Calibrationless Parallel Imaging in Multi Echo/Contrast Data

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martinos.org/~berkin/Joint_NLINV.zip

Plasma #28

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Declaration of Financial Interests or Relationships

Speaker Name: Kawin Setsompop

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

- Licensing agreements with Siemens, GE, Phillips and Samsung
- Research support from Siemens

Calibrationless Parallel Imaging

- Conventional parallel imaging requires auto-calibration signal (ACS) to estimate sensitivities or k-space kernels, which increases scan time

- Inconsistency due to motion or physiological noise in ACS may lead to artifacts [1]

- Dynamic, spectroscopic and non-Cartesian imaging, acquiring ACS can be challenging or not possible at all

- Emerging techniques use low-rank modeling [2-5] or
  jointly estimate sensitivities and images [6-8]

to reduce/eliminate dependence on calibration.

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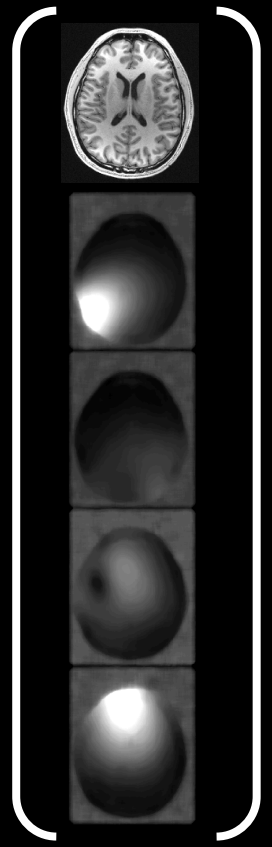
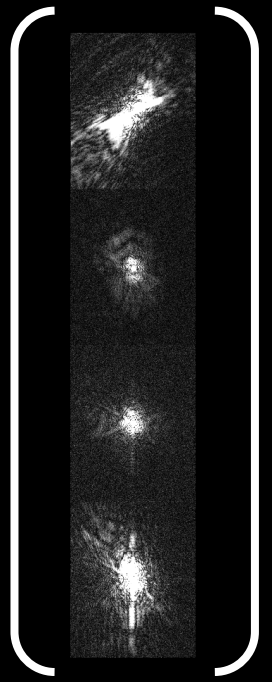
[1] JR Polimeni, MRM'16
[2] JD Trzasko, ASILOMAR'11
[3] PJ Shin, MRM'14
[4] JP Haldar, MRM'16
[5] KH Jin, IEEE TCI'16
[6] M Uecker, MRM'08
[7] F Knoll, MRM'12
[8] L Ying, MRM'07

Nonlinear Inversion

- We jointly recon sensitivities & image content by extending Nonlinear INVersion (NLINV) [1,2]

N  = 

Nonlinear Model

Image & Sens
5 Unknowns

Coil k-space
4 Equations

Under-determined even when fully-sampled

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[1] M Uecker, MRM'08
[2] F Knoll, MRM'12

Joint Nonlinear Inversion

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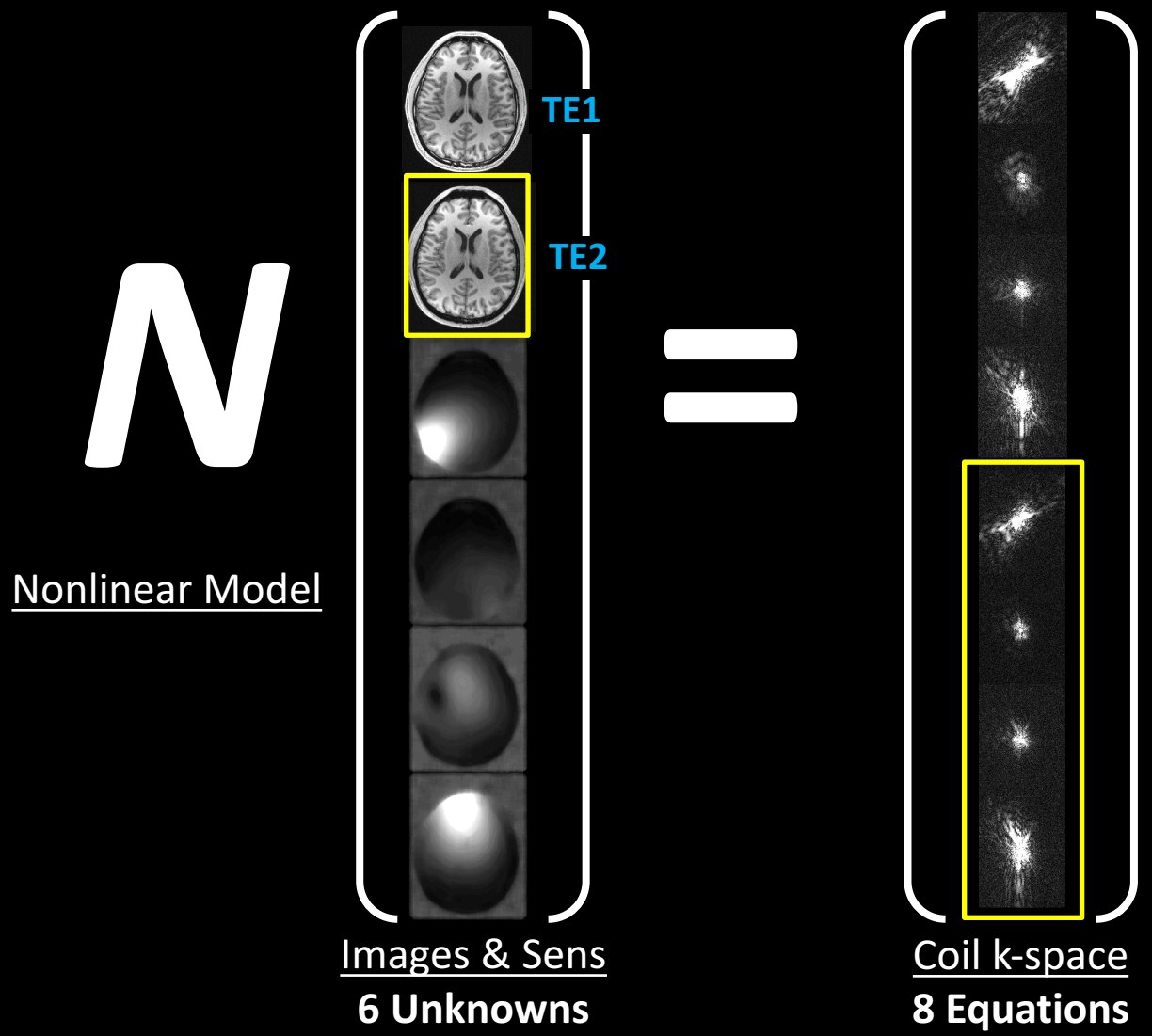


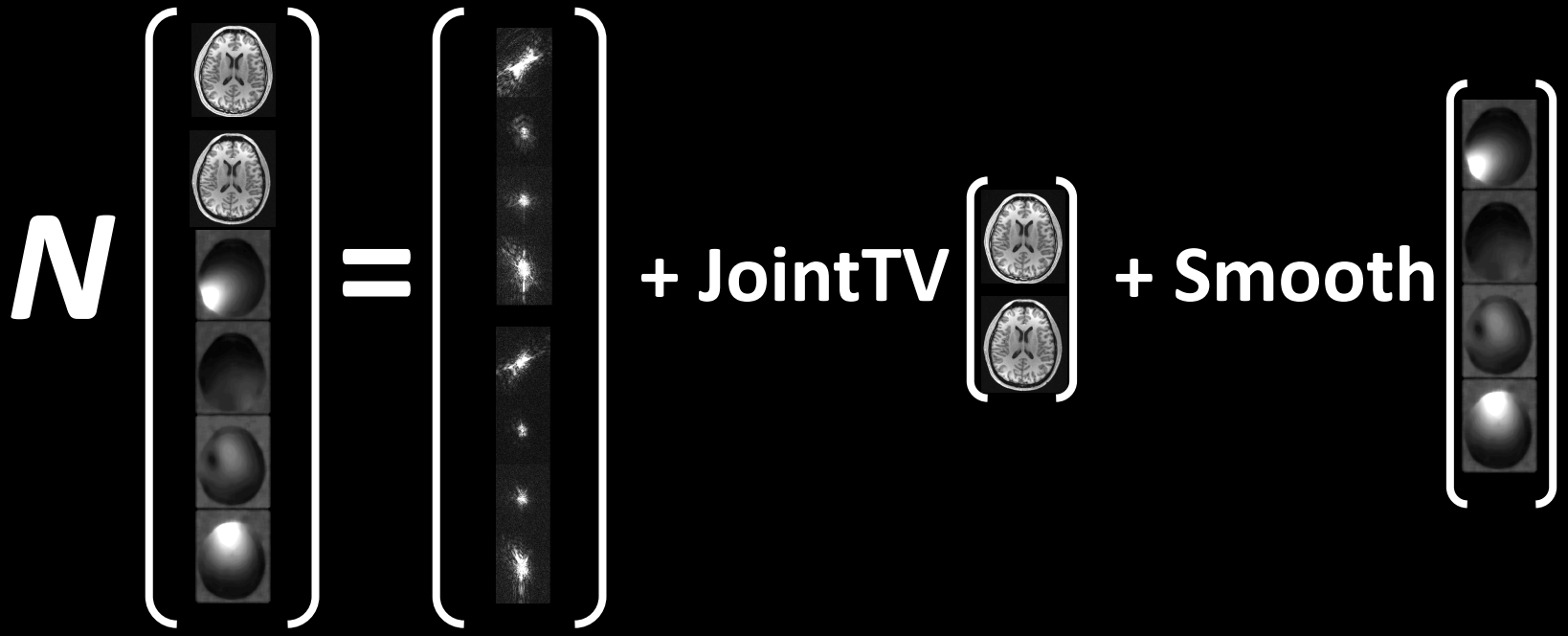
Adding more echos/contrasts improve conditioning

