# Fast Imaging Trajectories: EPI and PROPELLER

M229 Advanced Topics in MRI

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# Class Business

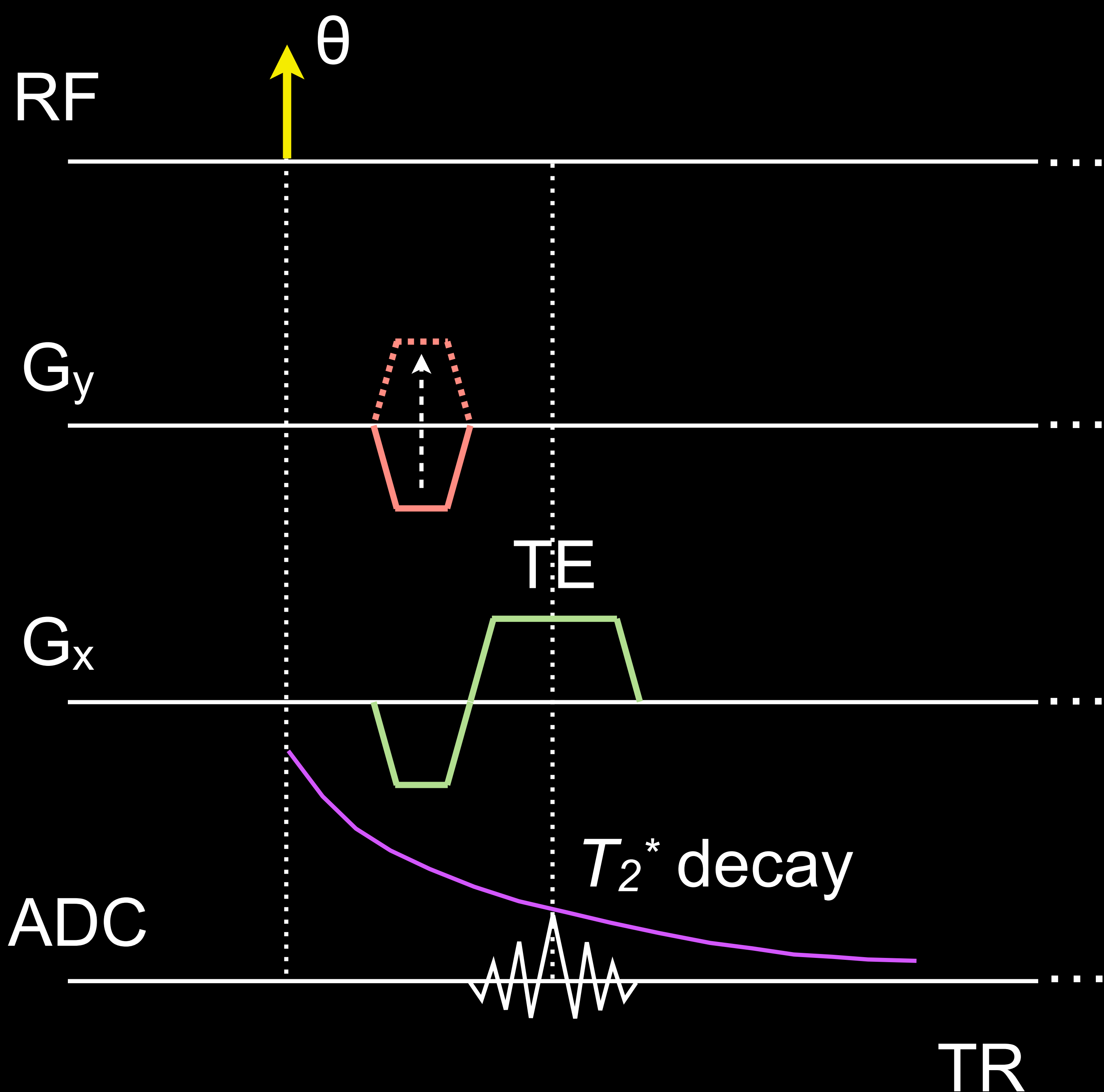
- Final project
  - Abstract due 6/6 Fri by 5 pm
  - Presentations and Q&A on 6/10 and 6/12

# Outline

- EPI[1]
  - Pulse sequence and design considerations
  - Alternatives
  - Artifacts and corrections
  - Applications
- PROPELLER[2]

*[1]Mansfield P, J Phys C: Solid State Phys., 1977*
*[2]Pipe JG, Magn. Reson. Med., 1999*

# Gradient Echo



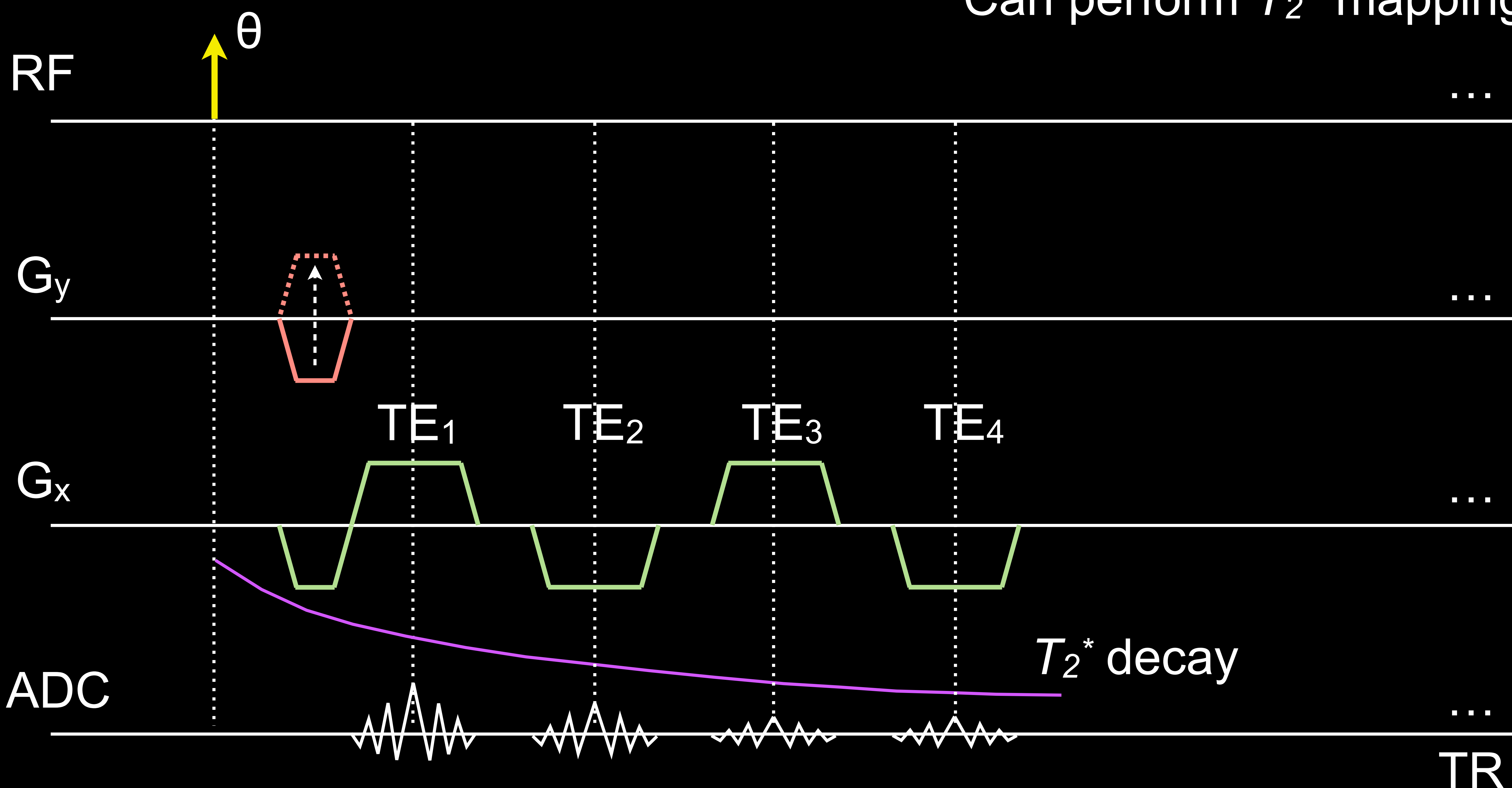

- Utilization of transverse magnetization
  - With $T_s = 8\ \mu s$ and $N_x = 128$, $T_{acq} = 1.024$ ms
  - <2% of $T_2^*$ in brain at 3 T![1]
- Scan time
  - $T_{GRE} = N_{pe} \times TR$
  - $TR = 10$ ms, $N_{pe} = 256$: $T_{GRE} = 2.56$ sec

