Accelerated QSM

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Accelerated QSM

- **Outline:**
  - Why QSM acquisition is slow
  - Parallel imaging
  - Efficient trajectories
  - Exploit unused sequence time
  - Multi-orientation sampling: COSMOS and STI

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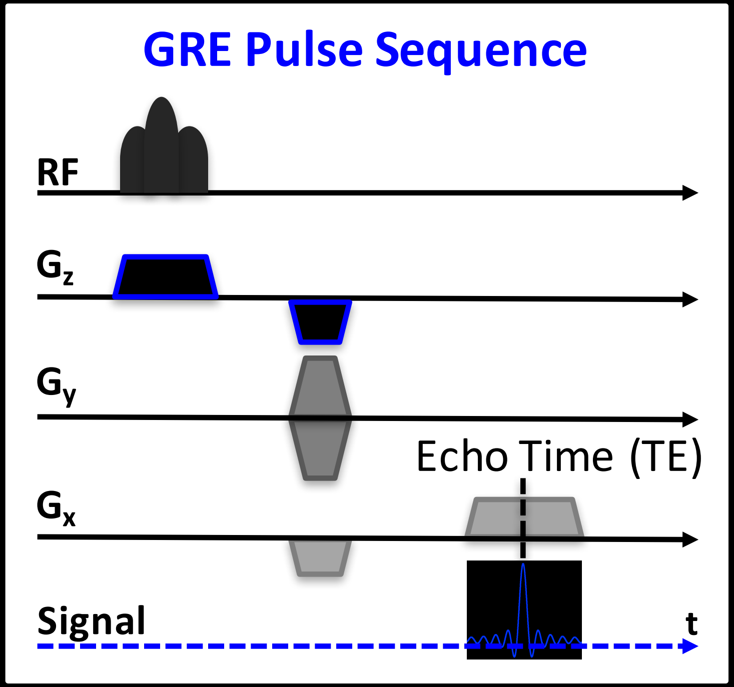
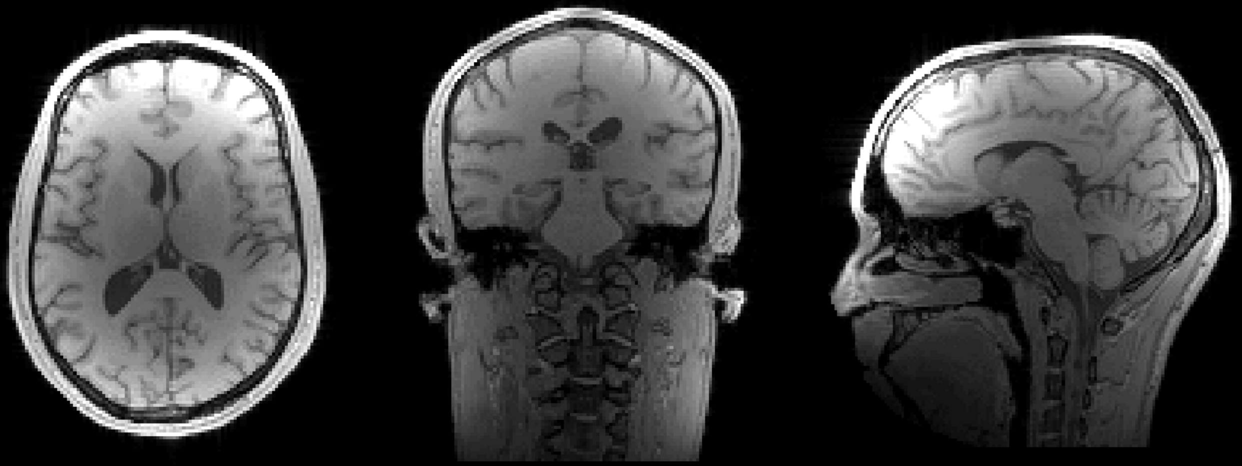
QSM Data Acquisition

- Basic GRE pulse sequence:
  - Readout pre-phasing gradient dephases spins
  - They are rephased using a readout gradient with opposite polarity
  - Peak signal occurs at Echo Time (TE)
  - Same module is repeated at Repetition Time (TR)



3D-GRE is Actually Fast

- 3D-GRE excites the whole imaging volume
- Collects one line of k-space per TR using the basic GRE module

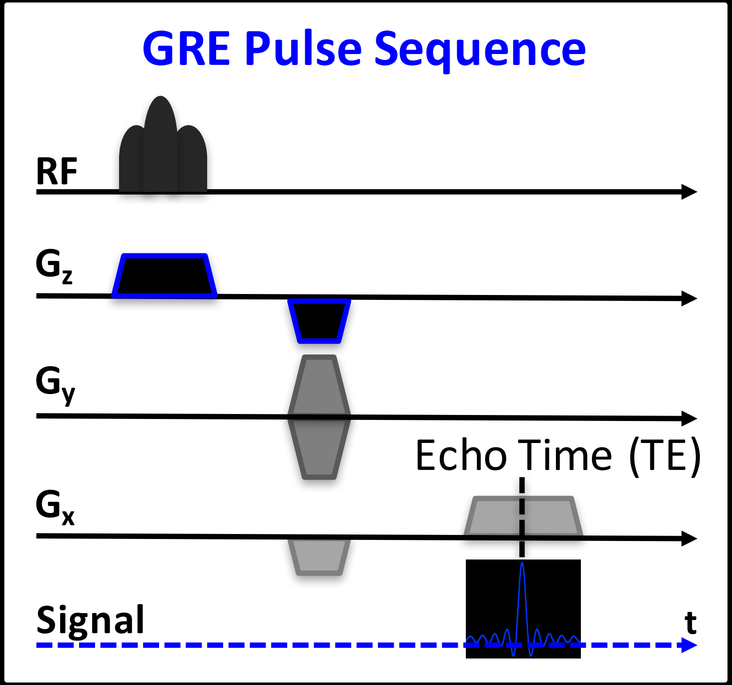


1.5 mm iso
160 x 160 x 128 mtx
$\Rightarrow$ 160 x 128 TR’s

TE = 3 ms, TR = 5 ms
$\Rightarrow$ **1:40 min acquisition**

TE for Optimal Phase SNR

- Since transverse signal decays due to T2*, shortest TE gives optimal **magnitude** SNR
- But phase evolves linearly with time, favoring long TE
- Phase SNR depends on transverse magnetization, T2* decay rate, and TE



$$TE_{optimal} = T2^*$$

@ 3T, $T2^*_{WM} \sim 45$ ms
$T2^*_{GM} \sim 40$ ms

Take **$TE_{optimal}$ = 40 ms**

Necessitate long TR => lengthy scan

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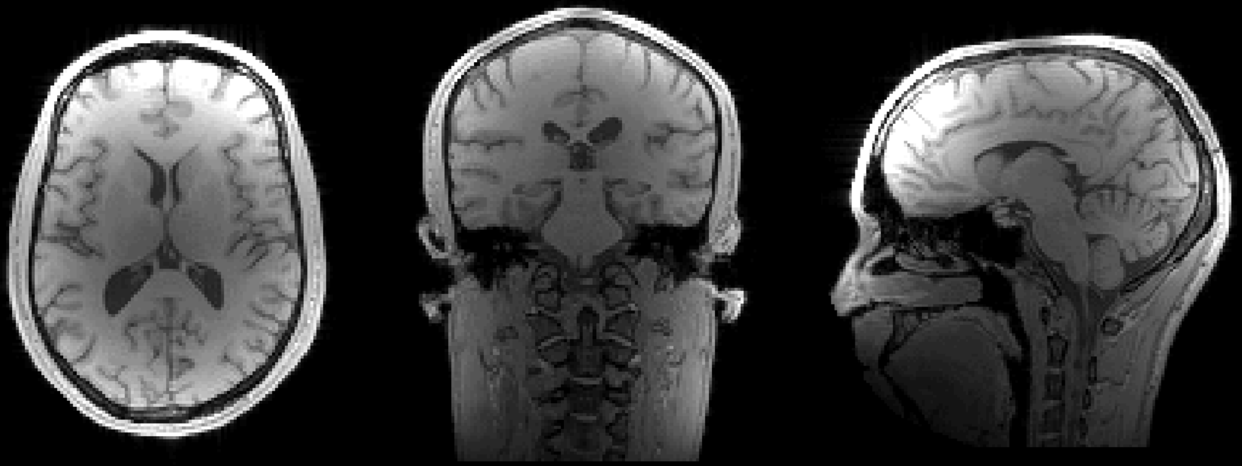
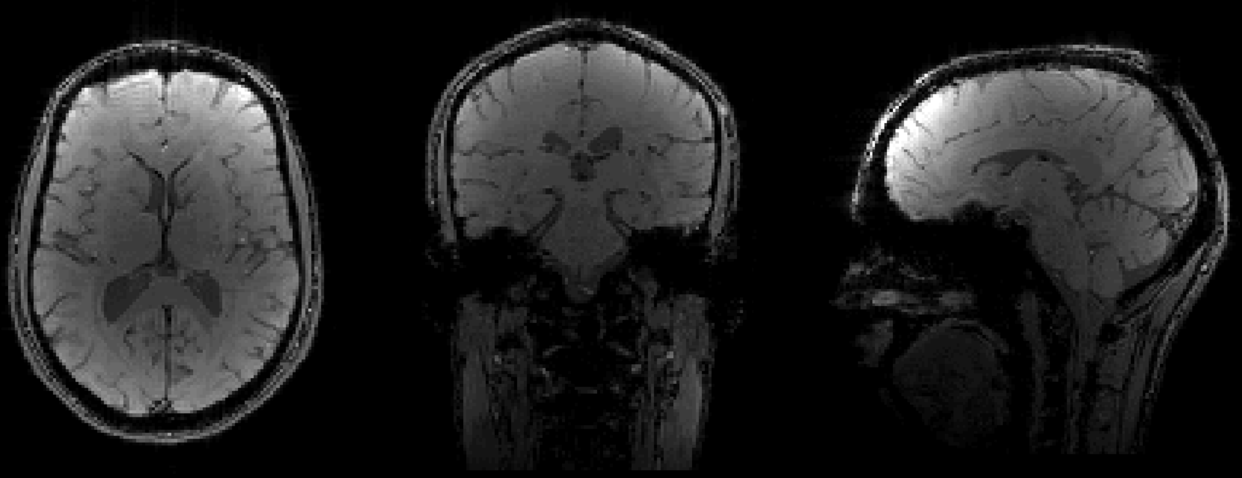


1.5 mm iso
160 x 160 x 128 mtx
$\Rightarrow$ 160 x 128 TR's

TE = 3 ms, TR = 5 ms
$\Rightarrow$ **1:40 min acquisition**

3D-GRE is Slow for QSM

- Need late TE to build up phase contrast
- But this leads to increased scan time

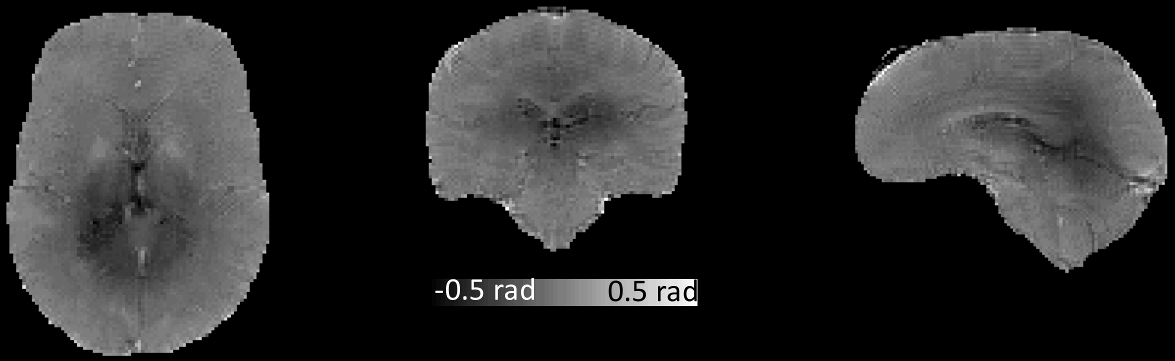


1.5 mm iso
160 x 160 x 128 mtx
$\Rightarrow$ 160 x 128 TR's

$TE_{optimal}$ = 40 ms, TR = 42 ms
$\Rightarrow$ 14:20 min acquisition

3D-GRE is Slow for QSM

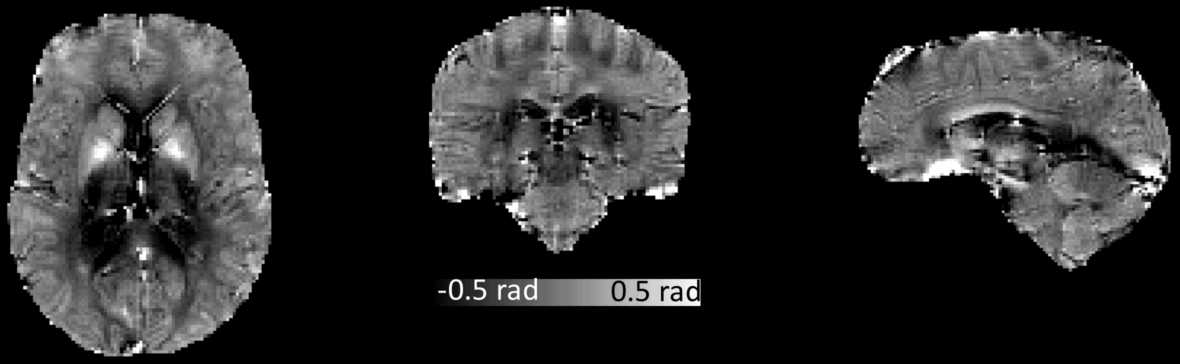
- Low phase contrast at short TE:



Tissue phase @ TE = 3 ms

3D-GRE is Slow for QSM

- Improved phase contrast at late TE:



Tissue phase @ TE = 19 ms

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Accelerated 3D-GRE Acquisition

- Parallel Imaging (e.g. SENSE [1], GRAPPA [2]) uses encoding power of receiver coils to reconstruct images from undersampled k-space

- Up to 3-fold acceleration with good quality

- In Partial Fourier, one half of k-space completely filled, and small amount of data in the other half is collected

