Simultaneous Multi-Slice Acquisition for Rapid Neuroimaging

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Acknowledgement

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

Overview

- Parallel Imaging for in-plane acceleration
  (slides: Jonathan Polimeni)

- Simultaneous Multi-Slice (SMS):
  Faster EPI using Blipped-CAIPI
  (slides: Kawin Setsompop)

- SMS Wave-CAIPI:
  Whole brain $1mm^3$ Turbo Spin Echo in 70 sec

Insights

- SMS removes the sqrt(R) SNR penalty induced by in-plane parallel imaging

- Controlled aliasing (Blipped- and Wave-CAIPI) reduces g-factor SNR penalty in SMS acquisition

- How Blipped- and Wave-CAIPI work

- Neuroimaging applications of SMS acquisition
  Diffusion, functional, structural imaging

Overview

- Parallel Imaging for in-plane acceleration
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❖ In-plane acceleration incurs both sqrt(R) and g-factor SNR penalty

- Simultaneous Multi-Slice (SMS):
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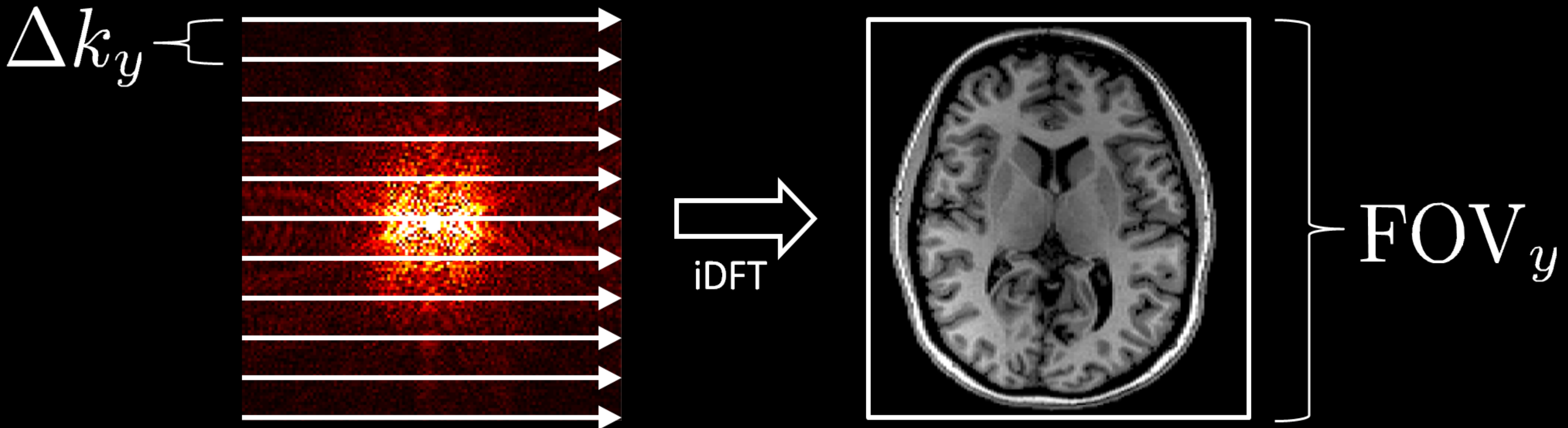
Parallel Imaging

- simultaneous measurement from multiple coil channels in parallel

- most commonly used for *accelerated* acquisitions

- other uses:
  - artifact reduction [distortion mitigation in EPI]
  - motion detection [FID navigators, Kober *et al.*, 2011, *MRM*]

