Basic MR image encoding

MGH-NMR Center

HST.583: Functional Magnetic Resonance Imaging: Data Acquisition and Analysis
Harvard-MIT Division of Health Sciences and Technology
Dr. Larry Wald

Physical Foundations of MRI

What is NMR?

The basic signal we excite and detect.

Tricks of NMR

The gradient and spin echo

How do we encode an image?

slice select, frequency and phase encoding.

What are some problems (artifacts) relevant to our application.

Physical Foundations of MRI

NMR: 60 year old phenomena that generates the signal from water that we detect.

MRI: using NMR to generate an image

Three magnetic fields (generated by 3 coils)

1) static magnetic field Bo
2) RF field that excites the spins B1
3) gradient fields that encode spatial info G_x, G_y, G_z

What is NMR?

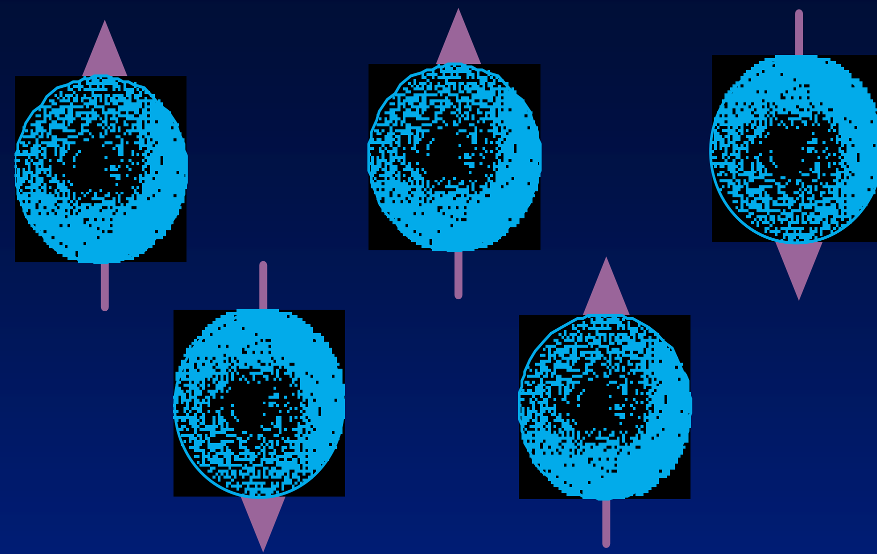
NUCLEAR

MAGNETIC

RESONANCE

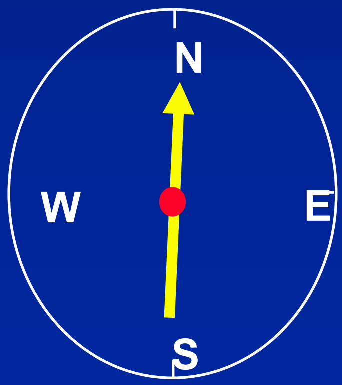
A magnet, a glass of water,
and a radio wave source and detector….

B



protons

Earth's
Field



compass

Nuclei and Magnetic Fields

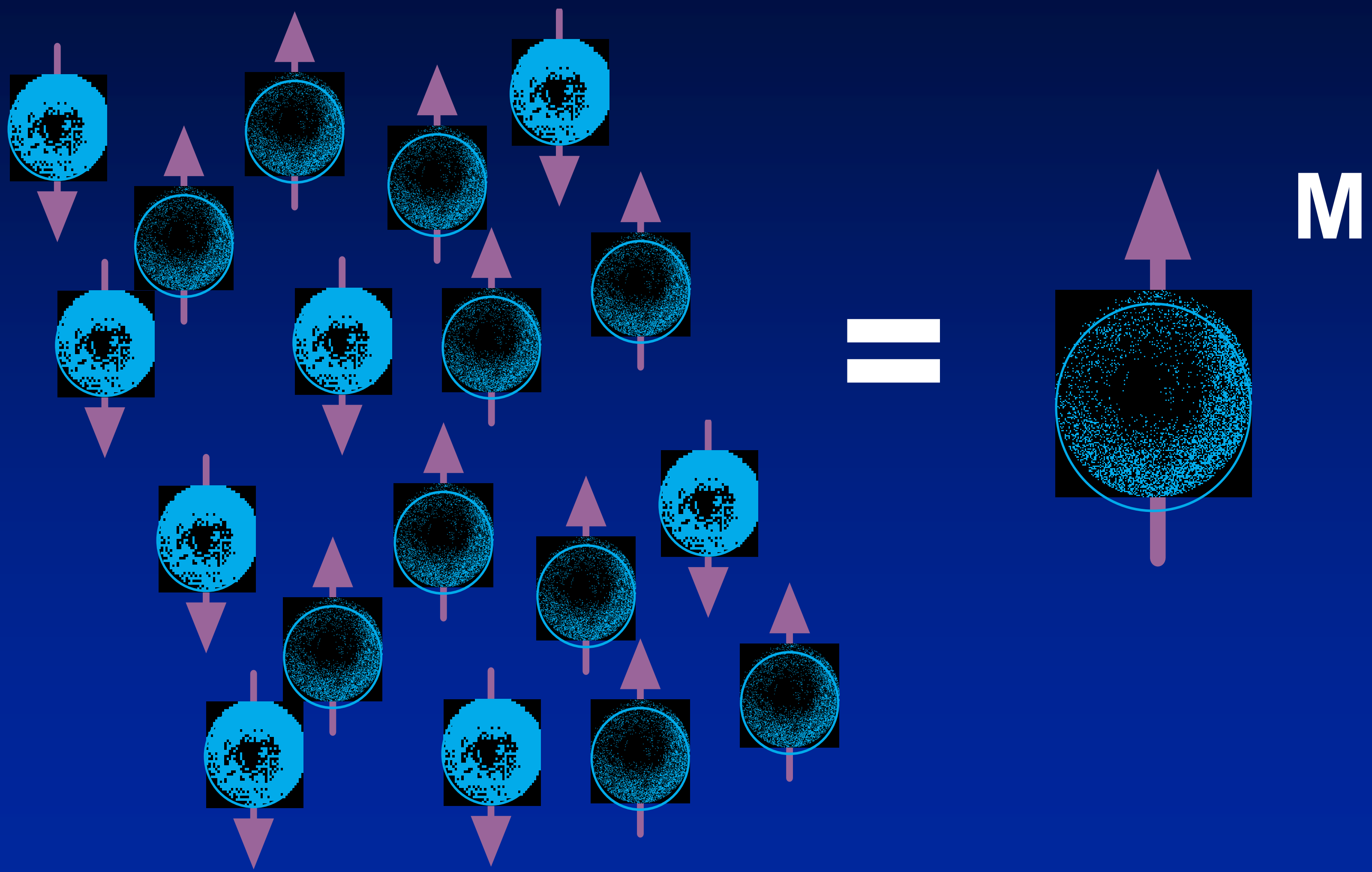
Not every nucleus lines up with applied magnetic field.

Why?

Direction of spins becomes randomized by thermal motion.

protons at 1.5 Tesla, at room temperature

net # aligned with field is 1 part in 100,000

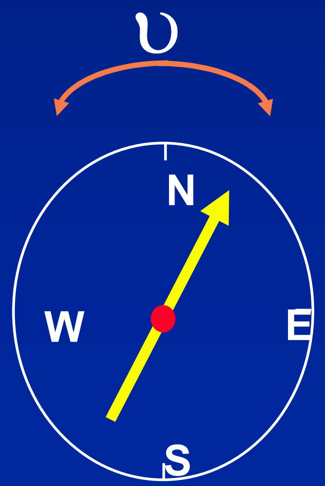

M

Compass needles

The vector sum of all the nuclei can be viewed as a compass needle.

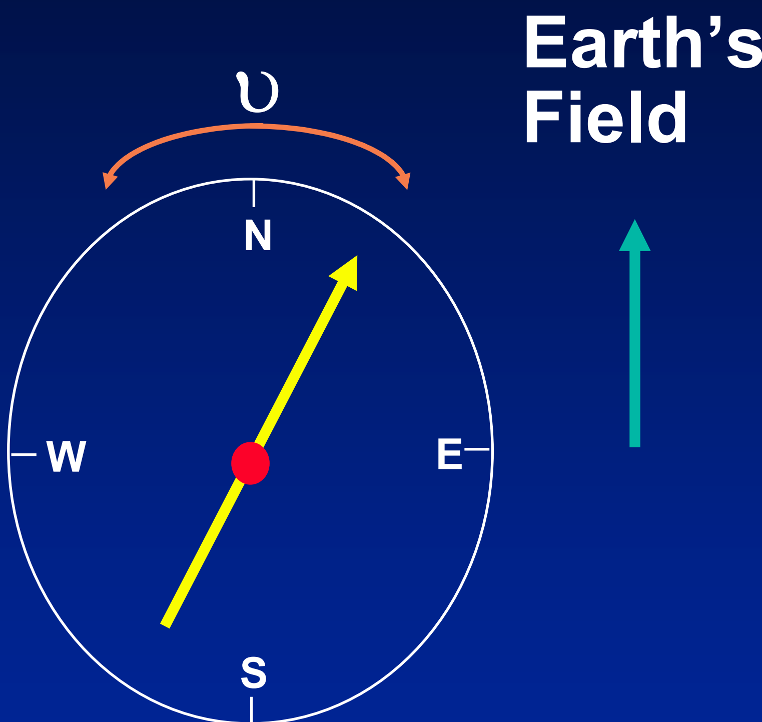
Points North. (aligns along the magnetic field lines of the external field (earth or MR magnet)

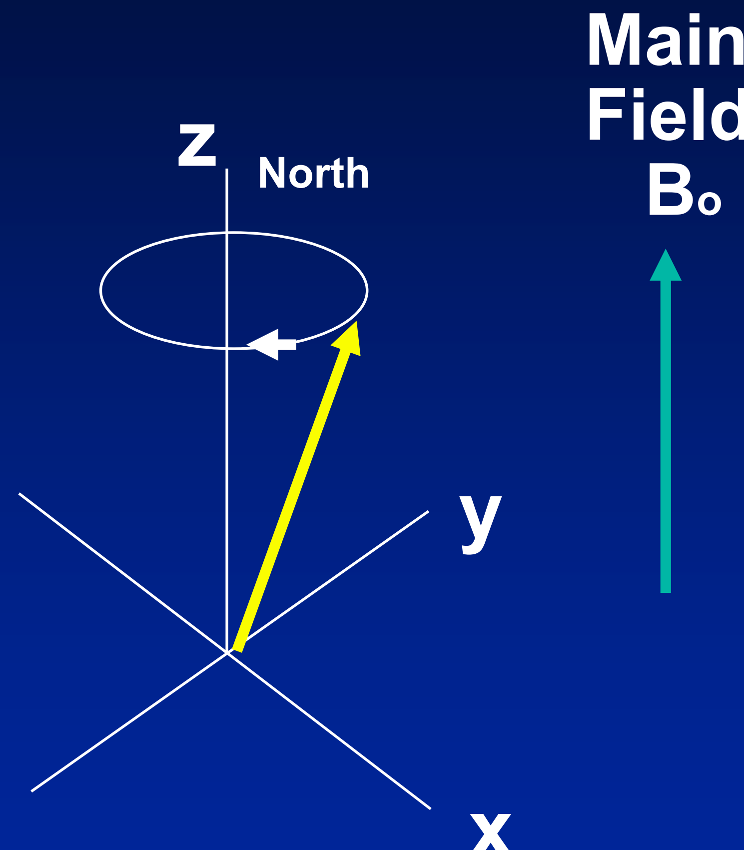
If displaced from North, it will wobble about north with a characteristic frequency (called Larmor freq.)



MGH-NMR Center

Compass needles





Freq = γ B

42.58 MHz/T

EXCITATION : Displacing the spins from Equilibrium (North)

Problem: It must be moving for us to detect it.

Solution: knock out of equilibrium so it oscillates

How? 1) Tilt the magnet or compass suddenly

2) Drive the magnetization (compass needle)

with a periodic magnetic field

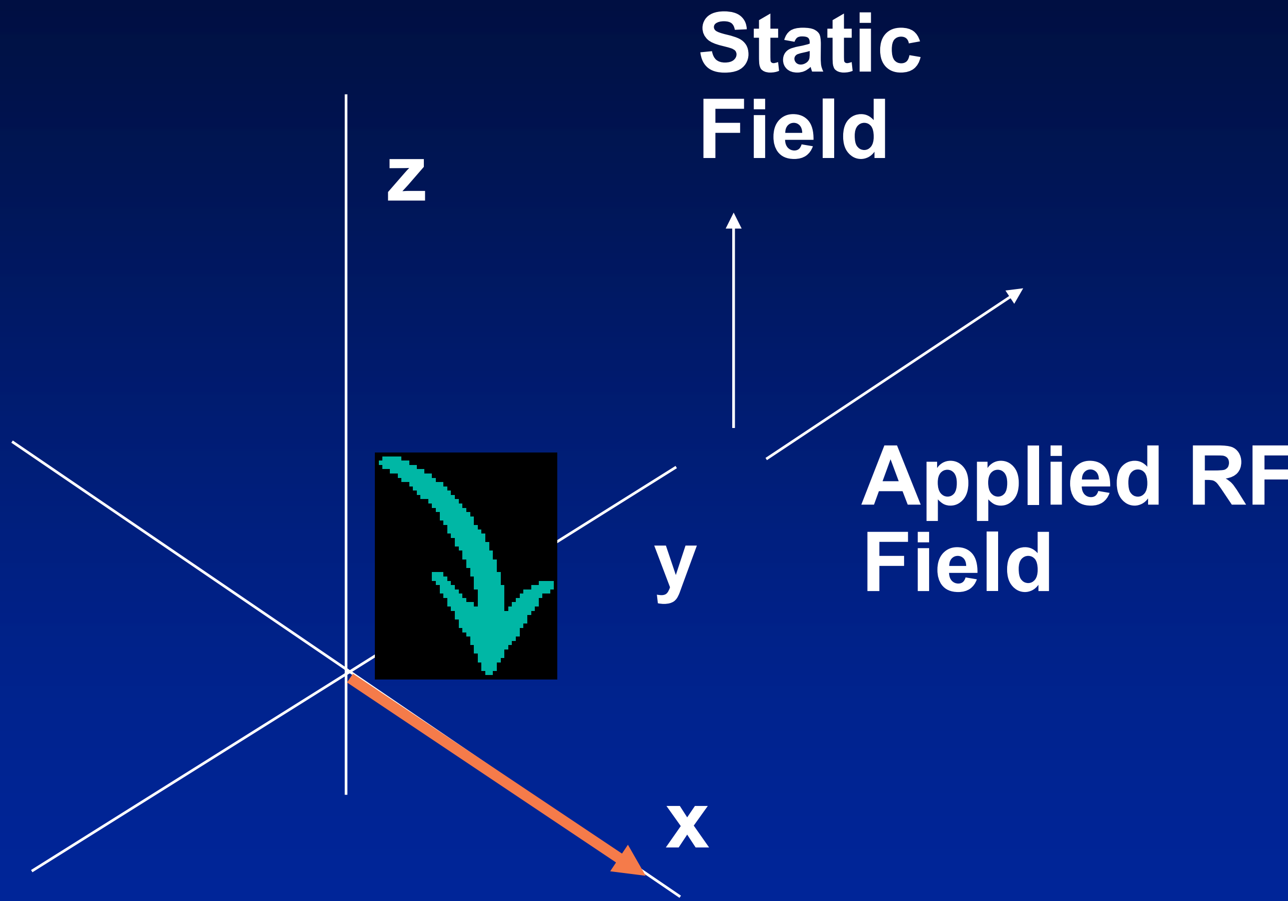
Excitation: Resonance

Why does only one frequency efficiently tip protons?

Resonant driving force.

It’s like pushing a child on a swing in time with the natural oscillating frequency.

z is "longitudinal" direction
x-y is "transverse" plane



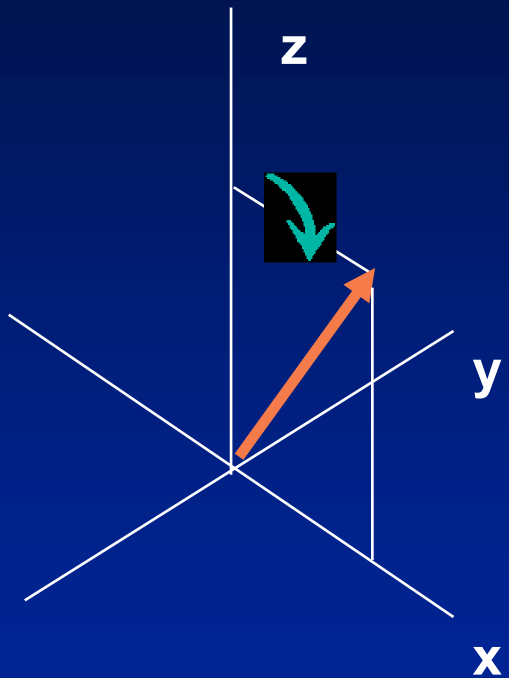
The RF pulse rotates Mo the about applied field

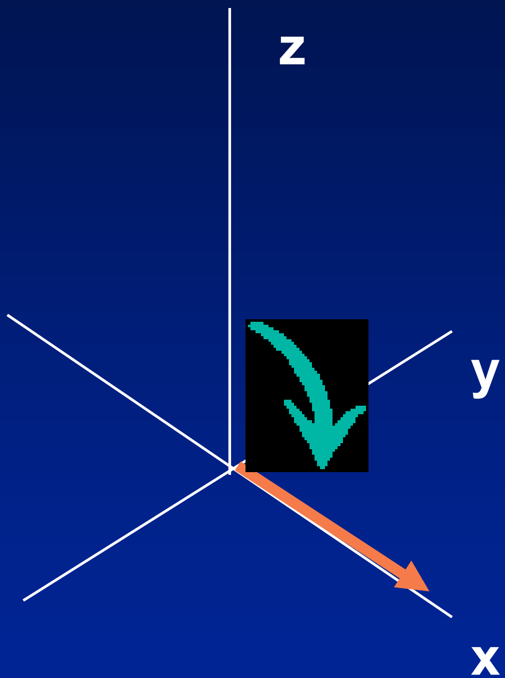
"Exciting" Magnetization

Magnetization processes about new axis (of oscillating RF B field) as long as resonant field is applied.

Total amount vector processes is called the "tip angle" of the excitation.

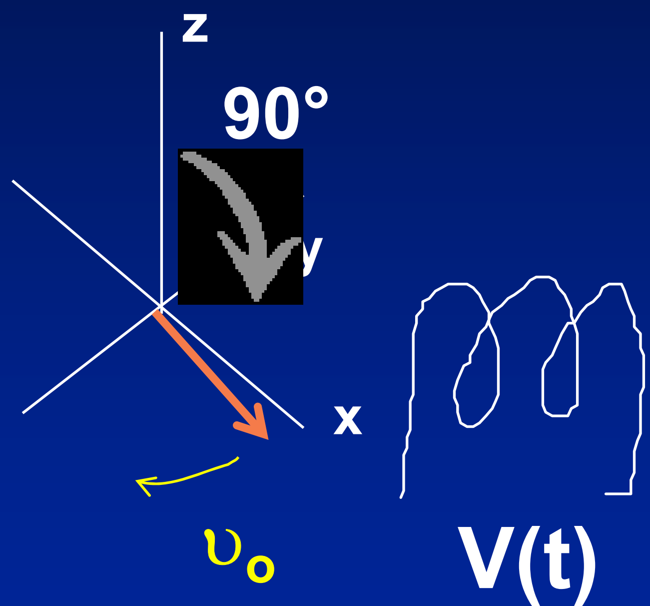
"Exciting" Magnetization
tip angle





MGH-NMR Center

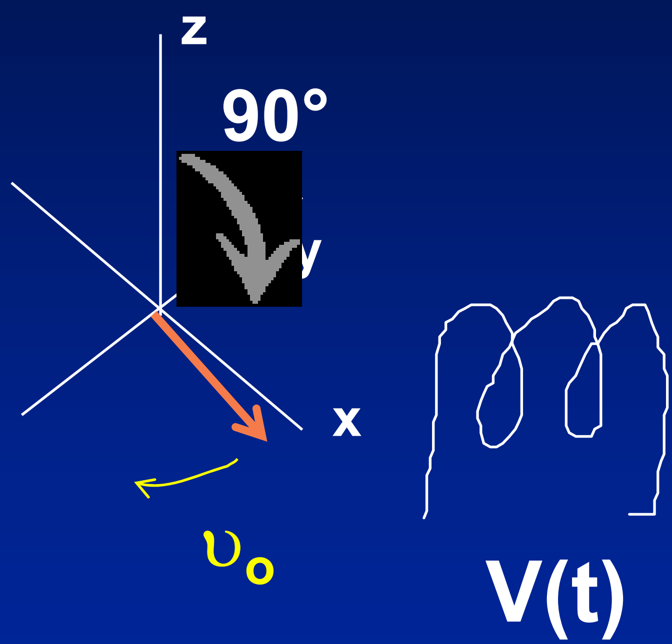
Detecting the NMR Signal



A moving bar magnet induces a Voltage in a coil of wire.
(a generator…)

The RF coil design is the #1 determinant of the system SNR

Detecting the NMR: the noise



Noise comes from electrical losses in the resistance of the coil or electrical losses in the tissue.

For a resistor:
Pnoise = 4kTRB

- Noise is white.
  >>Power α bandwidth
- Noise is spatially uniform.
- R is dominated by the tissue.
  >> big coil is bad.

Signal to Noise Ratio in MRI

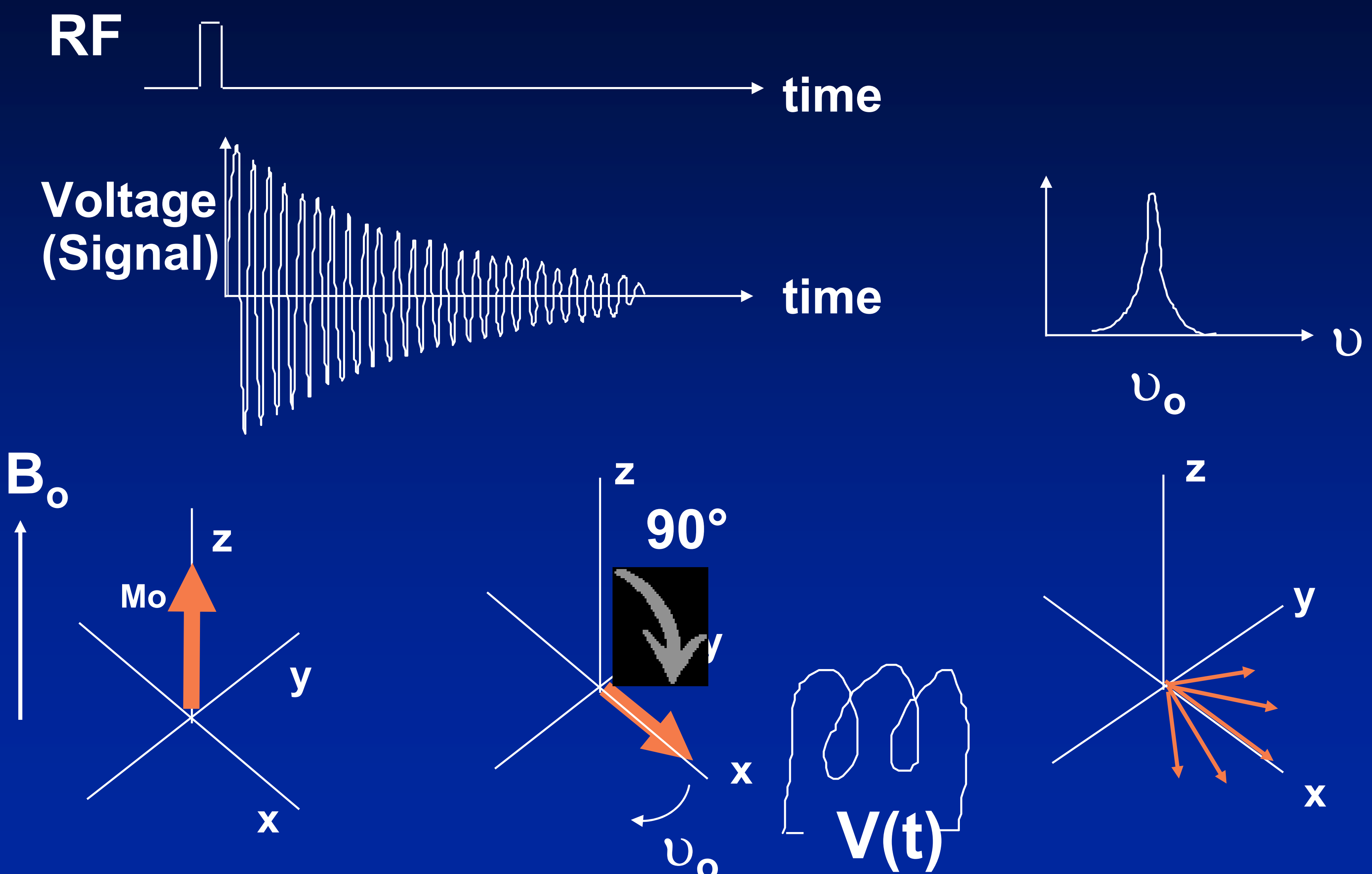
Most important piece of hardware is the RF coil.

