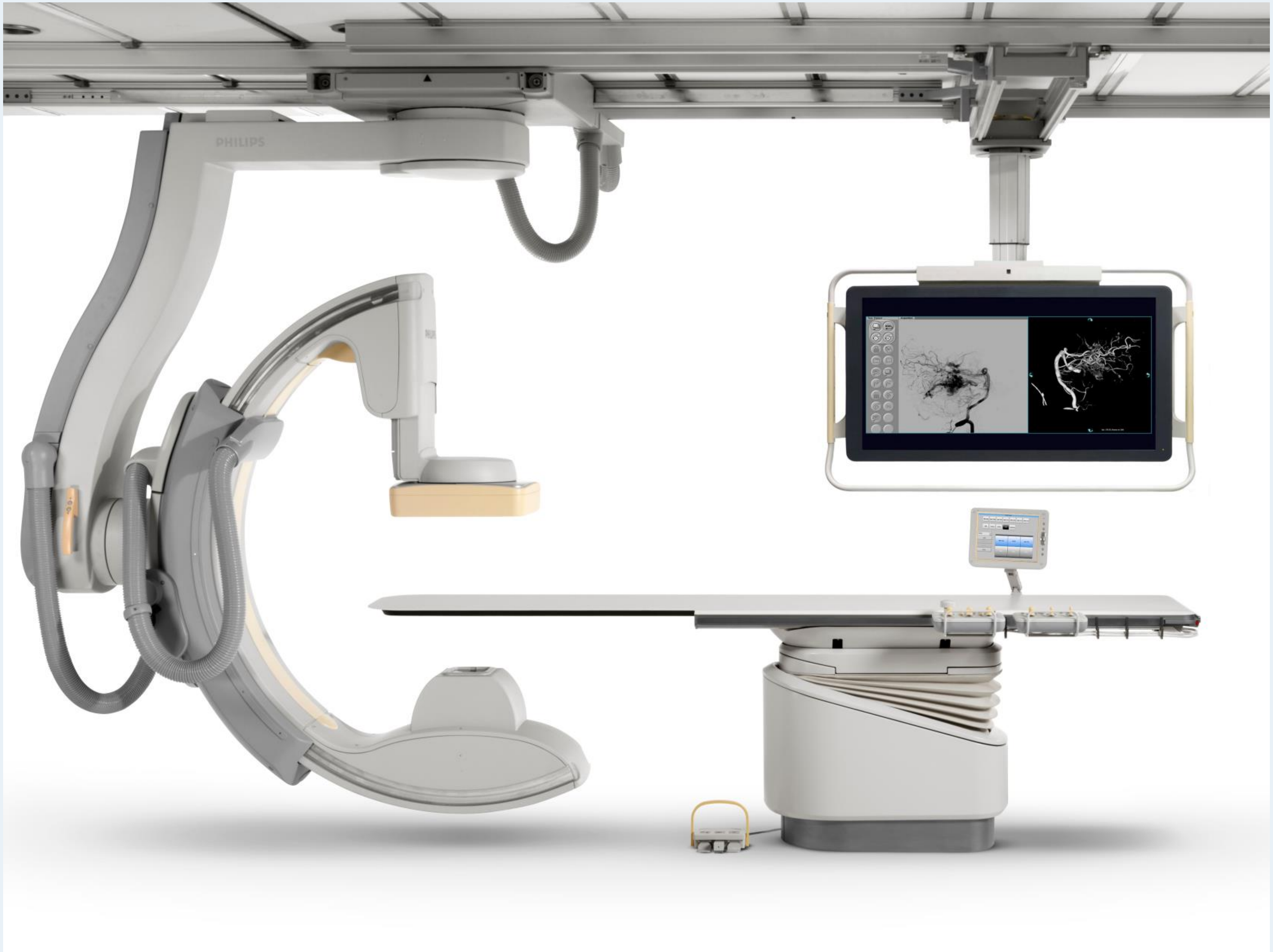
Cardiac C-arm computed tomography

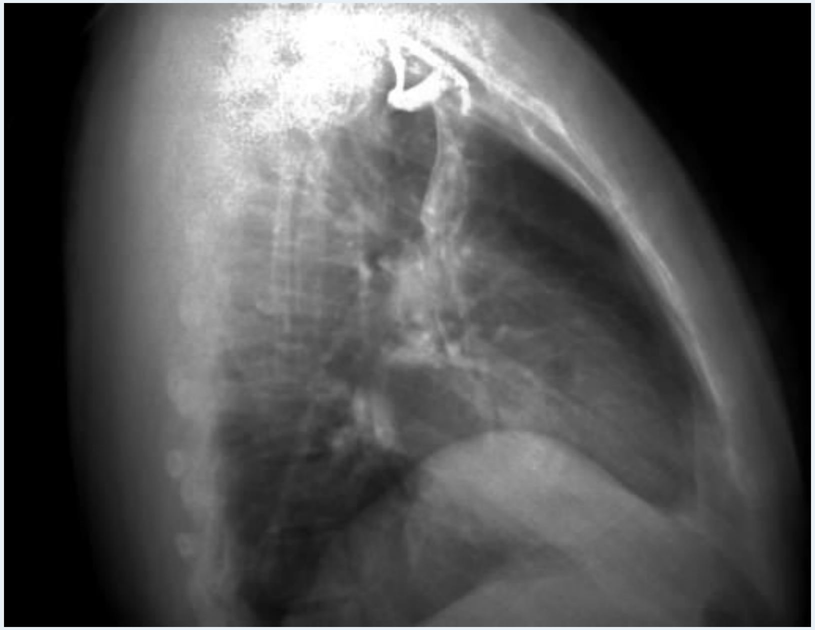
PhD defense
Cyril Mory

CREATIS, Lyon, France

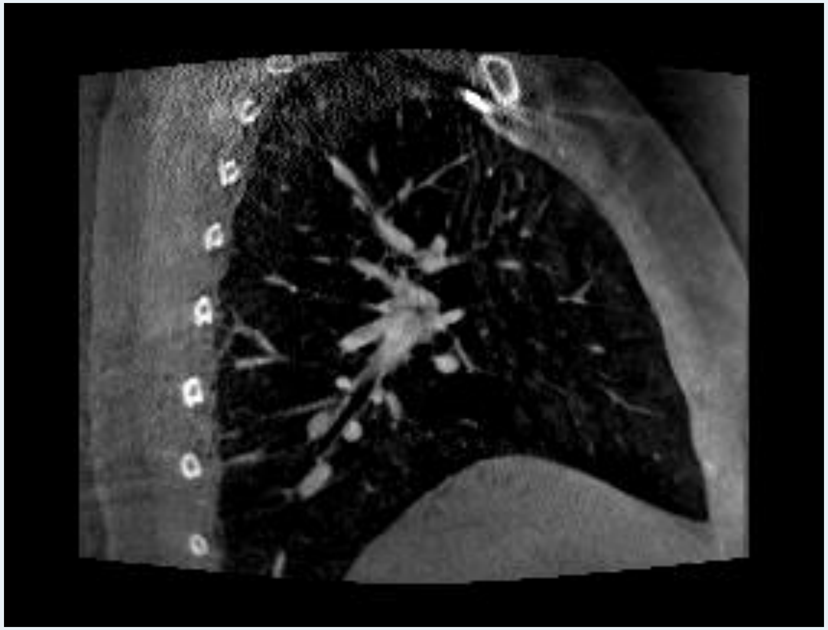
Introduction What is a C-arm ?



Projections



Volume



Contents Introduction

- **Introduction**
  - Two different problems
  - State of the art in cardiac C-arm CT
  - The acquisition protocol
  - Moving Shepp & Logan phantom
  - ECG-gating
  - Angular distribution of projections
  - Artifacts / Blur tradeoff
- **3D compressed sensing**
- **A bit of math**
- **4D compressed sensing**
- **Perspectives**
- **Conclusion**

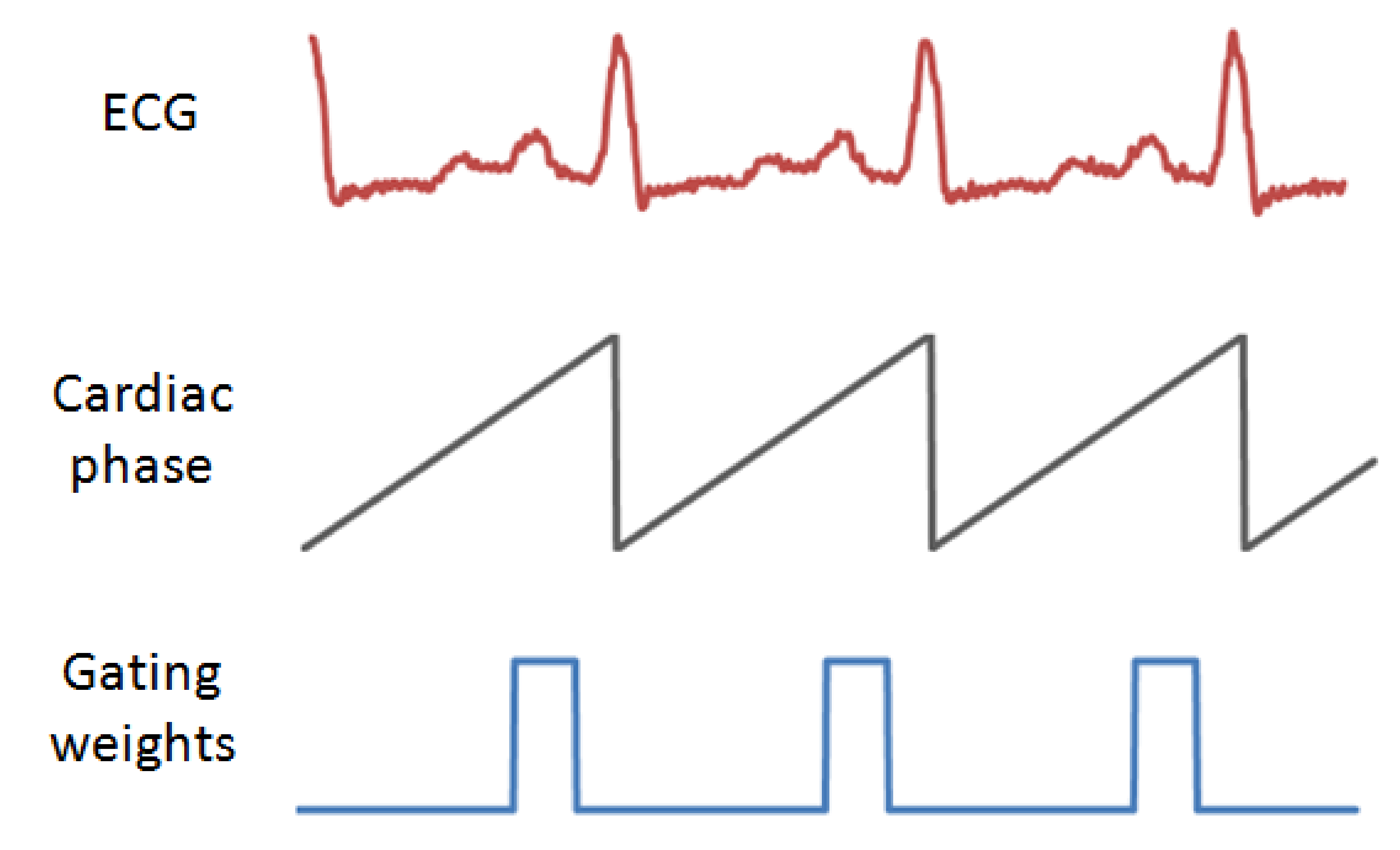
Introduction Two different problems

- **Soft tissue analysis**
  - 3D diastole reconstruction
  - Beating motion = trouble

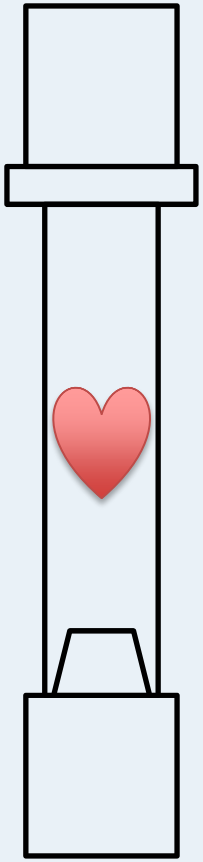
- **Functional analysis**
  - 3D + time reconstruction
  - Whole cardiac cycle
  - Beating motion = information

