Highly Accelerated 3D Imaging with Wave-CAIPI

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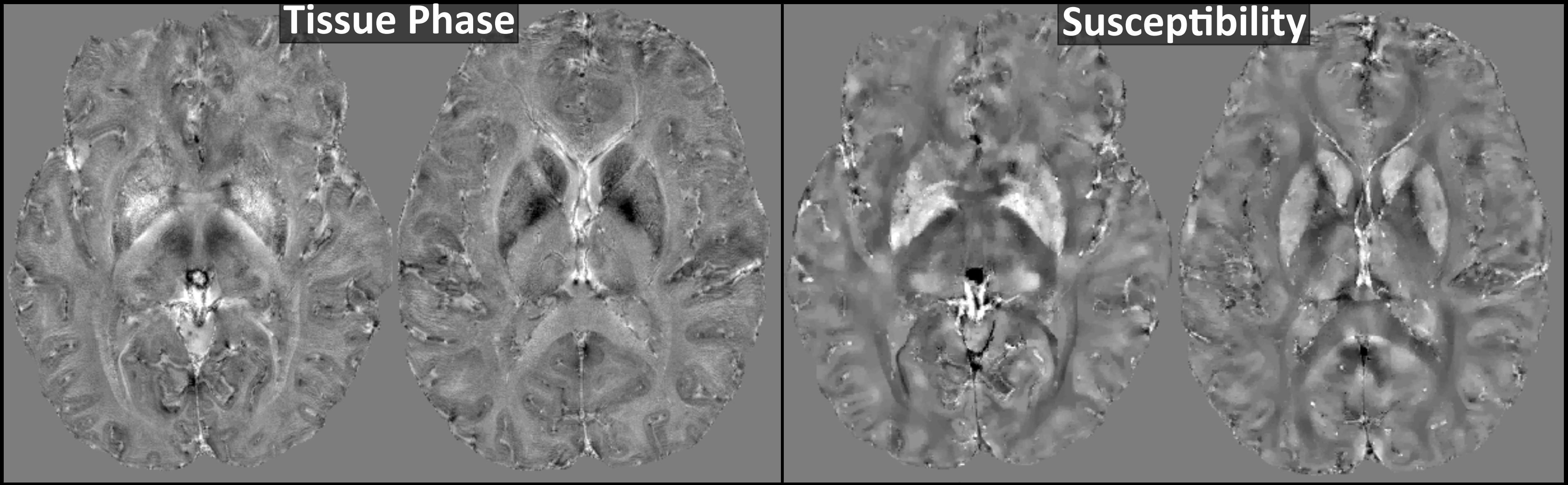
Highly Accelerated 3D Imaging

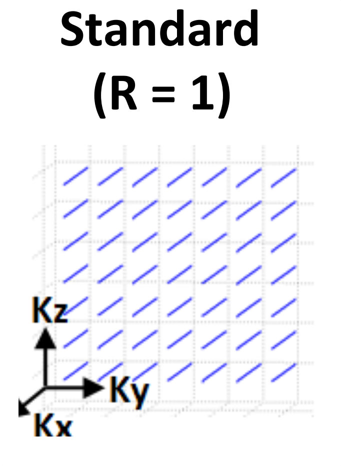
- 3D imaging enjoys high SNR because all spins in the excited volume contribute to noise averaging effect
- But susceptible to motion artifacts during the lengthy acquisition required for high resolution
- We target 3D Gradient Echo (GRE) imaging, and achieve **an order of magnitude acceleration with negligible noise amplification**

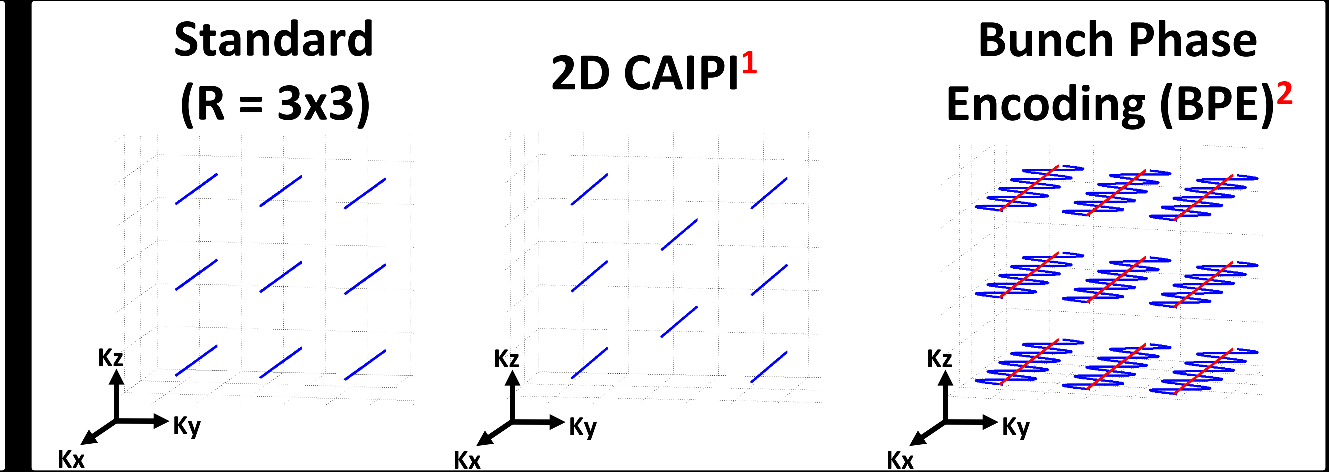


0.5 mm isotropic whole brain @ 7T in 5 minutes

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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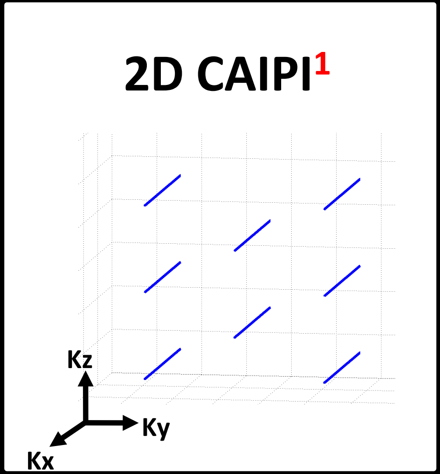

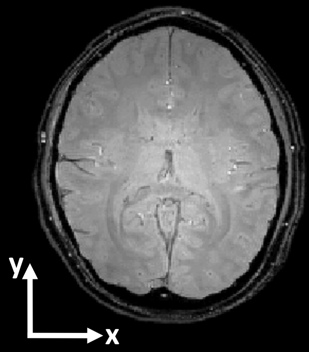

2D-CAIPI slice shift: →

Effect of slice shift in image space

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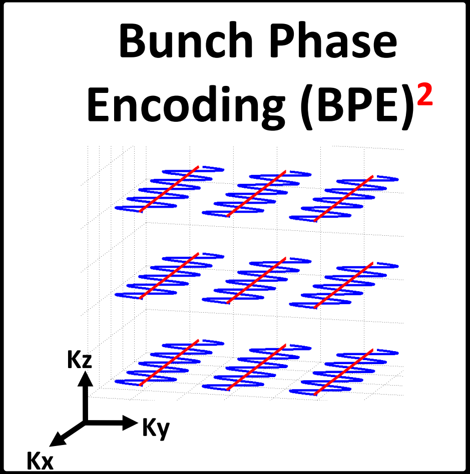
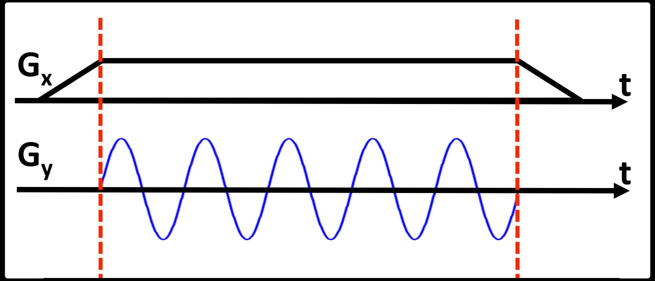
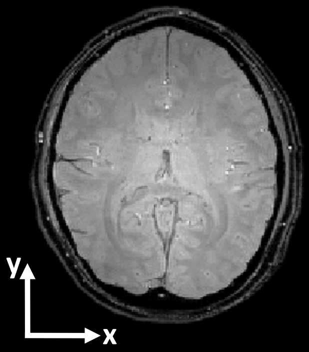


Bunch Phase Encoding (BPE)[2]





Bunch Phase: Zigzag G_y

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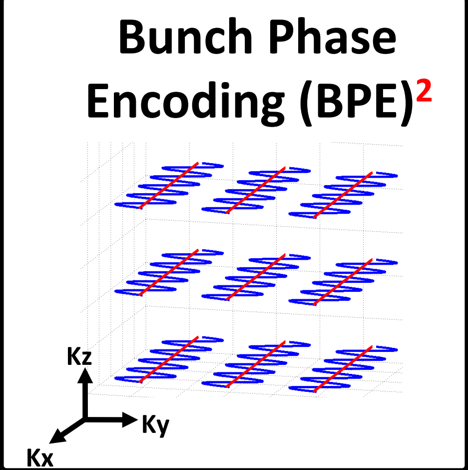

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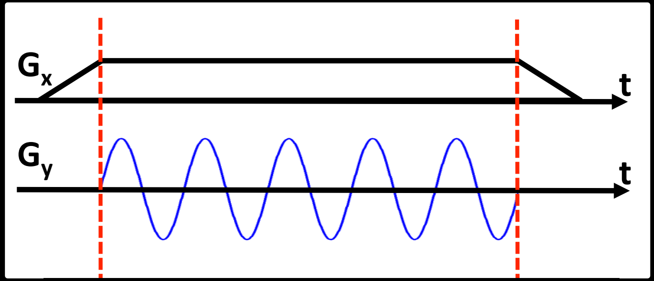

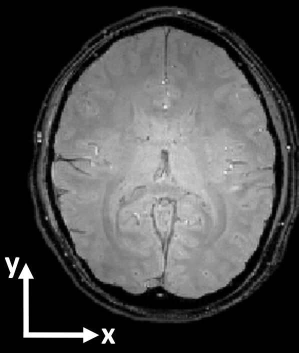

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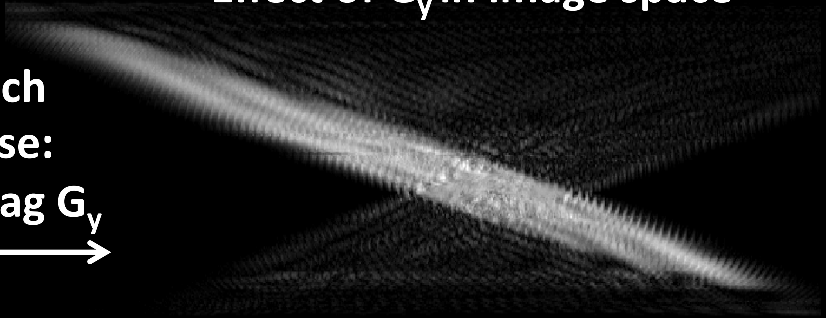
Effect of G_y in image space



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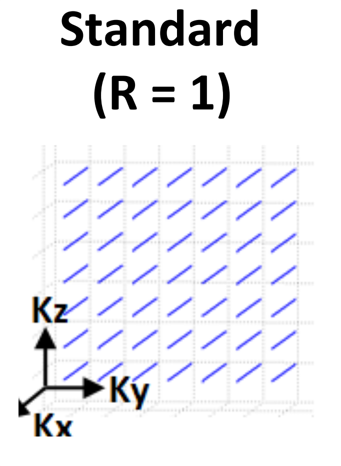
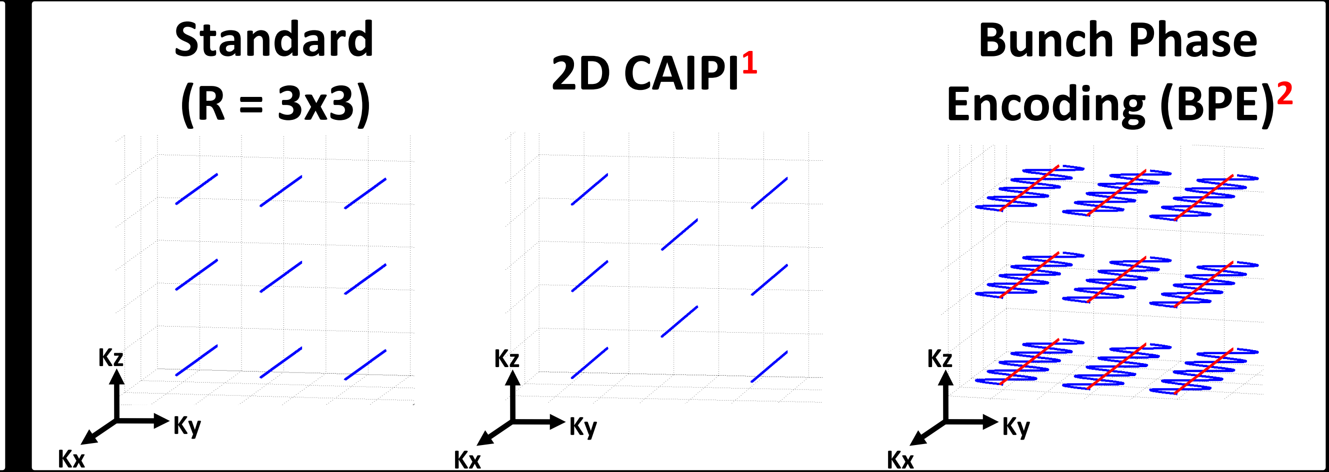
Wave-CAIPI Sampling

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

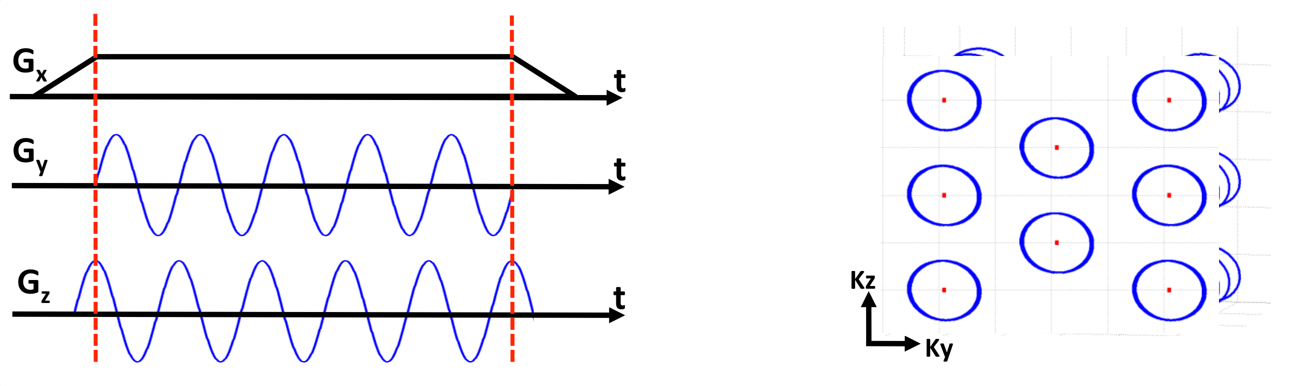

Standard
(R = 1)


Standard
(R = 3x3)

2D CAIPI[1]

Bunch Phase Encoding (BPE)[2]

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



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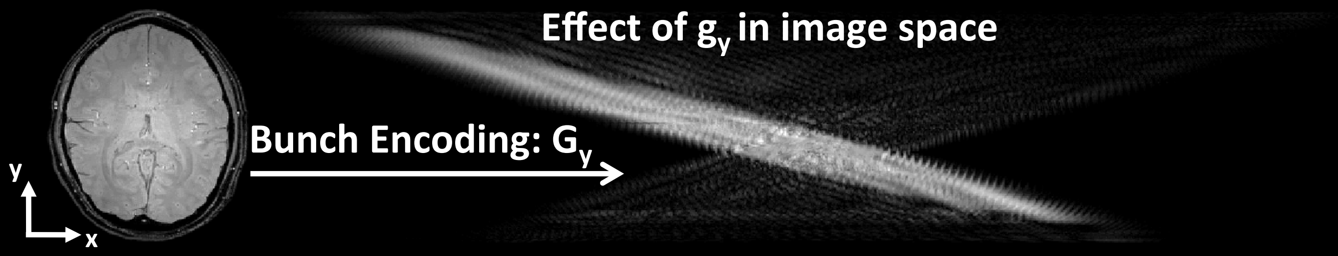
Wave-CAIPI causes voxel spreading in 3 dimensions

