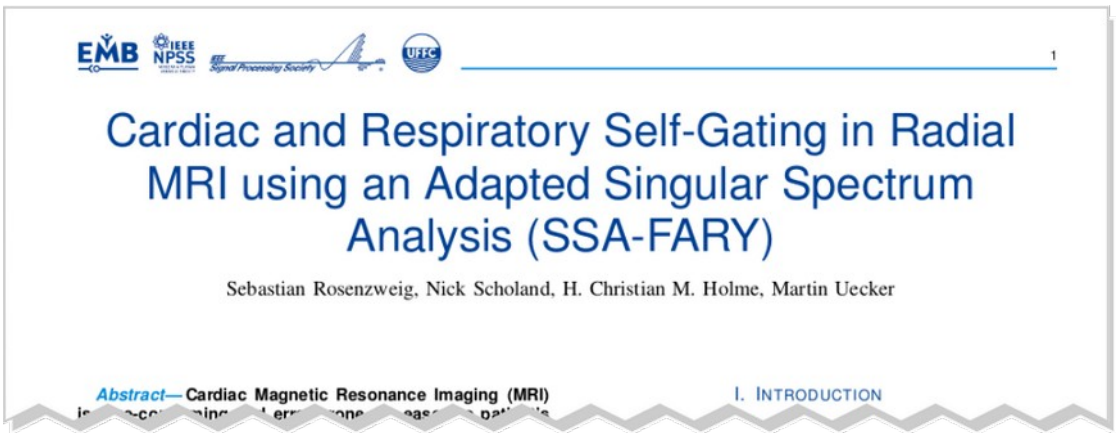
SSA-FARY
Gating without External Devices

Sebastian Rosenzweig
Diagnostic and Interventional Radiology
University Medical Center Göttingen

May 29, 2020



1

Cardiac and Respiratory Self-Gating in Radial MRI using an Adapted Singular Spectrum Analysis (SSA-FARY)

Sebastian Rosenzweig, Nick Scholand, H. Christian M. Holme, Martin Uecker

Abstract— Cardiac Magnetic Resonance Imaging (MRI)

I. Introduction

UNIVERSITÄTSMEDIZIN GÖTTINGEN : UMG

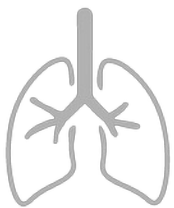
DZHK DEUTSCHES ZENTRUM FÜR HERZ-KREISLAUF-FORSCHUNG E.V.

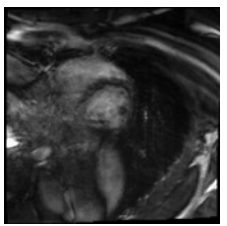
GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

