Stabilized Reconstruction and Materials Identification for Dual-energy CT

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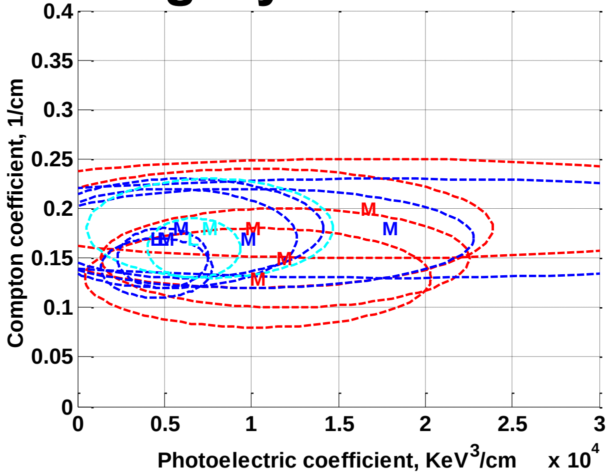
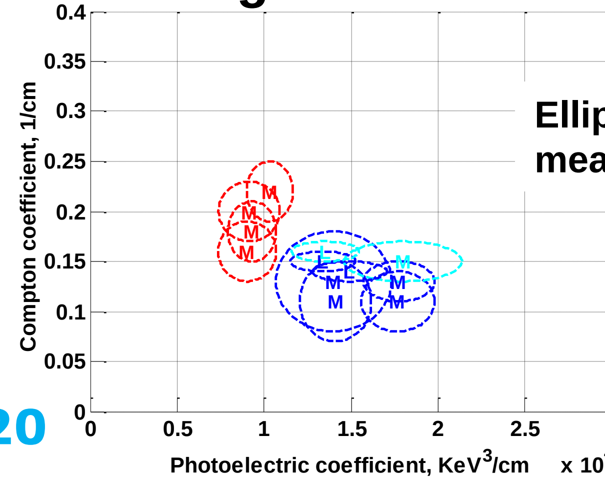
Materials Characterization "Clouds" Based on Stratovan Manual Segmentation

"Legacy" method

Patch-regularized ADMM

Low & Medium Clutter

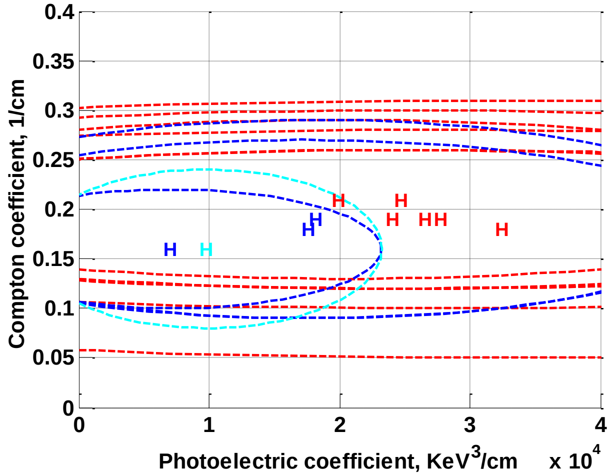




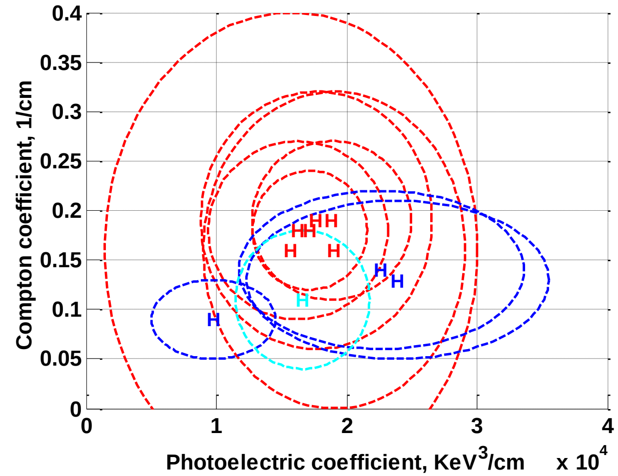
Ellipses: mean +/ 1 SD

Rubber
H20
Doped H20

High Clutter



Metal artifact problems!



Example Comparison to YNC
Medium Clutter 1, Slice 231

YNC method | **Patch-regularized ADMM**

Compton

Photoelectric

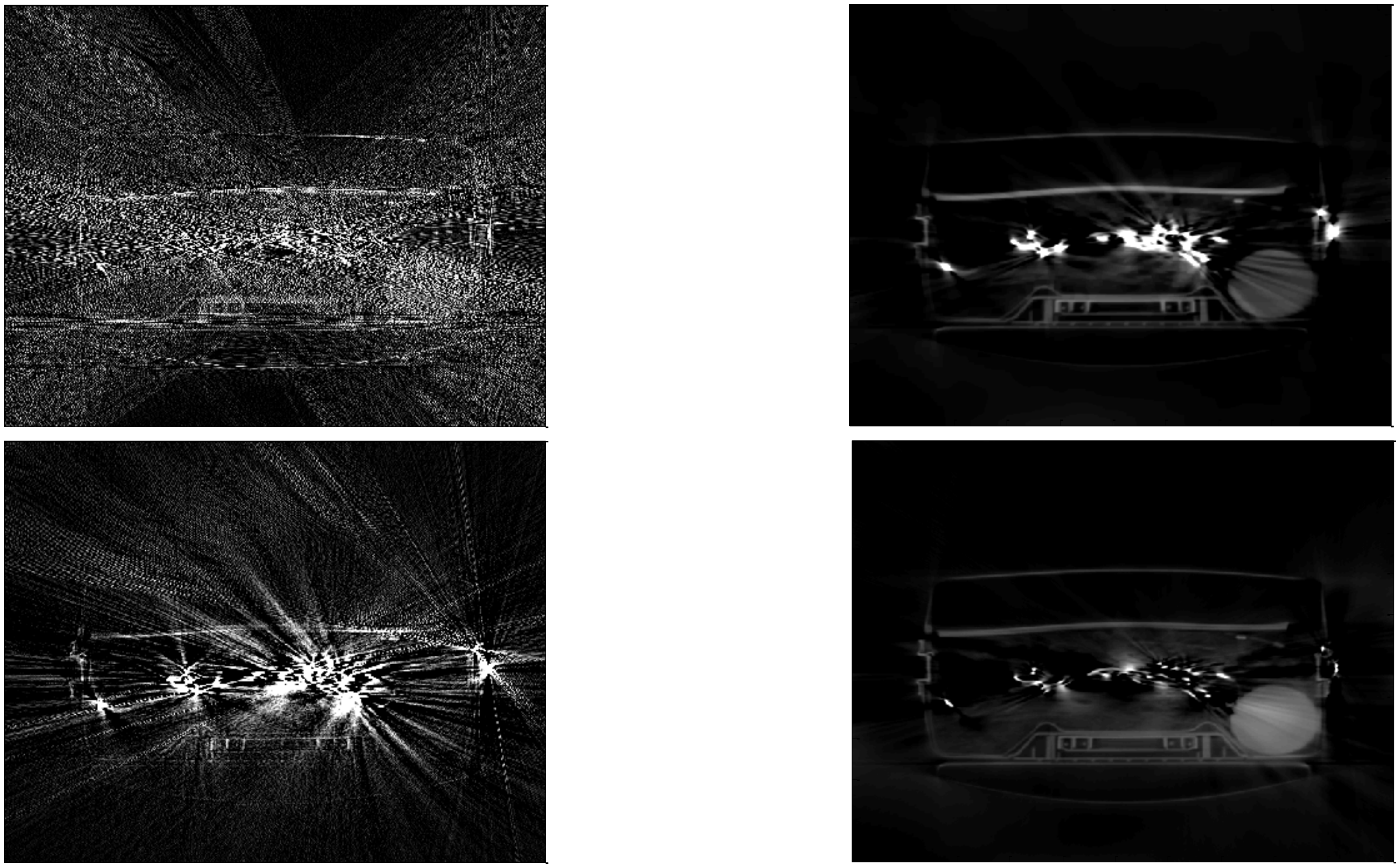
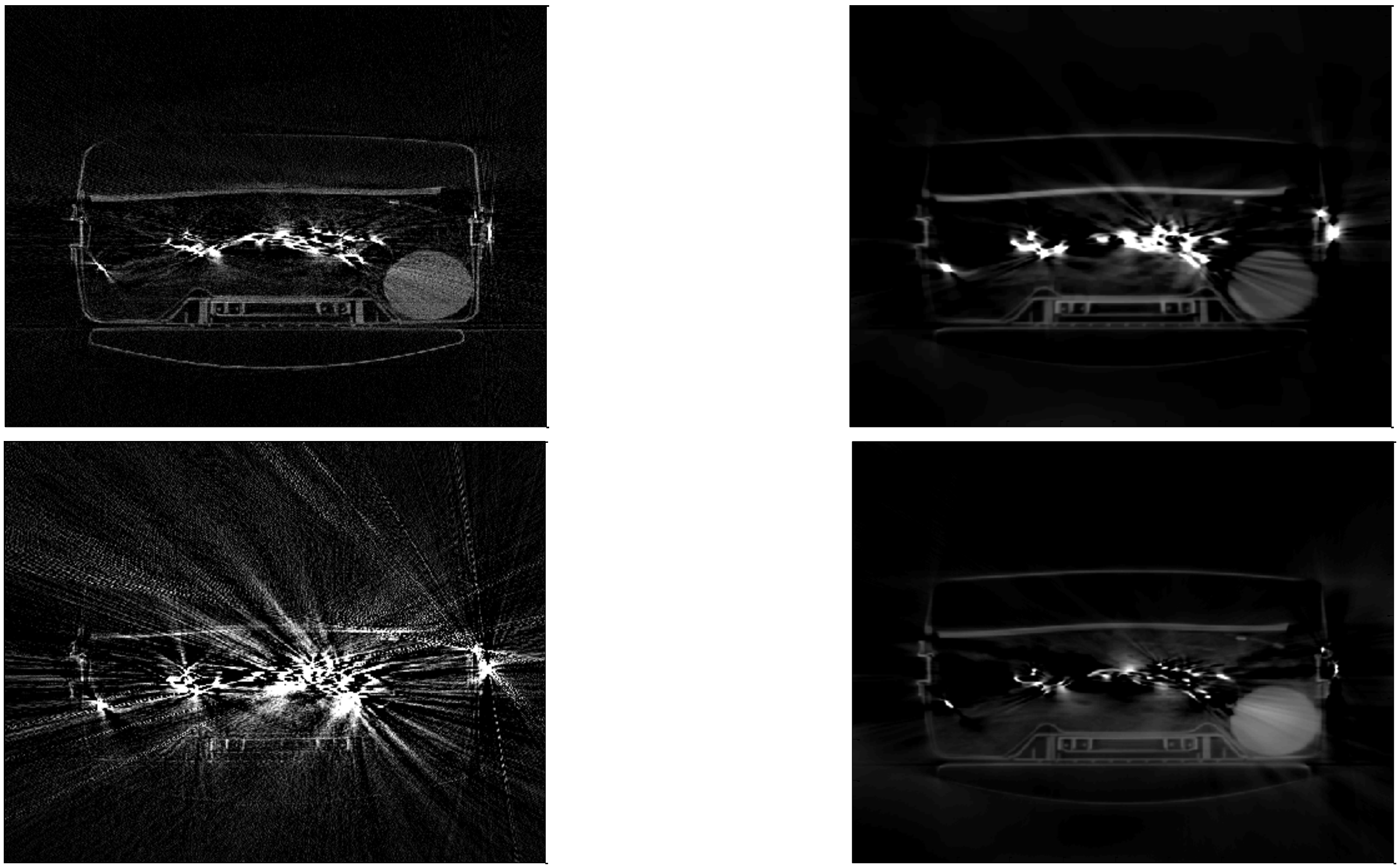