SNR α voxel volume (# of spins)

SNR α SQRT(total time of data collection)

SNR is also dependent on the amount of signal you throw away to get contrast.

Review: the NMR Signal



Three Steps in MR:

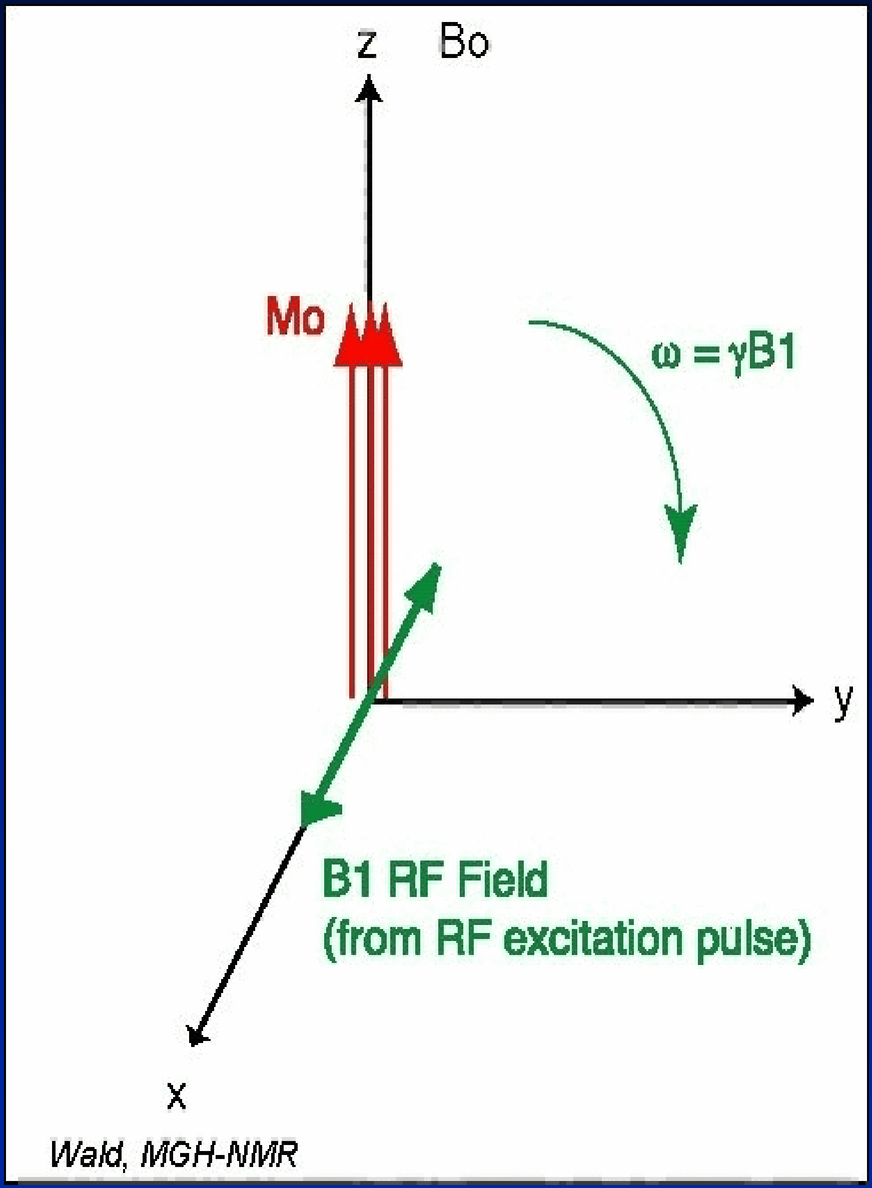
0) Equilibrium (magnetization points along Bo)

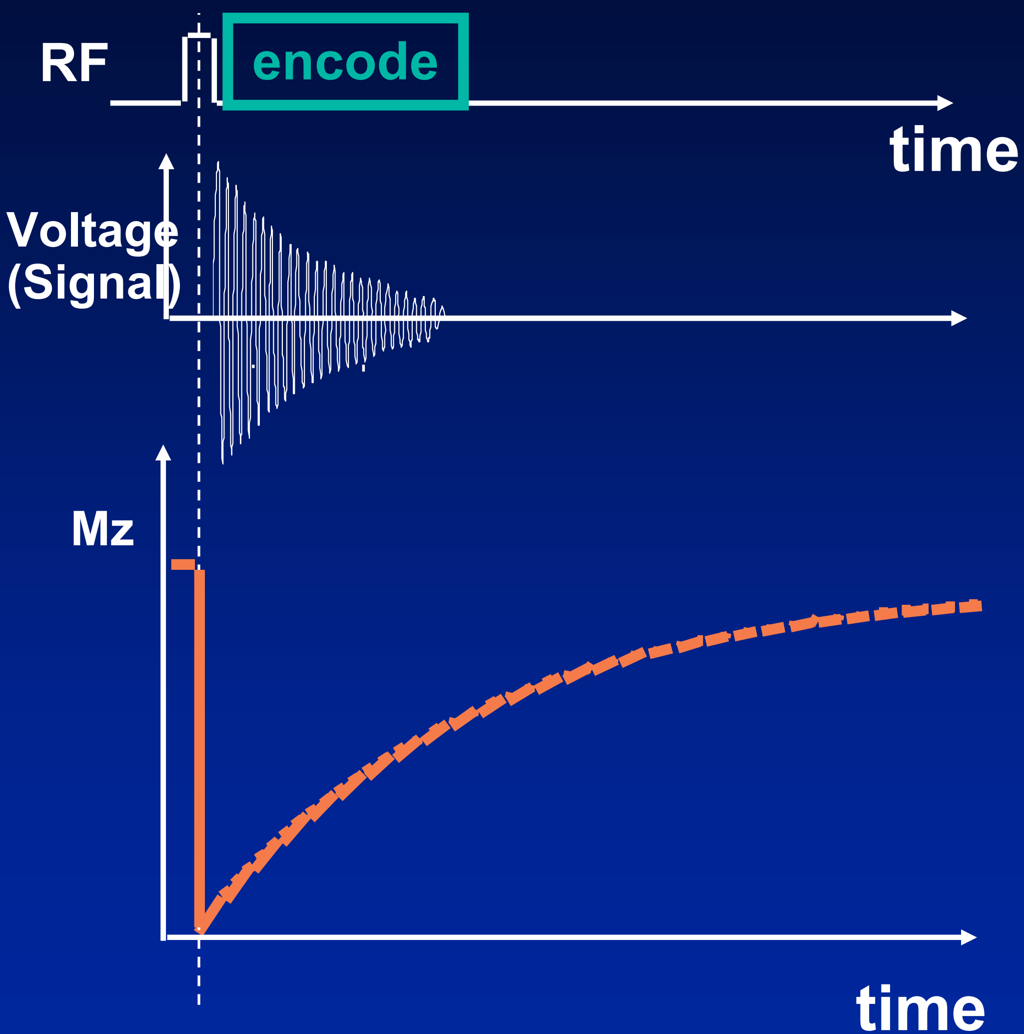
1) RF Excitation (tip magn. away from equil.)

2) Precession induces signal,
dephasing (timescale = T2, T2*).

3) Return to equilibrium (timescale = T1).

Magnetization vector durning MR





Three places in process to make a measurement (image)

0) Equilibrium (magnetization points along Bo)

1) RF Excitation (tip magn. away from equil.)

← proton density weighting

2) Precession induces signal, allow to dephase for time TE.

← T2 or T2* weighting

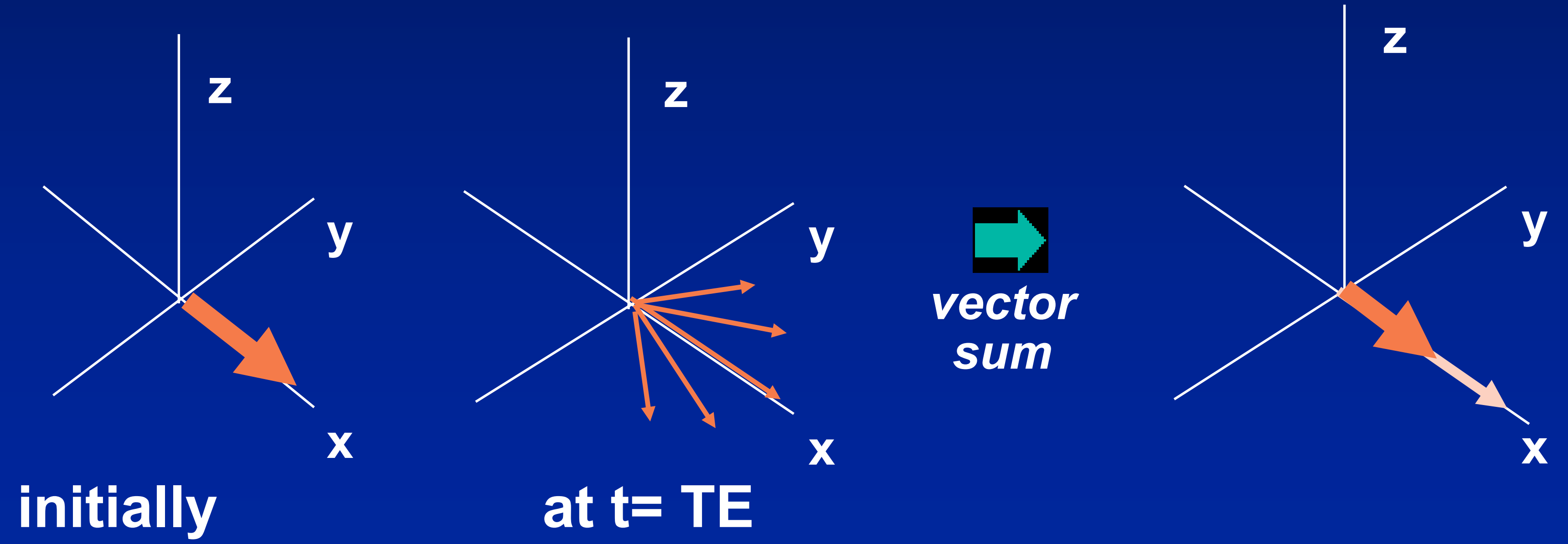
3) Return to equilibrium (timescale =T1).

← T1 Weighting

T2*-Weighting

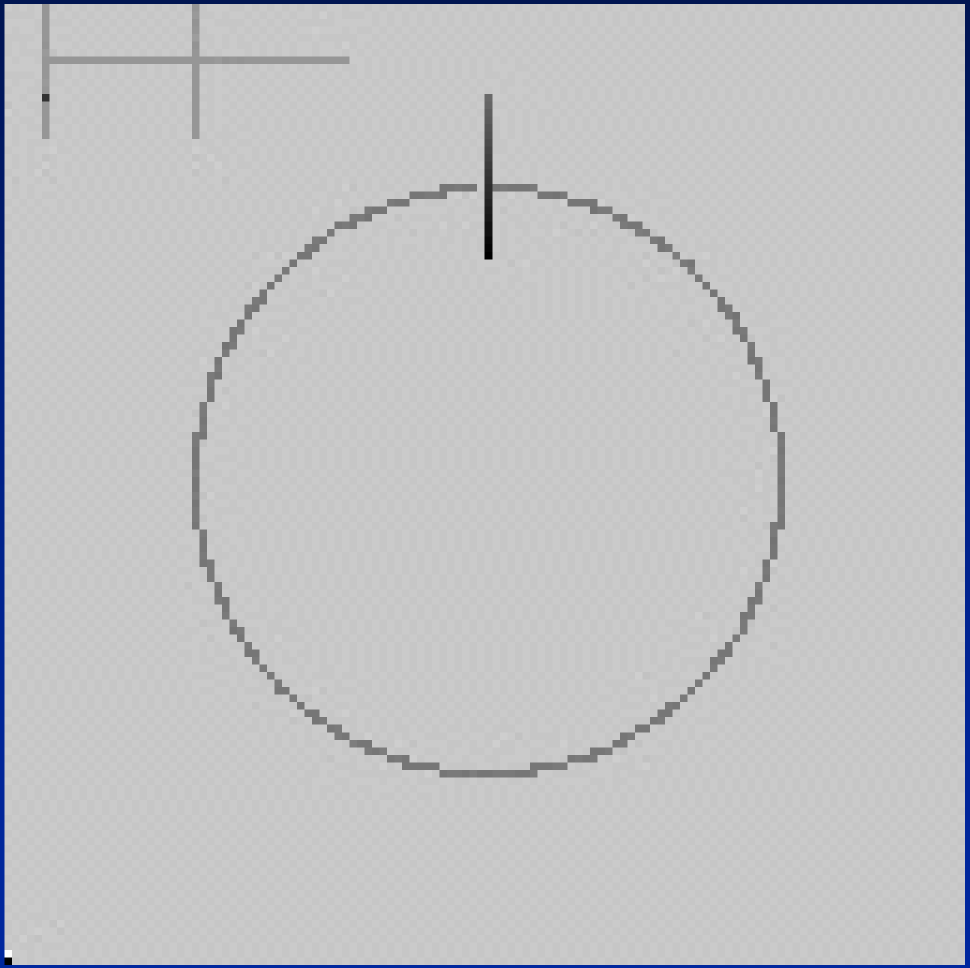
Wait time TE after excitation before measuring M.

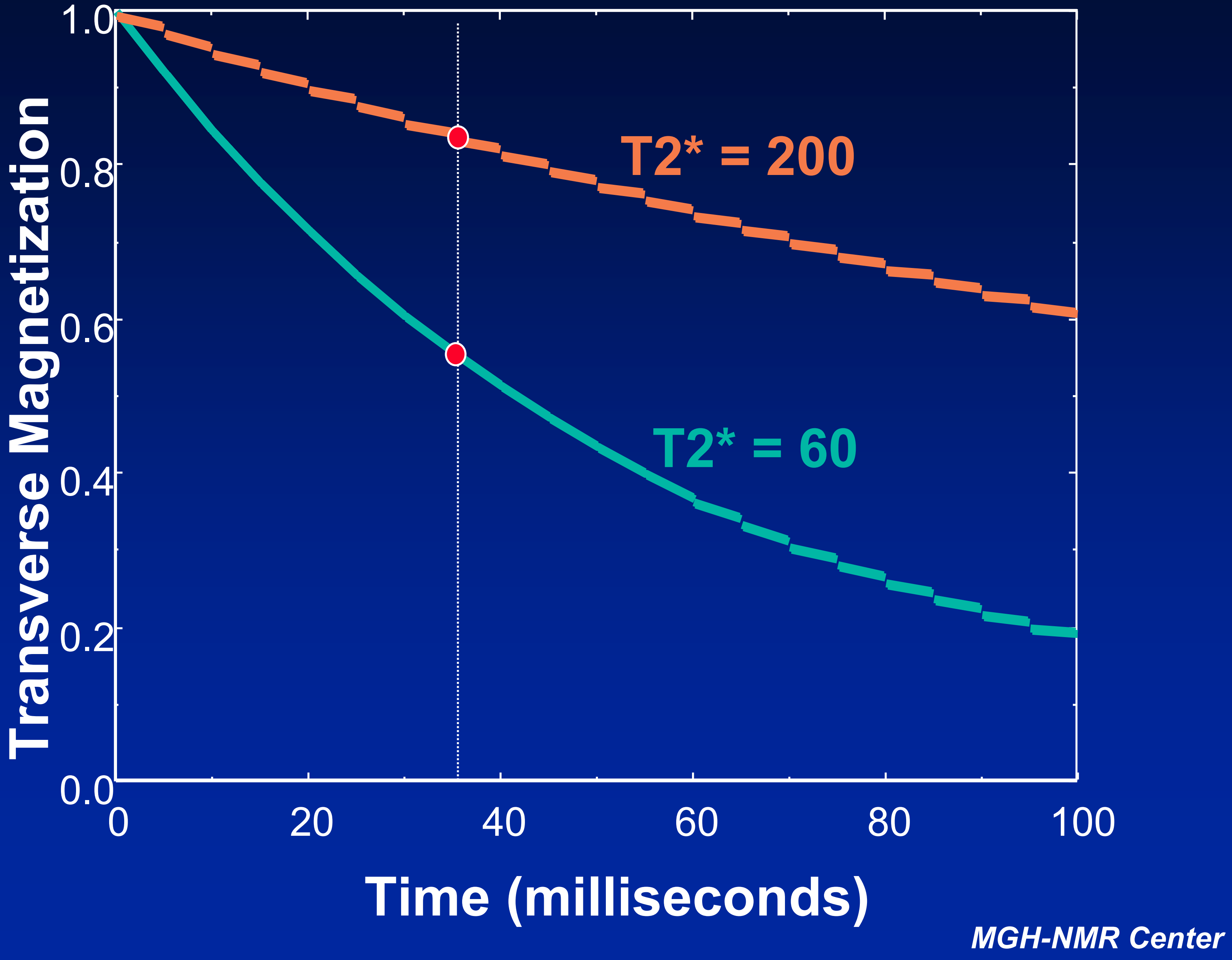
Shorter T2* spins have dephased



T2* Dephasing

Just the tips of the vectors…





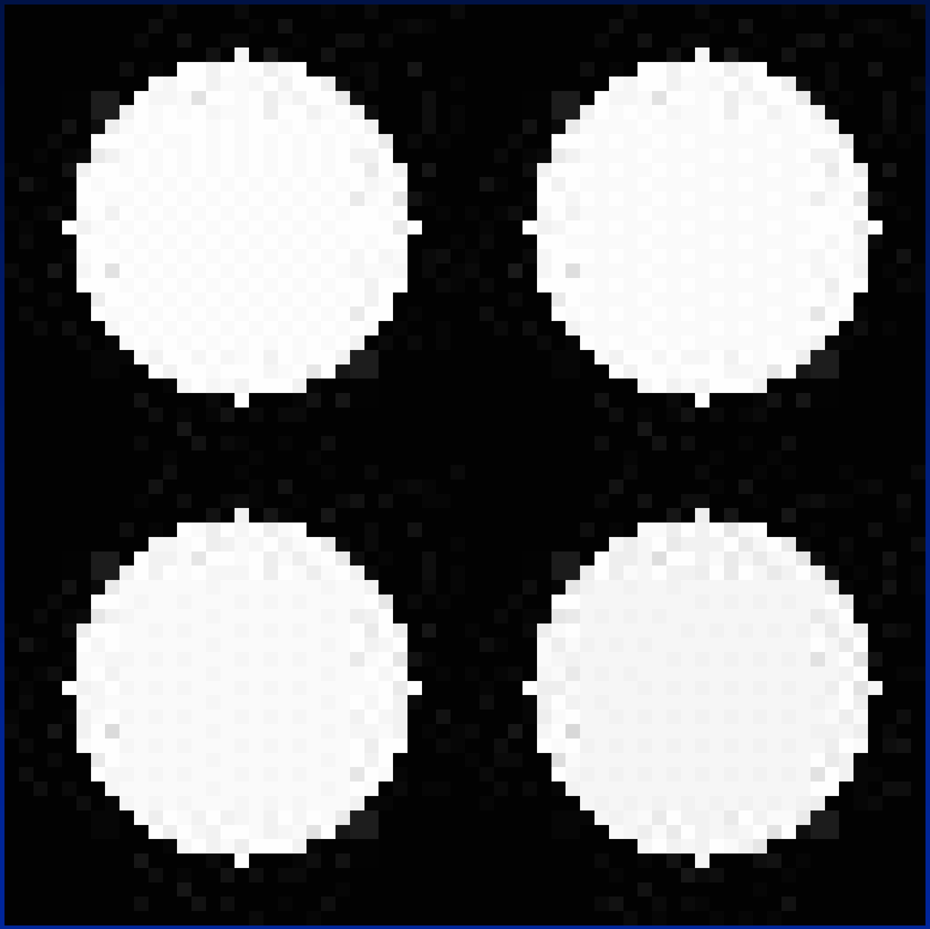
Transverse Magnetization
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
Time (milliseconds)
T2* = 200
T2* = 60
MGH-NMR Center

T2 Weighting

Phantoms with four different T2 decay rates...

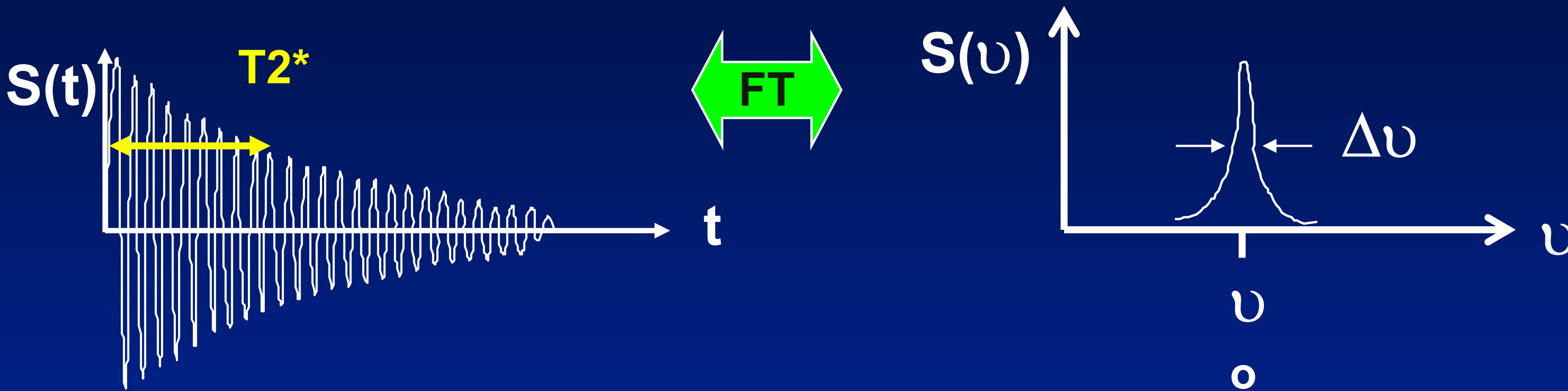
There is no contrast difference immediately after excitation, must wait (but not too long!).

