NIH National Institutes of Health
Turning Discovery Into Health

From Line Scanning to Tensor Imaging

fMRI Summer Course
July 2, 2024

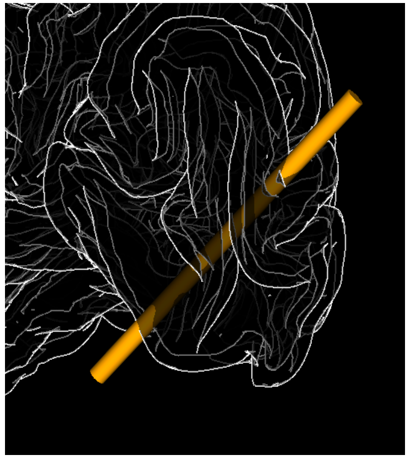
Tyler Morgan

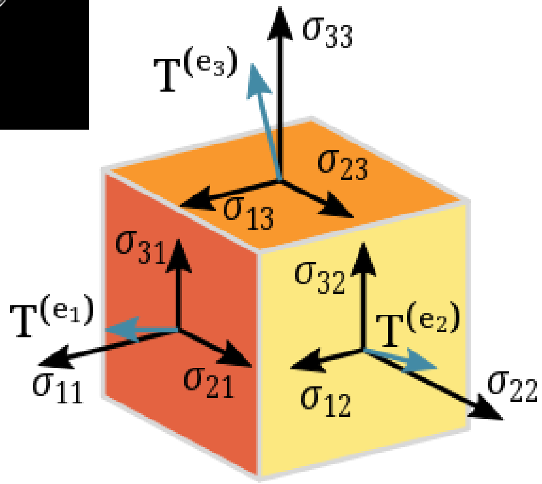
Functional MRI Core Facility
National Institute of Mental Health

FIM FMRIF NIH NIMH National Institute of Mental Health

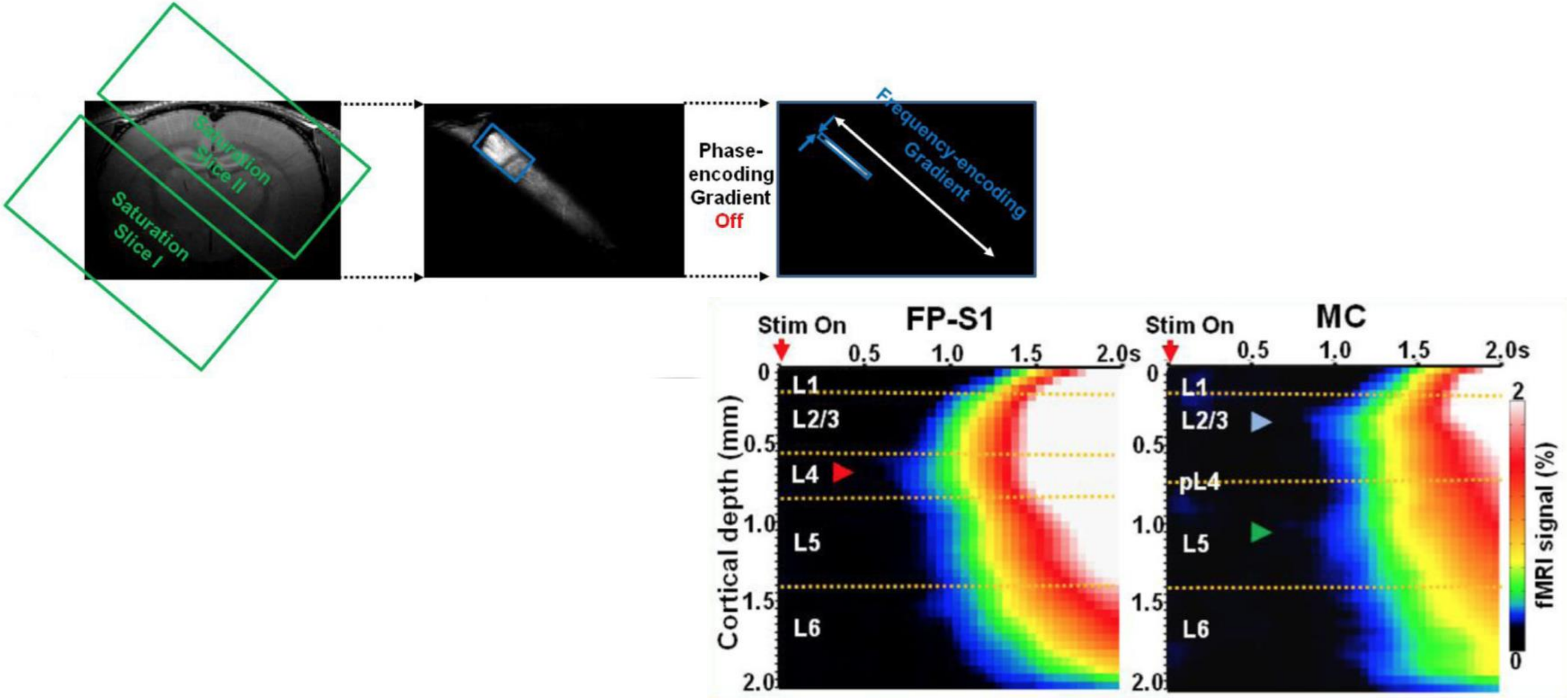
Why line scanning? Why tensor imaging?

- 2D and 3D imaging techniques (especially EPI) are amazing for doing many really useful things in fMRI
- But (!) they are not the only tools available to neuroscientists and clinicians
- Two examples of tools that can provide extra information for certain experiments are line scanning and tensor imaging





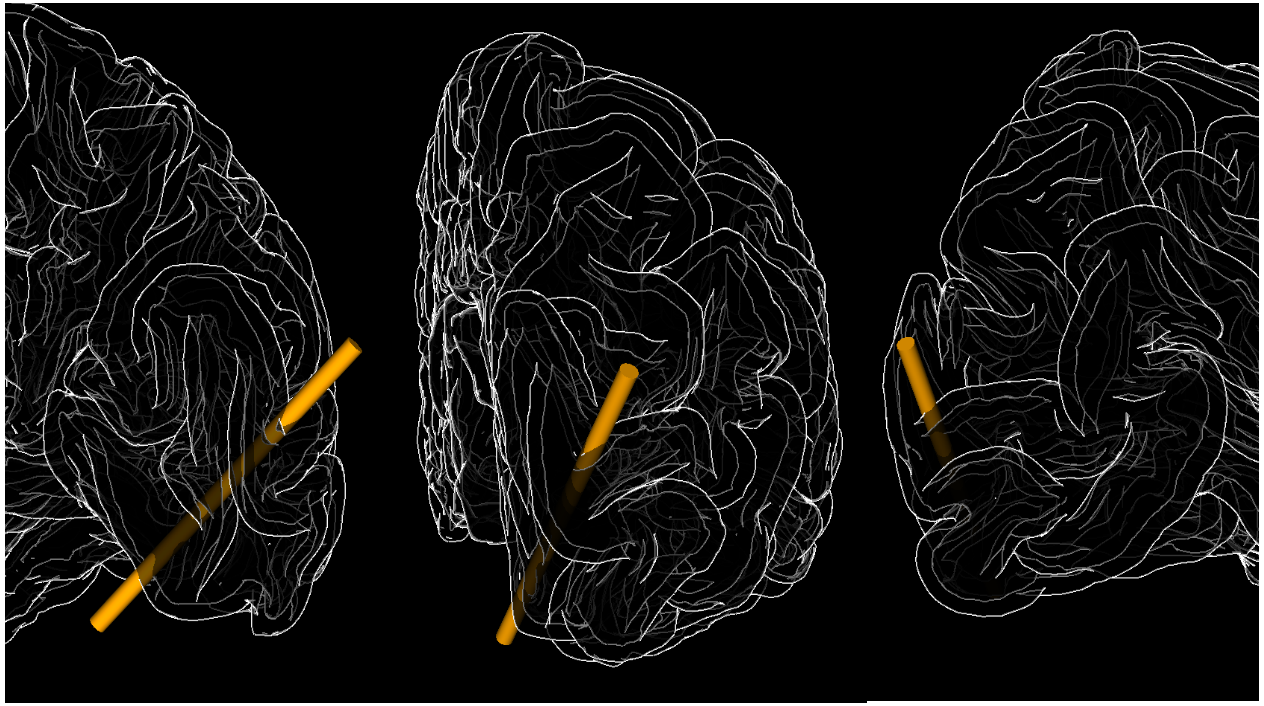
What is line scanning fMRI?



Yu, Qian, Chen, Dodd, Koretsky (2014)

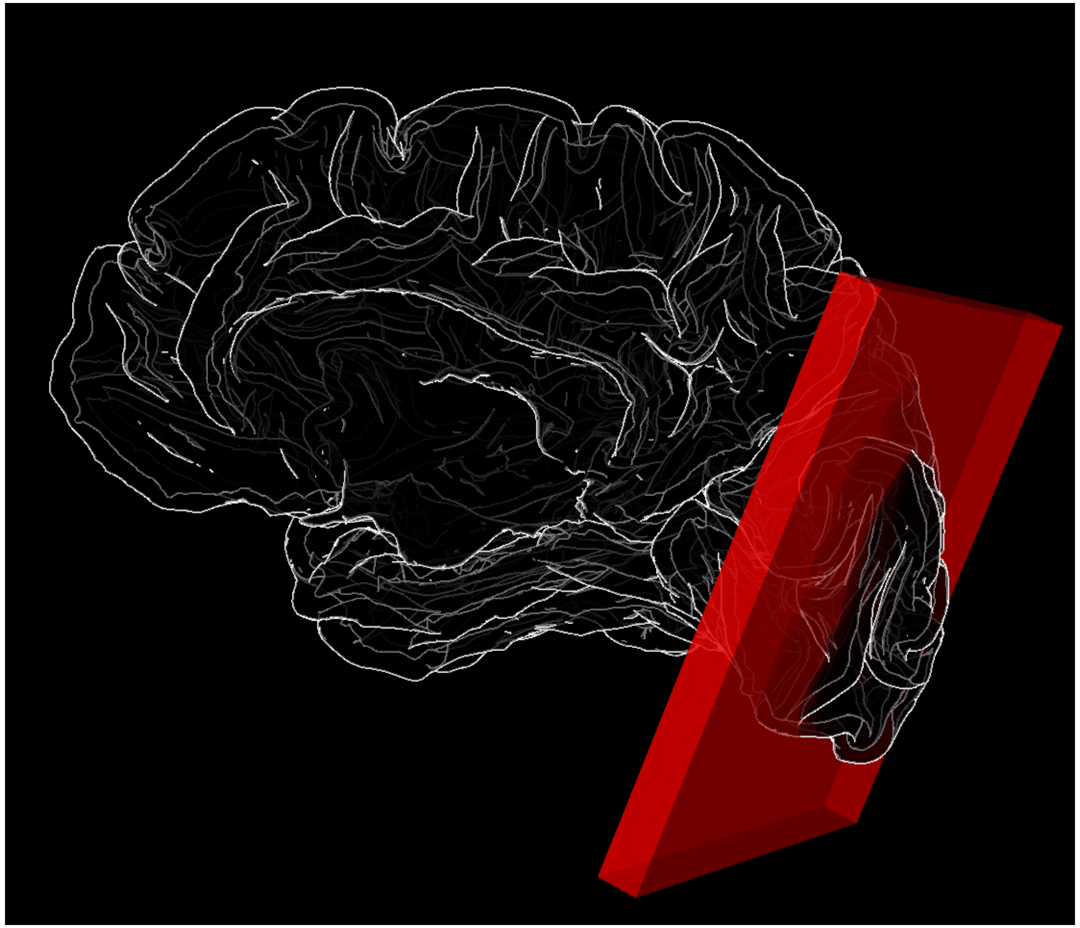
What is line scanning fMRI?

