HST.583 Functional Magnetic Resonance Imaging: Data Acquisition and Analysis
Fall 2008

HST.583: Functional Magnetic Resonance Imaging: Data Acquisition and Analysis, Fall 2008
Harvard-MIT Division of Health Sciences and Technology
Course Director: Dr. Randy Gollub.

MR physics and safety for fMRI

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Fast MR Imaging Techniques

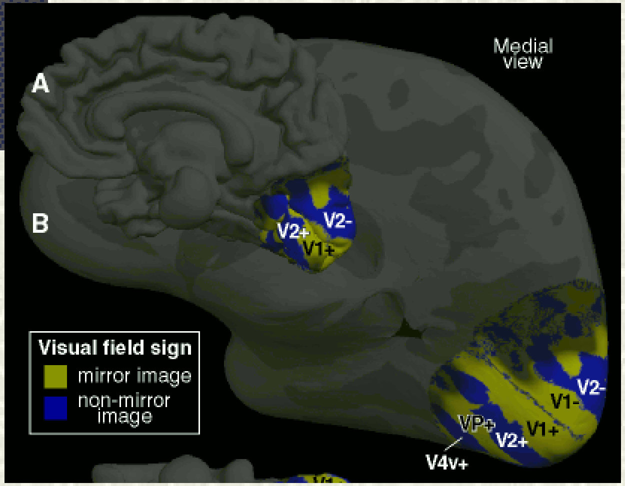
- **Why, introduction**

- **How: Review of k-space trajectories**

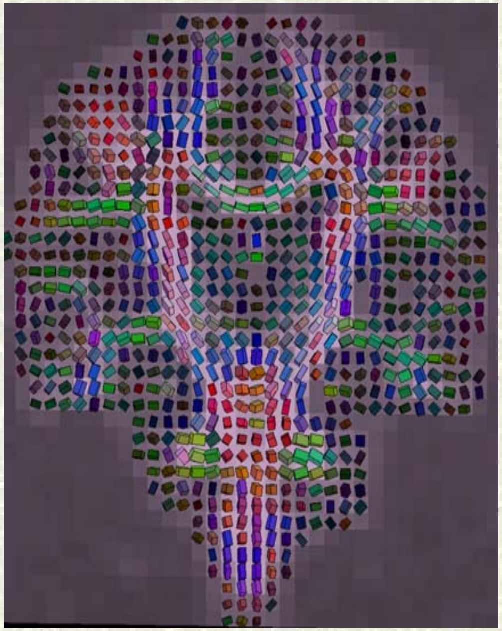
  Different techniques (EPI, Spiral)

- **Problems from B0 Susceptibility artifacts**

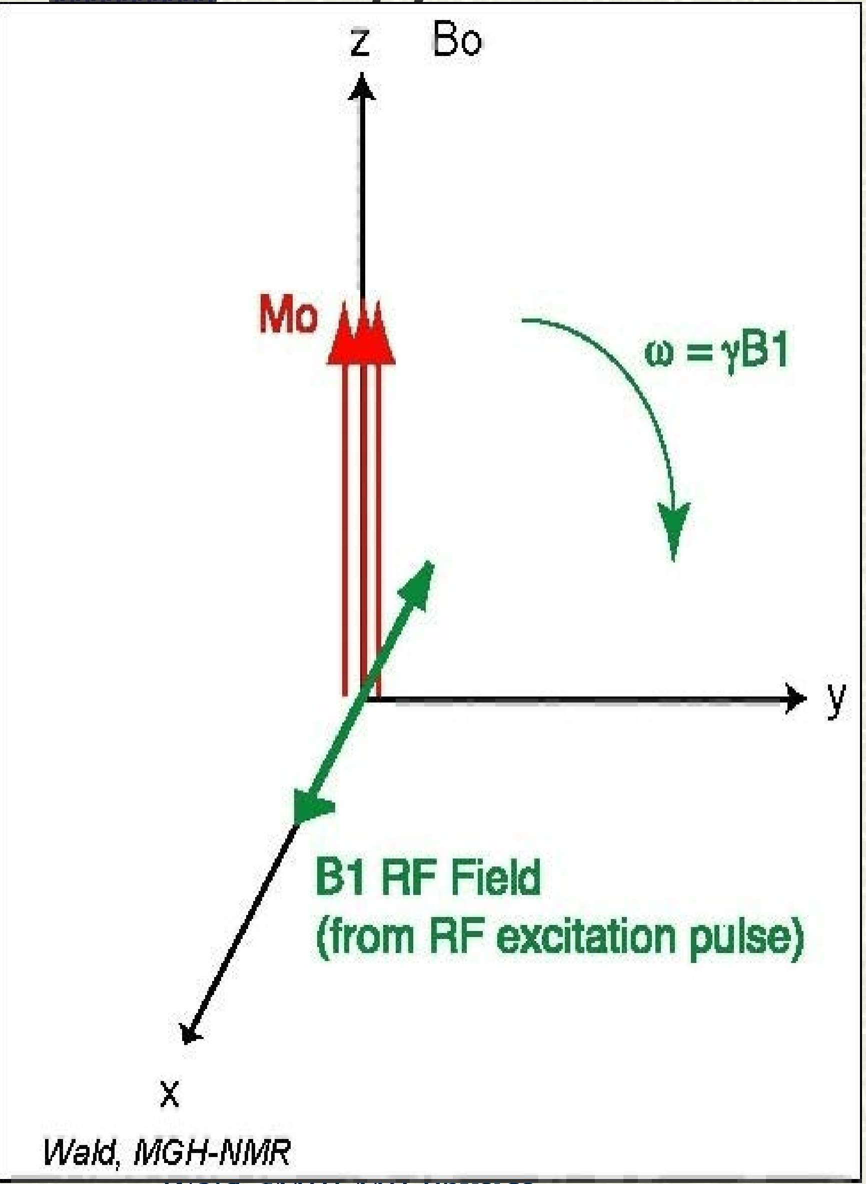
Why fast imaging

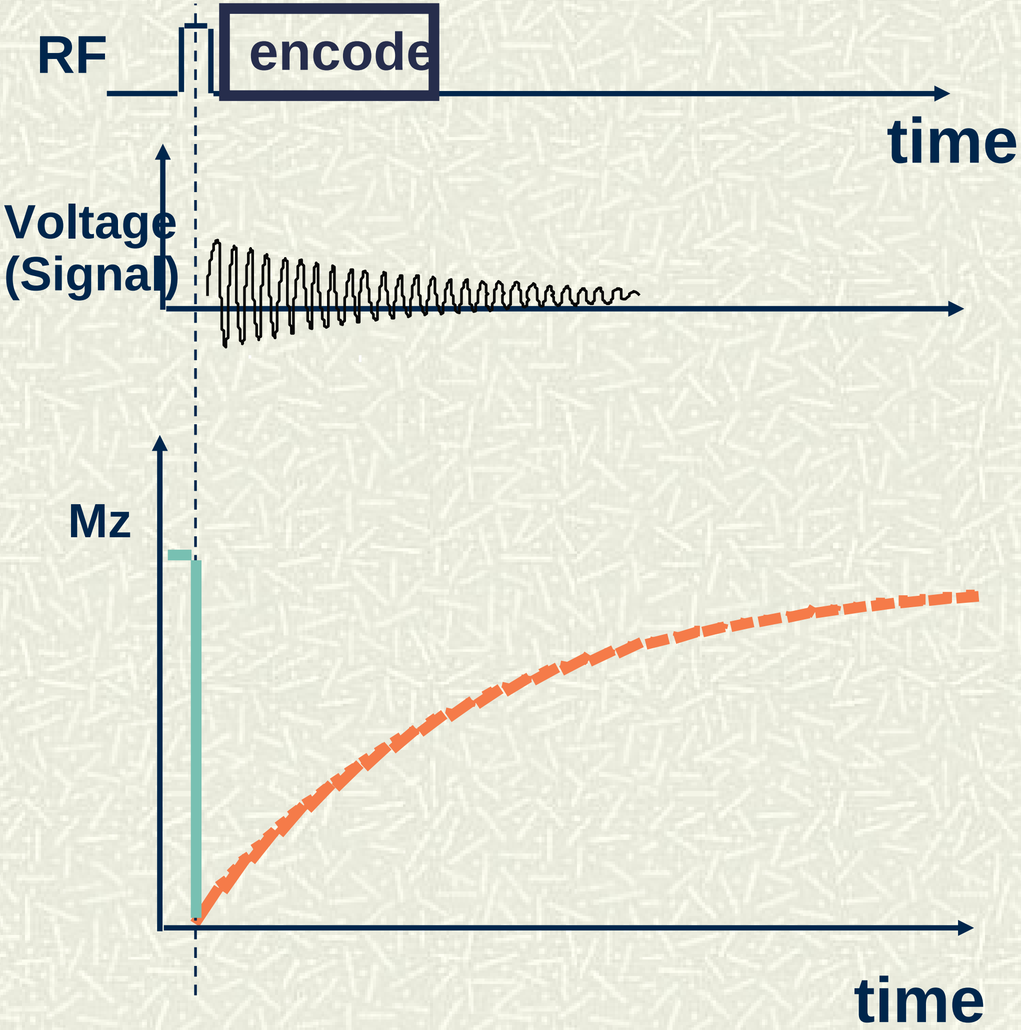


Capture time course,
(e.g. hemodynamic)
eliminate artifact from motion
(during encode.)



Magnetization vector durning MR





Review of Image encoding, journey through kspace

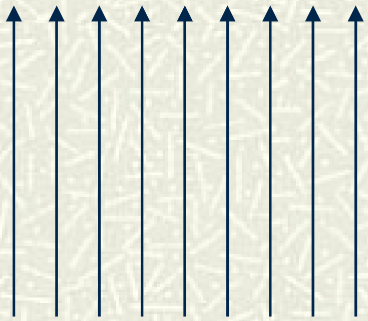
Two questions:

1) What does blipping on a gradient do to the water magnetization.

2) Why does measuring the signal amplitude after a blip tell you info about the spatial frequency composition of the image (k-space).

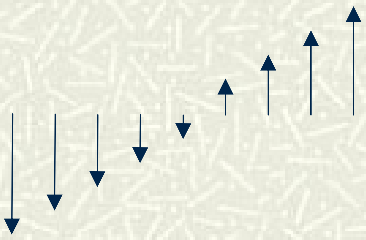
Aside: Magnetic field gradient

B_o



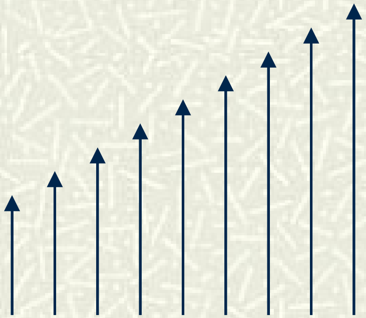
Uniform magnet

$G_x\ x$

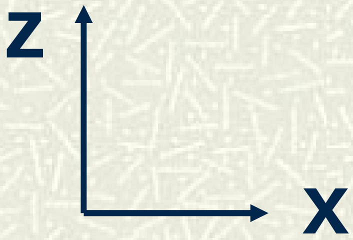


Field from gradient coils

$B_o + G_x\ x$

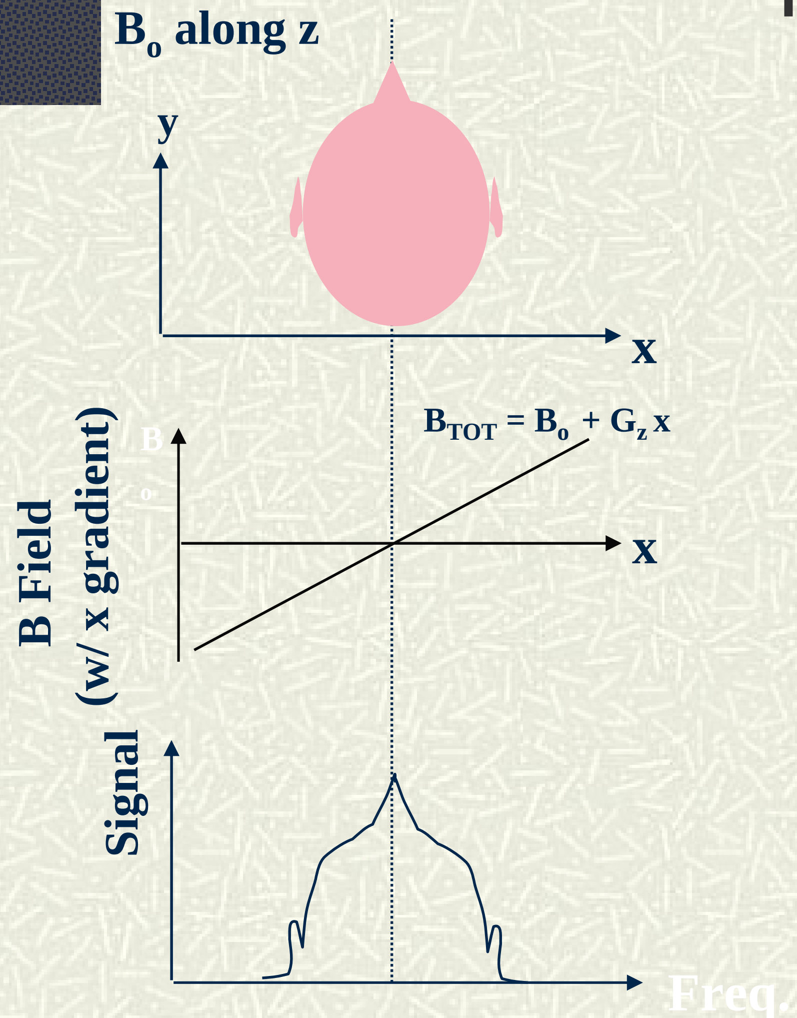


Total field



$$G_x = \partial B_z / \partial x$$

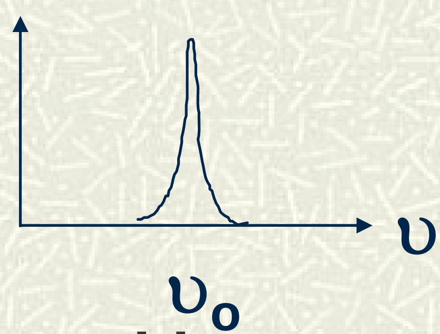
Step two: encode spatial info. in-plane



with gradient

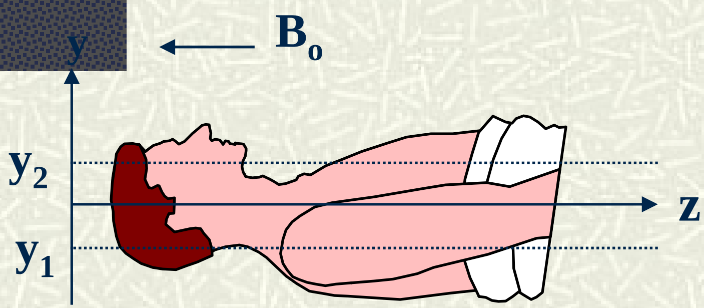
"Frequency encoding"

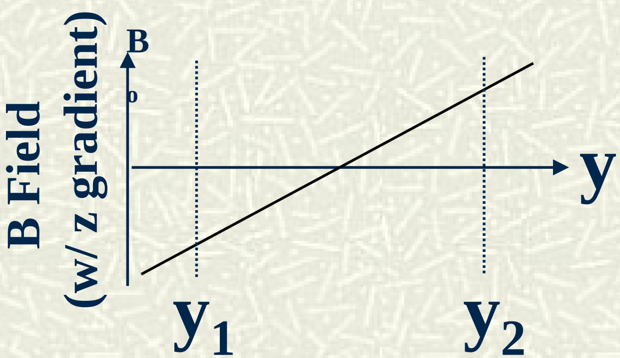
$$v = \gamma B_{TOT} = \gamma(B_o + G_x x)$$

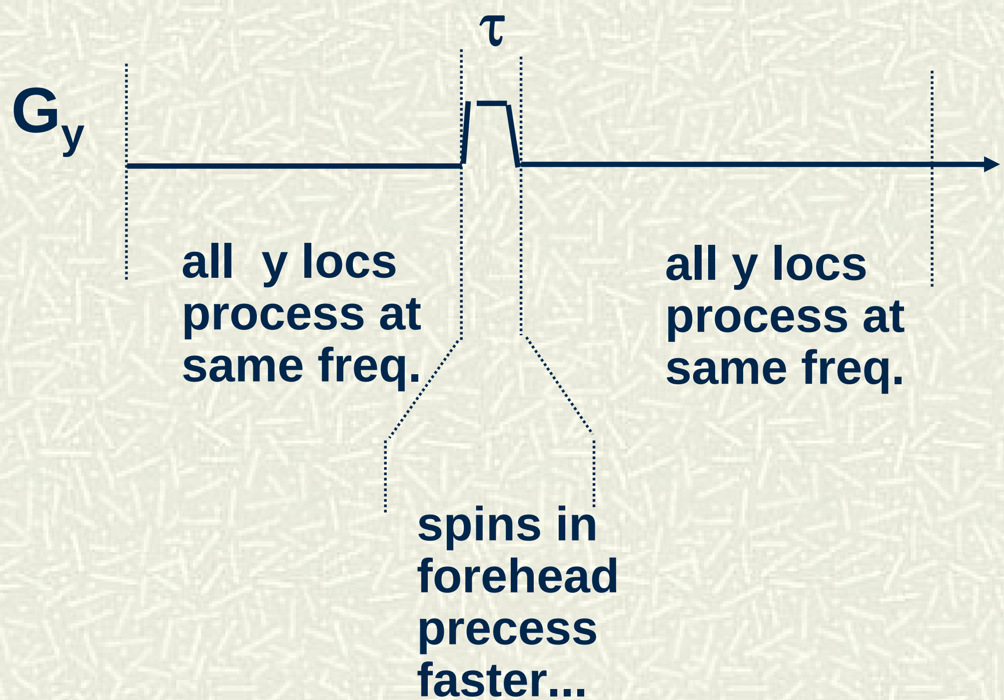


without gradient

How does blipping on a grad. encode spatial info?



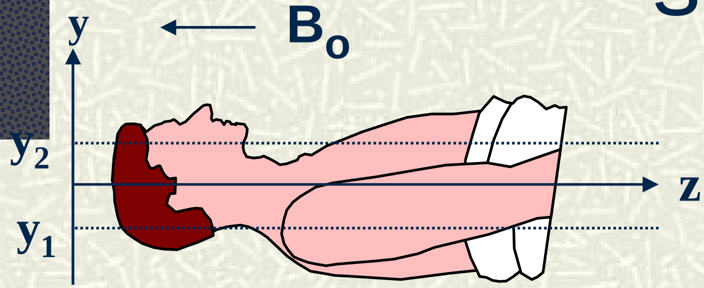




$$\upsilon(\mathbf{y}) = \gamma \mathbf{B}_{TOT} = \gamma\, \mathbf{B}_o\, \Delta\mathbf{y}\, \mathbf{G}_y$$

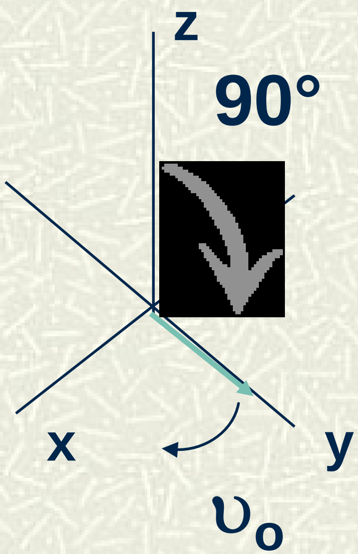
$$\theta\,(\mathbf{y}) = \upsilon(\mathbf{y})\,\tau = \gamma\, \mathbf{B}_o\, \Delta\mathbf{y}\, (\mathbf{G}_y\, \tau)$$

How does blipping on a grad. encode spatial info?

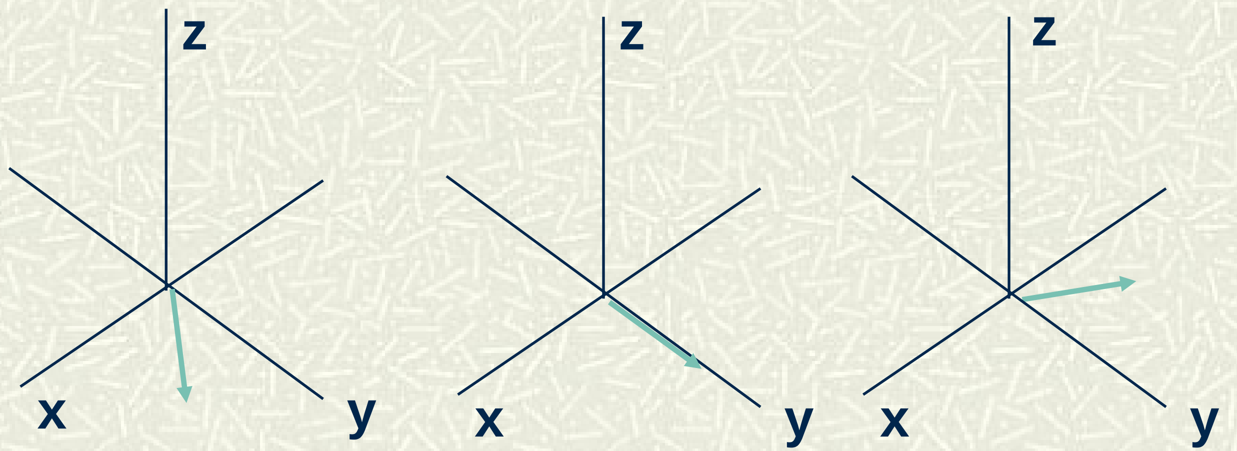


$$\theta\,(y) = \upsilon(y)\,\tau \;= \gamma\, B_o\, \Delta y\, (G_y\, \tau)$$

after RF



After the blipped y gradient...

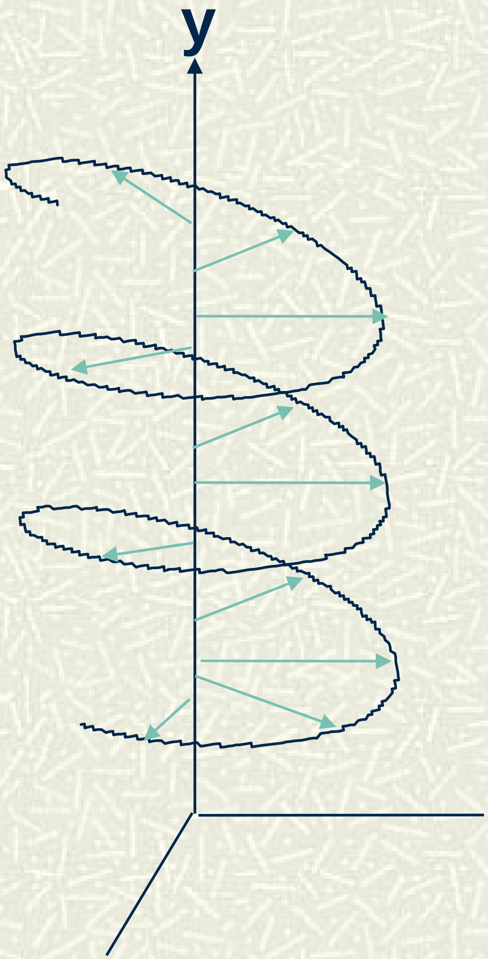


position y_1 **position 0** **position y_2**

How does blipping on a grad. encode spatial info?

