
Fast Imaging Trajectories: EPI and PROPELLER

M229 Advanced Topics in MRI

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Class Business

- Recorded lectures
- Homework 2 due 5/6 Fri by 5 pm
- Office hours
- Final project
 - Proposal due 5/9 Mon by 5 pm
 - Abstract due 6/3 Fri by 5 pm
 - Presentations and Q&A on 6/9 Thu 10-12

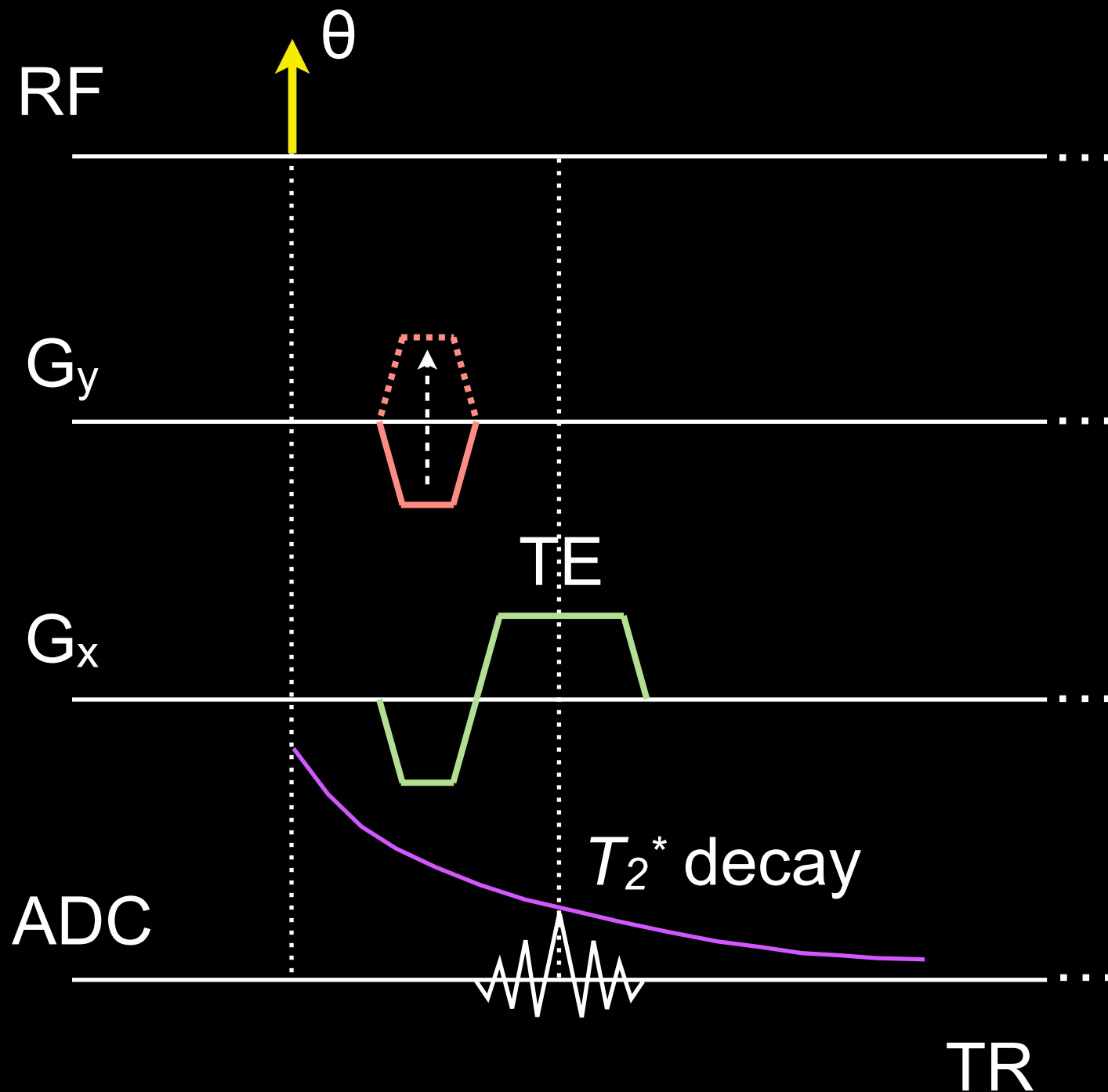
Outline

- EPI¹
 - Pulse sequence and design considerations
 - Alternatives
 - Artifacts and corrections
- PROPELLER²
 - Applications

¹Mansfield P, *J Phys C: Solid State Phys.*, 1977

²Pipe JG, *Magn. Reson. Med.*, 1999

Gradient Echo

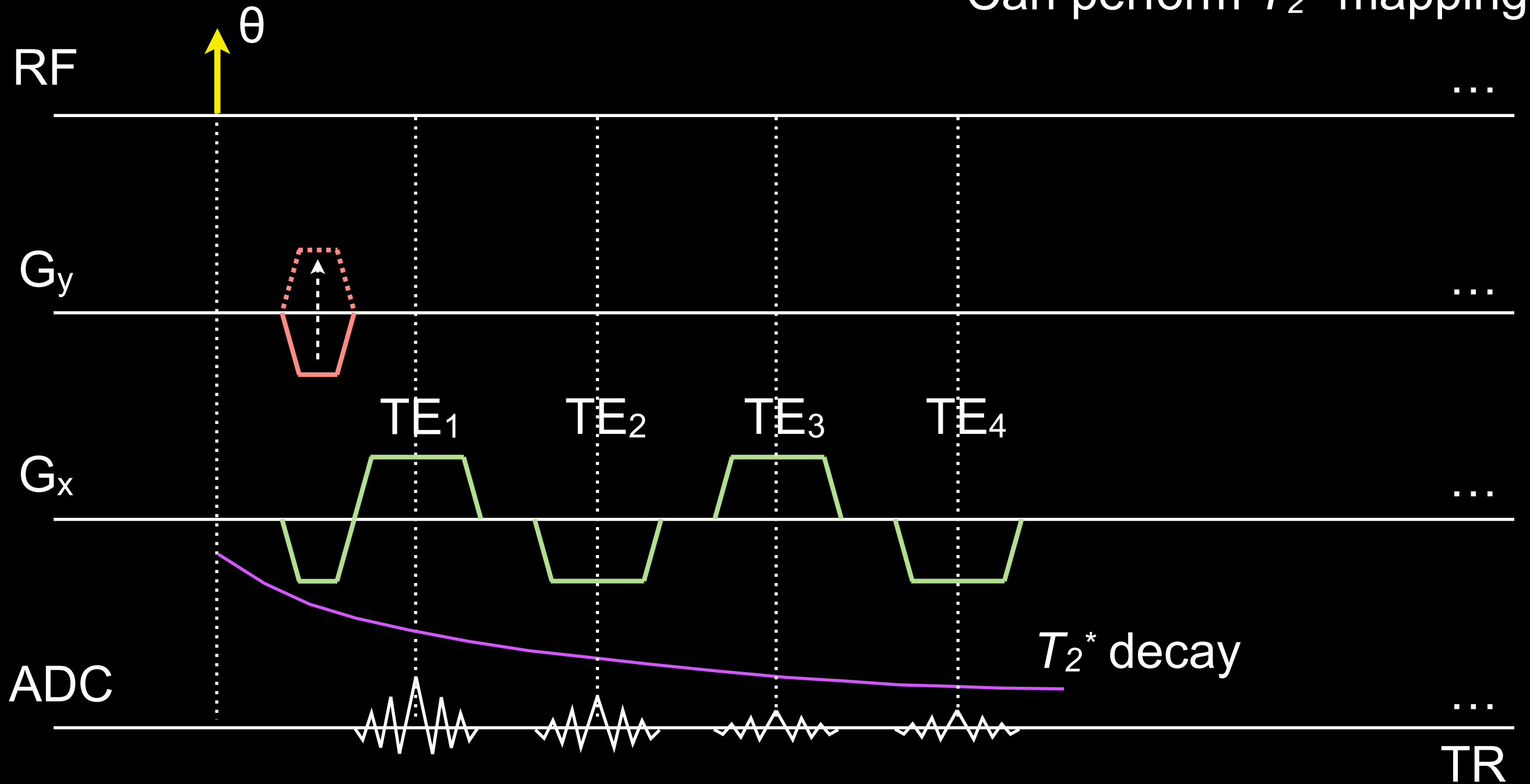


- Utilization of transverse magnetization
 - With $T_s = 8 \mu s$ and $N_x = 128$, $T_{acq} = 1.024 ms$
 - $<2\%$ of T_2^* in brain at 3 T!¹
- Scan time
 - $T_{GRE} = N_{pe} \times TR$
 - $TR = 10 ms$, $N_{pe} = 256$:
 $T_{GRE} = 2.56 sec$

