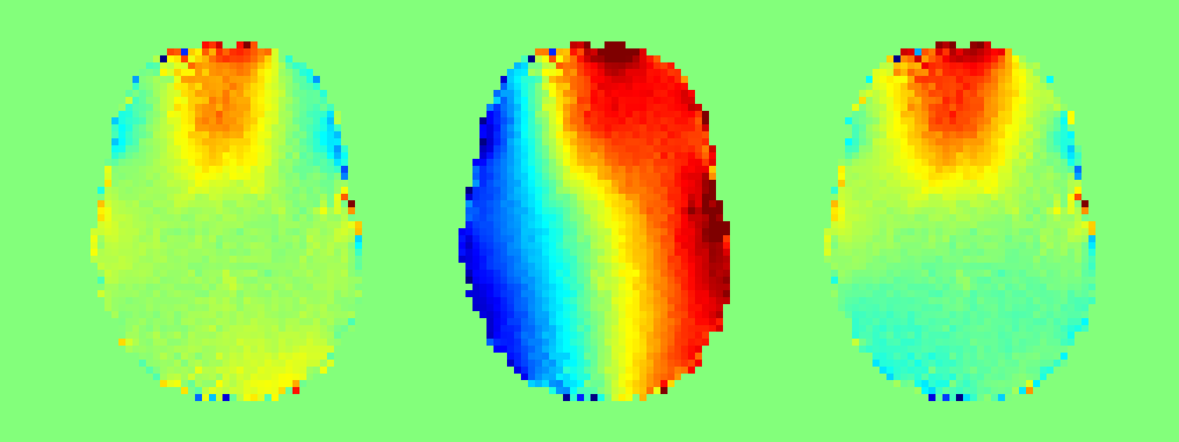
Advanced Topics and Diffusion MRI

Slides originally by Karla Miller, FMRIB Centre

Modified by Mark Chiew (mark.chiew@ndcn.ox.ac.uk)



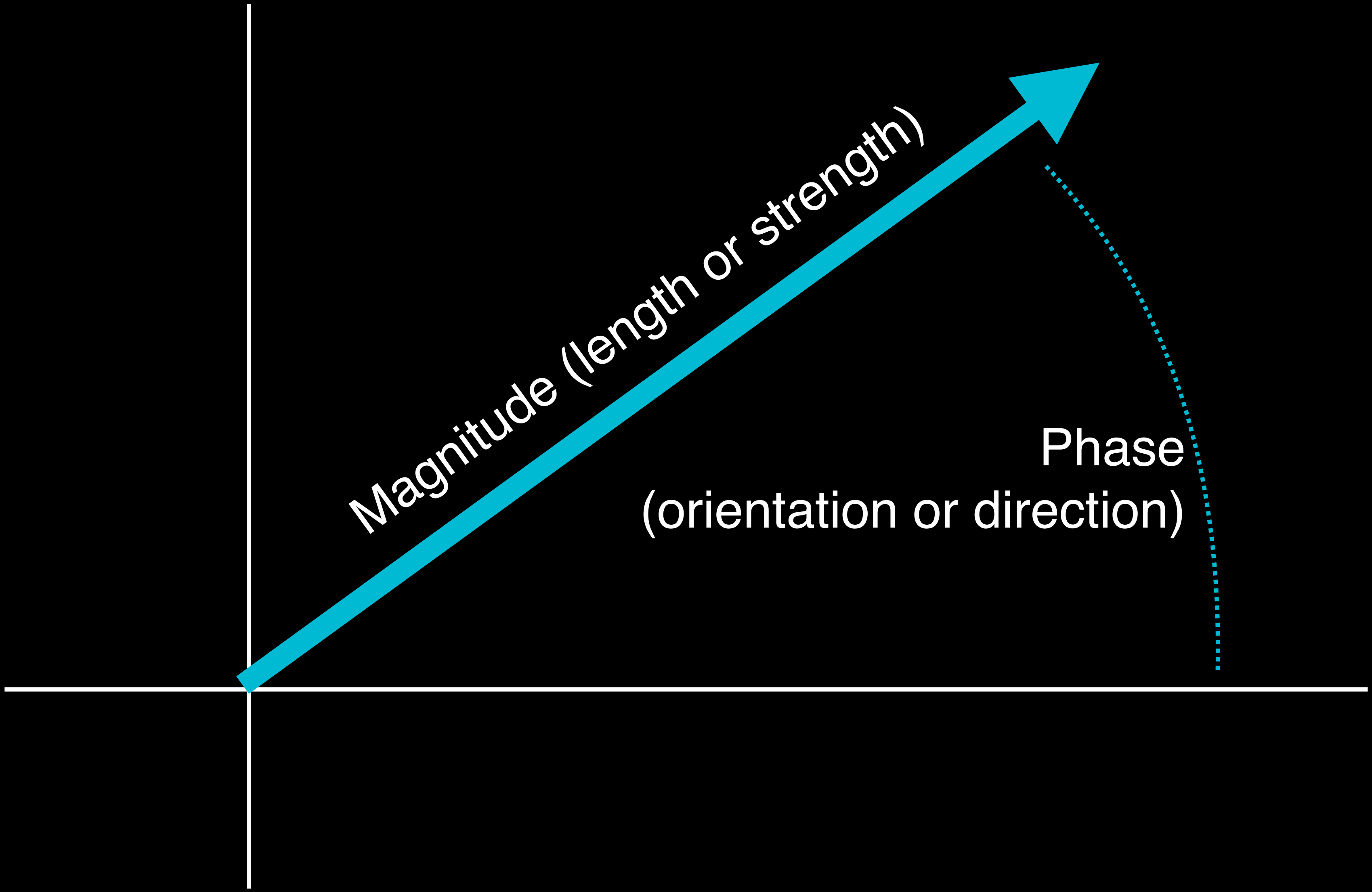
Slides available at:

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

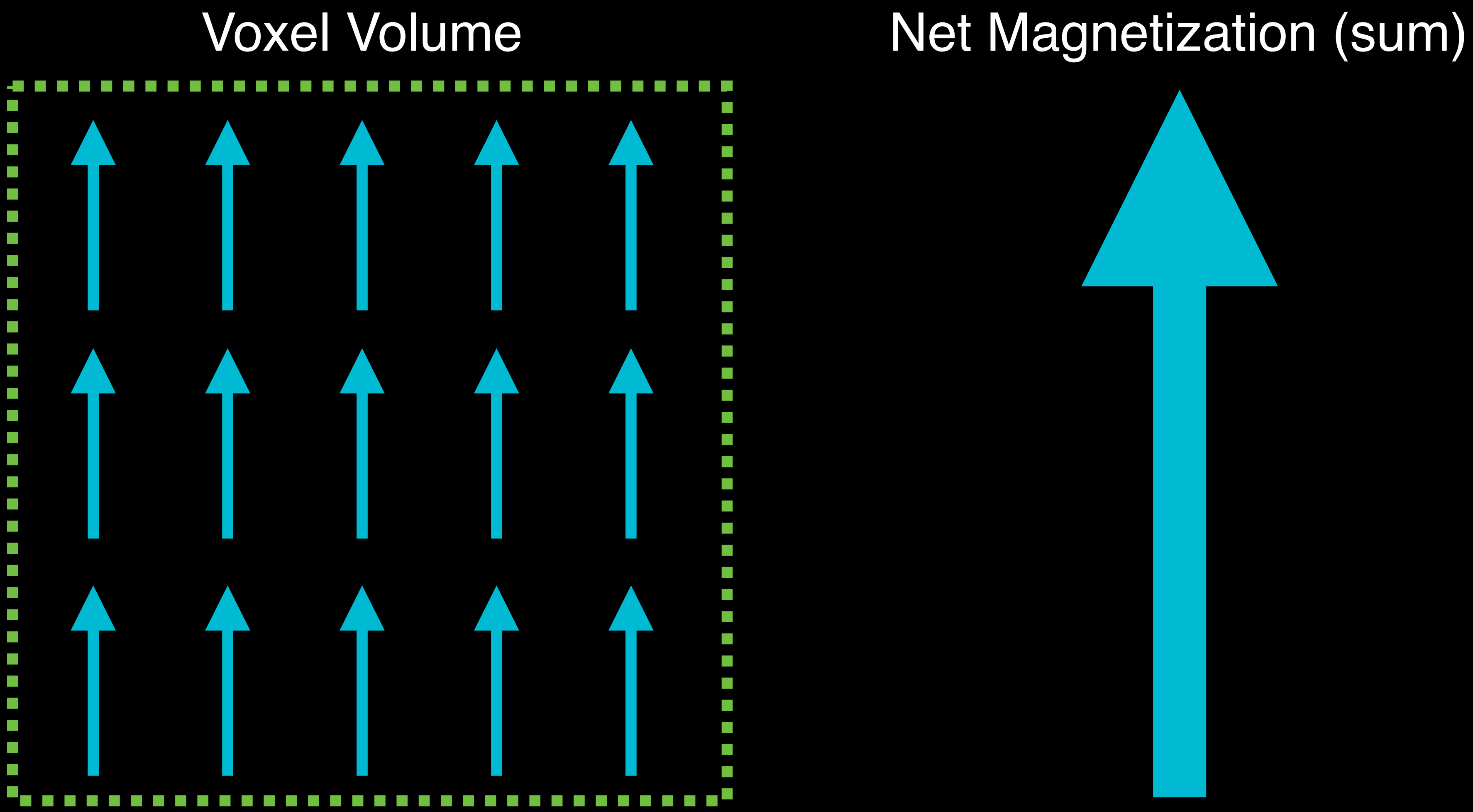
MRI Physics

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

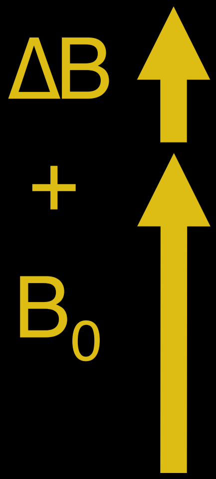
Phase

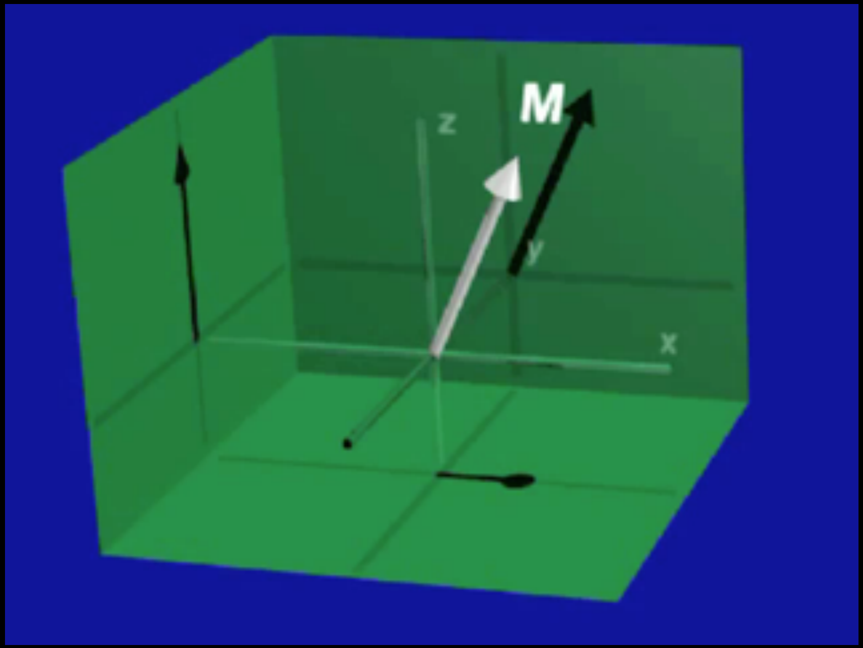

Magnitude (length or strength)
Phase
(orientation or direction)

Net Magnetization (in-phase)



Precession (in-phase)





courtesy of William Overall

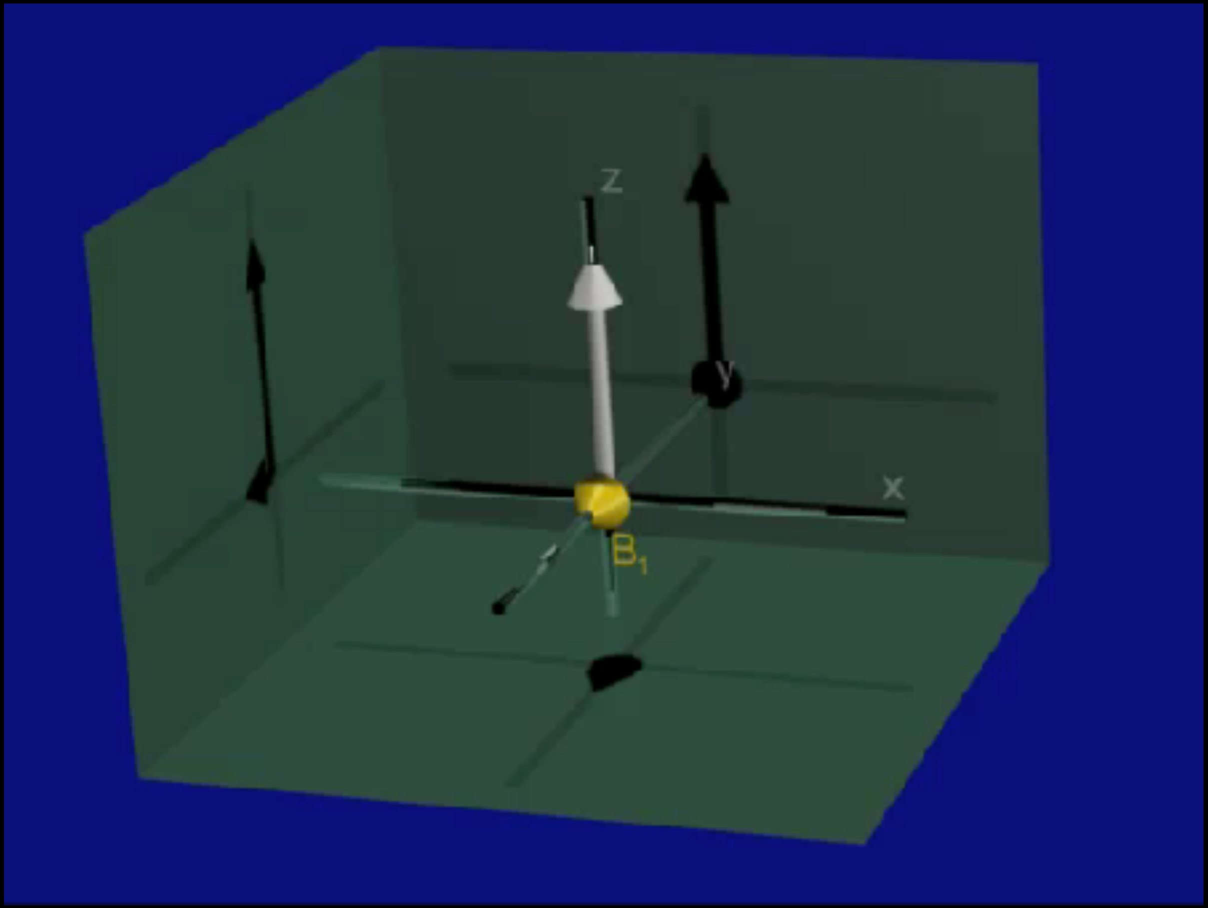
rotational frequency

$$\omega_0 = \gamma(B_0+\Delta B)$$

main field

offset (gradients or errors)

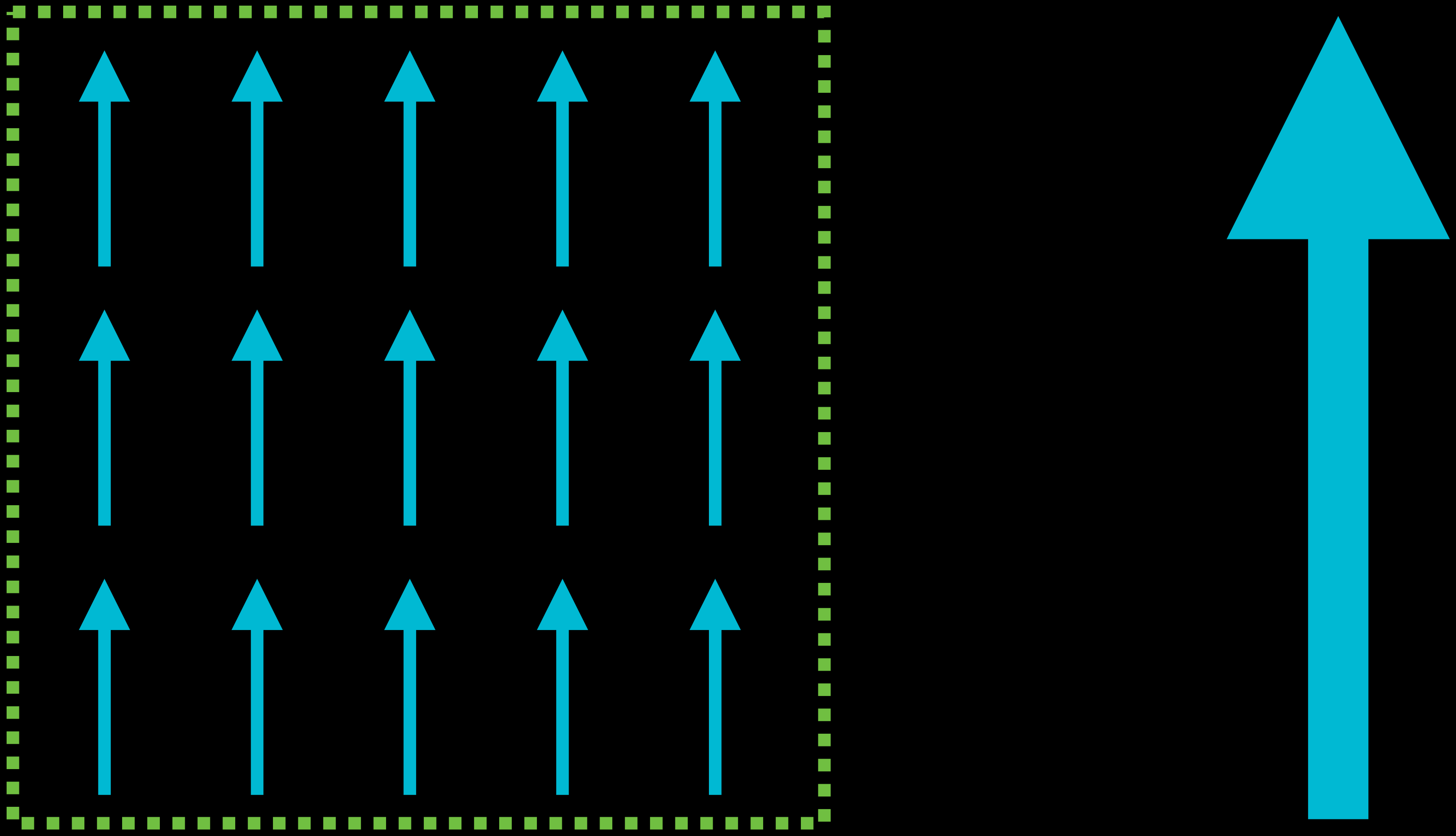
Magnetic field imperfections: T_2* decay



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

Over time, spins lose alignment (“dephase”)

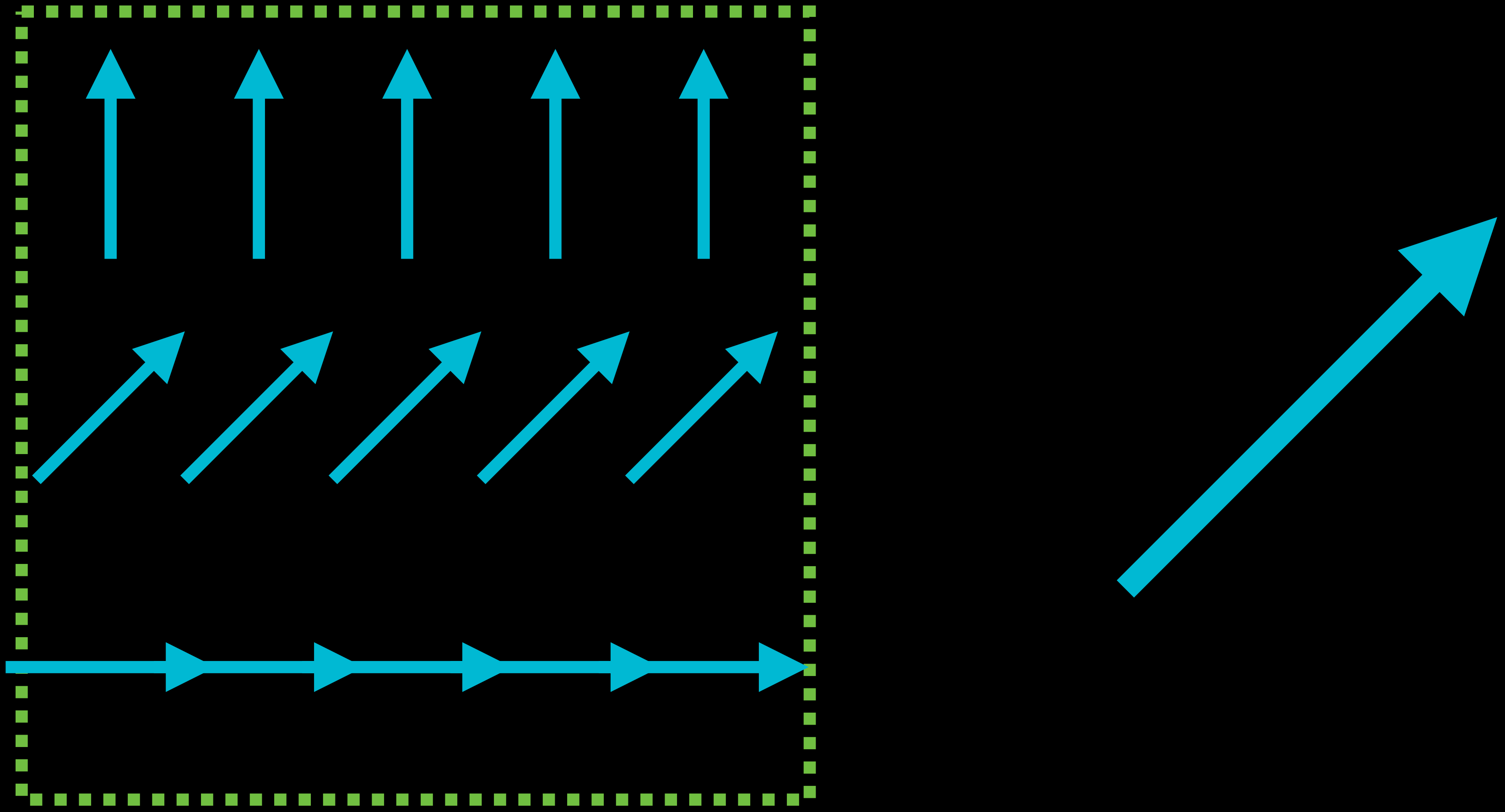
Net Magnetization (in-phase)



Voxel Volume

Net Magnetization (sum)

Net Magnetization (dephasing)