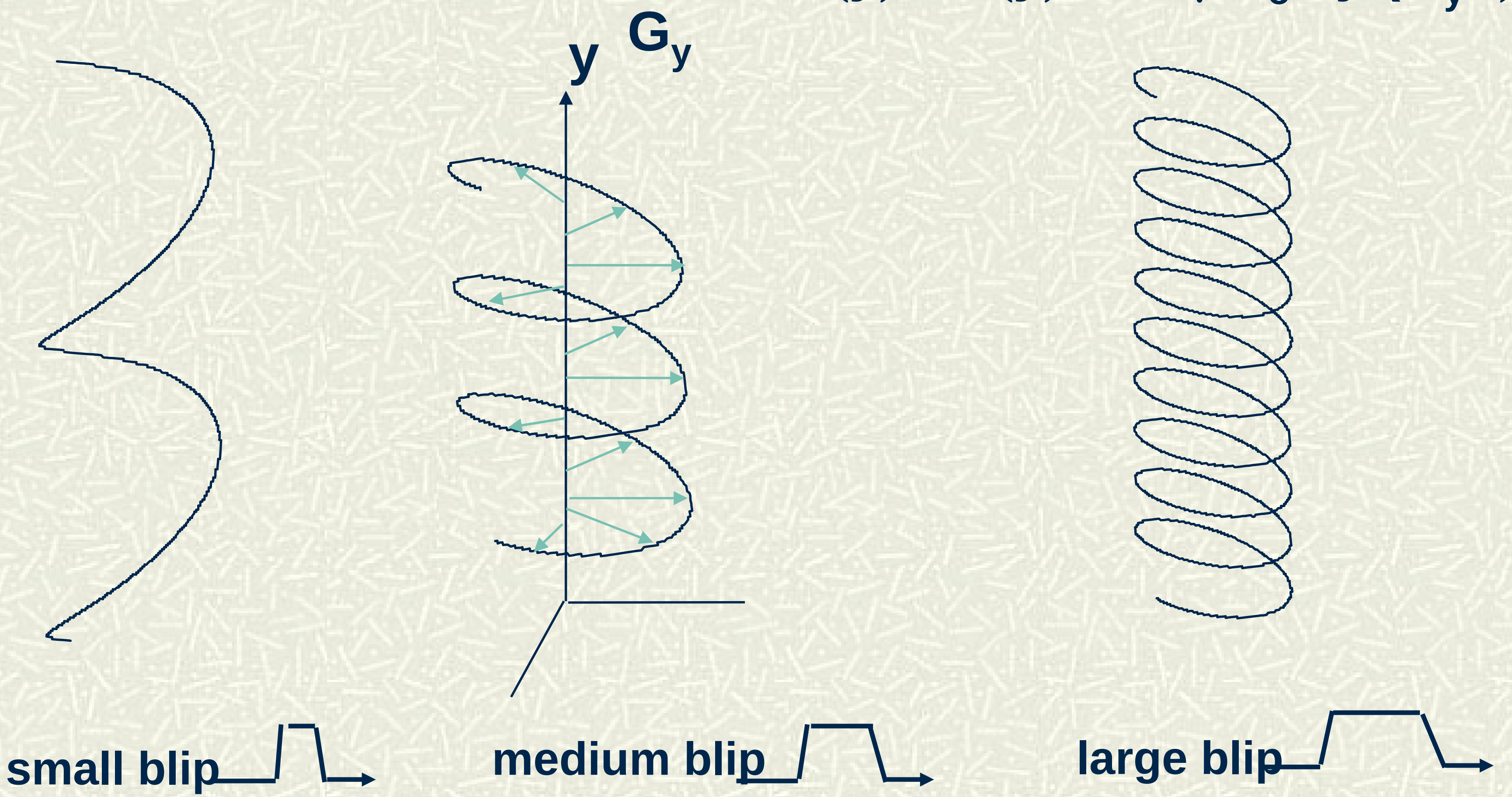
The magnetization vector in the xy plane is wound into a helix directed along y axis.

Phases are 'locked in' once the blip is over.



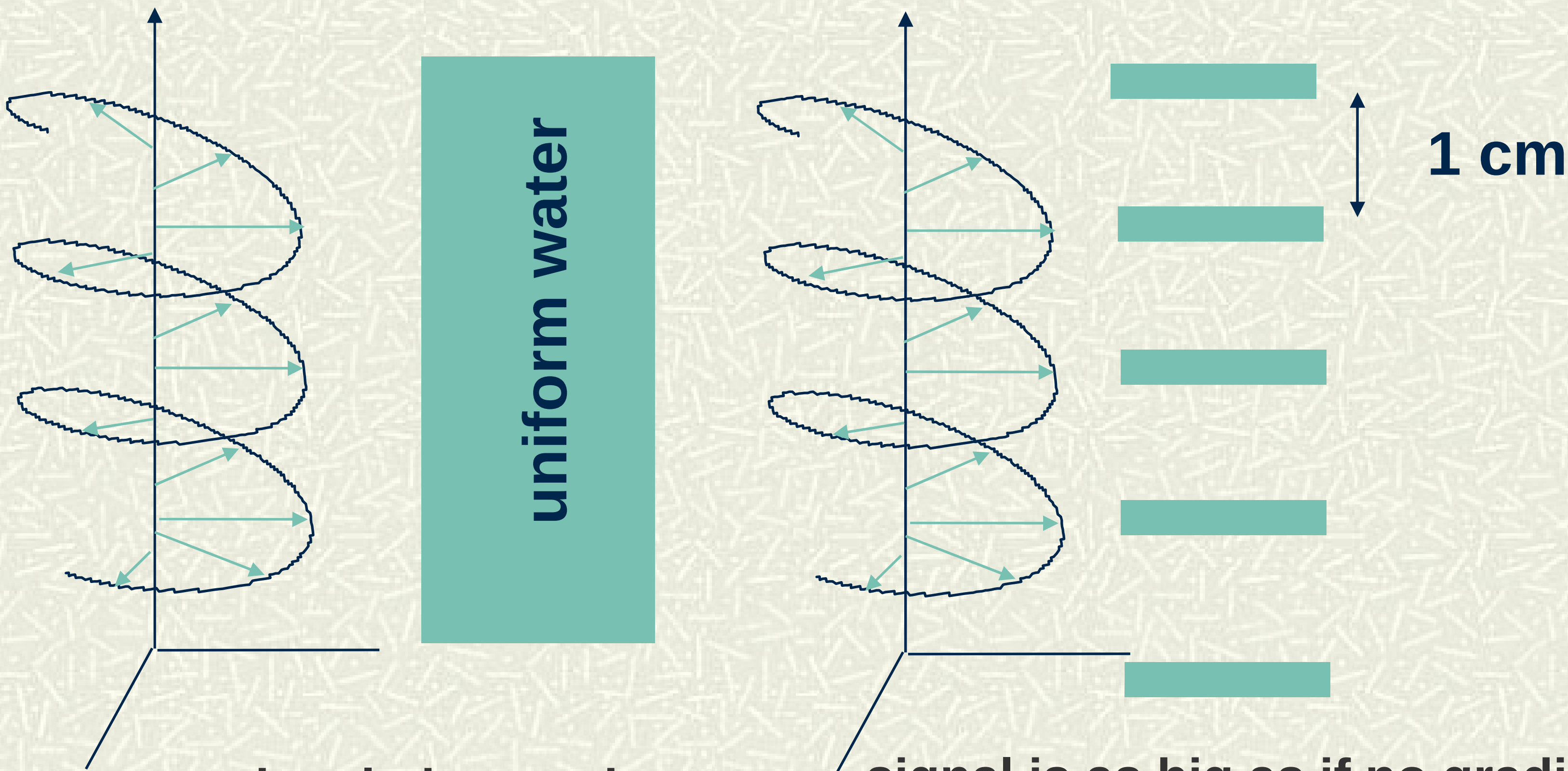
The bigger the gradient blip area, the tighter the helix

$$\theta(y) = \upsilon(y)\,\tau = \gamma B_o \Delta y\,(G_y \tau)$$



What have you measured?

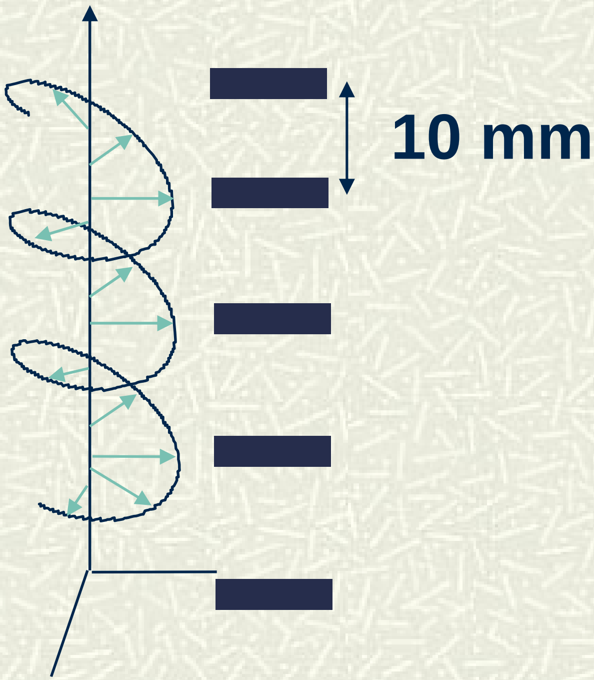
Consider 2 samples:

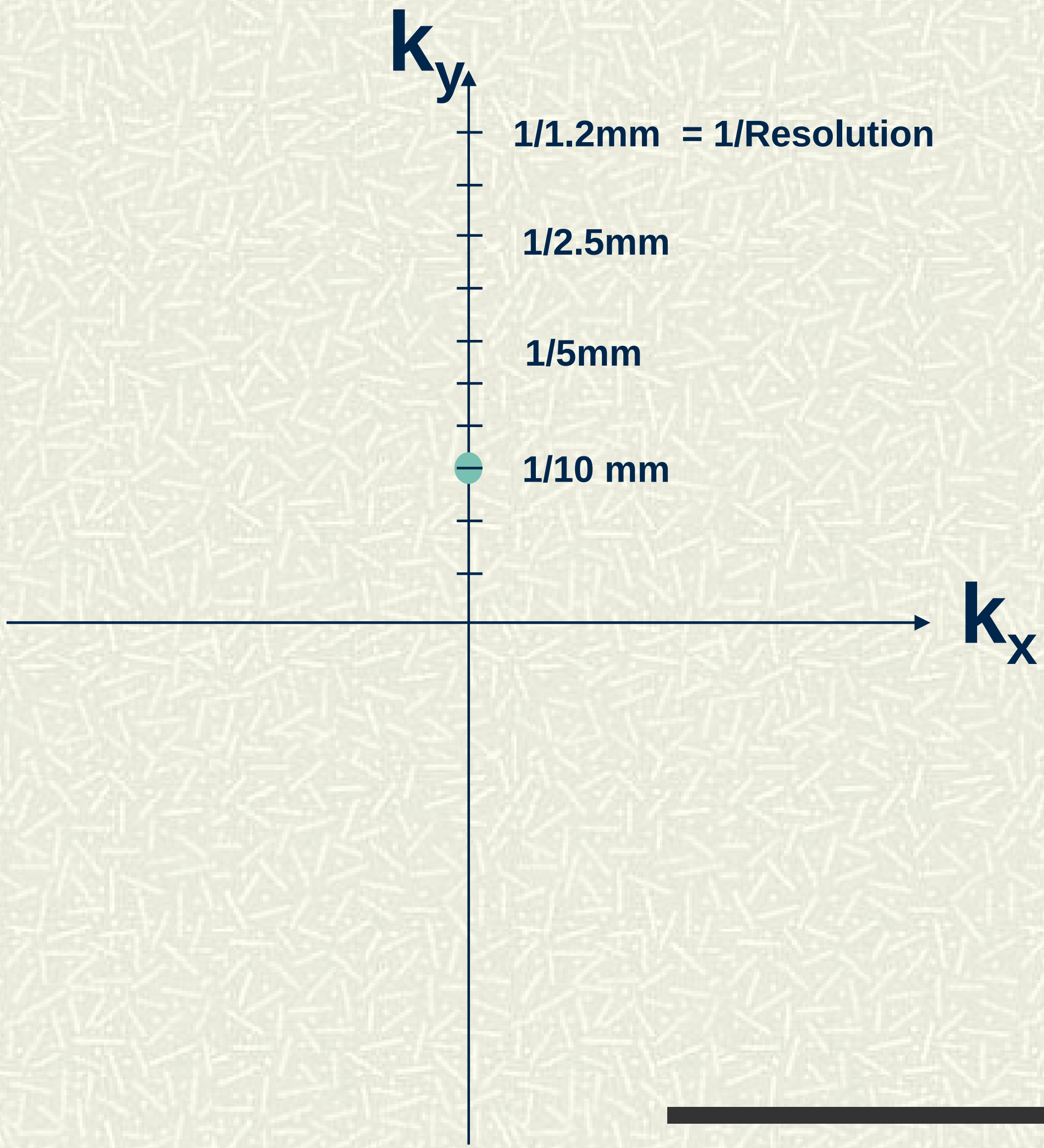


no signal observed

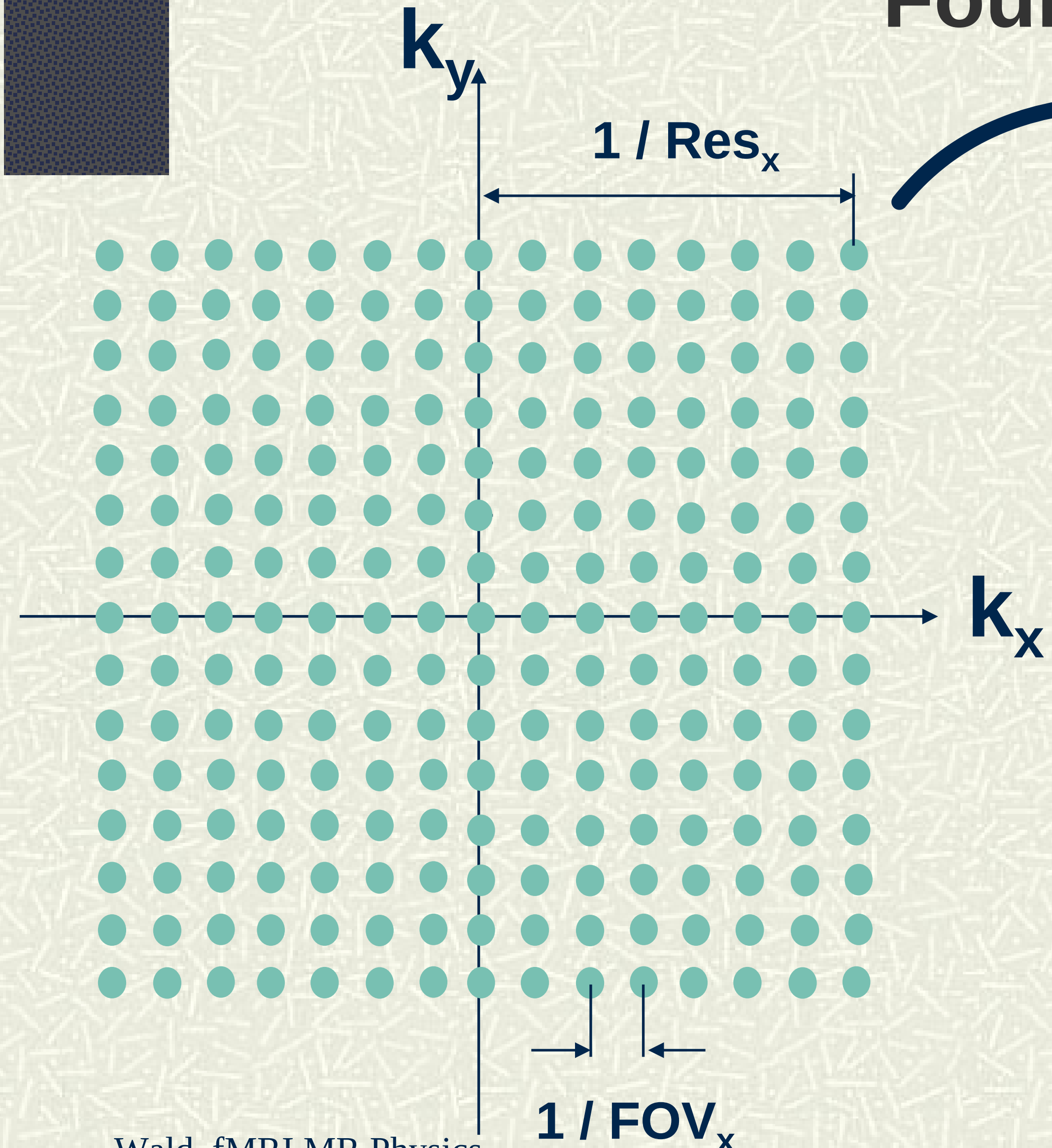
signal is as big as if no gradient

Measurement intensity at a spatial frequency...



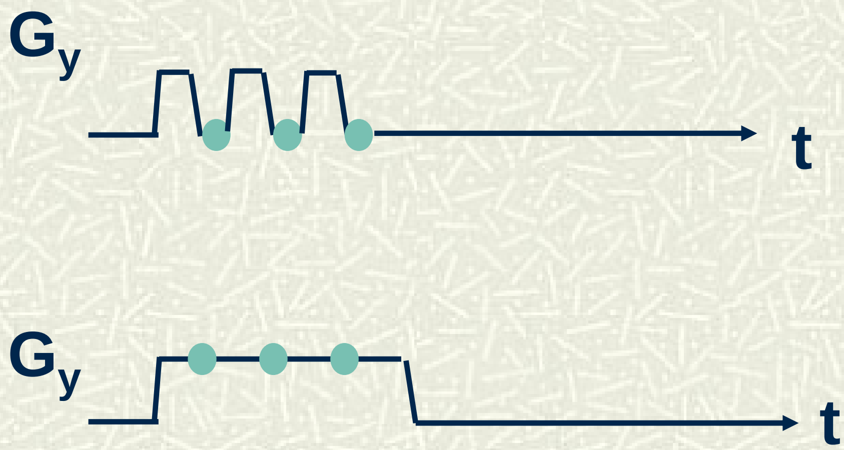


Fourier transform



FOV_x = matrix * Res_x

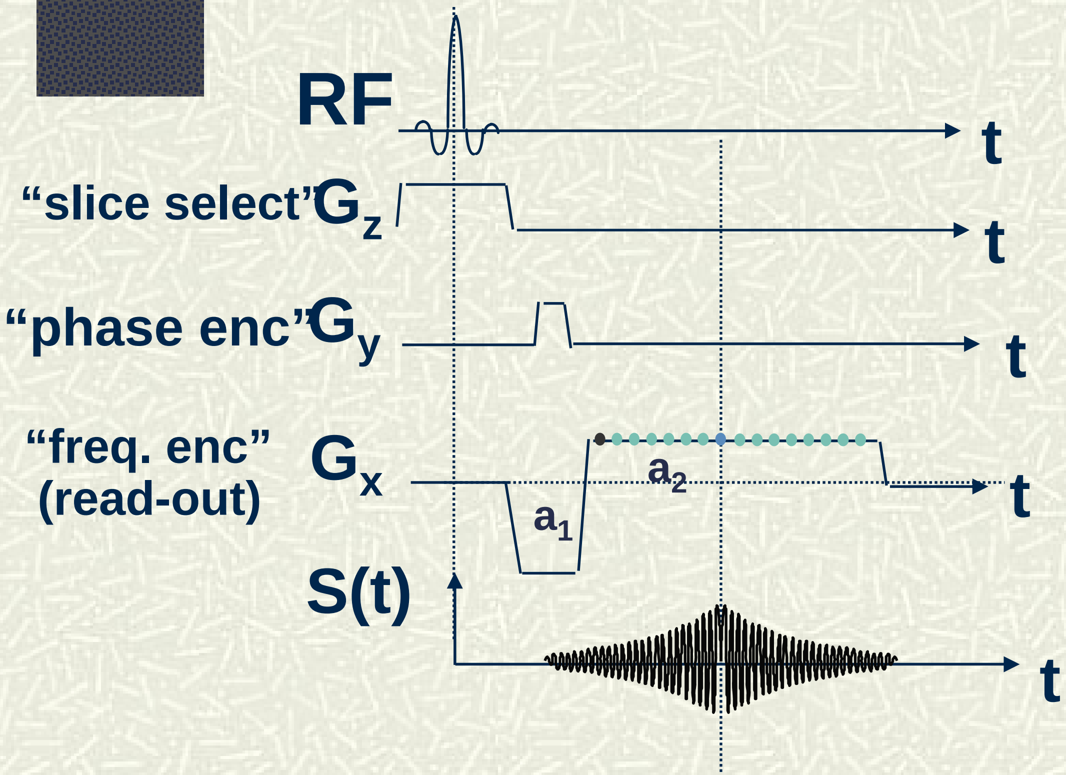
Sample 3 points in kspace

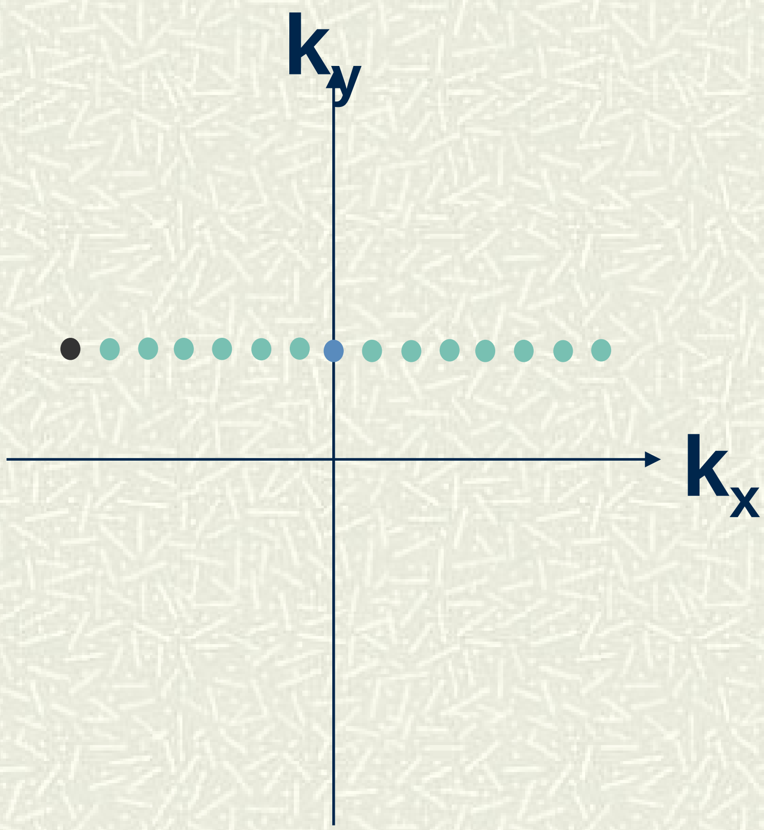


More efficient!

Frequency and phase encoding are the same principle!

Conventional "Spin-warp" encoding



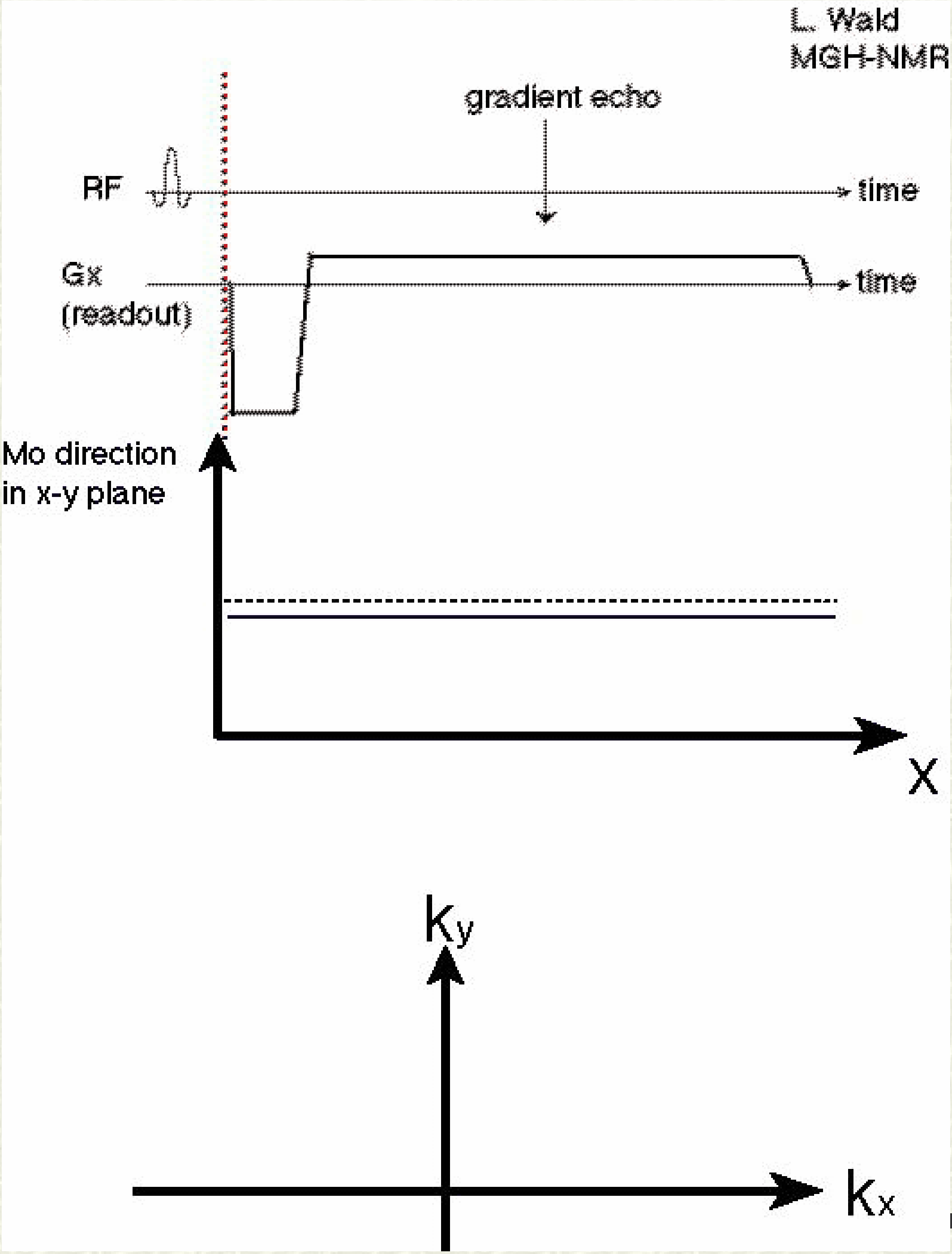


one excitation, one line of kspace...