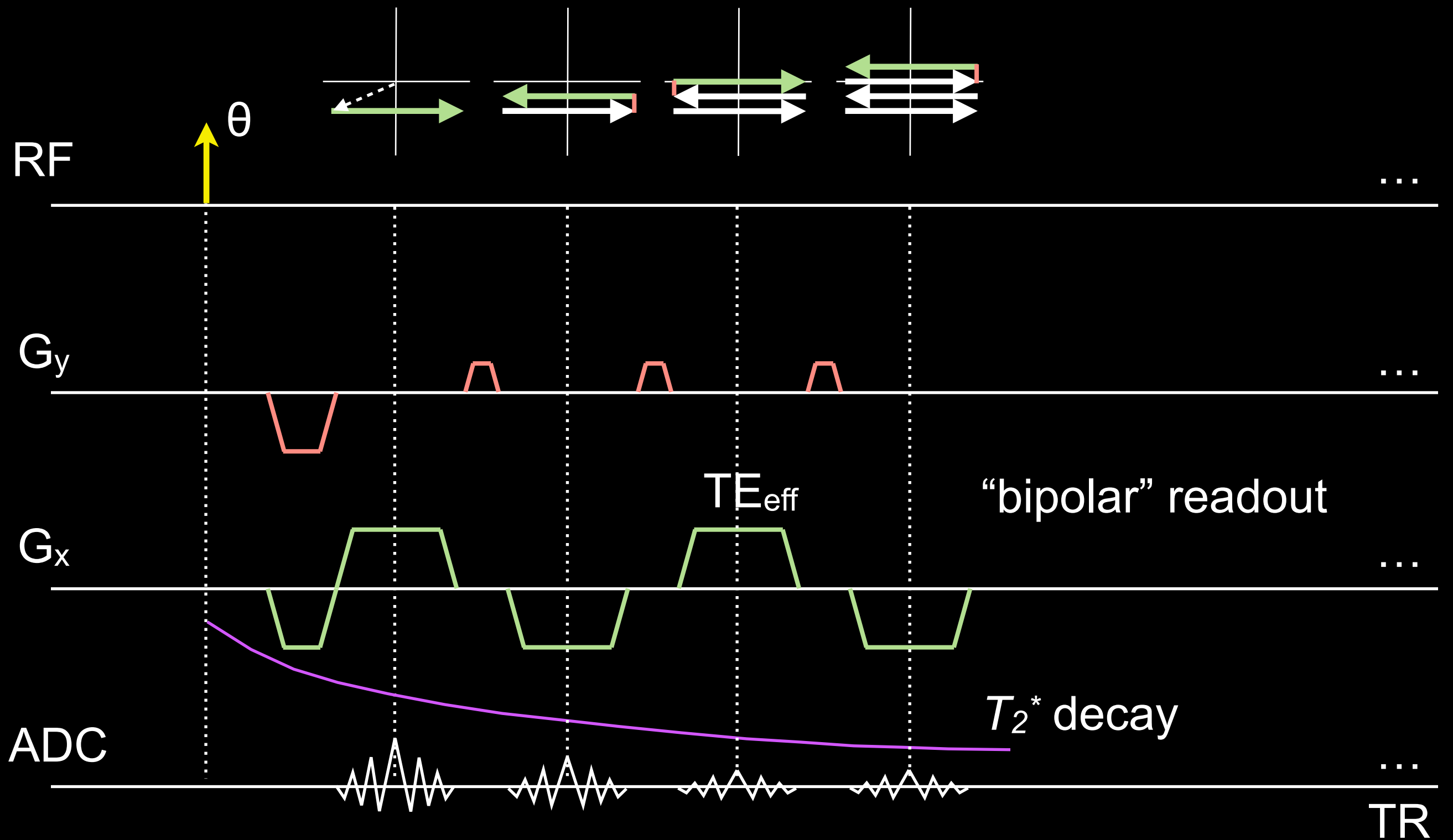
¹Peters, et al., Proc ISMRM 2006

Multi-echo Gradient Echo

ΔTE can be non-uniform
Can perform T_2^* mapping

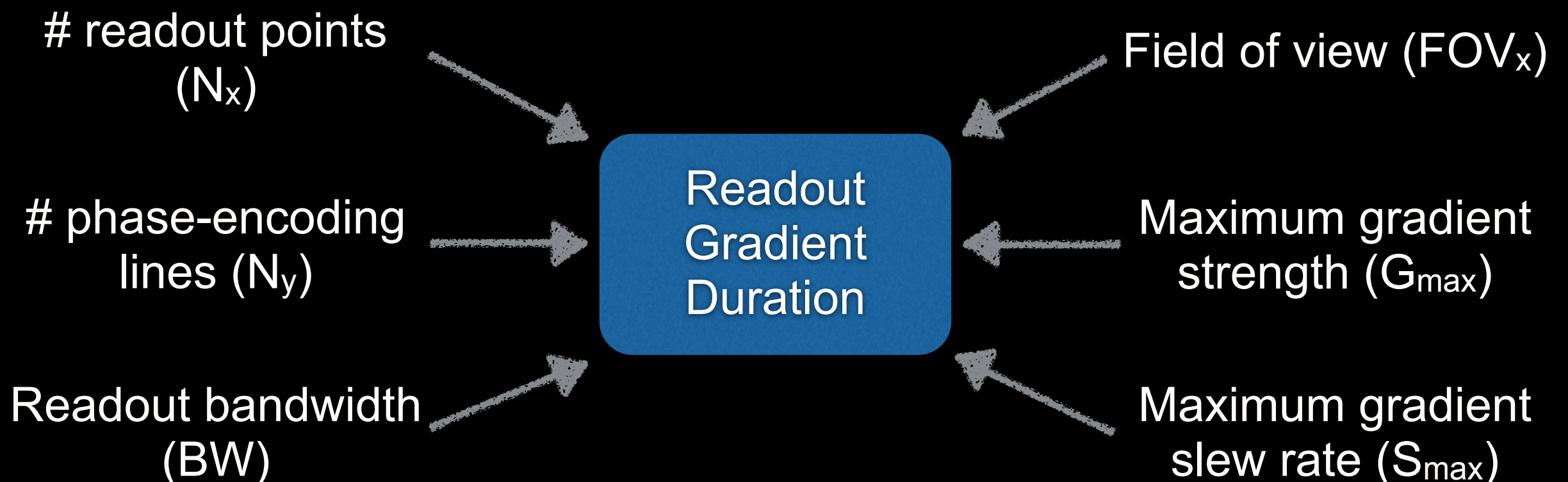


Gradient-Echo EPI

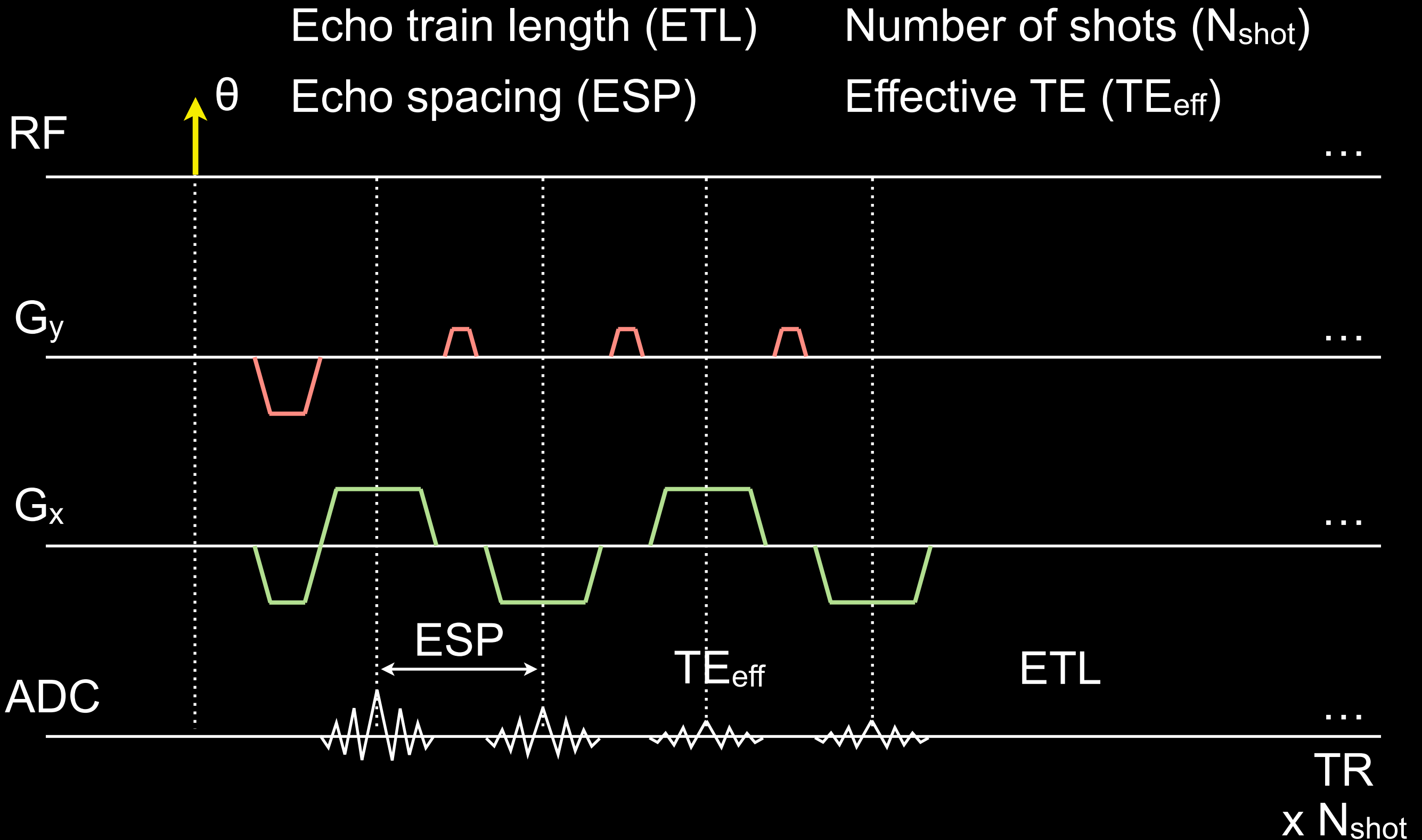


Design Basics

- 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

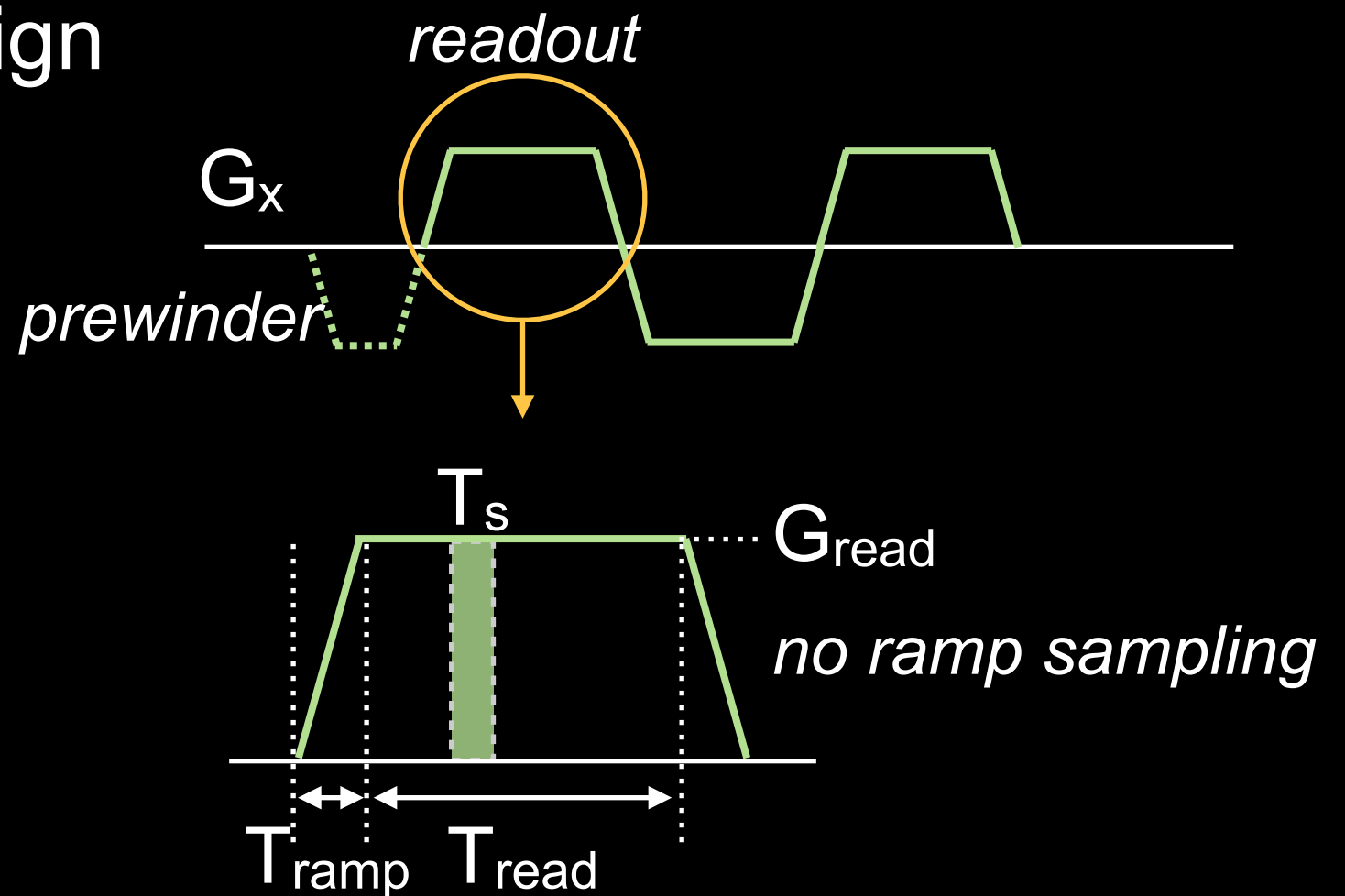
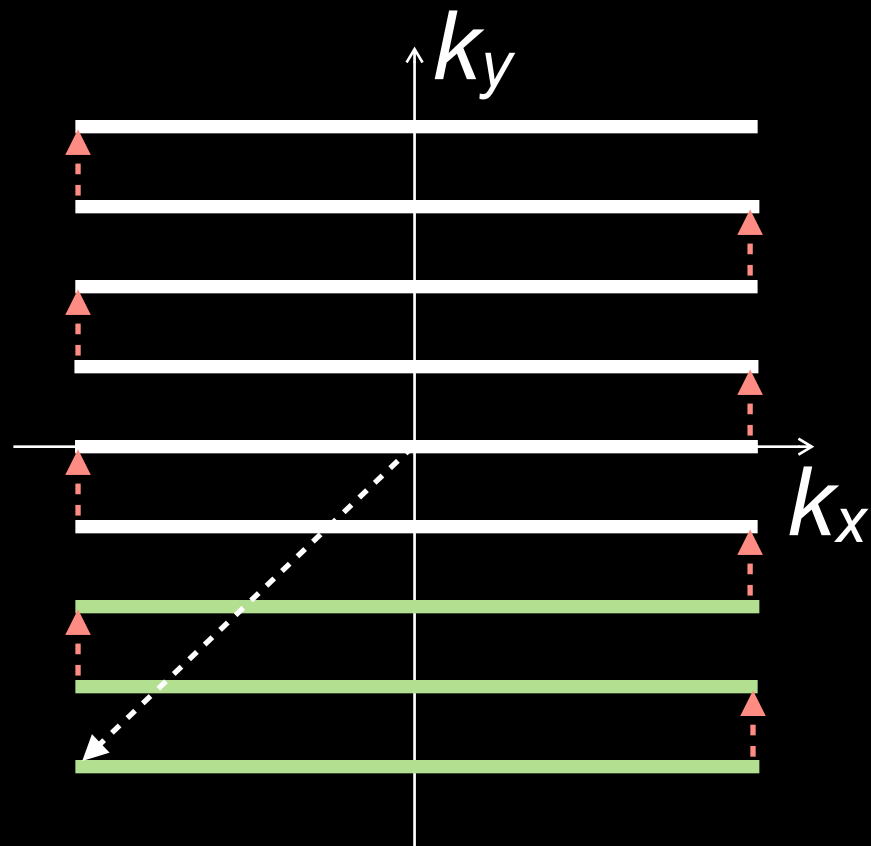


EPI Sequence Parameters



EPI Sequence Parameters

Readout Gradient Design



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

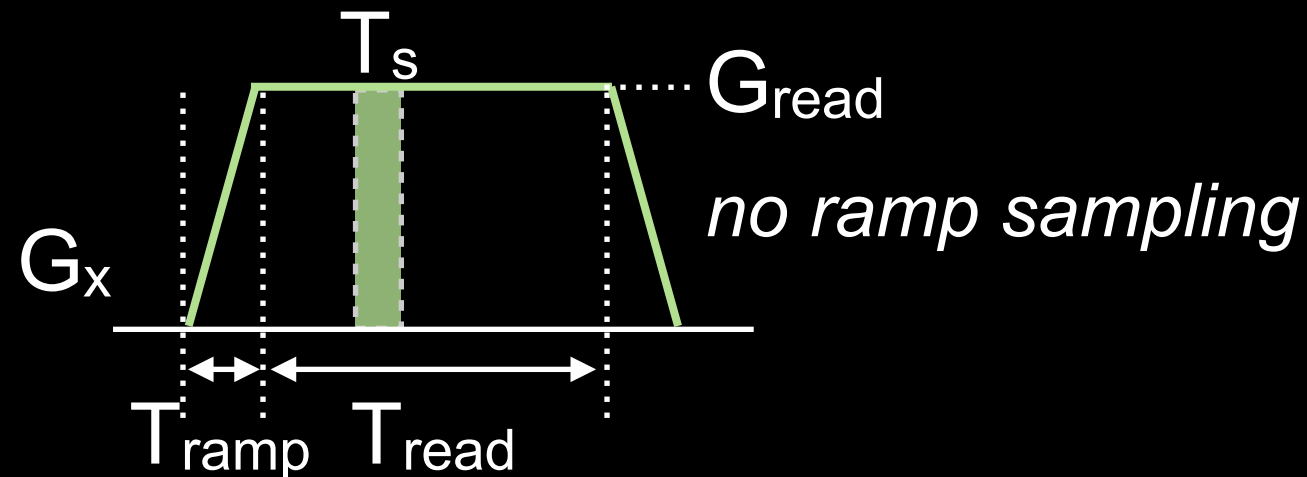
$$G_{\text{read}} \leq G_{\text{max}} \quad \text{SR} \leq S_{\text{max}}$$

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

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

EPI Sequence Parameters

Readout Gradient Design Example:



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

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

$$T_s = 8 \mu\text{s}; N_x = 128;$$
$$\text{FOV}_x = 22 \text{ cm}; \text{SR} = 120 \text{ T/m/s}$$

$$G_{\text{read}} = 13.3 \text{ mT/m}$$

$$\text{ESP} = 1.246 \text{ ms}$$

$$\text{If } T_s = 4 \mu\text{s}$$

$$\text{ESP} = 0.955 \text{ ms}$$

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

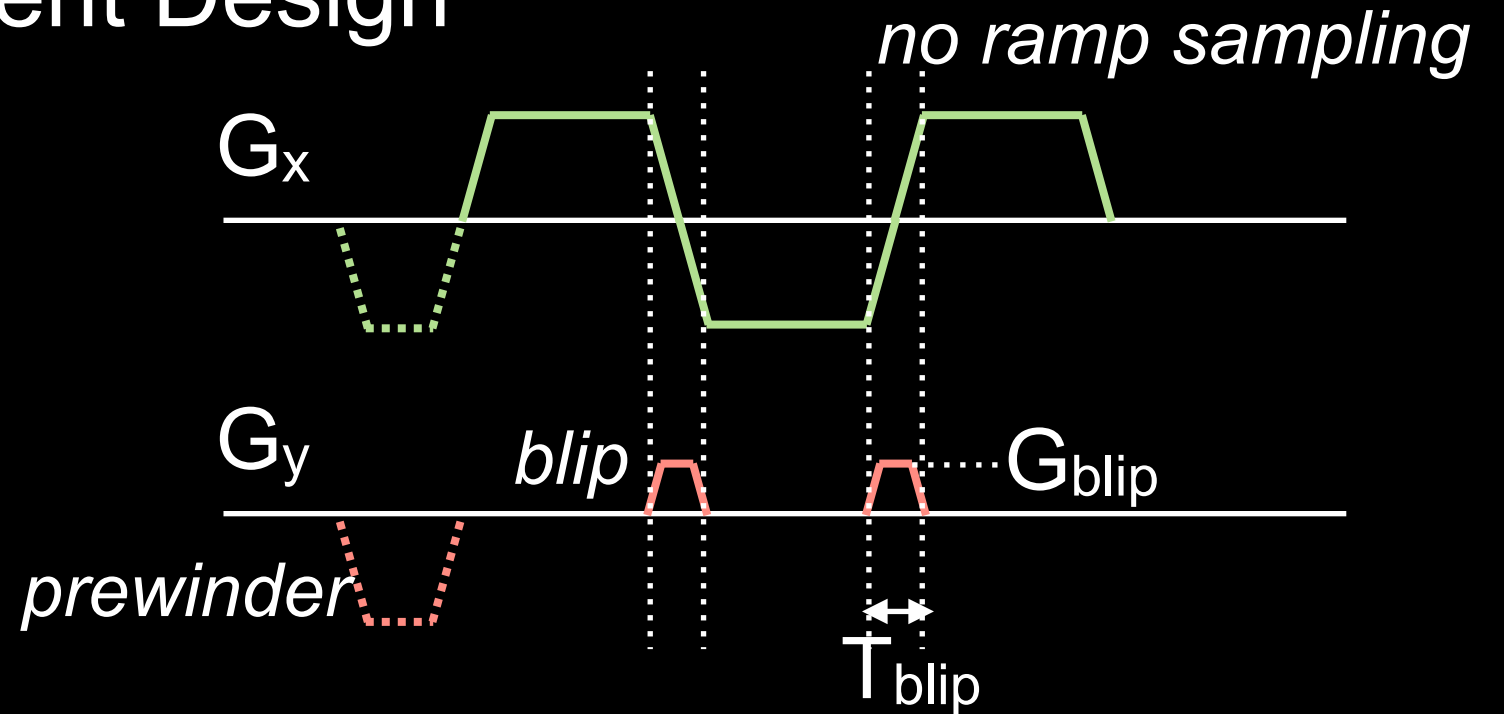
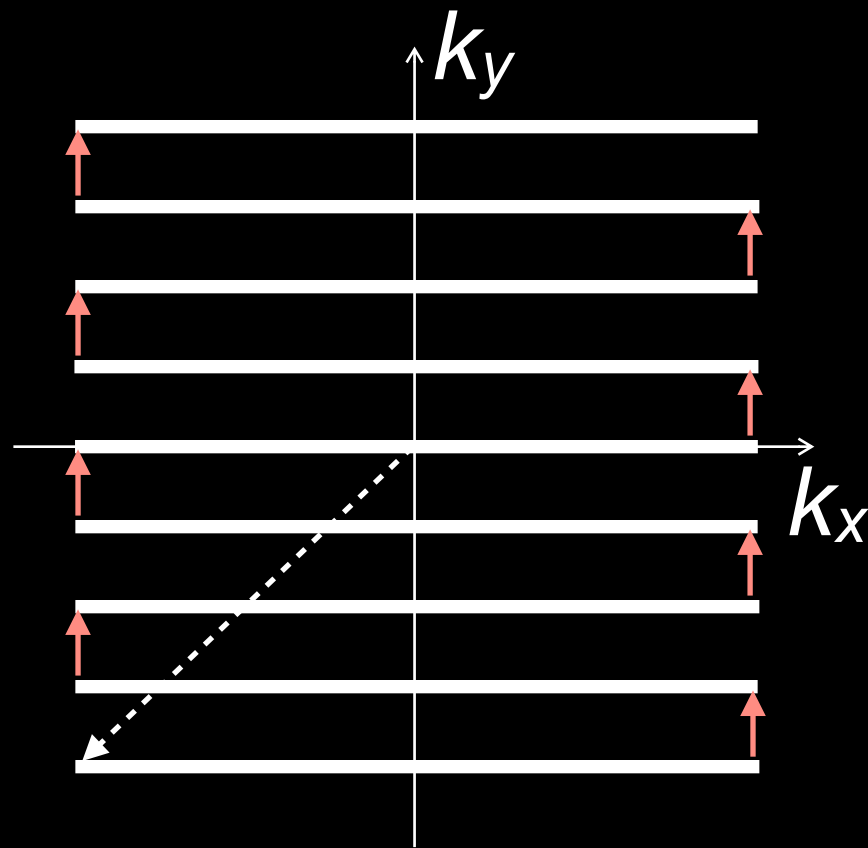
$$\text{ESP} = 2.354 \text{ ms}$$

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

$$\text{ESP} = 3.172 \text{ ms}$$

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

$PEbw = 1/ESP \sim 1$ kHz; more off-resonance artifacts

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

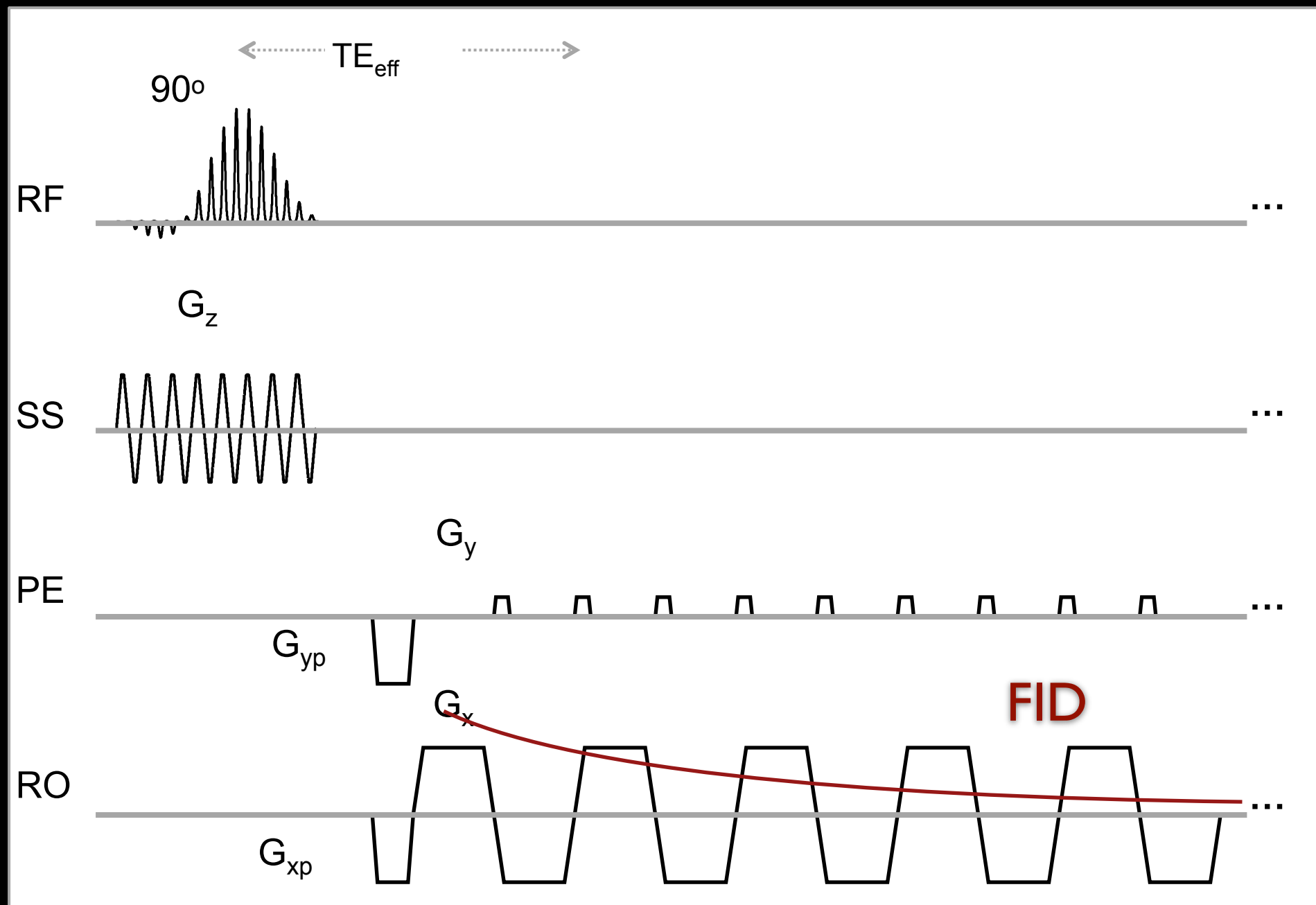
EPI Sequence Parameters

- 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
- Example: 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

