Rapid QSM Acquisition with Wave-CAIPI

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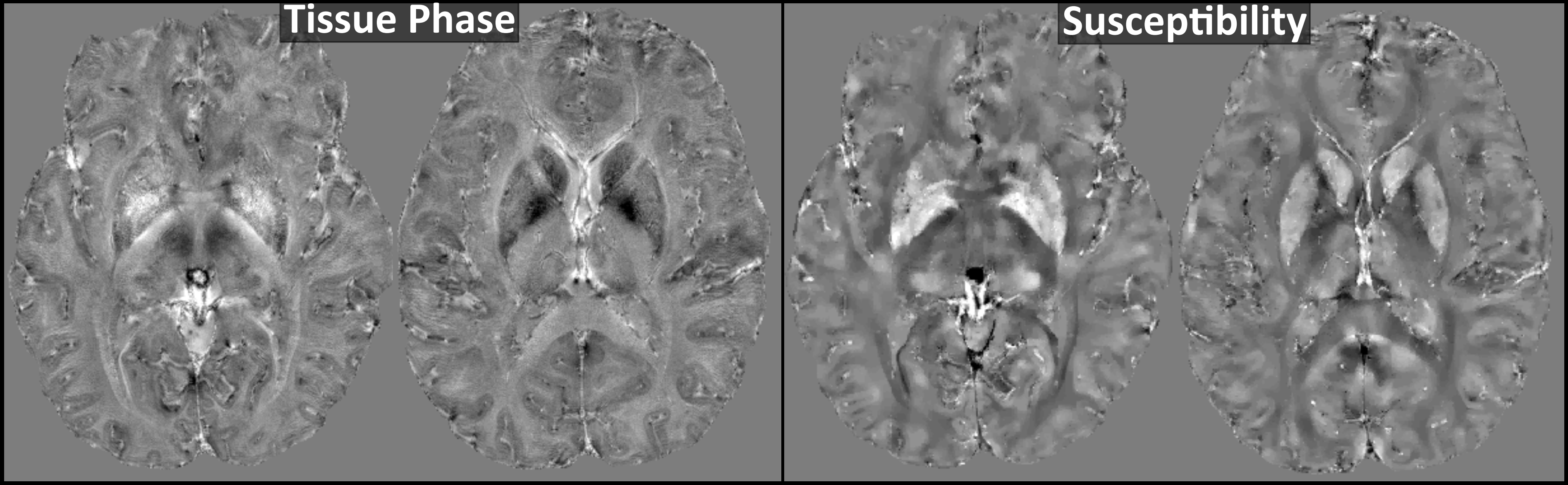
4 Massachusetts Institute of Technology, Cambridge, MA
5 Harvard-MIT Division of Health Sciences and Technology, Cambridge, MA

Wave-CAIPI accelerated QSM

- Quantitative Susceptibility Mapping (QSM) relies on phase data from 3D Gradient Echo (GRE)
- Long echo times (TE ≈ 30ms) are required for phase contrast ⟶ **TR ≥ 30ms very long scan time**

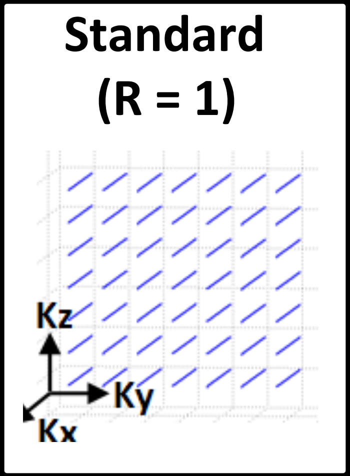


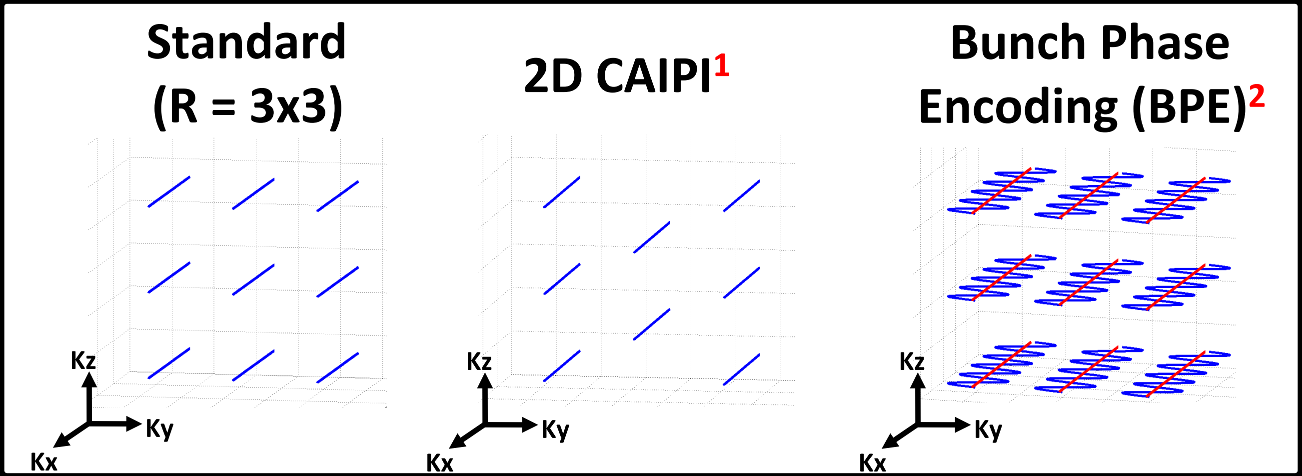
0.5 mm isotropic whole brain @ 7T in 5 minutes

Wave-CAIPI with 9-fold acceleration (TE/TR=20/30 ms)

Highly Accelerated 3D Cartesian Imaging

- Recent modifications to rectilinear k-space sampling provided more robust reconstructions of highly under-sampled datasets





1. Breuer F. et al, MRM 2006 2. Moriguchi H. et al, MRM 2006

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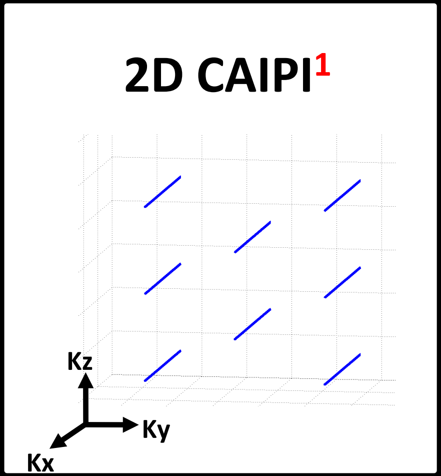

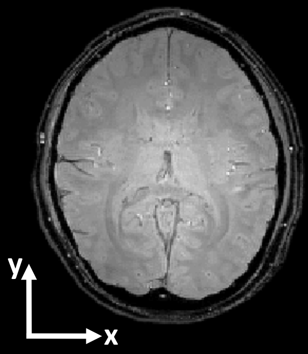

2D-CAIPI slice shift:

Effect of slice shift in image space

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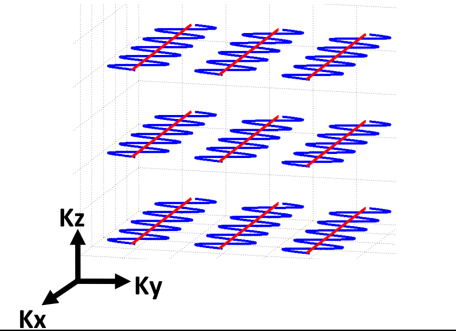
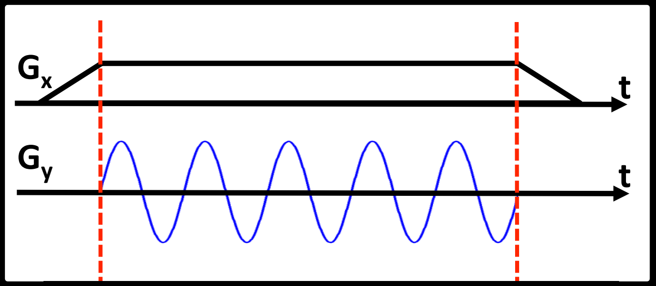
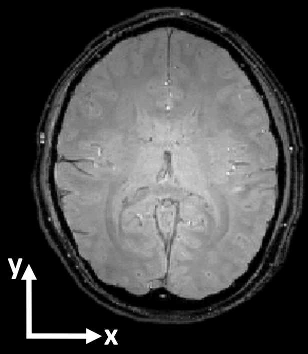
Bunch Phase Encoding (BPE)[2]







Bunch Phase: Zigzag G_y

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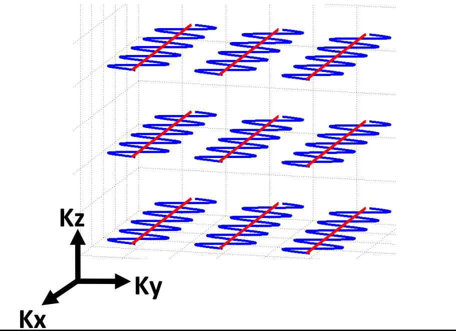
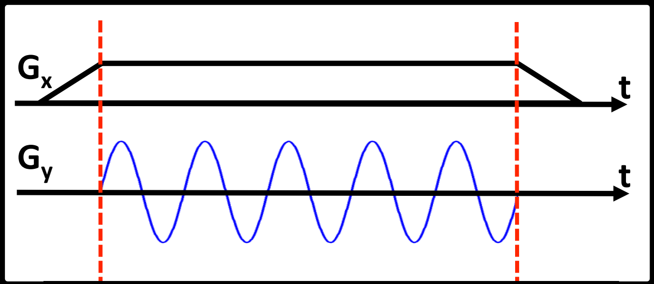
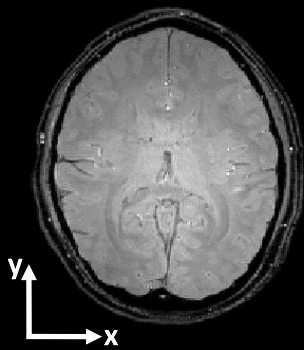
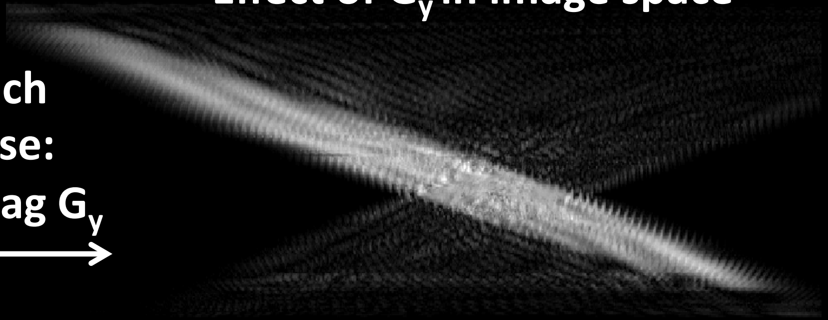






Bunch Phase: Zigzag G_y

Effect of G_y in image space



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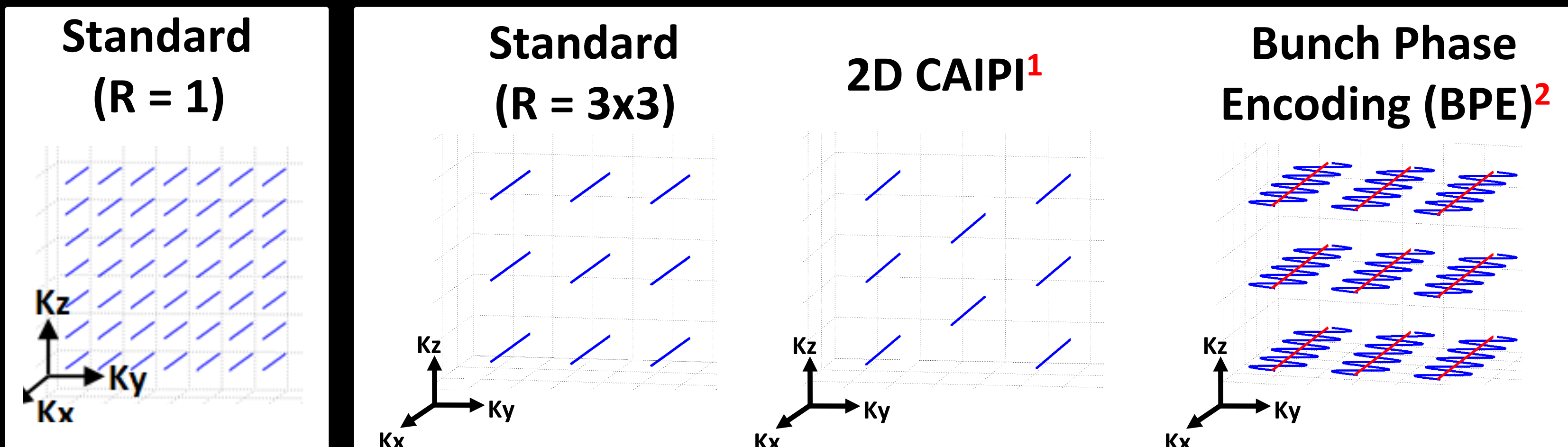
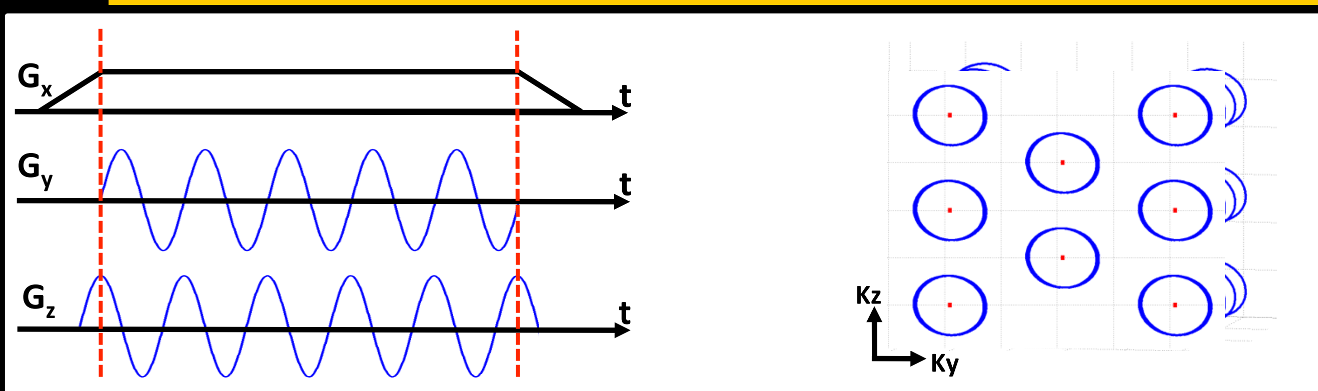
Wave-CAIPI Sampling

- Recent modifications to rectilinear k-space sampling provided more robust reconstructions of highly under-sampled datasets



- Wave-CAIPI: 2D CAIPI + BPE in 2 directions
- <u>Spread aliasing in 3D to take full advantage of 3D coil profiles</u>



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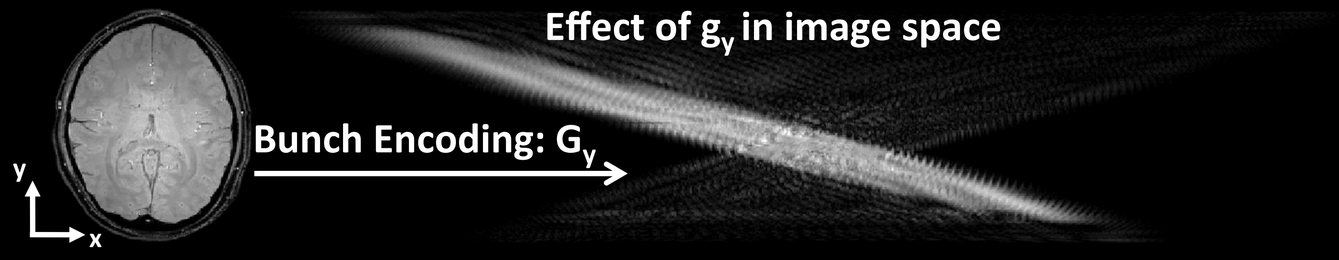
Wave-CAIPI causes voxel spreading in 3 dimensions