[1] *Peters, et al., Proc ISMRM 2006*

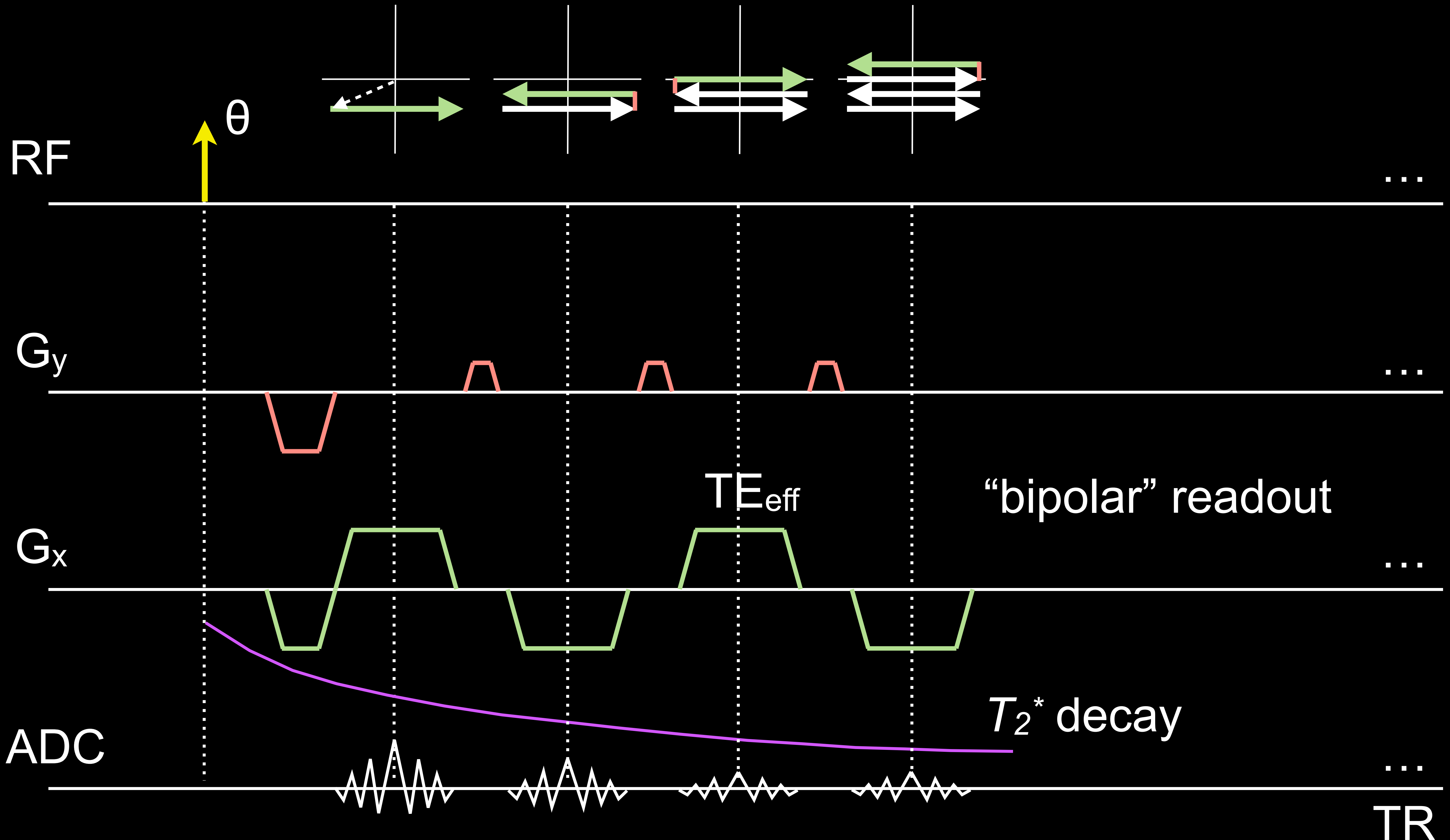
# Multi-echo Gradient Echo

ΔTE can be non-uniform

Can perform $T_2$* mapping

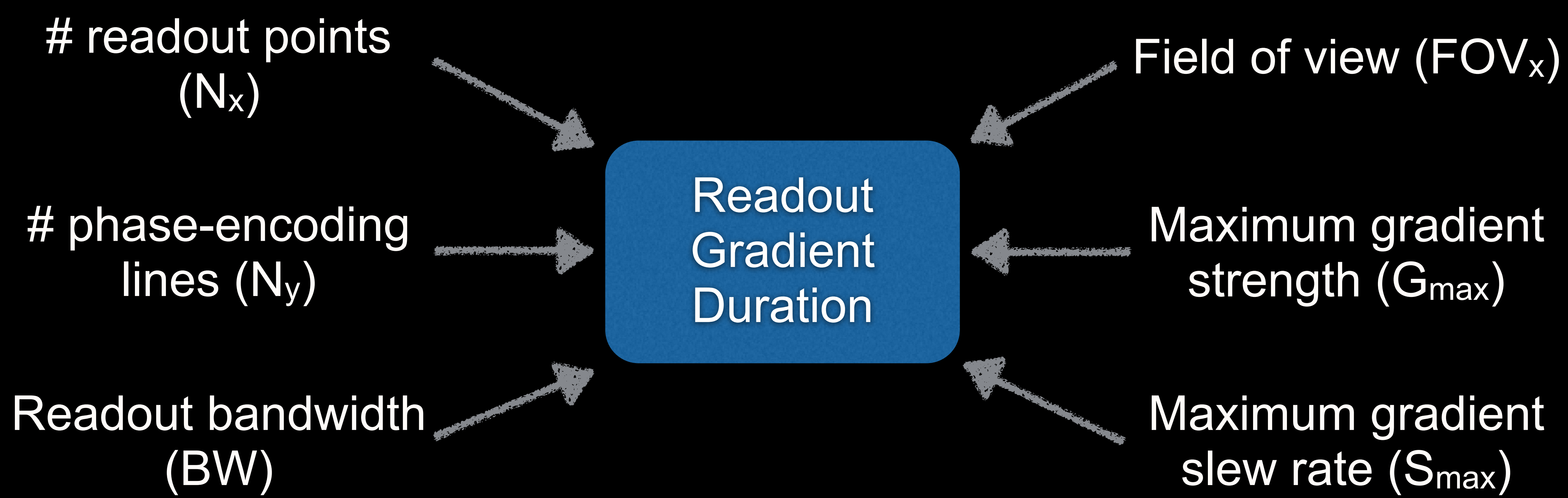


# Gradient-Echo EPI



# Design Basics

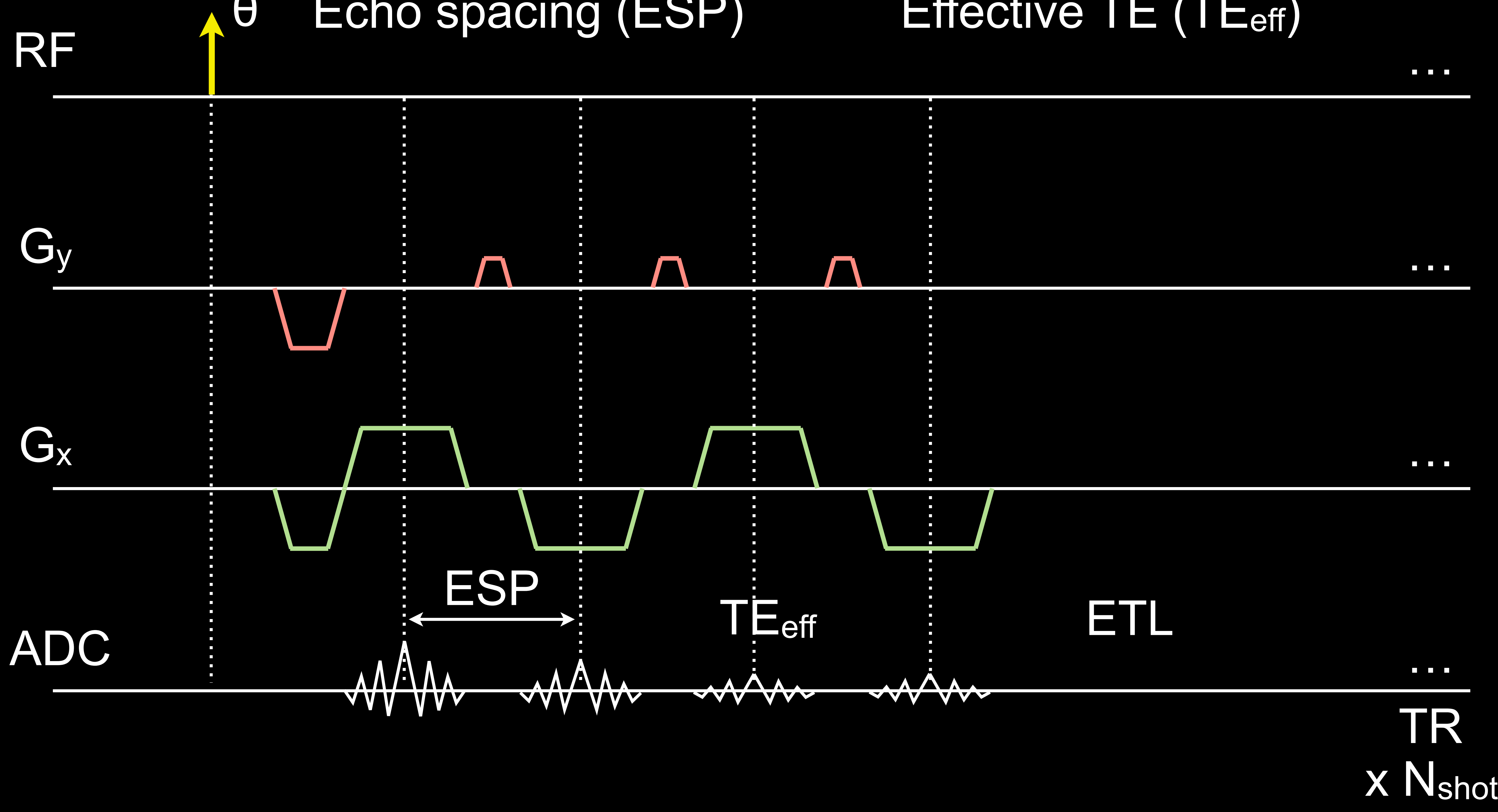
- What species are you imaging?
  - $T_2$, $T_2^*$?
  - Utilize transverse magnetization efficiently by sampling up to, e.g., $2 \times T_2^*$ (100 ms) → *Readout gradient duration in EPI*
  - Total readout durations of up to 100 ms



# EPI Sequence Parameters

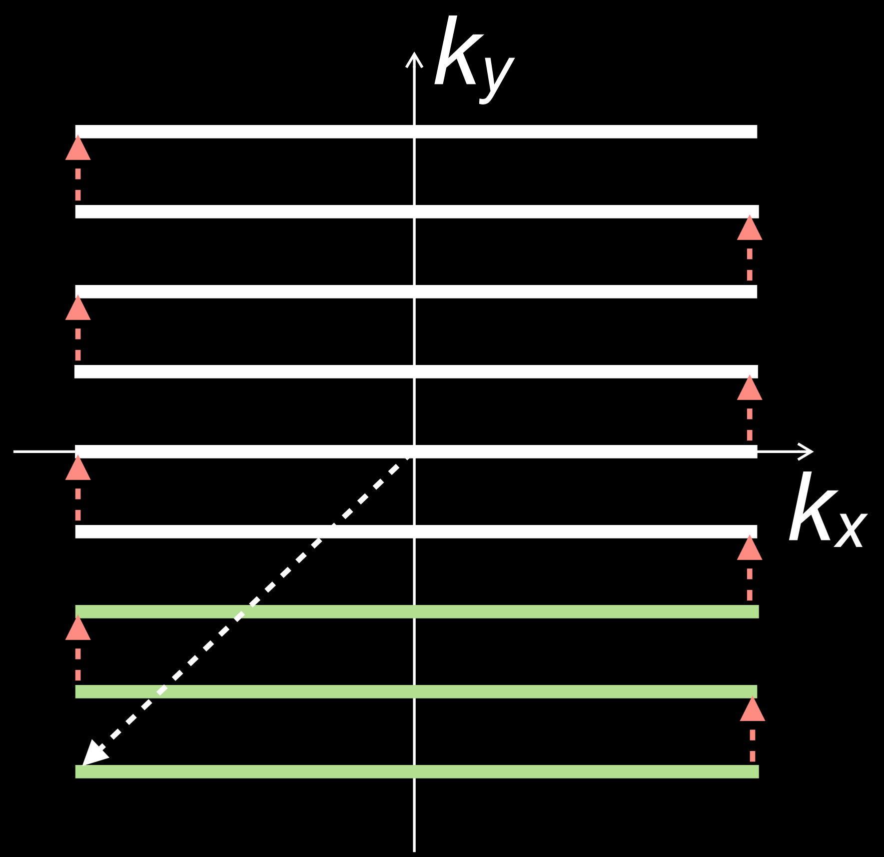
Echo train length (ETL) | Number of shots ($N_{shot}$)

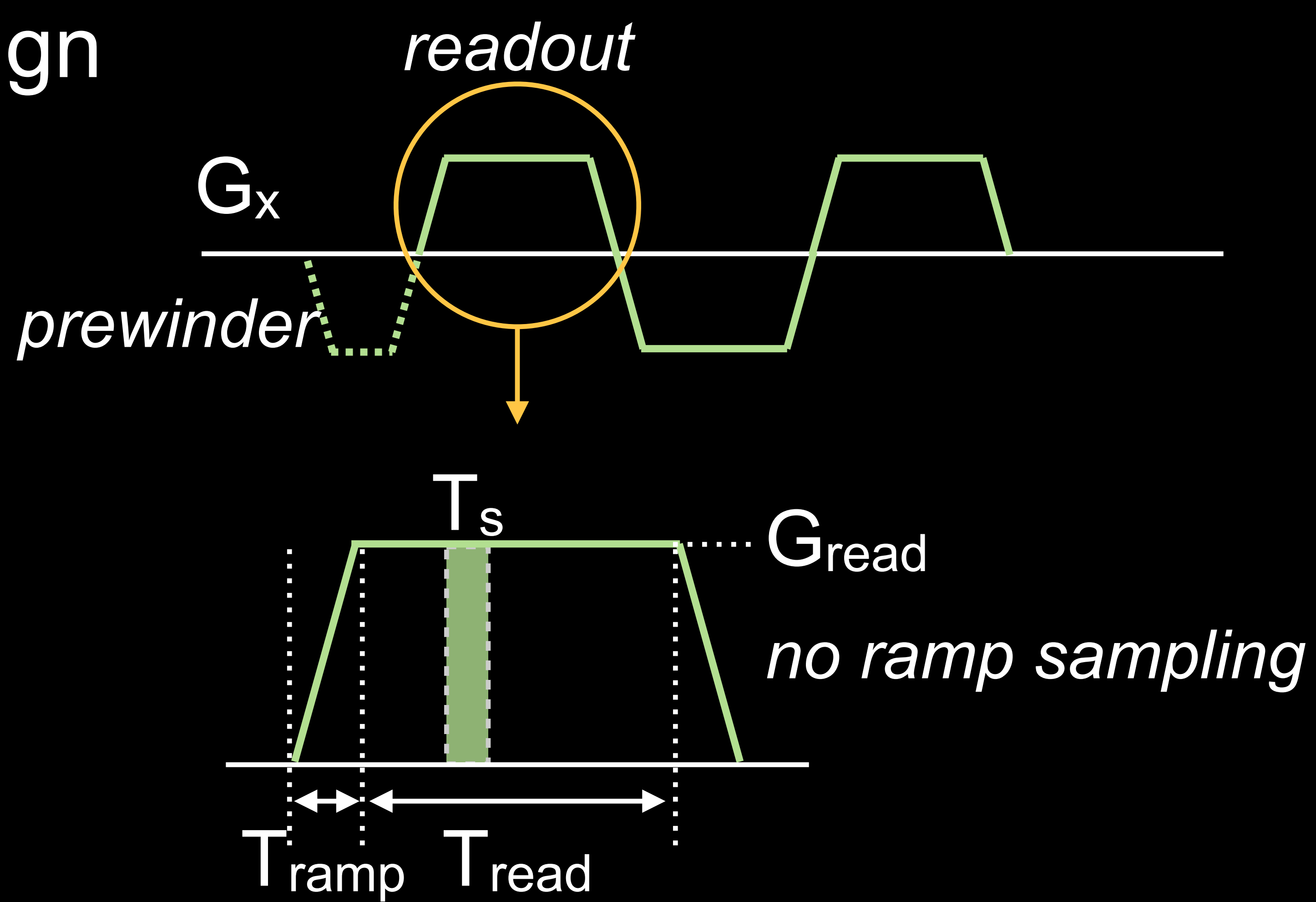
Echo spacing (ESP) | Effective TE ($TE_{eff}$)



# EPI Sequence Parameters

## Readout Gradient Design




$(\gamma/2\pi)\cdot G_{read}\cdot T_s = \Delta k_x \leq 1/FOV_x$

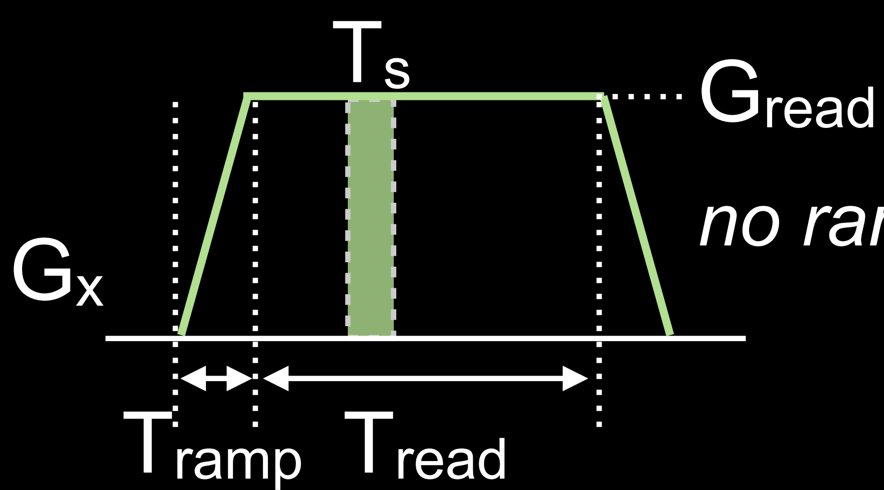
$G_{read} \leq G_{max}$ $\quad$ $SR \leq S_{max}$

$T_{read} = T_s \cdot N_x$ $\quad$ $T_{ramp} = G_{read}/SR$

$ESP \geq T_{read} + 2\cdot T_{ramp}$

# EPI Sequence Parameters

Readout Gradient Design Example:




*no ramp sampling*

$(\gamma/2\pi)\cdot G_{read}\cdot T_s = 1/FOV_x$

$ESP = (T_s \cdot N_x) + 2\cdot(G_{read}/SR)$

$T_s = 8\ \mu s$; $N_x = 128$;
$FOV_x = 22$ cm; SR = 120 T/m/s

$G_{read} = 13.3$ mT/m

ESP = 1.246 ms

If $T_s = 4\ \mu s$

ESP = 0.955 ms

If $T_s = 8\ \mu s$ and SR = 20 T/m/s

ESP = 2.354 ms

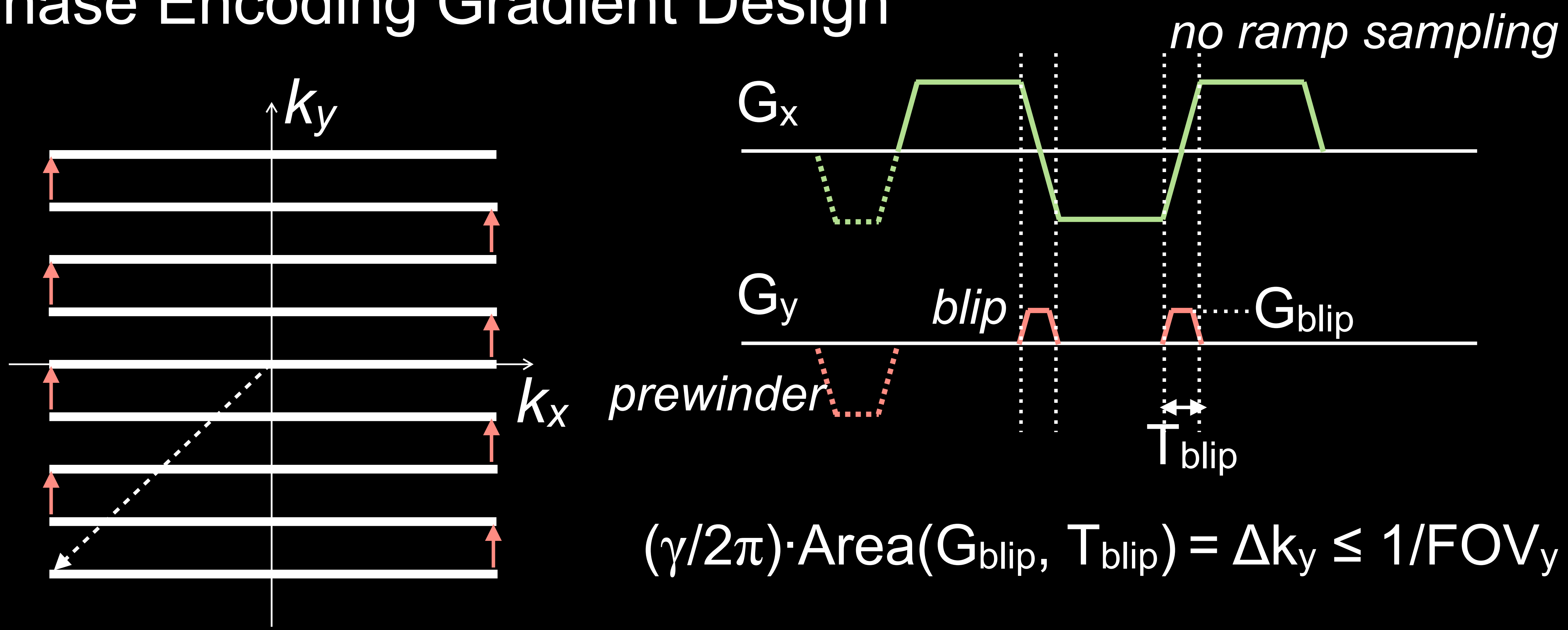
If $T_s = 4\ \mu s$ and SR = 20 T/m/s

ESP = 3.172 ms

*Bernstein et al., Handbook of MRI Pulse Sequences, Ch 16.1*

# EPI Sequence Parameters

Phase Encoding Gradient Design




$(\gamma/2\pi)\cdot\text{Area}(G_{blip}, T_{blip}) = \Delta k_y \leq 1/FOV_y$

Phase Encoding Bandwidth

*PEbw* = 1/ESP ~ 1 kHz; more off-resonance artifacts

cf. *RObw* up to 500 kHz ($T_s$ = 2 $\mu$s)

