Fast Imaging Trajectories: Non-Cartesian Sampling (1)

M229 Advanced Topics in MRI

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2018.05.03

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Class Business

- Homework 2 - due 5/4
- Project proposal - due 5/11
- Office hours

Outline

- Review of k-space sampling (2DFT)
- Radial
- Concentric rings

MR Signal Equation

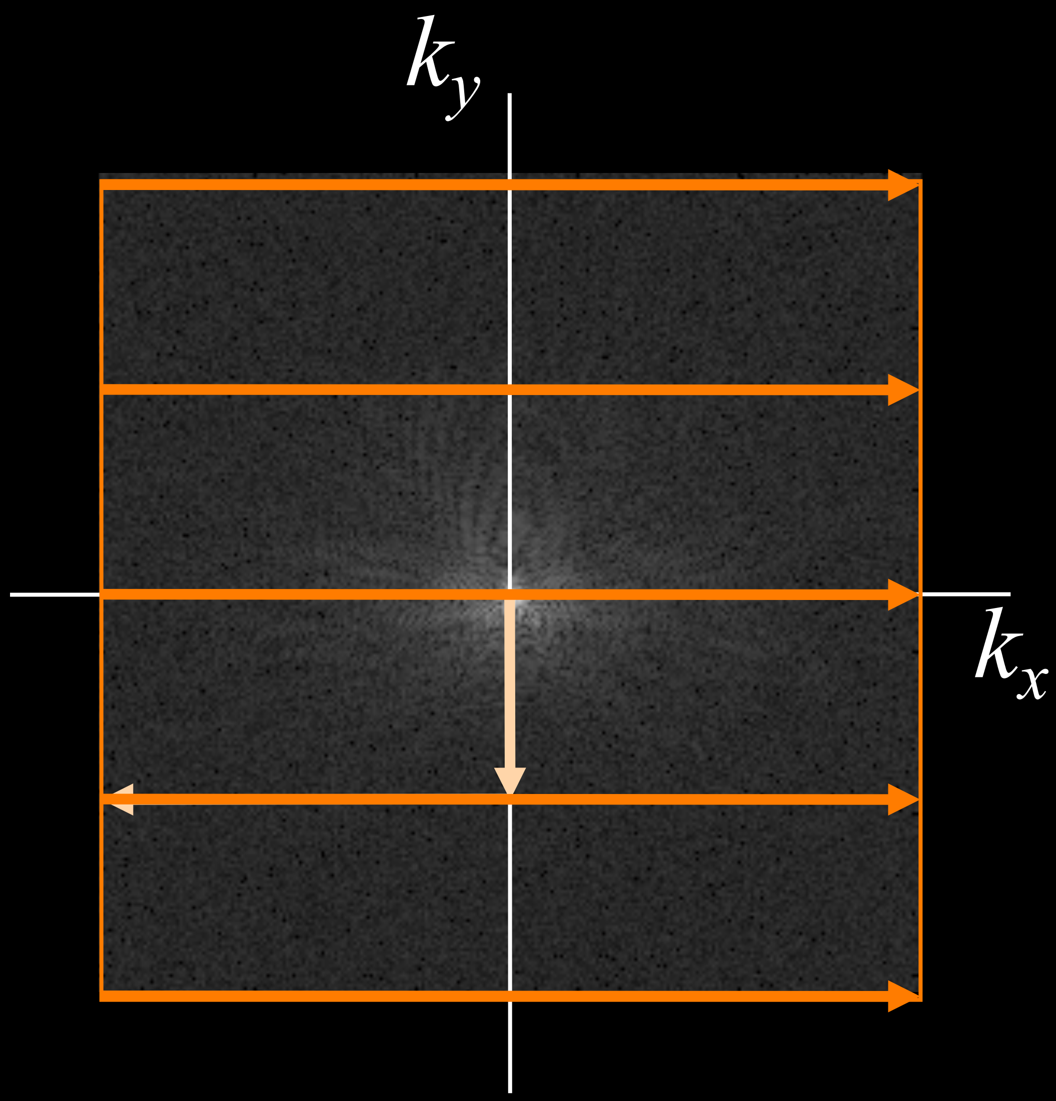
$$s(t) = \iint_{X,Y} M(x,y) \cdot \exp(-i2\pi \cdot [k_x(t)\, x + k_y(t)\, y])\, \mathrm{d}x\, \mathrm{d}y$$

$$= m(\, k_x(t), k_y(t)\,)$$

$$\boxed{k_x(t) = \frac{\gamma}{2\pi} G_x t,\; k_y(t) = \frac{\gamma}{2\pi} G_y t}$$

$$m = \mathcal{FT}(\, M(x,y)\,)$$

k-Space Sampling



set of $s(t)$ covers $m(k_x, k_y)$

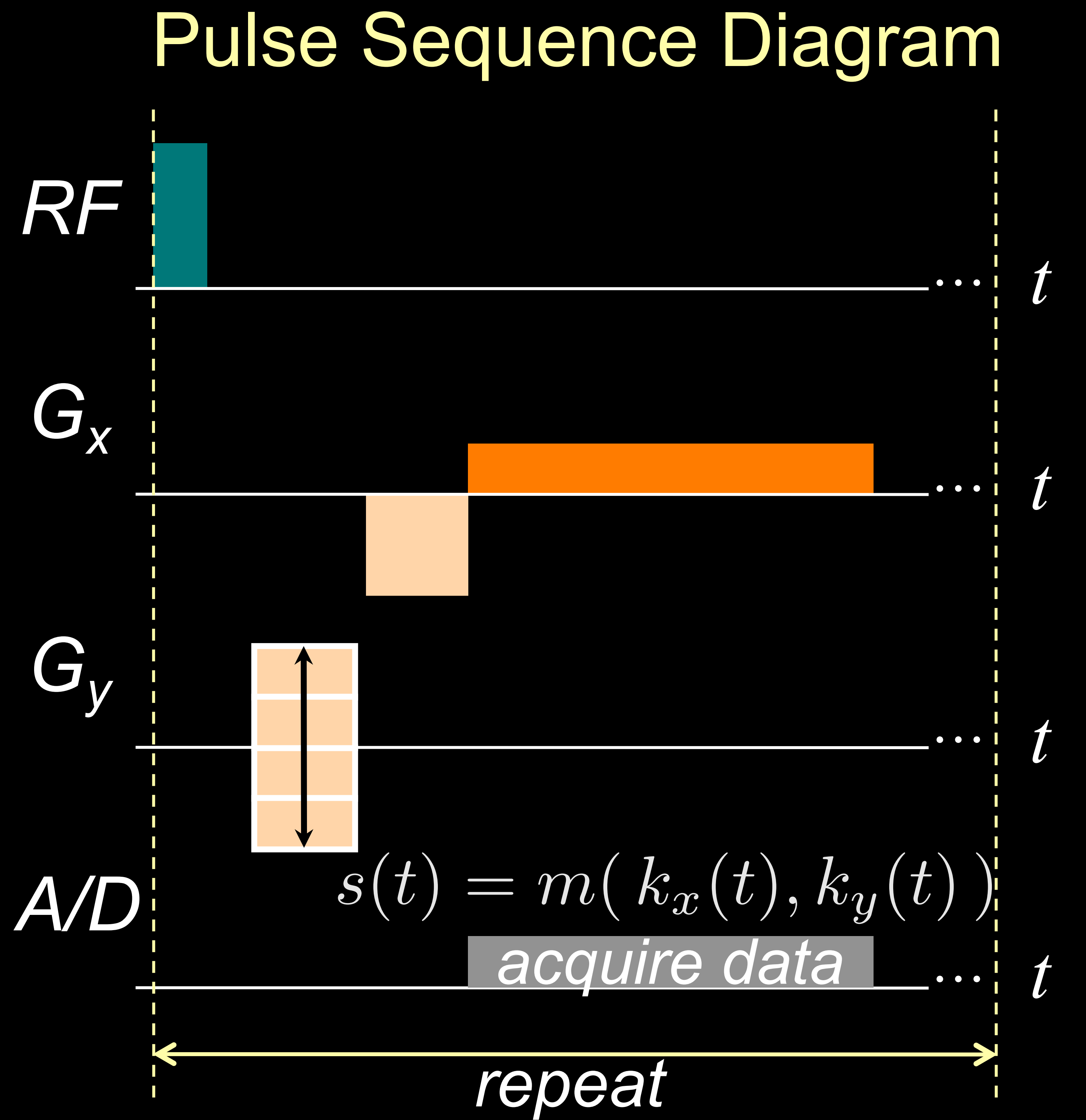
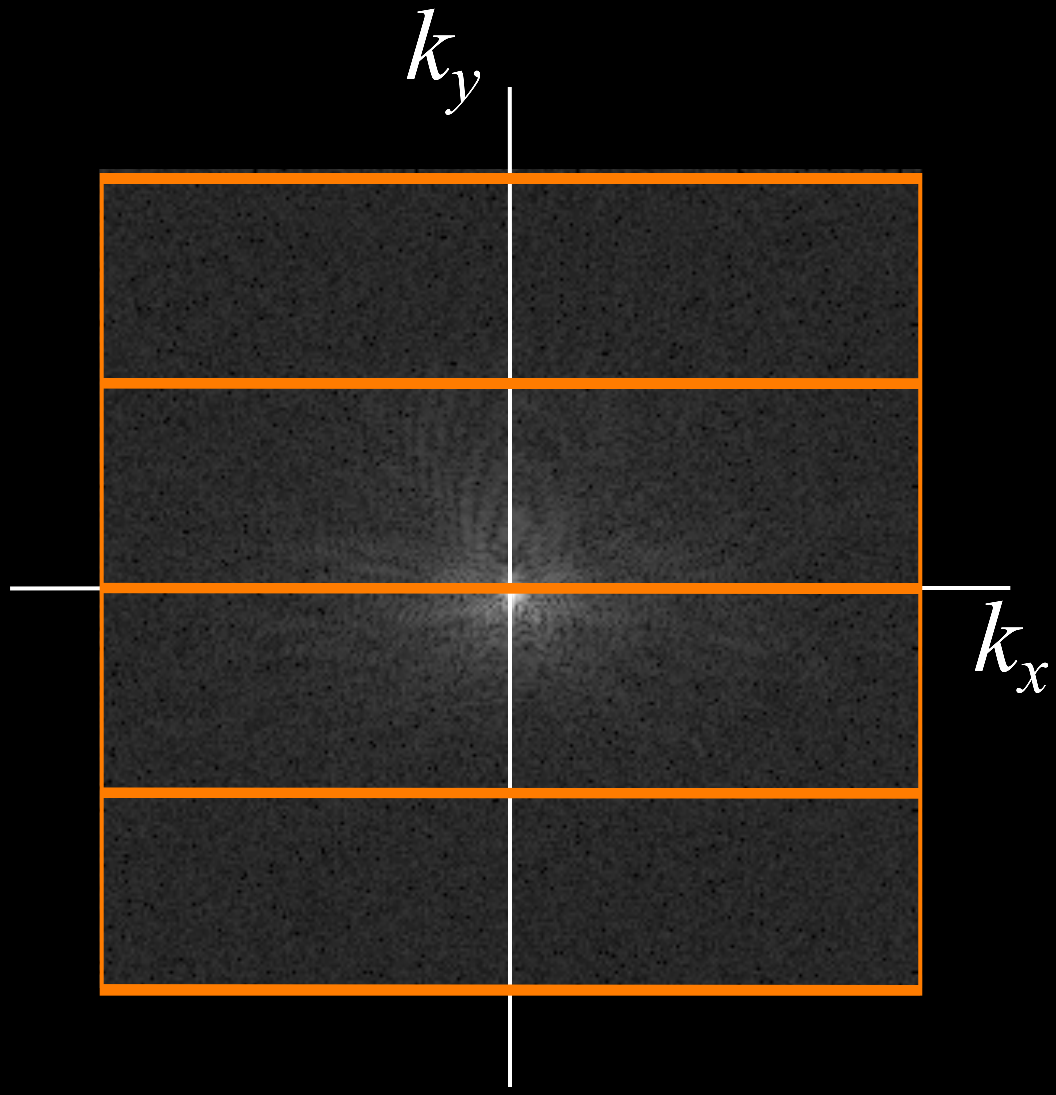


Image Reconstruction

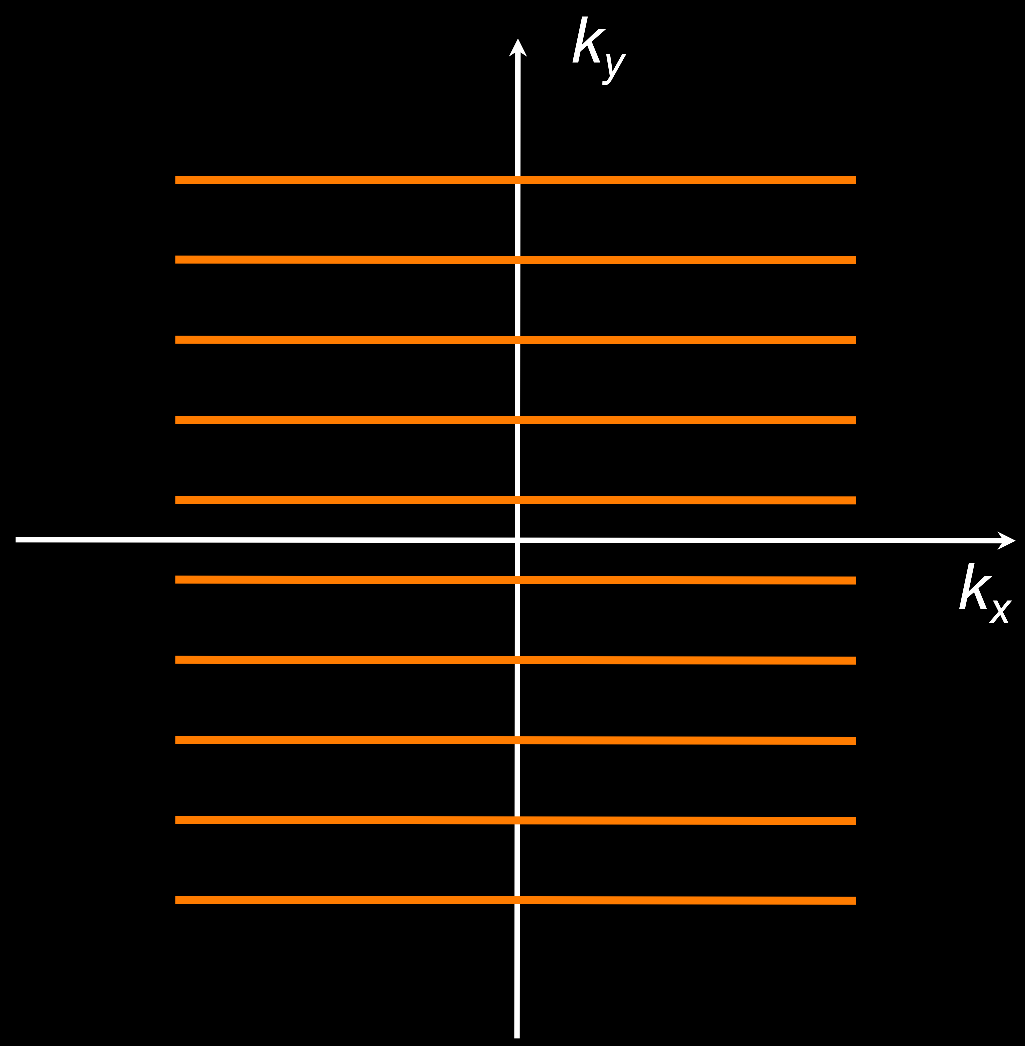


FT ⟷

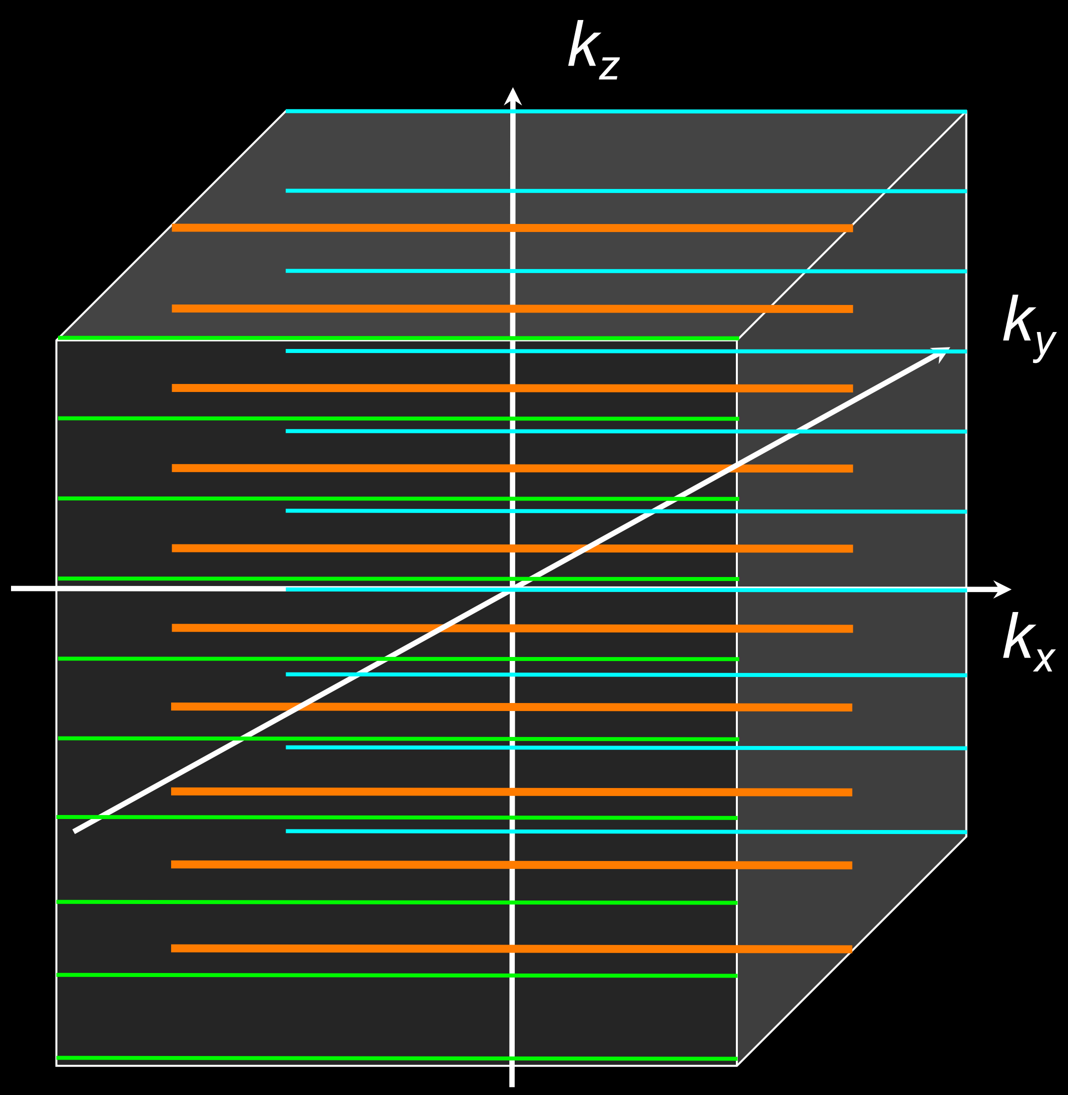
Complex data

Complex data

Cartesian Sampling



Cartesian 2DFT



Cartesian 3DFT

MR Signal Equation

$$s(t) = \iint\limits_{X,Y} M(x,y) \cdot \exp(-i2\pi \cdot [k_x(t)\, x + k_y(t)\, y])\, \mathrm{d}x\, \mathrm{d}y$$

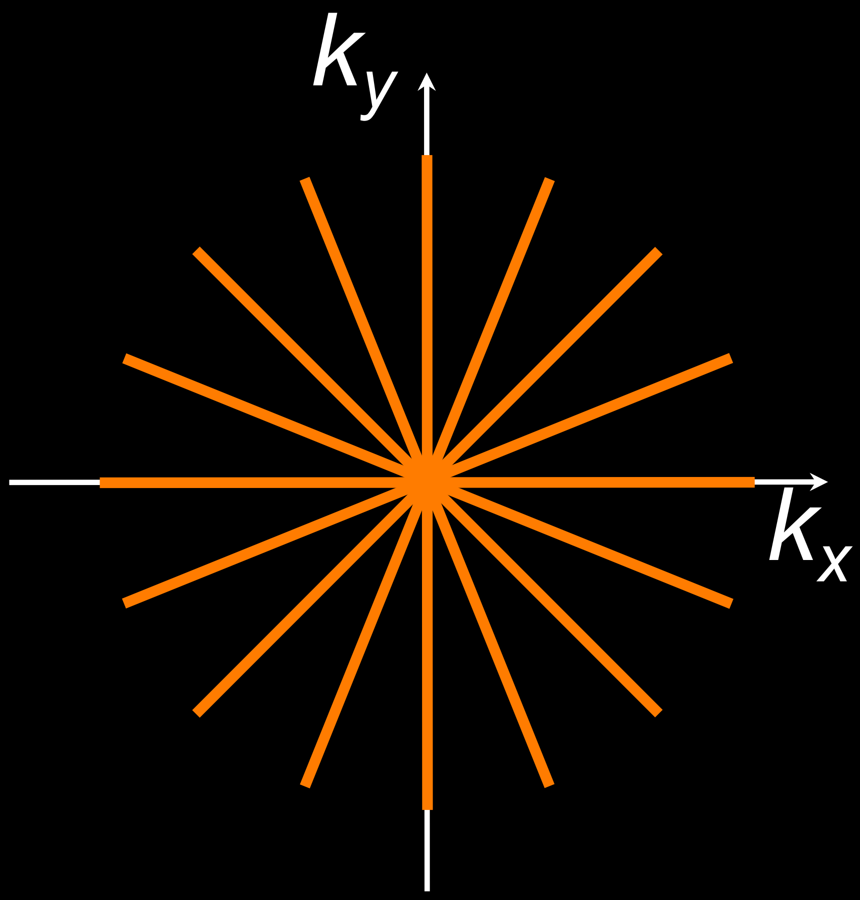
$$= m(\, k_x(t), k_y(t)\,)$$

$$\boxed{k_x(t) = \frac{\gamma}{2\pi} G_x t,\; k_y(t) = \frac{\gamma}{2\pi} G_y t}$$

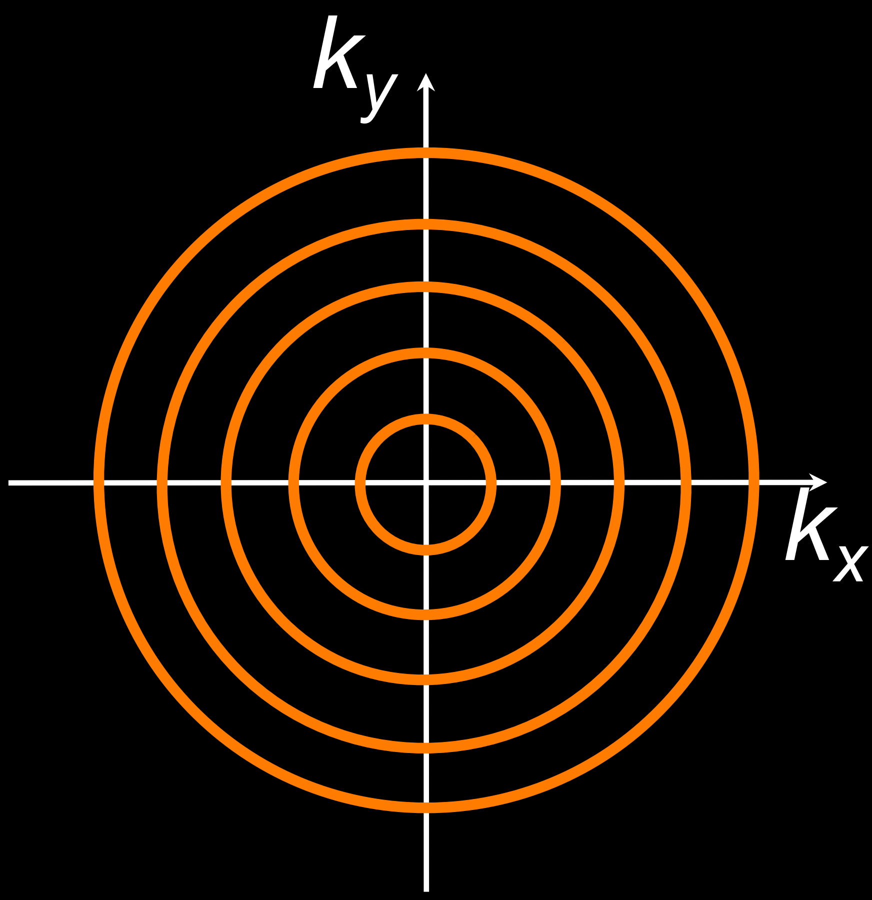
$$m = \mathcal{FT}(\, M(x,y)\,)$$

$$\boxed{k_x(t) = \frac{\gamma}{2\pi} \int_0^t G_x(\tau)\, \mathrm{d}\tau,\; k_y(t) = \frac{\gamma}{2\pi} \int_0^t G_y(\tau)\, \mathrm{d}\tau}$$

