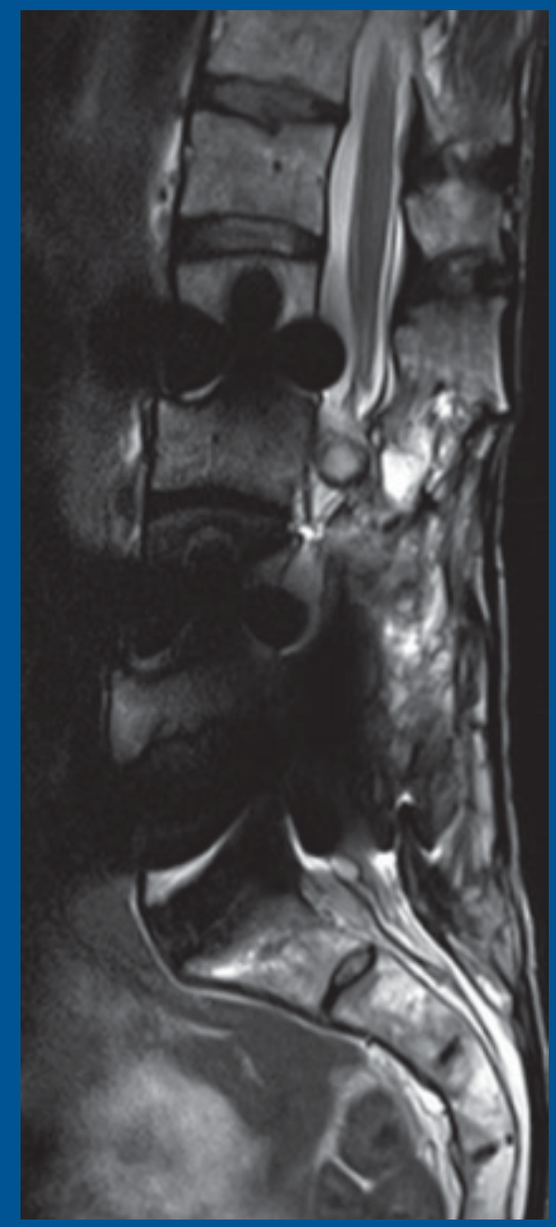
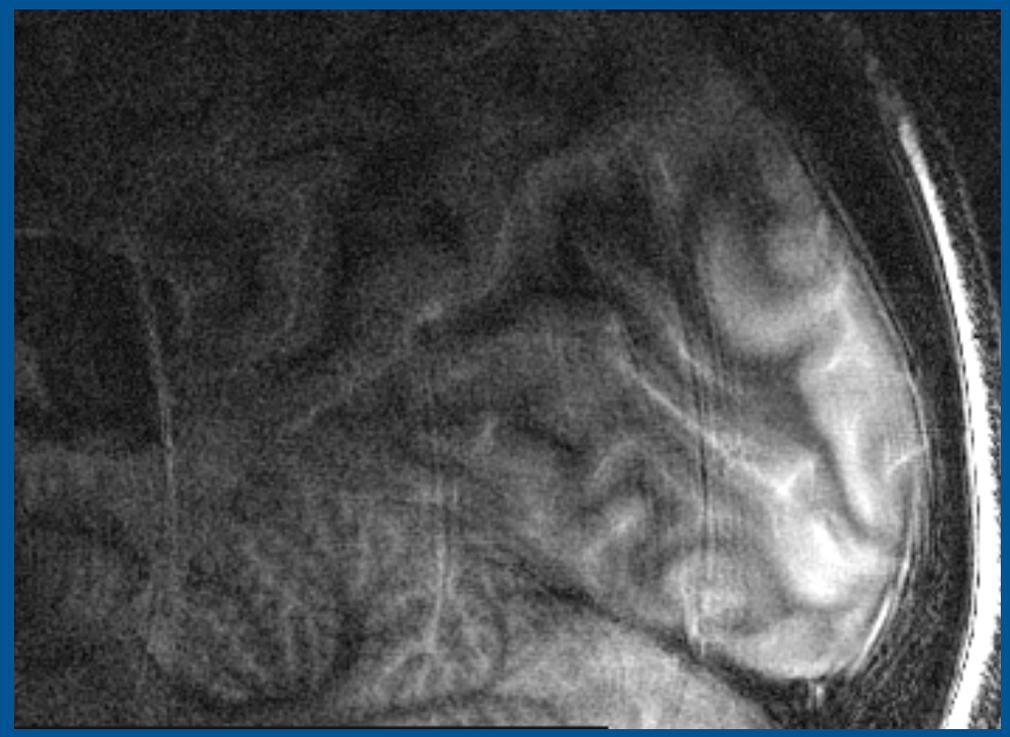


