Rapid Multi-Orientation Susceptibility Mapping with Wave-CAIPI

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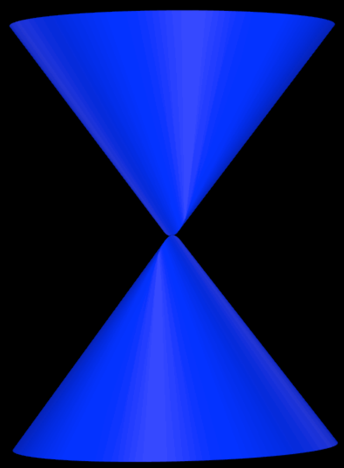
Declaration of
Financial Interests or Relationships

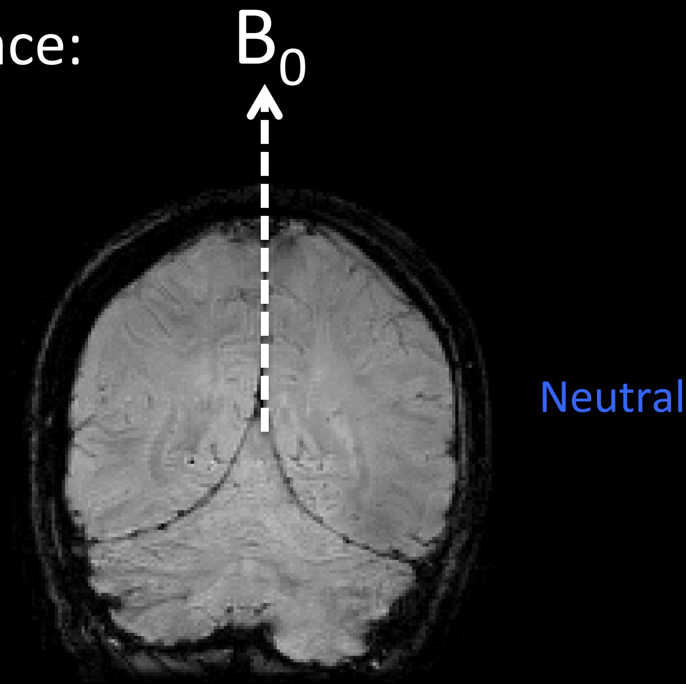
Speaker Name: Berkin Bilgic

I have no financial interests or relationships to disclose with regard to the subject matter of this presentation.

Multi-orientation susceptibility mapping

- Susceptibility inversion is made difficult by the zeros in the susceptibility kernel **D**
- These zeros lie on a conical surface:





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

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

Multi-orientation susceptibility mapping

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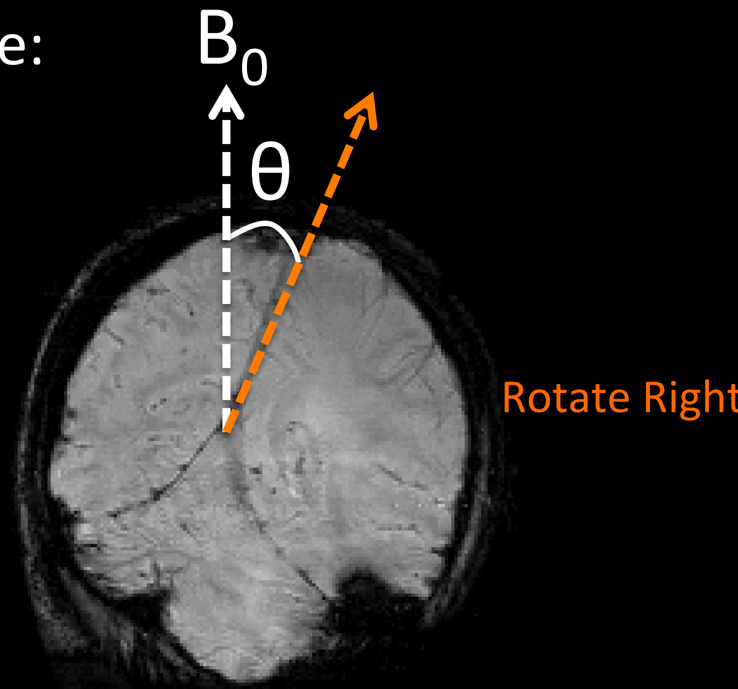

$$\delta_\theta = F^{-1} D_\theta F \chi$$

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

Multi-orientation susceptibility mapping

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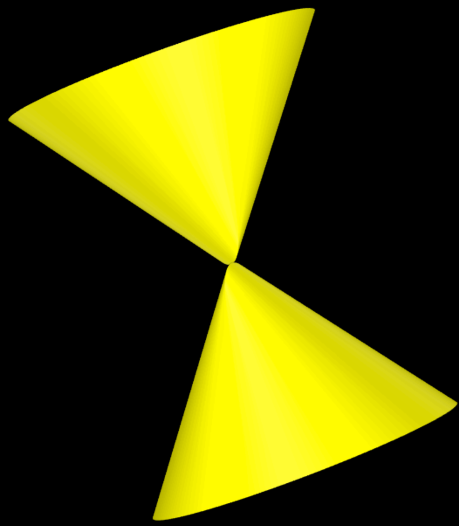

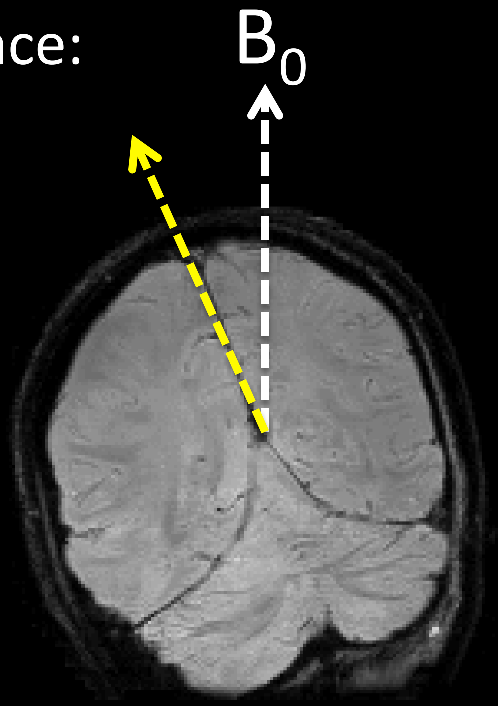

Rotate Left

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

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

Multi-orientation susceptibility mapping

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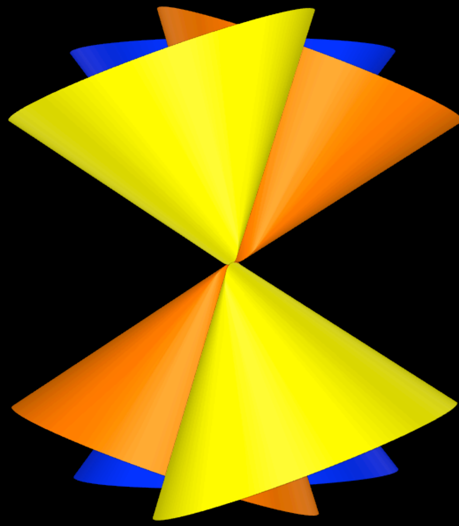
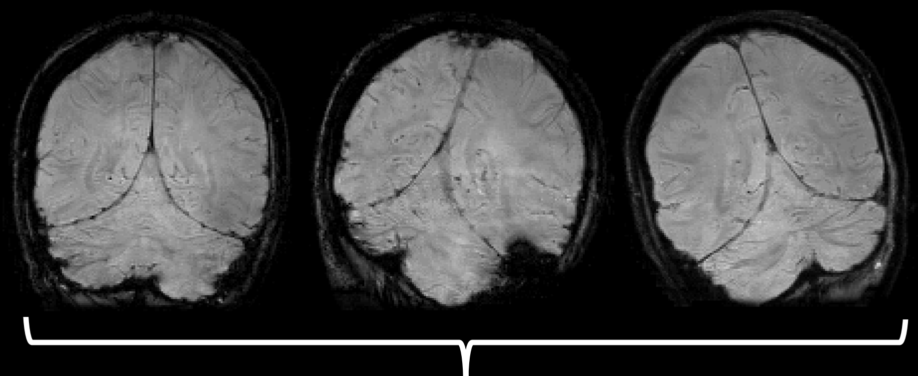