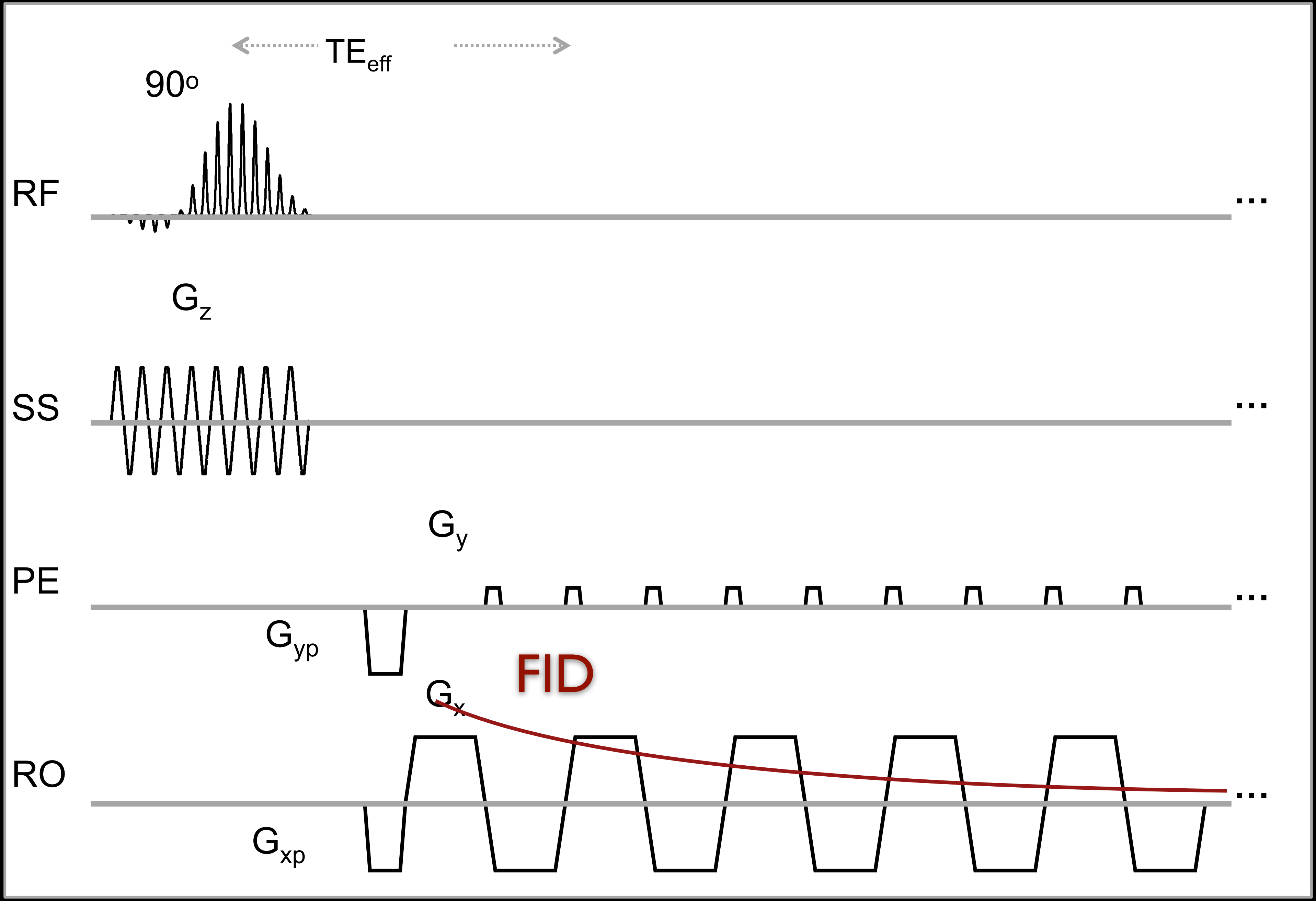
# EPI Sequence Parameters

- ETL can be 4-64 or higher
  - Limited by $T_2$* decay, off-resonance effects
  - aka “EPI factor”
- ESP typically ~1 ms
  - Must accommodate gradients and ADC
  - Short ESP facilitates high ETL
- <u>*Example:*</u> readout until $S = 0.2\ S_0$
  - $S = S_0 * \exp(-t/T_2^*)$; assume $T_2^* = 60$ ms
  - $t = 96.6$ ms
  - ESP = 1 ms; ETL = 96

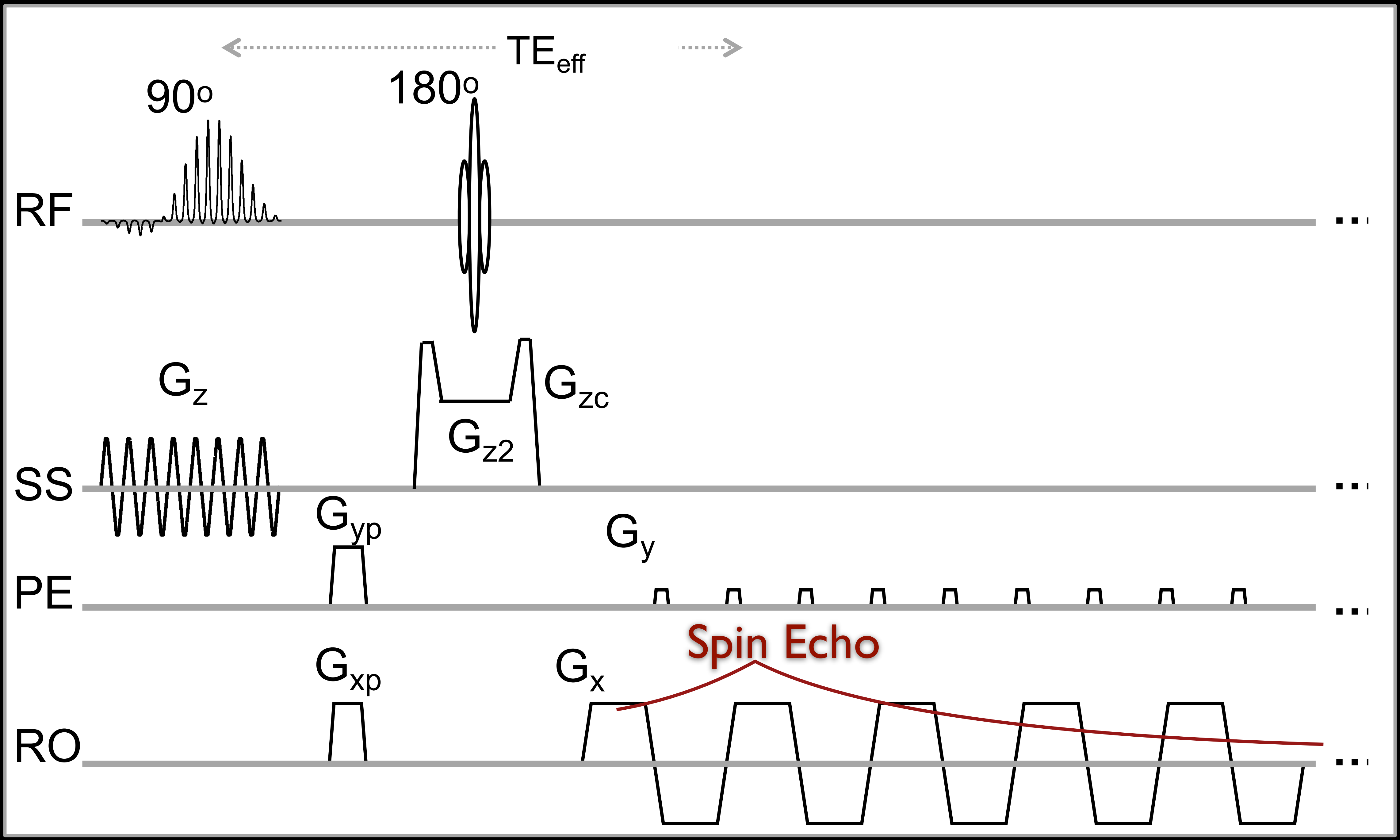
# Minimizing Readout Duration / ESP

- Higher gradient amplitudes and slew rates
- Higher readout bandwidths
- Sampling along the ramps
- Partial k-space acquisition
  - in x: “partial Fourier” < 1
  - in y: phase FOV can be < 1
- Parallel imaging
- Inner volume imaging

# Gradient-Echo (GRE) EPI

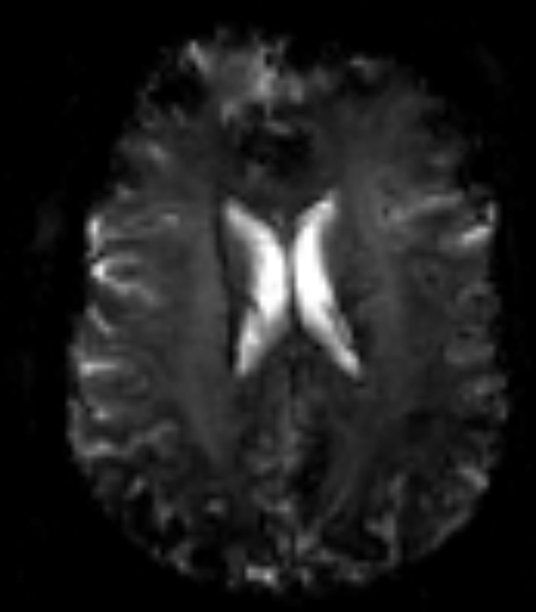


# Spin-Echo (SE) EPI

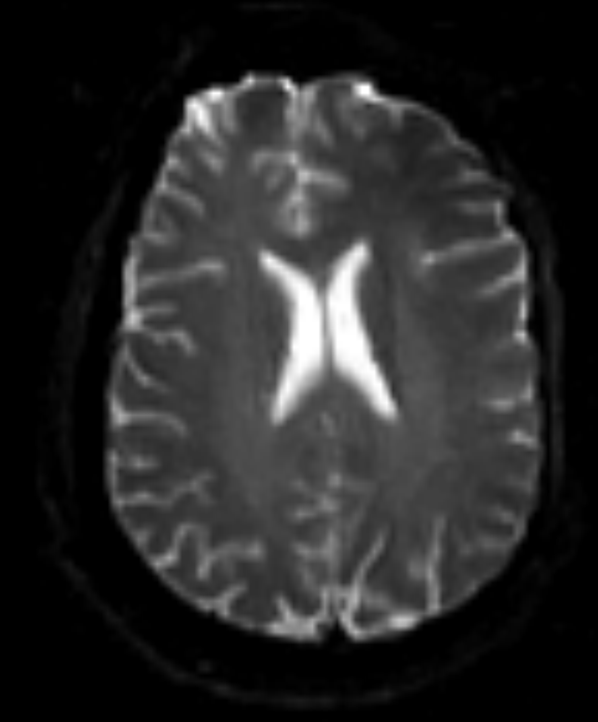


# Comparison

GRE-EPI



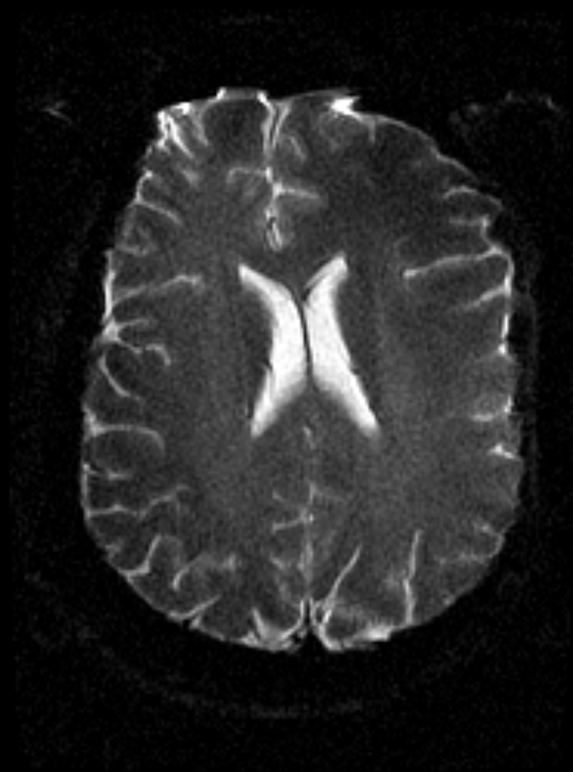
SE-EPI



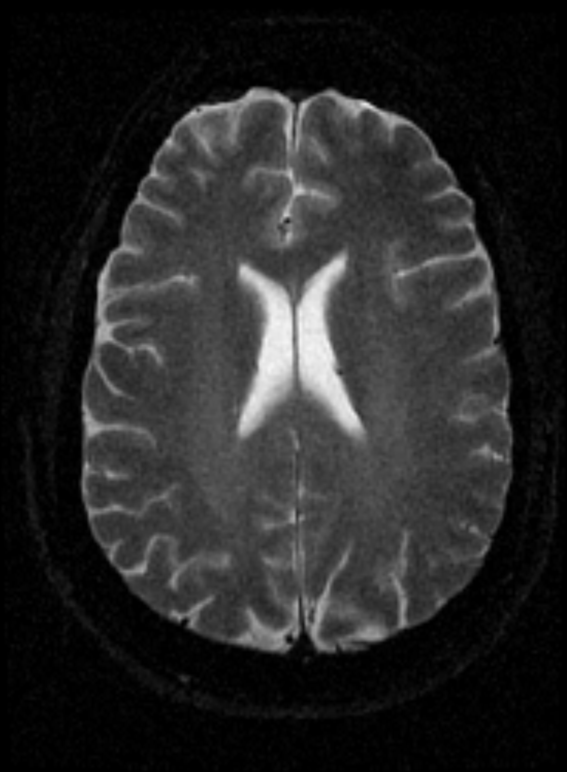
- GRE-EPI: More signal dropouts, distortion
- GRE-EPI: More susceptibility effects, better for functional MRI acquisition

# Managing EPI distortion

SE-EPI



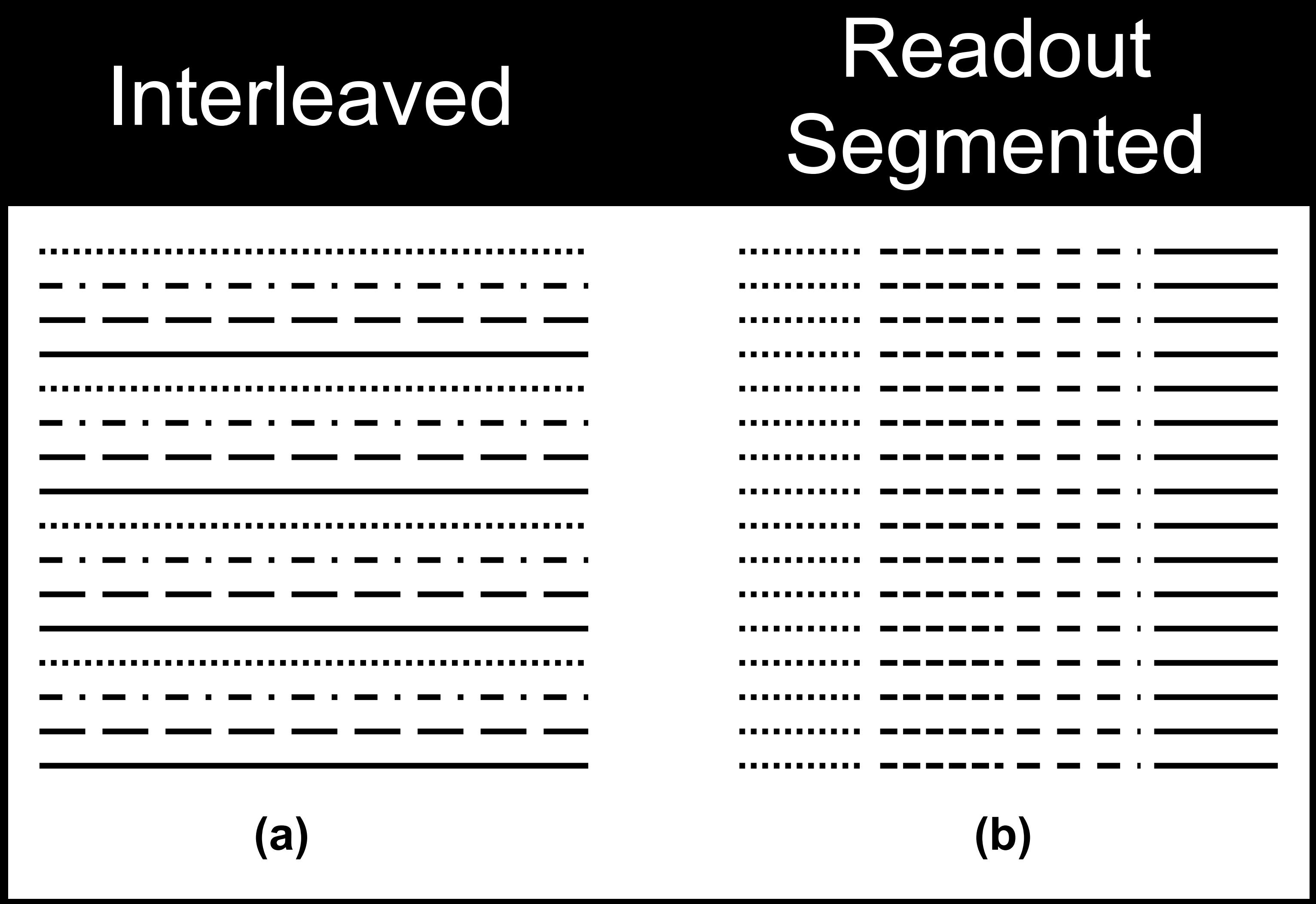
???