Image courtesy of Okell and Miller, 2014

- Affects all gradient echo acquisitions (like EPI)
- Severe artefacts near metallic implants
- **Solution:**
  - Reduce the echo time (TE)
  - "Refocus" the magnetisation using a spin-echo

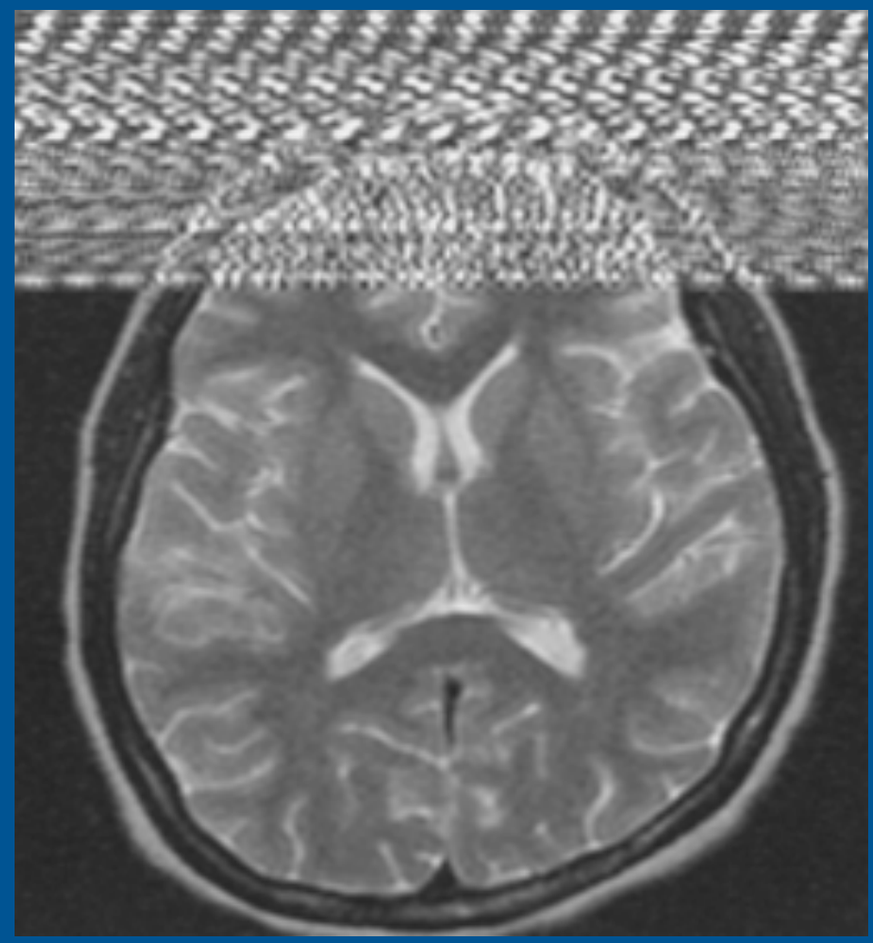
Subject Motion

- **Problem**:
  - Gross subject motion (discomfort, itch, cough etc.)
  - Involuntary movement (swallowing, blinking)
  - Multi-shot sequences: ghosting and blurring (different parts of k-space corrupted by different amounts)
  - Single-shot sequences: inconsistency across time
- **Solution**:
  - Maximise subject comfort, use pads and stress the importance of lying still
  - Post-hoc motion correction for single-shot sequences