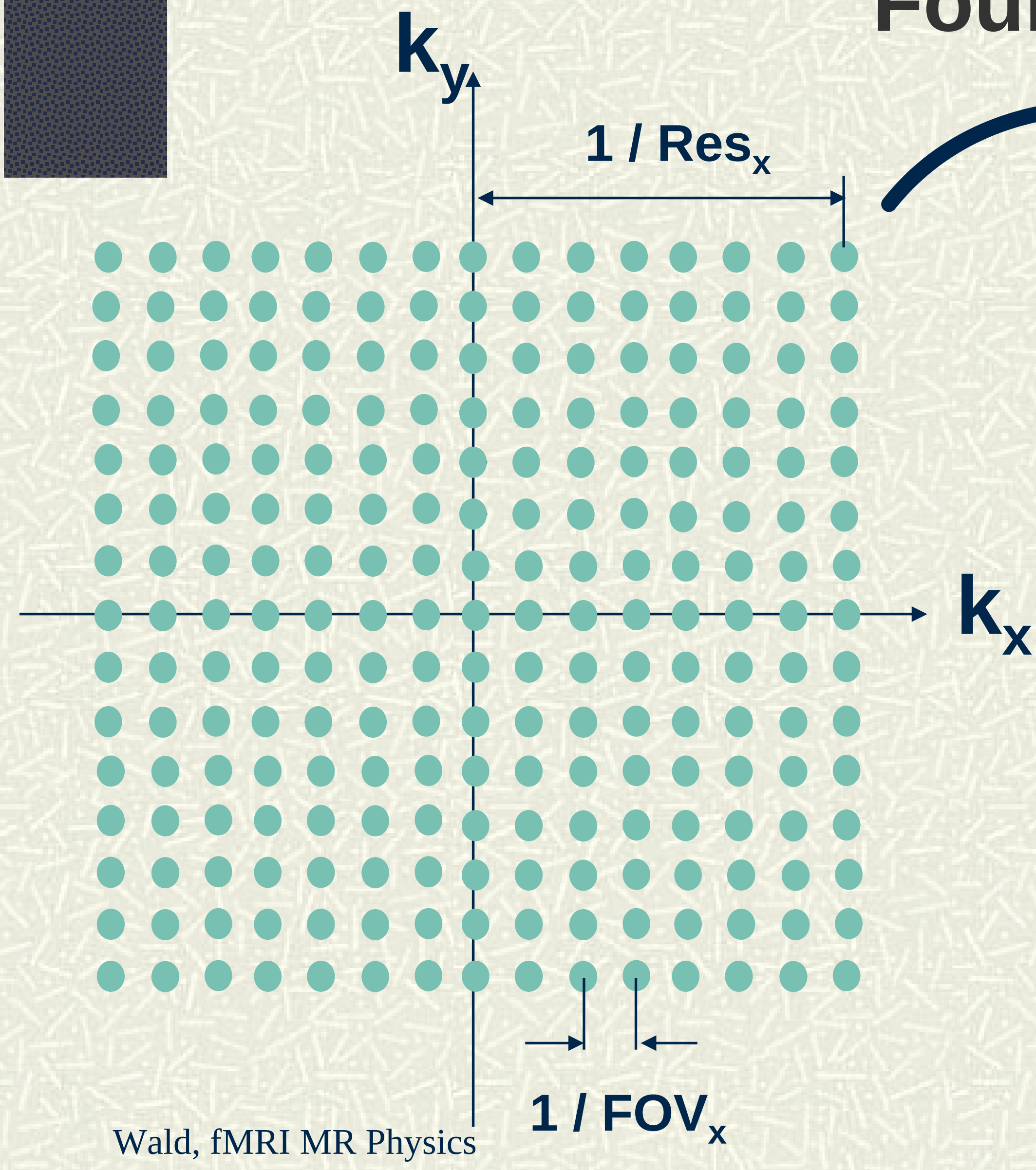
Image encoding,

"Journey through kspace"

The Movie…

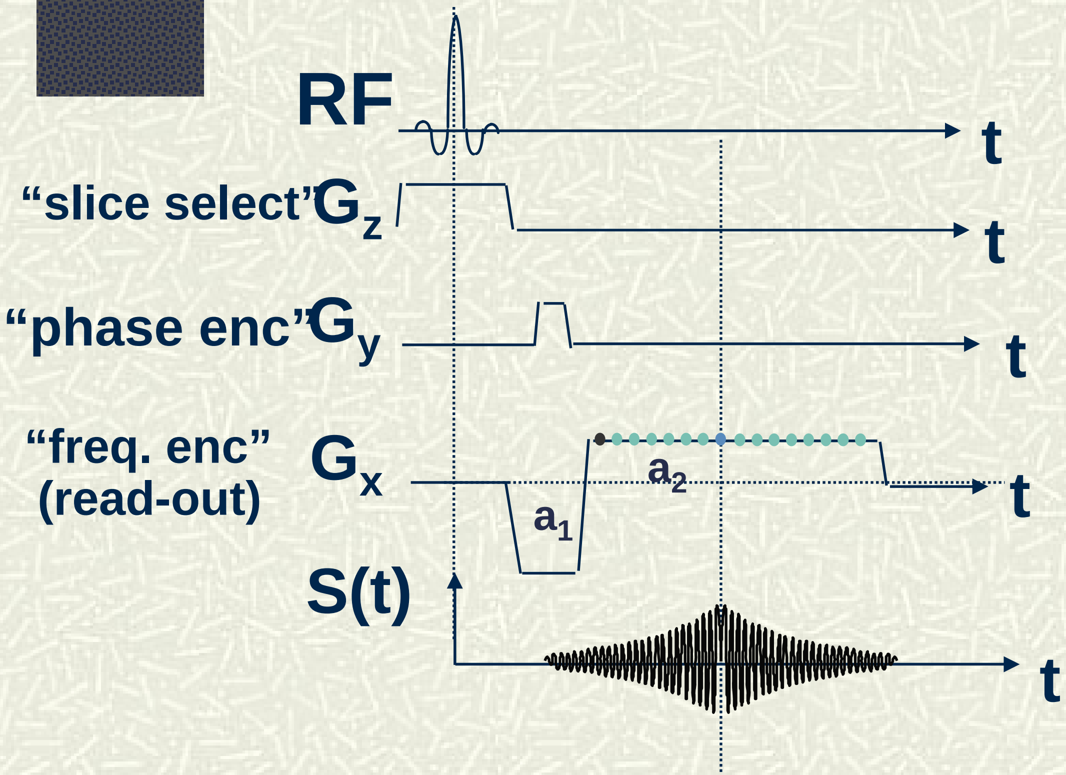


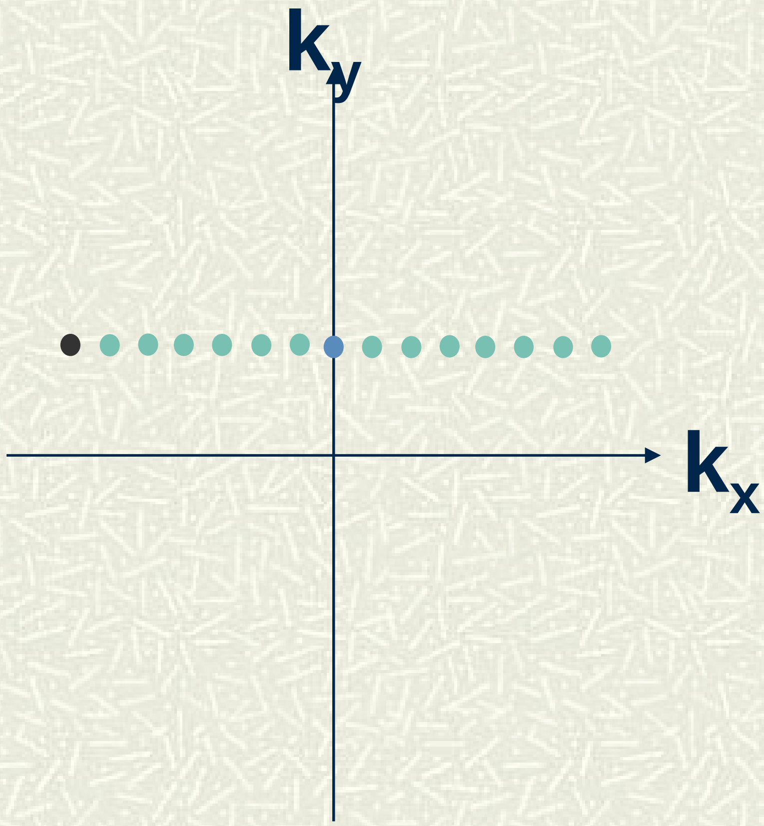
Fourier transform



FOV_x = matrix * Res_x

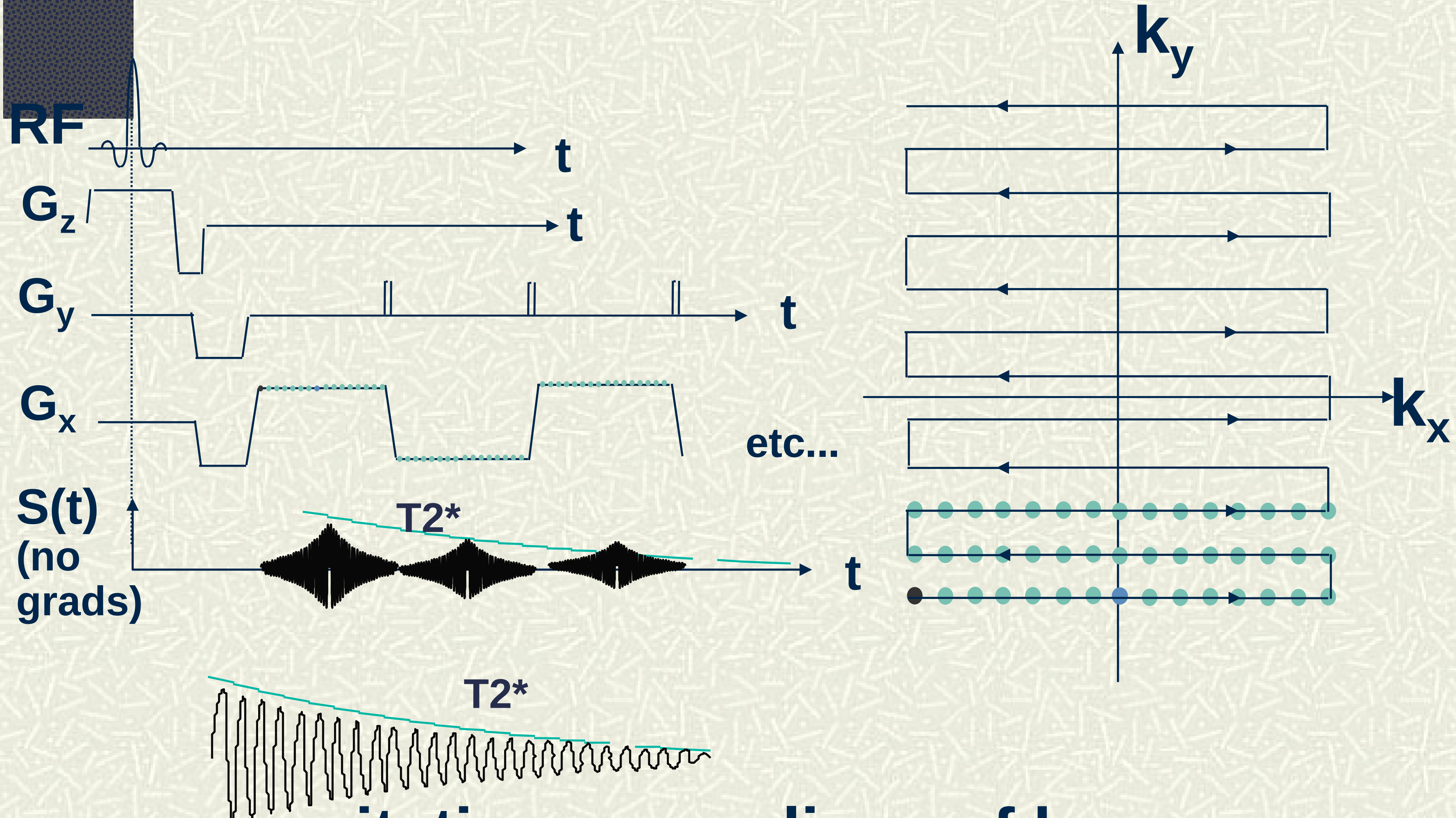
Conventional “Spin-warp” encoding





one excitation, one line of kspace...

“Echo-planar” encoding



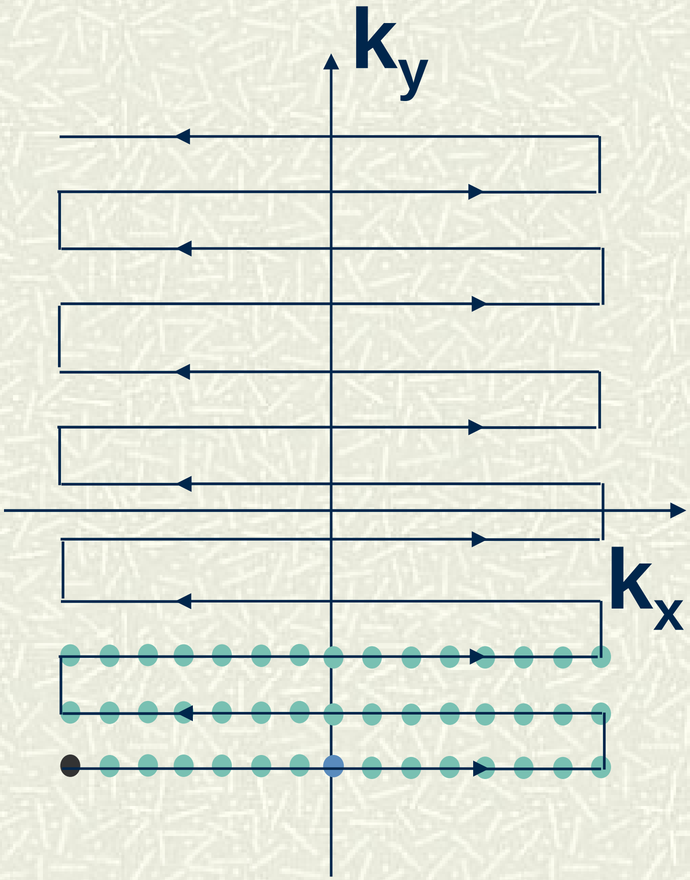
one excitation, many lines of kspace...

Bandwidth is asymmetric in EPI

- Adjacent points in k_x have short
  Δt = 5 us (high bandwidth)

- Adjacent points along ky are taken with long Δt (= 500us). (low bandwidth)

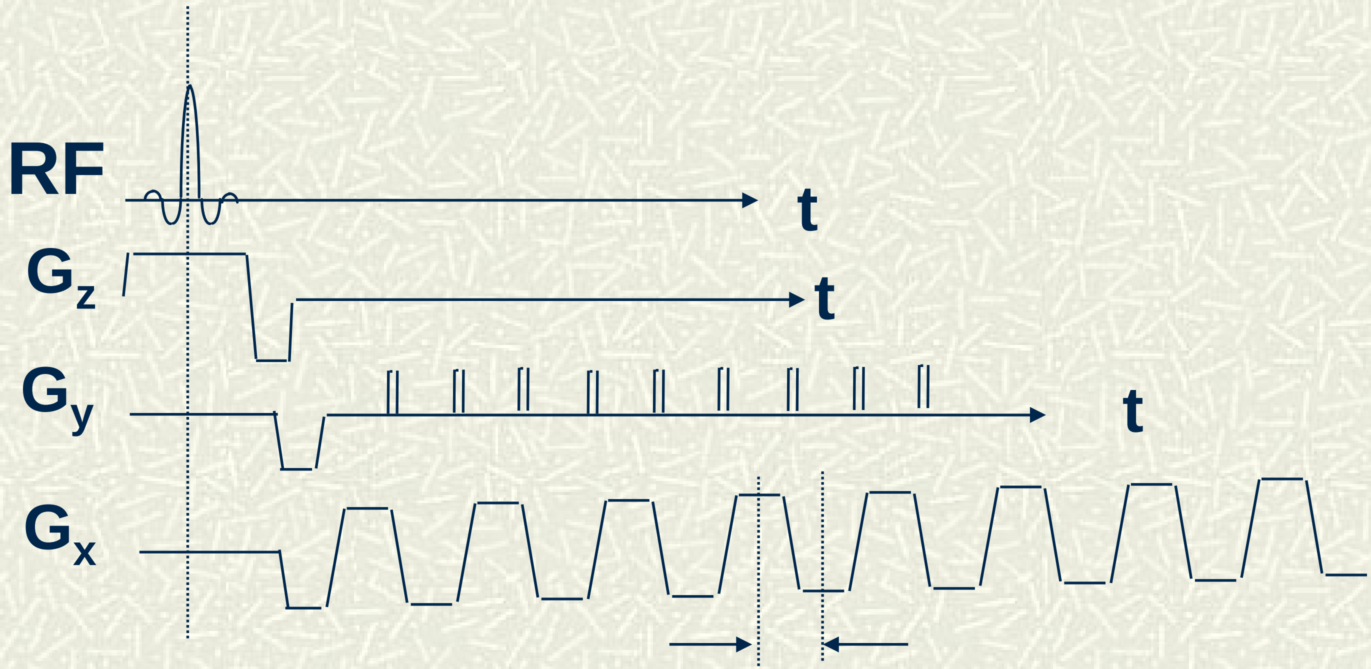
The phase error (and thus distortions) are in the phase encode direction.



Characterization of EPI performance

length of readout train for given resolution

or echo spacing (esp) or freq of readout…



esp = 500 us for whole body grads, readout length = 32 ms
esp = 270us for head gradients, readout length = 17 ms

What is important in EPI performance?

<u>Short image encoding time.</u>

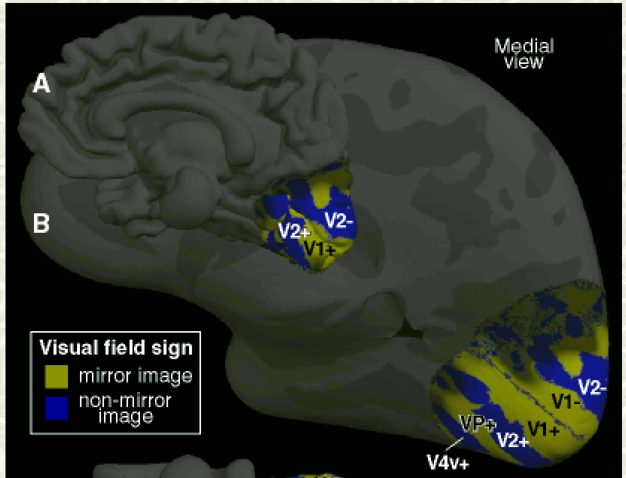
Parameters related to total encoding time:
1) echo spacing.
2) frequency of readout waveform.

Key specs for achieving short encode times:
1) gradient slew rate.
2) gradient strength.
3) ability to ramp sample.

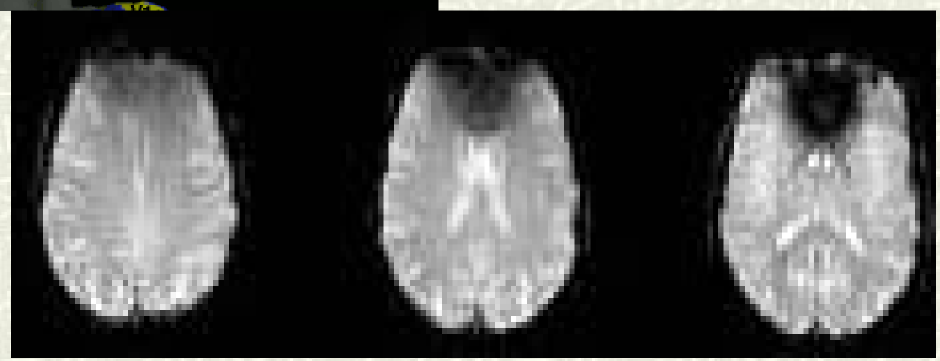
Good shimming (second order shims)

Susceptibility in MR

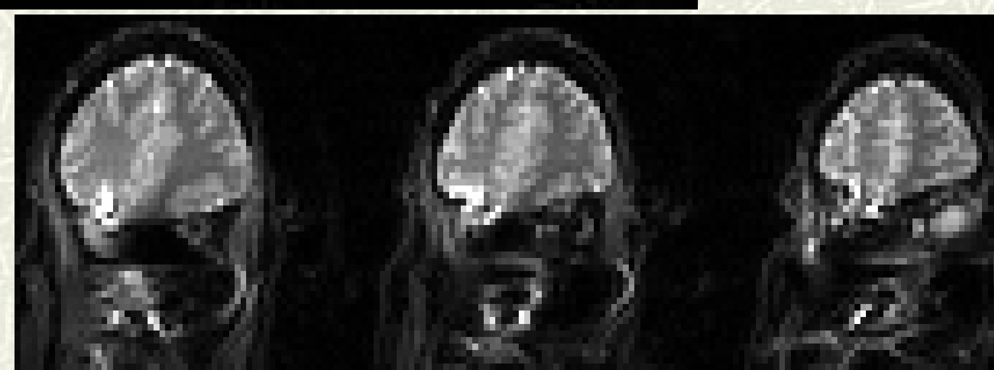
The good.



