Wave-CAIPI for efficient TSE and QSM acquisitions with application in brain tumors

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Acknowledgement

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Overview

- Improved controlled aliasing with Wave-CAIPI

- 3D Wave-CAIPI:

Whole-brain 0.5mm iso 3D-Gradient Echo (GRE) in 5 min

- SMS Wave-CAIPI:

Whole-brain 1mm iso Turbo Spin Echo (TSE) in 70 sec

- Preliminary data for pediatric brain tumor imaging

Insights

- Wave-CAIPI dramatically reduces the g-factor SNR penalty in both 3D and SMS acquisitions

- Neuroimaging application of Wave-CAIPI is powerful
  - Highly accelerated 3D-GRE enables whole-brain Quantitative Susceptibility Mapping (QSM) with high-resolution and high-contrast
  - SMS at high MultiBand (MB) factor with novel pulse design enables whole-brain isotropic TSE with high-resolution and low-SAR

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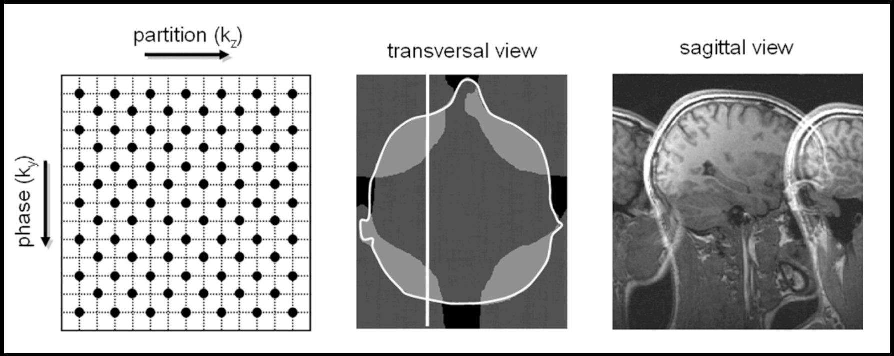
Controlled Aliasing in Parallel Imaging (CAIPI)

Increase distance btw aliasing voxels to make better use of 3D coil sensitivities

3D imaging

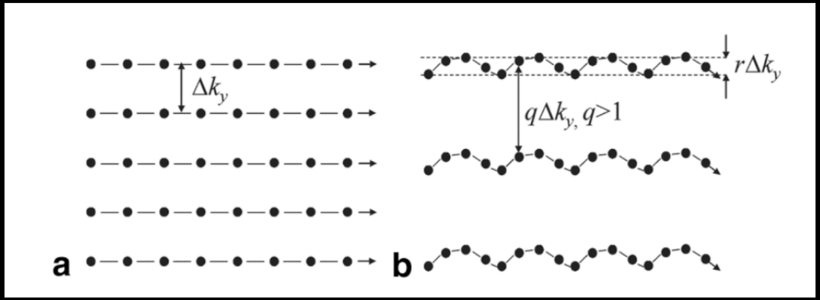
2D-CAIPI[1] (y-z)

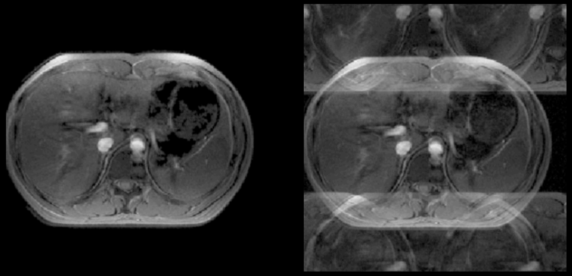


2D imaging

Bunched Phase Encoding[2]

Zigzag sampling[3] (x-y)

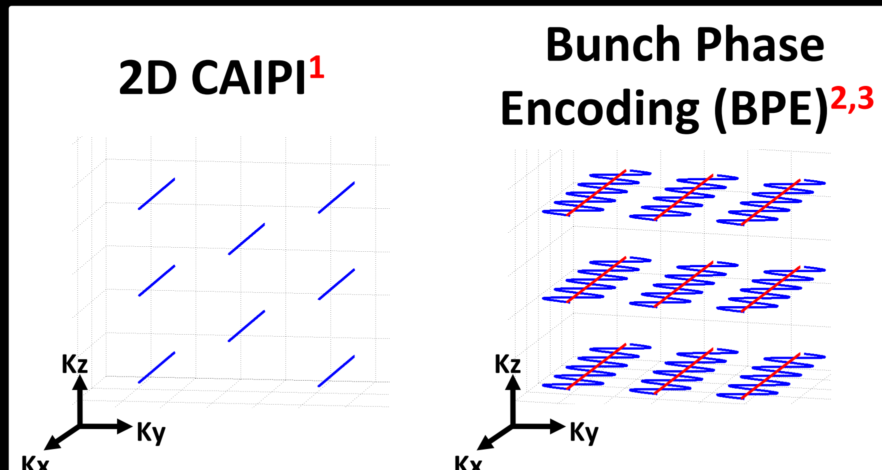




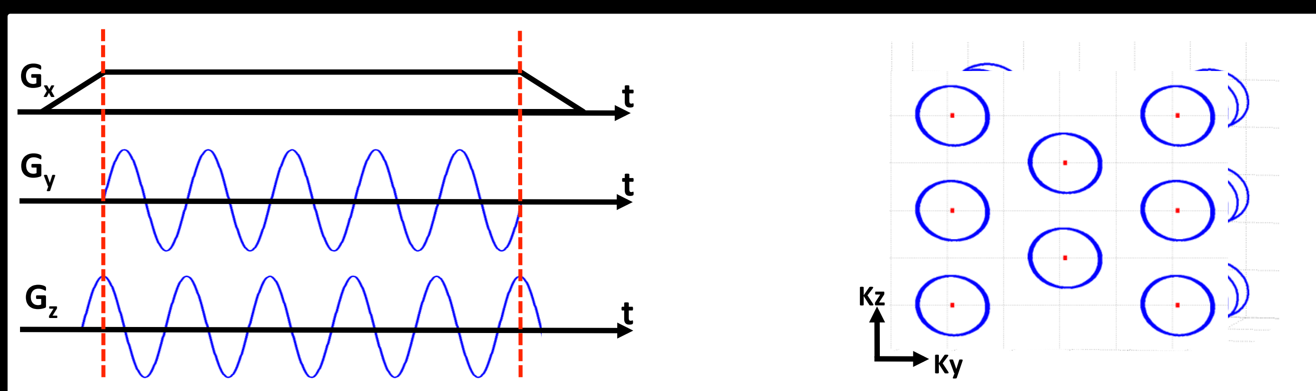
1. Breuer FA. et al, MRM 2006. 2. Moriguchi H. et al, MRM 2006. 3. Breuer FA. et al, MRM 2008.

Wave-CAIPI Sampling[4]

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



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



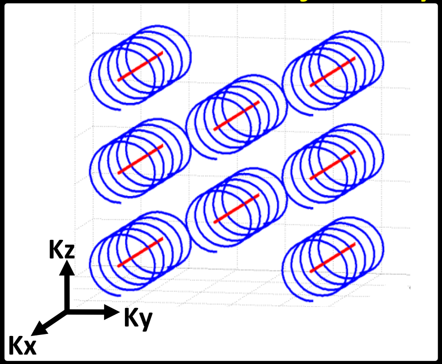
1. Breuer FA. et al, MRM 2006 2. Moriguchi H. et al, MRM 2006 3. Breuer FA. et al, MRM 2008 4. Bilgic B. et al, MRM 2014

Wave-CAIPI Improves G-factor

- Wave-CAIPI corkscrew trajectory incurs voxel spreading in the readout (x) direction

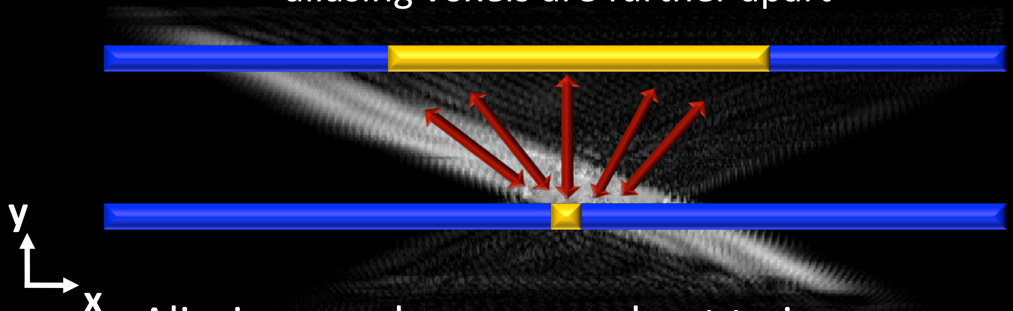
- For accelerated acquisitions, this spreads the aliasing in all 3D dimensions to substantially improve parallel imaging

