Joint Reconstruction of Phase-Cycled Balanced SSFP with Constrained Parallel Imaging

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martinos.org/~berkin/Joint_L1SPIRiT.zip

Plasma #16

Declaration of Financial Interests or Relationships

Speaker Name: Berkin Bilgic

I have the following financial interest or relationship(s) to disclose with regard to the subject matter of this presentation:

- Research support: Siemens
- Licensing agreement: Samsung

Balanced SSFP

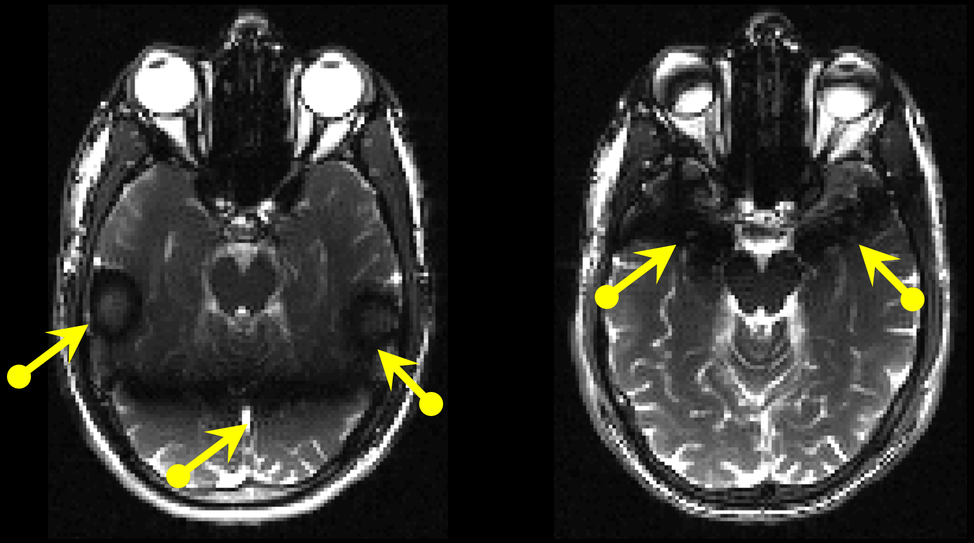
- bSSFP has unique T2 / T1 contrast
  inherent high SNR efficiency
  fast imaging time: short TE & TR

- Provides strong contrast between tissues with different T2 / T1 ratios
  - Cardiac [1] (blood – myocardium contrast)
  - Angio [2] (blood – surrounding tissue)
  - MSK [3] (fat – muscle)
  - Neuro [4] nerves at skull base (CSF – cranial nerve)

martinos.org/~berkin/Joint_L1SPIRiT.zip

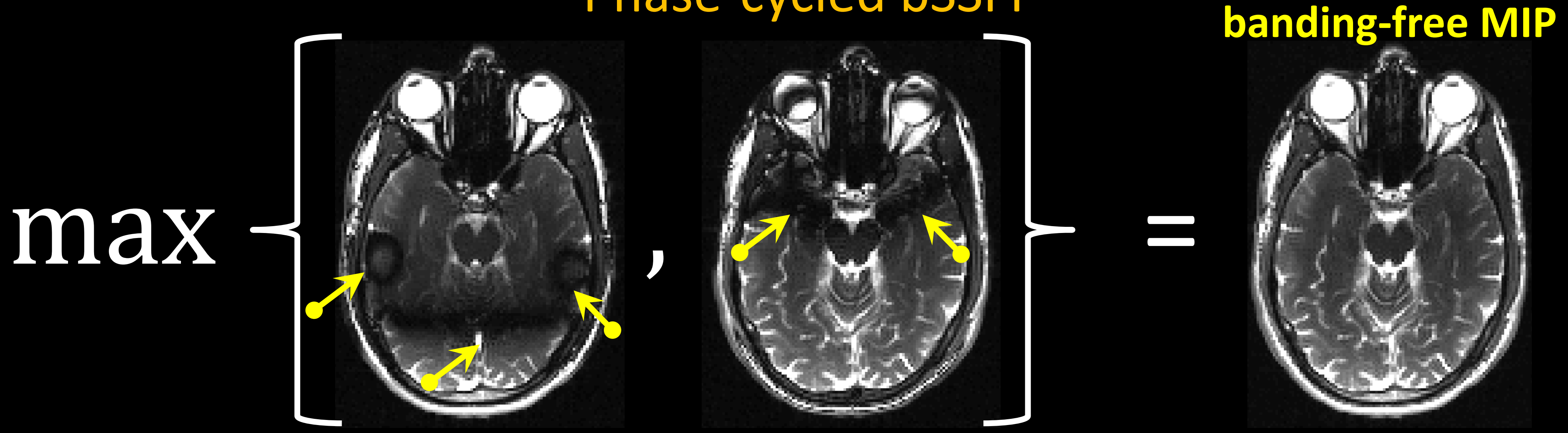
[1] DC Peters et al MRM 2002
[2] NK Bangerter et al MRM 2011
[3] GE Gold et al JMRI 2007
[4] JW Casselman et al Am Soc Neuroradiology 1993

Phase-cycled bSSFP



- But suffers from banding artifacts due to sensitivity to B0 inhomogeneity
- Can be mitigated by phase-cycling:
  - multiple acquisitions with different phase increment btw successive RFs
  - this shifts location of banding artifacts

Phase-cycled bSSFP



- But suffers from banding artifacts due to sensitivity to B0 inhomogeneity
- Can be mitigated by phase-cycling:
  - multiple acquisitions with different phase increment btw successive RFs
  - this shifts location of banding artifacts
  - combine cycles with Max Intensity Projection (MIP)

Phase-cycled bSSFP

- Phase-cycling mitigates banding artifacts
- But increases scan time, counteracting inherent efficiency of bSSFP
- Parallel Imaging [1,2] and Simultaneous MultiSlice (SMS) [3,4] employ receiver sensitivity encoding to reduce scan time
- And have been deployed in phase-cycled bSSFP for up to 4-fold acceleration [5,6]

[1] KP Pruessmann et al MRM 1999
[2] MA Griswold et al MRM 2002
[3] DJ Larkman et al JMRI 2001
[4] FA Breuer et al MRM 2005
[5] D Stab et al MRM 2011
[6] Y Wang et al MRM 2015

Joint Recon for Phase-cycled bSSFP

- We propose to **jointly recon phase-cycled images**

- We introduce **Joint L1-SPIRiT**:

  - recons all phase-cycles simultaneously to exploit their mutual info

  - fit SPIRiT kernels [1] **jointly across coils and phase-cycles**

  - analogous to *k-t* in dynamic imaging [2], *virtual coil* in diffusion imaging [3] and joint recon in TIAMO [4]

[1] M Lustig et al MRM 2010
[2] F Huang et al MRM 2005
[3] E Dai et al MRM 2016
[4] S Orzada et al MRM 2010

martinos.org/~berkin/Joint_L1SPIRiT.zip

Joint Recon for Phase-cycled bSSFP

- We propose to **jointly recon phase-cycled images**

- We introduce **Joint L1-SPIRiT**:
  - by creating virtual coils out of the phase-cycles,

    converts banding artifacts into useful, additional spatial encoding

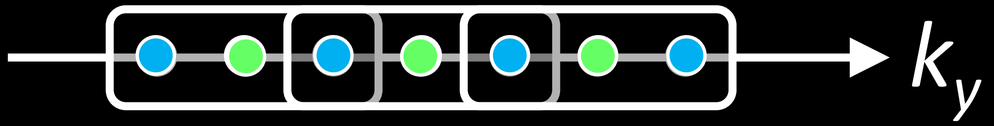
  - reduction in g-factor noise amplification is > 1.8-fold relative to GRAPPA

