Physics of MR Image Acquisition

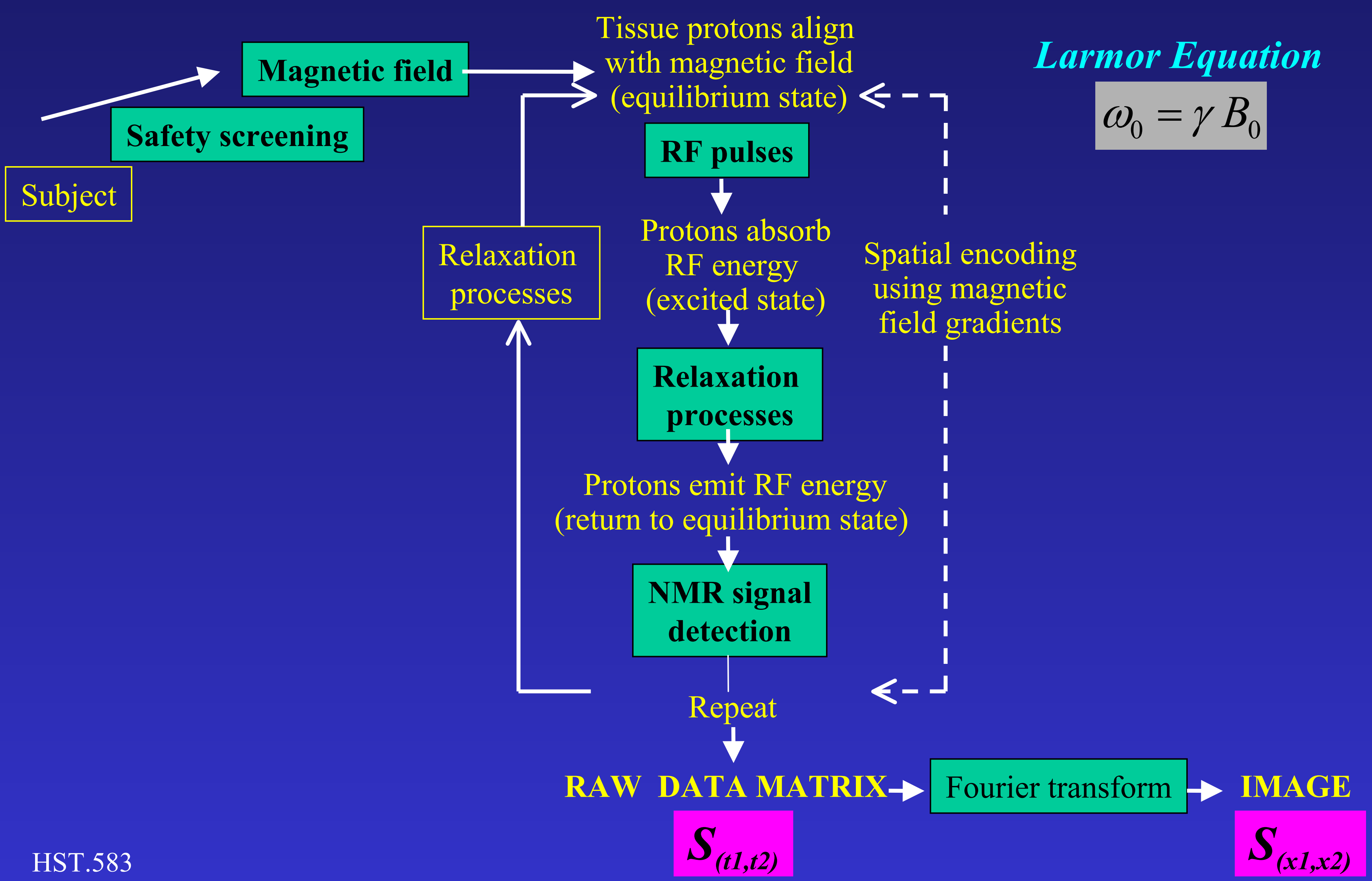
HST-583, Fall 2002

- **Review:**
  - MRI: Overview
  - MRI: Spatial Encoding

- **MRI Contrast: Basic sequences**
  - Gradient Echo
  - Spin Echo
  - Inversion Recovery

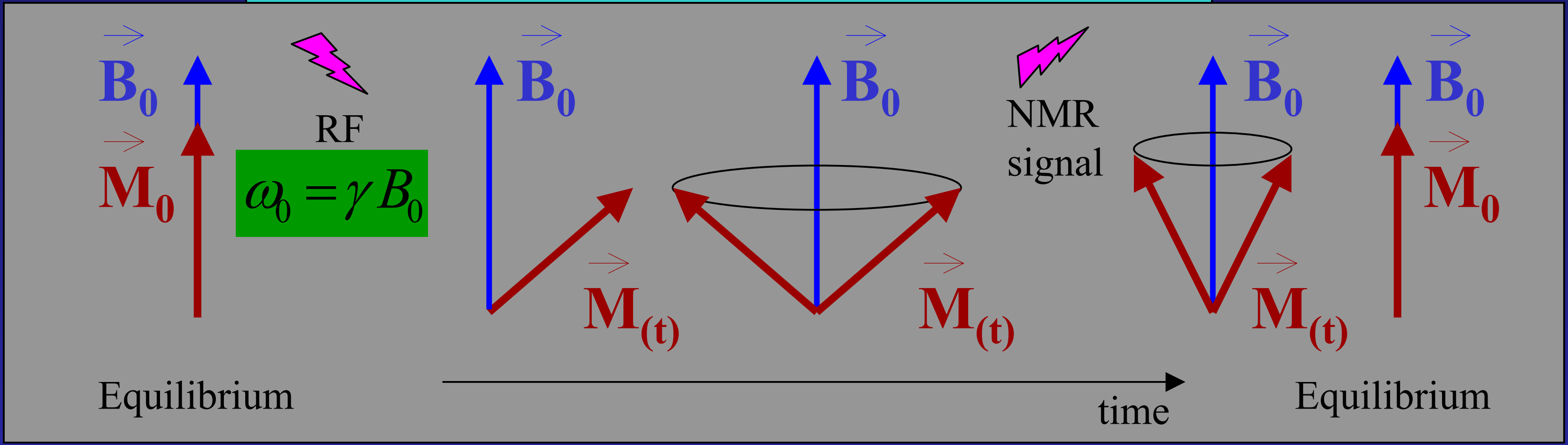
HST.583: Functional Magnetic Resonance Imaging: Data Acquisition and Analysis
Harvard-MIT Division of Health Sciences and Technology
Dr. Jorge Jovicich

Overview of an MRI procedure



Dynamics of the Magnetization

• Geometrical description: damped precession



• Mathematical Description: precession + relaxation (Bloch equations)

$$\frac{d\vec{M}_{(t)}}{dt} = \vec{M}_{(t)} \times \gamma \vec{B}_{ext(t)} - \frac{(M_x \hat{i} + M_y \hat{j})}{T_2^*} - \frac{(M_z - M_0)}{T_1} \hat{k}$$

Spatial Encoding in MRI

Key concept: $$\omega_{(r)} = \gamma\left(B_0 + G.r\right)$$

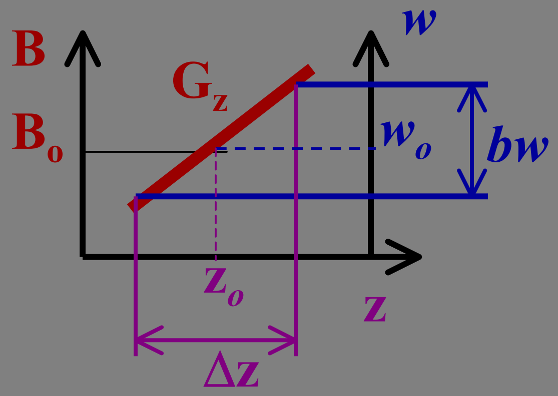
- **Slice Selection**
  - Location
  - Thickness
  - Rephasing/Refocussing
- **Frequency Encoding**
  - Fourier Transform
  - FOV
  - Gradient Echo Formation
- **Phase Encoding**
  - Phase / Frequency Equivalency
  - FOV

Slice Selection

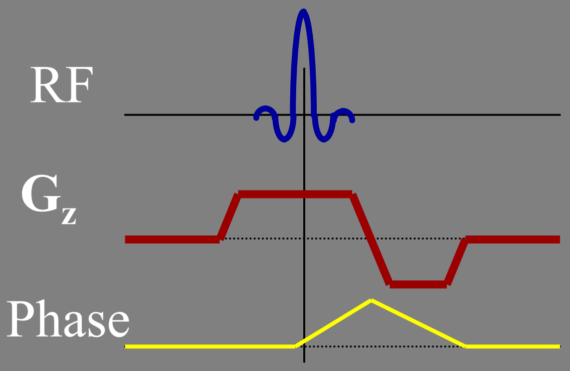
- RF excitation (selective bandwidth) + magnetic field gradient
- RF pulse properties
  - shape & duration ⇒ bandwidth (*bw*)
  - frequency (w_o)

- Magnetic field gradient (G_z)

$$\omega_{(r)} = \gamma\left(B_0 + G.r\right)$$

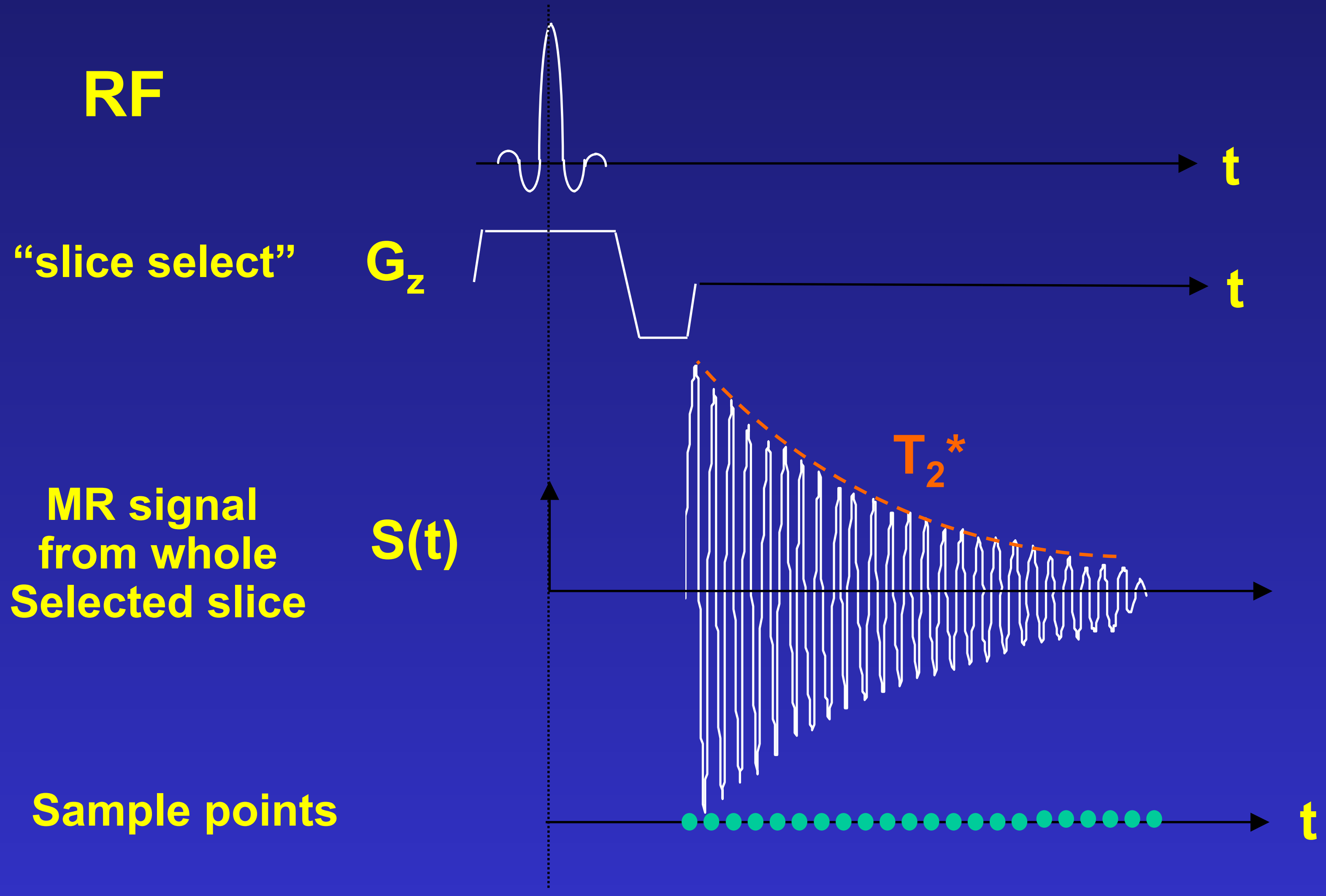


- Schematically



- Slice parameters
  - Slice thickness (Δz): $bw = \gamma\, G_z\, \Delta z$
  - Slice center (z_o): $w_o = \gamma\, G_z\, z_o$

