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Model-based Image Reconstruction in Looping-star MRI
Fessler group meeting

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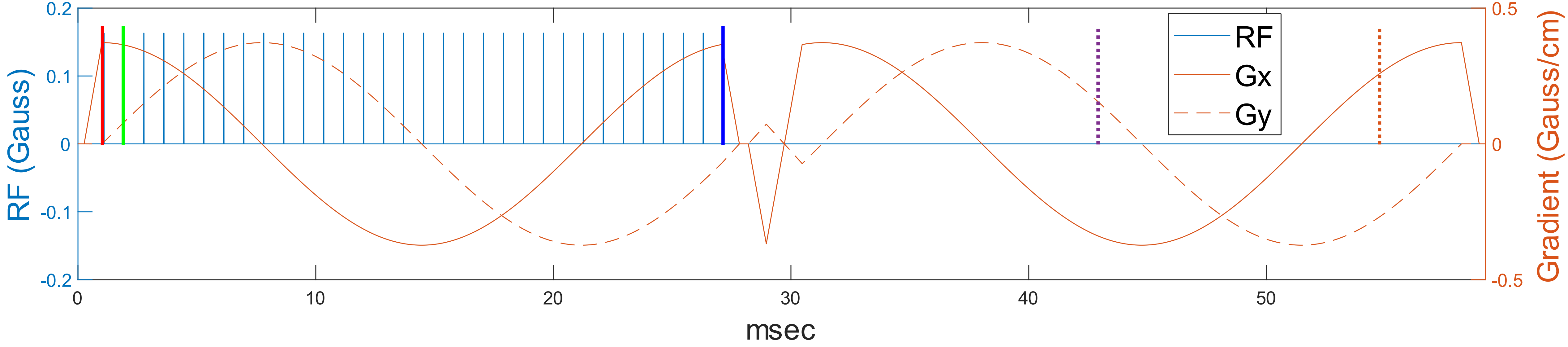
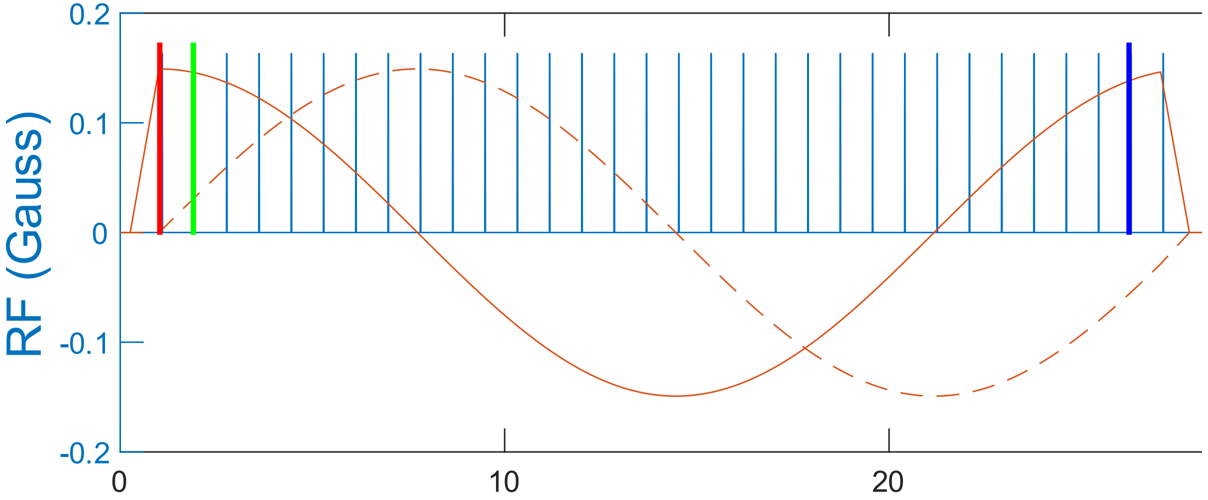
Introduction: 2D Looping-star MRI

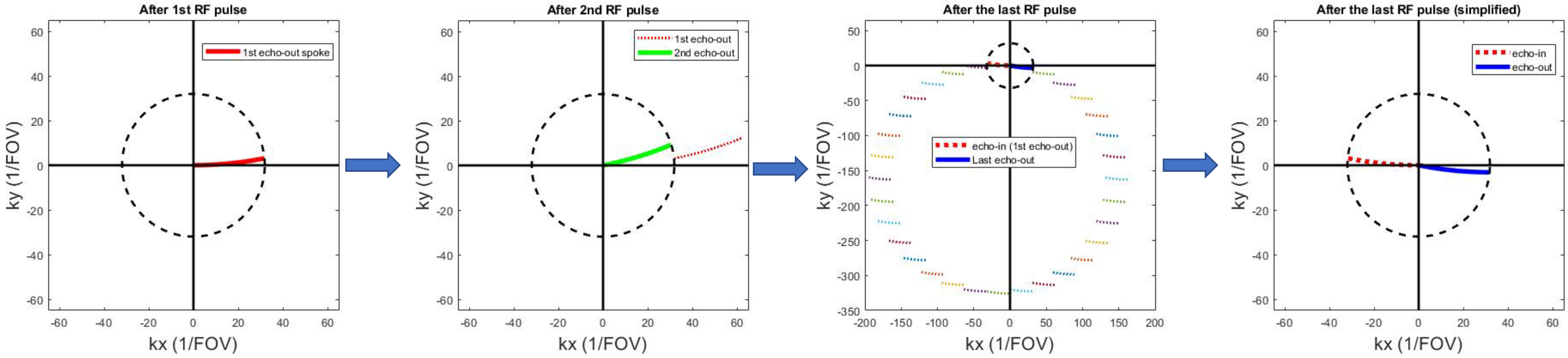
- Looping-star pulse [1] is a silent MRI ZTE pulse sequence that can be used for quantitative susceptibility mapping (QSM), T2* weighted imaging and fMRI.
  - Multiple hard short RF pulses
  - Slow-varying gradient
  - Looping k-space trajectories



