THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

CREATE CHANGE

Fast fMRI Acquisitions and Analyses

Spinoza User Meeting

Saskia Bollmann

Centre for Advanced Imaging, The University of Queensland

7T NIF Facility Fellow (Acting)

Overview

Acquisitions

- Echo-Planar Imaging (EPI)
- **Simultaneous Multislice (SMS) / Multiband**
- Advanced Methods
  - Line Scanning
  - Inl
  - MREG
  - T-Hex

Analyses (Applications)

- Block Designs
- Dynamic Stimuli
- DCMs
- Physiology
- EEG-FMRI
- Time-Varying Functional Connectivity

+ Challenges

- Spatial Correlations
- Temporal Correlations

Acquisitions

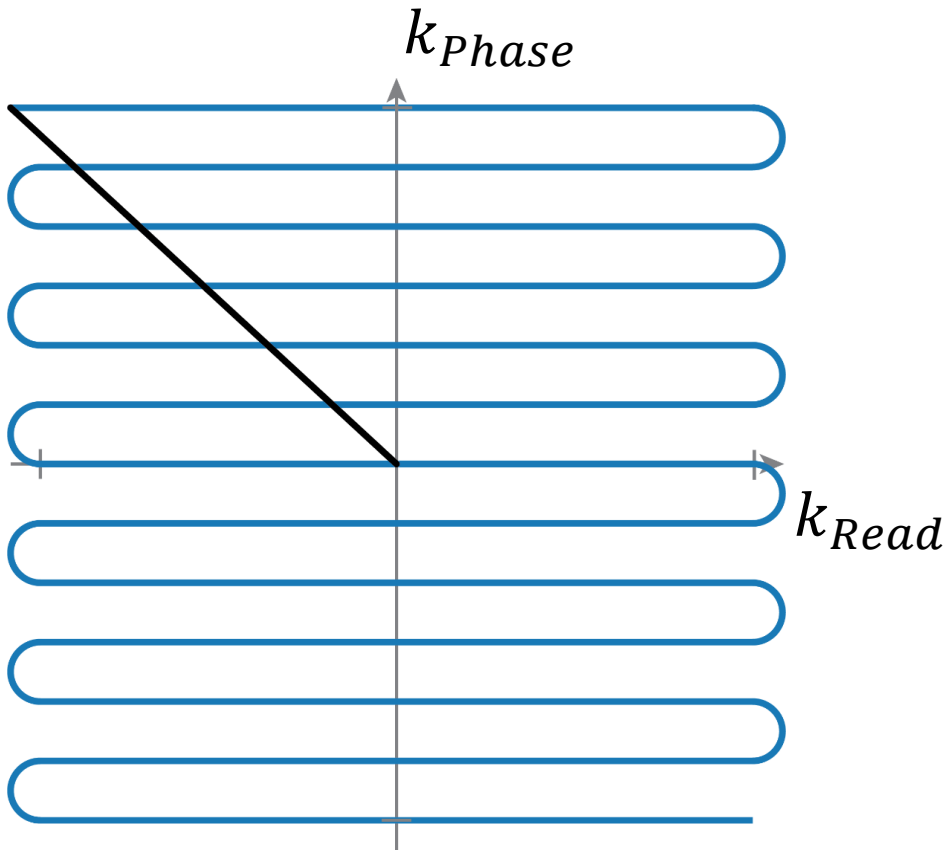
Echo-Planar Imaging (EPI)

Simultaneous Multislice (SMS) / Multiband

Advanced Methods

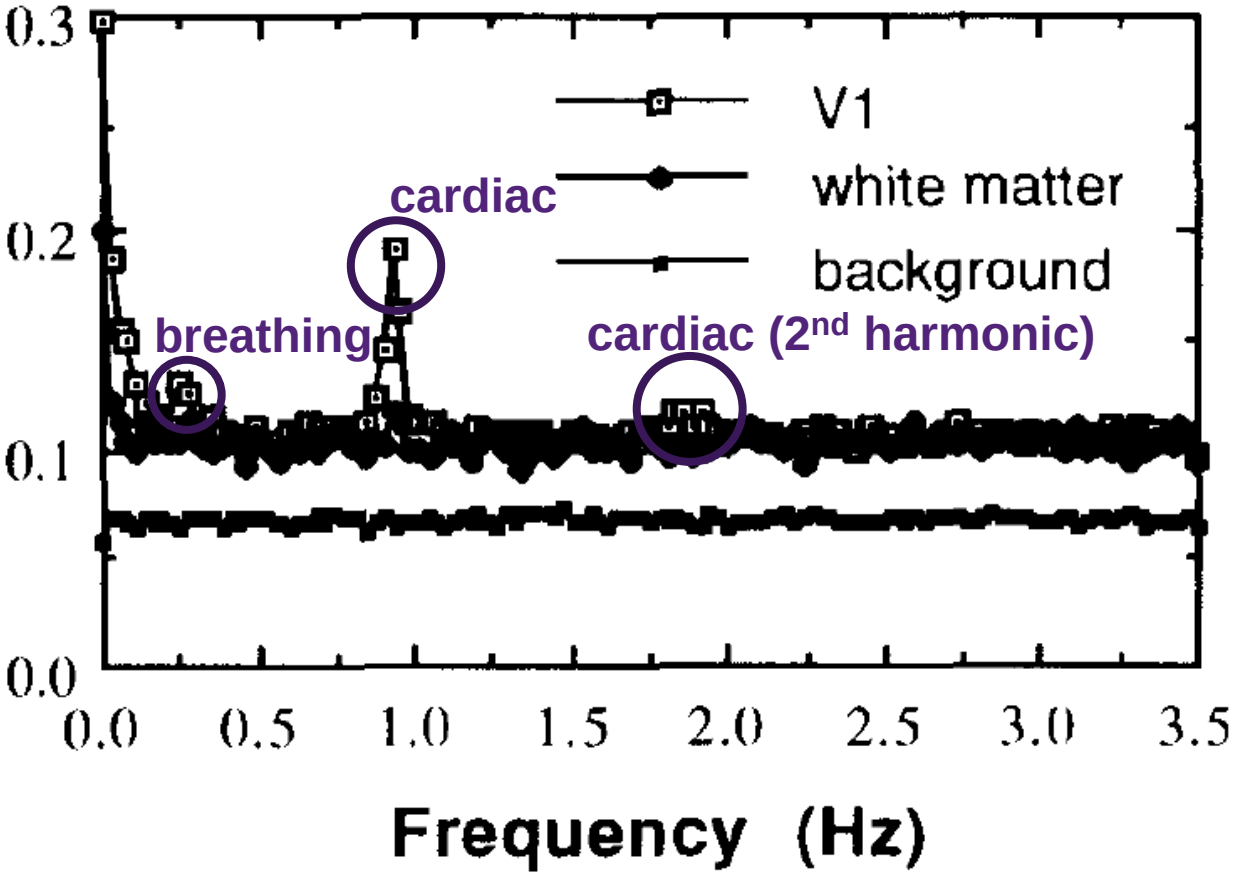
Echo-Planar Imaging (EPI)[1]

- One slice is excited and the complete 2D k-space is read out in a couple of tens of milliseconds



Weisskoff et al., 1993, SMRM

TR ~ 133 ms
(1 slice)



[1]Mansfield, 1977, J Phys C Solid State Phys

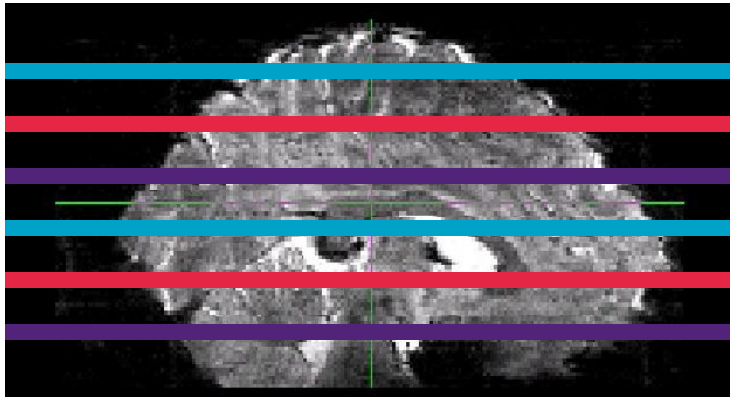
Acquisitions

Echo-Planar Imaging (EPI)

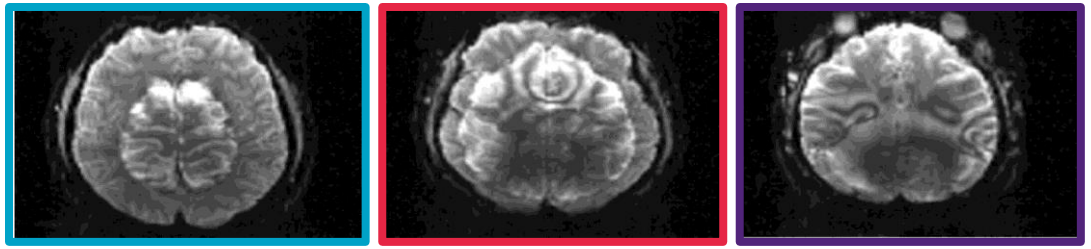
Simultaneous Multislice (SMS) / Multiband

Advanced Methods

Simultaneous Multislice (SMS) / Multiband[1,2]

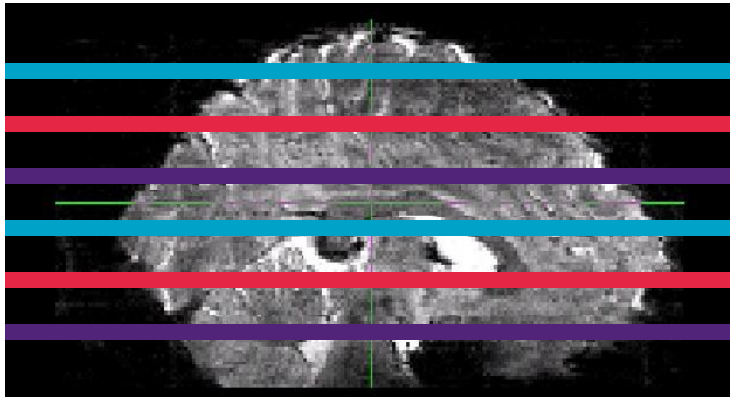


Uğurbil, 2013, NI

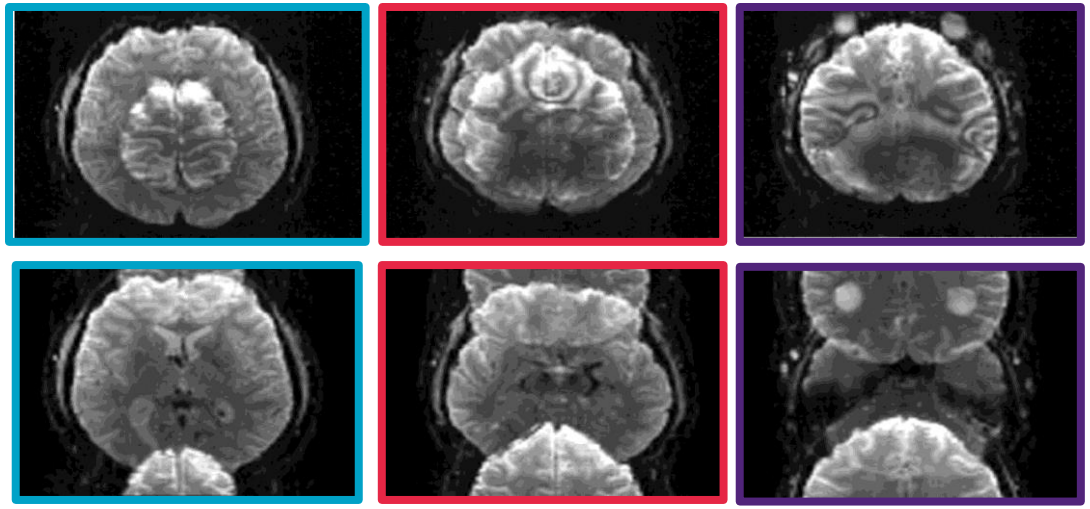


[1]Maudsley, 1980, JMR; [2]Müller, 1988, MRM;

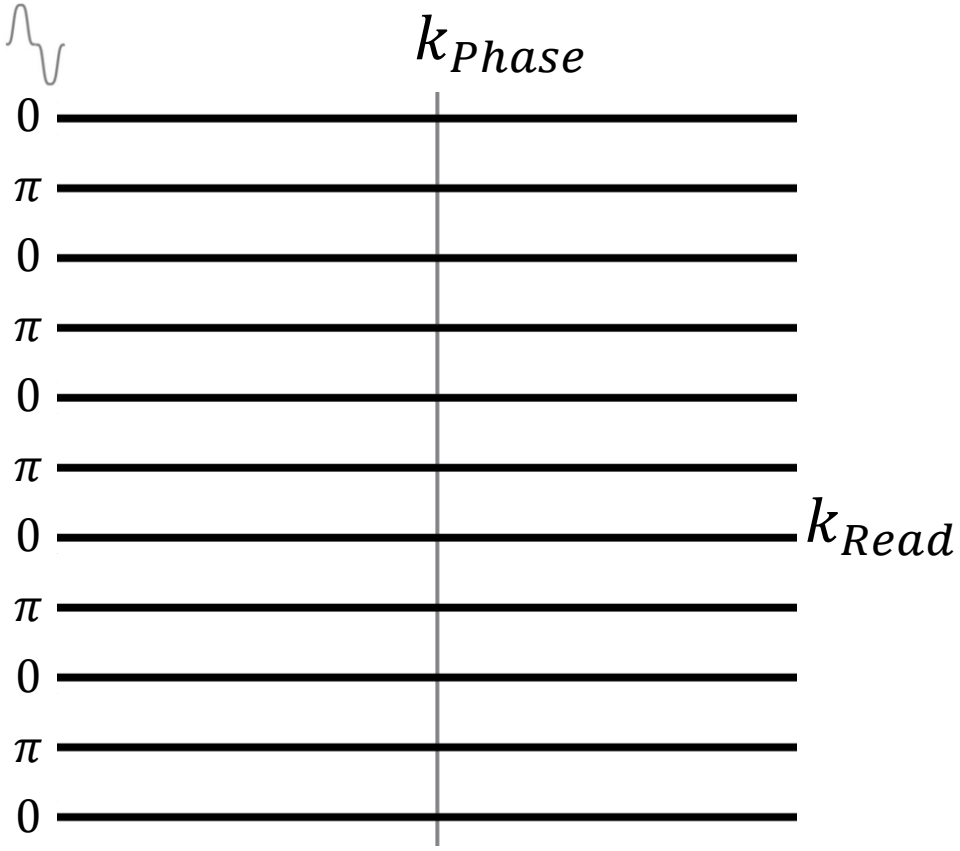
Simultaneous Multislice (SMS) / Multiband[1,2,3]



Uğurbil, 2013, NI



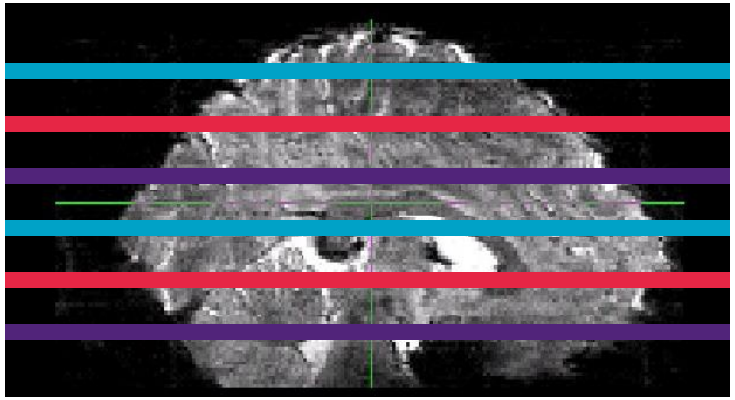
CAIPIRINHA[4]



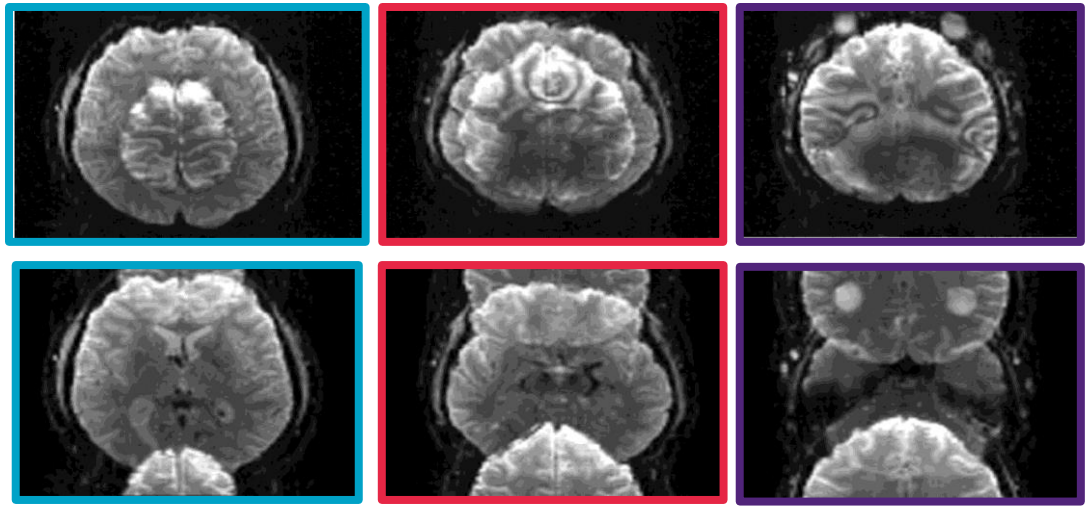
linear phase in k-space $\overset{\text{FT}}{\Longleftrightarrow}$ shift in image space

