Advanced Topics and Diffusion MRI

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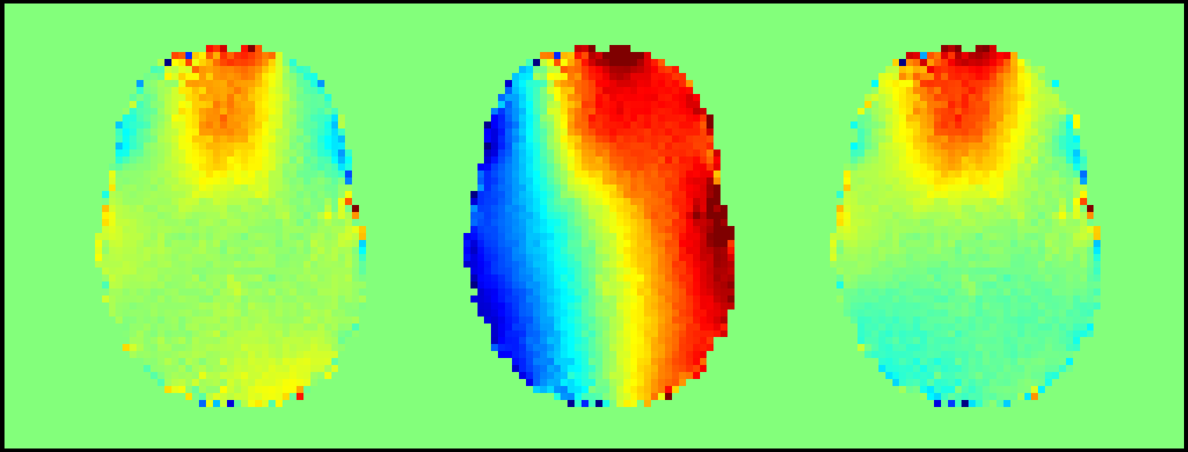
(with slides from Karla Miller)



Slides available at:

https://users.fmrib.ox.ac.uk/~mchiew/docs/fsl_diffusion.pdf

https://users.fmrib.ox.ac.uk/~mchiew/teaching

MRI Physics

- Revisiting Image Encoding

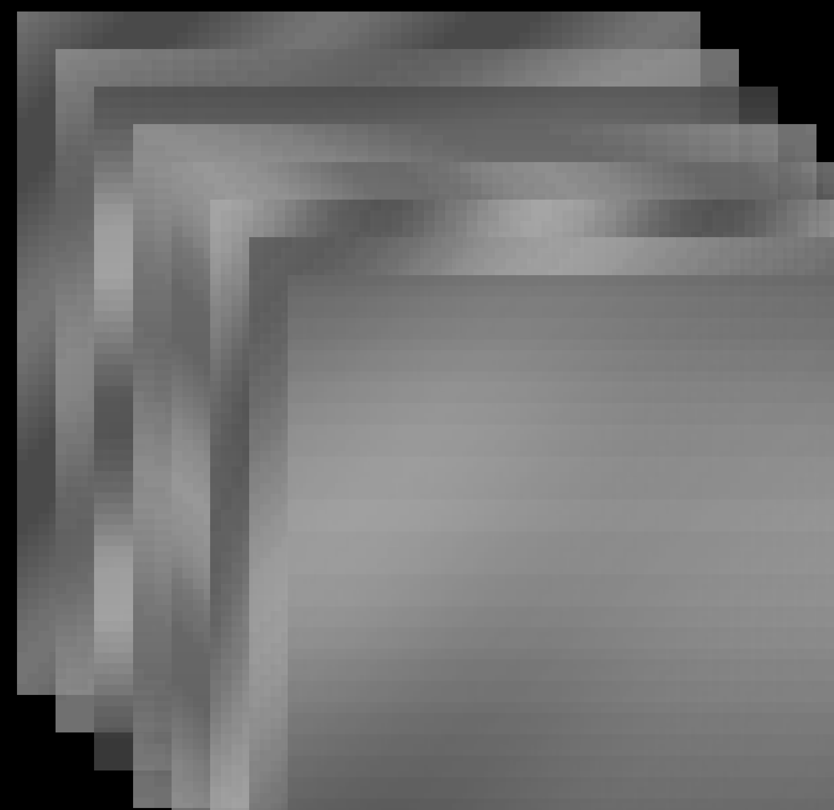
- Spin vs. gradient echo
- Fast imaging & artefacts
- Diffusion MRI
  - Diffusion weighting
  - Acquisition techniques
  - Tradeoffs & complications

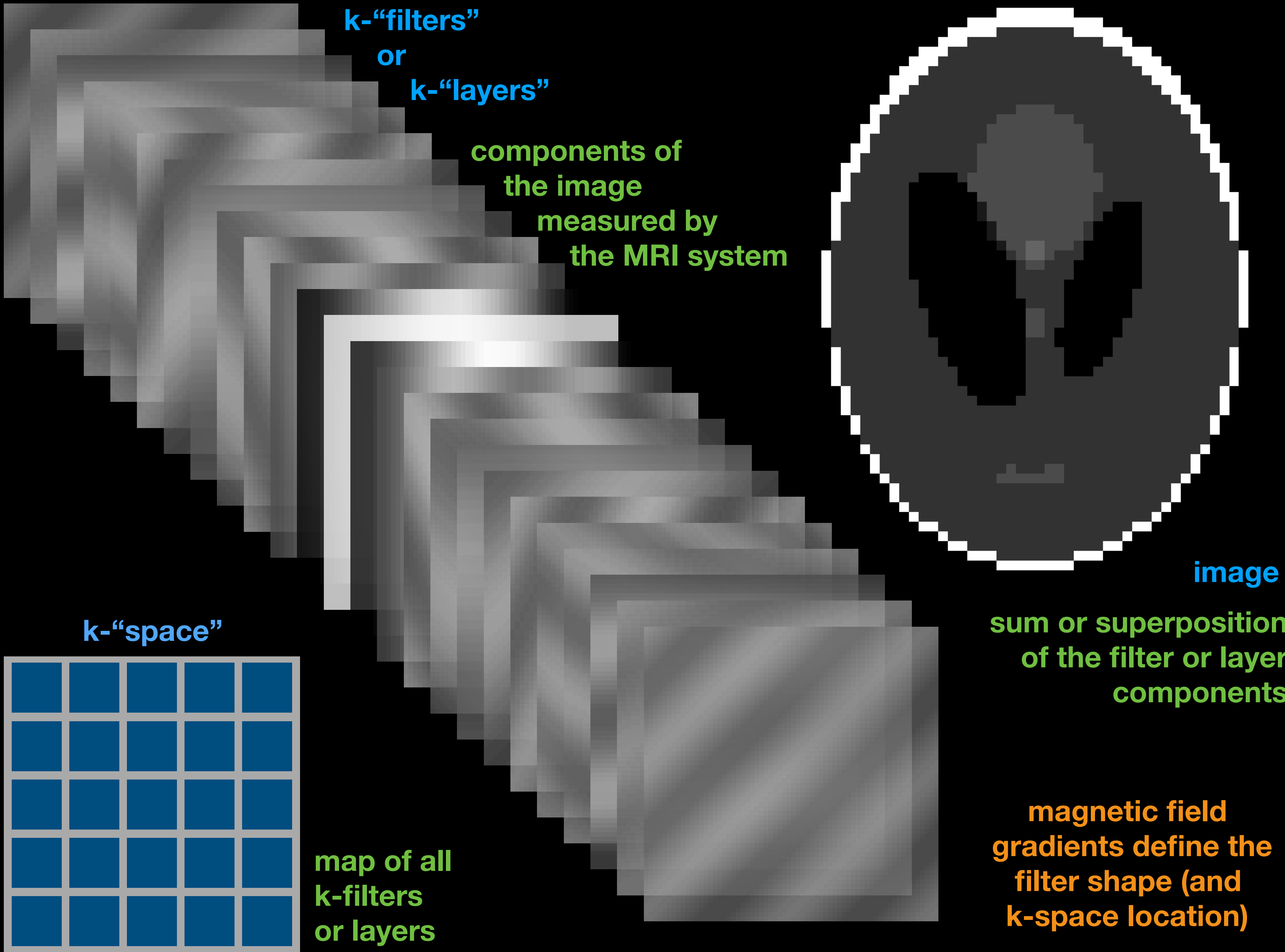
camera

“pixel-by-pixel”

k-space

“layer-by-layer”




k-“filters”
or
k-“layers”
components of
the image
measured by
the MRI system
image
k-“space”
sum or superposition
of the filter or layer
components
map of all
k-filters
or layers
magnetic field
gradients define the
filter shape (and
k-space location)

MRI Physics

- Revisiting Image Encoding

- Spin vs. gradient echo (T2 & T2*)
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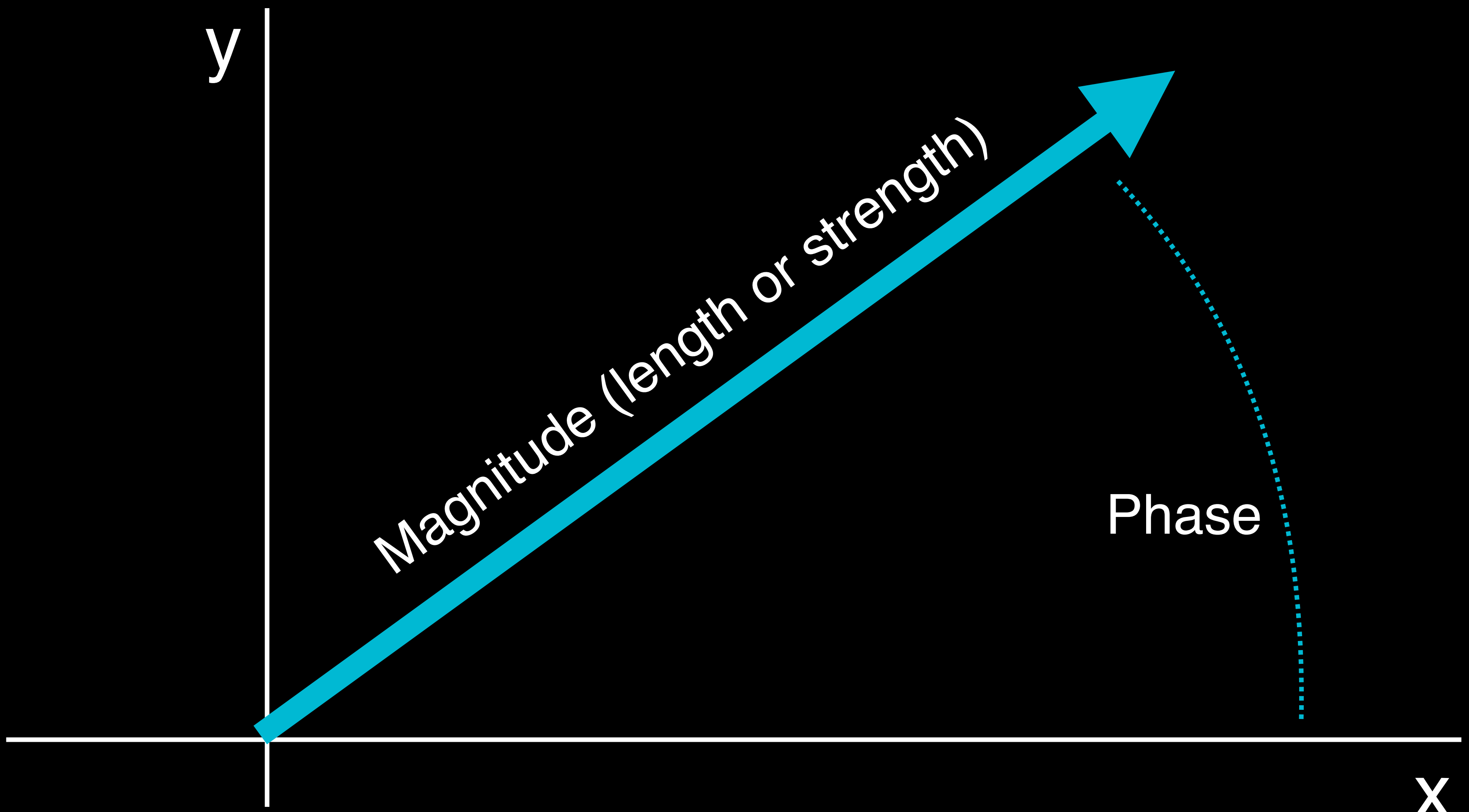
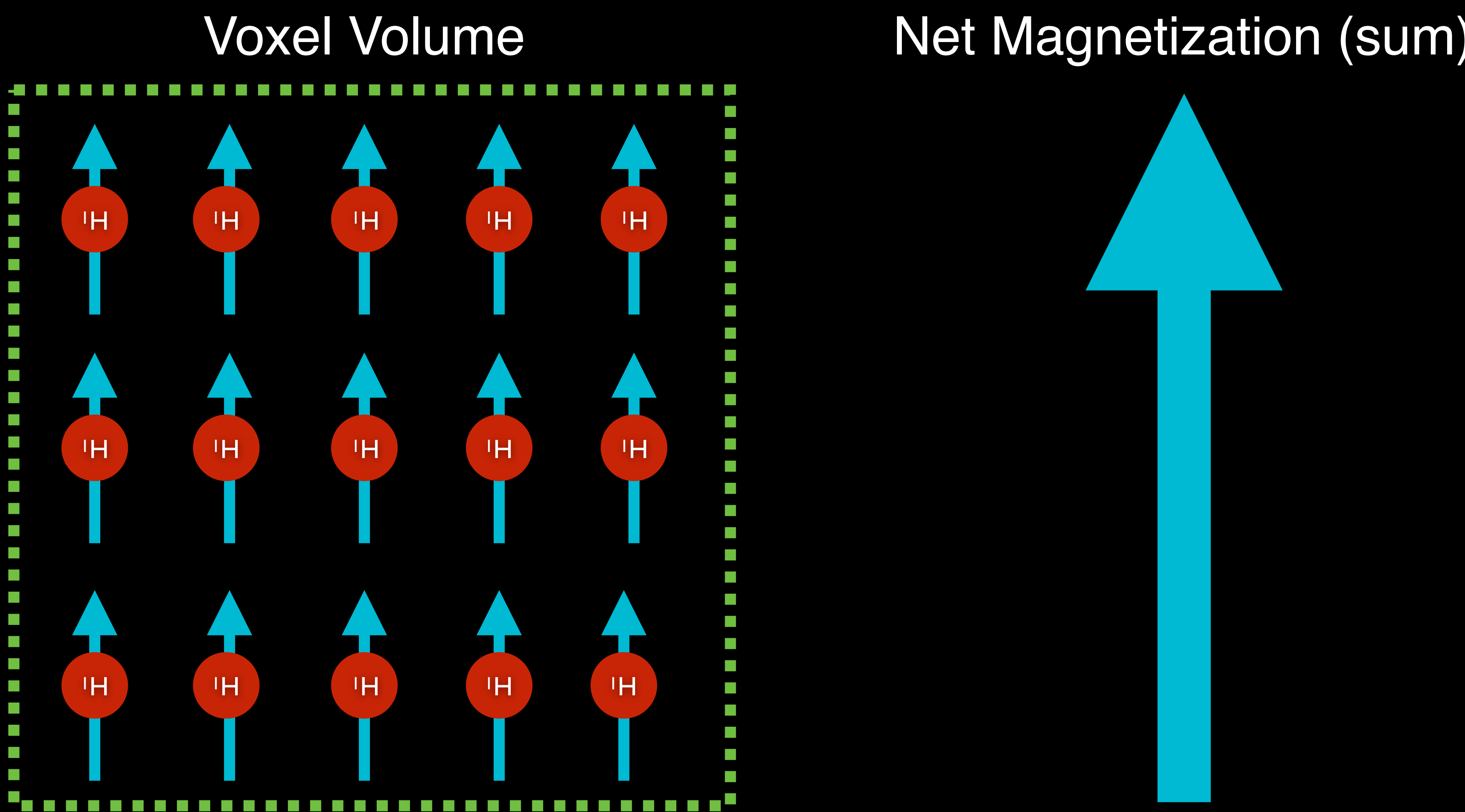
Phase

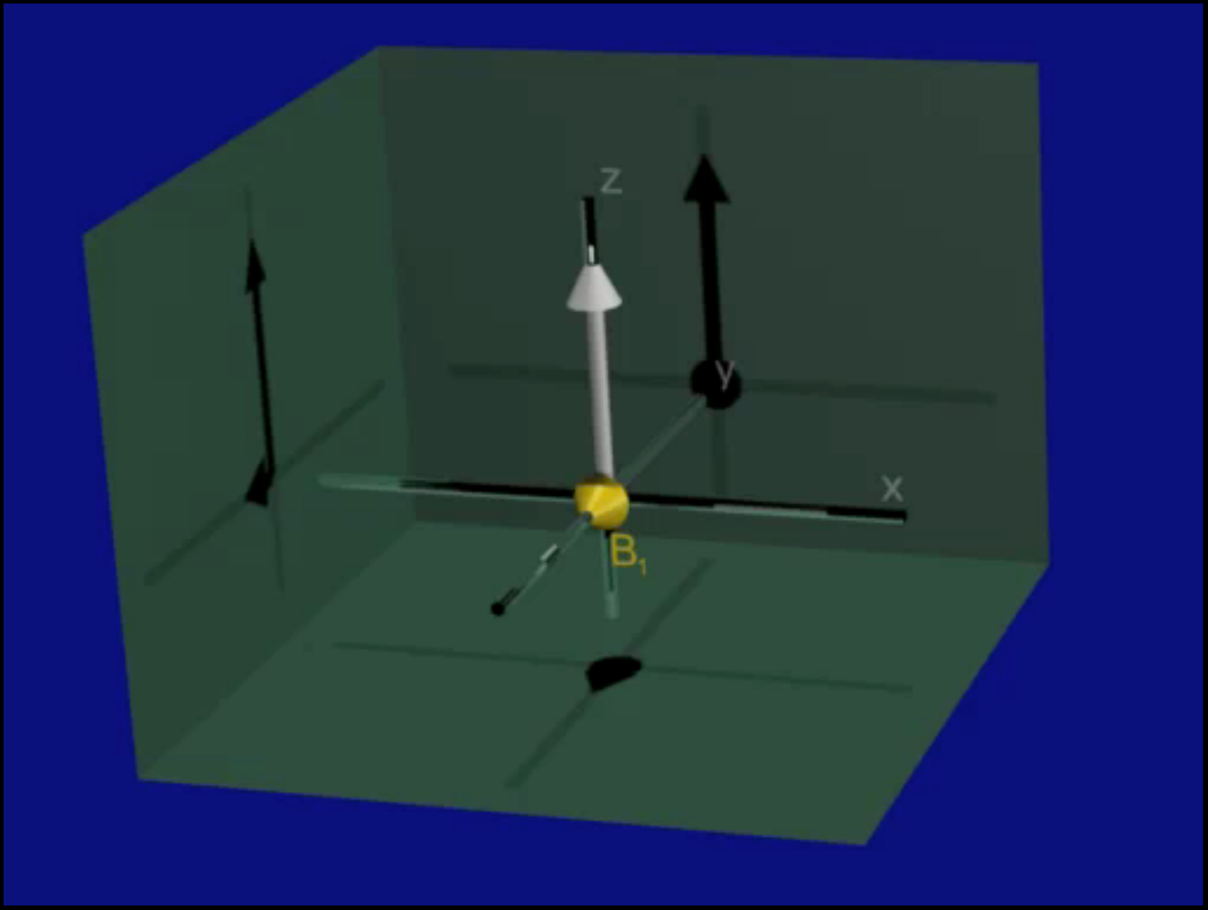


Angle / Rotation / Orientation / Direction
of the transverse Magnetisation

Net Magnetization (in-phase)



Magnetic field imperfections: T_2* decay

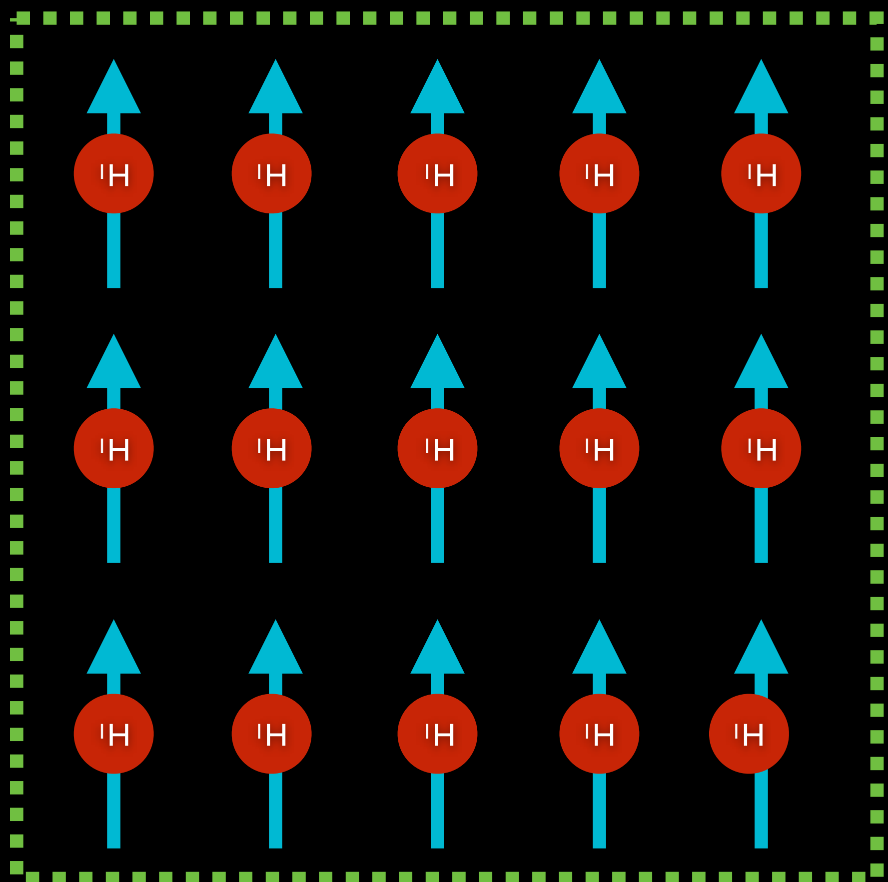


Always some local imperfections in magnetic field
= range of precession frequencies in a voxel

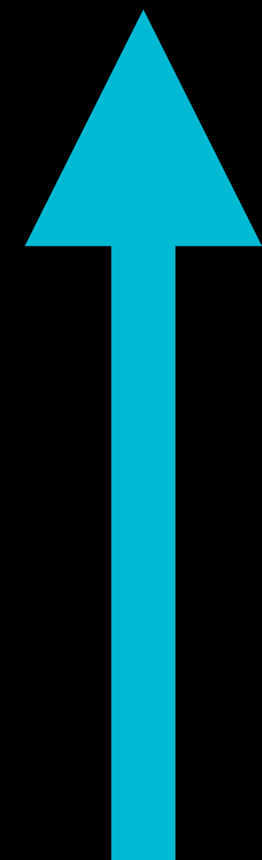
Over time, spins lose alignment (“dephase”)

Net Magnetization (in-phase)

Voxel Volume

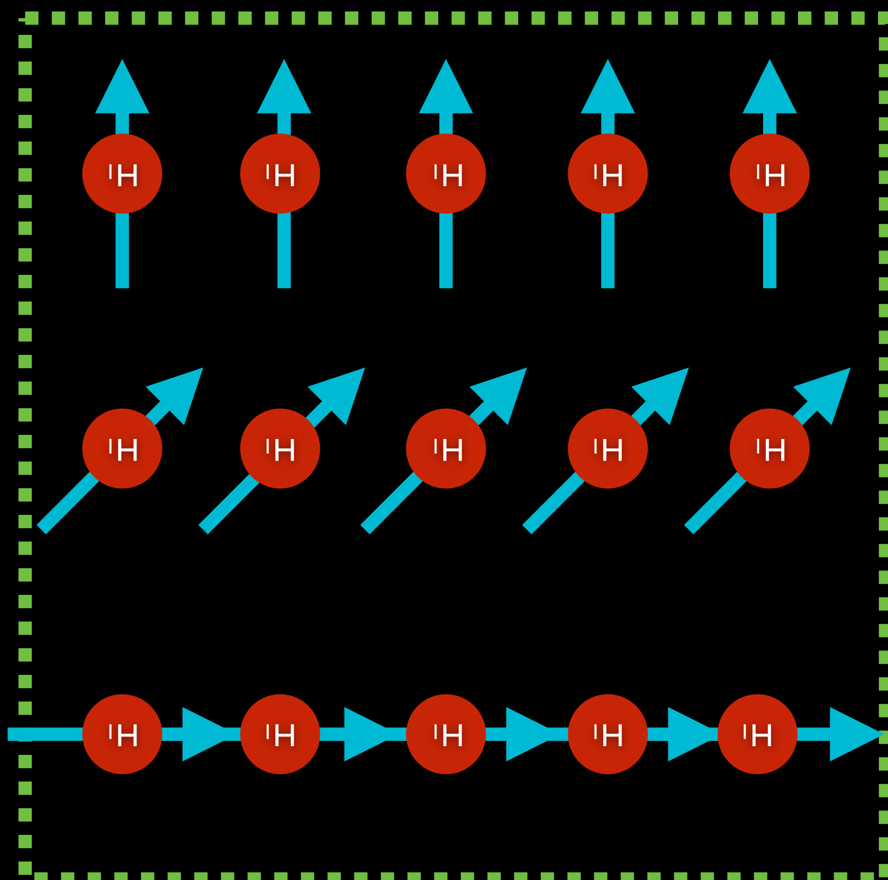


Net Magnetization (sum)