Wave-CAIPI trajectory



Wave-CAIPI: R=2 acceleration

aliasing voxels are further apart



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

Improved G-Factor

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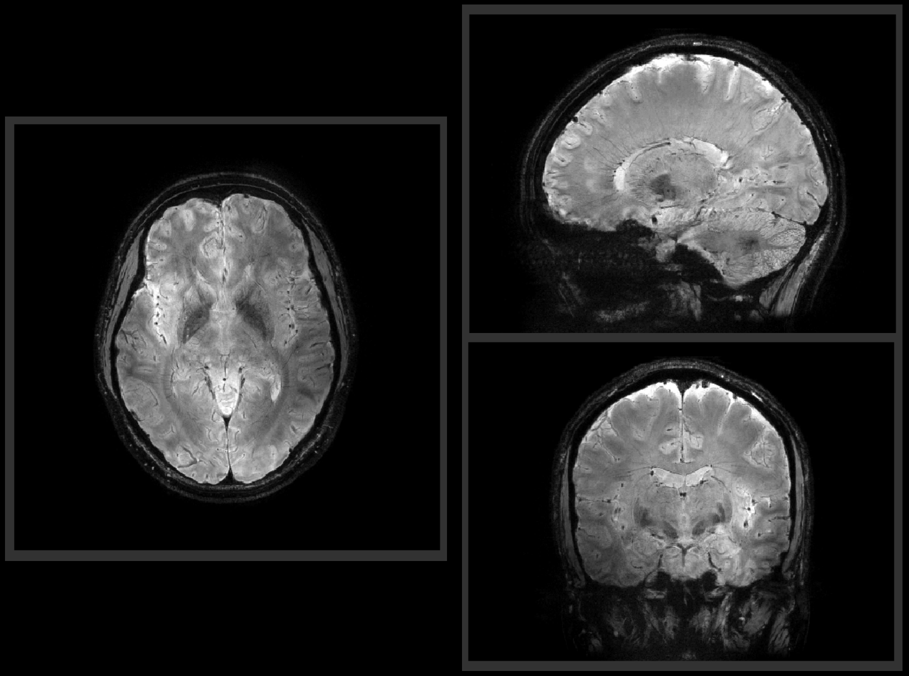
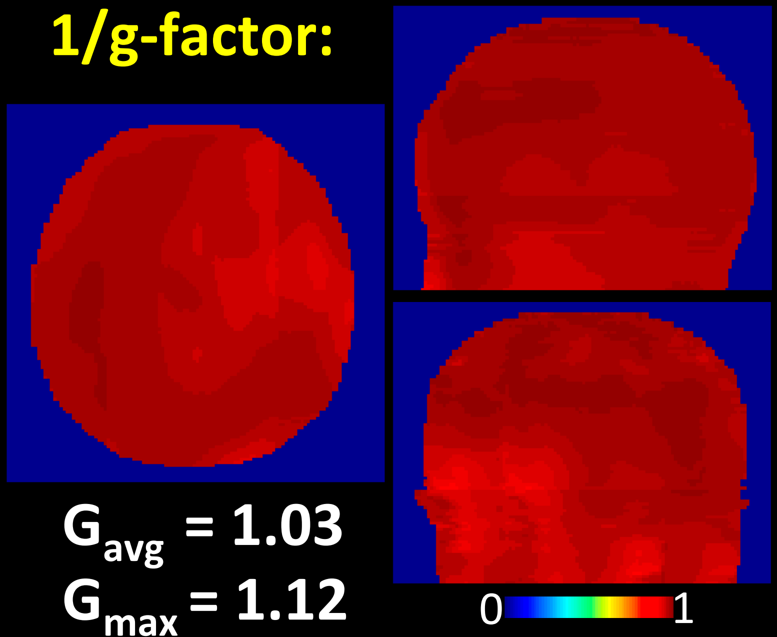
Rapid whole-brain, high resolution 3D-GRE @ 7T, 32 ch array





- Wave-CAIPI at R = 5×3 fold acceleration
- 5:35 min @ 0.5 mm iso
- TE / TR = 19.5 / 29 ms
- **Maximum g-factor noise amplification is 12%**

3D-GRE Phase for High CNR Imaging

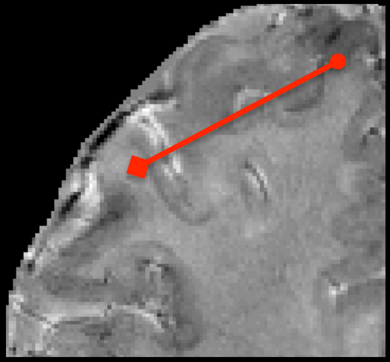
- Phase signal from 3D-GRE acquisition provides dramatic contrast-to-noise ratio (CNR) boost over magnitude [1]

3D-GRE Magnitude

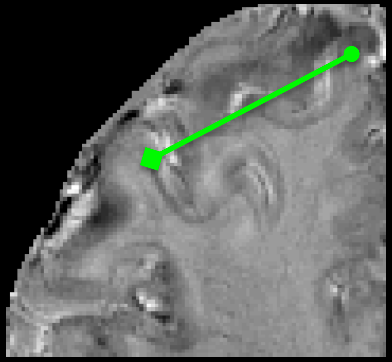
3D-GRE Phase

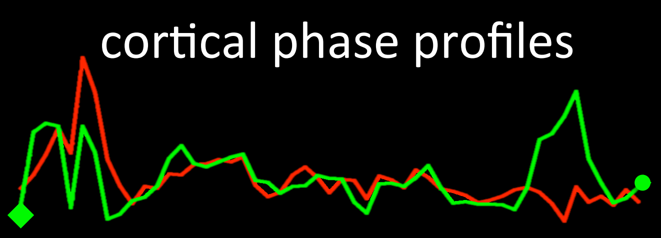
- Phase contrast is non-local, depends on head orientation relative to B0 and local tissue geometry

Orientation #1



Orientation #2





[1] Duyn J *et al.*, PNAS 2007

3D-GRE Phase for High CNR Imaging

- Phase signal from 3D-GRE acquisition provides dramatic contrast-to-noise ratio (CNR) boost over magnitude [1]

3D-GRE Magnitude | 3D-GRE Phase | QSM

- Phase contrast is non-local, depends on head orientation relative to B0 and local tissue geometry

- Quantitative Susceptibility Mapping (QSM) resolves the orientation dependence, and yields exquisite & quantitative contrast

[1] Duyn J *et al.*, PNAS 2007

Quantitative Susceptibility Mapping (QSM)

- QSM uses 3D-GRE phase to estimate the underlying magnetic susceptibility that gives rise to this phase signal

- Estimation of the susceptibility χ from the tissue phase φ involves solving an inverse problem[1],

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

measured

estimate

φ: 3D-GRE phase
F: Discrete Fourier Transform
D: susceptibility kernel

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

Quantitative Susceptibility Mapping (QSM)

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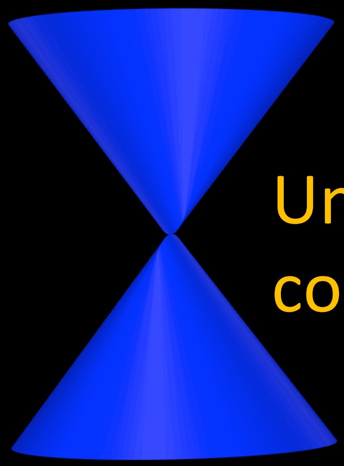
- Estimation of the susceptibility $\boldsymbol{\chi}$ from the tissue phase $\boldsymbol{\varphi}$ involves solving an inverse problem[1],

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

- Inversion is made difficult by zeros in kernel **D**

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

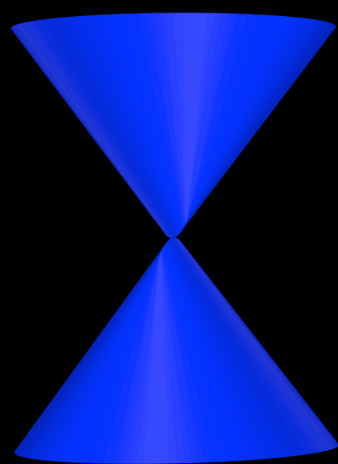


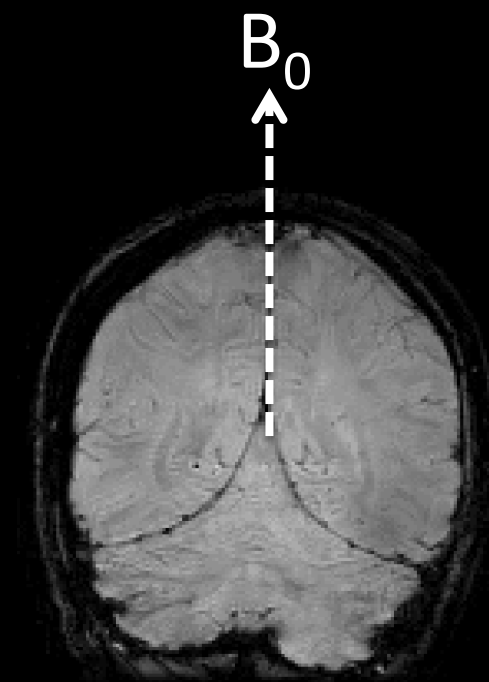
Undersampling on conical surface

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

QSM with Multiple Head Orientations

- To mitigate the undersampling in QSM inverse problem, acquire multiple 3D-GRE volumes at different head positions