Challenges in Cardiac MRI

RESPIRATORY MOTION

CARDIAC MOTION

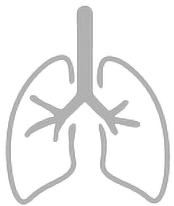


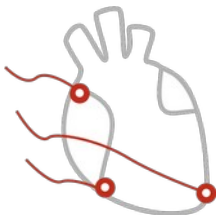


Challenges in Cardiac MRI

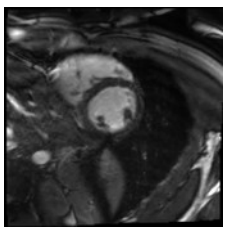
RESPIRATORY MOTION

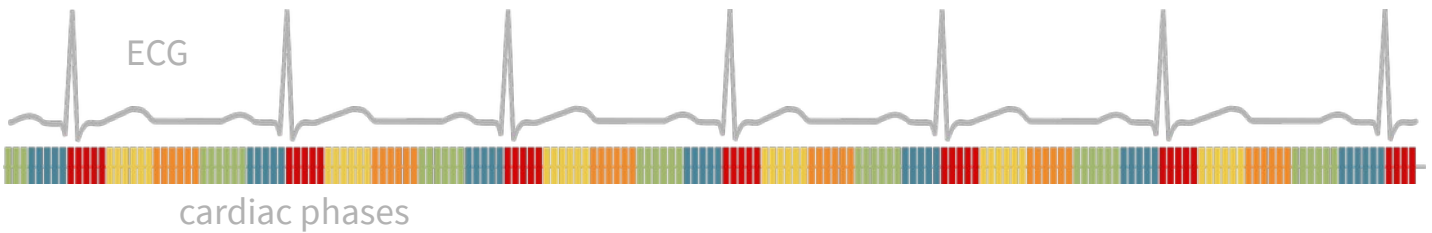
CARDIAC MOTION





ECG-gating

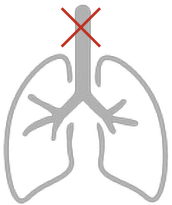


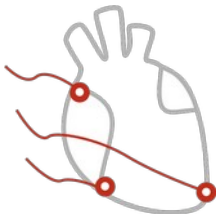


Challenges in Cardiac MRI

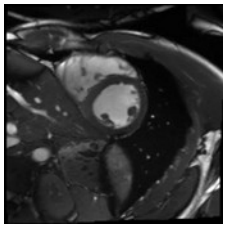
RESPIRATORY MOTION

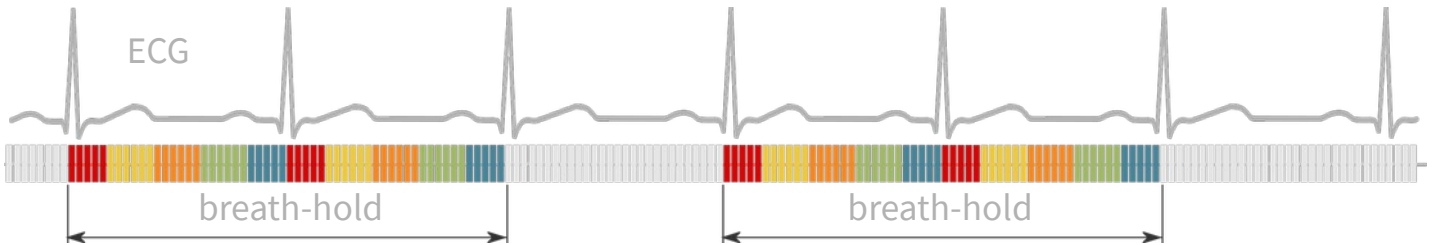
CARDIAC MOTION





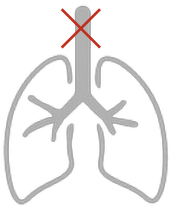
ECG-gating
breath-holds



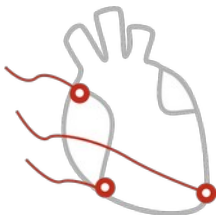


Challenges in Cardiac MRI

RESPIRATORY MOTION

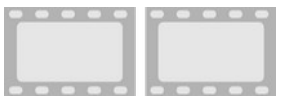


CARDIAC MOTION



ECG-gating
breath-holds

TEMPORAL INFORMATION



frame-by-frame

VOLUMETRIC INFORMATION

slice-by-slice

Challenges in Cardiac MRI

RESPIRATORY MOTION

CARDIAC MOTION

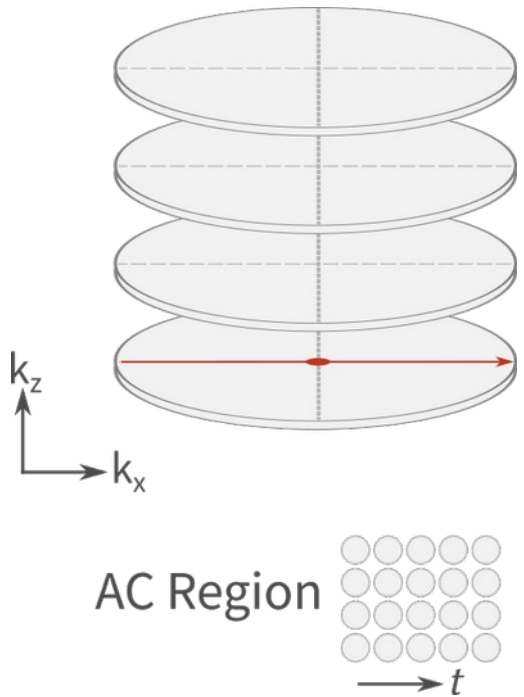
device-free
free-breathing

TEMPORAL INFORMATION

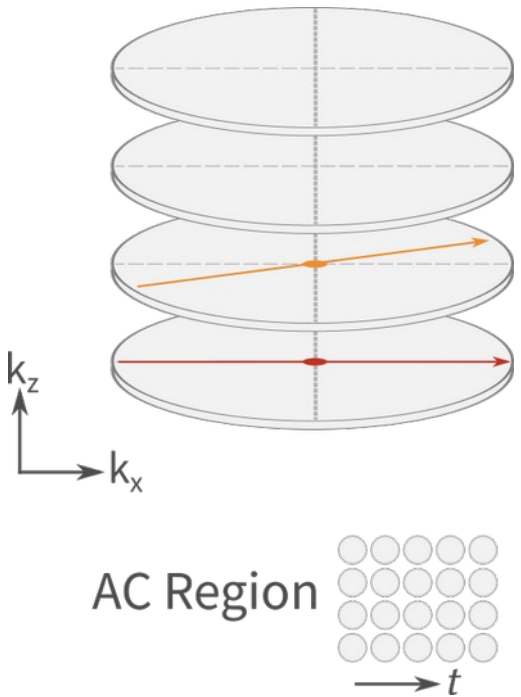
VOLUMETRIC INFORMATION

multi-dimensional

AC Region in Radial Imaging



AC Region in Radial Imaging



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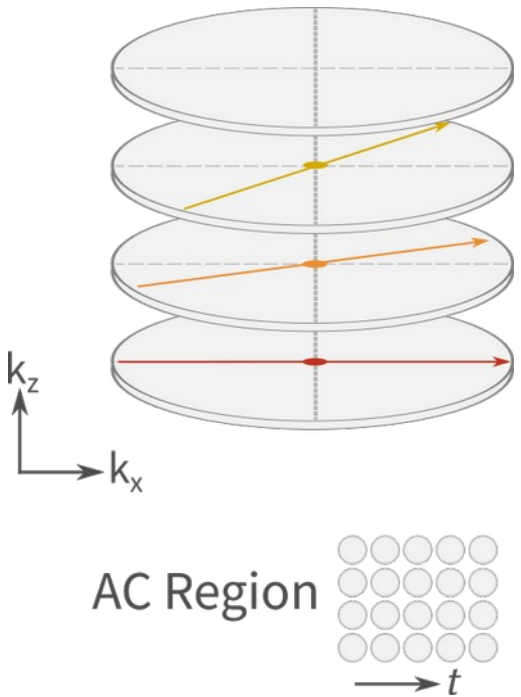
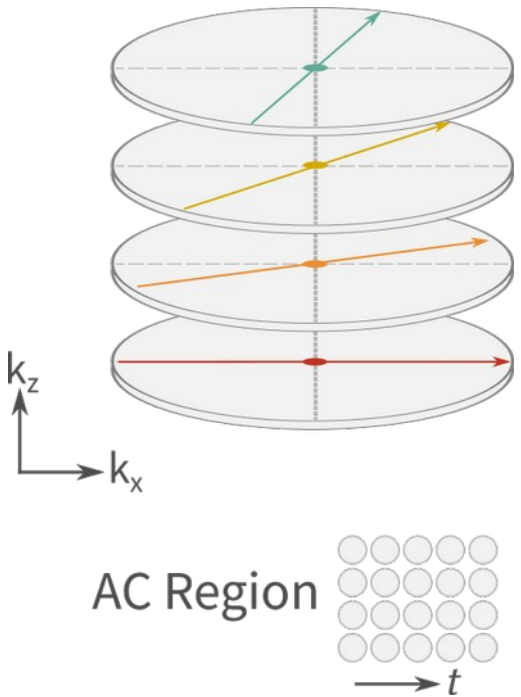
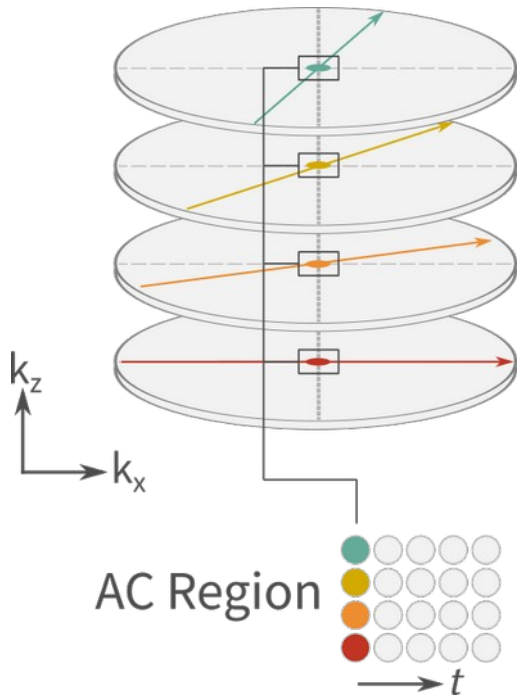


