Rad229 – MRI Signals and Sequences

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Lecture-13B — Sampling and Timing

Multidimensional Sampling and Timing

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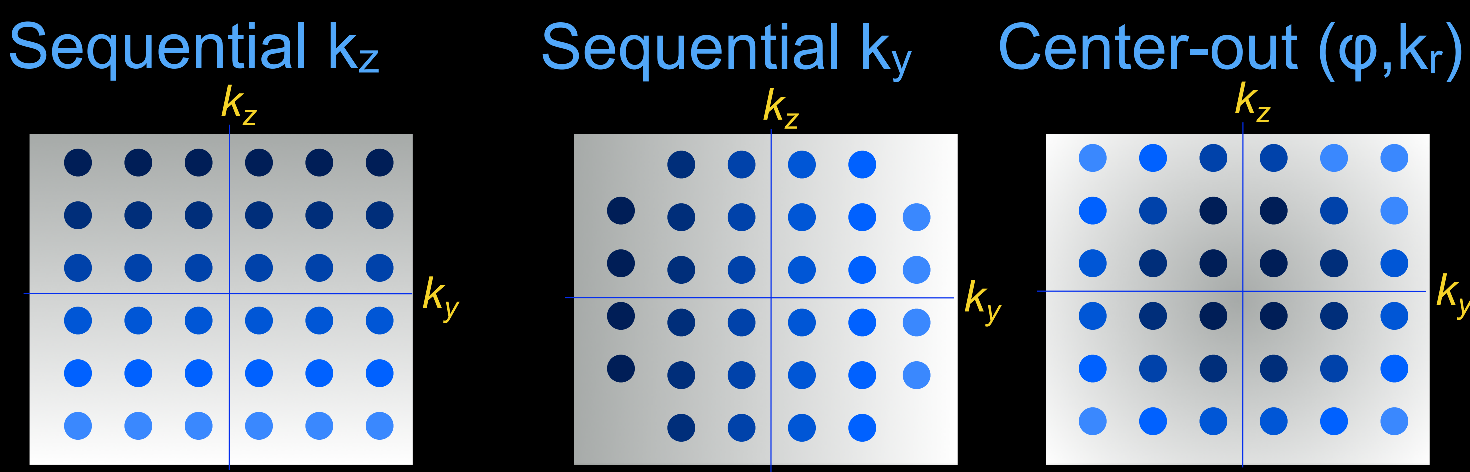
Learning Objectives

- Explain sampling approaches for 3D Cartesian imaging
- Describe temporal sampling approaches
- Understand strategies for slice interleaving
- Explain principles of multiband sampling and controlled aliasing

3D Image (k_y-k_z) View Ordering/Grouping

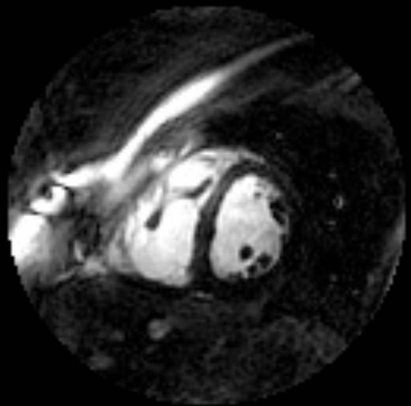
- Freedom to sample arbitrarily
- Centric (ordered by radius first or azimuth (φ) first)
- Segment groups by k_y, k_z, φ, k_r
- Sub-segment groups ($k_y, k_z, \varphi, k_r,$ randomly)



Cartesian sampling in 3D allows freedom to sample in arbitrary order in k_y-k_z

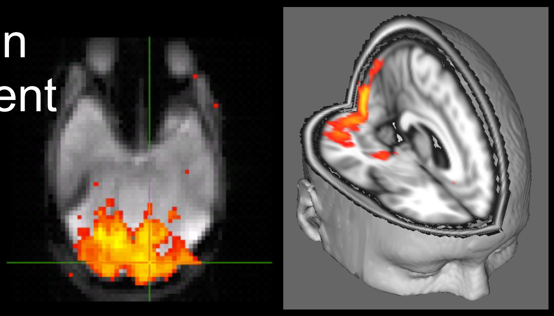
Dynamic Imaging Applications

- Often want to image over time:
  - Resolve motion: cardiac, joints, swallowing, perilstalsis (etc)
  - Contrast-enhancement
  - Functional MRI
- Spectroscopic imaging (related)

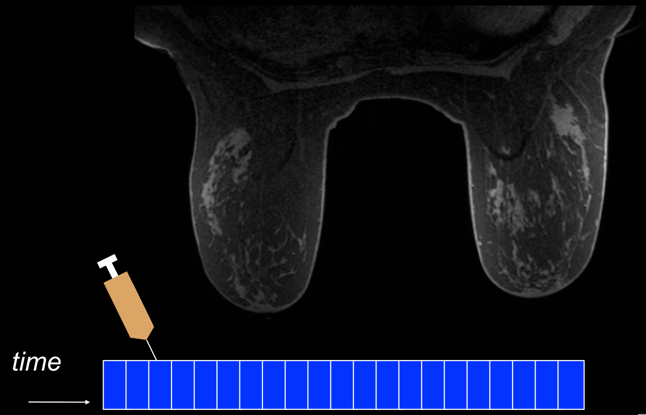


(Courtesy of Krishna Nayak)

Blood-Oxygen Level Dependent (BOLD)



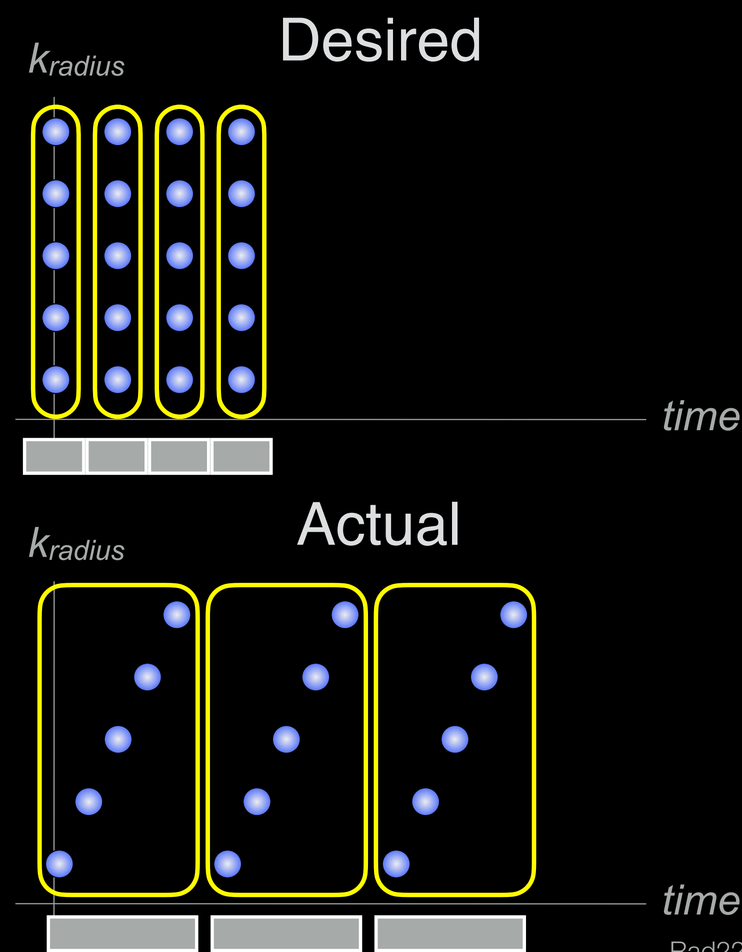
(Courtesy of Karla Miller)