Neutral

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

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

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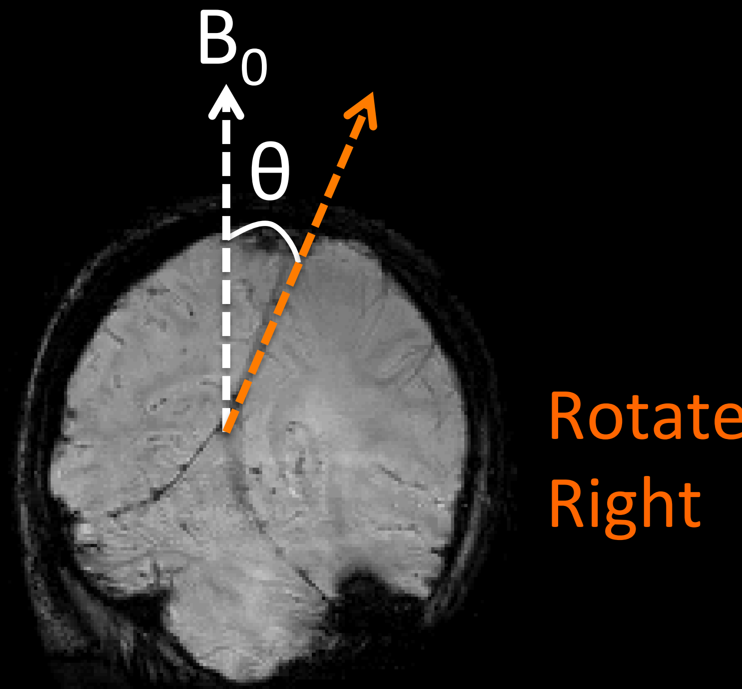

$$\delta_\theta = F^{-1} D_\theta F \chi$$

$$D_\theta = \frac{1}{3} - \frac{(k_z \cos\theta + k_y \sin\theta)^2}{k_x^2 + k_y^2 + k_z^2}$$

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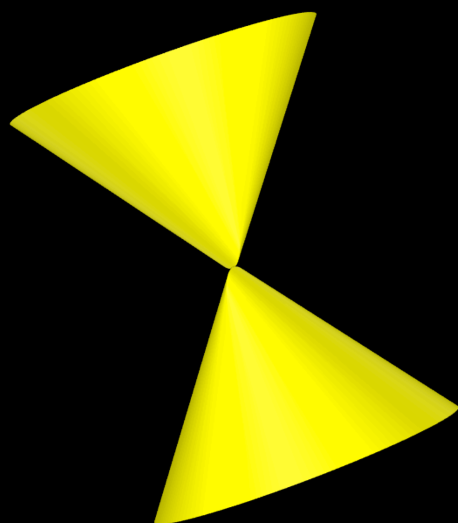

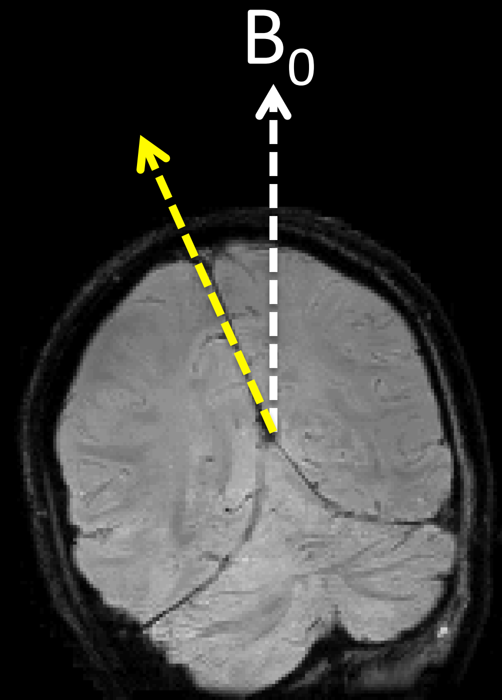

Rotate Left

$$\delta_\theta = F^{-1} D_\theta F \chi$$

$$D_\theta = \frac{1}{3} - \frac{(k_z \cos\theta + k_y \sin\theta)^2}{k_x^2 + k_y^2 + k_z^2}$$

QSM with Multiple Head Orientations

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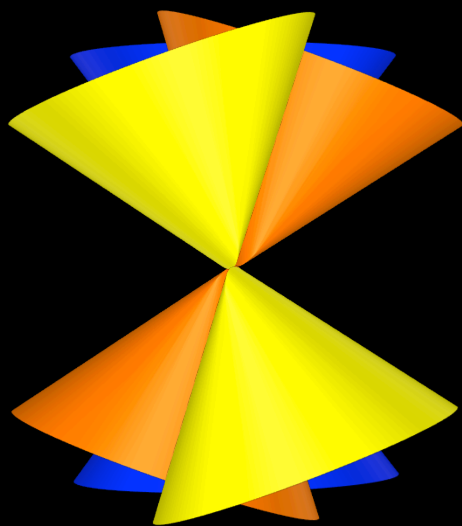
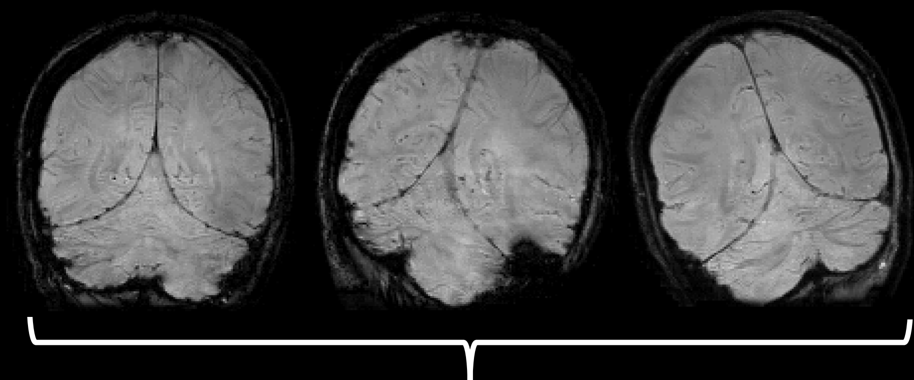




Combine multi-orientation for QSM inversion

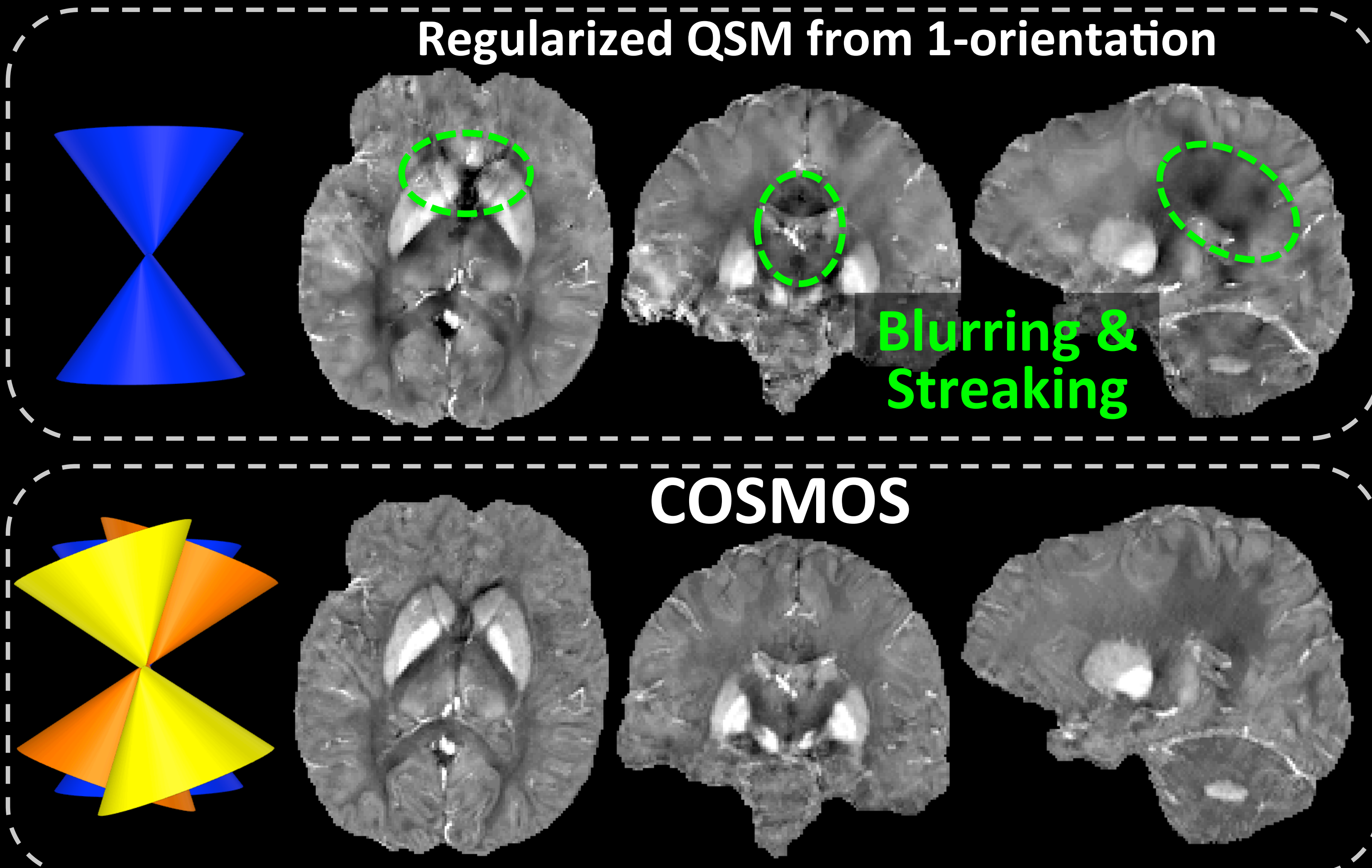
- Undersampling is substantially mitigated