- Line scanning is a “virtual electrode”
- This technique provides a method for non-invasively probing human cortical layers.
- The goal is to scan at ***very high*** spatial resolution *and* ***very high*** temporal resolution.
- Unfortunately, the technique is difficult for a couple of reasons…



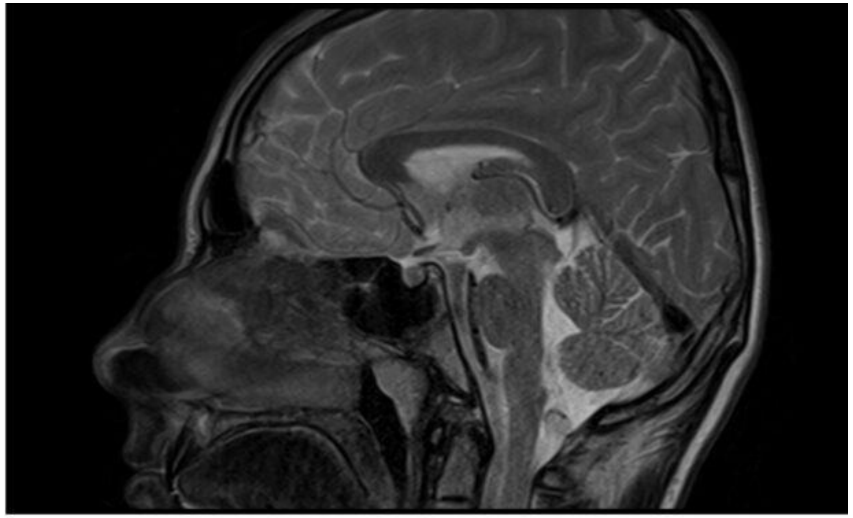
How does line scanning work?

- We would like to excite only the small column that we are interested in
- …but that's pretty difficult
(ask me why in the questions!)
- So normal slice selection gives us a good profile in one dimension, but not in two

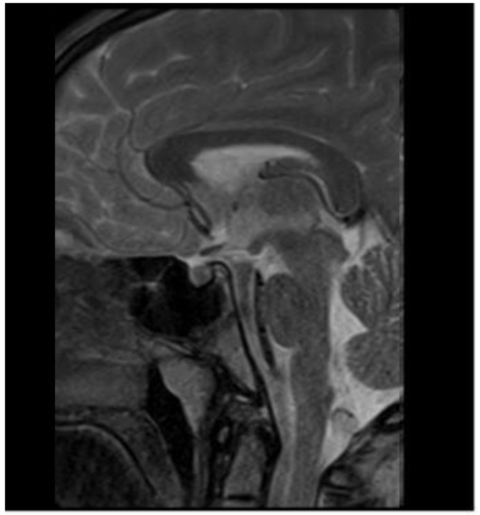


How does line scanning work?

- If we reduce our read field of view without any other modifications, we don’t get just the center of the image
- We get wrapping artifact because RF slice excitation affects the entire plane
- The most extreme case of this is line scanning, where the whole slice is wrapped into a single line!

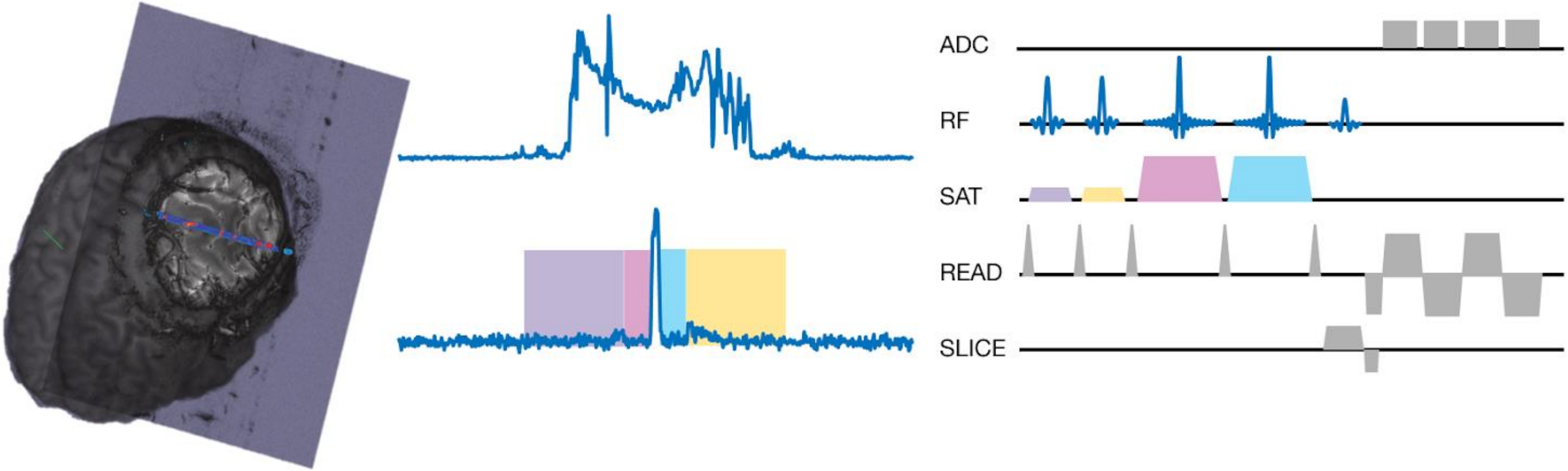


Phase FOV 100%



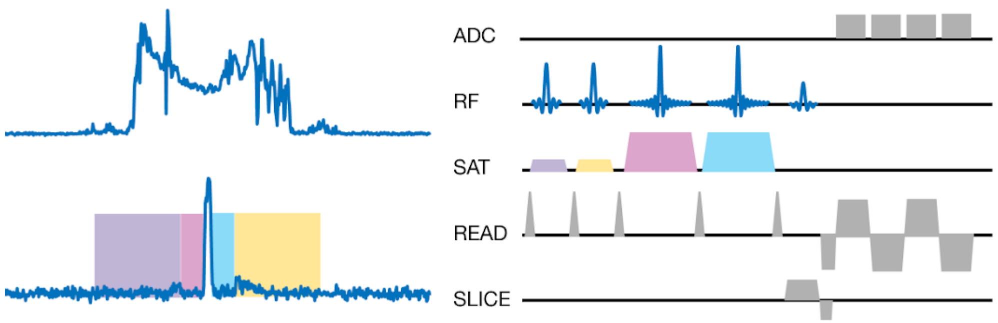
Phase FOV 50%

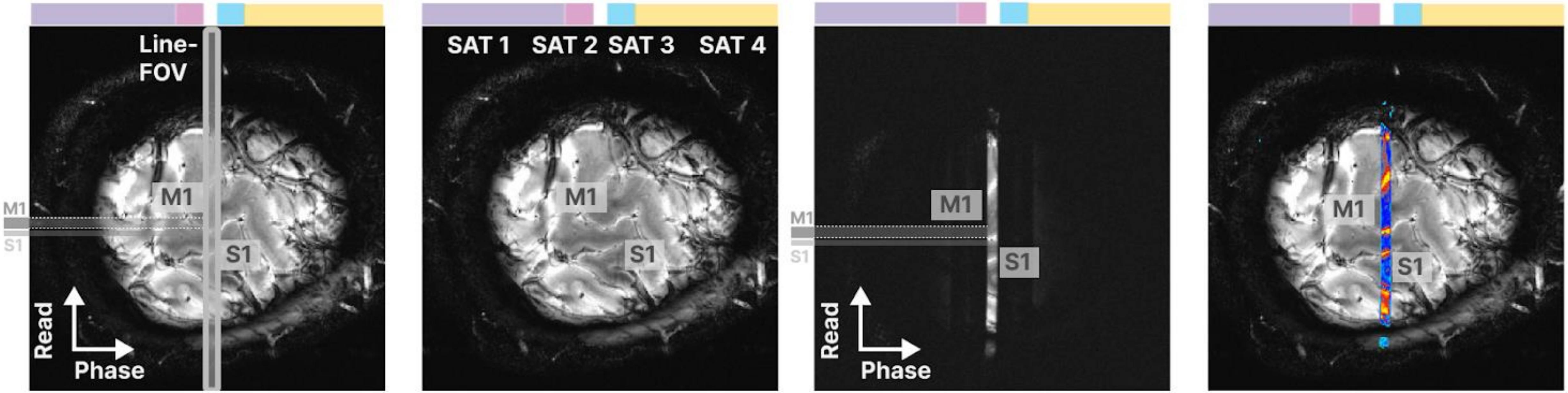
Saturation-based Line Scanning



Nothnagel, et al. (in submission)