[1] Wiesinger et al., "Looping-star", MRM 2019

Introduction: overlapping-echoes in FID





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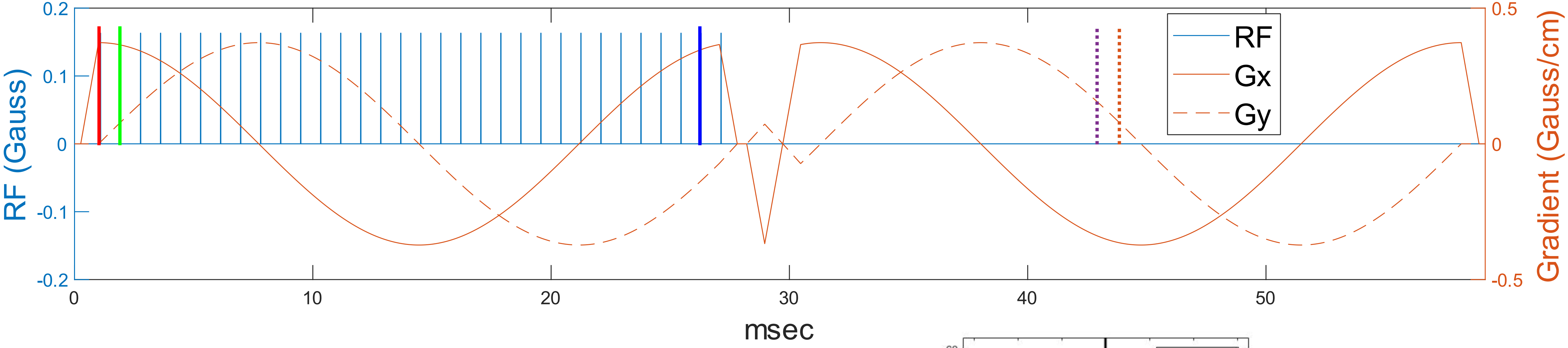
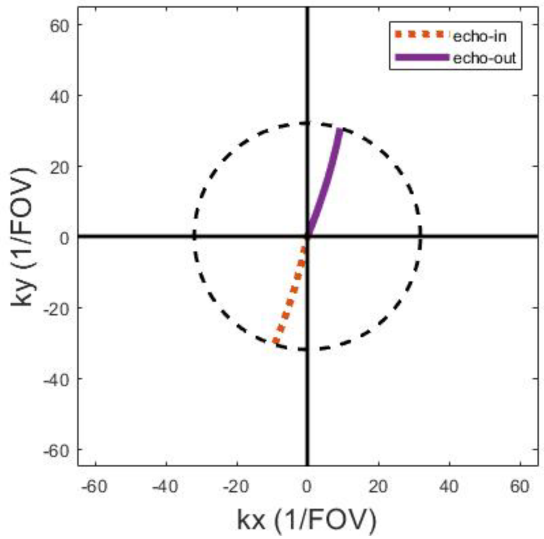
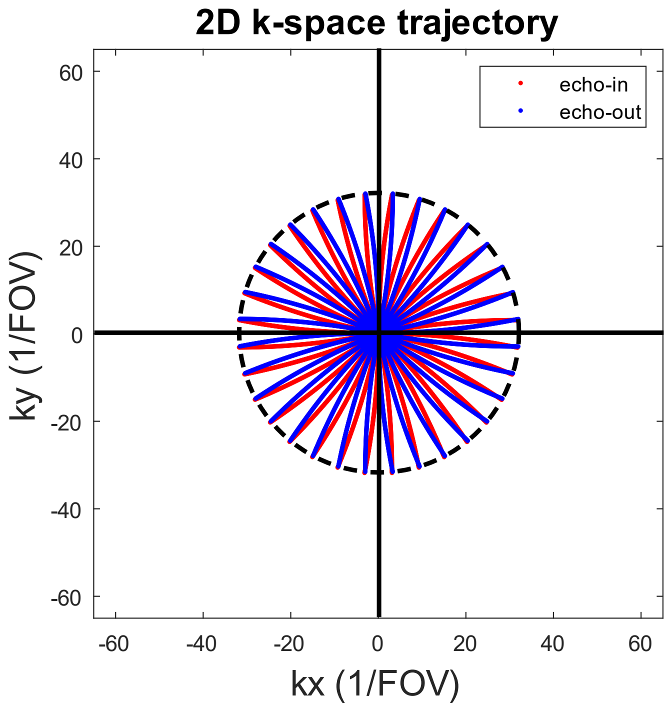
Introduction: overlapping-echoes in GRE