There are numerous applications that demand continuous imaging over time

Spatial and Temporal (Spatiotemporal) Resolution

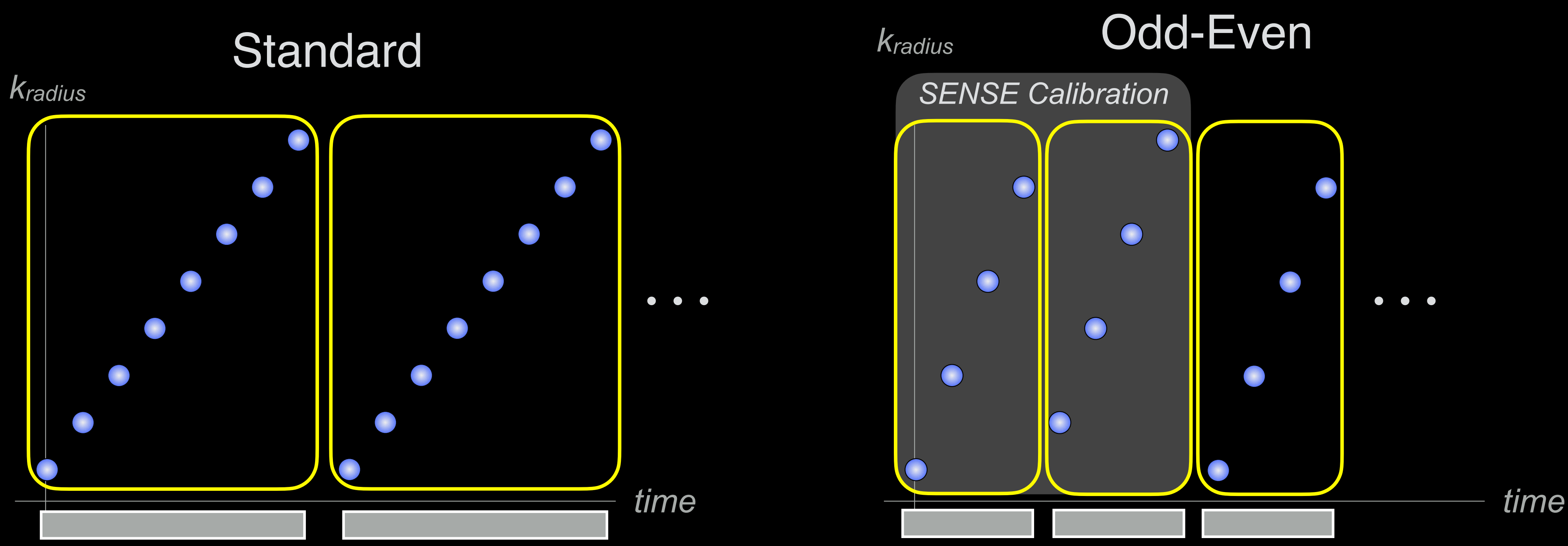
- Fundamental Trade-off
- Skip samples?
  - Reduce resolution
  - Reduce FOV
- Exploit temporal and spatial information



Since it takes finite time to obtain MR images, spatiotemporal imaging always involves a tradeoff between frame rate and image quality

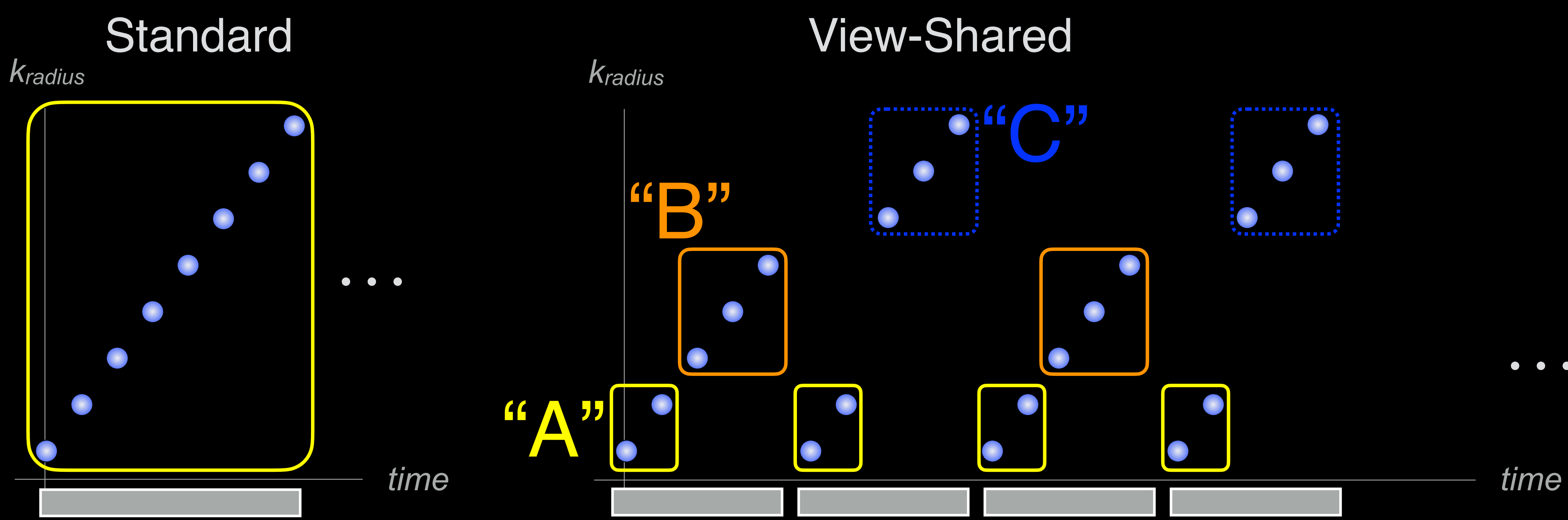
Question 1: Temporal Odd/Even Sampling?