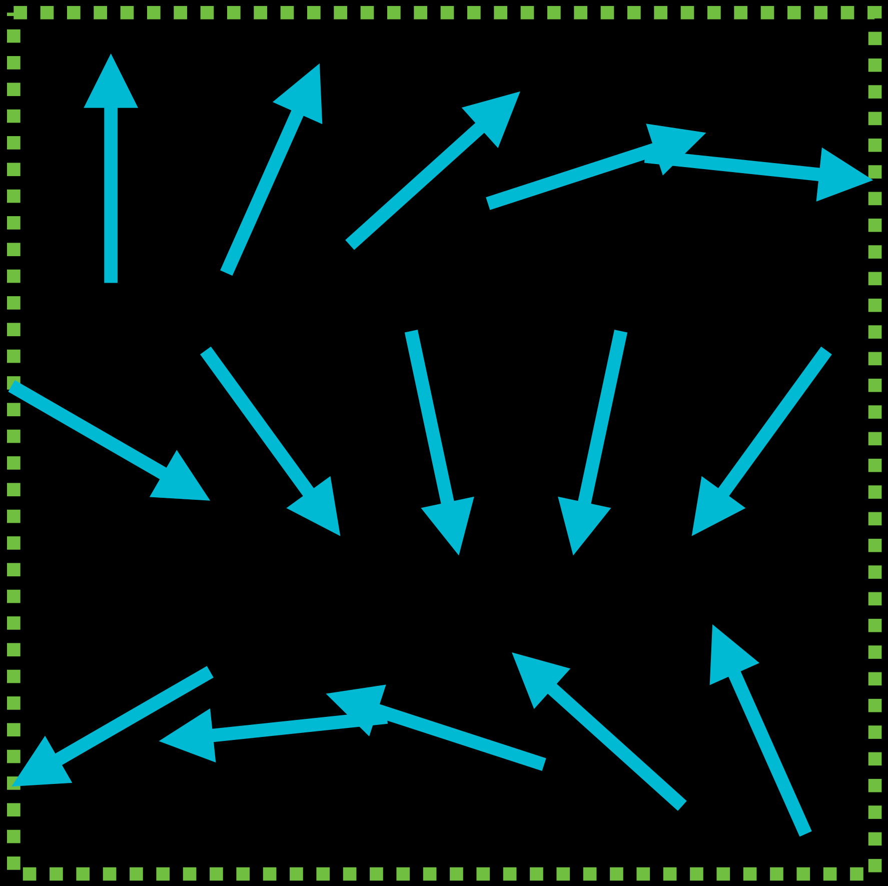


Voxel Volume

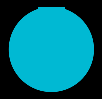
Net Magnetization (sum)

Net Magnetization (dephased)

Voxel Volume

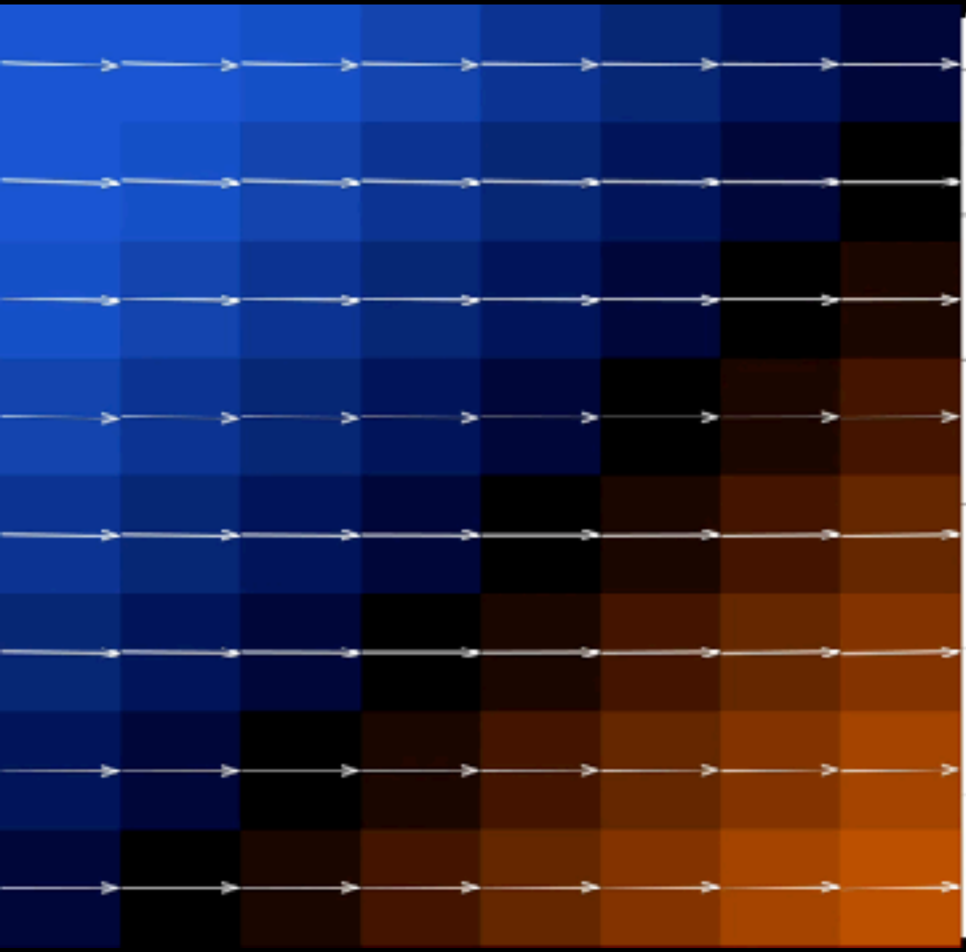


Net Magnetization (sum)



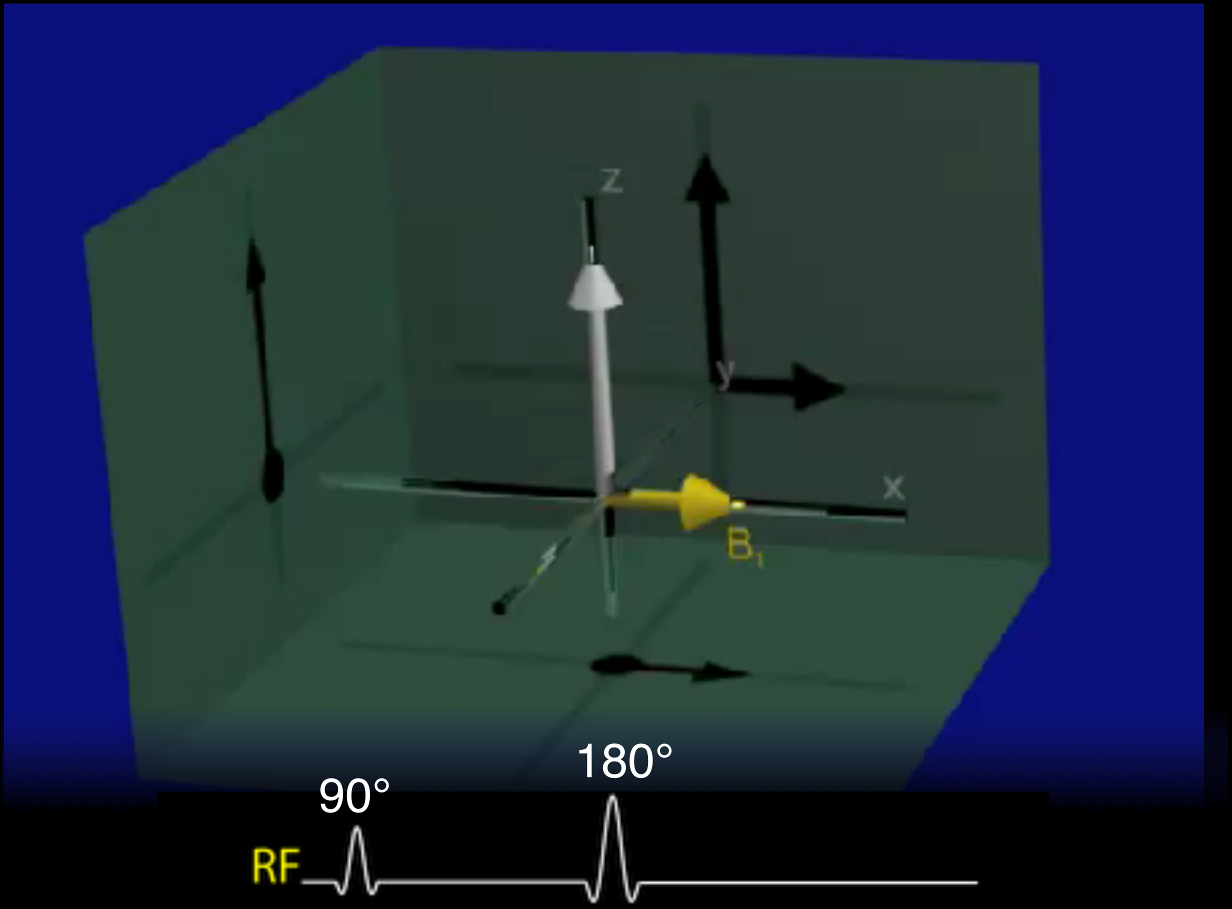
Dephasing

Simple Voxel Model



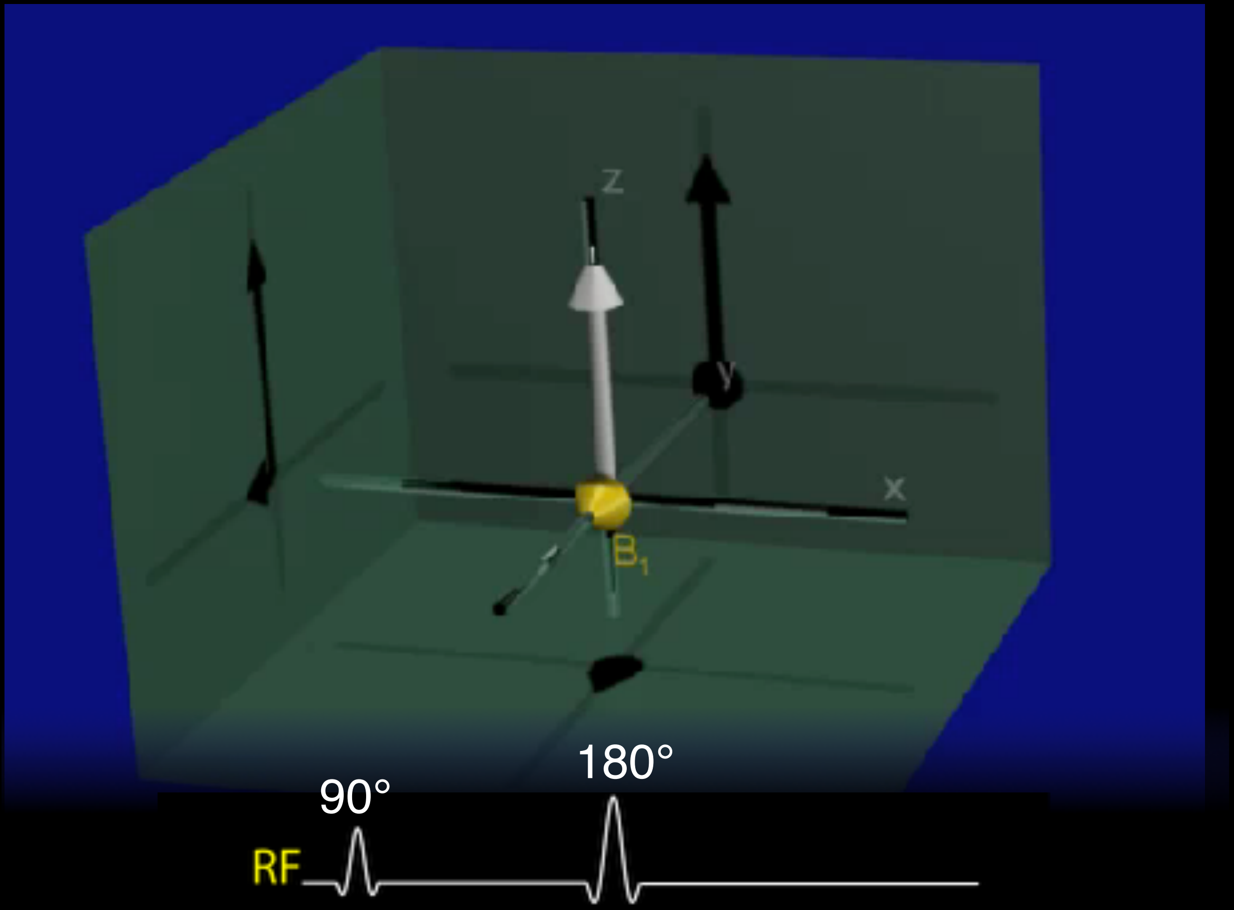
Voxel Signal

Refocusing (180° RF pulse) with no dephasing



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

Refocusing (180º RF pulse) with dephasing



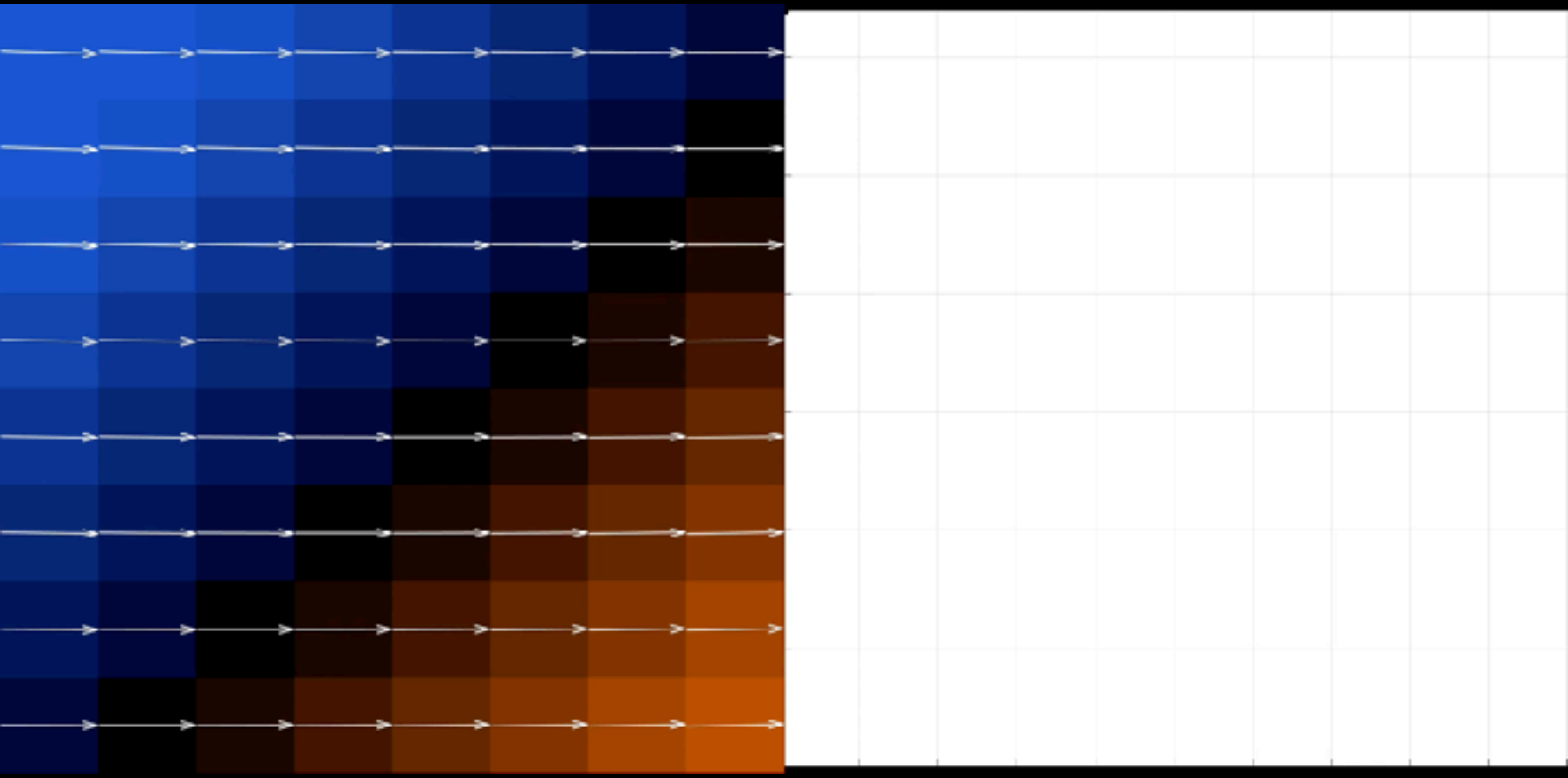
Spin echo: The time at which the spins are re-aligned

Refocusing pulse: 180º pulse that creates a spin echo

Dephasing

Simple Voxel Model

Voxel Signal

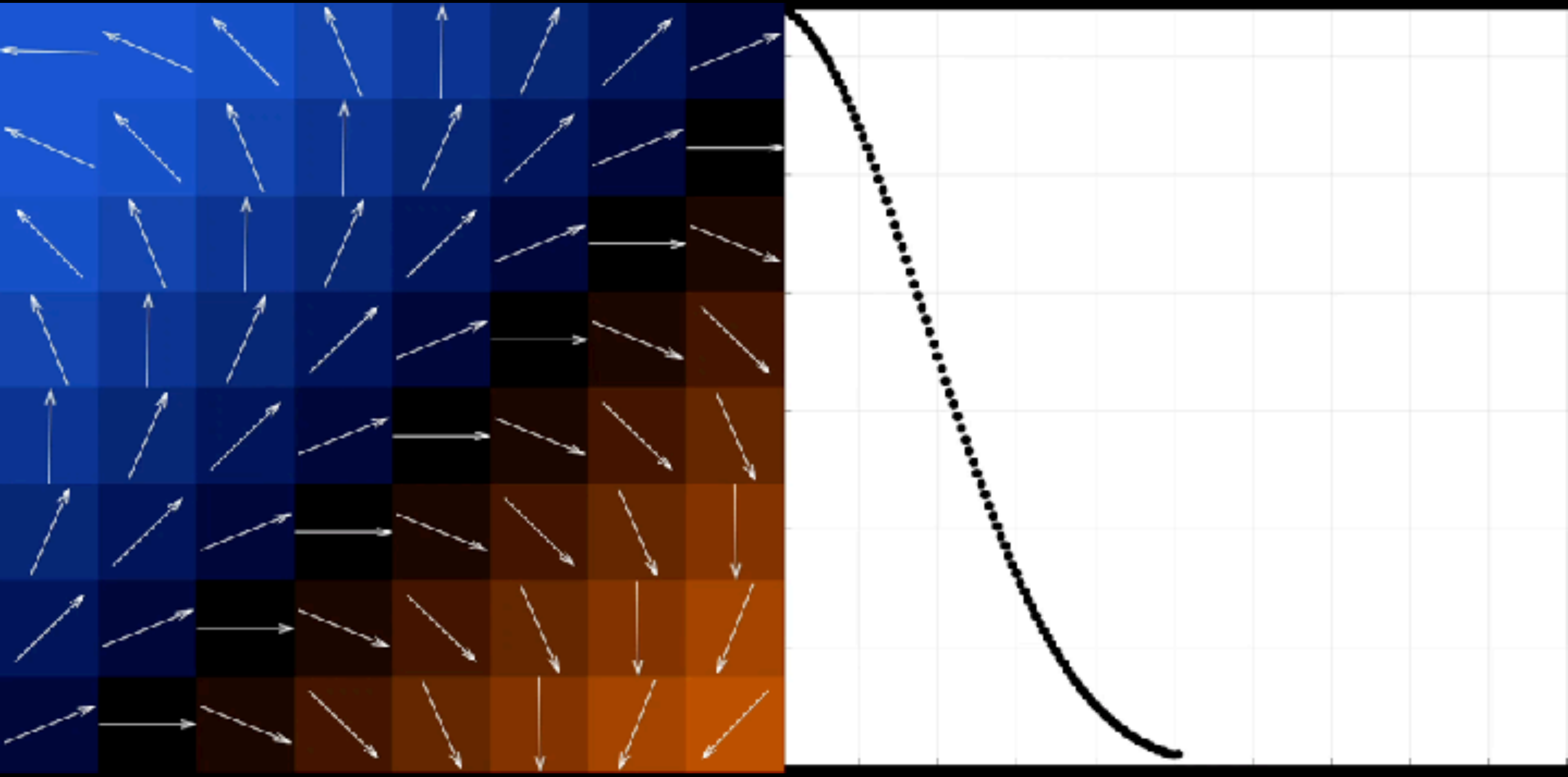


180º Refocusing Pulse!