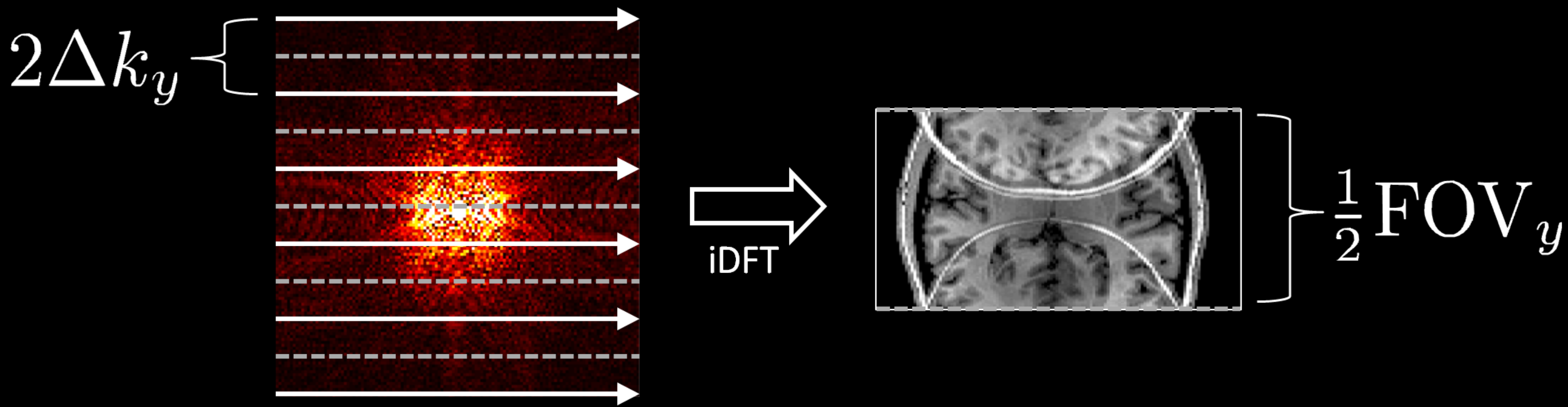
Fourier encoding



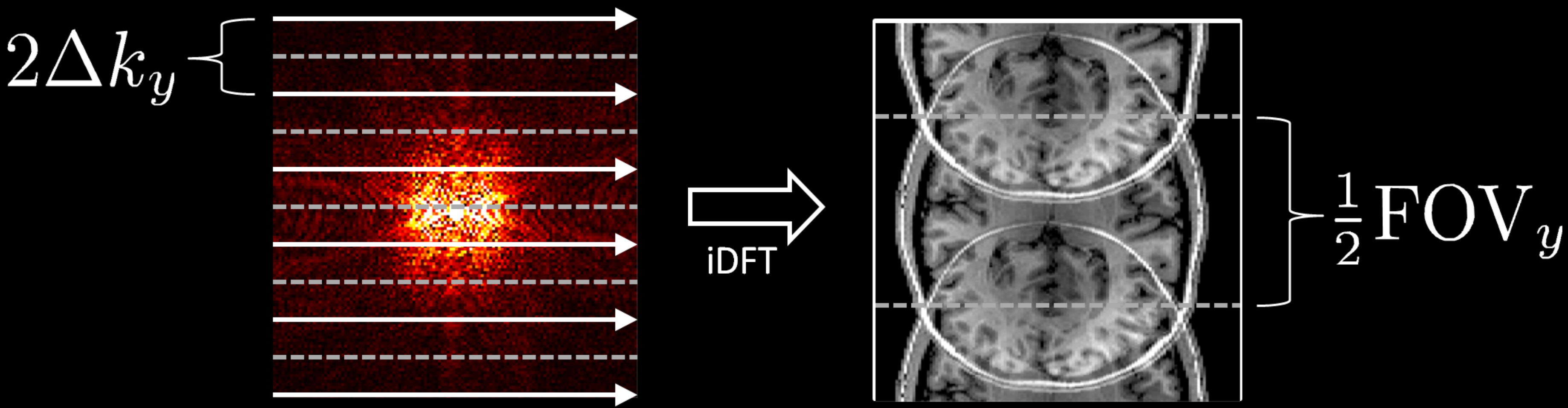
$$\mathrm{FOV}_y = 2\pi / \Delta k_y$$

Nyquist-sampled object

undersampled data – aliasing

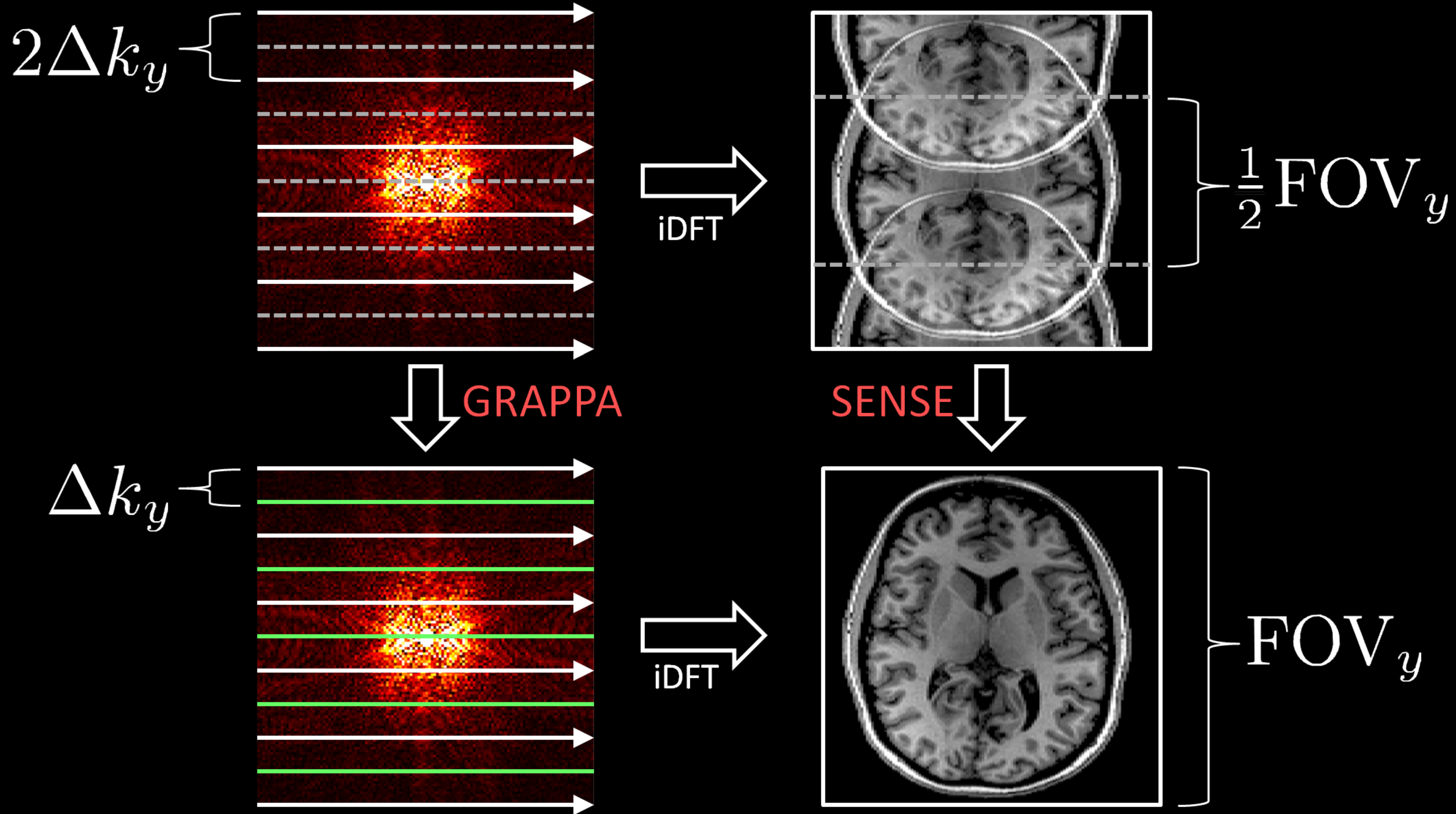


undersampled data – aliasing

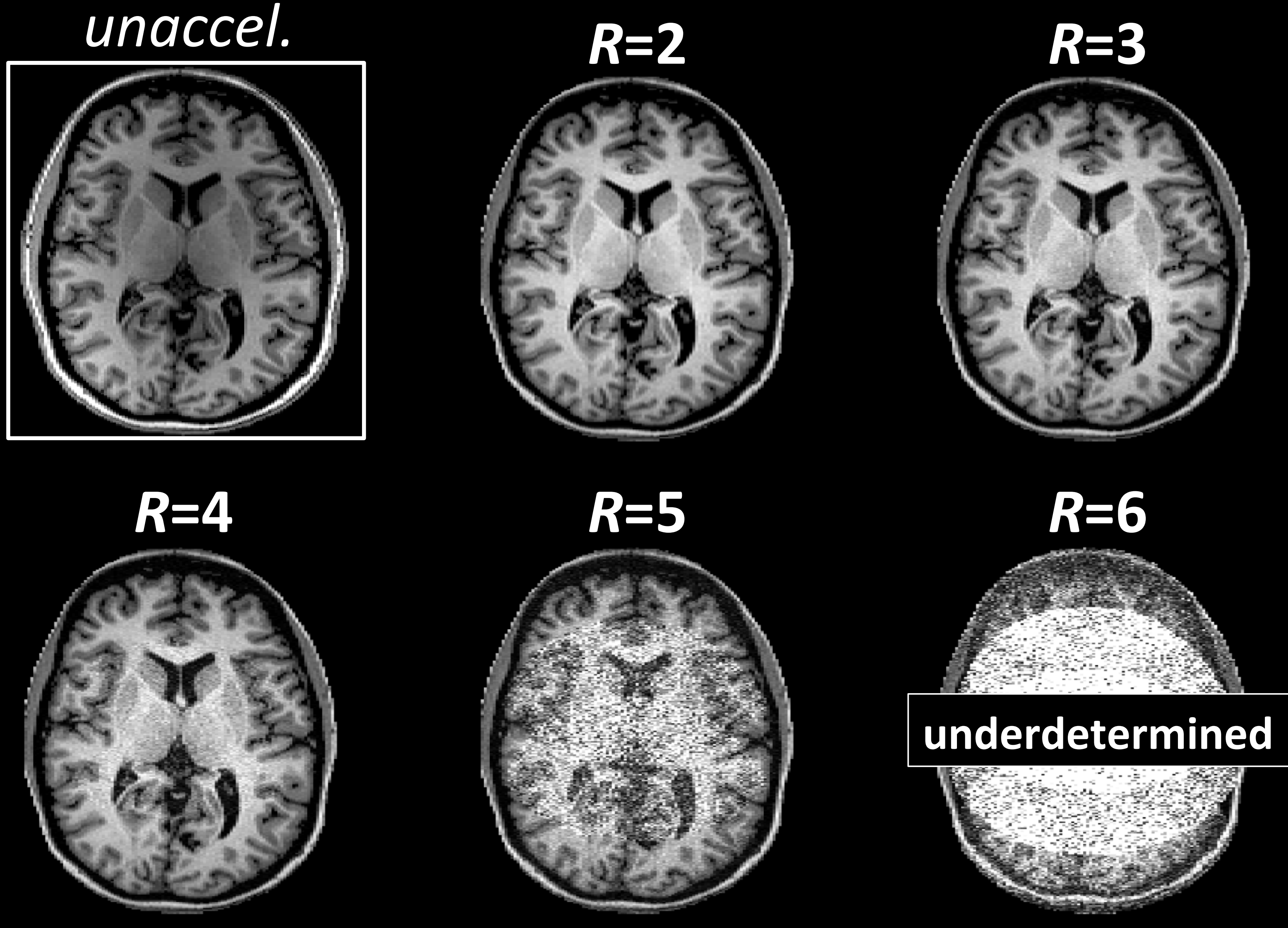


aliased replicates

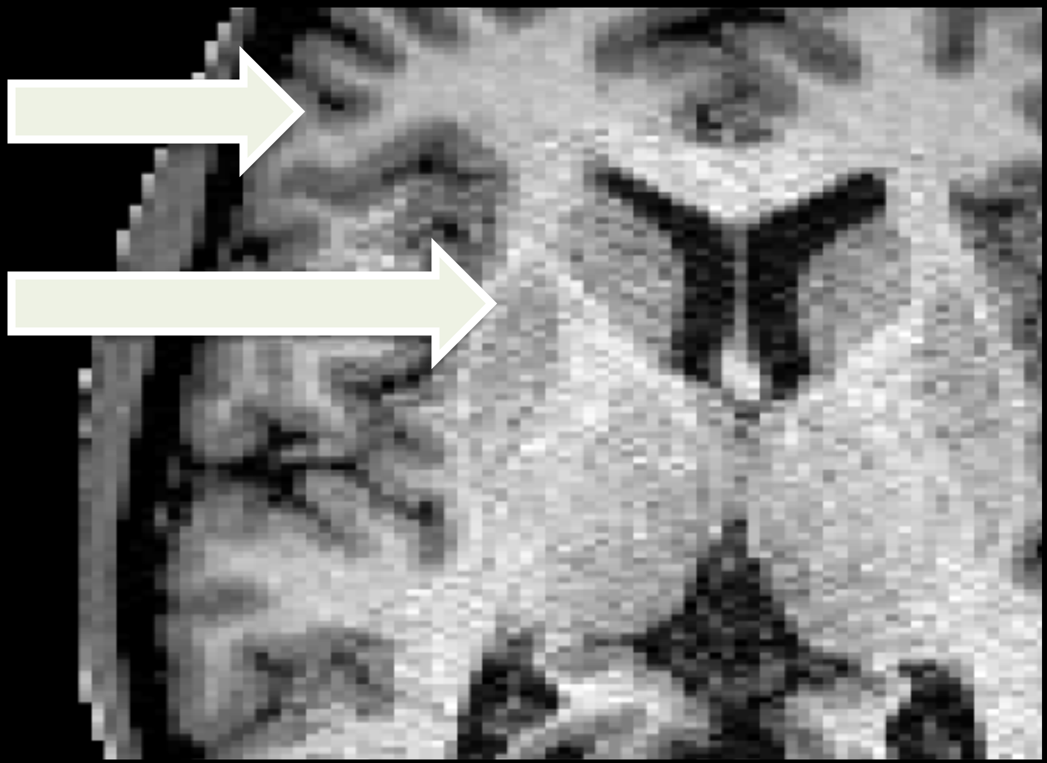
k-space vs. image-space approaches



limits on acceleration – 8 chan simulation



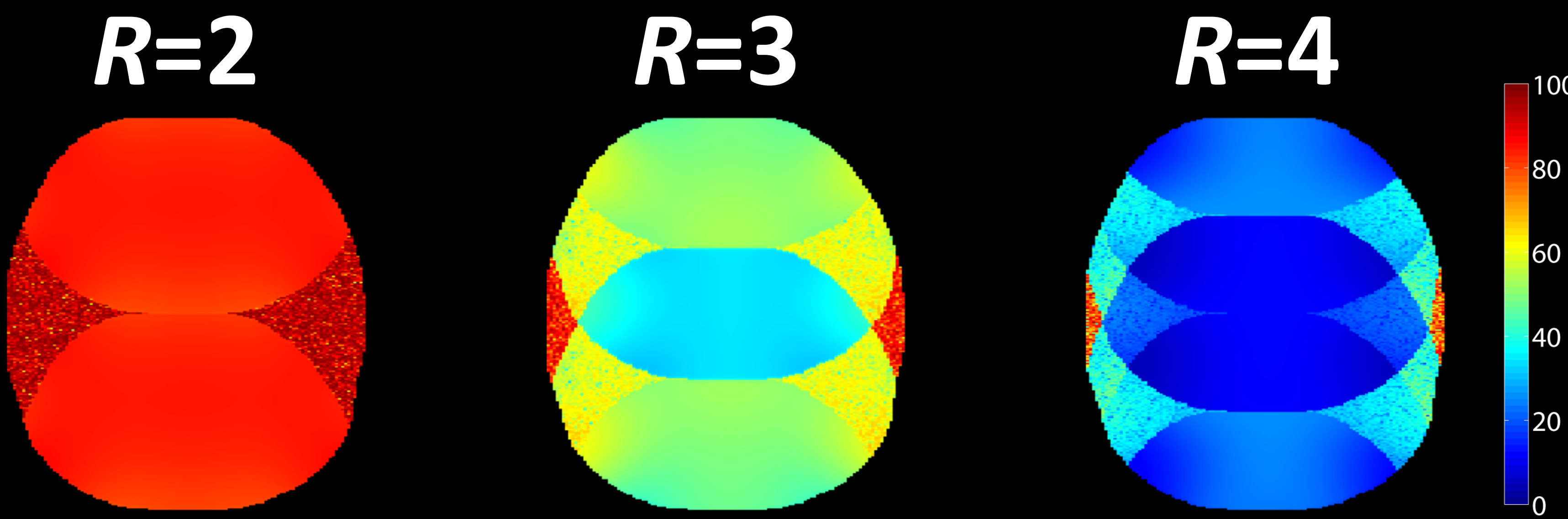
limits on acceleration – 8 chan simulation



***R*=4**

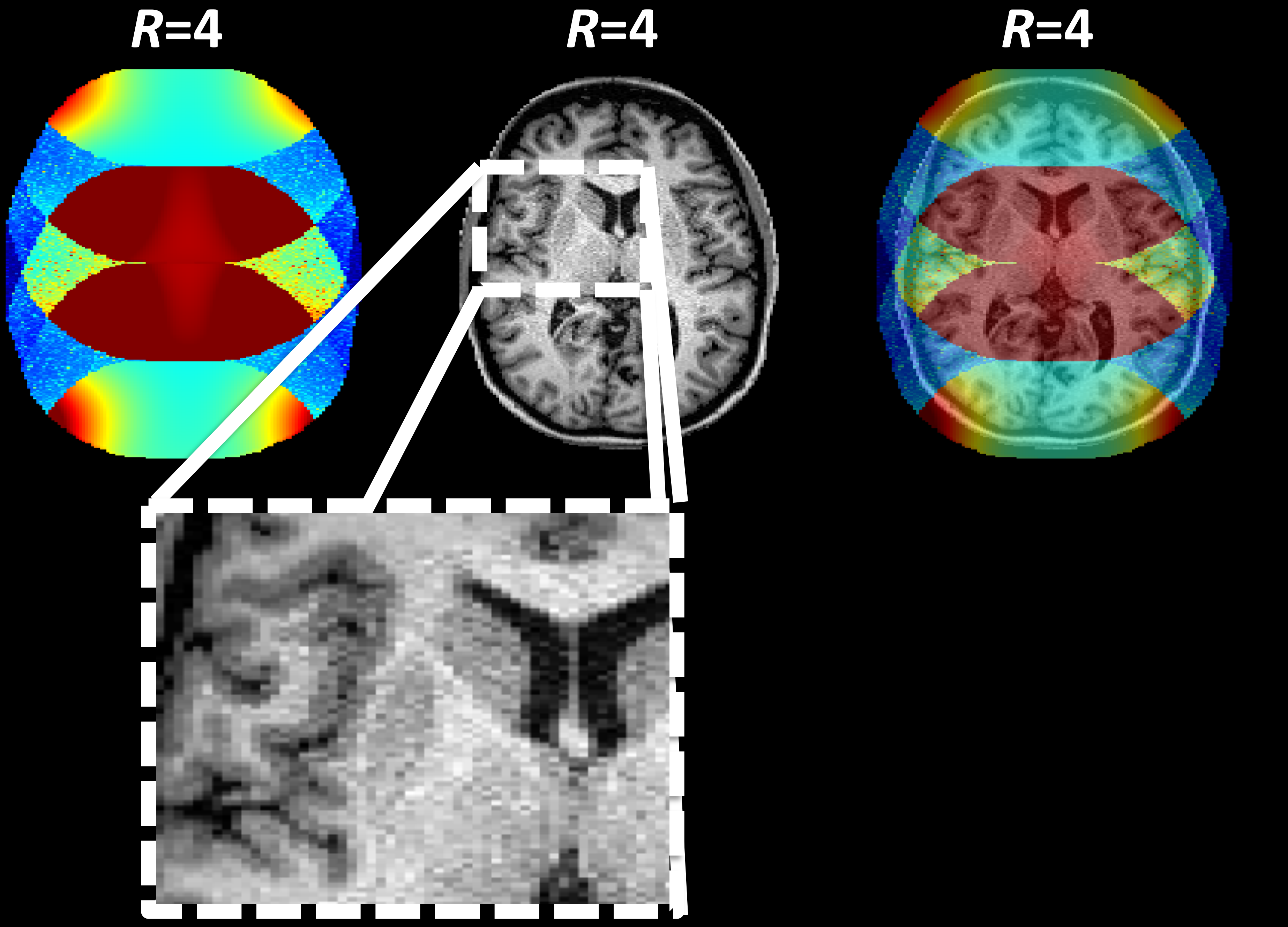
non-uniform noise: geometry factor

$$\mathrm{SNR}^{\mathrm{red}} = \mathrm{SNR}^{\mathrm{full}} / g\sqrt{R}$$



g ≥ 1: 1/g for visualization on same scale

[Pruessmann *et al.*, 1999, *MRM*]



R=4
R=4
R=4

Overview

- Parallel Imaging for in-plane acceleration
  (slides: Jonathan Polimeni)

- Simultaneous Multi-Slice (SMS):
  Faster EPI using Blipped-CAIPI
  (slides: Kawin Setsompop)

- SMS acceleration incurs only g-factor SNR penalty, removes sqrt(R)

- SMS Wave-CAIPI:
  Whole brain 1mm^3 Turbo Spin Echo in 70 sec

Improving EPI Efficiency

Slc 1	excitation	contrast encoding	EPI sampling
Slc 2	excitation	contrast encoding	EPI sampling
⋮			
Slc N	excitation	contrast encoding	EPI sampling

Slice-by-slice reception
is inefficient

Motivation: bring simultaneous multislice to EPI

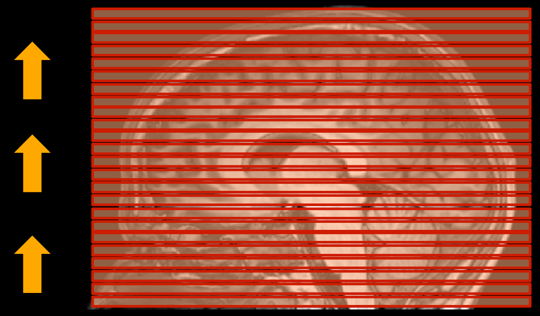
- Increase efficiency of high-res EPI for Diffusion, fMRI

  Whole brain acquisition with thin slices means long TR

  TR >> T_1 → inefficient SNR/time.
  → long acquisition time.