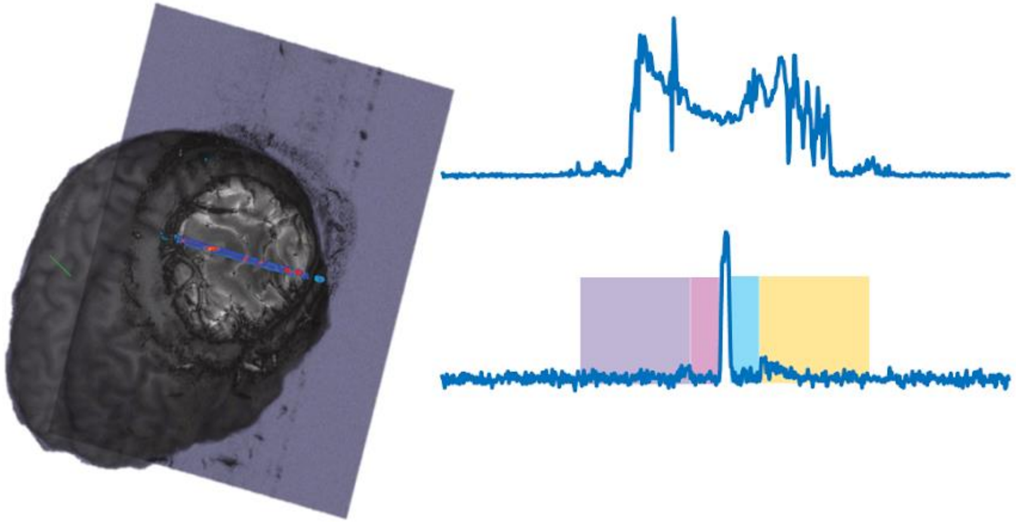
Saturation-based Line Scanning

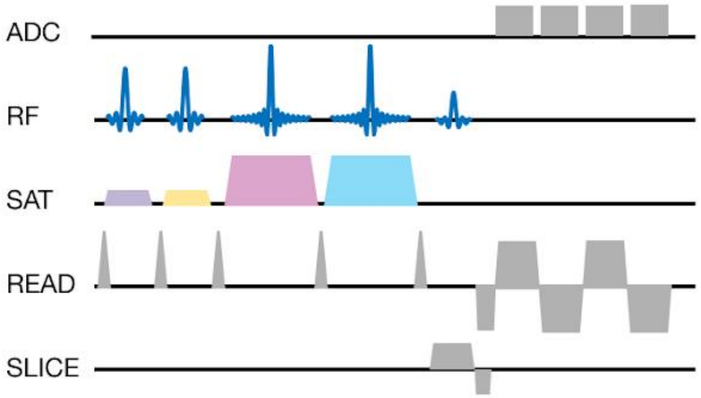


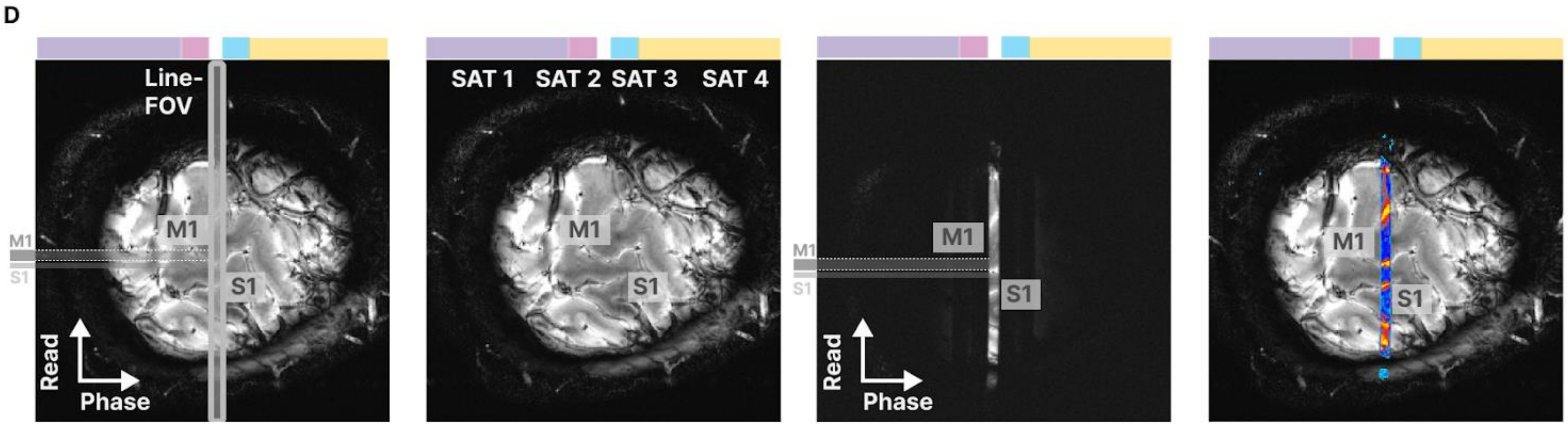


Nothnagel, et al. (in submission)

Saturation-based Line Scanning

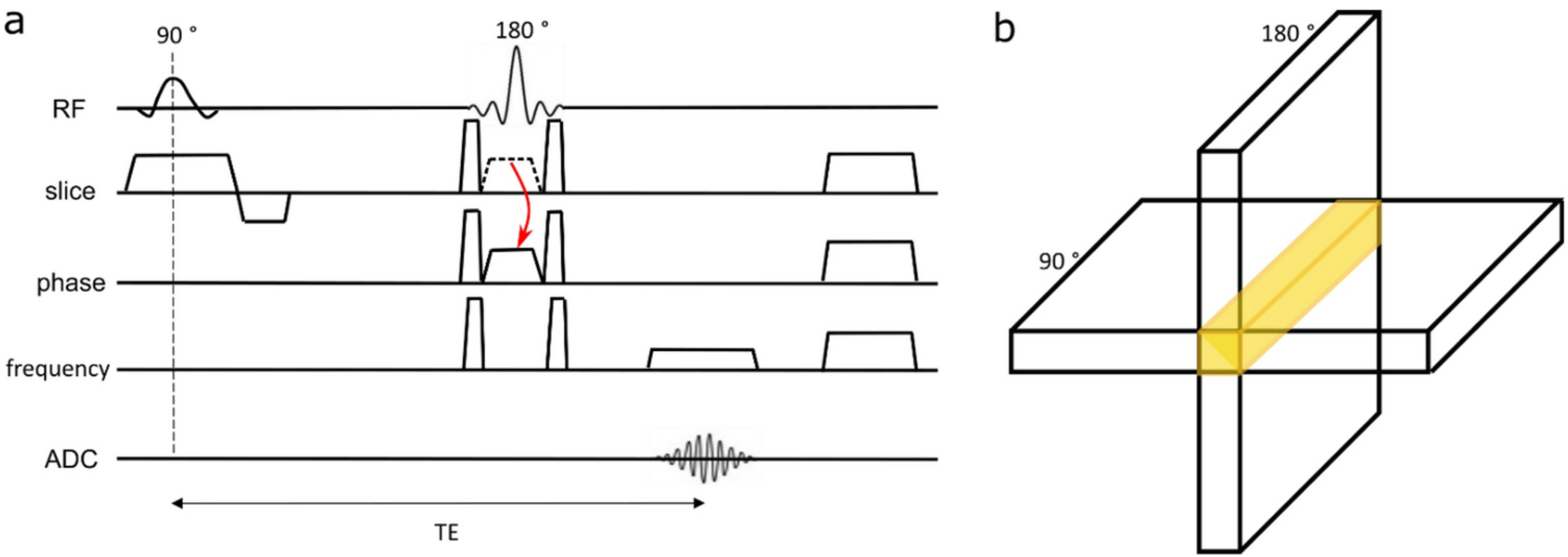






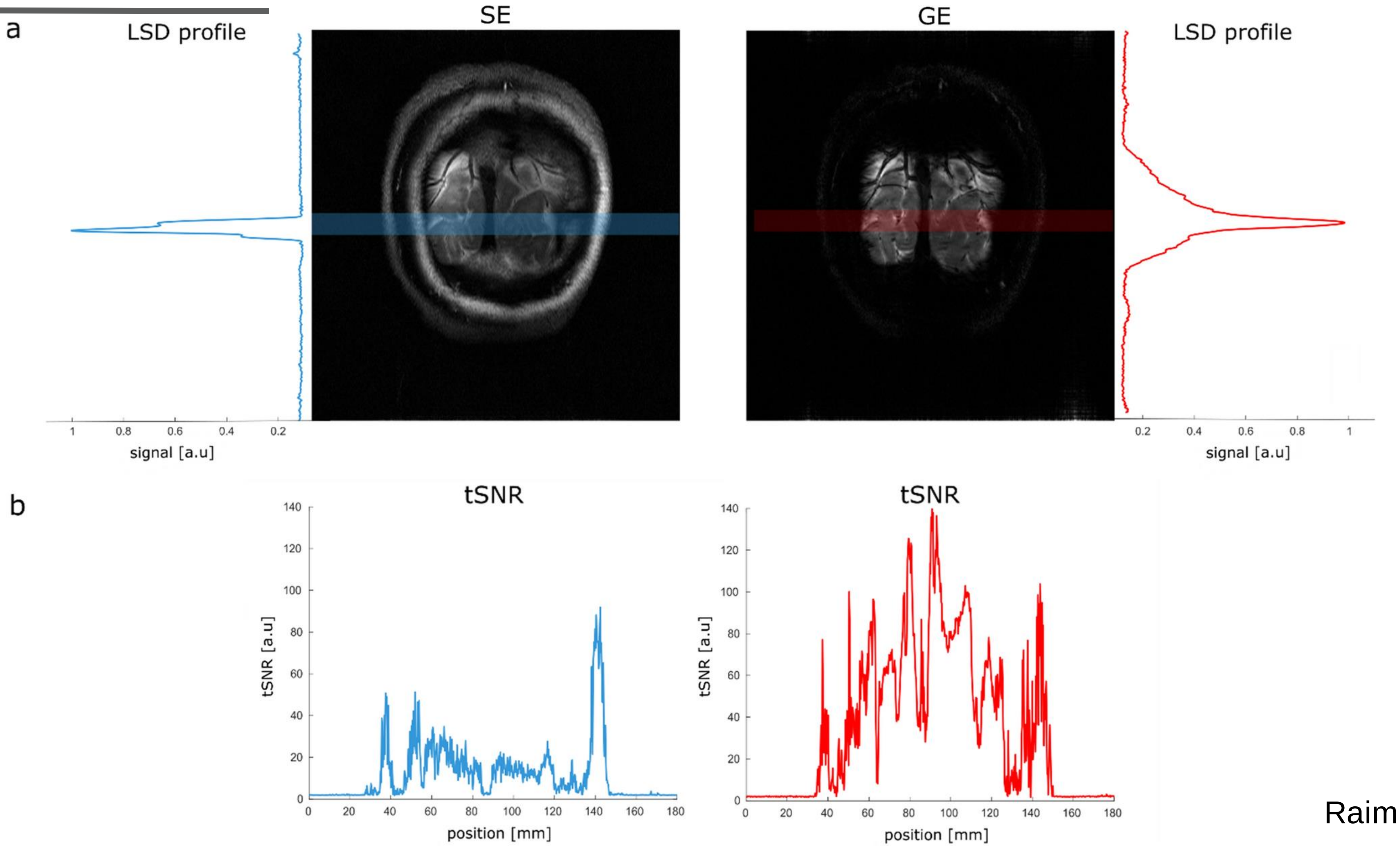
Nothnagel, et al. (in submission)

Spin Echo Line Scanning (SELINE)



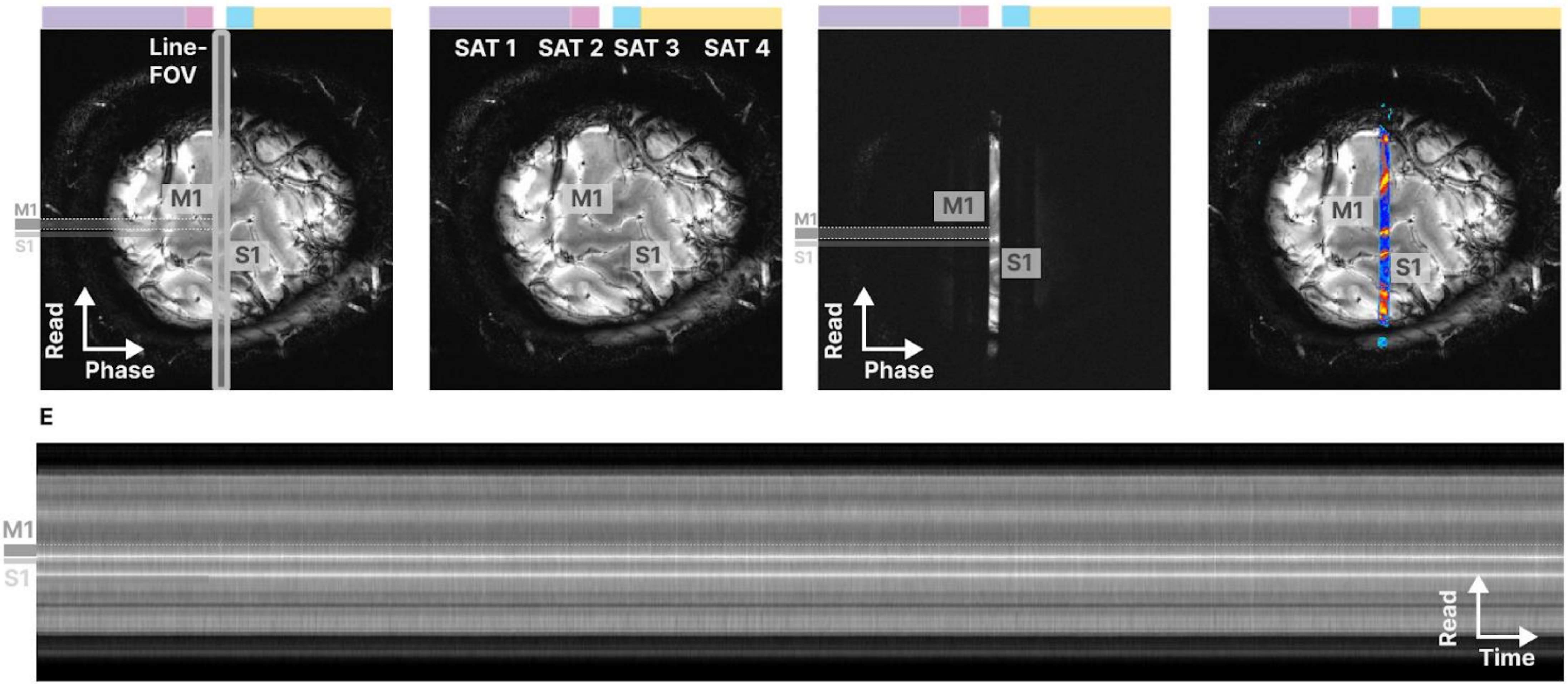
Raimondo, et al. 2023

Spin Echo Line Scanning (SELINE)