‘Pulse sequence’ so far

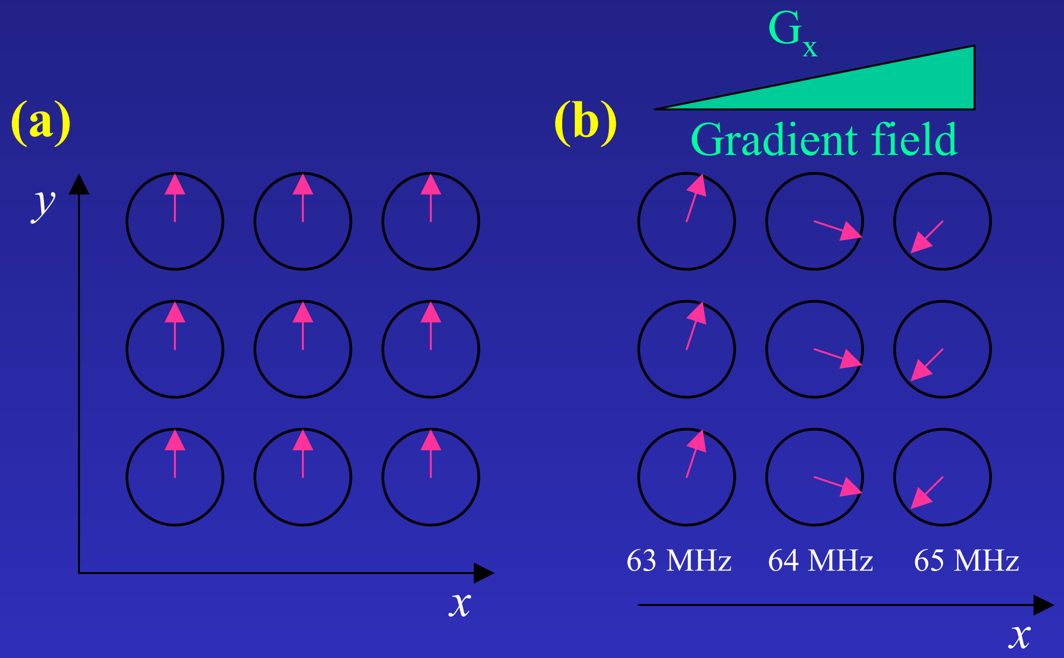


Courtesy of L. Wald

Frequency Encoding

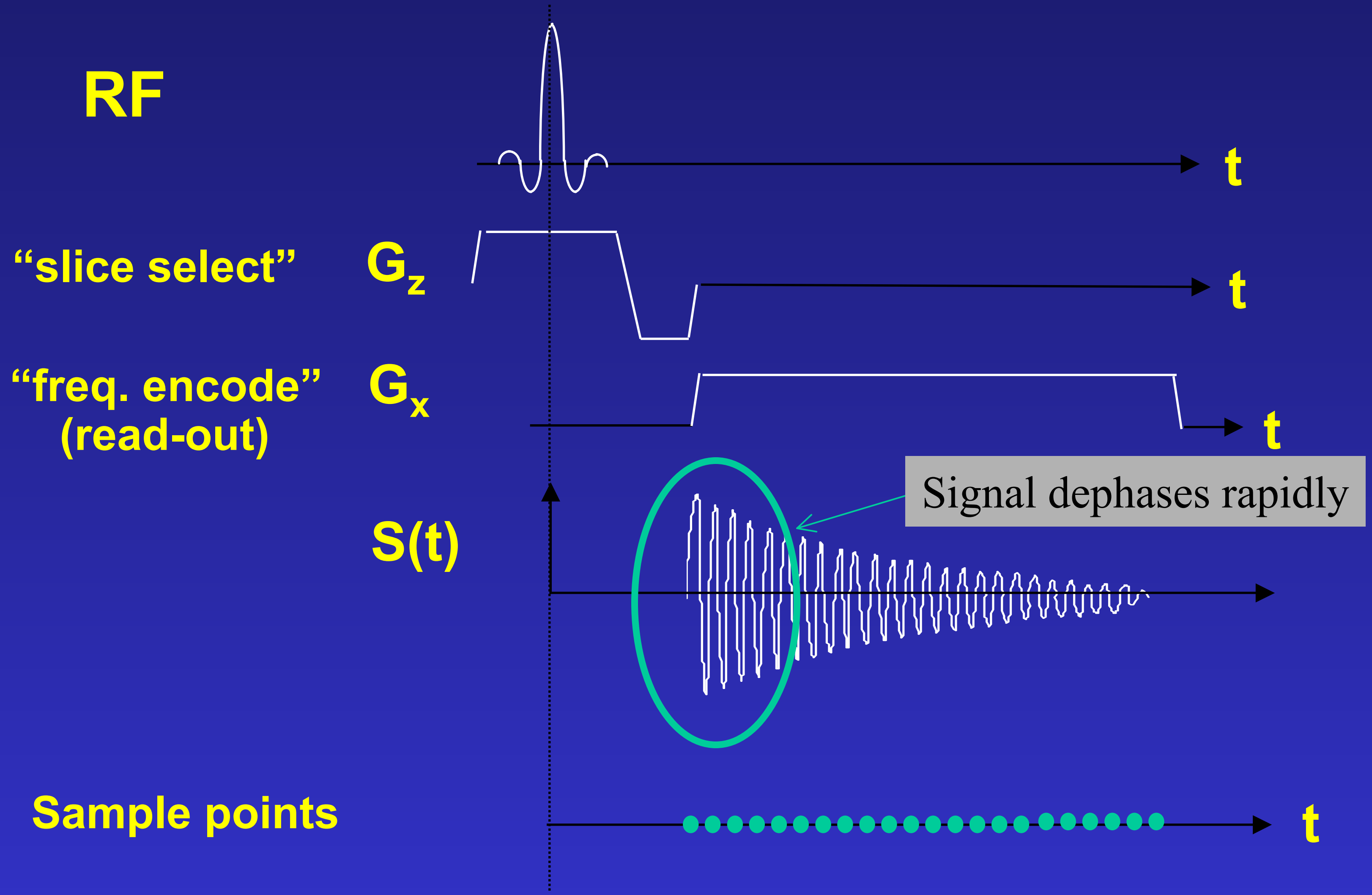
- After slice selection all spins in the selected plane have the same frequency and phase (a)

- Signal is acquired while a magnetic field gradient G_x is on (b)