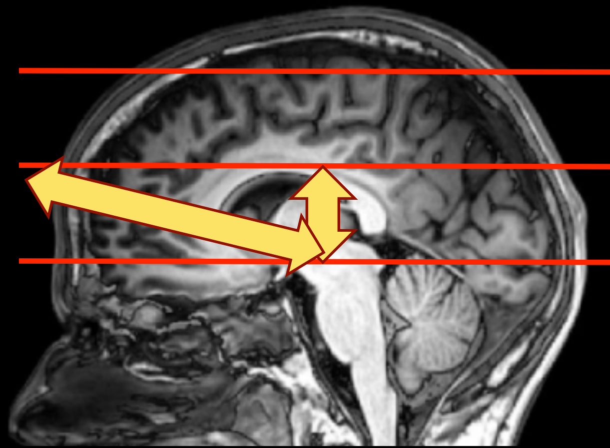
- In-plane acceleration <u>does not</u> reduce TR significantly for EPI
  Especially for long diffusion encoding
  or fMRI where TE = T_2^* for contrast

- Simultaneous Multi-Slice (SMS): excites & acquires multiple slices during each readout period.



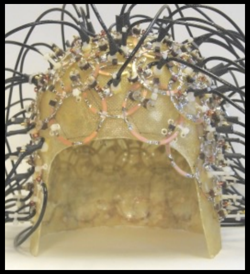
→ Reduced TR significantly.
→ No sqrt(R) penalty on SNR.

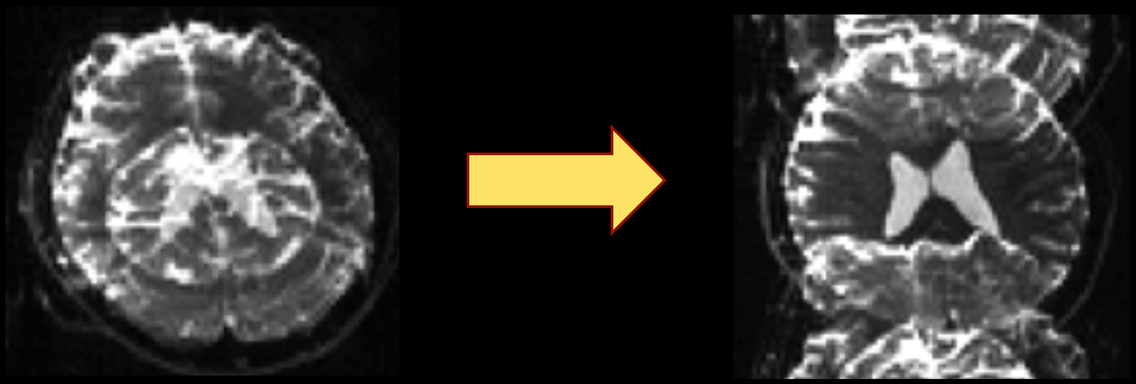
How to tease apart the acquired slices?



Parallel Imaging SMS

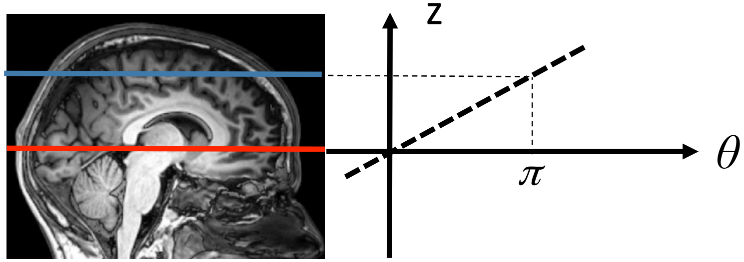
- high noise amplification (g-factor) [1-3]
- Controlled Aliasing In Parallel Imaging (CAIPI)[4] fixes this by inducing FOV/2 shift
  → not relevant to EPI
- Wideband shifting for EPI[5-6]
  → but unacceptable blurring
- blipped-CAIPI[7-8] fixes this blurring

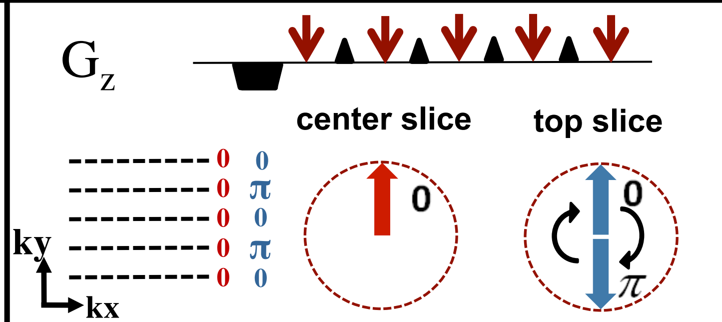




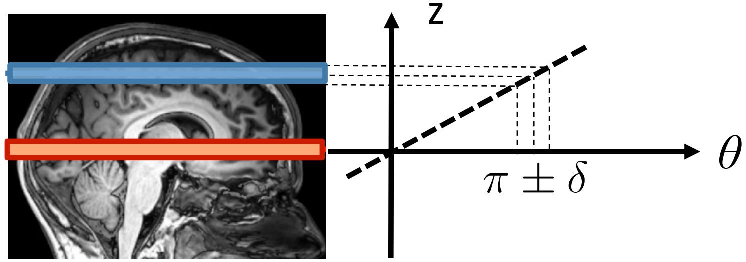
1. Larkman DJ. et al MRM 2002. 2. Moeller S. et al MRM 2010. 3. Feinberg D. et al PlosOne 2010 4. Breuer FA. et al, MRM 2005.
5. Paley MN. et al, MRI 2006. 6. Nunes RG. et al ISMRM 2006 7. Setsompop K. et al ISMRM 2010 8. Setsompop K. et al MRM 2012

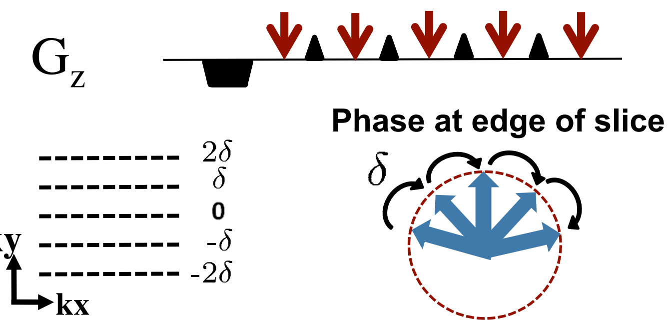
FOV/2 shifting in EPI: Wideband vs. Blipped-CAIPI



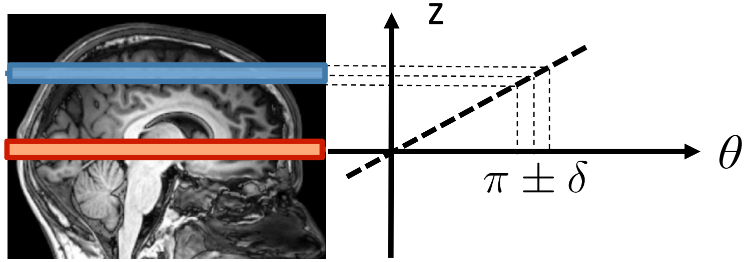
	Wideband	Blipped-CAIPI
Gz & phase diagrams		
Fourier Space Filter		
Impulse Response		

FOV/2 shifting in EPI: Wideband vs. Blipped-CAIPI



	Wideband	Blipped-CAIPI
Gz & phase diagrams		
Fourier Space Filter		
Impulse Response		

FOV/2 shifting in EPI: Wideband vs. Blipped-CAIPI



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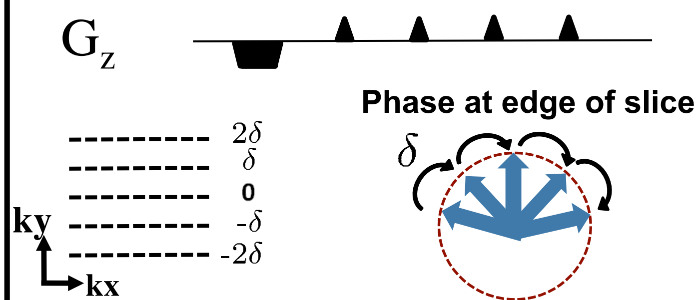
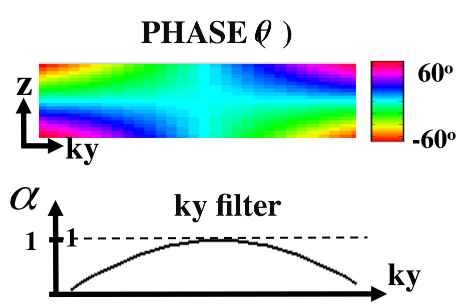
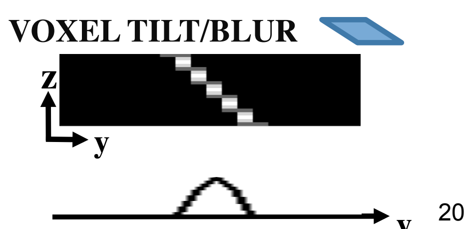
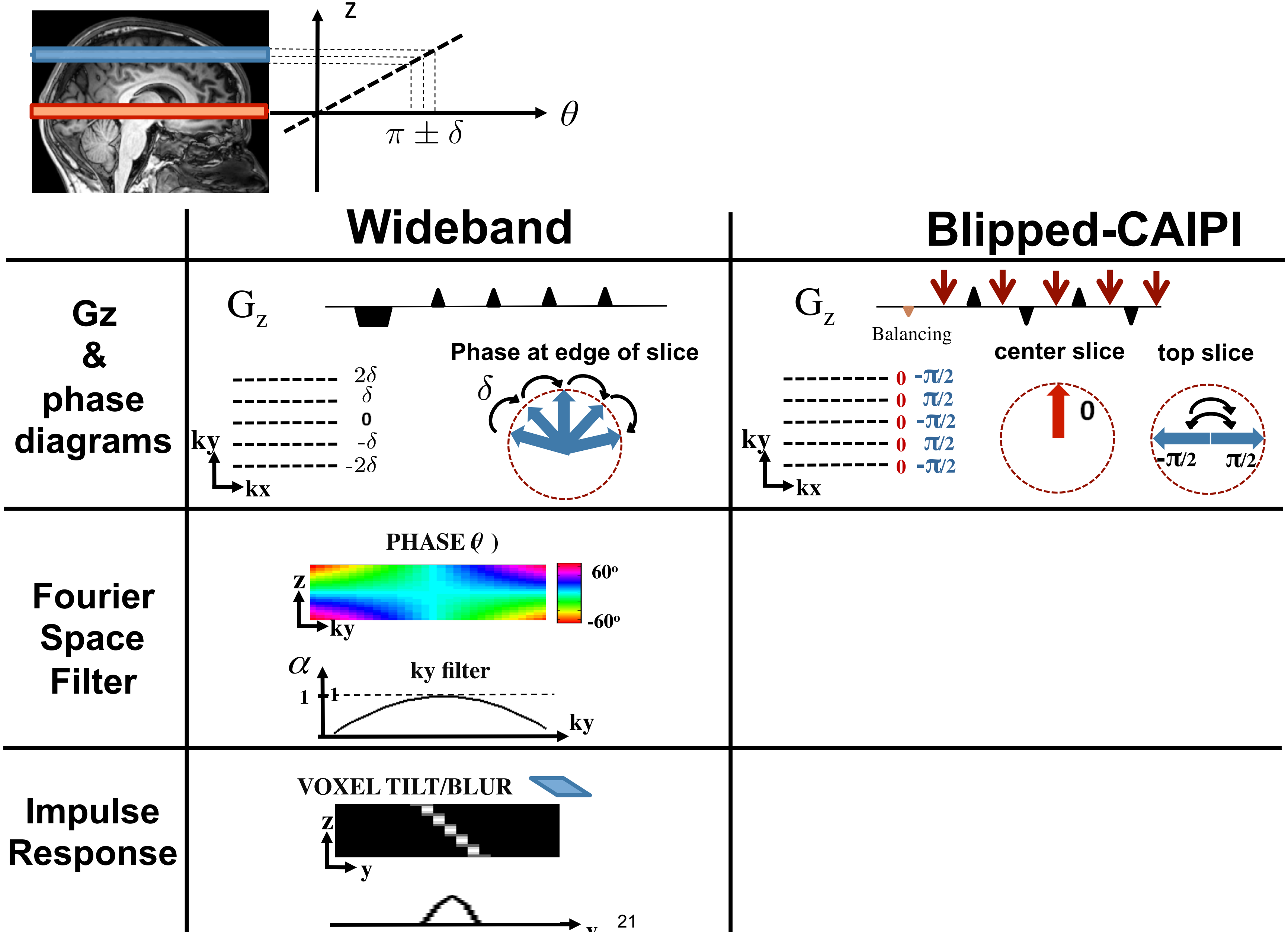
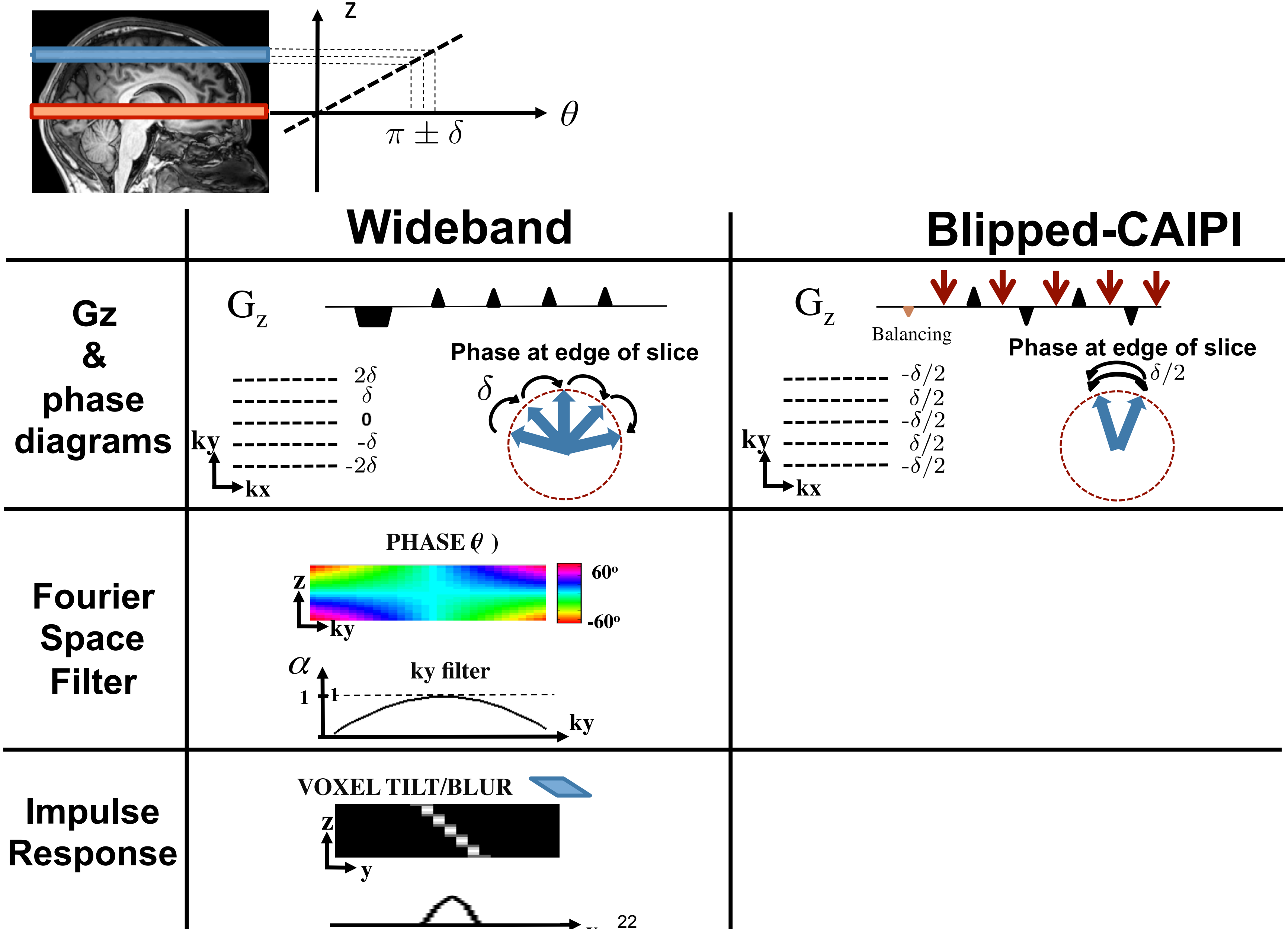
Gz & phase diagrams		
Fourier Space Filter		
Impulse Response		

