METHODS FOR ULTRA-HIGH SPATIAL ~~AND TEMPORAL~~ RESOLUTION FMRI

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06 Feb 2020

OUTLINE

- Overview of fMRI data acquisition methods
- Brief discussion of spatial resolution in MRI
- Selected examples of ultra-high spatial resolution fMRI

MR Data Acqusition through Cake Analogies

k-space is like a Cake Recipe

- Acquiring data is like gathering necessary ingredients
- Ingredients bear no resemblance to the final product
- The ingredients need to be transformed

2D EPI is like a Layer Cake

- Layers/slices are baked/acquired sequentially, then composed

2D Multi-Slice EPI is also like a Layer Cake

- Except multiple layers/slices are baked/acquired simultaneously
- State-of-the-Art protocol
  - MB=8 Whole Brain 2 mm isotropic at 720 ms TR

3D EPI is like a Big Solid Cake

- No layers/slices, just the whole cake baked at once

Ultra High Spatial Resolution Methods

Advantages of High Spatial Resolution

- Resolving small brain structures:
  - Spinal cord, brain-stem, sub-cortical nuclei, hippocampus, etc.
- Spatially-specific mapping of function
  - cortical layers (e.g. laminar or layer-specific fMRI)
  - cortical columns (e.g. ocular dominance columns)
  - fine representations (e.g. individual finger somatotopy)

Limitations of High Spatial Resolution

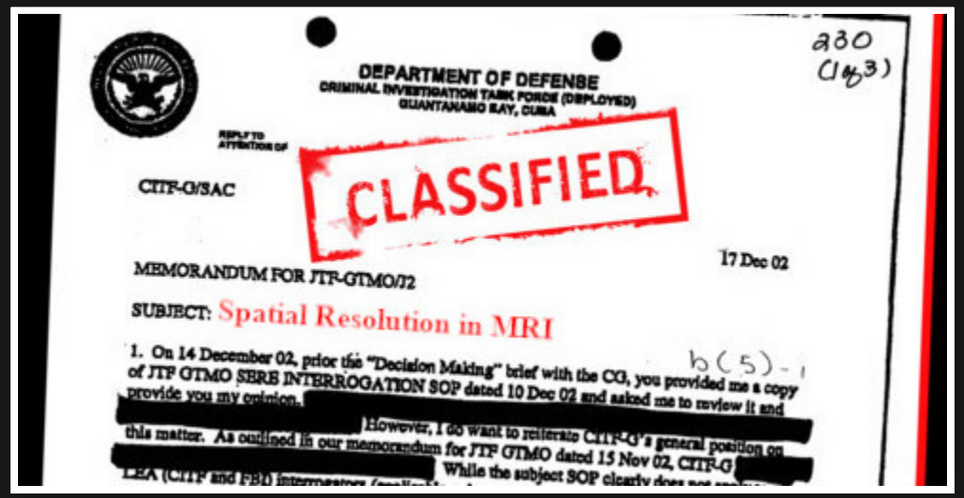
- Interpretation of voxel sizes
- Interpretation of BOLD signal

REVEALING THE SHOCKING TRUTH ABOUT MR IMAGES:

What does Spatial Resolution actually Mean?

and

What is a Voxel, honestly



DEPARTMENT OF DEFENSE
CRIMINAL INVESTIGATION TASK FORCE (DEPLOYED)
GUANTANAMO BAY, CUBA

CITF-G/SAC

CLASSIFIED

17 Dec 02

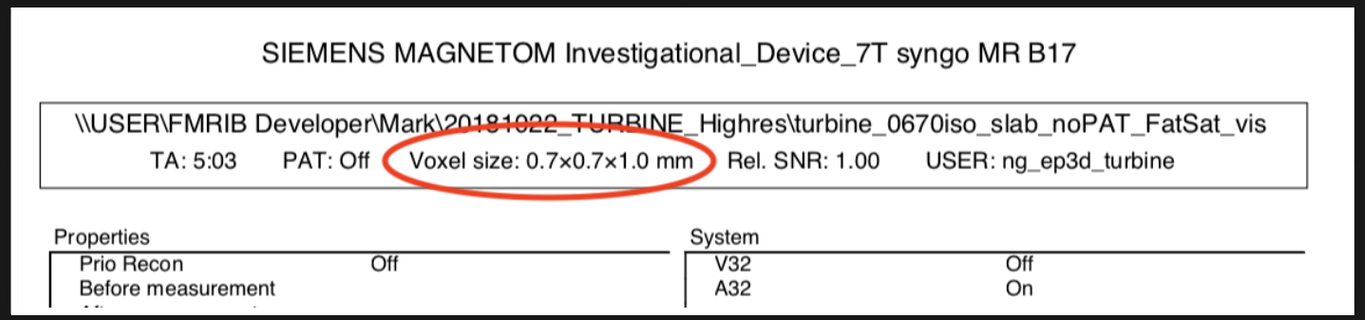
MEMORANDUM FOR JTF-GTMO/72

SUBJECT: Spatial Resolution in MRI

1. On 14 December 02, prior the "Decision Making" brief with the CG, you provided me a copy of JTF GTMO SERE INTERROGATION SOP dated 10 Dec 02 and asked me to review it and provide you my opinion. [redacted] However, I do want to reiterate CITF-G's general position on this matter. As outlined in our memorandum for JTF GTMO dated 15 Nov 02, CITF-G [redacted] While the subject SOP clearly [redacted] LEA (CITF and FBI) interrogators [redacted]

What does Spatial Resolution actually Mean?

- It is **not** defined by $\frac{FOV}{N}$
- It is also **not** defined by the distance between voxel centres
- **Nor** is it always the number written on your protocol:



SIEMENS MAGNETOM Investigational_Device_7T syngo MR B17

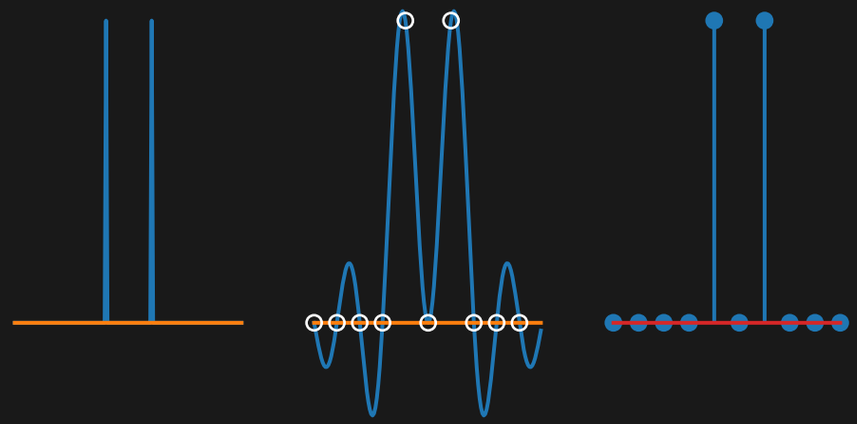
\\USER\FMRIB Developer\Mark\20181022_TURBINE_Highres\turbine_0670iso_slab_noPAT_FatSat_vis

TA: 5:03 PAT: Off Voxel size: 0.7×0.7×1.0 mm Rel. SNR: 1.00 USER: ng_ep3d_turbine

Properties		System	
Prio Recon	Off	V32	Off
Before measurement		A32	On

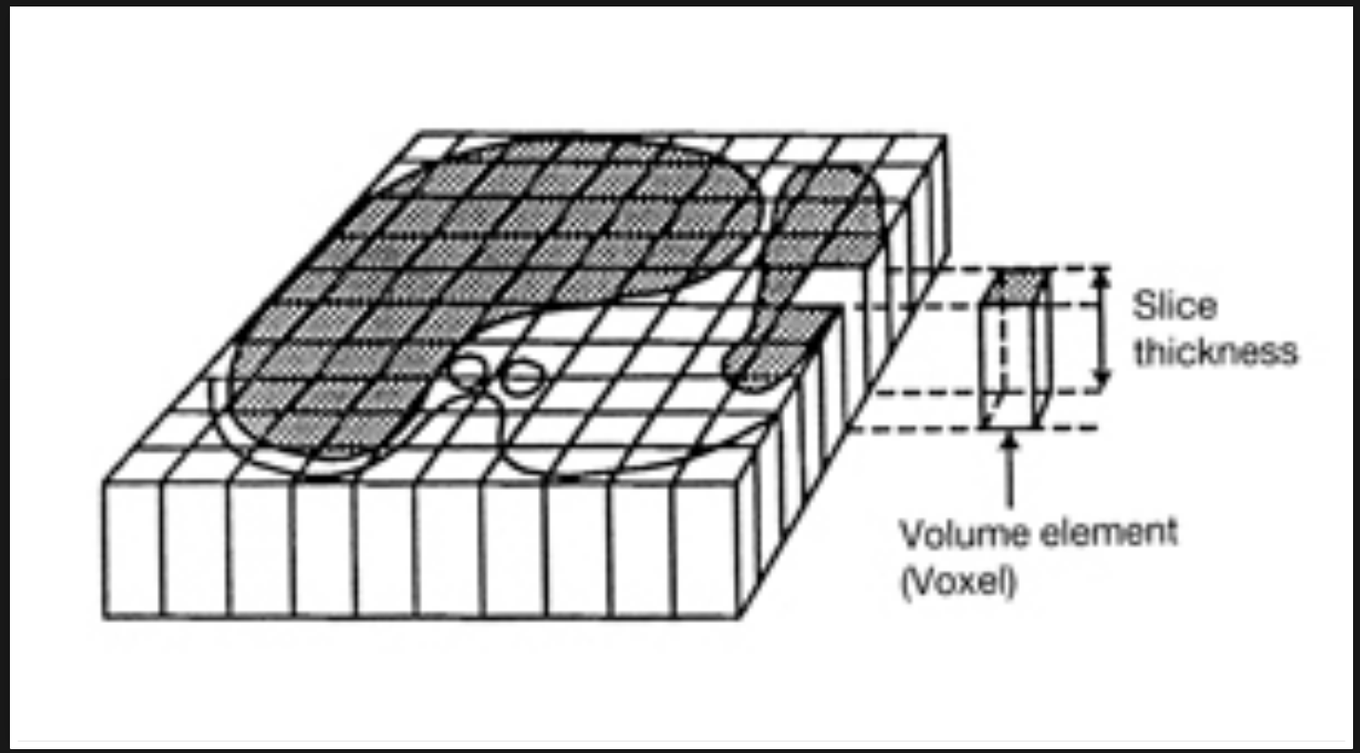
Spatial Resolution is the *minimum distance* that two points can be *distinguished*

by the imaging system (scanner + sequence + parameters)