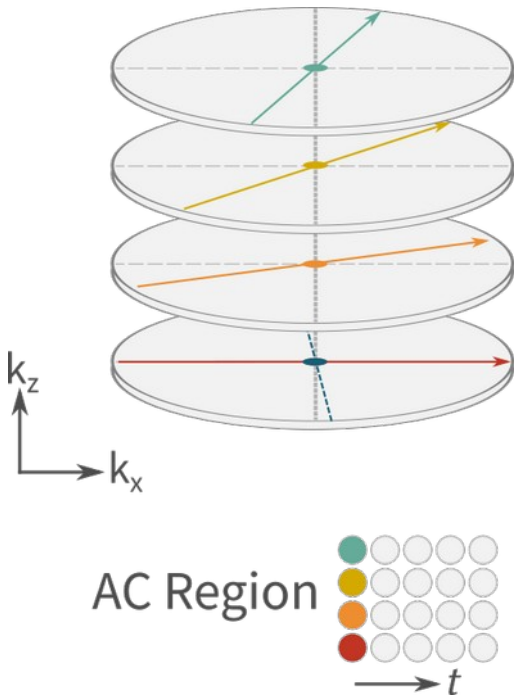
AC Region in Radial Imaging



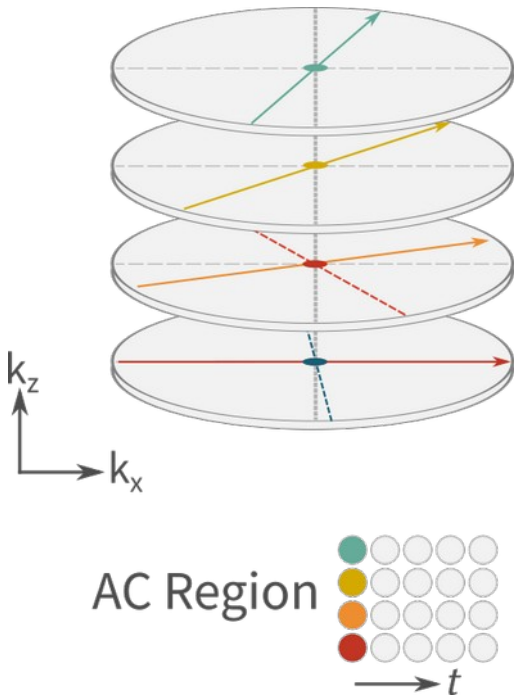
AC Region in Radial Imaging



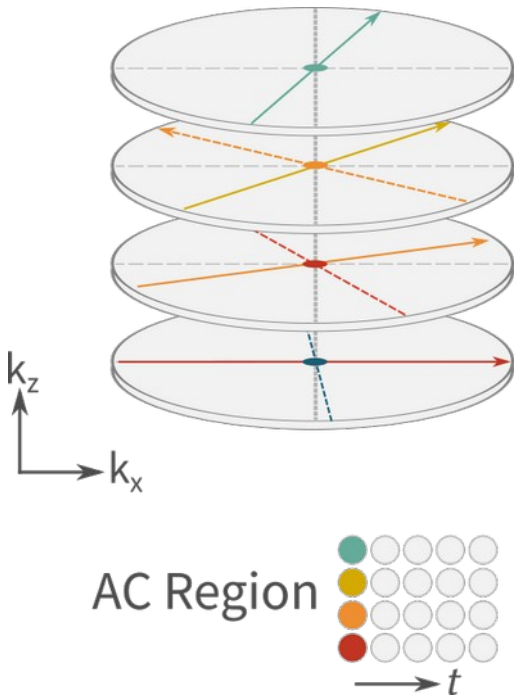
AC Region in Radial Imaging



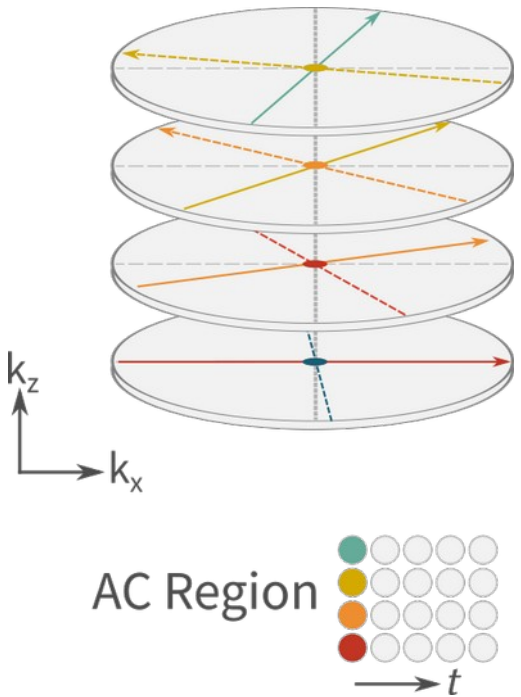
AC Region in Radial Imaging



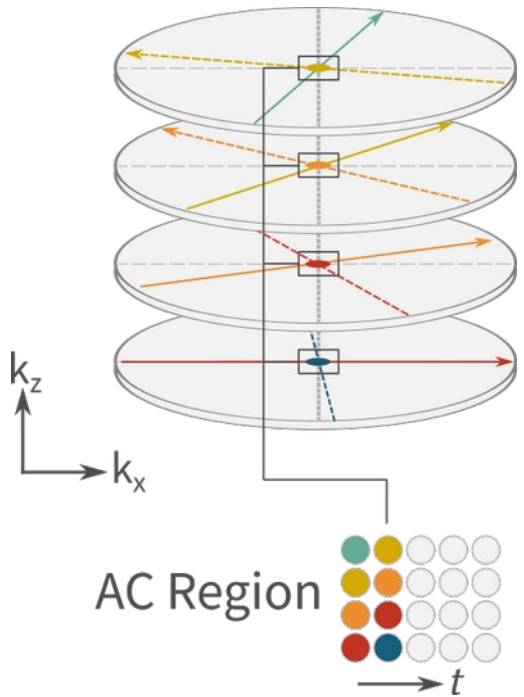
AC Region in Radial Imaging



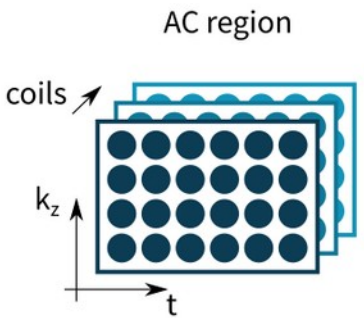
AC Region in Radial Imaging



AC Region in Radial Imaging

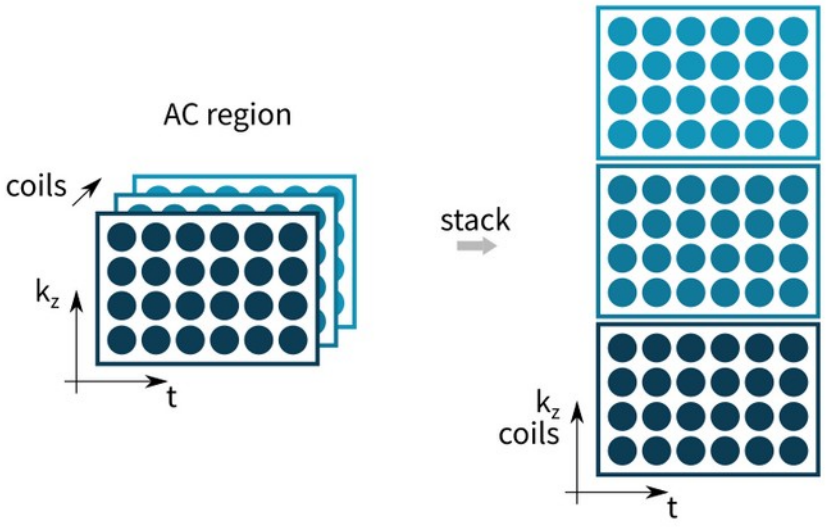


PCA



[1] Pang et al., Magn. Reson. Med. (2014)

PCA



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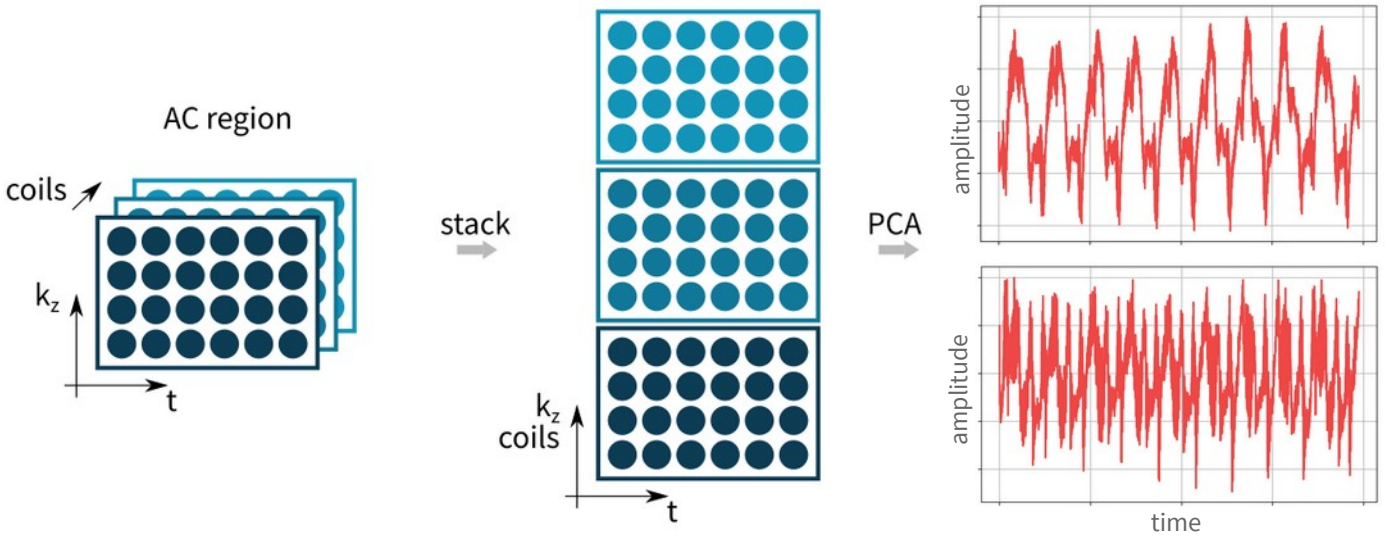
PCA



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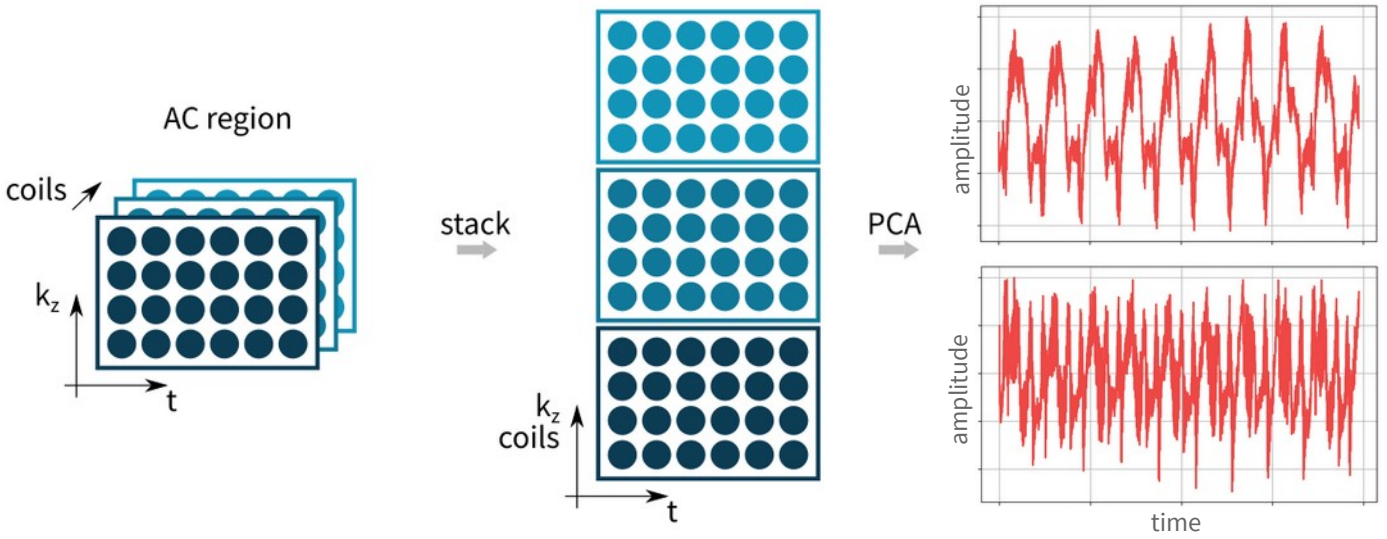
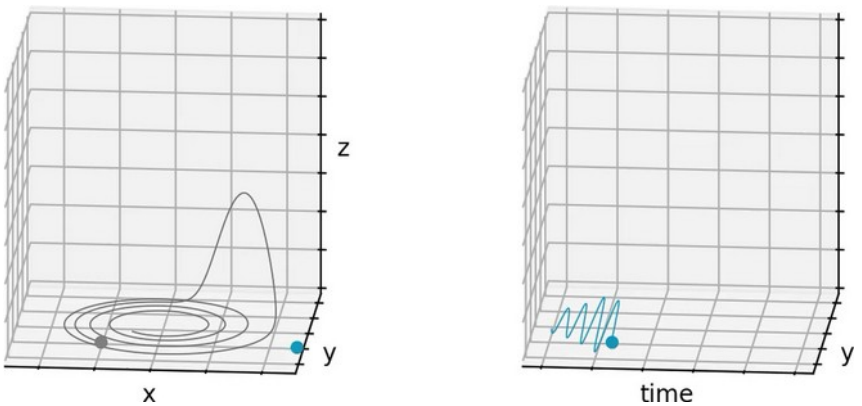
PCA