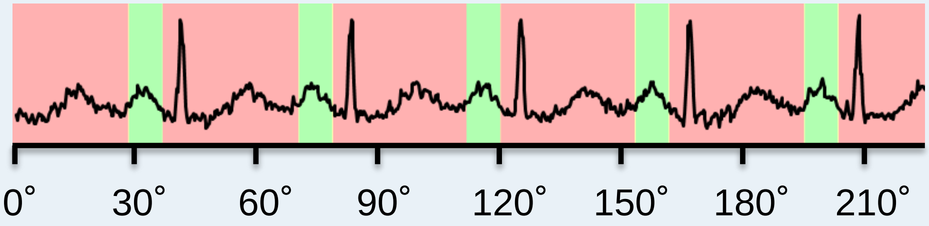
- **In both cases**
  - Respiratory motion = trouble

  => Apnea


ECG
Cardiac phase
Gating weights

Introduction Angular distribution of projections





- **packets of consecutive projections**
- **Large gaps between packets**
- **#Packets = #Cardiac cycles in acq.**

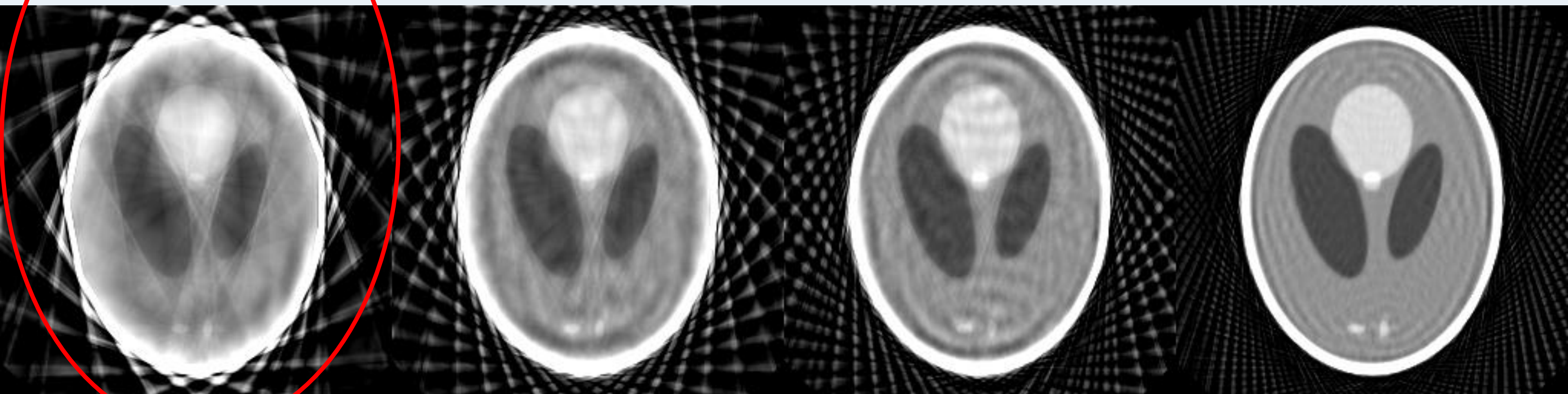
Moving Shepp & Logan phantom

- Sum of ellipsoids
- Exact line-integral calculation
- Modified to “beat”

Introduction Angular distribution of projections

SART reconstructions from 60 projections, starting from zero

10 packets of 6 projections | 20 packets of 3 projections | 30 packets of 2 projections | 60 “packets” of 1 projection



More packets = Less artifacts

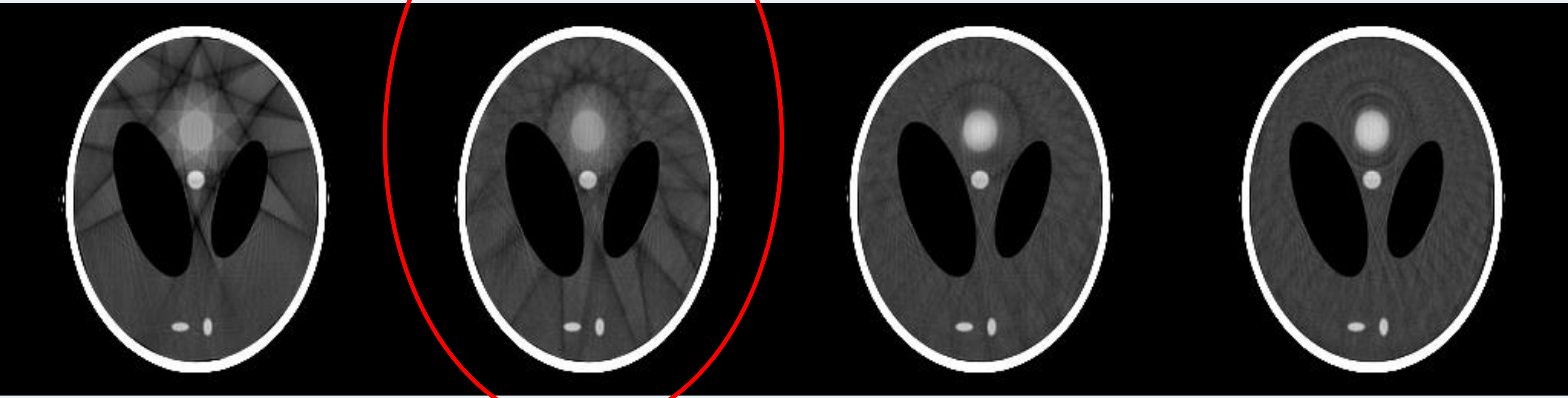
#Packets = #Cardiac cycles in acquisition

Fast beating heart

Long acquisition

SART reconstructions from 60 projections, starting from ungated

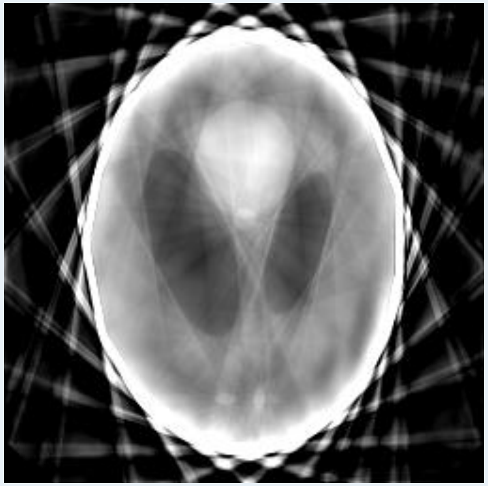
5 packets of 12 projections	10 packets of 6 projections	20 packets of 3 projections	30 packets of 2 projections



More packets = Less motion blur

Introduction Artifacts / Blur tradeoff

ECG gated



Ungated

Undersampling artifacts

- Amount of data used +

Motion blurring

Tradeoff ?

- **Multiple sweep acquisitions**
  - High image quality on a **single** phase
  - Motion-compensated reconstruction techniques
  - High dose
  - Long apnea (at least 12s, in practice around 20s)
  - High amount of contrast
  - Mostly used on animals as of today

Lauritsch, Jan Boese, Lars Wigström, Herbert Kemeth, and Rebecca Fahrig. “Towards Cardiac C-Arm Computed Tomography.” *IEEE Transactions on Medical Imaging* 25, no. 7 (July 2006): 922–934.

Prümmer, M., Joachim Hornegger, Guenter Lauritsch, Lars Wigström, Erin Girard-Hughes, and Rebecca Fahrig. “Cardiac C-Arm CT: A Unified Framework for Motion Estimation and Dynamic CT.” *IEEE Transactions on Medical Imaging* 28, no. 11 (November 2009): 1836–1849. doi:10.1109/TMI.2009.2025499.

Girard, Erin E, Amin Al-Ahmad, Jarrett Rosenberg, Richard Luong, Teri Moore, Günter Lauritsch, Jan Boese, and Rebecca Fahrig. “Contrast-Enhanced C-Arm CT Evaluation of Radiofrequency Ablation Lesions in the Left Ventricle.” *JACC. Cardiovascular Imaging* 4, no. 3 (March 2011): 259–268. doi:10.1016/j.jcmg.2010.11.019.

- **Single sweep acquisitions**
  - Compressed sensing techniques (ASD-POCS, PICCS)

  => Regularized images
  - Long apnea (14s in a 2012 paper) and high heart rate (around 90 bpm)
  - High amount of contrast (37 cc for a 10kg swine)

Lauzier, Pascal Thériault, Jie Tang, and Guang-Hong Chen. "Time-Resolved Cardiac Interventional Cone-Beam CT Reconstruction from Fully Truncated Projections Using the Prior Image Constrained Compressed Sensing (PICCS) Algorithm." Physics in Medicine and Biology 57, no. 9 (May 7, 2012): 2461–2476. doi:10.1088/0031-9155/57/9/2461.

Chen, G.-H., P. Theriault-Lauzier, J. Tang, B. Nett, S. Leng, J. Zambelli, Z. Qi, et al. "Time-Resolved Interventional Cardiac C-Arm Cone-Beam CT: An Application of the PICCS Algorithm." Medical Imaging, IEEE Transactions on 31, no. 4 (April 2012): 907 –923. doi:10.1109/TMI.2011.2172951.

Introduction The acquisition protocol

- **Single breath hold**
- **10.3 seconds**
- **308 projections**
  - 1024 * 792 pixels
  - 38 cm * 29 cm
  - 0.74 mm * 0.74 mm pixels
- **210° (short scan)**
- **About 60 cc of iodine**
- **ECG-recording**

=> Nothing in the literature with similar constraints

Contents 3D compressed sensing

- **Introduction**
- **3D compressed sensing**
  - Augmented Lagrangian + ADMM + total variation
  - Augmented Lagrangian + ADMM + wavelets
  - PICCS
  - Animated sequences
- **A bit of math**
- **4D compressed sensing**
- **Perspectives**
- **Conclusion**

3D compressed sensing AL + ADMM + TV

$$\hat{f} = \underset{f}{\arg\min} \|G(Rf - p)\|_2^2 + \alpha TV(f)$$

R is the forward projection operator (Radon or X-ray transform)

f is the volume we seek

G is the gating operator

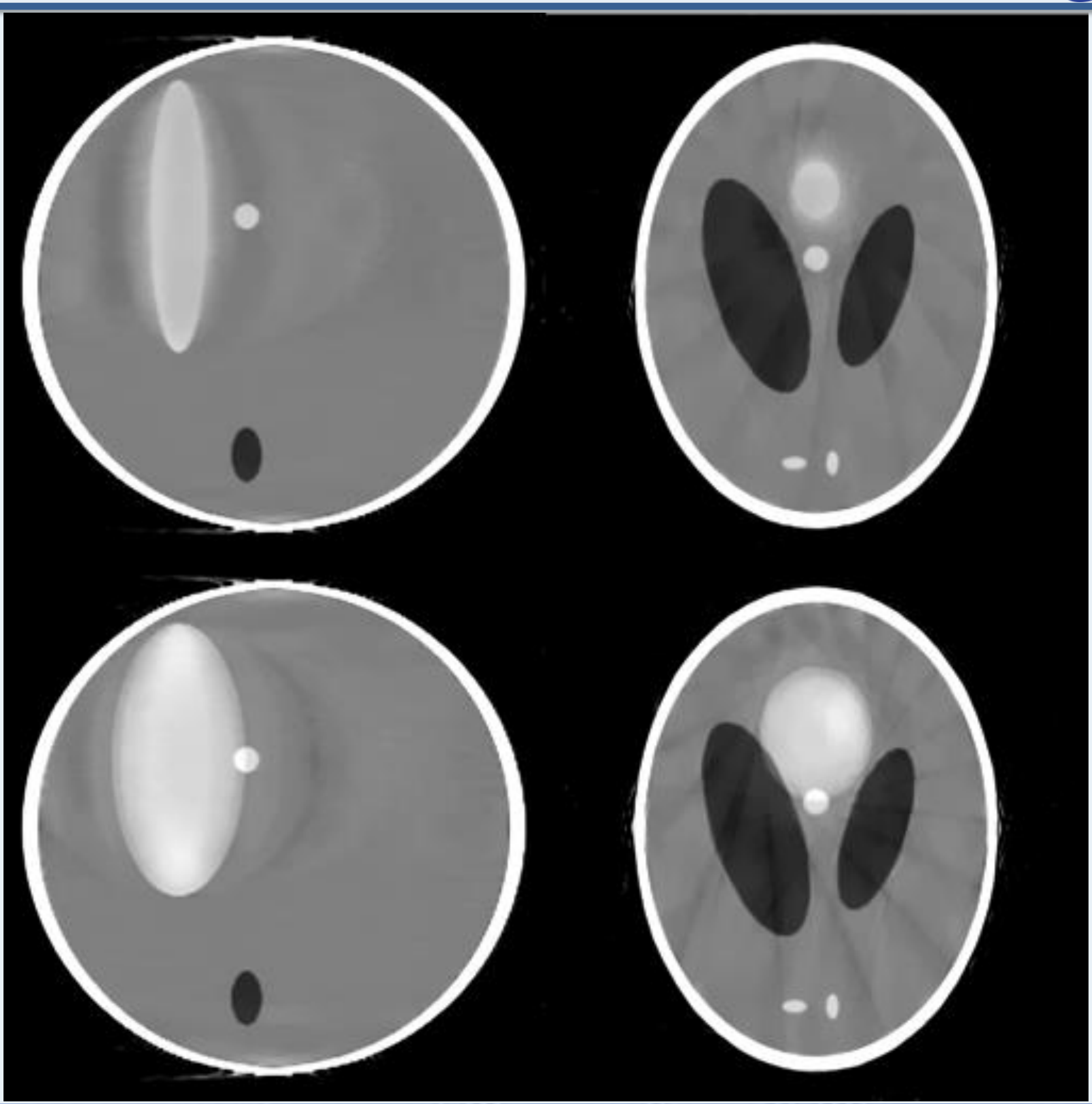
$$TV(f) = \sum_{v=1}^{V} \sqrt{[\nabla_\mathrm{x} f(v)]^2 + \left[\nabla_\mathrm{y} f(v)\right]^2 + [\nabla_\mathrm{z} f(v)]^2}$$