- Combination of G_y and G_z gradients with inter-slice shifts yields voxel spreading across three dimensions



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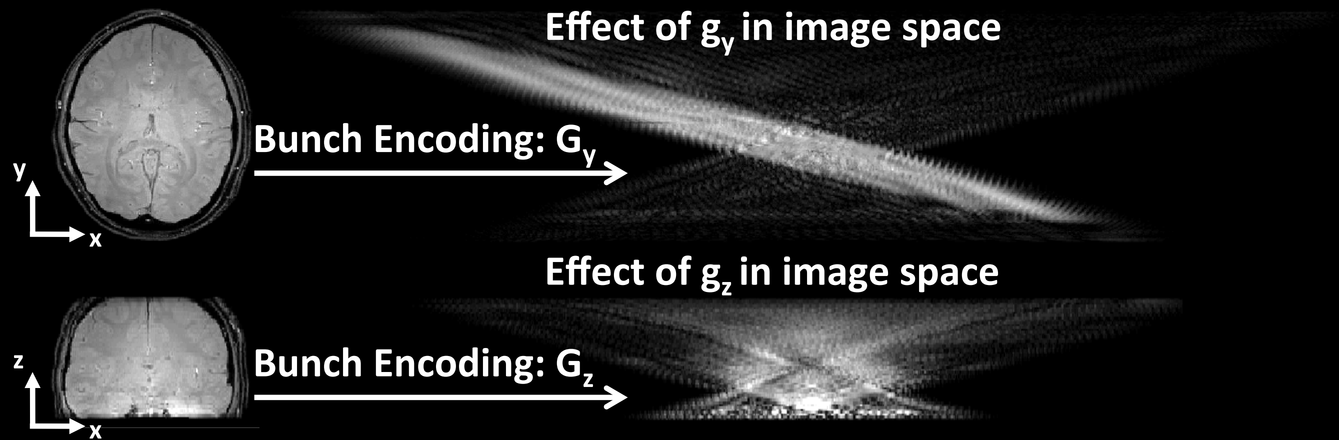

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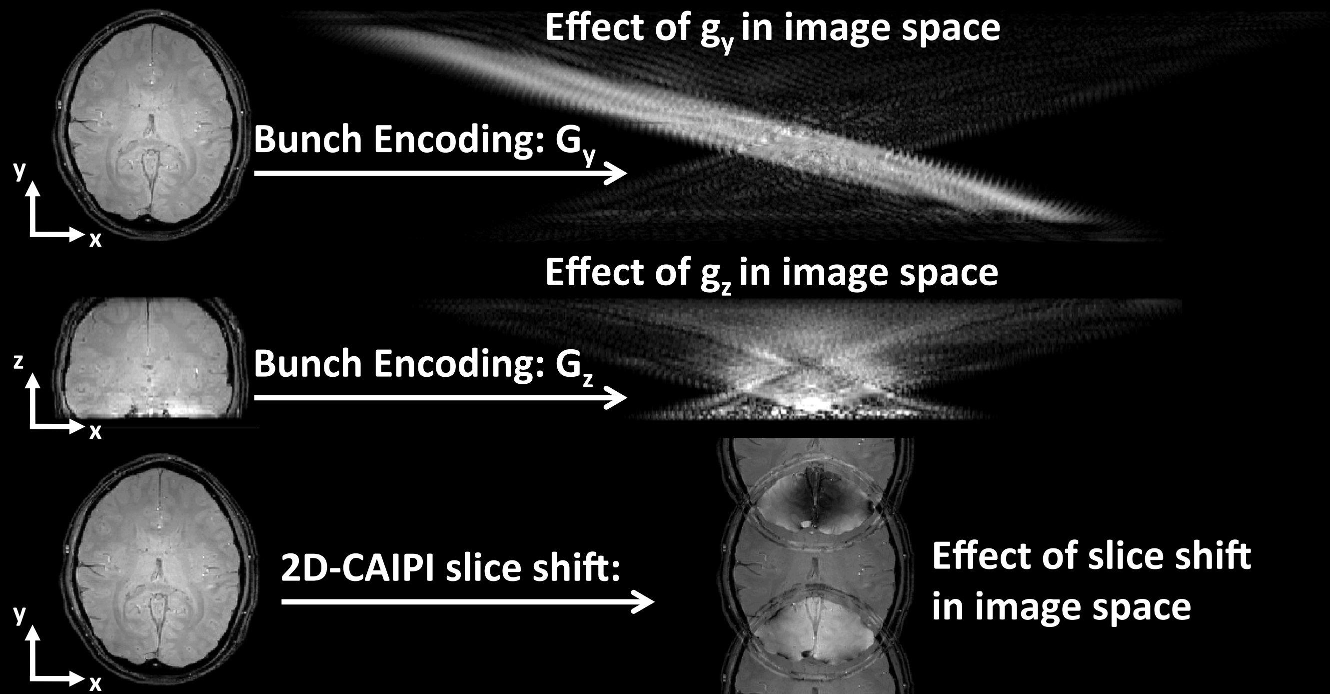

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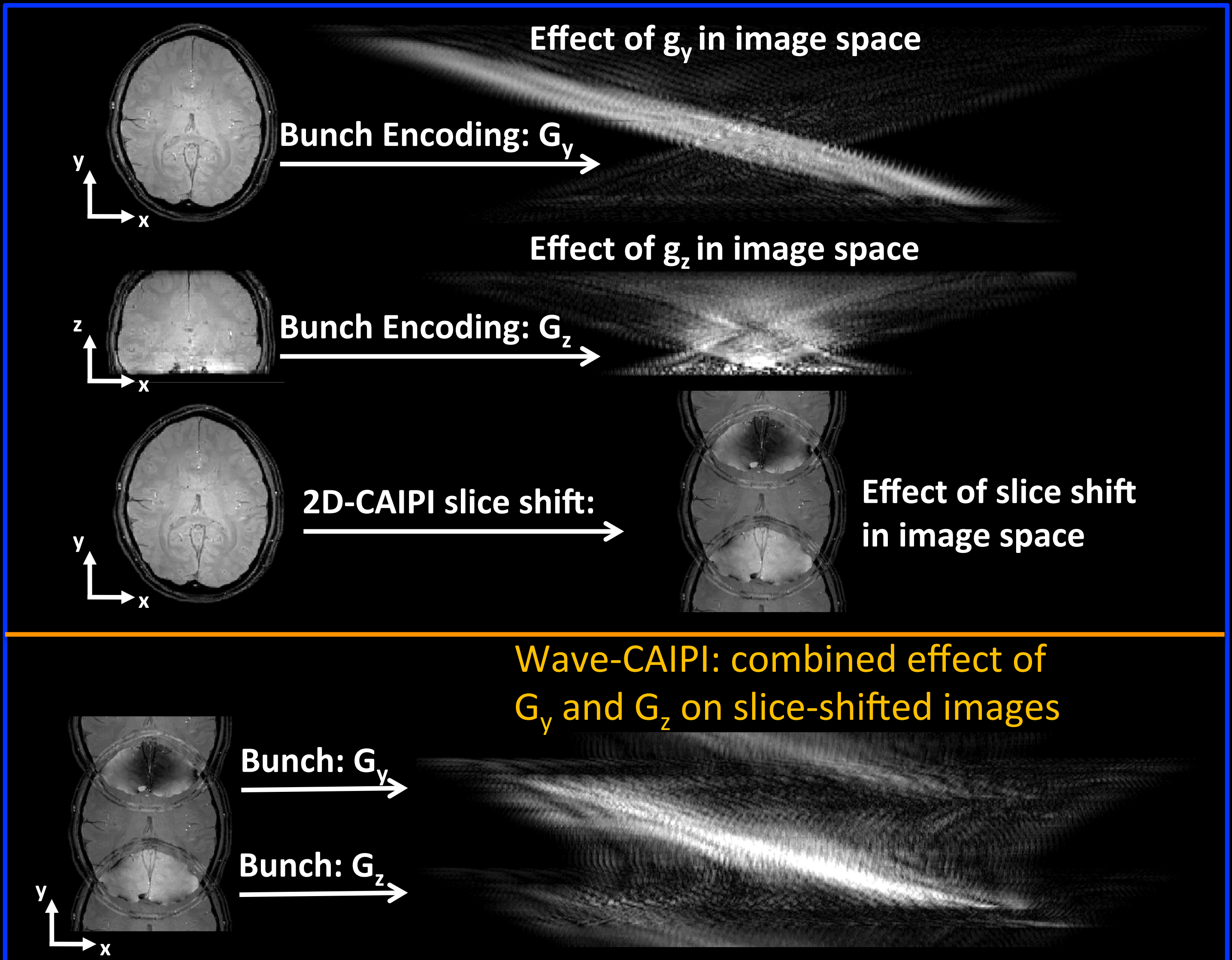

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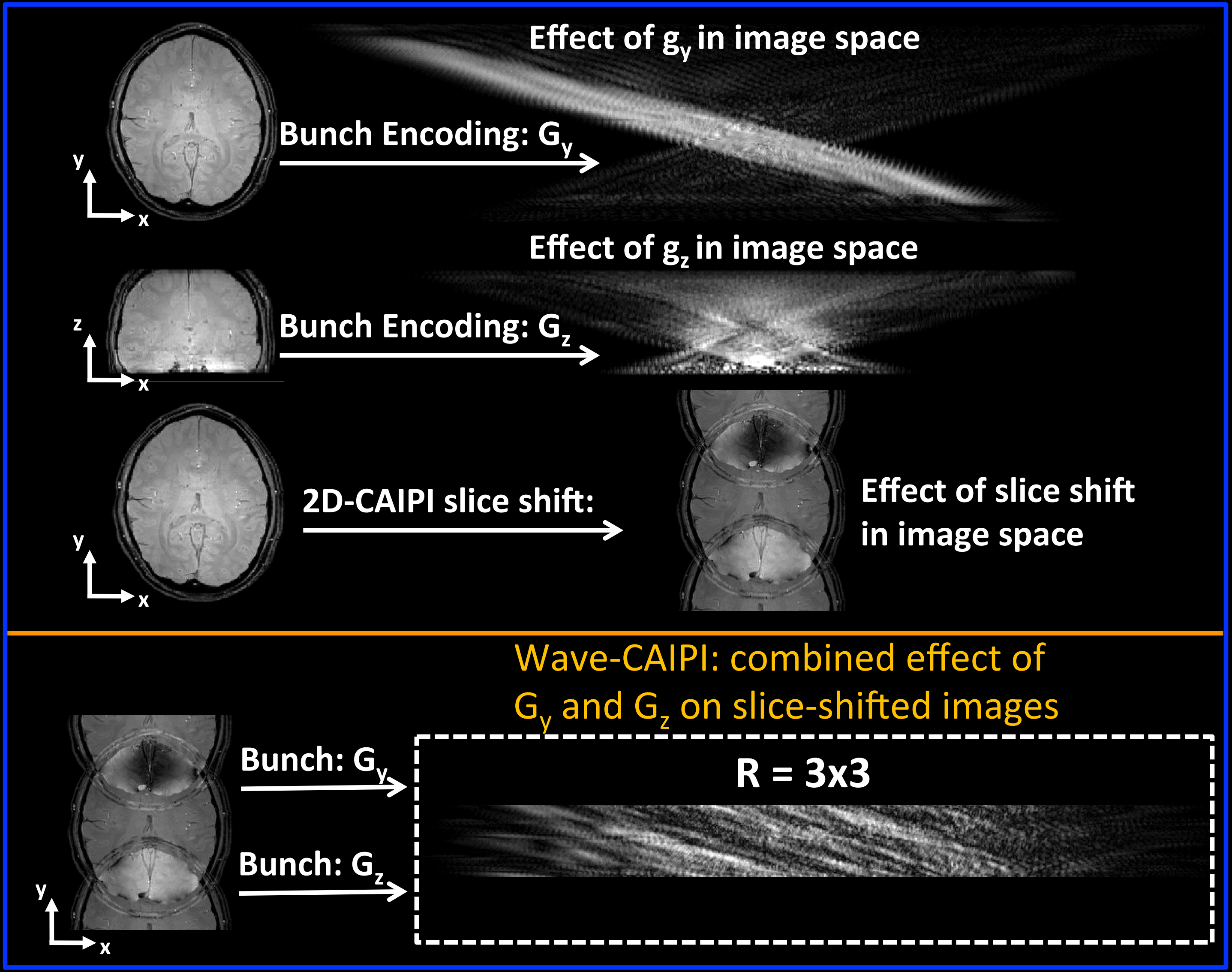
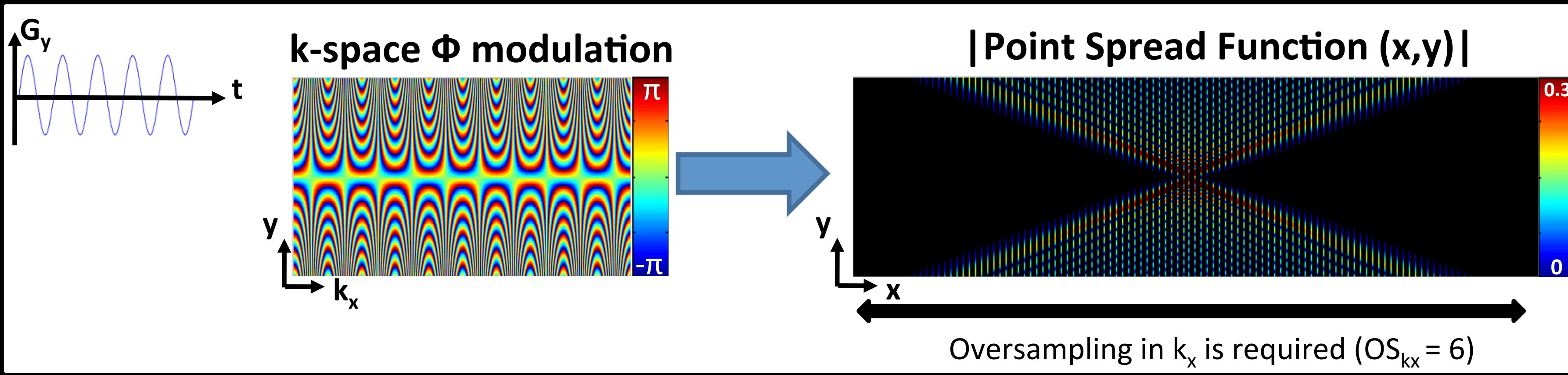
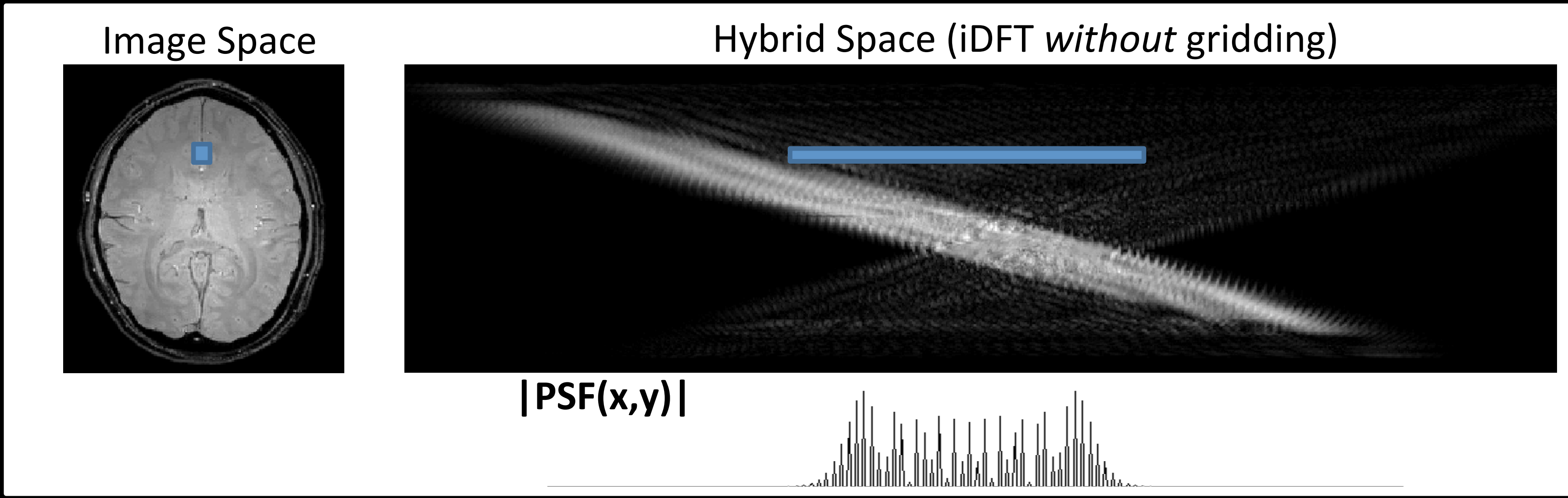