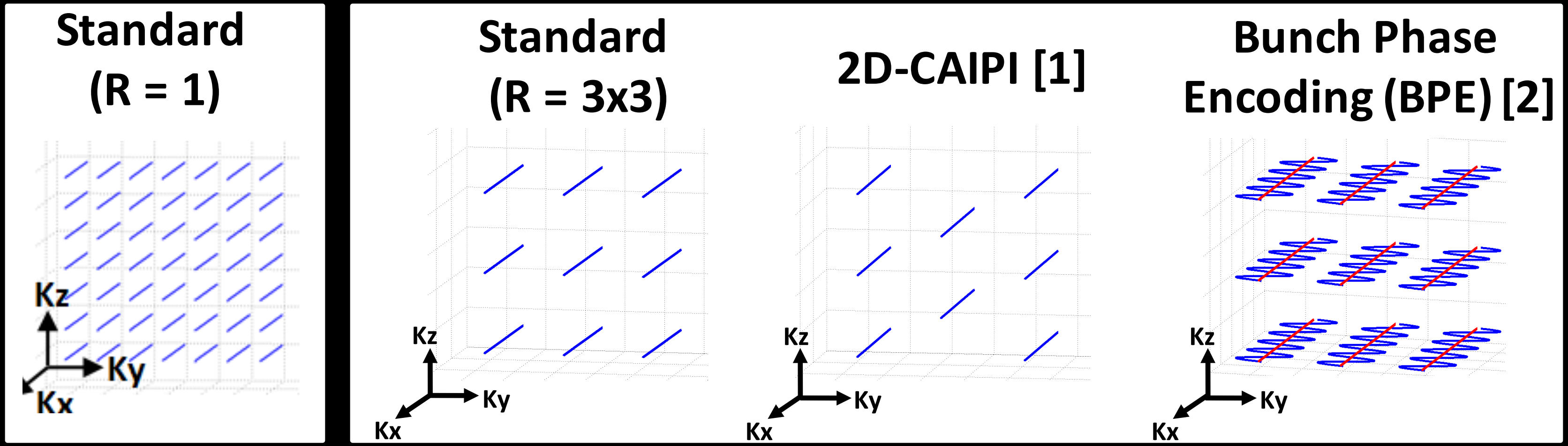
- Real signals have conjugate symmetric k-space:
  Enforce to fill up the missing half

- Combine Parallel Imaging & Partial Fourier for 4-fold accelerated 3D-GRE [3]

[1] KP Pruessmann et al, MRM 1999
[2] MA Griswold et al, MRM 2002
[3] AP Fan et al, MRM 2014

Highly Accelerated 3D-GRE

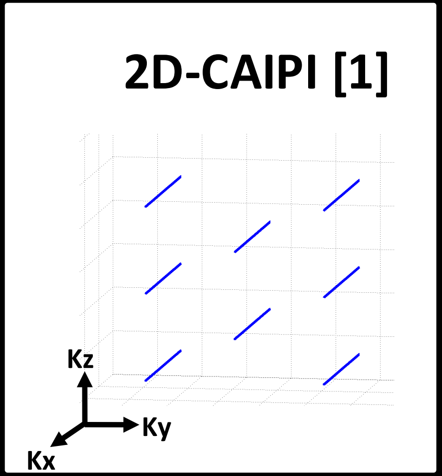
- For higher acceleration, undersample both in Ky and Kz phase encoding

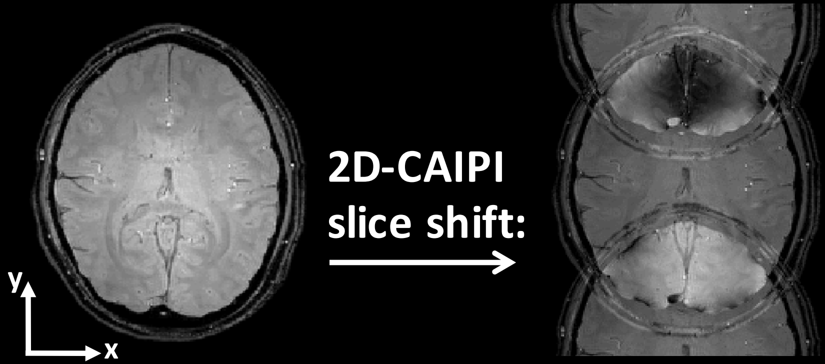


[1] FA Breuer et al, MRM 2006
[2] H Moriguchi et al, MRM 2006

Highly Accelerated 3D-GRE: 2D-CAIPI

- 2D Controlled Aliasing in Parallel Imaging (CAIPI) samples data in a honeycomb pattern [1]





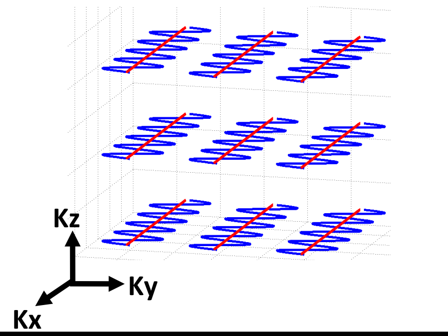
Effect of slice shift in image space

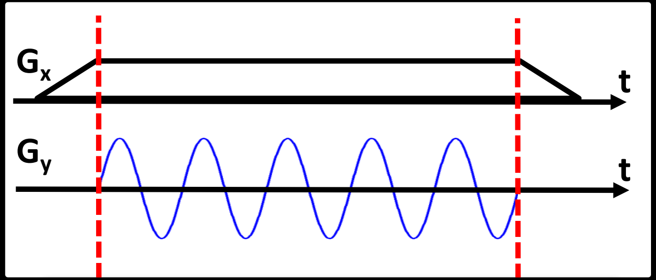
[1] FA Breuer et al, MRM 2006

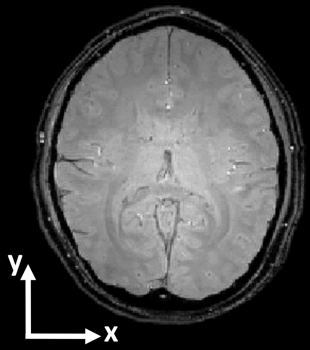
Highly Accelerated 3D-GRE: Bunch Encoding

- Bunch Encoding plays a sinusoidal gradient during readout to spread voxels along readout direction [2]

Bunch Phase Encoding (BPE) [2]







Bunch Phase: Zigzag G_y

[2] H Moriguchi et al, MRM 2006

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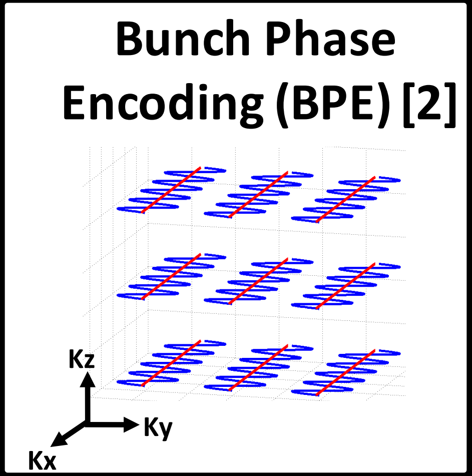
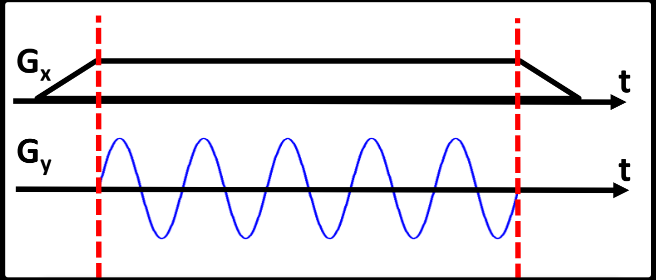
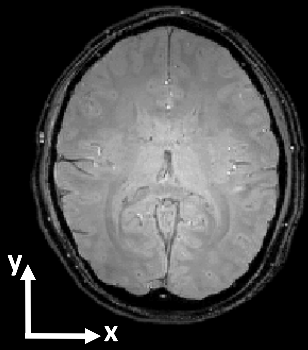
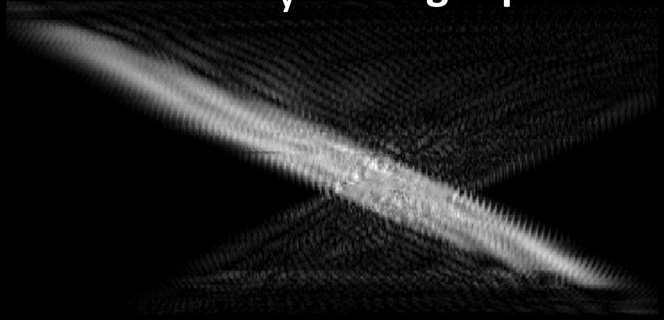






Bunch Phase: Zigzag G_y →

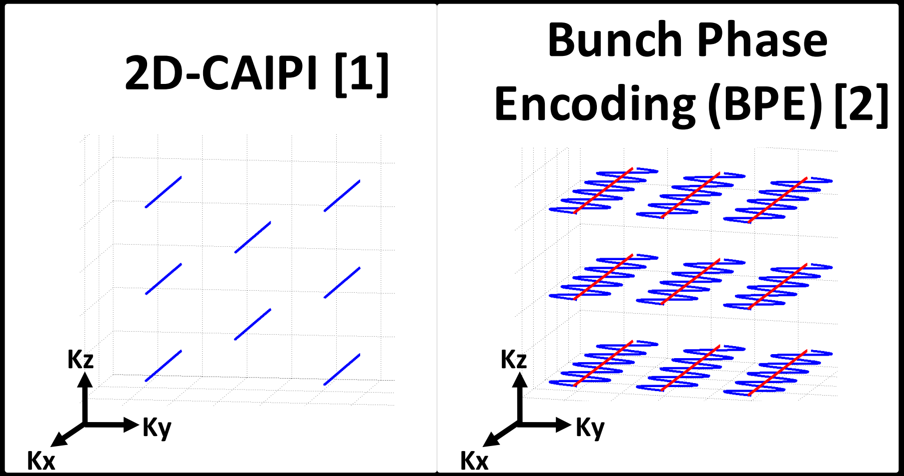
Effect of G_y in image space



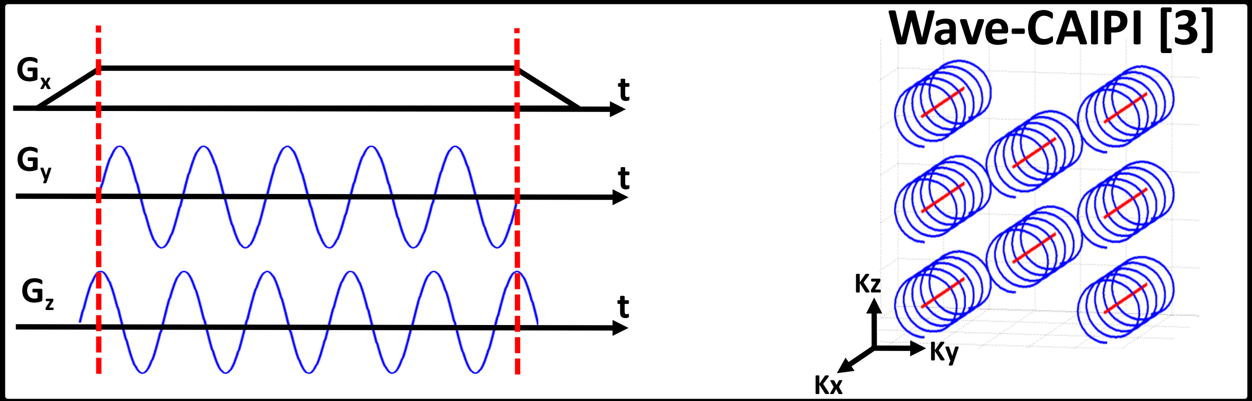
[2] H Moriguchi et al, MRM 2006

Highly Accelerated 3D-GRE: Wave-CAIPI

- Wave-CAIPI combines 2D-CAIPI honeycomb sampling with Bunch Encoding in both Gy and Gz axes [3]



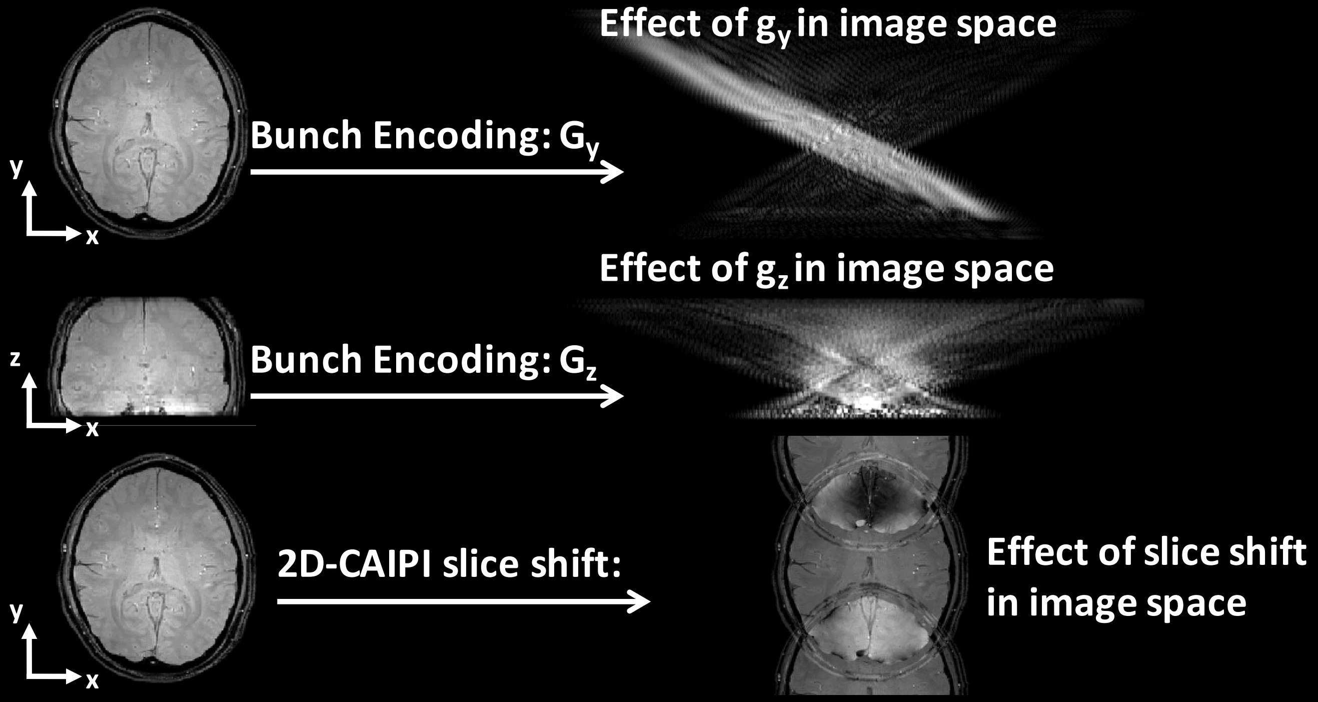
- <u>Spread aliasing in 3D to take full advantage of 3D coil profiles</u>



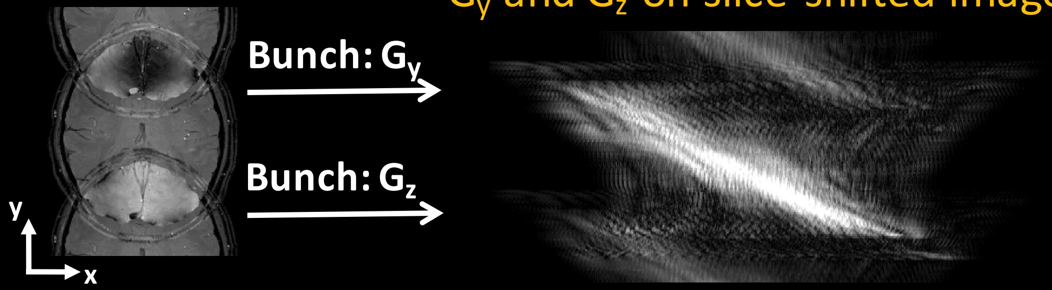
[1] FA Breuer et al, MRM 2006
[2] H Moriguchi et al, MRM 2006
[3] B Bilgic et al, MRM 2015