- incomplete separation
- noisy

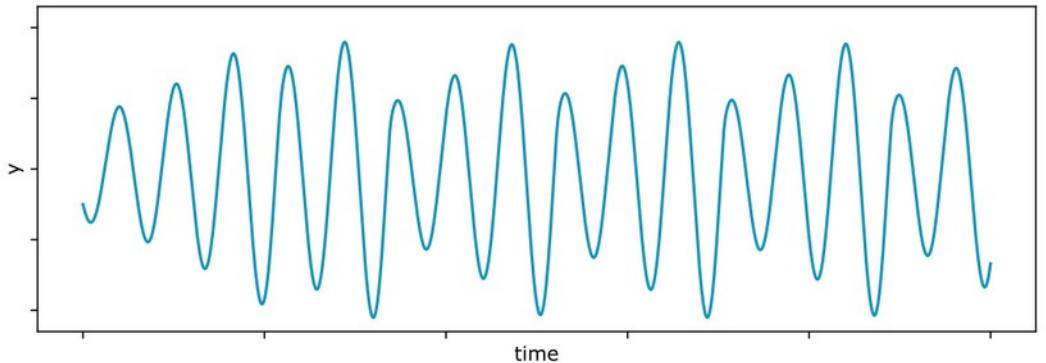
[1] Pang et al., Magn. Reson. Med. (2014)

Rössler Attractor

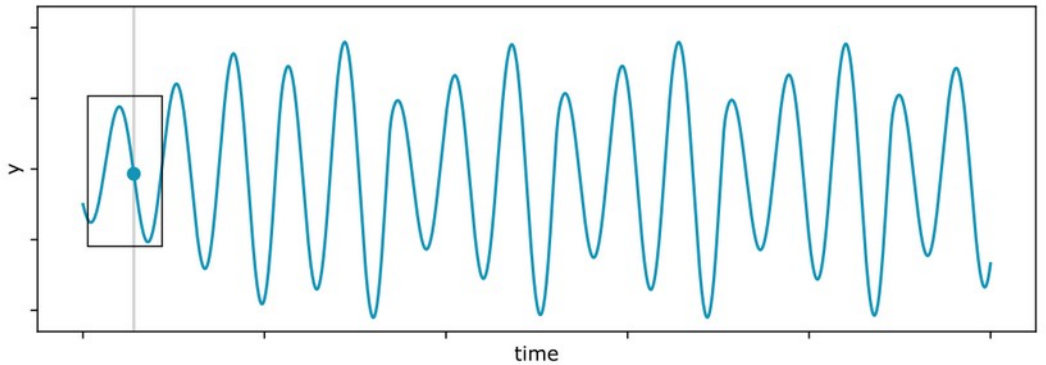


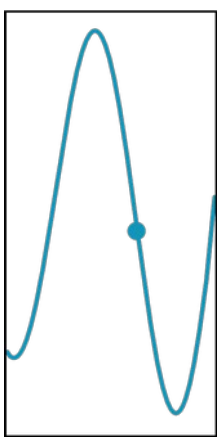
$$\dot{x} = -y - z$$
$$\dot{y} = x + ay$$
$$\dot{z} = b + z(x - c)$$

Time-Delayed Embedding



Time-Delayed Embedding





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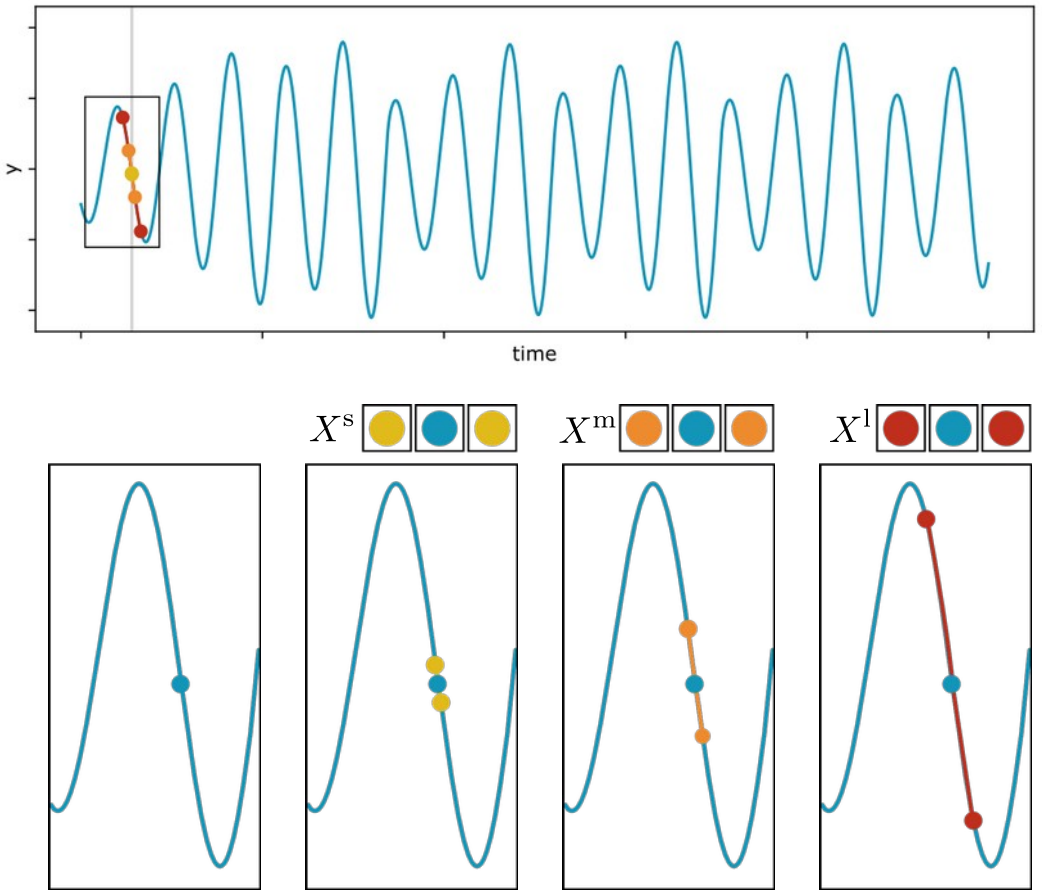
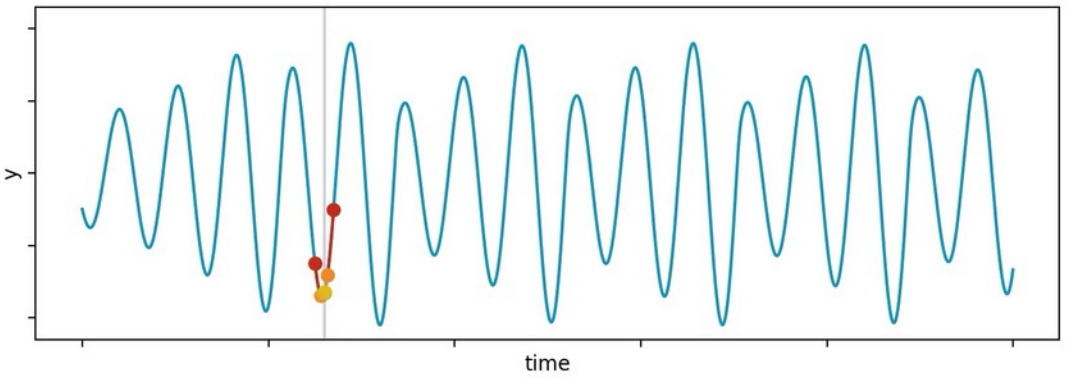
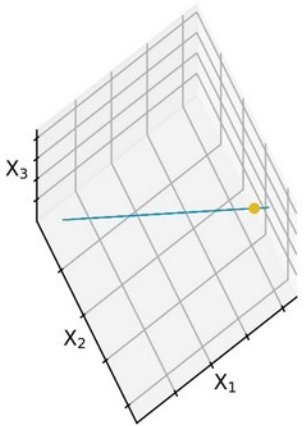
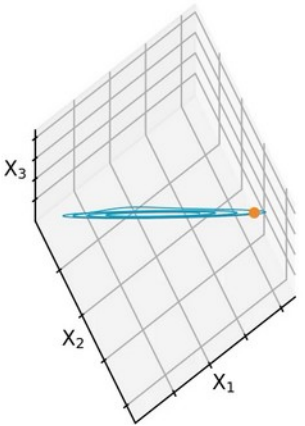
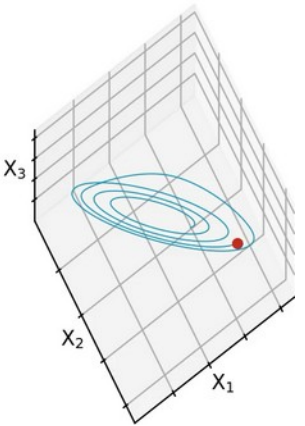