Choose TE for max. inten. difference.

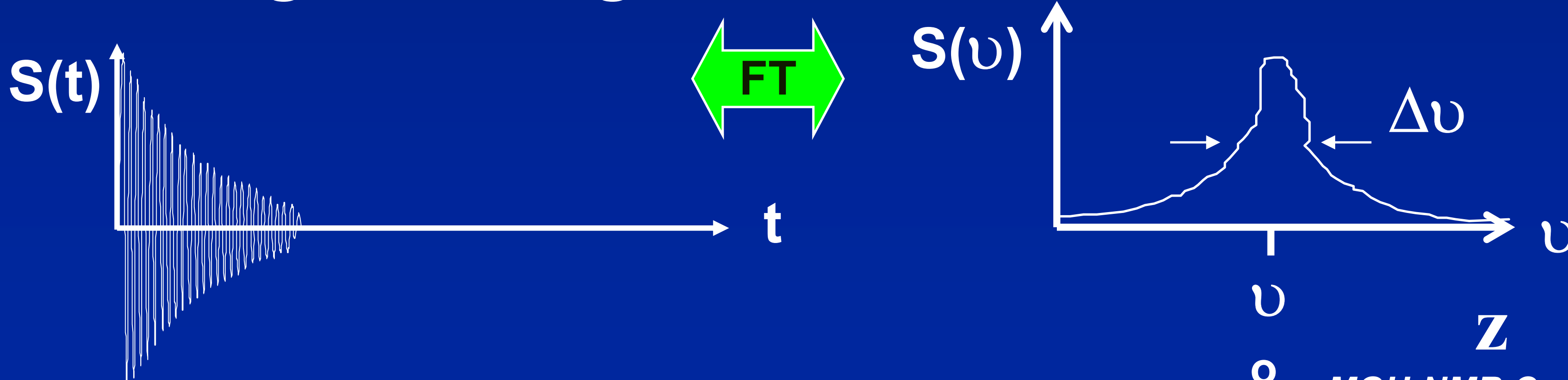


Dephasing: local field variations

homogeneous magnet.



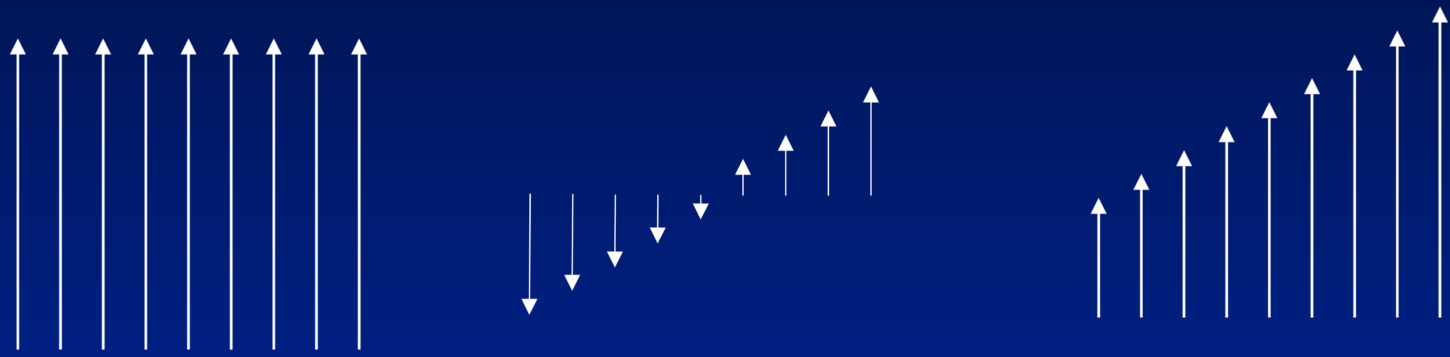
inhomogeneous magnet.



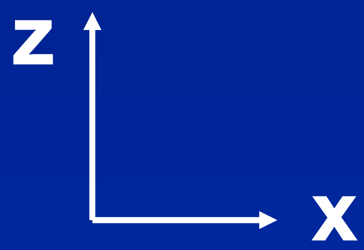
Z

Aside: Magnetic field gradient

B_o | $G_x\, x$ | $B_o + G_x\, x$



Uniform magnet | **Field from gradient coils** | **Total field**

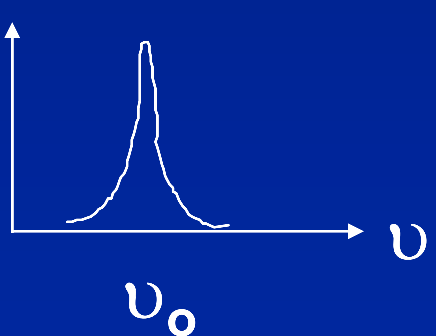


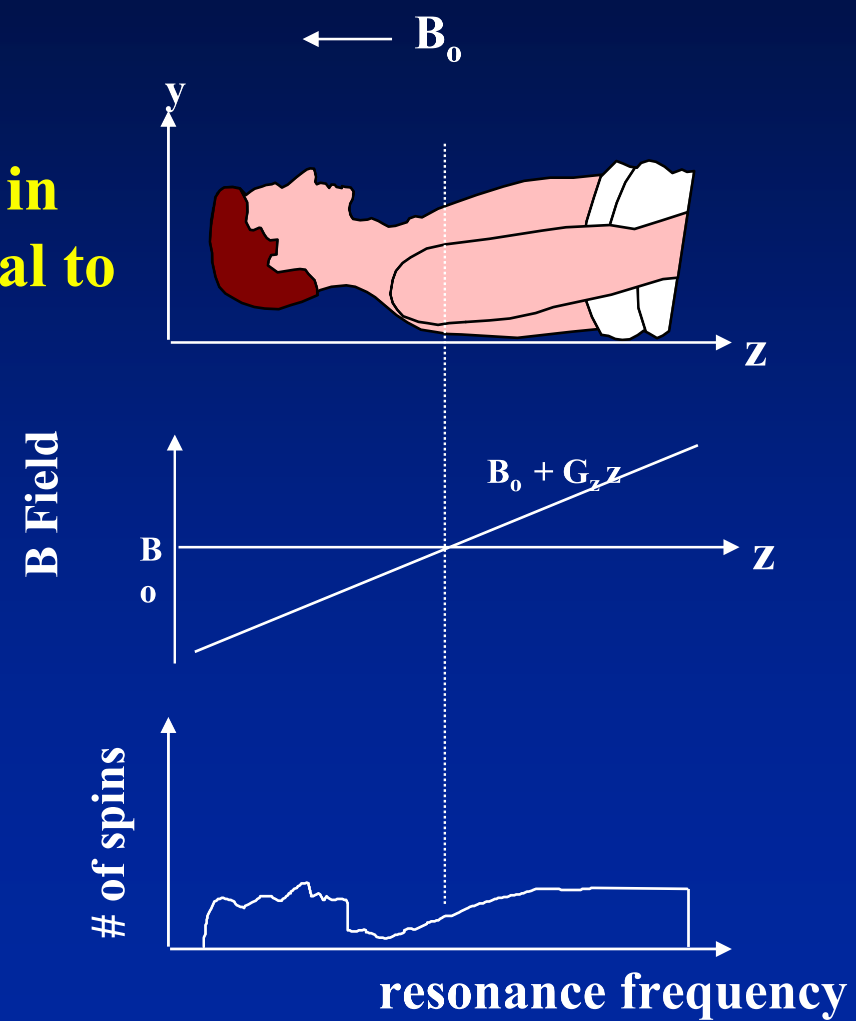
$$G_x = \partial B_z / \partial x$$

A gradient causes a spread of frequencies

MR frequency of the protons in a given location is proportional to the local applied field.

$$v = \gamma B_{TOT} = \gamma(B_o + G_z\, z)$$





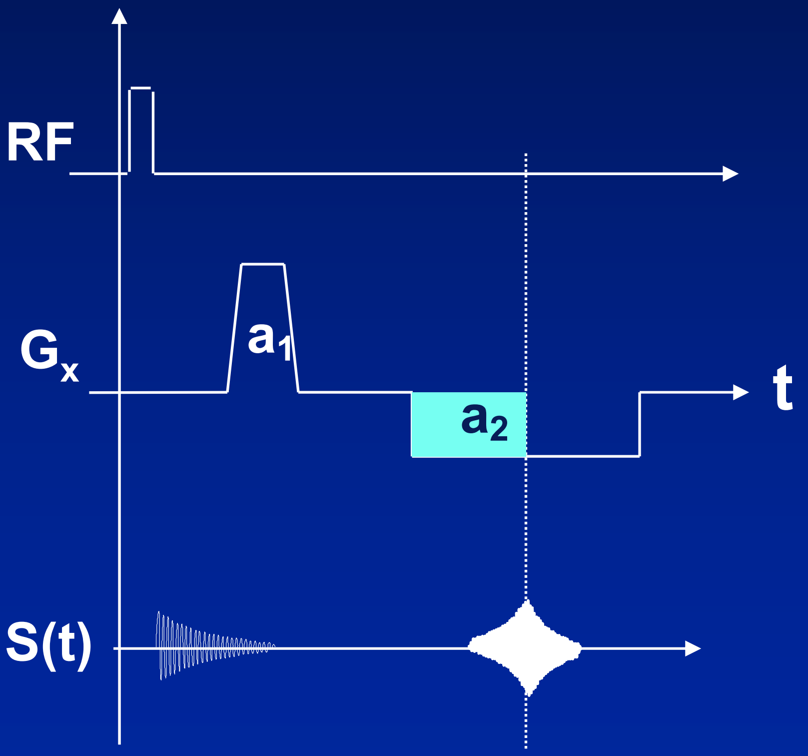
A gradient causes dephasing

I caused it, I can reverse it…
Gradient echo

$$\upsilon = \gamma B_{TOT} = \gamma\ B_o + G_z\ z$$

$$\Delta\upsilon = \gamma \Delta B_{TOT} = \gamma\ G_z\ z$$

$$\Delta\theta = \Delta\upsilon\ \tau = \gamma\ G_z\ z\ \tau$$



Gratuitous manipulation…
(?)

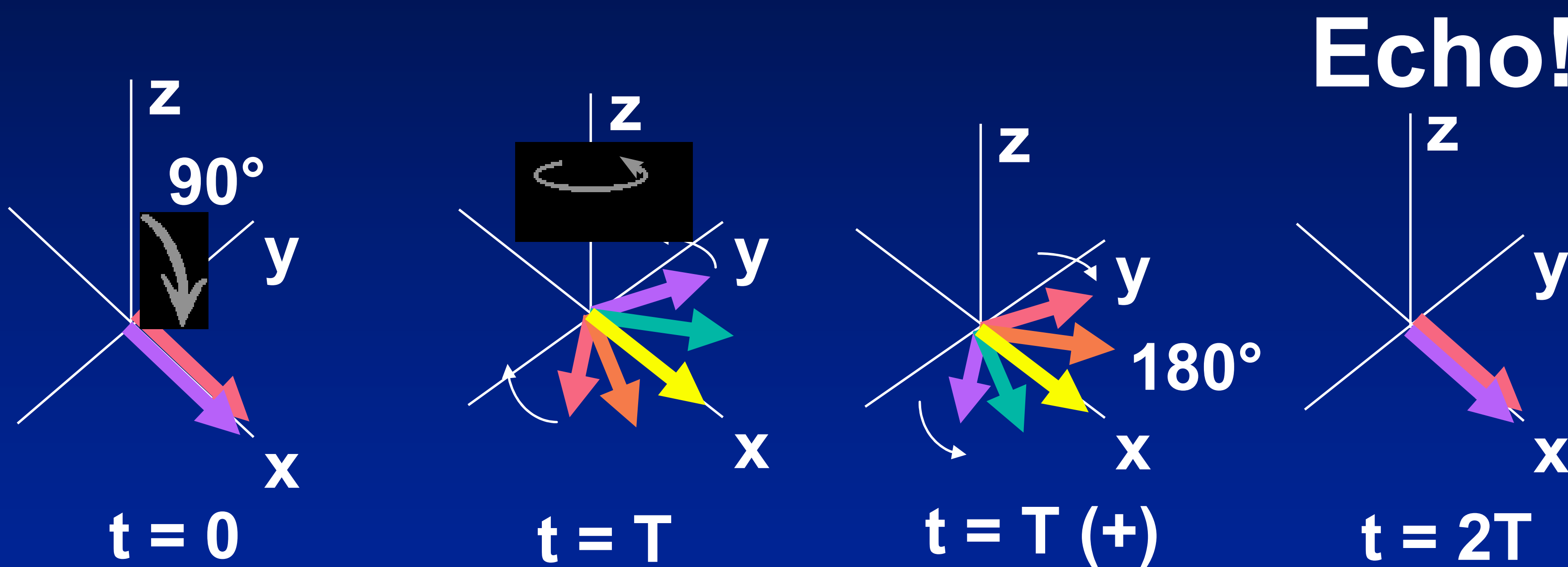
What happens if the spin moves?

Less trivial manipulation… the Spin Echo

Refocus the dephased signal without resorting to direct control of the B_o field.

Spin Echo

Some dephasing can be refocused because its due to static fields.



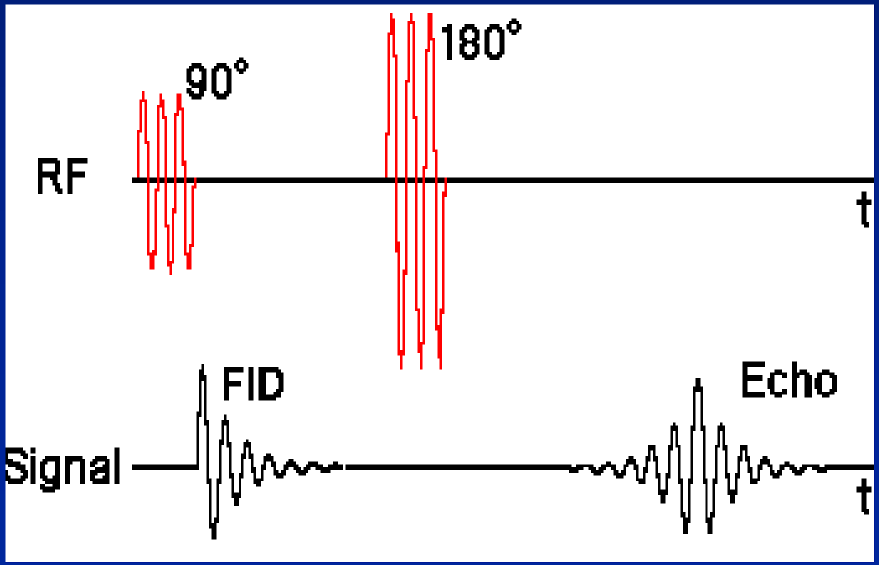
Blue/Green arrows precesses faster due to local field inhomogeneity than red/orange arrow

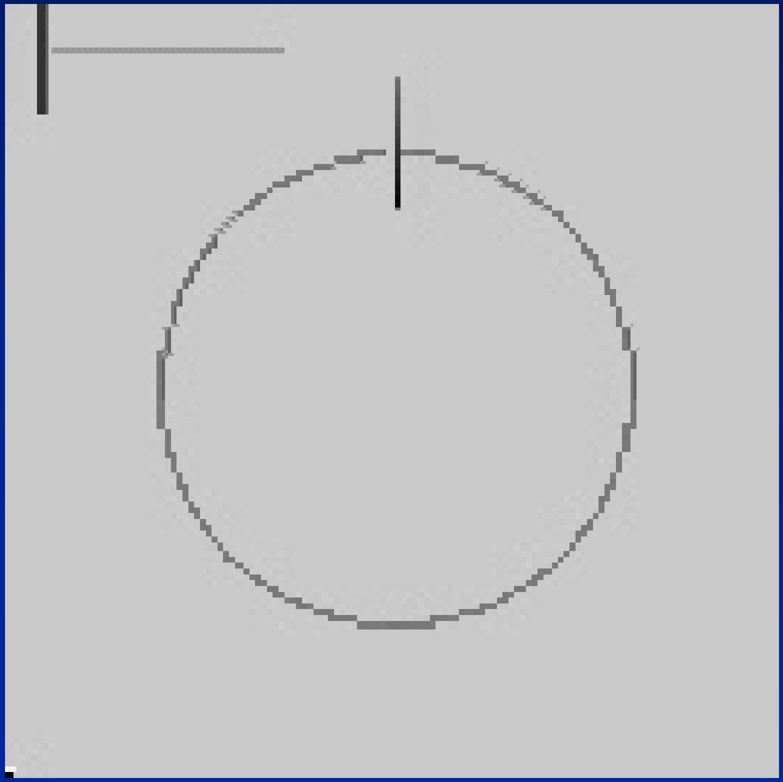
Spin Echo

180° pulse only helps cancel static inhomogeneity

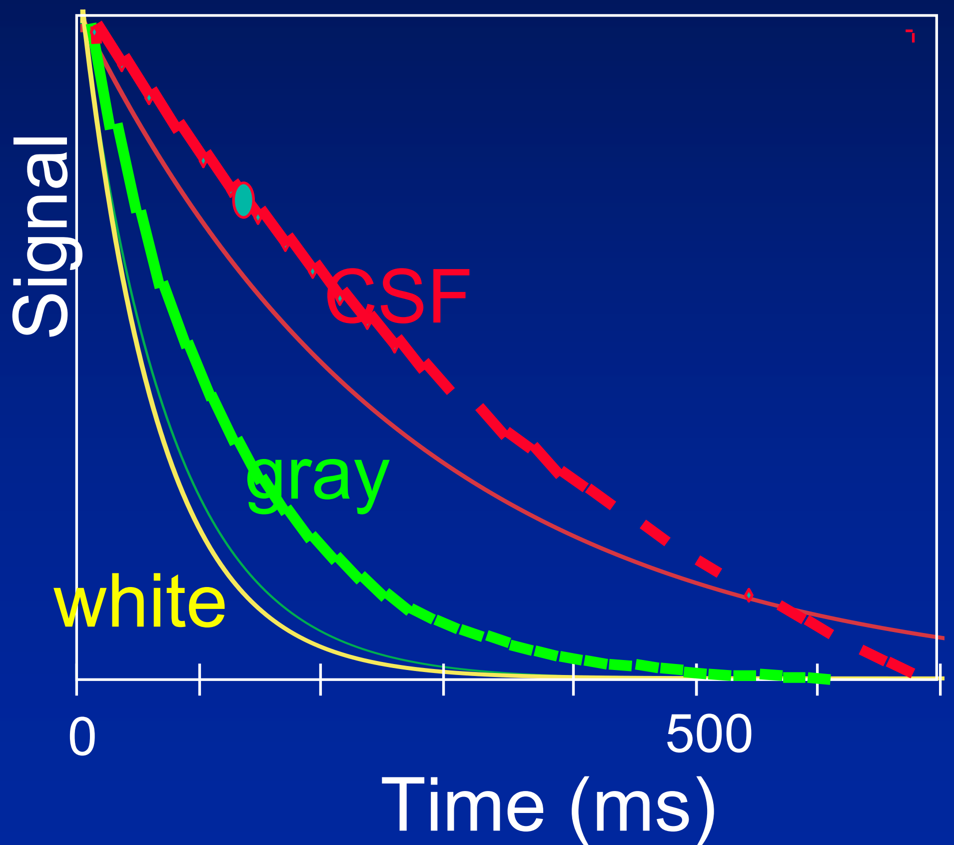
The “runners” can have <u>static</u> speed distribution.

If a runner trips, he will not make it back in phase with the others.





T2 weighed image



MGH-NMR Center

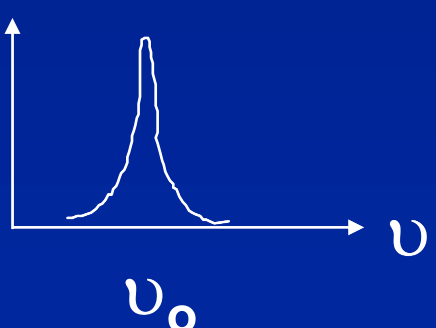
Part II

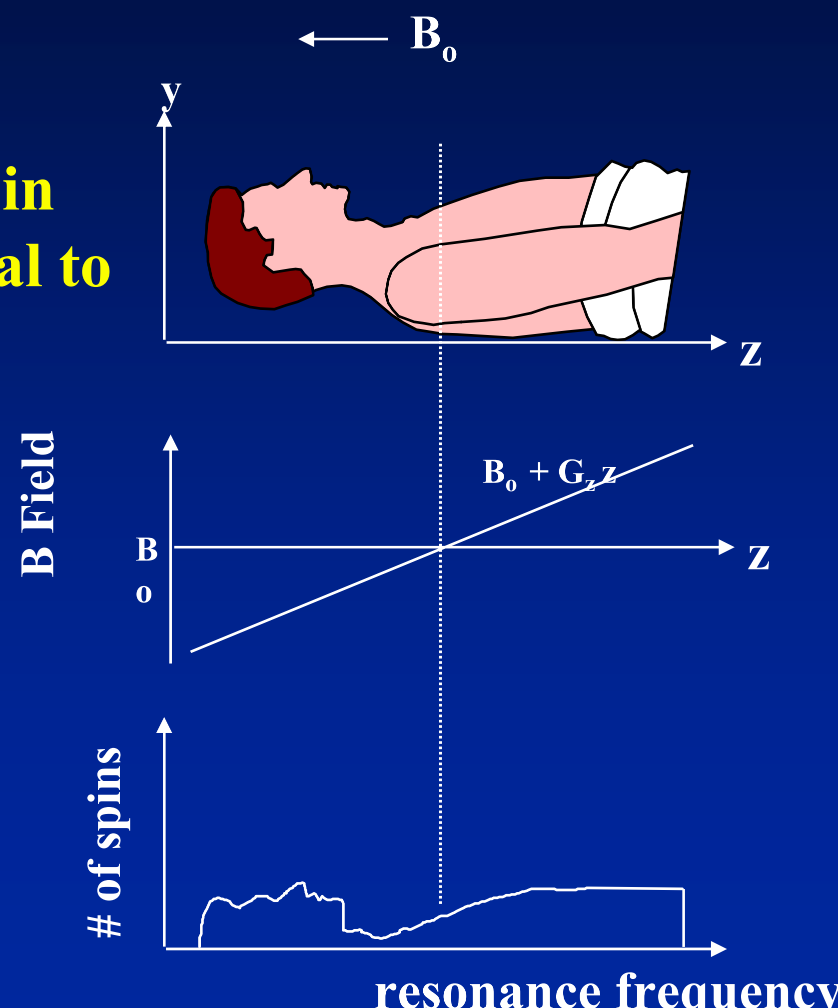
Image encoding

1D projection image

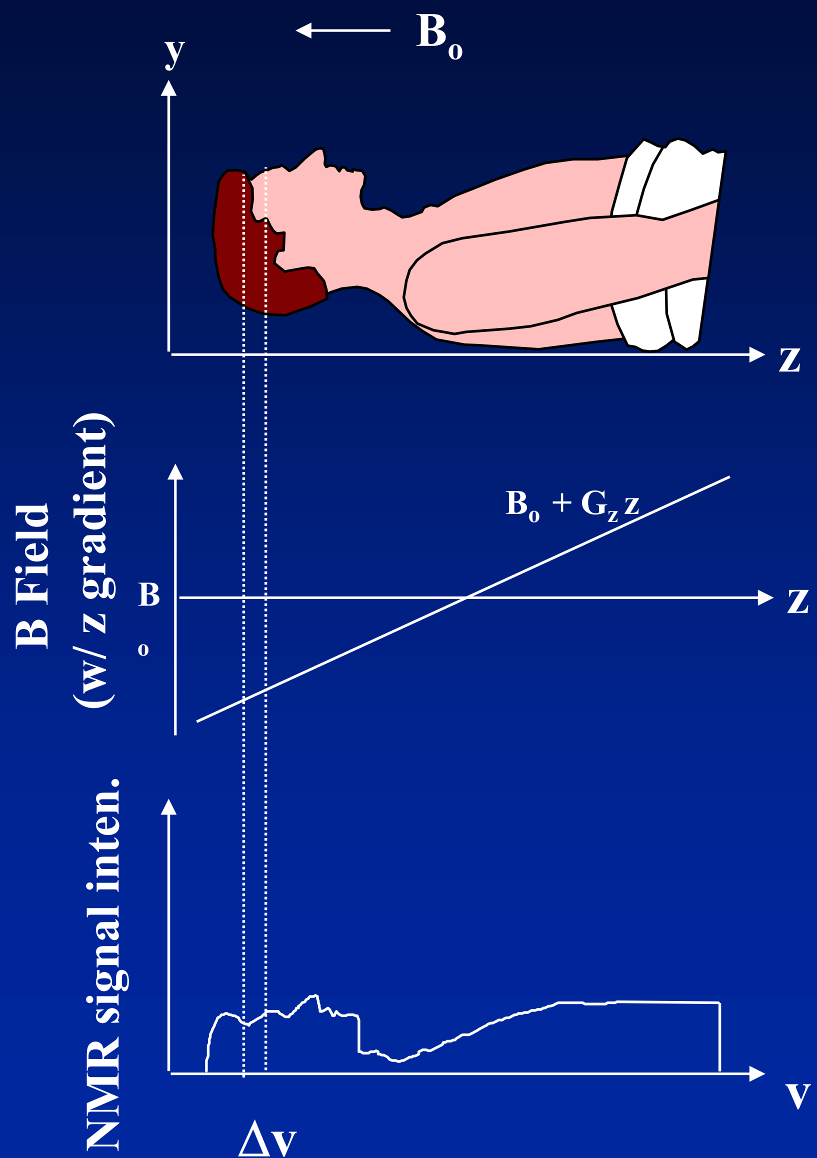
MR frequency of the protons in a given location is proportional to the local applied field.