Image dynamic range:
Compton 0-0.5 1/cm; Photoelectric 0-4e4 KeV/cm

Example Comparison to "Legacy"
Medium Clutter 1, Slice 231 – YNC + Inpainting

"Legacy" method | **Patch-regularized ADMM**

Compton / **Photoelectric**



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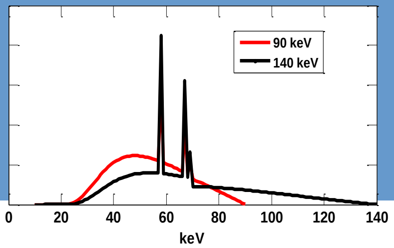
Research Team: Tufts LaISR Group

- Tufts Lab for Imaging Science Research (LaISR)
  - Inverse problems and image processing
  - Active collaboration with industry (AS&E, BBN, Schlumberger, consulting activities)
- This project builds on past ALERT-funded work:
  - multi-energy CT reconstruction, Semerci and Miller
  - patch-based denoising, Tracey

Problem Description



- We describe data using **physics-based** coefficients – Compton scatter and photoelectric effect (PE) images

$$\mu(x,y,E)= f_{KN}(E)\underbrace{a_c(x,y)}_{\text{Compton scatter}}+ f_p(E)\underbrace{a_p(x,y)}_{\text{photoelectric effect (PE)}}$$

- Dual scans -> two material parameters -> material ID

<u>Challenge</u>*:* Physics dictate that sensitivity to PE is low; accurately estimating PE is difficult (recovery is unstable)

<u>Legacy (YNC) dual-energy approach:</u>

- Decompose data into Compton and PE sinograms, then FBP both
- Use a **iterative, polyenergetic** solution, then destreak PE
- Does **not** work in image space, use expected Compton/PE shape similarity, or use knowledge of materials (beyond values >=0)

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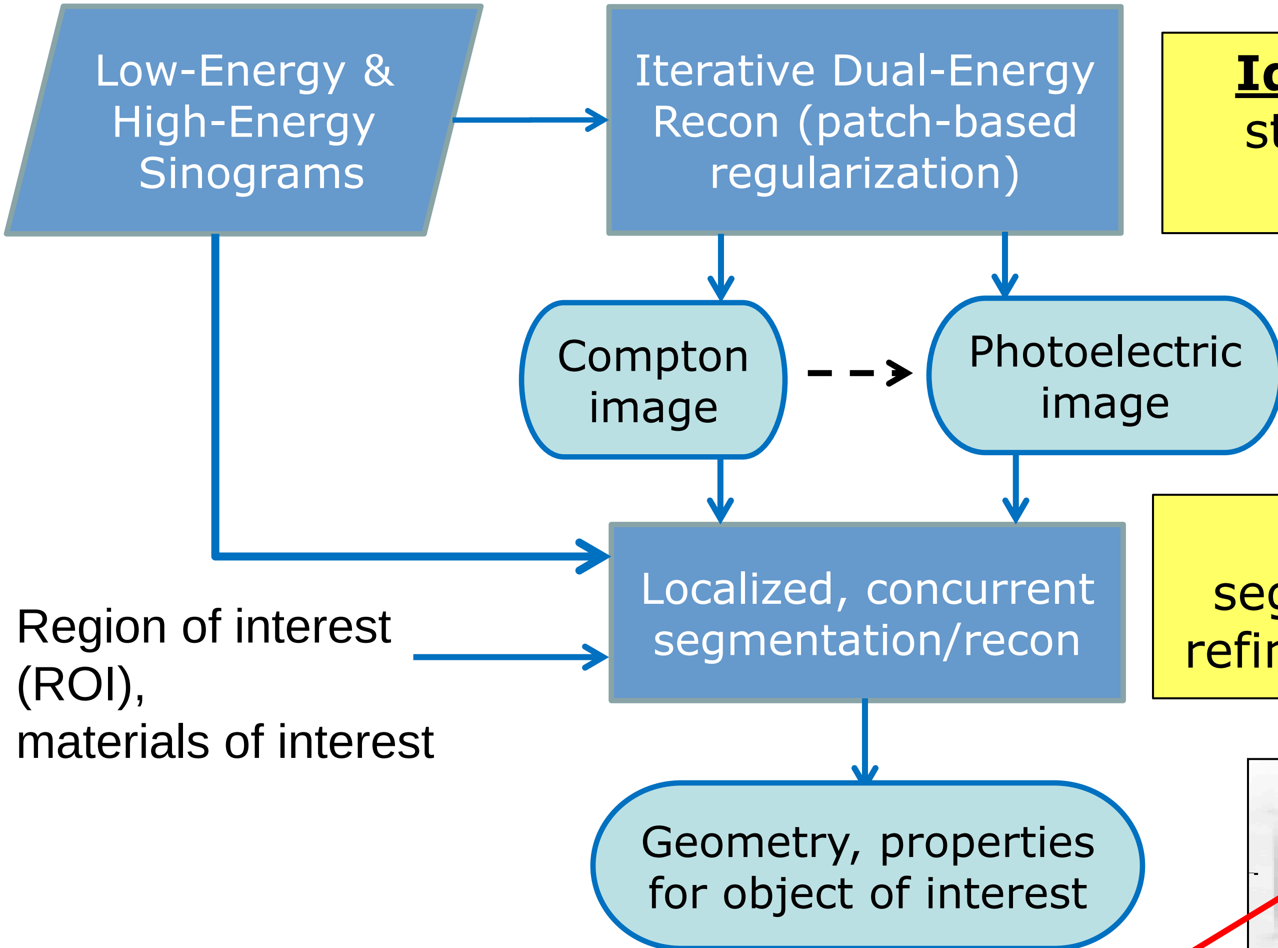
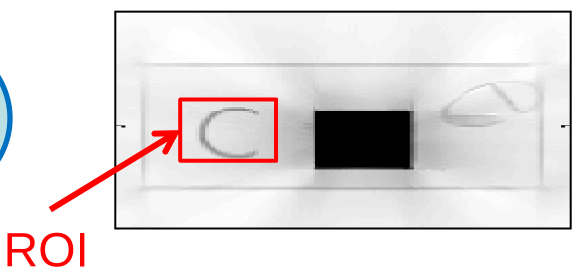
Overall Processing Concept



