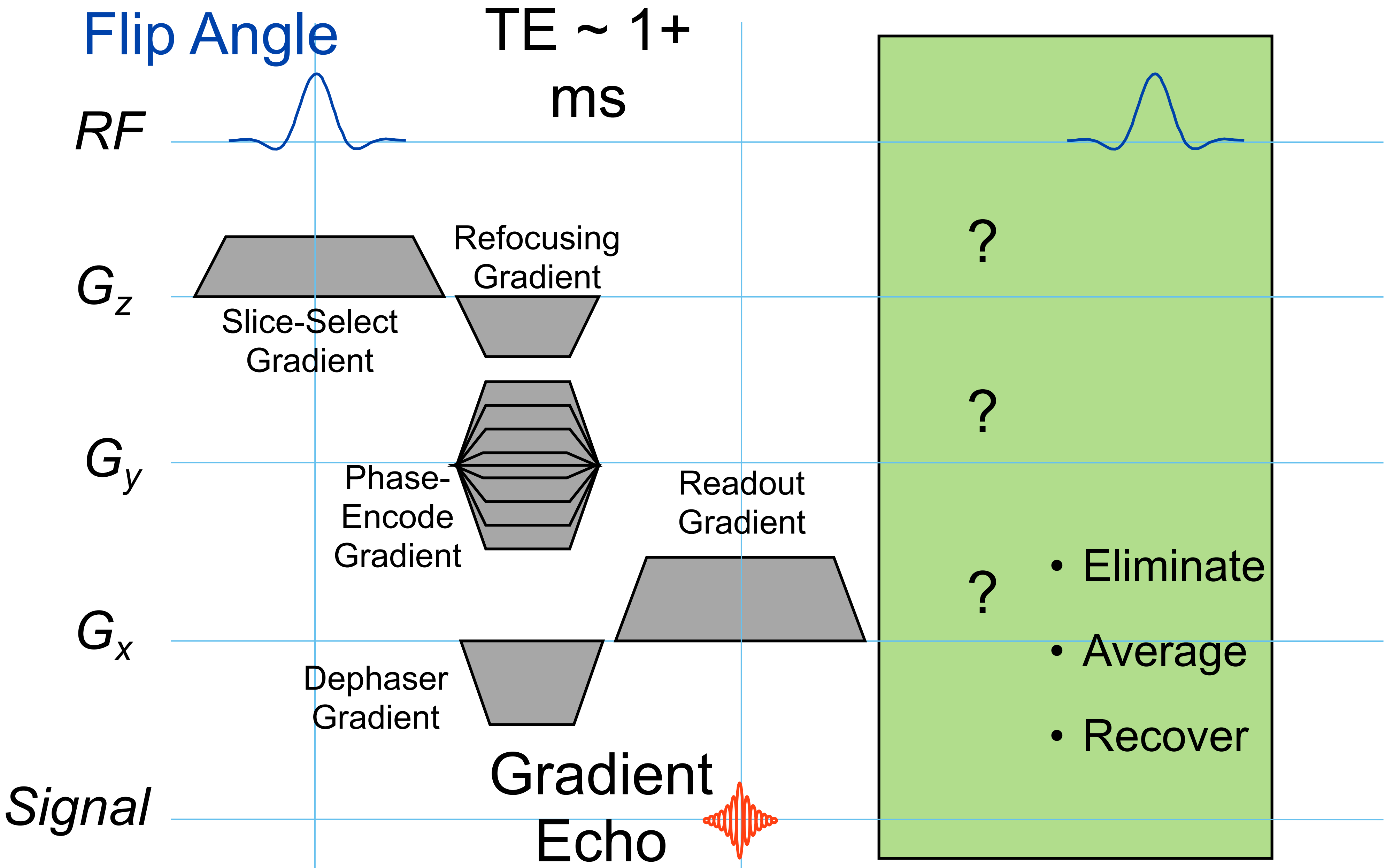
Gradient Echo Sequences

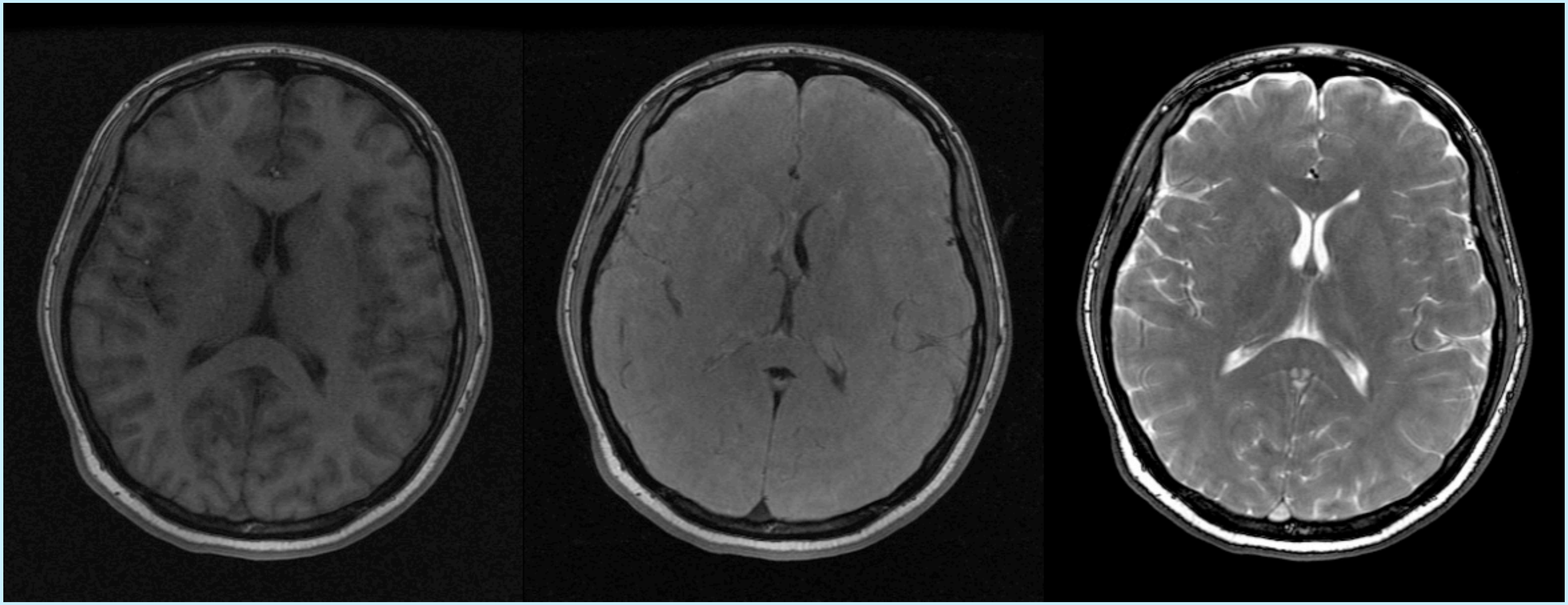
- Balanced SSFP
- Gradient Spoiled Sequences
- RF Spoiled Sequences
- Variations
  - Double-echo, Reversed
  - UTE, BOLD, T2*

Gradient Echo Pulse Sequence



Contrast Example

- Contrast based solely on end-of-TR action



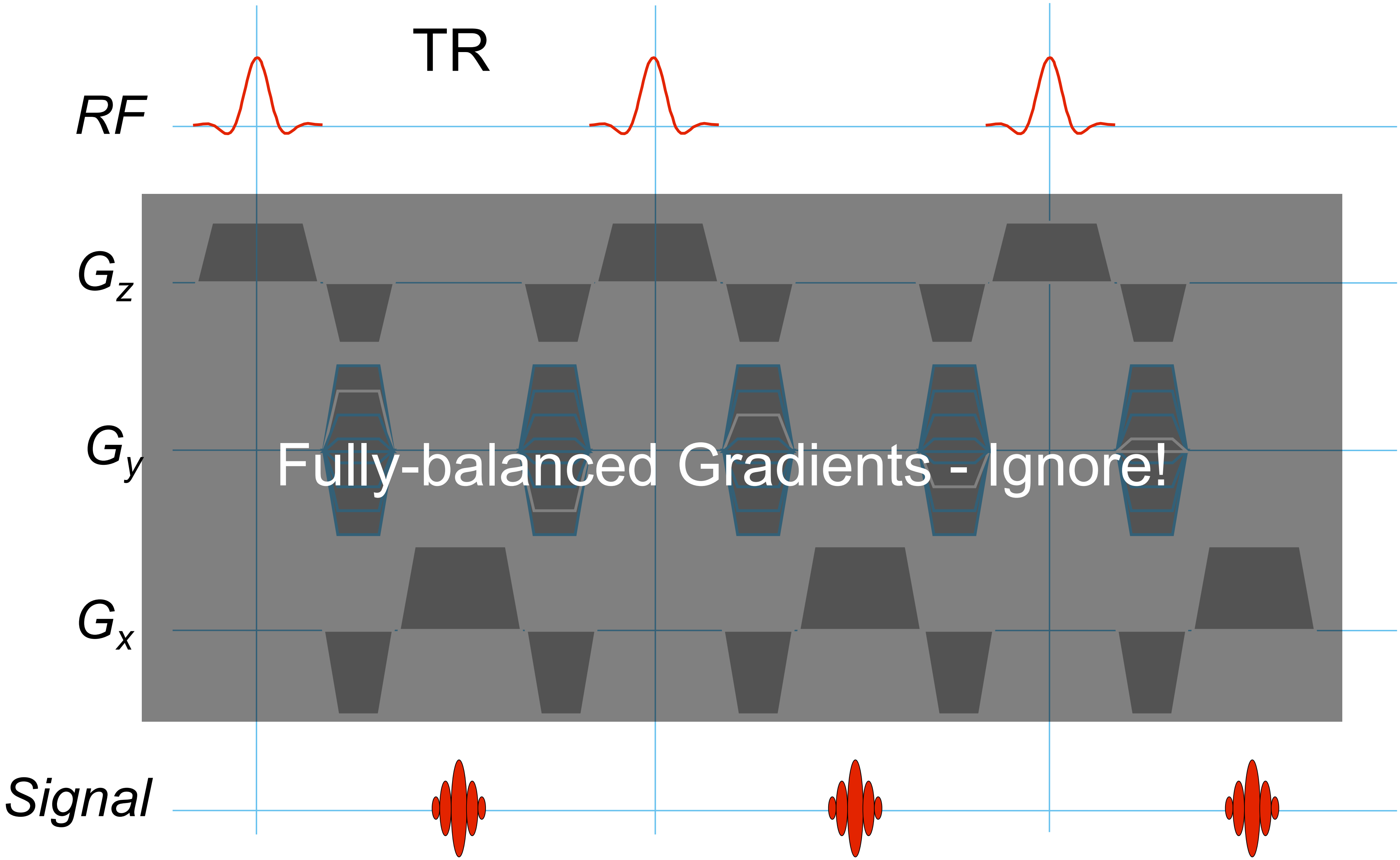
Balanced SSFP

- Goal: Maximize signal
  - Steady-state on-resonance
  - Steady-state off-resonance
  - Flip-angle effects
  - Transients