Wave-CAIPI spreads voxels in 3 dimensions

- Combination of G_y and G_z gradients with slice shifts yields voxel spreading across 3D



Wave-CAIPI: combined effect of G_y and G_z on slice-shifted images



Wave-CAIPI spreads voxels in 3 dimensions

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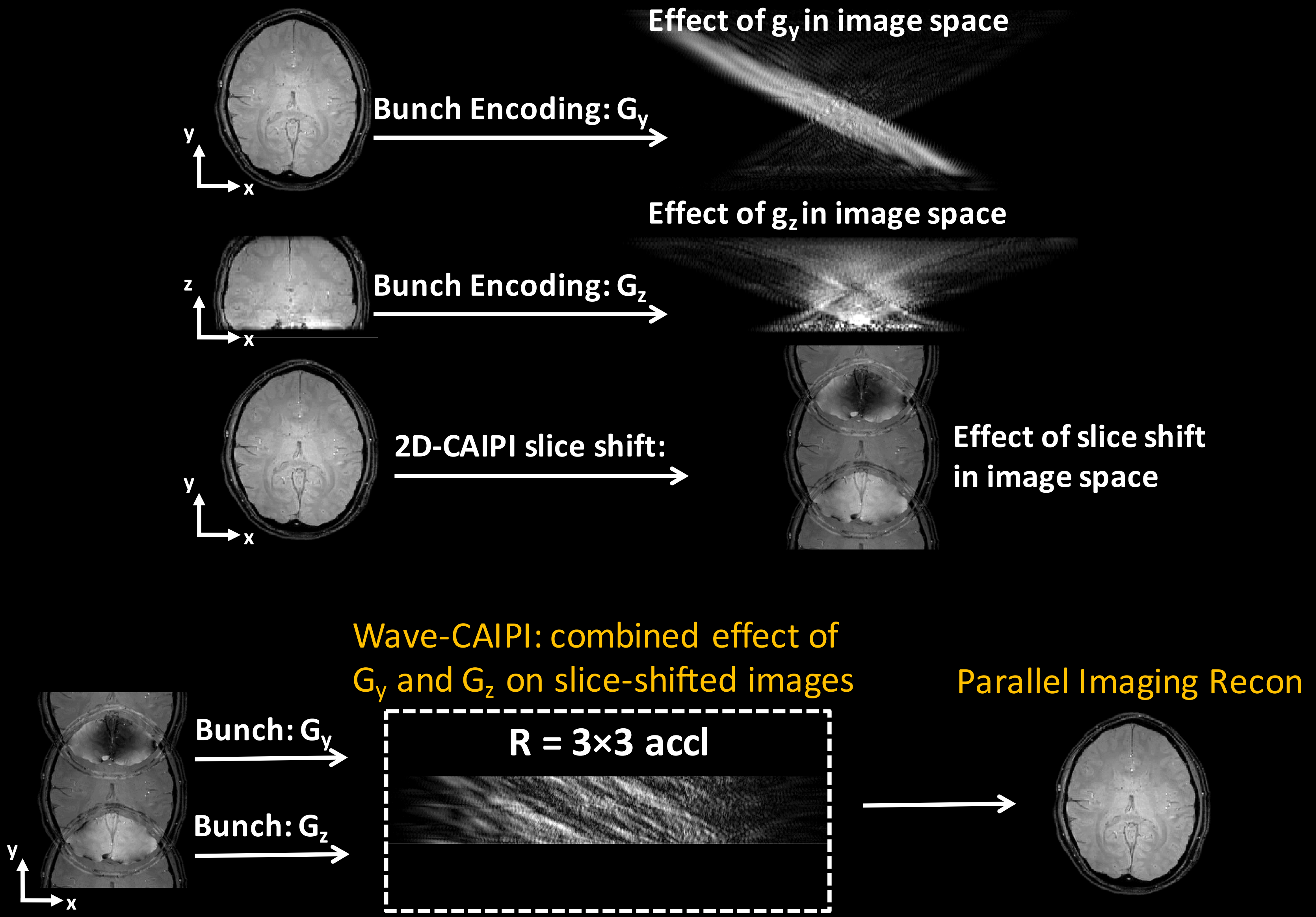
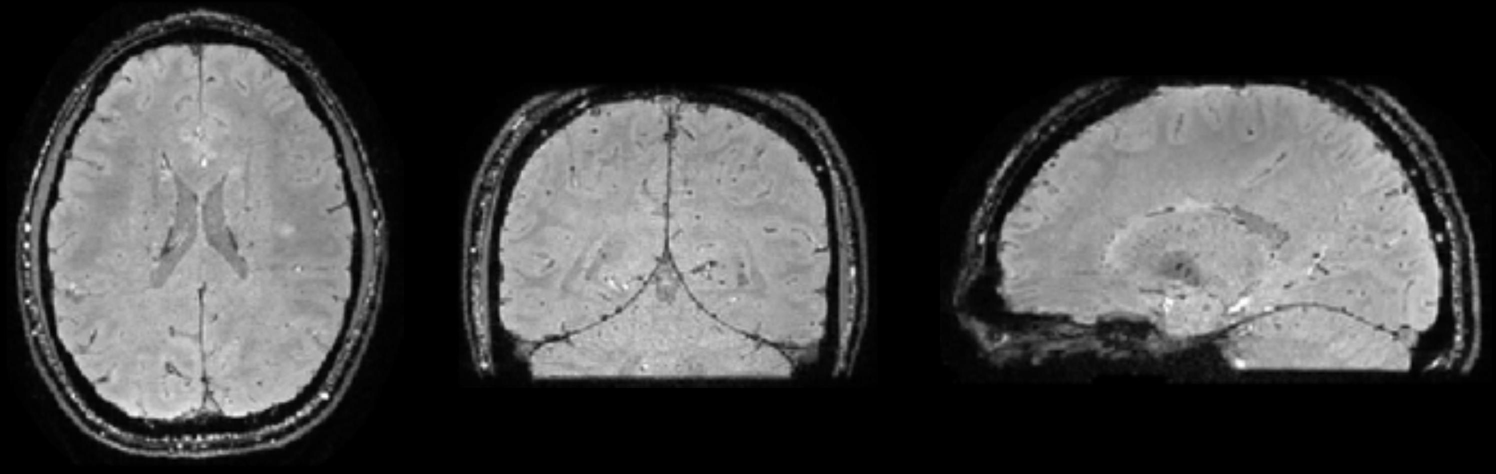


Automated Estimation of Wave-Caipi Trajectory

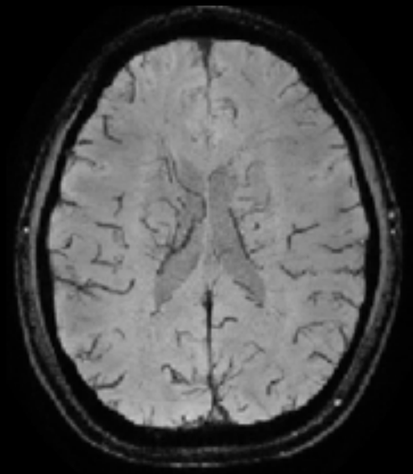
- Theoretical trajectory does not match the actual trajectory played on the gradients
- Since these are sinusoidal waveforms, just need to estimate amplitude and delay
- Trajectory coefficients and image content can be jointly estimated from undersampled data [1]

Wave-CAIPI: Dual Echo w/ flow comp, 1mm iso in 1min 51s



R=3×3 accl, TE = {15,32} ms

SWI MIP



Online Recon: 2 min

[1] SF Cauley et al, ISMRM’16

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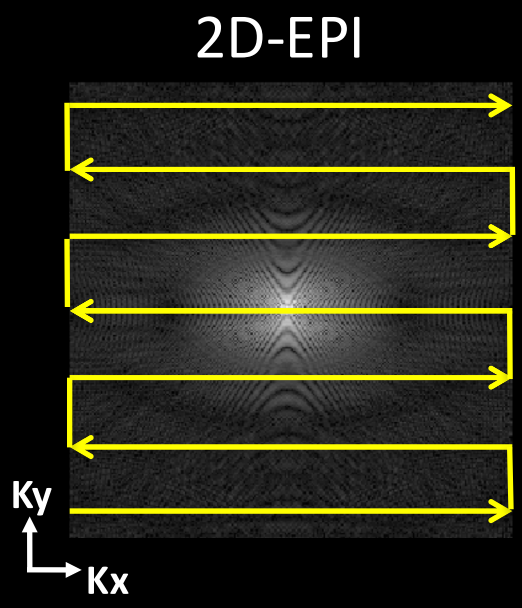
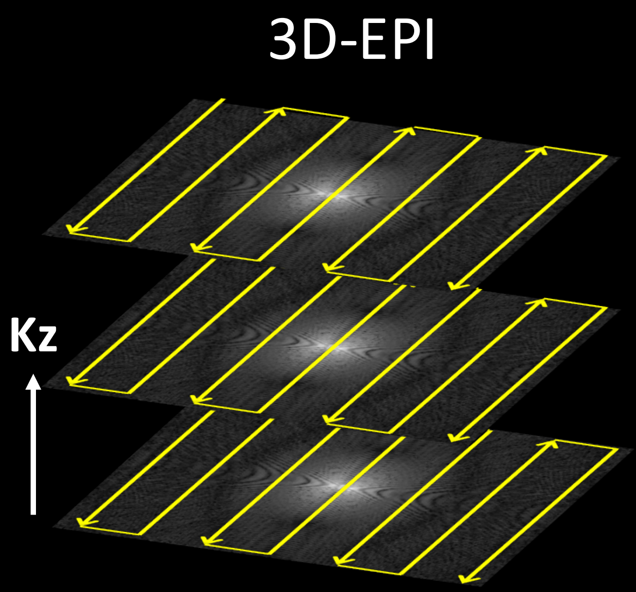
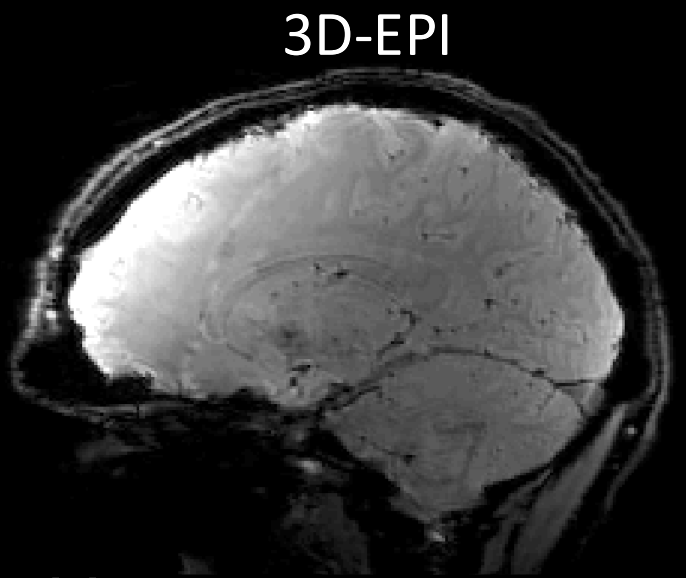
3D-EPI Acquisition

- 2D Echo Planar Imaging (EPI) collects the entire Kx-Ky plane per RF excitation
- This makes EPI very efficient for rapid imaging
- EPI can be extended to 3D imaging with phase encoding in Kz
- 3D-EPI is extremely fast [1,2]: **1 mm iso whole brain in 30 seconds**