Point Spread Function

- **Wave-CAIPI = BPE G_y + BPE G_z + CAIPI 2D**
- **View BPE G_y as extra modulation rather than modifying k-space traj.**





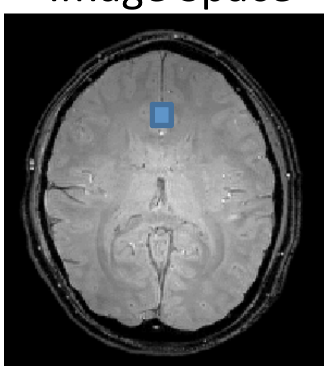
Point Spread Function

- **From signal equation:**

$$wave(x,y,z) = \sum_{k_x} e^{i2\pi x k_x/N} \cdot e^{-i2\pi W_y(k_x)y} \cdot \sum_x e^{-i2\pi x k_x/N} \cdot img(x,y,z)$$

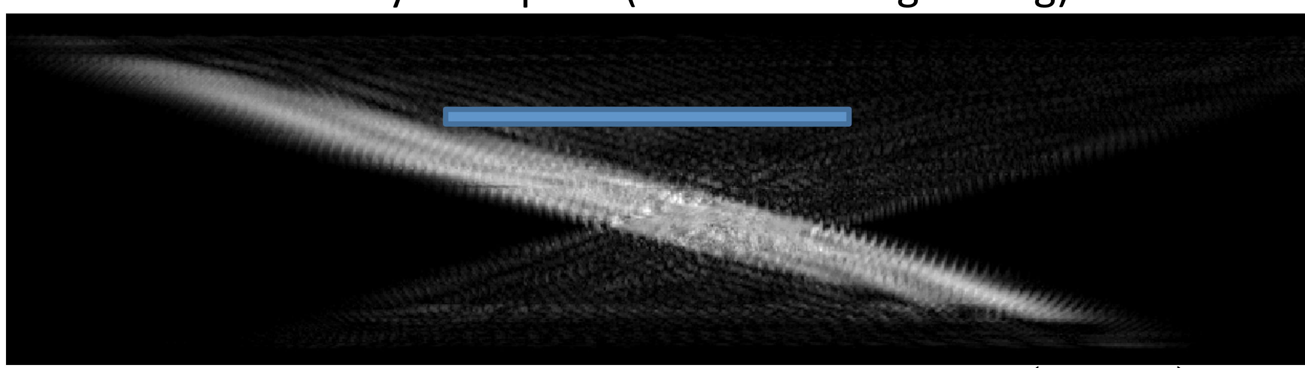
$wave(x,y,z)$	Wave image
$img(x,y,z)$	Underlying magnetization
$W_y(k_x(t)) = \frac{\gamma}{2\pi}\int_0^t G_y(\tau)\,d\tau$	k-space trajectory

Image Space



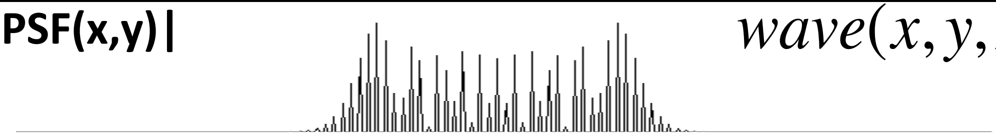
$img(x,y,z)$

Hybrid Space (iDFT *without* gridding)



$wave(x,y,z)$

|PSF(x,y)|

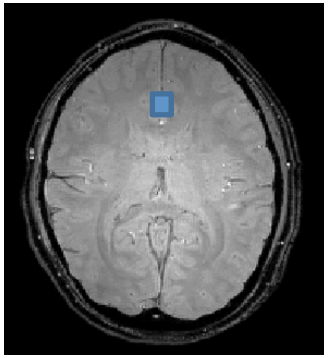


Point Spread Function

- **From signal equation:**

$$wave(x,y,z) = \underbrace{\sum_{k_x} e^{i2\pi x k_x/N}}_{\text{Inverse Discrete Fourier Transform}} \cdot e^{-i2\pi W_y(k_x)y} \cdot \underbrace{\sum_{x} e^{-i2\pi x k_x/N}}_{\text{Discrete Fourier Transform}} \cdot img(x,y,z)$$

Image Space



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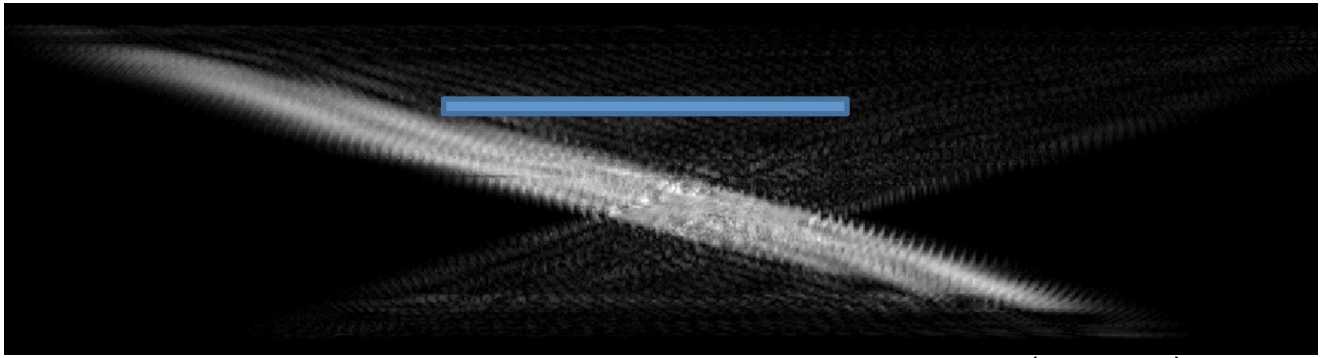

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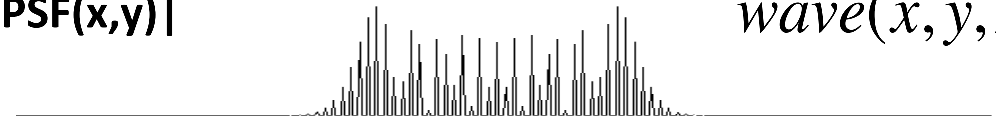


$wave(x,y,z)$

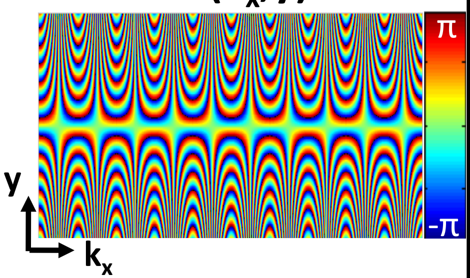
Point Spread Function

- **From signal equation:**

$$wave(x,y,z) = \mathrm{F}^{-1} \cdot \underbrace{e^{-i2\pi W_y(k_x)y}}_{\text{Point Spread Function (PSF)}} \cdot \mathrm{F} \cdot img(x,y,z)$$

No need for gridding, simple DFT

PSF(k_x,y)



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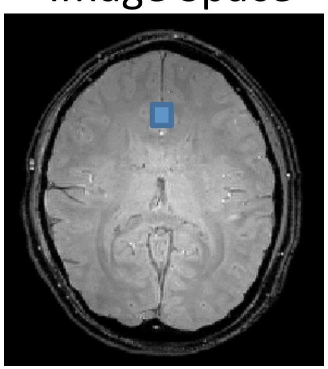

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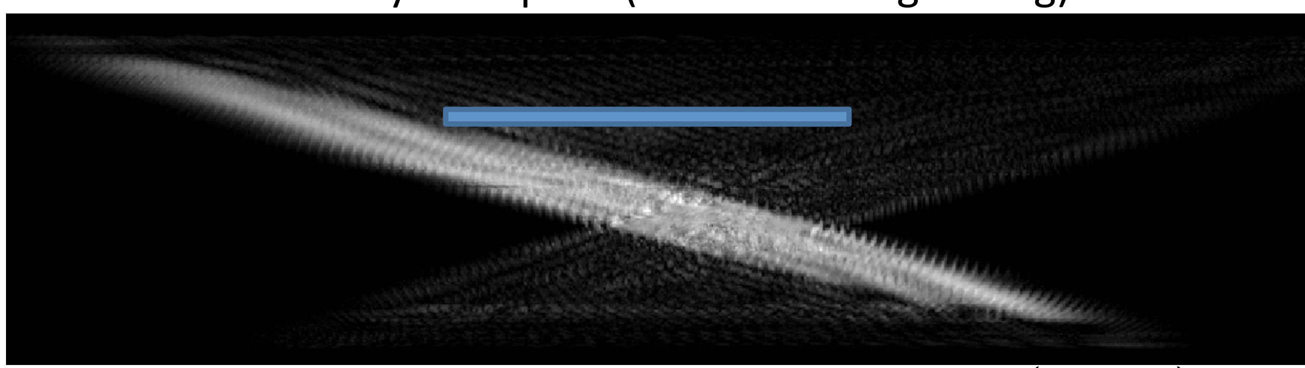

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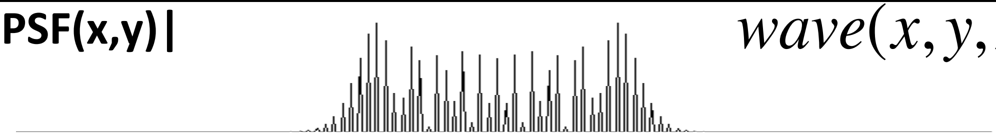
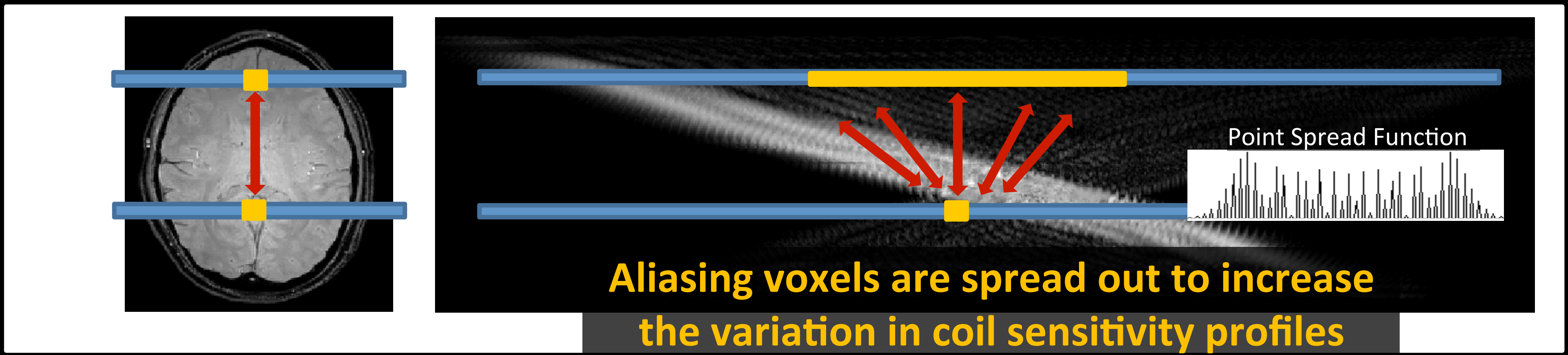


Reconstruction for accelerated acquisitions



- $R_{inplane} = 2$ => pair-wise aliasing of two rows of voxels
  => <u>small</u> Encoding matrix for each pair
  => separable and easy to solve
  => intuition on why Wave improves reconstruction

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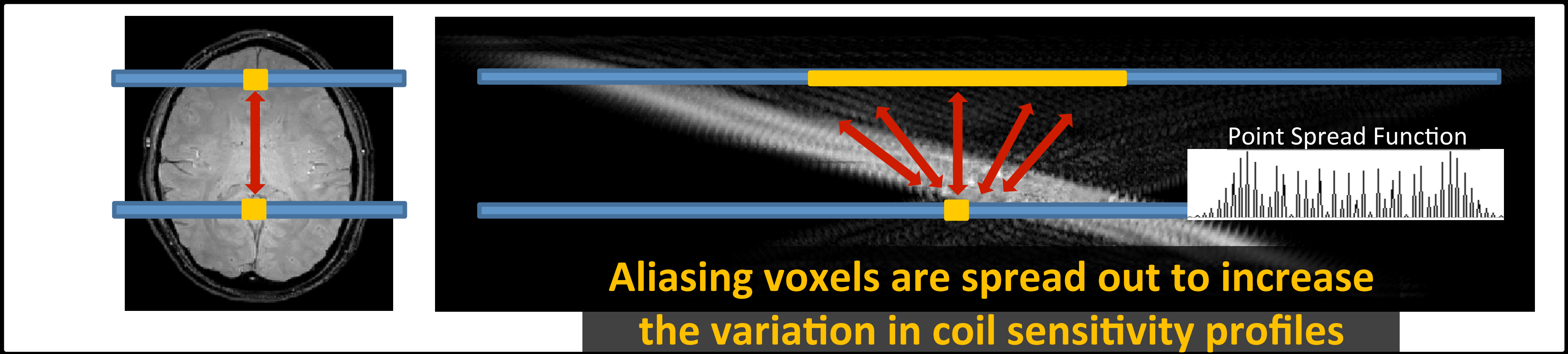

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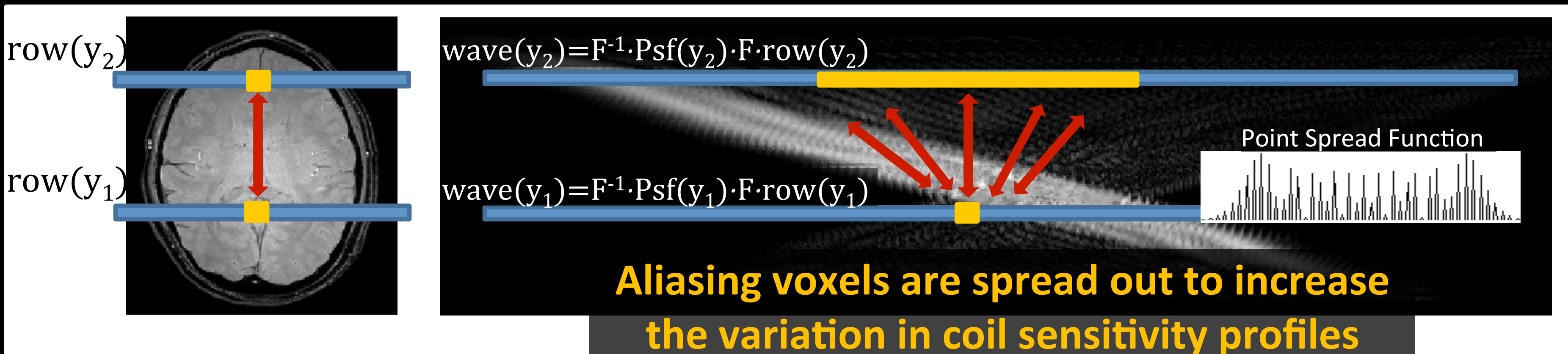