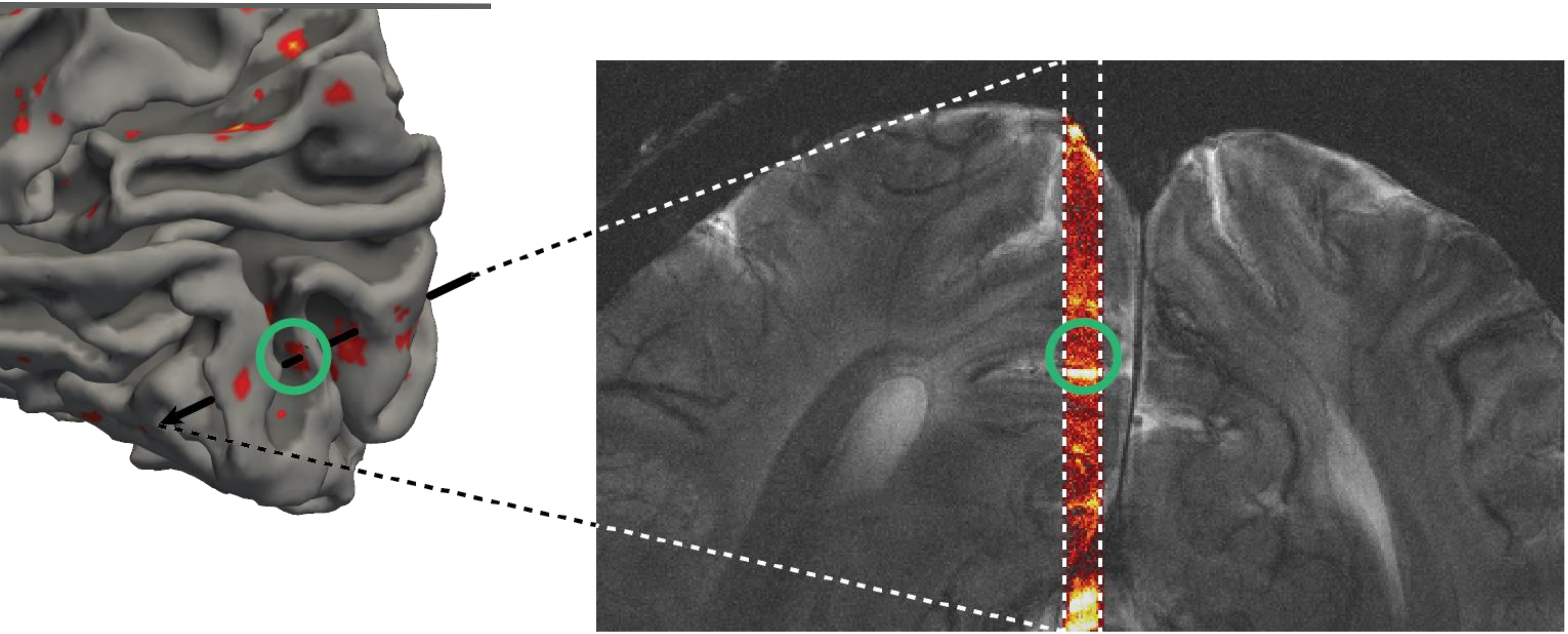
Raimondo, et al. 2023

What does line scanning look like?



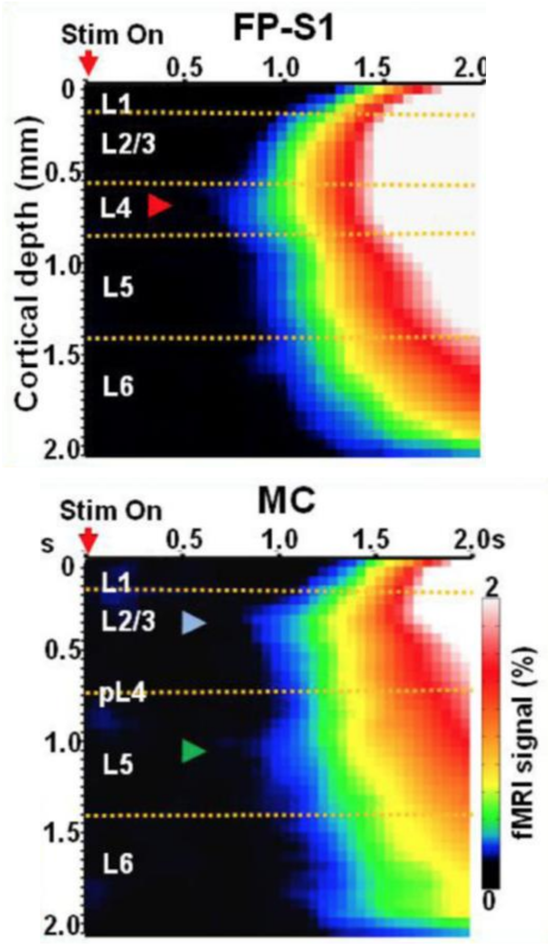
Nothnagel, et al. (in submission)

Line placement is a challenge

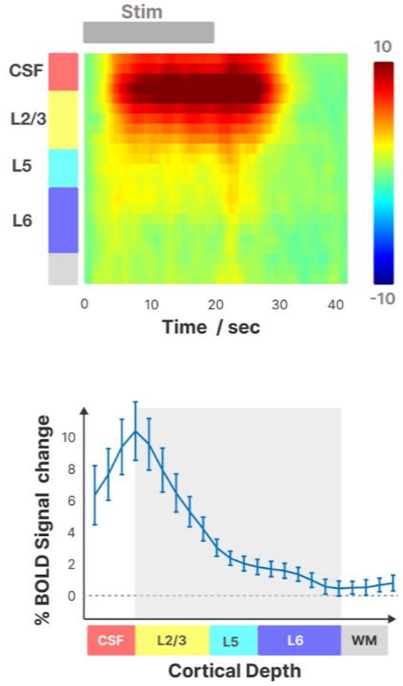


Morgan, Nothnagel, et al. 2020

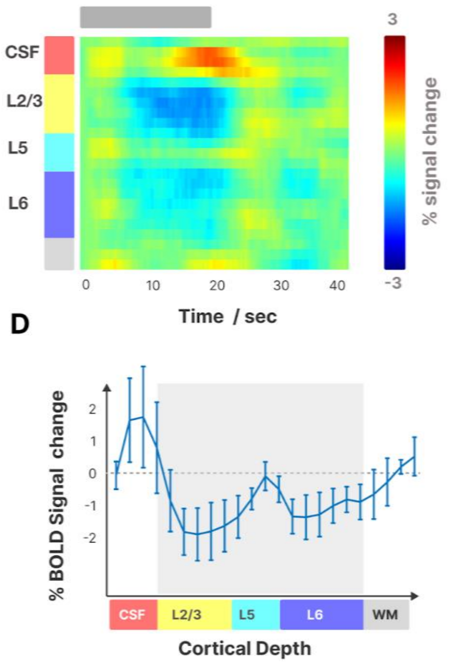
What can line scanning do?



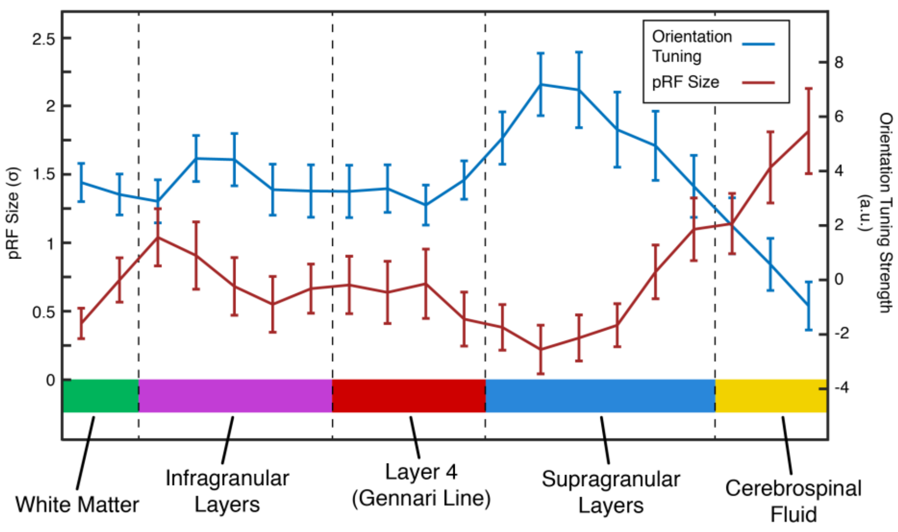
Contralateral tapping



Ipsilateral tapping



V1 Tuning



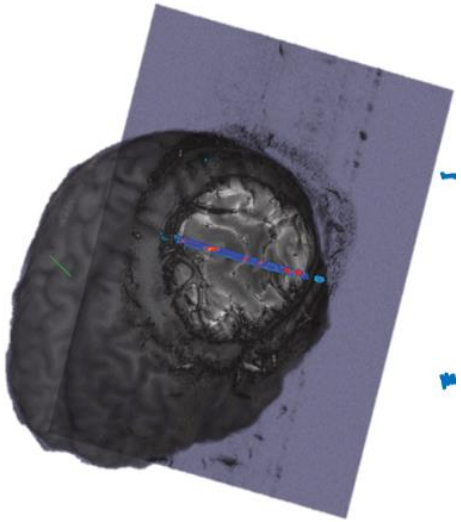
Yu, et al. 2014; Nothnagel, et al. (in submission); Morgan, Nothnagel, et al. 2020

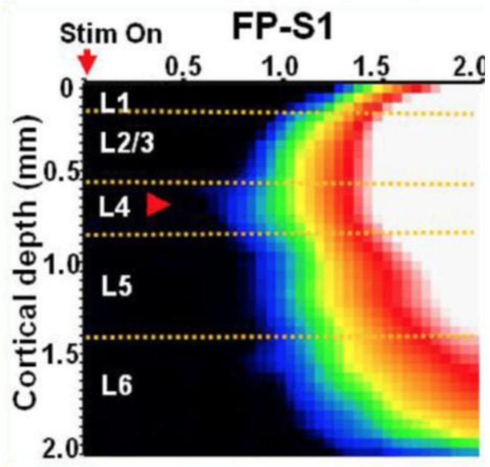
Wrapping up on line scanning

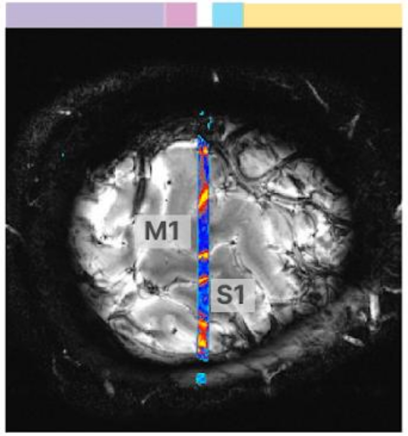
- Line scanning is a specialized technique for examining the brain in high spatial and temporal resolution

- But only in one dimension…

- Useful for examining cortical layers!