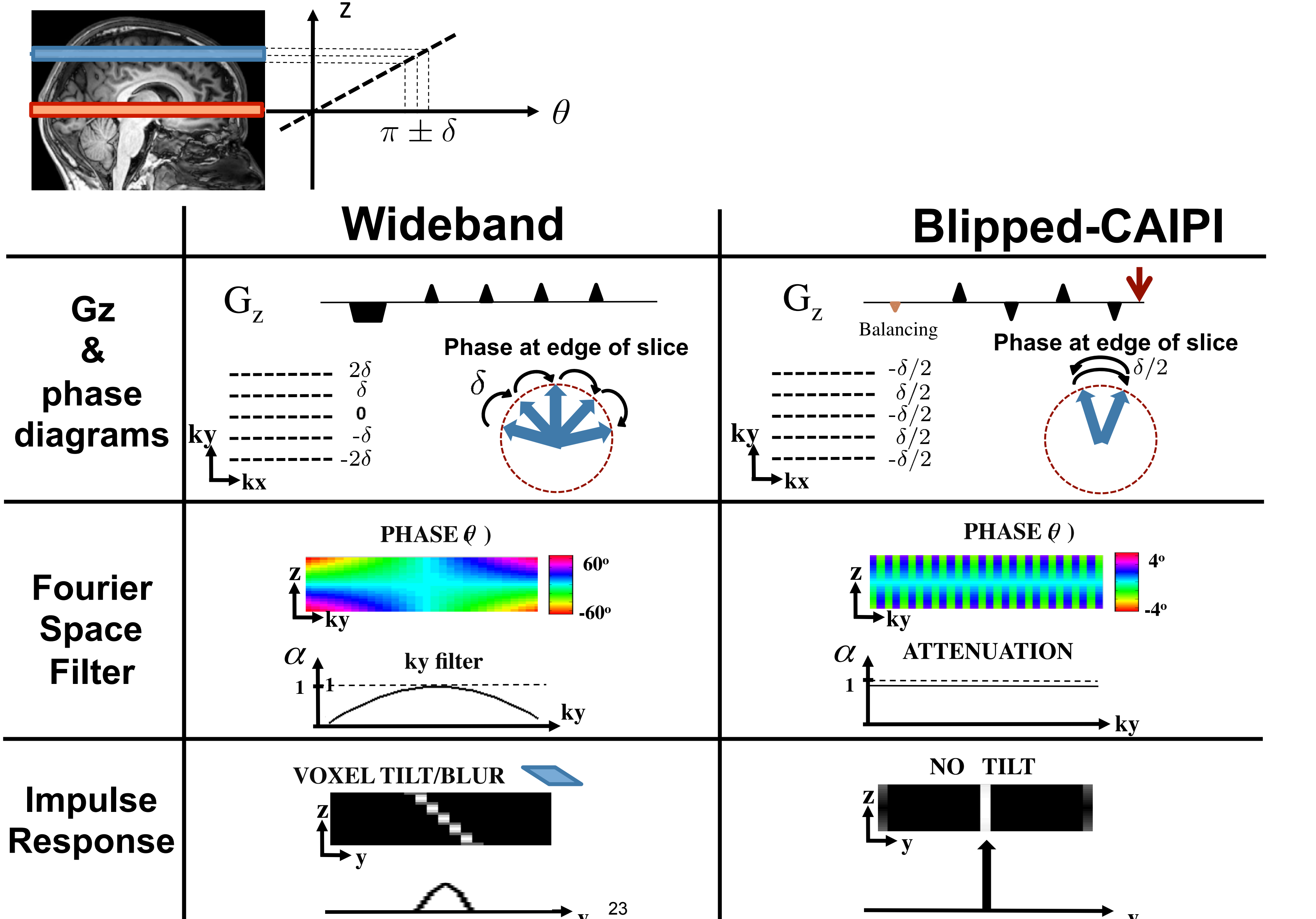
FOV/2 shifting in EPI: Wideband vs. Blipped-CAIPI



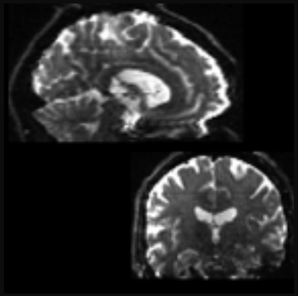
FOV/2 shifting in EPI: Wideband vs. Blipped-CAIPI



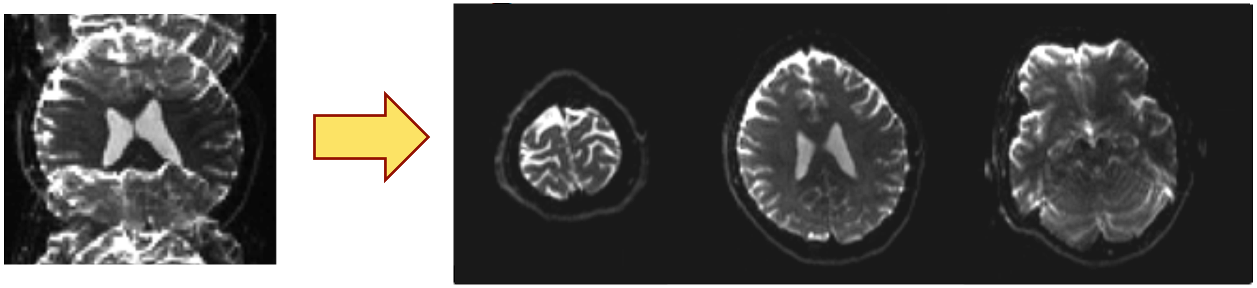
FOV/2 shifting in EPI: Wideband vs. Blipped-CAIPI



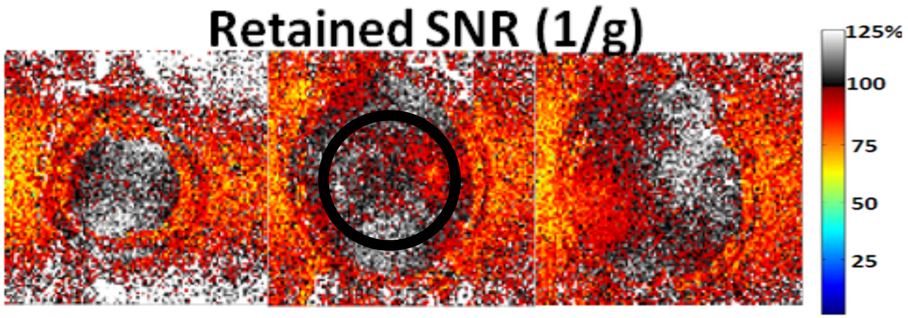
3x Blipped-CAIPI: 3T SE-EPI

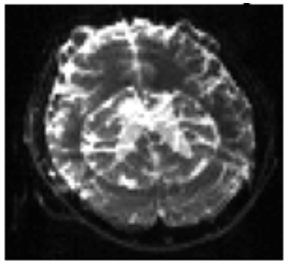


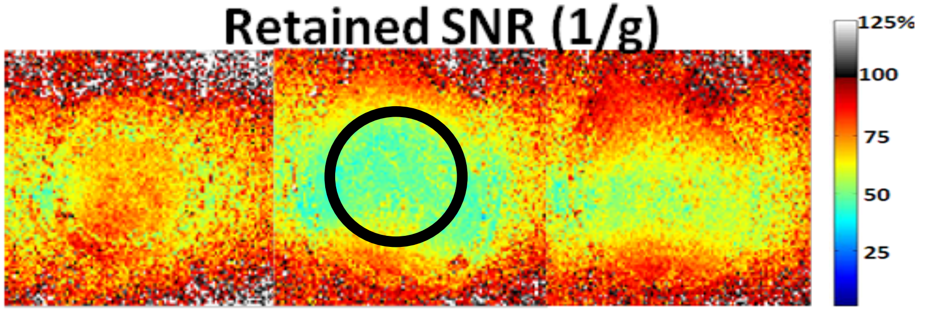
- 3x Blipped-CAIPI, 32 channel Siemens head coil



Blipped-CAIPI lowers g-factor SNR penalty by 2!