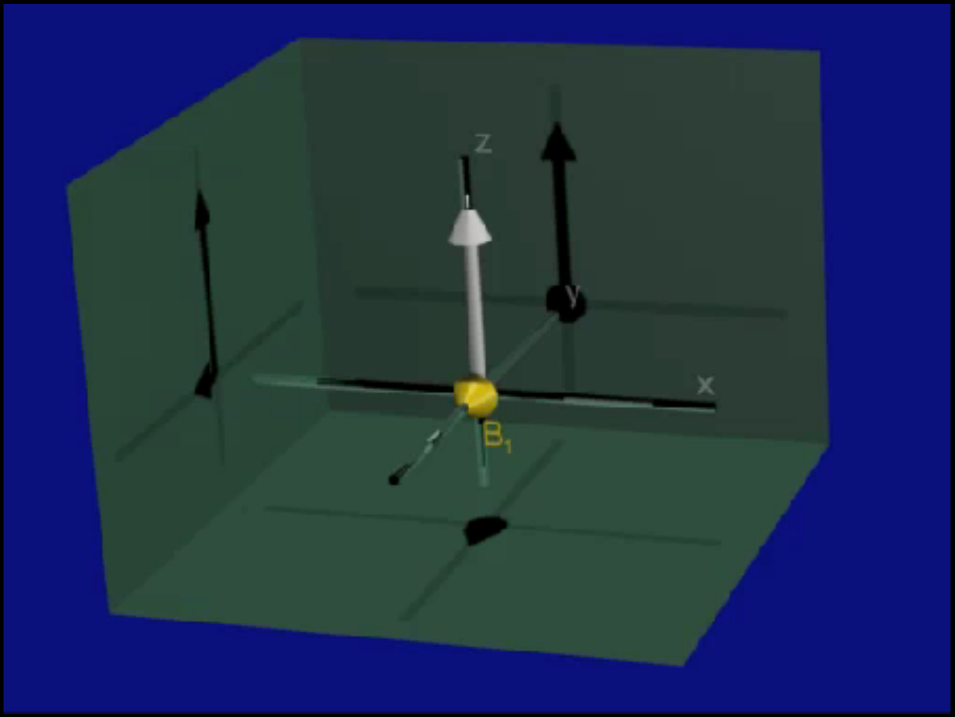
Rephasing After Spin Echo

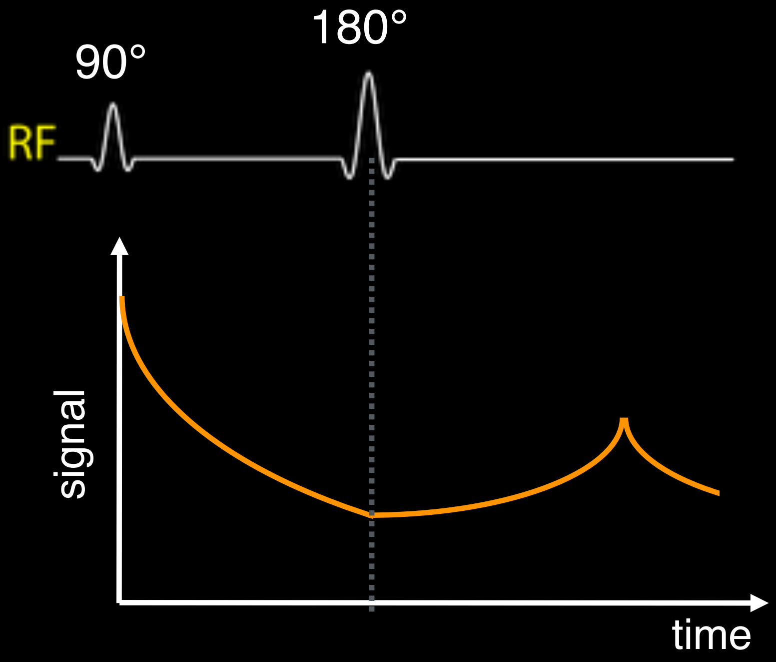
Simple Voxel Model

Voxel Signal



Refocusing (180° pulse) spin echo



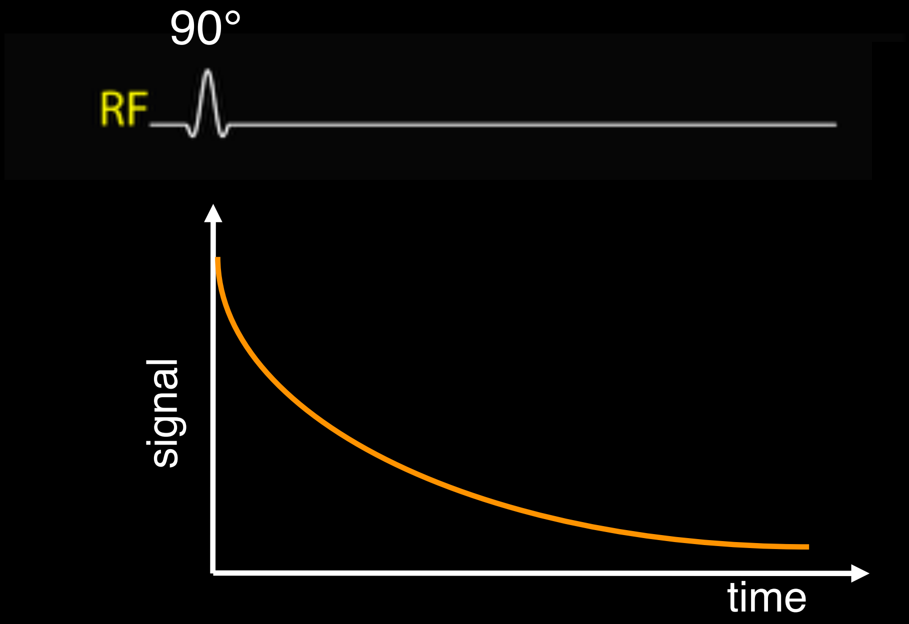


Spin echo: The time at which the spins are re-aligned

Refocusing pulse: 180° pulse that creates a spin echo

Gradient echo vs. spin echo

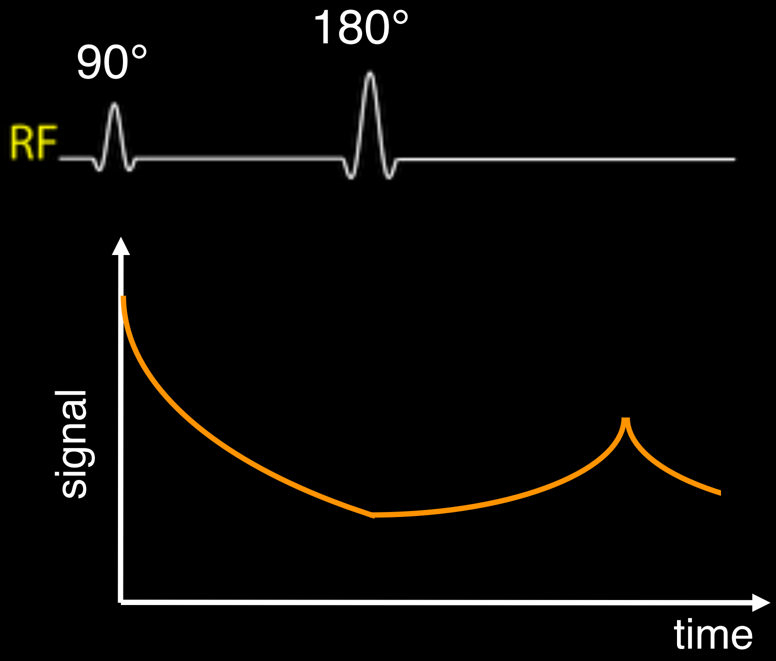
(i.e. no spin-echo)



GRE signal

(sometimes called a Free Induction Decay = FID)

pure signal decay

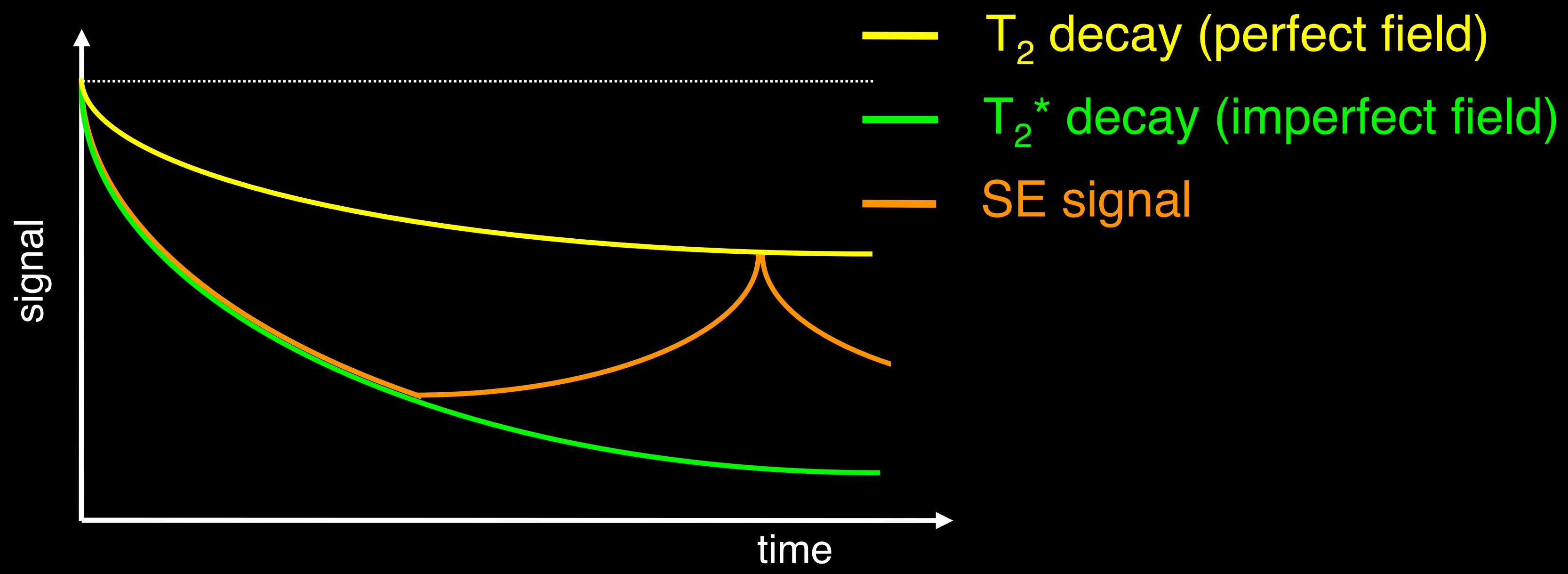


SE signal

(signal decays, then comes back as “echo”)

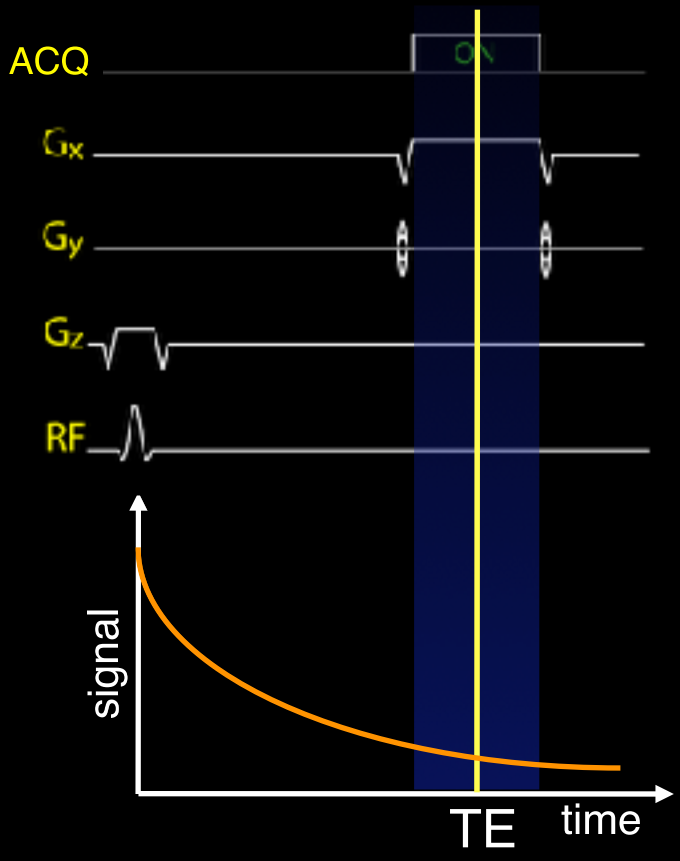
decay with partial recovery

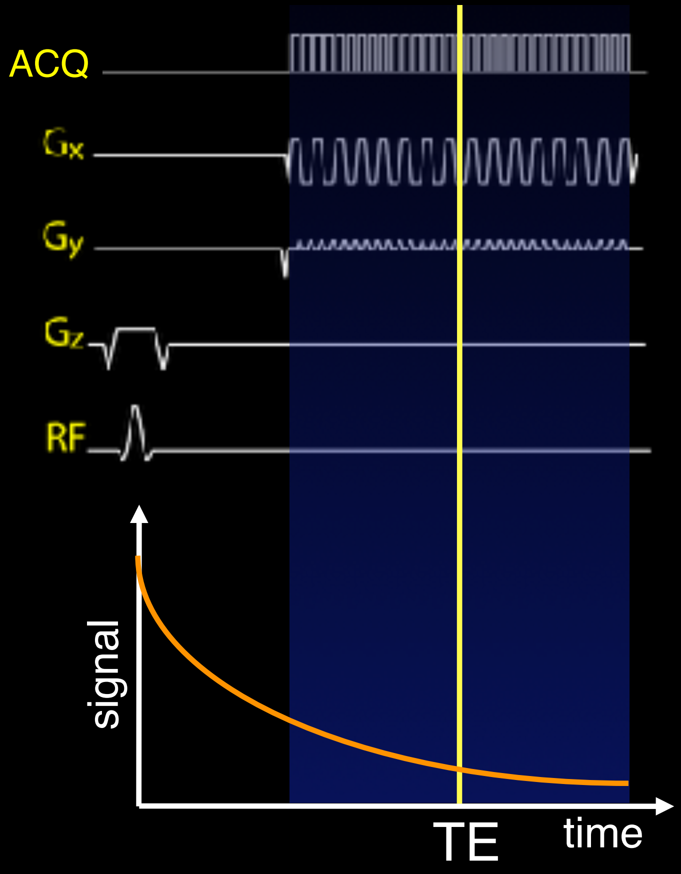
T_2 vs T_2^* Relaxation



- 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

What defines a gradient echo sequence?



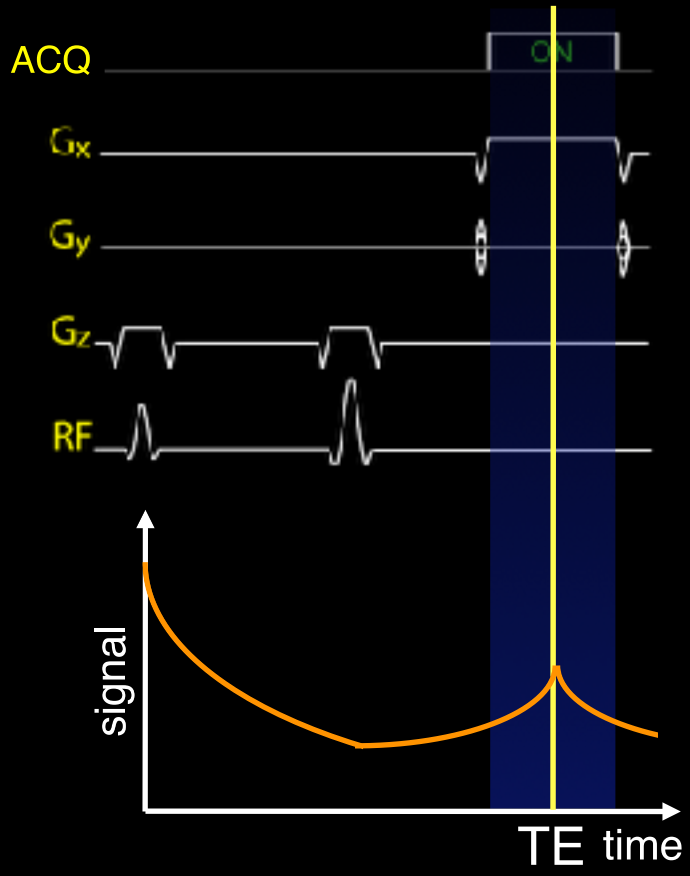


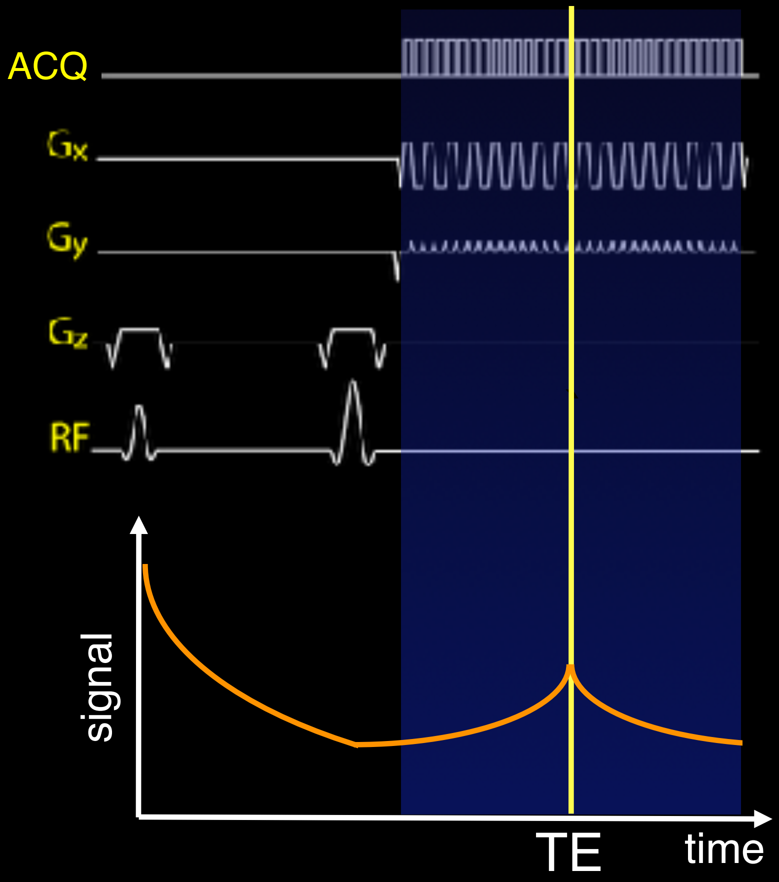
GRE refers to a sequence with: excitation-delay-readout

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

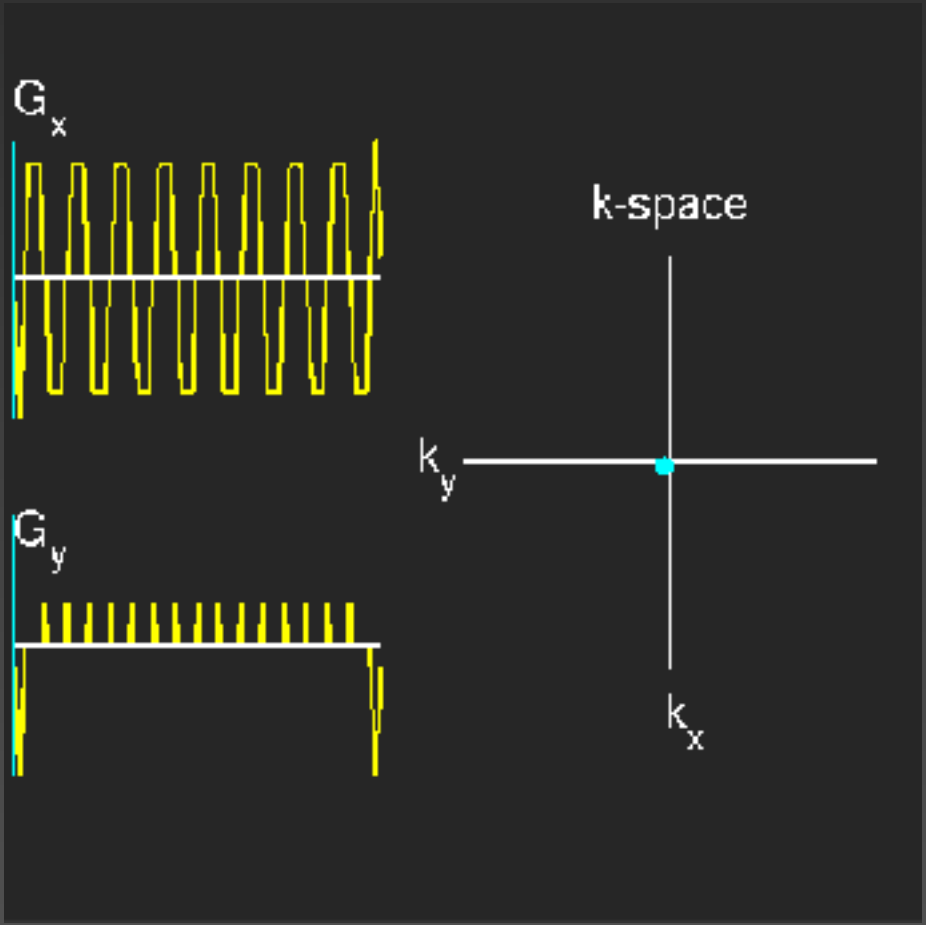
The key is the formation of an echo (signal peak)!

Like GRE, any kind of readout can be used

MRI Physics

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

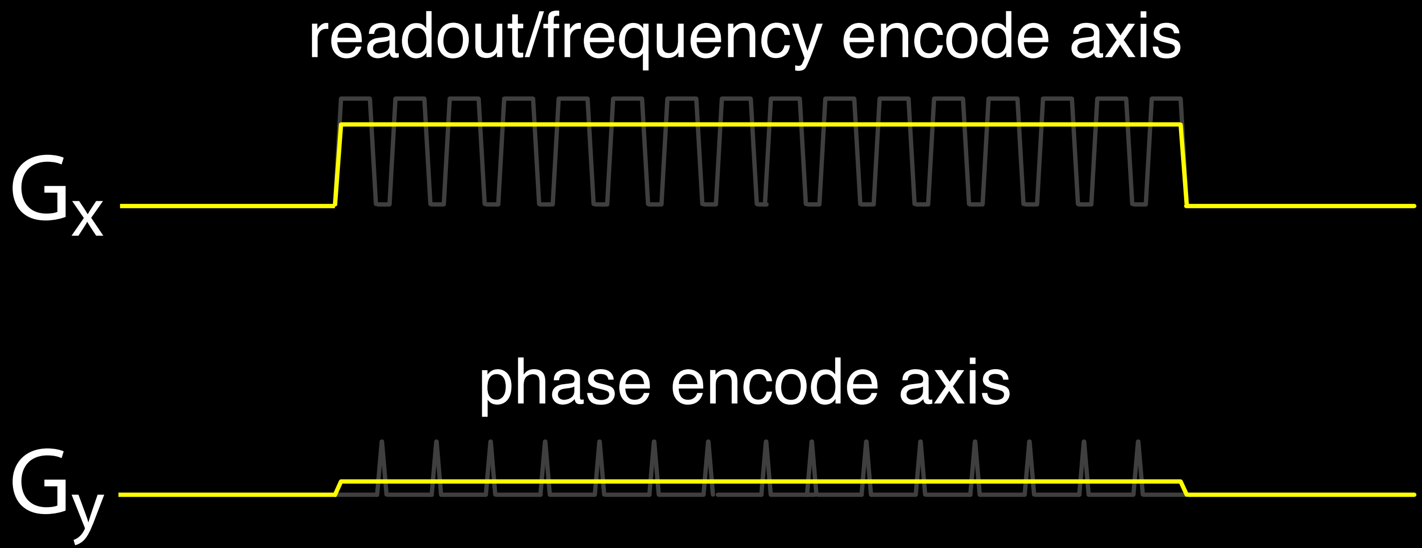
Echo-planar Imaging (EPI) Acquisition



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

Used for FMRI, diffusion imaging

EPI gradients: Approximation

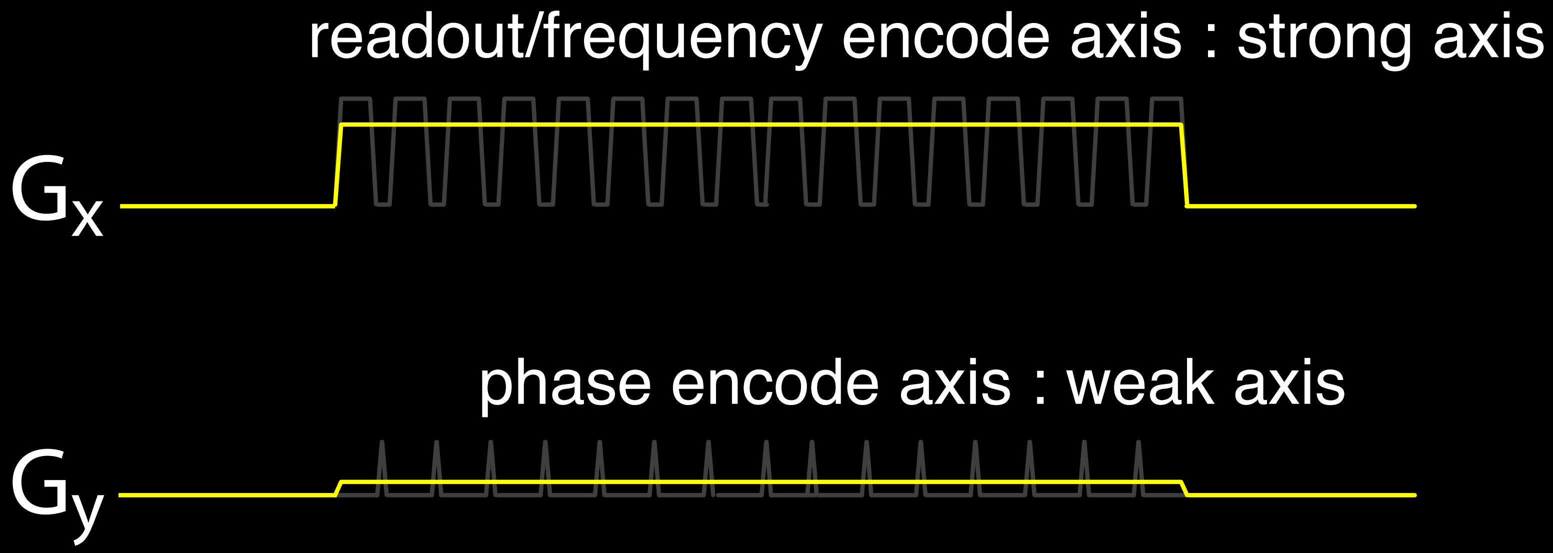


readout/frequency encode axis

phase encode axis

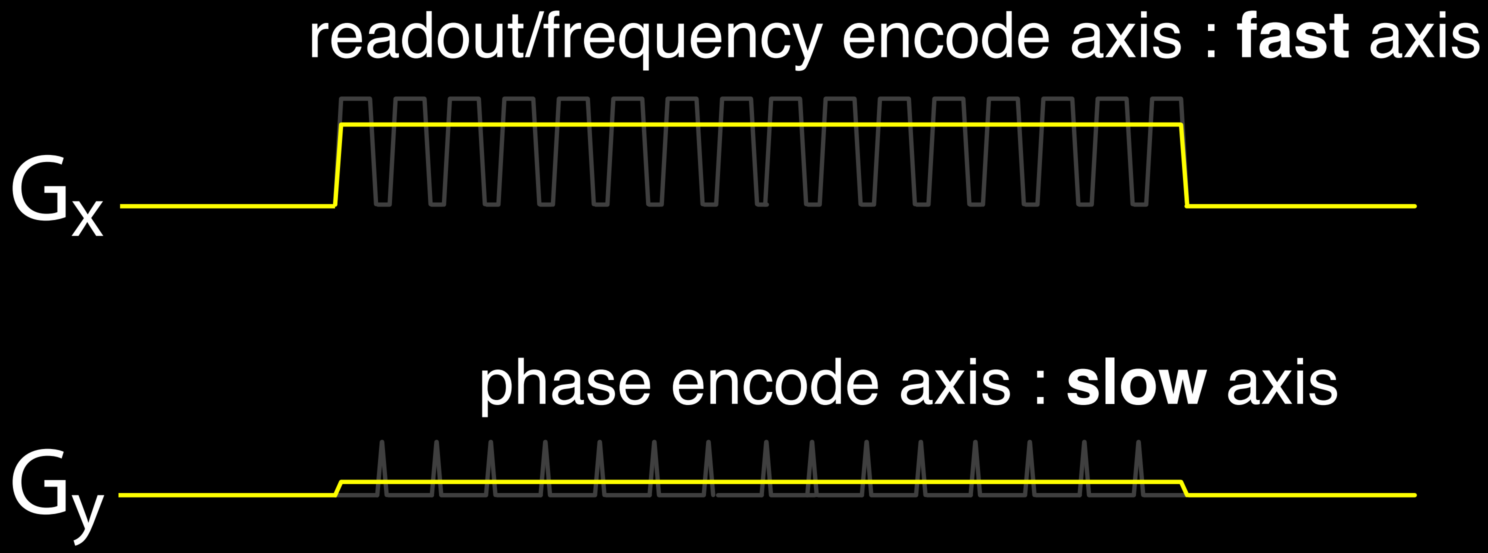
Simplify gradient sequence to understand source of image distortions...