- **TV favors piecewise constant images**
- **Real images are not piecewise constant**
- **Regularization must remain limited**

3D compressed sensing AL + ADMM + TV

S
Y
S
T
O
L
E

D
I
A
S
T
O
L
E

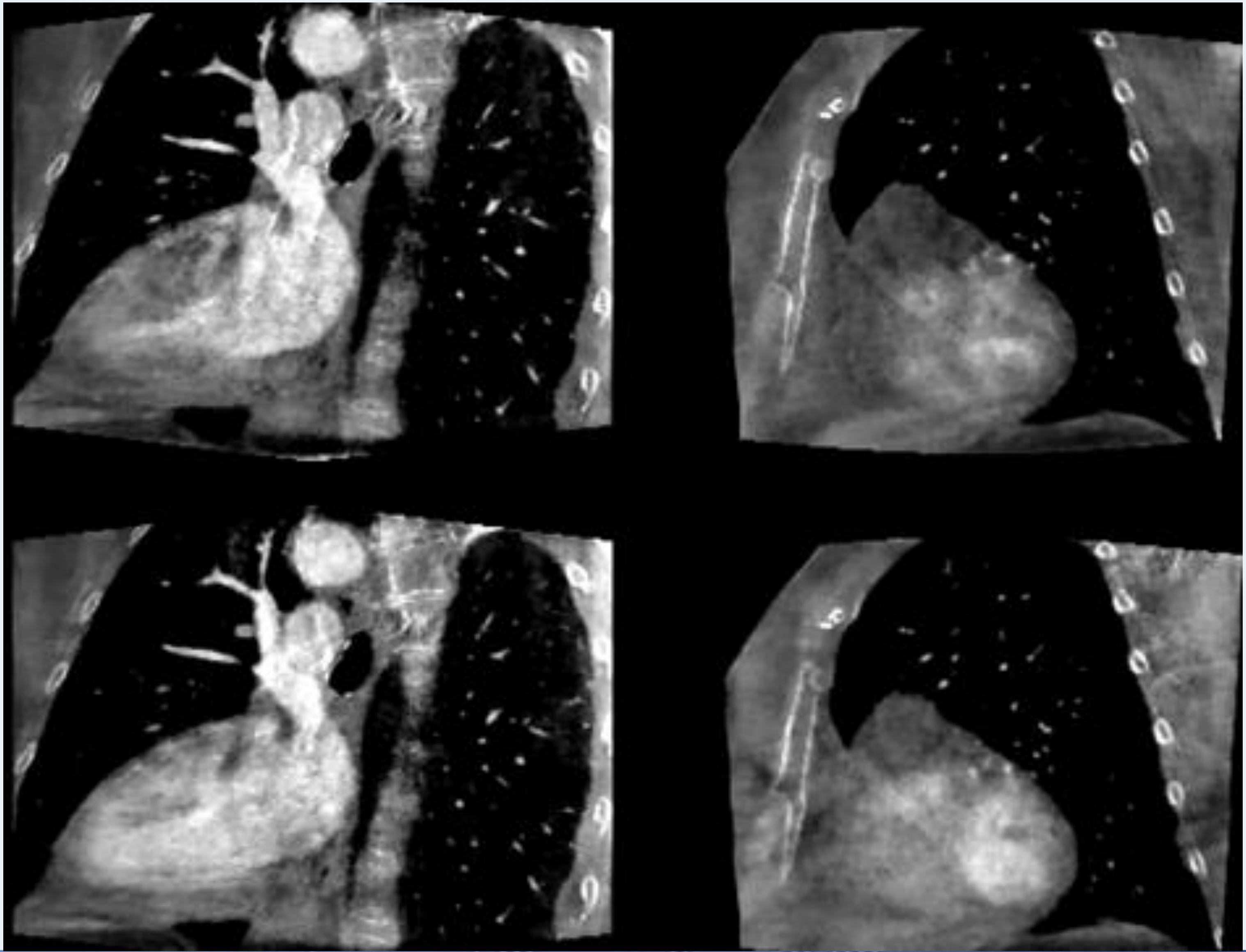


3D compressed sensing AL + ADMM + TV

Long axis | Short axis

S Y S T O L E

D I A S T O L E

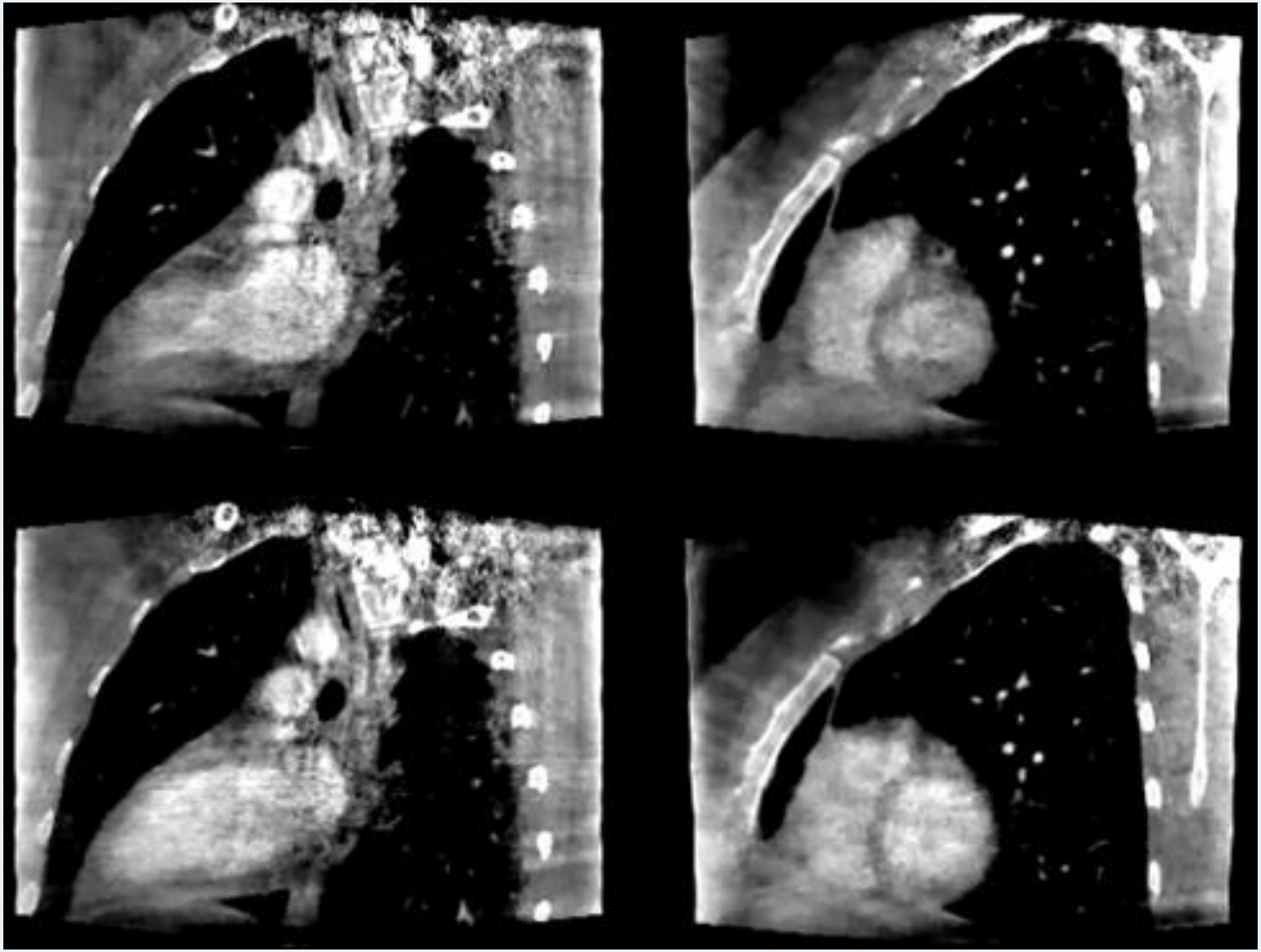


3D compressed sensing AL + ADMM + TV

Long axis | Short axis

S Y S T O L E

D I A S T O L E



3D compressed sensing AL + ADMM + Wavelets

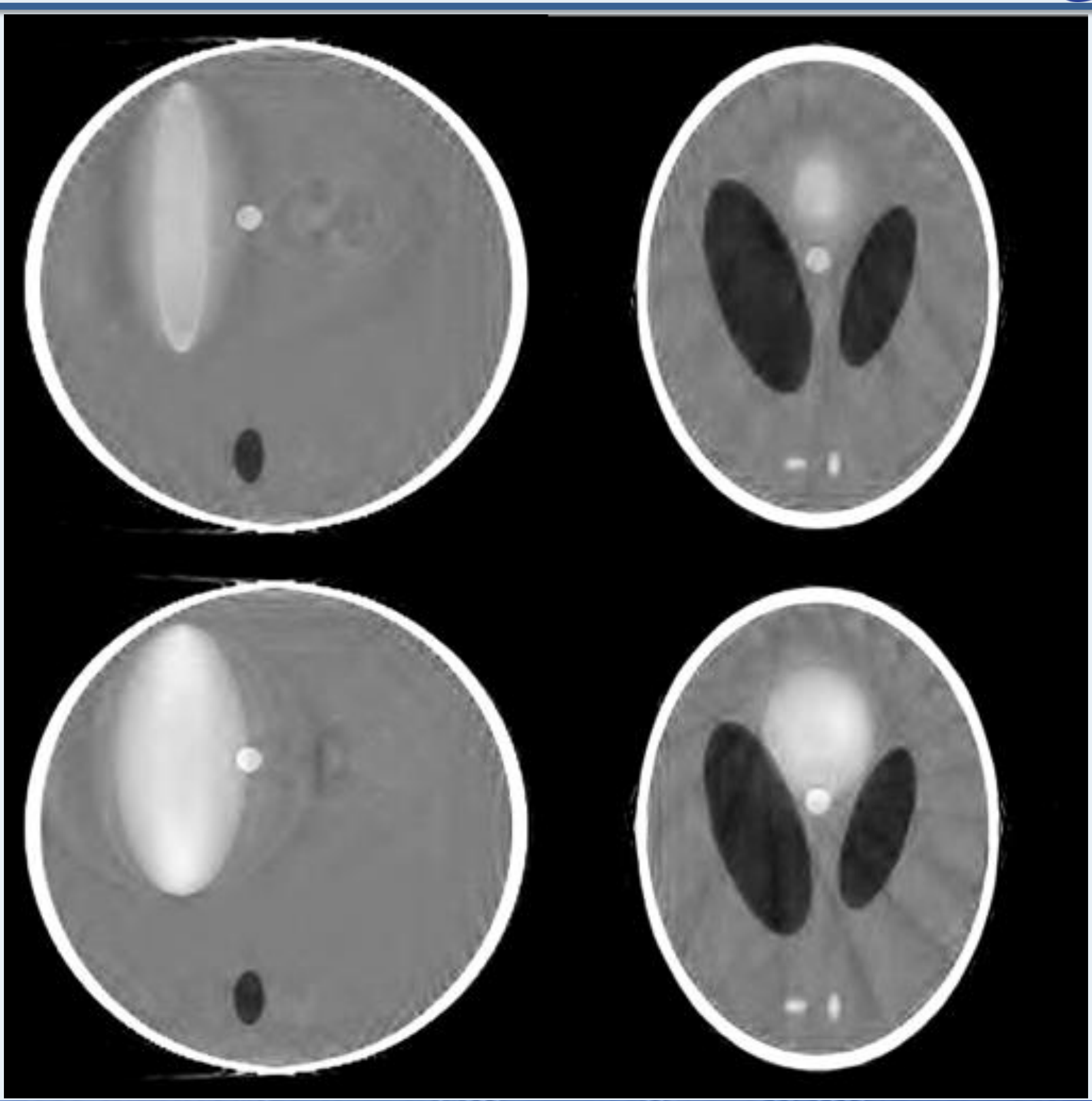
$$\hat{f} = \underset{f}{\arg\min} \|G(Rf - p)\|_2^2 + \alpha \|Wf\|_1$$