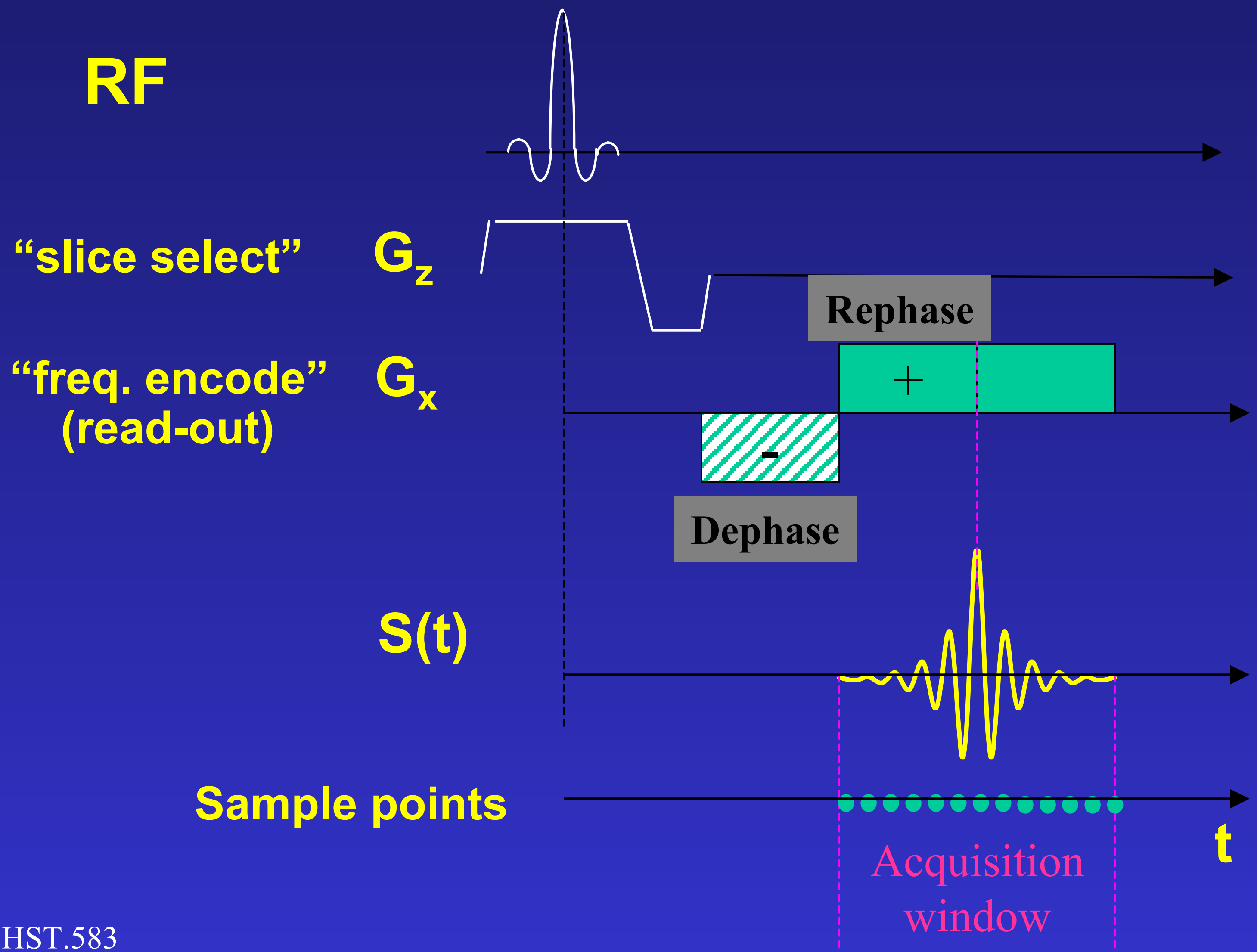
$$w_{(x)} = \gamma \, G_x \, x$$

‘Pulse sequence’ so far



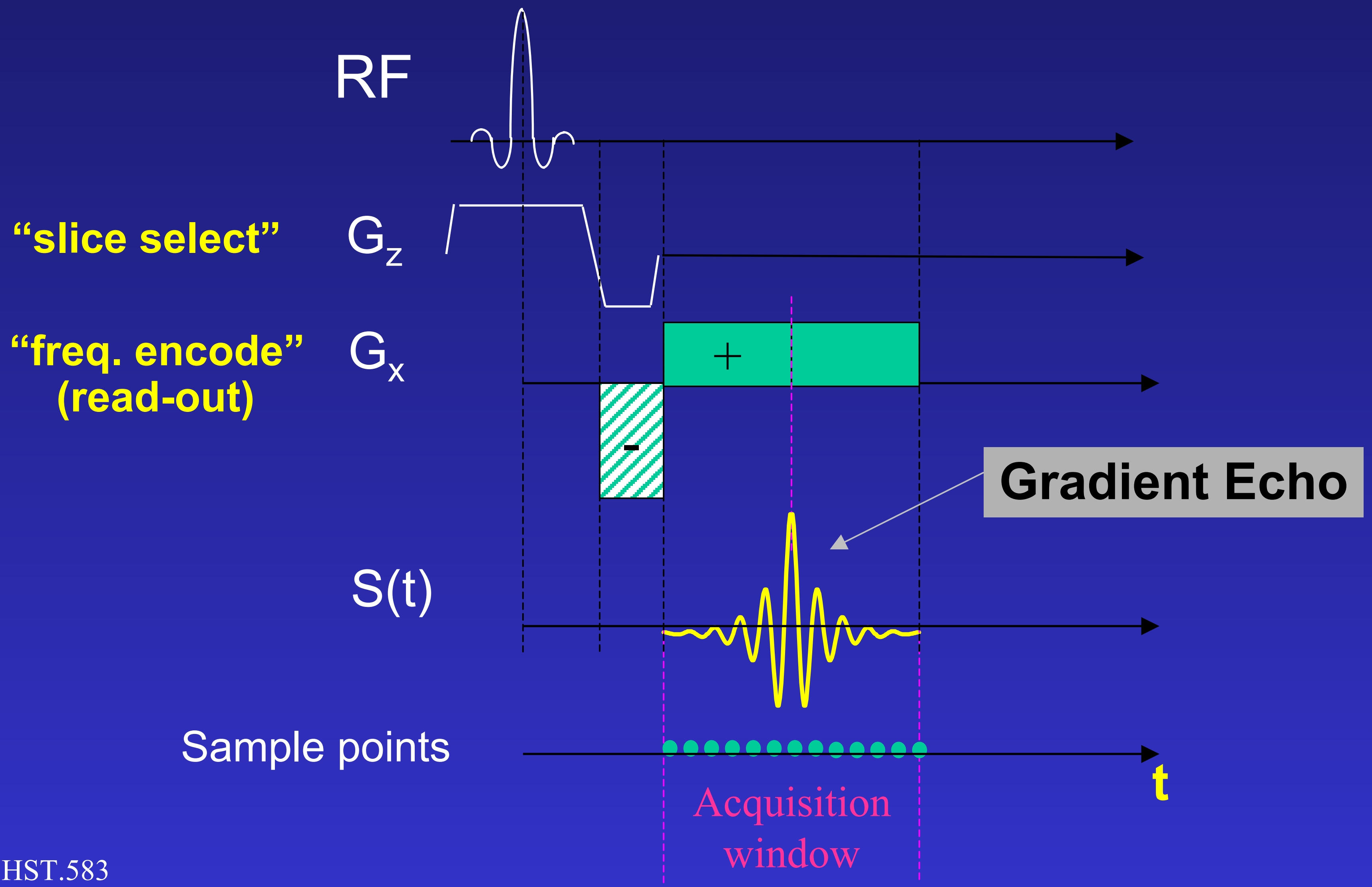
Courtesy of L. Wald

More signal can be obtained:



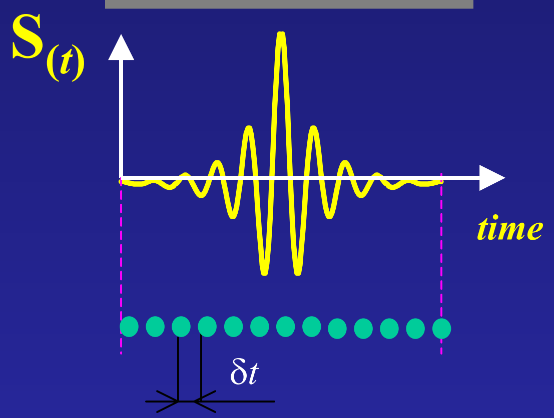
We can save some time …

‘Pulse sequence’ so far



Frequency Encoding

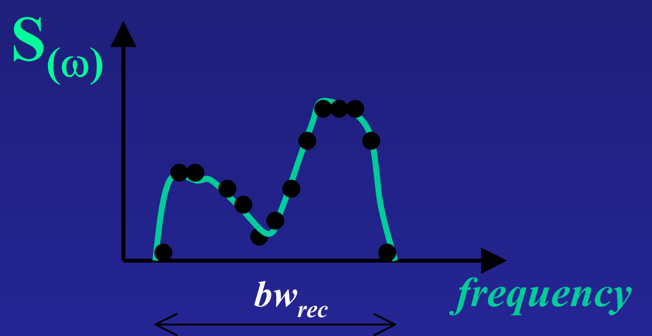
Measured signal: time domain



Sampling time $\delta t = 1/bw_{rec}$
N_x: number of samples

Fourier transform

Frequency spectrum: 1D x-projection

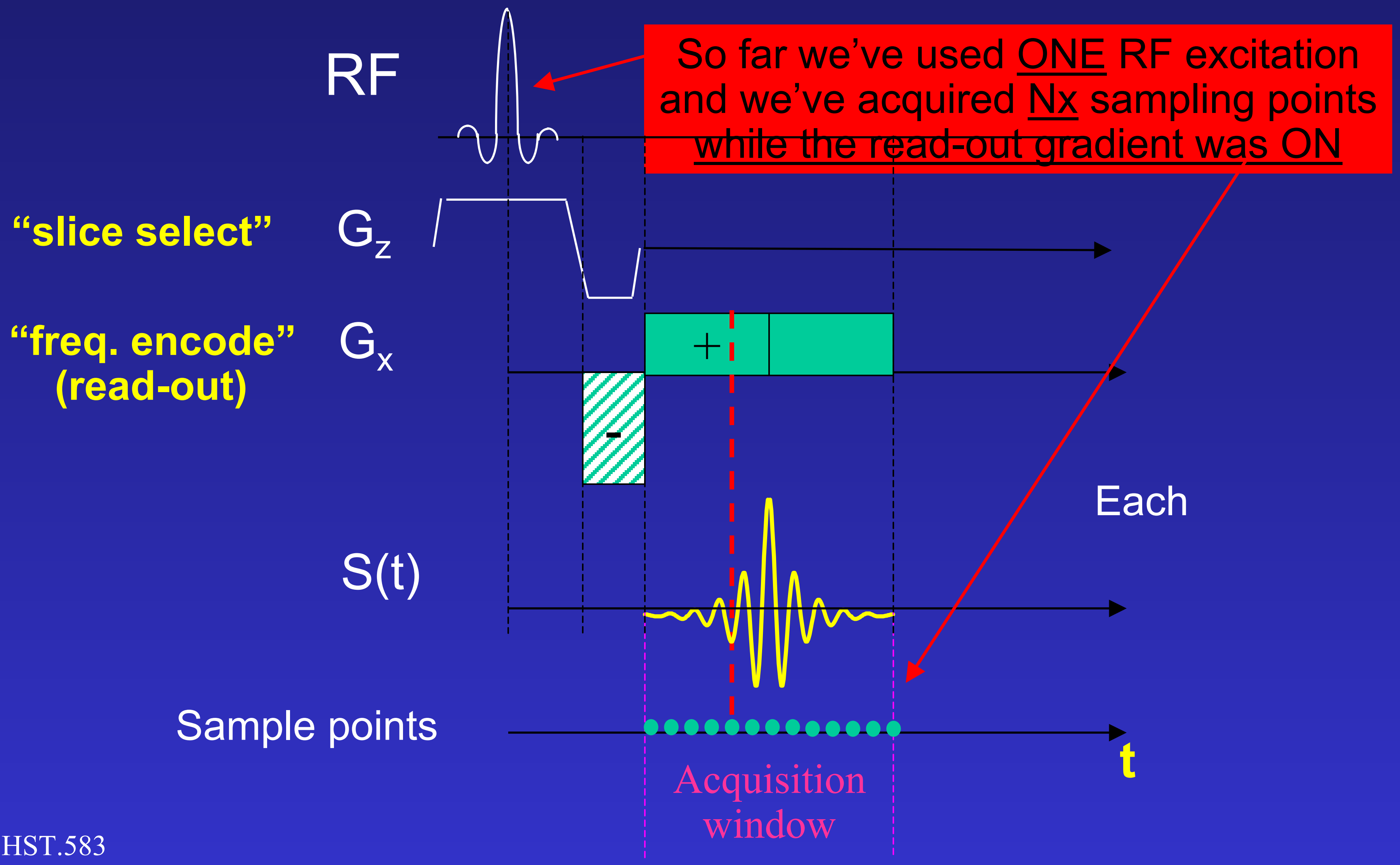


Receiver bandwidth (bw_{rec})

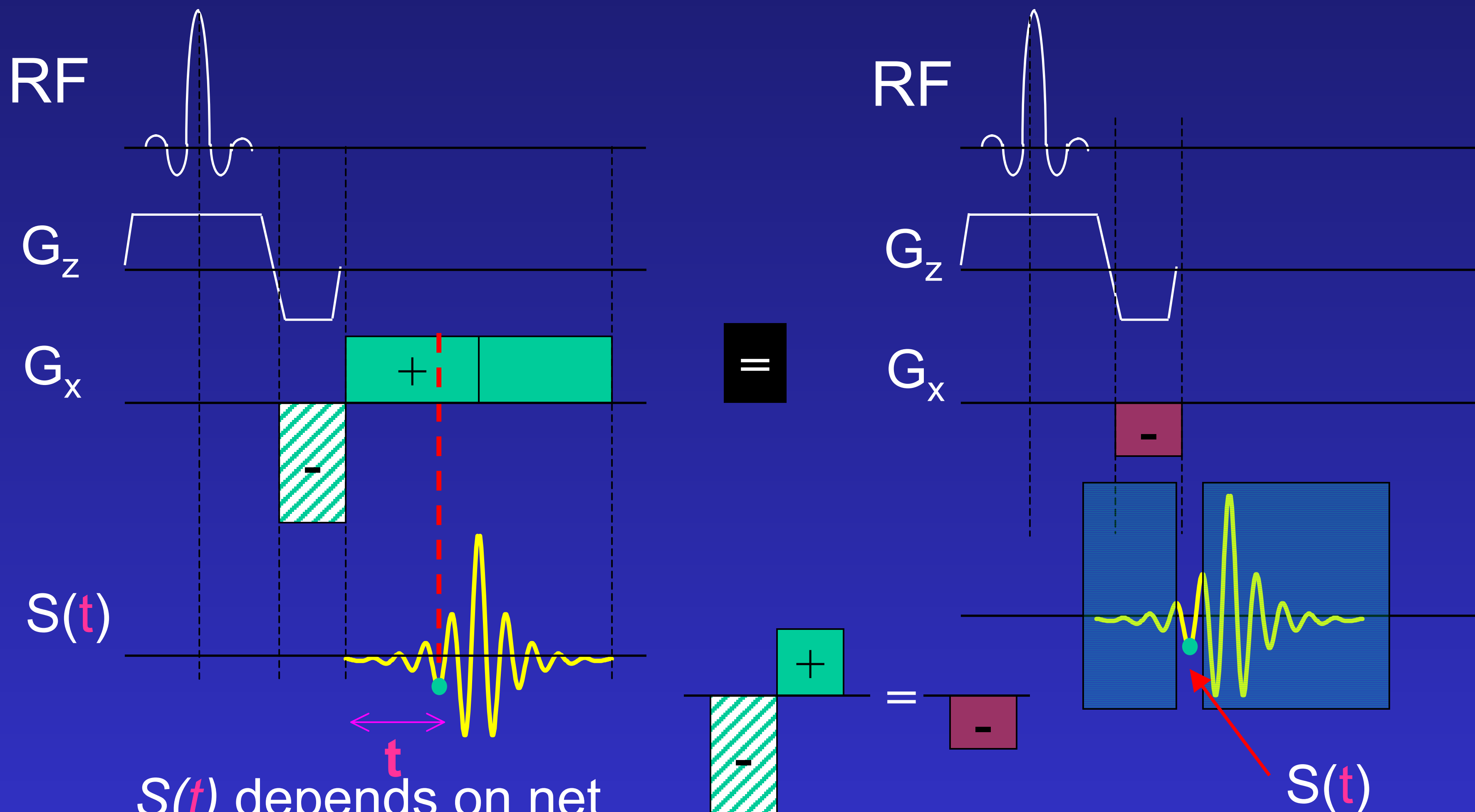
$$\omega_{(r)} = \gamma\left(B_0 + G.r\right)$$