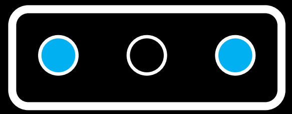
    SNR improvement is similar to 3 averages of GRAPPA recon

martinos.org/~berkin/Joint_L1SPIRiT.zip

GRAPPA Recon

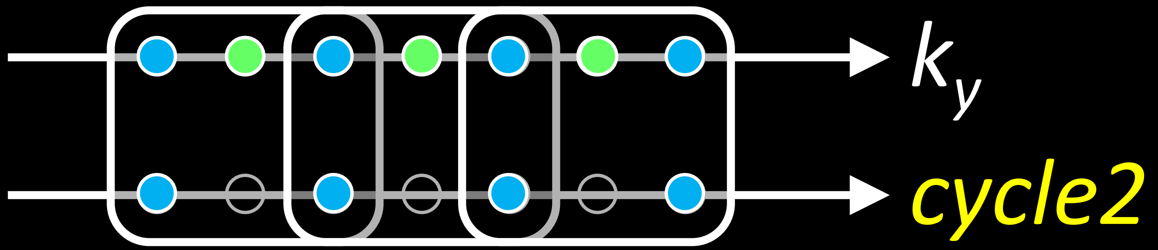
- R=2 acceleration, ignoring coil and readout axes

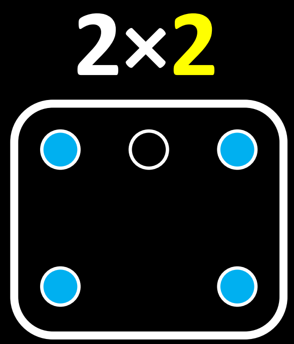




Joint GRAPPA

- Extend GRAPPA to jointly recon all phase-cycles [1]



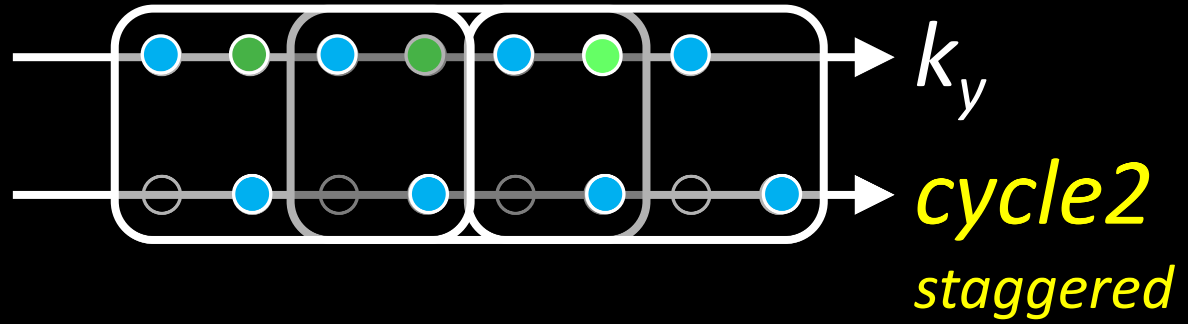


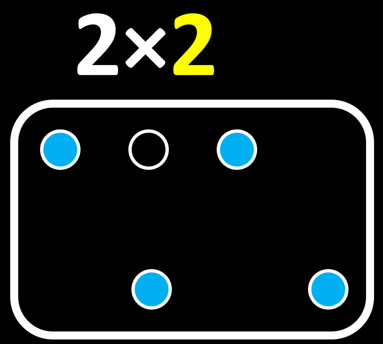
[1] B Bilgic et al ESMRMB'16

martinos.org/~berkin/Joint_L1SPIRiT.zip

Joint GRAPPA

- Staggered sampling for complementary k-space info:



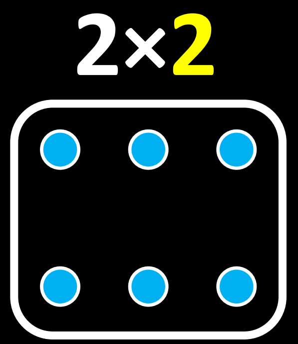


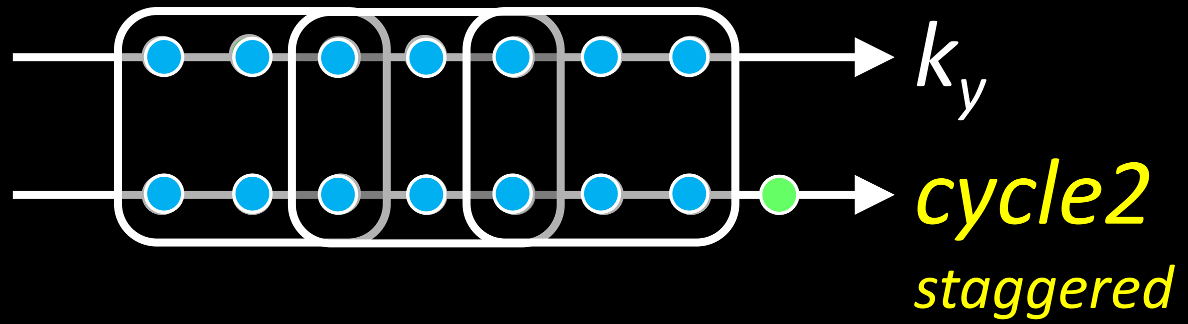
[1] B Bilgic et al ESMRMB'16

martinos.org/~berkin/Joint_L1SPIRiT.zip

Proposed: Joint L1-SPIRiT

- Staggered sampling for complementary k-space info:
- SPIRiT uses compact kernels and permits L1 regularization





+ Total Variation regularization

Data Reconstruction

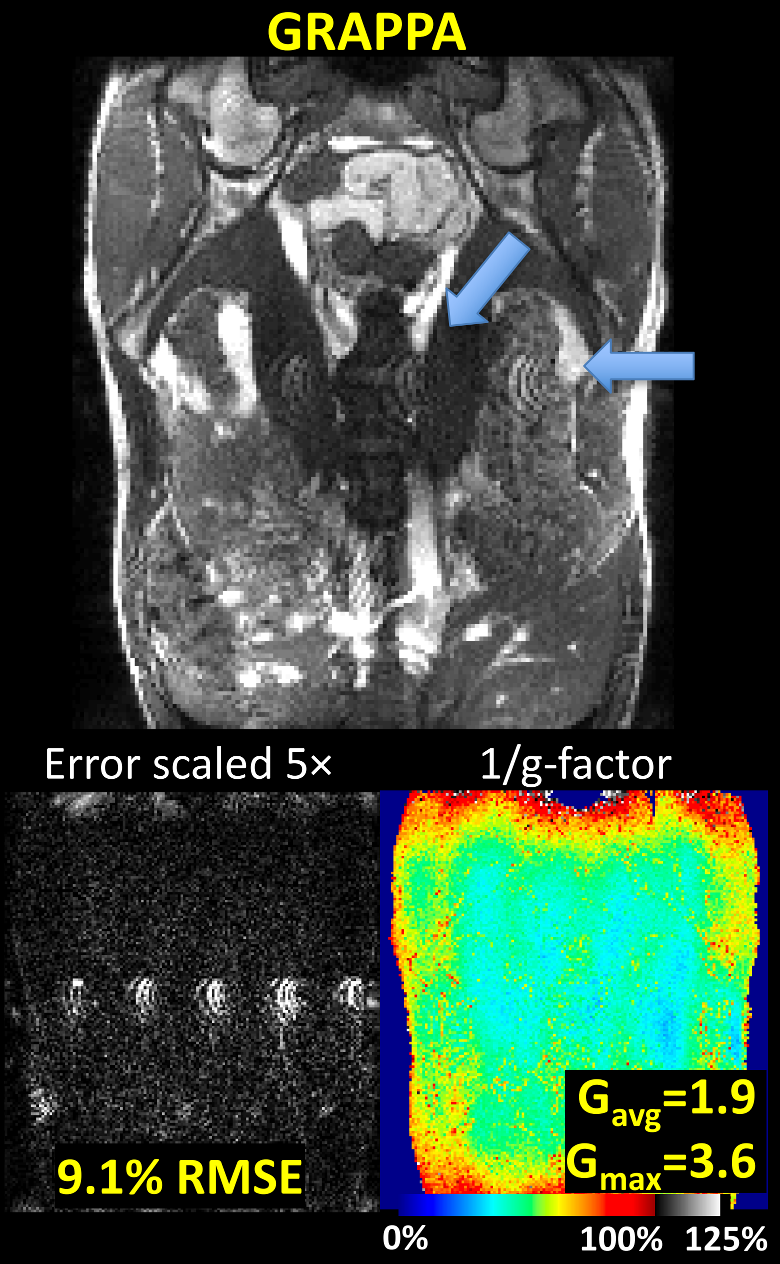
- GCC coil compression to 12 channels [1]
- Kernels estimated with Tikhonov regularization from 32 ACS lines
- Regularization, kernel sizes and staggering amount optimized for best RMSE
- G-factor from 300 Monte-Carlo iterations [2]

martinos.org/~berkin/Joint_L1SPIRiT.zip

[1] T Zhang et al MRM 2013
[2] FA Breuer et al MRM 2009

Abdominal 2D bSSFP acquisition

four phase-cycles, acceleration R=6



- four cycles {0, π/2, π, 3π/2}
- FOV = 380×380 mm^2,
- 5 mm thick slice
- mtx = 160×160
- TR/TE = 3.3/1.54 ms
- 34-chan