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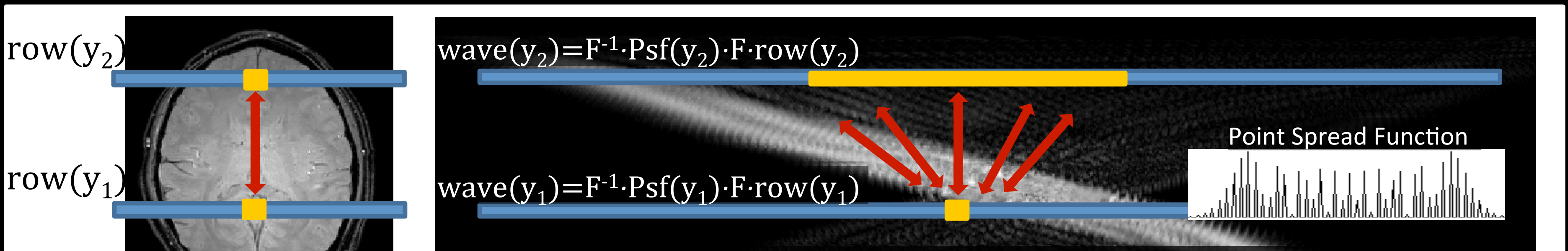
$$wave(y) = \mathrm{F}^{-1} \cdot \mathrm{Psf}(y) \cdot \mathrm{F} \cdot row(y)$$

$$\begin{bmatrix} \mathrm{F}^{-1} \cdot \mathrm{Psf}(y_1) \cdot \mathrm{F} \\ \mathrm{F}^{-1} \cdot \mathrm{Psf}(y_2) \cdot \mathrm{F} \end{bmatrix} \cdot \begin{bmatrix} row(y_1) \\ row(y_2) \end{bmatrix} = \left[wave(y_1) + wave(y_2) \right]$$

Reconstruction for accelerated acquisitions



Aliasing voxels are spread out to increase the variation in coil sensitivity profiles

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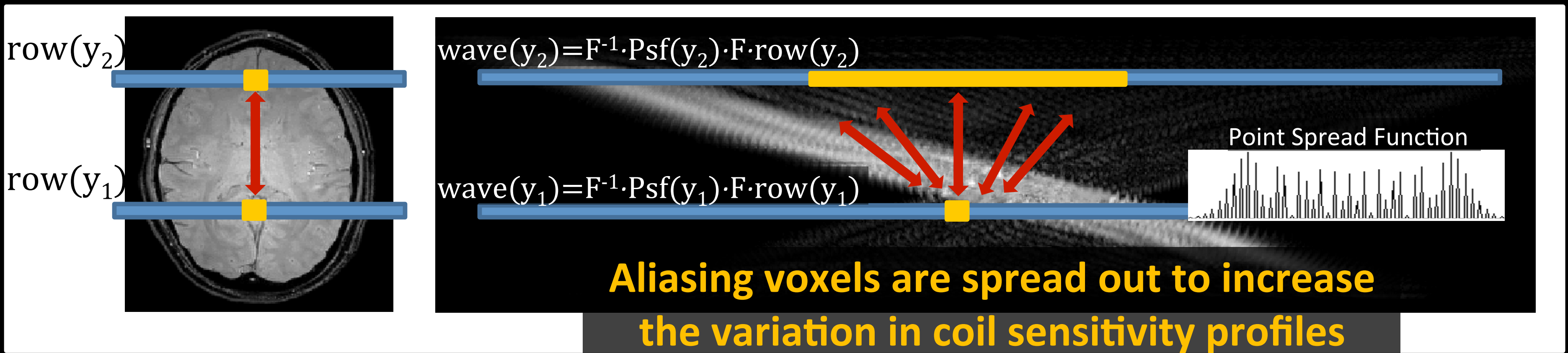

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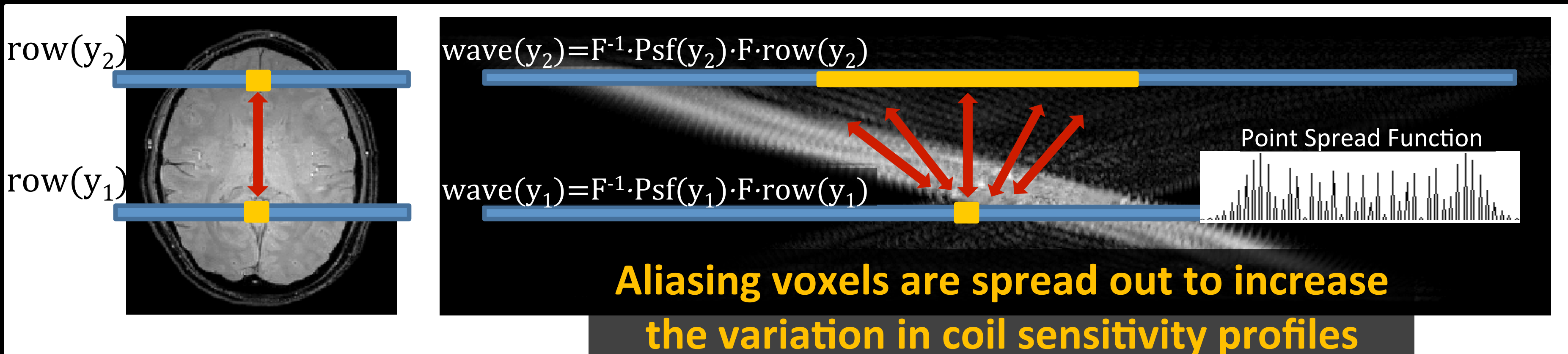
Reconstruction for accelerated acquisitions



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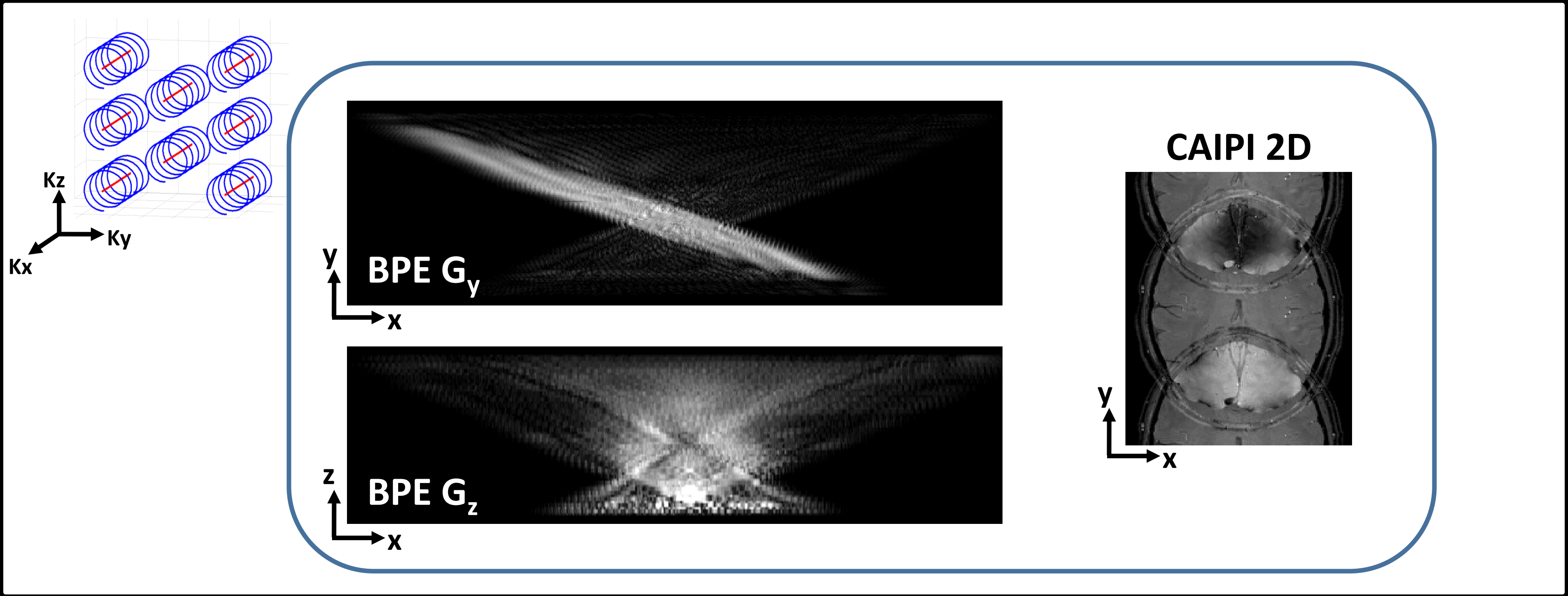
- Solve for each set of collapsed rows iteratively using LSQR

Wave-CAIPI reconstruction



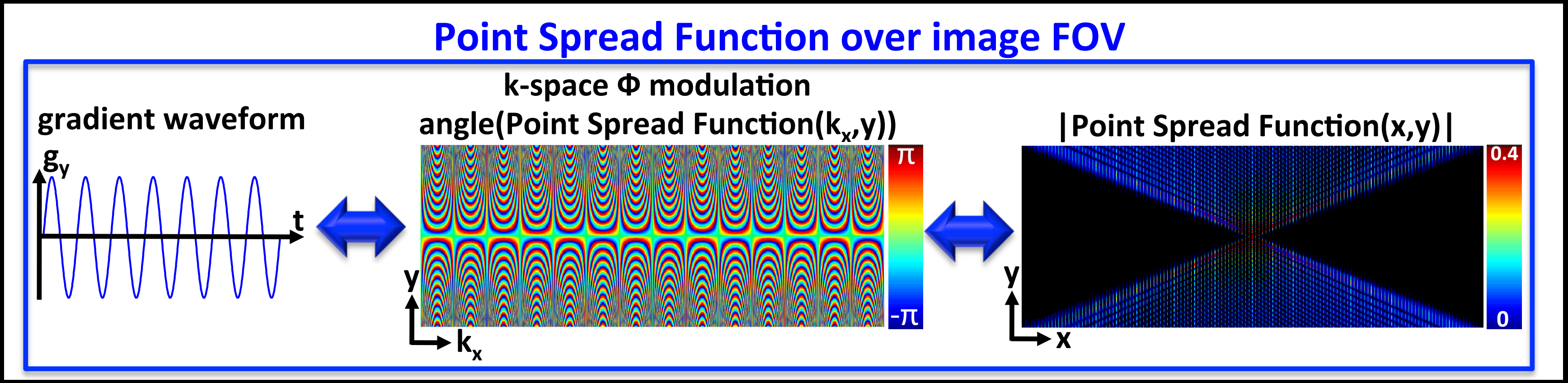
⇒ Wave gradients G_y and G_z create position dependent PSF

⇒ CAIPI 2D shift aliasing pattern

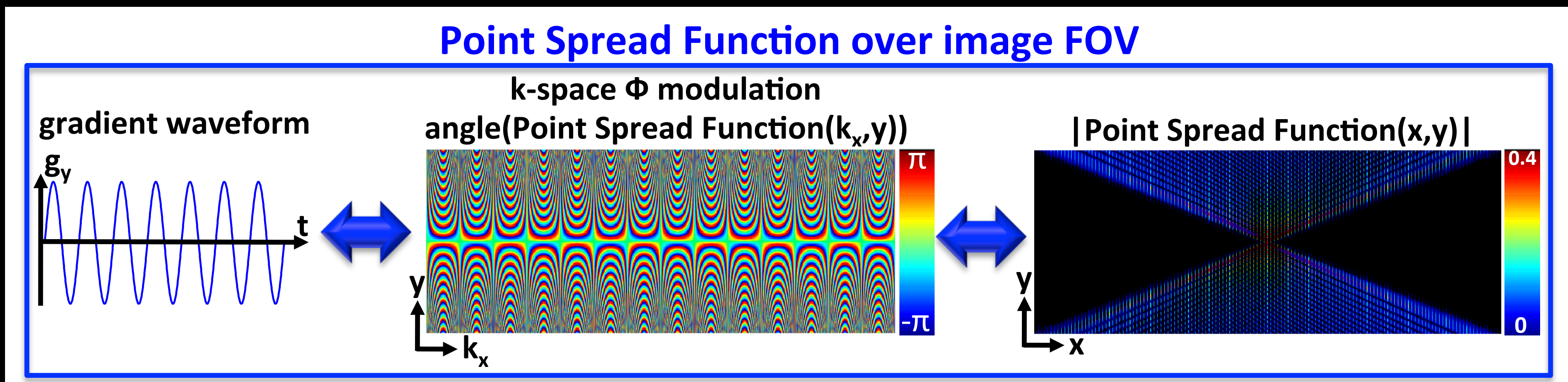
⇒ These are accounted for when generating the PSF-based Encoding matrices

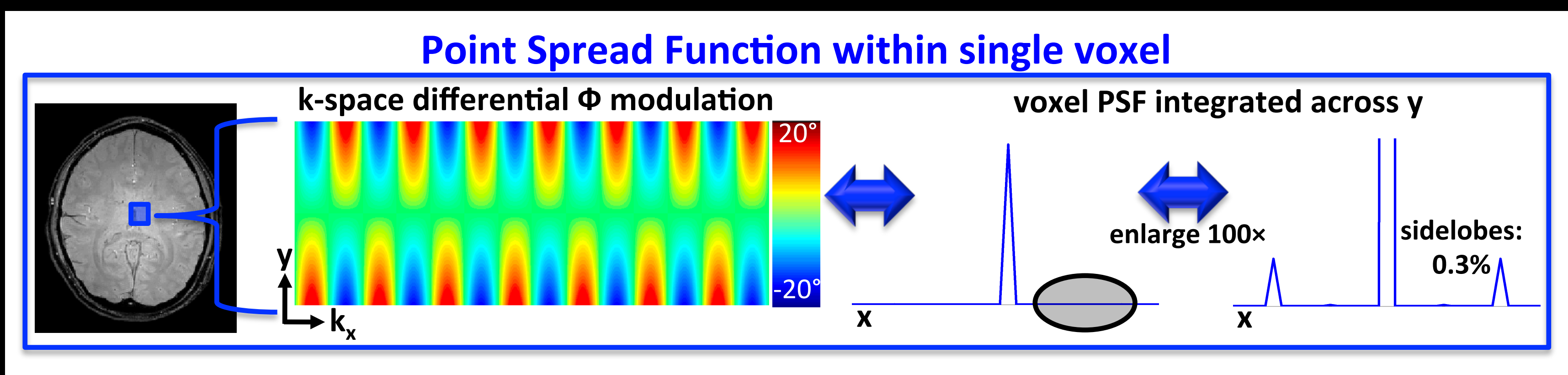
- ⇒ Ex: R = 3x3
  - ⇒ each Encoding matrix corresponds to 9 rows of the image
  - ⇒ grouping of rows is determined by CAIPI 2D
  - ⇒ amount of spreading in each row determined by G_y and G_z

Artifact Quantification



Artifact Quantification





In Vivo Acquisition Comparison

- Compare Wave-CAIPI and conventional SENSE
- Acquire **fully-sampled** data, then accelerate by R = 3x3
- Compute root-mean-square error (RMSE) and 1/g-factor maps (retained SNR)