To better understand this, we need to go even **deeper**

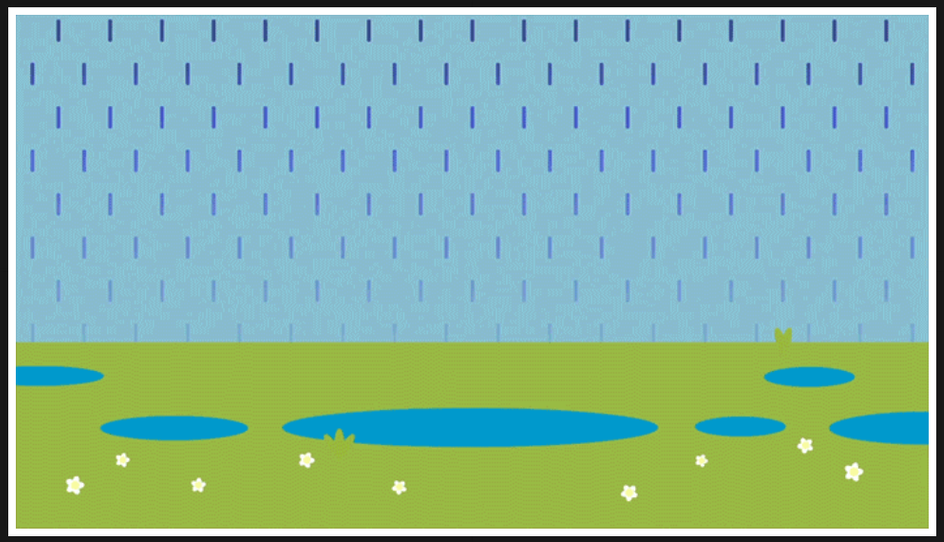
What are Voxels?



What are Voxels?

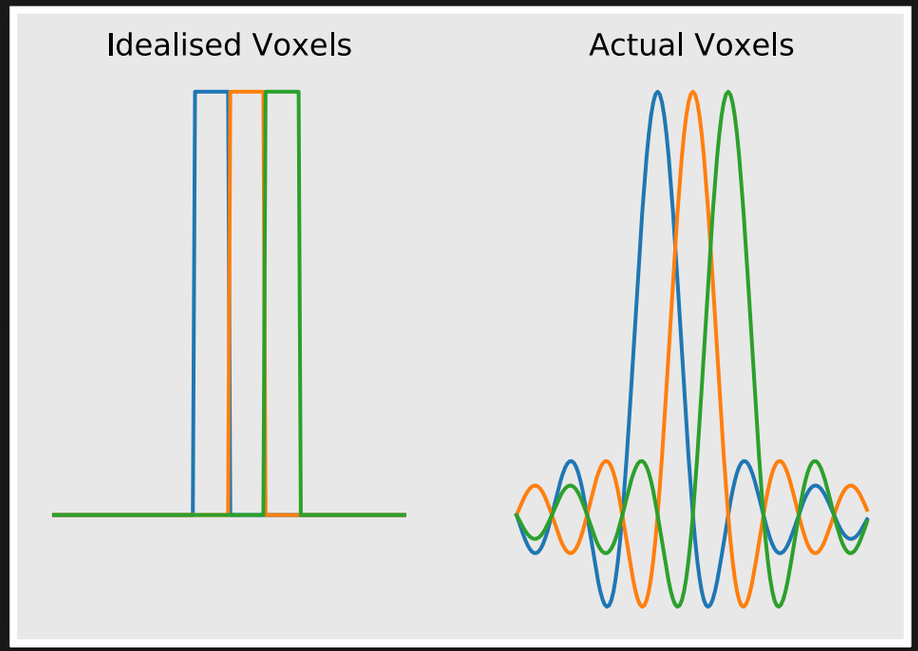
Voxels are not buckets or parcels

The truth about Voxels



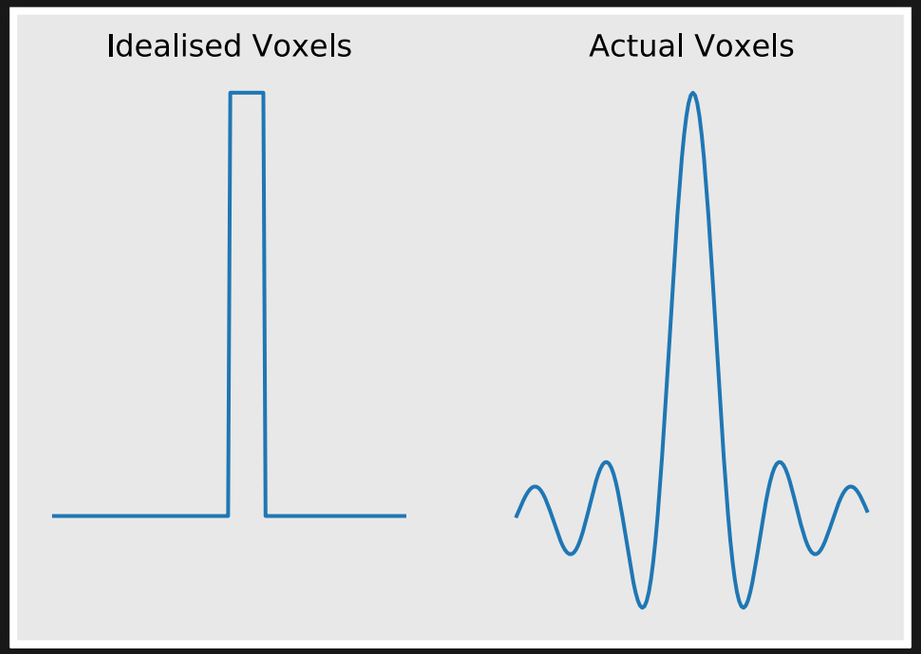
In reality, voxels are a lot more complex and non-local

Actual voxels



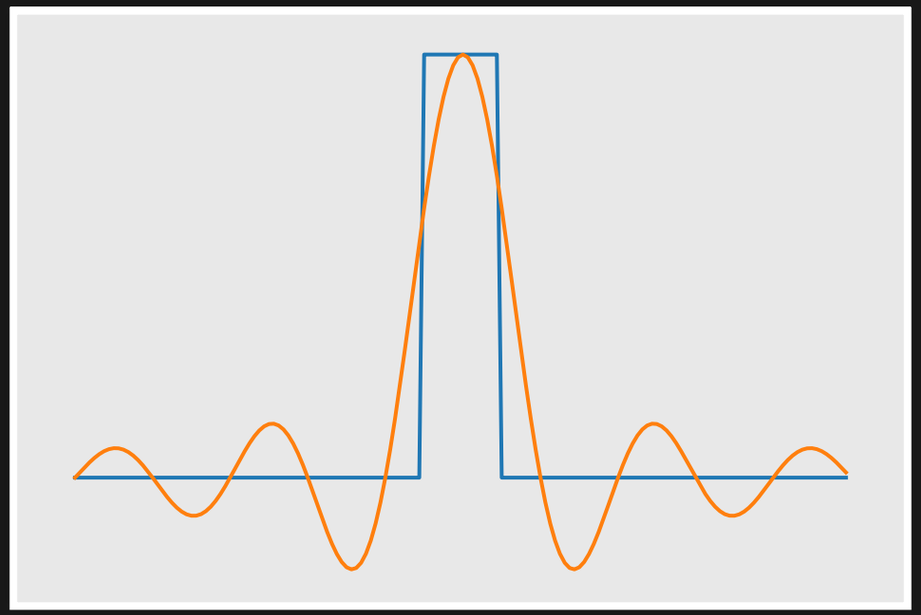
The voxel has contributions from regions far away from its nominal location The voxel is actually defined by this point-spread function

Actual voxels



The "signal" associated with each voxel is the weighted sum of the spin distribution with this point-spread function

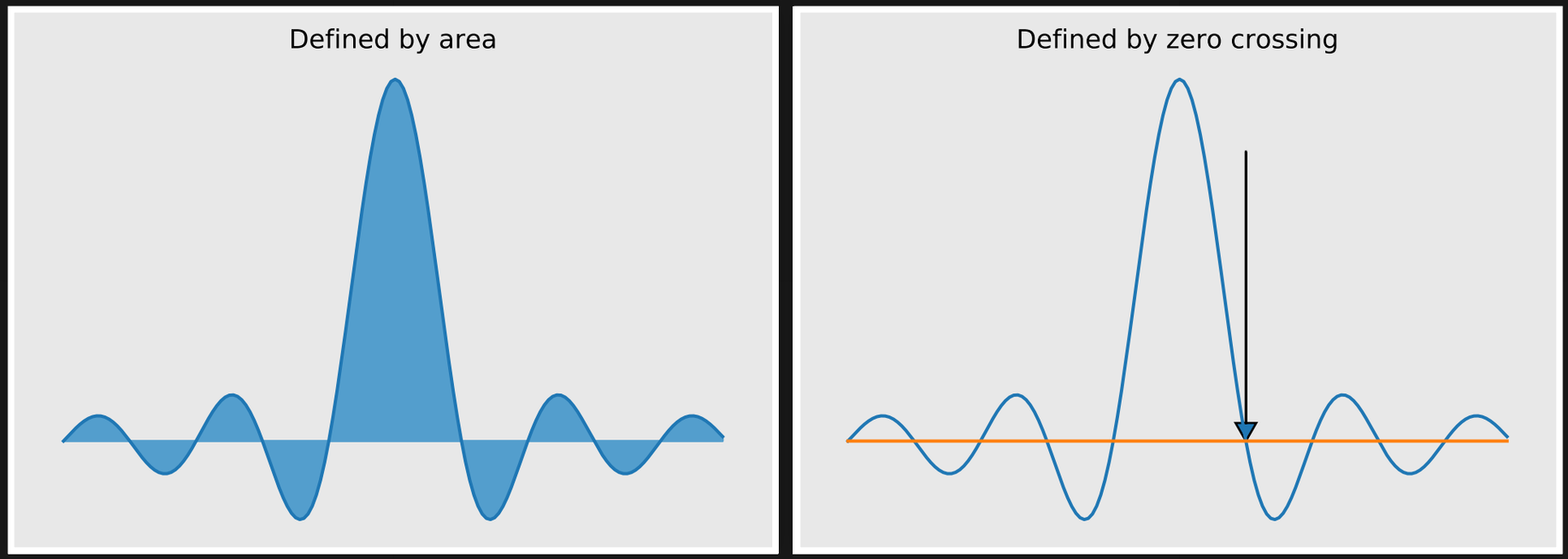
The Point Spread Function



The shape of the voxel's point-spread function is largely determined by:

- how you choose to sample k-space
- signal decay during the readout

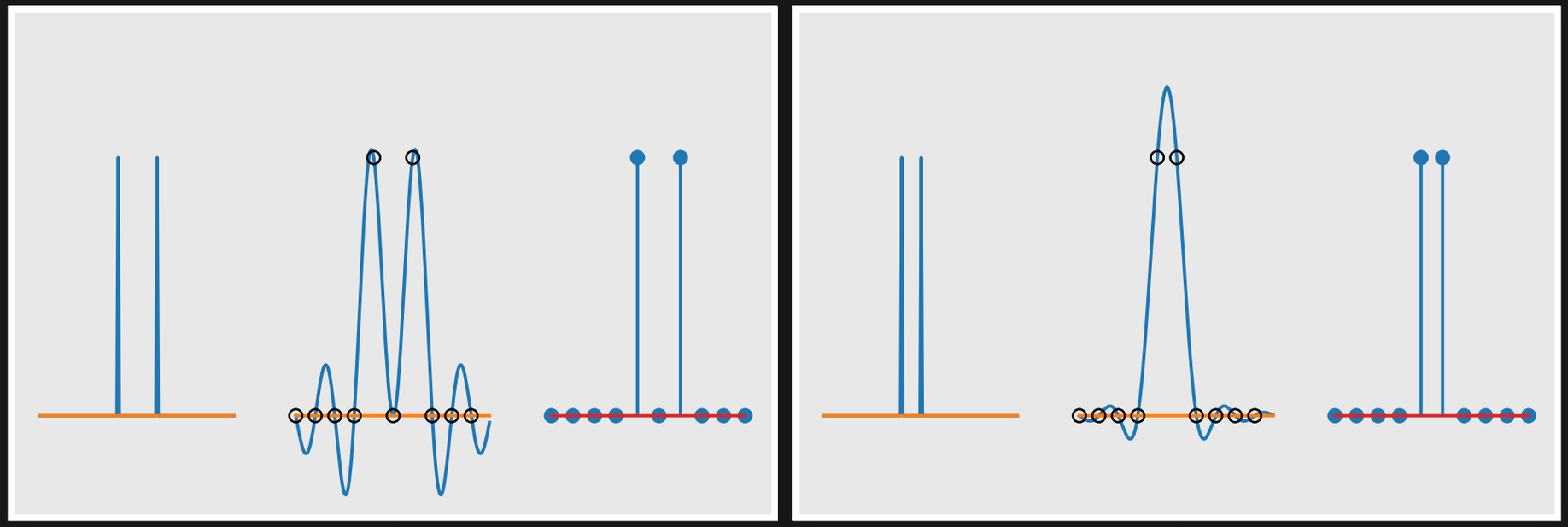
Defining Spatial Resolution



Two ways to define resolution from the point-spread function:

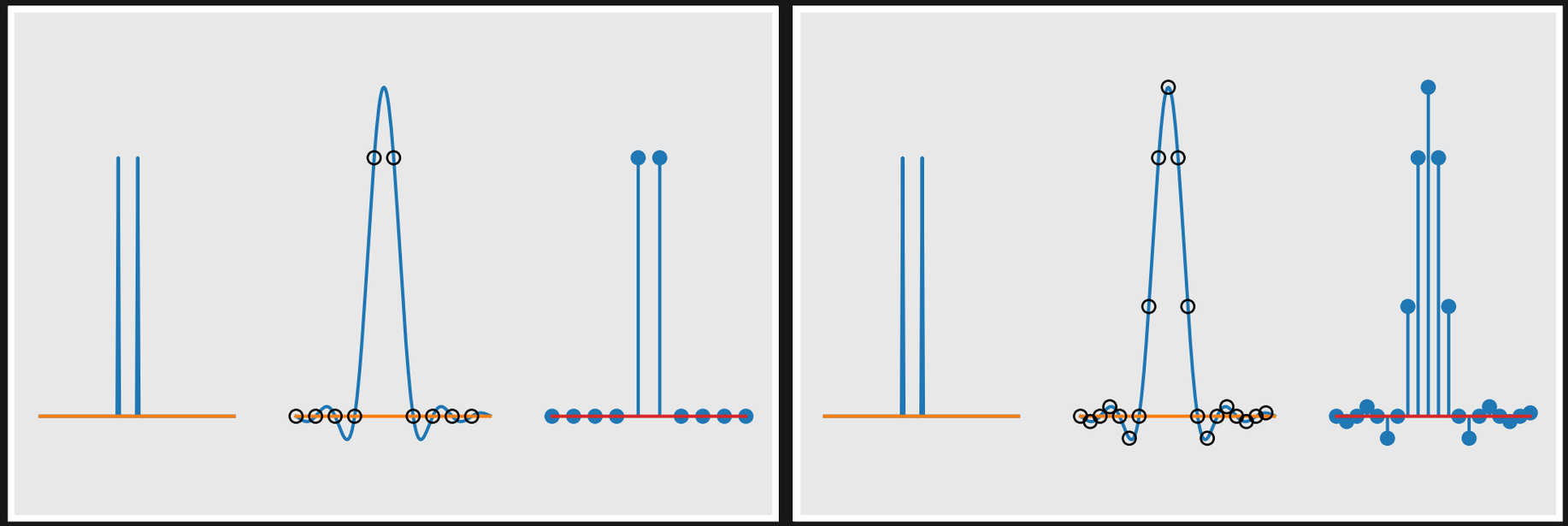
- total area relative to peak height
- distance to first zero-crossing

Defining Spatial Resolution



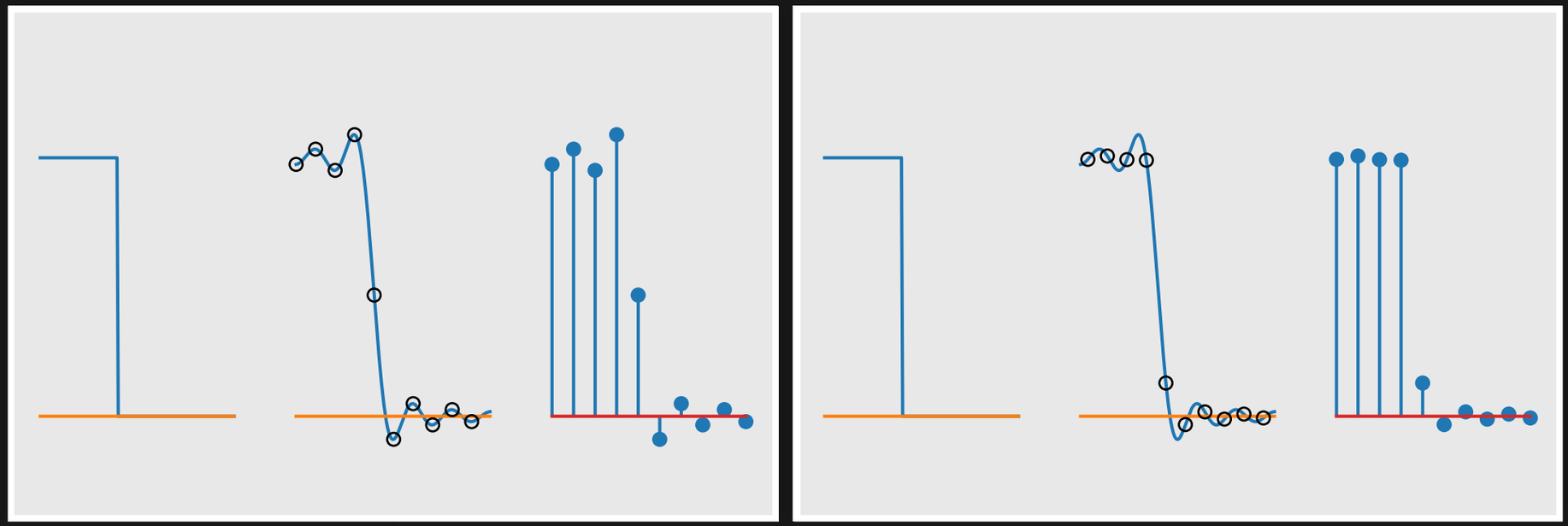
- Choice of voxel sampling can line up with zero-crossings
- While you are free to choose any voxel sampling locations, no choice ever increases resolution
- Ultimately, the image you get is some sampled version of the truth convolved with the point-spread function

