Introduction to MRI Acquisition

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FMRIB Physics Group

FSL Course, Bristol, September 2012

What are we trying to achieve?

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- **Informed decision making:**
  - Protocols need to be tailored to the problem (Motion? Effect size? Area of activation?)
  - Learning some physics will make this less daunting

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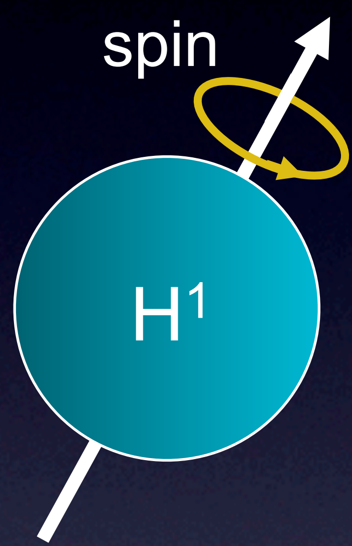
- **Informed decision making:**
  - Protocols need to be tailored to the problem (Motion? Effect size? Area of activation?)
  - Learning some physics will make this less daunting
- **A common language**:
  - Explain your needs to physicists/radiographers
  - Understand their response
  - There is a LOT of jargon, but you can master it!

MRI Physics

- Today:
  - Basics of (nuclear) Magnetic Resonance
  - Image Formation
  - Functional MRI
    - The BOLD effect
    - Acquisition and artefacts

Nuclear Spin



- Some elementary particles (eg Hydrogen) exhibit "spin"
- Appear to rotate about an axis
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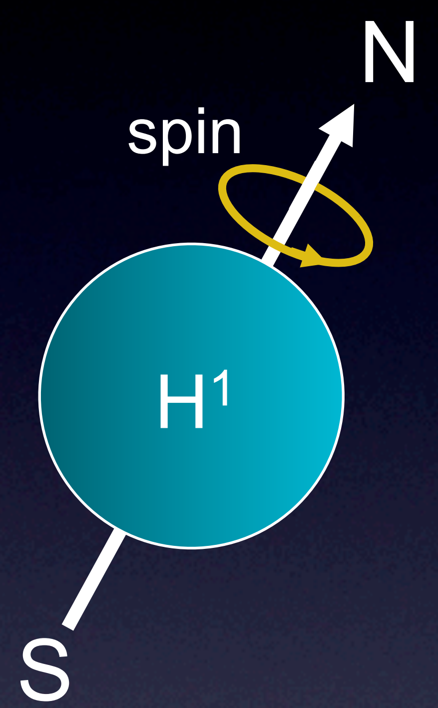

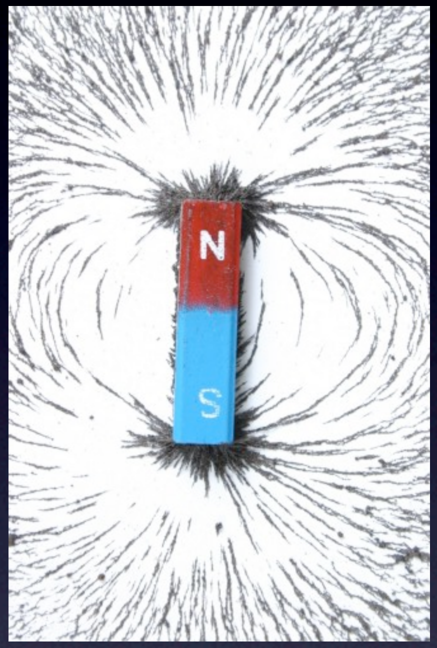

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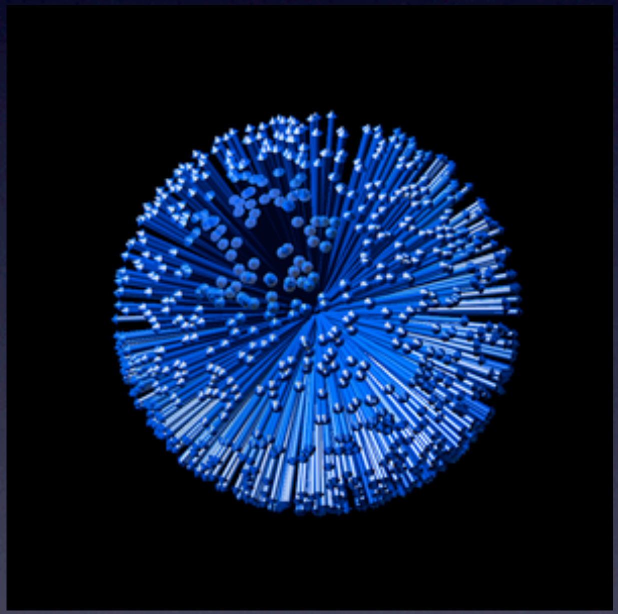
Magnetic Fields (B)

No Field



Magnetic Fields (B)

- What happens when you place a bunch of nuclei with spin into a magnetic field?

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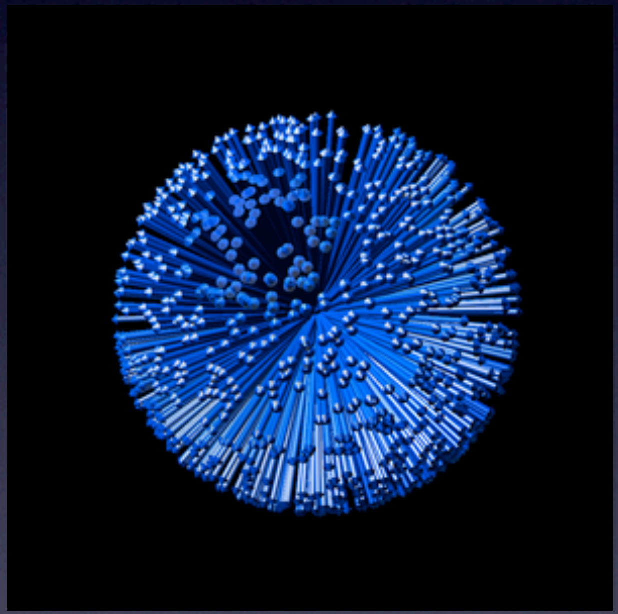

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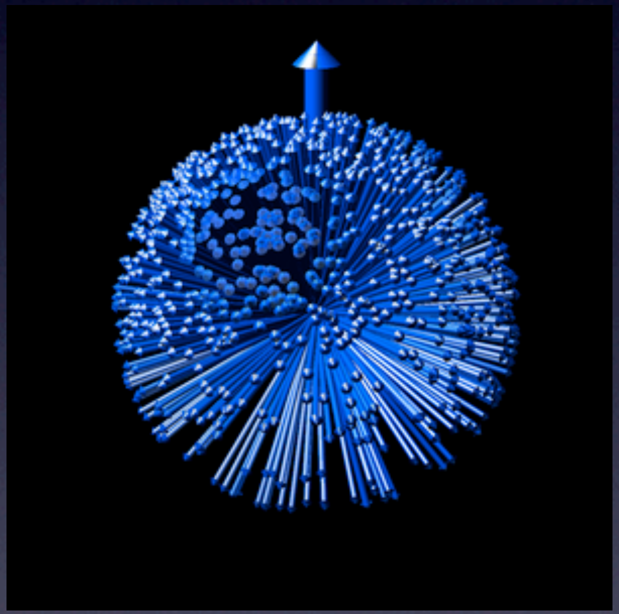
Main B Field



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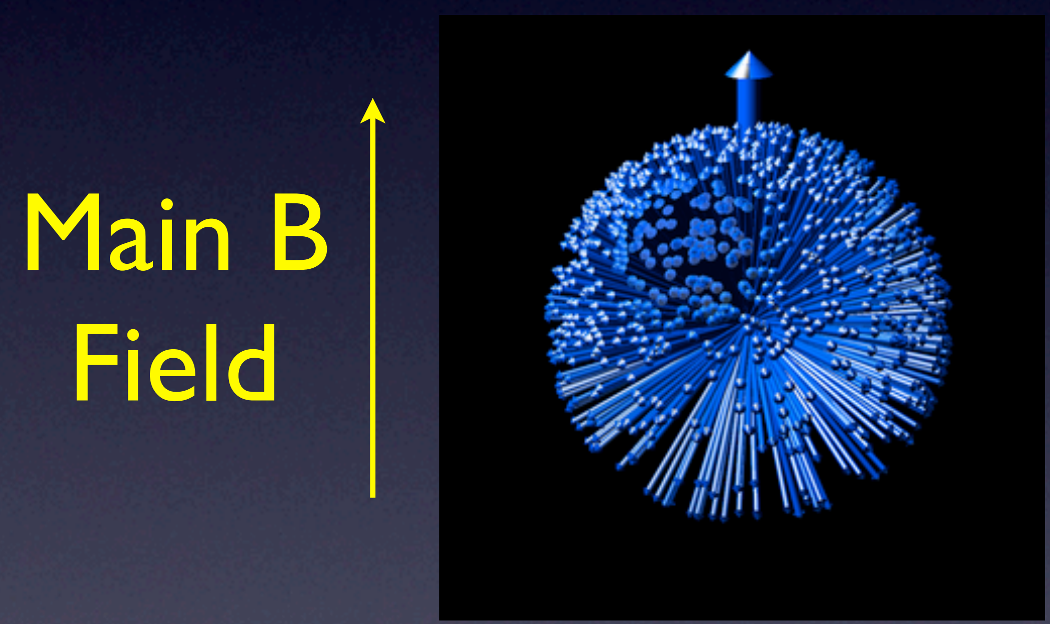


- *On average*, they'll tend to align with the field (a net magnetic moment)

Precession

- A force (Gravity or B Field) tries to tilt the spinning object
- But because of spin, the axis precesses instead of tilting

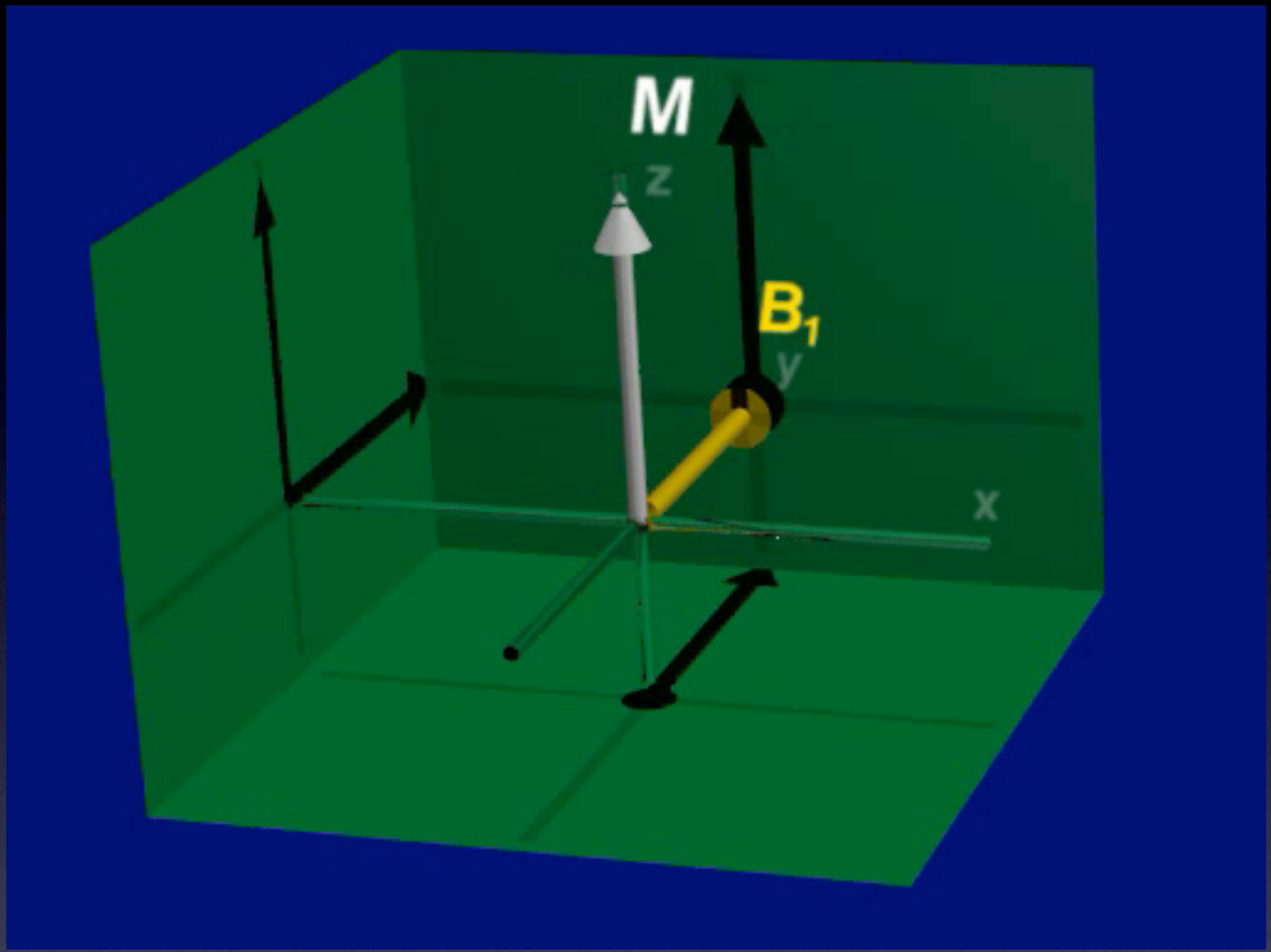
Excitation

courtesy of William Overall

$$\omega_0 = \gamma B_0$$

- Energy pulse tips magnetisation away from B_0
- ...if energy rotates at resonant frequency: RF pulse!

Excitation



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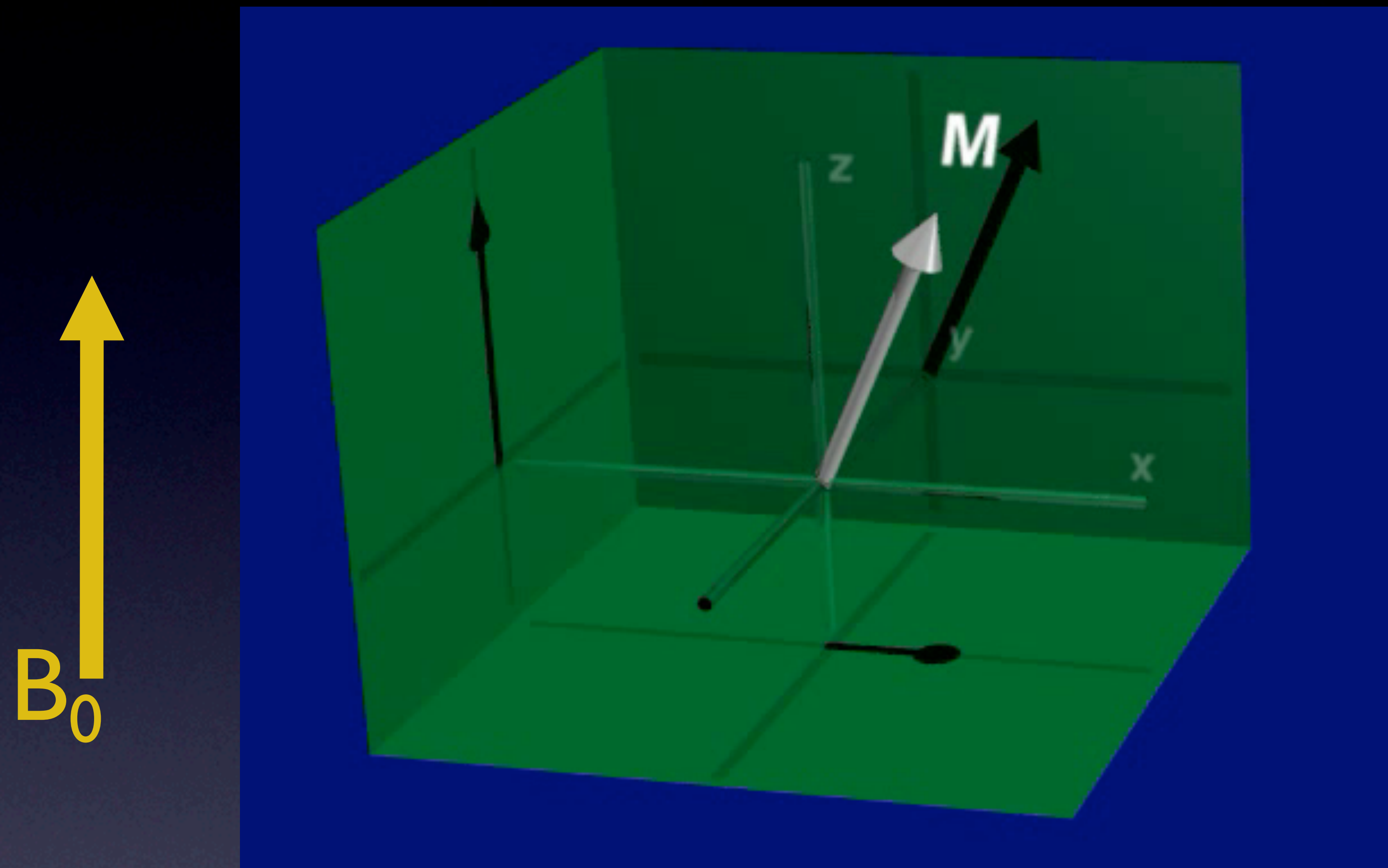

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Signal detection

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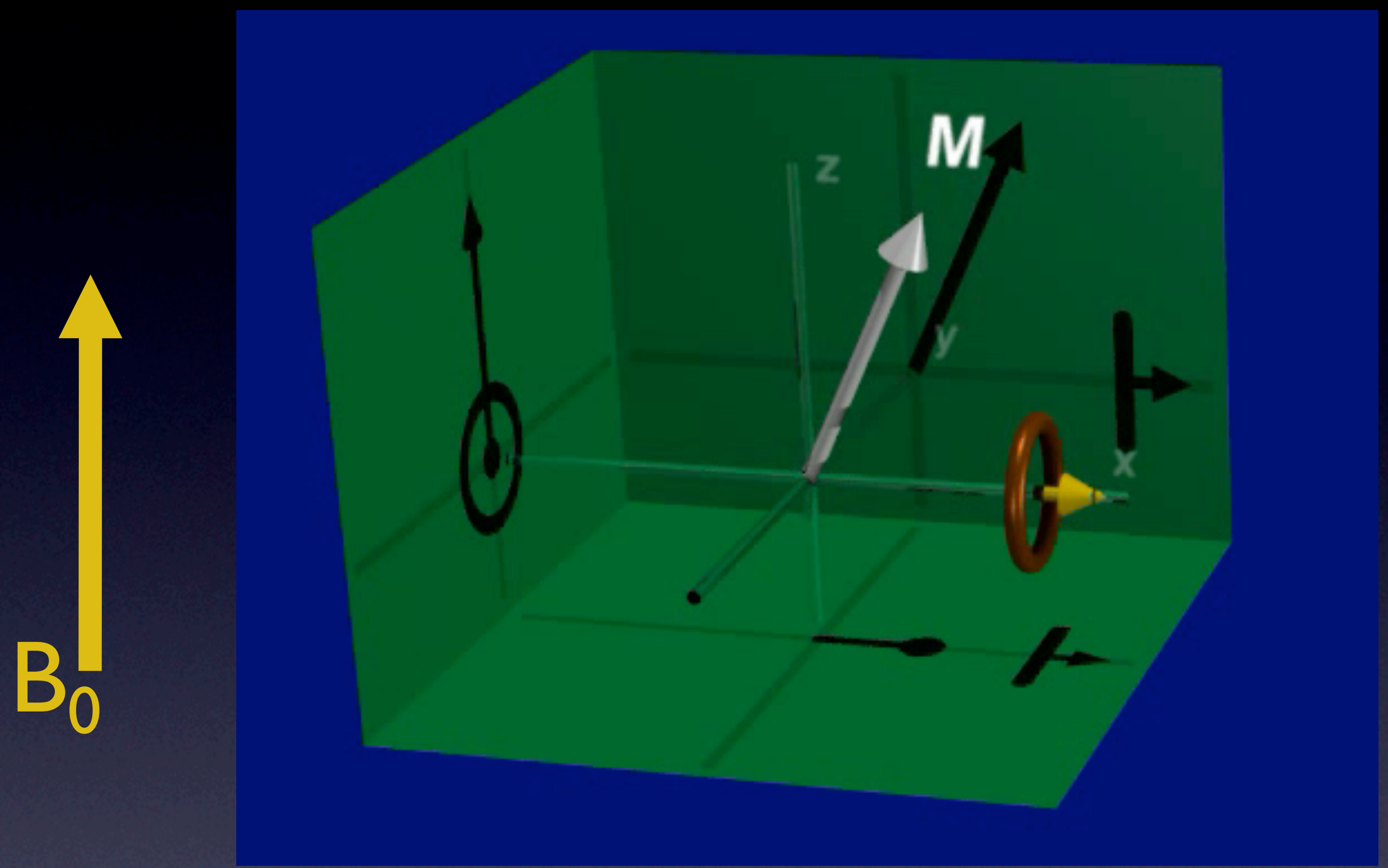
- Changing magnetic field induces current in wire
- Precessing magnetisation detected with coil
- Can only detect component in transverse (xy) plane

Signal detection



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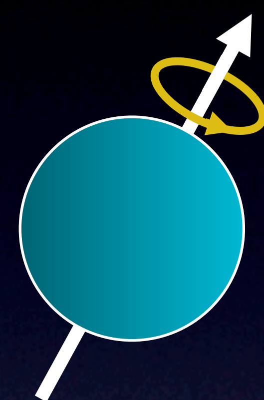
Magnetic Resonance



$$\omega_0 = \gamma B_0$$

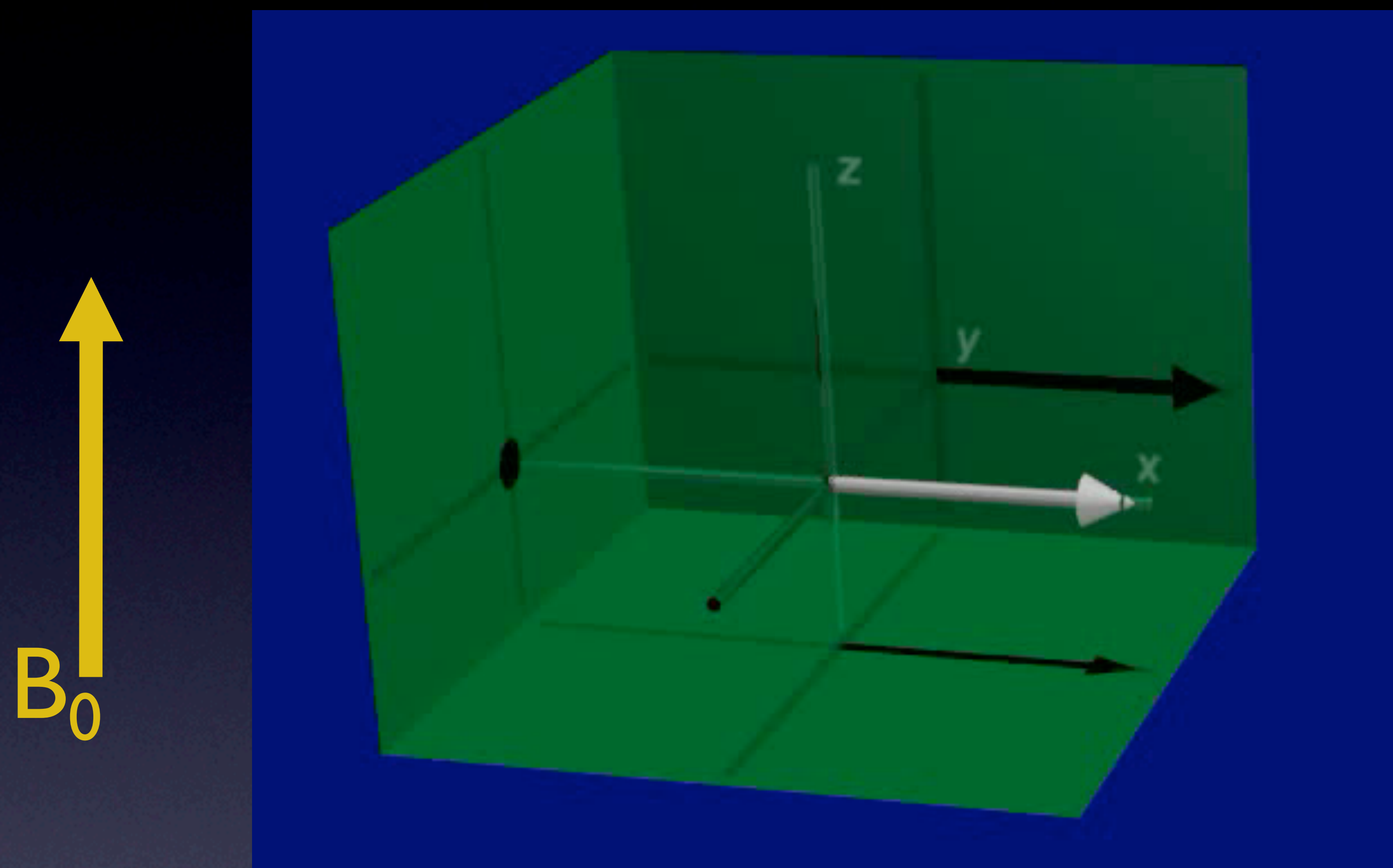
- **Magnetic**: external field (B0) magnetises sample
  - Usually detect hydrogen protons in water
  - Potentially any element with spin (^{1}H, ^{19}F, ^{31}P...)
- **Resonance**: magnetization has characteristic frequency
  - Also called the "Larmour" frequency
  - Proportional to the strength of the magnetic field the spin is in
  - For protons, resonance frequency is in RF range

Relaxation

courtesy of William Overall

- Magnetization "relaxes" back into alignment with B_0
- Speed of relaxation has time constants: T_1 and T_2