  Calculation of Susceptibility Through Multiple Orientation Sampling (COSMOS) [1,2]

[1] T Liu et al, MRM'09
[2] T Liu et al, MRM'11

COSMOS v Single-Orientation

- COSMOS yields exquisite susceptibility maps
- **Whole-brain COSMOS acquisition substantially increases scan time**



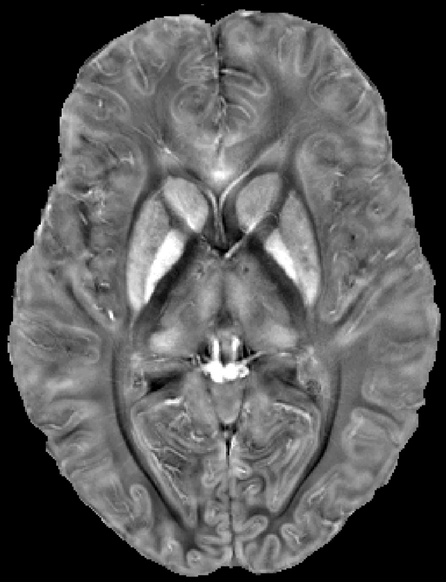
Towards in vivo Histology with QSM

- High-resolution COSMOS at ultra high field yields superb contrast to reflect the underlying anatomy [1-3]

- **High-resolution COSMOS requires > 1 hour of scanning [1-3]**

- **For the first time, Wave-CAIPI enables whole-brain COSMOS in clinically relevant scan time**

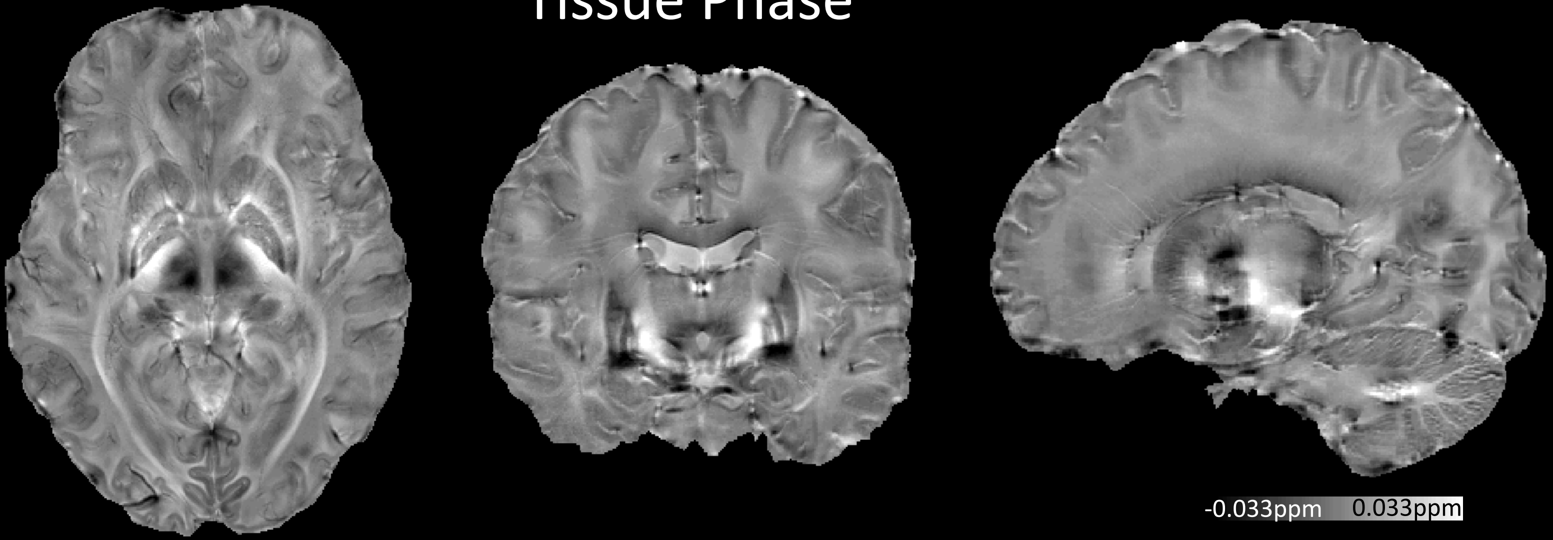
- Whole-brain, high resolution COSMOS @ 7T
  - 5:35 min / rotation @ 0.5 mm iso
  - **20 min total protocol for 3-orientations**



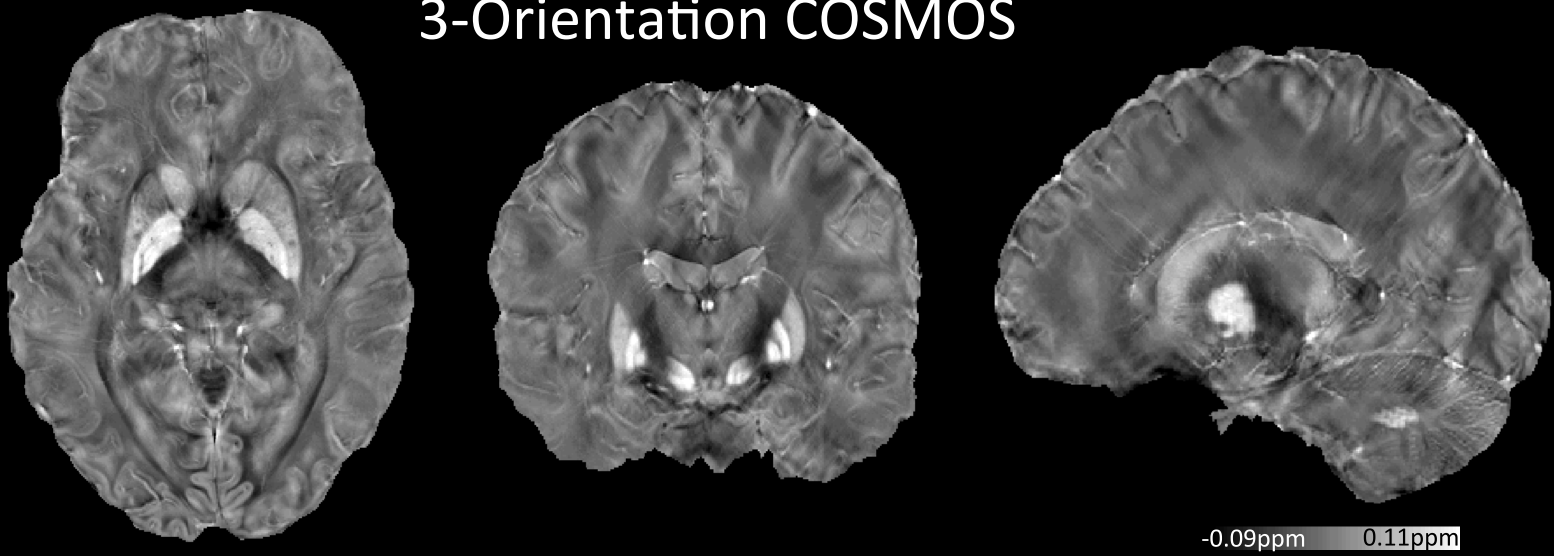
[1] A Deistung et al, NIMG'12 [2] D Khabipova et al, NIMG'15 [3] A Deistung et al, Frontiers'13