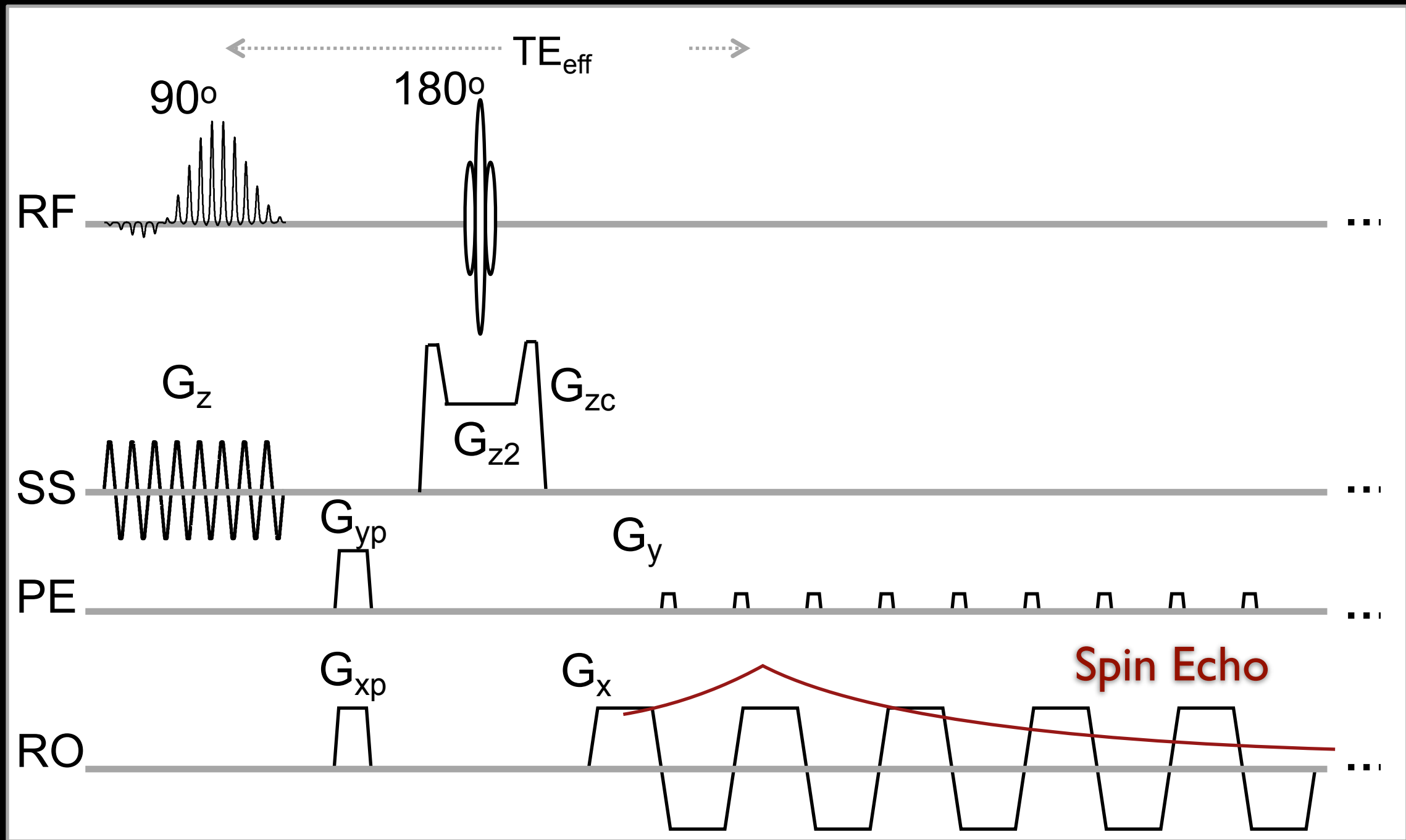
Minimizing Readout Duration / ESP

- 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 EPI

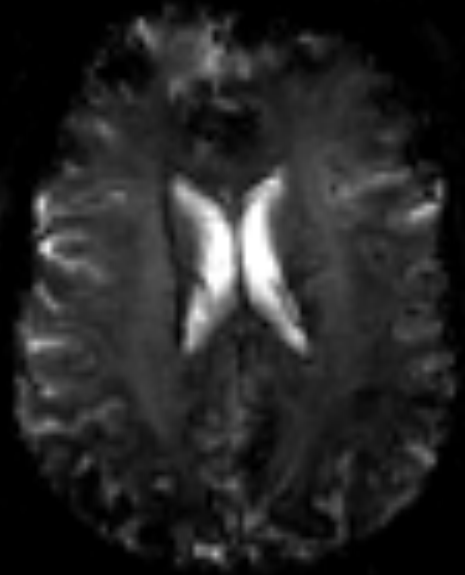


Spin-Echo EPI

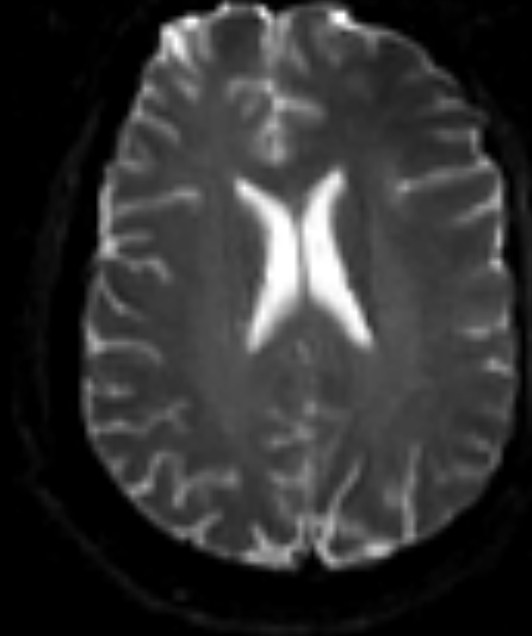


Comparison

GRE-EPI



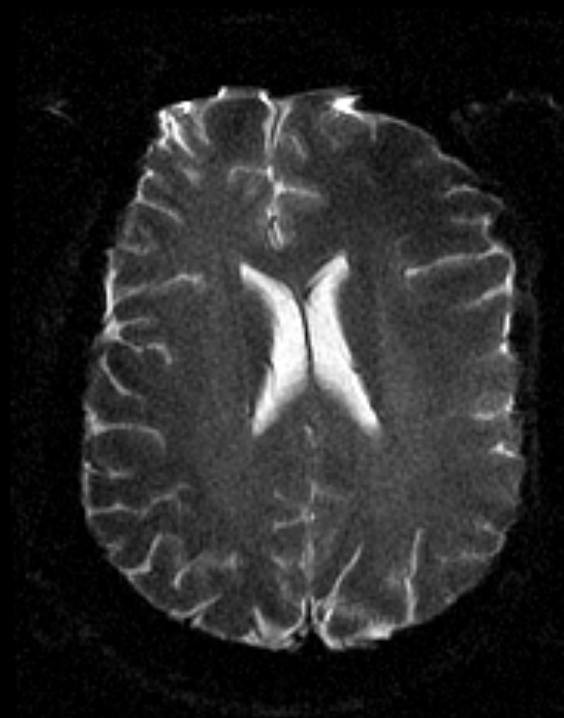
SE-EPI



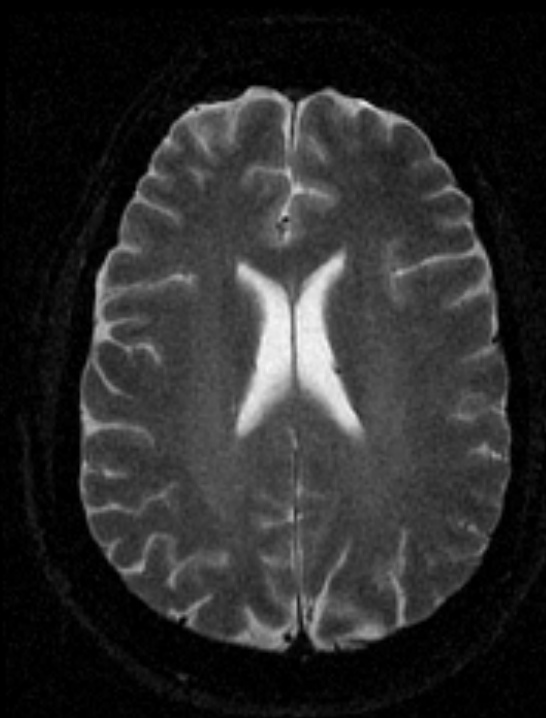
- GRE-EPI More signal dropouts, distortion
- GRE-EPI: More susceptibility effects, better for functional MRI acquisition

Managing EPI distortion

SE-EPI



???

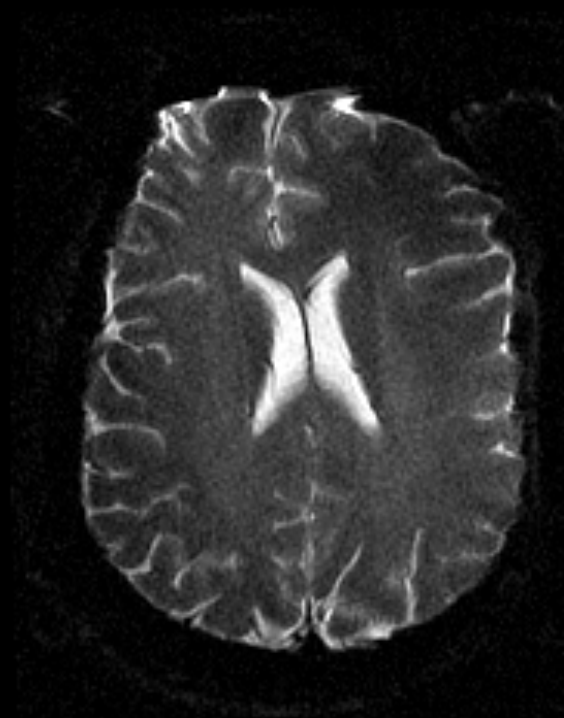


Multi-shot EPI

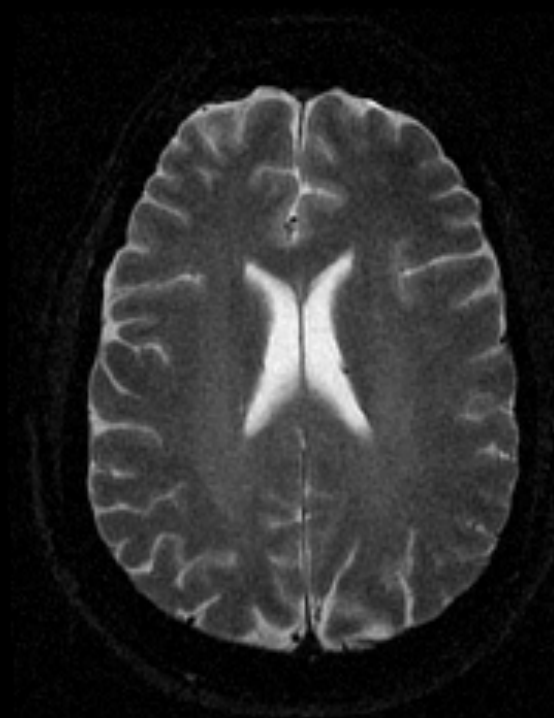
- Single-shot EPI (ssEPI)
 - minimal motion artifacts
 - low resolution
 - geometric distortion and signal loss
- Multi-shot EPI (msEPI)
 - aka interleaved or segmented EPI
 - higher resolution
 - less distortion & signal loss (improve PEbw)
 - **need to address motion and phase inconsistencies**

Comparison

ssEPI



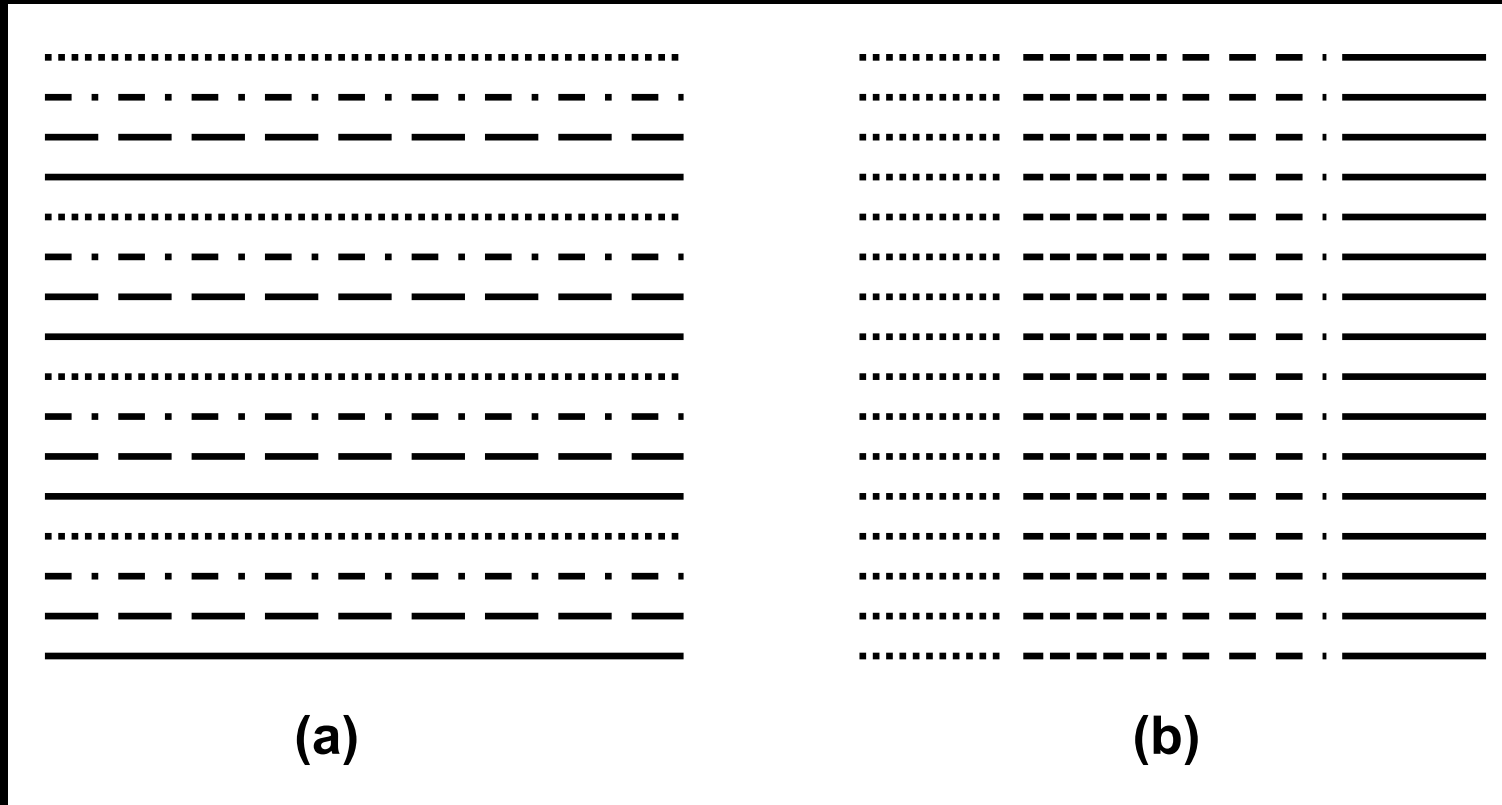
msEPI



Multi-shot EPI

Interleaved

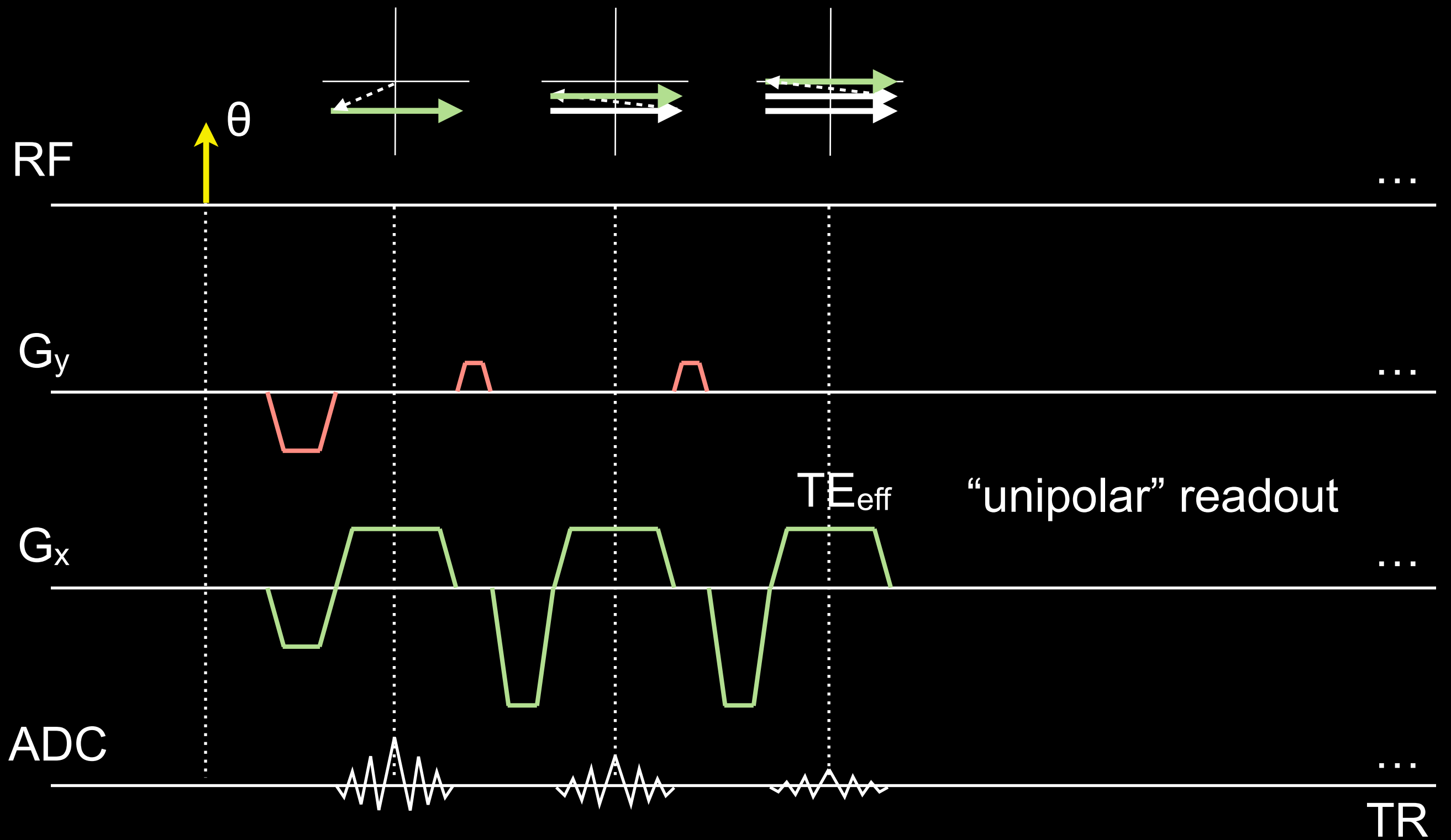
Readout
Segmented



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

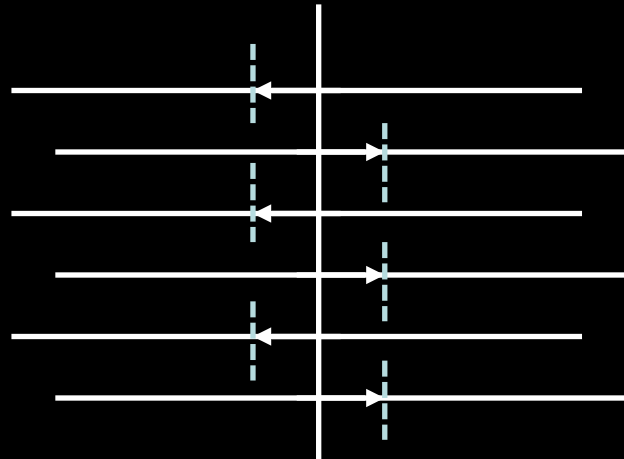
- 3D echo-volume imaging (EVI)
- Hybrid EPI + non-Cartesian (e.g., PROPELLER, EPI in a circular plane)
- Multi-echo chemical shift imaging
- Echo-planar spectroscopic imaging (EPSI), 2D and 3D