Relaxation



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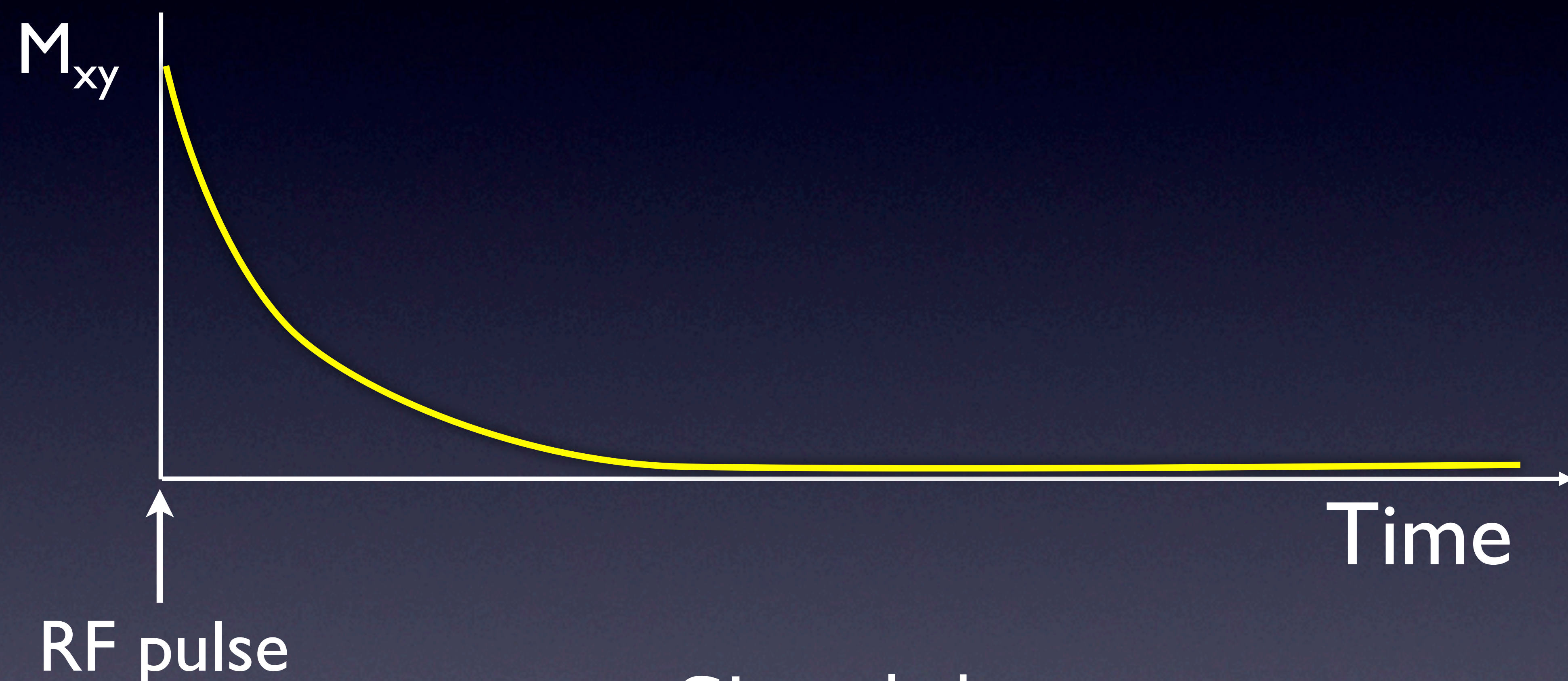
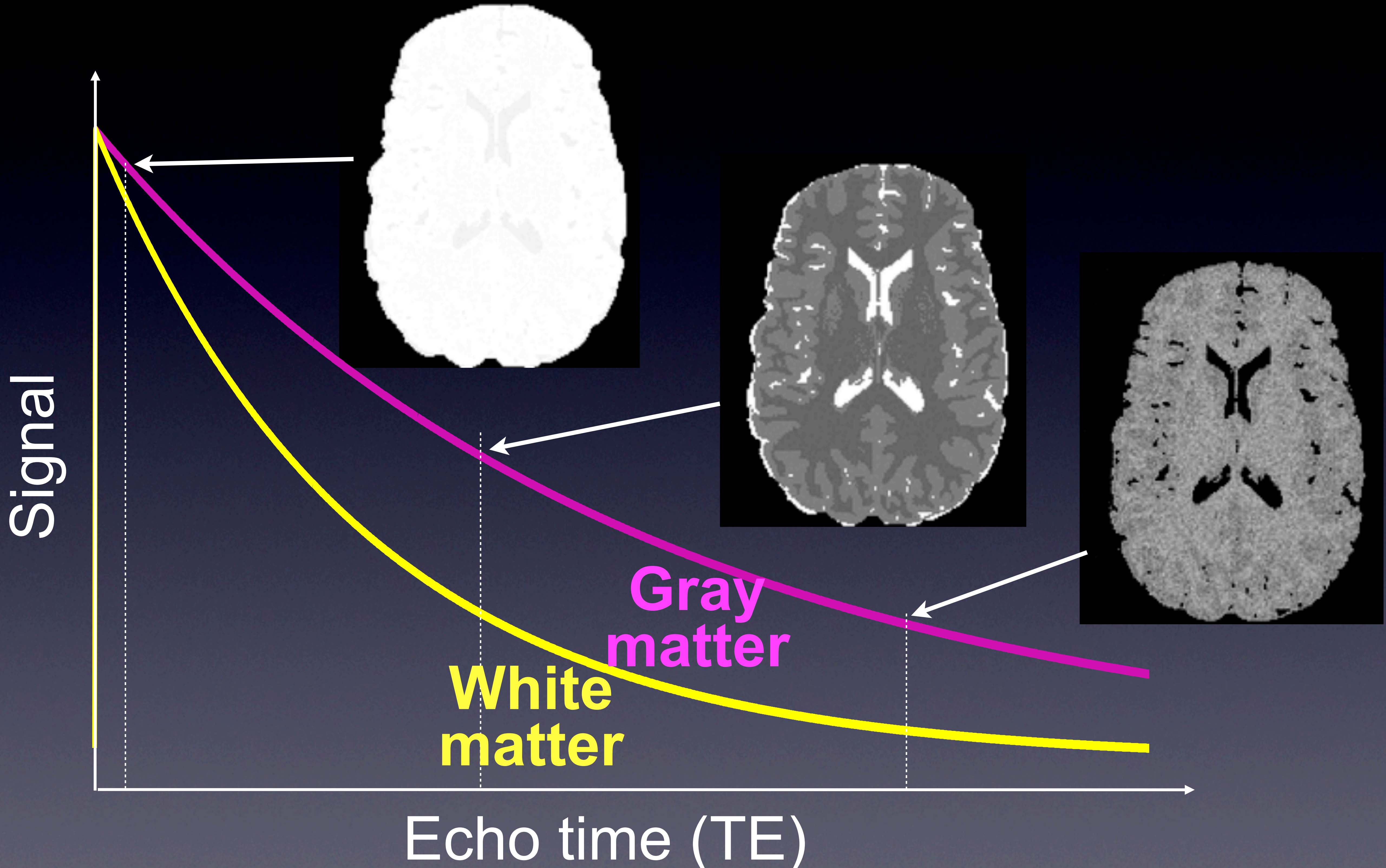
Relaxation: T_1 and T_2



Signal decays
according to T_2
in transverse plane

Echo time (TE) & T_2 contrast



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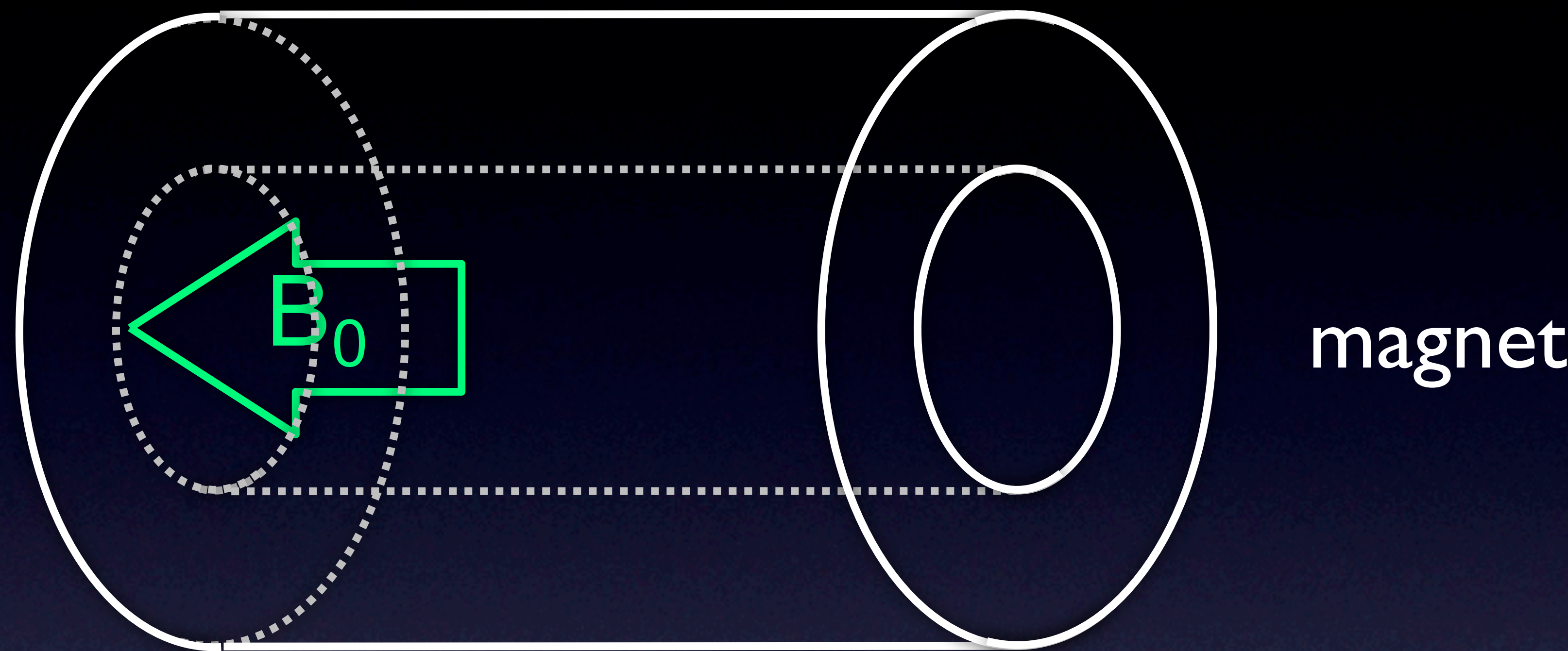
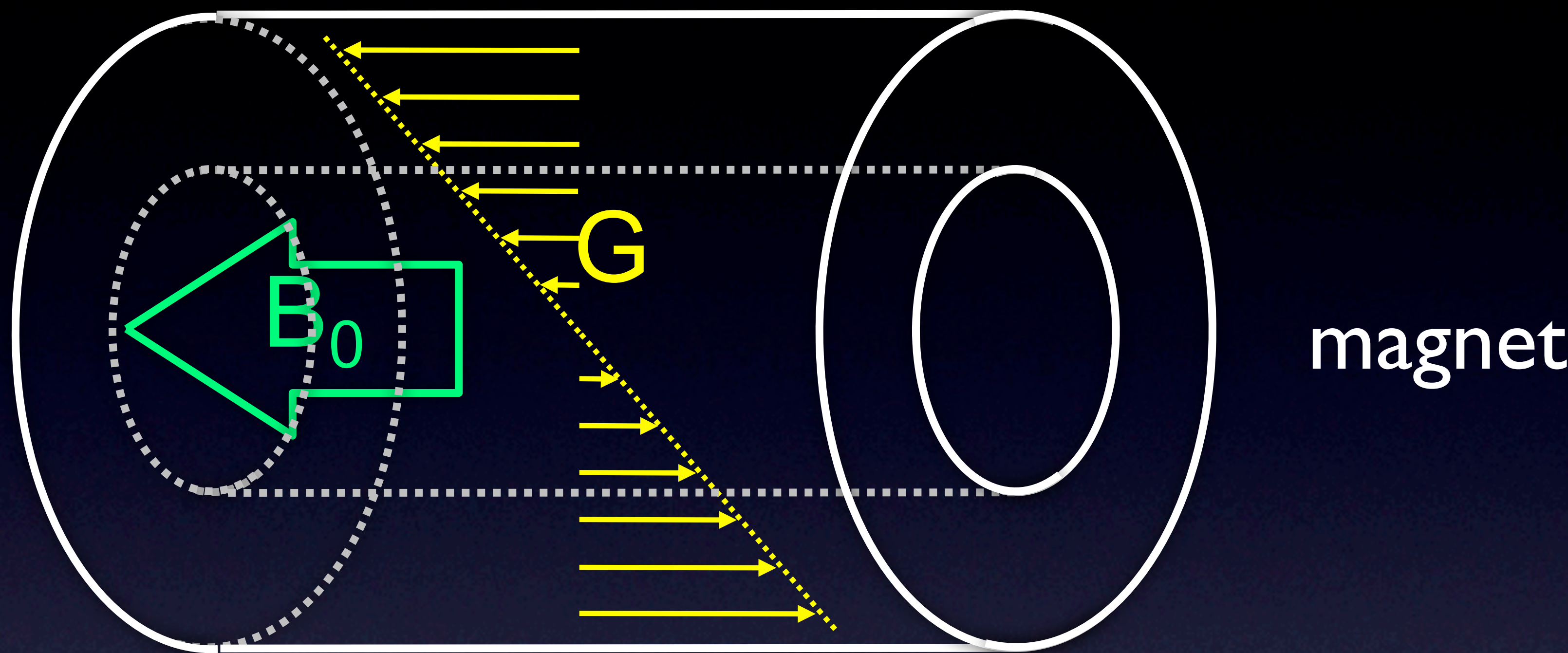
Making an image



Differentiate between signal from different locations

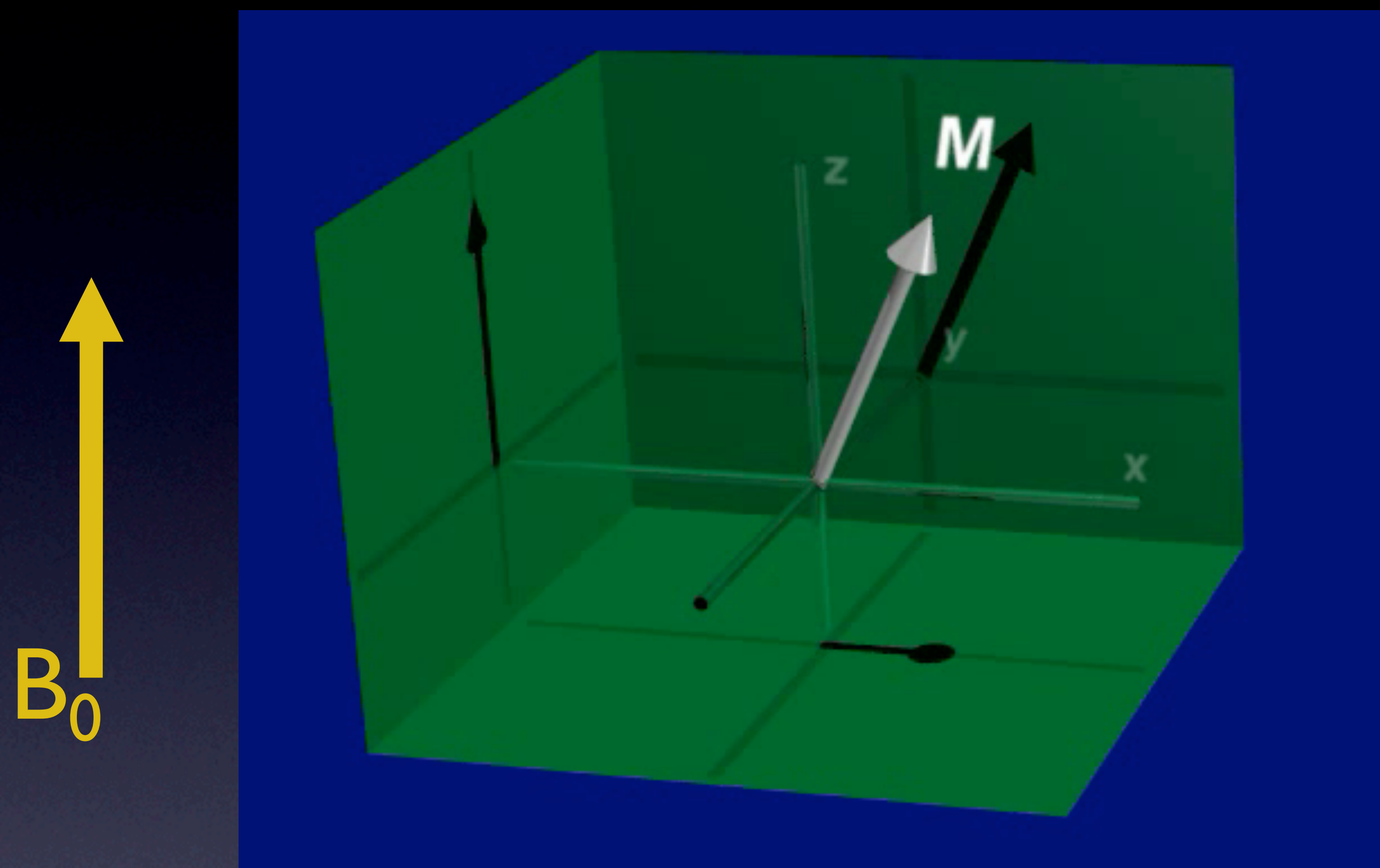
Making an image



Differentiate between signal from different locations

- Add a spatially varying magnetic field gradient (G)
- Field varies linearly along one direction
- Gradient field adds to or subtracts from B_0

Precession

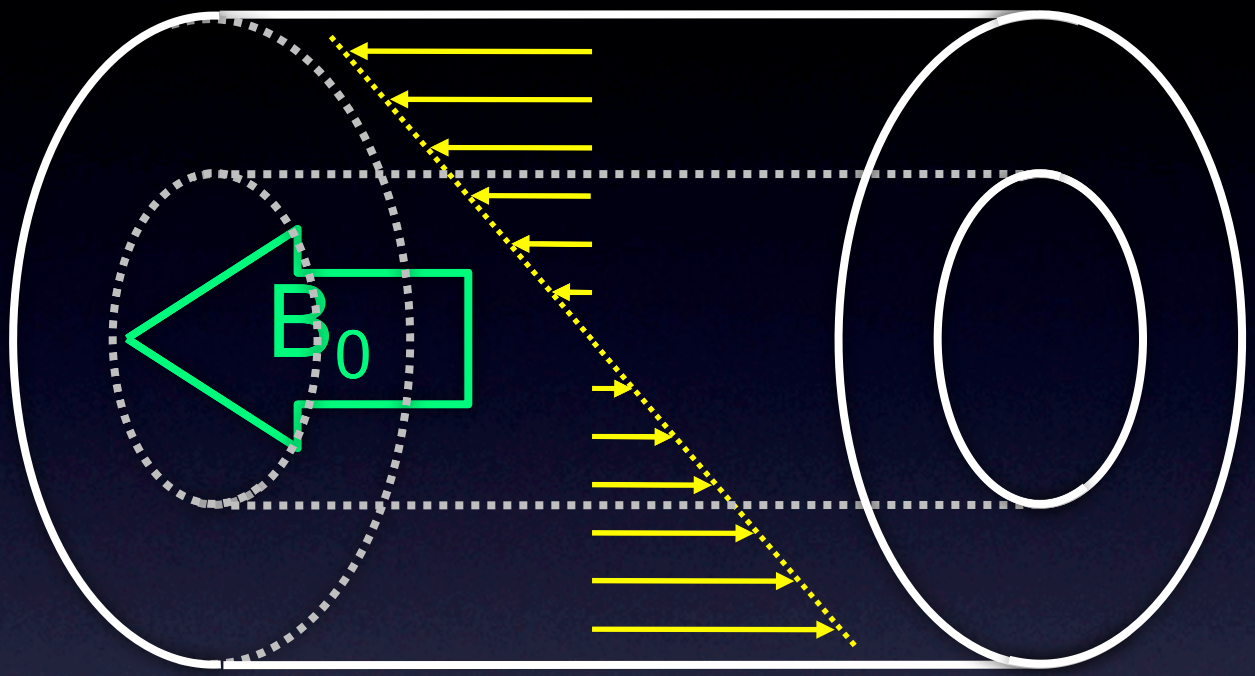


courtesy of William Overall

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

- Resonance frequency is proportional to total field

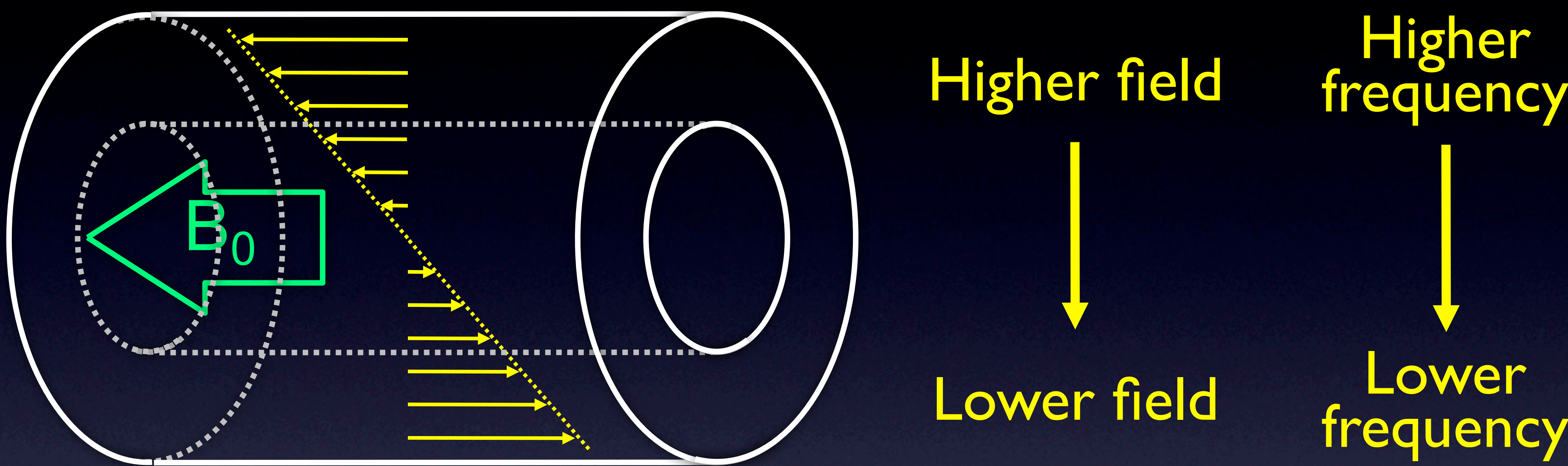
Magnetic gradients



Higher field → Lower field

Higher frequency → Lower frequency

Magnetic gradients



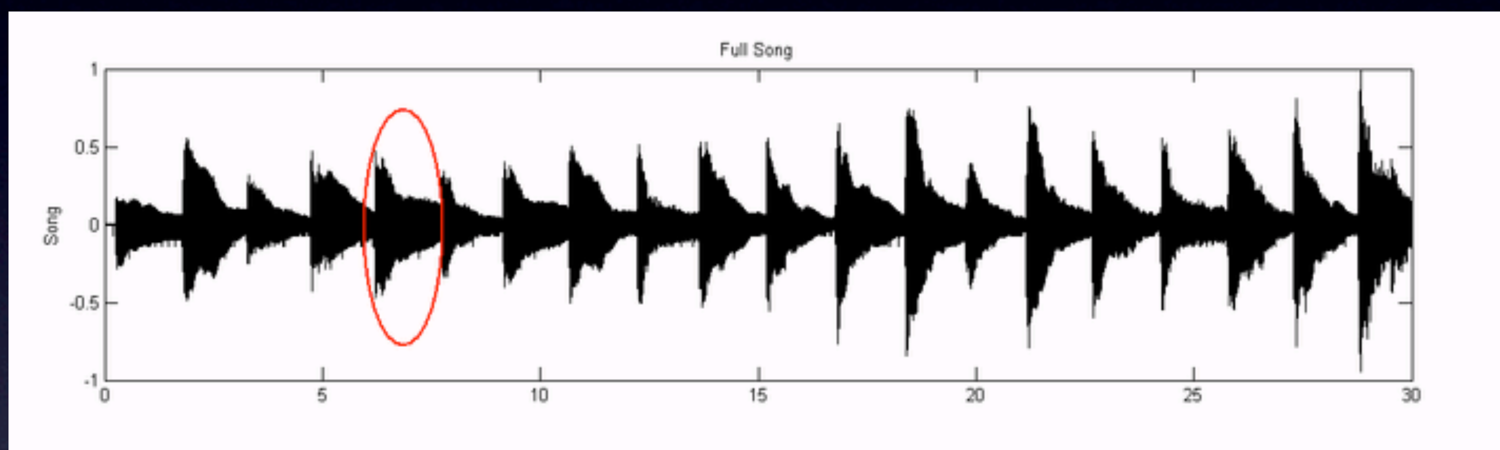
- Protons at each position *precess* at different frequencies
- RF coil *hears* all of the protons at once
- Distinguish material at a given position by selectively *listening* to that frequency

Decoding Frequency: The Fourier Transform

- Expresses a function of time as a function of frequency
- Imagine an orchestra: you differentiate between different instruments based on their frequency