More Voxels



More voxels does not mean better or higher resolution

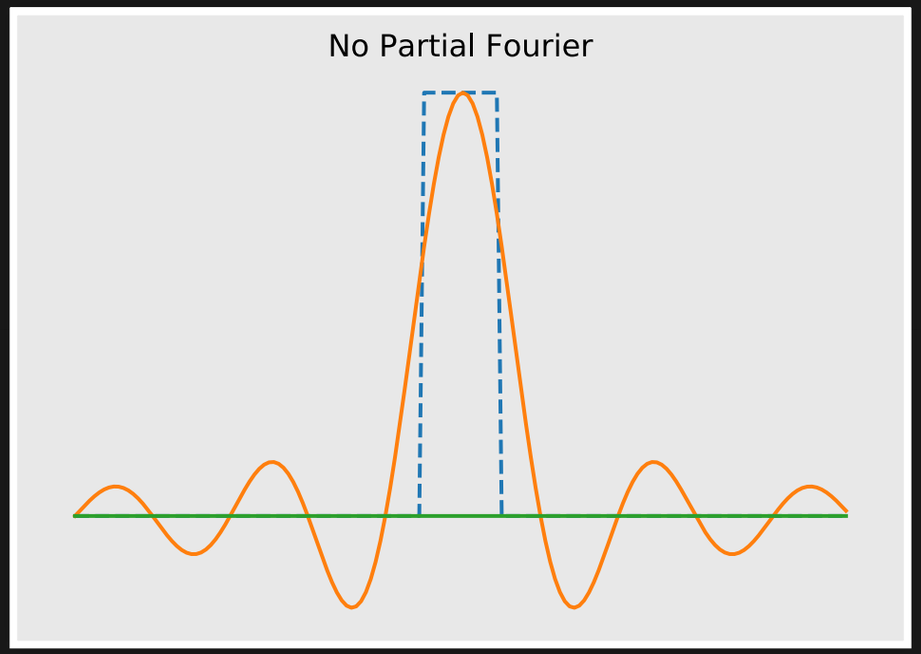
Also, Gibbs Ringing!



Gibbs ringing is a direct consequence of the point-spread function Artefact can depend on the exact choice of voxel sampling locations

Partial Fourier

Partial Fourier in EPI with default options = *fake resolution*



Partial Fourier

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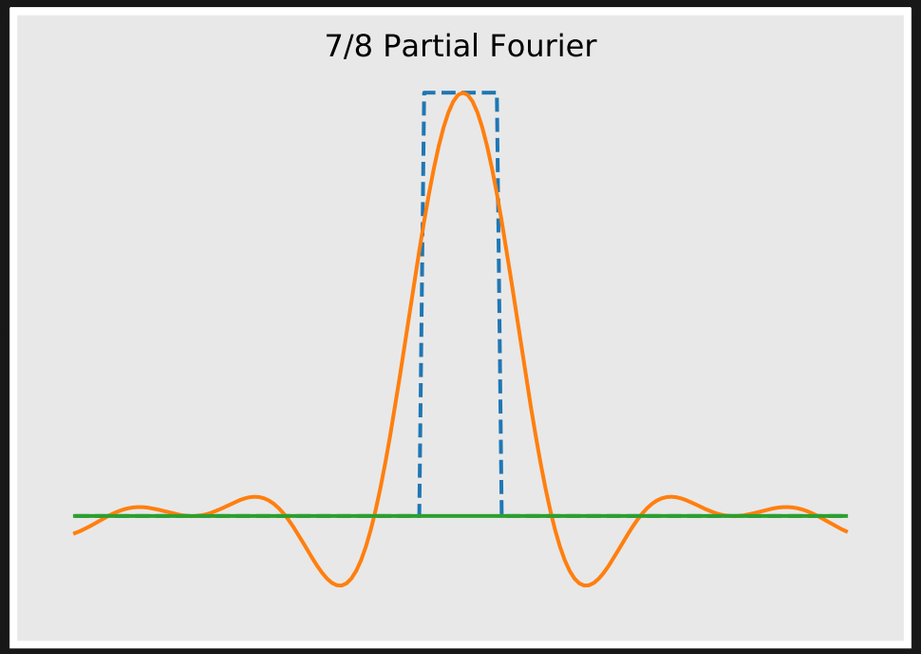

Partial Fourier

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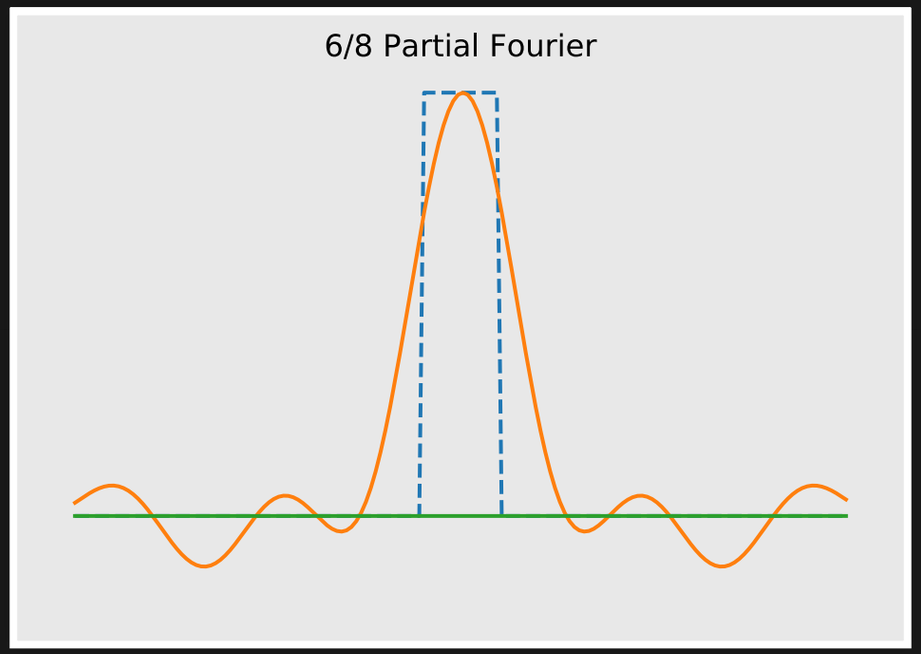

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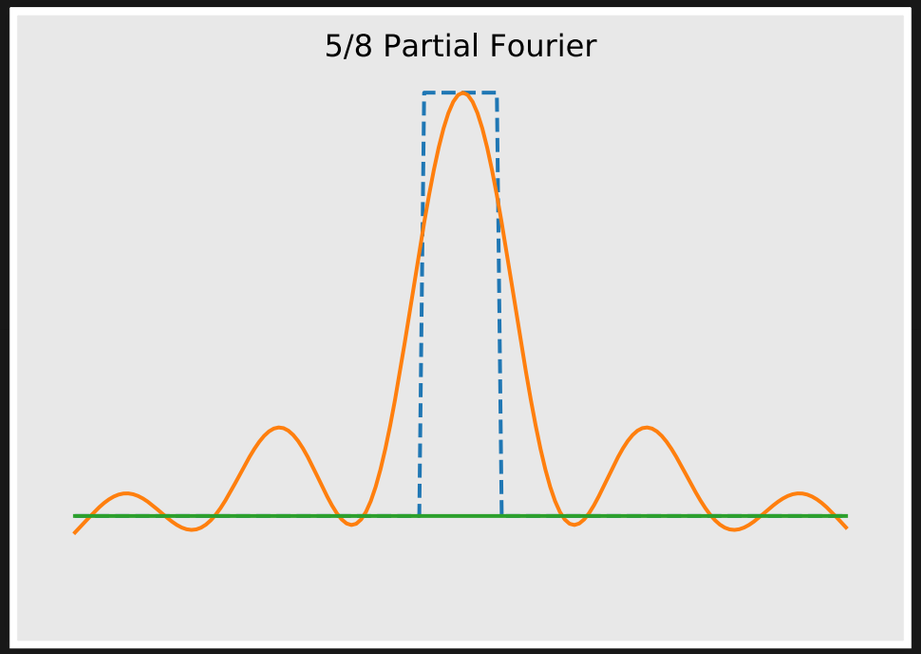
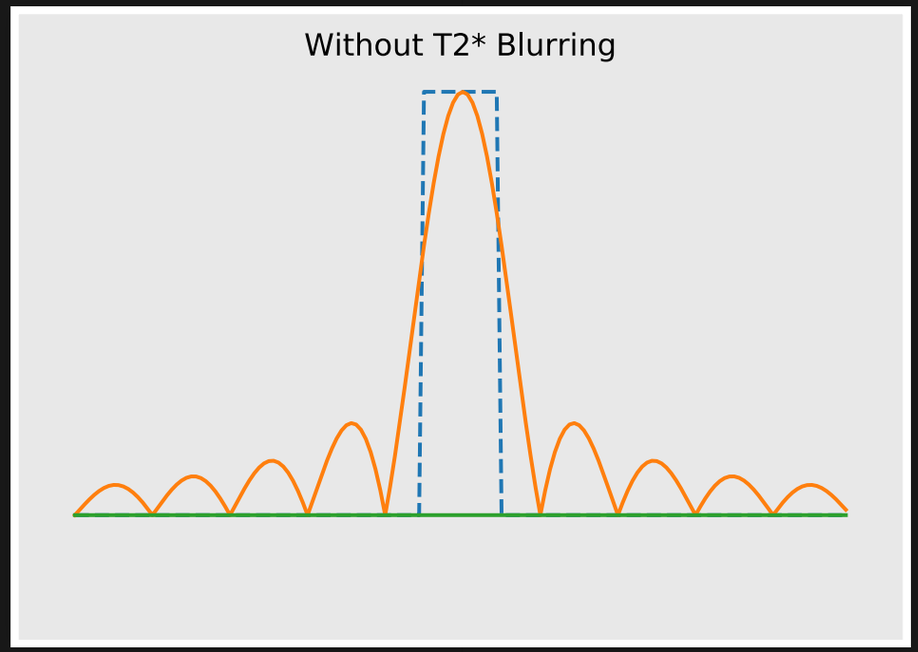
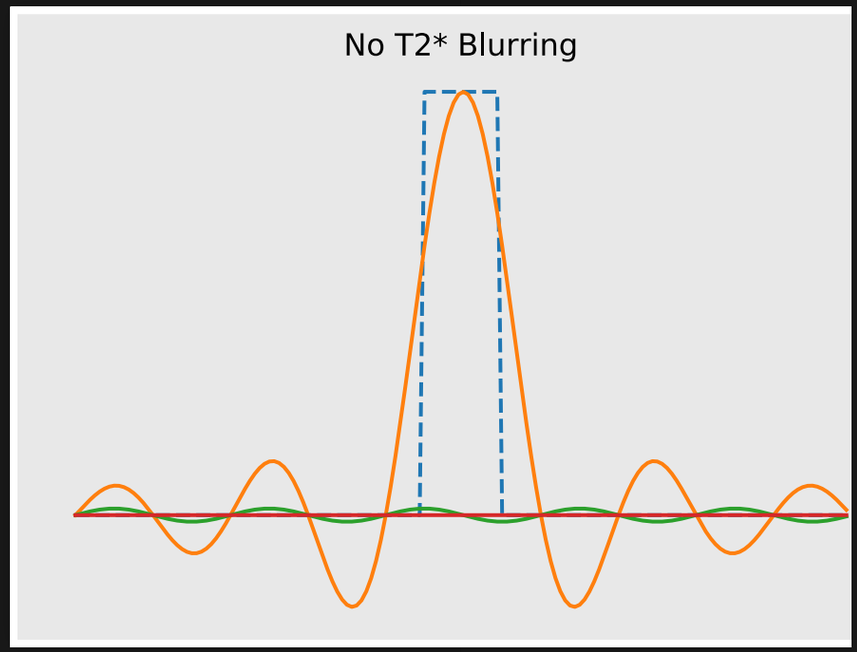