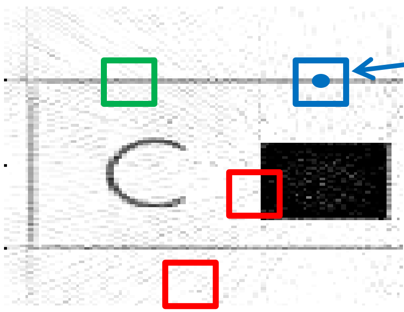
Idea 1: Exploit spatial structure from stably-estimated images

Idea 2: Iterative segmentation / recon to refine ID for key materials



Patch-based Regularization ("Idea 1")

1) **Calculate** patch similarities from more stable **Compton** data

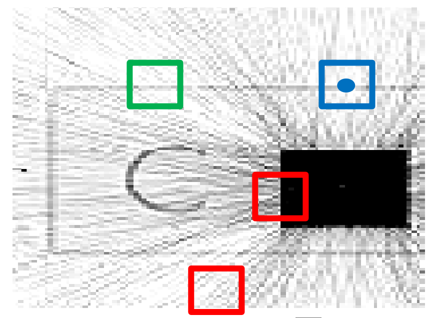


Patch for pixel being estimated

Good match

Poor match

2) **Apply** patch similarities to smooth the **PE** image (NLM)



Averaging weights **w** ~ patch similarity

3) **Define regularization term** that encourages PE estimate to match NLM-smoothed estimate

$$R_{nlm} = \lambda_{NLM} \sum_j \left(p_b(j) - NL^{(C)} p_b(j) \right)^2$$

4) **Iteratively solve** equations

- Minimize data mismatch + R_{nlm}
- Proposed by Buades *et al*., 2006, for image deblurring

Goal: Use stable image to reduce effects of noise during reconstruction

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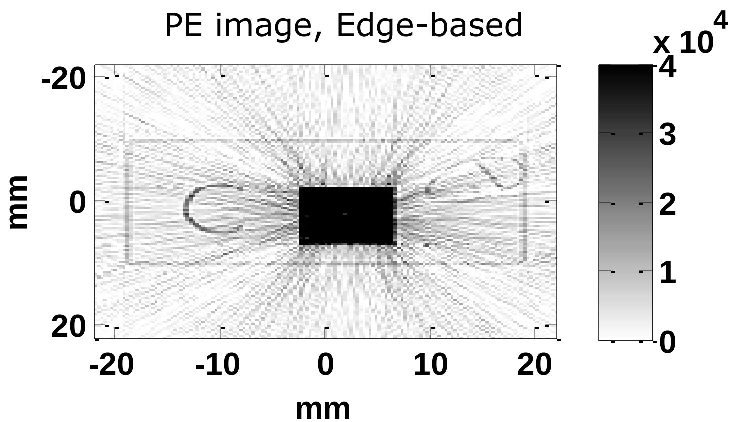
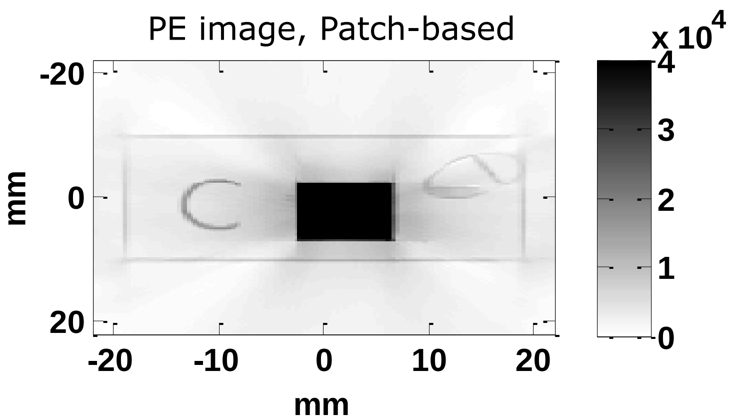
Why Consider Patch-based Methods?

- Previous Tufts work* sought **high correlation between edges** in Compton and PE
  - Simulations show patch-based approach may perform better
- Patch methods are **convex**; solvers (ADMM) allow **parallel computation**
  - Not possible with edge correlation
- Better **texture preservation** than penalties like Total Variation





Suitcase phantom, 60 dB SNR

* Semerici and Miller, IEEE Trans Image Proc, 2012

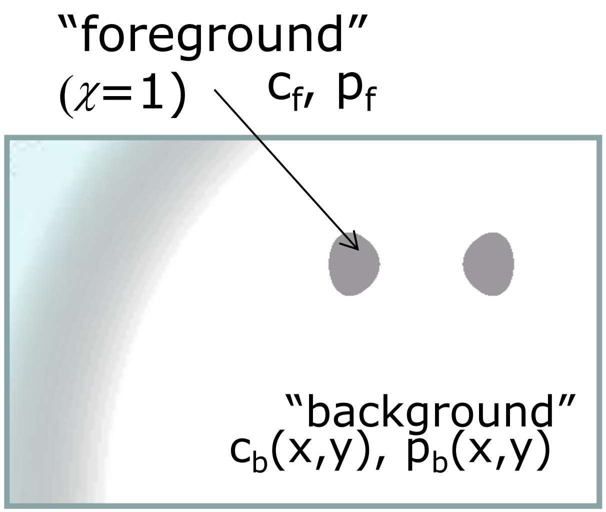
Simultaneous Segmentation / Reconstruction ("Idea 2")

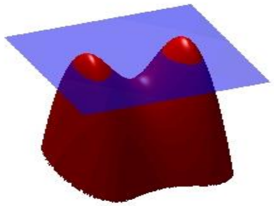
Model: homogenous material of interest on a varying background

$$c(x,y) = \chi(x,y)c_f + [1 - \chi(x,y)]\, c_b(x,y)$$
$$p(x,y) = \chi(x,y)p_f + [1 - \chi(x,y)]\, p_b(x,y)$$

where the χ is the *zero-level set* of a set of Gaussian "blobs"

Processing: iterative recon, updating material shape and properties





Example "blobs" w/ level set

Advantages:

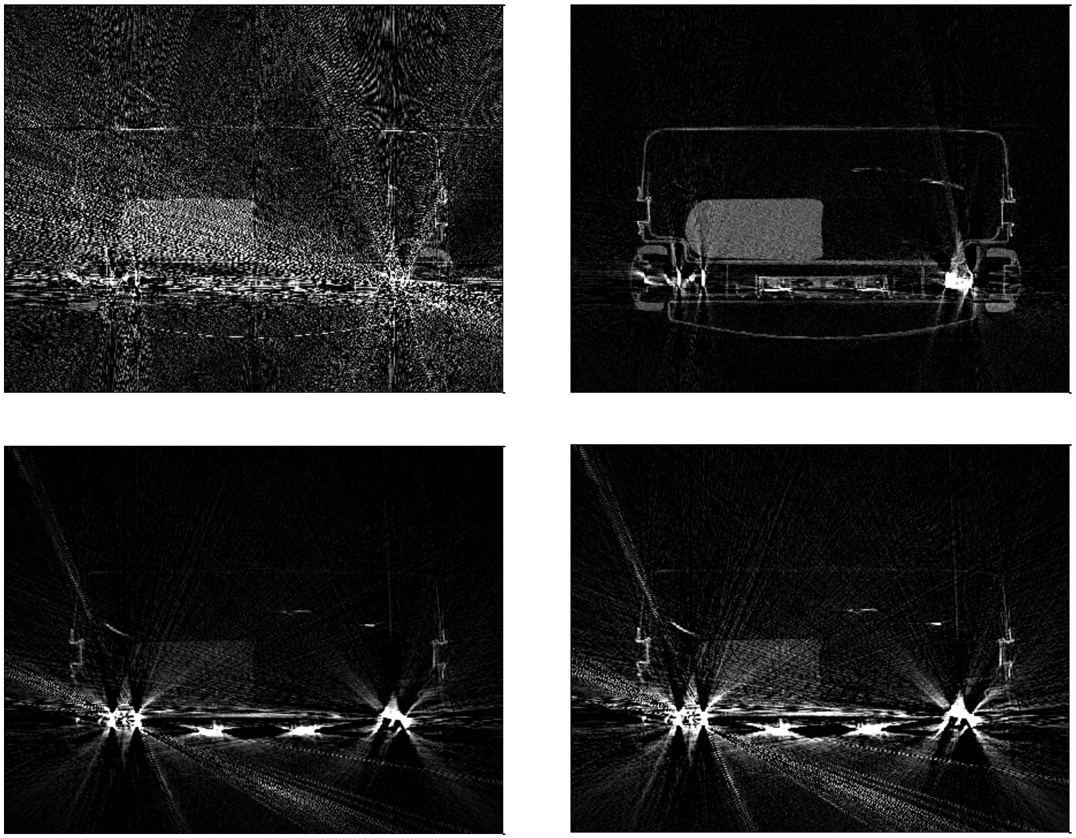
- A few Gaussians can represent complex shapes – easier recon
- Foreground values can be constrained by imperfect prior knowledge
- **Focus processing on materials of interest**