Time-Delayed Embedding



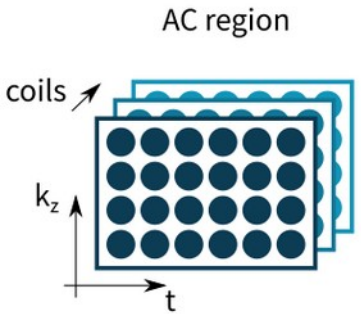




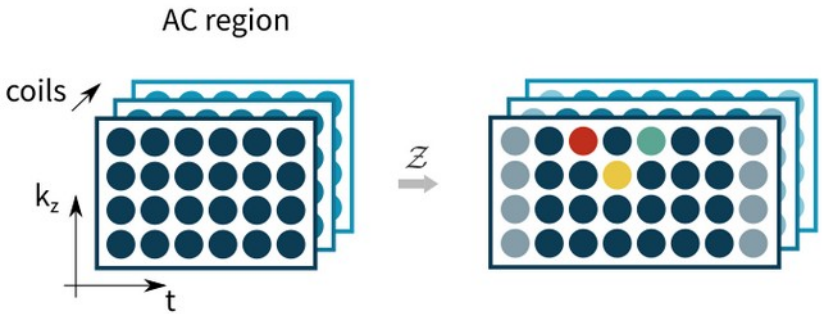


X^{s} X^{m} X^{l}

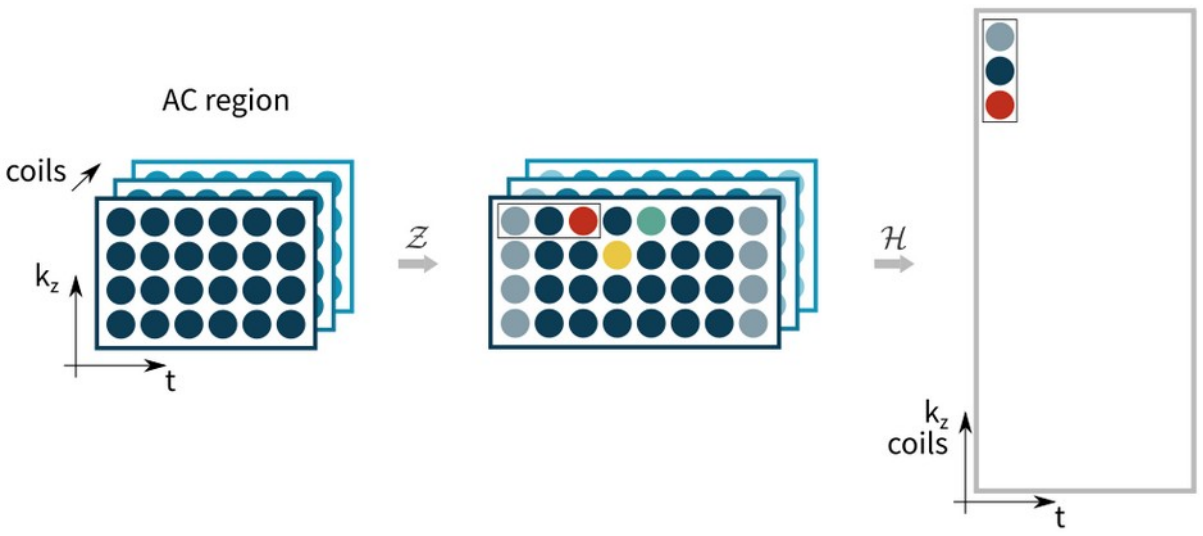
Basic Principle



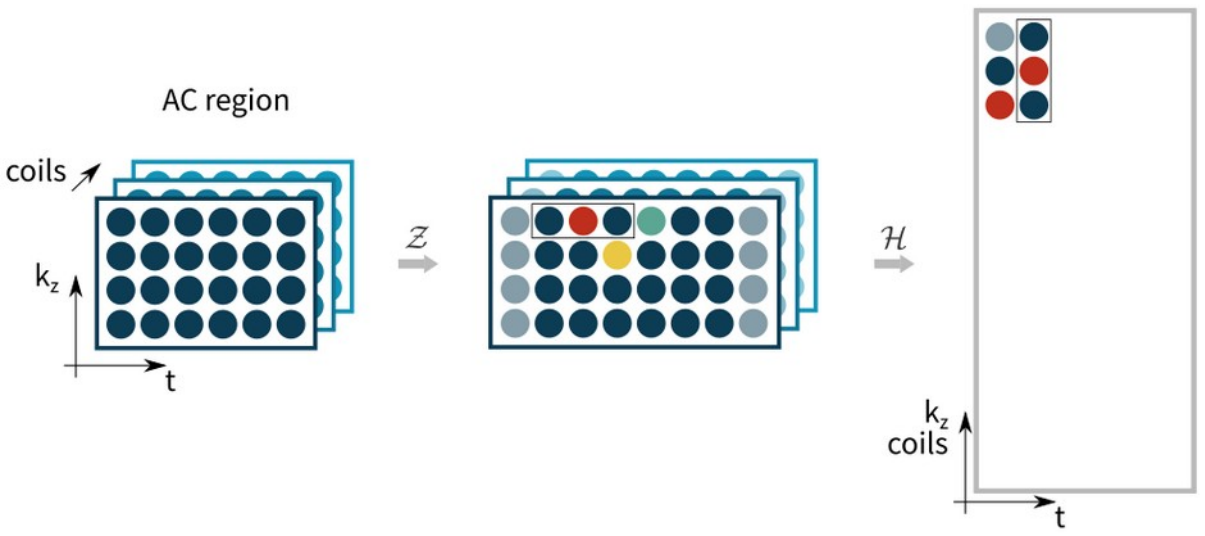
Basic Principle



Basic Principle



Basic Principle



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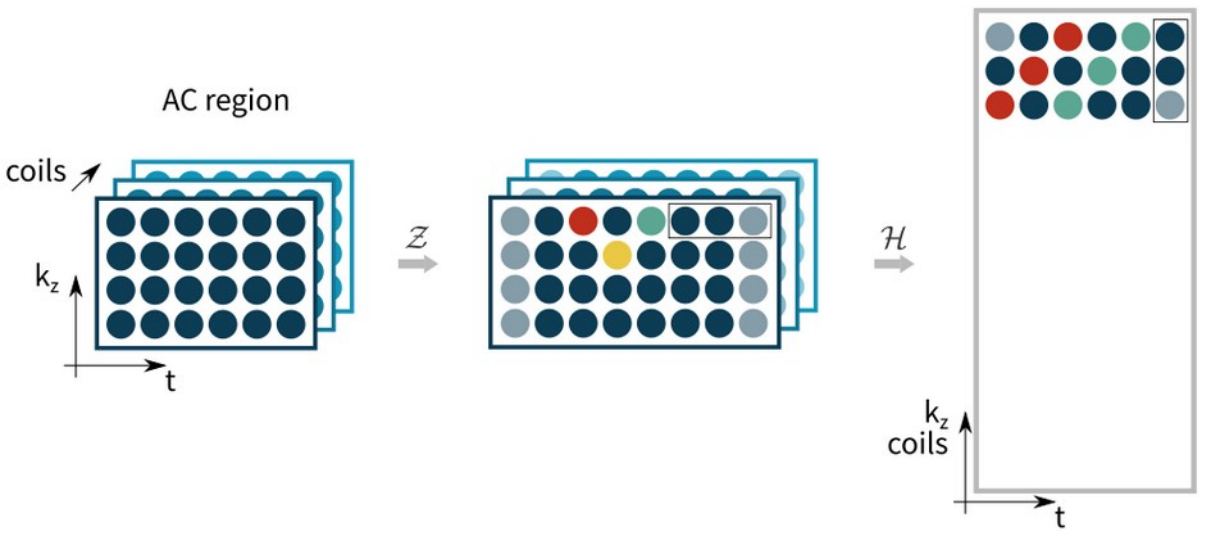

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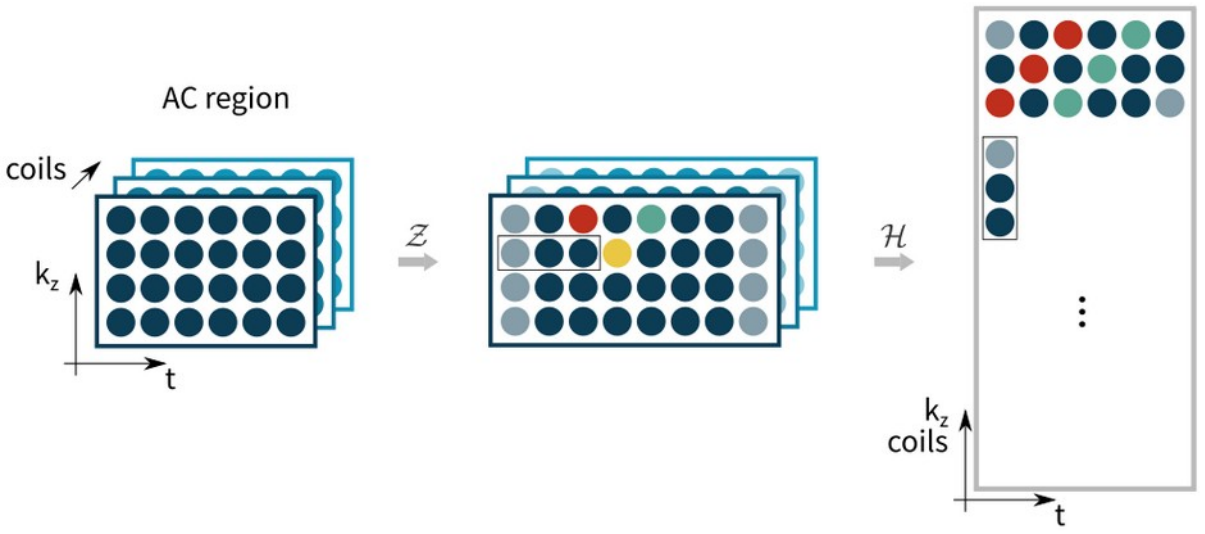