# Multi-shot EPI

- Single-shot EPI (ssEPI)
  - Minimal motion artifacts
  - Low spatial resolution
  - Geometric distortion and signal loss
- Multi-shot EPI (msEPI)
  - aka interleaved or segmented EPI
  - Higher spatial resolution
  - Less distortion & signal loss (improve PEbw)
  - Need to address motion and phase inconsistencies

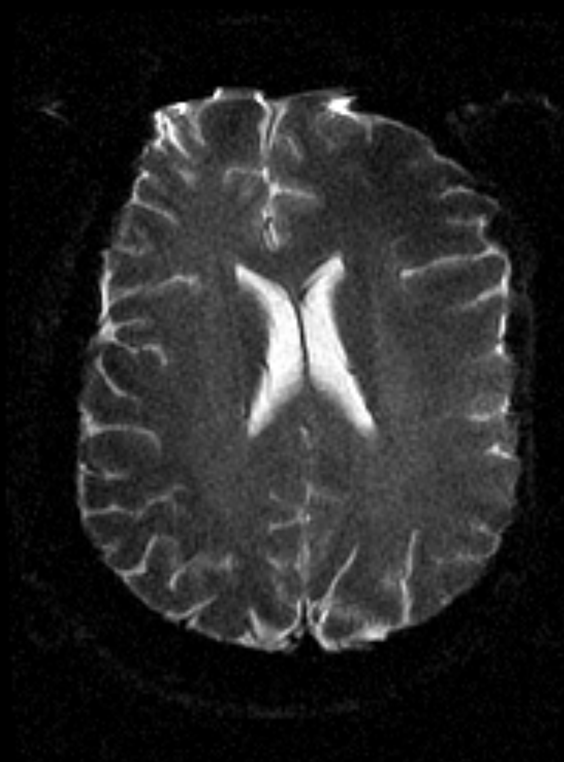
# Multi-shot EPI



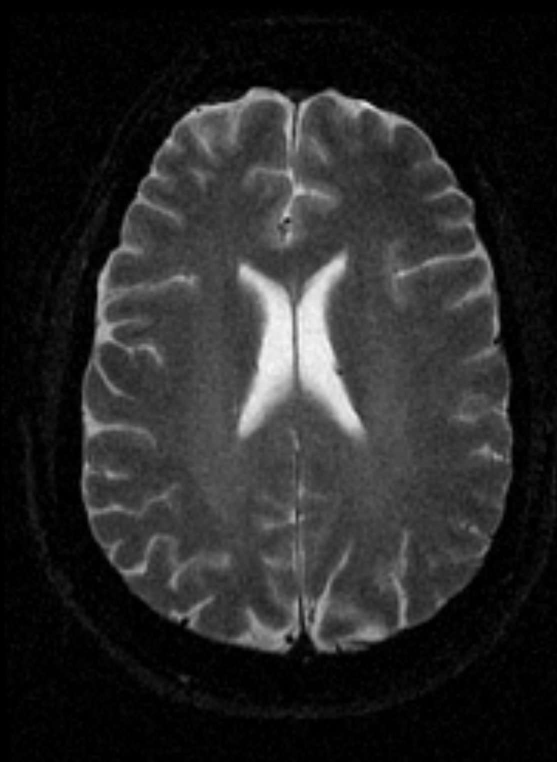

*Courtesy of Dr. Novena Rangwala*

# Comparison

ssEPI



msEPI

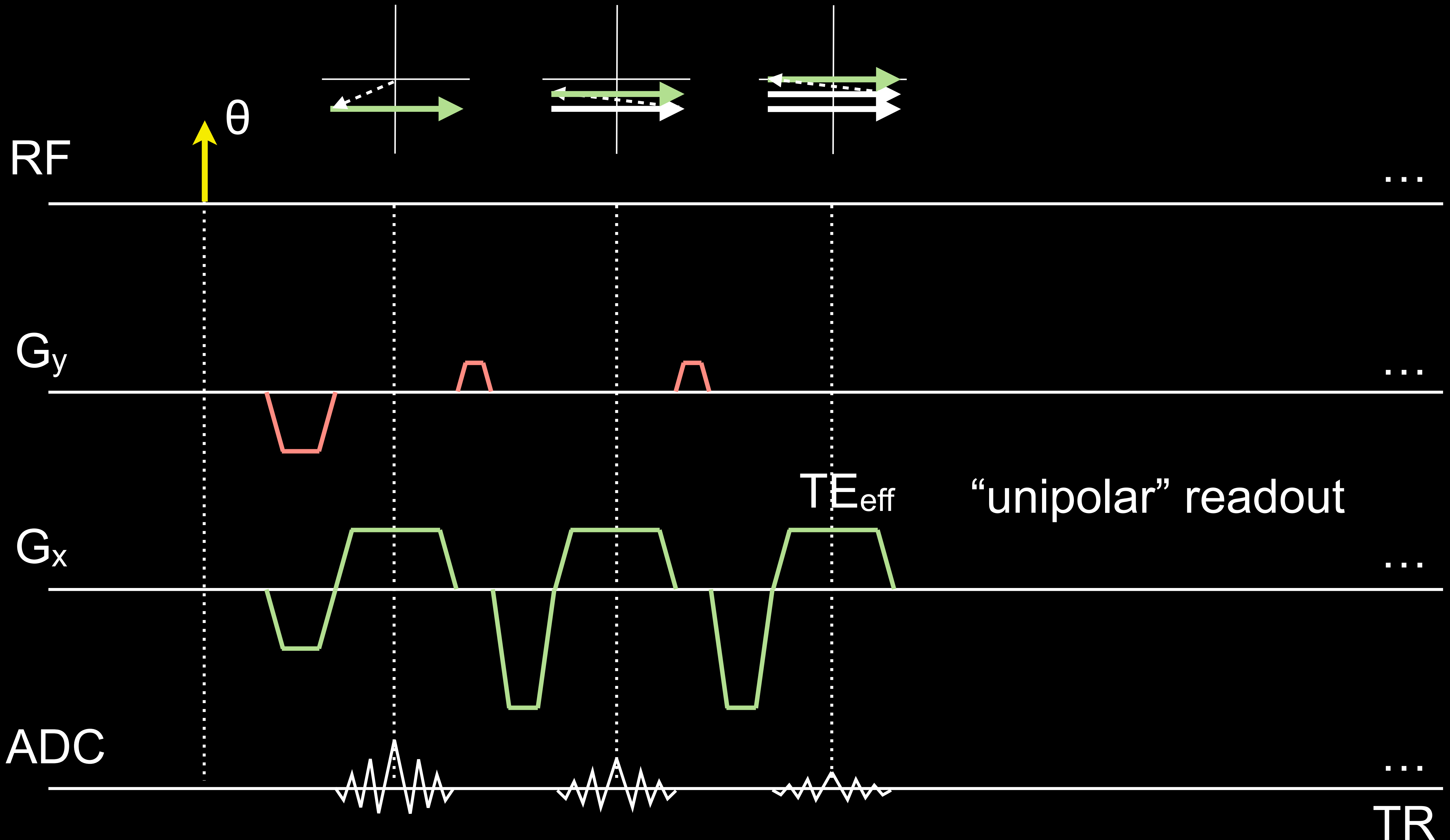


*Courtesy of Dr. Novena Rangwala*

# EPI Scan Time

- Scan time
  - Recall $T_{GRE} = N_{pe} \times TR_{GRE}$
  - $N_{shot} = N_{pe} / ETL$
  - $T_{EPI} = N_{shot} \times TR_{EPI} = (T_{GRE} / ETL) \times (TR_{EPI}/TR_{GRE})$
- *Example 1*
  - $N_{pe} = 256$; $ETL = 16$; $N_{shot} = 16$
  - $TR = 30$ ms: $T_{EPI} = 480$ ms
- *Example 2*
  - $N_{pe} = 64$; $ETL = 64$; $N_{shot} = 1$
  - $TR = 100$ ms: $T_{EPI} = 100$ ms

# Fly-Back GRE-EPI



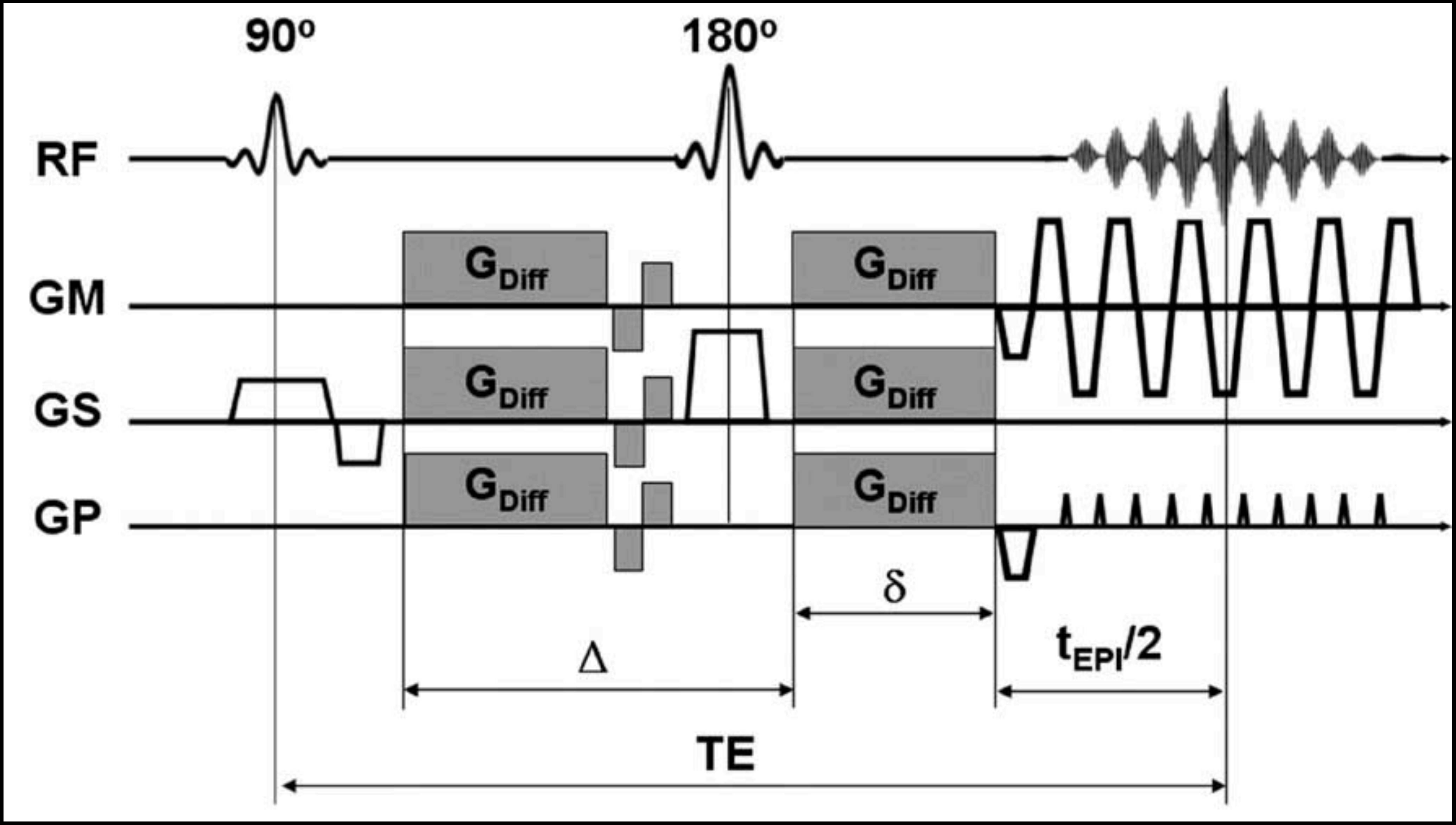
# Fly-Back GRE-EPI

- "Fly-back" gradients
  - No data sampling
  - Use max gradient amplitude/slew rate
- Advantages
  - All readouts in the same direction, minimal artifacts
- Disadvantages
  - Longer ESP than bipolar EPI

# Related Sequences

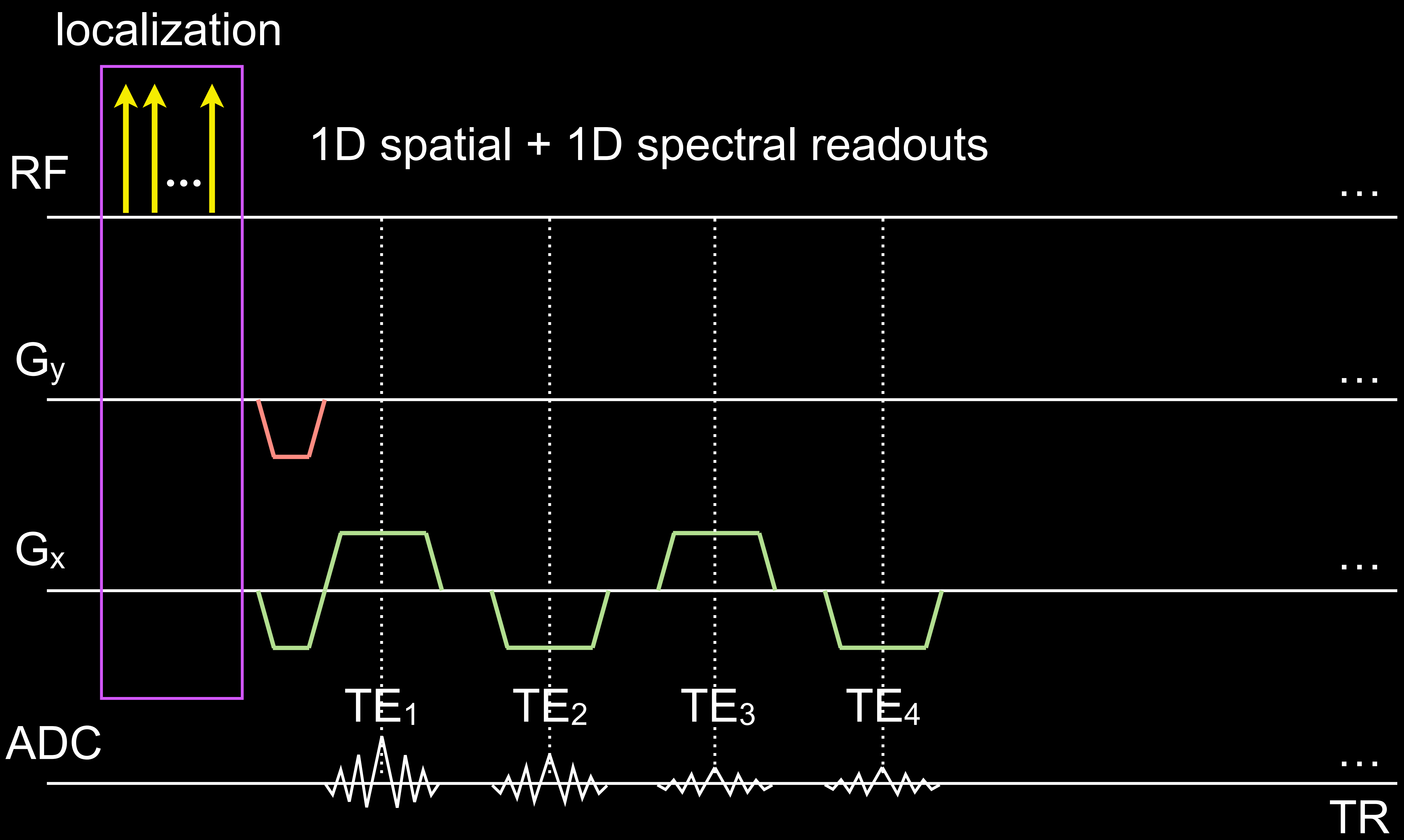
- Diffusion-weighted SE-EPI
- 3D echo-volume imaging (EVI)
- Hybrid EPI + non-Cartesian (e.g., PROPELLER, EPI in a circular plane)
- Multi-echo chemical shift imaging
- Echo-planar spectroscopic imaging (EPSI), 2D and 3D