Combine multiple orientations for QSM inversion

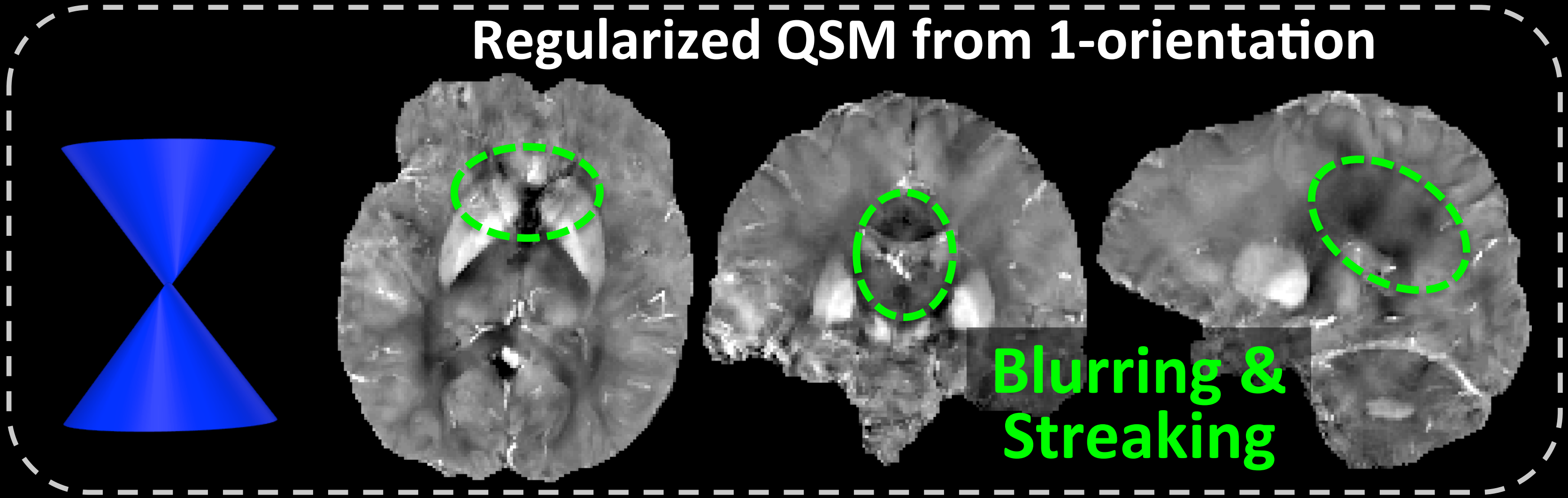
- Undersampling is substantially mitigated

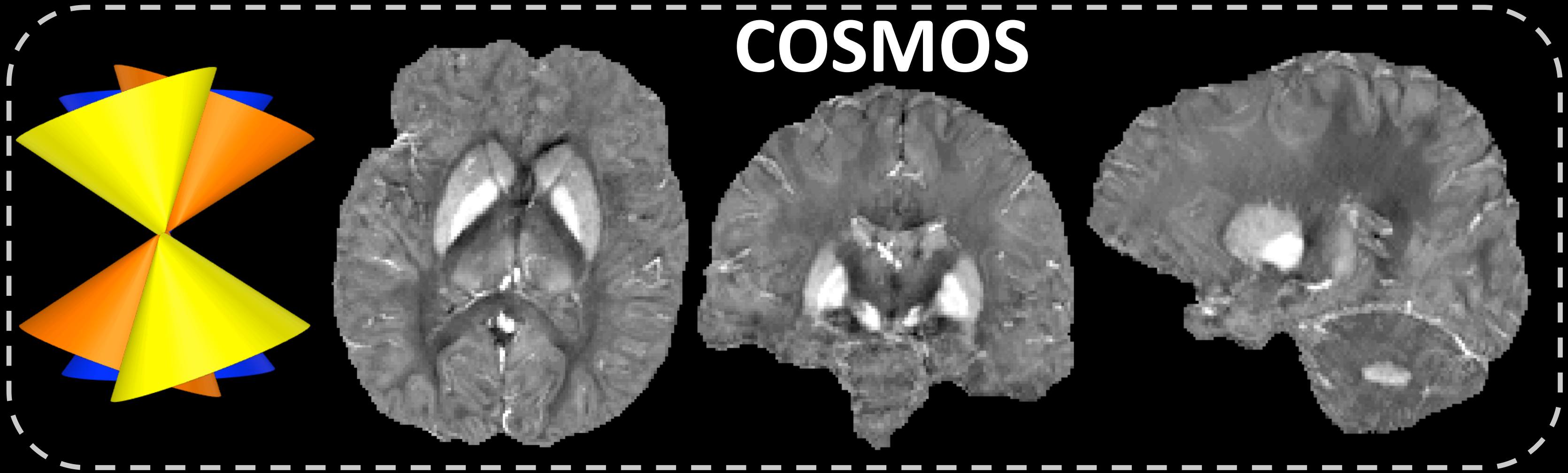
  Calculation of Susceptibility Through Multiple Orientation Sampling (COSMOS) [1,2]

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

COSMOS vs. Single-Orientation

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





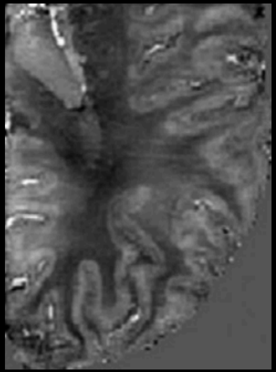
Towards in vivo Histology with QSM

- High-resolution COSMOS at ultra high field yields superb contrast to reflect the underlying anatomy [1,2]

- The contrast boost allows identification of substructures of the thalamus, basal ganglia, cortex and brain stem [1,2,3]

basal ganglia [1]

cortex [2]



midbrain [3]

- **High-resolution COSMOS requires more than 1 hour of scanning:**
  - 17 min / rotation @ 0.4 mm iso, 75% partial Fourier [1]
  - 11 min / rotation @ 0.66 mm iso, R=4 GRAPPA [2]

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

Susceptibility Tensor Imaging (STI)

- STI [1] models the susceptibility in each voxel as a tensor to capture its orientation dependence

- This entails the estimation of 6 entries in 3×3 tensor per voxel: **Requires data acquired at 6 or more head orientations**

- Previous in vivo human studies necessitated excessively long scan times at limited resolution:

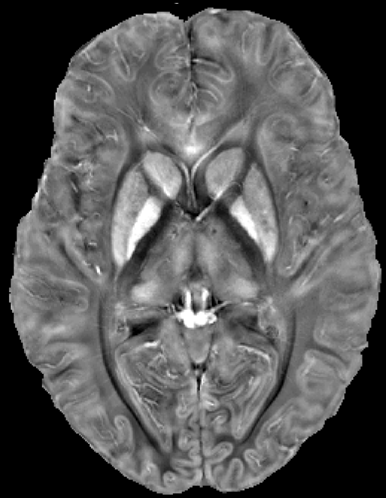
  - 16 min / rotation @ 2 mm iso [2]
  - 10 min / rotation @ 1.5 mm iso [3]
  - 5 min / rotation @ 1 mm iso, R=5 SENSE [4]

- **STI acquisition takes 2 – 4 hours, making it impractical for in vivo human imaging**

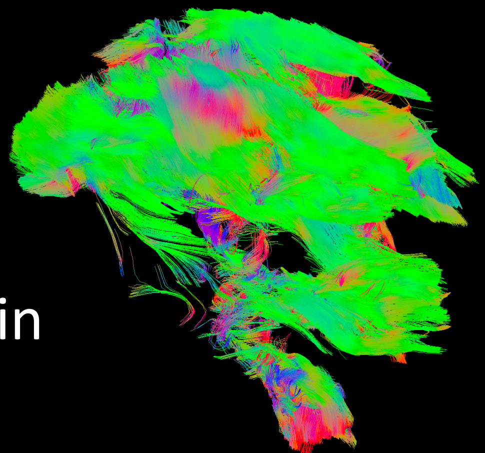
[1] C Liu, MRM'10
[2] W Li et al, NIMG'12
[3] C Wisnieff et al, NIMG'13
[4] X Li et al, NIMG'12

Wave-CAIPI for Rapid COSMOS and STI

- **For the first time, we enable whole-brain COSMOS and STI in clinically relevant scan times**
- **This is made possible by highly efficient Wave-CAIPI encoding [1]**



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



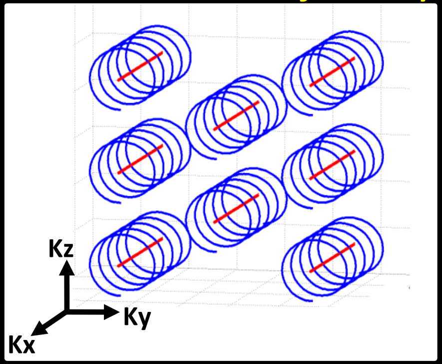
- Whole-brain STI @ 3T
  - 90 sec / rotation @ 1.1 mm iso
  - **30 min total protocol for 12-orientations**
  - First STI tractography for in vivo human brain