T2* Blurring

Magnitude

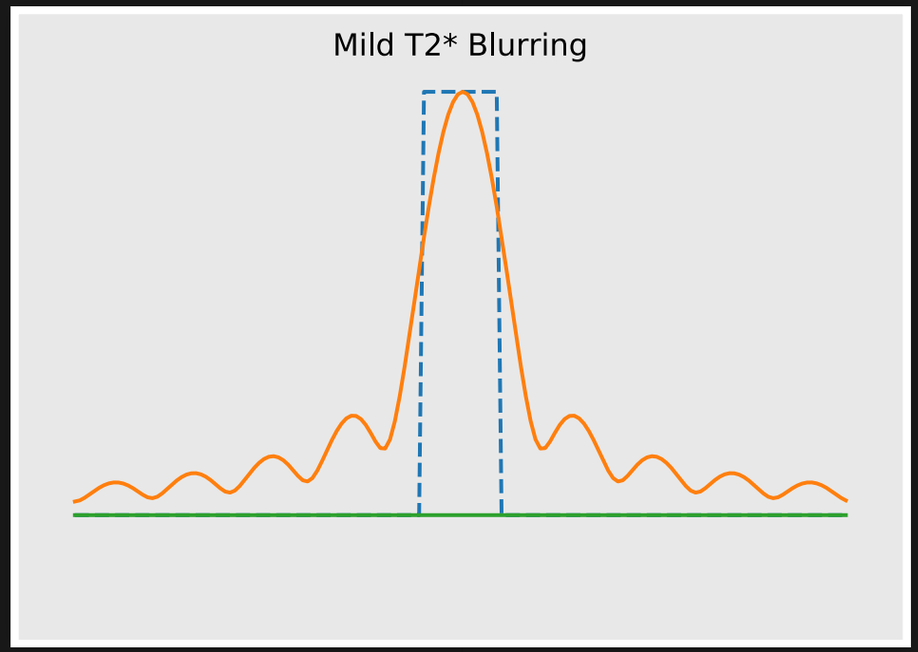


Real/Imag

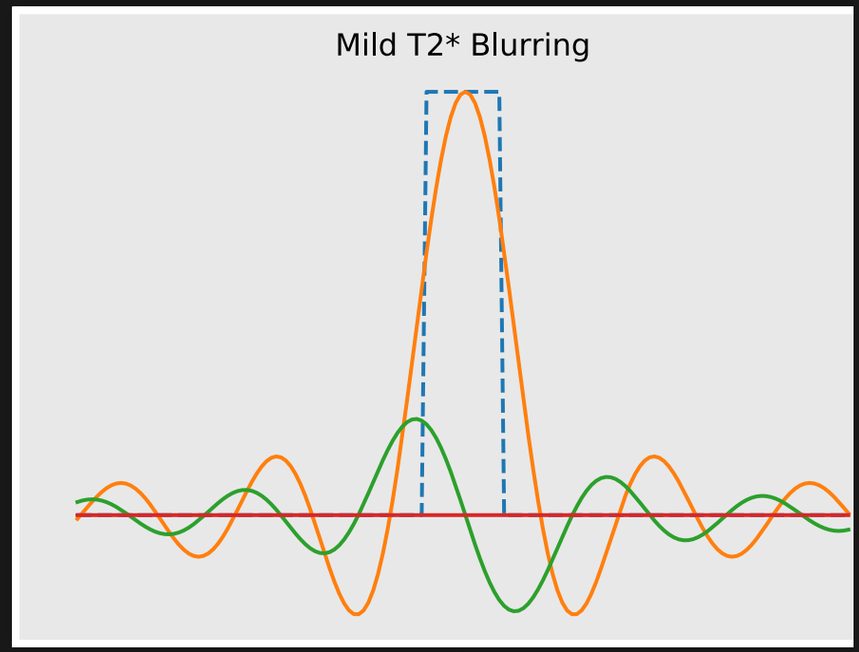


T2* Blurring

Magnitude

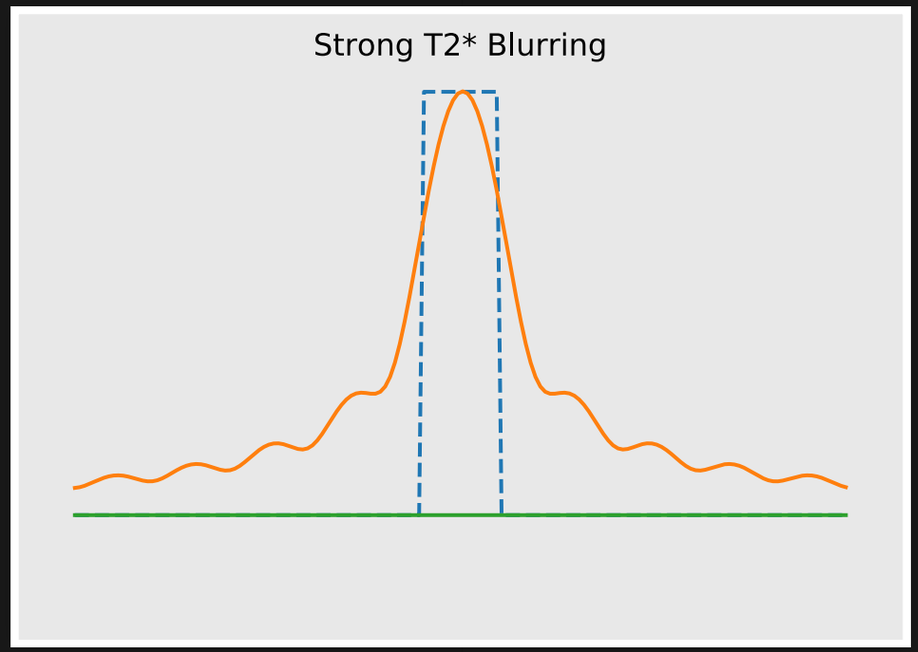


Real/Imag

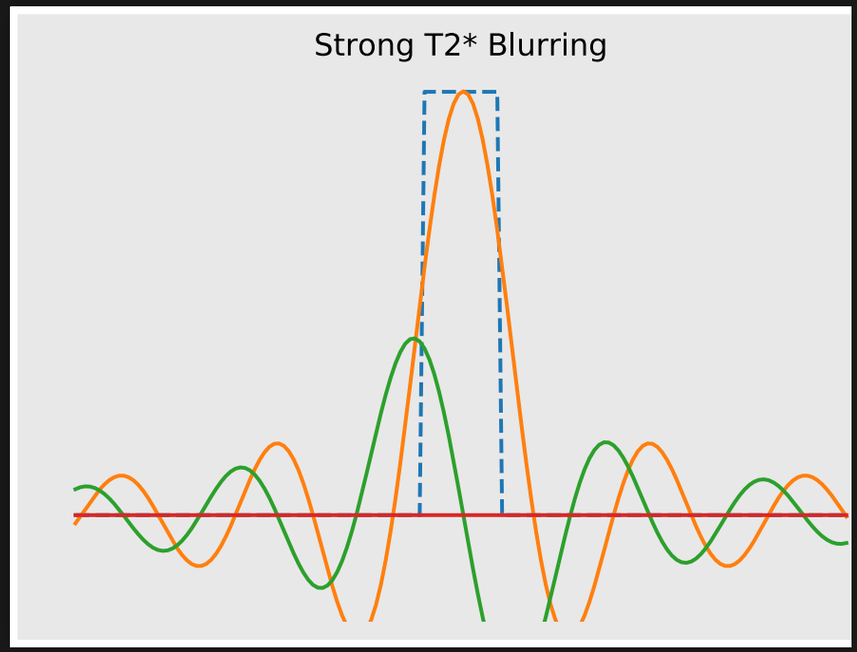


T2* Blurring

Magnitude

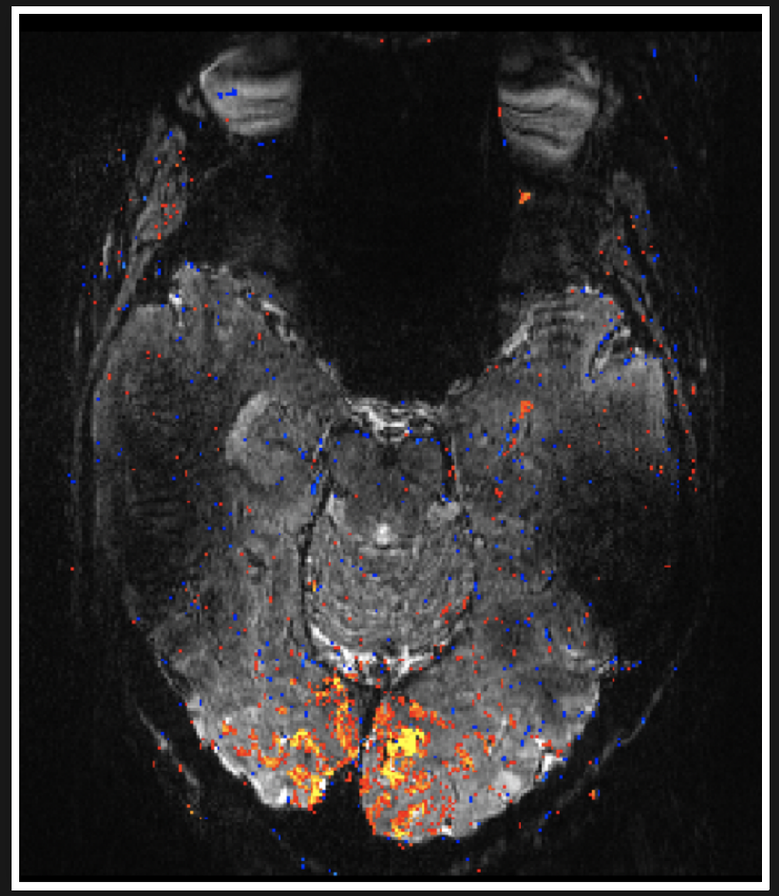


Real/Imag

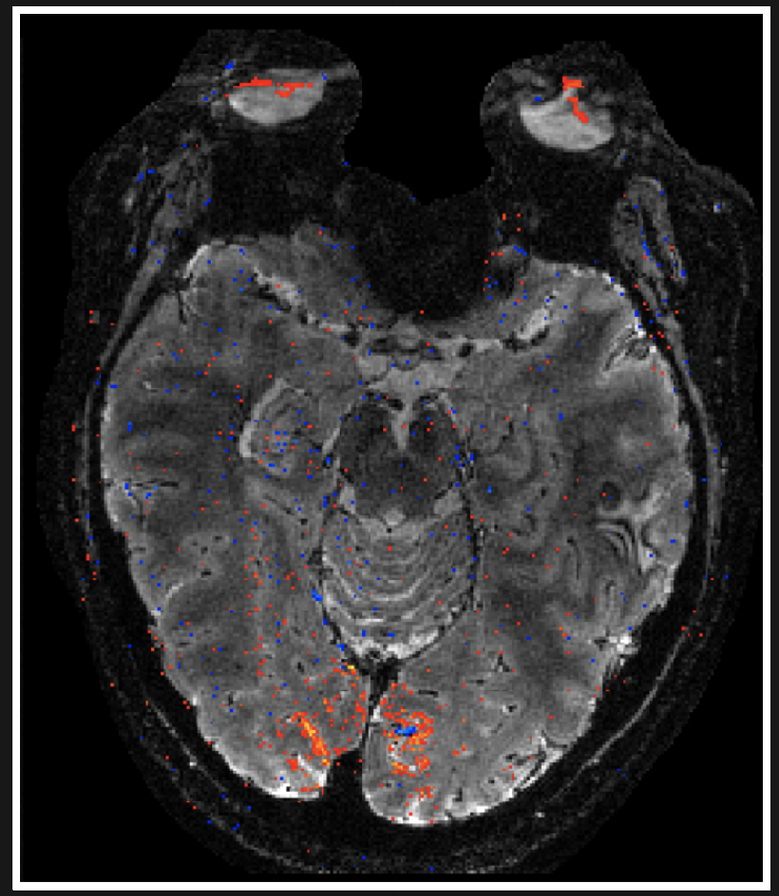


T2* Blurring Effects

with T2* blur