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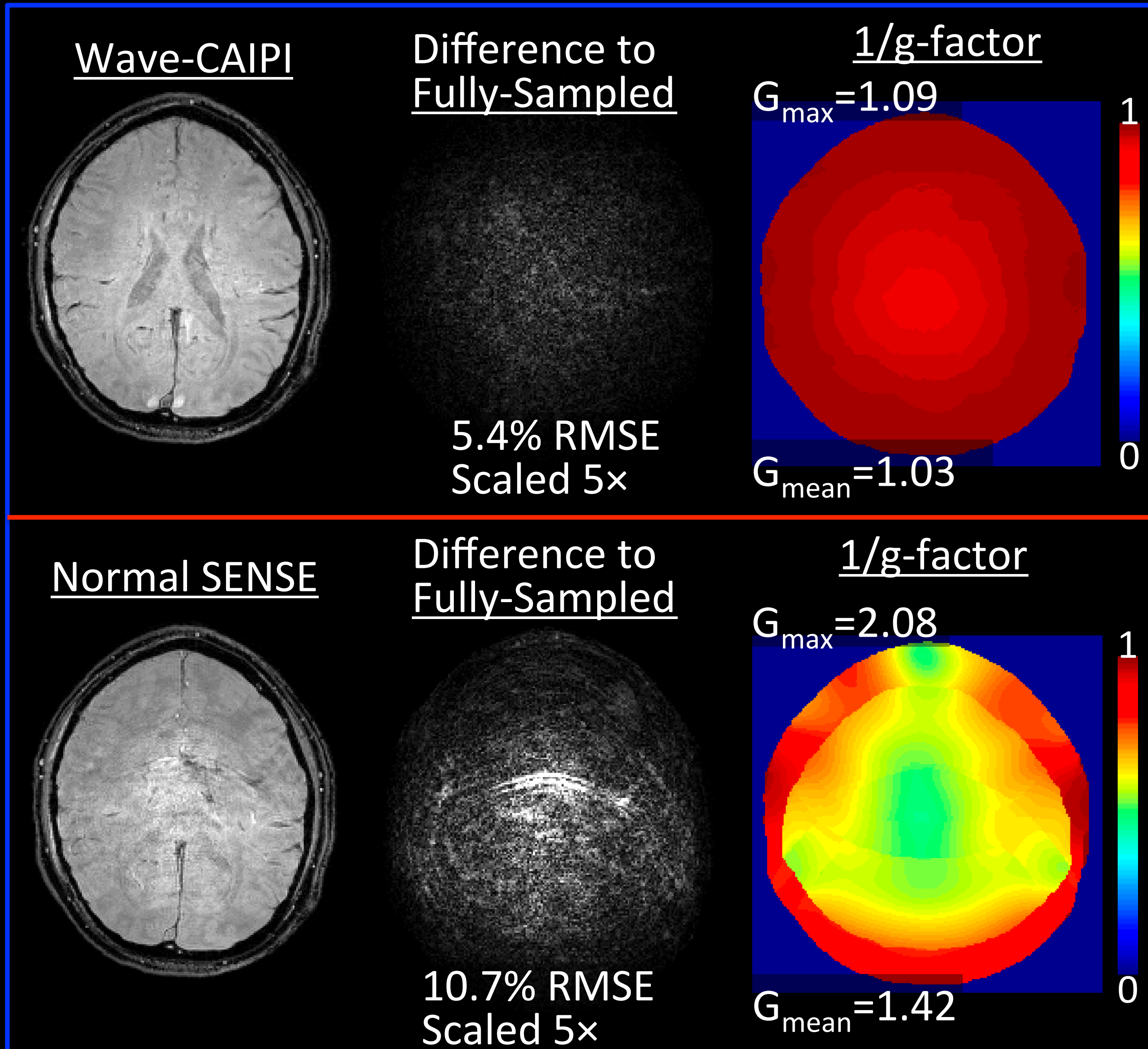
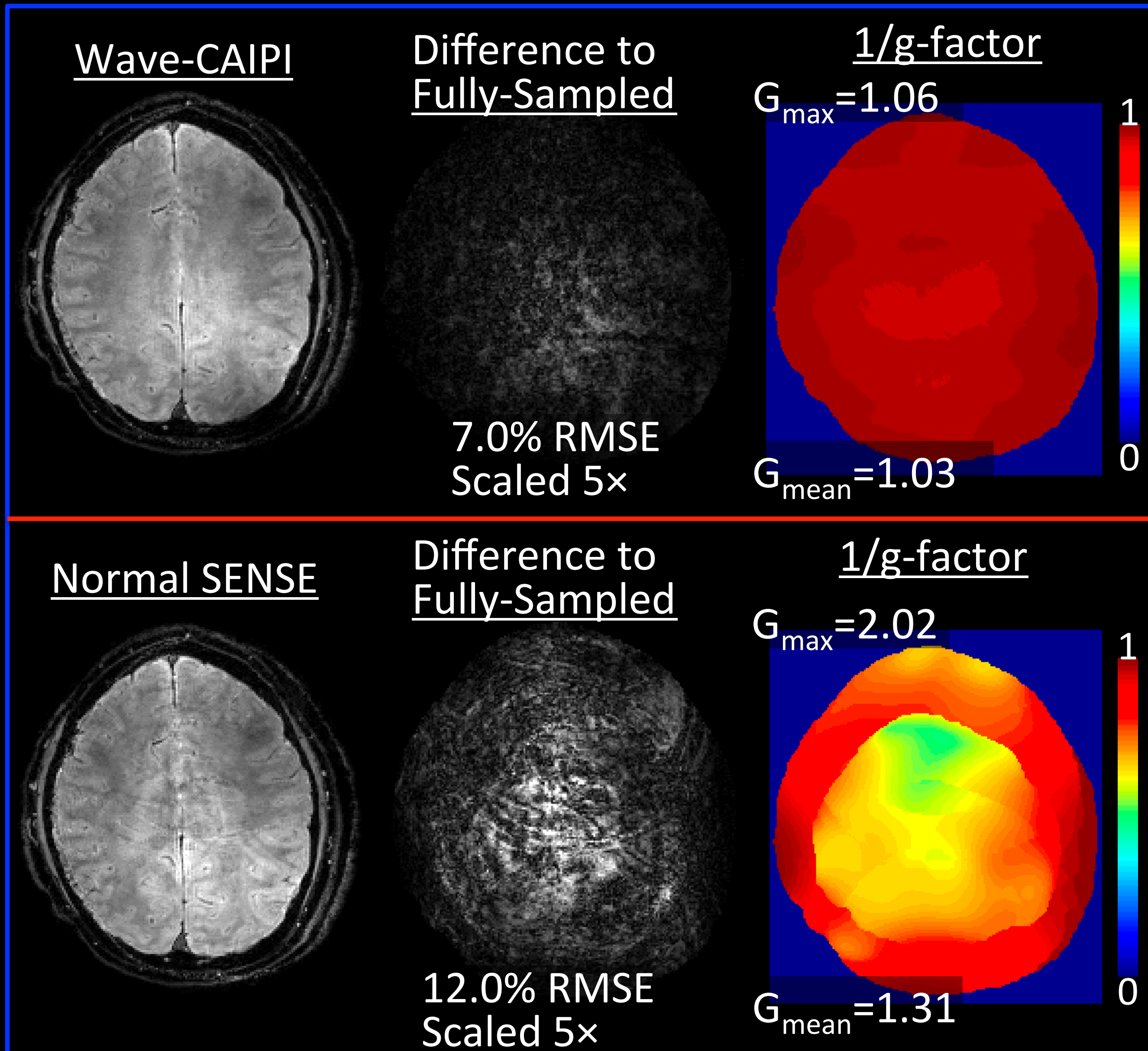
- Acquire **fully-sampled** data, then accelerate by R = 3x3
- Compute root-mean-square error (RMSE) and 1/g-factor maps (retained SNR)
- In vivo acquisitions:
  - At 3T and 7T
  - 1x1x2 mm resolution
  - 224x224x120 FOV

3 Tesla, R=3x3, 1x1x2 mm^3, T_{acq}=38s



TR/TE = 26/13.3 ms

7 Tesla, R=3x3, 1x1x2 mm^3, T_{acq}=40s



TR/TE = 27/10.9 ms

Accelerated Acquisition Comparison

- Compare Wave-CAIPI, 2D-CAIPI[1] and Bunch Phase[2]
- Acquire R = 3x3 accelerated data
- Compute 1/g-factor maps (retained SNR)

1. Breuer FA. et al, MRM 2006:55:549   2. Moriguchi H et al, MRM 2006:55:633

Accelerated Acquisition Comparison

- Compare Wave-CAIPI, 2D-CAIPI[1] and Bunch Phase[2]
- Acquire R = 3x3 accelerated data
- Compute 1/g-factor maps (retained SNR)
- In vivo acquisitions:
  - At 3T and 7T
  - 1x1x1 mm isotropic resolution
  - Acquisition time: 2.3 min
  - 240x240x120 FOV

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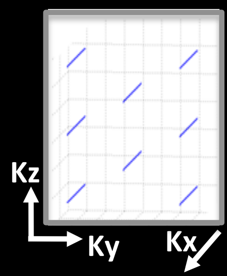
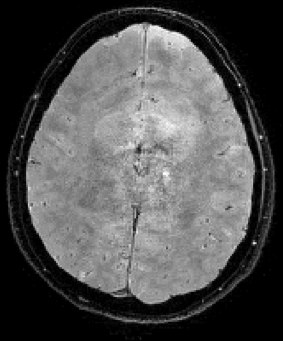
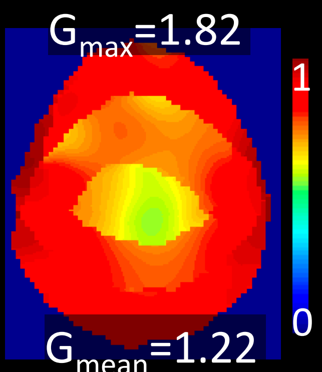
R=3x3 @ 3 Tesla, 1 mm iso, T_{acq}=2.3min

k-space **Recon** **1/G-factor**

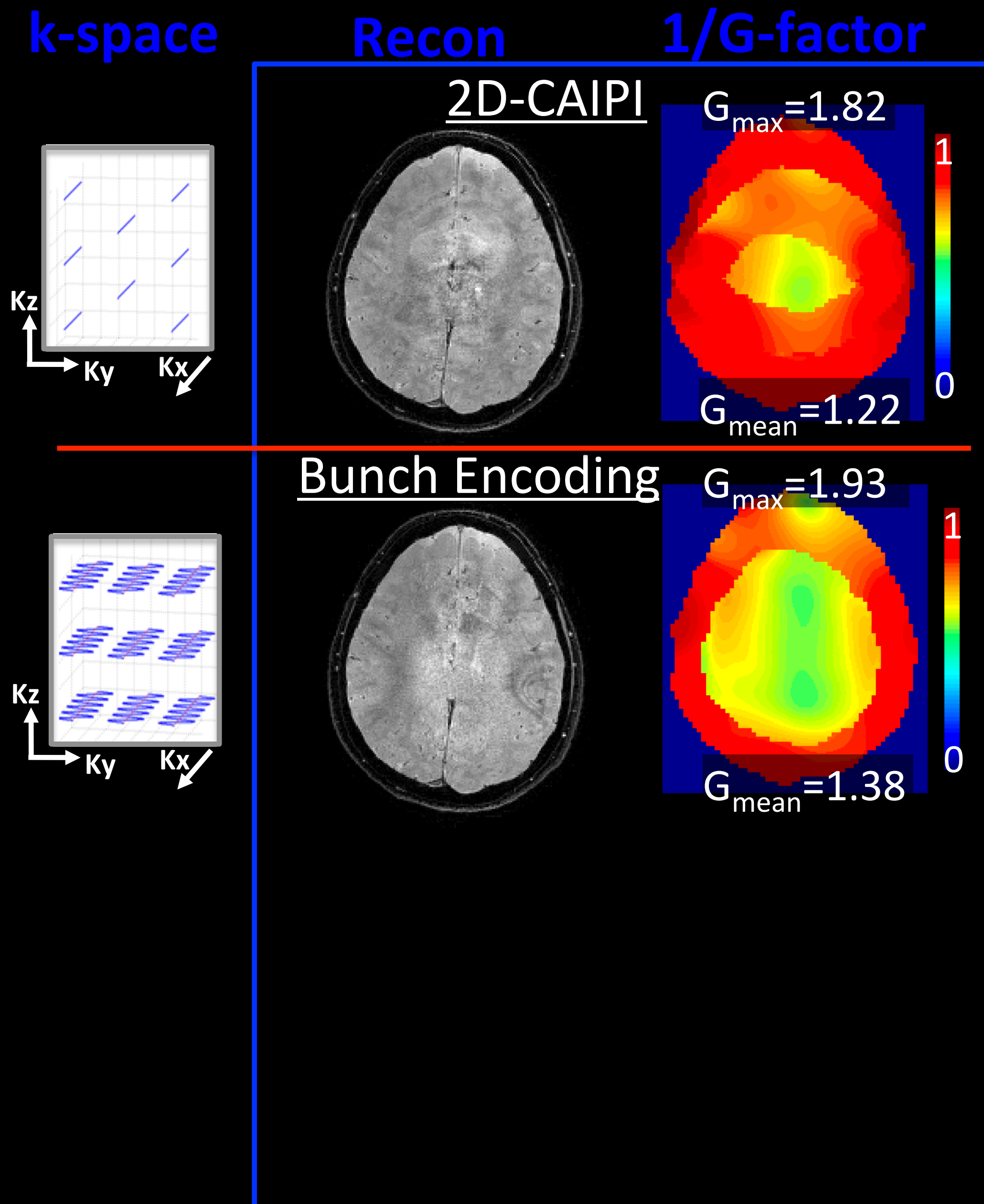


2D-CAIPI





R=3x3 @ 3 Tesla, 1 mm iso, T_{acq}=2.3min



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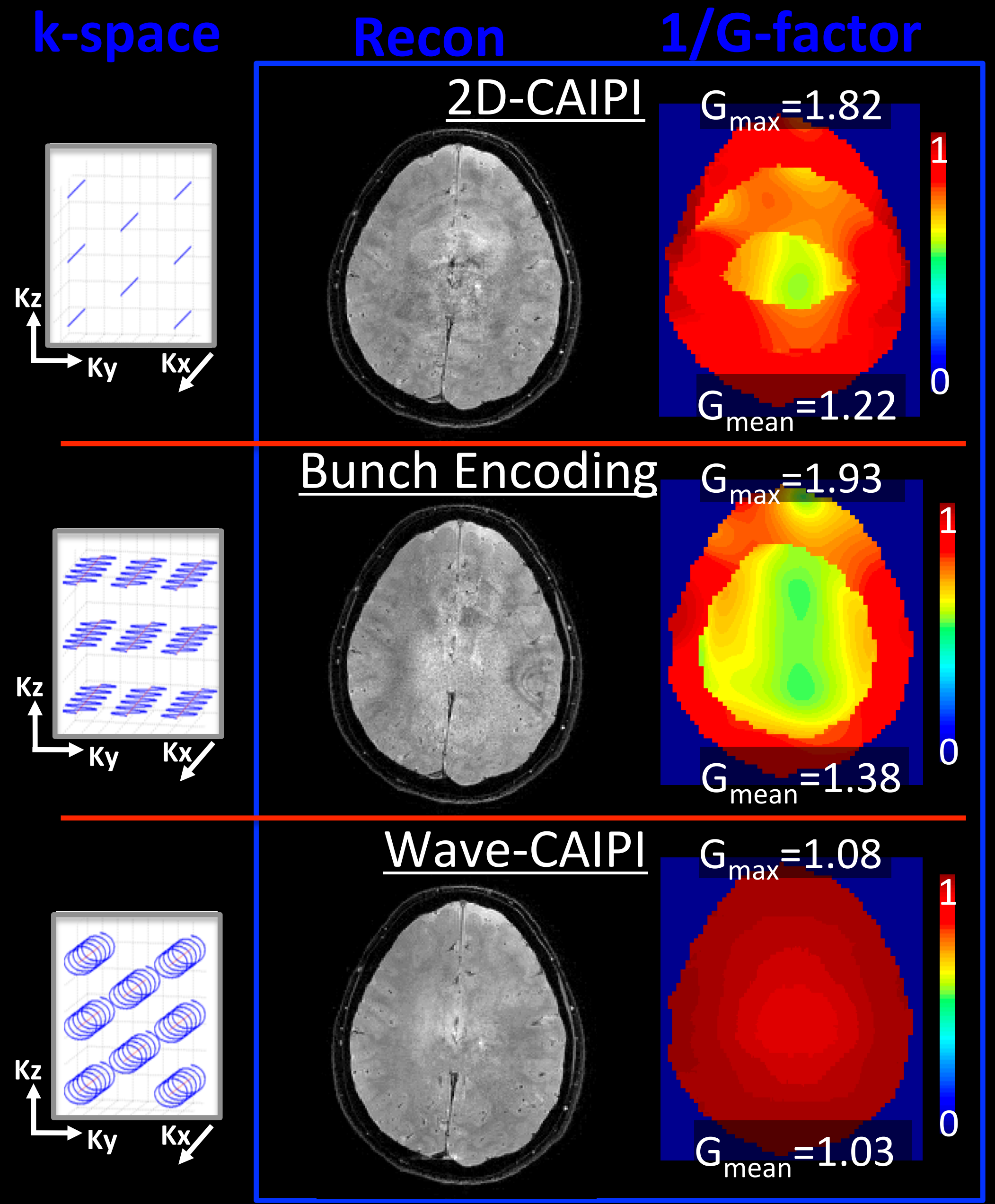
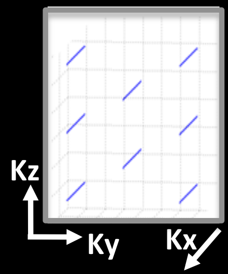
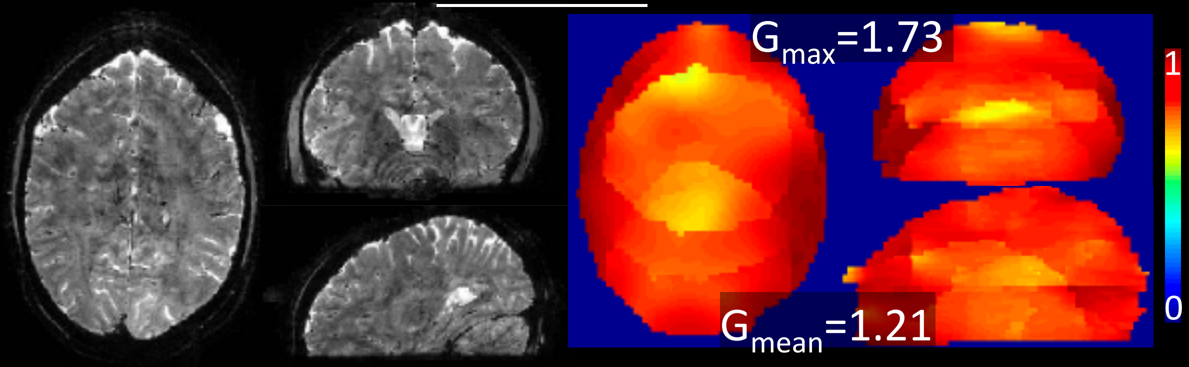