[1] B Bilgic, MRM'14

3D GRE with Wave-CAIPI

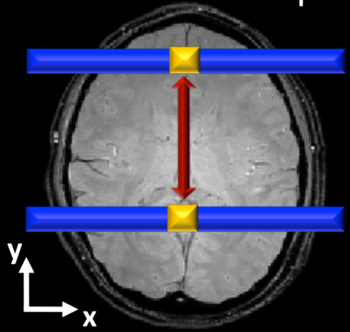
- Wave-CAIPI modifies the 3D GRE trajectory to follow a corkscrew along each readout line [1]
- For accelerated acquisitions, this spreads the aliasing in all 3D dimensions to substantially improve parallel imaging
- Acquisition has the same off-resonance characteristic as Normal GRE (voxel shift in readout), and reconstruction is fully Cartesian

Wave-CAIPI trajectory



Normal GRE

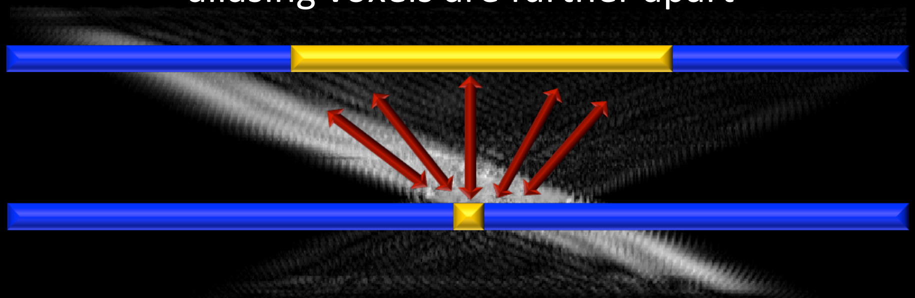
two voxels collapse



R=2 acceleration in Ky

Wave-CAIPI

aliasing voxels are further apart

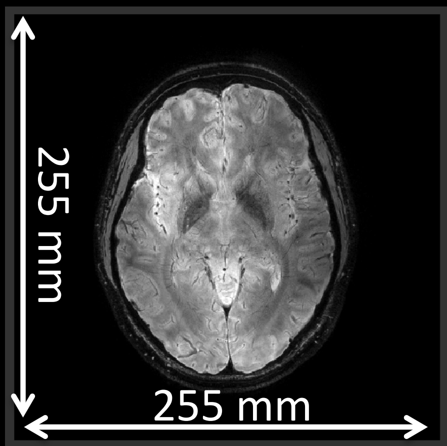


Aliasing voxels are spread out to increase the variation in coil sensitivity profiles:

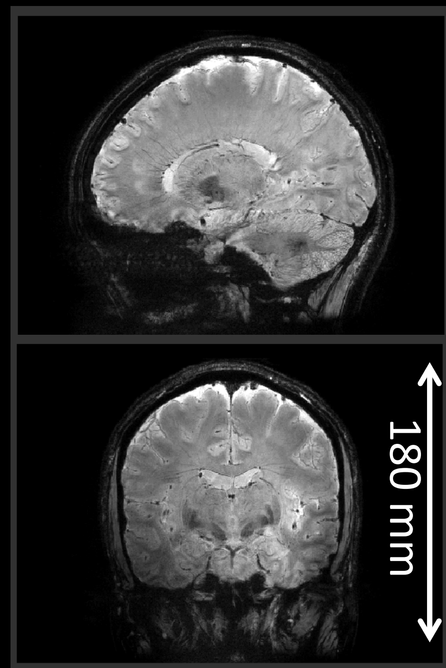
Improved G-Factor

[1] B Bilgic, MRM'14

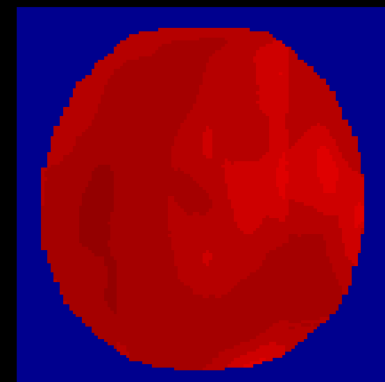
Rapid whole-brain, high resolution COSMOS @ 7T, 32 ch array



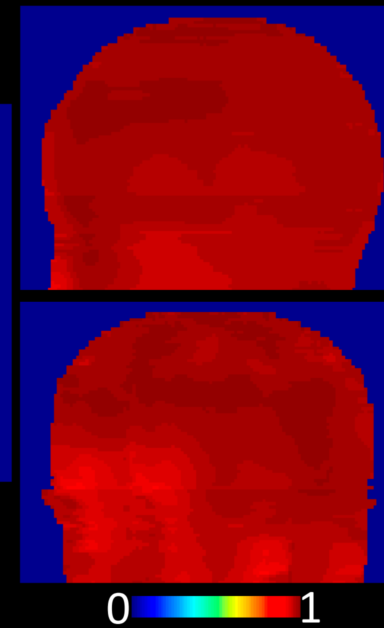
Large FOV to allow head rotation



1/g-factor:



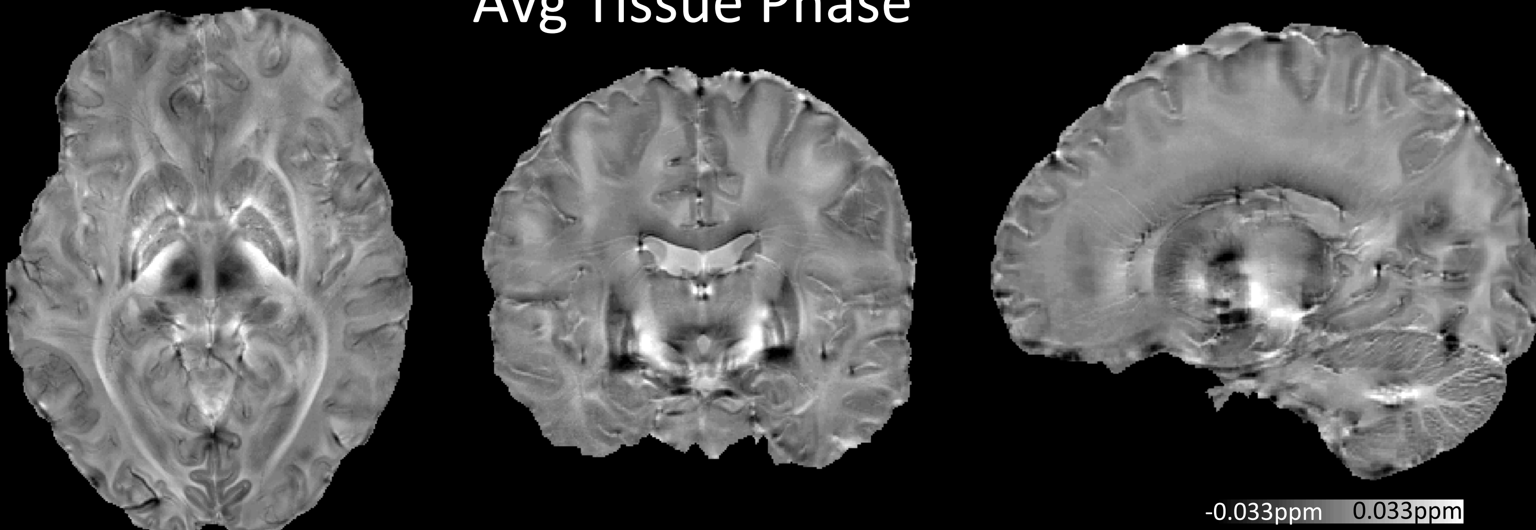
G_{avg} = 1.03
G_{max} = 1.12



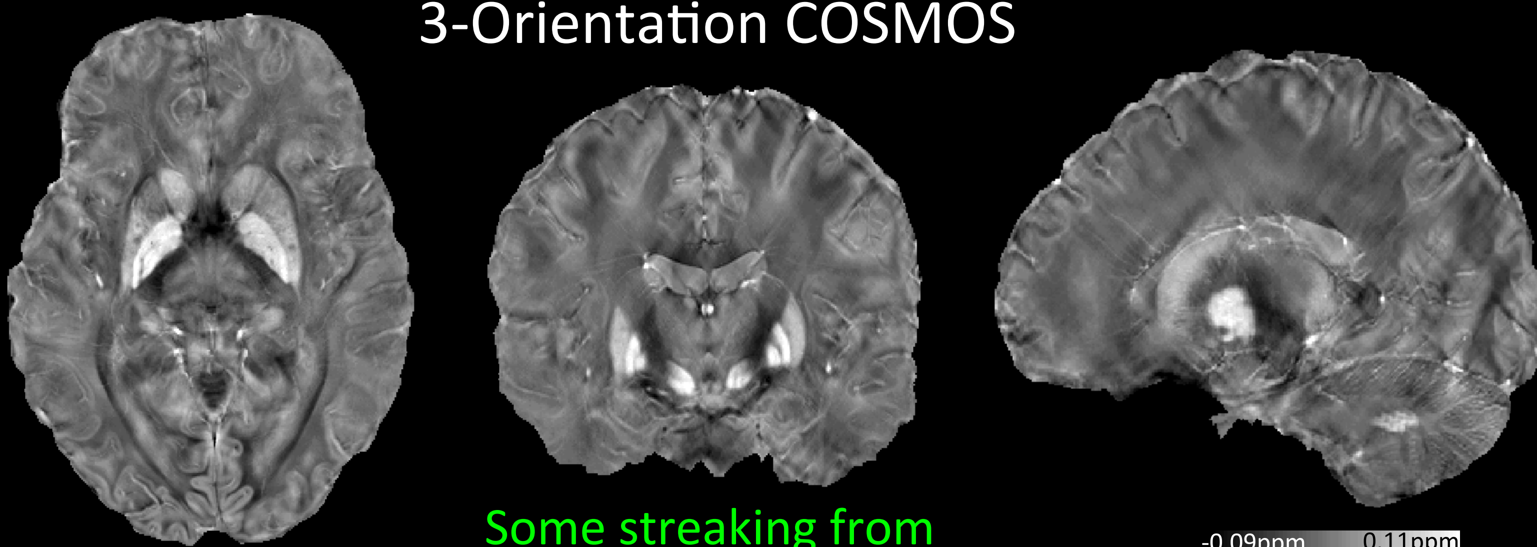
- Wave-CAIPI at R=5×3 fold acceleration
- 5:35 min / rotation @ 0.5 mm iso
- TE / TR = 19.5 / 29 ms
- 3 rotations @ 0°, 7°, 13°
- **Maximum g-factor noise amplification is 12%**

Rapid whole-brain, high resolution COSMOS @ 7T

Avg Tissue Phase

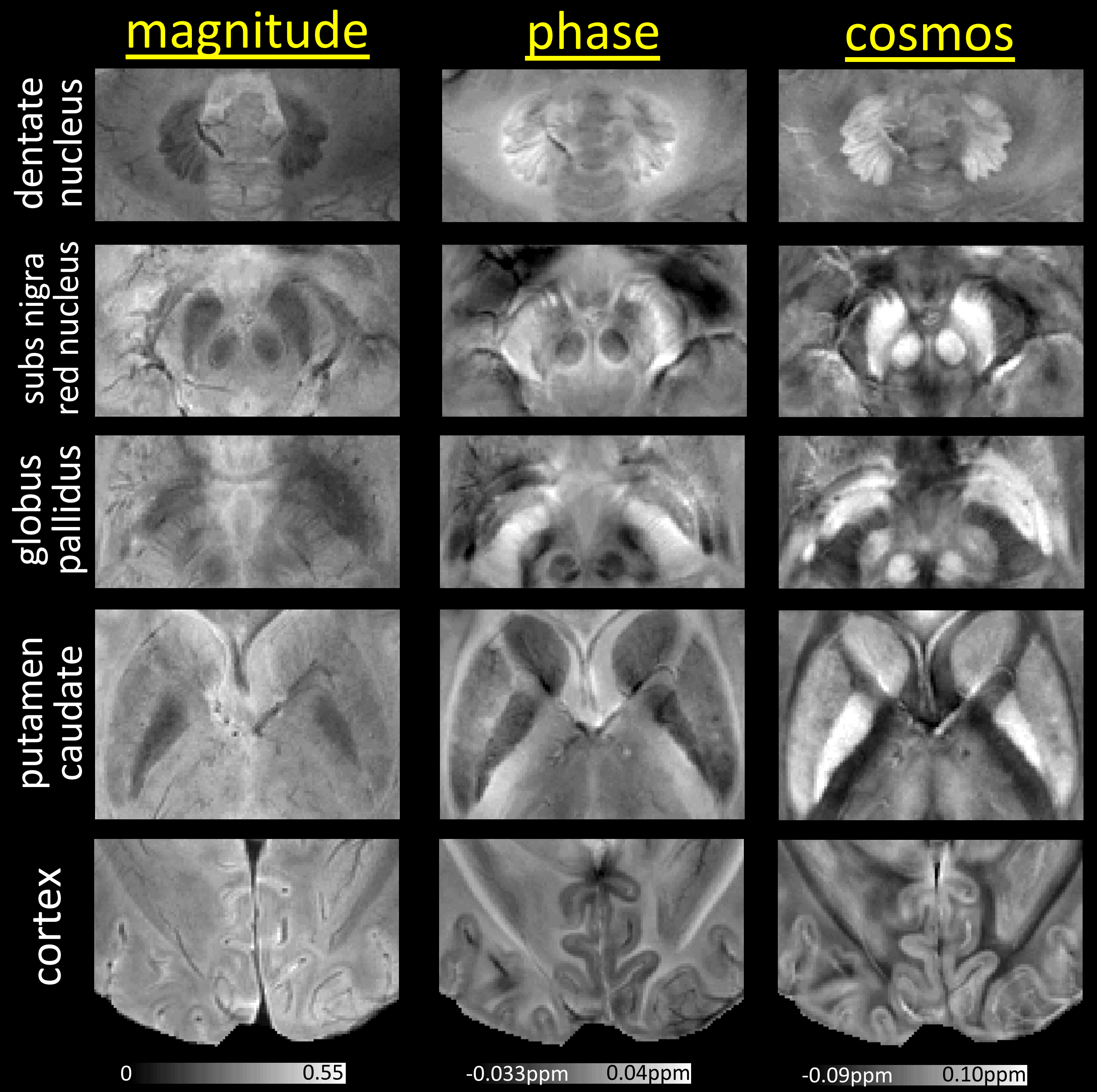


3-Orientation COSMOS



Some streaking from
small rotation angle

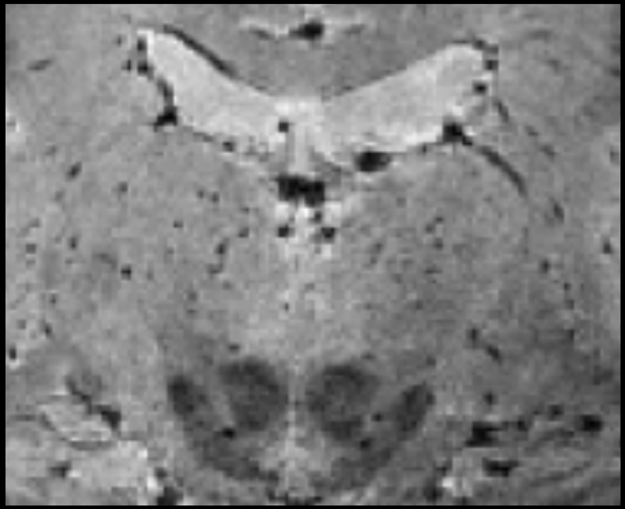
Rapid whole-brain, high resolution COSMOS @ 7T