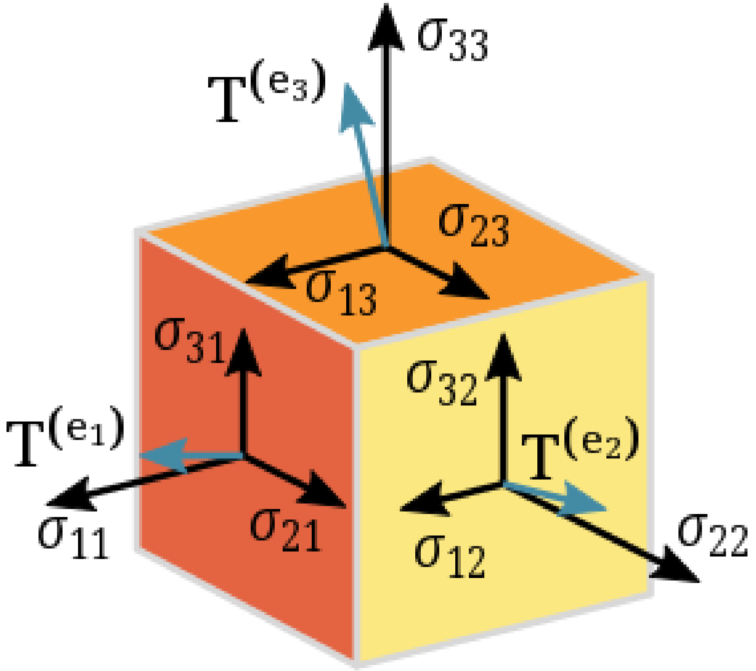




And now, for something completely different…

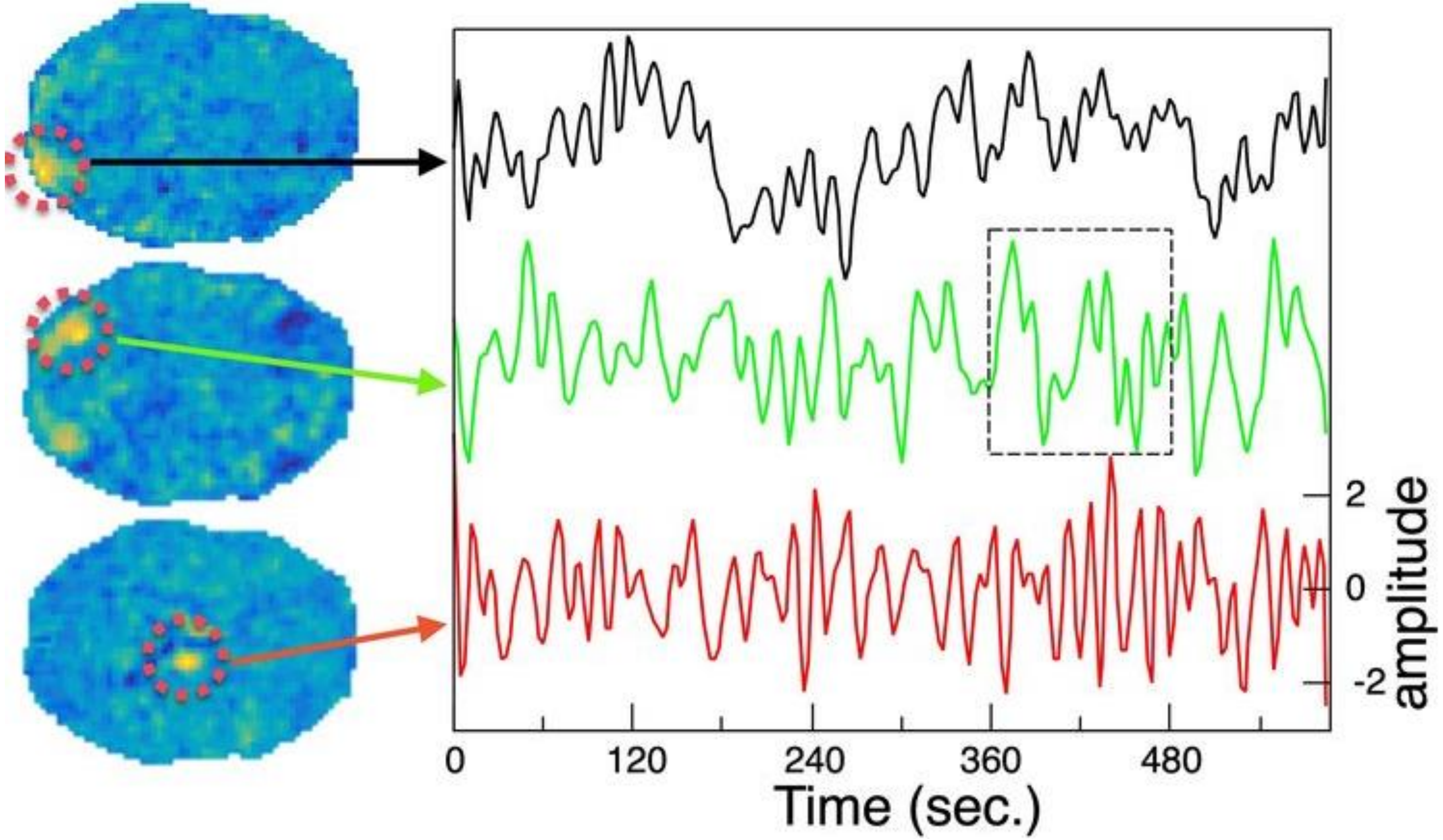
- Tensors! What are they? Why do we care?

- In simplest terms, a tensor is a generalized array for the cases when they don't already have names:
  - 0-dim: a point (or a tensor)
  - 1-dim: a line or vector (or a tensor)
  - 2-dim: a matrix (or a tensor)
  - 3-dim: a tensor (or a tensor)
  - and so on…



Tensors as arrays

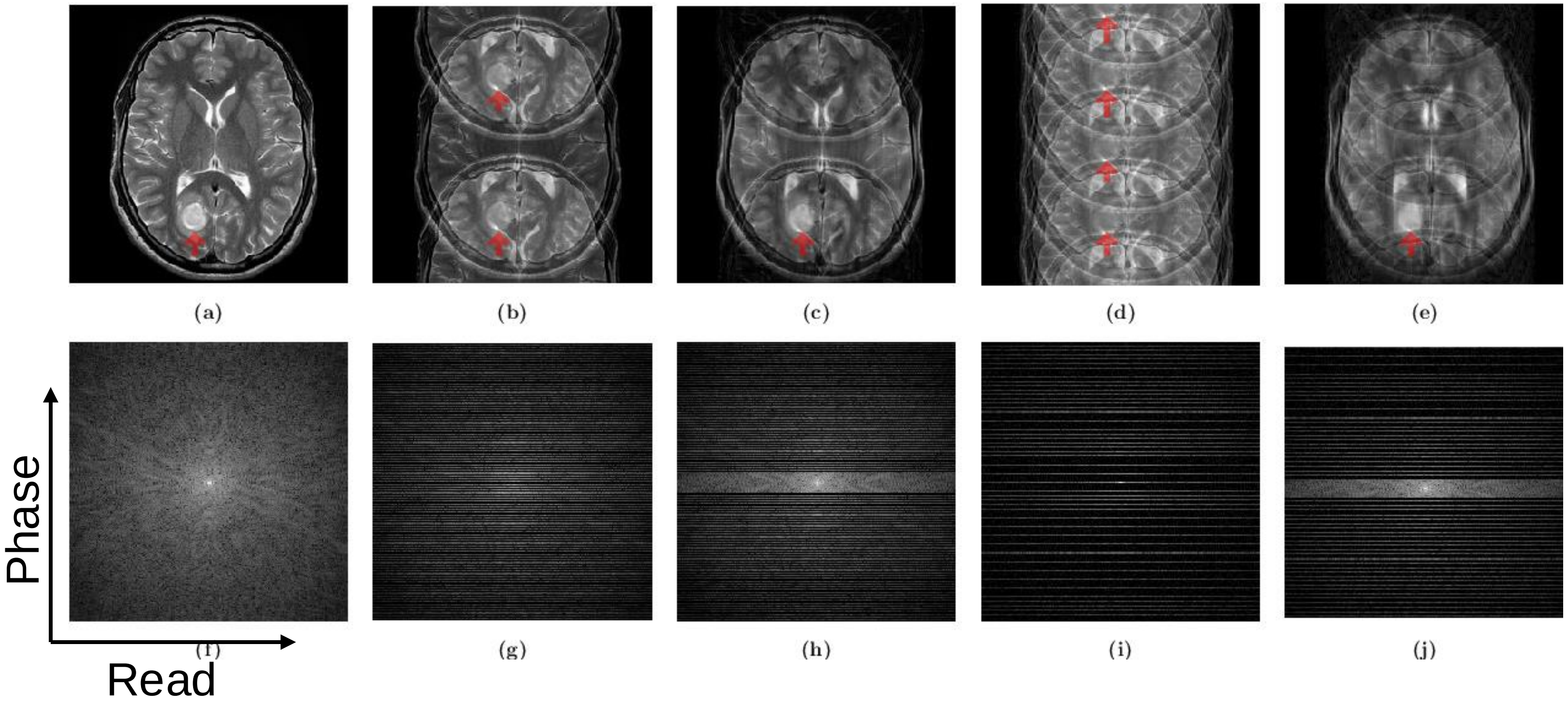
- The truth is, any data structure can be considered a tensor
- However, there is something to the idea of coordinates we care about being visible, and “additional” data being hidden
- This is super common in neuroimaging ;)



Tensors and undersampling go hand in hand

- The typical approach to speed things up is to just not collect an entire image.

- Data can then be interpolated using one of many available techniques (SENSE, GRAPPA, CAIPIRINHA, SMASH, etc.)



- These methods take advantage of correlations in k-space based on encoding information derived from the spatial locations of head coils

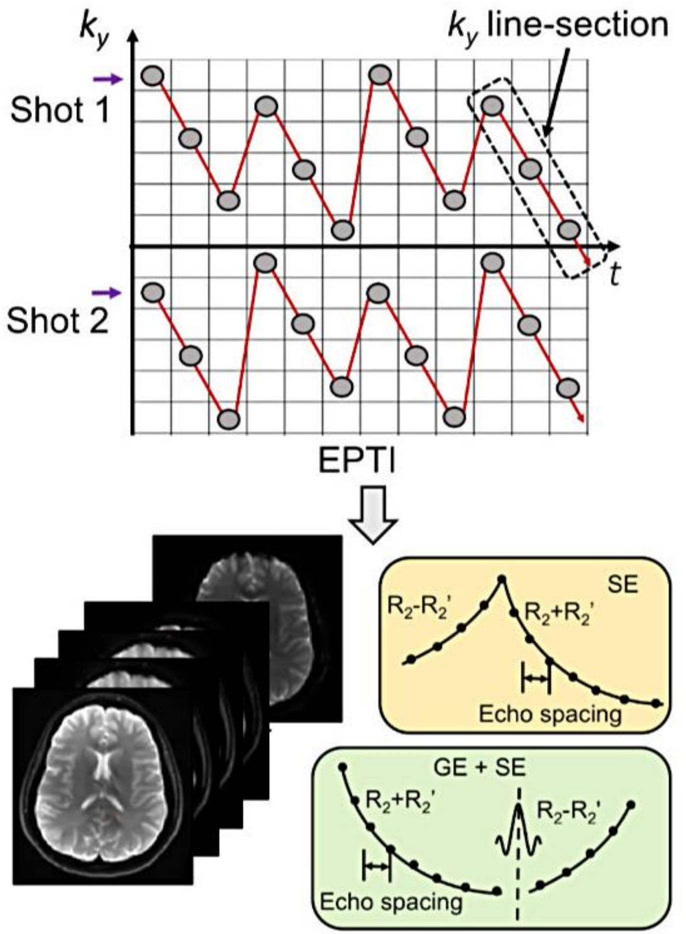
Under-sampling in ***time***

- The spatial layout of coils is not the only well-behaved domain that makes interpolation easy.