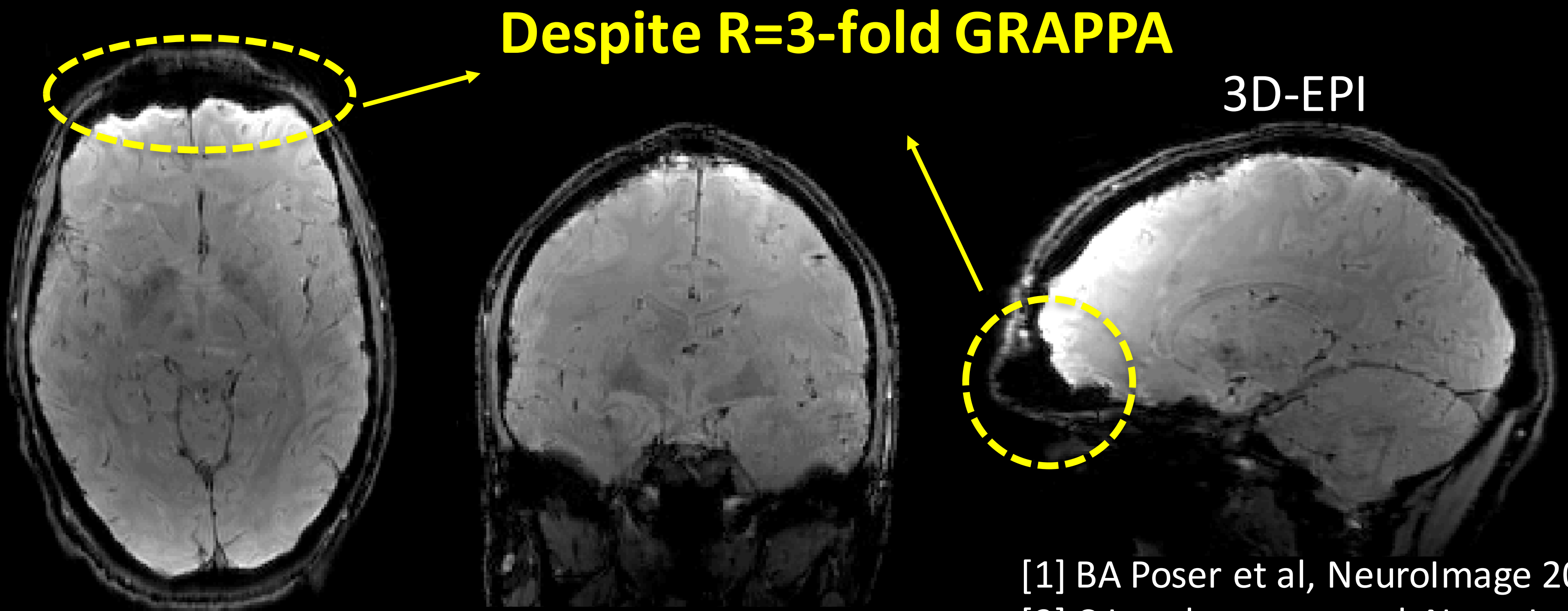




[1] BA Poser et al, NeuroImage 2010
[2] C Langkammer et al, NeuroImage 2015

3D-EPI Acquisition

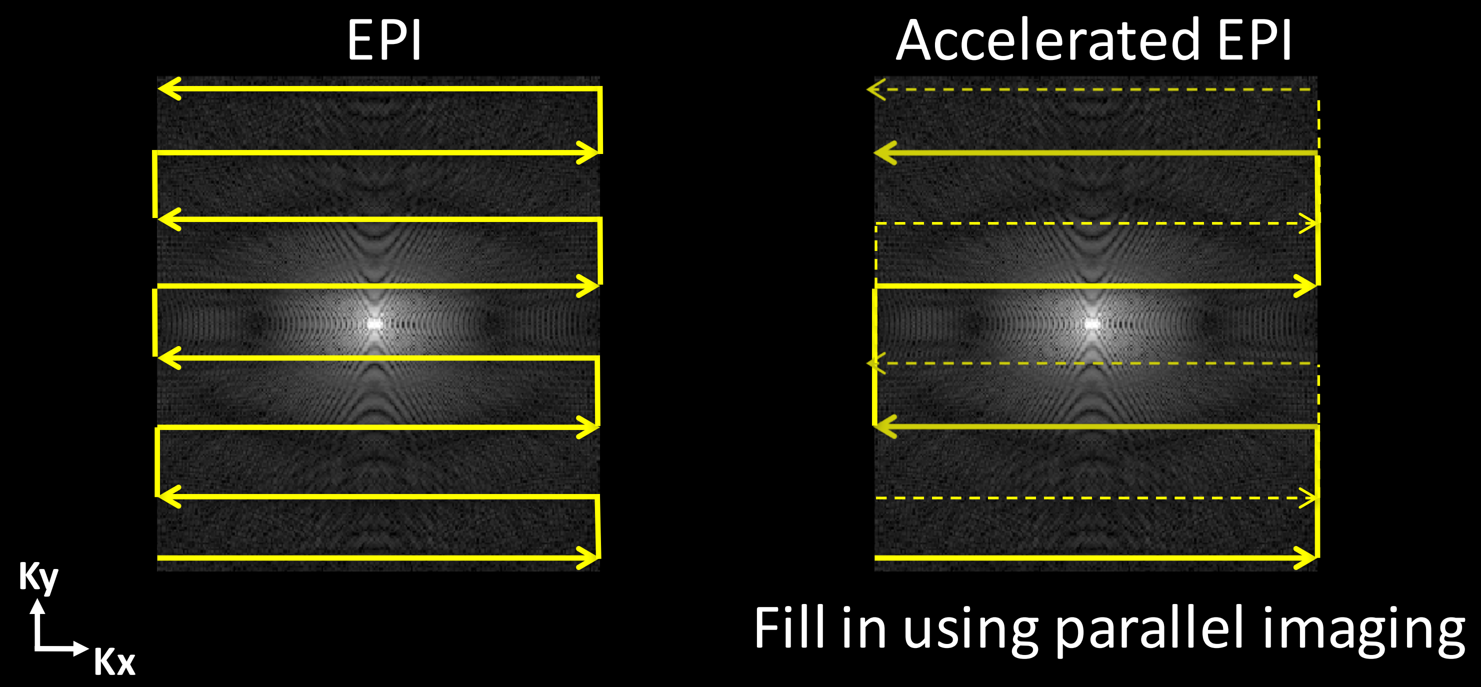
- 3D-EPI is extremely fast [1,2]: **1 mm iso whole brain in 30 seconds**
- A drawback of EPI is the distortion in phase encoding direction
- Can be mitigated with:
  - Parallel imaging
  - Segmented / multi-shot acquisition



[1] BA Poser et al, NeuroImage 2010
[2] C Langkammer et al, NeuroImage 2015

Highly Accelerated 3D-EPI

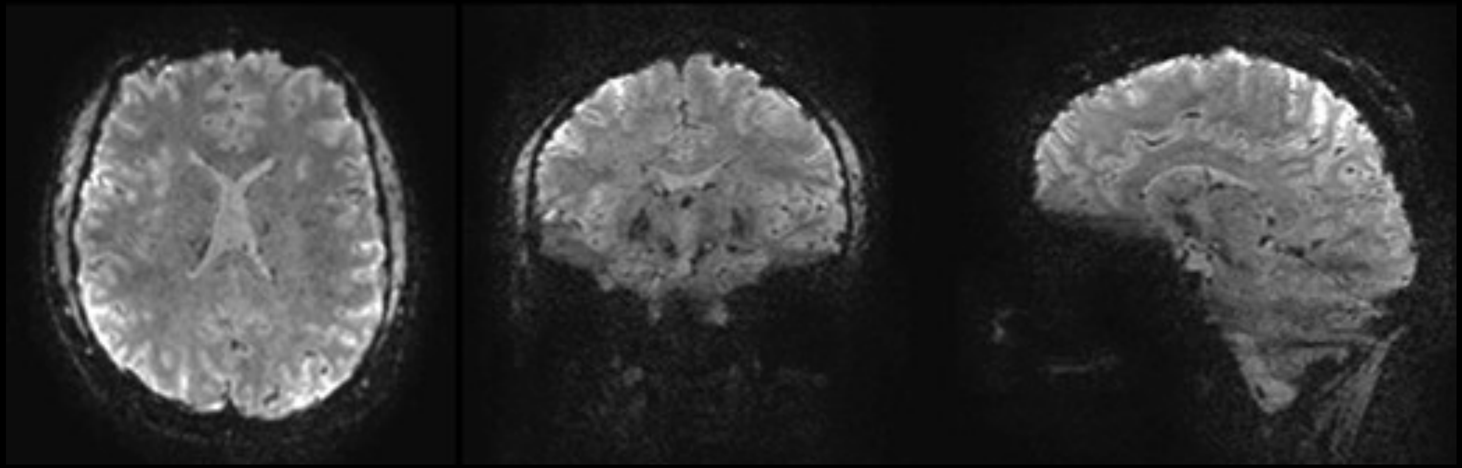
- Distortion in 3D-EPI can be reduced by high in-plane acceleration, thus shortening echo spacing



Highly Accelerated 3D-EPI

- Distortion in 3D-EPI can be reduced by high in-plane acceleration, thus shortening echo spacing

0.8 mm iso whole brain in 7.3 sec @ 3T



16-fold in-plane (Ky) acceleration using 2D-CAIPI [1,2]

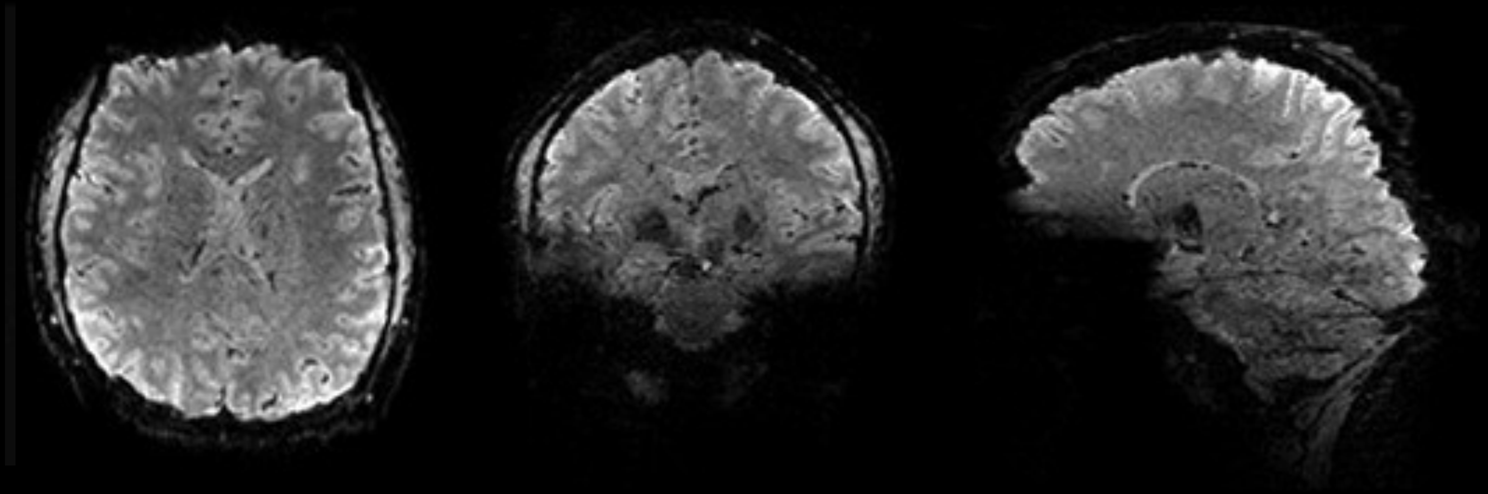
[1] BA Poser et al, ISMRM 2014
[2] M Narsude et al, MRM 2016

Highly Accelerated 3D-EPI

- Distortion in 3D-EPI can be reduced by high in-plane acceleration, thus shortening echo spacing

- Total acceleration can be distributed between Ky-Kz to trade speed for distortion

0.8 mm iso whole brain in 2.0 sec @ 3T

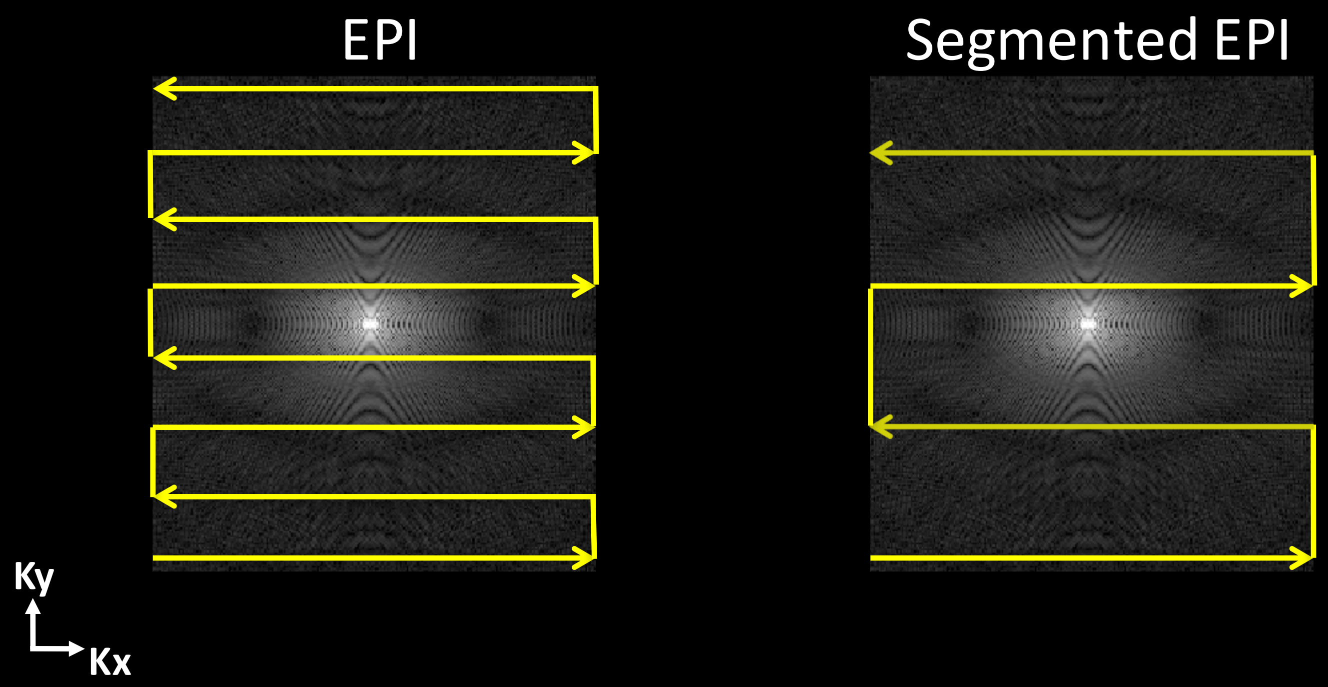


4-fold in-plane (Ky) acceleration
4-fold Kz acceleration using 2D-CAIPI [1,2]

[1] BA Poser et al, ISMRM 2014
[2] M Narsude et al, MRM 2016

Segmented 3D-EPI

- Distortion in 3D-EPI can be reduced by acquiring data in multiple segments, thus shortening echo spacing



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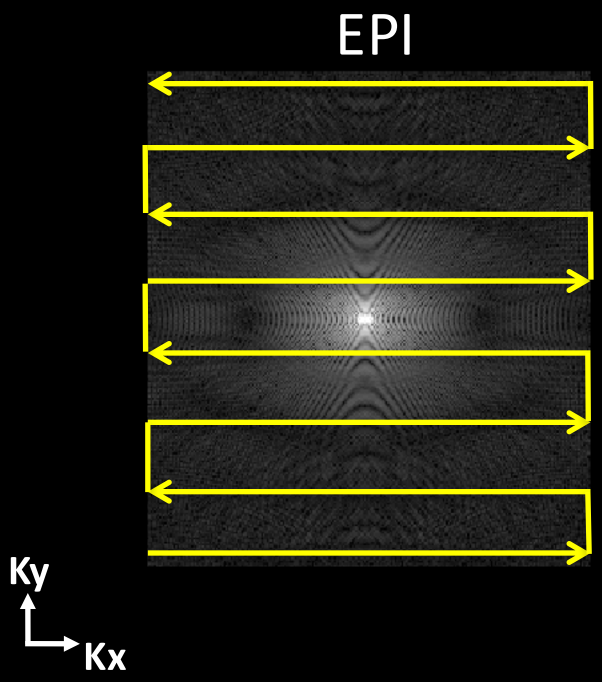
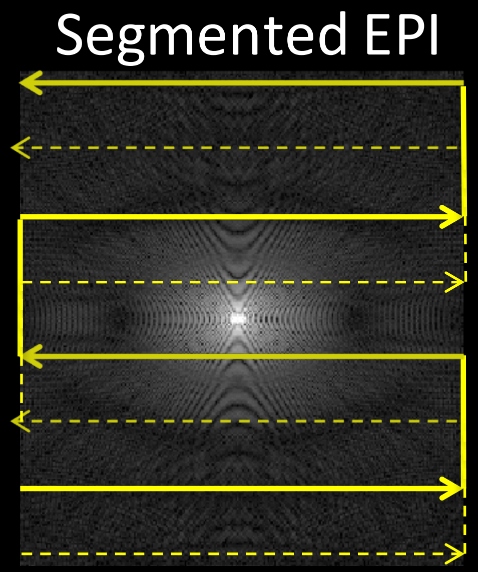