$$v = \gamma B_{TOT} = \gamma(B_o + G_z z)$$

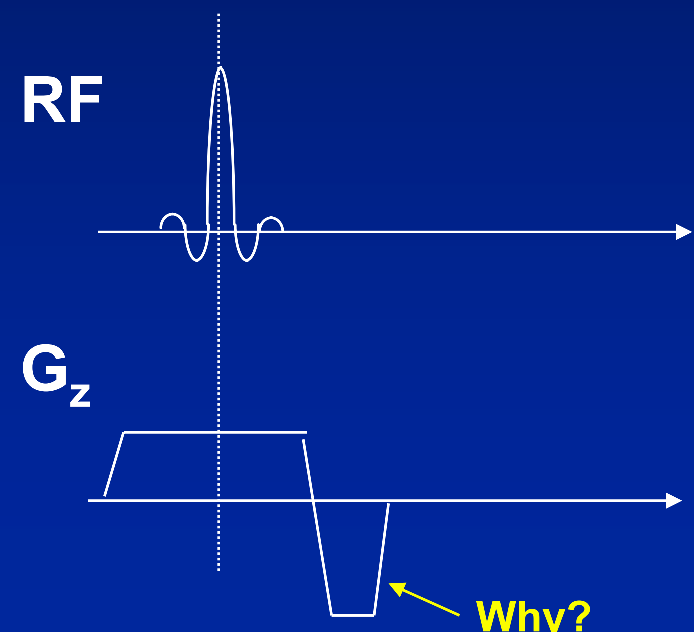




Step one: excite a slice

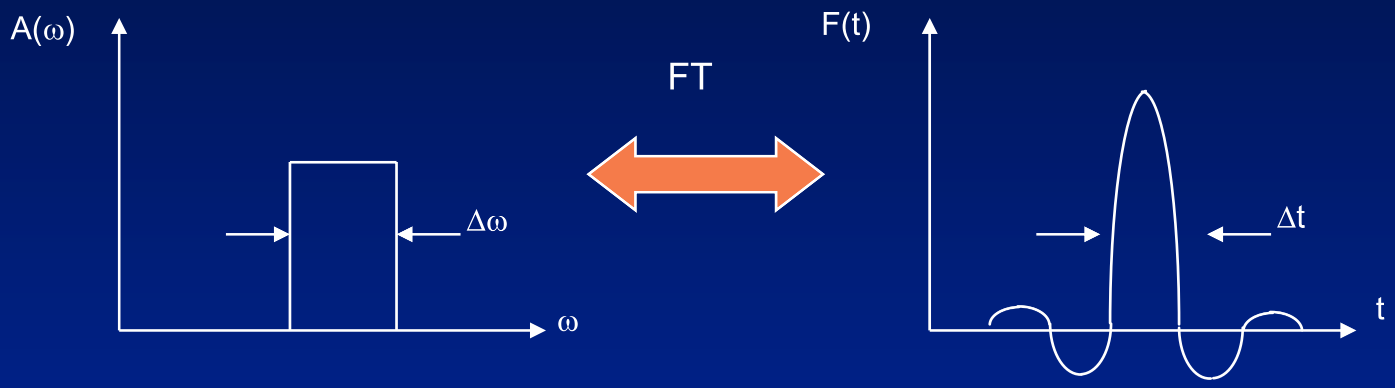


While the grad. is on, excite only band of frequencies.



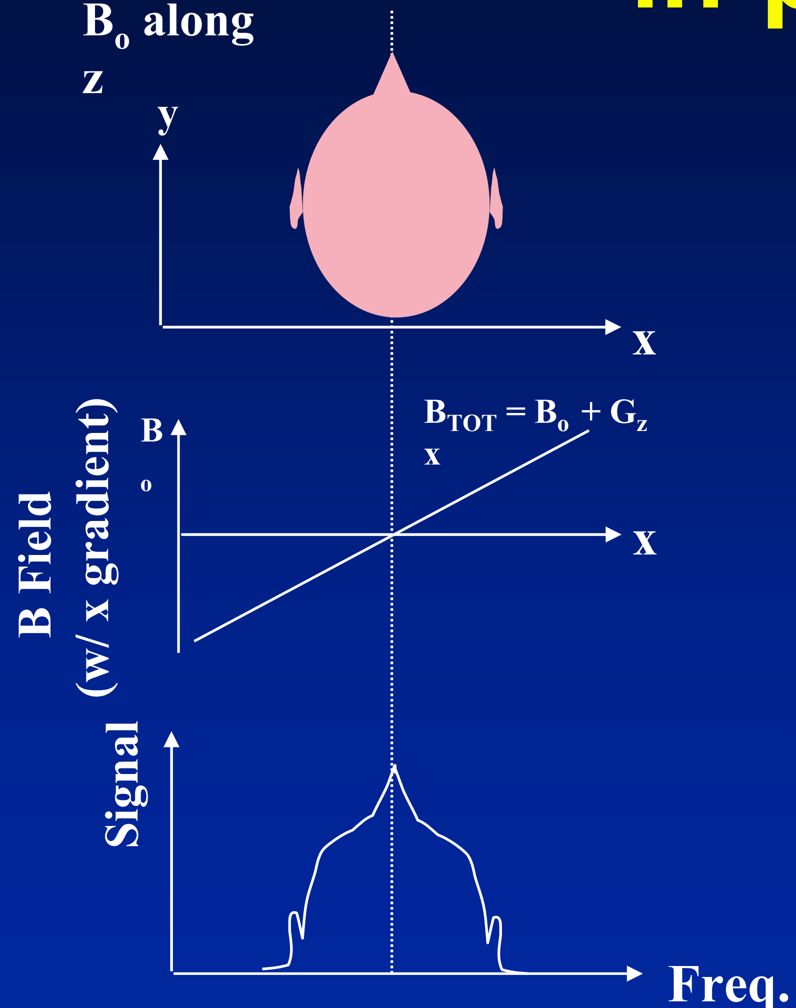
MGH-NMR Center

Slice profile considerations

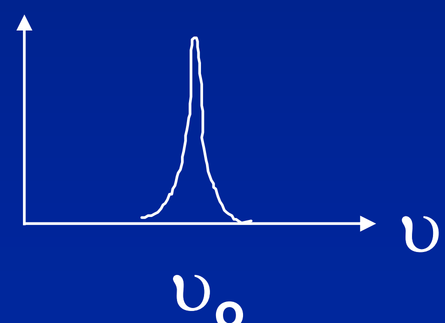


Step two: encode spatial info. in-plane

"Frequency encoding"

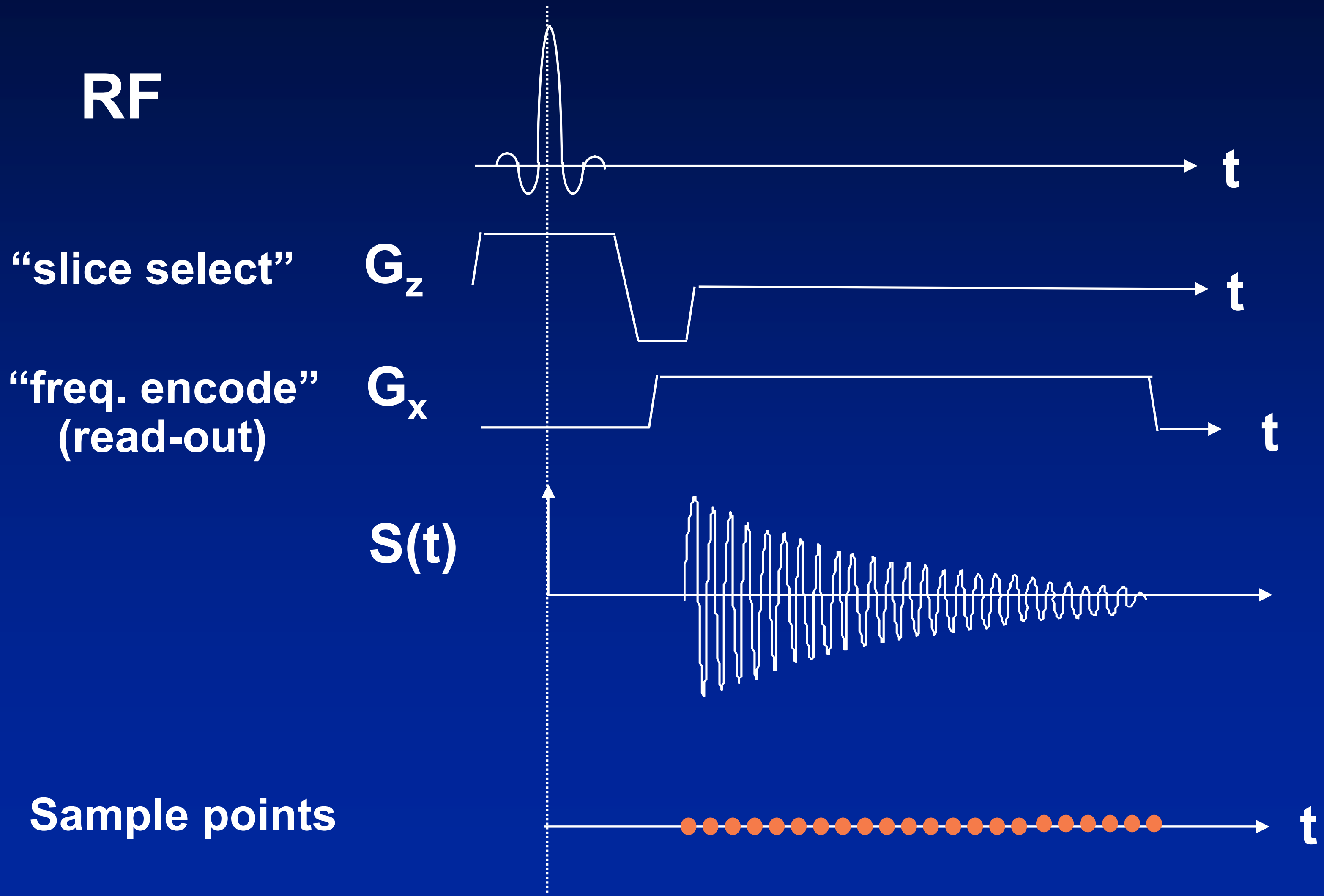


with gradient

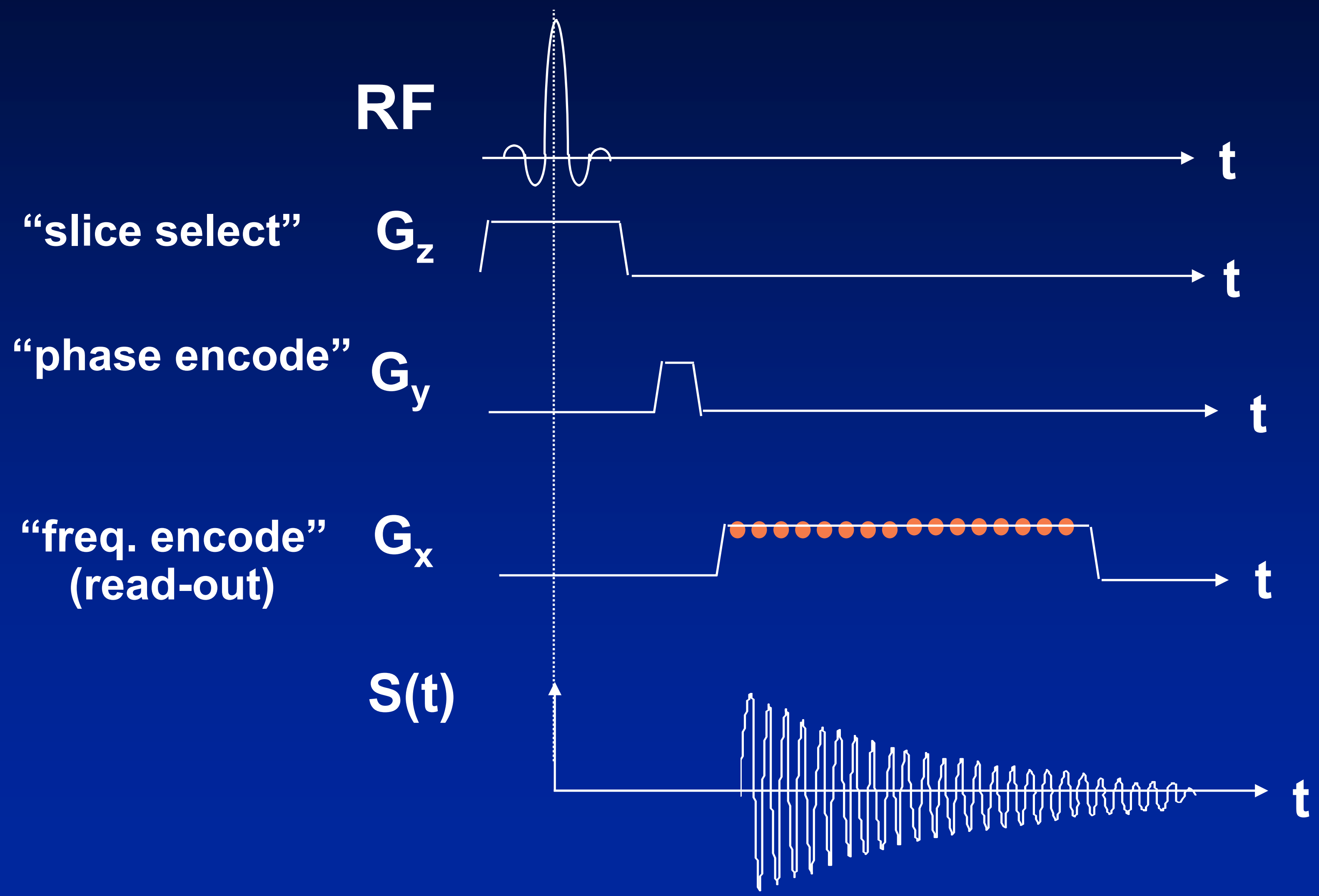


without gradient

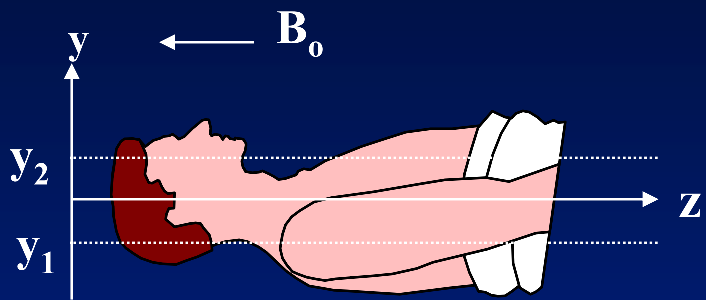
‘Pulse sequence’ so far

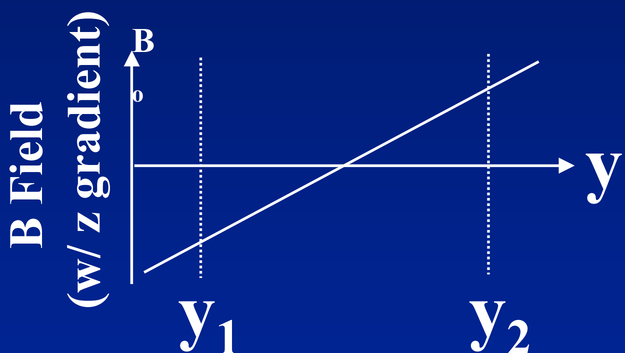


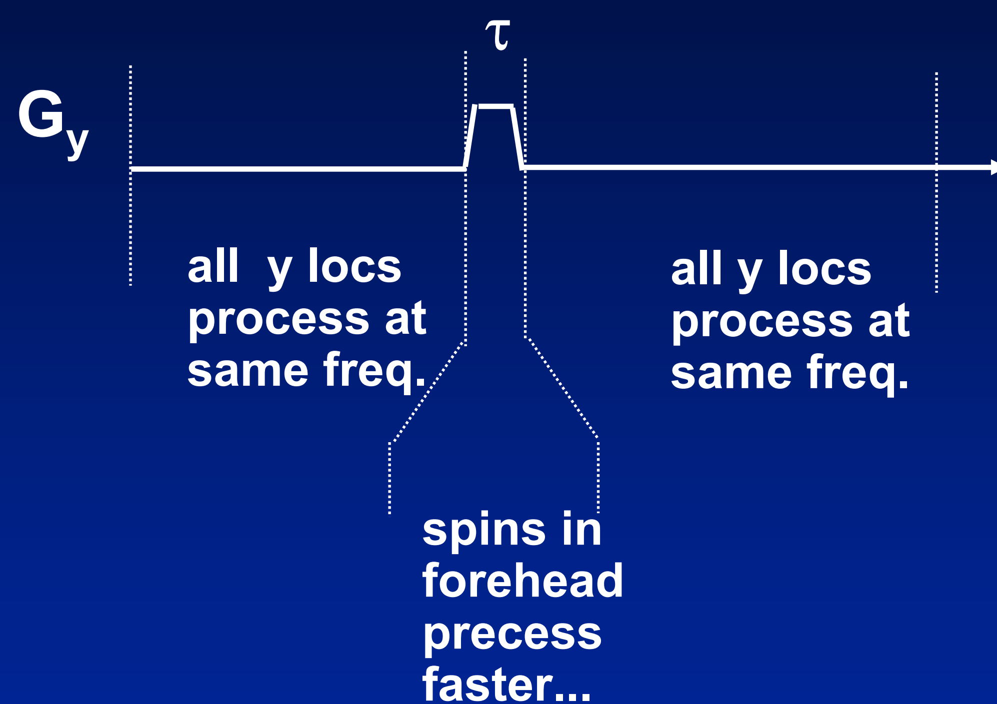
"Phase encoding"



How does blipping on a grad. encode spatial info?



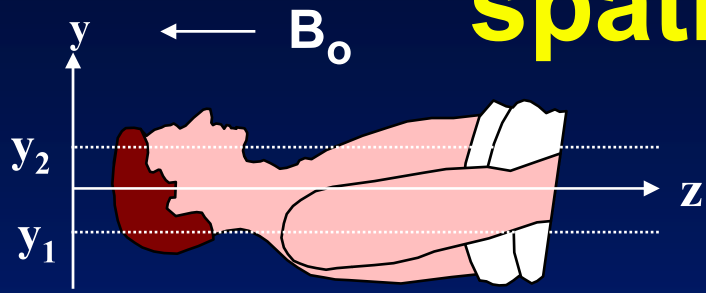




$$\upsilon(\mathbf{y}) = \gamma \mathbf{B}_{TOT} \quad = \gamma\ \mathbf{B}_o\ \Delta \mathbf{y}\ \mathbf{G}_y$$

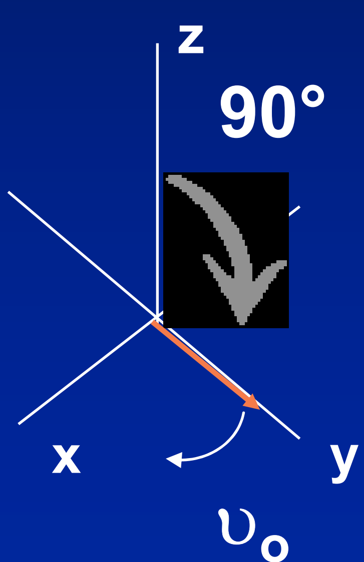
$$\theta\ (\mathbf{y}) = \upsilon(\mathbf{y})\ \tau \quad = \gamma\ \mathbf{B}_o\ \Delta \mathbf{y}\ (\mathbf{G}_y\ \tau)$$

How does blipping on a grad. encode spatial info?

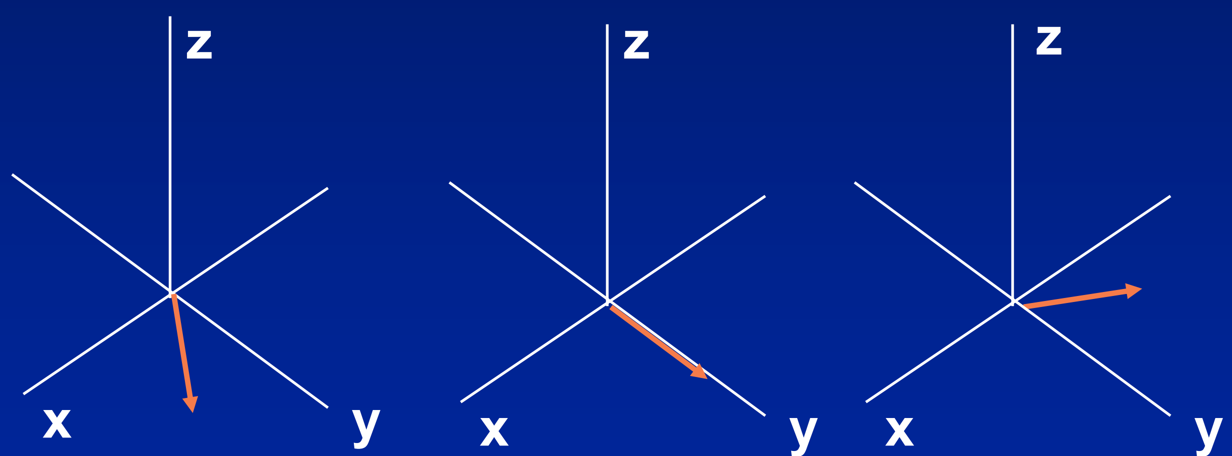


$$\theta\,(\mathbf{y}) = \upsilon(\mathbf{y})\,\tau \;\; = \gamma\, \mathbf{B_o}\, \Delta \mathbf{y}\, (\mathbf{G_y}\, \tau)$$

after RF



After the blipped y gradient...