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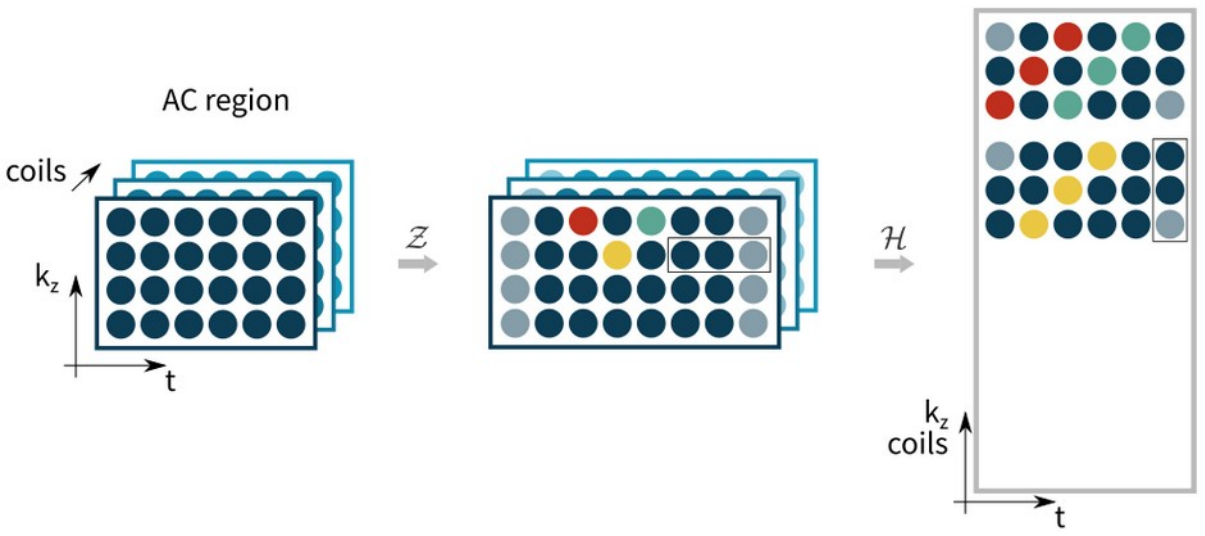

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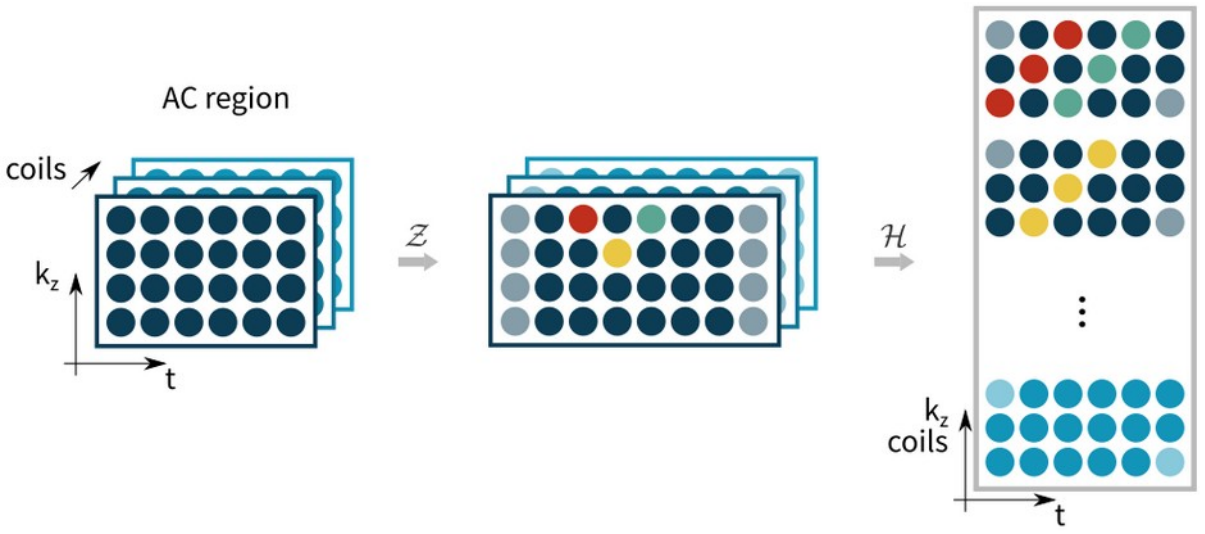
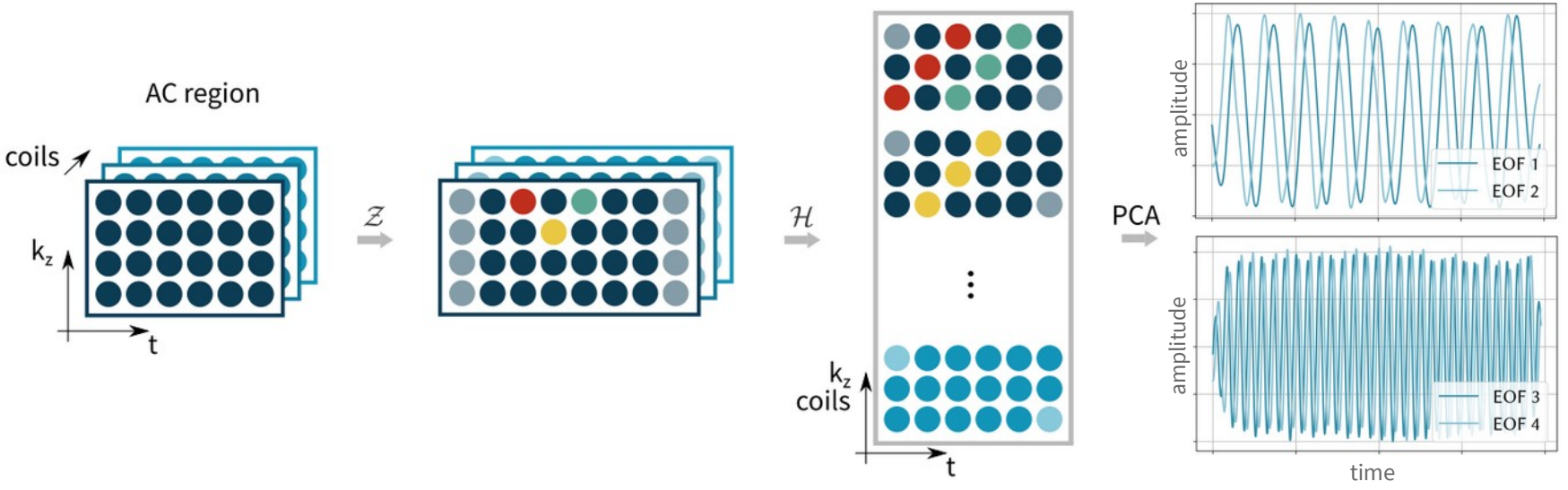
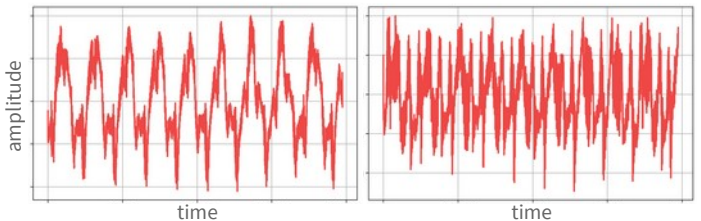


Basic Principle



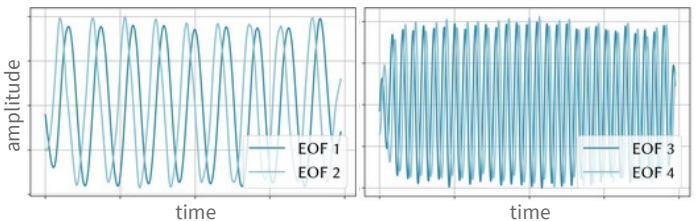
PCA vs. SSA-FARY

PCA



- incomplete separation
- noisy
- peak detection

SSA-FARY[1,2,3]

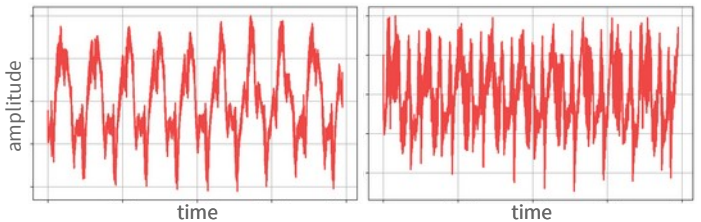


+ clear separation
+ intrinsic denoising
+ phase preserving

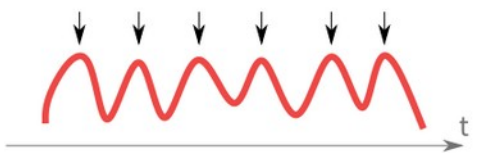
[1] Rosenzweig et al, IEEE (2020) [2] Broomhead and King, Physica D (1986) [3] Vautard and Ghil, Physica D (1989)