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



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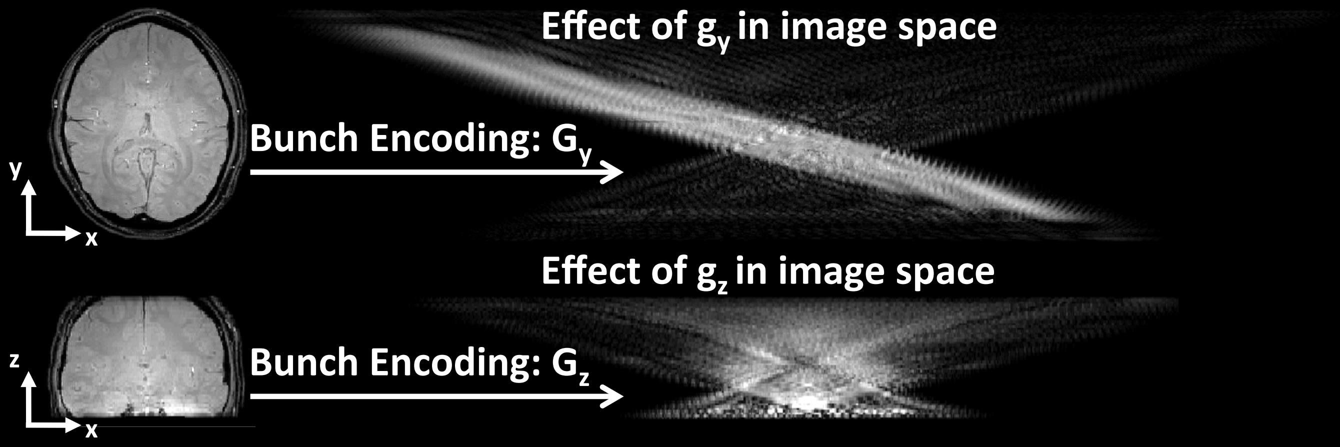

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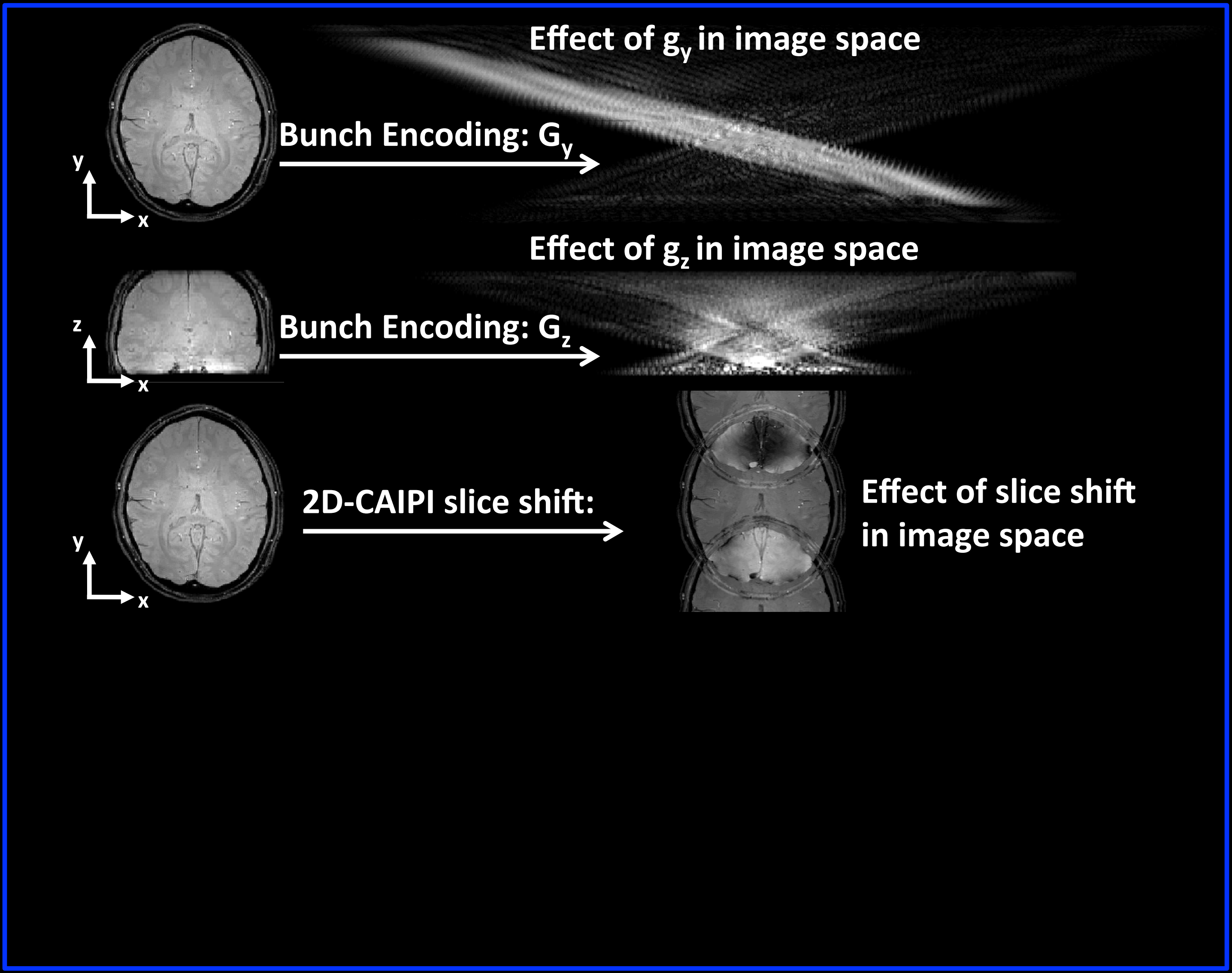

Effect of g_y in image space

Bunch Encoding: G_y

Effect of g_z in image space

Bunch Encoding: G_z

2D-CAIPI slice shift:

Effect of slice shift in image space

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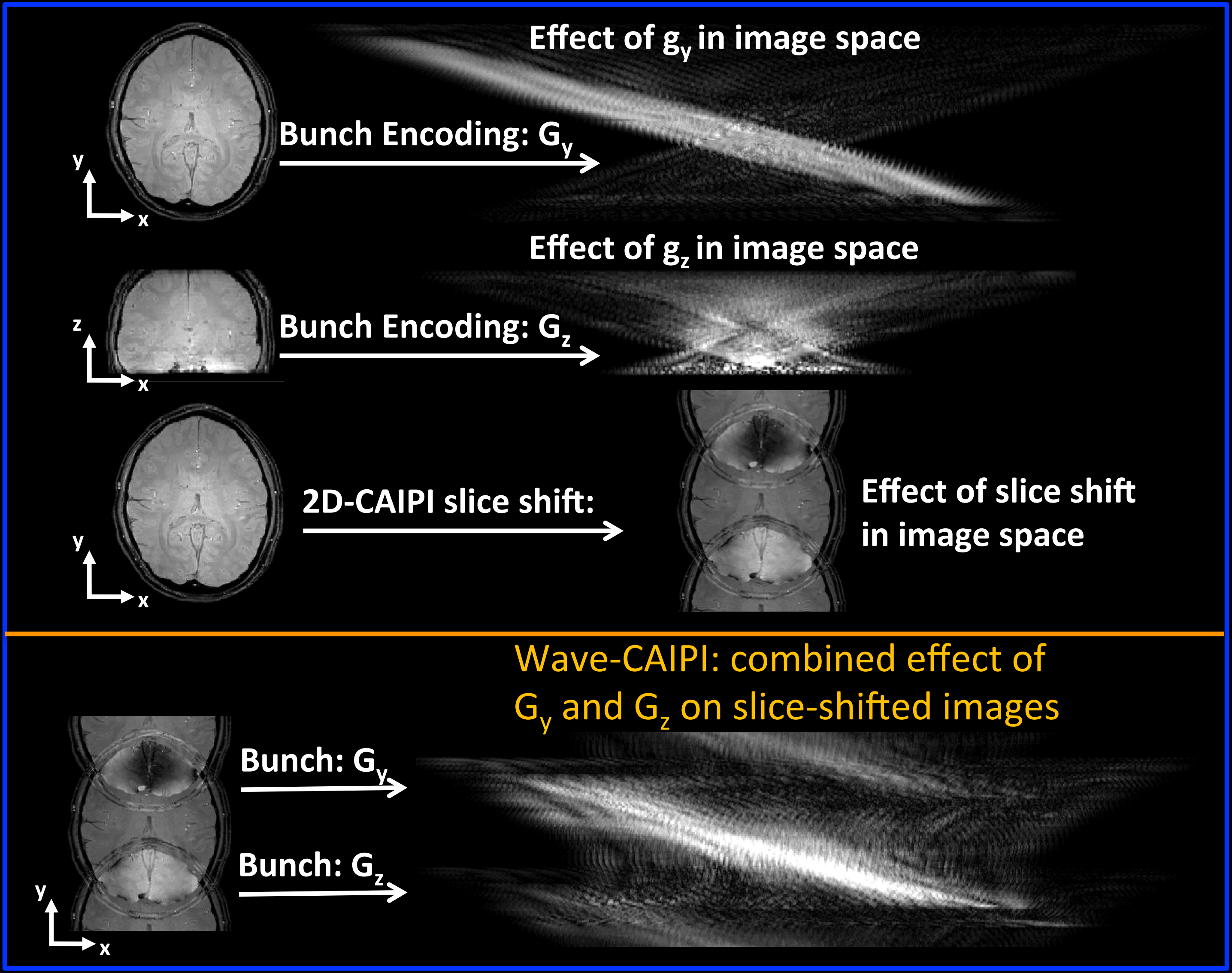

Effect of g_y in image space

Bunch Encoding: G_y

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Bunch Encoding: G_z

2D-CAIPI slice shift:

Effect of slice shift in image space

Wave-CAIPI: combined effect of G_y and G_z on slice-shifted images

Bunch: G_y

Bunch: G_z

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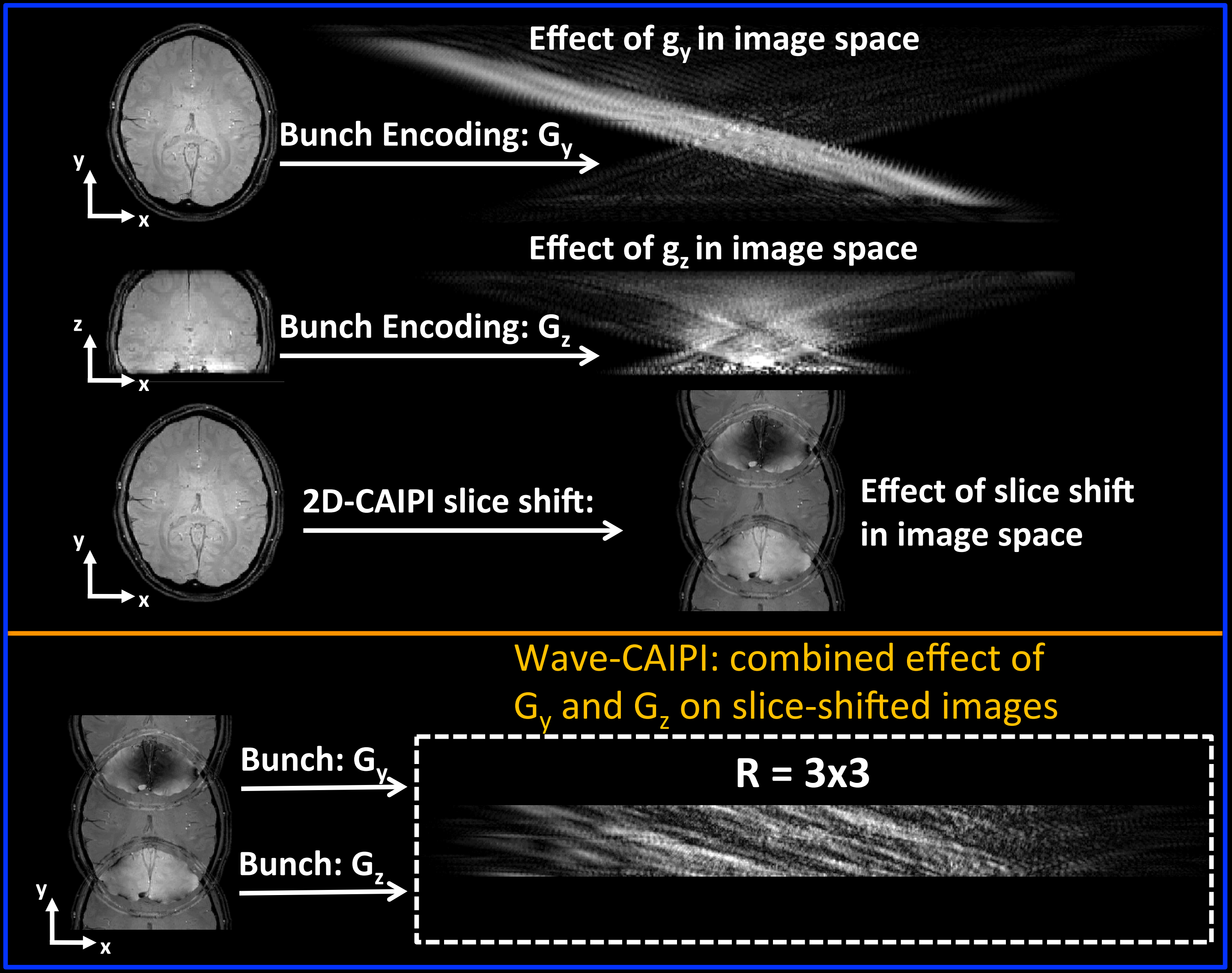


Effect of g_y in image space

Bunch Encoding: G_y

Effect of g_z in image space

Bunch Encoding: G_z

2D-CAIPI slice shift:

Effect of slice shift in image space

Wave-CAIPI: combined effect of G_y and G_z on slice-shifted images

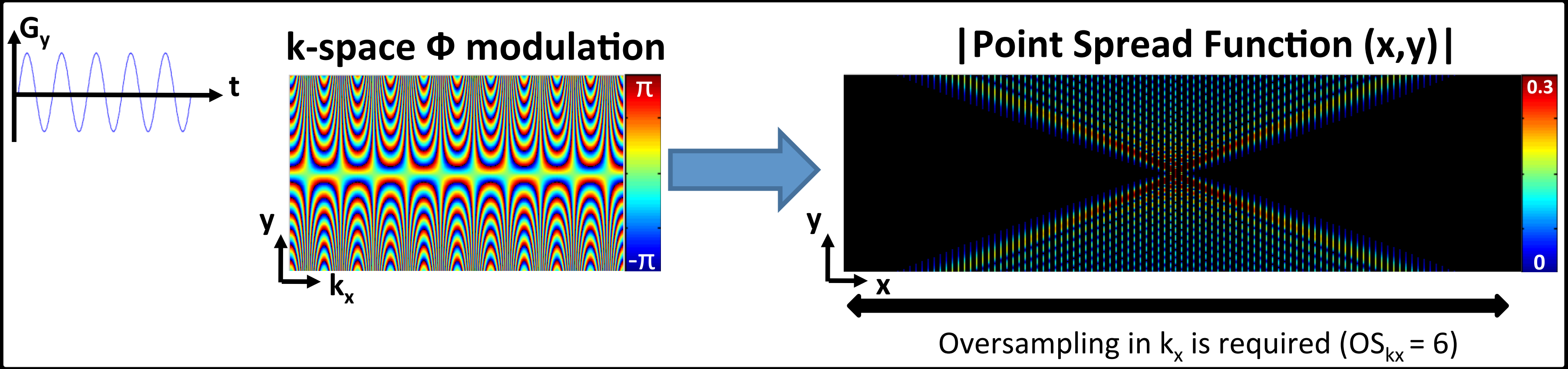
Bunch: G_y

Bunch: G_z

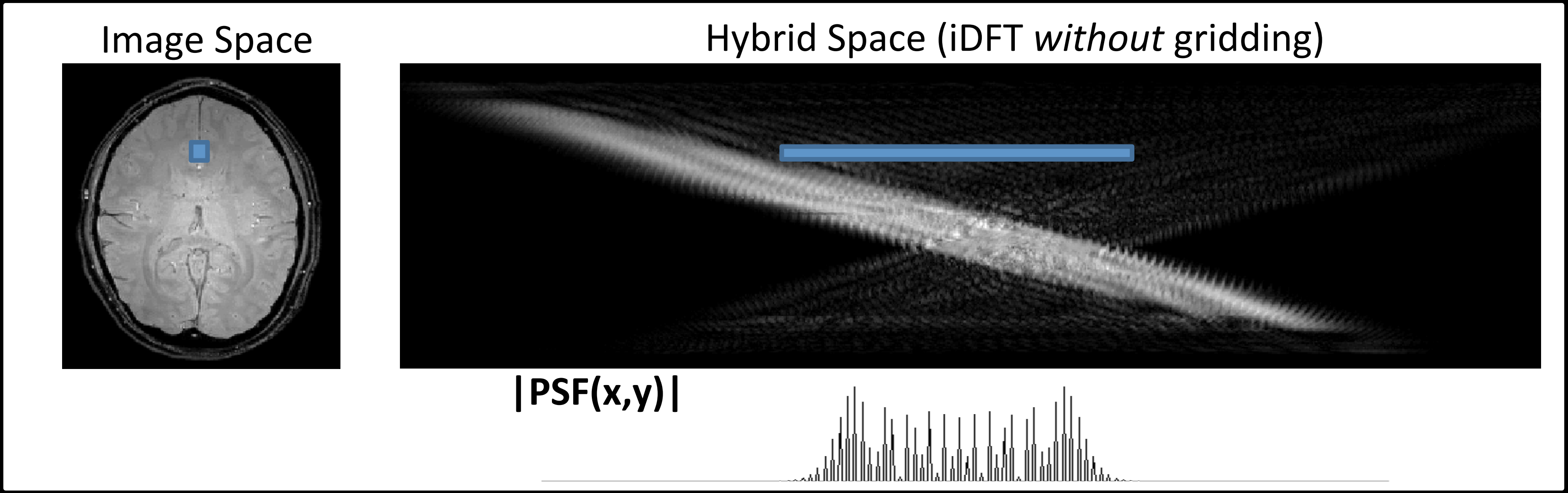
R = 3x3

Point Spread Function

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



Oversampling in k_x is required (OS_{kx} = 6)



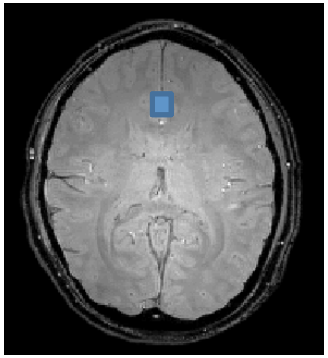
Point Spread Function

- **From signal equation:**

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

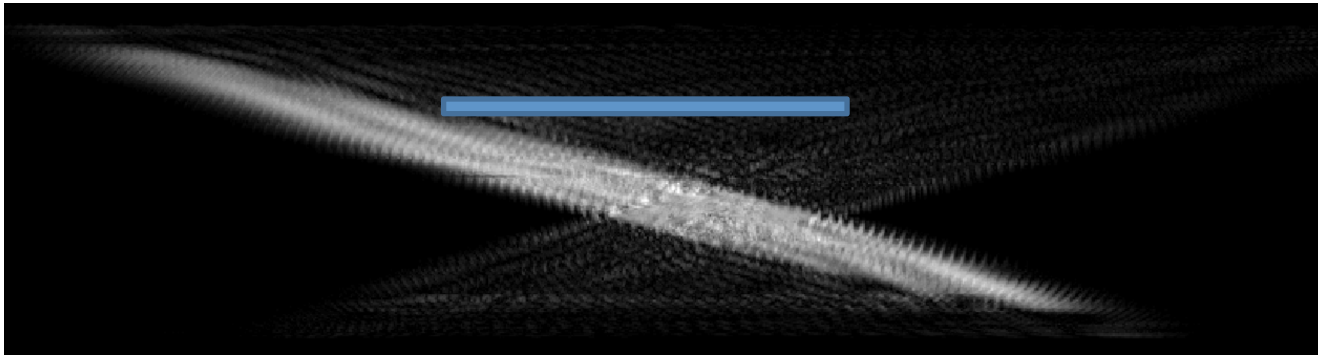
$wave(x,y,z)$	Wave image
$img(x,y,z)$	Underlying magnetization
$W_y(k_x(t)) = \frac{\gamma}{2\pi}\int_0^t G_y(\tau)d\tau$	k-space trajectory

Image Space



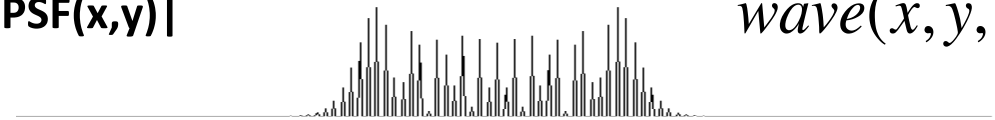
$img(x,y,z)$

Hybrid Space (iDFT *without* gridding)



$wave(x,y,z)$

|PSF(x,y)|

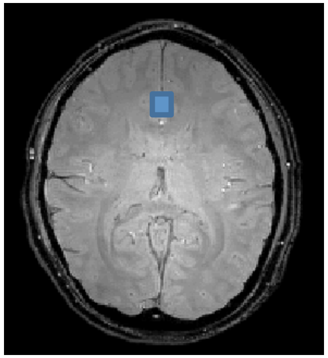


Point Spread Function

- **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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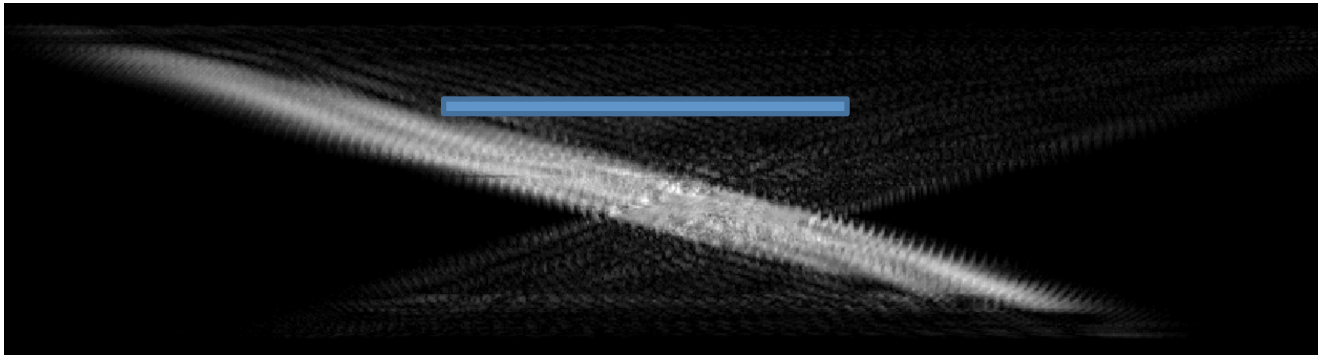

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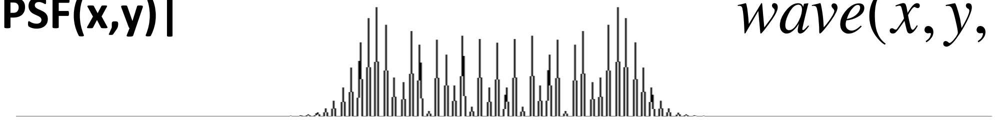


$wave(x,y,z)$

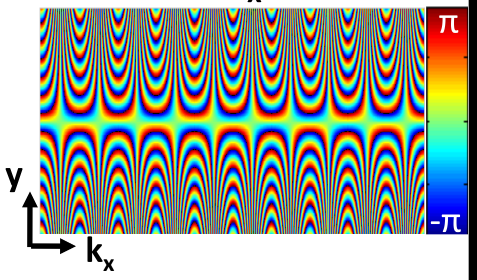
Point Spread Function

- **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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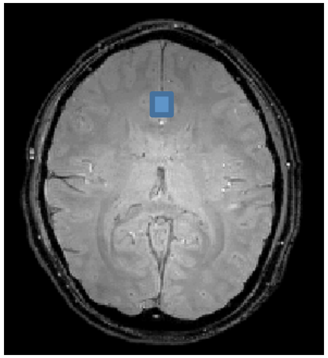

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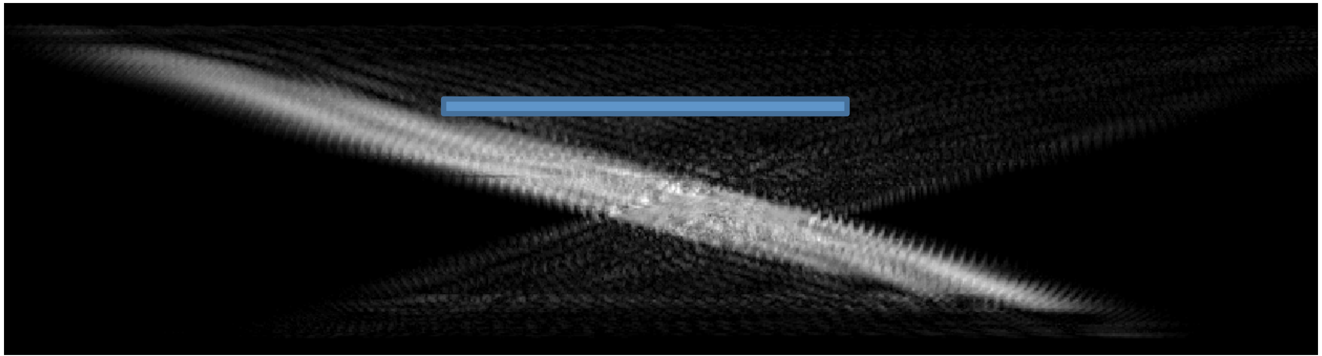

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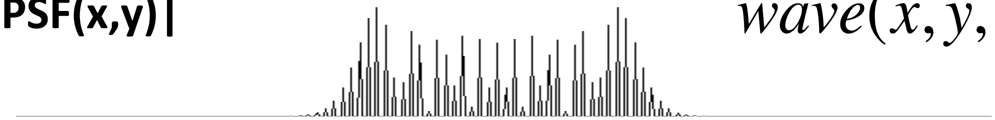
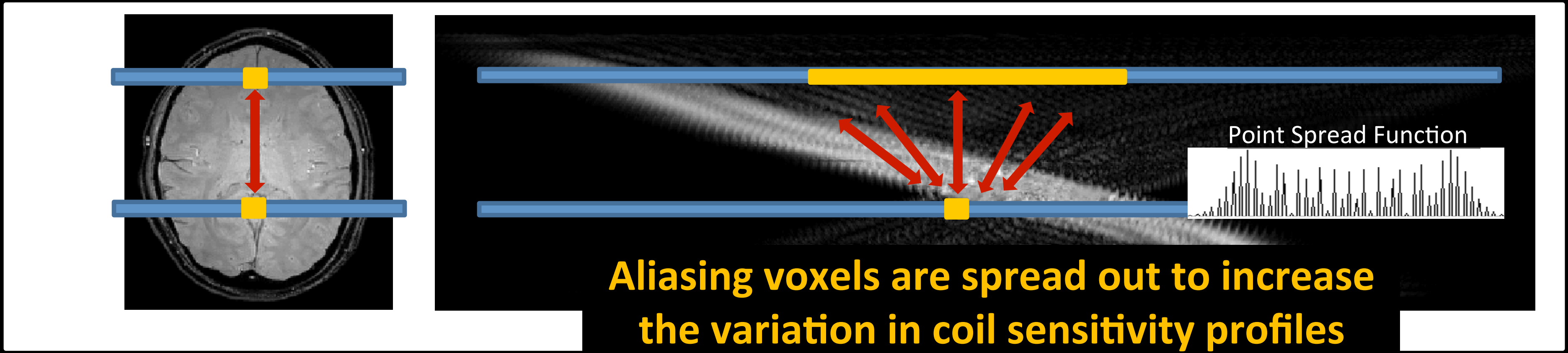


$wave(x,y,z)$

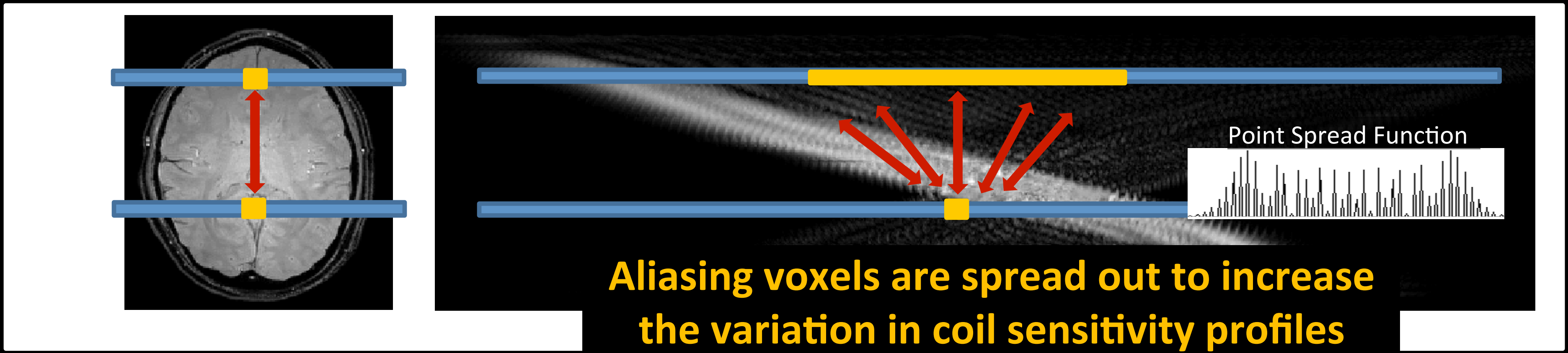
Reconstruction for accelerated acquisitions



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

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

Reconstruction for accelerated acquisitions



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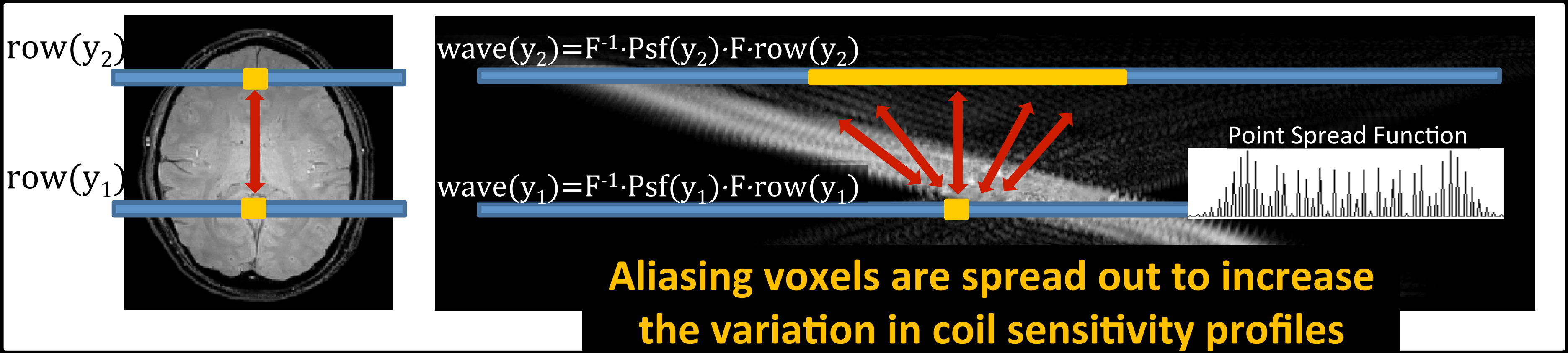