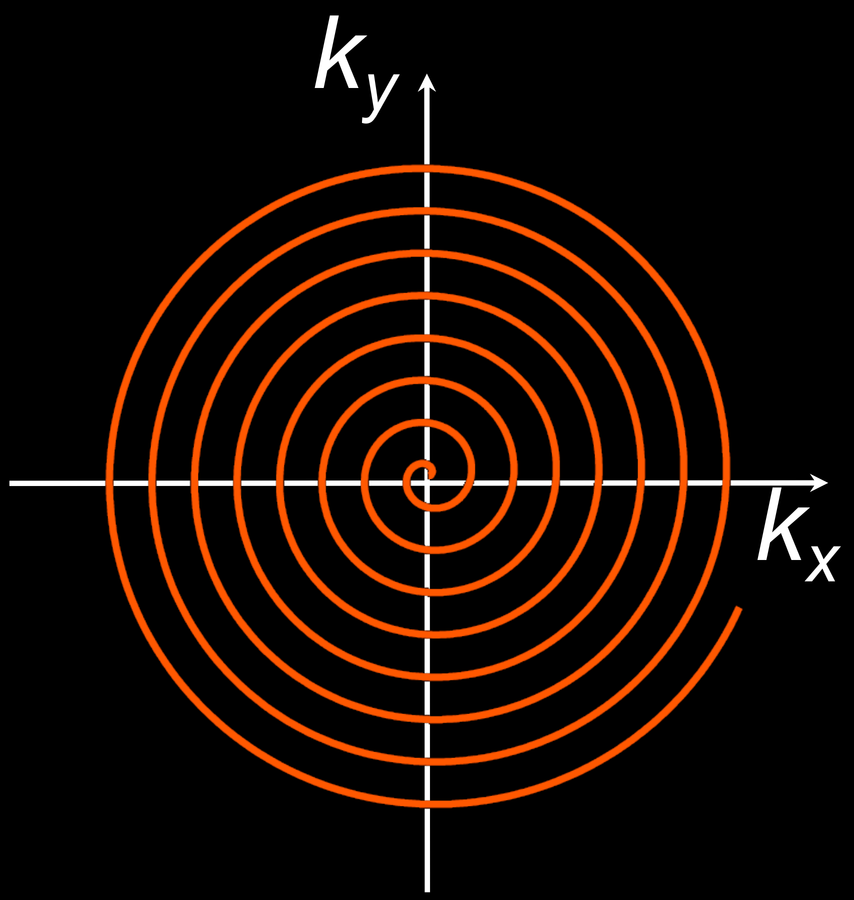
Non-Cartesian Sampling



2D Radial



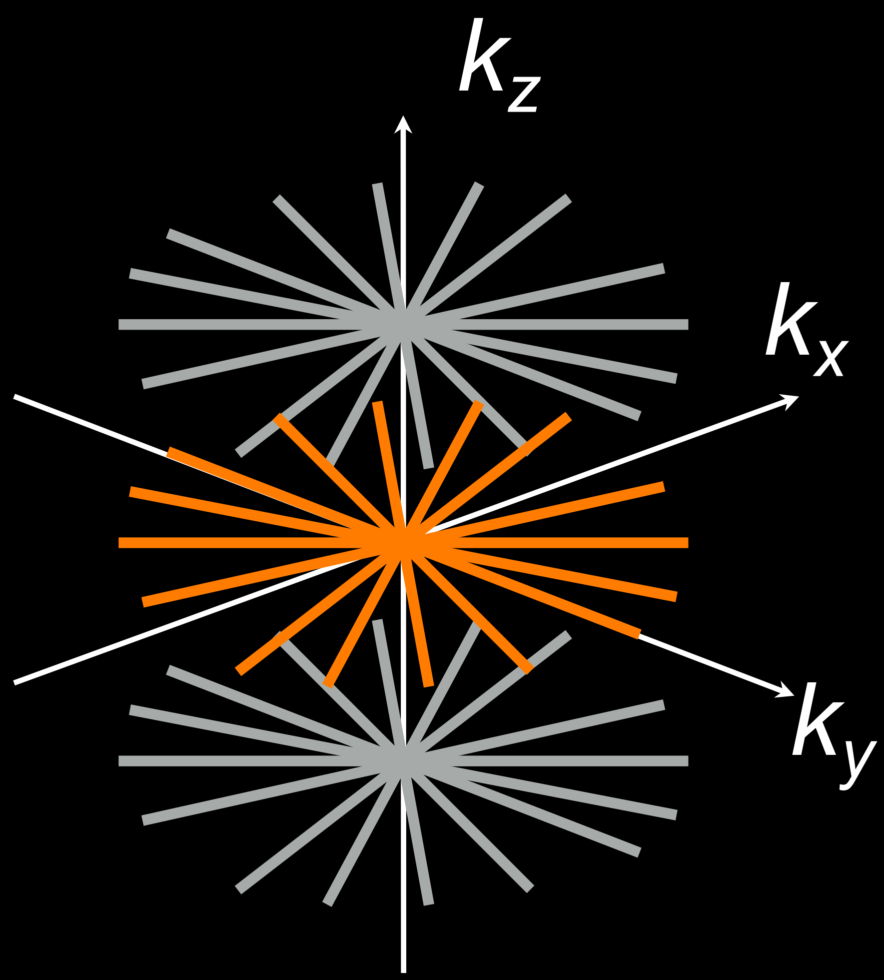
2D Concentric Rings



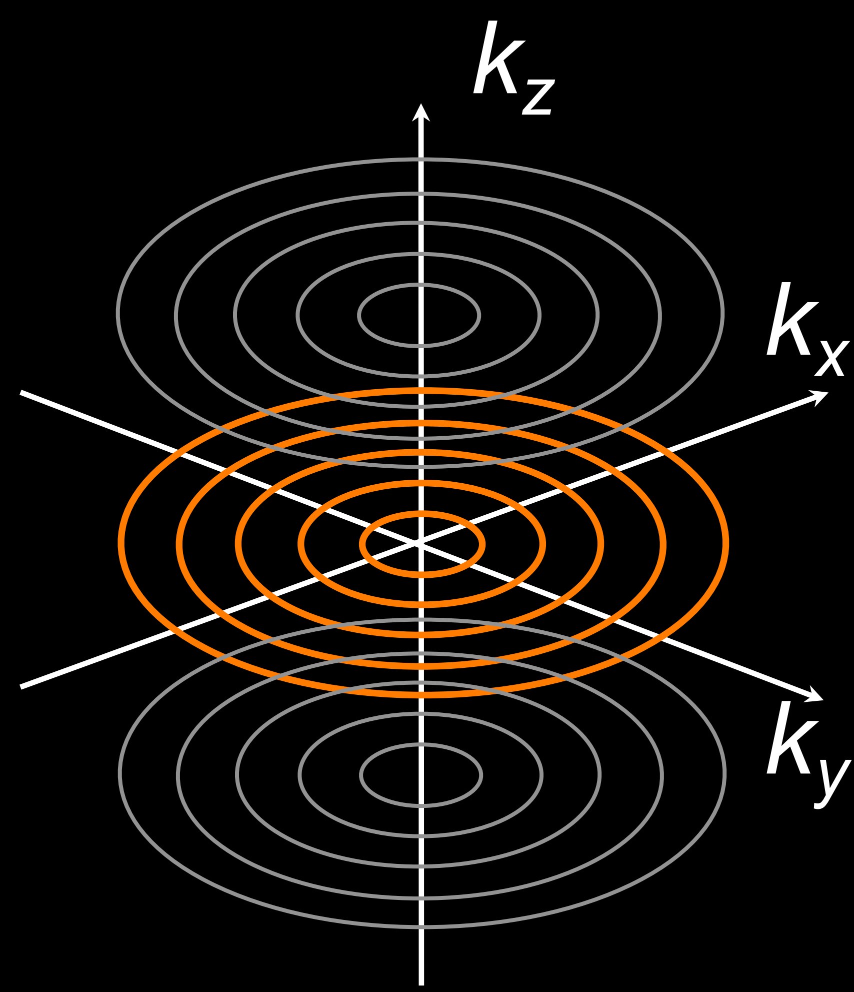
2D Spiral

and much more ...

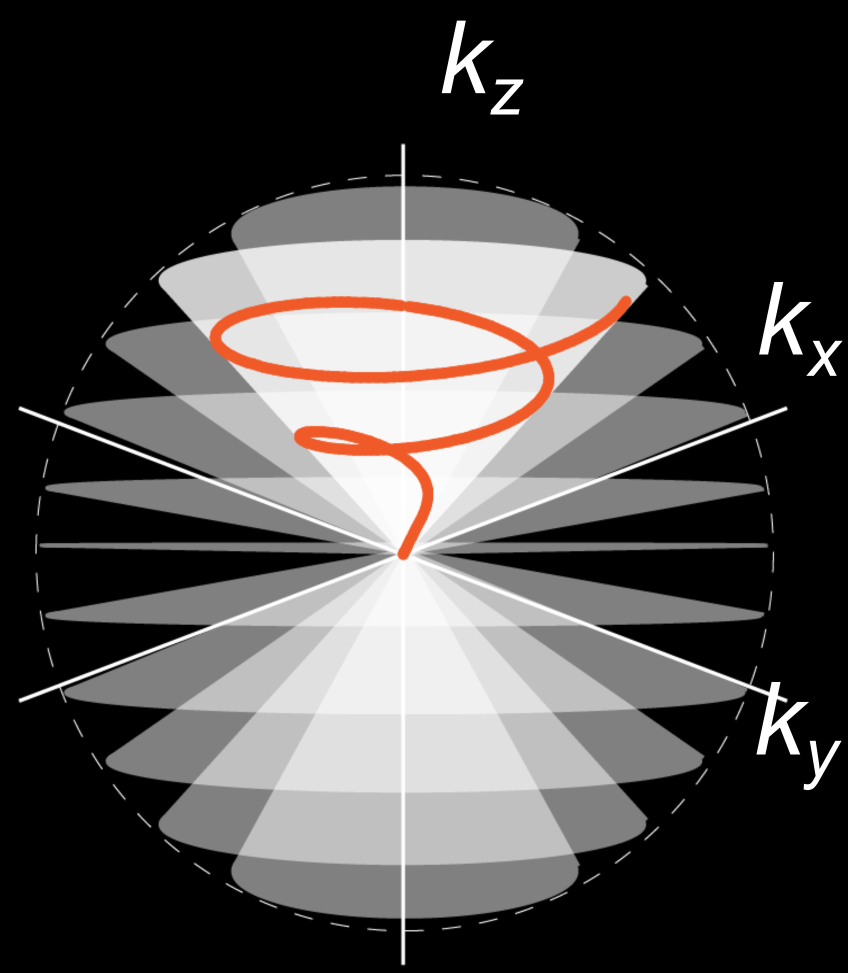
Non-Cartesian Sampling



3D Stack of Stars



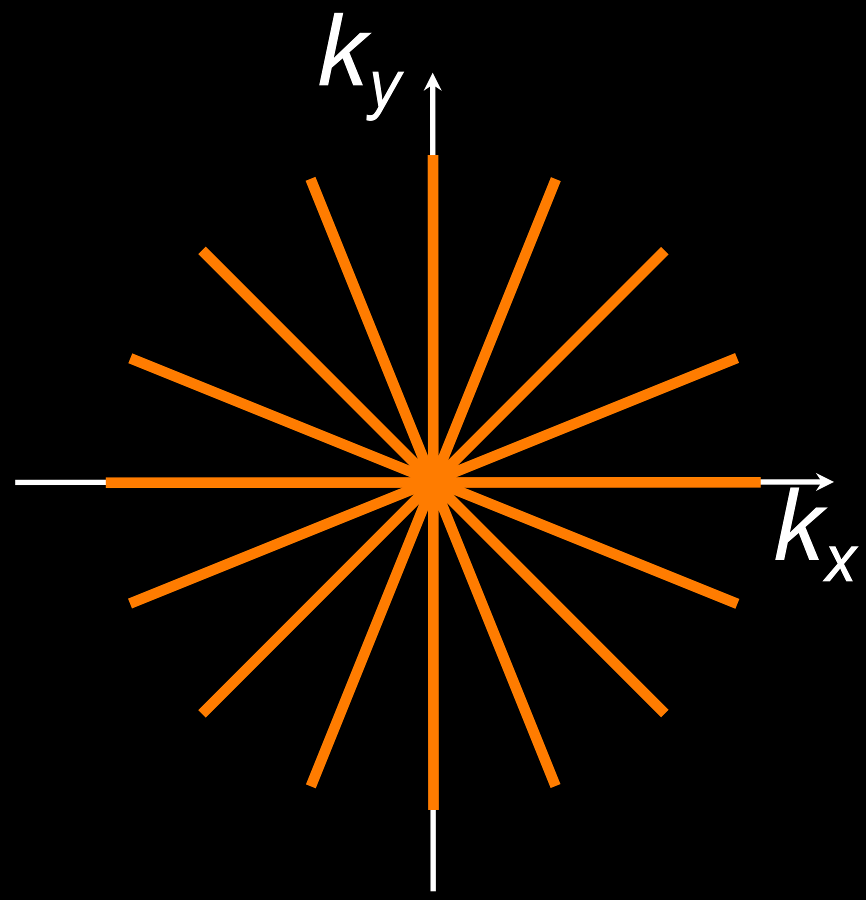
3D Stack of Rings



3D Cones

and much more ...

Radial



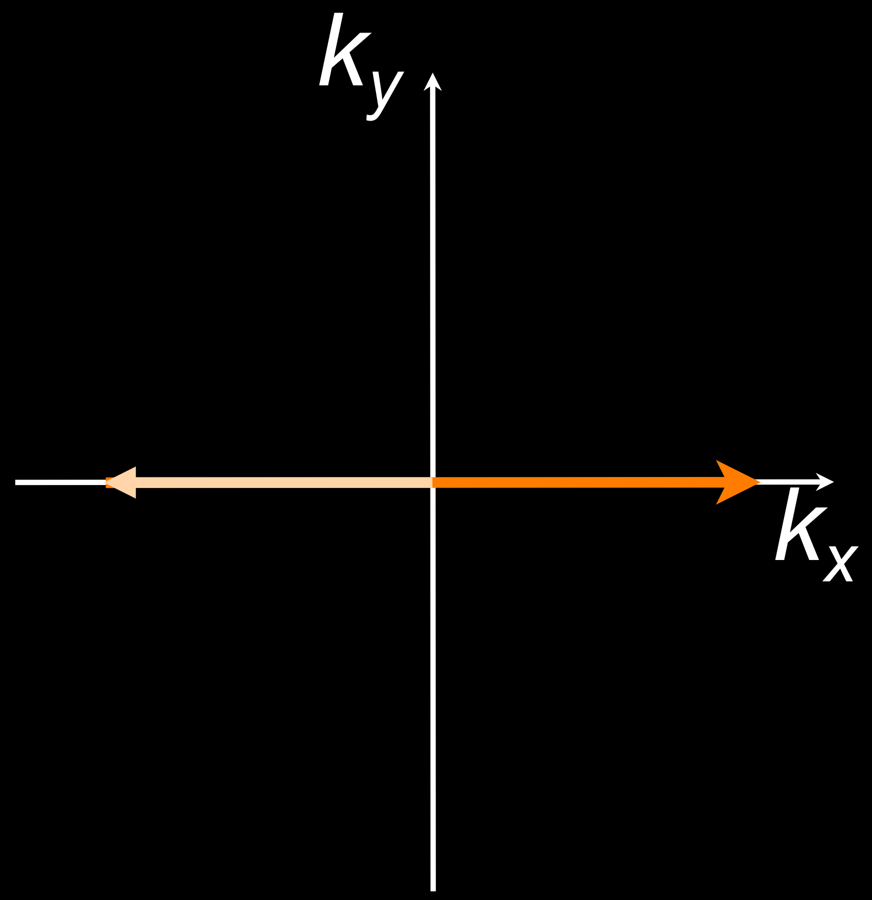
The original MRI trajectory!

- *Lauterbur, Nature 1973*

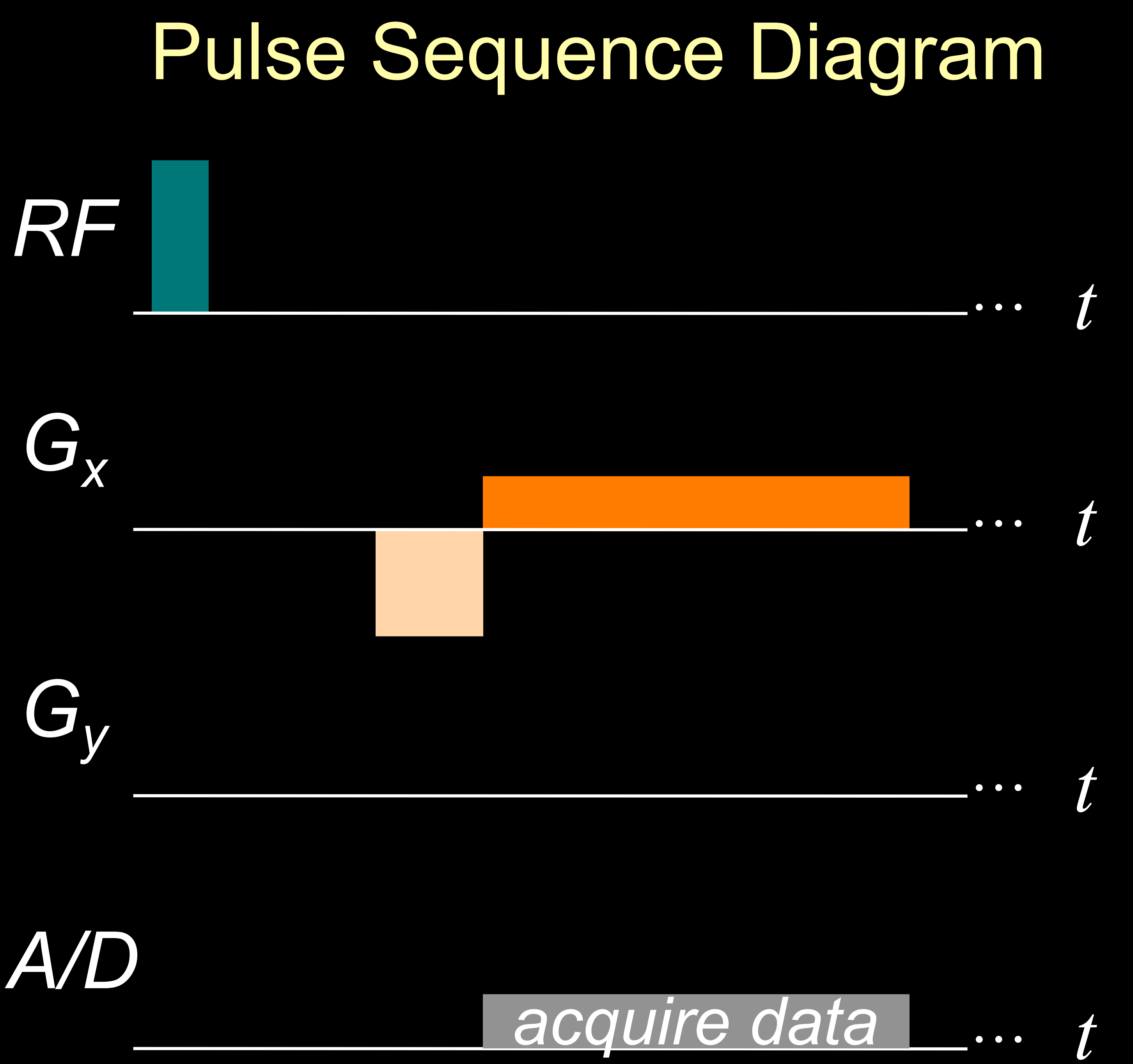
Samples k-space on a polar grid

- “Spokes” correspond to projections
- Projection reconstruction (2DPR)

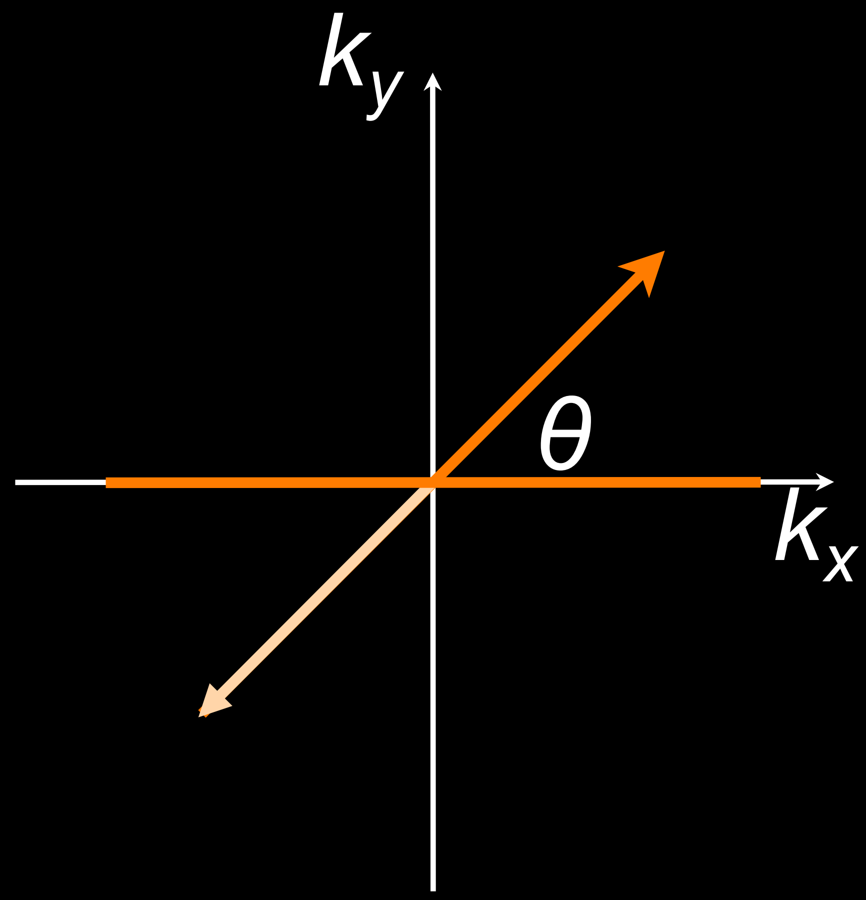
Radial: Gradient Design

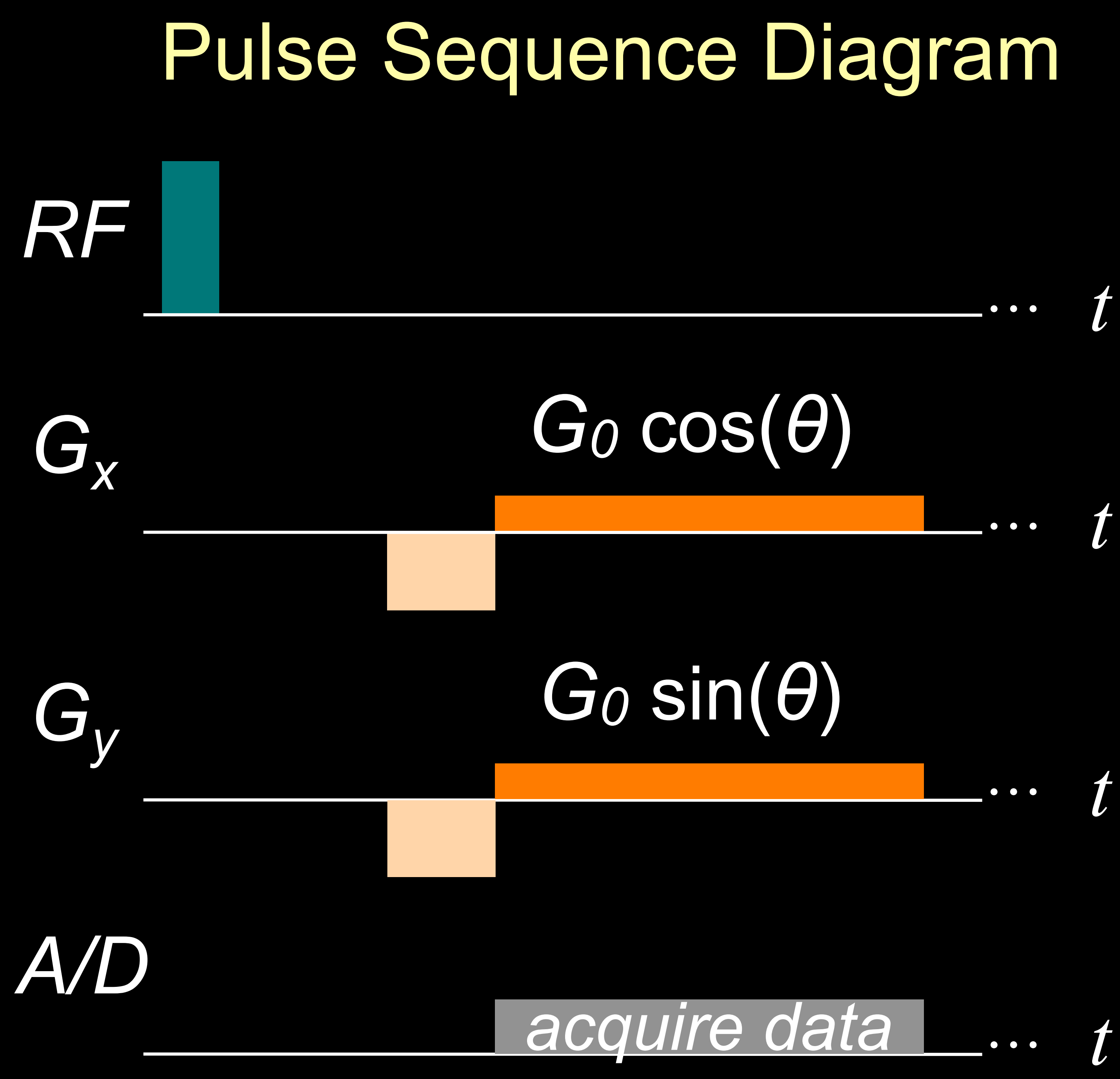


one "spoke"

