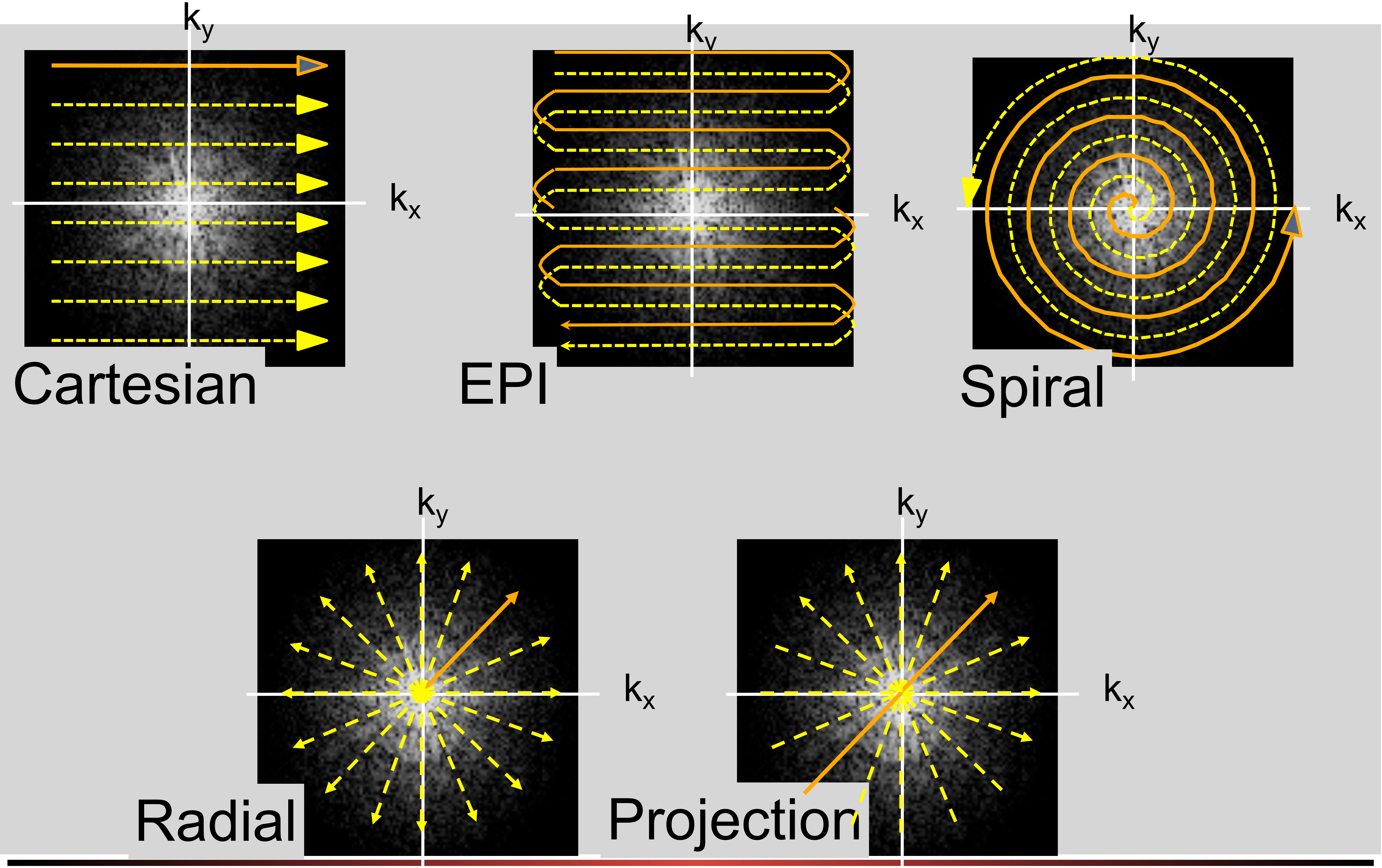
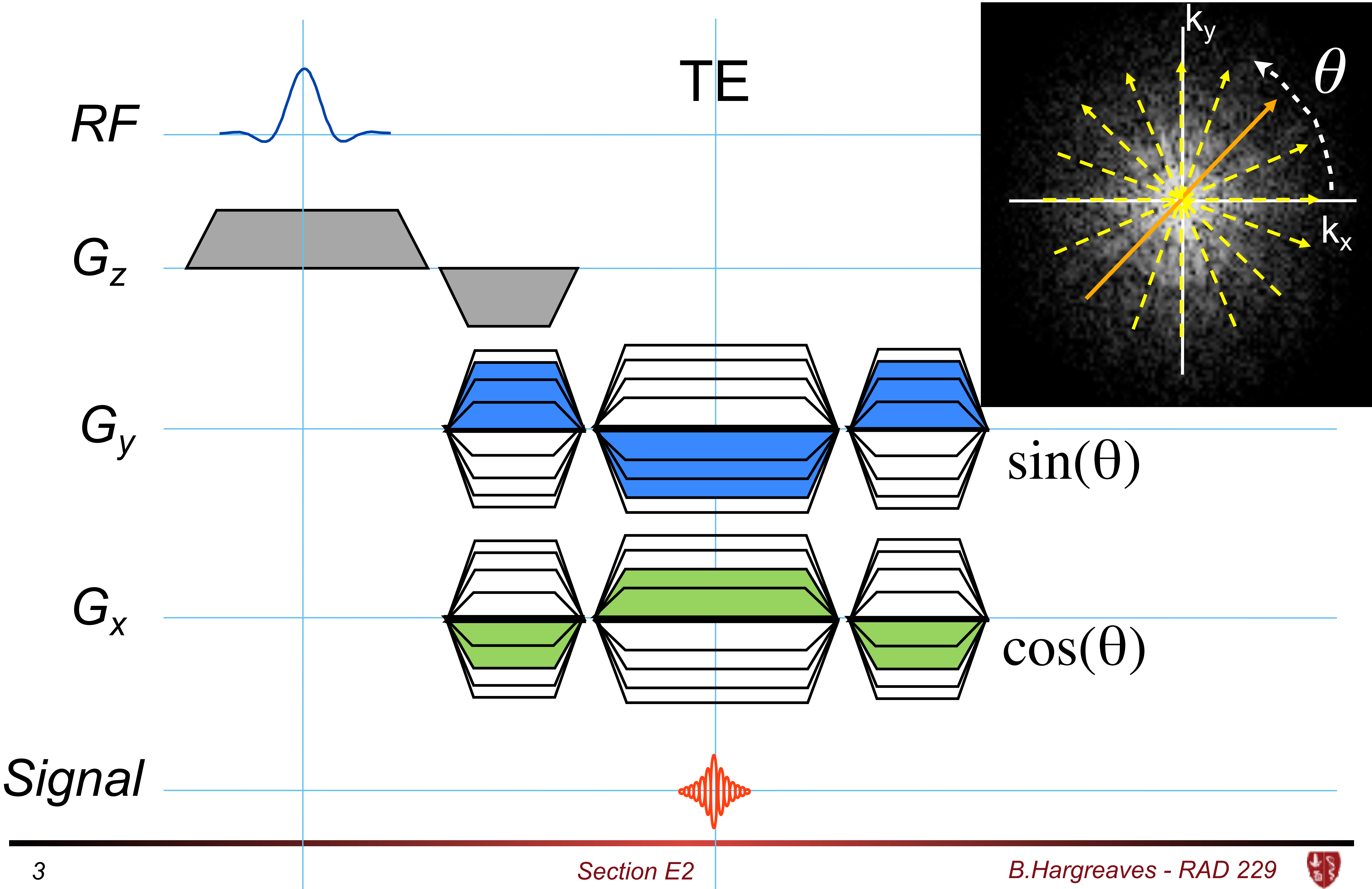
Advanced Imaging Trajectories



Radial and Projection Imaging

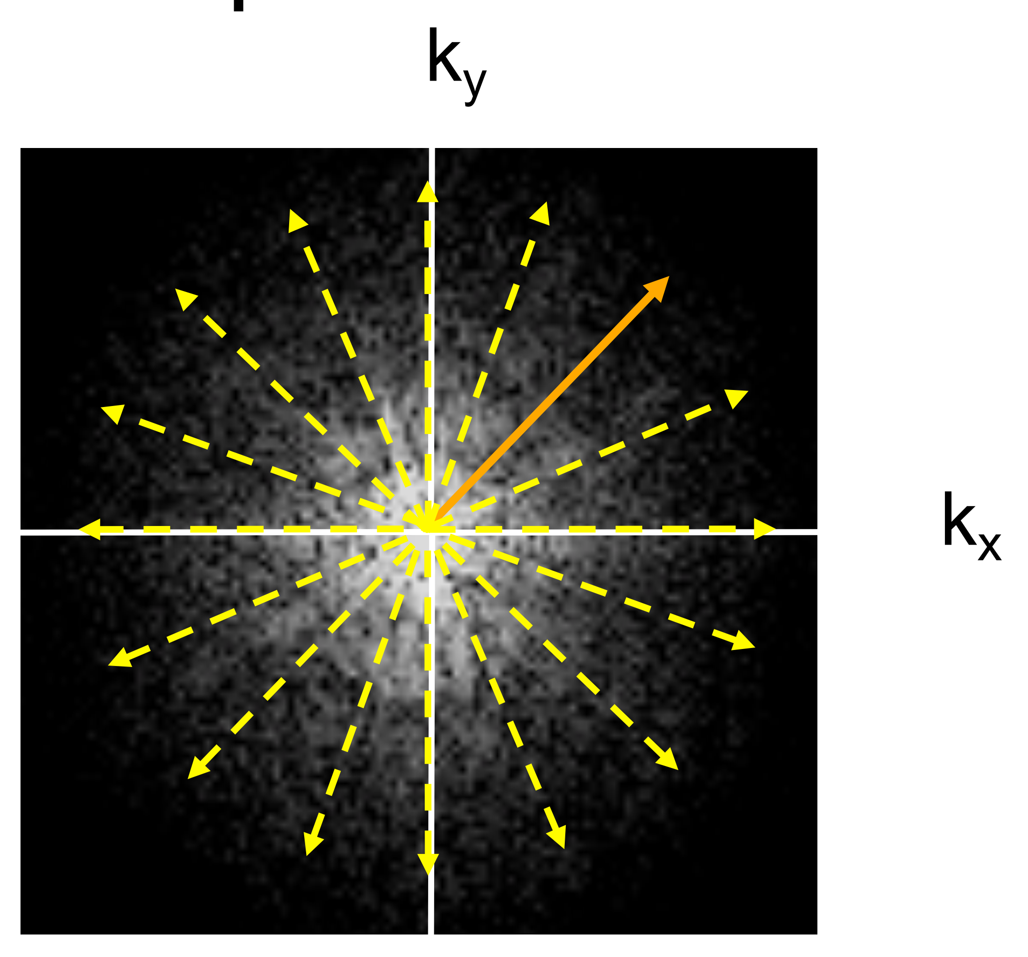
- Sample spokes
  - "Radial out": from $k=0$ to k_{max}
  - Projection: from $-k_{max}$ to k_{max}
- Trajectory design considerations (resolution, #shots)
- Reconstruction, PSF and "streak-like" aliasing
- SNR considerations
- Undersampling
- 3D Projection