The Fourier Transform

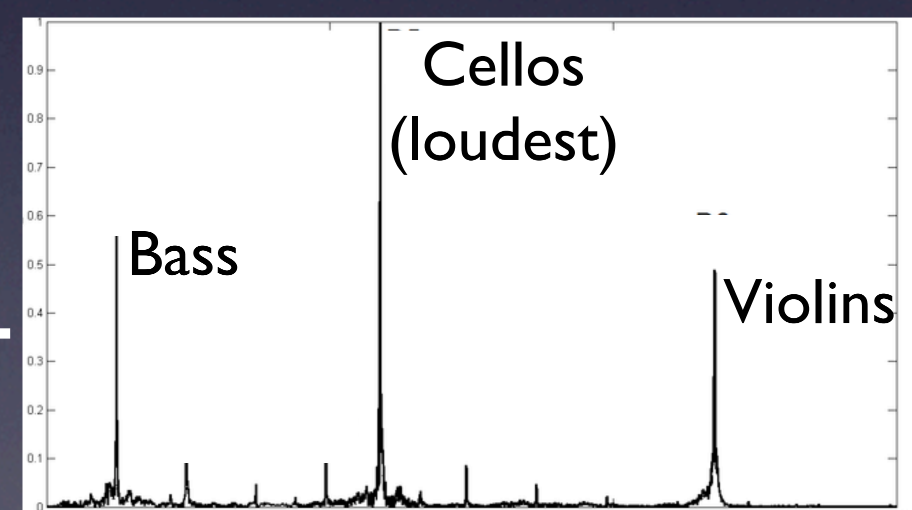
Amplitude



Time / s

Fourier transform

Amplitude



Frequency / Hz

Fourier transform

Spatial frequencies

Image
Space

Spatial frequencies

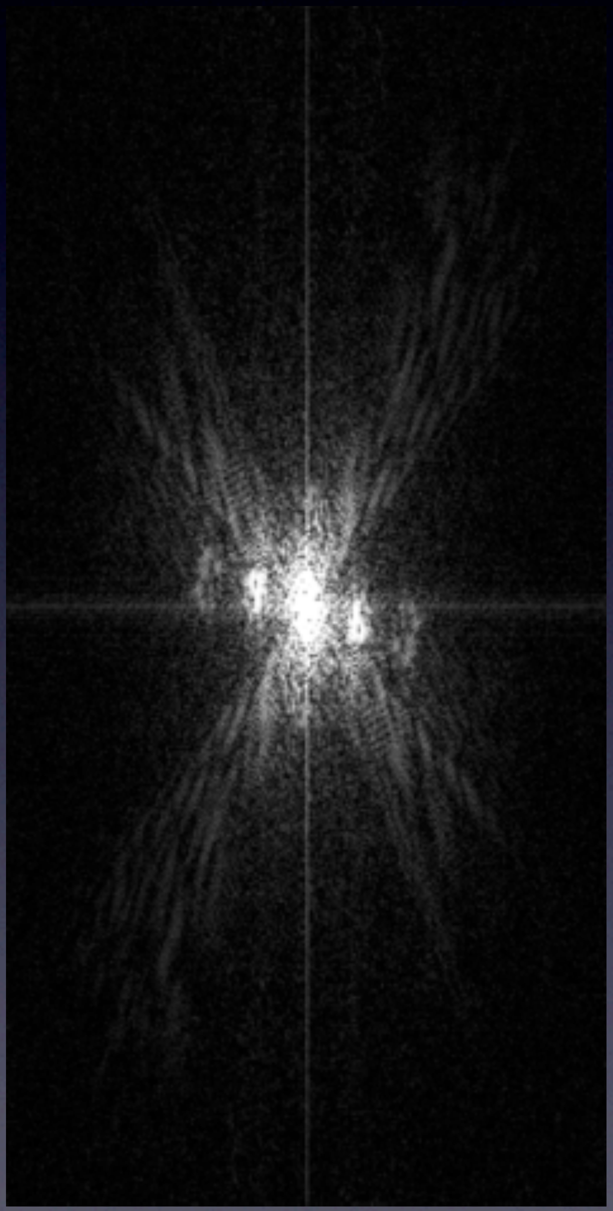
Image
Space

Fourier
Transform

Spatial frequencies

Image Space

Fourier Transform



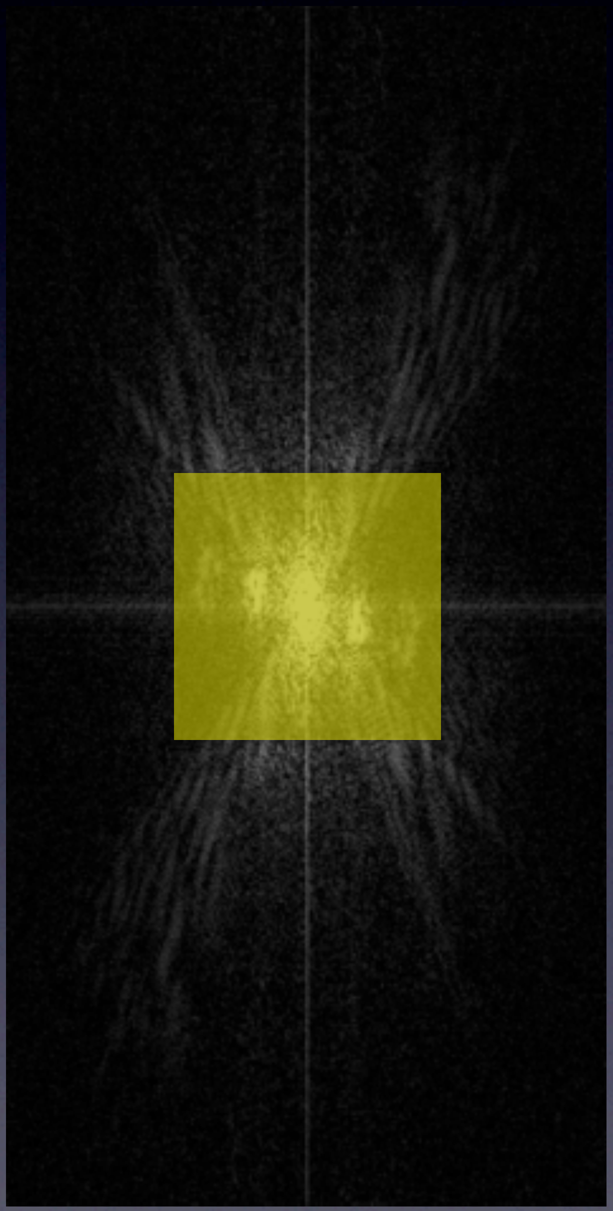
K-Space

Brightness = How much of this spatial frequency is in your image

Spatial frequencies

Image Space

Fourier Transform



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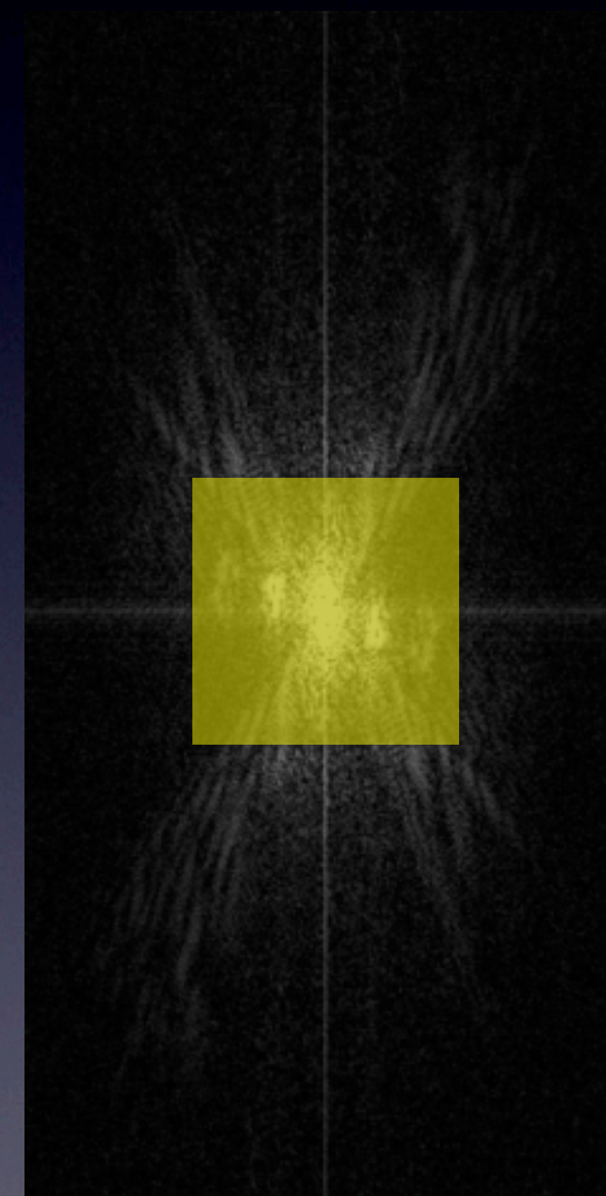
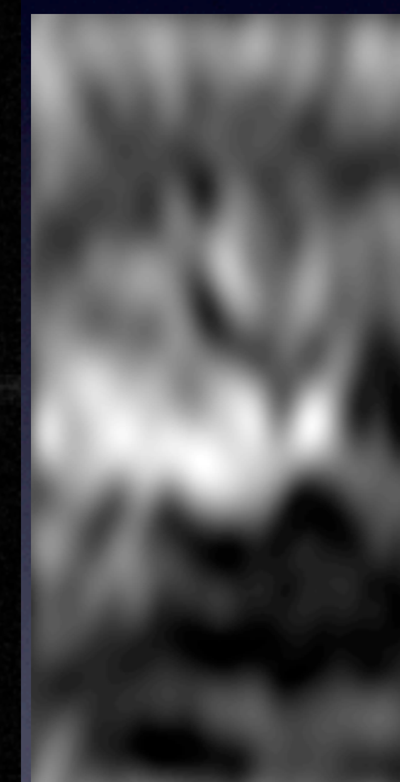


Low Spatial Frequencies



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Spatial frequencies

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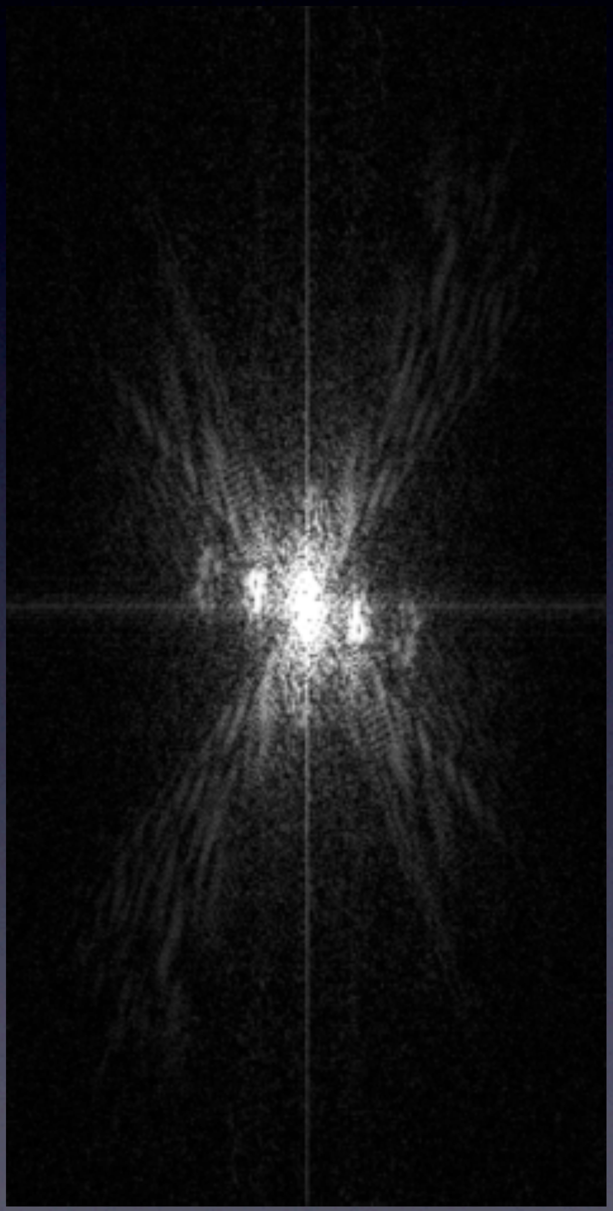
Fourier Transform ⟷



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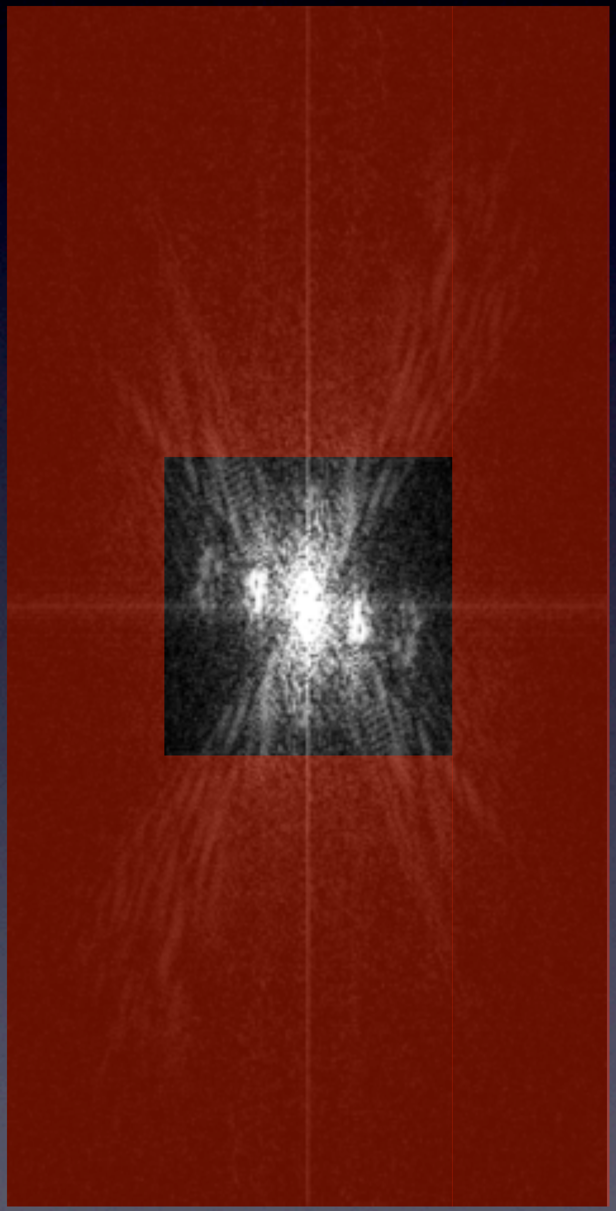

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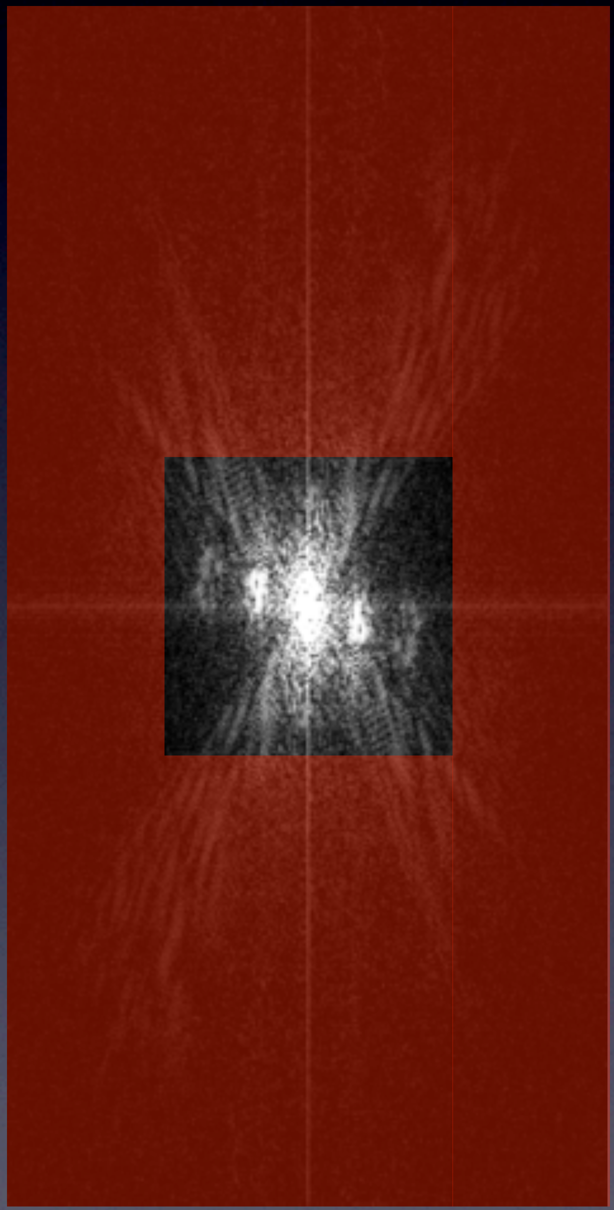

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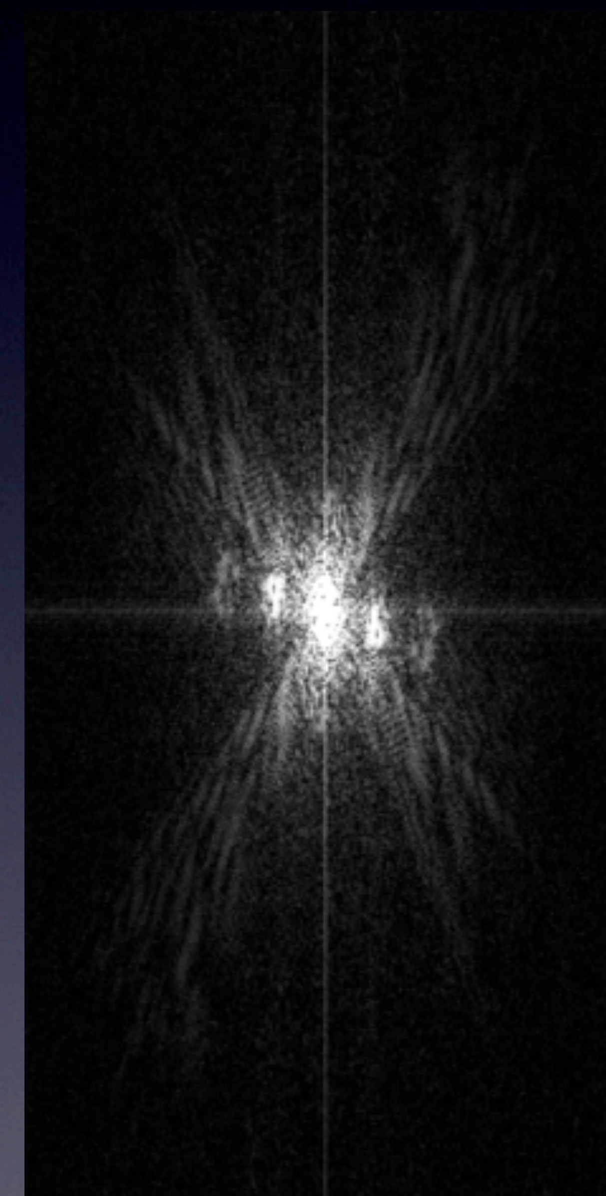

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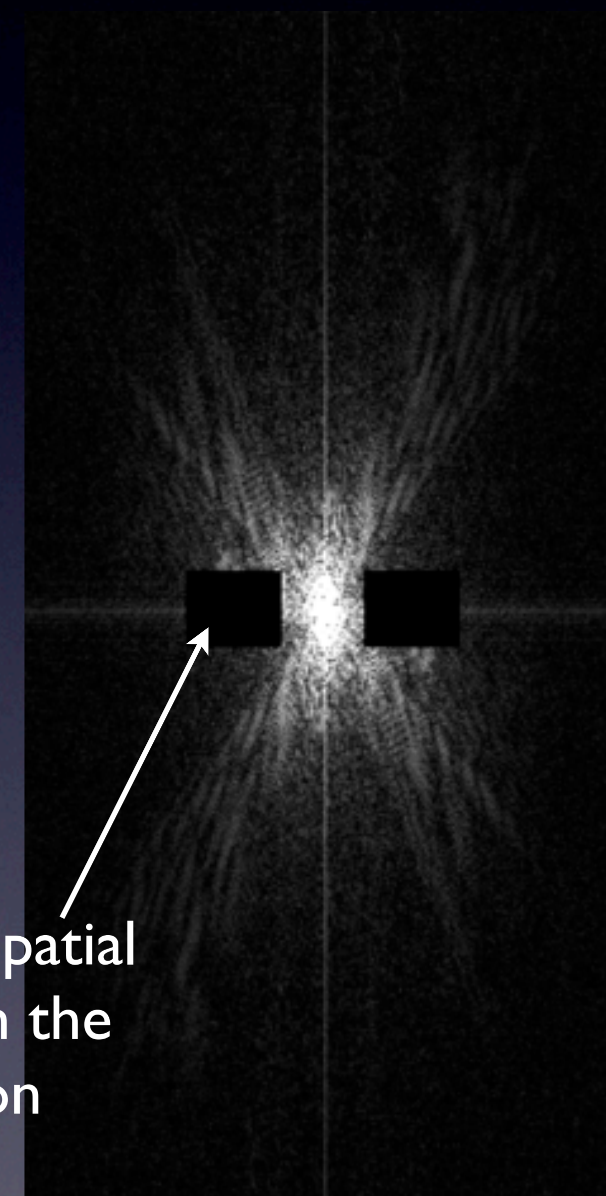


K-Space

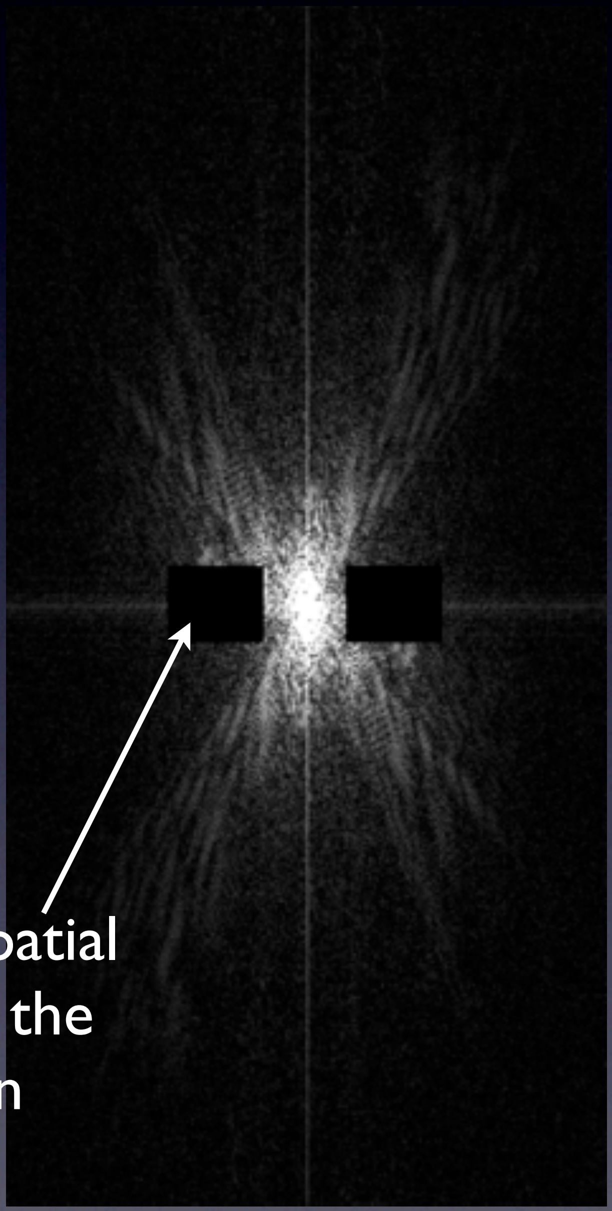
Delete some spatial frequencies in the LR direction

Brightness = How much of this spatial frequency is in your image

Spatial frequencies

Image Space

Fourier Transform



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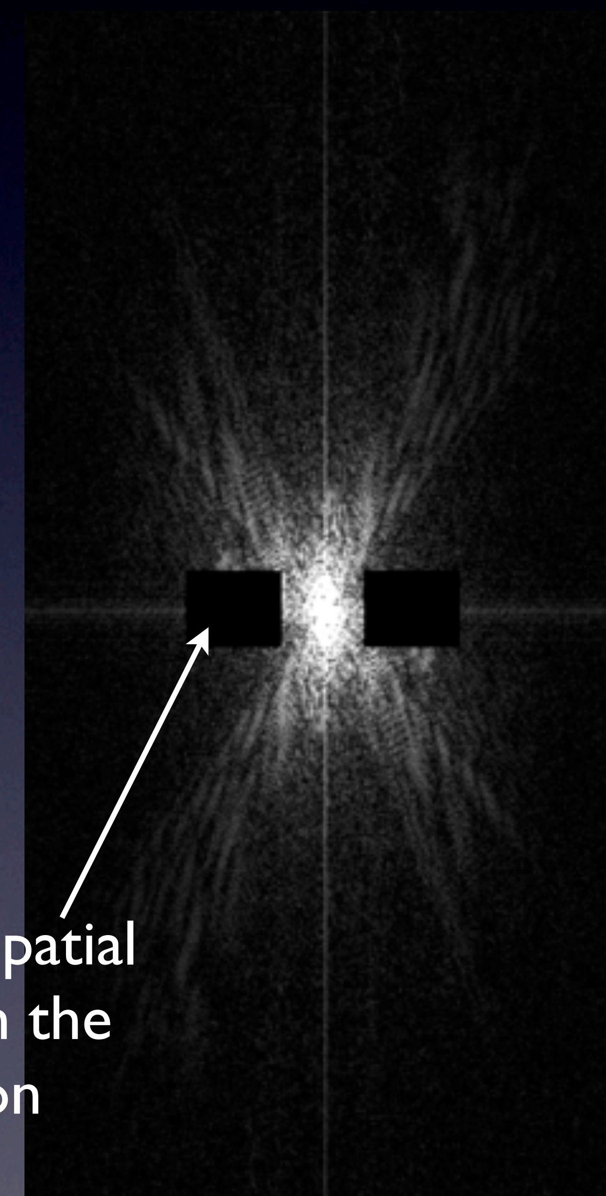

K-Space

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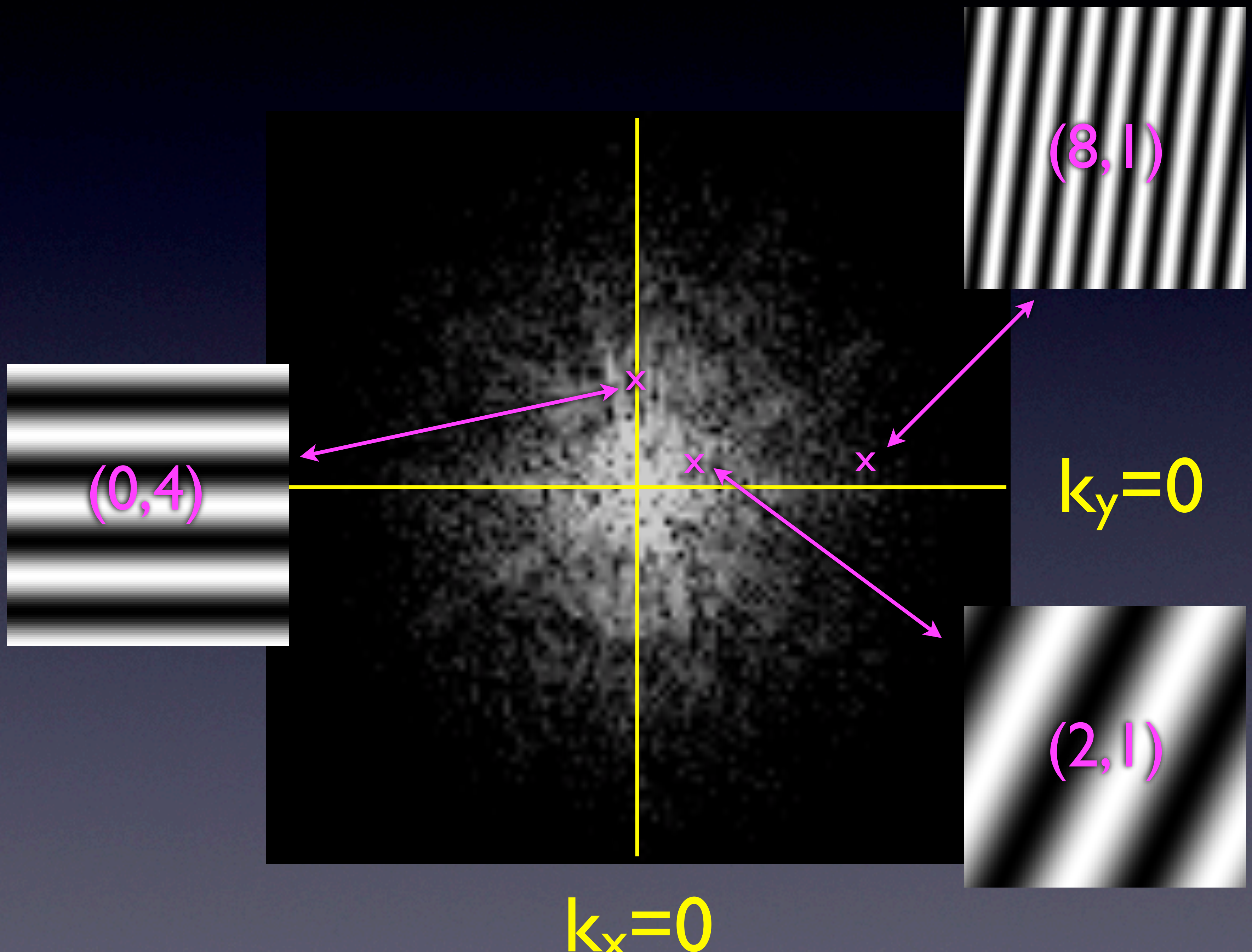
Brightness = How much of this spatial frequency is in your image

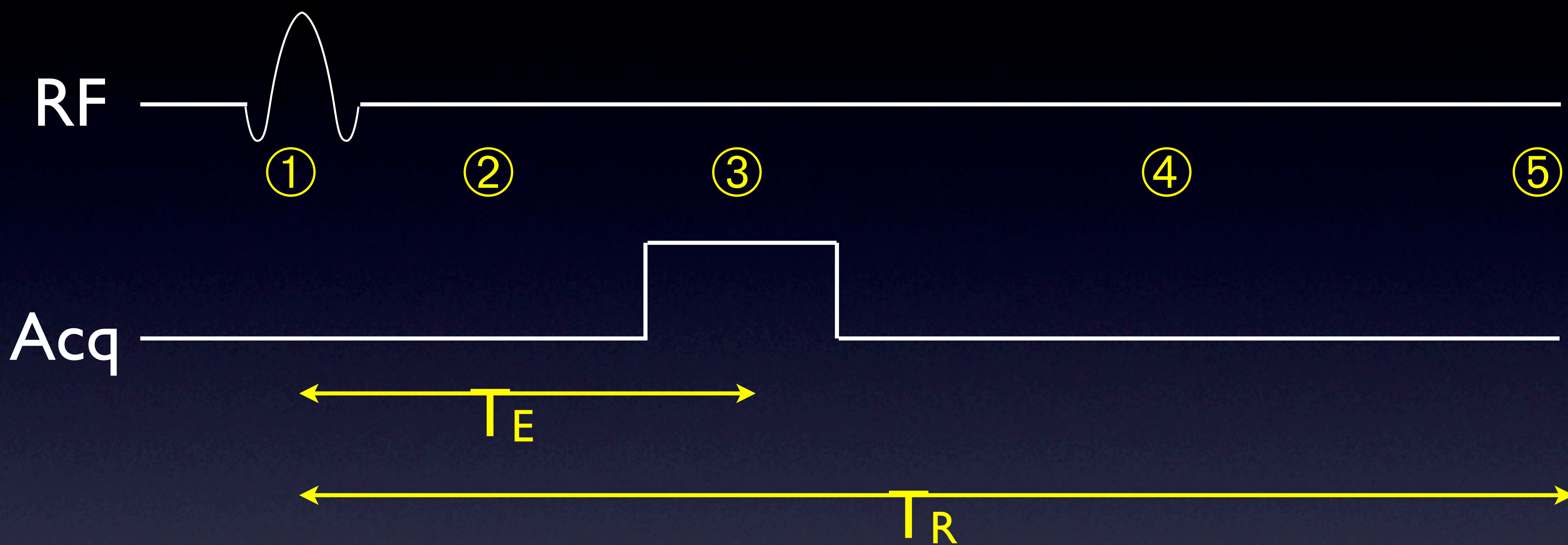
2D "k-space" describes contribution of each spatial frequency



What does this have to do with MRI?