Allows *Calibrationless* recon

[1] M Uecker, MRM'08
[2] F Knoll, MRM'12

Joint Nonlinear Inversion

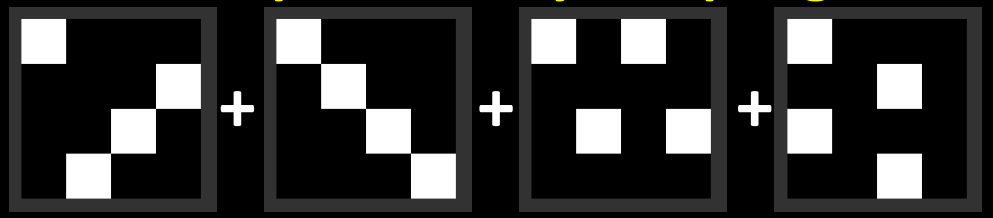
- We jointly recon sensitivities & image content by extending Nonlinear INVersion (NLINV) [1,2]



Adding more echos/contrasts improve conditioning

Allows *Calibrationless* recon

Complementary sampling



initial guess

reduced aliasing

[1] M Uecker, MRM'08
[2] F Knoll, MRM'12

Calibrationless Joint NLINV

- Calibrationless recon is made possible by:

  i. leveraging shared sensitivities across echos/contrasts to improve conditioning

  ii. employing Joint TV to exploit shared edge structures and sparsity

  iii. complementary sampling that improves collective k-space coverage and provides an image with *reduced aliasing* for initialization

Theory: Joint NLINV

- Solve for images $\rho_1 \ldots \rho_M$

and sensitivities $c_1 \ldots c_K$

$$\mathrm{F}_i \left(c_j \cdot \rho_i \right) = y_{ij}$$

undersampled DFT for image *i*

sens *j*

image *i*

k-space image *i* coil *j*

Theory: Joint NLINV

- Solve for images $\rho_1 \dots \rho_M$

and sensitivities $c_1 \dots c_K$

$$N \quad (x) \quad = \quad y$$

nonlinear operator

all unknowns

$$\begin{pmatrix} \rho_1 \\ \vdots \\ \rho_M \\ c_1 \\ \vdots \\ c_K \end{pmatrix}$$

all k-space

$$\begin{pmatrix} y_{11} \\ \\ \vdots \\ \\ y_{MK} \end{pmatrix}$$

Theory: Joint NLINV

- Linearize the nonlinear operation around an initial guess x^n

$$N(x^n + dx) \approx N(x^n) + DN(x^n)dx = y$$

constant Jacobian

- Solve for the update $dx = \begin{bmatrix} d\rho_1 \\ \vdots \\ d\rho_M \\ dc_1 \\ \vdots \\ dc_K \end{bmatrix}$

Theory: Joint NLINV

- We constrain the sensitivities to be smooth via Sobolev norm [1]

$$min_{dx} \underbrace{\| N(x^n) + DN(x^n)dx - y \|_2^2}_{\text{data consistency}} + \alpha^n \underbrace{\| W(c^n + dc) \|_2^2}_{\text{Sobolev norm}}$$

$$W = (1 + k^2)^8 \cdot F$$

Penalize high freq in k-space

martinos.org/~berkin/Joint_NLINV.zip

[1] M Uecker, MRM'08

Theory: Joint NLINV

- We enforce joint sparsity in edge structures with ℓ_{21} penalty

$$min_{dx} \| N(x^n) + DN(x^n)dx - y \|_2^2 + \alpha^n \| W(c^n + dc) \|_2^2 + \beta^n \underbrace{\| \nabla(\rho^n + d\rho) \|_{21}}_{\text{Joint TV}}$$

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[1] M Uecker, MRM'08

Theory: Joint NLINV

- Each Gauss-Newton step is minimized using Nonlinear Conjugate Gradient [1]

$$min_{dx} \| N(x^n) + DN(x^n)dx - y \|_2^2 + \alpha^n \| W(c^n + dc) \|_2^2 + \beta^n \| \nabla(\rho^n + d\rho) \|_{21}$$

- Reduce α^n and β^n 2-fold in each step to avoid over-smoothing

martinos.org/~berkin/Joint_NLINV.zip

[1] M Lustig, MRM'07

Calibrationless Joint NLINV

- We demonstrate calibrationless recon for:

  i. Multi-echo spin-echo

  ii. Multi-echo MPRAGE [1]

  iii. Phase-cycled balanced SSFP

  iv. Multi-contrast protocol

martinos.org/~berkin/Joint_NLINV.zip

[1] AJW van der Kouwe, NeuroImage'07

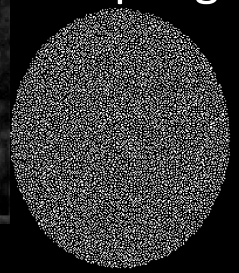
Multi-Echo Spin-Echo, **Calibrationless,** Acceleration R=2×2

NLINV
37.6% RMSE

Uniform sampling

SAKE
28.5% RMSE

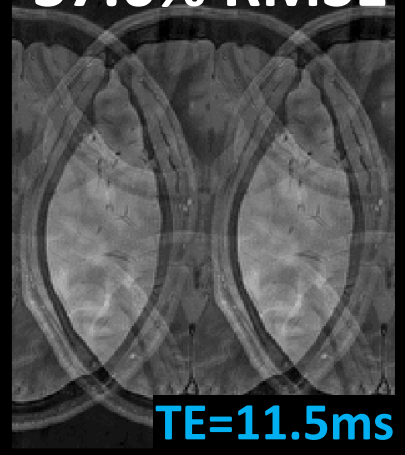
Poisson sampling



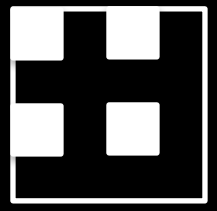
- 12-chan reception
- ΔTE = 11.5ms, 8 echoes,
- FOV = 240×180mm^2, slice thickness = 3mm
- Mtx = 256×208