[1]Maudsley, 1980, JMR; [2]Müller, 1988, MRM; [3]Larkman et al., 2001, JMRI; [4]Breuer et al., 2005, MRM

Simultaneous Multislice (SMS) / Multiband[1,2,3]

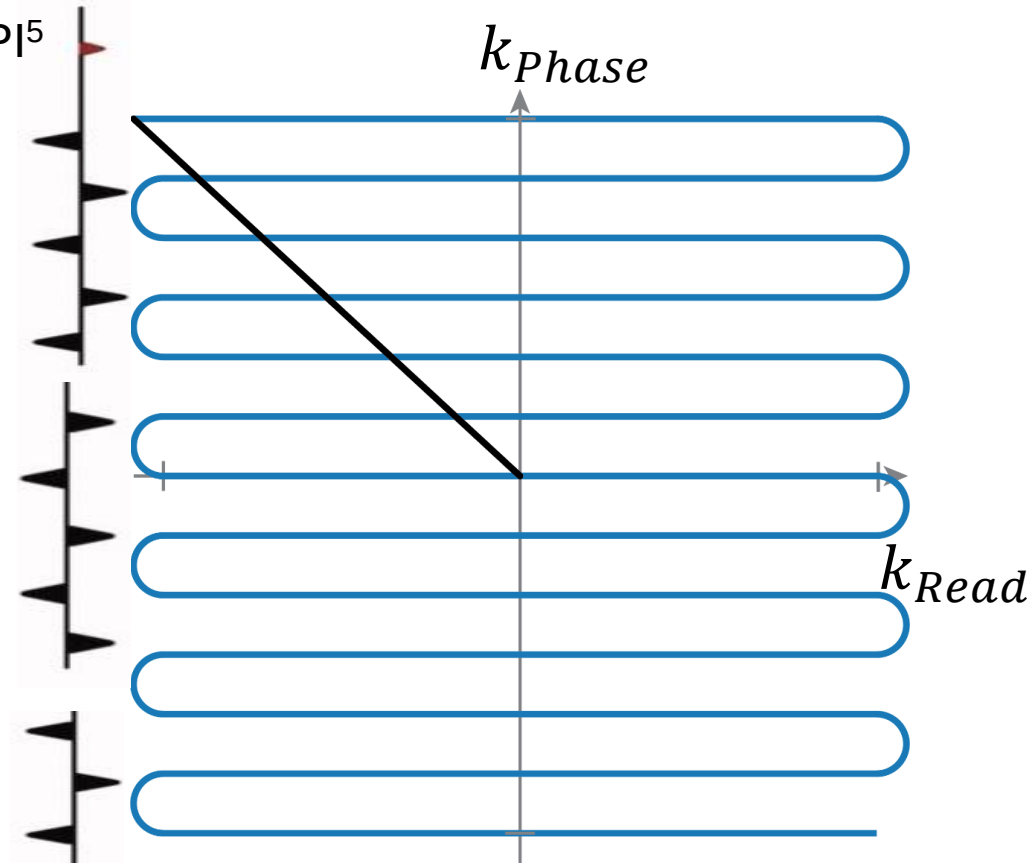


Uğurbil, 2013, NI



CAIPIRINHA[4]

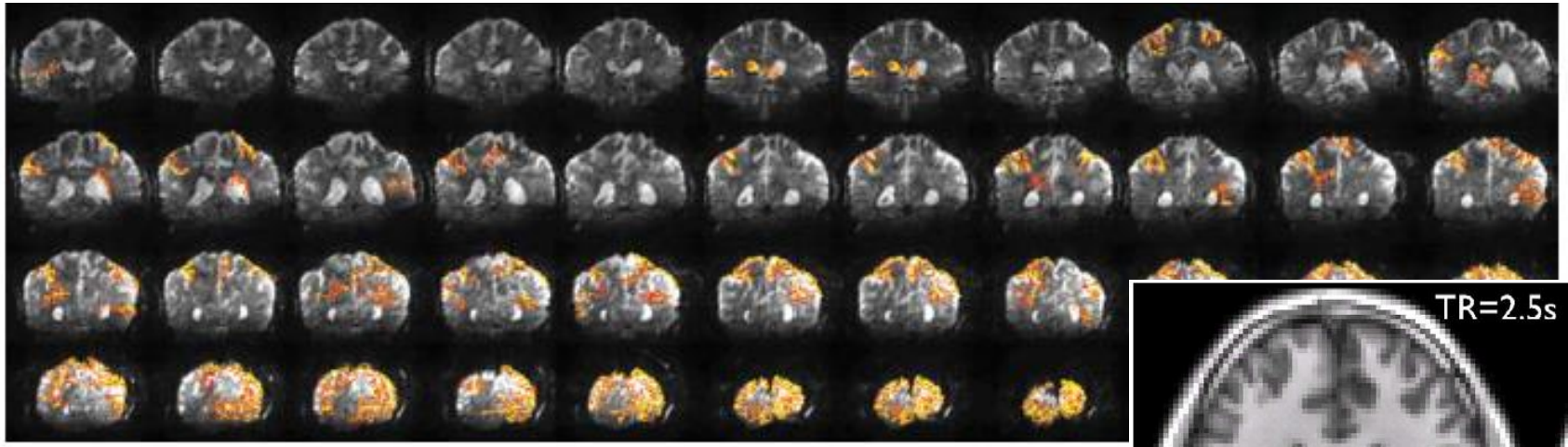
blipped-CAIPI[5]



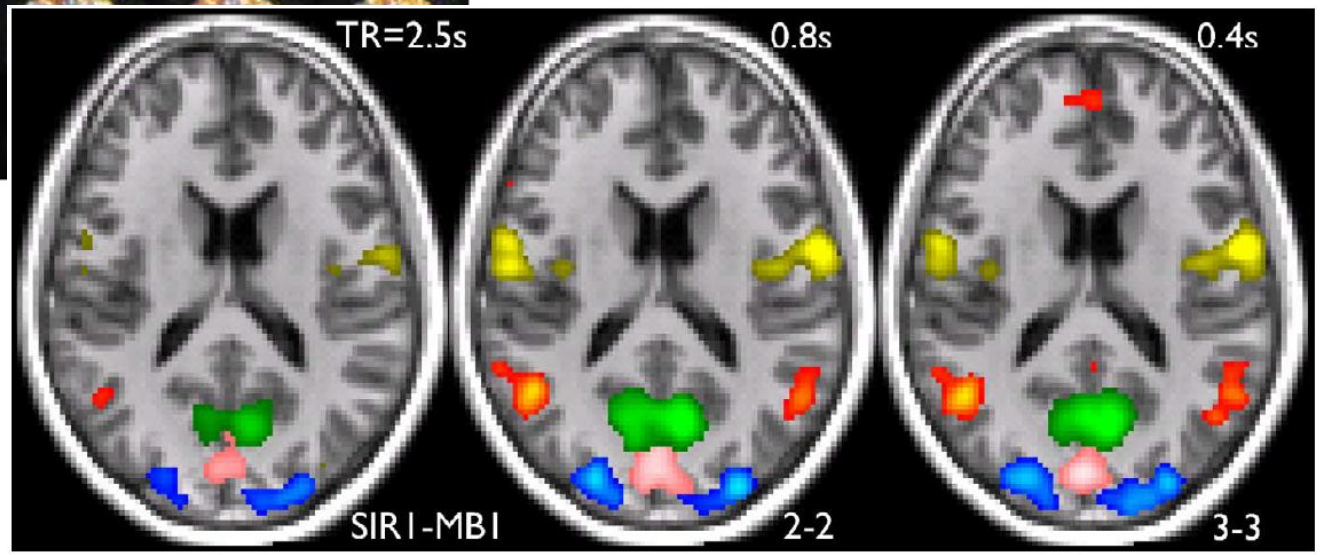
linear phase in k-space $\overset{\text{FT}}{\Longleftrightarrow}$ shift in image space

[1]Maudsley, 1980, JMR; [2]Müller, 1988, MRM; [3]Larkman et al., 2001, JMRI; [4]Breuer et al., 2005, MRM, [5]Setsompop et al., 2012, MRM

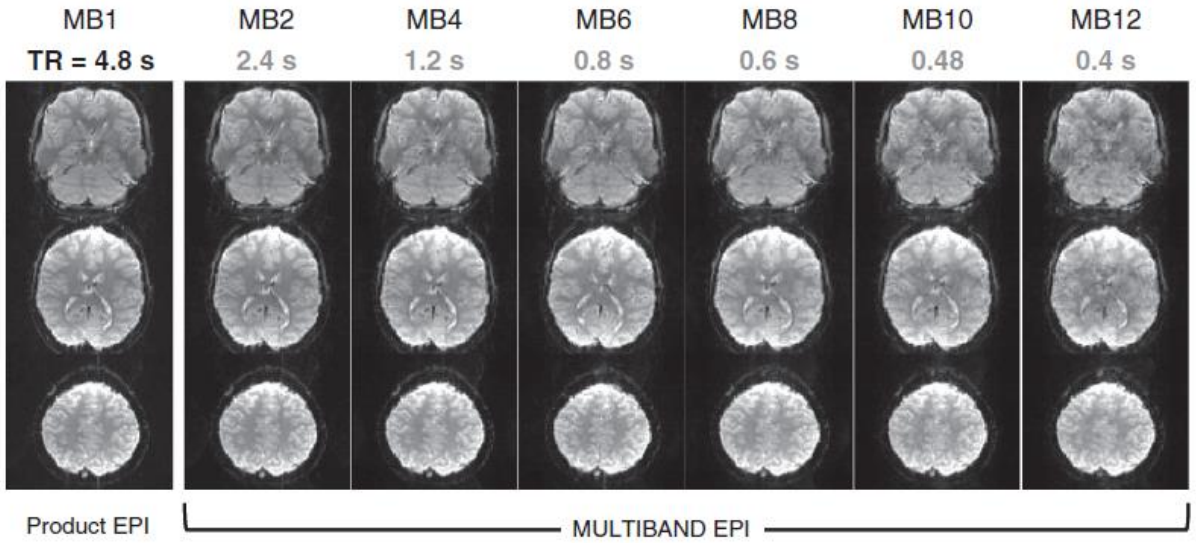
Simultaneous Multislice (SMS) / Multiband – Success



Moeller et al., 2010, MRM



Feinberg et al., 2010, PLoS ONE



Uğurbil et al., 2013, NI

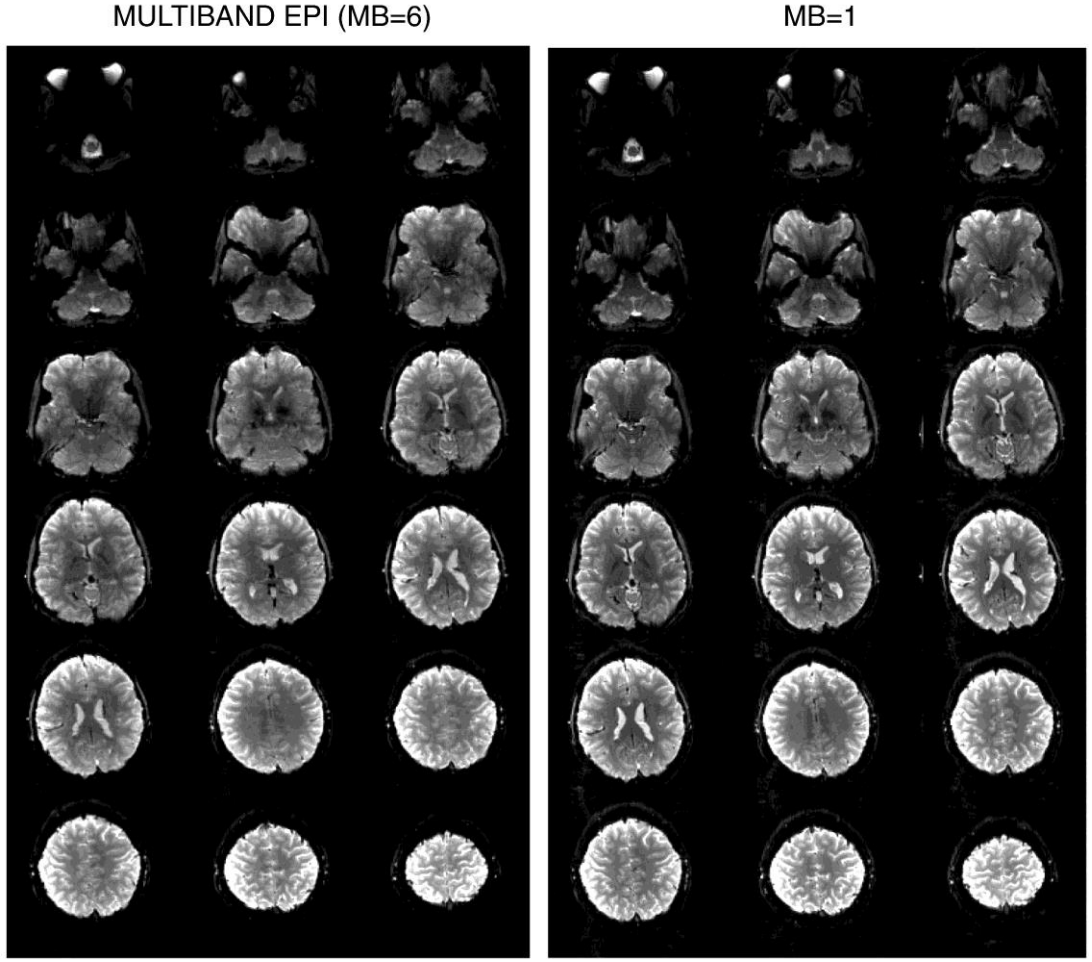
Simultaneous Multislice (SMS) / Multiband – Summary

Advantages

- Increased SNR efficiency ($\sqrt{N}$)
- Increased sampling rate

Disadvantages

- g-factor penalty
- Slice-leakage



Uğurbil, 2013, NI

Acquisitions

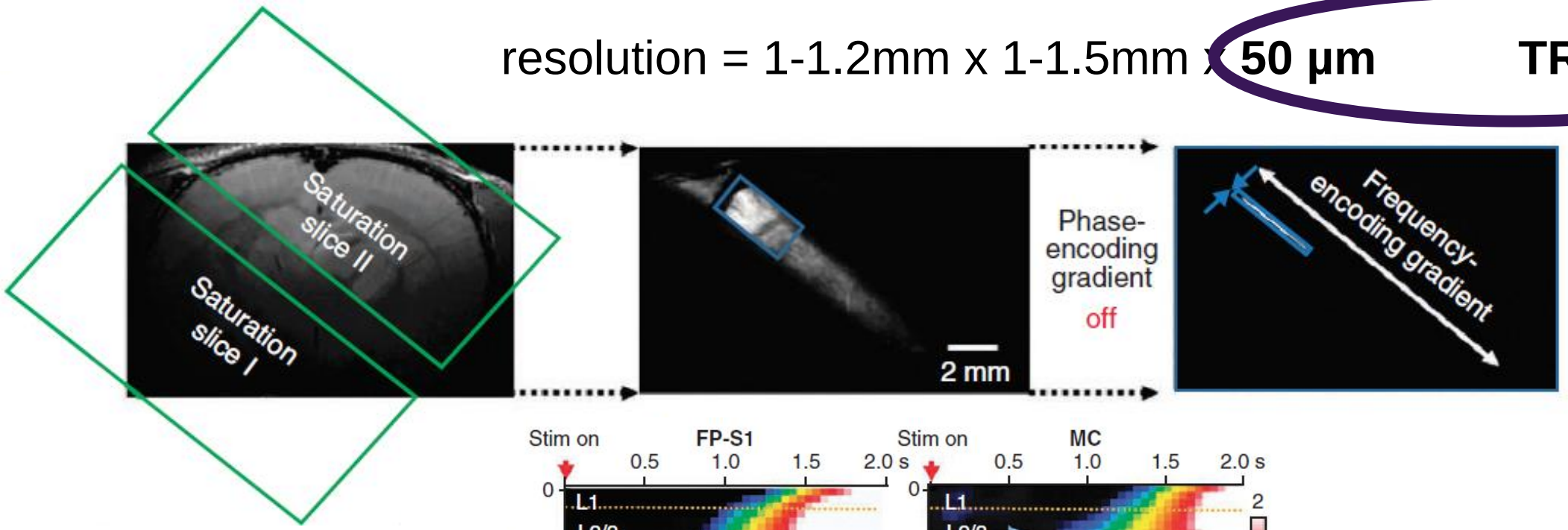
Echo-Planar Imaging (EPI)

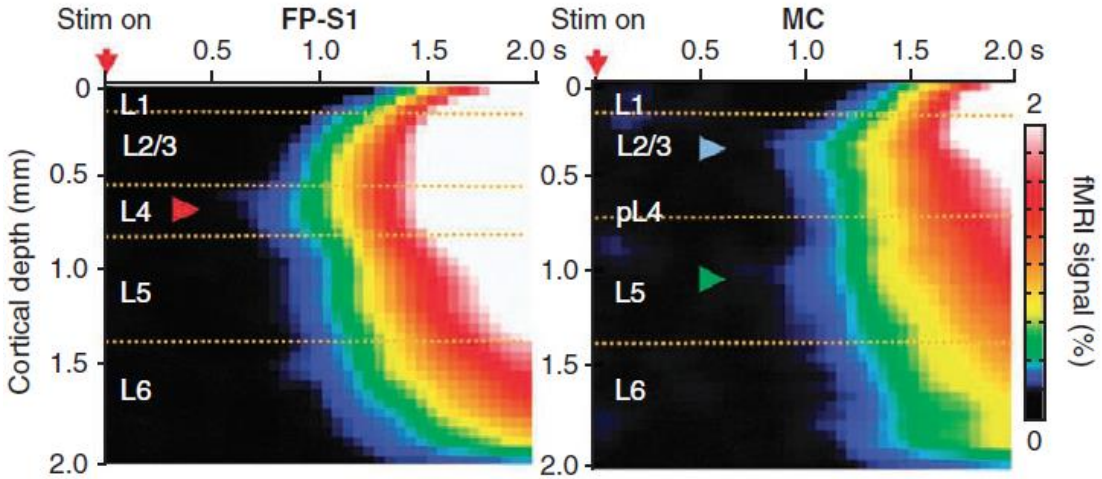
Simultaneous Multislice (SMS) / Multiband