Rapid whole-brain, high resolution COSMOS @ 7T

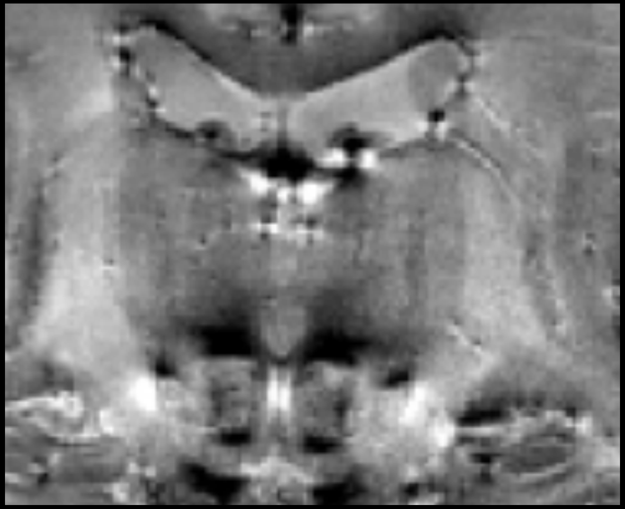
Thalamic substructures

magnitude



0.05 0.6

phase



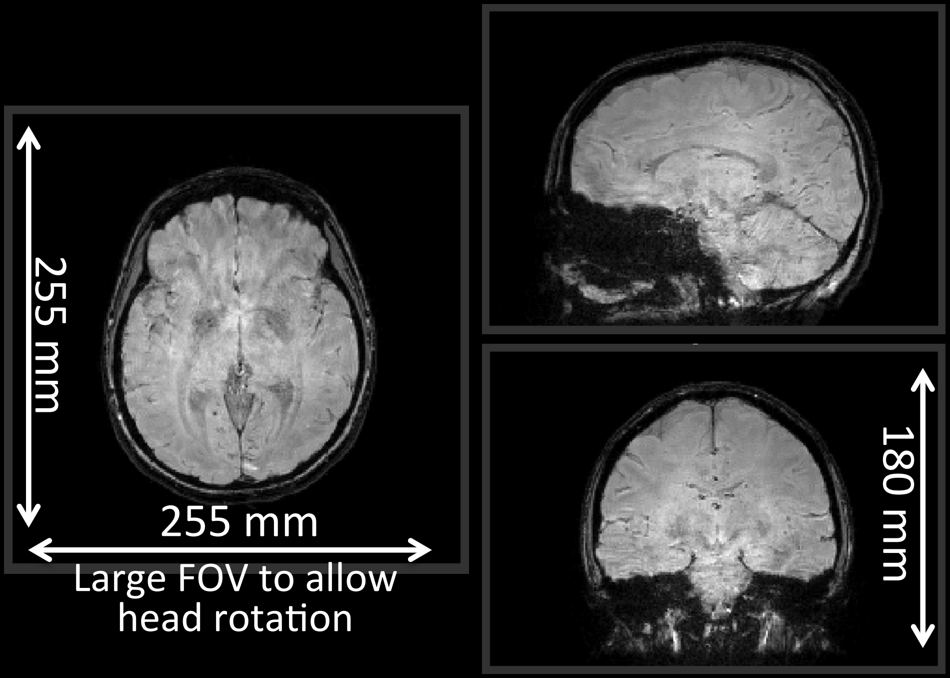
-0.03ppm 0.035ppm

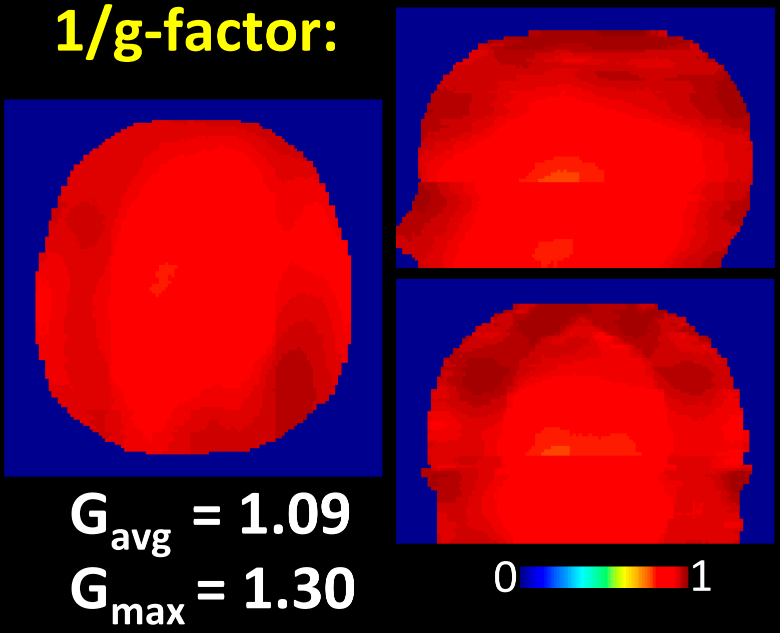
cosmos

-0.08ppm 0.09ppm

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

Rapid whole-brain STI @ 3T, 32 ch array

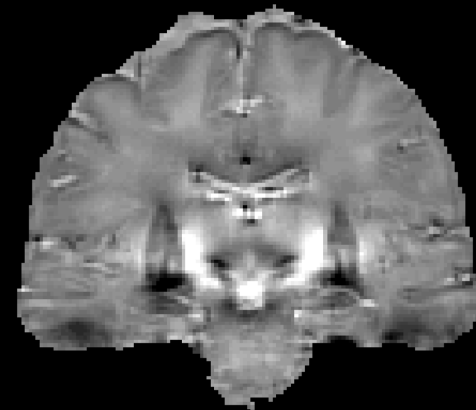
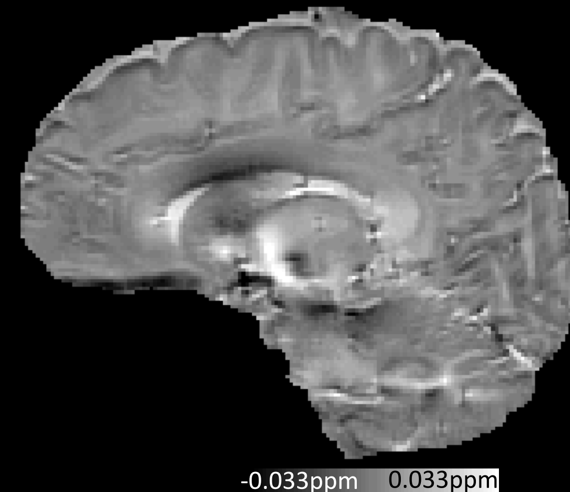




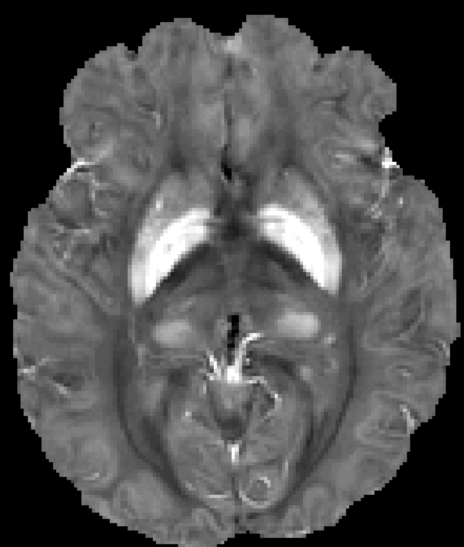
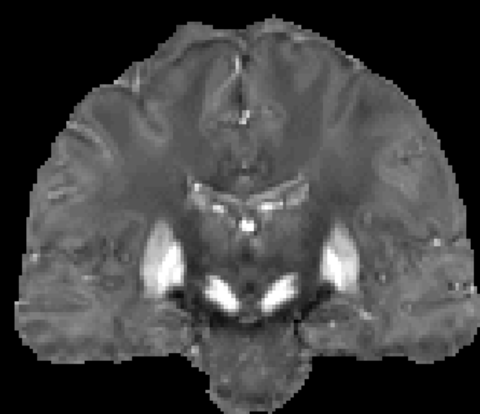
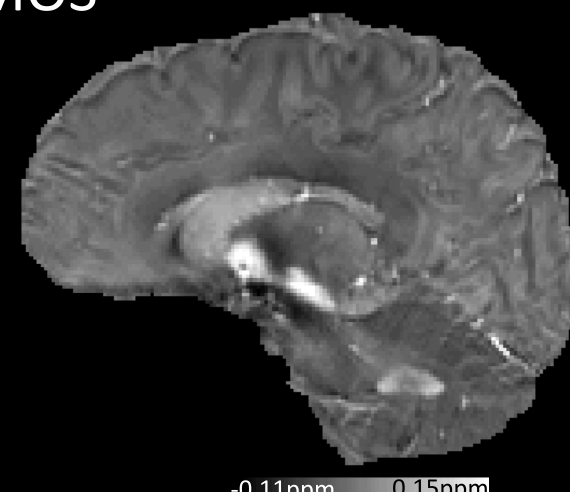
- Wave-CAIPI at R=5×3 fold acceleration
- 90 sec / rotation @ 1.1 mm iso
- TE / TR = 25 / 35 ms
- 12 rotations (up to 25°)
- **Maximum g-factor noise amplification is 30%**