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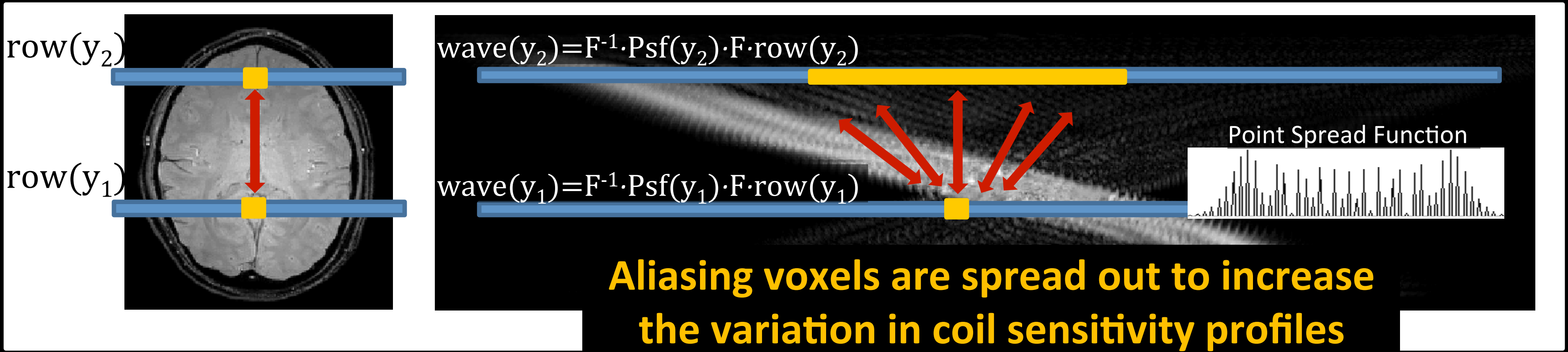
$$wave(y) = \mathrm{F}^{-1}\cdot \mathrm{Psf}(y)\cdot \mathrm{F}\cdot row(y)$$

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

Reconstruction for accelerated acquisitions



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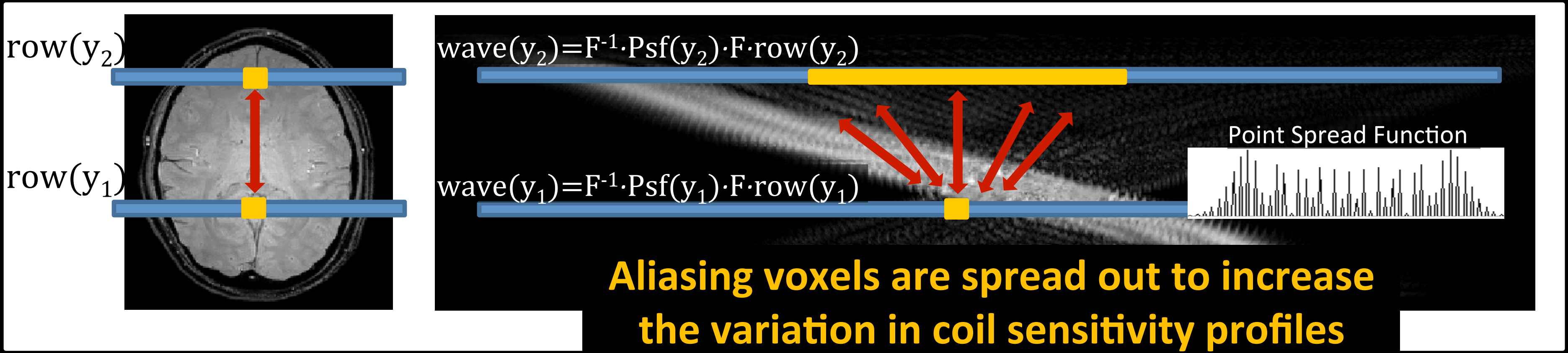

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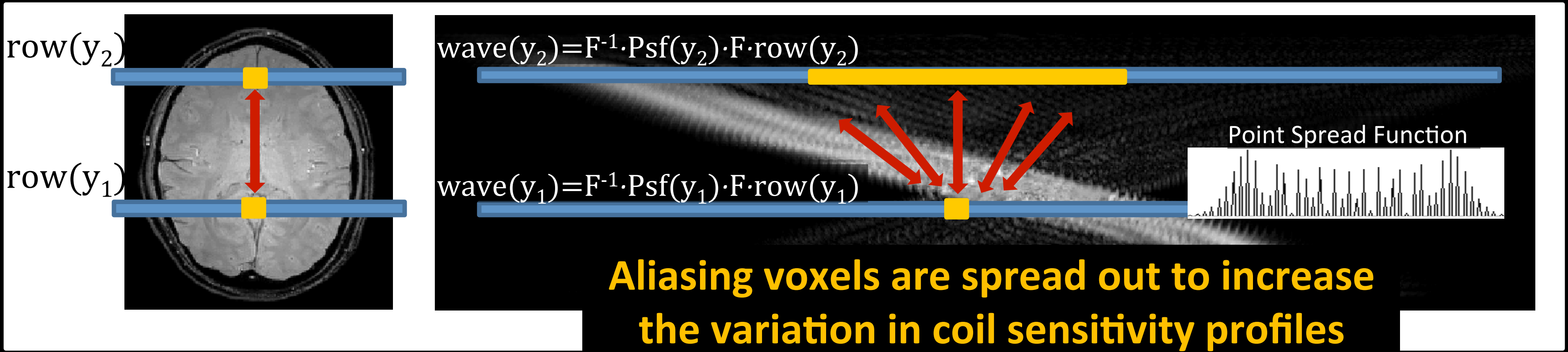
$$\underbrace{\begin{bmatrix} \mathrm{F}^{-1}\cdot \mathrm{Psf}(y_1)\cdot \mathrm{F}\cdot \mathrm{C}_1(y_1) \\ \dots \\ \mathrm{F}^{-1}\cdot \mathrm{Psf}(y_2)\cdot \mathrm{F}\cdot \mathrm{C}_{32}(y_2) \end{bmatrix}}_{\text{Encoding matrix}} \cdot \begin{bmatrix} row(y_1) \\ row(y_2) \end{bmatrix} = \begin{bmatrix} coil_1 \\ \dots \\ coil_{32} \end{bmatrix}$$

Reconstruction for accelerated acquisitions



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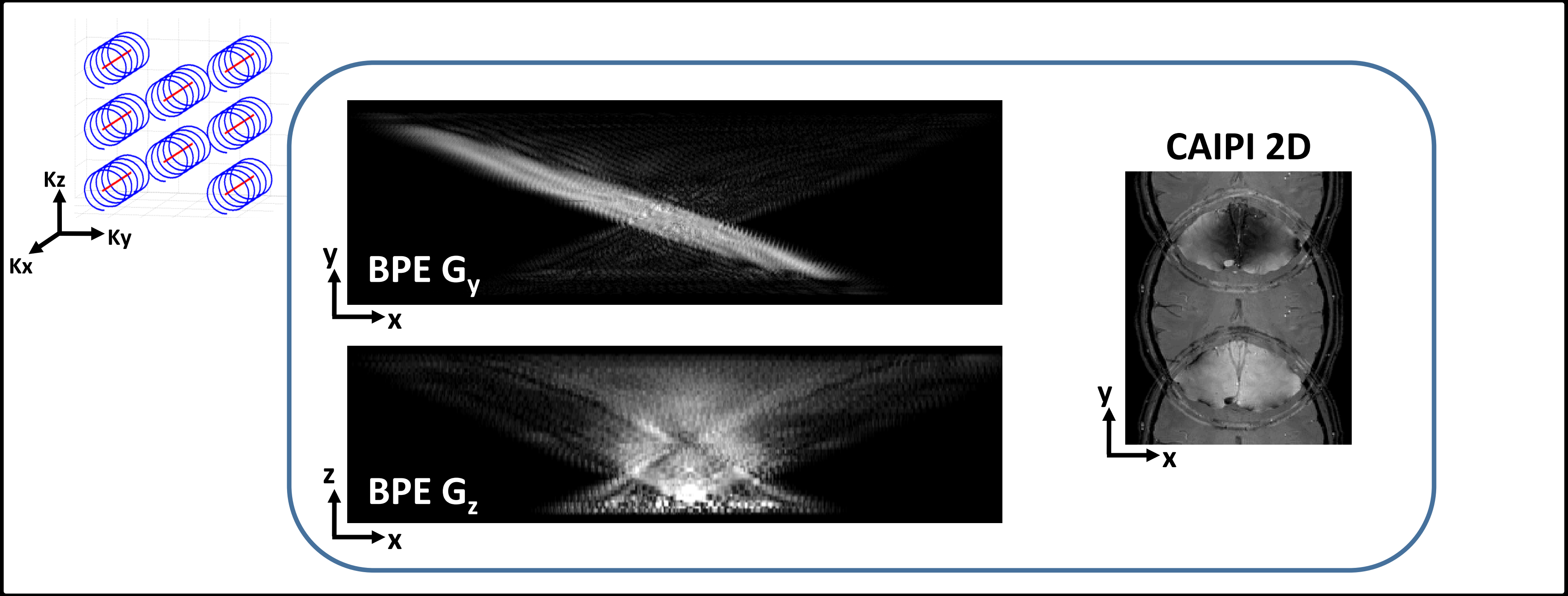
- Similar to SENSE reconstruction, except for PSF formulation

Wave-CAIPI reconstruction



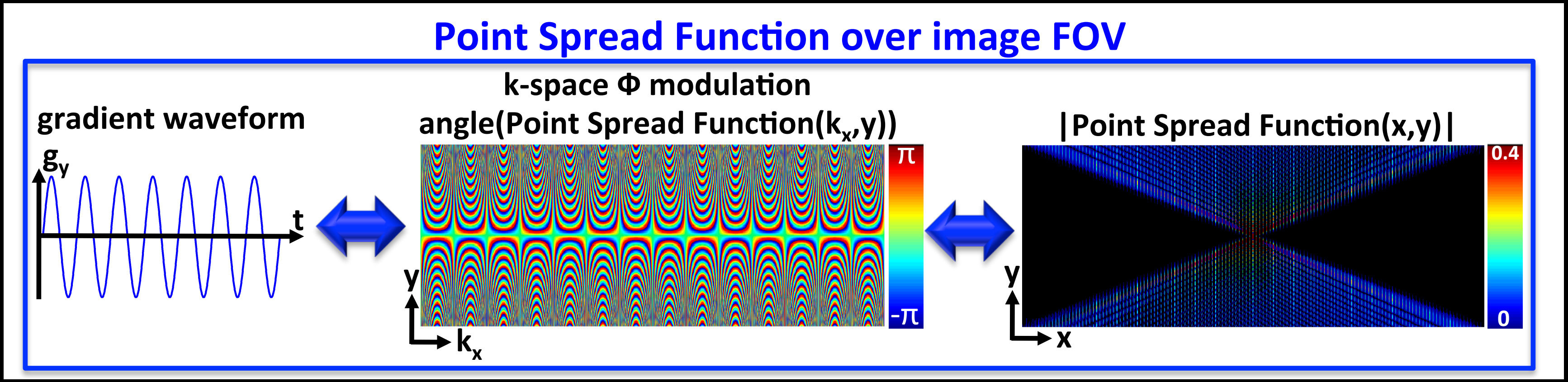
⇒ Wave gradients G_y and G_z create position dependent PSF

⇒ CAIPI 2D shift aliasing pattern

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

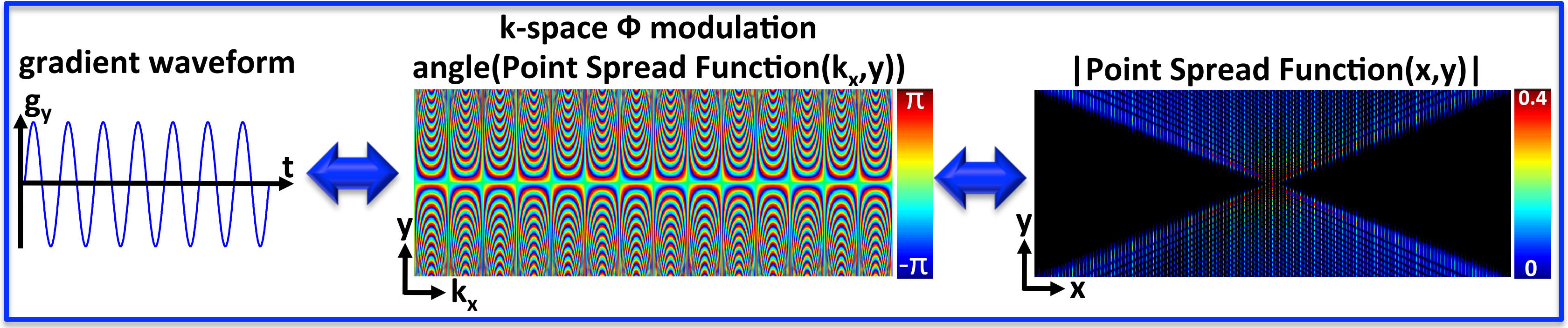
- ⇒ Ex: R = 3x3
  - ⇒ each Encoding matrix corresponds to 9 rows of the image
  - ⇒ grouping of rows is determined by CAIPI 2D
  - ⇒ amount of spreading in each row determined by G_y and G_z

Artifact Quantification

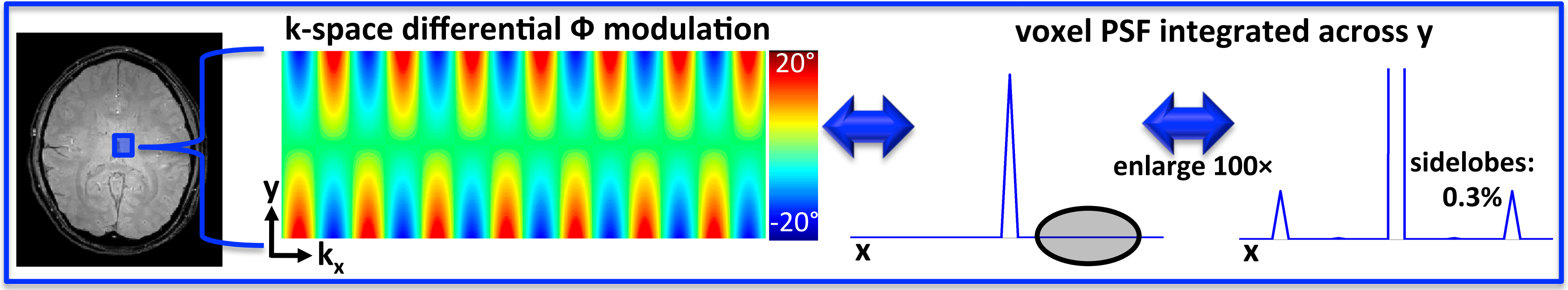


Artifact Quantification

Point Spread Function over image FOV



Point Spread Function within single voxel



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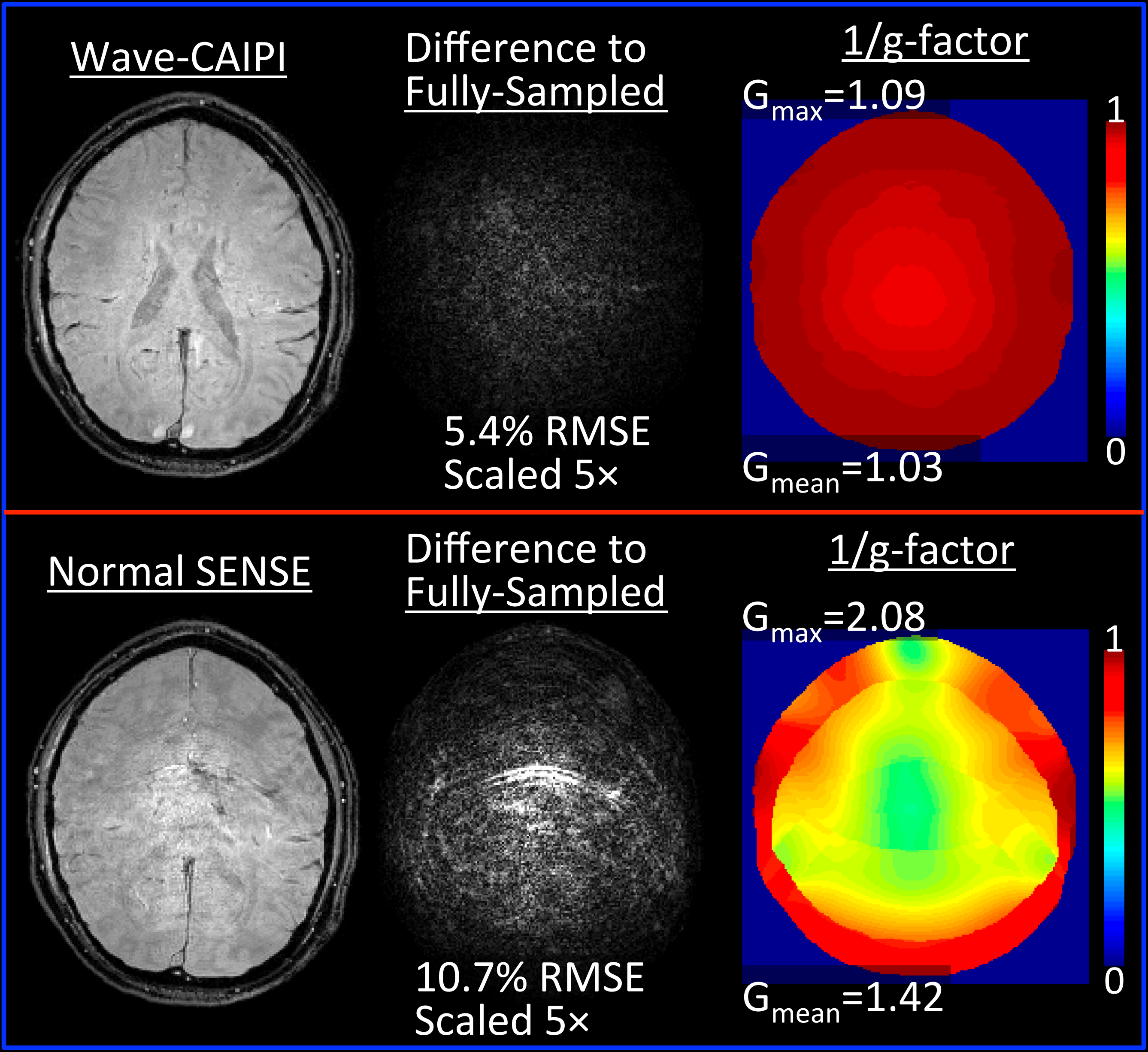
- Compare Wave-CAIPI and conventional SENSE
- Acquire **fully-sampled** data, then accelerate by R = 3x3
- Compute root-mean-square error (RMSE) and 1/g-factor maps (retained SNR)
- In vivo acquisitions:
  - At 3T and 7T
  - 1x1x2 mm resolution
  - 224x224x120 FOV