# Diffusion-Weighted SE-EPI




*Bammer R, EJR, 2003; 45: 169-184*

# Bipolar EPSI

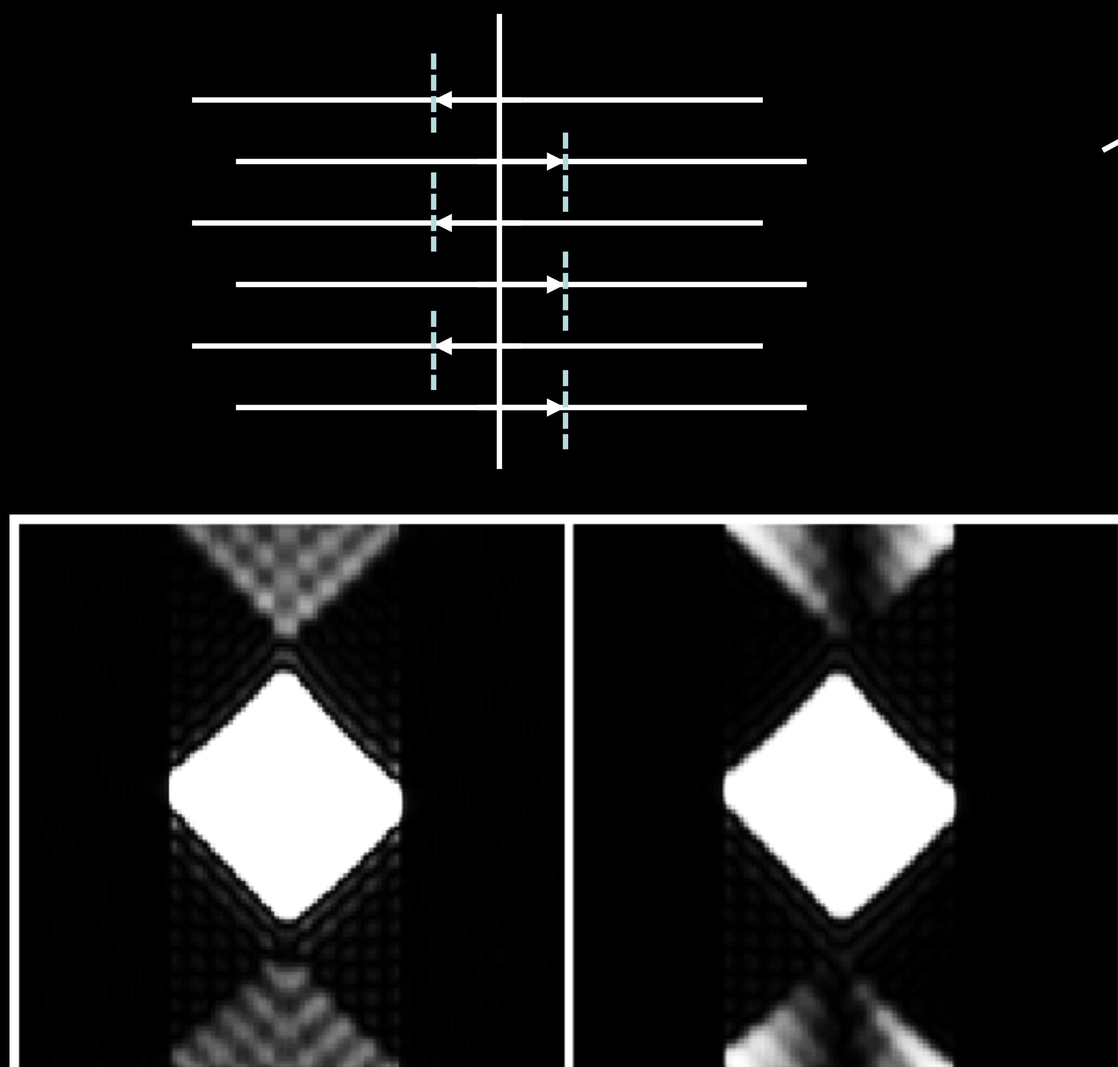


# EPI Artifacts

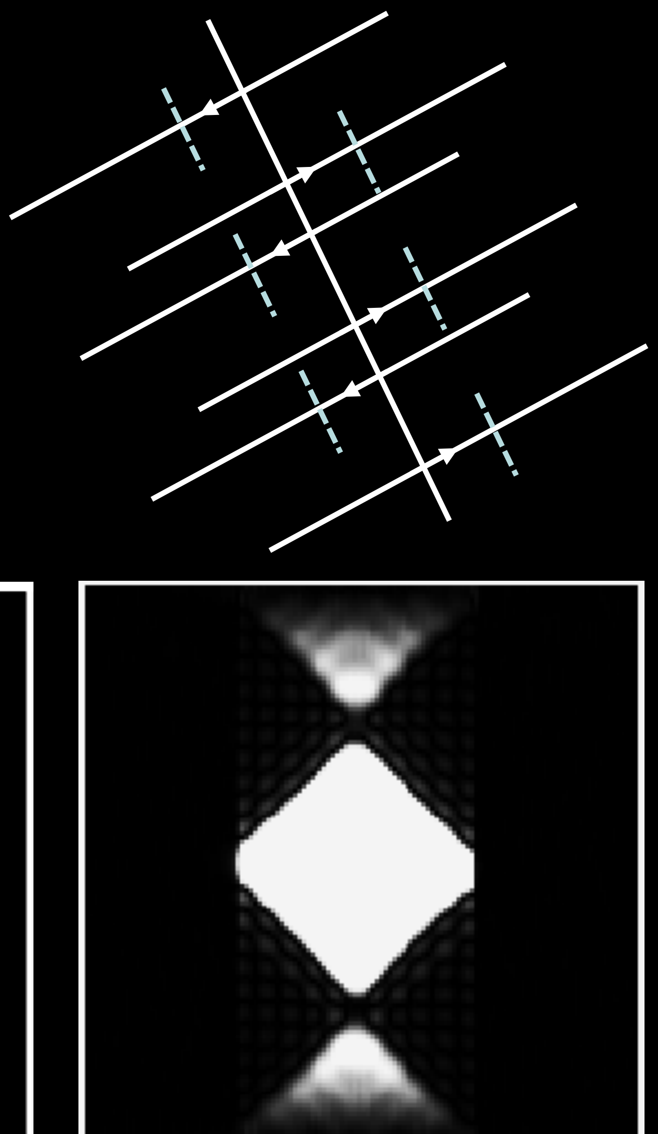
- Nyquist ghosting artifacts
- Chemical-shift artifacts, e.g., fat
- Signal drop-out or pile-up
- Geometric distortion

# EPI Ghosting Artifacts

'Orthogonal' Plane



'Oblique' Plane



# EPI Ghosting Artifacts

- Inconsistencies between even/odd echoes due to:
  - Spatially independent (constant):
    $B_0$ eddy currents, off-center freq mismatch
  - Linear and oblique phase errors:
    k-space shifts from gradient / timing errors
  - Higher order eddy current effects
  - Concomitant magnetic fields

# EPI Chemical Shift Artifacts

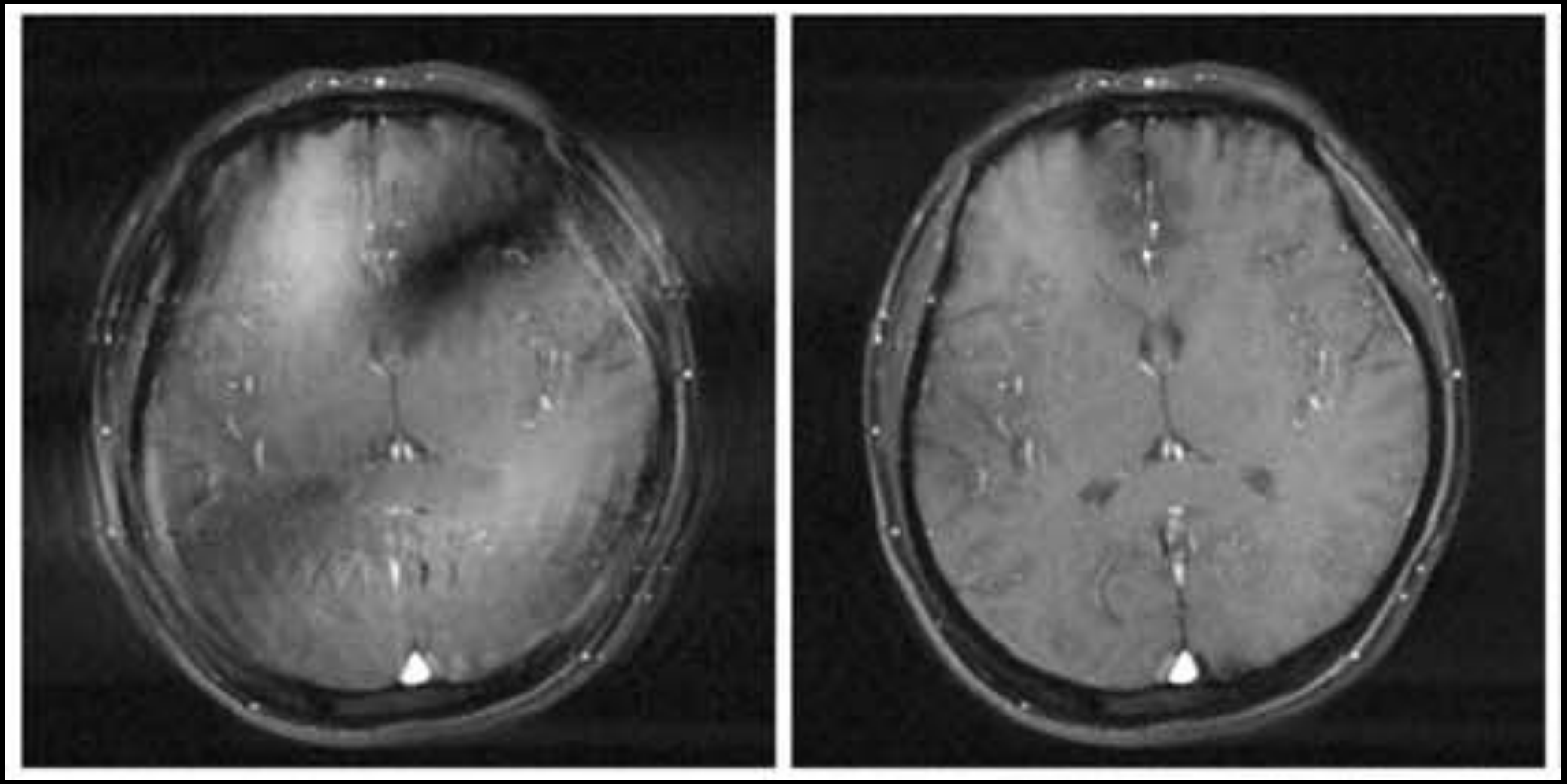
- Along readout
  - $\Delta x_{cs} = \Delta f_{cs} \cdot (FOV_x / RObw)$
  - At 1.5 T, $\Delta f_{WF} \sim 210$ Hz
    for FOVx = 32 cm and RObw = 250 kHz,
    $\Delta x_{cs} = 0.027$ cm
- Along phase encode
  - $\Delta y_{cs} = \Delta f_{cs} \cdot (FOV_y / PEbw)$,
    PEbw = 1 / ESP
  - for ESP = 1 ms, $\Delta y_{cs} = 6.72$ cm

# EPI Considerations

- Minimize ESP (covered earlier)
- Spatial-spectral excitation for fat signal suppression
- Reconstruction steps
  - Row flipping and phase correction
  - Ramp sampling correction
  - Fourier transformation
  - (Possible) $B_0$ inhomogeneity correction
  - (Possible) Gradient trajectory corrections

# EPI Considerations

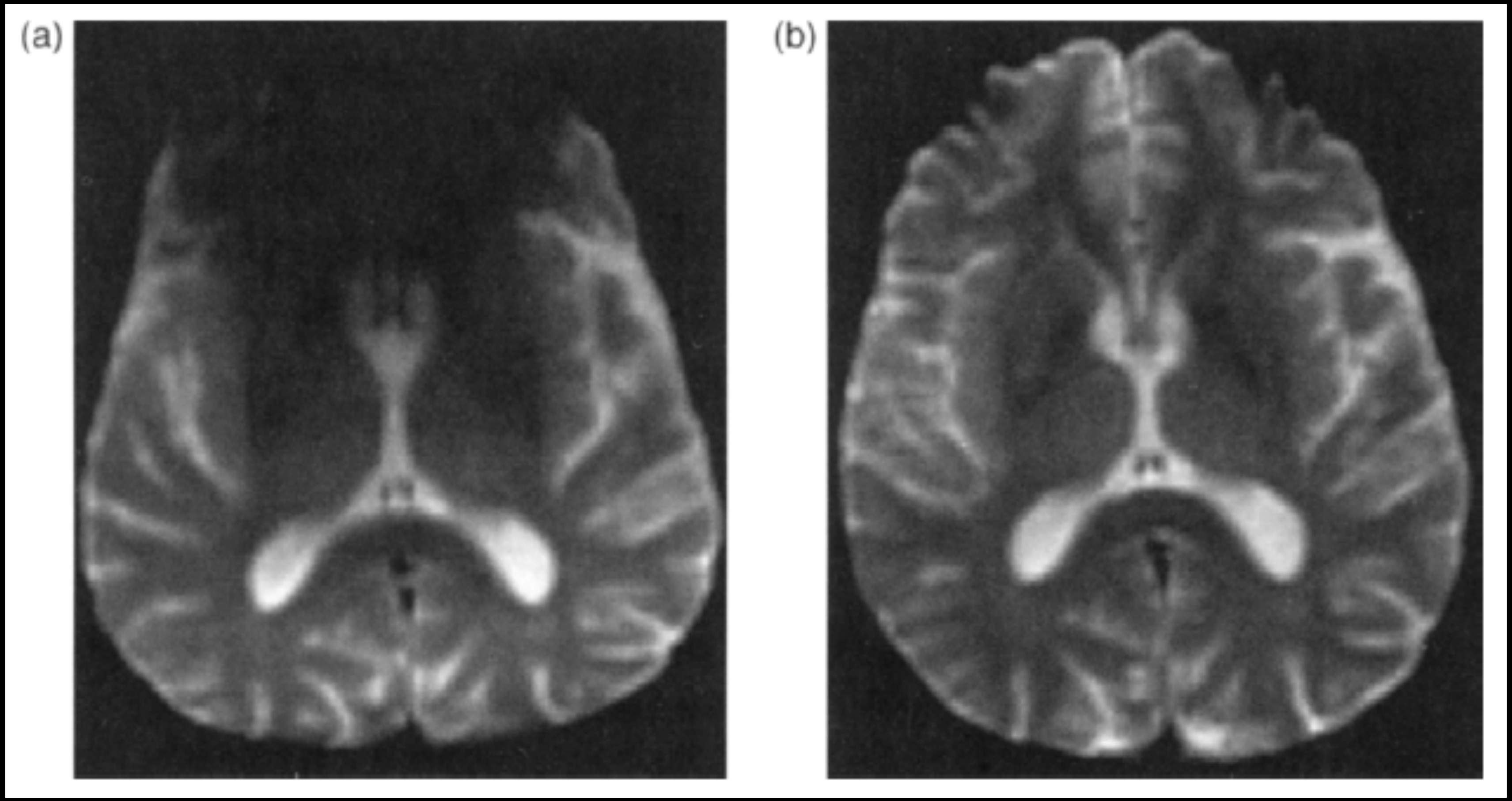
Axial EPI, before & after trajectory correction