"Legacy" Dual Energy Method
Medium Clutter 1, Slice 038

YNC | YNC + inpainting ("Legacy")

Compton

Photoelectric



- Ying, Naidu and Crawford 2006 describes sinogram decomposition method
- We implemented the YNC solution method and destreaking, but not calibration
- Non-negativity constraints lead to many zeros in sinogram, increasing noise
- We use simple sinogram inpainting/interpolation to control this; result is taken as "Legacy"

Image dynamic range:
Compton 0-0.5 1/cm; Photoelectric 0-4e4 KeV/cm

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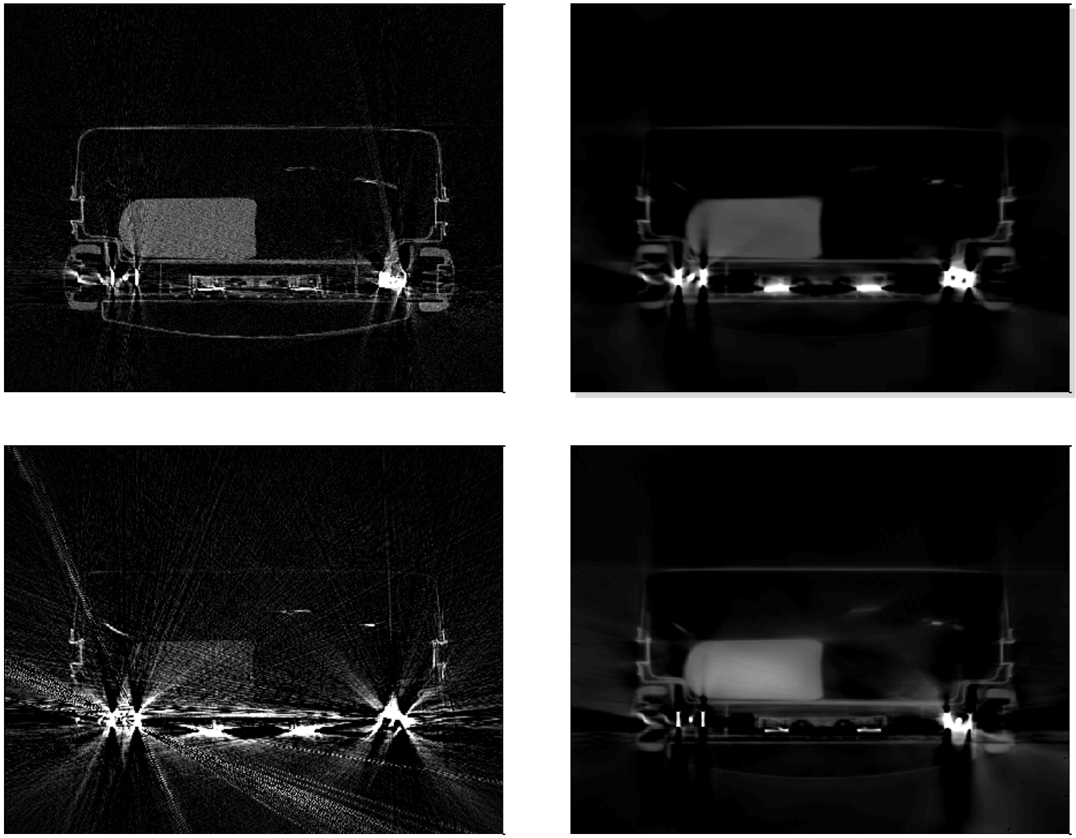
New method vs "Legacy"
Medium Clutter 1, Slice 038

Legacy | Regularized ADMM

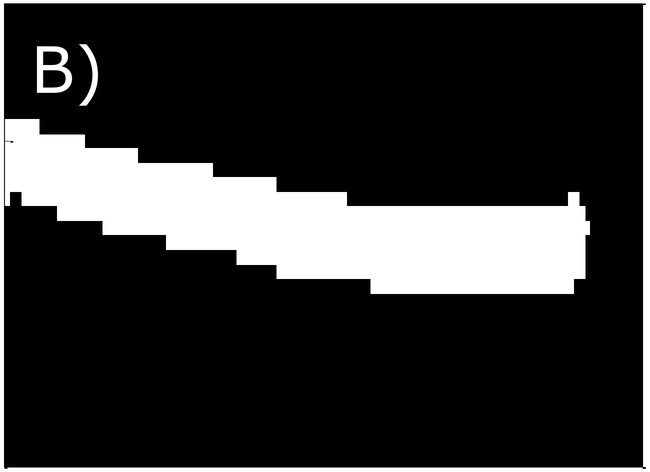
Compton / Photoelectric



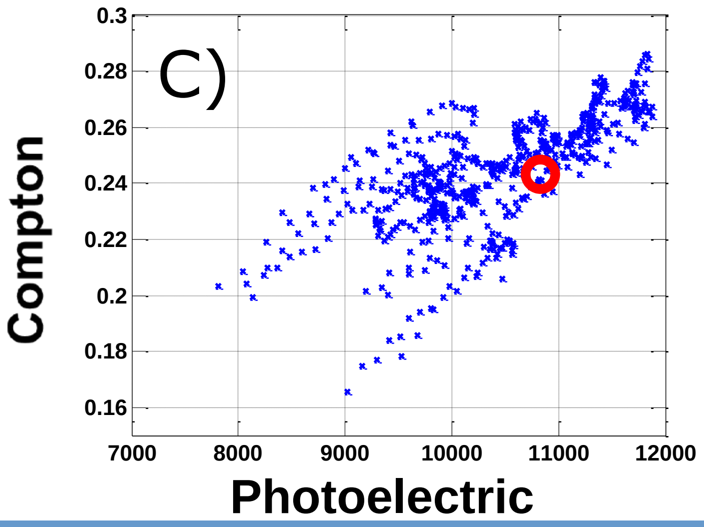
- PE shows greatest change
- Sharp edges are preserved
- Energy from streak artifacts is 'smeared' into background

- <u>Slight</u> benefit if apply patch-based to Compton, using FBP result as reference (faster solution)

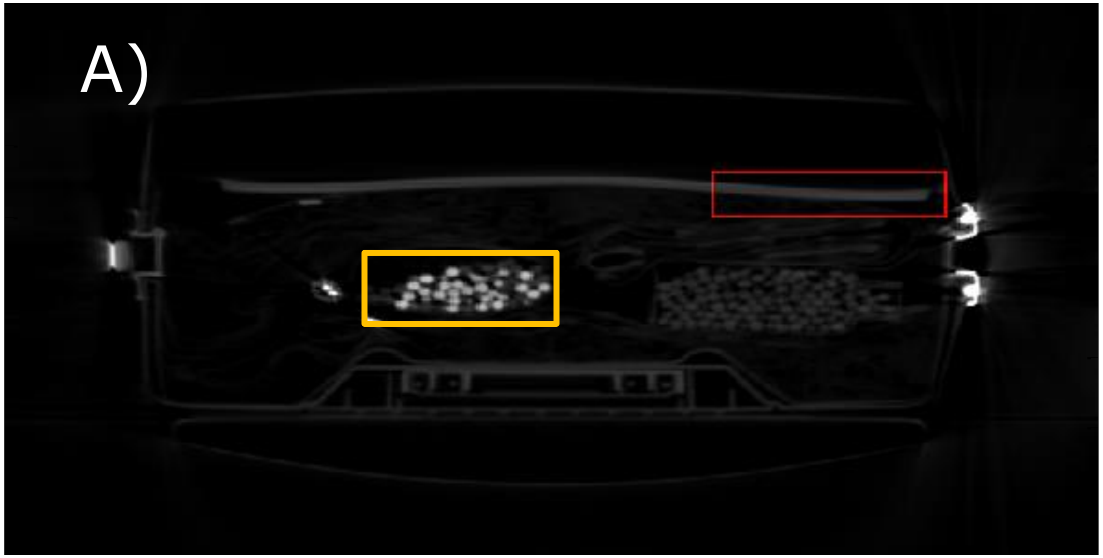
Example Region-of-Interest Analysis using Active Contours