Multi-Echo Spin-Echo, **Calibrationless,** Acceleration R=2×2

NLINV
37.6% RMSE

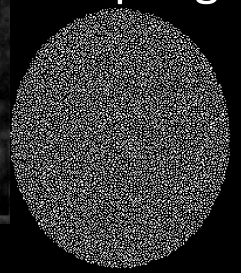


Uniform sampling

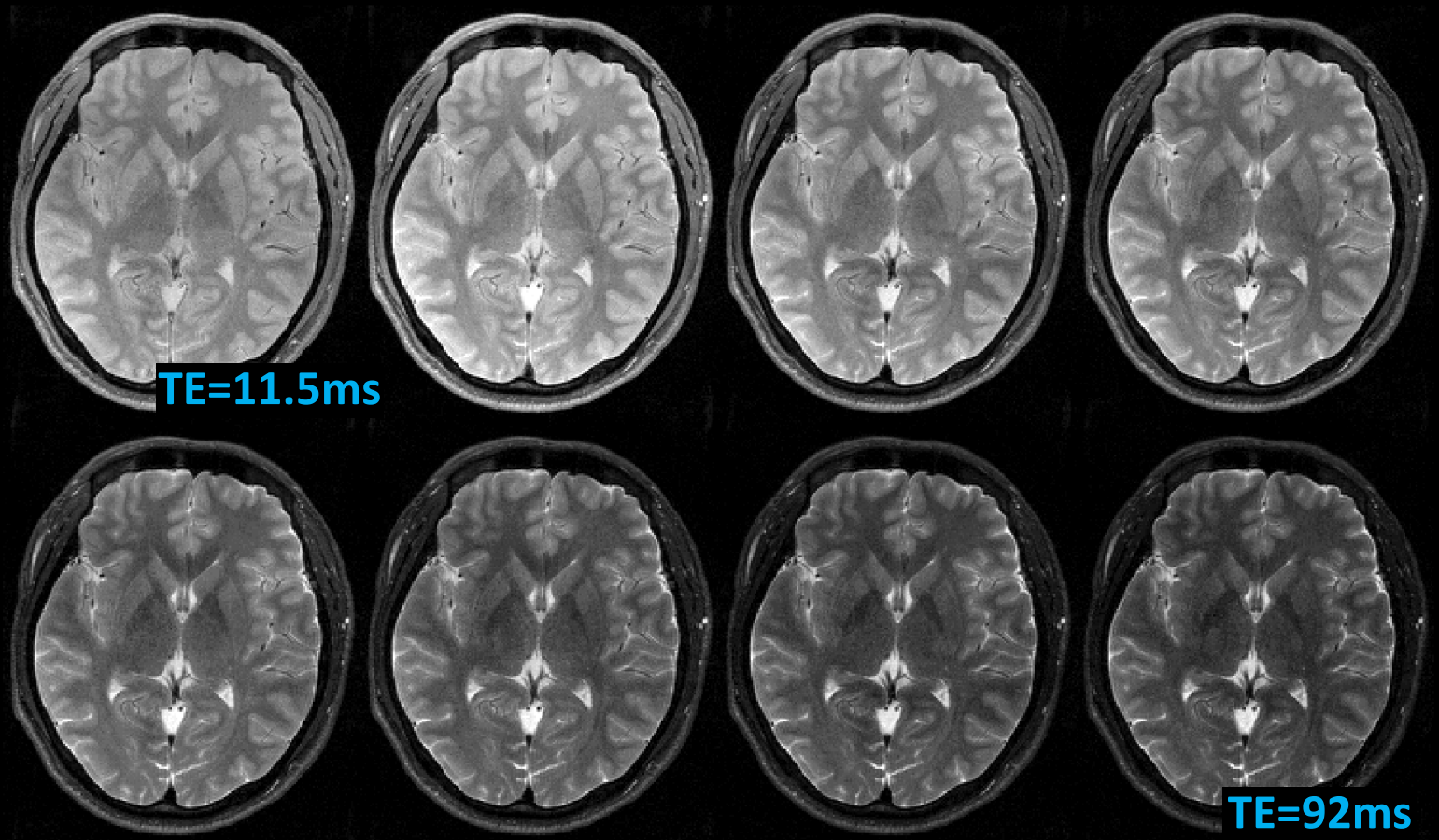


SAKE
28.5% RMSE

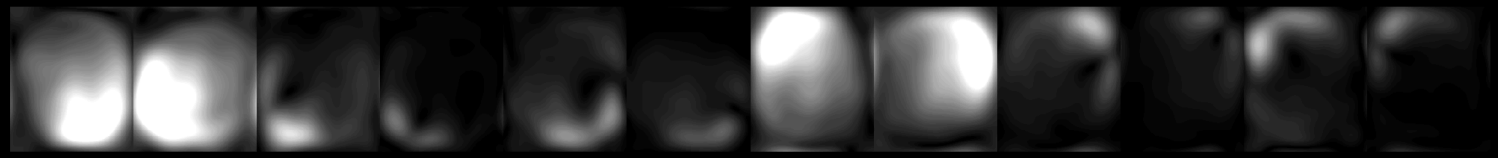
Poisson sampling



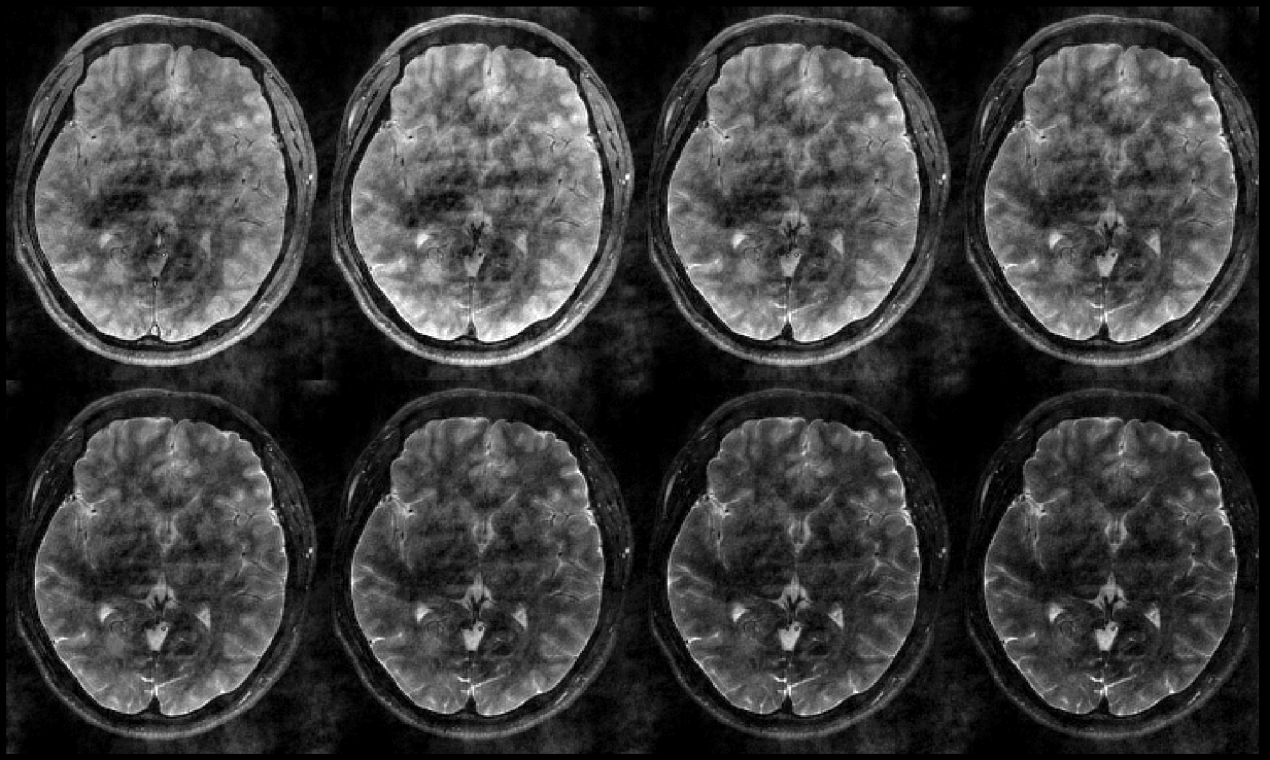
Proposed: Joint NLINV **6.0% RMSE**



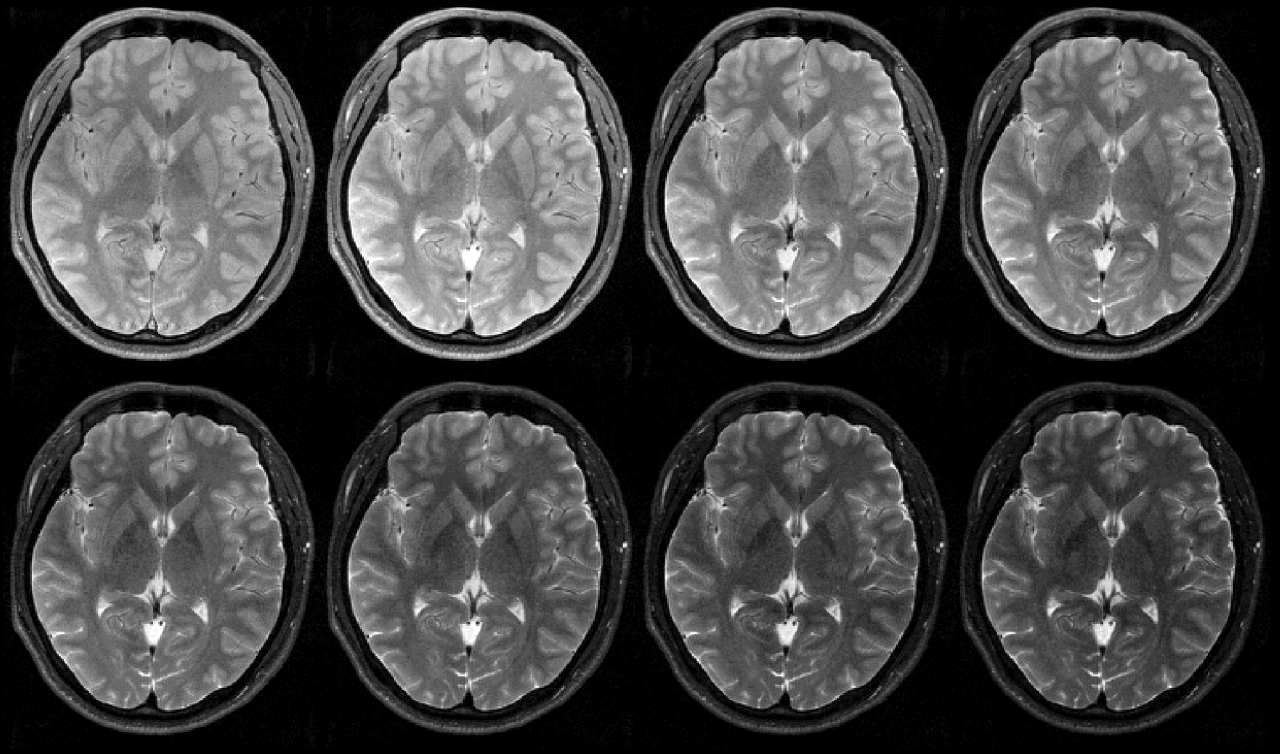
estimated 12 chan sensitivities



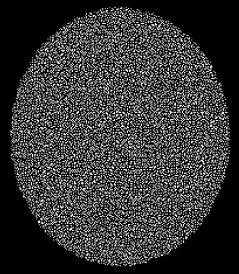
SAKE **28.5% RMSE**



Proposed: Joint NLINV **6.0% RMSE**

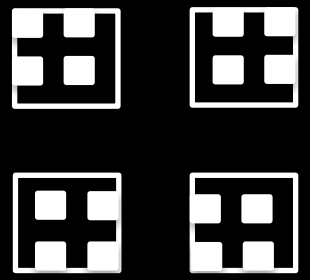


Poisson sampling



Recon time: 73 min
100 iter
Window= 6×6
Threshold = 1.4

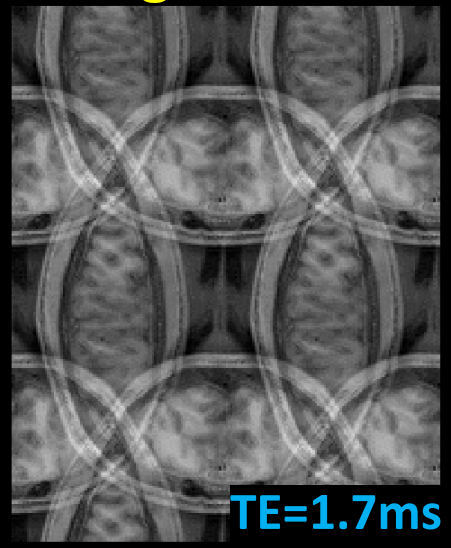
Uniform sampling



Recon time: 21 min
9 Newton iter
$\alpha_0 = 0.001$
$\beta_0 = 0.1$

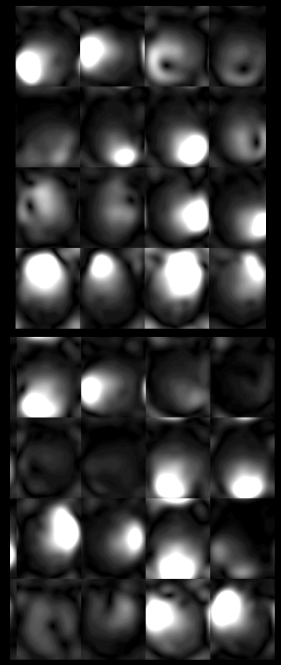
Multi-Echo MPRAGE, **Calibrationless,** Acceleration R=2×2