*Addy NO et al., MRM 2012*

# EPI Considerations

Image distortion and signal loss from dentures




w/ dentures

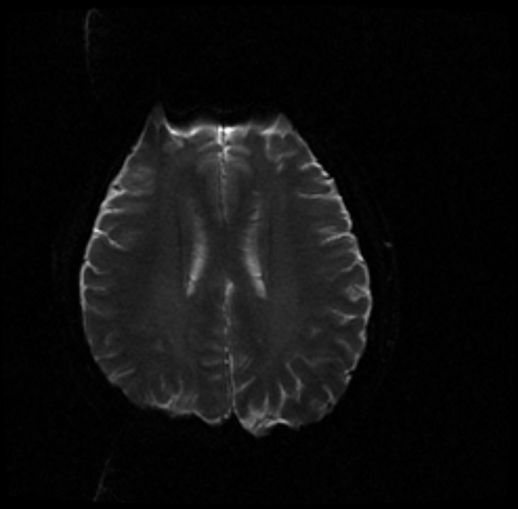
*Bernstein et al., Handbook of MRI Pulse Sequences, Ch 16.1*

# Summary

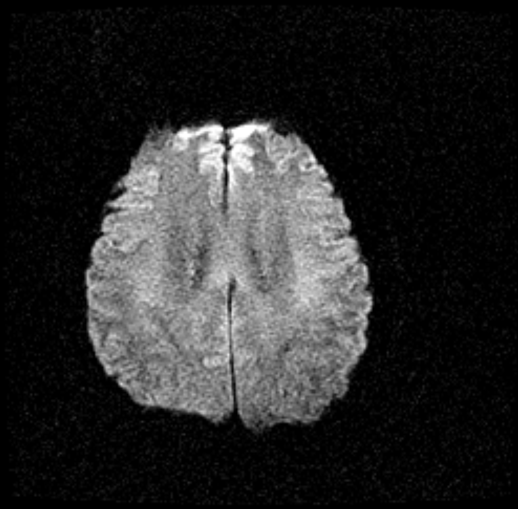
- Strengths
  - Very fast (~100 ms per image)
- Challenges
  - High demand on slew rate
  - $T_2^*$ decay -> image blurring, low spatial res
  - $B_0$ variation, susceptibility -> distortion
  - Chemical shift artifacts
  - Ghosting artifacts

# Clinical Applications

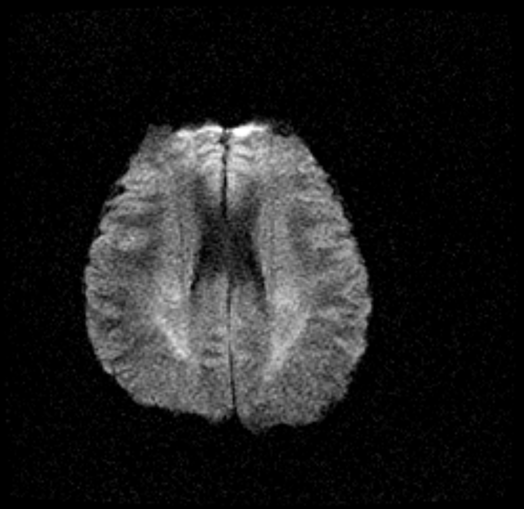
- BOLD fMRI
- ASL
- DWI (see figure)
- Real-time MRI
- MRSI
- *and more ...*



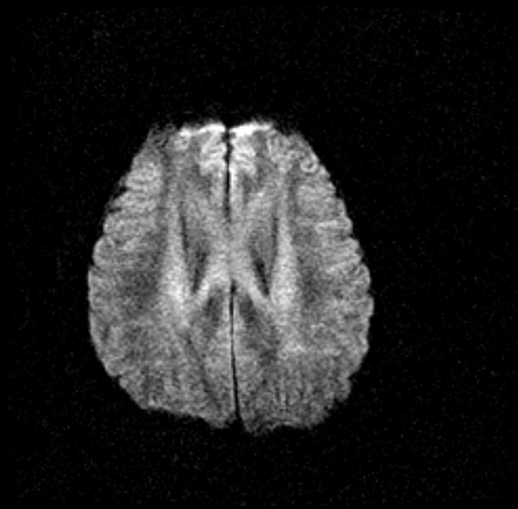
$b = 0$ s/mm$^2$



$b = 750$ s/mm$^2$, S/I



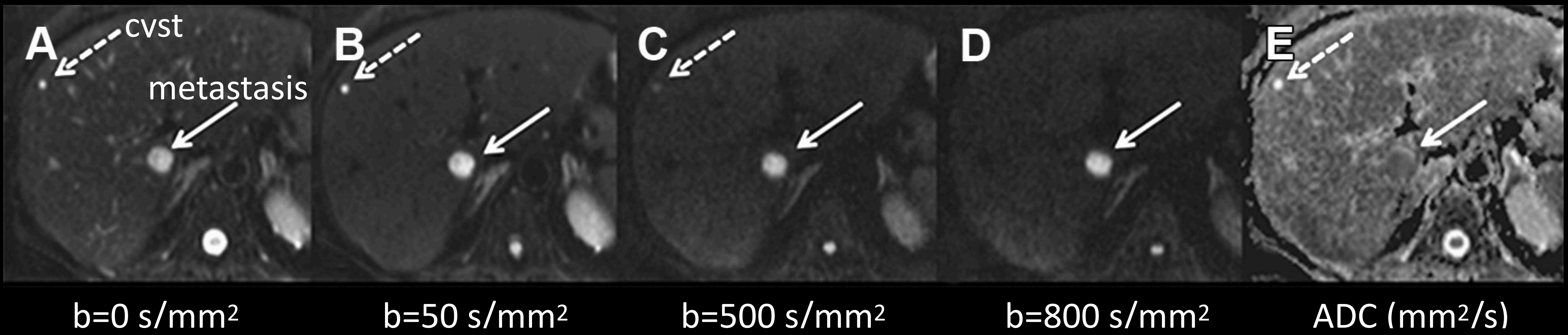
$b = 750$ s/mm$^2$, R/L



$b = 750$ s/mm$^2$, A/P

# Clinical Applications: DWI

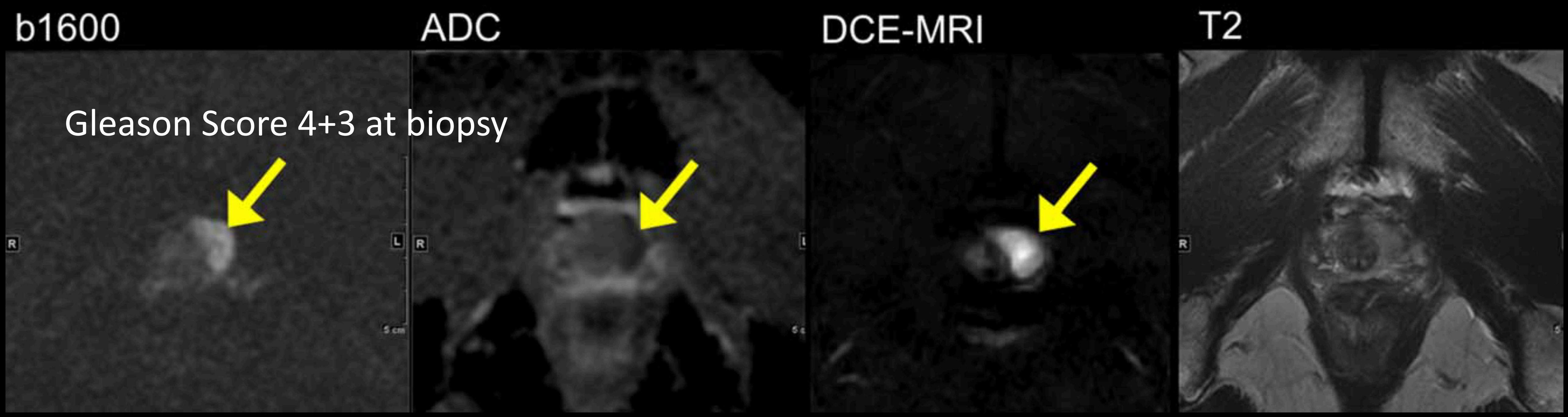
Respiratory-Triggered Single-Shot EPI DWI of the Liver at 1.5T




*Lewis S, MRI Clin N Am, 2014; 22: 373-395.*

# Clinical Applications: DWI

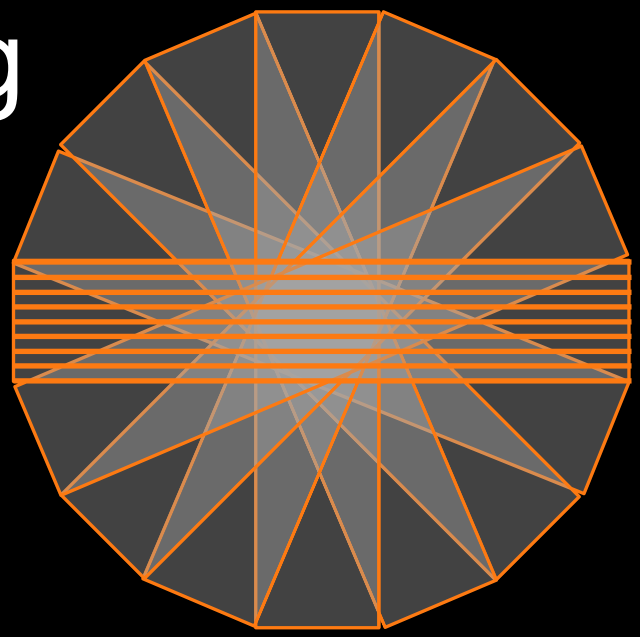
Reduced Field-of-View Single-Shot EPI DWI of the Prostate at 3T




*Taouli B, JMRI, 2016; 44: 521-540.*

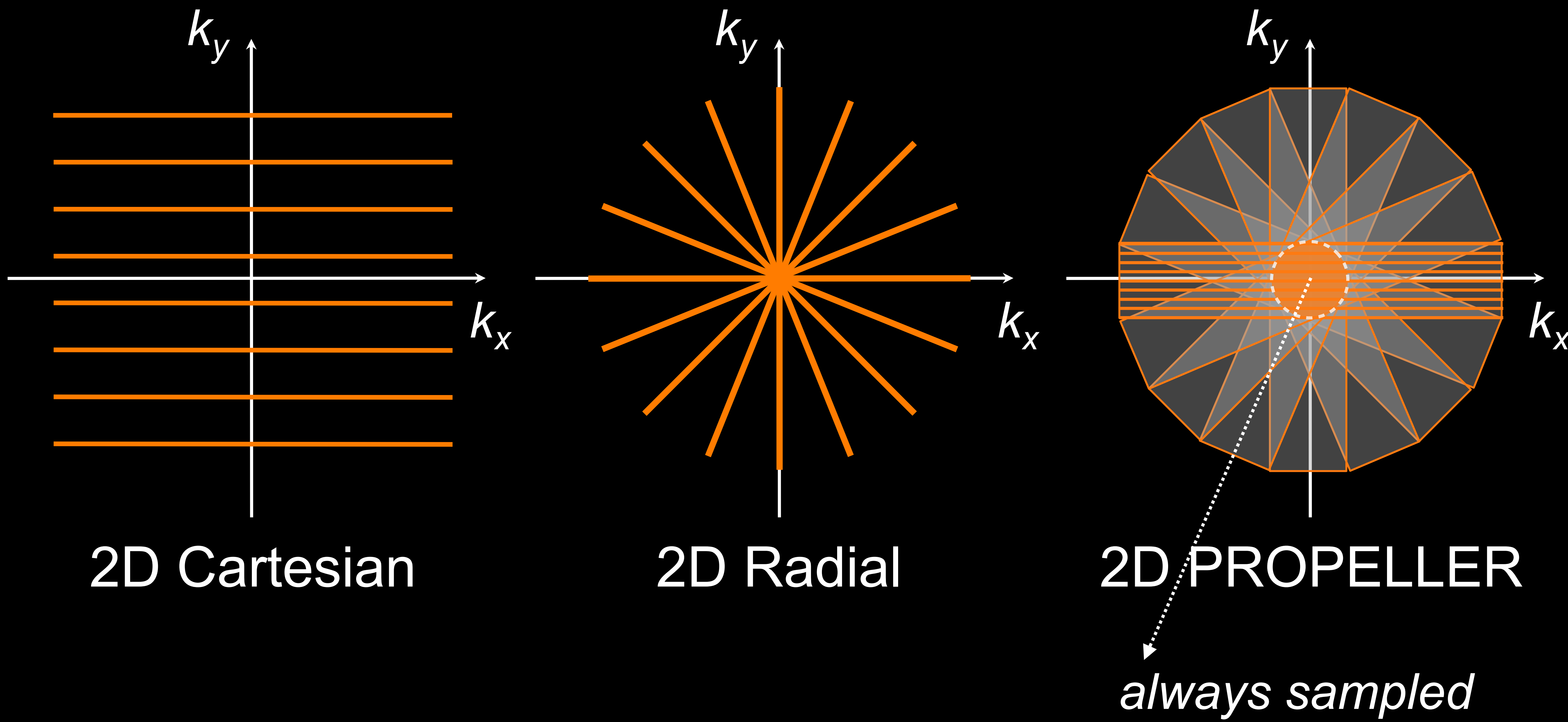
# PROPELLER

- Periodically Rotated Overlapping ParallEL Lines with Enhanced Reconstruction[1], aka BLADE
- Radial and Cartesian hybrid
- Oversampling at the center of k-space
  - correct inconsistencies between strips
  - reject data with through-plane motion
  - weigh strip contributions w.r.t. motion
  - average to decrease motion artifacts



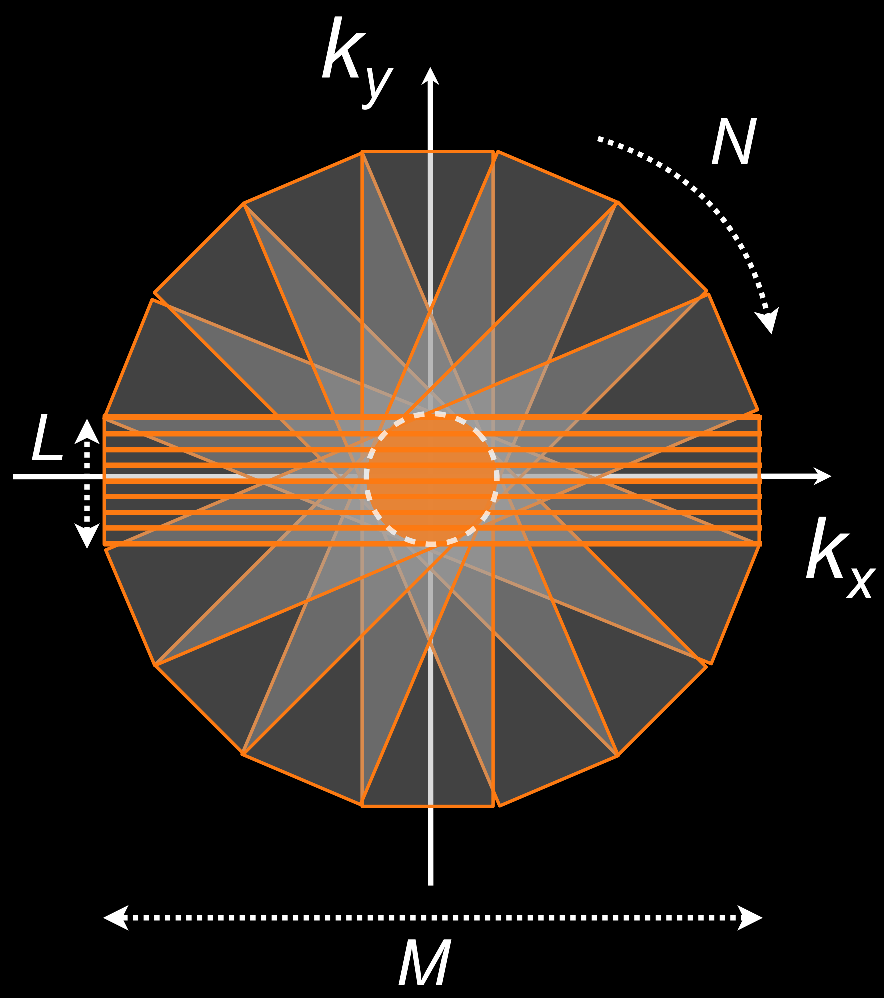
*[1]Pipe, MRM 1999; 42: 963-969*

# PROPELLER


$k_y$
$k_x$
2D Cartesian
$k_y$
$k_x$
2D Radial
$k_y$
$k_x$
2D PROPELLER
*always sampled*