- **Daubechies wavelets**
- **Ineffective on piecewise constant phantoms**
- **Well suited to real images**
- **Regularization can be strong**

3D compressed sensing AL + ADMM + Wavelets

SYSTOLE

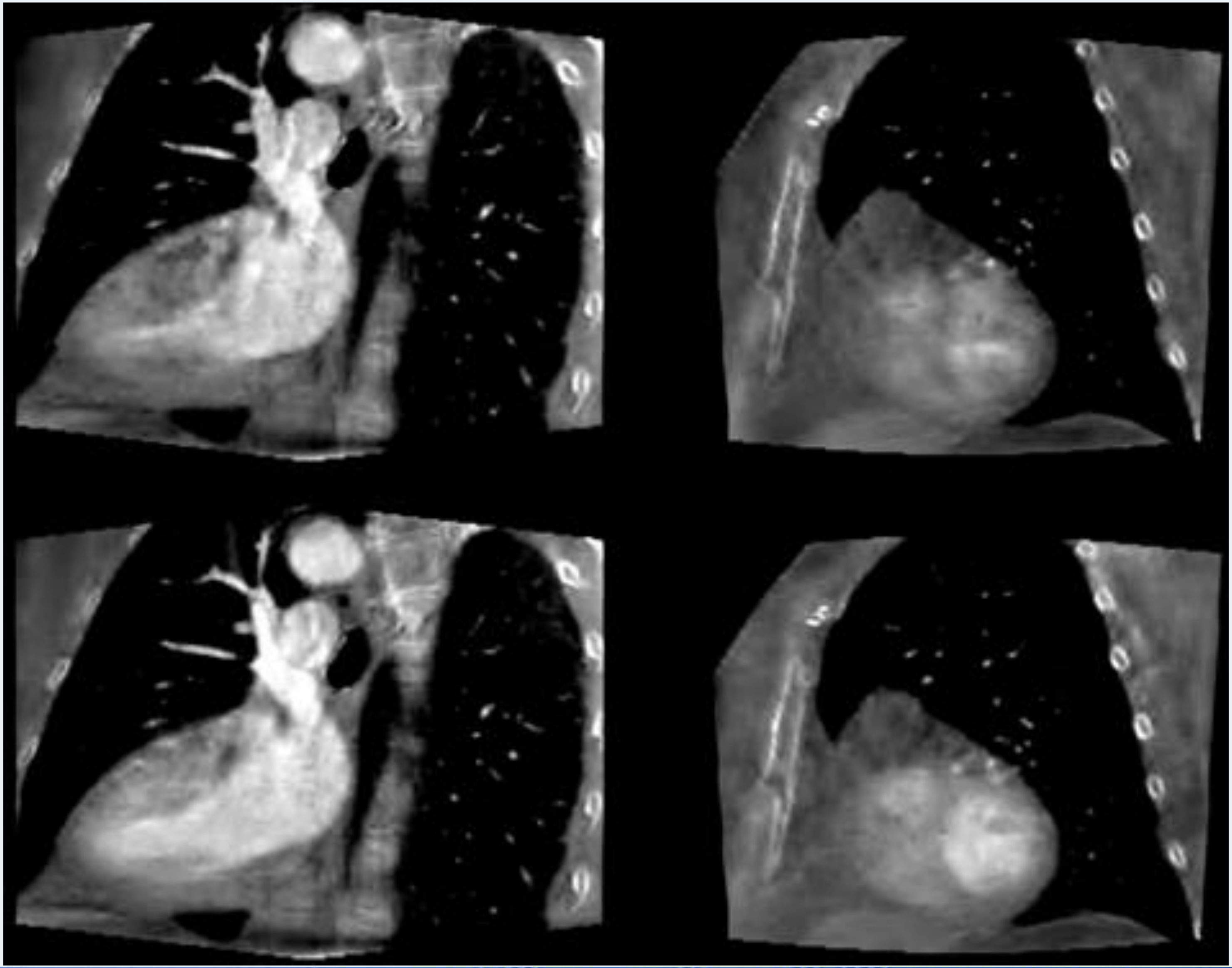
DIASTOLE



Long axis | Short axis

S Y S T O L E

D I A S T O L E

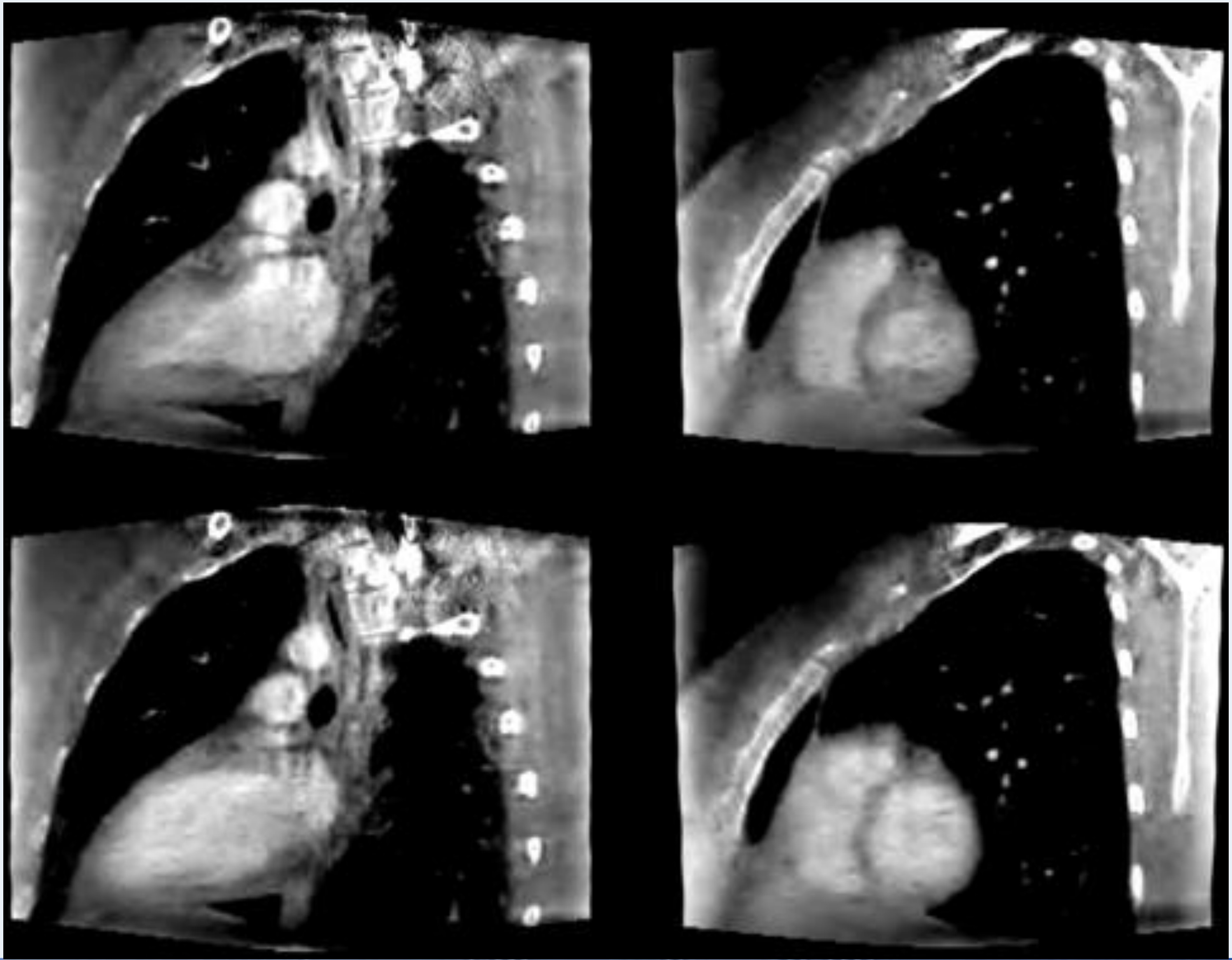


3D compressed sensing AL + ADMM + Wavelets

Long axis | Short axis

S Y S T O L E

D I A S T O L E



3D compressed sensing PICCS

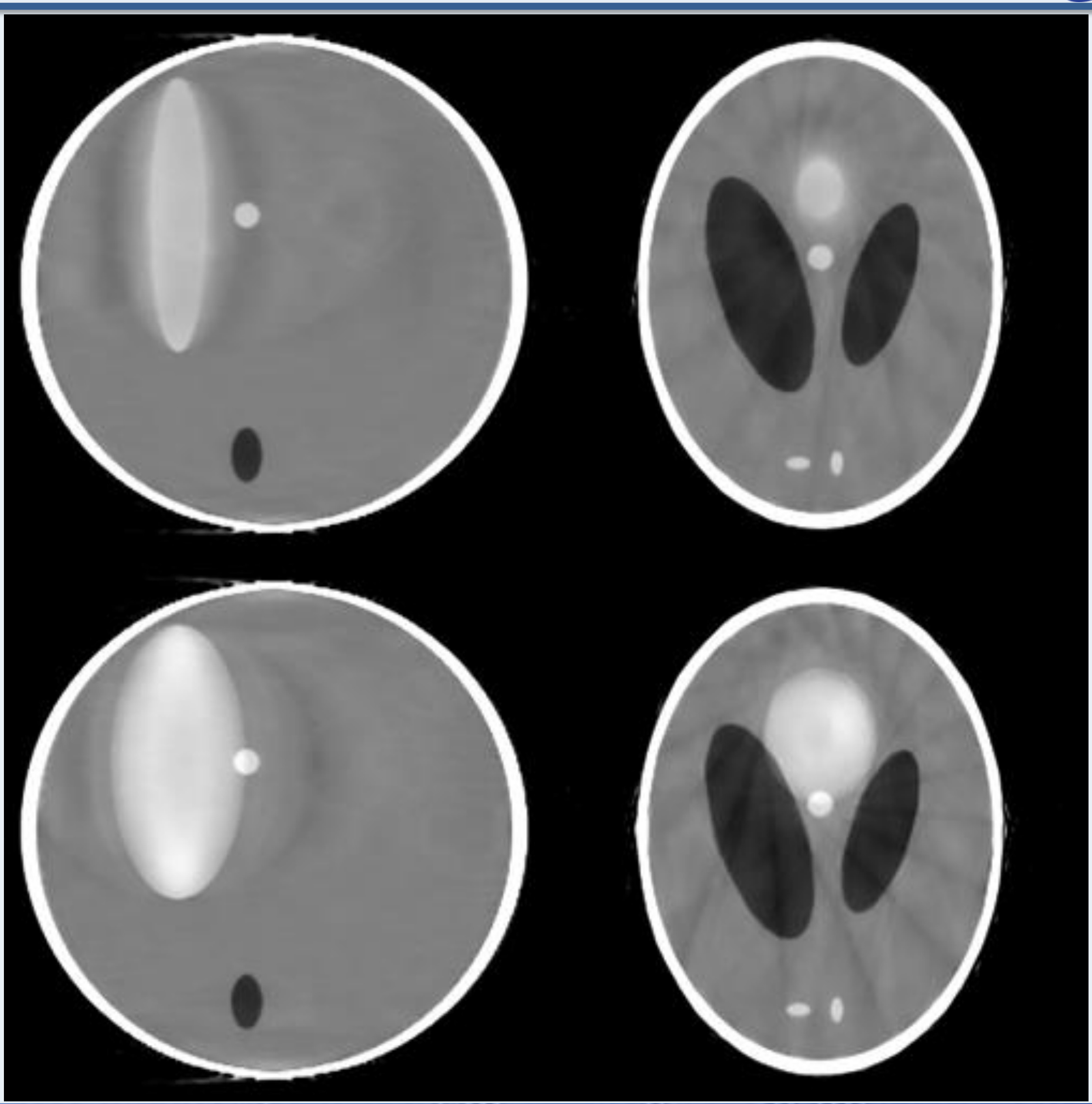
$$\hat{f} = \underset{f}{\arg\min}\, \mu \|G(Rf - p)\|_2^2 + (1-\alpha)TV(f) + \alpha TV(f - f^*)$$