EPI gradients: Approximation



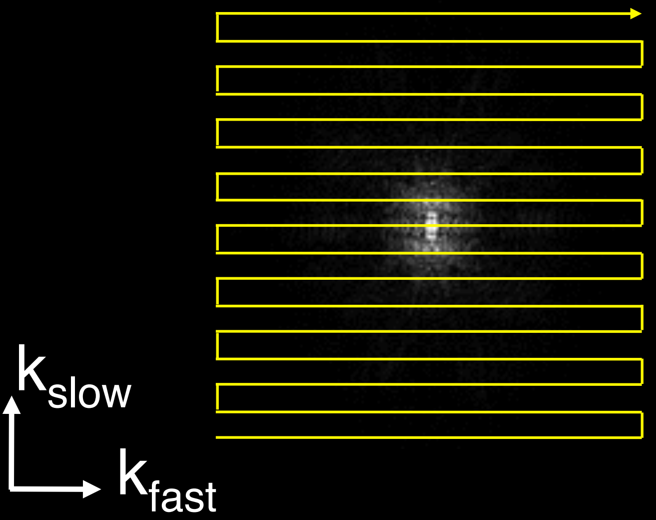
Simplify gradient sequence to understand source of image distortions...

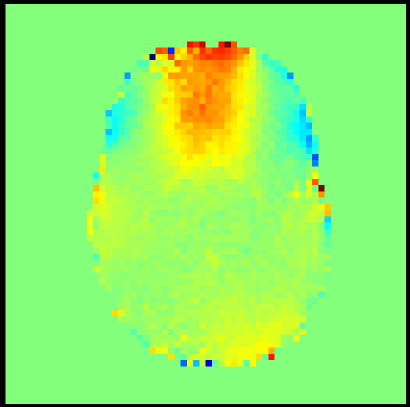
EPI gradients: Approximation



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

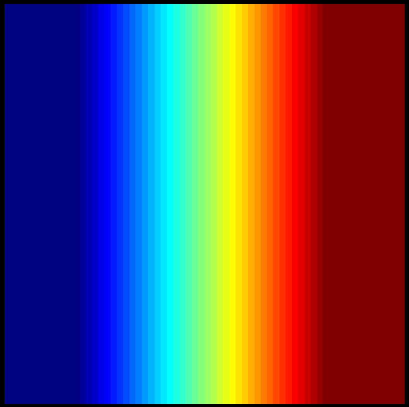
EPI undistorted along “fast” direction (frequency encode)





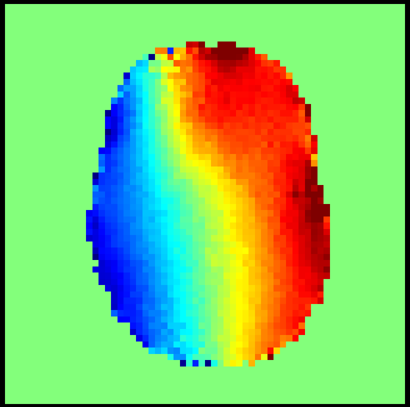
field map

+



fast gradient

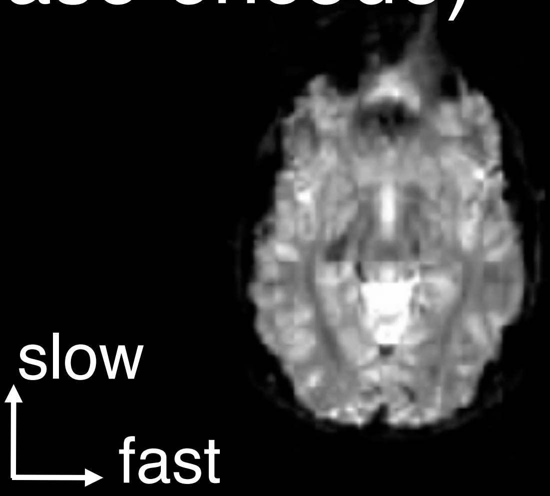
=

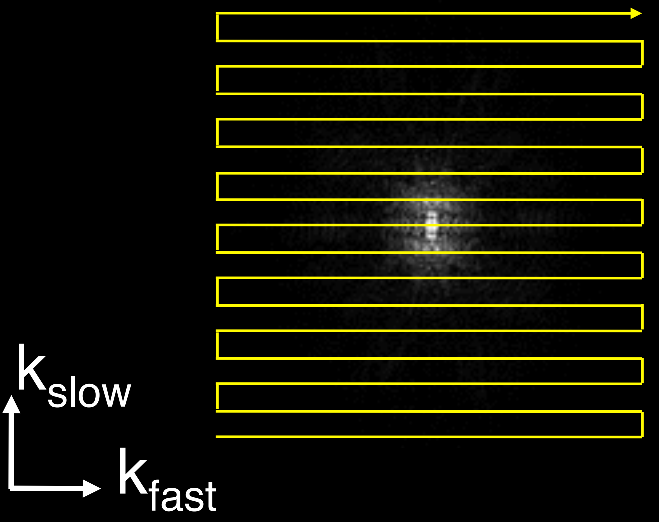


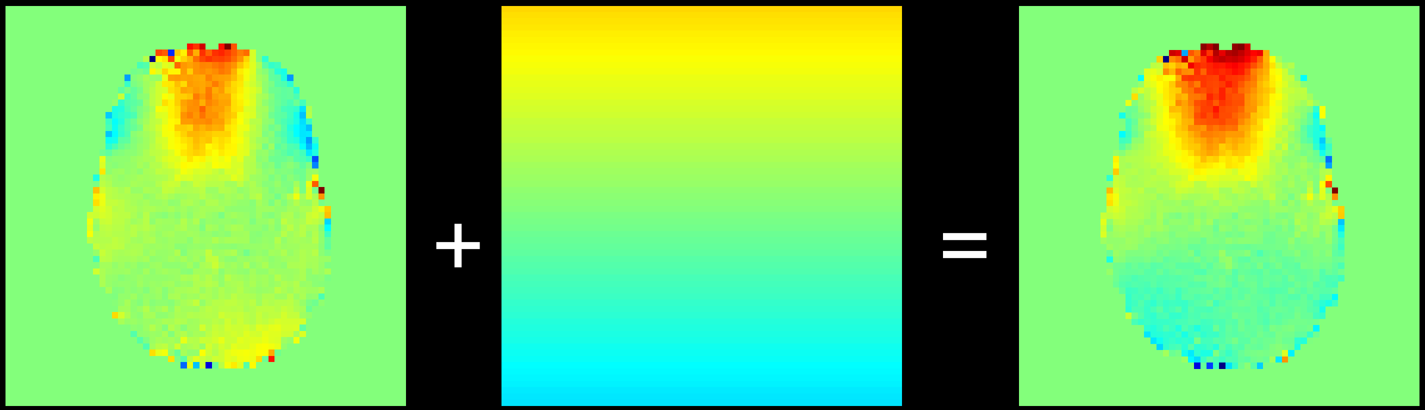
net (fast)

Field map errors have negligible effect on fast gradient

EPI distorted along “slow” direction (phase encode)







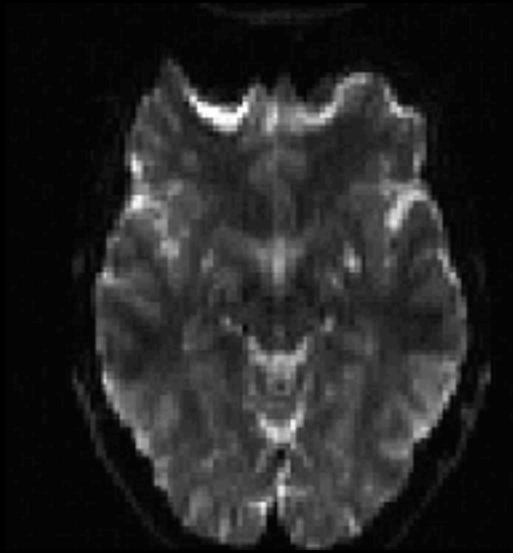
field map

slow gradient

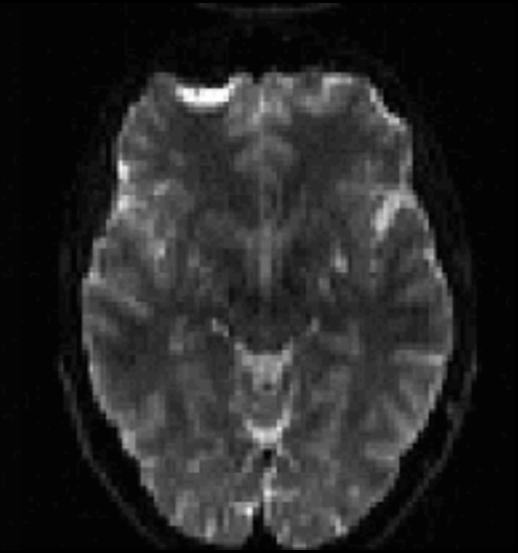
net (fast)

Field map errors dominate slow gradient, signal is misplaced

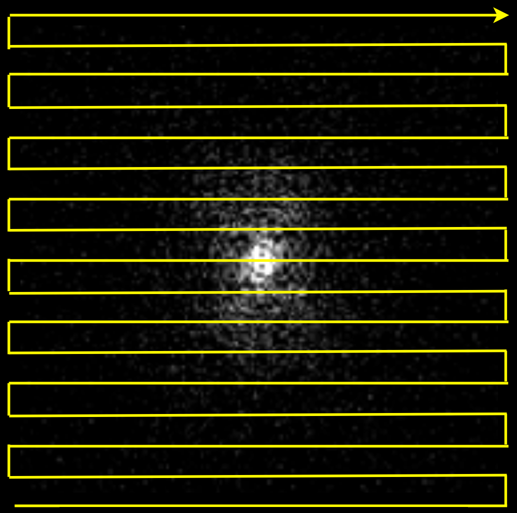
EPI distortion



Long inter-echo spacing



Short inter-echo spacing

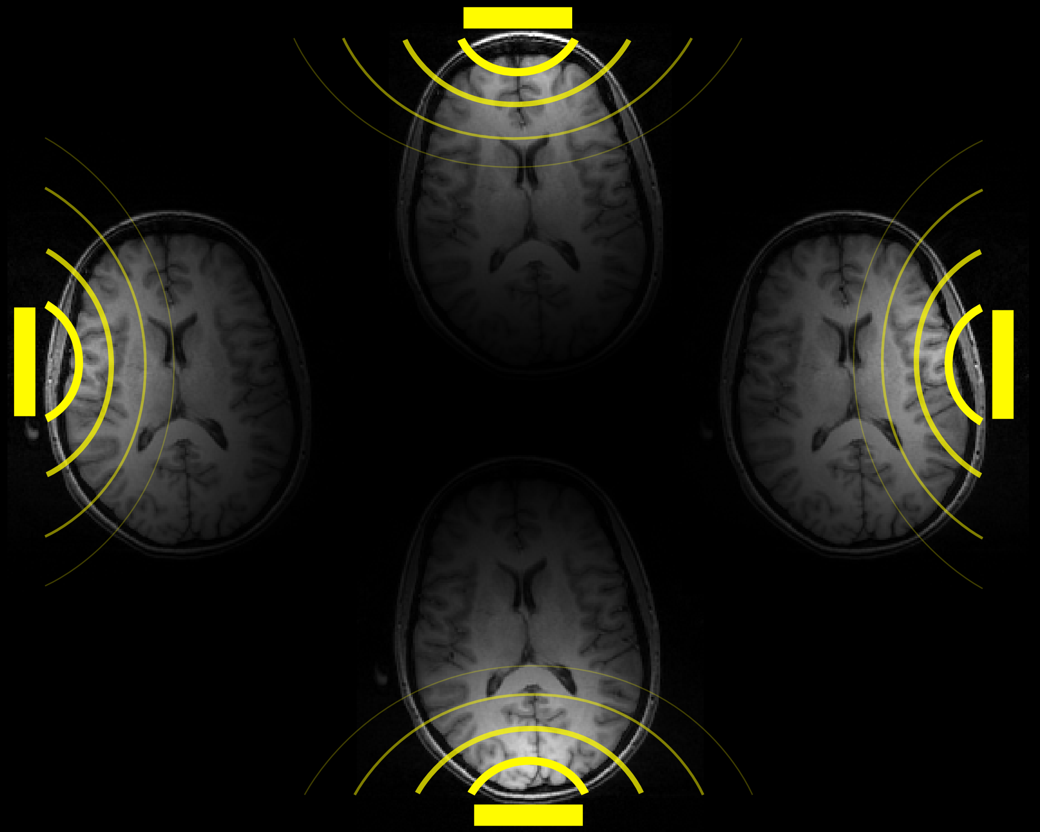


EPI trajectory

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

Long echo spacing = worse distortion

Parallel imaging (SENSE, GRAPPA, etc)

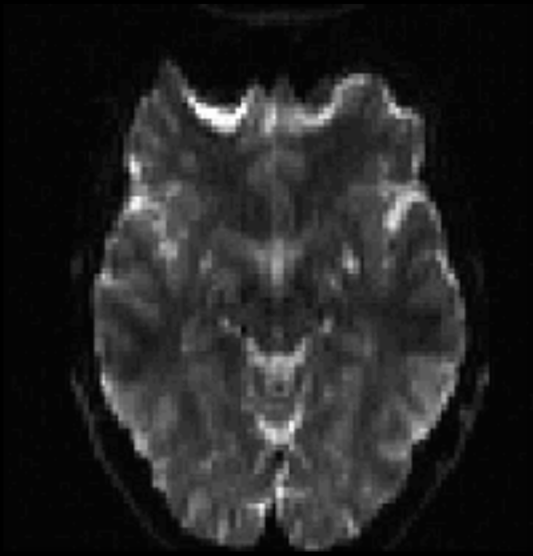


Coil sensitivity encodes spatial information

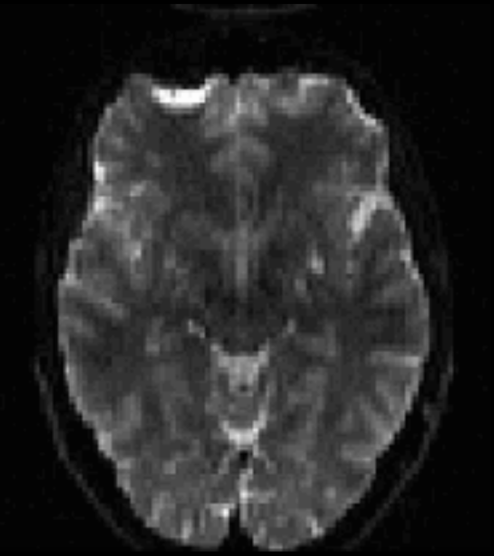
Skip lines in k-space, reconstruction fills in missing lines based on coil sensitivity

Allows “acceleration” of k-space acquisition

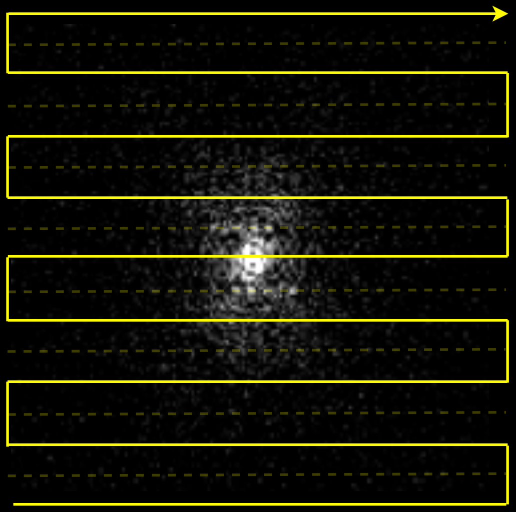
Parallel imaging



No Parallel
Imaging



Parallel
Imaging (2x)



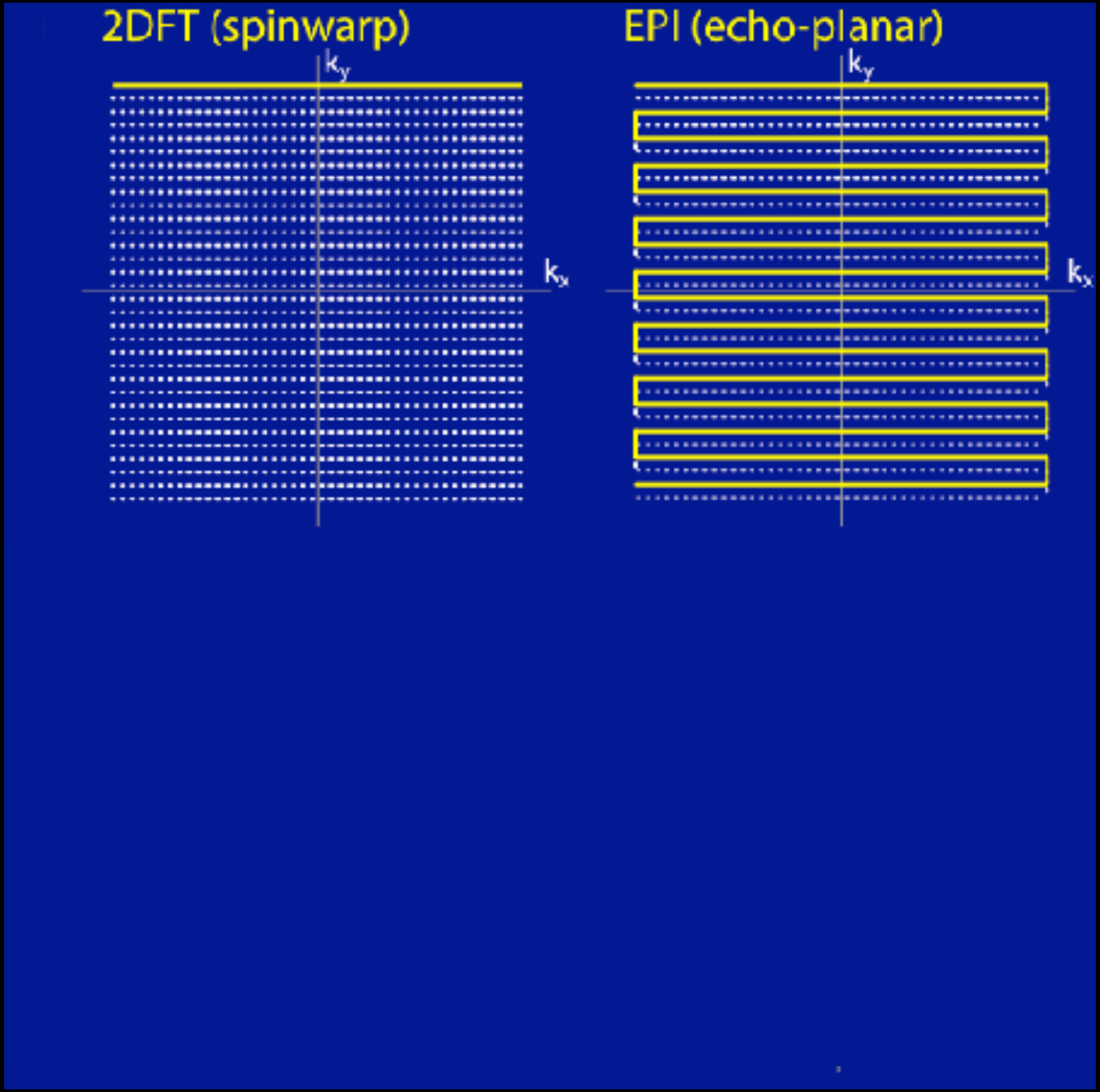
EPI trajectory

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

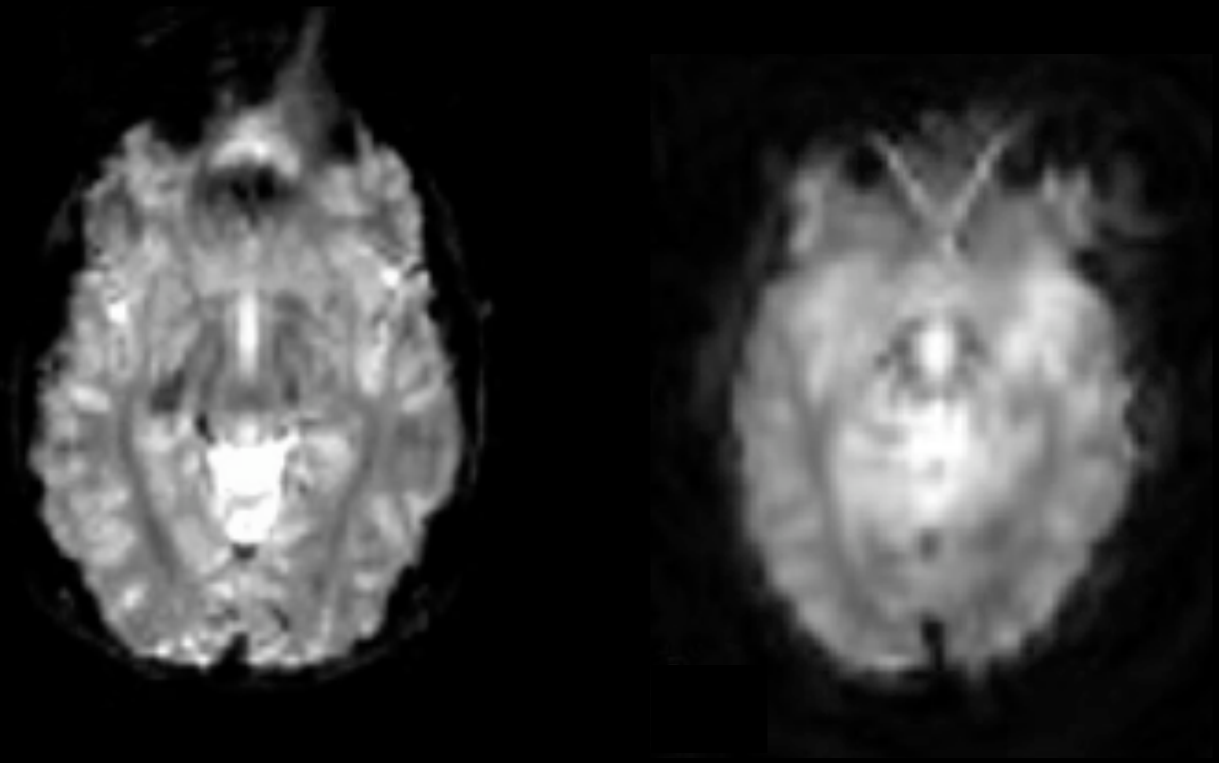
Enables “accelerated” acquisition with lower distortion