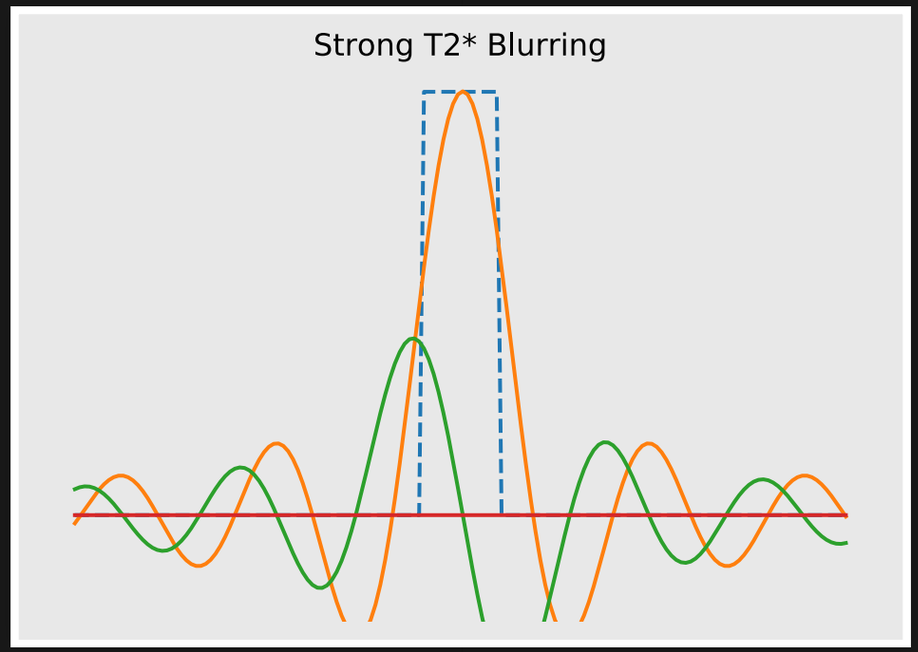


without T2* blur

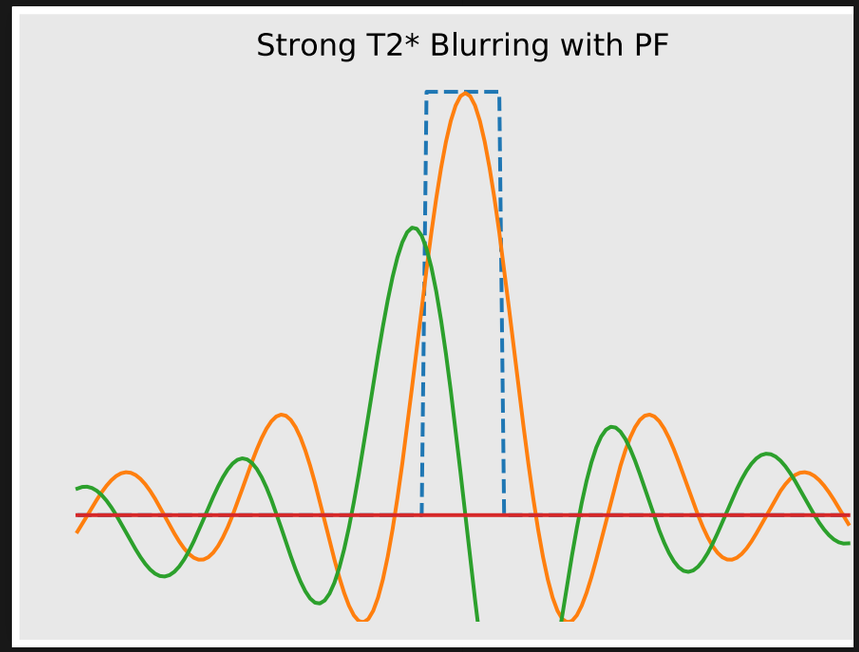


T2* Blurring and Partial Fourier

without Partial Fourier

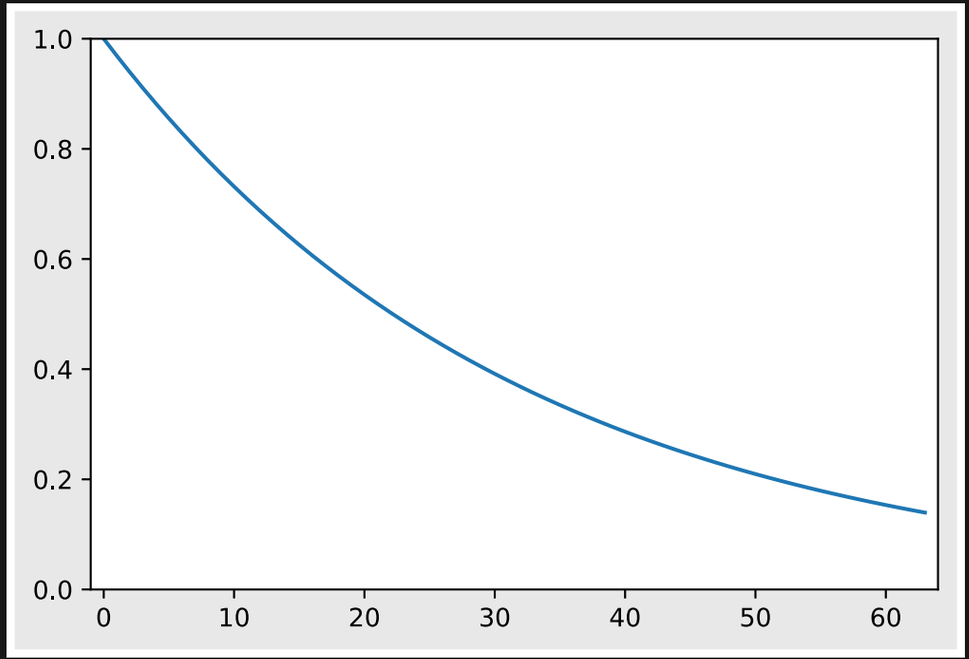


with Partial Fourier

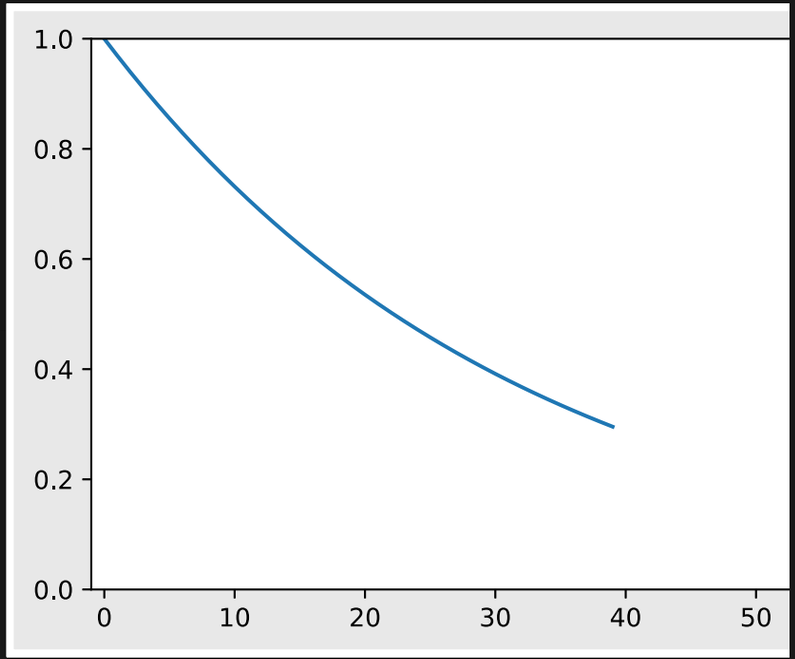


T2* Blurring and Partial Fourier

without Partial Fourier

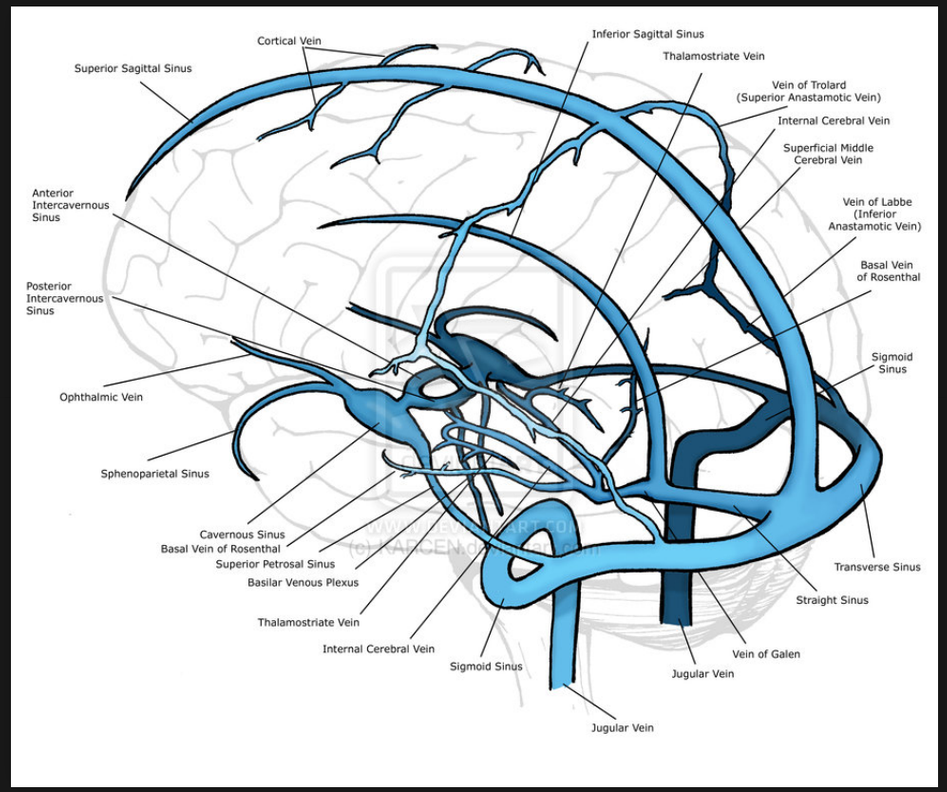


with Partial Fourie