- Prior Image Constrained Compressed Sensing
- State-of-the-art method
- SART to minimize data-attachment
- Steepest descent for TV minimization
- Prior = ungated FDK
- No texture-erasing effect

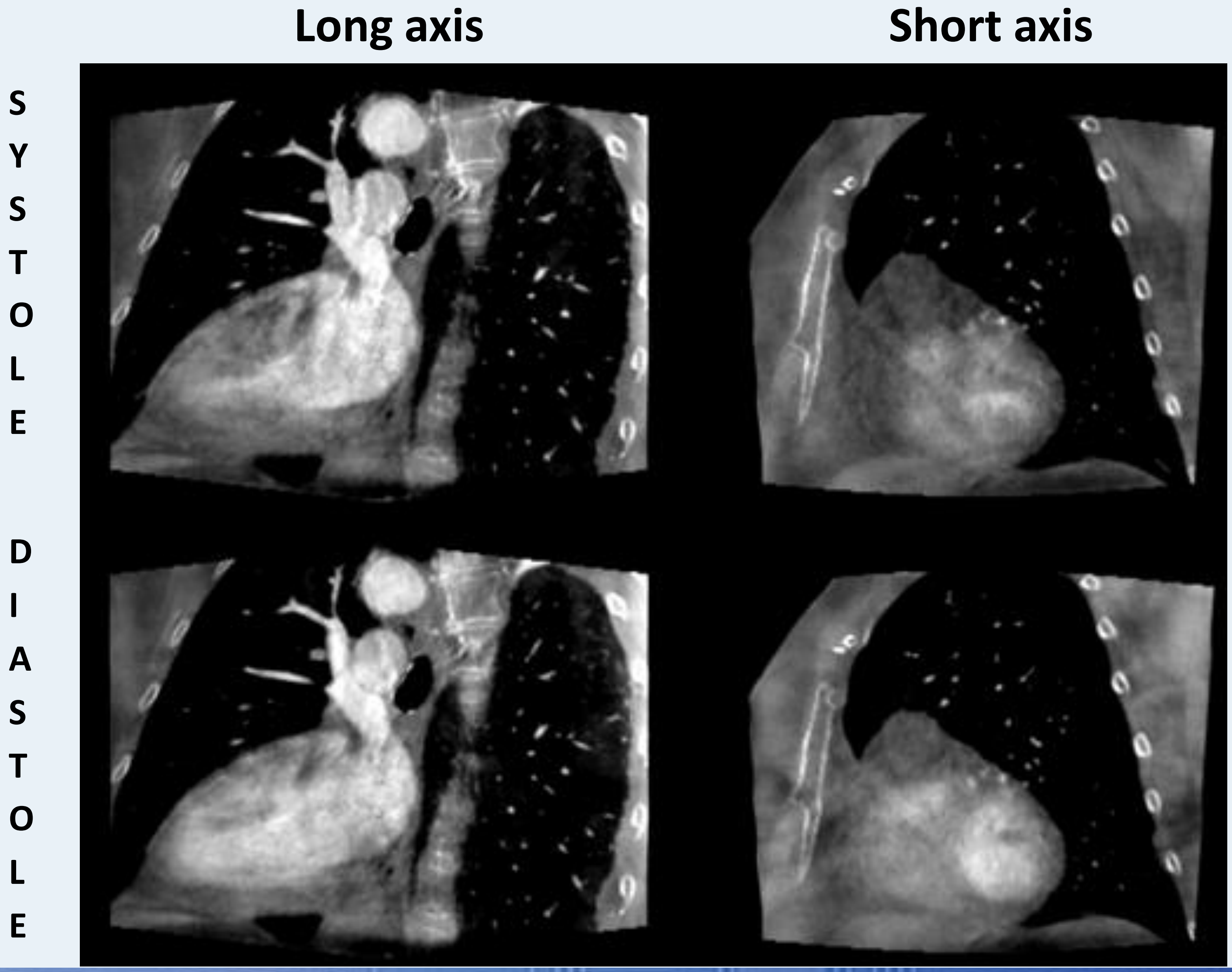
3D compressed sensing PICCS

S
Y
S
T
O
L
E

D
I
A
S
T
O
L
E



3D compressed sensing PICCS



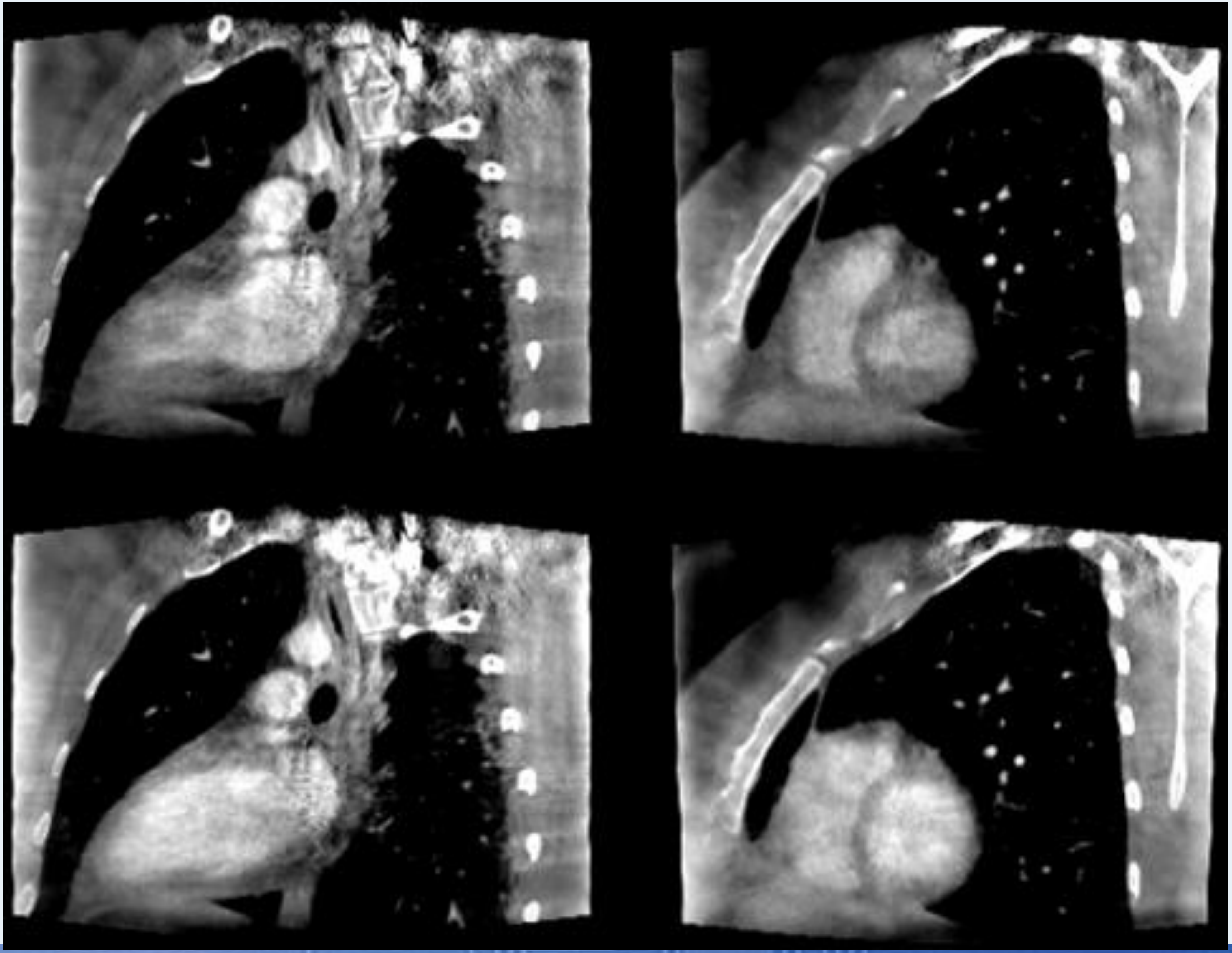
3D compressed sensing PICCS

Creatis

Long axis | Short axis

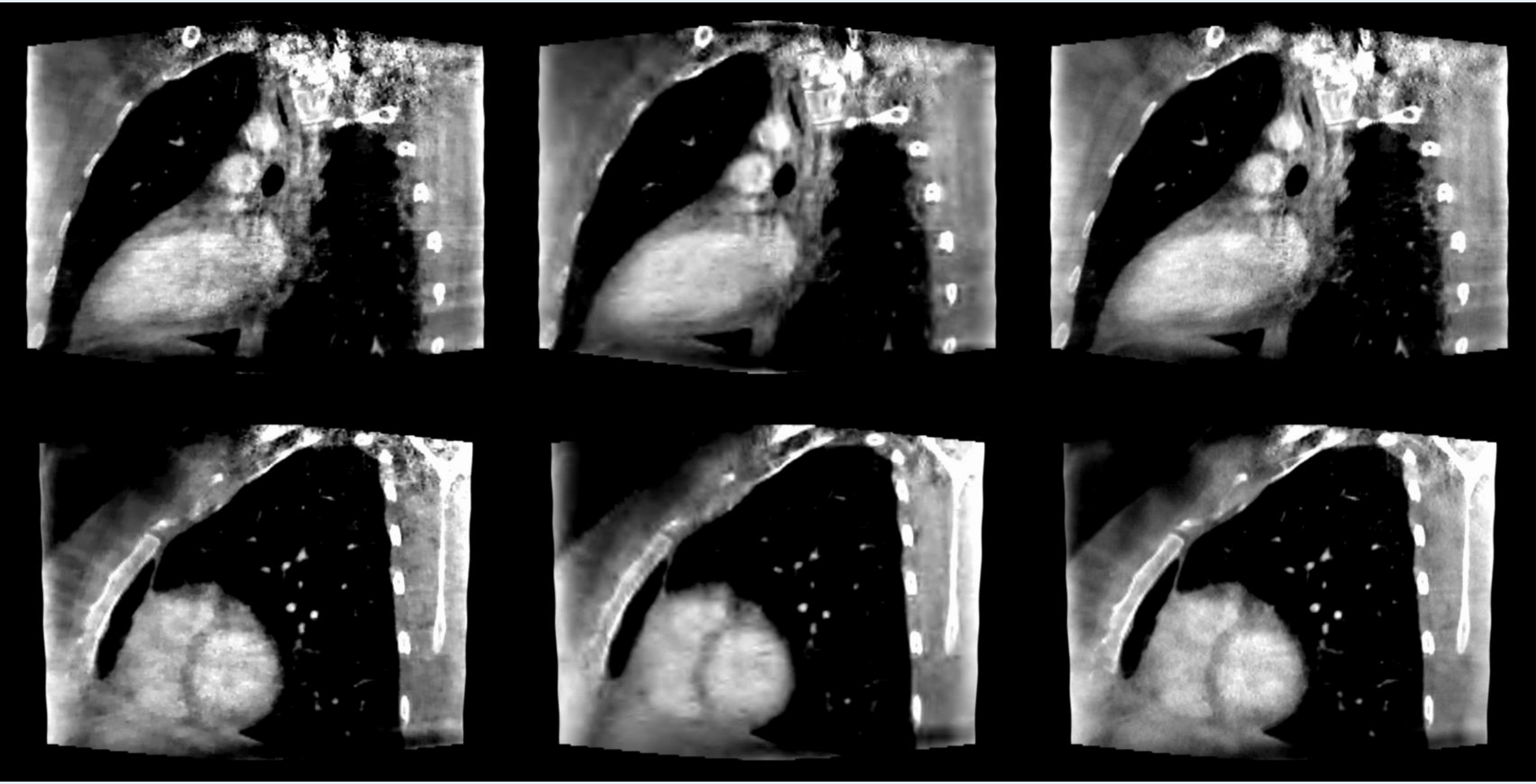
SYSTOLE

DIASTOLE



3D compressed sensing Animated sequences

ADMM 3D TV | ADMM 3D Wavelets | PICCS



Contents A bit of math

A bit of math On kernels

$$\hat{f} = \underset{f}{\arg\min} \|Rf - p\|_2^2$$

$$f = P_{Ker\,(R)}(f) + P_{Ker\,(R)^{\perp}}(f) = f_{Ker} + f_{\perp}$$

$$Rf = Rf_{Ker} + Rf_{\perp} = Rf_{\perp}$$

$\Rightarrow$ f_{Ker} **does not drive the search for** $\hat{f}$

A bit of math More on kernels

$$\hat{f} = \arg\min_{f} \|Rf - p\|_2^2$$

$$\nabla \|Rf - p\|_2^2 = 2R^T(Rf - p)$$

$$Im(R^T) \subset Ker(R)^{\perp}$$

$\Rightarrow$ **Gradient descent does not even modify** f_{Ker}

$\Rightarrow$ **Same for conjugate gradient**

A bit of math More on kernels

$$\hat{f} = \underset{f}{\arg\min} \|G(Rf - p)\|_2^2$$

$$\hat{f} = \underset{f}{\arg\min} \|GRf - Gp\|_2^2$$

$Ker(GR)$ **is huge**

A bit of math Initialization and regularization

- **20% gating window**