- Remember, we detect all excited protons in the object at the same time
- They're resonating at different frequencies due to the gradients
- We acquire the data in k-space!
- We then fill k-space & Fourier transform it to get the image

Simple MRI "pulse sequence"



- ① Excite magnetization (transmit RF pulse)
- ② Wait for time T_E ("echo time")
- ③ Acquire signal from transverse magnetization (M_{xy})
- ④ Wait until time T_R ("repetition time")
- ⑤ Repeat from ①

Linescan (2DFT) Acquisition

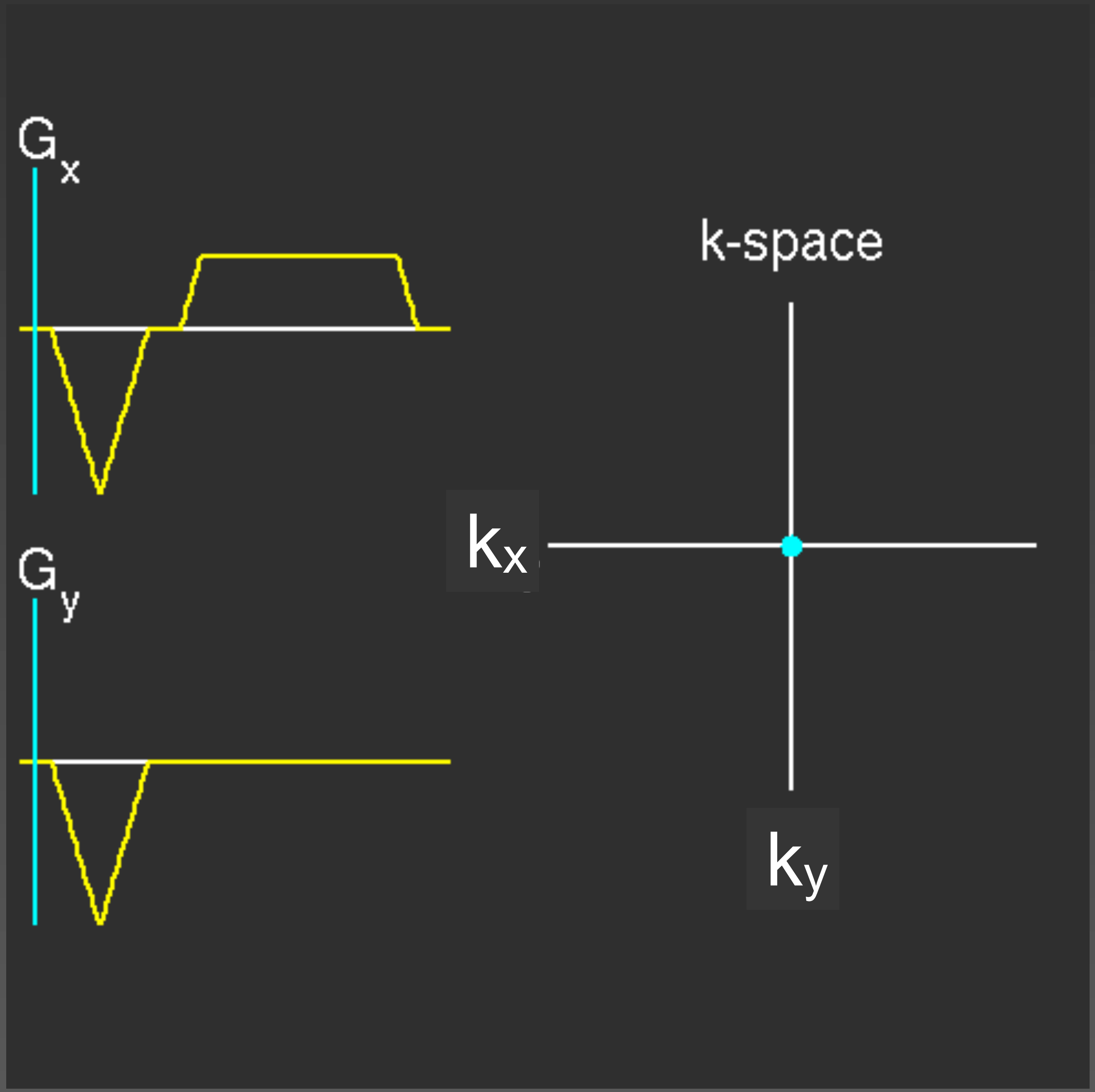
k_x

k_y

Acquire one line after each excitation

Useful for structural images (minimal artefacts)

Linescan (2DFT) Acquisition



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Echo-planar Imaging (EPI) Acquisition

k_x

k_y

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

Used for FMRI, diffusion imaging

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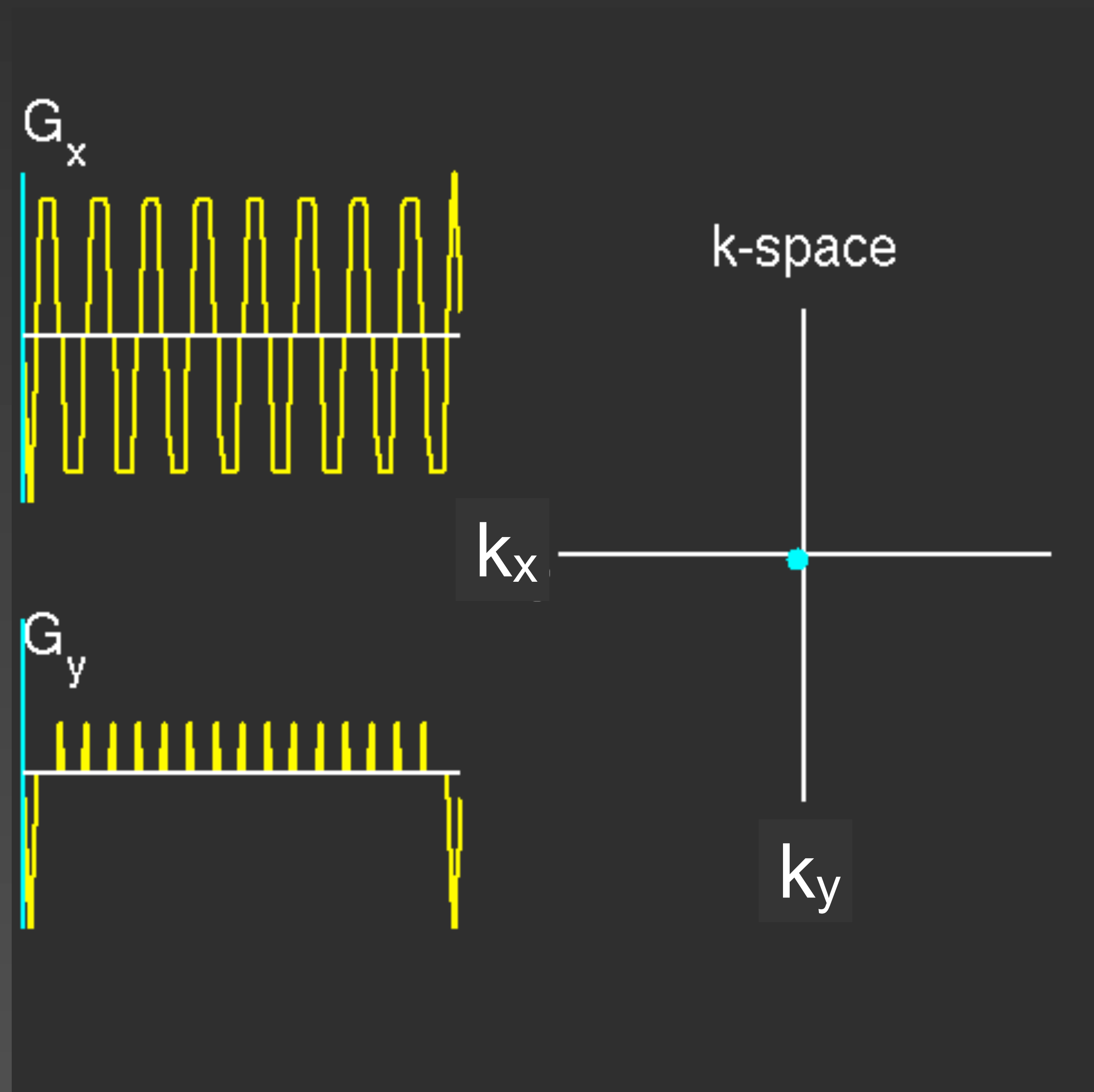

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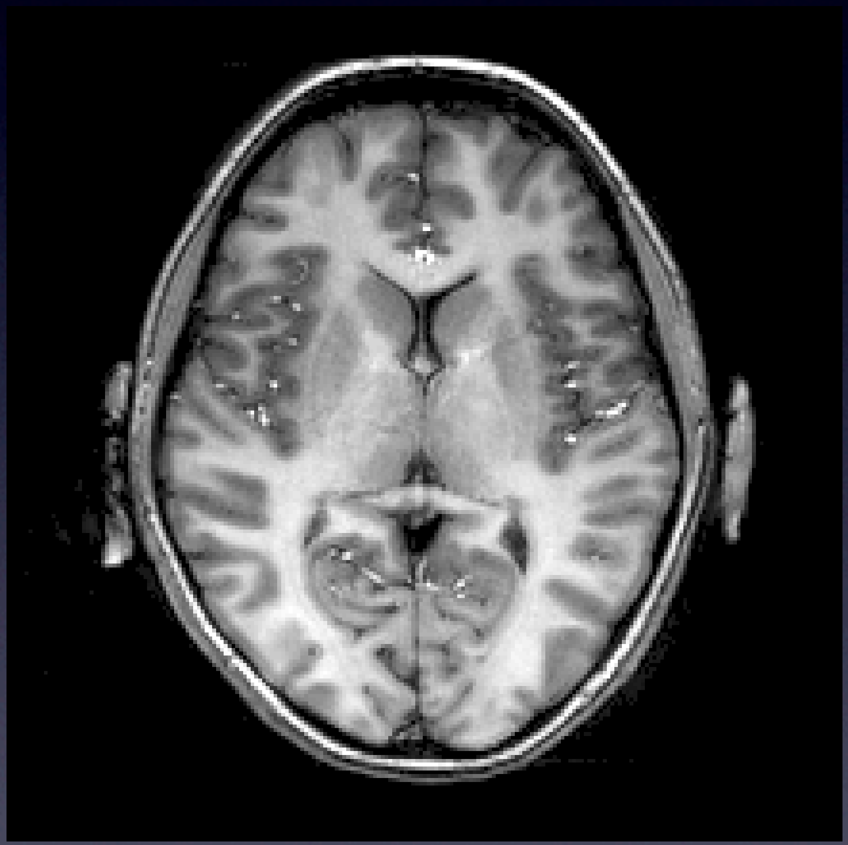
Used for FMRI, diffusion imaging

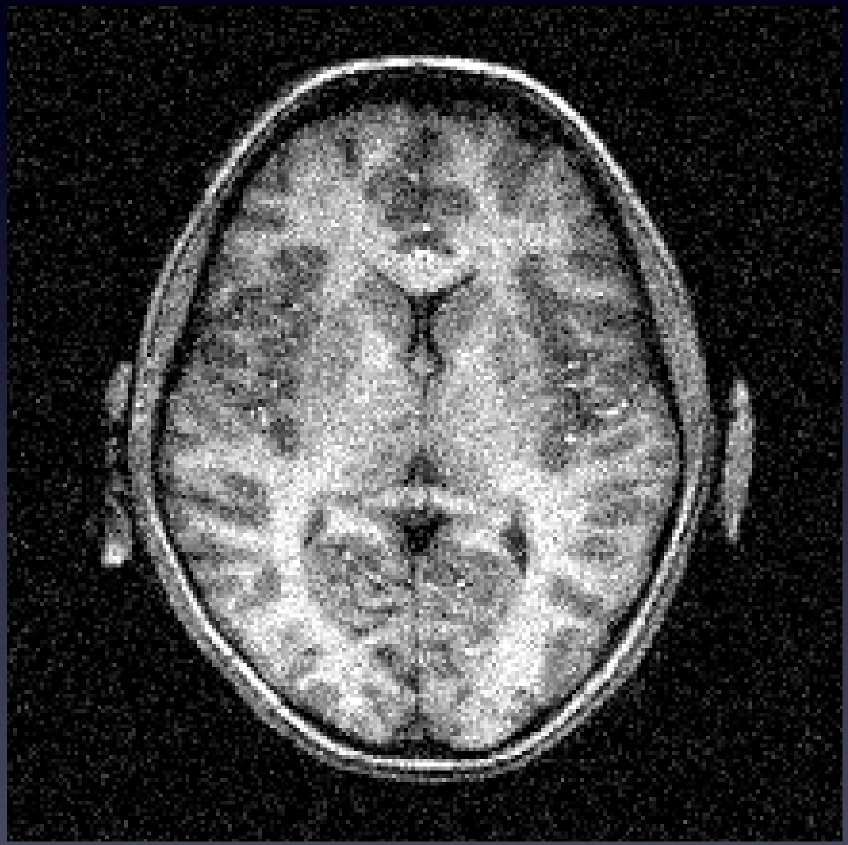
Signal-to-noise ratio (SNR)

Signal-to-noise ratio: describes signal "robustness"

All else being equal, we want to maximise SNR!!



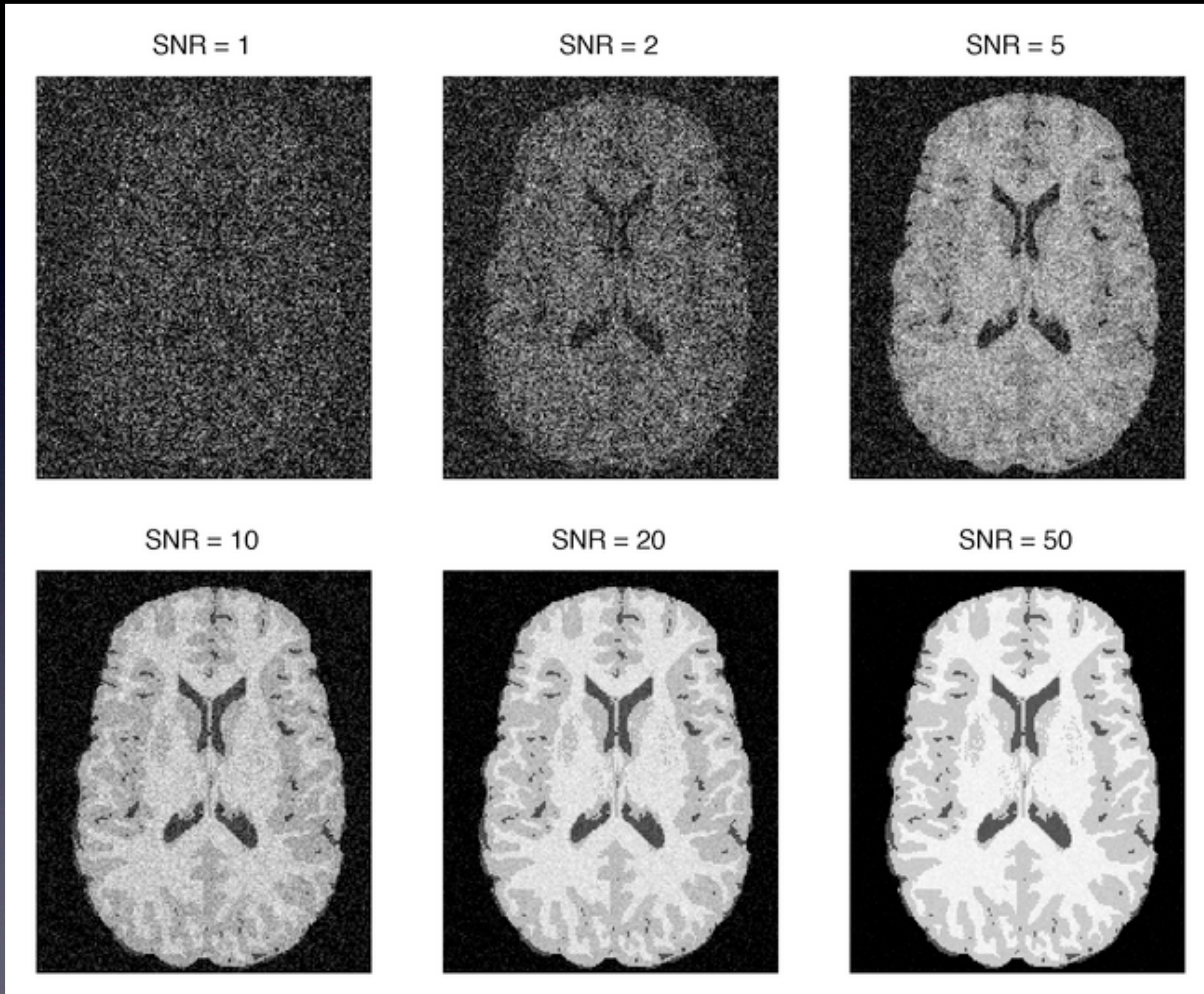
high SNR



low SNR

$$\text{SNR} = \frac{\text{Signal}}{\sigma_{noise}}$$

Signal-to-noise ratio (SNR)



Protocol choices affecting SNR...

- RF receive coil & field strength
- Timing: TE & TR
- Voxel volume
- Scan duration
- Anything affecting signal!!!

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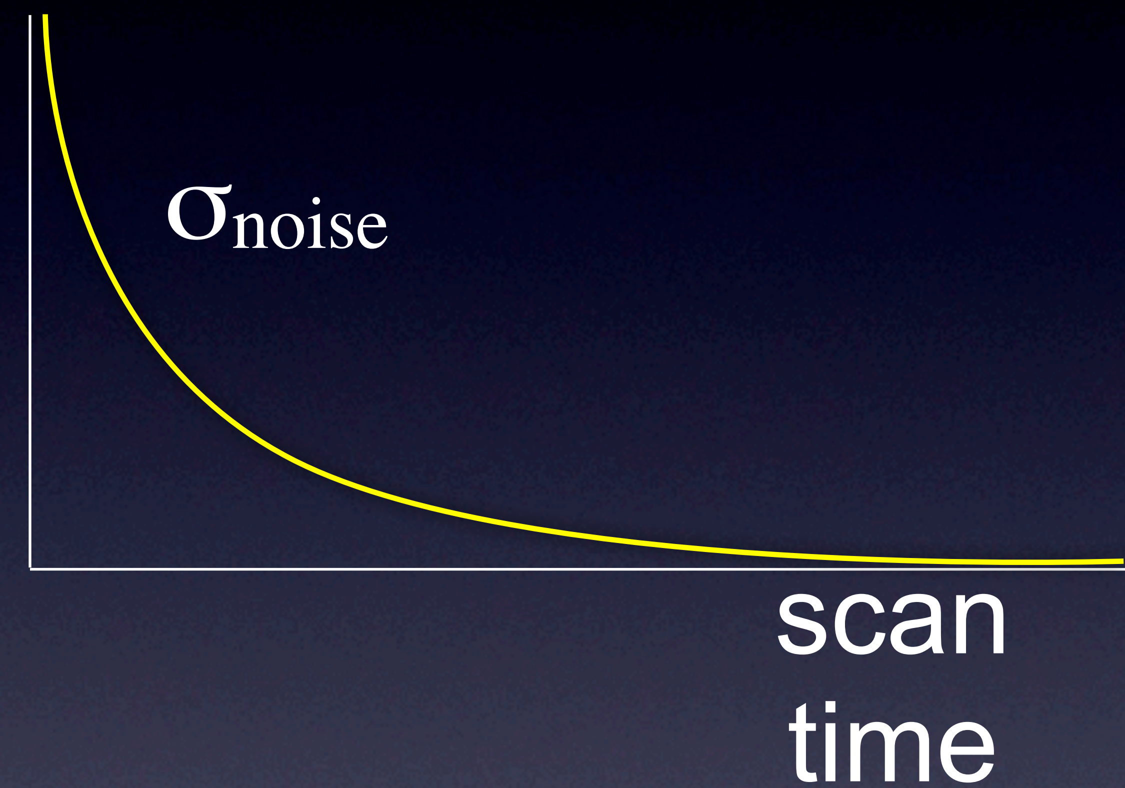
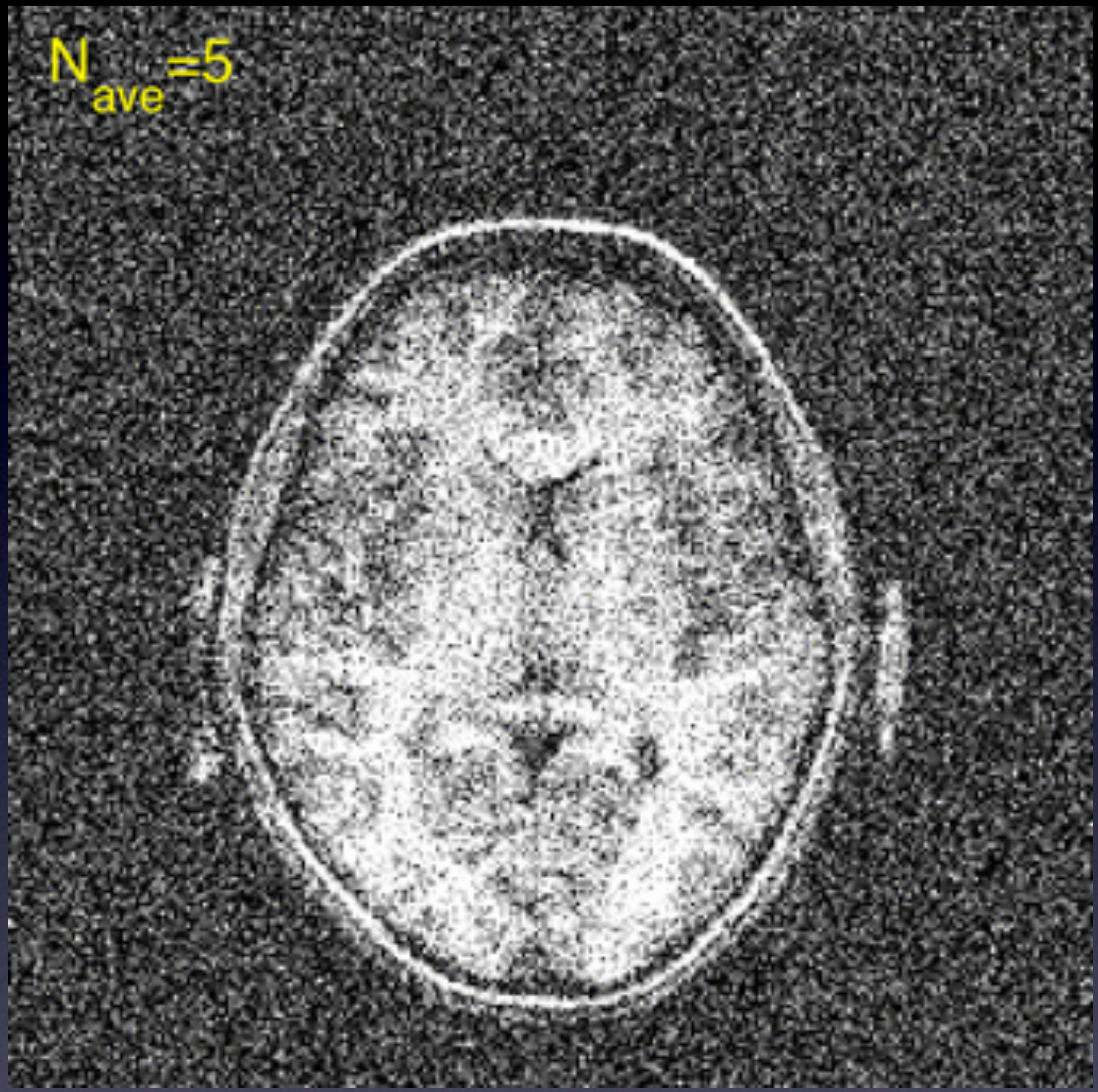
What affects noise? Acquisition time