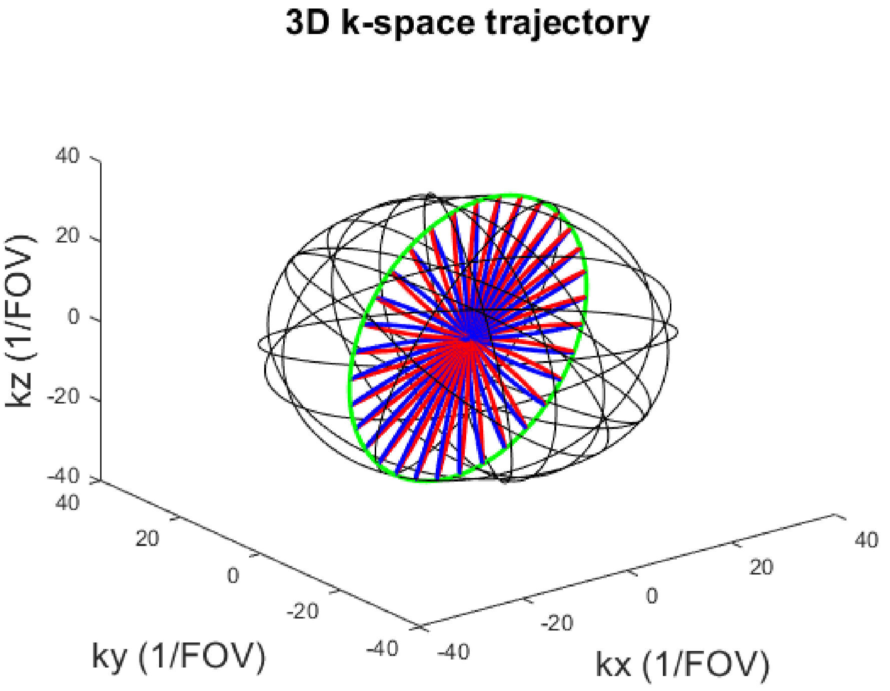




Introduction: Looping-star MRI in 3D

- Corresponding 2D and 3D k-space trajectories
- Sinusoid gradient (not optimized for uniform coverage in k-space)





Existing approach

- Simplification with a Fermi filter [2]
  - Assume echo-out and echo-in signal dominate the acquired signal at the beginning and the end respectively
  - Less spatial resolution and SNR

- RF-phase cycling [2]
  - Increase the SNR by sqrt(2) but at the cost of doubled scan time

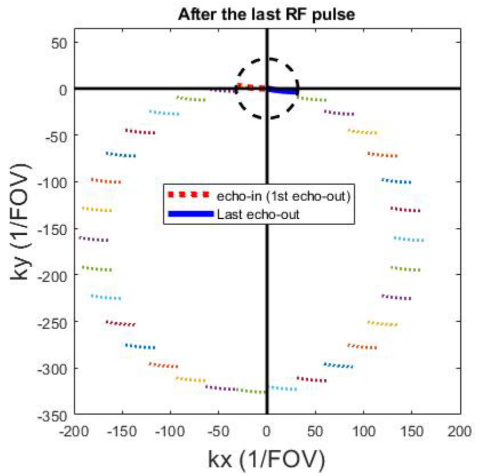
- Coherence-resolved looping star [3]
  - Increasing time interval between RF pulses
  - Almost half spokes (less data being used, lower SNR)

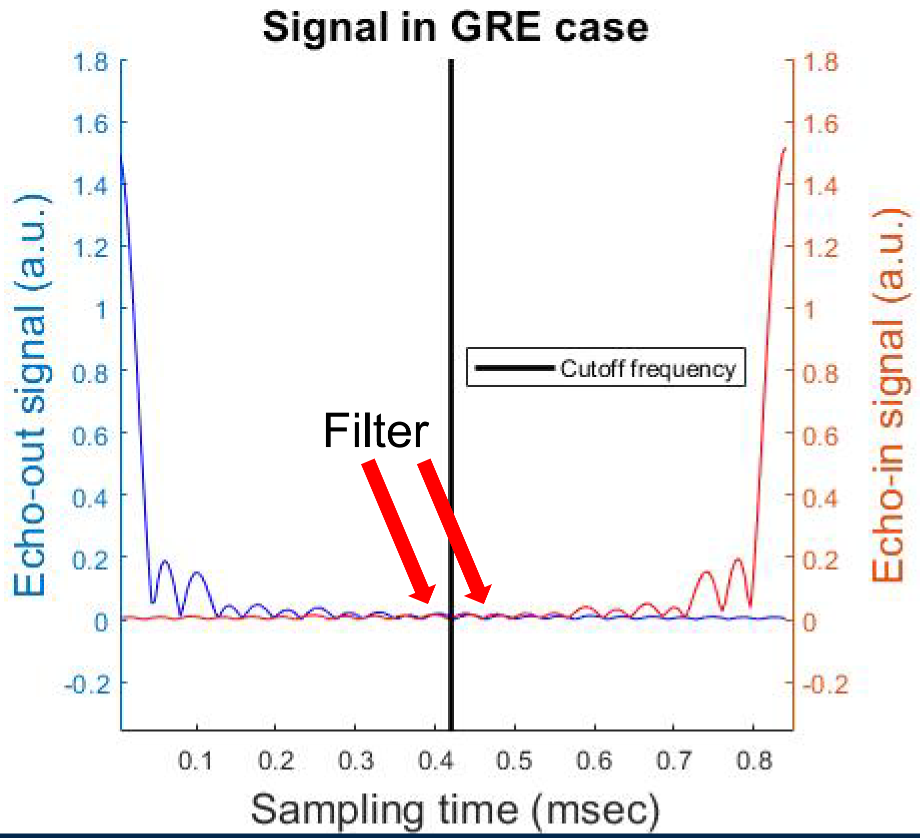
- **Goal:** A model-based reconstruction method that separate the overlapping-echoes without sacrificing resolution and SNR