- Relevant parameters
  - Acquisition time (t_{acq}): $t_{acq} = N_x\,\delta t = N_x / bw_{rec}$
  - Resolution (δx): $\delta x = FOV_x / N_x$
  - Field of view (FOV_x): $bw_{rec} = \gamma\, G_x\, FOV_x$

We could have measured '<u>exactly</u>' the same information differently:



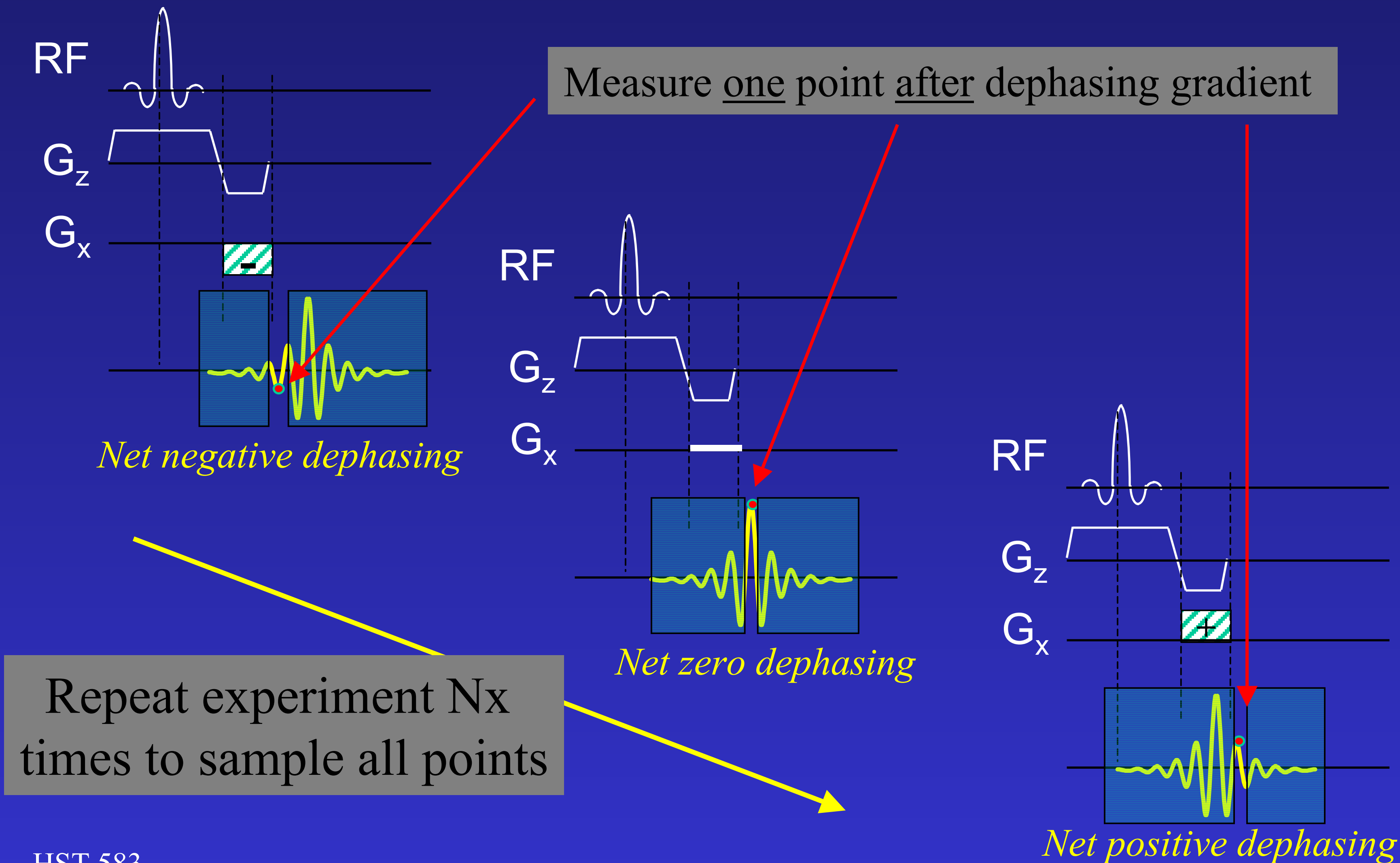
Let’s look at one arbitrary sampled point in the MR signal



S(t) depends on net dephasing during *t*

Same net dephasing

We can do the same for all Nx sampled points:



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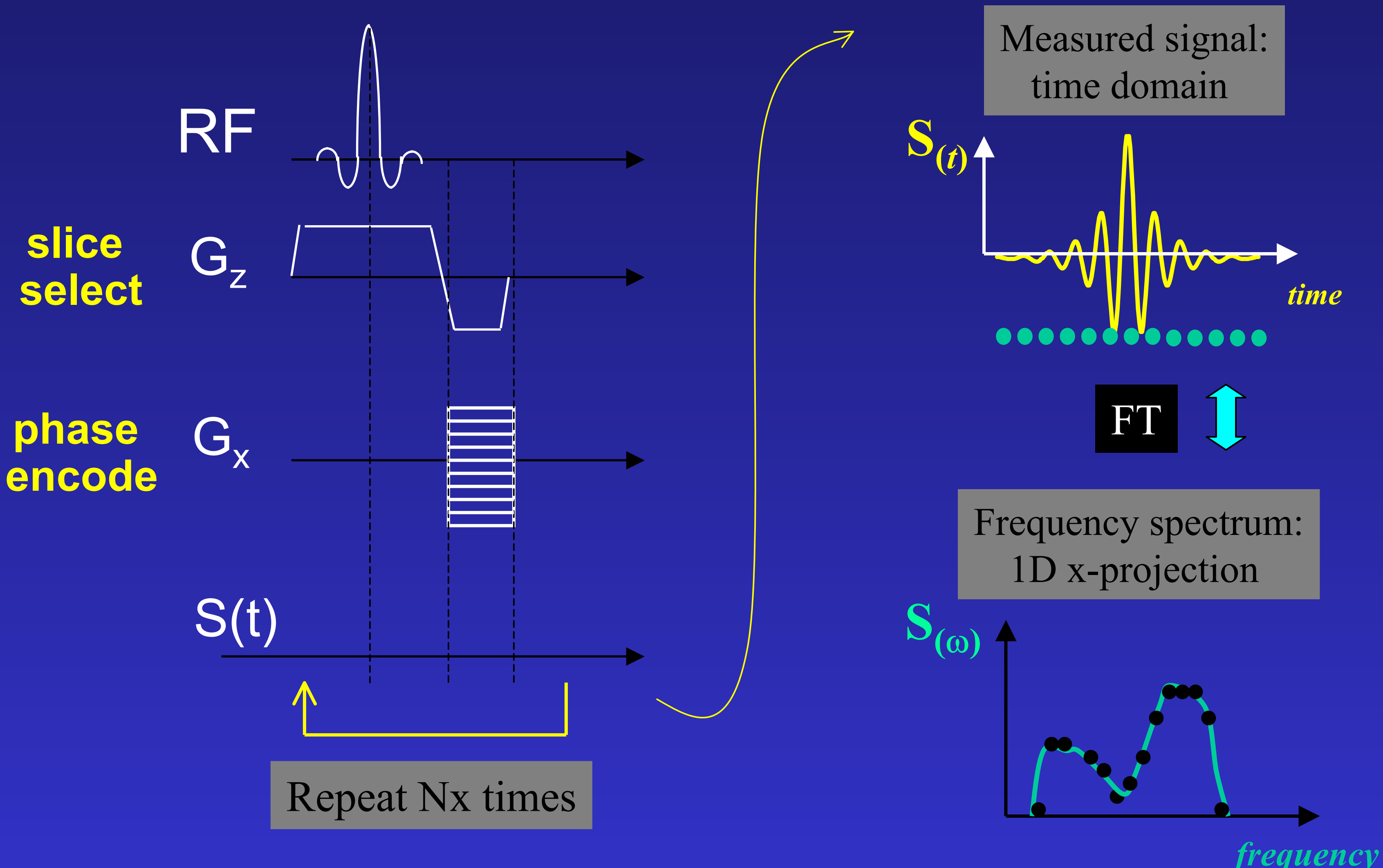
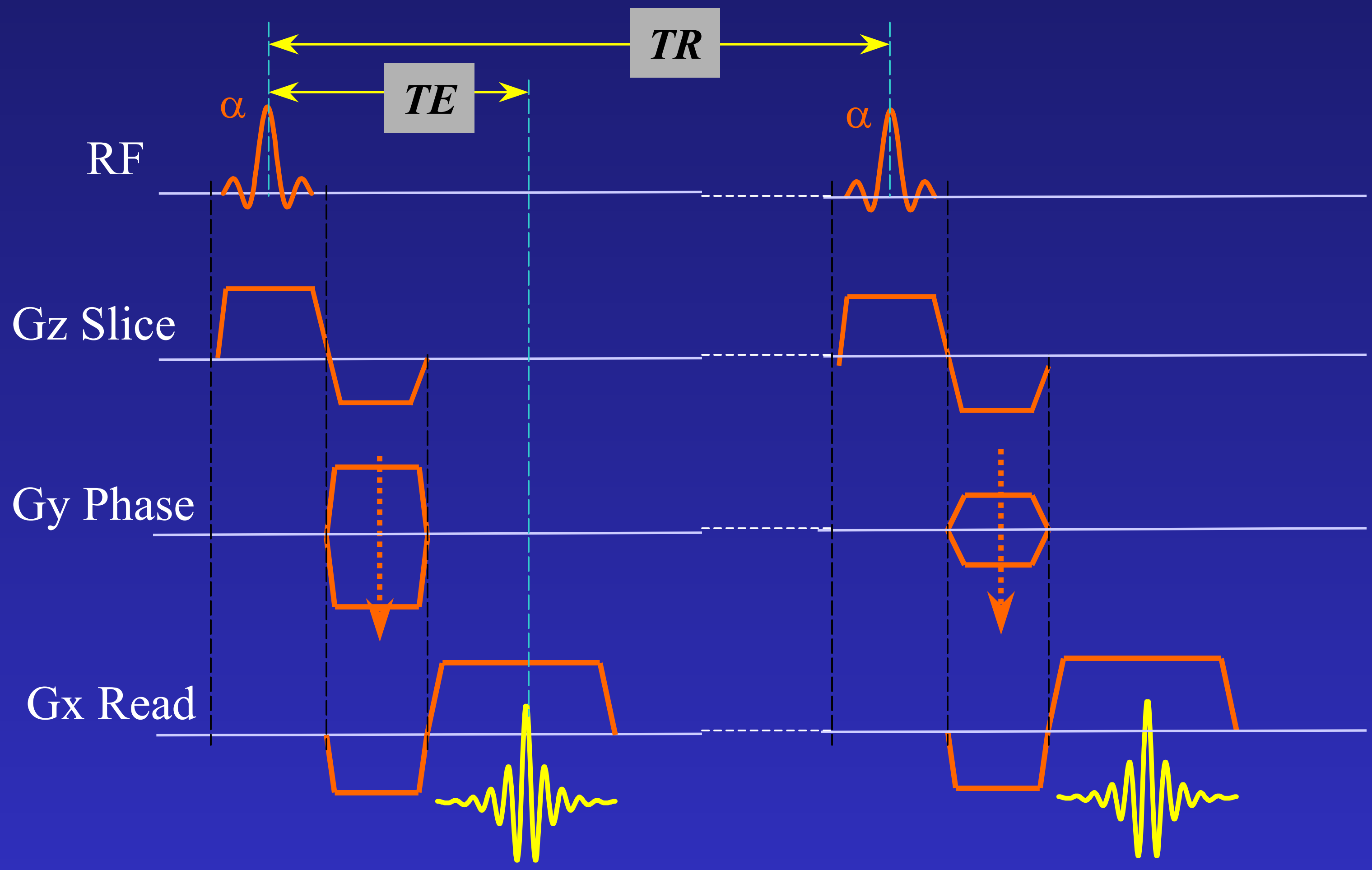
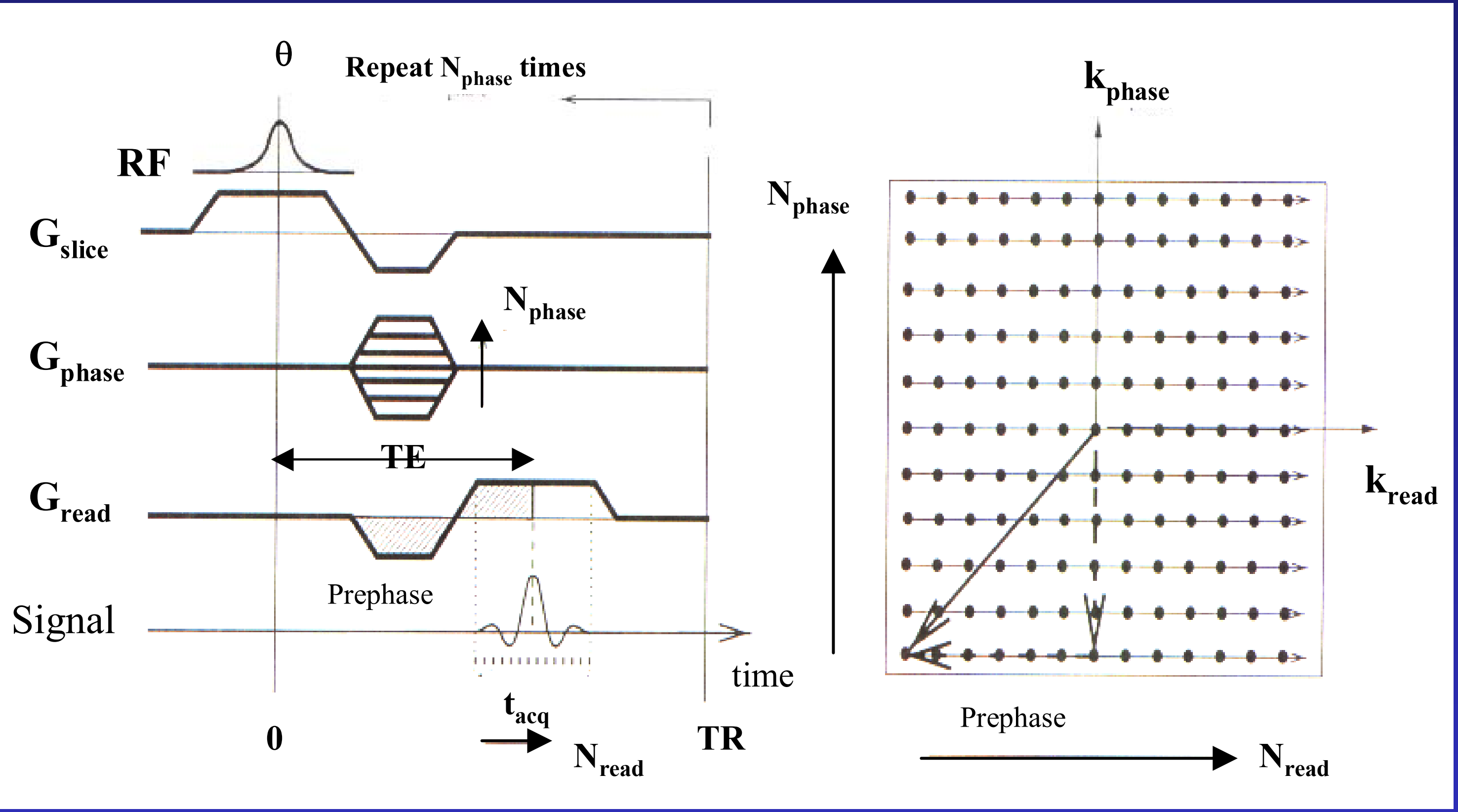


Basic Gradient Echo Sequence



Conventional spin-warp MRI sequence



The signal we measure is in spatial frequency space (*k*-space)

$$k_{(t)} = \frac{\gamma}{2\pi}\int_0^t G_{(t')}\, dt'$$

Pulse Sequences & Image Contrast

Contents:

- **Definition of Contrast**
- **Contrast parameters**
- **Concept of MRI contrast weighting**
- **Properties of pulse sequences & sequence parameters**

Image Contrast Definition

- **Goal**: maximise the contrast **(USEFUL IMAGES!)**
- **Contrast**: difference in MR signals between different tissues

Tissue 1 → T_1, T_2, T_2^*, ρ, Diffusion, Flow → S_1

Tissue 2 → T_1, T_2, T_2^*, ρ, Diffusion, Flow → S_2

Water protons' mobility/environment: T_1, T_2, T_2^*, ρ, Diffusion, Flow

MR signal: S_1, S_2

Contrast to Noise ratio:

$$CNR = \frac{S_1 - S_2}{\sigma_{noise}}$$

Some examples?

Image Contrast:
What can we manipulate?

Tissue Properties: fixed

Tissue	T_1 (ms)	T_2 (ms)	ρ*
Fat	260	84	0.90
White Matter	780	90	0.72
Gray Matter	920	100	0.84
CSF	3000	300	1.00

ρ*: % H_2O relative to CSF

Experimental Variables

- Pulse sequence
- Pulse sequence parameters
  - Repetition time: TR
  - Echo time: TE
  - Inversion time: TI
  - RF flip angle: α
- Contrast agent

What's the effect of these variables?

Image Contrast: Weighting the MR Signal

- **General MRI pulse sequence: combination of contrasts**

Signal Intensity:

$$S(x,y) = k \times \rho \times T_1 \times T_2 \times \ldots$$

- **Contrast Weighting: maximize one term, minimize the others**

Example: T_1-weighting

$$S(x,y) = k \times \rho \times T_1 \times T_2 \times \ldots$$

by choosing adequate sequence & sequence parameters

Some examples?

Typical MRI sequences

Gradient Echo:

- Proton Density weighting
- T1 weighting
- T2* weighting

Spin Echo:

- Proton Density weighting
- T1 weighting
- T2 weighting
- Double echo: PD & T2 weighting

Inversion Recovery:

- MP-RAGE: for high T1 contrast
- FLAIR: for PD or T2 weighting without CSF signal