Abdominal 2D bSSFP acquisition

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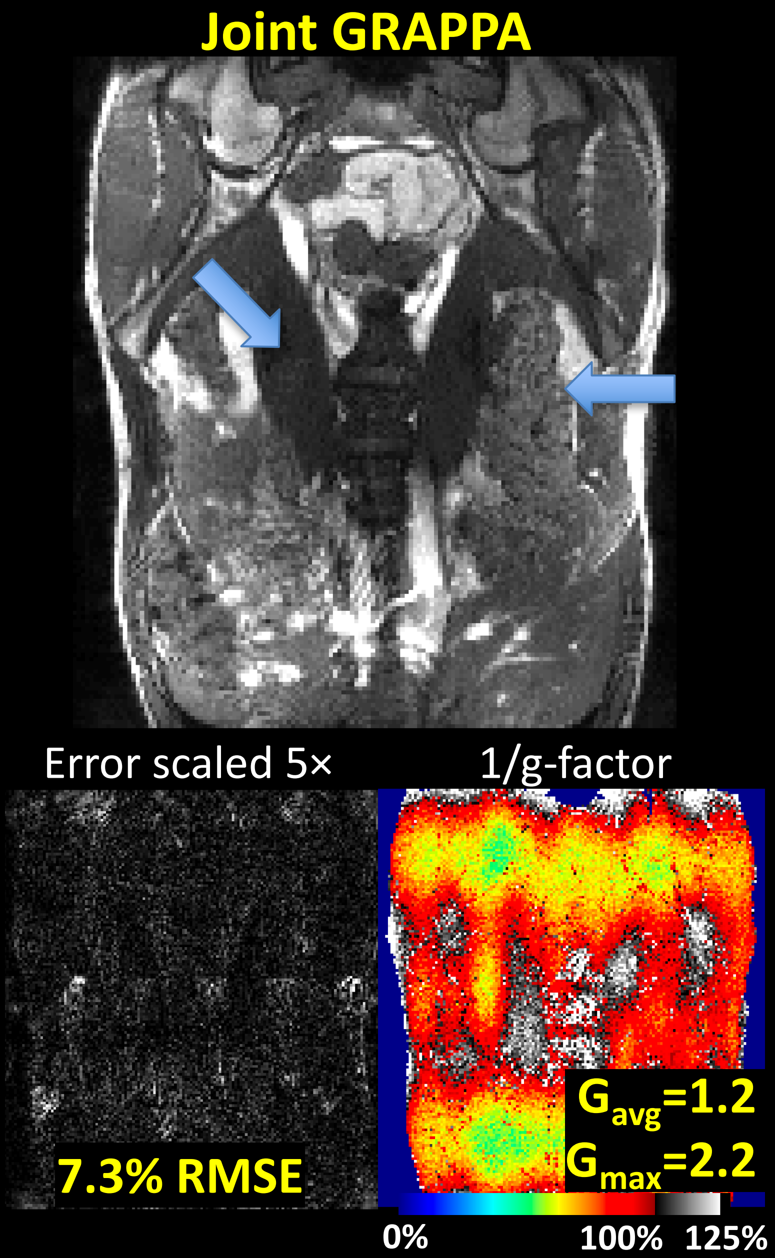

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Abdominal 2D bSSFP acquisition

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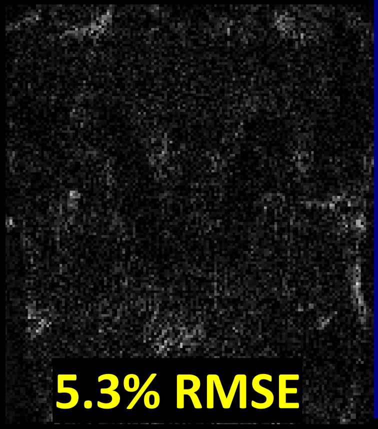
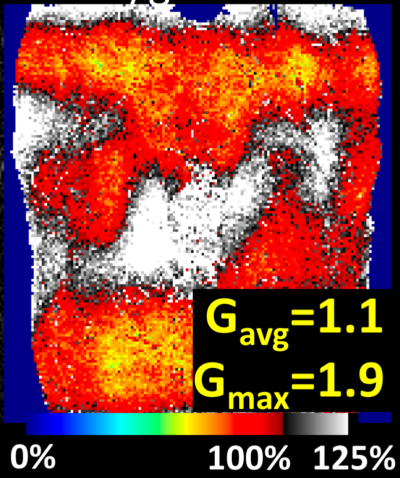
Proposed:
Joint L1-SPIRiT

Error scaled 5×



1/g-factor



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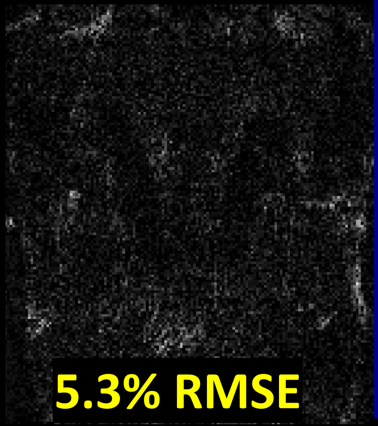
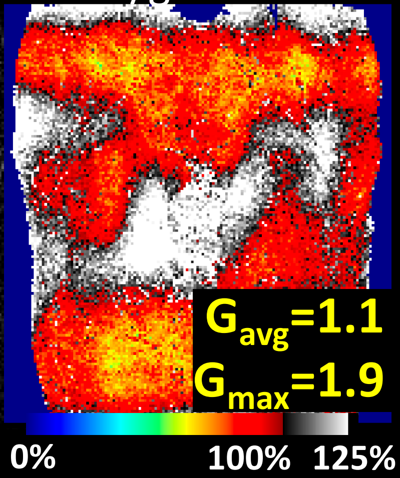


1/g-factor



RMSE reduced 70%

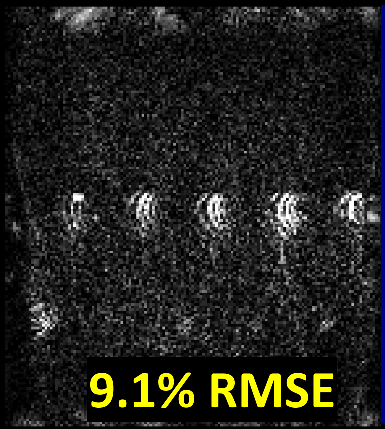
G_{max} reduced 1.9-fold

G_{avg} reduced 1.7-fold

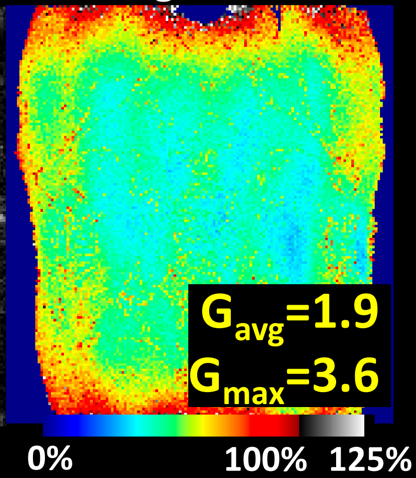
SNR improvement is ~3 averages of GRAPPA

