T_1 & Magnetization Transfer

Peter van Gelderen
AMRI, LFMI, NINDS, National Institutes of Health,
Bethesda, MD, United States

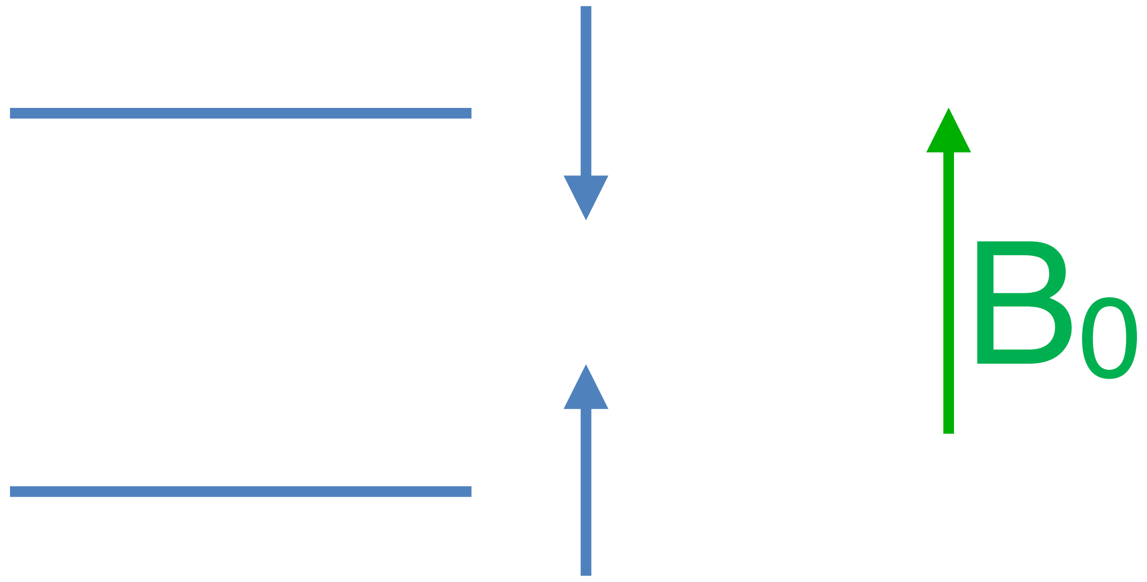
Outline

- T_1 and T_2
- Relevance for MRI
- Measuring T_1
- Magnetization Transfer (MT)
- Measuring MT
- Sources of T_1 contrast: T_1 & MT

Magnetization

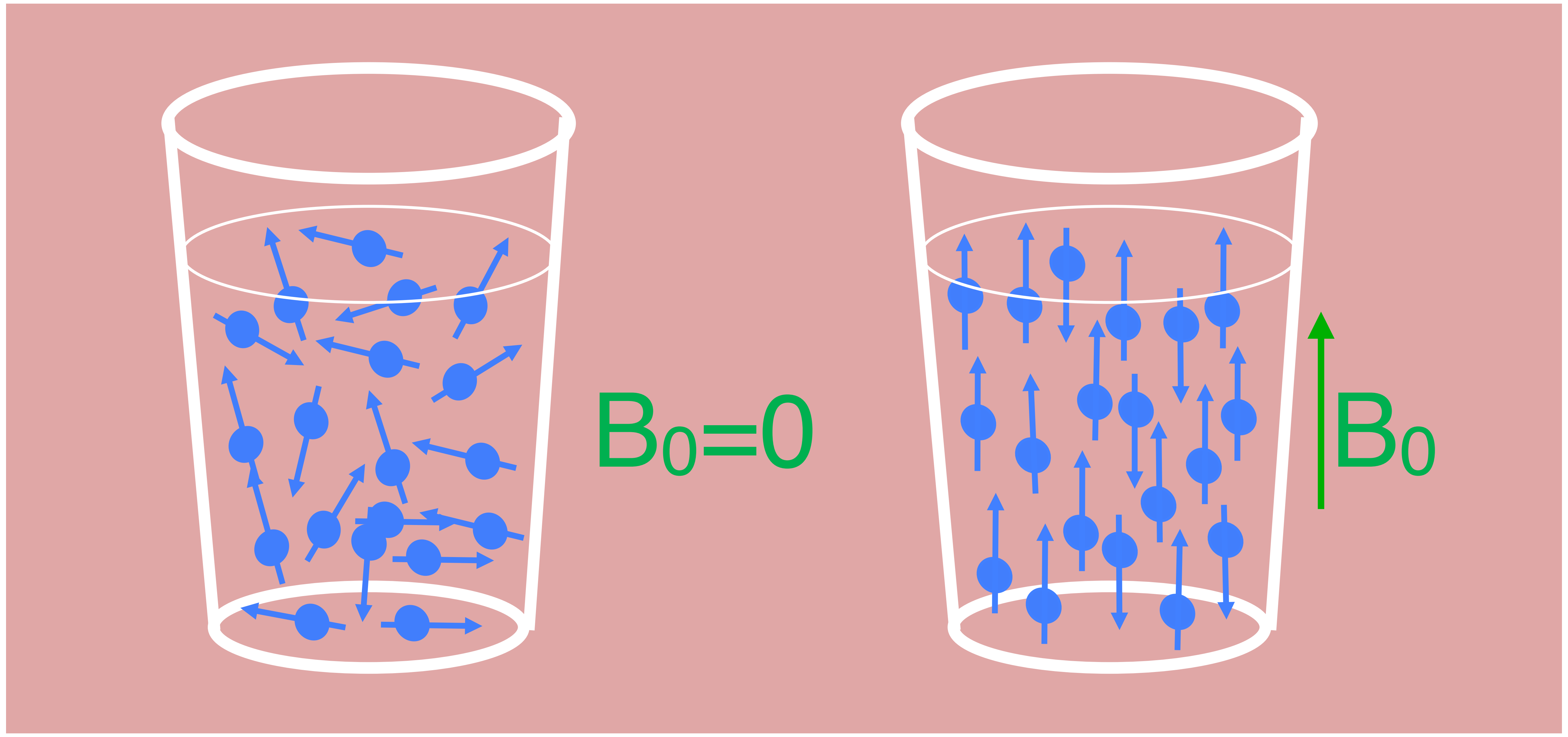
Nuclear spins polarize in a magnetic field

Energy:



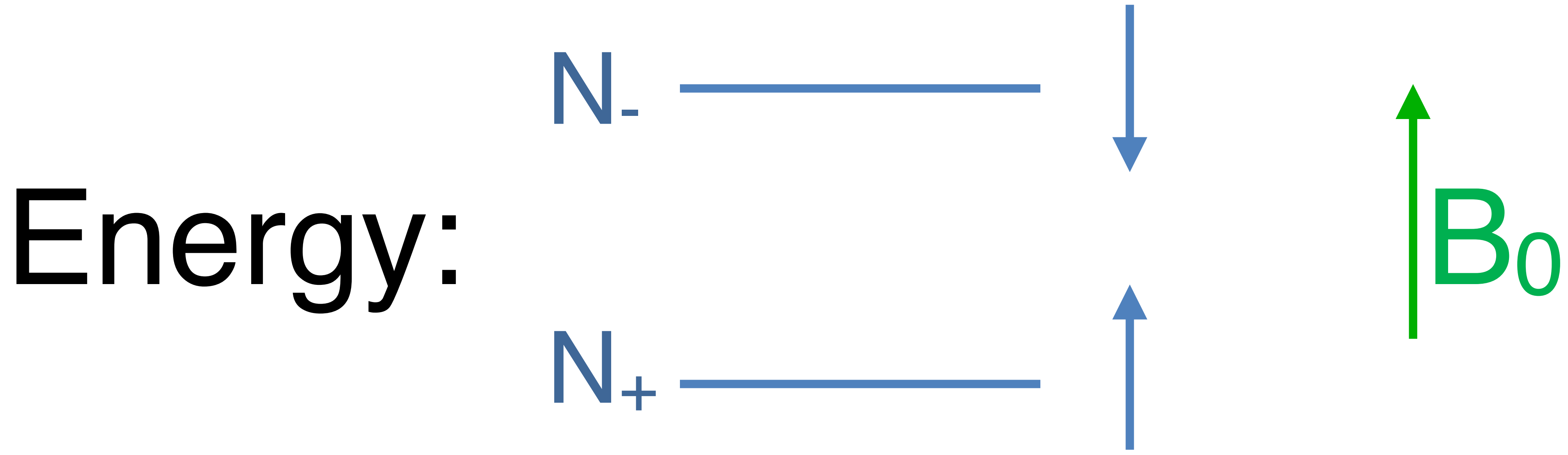
Magnetization

Nuclear spins polarize in a magnetic field



Magnetization

Nuclear spins polarize in a magnetic field



$$N_-/N_+ = e^{-h\gamma B_0/k_bT} \cong 1 - h\gamma B_0/k_bT = 1 - 6.5x10^{-6}B_0$$

Magnetization

Nuclear spins polarize in a magnetic field, but how fast?

Change in polarization requires energy transfer to different species.

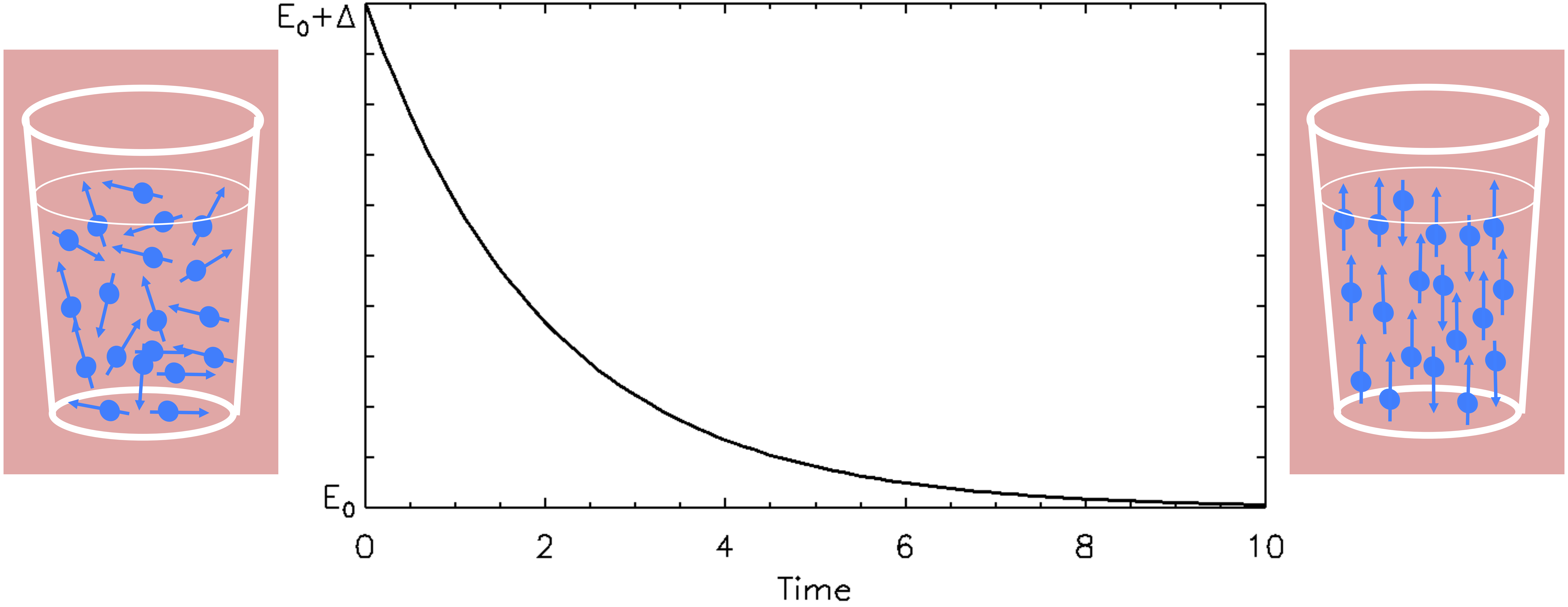
Pure water: little energy transfer -> slow (change in) polarization

Magnetization

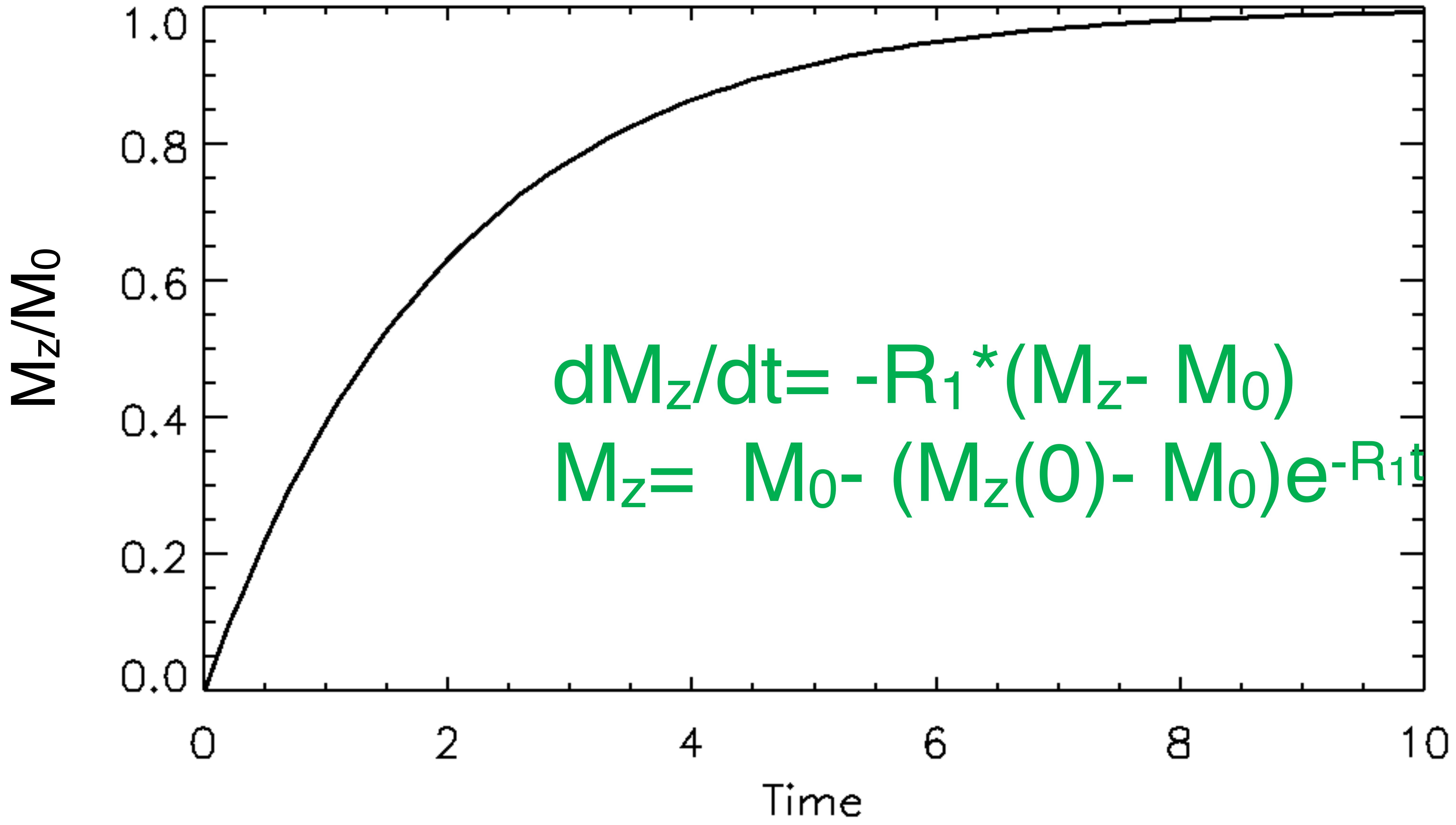
Time course:

- every spin has certain probability to transition
- P_- for ↓↑ P_+ for ↑↓ where P_- slightly higher than P_+ (due to ΔE)
- # spins: ↓↑ N_-P_-, ↑↓ N_+P_+
- $M = N_+ - N_-$
- change in $M = dM = (N_-P_- - N_+P_+)$
- $dM = 0$ for equilibrium (M_0), $N_{+0}/N_{-0} = P_-/P_+$
- $M = M_0 + \Delta$, $N_- = N_{-0} - \Delta/2$, $N_+ = N_{+0} + \Delta/2$,
- $dM = ((N_{-0} - \Delta/2)P_- - (N_{+0} + \Delta/2)P_+) = N_{-0}P_- - N_{+0}P_+ - \Delta/2(P_- + P_+) = -\Delta/2(P_- + P_+)$
- $dM/dt = -k(M - M_0)$, $k = R_1 = 1/T_1$

Magnetization



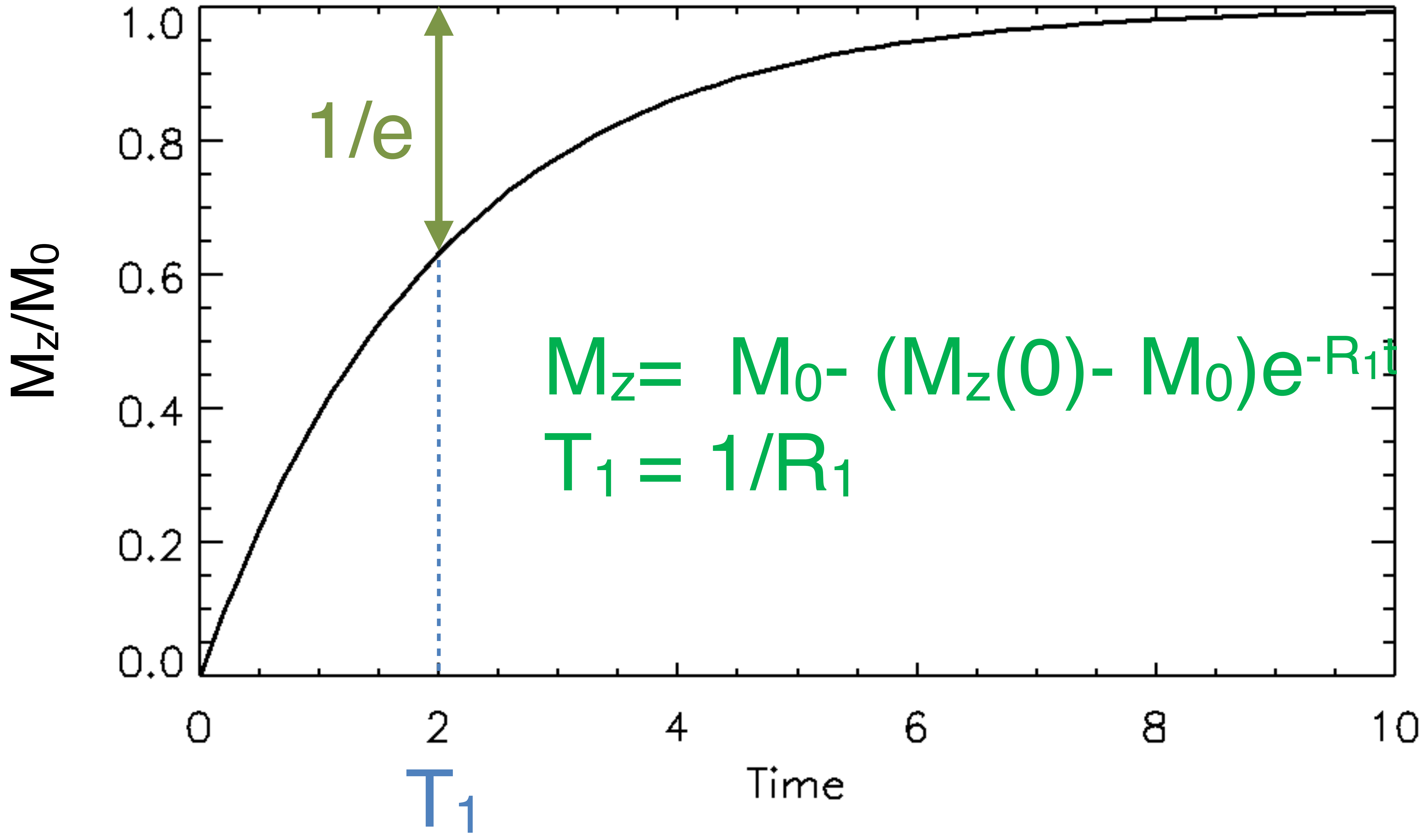
Magnetization



$$dM_z/dt = -R_1 * (M_z - M_0)$$

$$M_z = M_0 - (M_z(0) - M_0)e^{-R_1 t}$$

Magnetization

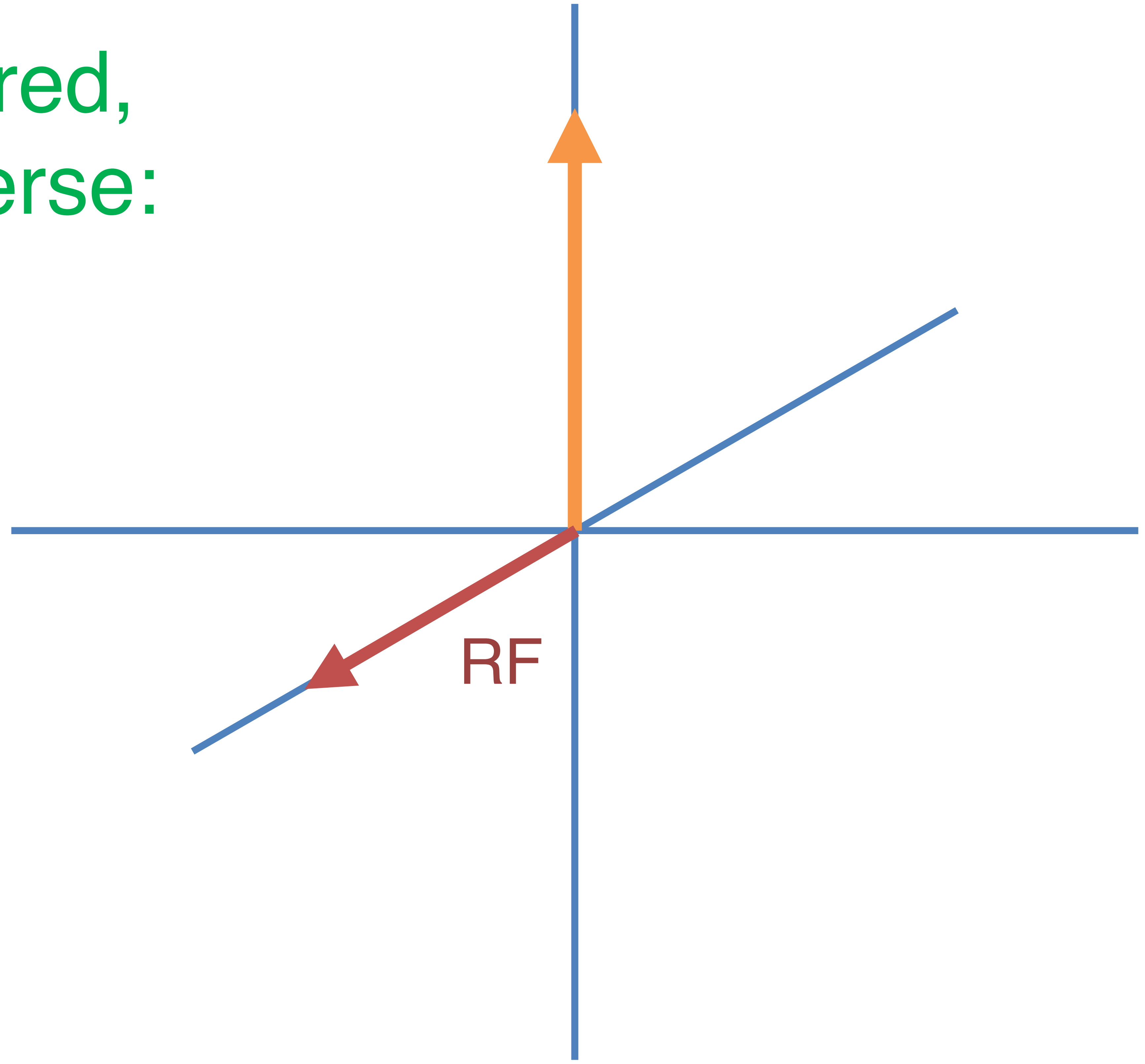


$M_z = M_0 - (M_z(0) - M_0)e^{-R_1 t}$

$T_1 = 1/R_1$

T_1-Relaxation in MRI

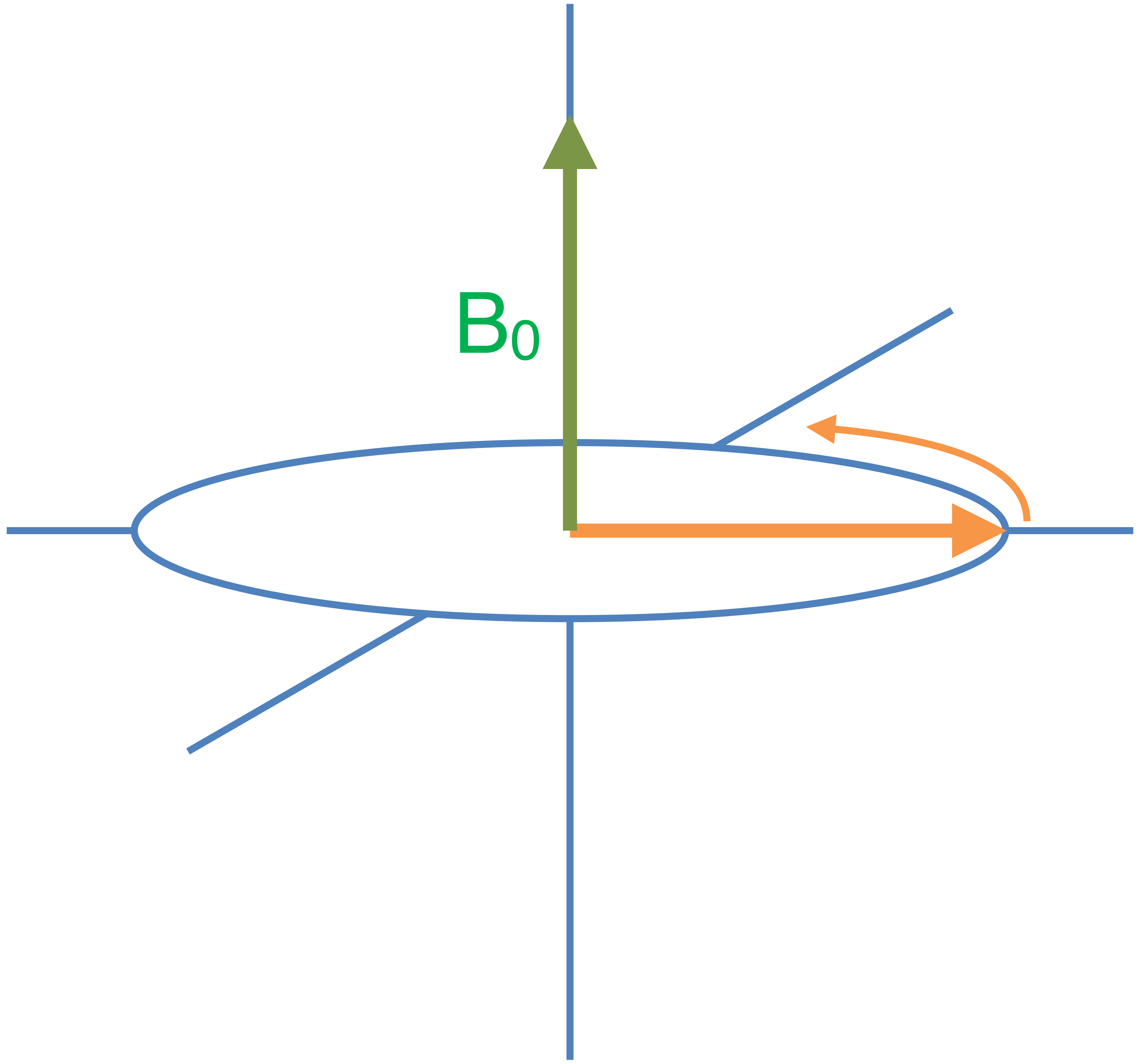
M_z not directly measured,
M needs to be transverse:



T_2-Relaxation

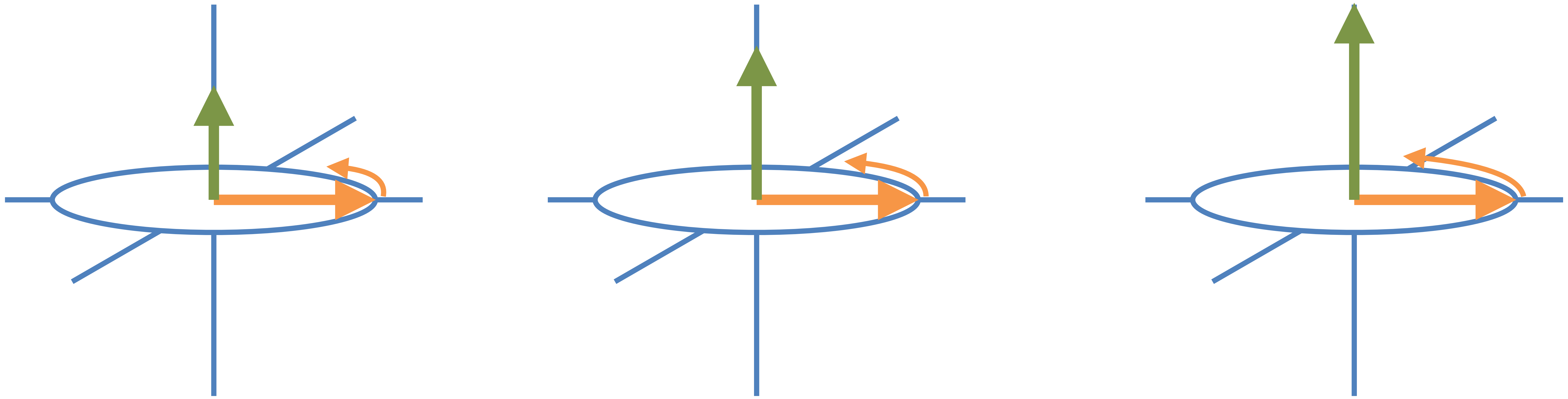
M rotates around B_0

Frequency: γB_0



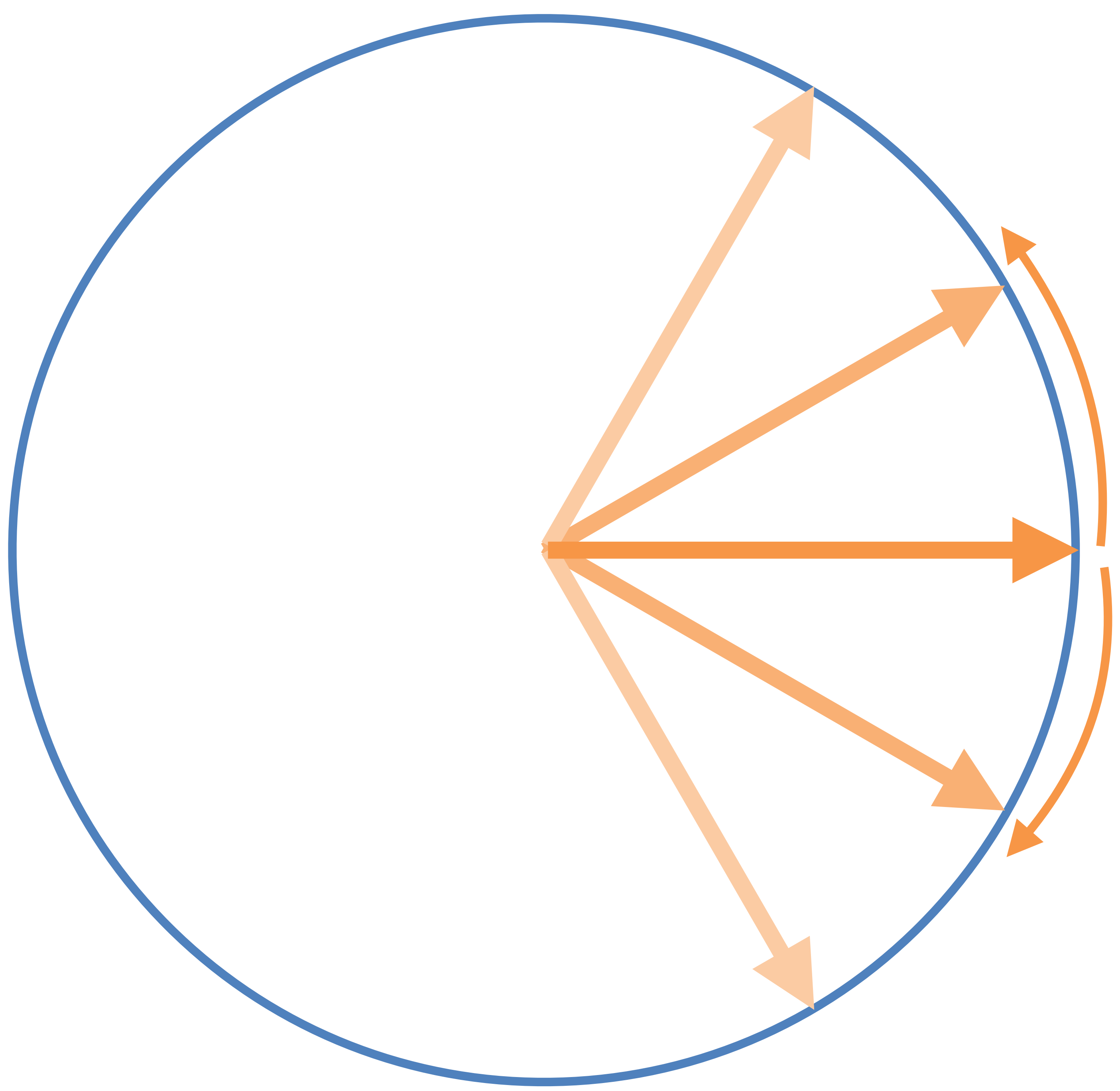
T_2-Relaxation

M rotates around B_0
Frequency: γB_0
B_0 not the same everywhere:
dispersion

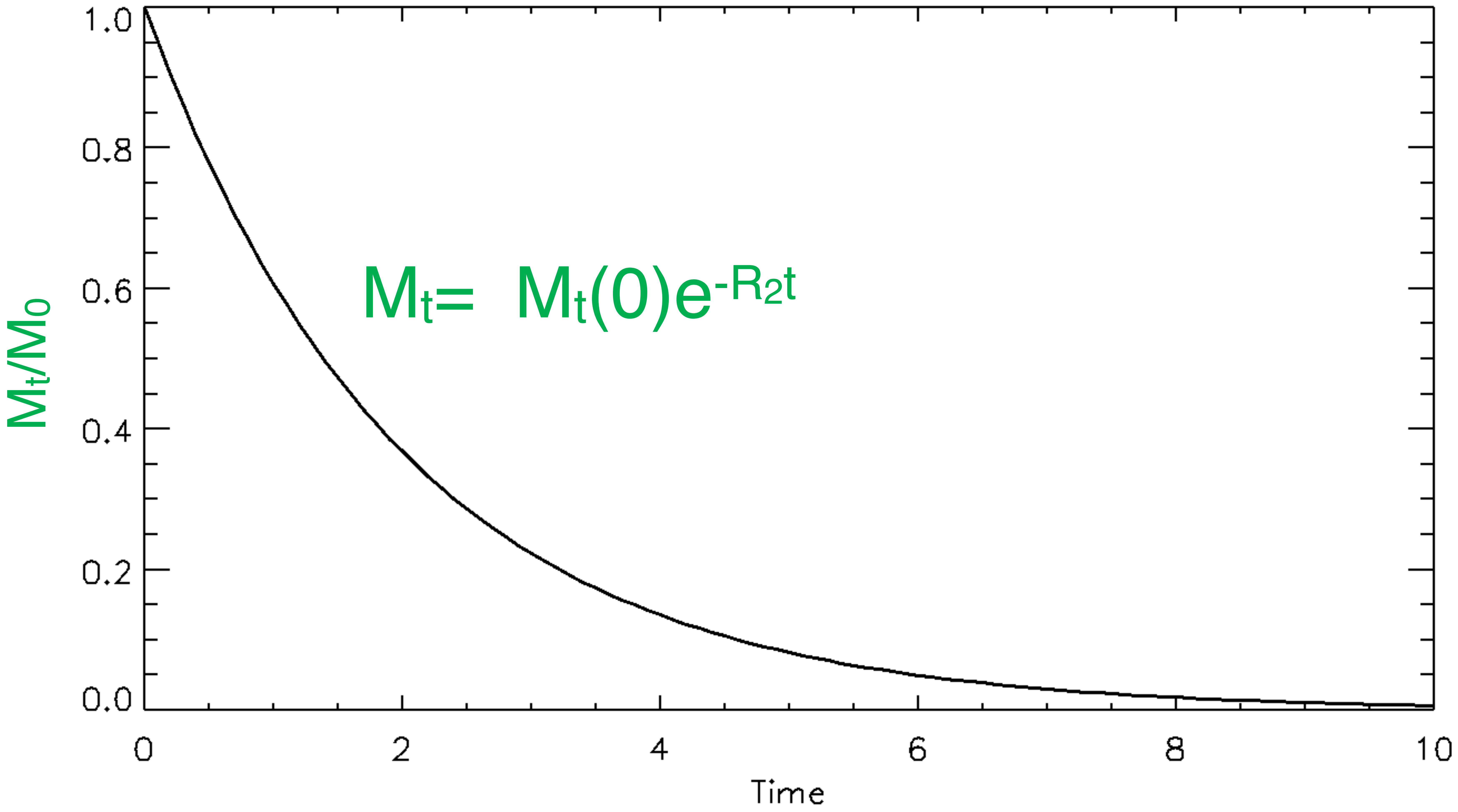


T_2-Relaxation

M_t in rotating frame:



T_2-Relaxation



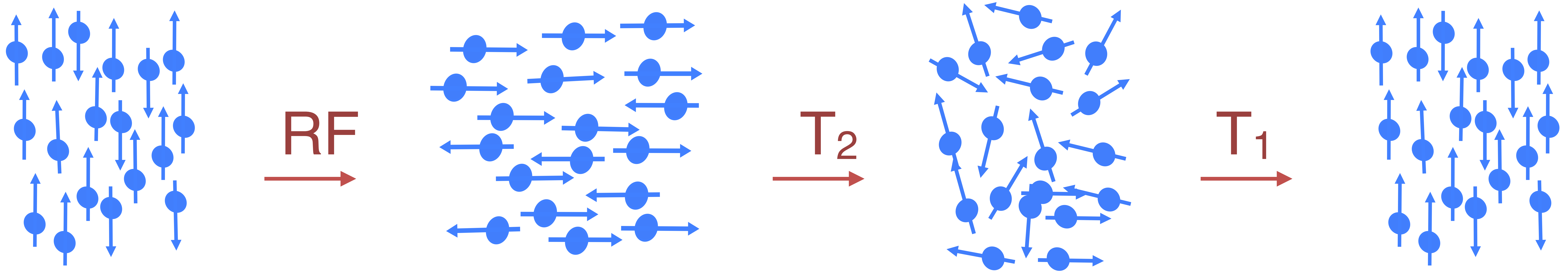
T_2-Relaxation

T_2 is dispersion of M in transverse plain
caused by frequency differences, from
- spin-spin interactions (true T_2)
- field inhomogeneity from magnet or local susceptibility (T_2^*)

No energy transfer, can be (much) faster then T_1

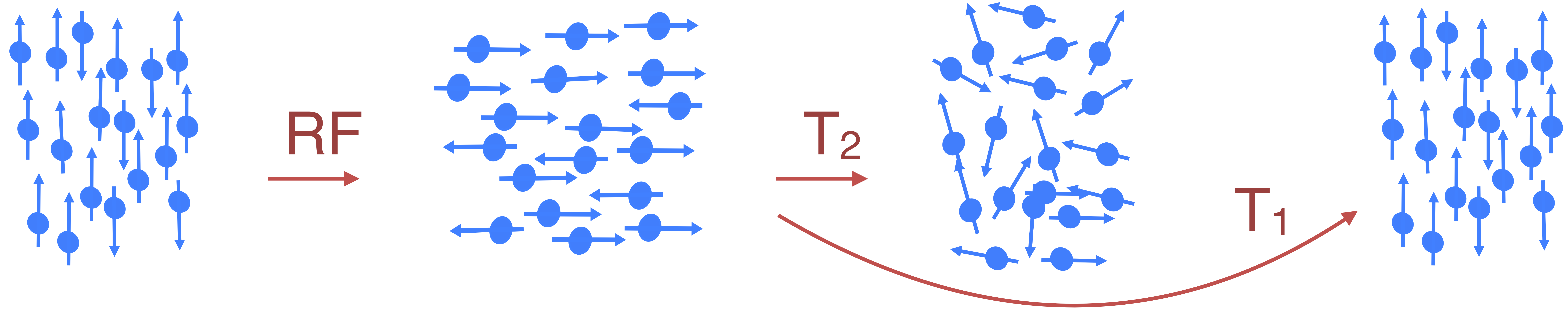
T_1-Relaxation

MR measurement:



T_1-Relaxation

Relevance for MR Imaging

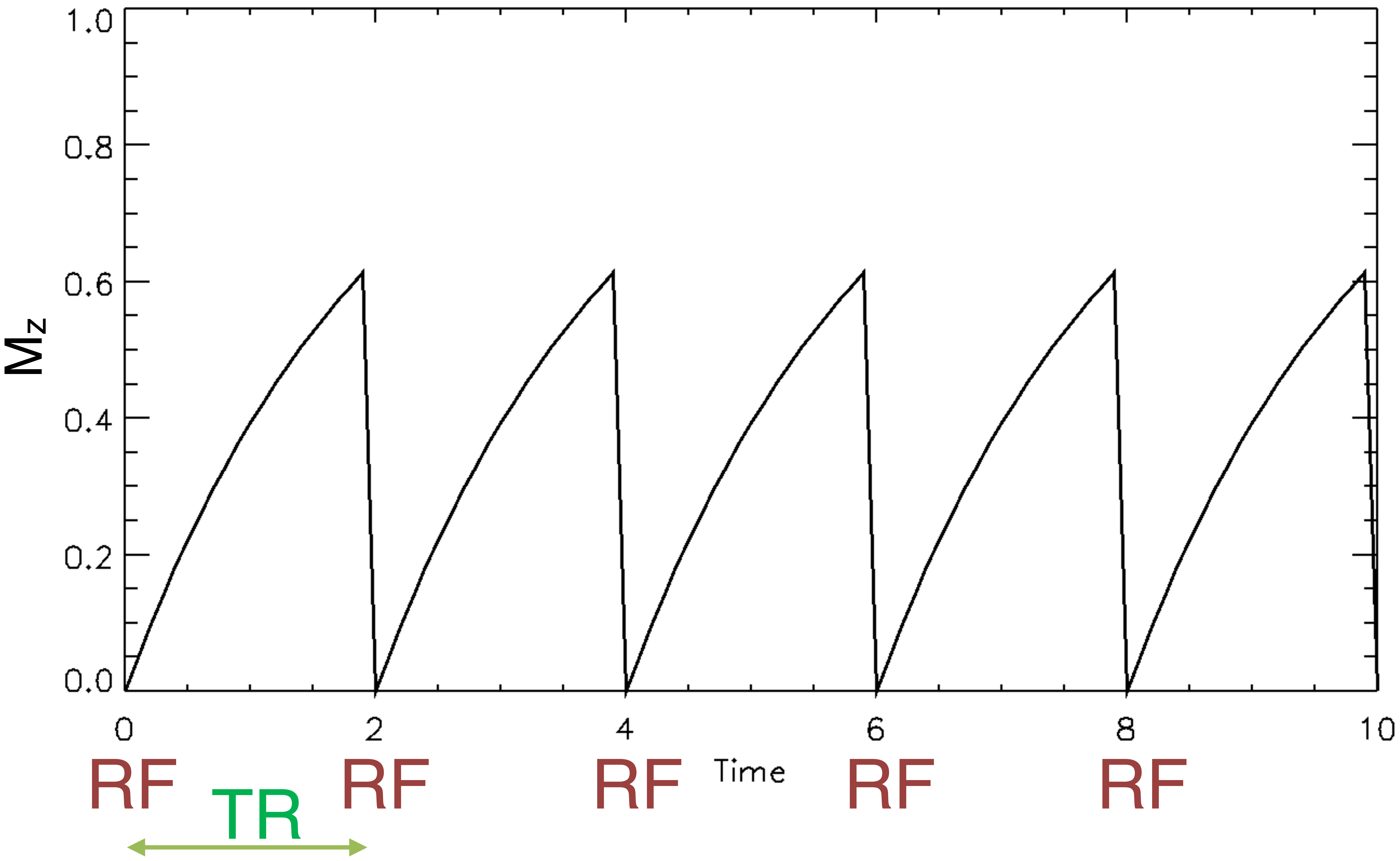


$M_t=0, M_z= 1$

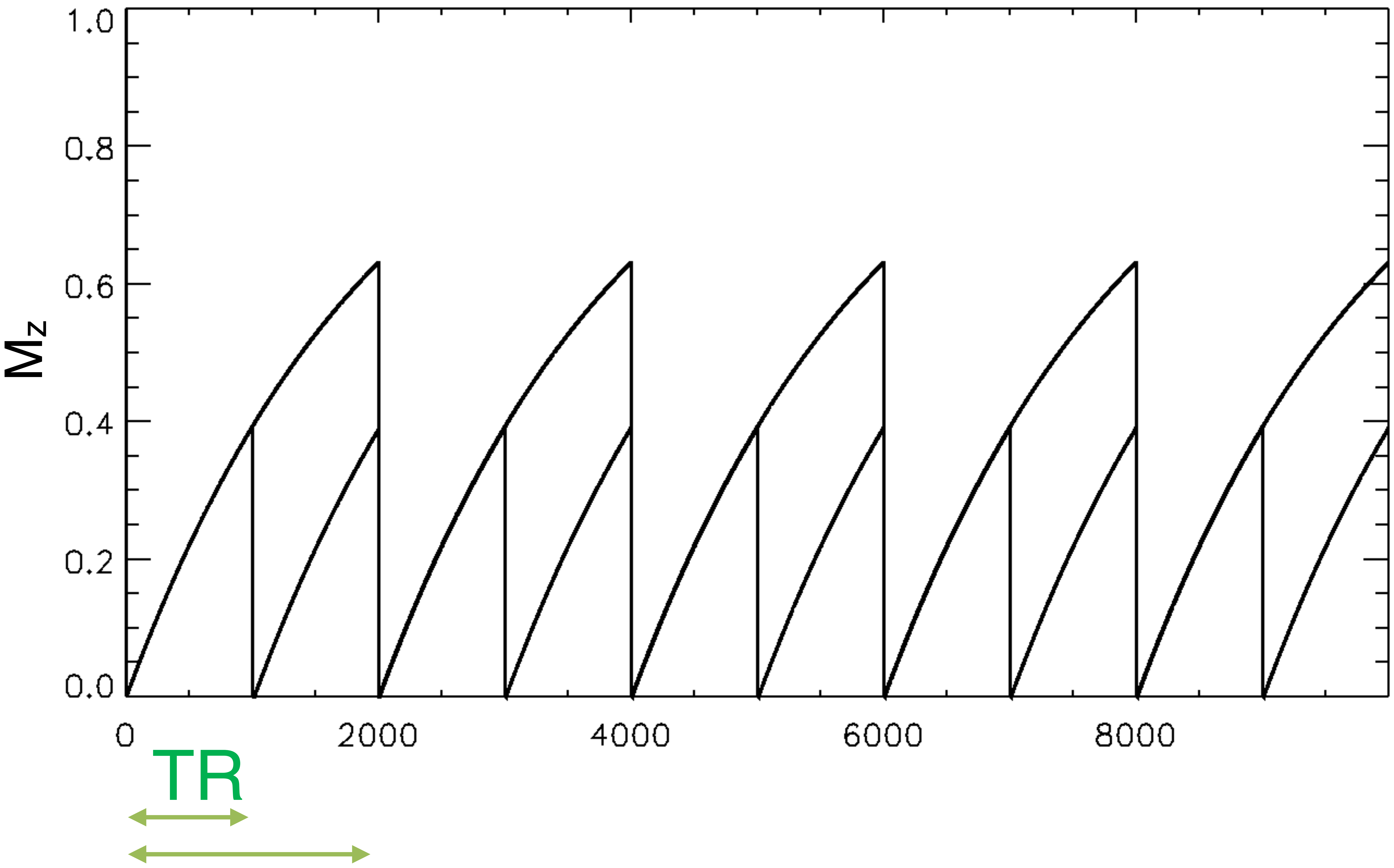
$M_t=1, M_z= 0$

$M_t=0, M_z= 0$

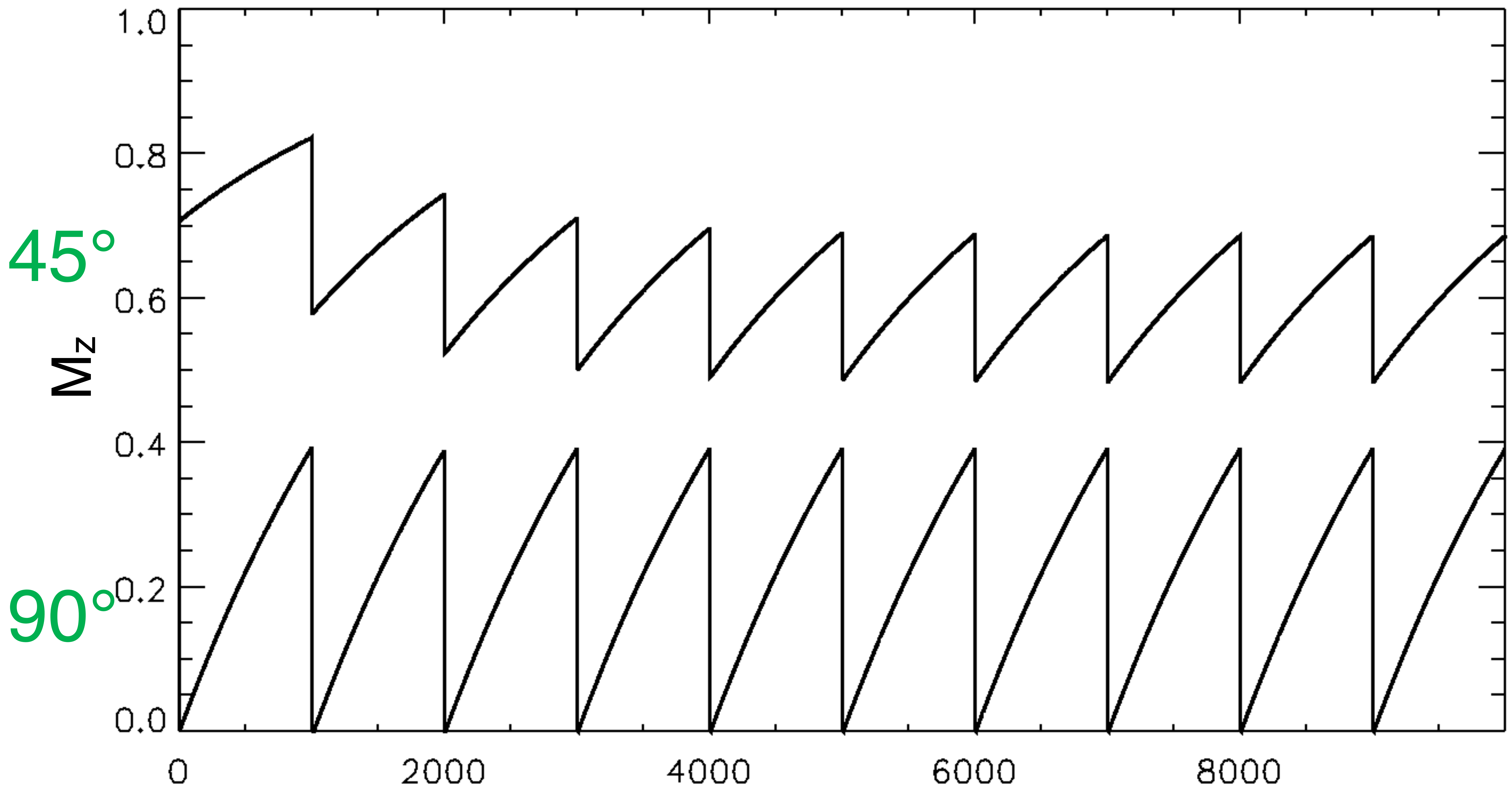
T_1-Relaxation & MRI



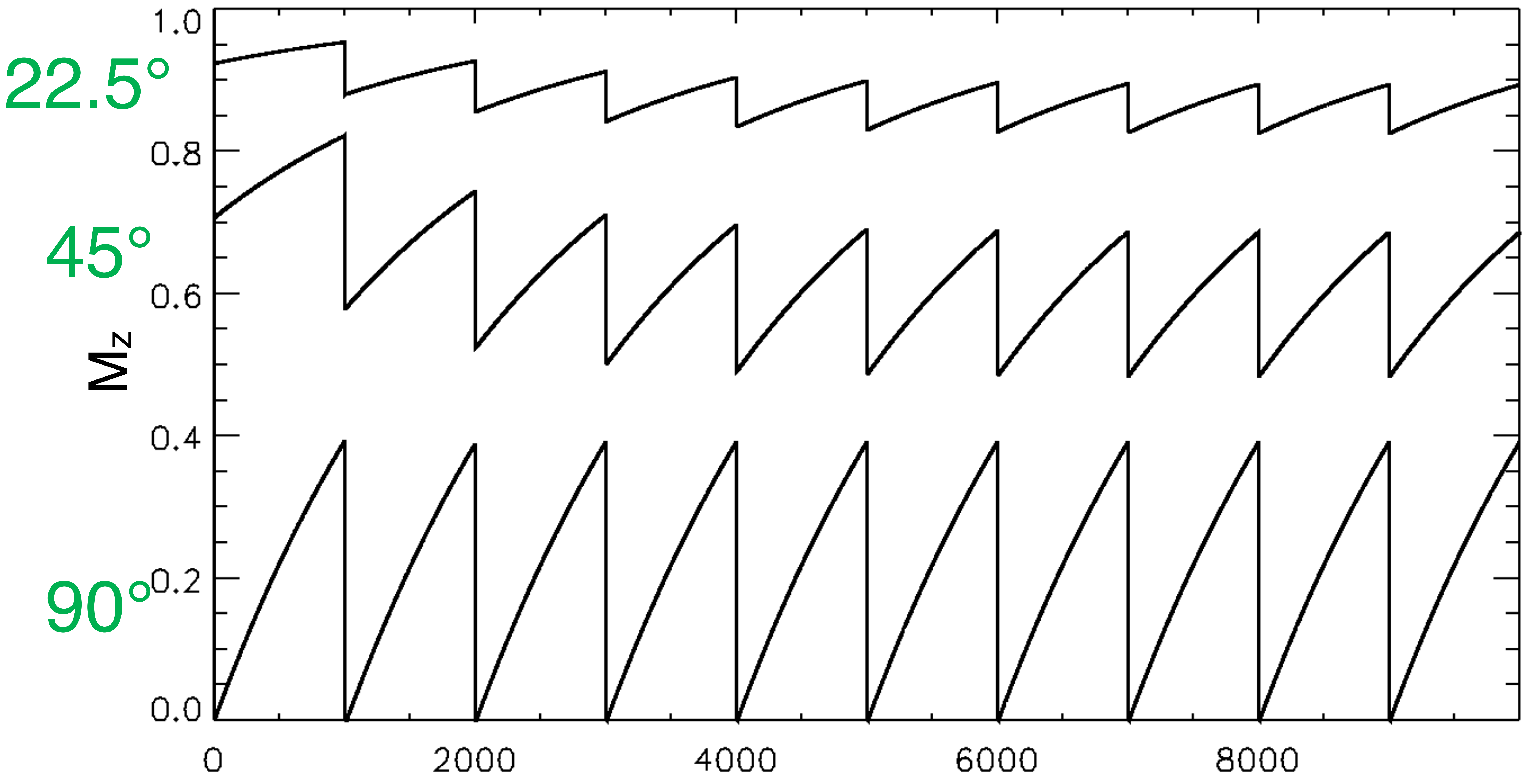
T_1-Relaxation & TR



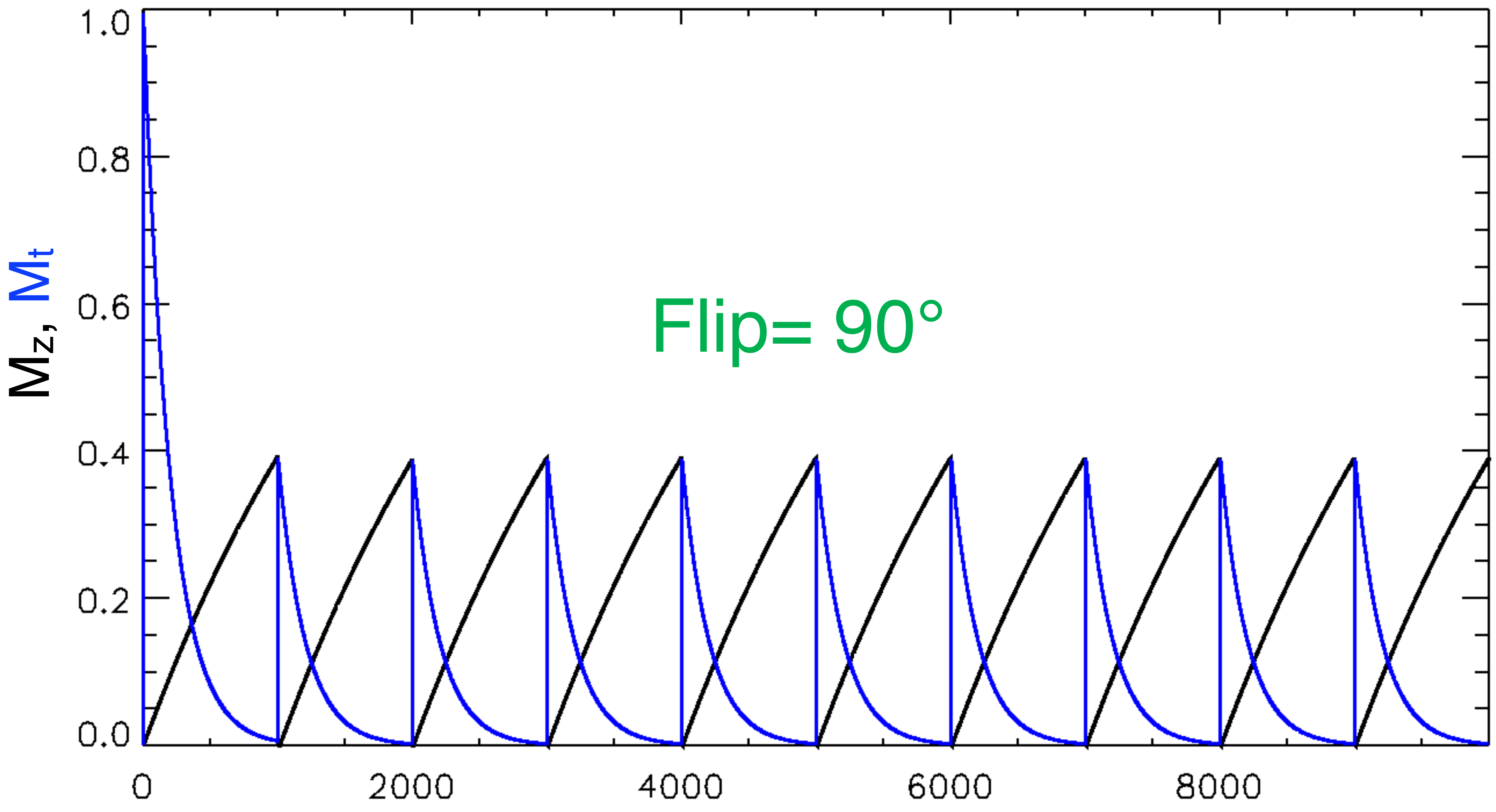
T_1-Relaxation & Flip Angle



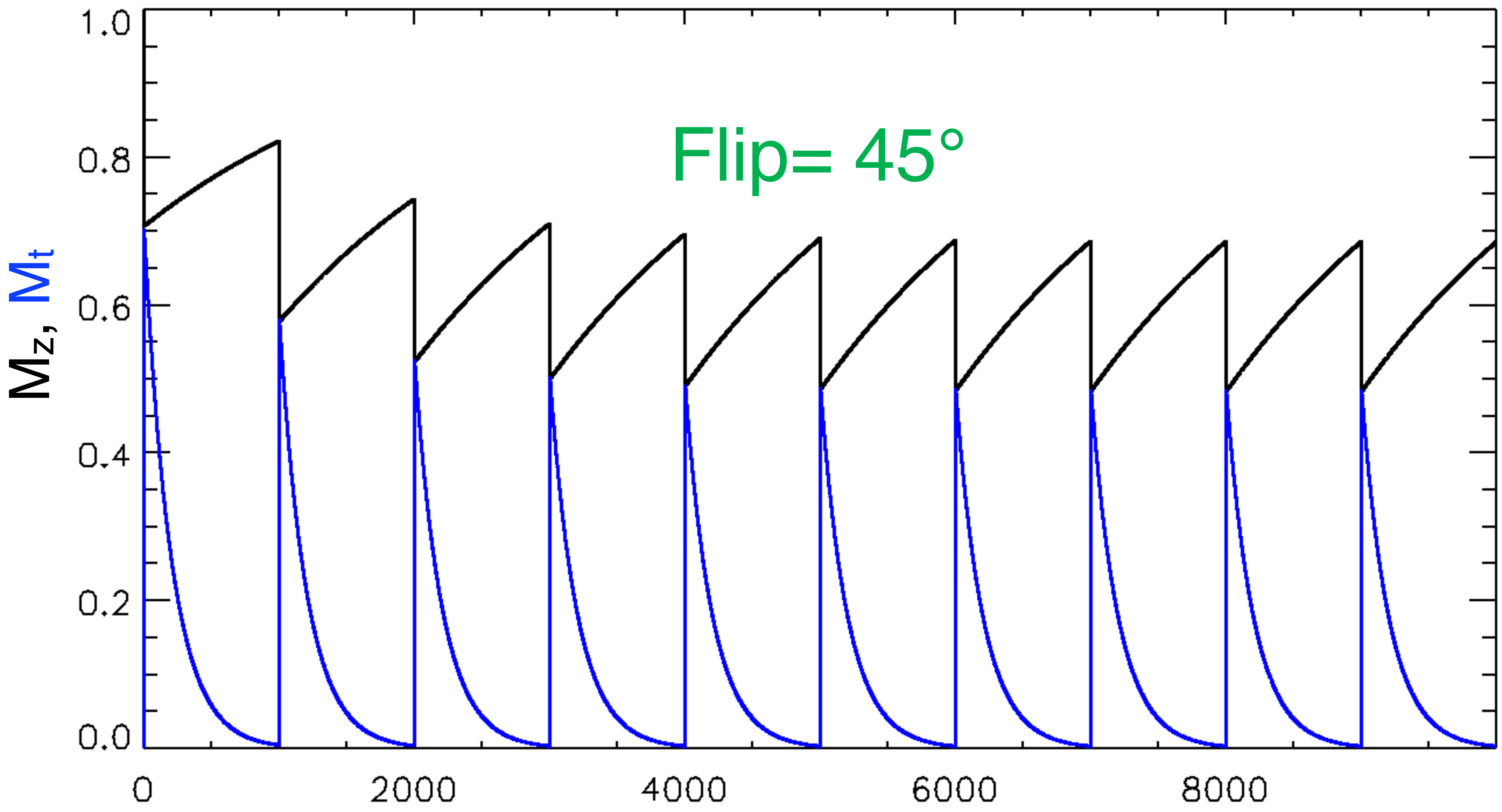
T_1-Relaxation & Flip Angle



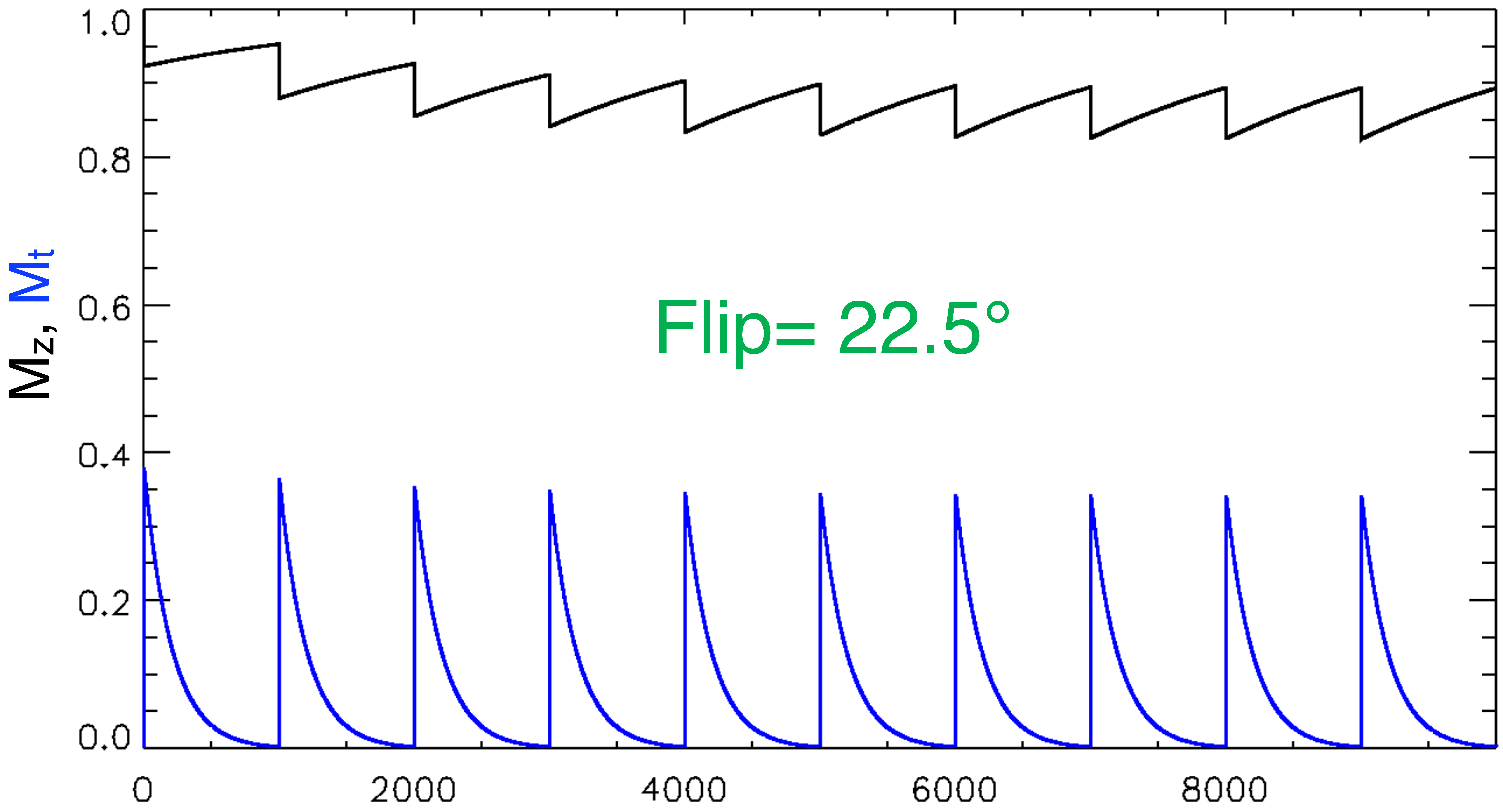
T_1-Relaxation & Signal



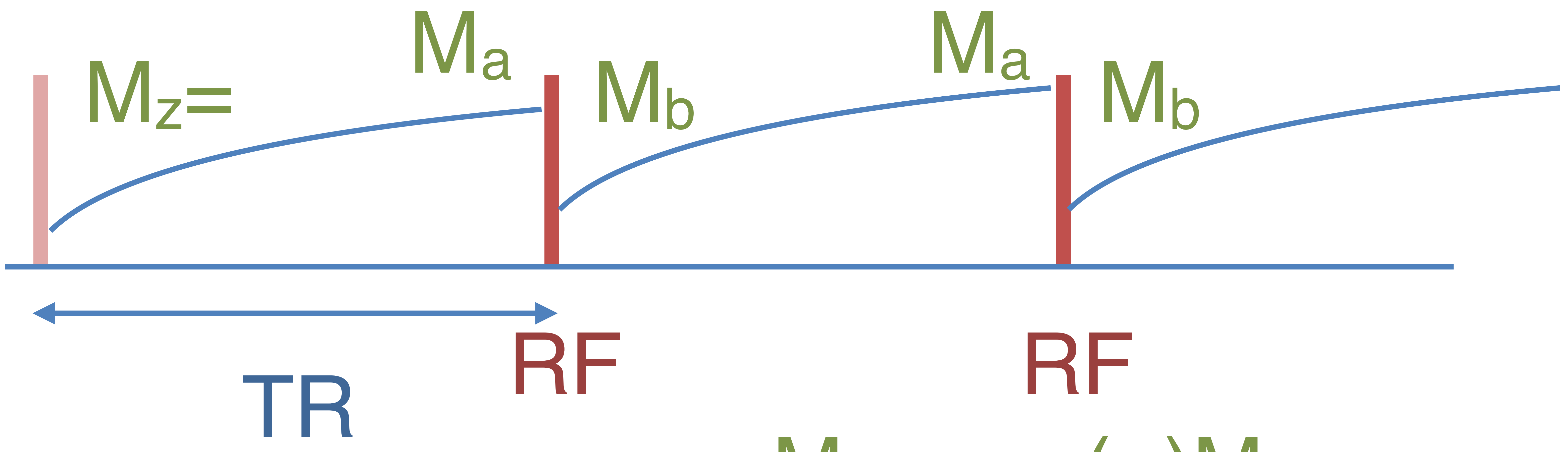
T_1-Relaxation & Signal



T_1-Relaxation & Signal



T_1-Relaxation: Signal Calculation



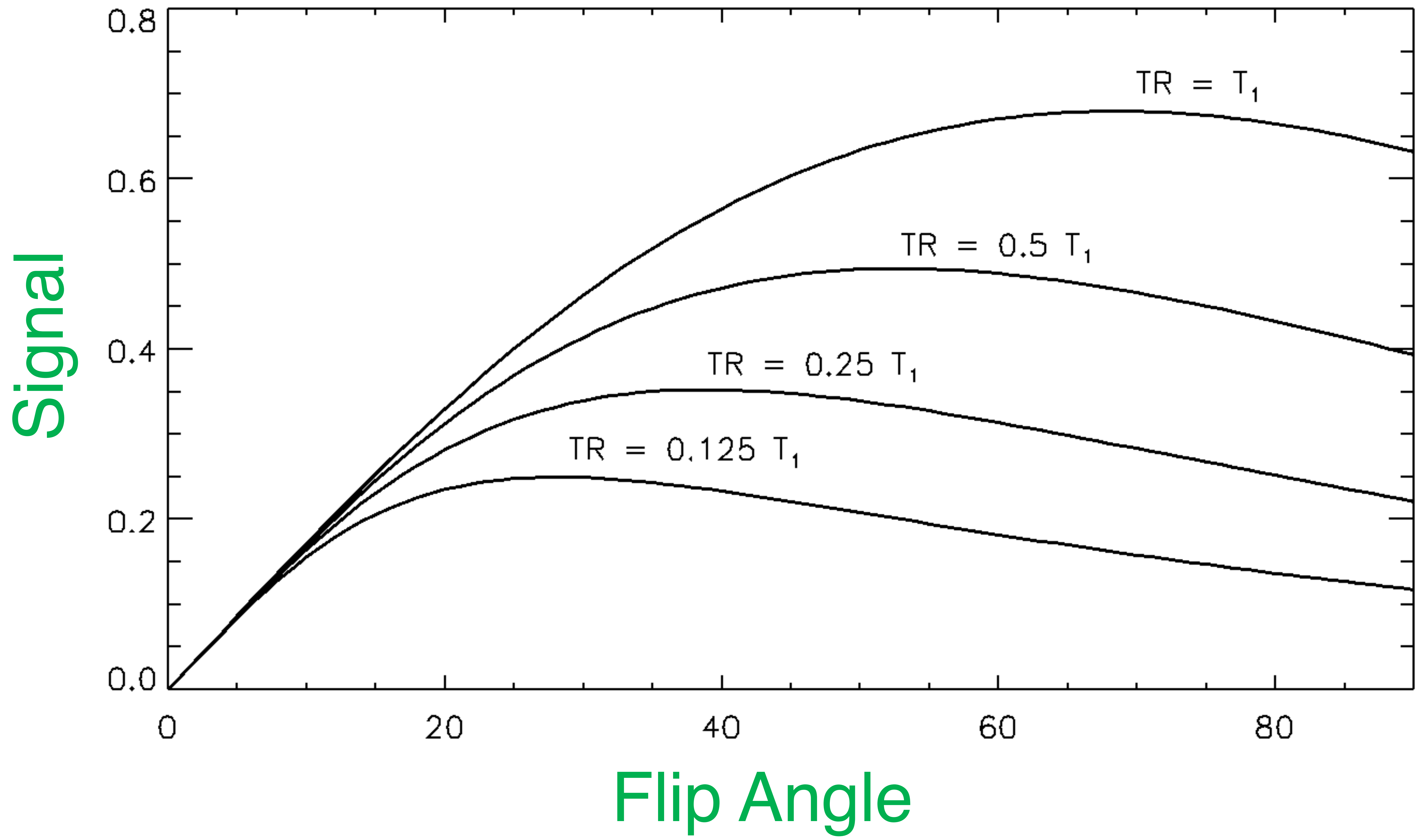
$M_b = \cos(\alpha) M_a$

$M_a = 1-(1-M_b)e^{-TR/T_1} = 1-(1-M_b)E_1$

Solution: $M_a = (1-E_1)/(1-\cos(\alpha)E_1)$

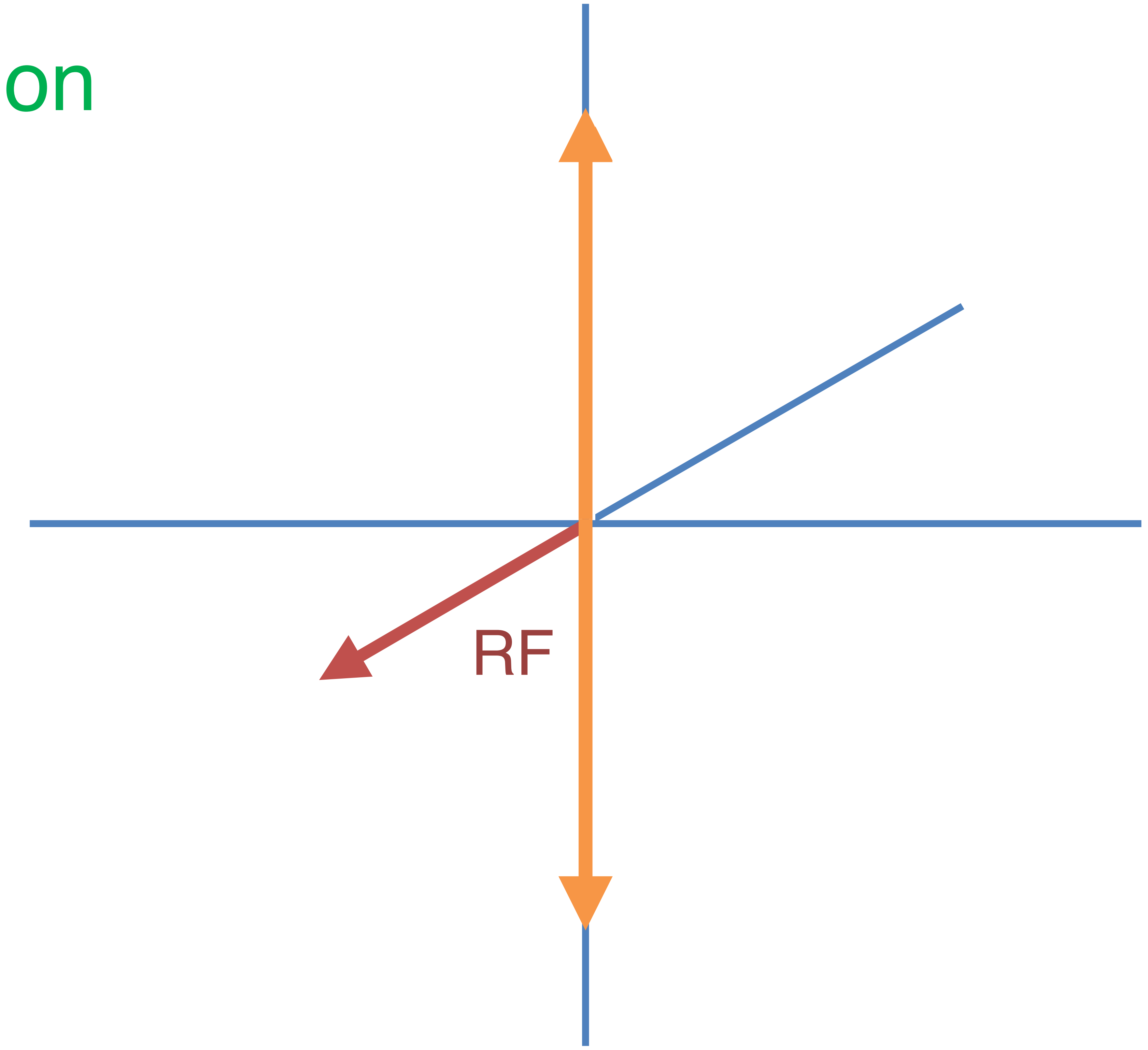
Signal: $M_t = \sin(\alpha) M_a$

T_1-Relaxation & Signal

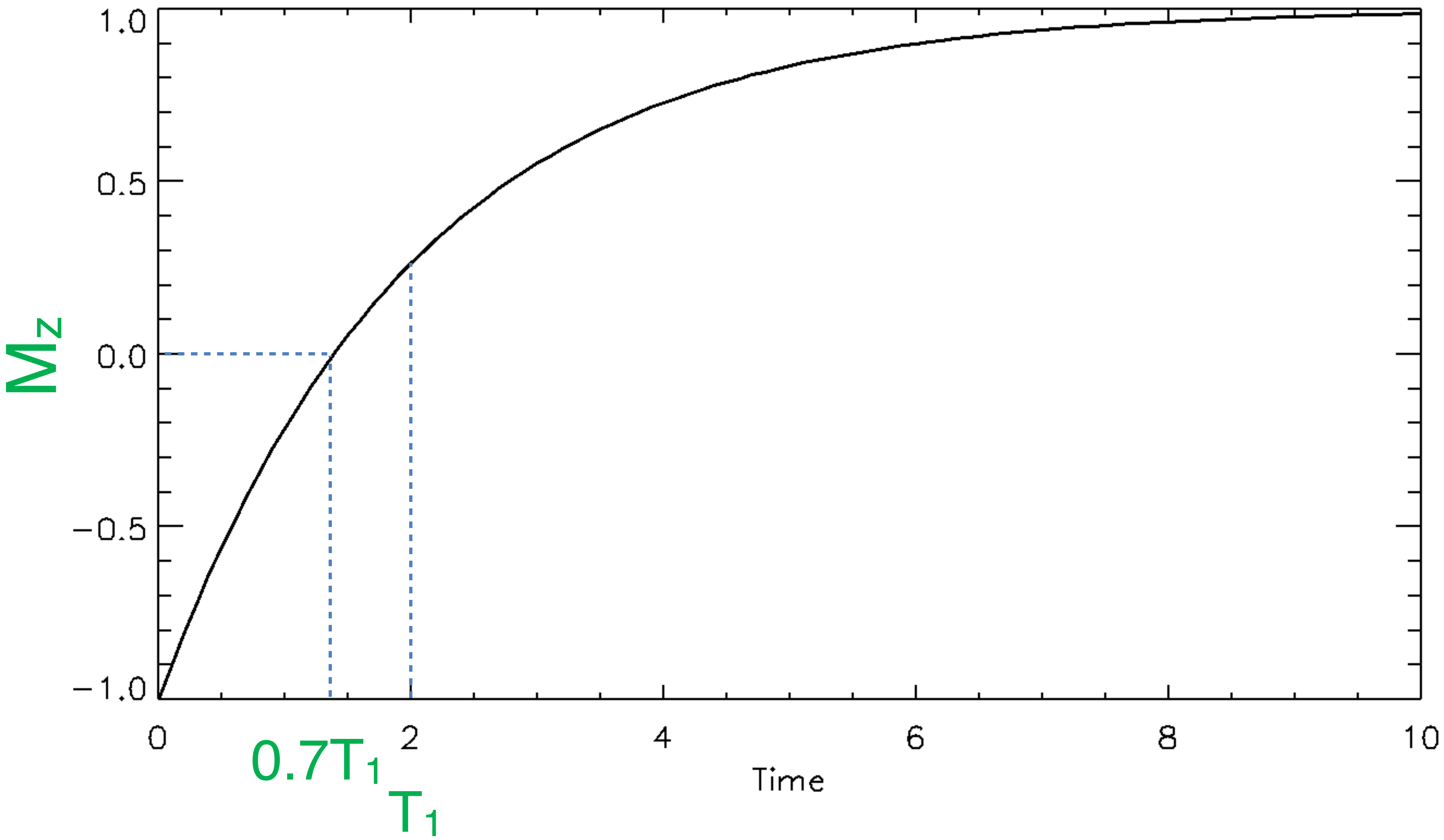


Inversion

More RF than excitation



Inversion Recovery

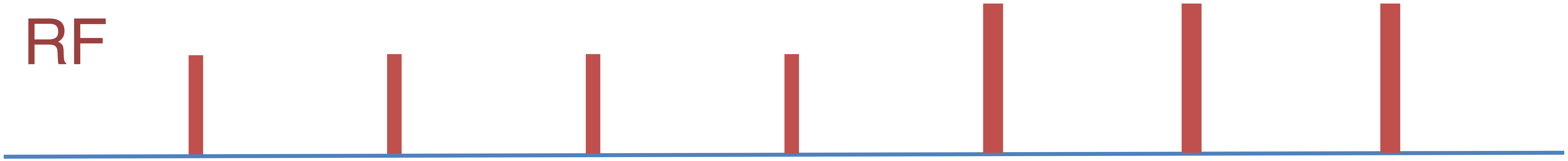


T_1 Measurement

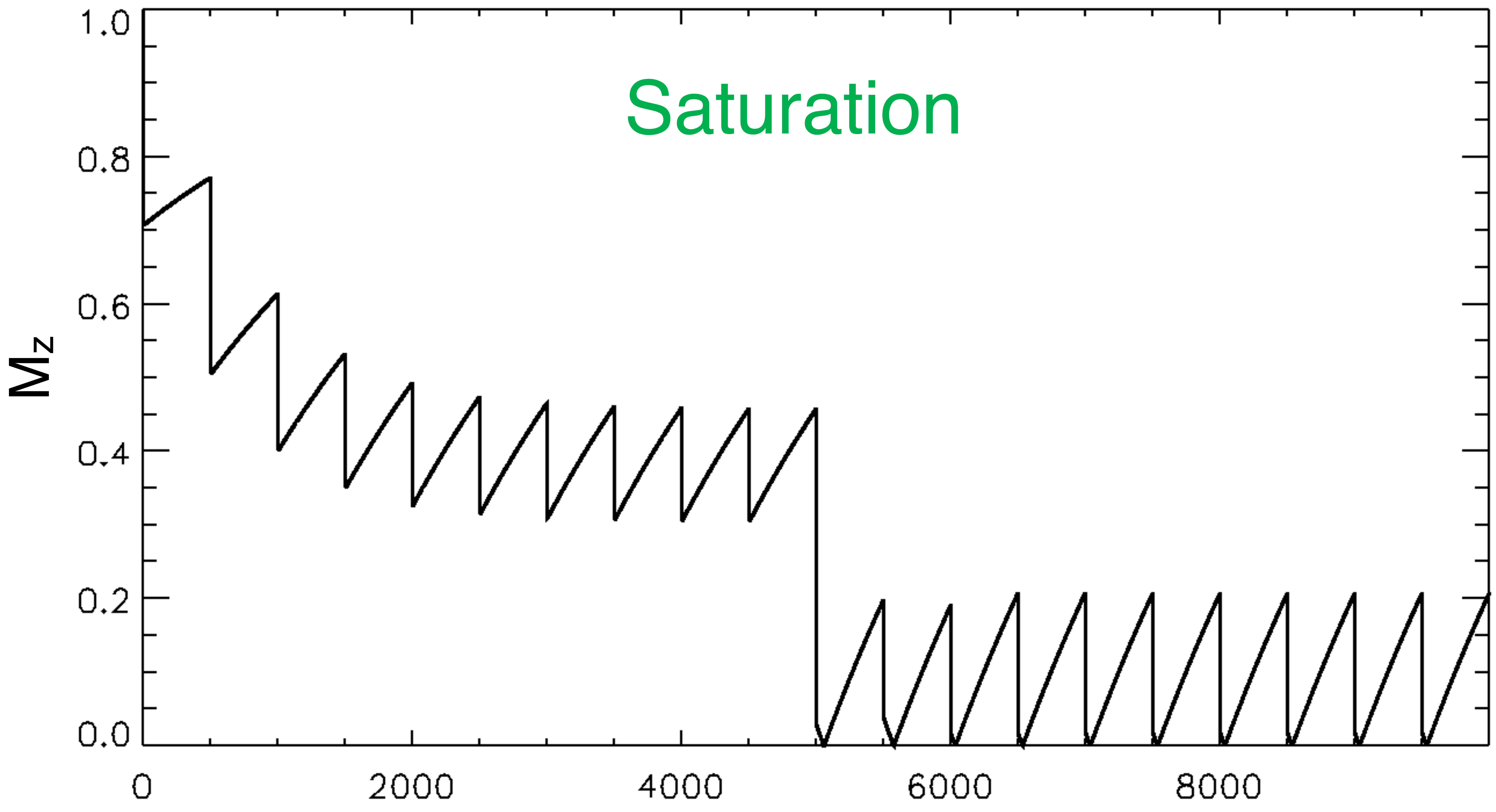
T_1 can be measured in two ways:
- saturation
- inversion recovery