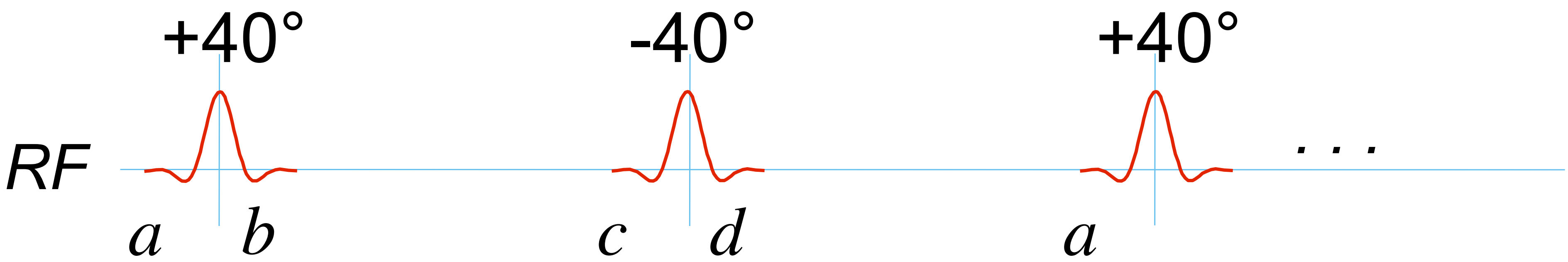
True-FISP, FIESTA, balanced FFE, BASG

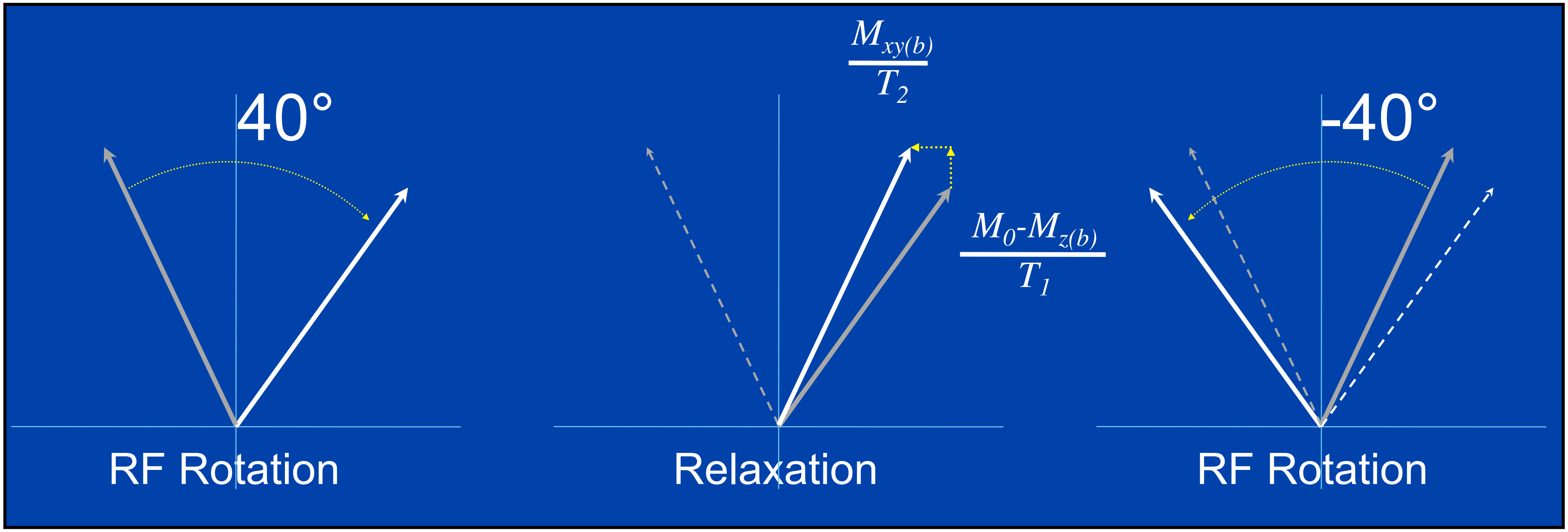
Oppelt 1986, Duerk 1997

Balanced SSFP



Example: Alternating RF, No precession



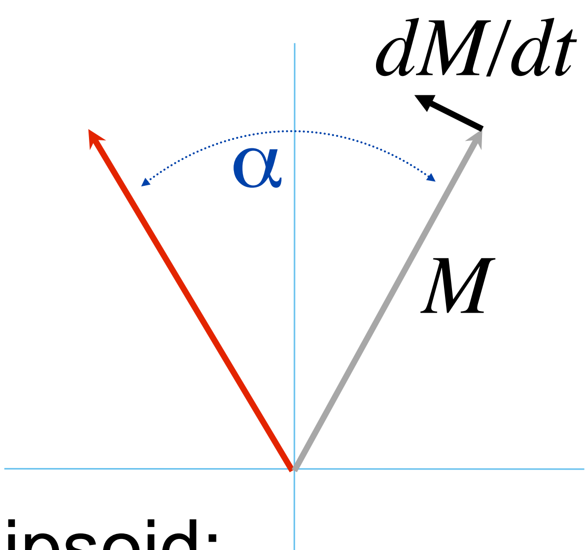


- Intuition: Relaxation does not affect direction much

Length Solution

- If Relaxation does not change length:

$$dM/dt \cdot M = 0$$



$$\frac{-M_x}{T_2}M_x + \frac{-M_y}{T_2}M_y + \frac{M_0 - M_z}{T_1}M_z = 0$$

x T_1 & Rearrange...

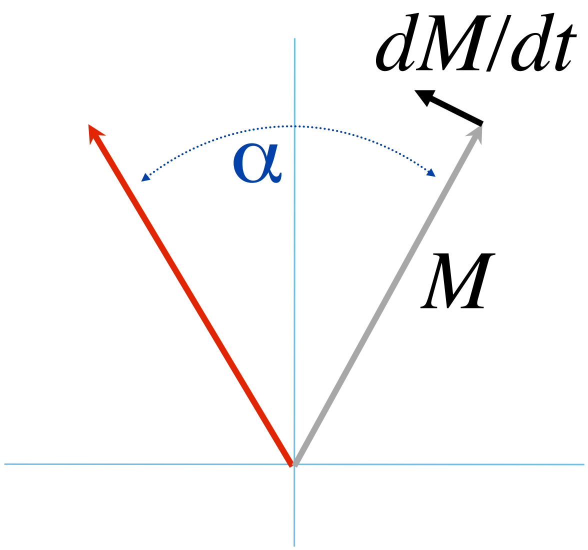
$$\left(M_z - \frac{M_0}{2}\right)^2 + \frac{M_x^2 + M_y^2}{T_2/T_1} = \left(\frac{M_0}{2}\right)^2$$

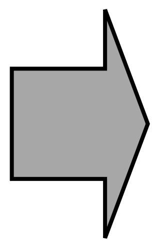
- Ellipsoid:
  - height M_0, half-width (signal) $M_0/2\sqrt{T_2/T_1}$
- T_2/T_1 contrast!

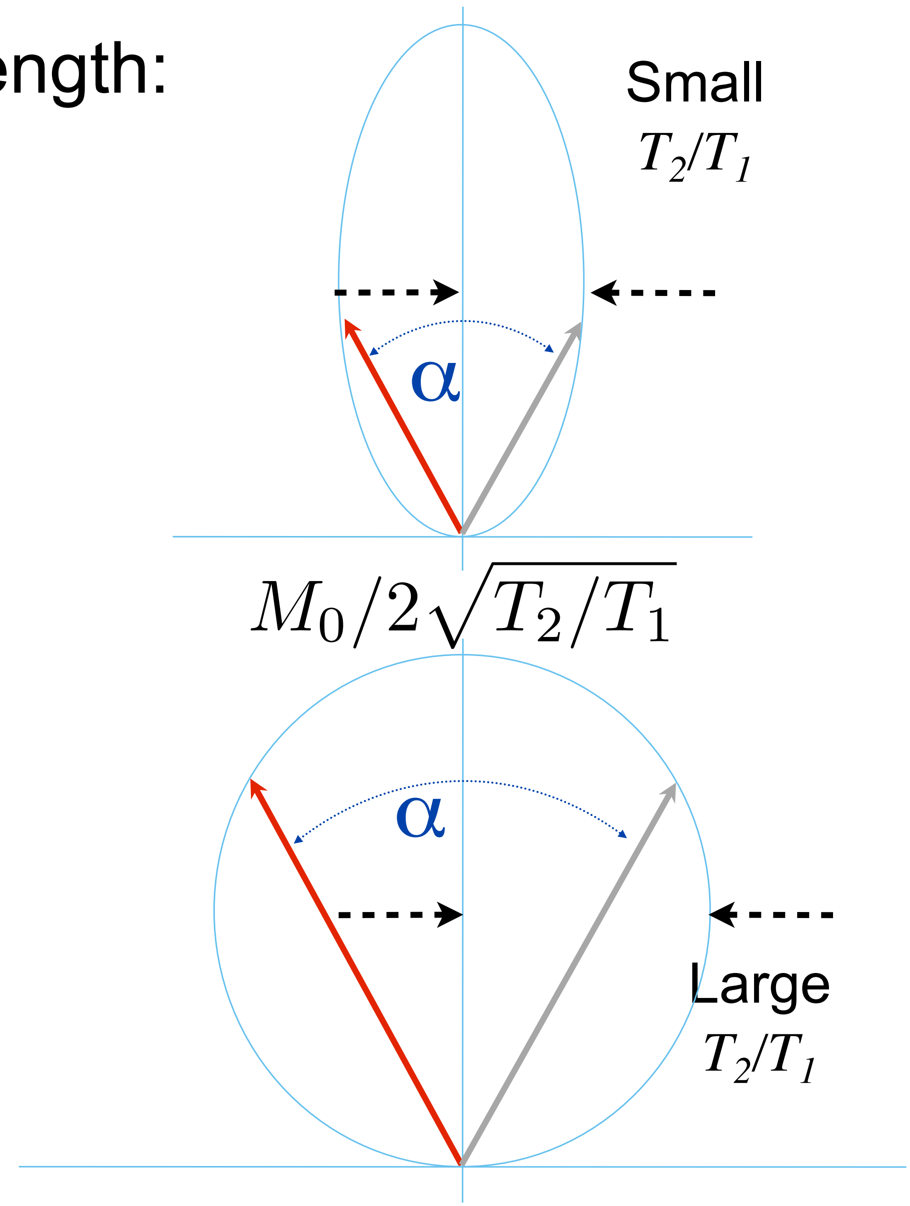
Full Solution

- If Relaxation does not change length:

$$dM/dt \cdot M = 0$$



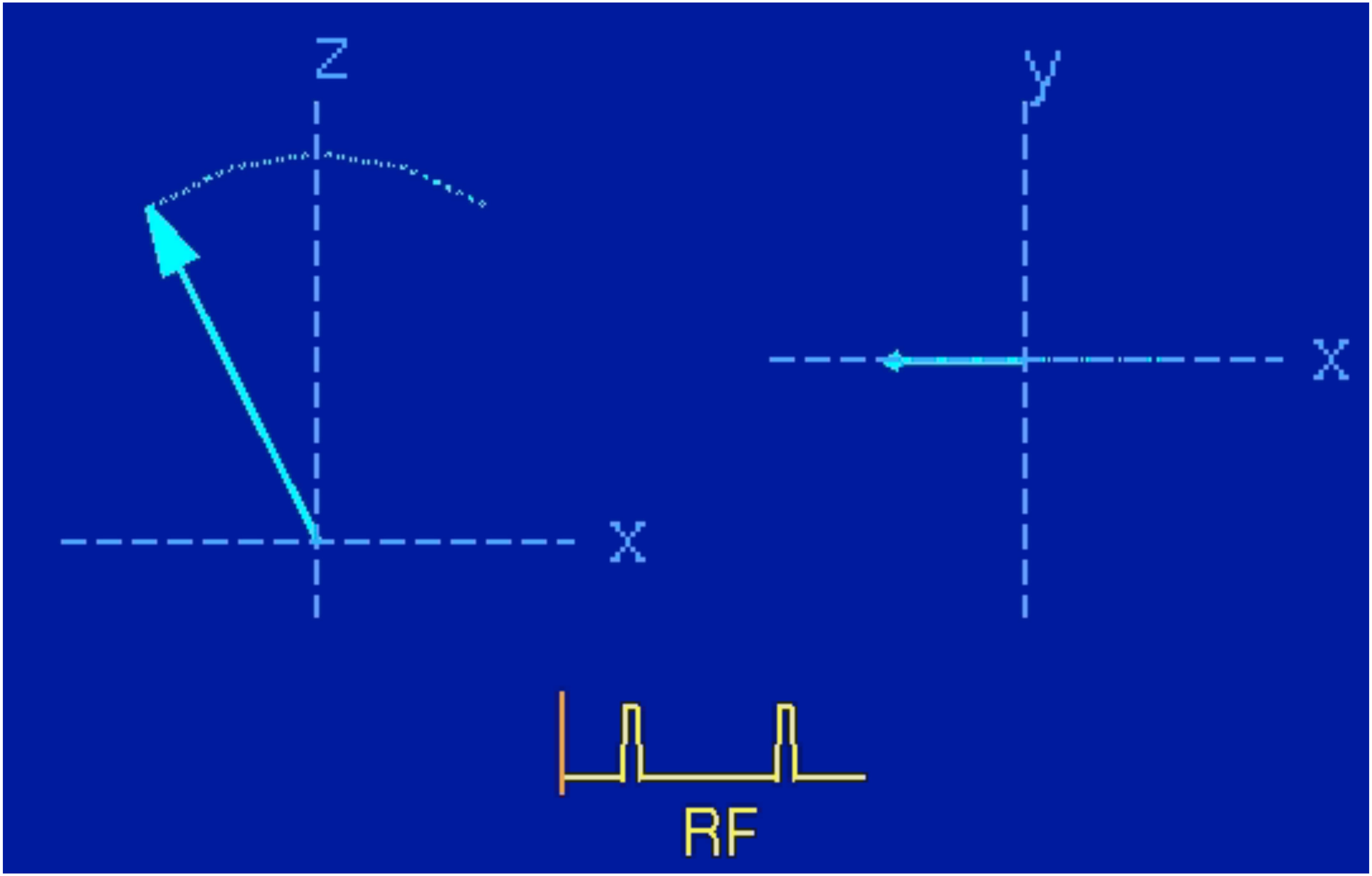




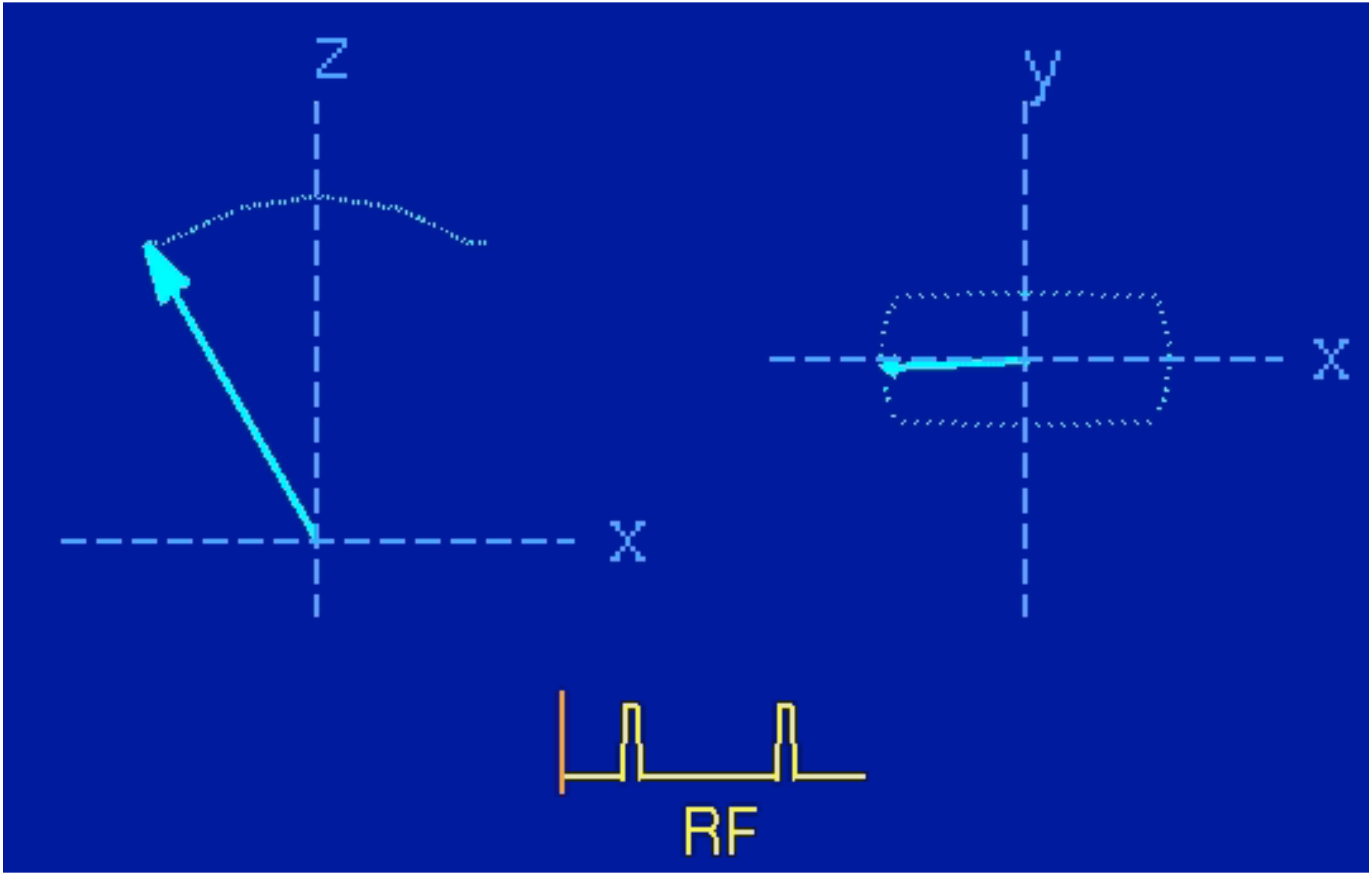
- Length: Ellipsoid intersection
- Direction: $\alpha/2$ angle from M_z