Current vendor coils enable 2-4x acceleration

Many possible trajectories through *k*-space…



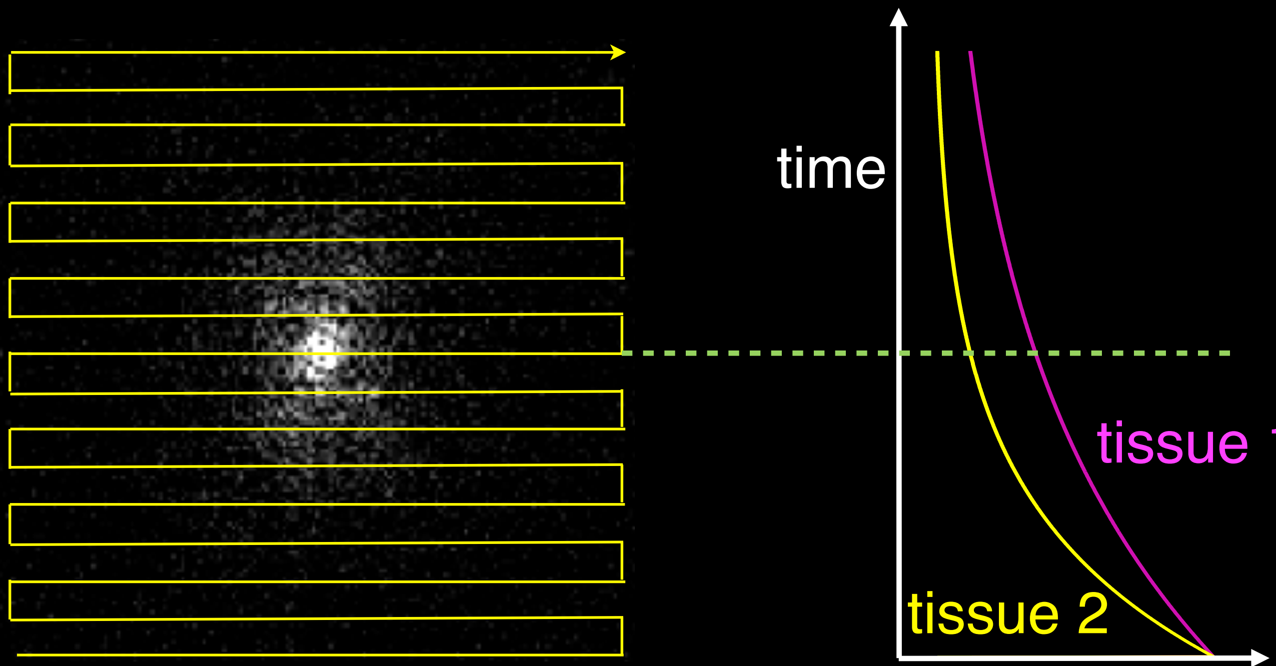
Cartesian vs Non-Cartesian: Image artifacts



EPI
distortion
& ghosting

Spiral
blurring
& streaking

Cartesian vs Non-Cartesian: Contrast



Single-shot acquisition takes 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)

MRI Physics

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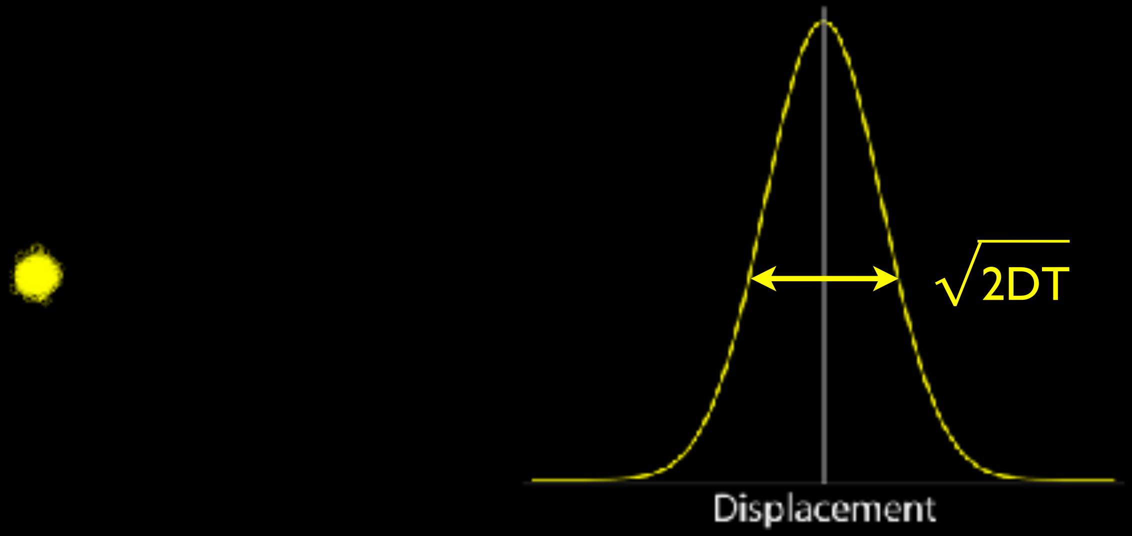
- Diffusion MRI
  - Diffusion weighting
  - Acquisition techniques
  - Tradeoffs & complications

What is diffusion?

What is diffusion?



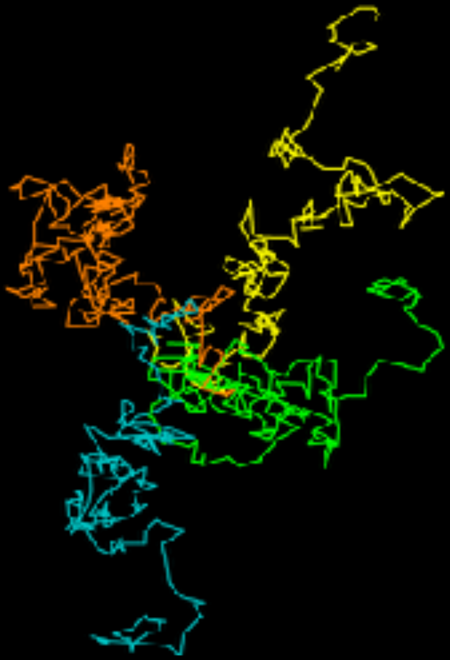
Random motion of particles due to thermal energy

Water molecules collide and experience net displacement

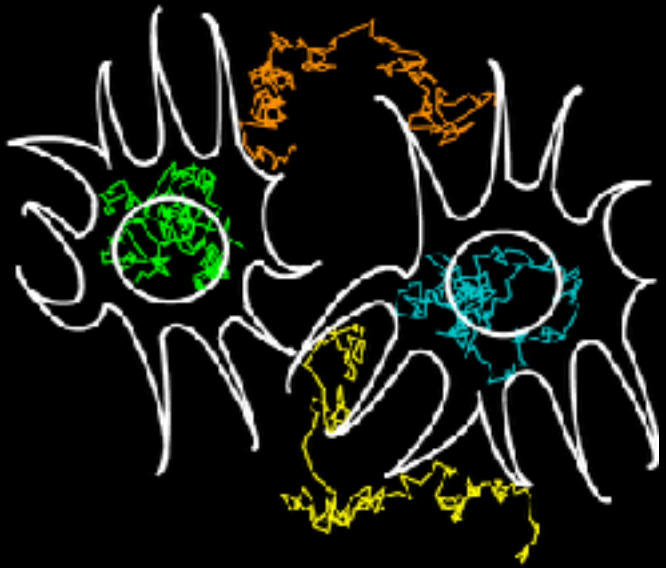
Displacement described by diffusion coefficient (D)

Normally, diffusion is isotropic (equal in all directions)

Why is diffusion interesting?



Unrestricted

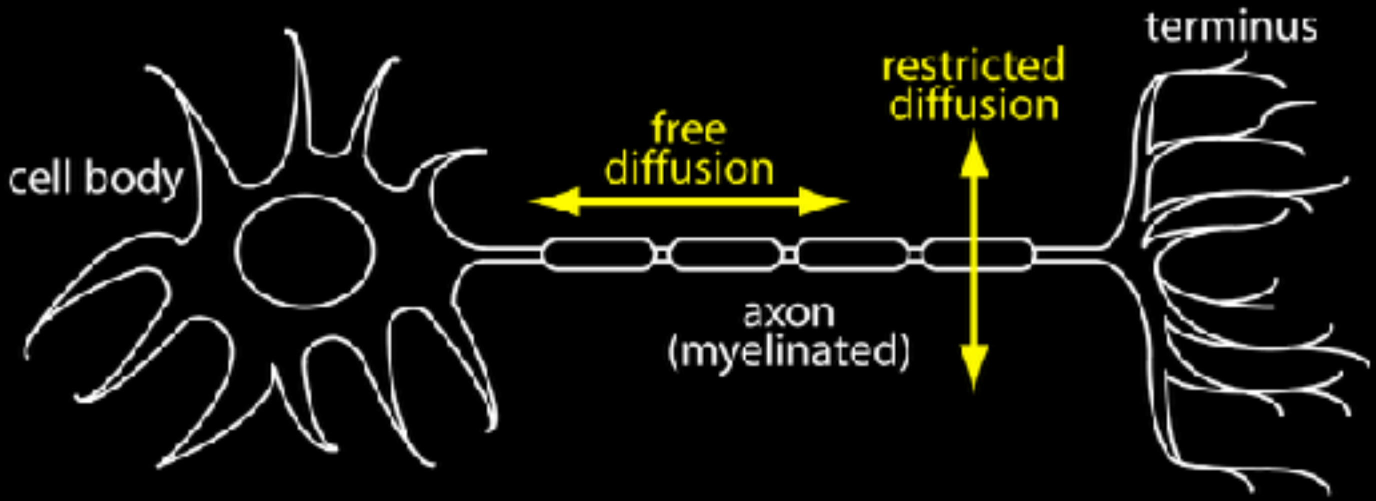


Tissue boundaries

Diffusion is restricted by tissue boundaries, membranes, etc

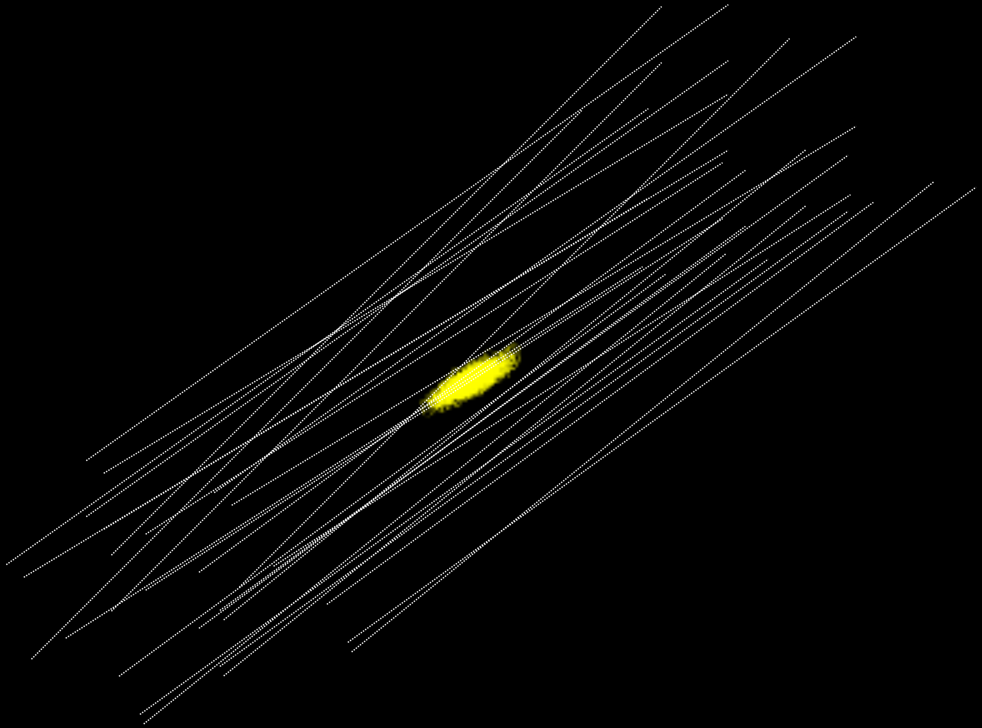
Marker for tissue microstructure (healthy and pathology)

Diffusion anisotropy in white matter



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

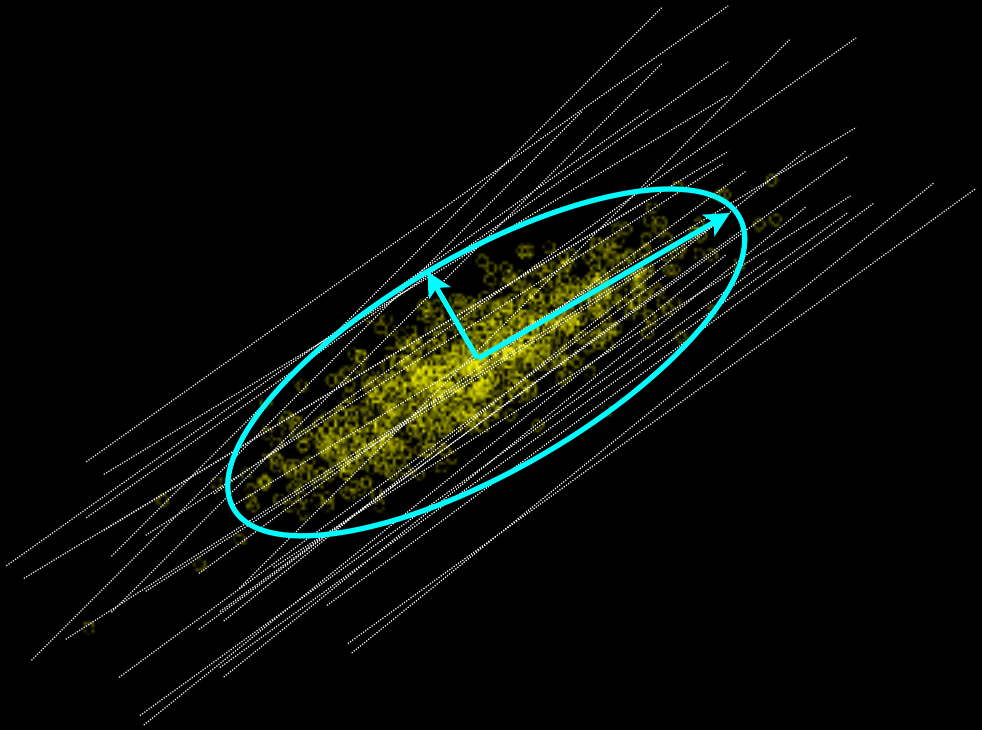
Diffusion anisotropy in white matter



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)

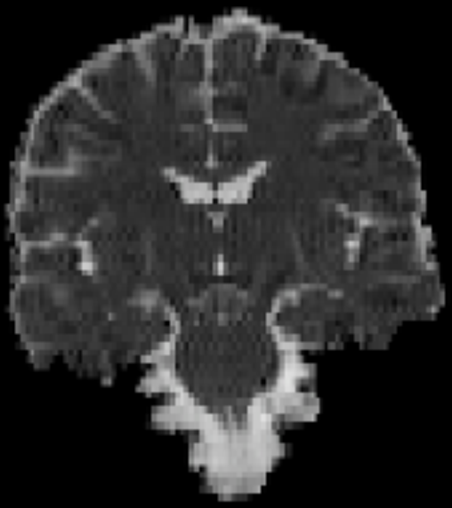
The diffusion tensor: Useful quantities

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

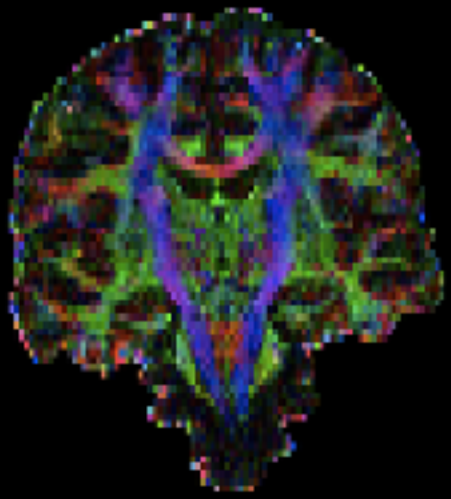
Mean diffusivity (MD): Info about tissue integrity

Diffusion tensor imaging



Mean diffusivity (MD)

Fractional anisotropy (FA)

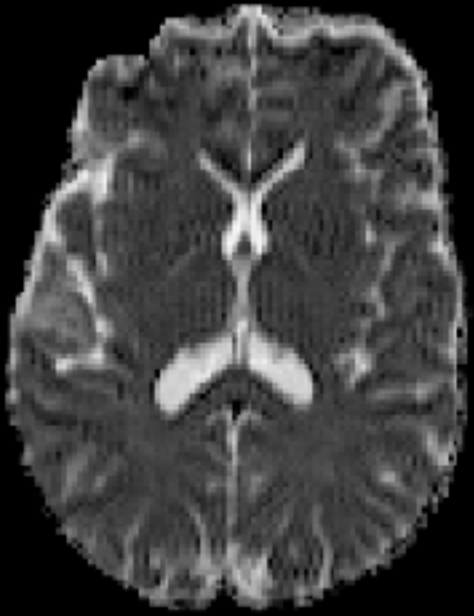


Principal diffusion direction (PDD)

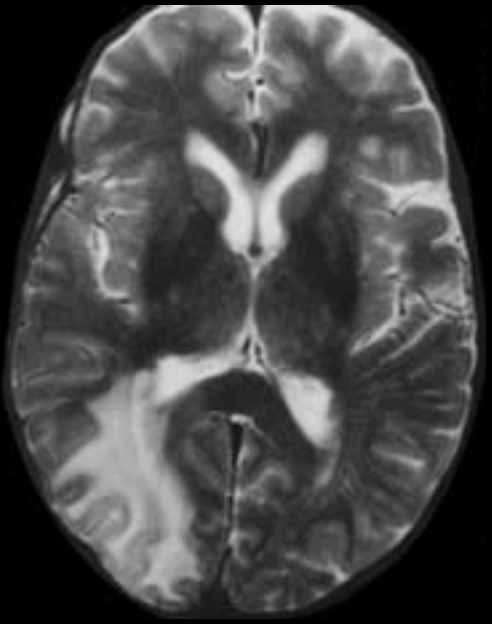
At each voxel, fit the diffusion tensor model

Can then calculate MD, FA, PDD from fitted parameters

Mean diffusivity (MD)



Control MD



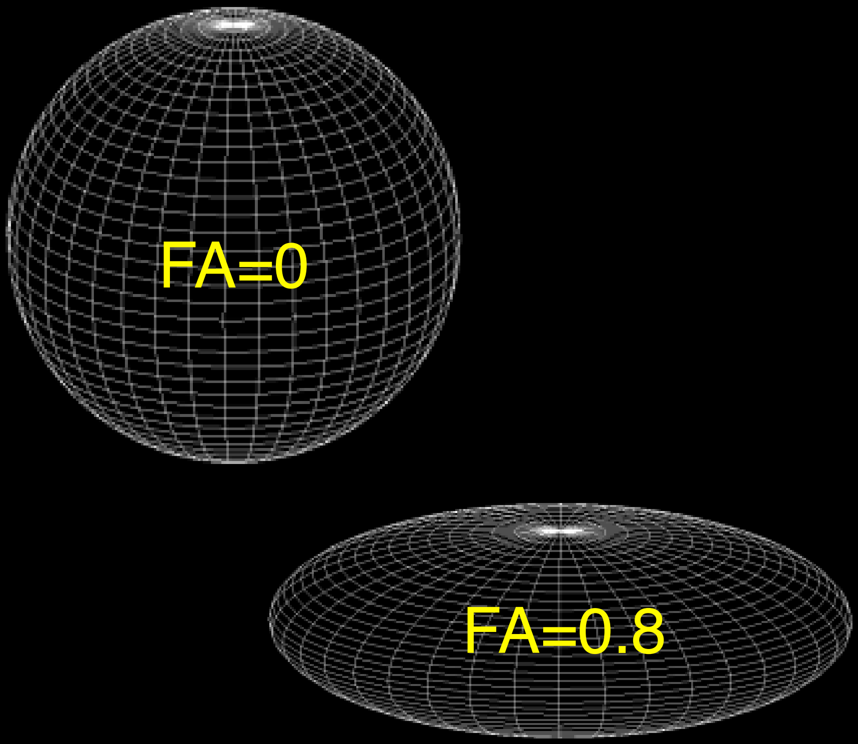
Acute Stroke

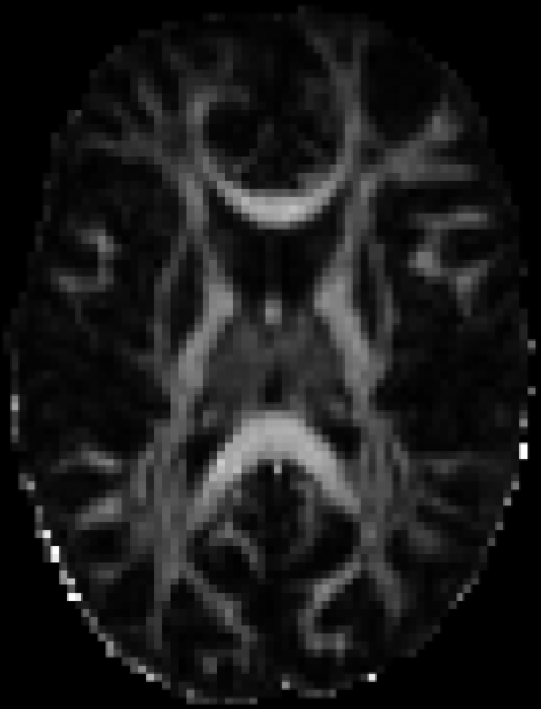
Mean diffusion coefficient across all directions

Correlate of tissue integrity (white and gray matter)

Example: MD is altered in acute and chronic stroke

Fractional Anisotropy (FA)