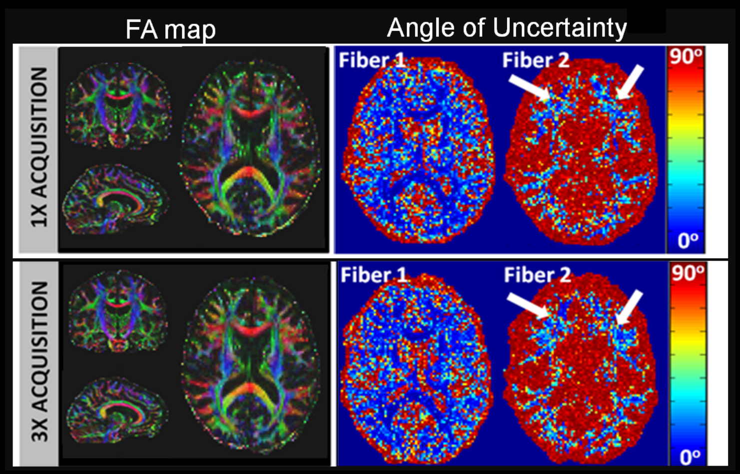




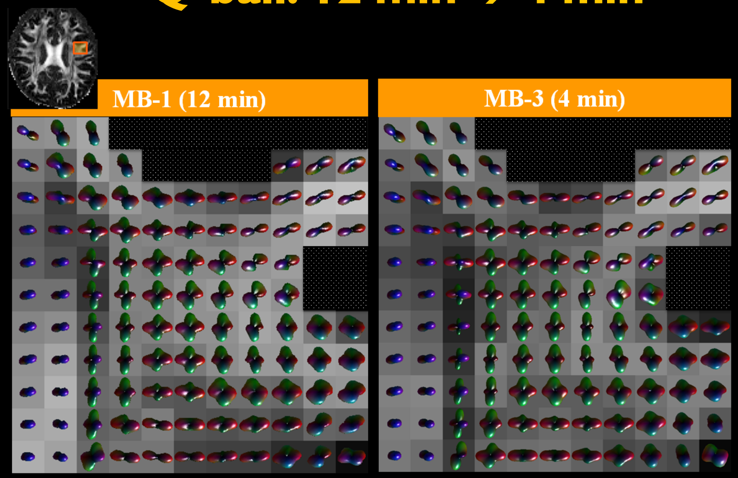
Diffusion acquisition with blipped-CAIPI

3x Faster w/ high quality[1]

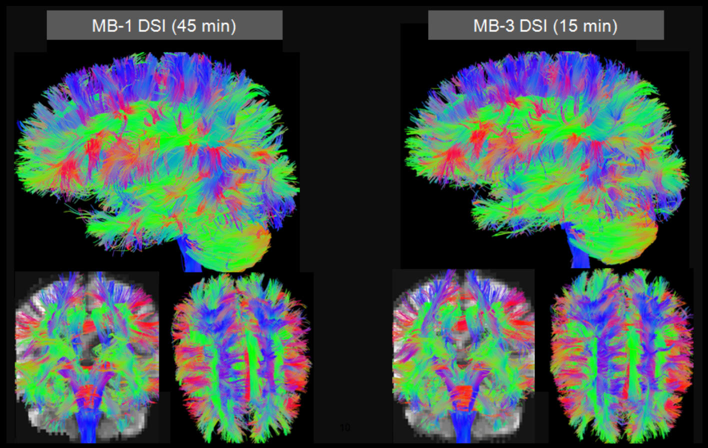
DTI: 10 min → 3 min



Q-ball: 12 min → 4 min



DSI: 45 min → 15 min

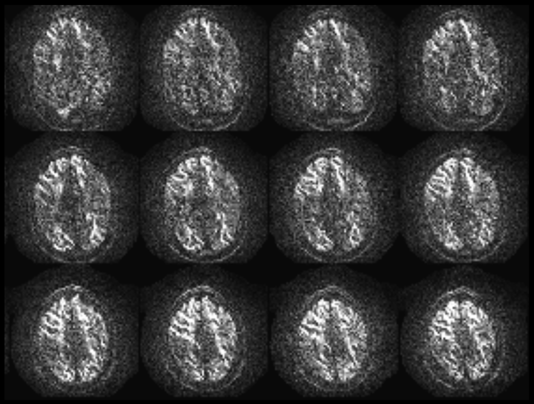


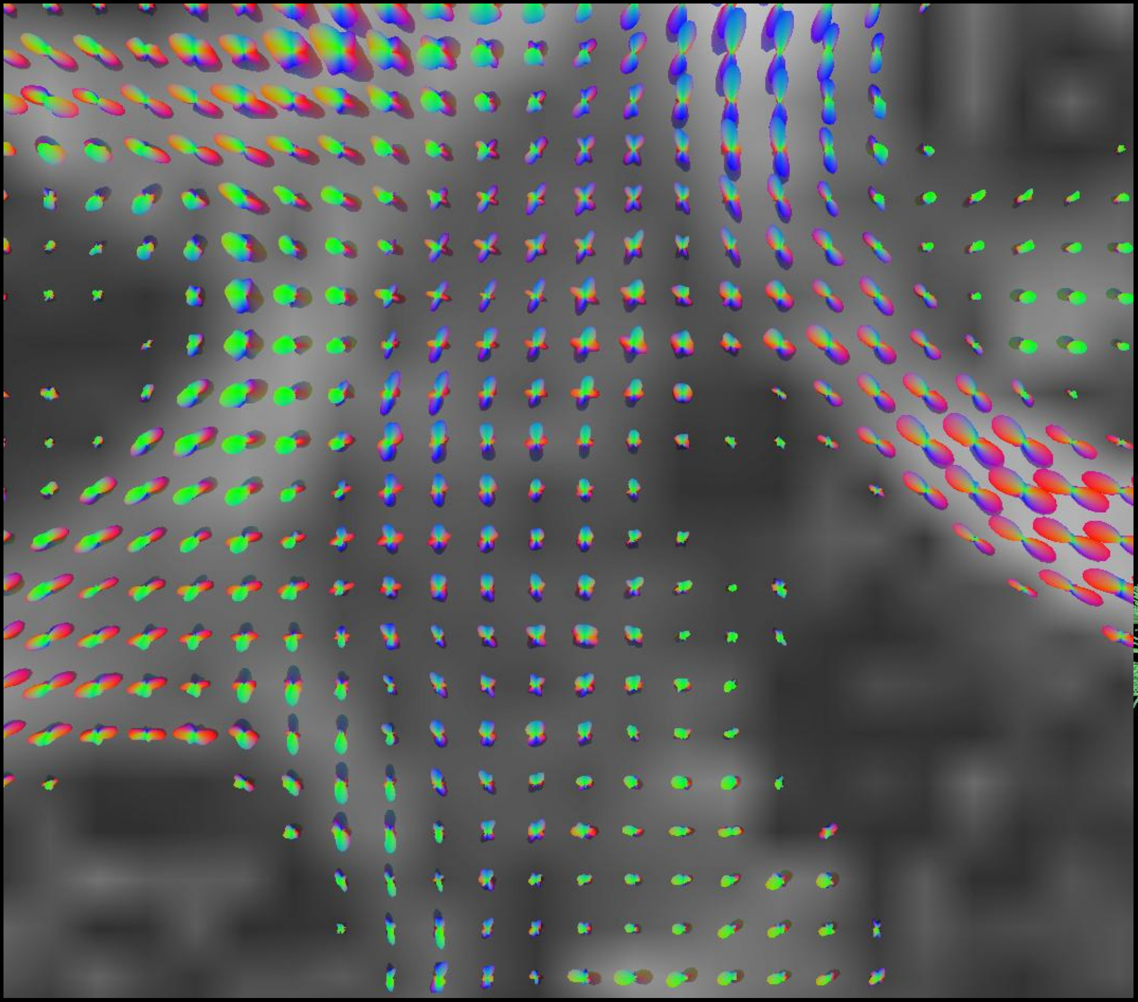
1. Setsompop K., et al Neuroimage 2012.

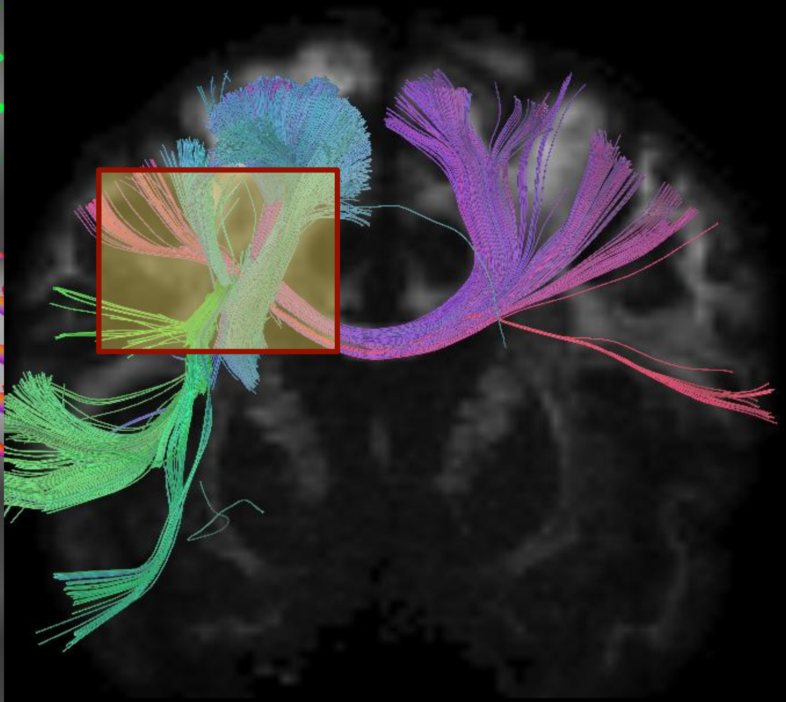
1.5 mm $R_{inplane}$3 + SMSx2, 10 min Q-ball at b 5k

High quality DI with SMS + $R_{inplane}$

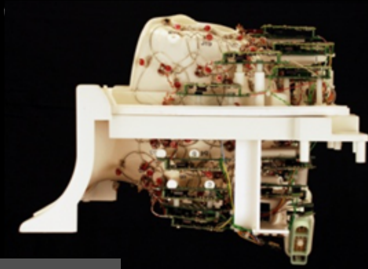
→ $R_{inplane}$ is to minimize distortion and blurring