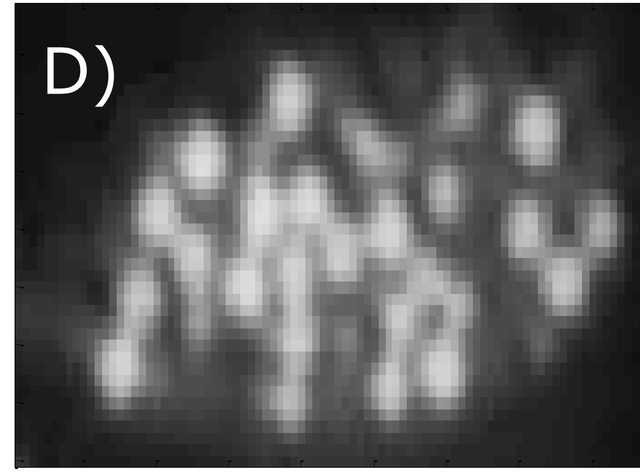


- Dual-energy iterative Compton and PE images form “background” A)
- Region of interest (ROI) is reprocessed, returning extracted “foreground” object B)
- In segmented region, Compton /PE “cloud” is replaced by single value C)



Example Region-of-Interest Analysis using Level Sets





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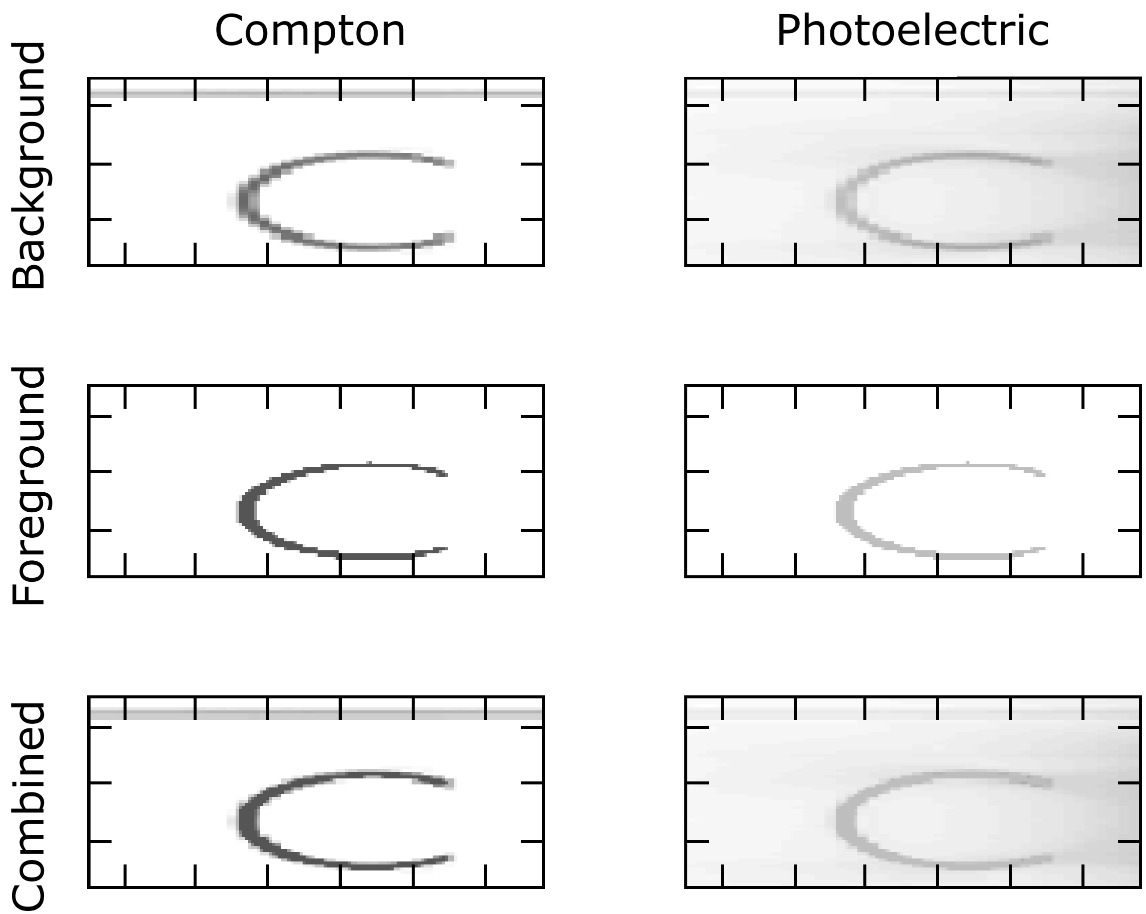
- In segmented region, Compton /PE "cloud" is replaced by single value C)
- In bead region, textured object (D) is poorly captured by homogenous model (E)

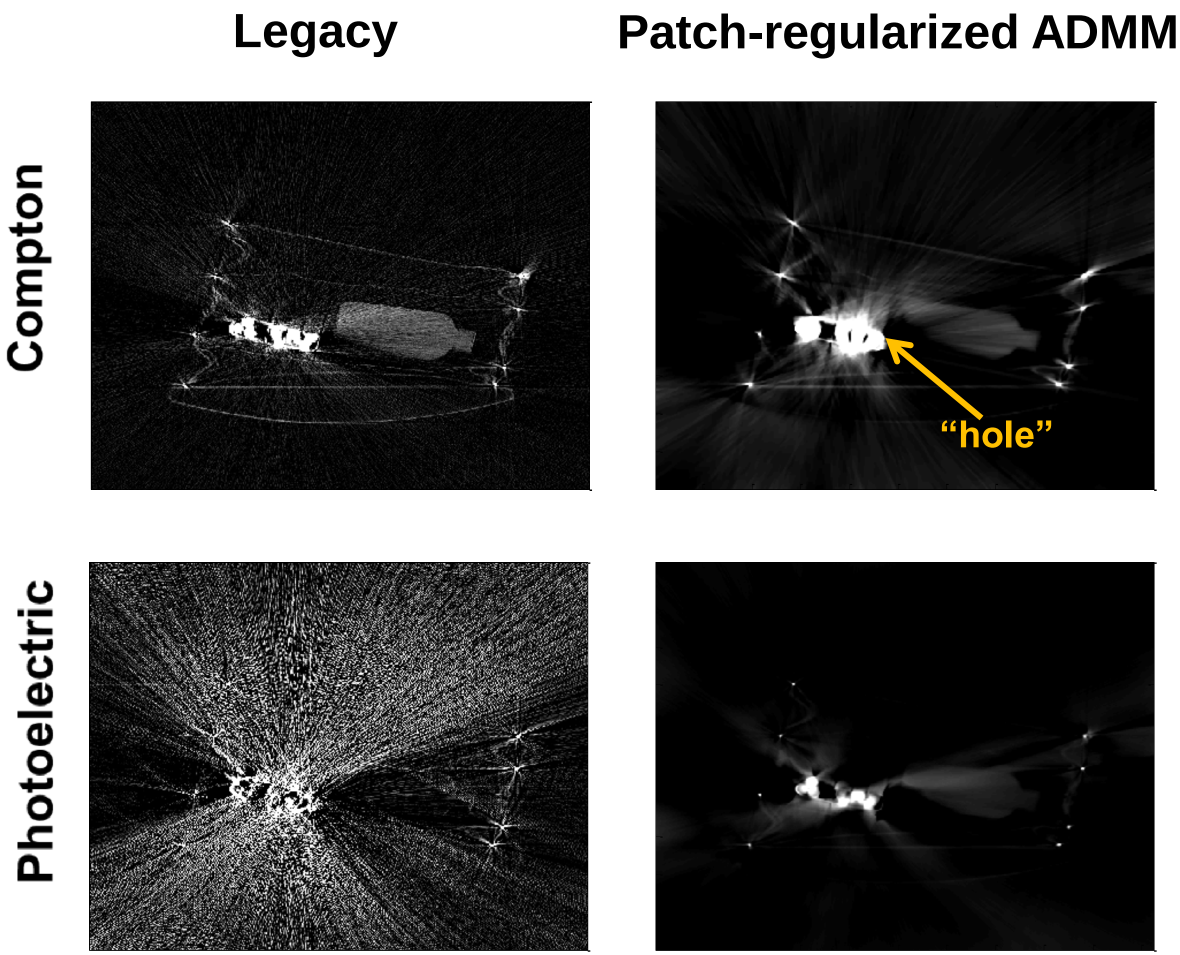
Approach Allows Higher Spatial Resolution near Object of Interest

- Here, 3*x* higher spatial resolution used to image the foreground (object of interest)
- Allows us to apply computation where it is most beneficial
- Simulation results (for data, we created project-standard 512x512 images)