PCA vs. SSA-FARY

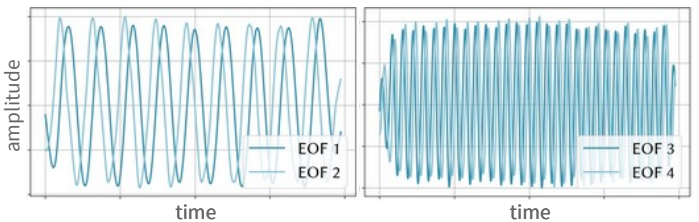
PCA



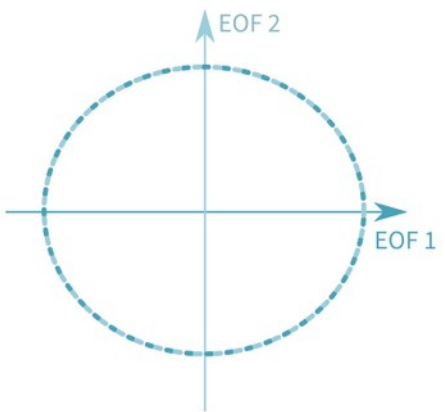
- incomplete separation
- noisy
- peak detection



SSA-FARY

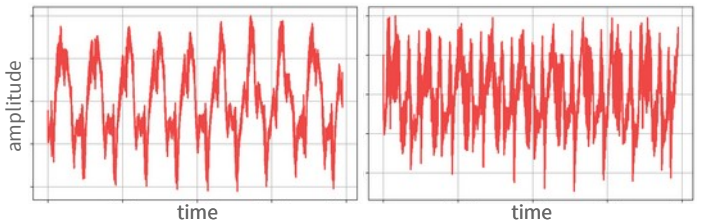


+ clear separation
+ intrinsic denoising
+ phase preserving

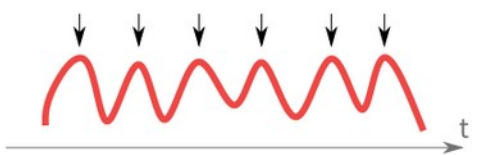


PCA vs. SSA-FARY

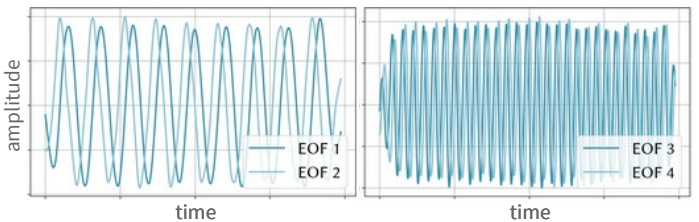
PCA



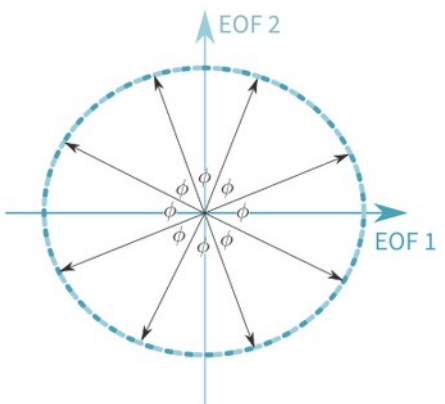
- incomplete separation
- noisy
- peak detection



SSA-FARY

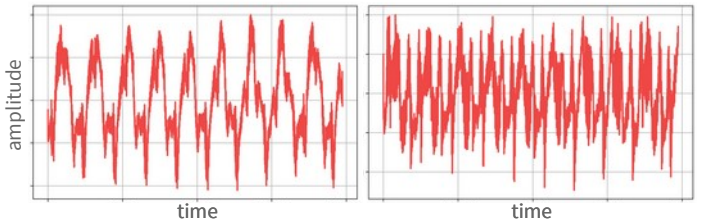


+ clear separation
+ intrinsic denoising
+ phase preserving

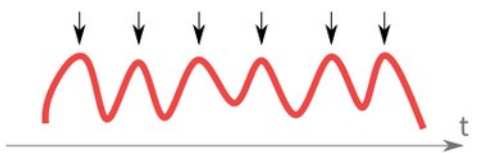


PCA vs. SSA-FARY

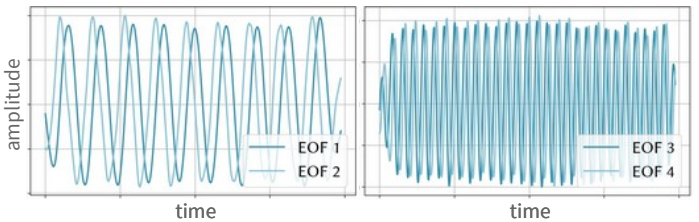
PCA



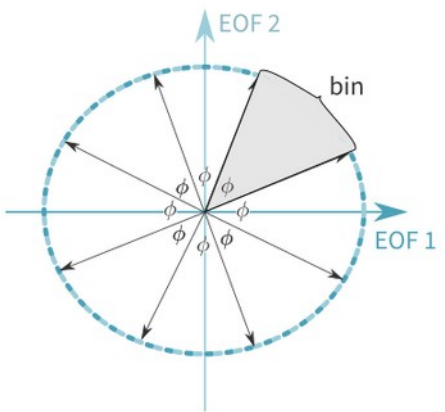
- incomplete separation
- noisy
- peak detection



SSA-FARY



+ clear separation
+ intrinsic denoising
+ phase preserving



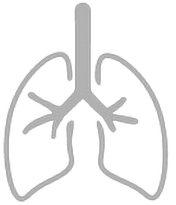
Comparison

ECG

standard deviation
from ECG trigger

$$\bar{\sigma} = 24(2)\ \mathrm{ms}$$

Belt & diaphragm



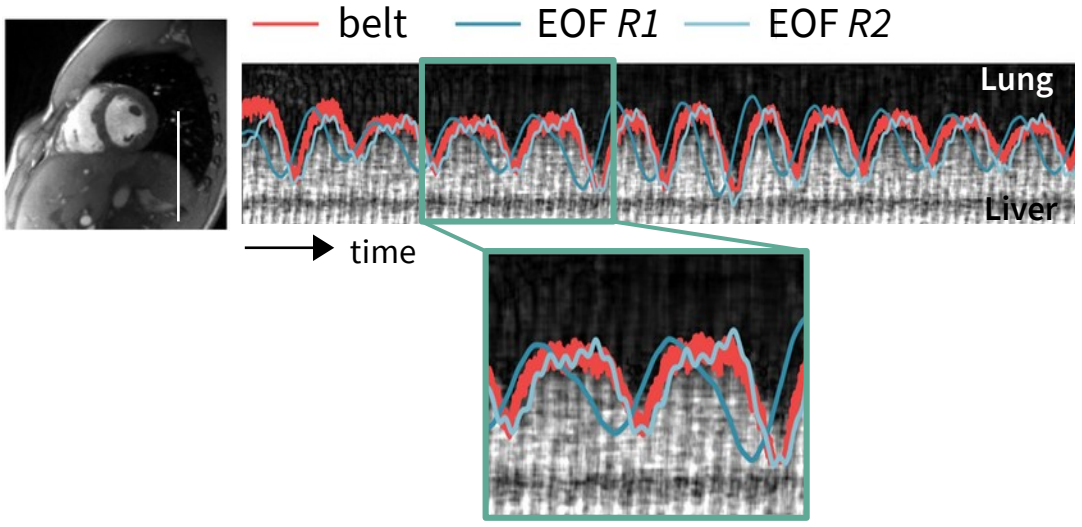


Image Reconstruction

$$\underset{\boldsymbol{x}}{\operatorname{argmin}} ||\boldsymbol{y} - P\mathcal{F}C\boldsymbol{x}||^2 + R(\boldsymbol{x})$$

Image Reconstruction

$$\underset{\boldsymbol{x}}{\operatorname{argmin}} ||\boldsymbol{y} - P\mathcal{F}C\boldsymbol{x}||^2 + R(\boldsymbol{x})$$

SSA-FARY
binning

Image Reconstruction

$$\underset{\boldsymbol{x}}{\operatorname{argmin}} ||\boldsymbol{y} - P\mathcal{F}C\boldsymbol{x}||^2 + R(\boldsymbol{x})$$

SSA-FARY
binning

RING[1]
gradient delay
estimation

[1] Rosenzweig et al., Magn. Reson. Med. (2018)

Image Reconstruction

$$\underset{\boldsymbol{x}}{\operatorname{argmin}} ||\boldsymbol{y} - P\mathcal{F}C\boldsymbol{x}||^2 + R(\boldsymbol{x})$$