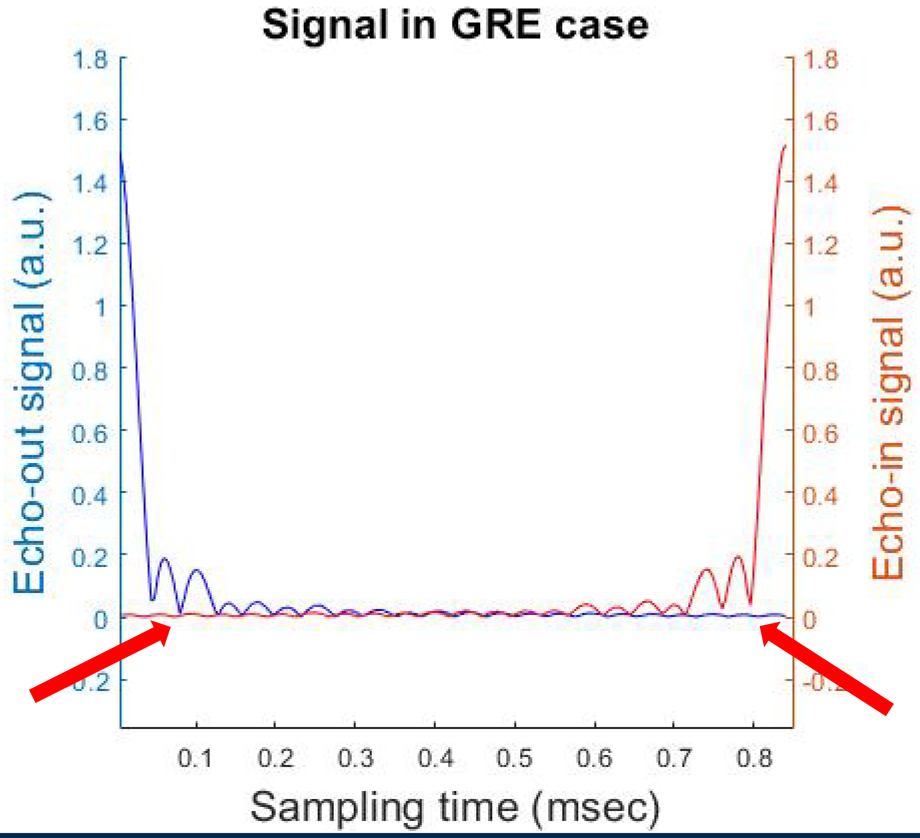
[2] Beatriz Dionisio-Parra et al. "Looping star fMRI", MRM 2020
[3] Florian Wiesinger et al., "Looping Star: Revisiting echo in/out separation", ISMRM 2020

Existing approach

- Simplification with a Fermi filter







High-freq signal not being used

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Methods: cost function

- **The goal:** develop a model-based reconstruction that can resolve the overlapping echoes, increase the image resolution, and improve the SNR.

- **Cost function:** A general form for model-based reconstruction

$$\hat{\boldsymbol{x}} = \arg\min_{\boldsymbol{x}} \|\boldsymbol{s} - \boldsymbol{A}\boldsymbol{x}\|_2^2 + \beta R(\boldsymbol{x})$$

  - *'x'* is the underlying complex images
  - *'s'* is the sampled signal, possibly sum of many signals from multiple spokes
  - *'A'* is the system matrix that models k-space trajectories, coil sensitivity maps, field map et al.
  - *'R()'* is the regularizer, usually quadratic roughness or edge-preserving

- **Optimization:** iterative conjugate gradient method using NUFFT (MIRT toolbox [4])

[4] Jeffrey A Fessler, "Michigan Image Reconstruction Toolbox"

Methods: modeling the spokes

- Due to the memory limitation and computational speed, only echo-in and echo-out spokes are considered in current implementation

- The sampled signal is approximately the sum of echo-in and echo-out signals, so the overall system matrix is also the sum of echo-in and echo-out

$$\boldsymbol{A} = \boldsymbol{A}_1 + \boldsymbol{A}_2$$

- Each system matrix is decided by its k-space trajectories, voxel indicator function, and coil sensitivity maps.

$$a_{ljmn} = B(\boldsymbol{k}(t_{l,m}))c_j(\vec{r}_n)\mathrm{e}^{-z(\vec{r}_n)t_{l,m}}\mathrm{e}^{-\imath 2\pi \vec{k}_l(t_m)\cdot\vec{r}_n}$$

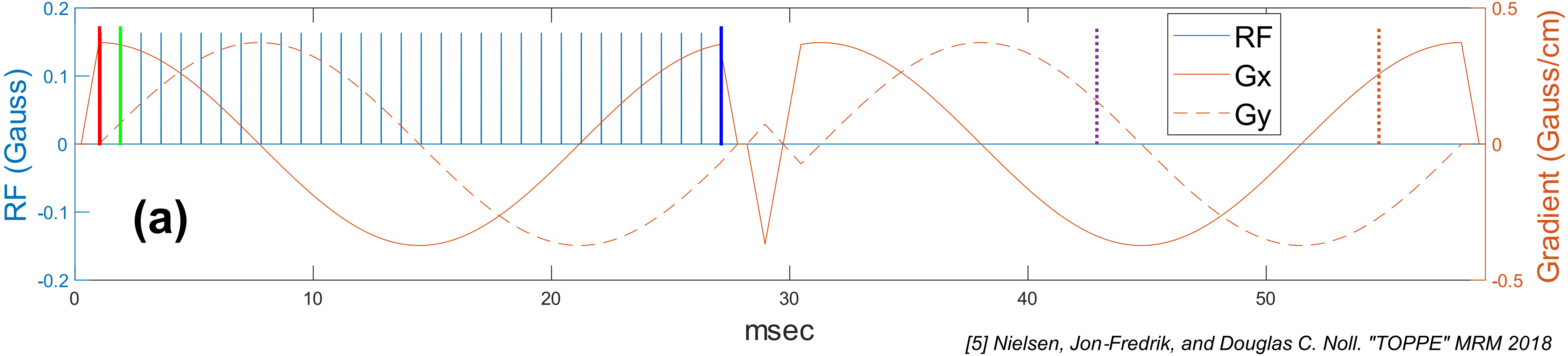
  - *'l'* index for spokes, *'j'* index for coils, *'m'* index for discrete time points, *'n'* index for discrete spatial grid
  - *'B()'* is the voxel indicator function, *'k'* is the k-space trajectory for this spoke, *'t'* is the time, *'c'* is the sensitivity maps, *'z'* is the rate map, and *'r'* is the spatial vector