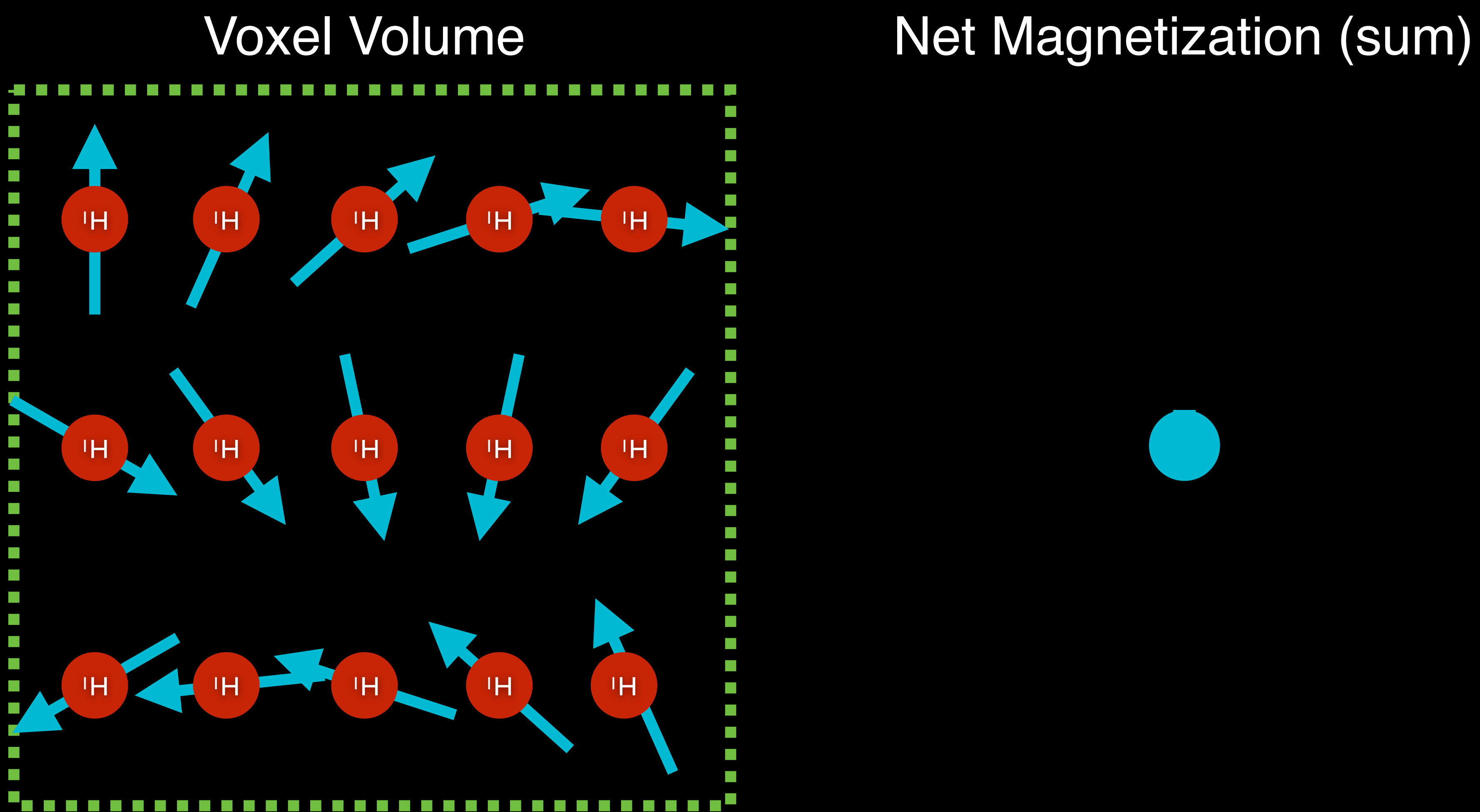
Net Magnetization (dephasing)

Voxel Volume



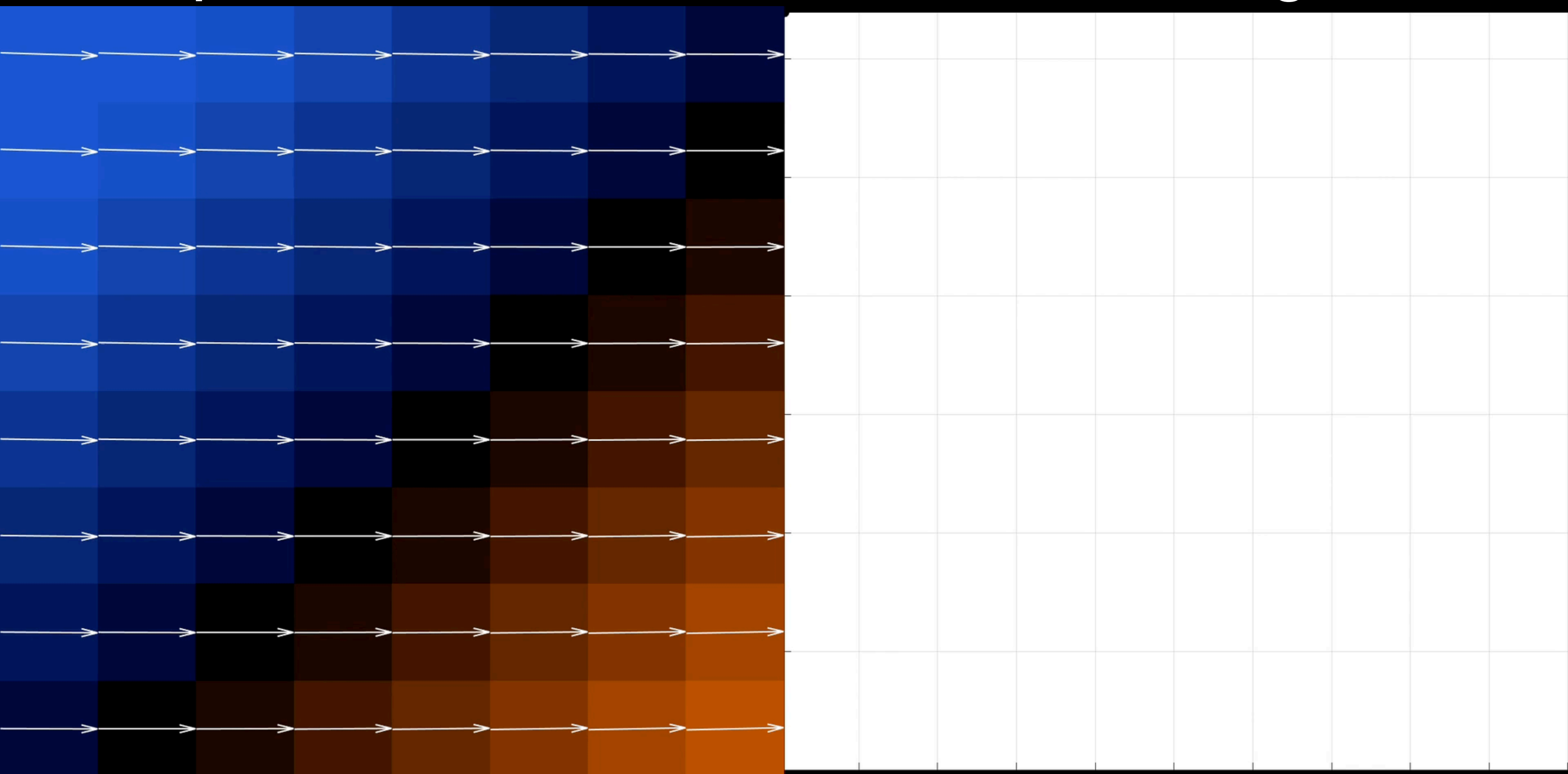
Net Magnetization (sum)

Net Magnetization (dephased)