SSA-FARY
binning

RING[1]
gradient delay
estimation

SMS-NLINV[2]
coil sensitivity
estimation

[1] Rosenzweig et al., Magn. Reson. Med. (2018) [2] Rosenzweig et al., Magn. Reson. Med. (2017)

Image Reconstruction

$$\underset{\boldsymbol{x}}{\operatorname{argmin}} ||\boldsymbol{y} - P\mathcal{F}C\boldsymbol{x}||^2 + R(\boldsymbol{x})$$

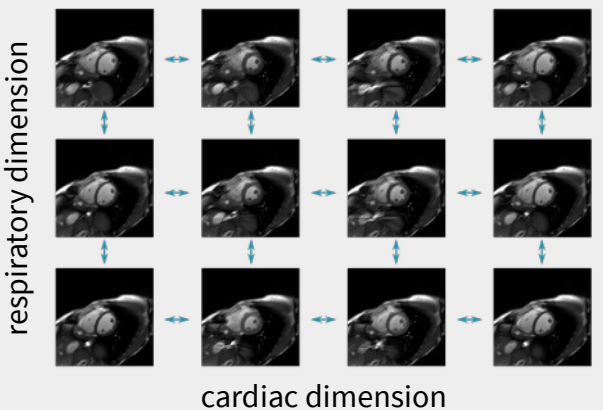
SSA-FARY
binning

RING[1]
gradient delay
estimation

SMS-NLINV[2]
coil sensitivity
estimation

MULTI-DIMENSIONAL REGULARIZATION[3]

Total-Variation constraint



[1] Rosenzweig et al., Magn. Reson. Med. (2018) [2] Rosenzweig et al., Magn. Reson. Med. (2017) [3] Feng et al., Magn. Reson. Med. (2015)

Image Reconstruction

$$\underset{\boldsymbol{x}}{\operatorname{argmin}} ||\boldsymbol{y} - P\mathcal{F}C\boldsymbol{x}||^2 + R(\boldsymbol{x})$$

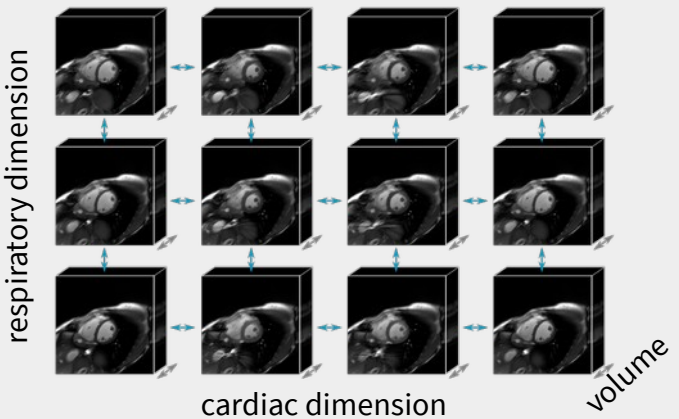
SSA-FARY
binning

RING[1]
gradient delay
estimation

SMS-NLINV[2]
coil sensitivity
estimation

MULTI-DIMENSIONAL REGULARIZATION[1]

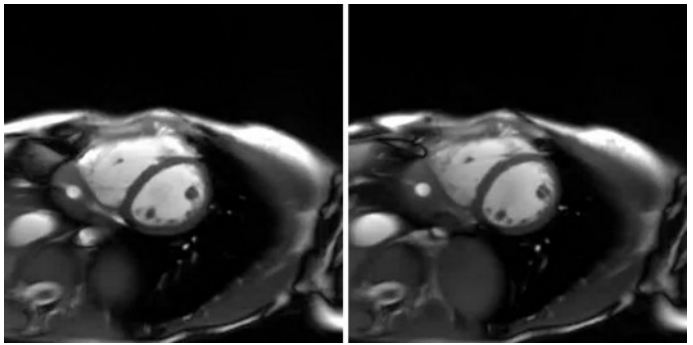
Total-Variation constraint



[1] Rosenzweig et al., Magn. Reson. Med. (2018) [2] Rosenzweig et al., Magn. Reson. Med. (2017) [3] Feng et al., Magn. Reson. Med. (2015)

Single Slice

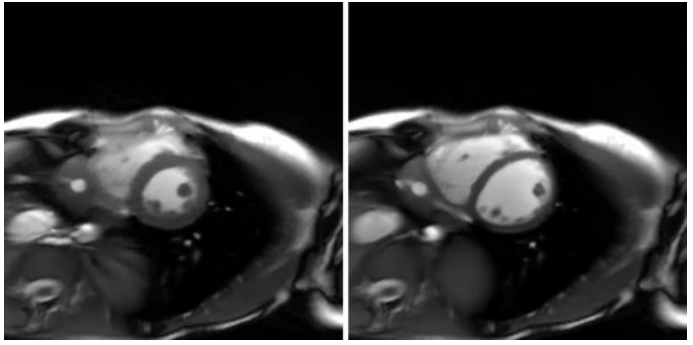
end-inspiration end-expiration



25 cardiac phases

Single Slice

end-systole end-diastole



9 respiratory phases

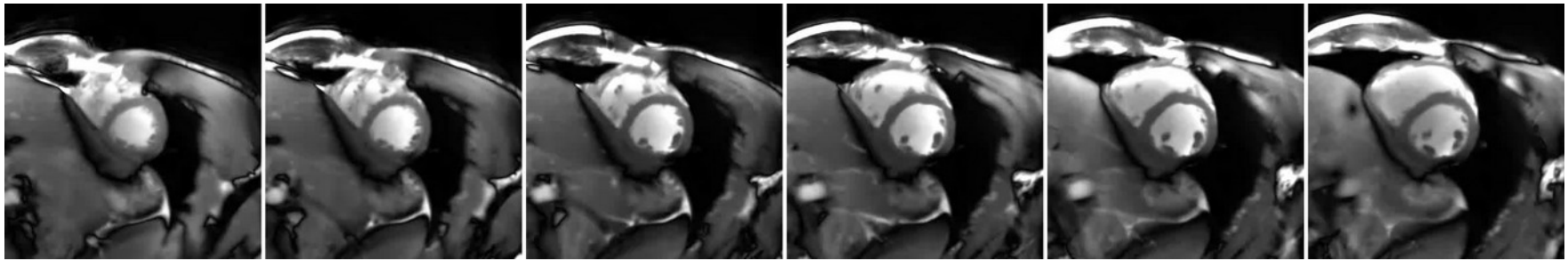
[interpolated]

SSA-FARY

Stack-of-Stars

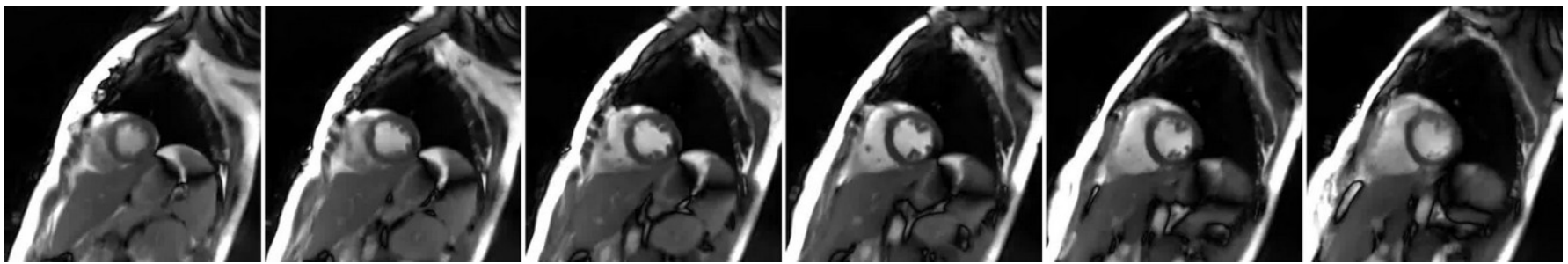
6 out of 14 slices

end-expiration



6 out of 14 slices

end-expiration



Wrap Up

SUMMARY

- time-delayed embedding + PCA
- data-adaptive filtering

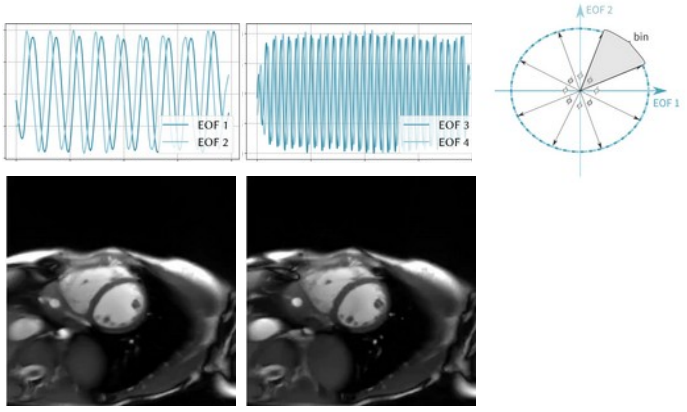
→ denoising, separation & binning
→ device-free gating

LIMITATIONS

- arrhythmia
- parameter dependence

OUTLOOK

- high-resolution imaging
- quantitative MRI



https://github.com/mrirecon/ssa-fary