R=3x3 @ 7 Tesla, 1 mm iso, T_{acq}=2.3min

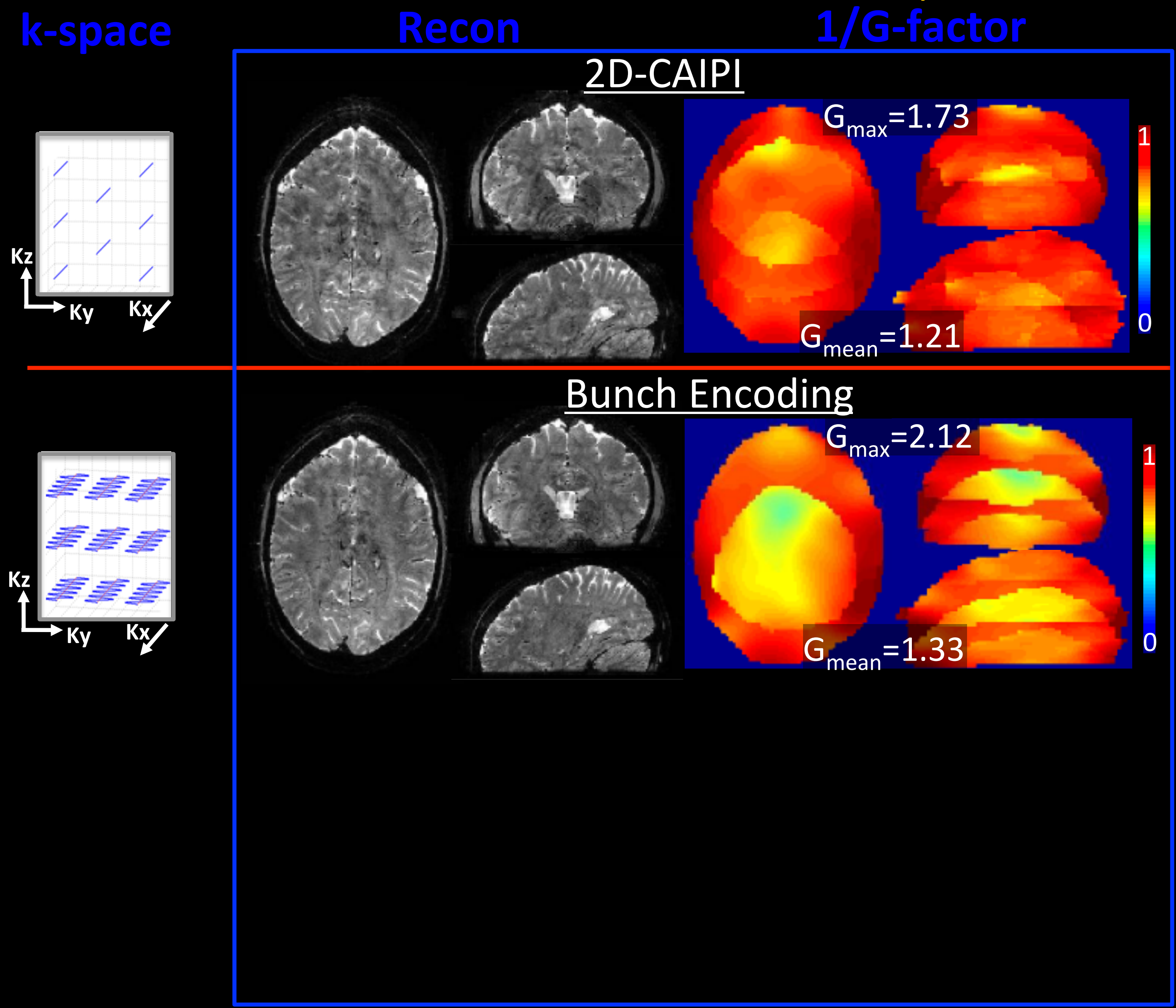
k-space **Recon** **1/G-factor**



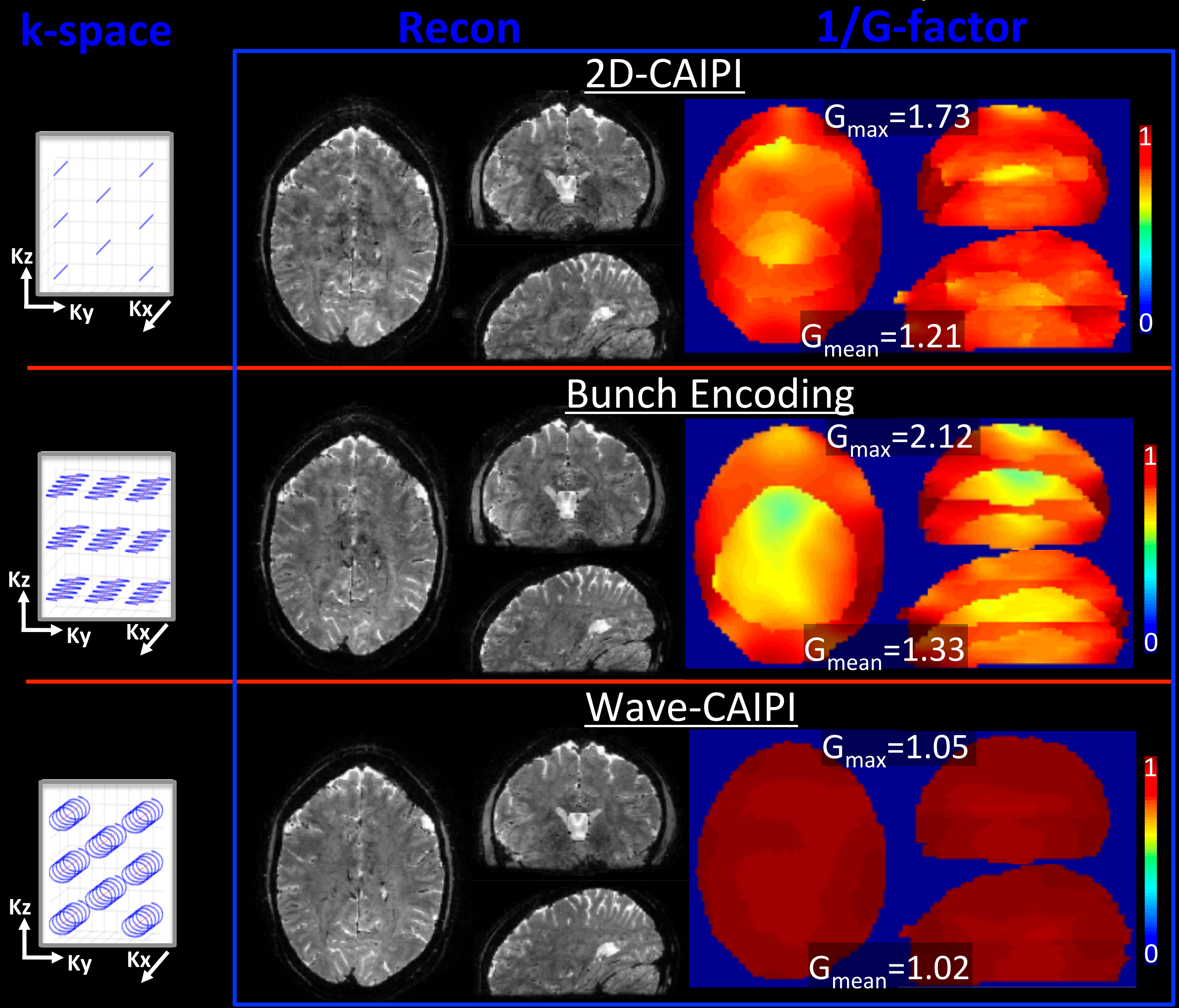
2D-CAIPI



R=3x3 @ 7 Tesla, 1 mm iso, T_{acq}=2.3min



R=3x3 @ 7 Tesla, 1 mm iso, T_{acq}=2.3min



Quantitative Susceptibility Mapping (QSM)

- QSM estimates the underlying magnetic susceptibility that gives rise to subtle changes in the magnetic field

- Estimation of the susceptibility map $\boldsymbol{\chi}$ from the unwrapped phase $\boldsymbol{\varphi}$ involves solving an inverse problem[1],

$$\underbrace{\boldsymbol{\delta}}_{\text{measured}} = \mathbf{F}^{-1}\,\mathbf{D}\,\mathbf{F}\,\underbrace{\boldsymbol{\chi}}_{\text{estimate}}$$

F: Discrete Fourier Transform

D: susceptibility kernel

$\boldsymbol{\delta} = \boldsymbol{\varphi}/(\gamma \bullet TE \bullet B_0)$: normalized field map

[1] Marques JP *et al*., Concepts in Magn Res 2005

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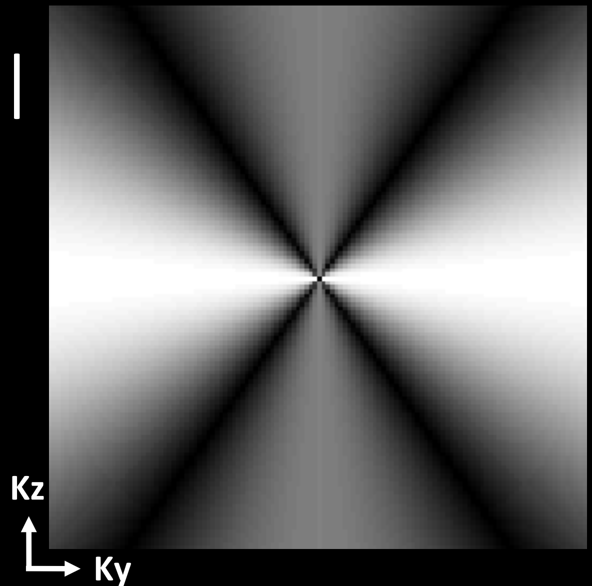
$$\boldsymbol{\delta = F^{-1}\, D\, F\, \chi}$$

- The inversion is made difficult by zeros in susceptibility kernel **D**

$$\mathrm{D} = \frac{1}{3} - \frac{k_z^2}{k_x^2 + k_y^2 + k_z^2}$$

|D|



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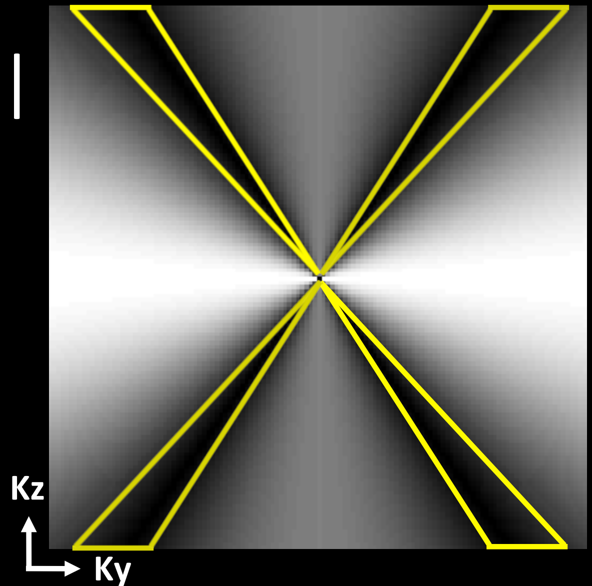
- Undersampling is due to physics

  Not in our control

|D|



Regularized Susceptibility Inversion

- Use prior knowledge to estimate susceptibility map in the presence of undersampling
- **Prior:** Susceptibility is tied to the magnetic properties of the underlying tissue; hence it should vary smoothly within anatomical boundaries.
- Employ regularization that encourages smoothness within tissues, but avoids smoothing across boundaries.