Spatiotemporal Trade-offs: FOV



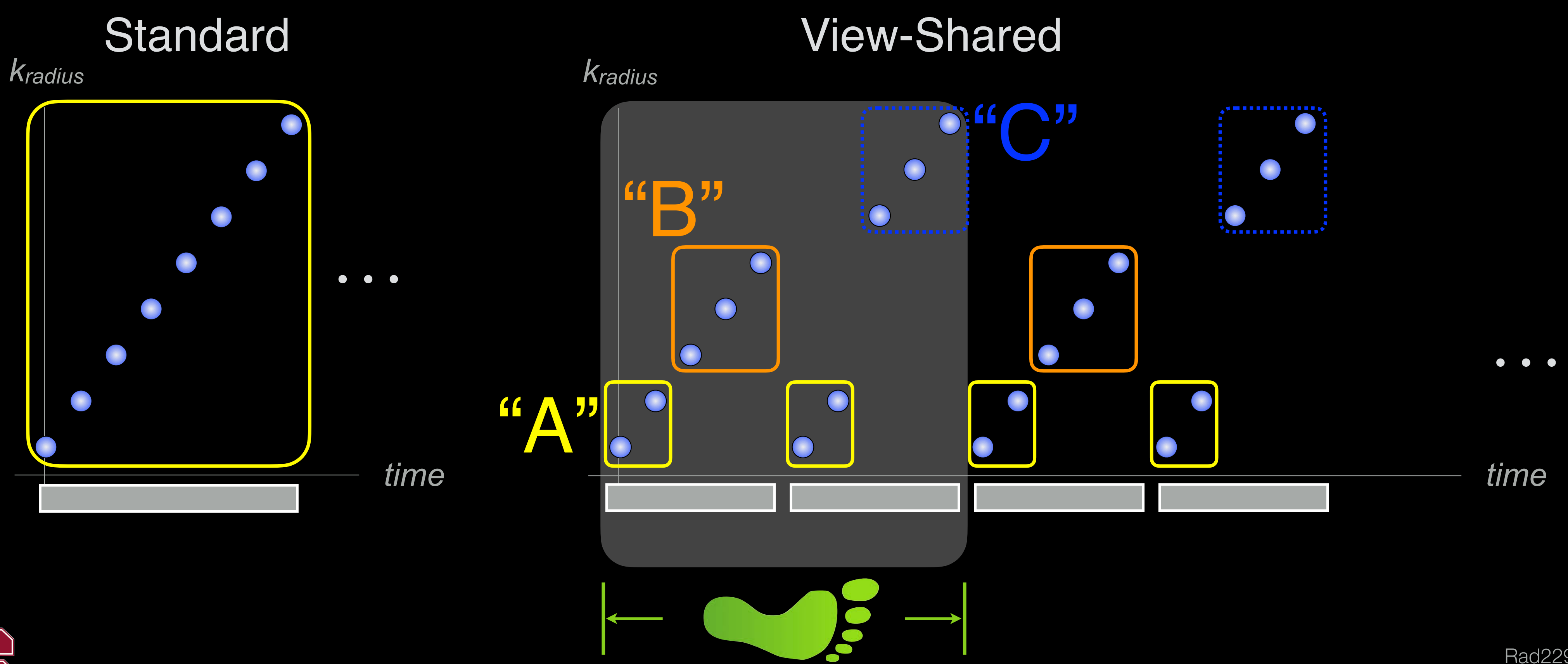
“TSENSE” Kellman P MRM 2001, Han M, MRM 2009

Spatiotemporal Trade-offs: View-Sharing



View-sharing is standard in many dynamic acquisitions as contrast changes in low-spatial frequencies are dominant

Spatiotemporal Trade-offs: View-Sharing



View-sharing is standard in many dynamic acquisitions as contrast changes in low-spatial frequencies are dominant

Temporal k_y-k_z Undersampling Patterns

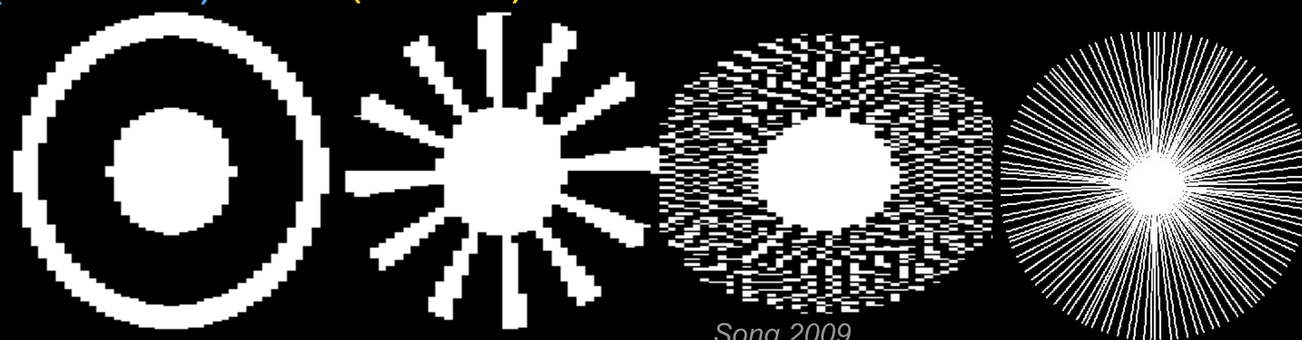
Time-Resolved Imaging of Contrast Kinetics **(TRICKS)**

Cartesian Acquisition with Projection Reconstruction **(CAPR)**

DISCO, TWIST

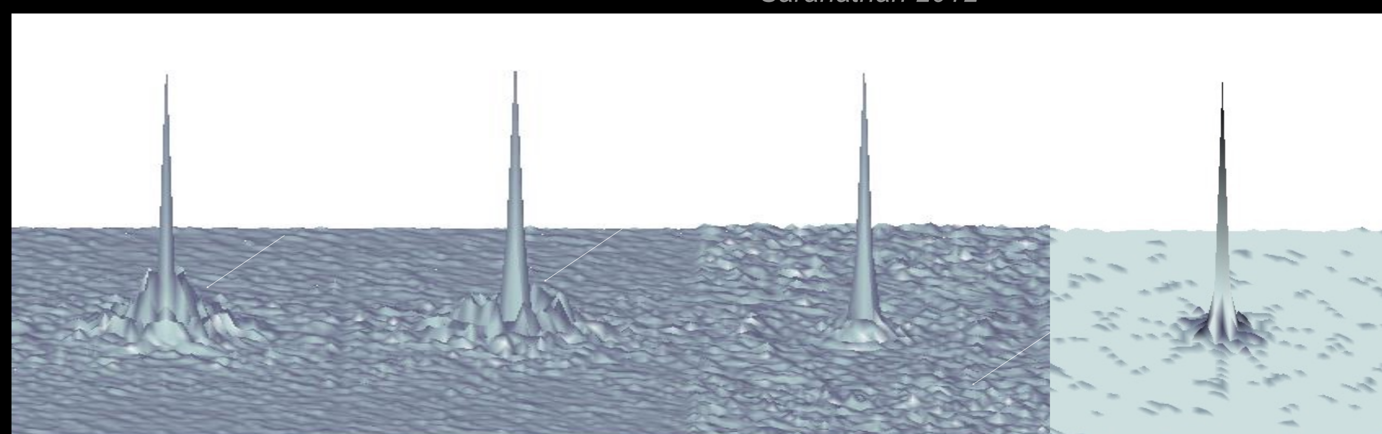
Radial (Golden Angle)