NLINV: single echo

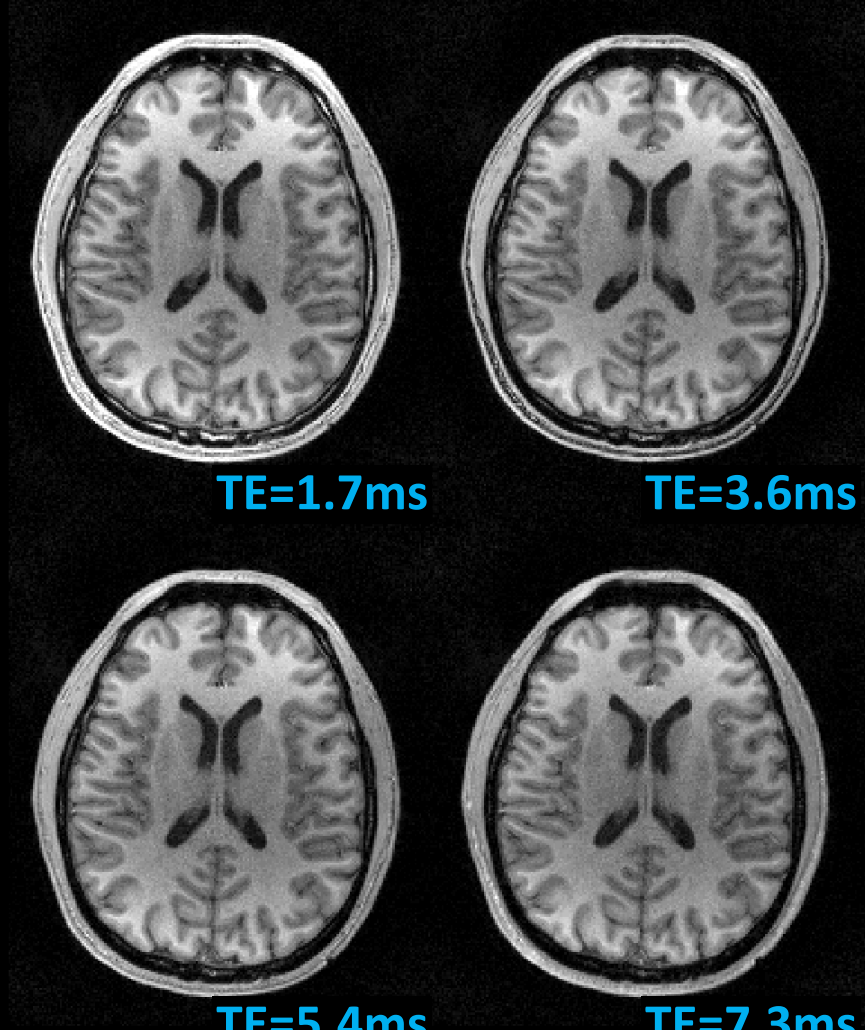


67.4% RMSE

32 chan sens

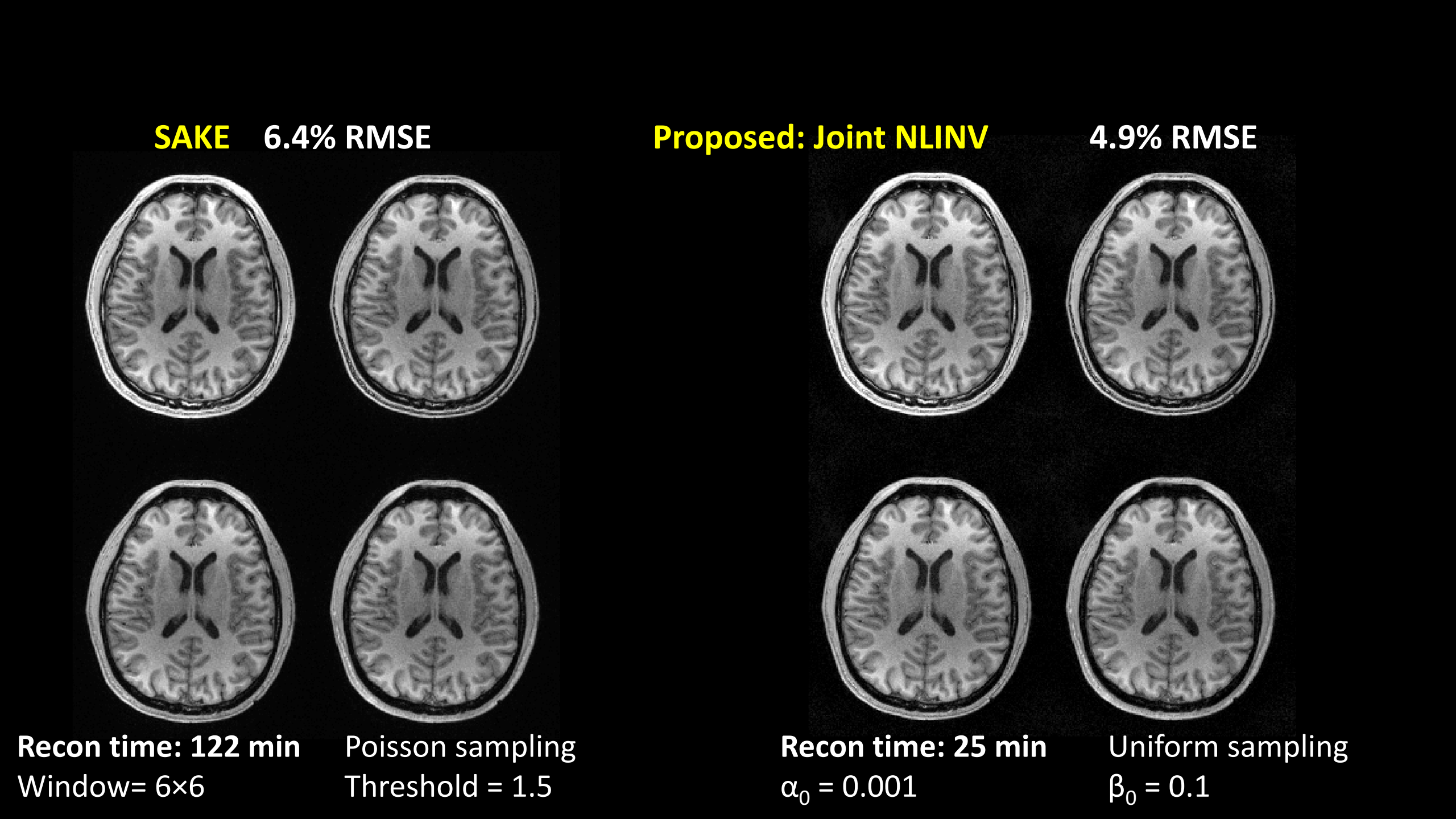


Proposed: Joint NLINV **4.9% RMSE**

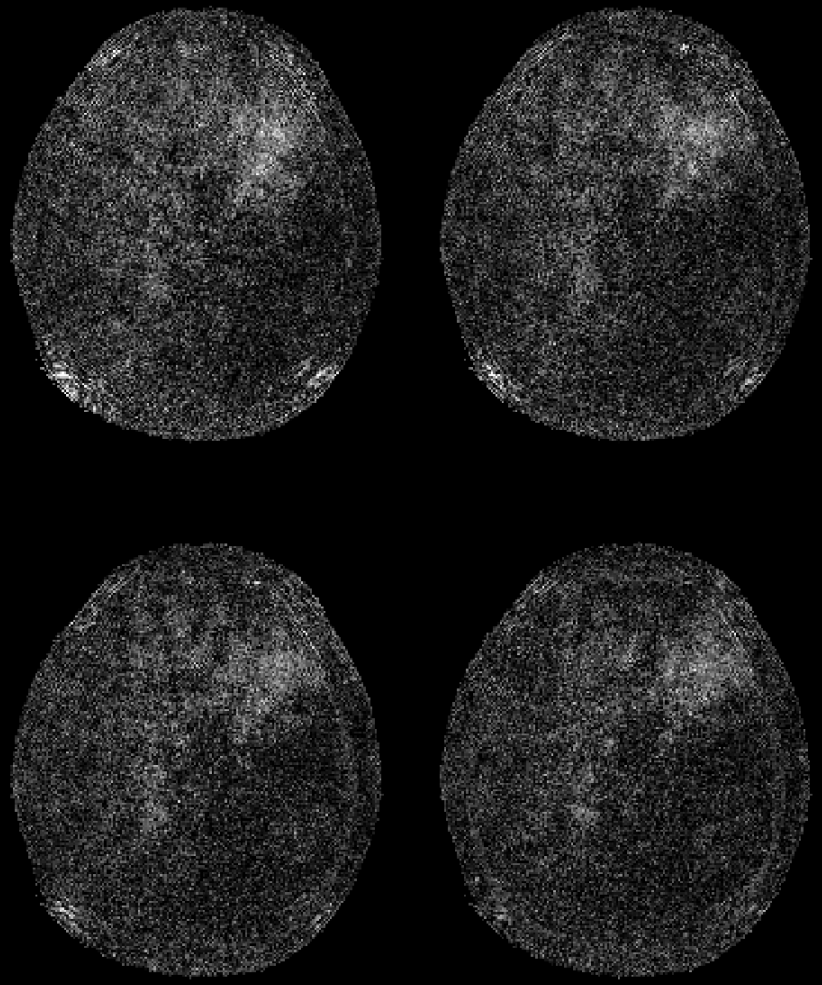


- 32-chan reception
- Mtx = 256×240×192

1 mm isotropic
BW = 651Hz/pixel

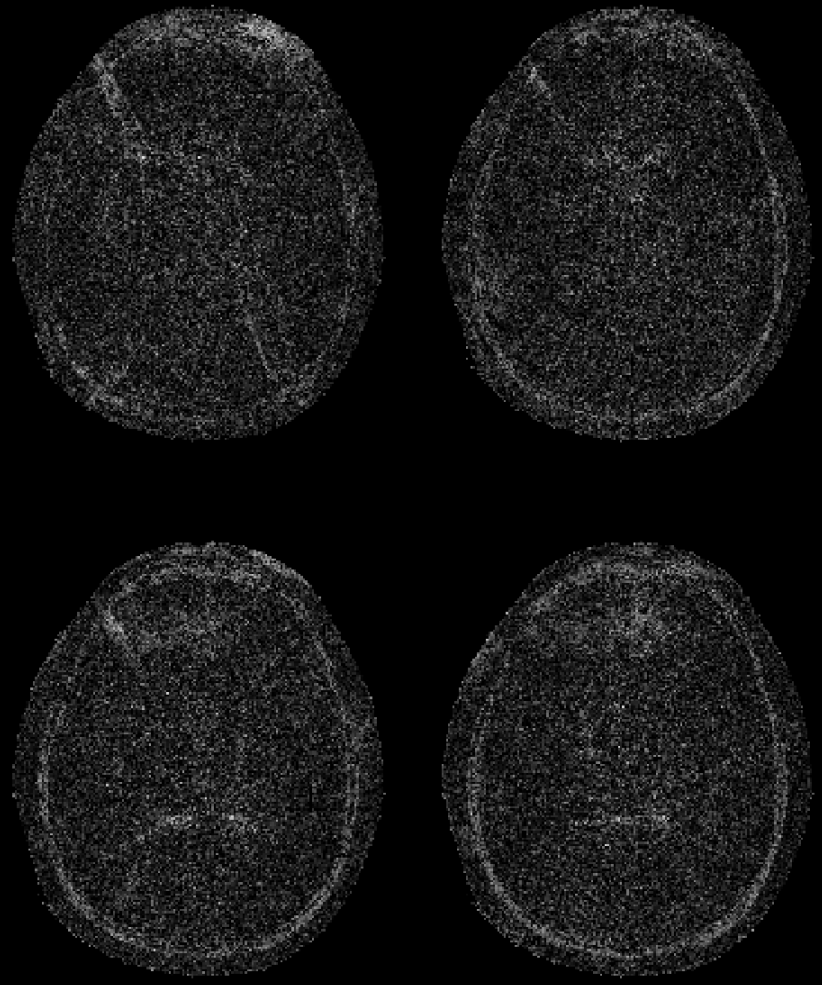

SAKE 6.4% RMSE
Proposed: Joint NLINV 4.9% RMSE
Recon time: 122 min
Window= 6×6
Poisson sampling
Threshold = 1.5
Recon time: 25 min
α_0 = 0.001
Uniform sampling
β_0 = 0.1