Problems with metal artifacts

Example: High Clutter 1, Slice 350



- Our main focus has been on **stabilizing PE**
- *No* metal artifact reduction implemented – but effects can be large

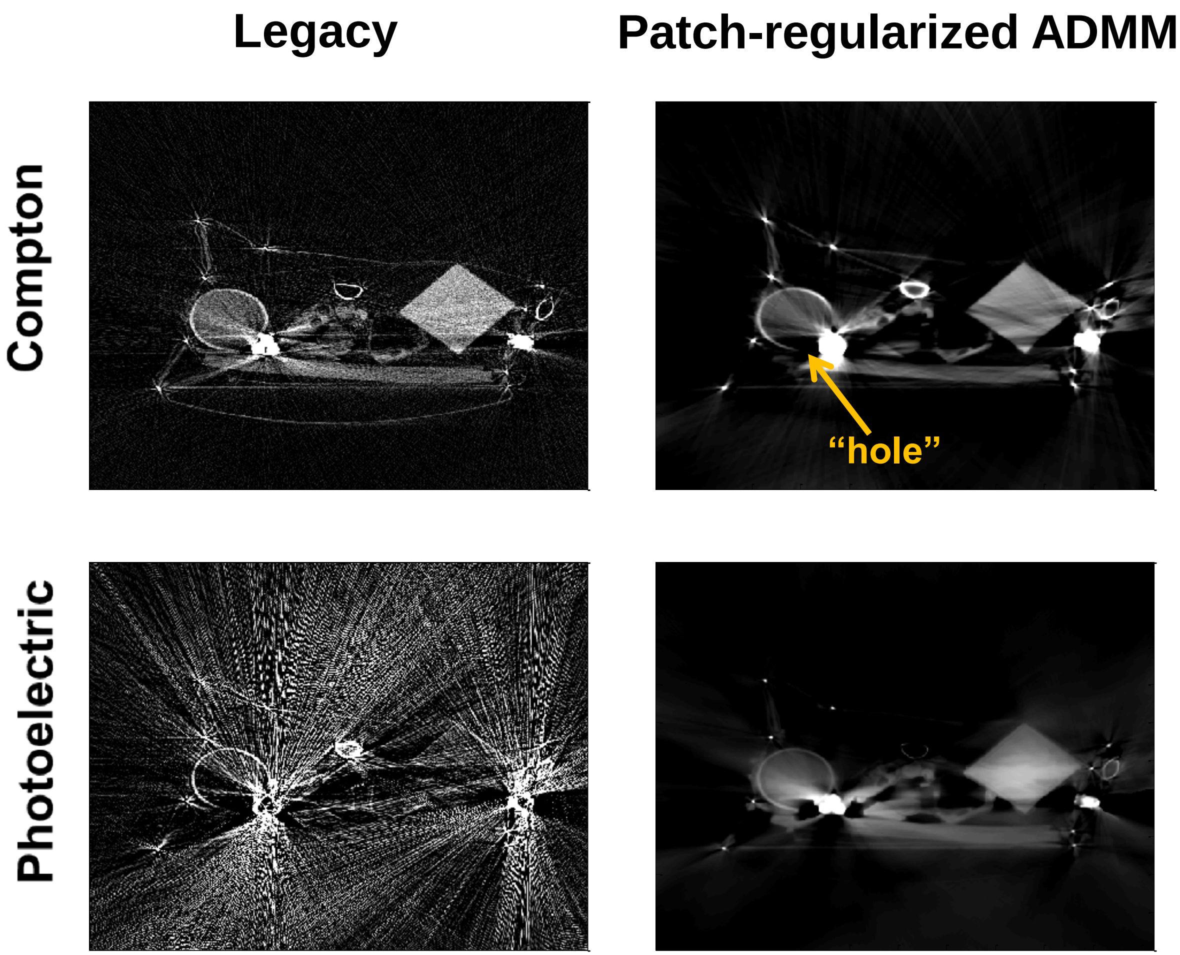
Possible solutions:

a) Include metal artifact reduction steps in processing

b) Consider level-sets for localizing metal

Image dynamic range:
Compton 0-0.5 1/cm; Photoelectric 0-7e4 KeV/cm

Problems with metal artifacts
Example: High Clutter 1, Slice 220



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Pros | Cons

Patch-based regularization methods

Pros	Cons
• Much more stable reconstruction of PE image, reflected in tighter clouds for parameter estimates • Formulated using ADMM approach – so parallel implementation is possible	• Noise in PE image is "smeared", increasing background levels • Regularization scheme is less effective for Compton than for PE • Metal artifacts challenging

Simultaneous segmentation/ reconstruction

Pros	Cons
• Allows use of prior knowledge about materials • Reduces (eliminates!) scatter in material properties inside object	• Current method limited to homogenous objects • Depends on good initialization • Computation grows with ROI area

Recommendations for Future Work

- **Correct for metal!**

- **Patch-based regularization**:
  - Apply to limited-view scenarios (see final report)
  - Apply to multi-energy data
  - Apply to sinogram pre-processing methods, such as YNC
  - Exploit convexity: explore speed gains from ADMM-type algorithms

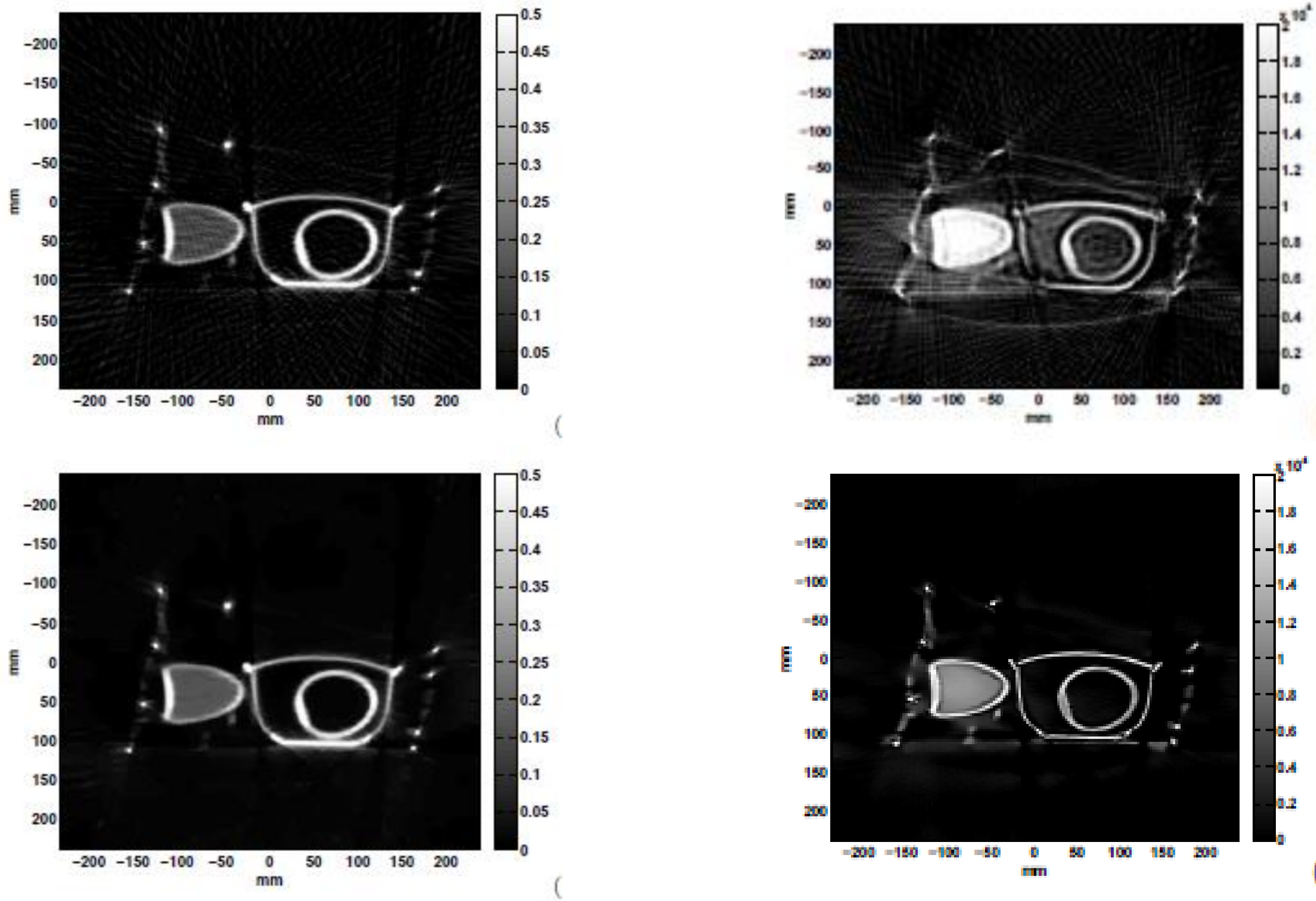
- **Level-set methods**:
  - Move beyond homogeneous objects to *texture-based* segmentation
  - Explore convex formulations that would reduce sensitivity to initialization and allow reprocessing of entire image, not just ROI

Subsampled data – HC1, Slice 70

Compton | Photoelectric

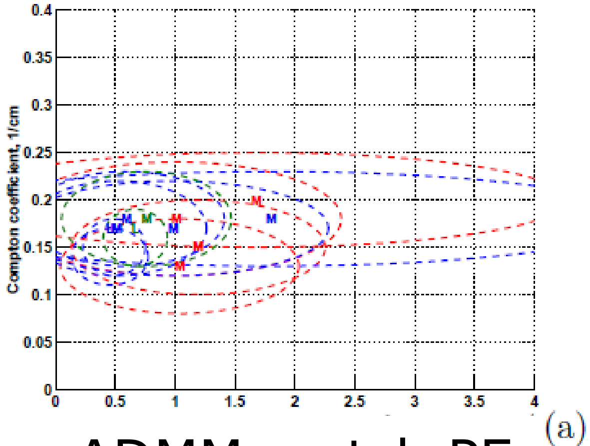
Iterative, no reg.