Projection-Reconstruction (PR) Sequence

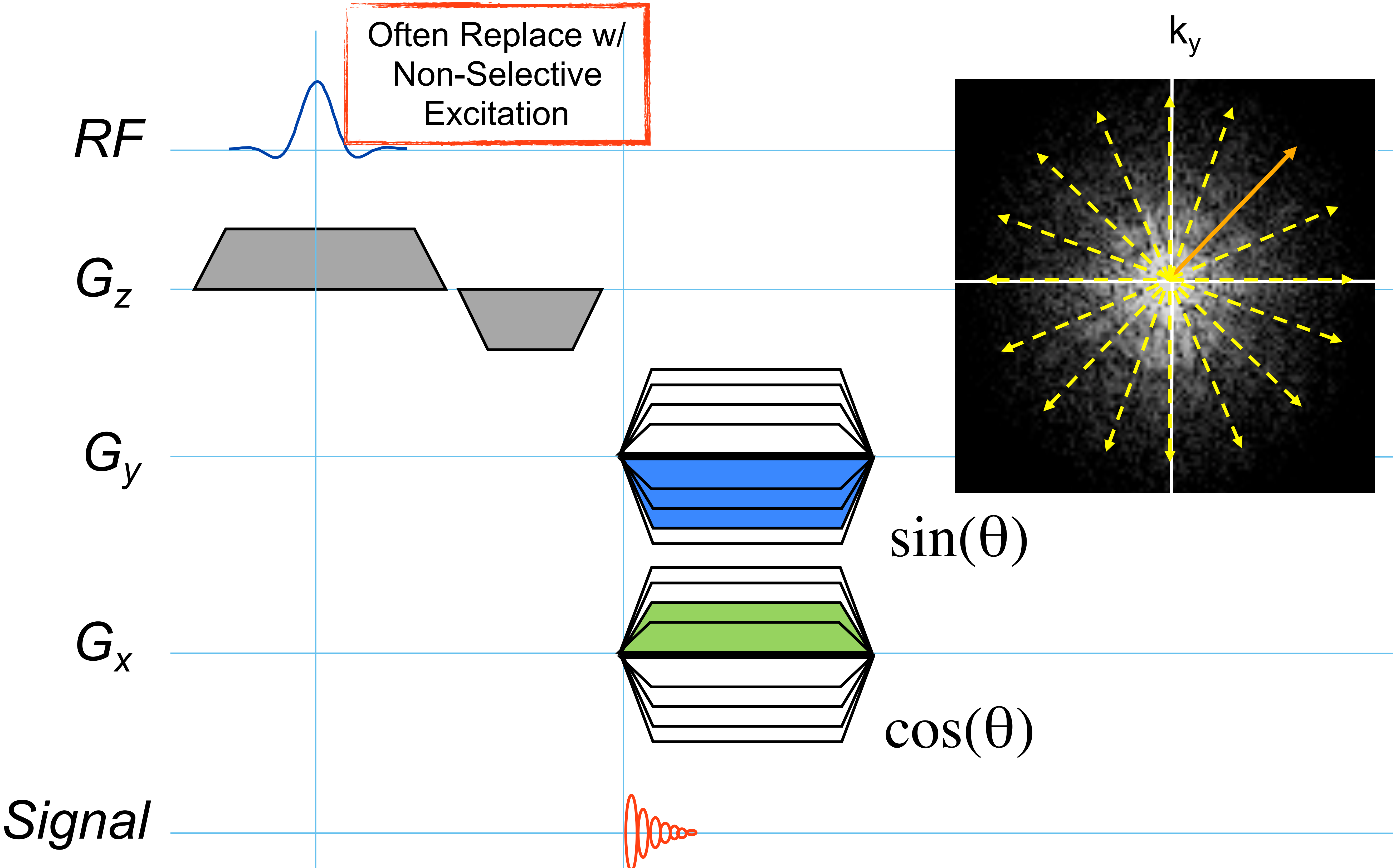


Radial (k=0 outward)

- Similar to Full Projection, but center-out readouts
- Shortest TE (~0) of any sequence
- Low first-moments
- Fastest way to reach high-spatial frequencies
- Impact of delays
- Can do odd/even sampling
- Impact of ramp sampling