Data Acquisition (k_y-k_z, except radial)



Korosec 1996 | *Madhuranthakam 2006* | *Song 2009, Saranathan 2012* | *Winkelmann 2007*

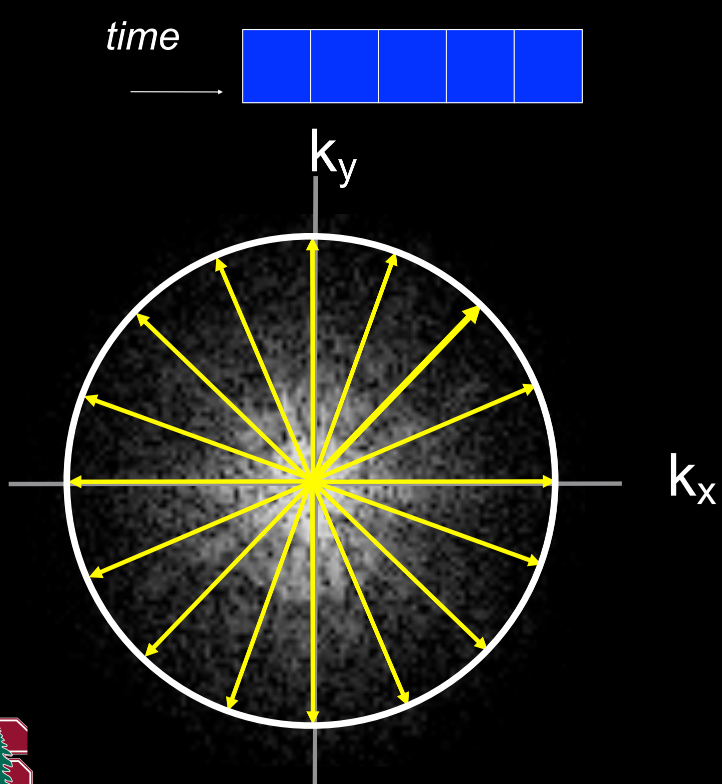
Single-Frame Point-Spread Functions

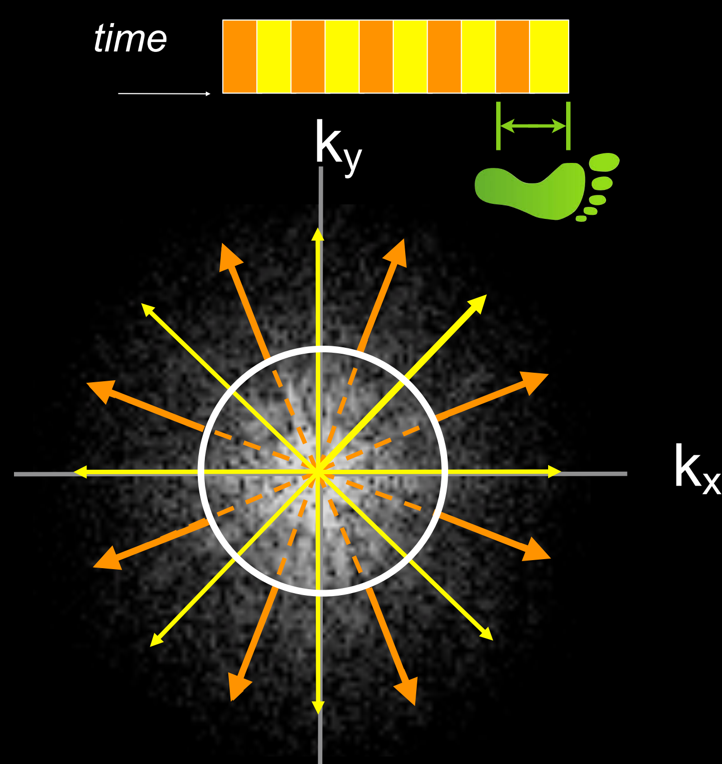


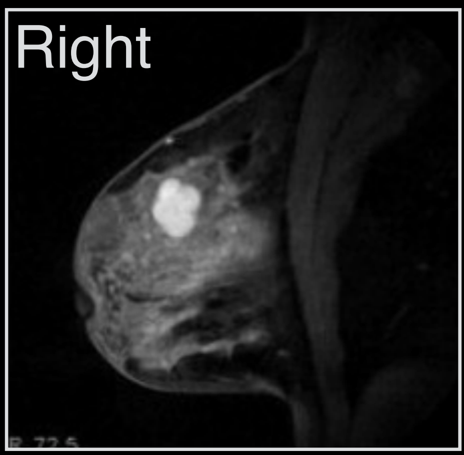
View-sharing performance can be compared by looking at the PSF of a single frame

Radial Imaging Options

- Low-resolution image from reduced #spokes
- Retrospective Spatial vs temporal resolution tradeoff