EPI Artifacts

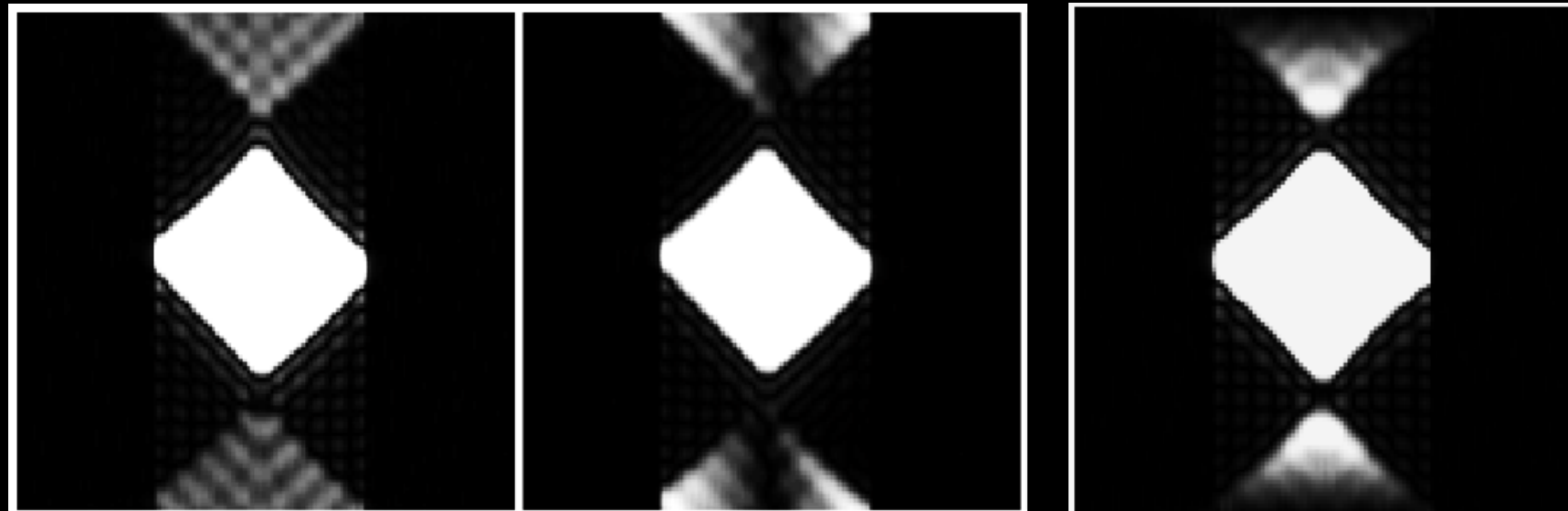
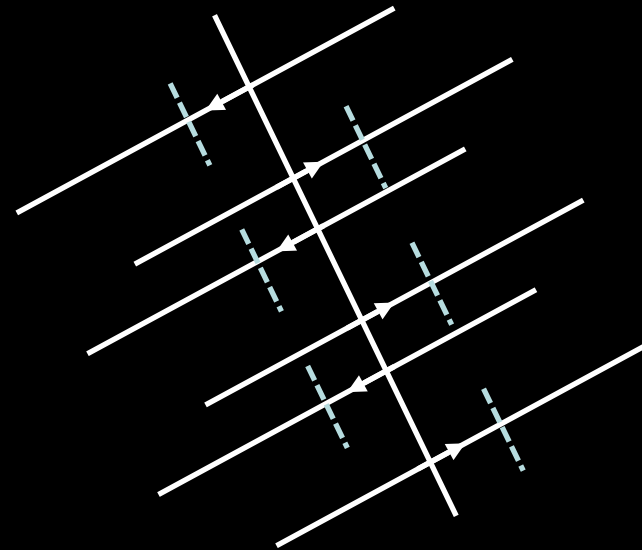
- Nyquist ghosting artifacts
- Chemical-shift artifacts, e.g., fat
- Signal drop-out
- Geometric distortion

EPI Ghosting Artifacts

'Orthogonal' Plane



'Oblique' Plane



EPI Ghosting Artifacts

- Inconsistencies between even/odd echoes due to:
 - Spatially independent (constant):
B₀ 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

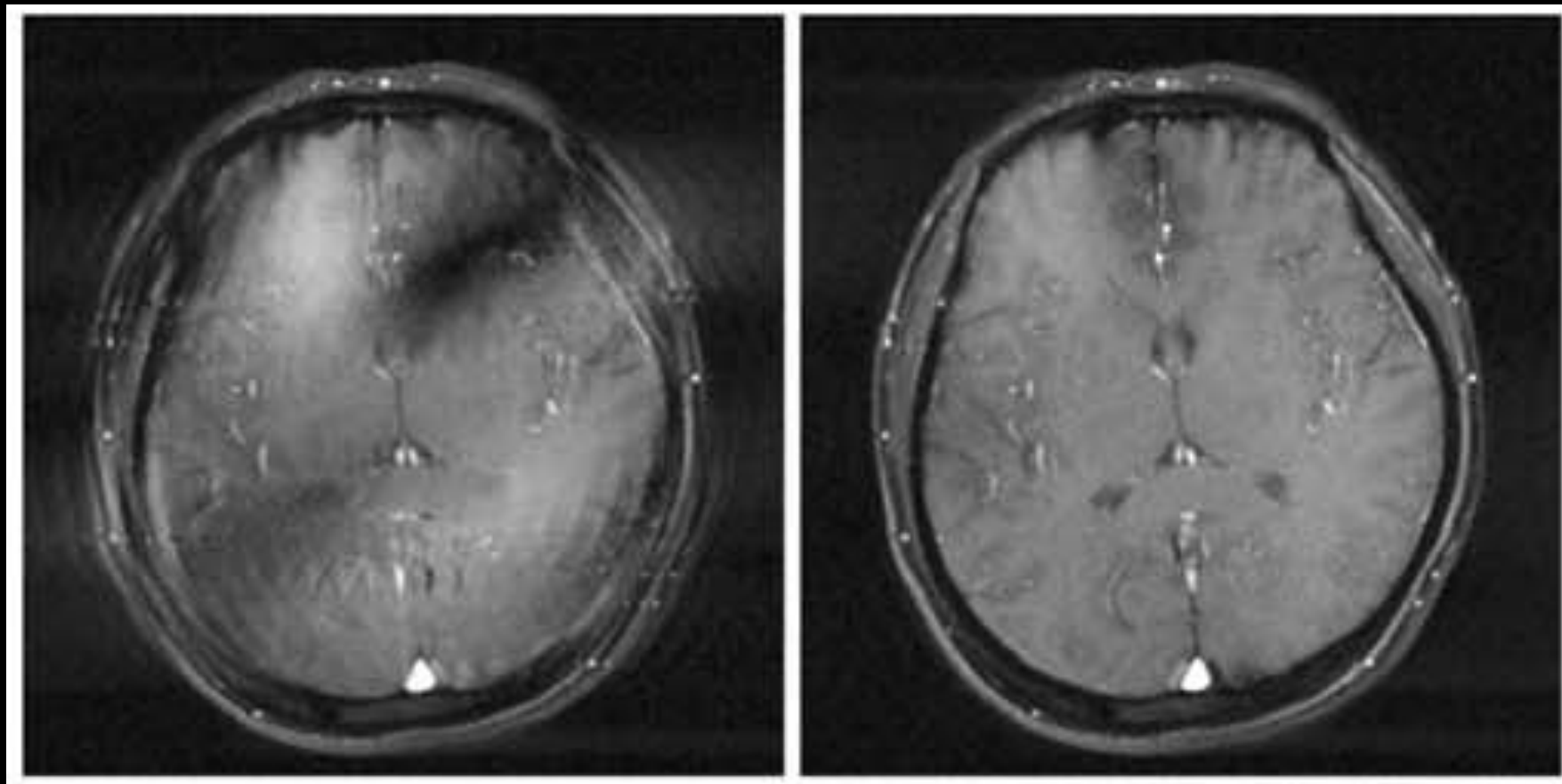
- Along readout
 - $\Delta x_{cs} = \Delta f_{cs} \cdot (FOV_x / RObw)$
 - At 1.5 T, $\Delta f_{WF} \sim 210$ Hz
for $FOV_x = 32$ cm and $RObw = 250$ kHz,
 $\Delta x_{cs} = 0.027$ cm
- Along phase encode
 - $\Delta y_{cs} = \Delta f_{cs} \cdot (FOV_y / PEbw)$,
 $PEbw = 1 / ESP$
 - for $ESP = 1$ ms, $\Delta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

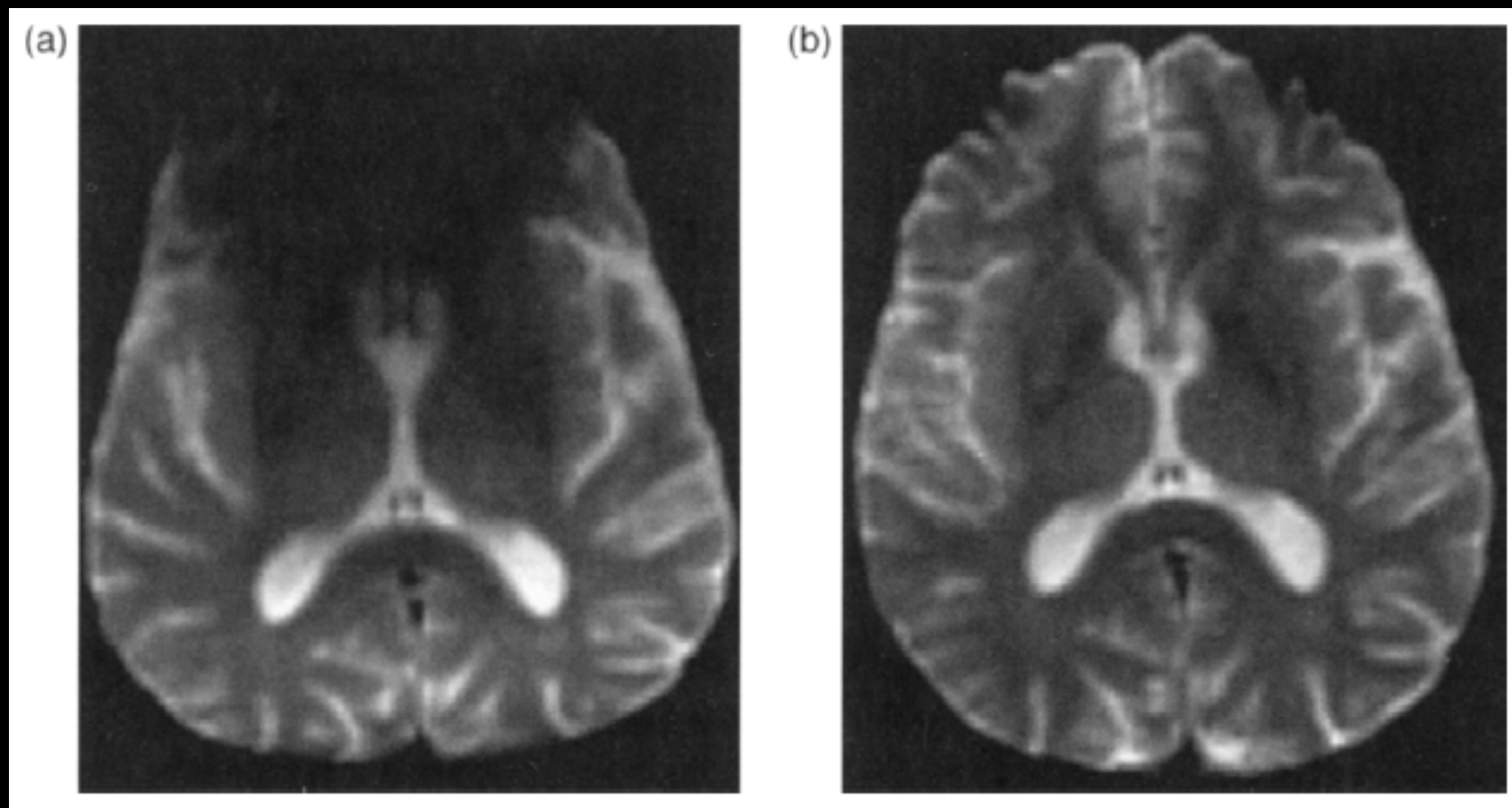
EPI Considerations

Axial EPI, before & after trajectory correction



EPI Considerations

Image distortion and signal loss from dentures



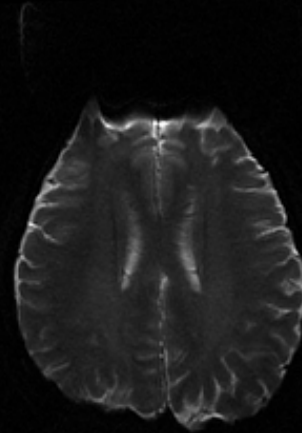
w/ dentures

Summary

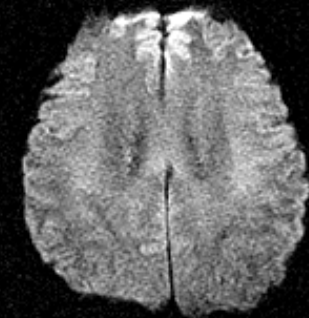
- Strengths
 - very fast
- Challenges
 - T_2^* decay
 - high demand on slew rate
 - artifacts

Clinical Applications

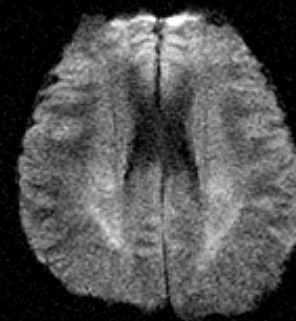
- BOLD fMRI
- ASL
- DWI (see figure)
- Real-time MRI
- MRSI
- *and more ...*