T_1 Measurement

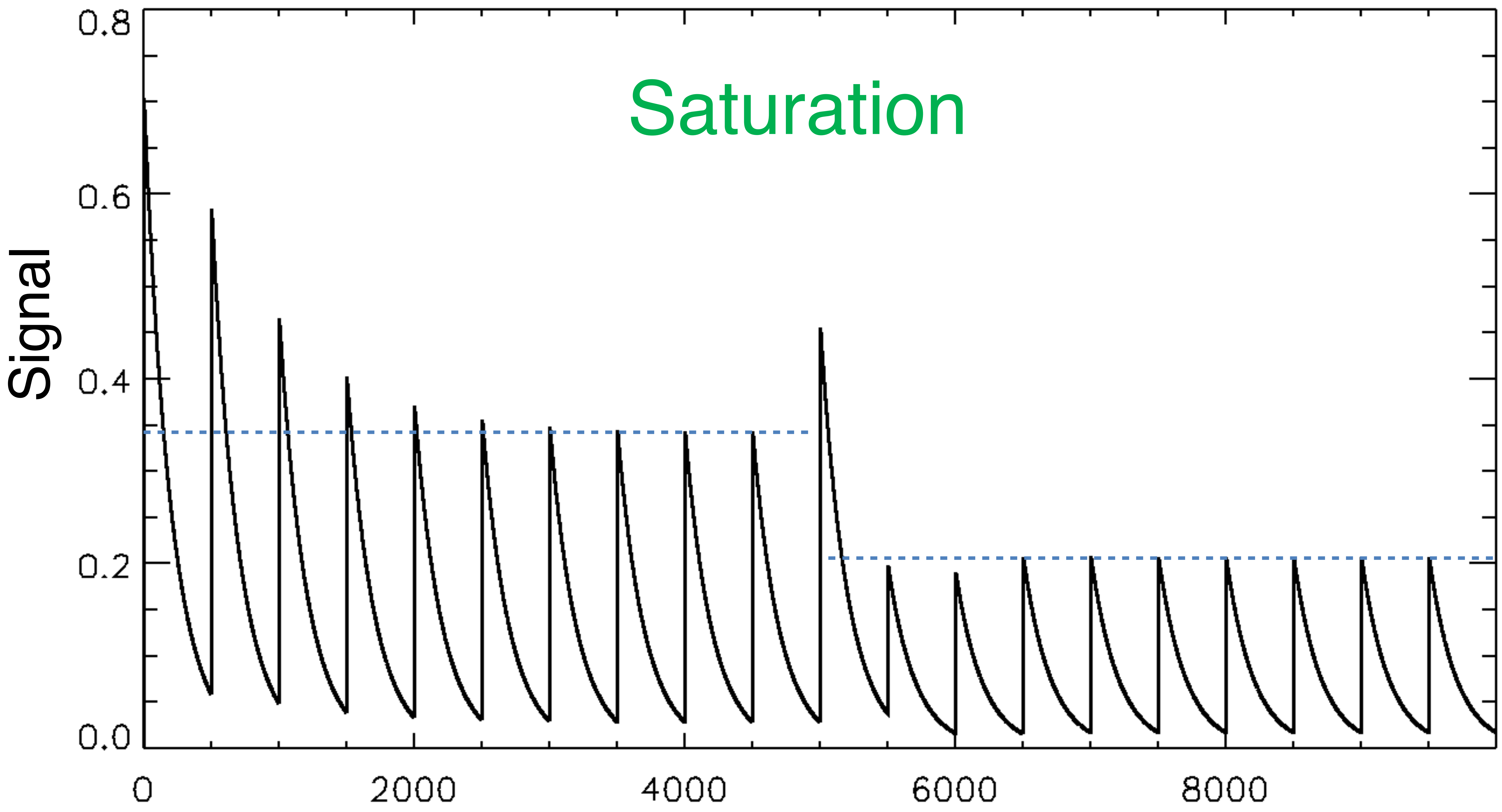
Saturation



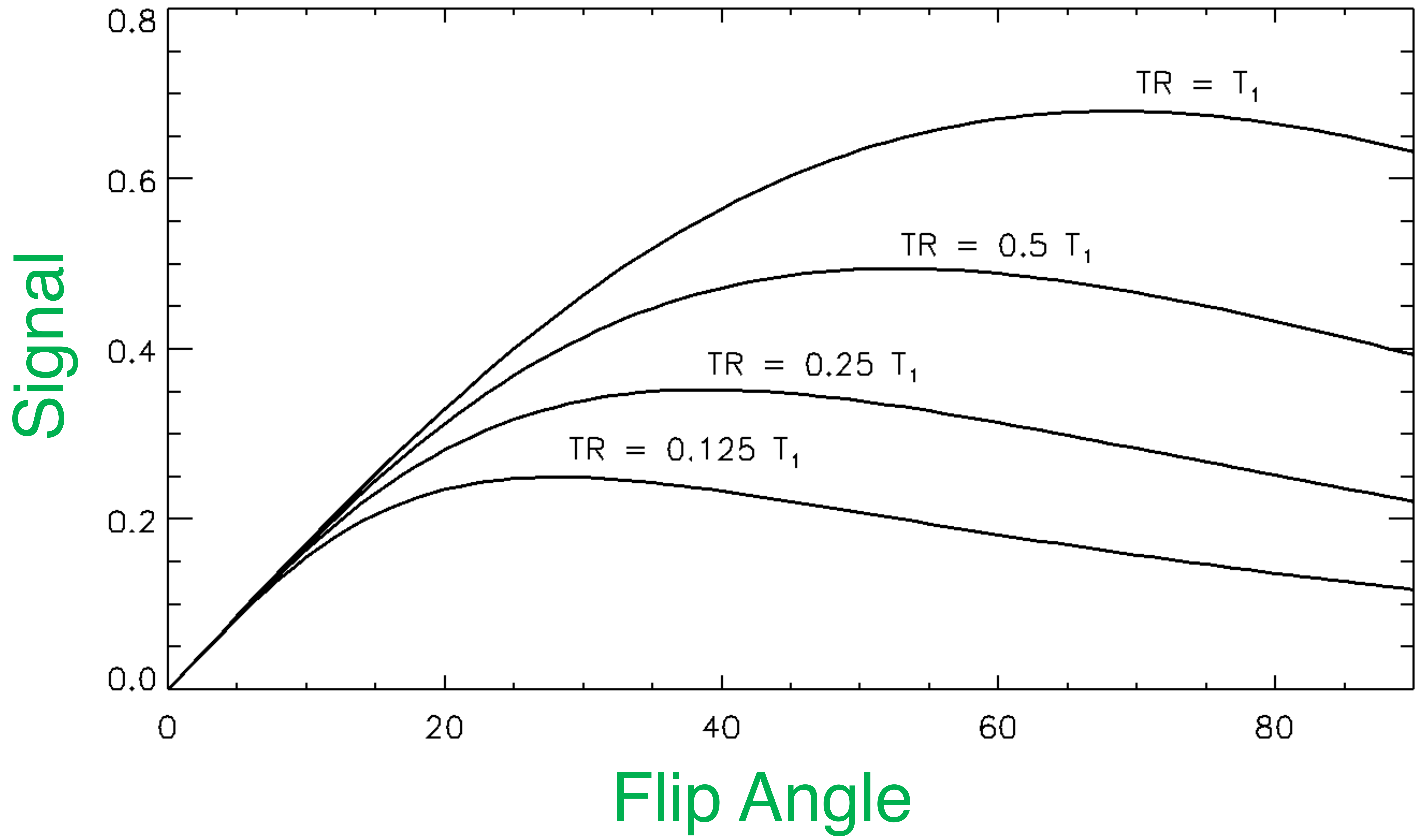
T_1 Measurement



T_1 Measurement

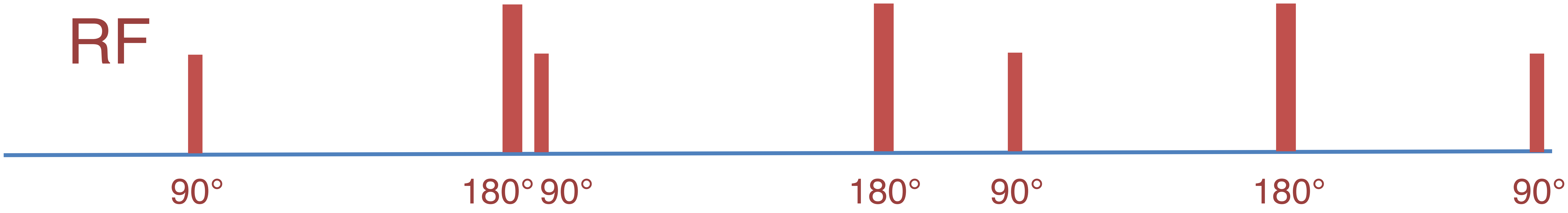


T_1-Relaxation & Signal

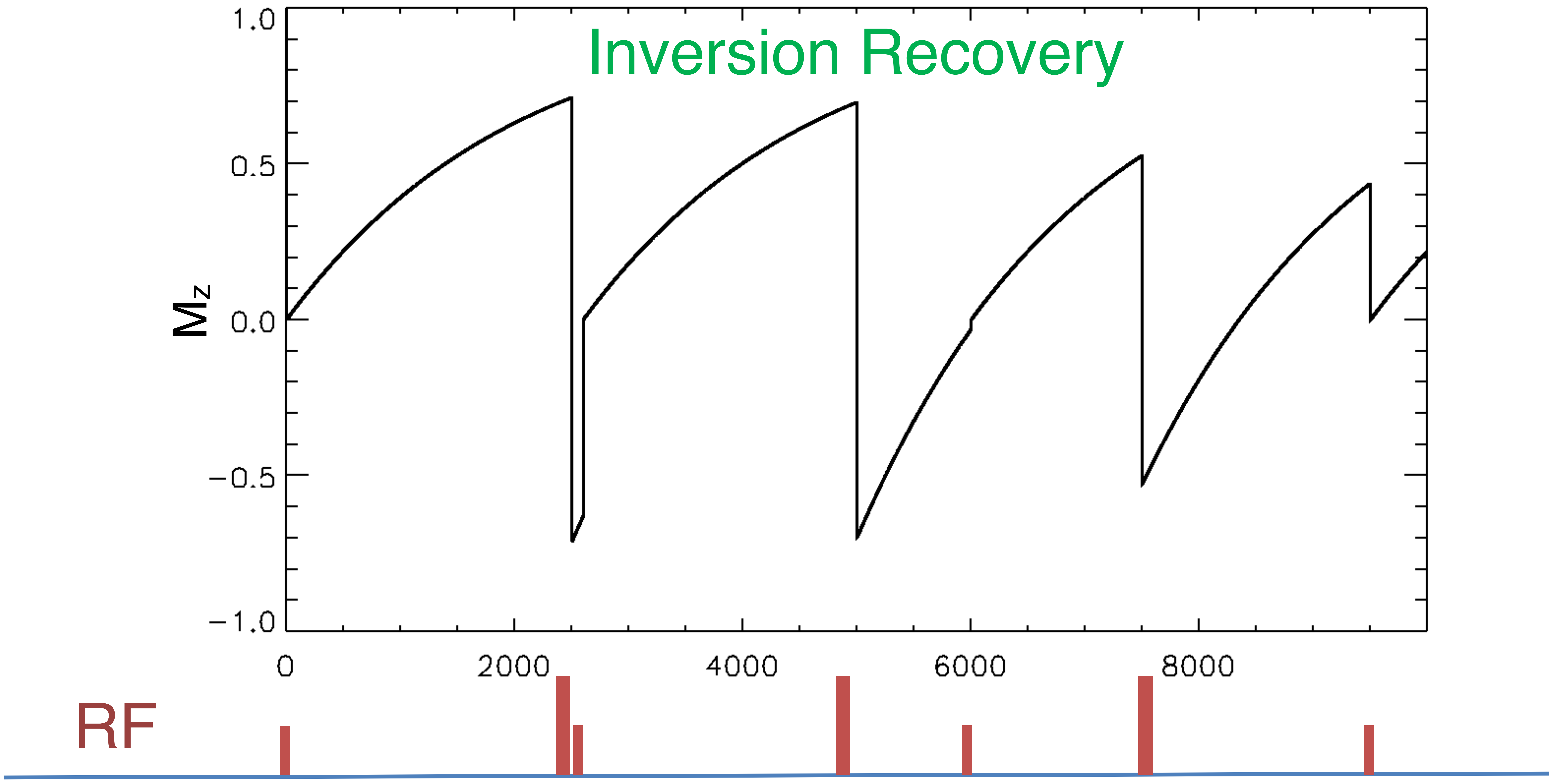


T_1 Measurement

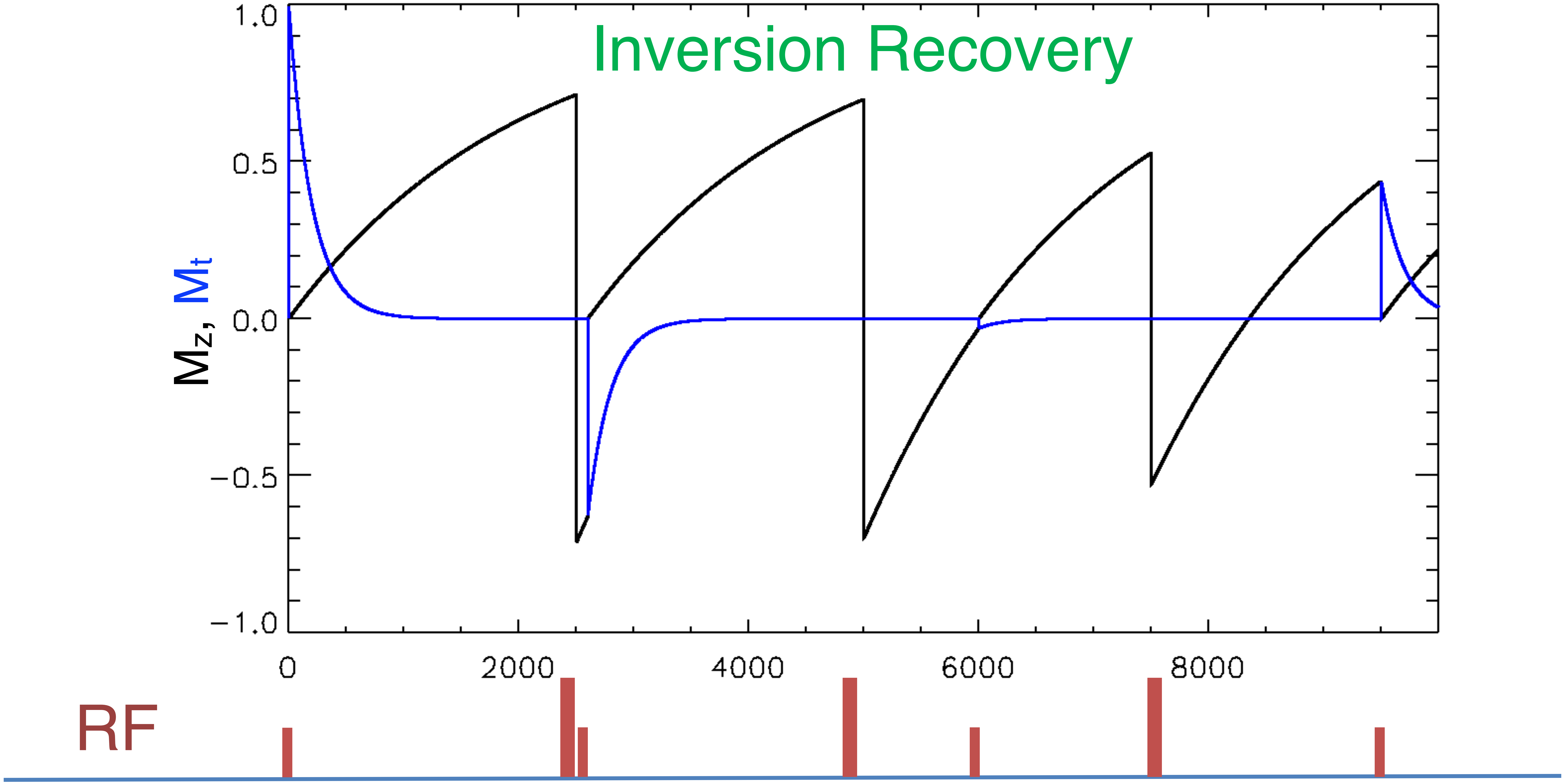
Inversion Recovery



T_1 Measurement

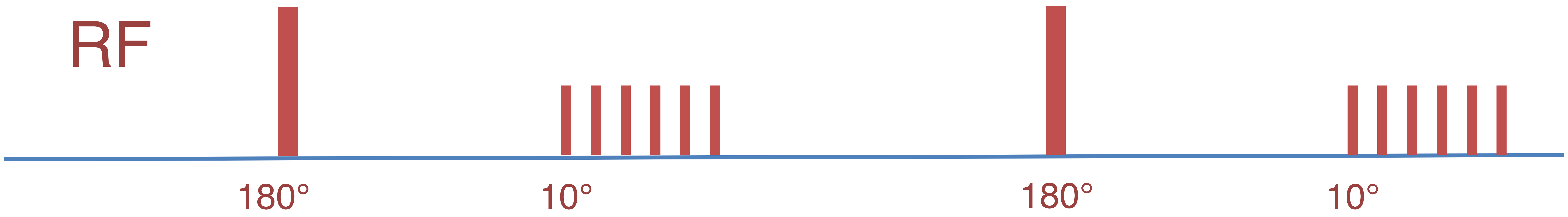


T_1 Measurement

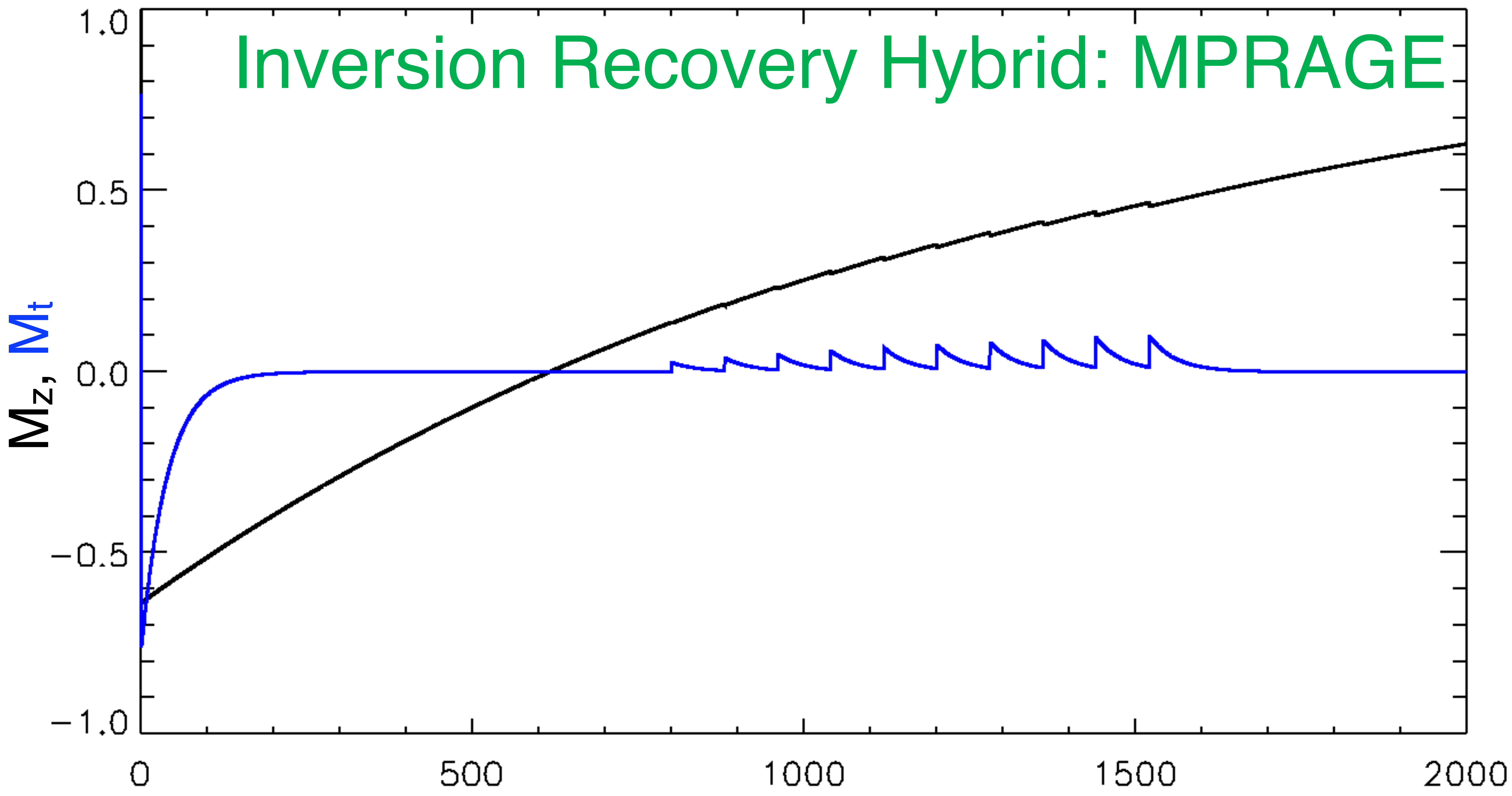


T_1 Measurement

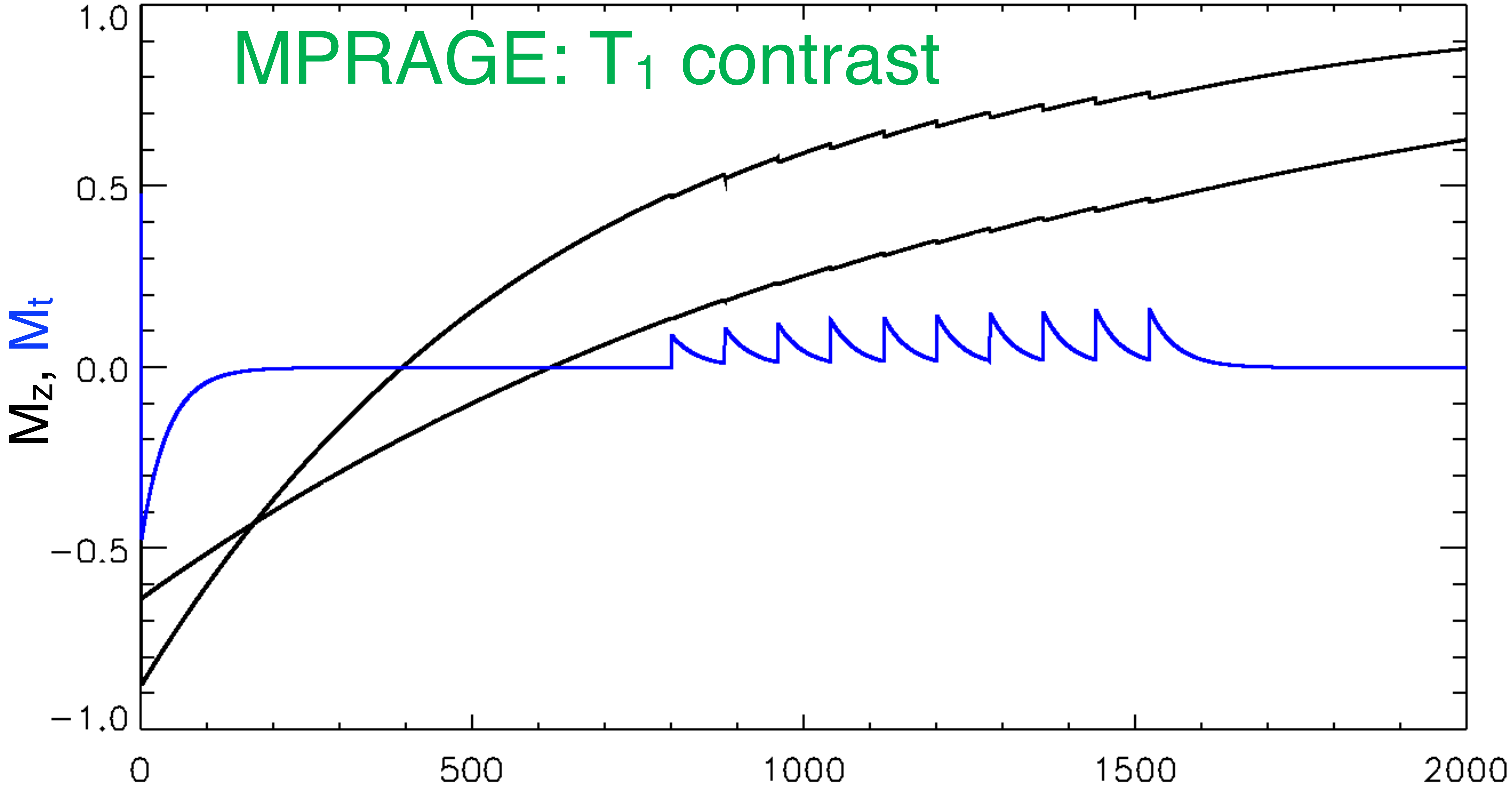
Inversion Recovery Hybrid: MPRAGE



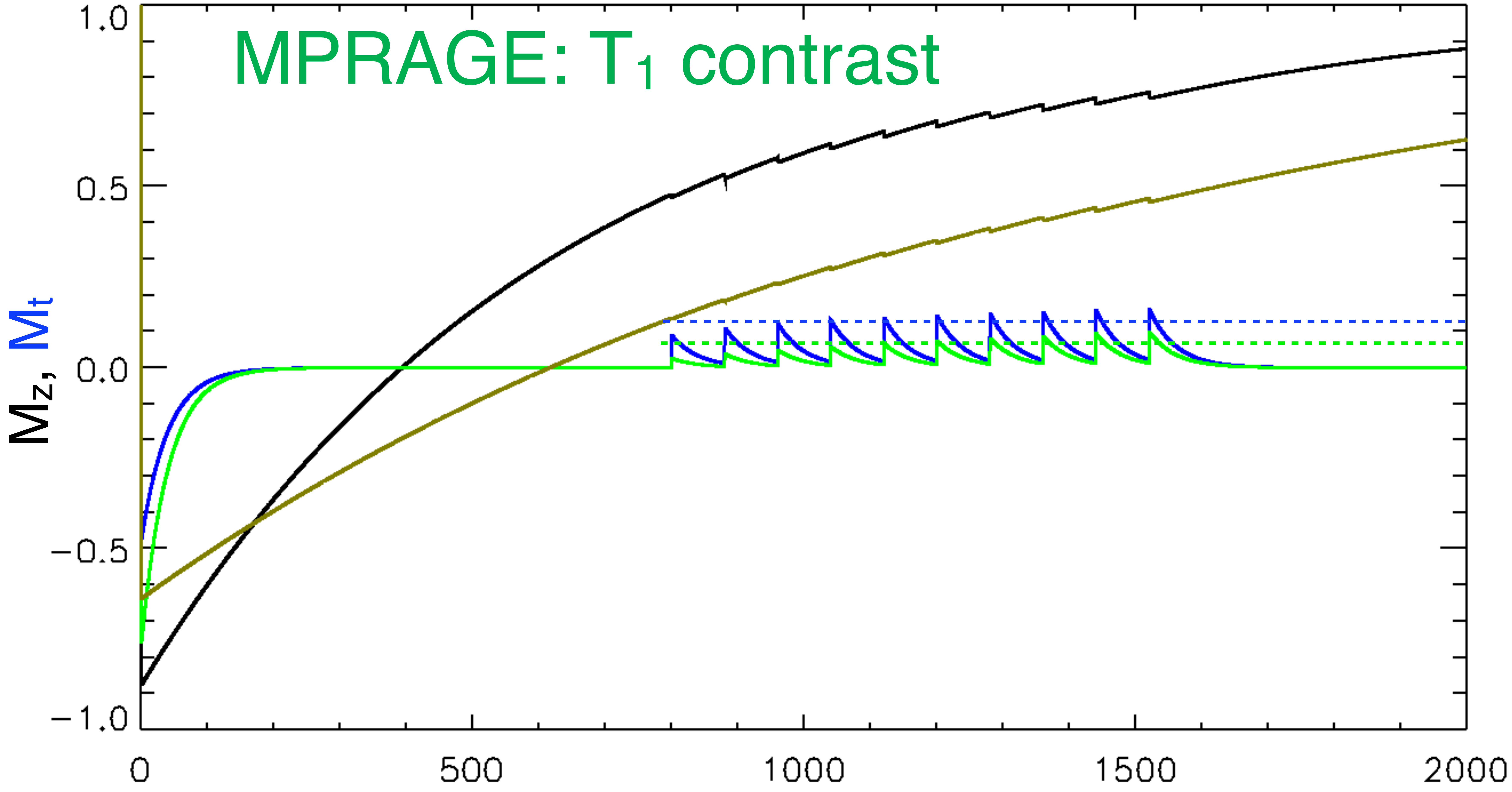
T_1 Measurement



T_1 Measurement



T_1 Measurement



T_1 Measurement

Complications

Signal depends on T_1, but also on:

- $T_2^{(*)}$
- RF (flip angle): Transmit coil, Dielectric effects, Calibration
- Receive sensitivity: Coils, System amplification
- Proton density

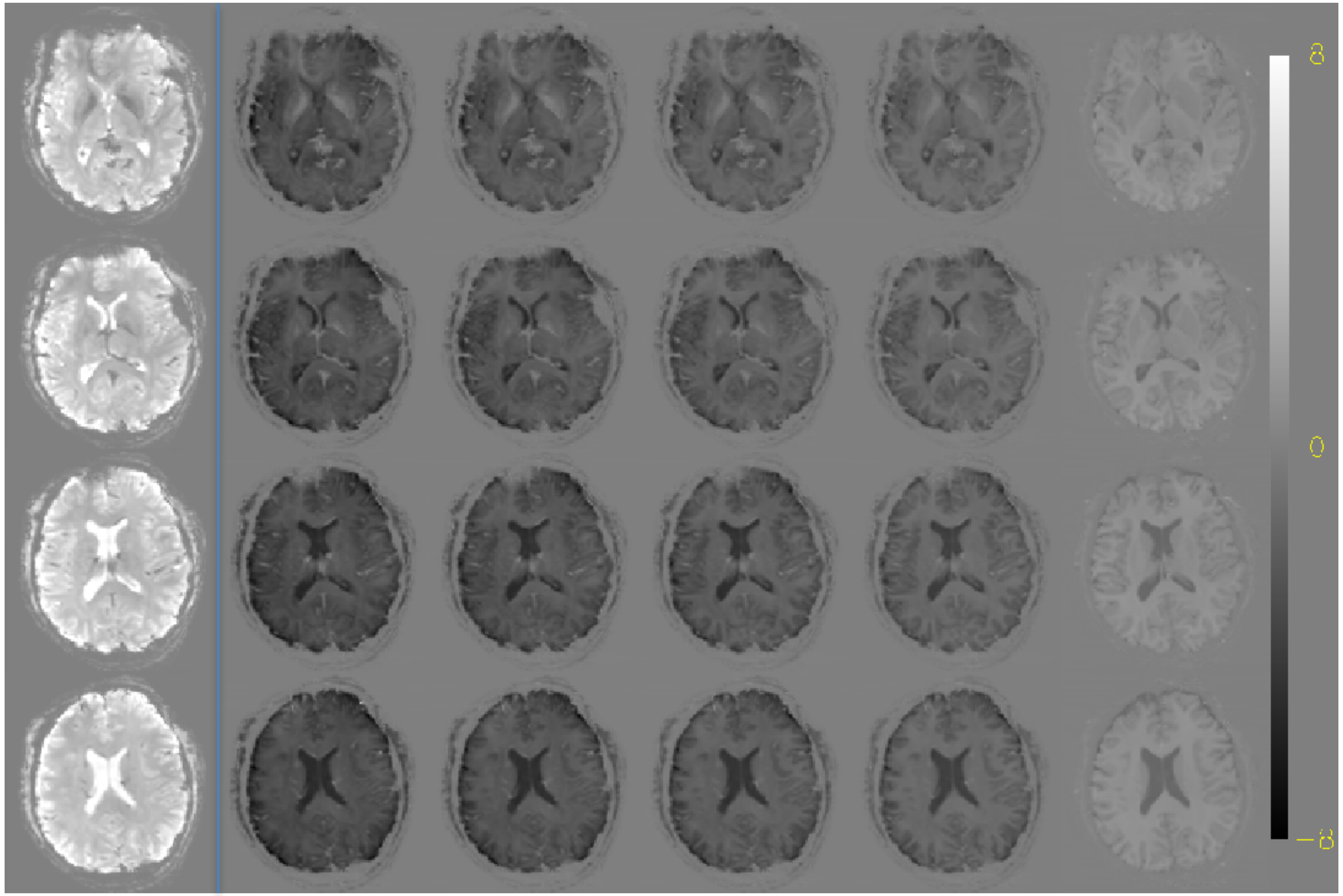
T_1 Measurement

Choosing a method

Inversion Recovery: best quantification, slow
Saturation: fast, but mixed with RF and some T_2
MPRAGE: fast and useful contrast, hard to quantify,
and potential for spatial blurring.
MPRAGE with second scan (MP2RAGE) can compensate some
of the coil contrast etc.

T_1 Measurement

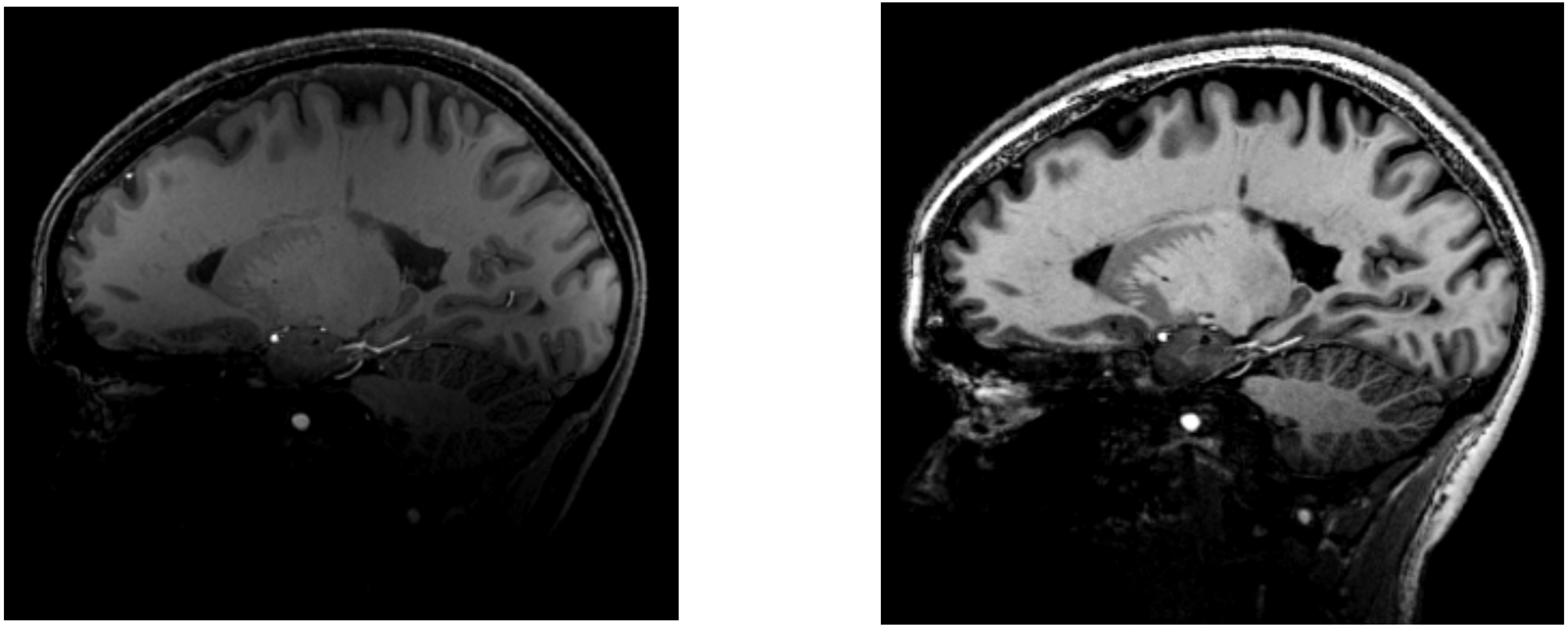
Examples: 7T IR with EPI



REF TI: 7 64 145 256 1200 ms

T_1 Measurement

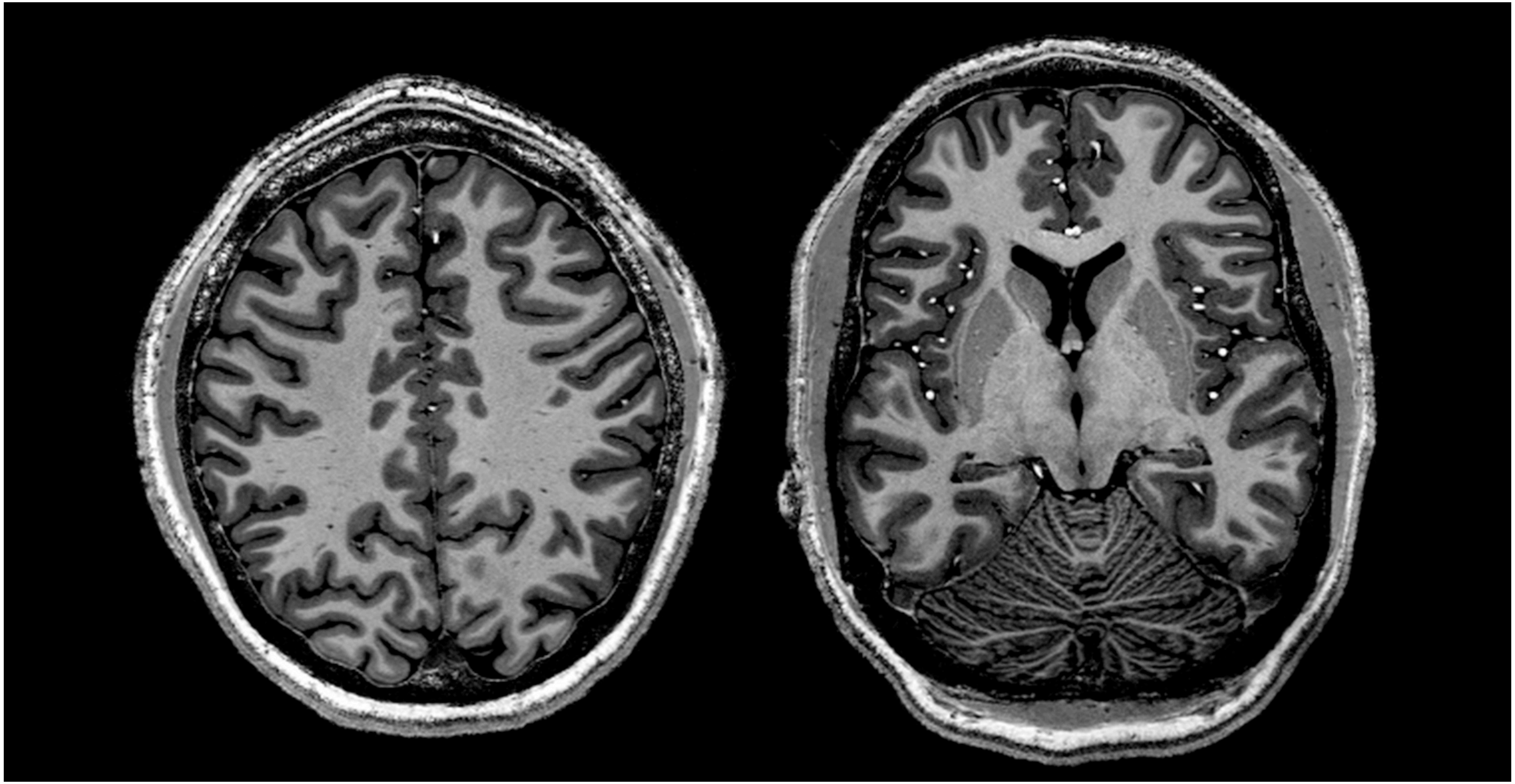
Examples: MPRAGE, MP2RAGE



Curtesy of Pascal Sati, NINDS

T_1 Measurement

Examples: 7T 0.5mm MP2RAGE

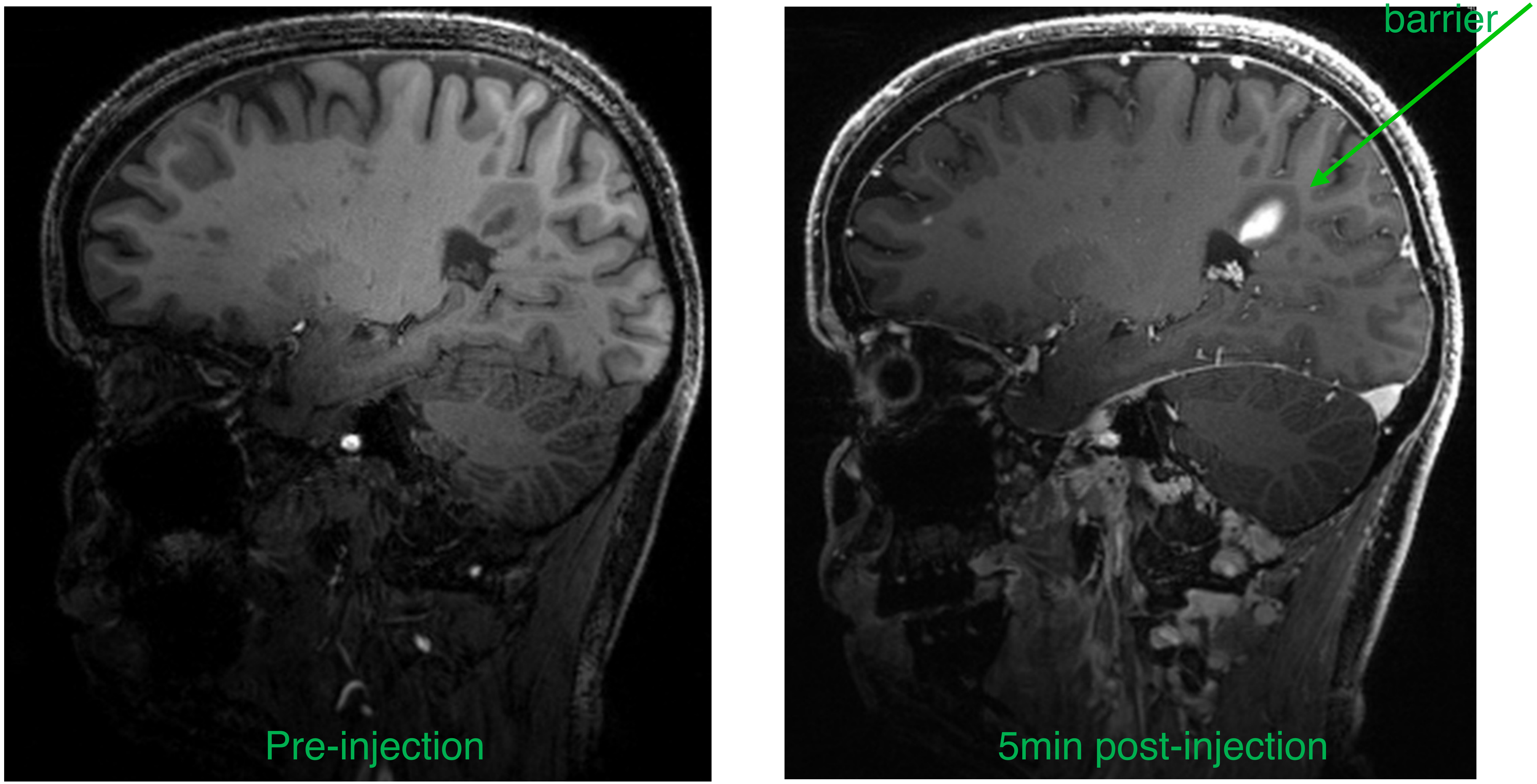


Curtesy of Pascal Sati, NINDS

T_1 Measurement

Examples: 7T, MPRAGE, Gd-injection

Enhancing lesion due to open blood -brain barrier



Pre-injection

5min post-injection

Curtesy of Pascal Sati, NINDS

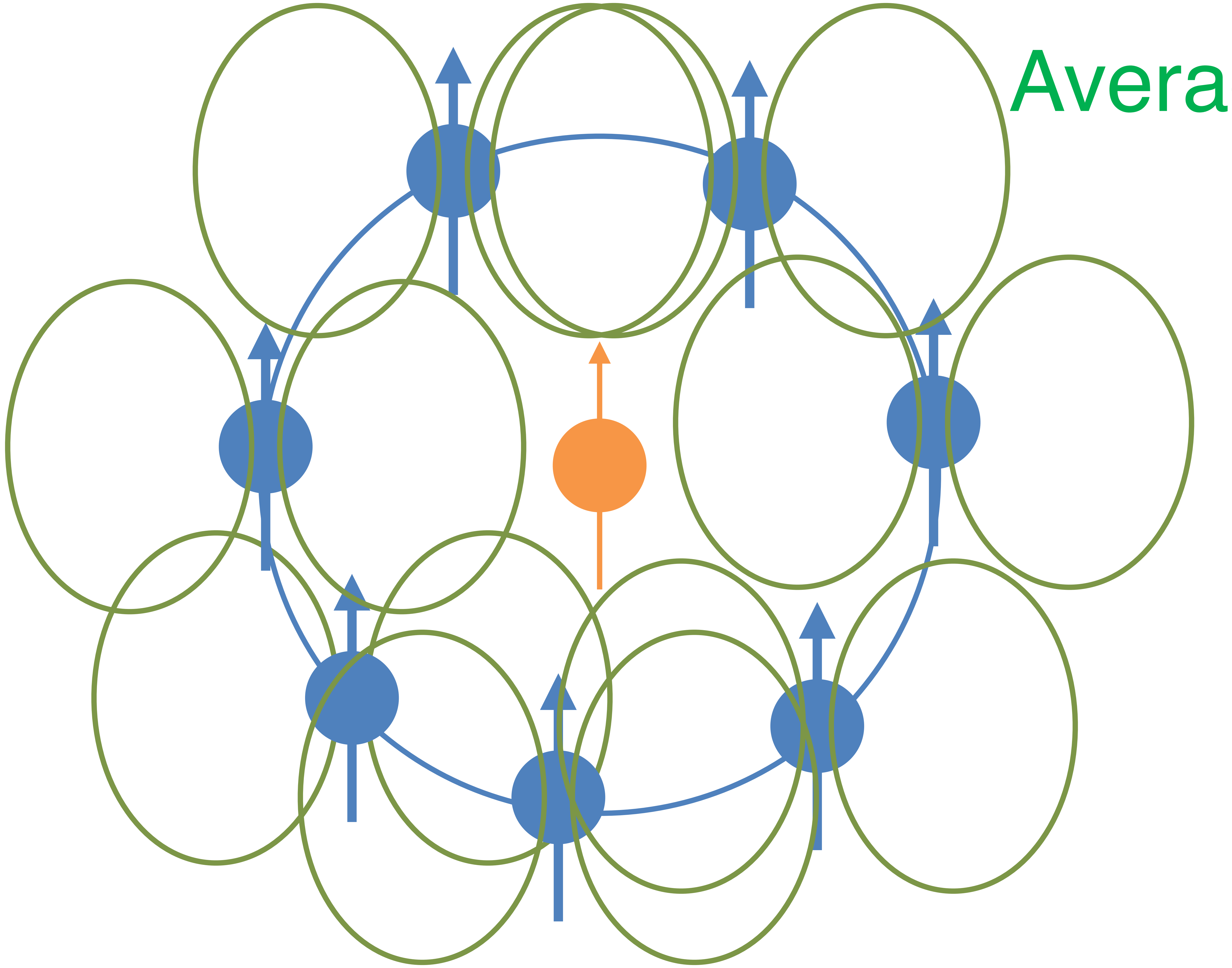
T_1: Sources

Pure water: very little energy transfer -> slow relaxation

Interaction with other molecules required:
in the brain, mostly lipids and protein