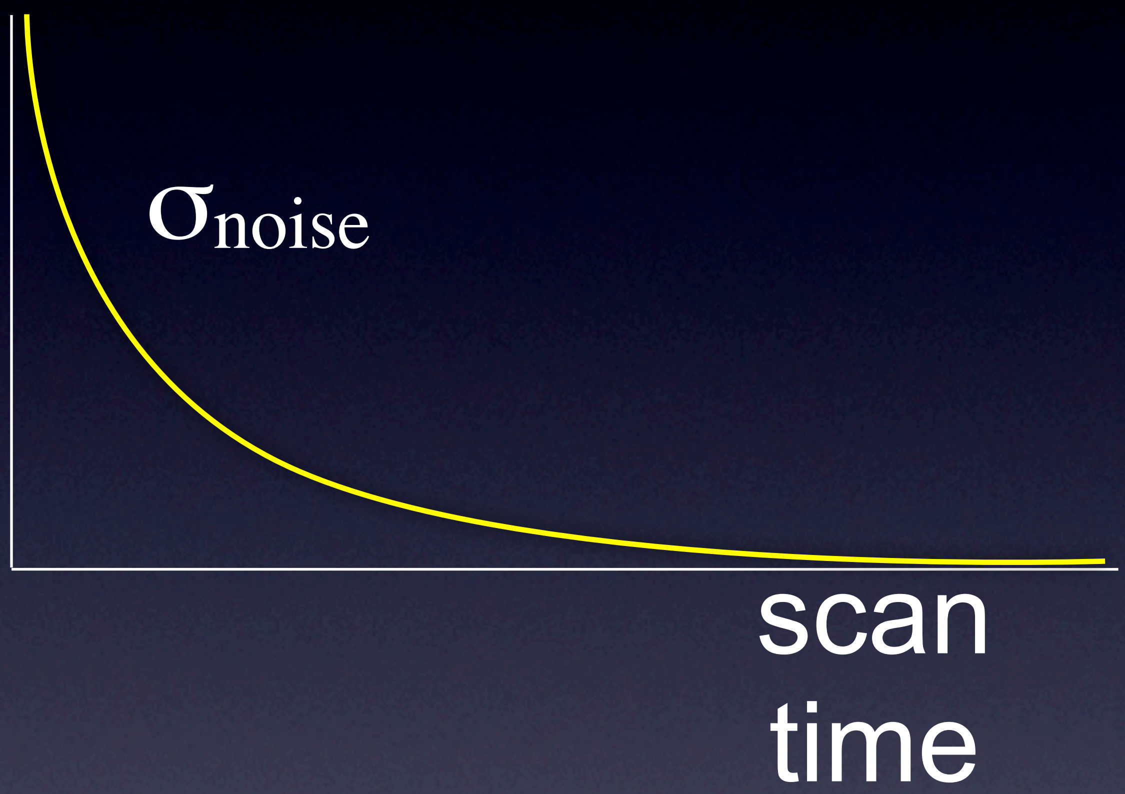


Longer acquisition ⇒ less noise ⇒ higher SNR

SNR improves with the *square root* of scan time

What affects noise? Acquisition time





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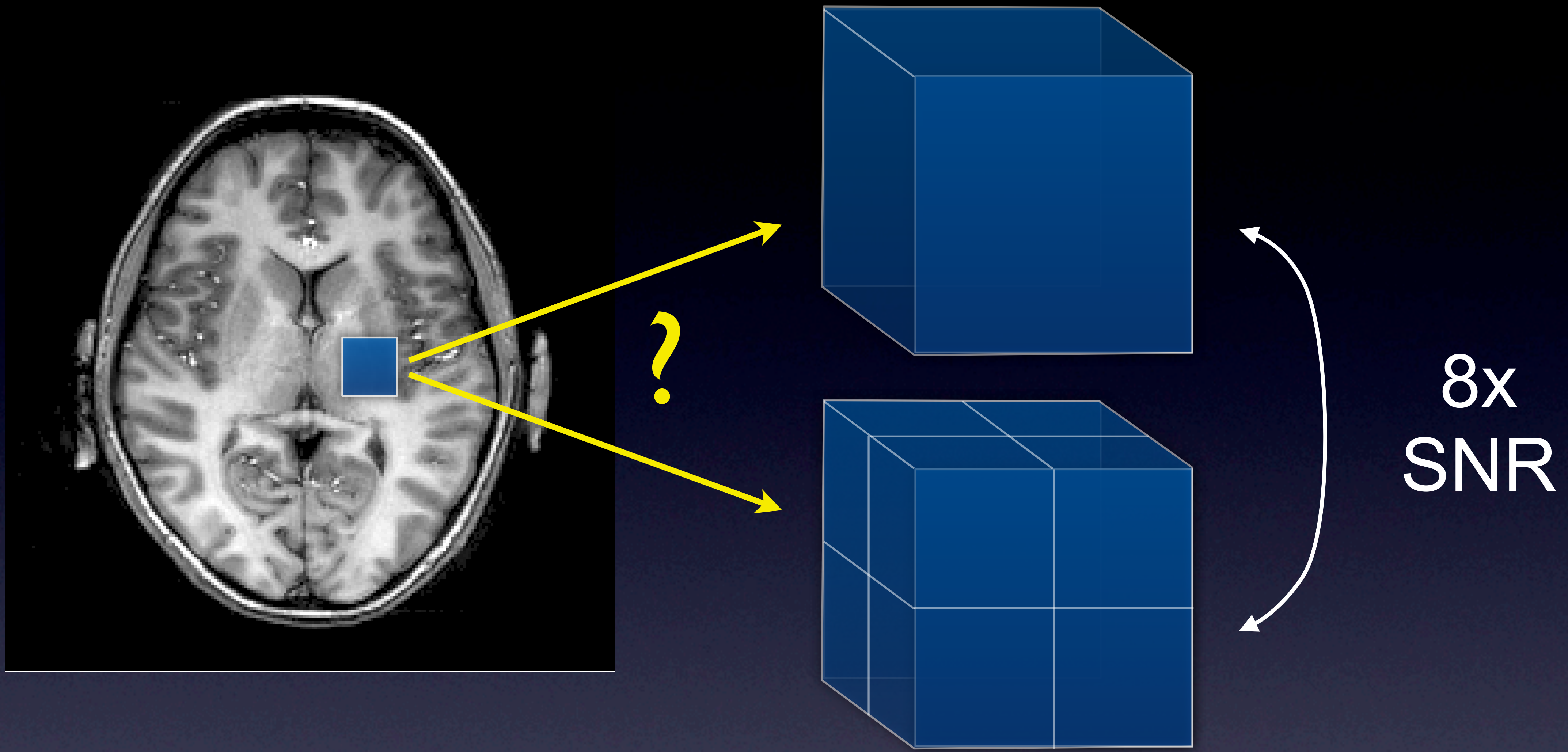
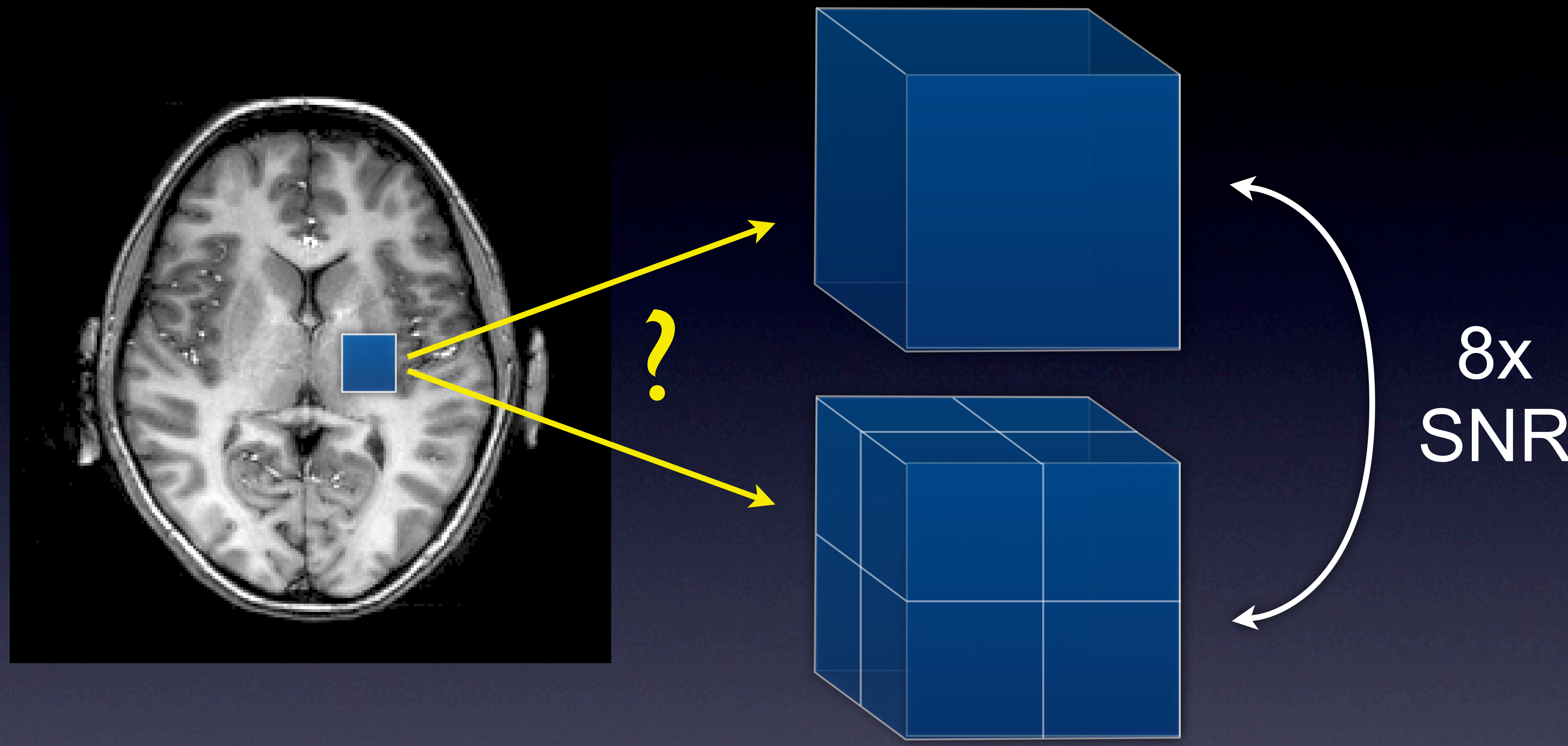
What affects signal? Voxel volume



Larger voxels have signal from more tissue!

- Signal proportional to voxel volume
  - 2x2x2mm has 8x higher SNR than 1x1x1mm!

Averaging to achieve high resolution



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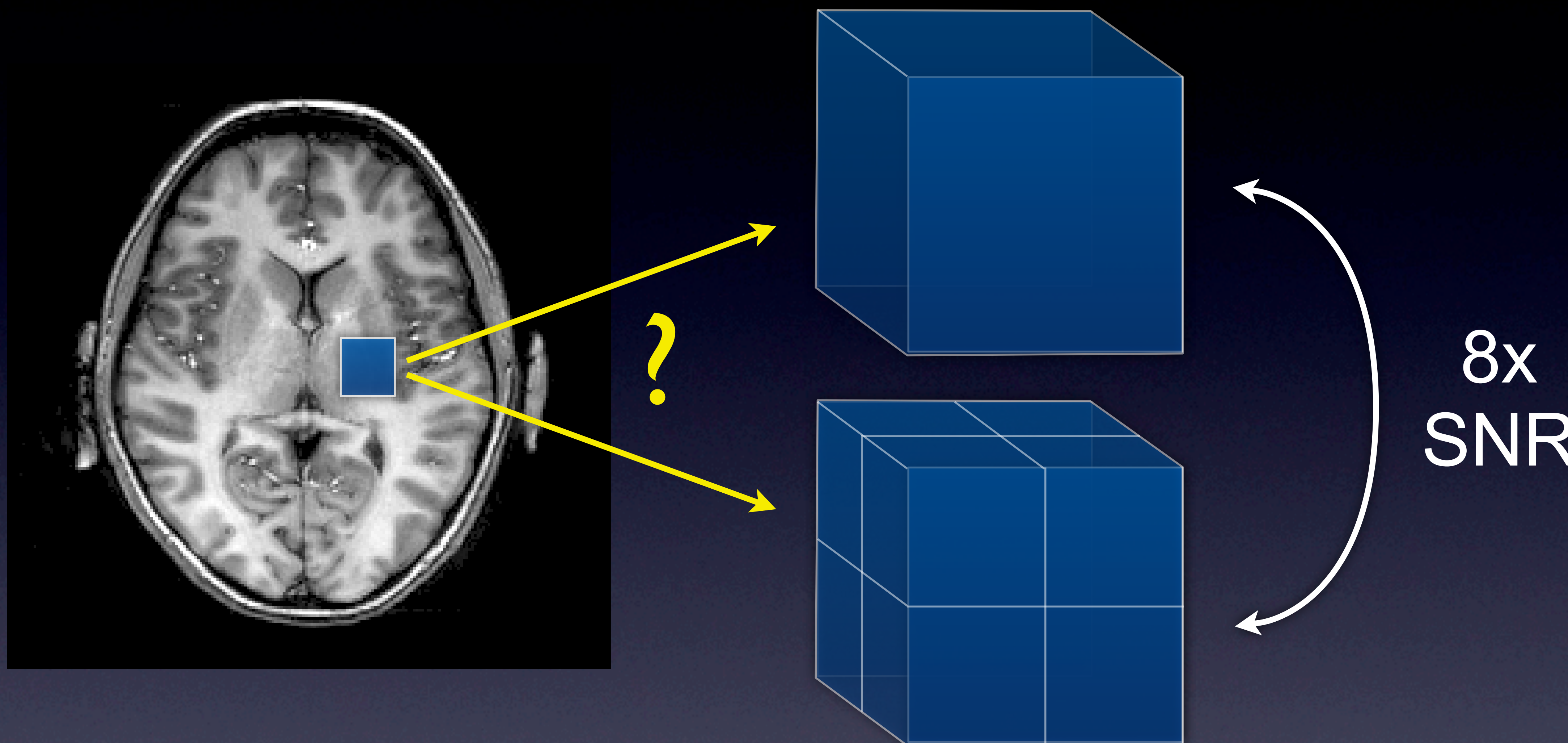
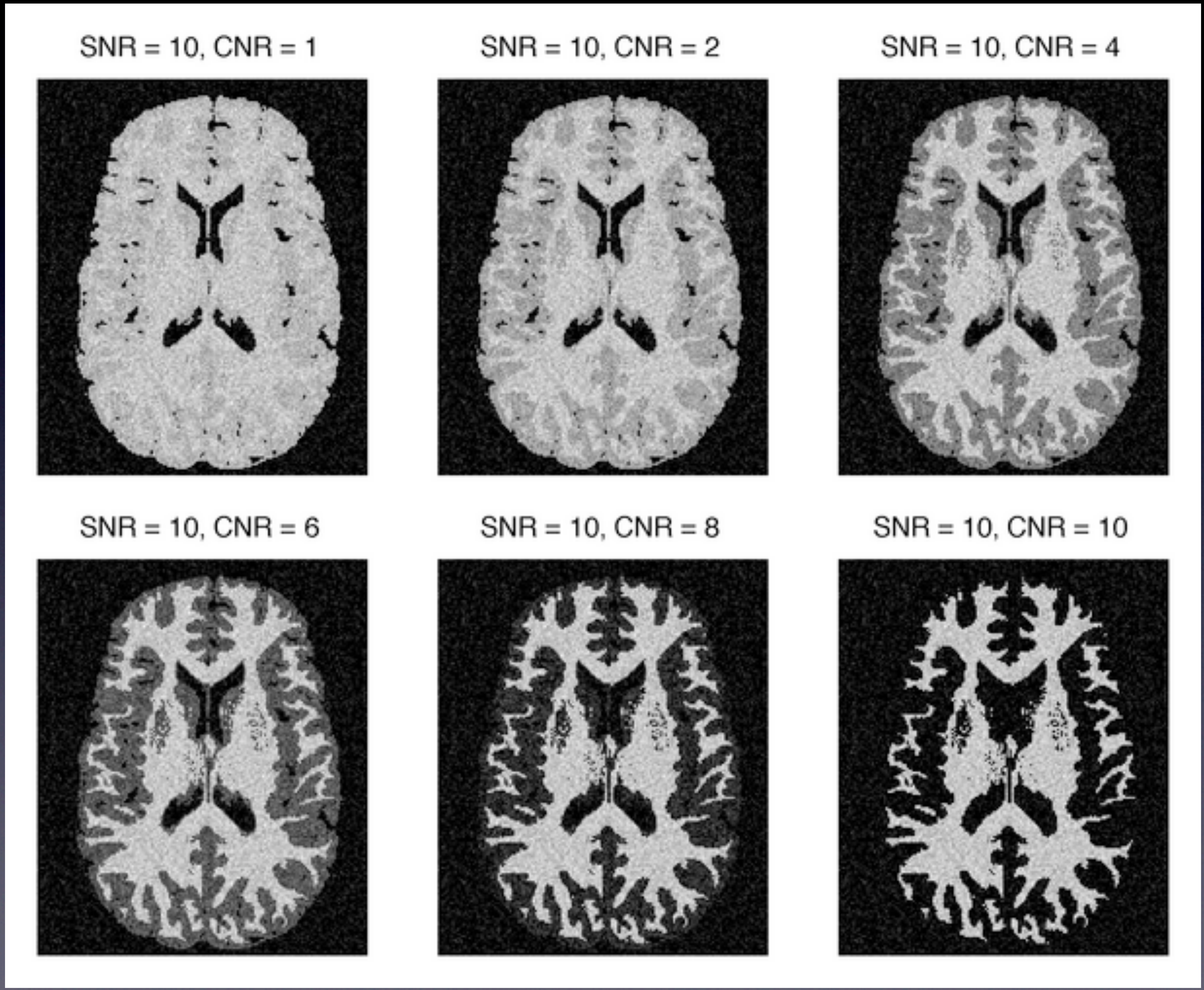


Can we recover lost SNR by averaging?

Yes! But it requires a 64-fold increase in scan time!

Contrast-to-noise ratio (CNR)



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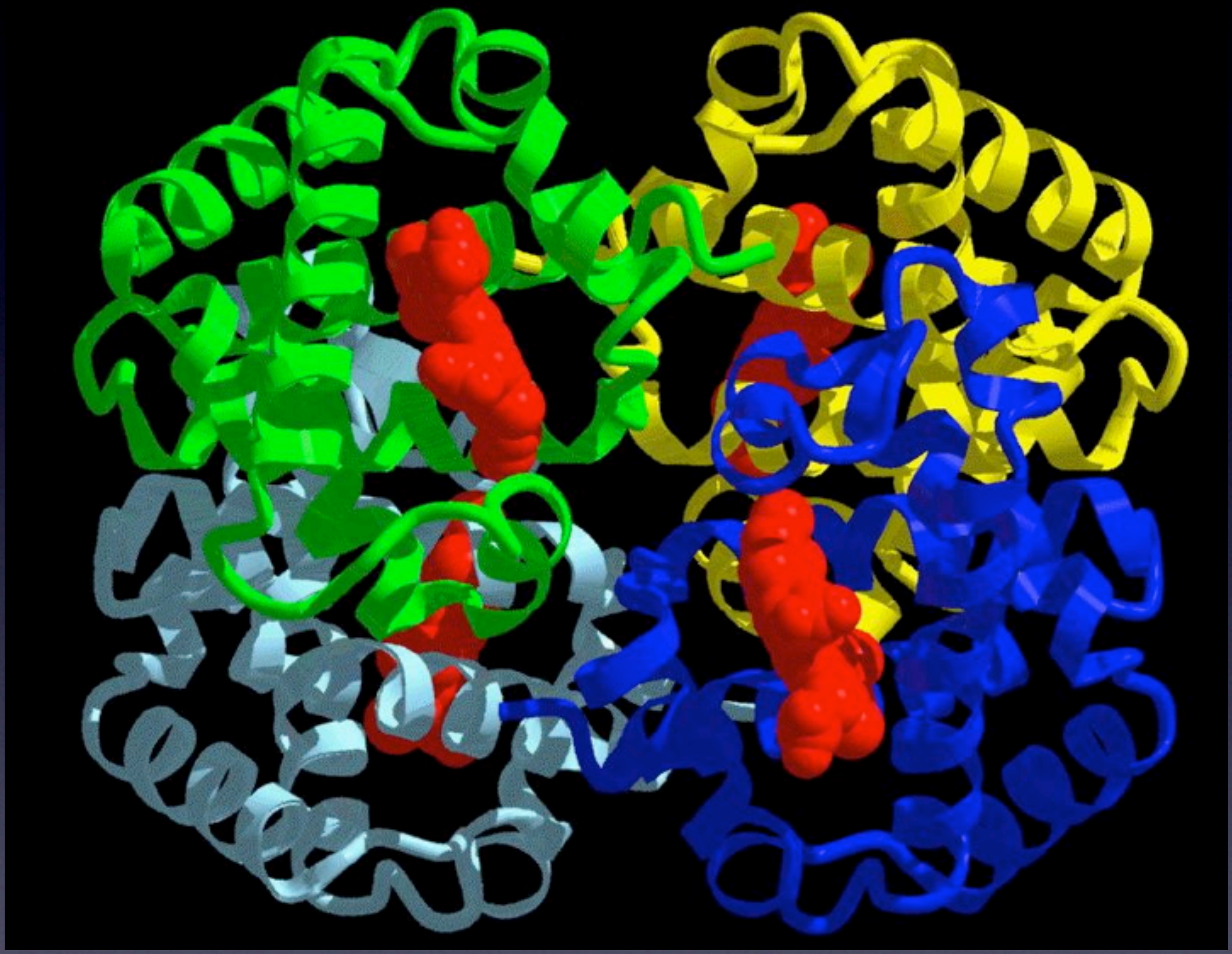
Deoxyhemoglobin is the source of FMRI signal

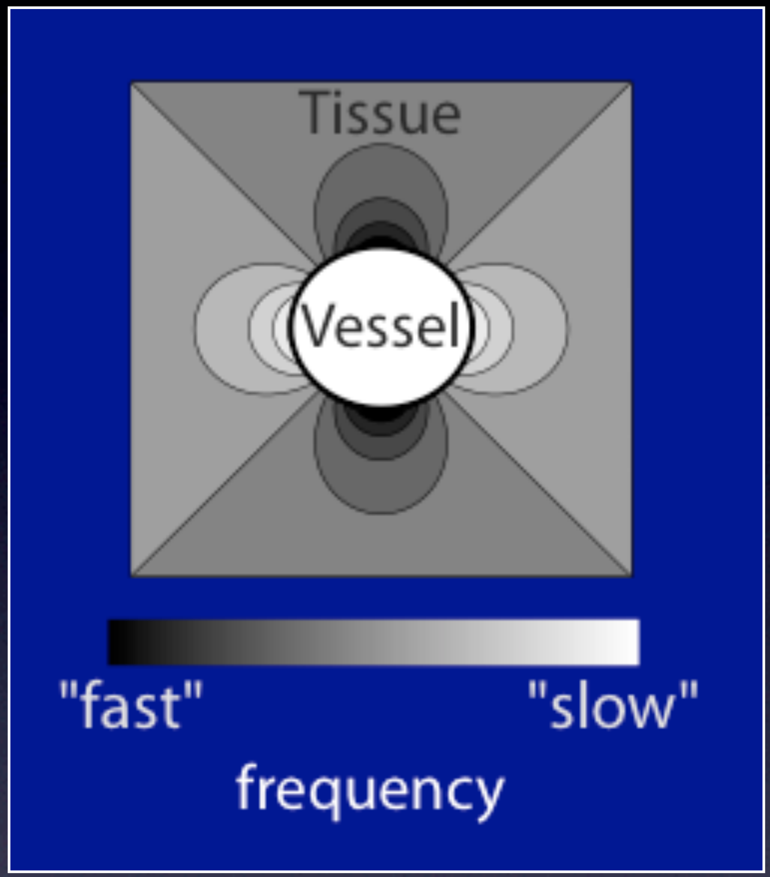


Oxyhemoglobin: diamagnetic (same as tissue)

Deoxyhemoglobin: paramagnetic (magnetic)

The BOLD Effect

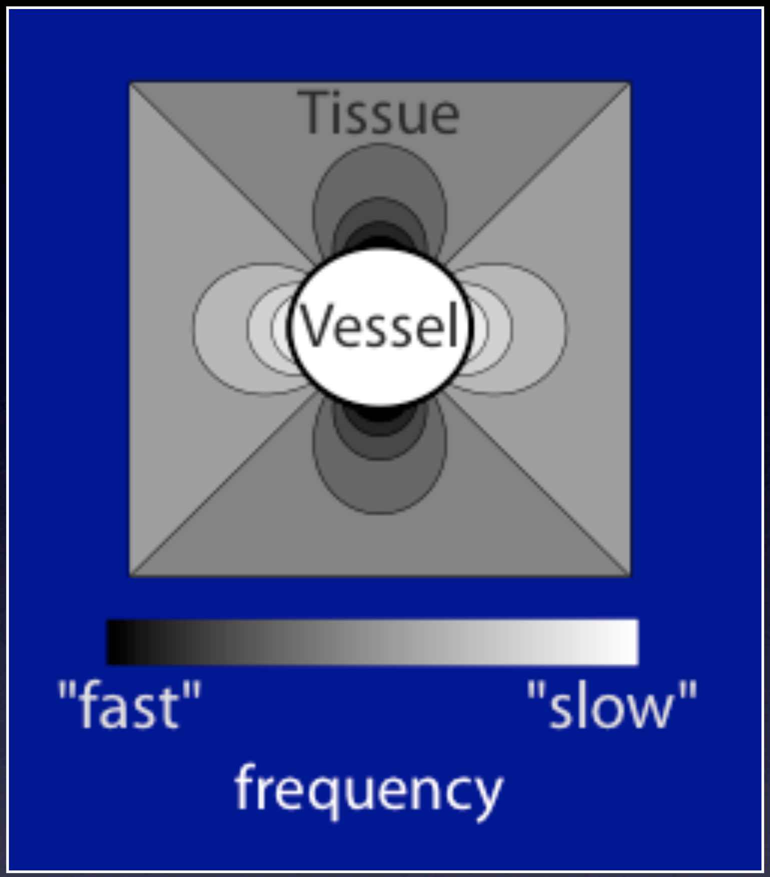
[Ogawa et al, 1990]

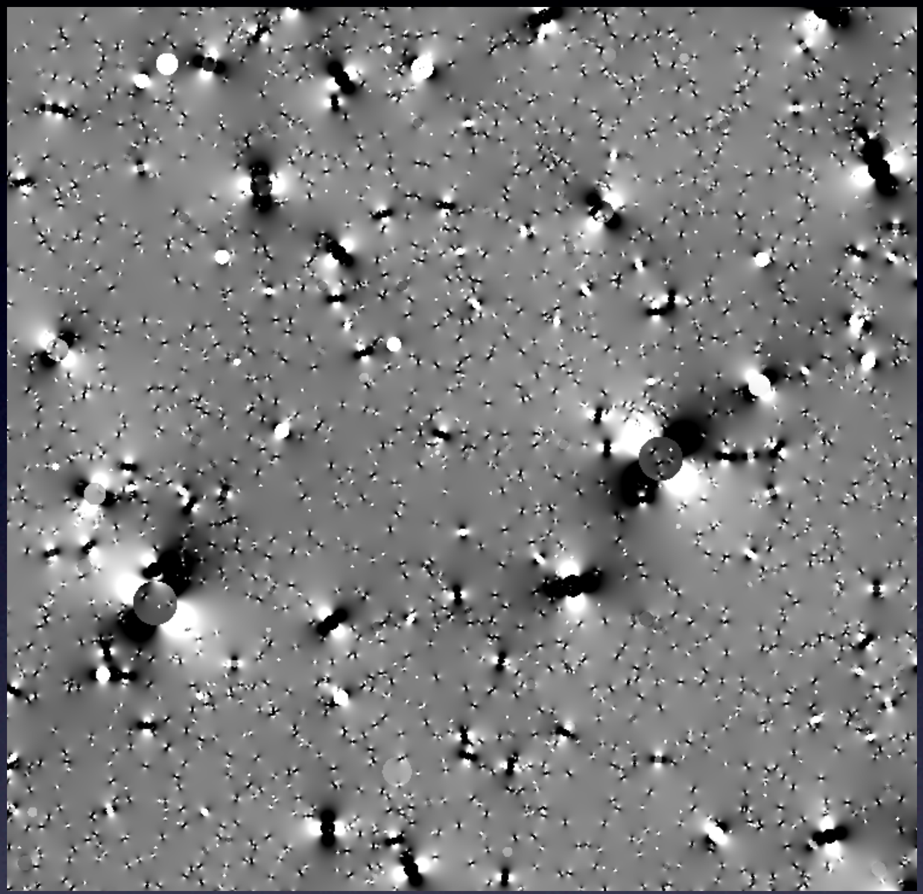


Blood Oxygenation Level Dependent (BOLD) effect

The BOLD Effect

[Ogawa et al, 1990]