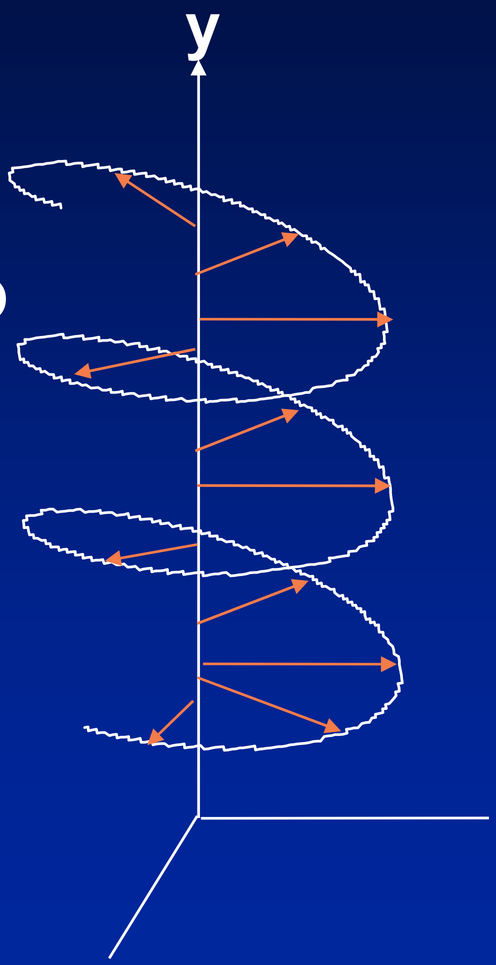


position y_1 **position 0** **position y_2**

How does blipping on a grad. encode spatial info?

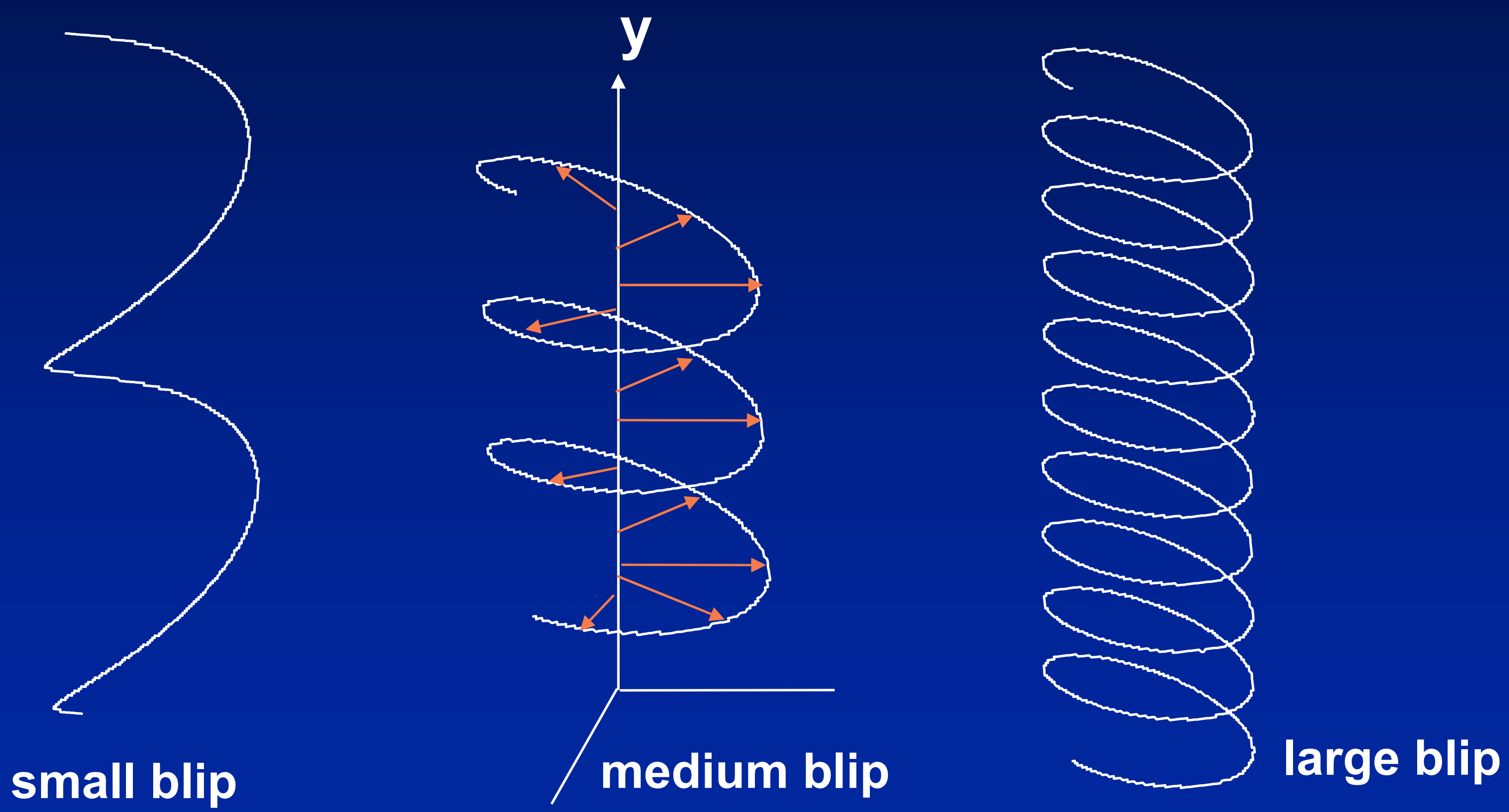
The magnetization vector in the xy plane is wound into a helix directed along y axis.

Phases are ‘locked in’ once the blip is over.



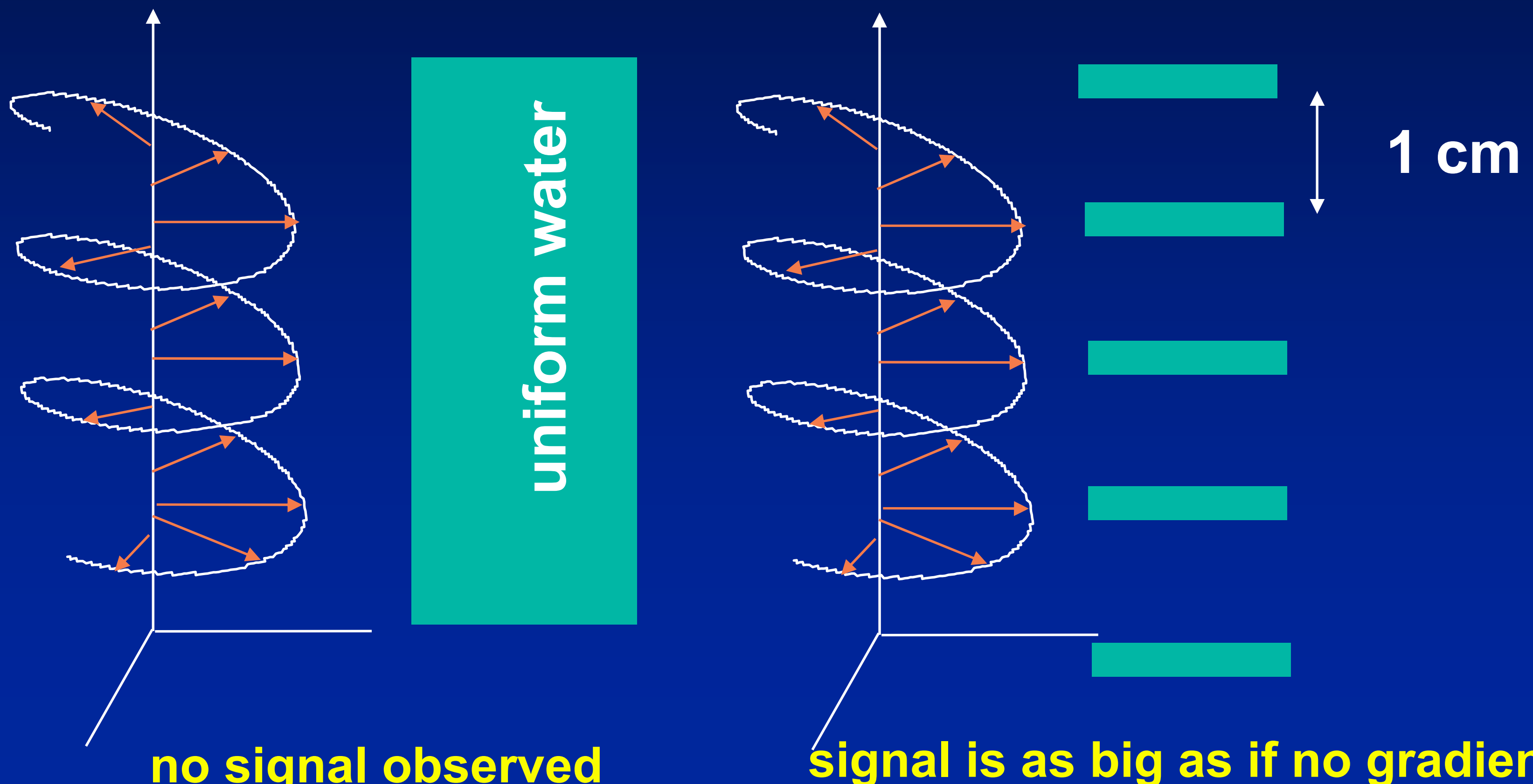
The bigger the gradient blip area, the tighter the helix

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

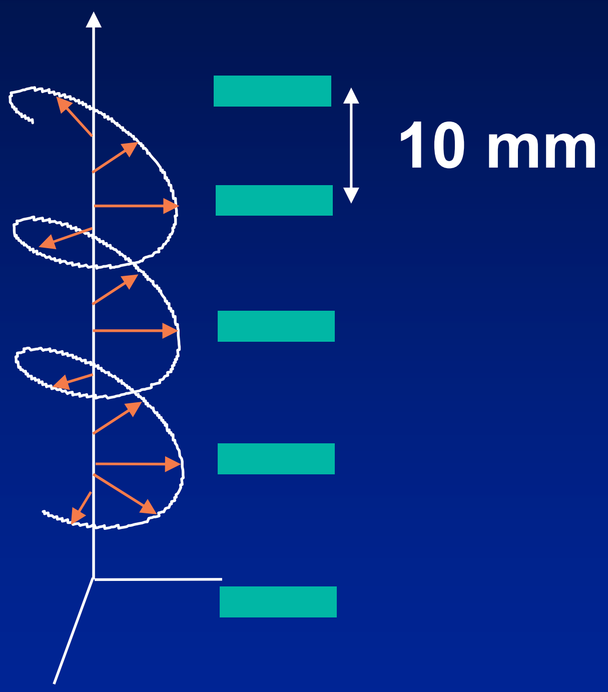


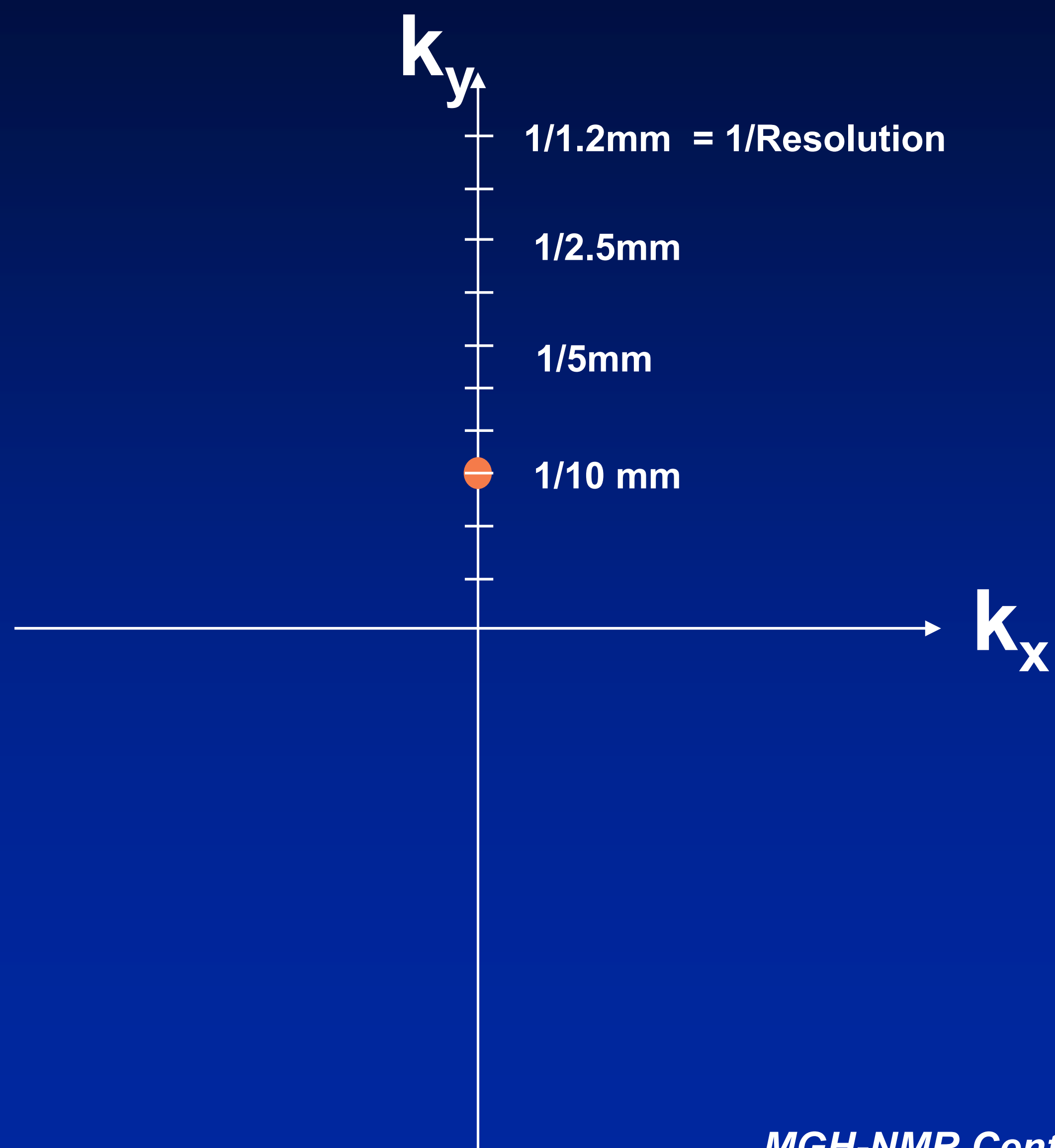
What have you measured?

Consider 2 samples:

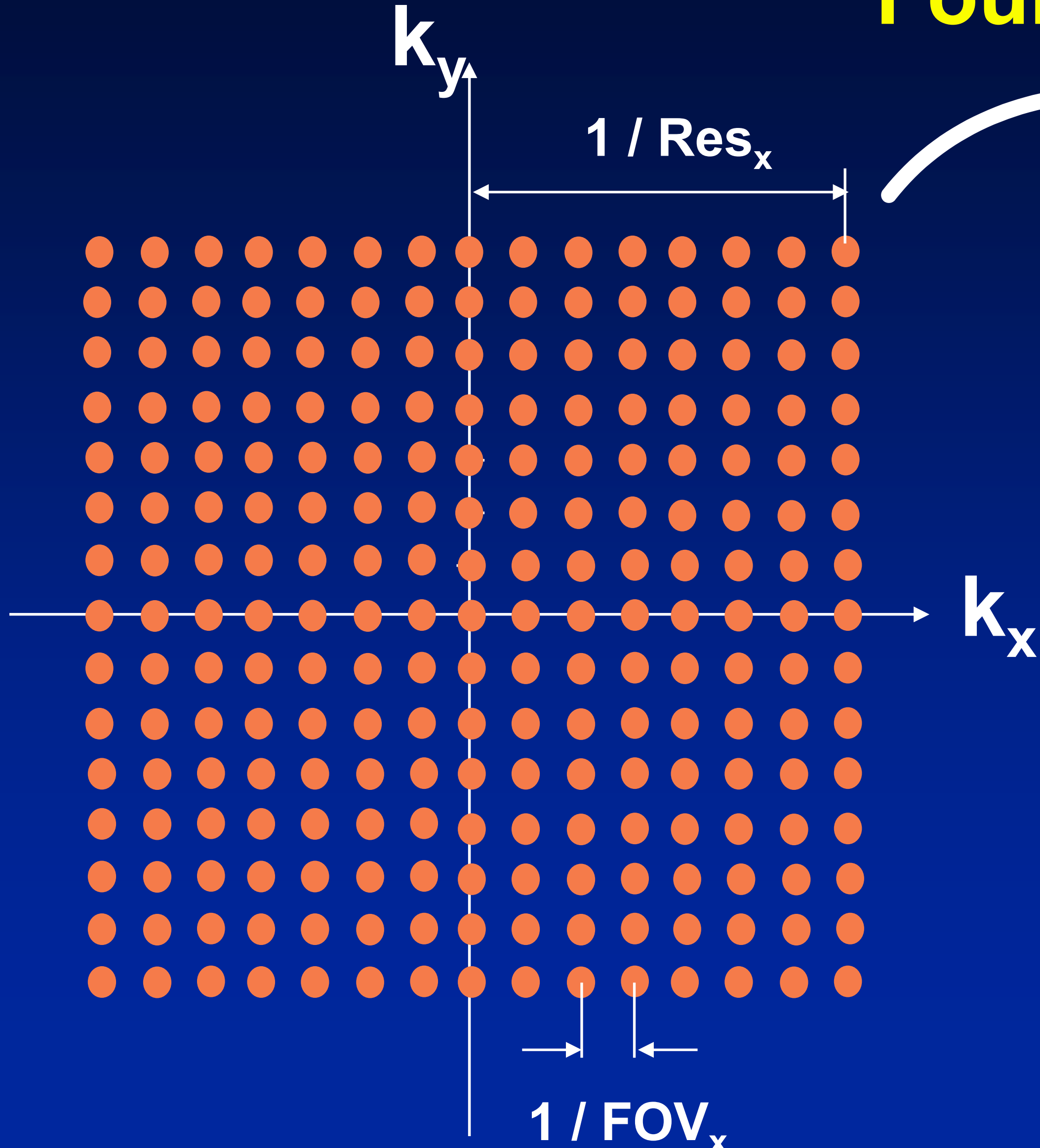


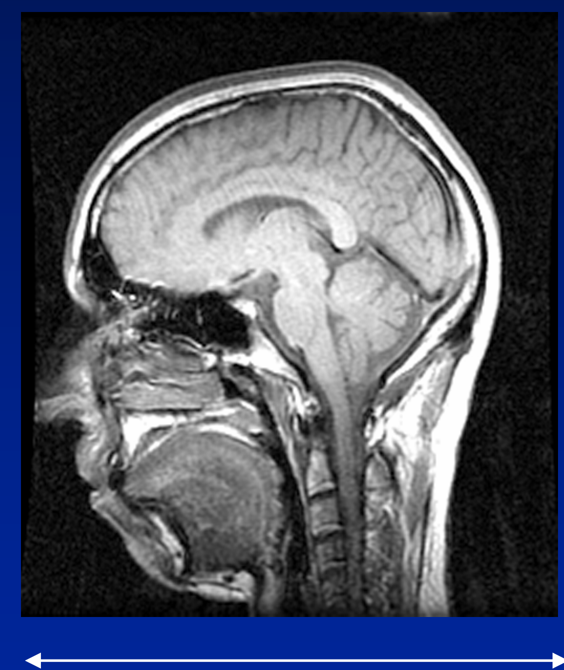
Measurement intensity at a spatial frequency...