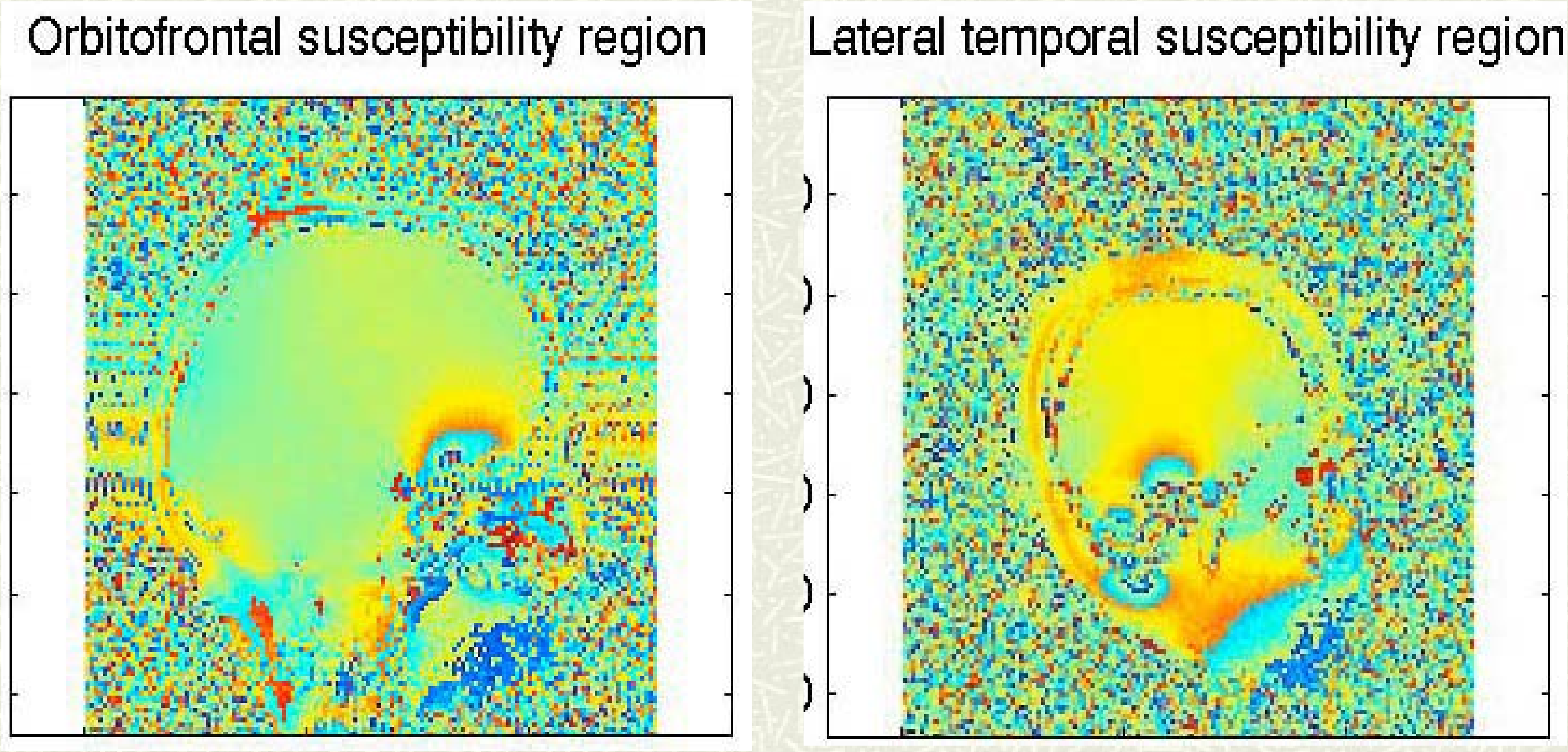
The bad.



The ugly.

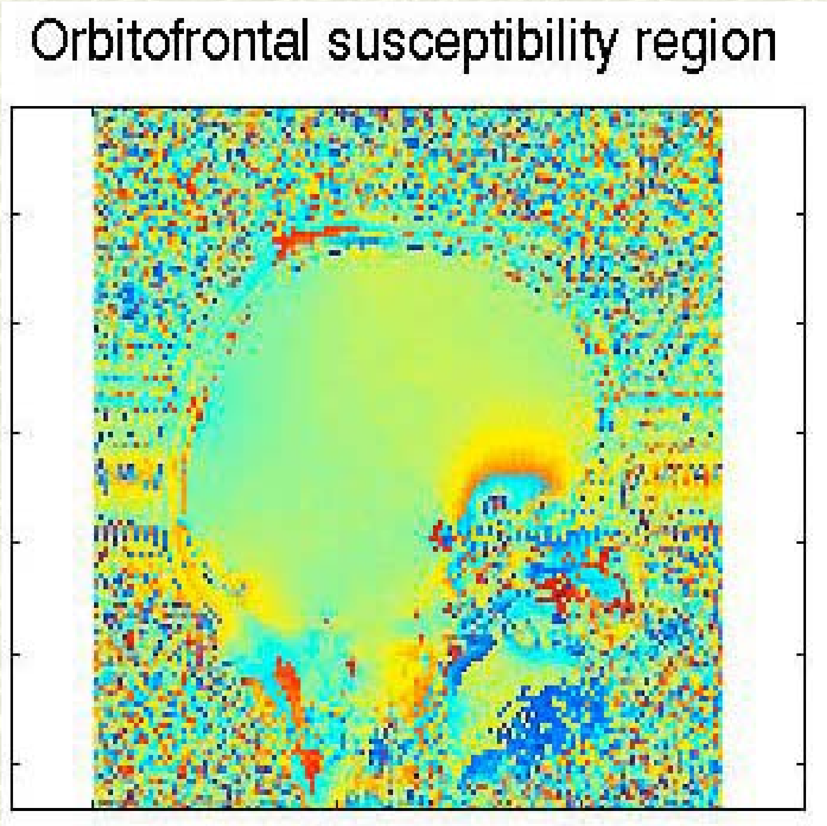


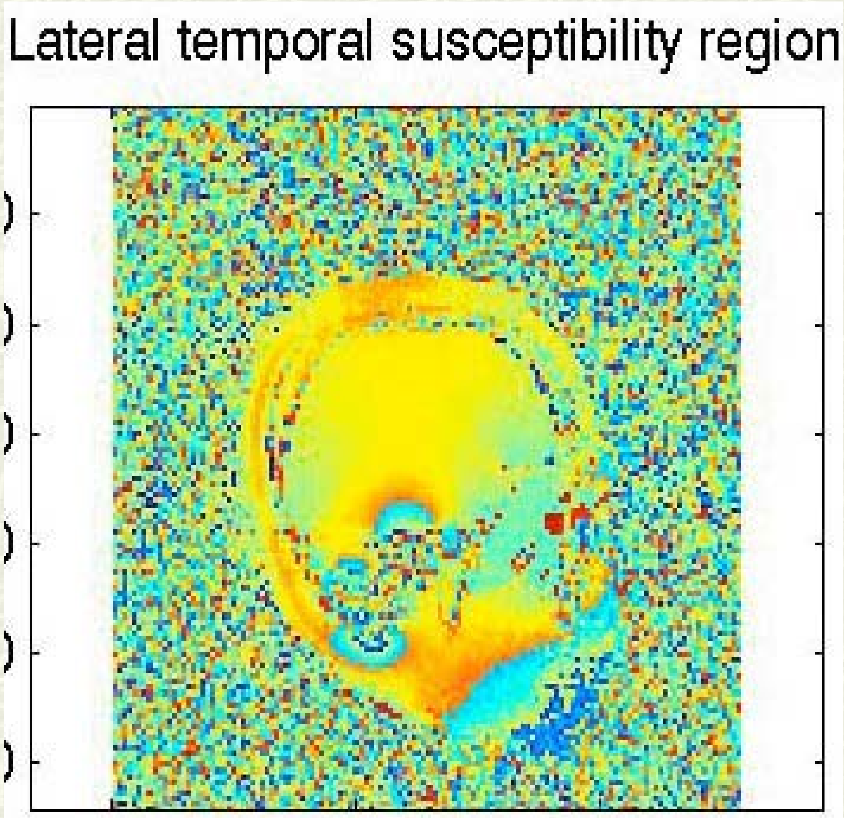
Enemy #1 of EPI: local susceptibility gradients



B_0 field maps in the head

Enemy #1 of EPI: local susceptibility gradients





B_0 field maps in the head

What do we mean by “susceptibility”?

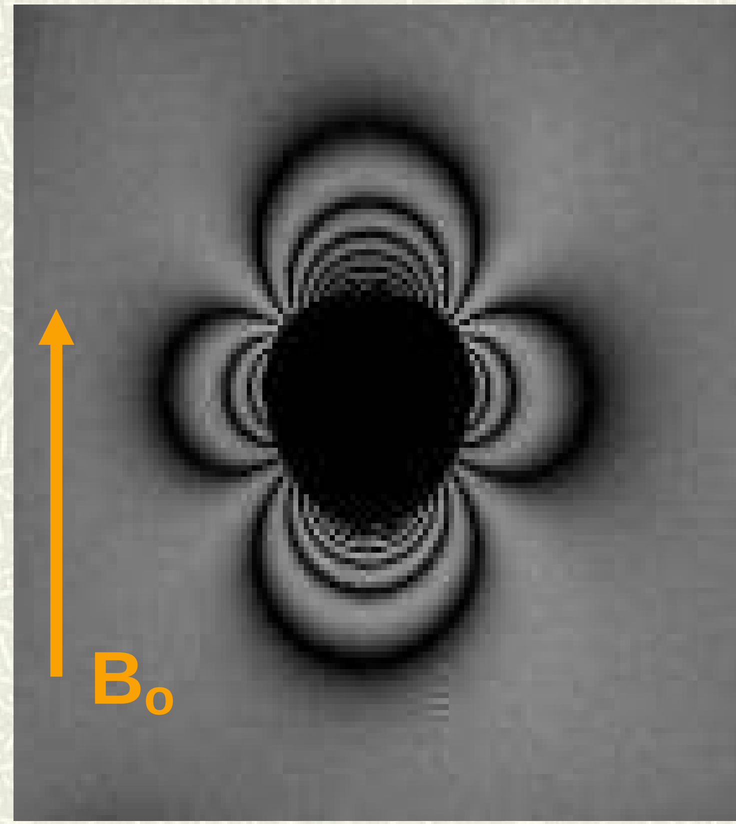
In physics, it refers to a material’s tendency to magnetize when placed in an external field.

In MR, it refers to the effects of magnetized material on the image through its local distortion of the static magnetic field B_o.

Ping-pong ball in water…

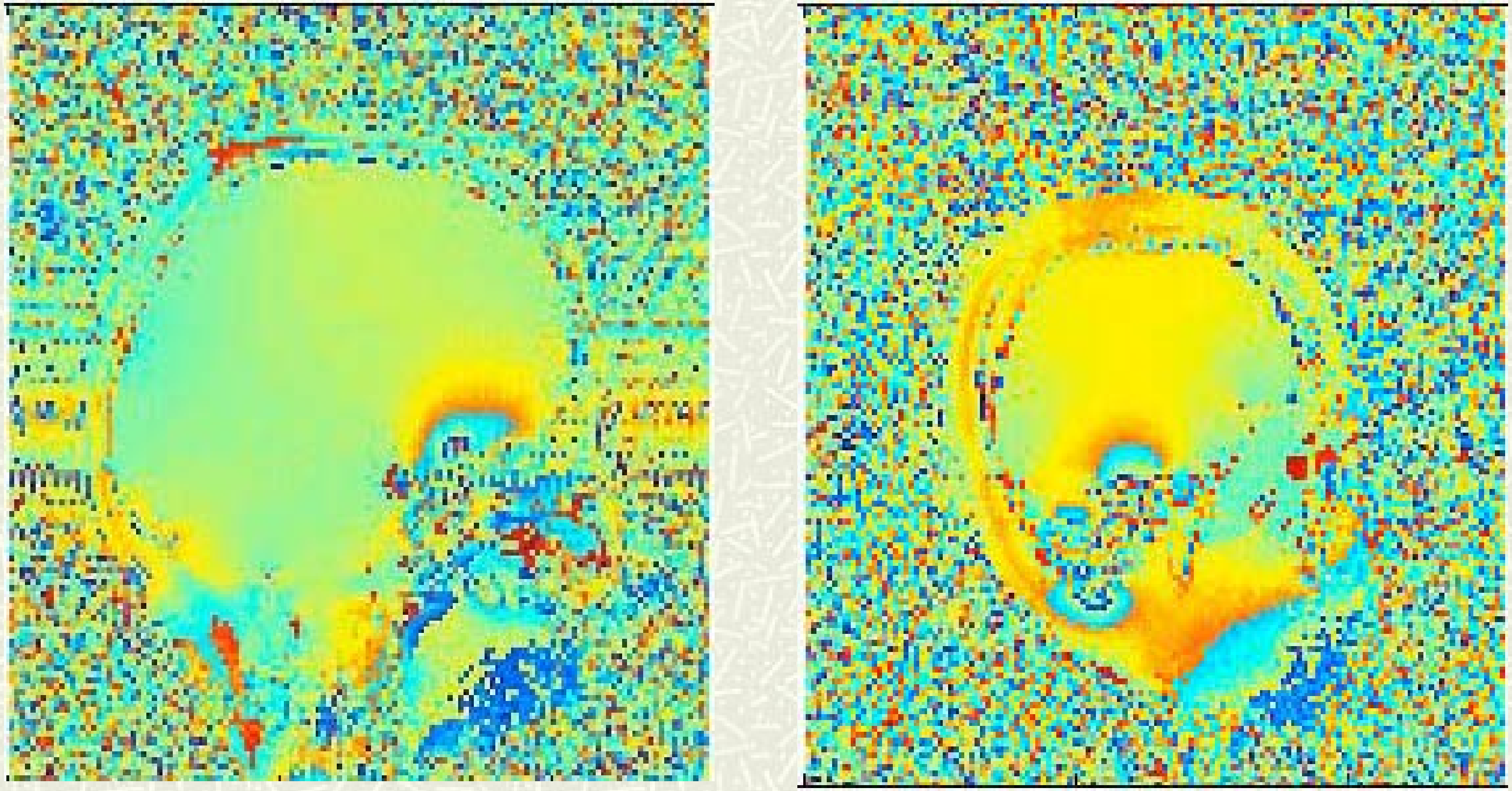
Susceptibility effects occur near magnetically dis-similar materials

Field disturbance around air surrounded by water (e.g. sinuses)



Field map (coronal image) 1.5T

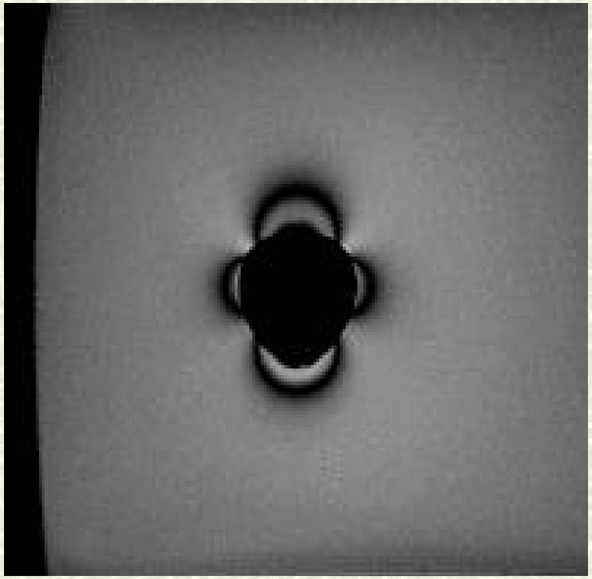
B_o map in head: it's the air tissue interface…



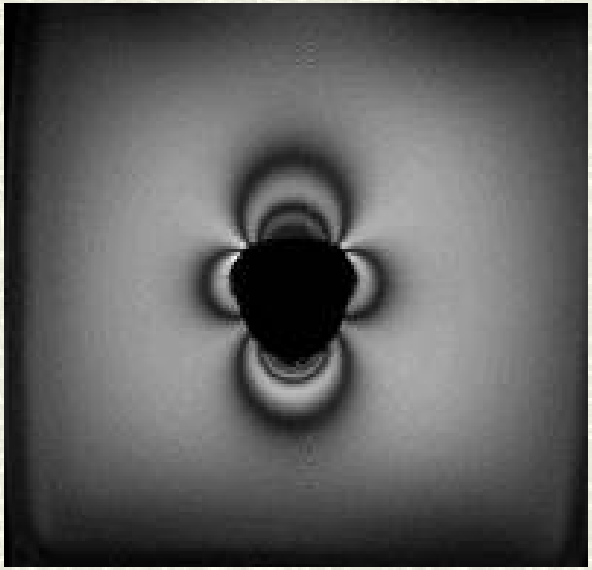
Sagittal Bo field maps at 3T

Susceptibility field (in Gauss) increases w/ B_o

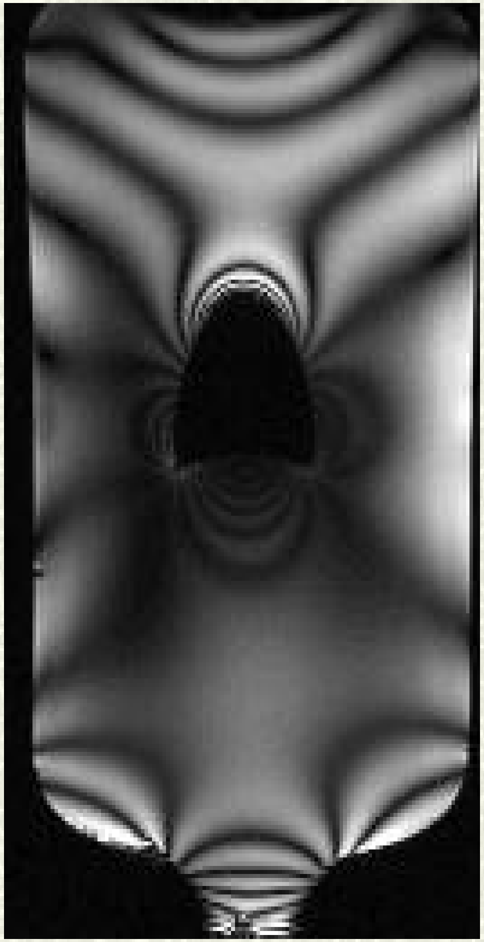
Ping-pong ball in H_20:
Field maps (ΔTE = 5ms), black lines spaced by 0.024G (0.8ppm at 3T)



1.5T

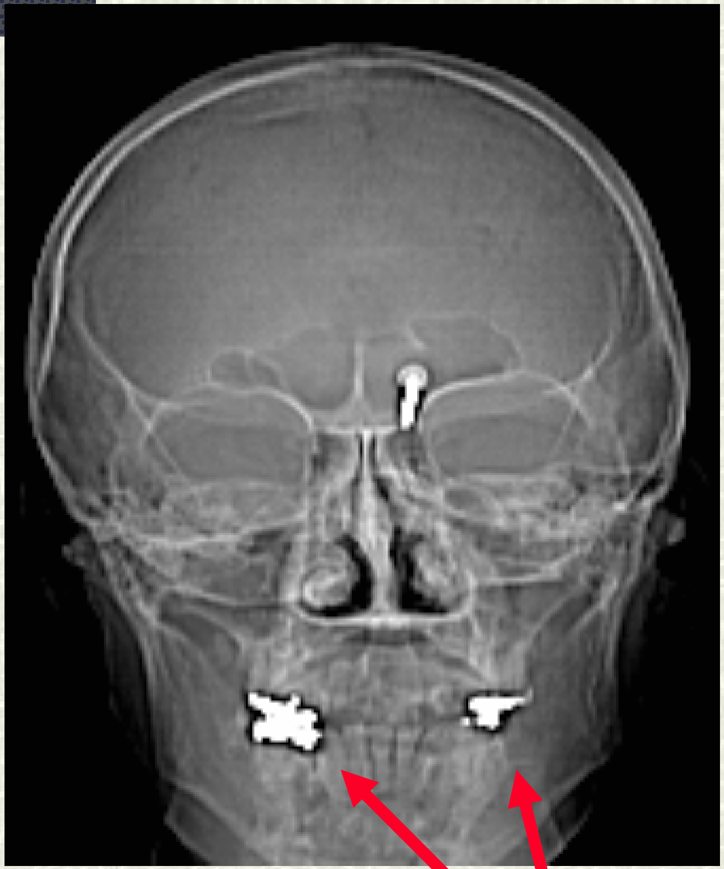


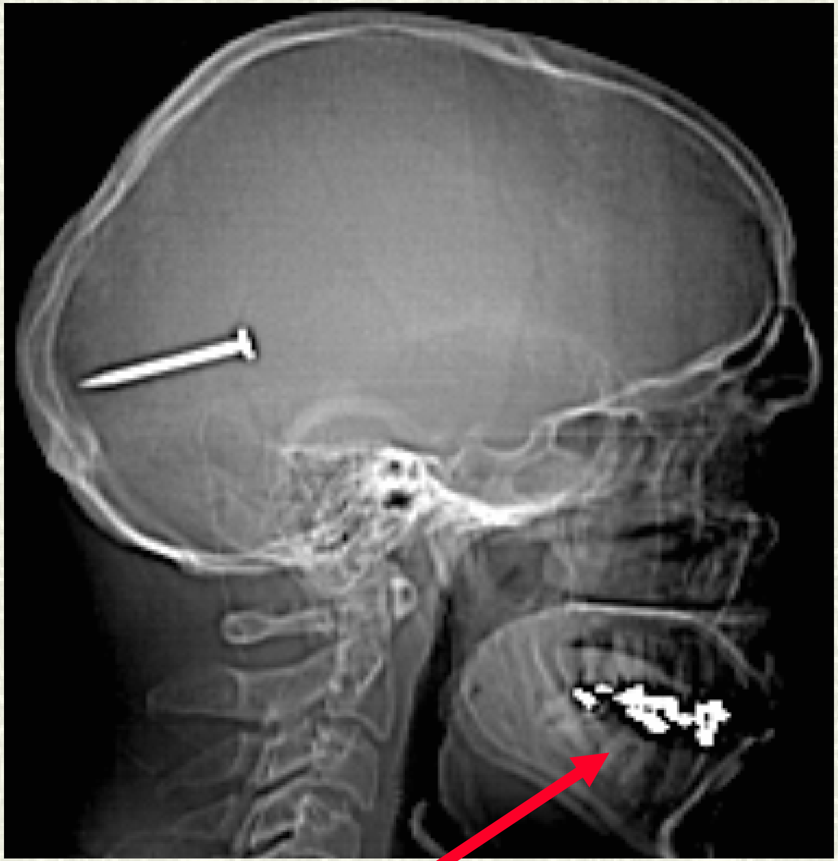
3T



7T

Other Sources of Susceptibility You Should Be Aware of…





Those fillings might be a problem…

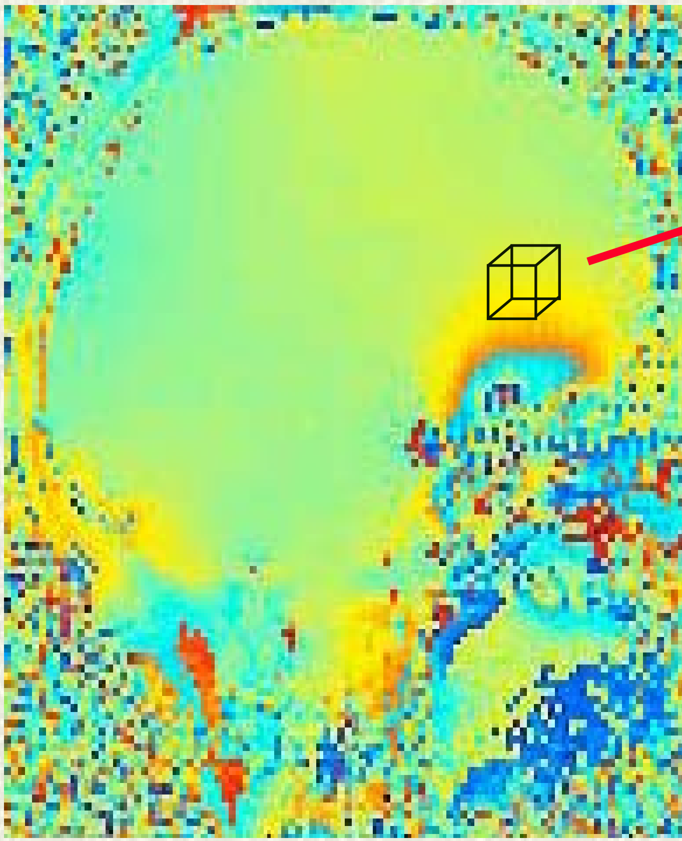
Local susceptibility gradients: 2 effects

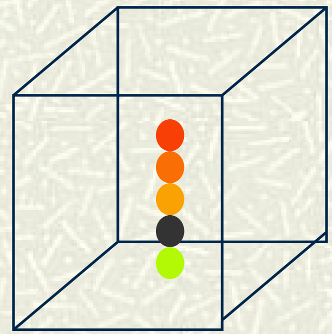
1) **Local dephasing of the signal (signal loss) within a voxel, mainly from thru-plane gradients**

2) **Local geometric distortions, (voxel location improperly reconstructed) mainly from local in-plane gradients.**