Regularlized

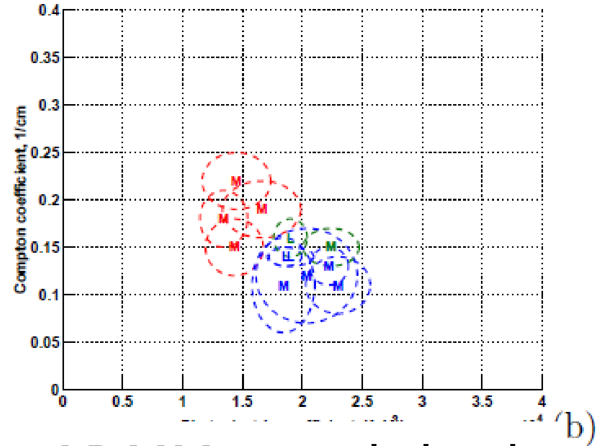


Low/Medium "Clouds vs Method

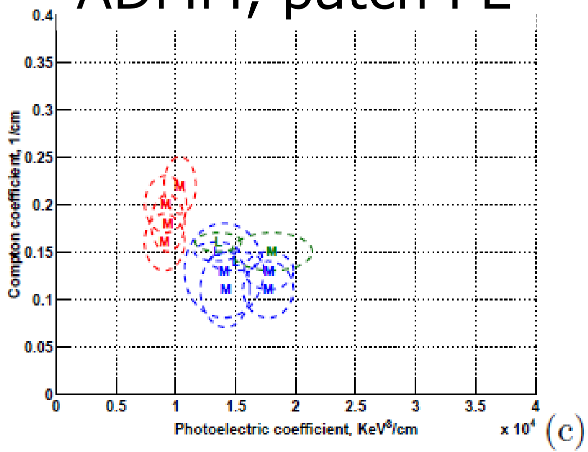
"Legacy"



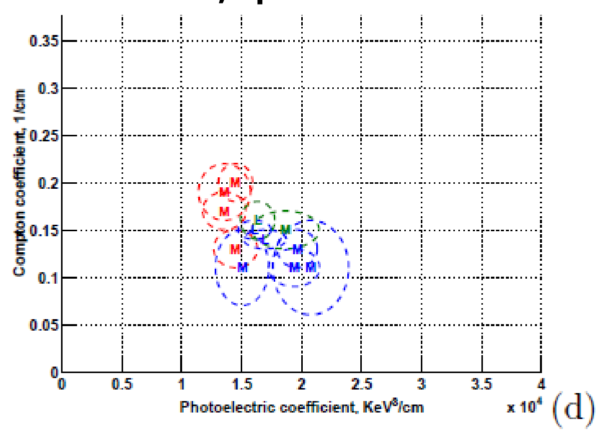
Cyclic Descent



ADMM, patch PE



ADMM, patch both

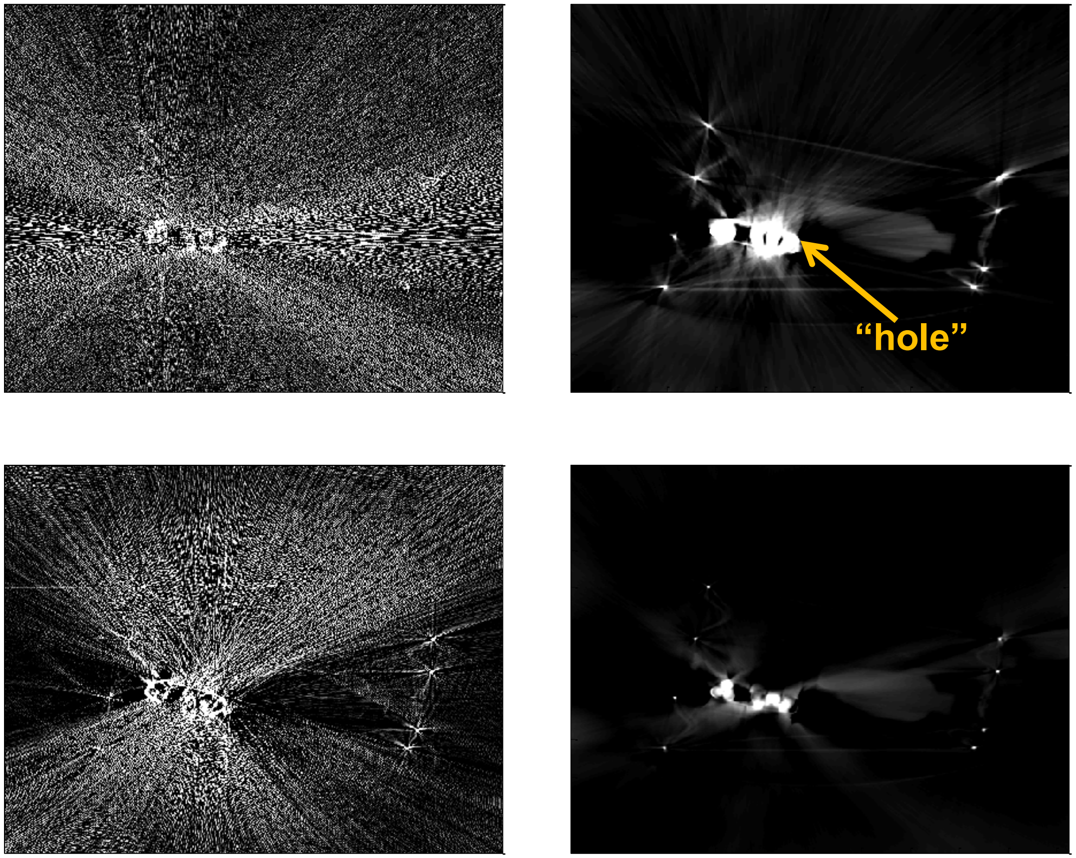


Problems with metal artifacts
Example: High Clutter 1, Slice 350

Legacy | Patch-regularized ADMM

Compton

Photoelectric



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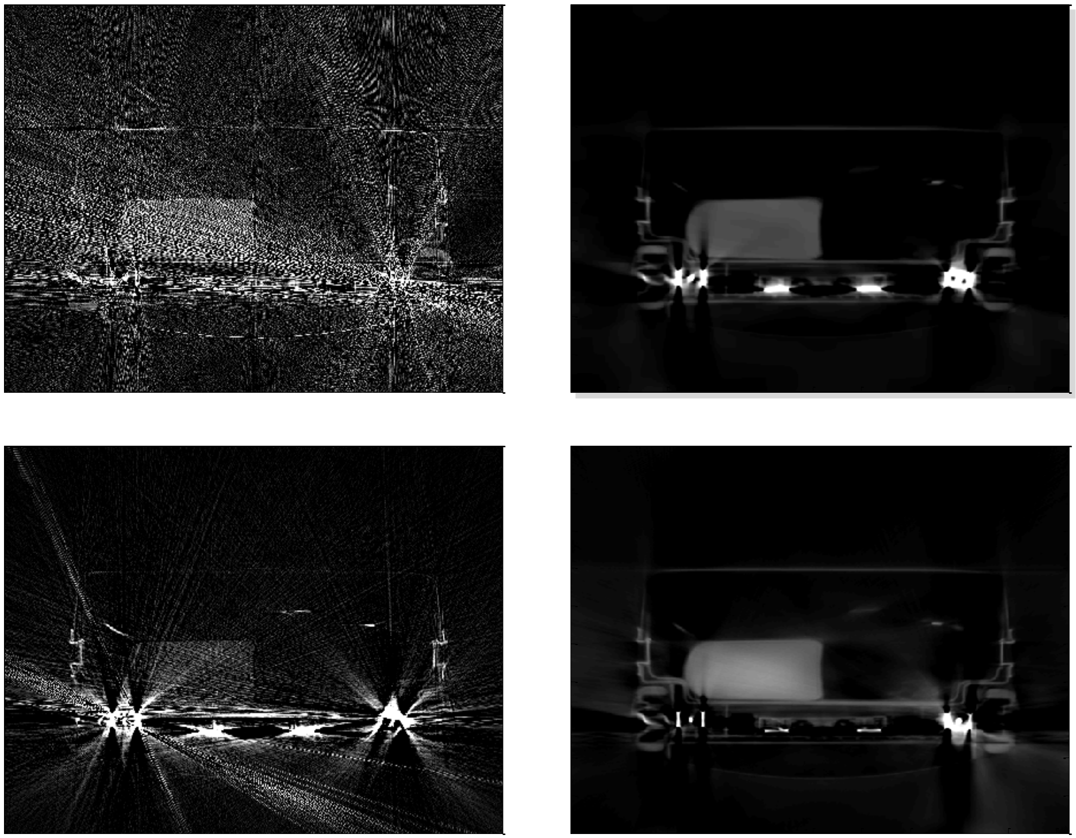
New method vs "Legacy"