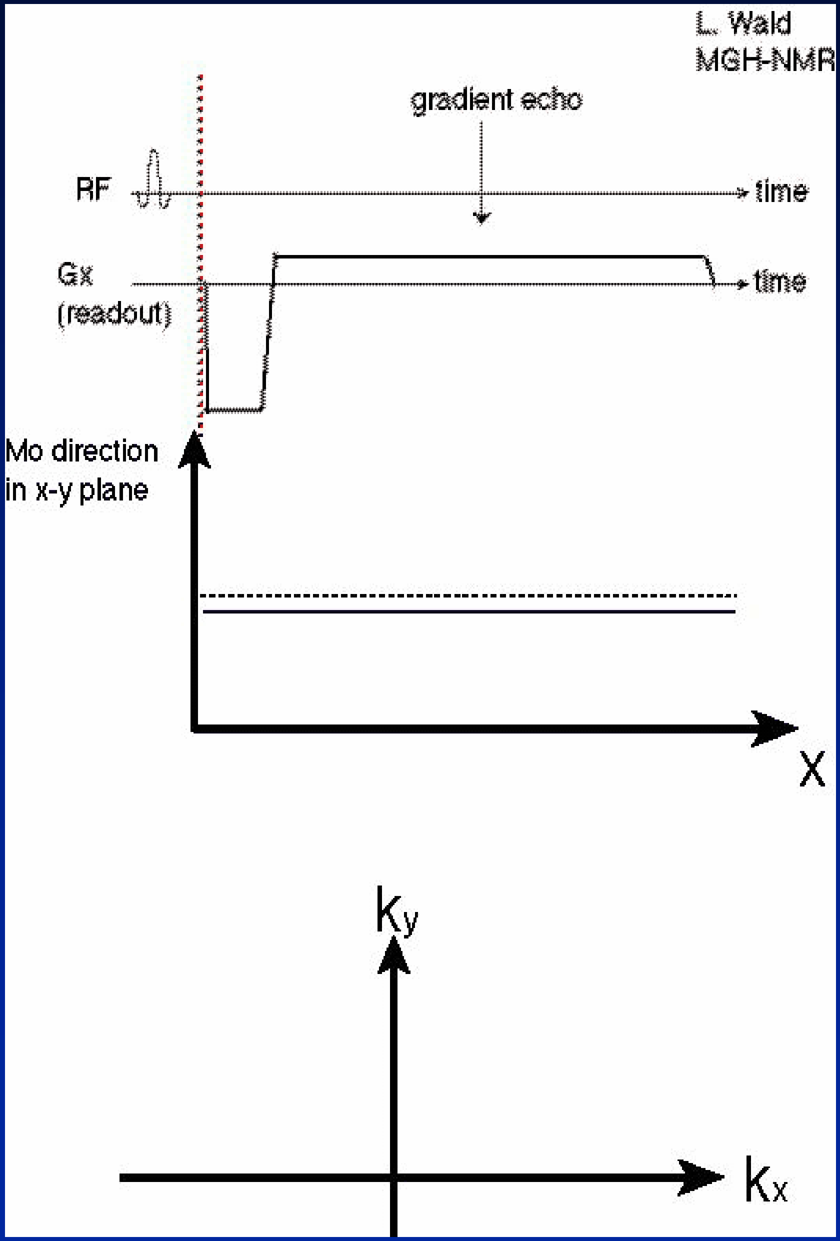
Fourier transform

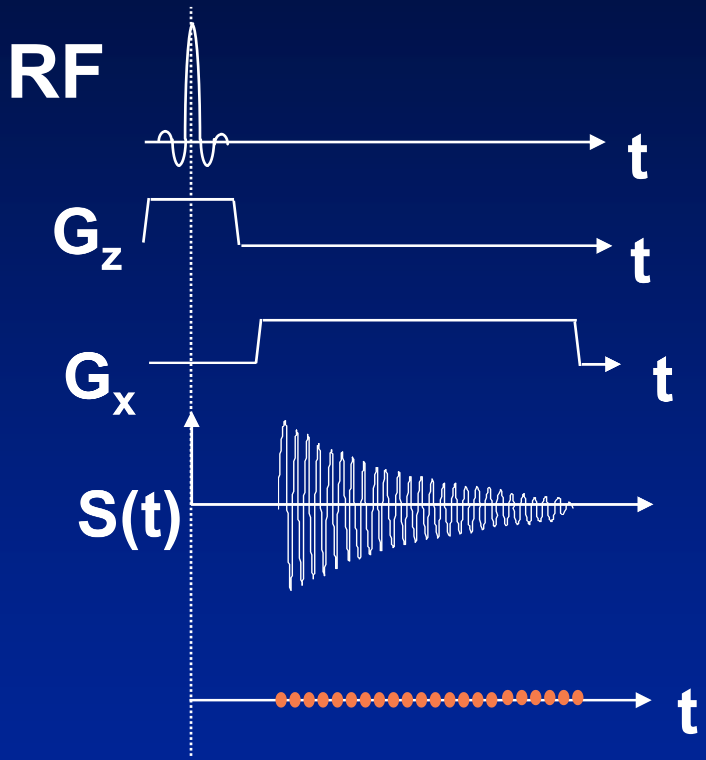




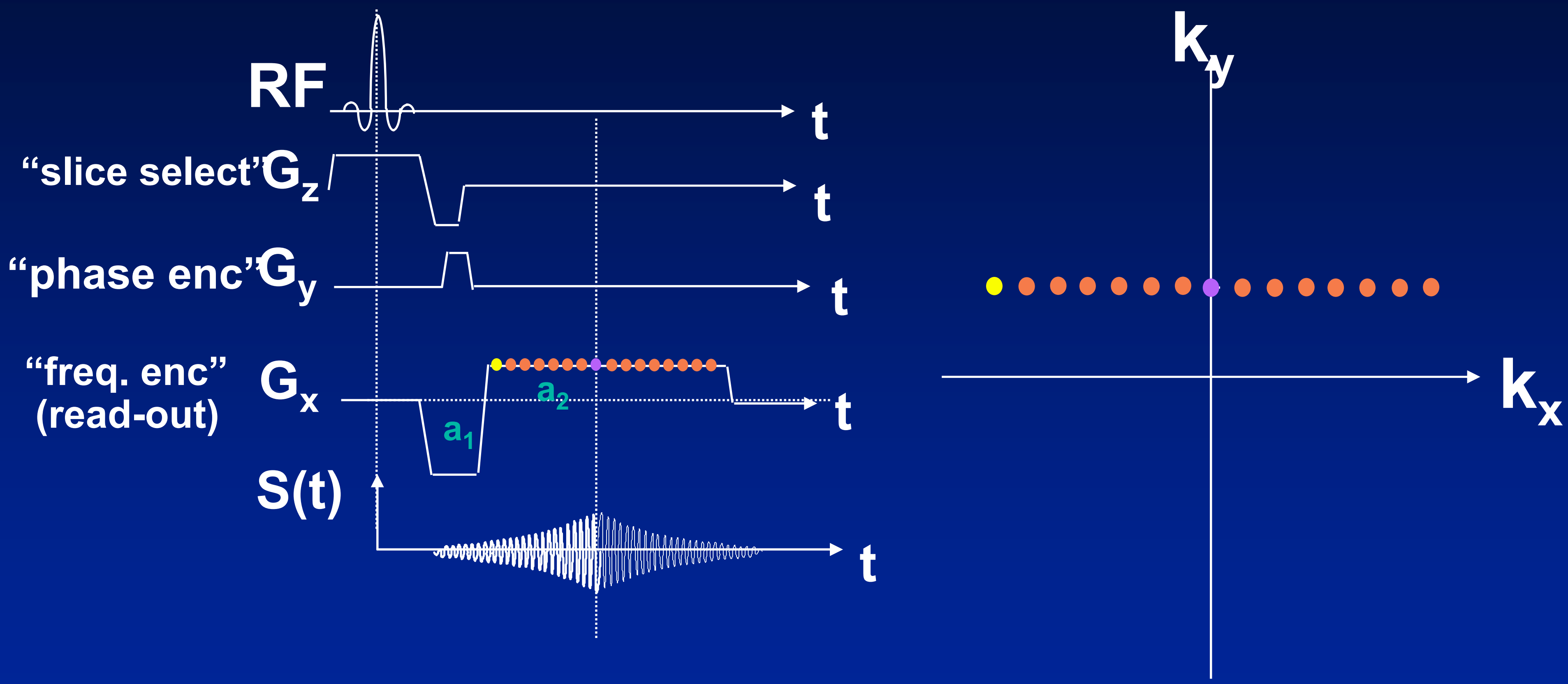
FOV_x = matrix * Res_x

Frequency encoding revisited





“Spin-warp” encoding



one excitation, one line of kspace...

"Spin-warp" encoding mathematics

The "image" is the spin density function: $\rho(x)$

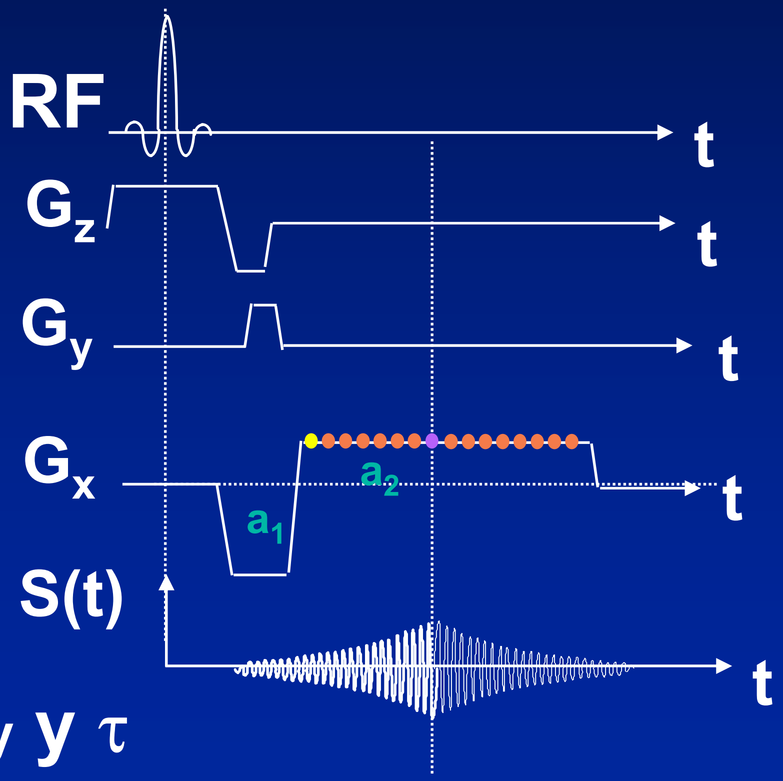
Phase due to readout:

$$\theta(t) = \omega_o t + \gamma G_x x t$$

Phase due to P.E.

$$\theta(t) = \omega_o t + \gamma G_y y \tau$$

$$\Delta\theta(t) = \omega_o t + \gamma G_x x t + \gamma G_y y \tau$$



“Spin-warp” encoding mathematics

Signal at time t from location (x,y)

$$S(t) = \rho(x,y)e^{i\gamma G_x xt + i\gamma G_y y\tau}$$

The coil integrates over object:

$$S(t) = \iint_{object} \rho(x,y)e^{i\gamma G_x xt + i\gamma G_y y\tau}dxdy$$

Substituting $k_x = -\gamma\ G_x\ t$ and $k_x = -\gamma\ G_x\ t$:

$$S(k_x, k_y) = \iint_{object} \rho(x,y)e^{-ik_x x - ik_y y}dxdy$$

"Spin-warp" encoding mathematics

View signal as a matrix in k_x, k_y…

$$S(k_x,k_y)=\iint_{object}\rho(x,y)e^{-ik_x x-ik_y y}dxdy$$

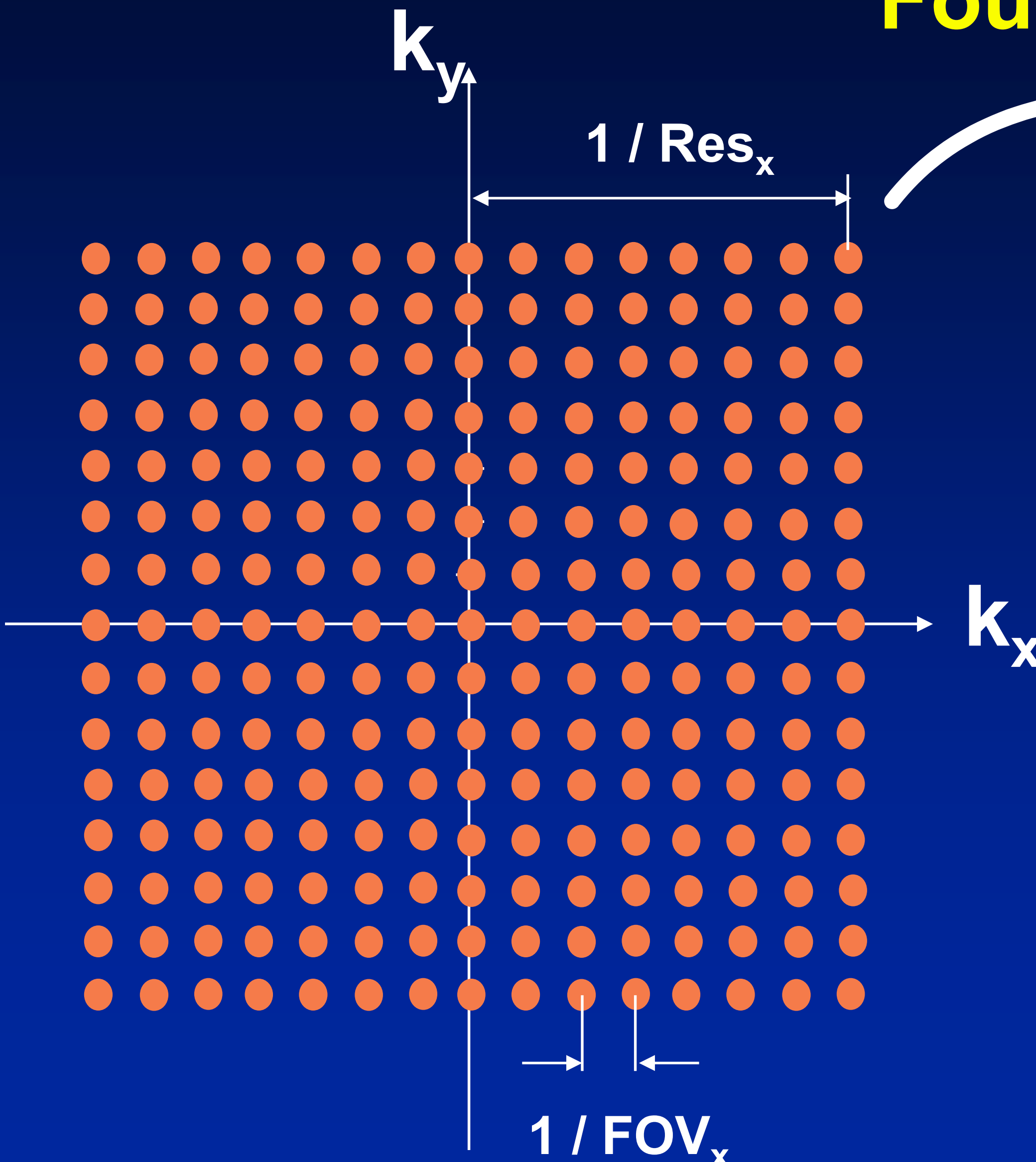
:

Solve for $\rho(x,y,)$

$$\rho(x,y)=FT^{-1}\left[S(k_x,k_y)\right]$$

$$\rho(x,y)=\iint_{kspace}S(k_x,k_y)e^{ik_x x+ik_y y}dk_x dk_y$$

Fourier transform



Kspace facts

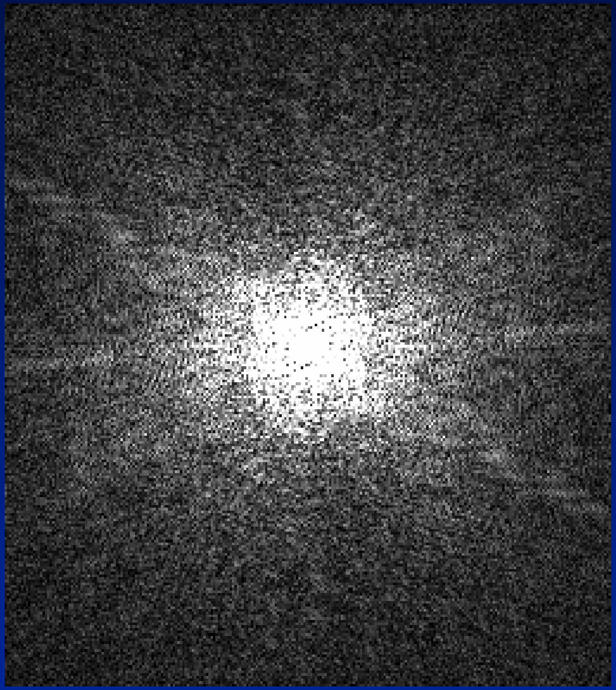
Resolution is determined by the largest spatial freq sampled.

FOV = matrix * resolution

If the object is real, half the information in kspace matrix is redundant. We only need to record half of it.

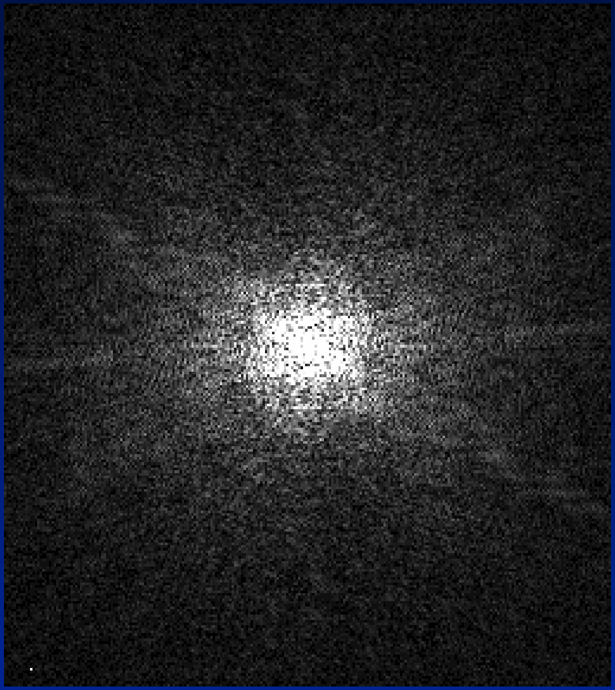
kspace

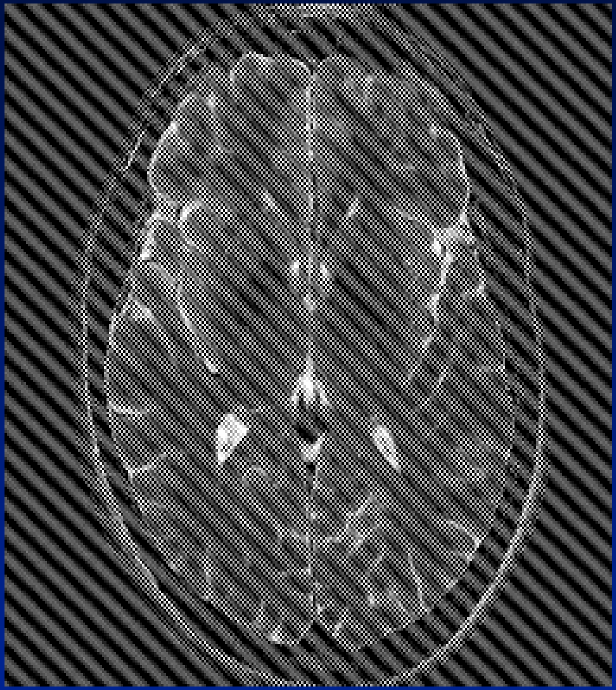
Image space (magnitude)



kspace (magnitude)

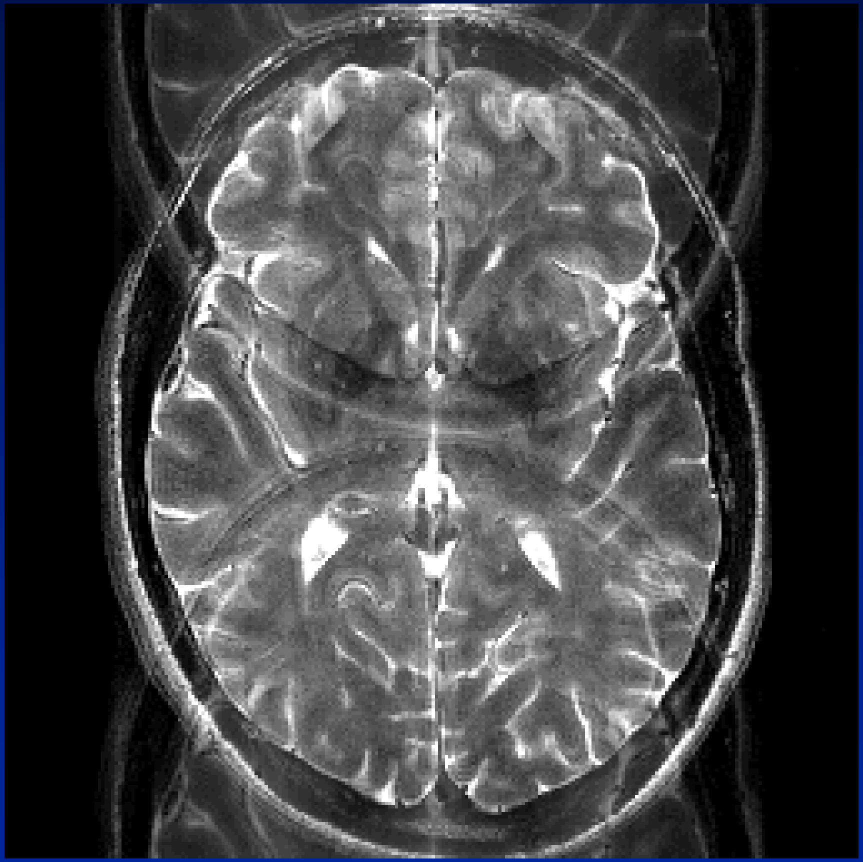
kspace artifacts: spike





One “white pixel” in kspace from a electric spark

Kspace artifacts: Symmetric N/2 ghost



Even numbered lines got
exp($i\phi$)

Odd numbered lines got
exp($-i\phi$)

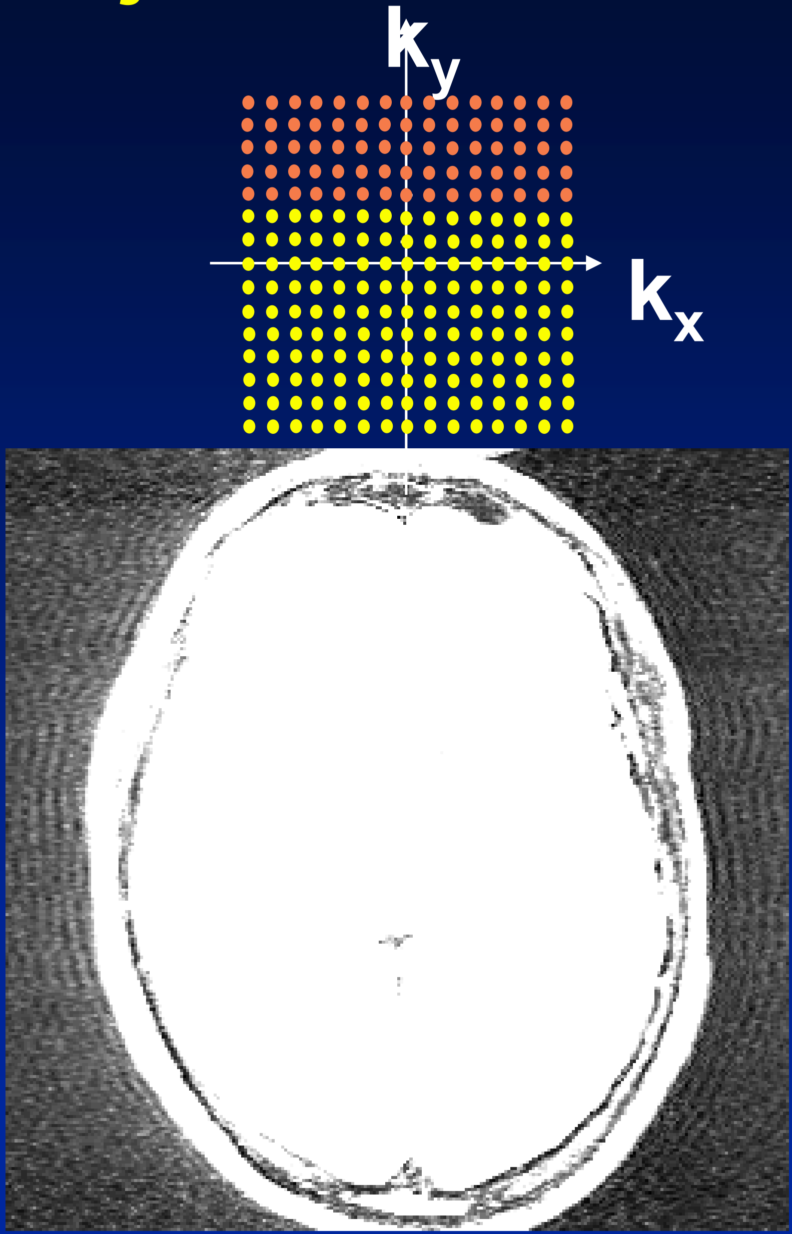
ϕ = 12 degrees

kspace artifacts: subject motion

Yellow = position1
Orange = moved 2 pixels

Movement in real space = linear phase shift across kspace.

=> Orange points have linear phase $\theta = a\, k_y$



Fast Imaging

"Dost thou love life?
Then do not squander time,
for that's the stuff
life is made of."