Signal Question

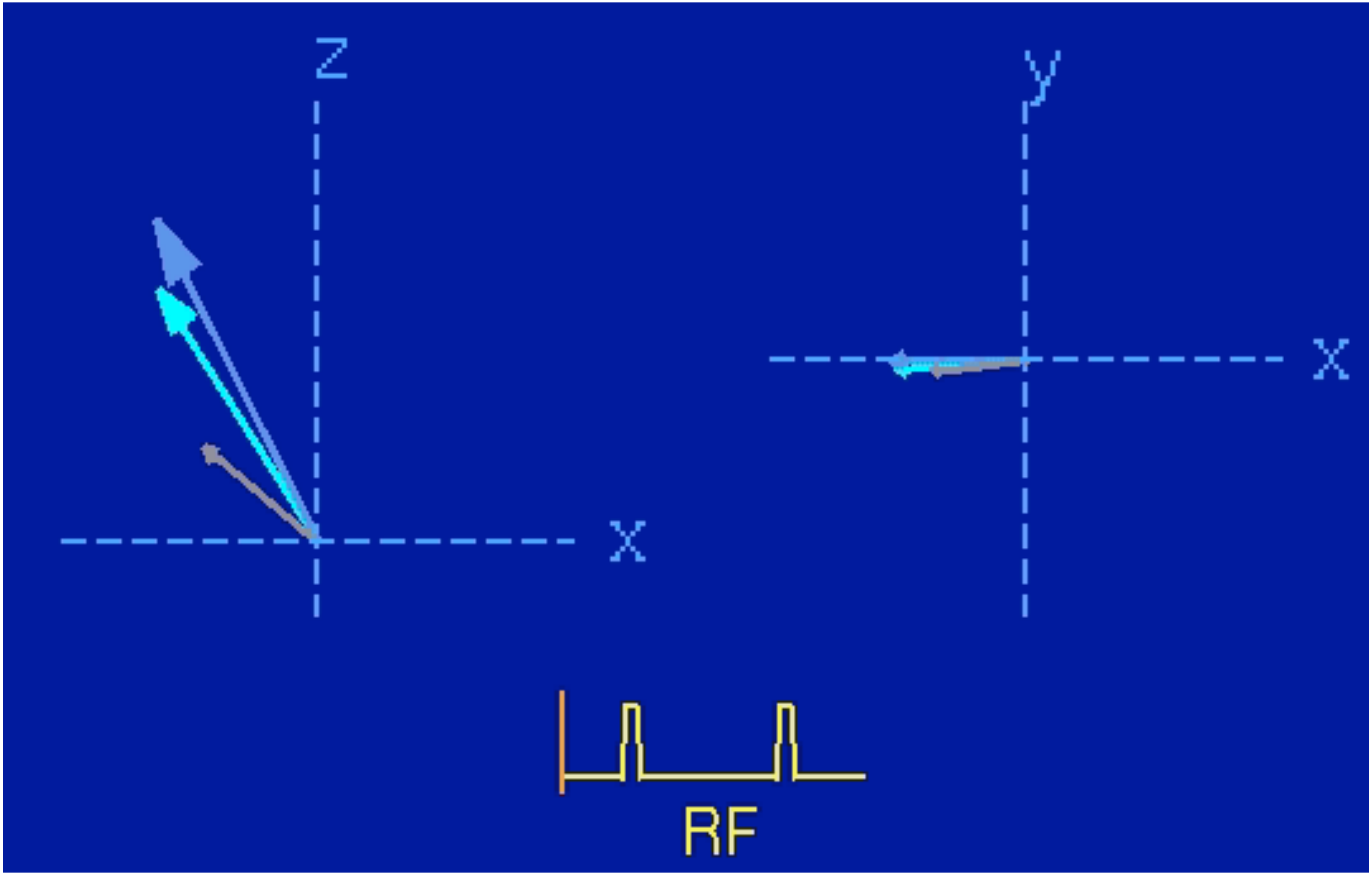
Steady State: No Precession



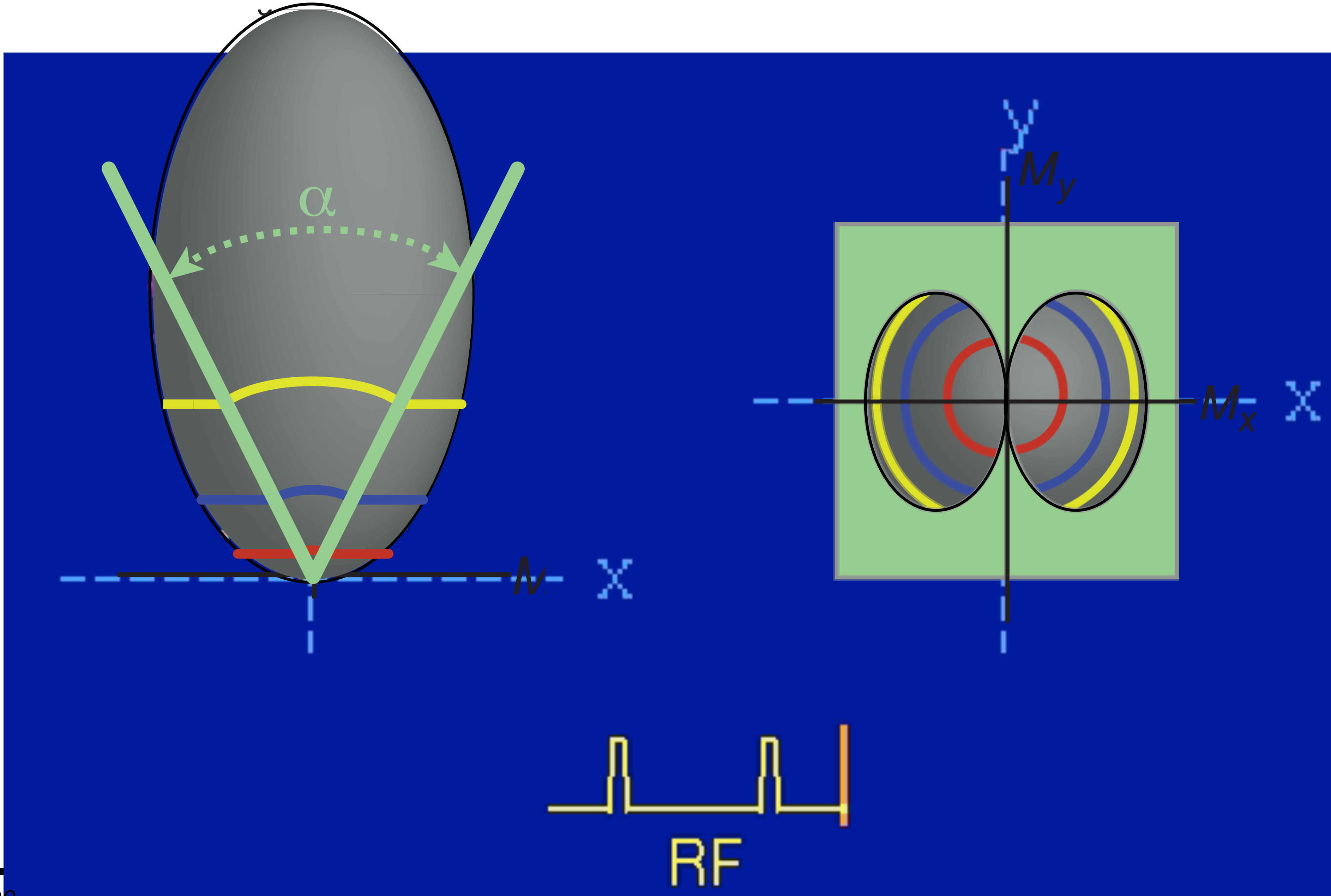
Off-Resonance: Precession



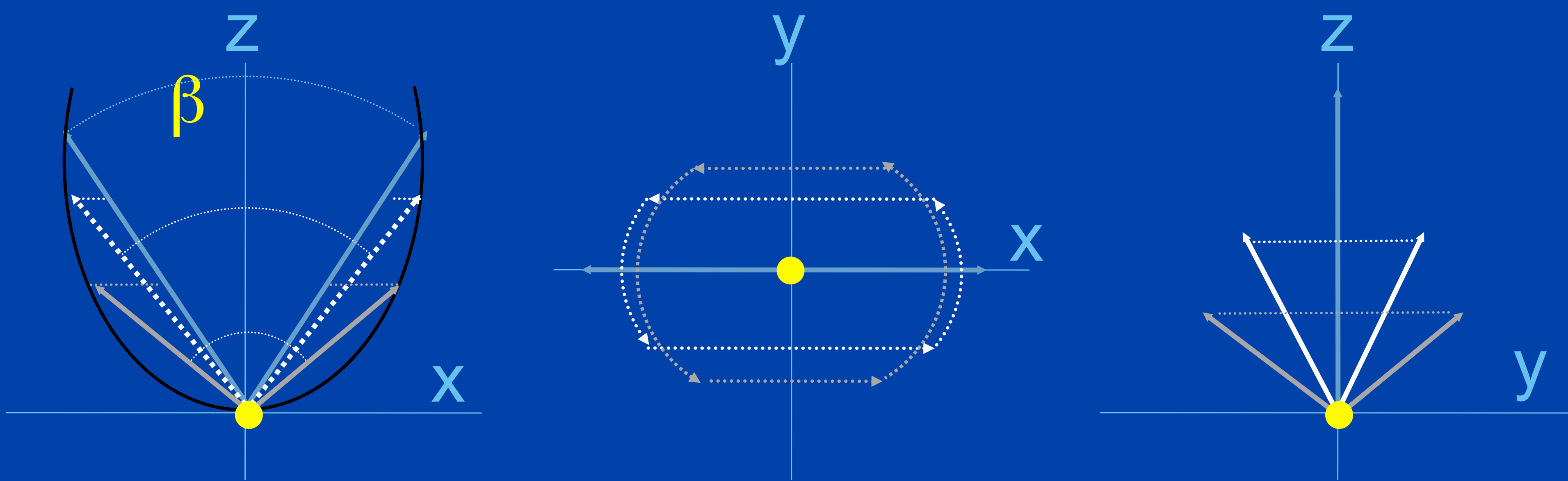
Increasing Precession



Balanced SSFP (FIESTA)



Precession and "Effective flip angle"



- Larger precession gives a larger "effective flip," β
- $\tan(\alpha/2) = \tan(\beta/2)\cos(\phi/2)$
- $\beta >= \alpha$
- Can replace flip (α) with effective flip (β) for all calculations
- Limiting case (•) where β = 180°

(Schmitt MRM 2006, Zun, ISMRM 2006)

"Ellipsoid" Derivation of Signal

- Starting with ellipsoid:

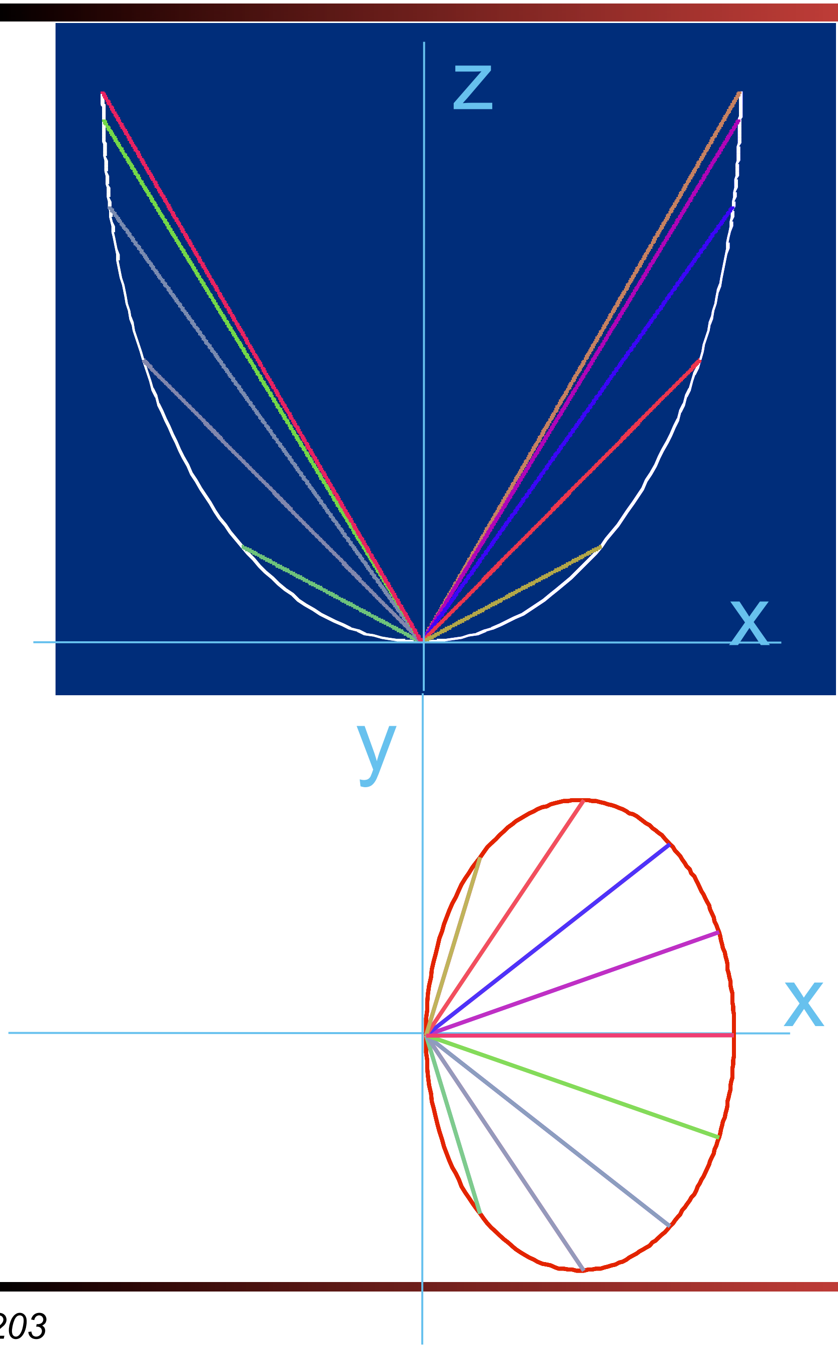
$$\left(M_z - \frac{M_0}{2}\right)^2 + \frac{M_x^2 + M_y^2}{T_2/T_1} = \left(\frac{M_0}{2}\right)^2$$

$$\left[M\cos(\beta/2) - \frac{M_0}{2}\right]^2 + \frac{M^2\sin^2(\beta/2)}{T_2/T_1} = \left[\frac{M_0}{2}\right]^2$$