Rapid whole-brain, high resolution COSMOS @ 7T

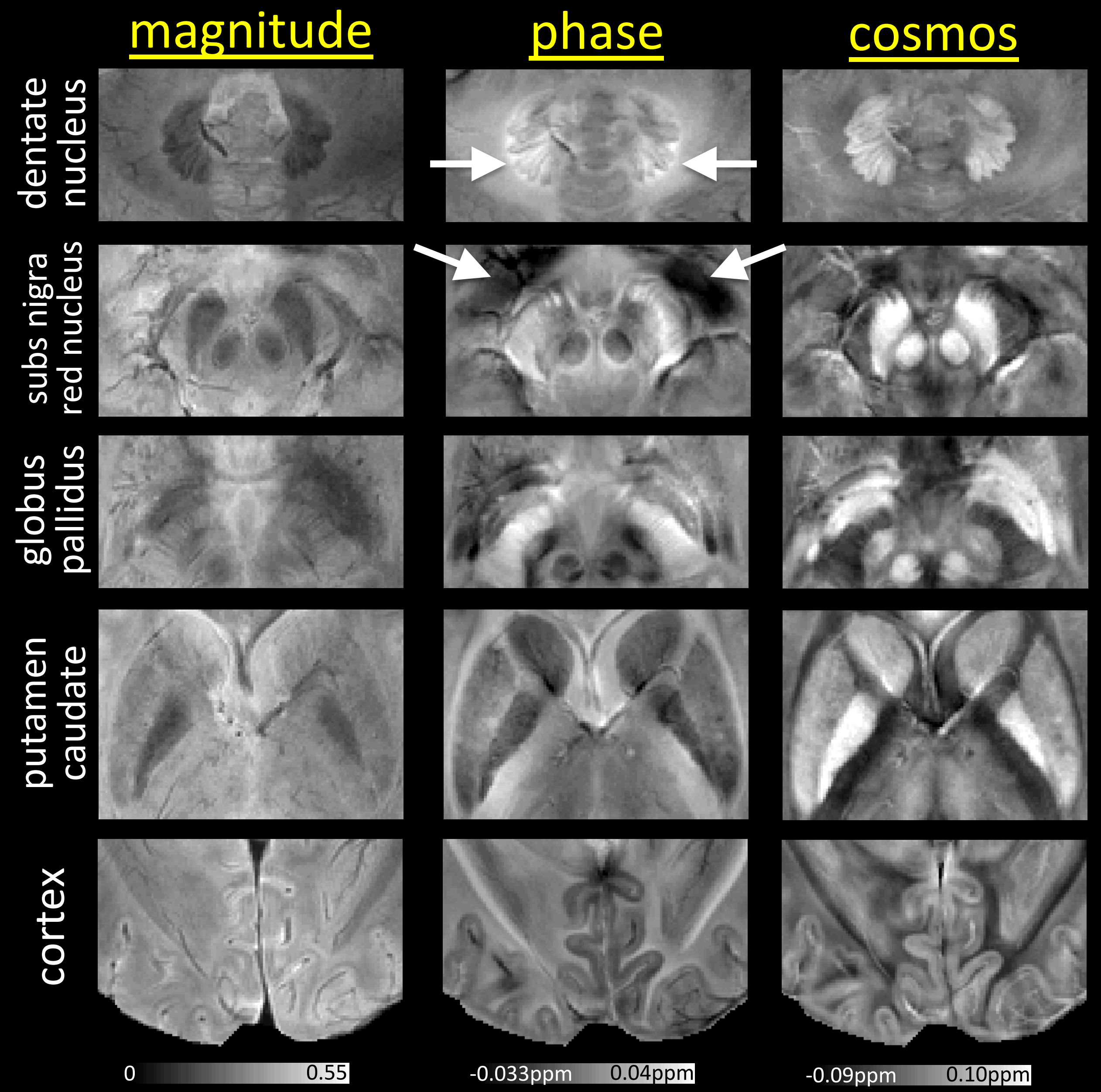
Tissue Phase



3-Orientation COSMOS



Rapid whole-brain, high resolution COSMOS @ 7T



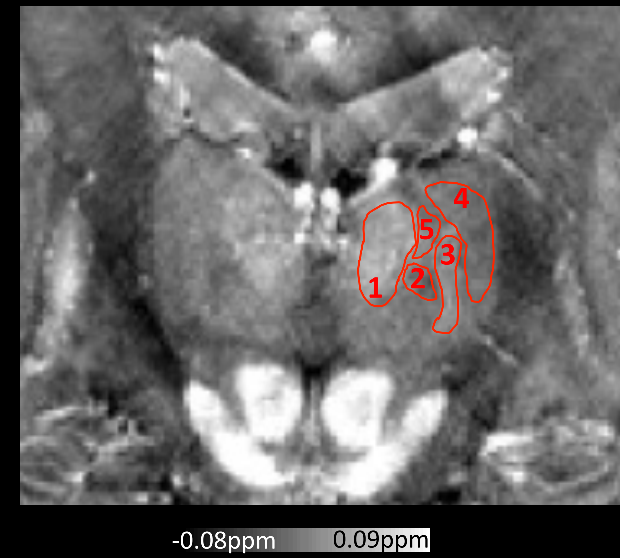
Rapid whole-brain, high resolution COSMOS @ 7T

Thalamic substructures

magnitude

phase

cosmos



1. Medial dorsal
2. Centromedian
3. Ventral posterior
4. Ventral lateral
5. Intralaminar nuclei

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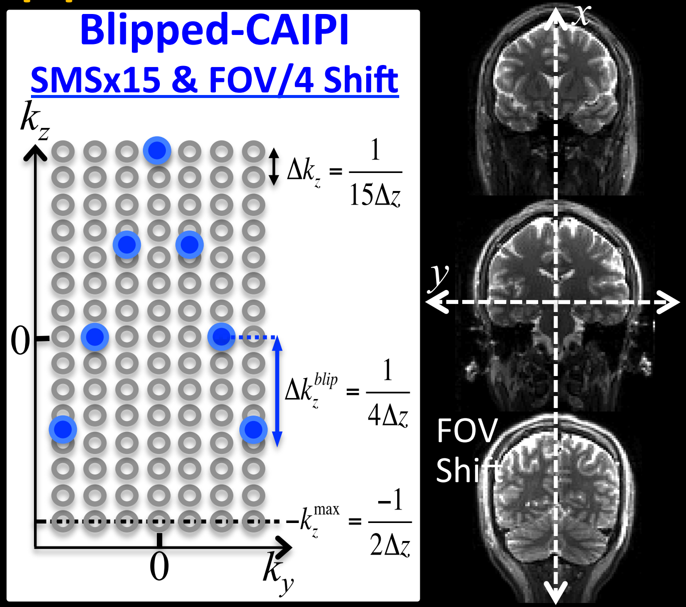
SMS Wave-CAIPI for Turbo Spin Echo (TSE)

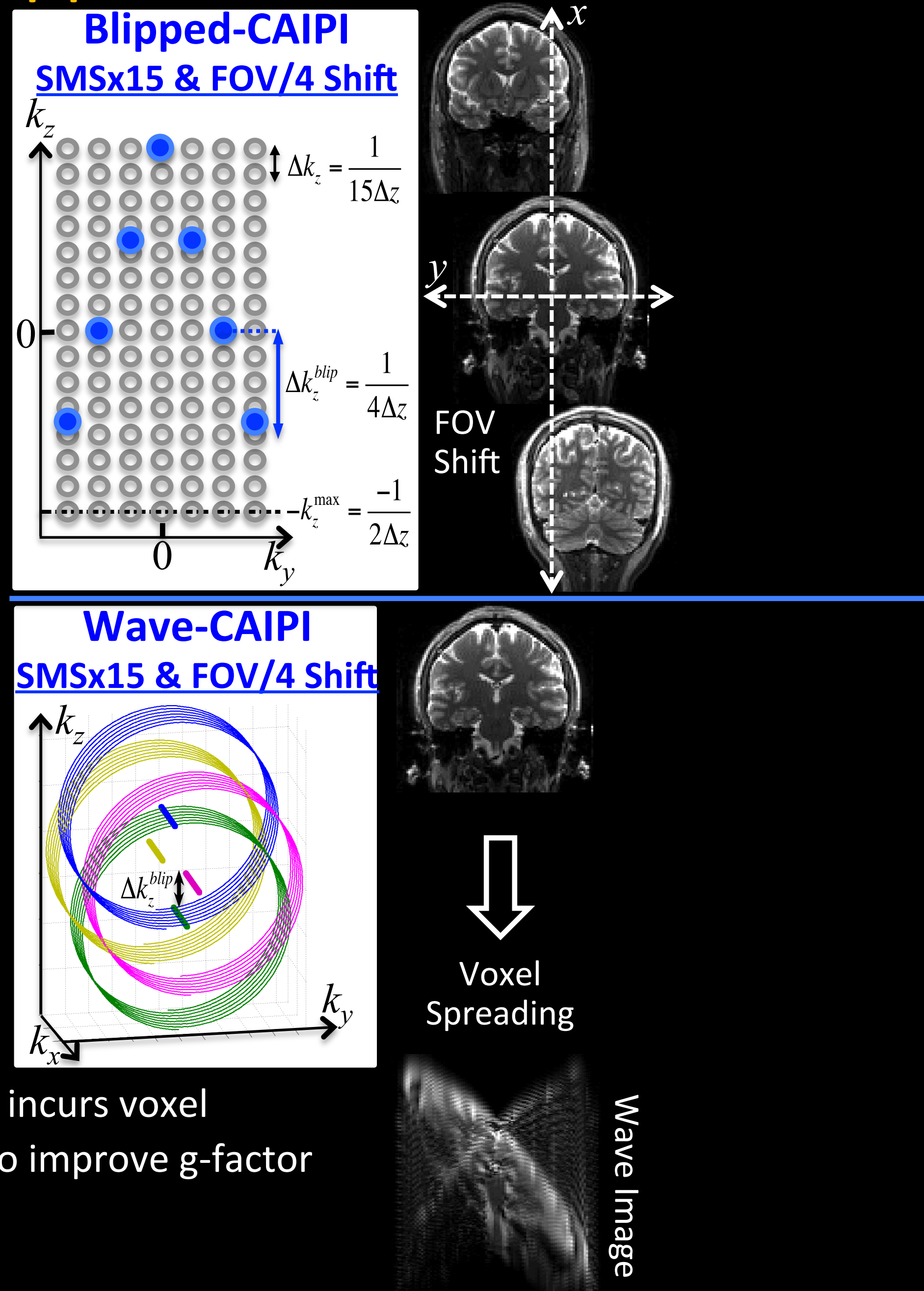
- TSE is the most commonly used clinical sequence, allowing rapid acquisition by sampling multiple k-space lines per 90° RF
- In-plane acceleration can improve efficiency, but suffers from intrinsic $\sqrt{R}$ SNR penalty and g-factor noise amplification
- SMS enables acceleration without $\sqrt{R}$ penalty, since number of k-space lines is not reduced
- SMS Wave-CAIPI further improves g-factor [1]
- MultiPINS pulses allow low-SAR refocusing [2]