- Benjamin Franklin

Requirements for brain mapping

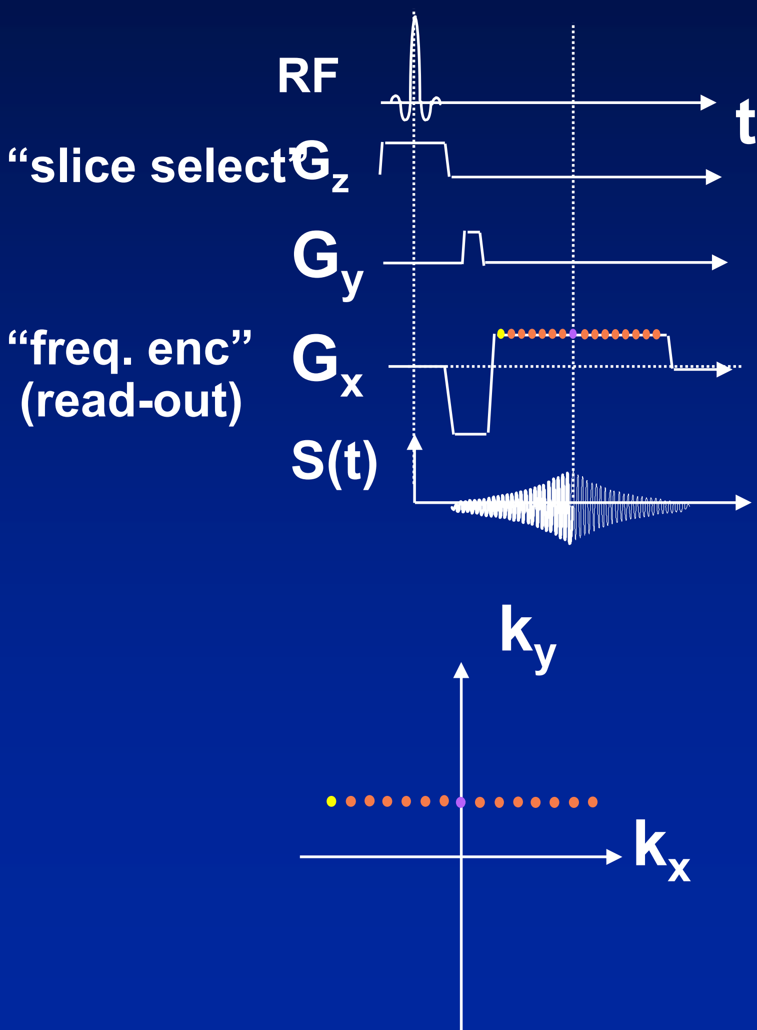
Considerations:

- Signal increase = 0 to 5% (small)
- Motion artifact on conventional image is 0.5% - 3%
- Need to see changes on timescale of hemodynamic changes (seconds)

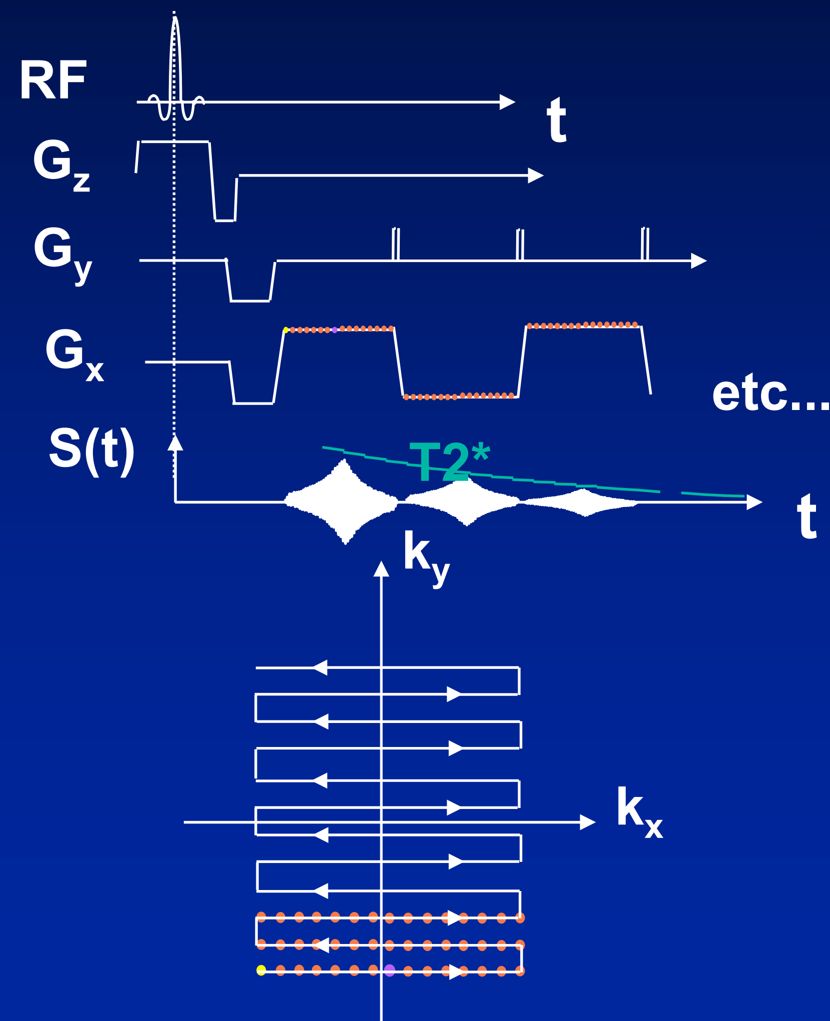
Requirement: Fast, “single shot” imaging, image in 80ms, set of slices every 1-3 seconds.

What's the difference?

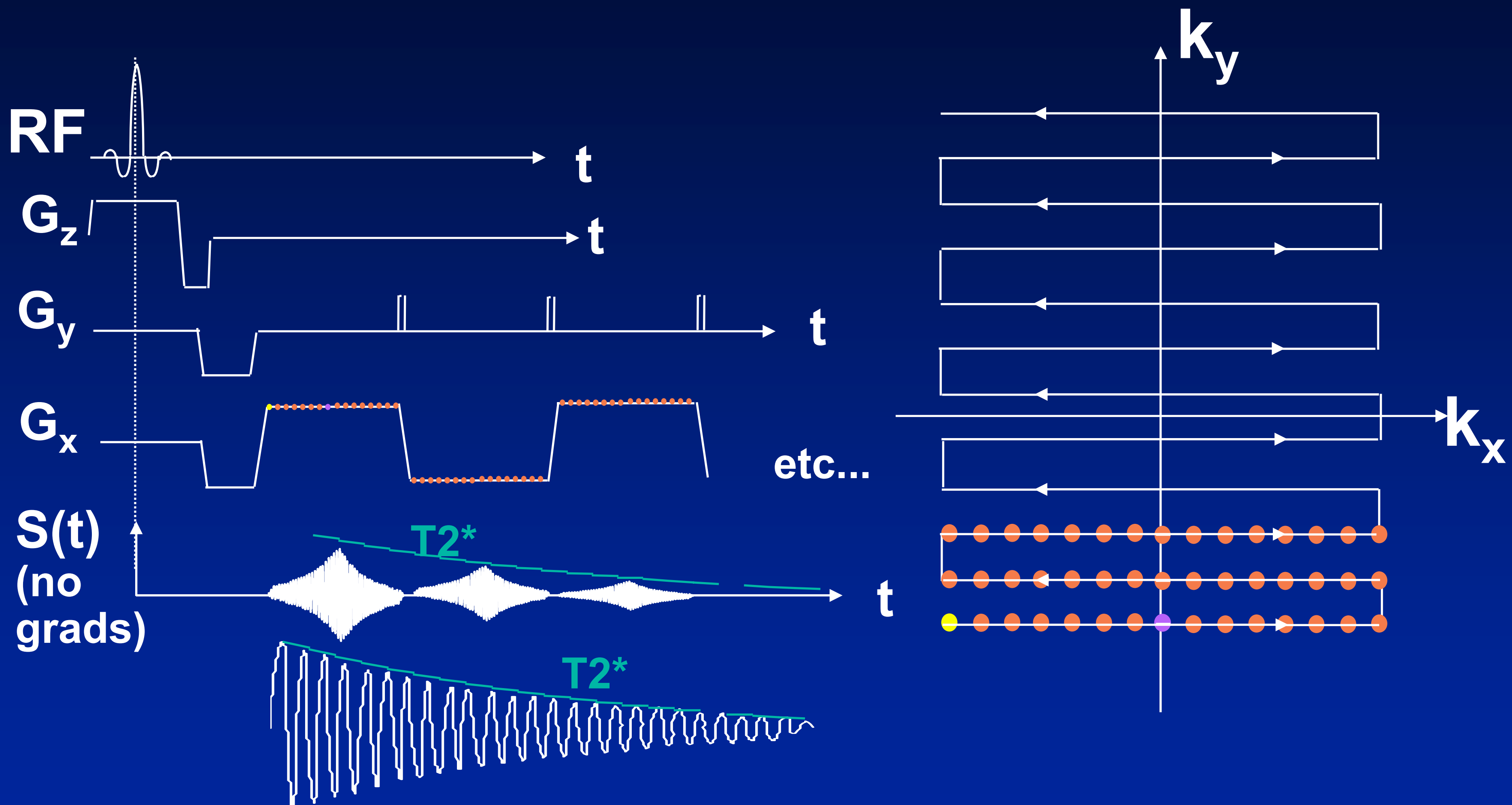
conventional MRI



echoplanar imaging



"Echo-planar" encoding



one excitation, many lines of kspace...

“Echo-planar” encoding

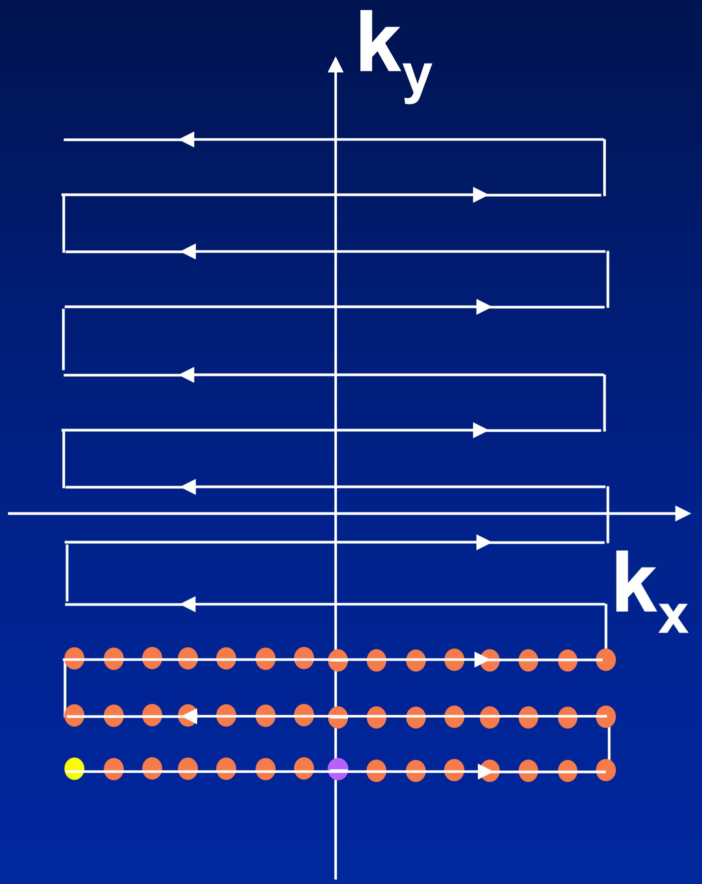
Observations:

• Adjacent points along kx are taken with short Δt (= 5 us). (high bandwidth)

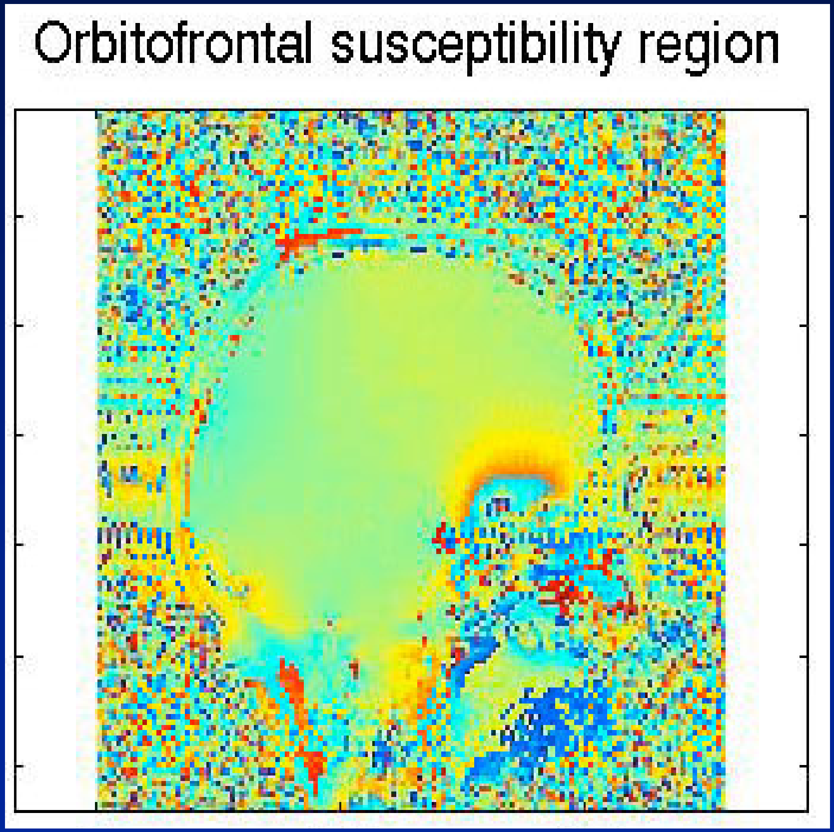
• Adjacent points along ky are taken with long Δt (= 500us). (low bandwidth)

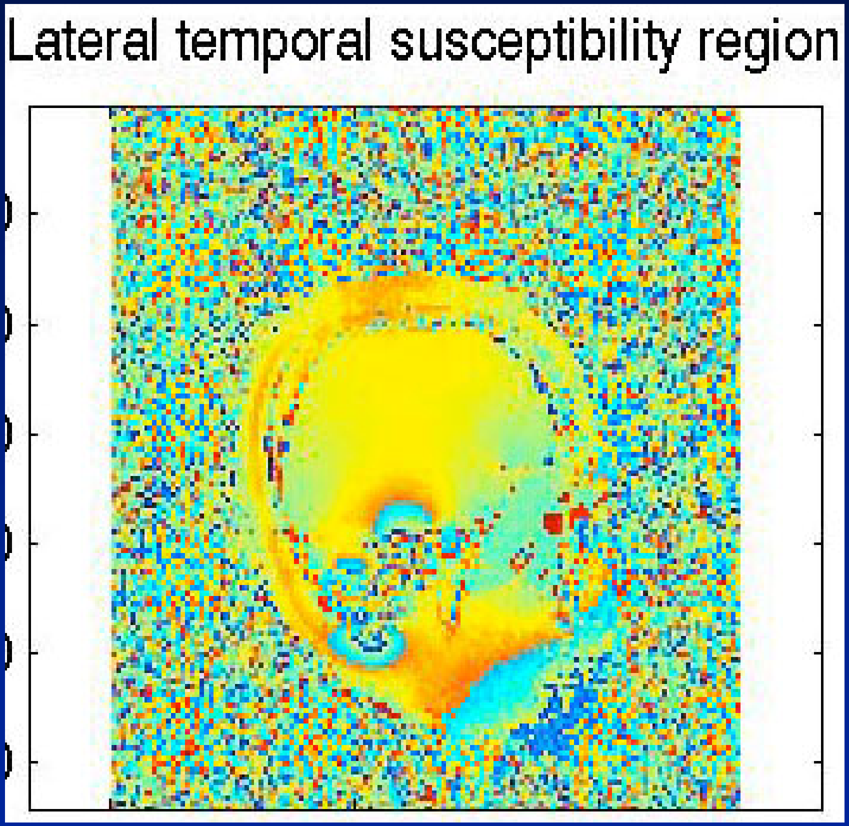
• A given line is read quickly, but the total encode time is longer than conventional Imaging.

• Adjacent lines are traversed in opposite directions.



Enemy #1 of EPI: local susceptibility gradients





B_o field maps in the head

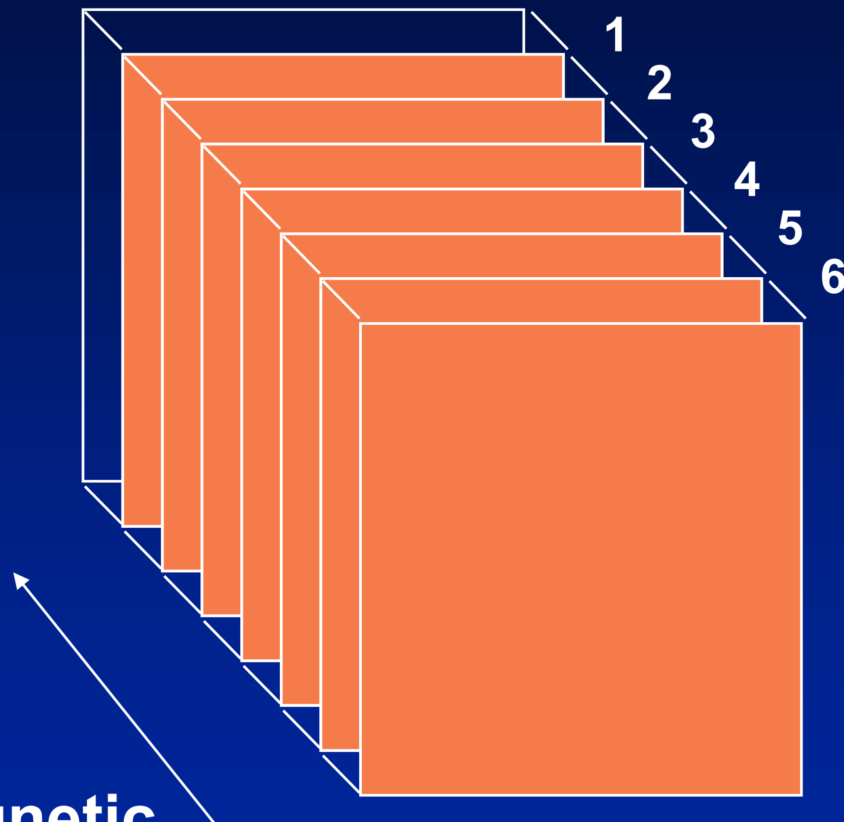
EPI: Local susceptibility gradients

Local susceptibility gradients have 2 effects:

1) Local dephasing of the signal (signal loss) mainly from thru plane gradients

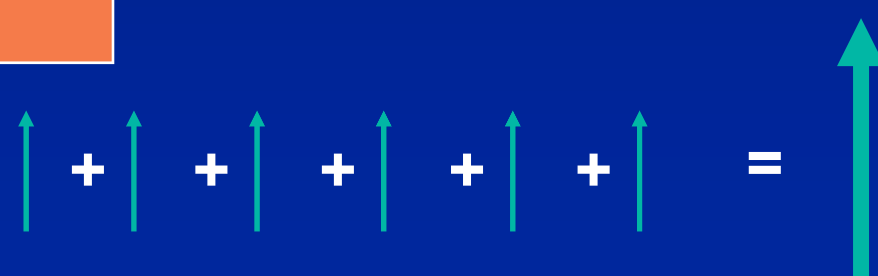
2) Local geometric distortions, mainly from local in-plane gradients.

Susceptibility: thru plane dephasing

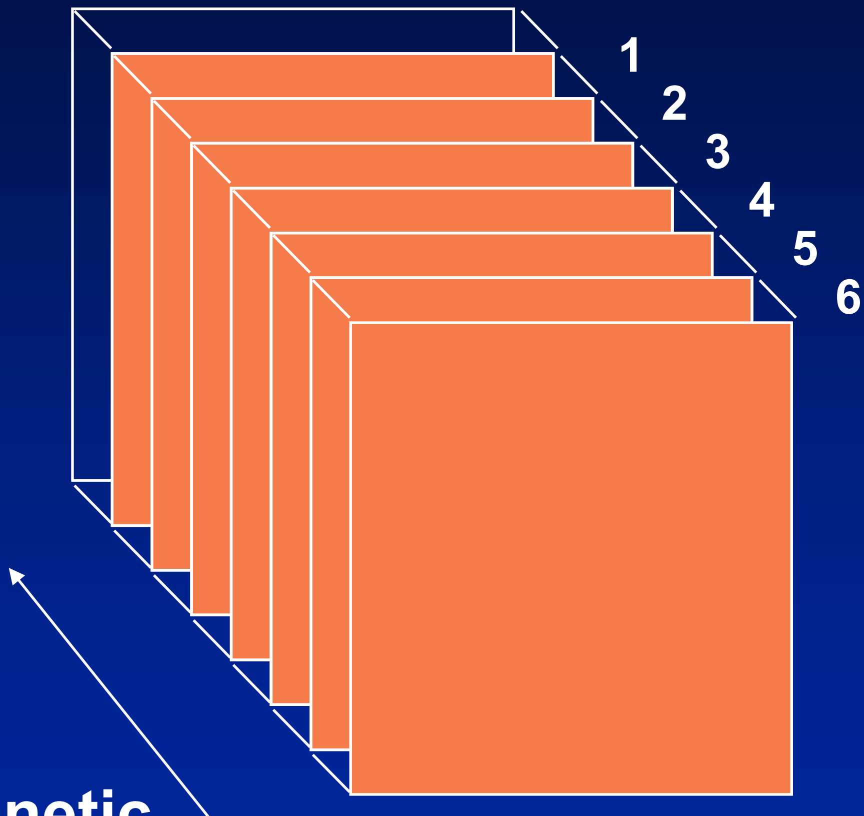


Magnetic
Field Uniform

Signal from whole slice comes from adding together the MR vectors. When in phase, add constructively, SNR increases like slice thickness.

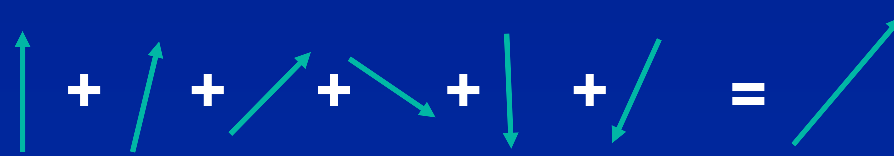


Susceptibility Artifact and Slice Thickness



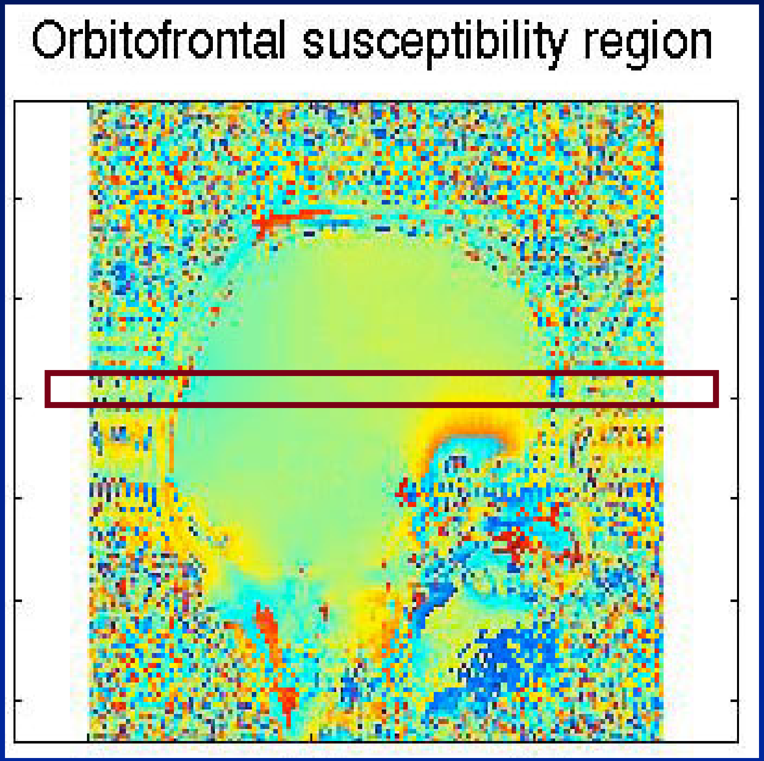
Signal from whole slice comes from adding together the MR vectors, which get out of phase when the magnetic field is not uniform

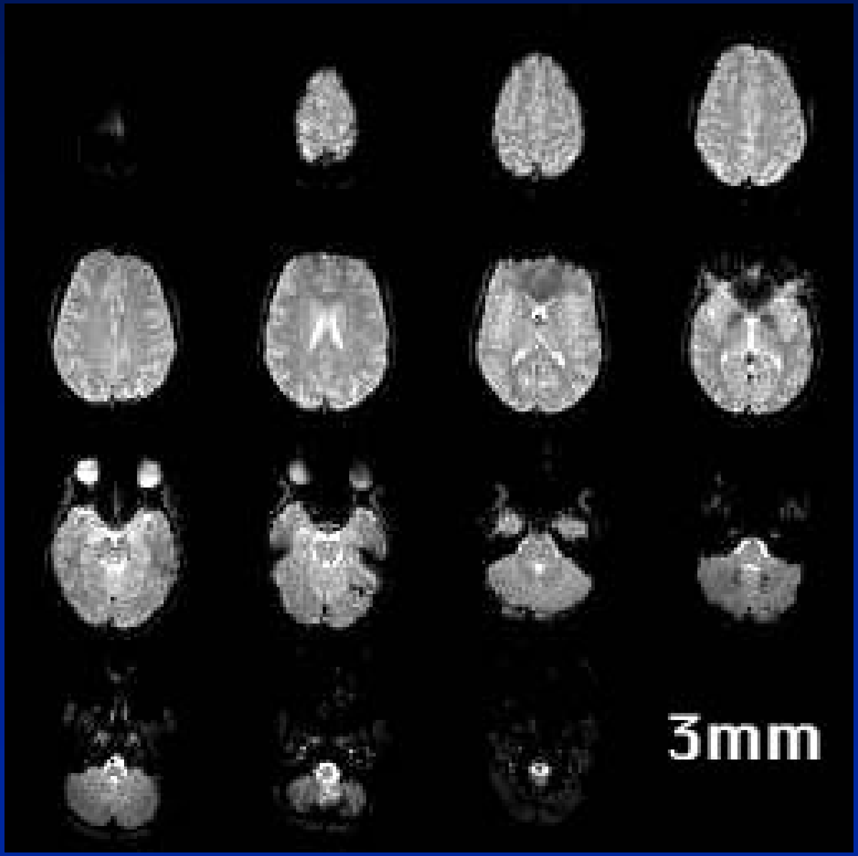
Magnetic
Field NONUniform



Local susceptibility gradients: thru-plane dephasing

Bad for thick slice above frontal sinus…





Local gradients: geometric distortion

Local gradient alters the helix of phase we have so carefully wound.