SAKE 6.4% RMSE



Error scaled 5x

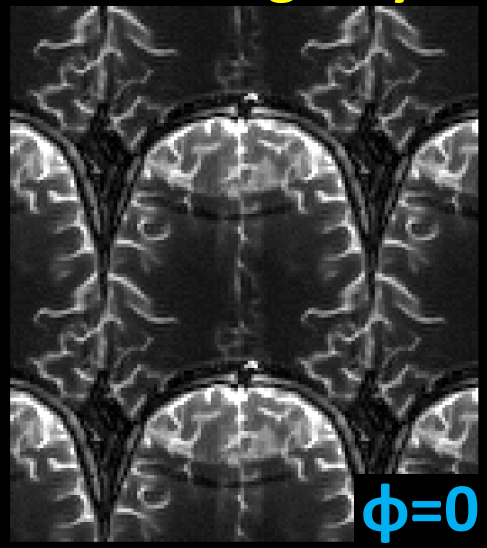
Proposed: Joint NLINV 4.9% RMSE



Error scaled 5x

Phase-Cycled bSSFP, **Calibrationless,** Acceleration R=2×2

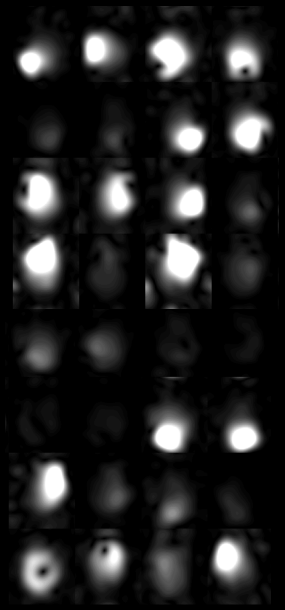
NLINV: single cycle



ϕ=0

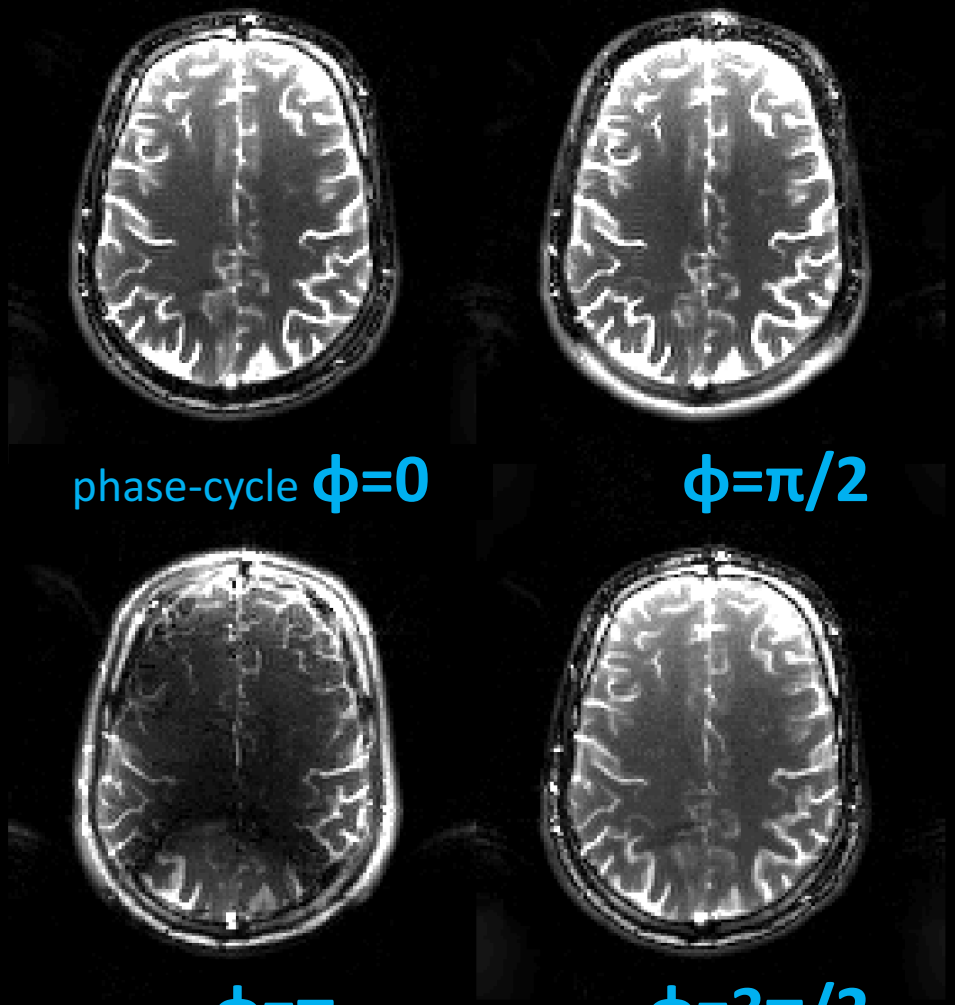
75.1% RMSE

32 chan sens



Proposed: Joint NLINV

3.3% RMSE



phase-cycle **ϕ=0**

ϕ=π/2

ϕ=π

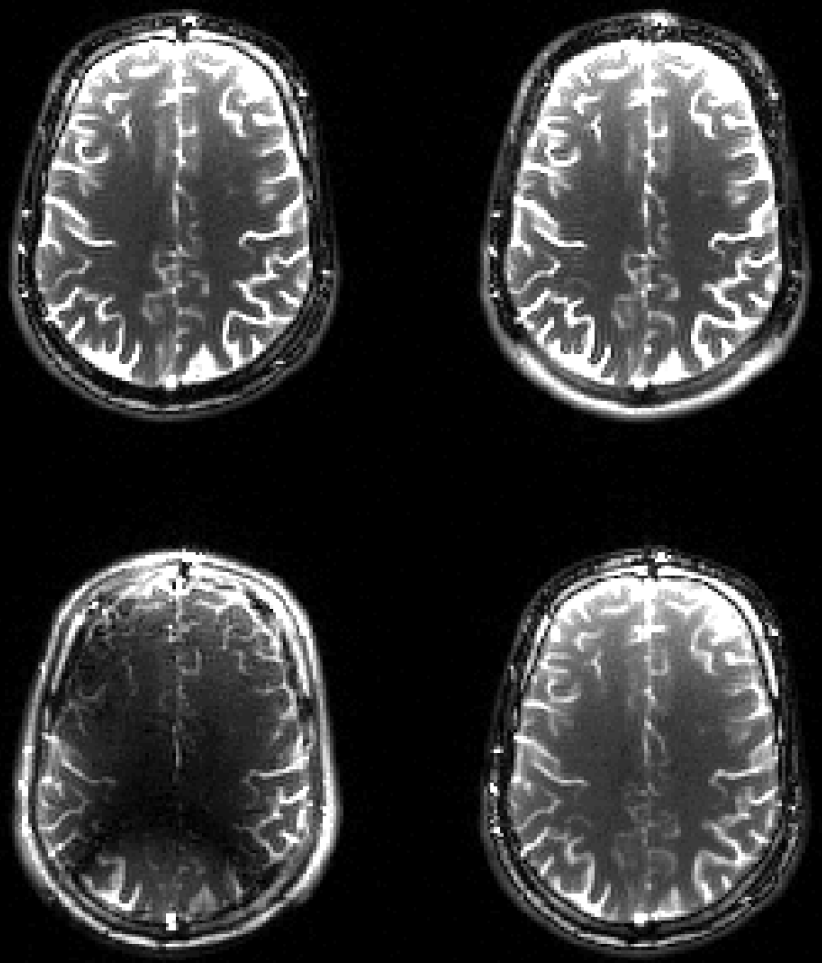
ϕ=3π/2

- 32-chan reception
- Mtx = 160×160
- FOV = 240×240