[1] B Gagoski et al, MRM'15 [2] C Eichner et al, MRM'14

Blipped- and Wave-CAIPI for SMS

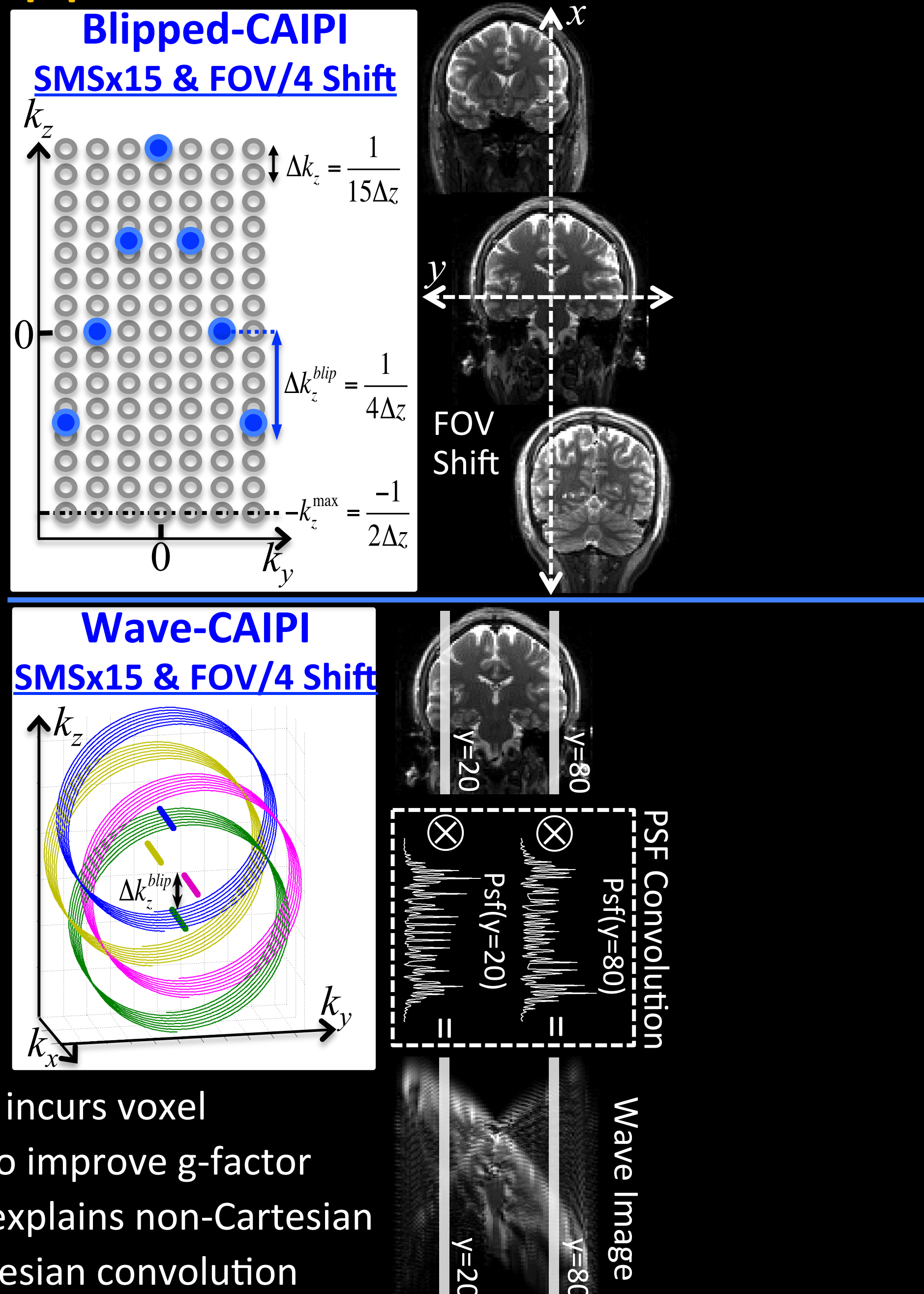


Blipped- and Wave-CAIPI for SMS



- Helix trajectory incurs voxel spreading in 3D to improve g-factor

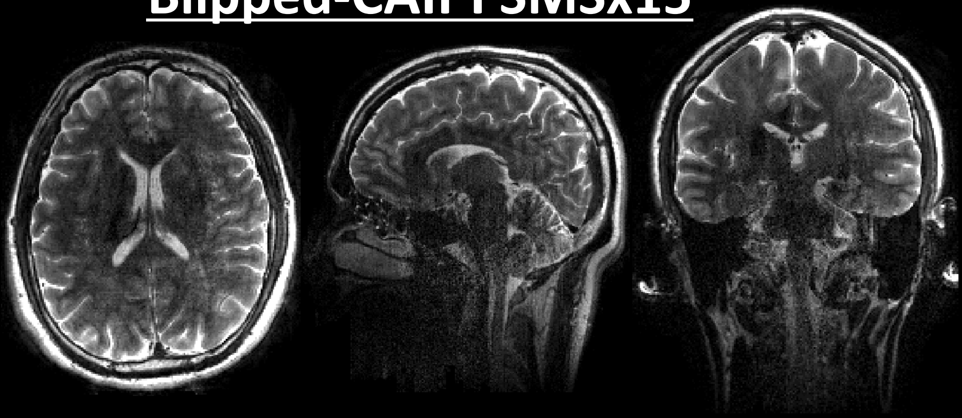
Blipped- and Wave-CAIPI for SMS



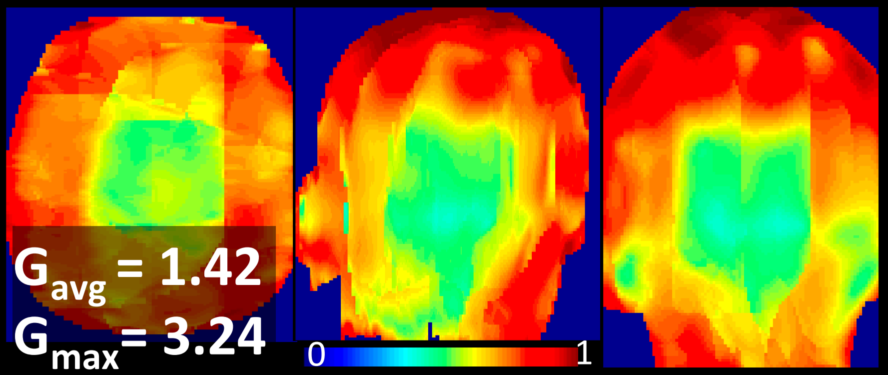
- Helix trajectory incurs voxel spreading in 3D to improve g-factor
- PSF formalism explains non-Cartesian sampling via Cartesian convolution