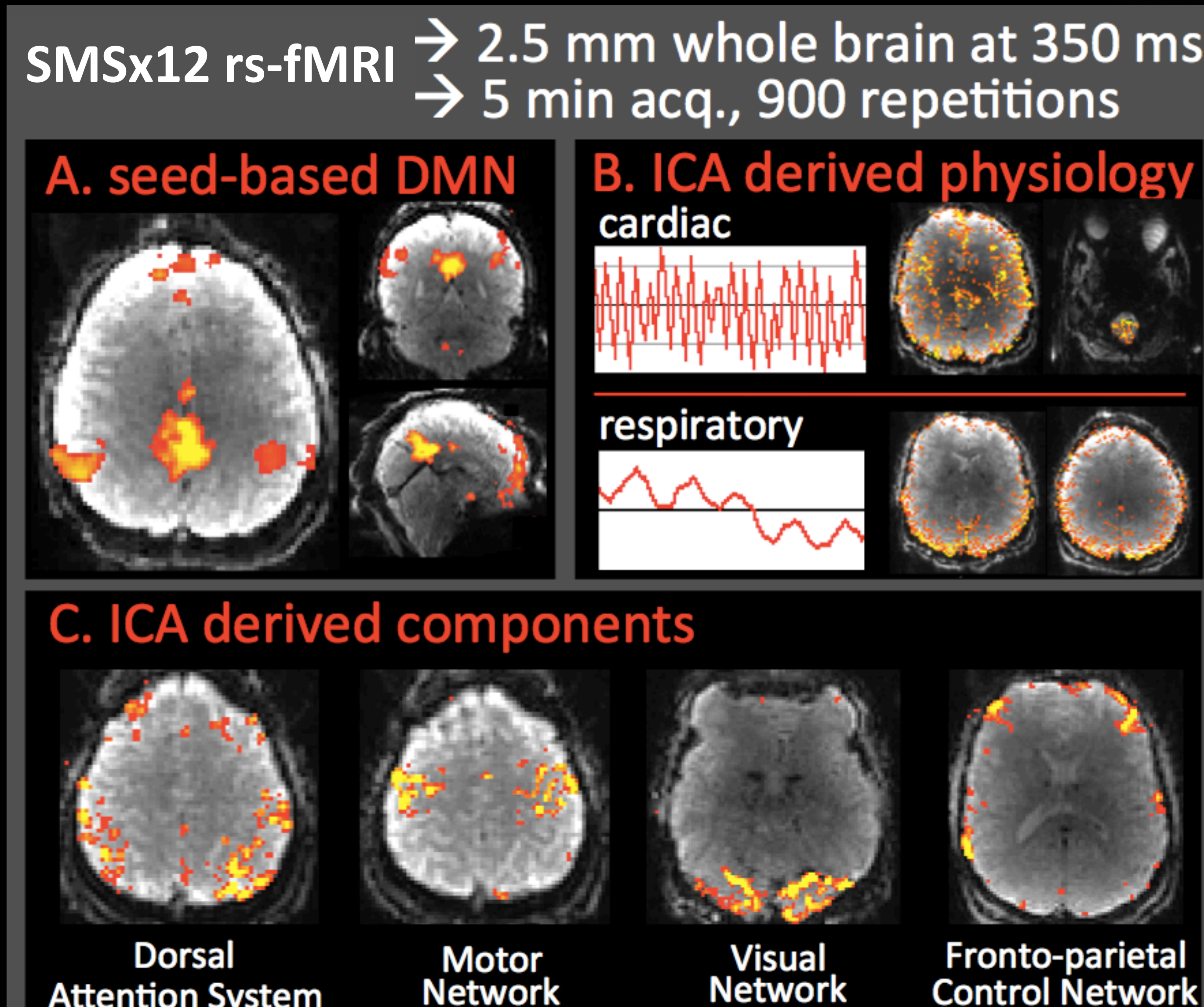




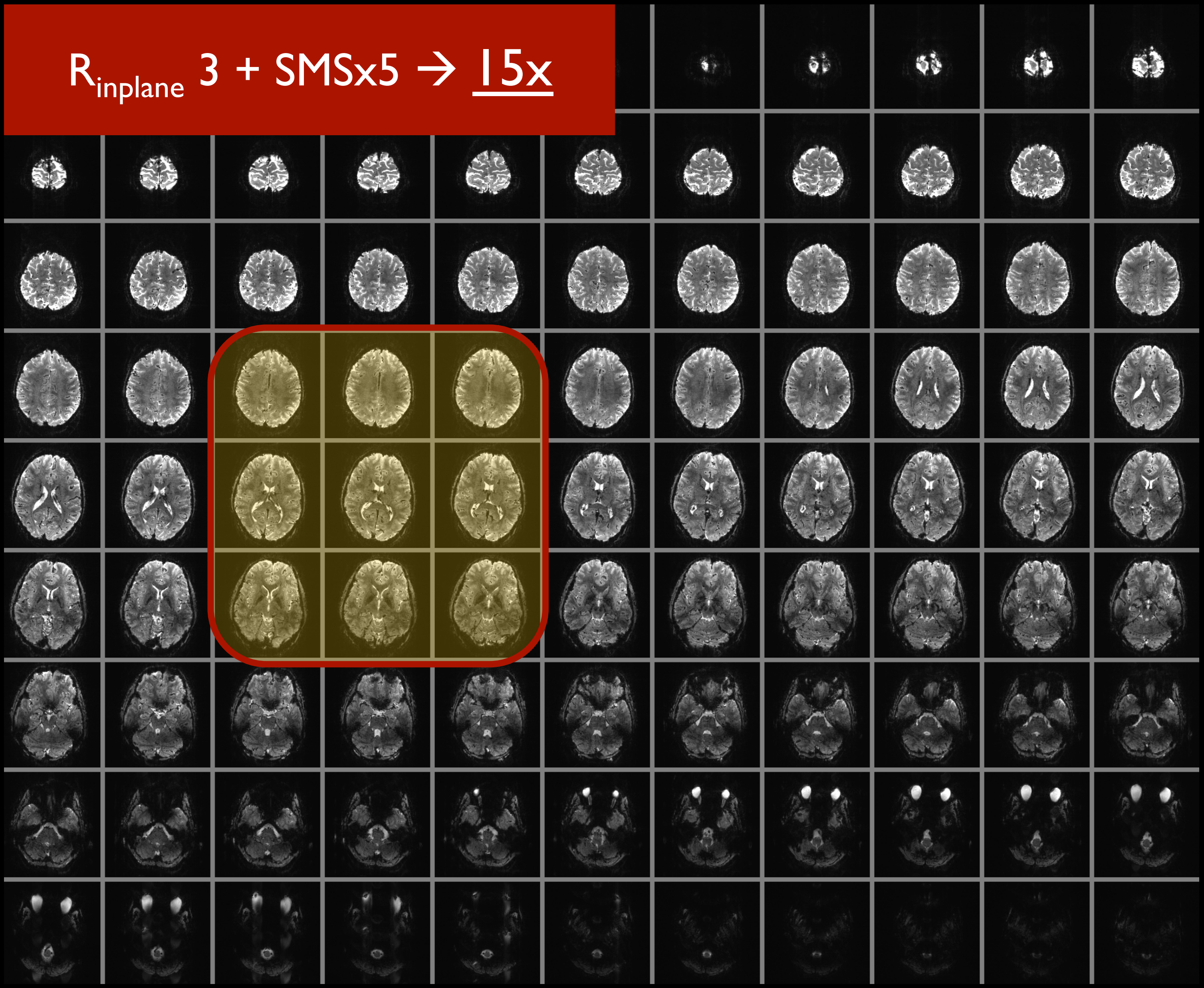


Resting State at 3T with 64 chn coil



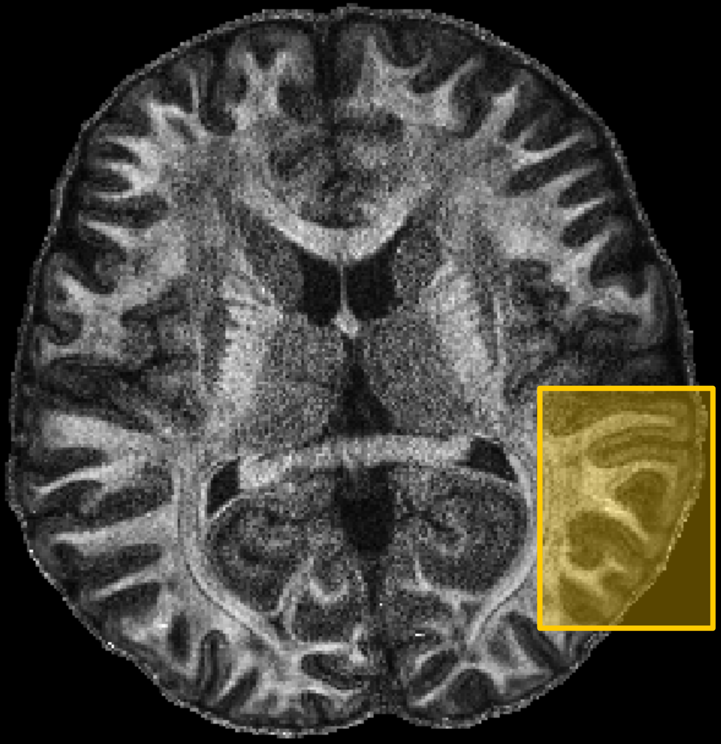


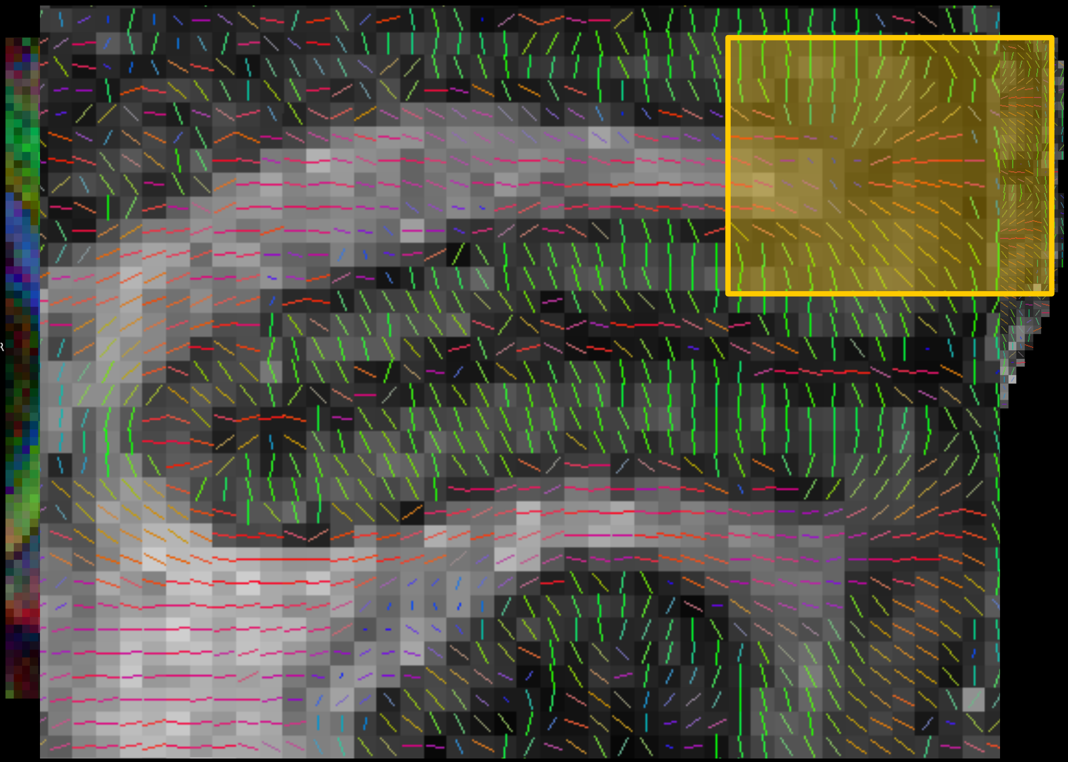
7T, 32 chn. coil, 1.5mm isotropic



Super-resolution & SMS [1]: 660 µm isotropic, whole-brain, b = 1500 s/mm^2

Fractional Anisotropy (FA)





Multiple voxels across Gray Matter at this resolution

SMSx2

$R_{zoom} \times R_{grappa} = 3.5\ (1.74 \times 2)$

64 directions

scan time: 1hr 40 min

1. K Setsompop et al ISMRM'15

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  (slides: Kawin Setsompop)

- SMS Wave-CAIPI:
  Whole brain 1mm^3 Turbo Spin Echo in 70 sec

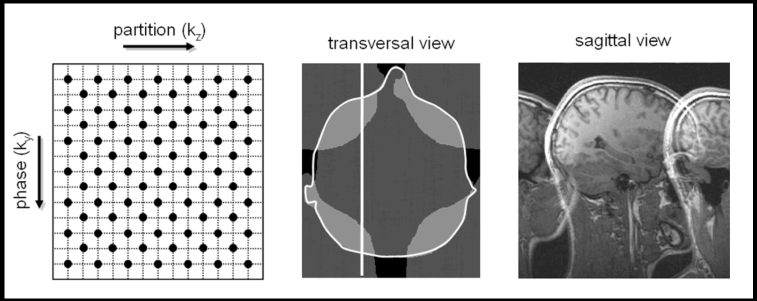
- Wave-CAIPI provides even better g-factor than Blipped-CAIPI

Controlled Aliasing in Parallel Imaging (CAIPI)

Increase distance btw aliased voxel to make better use of 3D coil sensitivities

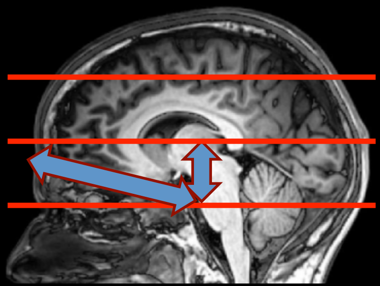
Full 3D imaging

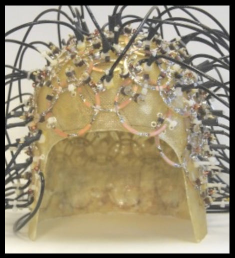
2D-CAIPI[2] (y-z)

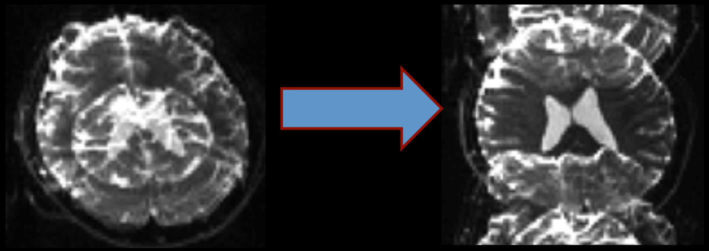


Simultaneous MultiSlice (SMS)

Blipped-CAIPI[1]

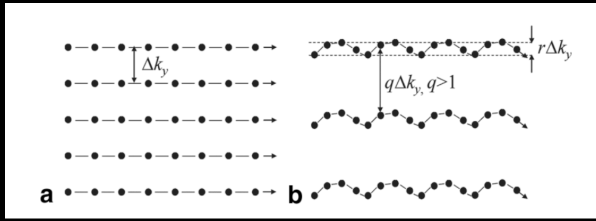


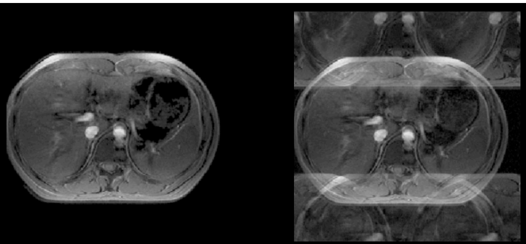




2D imaging

Bunched Phase Encoding[3] (x-y)