  - 4 times more information in f_{Ker} than in $f_{\perp}$
  - A good f_{Ker} is crucial
- **Initialization**
  - f_{Ker} remains in its initial state throughout iterations
- **Regularization**
  - Updates f_{Ker} from $f_{\perp}$
  - More regularization = better reconstruction of motion

Contents 4D compressed sensing

- **Introduction**
- **3D compressed sensing**
- **A bit of math**
- **4D compressed sensing**
  - Augmented Lagrangian + ADMM + TV
  - 4D ROOSTER
  - Animated sequences
- **Perspectives**
- **Conclusion**

4D compressed sensing AL + ADMM + TV

$$\hat{f} = \arg\min_{f} \sum_{\theta} \|R_\theta S_\theta f - p_\theta\|_2^2 + \alpha ROI\_TV(f)$$

- f : **4D sequence of volumes**
- R_θ : **projection operator, source at angle θ**
- S_θ : **linear interpolation operator**
- p_θ : **measured projection, source at angle θ**

- **Example, with a 4D sequence of 10 phases**
  - Projection p_{θ_0} was acquired at 87% of the cardiac cycle
  - S_{θ_0} will interpolate between phase 80% and phase 90%
  - $S_{\theta_0} f = 0.3 f_8 + 0.7 f_9$

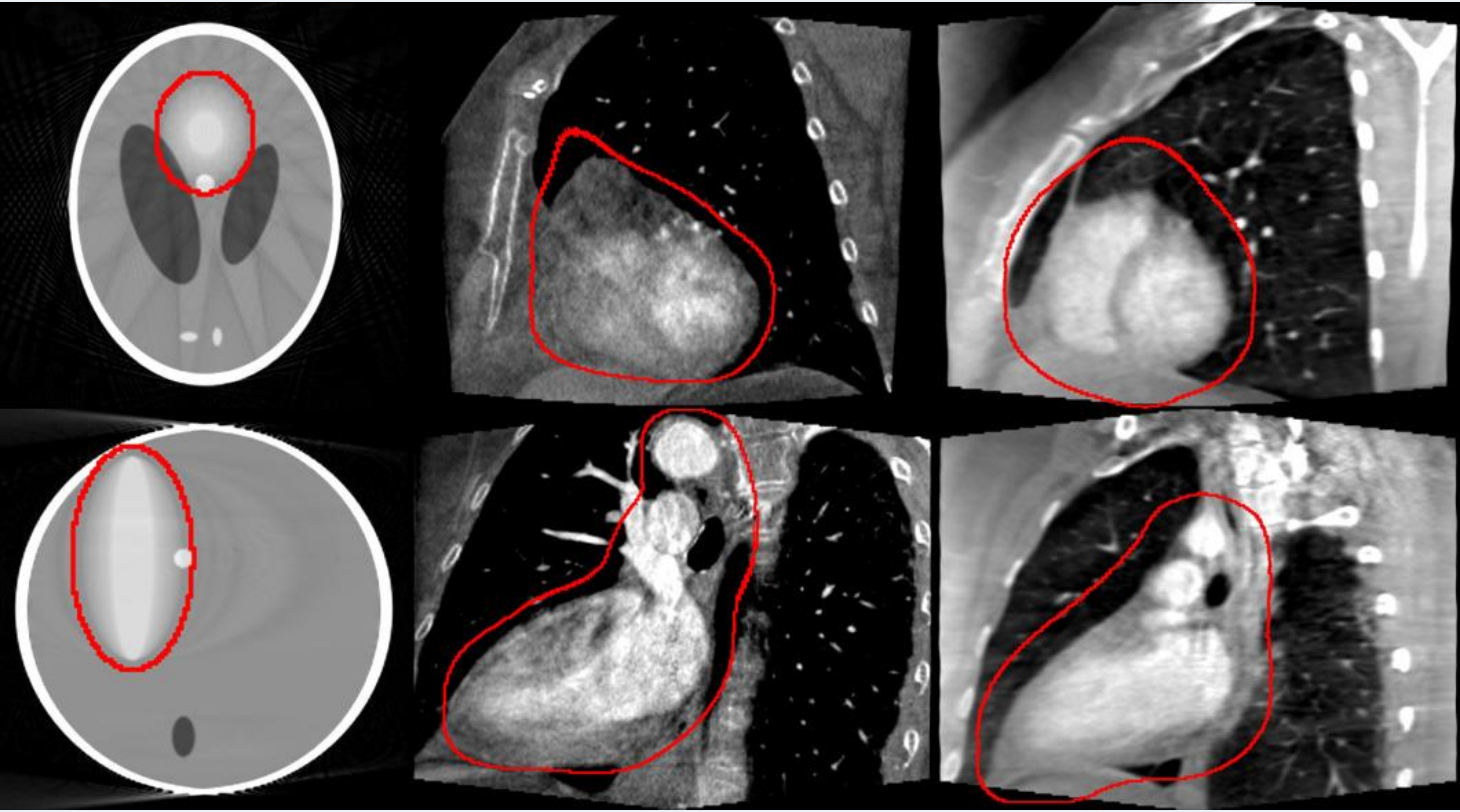
4D compressed sensing AL + ADMM + TV

$$\hat{f} = \arg\min_{f} \sum_{\theta} \|R_\theta S_\theta f - p_\theta\|_2^2 + \alpha ROI\_TV(f)$$

$$ROI\_TV(f) = \sum_{m=1}^{M} \sqrt{[\nabla_{\mathrm{x}} f(m)]^2 + \left[\nabla_{\mathrm{y}} f(m)\right]^2 + [\nabla_{\mathrm{z}} f(m)]^2 + [\omega(m)\nabla_t f(m)]^2}$$