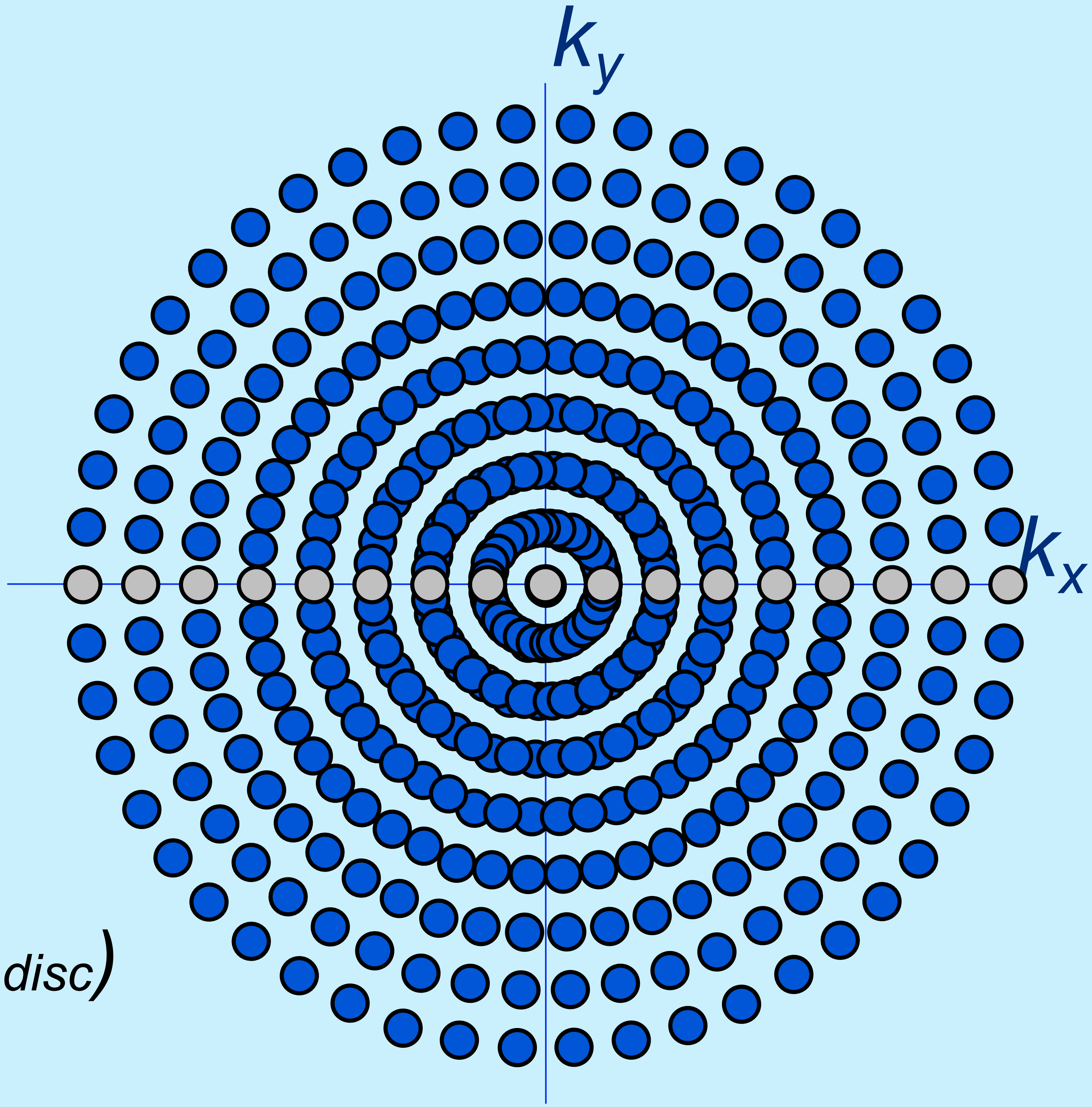


Radial (out) Sequence



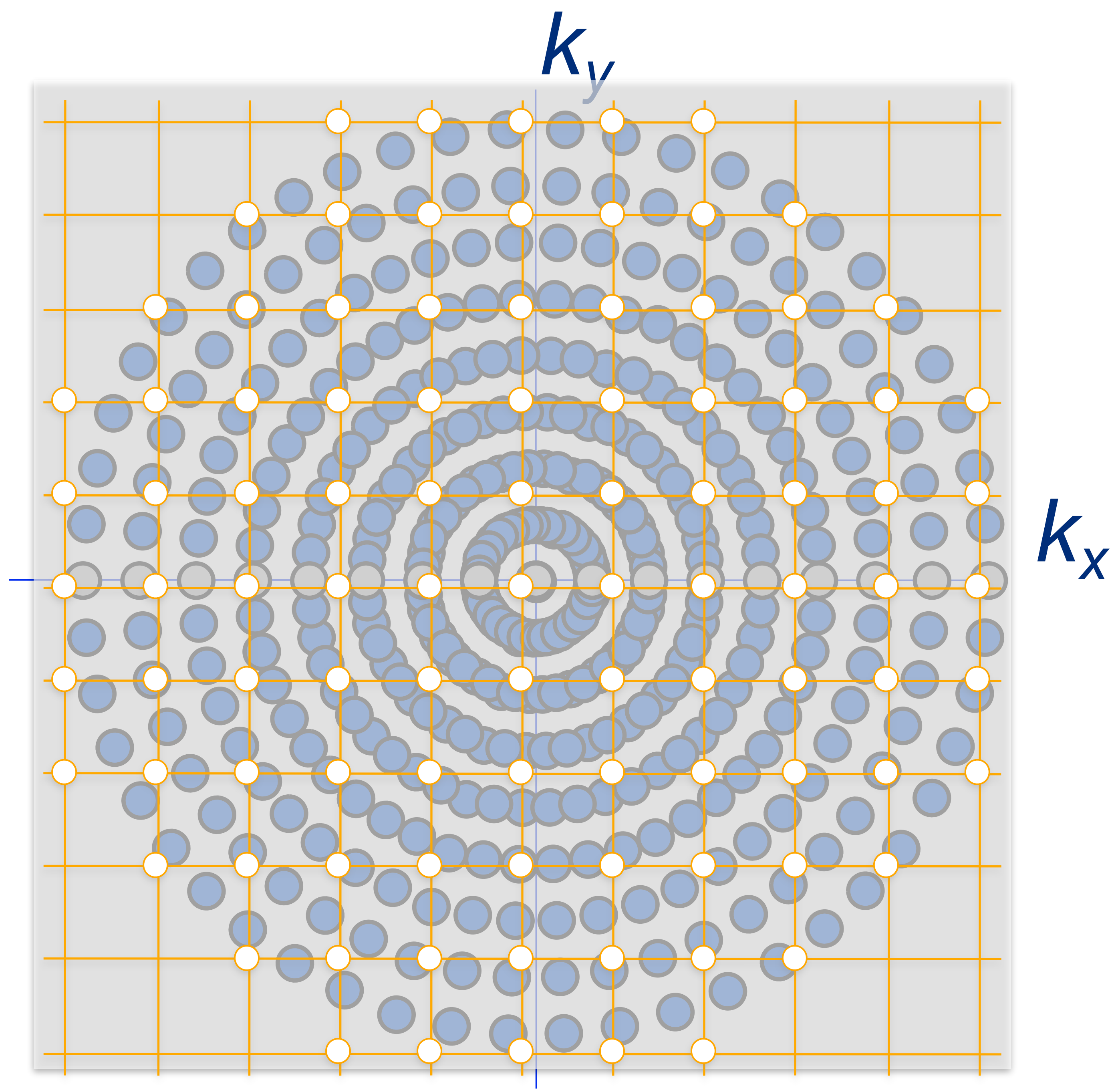
Projection (PR): Design Considerations

- Readout Resolution?
  - Same as Cartesian
- Readout FOV?
  - Same as Cartesian
- Number of angles?
  - $(\pi/2)N_{read}$ *(Full Projection)*
  - πN_{read} *(Radial-Out)*
  - *(Note: N_{read} = # points across disc)*
  - May undersample



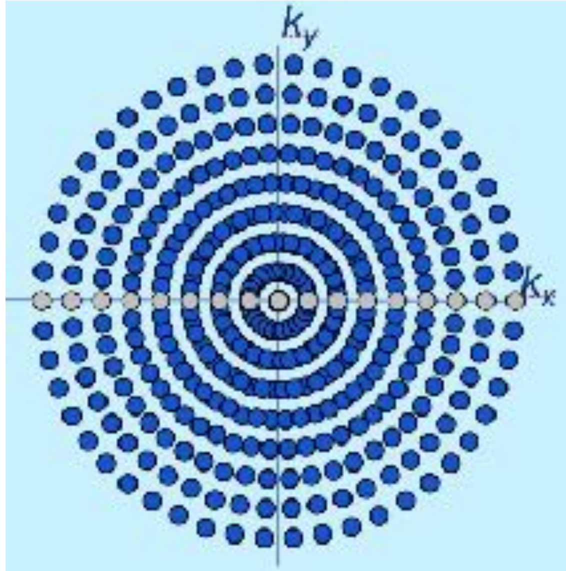
Projection Reconstruction

- Non-Cartesian Sampling
- Filtered back-projection
- Gridding + FFT
  - Both use $|k_r|$ density compensation

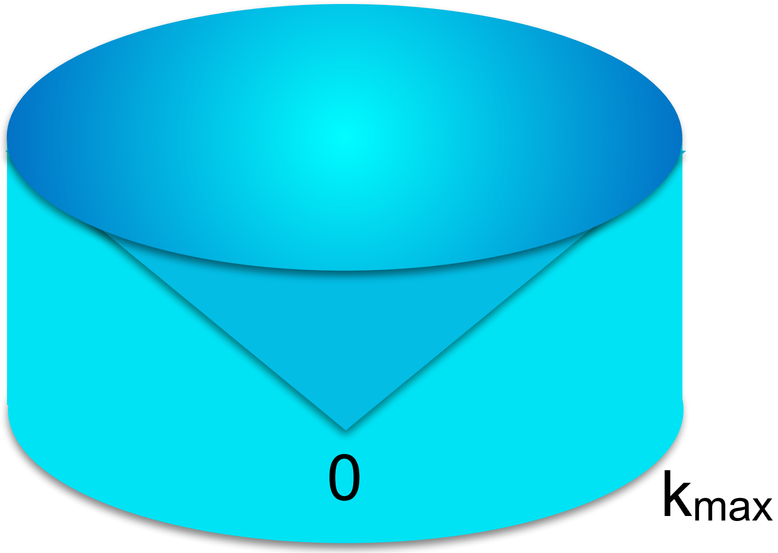


gridmat.m

Radial Sampling Efficiency



- Number of samples per-unit-area of k-space:
  - Cartesian requires NxN samples, Area $4k_{max}^2$
  - Radial requires (π/2)NxN samples, Area πk_{max}^2
  - Radial requires (π/2)/(π/4) = 2x samples / unit area
    - Penalty 1/sqrt(2)
- Noise variance averaged over k-space area
  - average of k_r (Density compensation)
  - "pill-box minus cone" = 2/3



- Overall Efficiency is 1 / sqrt(2 x 2/3) = $\sqrt{3}/2 = 0.87$

Reduced aliasing artifacts using variable-density k-space sampling trajectories. Tsai CM, Nishimura DG. Magn Reson Med. 2000 Mar;43(3):452-8.

Radial/Projection: SNR Efficiency (η)

- Radial density $D = k_{max}/k_r$, extent [-1,1]

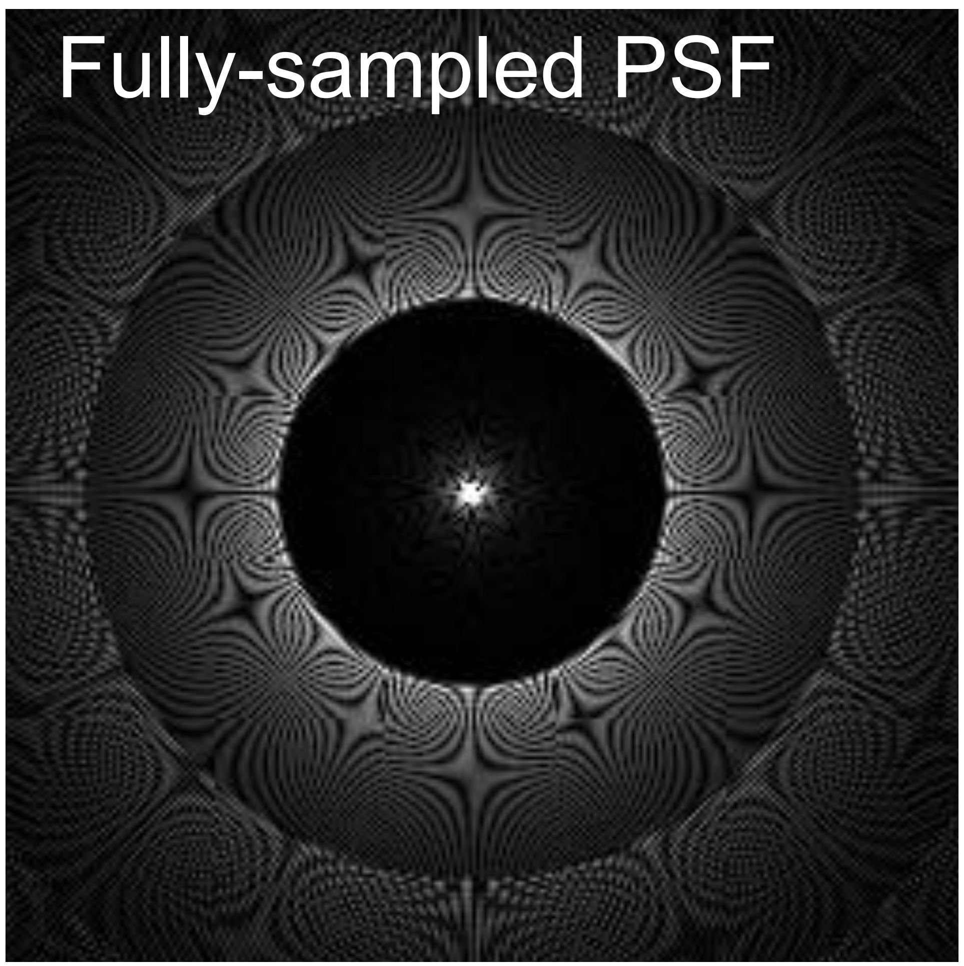
Quantity	Symbol	Cartesian	2D Radial
k-space area	(A)	4	π
#samples needed to cover area	$\int_A D$	4	2π
Integrated density compensation	$\int_A 1/D$	4	2π/3
Efficiency	$\eta = \frac{A}{\sqrt{\int_A D \int_A 1/D}}$	1	$\sqrt{3}/2 = 0.87$