Rapid whole-brain STI @ 3T

Avg Tissue Phase

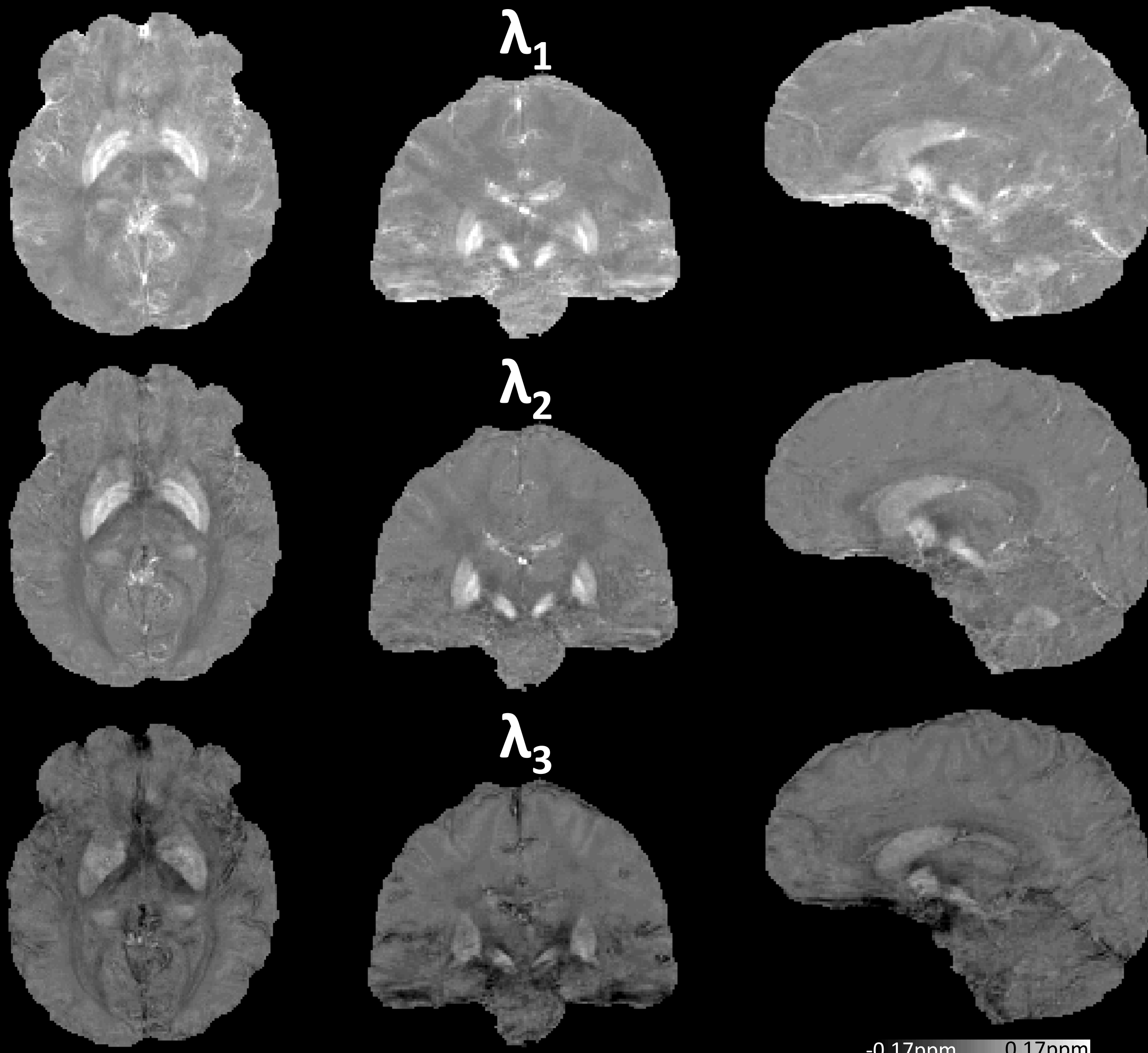
12-Orientation COSMOS

No streaking: many rotations & larger angle

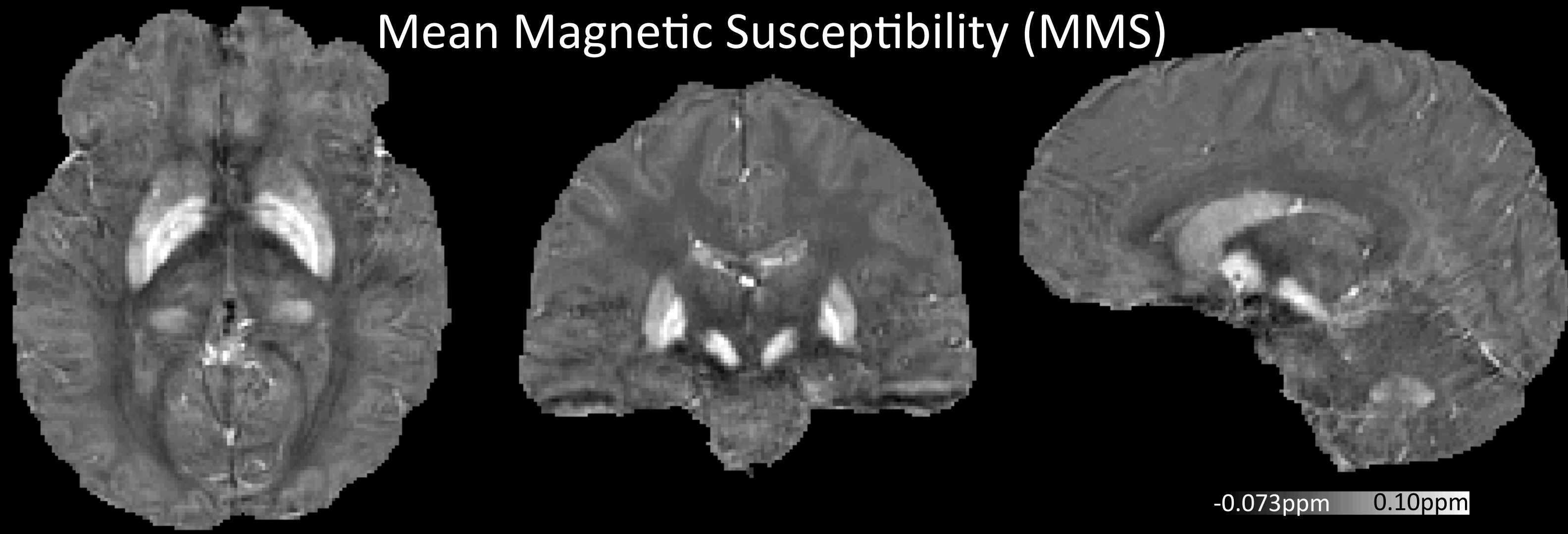
Rapid whole-brain STI @ 3T

STI Eigenvalues

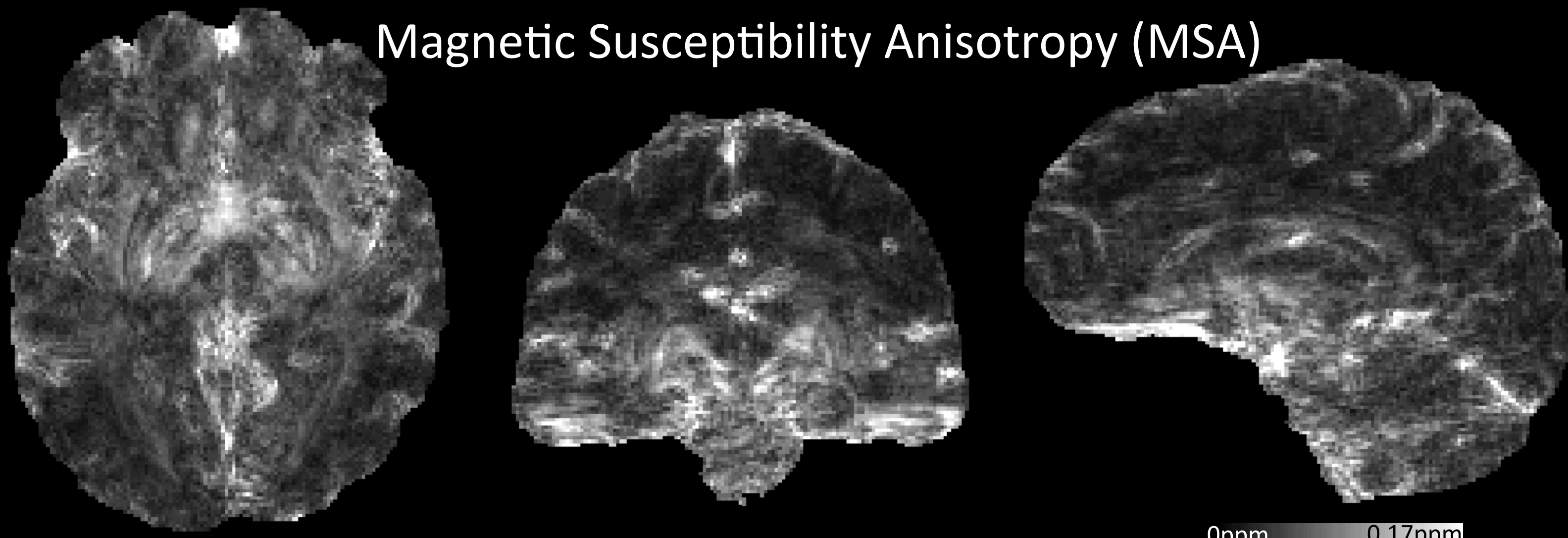


Rapid whole-brain STI @ 3T

Mean Magnetic Susceptibility (MMS)