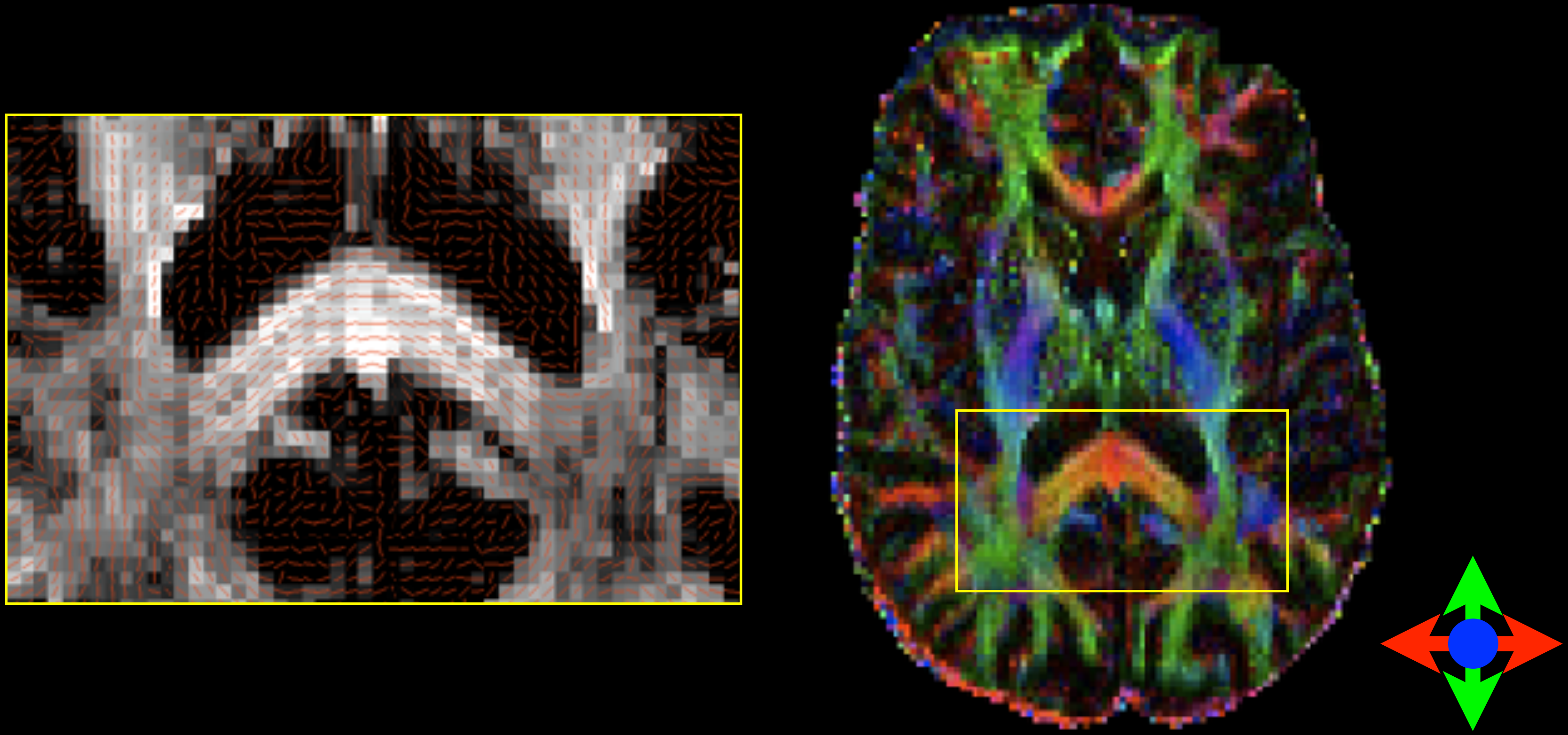


Inequality of diffusion coefficient across different directions

High in regions where diffusion is most directional

Relates to integrity of white matter fibre bundles

Principal diffusion direction (PDD)



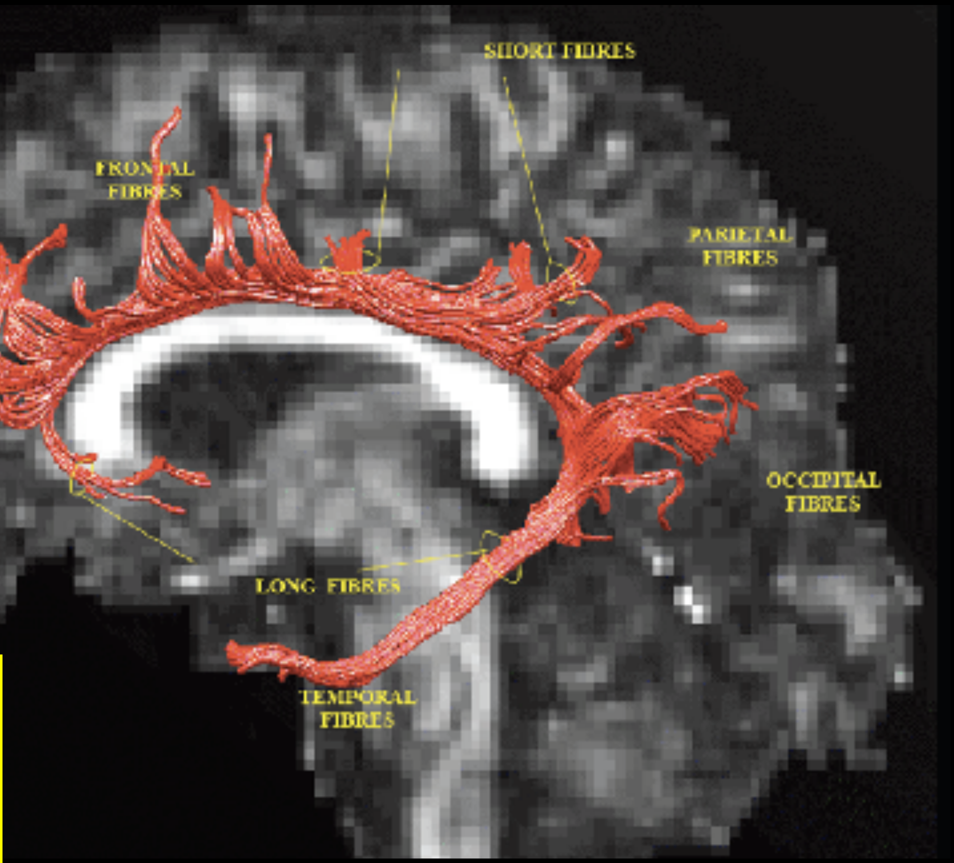
Direction along which greatest diffusion occurs

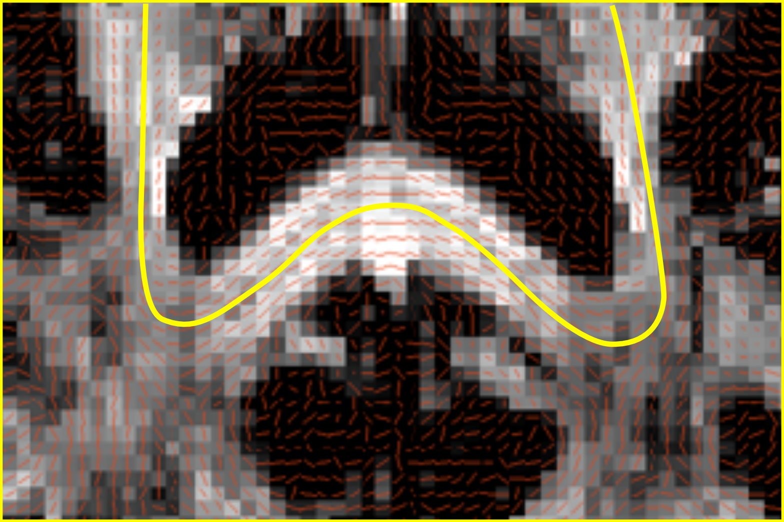
Relates to direction of fibre orientations

Typically, will use this as starting point for fibre tracking

Diffusion tractography

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



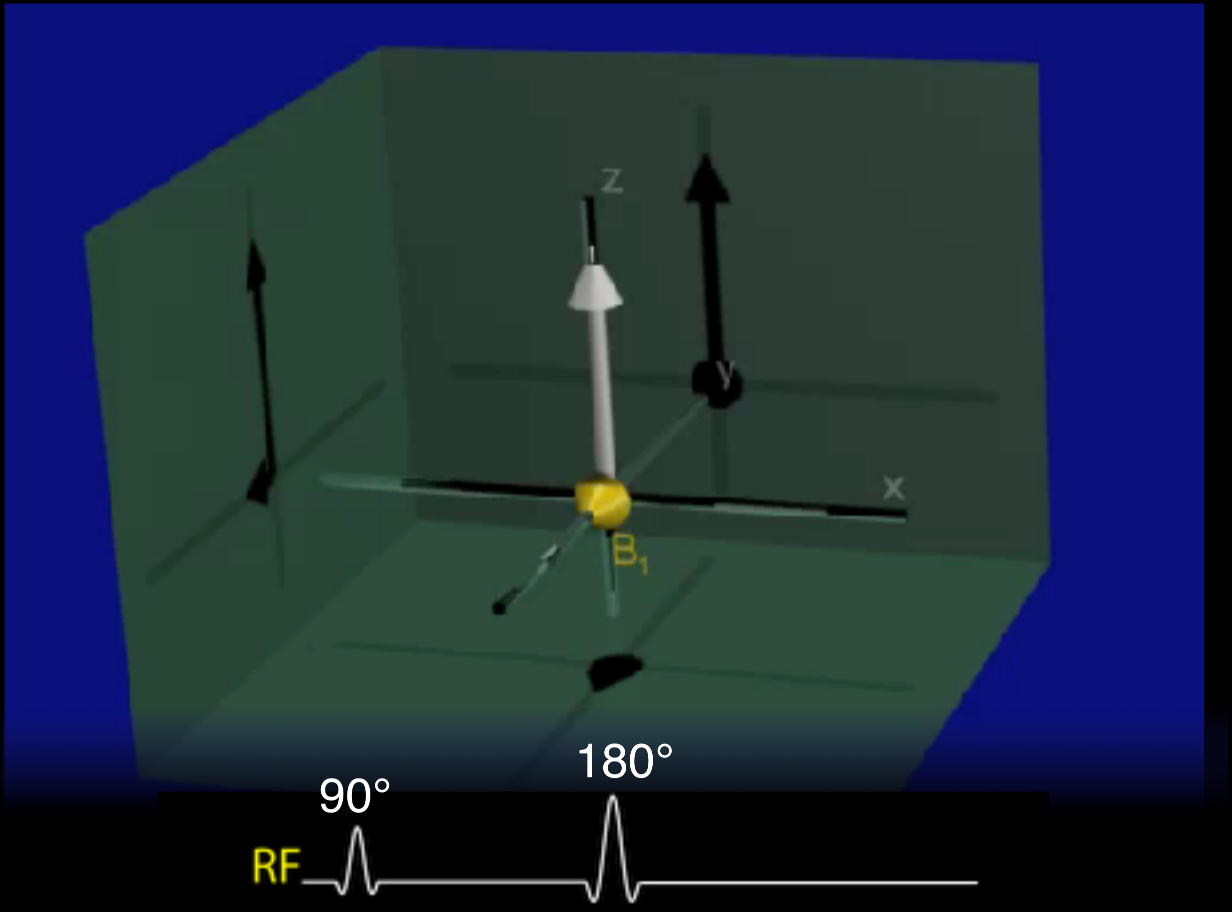


Jones et al

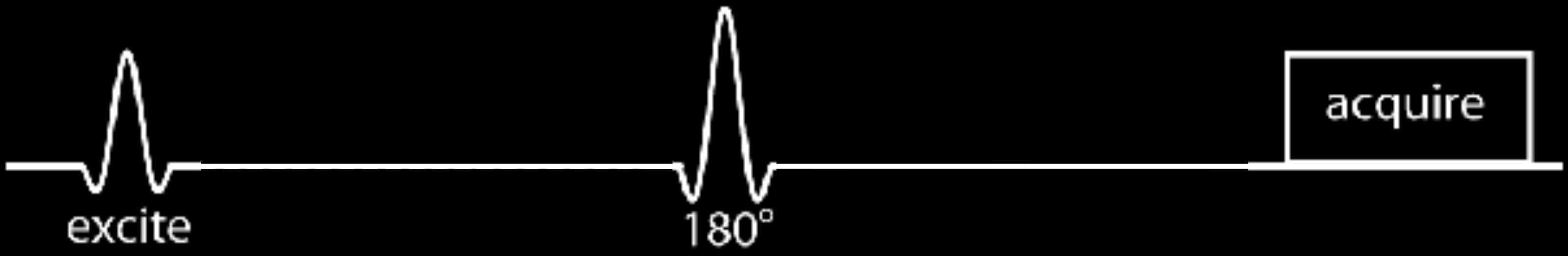
MRI Physics

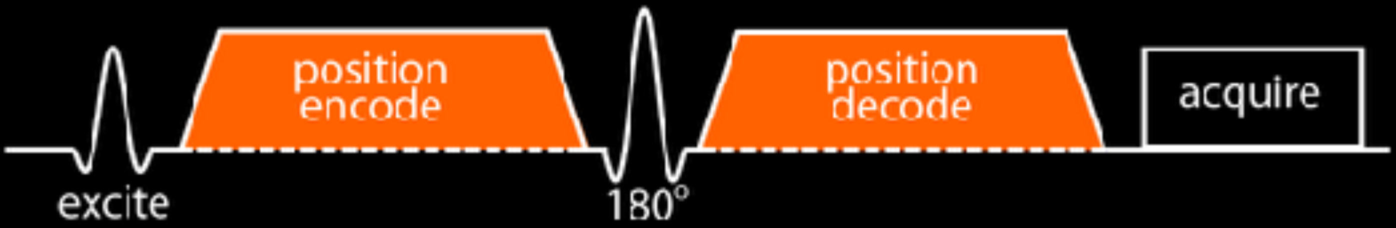
- Spin vs. gradient echo
- Fast imaging & artefacts
- Diffusion MRI
  - Diffusion weighting
  - Acquisition techniques
  - Tradeoffs & complications