Phase error accumulates over entire kspace.

(conventional imaging phase is reset every line)

>> faster encoding is better.

Readout points are taken close together (~5us)

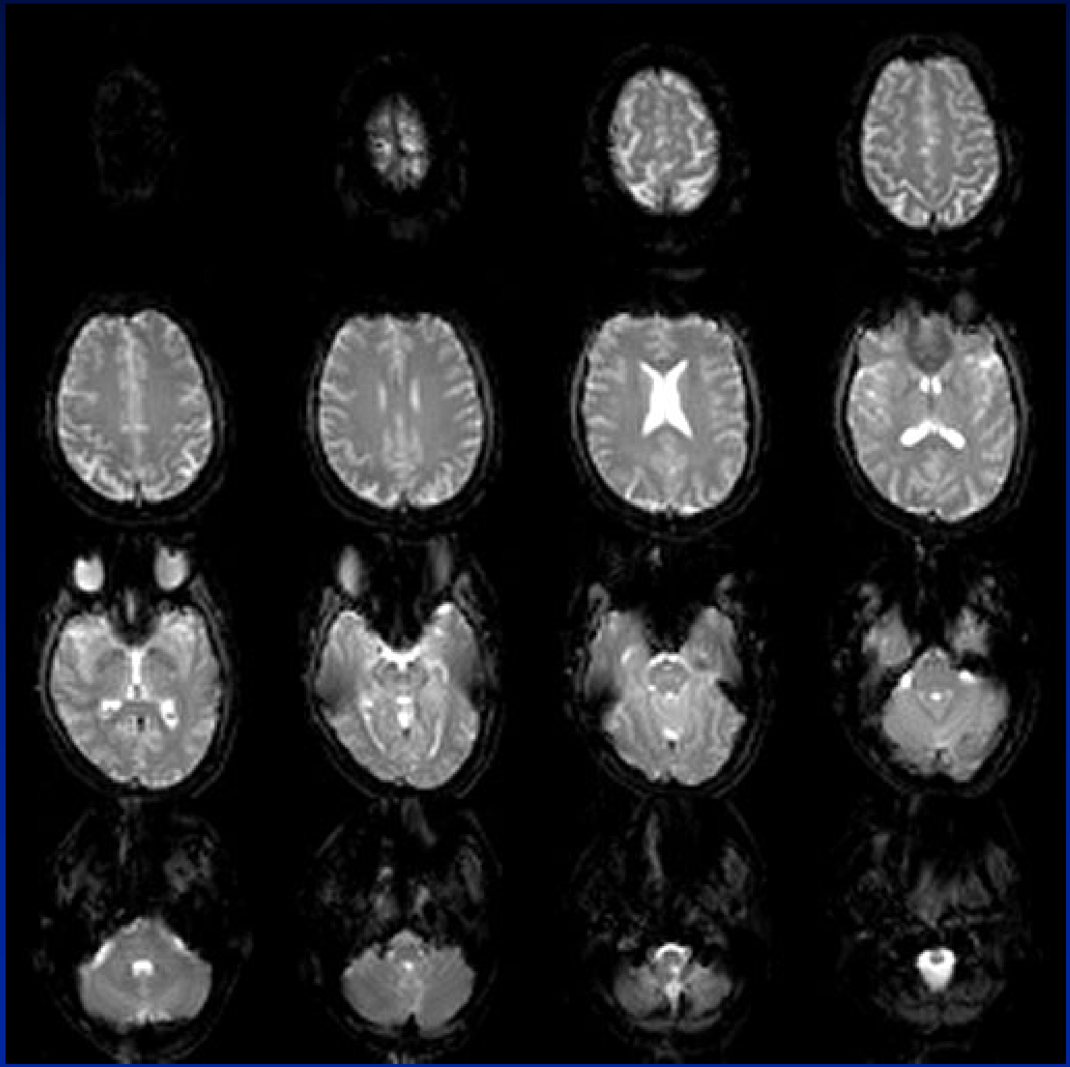
Phase encode points are taken farther apart (~500us)

>> distortion occurs in P.E. direction.

Local gradients: geometric distortion

Two sets of EPI:

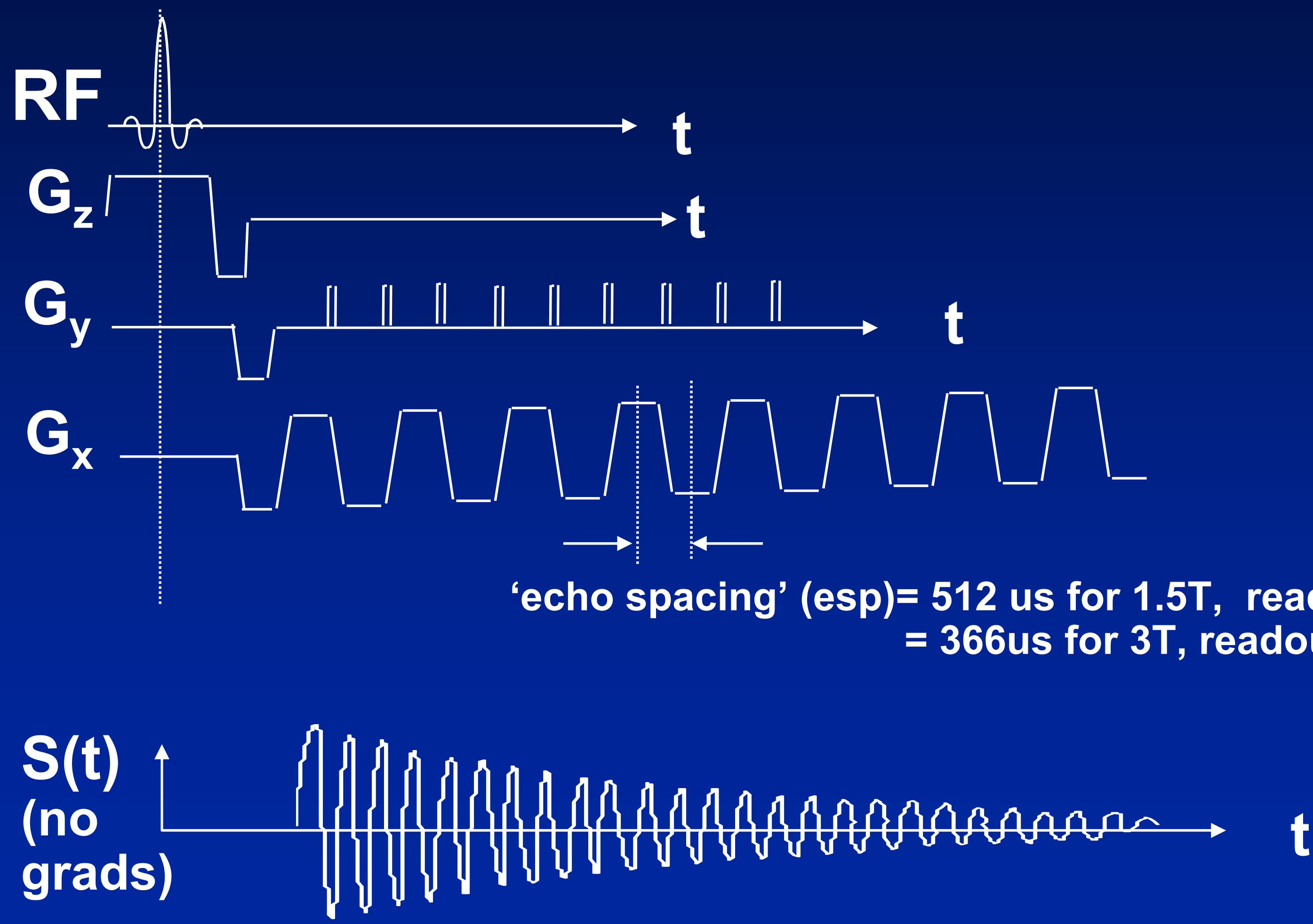
1) encode in 32ms
2) encode in 23ms



Characterization of grad. performance

- **length of readout train for given resolution**

(requires fast slew and high grad amplitude)



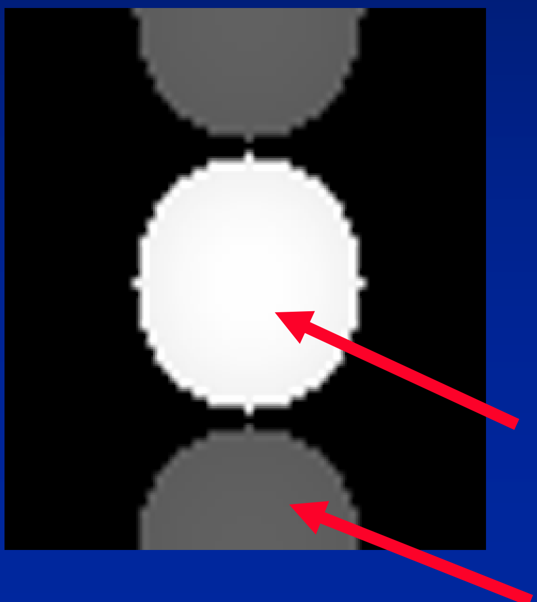
MGH-NMR Center

EPI problems: N/2 ghost

Asymmetry in alternate lines gives N/2 image ghost.

Asymmetry from:

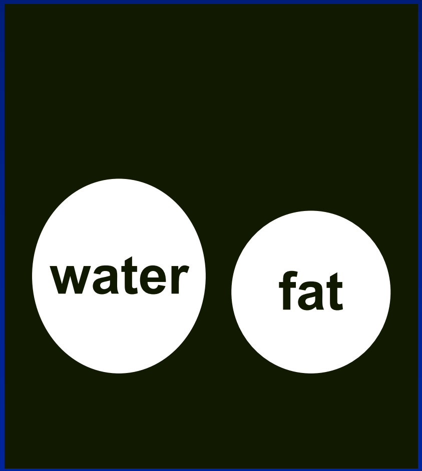
Eddy currents
receiver filter
receiver timing
head coil tuning.



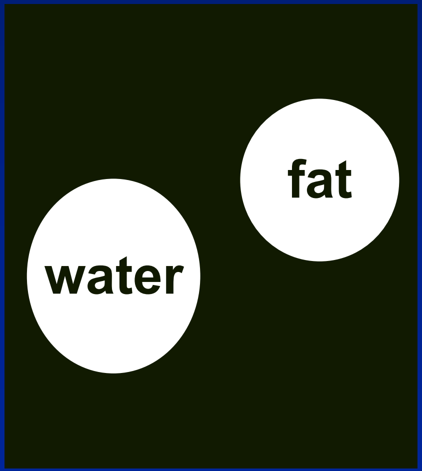
MGH-NMR Center

EPI problems: frequency offset

If one object has a different NMR frequency (e.g. fat and water) it gets shifted in PE direction. (why?)

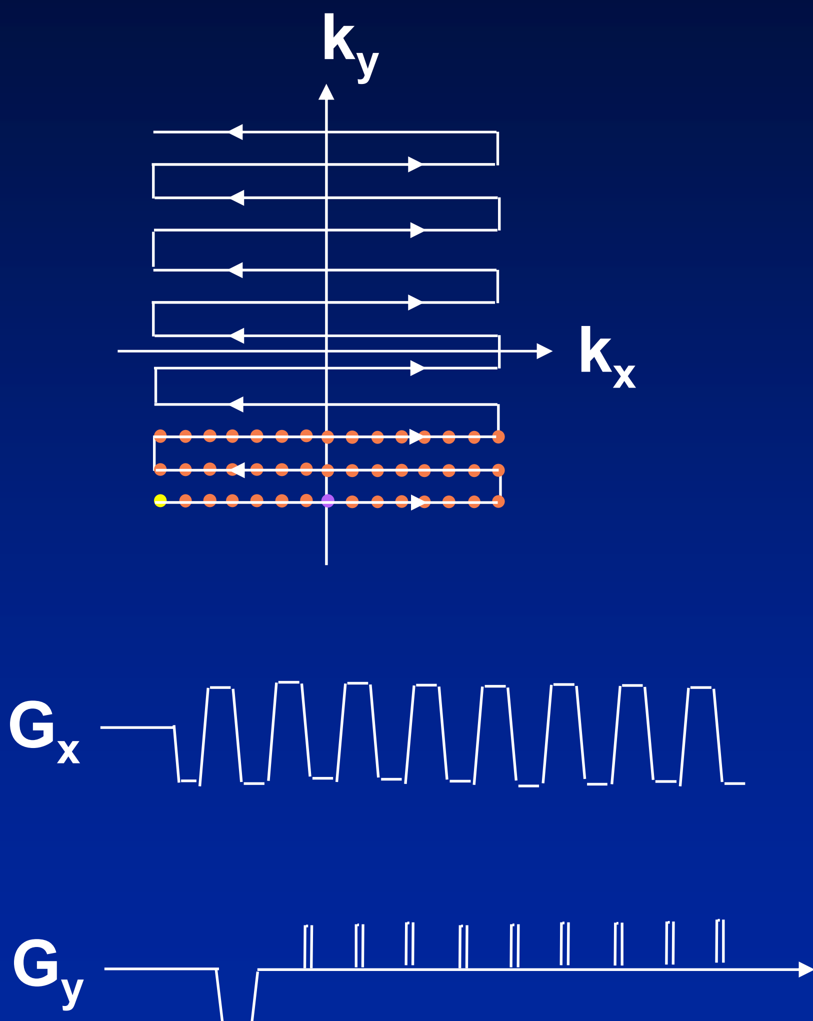


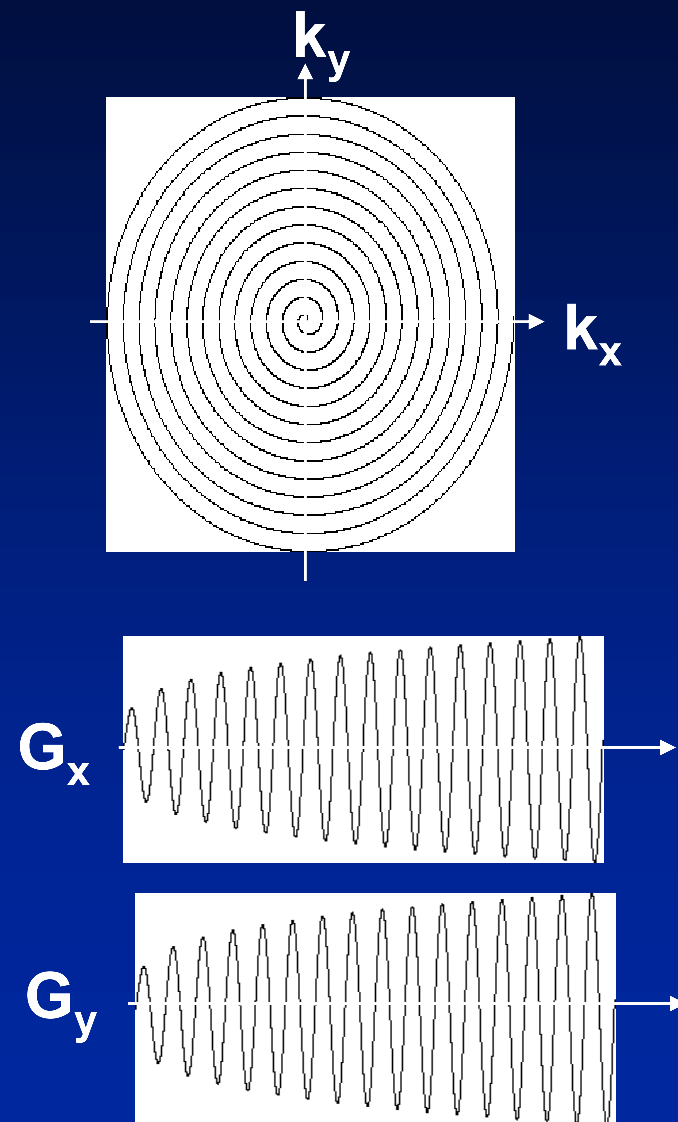
True location



Echoplanar image

EPI and Spirals

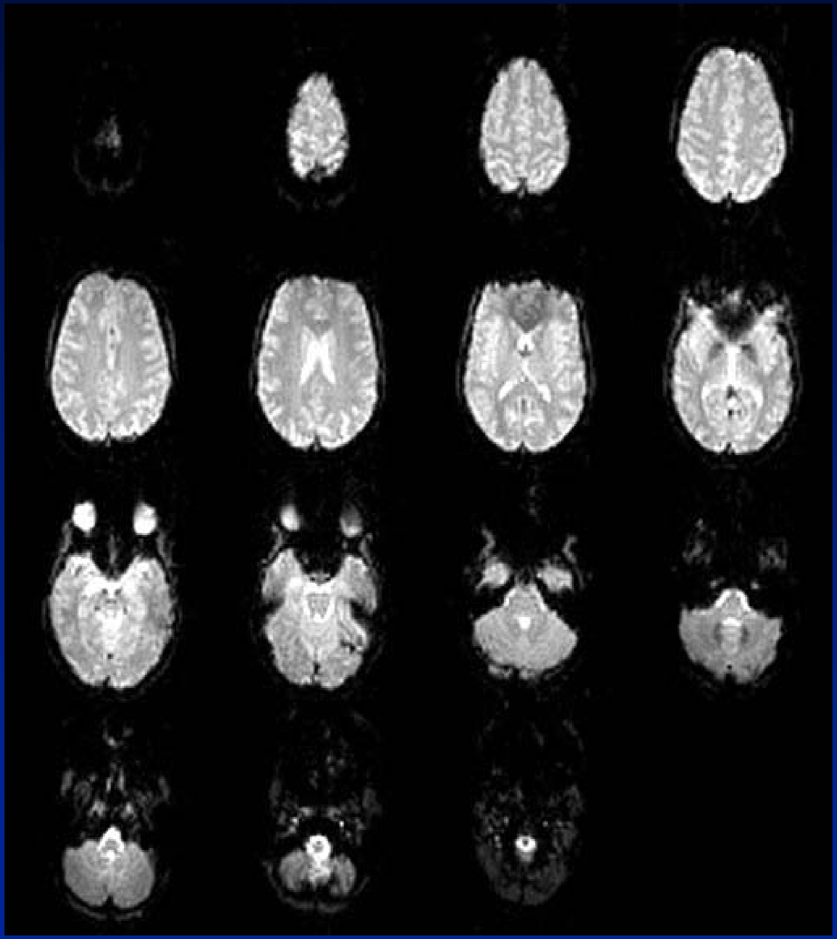




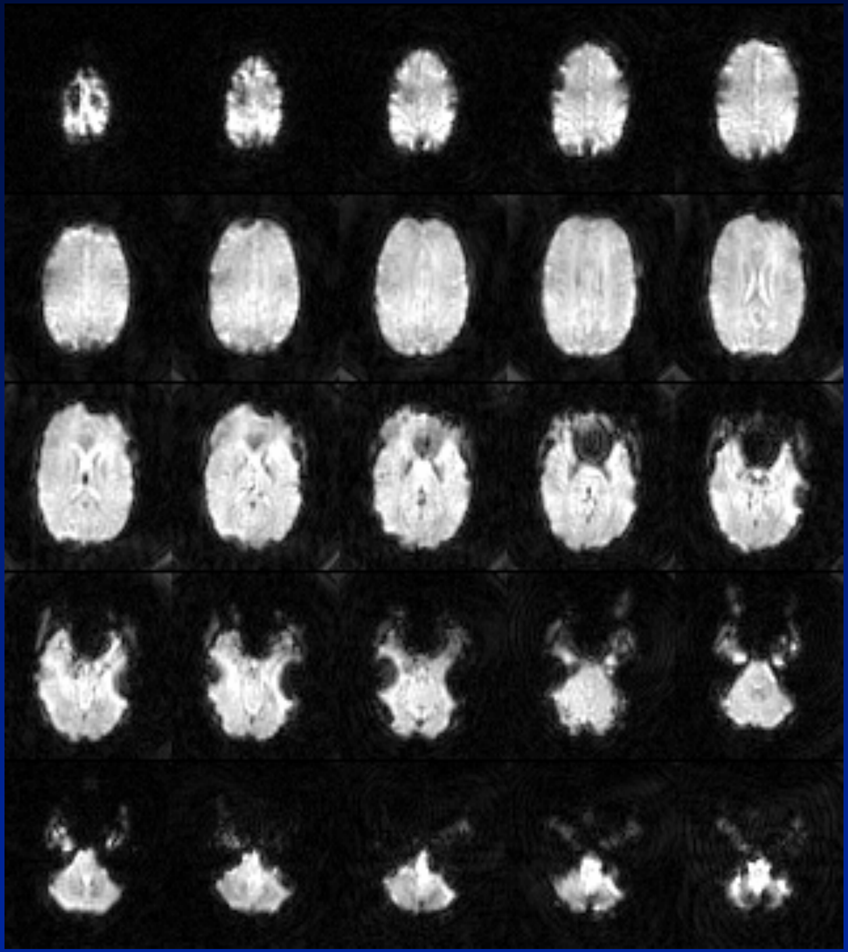
MGH-NMR Center

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

EPI and Spirals



EPI at 3T



Spirals at 3T
(from G. Glover)