- Another option is ***time***, which leads to *time-resolved undersampling*.

- A recent exciting development using decay/echo time undersampling is ***EPTI*** (*Echo-planar Time-resolved Imaging*)

  [the inspiration for the current work]

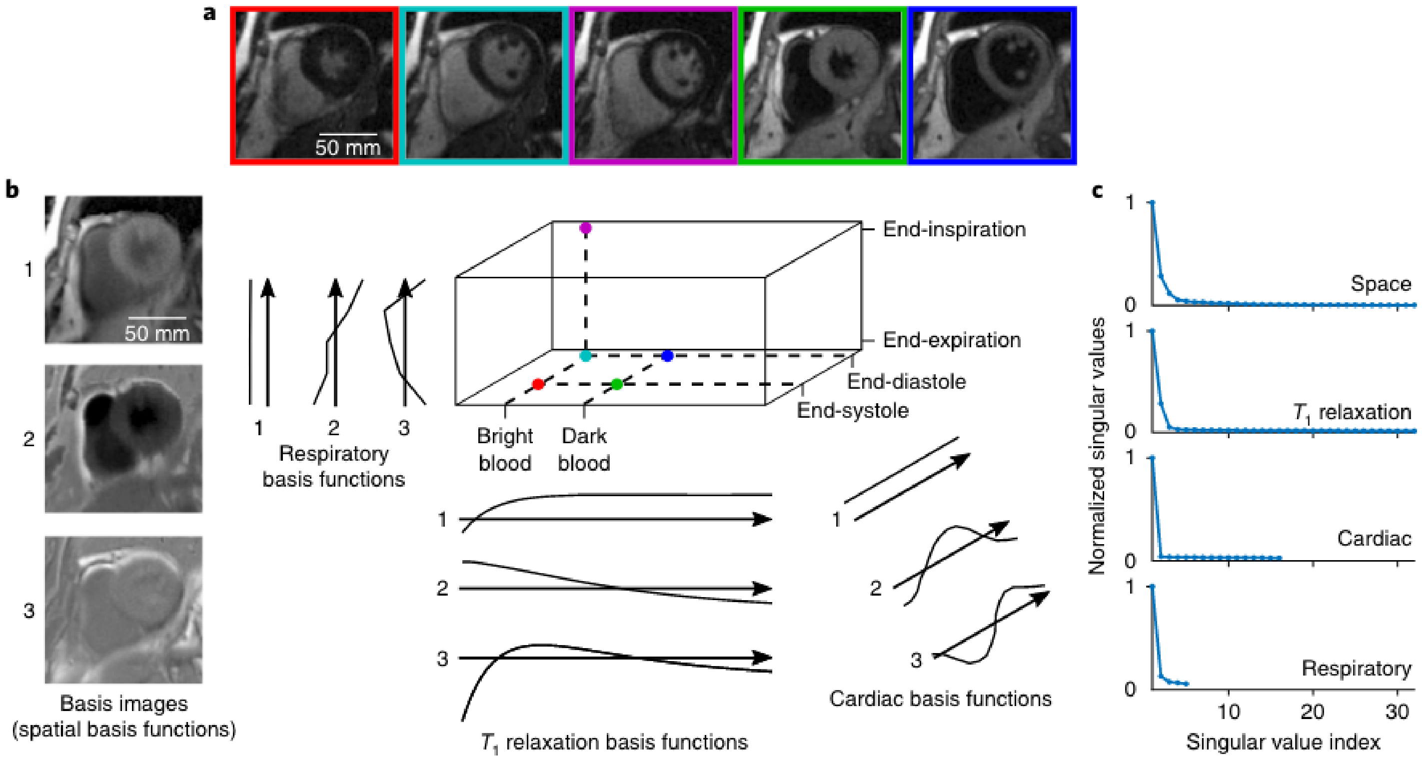


Distortion and blurring-free multi-contrast images

Wang, et al. 2020

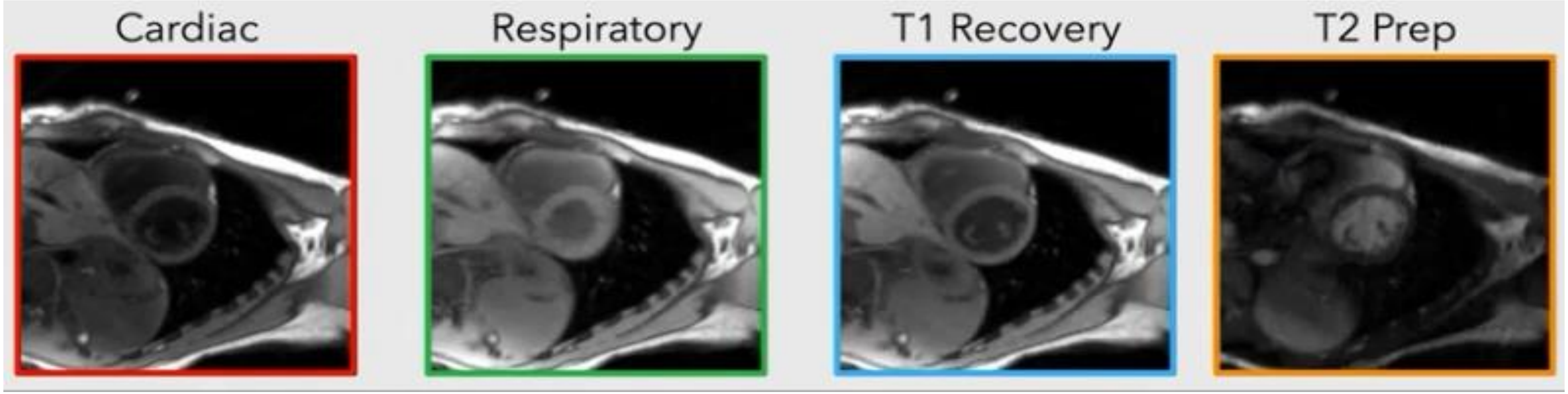
Under-sampling in ***many dimensions***

- Like many other exciting MRI techniques, this idea has existed in some form since the 1990s.
- Cardiac imaging takes advantage of multiple time dimensions that are predictable (low-rank)
- These dimensions can be organised as tensor structures to take advantage of the cumulative correlations in each dimension.



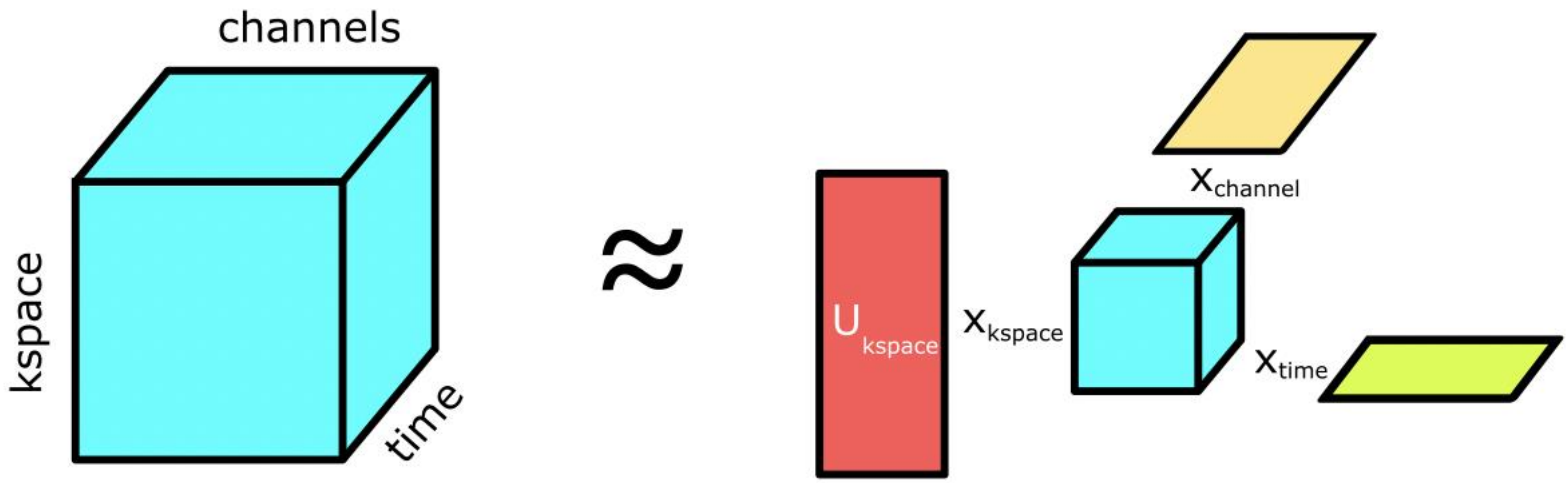
Christodoulou, et al. 2018

Under-sampling in ***many dimensions***

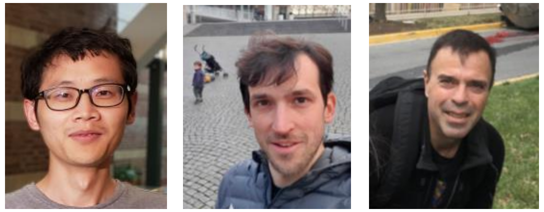


Christodoulou, et al. 2018
(via Frank Ong's 2020 ISMRM Educational Session)