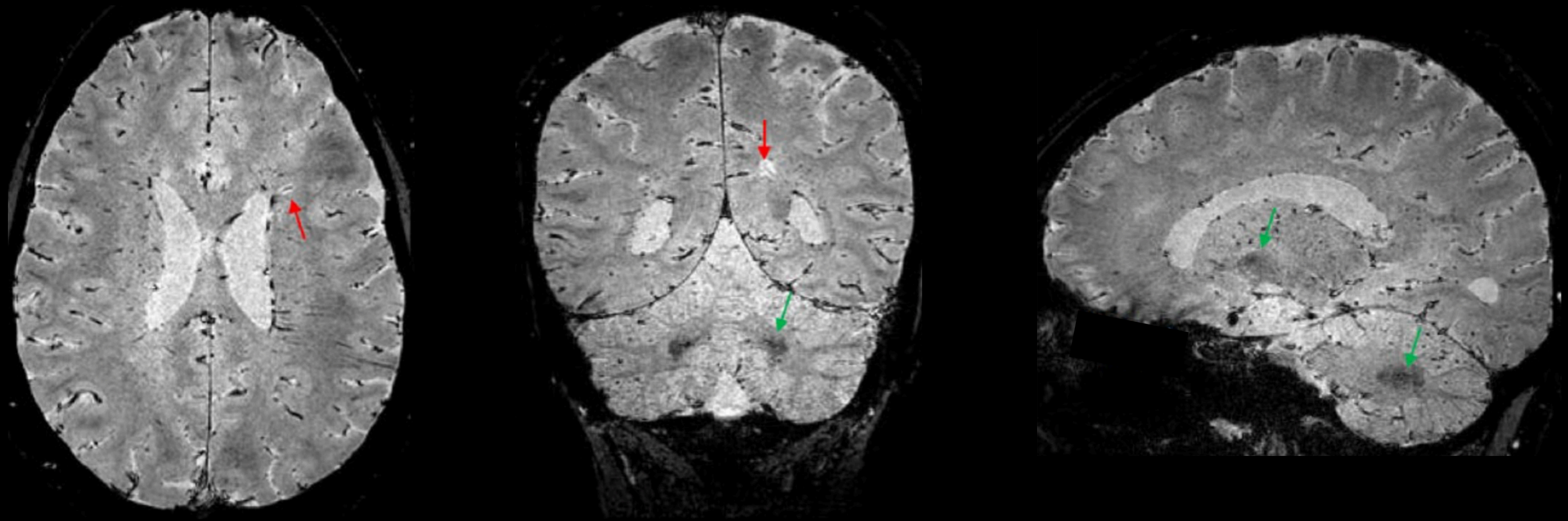
Segmented 3D-EPI

- Distortion in 3D-EPI can be reduced by acquiring data in multiple segments, thus shortening echo spacing

- Allows high resolution 3D-EPI with low distortion [1]

- At the expense of some reduction in efficiency

0.55 mm iso whole brain in 4 min @ 3T



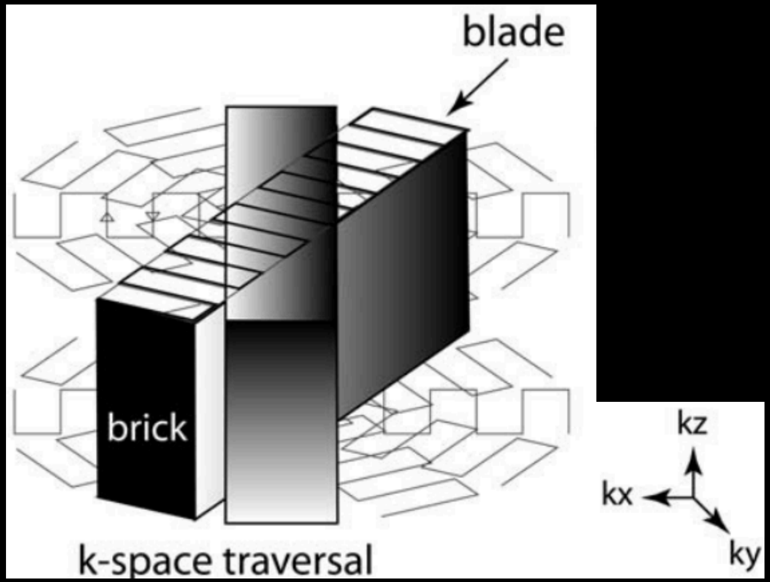
[1] P Sati et al, MS Journal 2014

Segmented 3D-EPI

- Distortion in 3D-EPI can be reduced by acquiring data in multiple segments, thus shortening echo spacing
- Another way is **3D Propeller-EPI**, where blades of EPI segments are acquired sequentially [1]:
- Distortion is reduced by a factor of $\mathbf{N_{read} / N_{blade}}$

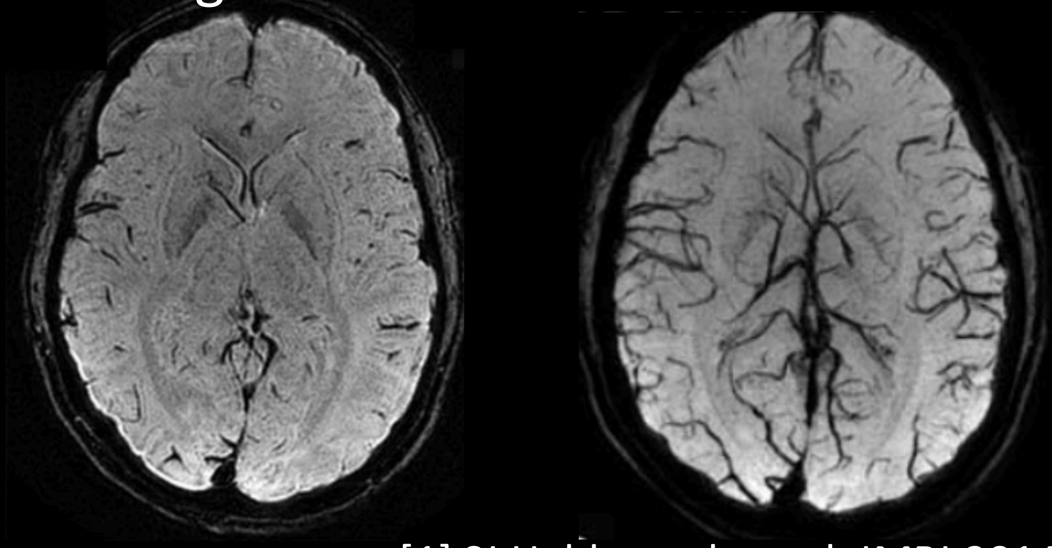
  $\mathbf{N_{read}}$: target readout width

  $\mathbf{N_{blade}}$: blade width



1x1x2 mm whole brain in 2 min

Magnitude SWI



[1] SJ Holdsworth et al, JMRI 2014

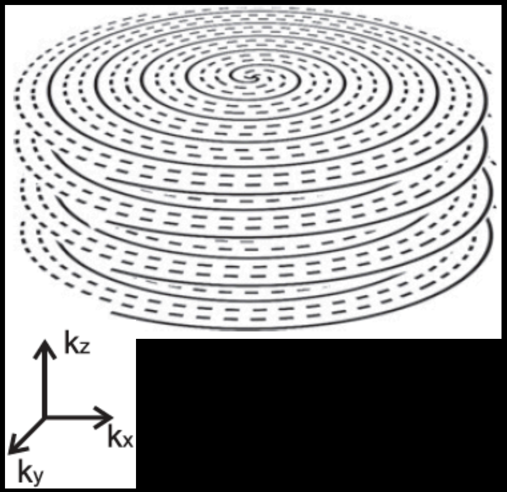
3D-Spiral Acquisition

- Alternative readout strategy is the spiral trajectory, which allows rapid and efficient coverage of k-space

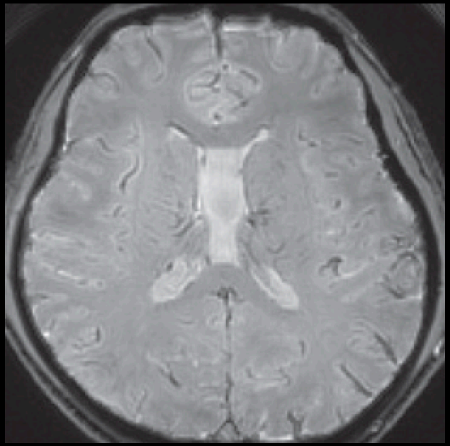
- It can be extended to 3D with stack-of-spirals using phase encoding along Kz [1]:

- Multiple shots (interleaves) are required to achieve FOV

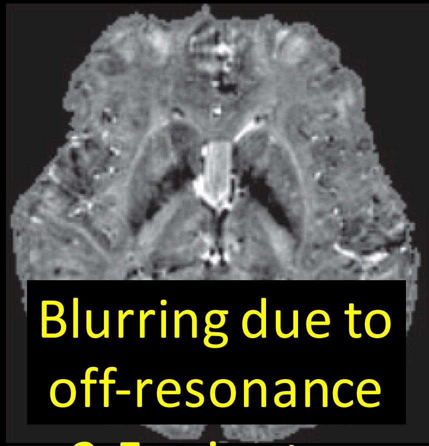
Multi-shot 3D-Spiral



1 mm iso whole brain in 2.5 min

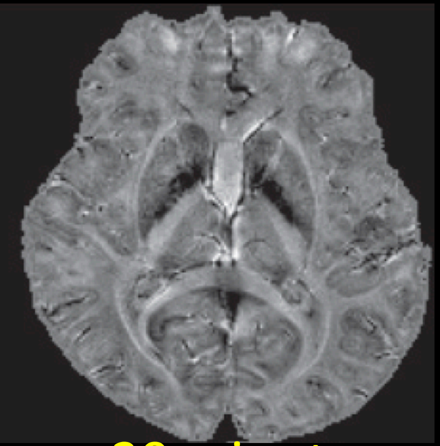


3D-Spiral Tissue Phase



2.5 minutes

3D-GRE Tissue Phase



20 minutes

[1] B Wu et al, NeuroImage 2012

	PROS	CONS
3D-GRE	▪ No distortion, only voxel shift in readout due to off-resonance ▪ Simple recon: FFT ▪ Simple Parallel Imaging	▪ Slow acquisition
3D-EPI	▪ Very fast ▪ Relatively simple recon: FFT ▪ Relatively simple Parallel Imaging	▪ Off-resonance causes distortion
3D-Spiral	▪ Very fast ▪ No geometric distortion ▪ Spiral-in allows TE close to TR	▪ Difficult recon: Non-Cartesian ▪ Off-resonance causes blurring
Wave-CAIPI	▪ Fast ▪ No distortion, only voxel shift in readout due to off-resonance ▪ Relatively simple Parallel Imaging	▪ Relatively slow recon

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Echo-Shift

- Long TE desired to build up phase contrast leads to long TR and acquisition time

- Echo-shift exploits unused sequence time and interleaves multiple echos within a single TR

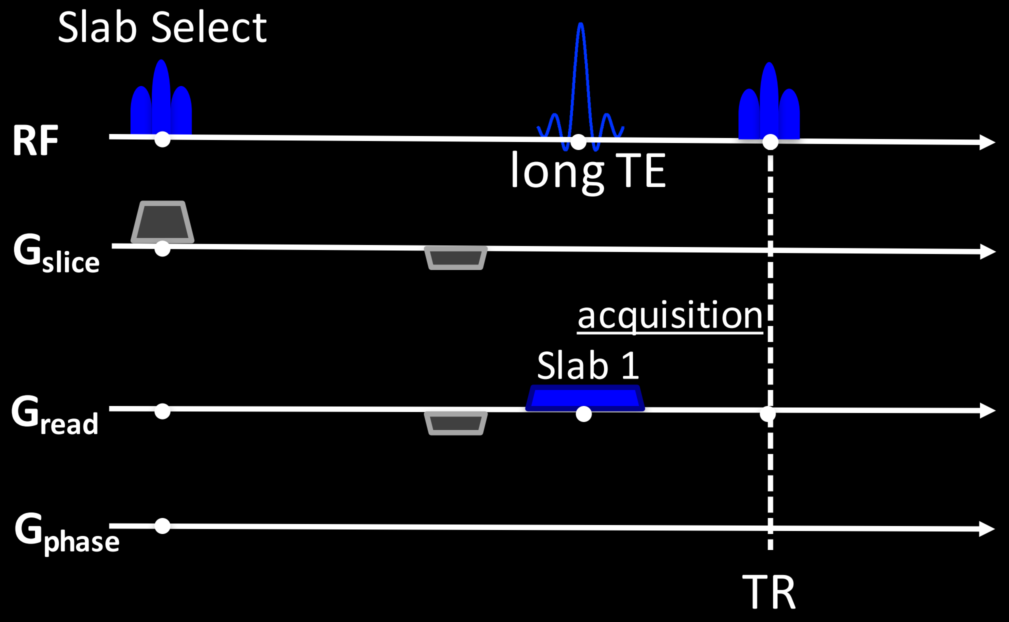
- This improves efficiency in 2D [1] or 3D [2] acquisitions

- Echo-shift is known as PRESTO in fMRI [3], and has been combined with Simultaneous MultiSlice (SMS) [4] for highly accelerated 2D imaging

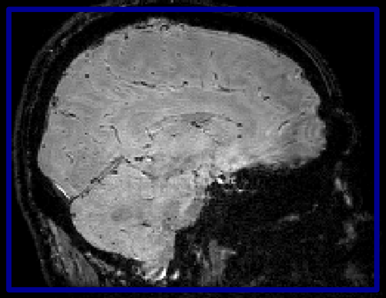
[1] CTW Moonen et al, MRM 1992
[2] YJ Ma et al, MRM 2015
[3] G Liu et al, MRM 1993
[4] R Boyacioğlu et al, MRM 2016