RadioFrequency Interference

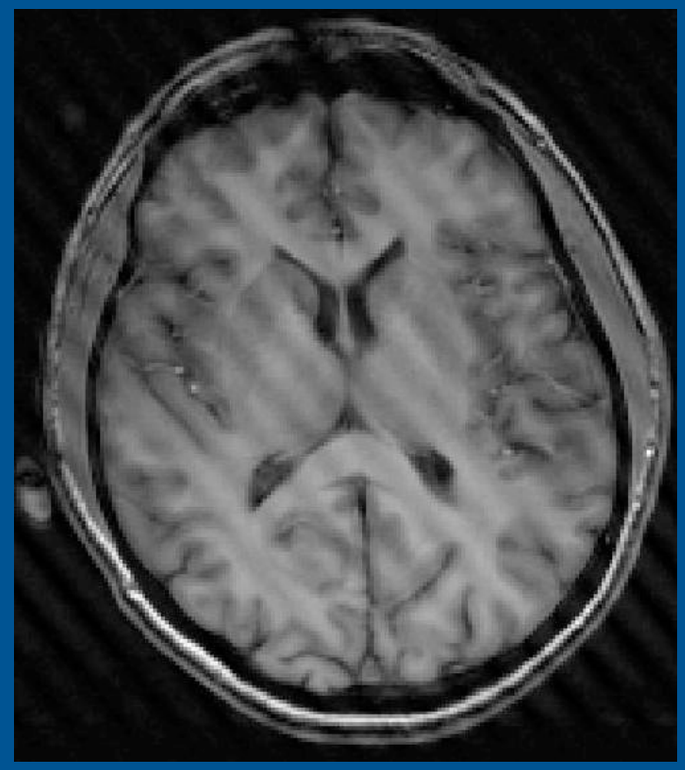
- **Problem**:
  - Door of the scan room left open
  - Unshielded or unfiltered cables
  - Custom electrical equipment within the room



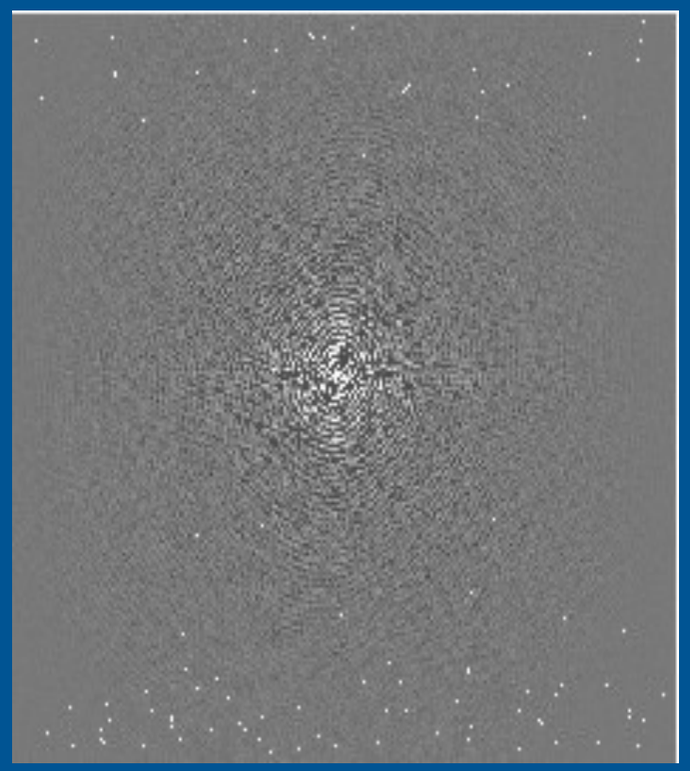
- **Solution**:
  - Close doors or fix equipment

Spiking

- **Problem**:
  - Metal to metal contacts (e.g. broken RF coil or cables)
  - Arcing within gradient coil



- **Solution**:
  - Call the scanner manufacturer!



Conclusion

In MRI, the rich and complex interactions of particles (like the Hydrogen protons bound to water) with magnetic fields is used to generate images

The "indirectness" of the MR imaging process is what allows so many different manipulations to be made on the way measurement is performed (i.e. fast vs. high quality images)

However, this flexibility is is paid for in full by having many different avenues for error and image artefacts

The End