3 Tesla, R=3x3, 1x1x2 mm^3, T$_{acq}$=38s



Wave-CAIPI

Difference to Fully-Sampled

5.4% RMSE
Scaled 5×

1/g-factor

G_{max}=1.09

G_{mean}=1.03

Normal SENSE

Difference to Fully-Sampled

10.7% RMSE
Scaled 5×

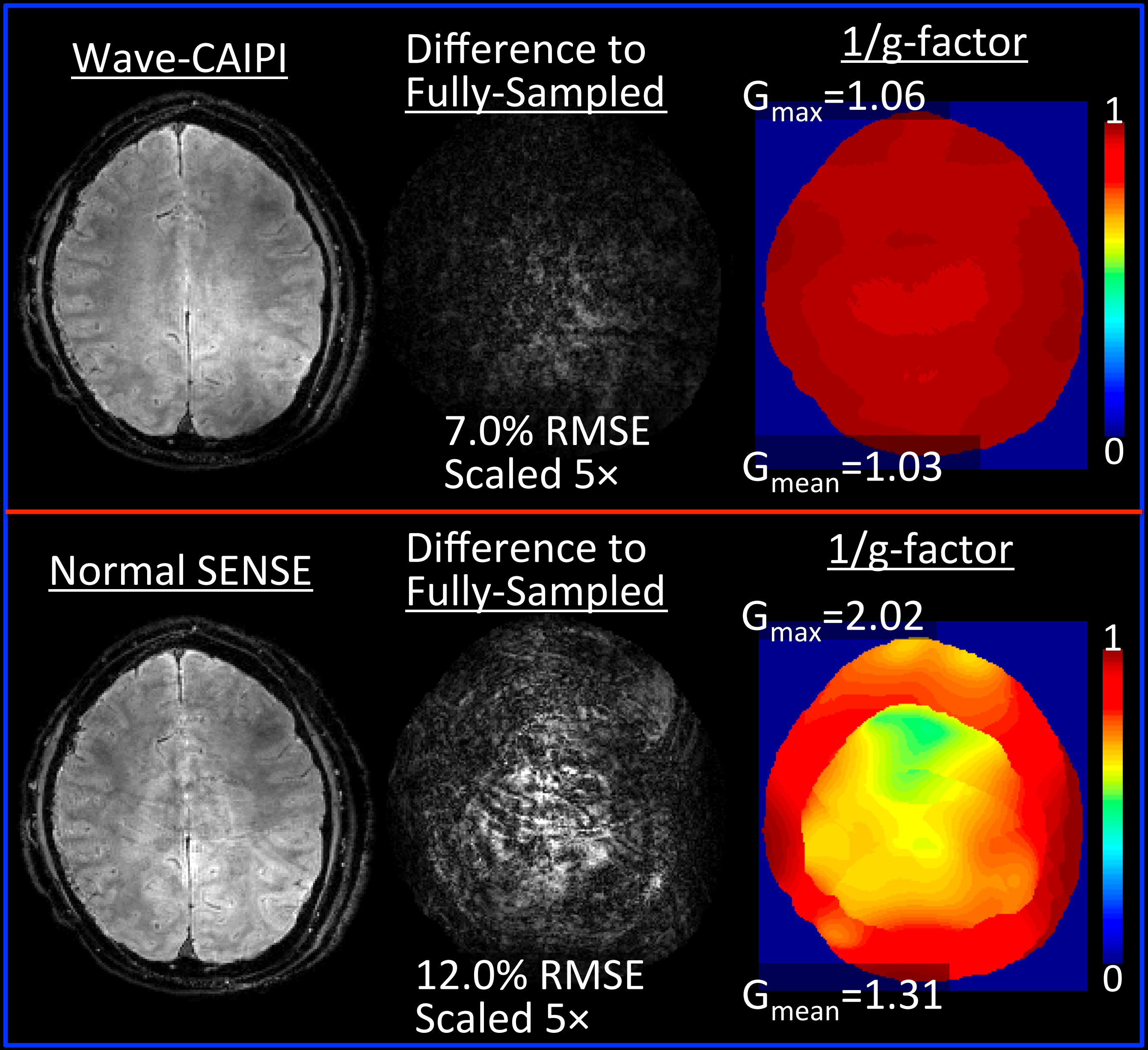
1/g-factor

G_{max}=2.08

G_{mean}=1.42

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

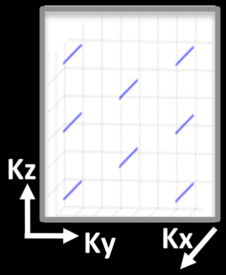
Accelerated Acquisition Comparison

- 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

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

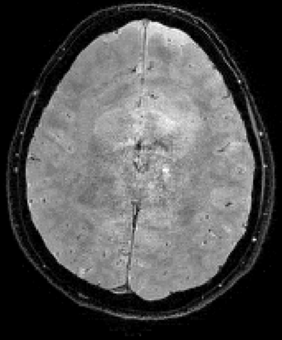
R=3x3 @ 3 Tesla, 1 mm iso, T_{acq}=2.3min

k-space

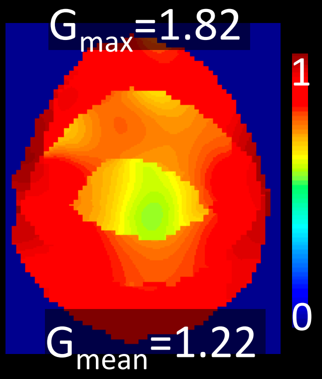


Recon

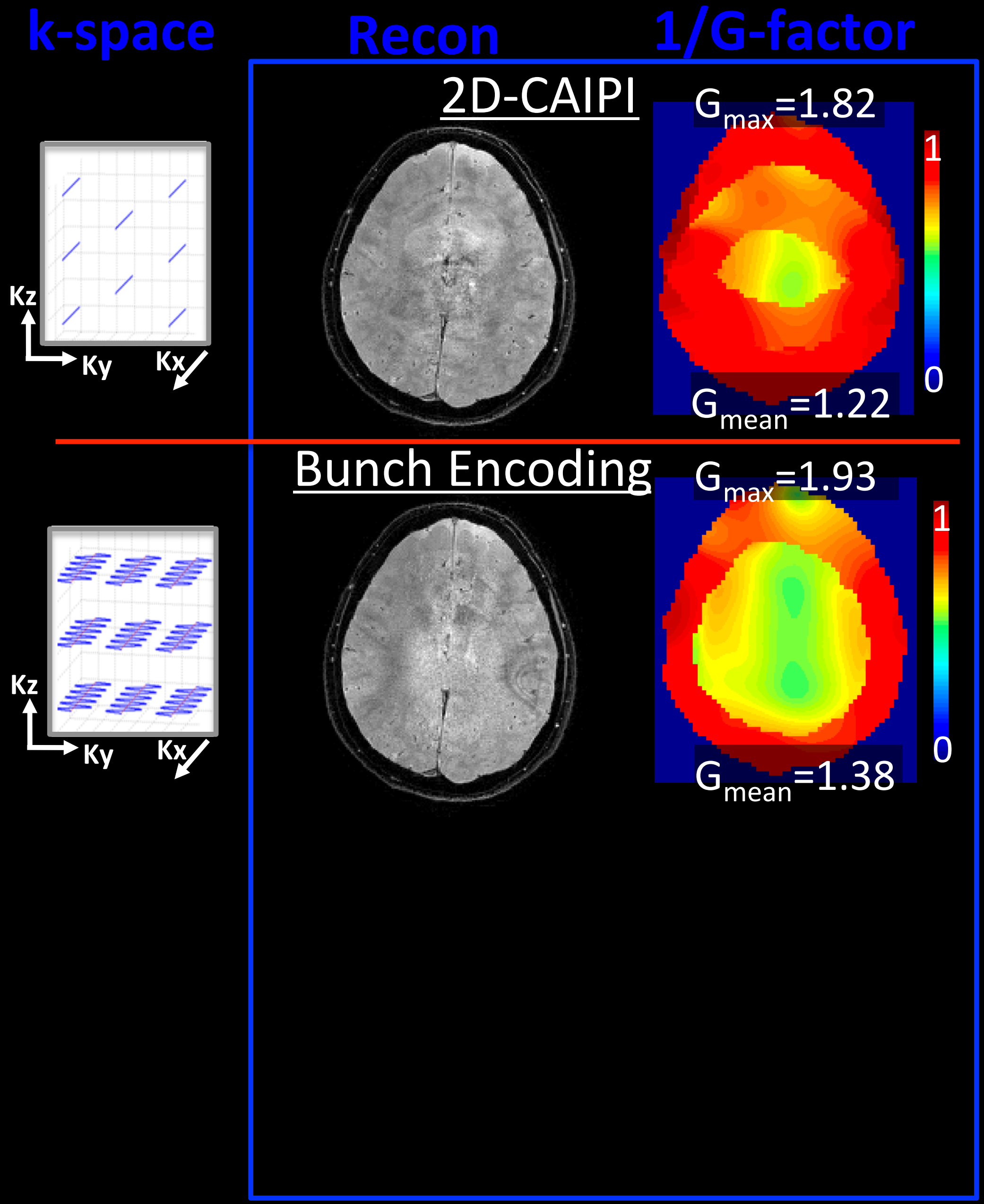
2D-CAIPI



1/G-factor



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



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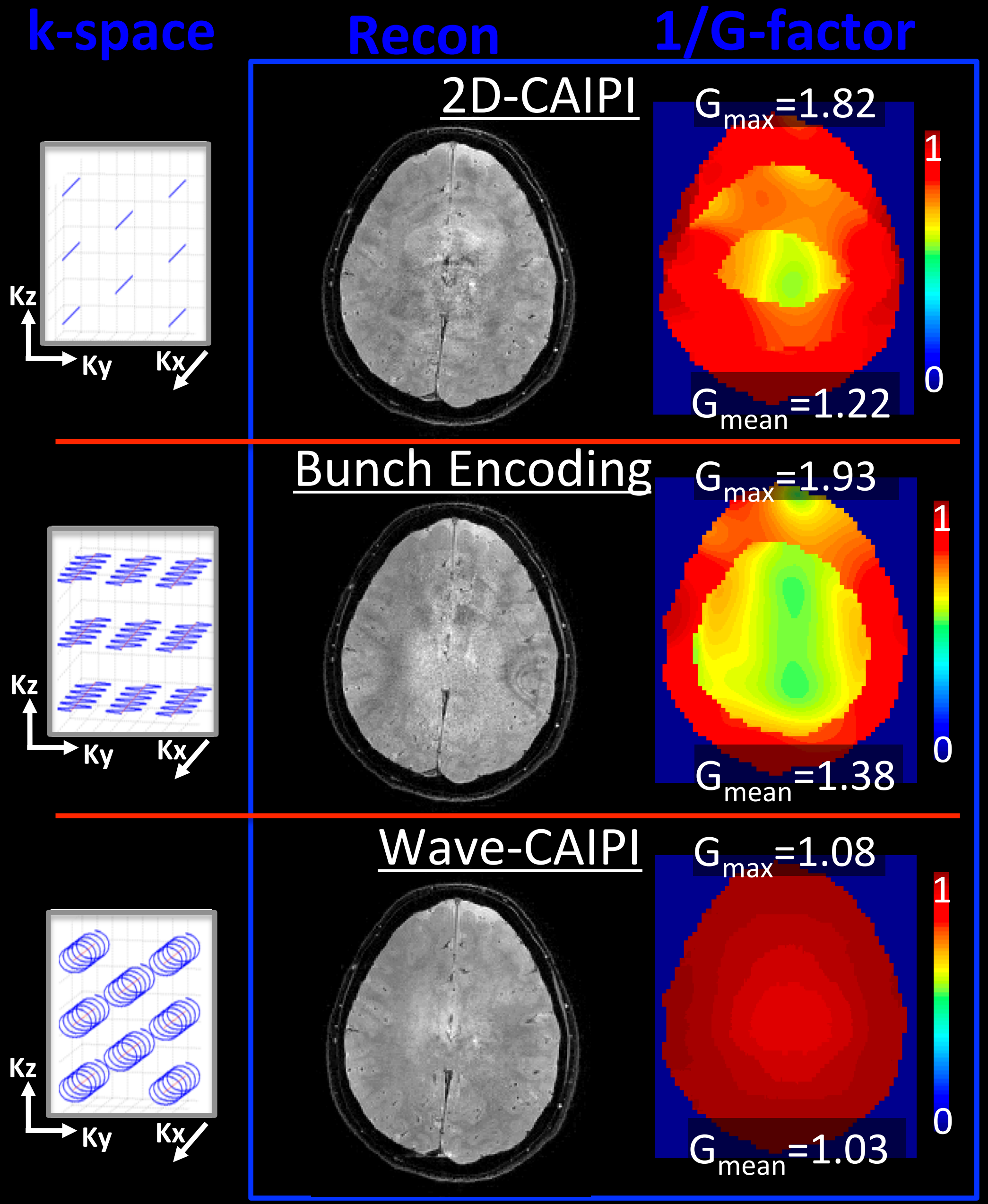
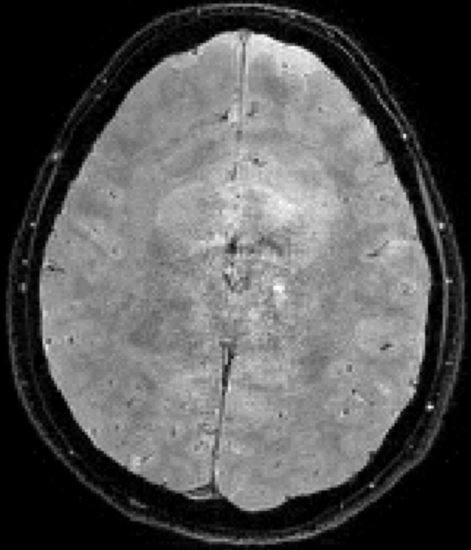
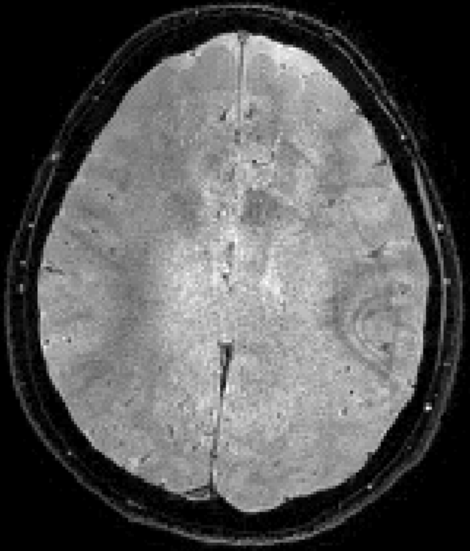