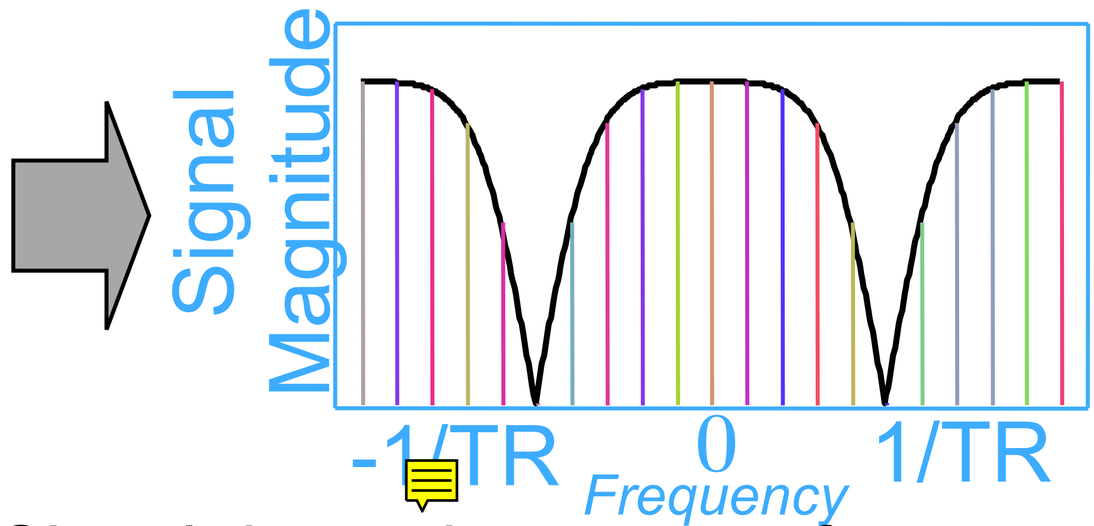
$$S = \frac{M_0}{\cot(\beta/2) + (T_1/T_2)\tan(\beta/2)}$$

- Signal drops with increasing T_1/T_2
- At $\beta = 180^{o}$ signal is 0

Signal vs Precession/Frequency



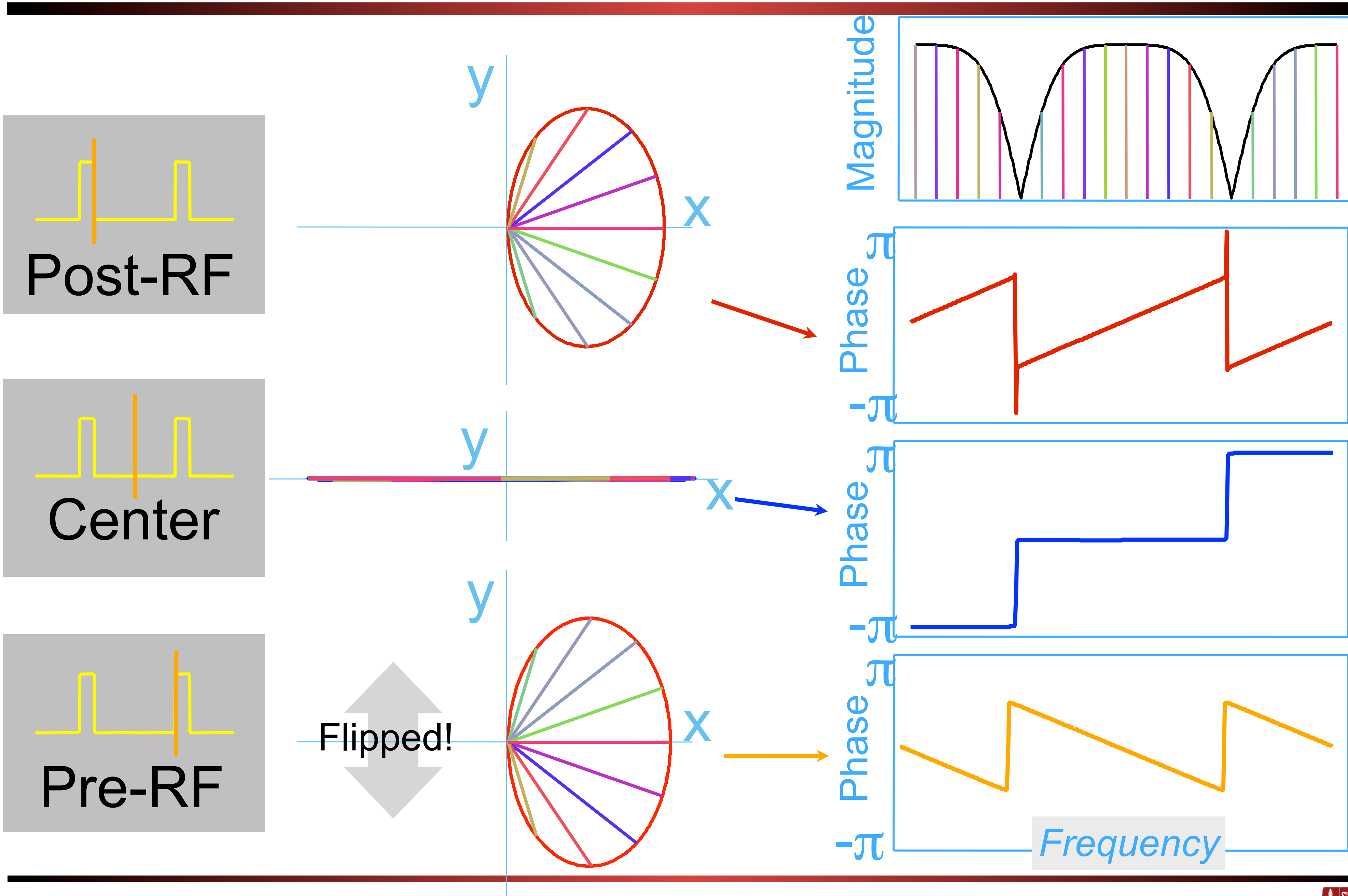
Freeman 1971



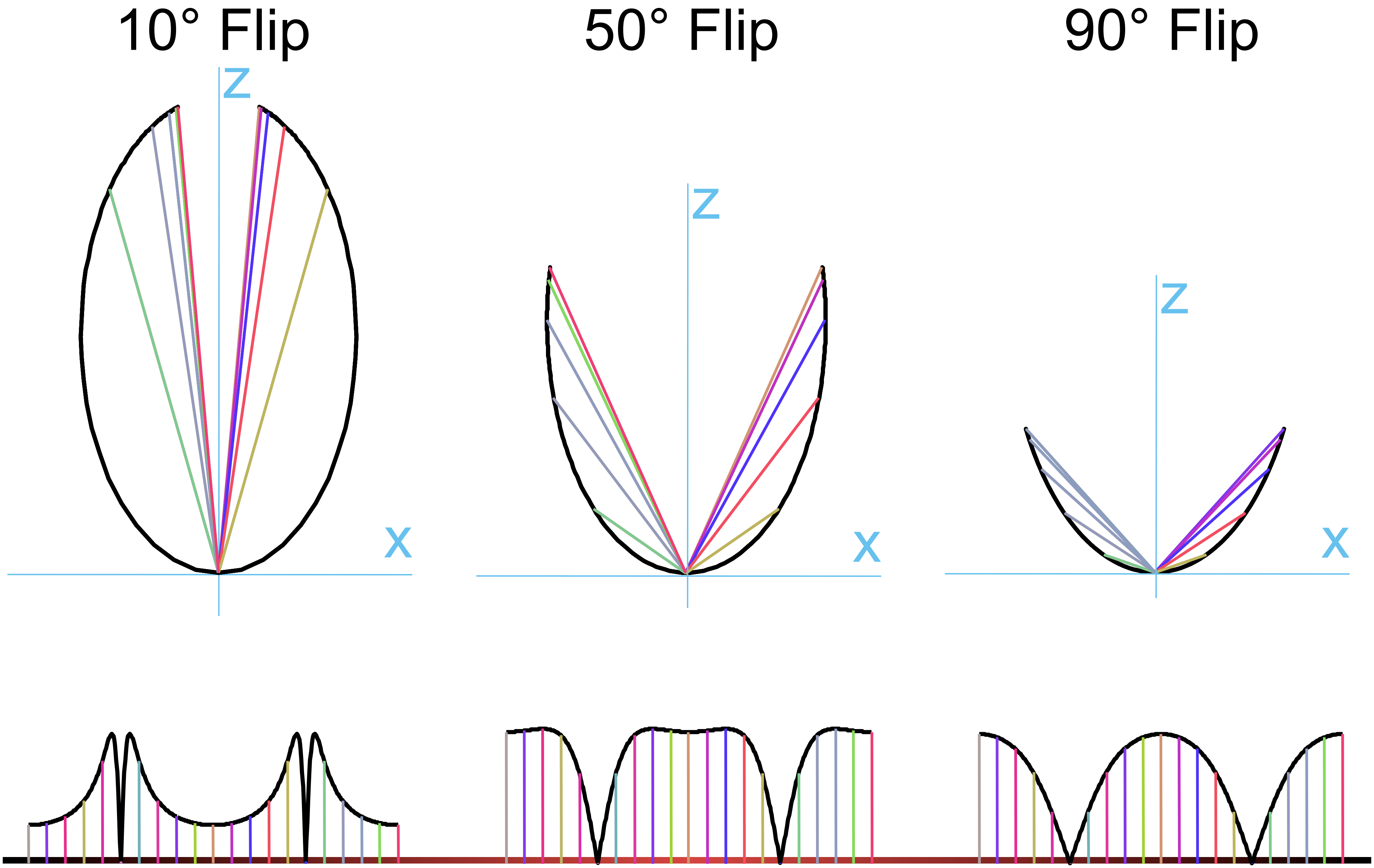
Signal depends on many factors:

- *Resonant frequency*
- T1, T2 (contrast)
- TR, TE
- RF flip / phase

Signal vs Frequency: Phase



Flip angle effects

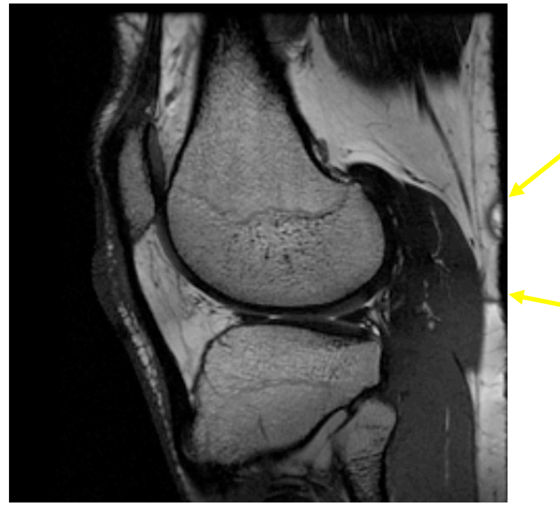


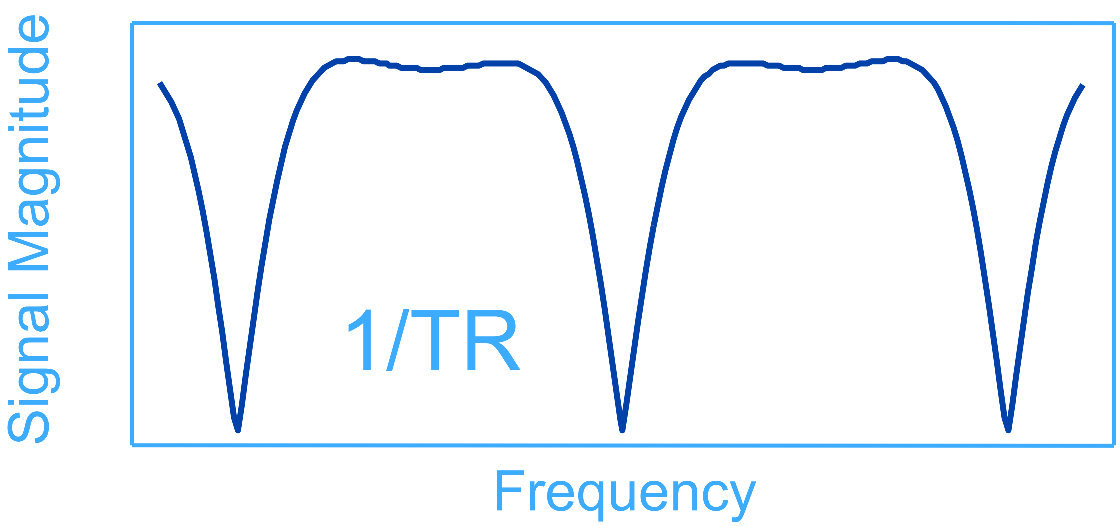
bSSFP Dark Bands

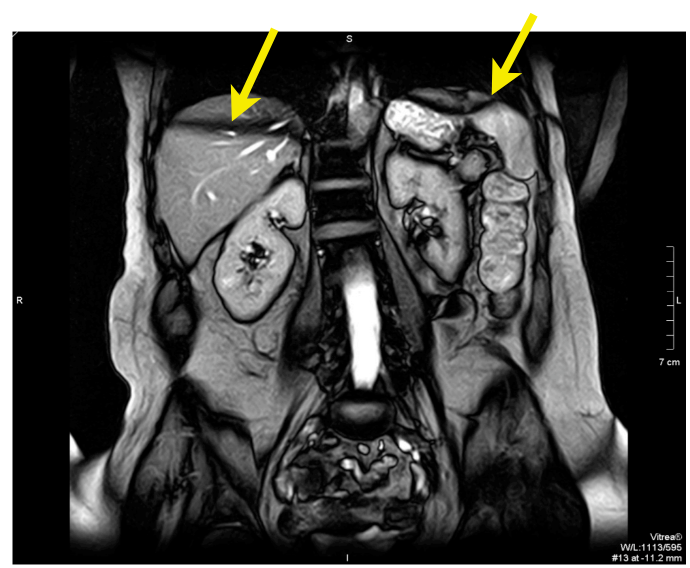
Must limit precession:

Short TR

Limits resolution

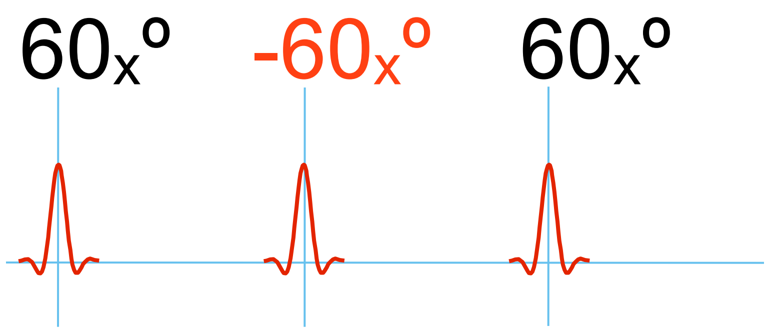


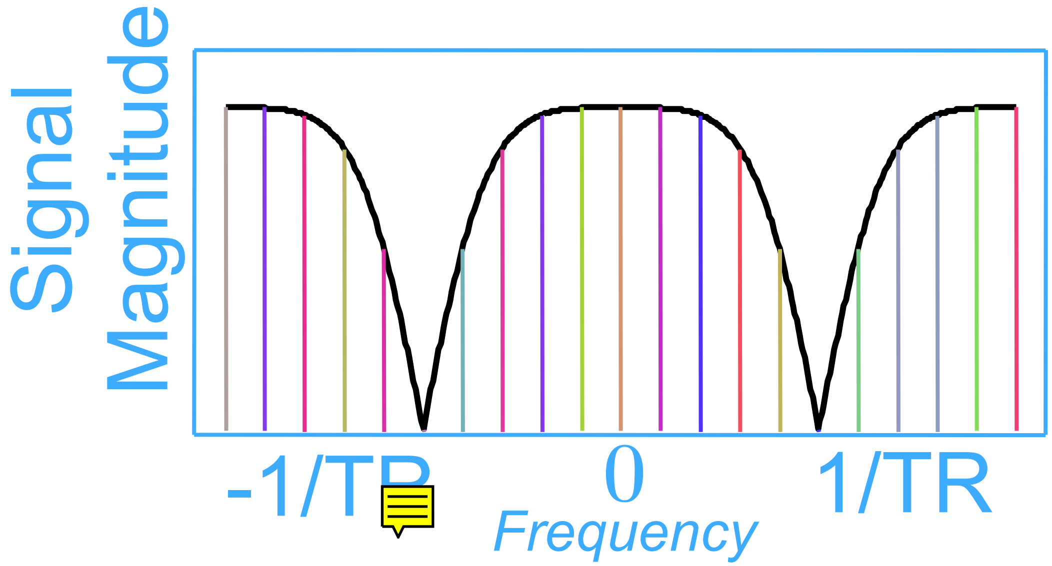


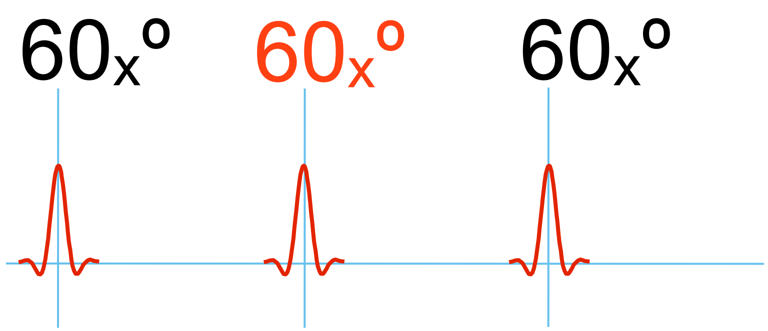


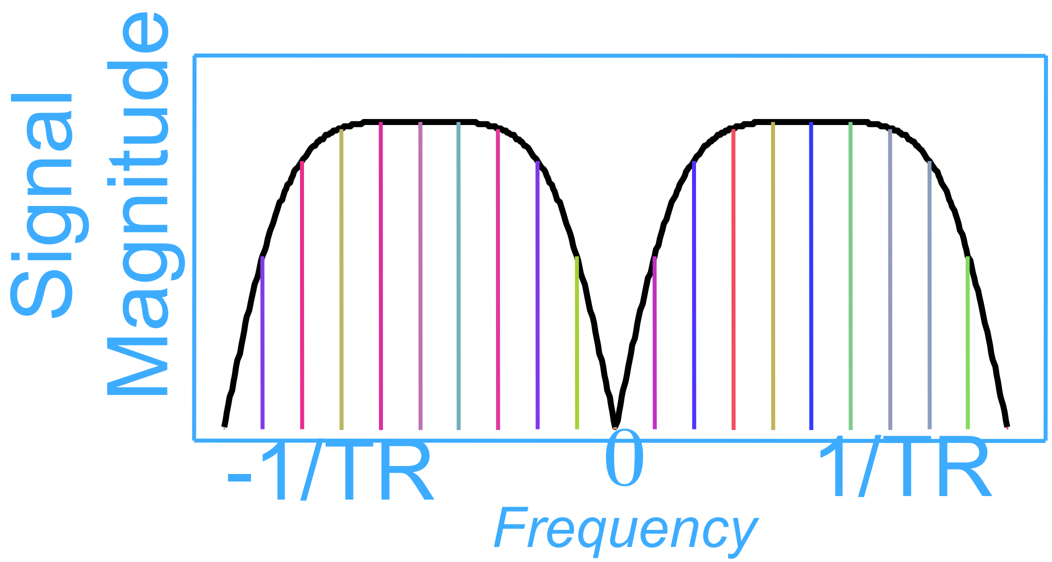
Phase Cycling

Hinshaw 1976





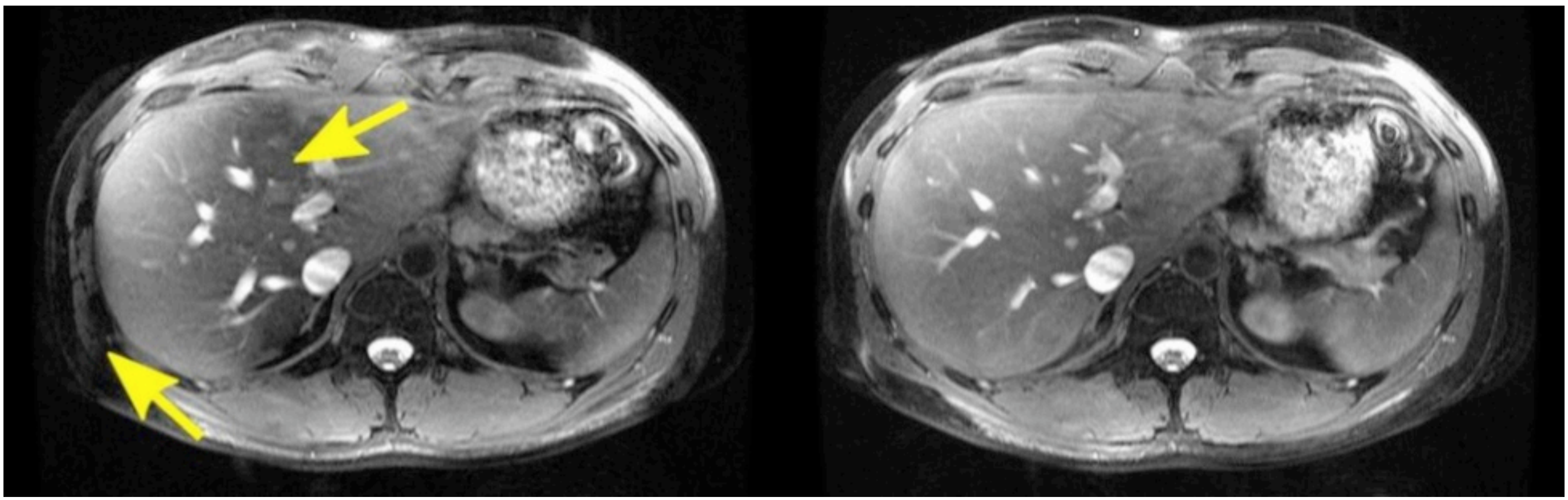


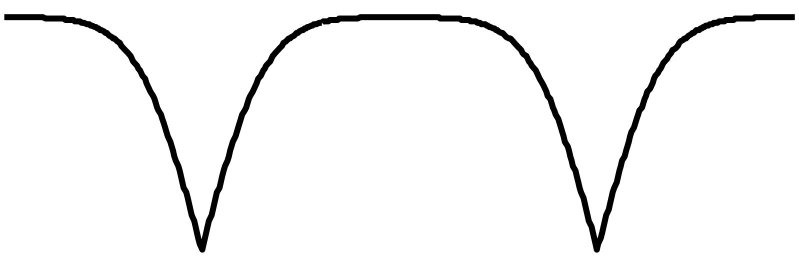


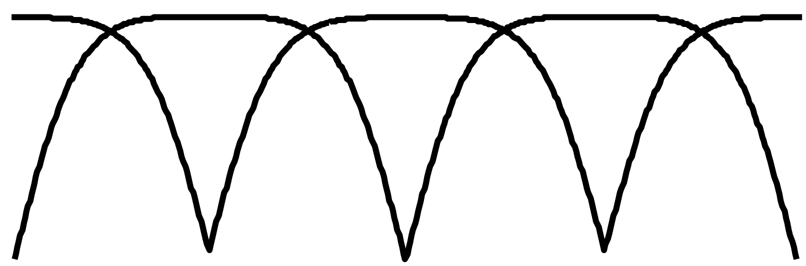
Review Question: Phase Cycling

Balanced SSFP Abdomen Example

Alternating RF | Combined Acquisition

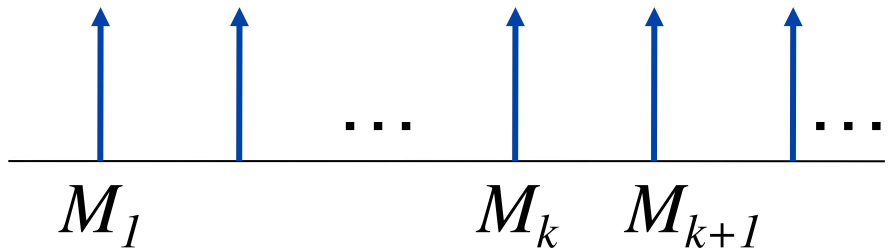






Matrix Solutions

(Jaynes 1955)



Apply 3x3 matrix scheme:

$$M_{k+1} = A\, M_k + B \qquad [1]$$

In steady-state:

$$M_{ss} = AM_{ss} + B \qquad [2]$$

$$M_{k+1} - M_{ss} = A(M_k - M_{ss}) \qquad [1\text{-}2]$$

Consider Eigenvector Decomposition:

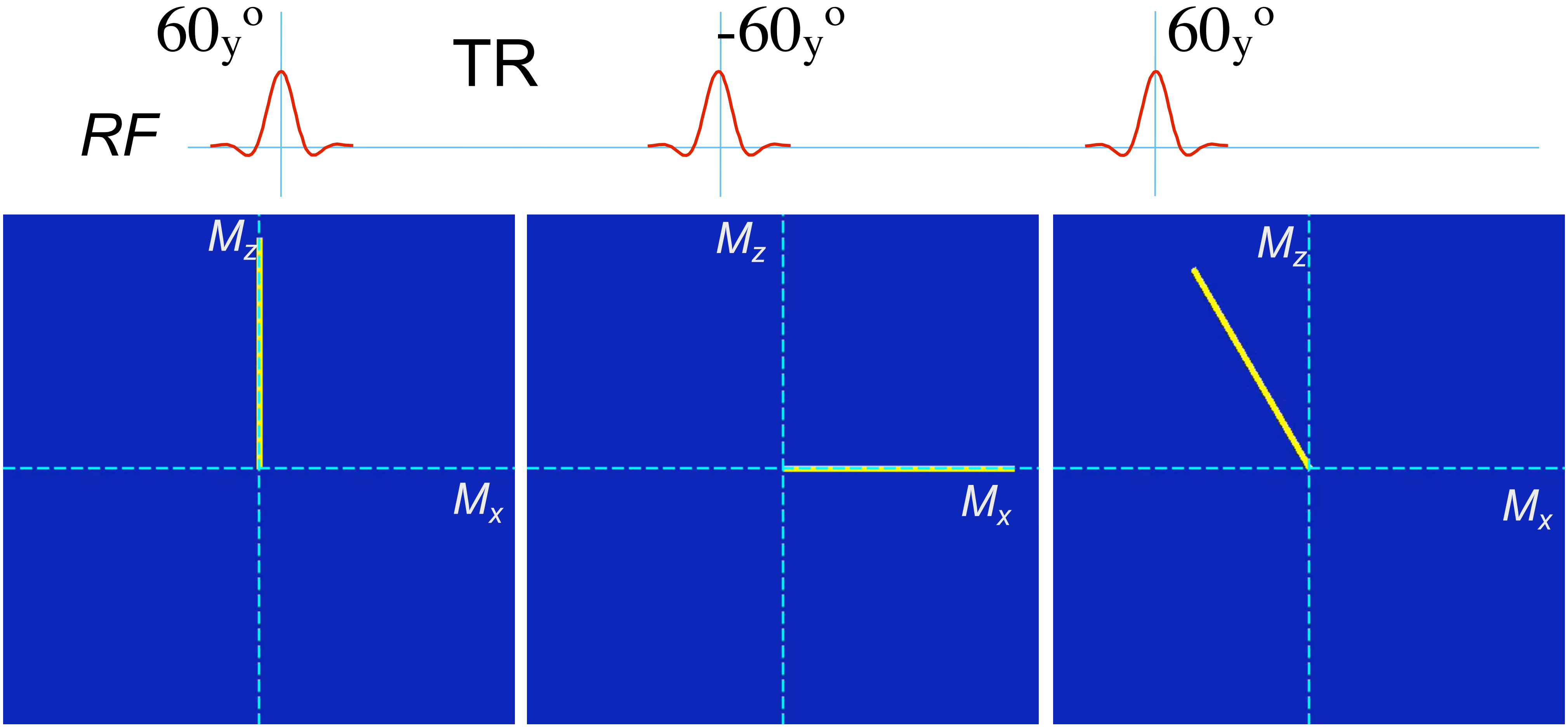
$$A = V\Lambda V^{-1} \qquad M_{k+1} - M_{ss} = (V\Lambda)\; V^{-1}(M_k - M_{ss})$$

At least one eigenvector/value is real.

Others often oscillatory and die out in steady state

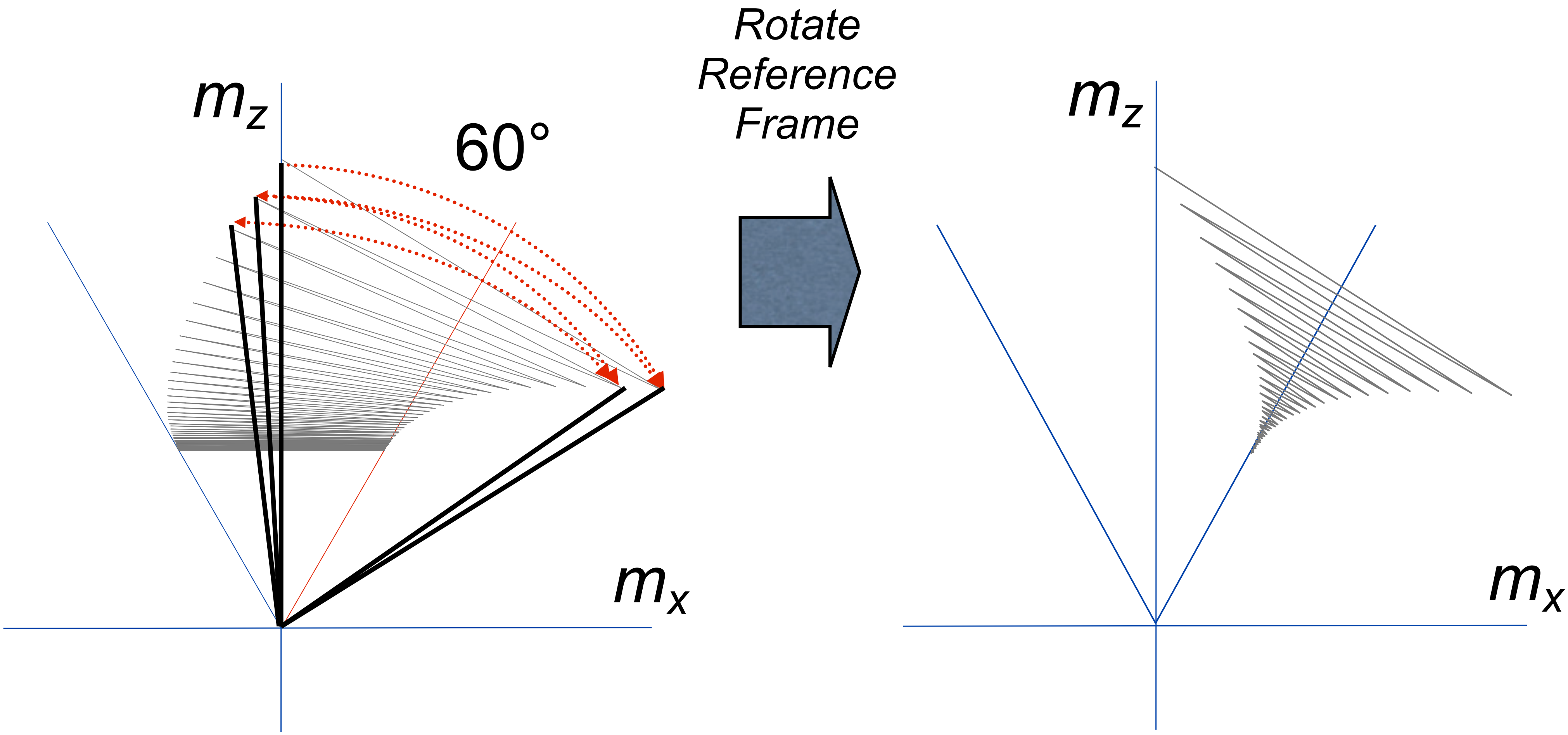
Note in [2] A is mostly rotation, B is small, so M_{ss} lies almost along the real-valued eigenvector