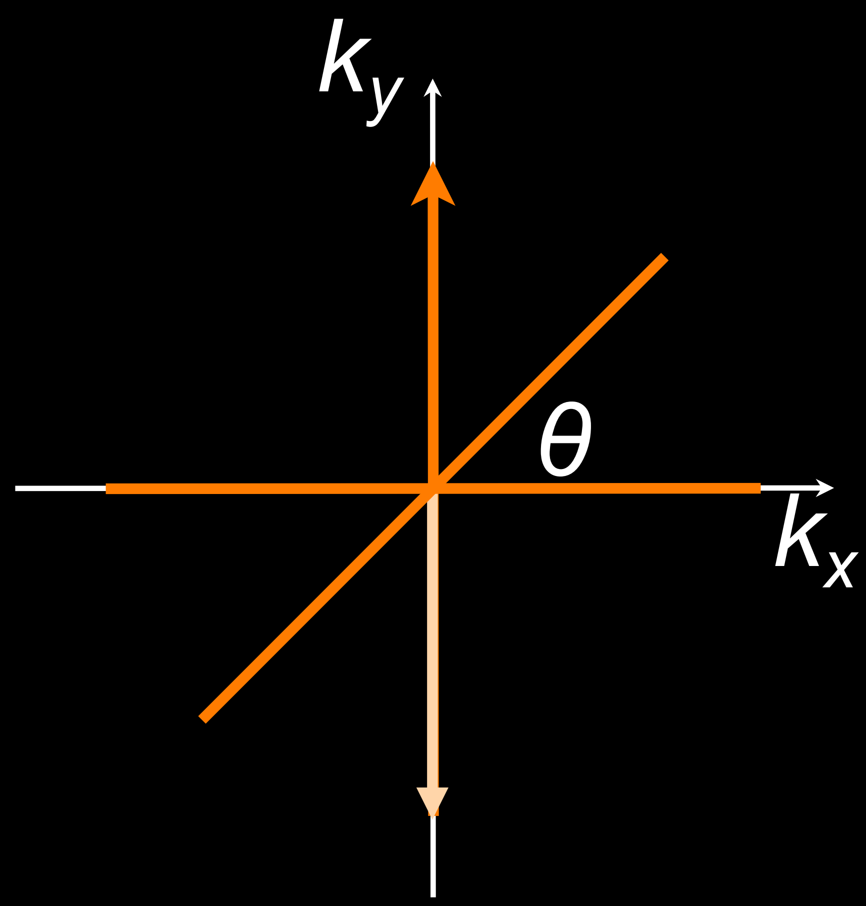


Radial: Gradient Design

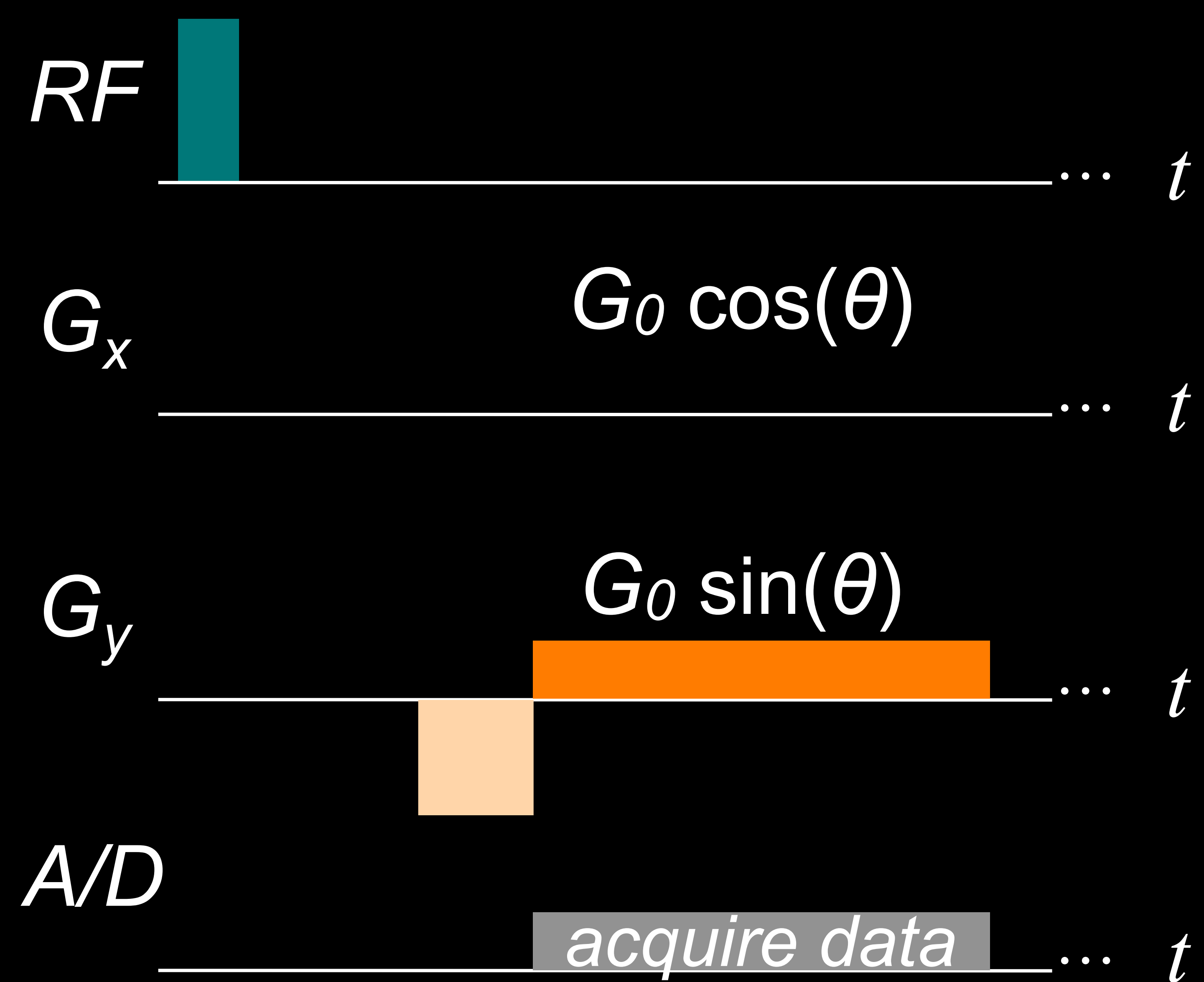




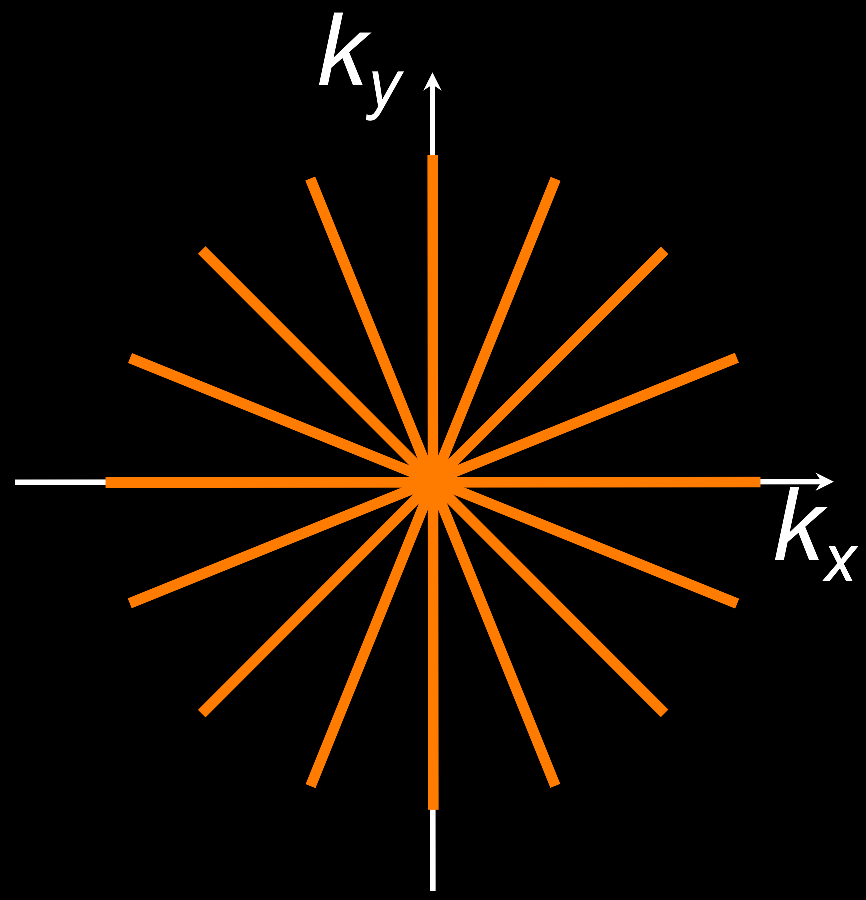
Radial: Gradient Design

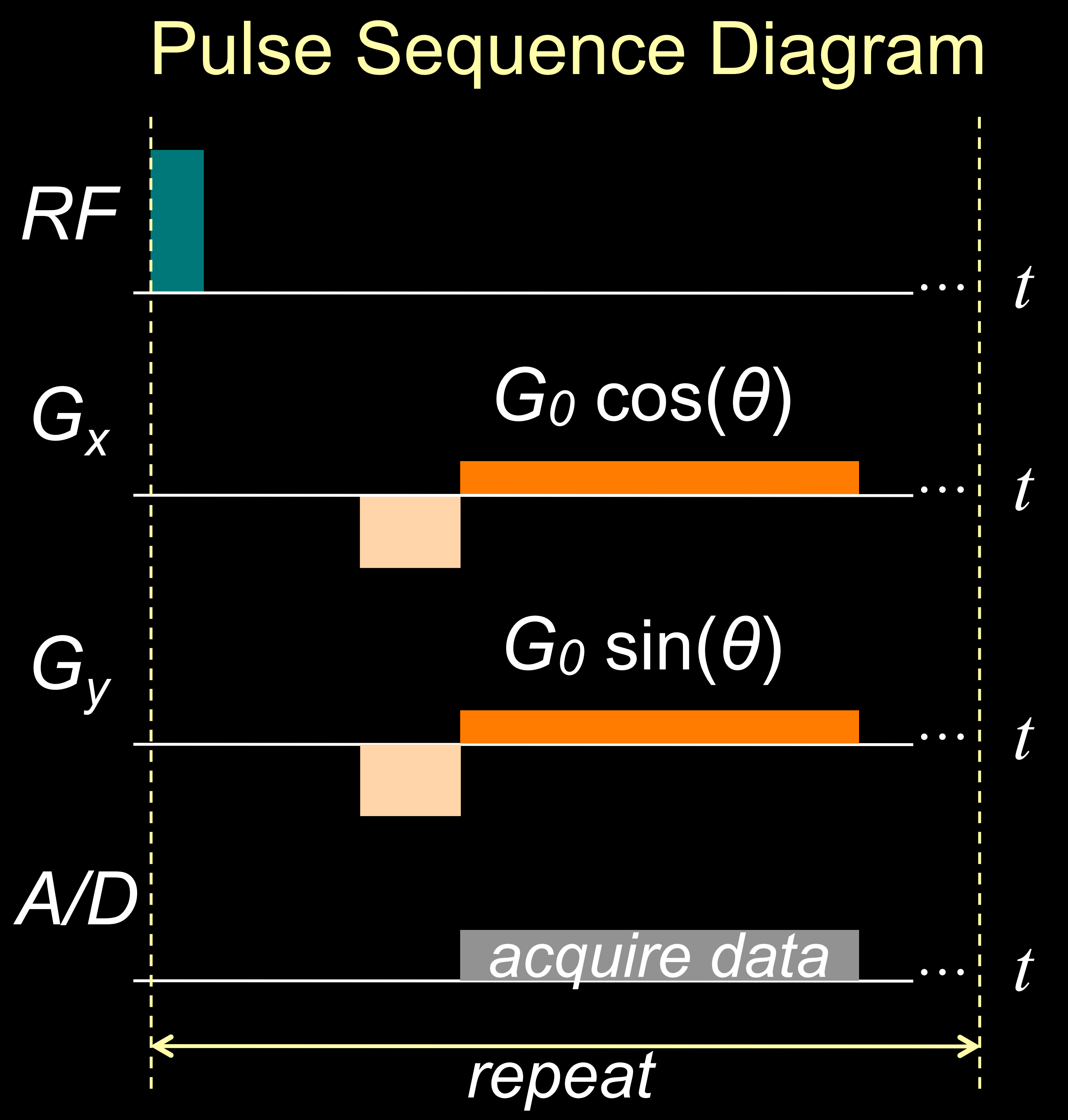


Pulse Sequence Diagram

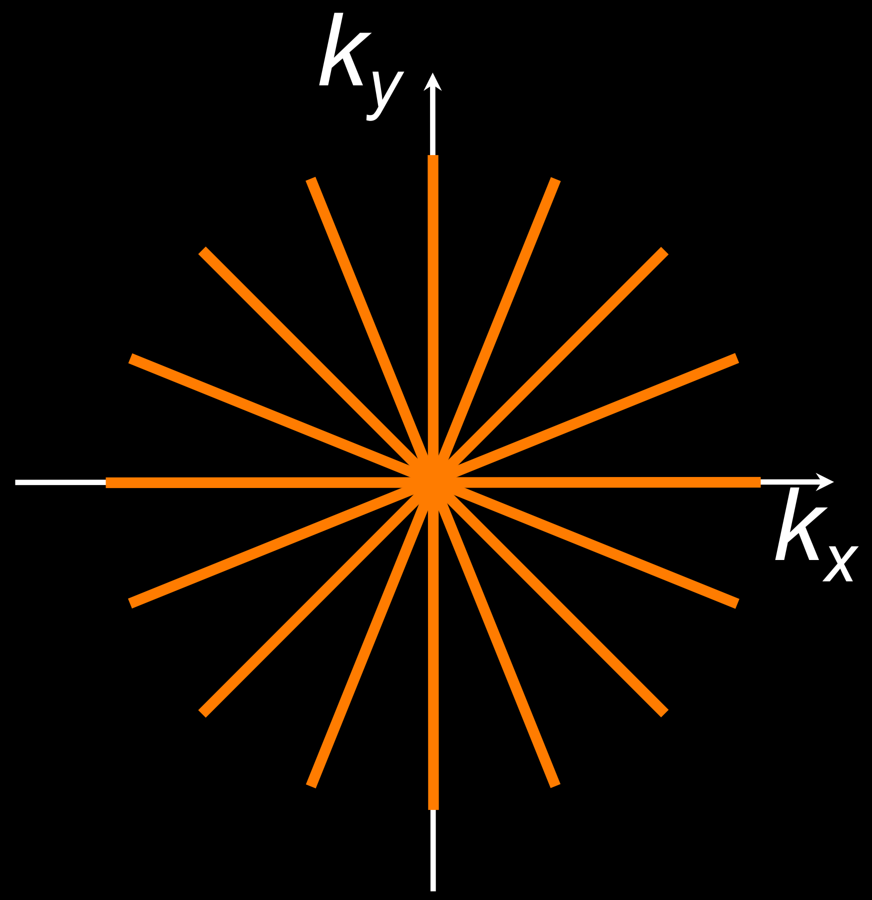


Radial: Gradient Design



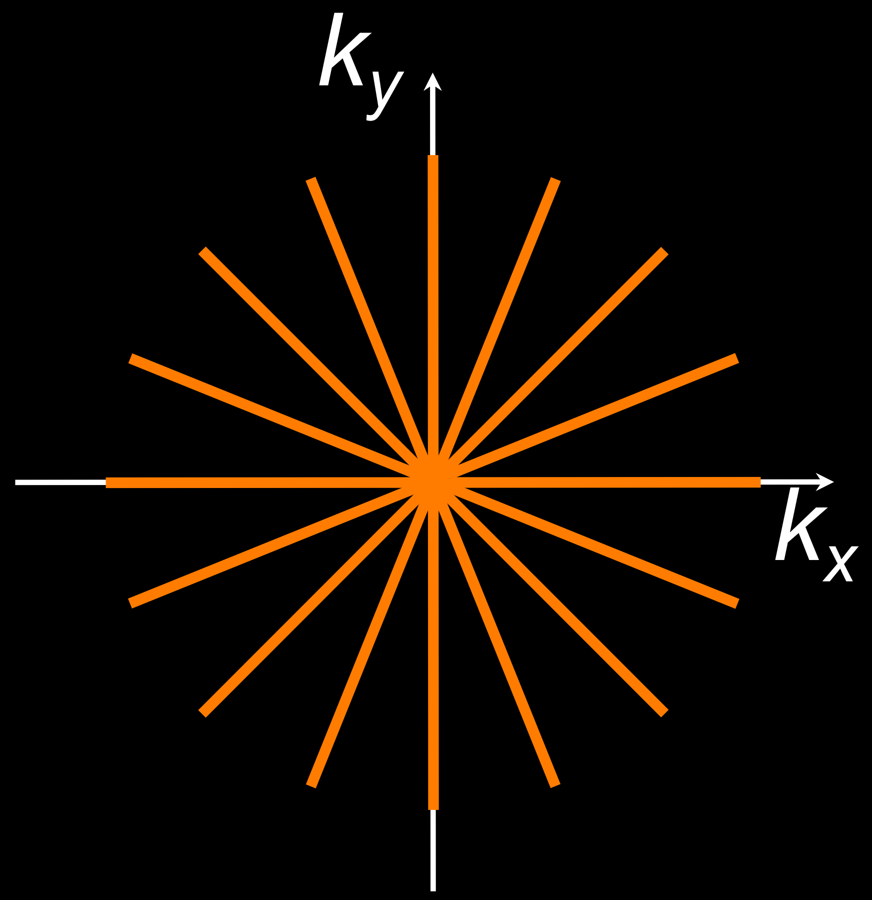


Radial: Sampling Requirements



To the board ...

Radial: Sampling Requirements



$$N_r \quad \text{points/spoke}$$

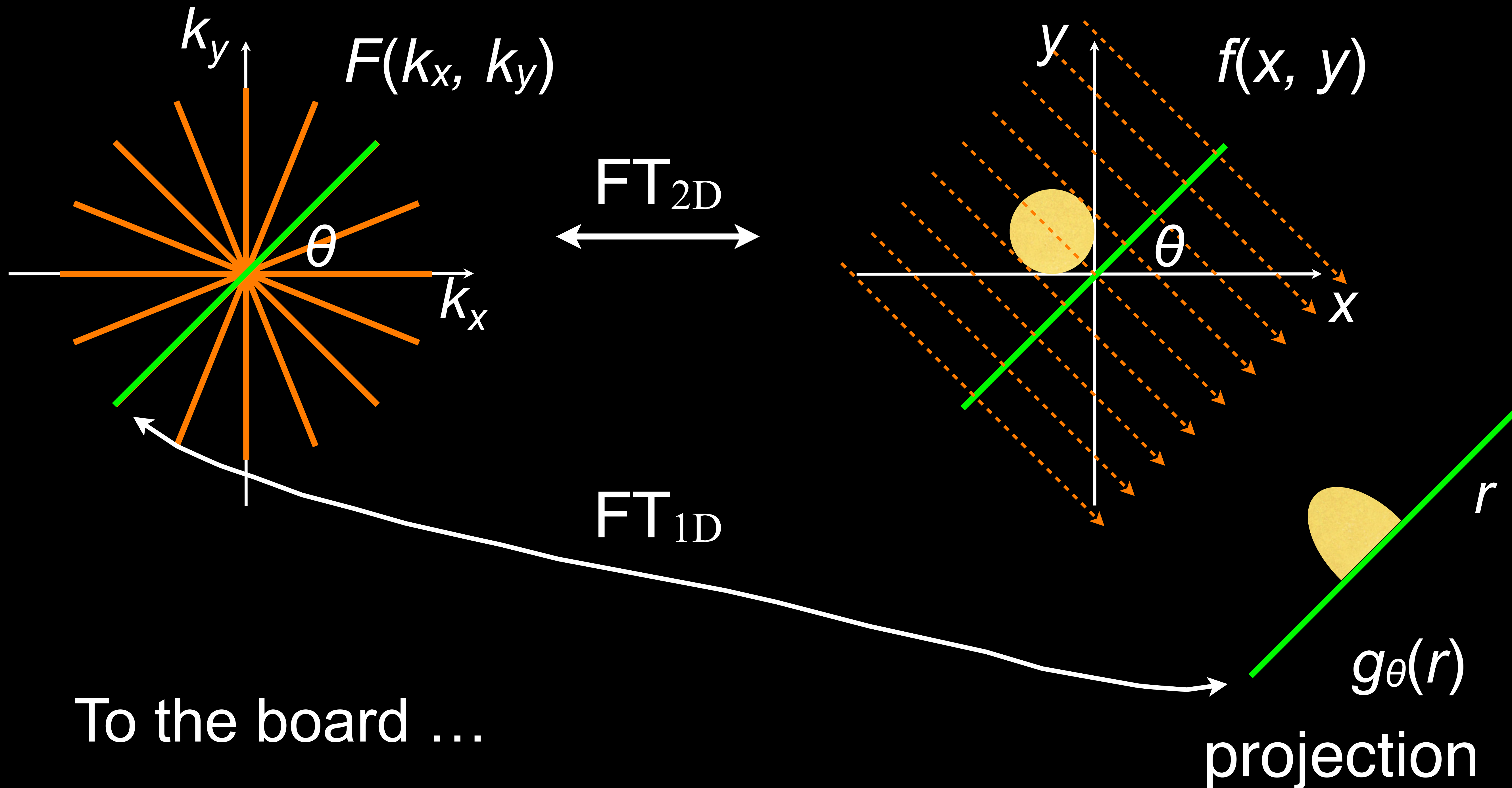
$$\mathrm{d}k_r \leq \frac{1}{\mathrm{FOV}}$$

To satisfy Nyquist at edges of k-space:

$$N_{sp} \geq \frac{\pi}{2} N_r$$

Radial: Image Reconstruction

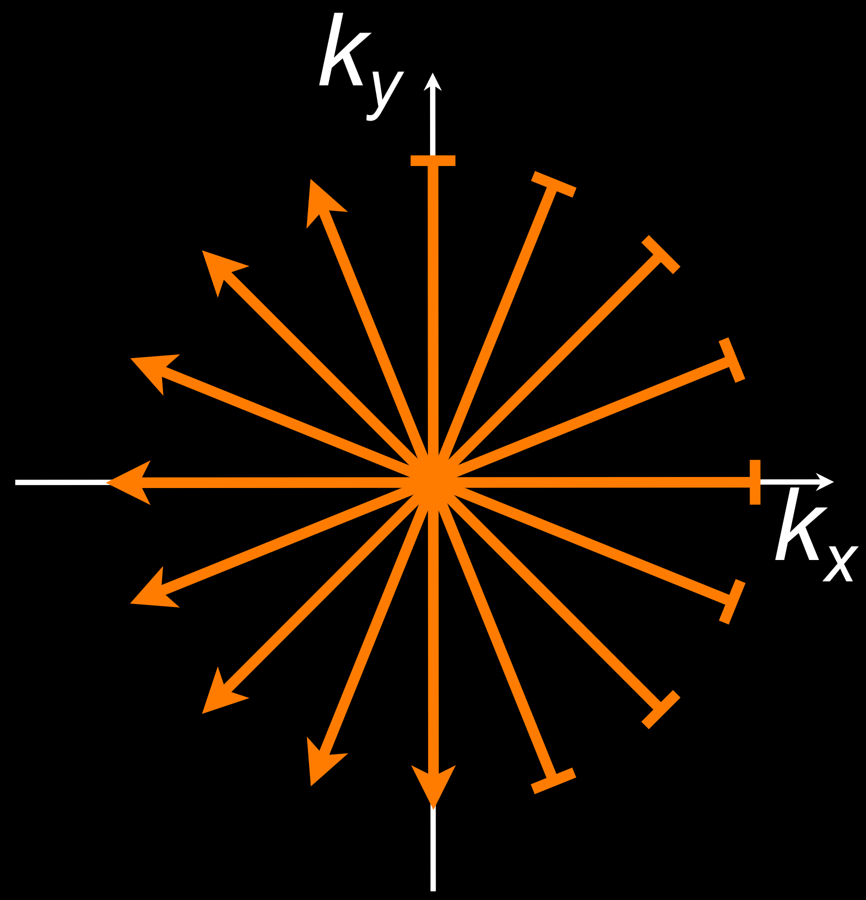
Central Section Theorem

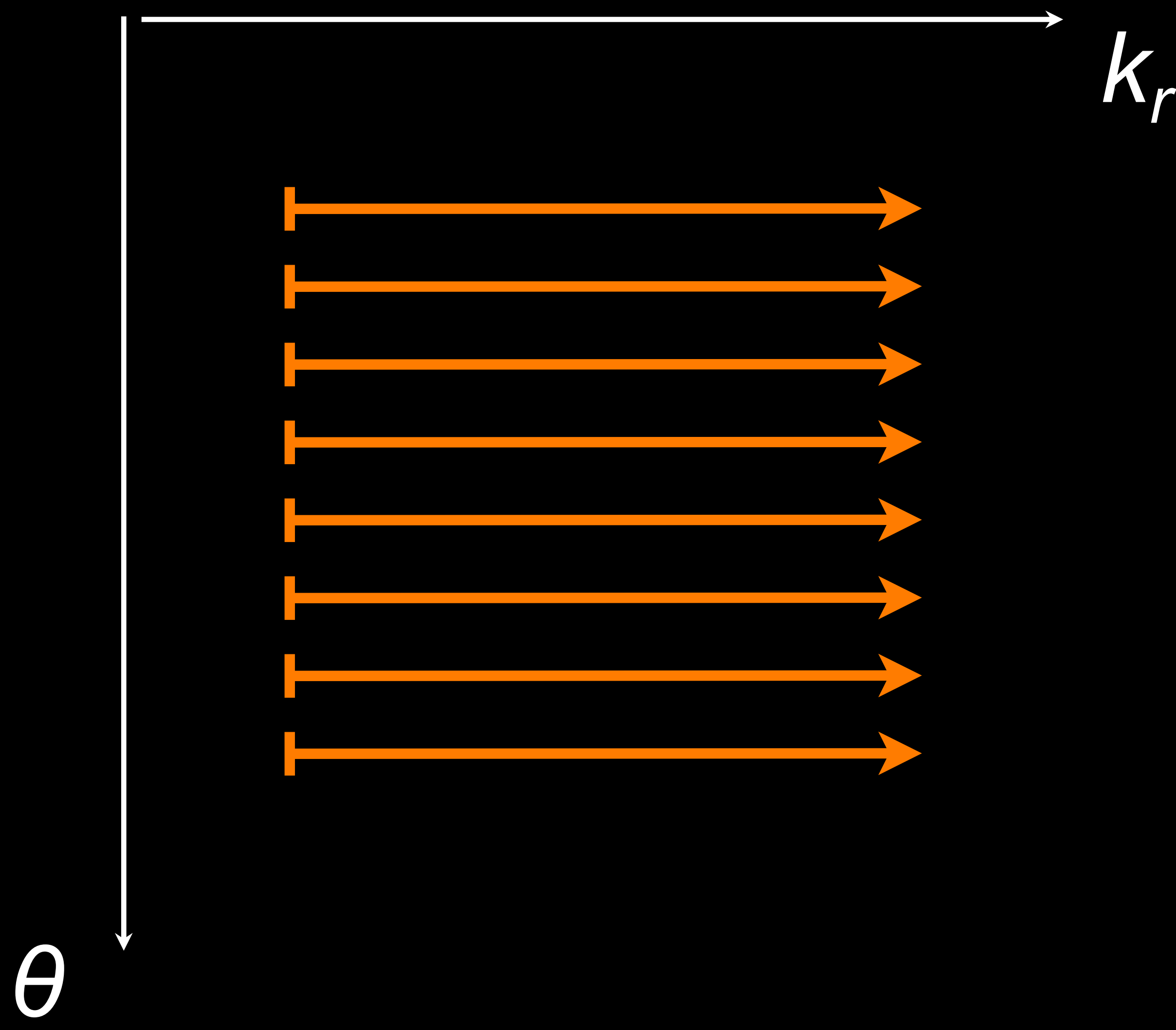


To the board …

Radial: Image Reconstruction

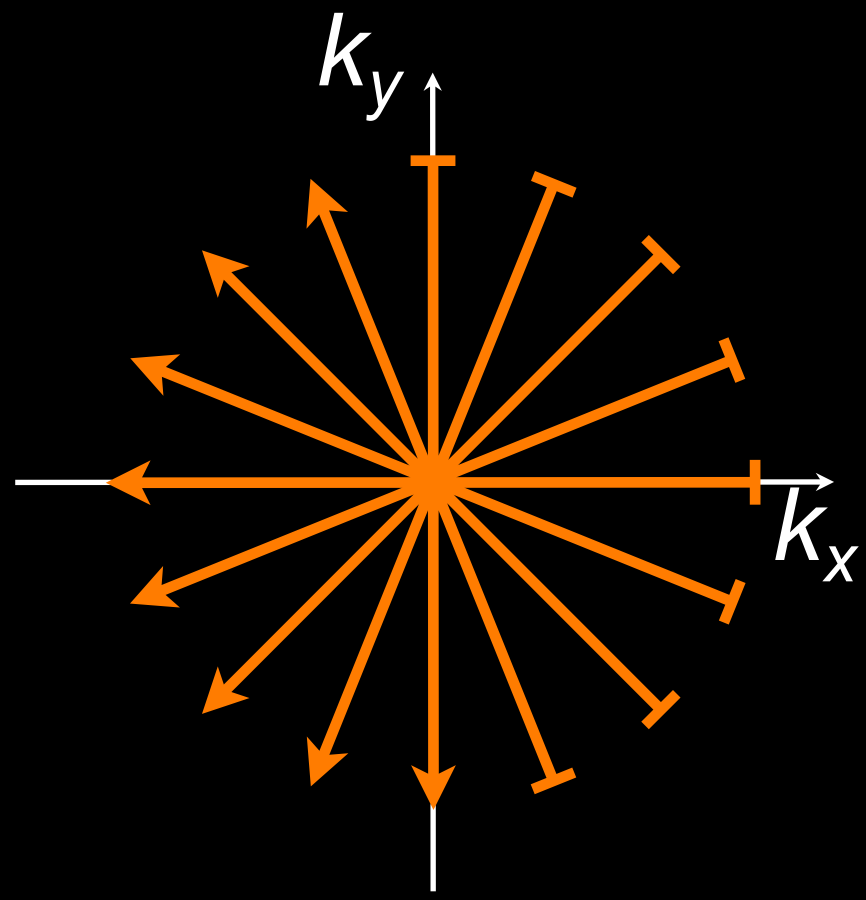
Collect spokes into (k_r, θ) matrix →

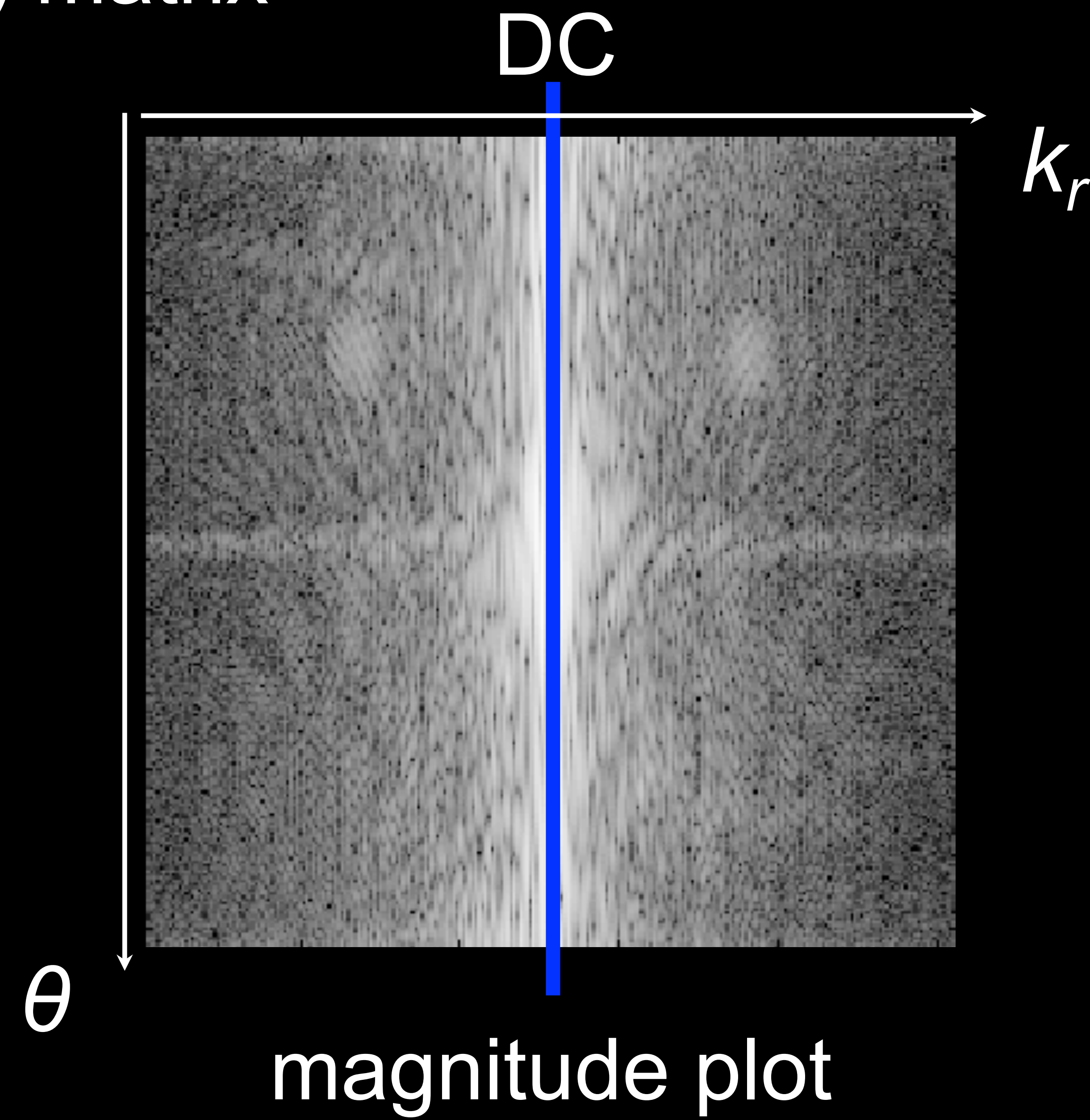




Radial: Image Reconstruction

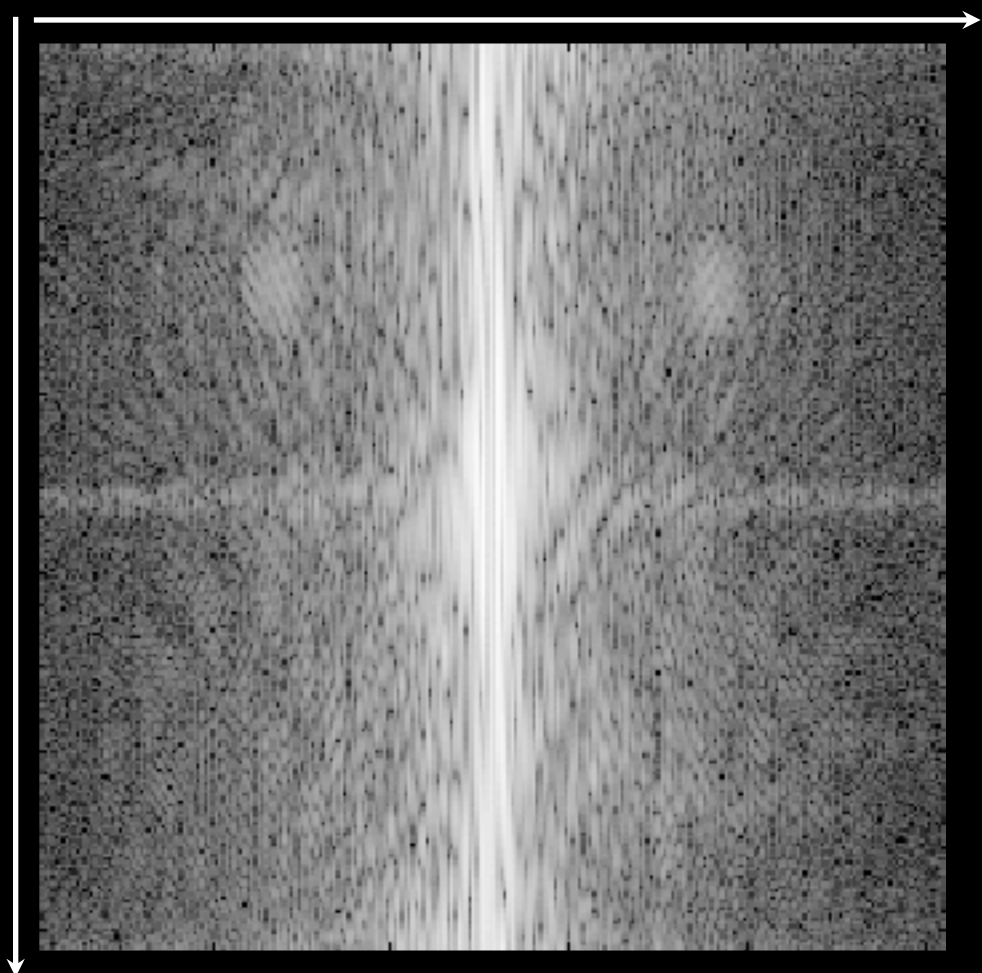
Collect spokes into (k_r, θ) matrix →



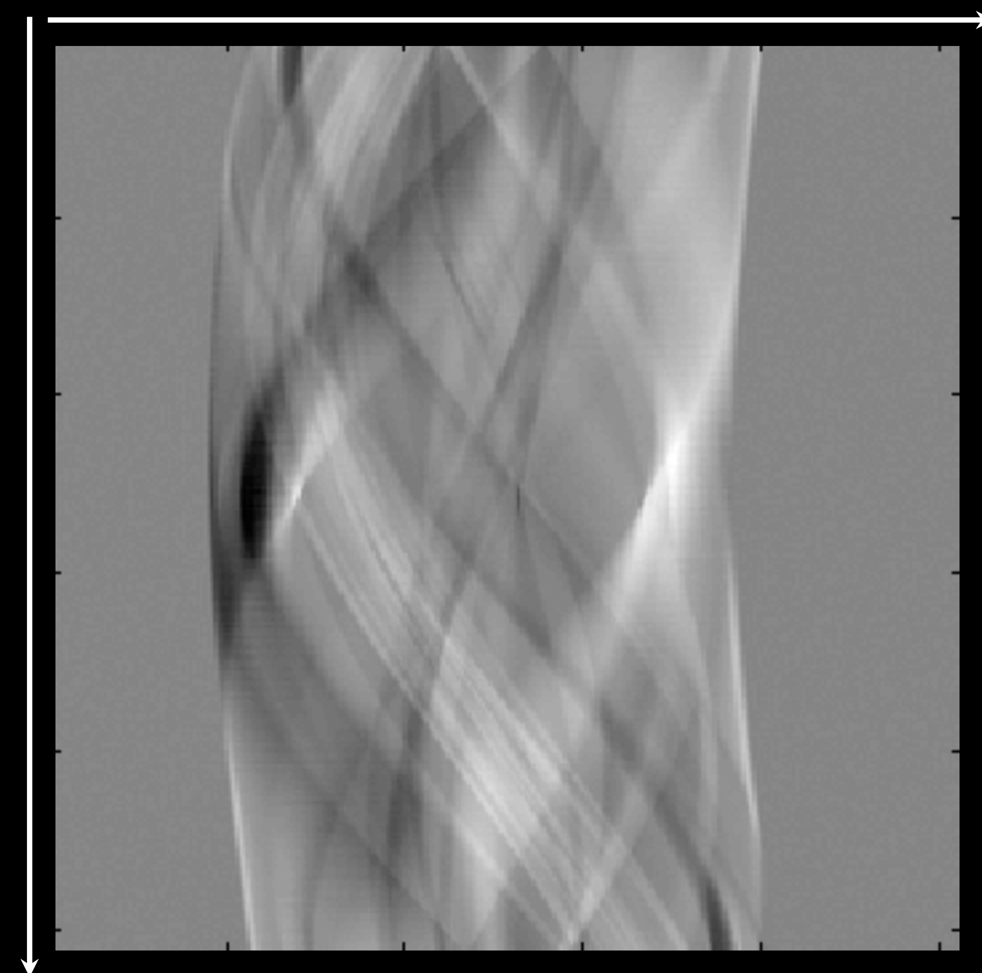


Radial: Image Reconstruction

1DFT of each spoke along k_r $\rightarrow$ *"Sinogram"*



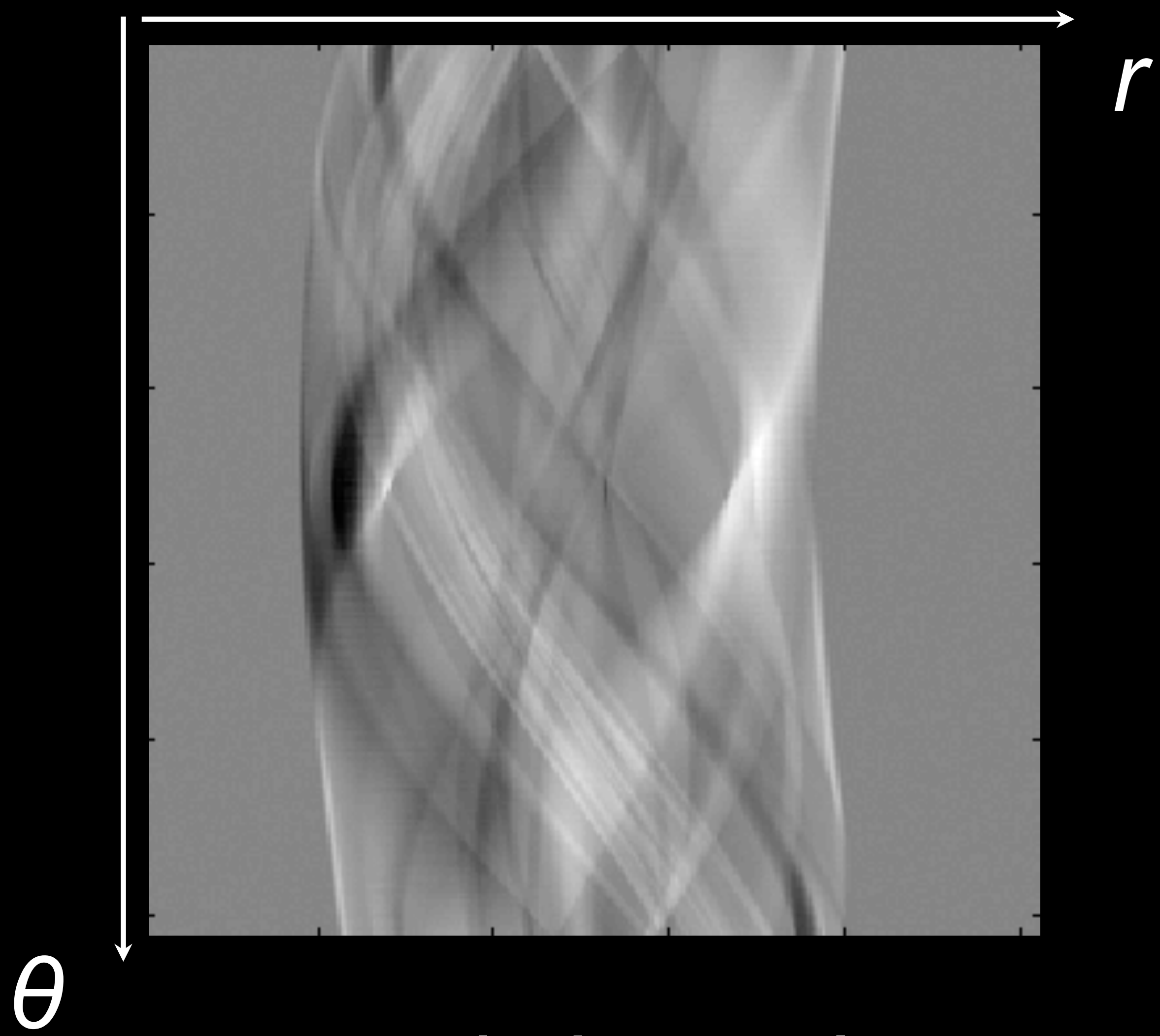
magnitude plot



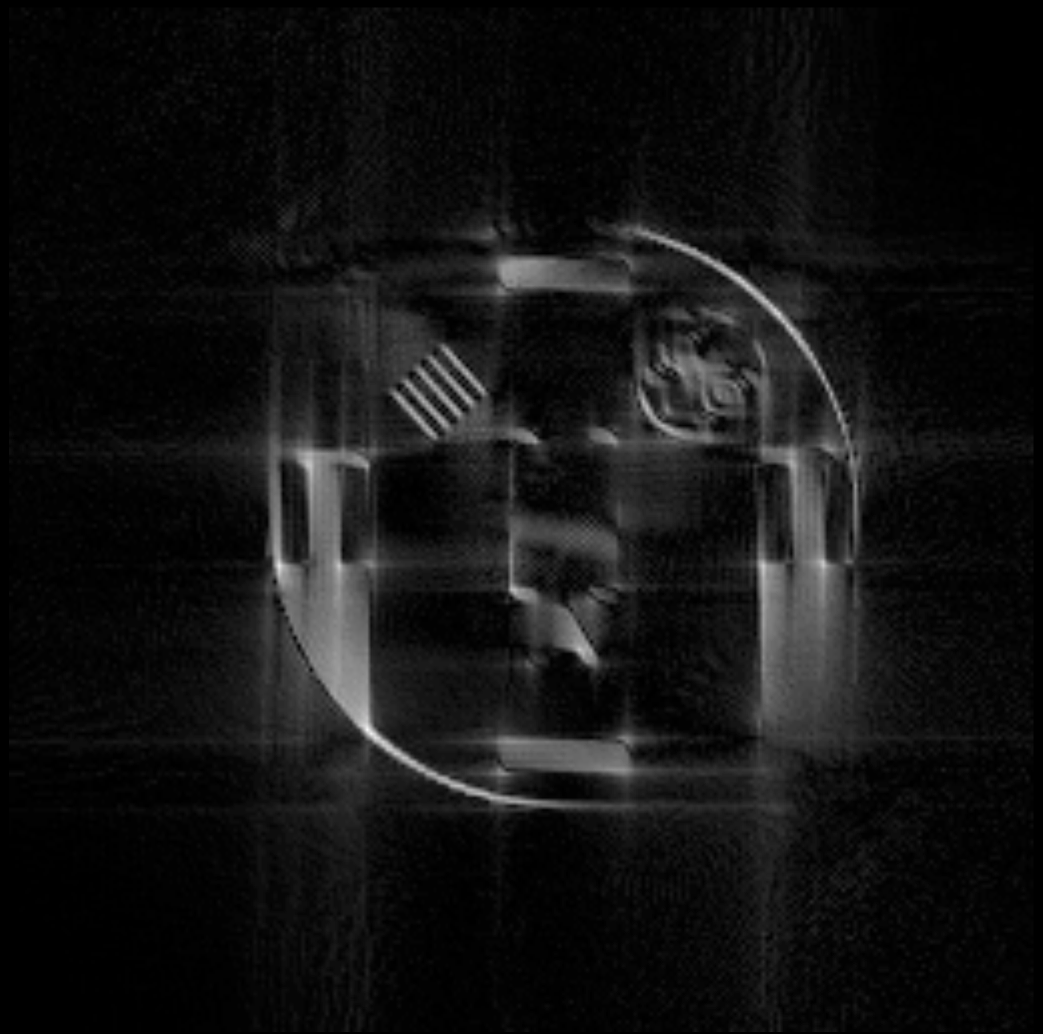
real channel

Radial: Image Reconstruction

Filtered back projection → Image



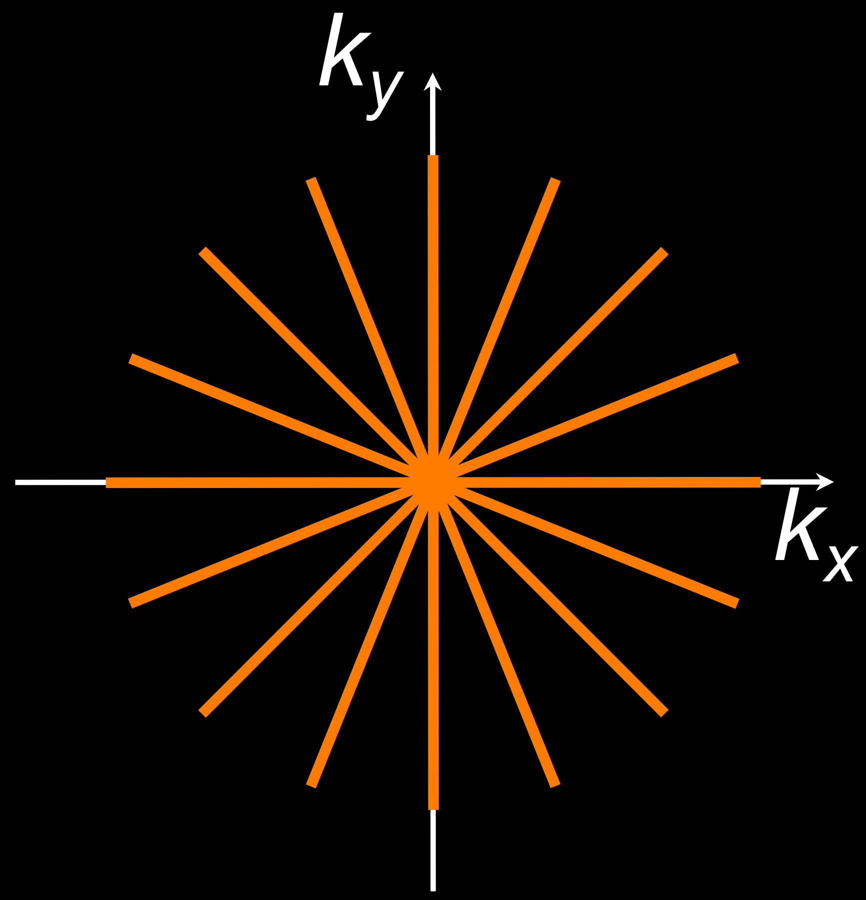
real channel



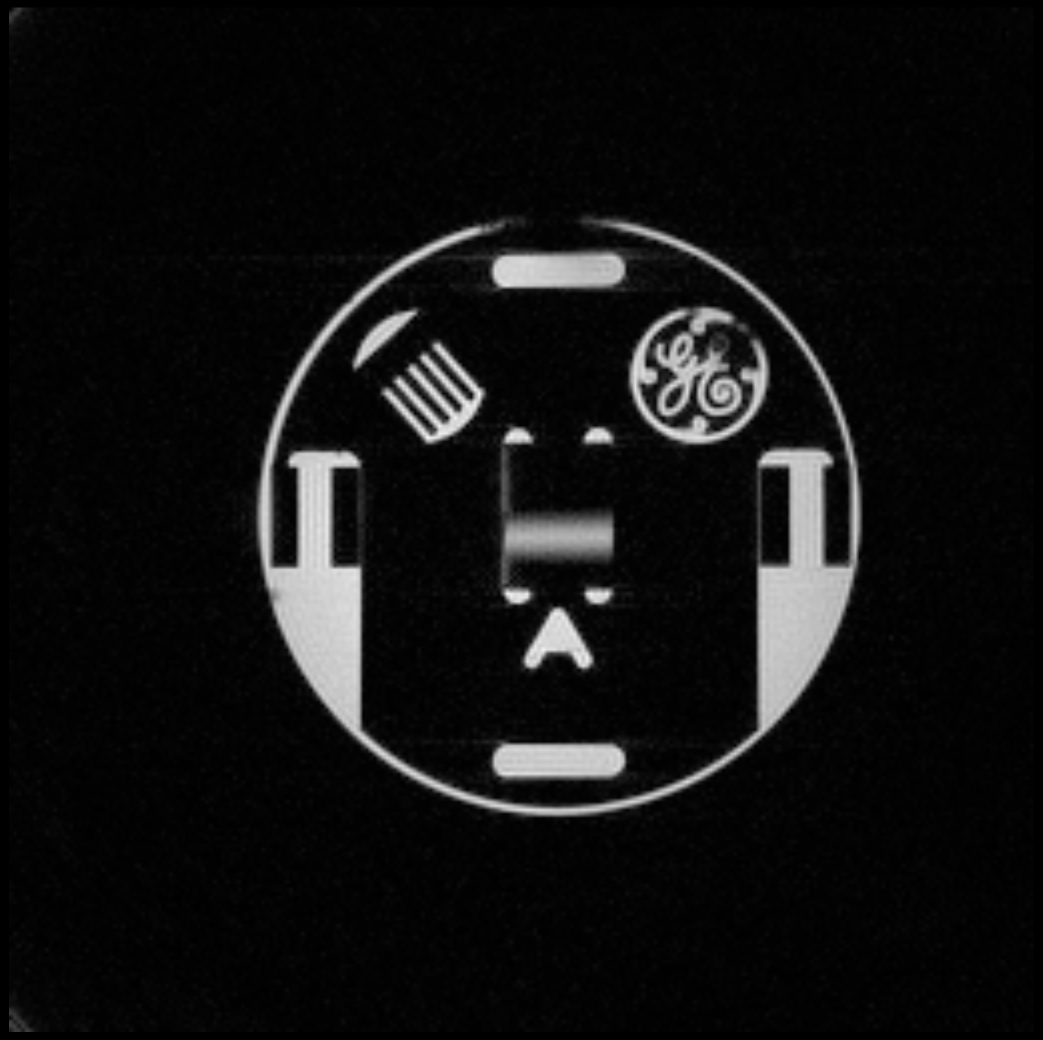
magnitude

alternatively, can use "gridding" reconstruction

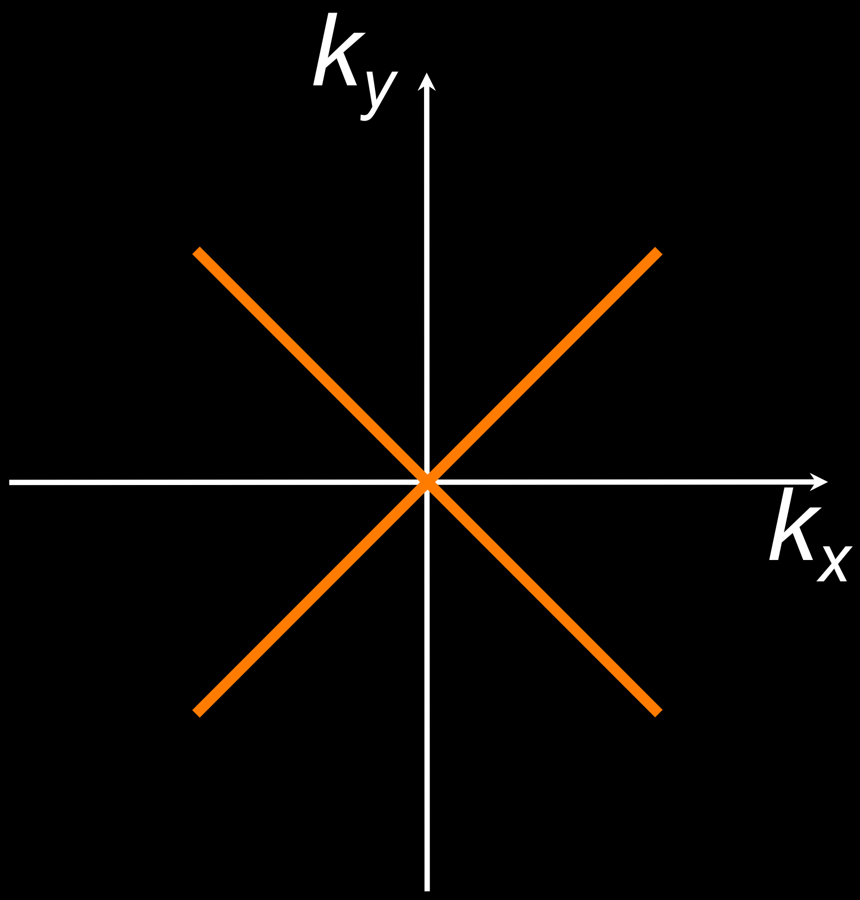
Radial: Undersampling



fully sampled



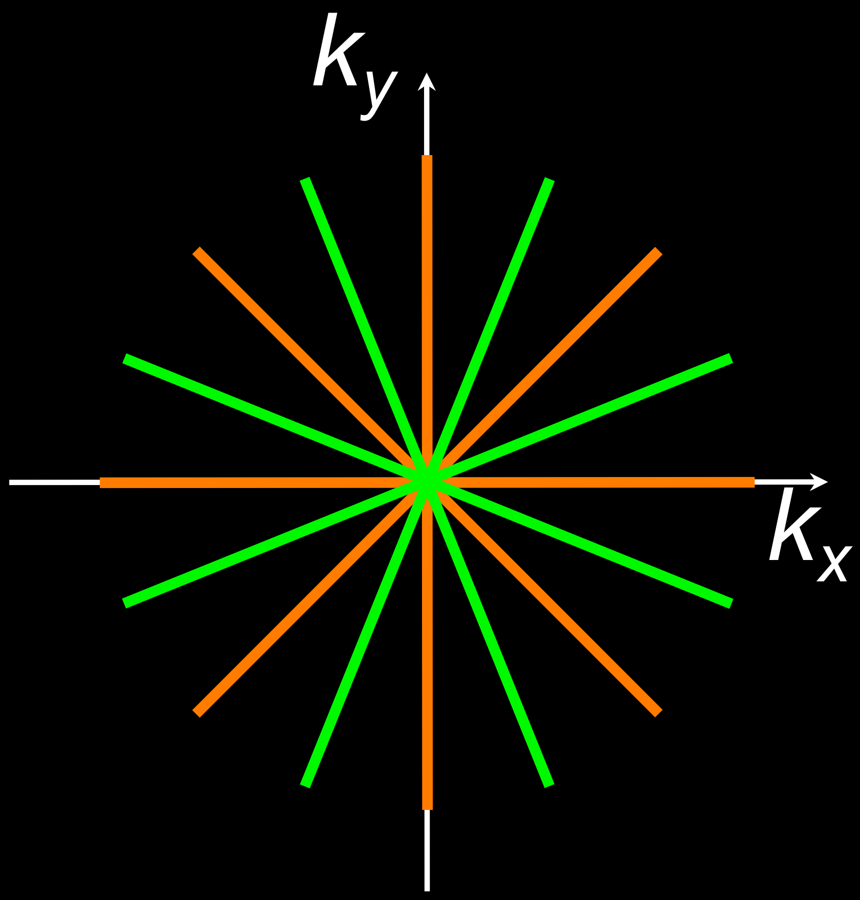
Radial: Undersampling



undersampled

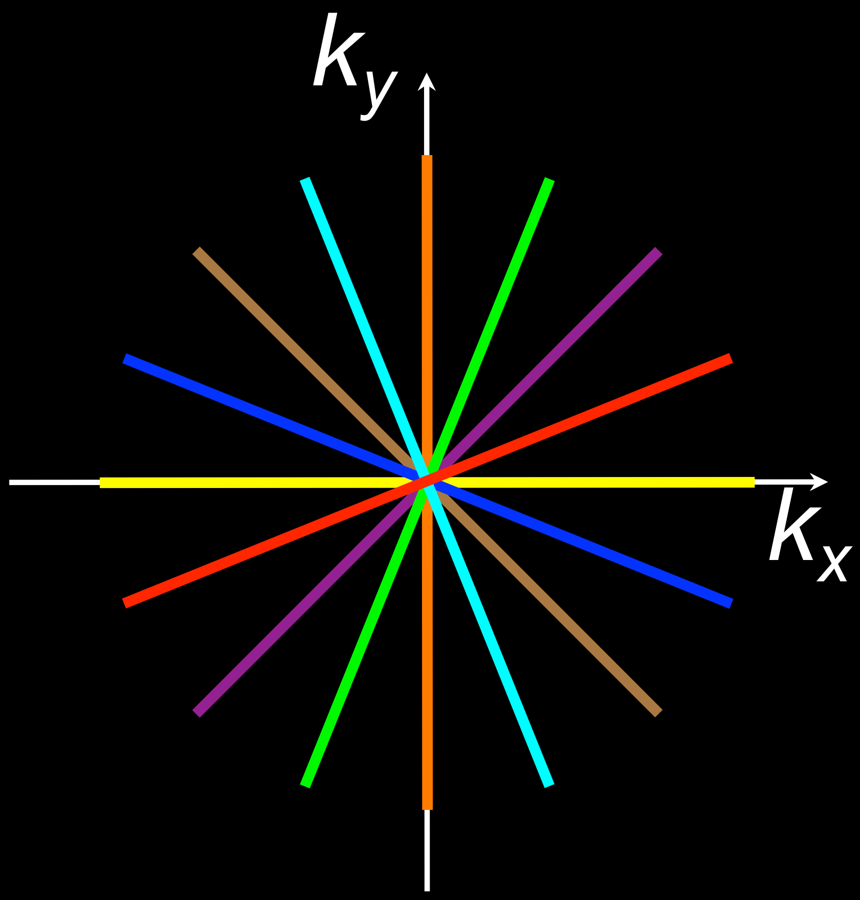
streaking artifacts

Radial: Acq Ordering



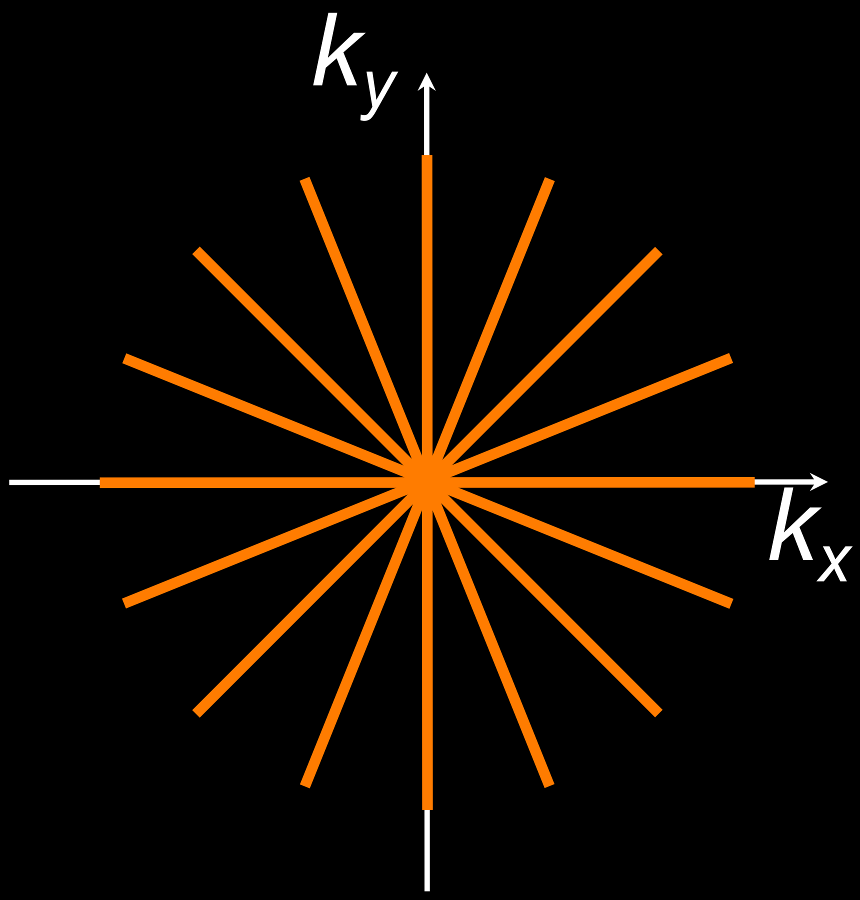
interleaved acq

Radial: Acq Ordering



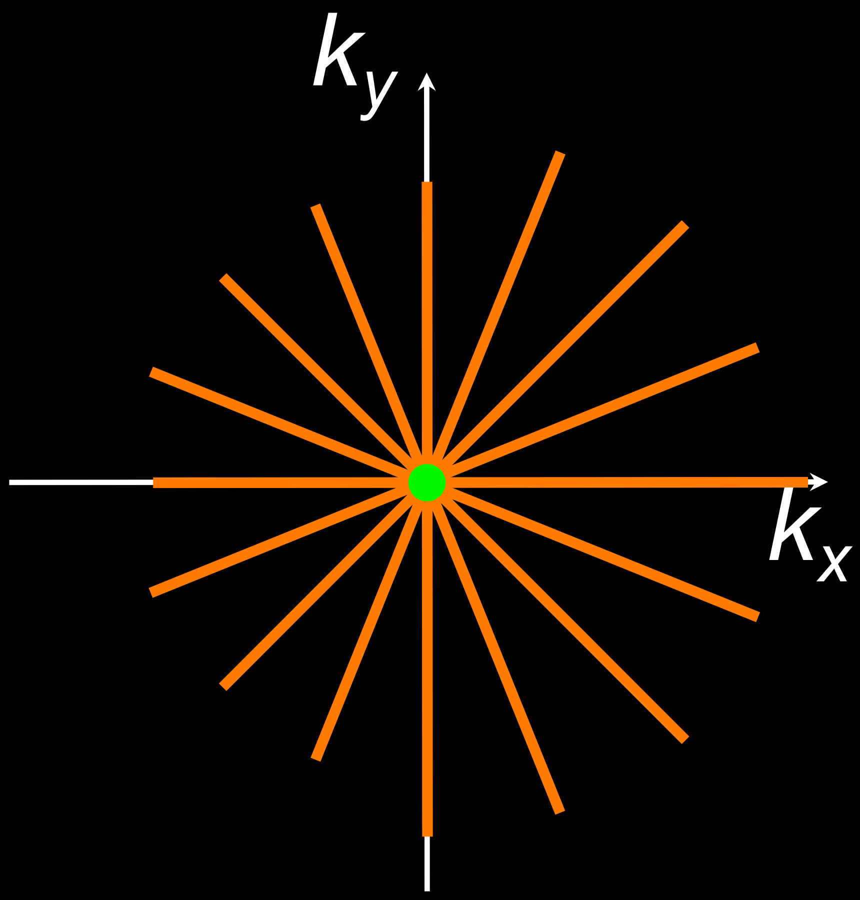
random acq

Radial: Gradient Delays



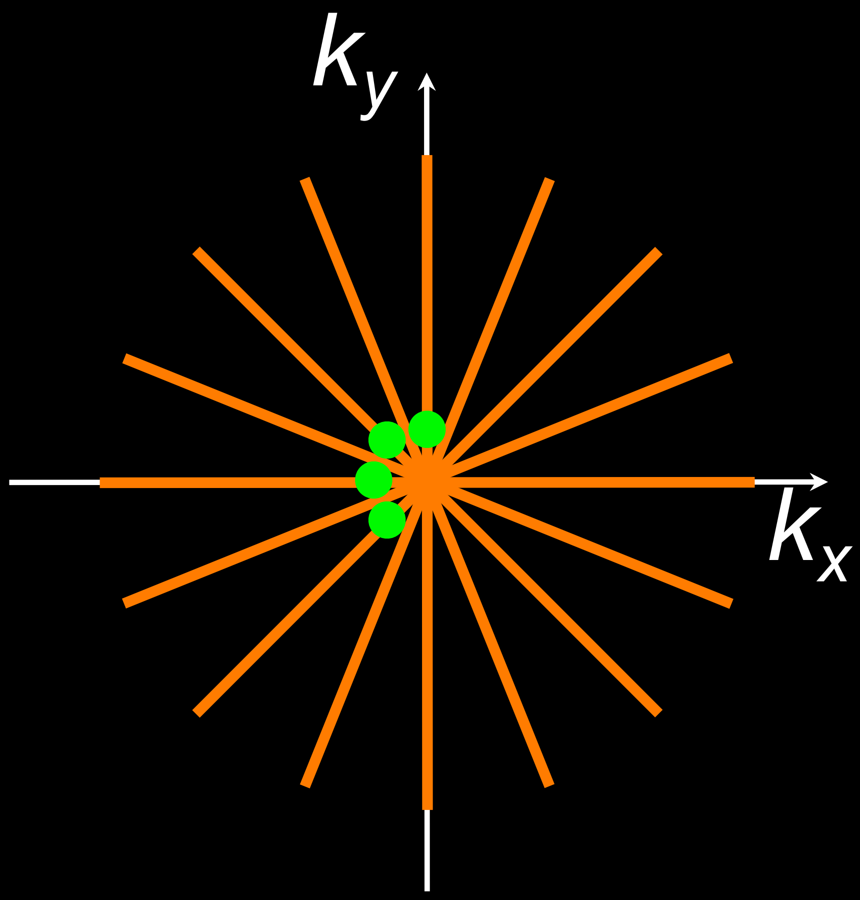
calibrated

Radial: Gradient Delays

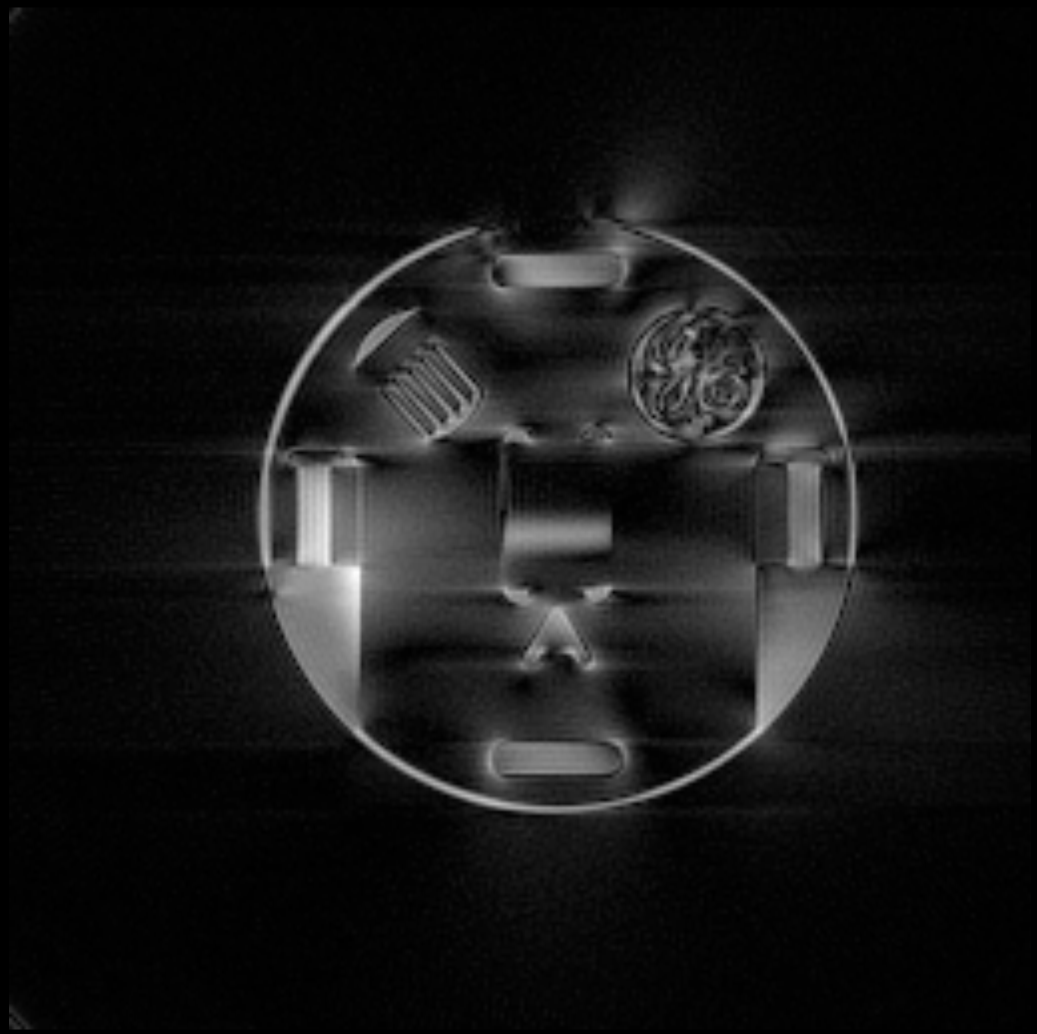