R=3x3 @ 3 Tesla, 1 mm iso, T_{acq}=2.3min

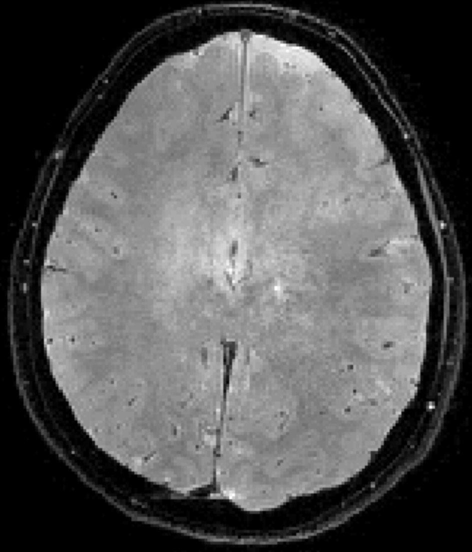
2D-CAIPI



Bunch Encoding



Wave-CAIPI

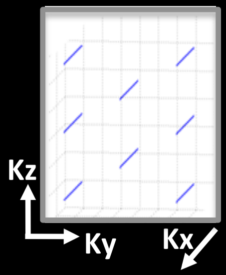


R=3x3 @ 7 Tesla, 1 mm iso, T_{acq}=2.3min

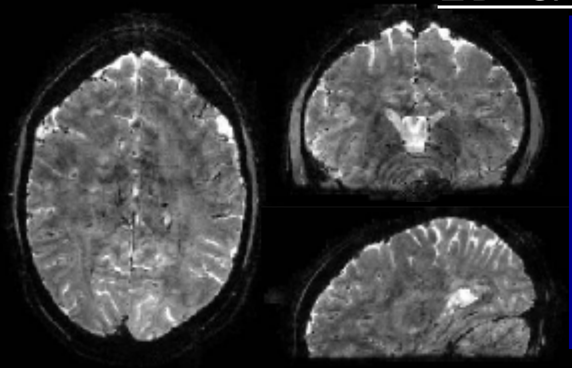
k-space

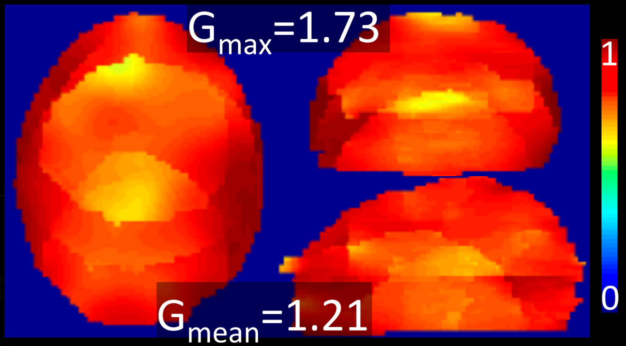
Recon

1/G-factor



2D-CAIPI

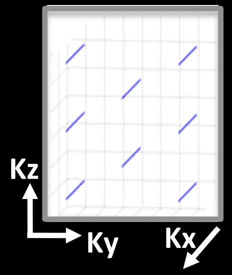


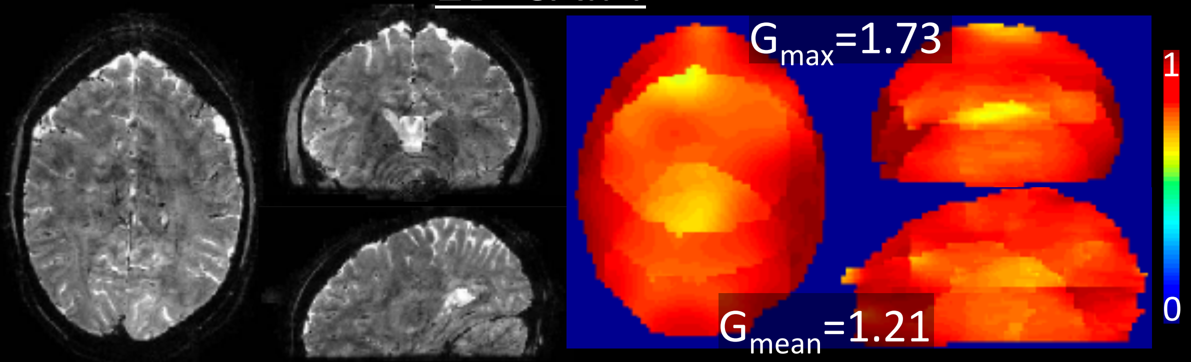


R=3x3 @ 7 Tesla, 1 mm iso, T_{acq}=2.3min

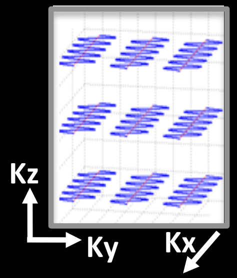
k-space **Recon** **1/G-factor**

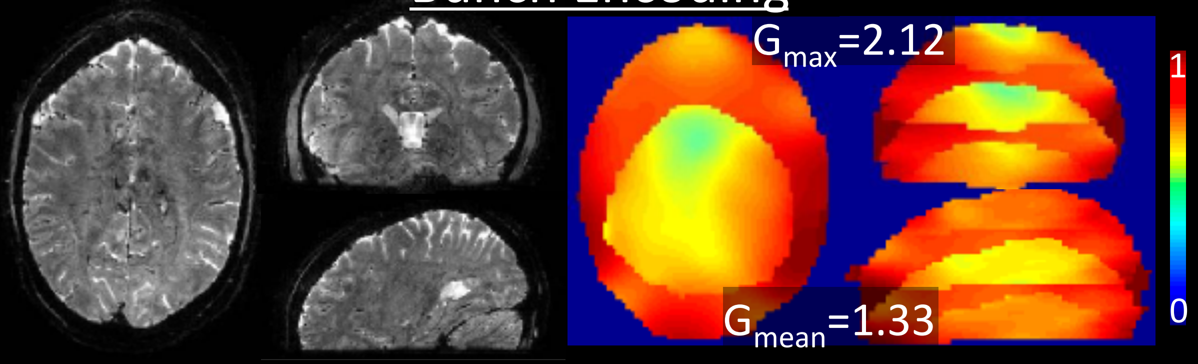
2D-CAIPI





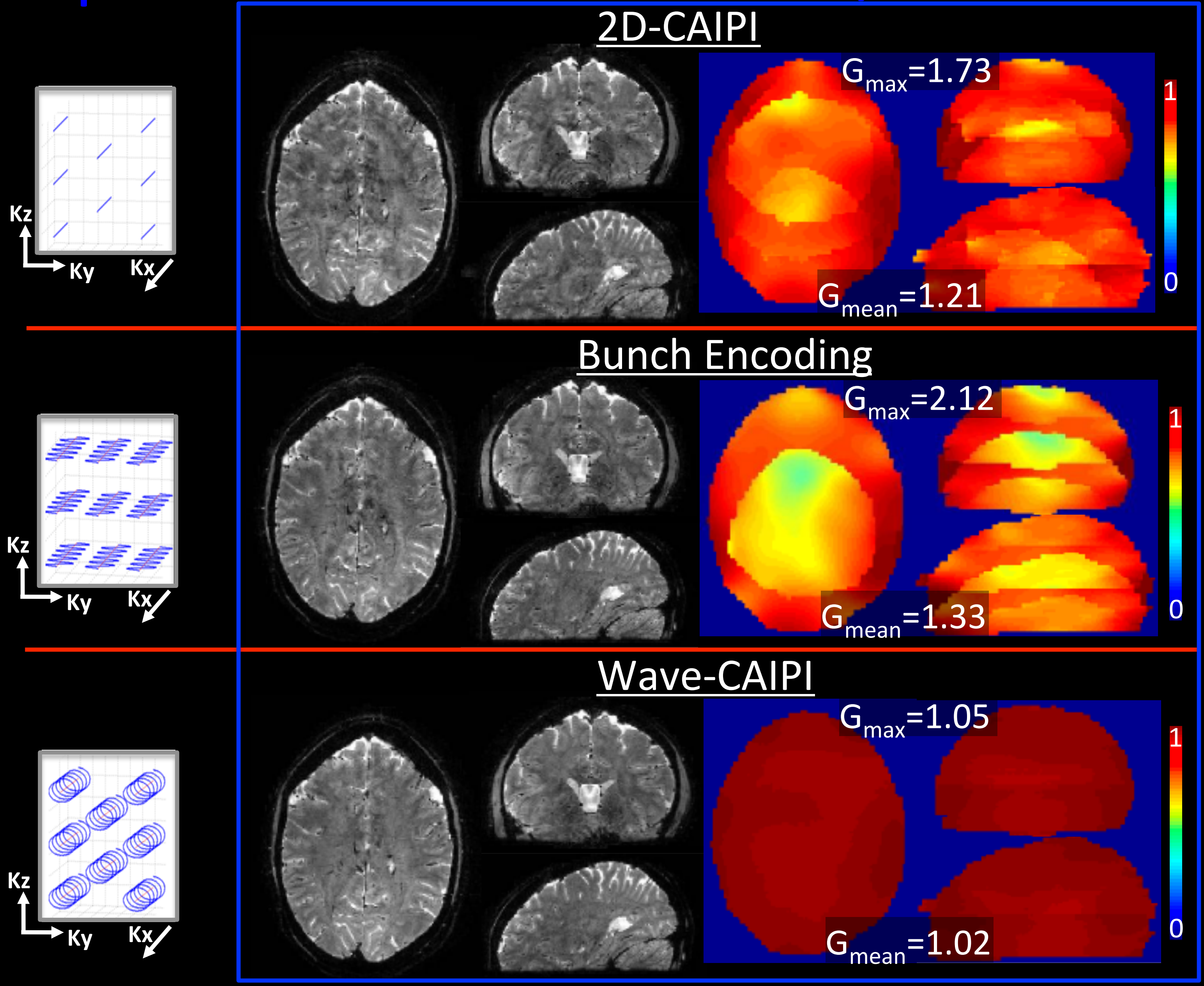
Bunch Encoding





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

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



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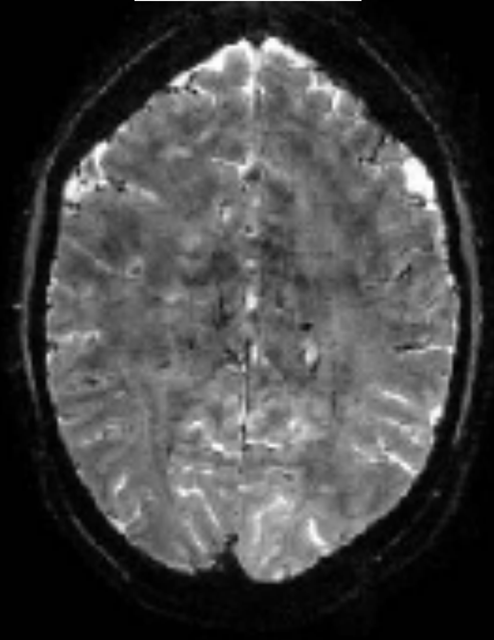
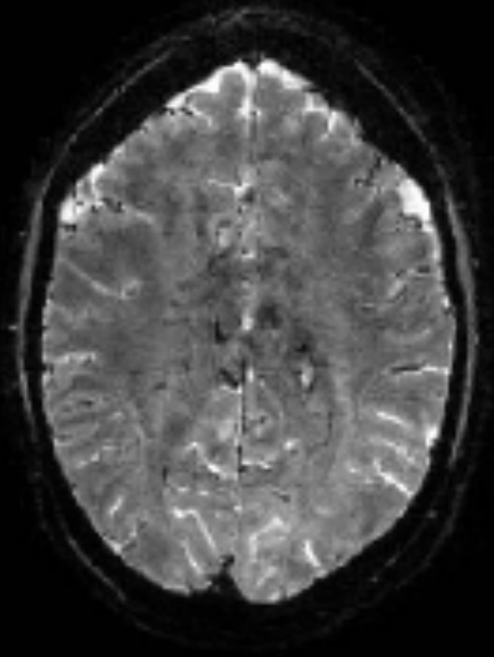
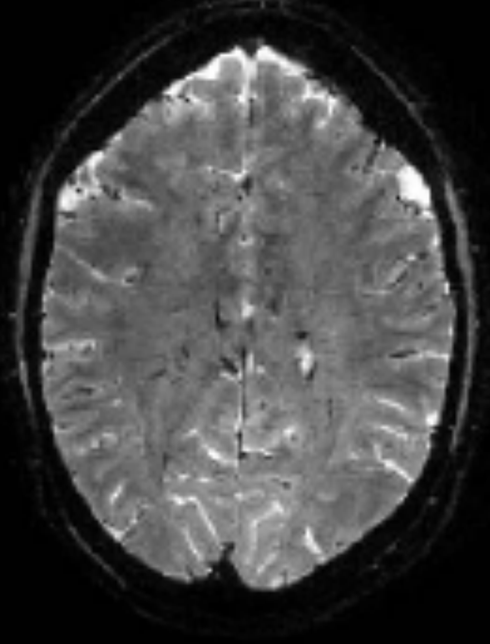


Bunch Encoding



Wave-CAIPI



Quantitative Susceptibility Mapping (QSM)

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

- And finds important applications in
  - ❖Tissue iron quantification[1] (Multiple Sclerosis, Huntington's, Alzheimer's)
  - ❖Vessel oxygenation estimation[2]
  - ❖Tissue contrast enhancement (~SWI[3])

- Susceptibility mapping relies on phase signal from a 3D Gradient Echo (GRE) acquisition

[1] Langkammer C *et al.*, Neuroimage 2012

[2] Fan AP *et al.*, MRM 2013

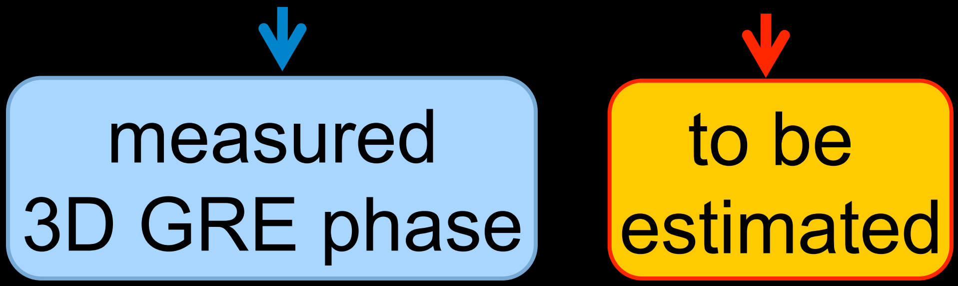
[3] Haacke EM *et al.*, MRM 2004

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],

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



measured 3D GRE phase

to be estimated

F: Discrete Fourier Transform

D: susceptibility kernel

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

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

Quantitative Susceptibility Mapping (QSM)

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

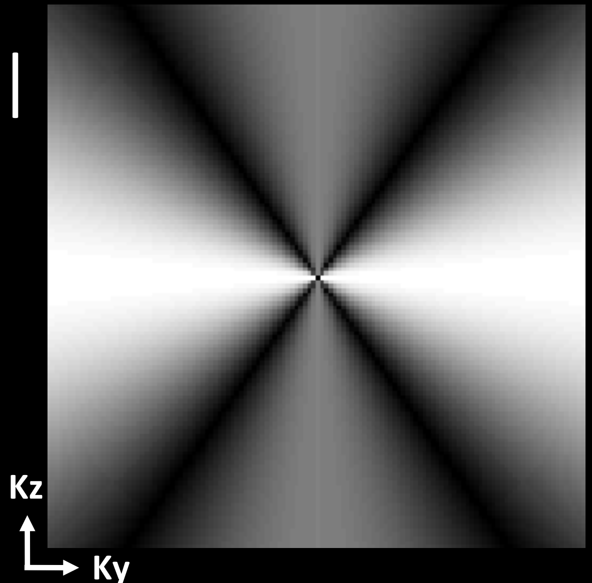
- Estimation of the susceptibility map χ from the unwrapped phase φ involves solving an inverse problem,