TR/TE = 3.37/1.57 ms
slice thickness = 4.5 mm
BW = 651Hz/pixel

Phase-Cycled bSSFP, **Calibrationless,** Acceleration R=2×2

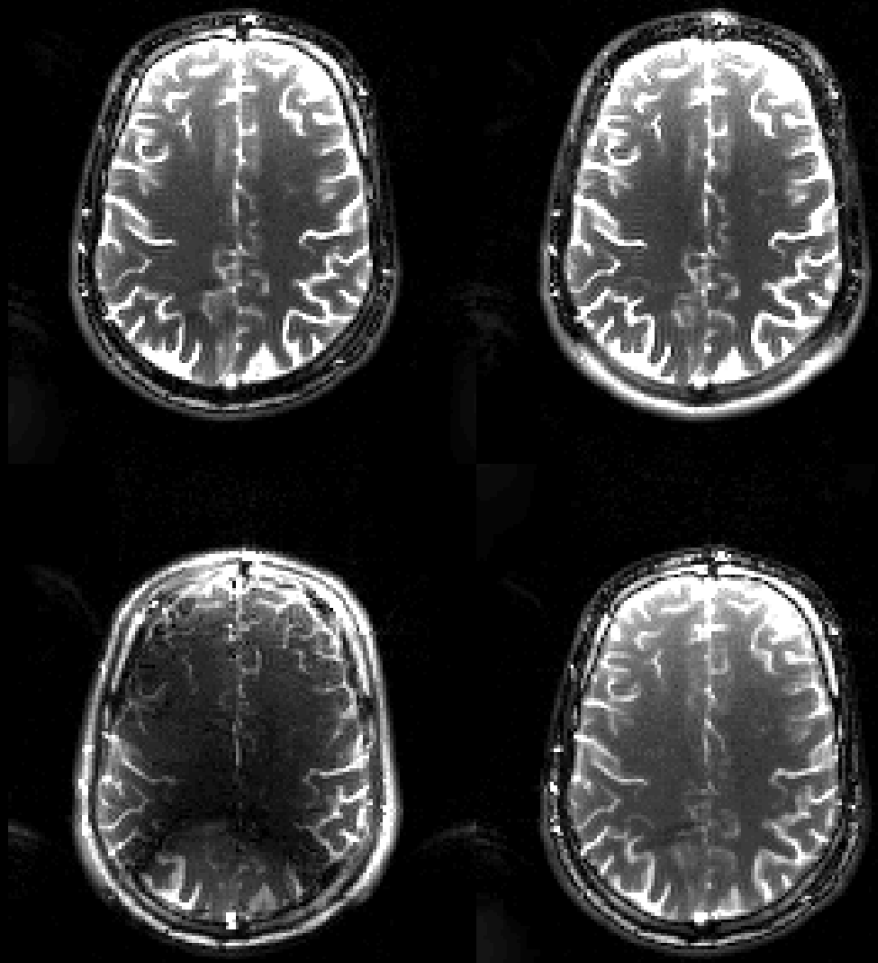
SAKE **5.2% RMSE**



Recon time: 82 min
Window= 6×6

Poisson sampling
Threshold = 1.3

Proposed: Joint NLINV **3.3% RMSE**

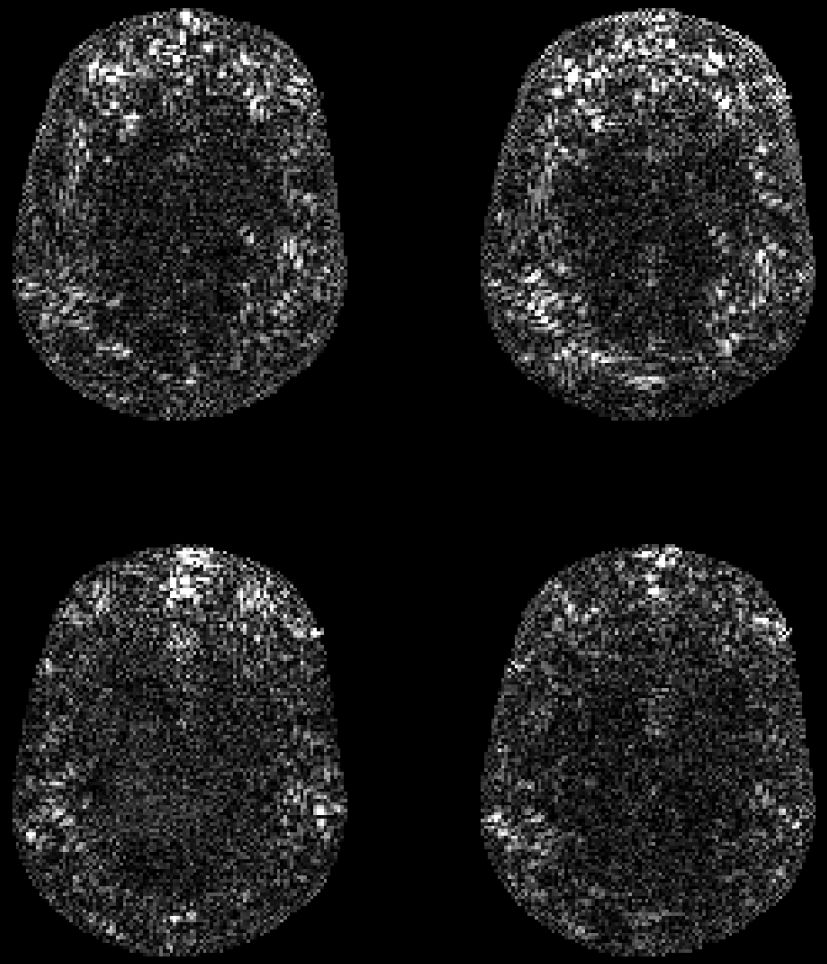


Recon time: 13 min
α_0 = 0.01

Uniform sampling
β_0 = 0.1

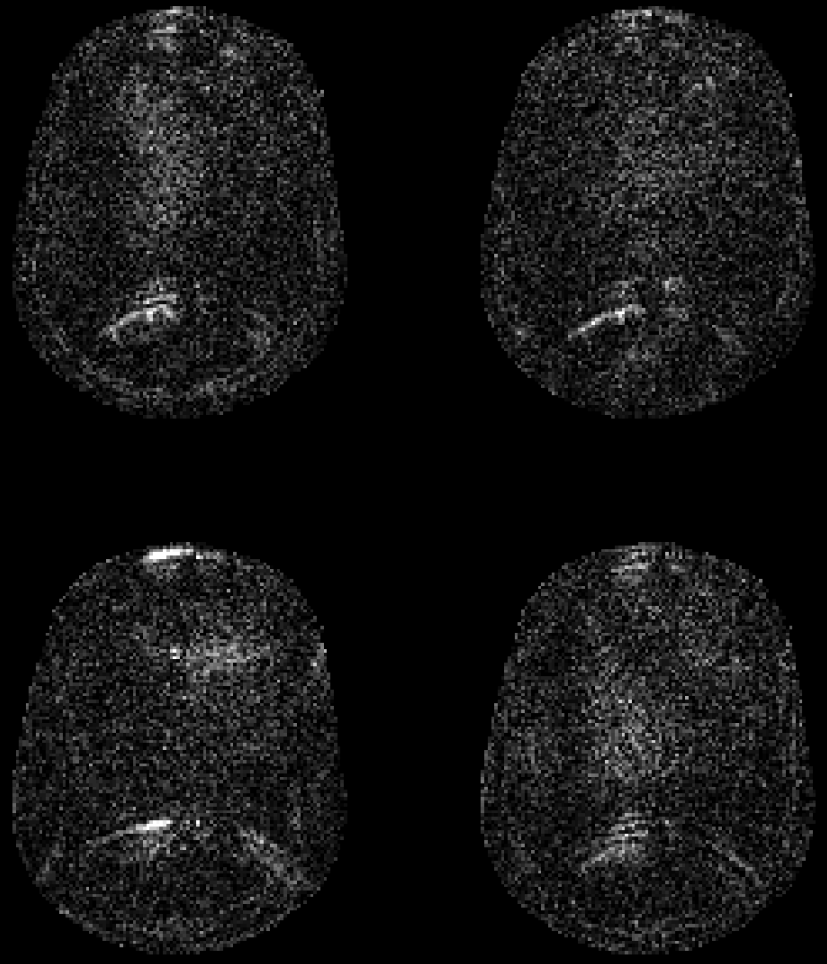
Phase-Cycled bSSFP, **Calibrationless,** Acceleration R=2×2