grad-acq delay

Radial: Gradient Delays

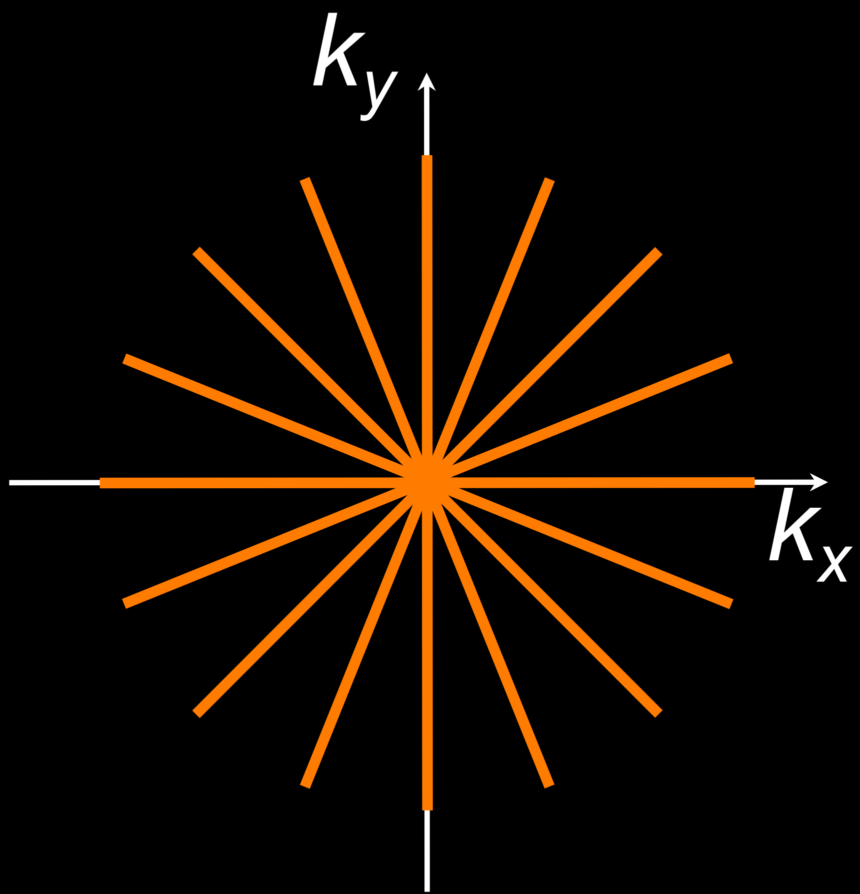


recon unaware of delays
mis-aligned DC



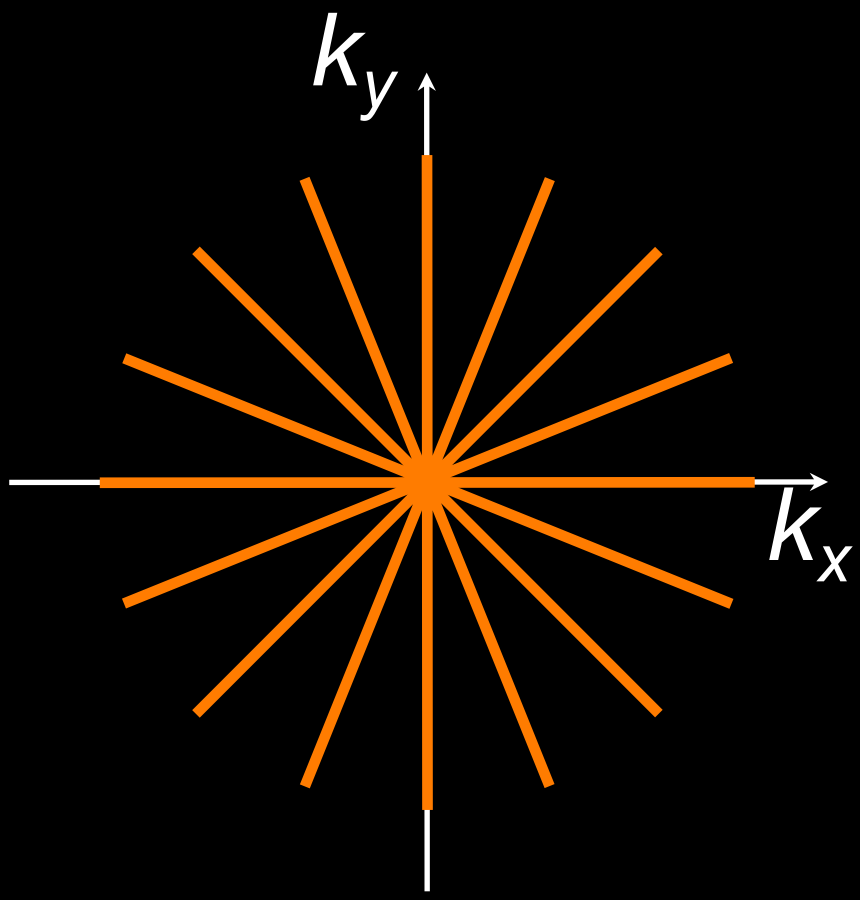
misalignment artifacts

Radial: Off-resonance Effects

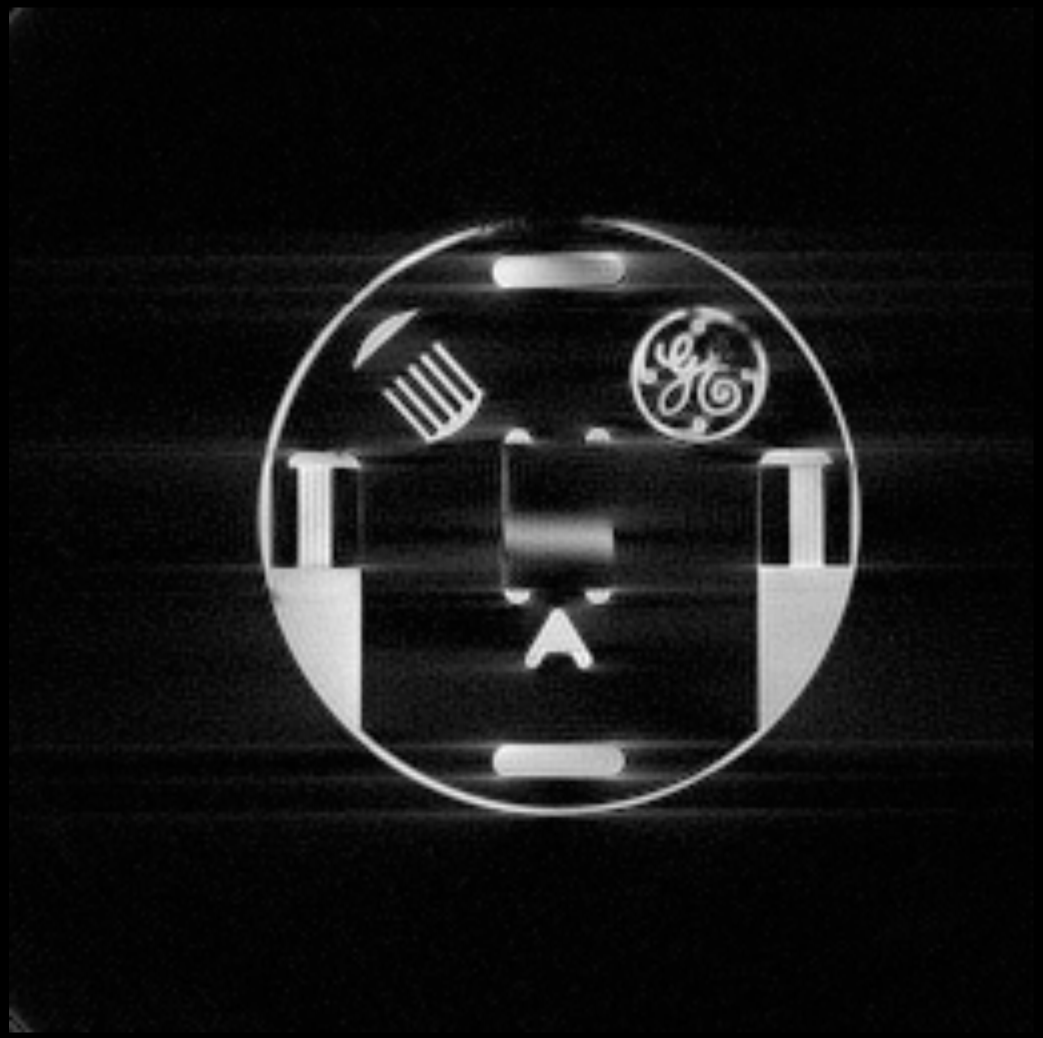


on resonance

Radial: Off-resonance Effects



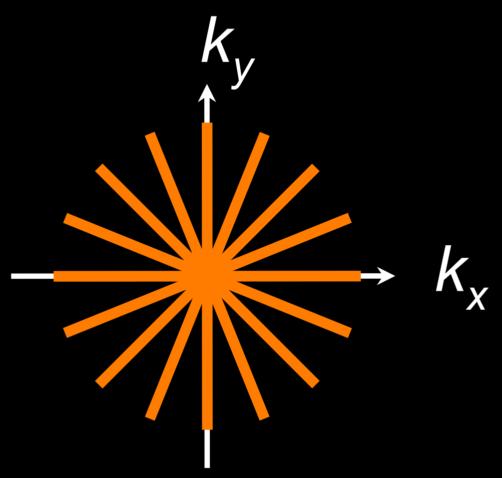
+200 Hz globally



off-res blurring

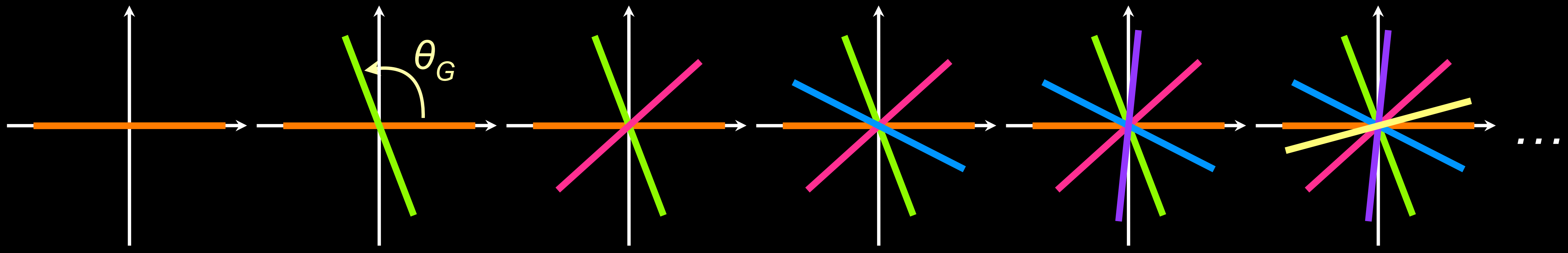
Radial: Real-time MRI

2D Radial MRI



- Robust to motion (oversample center of k-space)
- Can tolerate a lot of undersampling

Golden Angle Ordering

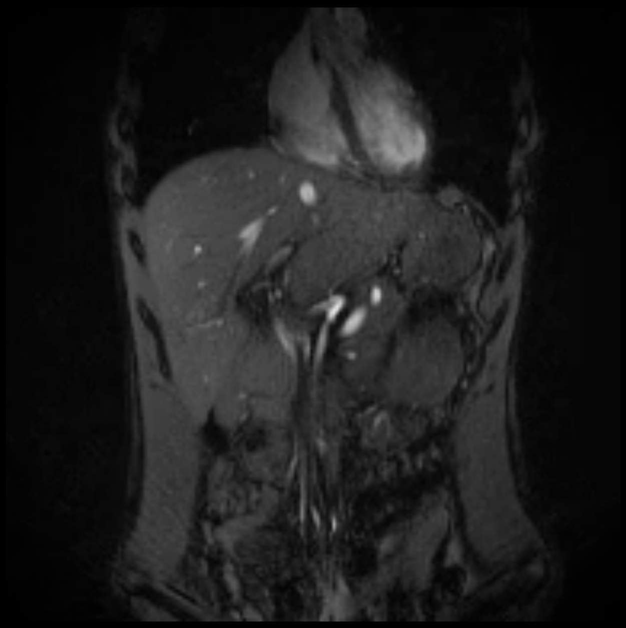


- Almost uniform sampling of *k-t* space
- Flexible choice of temporal frame location and width

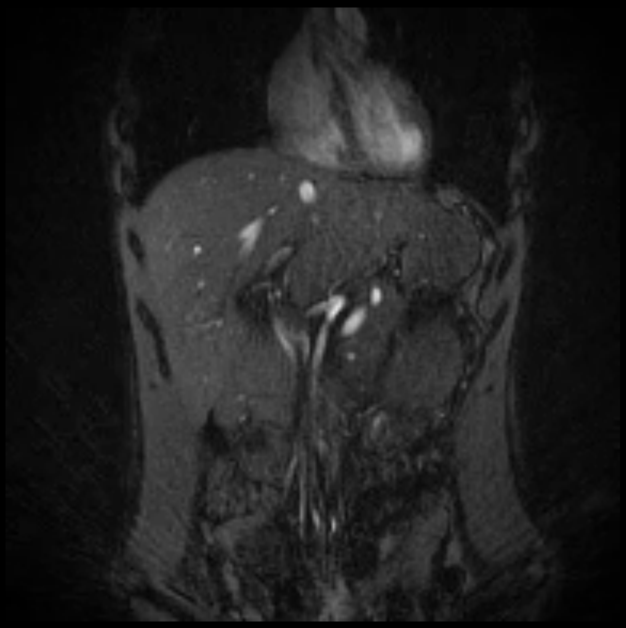
Radial: Real-time MRI

<u>Radial FLASH</u>
- golden-angle ordering
- 192 x 192 matrix
- TR = 3.1 ms
  (1 spoke per TR)
- 3.0 T

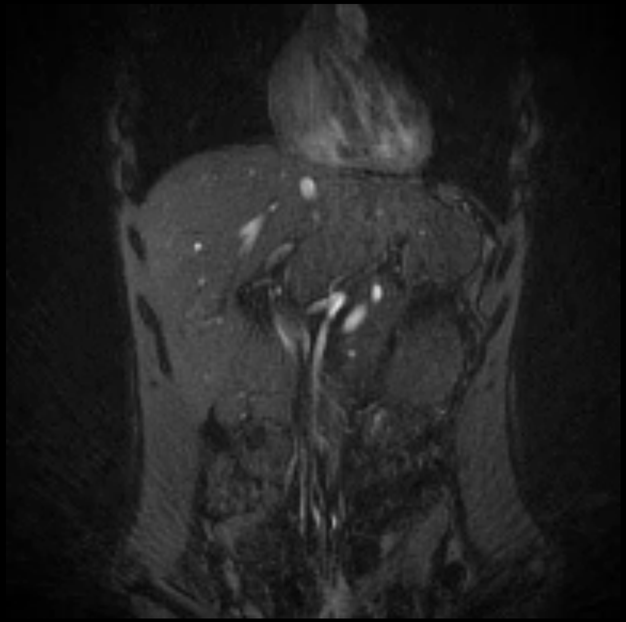
<u>Reconstruction</u>
- sliding window of 20 TRs
  (display at 16 frames/sec)
- gridding only
  (300 spokes for Nyquist)



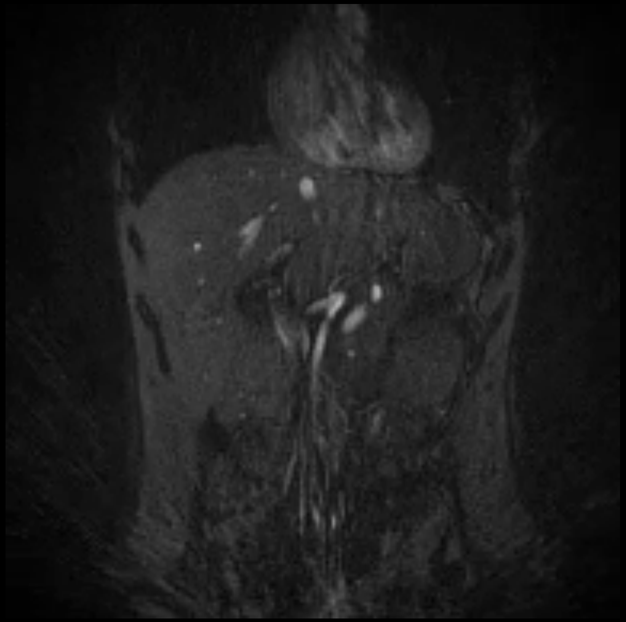
255 spokes/frame
(791 ms/frame)



144 spokes/frame
(446 ms/frame)



89 spokes/frame
(276 ms/frame)



55 spokes/frame
(171 ms/frame)

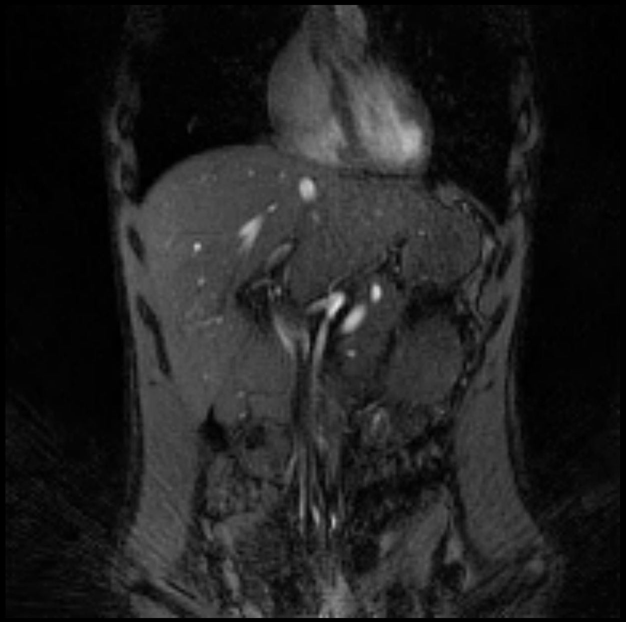
courtesy of Samantha Mikaiel

Radial: Real-time MRI

<u>Radial FLASH</u>
- golden-angle ordering
- 192 x 192 matrix
- TR = 3.1 ms
  (1 spoke per TR)