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

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

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

|D|



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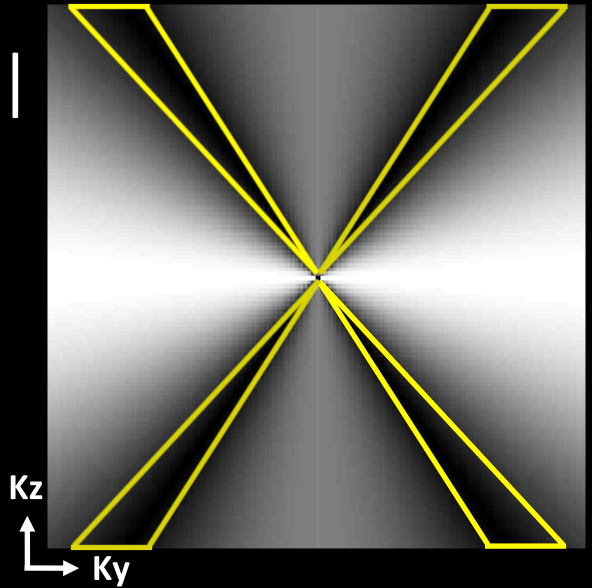
- Undersampling is due to physics

  Not in our control



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,

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

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

- QSM relies on phase signal from a 3D 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:

T_{acq} = 2.3 min at R=3×3

Wave-CAIPI accelerated QSM

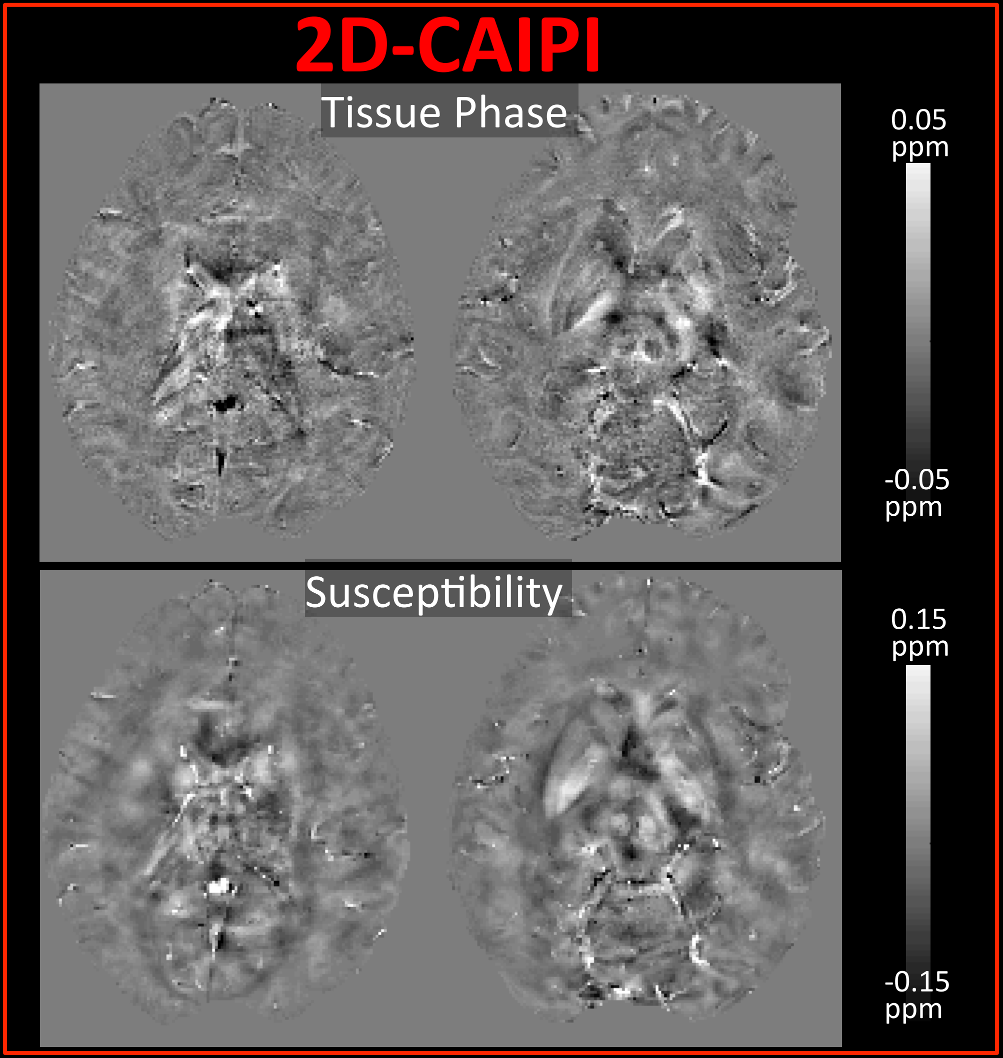
- Compare in vivo phase and QSM from Wave-CAIPI, 2D-CAIPI and Bunch Phase Encoding:
  - At 3T and 7T
  - R = 3x3 acceleration, scan time = 2.3 min
  - 1 mm isotropic resolution
- Phase Processing:
  - Laplacian unwrapping[1] and
  - SHARP filtering for background removal[2]