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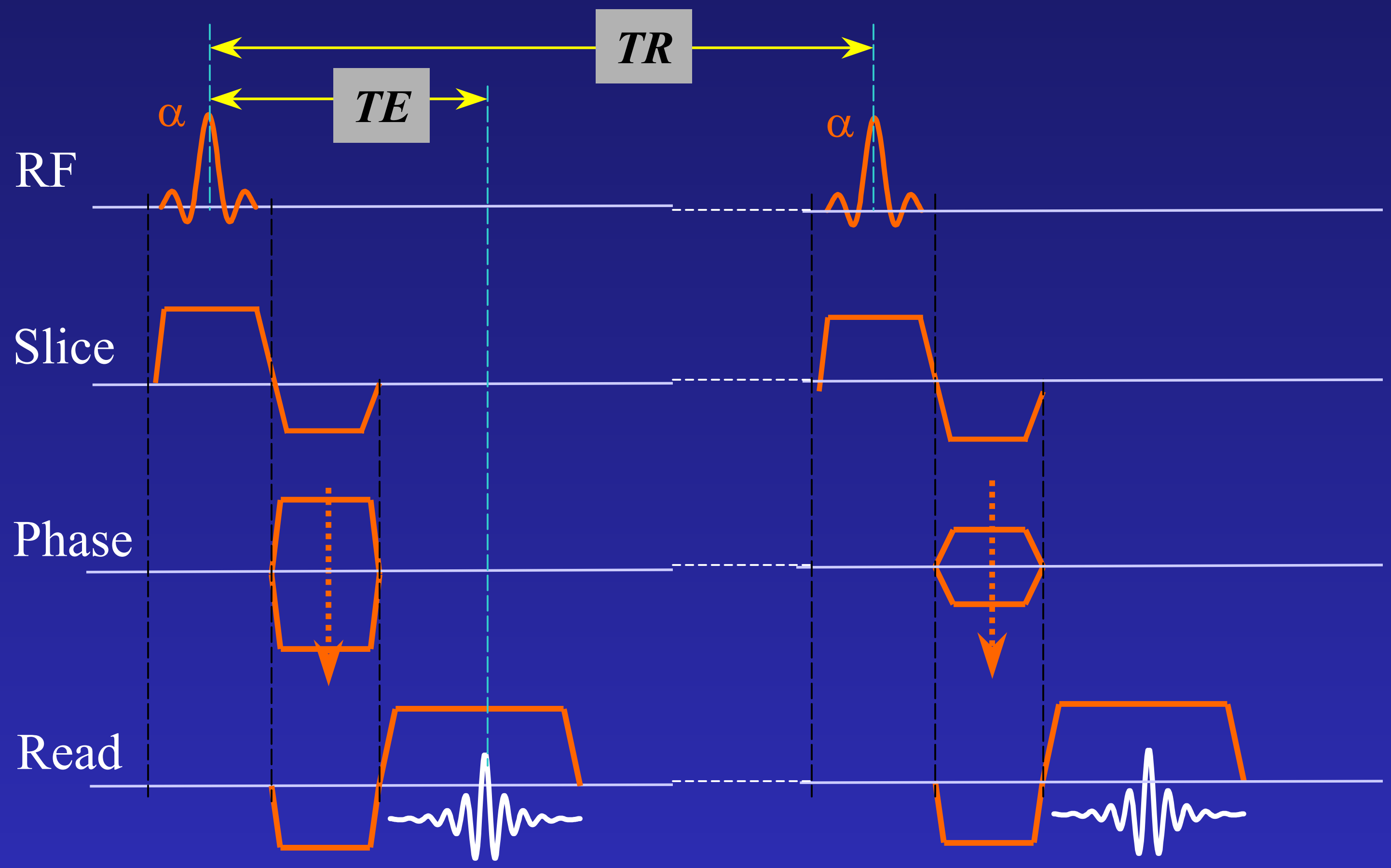
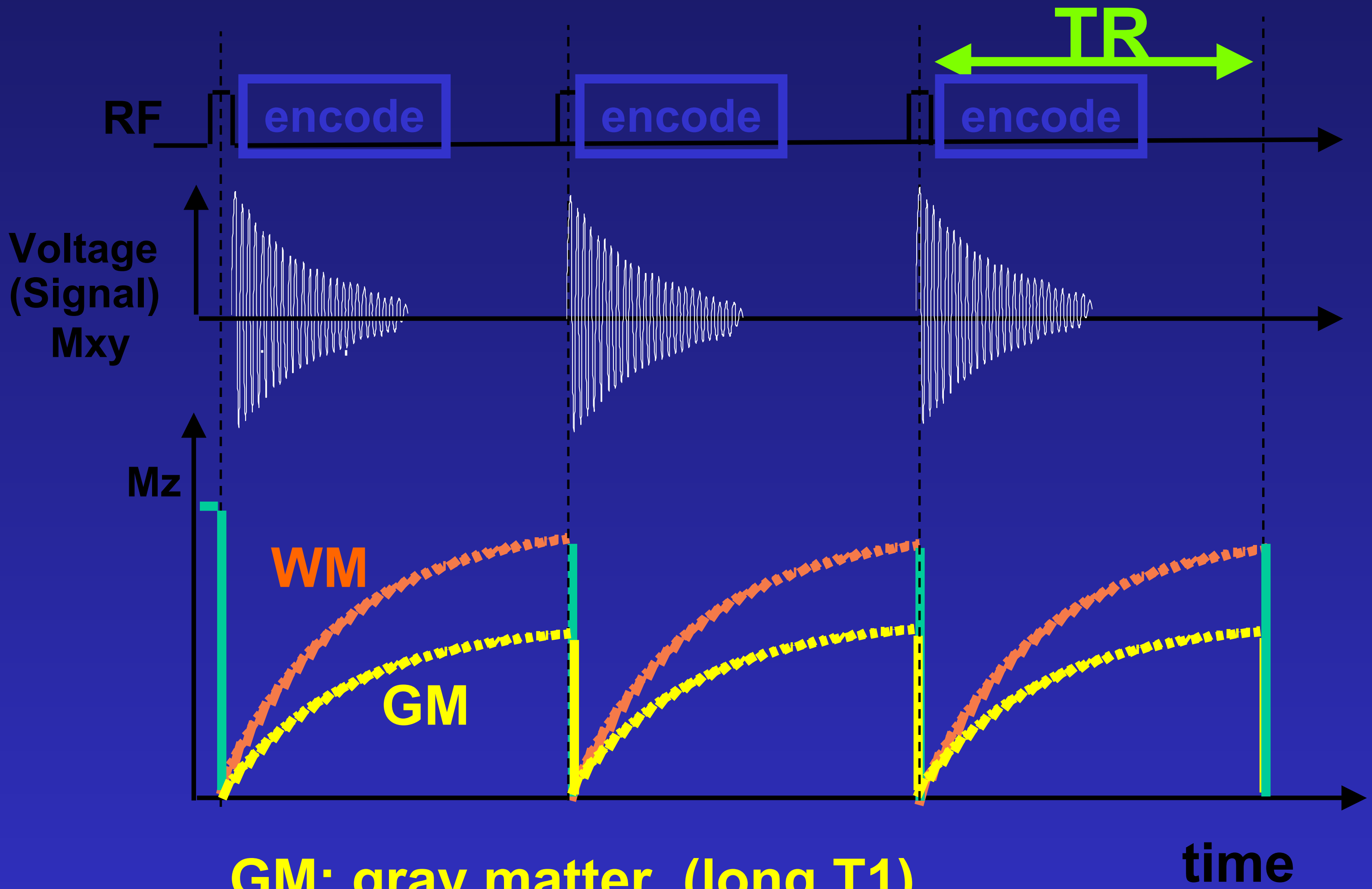
Basic Gradient Echo Sequence



MR Signal:

$$S_{GRE} = M_0 \sin\alpha \left[1 - \exp\left(-\frac{TR}{T_1}\right)\right] \exp\left(-\frac{TE}{T_2^*}\right)$$

Repetition Time (TR): T1 contrast



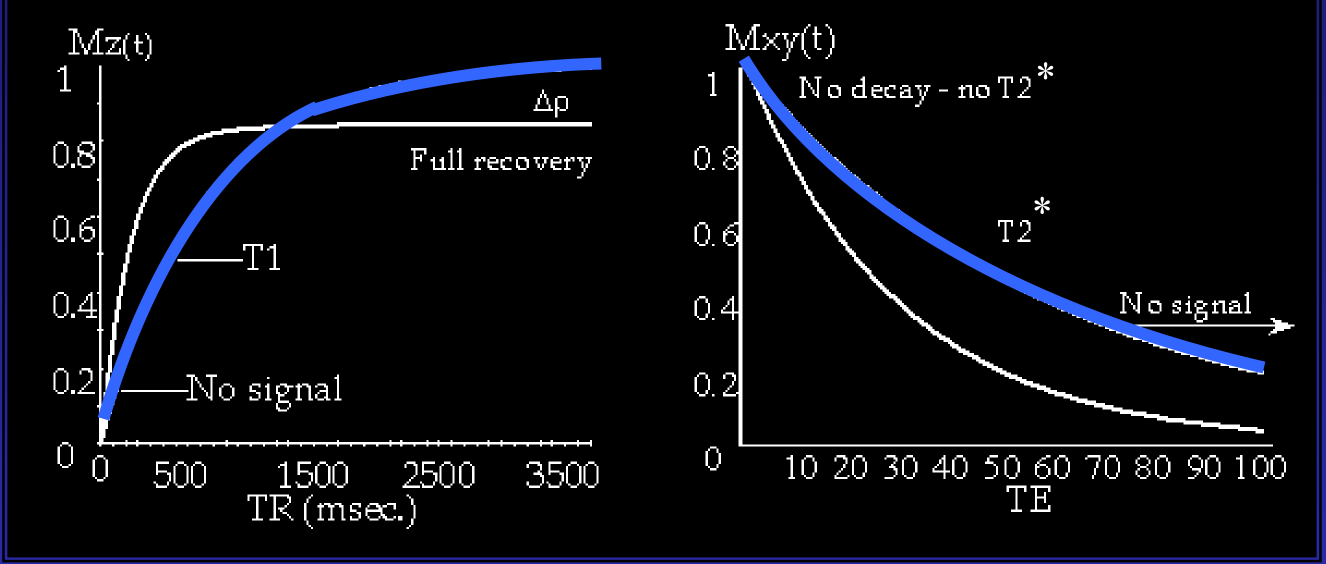
GM: gray matter (long T1)

WM: white matter (short T1)

Courtesy of L. Wald

Gradient Echo Sequence

$$S_{GRE} = M_0 \sin\alpha \left[1 - \exp\left(-\frac{TR}{T_1}\right)\right] \exp\left(-\frac{TE}{T_2^*}\right)$$



Proton Density weighting

(TR >>T1, short TE, sin α ~ 1)

Water density

T1 weighting

(TR ~ T1, short TE, sin α ~ 1)

Gray / White matter / CSF

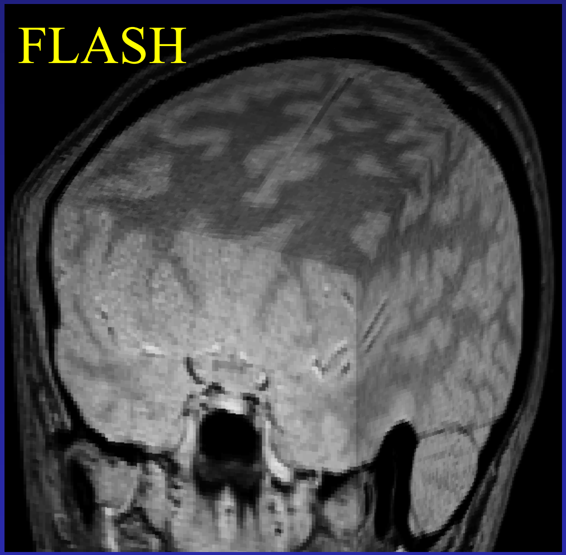
T2* weighting

(TR >>T1, TE ~ T2*)