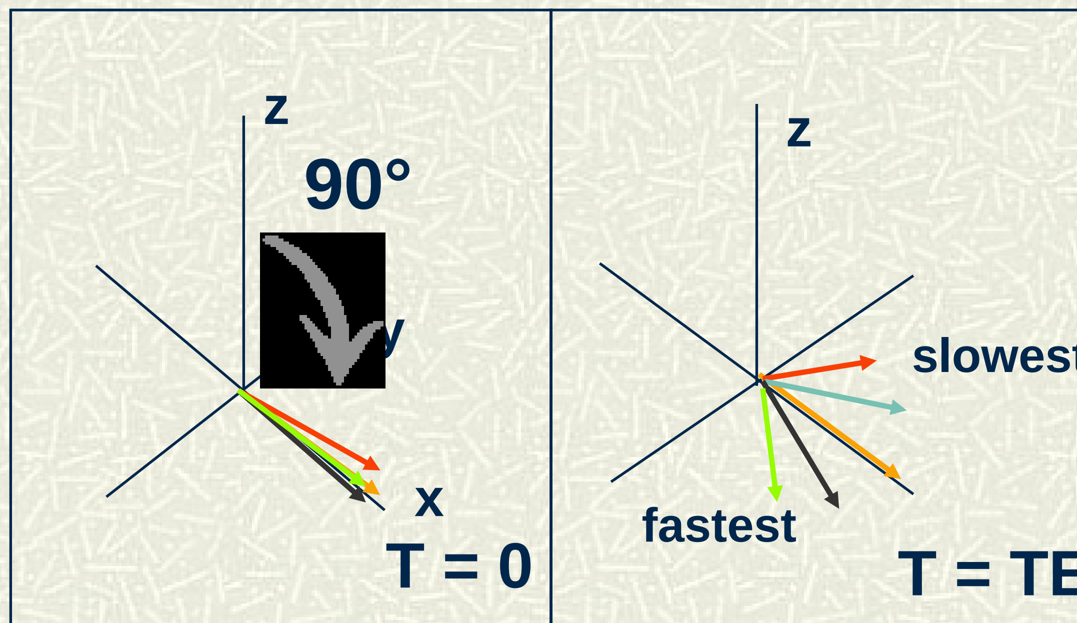
1) Non-uniform Local Field Causes Local Dephasing

Sagittal B_o field map at 3T



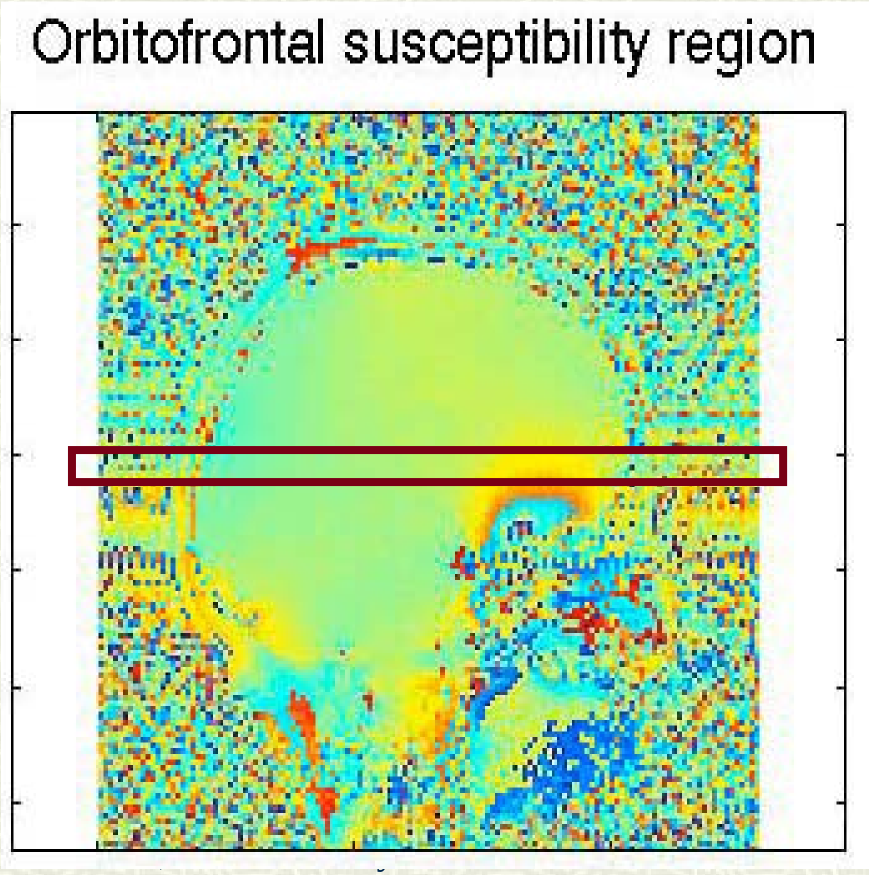


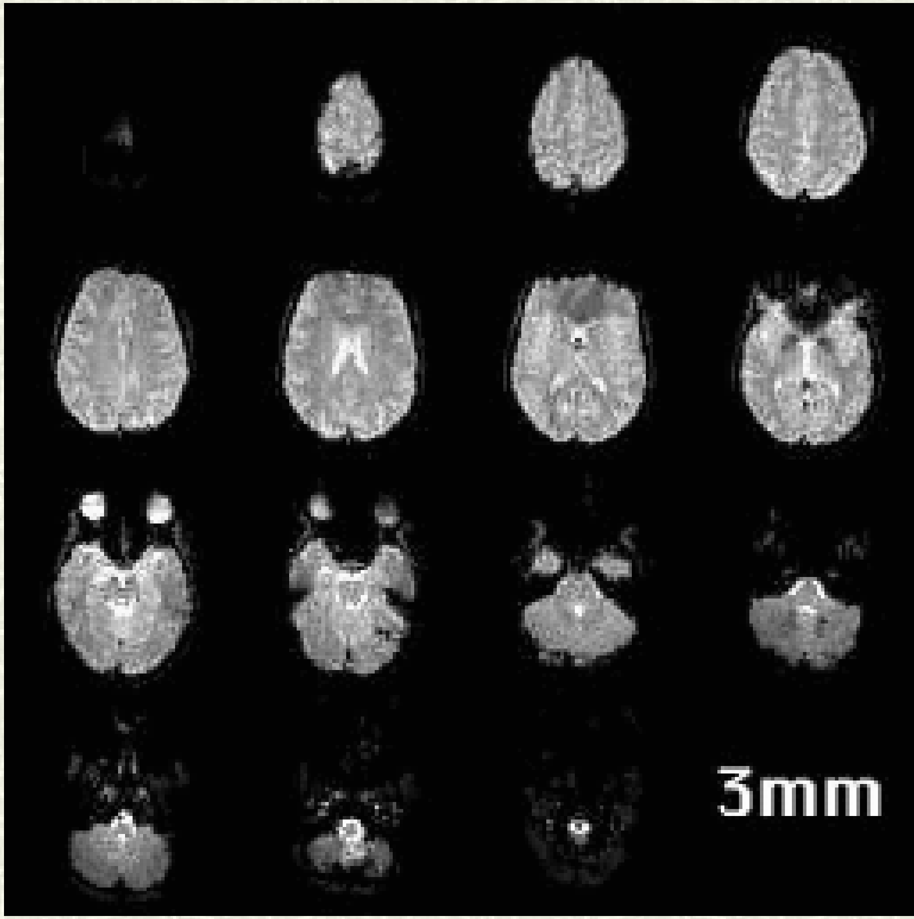
5 water protons in different parts of the voxel…



Local susceptibility gradients: thru-plane dephasing in grad echo EPI

Bad for thick slice above frontal sinus…



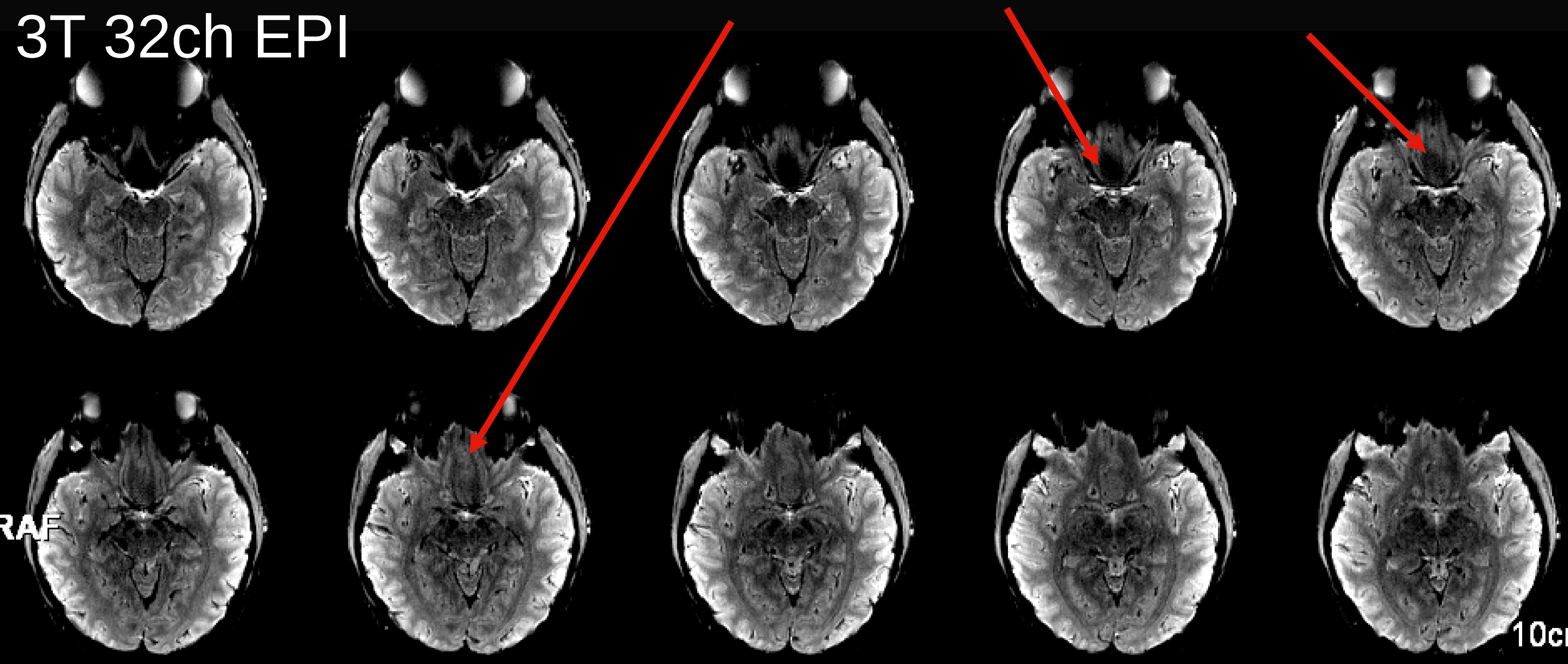


3T

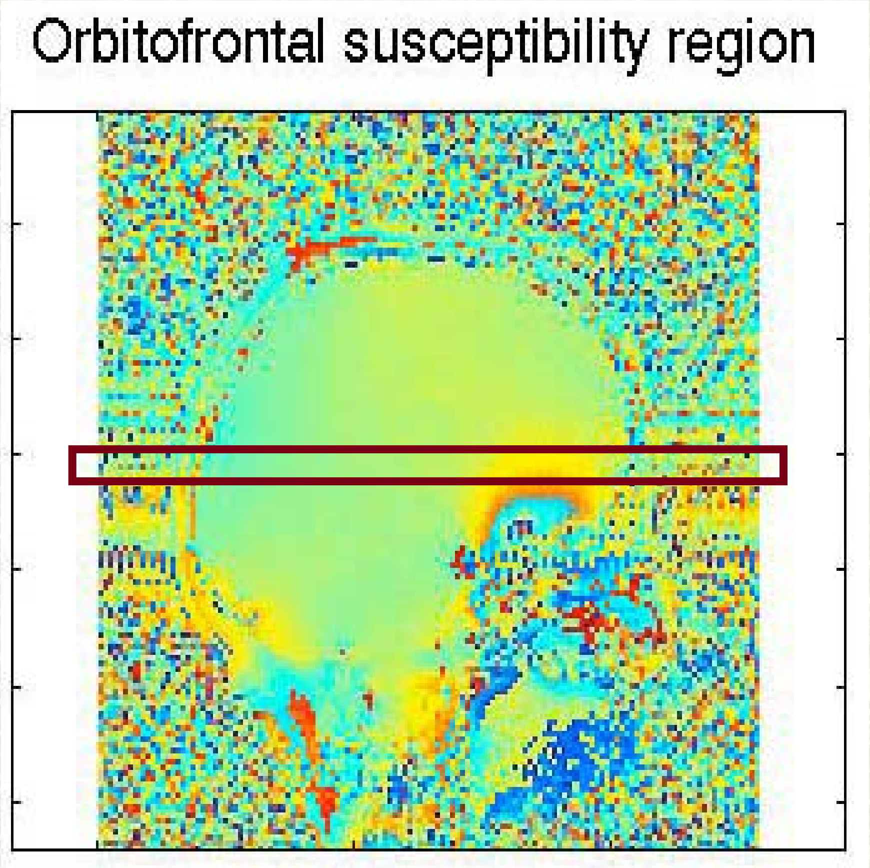
Solution: high resolution

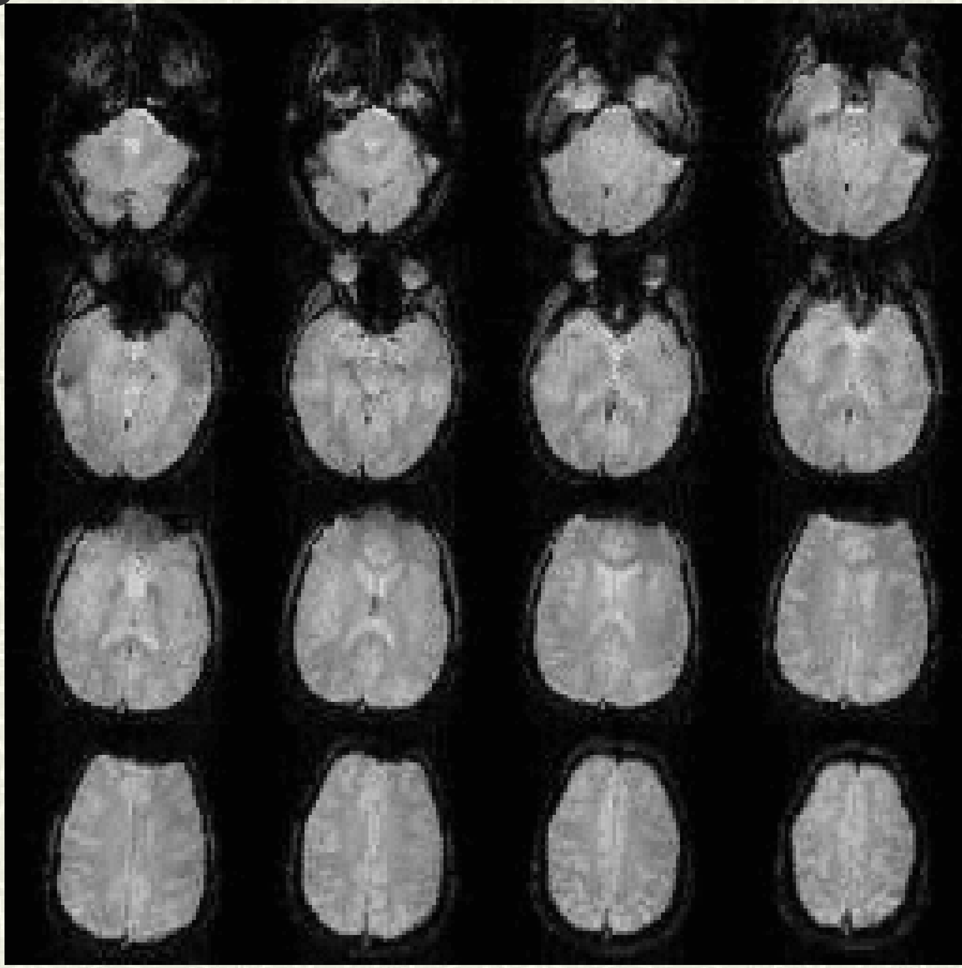
1mm isotropic
TE=30ms, GRAPPA =2
6/8 part-Fourier

Minimal OFC drop-out issues with 3T 1mm isotropic



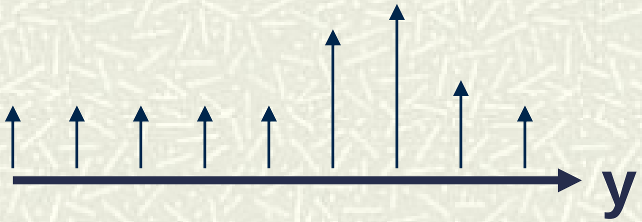
Thru-plane dephasing gets worse at longer TE



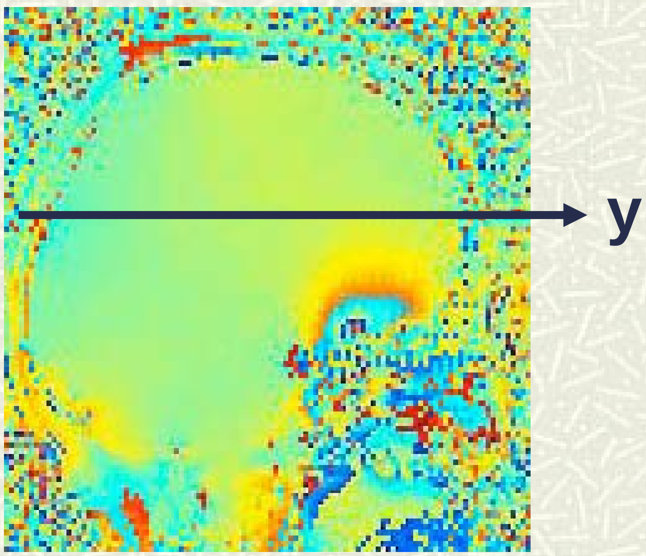


3T, TE = 21, 30, 40, 50, 60ms

Problem #2 Susceptibility Causes Image Distortion in EPI



Field near sinus

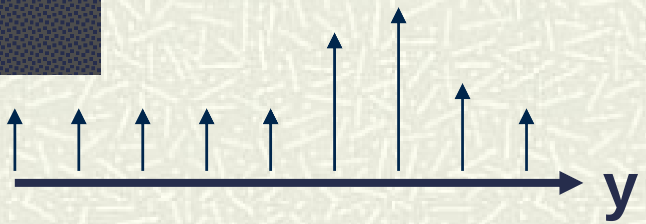


To encode the image, we control phase evolution as a function of position with applied gradients.

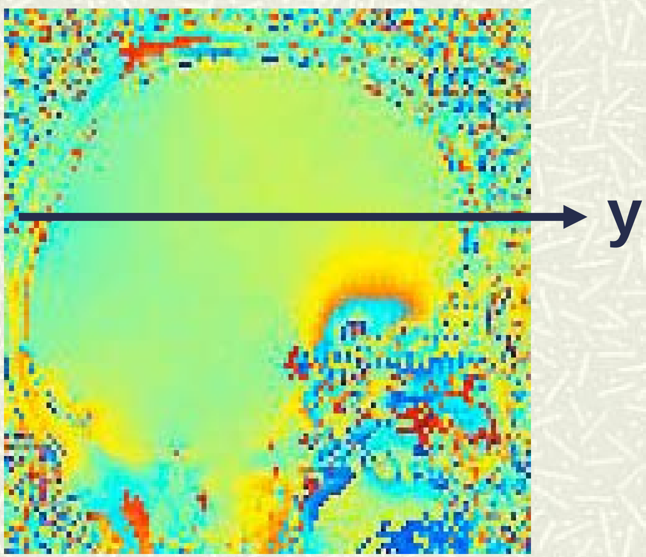
Local suscept. Gradient causes unwanted phase evolution.

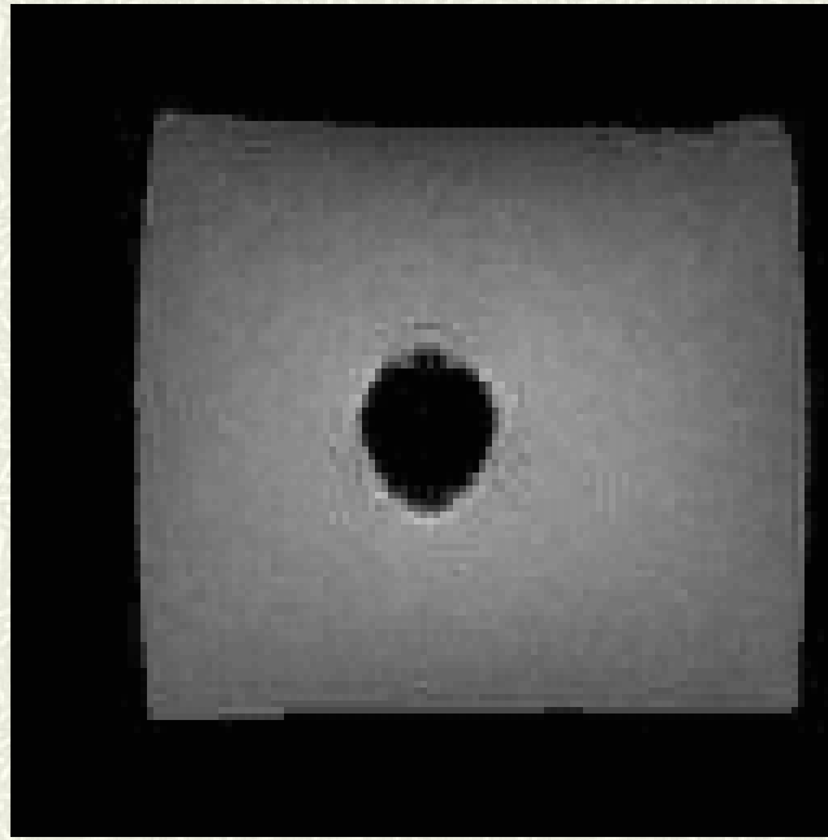
The phase encode error builds up with time. $\Delta\theta = \gamma B_{local} \Delta t$

Susceptibility Causes Image Distortion



Field near sinus



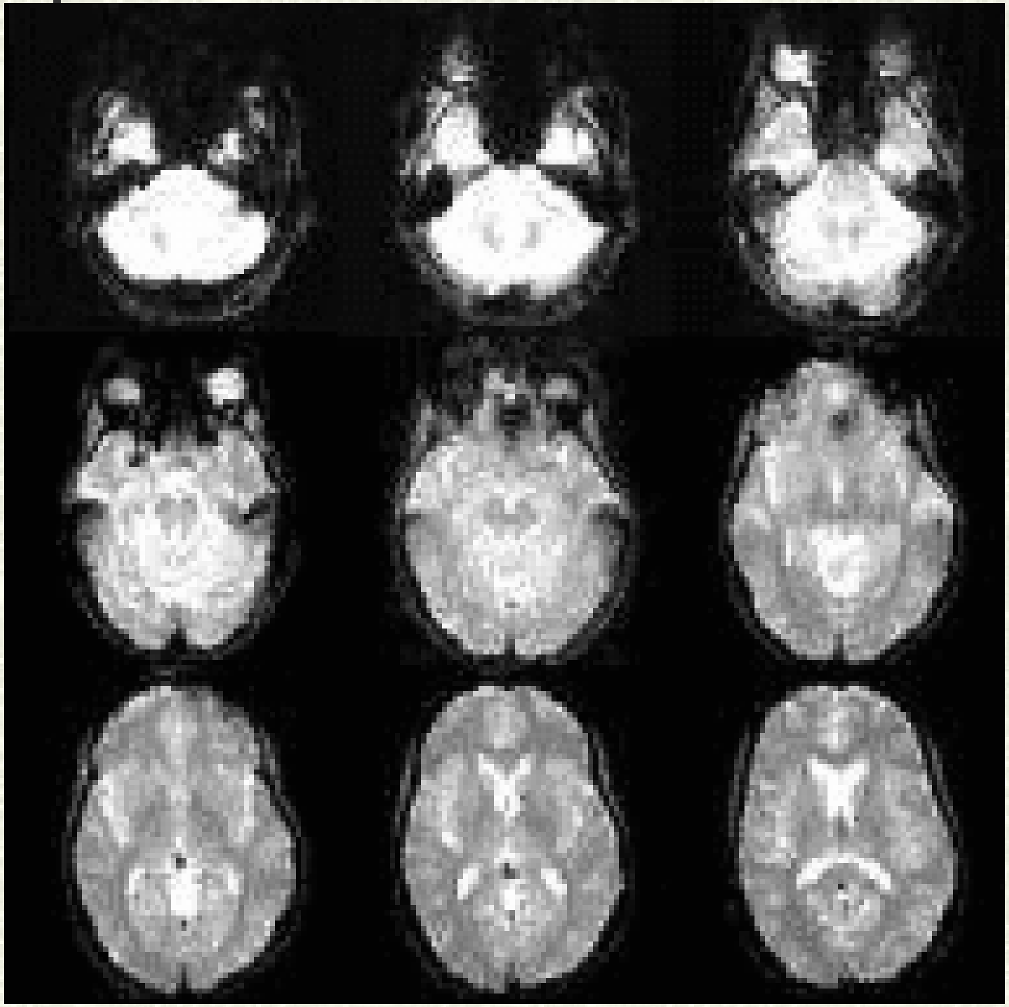


Conventional grad. echo,
$\Delta\theta$ α encode time α 1/BW

Susceptibility in EPI can give either a compression or expansion

Altering the direction kspace is transversed causes either local compression or expansion.