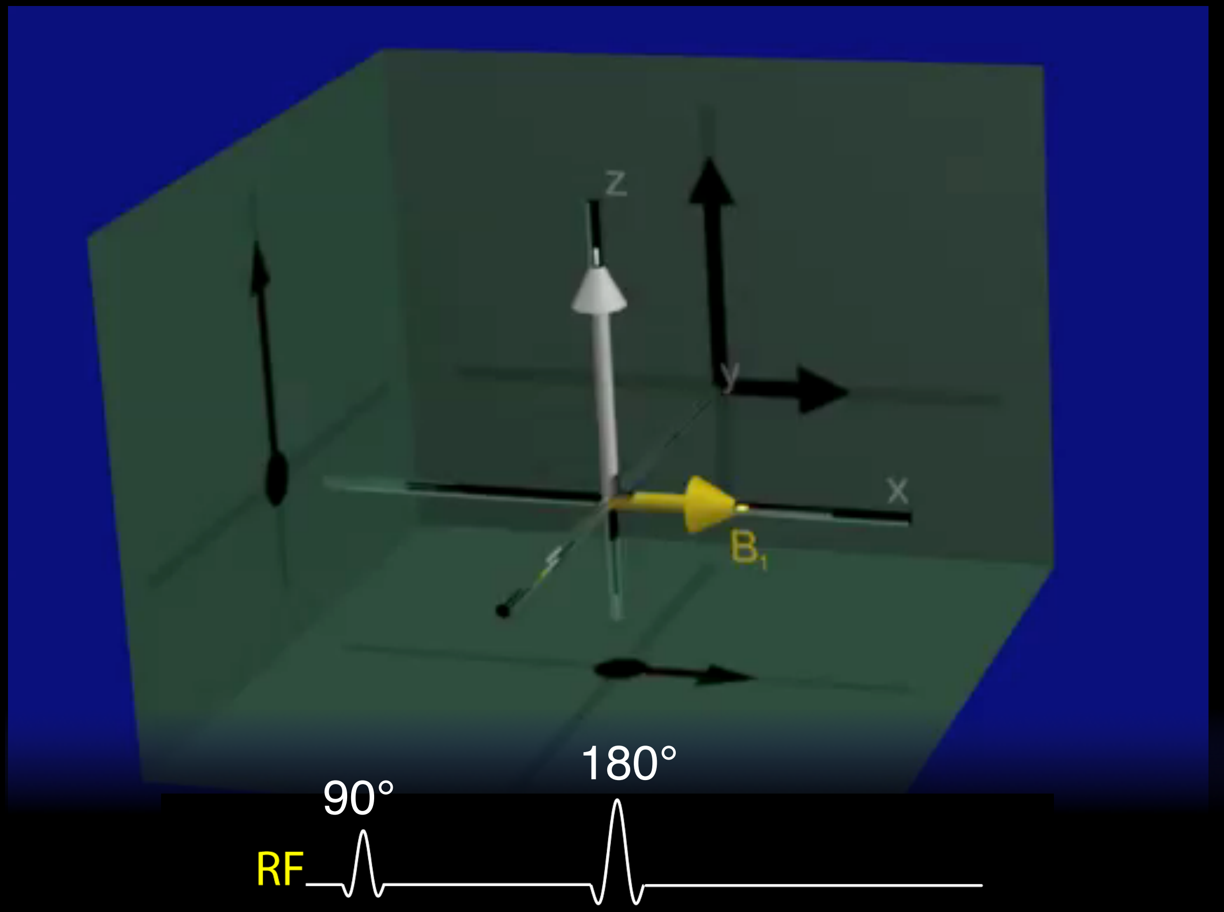
Dephasing

Simple Voxel Model | Voxel Signal



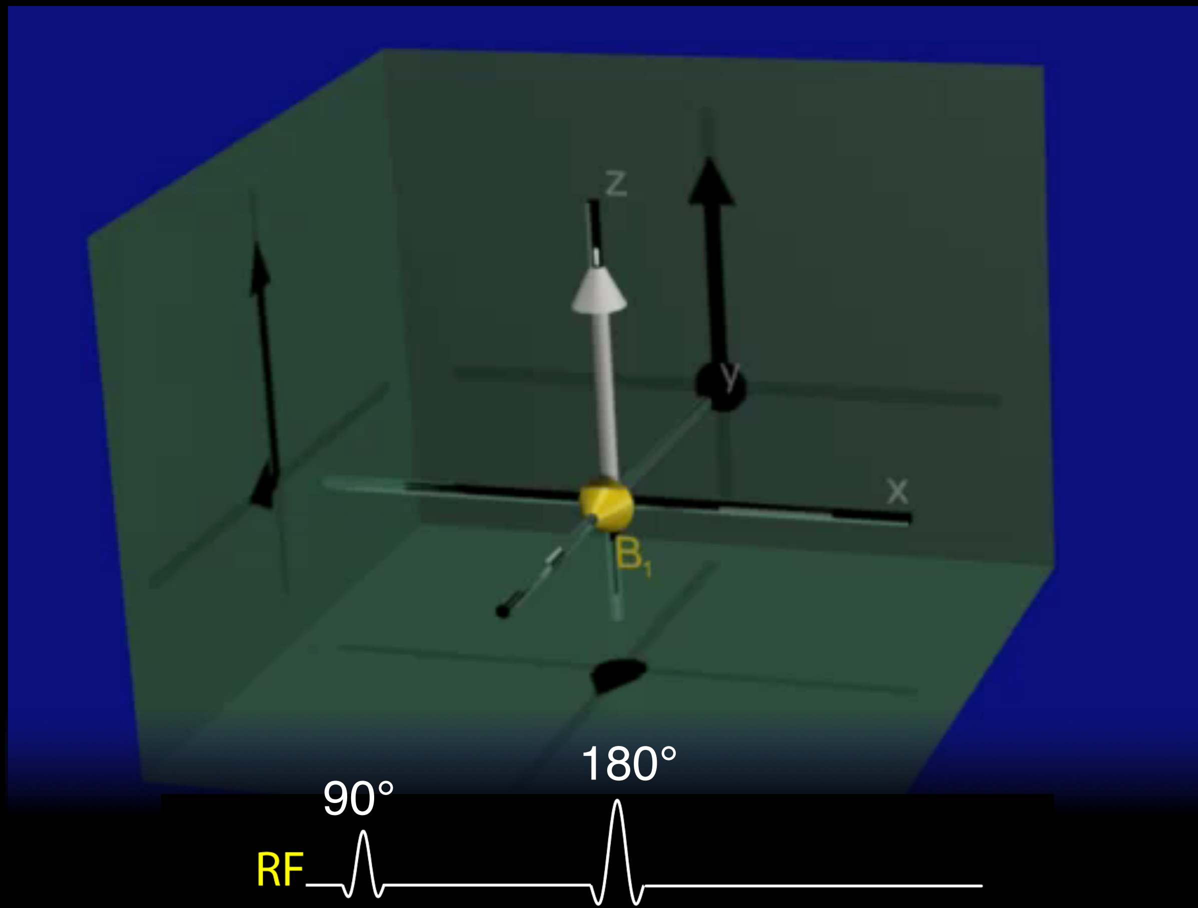
Negative gradient | Positive gradient

Refocusing (180º RF pulse) with no dephasing



The 180º RF pulse complete “flips” the magnetisation around an axis

Refocusing (180º RF pulse) with dephasing

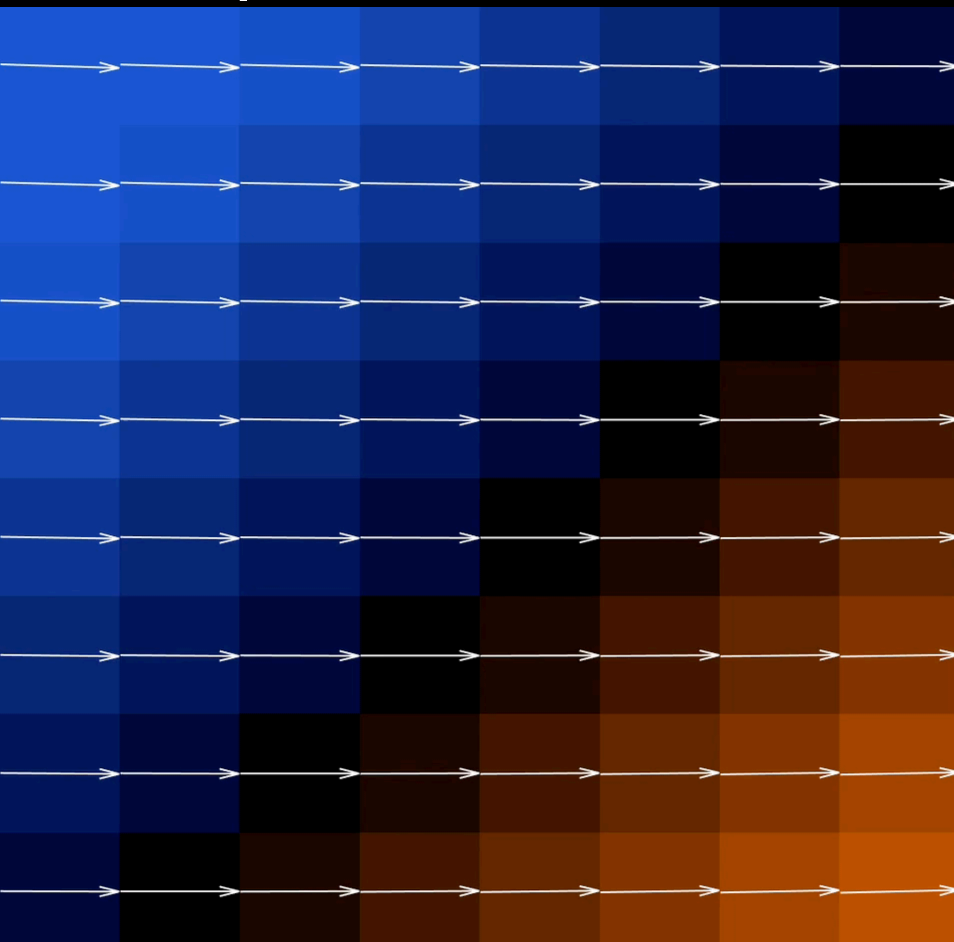


Spin echo: The time at which the spins are re-aligned

Refocusing pulse: 180º pulse that creates a spin echo

Dephasing

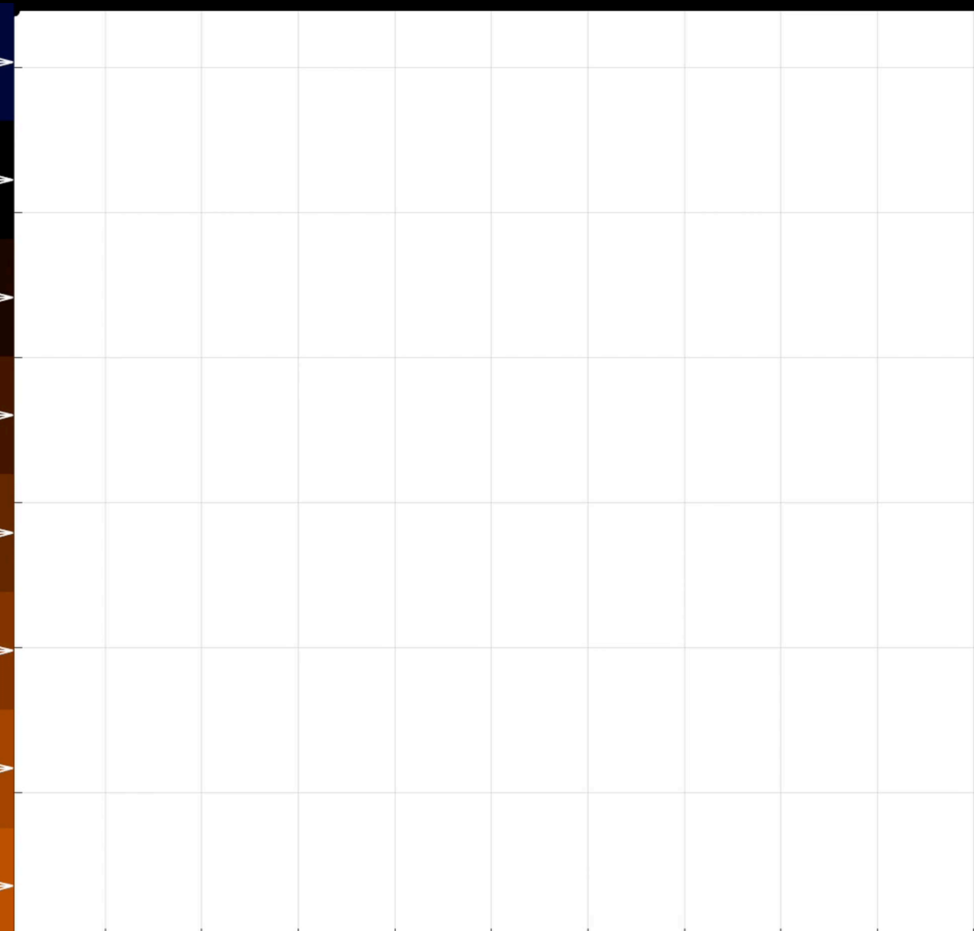
Simple Voxel Model



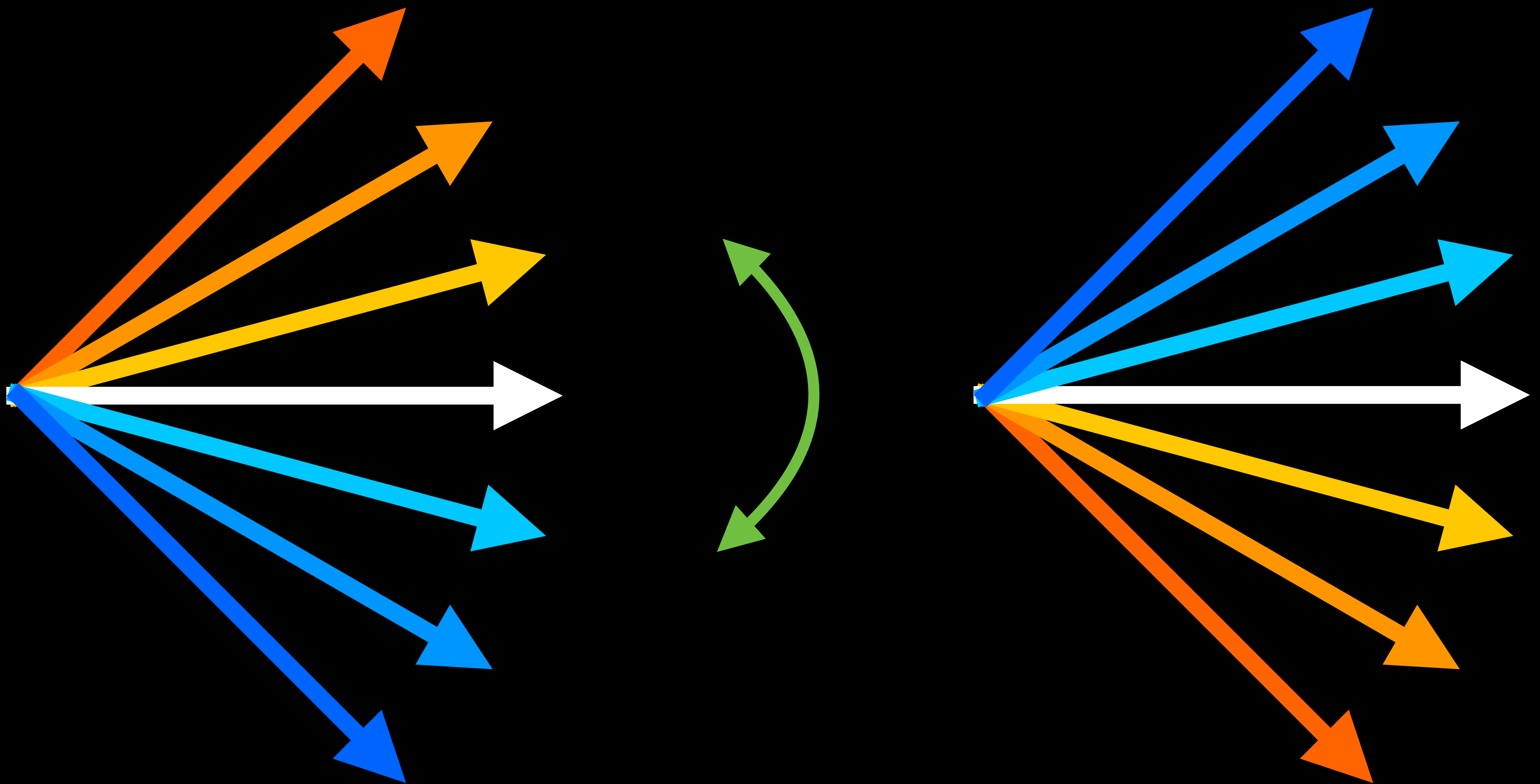
clockwise

counter clockwise

Voxel Signal

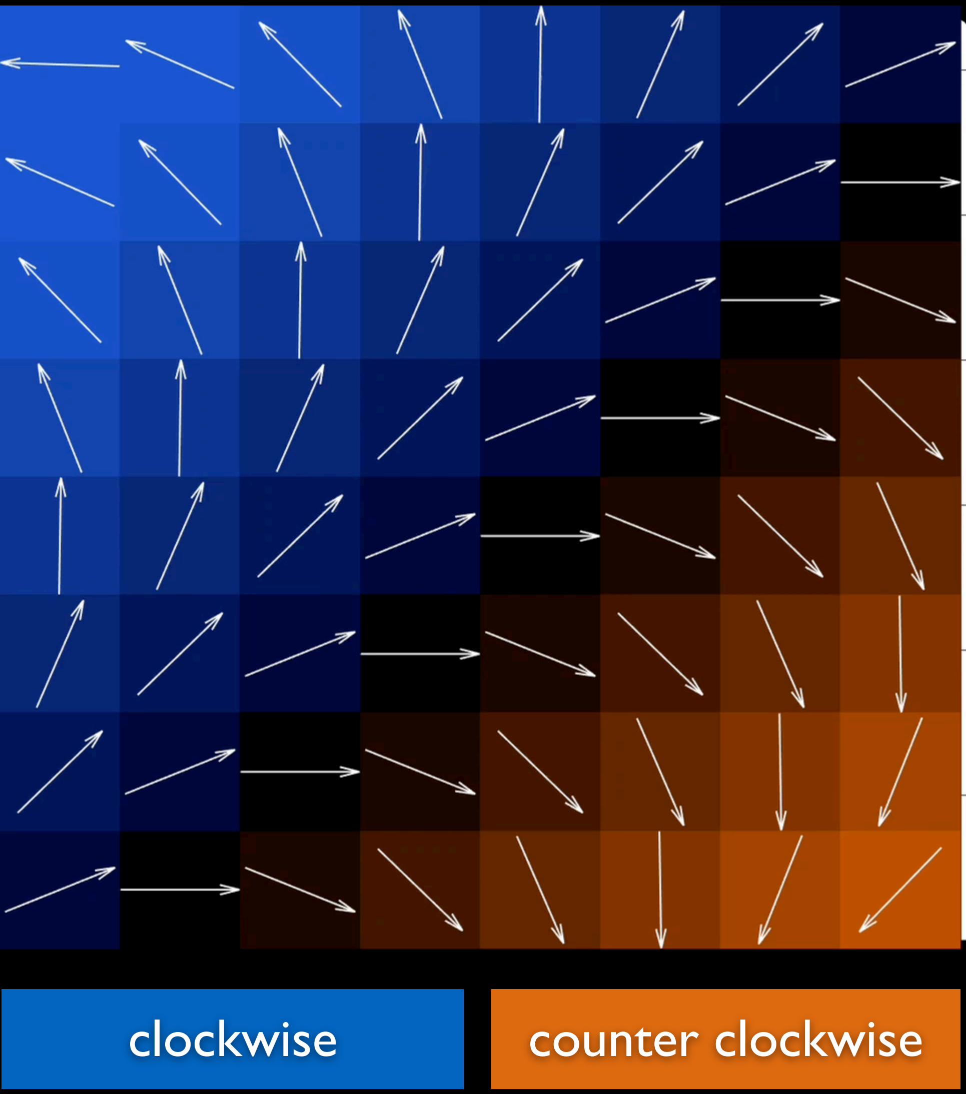


180º Refocusing Pulse!

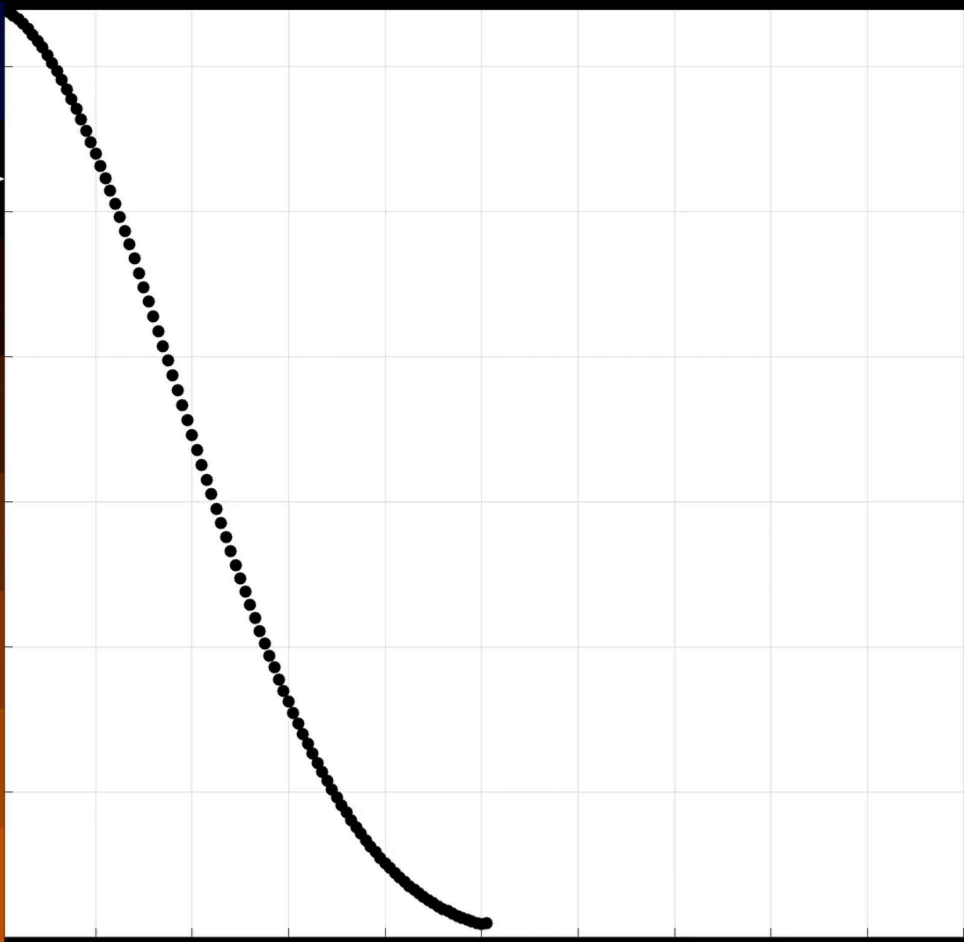


Rephasing After Spin Echo

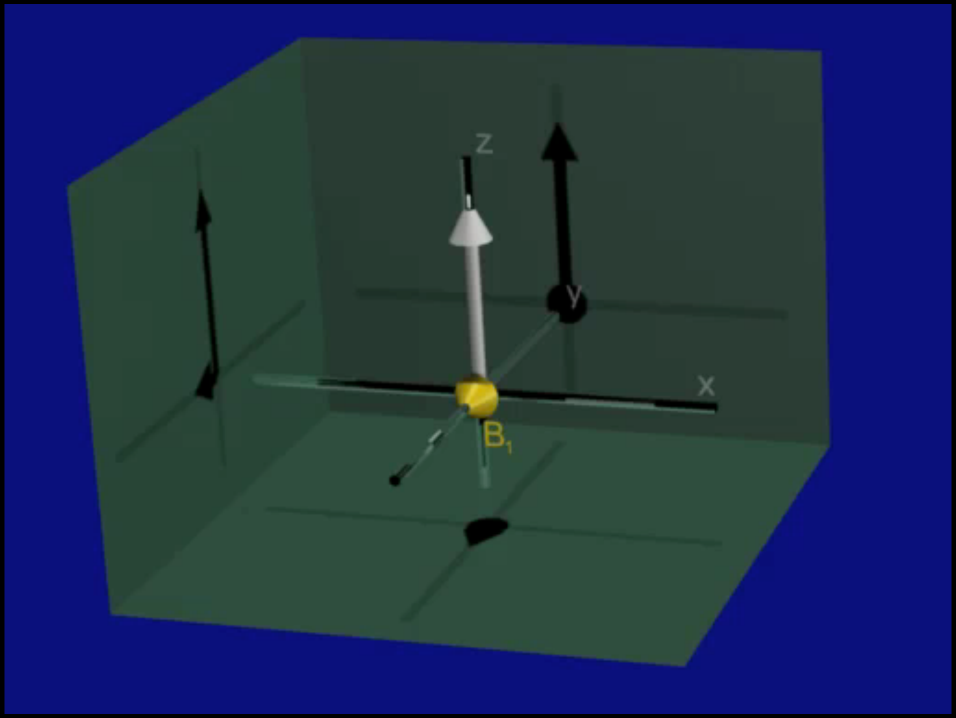
Simple Voxel Model

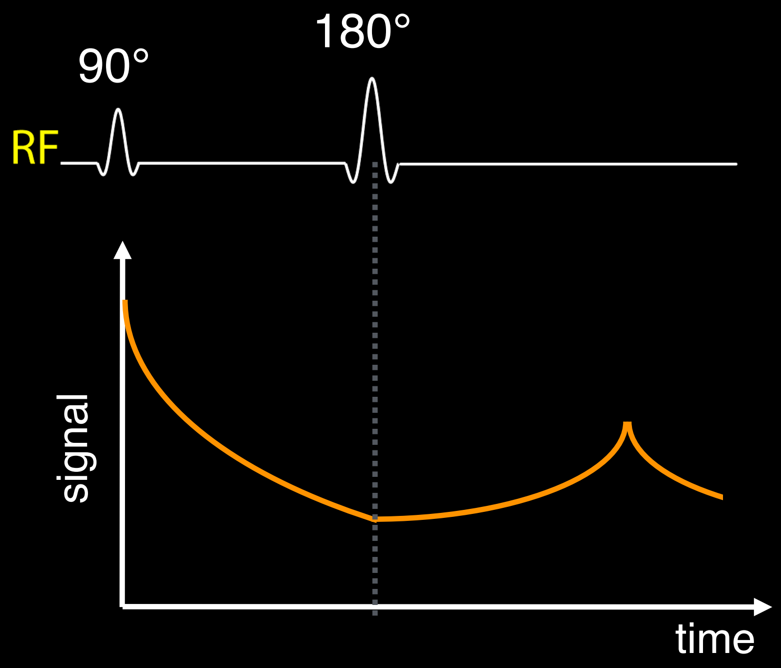


Voxel Signal



Refocusing (180° pulse) spin echo





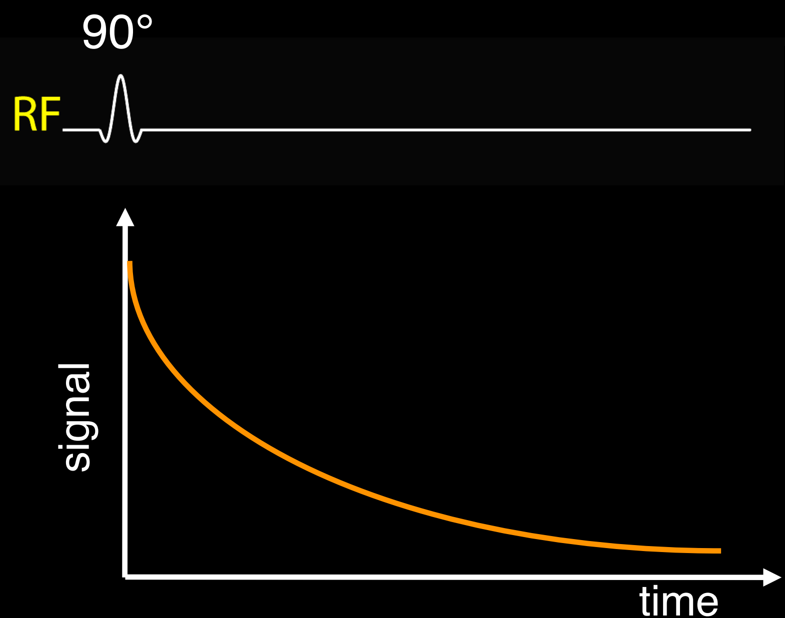
Spin echo: The time at which the spins are re-aligned

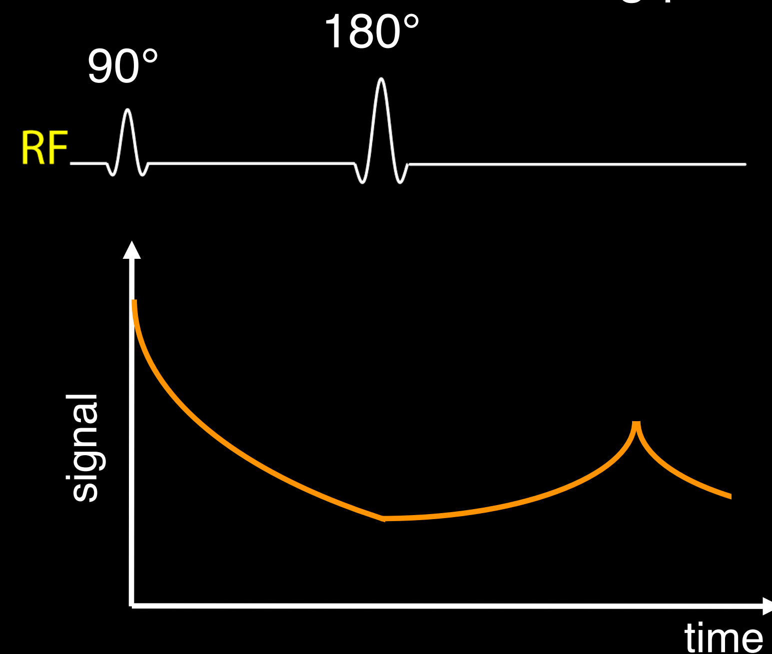
Refocusing pulse: 180° pulse that creates a spin echo

Gradient echo vs. spin echo

(i.e. no spin-echo, no 180° refocusing pulse)

(i.e. has spin-echo, has 180° refocusing pulse)





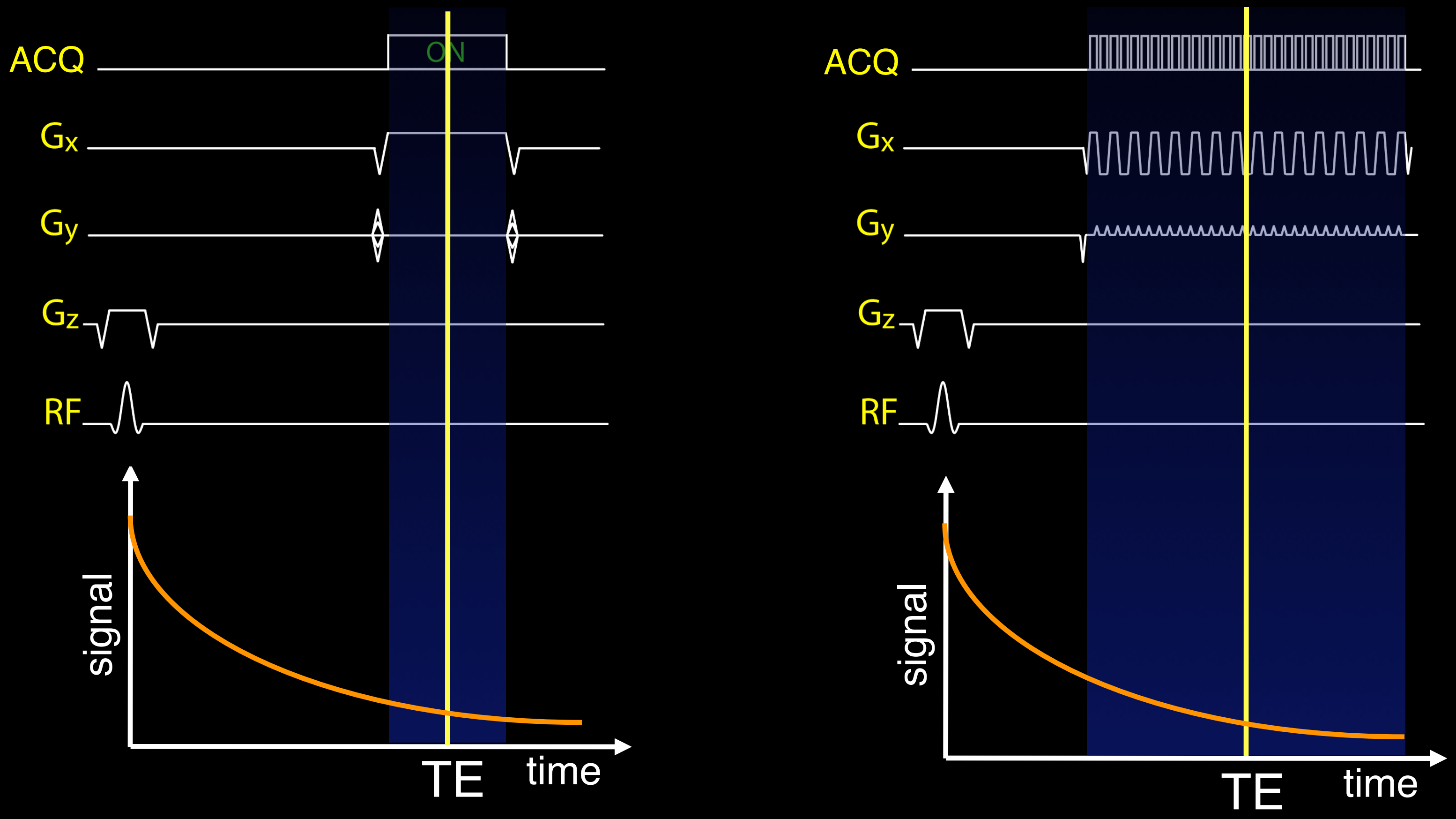
GRE signal
(sometimes called a Free Induction Decay = FID)

SE signal
(signal decays, then comes back as "echo")

pure signal decay

decay with partial recovery

What defines a gradient echo sequence?

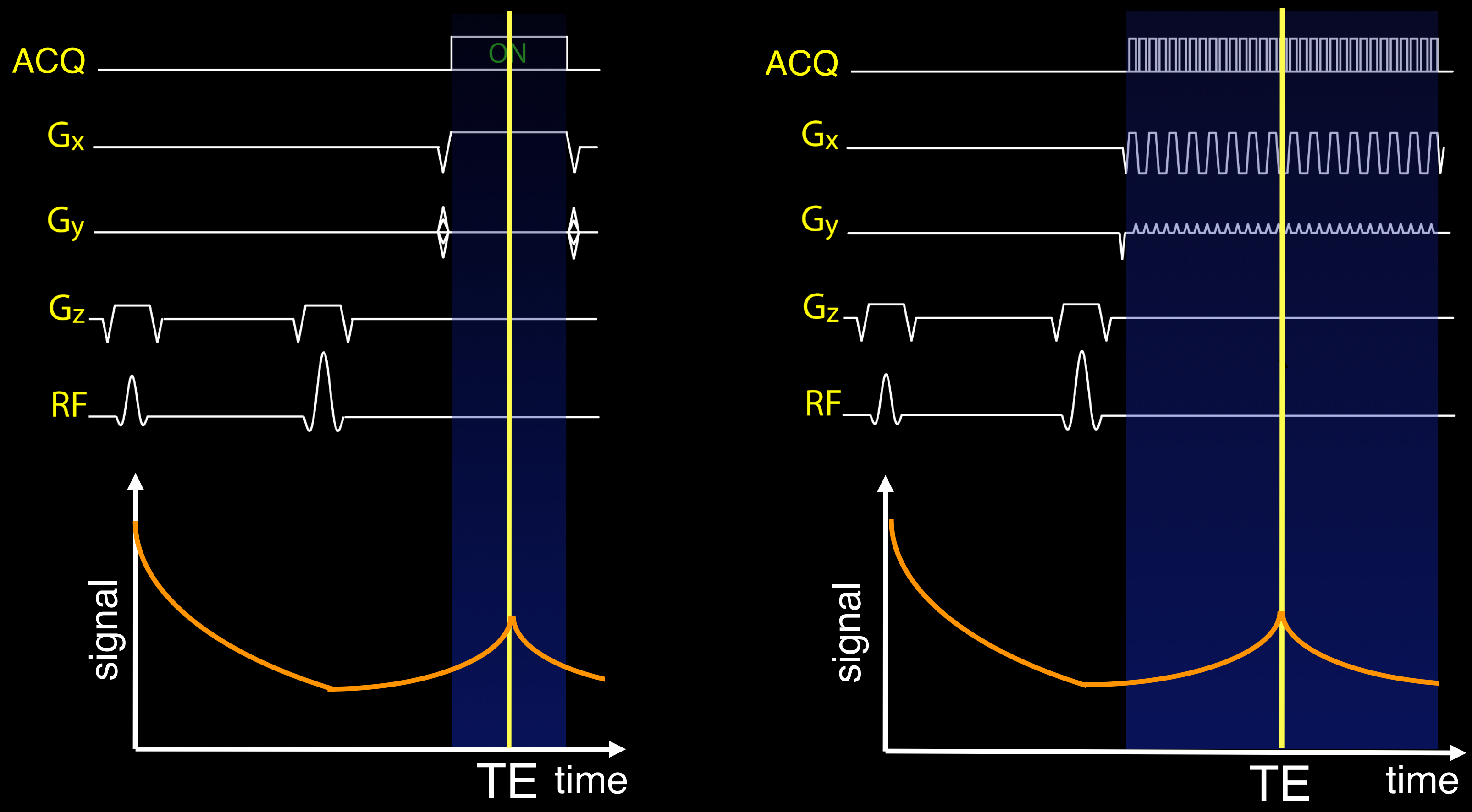


GRE refers to a sequence with: excitation-delay-readout

Any kind of readout can be used (linescan, EPI, spiral…)

Image signal depends on TE, but not on readout method!

What defines a spin echo sequence?

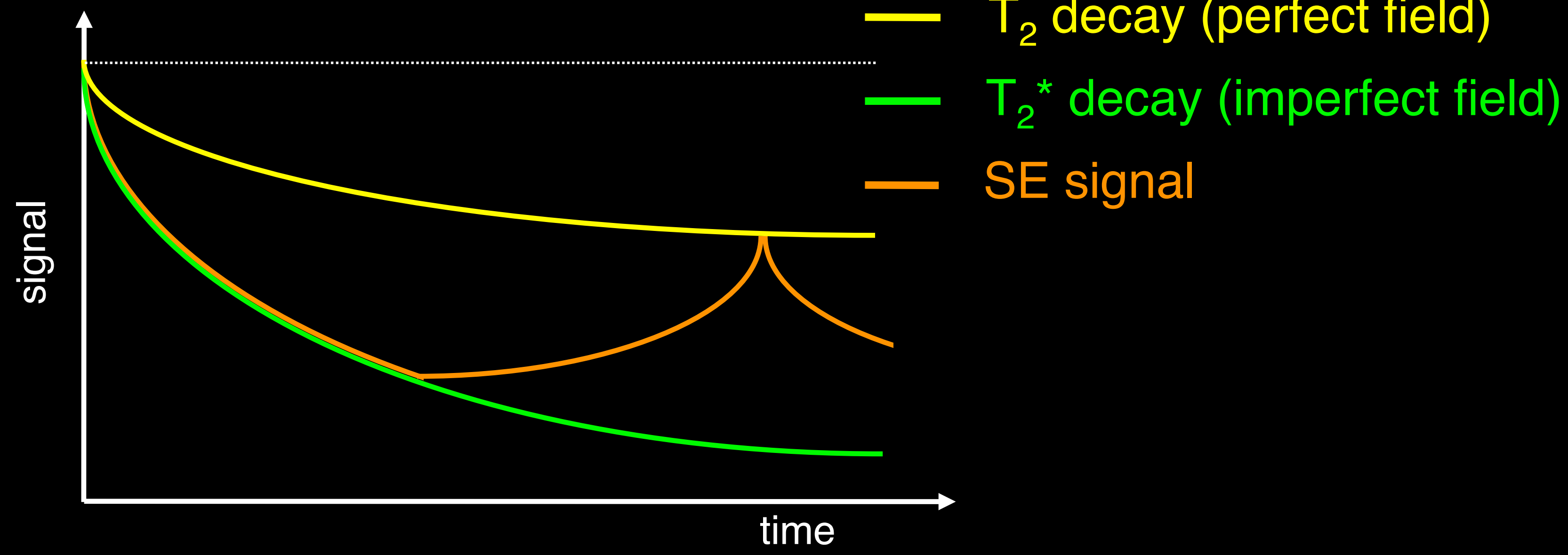


SE refers to a sequence with: excitation-refocus-readout

The key is the formation of an echo (signal peak)!