- $\omega(m)$: **motion weighting, high outside ROI, low inside**

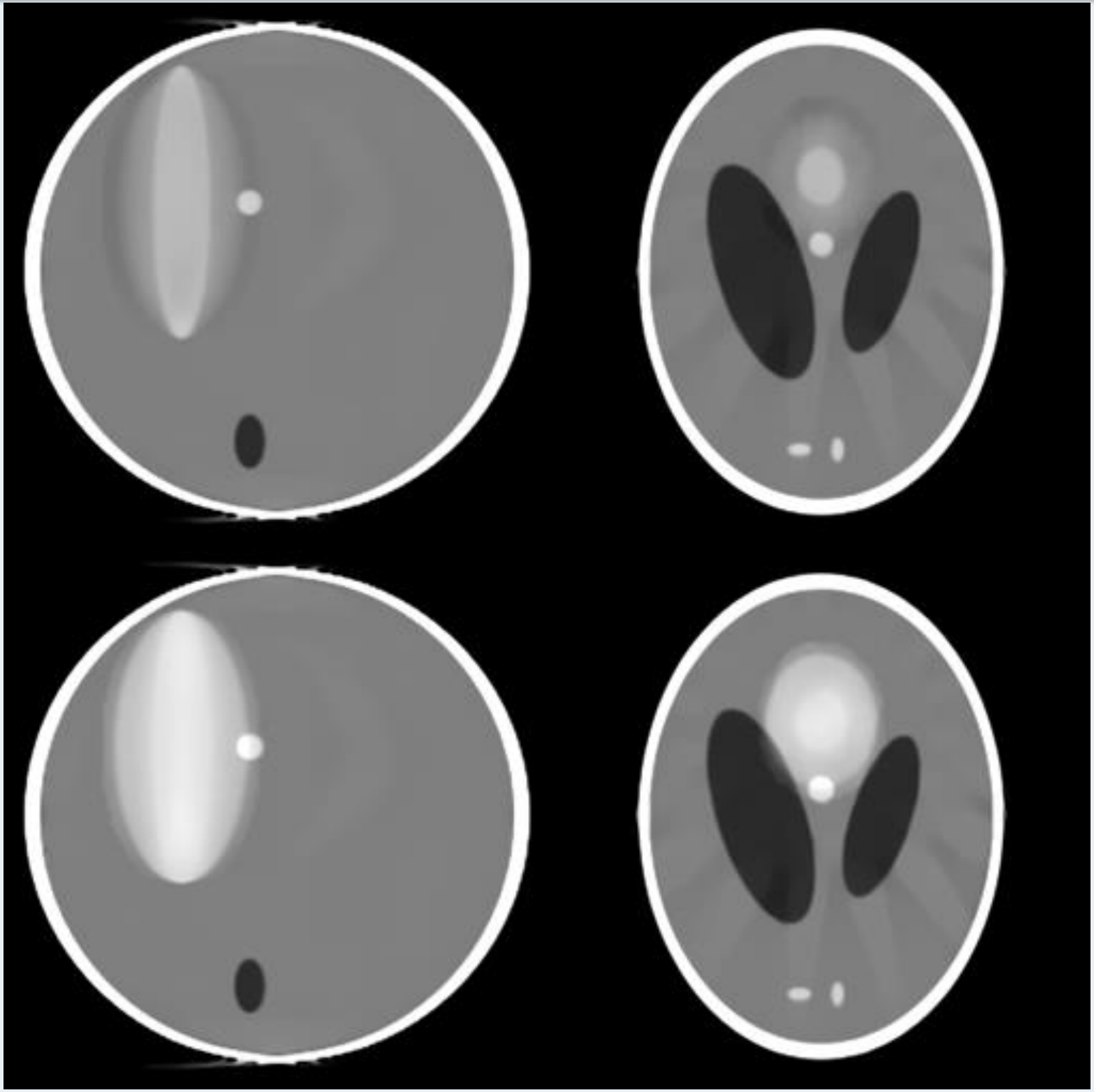
4D compressed sensing AL + ADMM + TV



4D compressed sensing AL + ADMM + TV

S
Y
S
T
O
L
E

D
I
A
S
T
O
L
E

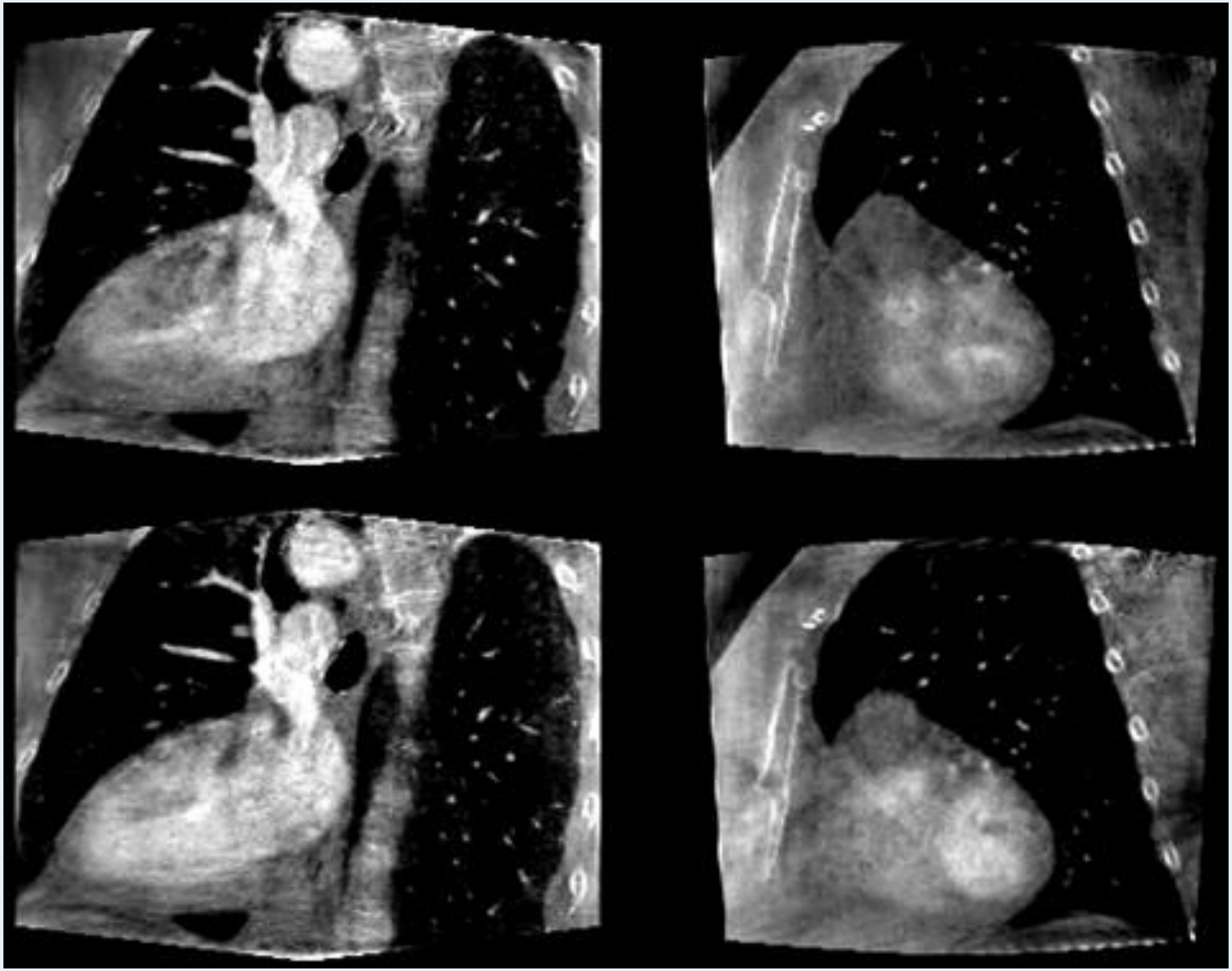


4D compressed sensing AL + ADMM + TV

Long axis | Short axis

S Y S T O L E

D I A S T O L E

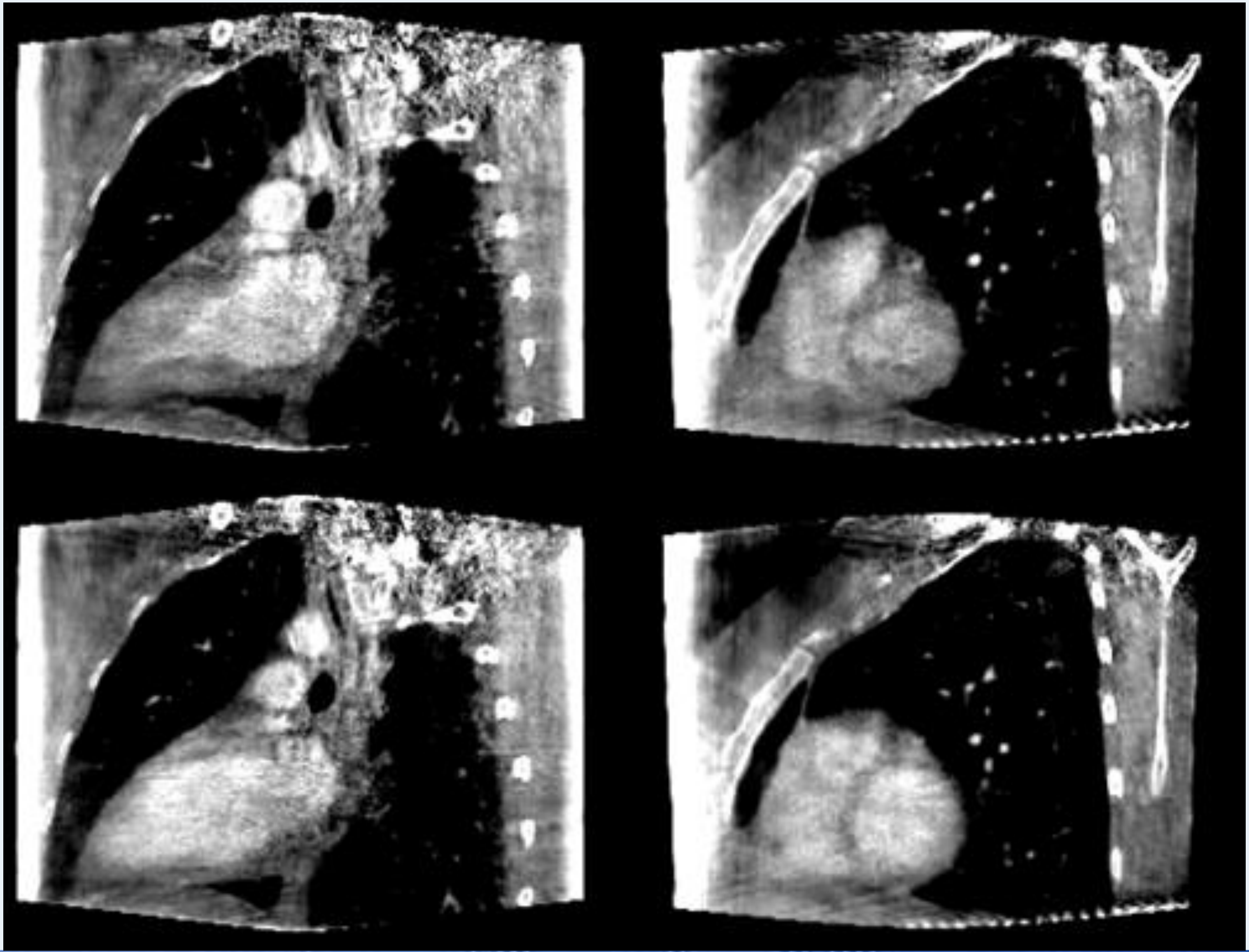


4D compressed sensing AL + ADMM + TV

Long axis | Short axis

S Y S T O L E

D I A S T O L E



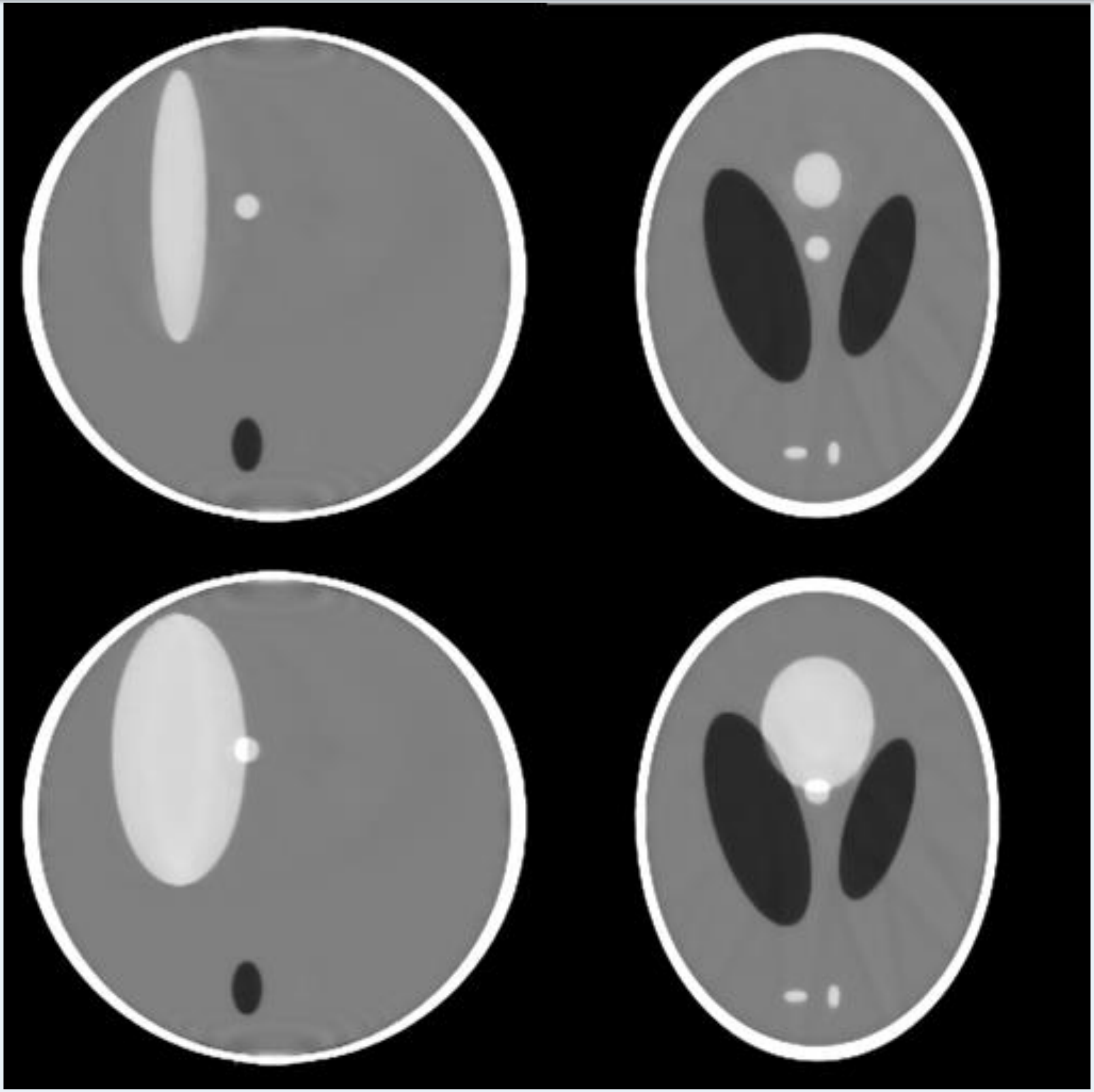
4D RecOnstructiOn using Spatial and TEmporal Regularization

- **For iter = 1 to max_iter**
  - Conjugate gradient on $\sum_{\theta} \| R_\theta S_\theta f - p_\theta \|_2^2$
  - Positivity enforcement
  - Averaging along time outside ROI
  - Spatial TV minimization
  - Temporal TV minimization