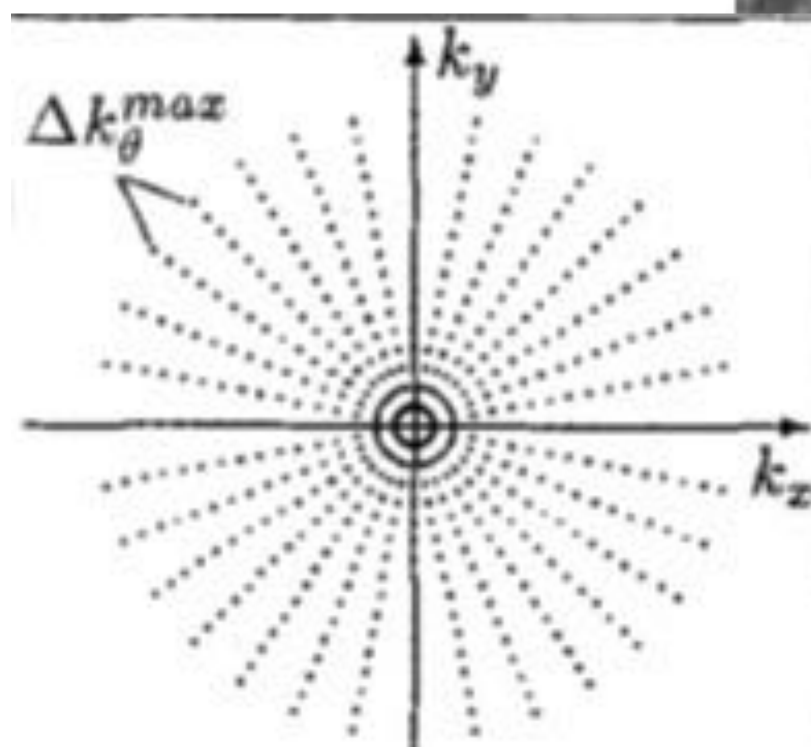
- Note that the density variation affects efficiency

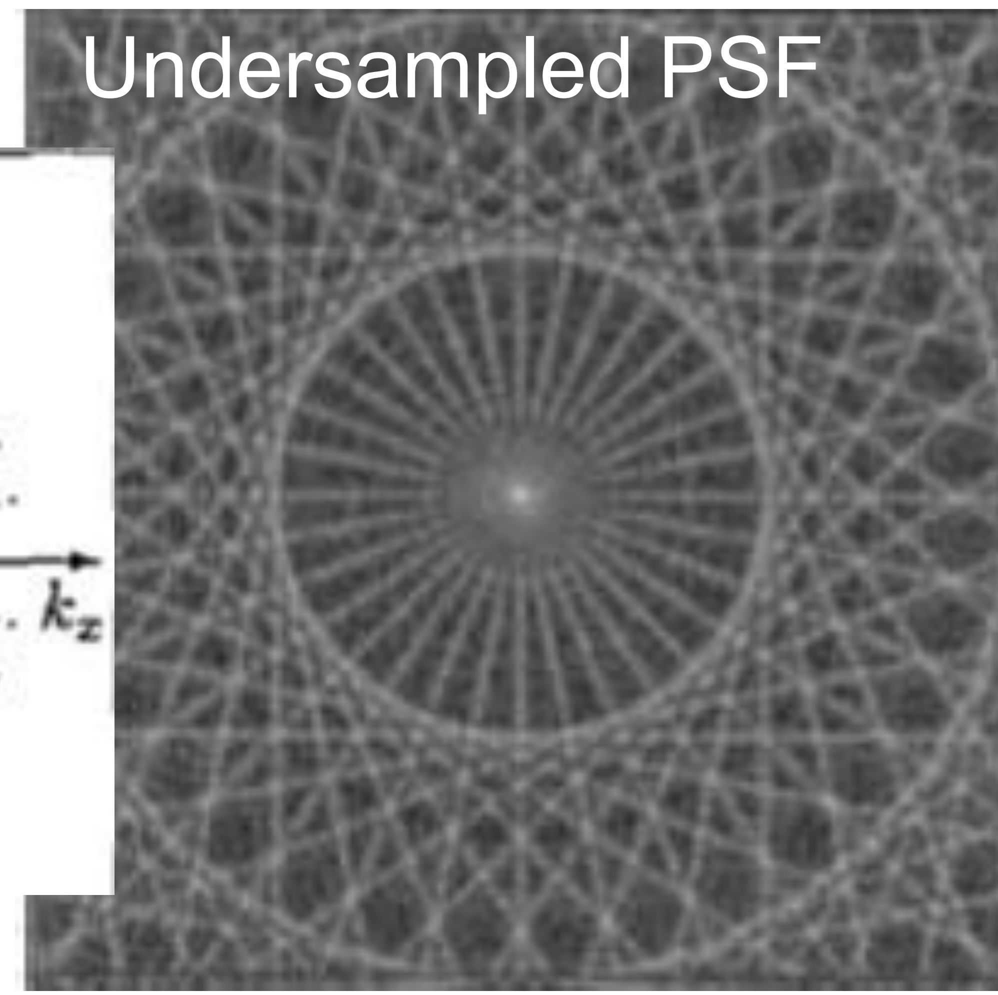
Radial-Outward Design Example

Projection-Reconstruction PSF / Undersampling

- PSF has a “ring” of aliasing (less coherent)
  - Intuition: No “preferred” direction for coherent peak
- Undersampling tends to result in streak artifacts



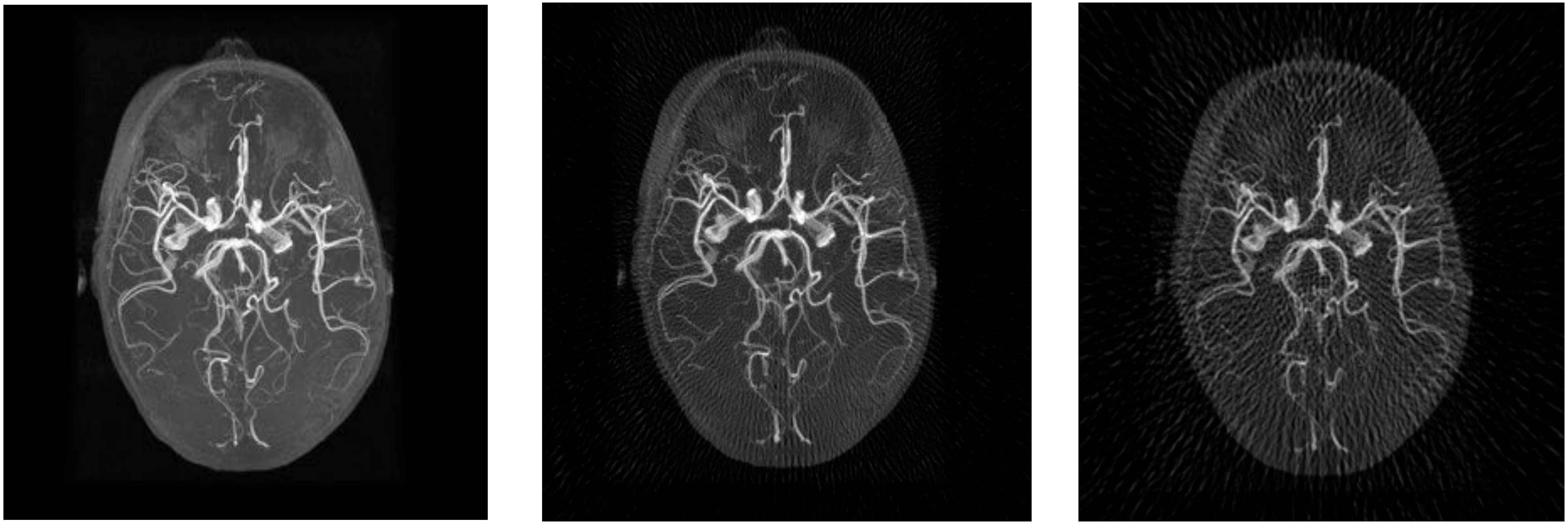




From Scheffler & Hennig, MRM 1998

Undersampled PR: Streak Artifacts

- Reduced sampling leads to streaks
- With reasonable undersampling the artifact is often benign