Like GRE, any kind of readout can be used

T_2 vs T_2* Relaxation



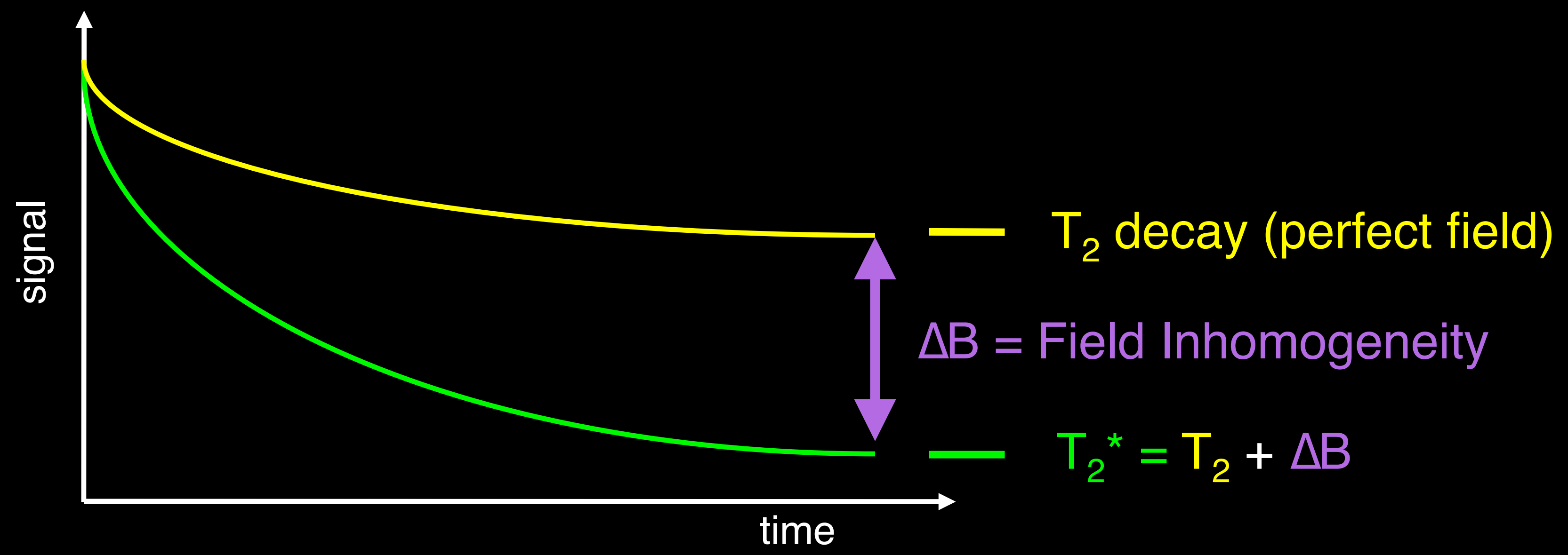
Spin echo refocuses part of the signal decay

- T_2* includes parts that can be refocused
- Without refocusing, signal will have T_2* contrast

Even spin echo signal experiences some decay

- T_2 refers to signal decay that cannot be refocused
- With refocusing, signal will have T_2 contrast

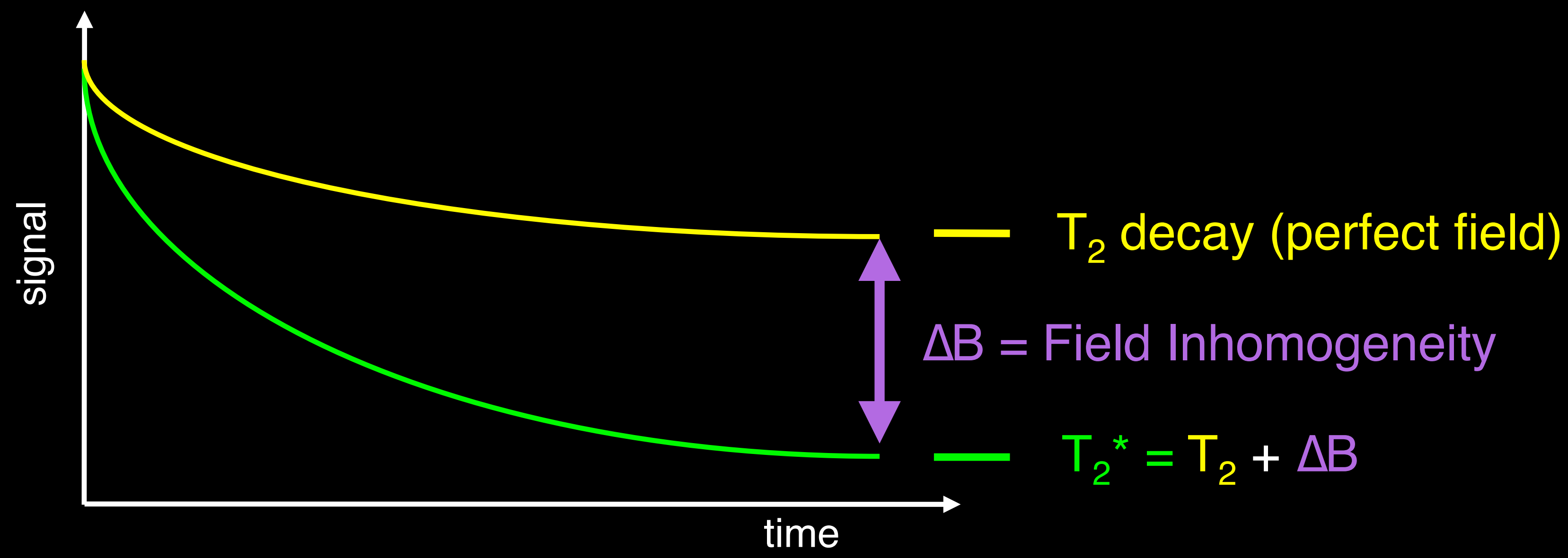
T_2 vs T_2*, Spin and Gradient Echo



Gradient Echo (GRE) gives you T2* (no refocusing of ΔB)

Spin Echo (SE) gives you T2 (refocuses ΔB)

T_2 vs T_2^*, Spin and Gradient Echo



Gradient Echo (GRE) gives you T2* (no refocusing of ΔB)

Spin Echo (SE) gives you T2 (refocuses ΔB)

T_2^* of gray matter :: colour of this Dalmatian in "uncorrected" lighting

T_2 of gray matter :: colour of this Dalmatian in “corrected” lighting

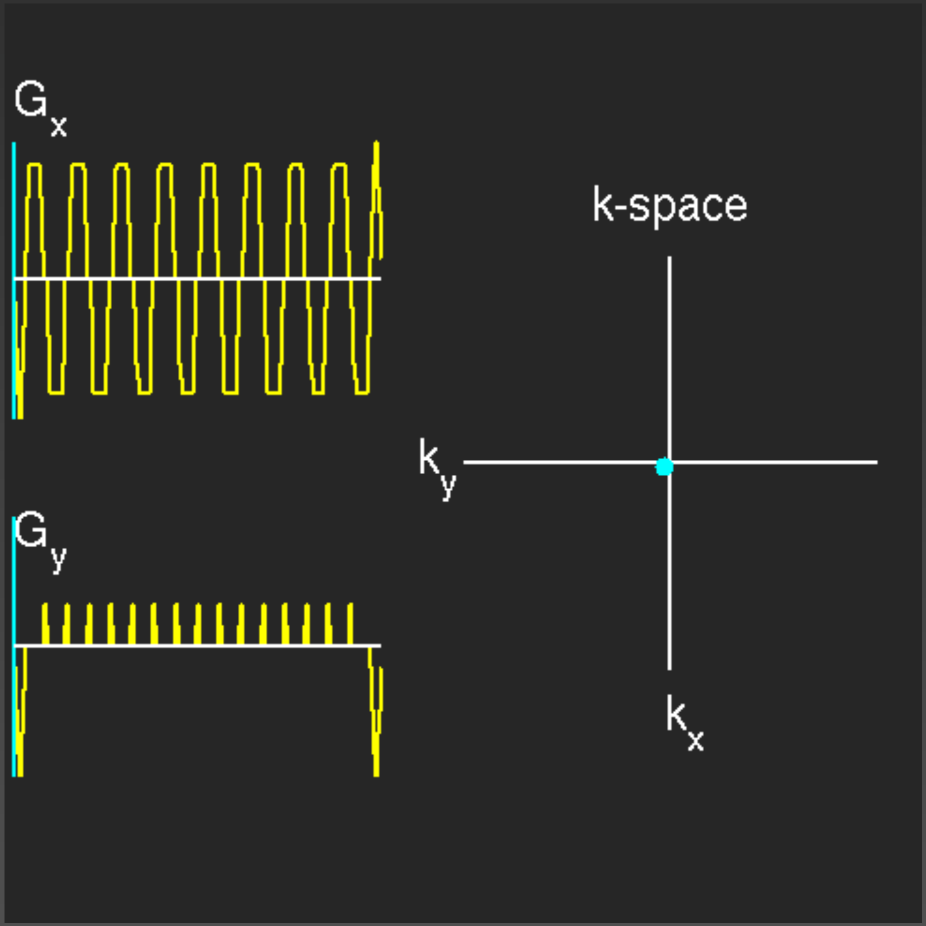
spin echo

MRI Physics

- ★ Revisiting Image Encoding

- ★ Spin vs. gradient echo (T2 & T2*)
- ★ Fast imaging & artefacts
- ★ Diffusion MRI
  - ✦ Diffusion weighting
  - ✦ Acquisition techniques
  - ✦ Tradeoffs & complications

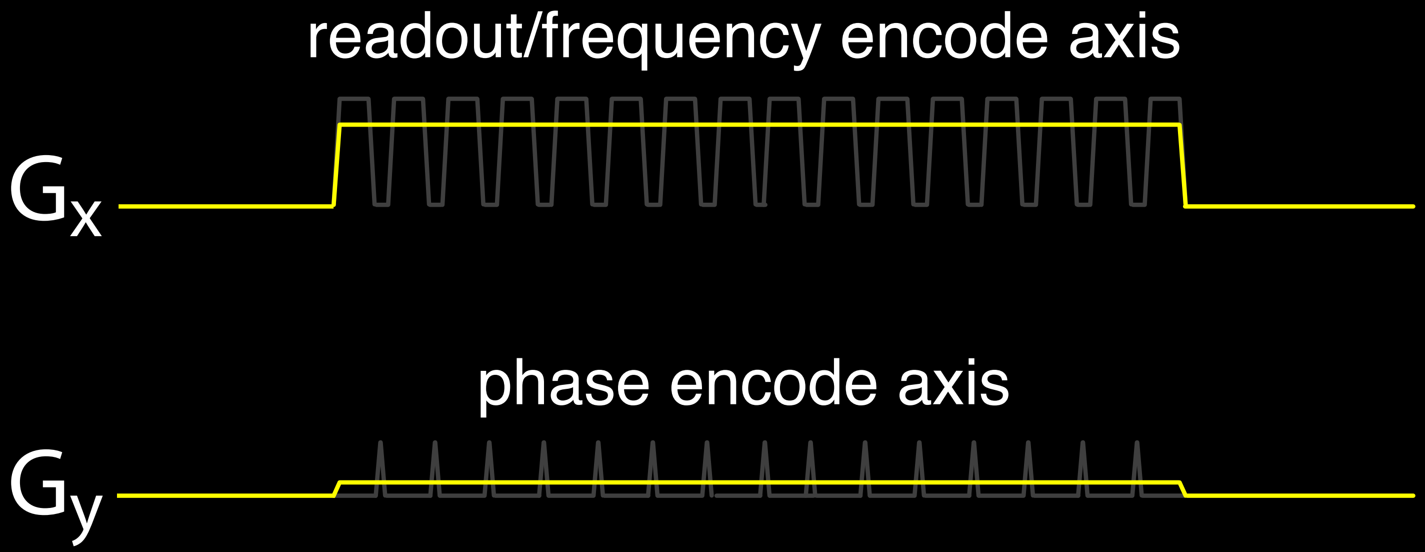
Echo-planar Imaging (EPI) Acquisition



Acquire all of k-space in a “single shot”

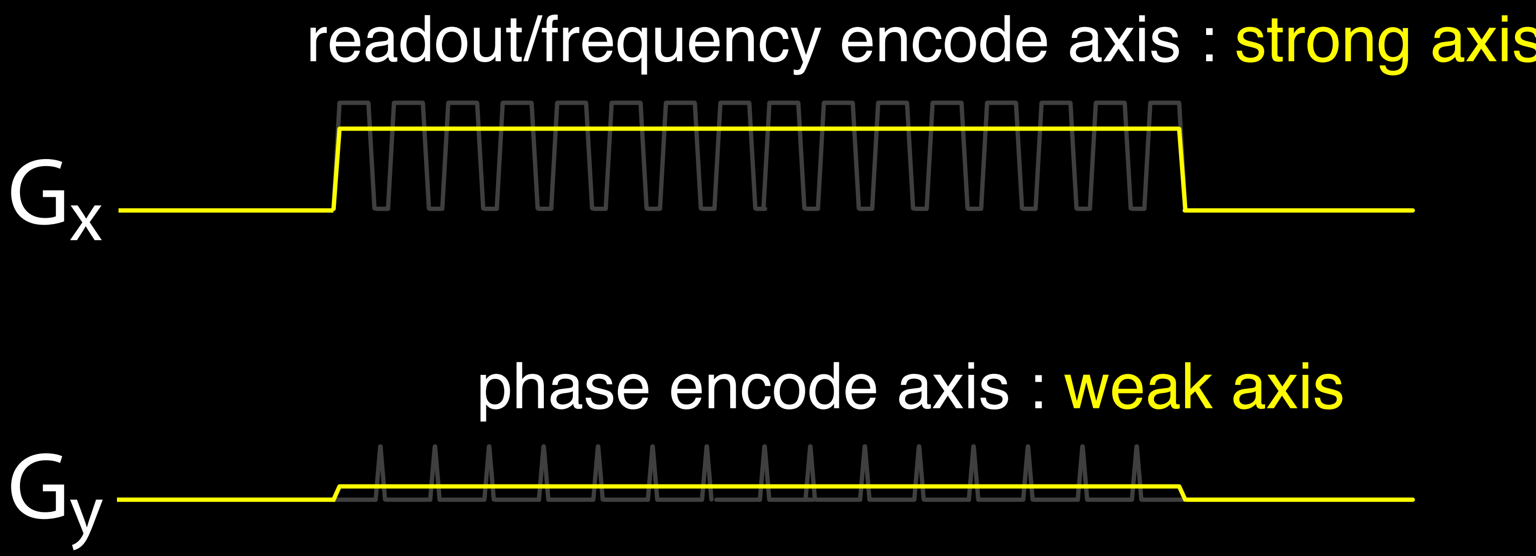
Used for FMRI, diffusion imaging

EPI gradients: Approximation



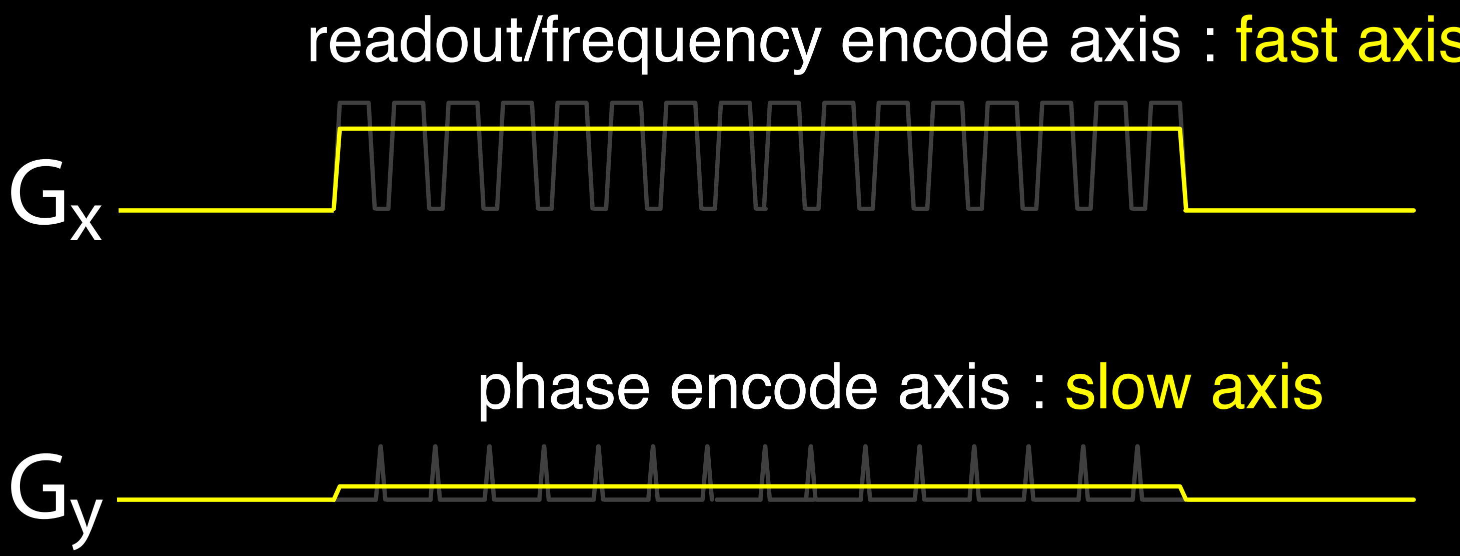
Simplify gradient sequence to understand source of image distortions...

EPI gradients: Approximation



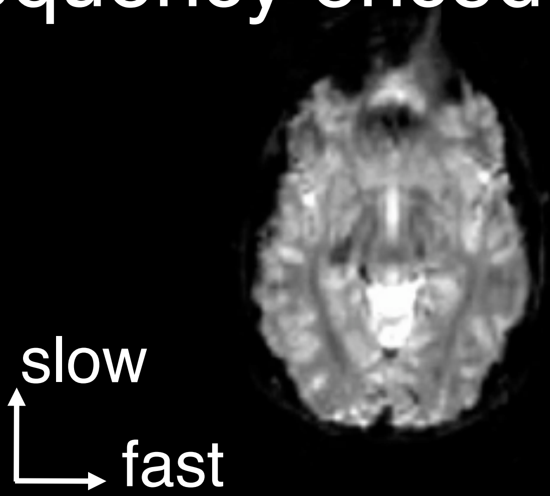
Simplify gradient sequence to understand source of image distortions...

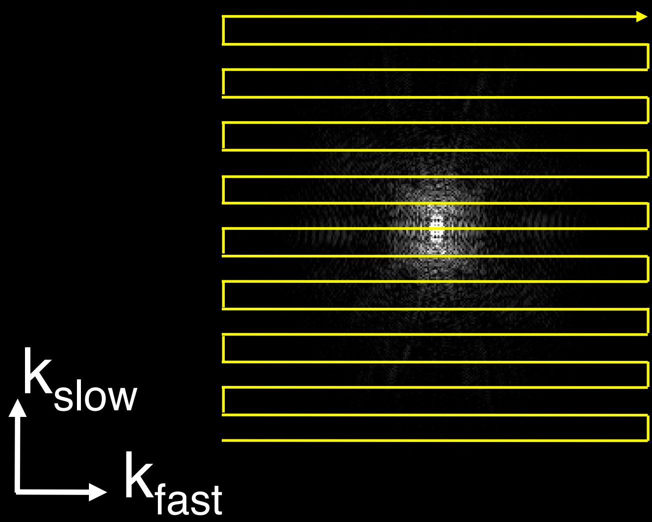
EPI gradients: Approximation

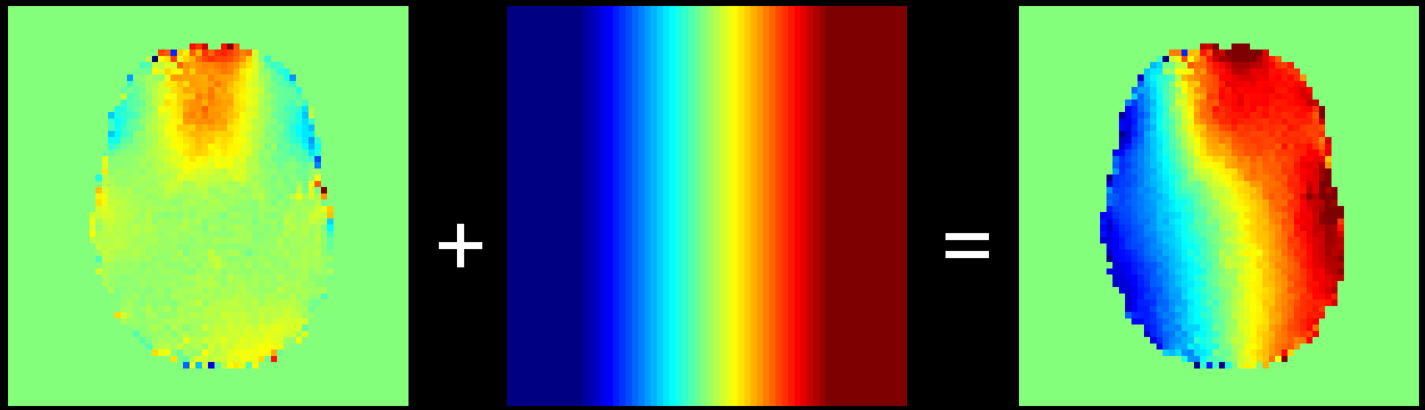


Simplify gradient sequence to understand source of image distortions...