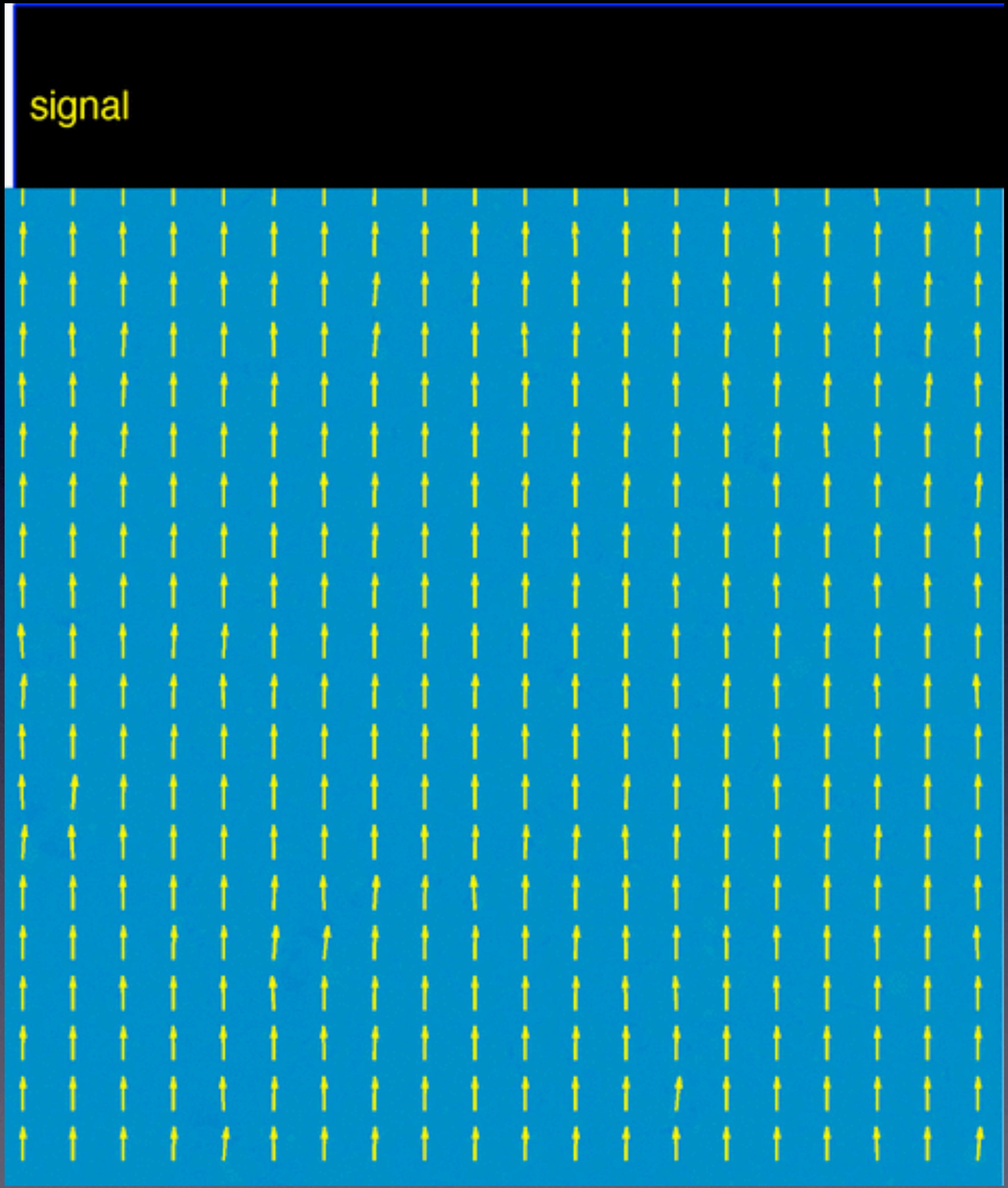




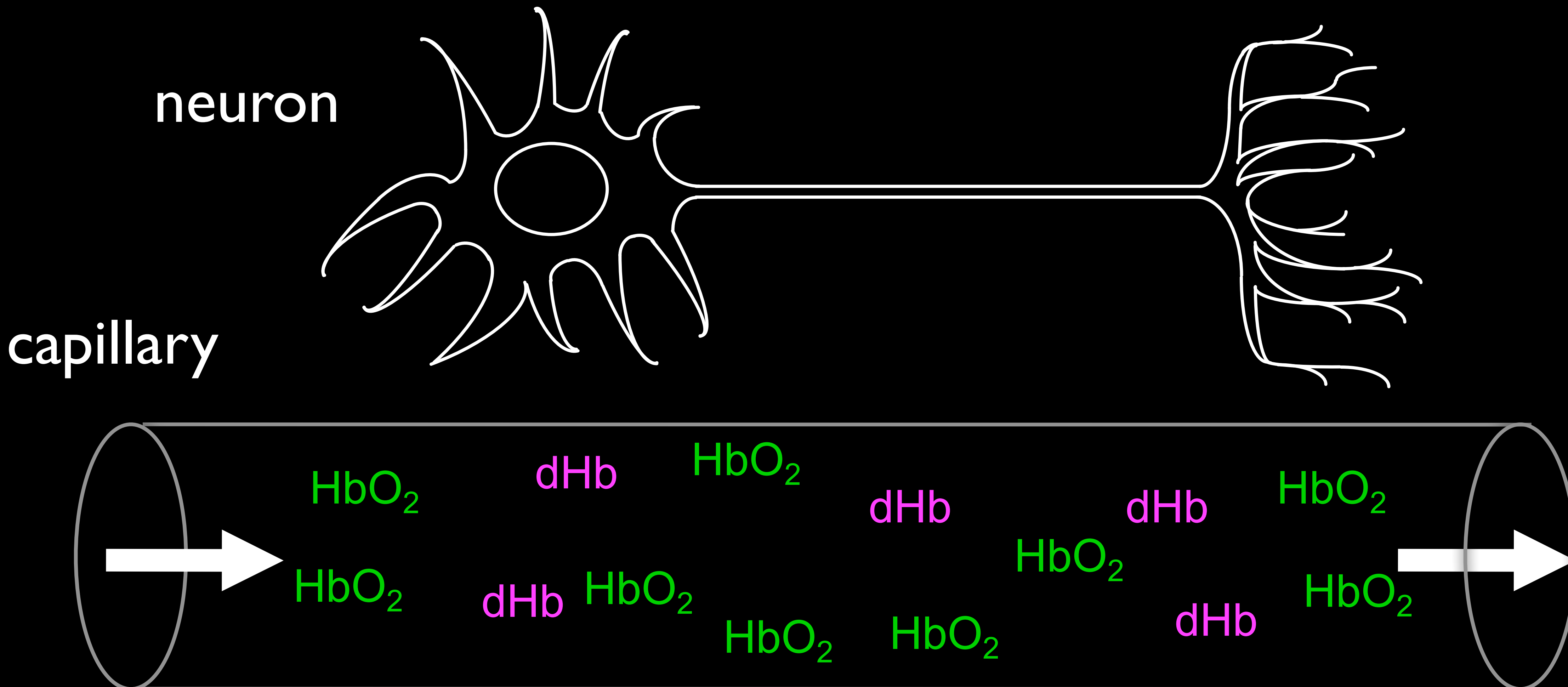
imaging voxel

Blood Oxygenation Level Dependent (BOLD) effect

Creates a range of frequencies in imaging voxel


signal

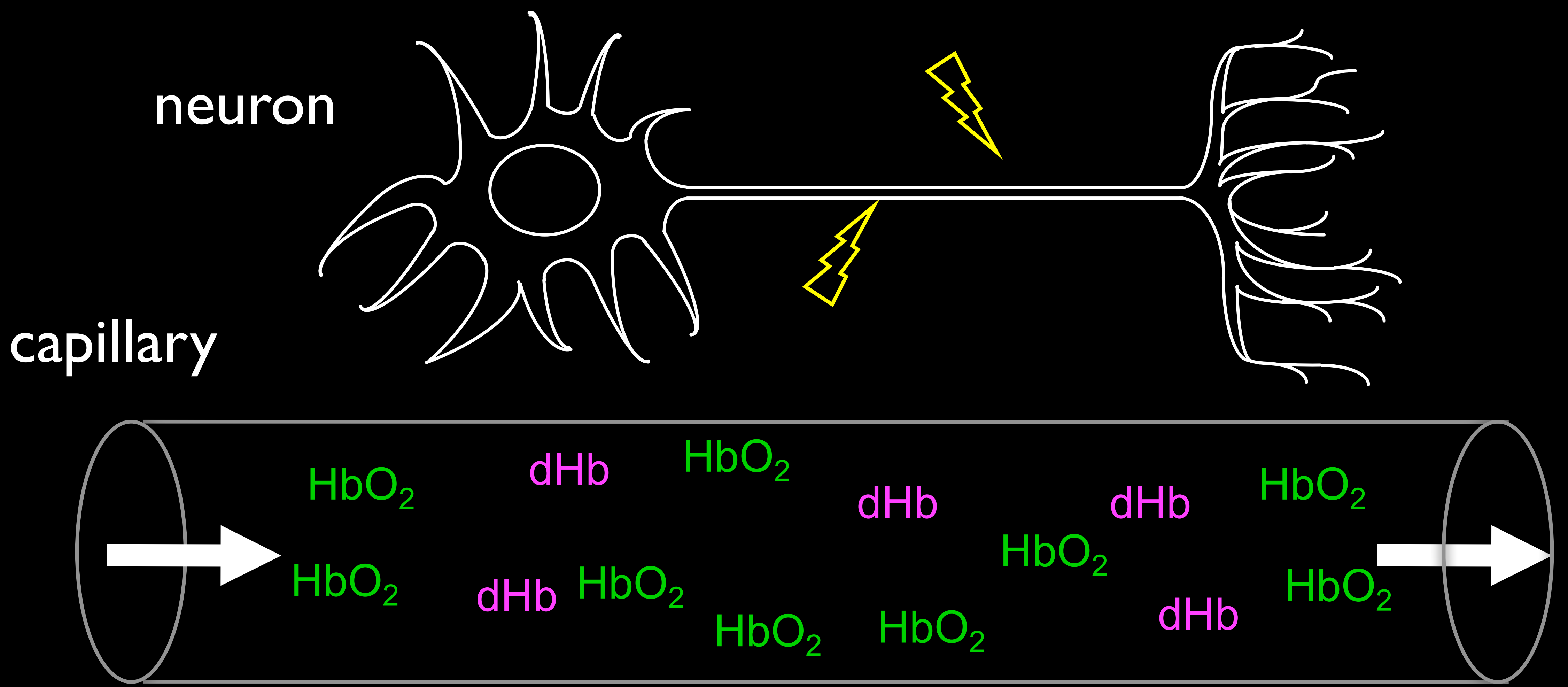
Vascular Response to Activation



HbO_2 = oxyhemoglobin

dHb = deoxyhemoglobin

Vascular Response to Activation



HbO_2 = oxyhemoglobin

dHb = deoxyhemoglobin

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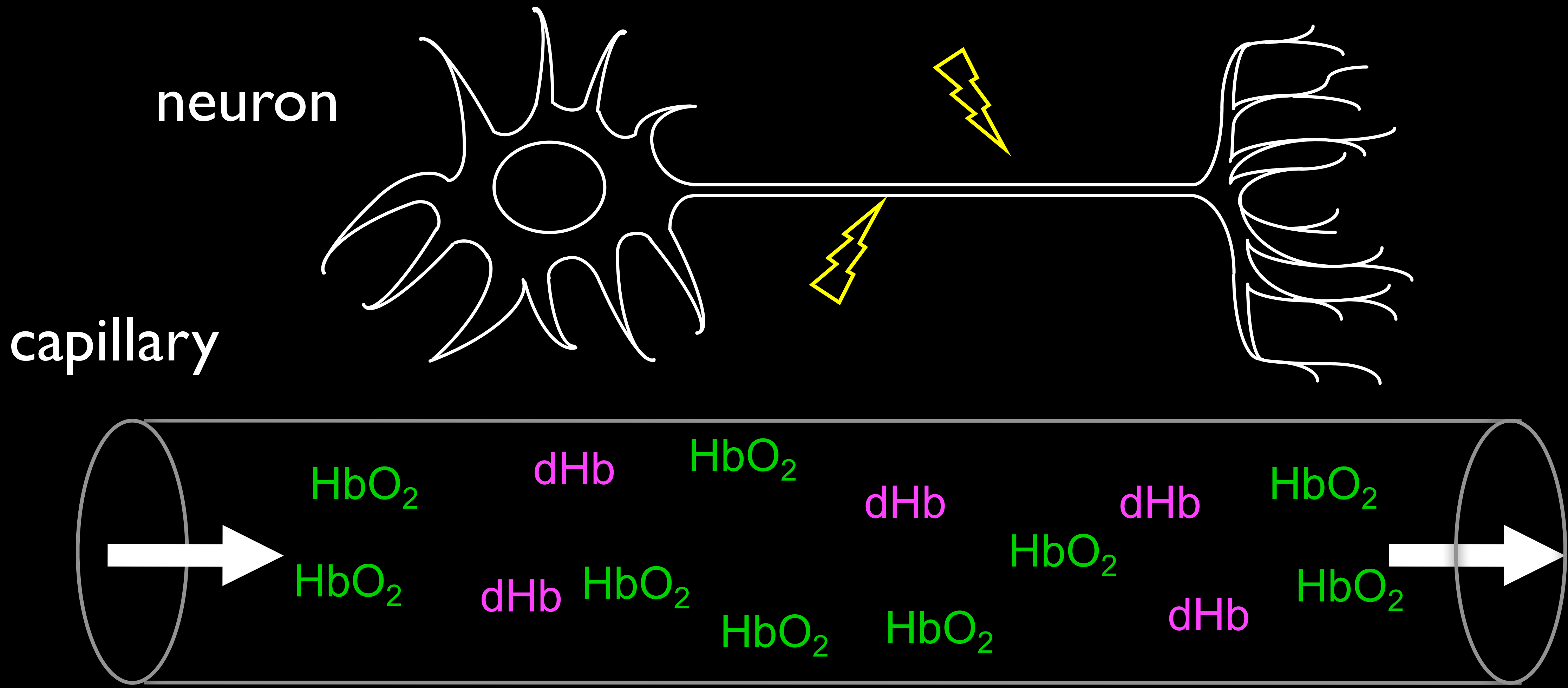

↑ O_2 metabolism ↑ dHb

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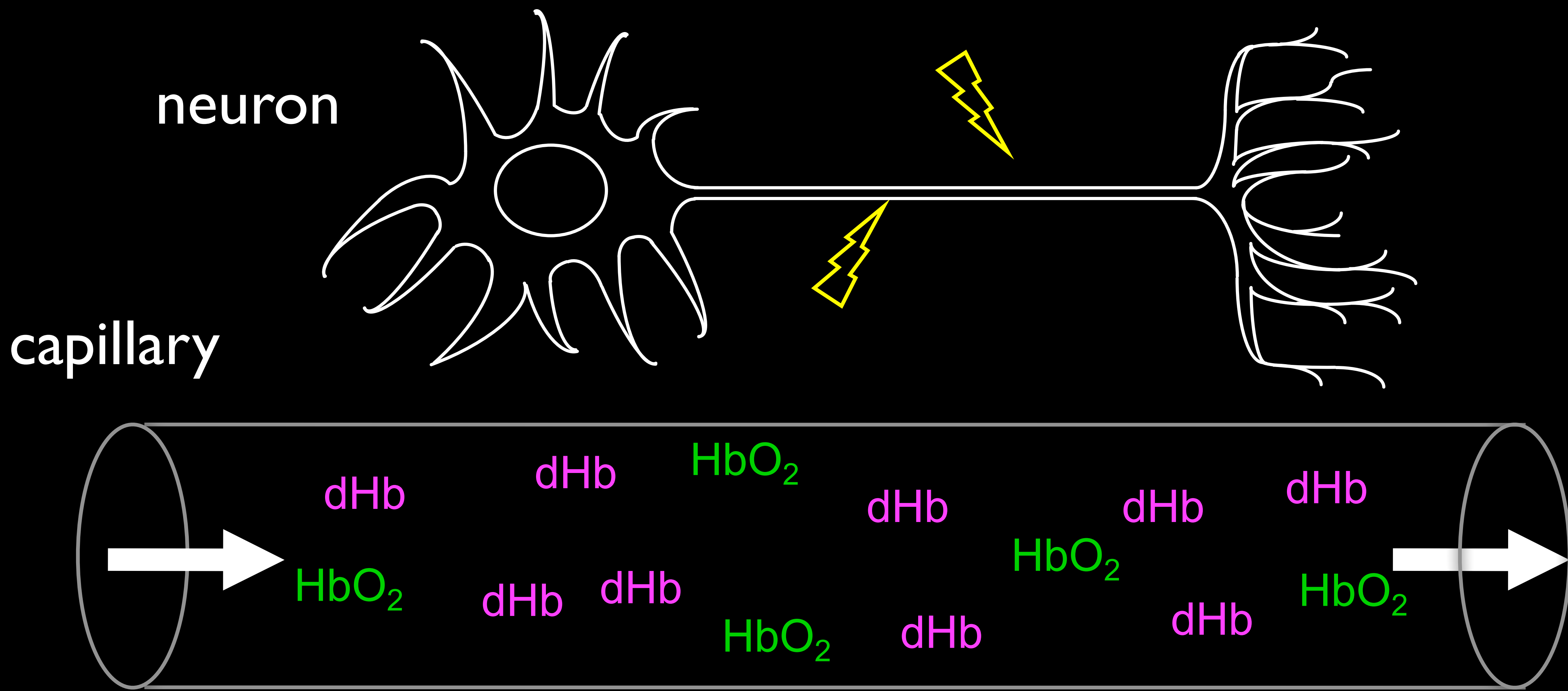

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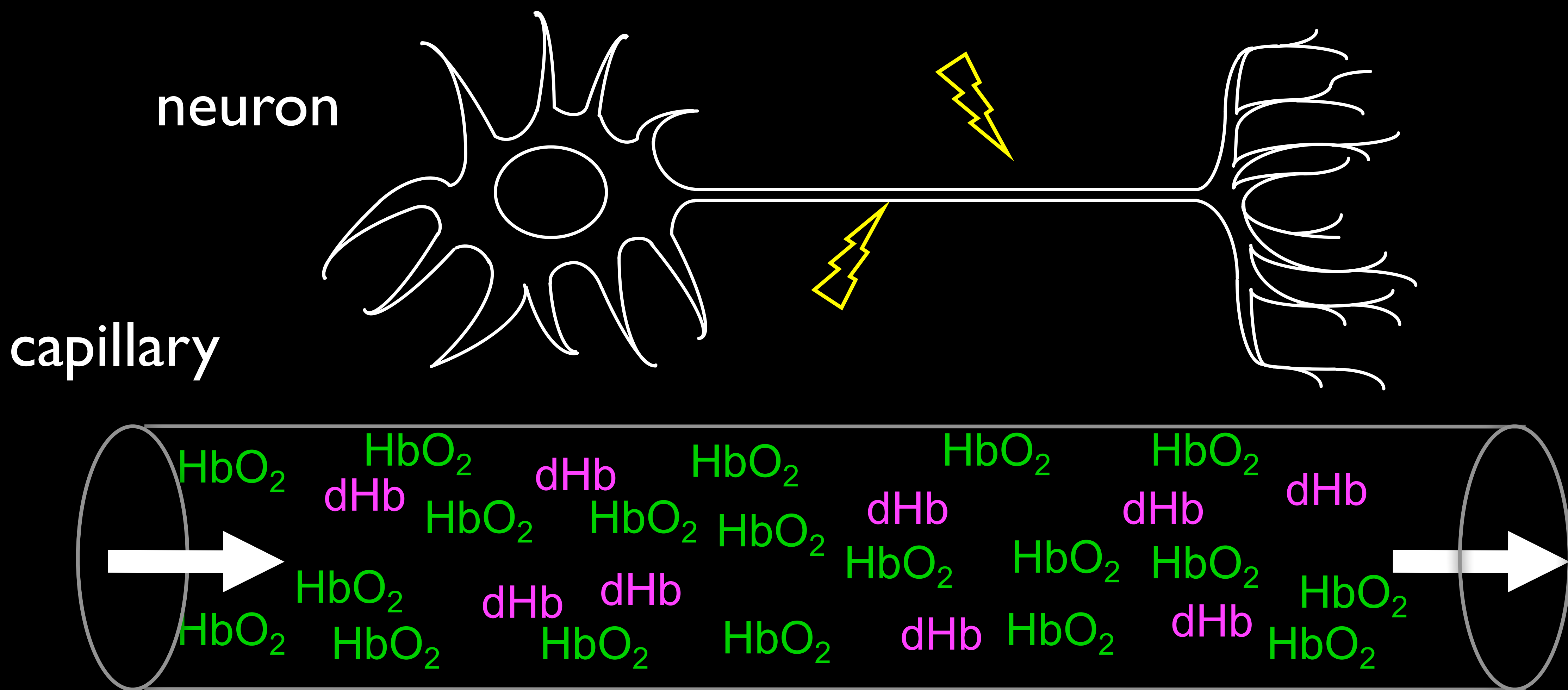

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↑ O_2 metabolism ↑ dHb

↑ blood flow ↑ HbO_2

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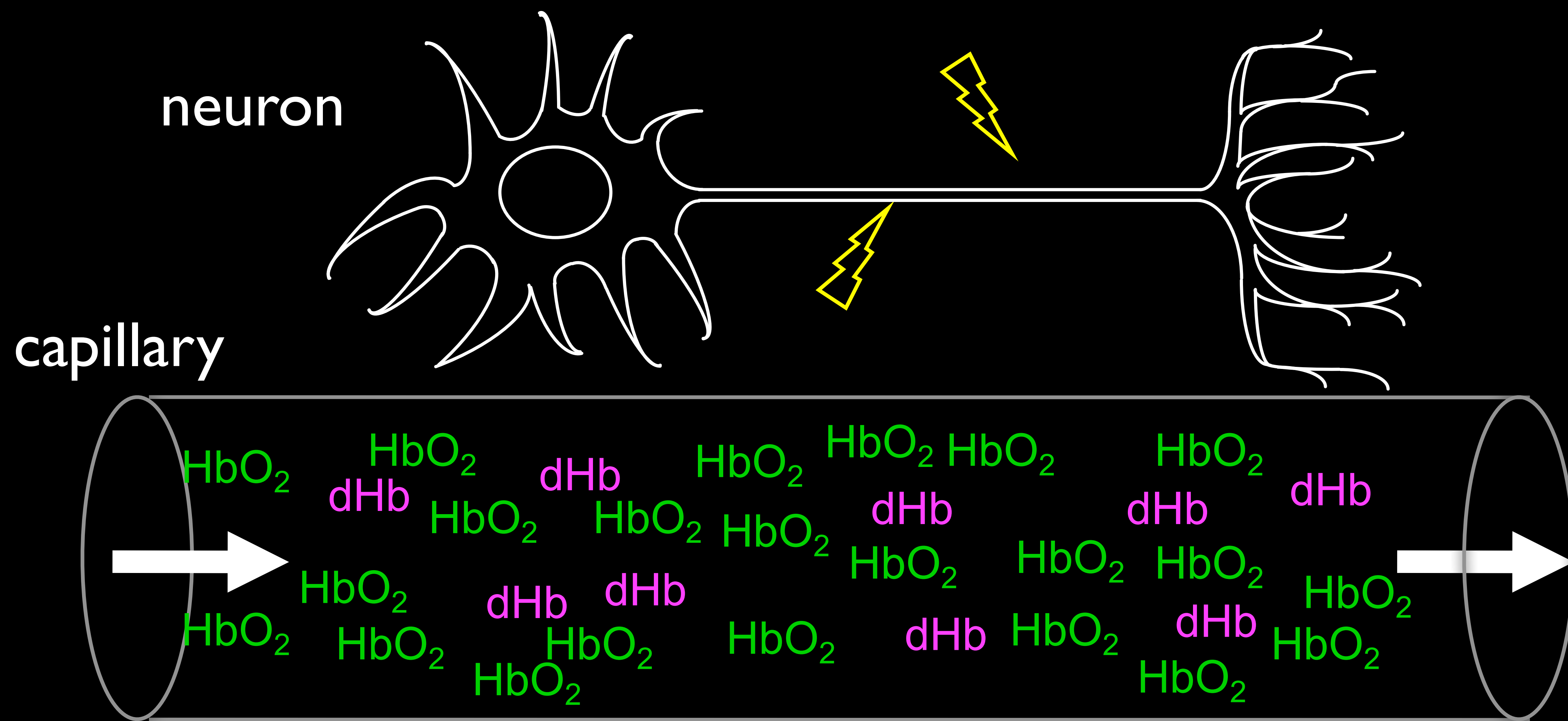

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↑ blood volume ↑ HbO_2

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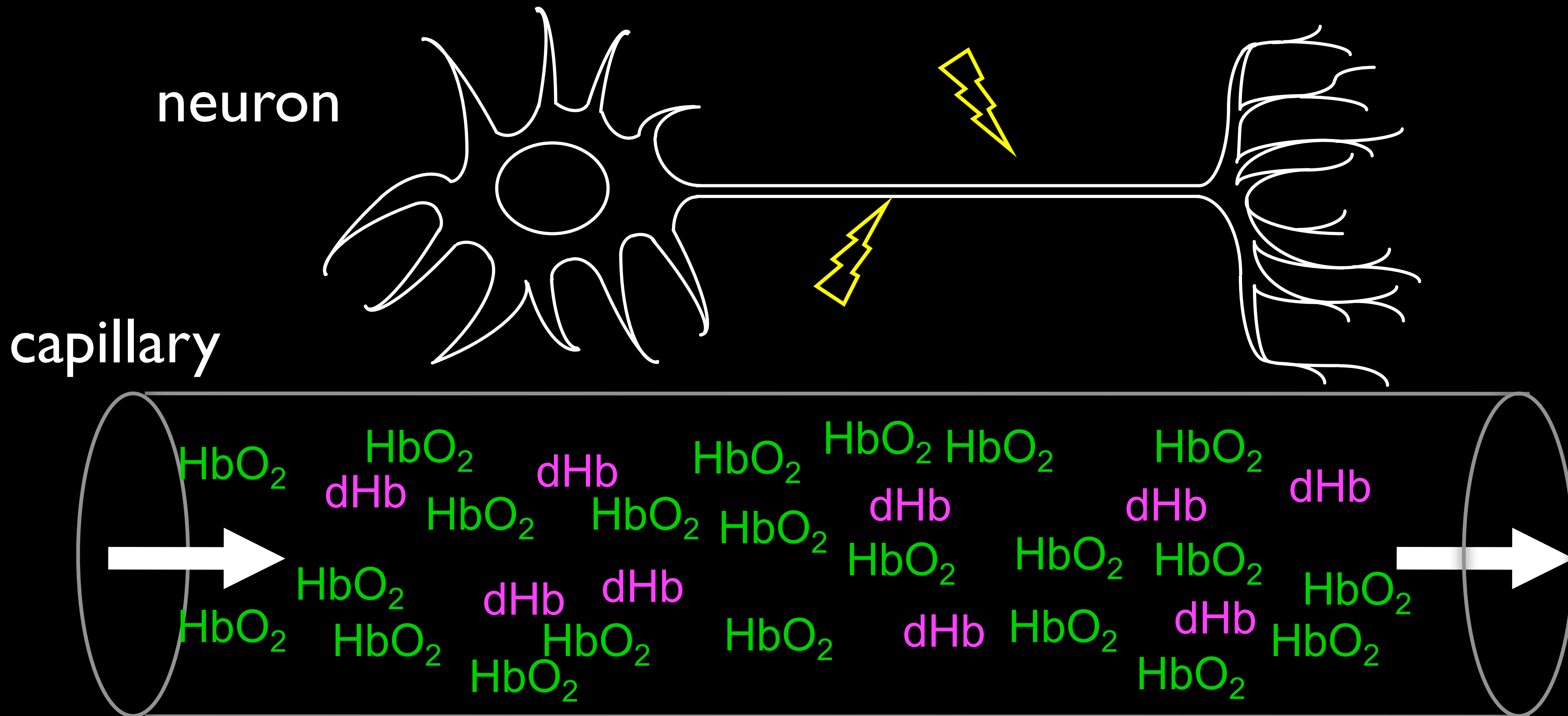

HbO_2 = oxyhemoglobin

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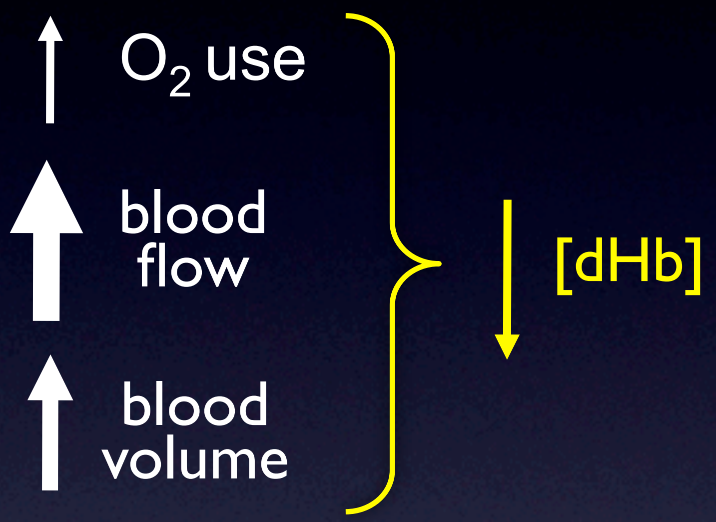
↑ O_2 metabolism — ↑ dHb

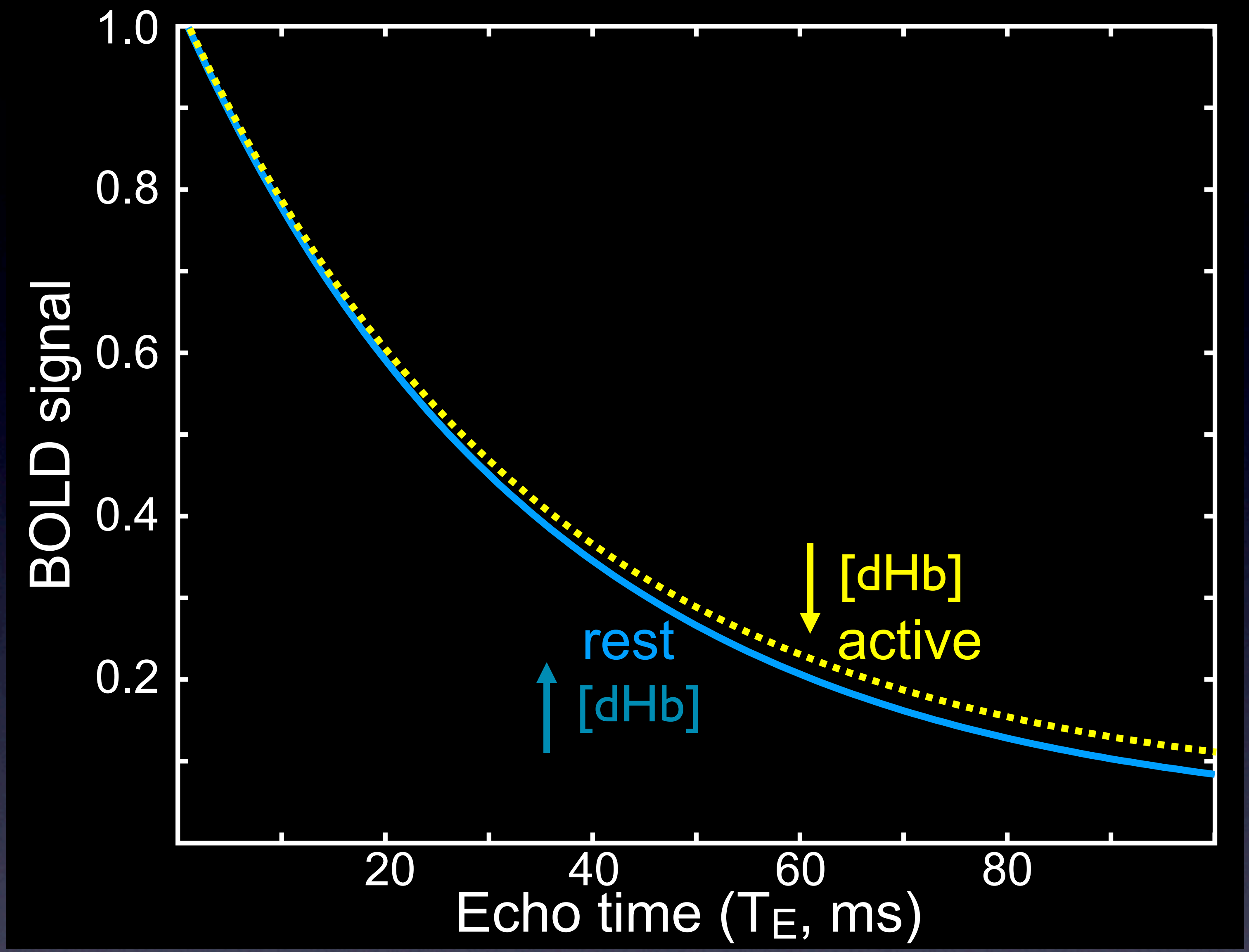
↑ blood flow — ↑ HbO_2

↑ blood volume — ↑ HbO_2

} ↓ [dHb]