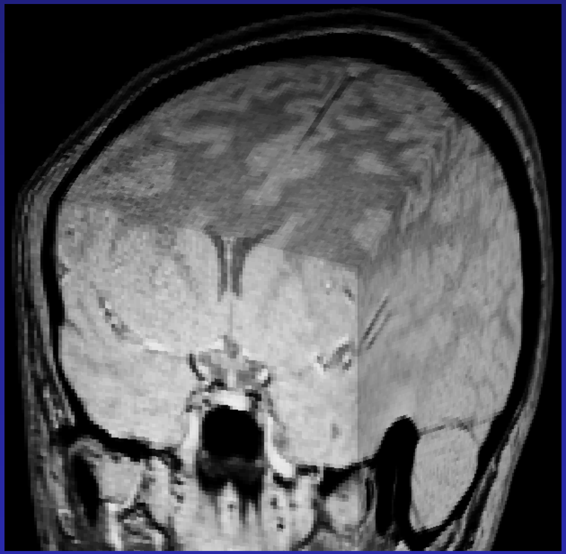
Hemorrhage

Gradient Echo Sequence

Proton Density Weighting → T_1 Weighting



FA = 3°



FA = 5°

FA = 30°

Manipulating contrast with flip angle

Courtesy of A. Dale and B. Fischl

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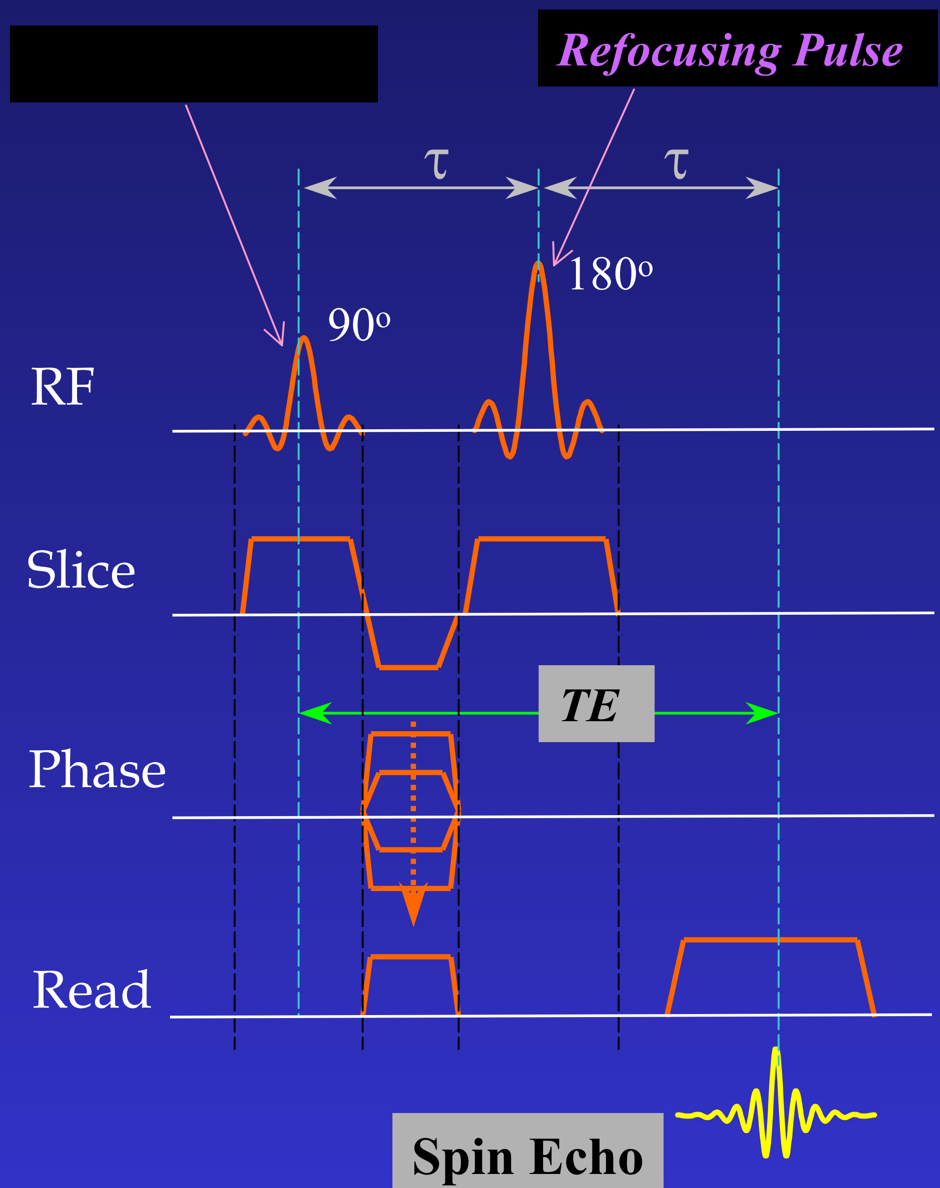
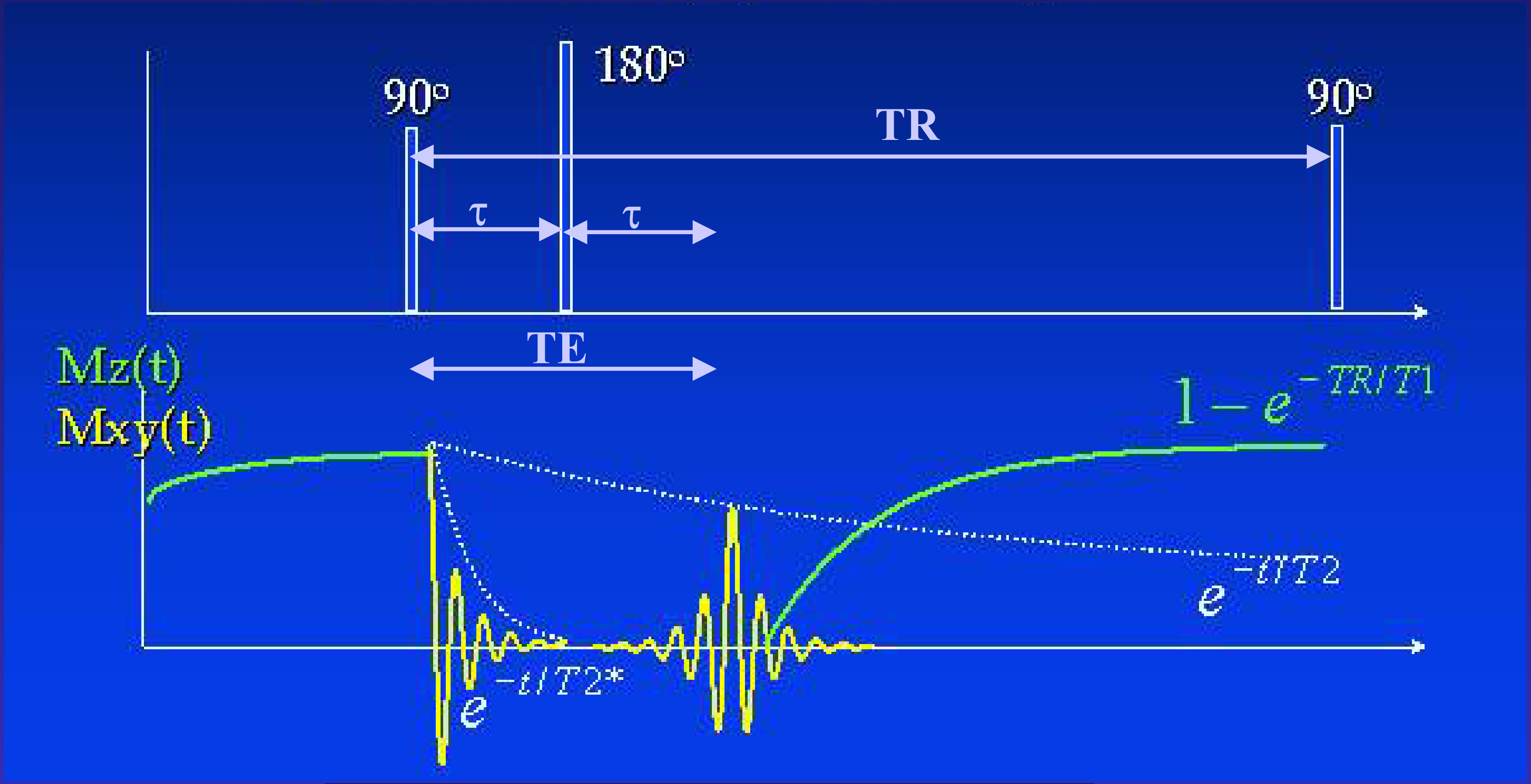
Basic Spin-Echo Sequence



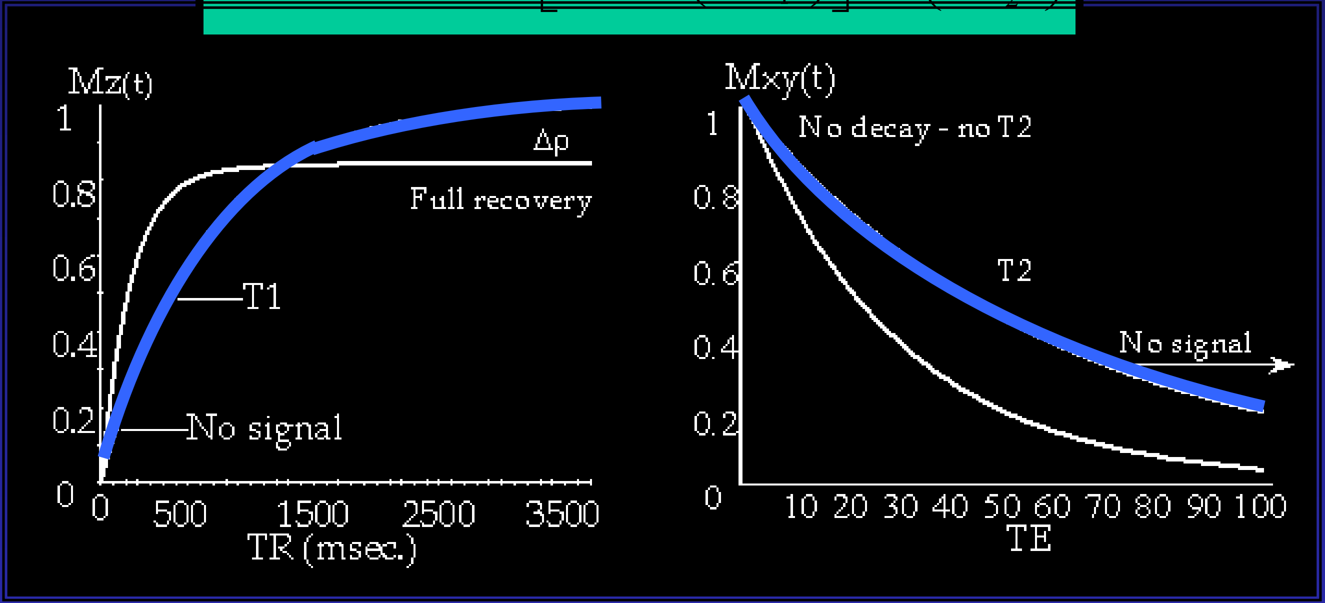
Spin-Echo Sequence: The MR Signal



$$S_{SE} = M_0\left[1-\exp\left(-\frac{TR}{T_1}\right)\right]\exp\left(-\frac{TE}{T_2}\right)$$

Spin Echo Sequence

$$S_{GRE} = M_0 \sin\alpha \left[1 - \exp\left(-\frac{TR}{T_1}\right)\right] \exp\left(-\frac{TE}{T_2}\right)$$



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Water density

T1 weighting

(TR ~ T1, short TE, sin α ~ 1)

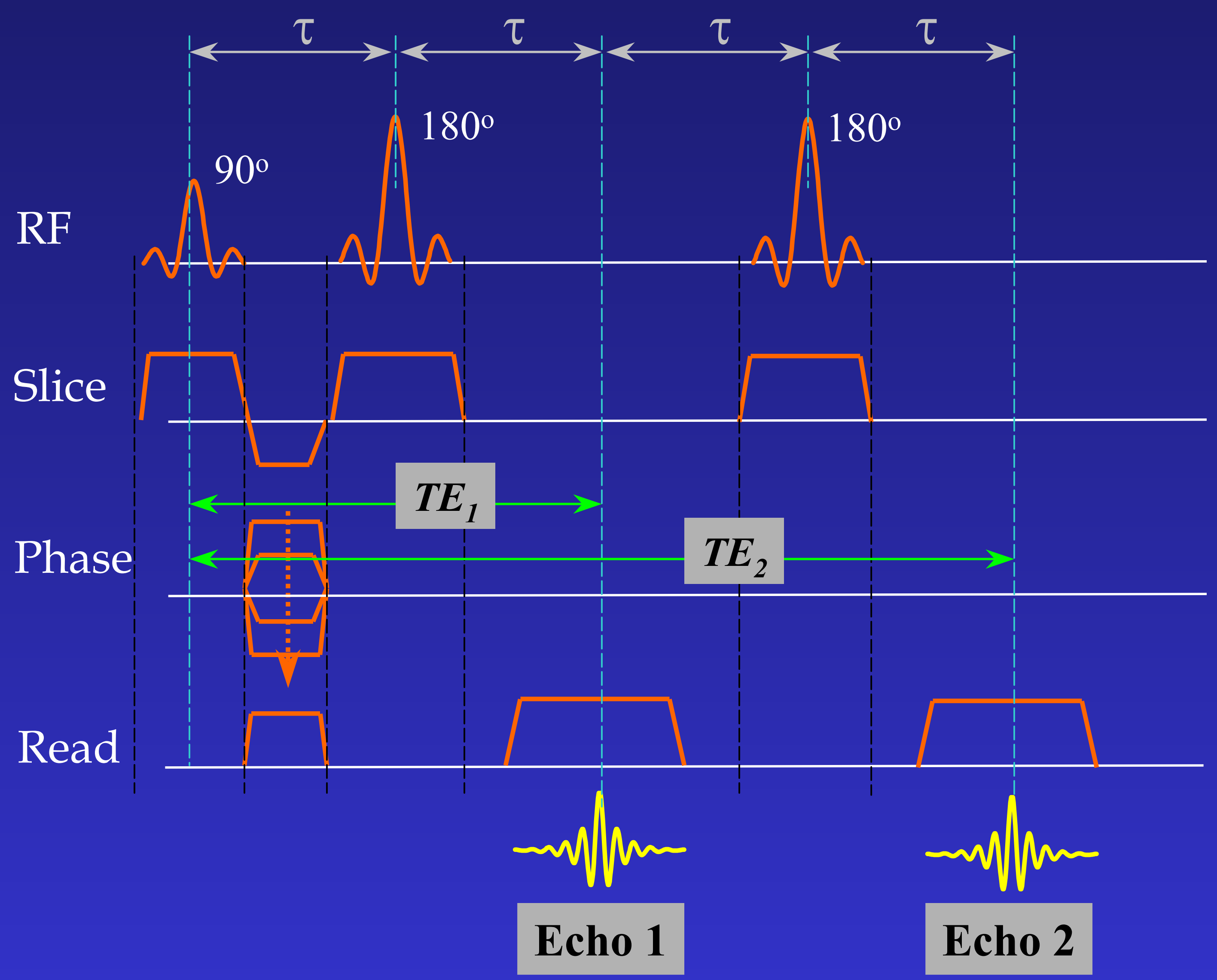
Gray / White matter / CSF

T2 weighting

(TR >>T1, TE ~ T2)