Advanced Methods

The Potential of Fast fMRI: Line Scanning in Rodents

resolution = 1-1.2mm x 1-1.5mm x **50 µm** **TR = 50 ms**



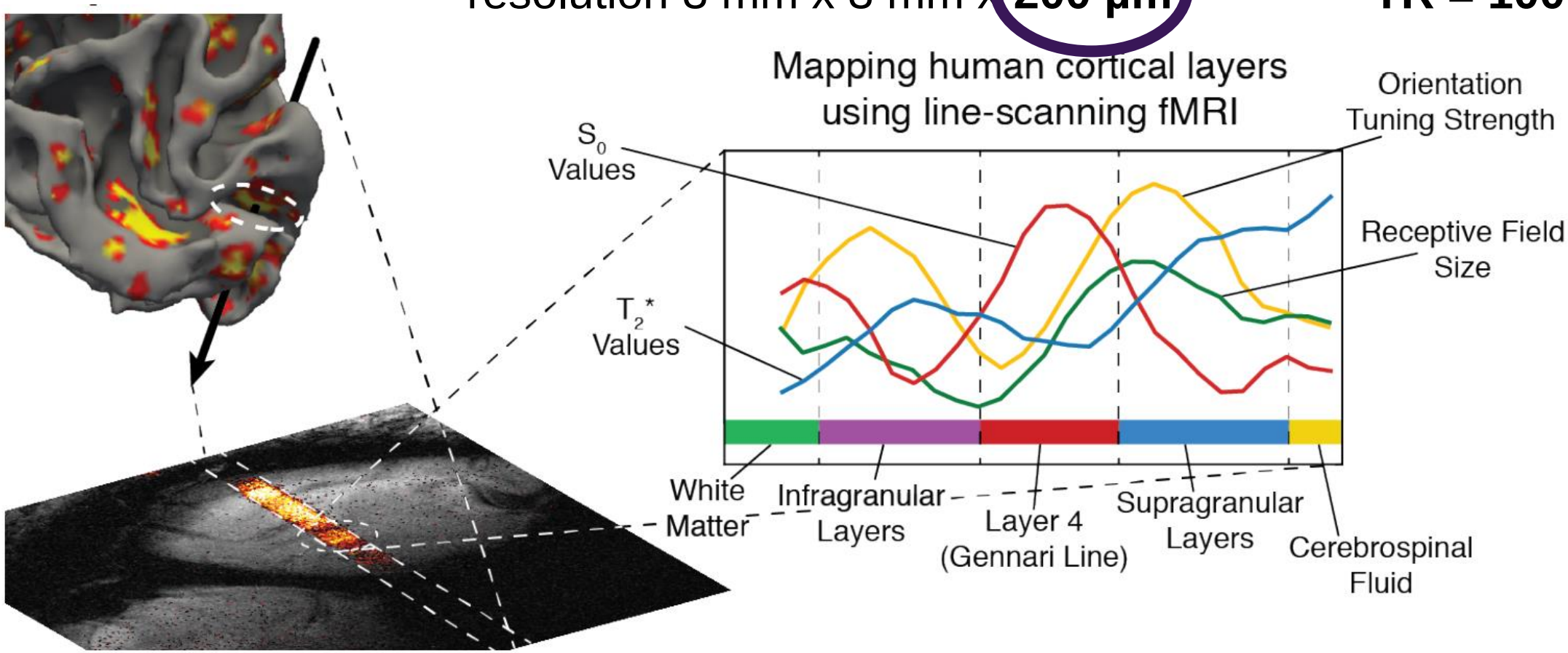


Yu et al., 2014, Nature Methods; not replicated by Albers et al., 2018, NI

Line Scanning in Humans

resolution 3 mm x 3 mm x **200 µm**

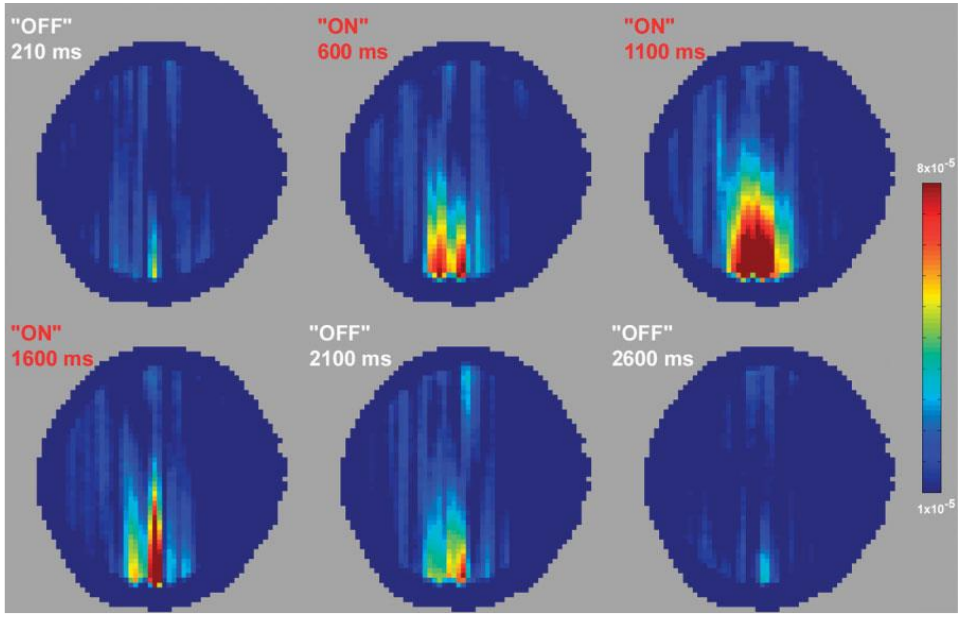
TR = 100 ms



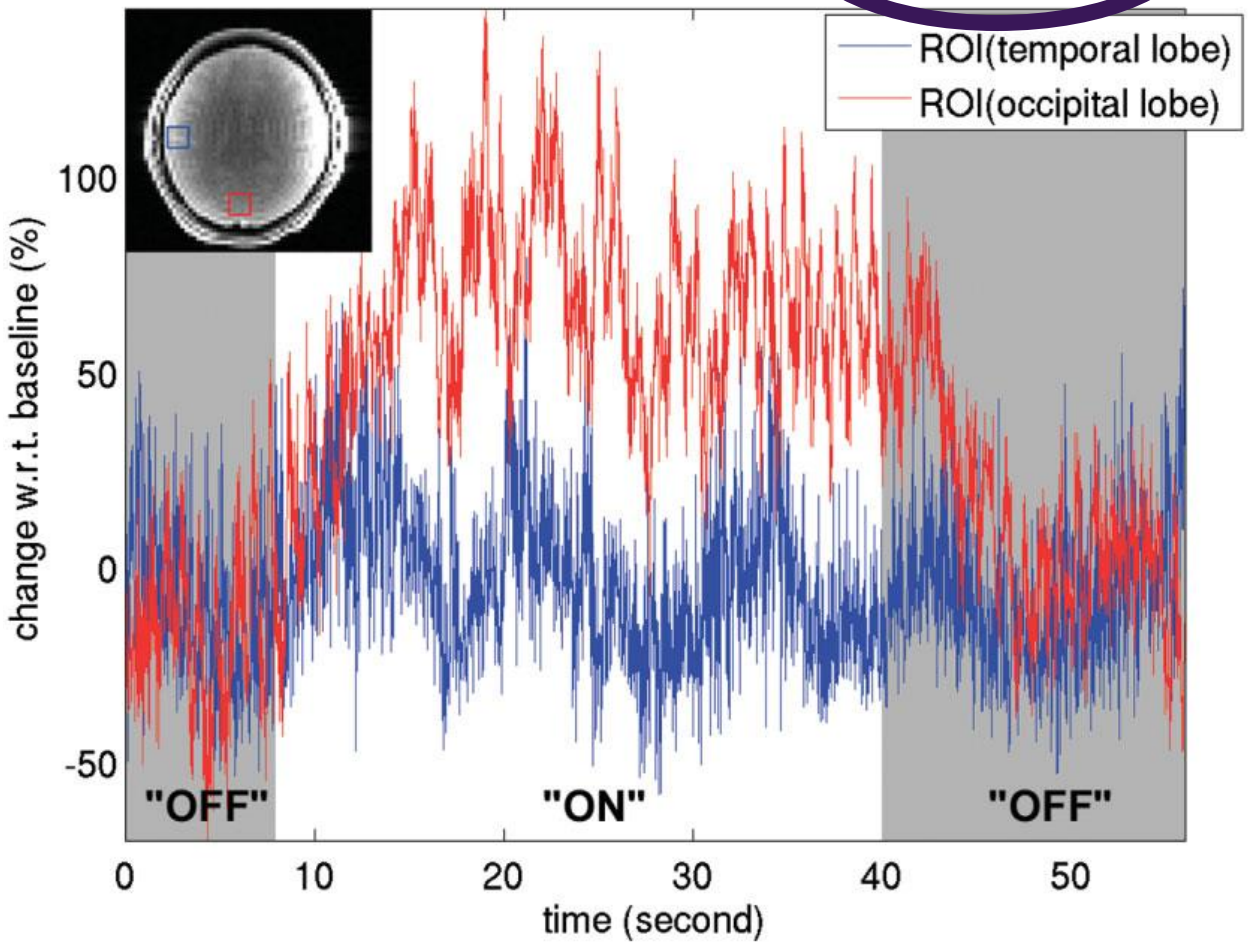
Morgan et al., 2020, bioRxiv; Morgan et al., 2020, ISMRM

Dynamic Inverse Imaging (InI)[1]

- Inspired by MEG source localization
- No spatial encoding with gradients
- Solves under-determined inverse (and ill-posed) problem (e.g. MNE)
- Needs spatial prior to resolve dynamic images



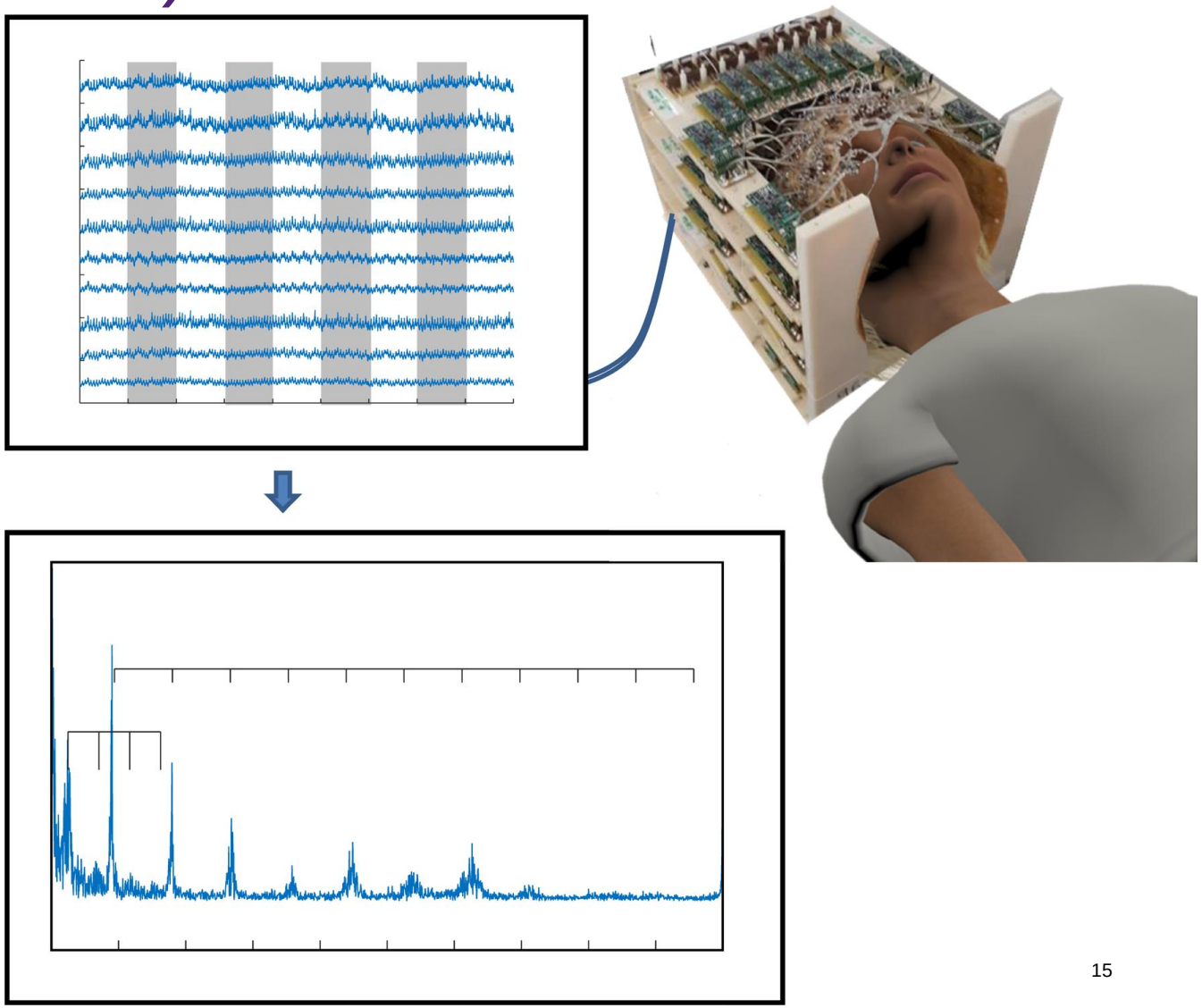
resolution 5 – 12 mm aPSF **TR = 20 ms**



Lin et al., 2006, MRM

MR-Encephalography (MREG)[1]

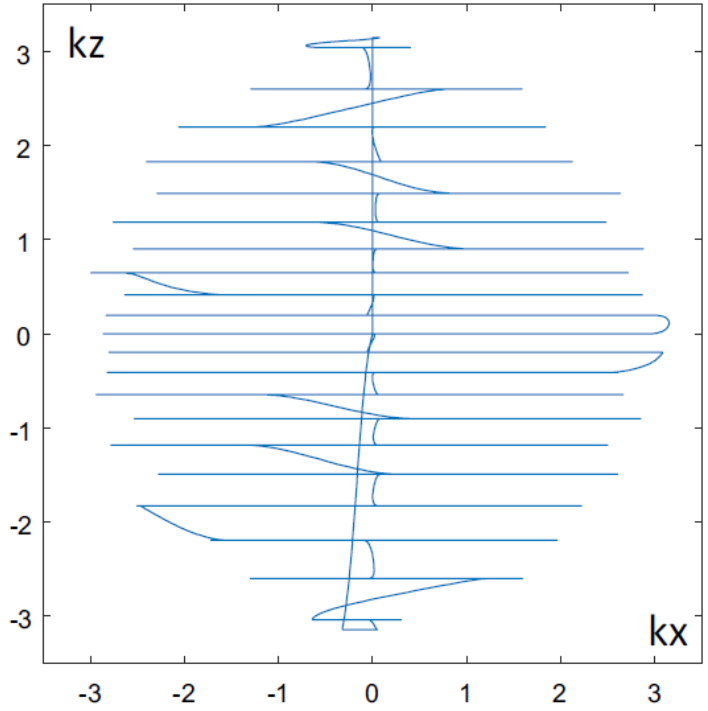
- no readout → one voxel one coil (OVOC[2])

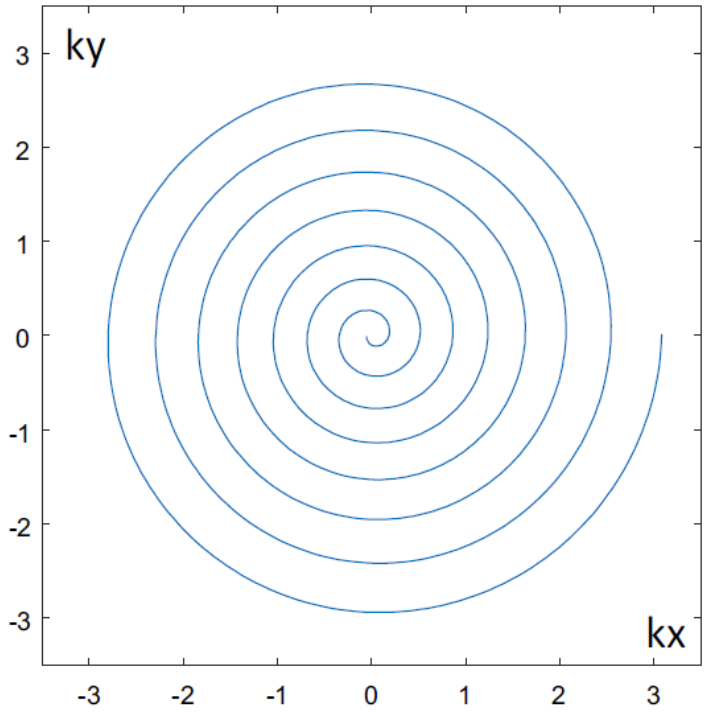


[1]Hennig et al., 2007, NI; Hennig et al., 2021, Magn Reson Mater Phy;
[2]Hutchinson and Raff, 1988, MRM

MR-Encephalography (MREG)[1]

- no readout → one voxel one coil (OVOC[2])
- a little bit of encoding
  - stack-of-spirals trajectory[3]