Interaction: Magnetization Transfer (= part 2)

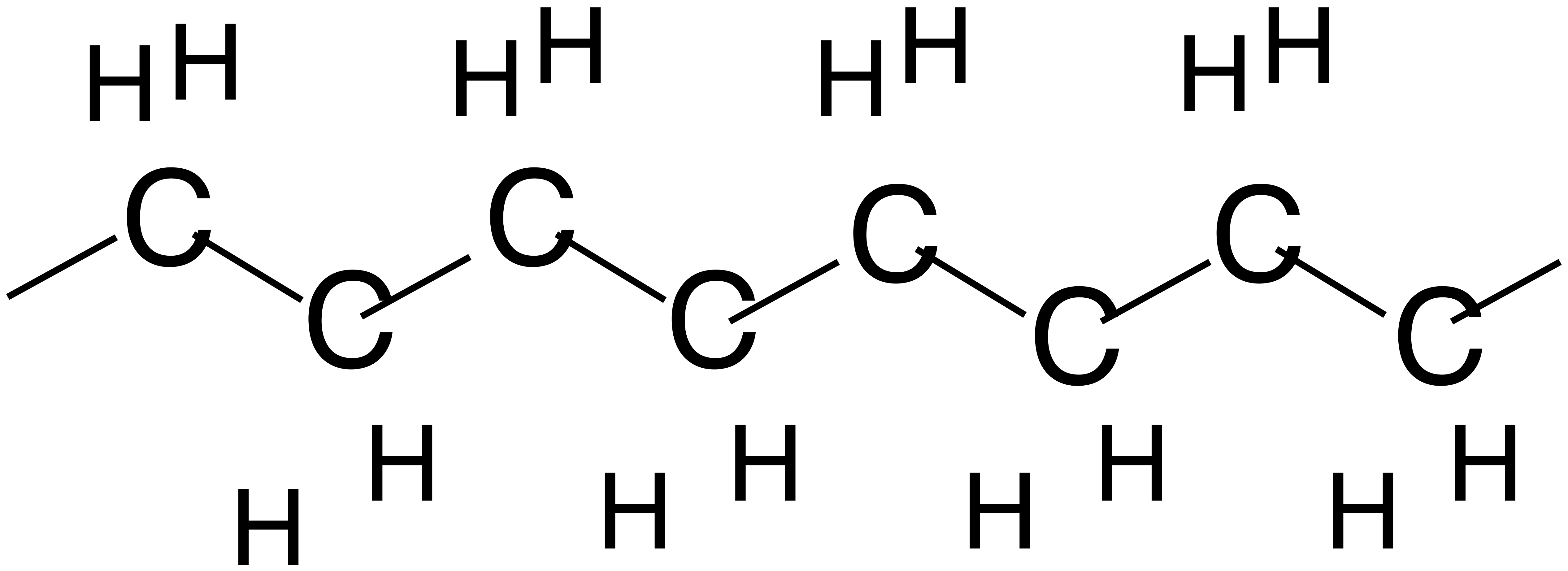
MT: T_2



Average field

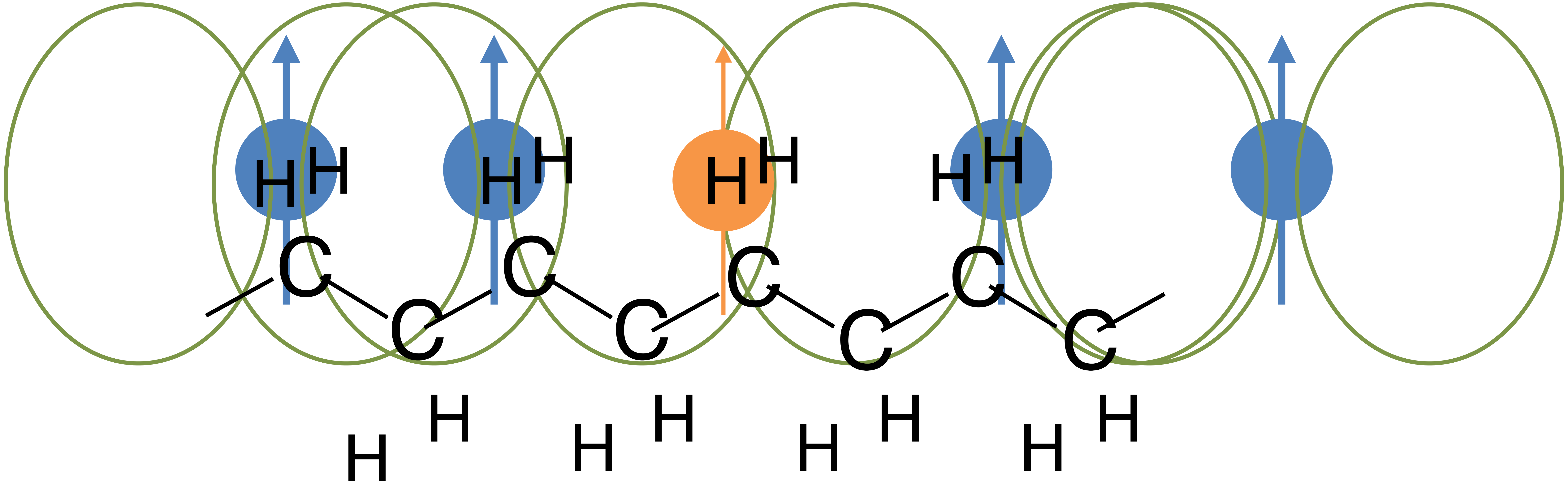
MT: T_2

Lipid has more structure



MT: T_2

Average field ≠ 0: short T_2



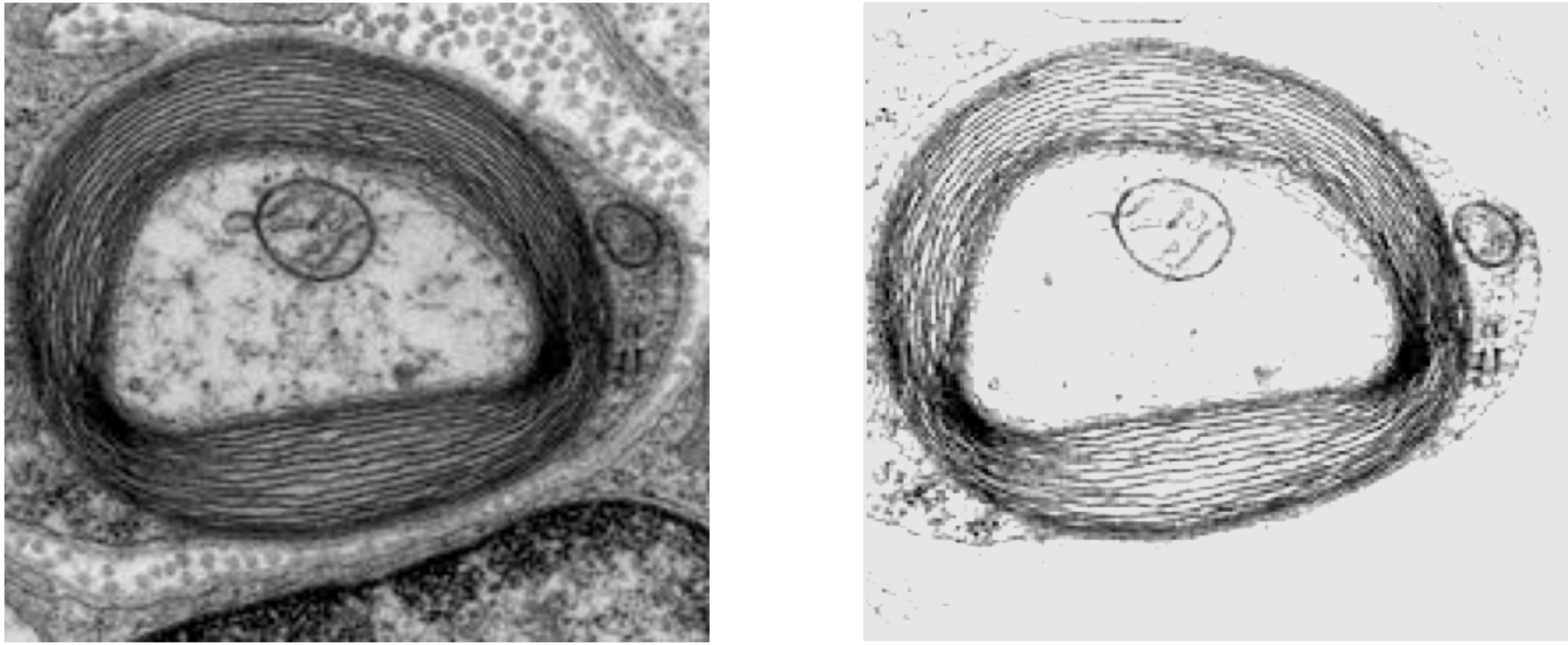
MT: T_2

Short T_2

$T_2 \ll 1$ ms : not visible in MRI

But: ‘hidden’ magnetization interacts with water

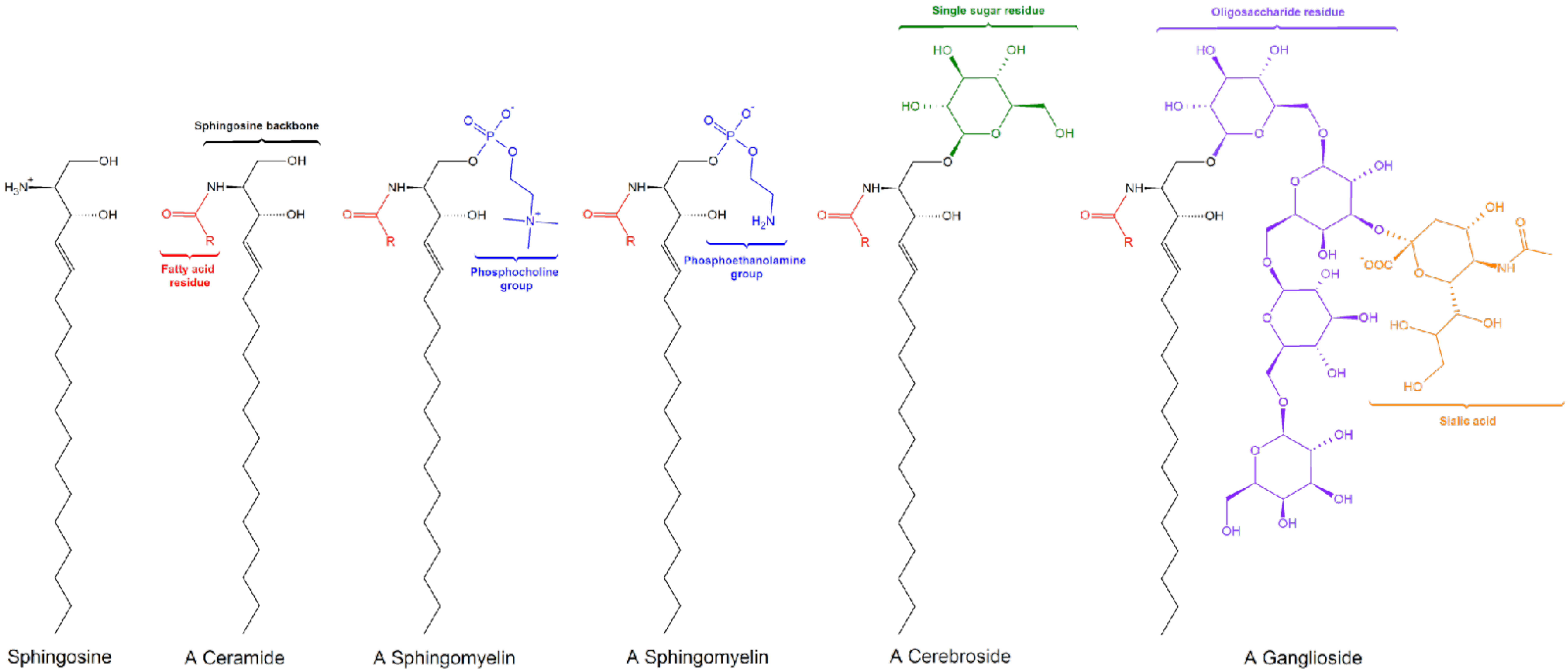
Solids in White Matter



Trinity College, Hartford, CT

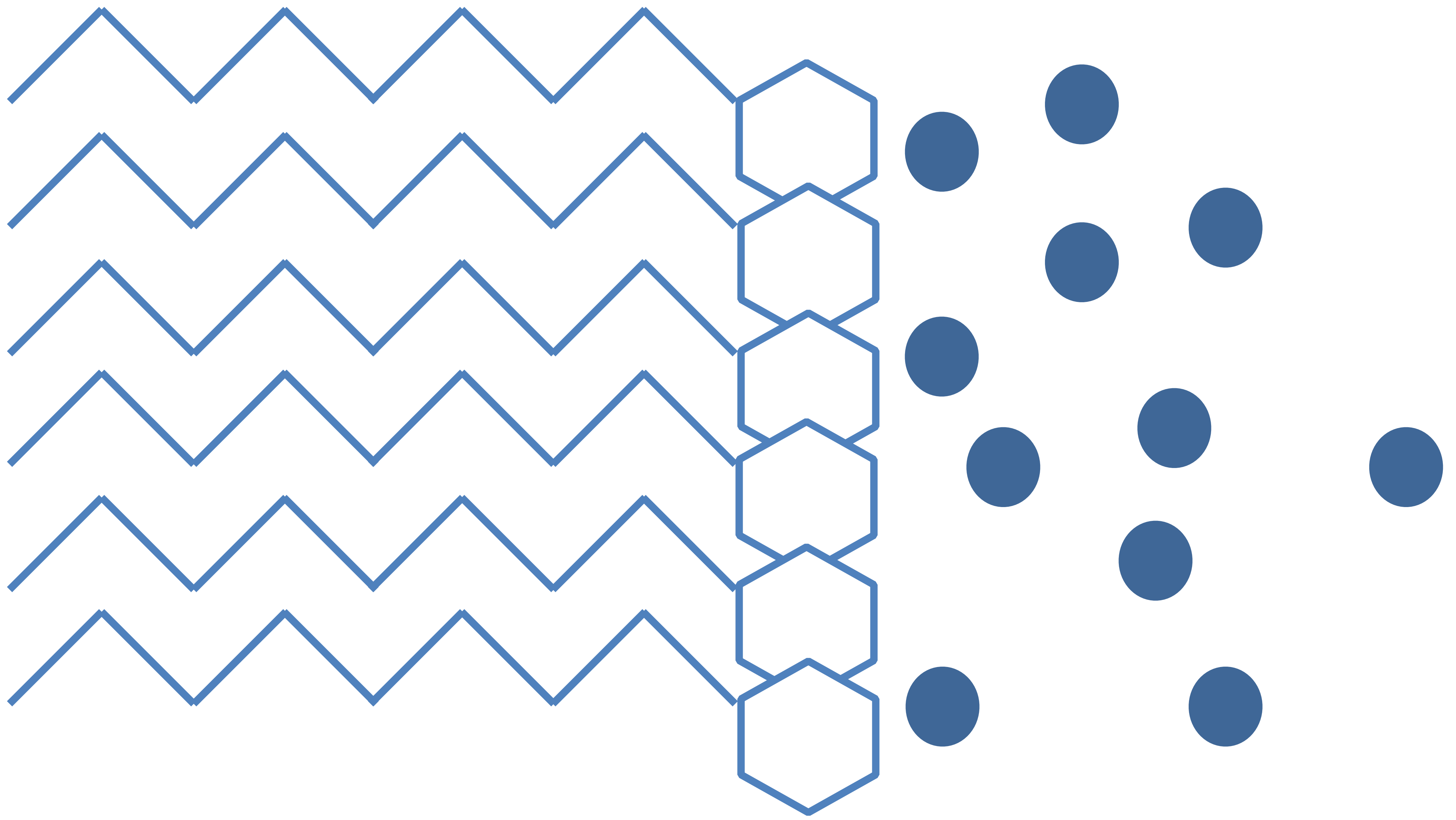
MT: T_2

Lipid and Exchange



MT: T_2

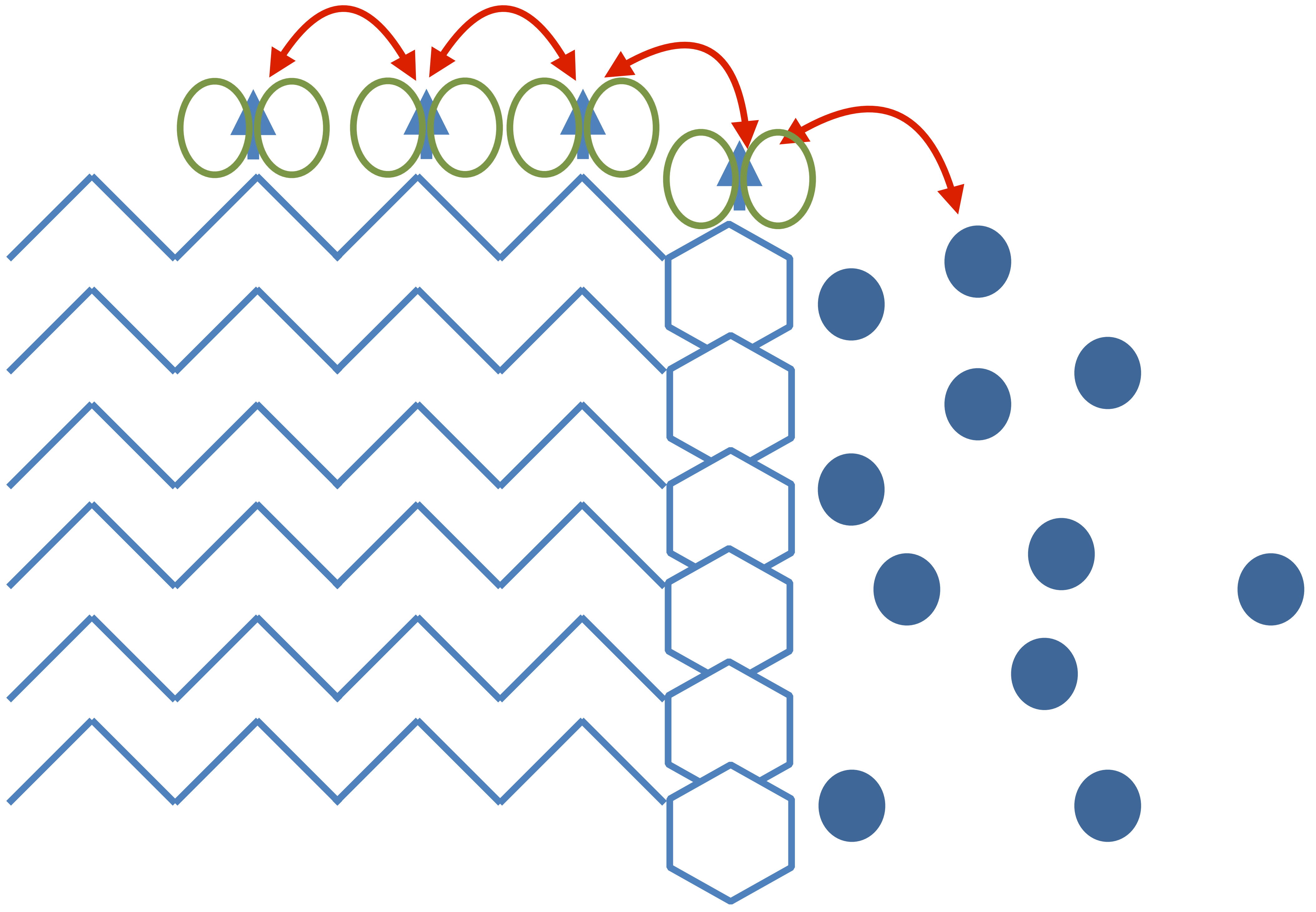
Lipid and Exchange



Lipid Membrane Water

MT

Lipid and Exchange

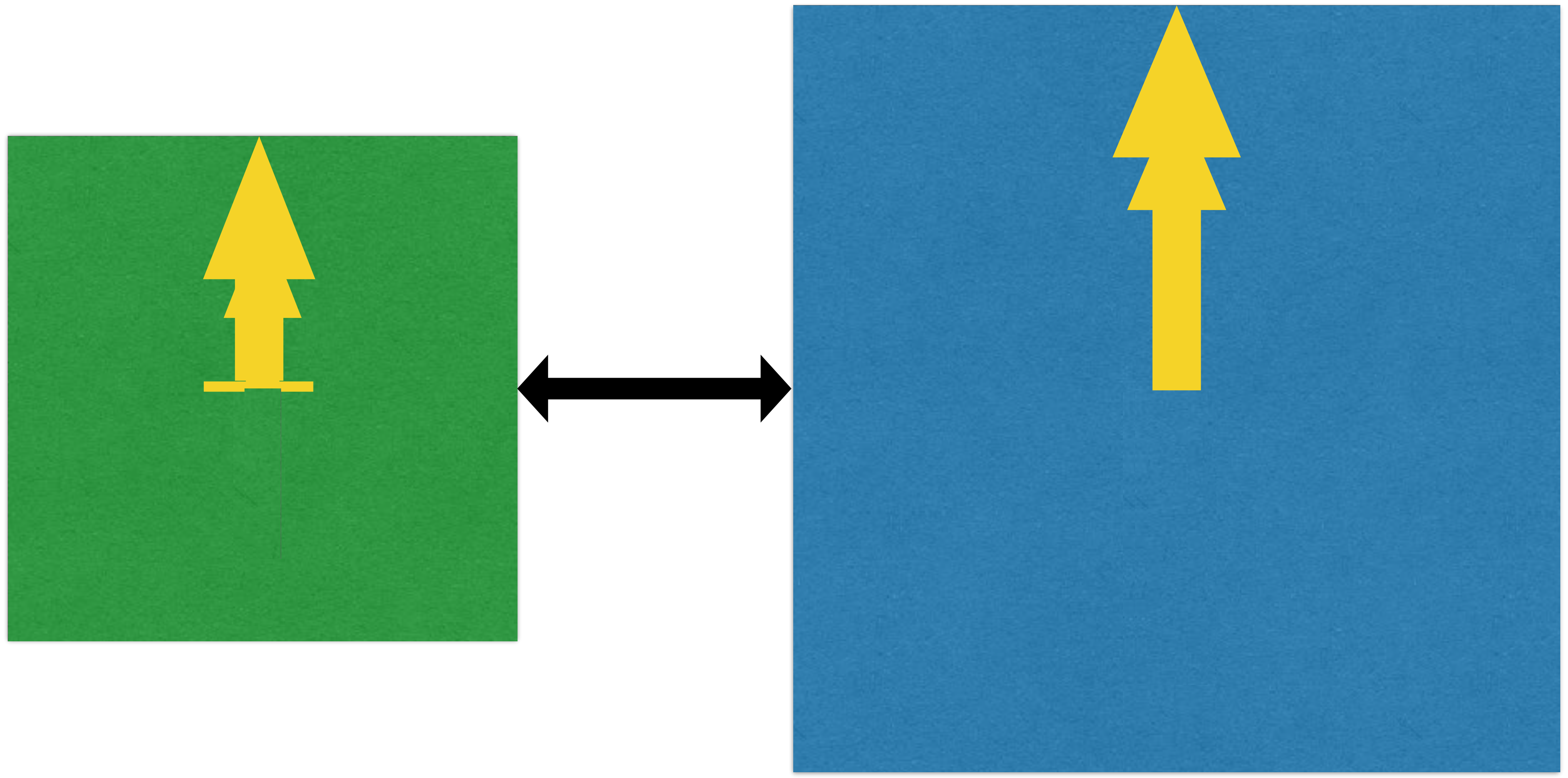


Lipid Membrane Water

Exchange:
- Magnetic
- Chemical

MT

Lipid and Exchange

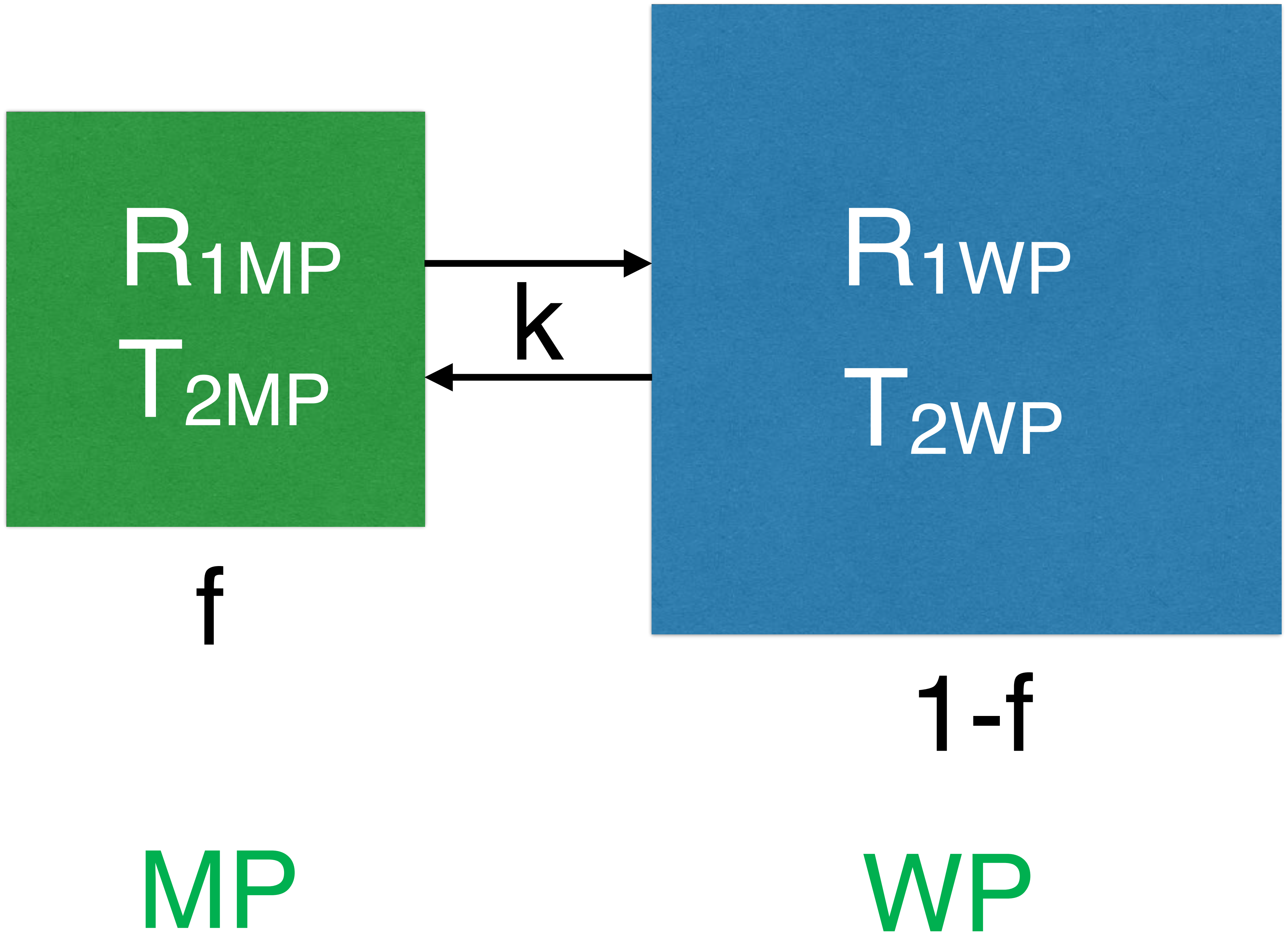


Macro Molecular Protons

Water Protons

MT

Parameters



R_{1MP}

T_{2MP}

k

R_{1WP}

T_{2WP}

f

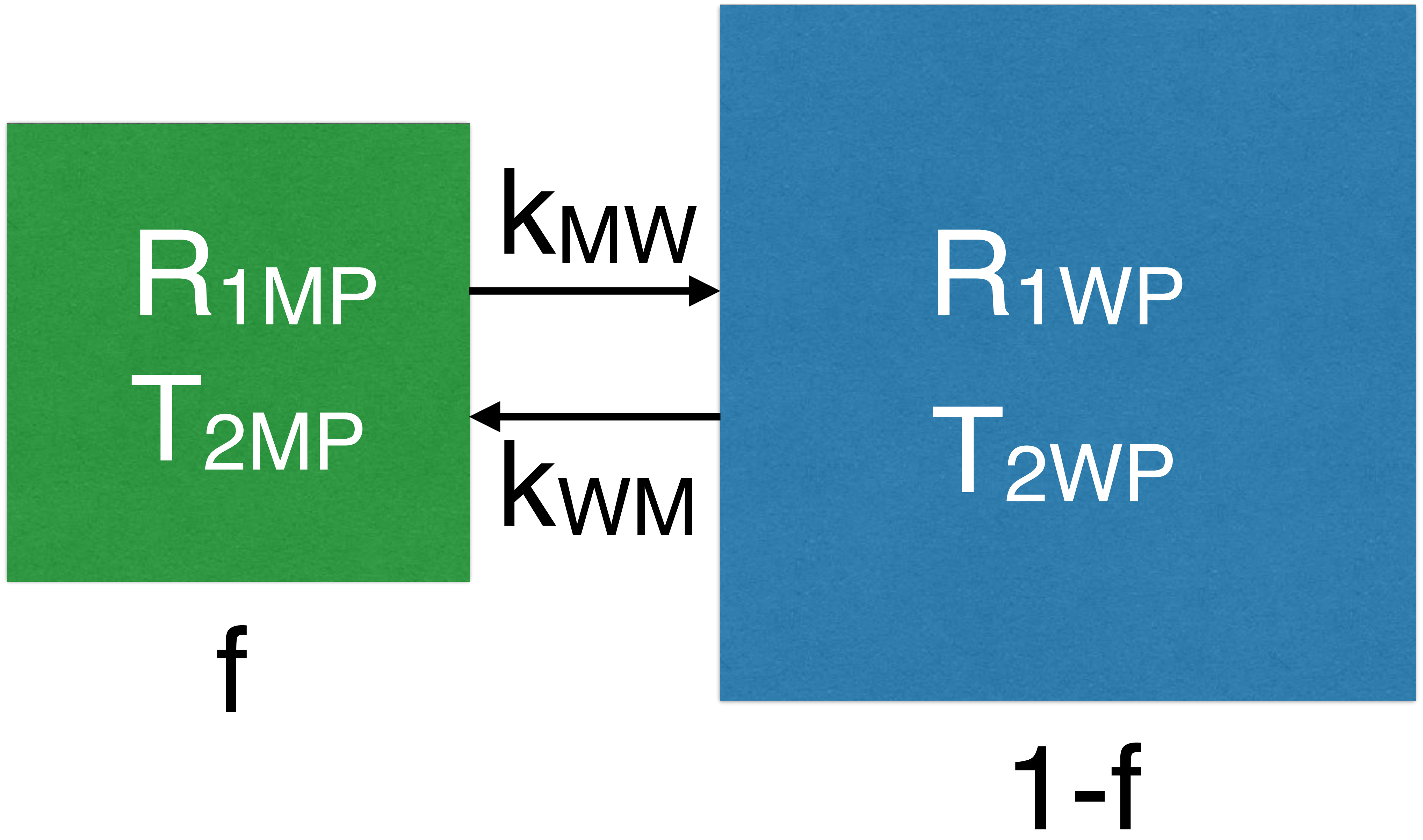
1-f

MP

WP

MT

Parameters



R_{1MP}

T_{2MP}

k_{MW}

k_{WM}

R_{1WP}

T_{2WP}

f

$1\text{-}f$

MP

WP

MT

Equations

Magnetization measured relative to some baseline:
normalization changes the equations and definition of variables

Normalization can be for total magnetization, the sum of the water pools (for more complex models), or per pool individually.