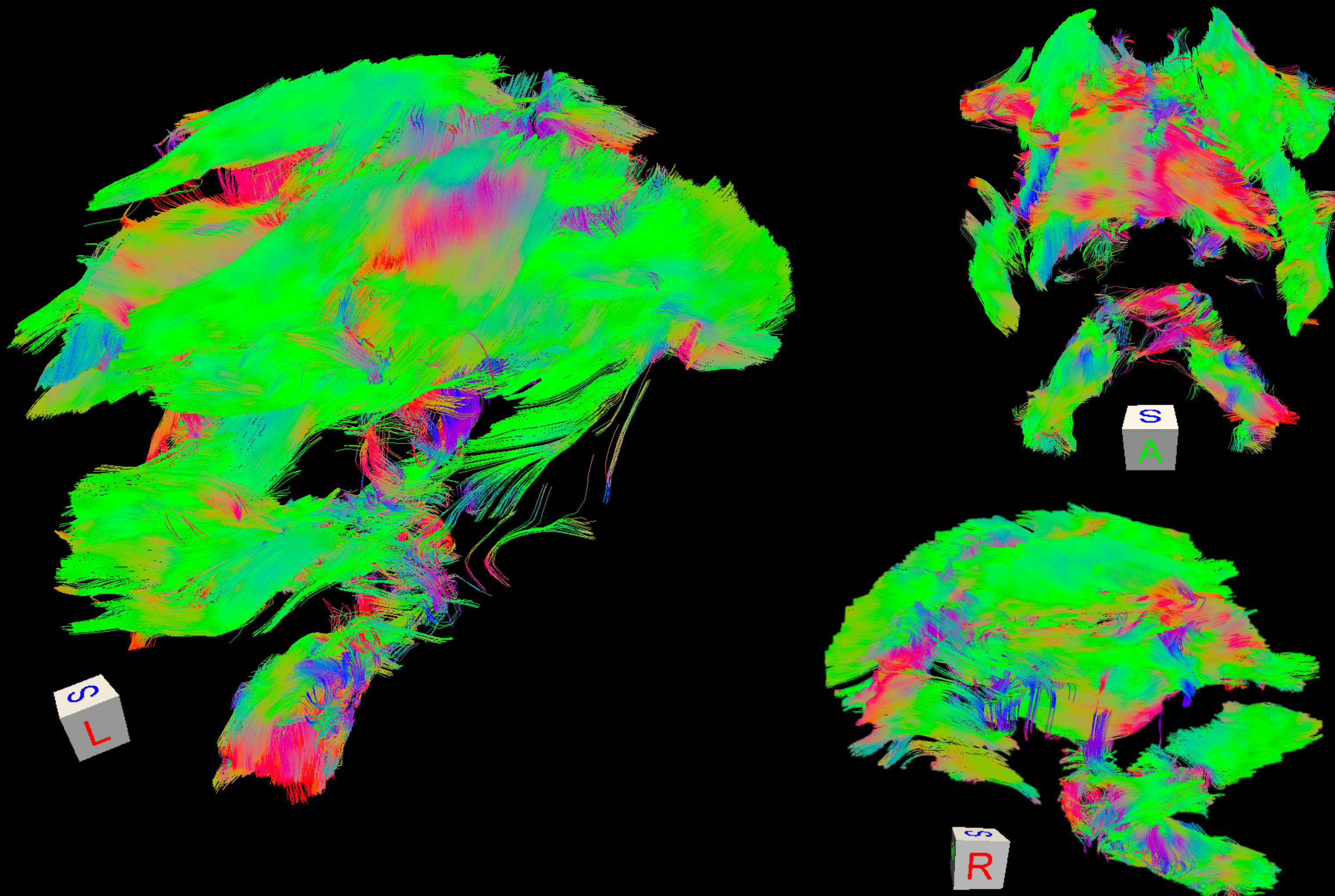


Magnetic Susceptibility Anisotropy (MSA)



Rapid whole-brain STI @ 3T

STI Tractography from 12 Orientations



Detailed analysis: G-factor and Time-SNR

1. Use g-factor to quantify noise amplification in parallel imaging

- Compare R=5×3 Normal GRE
  R=5×3 Wave-CAIPI
- Acquire 1.1 mm iso @ 3T

Detailed analysis: G-factor and Time-SNR

1. Use g-factor to quantify noise amplification in parallel imaging

2. Use Time-SNR metric to quantify robustness and stability

$$\text{Time-SNR map} = \frac{\text{Mean signal over N avg}}{\text{Standard deviation}}$$

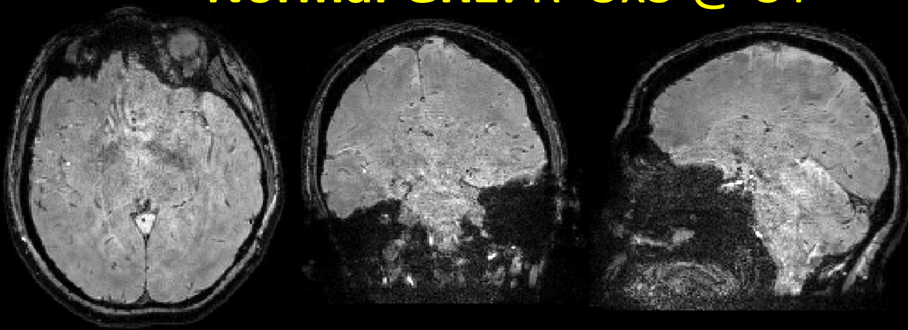
- Compare

Compare	R=5×3	Normal GRE	[whole-brain FOV]
	R=5×3	Wave-CAIPI	[whole-brain FOV]
	R=1	Normal GRE	[reduced FOV, time-matched]

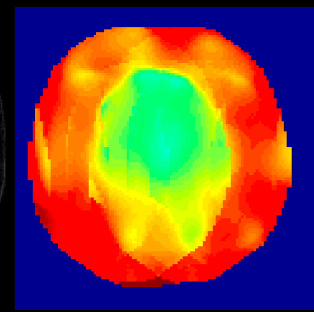
- Acquire 7 avg @ 1.1 mm resolution, 90 sec / avg

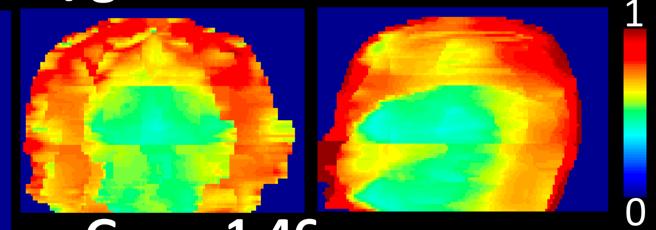
G-factor comparison

Normal GRE: R=5x3 @ 3T



1/g-factor:

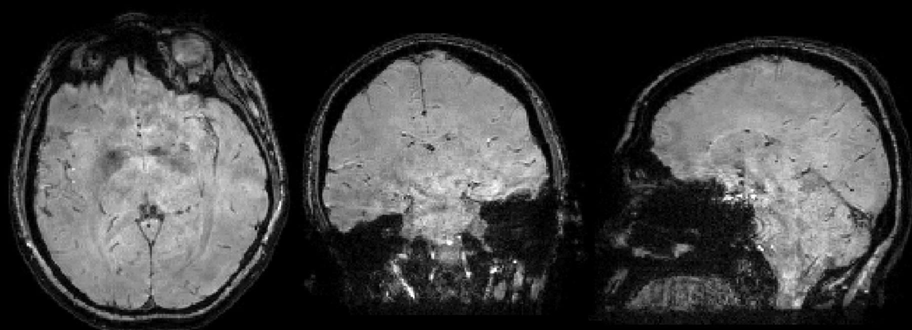




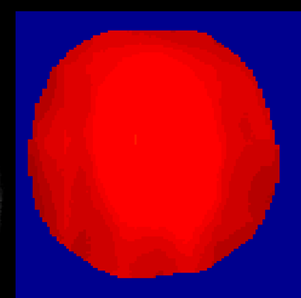
$G_{avg} = 1.46$

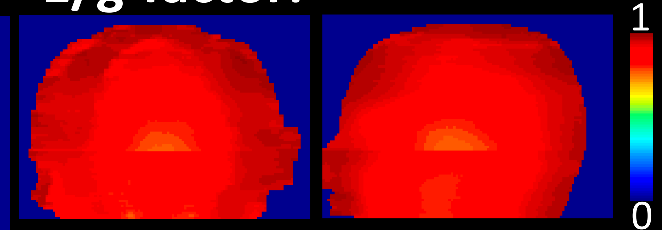
$G_{max} = 3.33$

Wave-CAIPI: R=5x3 @ 3T



1/g-factor:



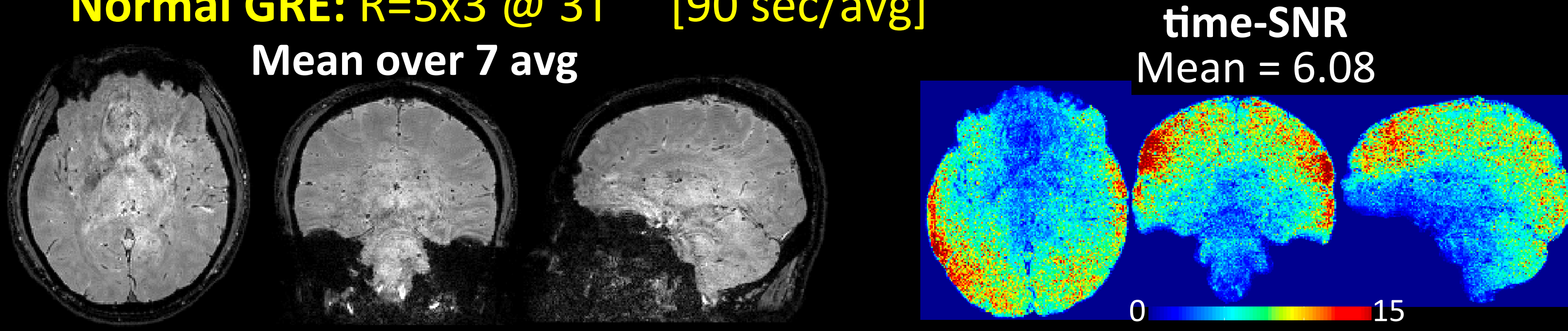


$G_{avg} = 1.10$

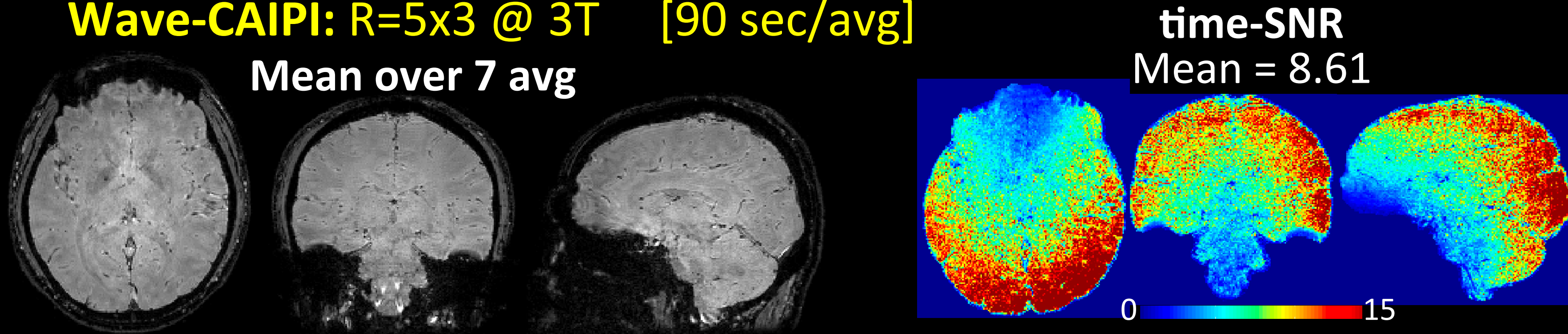
$G_{max} = 1.42$

Time-SNR comparison

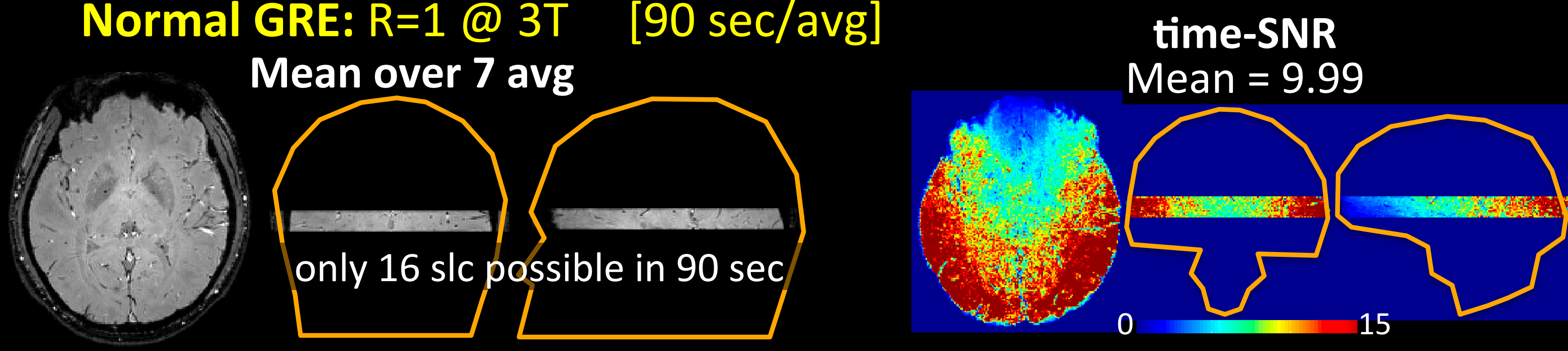
Normal GRE: R=5x3 @ 3T [90 sec/avg]



Wave-CAIPI: R=5x3 @ 3T [90 sec/avg]



Normal GRE: R=1 @ 3T [90 sec/avg]

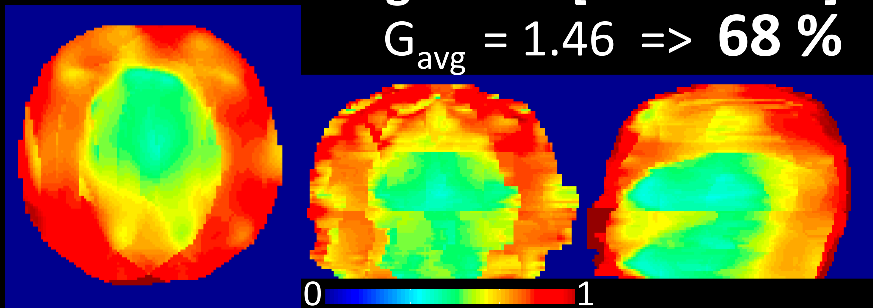


Time-SNR comparison

Normal GRE:

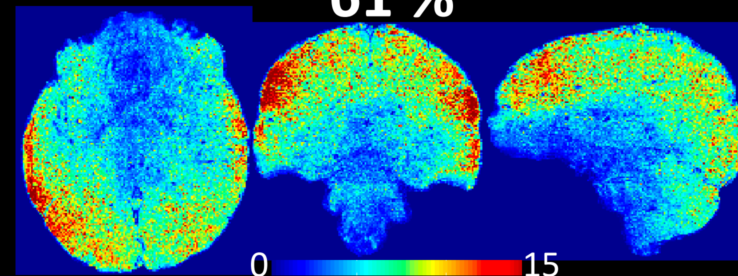
g-factor [simulation]

G_{avg} = 1.46 => **68 %**



time-SNR [measured]

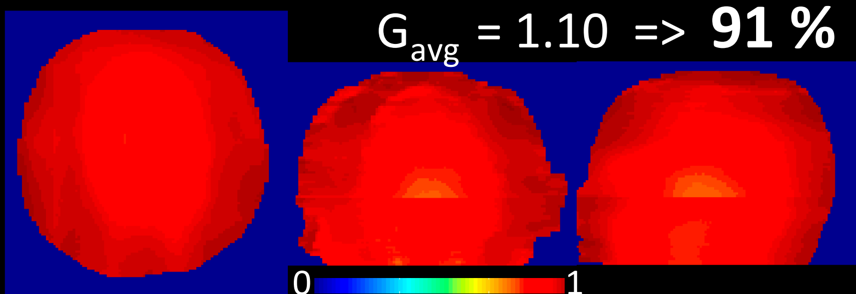
61 %



Wave-CAIPI:

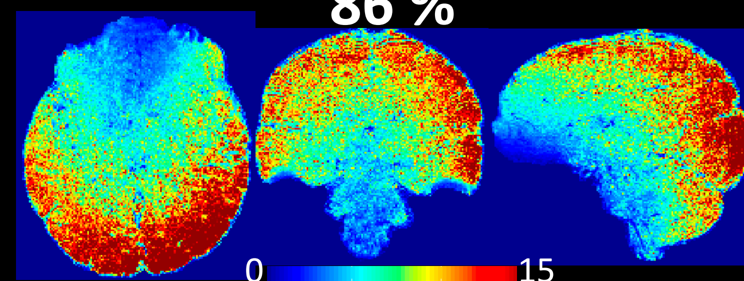
g-factor [simulation]

G_{avg} = 1.10 => **91 %**



time-SNR [measured]

86 %



- Noise amplification metrics from simulation and measurement agree

Conclusion: Rapid Multi-orientation QSM with Wave-CAIPI

- Wave-CAIPI enables whole-brain COSMOS and STI in clinically relevant times

- At R=5×3 accl, 20 min COSMOS @ 3 rotation & 0.5 mm
  30 min STI @ 12 rotation & 1.1 mm

- Wave-CAIPI reduces max g-factor by > 2× relative to Normal GRE

- And retains 86% of Time-SNR relative to fully-sampled acquisition

Conclusion: Rapid Multi-orientation QSM with Wave-CAIPI

- Matlab software and data online for Wave-CAIPI:

  martinos.org/~berkin

- **Acknowledgement**

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Thank you for your attention