Methods: comparison of gridding and model-based method

Gridding	Model-Based
Signals placed directly into k-space matrix	Signals are modeled from estimated image and MRI physics
Overlapping signals results in incorrect assignment of k-space locations for some signal components	Overlapping echo-in and echo-out signal components (and possibly more) are explicitly modeled
Undersampling artifacts partially suppressed by coil combination method	Approach is fully compatible with SENSE, GRAPPA-like methods and compressed sensing
Simple (3D FT) reconstruction (fast)	Iterative optimization to find images that best matches acquired signals (slow)

Methods: TOPPE implementation

- TOPPE [5] is a simple, modular framework for rapid prototyping of pulse sequences on General Electric MRI scanners
  - Arbitrary rotations of gradients in 3D
  - FID module:
    - No sampling for FID
    - Sinusoid gradient
  - GRE module
    - Ramp up and ramp down gradient

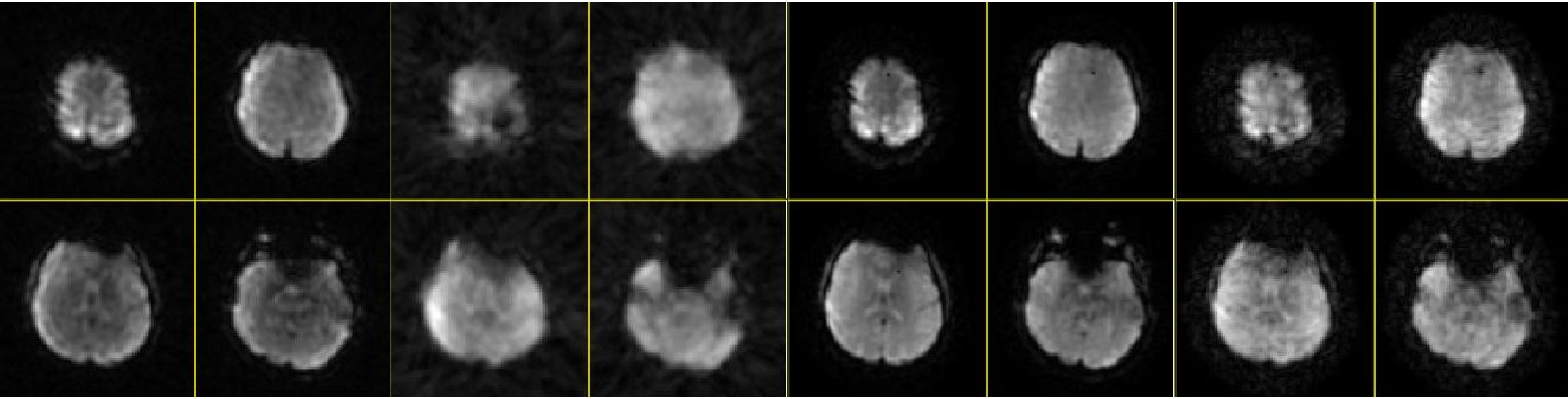


[5] Nielsen, Jon-Fredrik, and Douglas C. Noll. "TOPPE" MRM 2018

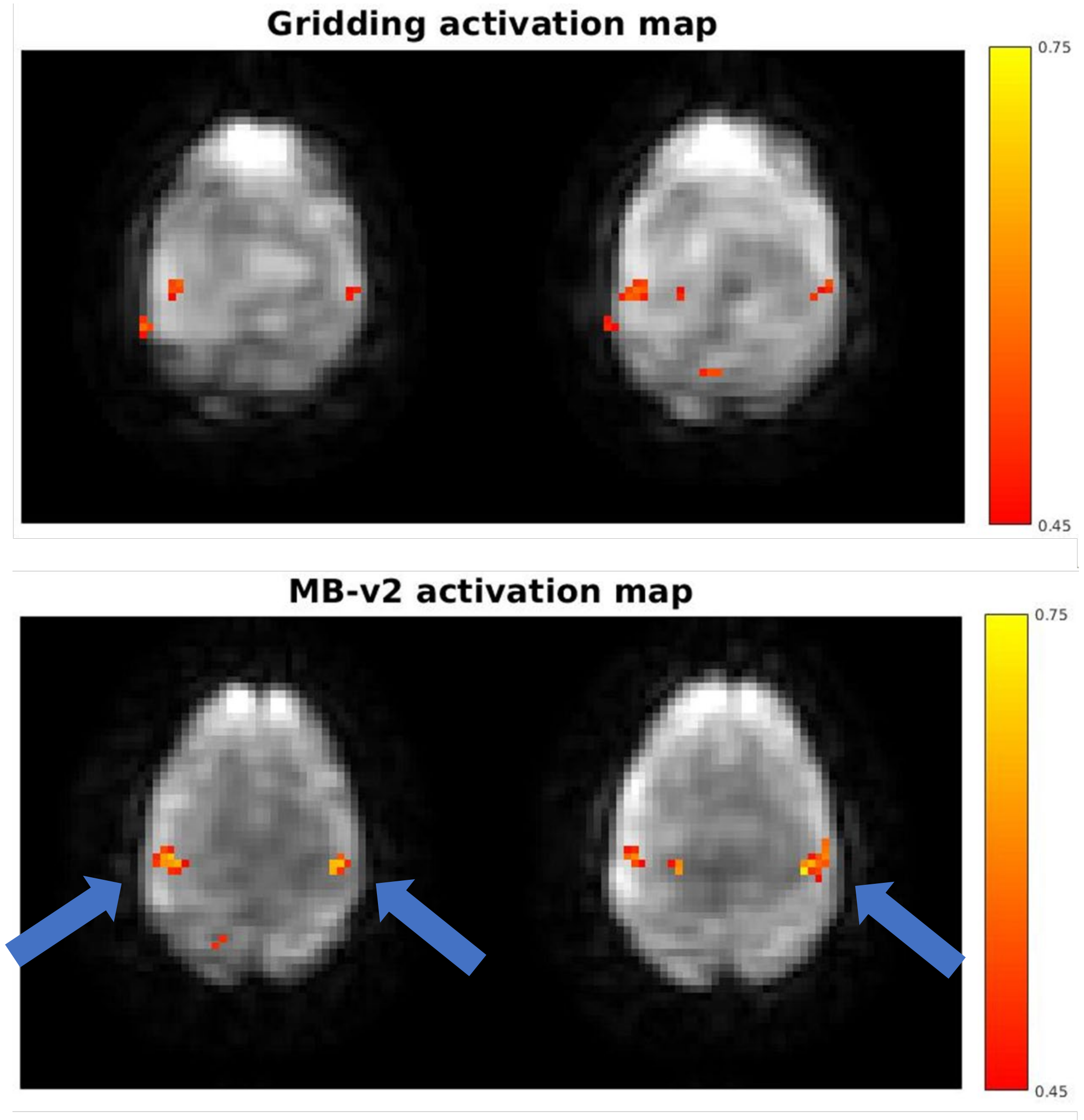
Results: fMRI reconstruction

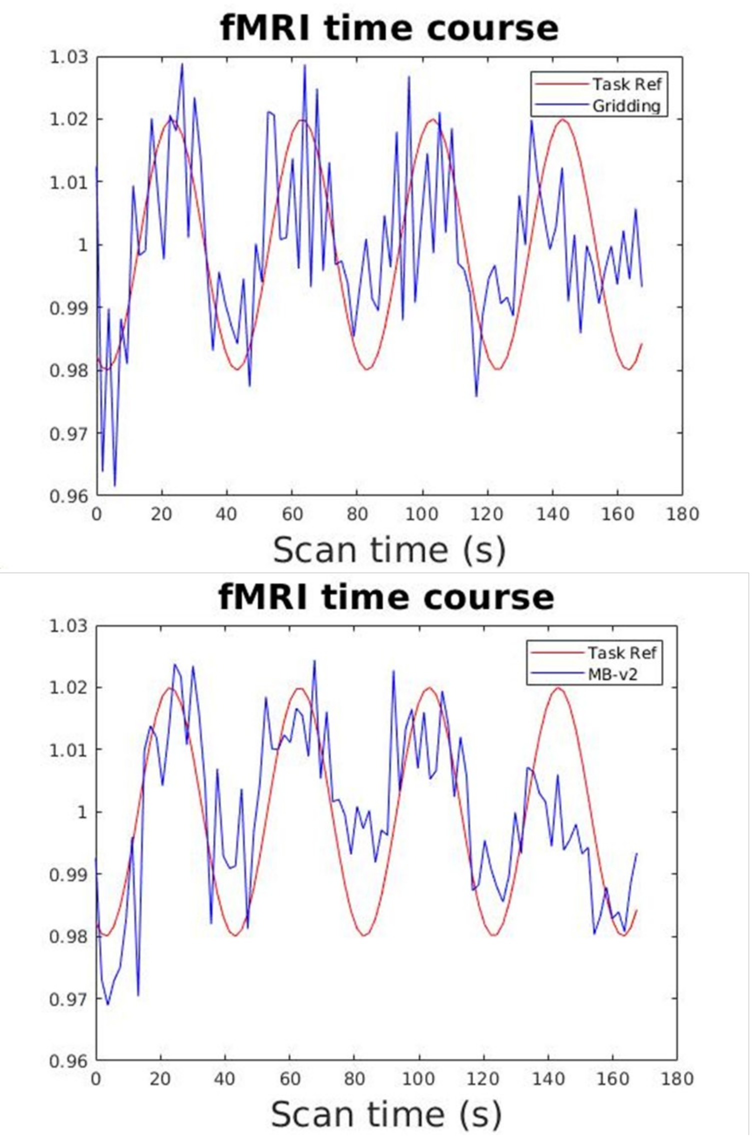
- Resolution: 3mm isotropic
- Under-sampling factor
    - 40s scan: 1.35x
    - 2s scan: 26x
- Computational time: ~30 min

Gridding (40s) Gridding (2s) Model-based (40s) Model-based (2s)