L2 Regularized Susceptibility Inversion

- We solve for the susceptibility distribution with a convex program,

$$\min \underbrace{\left\| F^{-1} D F \chi - \delta \right\|_2^2}_{\text{Data consistency}} + \lambda \cdot \underbrace{\left\| M G \chi \right\|_2^2}_{\text{Regularizer}}$$

[1] Bilgic B, MRM 2013

L2 Regularized Susceptibility Inversion

- We solve for the susceptibility distribution with a convex program,

$$\min \left\| \mathrm{F}^{-1}\mathrm{D}\mathrm{F}\,\chi - \delta \right\|_2^2 + \lambda \cdot \left\| \mathrm{M}\mathrm{G}\,\chi \right\|_2^2$$

G : Spatial gradient operator in 3D

M : Binary mask derived from magnitude image, prevents smoothing across edges

λ : Determines the amount of smoothness

[1] Bilgic B, MRM 2013

L2 Regularized Susceptibility Inversion

- We solve for the susceptibility distribution with a convex program,

$$\min \left\| \mathrm{F}^{-1}\mathrm{DF}\,\chi - \delta \right\|_2^2 + \lambda \cdot \left\| \mathrm{MG}\,\chi \right\|_2^2$$

Optimizer given by the solution of:

$$(\mathrm{F}^{-1}\mathrm{D}^2\mathrm{F} + \lambda \cdot \mathrm{G}^T\mathrm{MG})\,\chi = \mathrm{F}^{-1}\mathrm{D}^T\mathrm{F}\,\delta$$

Large linear system, solve rapidly with Preconditioned Conjugate Gradient[1]

[1] Bilgic B, MRM 2013

Wave-CAIPI accelerated QSM

- Susceptibility mapping relies on phase signal from a 3D Gradient Echo (GRE) acquisition
- Long echo times (TE≈30ms) are required for phase evolution to improve SNR
- This constraint on repetition time (TR) further increases QSM data acquisition time:

Whole-brain 3D GRE at 1mm^3 resolution:

$$\left.\begin{array}{l}\text{240x240x120 FOV}\\ \text{TR = 40 ms}\end{array}\right\} \mathbf{T_{acq} = 19\ min\ if\ fully\text{-}sampled}$$

Wave-CAIPI allows rapid QSM acquisition:

$$\mathbf{T_{acq} = 2.3\ min\ at\ R=3\times 3}$$

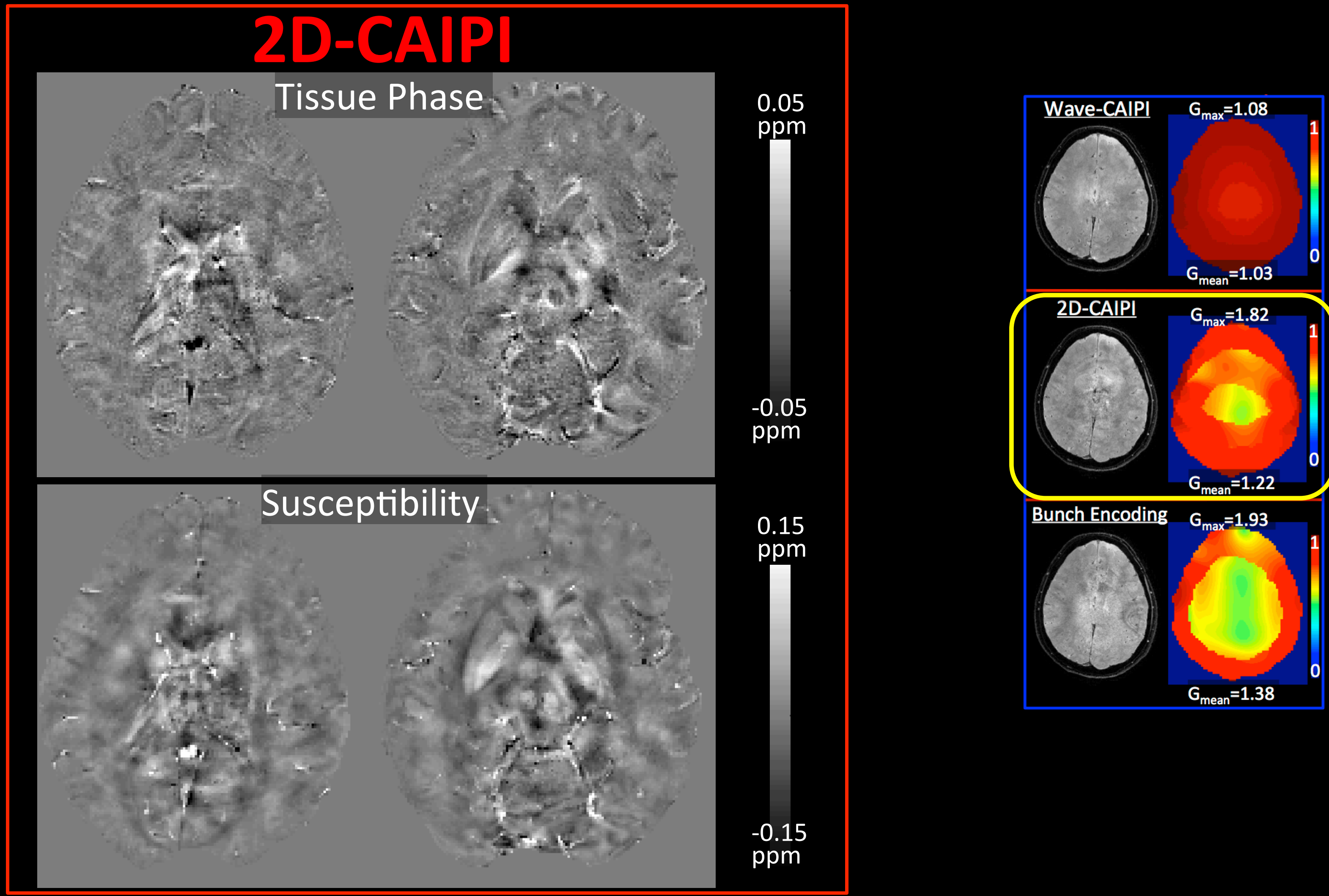
Wave-CAIPI accelerated QSM

- Compare in vivo phase and QSM from Wave-CAIPI, 2D-CAIPI and Bunch Phase Encoding:
  - At 3T and 7T
  - R = 3x3 acceleration, scan time = 2.3 min
  - 1 mm isotropic resolution
- Phase Processing:
  - Laplacian unwrapping[1] and
  - SHARP filtering for background removal[2]

  14 seconds
- Susceptibility Inversion:
  - Fast L2-regularized inversion[3]

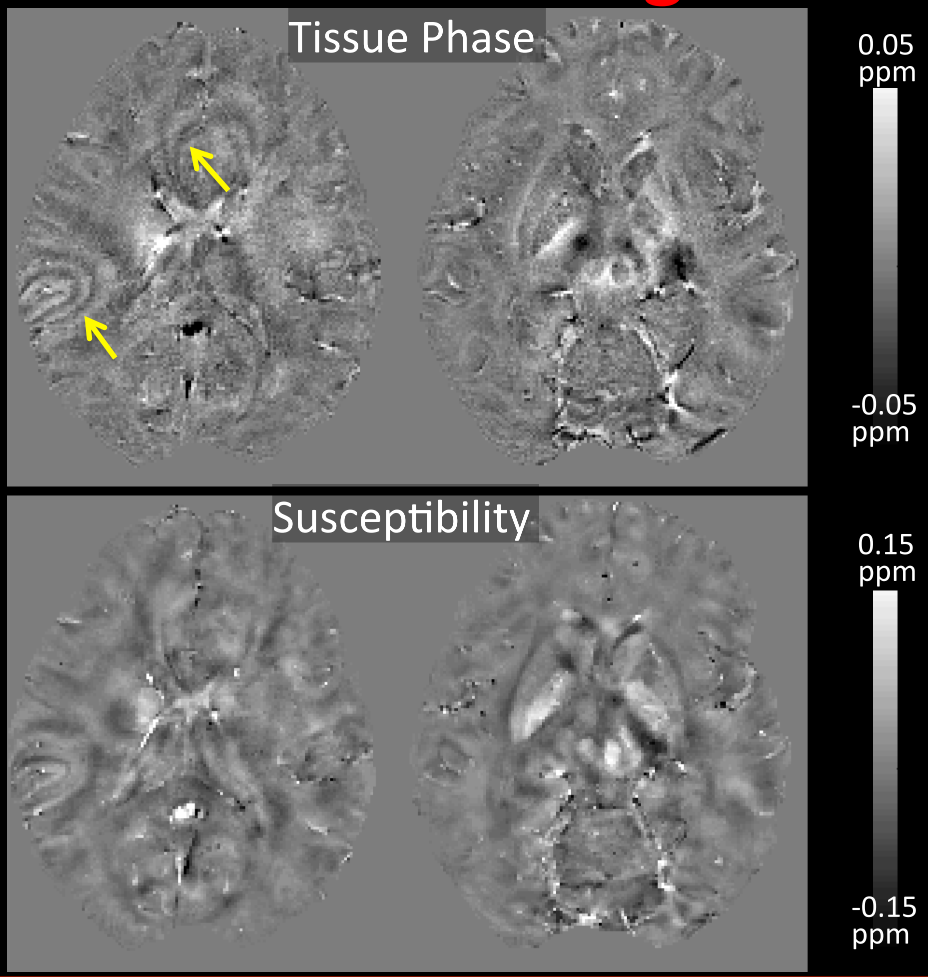
  32 seconds

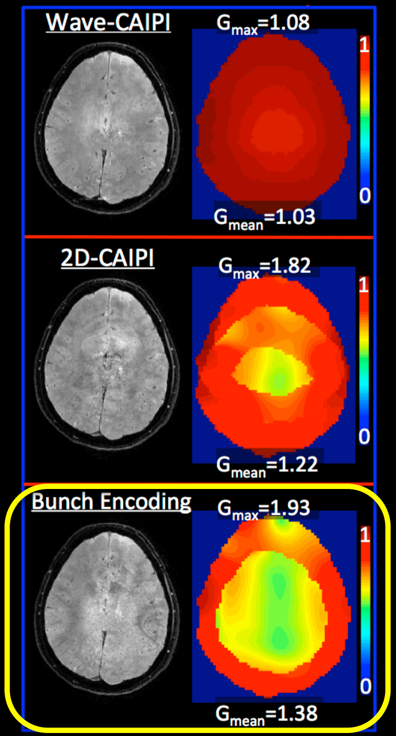
3 Tesla, R=3x3, 1 mm iso, 2.3 min acq



3 Tesla, R=3x3, 1 mm iso, 2.3 min acq

Bunch Encoding





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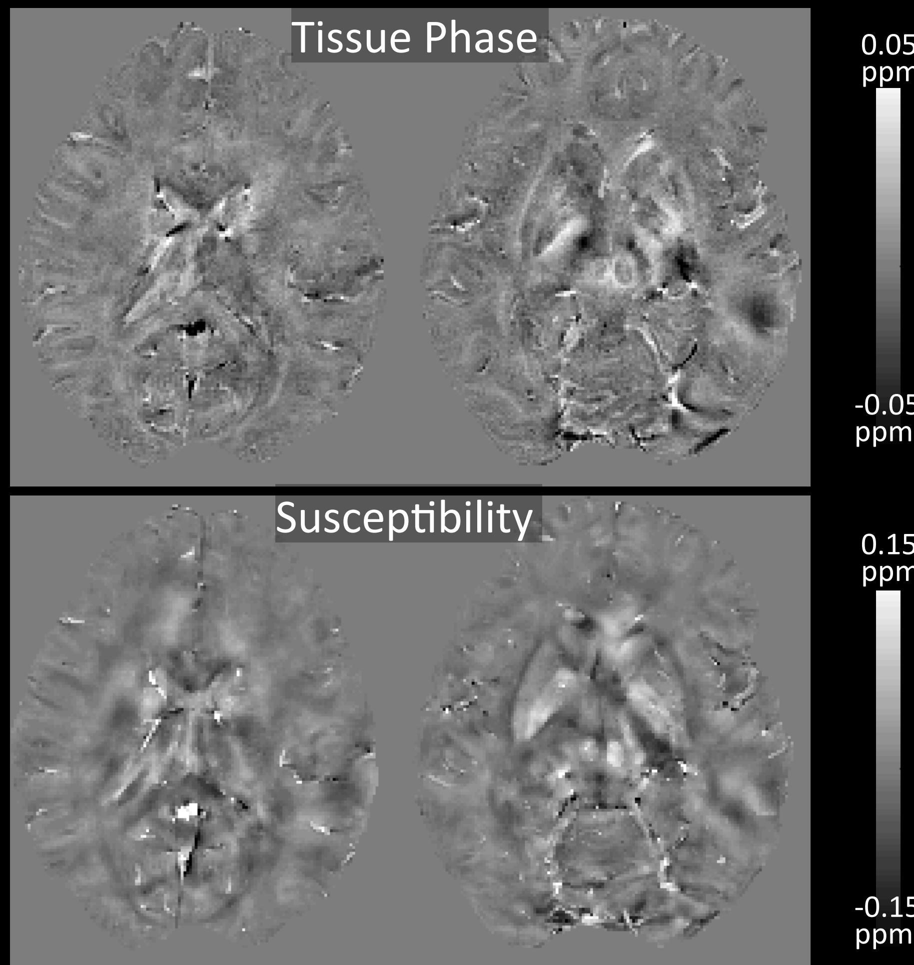
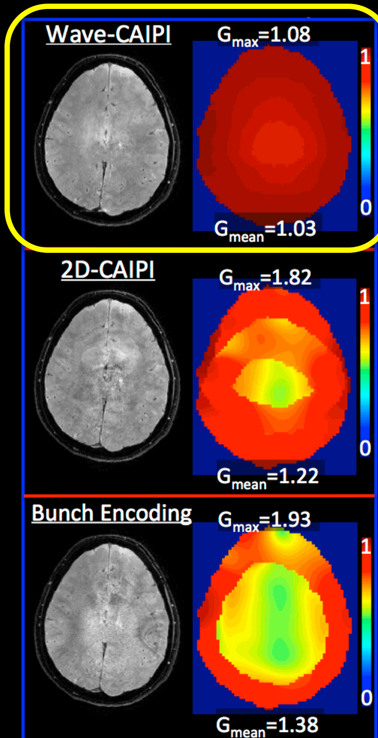
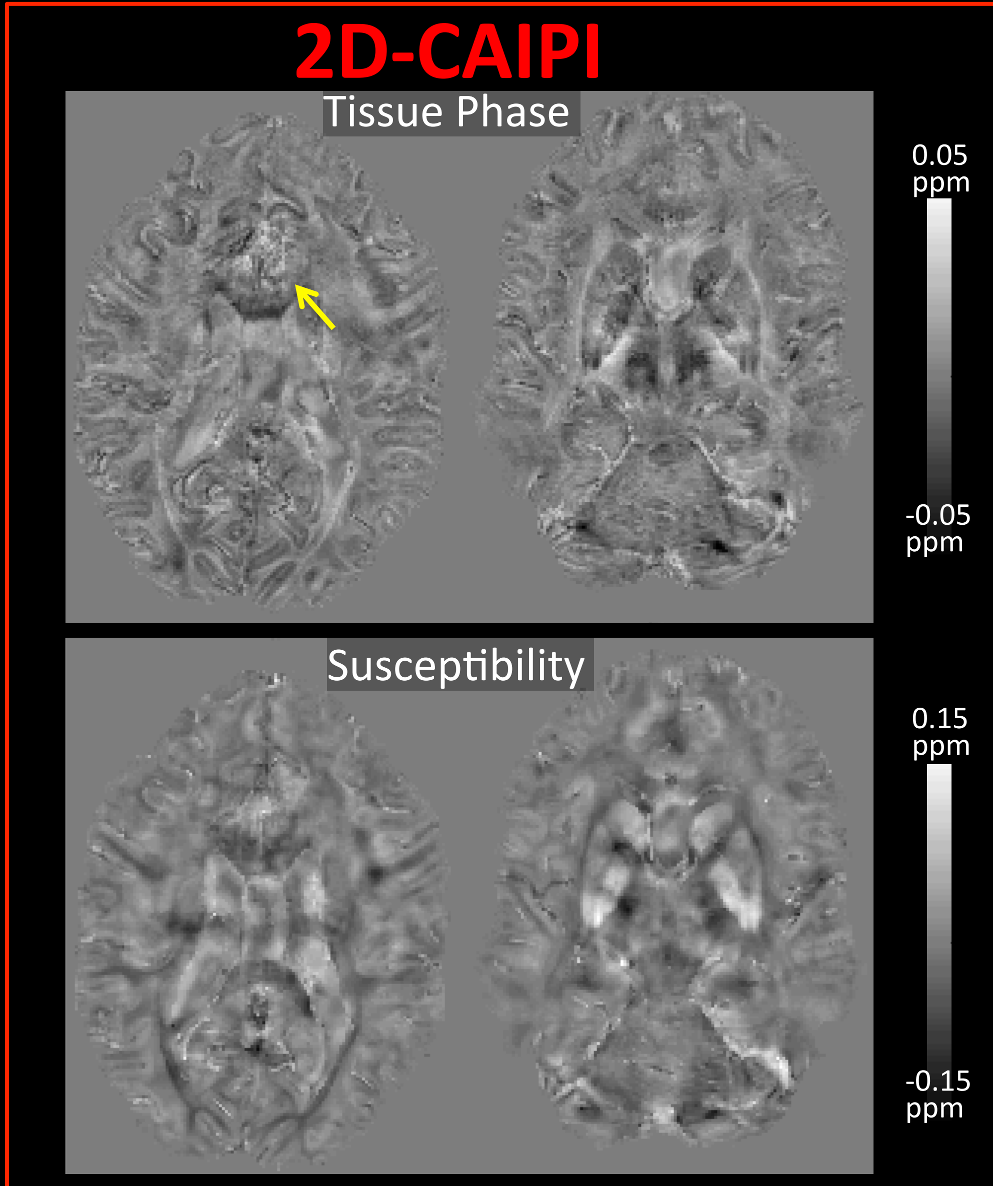
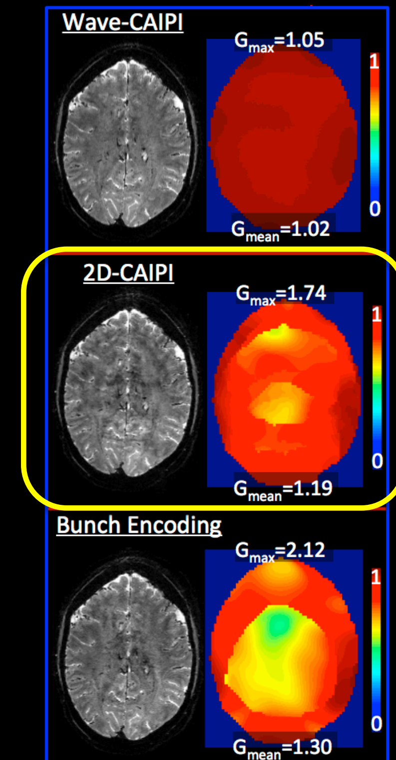
Wave-CAIPI