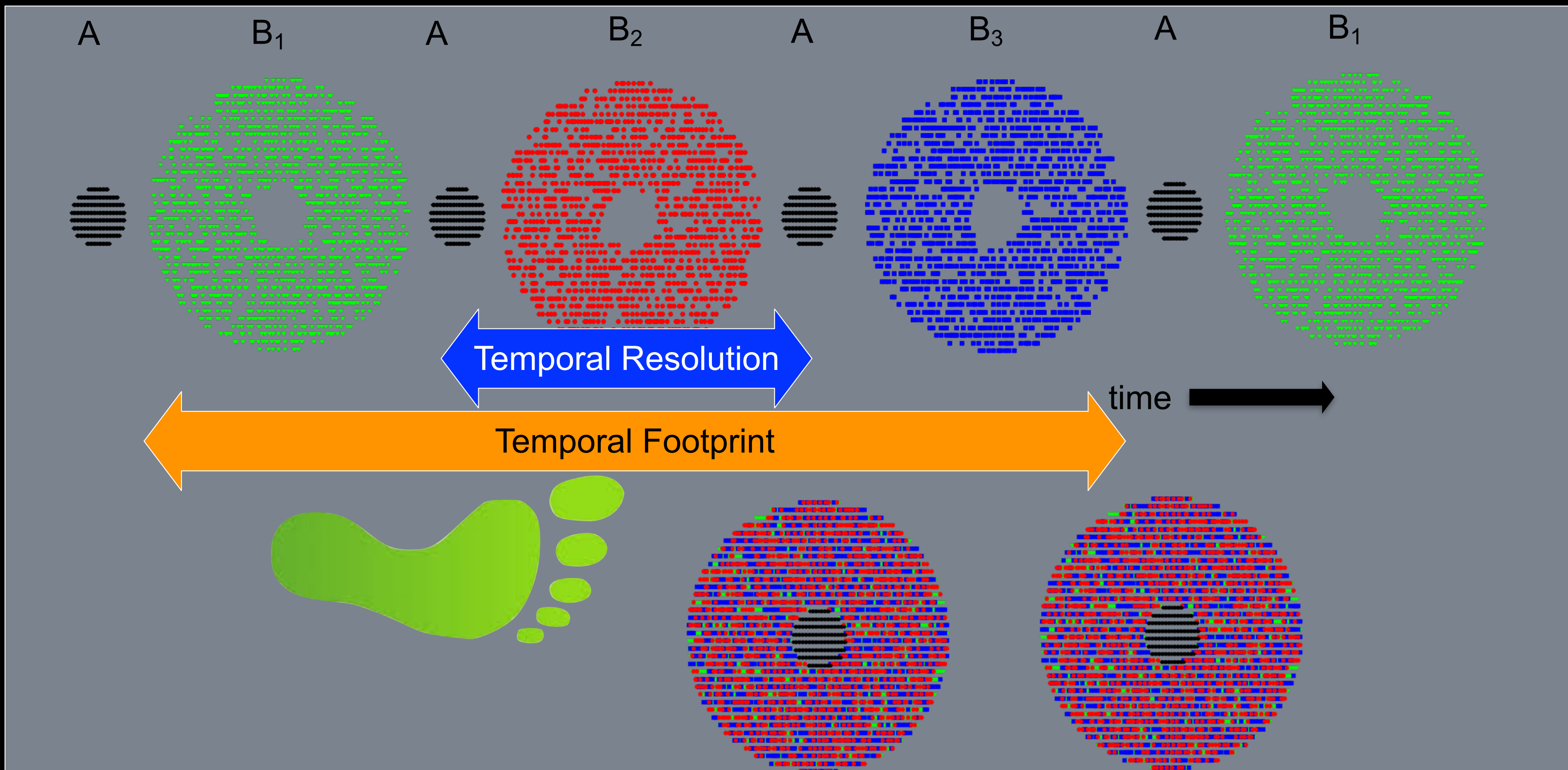






Song HK, et al MRM 2004 and Dougherty L, et al MRM 2007

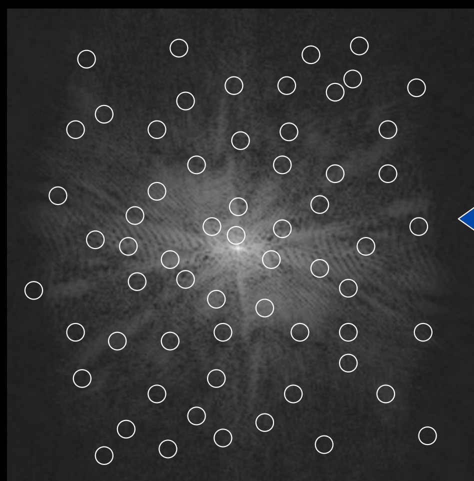
DISCO k_y - k_z - time Pattern (TWIST similar)



Saranathan M, MRM 2012, Song MRM 2009, Tudorica LA MRI 2012

Compressed Sensing MRI

MRI Data



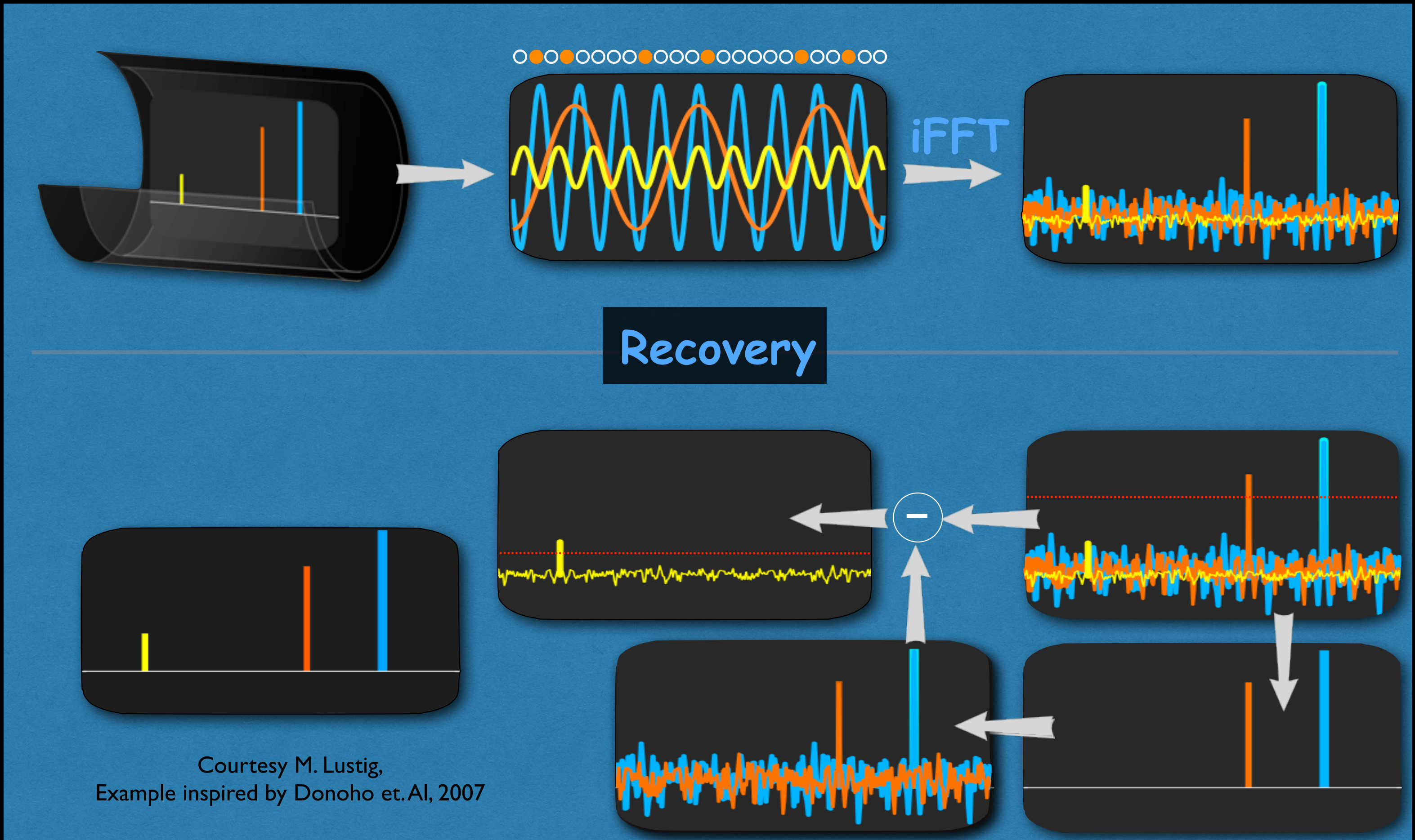
- Sample less data
- Choose image matching data that is most “compressible” (sparse)