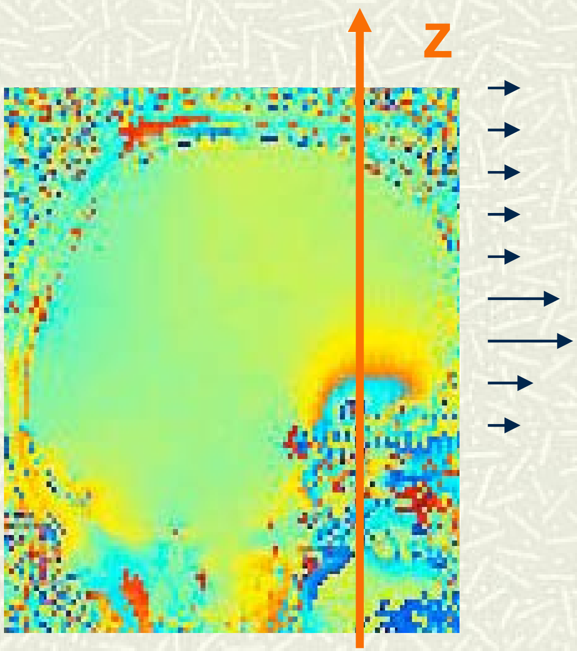
choose your poison…



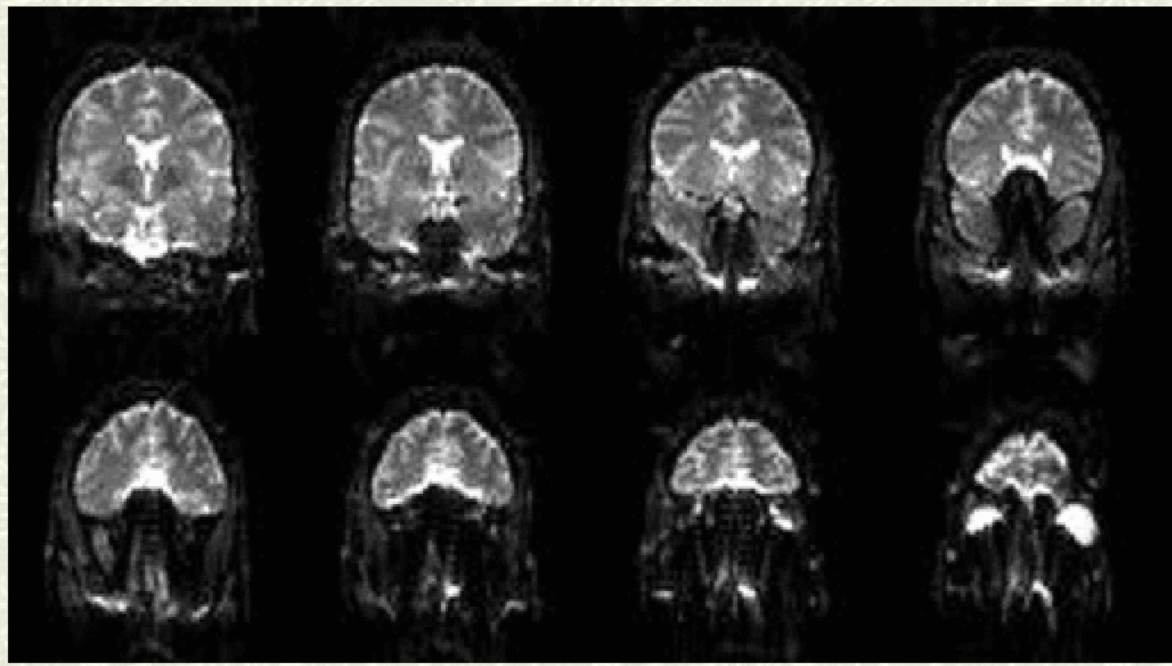
3T whole body gradients

Susceptibility Causes Image Distortion

Echoplanar Image,
$\Delta\theta$ α encode time α 1/BW



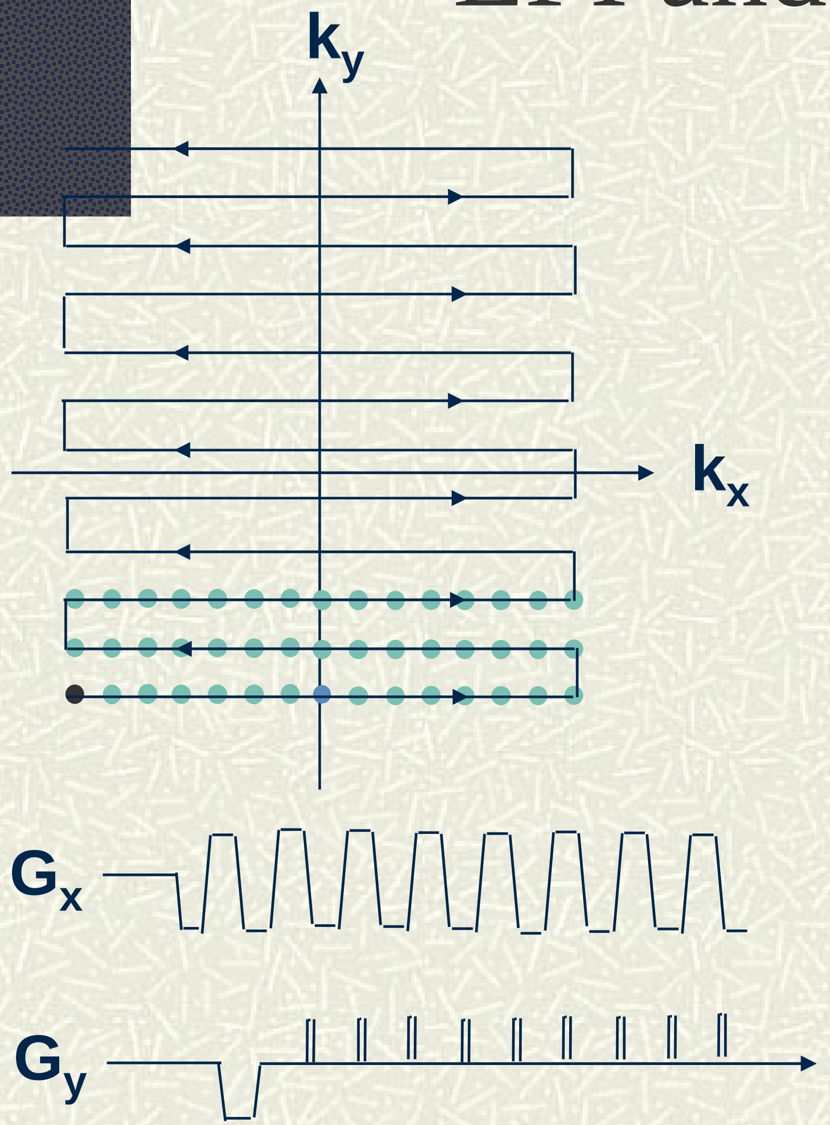
Field near sinus

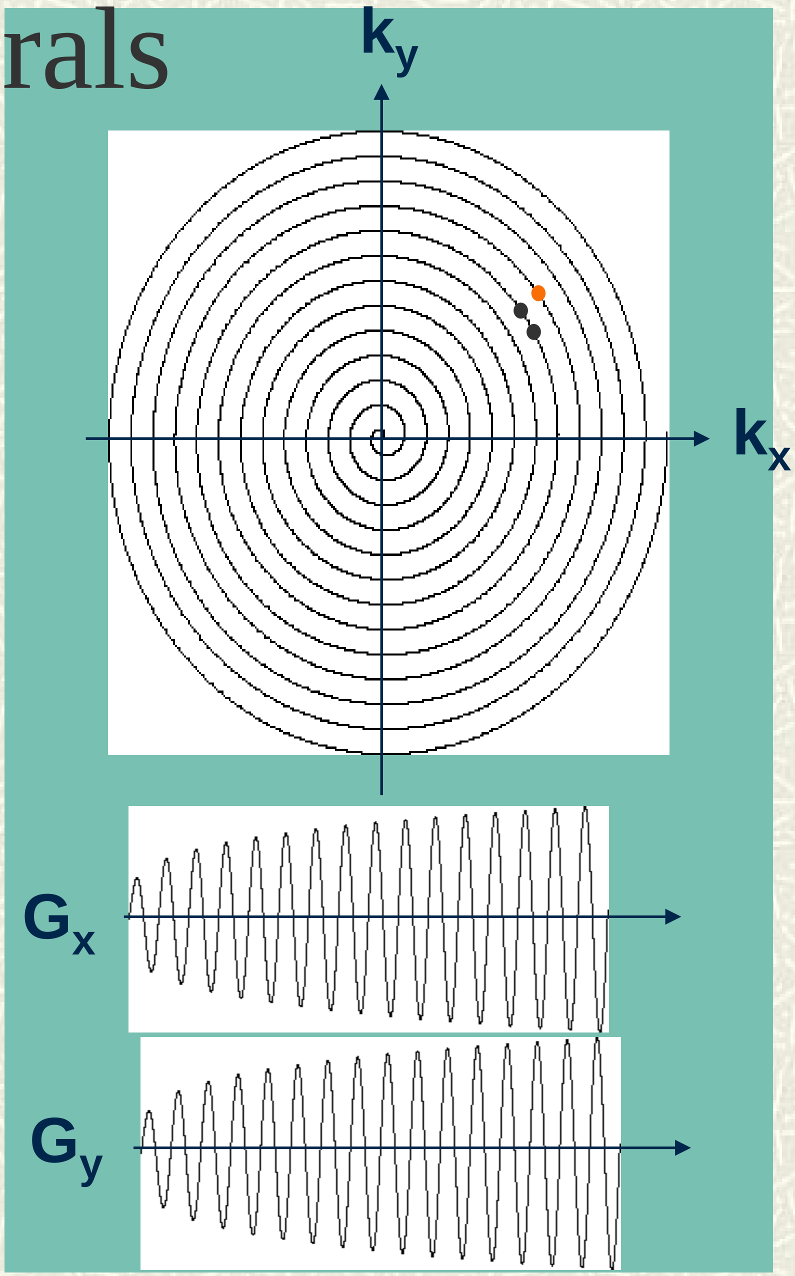


3T head gradients

Encode time = 34, 26, 22, 17ms

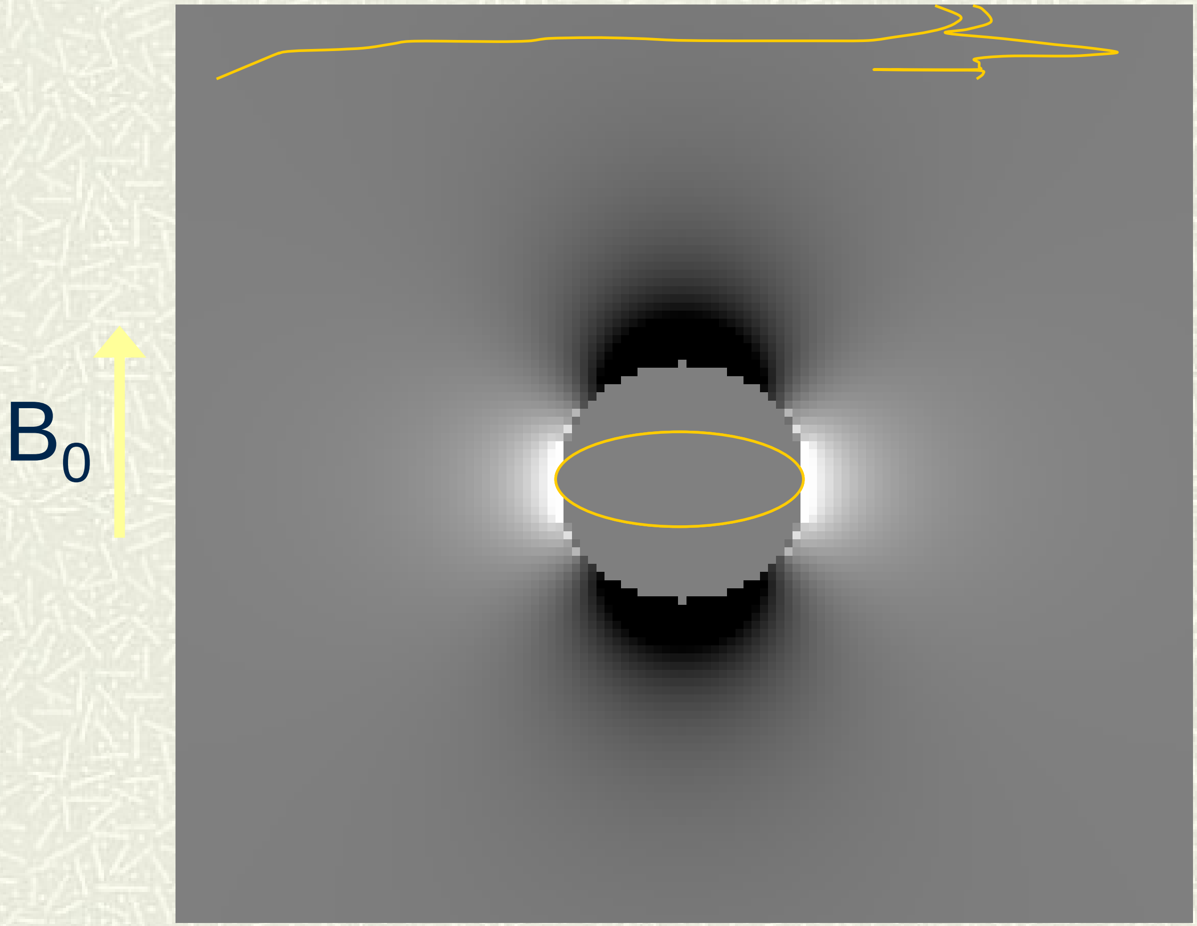
EPI and Spirals



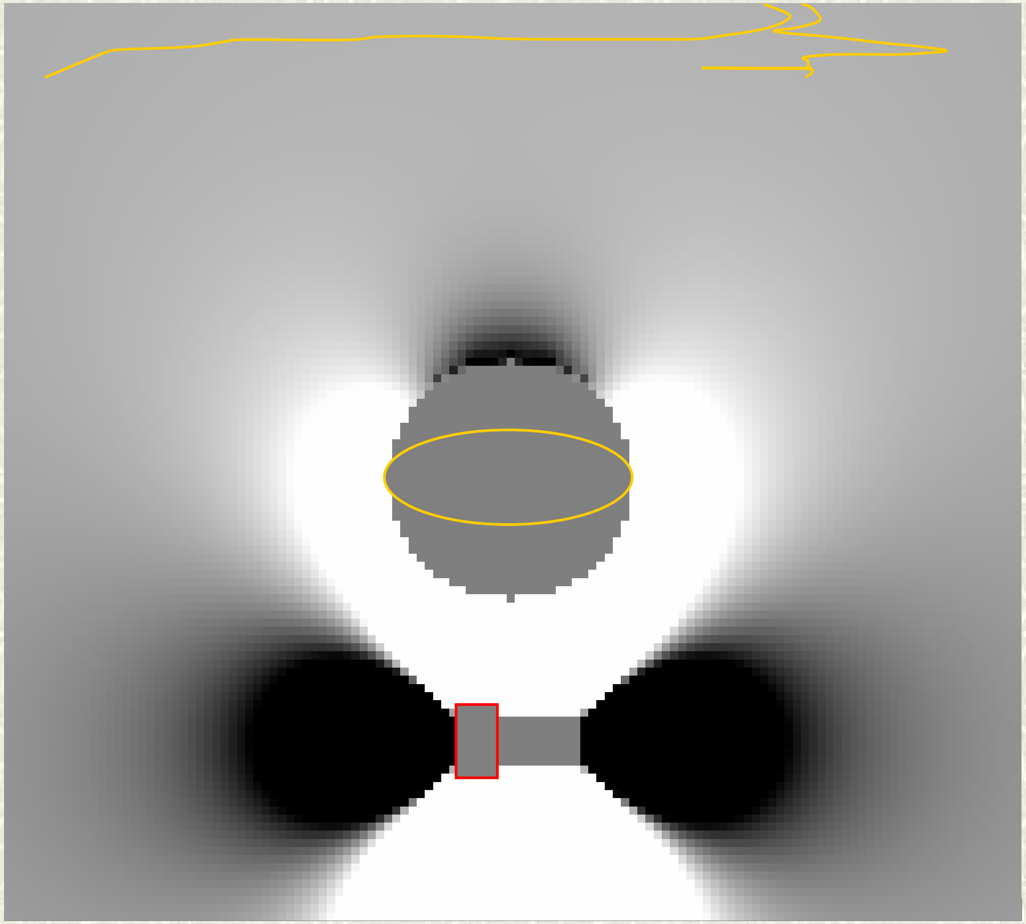


	EPI	Spirals
Susceptibility:	distortion, dephasing	blurring, dephasing
Eddy currents:	ghosts	blurring
k = 0 is sampled:	1/2 through	1st
Corners of kspace:	yes	no
Gradient demands:	very high	pretty high