GRAPPA

Error scaled 5×

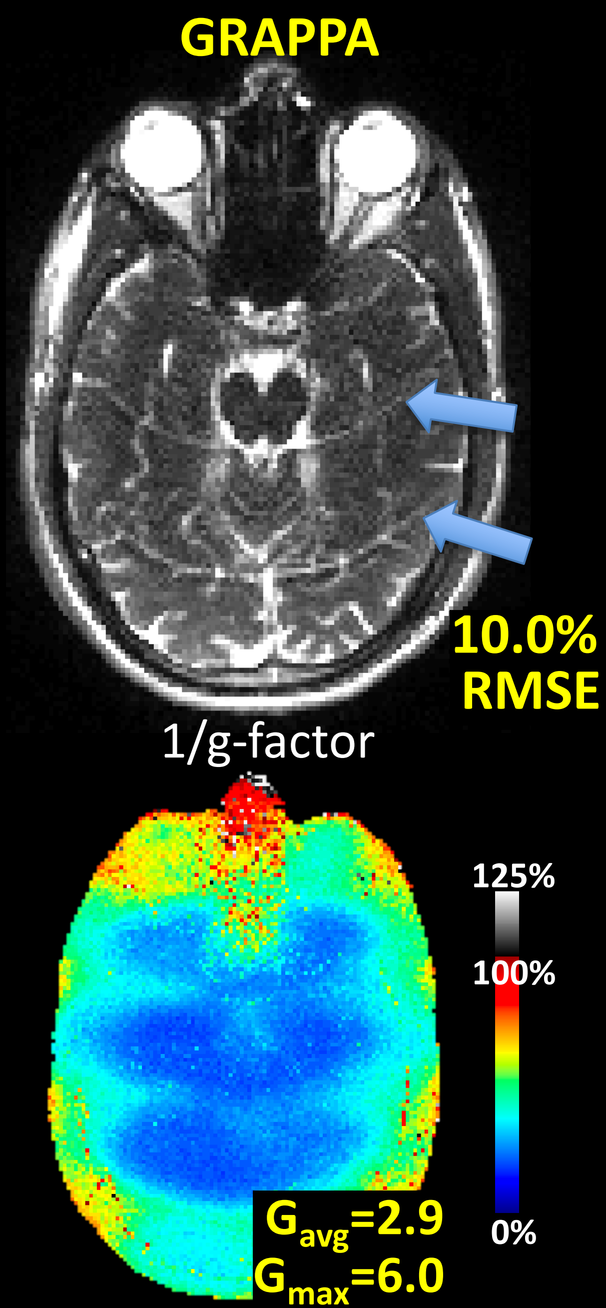


1/g-factor



Neuro 2D bSSFP acquisition

four phase-cycles, acceleration R=6

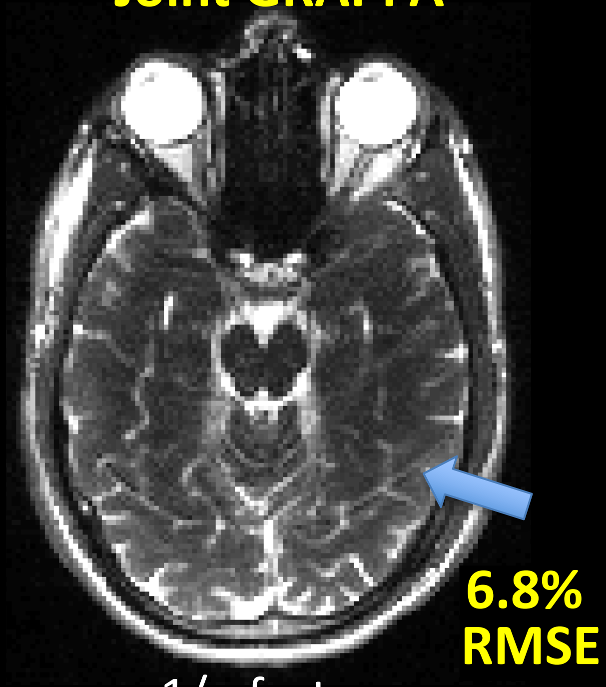


- four cycles {0, π/2, π, 3π/2}
- FOV = 240×240 mm^2,
- 4.5 mm thick slice
- mtx = 160×160
- TR/TE = 3.4/1.6 ms
- 32-chan

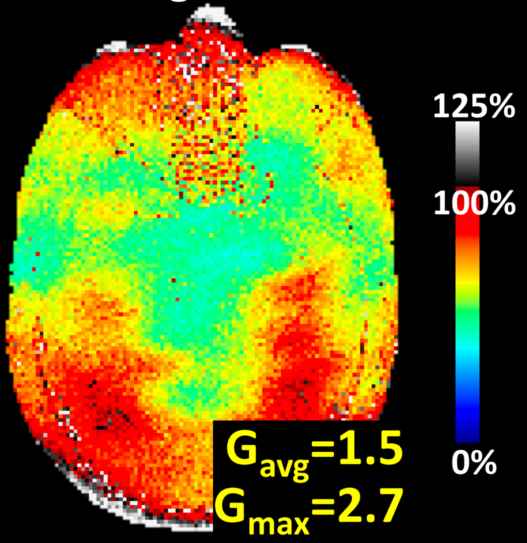
Neuro 2D bSSFP acquisition

four phase-cycles, acceleration R=6

Joint GRAPPA



1/g-factor



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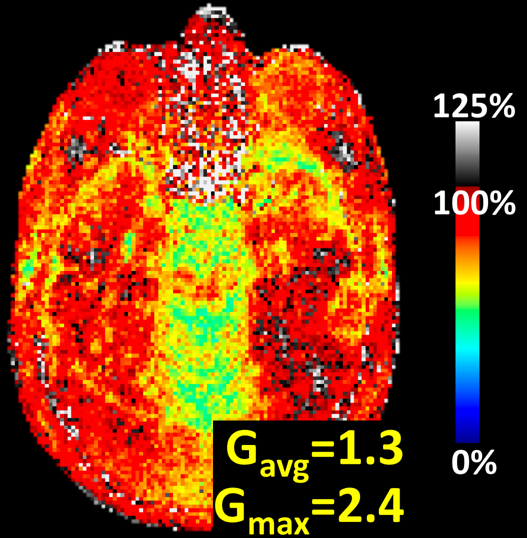
Neuro 2D bSSFP acquisition

four phase-cycles, acceleration R=6

Proposed: Joint L1-SPIRiT

5.2% RMSE

1/g-factor



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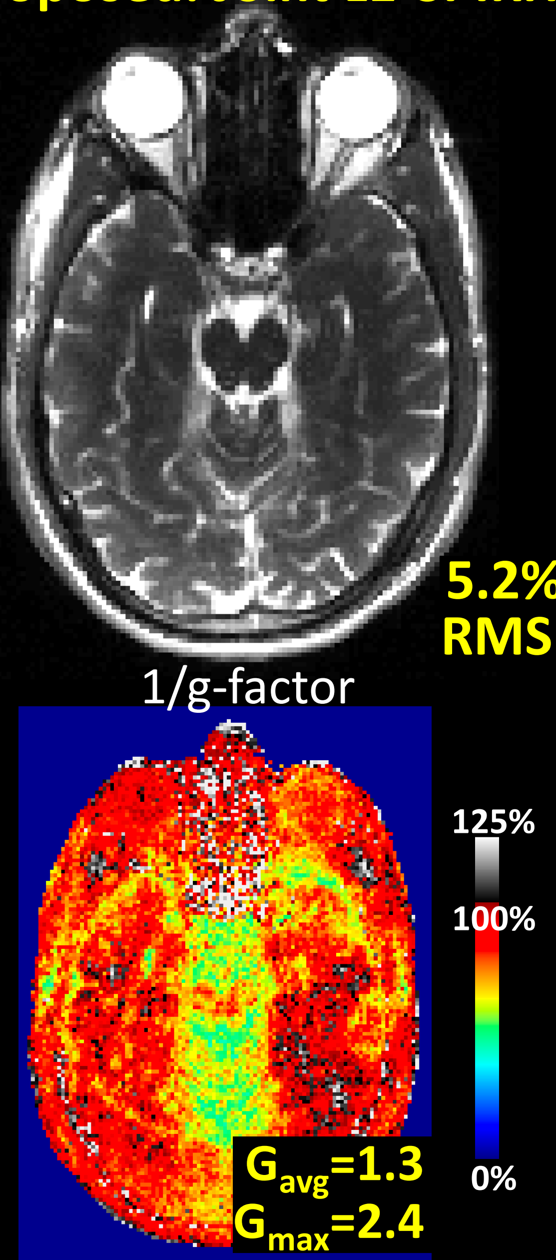
Neuro 2D bSSFP acquisition