fTR-fMRI as a ***Low-Rank Structure***

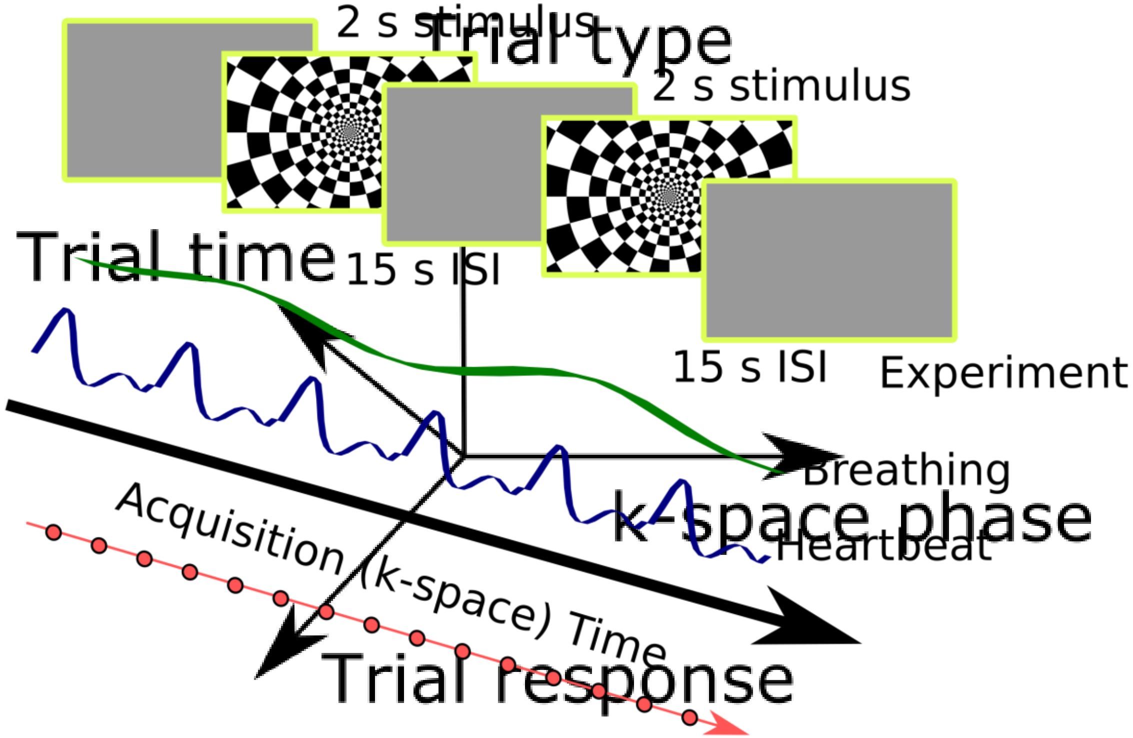


Functionally Time-Resolved fMRI



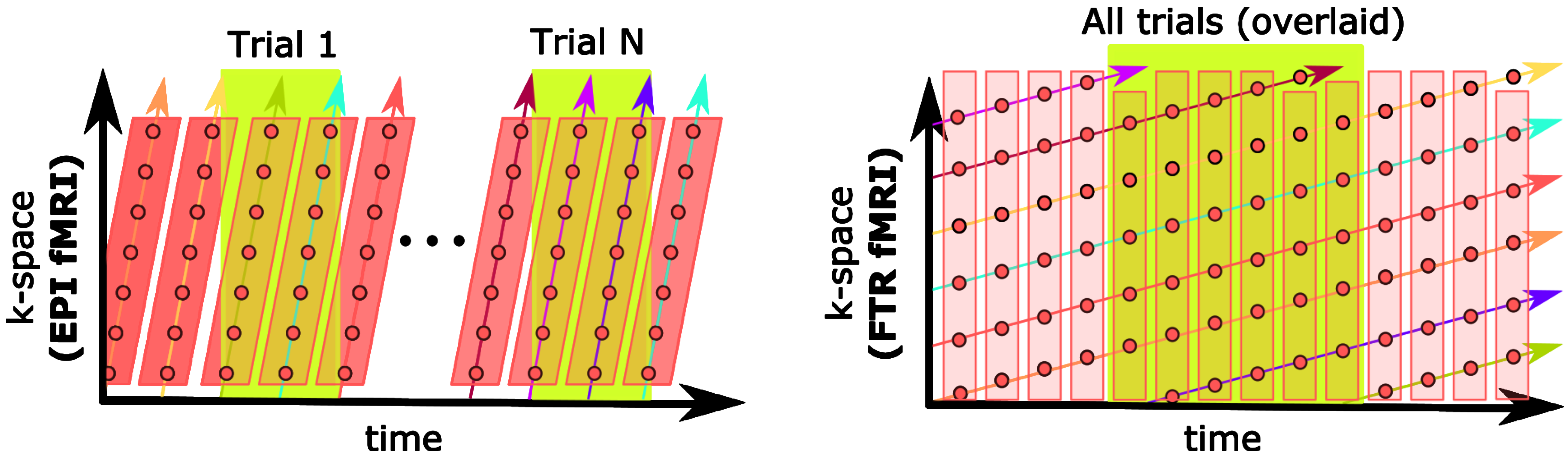
Yuhui Chai Renzo Huber Peter Bandettini

- High-resolution fMRI using EPI readouts and BOLD contrast suffer from spatial distortions and T2* blurring due to long readout trains.
- Functionally Time-Resolved fMRI (fTR-fMRI) expands time-resolved methods (EPTI; SILK) to incorporate neuroscientific experimental designs into fMRI reconstruction
- Resolves k-space data onto the dimensions relevant to image formation in fMRI experiments.