EPI undistorted along “fast” direction (frequency encode)



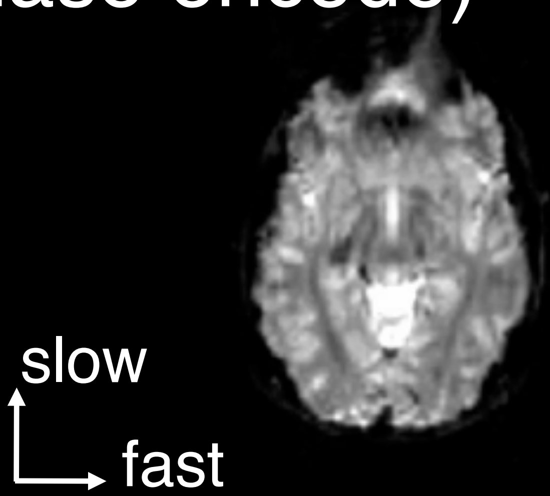


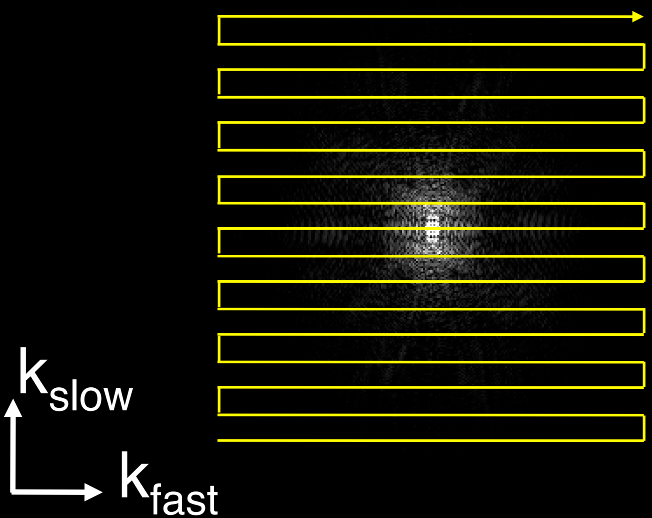


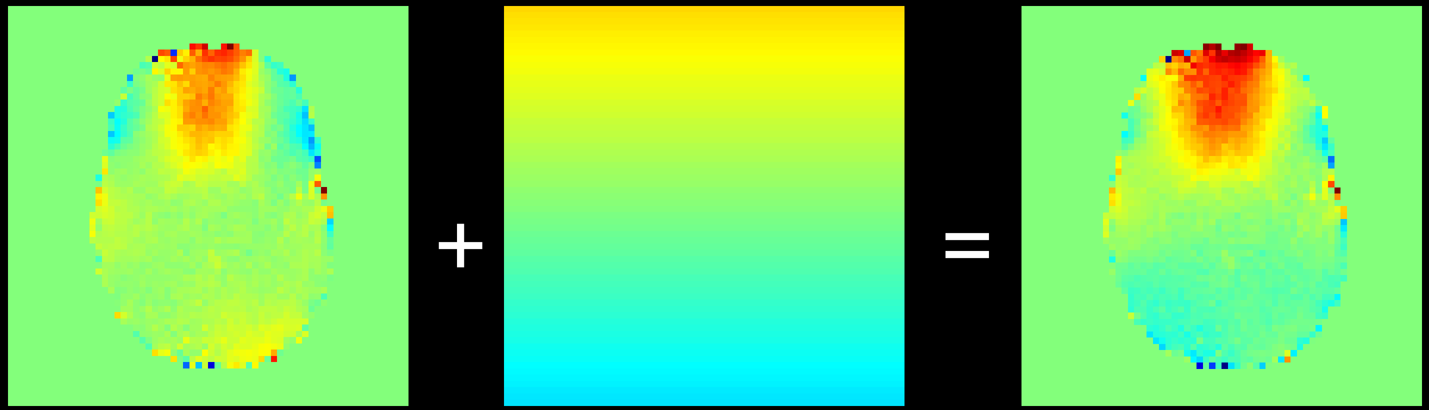
field map fast/strong gradient net

Fast/strong gradients dominate the net field: signal is correctly localised

EPI distorted along “slow” direction (phase encode)



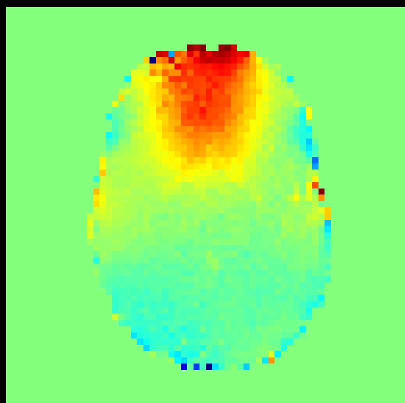




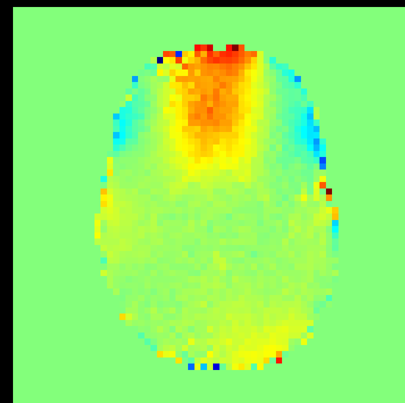
field map slow/weak gradient net

Field map errors dominate the net field:
signal is misplaced

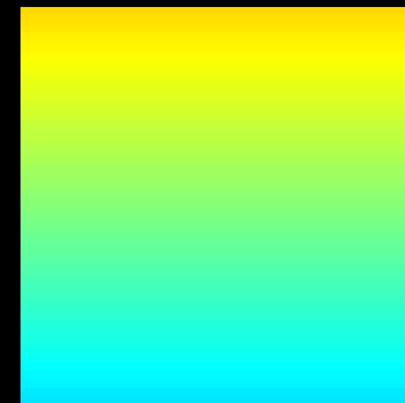
Correcting Distortion

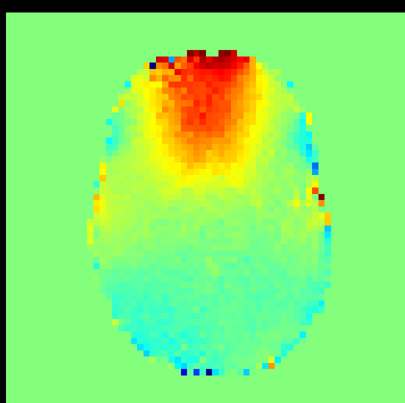

net field

–

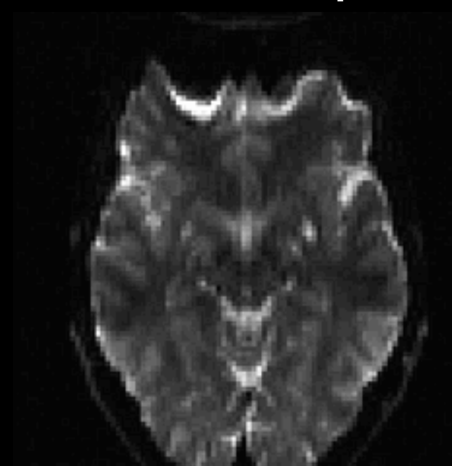

field map

=

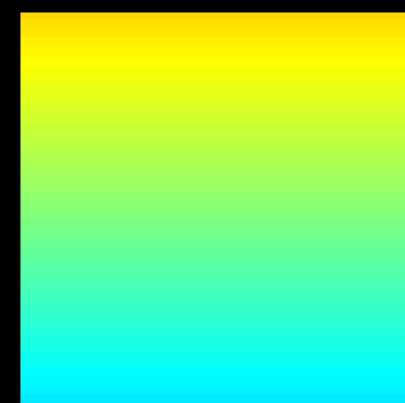

ideal encoding


net field

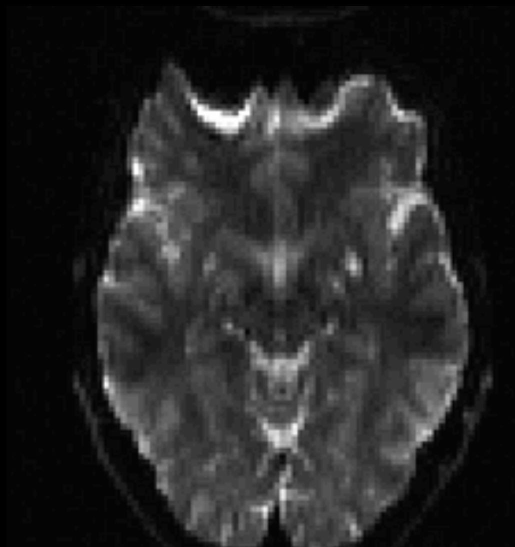
–


2 opposite PE direction images

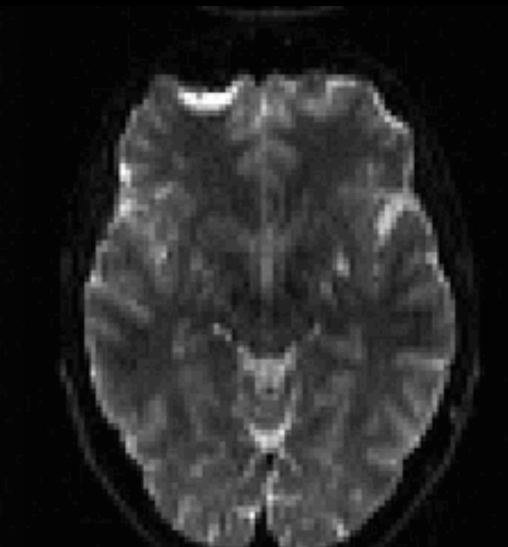
=


ideal encoding

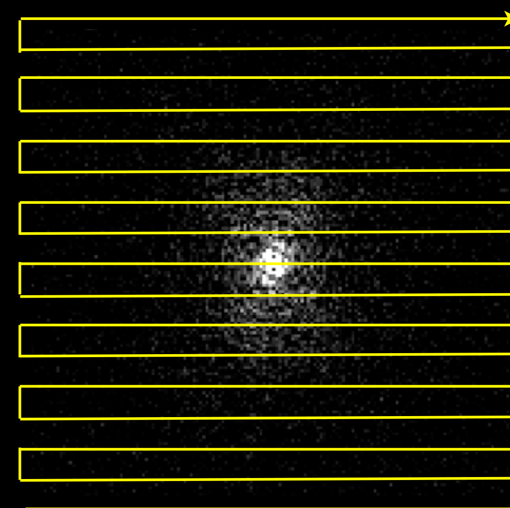
EPI distortion



Long inter-echo spacing



Short inter-echo spacing

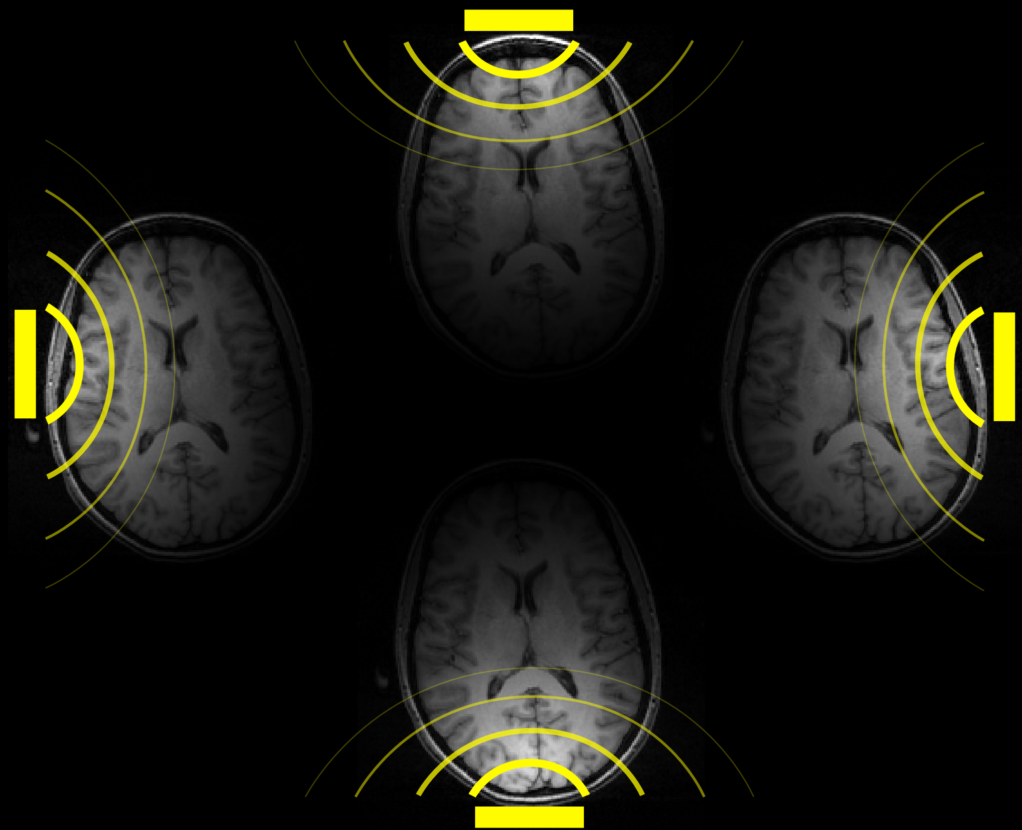


EPI trajectory

Echo spacing: time between acquisition of adjacent lines ("speed" along slow axis")

Long echo spacing = worse distortion

Parallel imaging (SENSE, GRAPPA, etc)

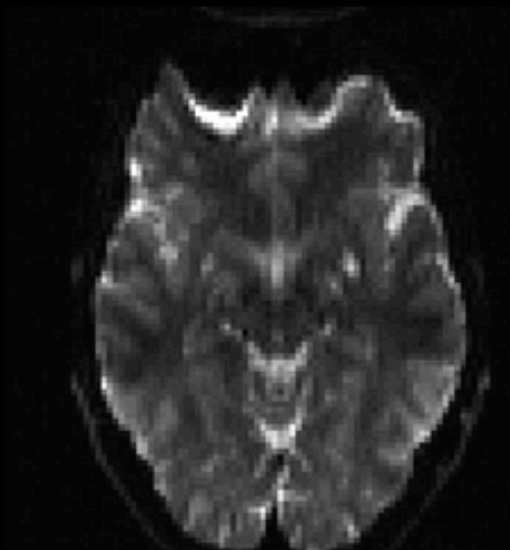


Coil sensitivity encodes spatial information

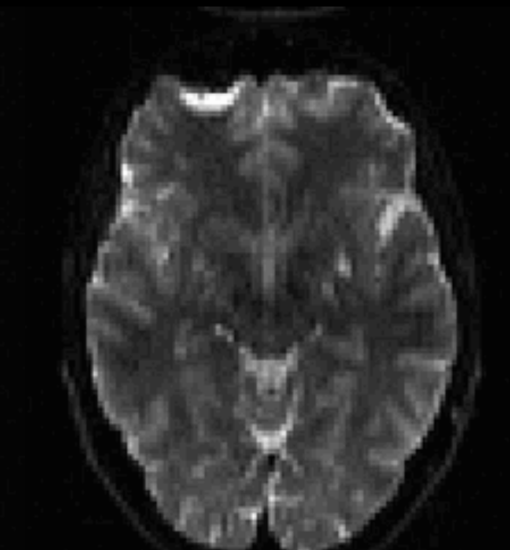
Skip lines in k-space, reconstruction fills in missing lines based on coil sensitivity

Allows “acceleration” of k-space acquisition

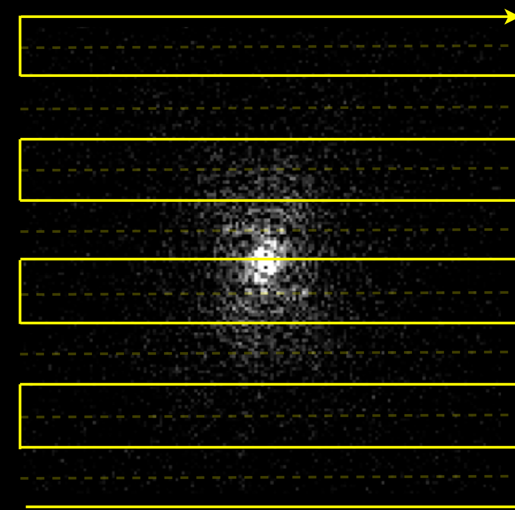
Parallel imaging



No Parallel Imaging



Parallel Imaging (2x)



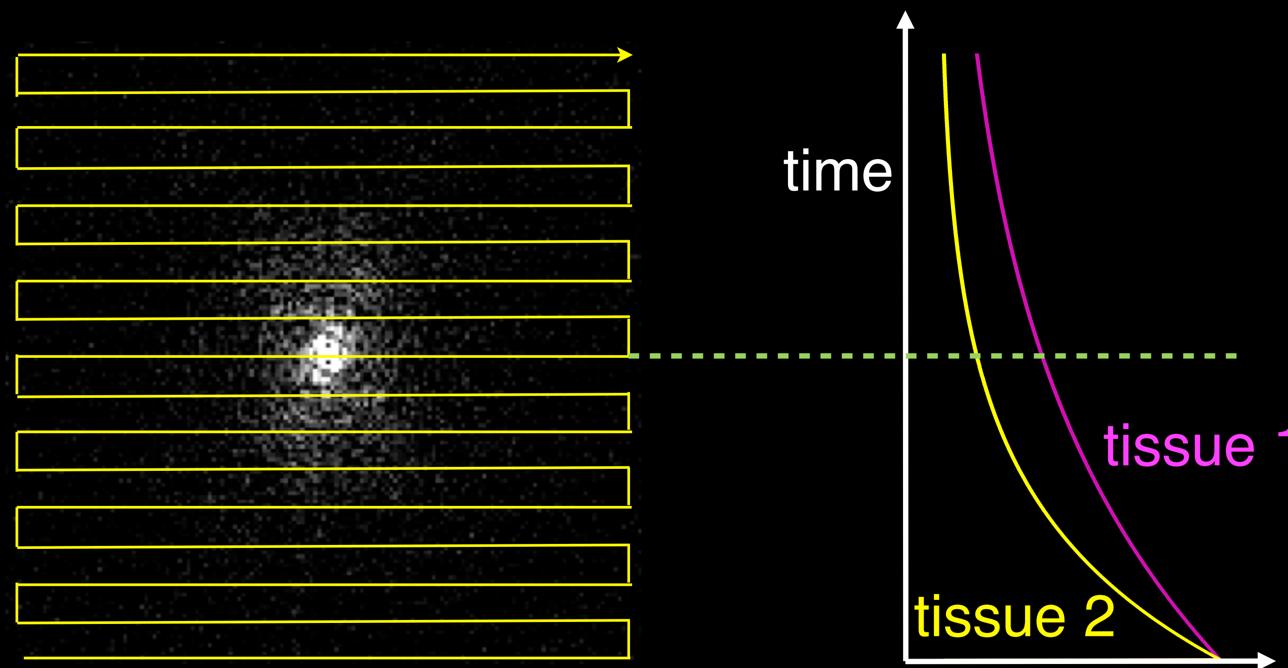
EPI trajectory

Parallel imaging (SENSE, GRAPPA, etc) can reconstruct complete image from subset of k-space lines

Enables “accelerated” acquisition with lower distortion

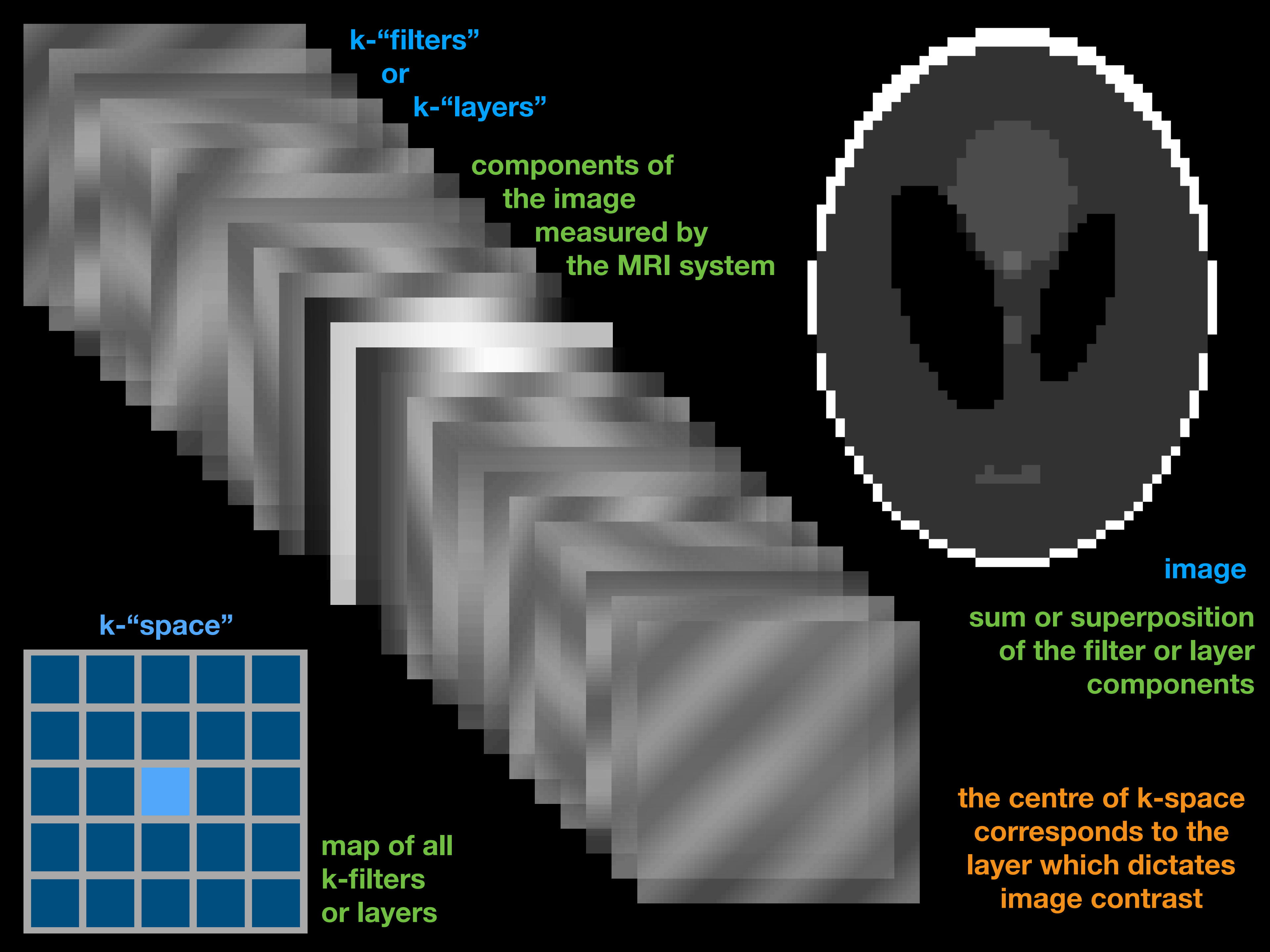
Current vendor coils enable 2-4x acceleration

Contrast over long readouts



Single-shot acquisitions take 30-40 ms, so T_2/T_2^* contrast varies during acquisition... what is contrast of image?

Rule of thumb: contrast of image reflects time at which central k-space was acquired (“effective” TE)


k-“filters”
or
k-“layers”
components of
the image
measured by
the MRI system
image
sum or superposition
of the filter or layer
components
k-“space”
map of all
k-filters
or layers
the centre of k-space
corresponds to the
layer which dictates
image contrast

MRI Physics

- Revisiting Image Encoding

- Spin vs. gradient echo (T2 & T2*)
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- Diffusion MRI
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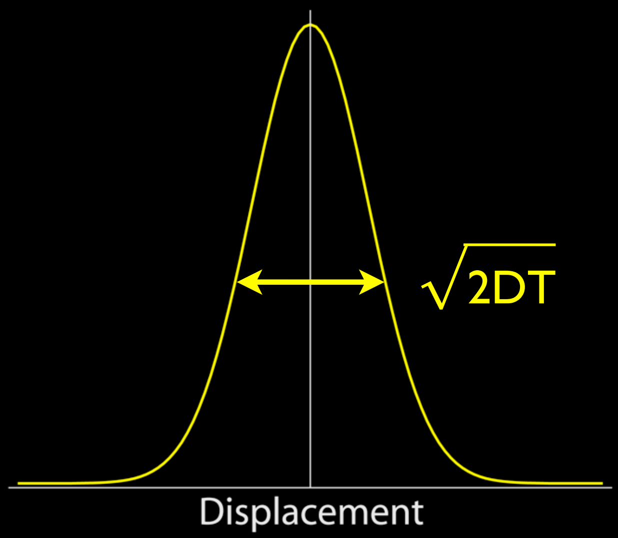
What is diffusion?

What is diffusion?



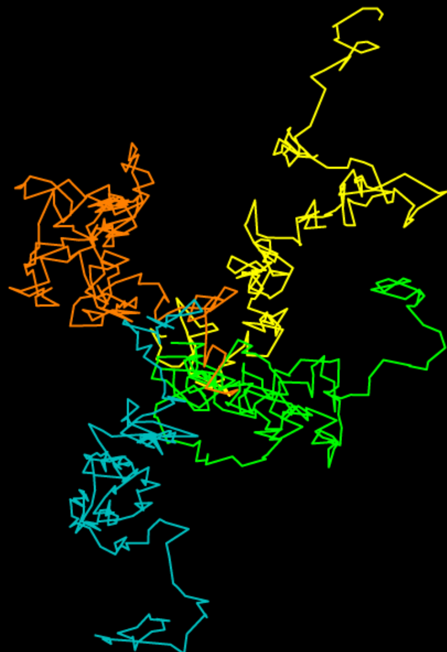
Random motion of particles due to thermal energy

Water molecules collide and experience net displacement

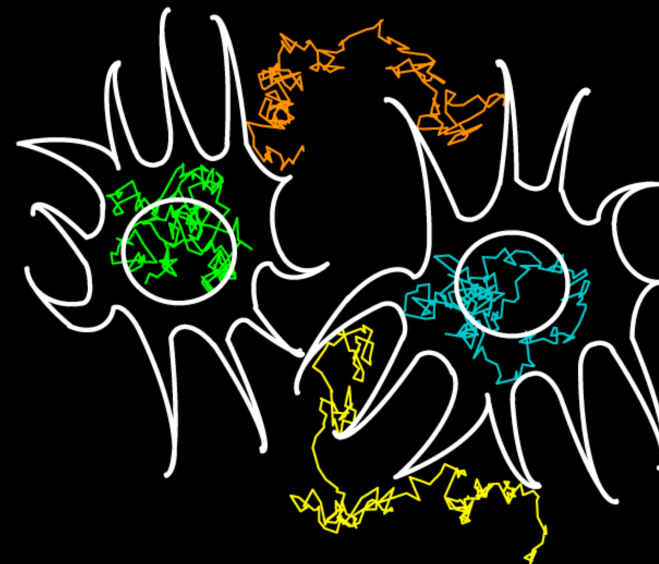
Displacement described by diffusion coefficient (D)

Normally, diffusion is isotropic (equal in all directions)

Why is diffusion interesting?