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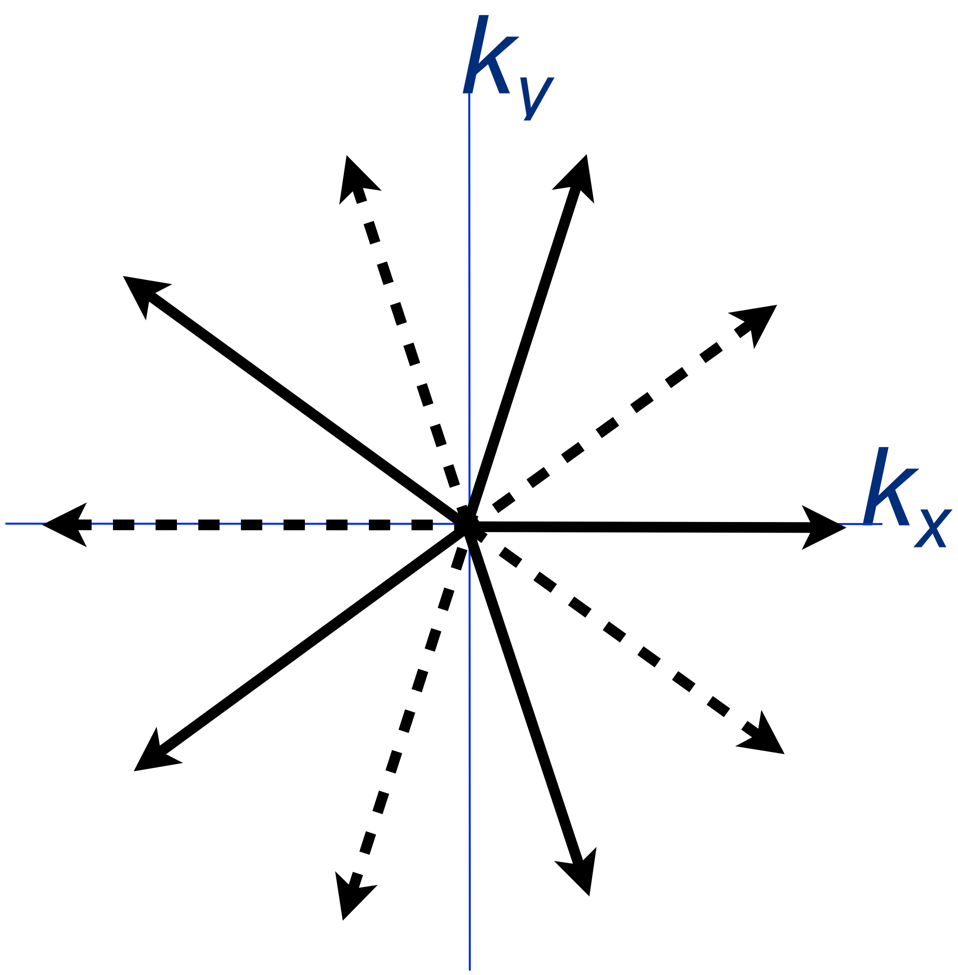
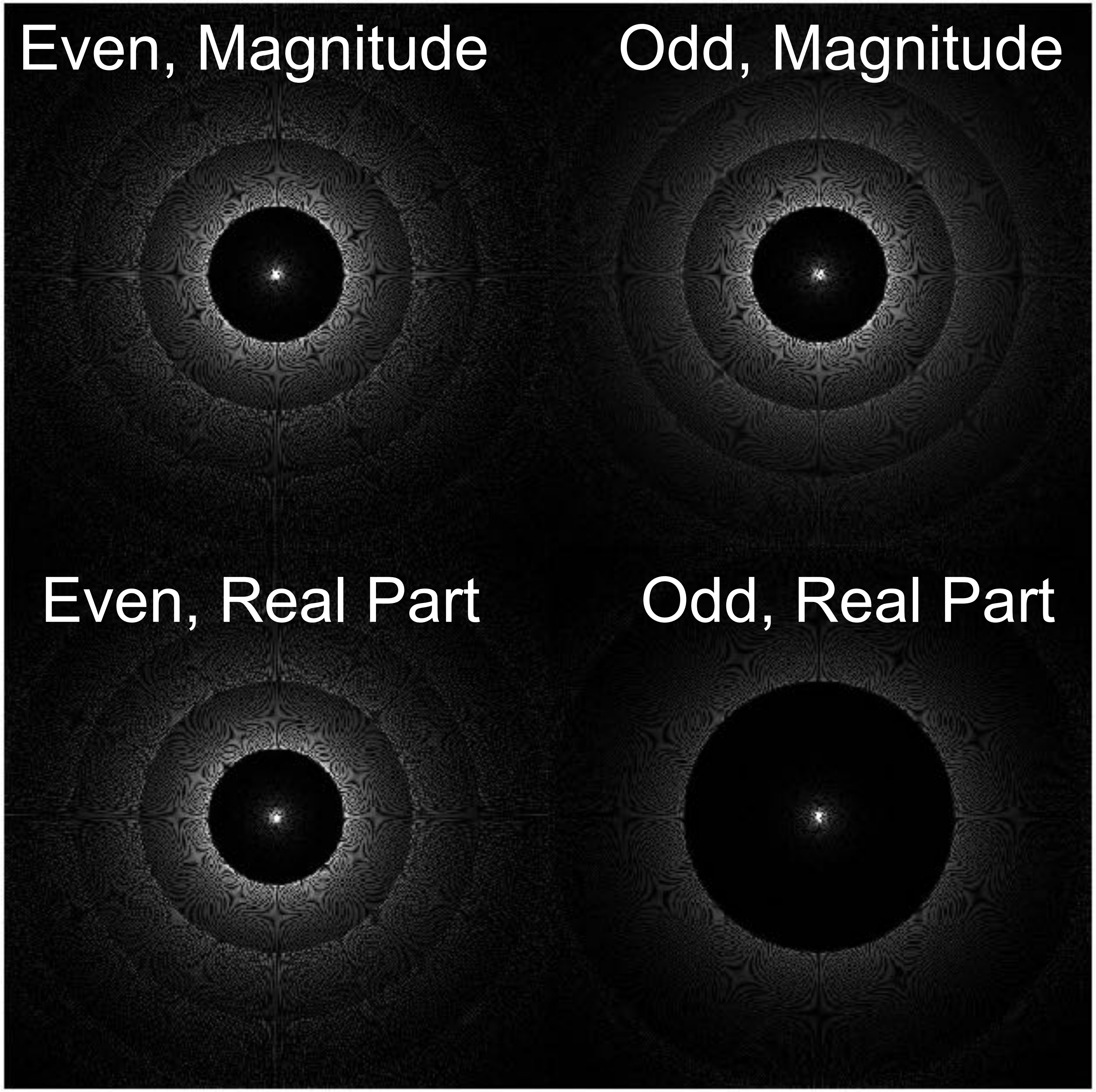
Radial Out - Odd vs Even #Spokes

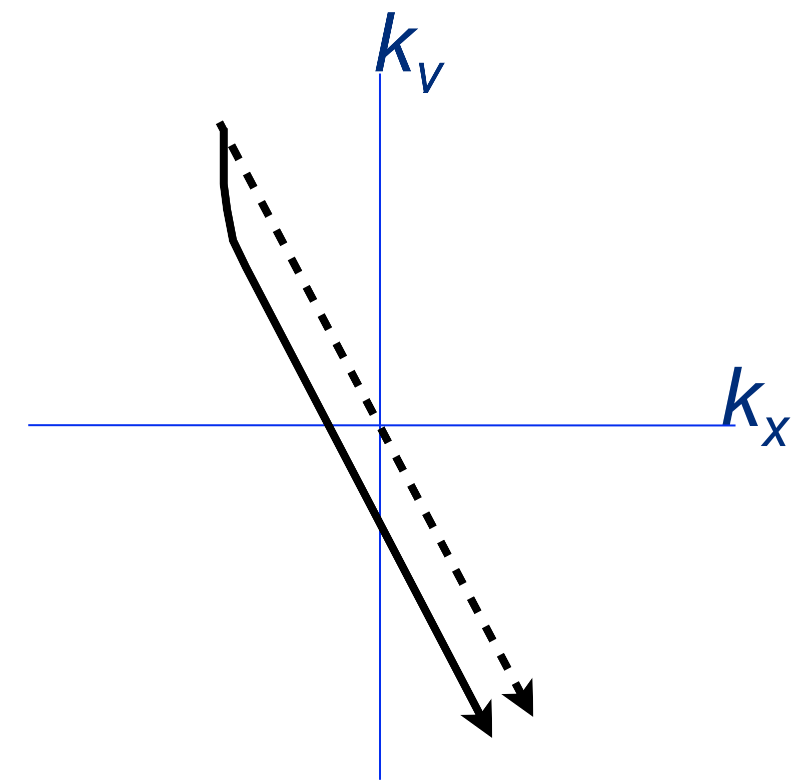
- Odd N is a half-Fourier trajectory
- Difficult to do homodyne, but quadrature aliasing