Nasal Sinus

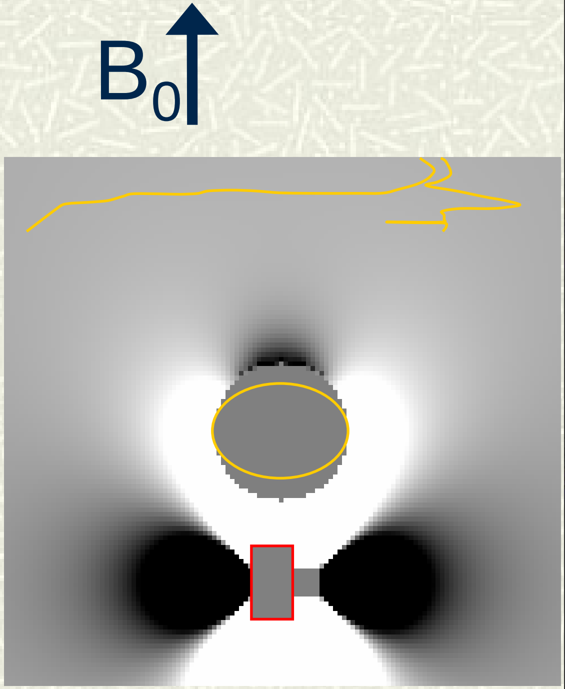


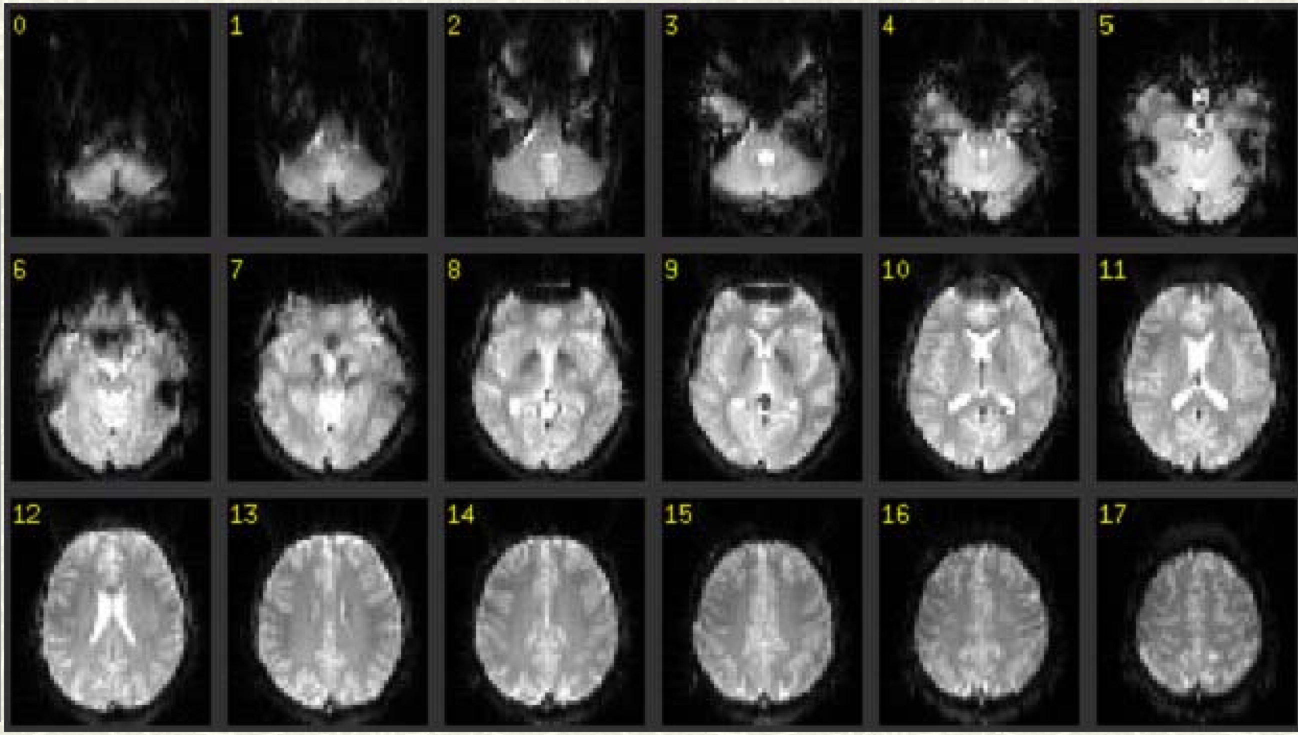
Nasal Sinus + mouth shim



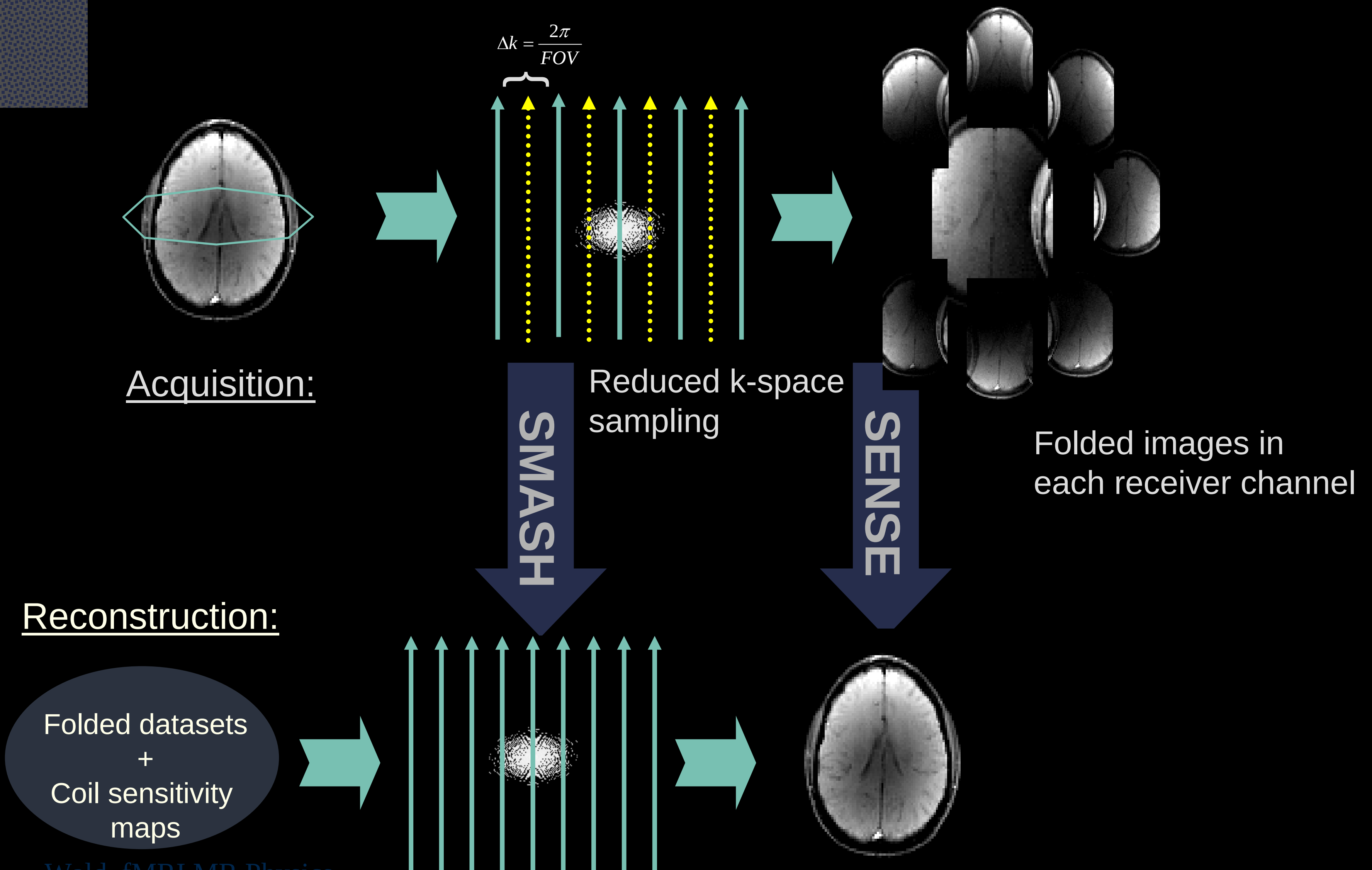
B_0

Effect of Ear & Mouth Shim on EPI

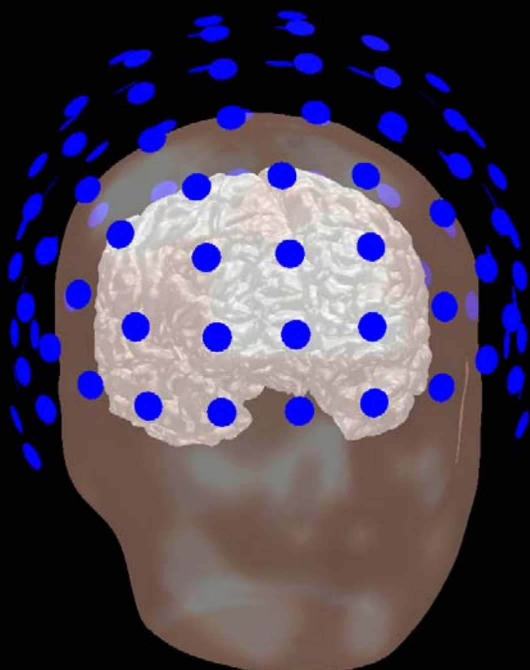




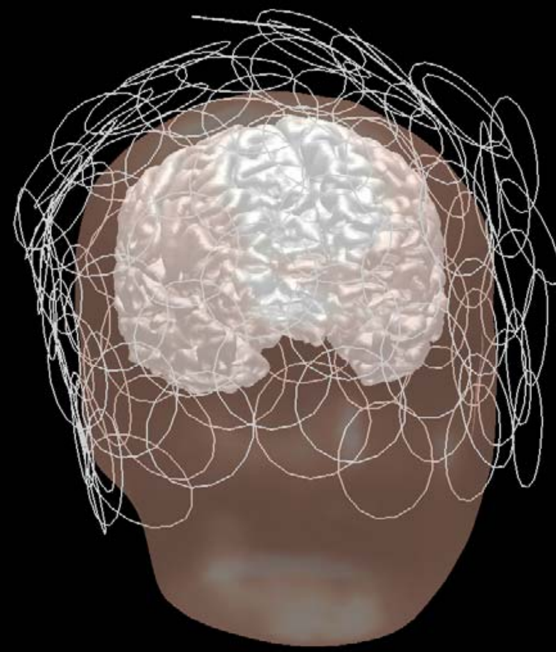
With fast gradients, add parallel imaging



Using the detector array to encode image

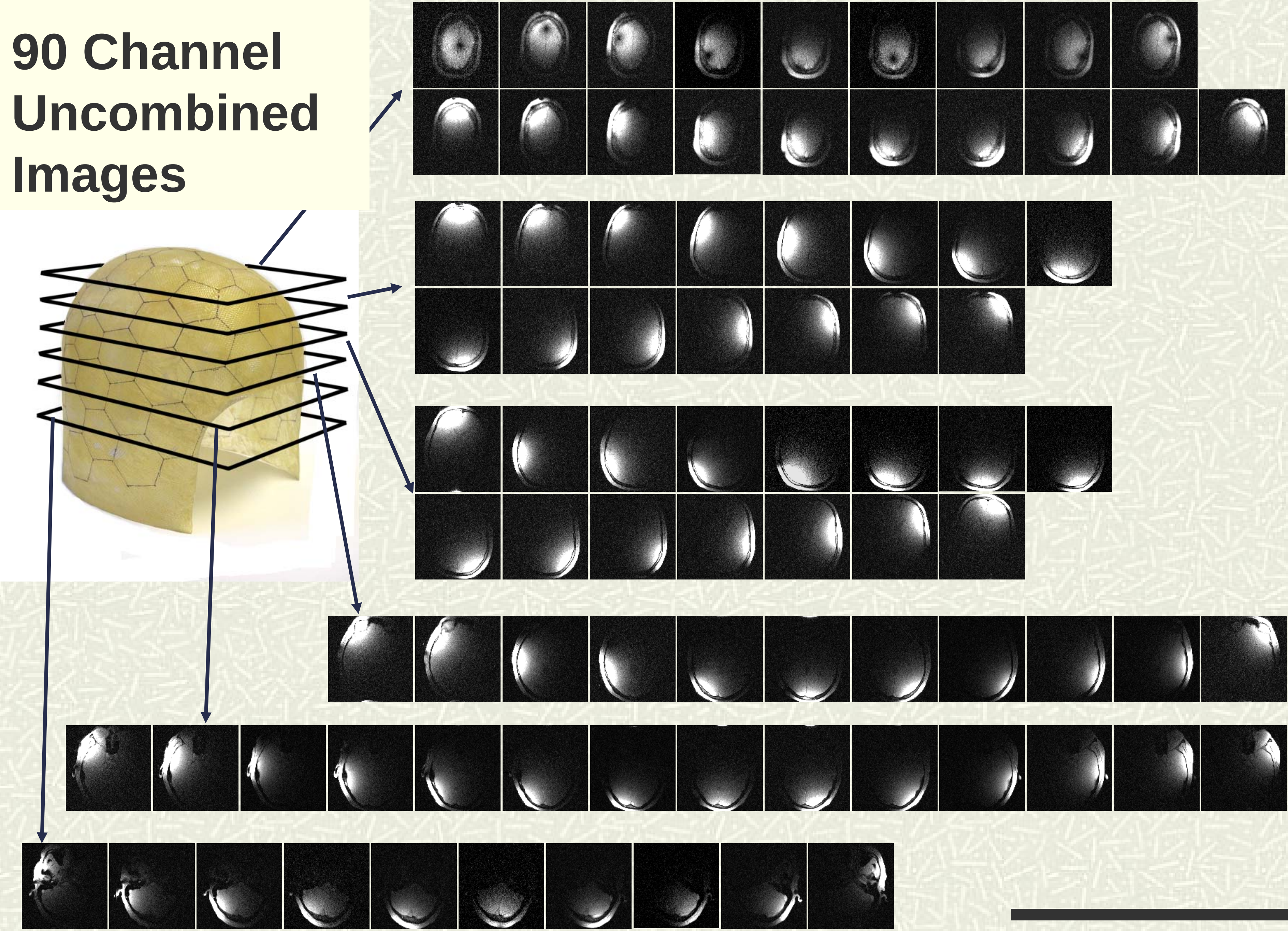


306-channel MEG



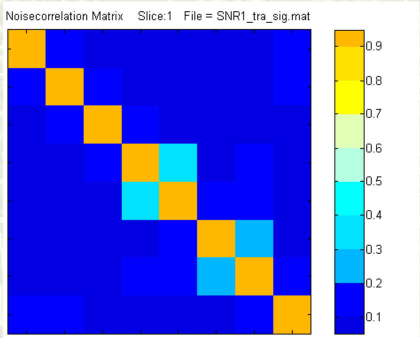
90-channel MRI

90 Channel Uncombined Images

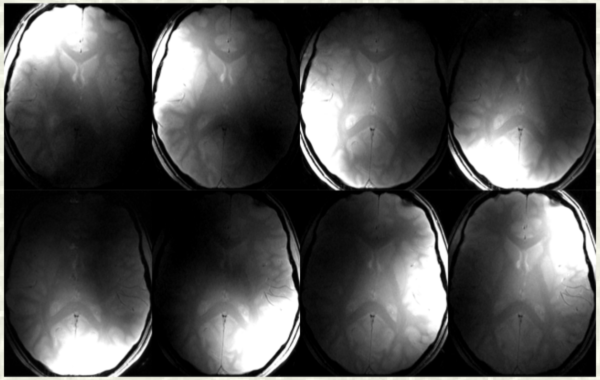


Parallel acquisition: noise penalties
Calculating the g-factor map

$$SNR_{accel} = \frac{SNR_{full-k}}{G\sqrt{R}}$$

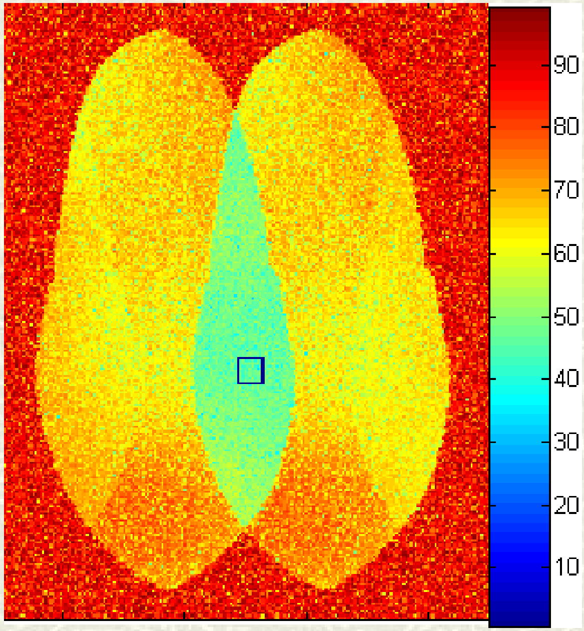


noise correlation matrix



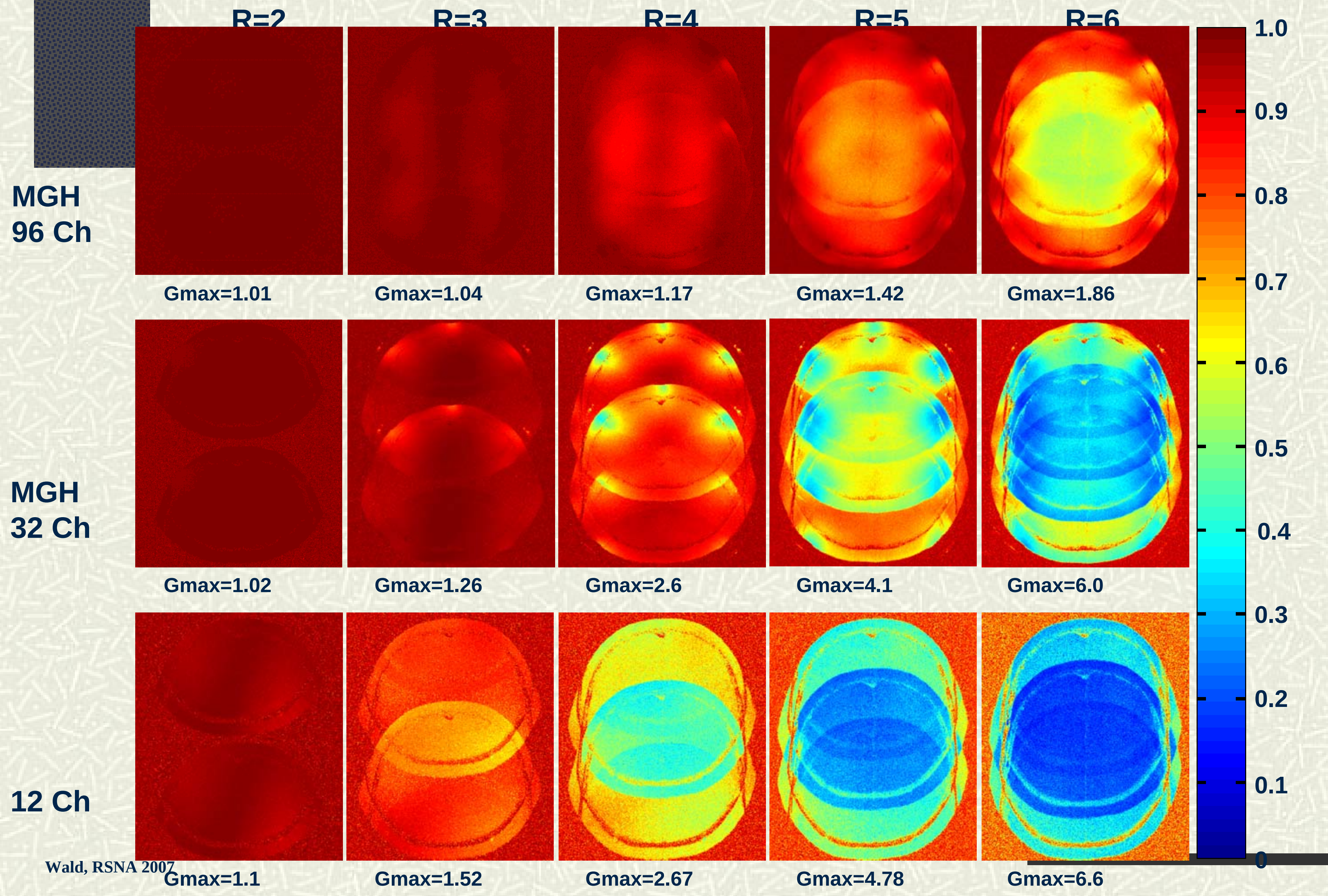
coil sensitivity profiles

map of 1/G



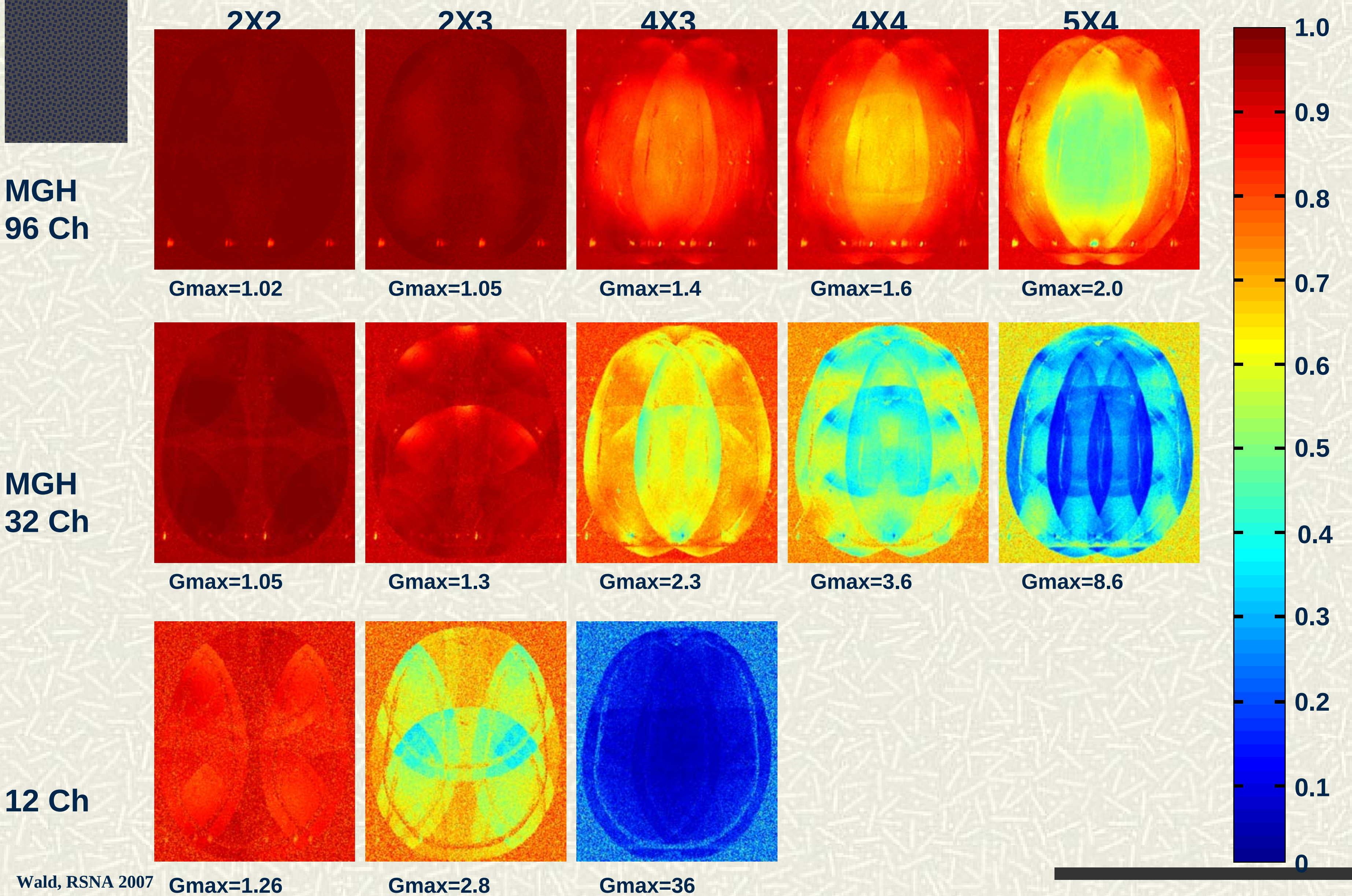
Rate = 4
Gmax=2.17

1/G-factor Maps, 3 Tesla



Wald, RSNA 2007

1/G-factor, 2D Acceleration

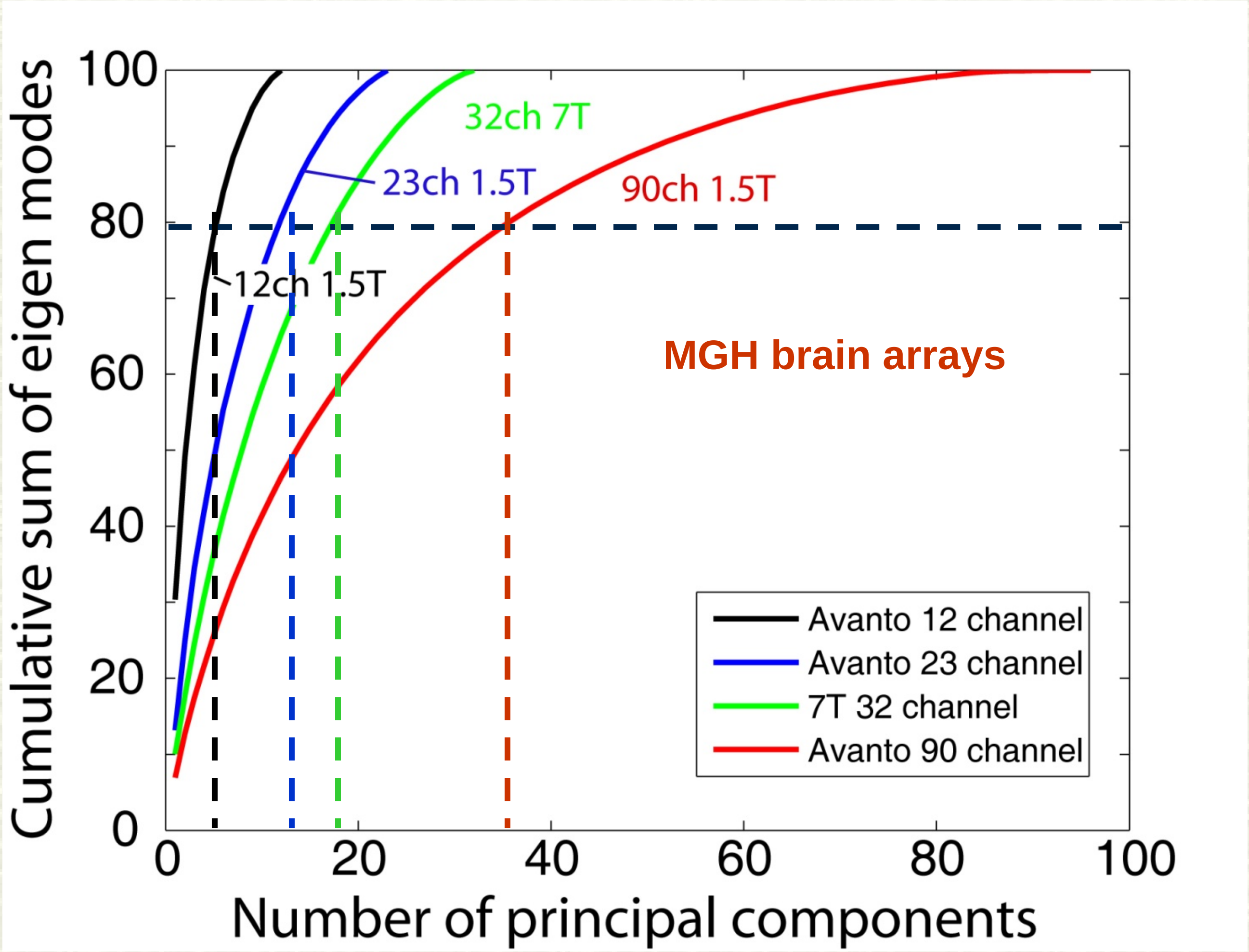


Wald, RSNA 2007

3D encoding power of the array: eigenmodes of the sensitivity maps

Analysis following:
Univ. Würzburg

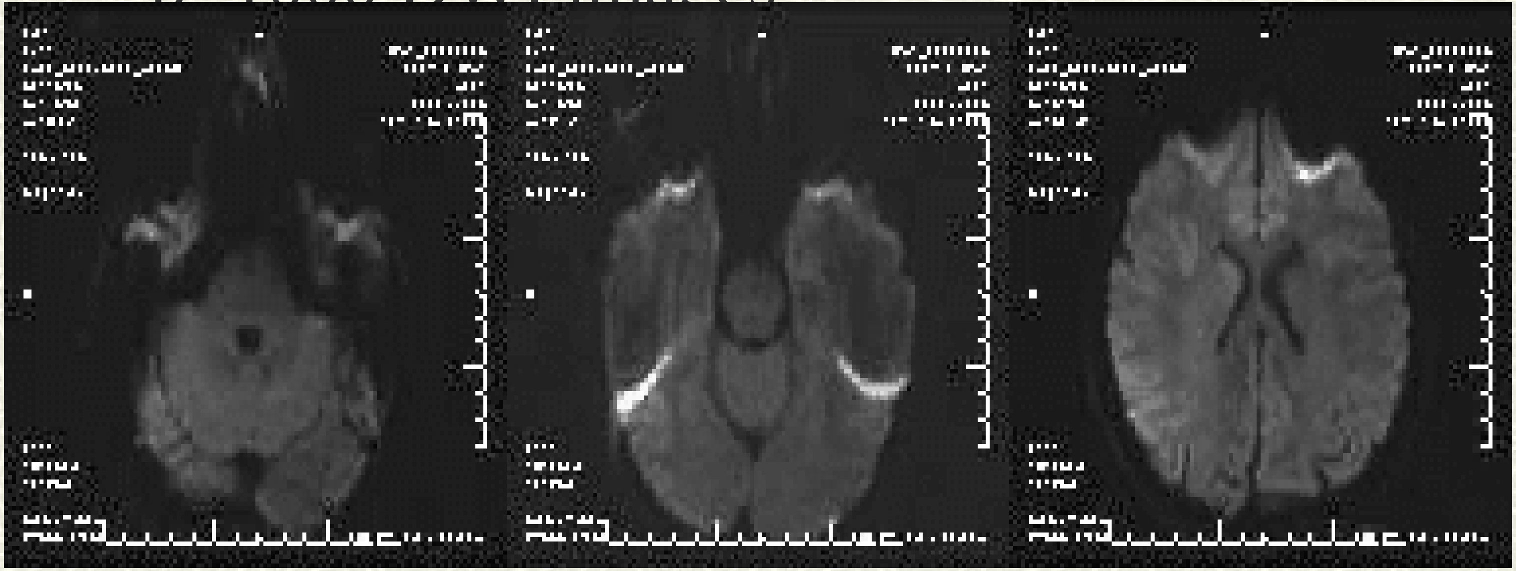
Breuer et al.
ISMRM 2005 p2668



The 90ch coil
still has significant
components over 32ch.