- 3.0 T

<u>Reconstruction</u>
- sliding window of 20 TRs
  (display at 16 frames/sec)
- parallel imaging (SPIRiT)
  (300 spokes for Nyquist)

255 spokes/frame
(791 ms/frame)



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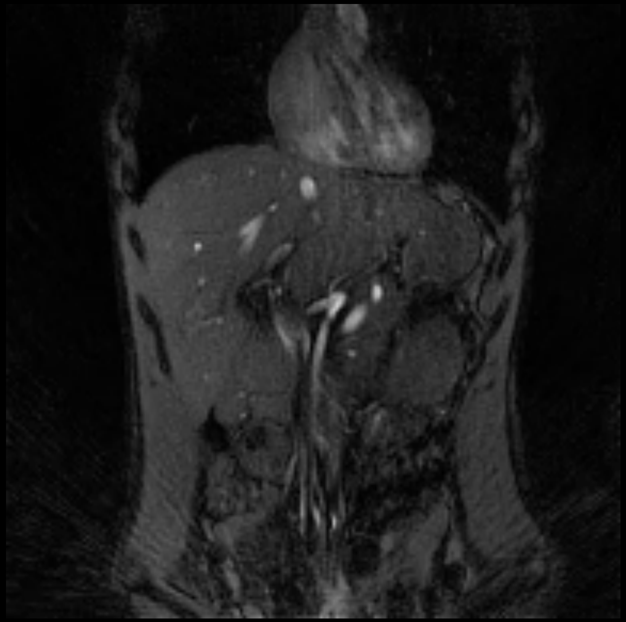

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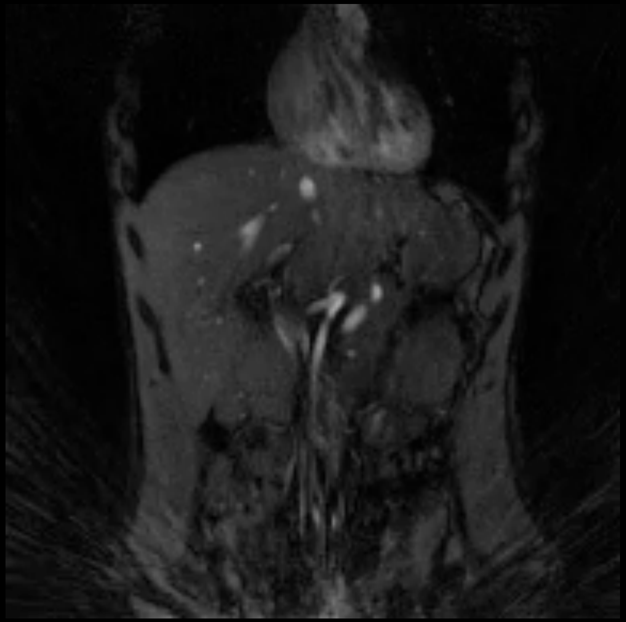
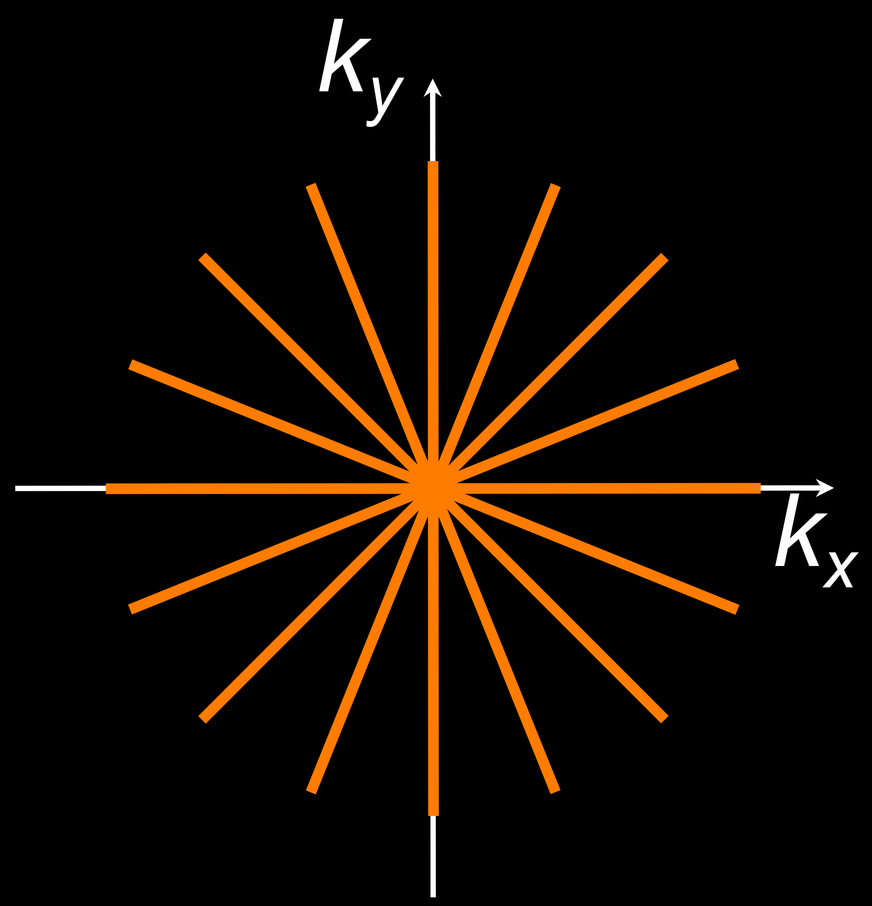


55 spokes/frame
(171 ms/frame)

courtesy of Samantha Mikaiel

Radial: Pros and Cons



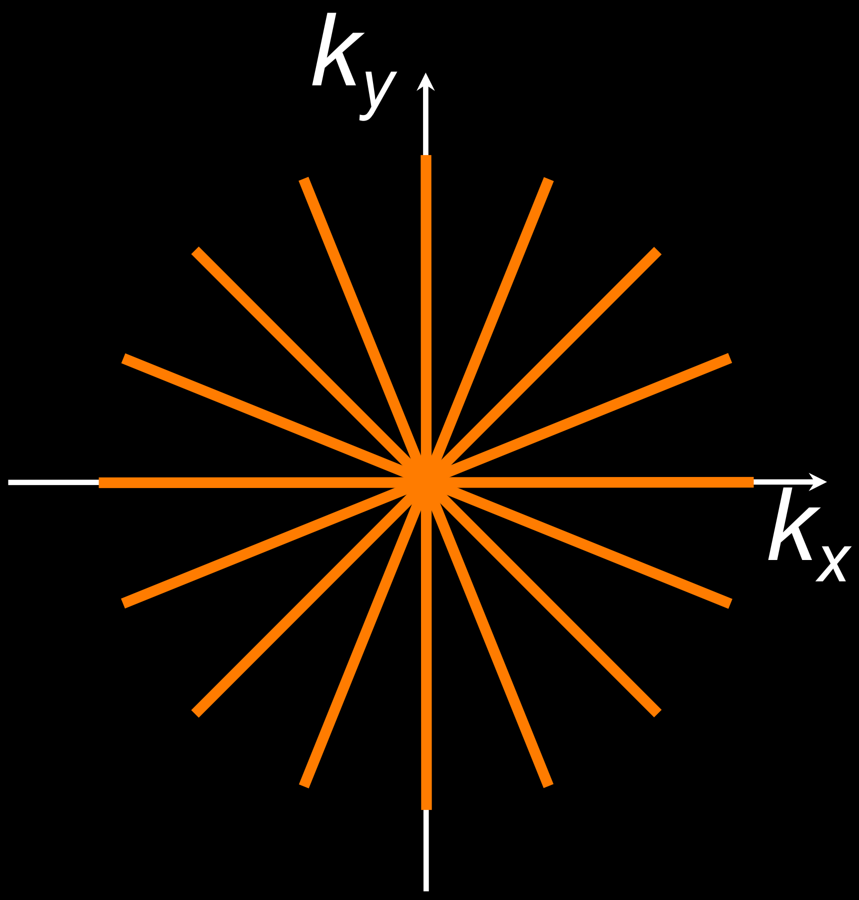
Pros

- Robust to motion (get DC every TR)
- Can tolerate a lot of undersampling
- Half-spoke PR has very short TE

Cons

- SNR penalty (non-uniform density)
- May have mixed contrast
- Sensitive to gradient delays
- Sensitive to off-resonance effects

Radial: Extensions



3D stack of stars

3D koosh ball

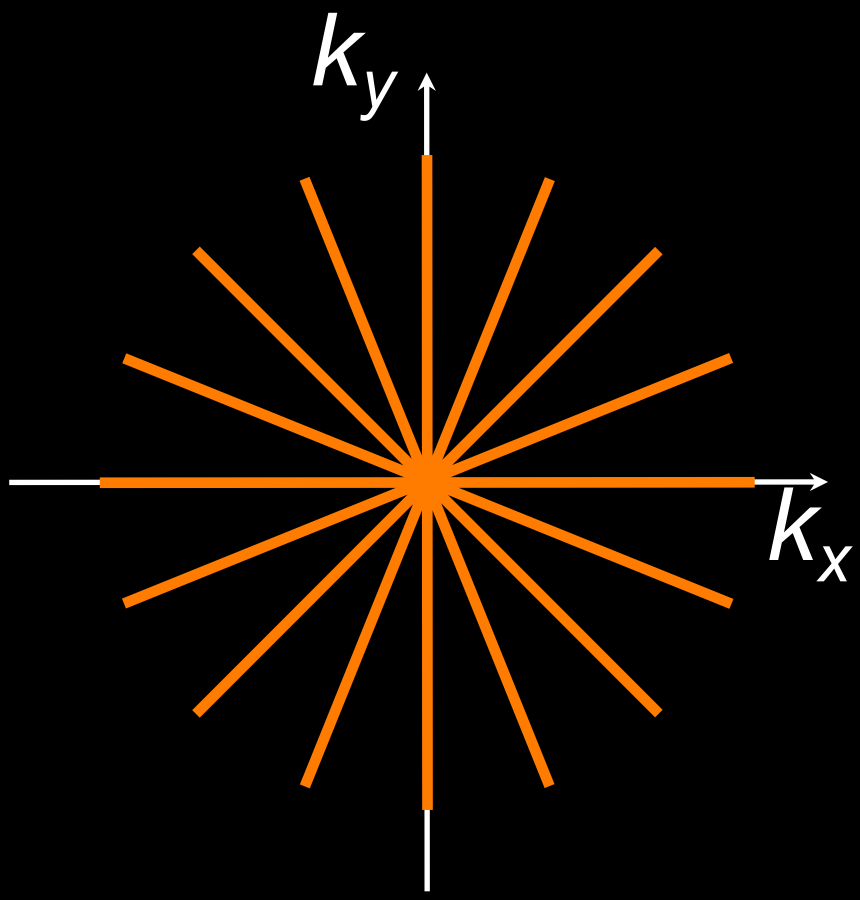
Multiple spokes per TR

Golden angle ordering

Parallel imaging

Partial Fourier

Radial: Applications



<u>Fast imaging</u>

- Cardiac MRI

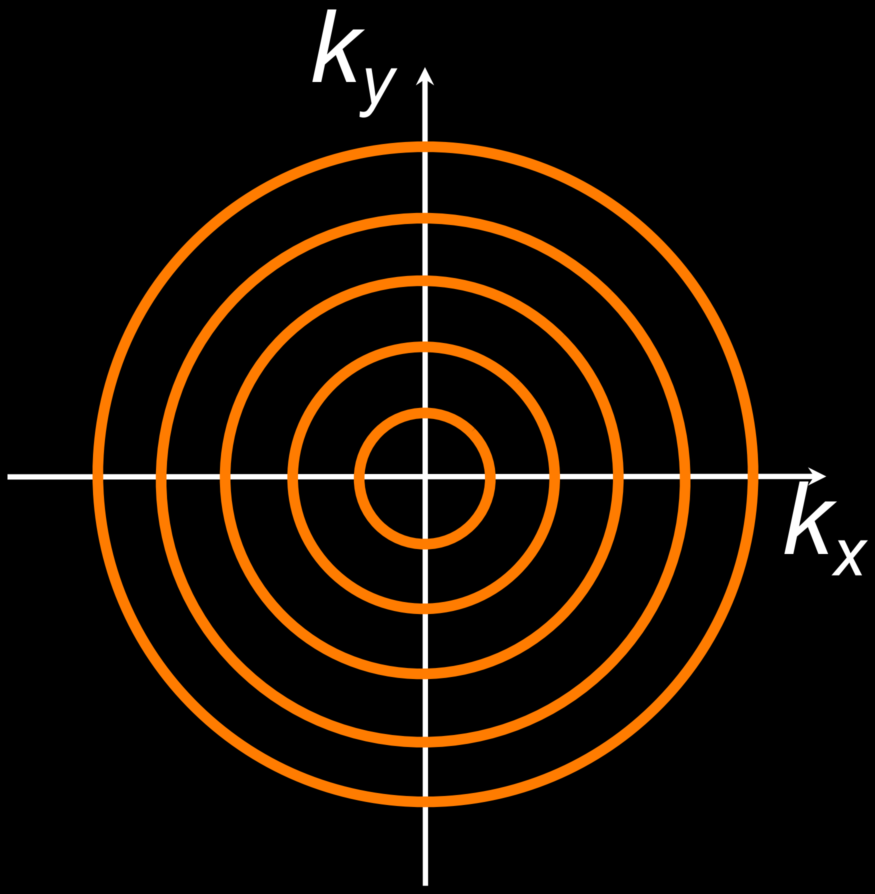
<u>Improve motion robustness</u>

- Cardiac MRI
- Abdominal MRI

<u>Ultra-short TE (UTE) imaging</u>

- Musculoskeletal MRI
- Lung MRI

Concentric Rings

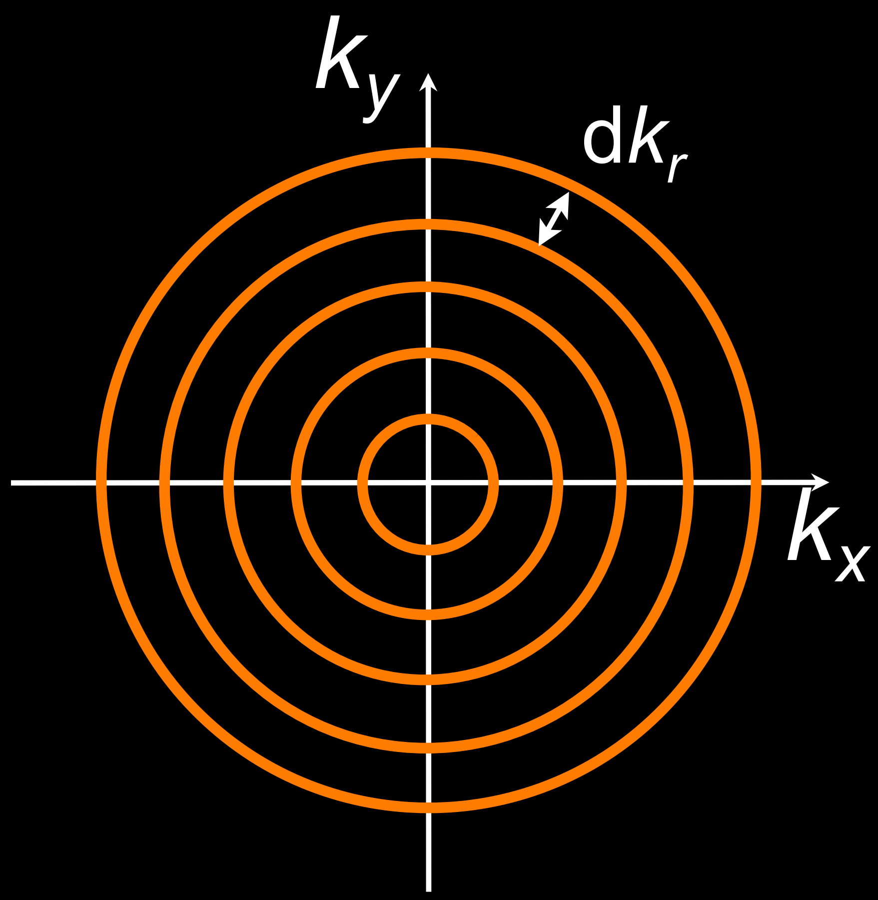


<u>Non-rectilinear sampling!</u>

<u>Samples k-space on a polar grid</u>

- “dual” of radial sampling
- shares some properties of 2DPR
- exhibits distinct characteristics