Unrestricted

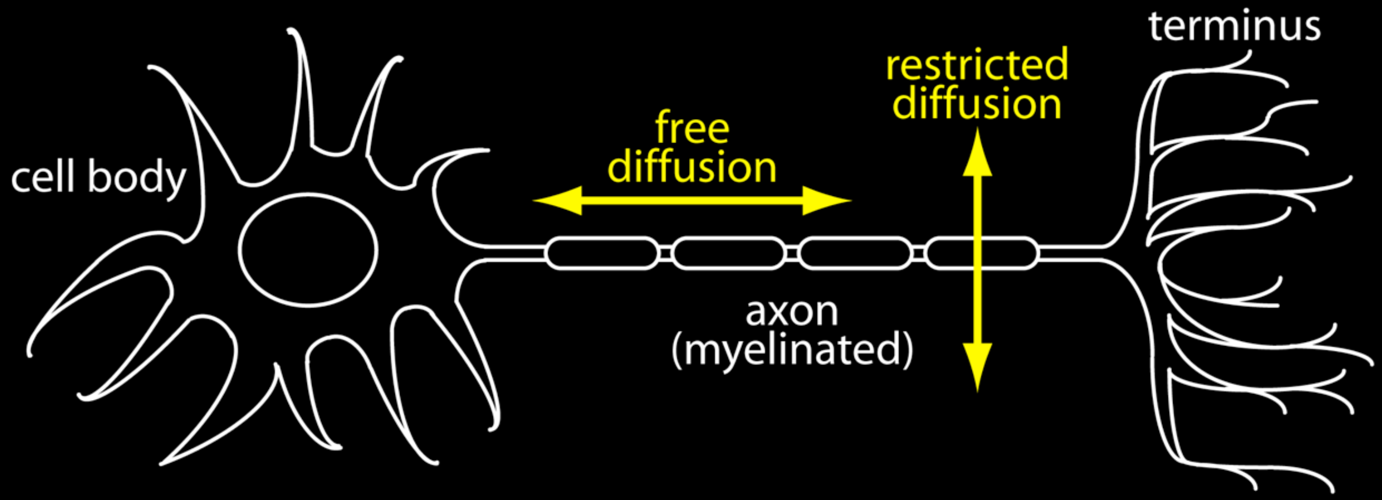


Tissue boundaries

Diffusion is restricted by tissue boundaries, membranes, etc

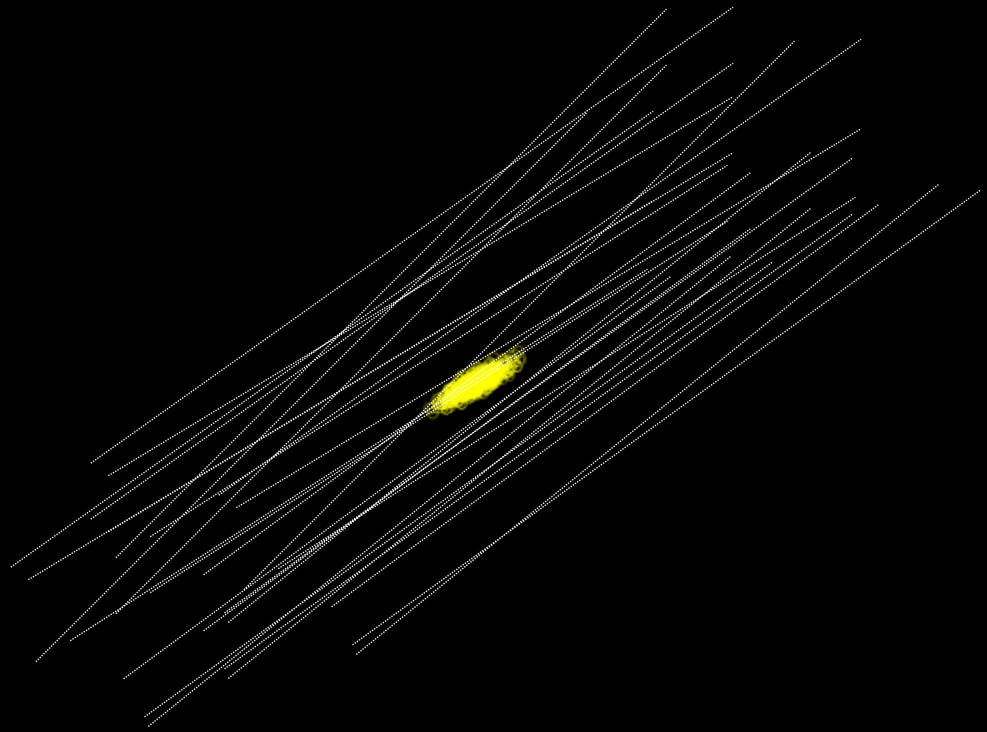
Marker for tissue microstructure (healthy and pathology)

Diffusion anisotropy in white matter



Water can diffuse more freely along white matter fibres than across them

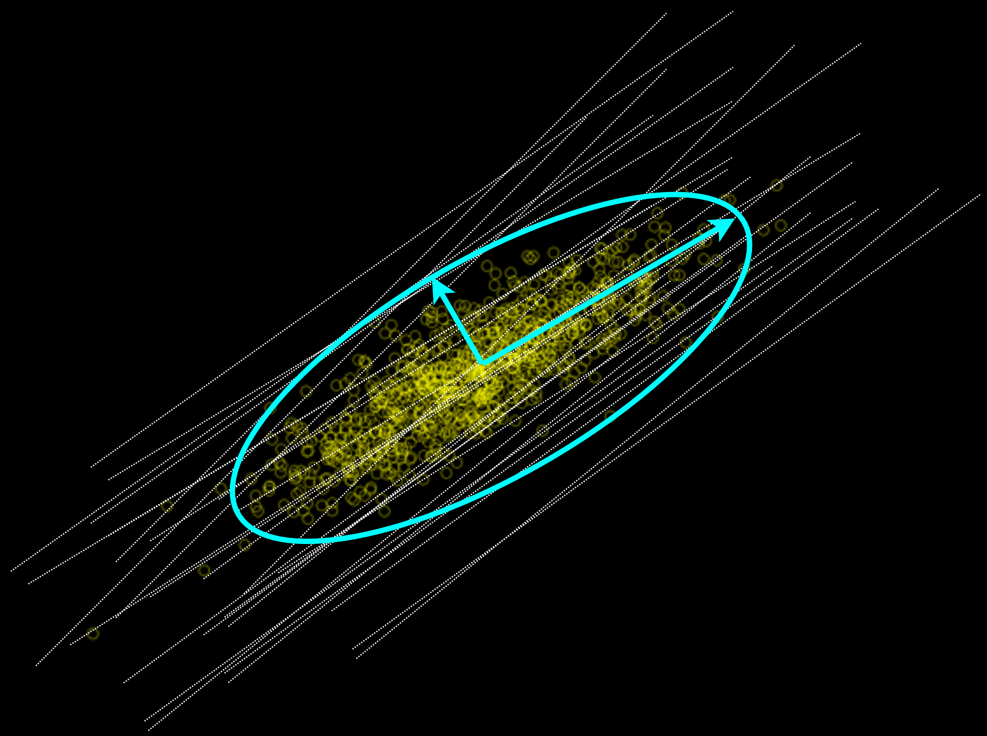
Diffusion anisotropy in white matter



Diffusion in white matter fibres is “anisotropic”

Directionality of diffusion tells us about fibre integrity/ structure and orientation

The diffusion tensor

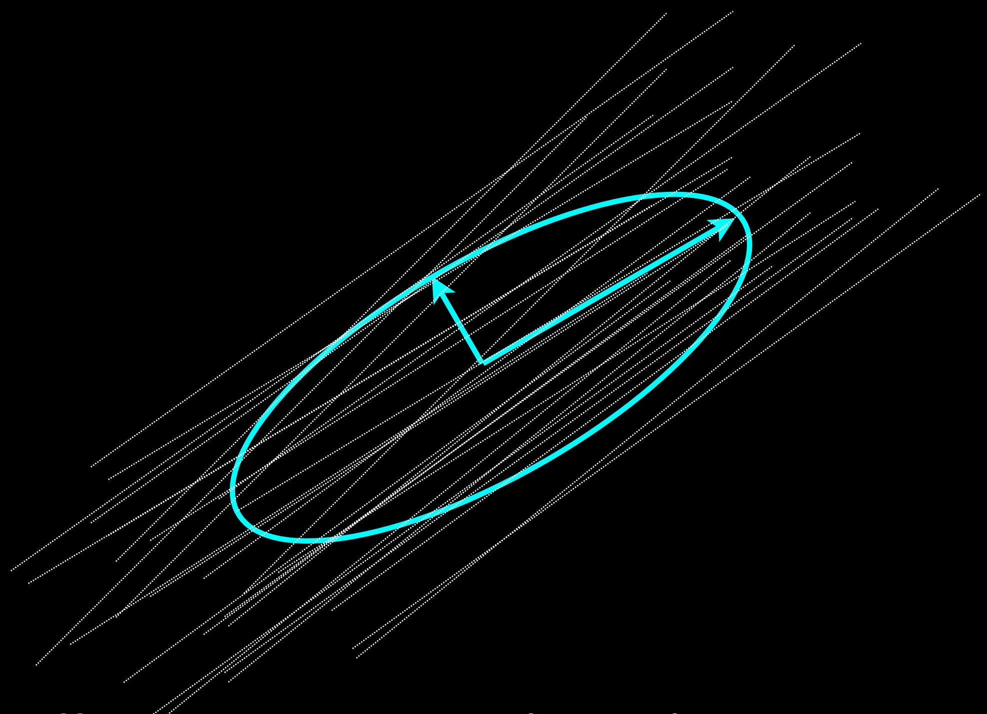


Displacement due to diffusion is approximately ellipsoidal

Eigenvectors = axes of ellipsoid (direction of fibres)

Eigenvalues = size of axes (strength of diffusion)

The diffusion tensor: Useful quantities



Principal diffusion direction (**PDD**): what direction is greatest diffusion along? Info about fibre orientation

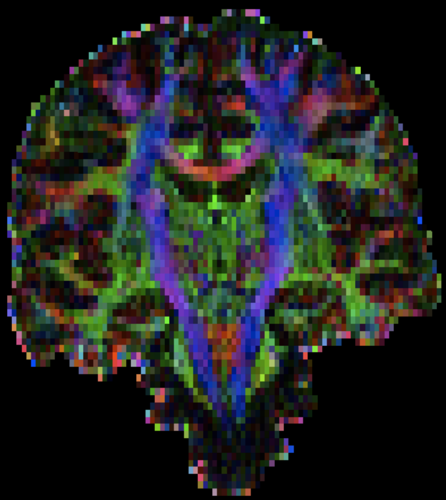
Fractional anisotropy (**FA**): how elongated is the ellipsoid? Info about fibre integrity

Mean diffusivity (**MD**): Info about tissue integrity

Diffusion tensor imaging

Mean diffusivity (MD)

Fractional anisotropy (FA)

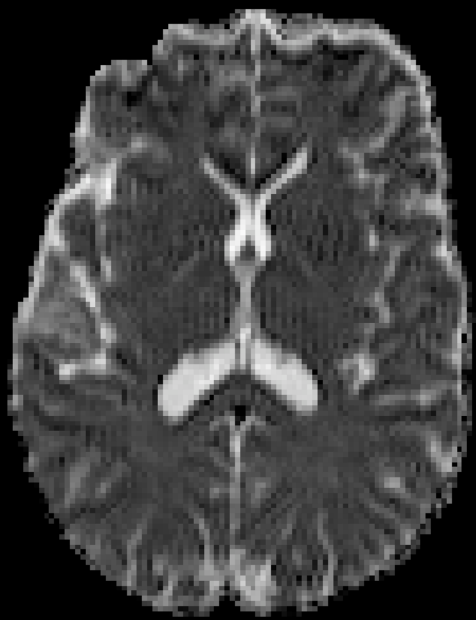


Principal diffusion direction (PDD)

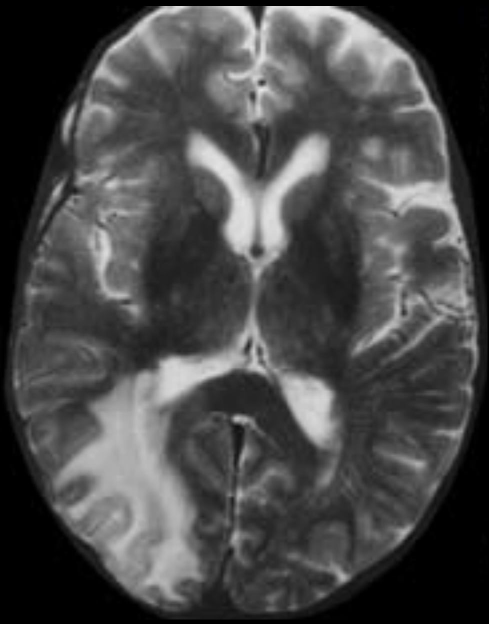
At each voxel, fit the diffusion tensor model

Can then calculate MD, FA, PDD from fitted parameters

Mean diffusivity (MD)



Control MD



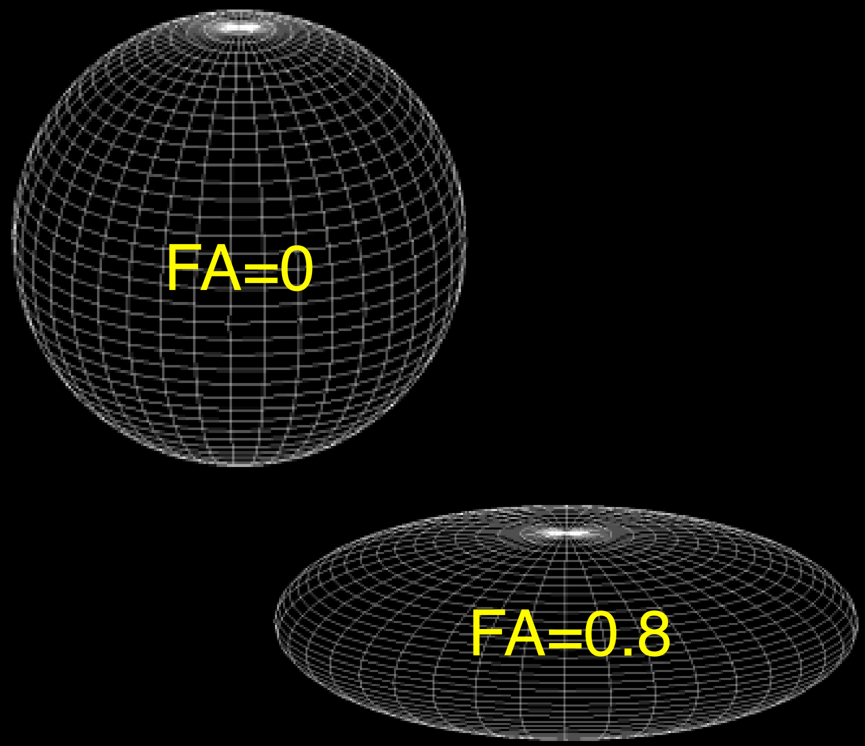
Acute Stroke

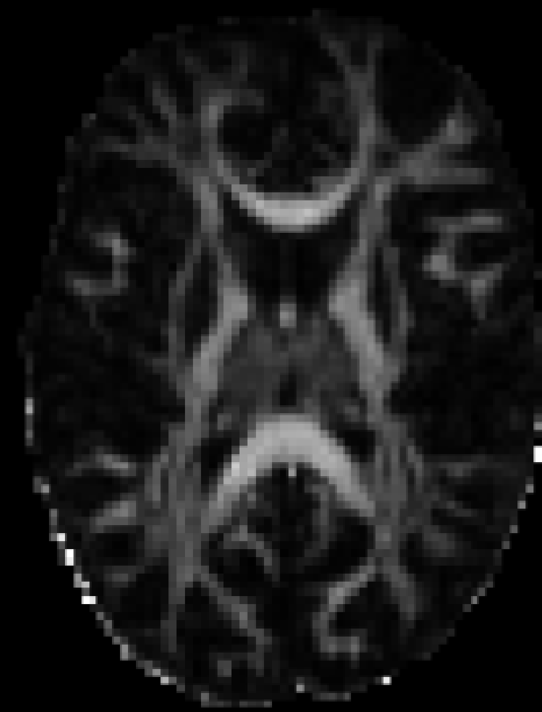
Mean diffusion coefficient across all directions

Correlate of tissue integrity (white and gray matter)

Example: MD is altered in acute and chronic stroke

Fractional Anisotropy (FA)



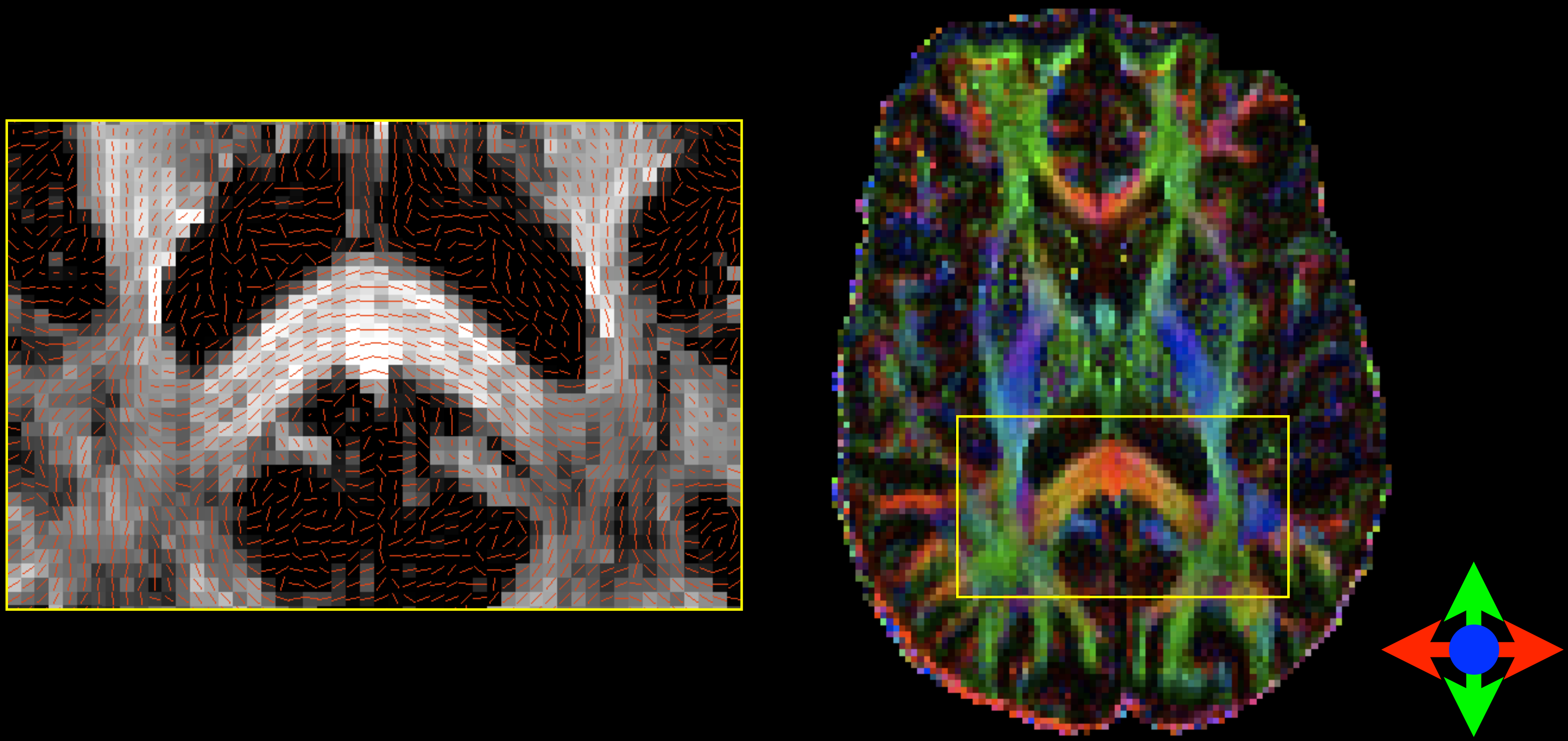


Inequality of diffusion coefficient across different directions

High in regions where diffusion is most directional

Relates to integrity of white matter fibre bundles

Principal diffusion direction (PDD)



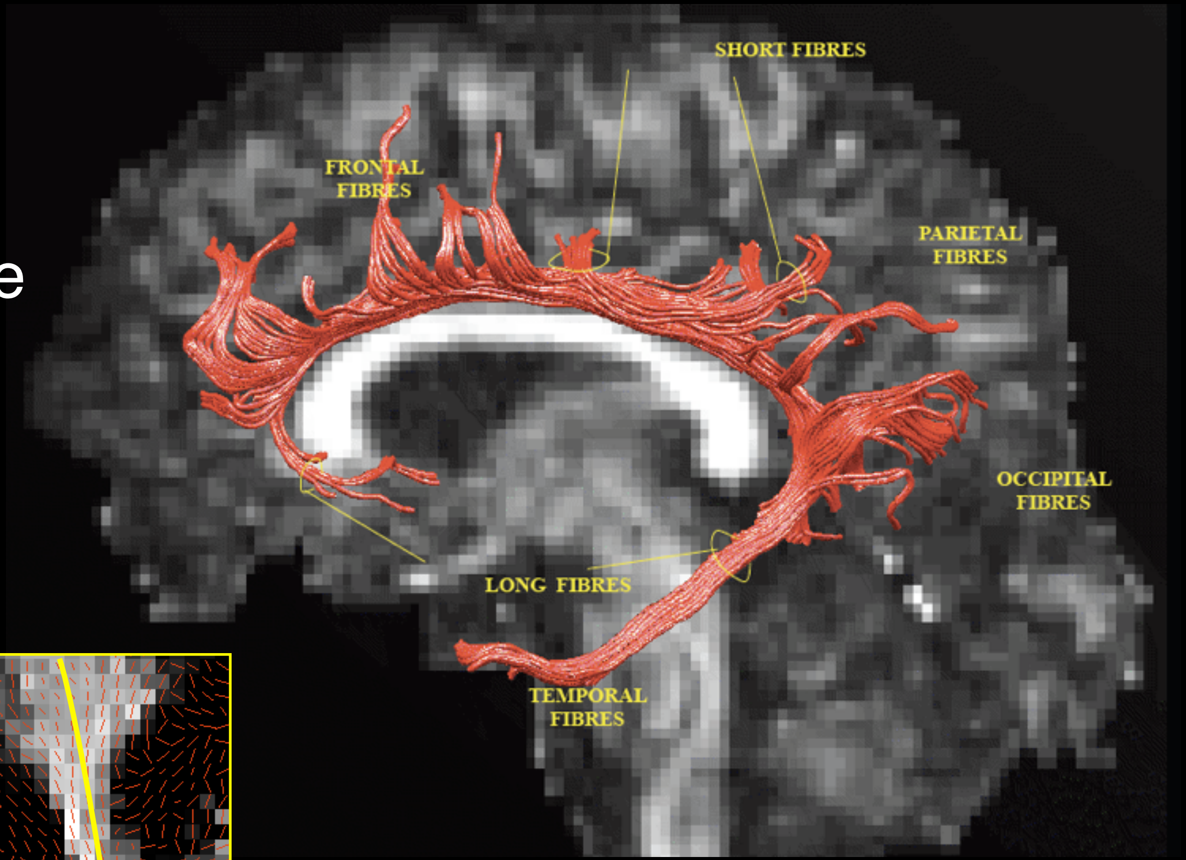
Direction along which greatest diffusion occurs

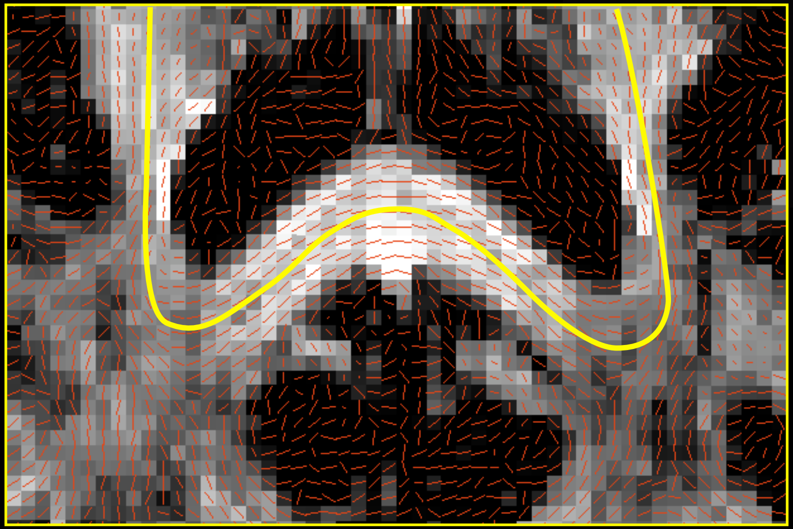
Relates to direction of fibre orientations

Typically, will use this as starting point for fibre tracking

Diffusion tractography

Follow PDD to trace white matter fibers ("tractography")