$$\min_{x} ||D_t F S x - d_t||_2 + \lambda_{CS} ||\Psi x||_1$$

Data Match — Sparsity

Lustig, et al. MRM 2007

CS Reconstruction and PSFs

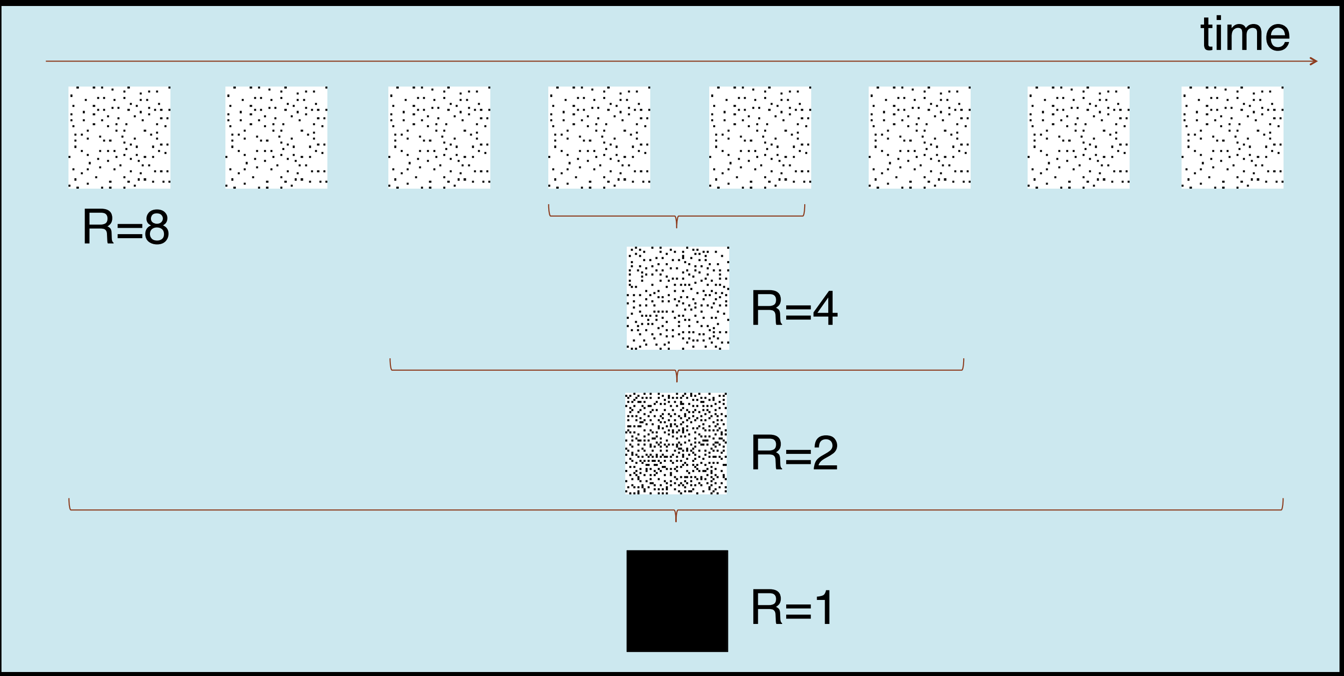


Courtesy M. Lustig,
Example inspired by Donoho et. Al, 2007

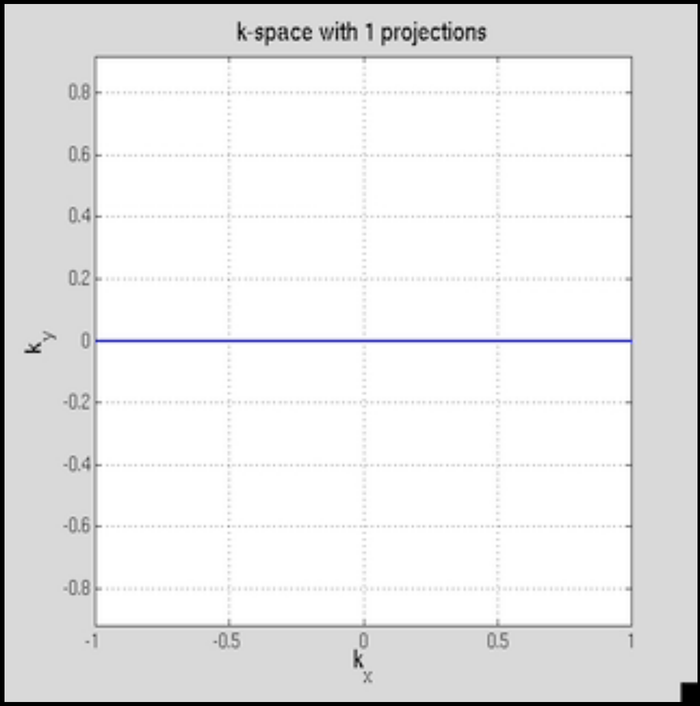
Constrained reconstruciton can remove noise-like artifact from random undersampling