MT

Equations

Starting point: Bloch equation for M_z for one pool:

$d\,M_{wp} / dt = -R_{1wp}\,(M_{wp} - M_{wp,0})$

Normalize to $M_{wp,0}$:

$d\,M_{wp} / dt = -R_{1wp}\,(M_{wp} - 1)$

MT

Equations

Add second pool (each pool normalized to one):

$d\,M_{wp} / dt = -R_{1wp}\,(M_{wp} - 1)$
$d\,M_{mp} / dt = -R_{1mp}\,(M_{mp} - 1)$

multiply by relative sizes:

$(1-f)d\,M_{wp} / dt = -(1-f)R_{1wp}\,(M_{wp} - 1)$
$f\,d\,M_{mp} / dt = -f\,R_{1mp}\,(M_{mp} - 1)$

MT

Equations

Add exchange:

$$(1-f)\,d M_{wp} / dt = -(1-f) R_{1wp} (M_{wp} - 1) - k M_{wp} + k M_{mp}$$
$$f\, d M_{mp} / dt = -f R_{1mp} (M_{mp} - 1) - k M_{mp} + k M_{wp}$$

k= fraction of spin exchanging compared to total

MT

Equations

Alternative form (1), divide by size:

$$d\,M_{wp} / dt = -R_{1wp}\,(M_{wp} - 1) - k/(1\text{-}f)\,M_{wp} + k/(1\text{-}f)\,M_{mp}$$
$$d\,M_{mp} / dt = -R_{1mp}\,(M_{mp} - 1) - k/f\,M_{mp} \qquad + k/f\,M_{wp}$$

with k_{mp}=k/f and k_{wp}= k/(1-f):

$$d\,M_{wp} / dt = -R_{1wp}\,(M_{wp} - 1) - k_{wp}\,M_{wp} + k_{wp}\,M_{mp}$$
$$d\,M_{mp} / dt = -R_{1mp}\,(M_{mp} - 1) - k_{mp}\,M_{mp} + k_{mp}\,M_{wp}$$

MT

Equations

Alternative form (2), normalized to sum of pools, substituting $M'_{wp} = (1-f)M_{wp}$, and $M'_{mp} = f\,M_{mp}$

$$d\,M'_{wp} / dt = -R_{1wp}\,(M'_{wp} - 1) - k/(1-f)\,M'_{wp} + k/f\,M'_{mp}$$
$$d\,M'_{mp} / dt = -R_{1mp}\,(M'_{mp} - 1) - k/f\,M'_{mp} + k/(1-f)\,M'_{wp}$$

with $k_{mp}=k/f$ and $k_{wp}= k/(1-f)$:

$$d\,M'_{wp} / dt = -R_{1wp}\,(M'_{wp} - 1) - k_{wp}\,M'_{wp} + k_{mp}\,M'_{mp}$$
$$d\,M'_{mp} / dt = -R_{1mp}\,(M'_{mp} - 1) - k_{mp}\,M'_{mp} + k_{wp}\,M'_{wp}$$

MT

Equations Summary

$$(1-f)d\,M_{wp}/dt = -(1-f)R_{1wp}\,(M_{wp}-1) - k\,M_{wp} \quad + k\,M_{mp}$$
$$f\,d\,M_{mp}/dt = \quad -f\,R_{1mp}\,(M_{mp}-1) - k\,M_{mp} \quad + k\,M_{wp}$$

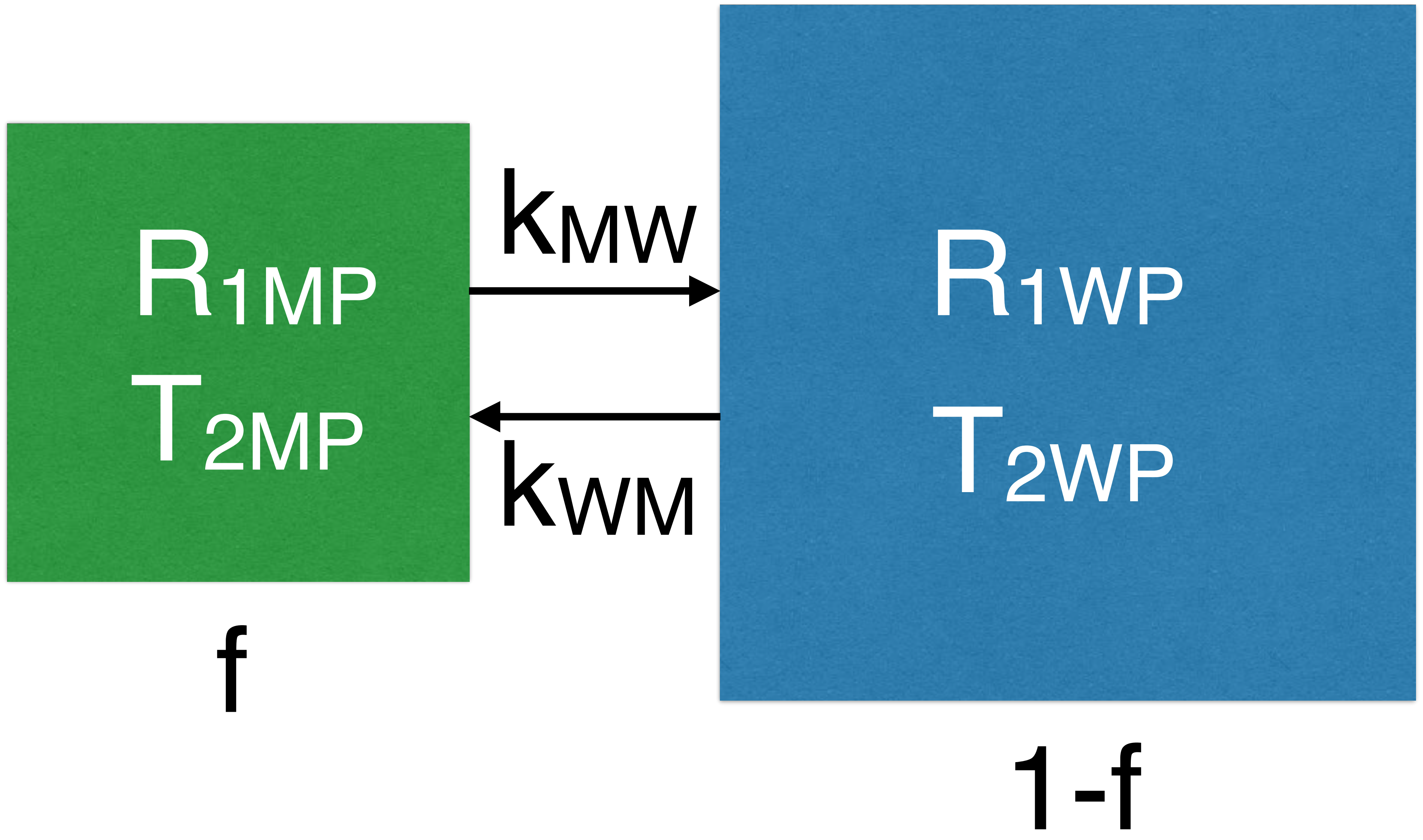
$$d\,M_{wp}/dt = \quad -R_{1wp}\,(M_{wp}-1) - k_{wp}\,M_{wp} + k_{wp}\,M_{mp}$$
$$d\,M_{mp}/dt = \quad -R_{1mp}\,(M_{mp}-1) - k_{mp}\,M_{mp} + k_{mp}\,M_{wp}$$

$$d\,M'_{wp}/dt = \quad -R_{1wp}\,(M'_{wp}-1) - k_{wp}\,M'_{wp} + k_{mp}\,M'_{mp}$$
$$d\,M'_{mp}/dt = \quad -R_{1mp}\,(M'_{mp}-1) - k_{mp}\,M'_{mp} + k_{wp}\,M'_{wp}$$

$k_{mp}=k/f$, $k_{wp}= k/(1-f)$, $(1-f)k_{wp}= f\,k_{mp}$

MT

Parameters



R_{1MP}

T_{2MP}

k_{MW}

k_{WM}

R_{1WP}

T_{2WP}

f

$1-f$

$k_{mp}=k/f$, $k_{wp}= k/(1-f)$, $(1-f)k_{wp}= f\ k_{mp}$

MT

Equations

Saturation: $S = 1 - M_z$

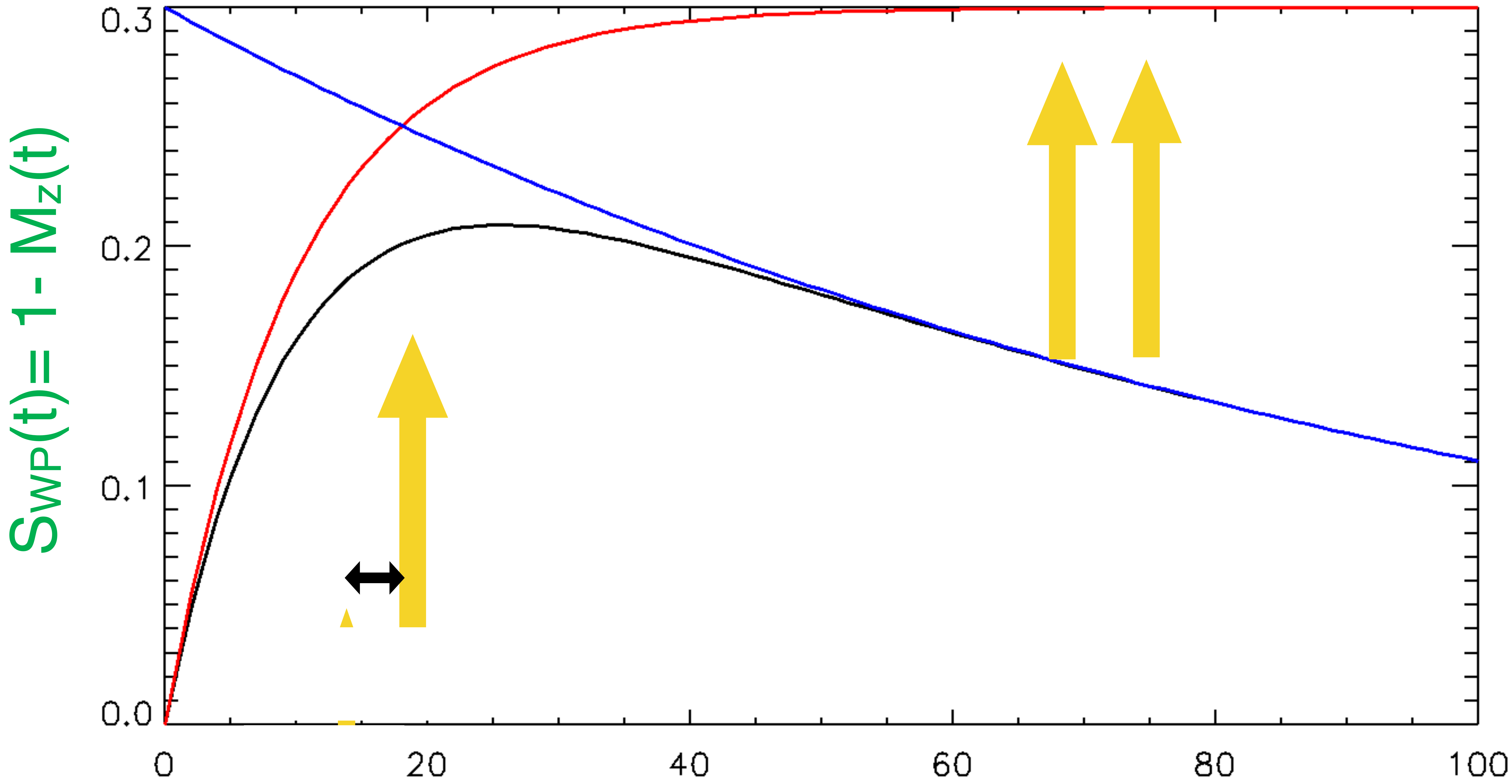
$$d\,S_{WP} / dt = -R_{1wp}\,S_{WP} - k_{WM}\,S_{WP} + k_{WM}\,S_{MP}$$
$$d\,S_{MP} / dt = -R_{1mp}\,S_{MP} - k_{MW}\,S_{MP} + k_{MW}\,S_{WP}$$

$d\,\mathbf{S} / dt = R_x\,\mathbf{S}$; R_x= matrix, solution:

$S_{WP}(t) = a_1 e^{-\lambda_1 t} + a_2 e^{-\lambda_2 t}$; $\lambda_{1,2}$ eigenvalues of R_x

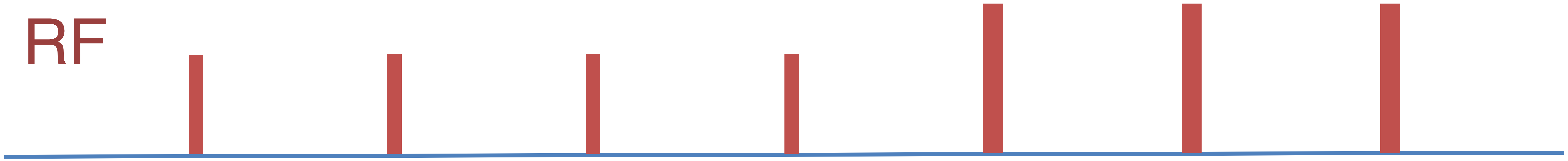
MT

Saturation $S_{WP}(t) = a_1e^{-\lambda_1 t} + a_2e^{-\lambda_2 t}$



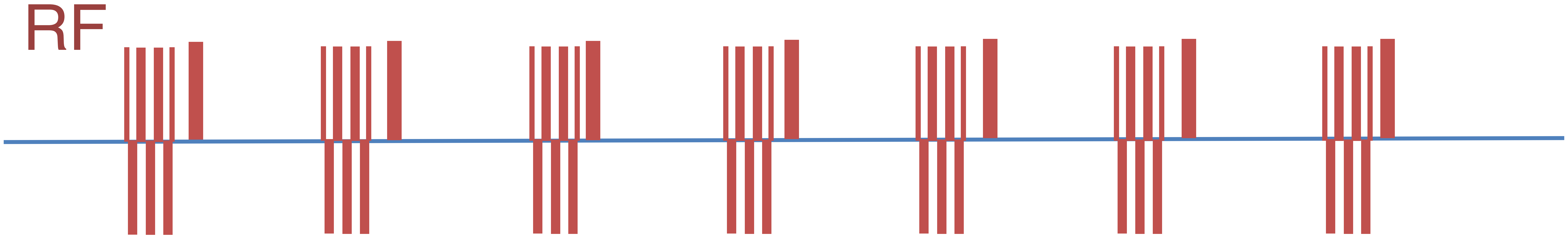
T_1 Measurement

Saturation



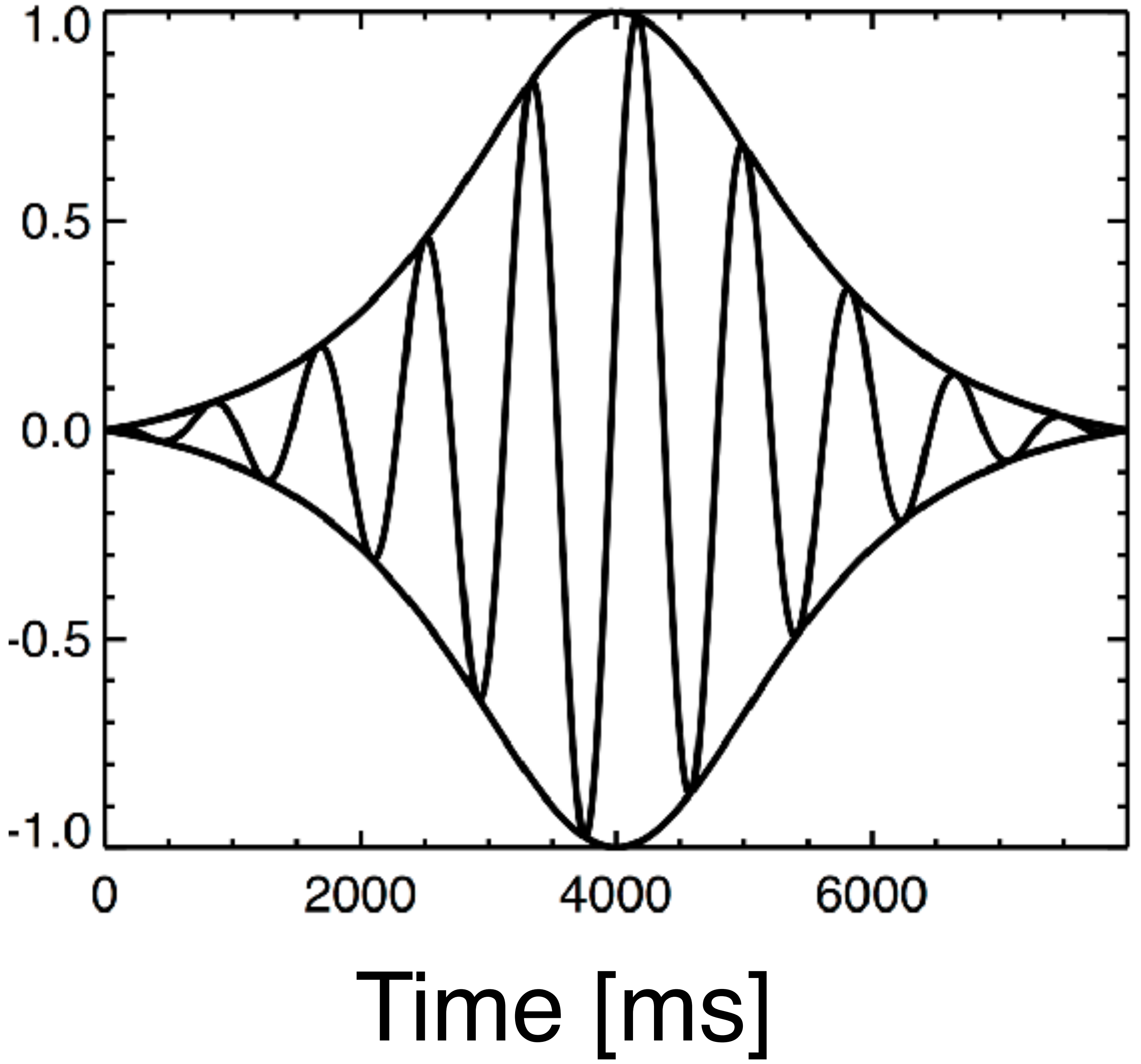
MT Measurement

MT Saturation Equilibrium

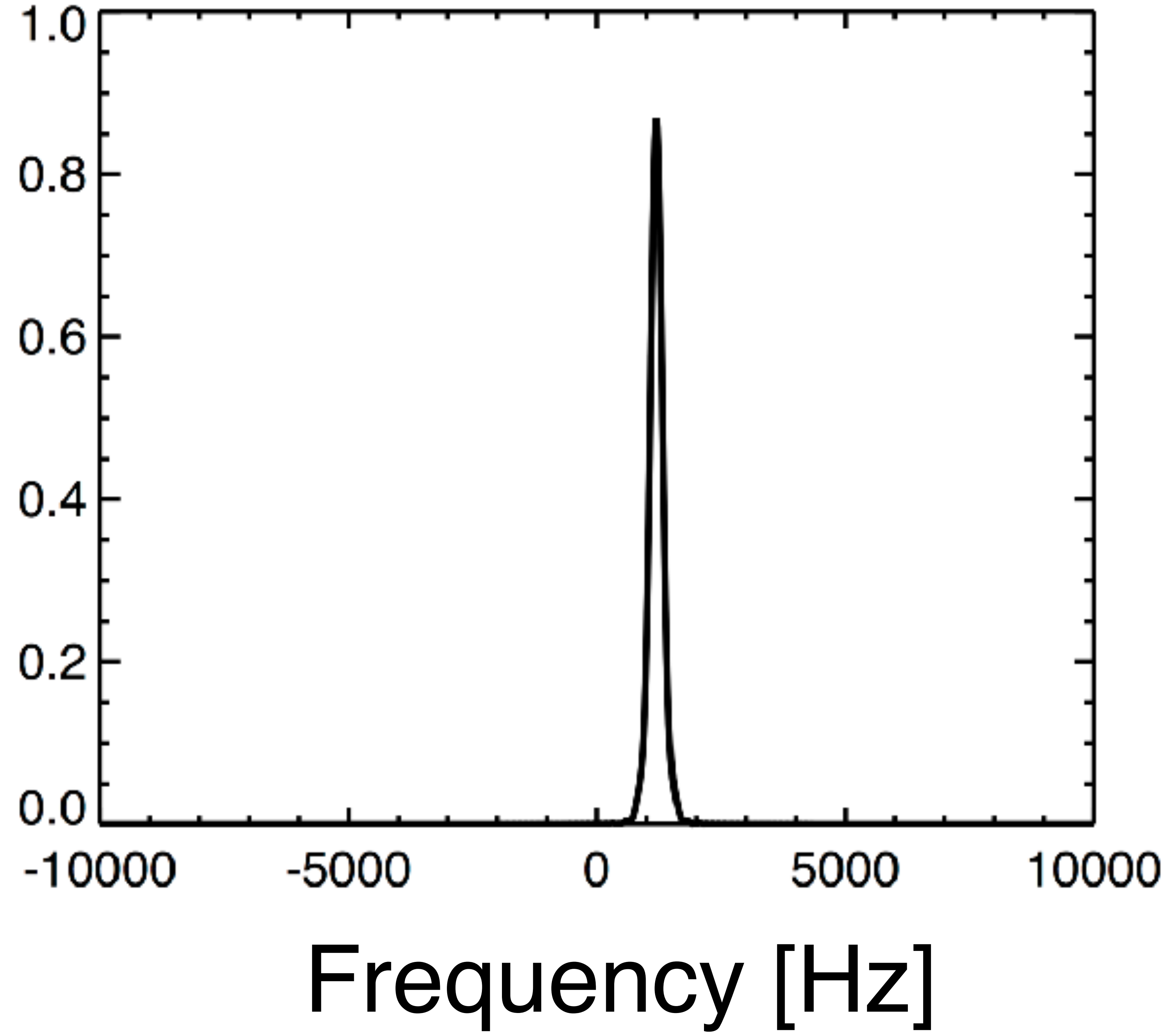


MT Saturation in balance with T_1

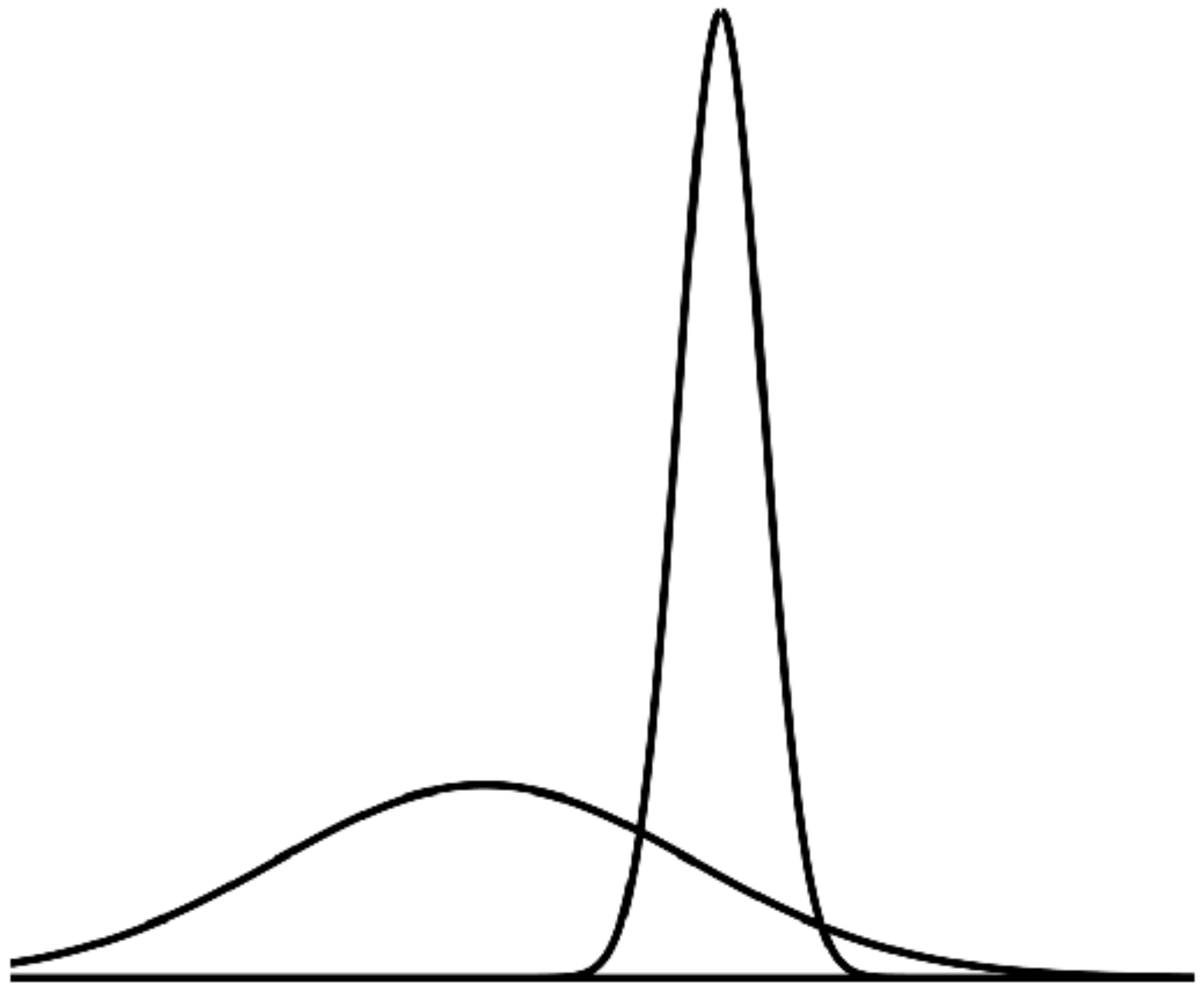
Saturation by off-resonance RF

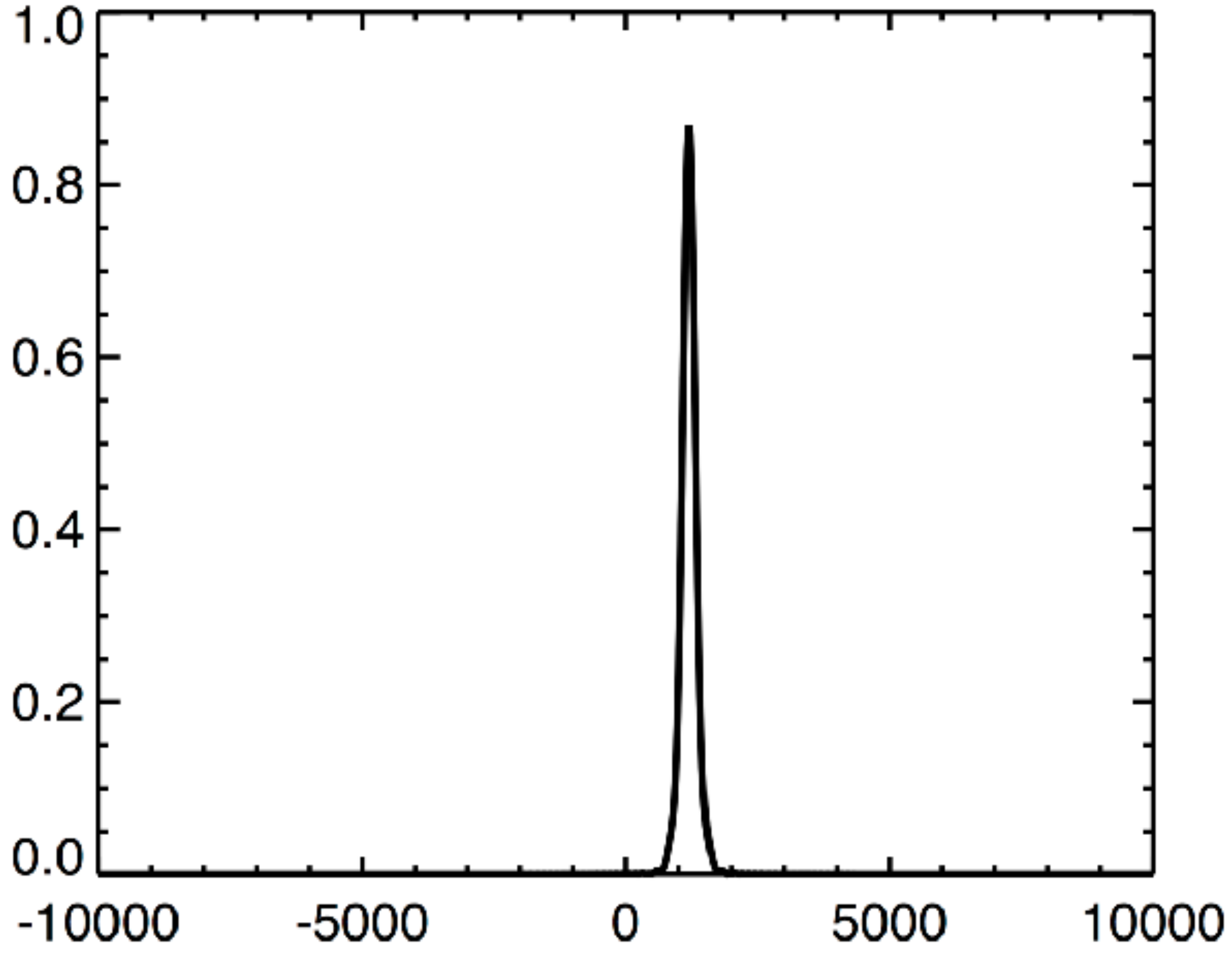


FT



Saturation by off-resonance RF

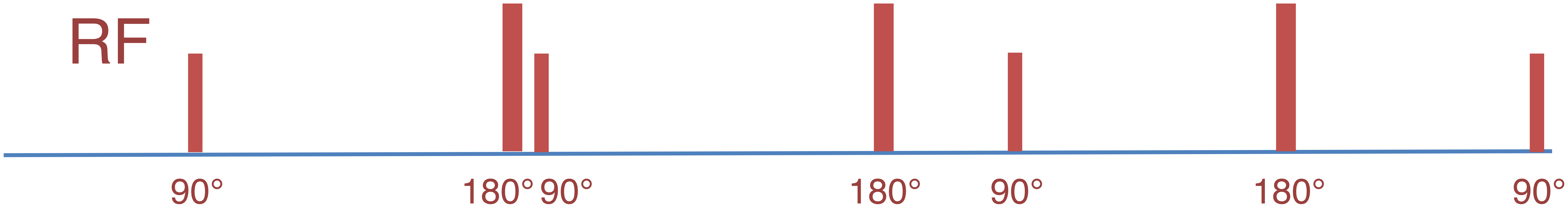




Frequency [Hz]