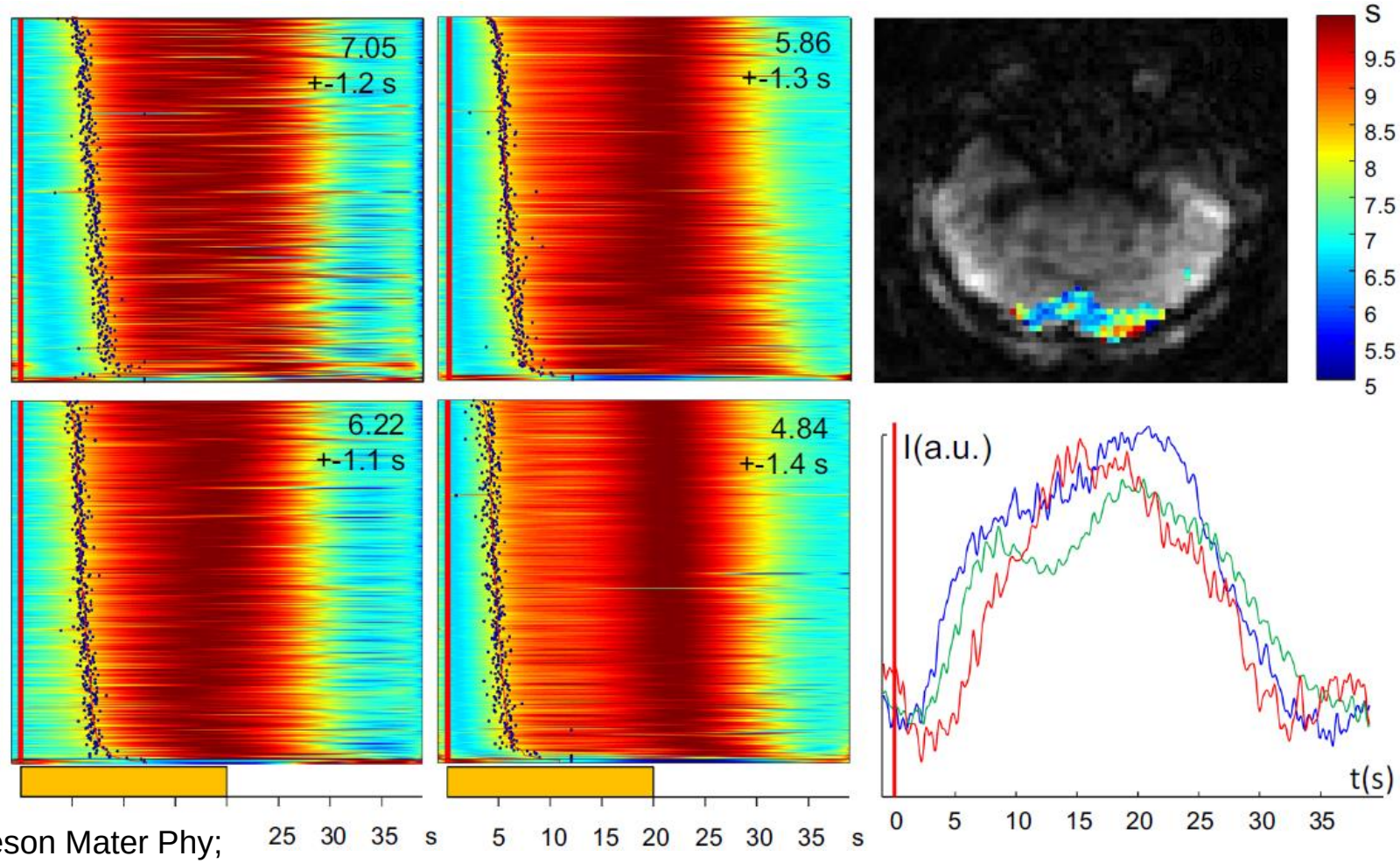


[1]Hennig et al., 2007, NI; Hennig et al., 2021, Magn Reson Mater Phy;
[2]Hutchinson and Raff, 1988, MRM; [3]Assländer et al., 2013, NI

MR-Encephalography (MREG)[1]

- no readout → one voxel one coil (OVOC[2])
- a little bit of encoding
  - stack-of-spirals trajectory[3]
- example
  - BOLD-arrival-time mapping in 160 seconds

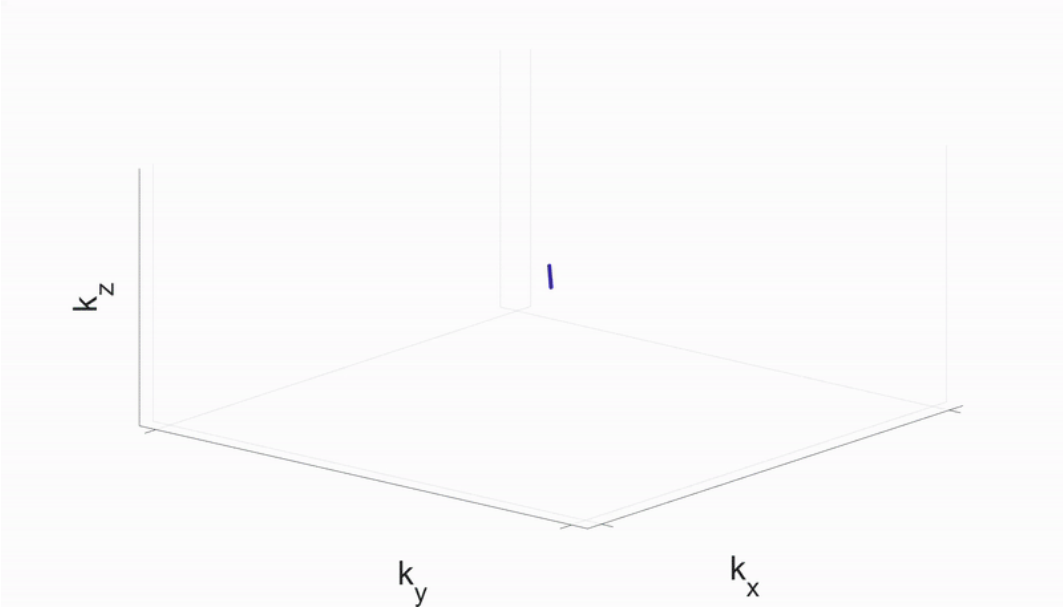
resolution >> 3 mm **TR = 100 ms**

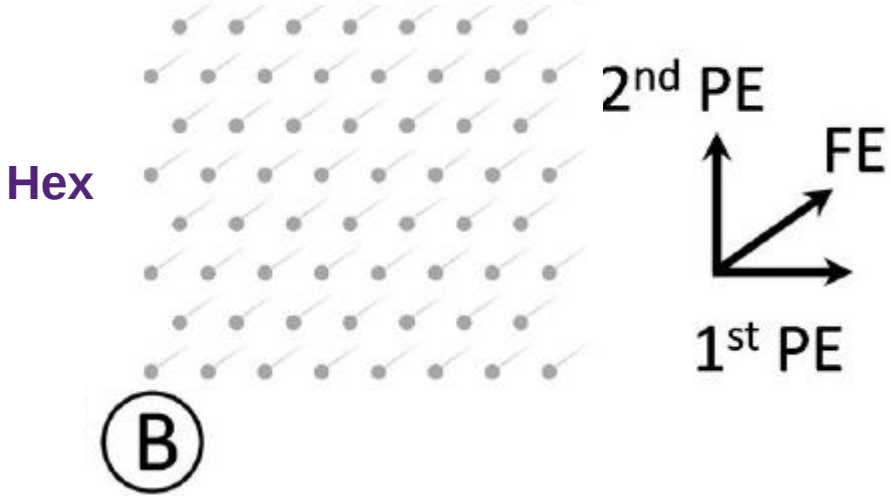


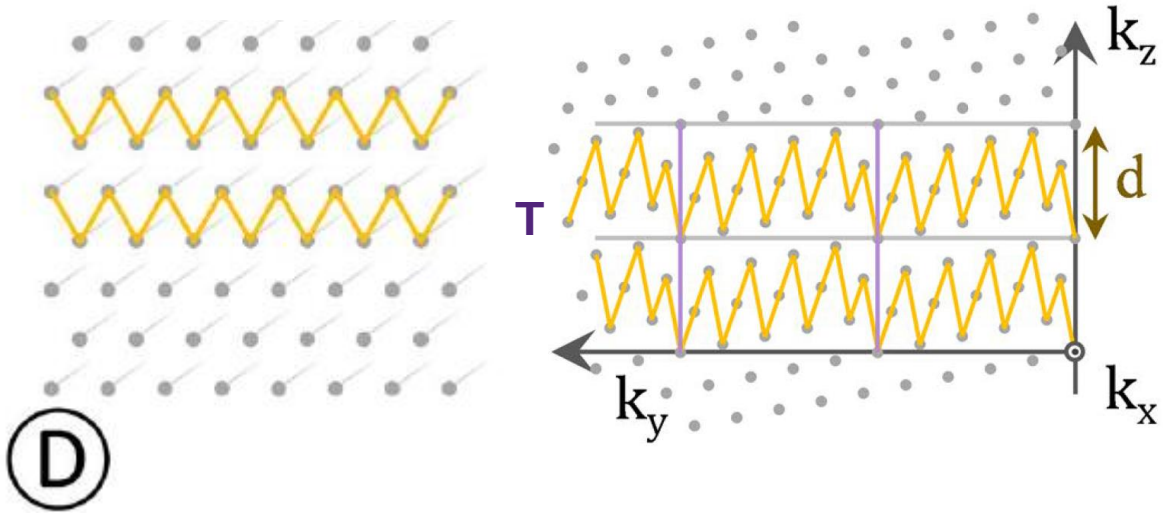
[1]Hennig et al., 2007, NI; Hennig et al., 2021, Magn Reson Mater Phy;
[2]Hutchinson and Raff, 1988, MRM; [3]Assländer et al., 2013, NI

T-Hex: Tilted Hexagonal Grids for Rapid 3D Imaging[1]

- 3D readout strategy with flexible and time-efficient k-space segmentation, smooth T2*-weighting, uniform sampling density, and high average speed along trajectories







[1]Engel et al., 2020, MRM;
[2]Engel et al, 2019, ISMRM

T-Hex: Tilted Hexagonal Grids for Rapid 3D Imaging[1]

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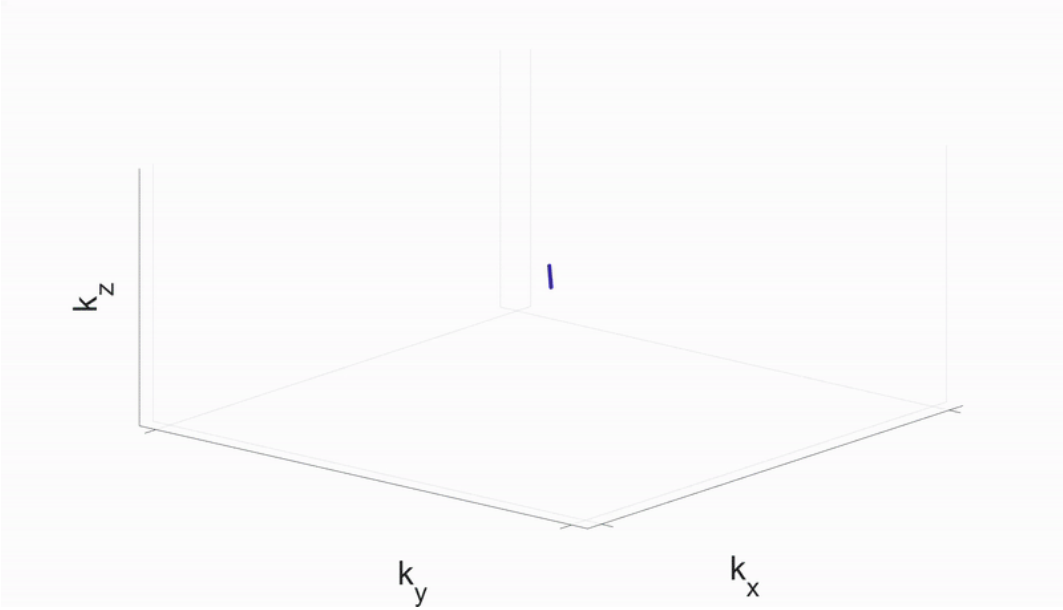
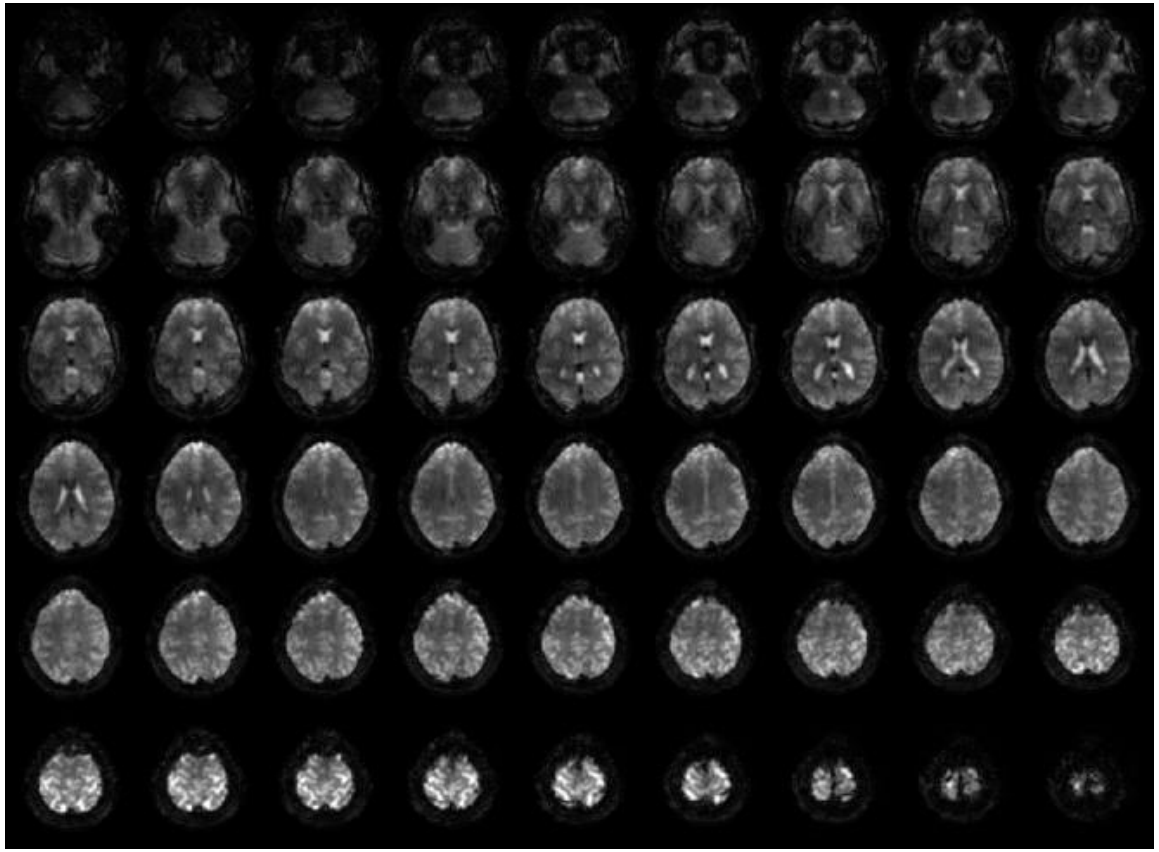


resolution 2.8 mm **TR = 200 ms[2]**



[1]Engel et al., 2020, MRM;
[2]Engel et al, 2019, ISMRM

Advanced Methods - Summary

- Offer temporal resolution 20 – 200 ms

- Challenges
  - Line scanning → small FOV + susceptibility to motion
  - InI
  - MREG
  - T-Hex

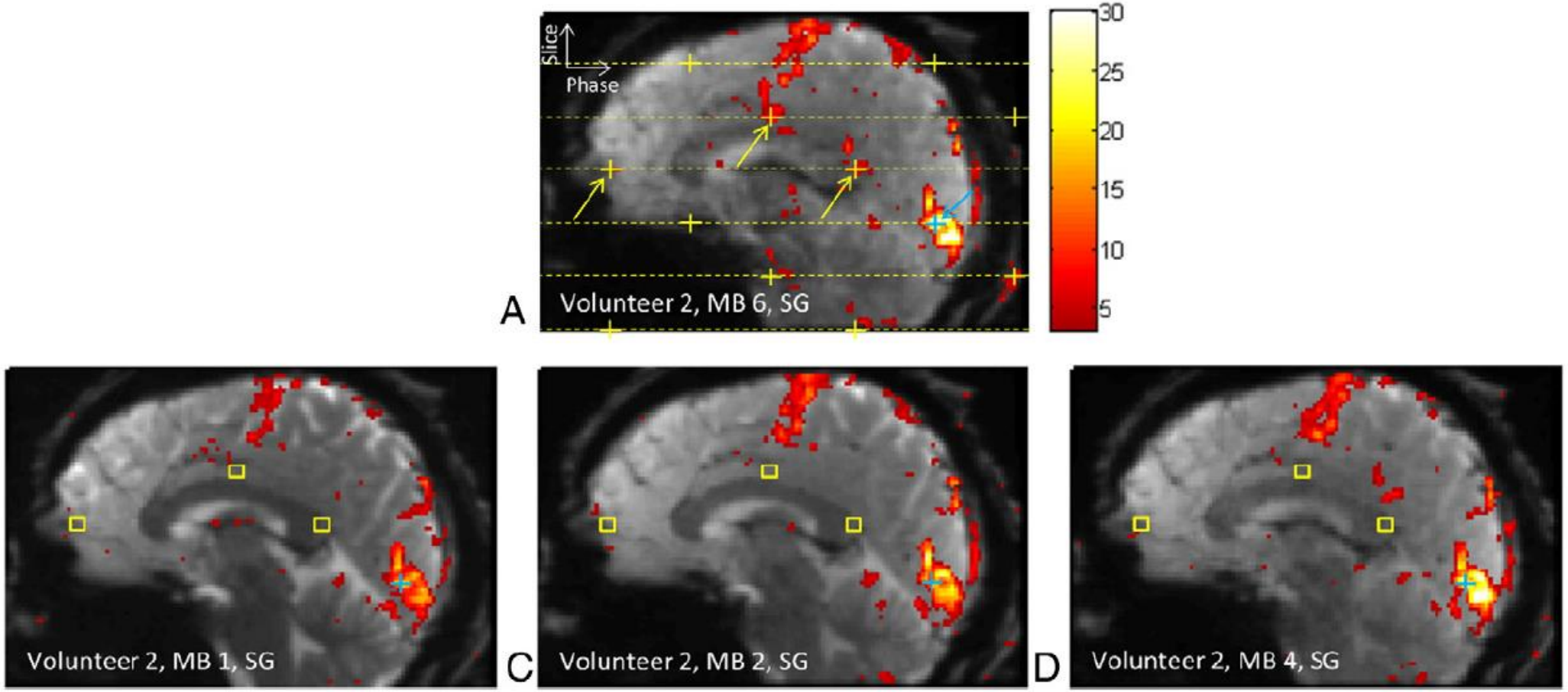
  } hardware requirements + computational complexity