Spin Echo

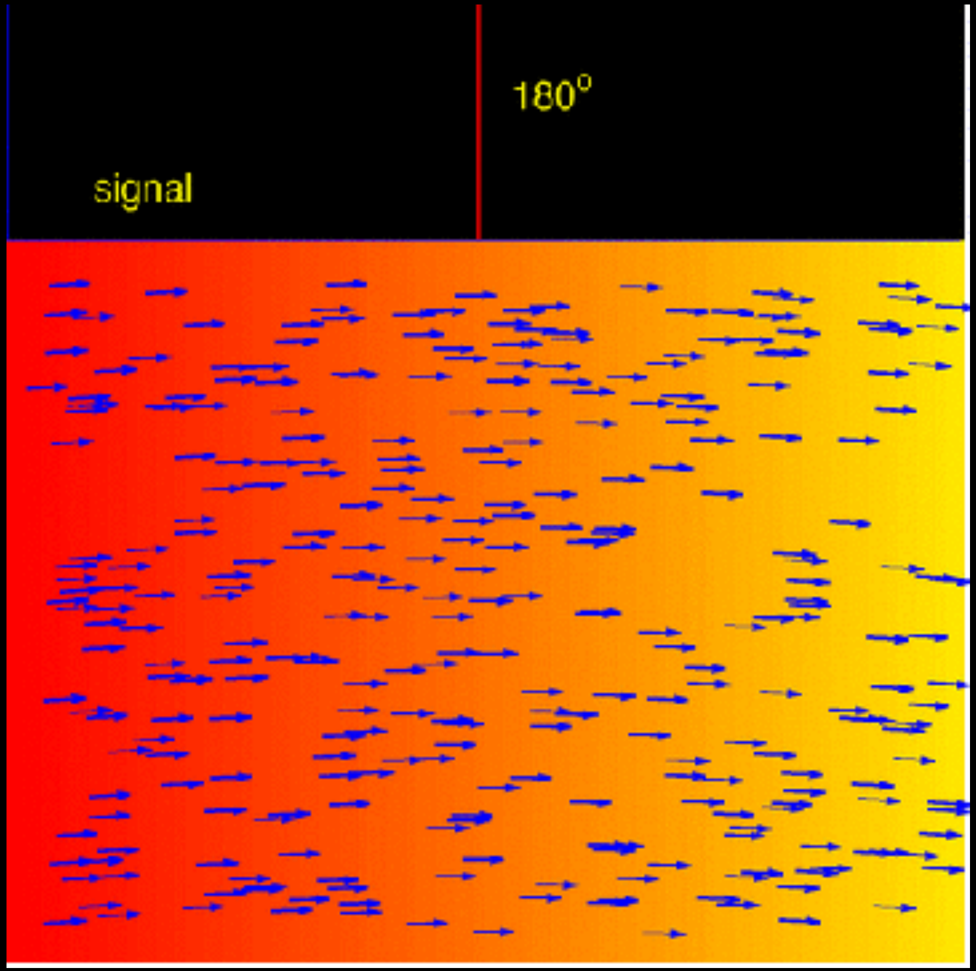


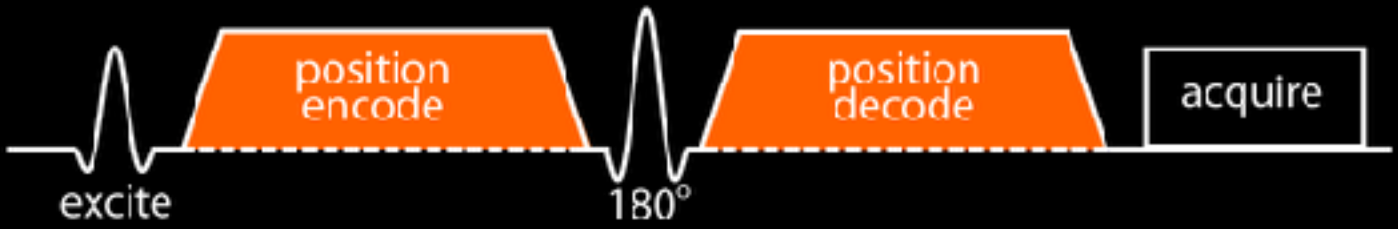
Diffusion-weighted spin echo

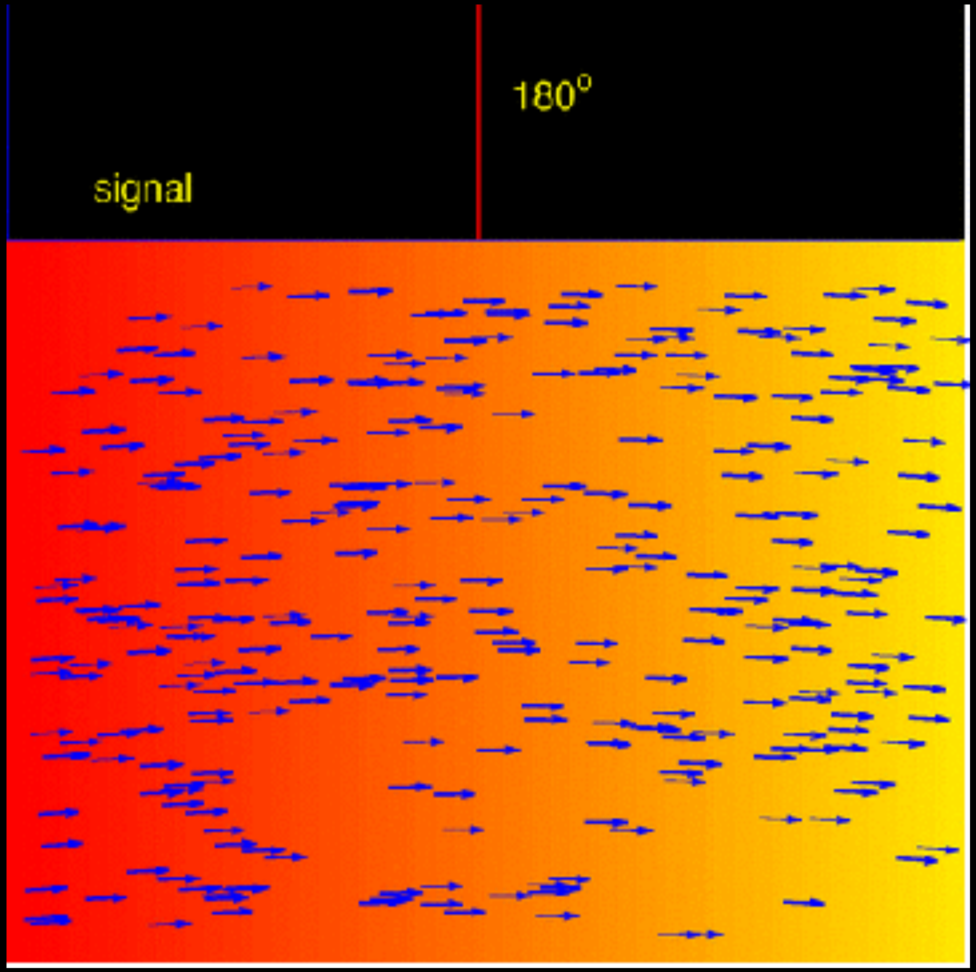




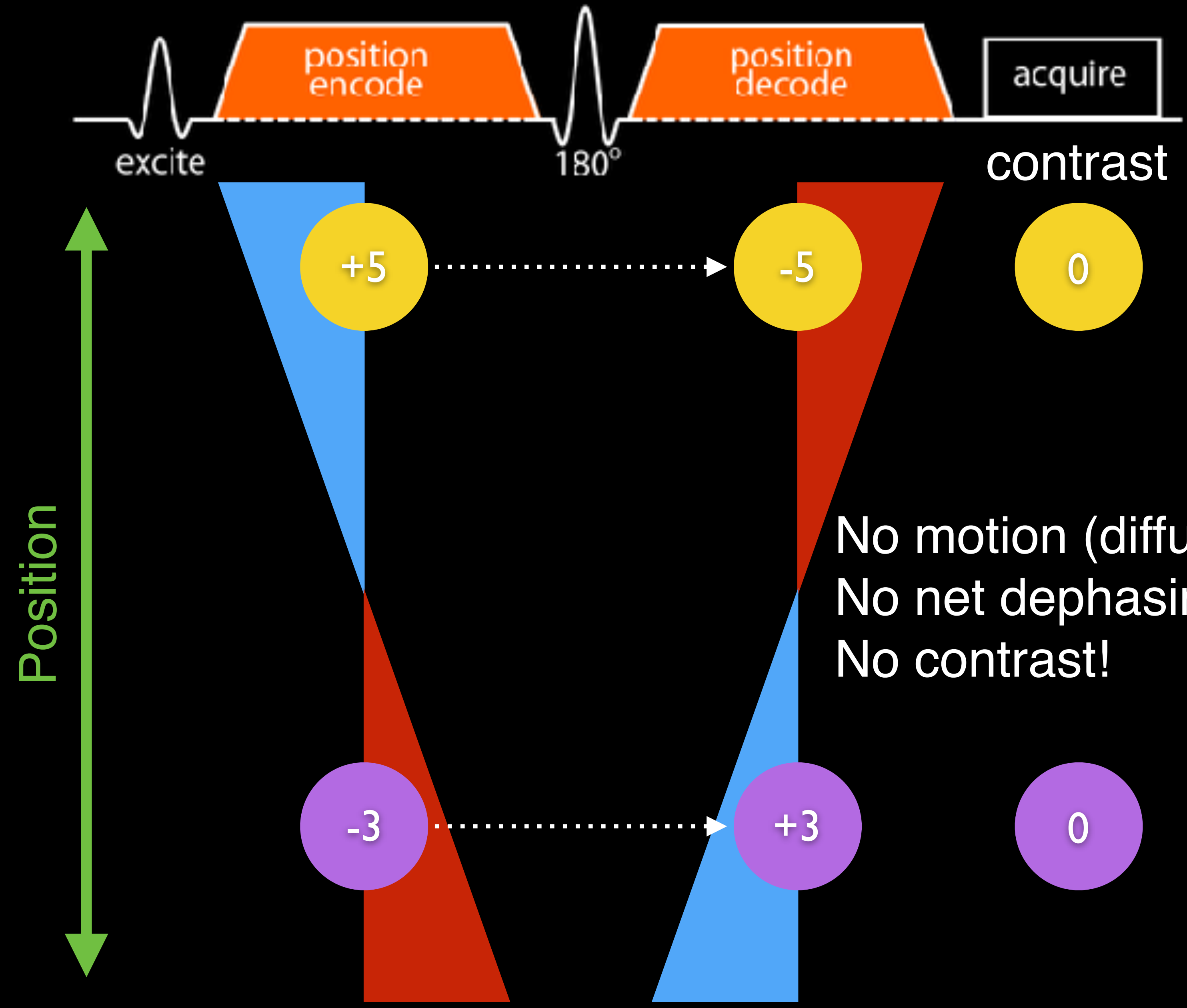
Case 1:
No diffusion





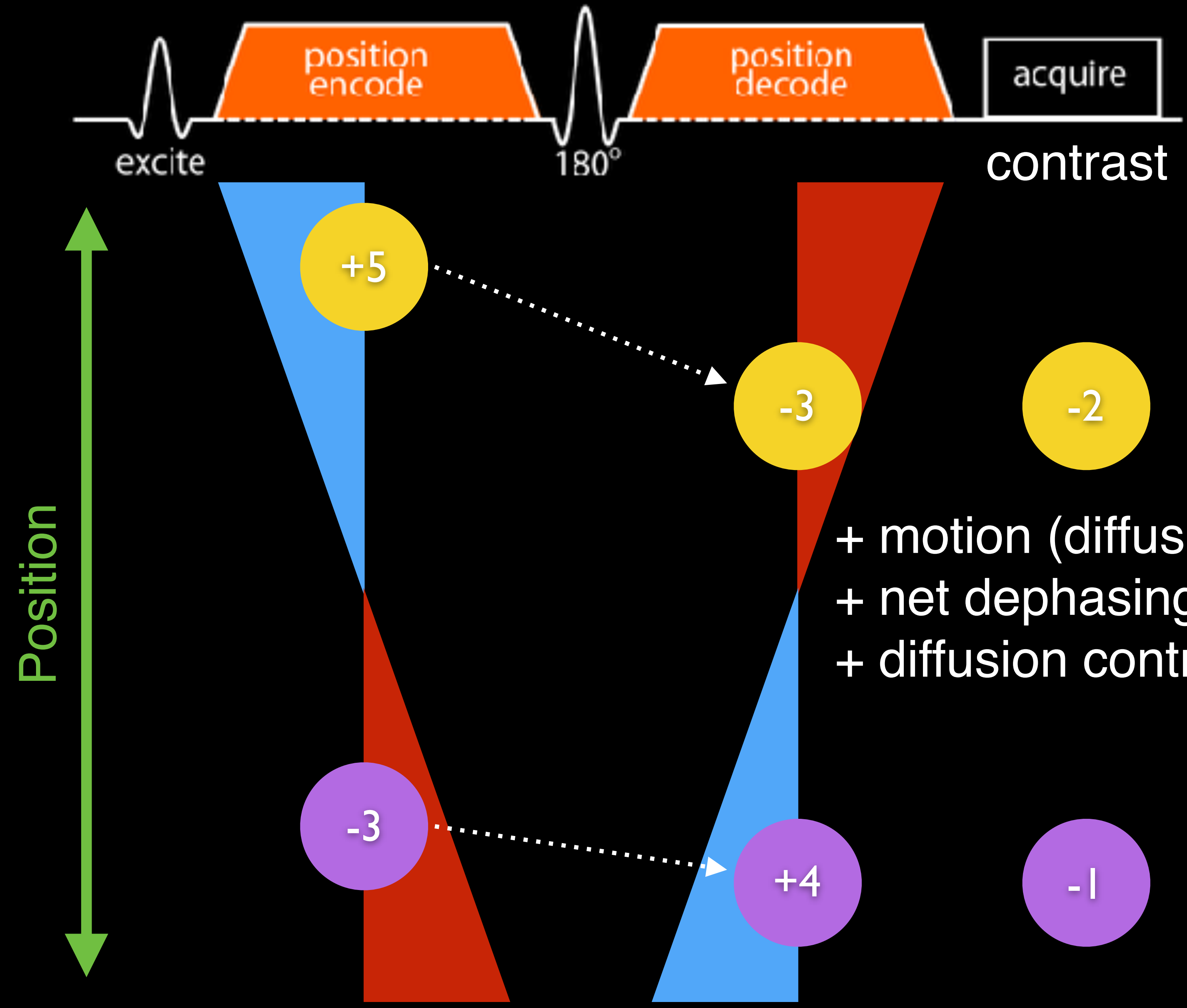


Case 2:
Diffusion



No motion (diffusion)
No net dephasing
No contrast!

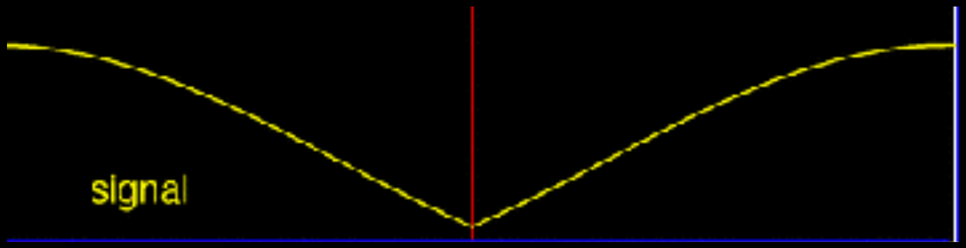
contrast



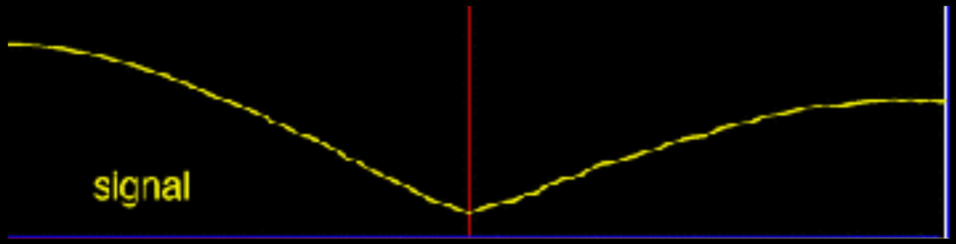
+ motion (diffusion)
+ net dephasing
+ diffusion contrast!

Diffusion contrast

No diffusion



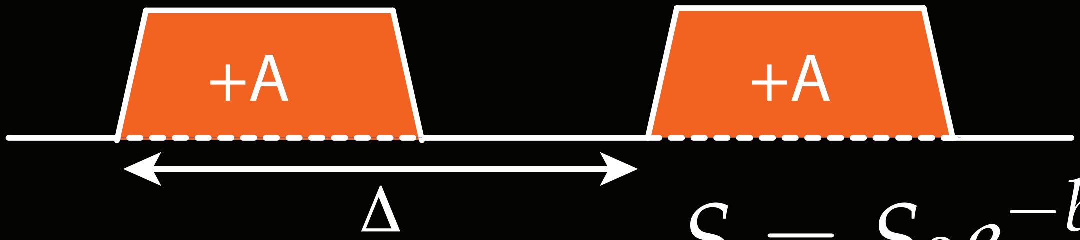
Diffusion



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

Greater Diffusion = Less Signal

Diffusion contrast



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

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

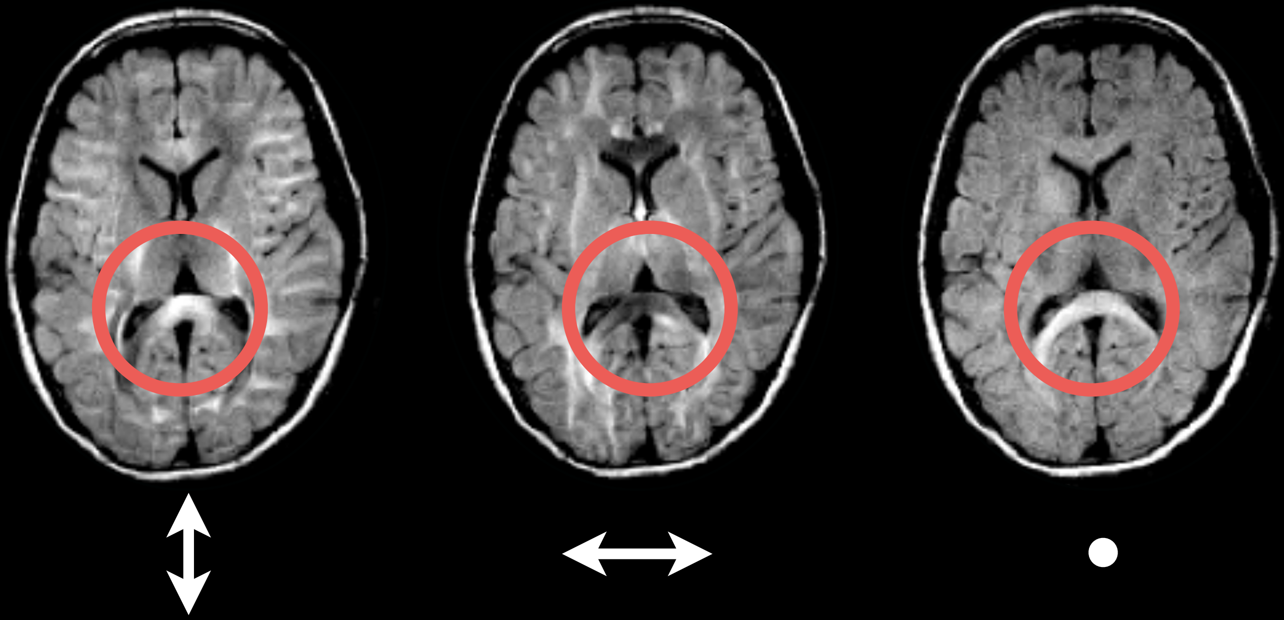
diffusion coefficient

diffusion weighting

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

Greater Diffusion = Less Signal

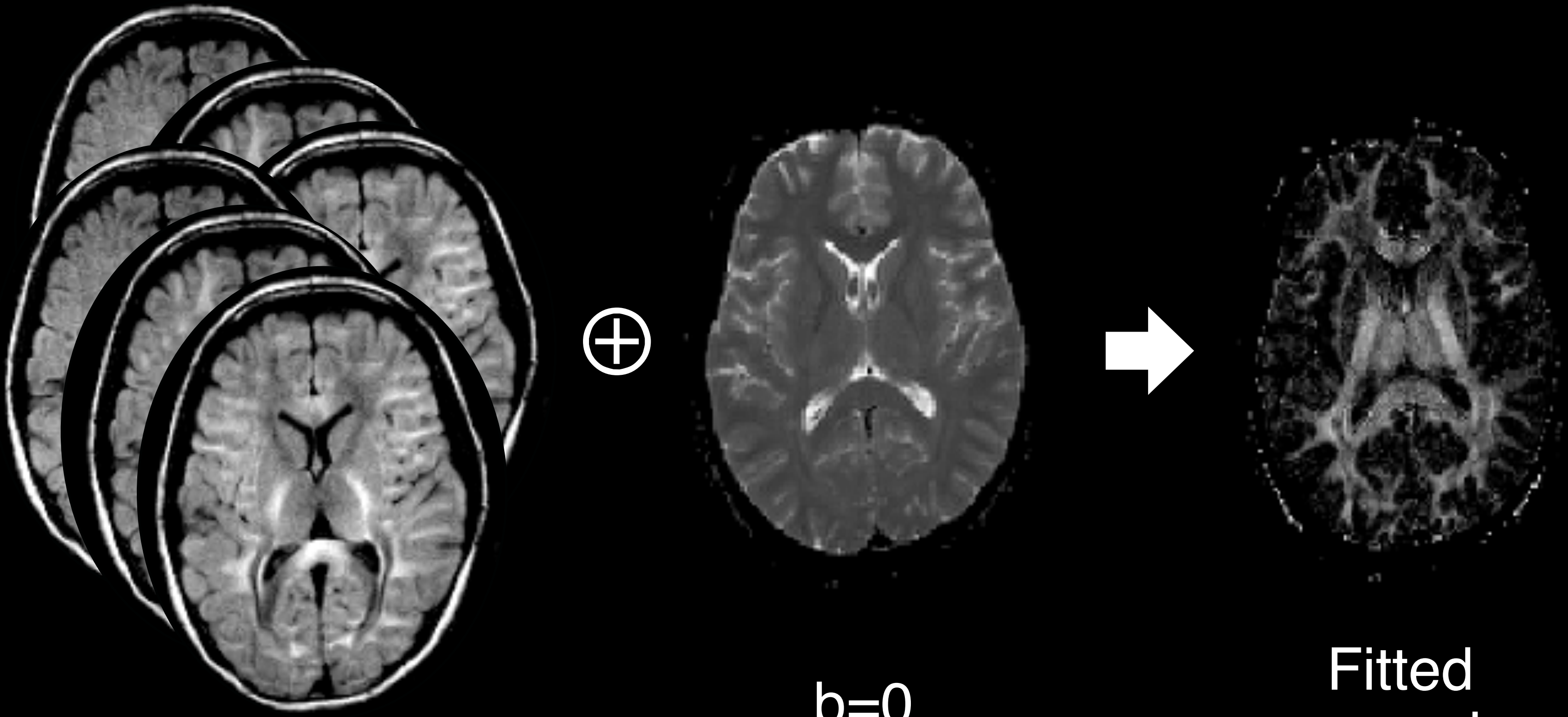
Diffusion contrast



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

Greater Diffusion = Less Signal

Diffusion-weighted imaging



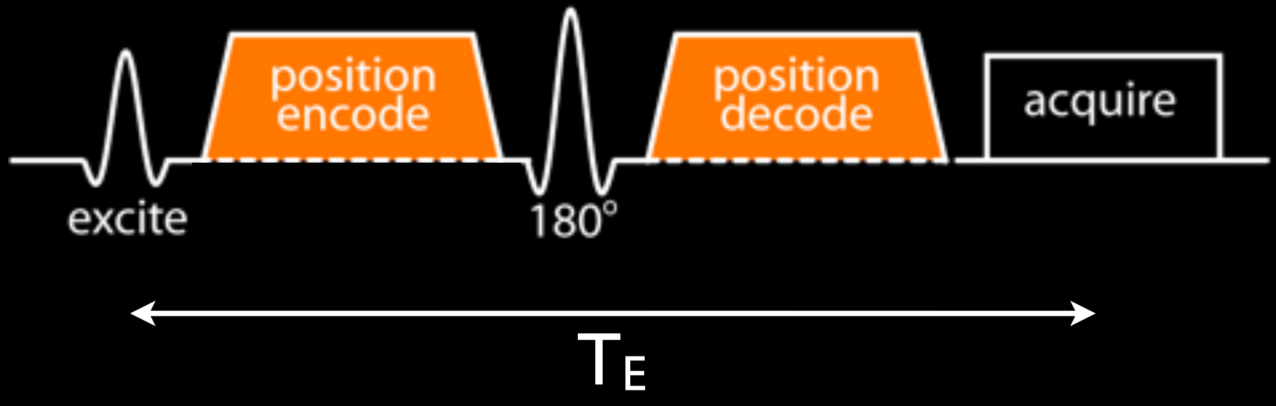
Directional encoding

⊕

b=0

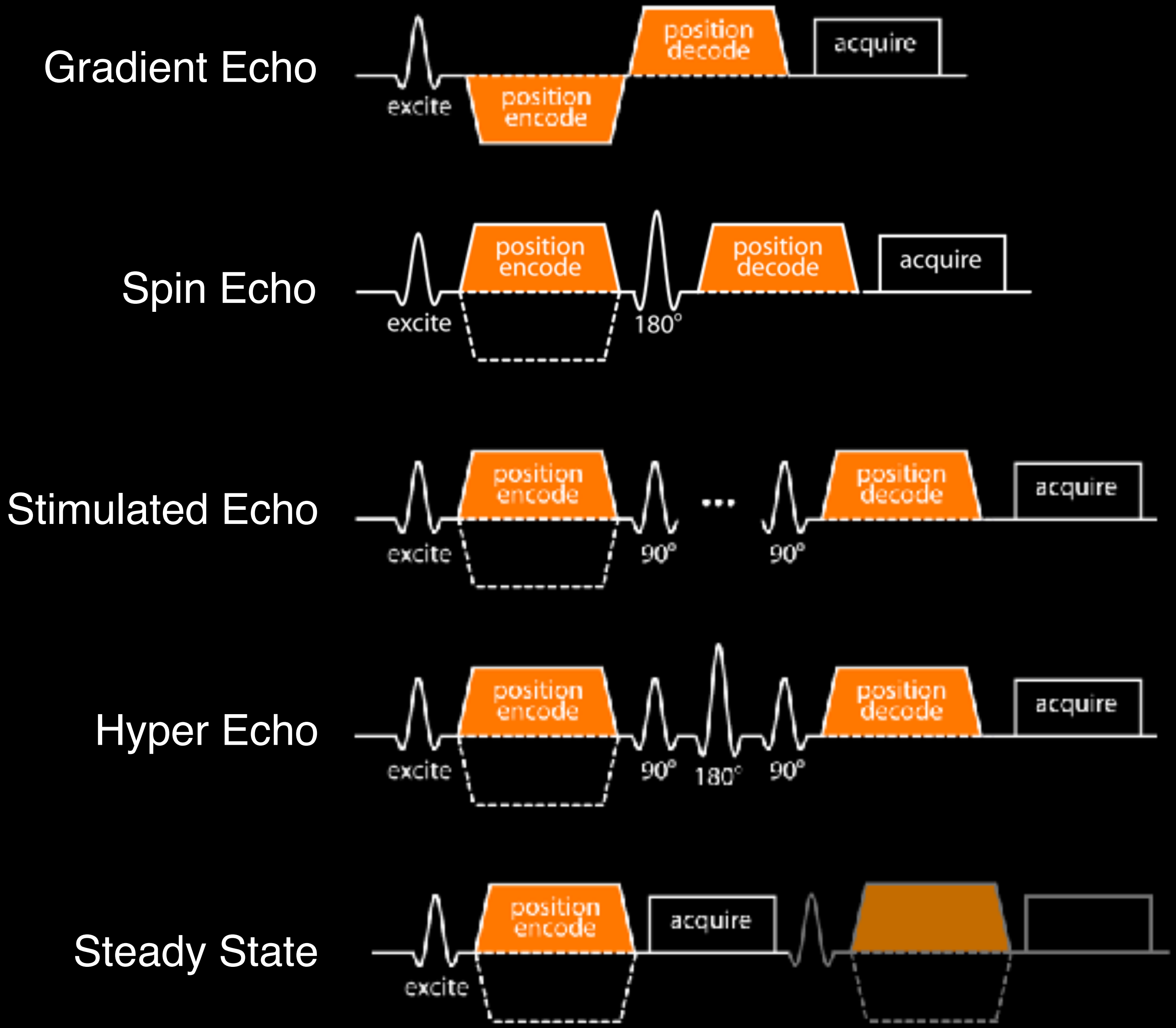
Fitted parameter maps

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

Spin Echo

Stimulated Echo

Hyper Echo

Steady State

MRI Physics

- Spin vs. gradient echo
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- Diffusion MRI
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  - Acquisition techniques
  - Tradeoffs & complications

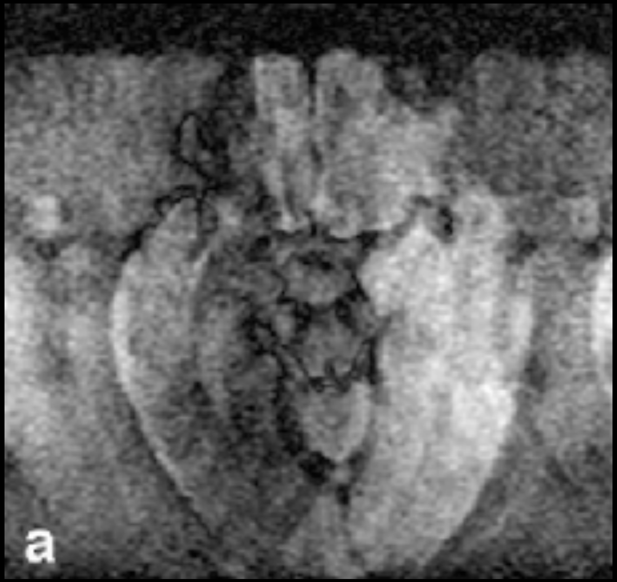
Acquiring the image

Theoretically, any acquisition can be used

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

In practice, motion sensitivity dictates what is possible

Motion in DWI



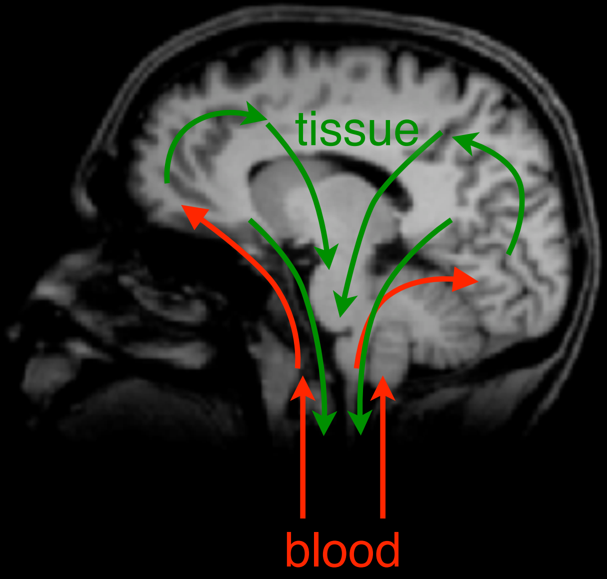
Linescan diffusion image

Diffusion gradients encode tiny displacement

Subject motion is also accidentally encoded

Image artefacts if we try to combine data from multiple excitations (different motion)

Can motion be avoided?



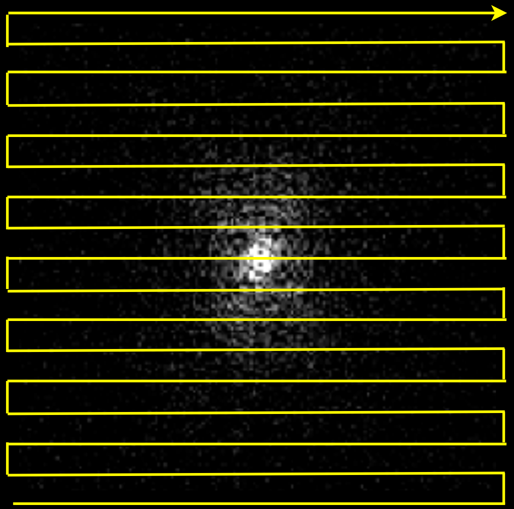
Subject restraints can reduce bulk motion, but...