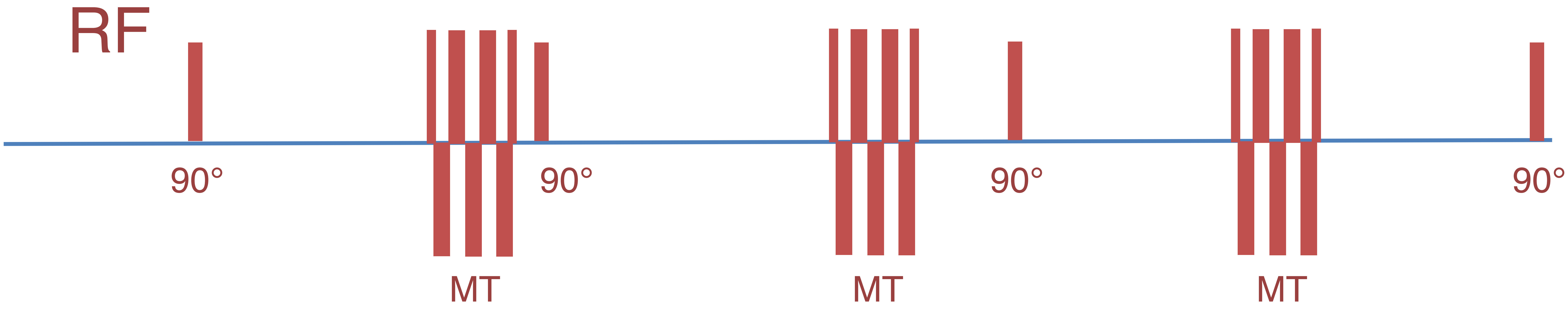
T_1 Measurement

Inversion Recovery



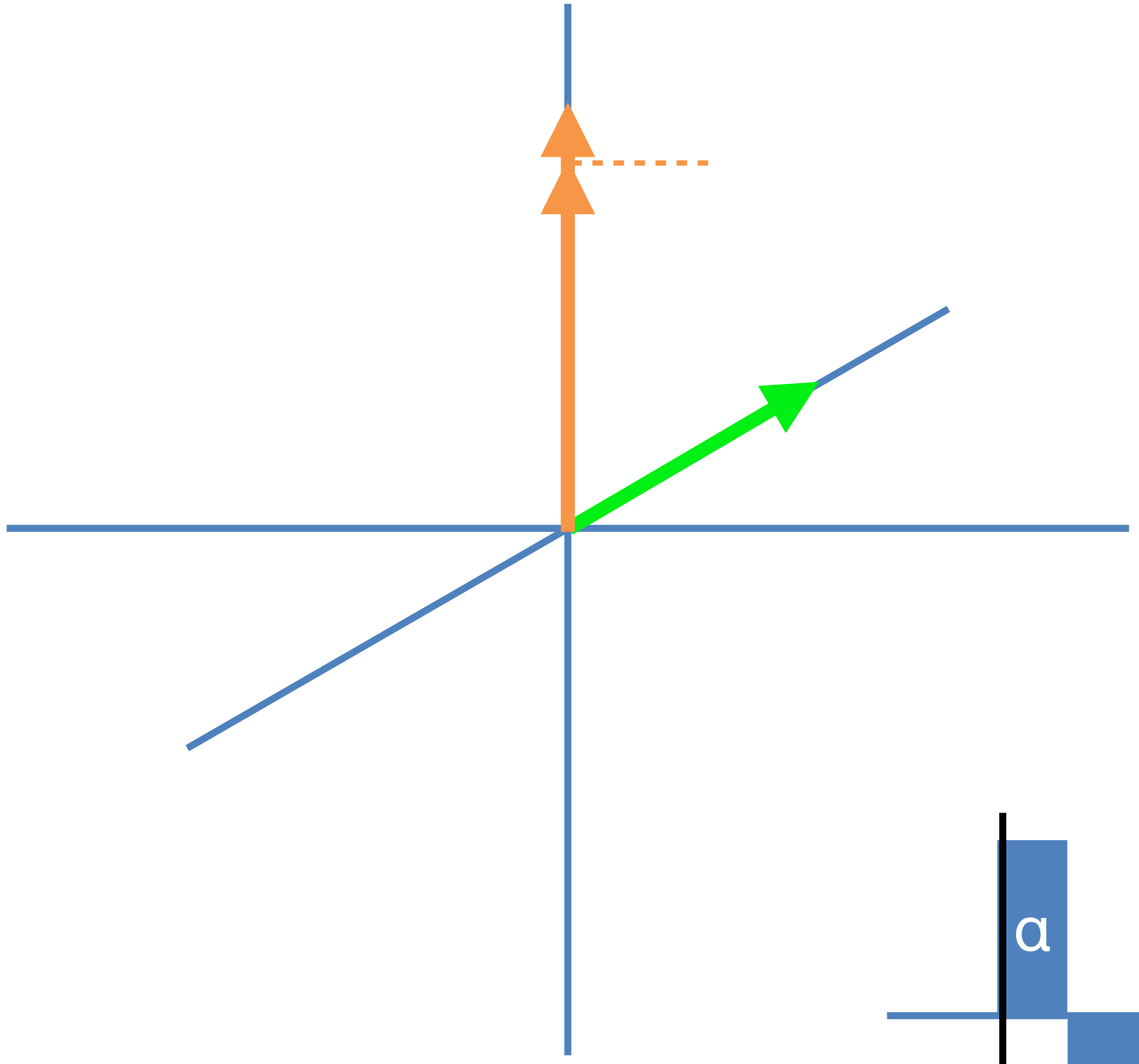
MT Measurement

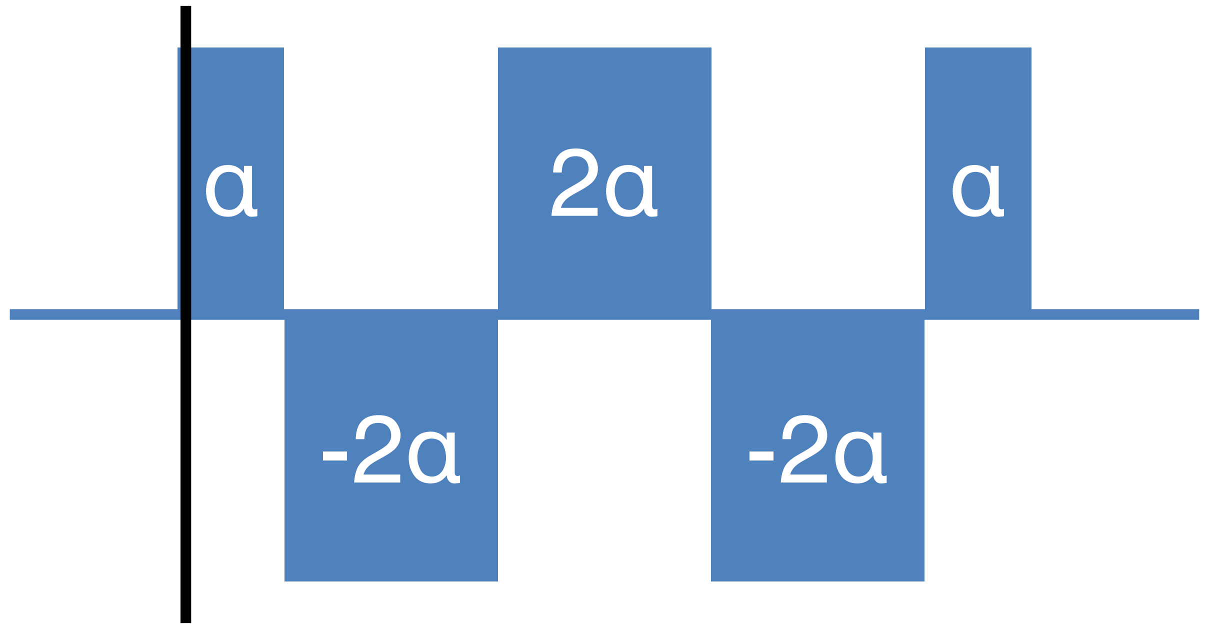
MT Saturation Recovery



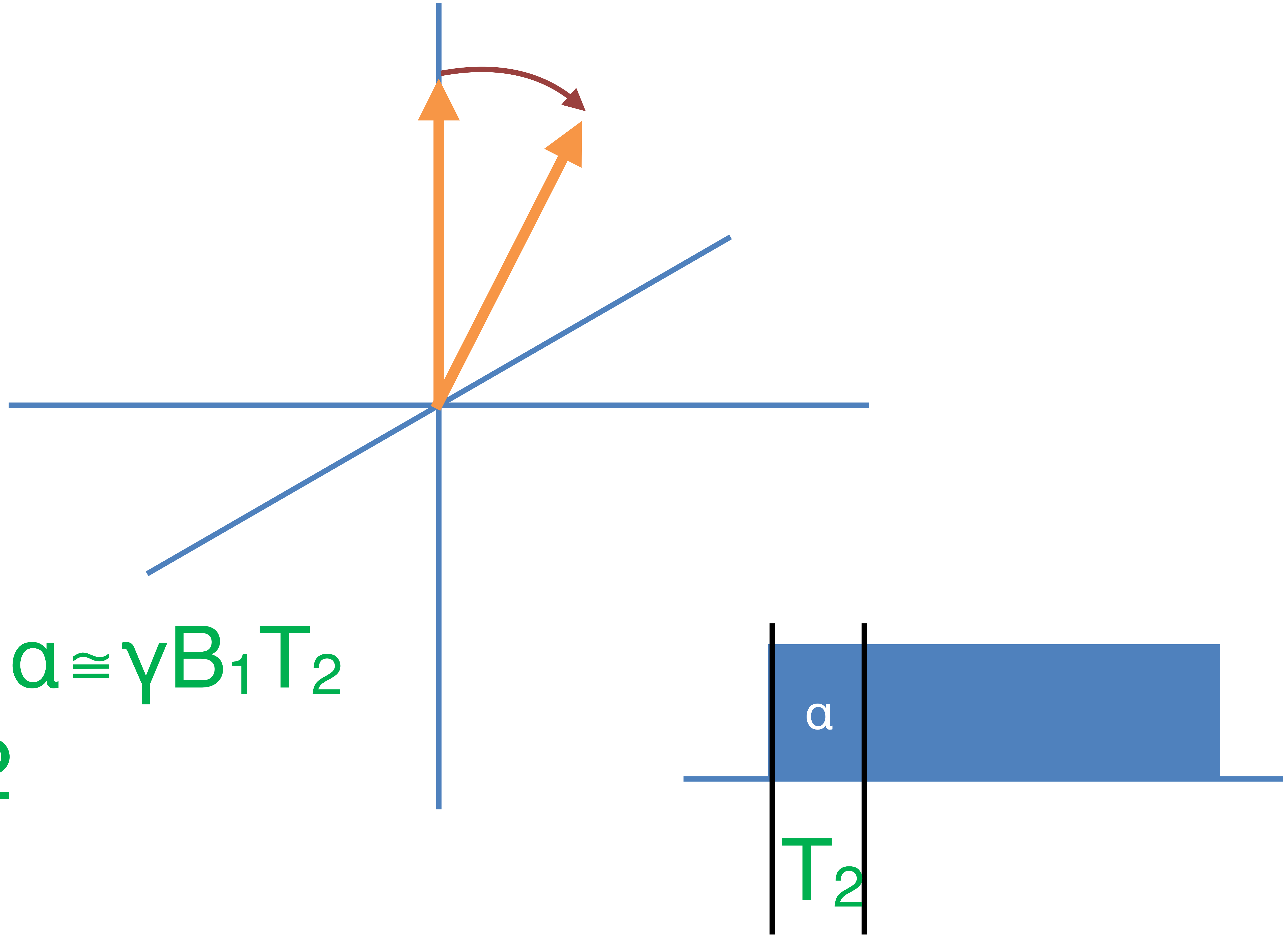
Pulse Design

Short T_2





Pulse Design

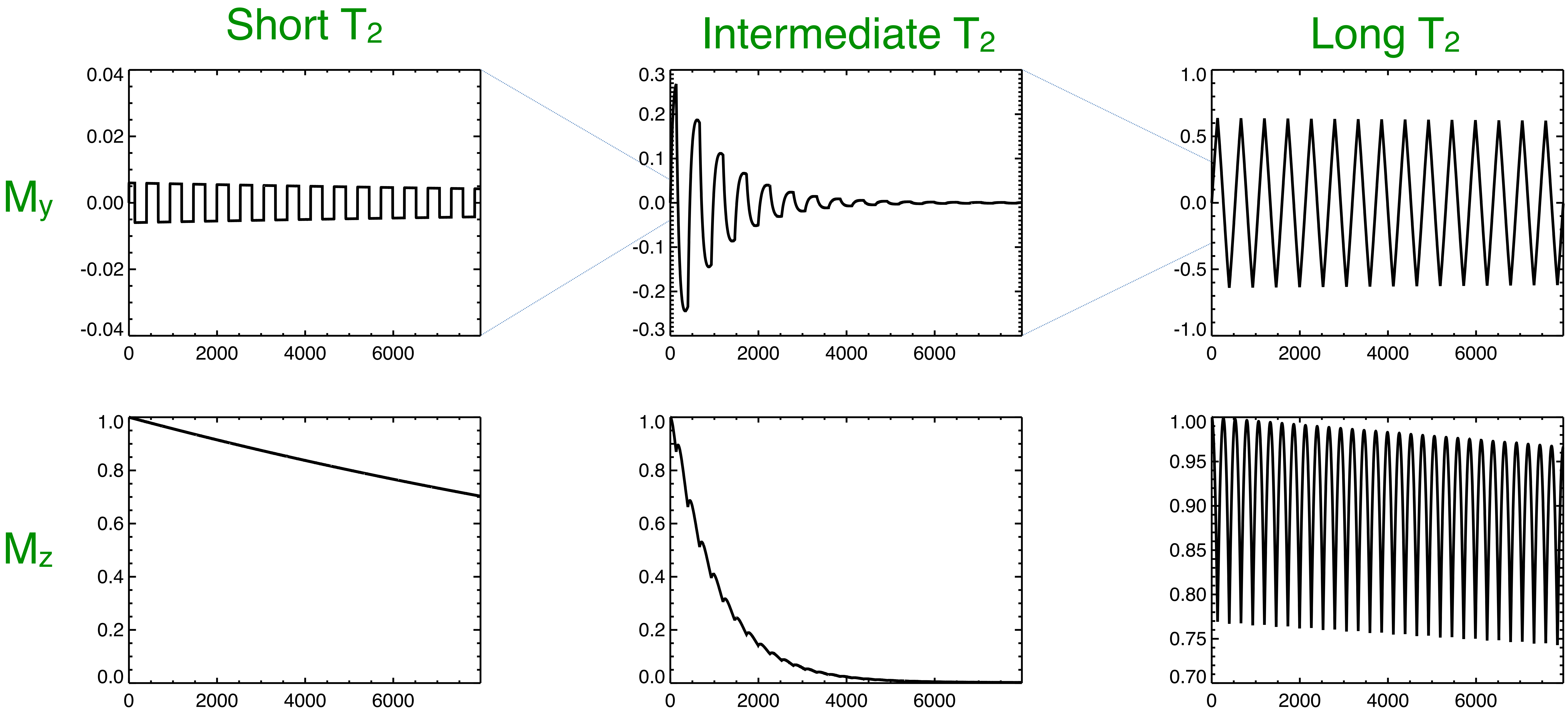


Effective flip angle $\alpha \cong \gamma B_1 T_2$

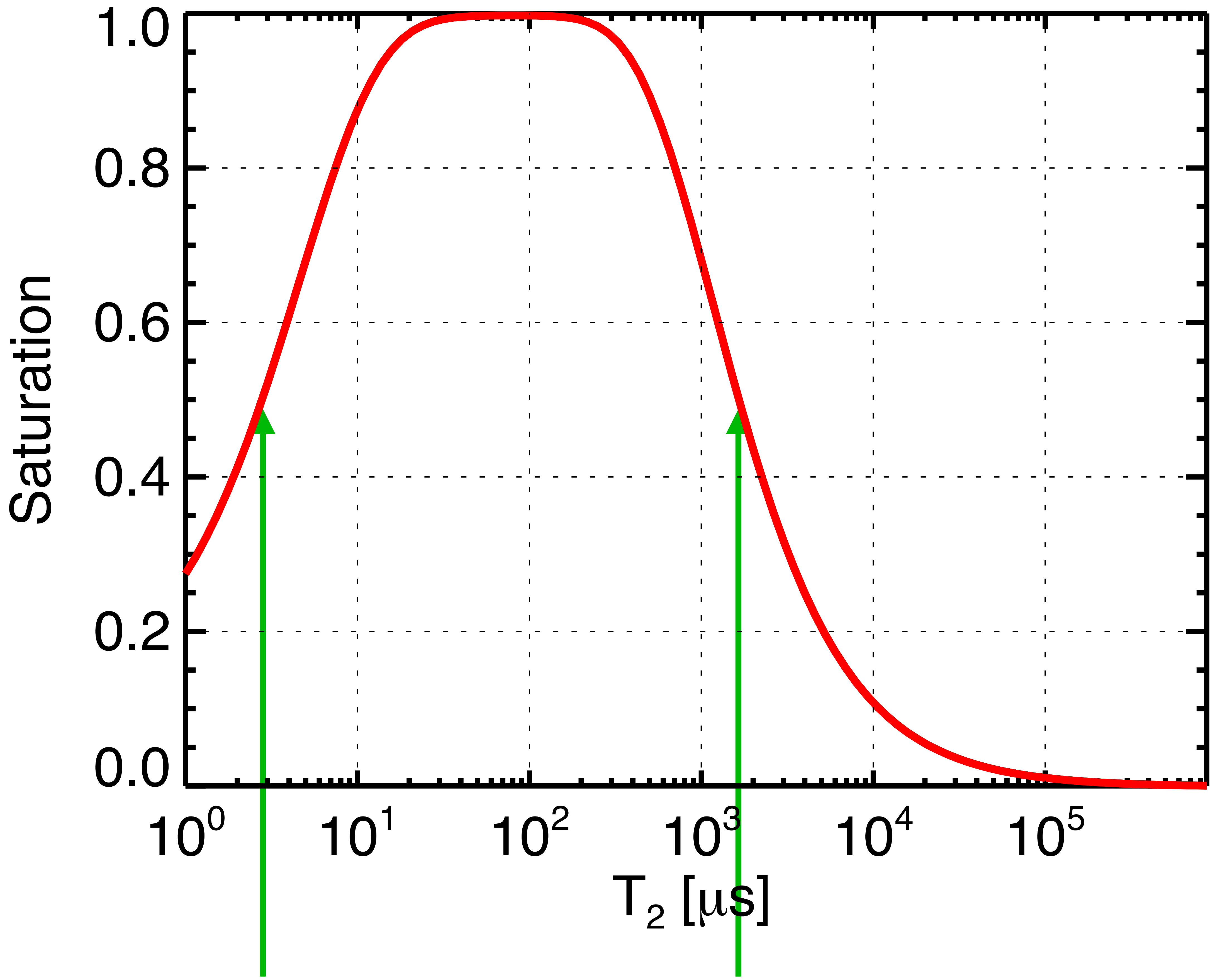
$M_z = \cos(\alpha) = 1 - \alpha^2/2$

PW/T_2 times

Pulse Effect

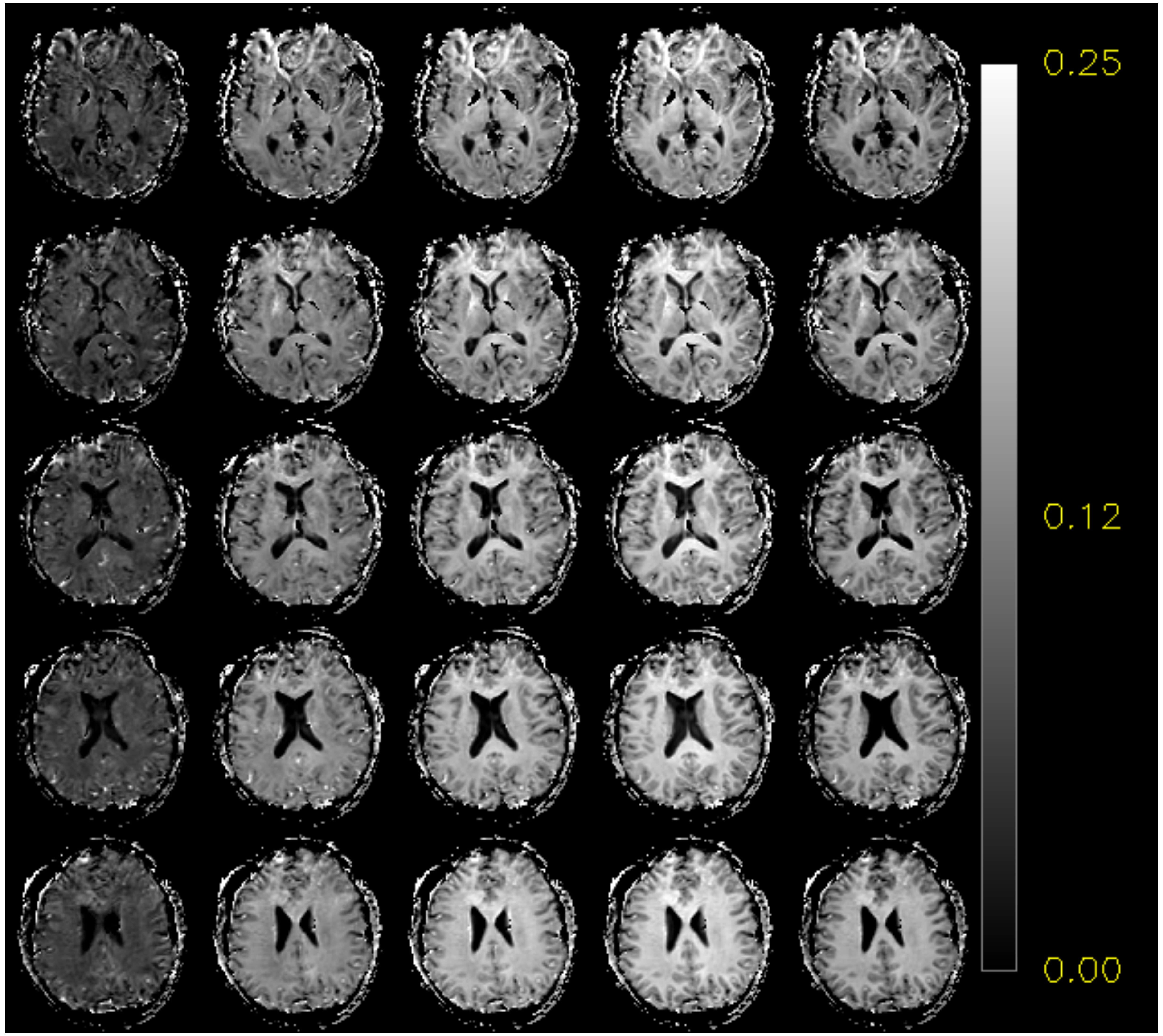


Pulse Design



Approximate Transitions: Short T_2: $(\gamma B_1)^2 PW/2$ Long T_2: $\sin(\alpha)^2 PW/2$

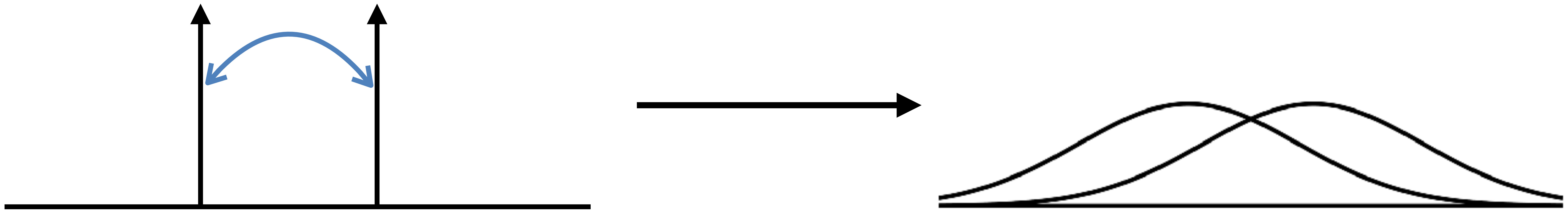
MT Recovery



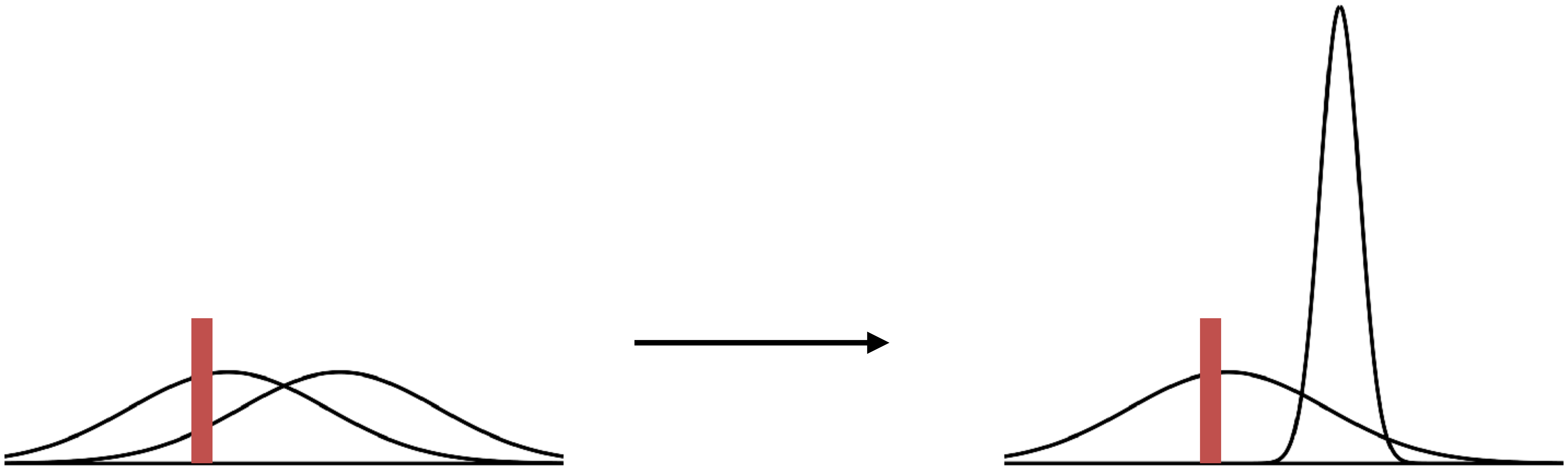
Normalized difference with reference

TI: 7 64 145 256 380 ms

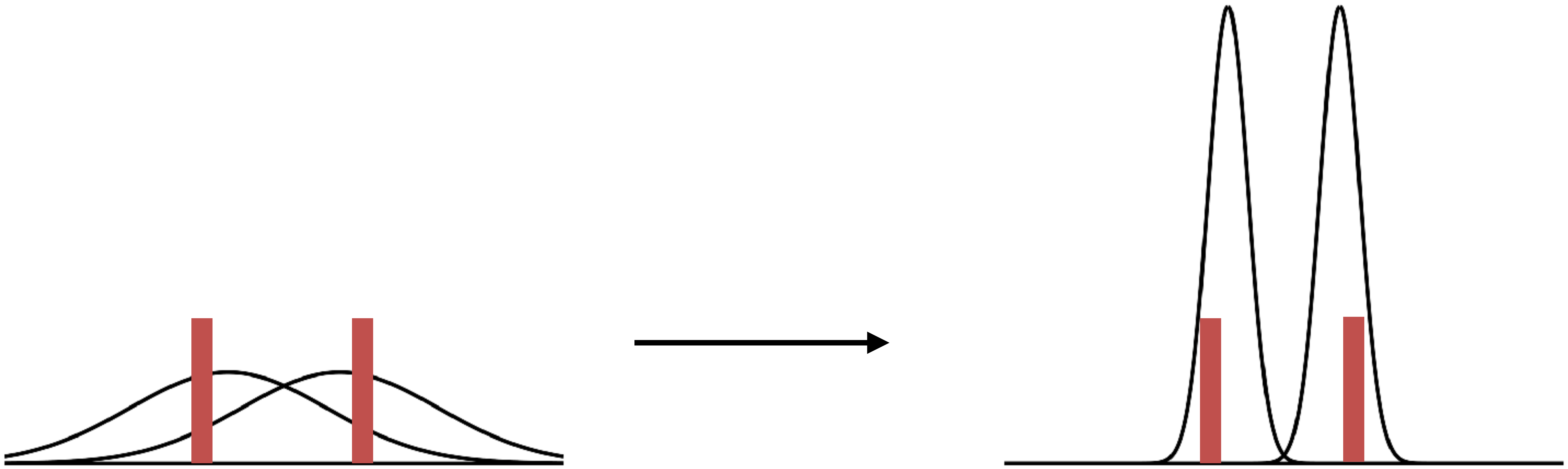
Saturation efficiency



Saturation efficiency



Saturation efficiency

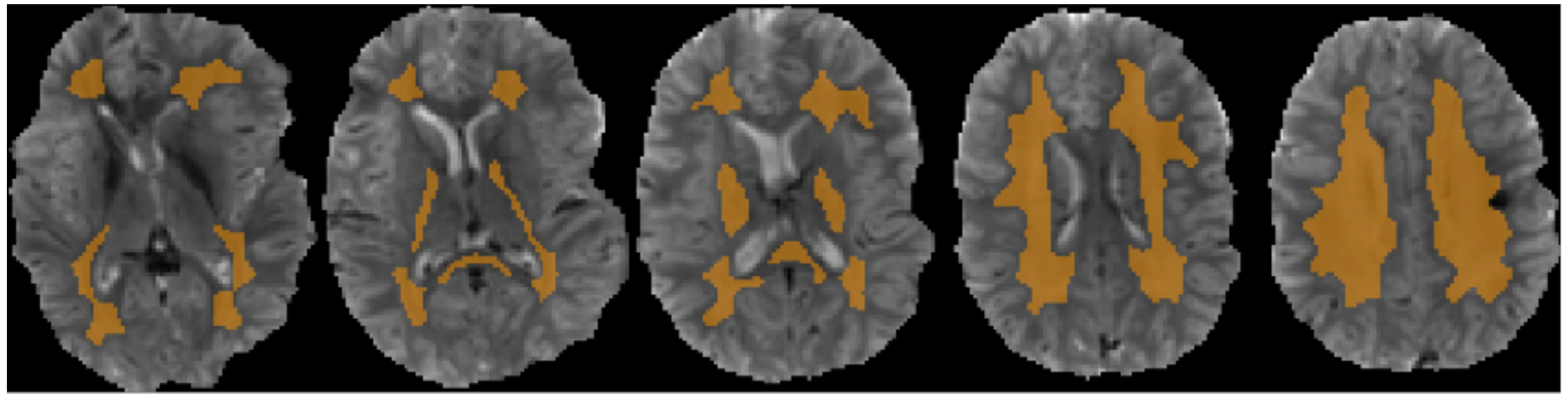


MT and spectral properties MPs in human brain **Roger Jiang**

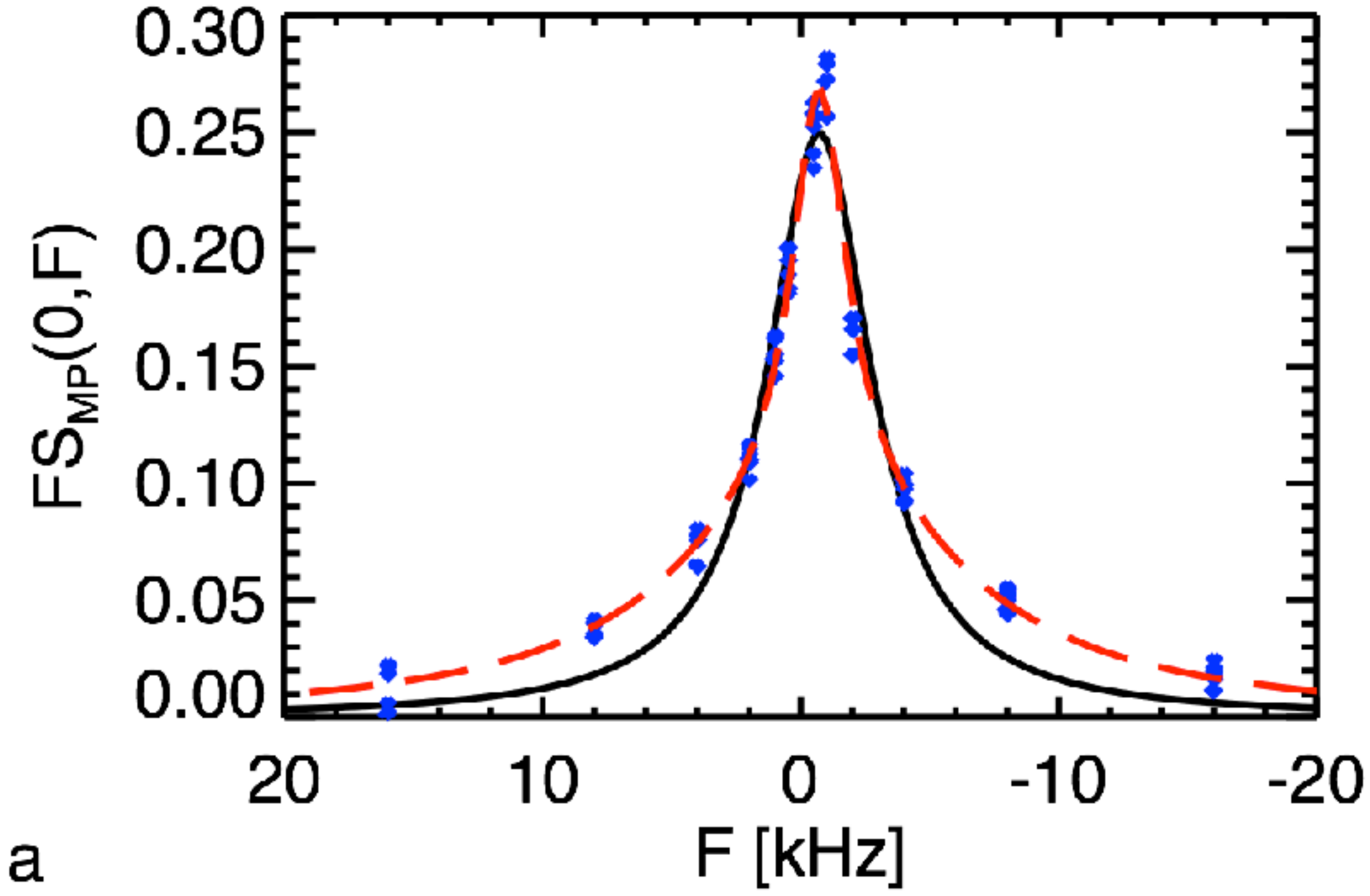
- MP spectral properties (the saturation effects on MPs as a function of frequency offset):
  - Calculate pair of amplitudes (a_1(F), a_2(F)) for every voxel at each *F*, using decay rates (λ_1, λ_2)
  - Calculate $FS_{MP}(0,F) = \frac{a_1(F)(-\lambda_1+k_{WM}+R_{1,WP})}{k_{WM}} + \frac{a_2(F)(-\lambda_2+k_{WM}+R_{1,WP})}{k_{WM}}$

Frequency offset *F* (from left to right: -16, -8, -4, -2, -1, -0.5, 0.5, 1, 2, 4, 8, 16 kHz)

- Average in WM ROI's



MT and spectral properties MPs in human brain Roger Jiang

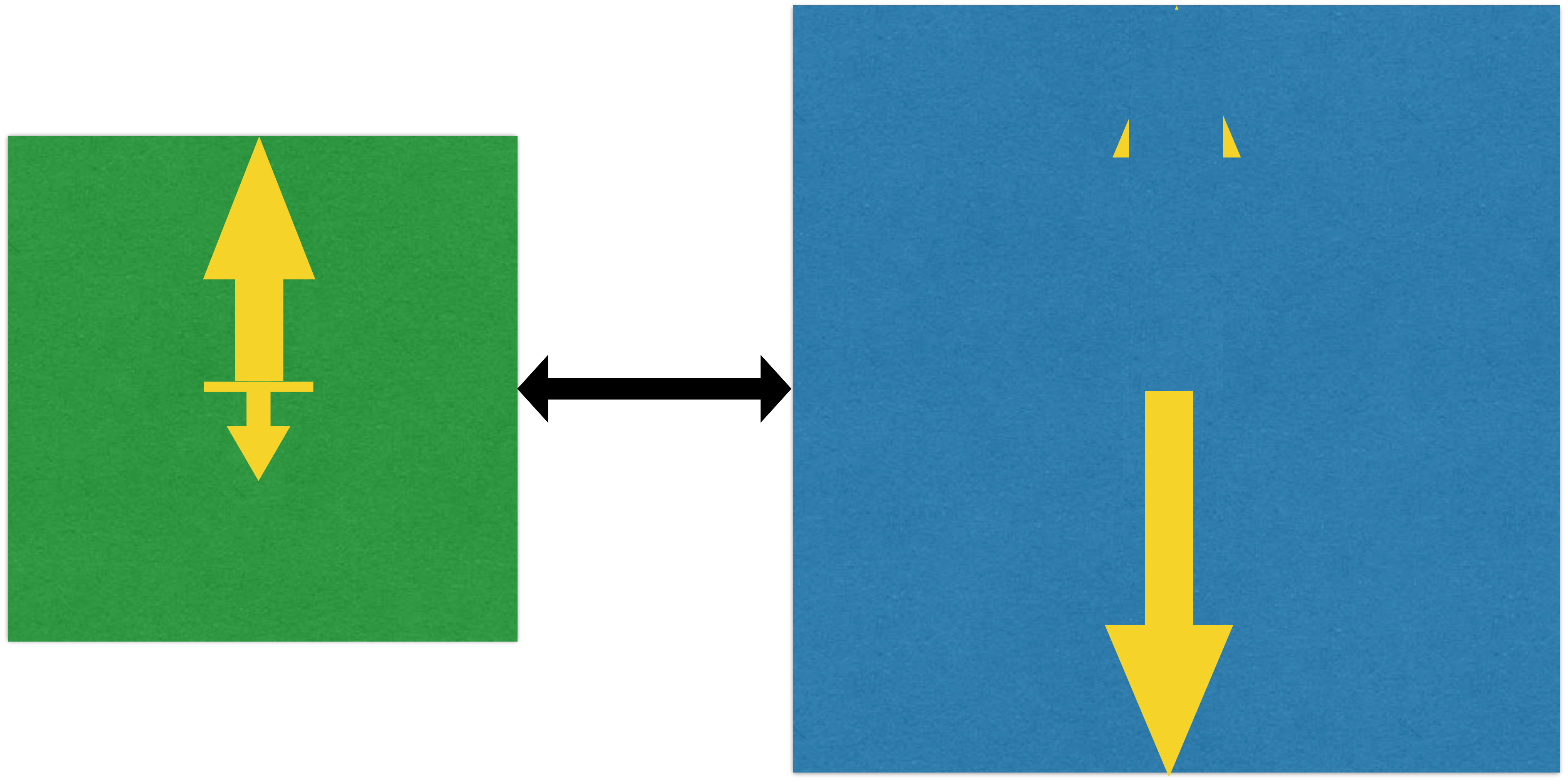


	Single Lorentzian	Sum of 2 Lorentzians
T_2 (μs)	65±2	23±5 124±13
ΔF(Hz)	-727±28	-727
R^2	0.939±0.01	0.989±0.003

- A Lorentzian line (the black solid curve) and sum of two Lorentzian lines (the red dashed curve) fitting to $FS_{MP}(0,F)$.
- *ΔF* of -727 Hz (-2.42ppm), close to -2.34 ppm at 3 T (Hua et al, *MRM* 2007) and -2.55 ppm at 4.7 T (Pekar et al, MRM 1996).
- 2-Lorentzian fitting: a component (73%) with T_2 of 23 μs was found, consistent with the results in the study on fixed marmoset brain.