Challenges

Spatial correlations

Temporal correlations

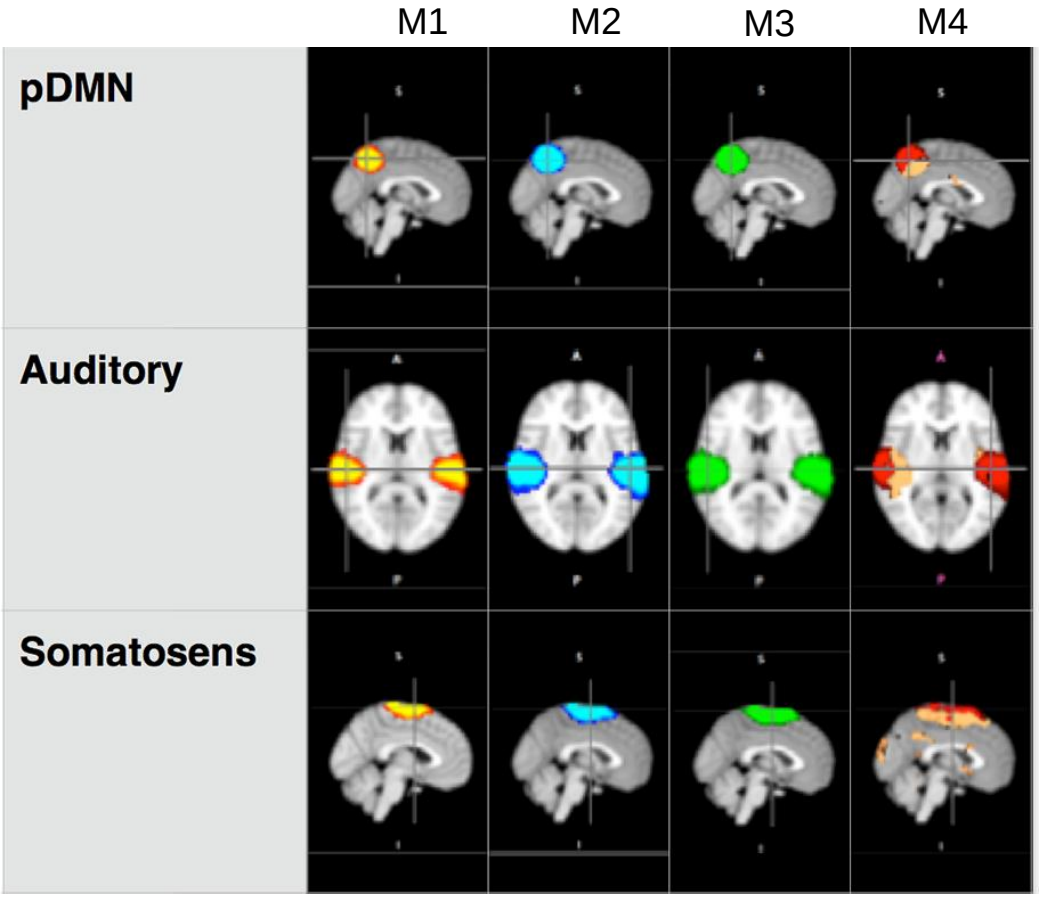
False-Positive Activation due to Signal Leakage between Simultaneously Excited Slices

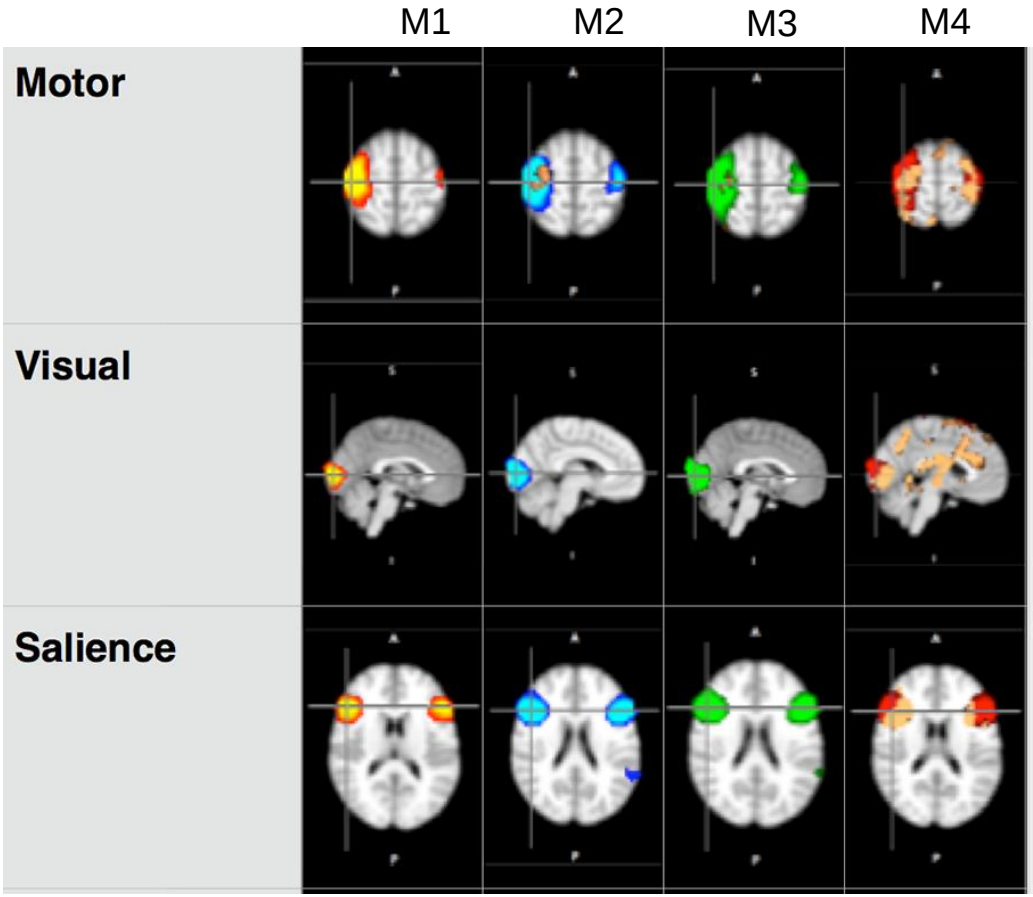


@ 3T with 32-channel coil, GRAPPA 2

Todd et al., 2016, NI

Strong Variability in Resting-State Networks at High Acceleration Factors



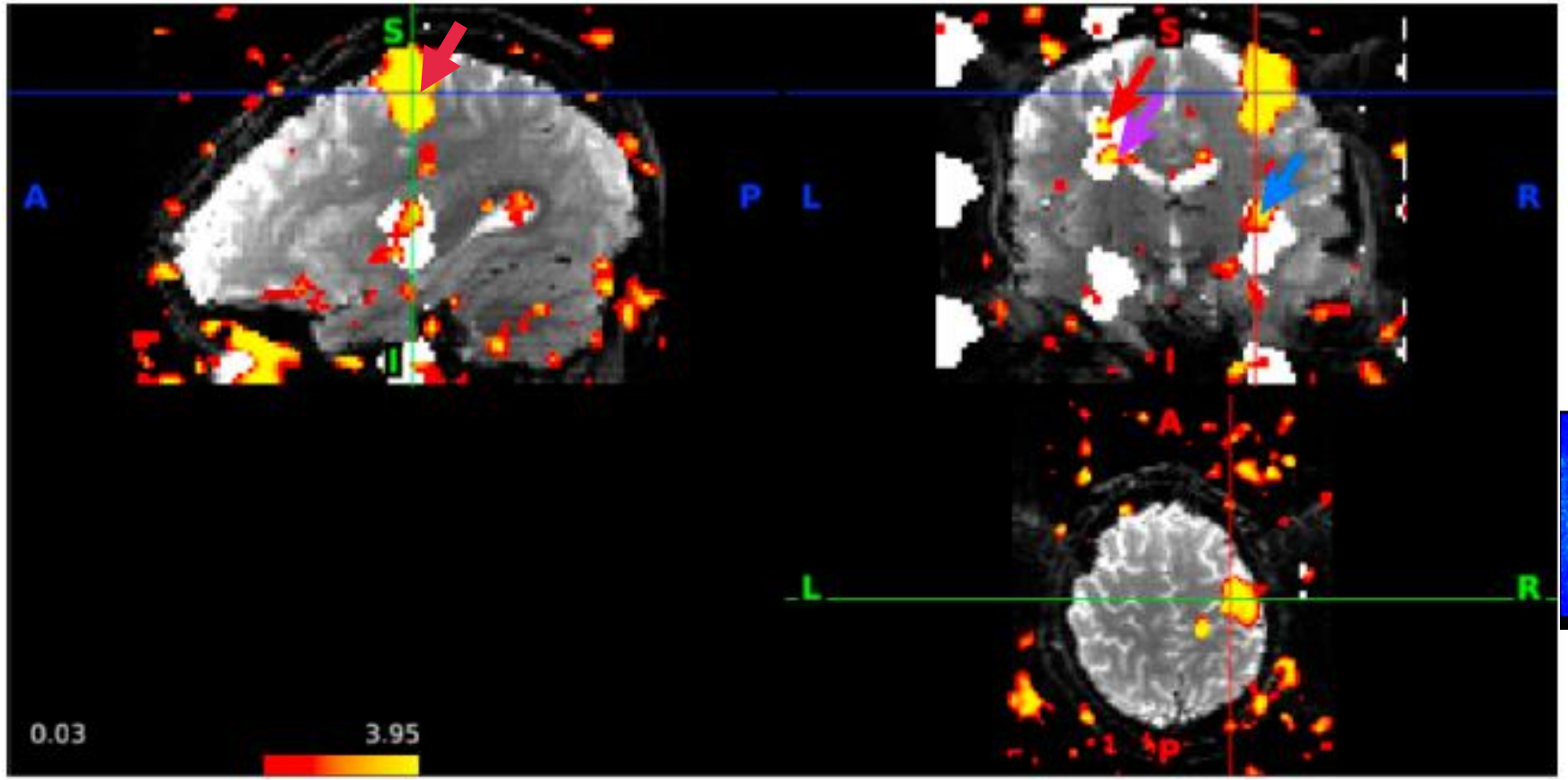


@ 3T with 32-channel coil, SENSE 2

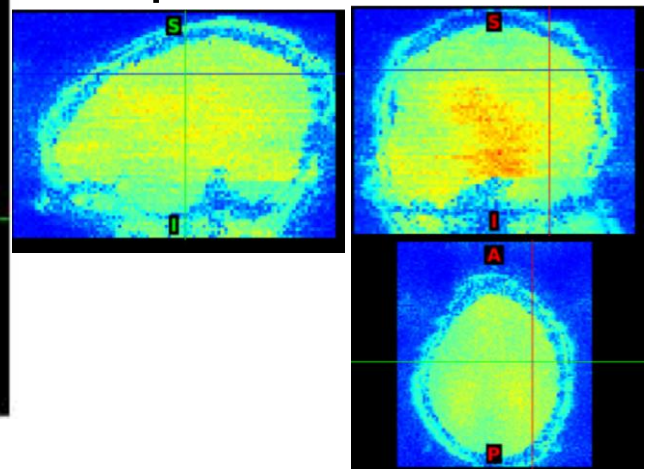
Preibisch et al., 2015, PLOS One

Slice-Leakage in the HCP 100 Release[1]

motor task



As much acceleration as necessary, as little as possible!



Split slice-GRAPPA[2] necessary to reduce slice leakage

@ 3T with 32-channel coil

[1]Risk et al., 2018, NI; Cauley et al., 2014, MRM

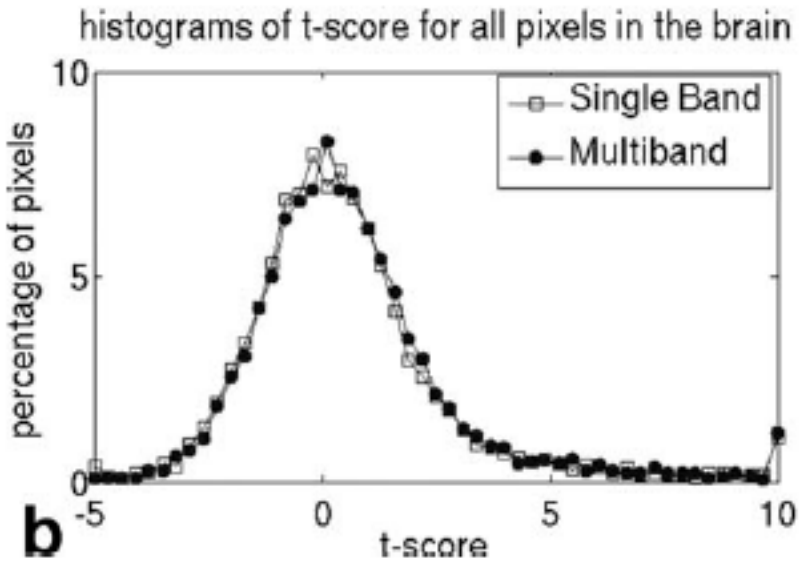
Challenges

Spatial correlations

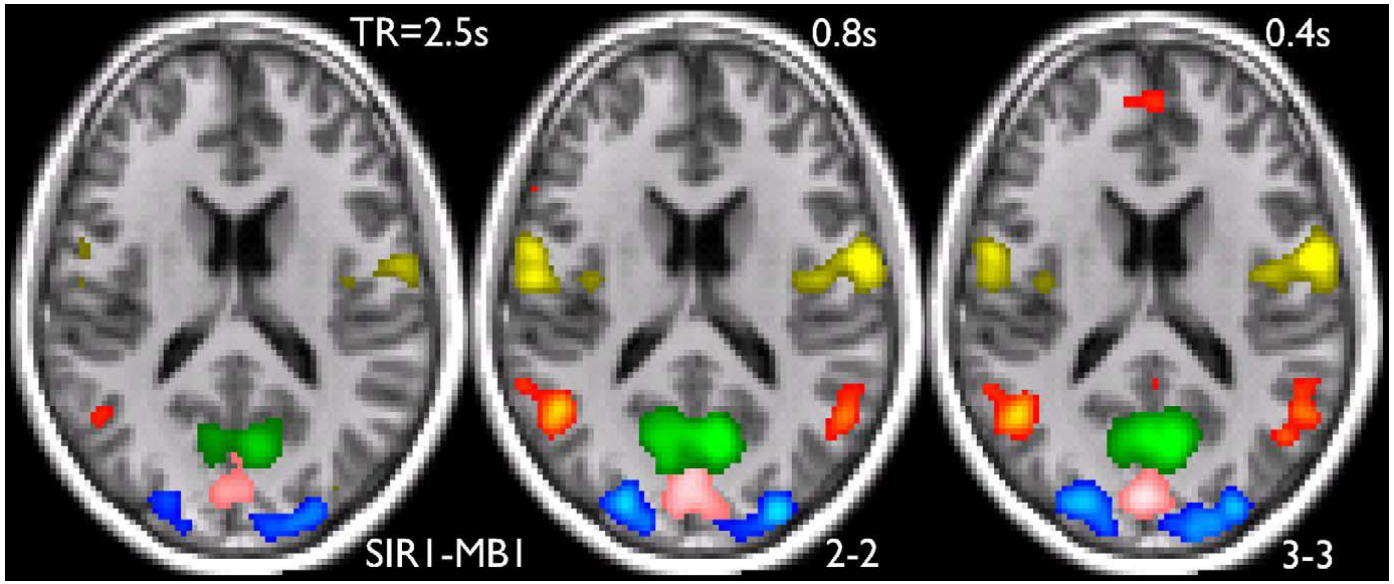
Temporal correlations

Temporal (Serial, Auto)-Correlation of the Noise

- Increased number of sampling points does not increase the degrees of the freedom at the same rate, because of serial correlations in the noise[1]