Conventional 3D-GRE

- Conventional 3D-GRE: substantial unused time due to late TR

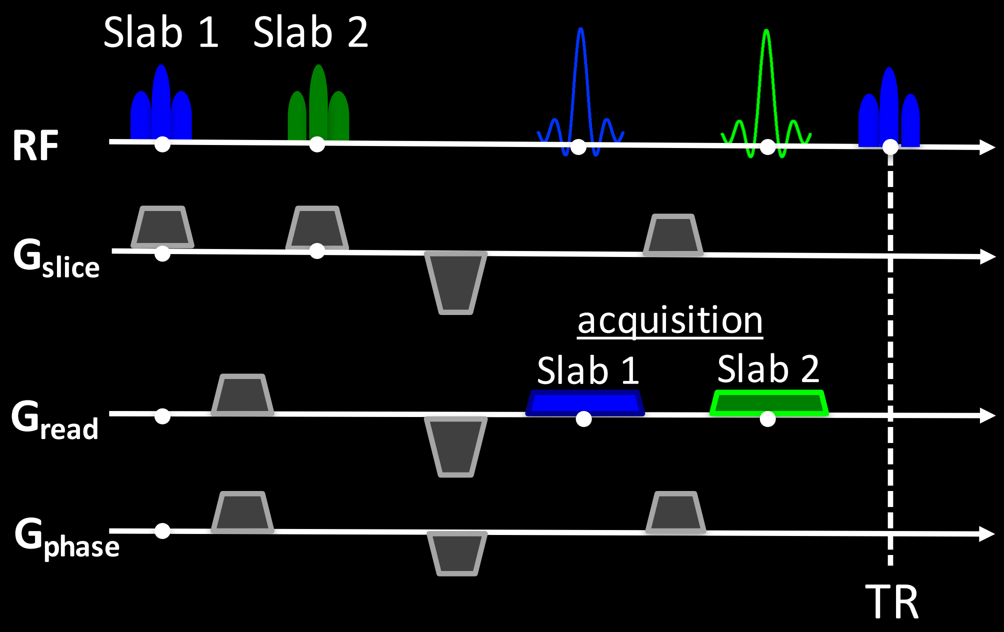


Conventional
3D encoding

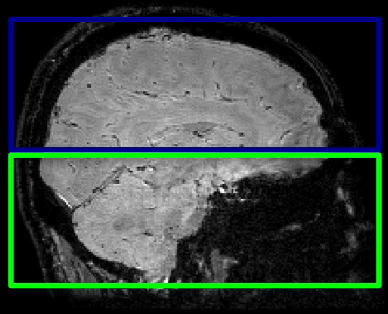


Multi-Slab Echo-Shift for 3D-GRE

- Multi-Slab Echo-Shift [1]: add a second readout for faster encoding



Multi-Slab Echo-Shift

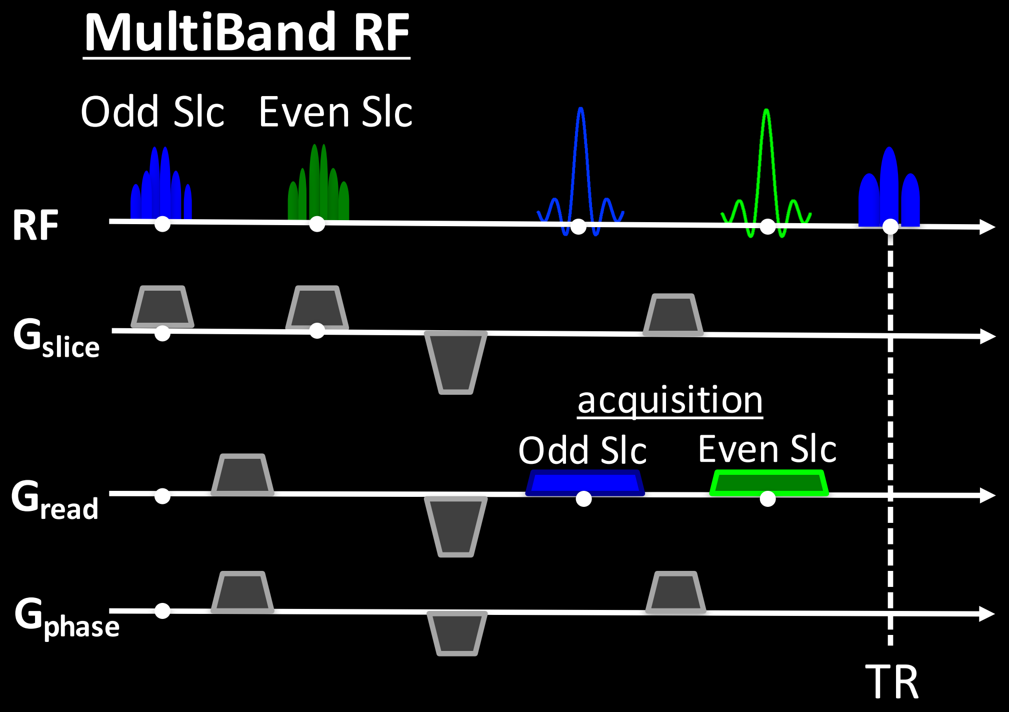


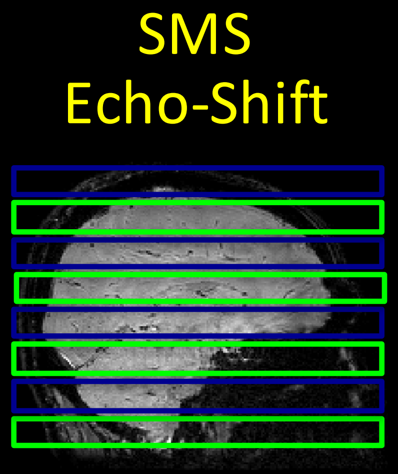
- Slab boundary artifact
- Acceleration in head-foot more difficult since distance between aliasing voxels reduced by half

[1] YJ Ma et al, MRM 2015

Simultaneous MultiSlice Echo-Shift for 3D imaging

- SMS Echo-Shift [1]: excite and encode comb slice groups





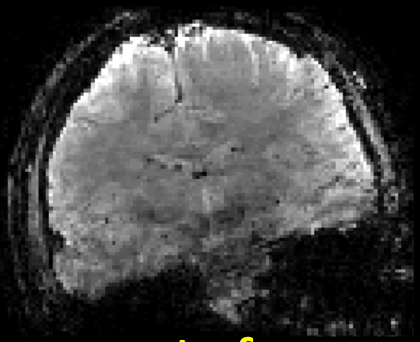
[1] H Ye et al, ISMRM 2016

Simultaneous MultiSlice Echo-Shift for 3D imaging

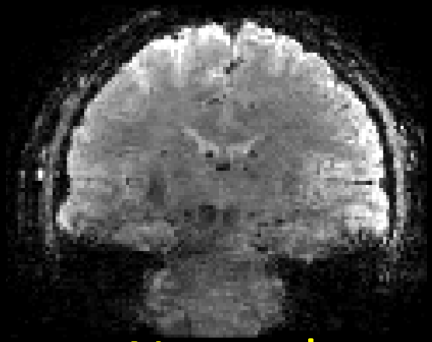
3-fold Echo-Shift Acceleration

- $1{\times}1{\times}1.5mm^3$ in 5min 45s
- Long TE_{eff} = 40ms
- Combine with parallel imaging or efficient trajectories for further speed-up

Echo-Shift CS-Wave with R=15×2 acceleration



Left



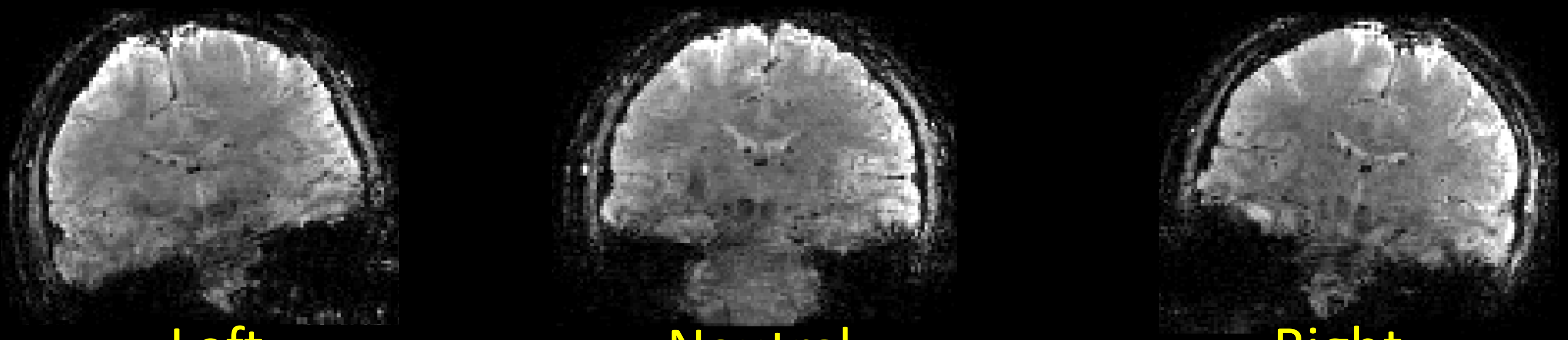
Neutral

Right

- 2-fold Echo-Shift with 15-fold Compressed Sensing Wave acceleration [1]
- 1.5 mm iso
- Long TE = 35 ms (TR = 47 ms)
- **T_{acq} = 24 sec**

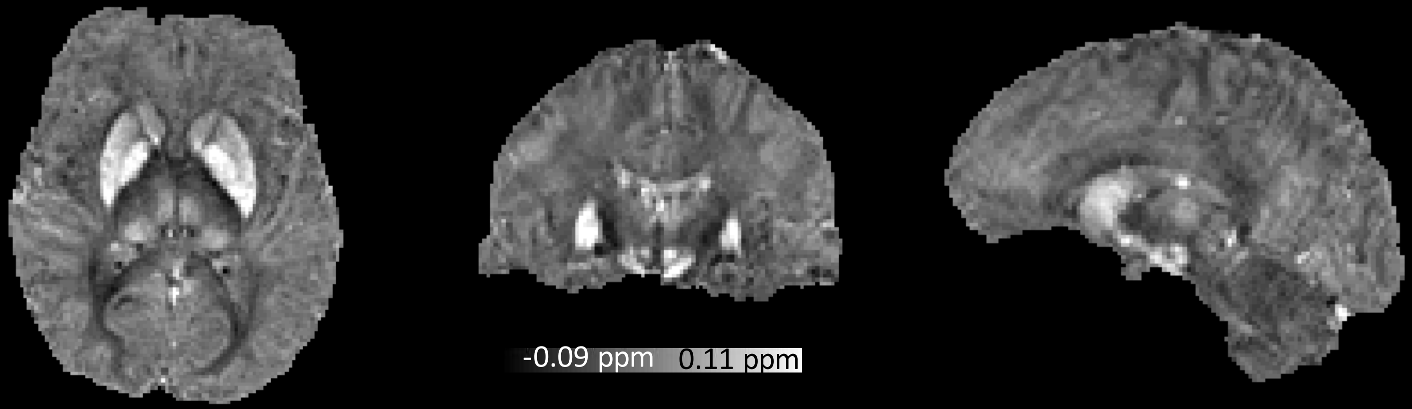
[1] B Bilgic et al, ISMRM 2016

Echo-Shift CS-Wave with R=15×2 acceleration



Left Neutral Right

QSM from 3 orientations: T_{total} = 72sec

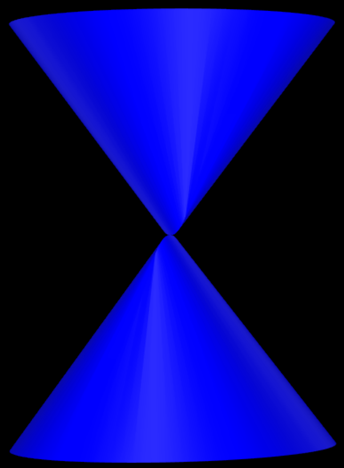


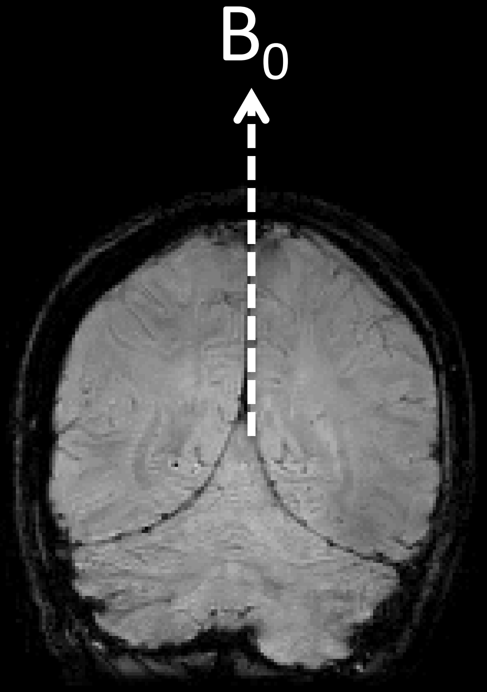
Accelerated QSM

- **Outline:**
  - Why QSM acquisition is slow
  - Parallel imaging
  - Efficient trajectories
  - Exploit unused sequence time
  - Multi-orientation sampling: COSMOS and STI

Multi-orientation QSM

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





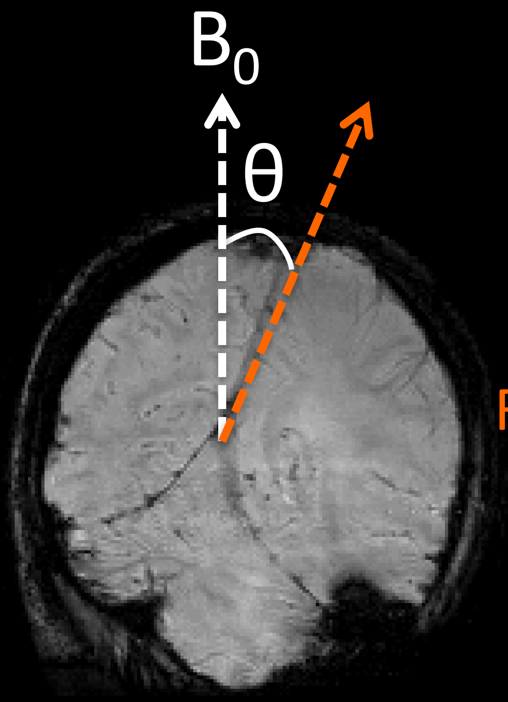
Neutral

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

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

Multi-orientation QSM

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

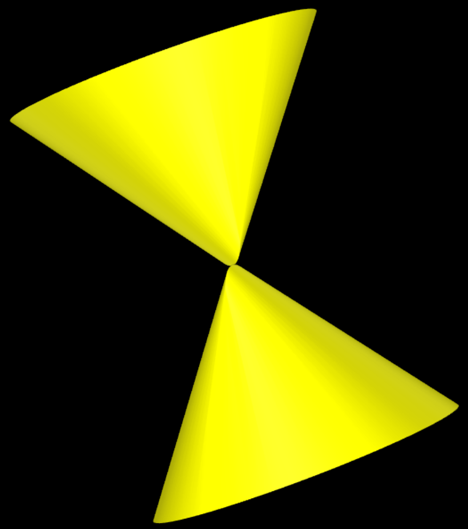


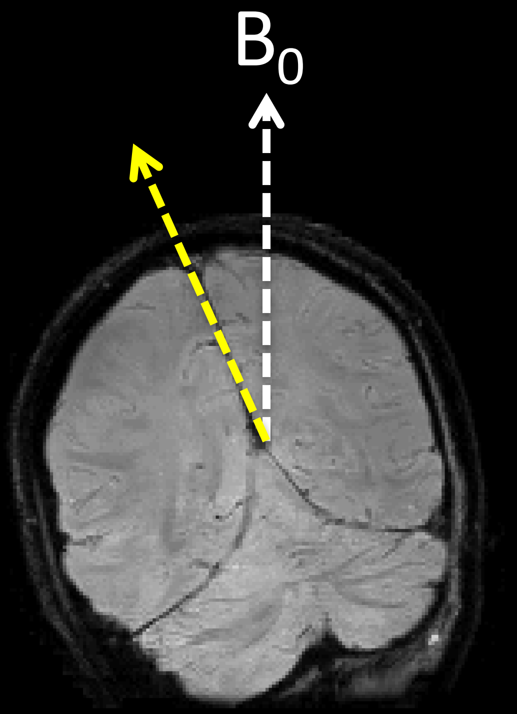
$$\delta_\theta = F^{-1} D_\theta F \chi$$