Results: finger-tapping fMRI





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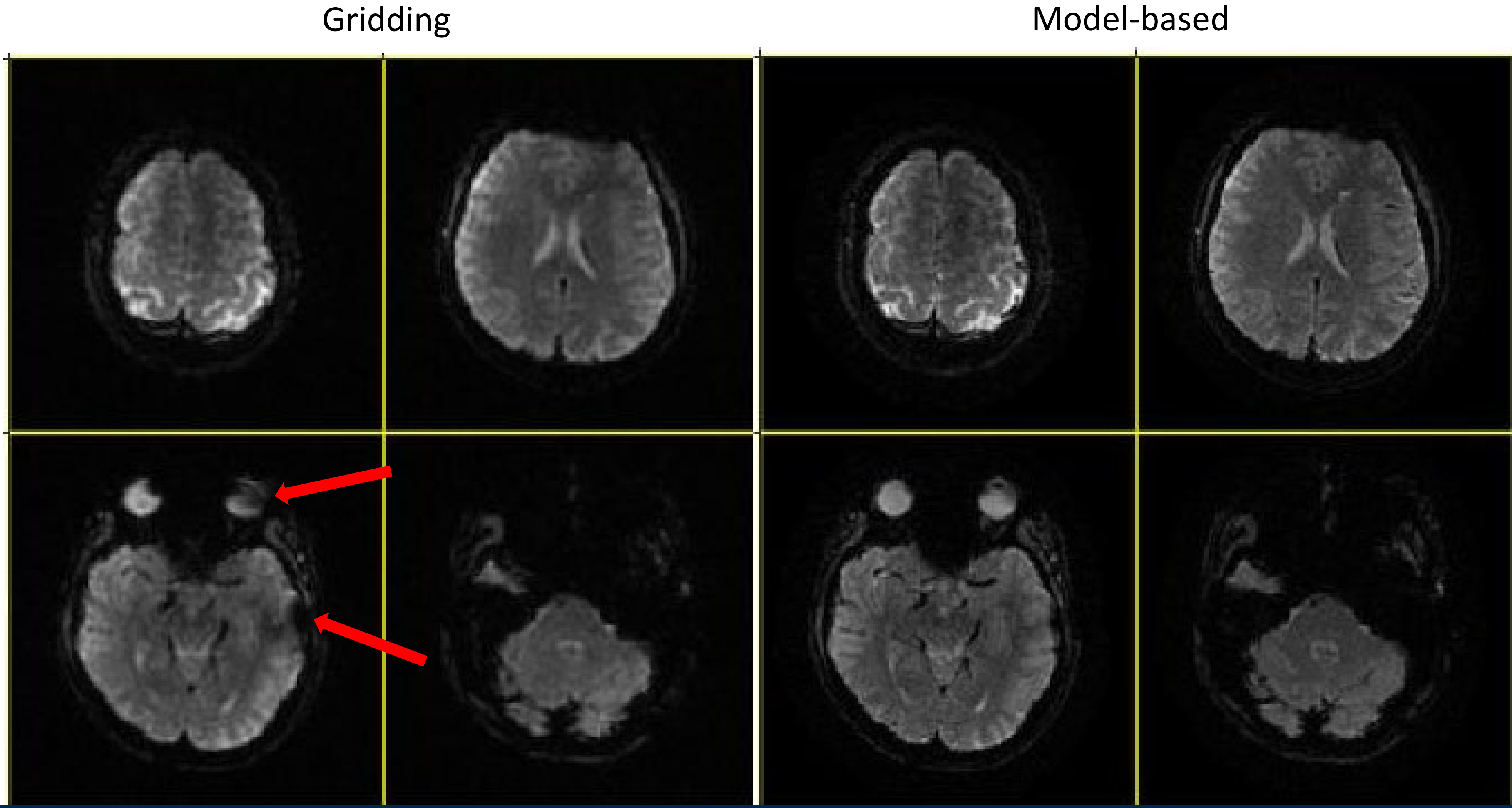
Results: high-res protocol (1st echo)

- Resolution: 1.25 mm^3
- # of GRE echoes: 2
- # of spokes: 56832
- Scan time: 6:51 min



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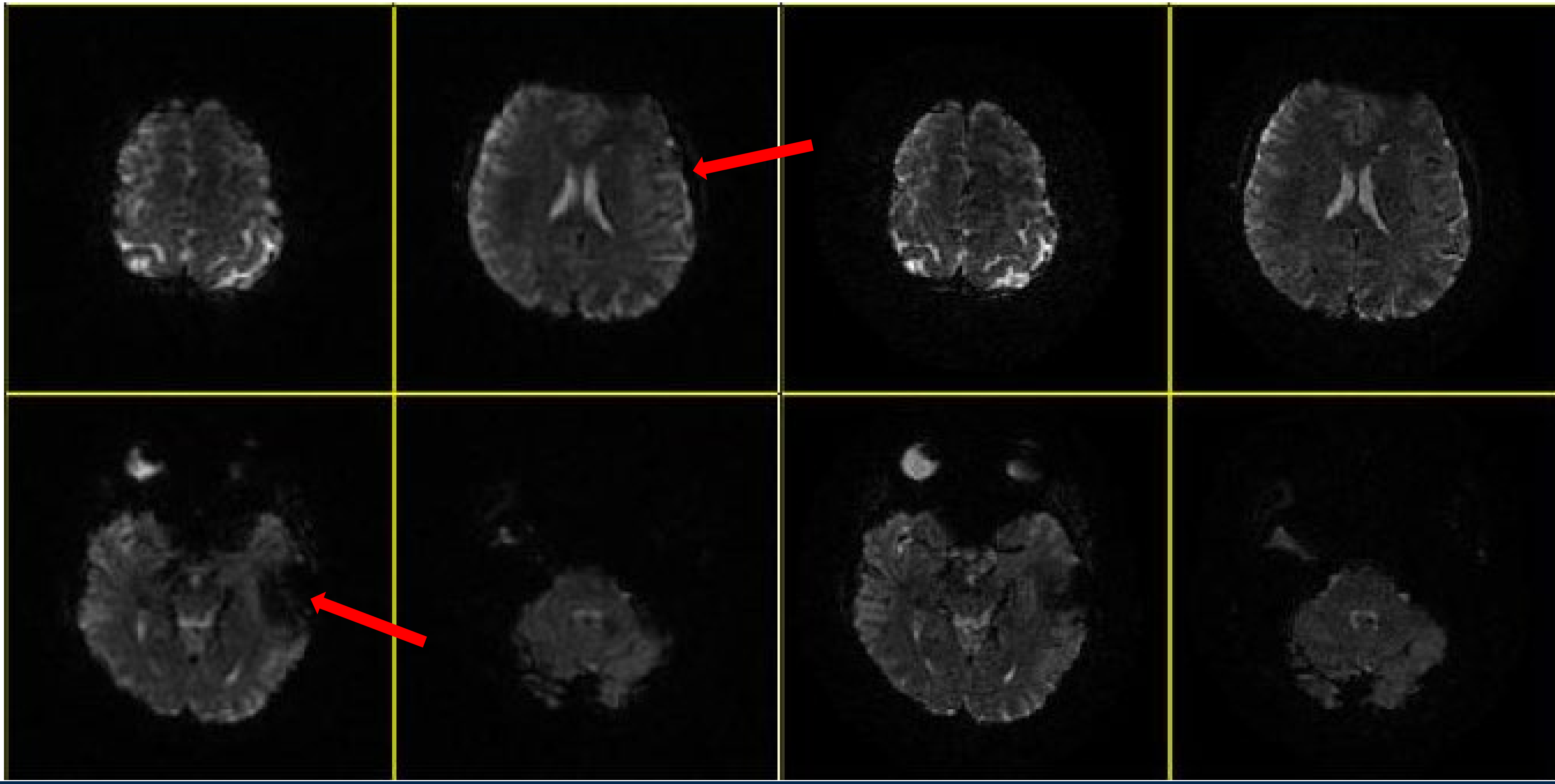
Results: high-res protocol (2nd echo)