Moeller et al., 2010, MRM;
Same TR and number of volumes

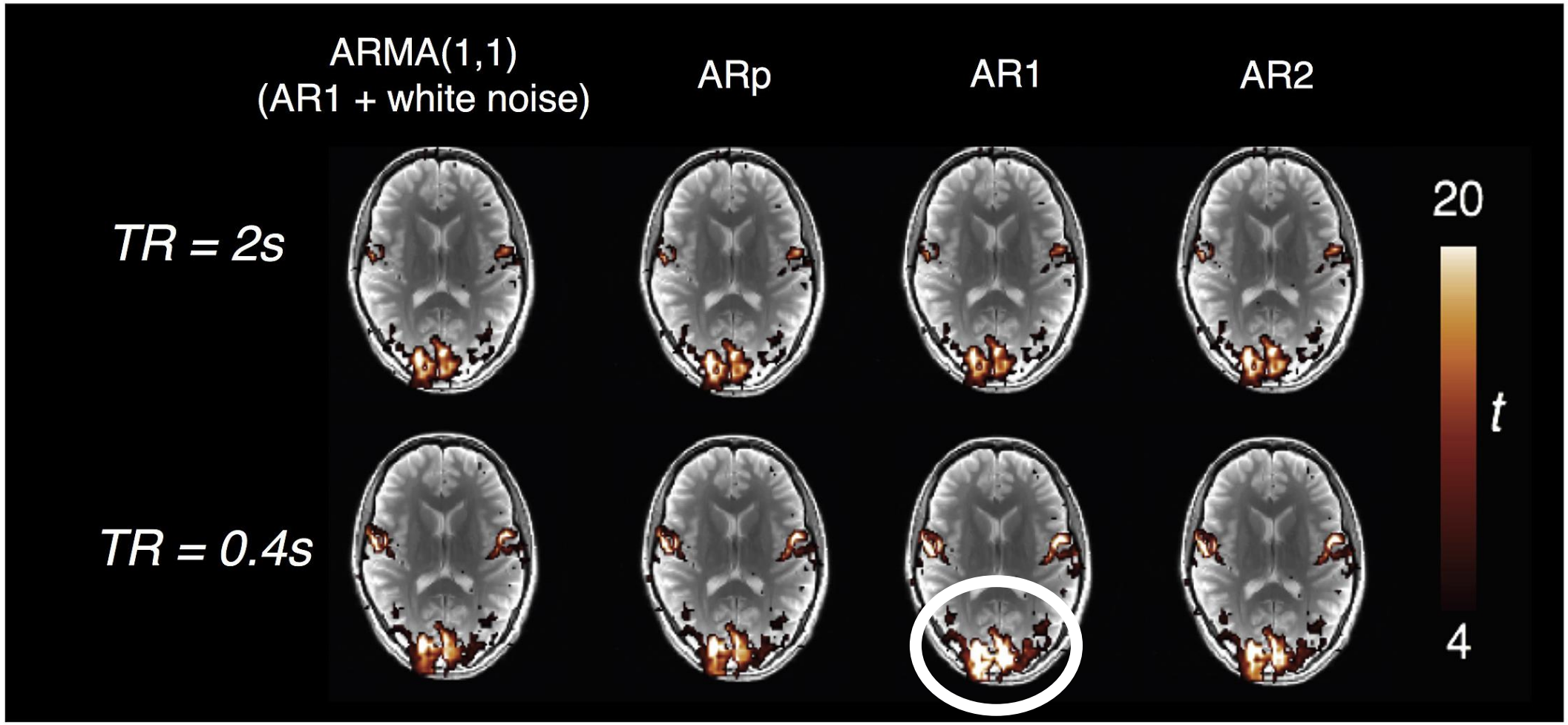


Feinberg et al., 2010, PloS ONE;
Mixture-modelling

[1]Worsley and Friston, 1995, NI;

Increased false-positive rates[1,2,3,4,5]

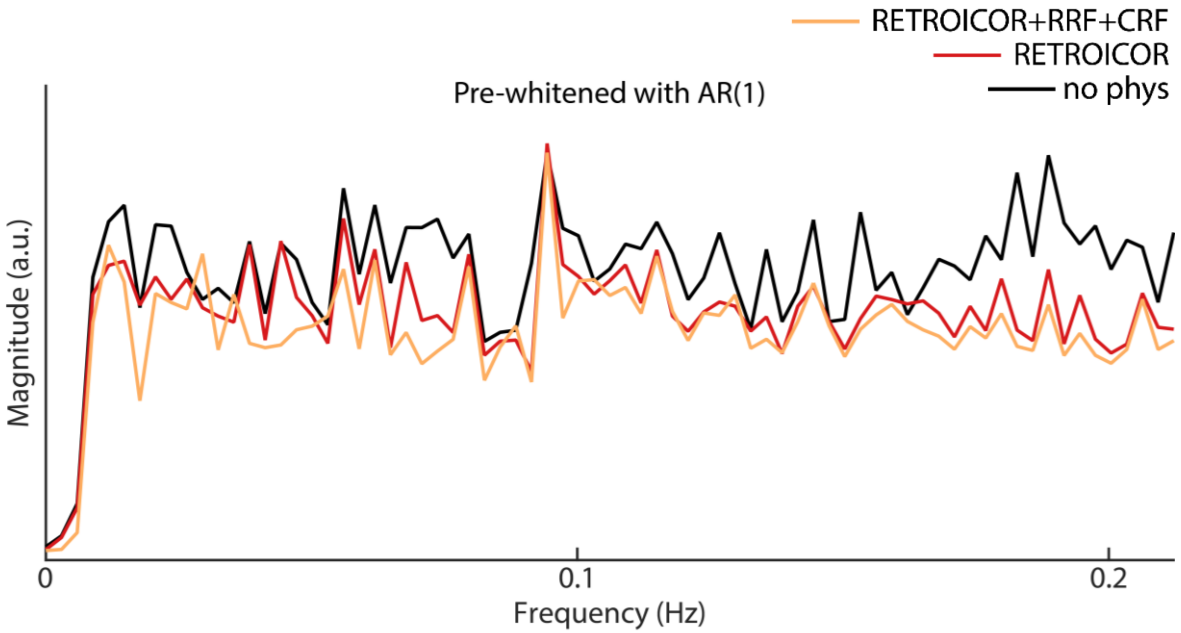
Chen et al., 2019, NI



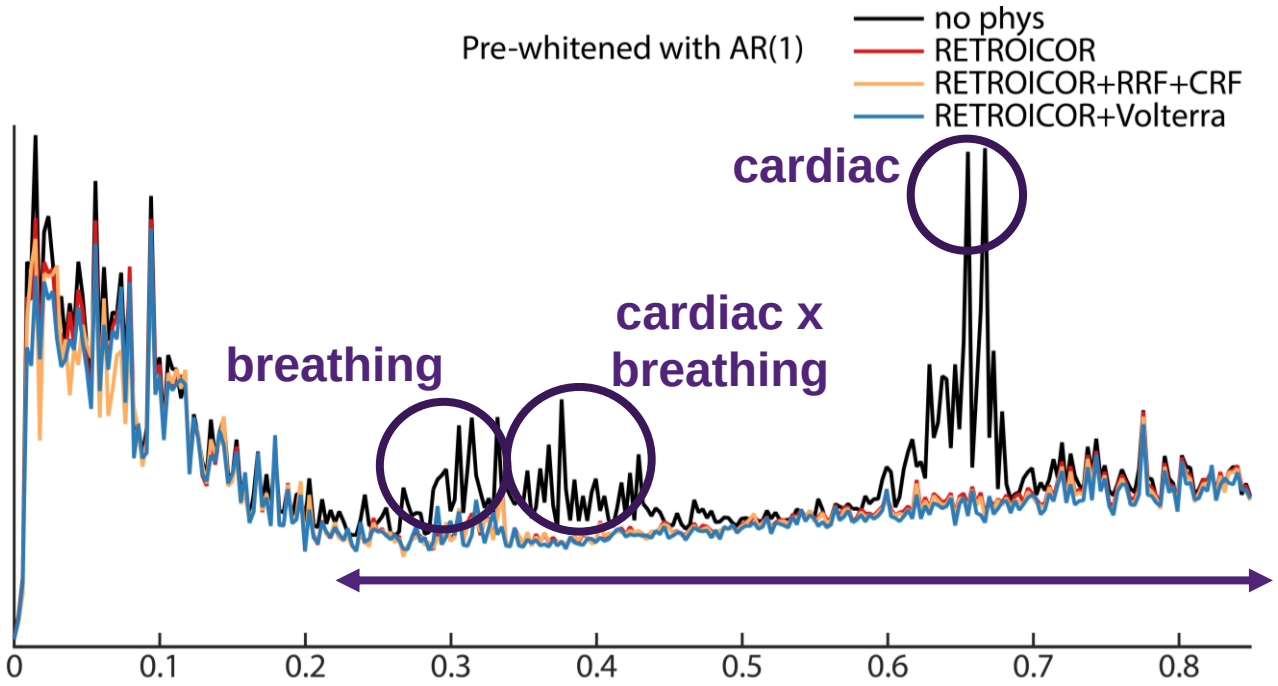
[1]Eklund et al., 2012, NI; [2]Sahib et al., 2016, MRM; [3]Bollmann et al., 2018, NI; [4]Corbin et al., 2018, HBM; [5]Olszowy et al., 2019, Nat Com

Noise Spectrum in Fast Acquisitions

TR = 2356 ms



TR = 589 ms



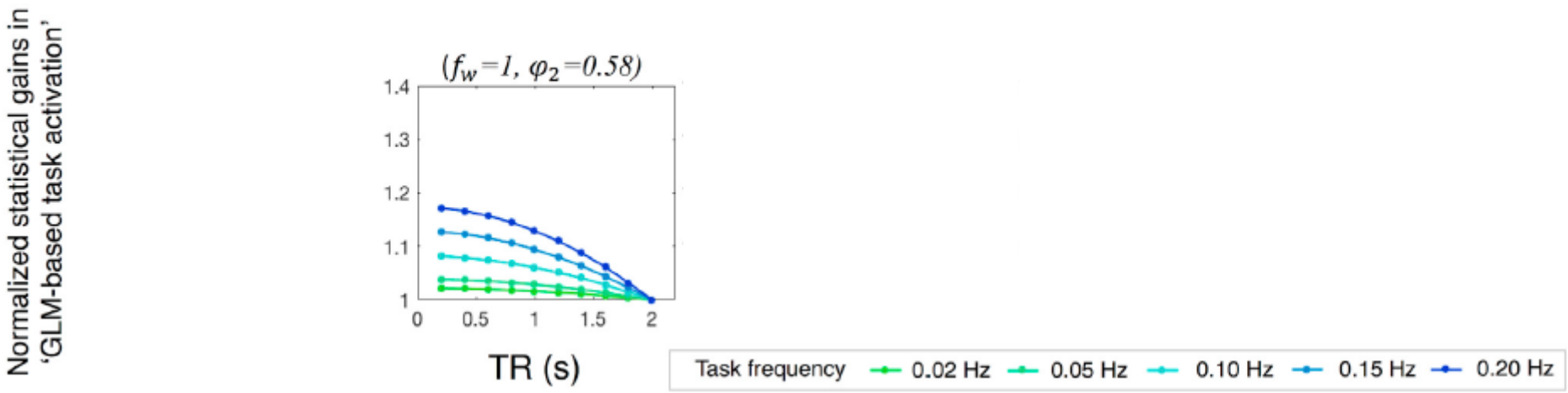
Bollmann et al., 2018, NI

Better pre-whitening performance

- AFNI: ARMA(1,1)
- SPM: FAST

On the Analysis of Rapidly Sampled fMRI Data[1]

Task



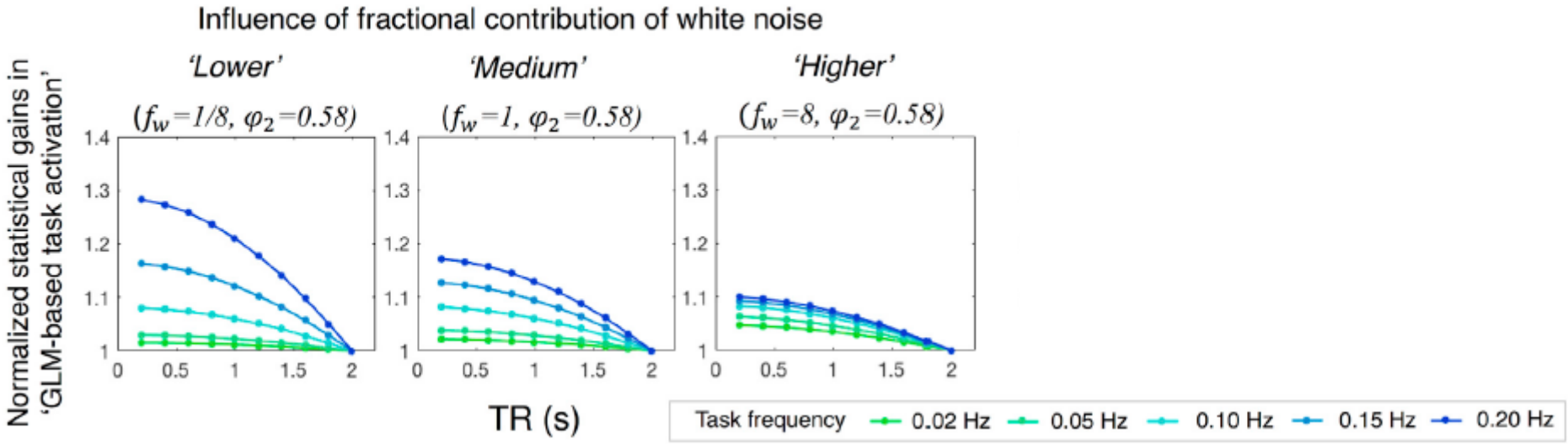
More statistical gains for

- Faster task

[1]Chen et al., 2019, NI

On the Analysis of Rapidly Sampled fMRI Data[1]

Task



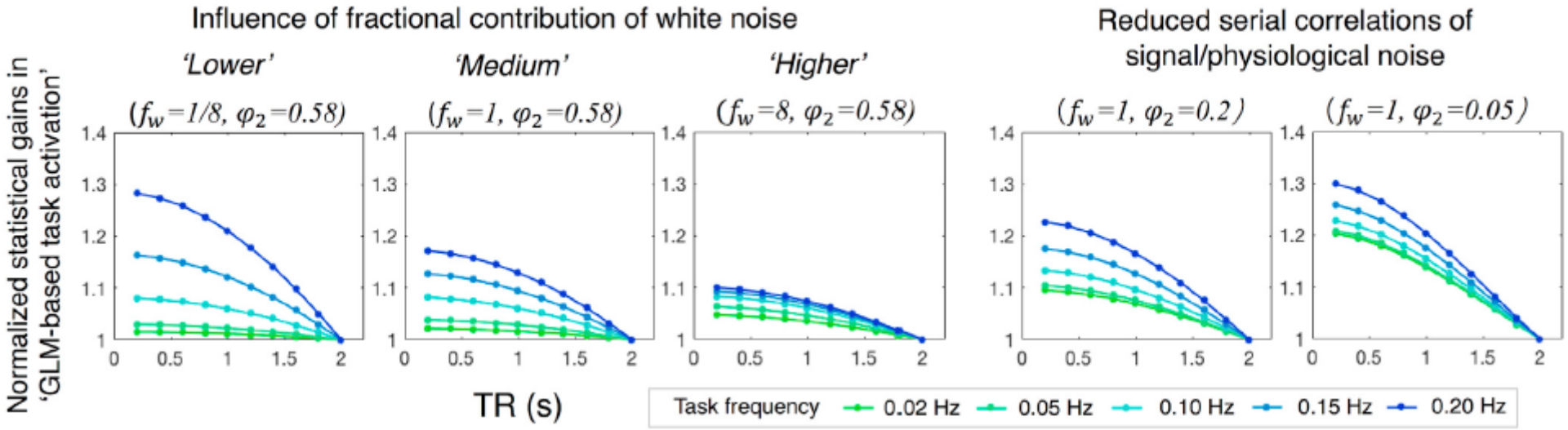
More statistical gains for

- Faster task
- Less white noise

[1]Chen et al., 2019, NI

On the Analysis of Rapidly Sampled fMRI Data[1]

Task



More statistical gains for

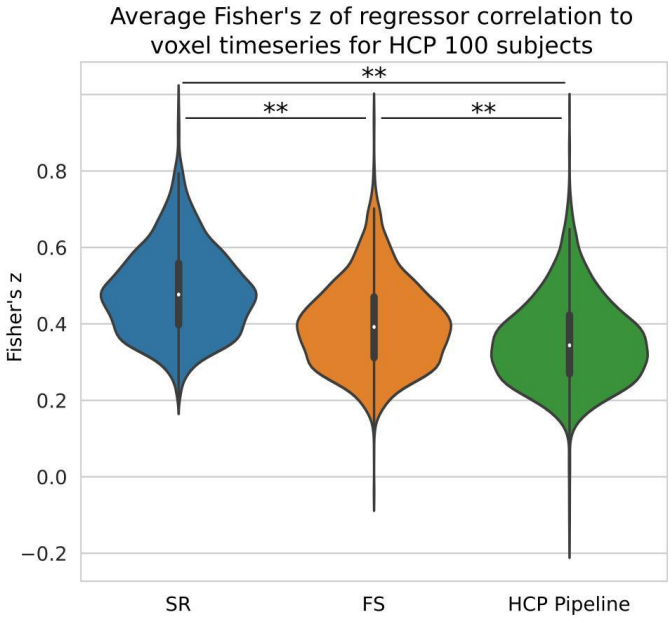
- Faster task
- Less white noise
- Less serial correlations

[1]Chen et al., 2019, NI

Bonus Slide

Slice Timing Correction for Fast fMRI Data

- Benefits of slice-timing correction assumed to be negligible for fast acquisitions[1]
- Temporal and dispersion derivates are assumed to account for shifts < 1 second[2]



Reference slice?
Temporal/Dispersion derivatives?
Temporal filtering?

SR: Shifted Regressor
FS: FilterShift

[1]Gasser et al., 2013, NI; [2]Sladky et al., 2011, NI; [3]Parker and Razlighi, 2019, Front. Neurosci.