four phase-cycles, acceleration R=6

Proposed: Joint L1-SPIRiT



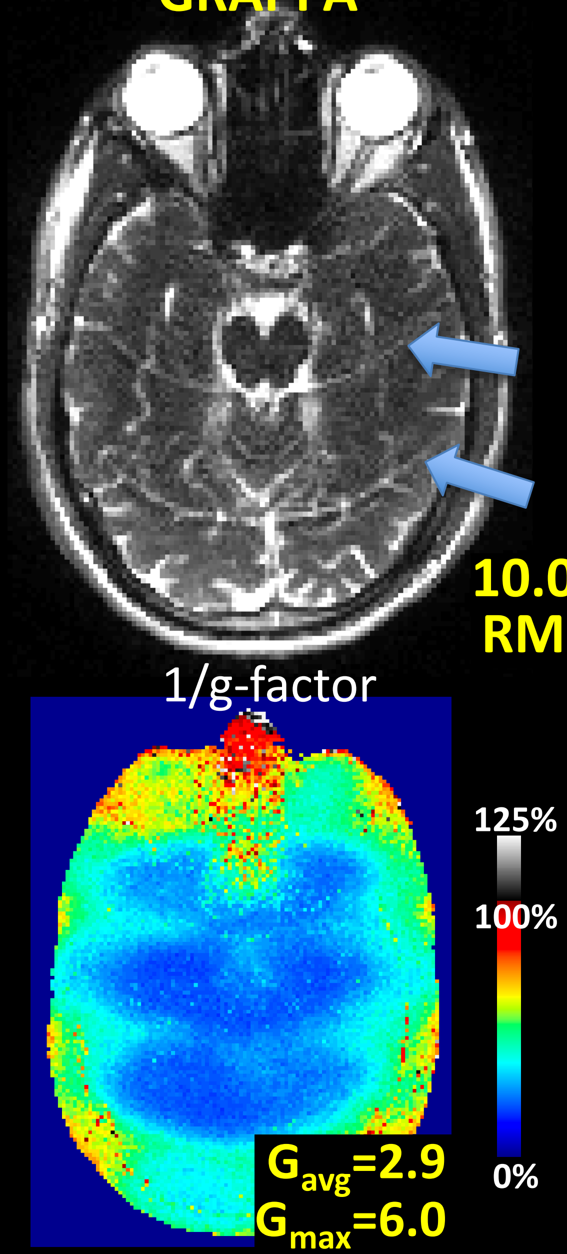
RMSE reduced 90%

G_{max} reduced 2.5-fold

G_{avg} reduced 2.2-fold

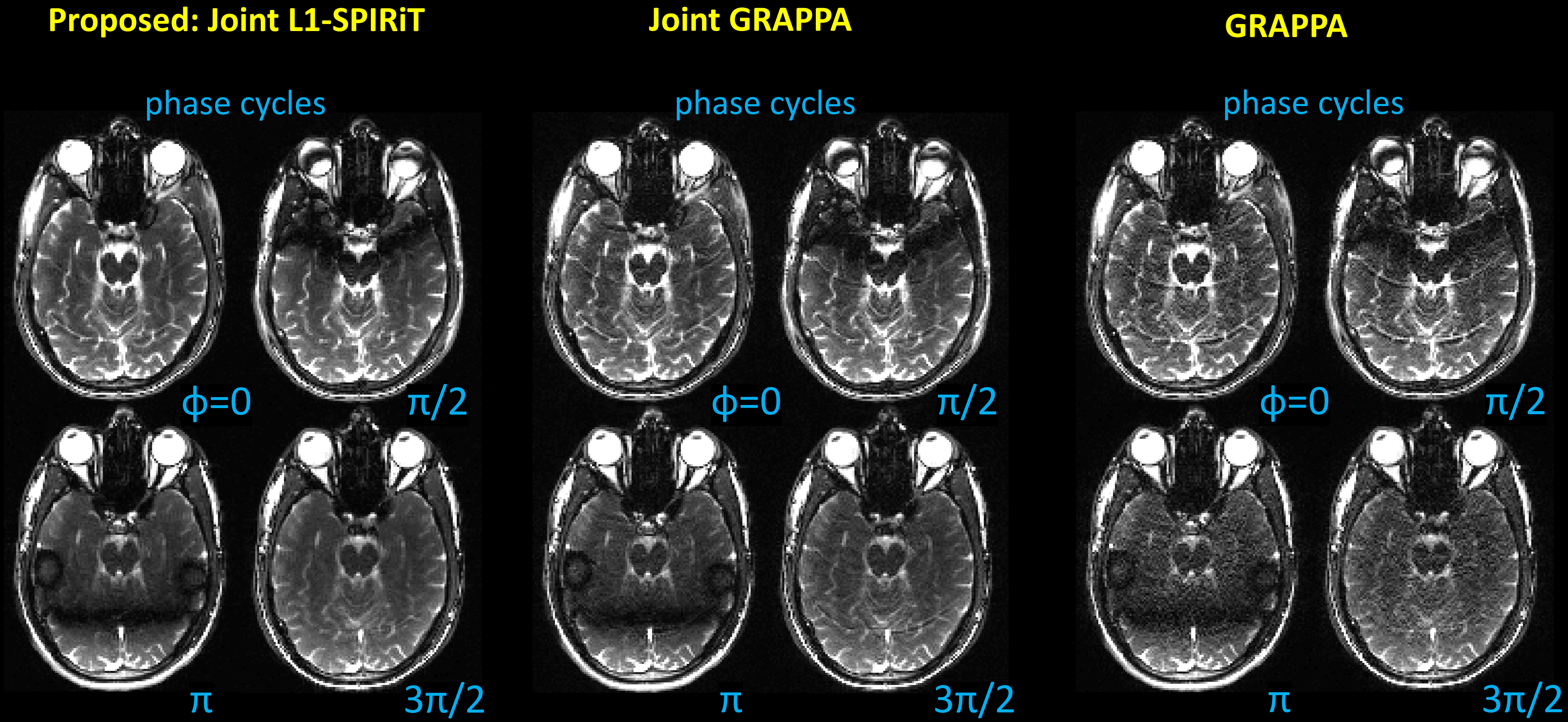
SNR improvement is >4 averages of GRAPPA