TSE @ 3T, 1 mm^3 voxels, T_{acq}=70 sec
SMSx15

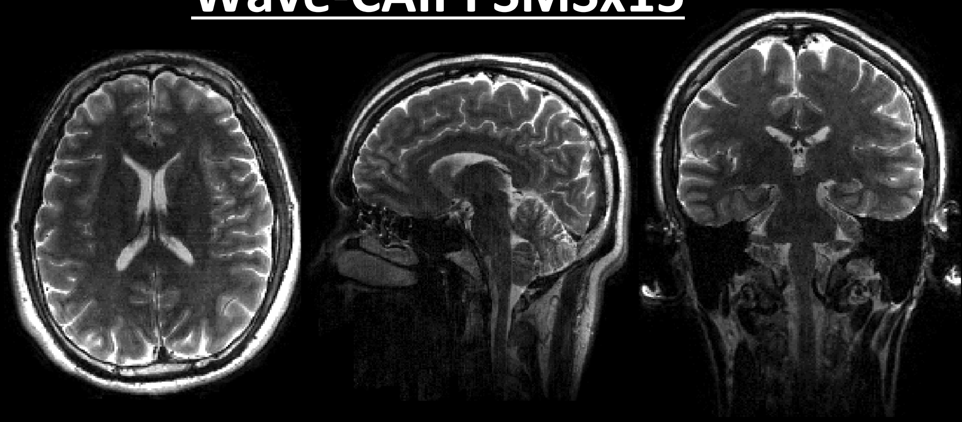
Blipped-CAIPI SMSx15



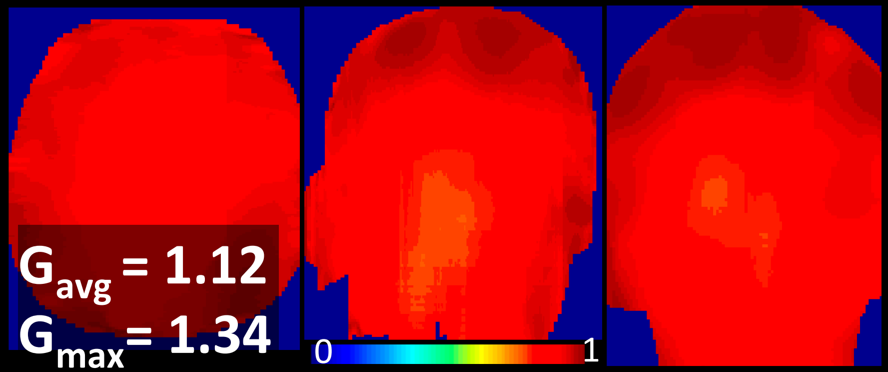
1/g-factor: Blipped-CAIPI SMSx15



Wave-CAIPI SMSx15



1/g-factor: Wave-CAIPI SMSx15



avg over 3mm slabs

TSE @ 1 mm^3 iso voxels, T_{acq} = 70 sec

SENSE
R=5x In-plane

both g-factor
and sqrt(R)
noise penalty

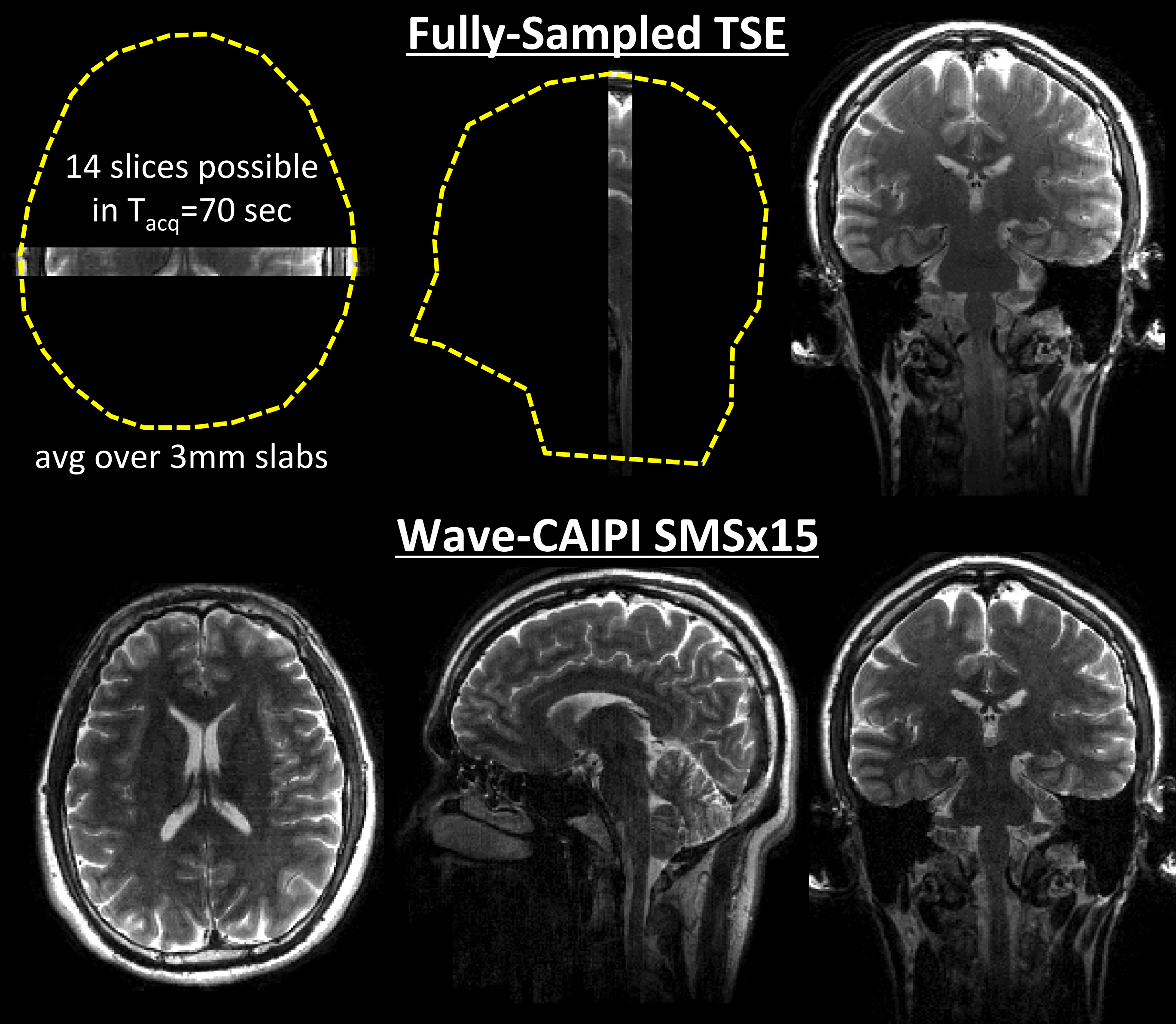
Blipped-CAIPI
SMSx15

only g-factor
no sqrt(R)
noise penalty

Wave-CAIPI
SMSx15

small g-factor
no sqrt(R)
noise penalty

SMS Wave-CAIPI at SMSx15 allows whole-brain TSE @ 1 mm^3 iso in 70 sec



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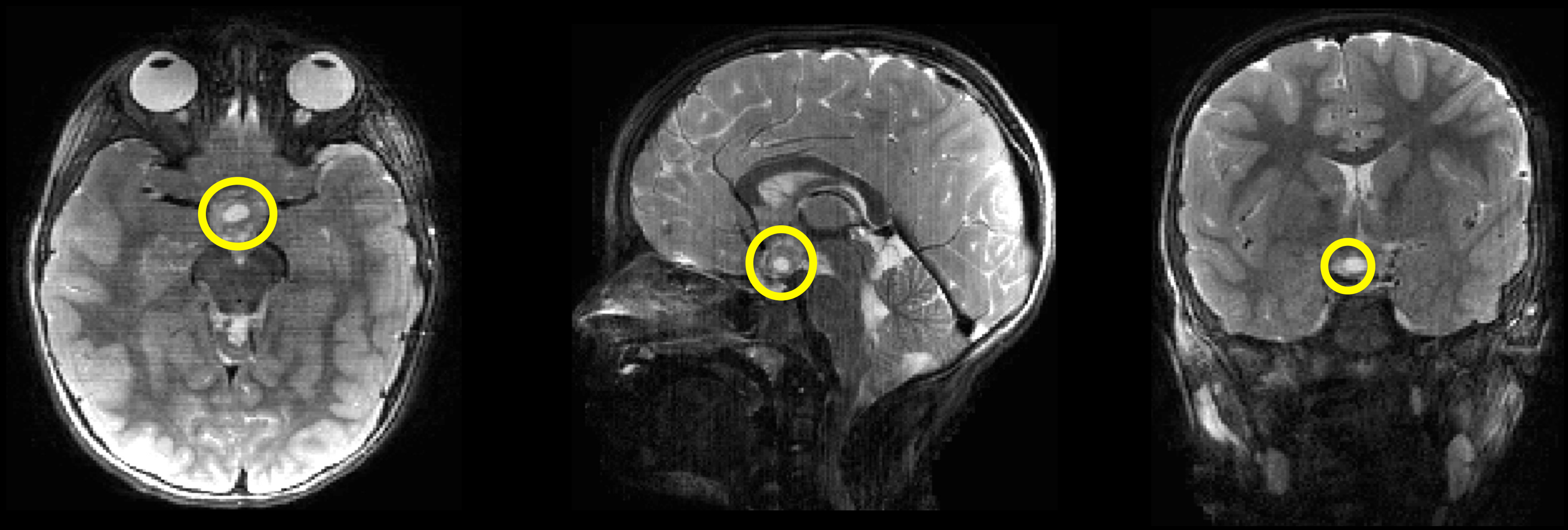
TSE: 15x SMS Wave-CAIPI: 1-mm iso in 70 sec