Partial Fourier truncation is less harmful in the presence of T2* blurring because the T2* decay essentially truncates anyway

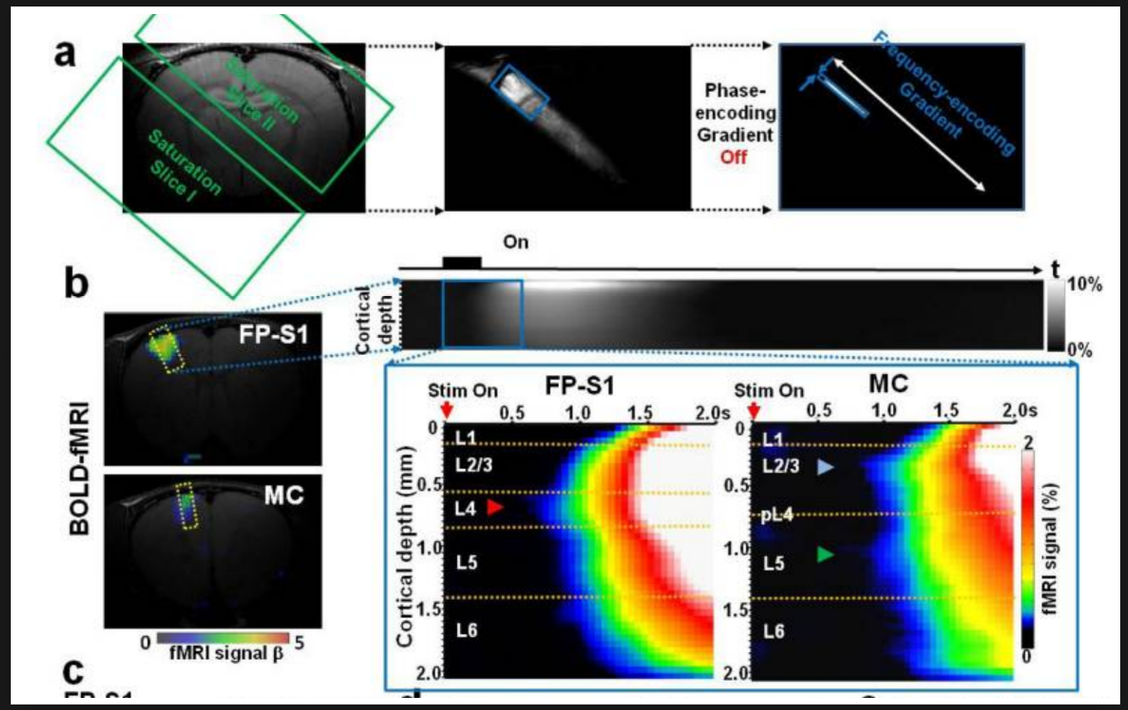
Interpretation of BOLD effects



High resolution sampling will still be susceptible to large draining vein bias in gradient-echo BOLD fMRI

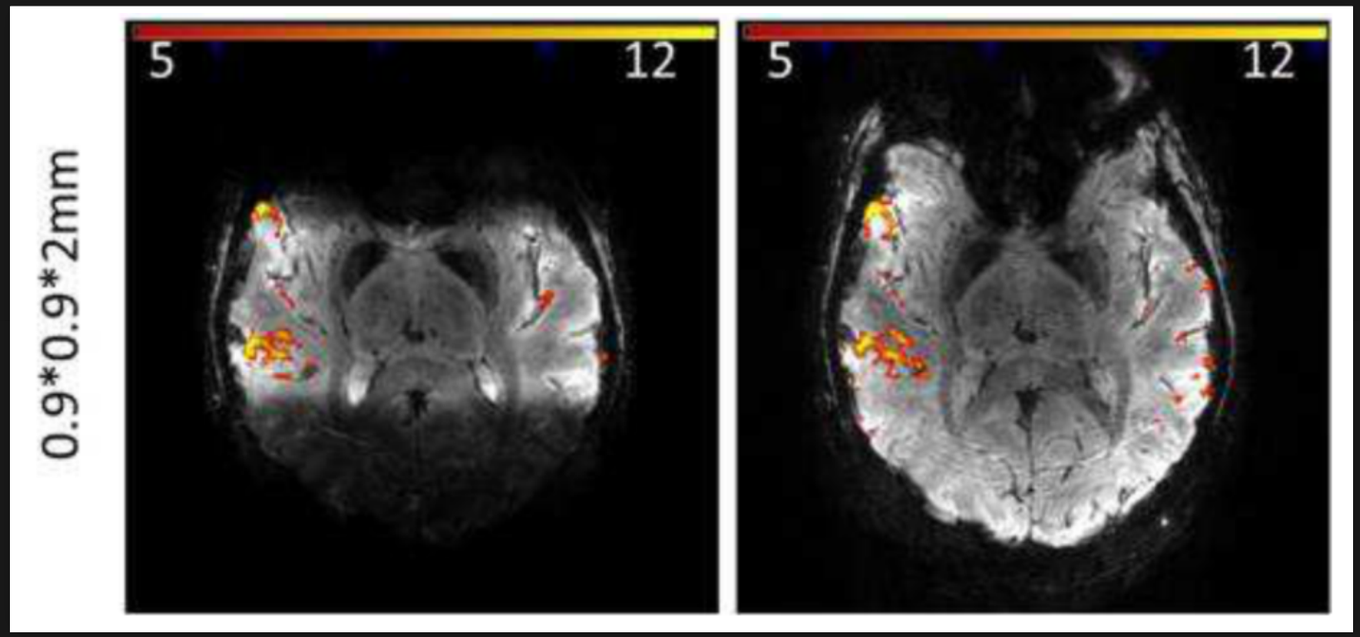
EXAMPLES OF ULTRA-HIGH SPATIAL RESOLUTION FMRI