GRAPPA



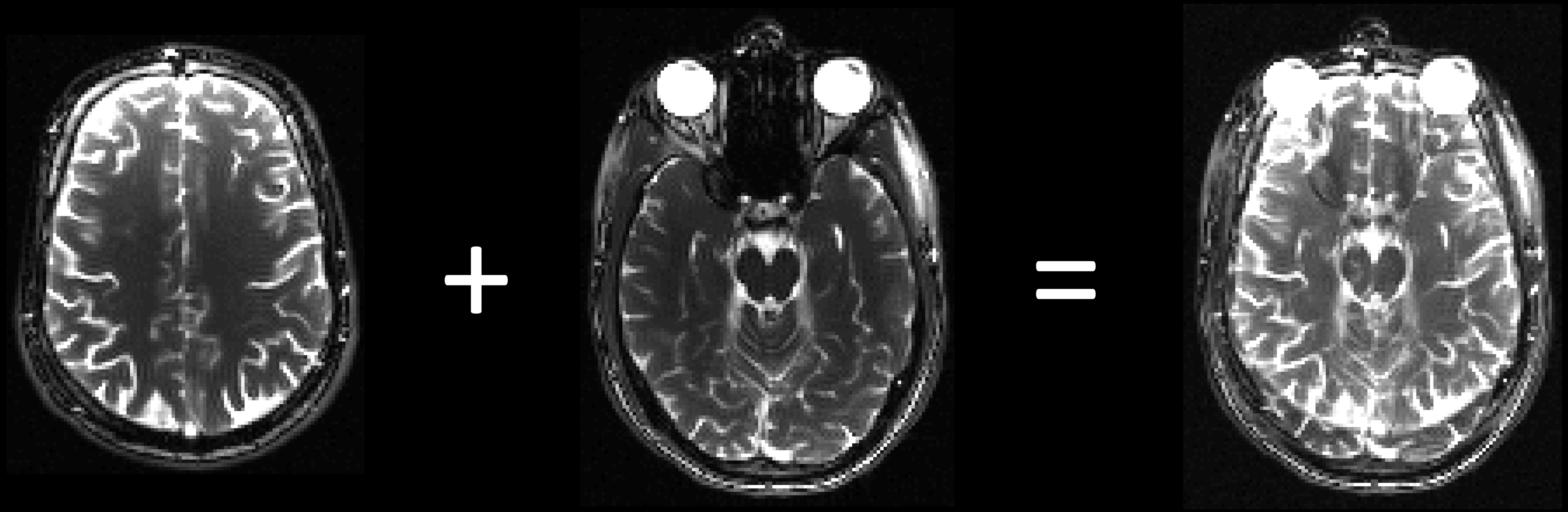
Neuro 2D bSSFP acquisition

four phase-cycles, acceleration R=6



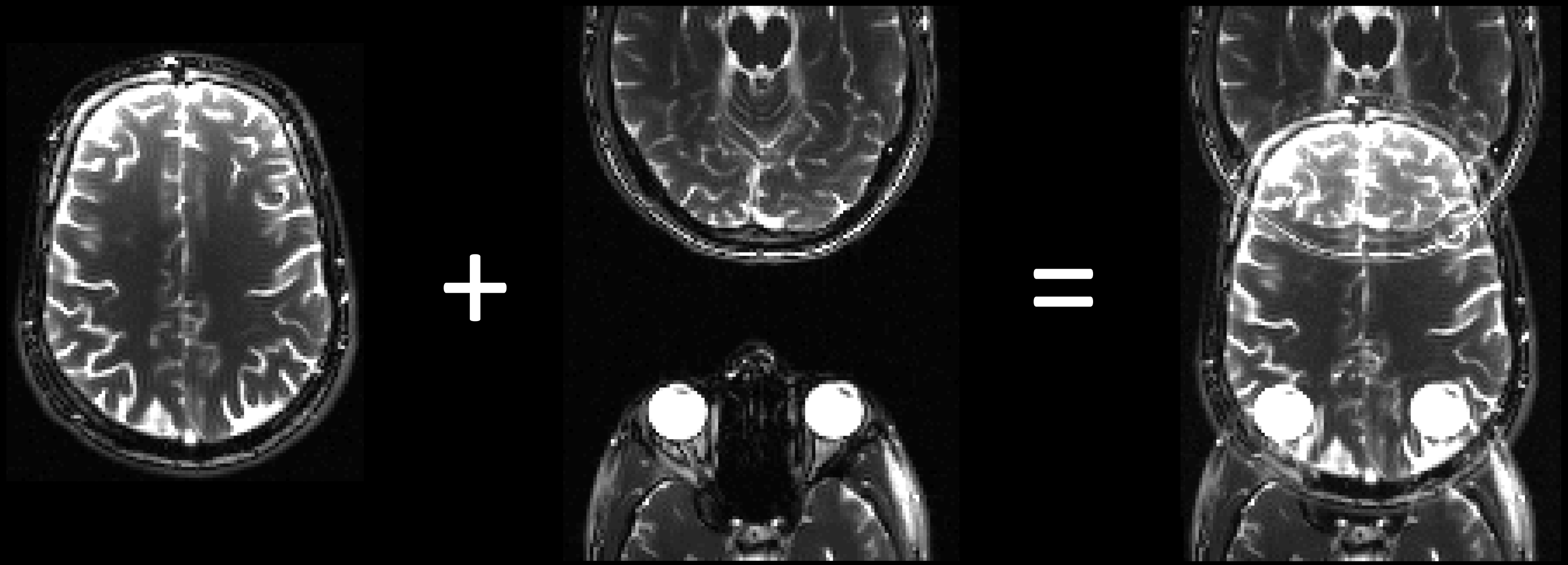
Simultaneous MultiSlice bSSFP

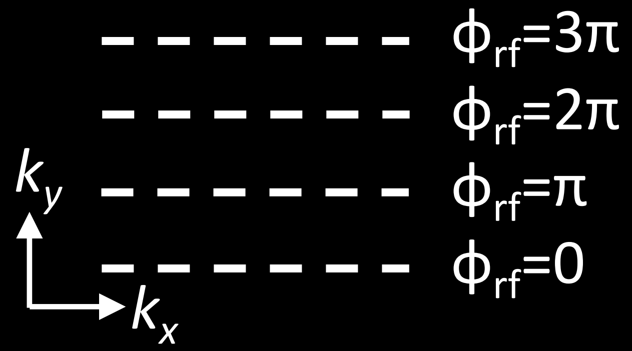
- SMS: simultaneously excite and encode multiple slices



Simultaneous MultiSlice bSSFP

- SMS: simultaneously excite and encode multiple slices
- Incur FOV shift across slices to improve parallel imaging





Simultaneous MultiSlice bSSFP

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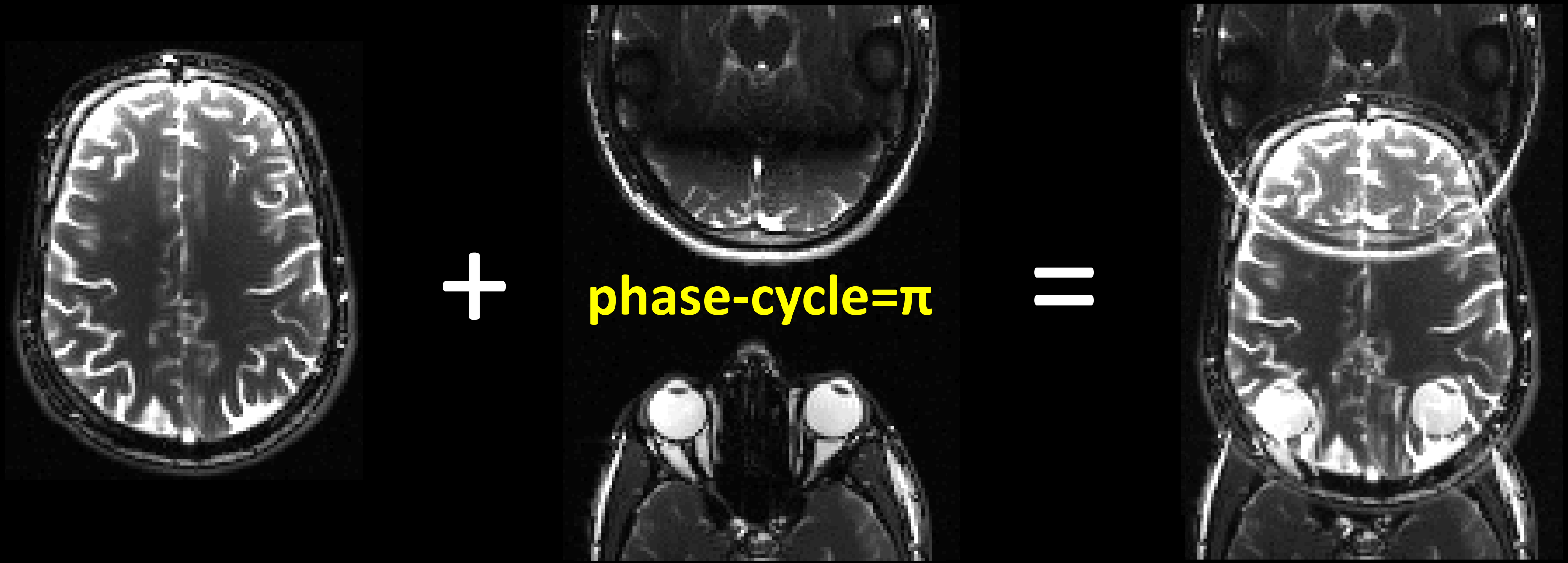
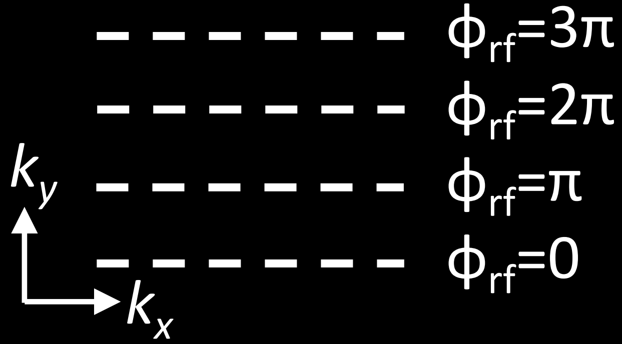
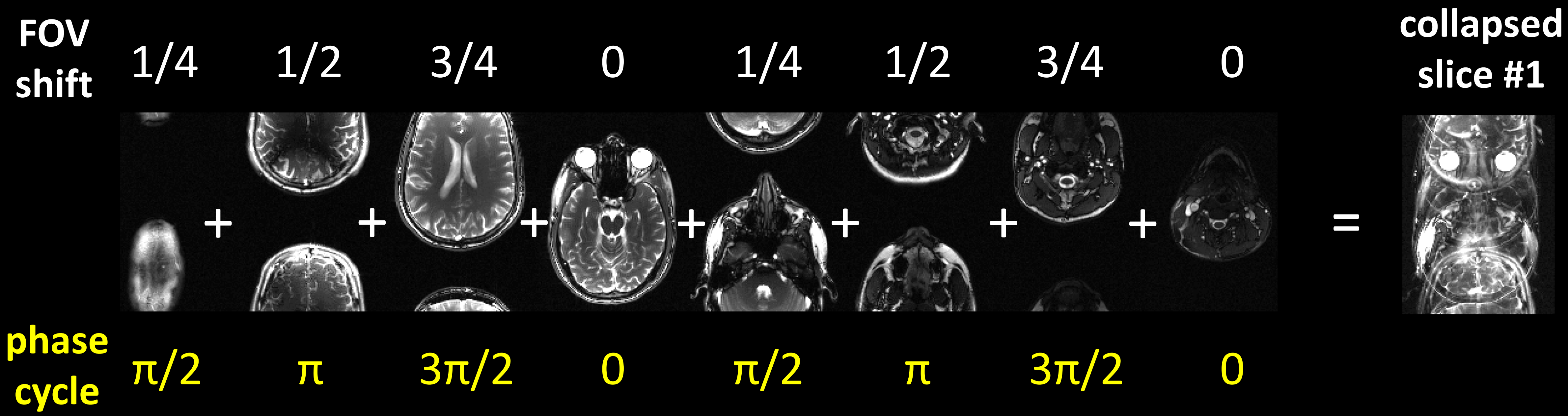