bSSFP: Transients and Steady States



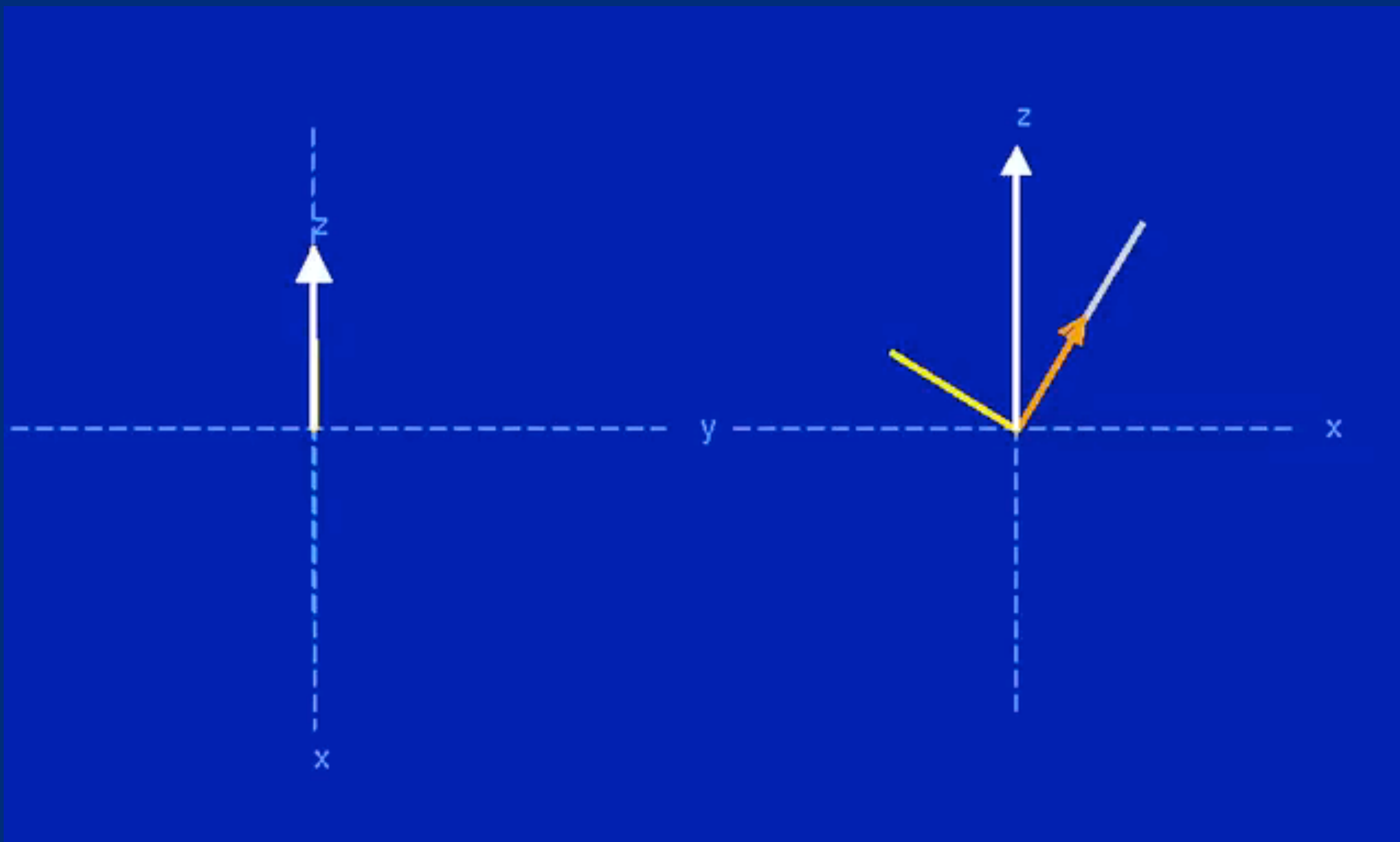
- Same periodic steady state
- Transient paths differ based on initial state

Balanced SSFP: Transient



Transient: Off-resonance

Viewed along Steady-State Vector   Orthogonal View



Orthogonal Component
Parallel Component
Transient
Steady-State

Transients (General)

- Generally include two components:
  - Smooth exponential (useful!)
  - Oscillatory (problematic)

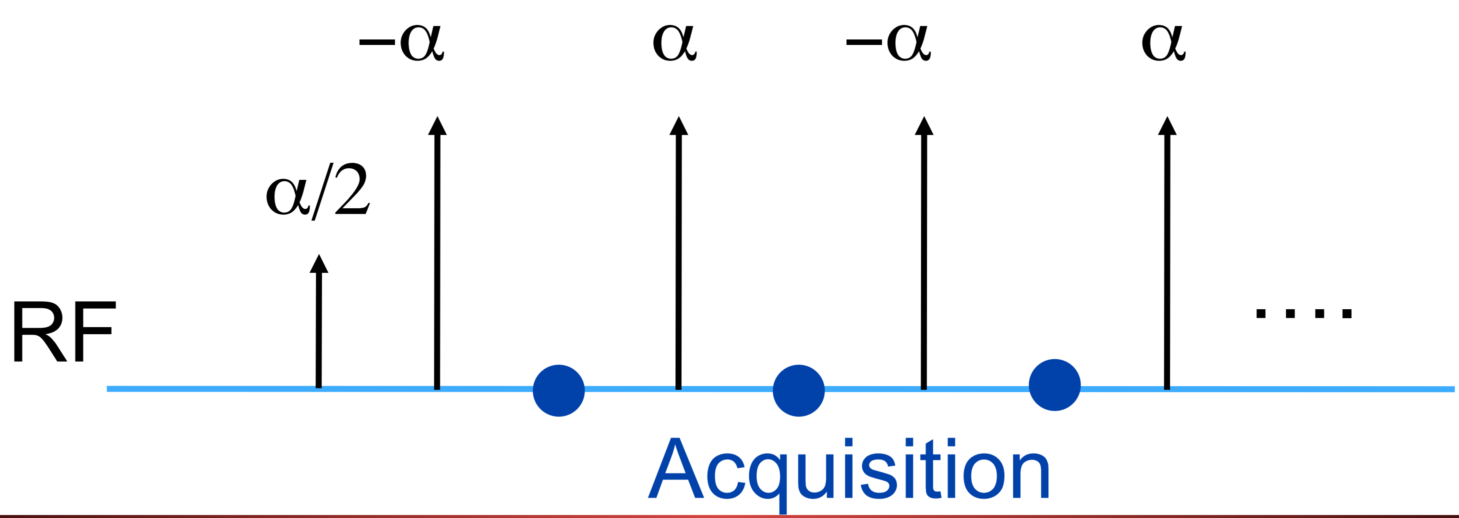
- Smooth transient is along steady-state direction
- Manipulate to steady-state direction to avoid oscillations

Review Question: Transients

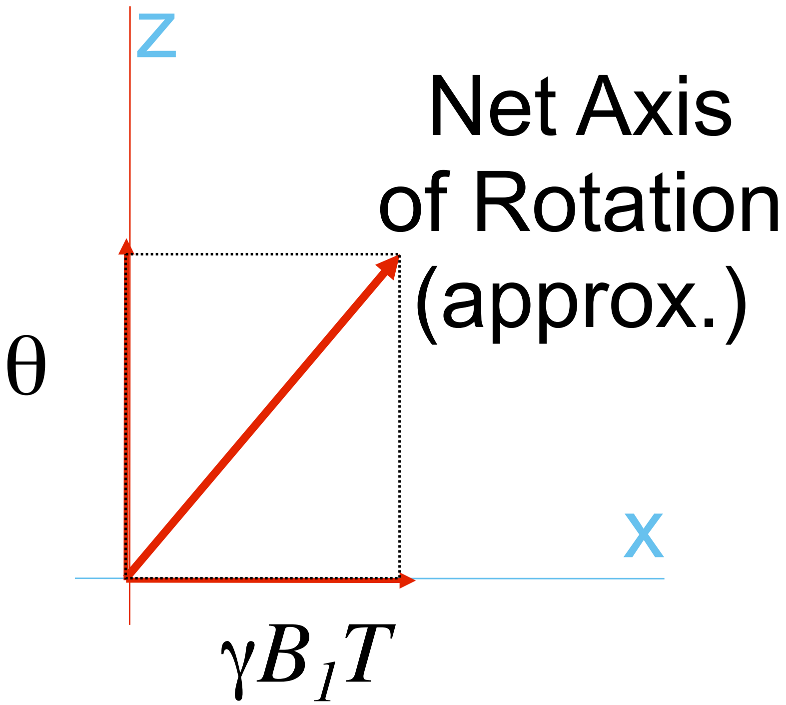
Half-TR, α/2 Setup

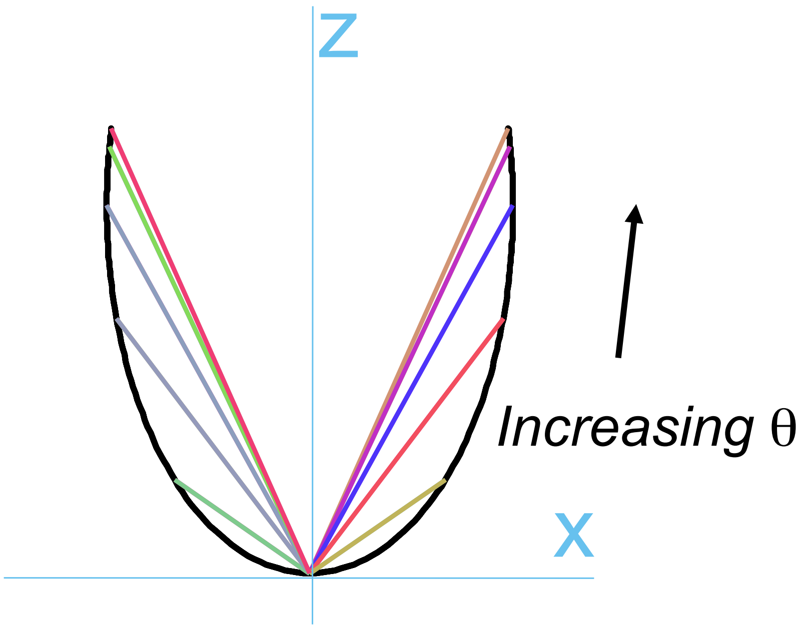
Deimling and Heid, 1994

- First RF pulse has half-amplitude
- Pulse applied TR/2 before next RF pulse
- (More complicated schemes exist)



bSSFP Direction: Some Intuition





- Magnetization aligns to rotation axis
- Rotation θ includes RF phase-increment
- As θ approaches 0°, axis is transverse, signal dies out
- Negative θ means steady state on -x

bSSFP Steady-State: Summary

- Ellipsoidal distribution: shape given by T_2/T_1
- Path depends on flip angle and precession
- Signal very sensitive to resonant frequency