Example 1



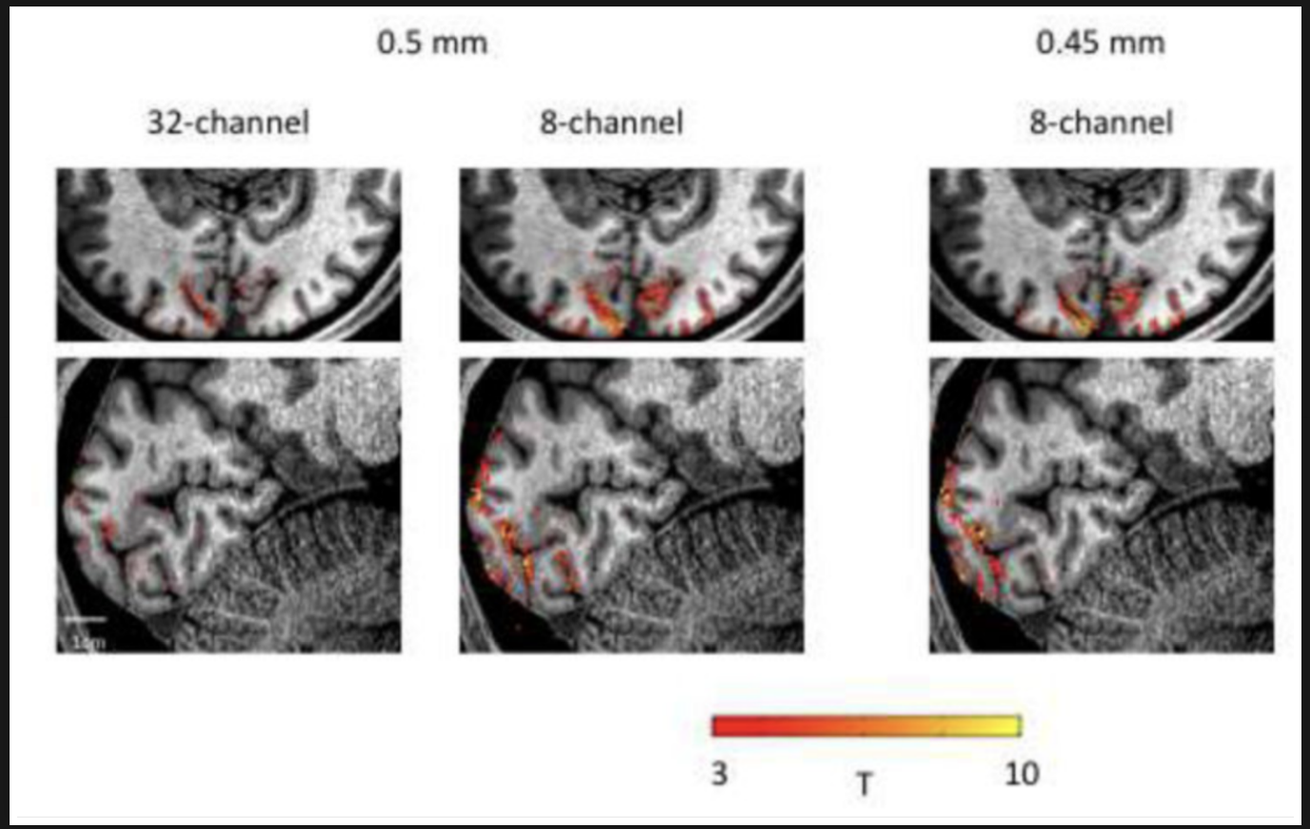
- 1x1x0.05 mm line-scanning fMRI at 11.7 T
  - Yu et al., *Nature Methods* 2014

Example 2



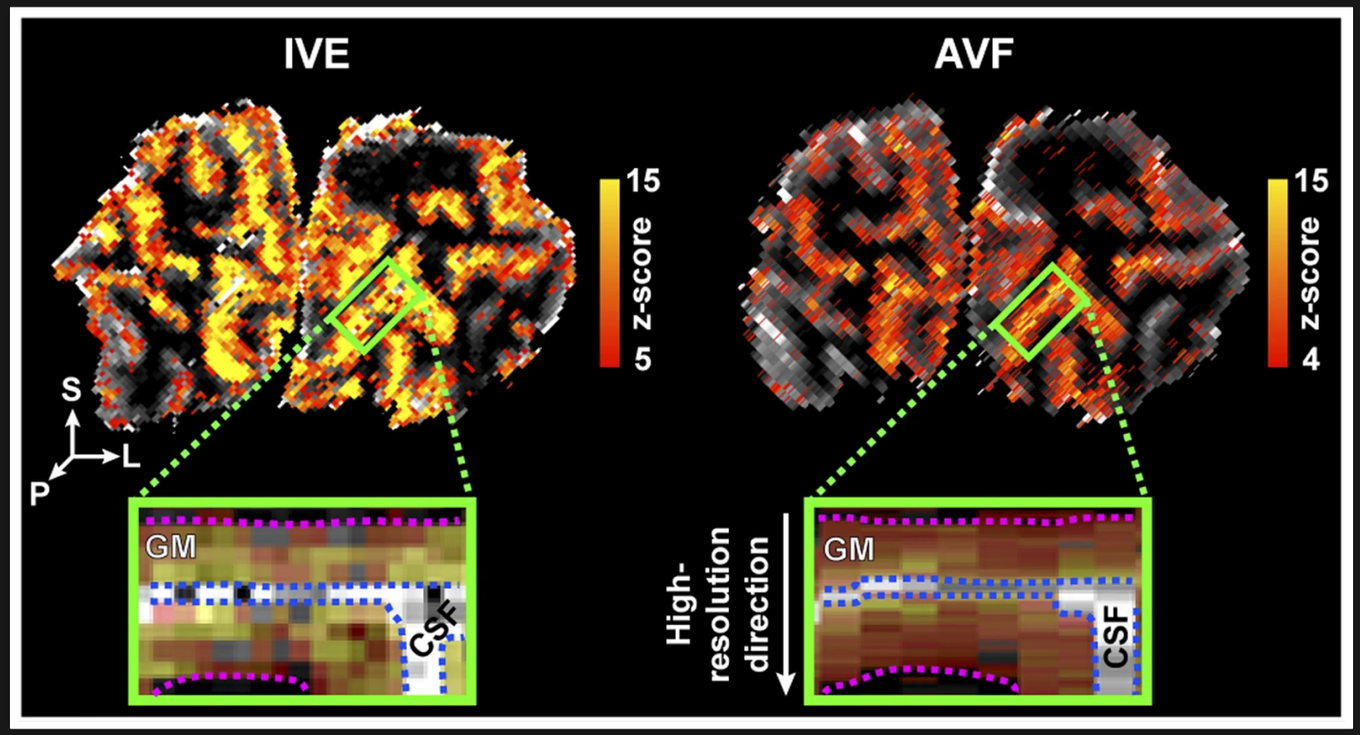
- 0.9 mm isotropic 3D EPI at 7 T
  - van der Zwaag et al., *Magn Reson Med* 2018

Example 3



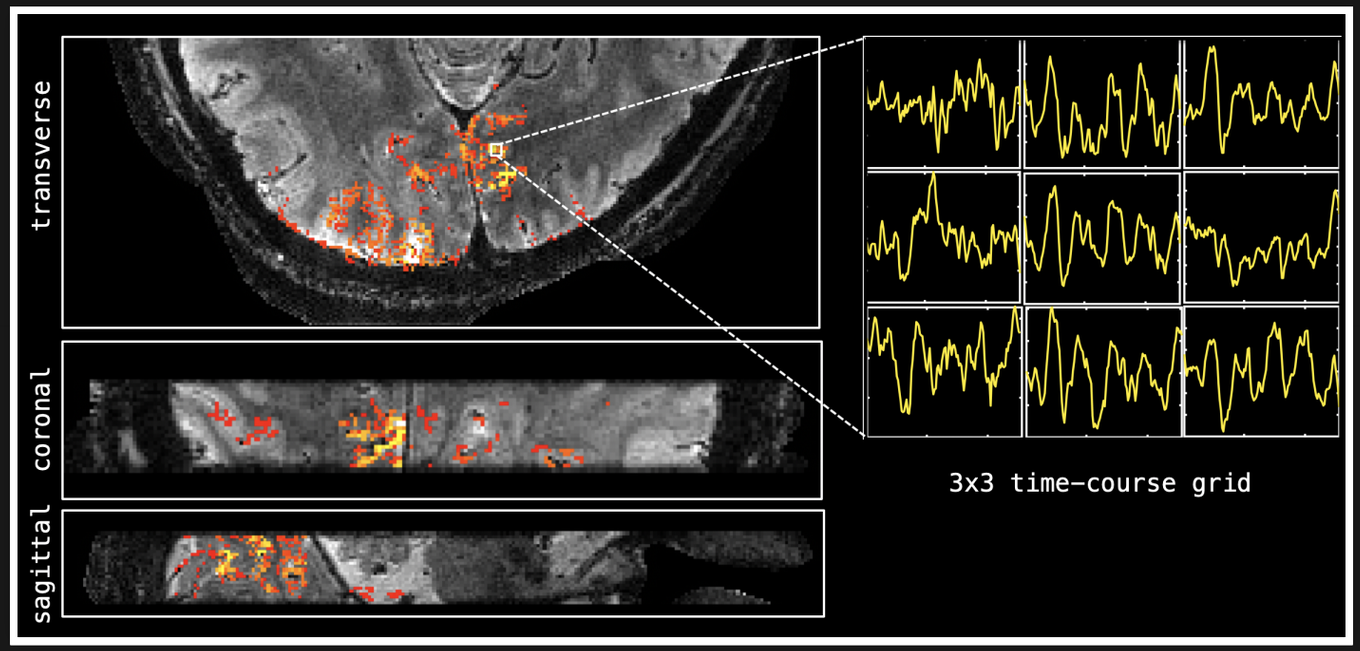
- 0.45-0.50 mm isotropic SMS-EPI at 7 T
  - Feinberg et al., *NeuroImage* 2018

Example 4



- 0.1x1.4x2.0 mm anisotropic FLASH at 7 T
  - Kashyap et al., *Scientific Reports* 2018

Example 5



- 0.67 mm isotropic 3D Radial-Cartesian (TURBINE) at 7 T
  - Graedel et al., *ISMRM* 2019

THE END