FOV/2 slice shift also causes off-resonance shift by π

Simultaneous MultiSlice bSSFP @ MultiBand=8

- At MultiBand=8, each collapsed slice has contribution from four phase-cycles:



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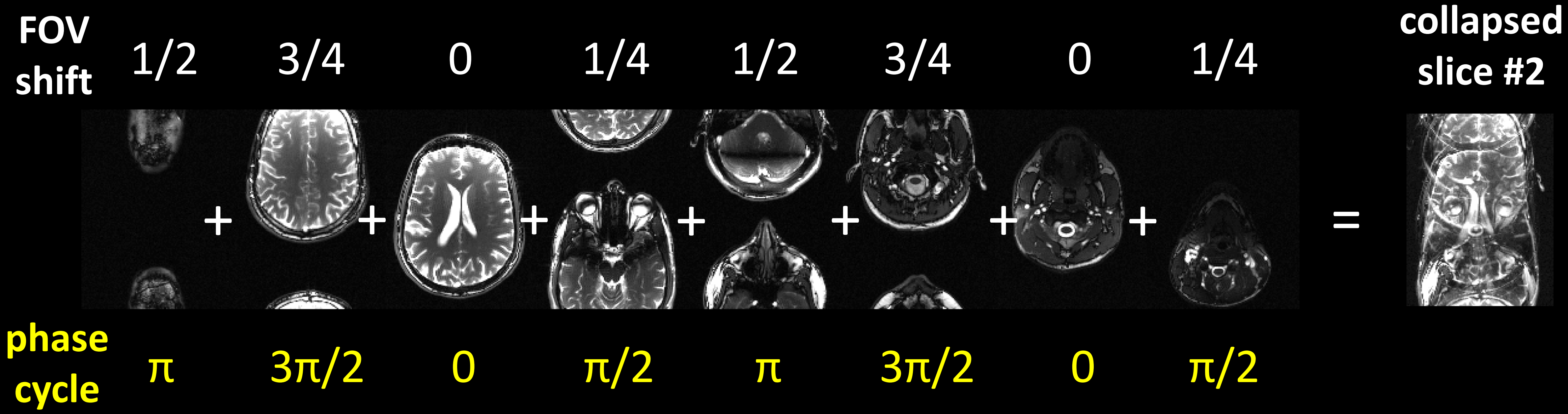
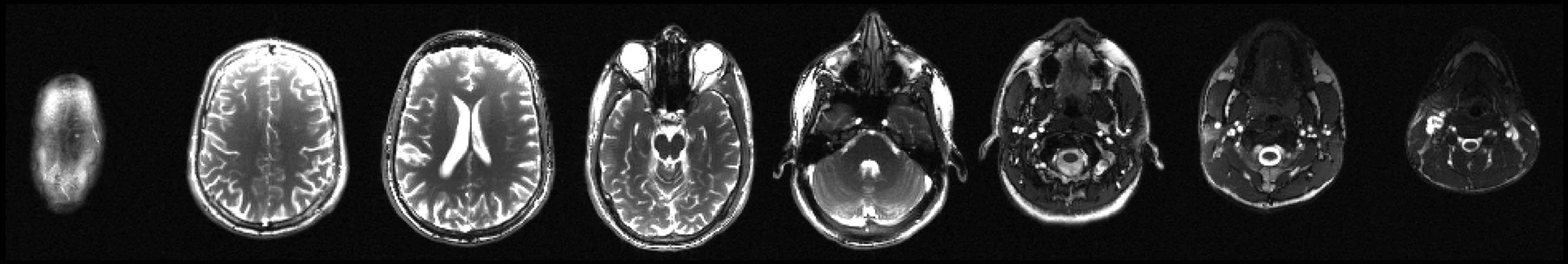


Simultaneous MultiSlice bSSFP @ MultiBand=8

- At MultiBand=8, each collapsed slice has contribution from four phase-cycles
- After unaliasing collapsed slices and shifting slices back, apply MIP combination:

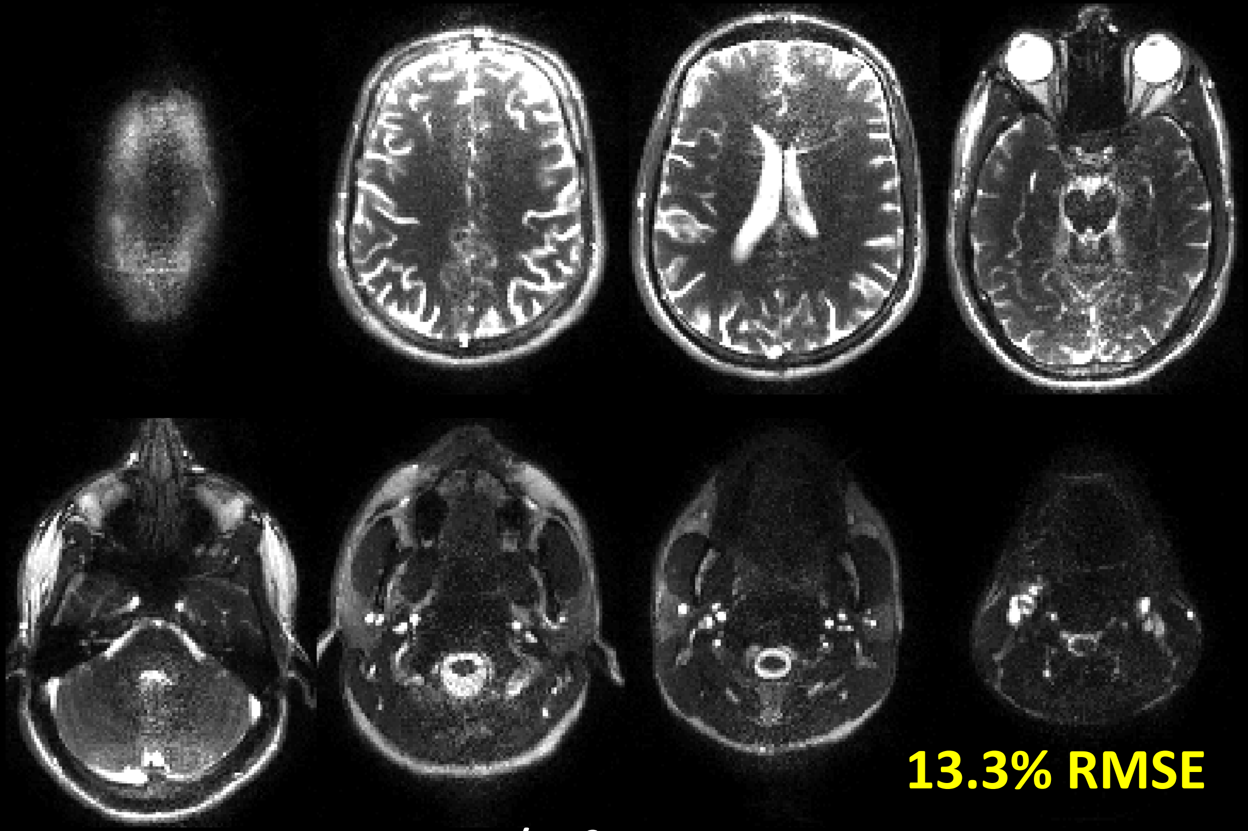


MIP combination

Neuro SMS acquisition

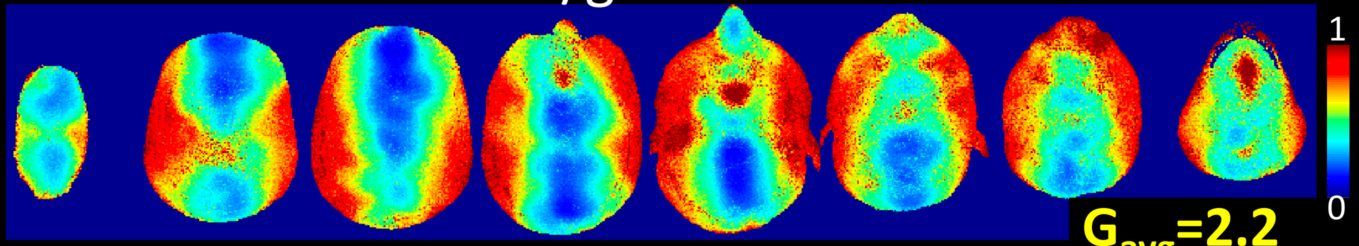
four cycles, MultiBand = 8

Split Slice GRAPPA



13.3% RMSE

1/g-factor



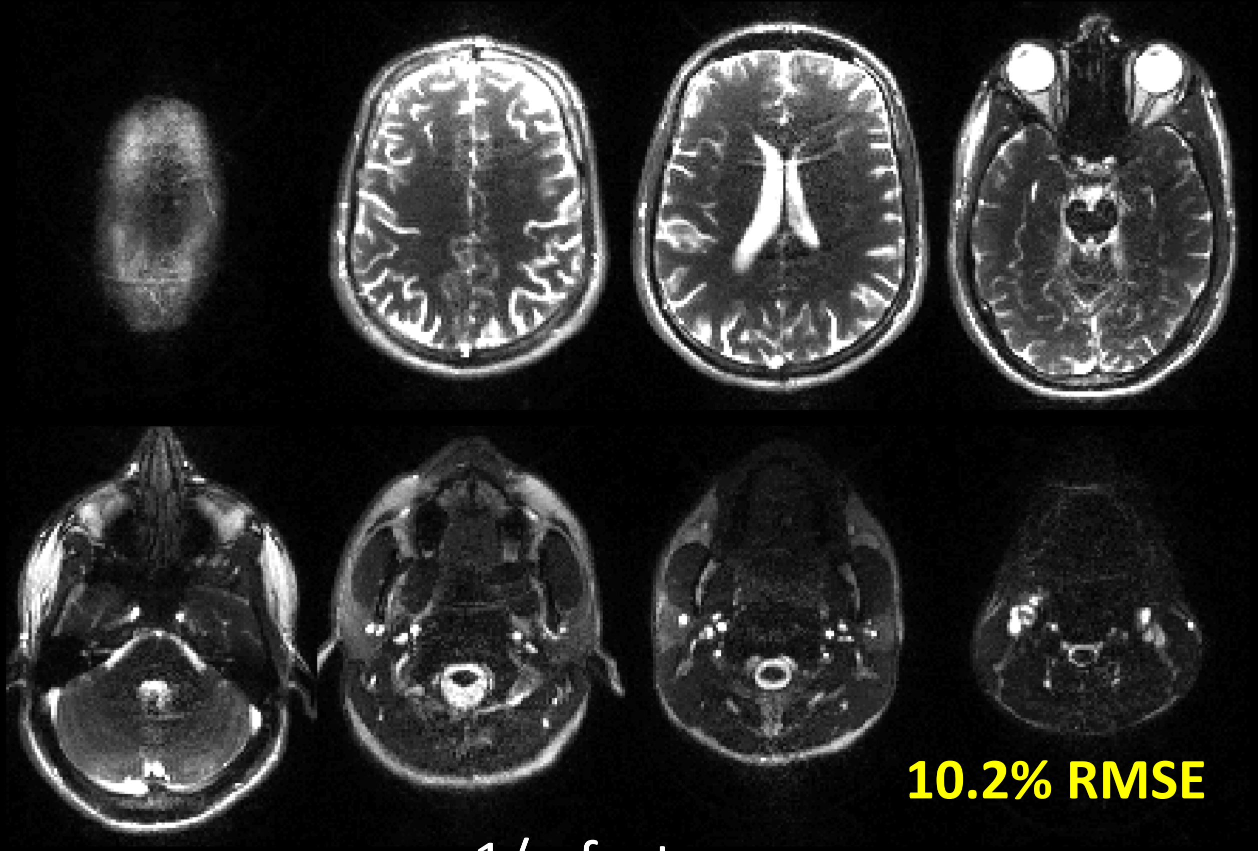
G_{avg}=2.2
G_{max}=11.3

- 8 slices acquired separately
- Collapsed retrospectively
- FOV/4 slice shift

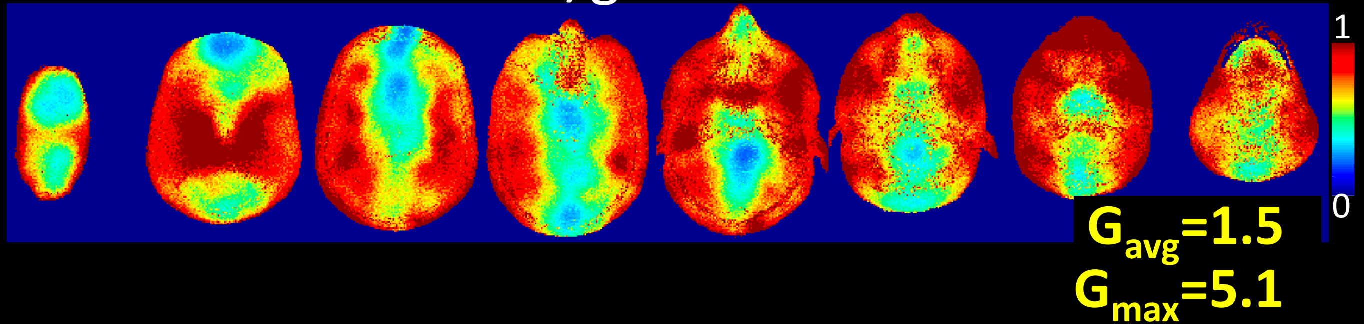
Neuro SMS acquisition

four cycles, MultiBand = 8

Joint Slice GRAPPA



1/g-factor



RMSE reduced 30%

G_{max} reduced 2.2-fold

G_{avg} reduced 1.5-fold

SNR improvement is >2 averages of GRAPPA

Conclusion

- Joint L1-SPIRiT improves parallel imaging for phase-cycled bSSFP, with substantial reduction in noise amplification and recon error
- This allows high acceleration to mitigate scan time burden of phase-cycling
- **Limitations include:**
  - Cycles need to be registered for joint recon → gating, breath-hold
  - No of kernels scale with $(\text{no of cycles})^2$ → smaller no of GCC channels

Thanks!

Questions / Comments:

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martinos.org/~berkin

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R01 EB020613
R01 EB017337
U01 HD087211