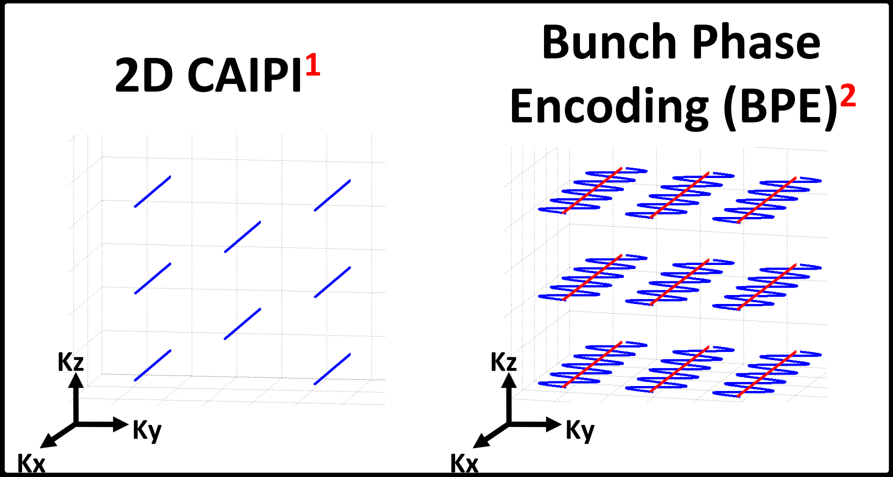




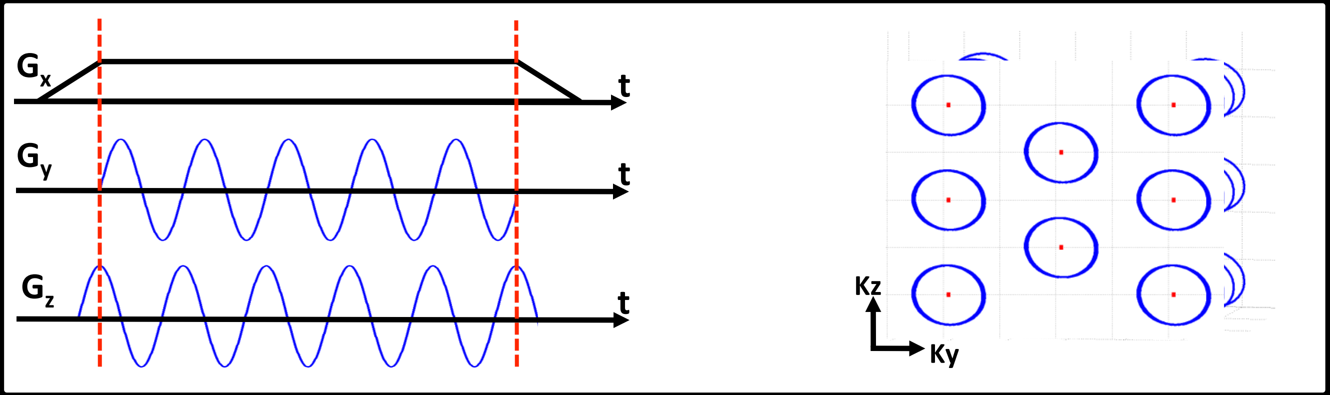
1. Breuer FA. et al, MRM 2005. 2. Breuer FA. et al, MRM 2006. 3. Moriguchi H. et al, MRM 2006.

Wave-CAIPI Sampling[3,4]

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



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

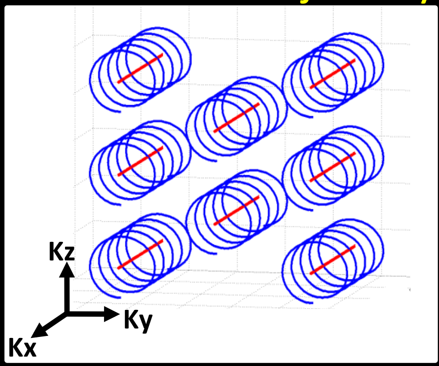


1. Breuer F. et al, MRM 2006 2. Moriguchi H. et al, MRM 2006 3. Setsompop K. et al, ISMRM 2011 4. Bilgic B. et al, MRM 2014

Wave-CAIPI Improves G-factor

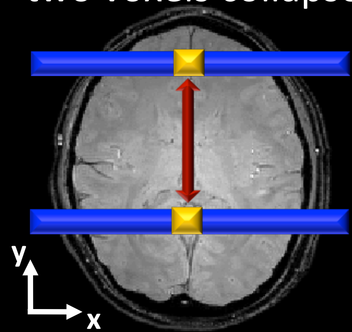
- Wave-CAIPI modifies the 3D acquisition trajectory to follow a corkscrew along each readout line [1]
- This trajectory incurs voxel spreading in the readout (x) direction
- For accelerated acquisitions, this spreads the aliasing in all 3D dimensions to substantially improve parallel imaging

Wave-CAIPI trajectory



Normal SENSE

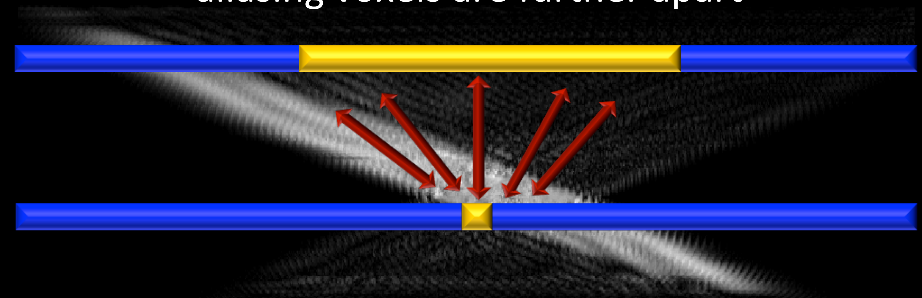
two voxels collapse



R=2 acceleration in Ky

Wave-CAIPI

aliasing voxels are further apart



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

Improved G-Factor

[1] B Bilgic, MRM'14

SMS Wave-CAIPI for Turbo Spin Echo (TSE)

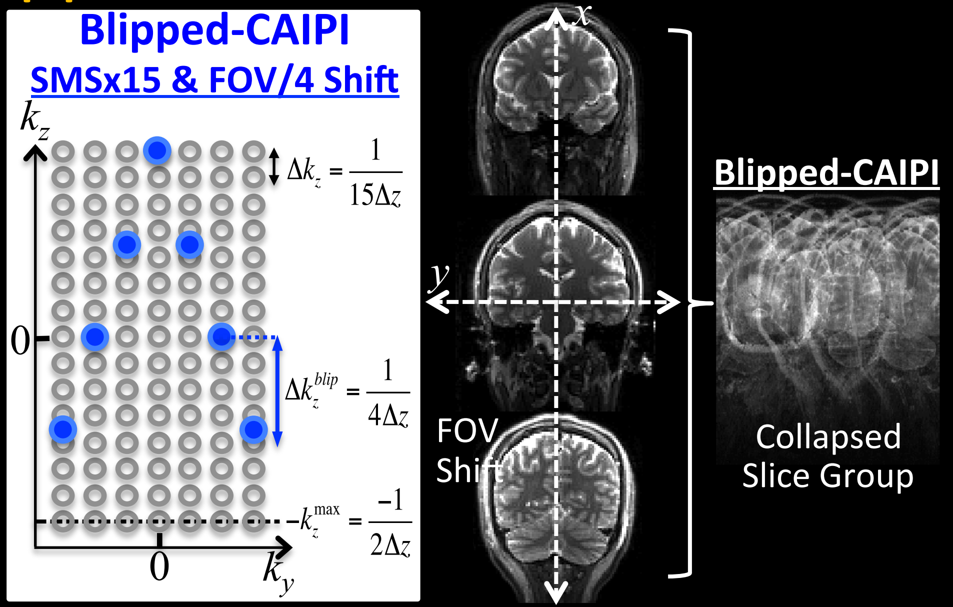
- TSE is the most commonly used clinical sequence, allowing rapid acquisition by sampling multiple k-space lines per 90° RF

- In-plane acceleration can improve efficiency, but suffers from intrinsic √R SNR penalty and g-factor noise amplification

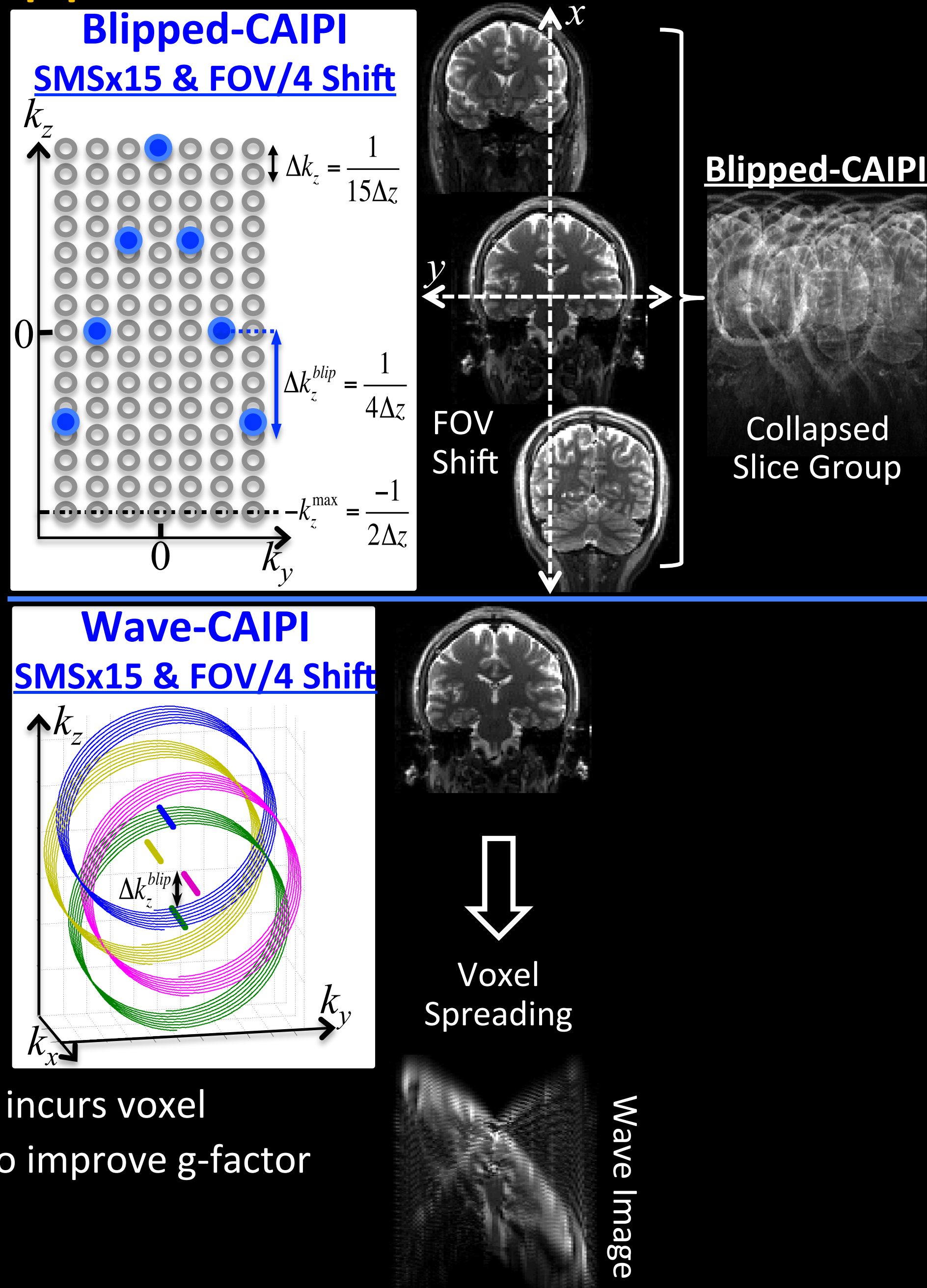
- SMS enables acceleration without √R penalty, since number of k-space lines is not reduced