Hemorrhage

Double Spin Echo Sequence



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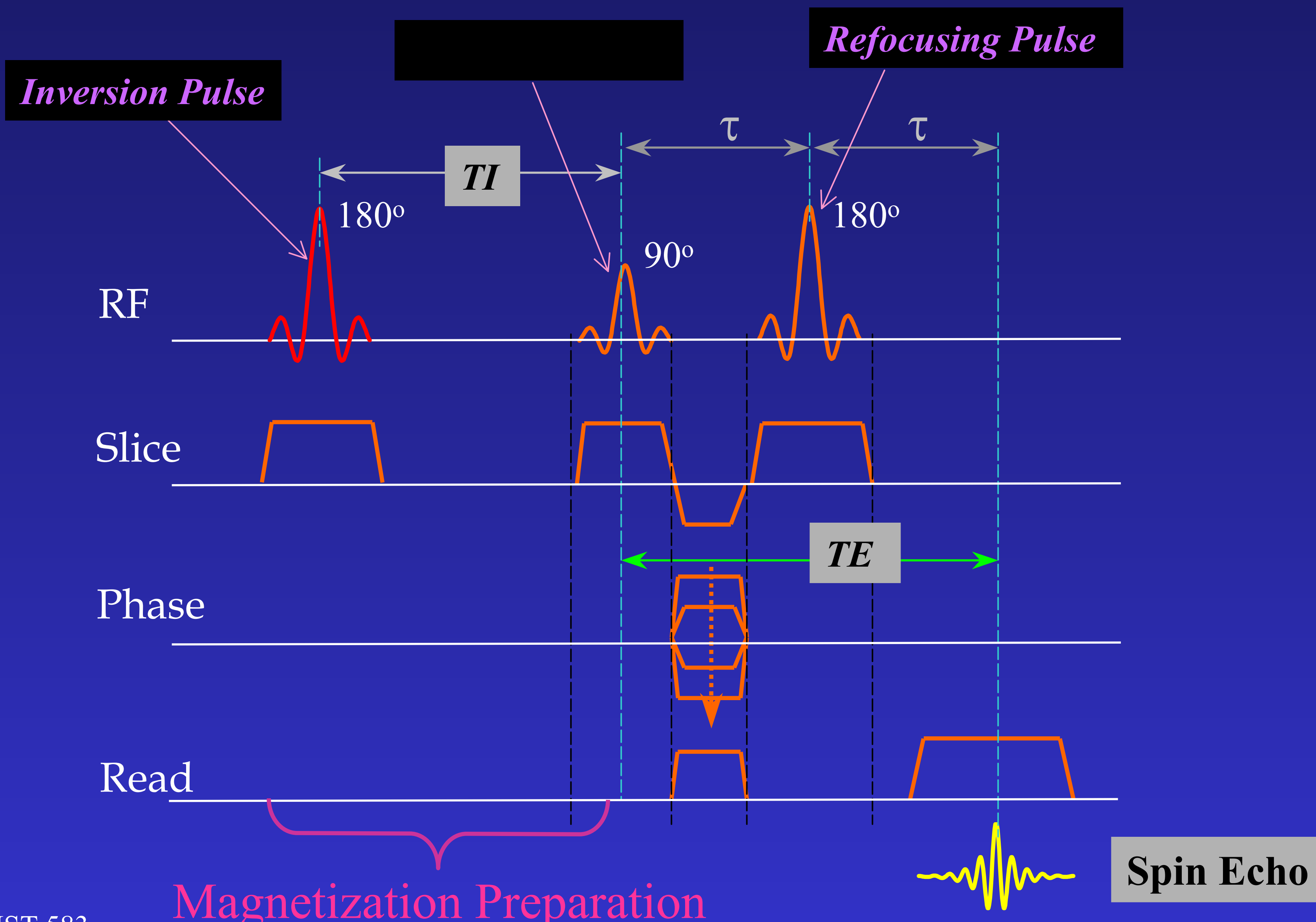
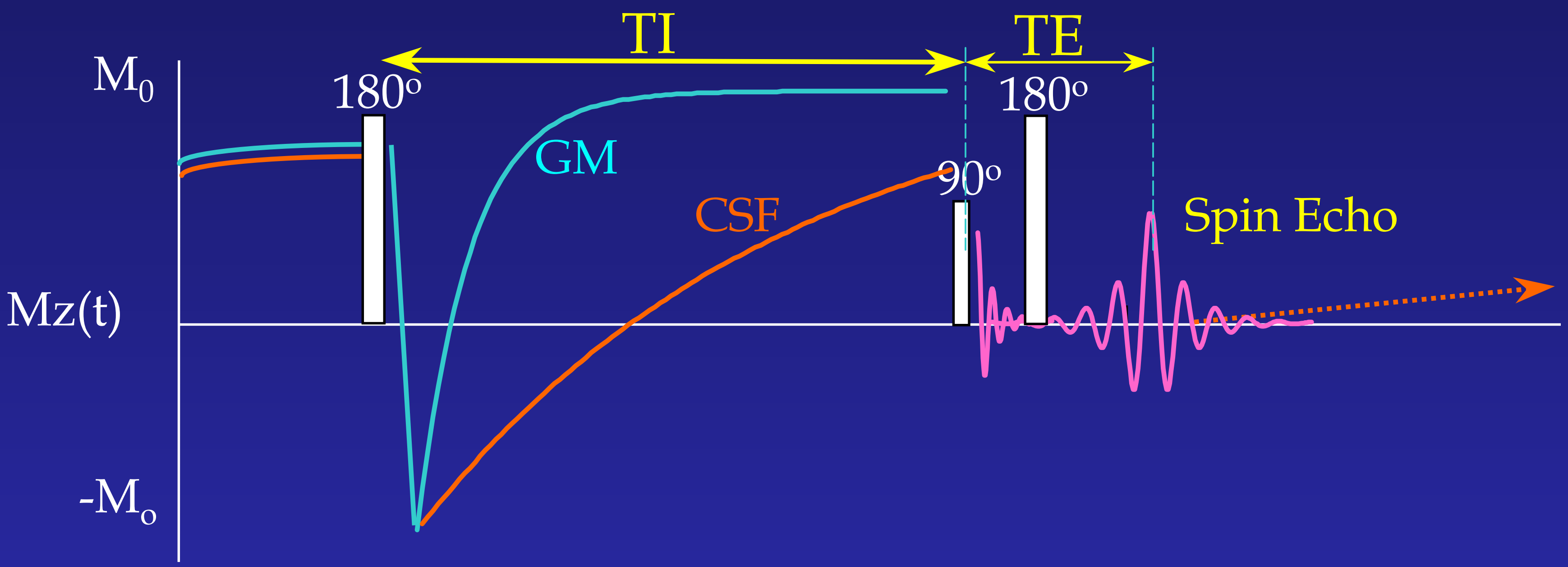
Inversion Recovery



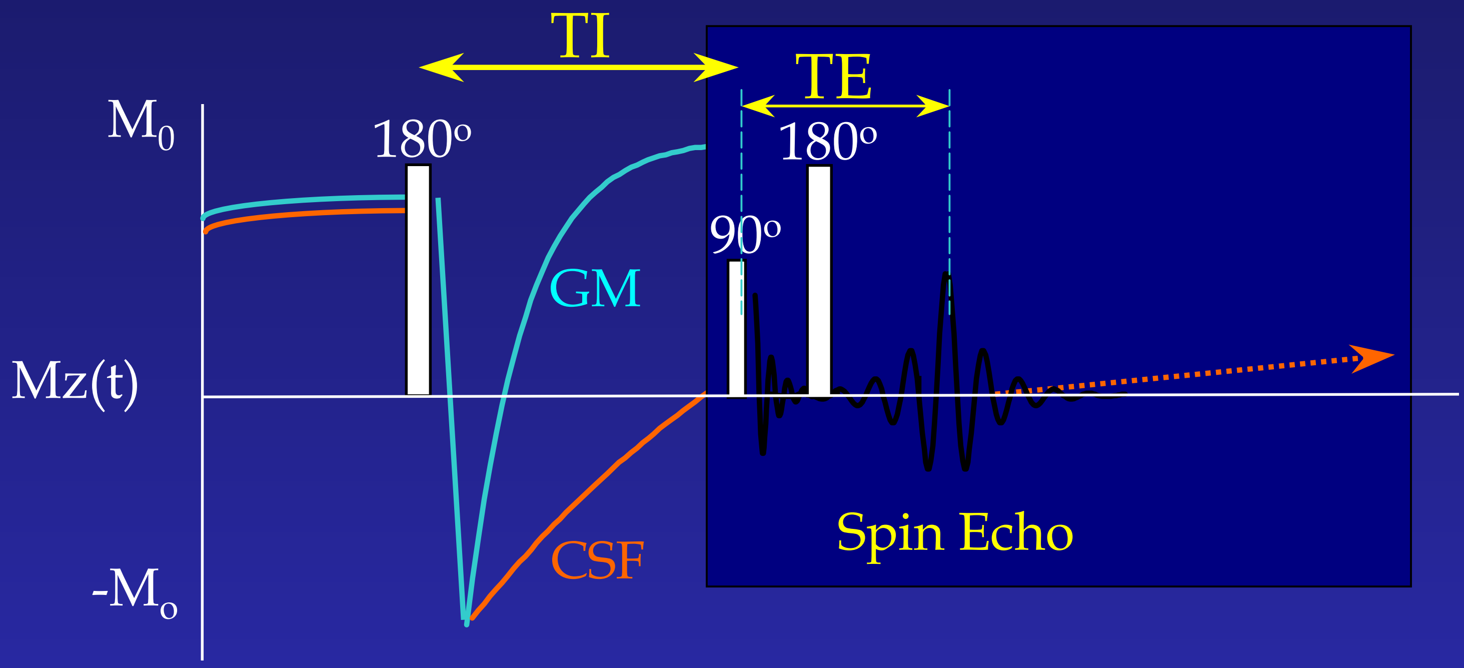
Enhanced T_1-weighting: Inversion Recovery



180° Inversion: prepare magnetization prior to Spin Echo detection

$$\text{Signal} \propto \rho\left(1 - 2e^{-TI/T1} + e^{-TR/T1}\right) e^{-TE/T2}$$

Fluid Attenuation Inversion Recovery (*FLAIR*)



Signal null at: *TI = ln(2)* T1*

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