(iPAT) GRAPPA for EPI susceptibility

3T Trio, MRI Devices Inc. 8 channel array
b=1000 DWI images



iPAT (GRAPPA) = 0, 2x, 3x

Fast gradients are the foundation, but EPI still suffers distortion

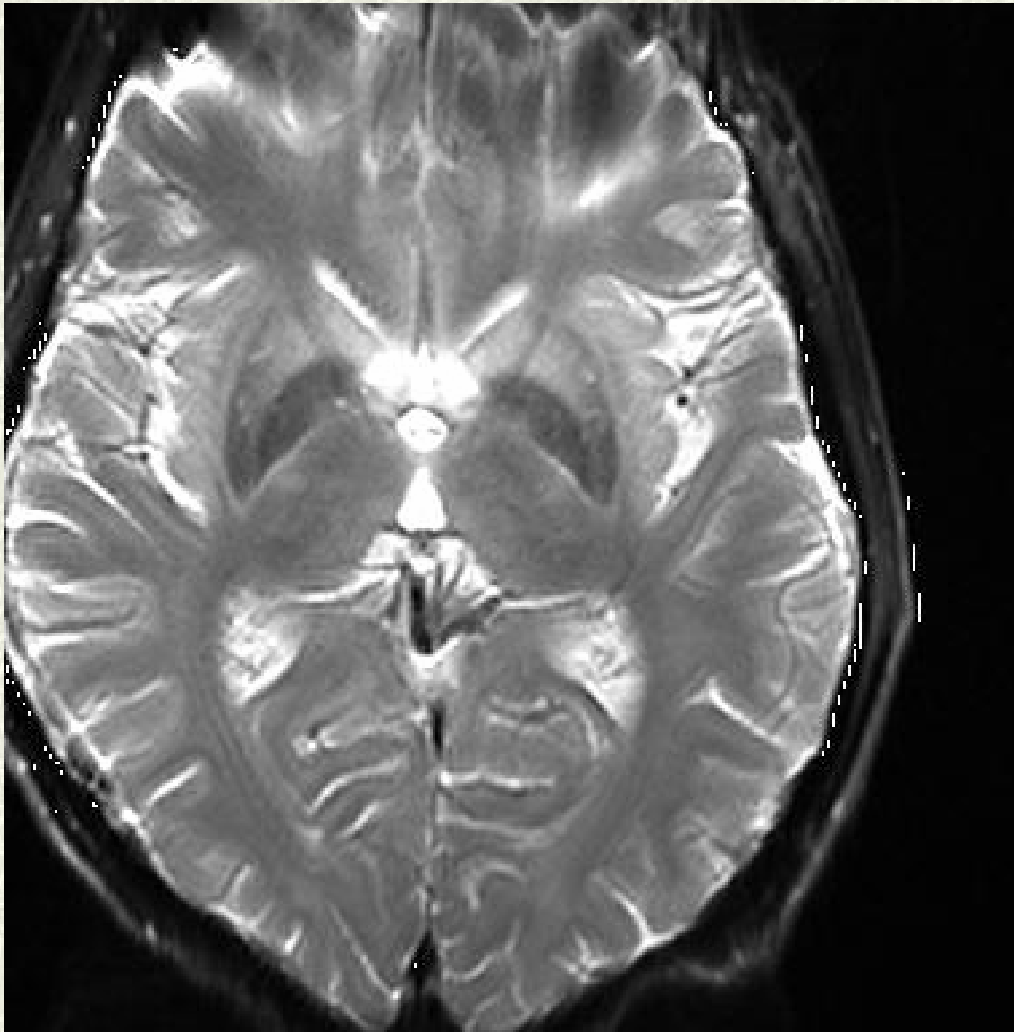
Encoding with RF…

4 fold acceleration of single shot sub-millimeter SE-EPI: 23 channel array

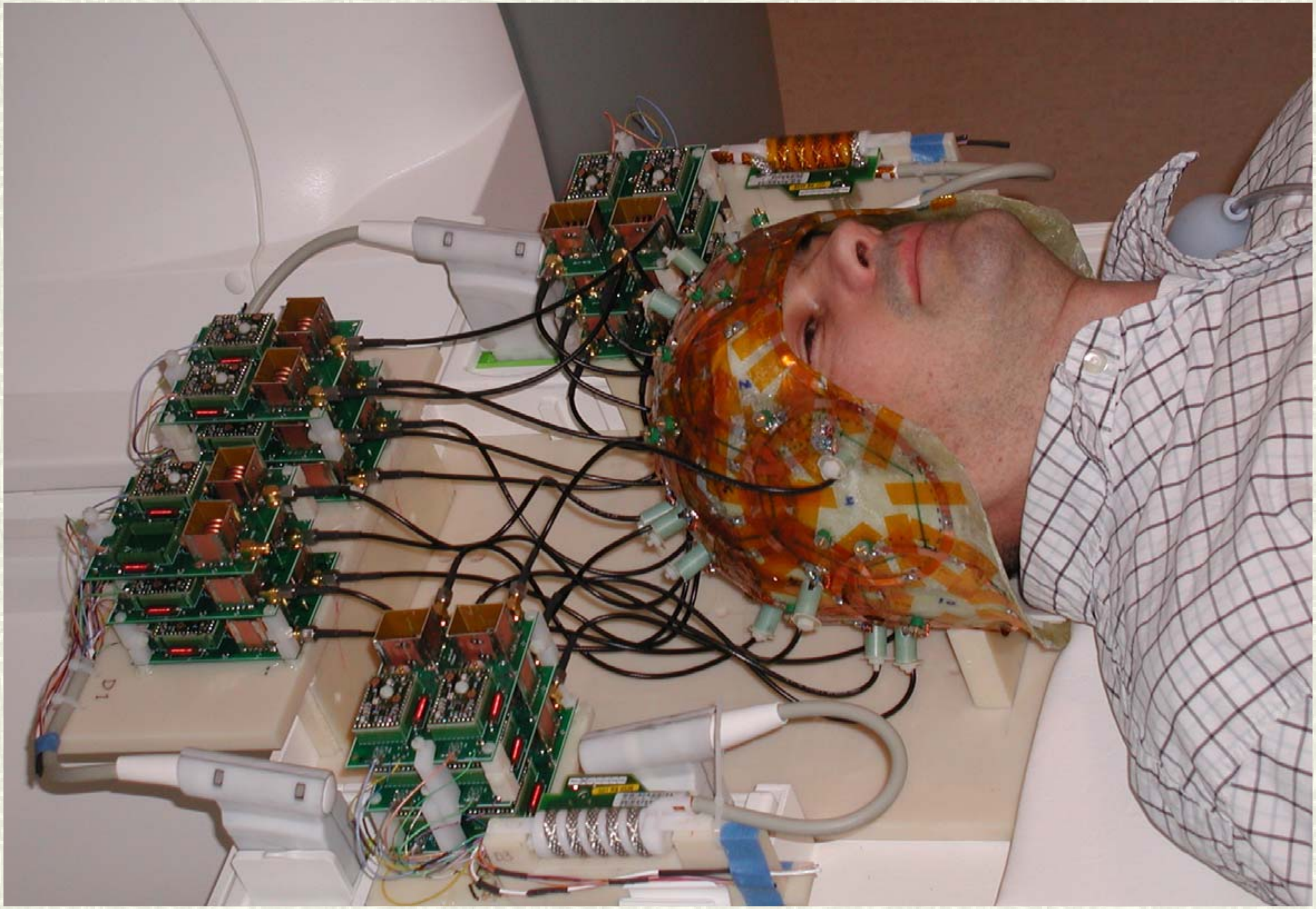
23 Channel array at 1.5T

With and without 4x Accel.

Single shot EPI,
256x256, 230mm FOV
TE = 78ms



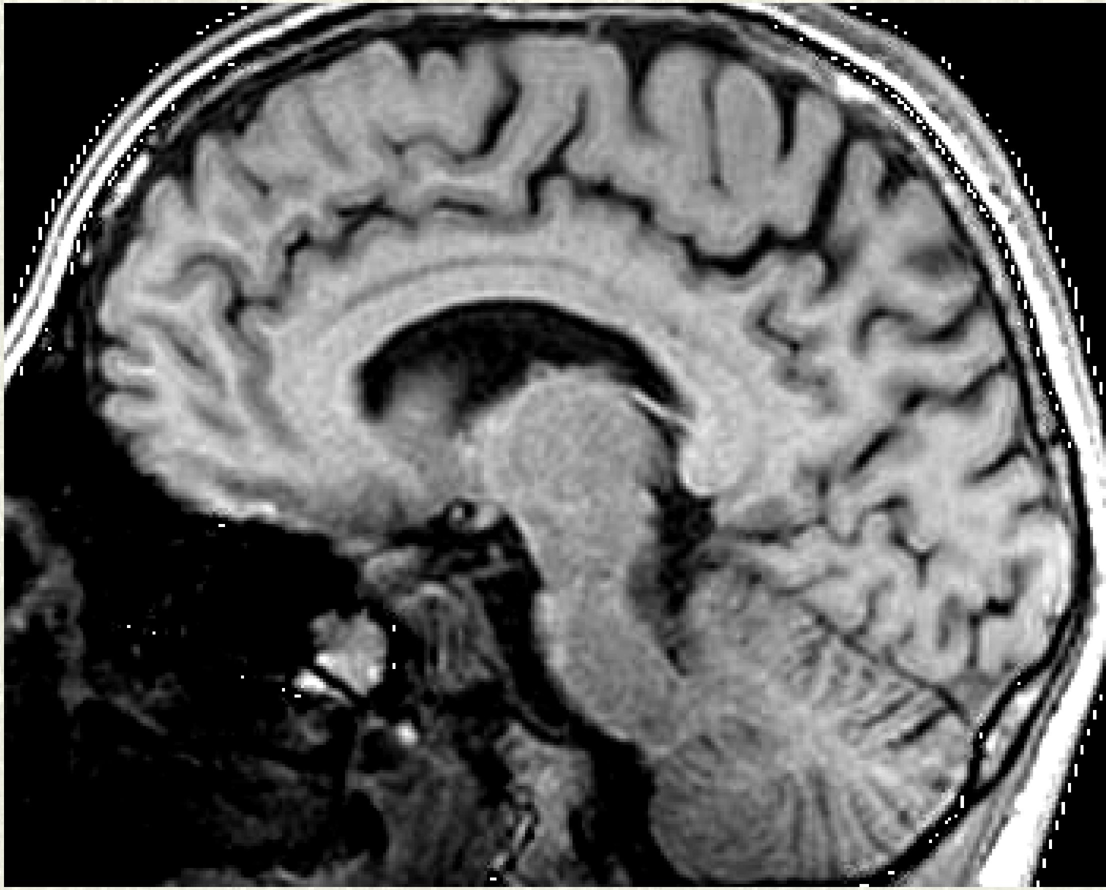
Extending the phased array to more channels:
23 channel "Bucky" array for 1.5T



9 Fold GRAPPA acceleration 3D FLASH

9 minute scan down to 1 minute…

23 Channel array at 1.5T
Can speed up encoding by
an order of magnitude!

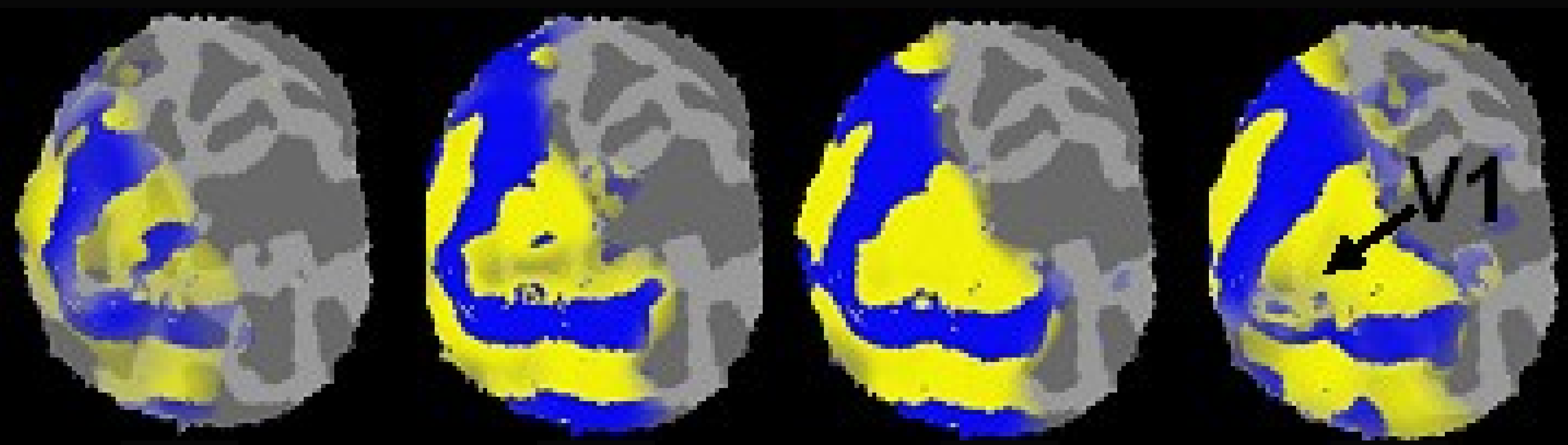


3D Flash, 1mm x 1mm x 1.5mm, 256x256x128

32 channel coil improves fMRI

12 channel coil

32 channel coil



1 run

3 run

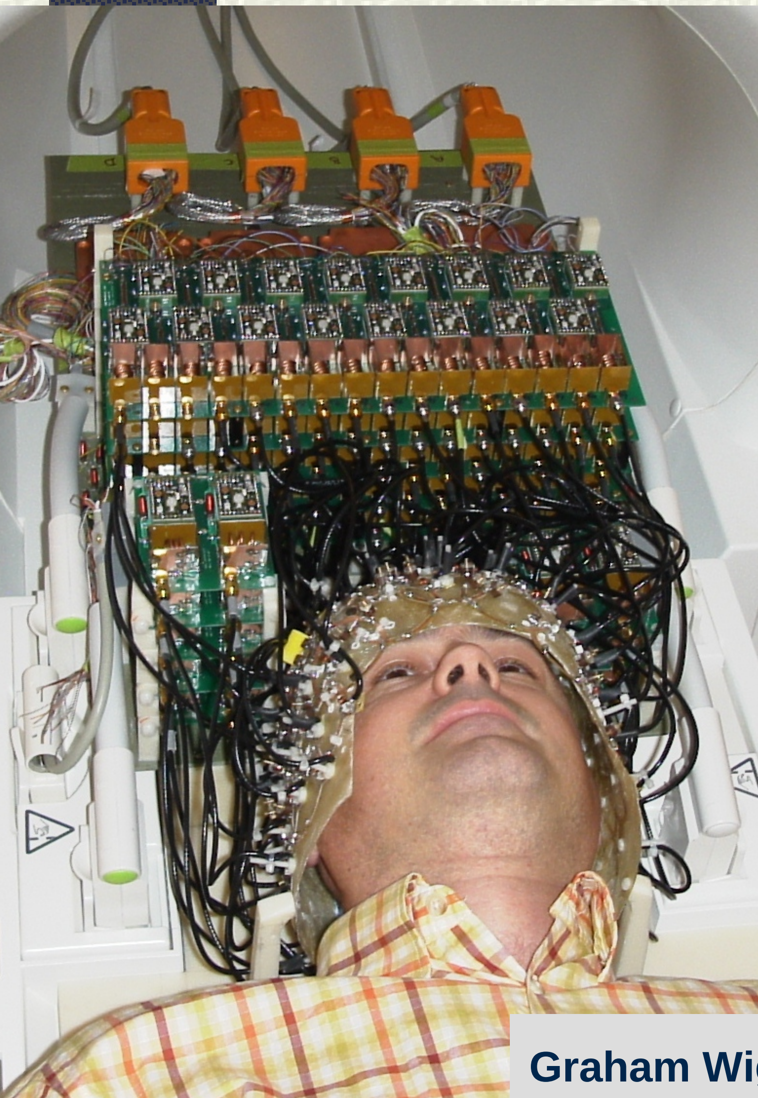
5 run

1 run

3T Retinotopic mapping

Triantafyllou, Hinds, MIT

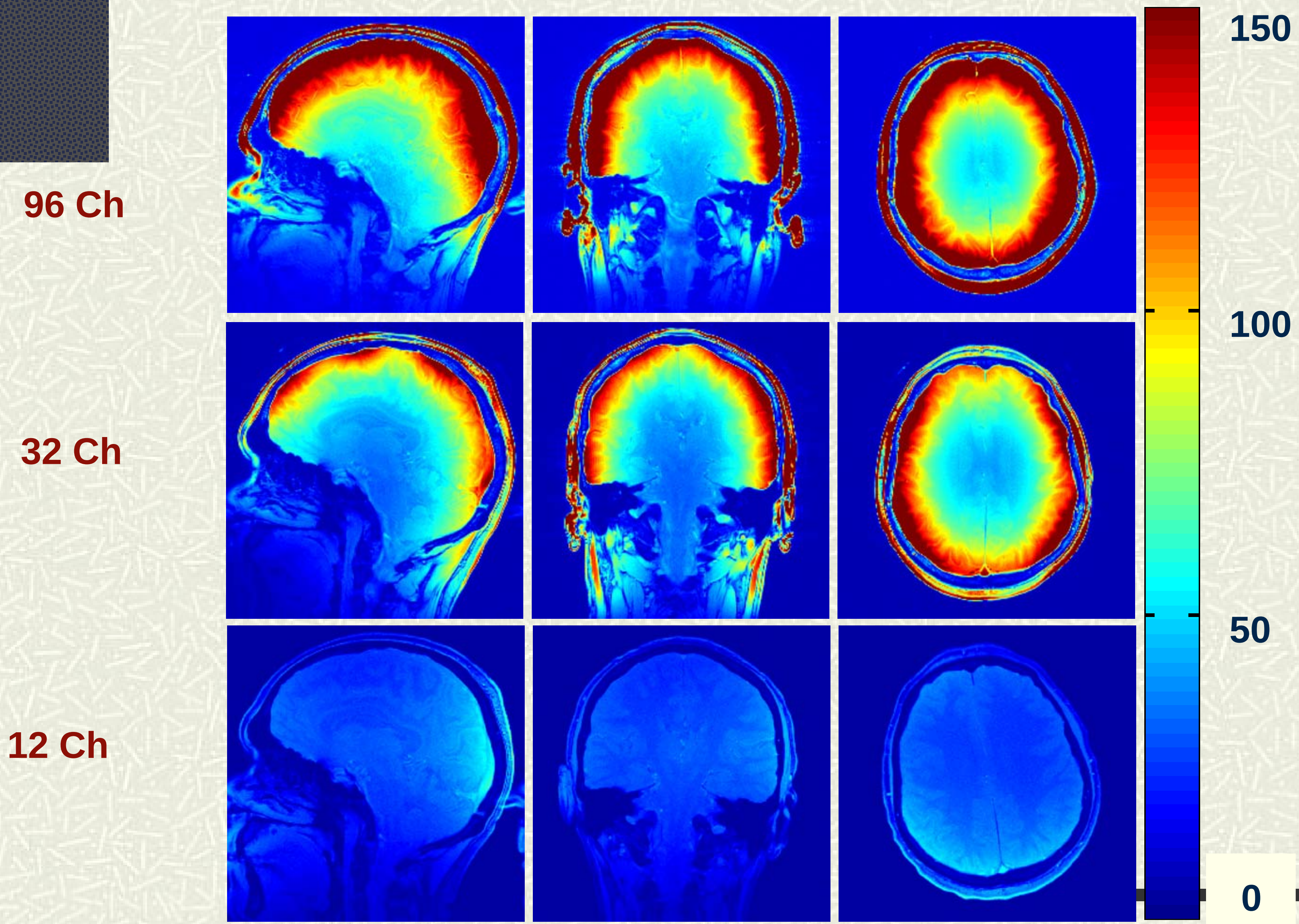
90 ch 1.5T



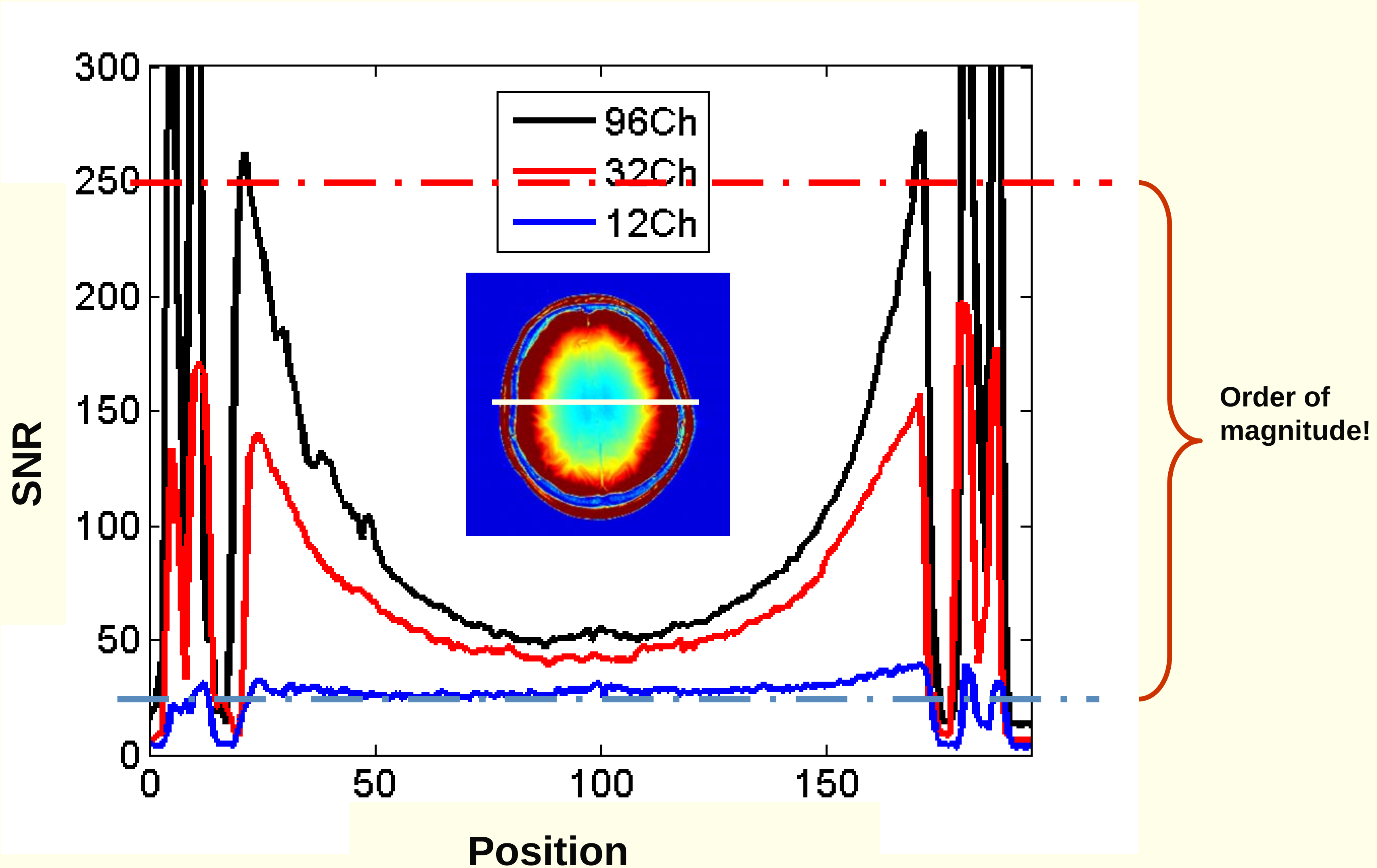
96 ch 3T

Graham Wiggins

3T SNR Maps



3T SNR Profiles



Questions, comments to:

Larry Wald