...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

MRI Physics

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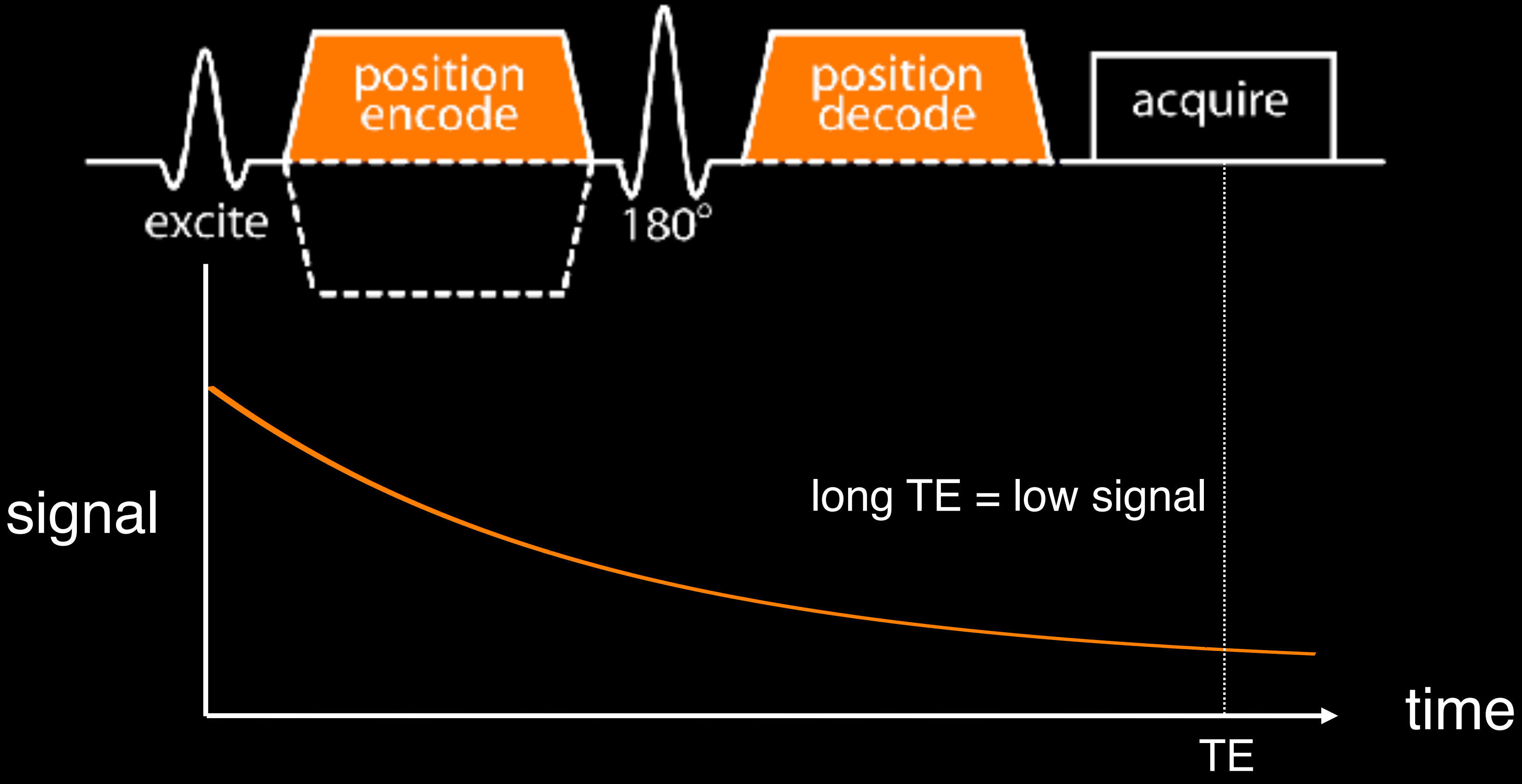
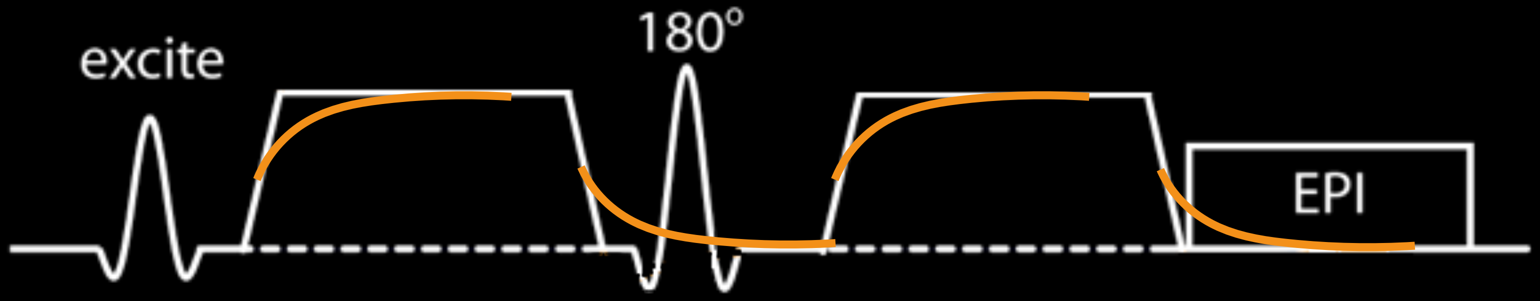
Tradeoff: diffusion weighting vs TE



Eddy Currents

Eddy currents "resist" gradient field changes



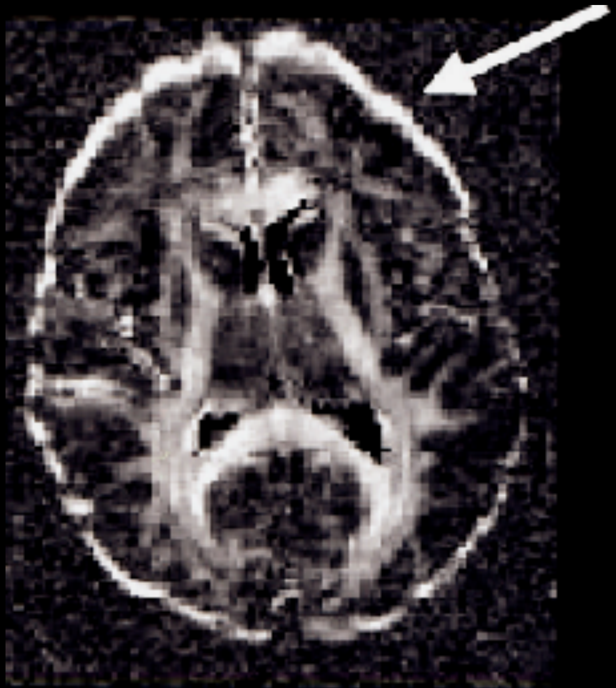
effective gradient fields

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

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

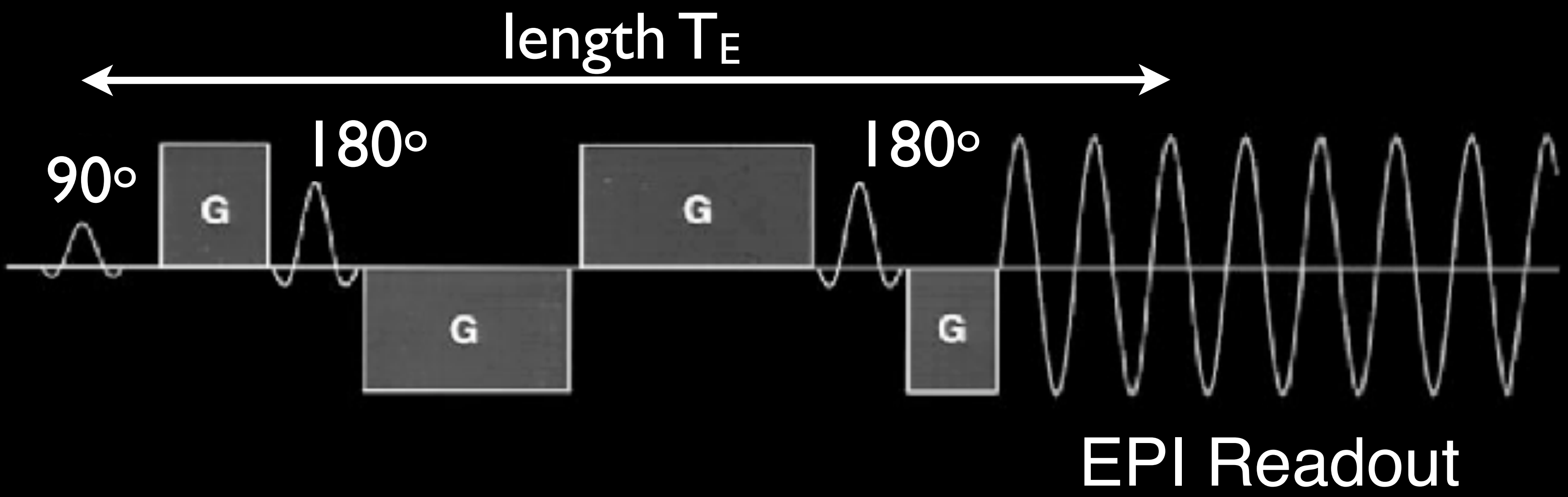
Eddy Currents

Diffusion-weighted
directions

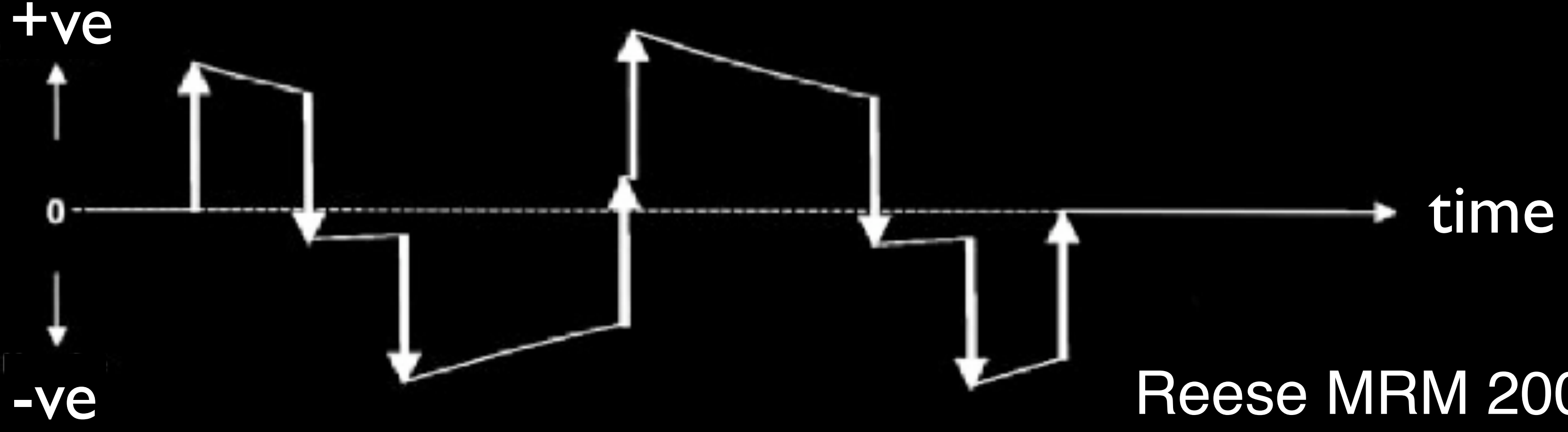


Fractional Anisotropy
("variance")

Twice Refocused Spin Echo



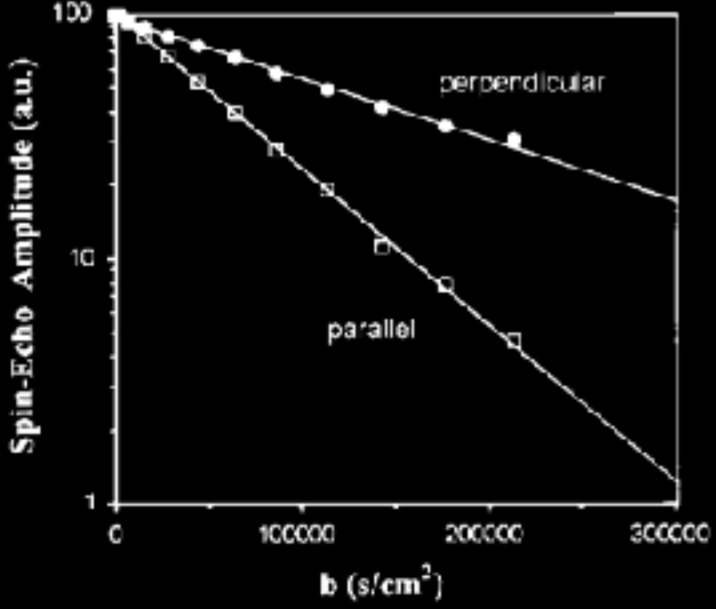
Eddy Currents



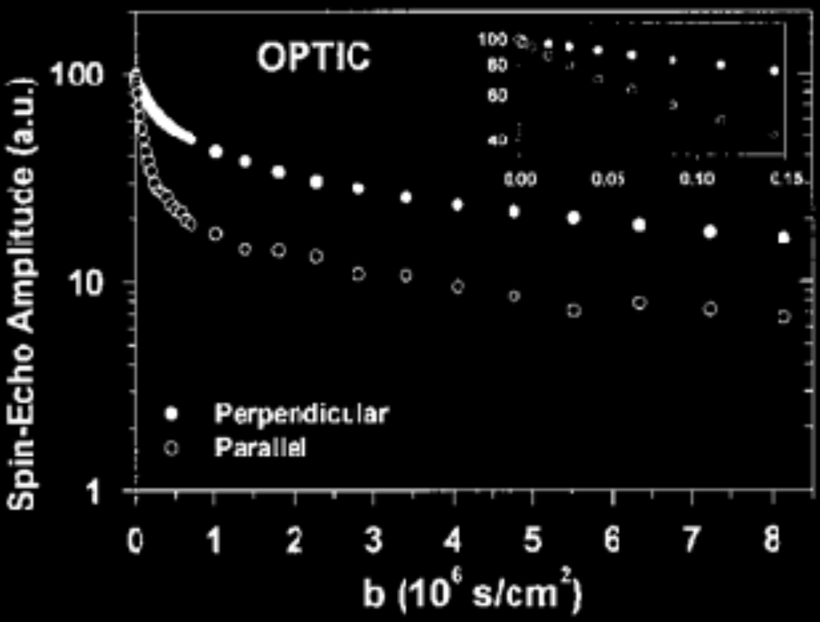
Reese MRM 2003

Signal dependence: b-value

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



Theory



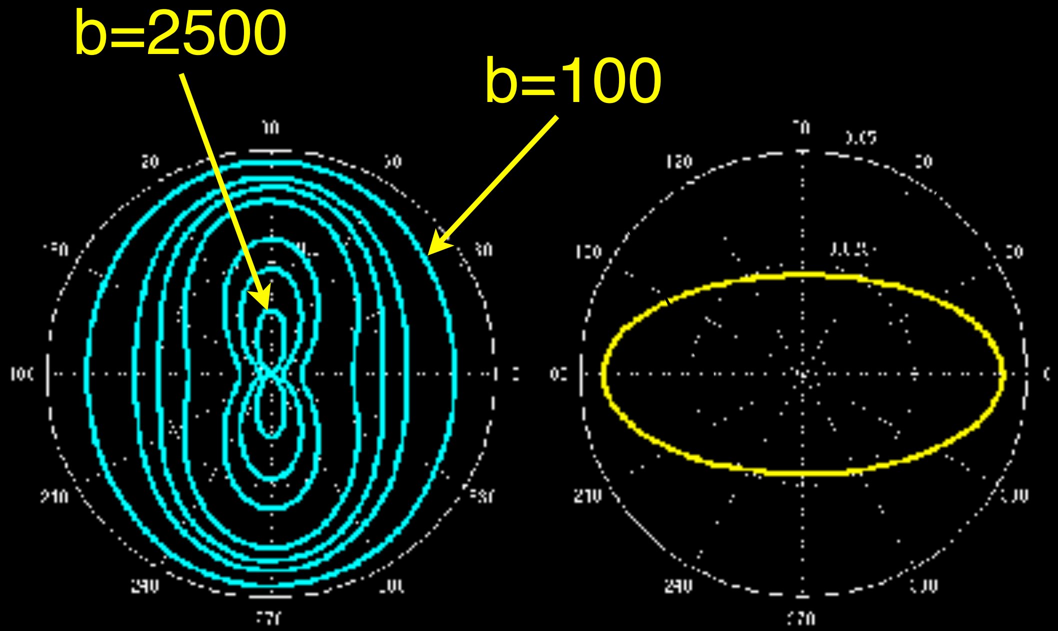
Measurement

Signal is not a mono-exponential decay with b-value!

“Apparent diffusion coefficient” (ADC)

Beaulieu 2002

Signal dependence: Orientation



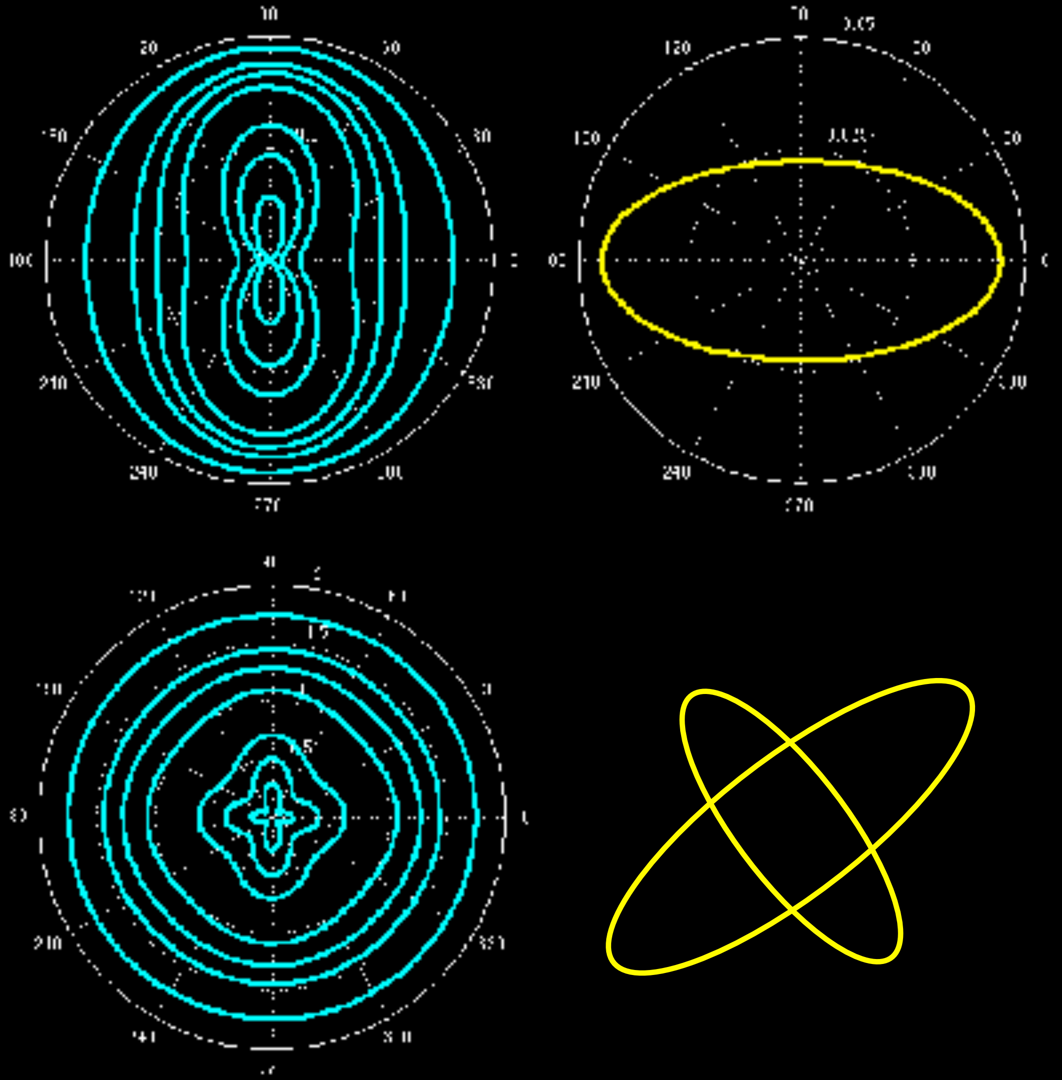
b=2500

b=100

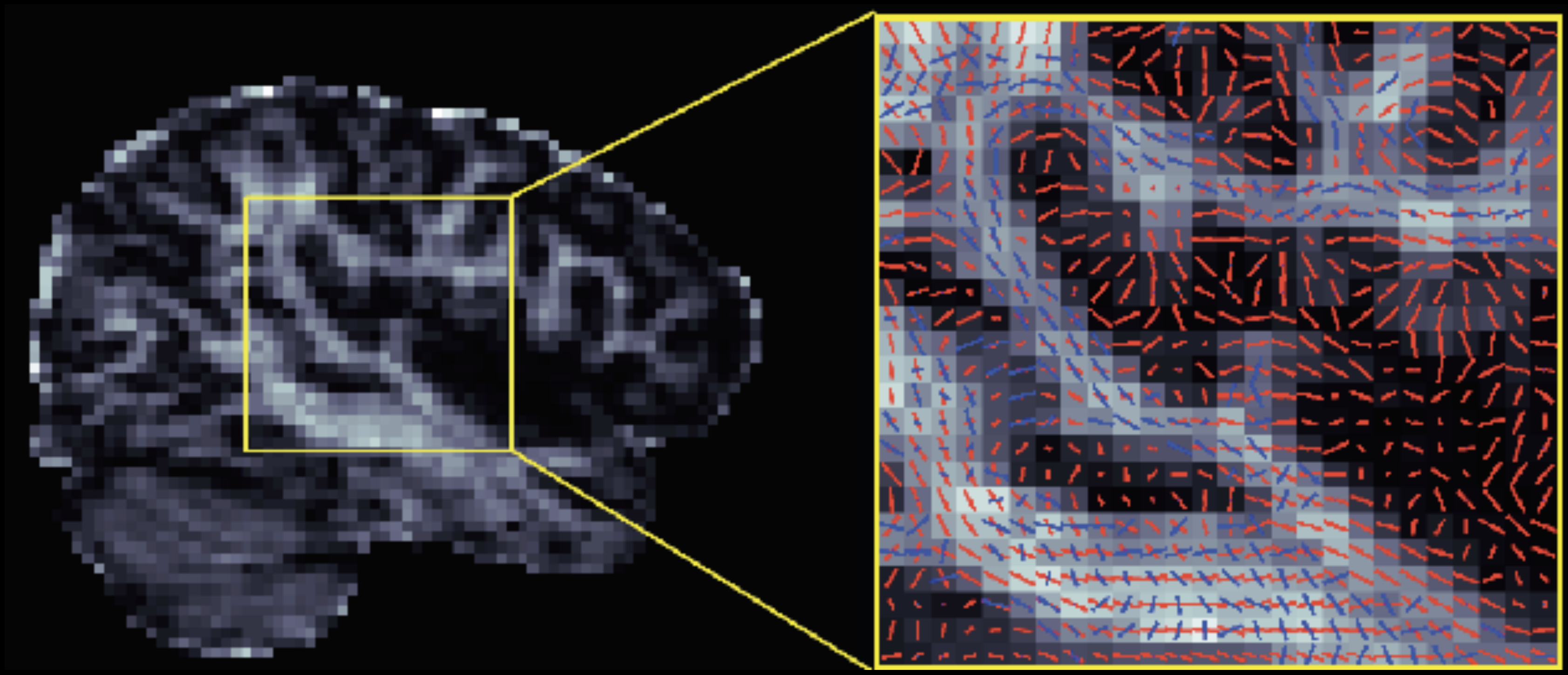
Signal

Displacement Ellipsoid

More complicated models: Crossing fiber populations



More complicated models: Crossing fiber populations



Thank you for your attention!

Questions:

mark.chiew@ndcn.ox.ac.uk