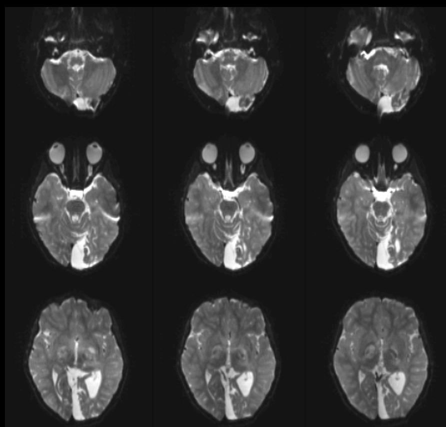
5 year old w/ Craniopharyngioma: monitoring exam



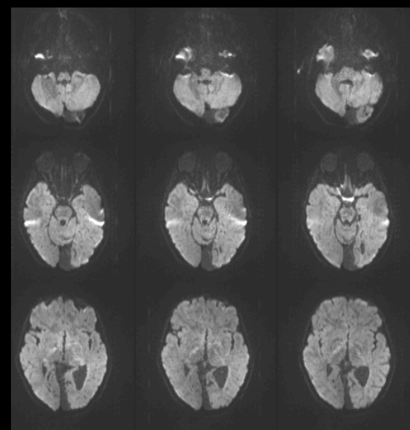
7 year old w/ tumor removed: monitoring exam

DTI w/ Blipped-CAIPI SMS-EPI

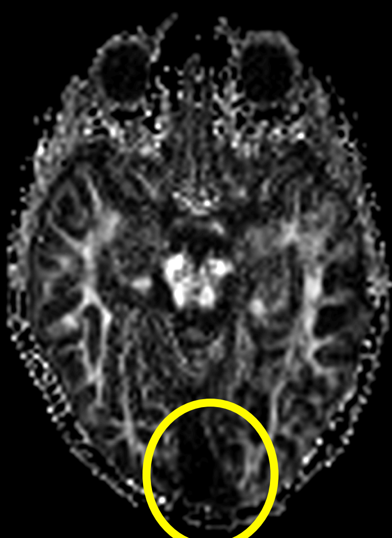
b 0

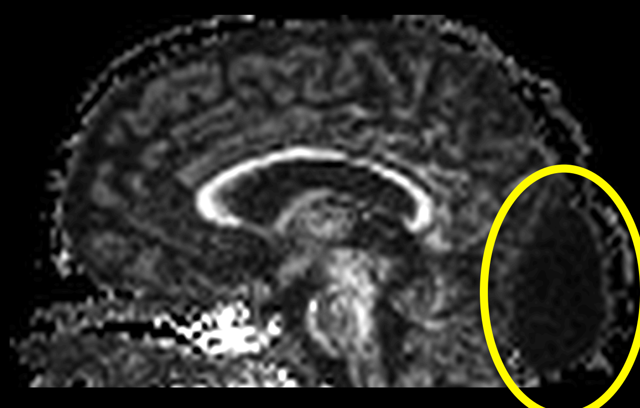


b 1k



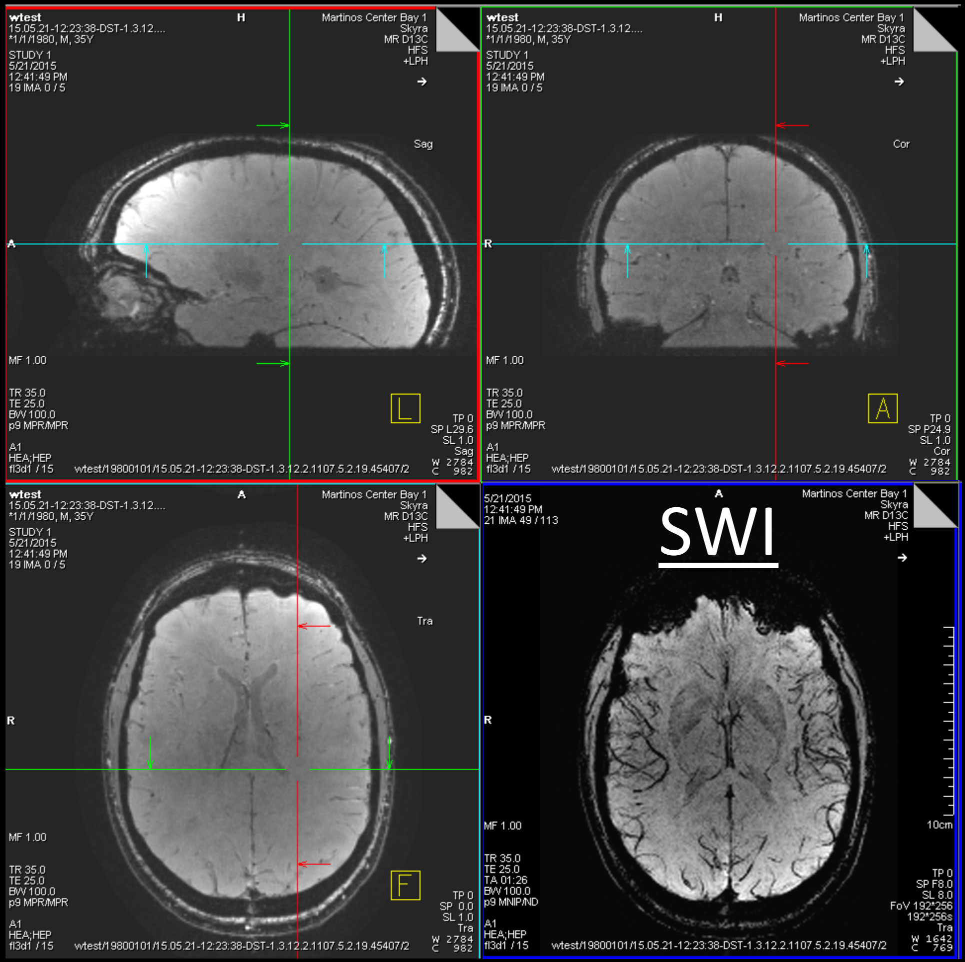
Functional Anisotropy (FA)





TSE: 15x SMS Wave-CAIPI

Online Recon for 3D-GRE Wave-CAIPI



R = 3x3 acceleration

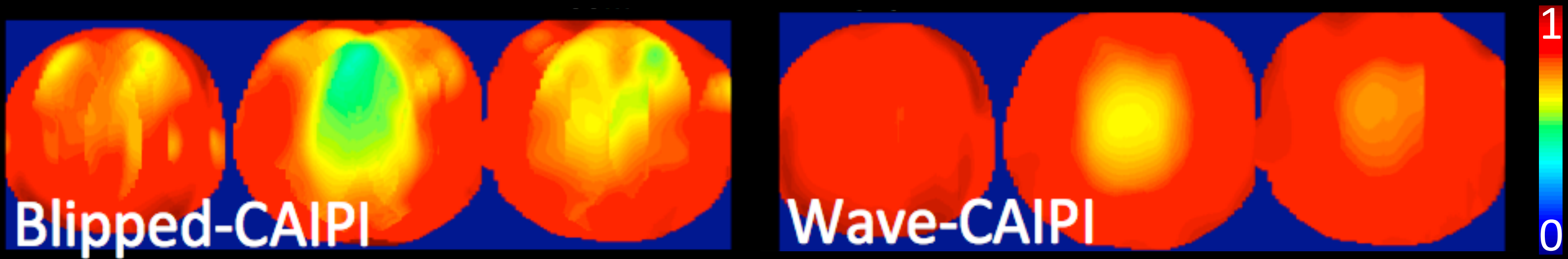
Acquisition: 1 mm iso in 90 seconds

Reconstruction: 80 seconds

Wave-CAIPI for SMS-EPI

- Wave-CAIPI is also applicable to high bandwidth EPI acquisition
- Potential to provide substantial g-factor improvement over blipped-CAIPI

1/g-factor simulation $R_{inplane}3 \times MB3$ @ BW 1000 Hz/pixel



$G_{avg} = 1.4$
$G_{max} = 2.4$

$G_{avg} = 1.2$
$G_{max} = 1.5$

- Questions / comments:
  berkin@nmr.mgh.harvard.edu

- Matlab software and data online for 3D and SMS Wave-CAIPI:
  martinos.org/~berkin

- **Acknowledgement**
  NIH NIBIB P41-EB015896, 1U01MH093765,
  R00EB012107, R24MH106096

Thank you for your attention