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

Multi-orientation QSM

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





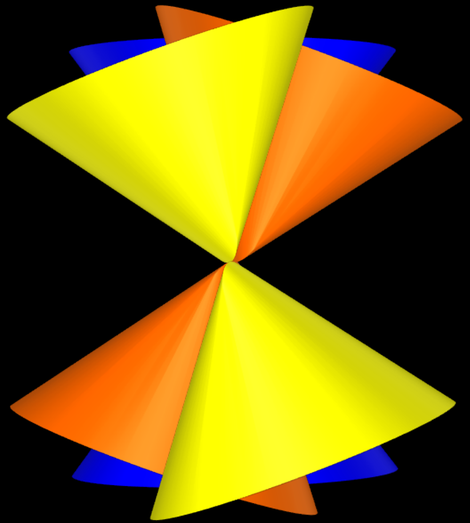
Rotate Left

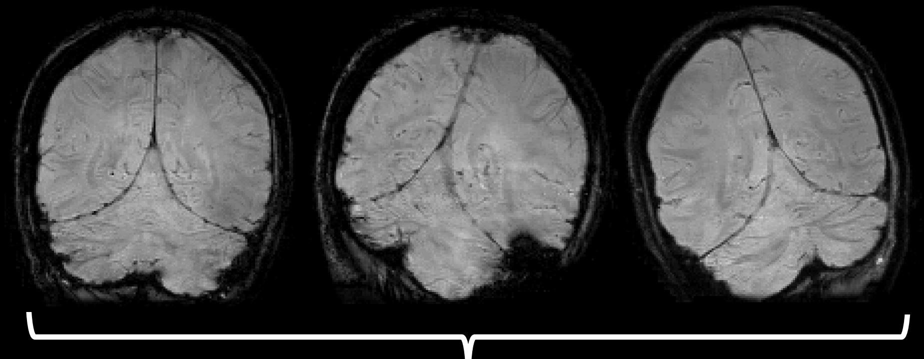
$$\boldsymbol{\delta_\theta = F^{-1} D_\theta F \chi}$$

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

Multi-orientation QSM

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





Combine multiple orientations for QSM inversion

- Undersampling is substantially mitigated

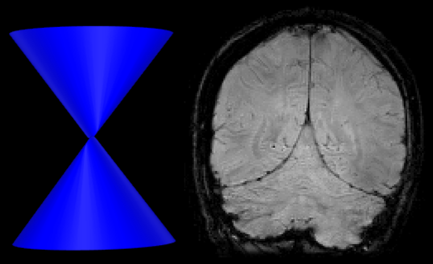
Calculation of Susceptibility Through Multiple Orientation Sampling (COSMOS) [1,2]

[1] T Liu et al, MRM 2009
[2] T Liu et al, MRM 2011

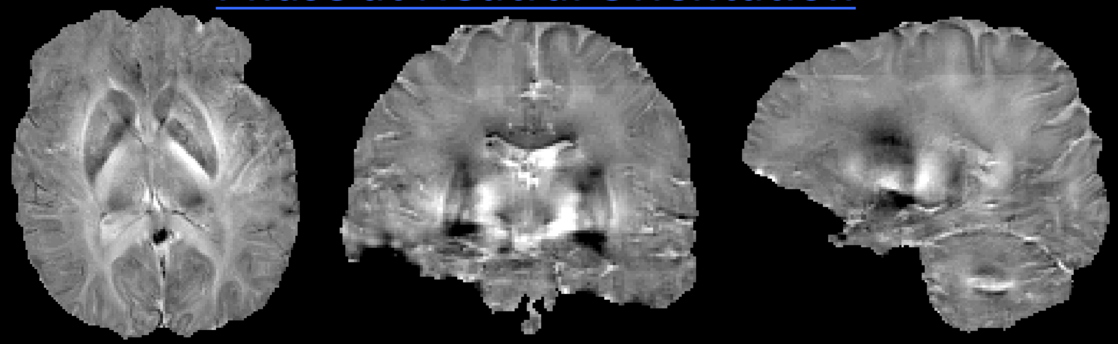
Multi-orientation QSM

- After phase processing and spatial registration:

Neutral

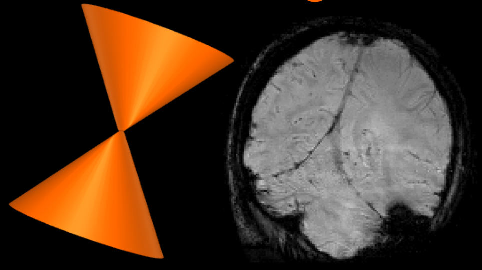


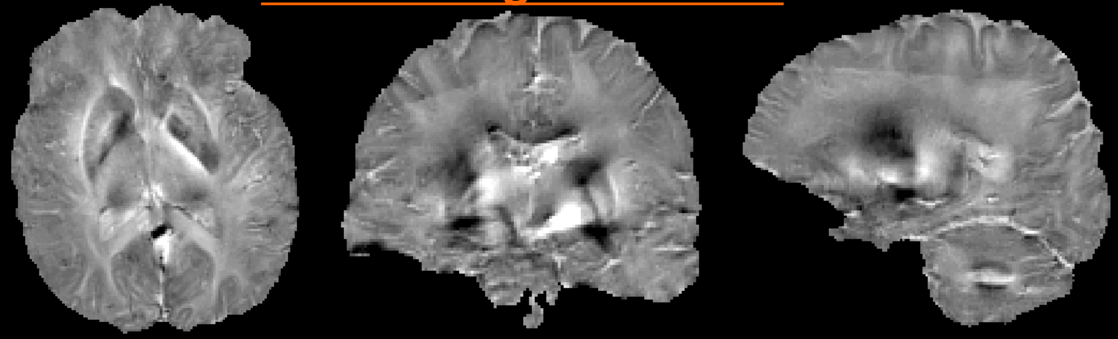
Phase at Neutral Orientation



Multi-orientation QSM

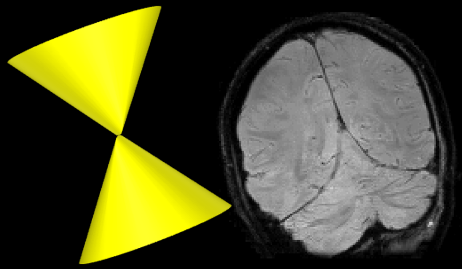
- After phase processing and spatial registration:

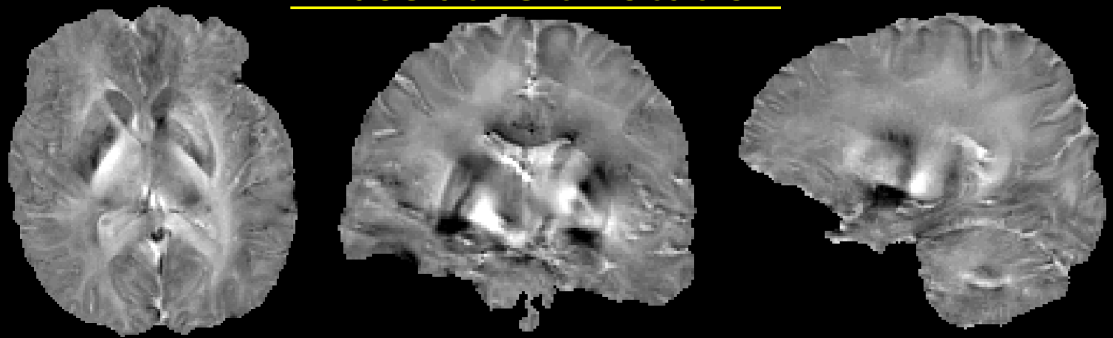




Multi-orientation QSM

- After phase processing and spatial registration:





Multi-orientation QSM

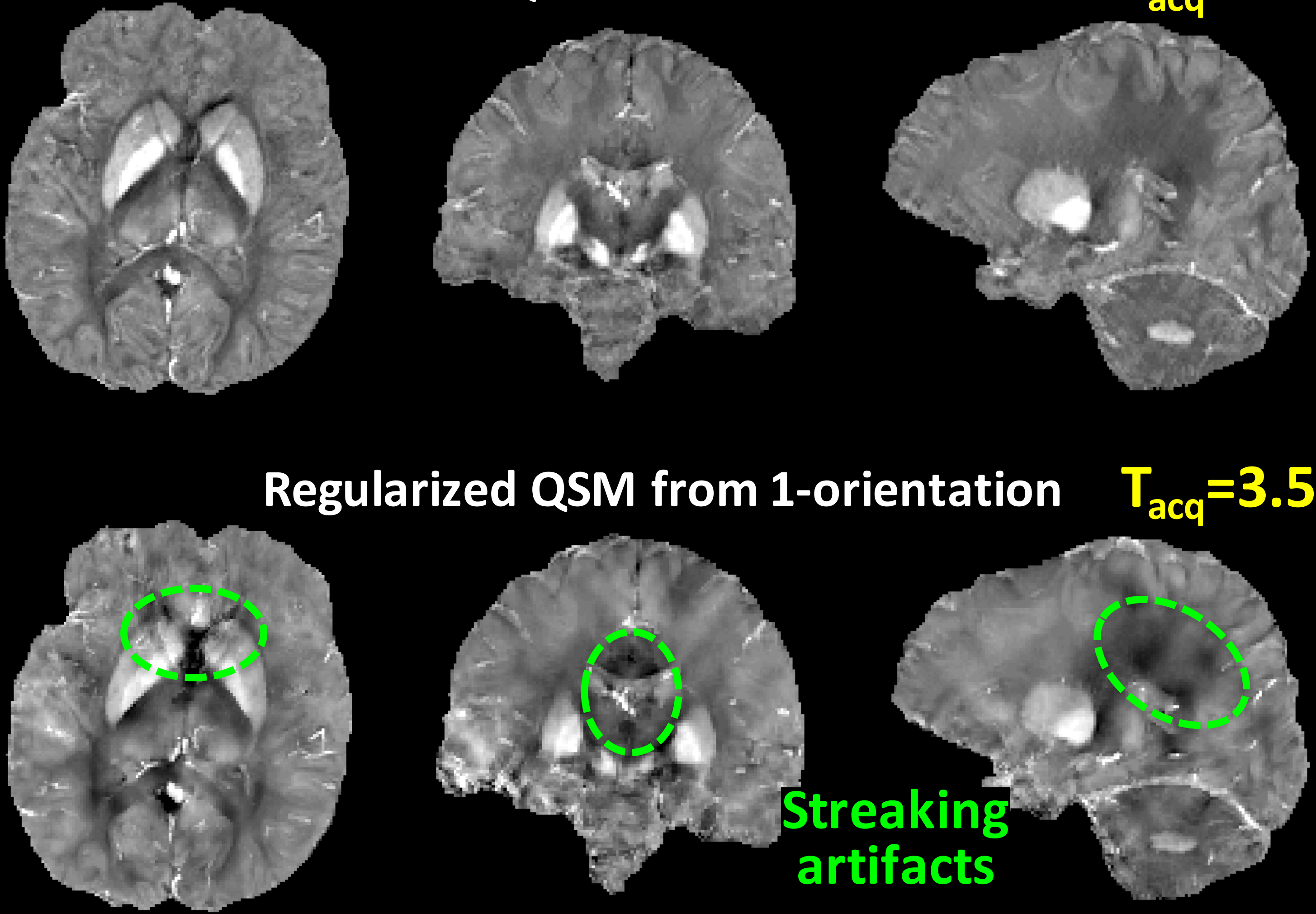
- COSMOS improves conditioning of the inverse problem at the expense of scan time:

Wave-CAIPI
R = 3×3
Large FOV:
240×240×192

T_{acq}=3.5 min per orientation

COSMOS QSM from 4 orientations **T_{acq}=14 min**

Regularized QSM from 1-orientation **T_{acq}=3.5 min**

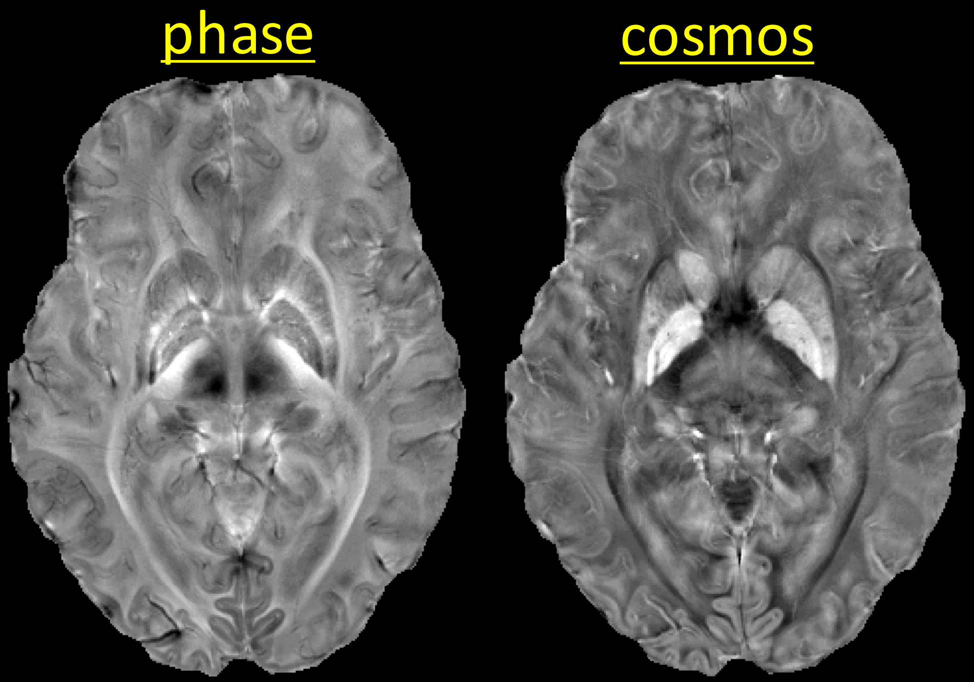


Towards in vivo Histology with QSM

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

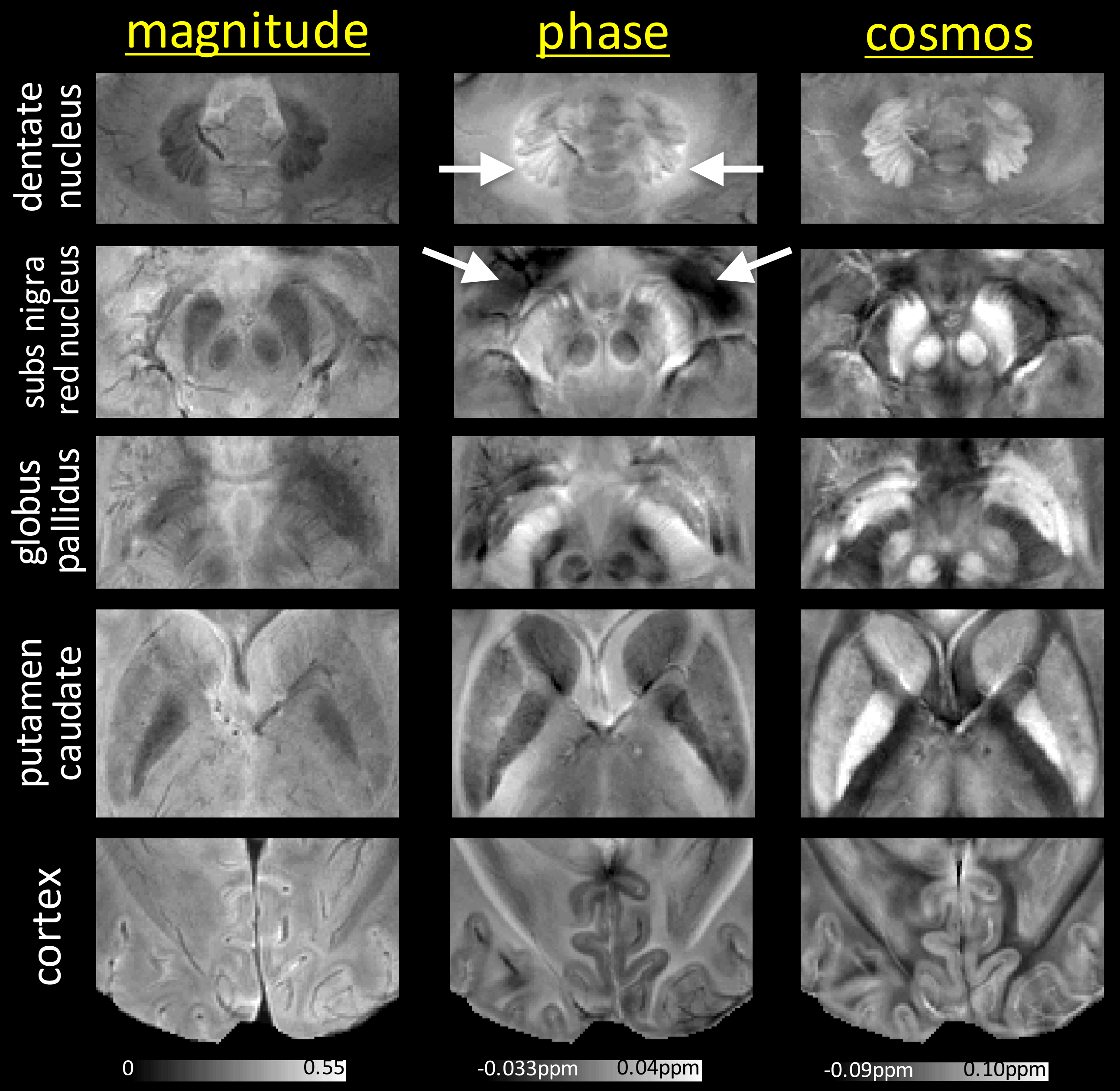
- High-resolution COSMOS requires > 1 hour of scanning [1-3]

- Whole-brain, high resolution COSMOS @ 7T
  - Wave-CAIPI with R=5×3 fold acceleration [4]
  - 5:35 min / rotation @ 0.5 mm iso
  - **20 min total protocol for 3-orientations**



[1] A Deistung et al, NeuroImage 2012
[2] D Khabipova et al, NeuroImage 2015
[3] A Deistung et al, Frontiers 2013
[4] B Bilgic et al, NeuroImage 2016

Rapid whole-brain, high resolution COSMOS @ 7T



Susceptibility Tensor Imaging (STI)

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

- STI is more sensitive to myelin than Diffusion Anisotropy [2]

- Entails estimation of 6 unknowns in 3×3 tensor per voxel:

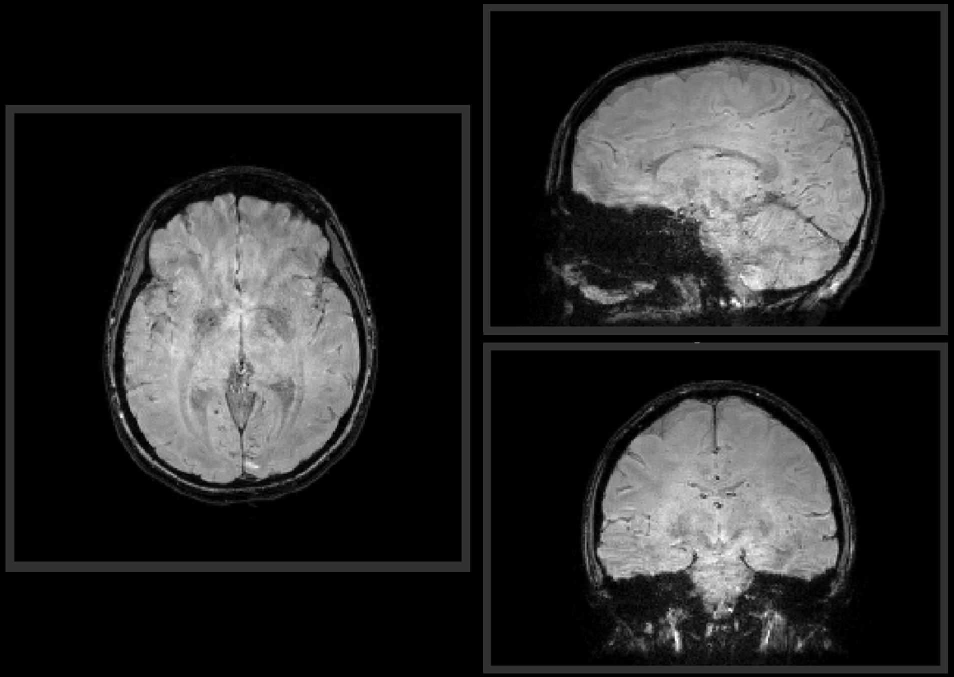
  Requires data acquired at 6+ head orientations

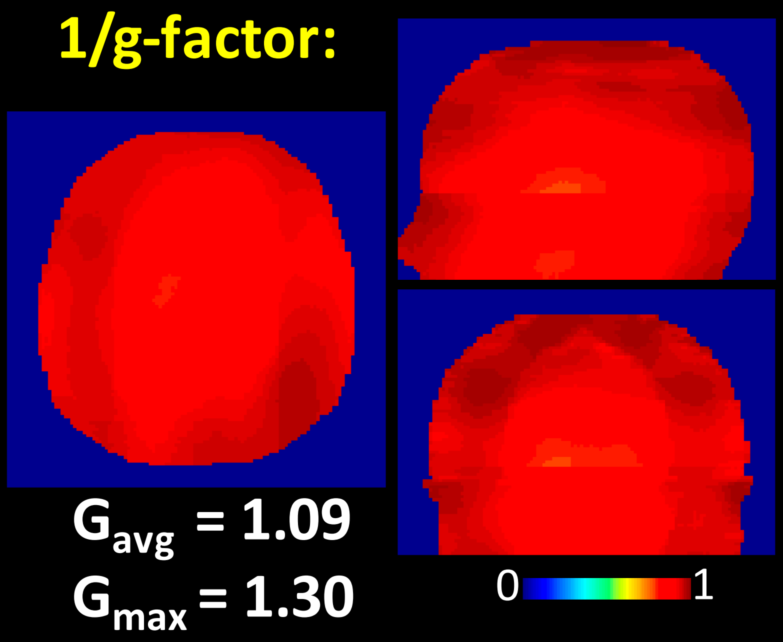
- In vivo human studies necessitate very long scans at limited resolution [3,4]

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

[1] C Liu, MRM 2010
[2] C Liu et al, NeuroImage 2011
[3] X Li et al, NeuroImage 2012
[4] C Wisnieff et al, NeuroImage 2013

Rapid whole-brain STI @ 3T





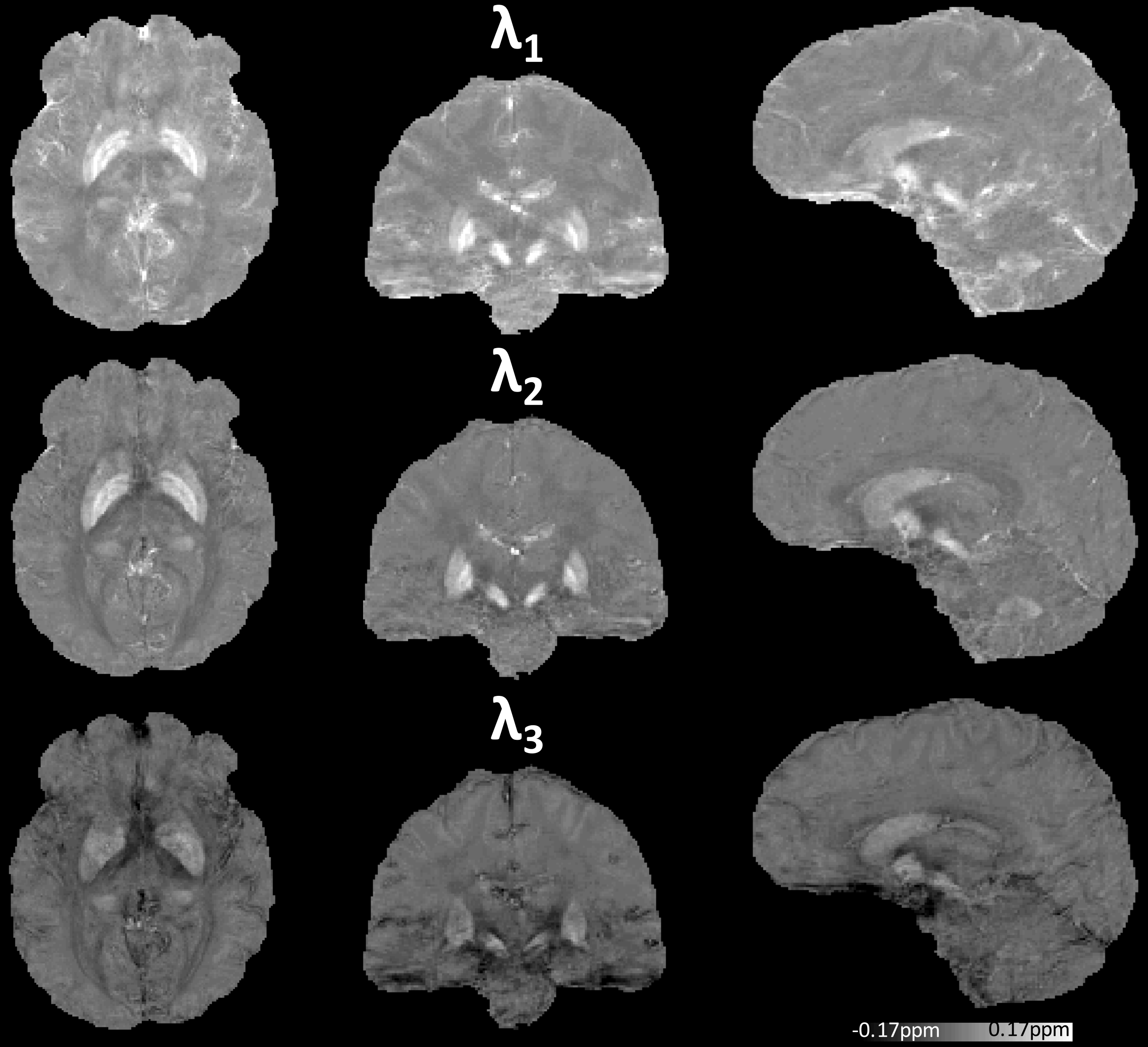
- Wave-CAIPI at R=5×3 fold acceleration [1]
- 90 sec / rotation @ 1.1 mm iso
- **30 min total protocol for 12-orientations**

(including shimming, sensitivity calibration per orientation)

[1] B Bilgic et al, NeuroImage 2016

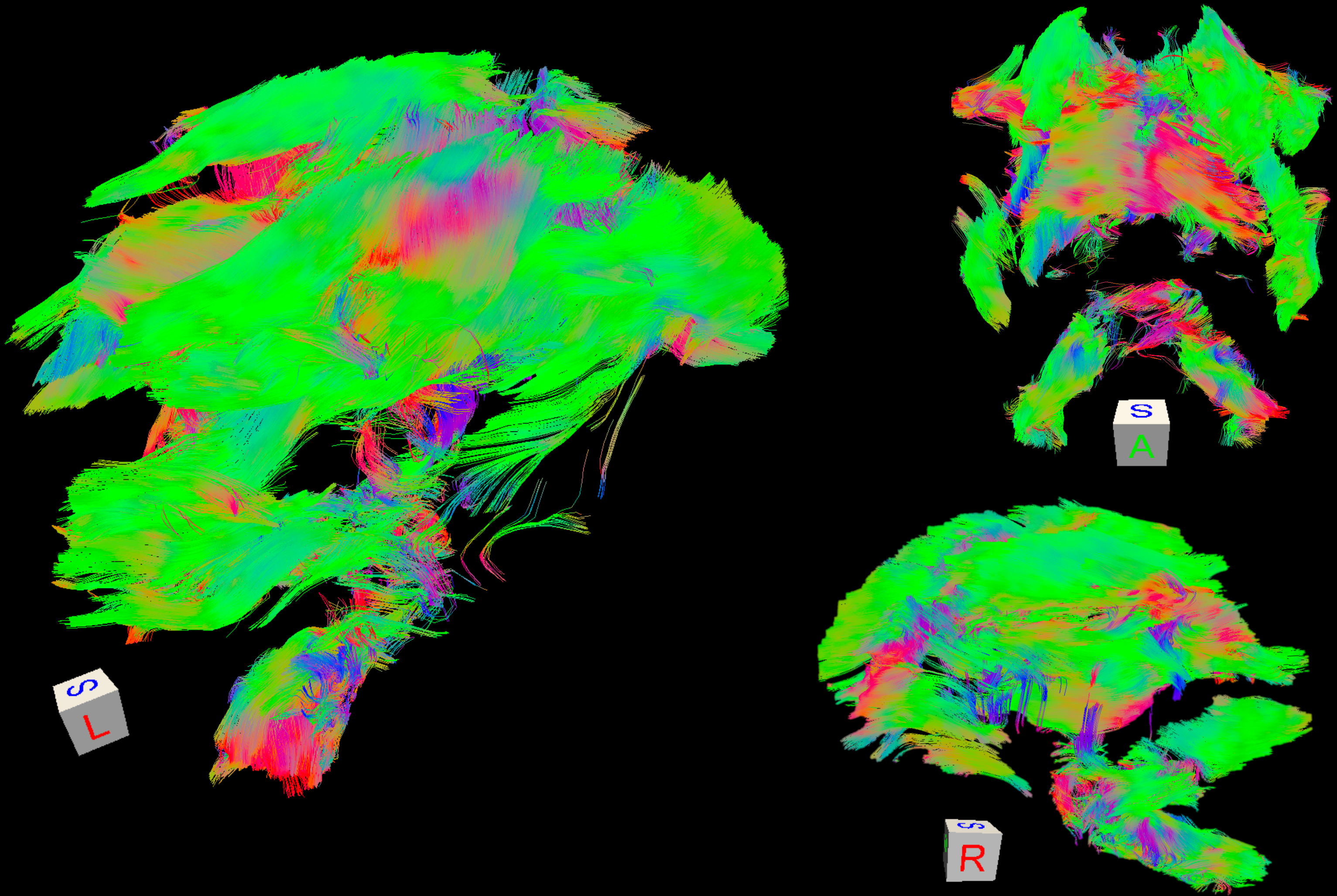
Rapid whole-brain STI @ 3T

STI Eigenvalues



Rapid whole-brain STI @ 3T

STI Tractography from 12 Orientations



Thanks!

Questions / Comments:

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