Rings: Sampling Requirements



N concentric rings

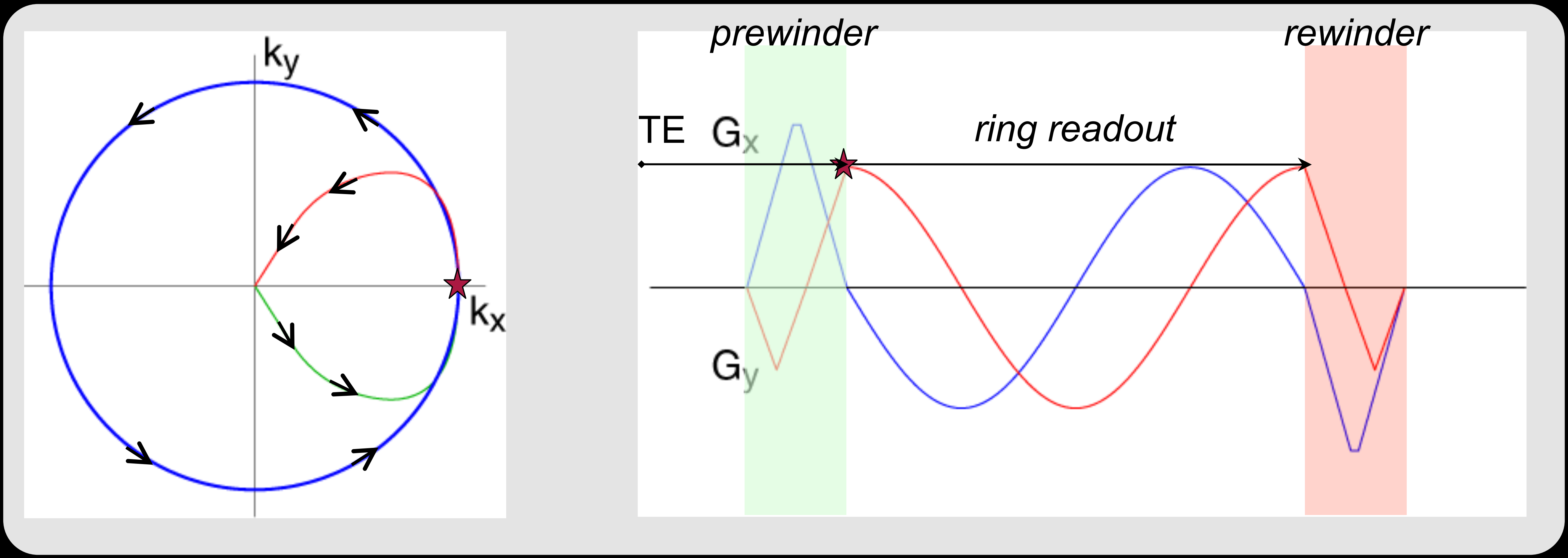
uniform spacing of dk_r

$$\frac{1}{\mathrm{FOV}} = \mathrm{d}k_r$$

$$k_{r,max} = (N-1) \cdot \mathrm{d}k_r$$

Subject to hardware limits

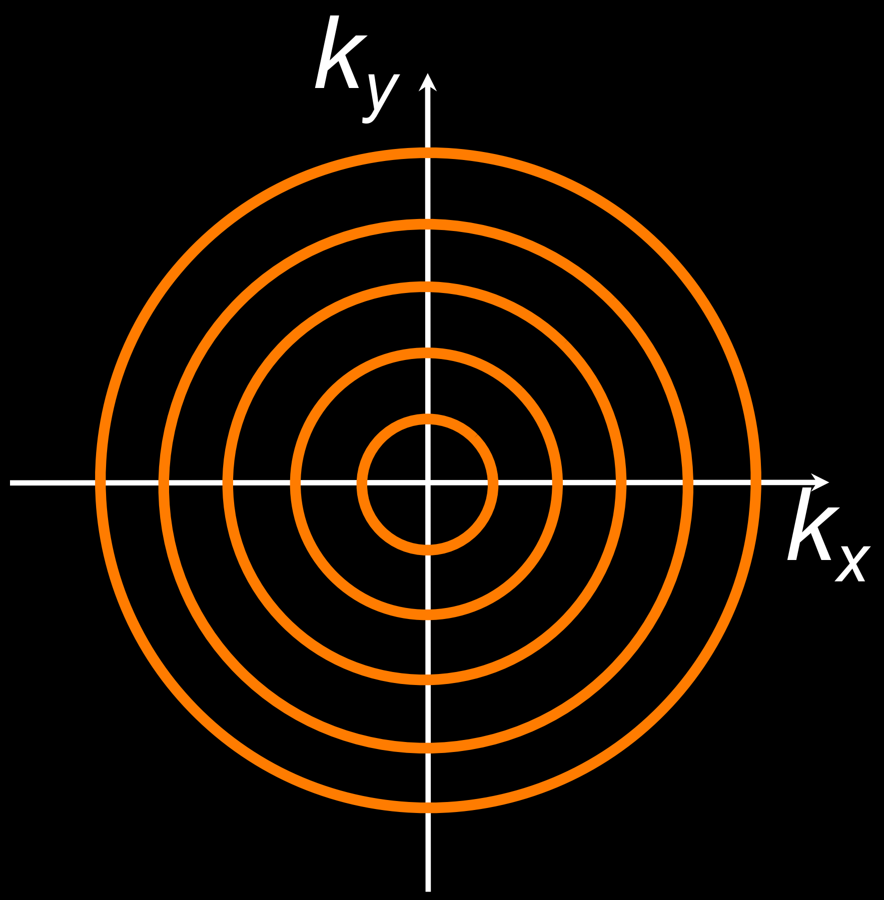
Rings: Gradient Design



Scale down gradients for outermost ring

- Sampling density identical to 2DPR
- Robust to gradient delays & timing errors

Rings: Scan Time



For an M x M image,

need $N = M/2$ rings

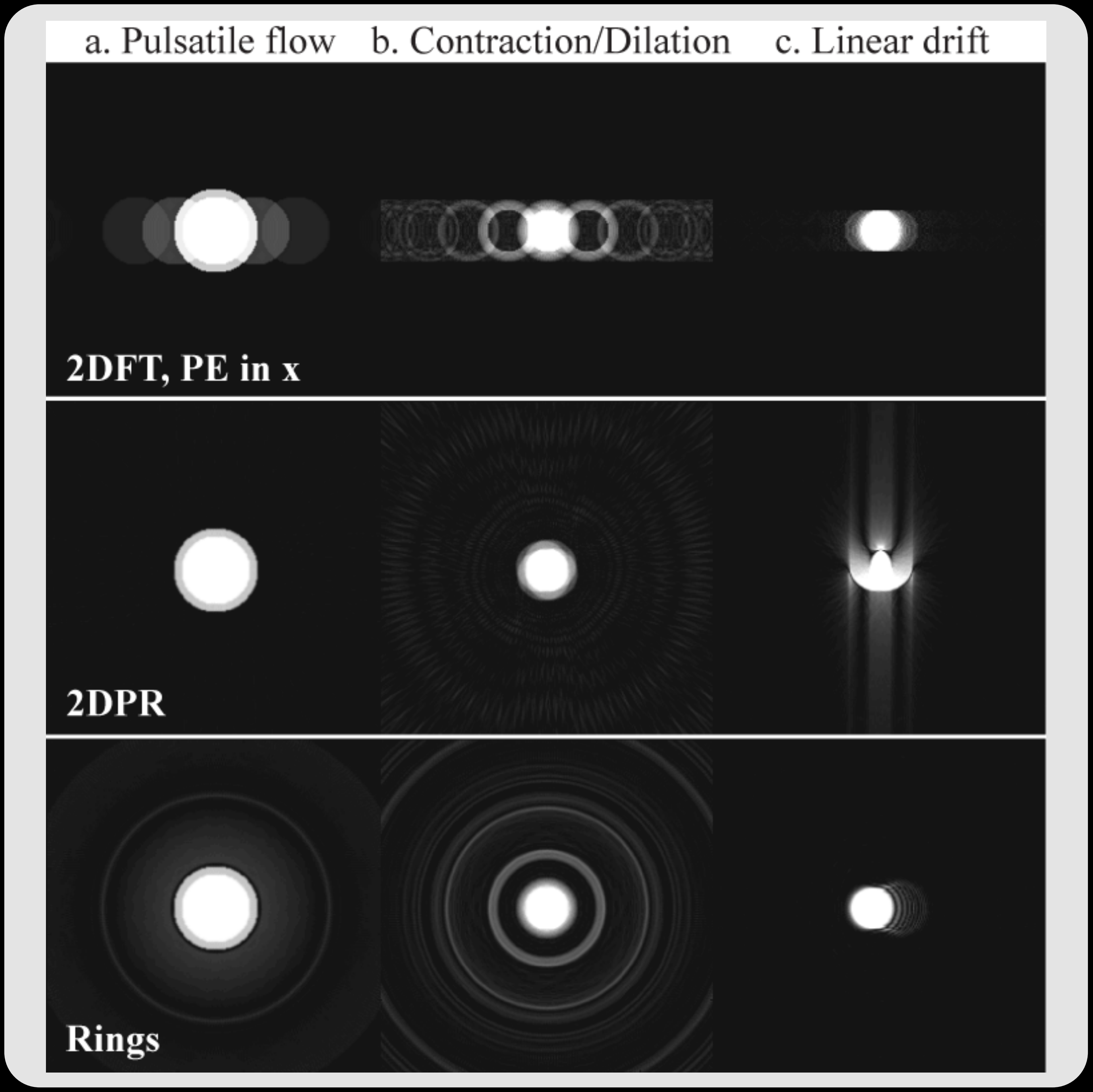
Scan time = $(M/2)$ x TR_{ring}

Compare with 2DFT:

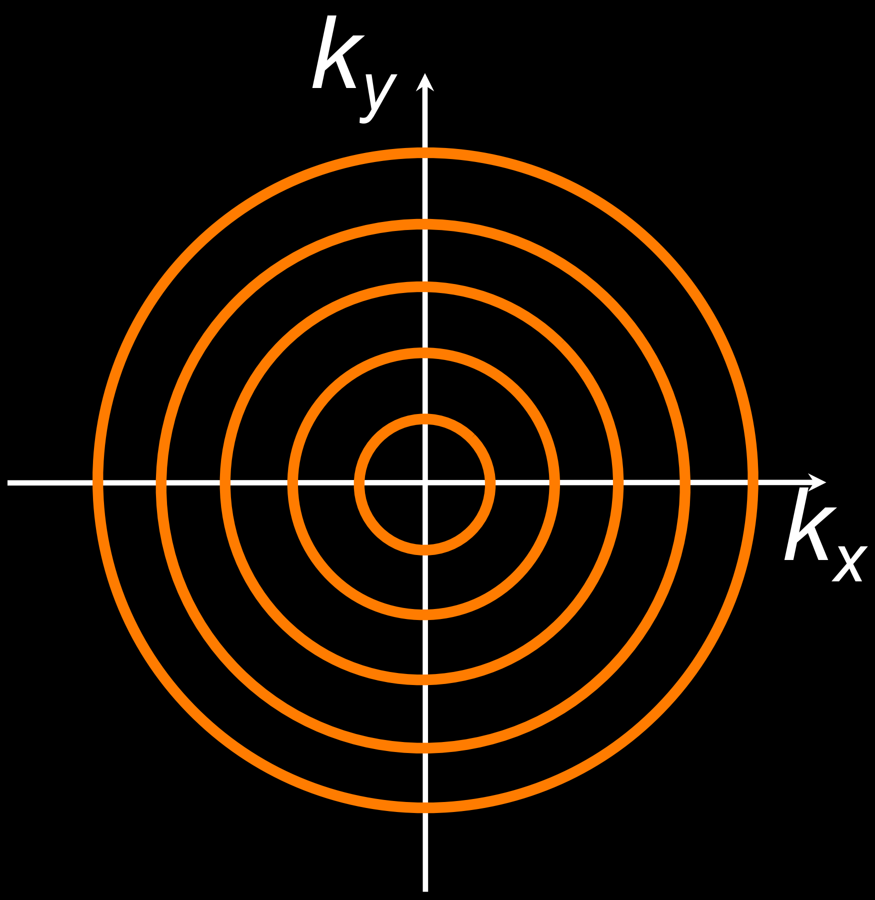
Scan time = M x TR_{line}

Rings offer ~2x acceleration

Rings: Motion and Flow



Rings: Image Reconstruction



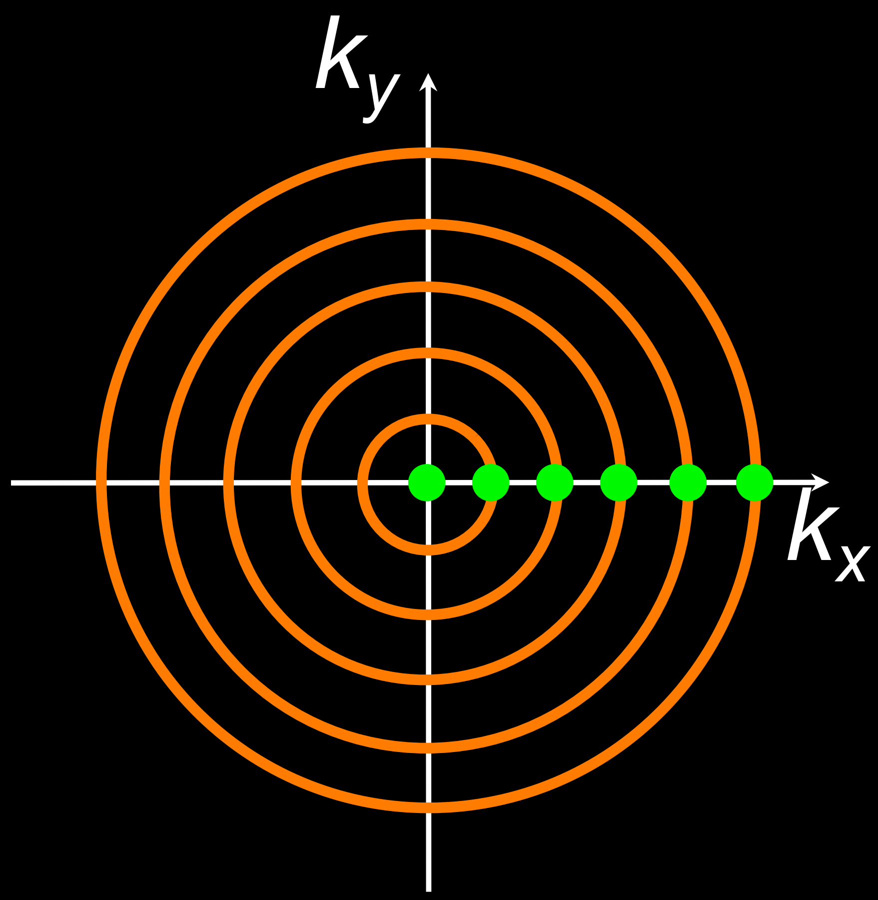
<u>Reformat into spokes</u>

- filtered back projection

<u>Resample onto Cartesian grid</u>

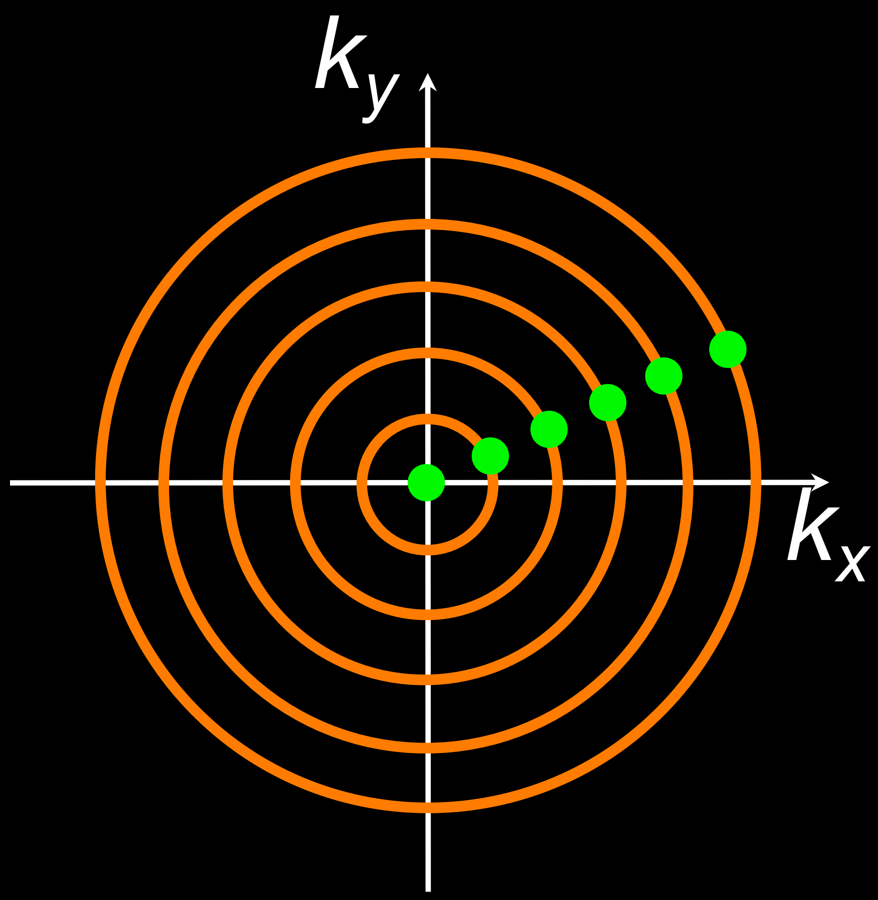
- “gridding” reconstruction

Rings: Gradient Delays



calibrated

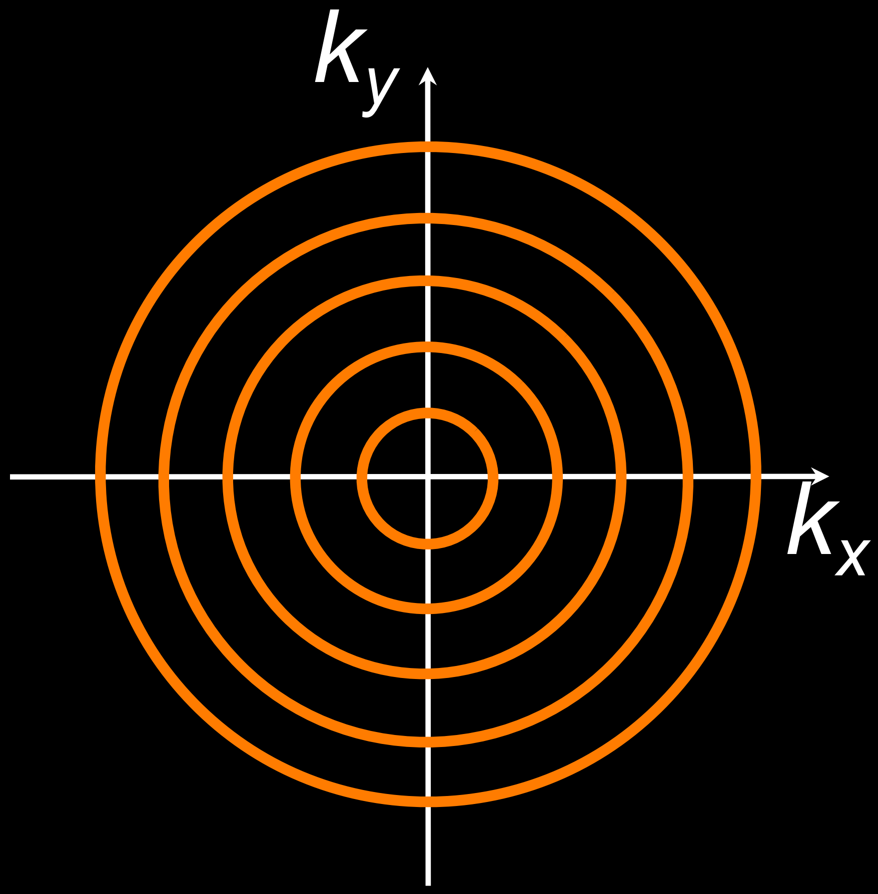
Rings: Gradient Delays



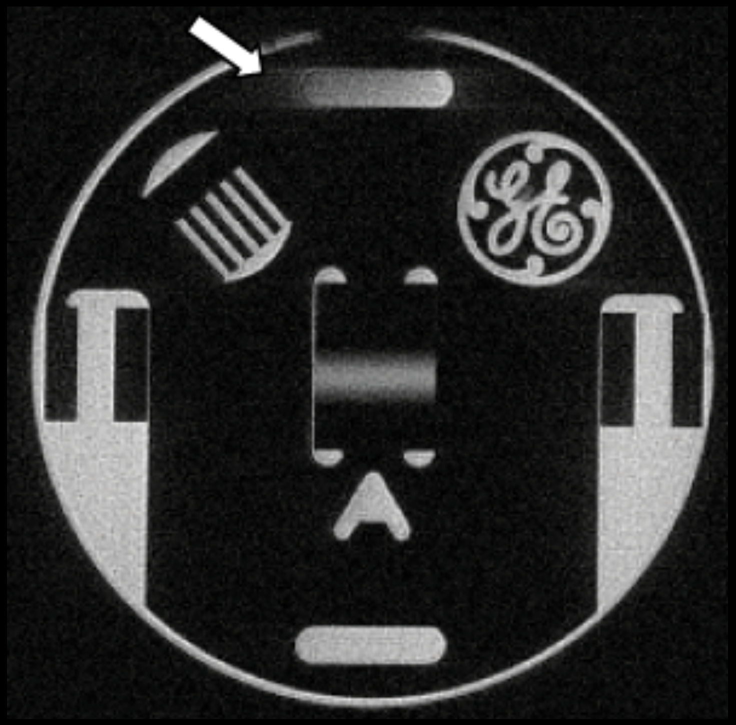
grad-acq delay

in-plane rotation

Rings: Off-resonance Effects

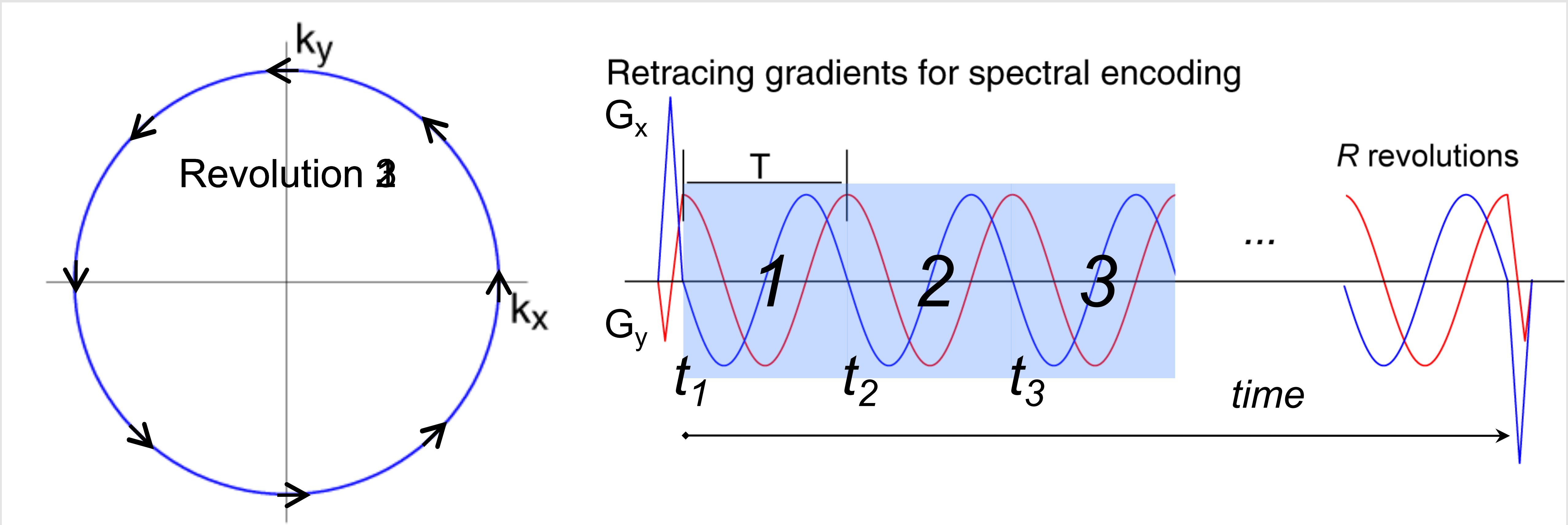


w/spatially
varying off-res



off-res blurring

Rings: Resolving Off-Res Effects



Encodes (k_x, k_y, *time*) simultaneously

- Resolve off-resonance effects
- “Spectral” encoding

Rings: Resolving Off-Res Effects

Concentric Rings with 2 Revolutions / TR

Regular recon   Field map   ORC image

Rings: Resolving Off-Res Effects

Concentric Rings with 3 Revolutions / TR

Field map

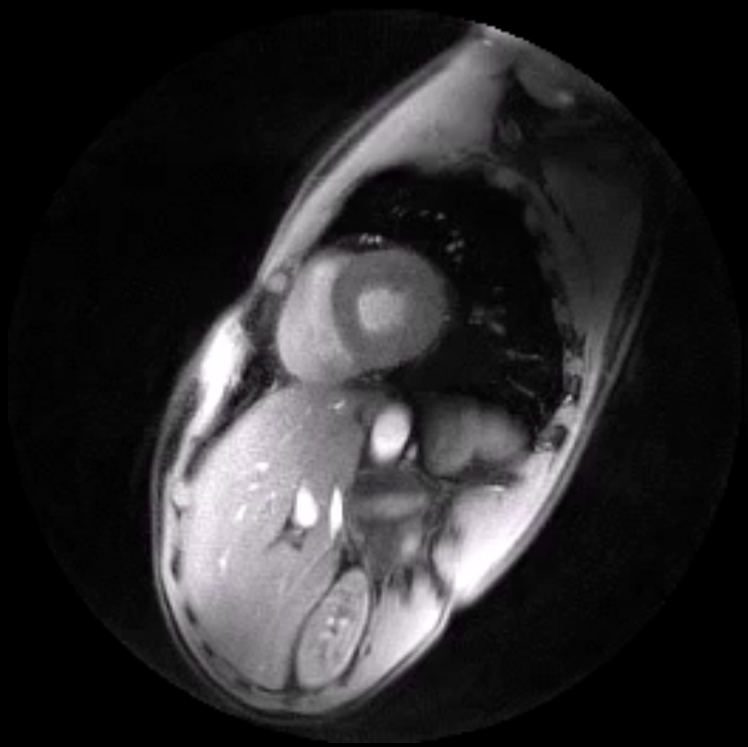
Water image

Fat image

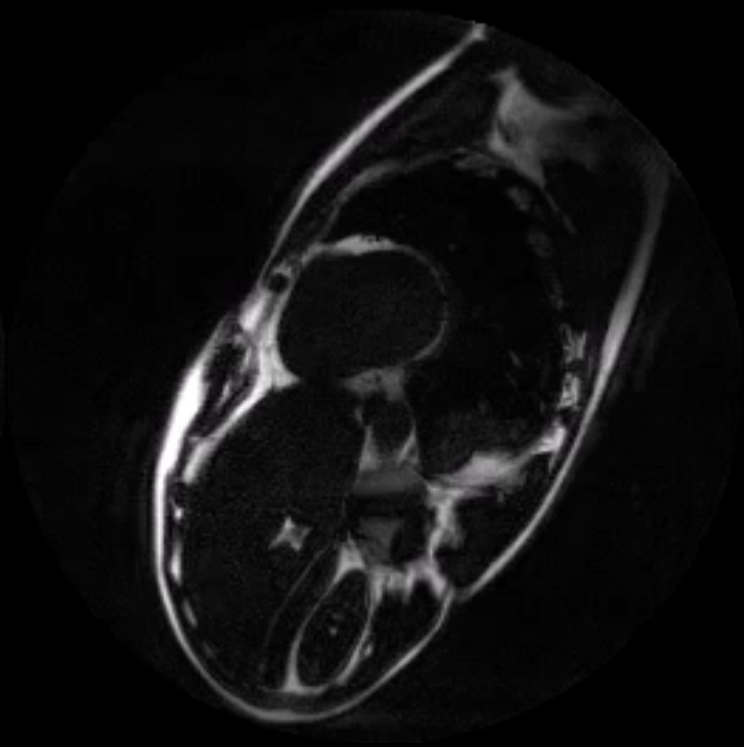
Rings: Resolving Off-Res Effects

1.5 T, 2D GRE, Cardiac F/W Cine

13-HB BH scan (with add’l 3-fold *k-t* BLAST acceleration)



Water



Fat

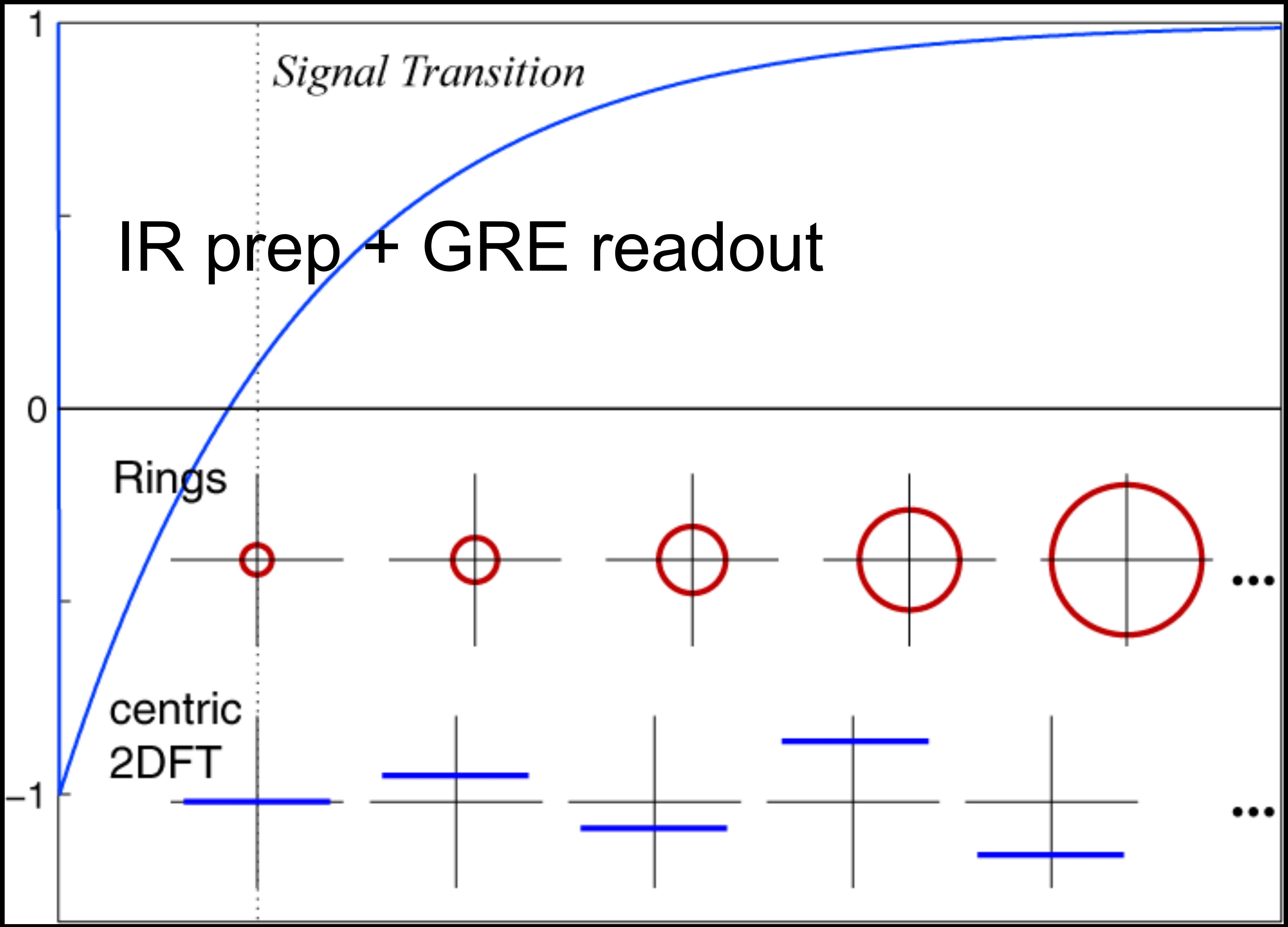
Combined

Wu HH et al., ISMRM 2011, p4366

Rings: Magnetization-Prepared MRI

Inherent 2D centric ordering

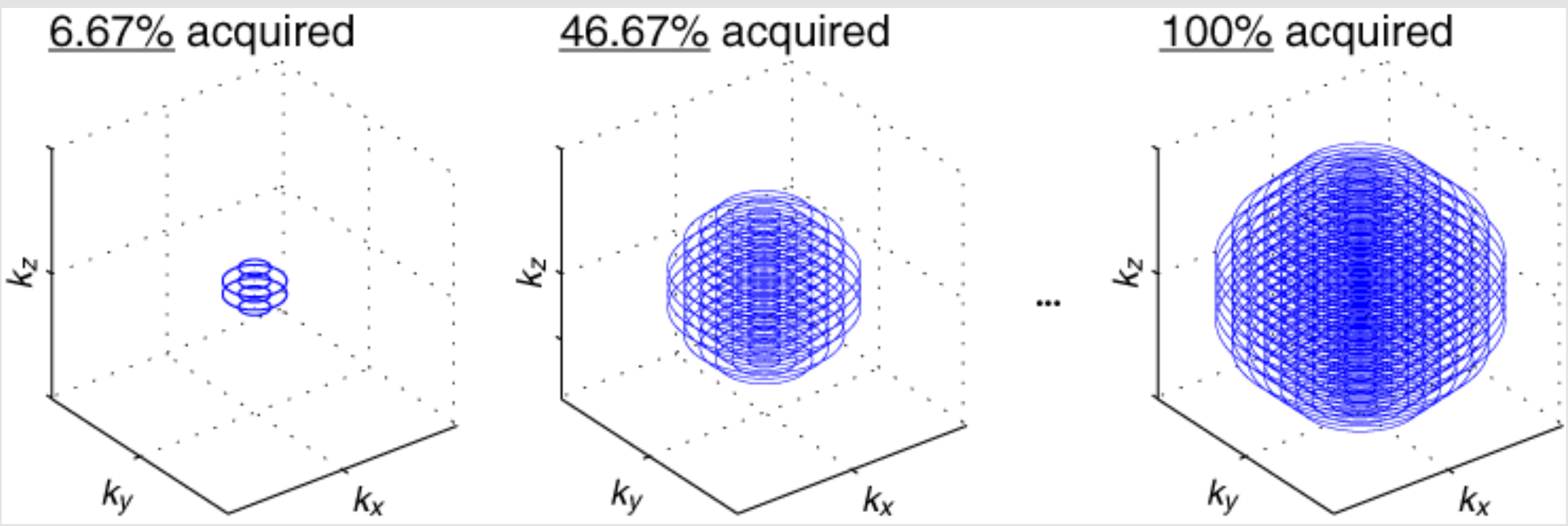
- improved mag-prep contrast and k-space weighting



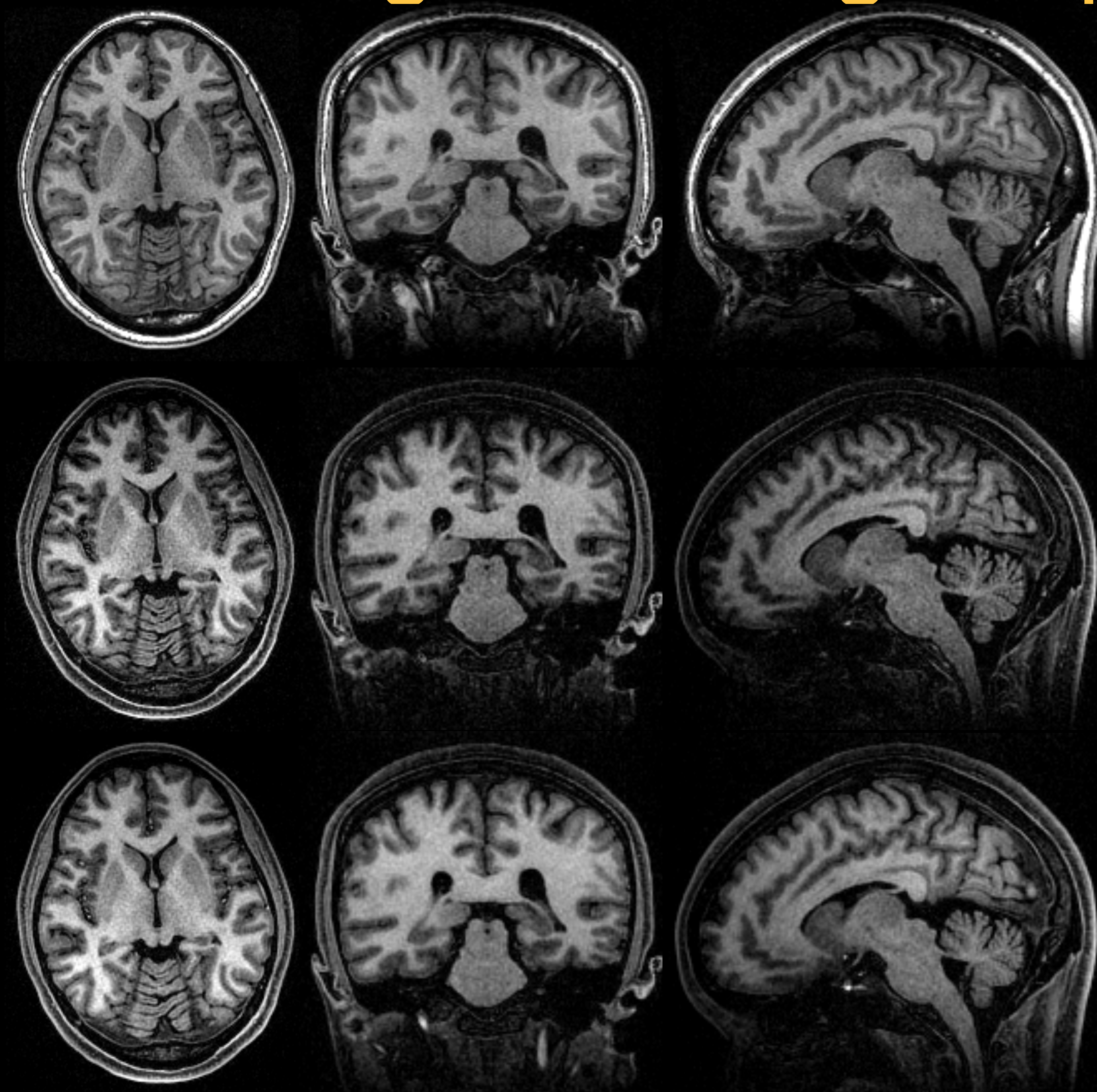
Rings: 3D Mag-Prep MRI

Fully 3D centric ordering

- improved mag-prep contrast and k-space weighting
- spherical k-space coverage saves time



Rings: 3D Mag-Prep MRI

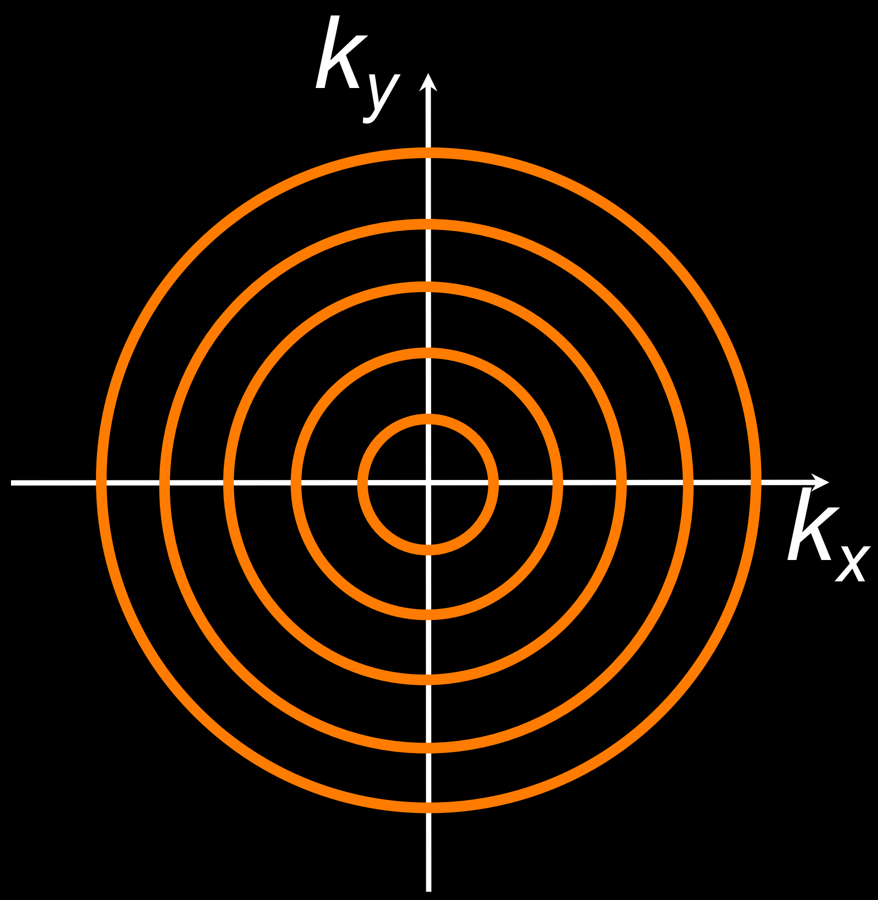


Product 3DFT
TI/TD = 600/----- ms
9 min 34 s
SNR_{WM} 24.07
CNR_{GW} 8.86

3D Rings, Protocol **A**
TI/TD = 600/----- ms
4 min 52 s
SNR_{WM} 25.78
CNR_{GW} 12.05

3D Rings, Protocol **B**
TI/TD = 900/600 ms
7 min 00 s
SNR_{WM} 33.46
CNR_{GW} 16.19

Rings: Pros and Cons



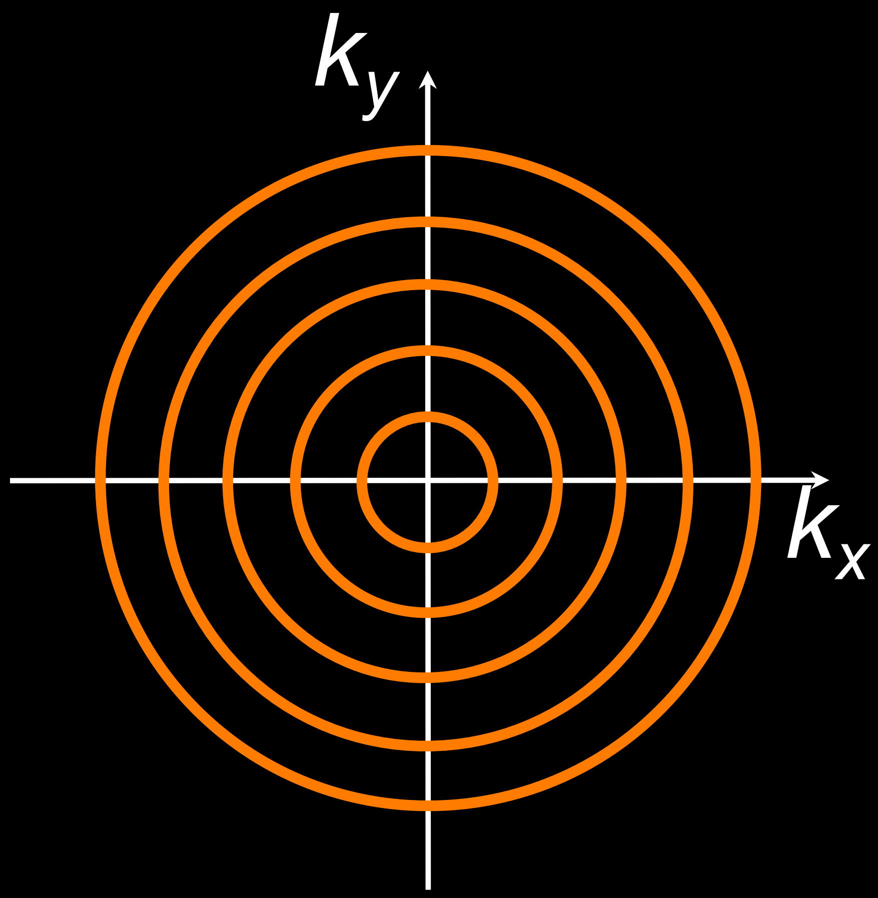
Pros

- 2x reduction in #TRs (vs. Cartesian)
- Favorable motion/flow properties
- Robust to gradient delays
- Efficient spatial/spectral encoding
- Effective for mag-prep MRI

Cons

- SNR penalty (non-uniform density)
- Scale-down design not optimal

Rings: Extensions



Variable density sampling

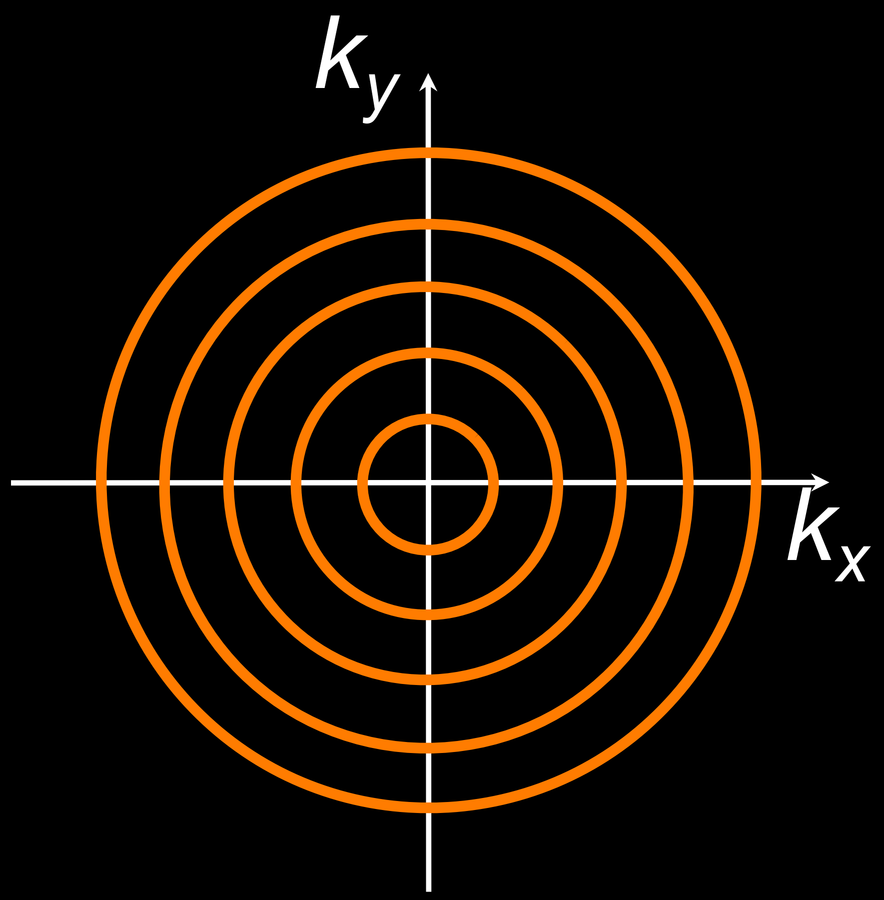
Multiple rings per TR

3D concentric cylinders

Parallel imaging

Partial Fourier

Rings: Applications



Fast imaging

- Cardiac MRI

Chemical shift imaging

- Fat/water separation
- MR spectroscopic imaging

Mag-prep imaging

- Neuro MRI
- Non-con MR angiography (MRA)
- Contrast-enhanced MRA

Non-Cartesian Sampling

- Benefits
  - Reduced scan time
  - Robustness to motion and flow
  - Short echo time
- Applications
  - Dynamic MRI
  - Real-time MRI
  - Cardiovascular MRI
  - Short-TE MRI
- Challenges
  - Hardware performance
  - Gradient fidelity
  - Off-resonance effects
  - Implementation
- Challenges addressed
- On-going research
- Use judiciously!

Thanks!

- Further reading
  - Bernstein et al., Handbook of MRI Sequences
- Next week
  - Spiral, 3D Non-Cartesian trajectories
  - Gridding reconstruction
  - Trajectory measurement
  - Off-resonance correction

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