BOLD Contrast



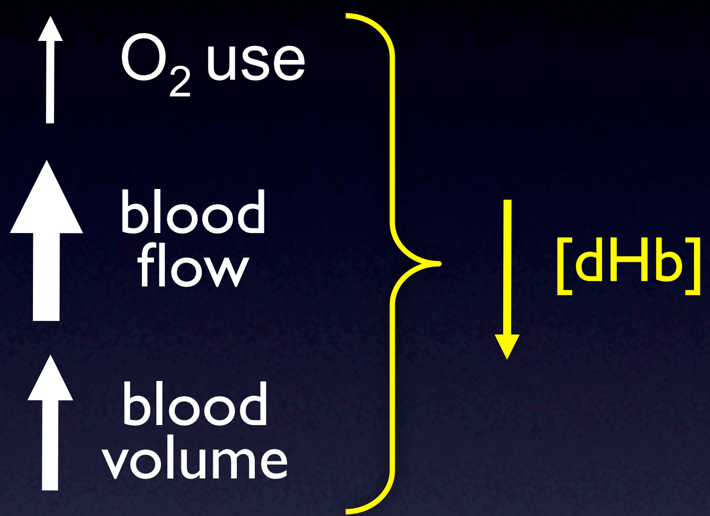


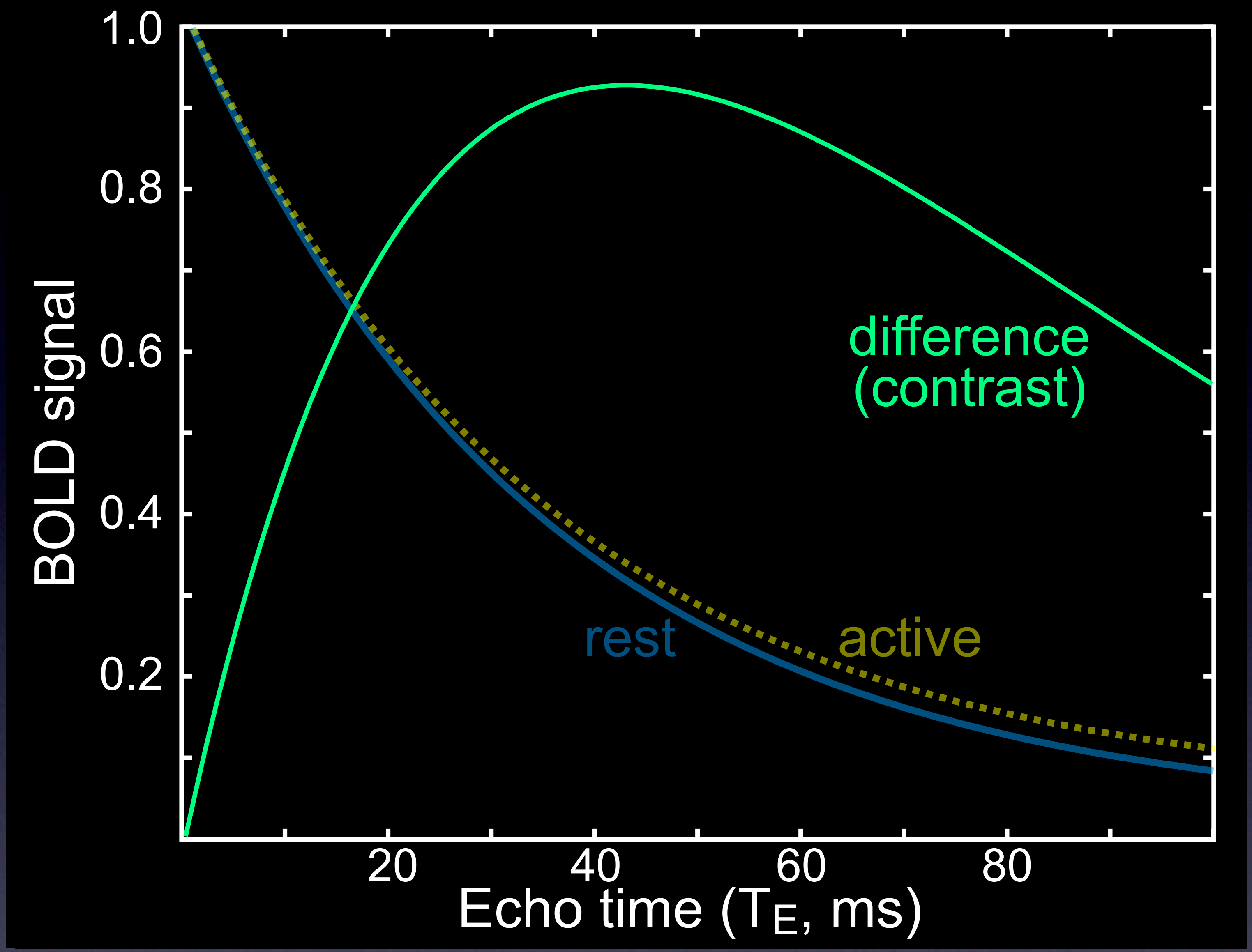
Signal increases during activation (less decay)

Signal change for longer delay (T_E)

Typically, 1–5% signal change

BOLD Contrast





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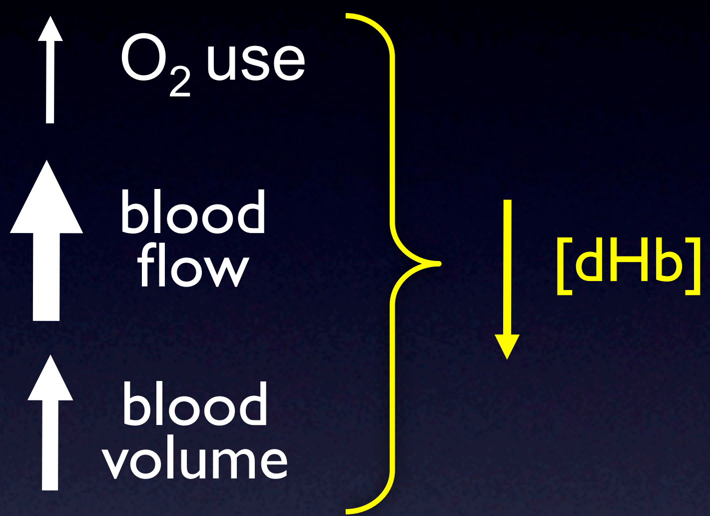

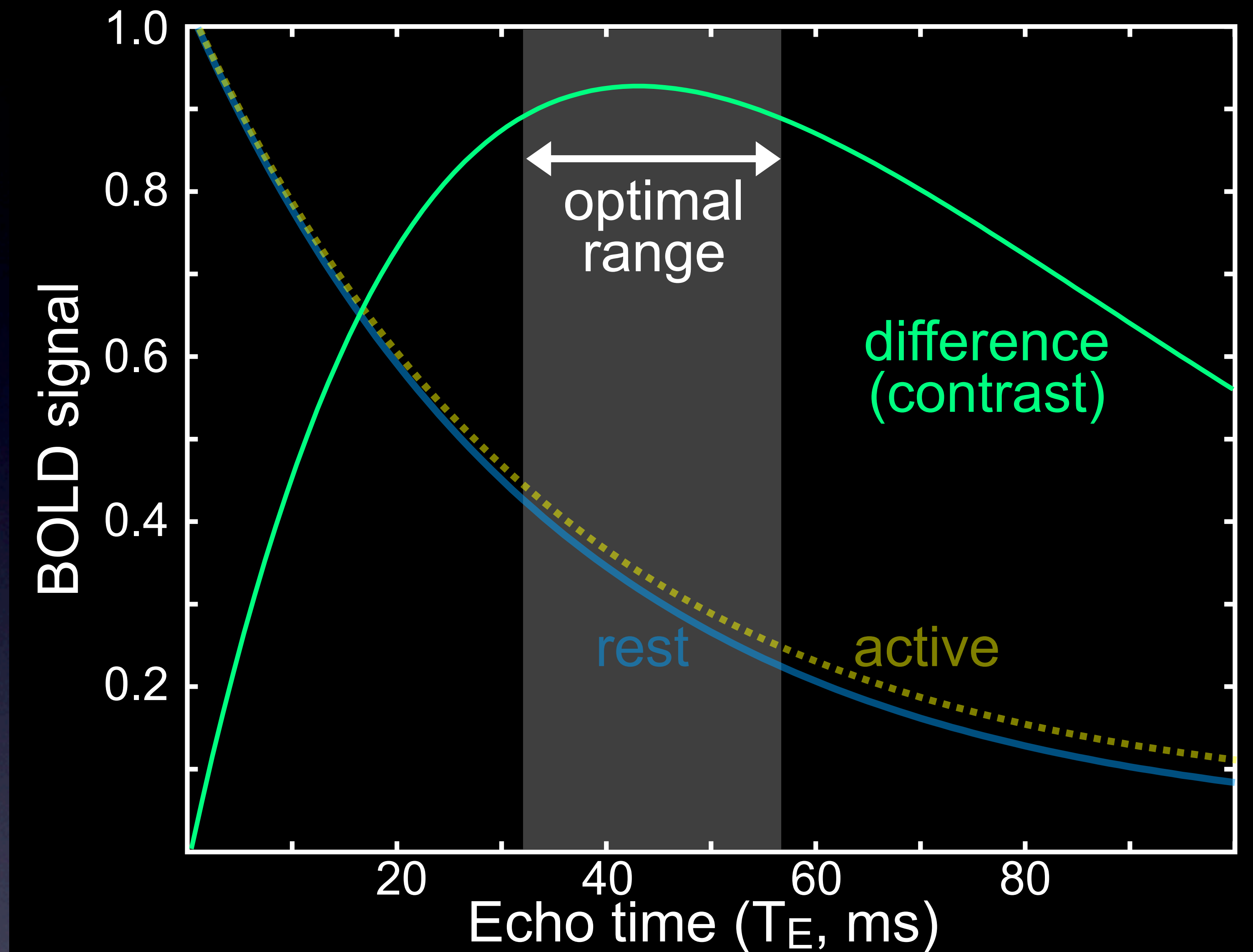

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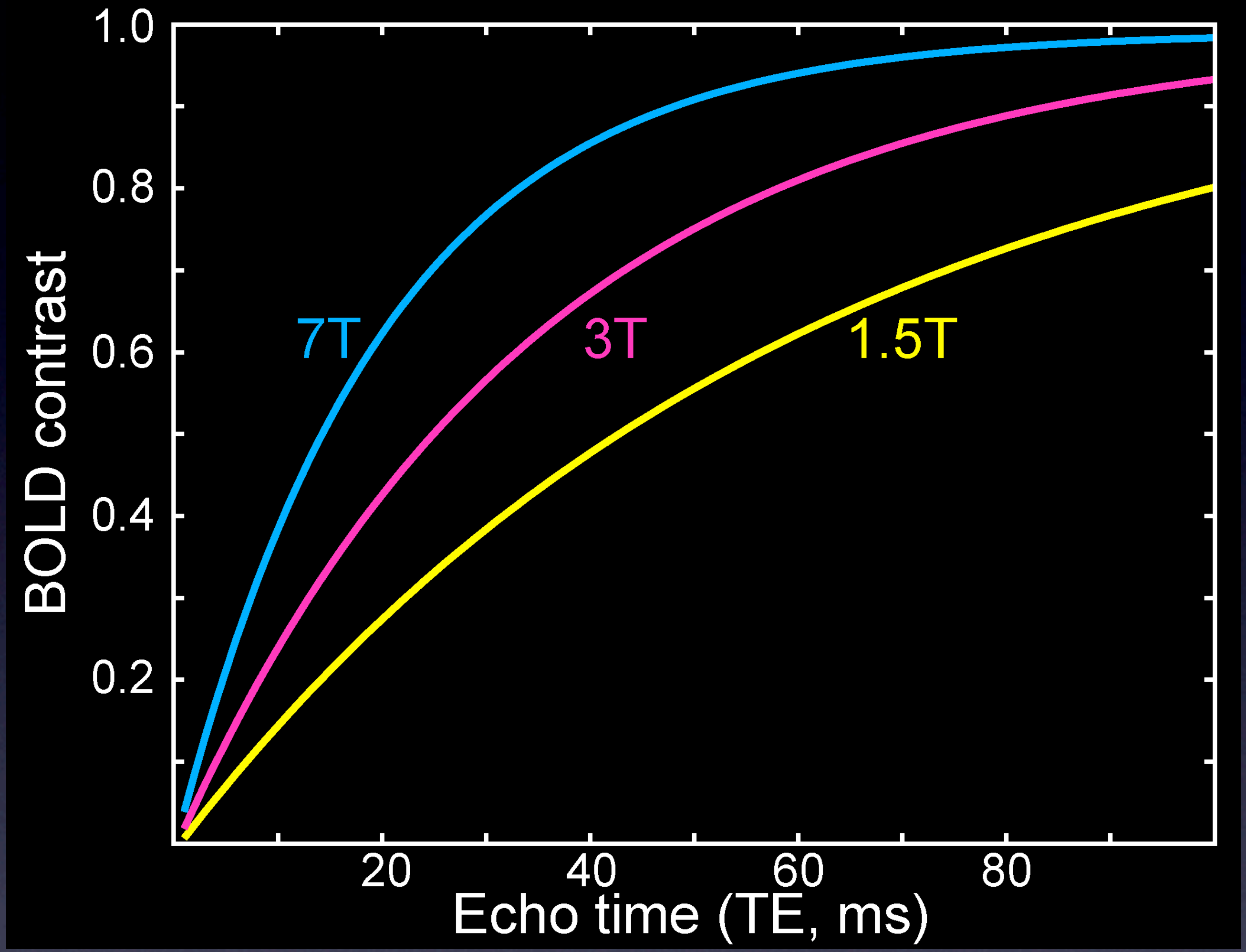
BOLD signal and field strength (B_0)

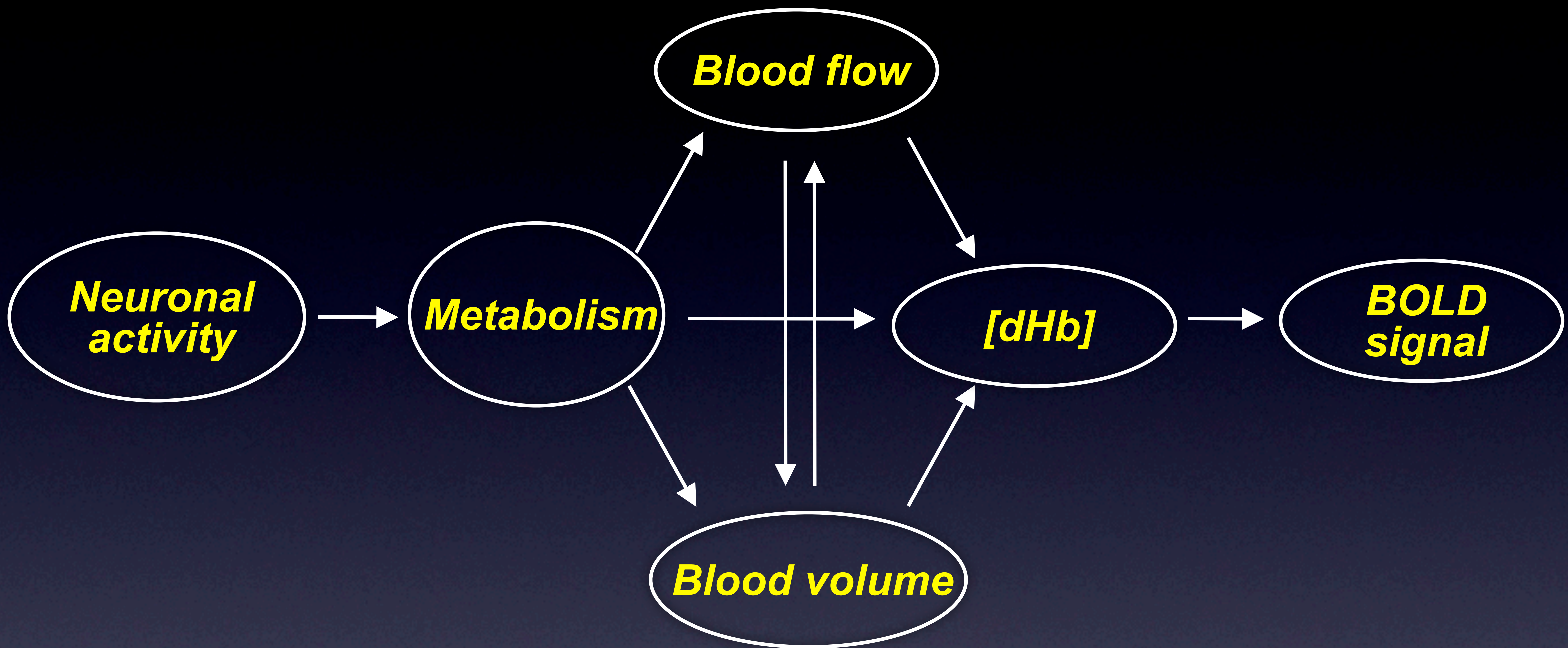


SNR *and* BOLD increase with field strength

Image artefacts worse at higher field strength

3T is currently a good tradeoff of signal vs artefacts

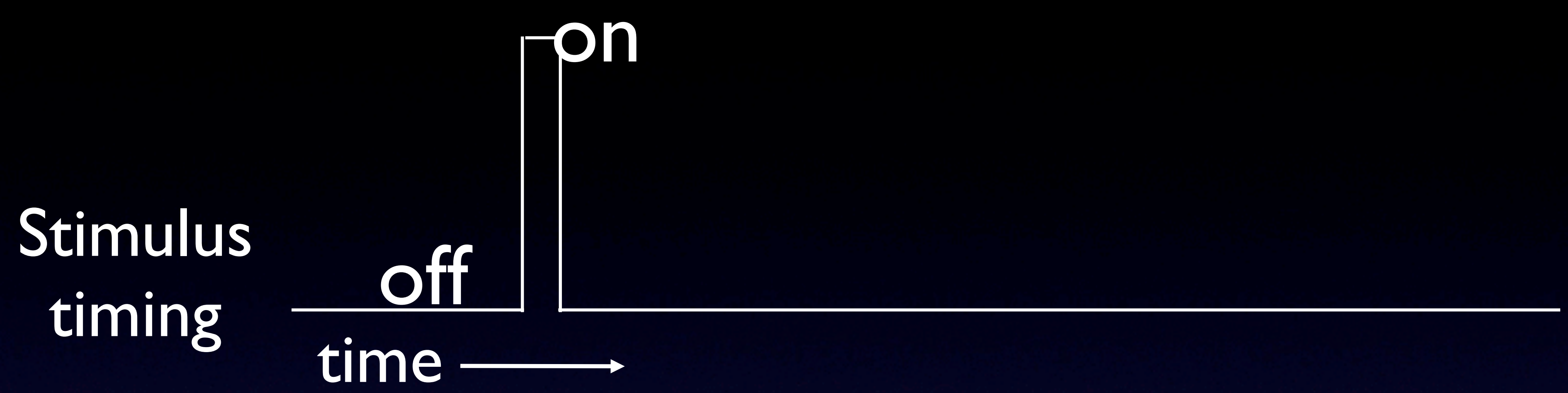
Sources of BOLD Signal



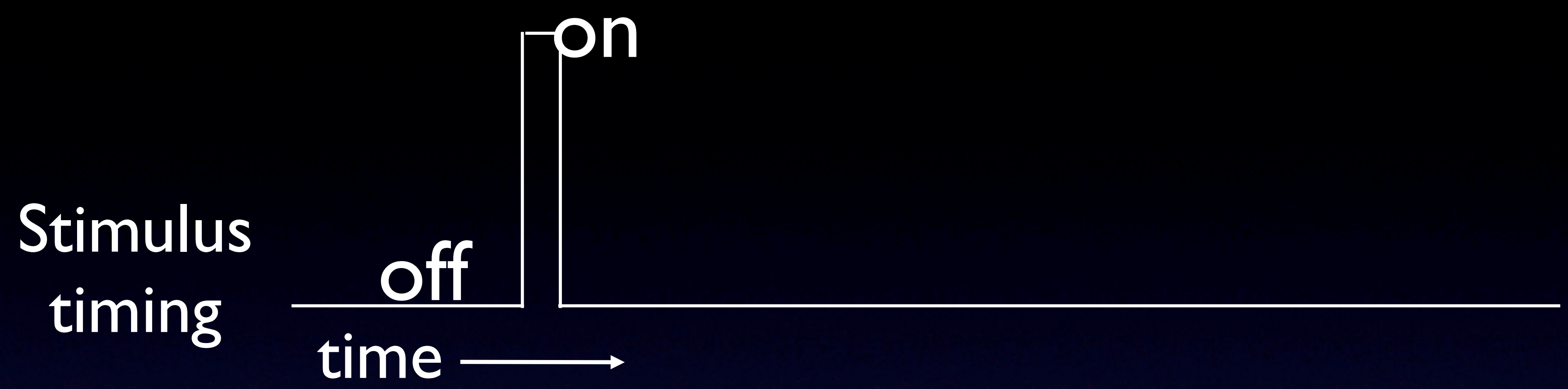
Indirect measure of activity (via metabolism!)

Subject's physiological state & pathology can change neurovascular coupling, muddying interpretation

Hemodynamic response function (HRF)

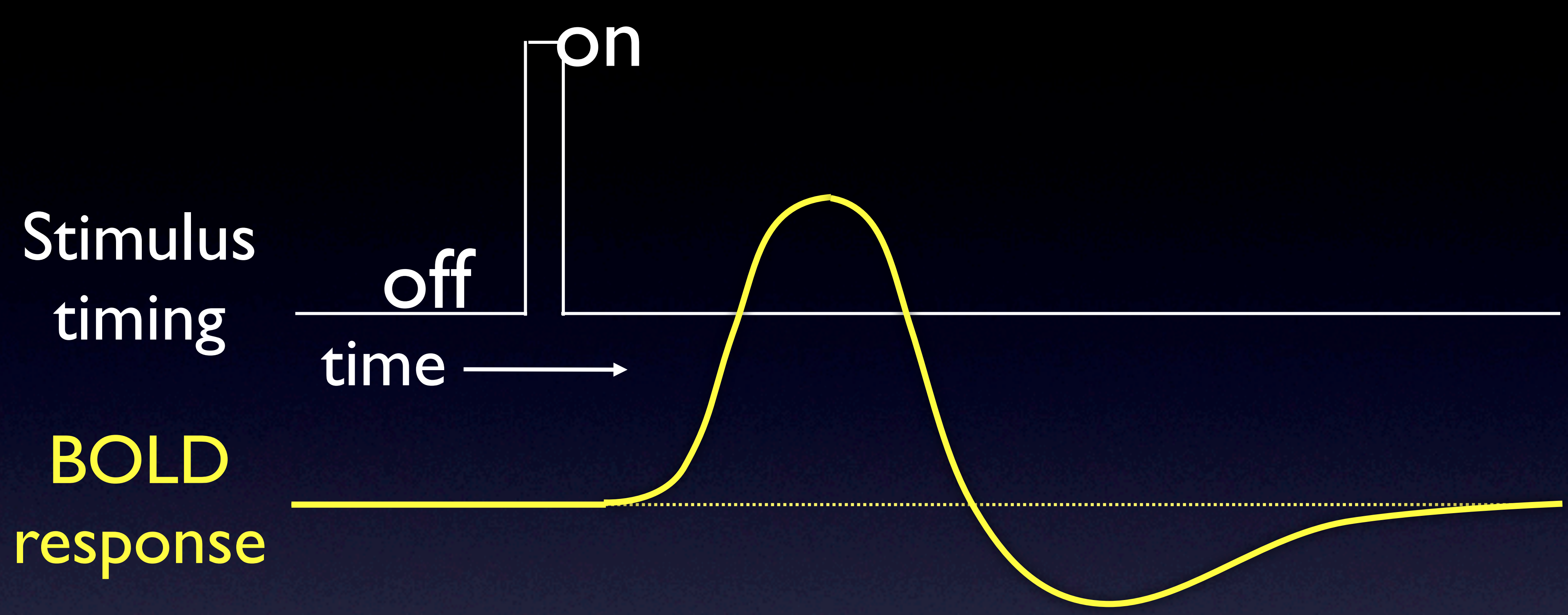


Hemodynamic response function (HRF)



- Vascular response to activity is delayed & blurred

Hemodynamic response function (HRF)



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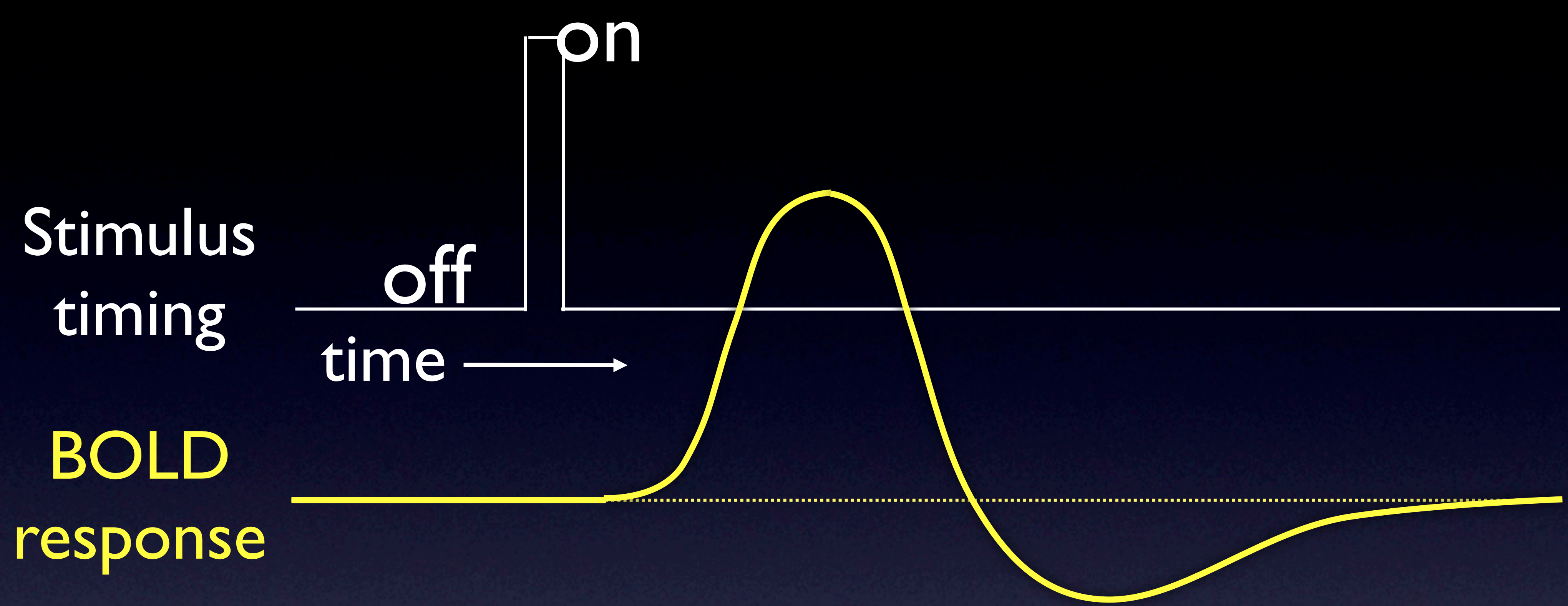
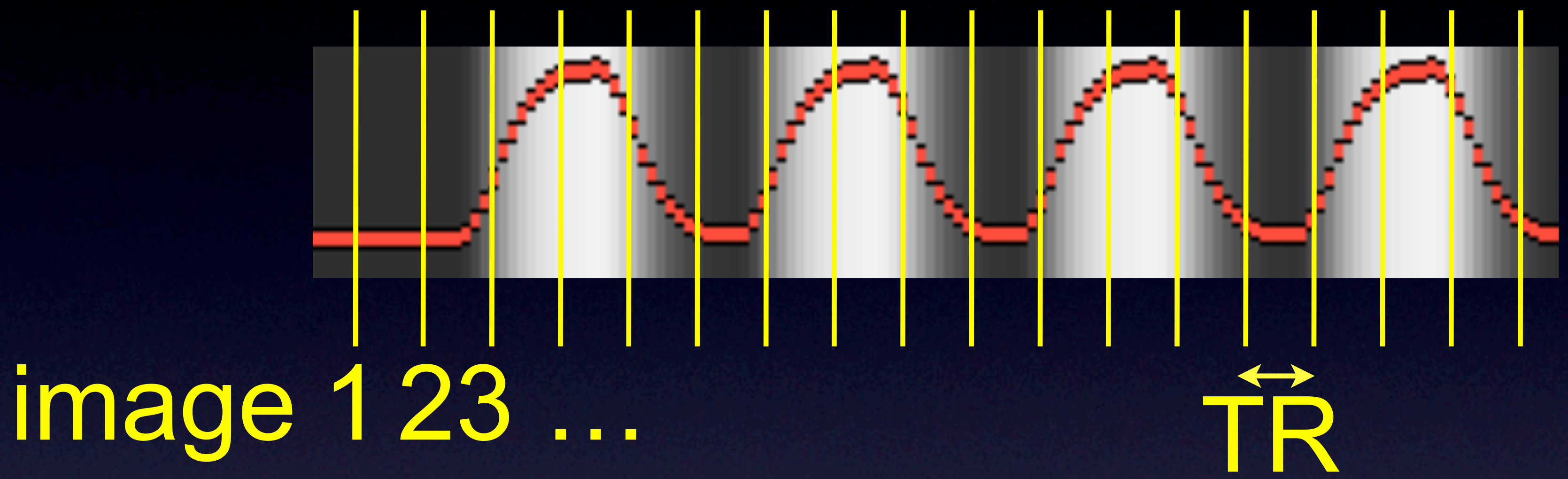
Hemodynamic response function (HRF)



- Vascular response to activity is delayed & blurred
- Described by "hemodynamic response function"
- Limits achievable temporal resolution
- Must be included in signal model

What is required of the scanner?