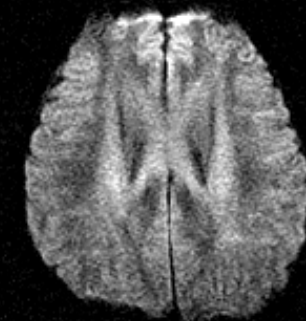
$b = 0 \text{ s/mm}^2$



$b = 750 \text{ s/mm}^2, \text{ S/I}$



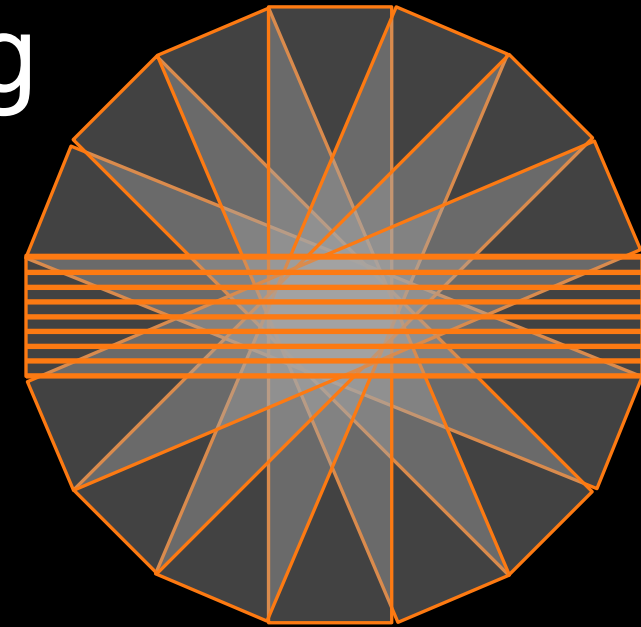
$b = 750 \text{ s/mm}^2, \text{ R/L}$



$b = 750 \text{ s/mm}^2, \text{ A/P}$

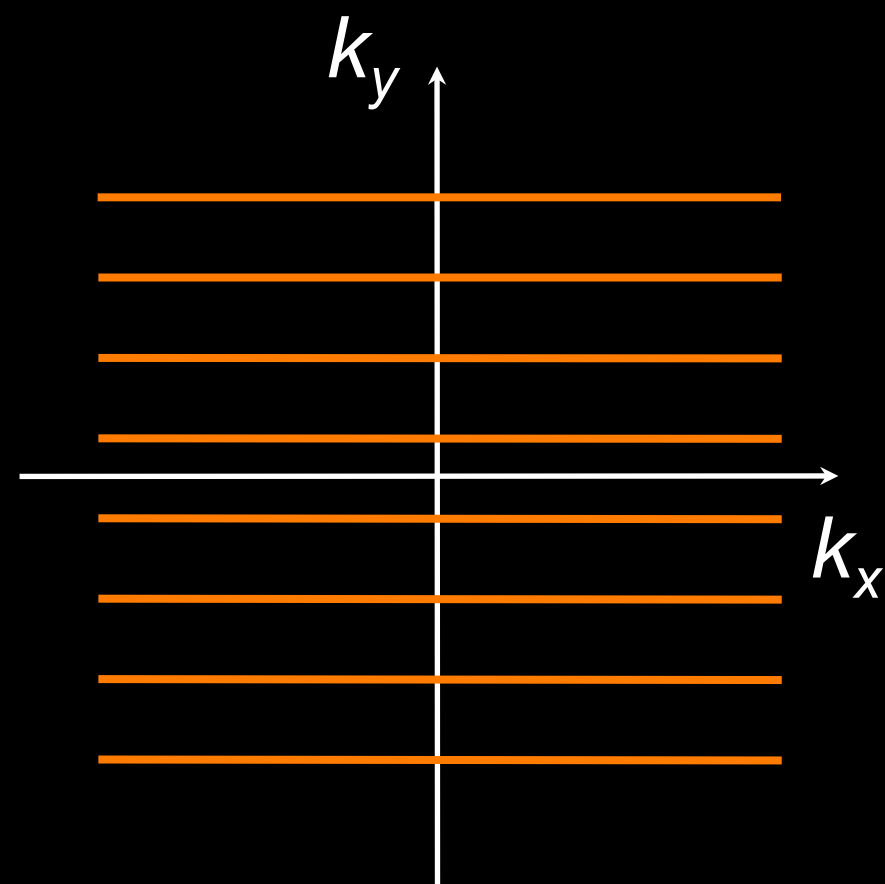
PROPELLER

- Periodically Rotated Overlapping ParalleL Lines with Enhanced Reconstruction¹, 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

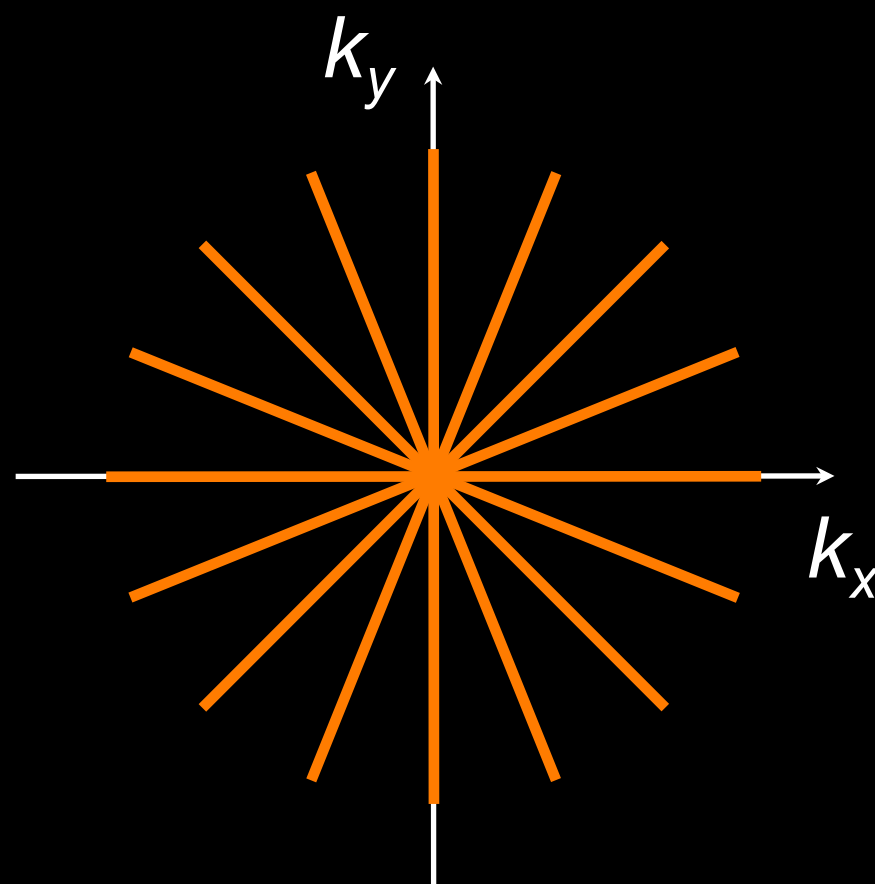


¹Pipe, MRM 1999; 42: 963-969

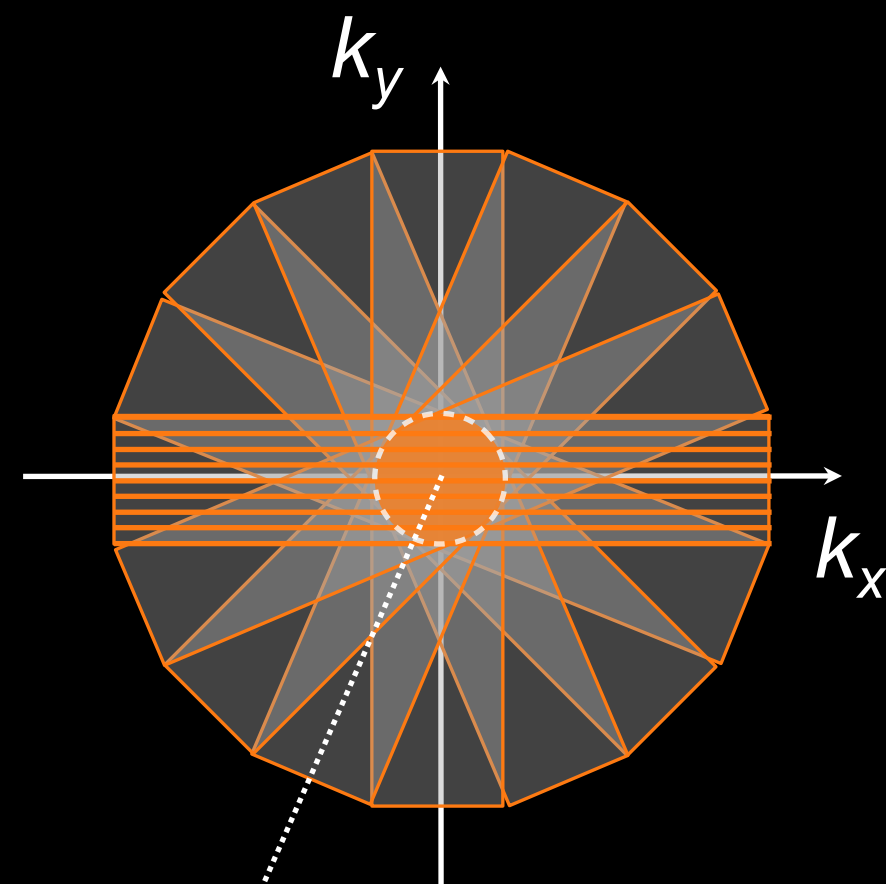
PROPELLER



2D Cartesian



2D Radial

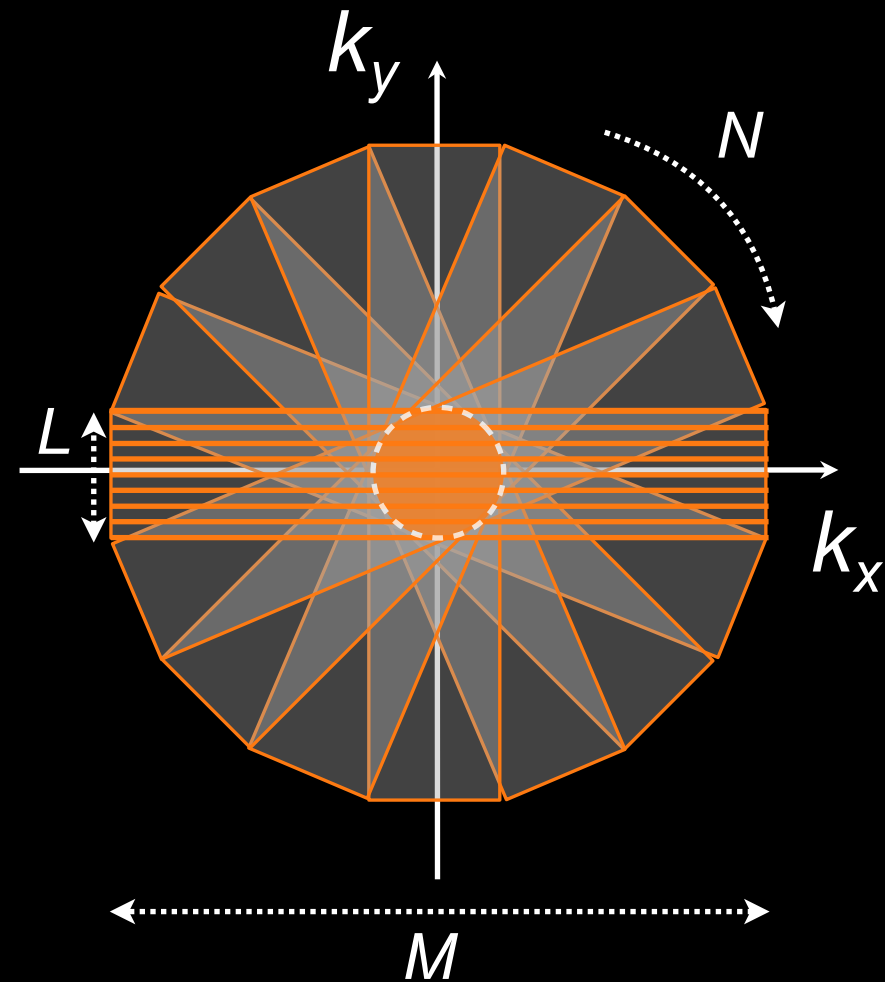


2D PROPELLER

always sampled

PROPELLER

Trajectory Design:



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

L lines per strip, M points per line

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

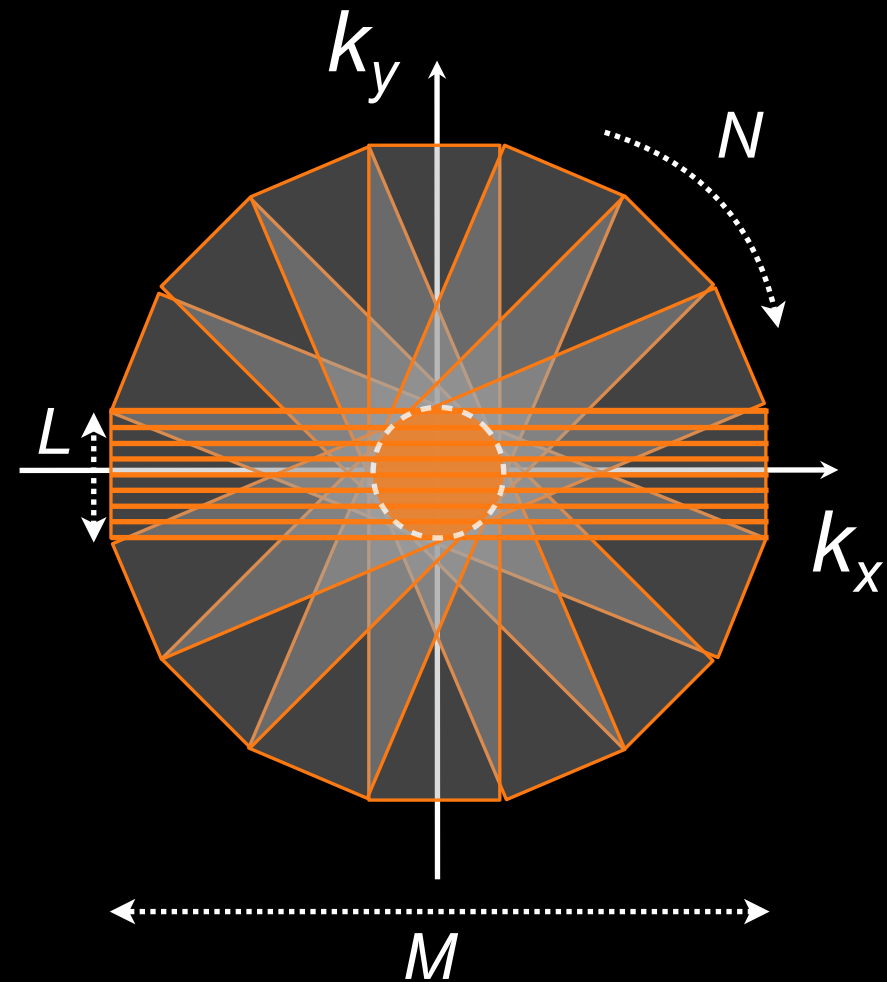
central oversampled circle of diameter L