- Resolution: 1.25 mm^3
- # of GRE echoes: 2
- # of spokes: 56832
- Scan time: 6:51 min

Gridding Model-based



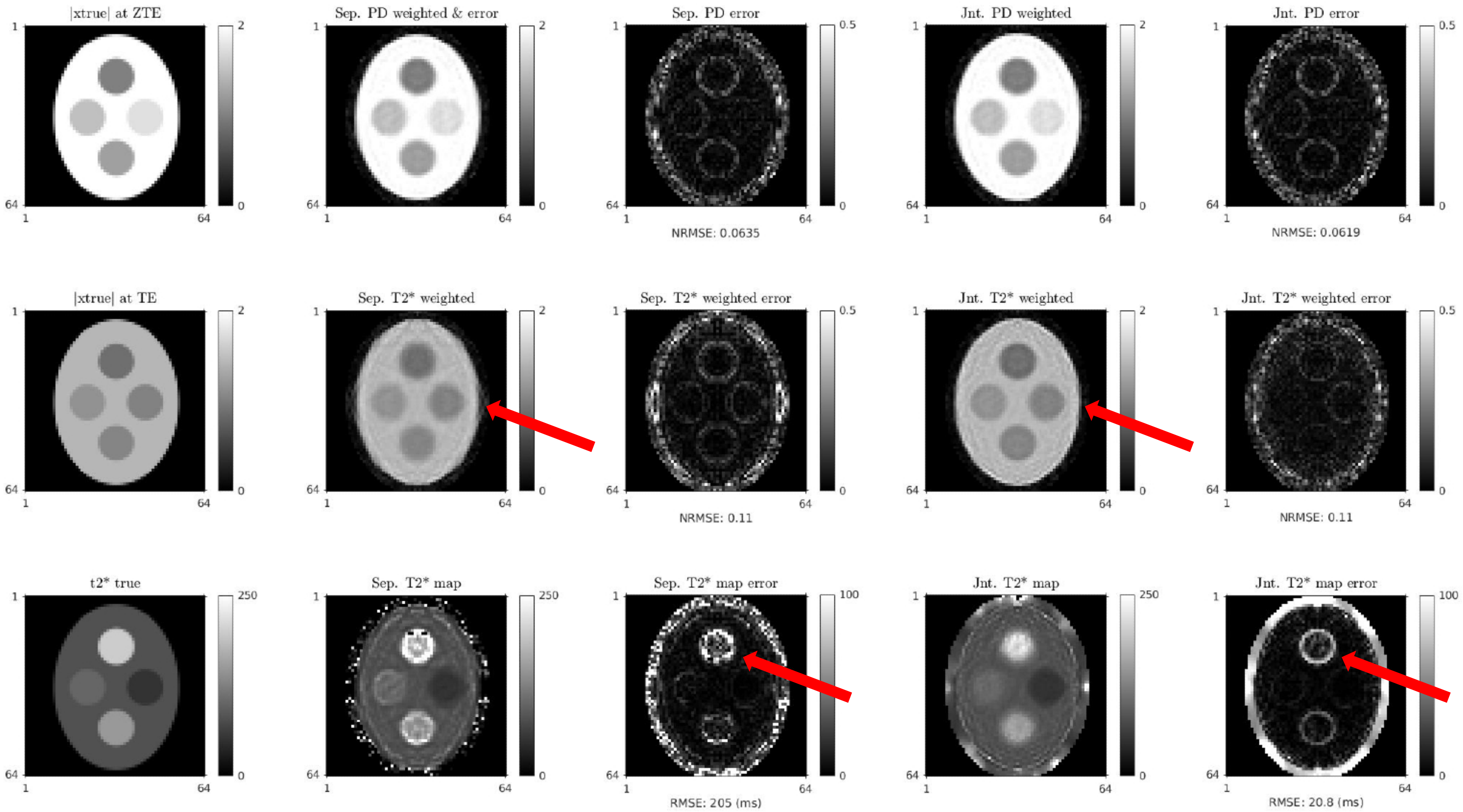
Joint reconstruction of FID and GRE data

- Cost function

$$(\hat{\boldsymbol{\rho}}, \hat{\boldsymbol{z}}) = \arg\min_{\boldsymbol{\rho}, \boldsymbol{z}} \left\| \begin{pmatrix} \boldsymbol{s}_f \\ \boldsymbol{s}_g \end{pmatrix} - \begin{pmatrix} \boldsymbol{A}_f & 0 \\ 0 & \boldsymbol{A}_g \end{pmatrix} \begin{pmatrix} \boldsymbol{\rho} \\ \boldsymbol{\rho} \cdot \boldsymbol{z} \end{pmatrix} \right\|_2^2 + \beta_1 R_1(\boldsymbol{\rho}) + \beta_2 R_2(\boldsymbol{z}),$$

- ρ is the density map, z is the rate map including field map and T2* decay

Joint reconstruction of simulation data



Conclusions

- The model-based method shows improved image quality in terms of reduced artifacts and increased image resolution.

- The fMRI test shows that model-based reconstruction has better activation map with higher correlation and smoother time series.

- In high-resolution looping-star, model-based reconstruction achieved designed resolution and almost free of the overlapping echo artifacts.

Future work

- Optimization of the k-space trajectories in 2D and 3D
- Develop (varying) flip angle scheme to maximize magnetization
- Joint reconstruction of multi-echo data

Results: phantom data (todo)

- Need to replace old result with new gridding reconstruction
- Demonstrate the overlapping-echoes artifact vs k-space radius