Variable View Sharing

Uniform Random Density



Golden Angle Radial

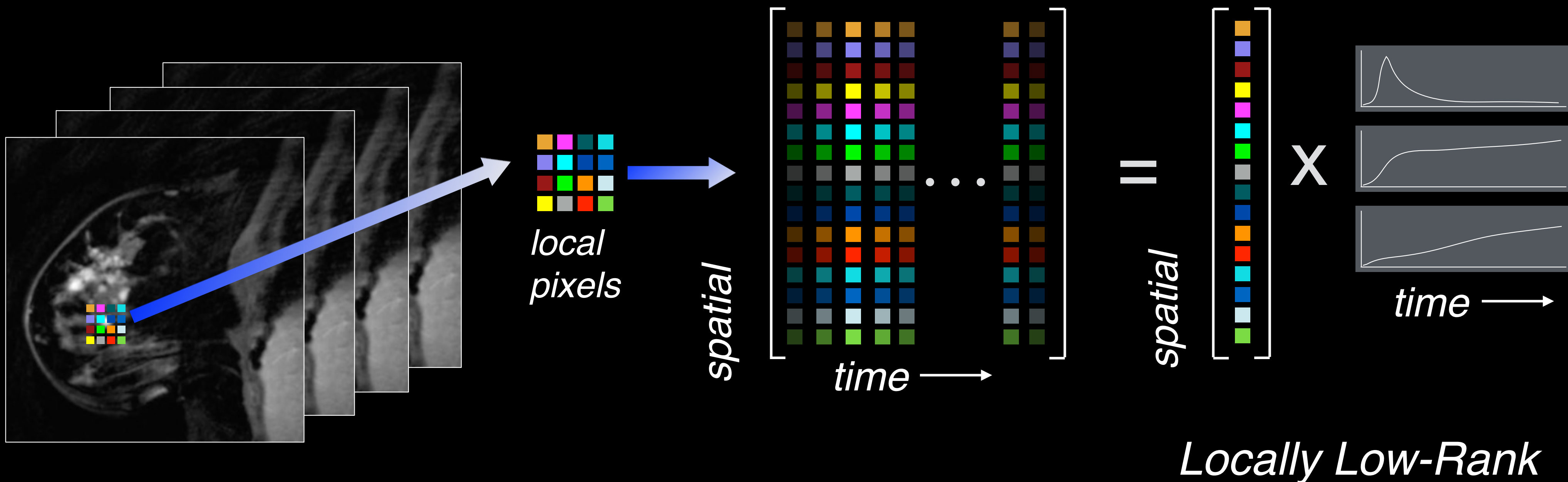


- Retrospectively select temporal footprint

Levine E, et al. MRM 2016 Winkelmann S, et al. IEEE TMI 2007

Locally Low-Rank

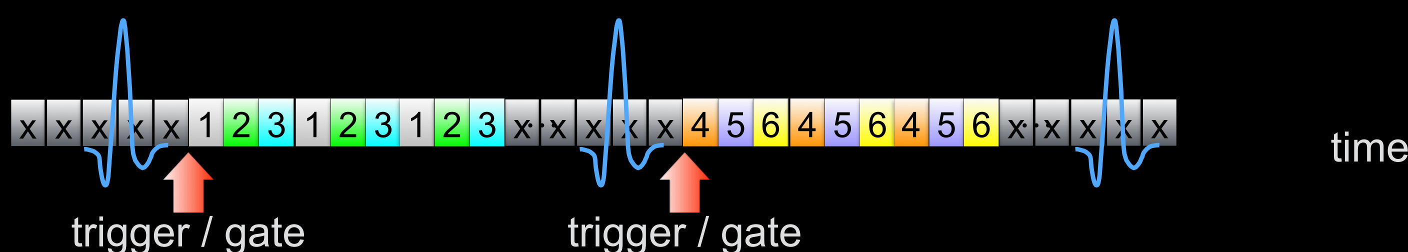
- Model-free, Data-driven, Sparsity



Locally-low-rank reconstruction exploits correlations across dimensions — Otazo R. Magn Reson Med 2015

Cardiac/Respiratory Acquisition Timing

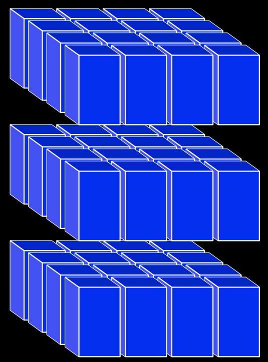
- Cine: Exploit periodicity of cardiac/respiratory cycle
  - Sample N k_y lines repeatedly, next N lines on next heartbeat.
  - High frame rate and spatial resolution
- Triggering: Start acquisition based on external trigger (EKG, plethysmograph, respiratory bellows)
- Gating: Excite continuously, but acquire only after trigger
- Can combine any/all of these

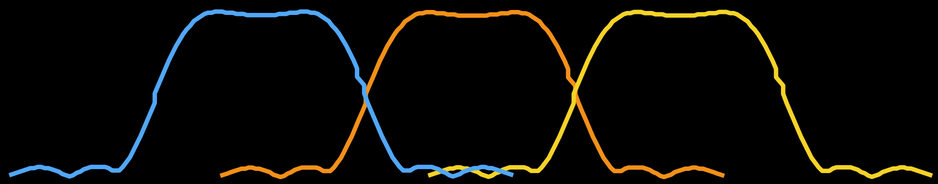


Question 2: Cine Acquisition?

Slice Interleaving

- Multislice acquisitions allow volumetric imaging
- Acquisitions can be *sequential* or *interleaved*
- Interleaving is time efficient if there is “dead time”
- Different ways to interleave (reduce adjacent-slice-saturation)
    - Sequential: 0, 1, 2, 3, 4, 5, 6, 7
    - Odd/Even: 0, 2, 4, 6, 1, 3, 5, 7
    - Bit-reversed: 0, 4, 2, 6, 1, 5, 3, 7

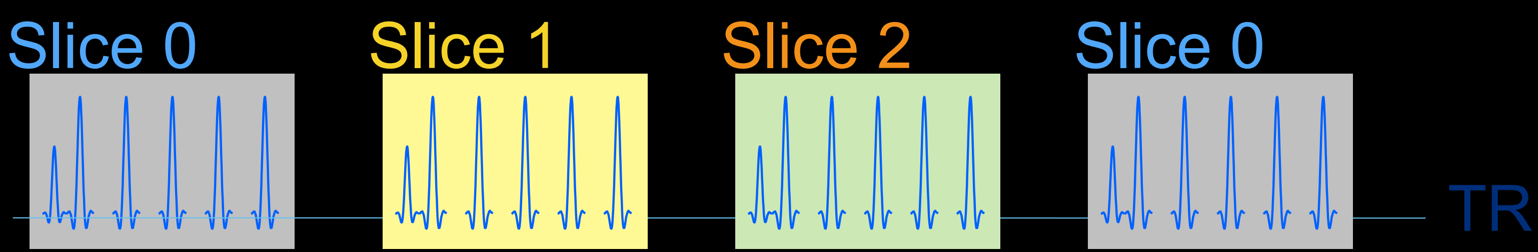




Interleaving is a common approach to improve acquisition efficiency for multislice scans

How Many Slices to Interleave?

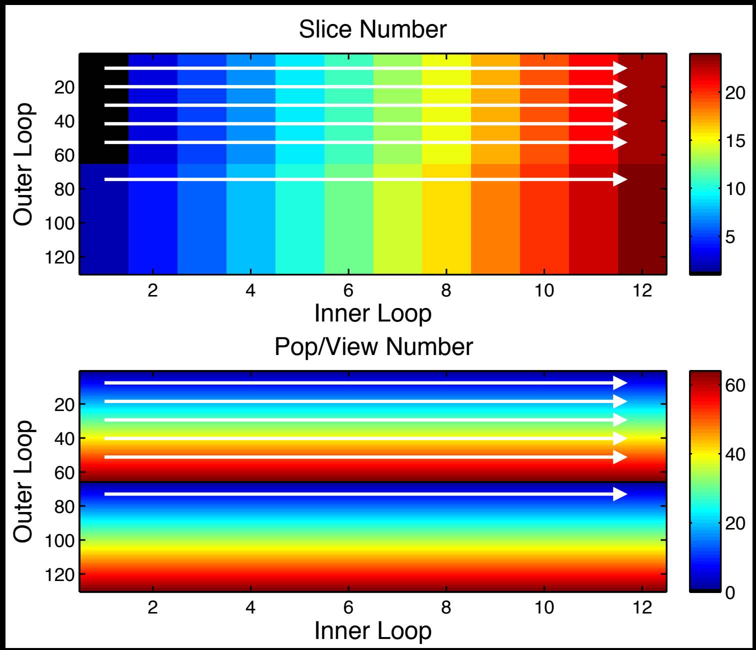
- Usually specify TR, TI, Echo-train-length (ETL), Resolution, ...
  - Give "pulse durations" (T_{seq}) and RF power (T_{min})
  - $N_{max} = TR / T_{seq}$ or TR / T_{min}
  - Can re-order slices in "time slots"
  - Additional slices require another "acquisition"