Typical stimulus lasts 1–30 s

Rapid imaging: one image every few seconds

Anatomical images take minutes to acquire!

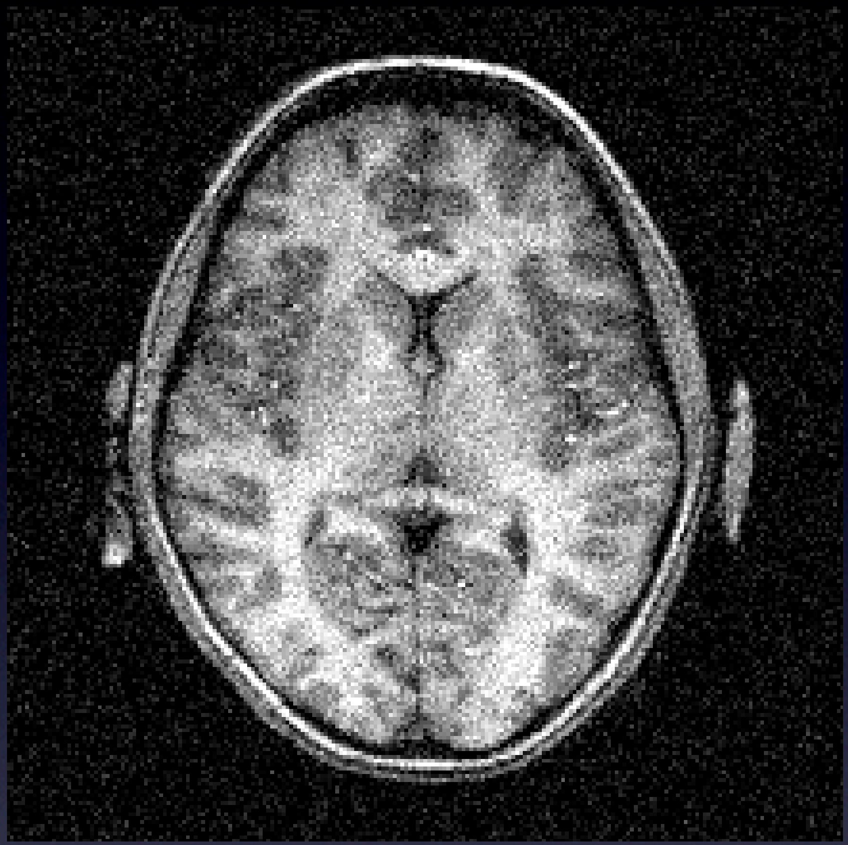
Acquire “single-shot” images (e.g., EPI)

Typical* FMRI Parameters

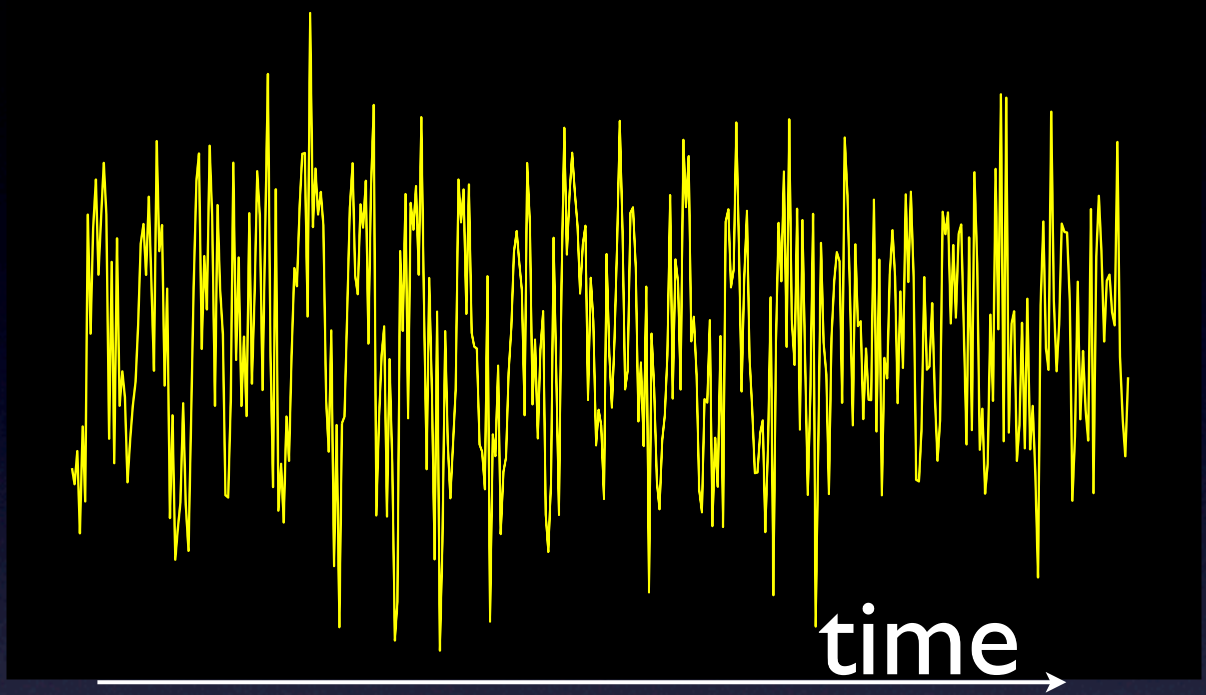
* Typical, *not* fixed!!

Parameter	Value	Relevant points
T_E (echo time)	1.5T: 60 ms 3.0T: 30-40 ms 7.0T: 15-20 ms	Determines functional contrast, set $\approx$T2*
T_R (repeat time)	1–4 s	HRF blurring < 1s; Poor resolution > 6s
Matrix size / Resolution	64x64 / 2-3 mm	Limited by distortion, SNR, FOV
Scan duration	2-60 mins	Lower limit: sensitivity Upper limit: compliance

Confounds: Noise



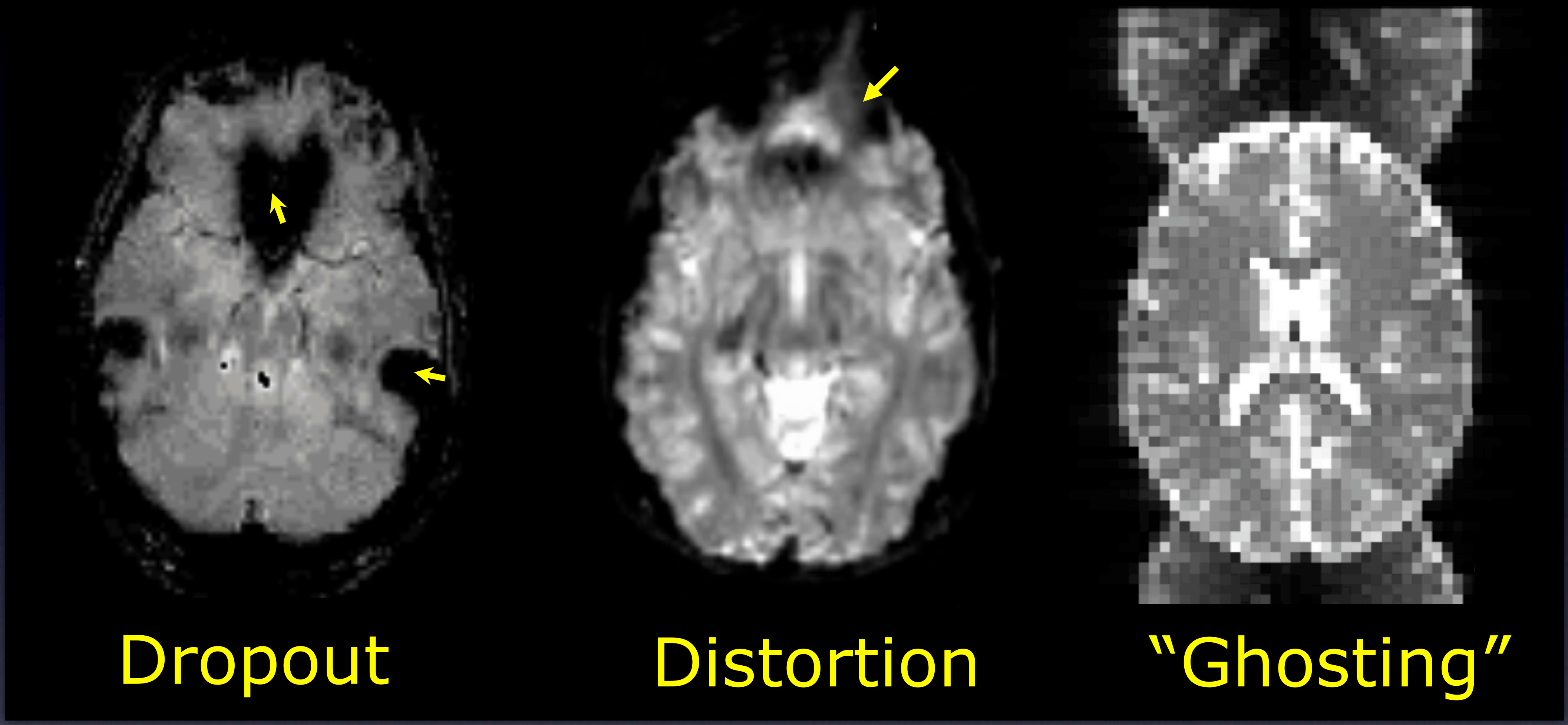
Purely random noise
(example: "thermal")



Structured noise
(example: "physiological")

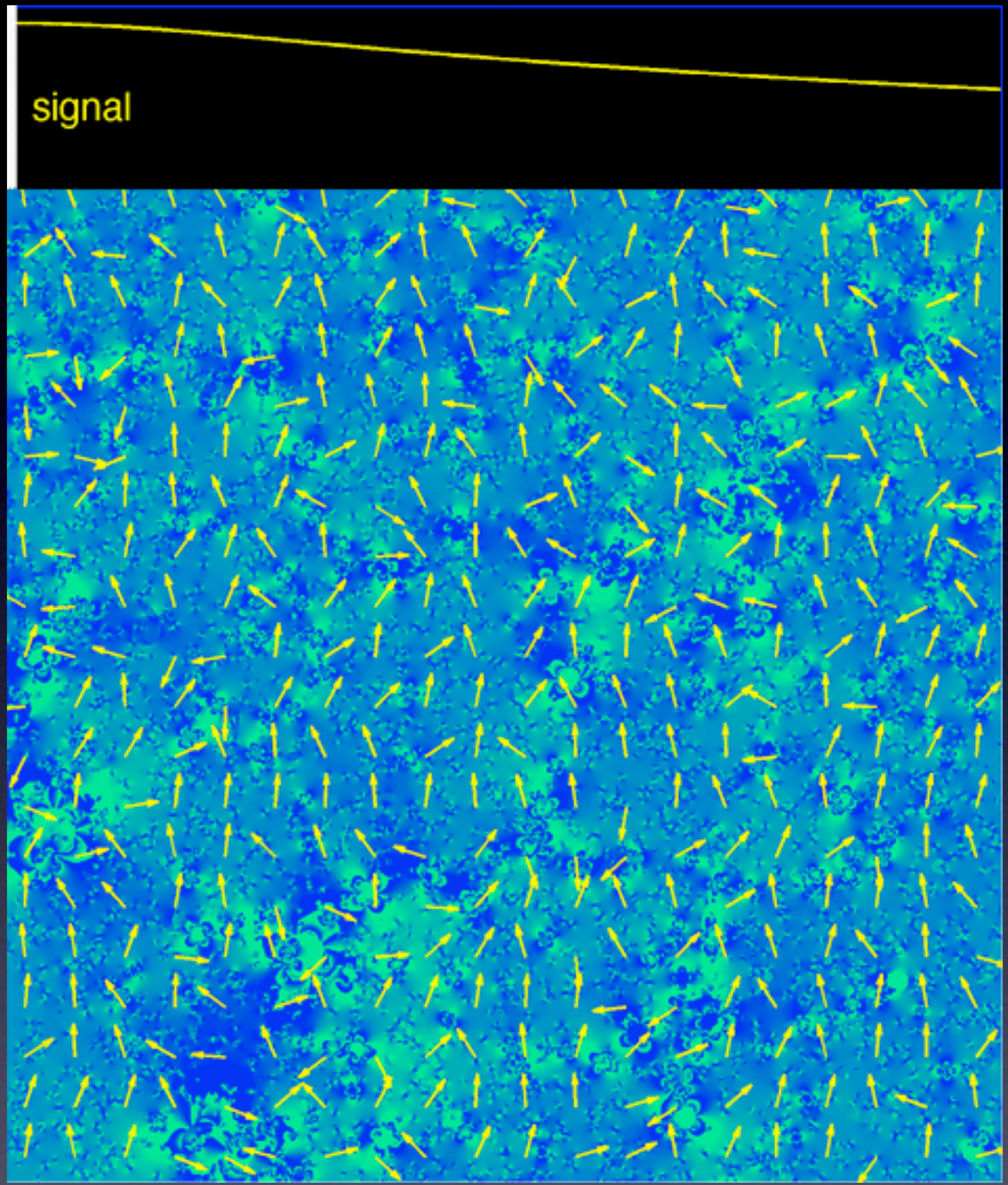
- Noise: signal fluctuations leading to less robust detection with respect to statistical measures

Confounds: Artefacts



Artefacts: systematic errors that interfere with interpretability of data/images

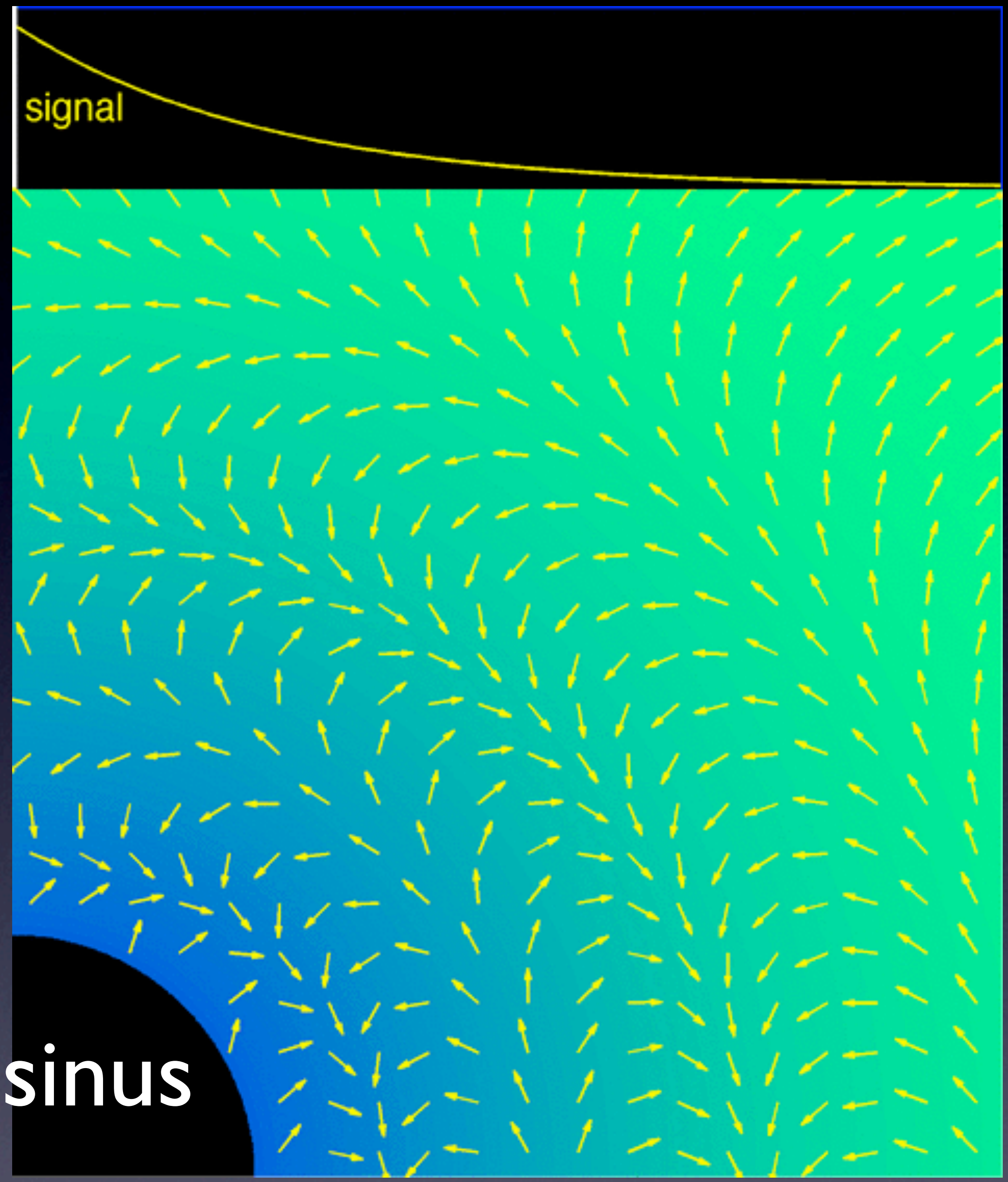
Source of signal dropout



BOLD contrast is based on signal dephasing

BOLD imaging requires long delay (T_E) for contrast

Source of signal dropout

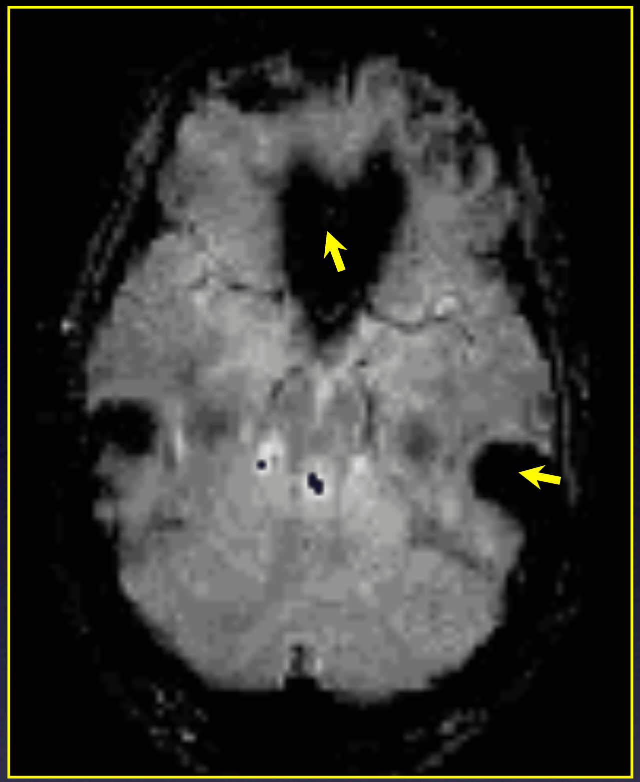


Dephasing also occurs near air-tissue boundaries

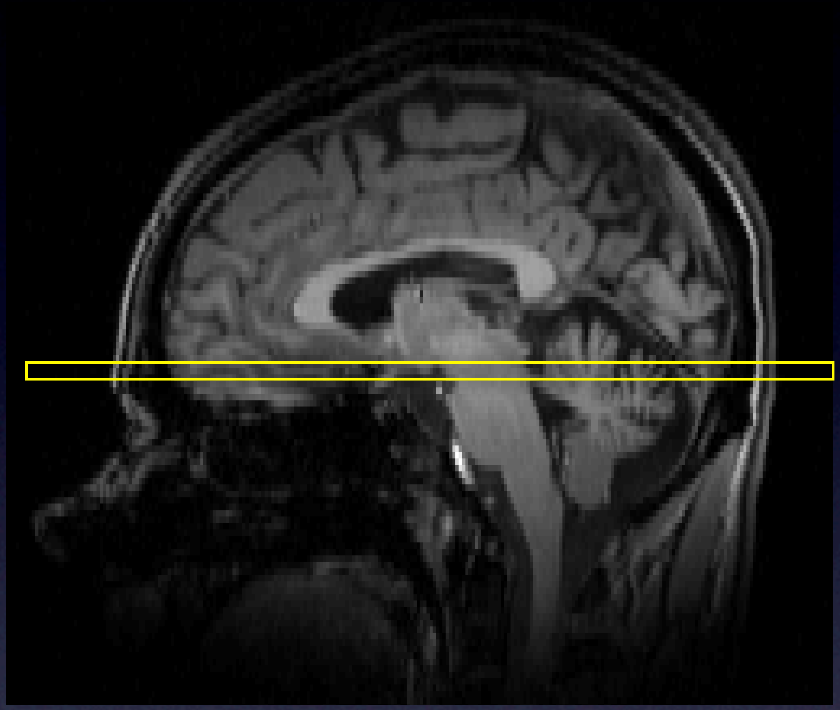
Sensitivity to BOLD effect reduces near air-tissue boundaries

BOLD Signal Dropout

Short TE



Long TE

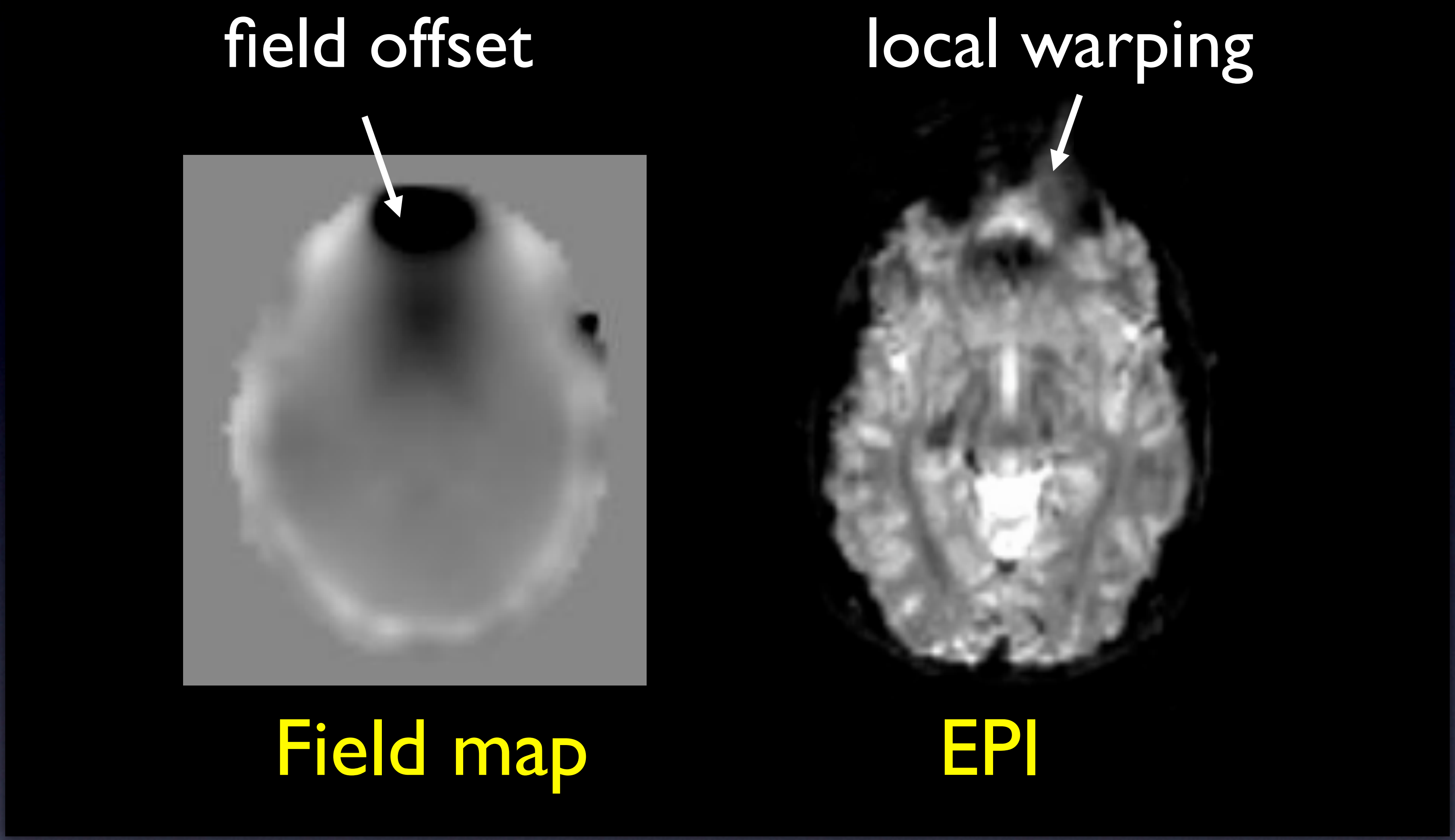


Dephasing near air-tissue boundaries (e.g., sinuses)

BOLD contrast coupled to signal loss ("black holes")

Air-tissue effect is often larger than BOLD effect surrounding vessels!

Image distortion



We think frequency maps to spatial location...

So errors in frequency cause spatial mis-localization!

Non-BOLD fMRI

- BOLD depends on CBF, CBV, CMRO2
- Consider looking at these variables separately for longitudinal studies:
  - CBF - Arterial Spin Labeling (ASL)
  - CBV - Vascular Space Occupancy (VASO)
  - CMRO2 - Calibrated BOLD

Final Thoughts

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Final Thoughts

- Learn how different experimental parameters affect **SNR and image artefacts**
- Tradeoffs: **you can't get something for nothing**, but you do have options
- Get to know a **physicist/radiographer**: get help setting up study protocols, show them your artefacts
- Quality assurance: **always look at your data**, even if you are running a well-tested protocol

Acknowledgements

- Karla Miller for slides
- Previous years lecture (and more) available at www.fmrib.ox.ac.uk/~karla
- PractiCal fMRI (UC Berkeley) www.practicalfmri.blogspot.co.uk
- Animations: Spinbench

Thank you!