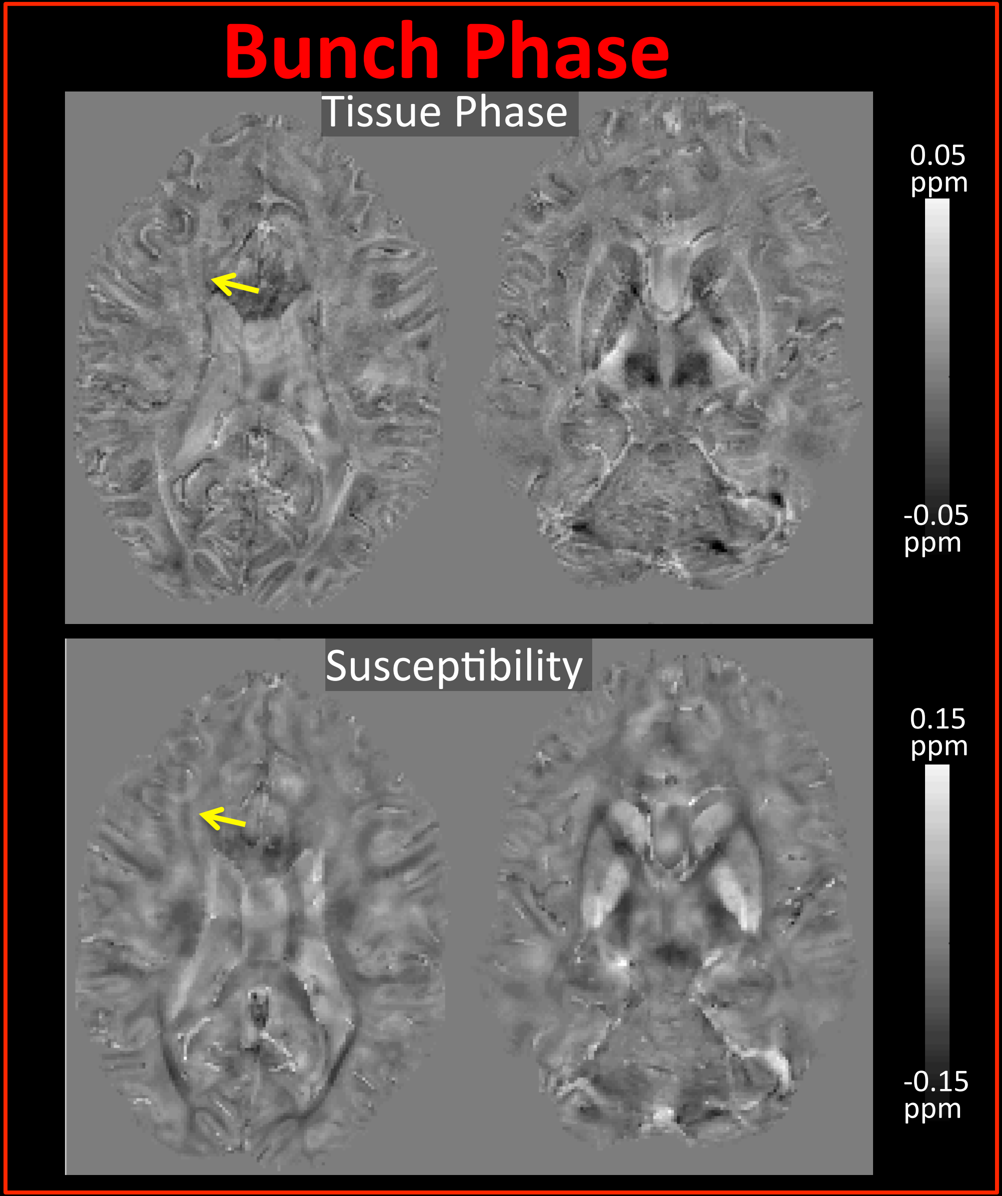


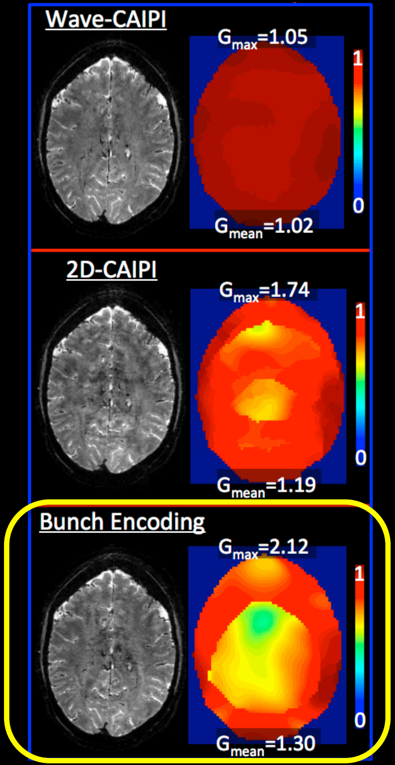
7 Tesla, R=3x3, 1 mm iso, 2.3 min acq



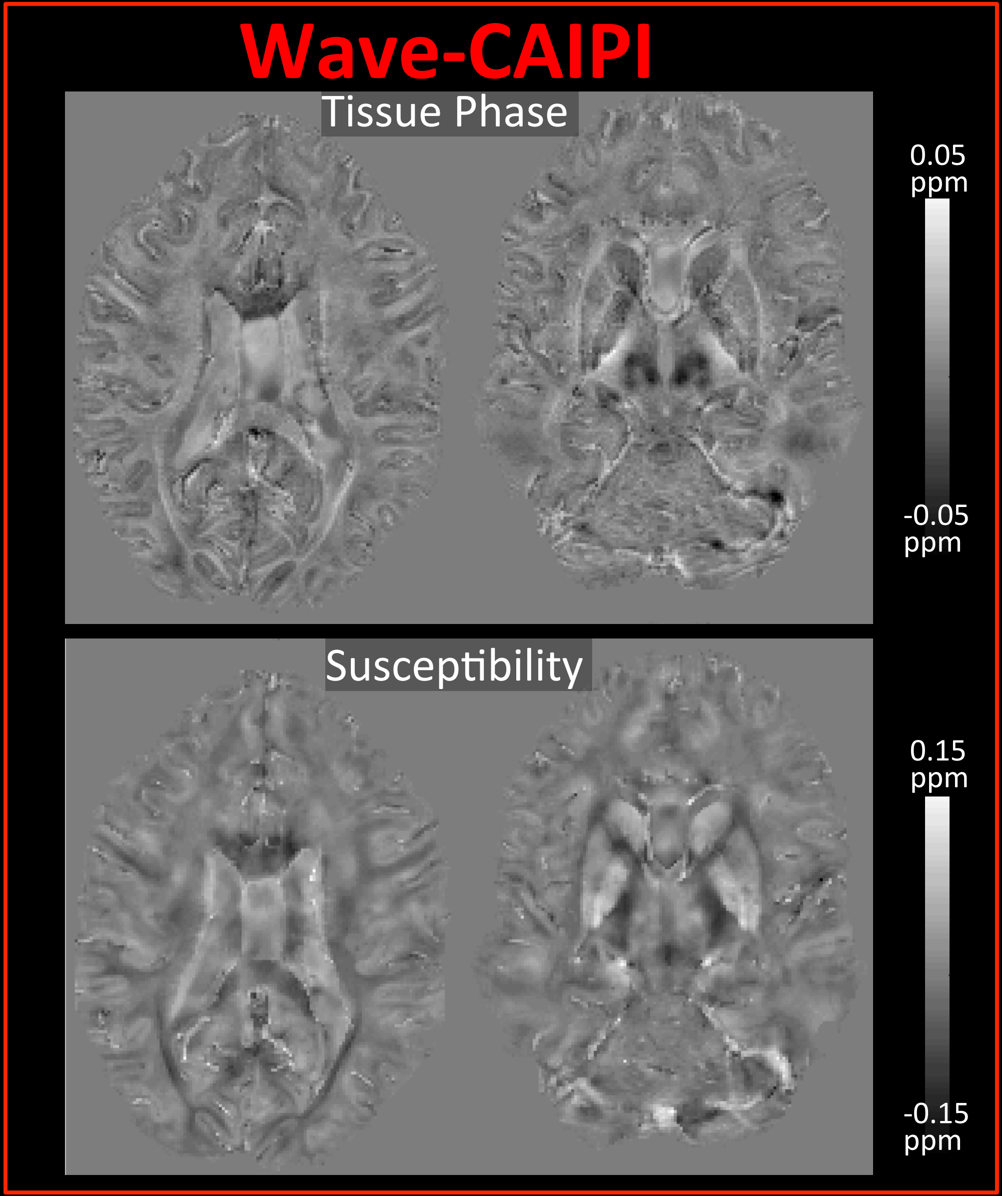


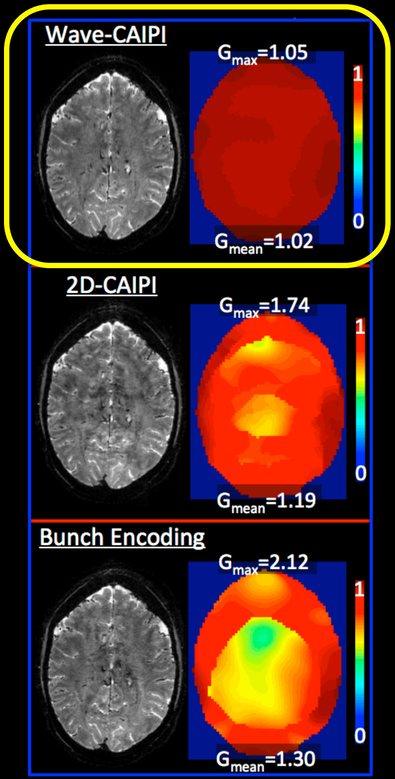
7 Tesla, R=3x3, 1 mm iso, 2.3 min acq



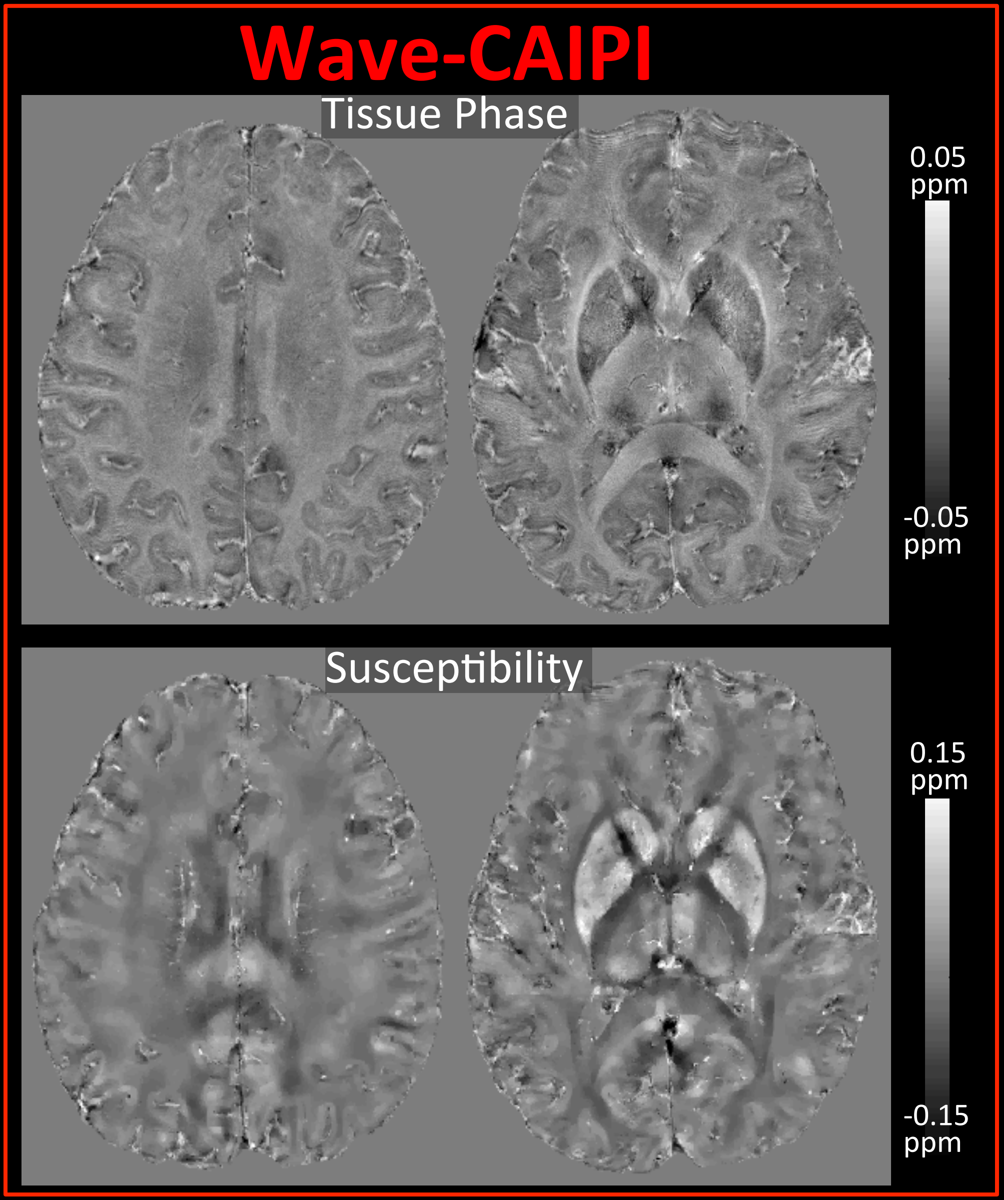


7 Tesla, R=3x3, 1 mm iso, 2.3 min acq





7 Tesla, R=3x3, 0.5 mm iso, 5.1 min acq



Summary

- Propose Wave-CAIPI acquisition/reconstruction scheme for highly accelerated 3D imaging

- Wave-CAIPI offers 2-fold improvement in g-factor and image artifact penalties compared to 2D-CAIPI and Bunch Phase Encoding

Summary

- Propose Wave-CAIPI acquisition/reconstruction scheme for highly accelerated 3D imaging
- Wave-CAIPI offers 2-fold improvement in g-factor and image artifact penalties compared to 2D-CAIPI and Bunch Phase Encoding
- Deployed in GRE imaging, Wave-CAIPI allows 9-fold acceleration with ~perfect SNR retention at 3T and 7T
- Combined with fast phase and susceptibility processing methods, it enables QSM at 1 mm resolution in 2.3 min

Thank you for your attention