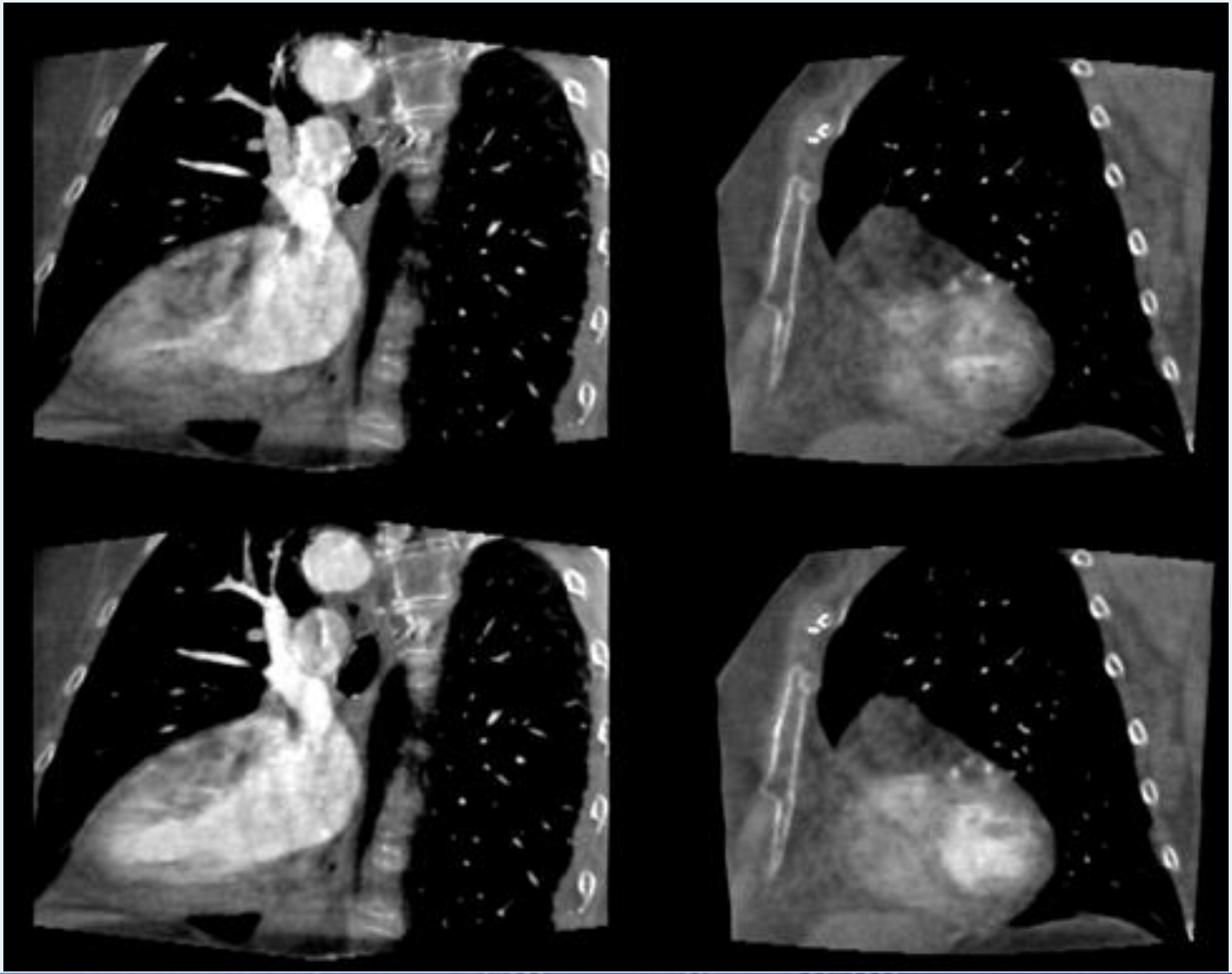
4D compressed sensing 4D ROOSTER

S
Y
S
T
O
L
E

D
I
A
S
T
O
L
E



4D compressed sensing 4D ROOSTER

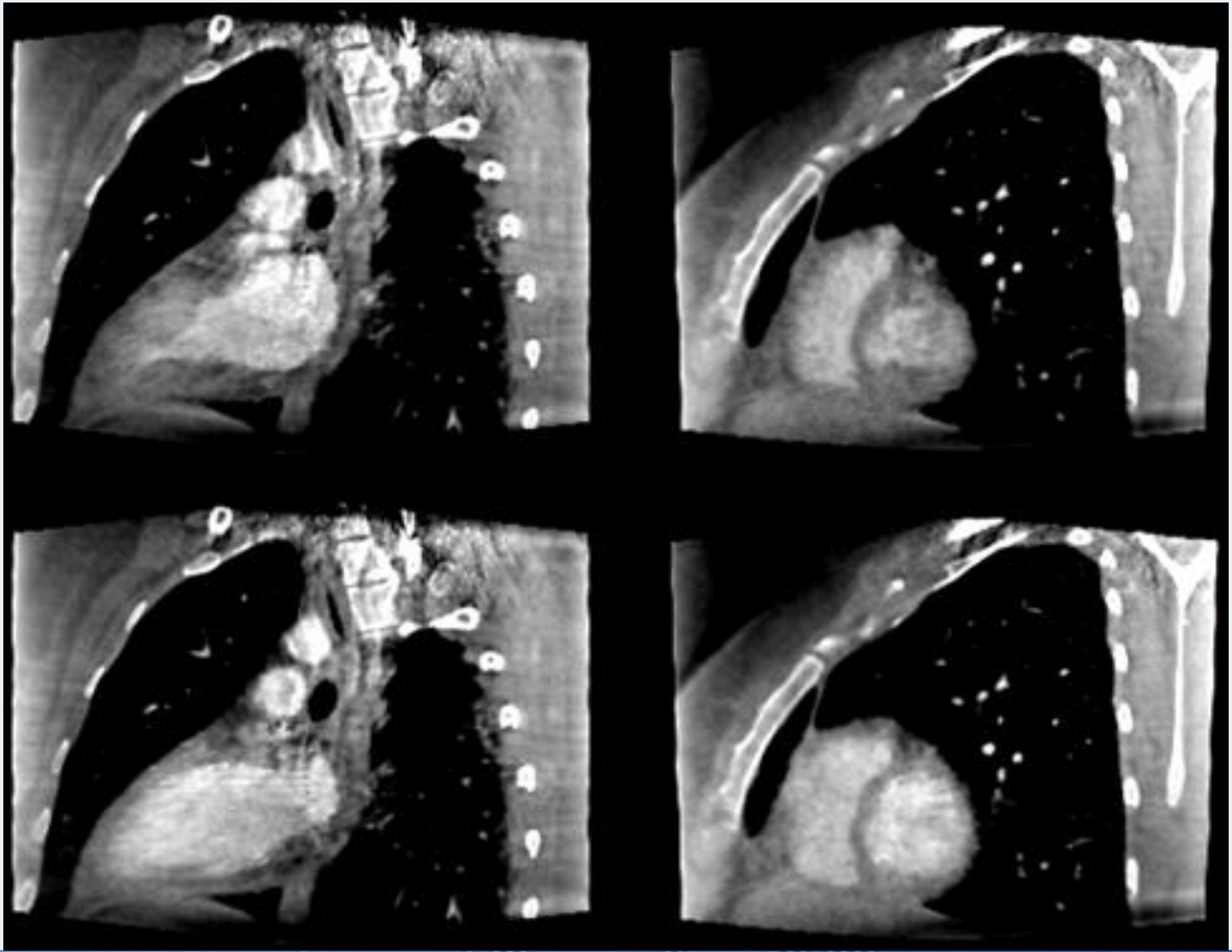
	Long axis	Short axis
SYSTOLE		
DIASTOLE		

4D compressed sensing 4D ROOSTER

Long axis | Short axis

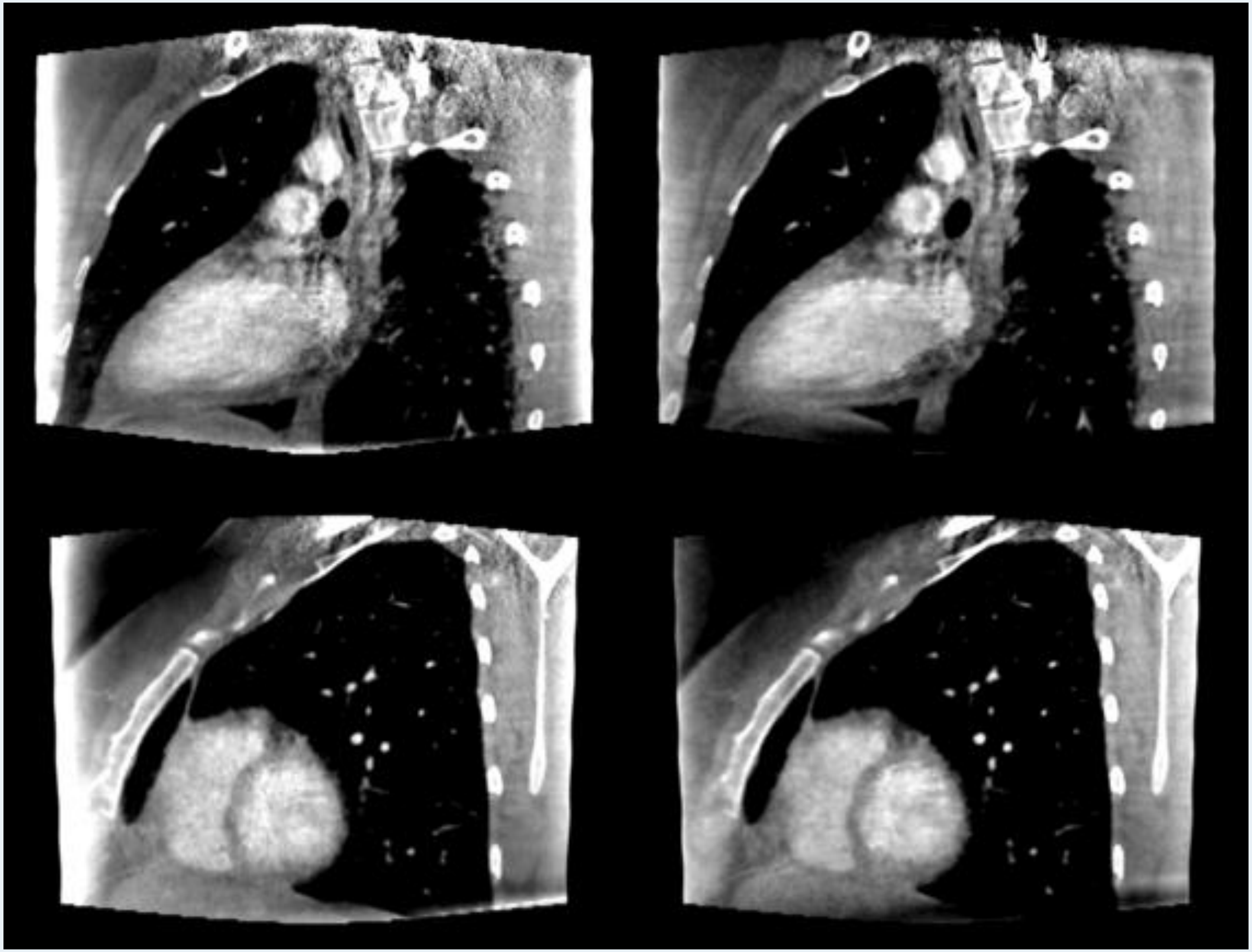
S
Y
S
T
O
L
E

D
I
A
S
T
O
L
E



3D compressed sensing Animated sequences

ADMM 4D TV | 4D ROOSTER



Contents Perspectives

- **Introduction**
- **3D compressed sensing**
- **A bit of math**
- **4D compressed sensing**
- **Perspectives**
  - The 4D ROOSTER method
  - Clinical use
- **Conclusion**

Perspectives The 4D ROOSTER method

- **Other regularization methods**
  - Spatial TV => Wavelets
  - Temporal Non-Local Means

- **Fully automatic heart segmentation**
  - Currently performed manually (semi-automatic tool)

- **Improve performance**
  - Already implemented in CUDA
  - Can probably be optimized

Perspectives Clinical use

- **Online processing for injected data**
  - Requires a prototype
- **Offline processing for late enhancement**
  - Disappointing
- **Compressed sensing in cardiac MRI**
  - Replace projection by Fourier transform
- **Free-breathing thorax imaging**
  - Replace ECG-gating by respiratory gating

Contents Conclusion

- **Introduction**
- **3D compressed sensing**
- **A bit of math**
- **4D compressed sensing**
- **Perspectives**
- **Conclusion**
  - Improvement over PICCS
  - Take-home messages

Conclusion Improvement over PICCS

- **PICCS is the current state of the art in cardiac C-arm CT**
  - Results published only on animals
  - Our study demonstrates PICCS on human cardiac C-arm CT

- **4D ROOSTER outperforms PICCS**
  - No motion outside the heart
  - Consistent motion inside the heart
  - Sharper edges
  - Lower noise

Conclusion Take-home messages

Limited data ?

- Try to reduce the number of unknowns
- Use compressed sensing iterative methods
- Regularize as much as possible
- Initialize carefully
- Test by starting from zero

Thank you for you attention