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; $L = 28$

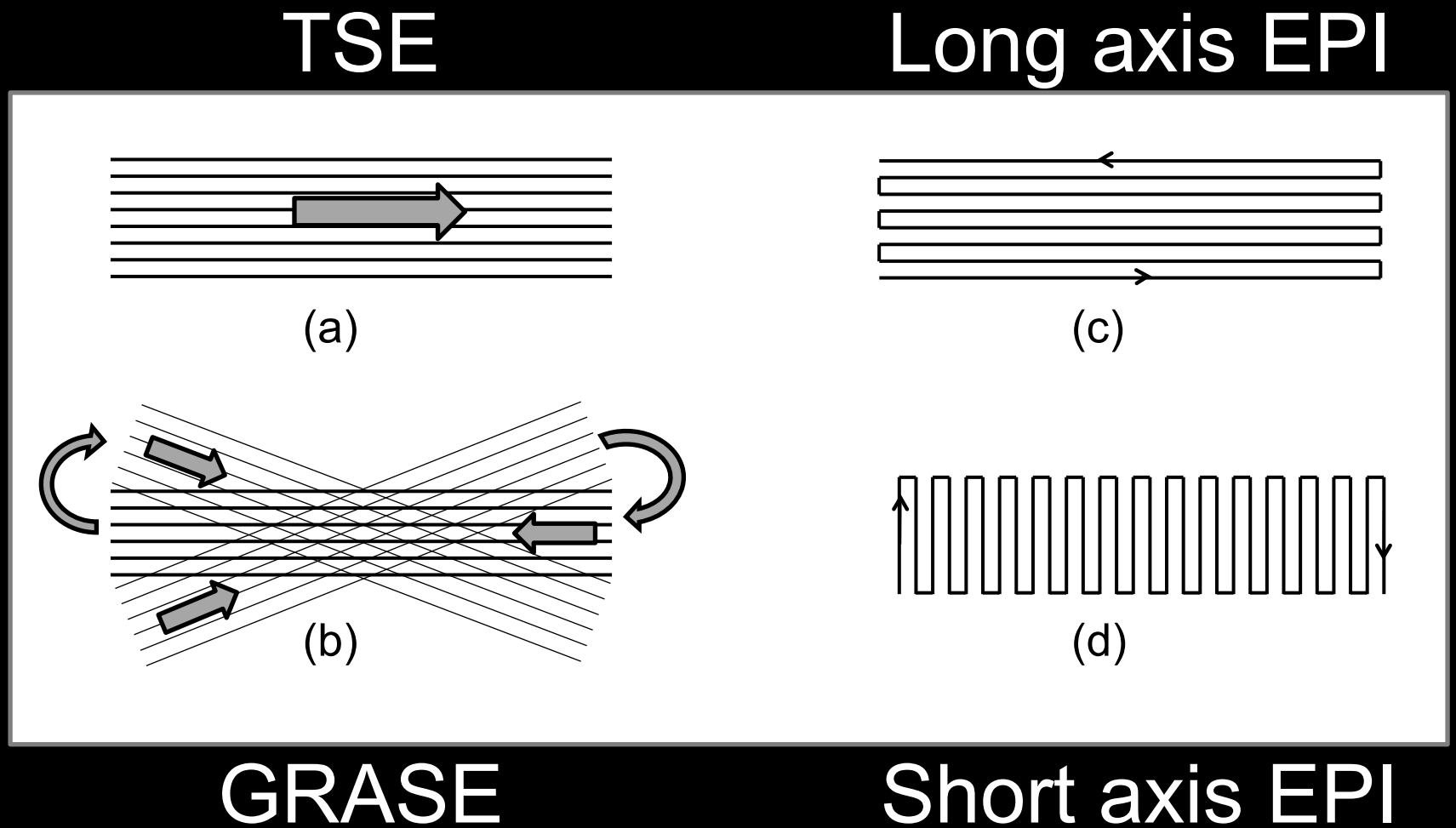
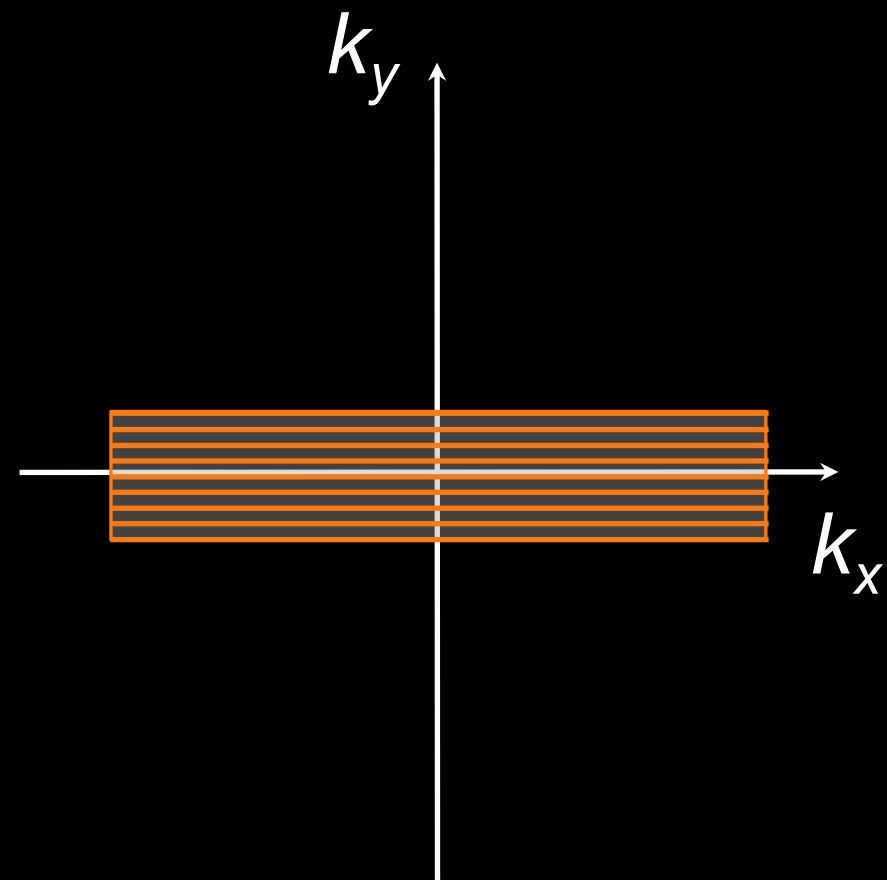
$$M = \text{FOV}/\text{resln} = 480$$

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

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

PROPELLER

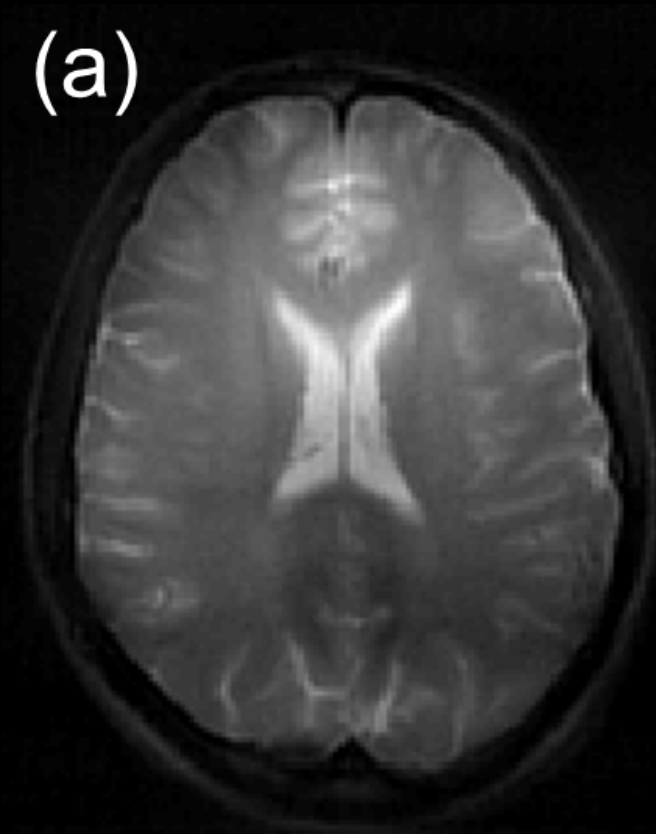
Trajectory Design:



PROPELLER

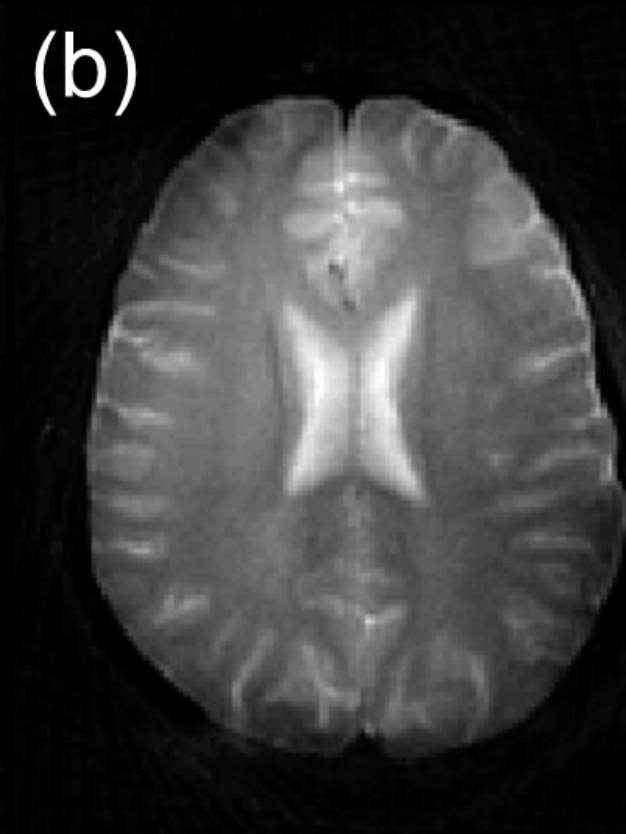
TSE

(a)



GRASE

(b)



Long axis EPI

(c)



PROPELLER

Motion correction:

Rotation in image space \leftrightarrow rotation in k-space

Compare k-space magnitude between strips

Translation in image space \leftrightarrow linear phase in k-space

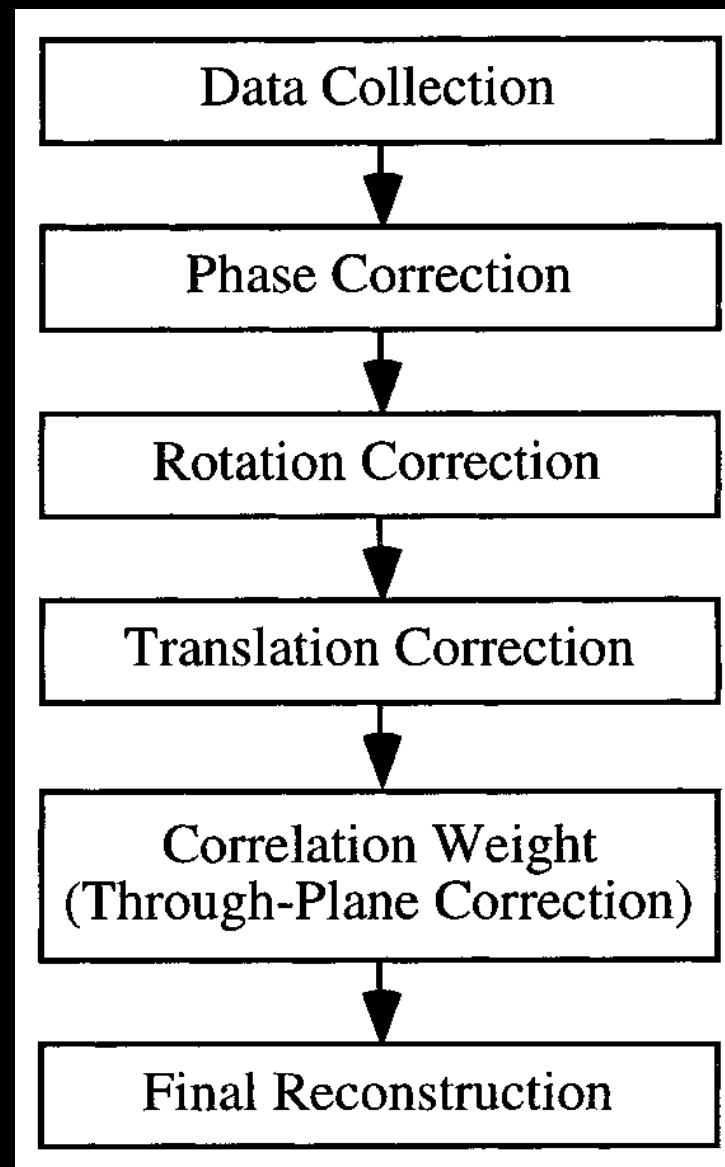
Compare k-space phase between strips

Other motion in image space \leftrightarrow k-space mag/phase

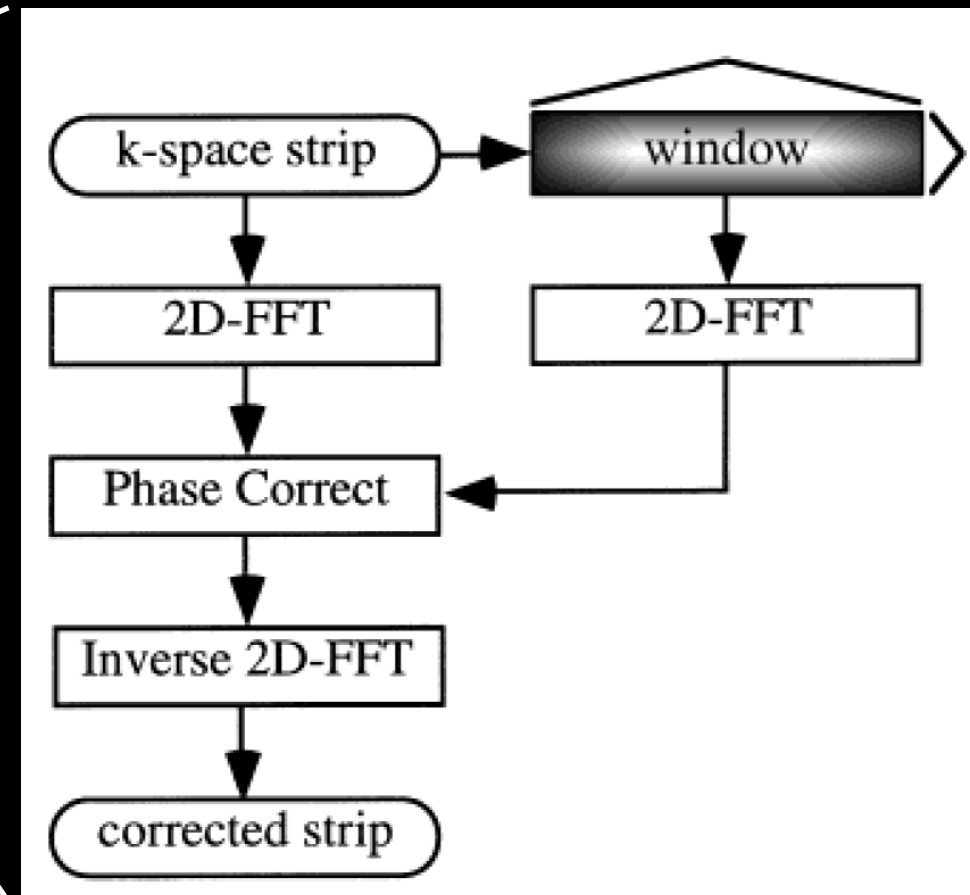
Compare and weigh importance of strips

PROPELLER

Reconstruction:



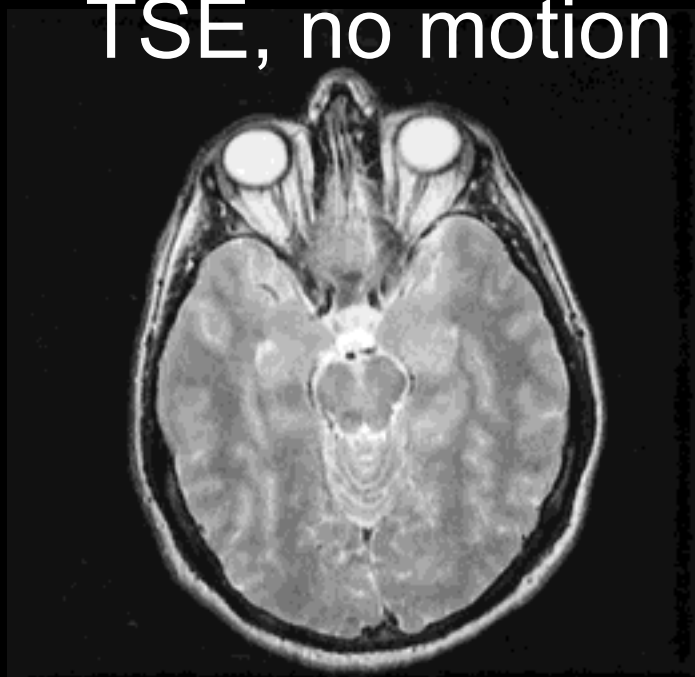
For each strip:



density compensation

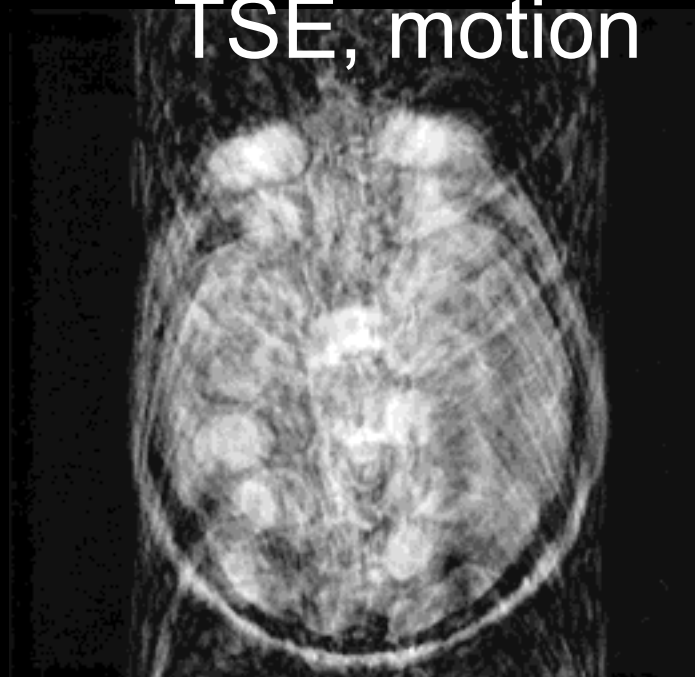
PROPELLER

TSE, no motion



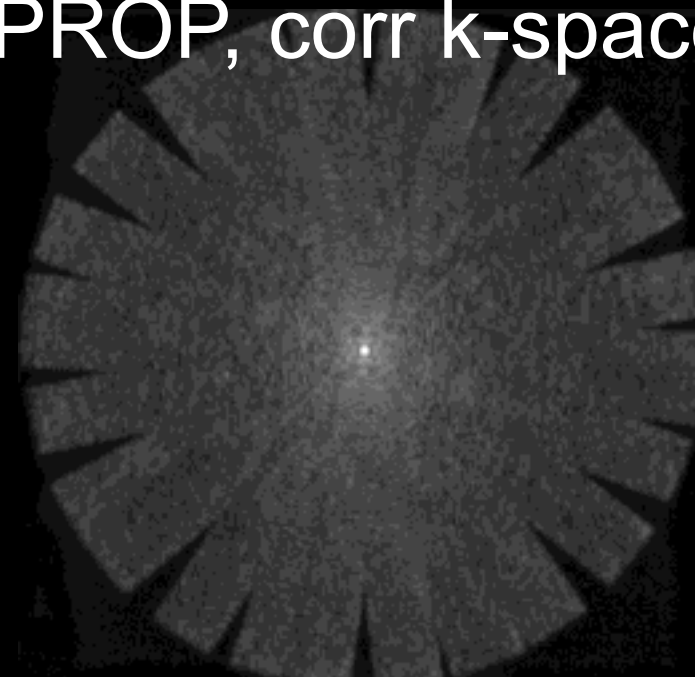
a

TSE, motion



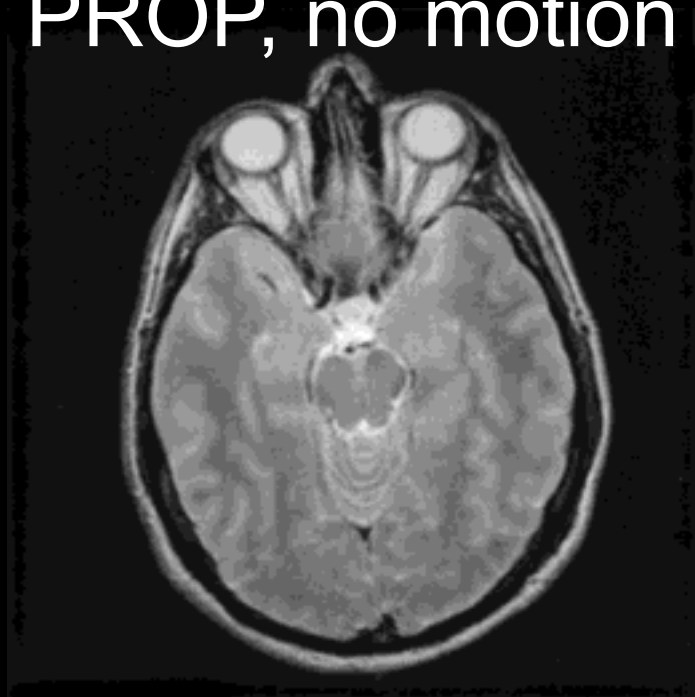
b

PROP, corr k-space



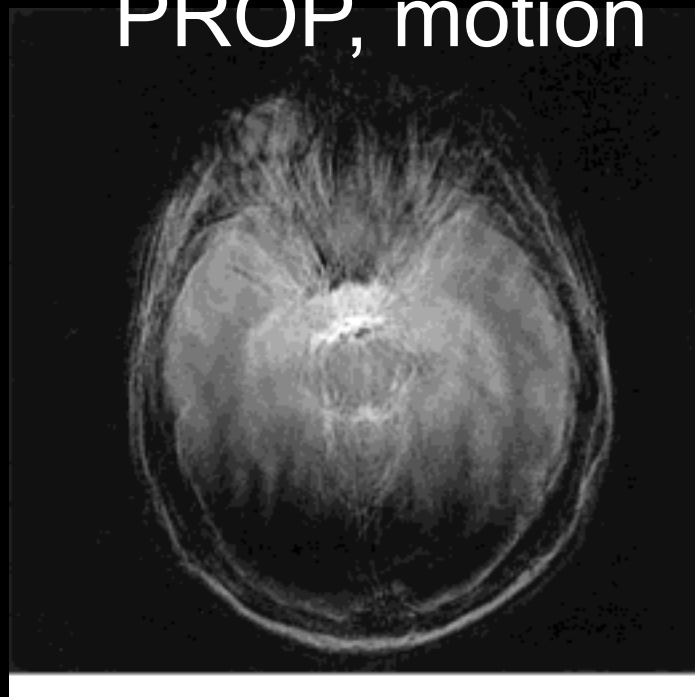
g

PROP, no motion



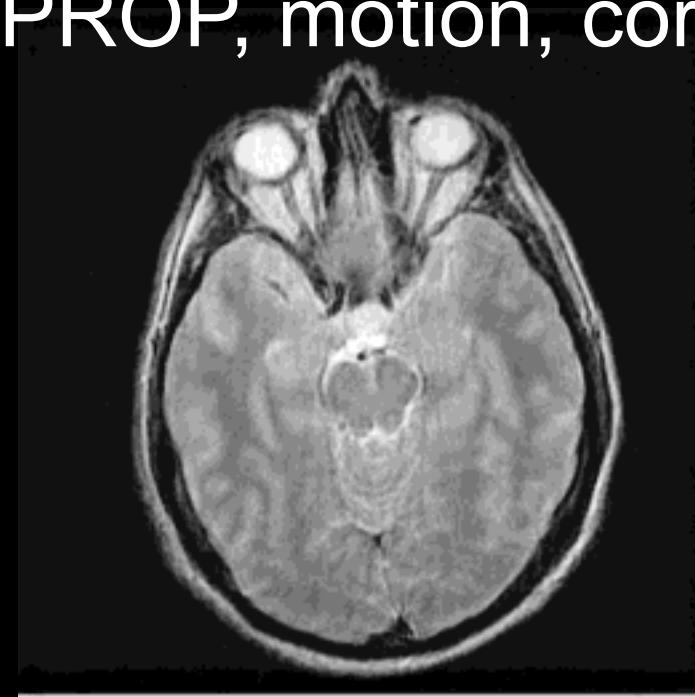
c

PROP, motion



d

PROP, motion, corr

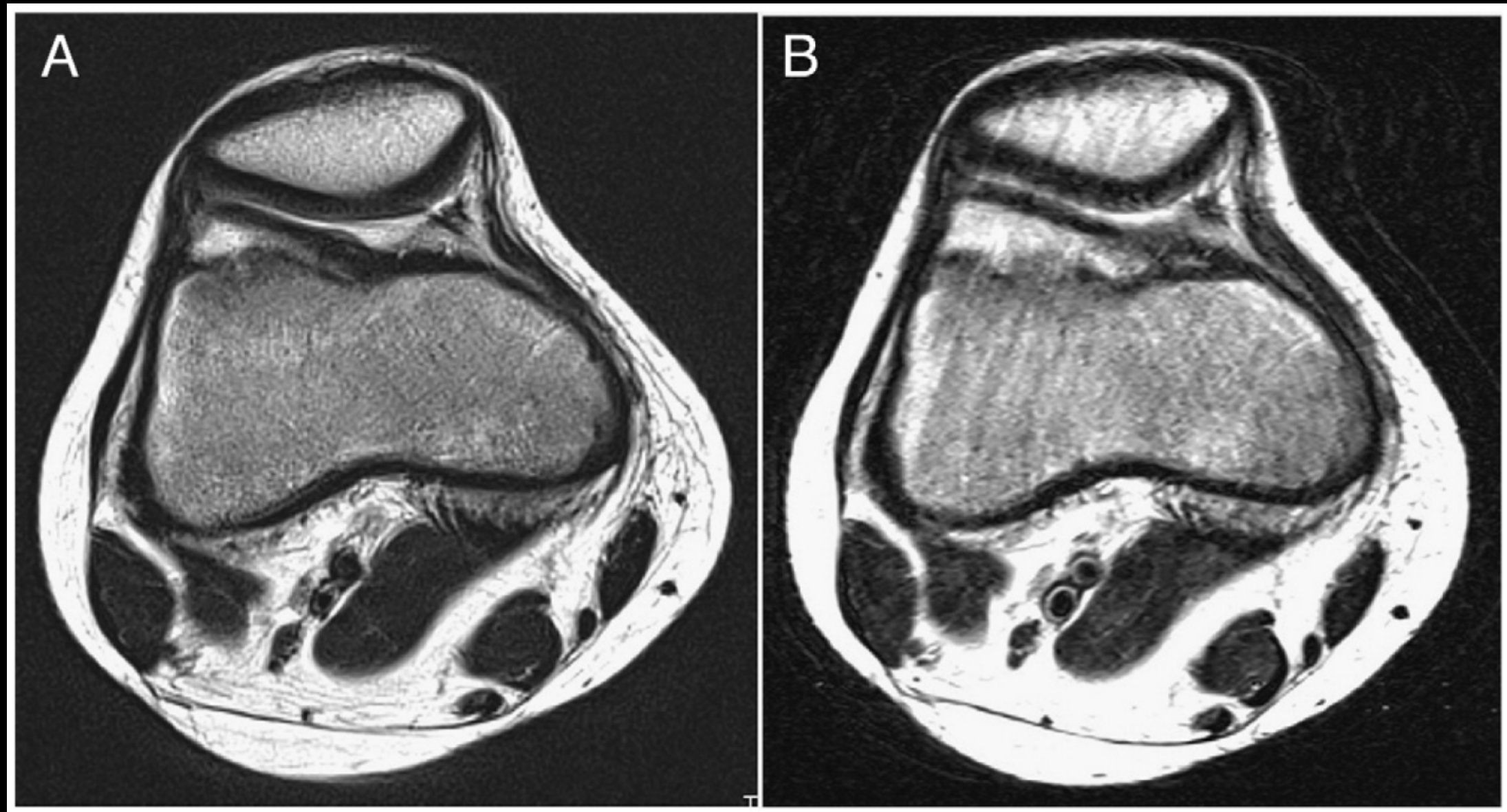


i

PROPELLER

T2 TSE BLADE

T2 TSE



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
- Next time: Non-Cartesian sampling

Thanks!

- Further reading
 - Bernstein et al., Handbook of MRI Sequences
 - pubmed.org
- Acknowledgments
 - Novena Rangwala

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<http://mrrl.ucla.edu/wulab>