SAKE **5.2% RMSE**



Error scaled 10x

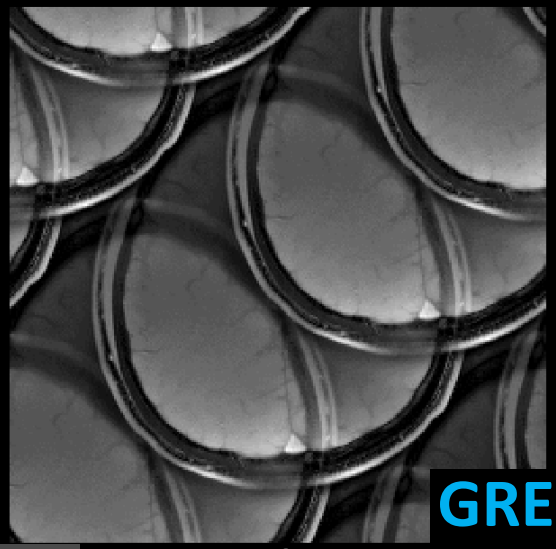
Proposed: Joint NLINV **3.3% RMSE**

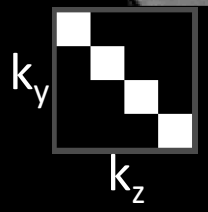


Error scaled 10x

Multi-Contrast, **Calibrationless,** Acceleration R=2×2

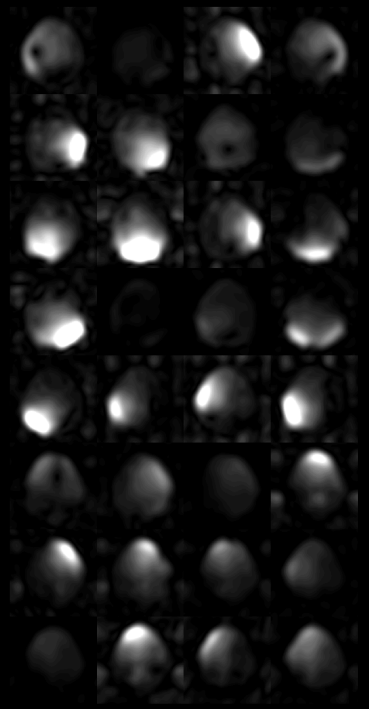
NLINV: single contrast





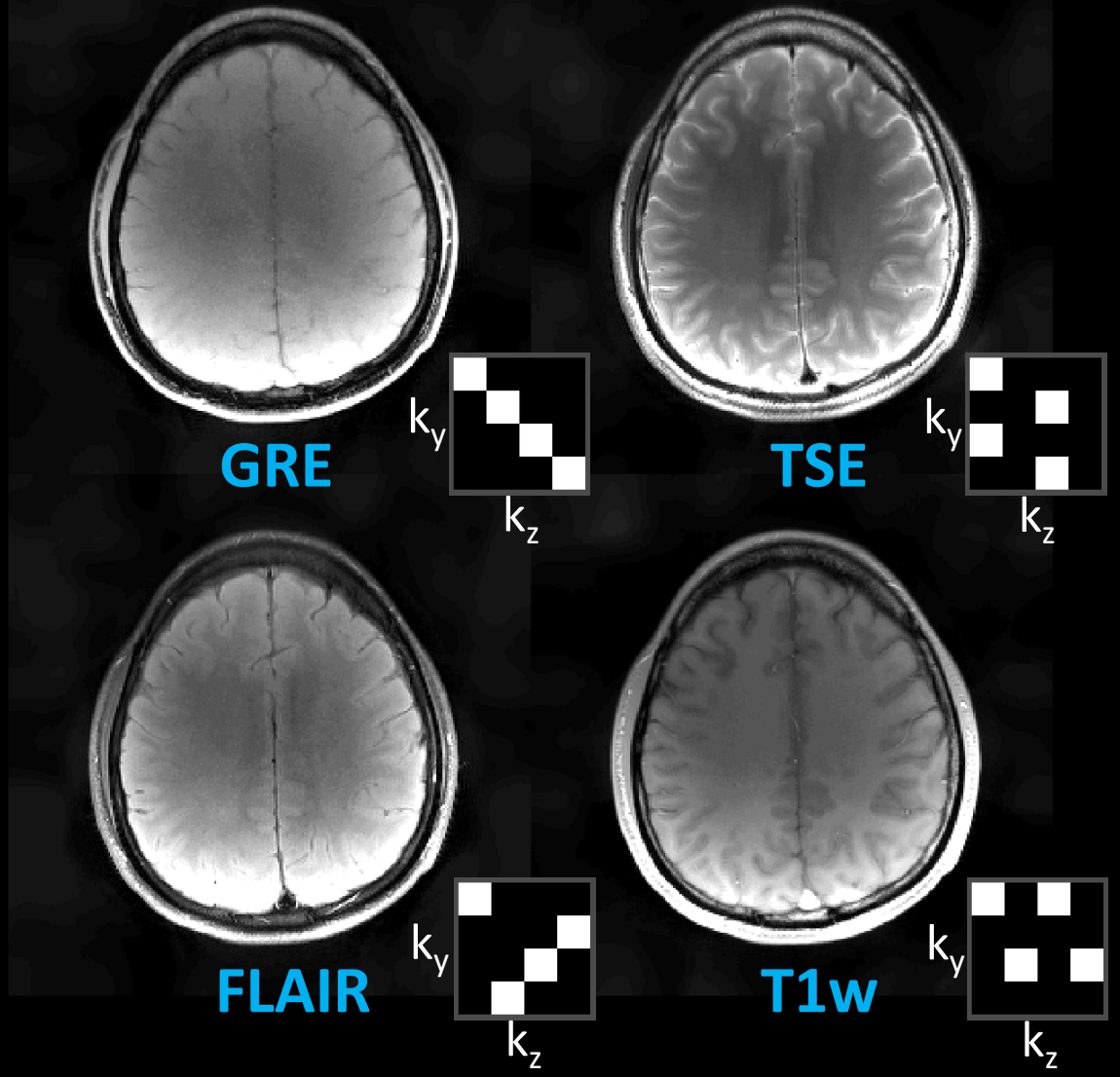
70.2% RMSE

32 chan sens



Proposed: Joint NLINV

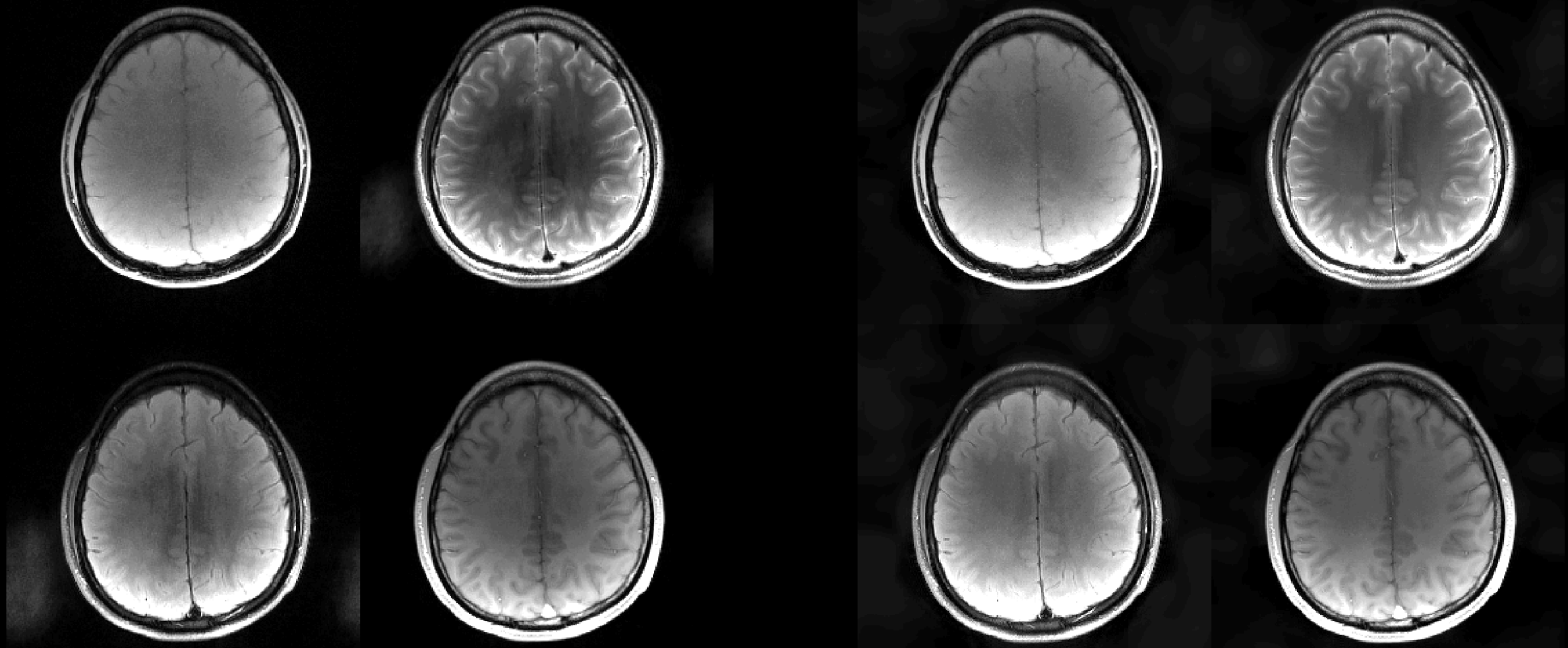
5.2% RMSE



Multi-Contrast, **Calibrationless,** Acceleration R=2×2

SAKE **8.9% RMSE**

Proposed: Joint NLINV **5.2% RMSE**



Recon time: 171 min
Window= 6×6

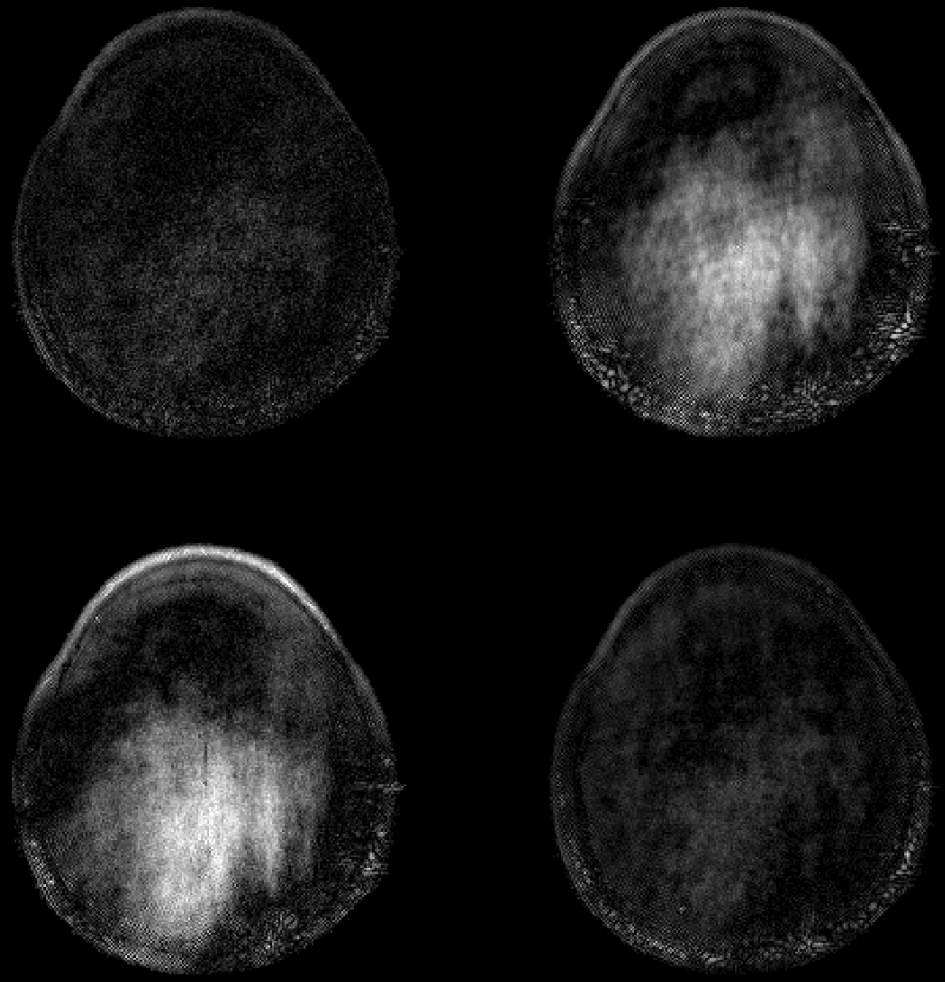
Poisson sampling
Threshold = 1.3

Recon time: 31 min
$\alpha_0 = 0.1$

Uniform sampling
$\beta_0 = 0.1$

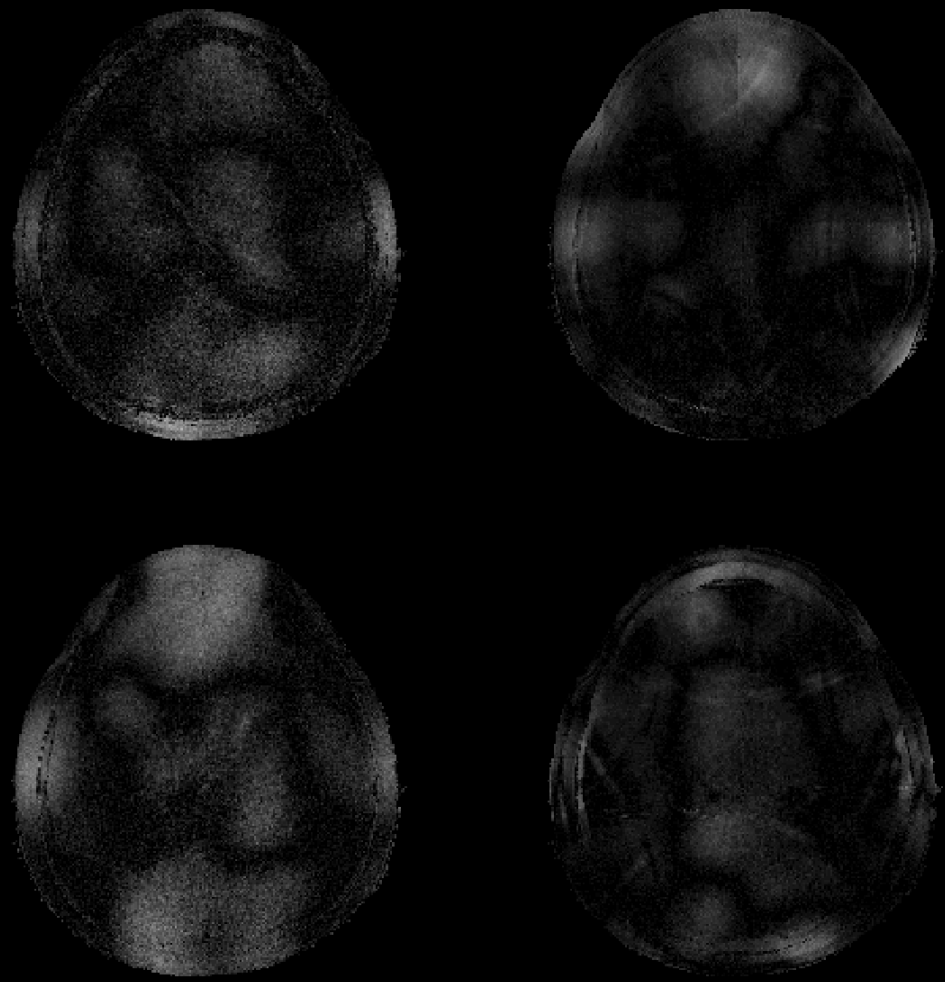
Multi-Contrast, **Calibrationless,** Acceleration R=2×2

SAKE **8.9% RMSE**



Error scaled 5x

Proposed: Joint NLINV **5.2% RMSE**



Error scaled 5x

Discussion

- Standard NLINV without calibration is ill-conditioned and results in large errors
- Joint NLINV exploits shared sensitivities and joint sparsity across multiple echoes/contrasts to dramatically improve the recon
- This obviates the need for calibration, with >6-fold reduced RMSE over standard NLINV

Discussion

- Complementary sampling permits formation of a composite image by summing the k-space across echoes
- For spin-echo and MPRAGE where phase discrepancy between echoes is low, composite image has reduced aliasing and is used for initialization
- For phase-cycled bSSFP and multi-contrast, composite image contains significant aliasing and was not used
- This necessitated a larger starting parameter α_0, which is reduced over iterations to result in negligible regularization in the final recon

Discussion

- SAKE: calibrationless from single image

  elliptical Poisson sampling [1]

- Joint NLINV: allowed 30 – 70 % reduction in RMSE for 32-chan experiments

  recon time reduced by 3× – 6× fold

[1] PJ Shin, MRM'14

martinos.org/~berkin/Joint_NLINV.zip

Thanks!

Questions / Comments:

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Support: NIH R24 MH106096
R01 EB020613
R01 EB017337
U01 HD087211