# PROPELLER

## Trajectory Design:




*N* strips, successively rotated by $d\alpha = \pi/N$

*L* lines per strip, *M* points per line

For an *M* x *M* image, need $L \cdot N = M \cdot (\pi/2)$

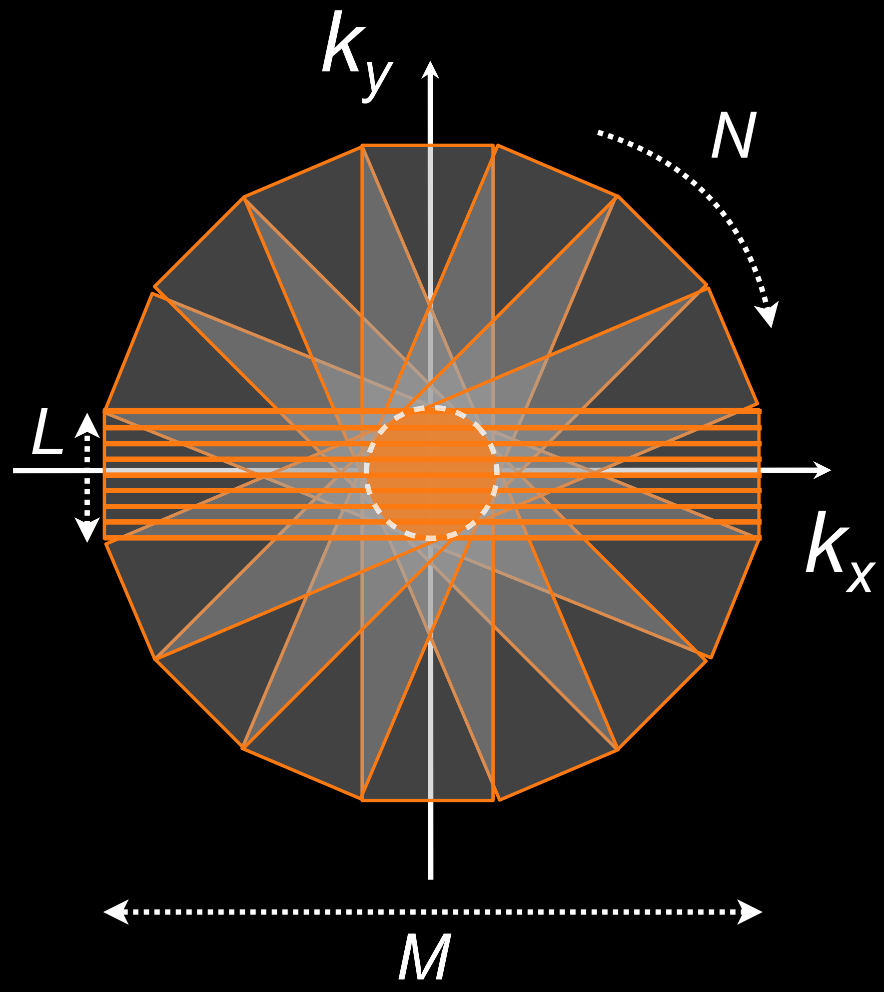
central oversampled circle of diameter *L*

Scan time trade-offs based on *L* and *N*

Asymmetric FOV also possible

# PROPELLER

## Trajectory Design Example:




24-cm FOV; 0.5 mm in-plan resln; $L$ = 28

$M$ = FOV/resln = 480

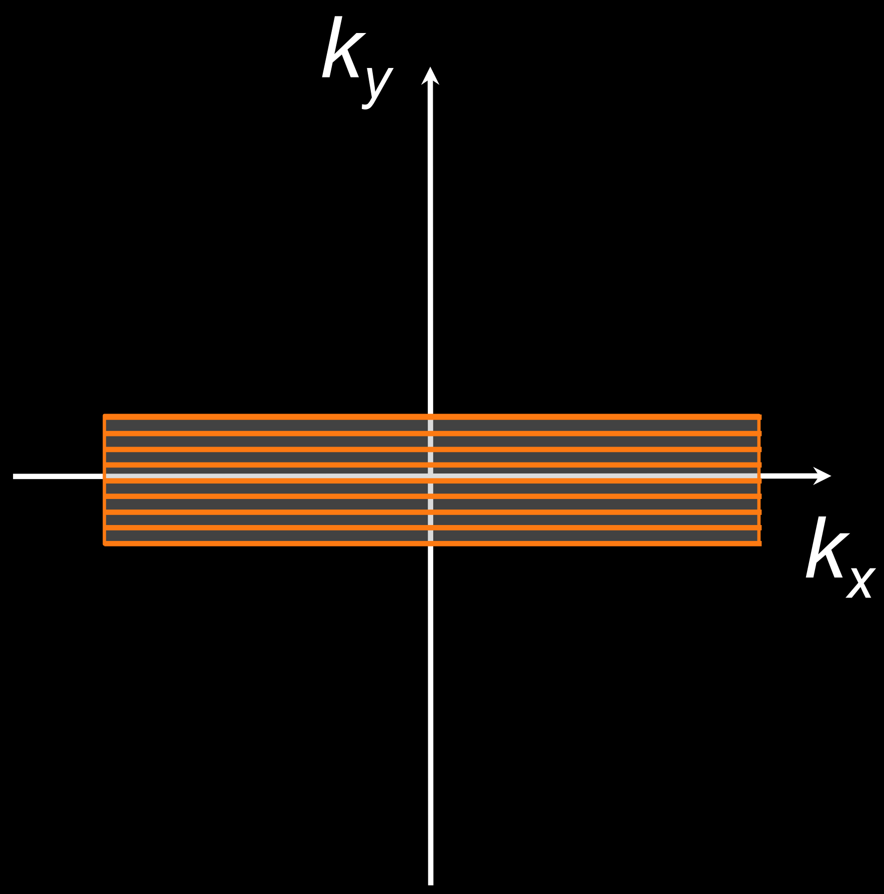
$N = (M/L)\cdot(\pi/2) \sim 27$

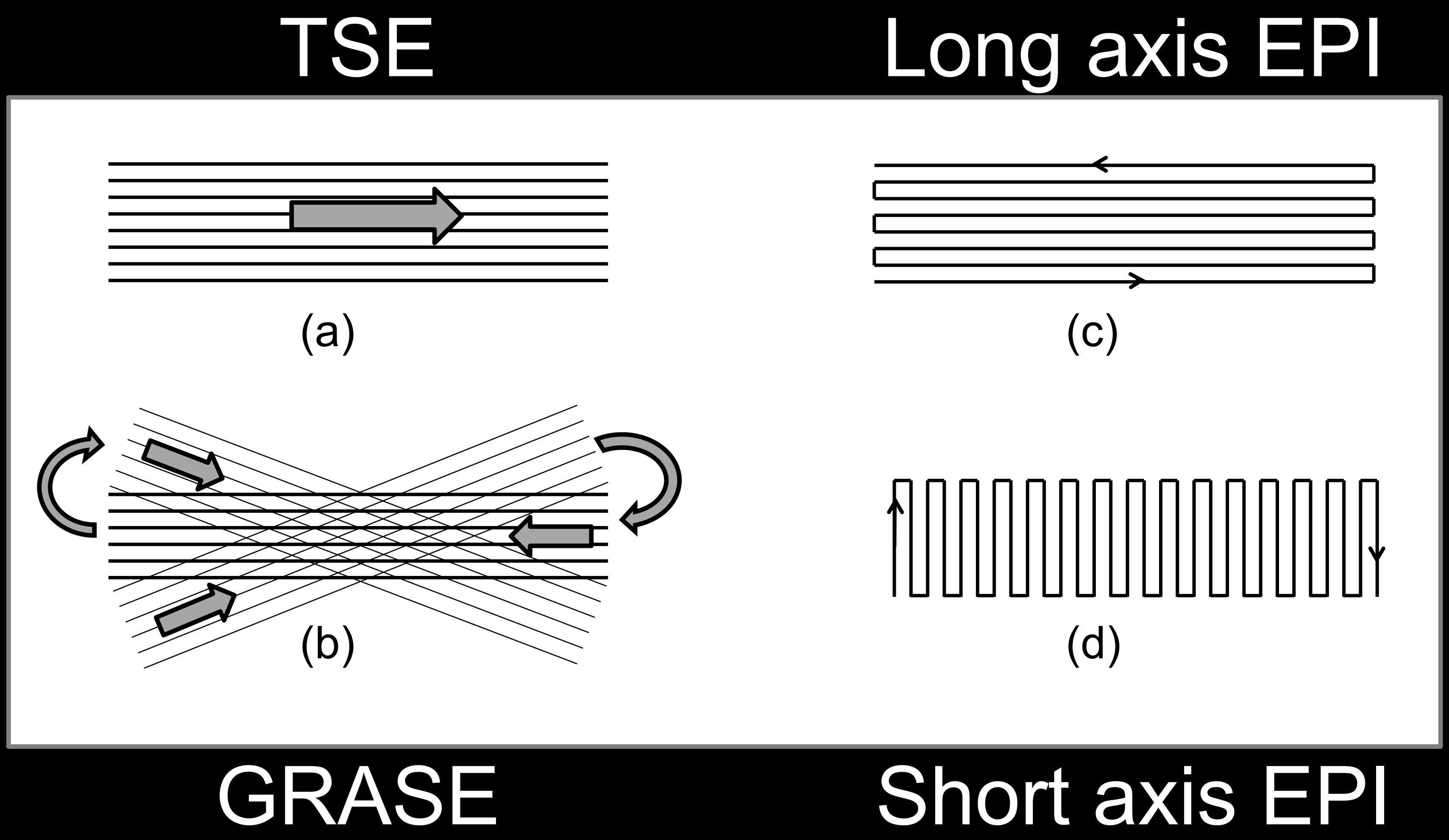
TR = 4000 ms, $T_{scan} = N\cdot\text{TR}$ = 1 min 48 s

*Bernstein et al., Handbook of MRI Pulse Sequences, Ch 17.5*

# PROPELLER

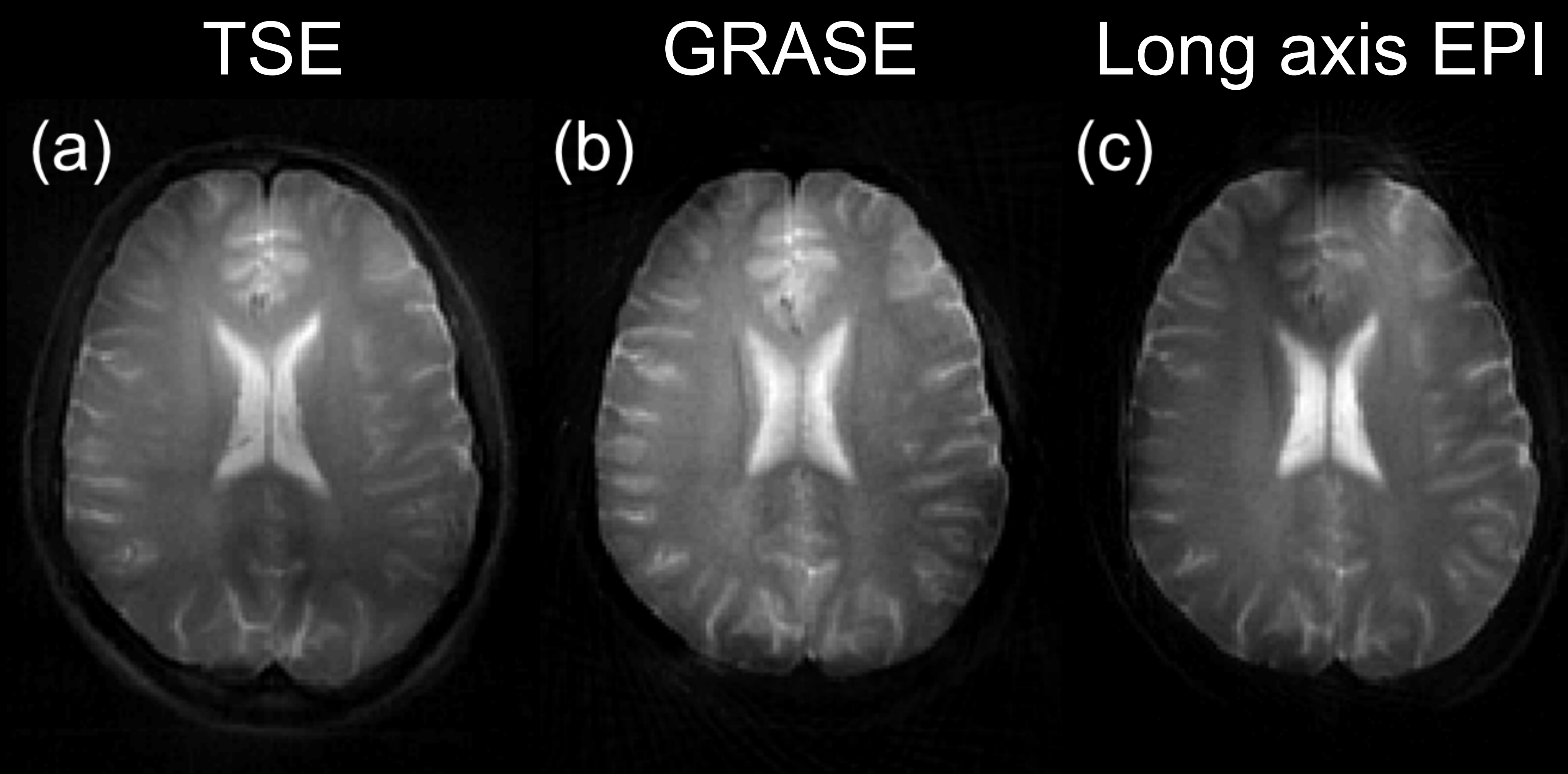
Trajectory Design:




*Courtesy of Dr. Novena Rangwala*

# PROPELLER




*Courtesy of Dr. Novena Rangwala*

# PROPELLER

Motion correction:

Rotation in image space ⟷ rotation in k-space

*Compare k-space magnitude between strips*

Translation in image space ⟷ linear phase in k-space

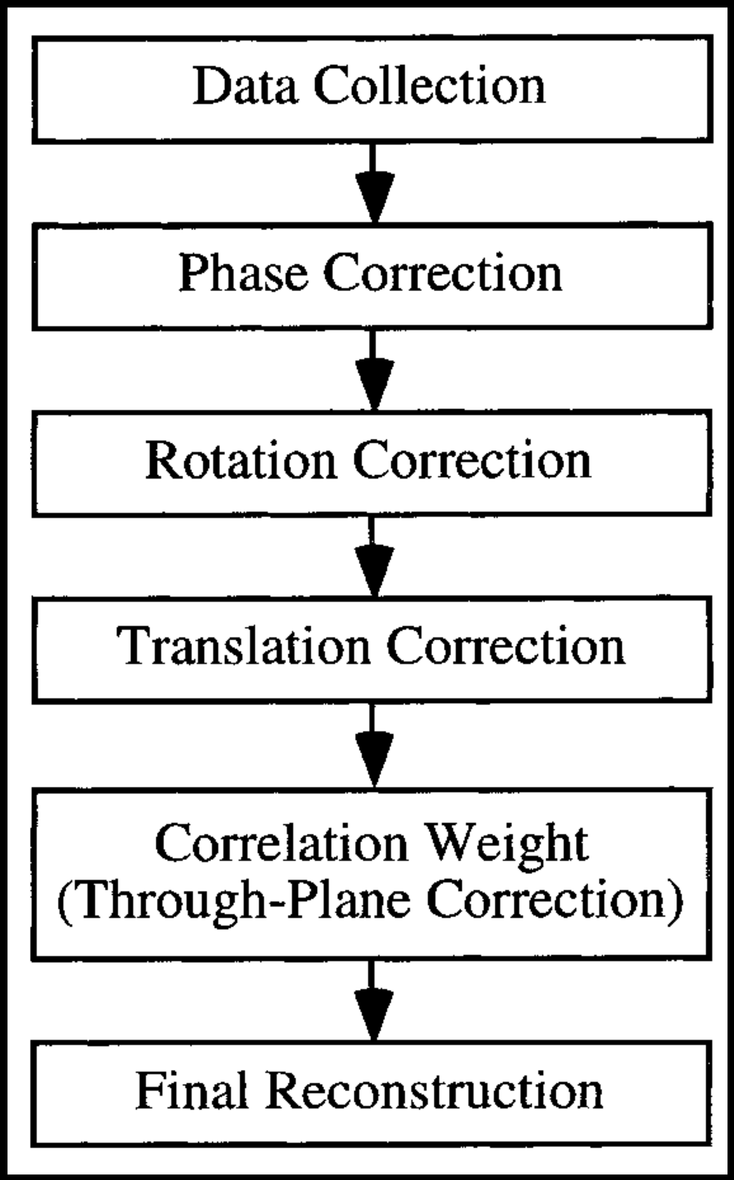
*Compare k-space phase between strips*

Other motion in image space ⟷ k-space mag/phase

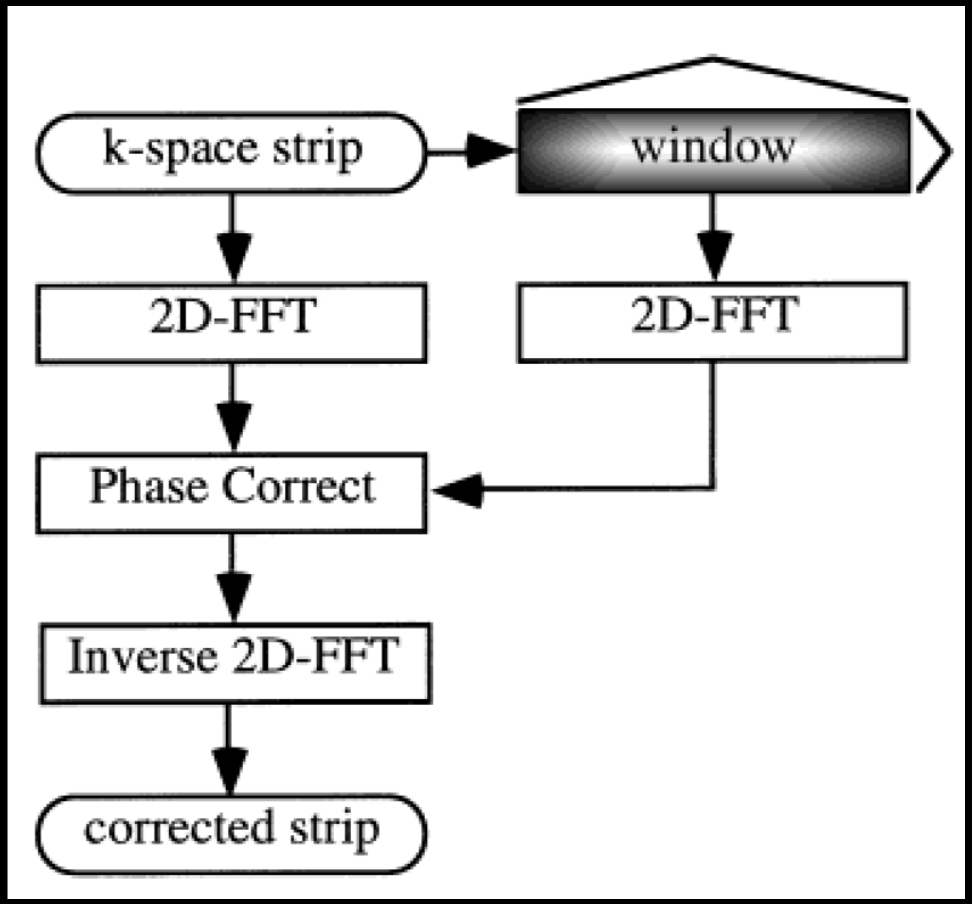
*Compare and weigh importance of strips*

# PROPELLER

Reconstruction:



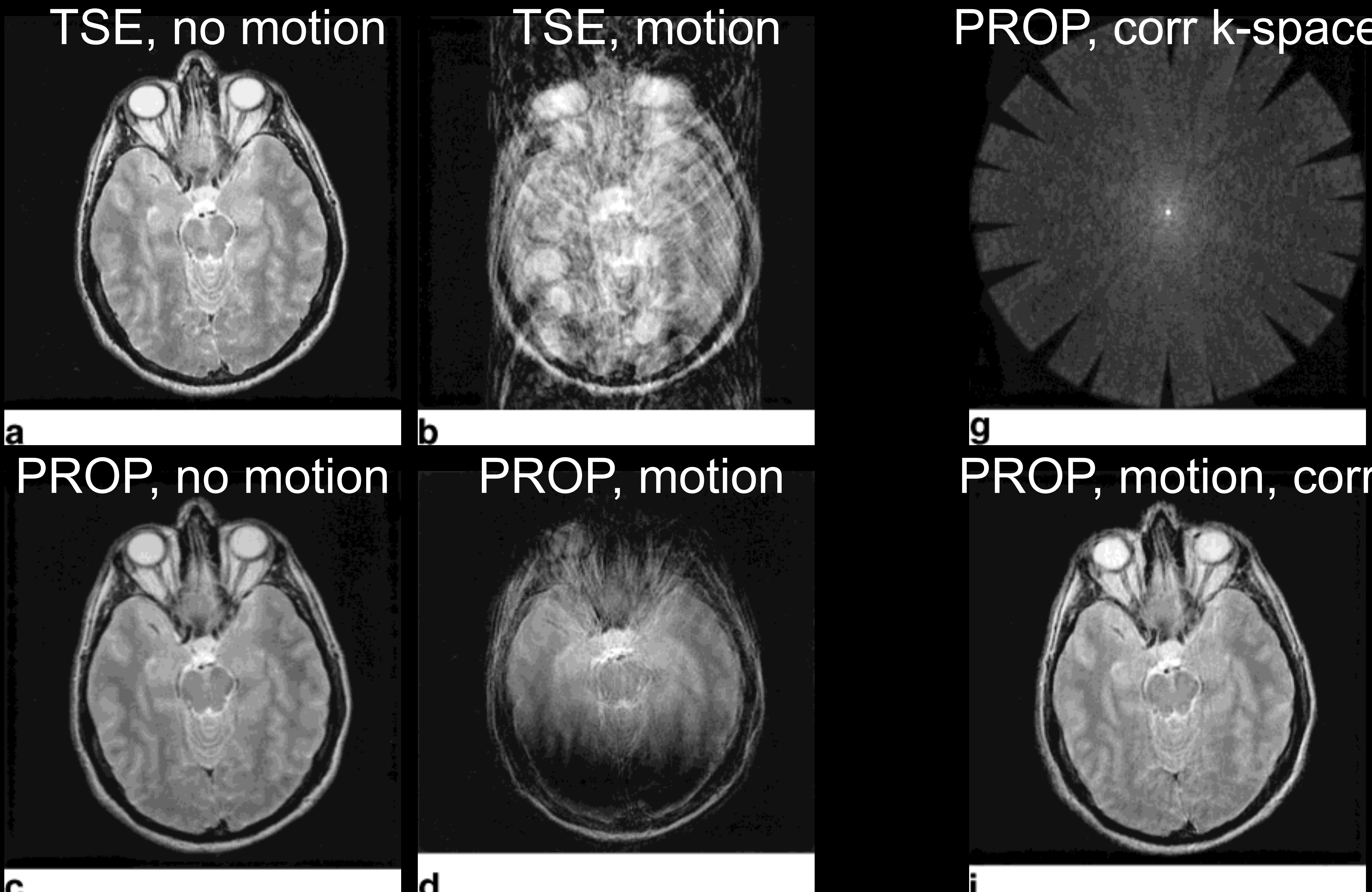

*For each strip:*




*density compensation*

*Pipe, MRM 1999; 42: 963-969*

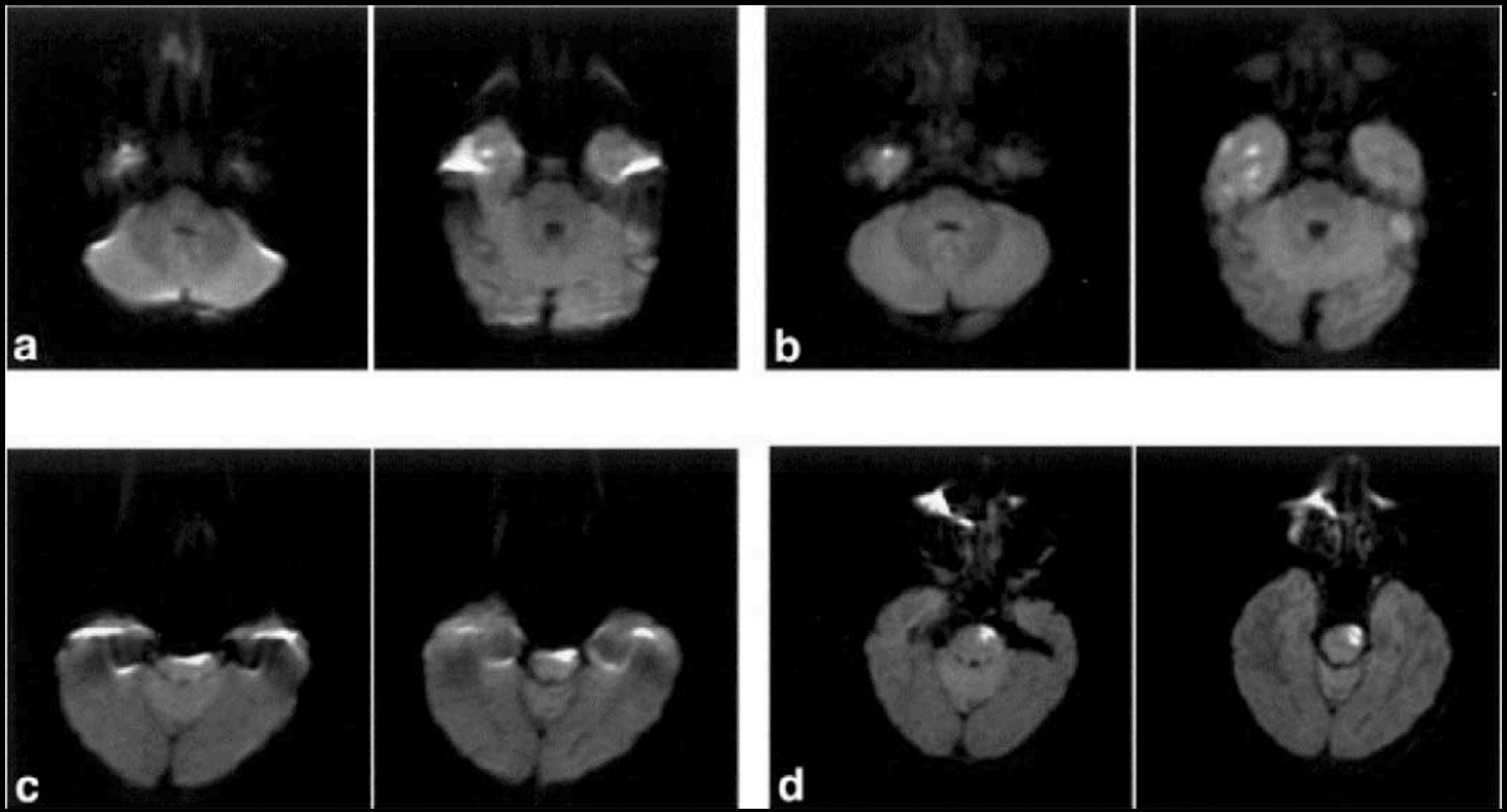
# PROPELLER




*Pipe, MRM 1999; 42: 963-969*

# PROPELLER

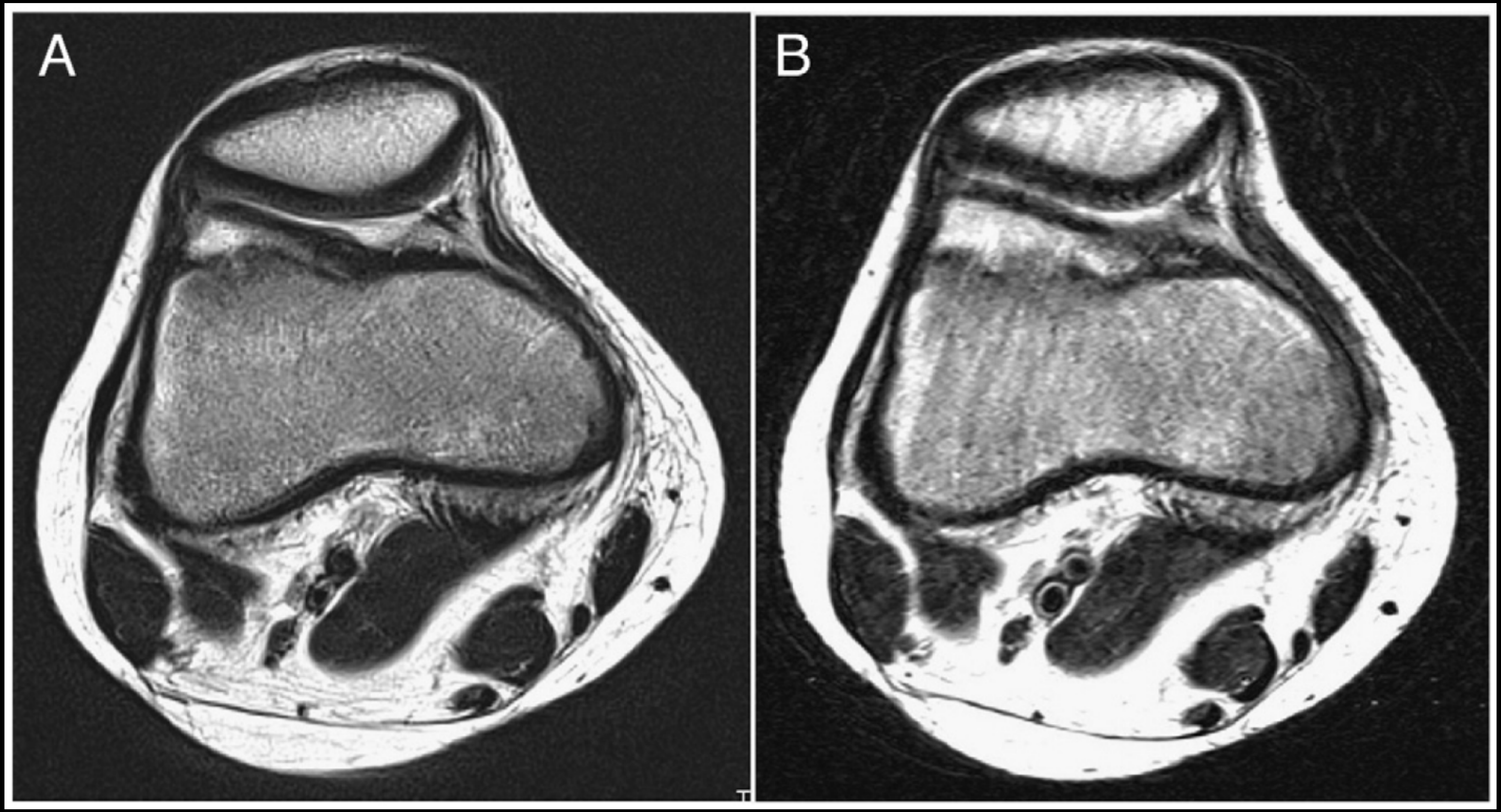
Single-Shot EPI DWI | PROPELLER DWI




*Bammer R, EJR, 2003; 45: 169-184*

# PROPELLER

T2w TSE BLADE | T2w TSE




*Lavdas E, et al., MRI 2012; 30: 1099-1110*

# PROPELLER

- Advantages
  - Robust to motion
- Disadvantages
  - Increased scan time
- Extensions
  - 3D blocks; 3D rods (TORQ)

# Clinical Applications

- Brain
- Abdomen/Pelvis
- MSK
- Diffusion-weighted imaging (high-resolution)

# Summary

- EPI
  - Very popular for fast MRI!
  - Design, recon, corr drives a lot of research
- PROPELLER
  - Very robust to motion
  - Philosophy can be adapted to other seq

# Thanks!

- Further reading
  - Bernstein et al., Handbook of MRI Sequences
  - pubmed.org
- Acknowledgments
  - Novena Rangwala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http://mrrl.ucla.edu/wulab