Inversion & MT

IR and Exchange

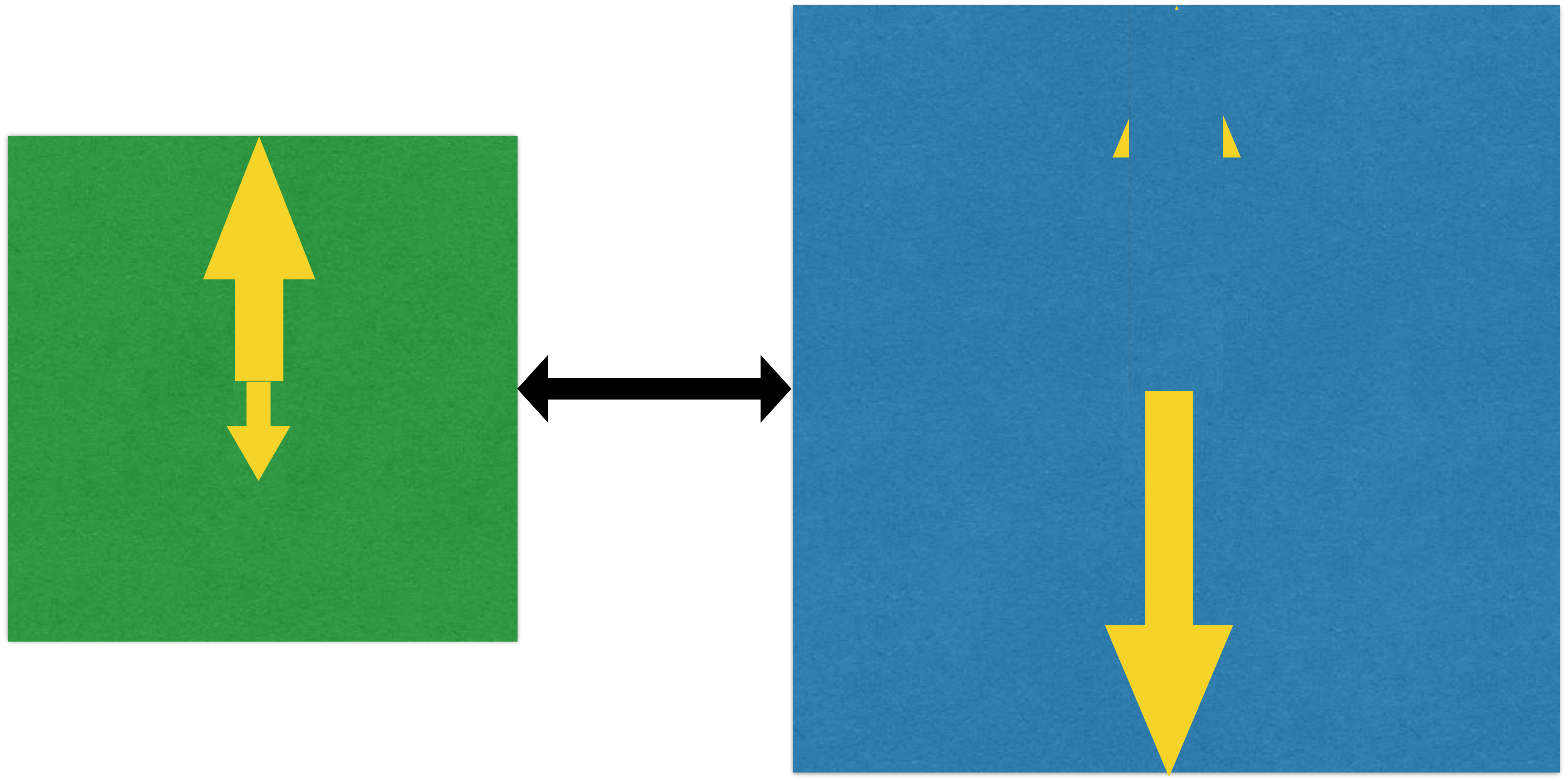


MP

WP

Inversion & MT

IR and Exchange



MP

WP

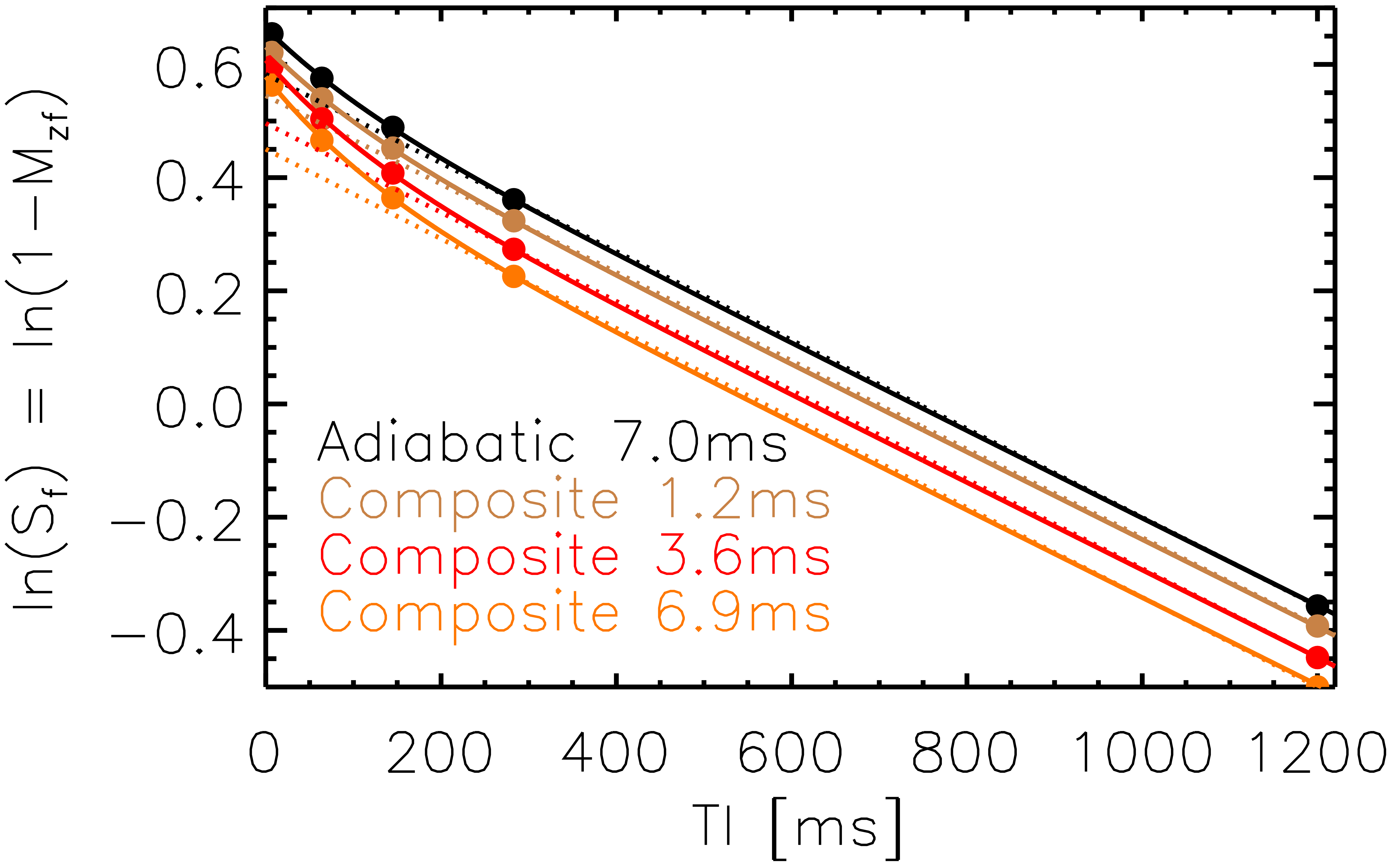
Inversion & MT

IR and Exchange

In an IR experiment initial saturation of MP depends on RF power
Early part of IR dominated by exchange

Inversion & MT

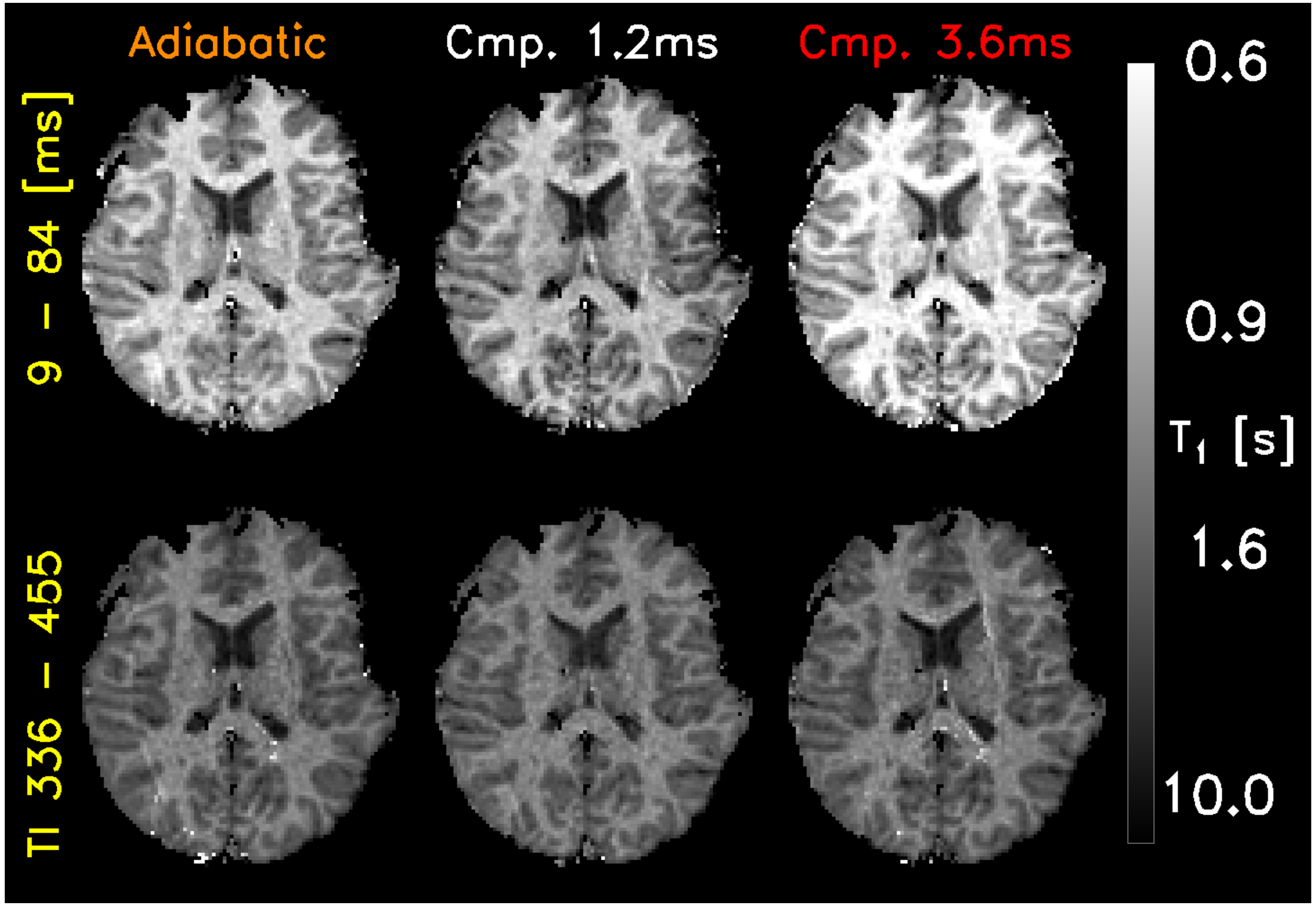
IR double exponential and RF dependent



Inversion & MT

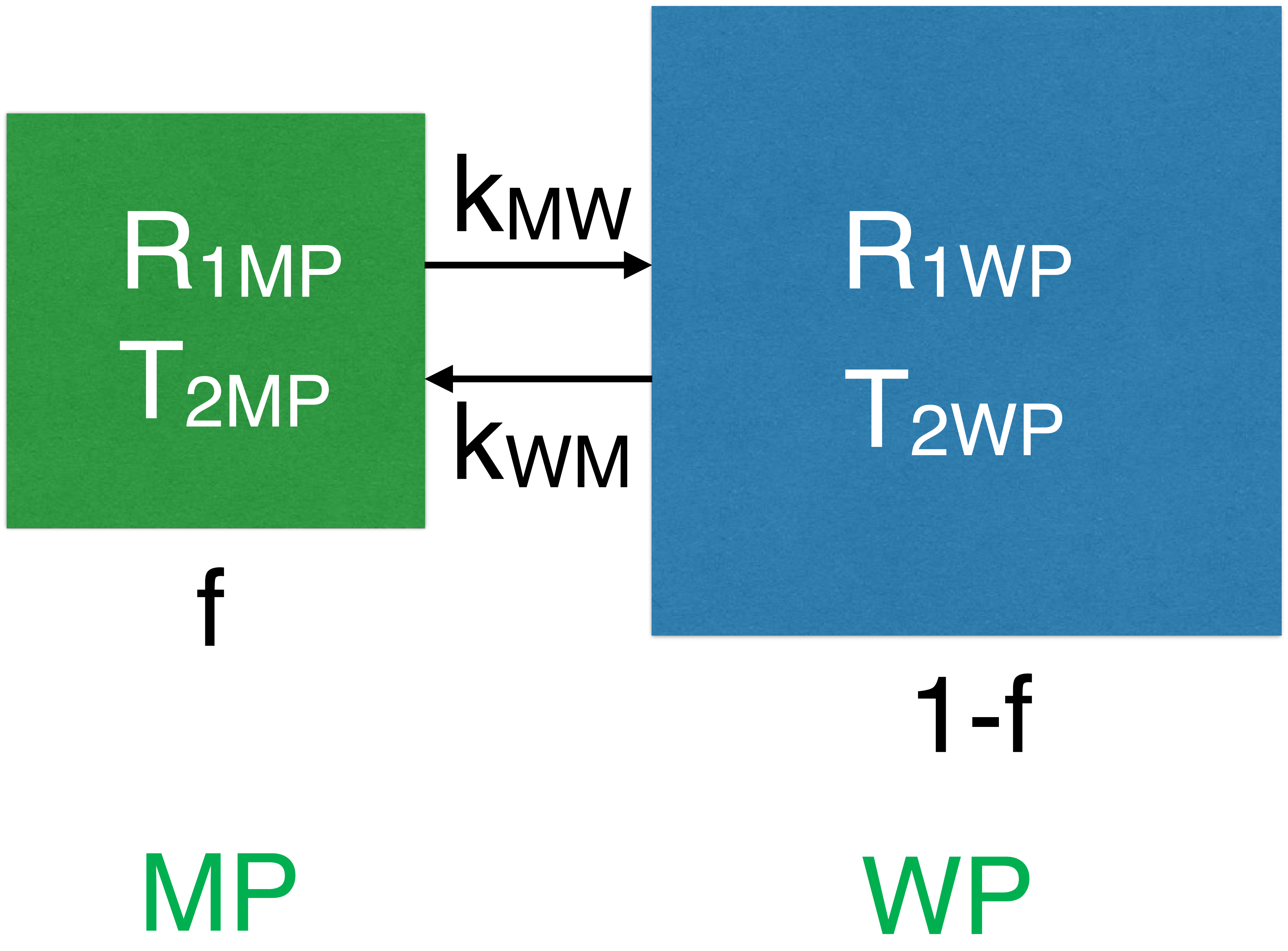
Calculated T_1 as function of TI

High RF Low RF



MT

Equations



R_{1MP}

T_{2MP}

k_{MW}

k_{WM}

R_{1WP}

T_{2WP}

f

1-f

MP

WP

$d\,S_{WP} / dt = -R_{1WP}\,S_{WP} - k_{WM}\,S_{WP} + k_{WM}\,S$

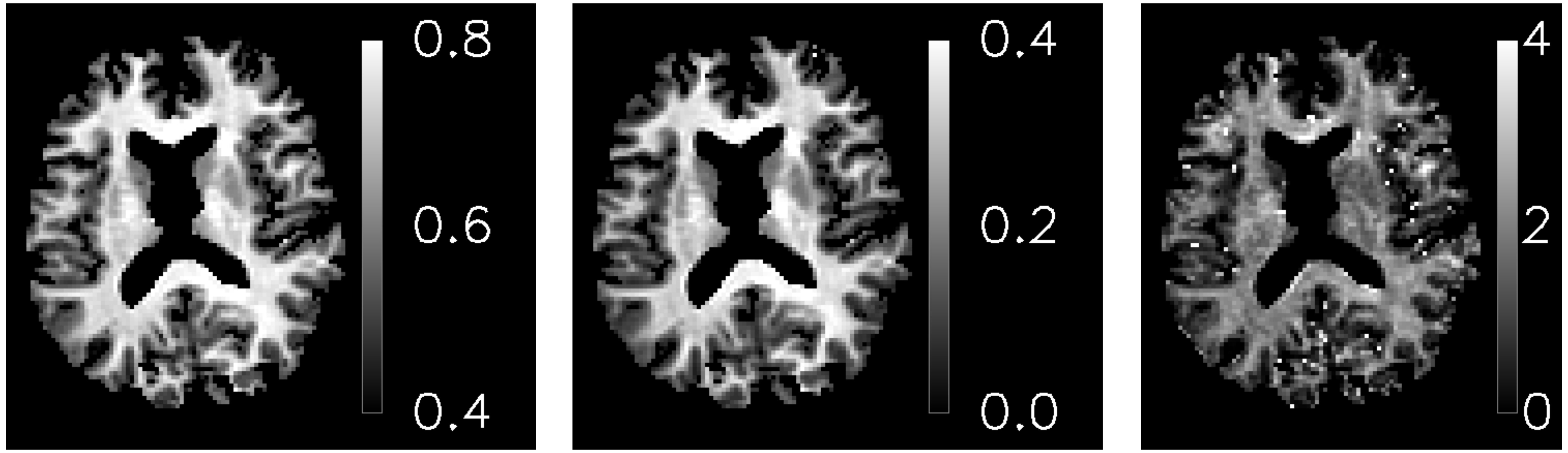
$d\,S_{MP} / dt = -R_{1MP}\,S_{MP} - k_{MW}\,S_{MP} + k_{MW}\,S$

$f\,k_{MW} = (1-f)\,k_{WM}$

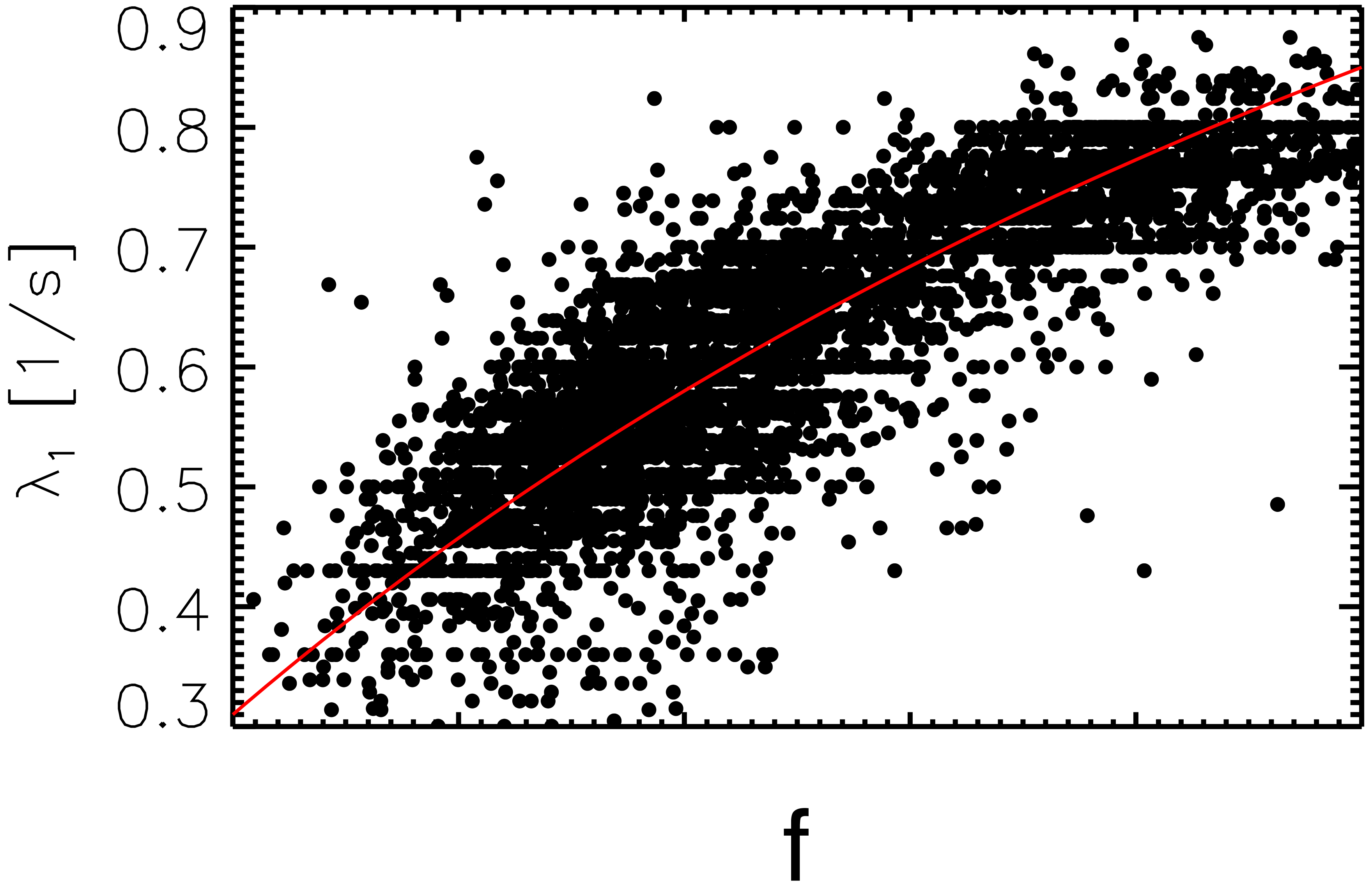
$S_{WP}(t) = a_1 e^{-\lambda_1 t} + a_2 e^{-\lambda_2 t}$

$\lambda_1 \simeq (1-f)R_{1WP} + fR_{1MP}$

Inversion & MT



λ_1 f k_{wm}



$$R_{1eff} = \lambda_1 \approx (1-f)R_{1WP} + fR_{1MP}$$

T_1 & MT

Summary

- Pure water has a very long T_1
- Main source of T_1 relaxation is semi-solid lipids & other macro molecules through MT between water and MP
- Consequences:
  :: MT and T_1 contrast both measure MP
  :: T_1 relaxation (at least) bi-exponential

T_1 & MT

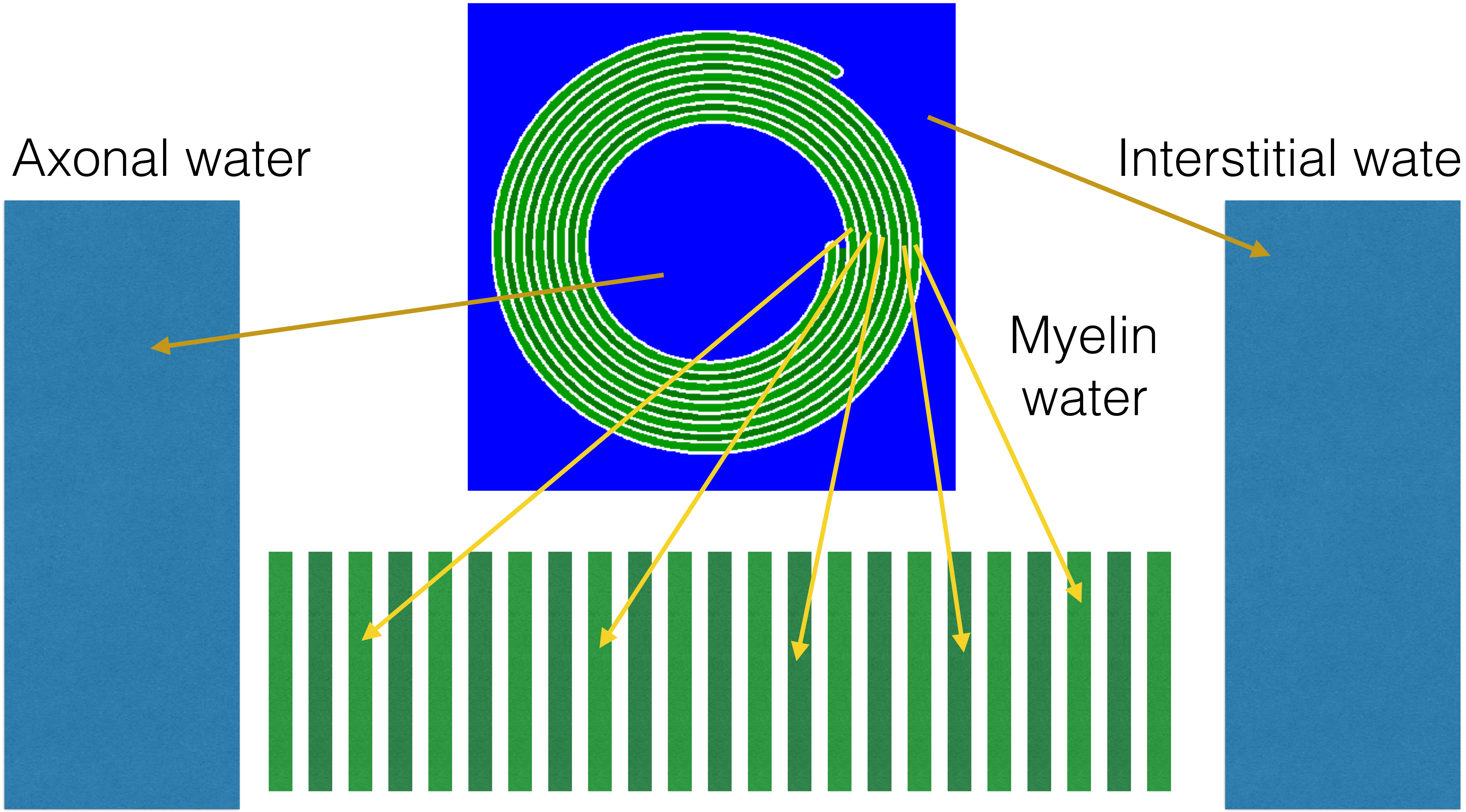
Summary

Reality more complex:

- multiple pools of water (intra-, extra- cellular, myelin)
- multiple kinds of MP, each with R_1, T_2 etc.

Two pool T_1 generally sufficient, fast component more important at higher field

Many compartments

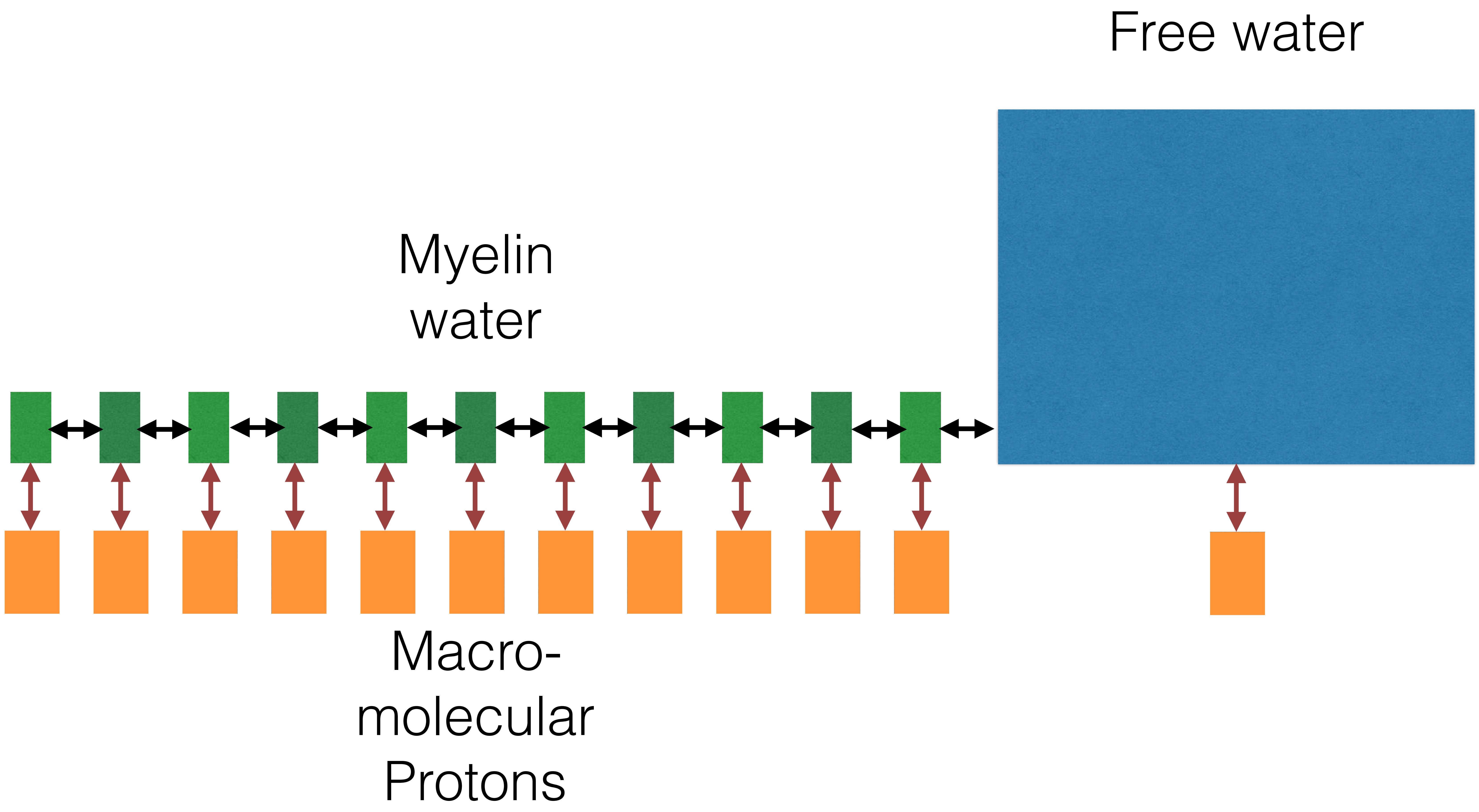


Axonal water

Interstitial water

Myelin water

Many compartments



Free water

Myelin water

Macro-
molecular
Protons

T_1 & MT

The
End