- SMS Wave-CAIPI further improves g-factor

Blipped- and Wave-CAIPI for SMS

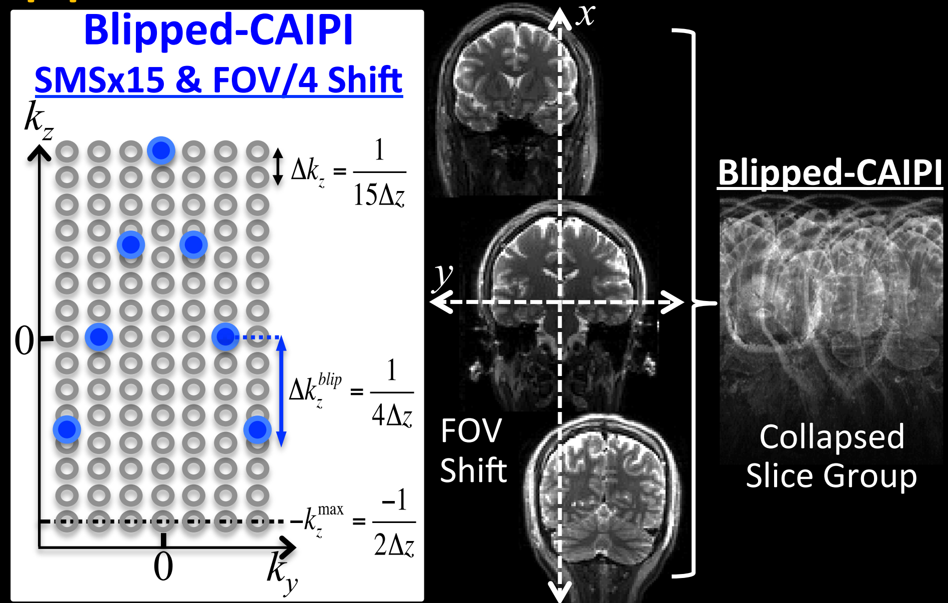


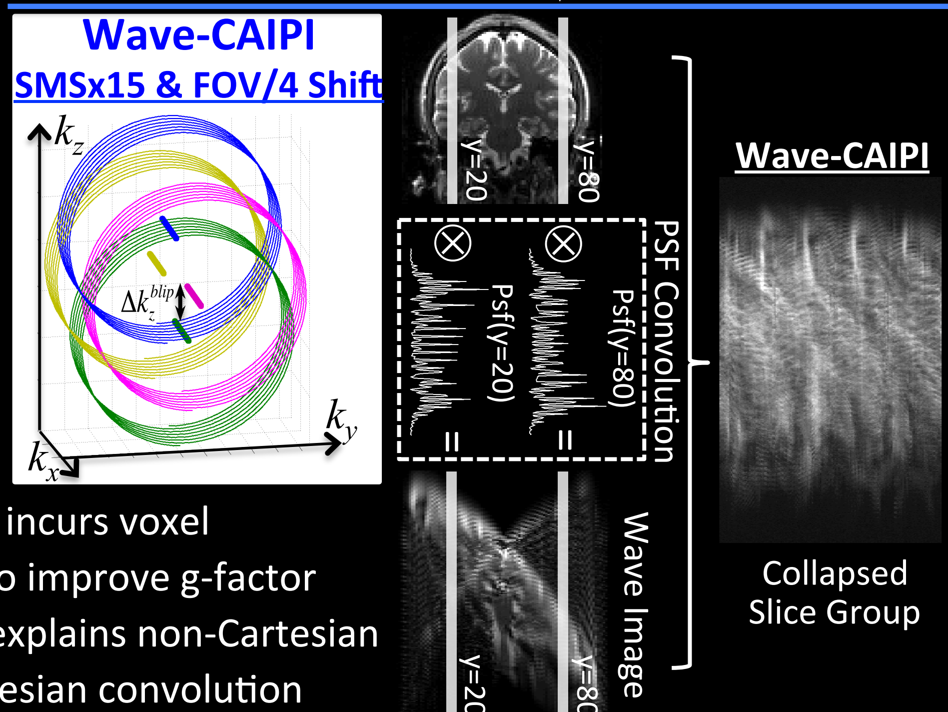
Blipped- and Wave-CAIPI for SMS



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

Blipped- and Wave-CAIPI for SMS



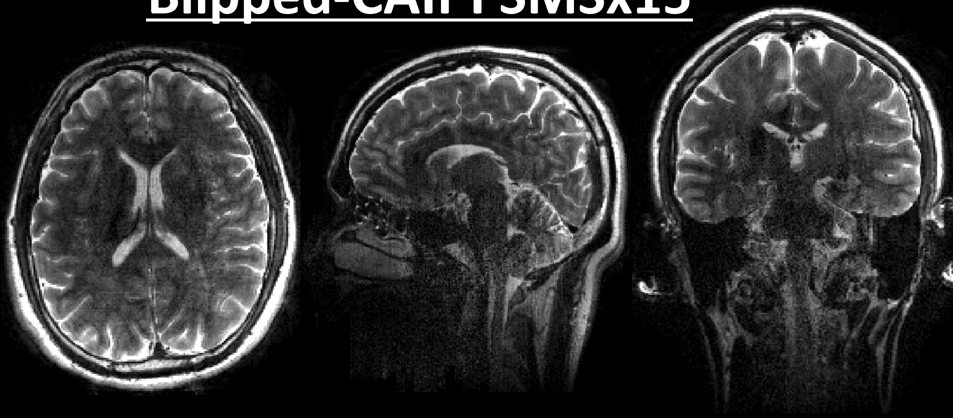


- Helix trajectory incurs voxel spreading in 3D to improve g-factor
- PSF formalism explains non-Cartesian sampling via Cartesian convolution

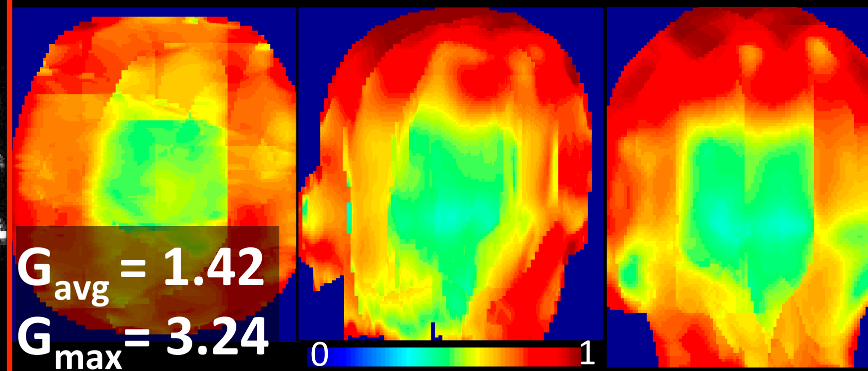
TSE @ 3T, 1 mm^3 voxels, T_{acq}=70 sec

SMSx15

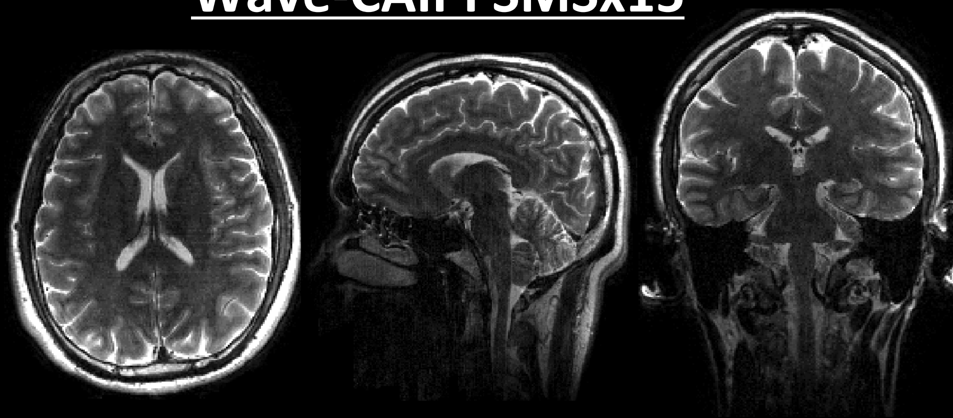
Blipped-CAIPI SMSx15



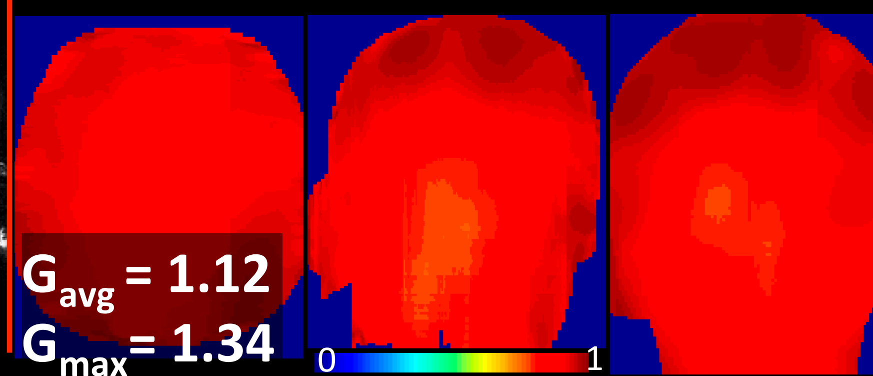
1/g-factor: Blipped-CAIPI SMSx15



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

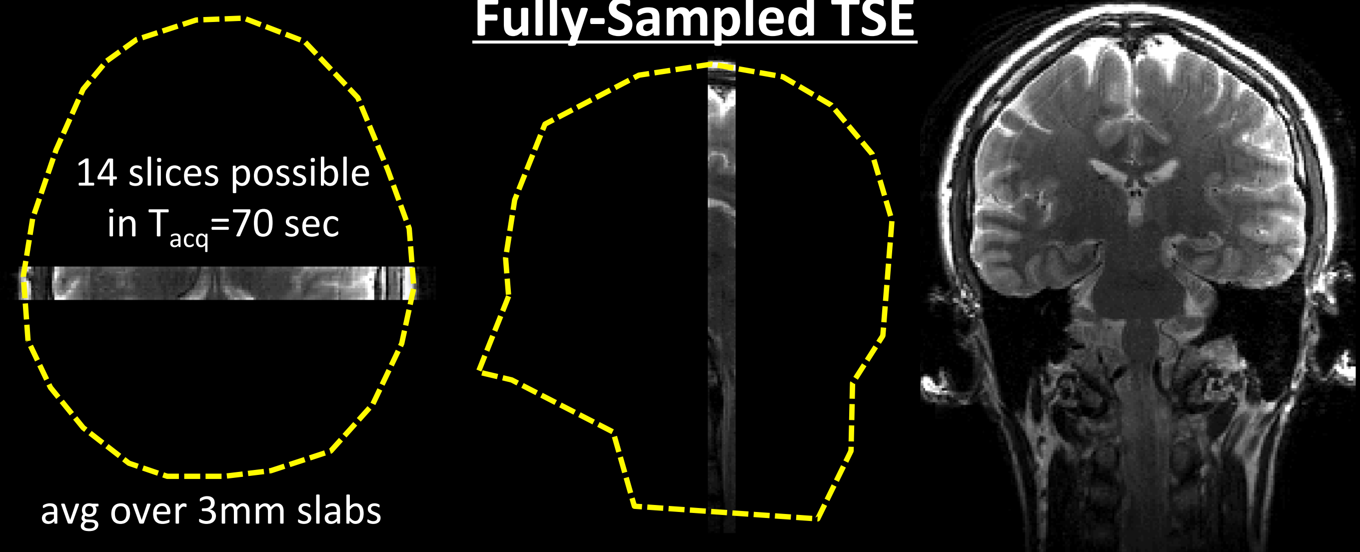
only g-factor
no sqrt(R)
noise penalty

Wave-CAIPI
SMSx15

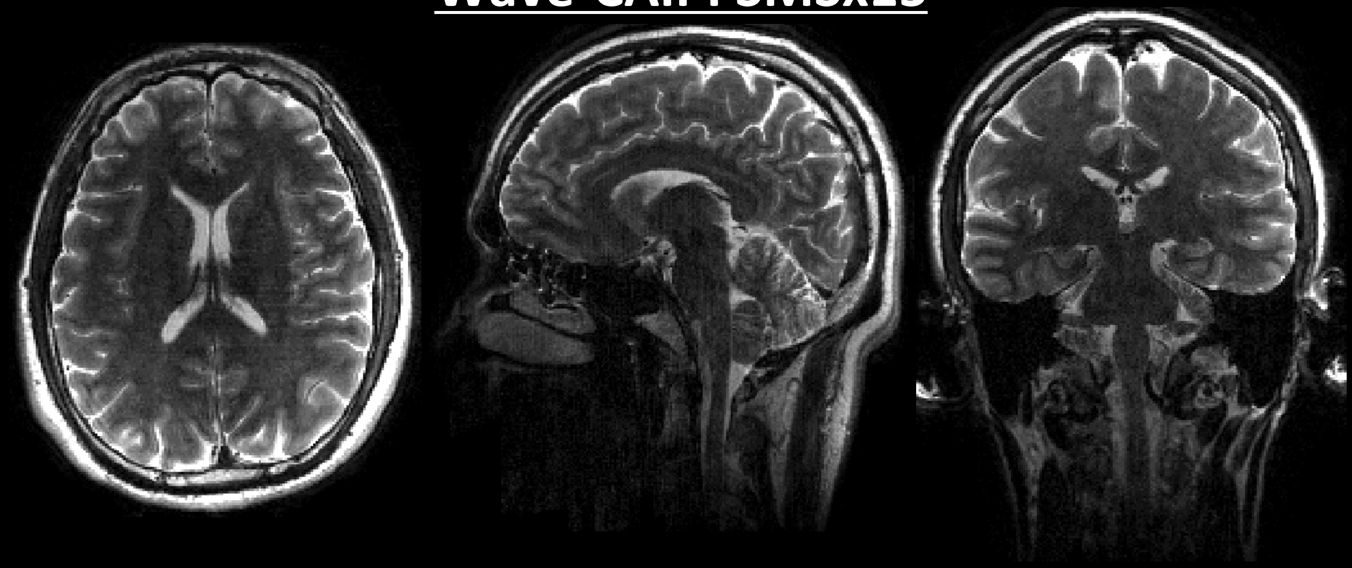
small g-factor
no sqrt(R)
noise penalty

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

Fully-Sampled TSE



Wave-CAIPI SMSx15



- Questions / comments:

  berkin@nmr.mgh.harvard.edu

- Matlab software and data online for SMS Wave-CAIPI:

  martinos.org/~berkin

- **Acknowledgement**

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

Thank you for your attention