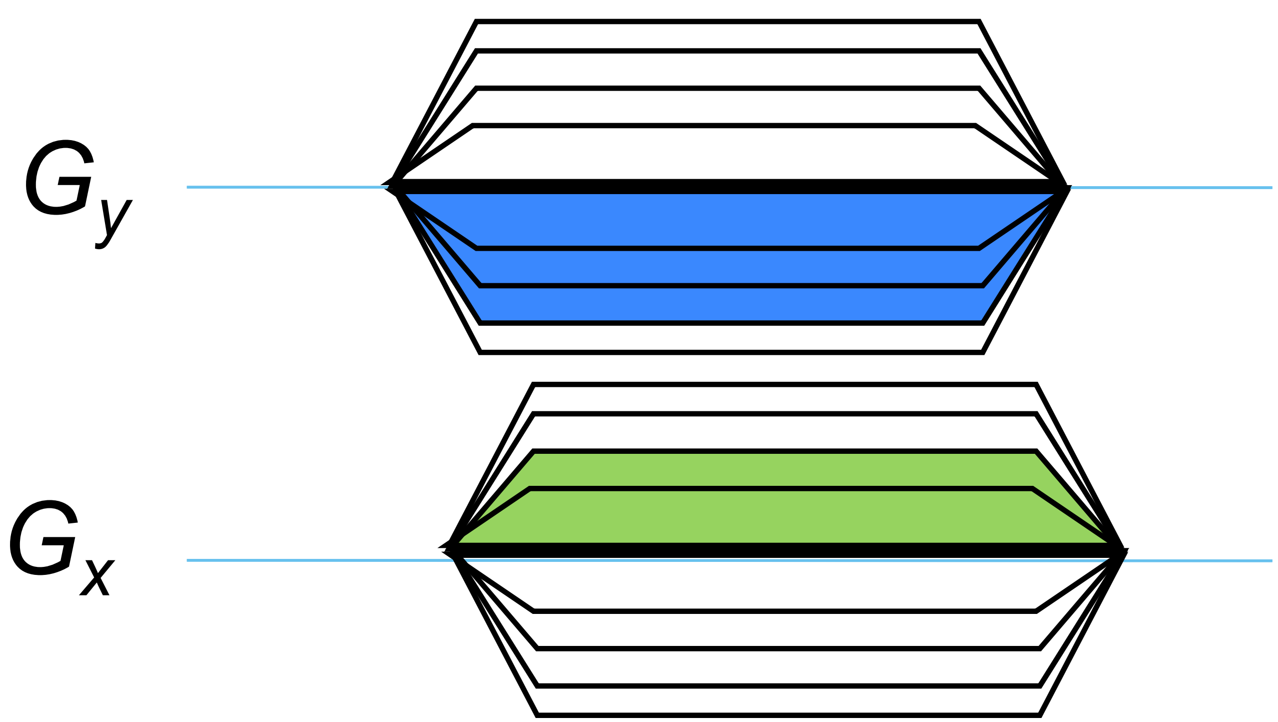


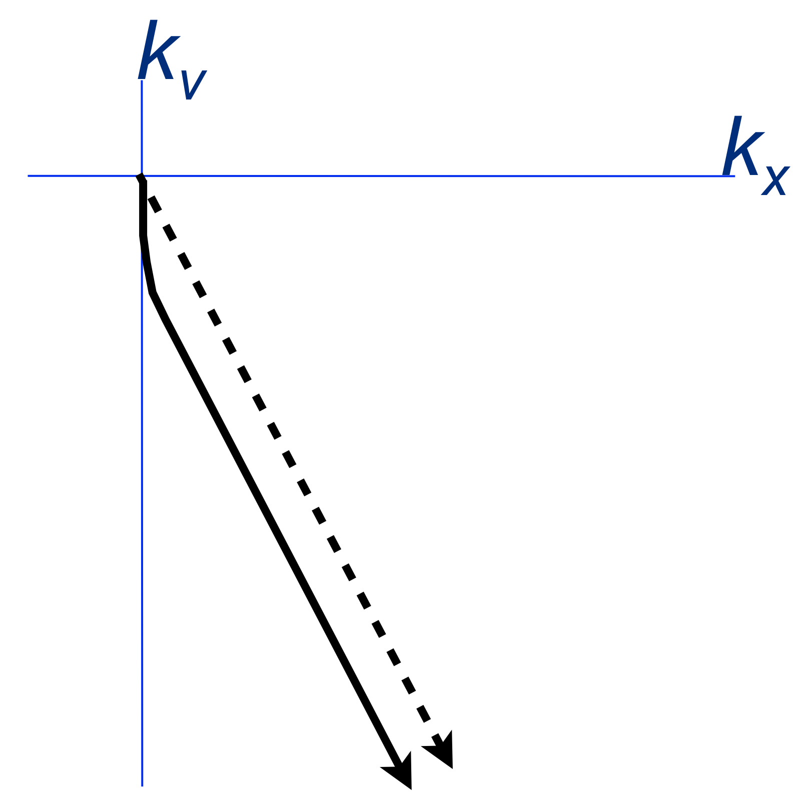


Gradient Delay Considerations

- Full projection
  - Global Delay: Shift center
  - Inter-axis: May miss center
- Radial out:
  - Global Delay: Shifts along traj.
  - Inter-axis: Warping of trajectory

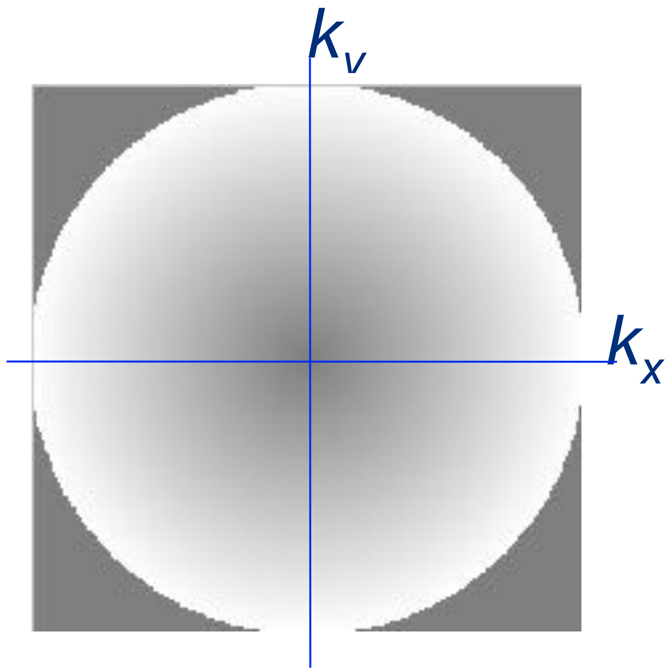




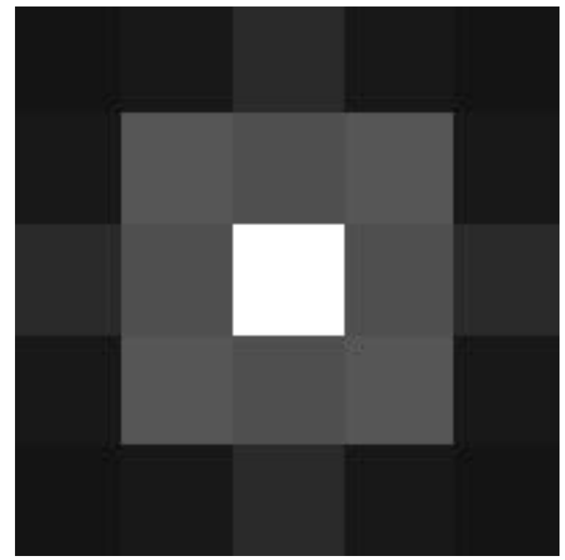


Off-Resonance Effects

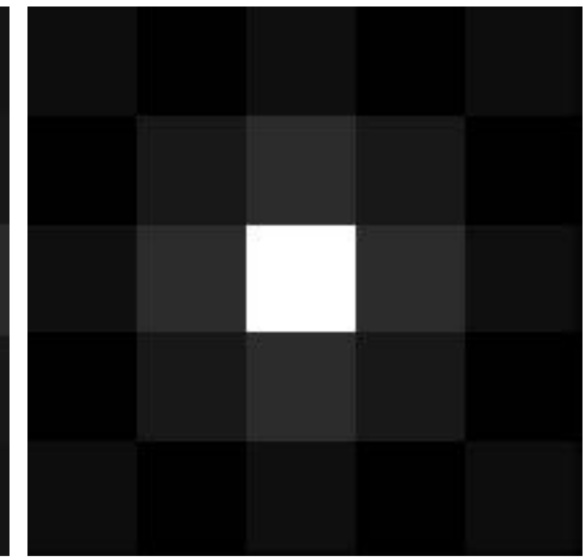
Radial-out (0 to π variation)



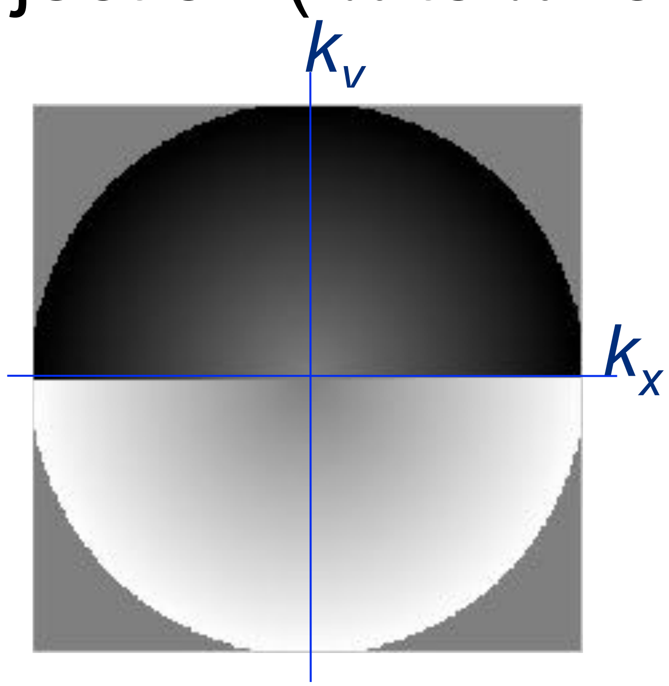
PSF



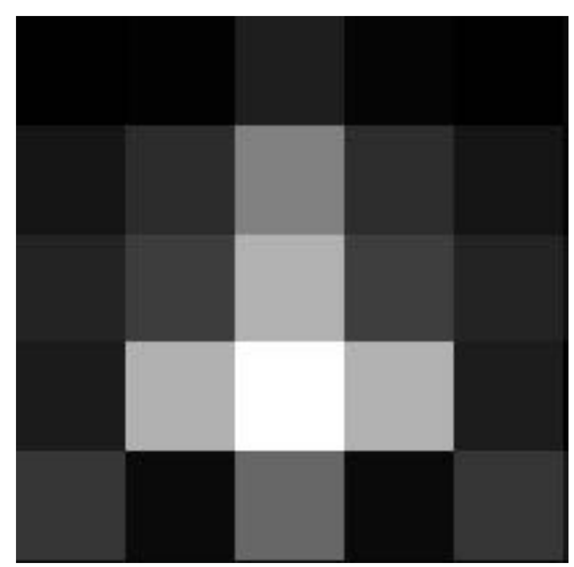
Reference



Full Projection (-π to π variation)



PSF



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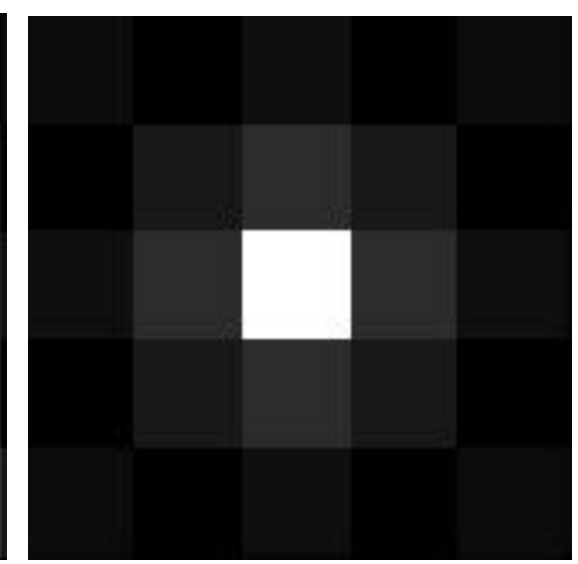
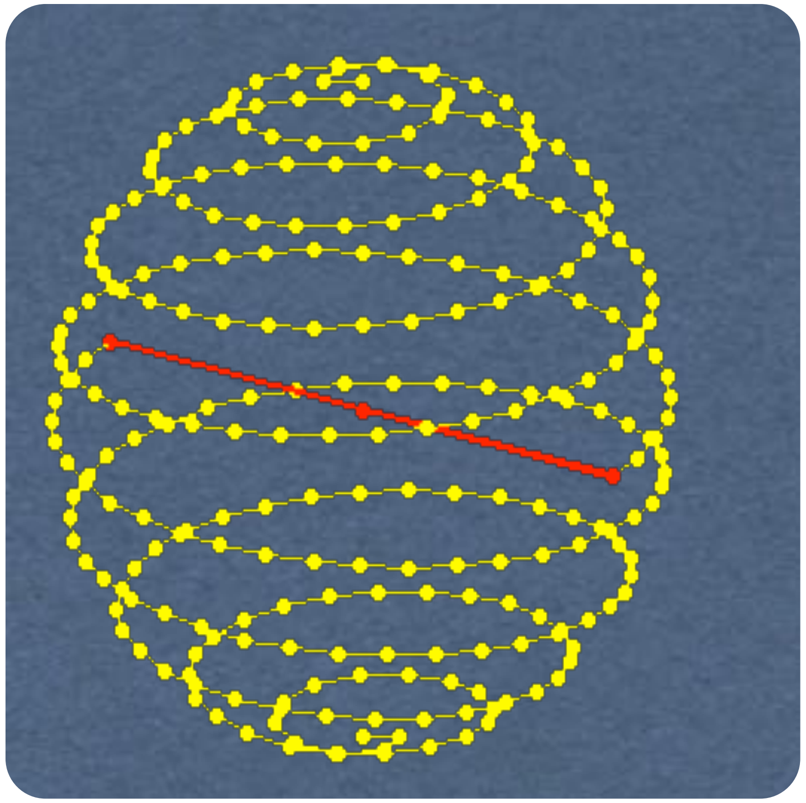