Applications

Block Designs

Dynamic Stimuli

DCMs

Physiology

EEG-FMRI

Time-Varying Functional Connectivity

Impact

Applications

Block Designs

Dynamic Stimuli

DCMs

Physiology

EEG-FMRI

Time-Varying Functional Connectivity

Benefits of Fast Sampling for Group Studies with Block-Designs

'While results will not be dramatically changed by the use of multiband, our results suggest that MB will bring a moderate but significant benefit.'[1]

'In this experiment inter-subject variability determined the sensitivity of the random effects analysis for most brain regions, making the impact of EPI pulse sequence improvements less relevant or even negligible for random-effects analyses.'[2]

[1]Bhandari et al., 2020, NI; [2]Kirilina et al., 2016, NI

On Random-Effects Models and Unbiased Estimates

The hierarchical random-effects model (mixed-effects model) has variance $Var\left[\widehat{w}_{pop}\right] = \frac{\sigma_b^2}{N} + \frac{\sigma_w^2}{Nn}$

→ Between-subject variance (σ_b^2) usually far outweighs the within-subject variance (σ_w^2)[1]

The pseudoinverse of X produces an unbiased effect estimate (β) – even when neglecting serial correlations or using a wrong correlation model[2]

[1]Penny and Holmes, 2007, Chapter 12 SPM book; [2]Worsley et al., 2002, NI;

Applications

Block Designs

Dynamic Stimuli

DCMs

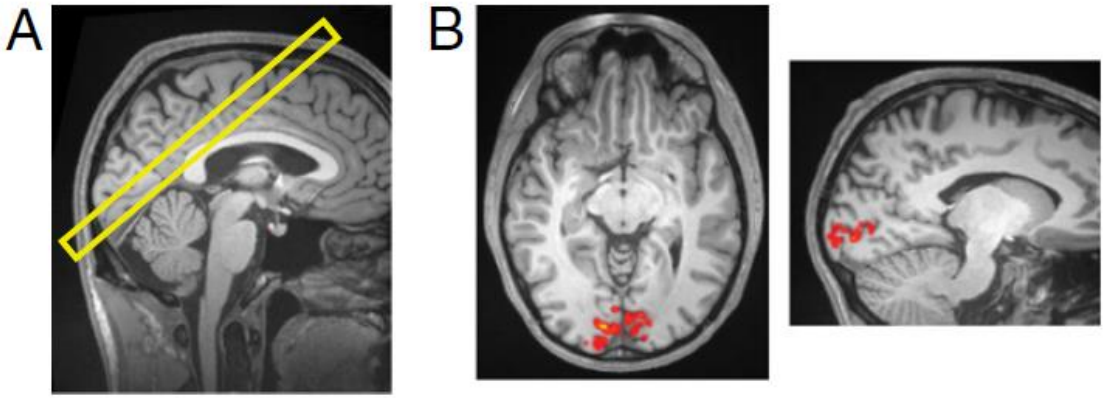
Physiology

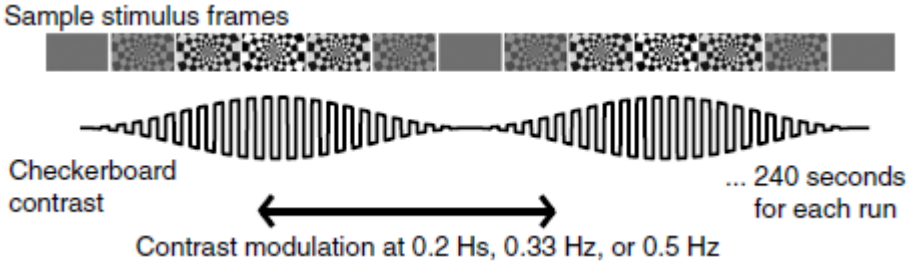
EEG-FMRI

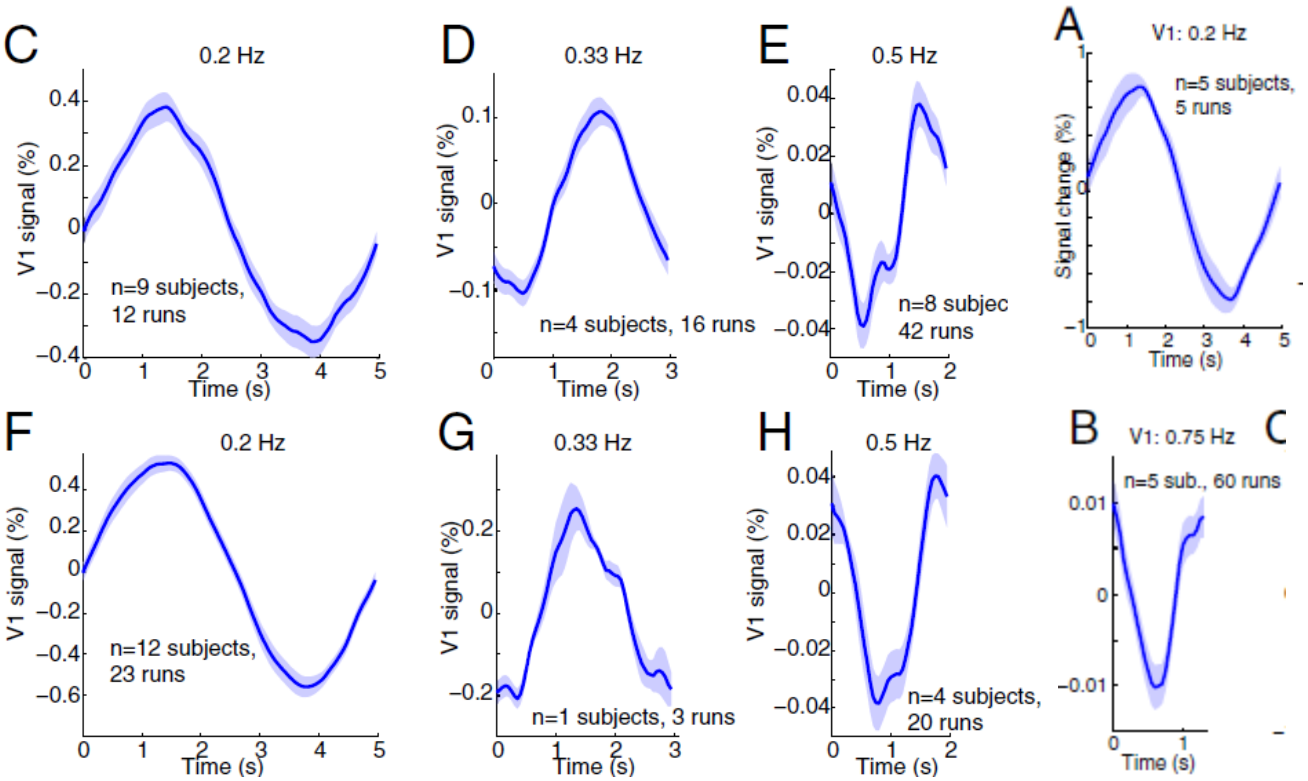
Time-Varying Functional Connectivity

Fast fMRI Can Detect Oscillatory Neural Activity in Humans[1]

resolution 2.5 mm iso **TR = 246 ms**







3T **7T**

[1]Lewis et al., 2016, PNAS

Applications

Block Designs

Dynamic Stimuli

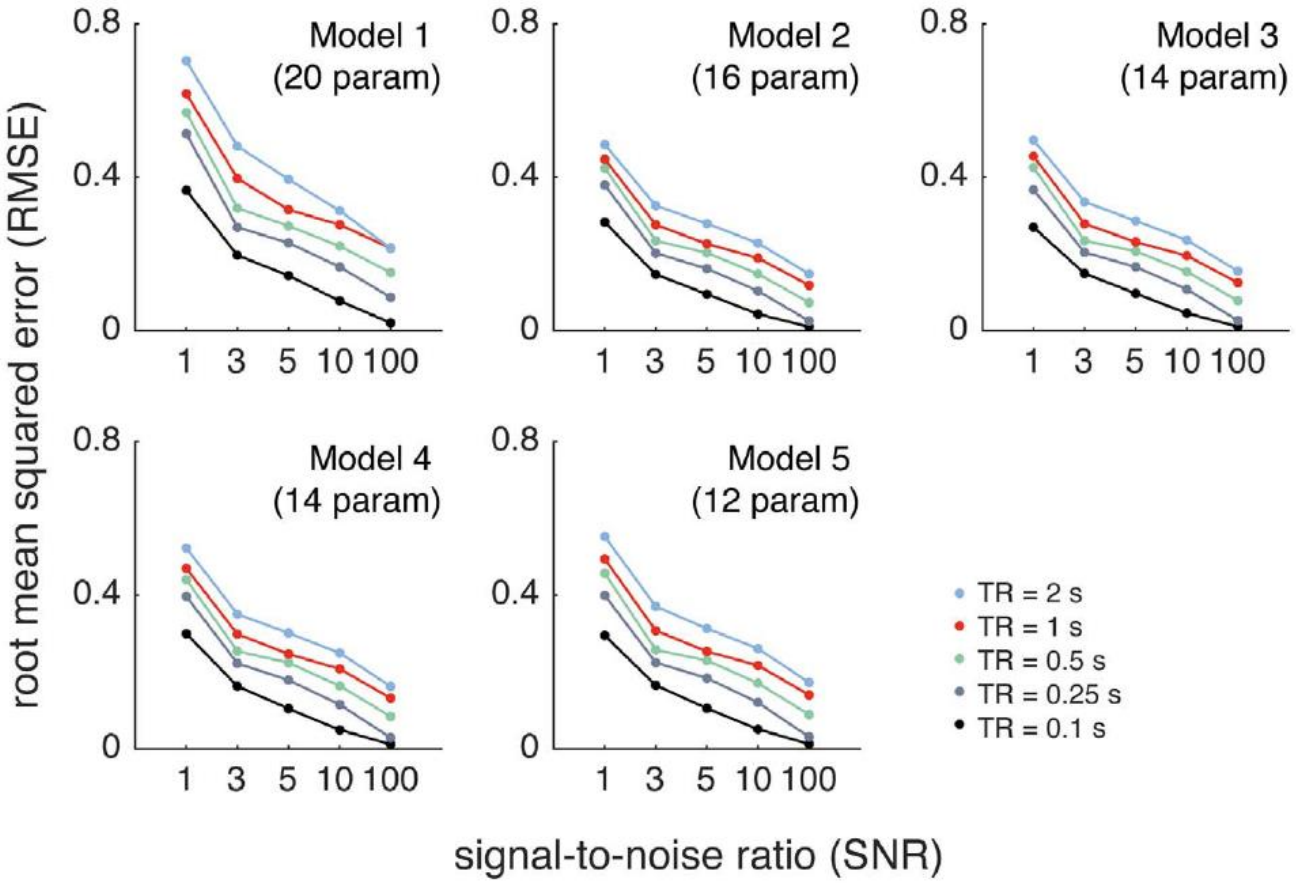
DCMs

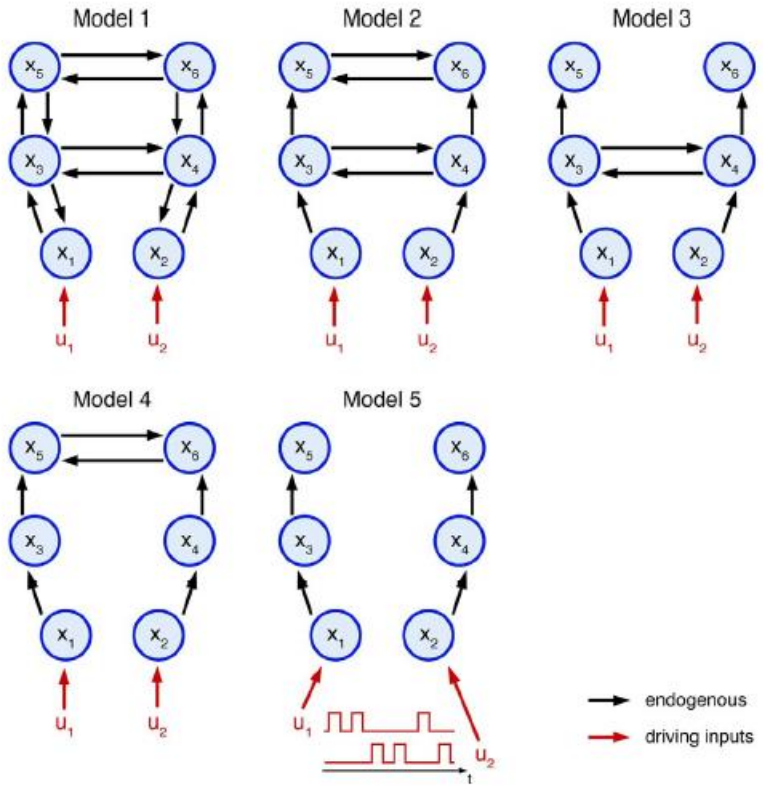
Physiology

EEG-FMRI

Time-Varying Functional Connectivity

Regression DCM for fMRI





[1]Frässle et al., 2017, NI

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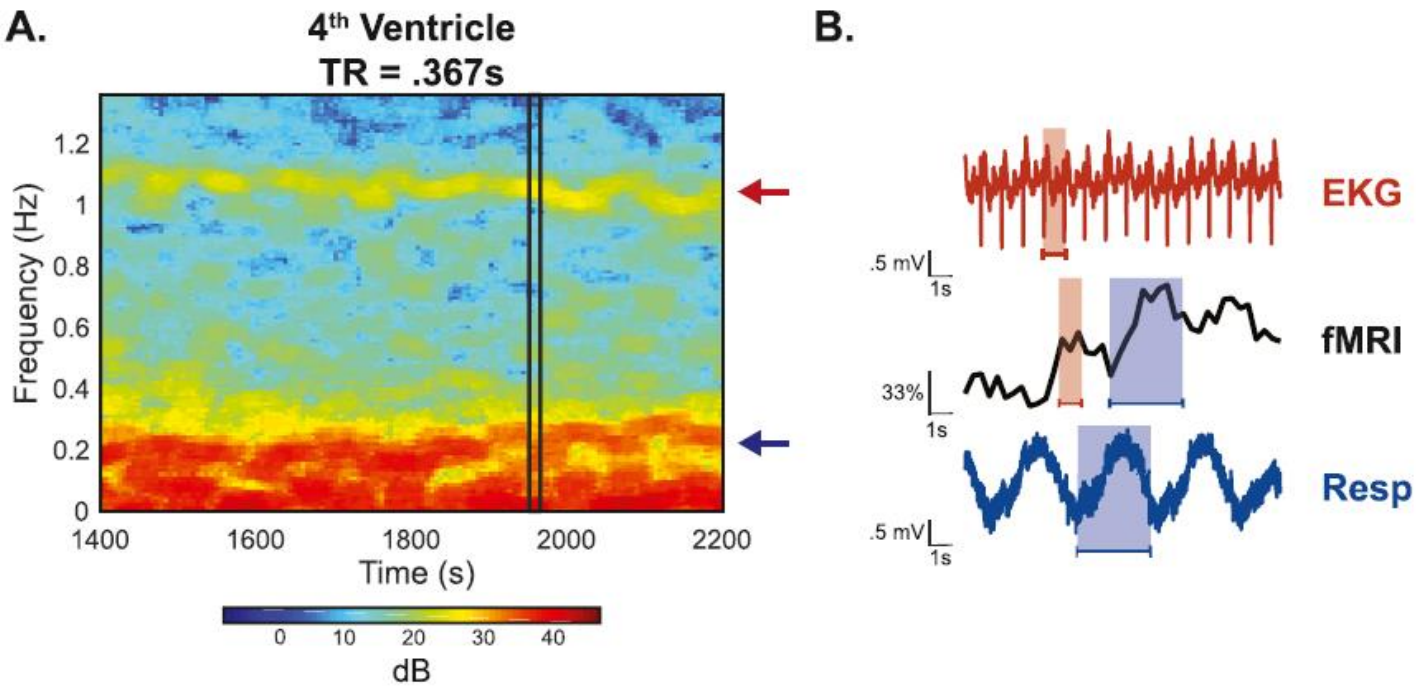
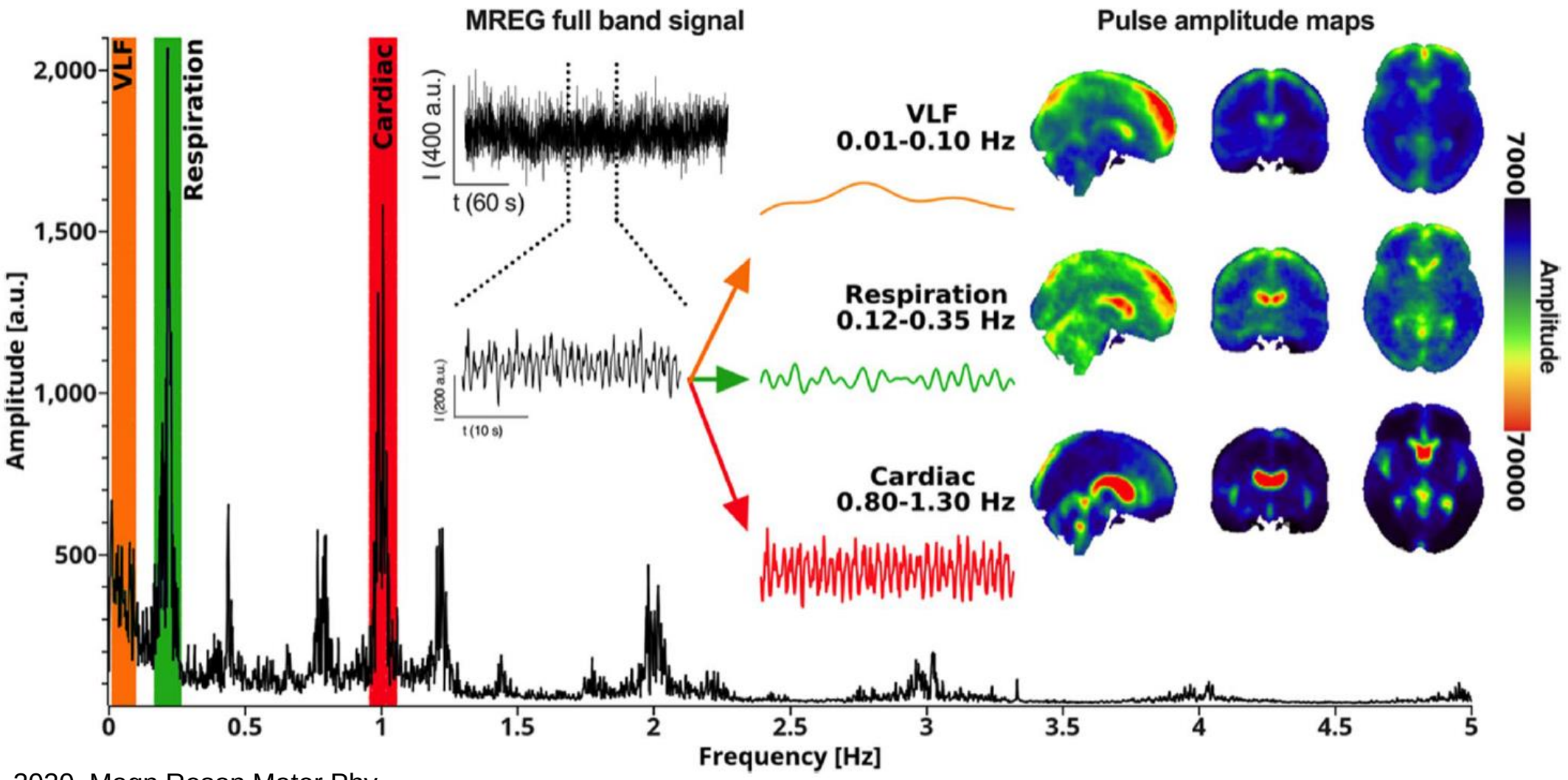
Model-Based Physiological Noise Removal in Fast fMRI[1]