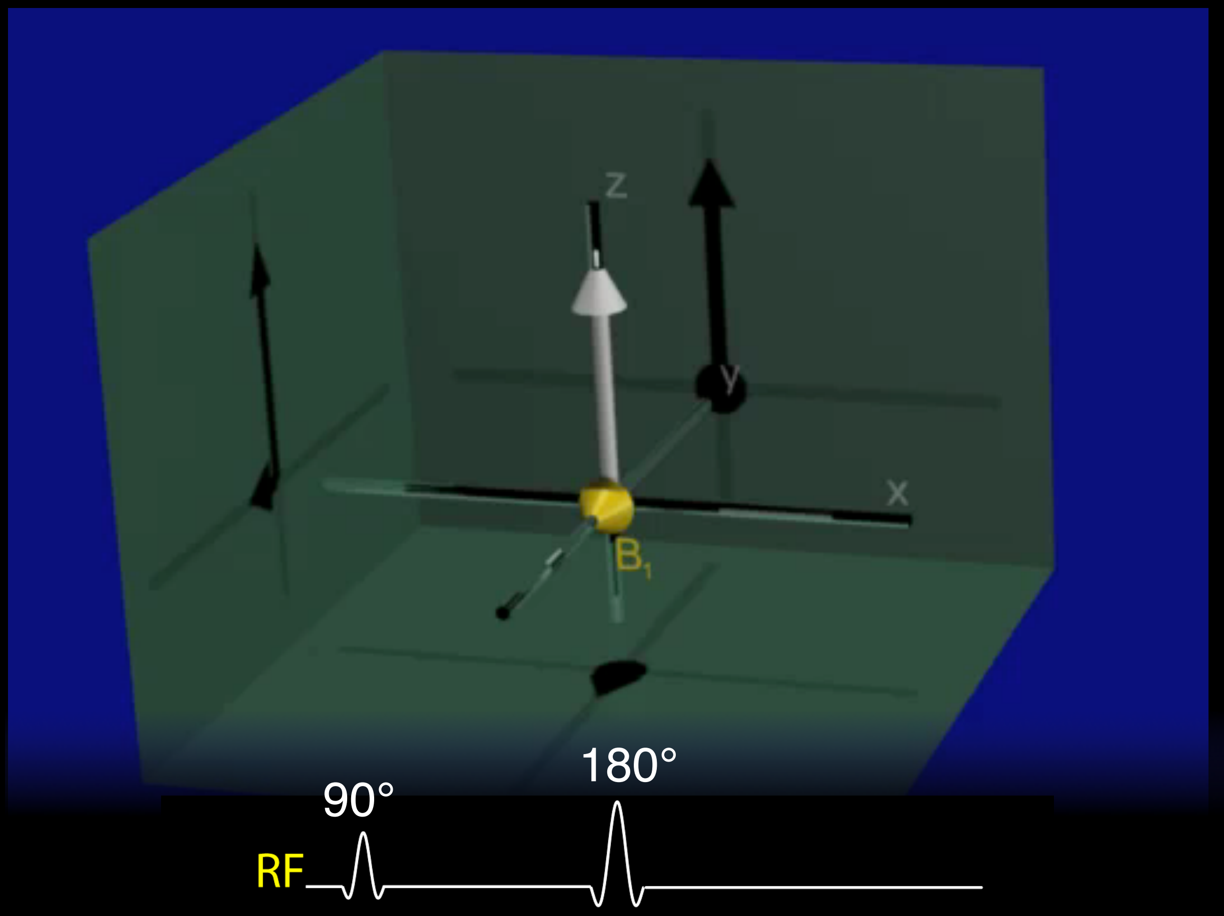
Jones et al

MRI Physics

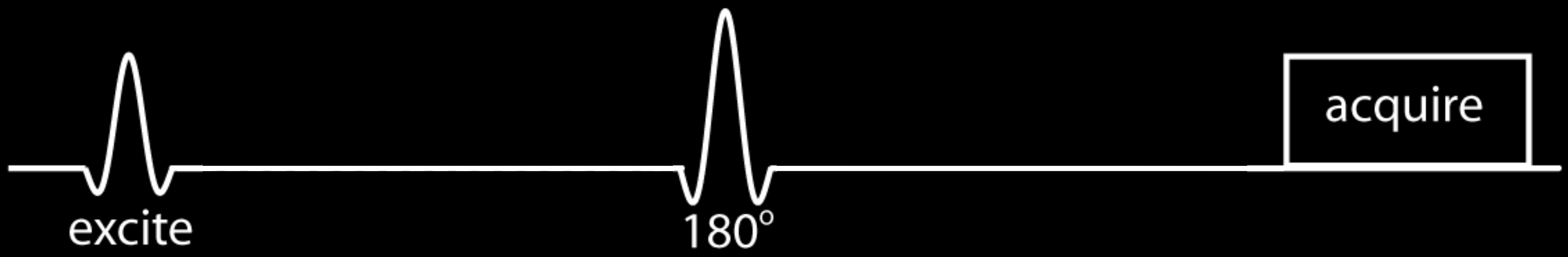
- Revisiting Image Encoding

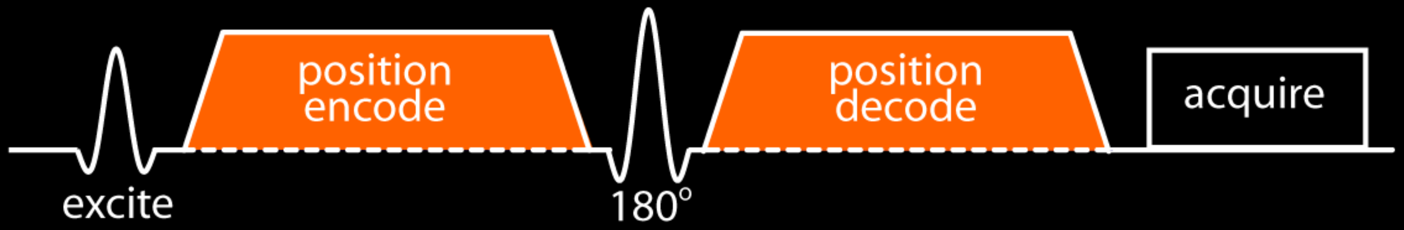
- Spin vs. gradient echo (T2 & T2*)
- Fast imaging & artefacts
- Diffusion MRI
  - Diffusion weighting
  - Acquisition techniques
  - Tradeoffs & complications

Spin Echo

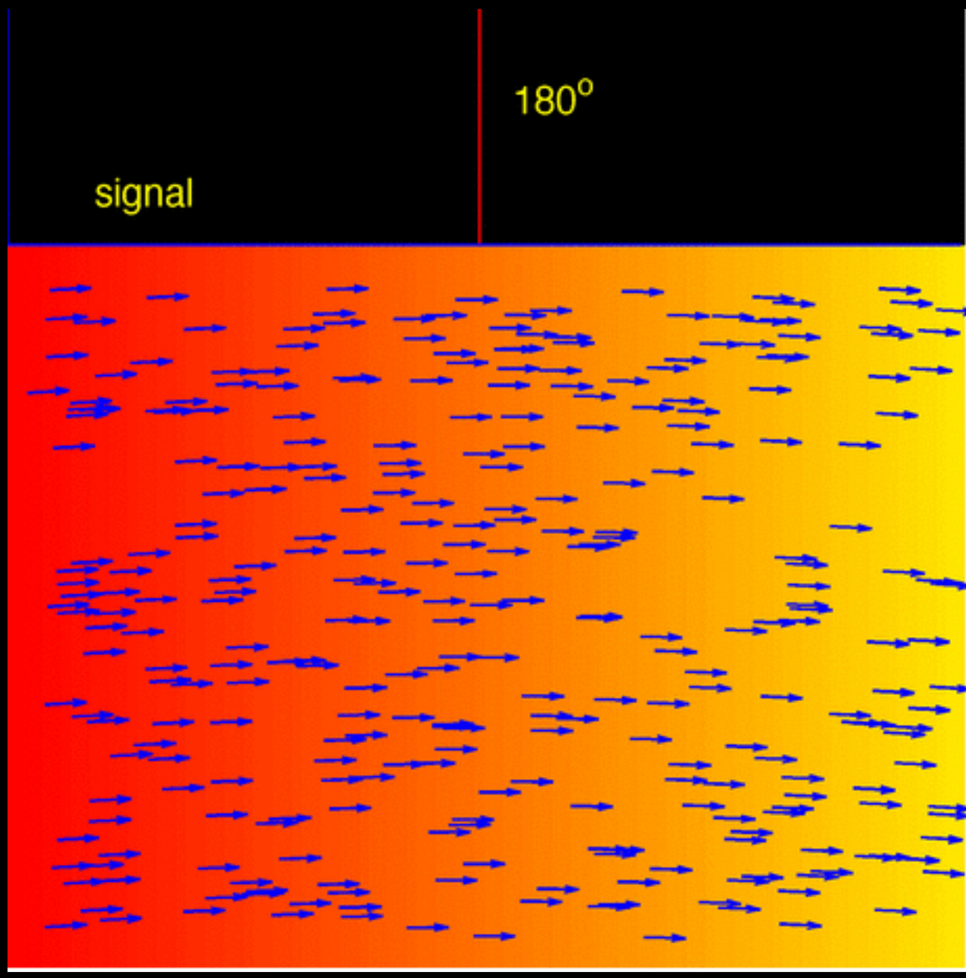


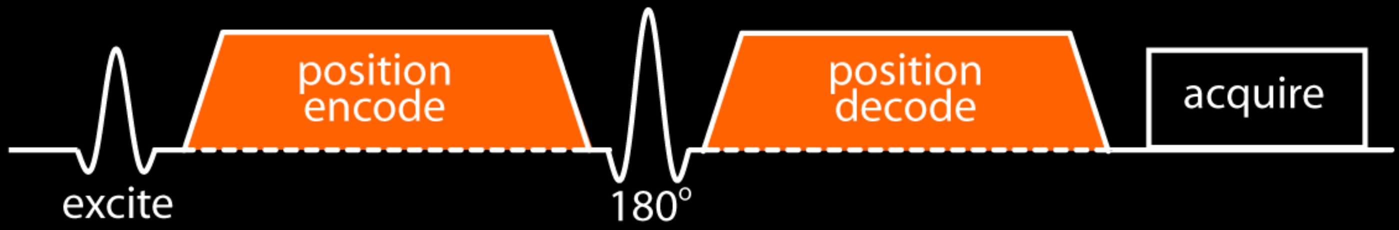
Diffusion-weighted spin echo



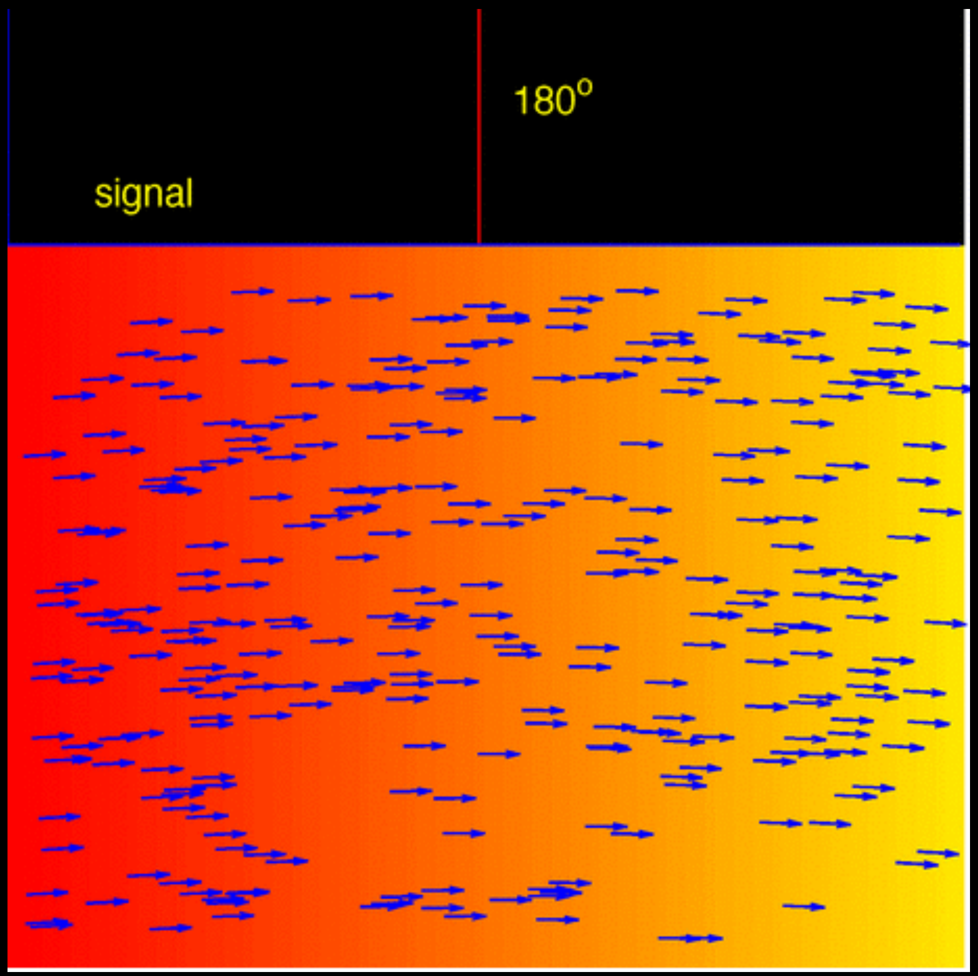


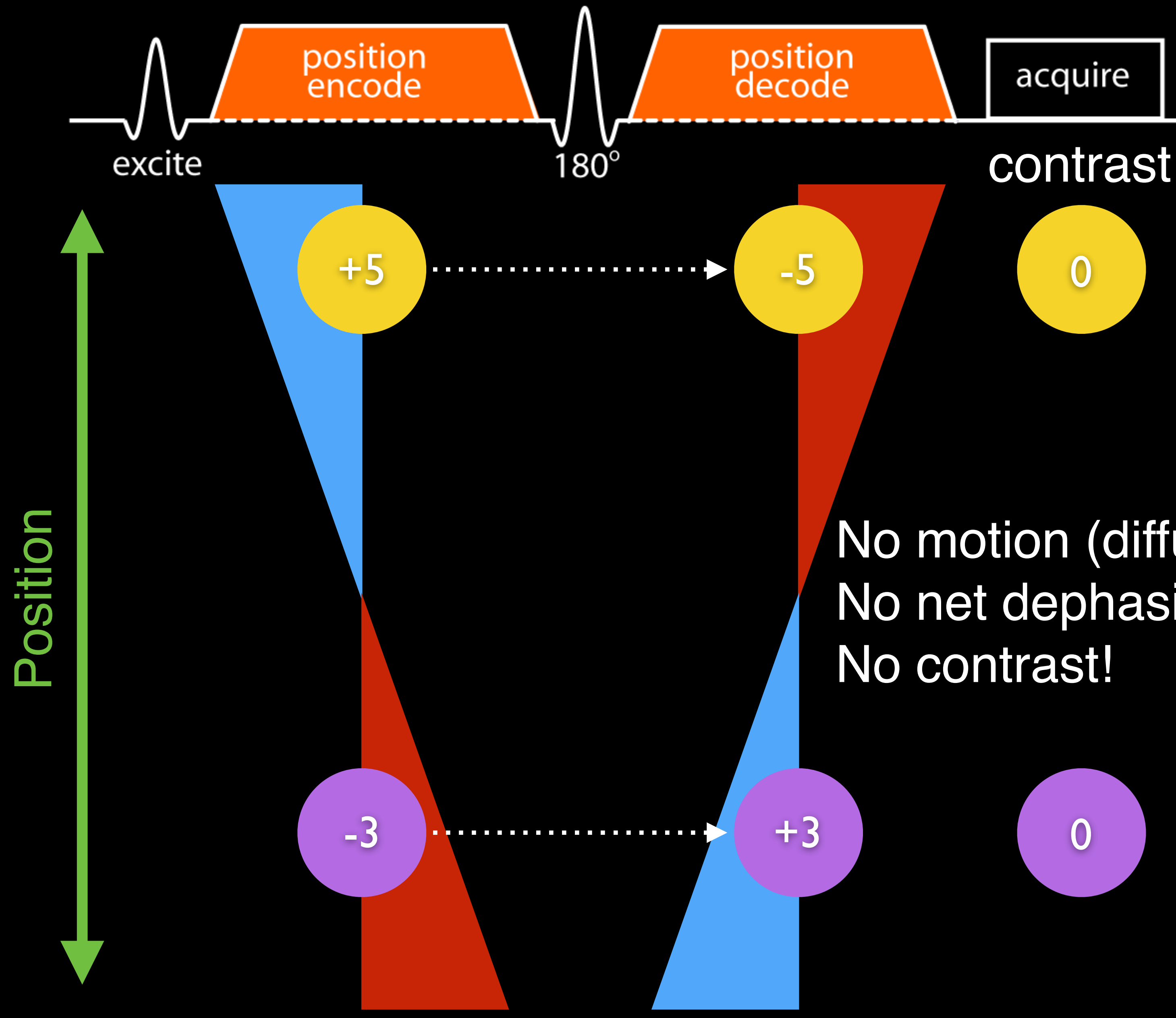
Case 1:
No diffusion



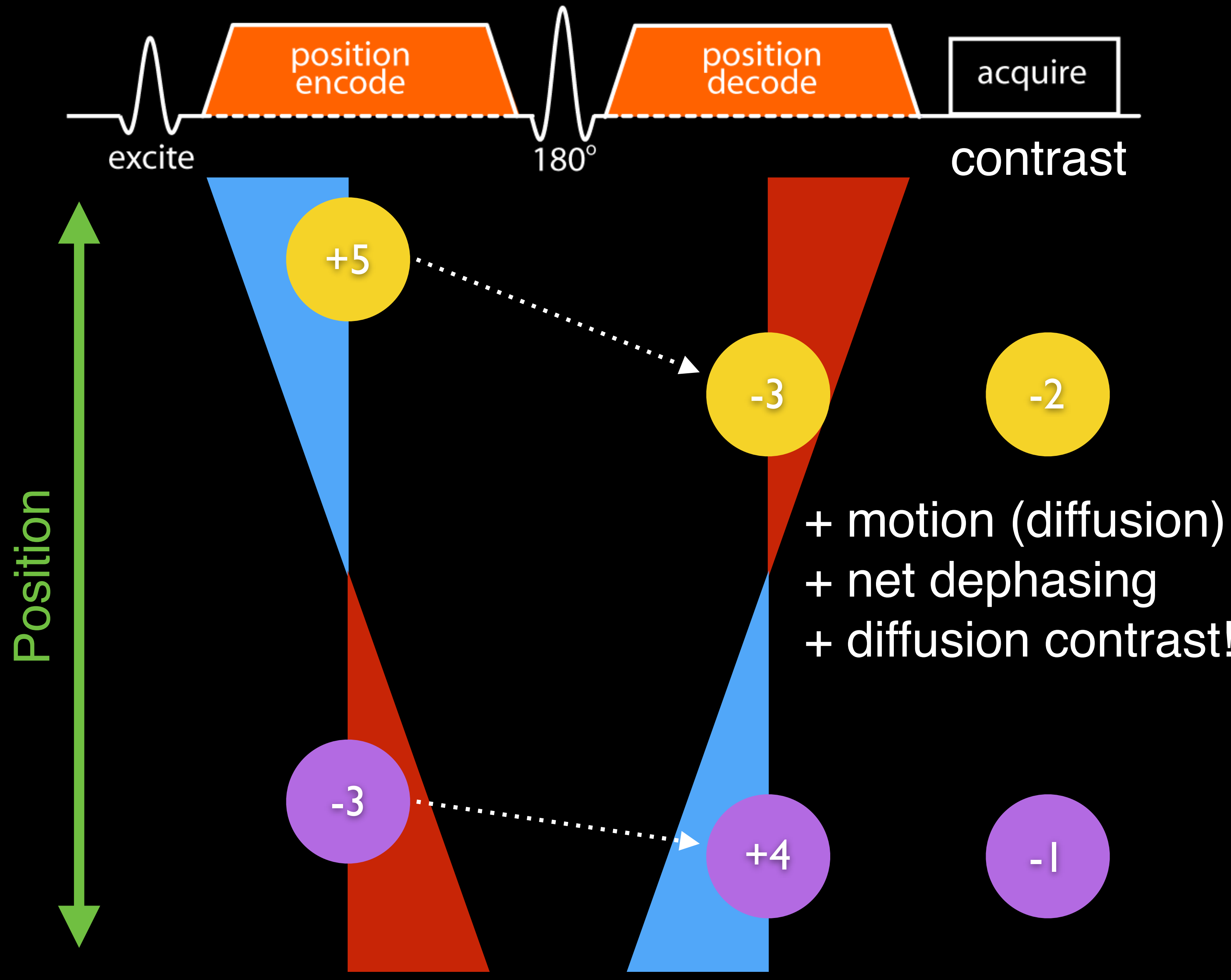


Case 2:
Diffusion





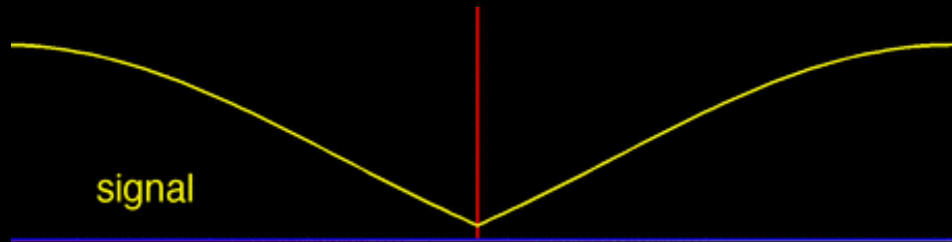
No motion (diffusion)
No net dephasing
No contrast!



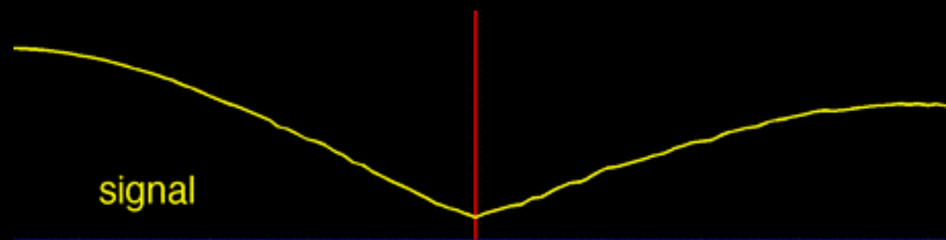
position encode
position decode
acquire
excite
180°
contrast
Position
+5
-3
-2
-3
+4
-1
+ motion (diffusion)
+ net dephasing
+ diffusion contrast!

Diffusion contrast

No diffusion



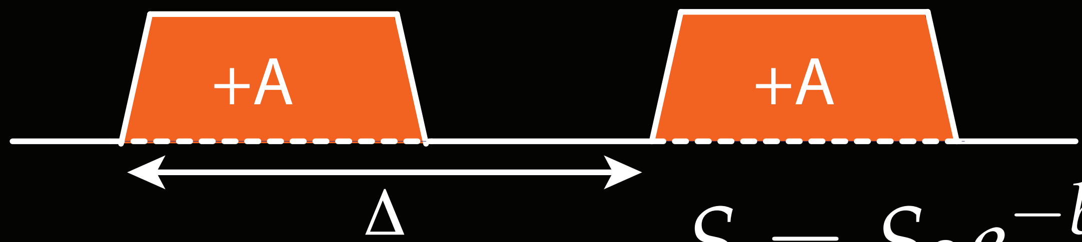
Diffusion



If diffusion is present, gradients cause a drop in signal.

Greater Diffusion = Less Signal

Diffusion contrast



diffusion coefficient

$$S = S_0 e^{-bD}$$

$$b \propto A^2 \Delta$$

diffusion weighting

If diffusion is present, gradients cause a drop in signal.