3D Projection-Reconstruction

- Encode in k_x, k_y, k_z (θ,φ end-point parameterization)
- Density $(1/k_r)^2$, compensate by multiplying by k_r^2
- SNR efficiency now 0.75
- Can undersample more though!



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3D Radial/Projection: SNR Efficiency (η)

- Radial density $D = (k_{max}/k_r)^2$, extent [-1,1]

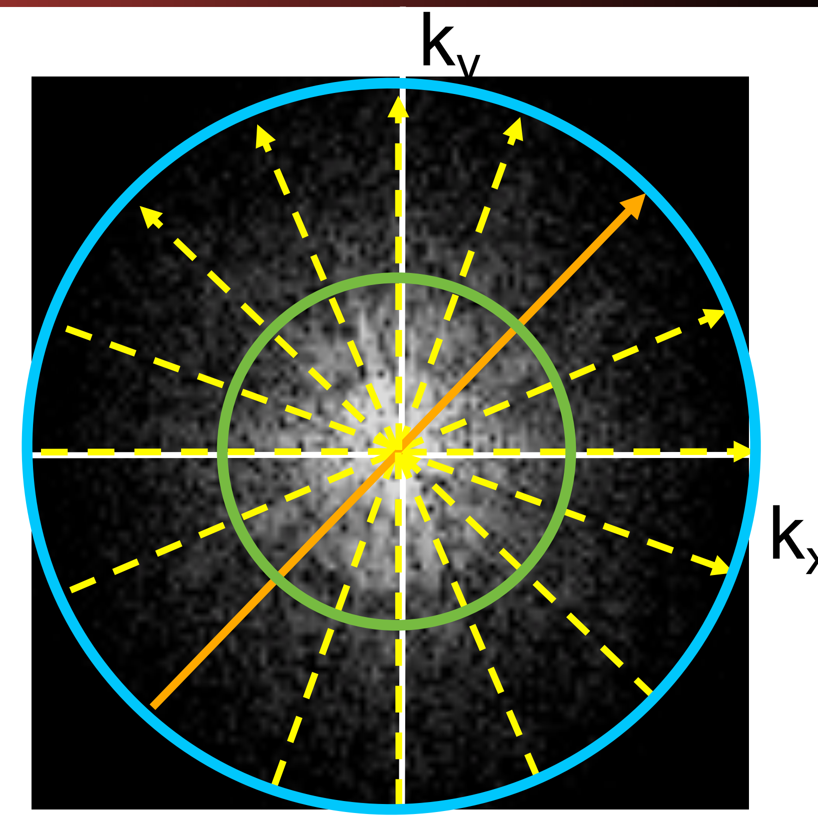
Quantity	Symbol	Cartesian	3D Radial
k-space volume	(V)	8	4/3π
#samples needed to cover volume	$\int_V D$	8	4π
Integrated density compensation	$\int_V 1/D$	8	4π/5
Efficiency	$\eta = \frac{V}{\sqrt{\int_V D \int_V 1/D}}$	1	$\sqrt{5}/3 = 0.75$

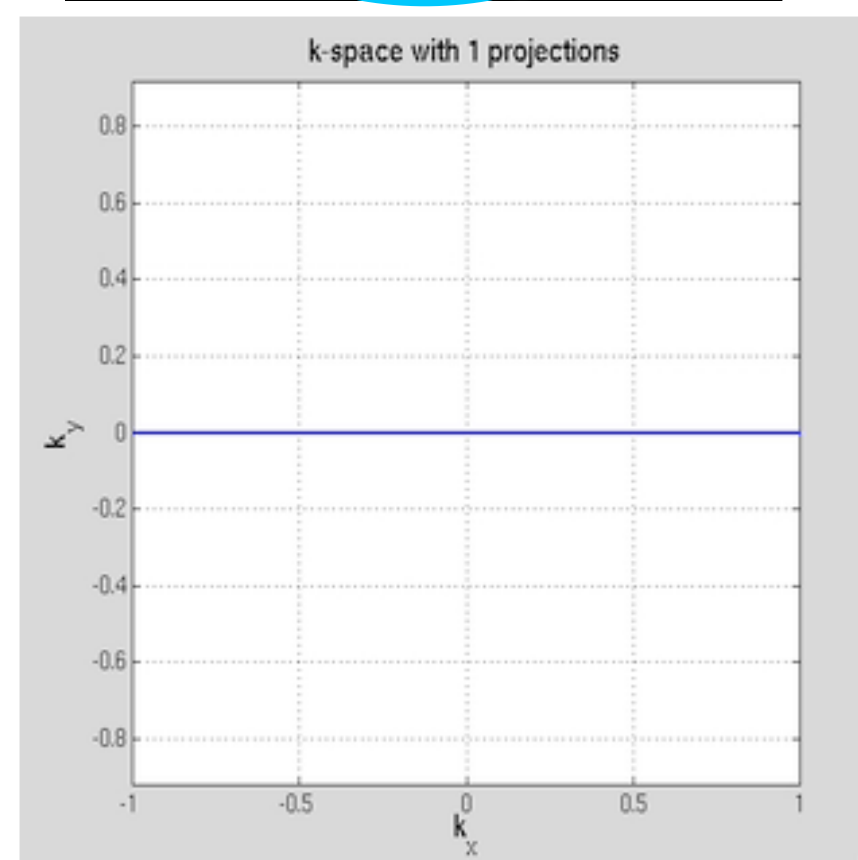
Temporal Radial Patterns

- Reduction R gives a fully-sampled image with R lower resolution
- Vary spatio-temporal resolution
  - "KWIC: k-space weighted image contrast"
  - Field map generation by delaying odd vs even lines
  - Golden-angle increment: 111.246º

    180º / 111.246º = (sqrt(5)+1)/2

    - Arbitrary N_s<N has "uniform" angular spacing

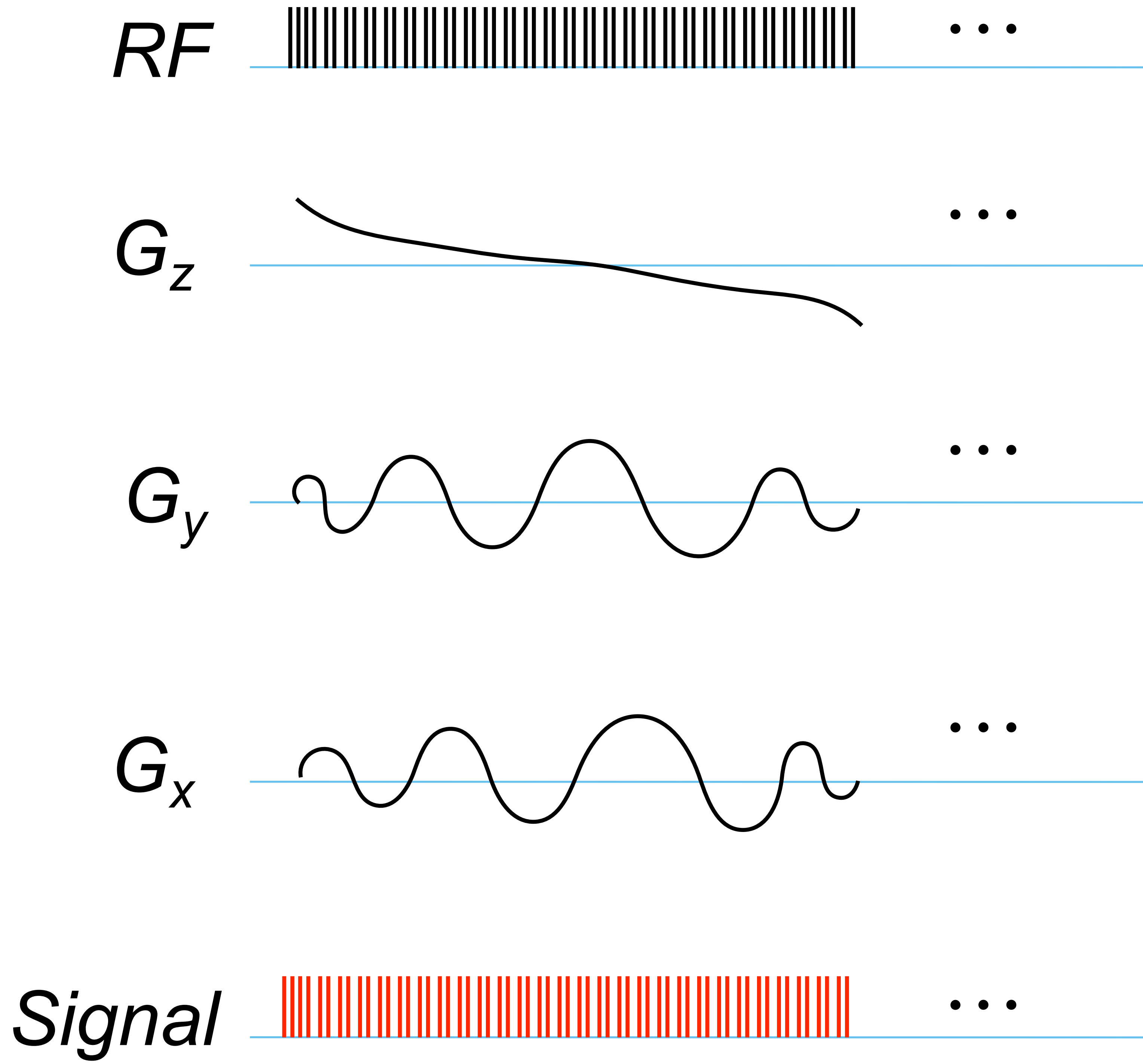




IEEE Trans Med Imaging. 2007 Jan;26(1):68-76.
An optimal radial profile order based on the Golden Ratio for time-resolved MRI.
Winkelmann S, Schaeffter T, Koehler T, Eggers H, Doessel O.