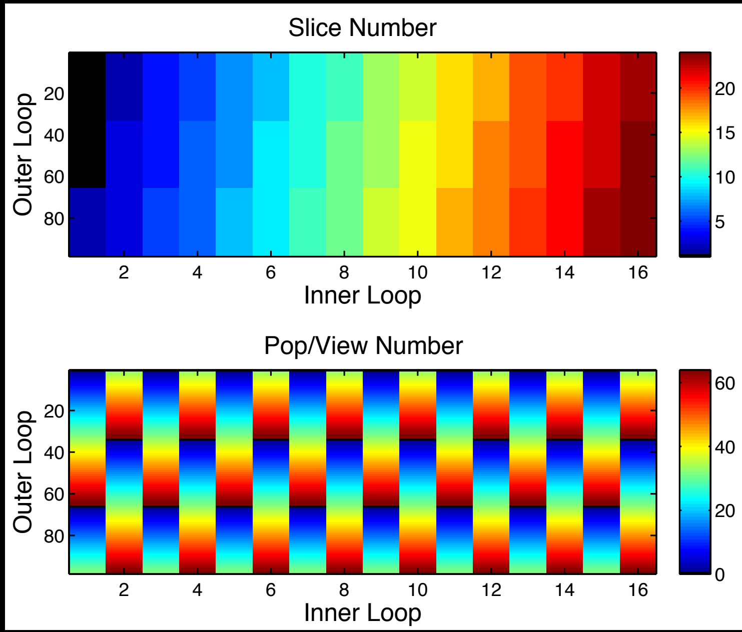


Maximum number of slices to interleave is a fairly simple calculation based on timing and RF power

More Flexible Interleaving

- Typically consider slice number and phase-encode number
- If $N_{slices} > N_{max}$, scan is 2x, 3x, ... longer
- Decoupling phase encode number allows flexible interleaving

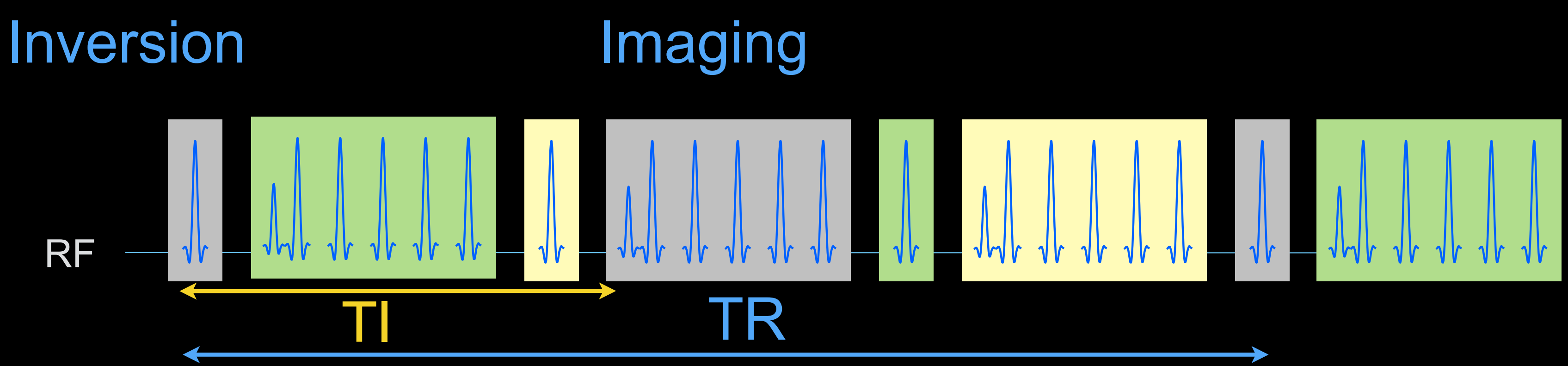




A simple "table" can be filled out column-first and read out row-first to interleave slices more efficiently

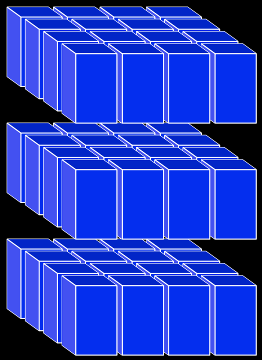
FLAIR / STIR?

- Additional dead-time during TI interval
- Can sometimes interleave other acquisitions
- Additional constraints on TR, TI, Tseq



Interleaving acquisitions with IR blocks offers efficiency improvements

Multiband Imaging



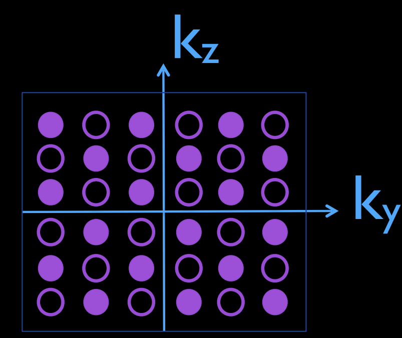
- Imaging multiple slices simultaneously
- Excitation: Multiply RF(t) by cos(t+ϕ)
  - Increases SAR
- Imaging:
  - Hadamard: Excite "1,1" and "1,-1" pattern, add & subtract
  - POMP: Alternate patterns, increase y FOV
  - Parallel Imaging: Use coils to separate slices
  - Blipped sequences: G_z "blips" induce slice-dependent phase
    - Like 3D k-space with limited excitation
    - Similar to Dixon water/fat: slices are like spectral peaks

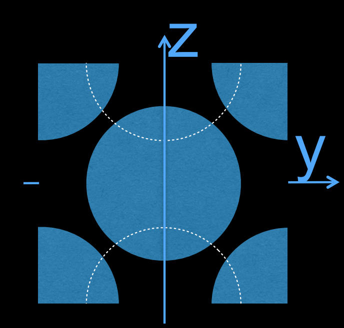
Simultaneous multislice imaging (SMS) offers flexibility in ways to acquire multiple slices

Question 3: Slice-encoding Variations?

“Controlled Aliasing in Parallel Imaging” (CAIPIRINHA)

- 3D (ky-kz) sampling:
  - Hexagonal sampling offsets replicas
  - Reduced aliasing (further apart)
- 2D Multislice:
  - Alternating phase during excitation or blips
  - Offset replicas allows in-plane coil sensitivities to help separate slices
  - Can think of as 3D k-space





Modulation of slices (via k-space or RF) modifies aliasing patterns — Breuer F, MRM 2005, 2006

Question 4: Multiband Encoding?

Starting with a 1 kHz BW excitation, we want to excite two slices that are 5mm thick and 2cm apart (center-to-center)

- How do we modulate the pulse to excite 2 slices?

1kHz … 5mm, +/-2kHz … 2cm. Modulate with cos(2π 2000 t)

What is the image if we alternate excitations using the sequence cosine, sin, -cosine, -sin, … modulation on successive ky lines, assuming slices are each 1cm away from center?

Slices are both shifted 1/4 FOV

Which FOV should we encode for 2x parallel imaging if we have 2 coils along y?

Large enough to separate objects (including parallel imaging)

Summary

- Multidimensional sampling:
  - ky-kz order
  - k-t sampling for dynamic imaging
  - View sharing and PSFs
  - Random/incoherent sampling and compressed sensing
- Multislice interleaving
- Simultaneous multislice imaging / controlled aliasing

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