- Estimates physiological noise based on the fast fMRI data (TR < 0.5)
- Joint estimation (and removal) of physiological noise and autocorrelation
- Windowed estimation approach to let amplitude and frequency vary over time



[1]Agrawal et al., 2020, NI

Ultrafast Scanning as a Tool for Physiological Pulse Mapping[1]



[1]Hennig et al., 2020, Magn Reson Mater Phy

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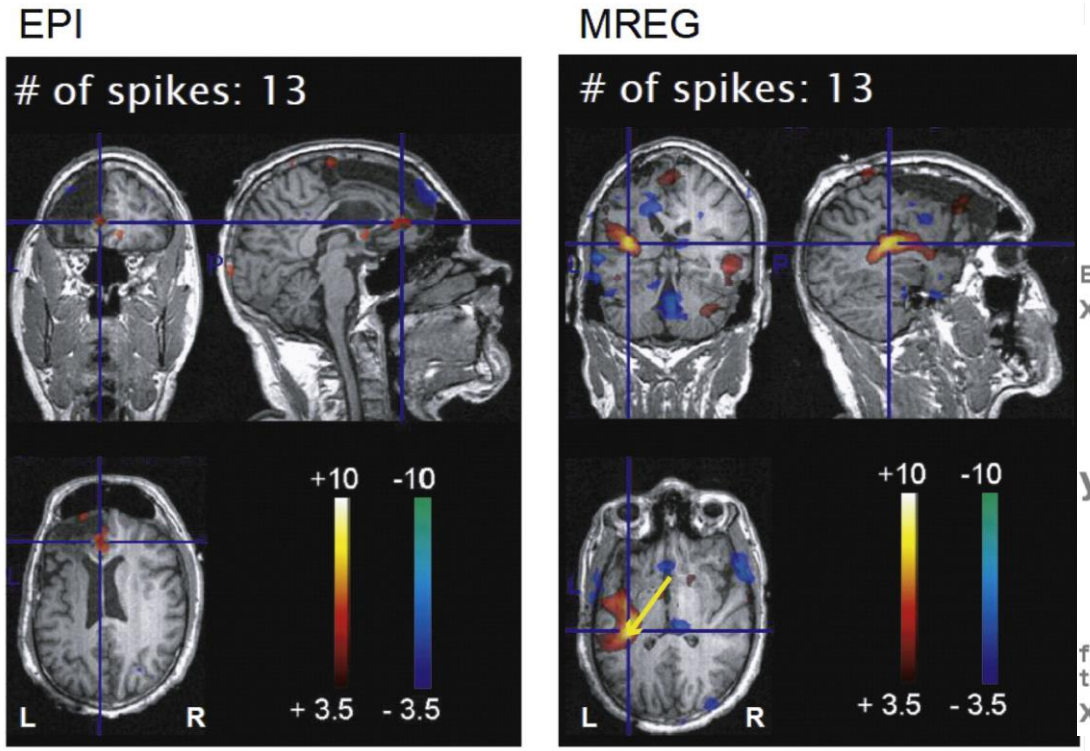
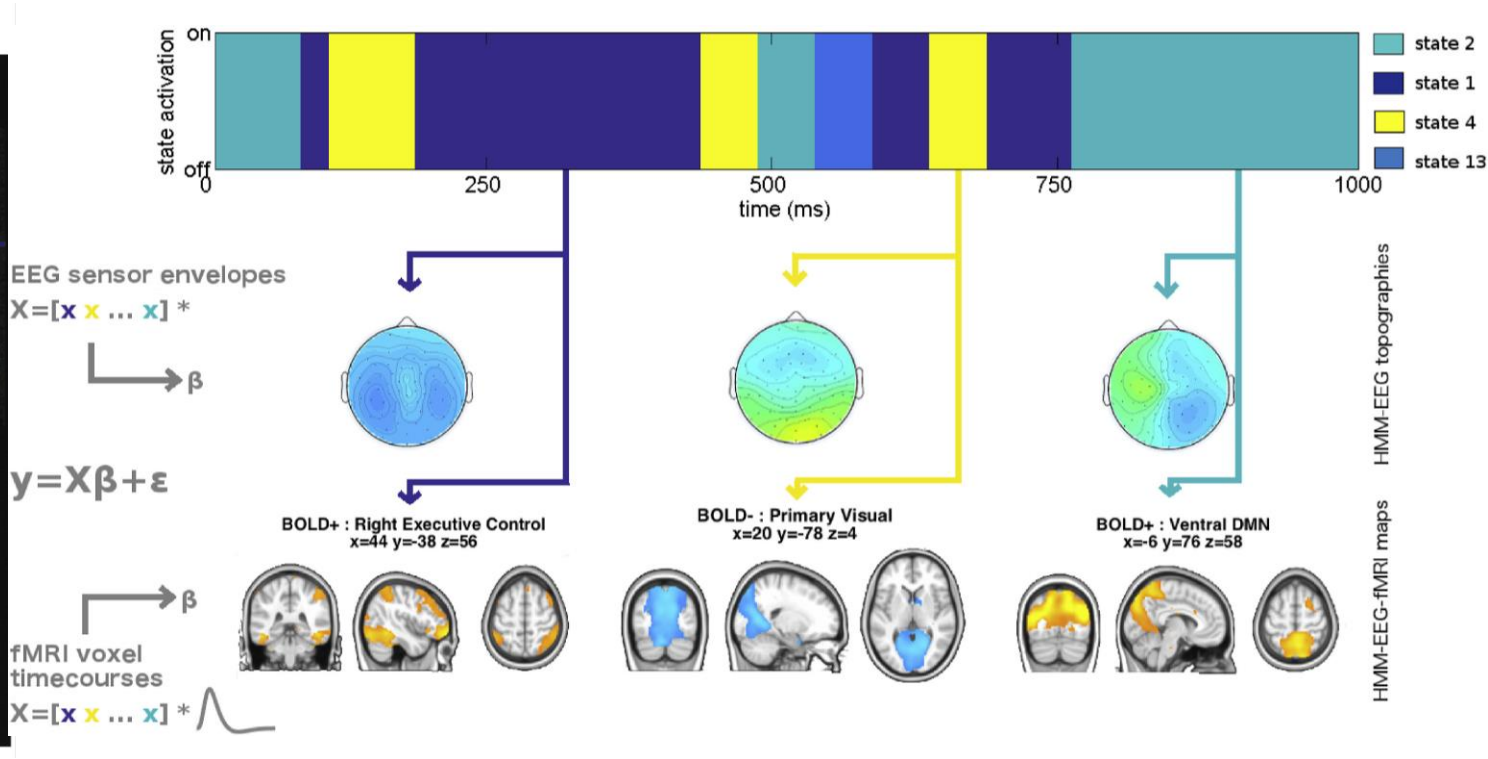
EEG-fMRI





Higher statistical power
Success also with few spike events

Jacobs et al., 2014, NI; Safi-Harb et al., 2015; NI

'links between the network dynamics at fast sub-second time-scales, accessible with EEG, and brain network activity at slower (>1sec) time-scales in fMRI'

Hunyadi et al., 2019, NI; Chang and Chen, 2021, COBME

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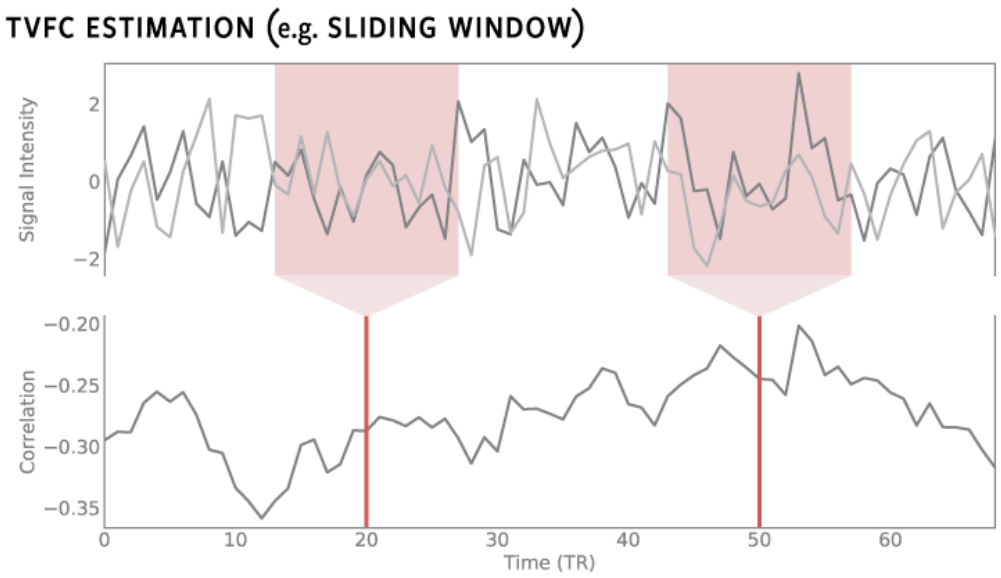
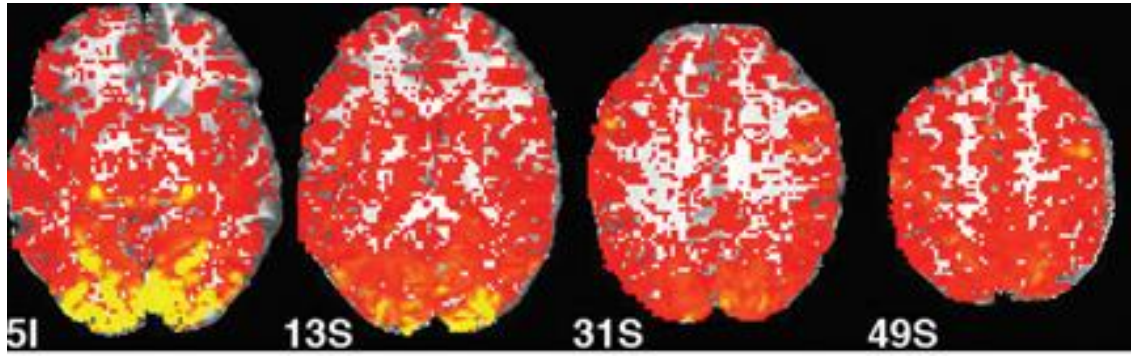
Time-Varying Functional Connectivity

Time-Varying Functional Connectivity

- ’ The brain is a complex, multiscale dynamical system composed of many interacting regions.’[1]
- 100 5-minute runs showed that 86% of the grey matter became significantly active[2]
- Denser temporal sampling might support
  - smaller window sizes
  - various HRF models
  - single-trial analyses
  - …





[1]Lurie et al., 2020, Network Neursci; [2]Gonzalez-Castillo et al., 2015, Cerebral Cortex

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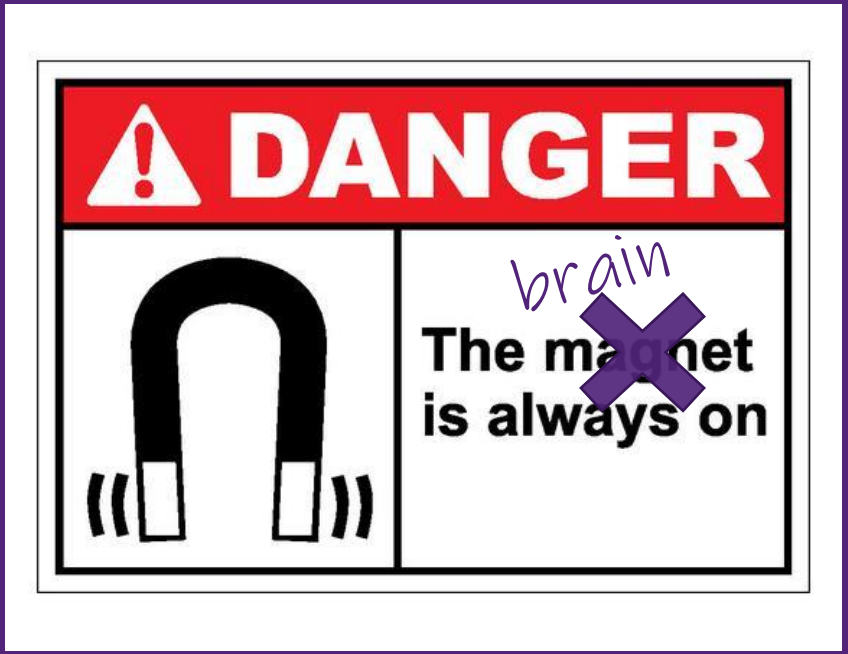

Impact ?

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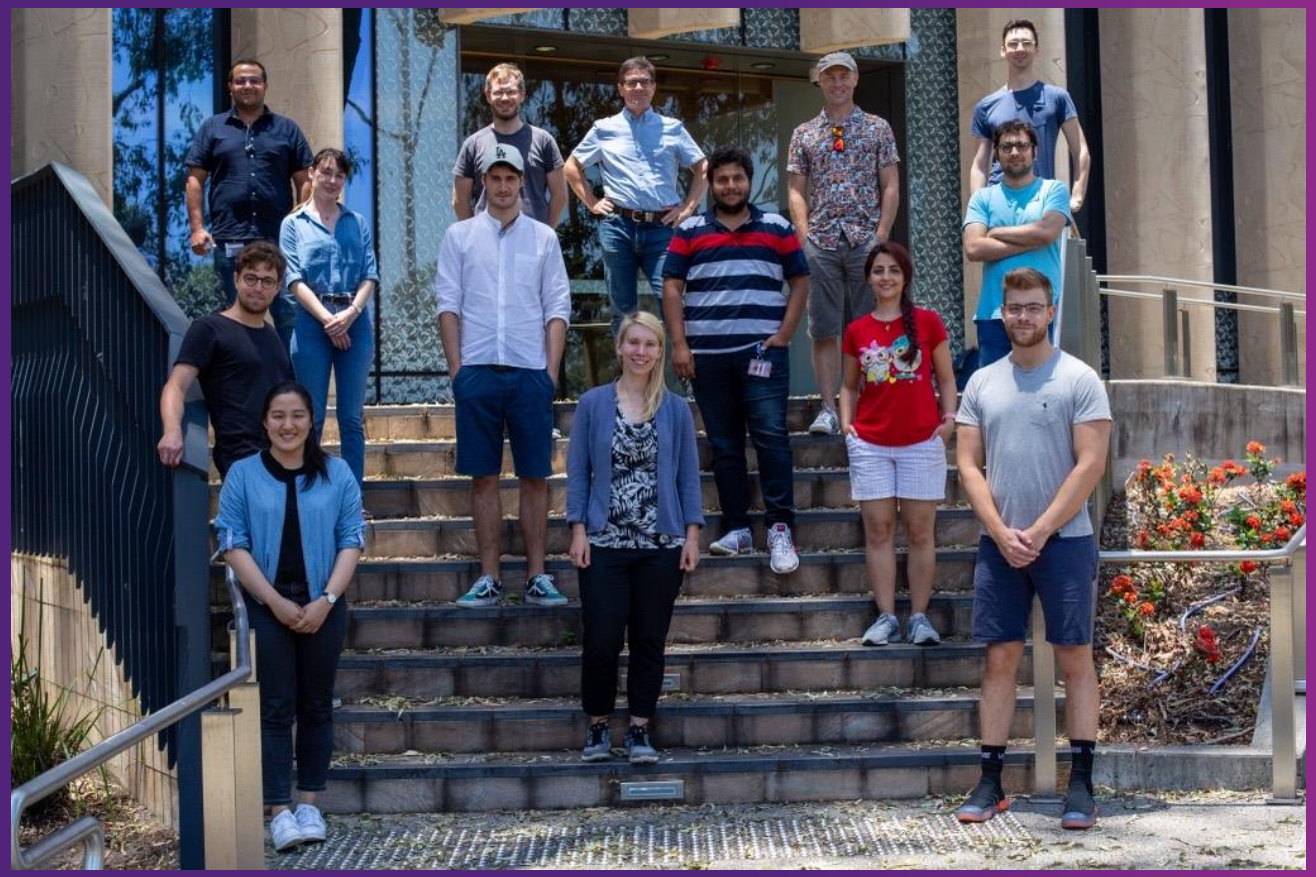
Acknowledgements

Markus Barth
Simon Robinson
Lars Kasper
Barth Group @ CAI



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National Imaging Facility