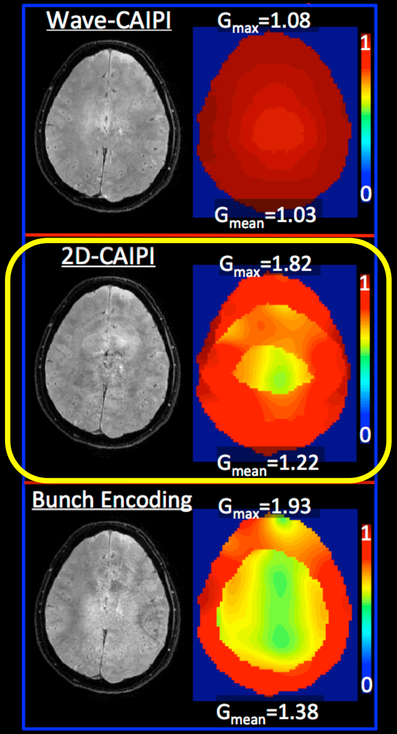
14 seconds

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

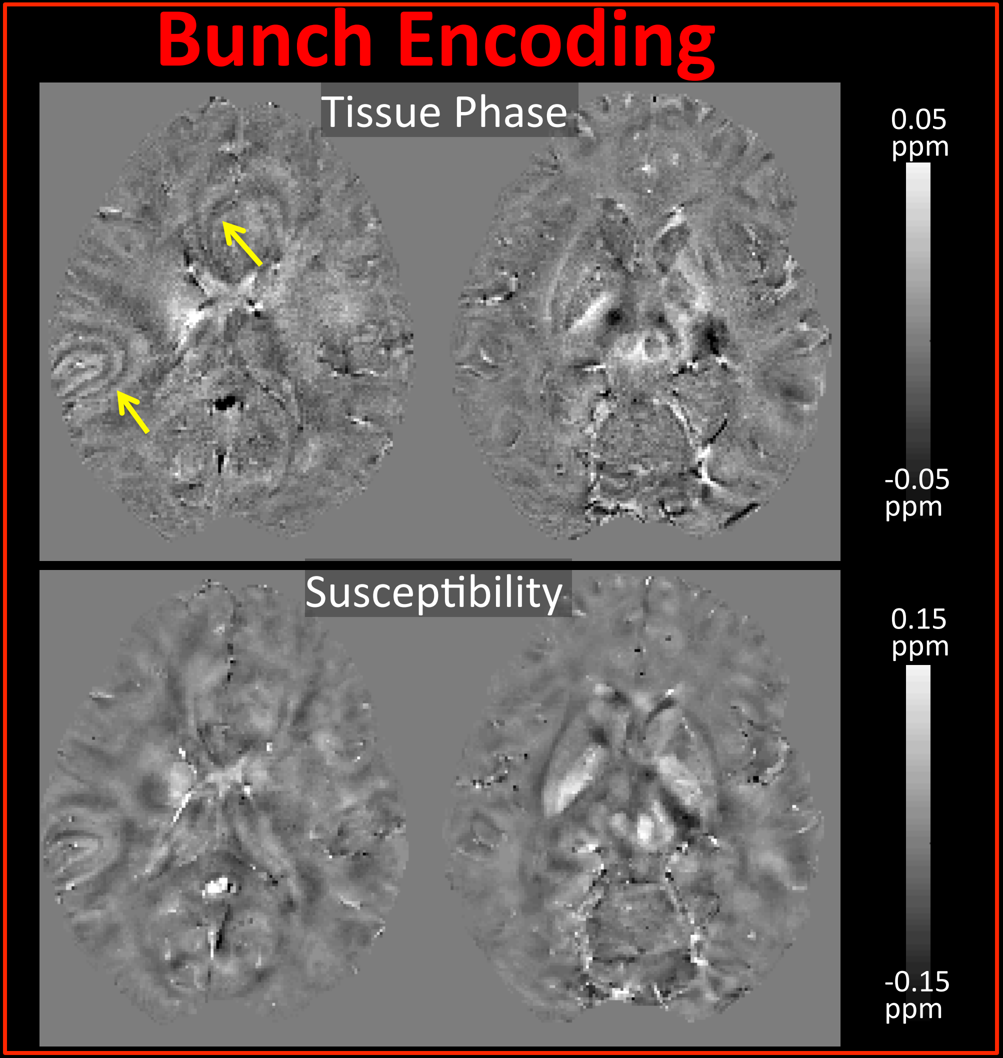
32 seconds

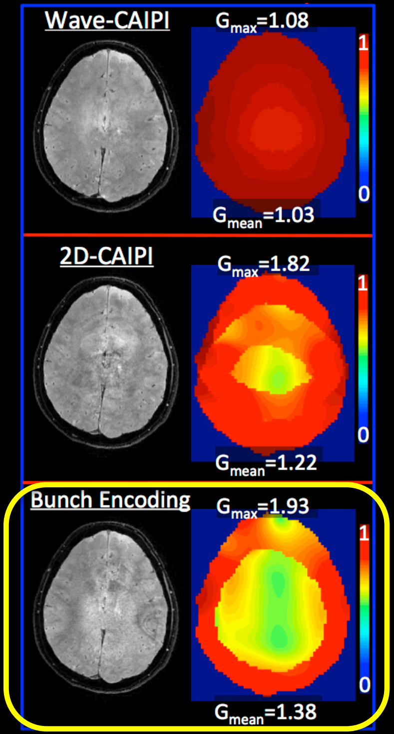
3 Tesla, R=3x3, 1 mm iso, 2.3 min acq



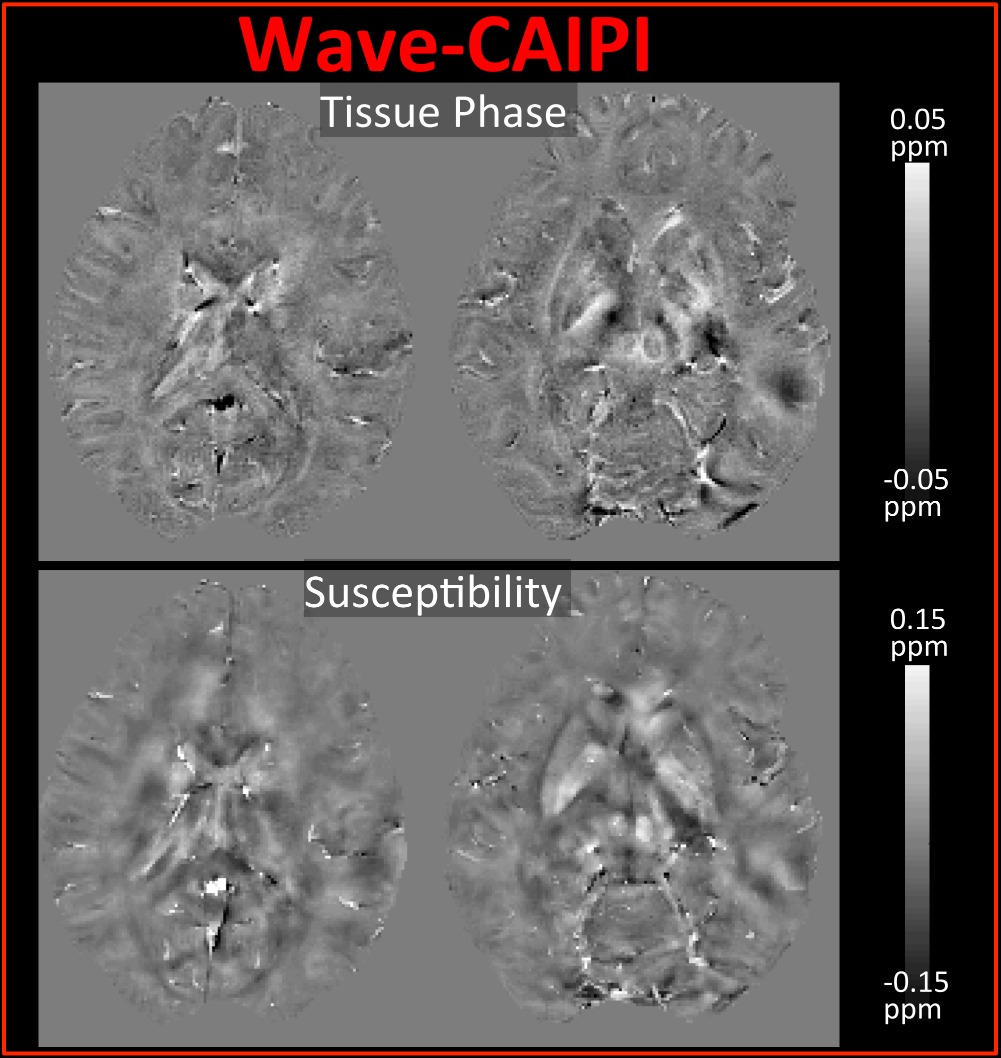


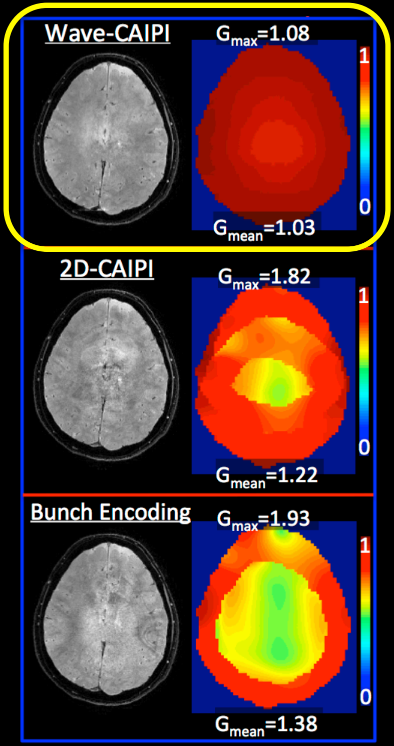
3 Tesla, R=3x3, 1 mm iso, 2.3 min acq



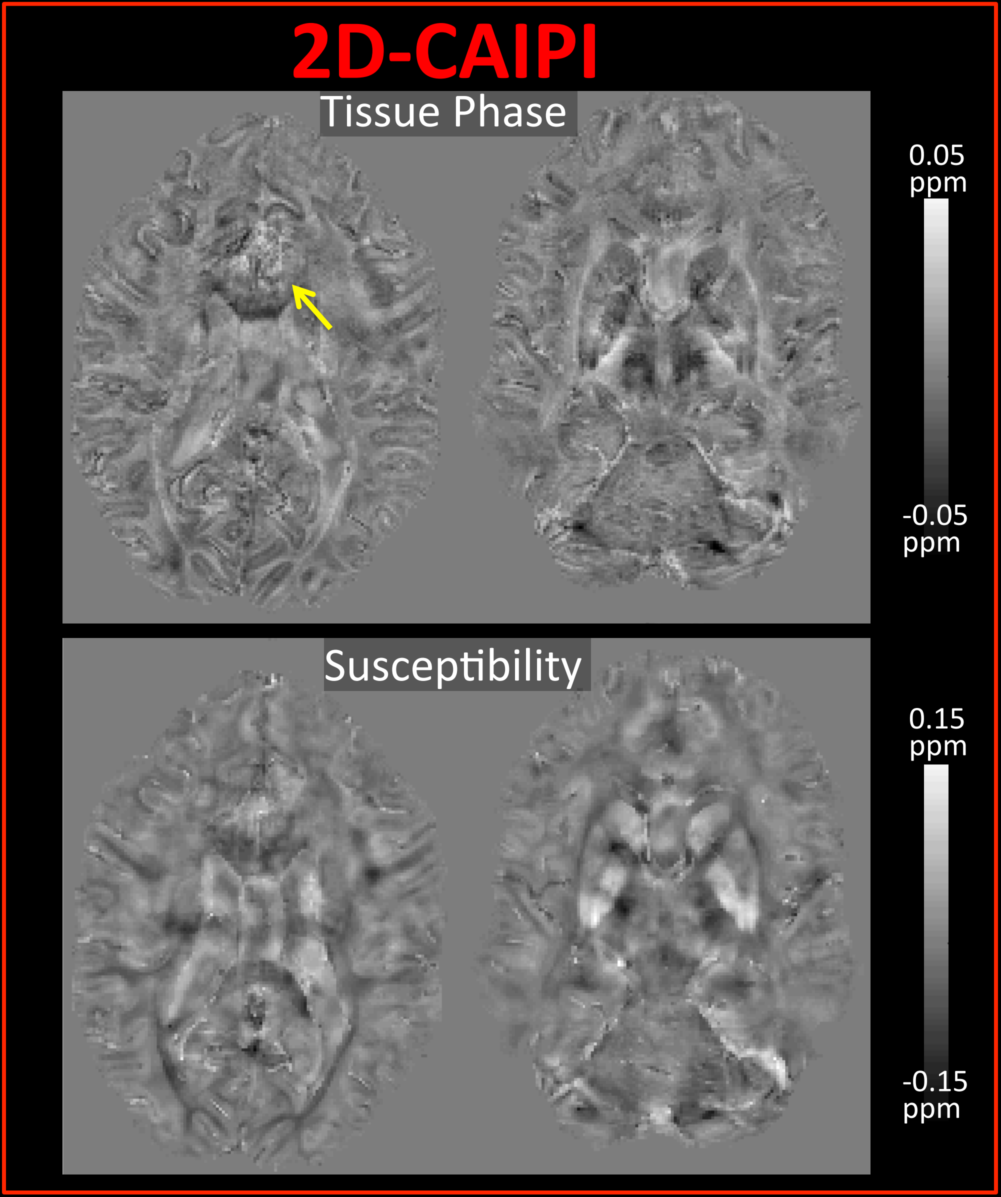


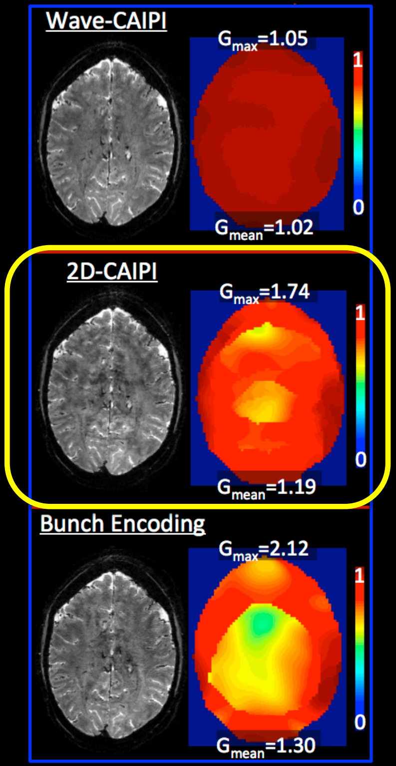
3 Tesla, R=3x3, 1 mm iso, 2.3 min acq





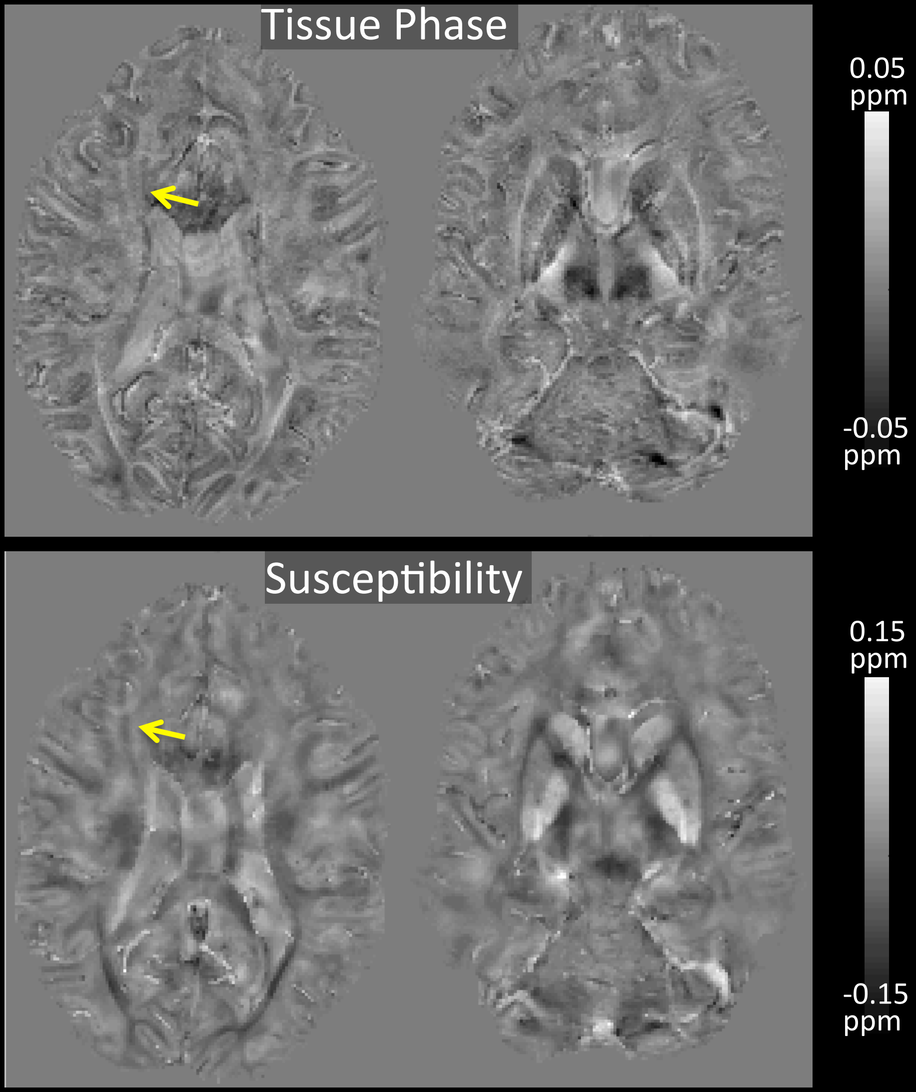
7 Tesla, R=3x3, 1 mm iso, 2.3 min acq

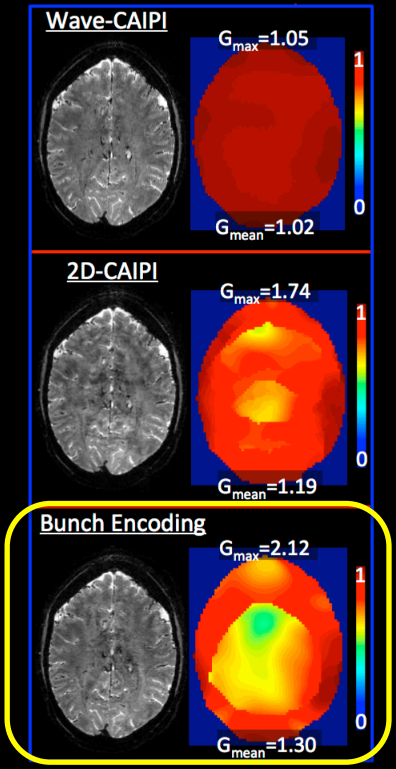




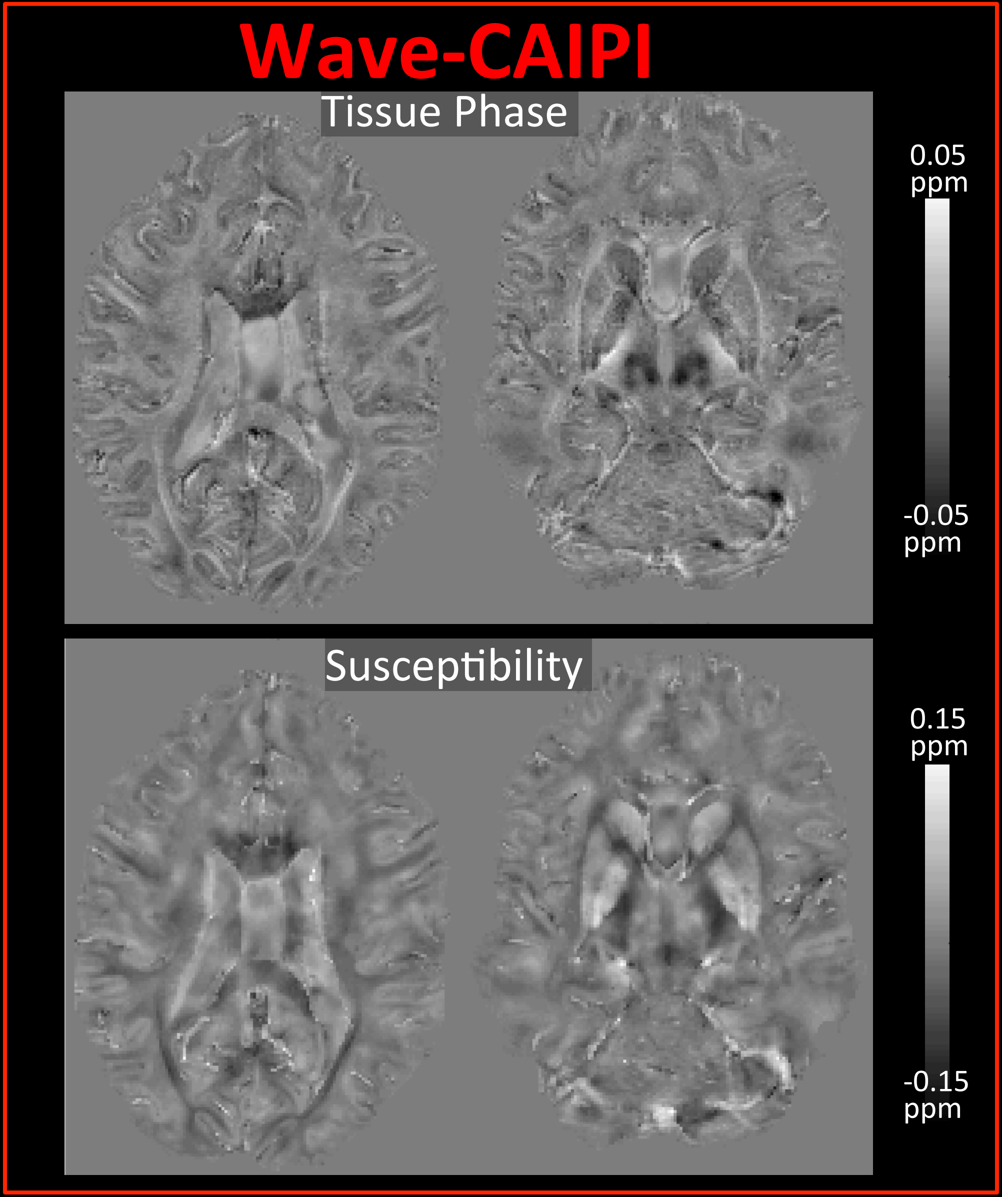
7 Tesla, R=3x3, 1 mm iso, 2.3 min acq

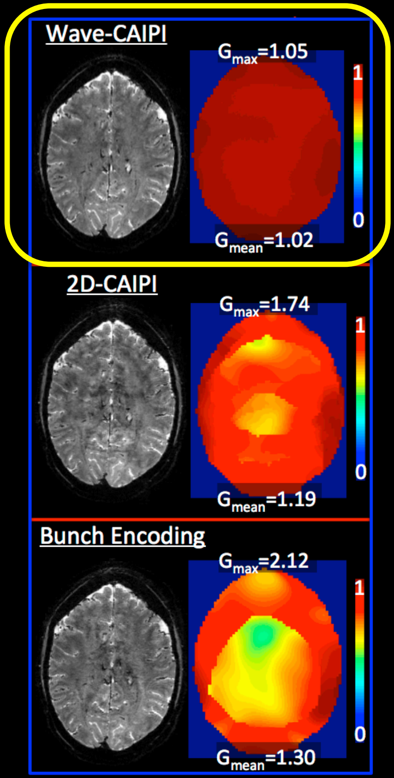
Bunch Phase





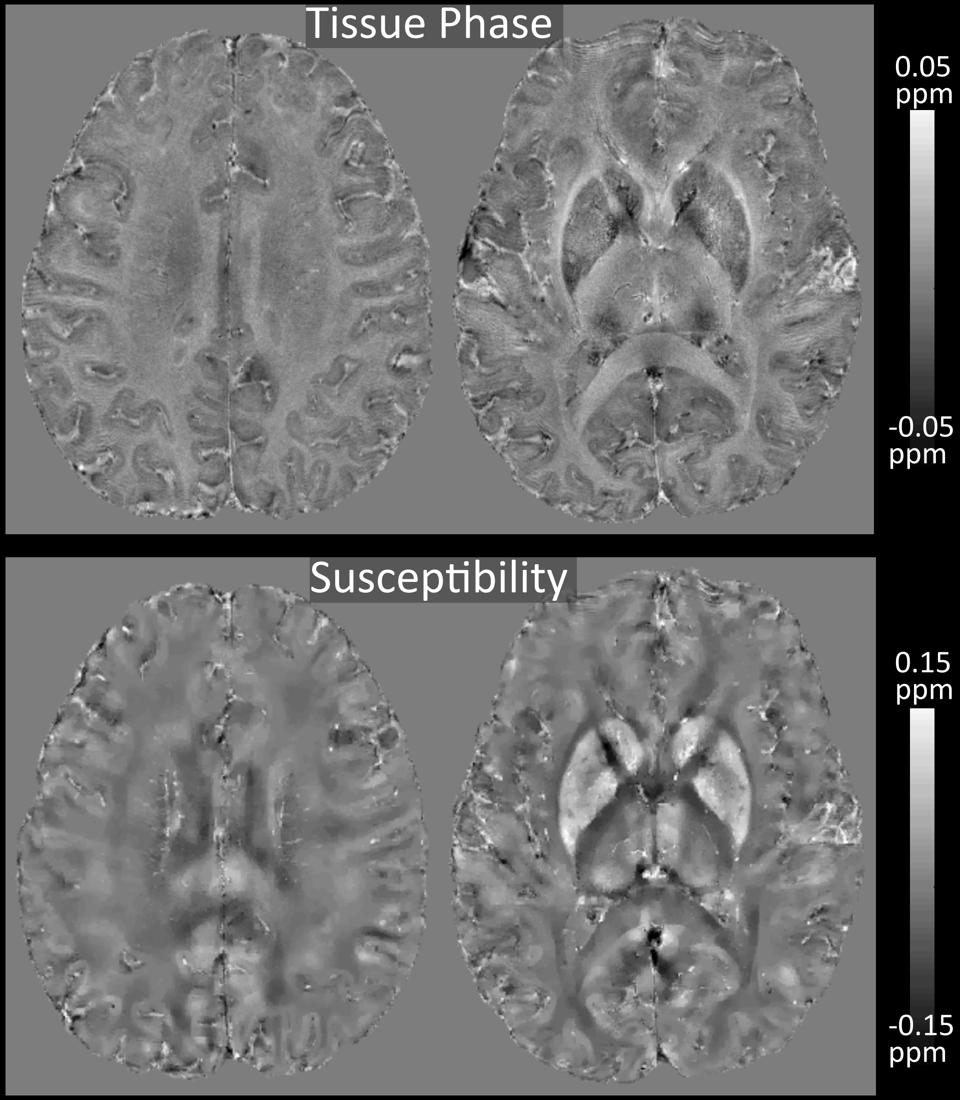
7 Tesla, R=3x3, 1 mm iso, 2.3 min acq





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

Wave-CAIPI



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