Zero Echo-Time (ZTE)

- Gradients always on!
- Radial sampling
- Very short RF
    - Low flip angle (SAR)
    - Actual RF excites slab with varying direction



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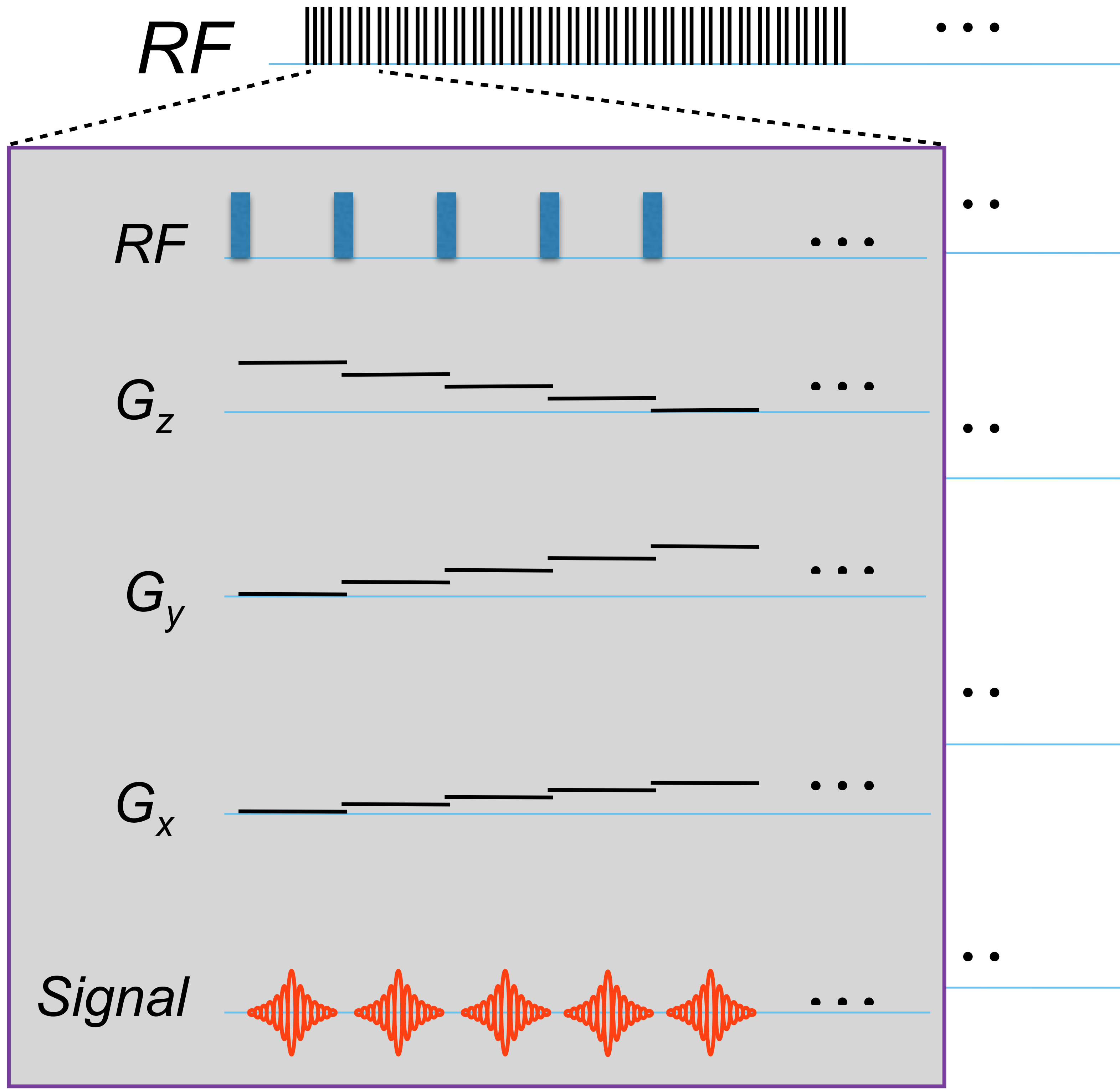
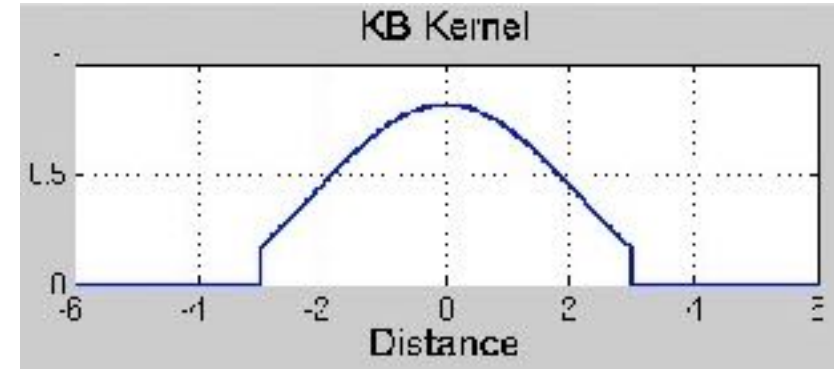


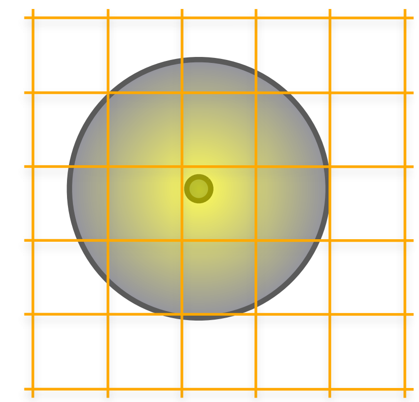
Radial and Projection: Summary

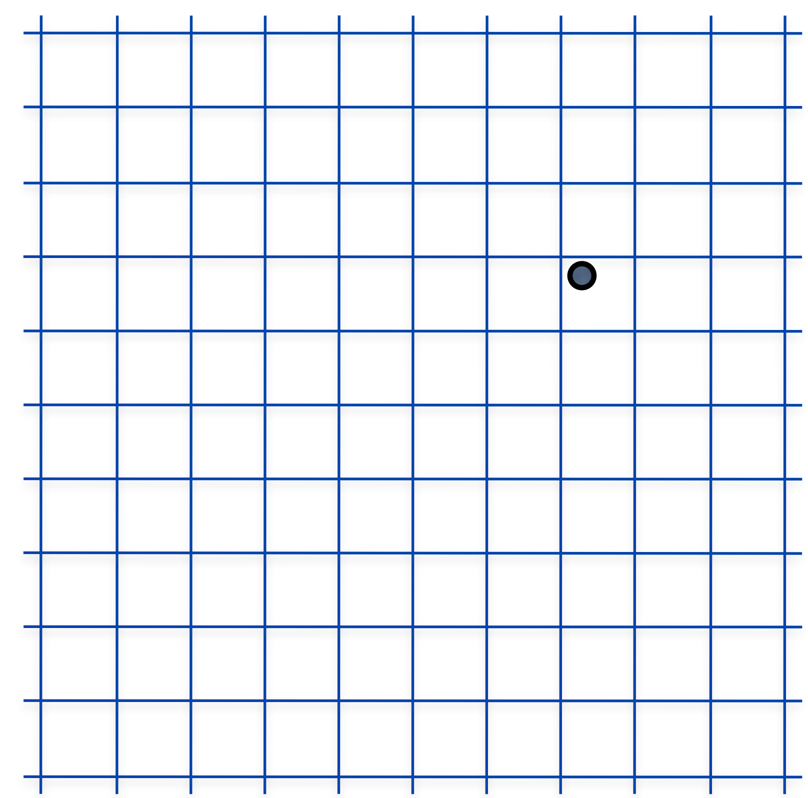
- Non-Cartesian, requires gridding reconstruction
- Incoherent undersampling artifact (similar to CS)
- Short TE (and UTE) imaging
- 2D and 3D options
- No phase-encoding ~ can be efficient
- Off-resonance causes blurring
- SNR efficiency loss due to high-density near center, but resampling the center can be advantageous

Gridding Code: gridmat.m

- Designed to be reasonably fast, but Matlab (readable)
- Uses Kaiser-Bessel interpolation kernel (precalculated)
- For each k-space sample M(k):
  - Build a “neighborhood” of affected grid points k_{grid}
  - Calculate contribution at each grid point:
    - $M(k) \times kernel(k-k_{grid})$
  - Add the values to a full-size grid
  - No deapodization







gridmat.m

- Inputs:
  - ksp = list of k-space locations, $k_x + ik_y$
  - kdat = data samples, ie $M(k_x,k_y)$
  - dcf = density compensation factors at each k-space location
  - gridsize = size of grid
- Convention:
  - k is in “inverse reconstructed pixels”
  - $|k| < 0.5$
- Larger gridsize zero-pads image (reduce apodization)
- Scale ksp smaller to “fill” FOV and interpolate pixels