Greater Diffusion = Less Signal

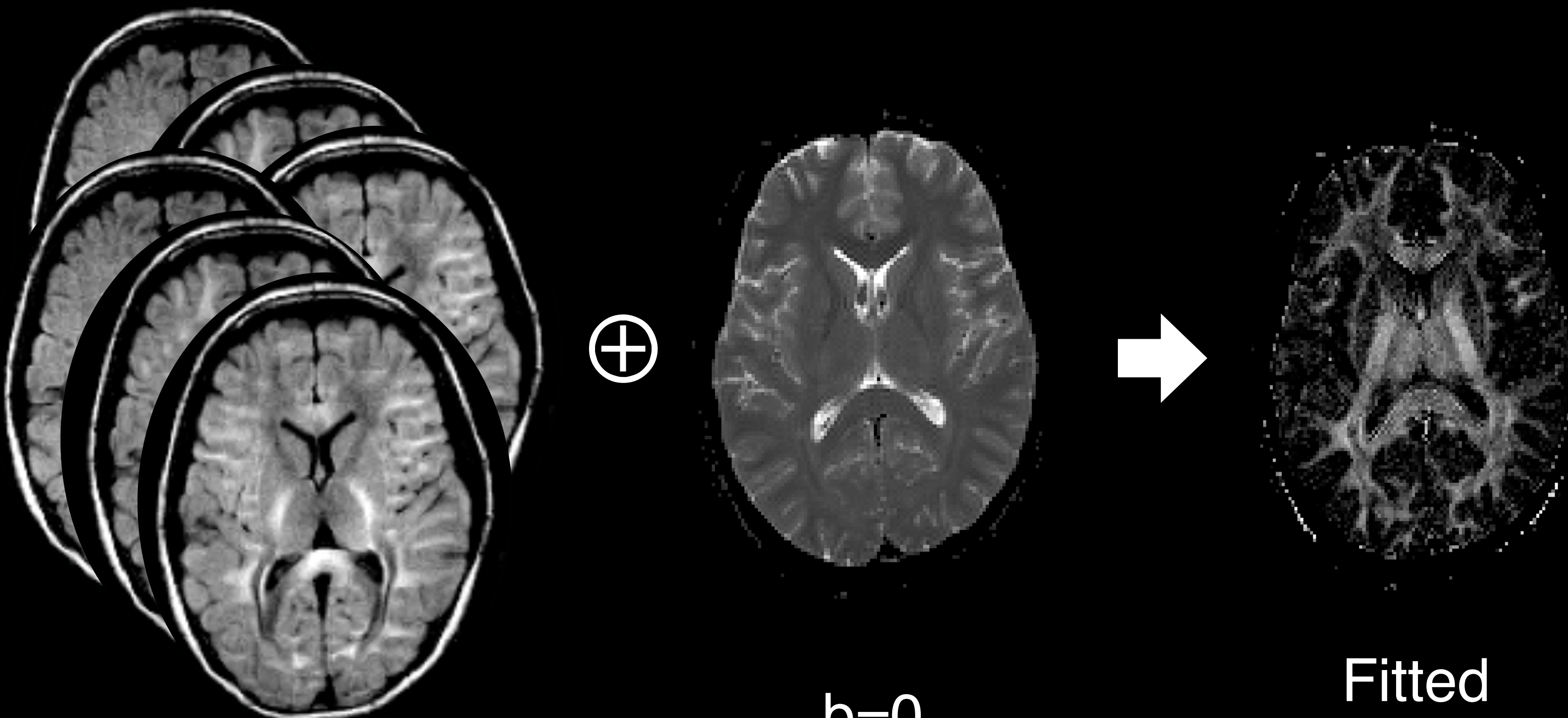
Diffusion contrast

gradient direction: ↕ ↔ •

If diffusion is present, gradients cause a drop in signal.

Greater Diffusion = Less Signal

Diffusion-weighted imaging



Directional encoding

b=0

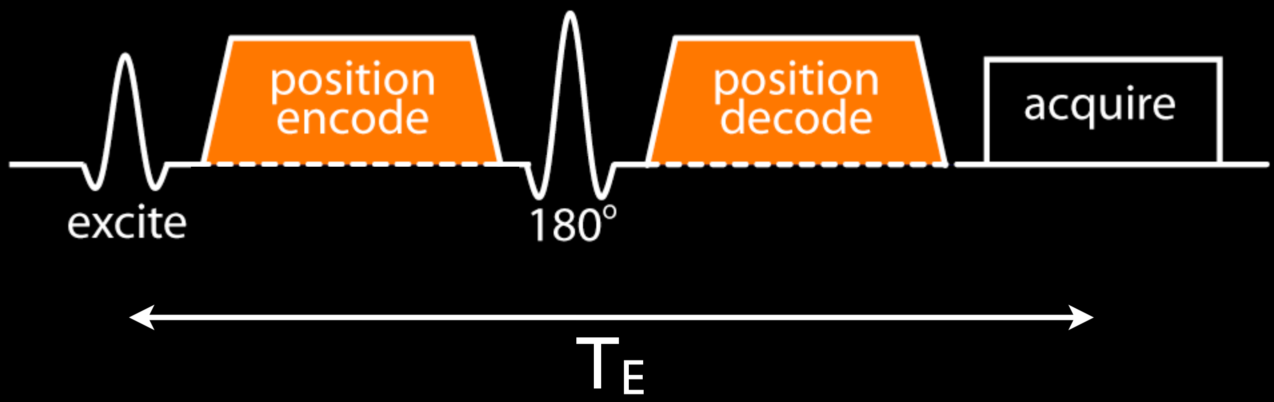
Fitted parameter maps

MRI Physics

- ★ Revisiting Image Encoding

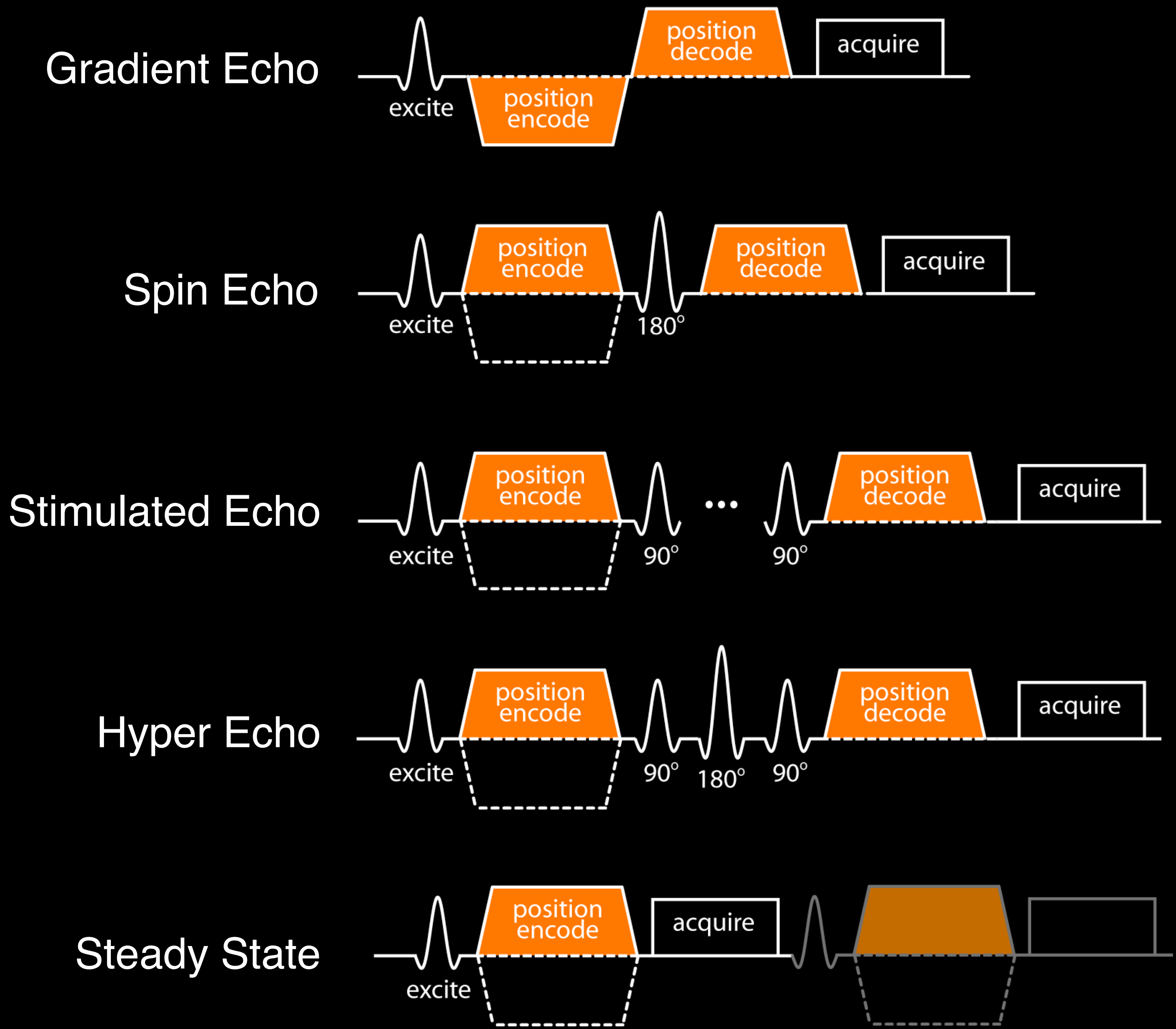
- ★ Spin vs. gradient echo (T2 & T2*)
- ★ Fast imaging & artefacts
- ★ Diffusion MRI
  - ✦ Diffusion weighting
  - ✦ Acquisition techniques
  - ✦ Tradeoffs & complications

Spin Echo

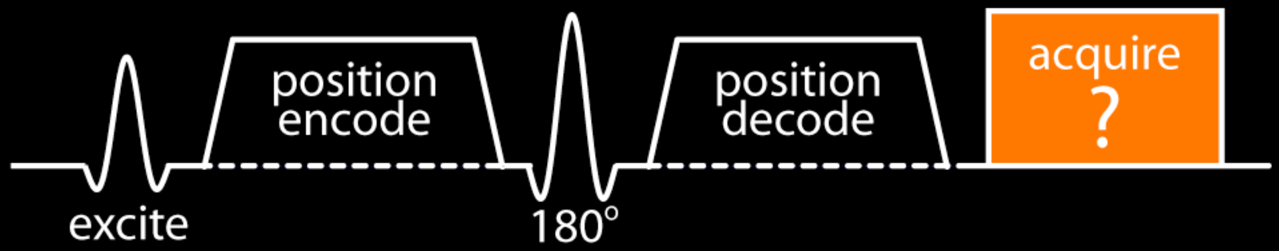


Most commonly used sequence in diffusion imaging

- Spin echo reduces image artefacts
- Efficient diffusion preparation
- Long $T_E \Rightarrow$ strong T_2 decay


Gradient Echo
position decode
acquire
excite
position encode
Spin Echo
position encode
position decode
acquire
excite
180°
Stimulated Echo
position encode
position decode
acquire
excite
90°
90°
Hyper Echo
position encode
position decode
acquire
excite
90°
180°
90°
Steady State
position encode
acquire
excite

Acquiring the image

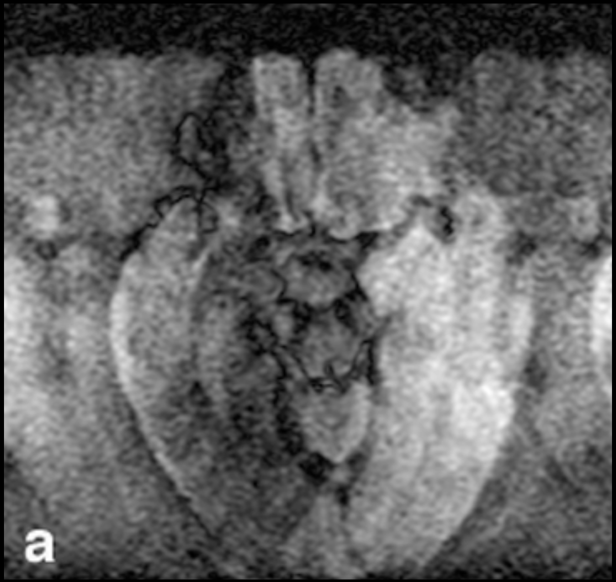


Theoretically, any acquisition can be used

- linescan
- rapid scan (EPI)
- etc...

In practice, motion sensitivity dictates what is possible

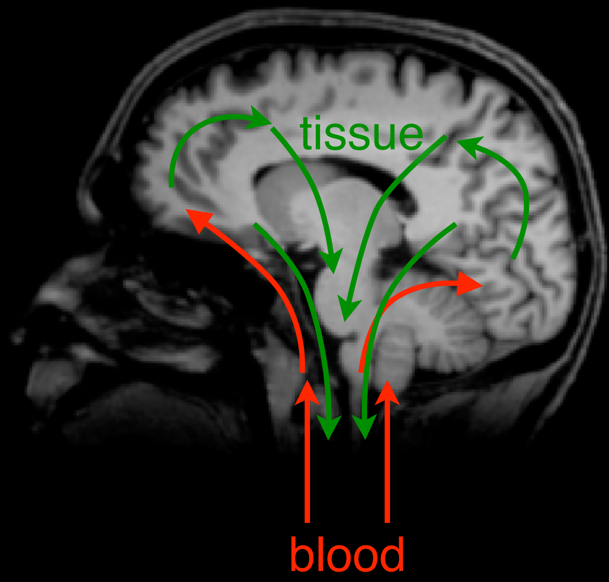
Motion in DWI



Motion corrupted diffusion image

- Diffusion gradients encode tiny displacement
- Subject motion is indistinguishable from diffusion
- Image artefacts if we try to combine data from multiple excitations (different motion)

Can motion be avoided?



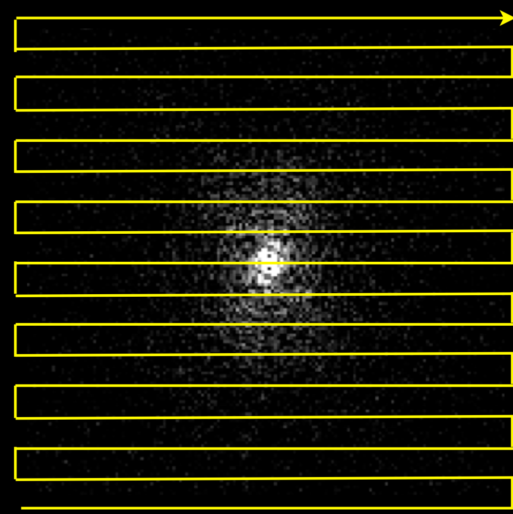
Subject restraints can reduce bulk motion, but...

...in the brain, there is significant non-rigid motion from cardiac pulsatility

cardiac gating helps, but brain is never very still!

Single-shot echo-planar imaging (EPI)

magnetization



EPI acquisition

b=1000 s/mm^2

Single-shot imaging freezes motion

Most common method is echo-planar imaging (EPI)

Images have serious distortion and limited resolution

Typical* Diffusion Imaging Parameters

* Typical, not fixed!!

Parameter	Value	Relevant points
T_E (echo time)	100 ms	Limited by b-value
Matrix size / Resolution	128x128 / 2 mm	Limited by distortion, SNR
Number of directions	6-60	Lower limit: tensor model Upper limit: scan time
b-value	1000 s/mm^2	Larger b = more contrast Smaller b = more signal

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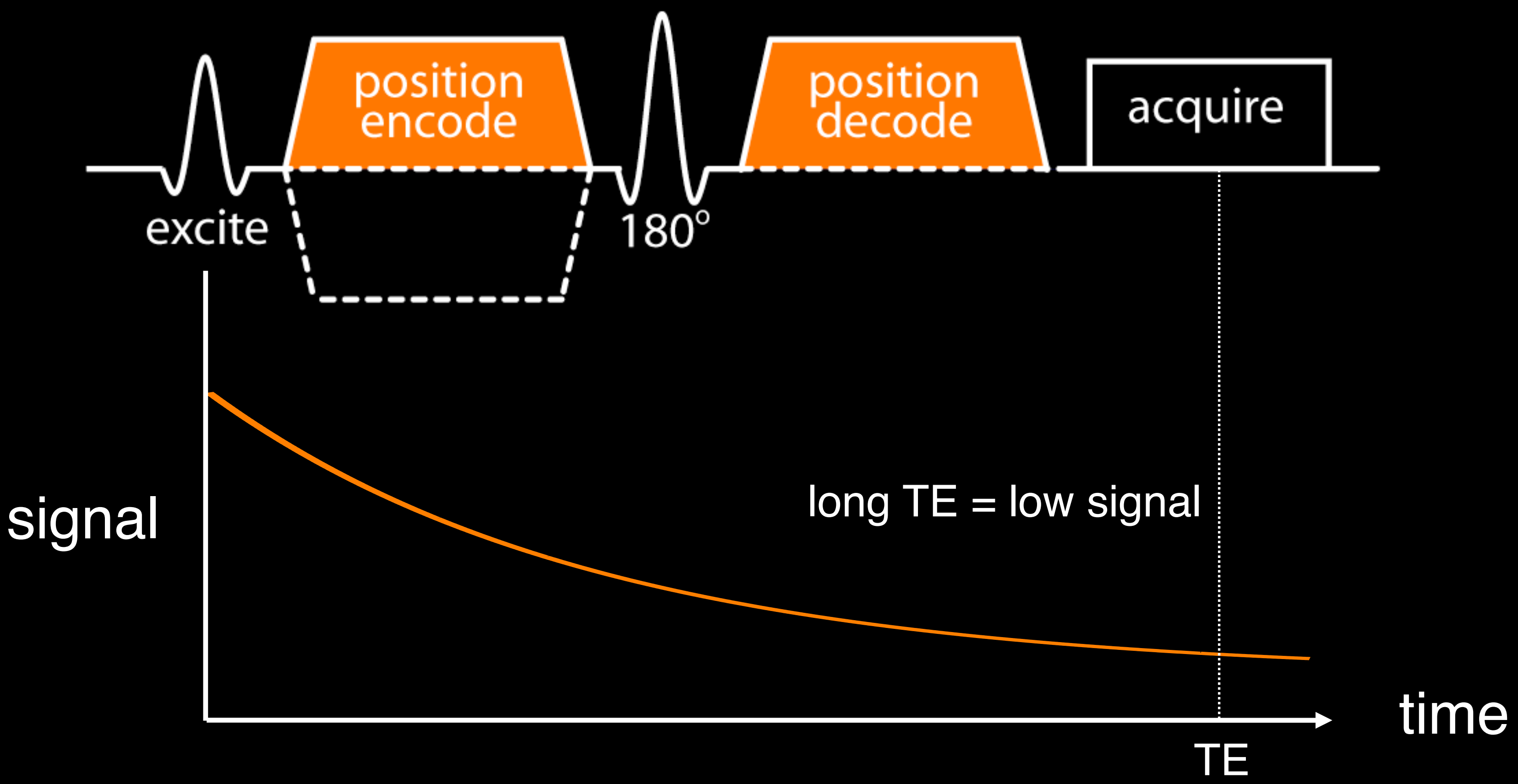
Tradeoff: diffusion weighting vs TE



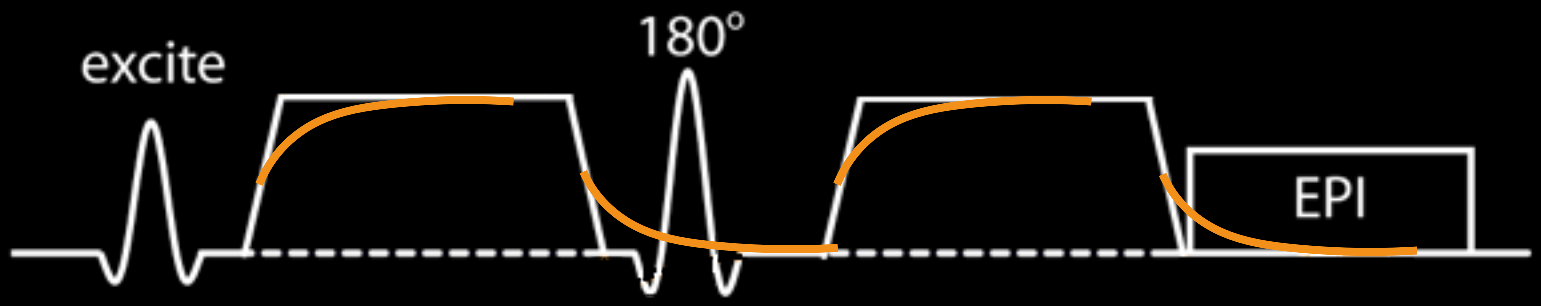
Eddy Currents

Eddy currents "resist" gradient field changes

An "inertia" or "unwillingness" to change

Eddy Currents

Eddy currents “resist” gradient field changes



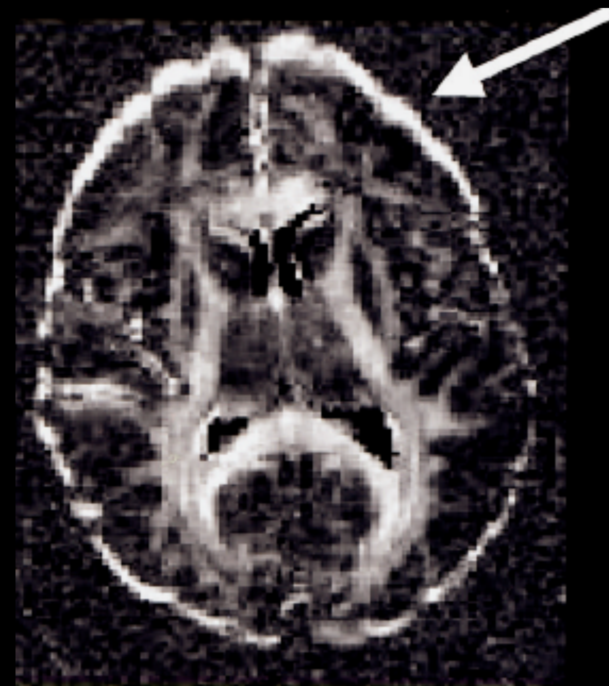
effective gradient fields

Diffusion gradients create large eddy currents, which persist into acquisition window

Distort the k-space trajectory, casing shears/scaling of images

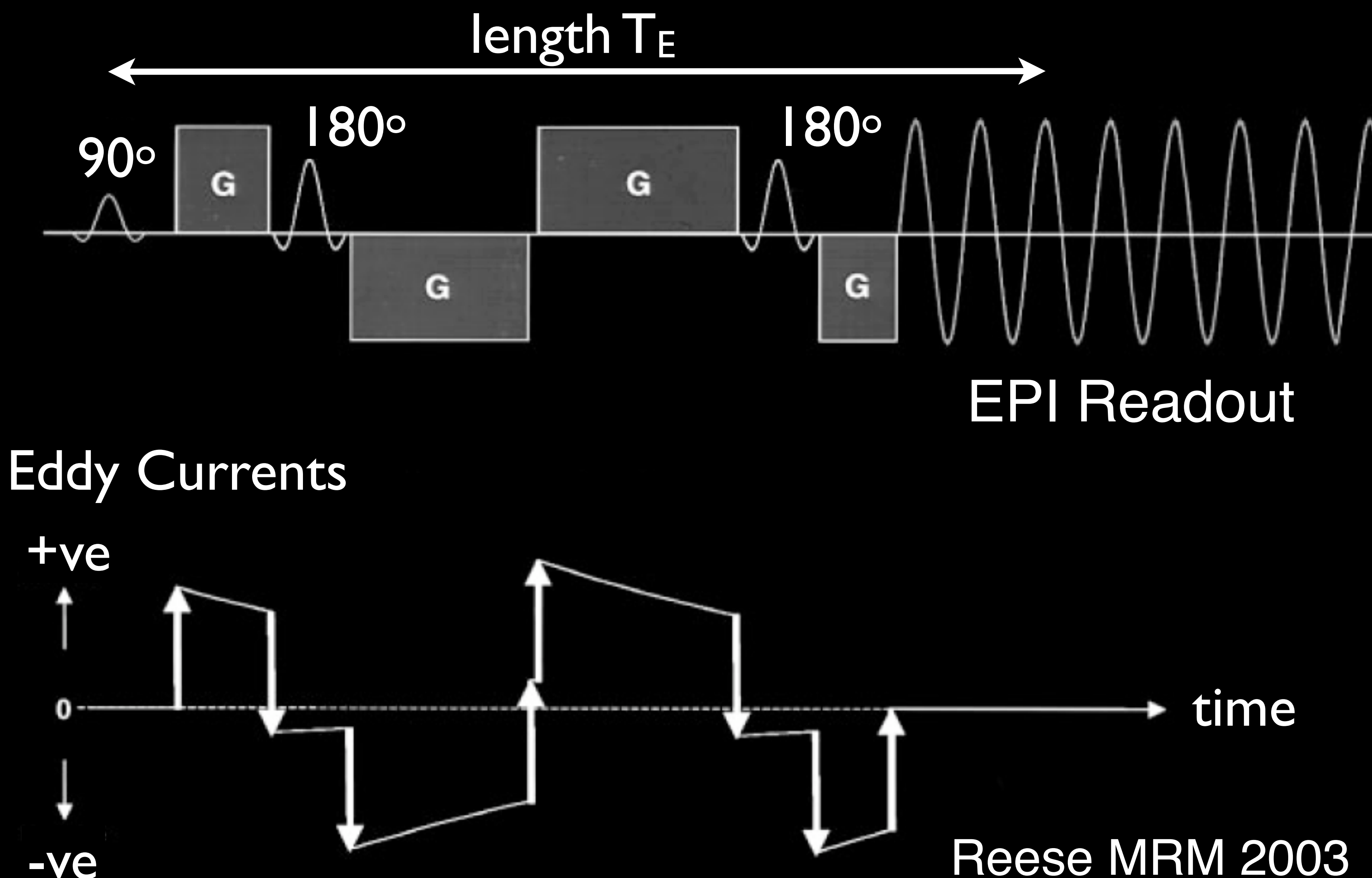
Eddy Currents

Diffusion-weighted
directions



Fractional Anisotropy
("variance")

Twice Refocused Spin Echo



Reese MRM 2003

The biological relevance of MR signals

T1 & T2 contrast:

Tissue *content*

T2* BOLD contrast:

Tissue *function*

Diffusion contrast:

Tissue *micro-structure*

Thank you for your attention!

Questions:

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