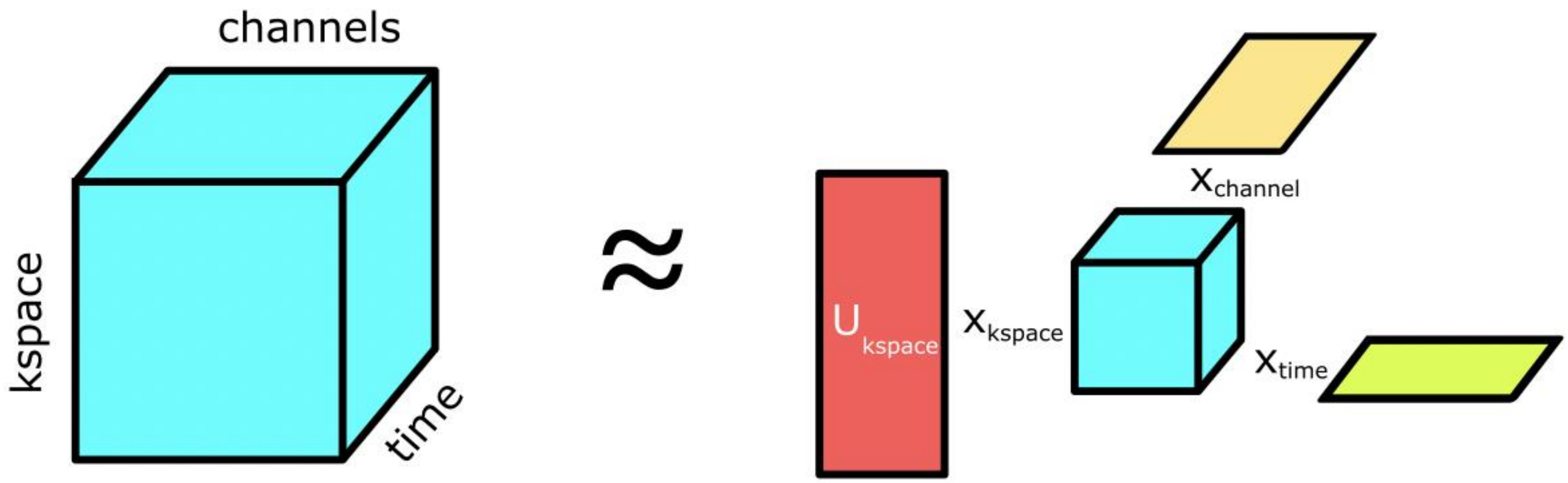


Wang, et al. 2019; Vu, et al. 2018

Functionally Time-Resolved fMRI Encoding

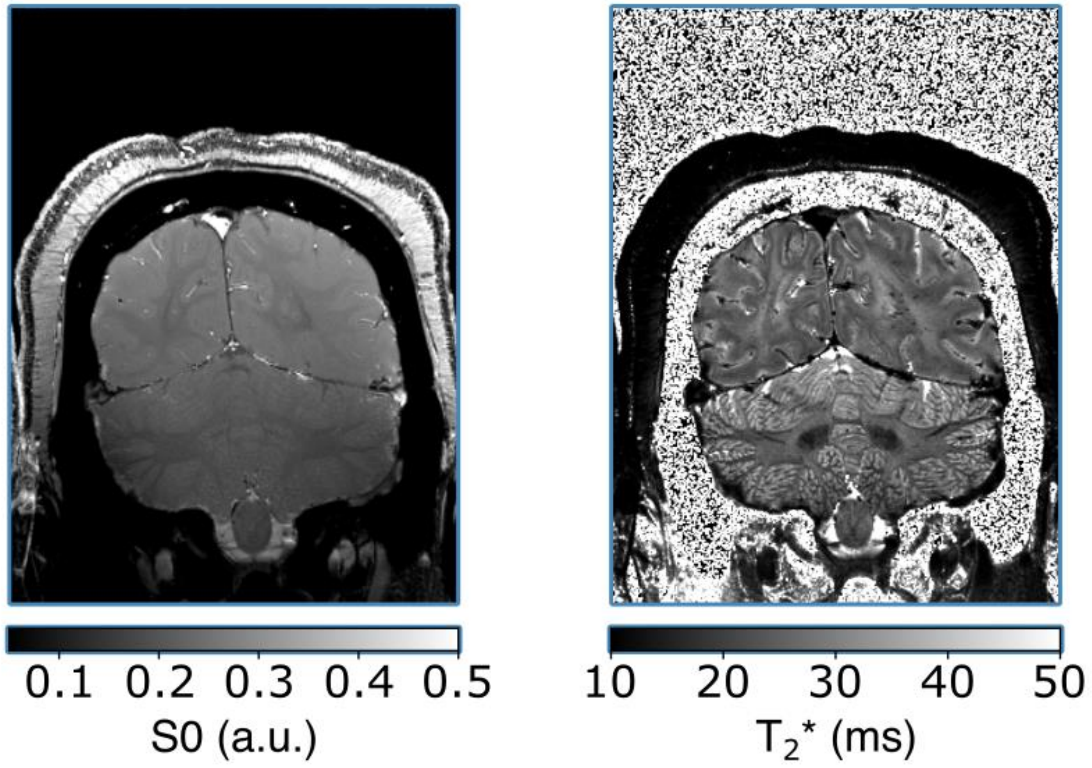


Functionally Time-Resolved fMRI Encoding

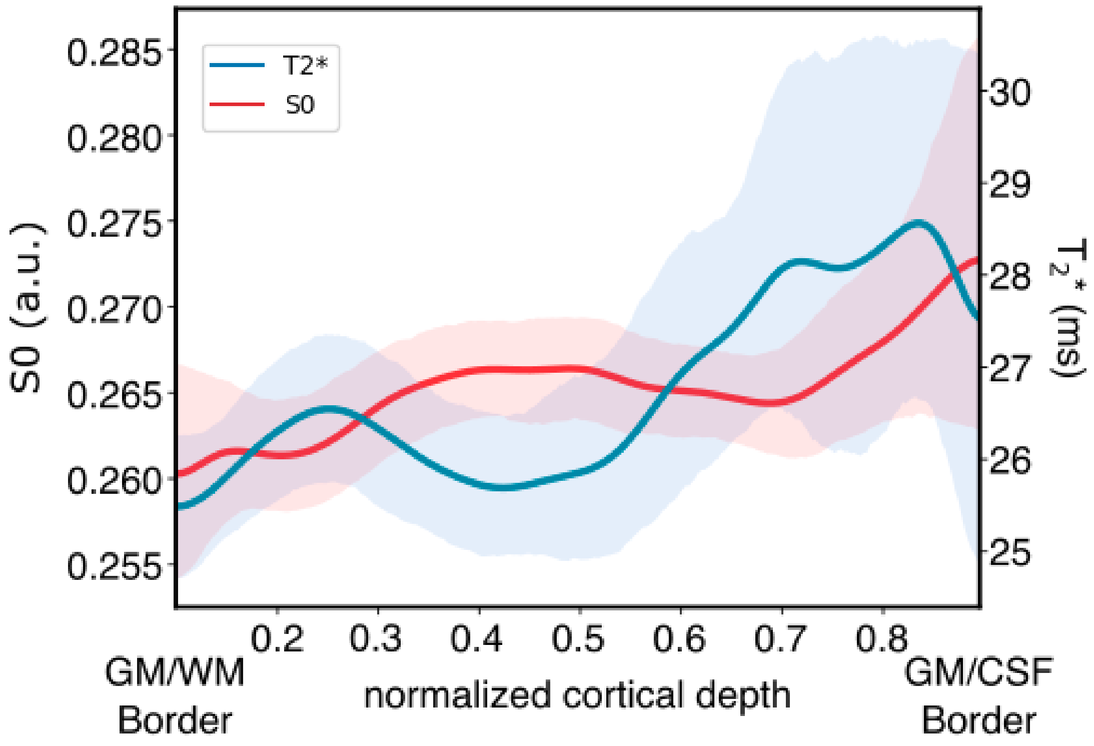


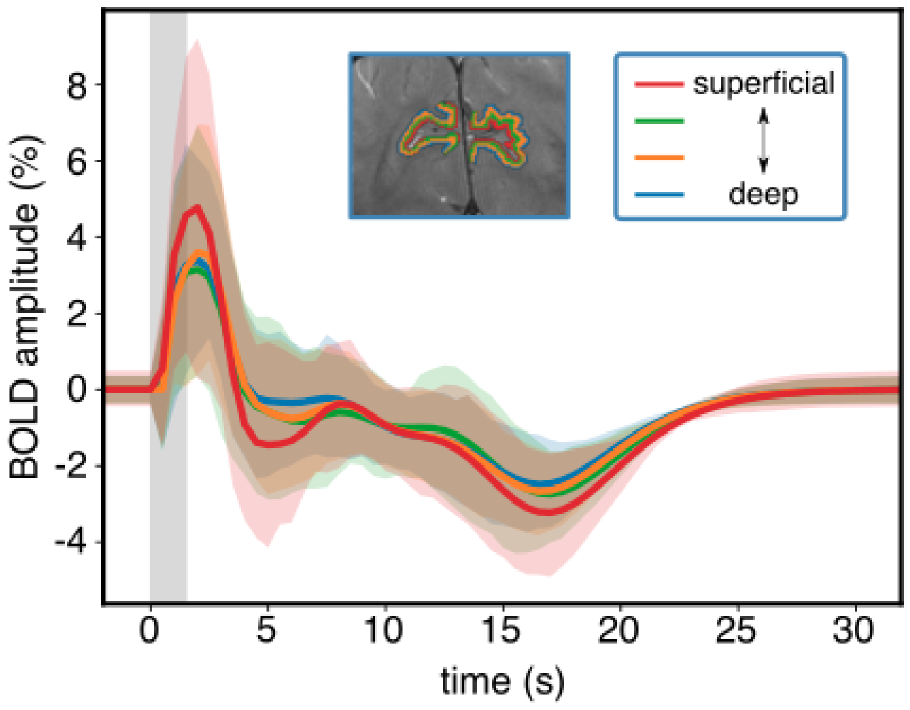
Functionally Time-Resolved fMRI: 0.5 mm / 0.5 s resolution laminar fMRI

- fTR-MRI produces high-resolution, distortion-free multi-echo images from a gradient echo sequence.
- The precise acquisition time of each k-space line can be used to compute functional responses to experimental events.



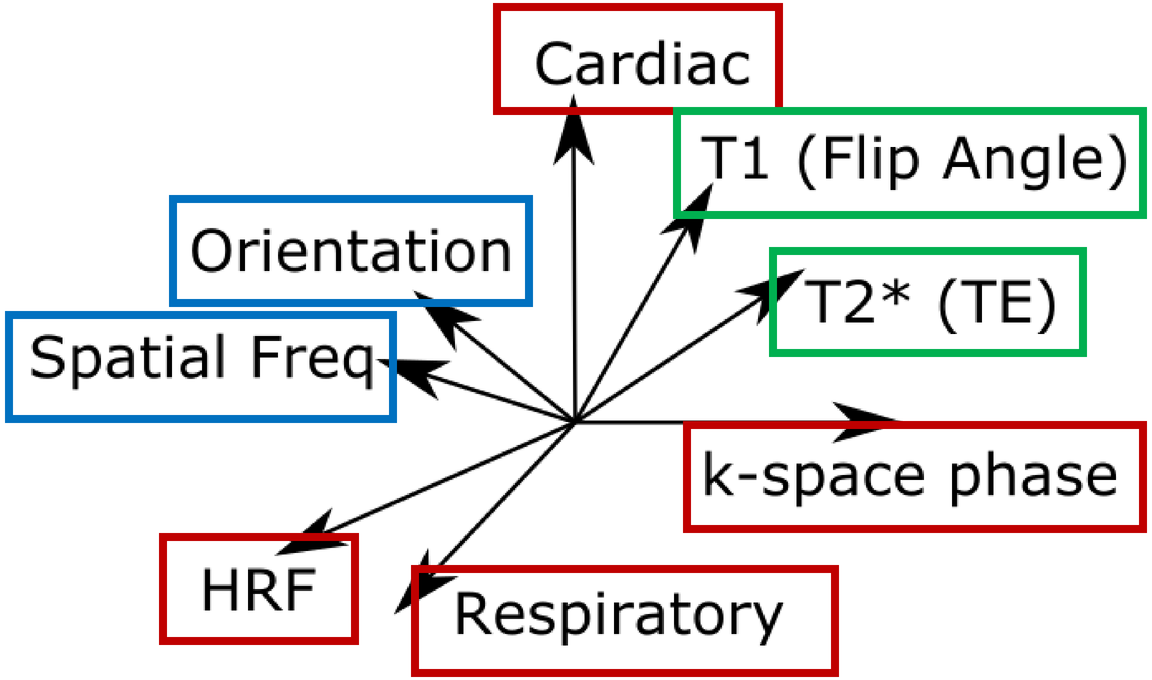
Functionally Time-Resolved fMRI: 0.5 mm / 0.5 s resolution laminar fMRI



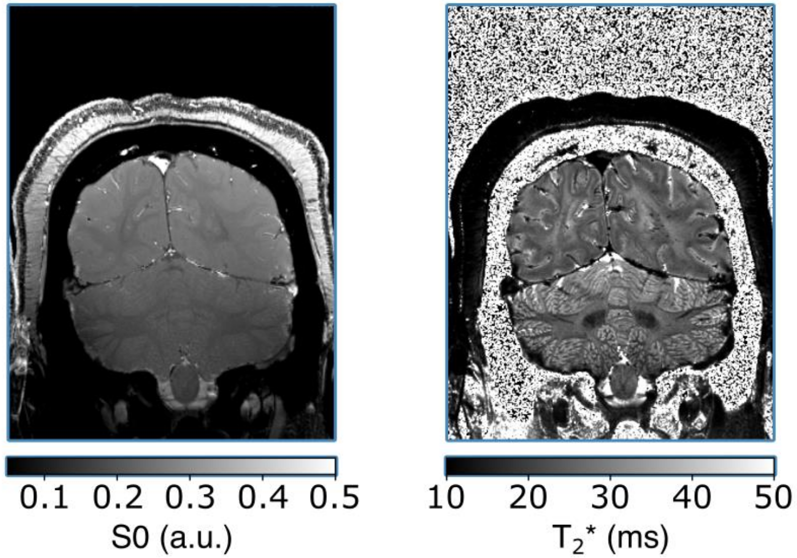


Where to go from here?

- EPI is a much better imaging technique for traversing k-space quickly (many lines after RF excitation).
- fTR-MRI can expand undersampling schemes to as many dimensions we want.
- Cardiac and respiratory signals could be incorporated into layer imaging

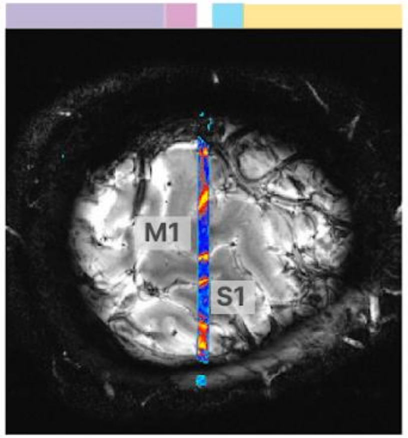


Overall thoughts

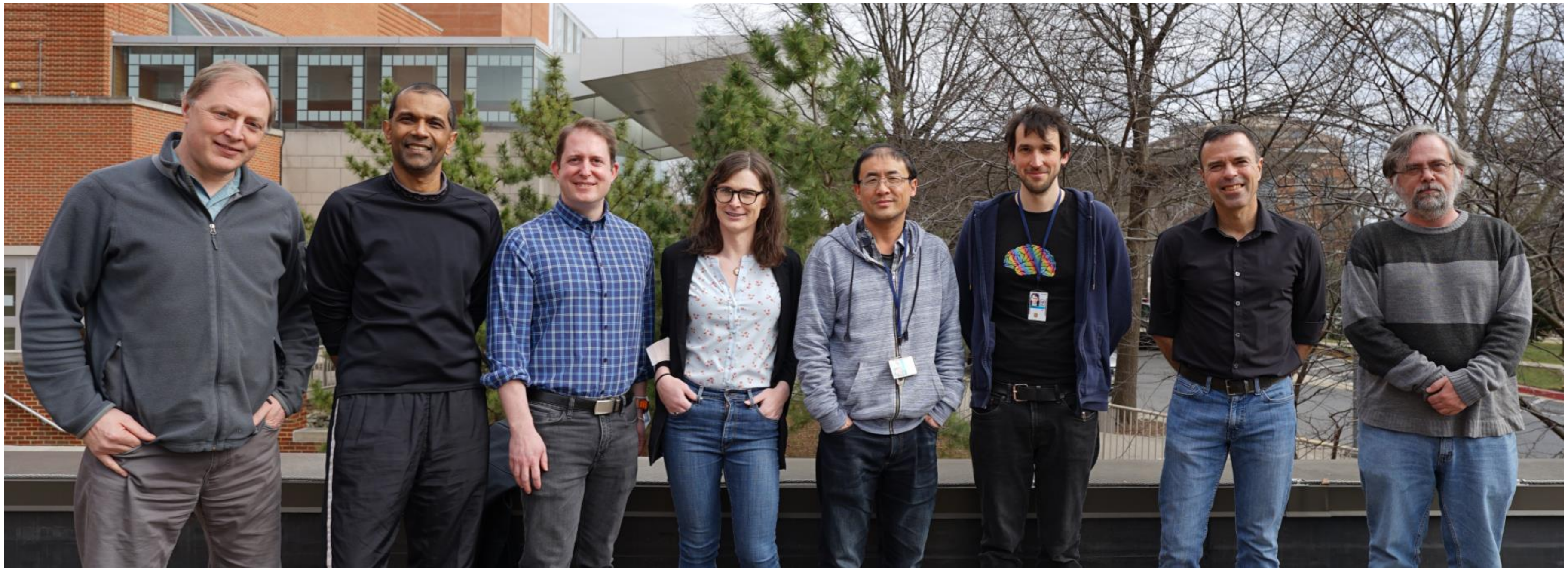


- fMRI relies on 2D/3D scanning for many applications

- However, some detailed scientific questions call for specialized imaging techniques



Thank you!



External Collaborators

- Nils Nothnagel
- Jozien Goense
- Lucy Petro
- Lars Muckli

FMRIF@NIH

- Renzo Huber
- Pete Molfese
- Andy Derbyshire
- Vinai Roopchansingh
- Linqing Li
- Dorian Van Tassell
- Peter Bandettini