Medium Clutter 1, Slice 038

Legacy | Regularized ADMM

Compton | Photoelectric



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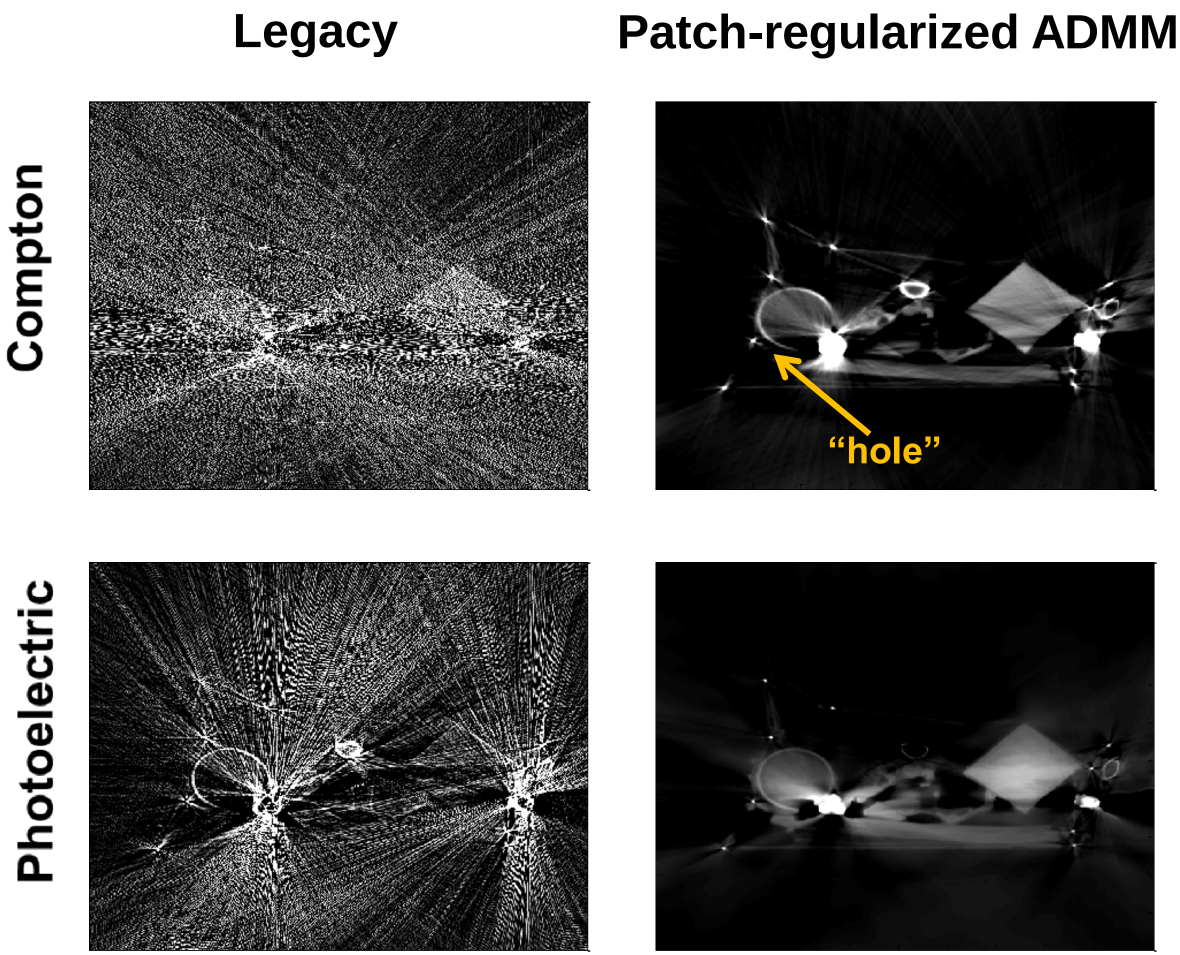
Problems with metal artifacts

Example: High Clutter 1, Slice 220



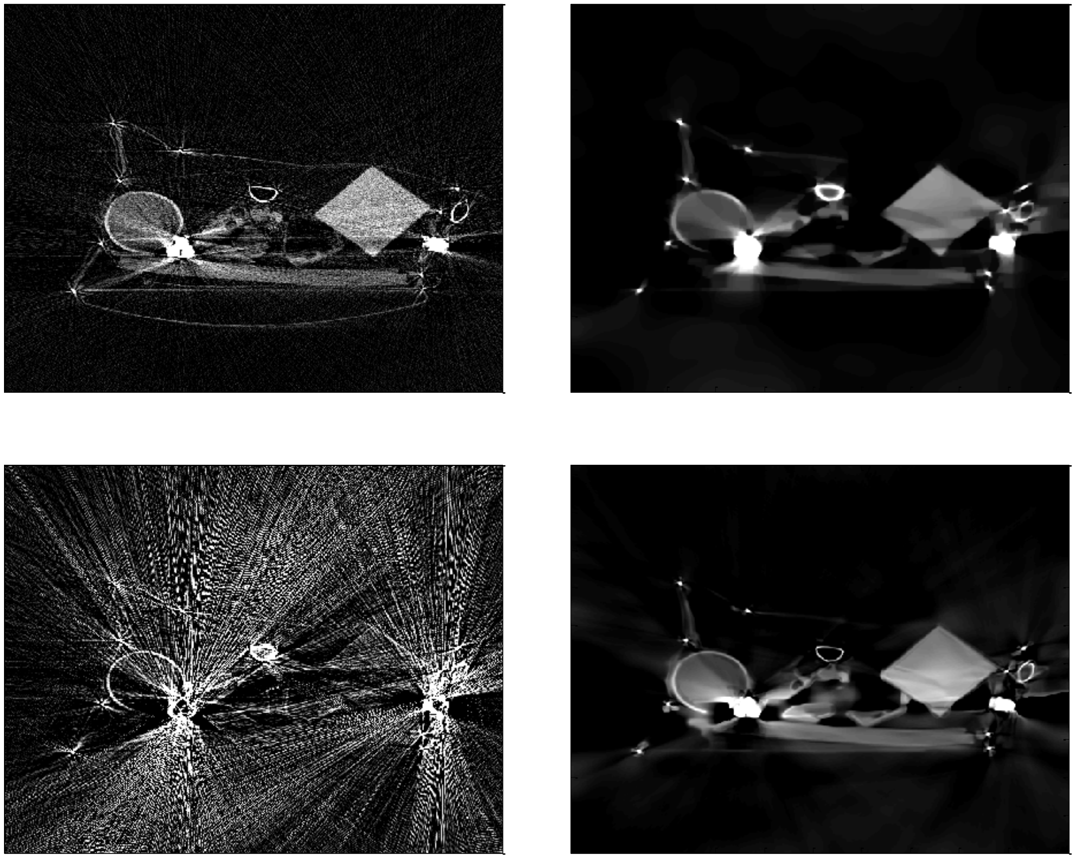
- Impact on water bottle

Image dynamic range:
Compton 0-0.5 1/cm; Photoelectric 0-6e4 KeV/cm

Problems with metal artifacts
Example: High Clutter 1, Slice 220

Legacy | **Patch-regularized ADMM High TV on Compton**

Compton / **Photoelectric**



- Impact on water bottle
- Can **partially** control Compton artifacts through regularization - here, Total Variation
- However, need for additional metal artifact handling

Image dynamic range:
Compton 0-0.5 1/cm; Photoelectric 0-6e4 KeV/cm

Example Comparison to YNC

Medium Clutter 1, Slice 231

YNC method | **Patch-regularized ADMM**

Compton

Photoelectric

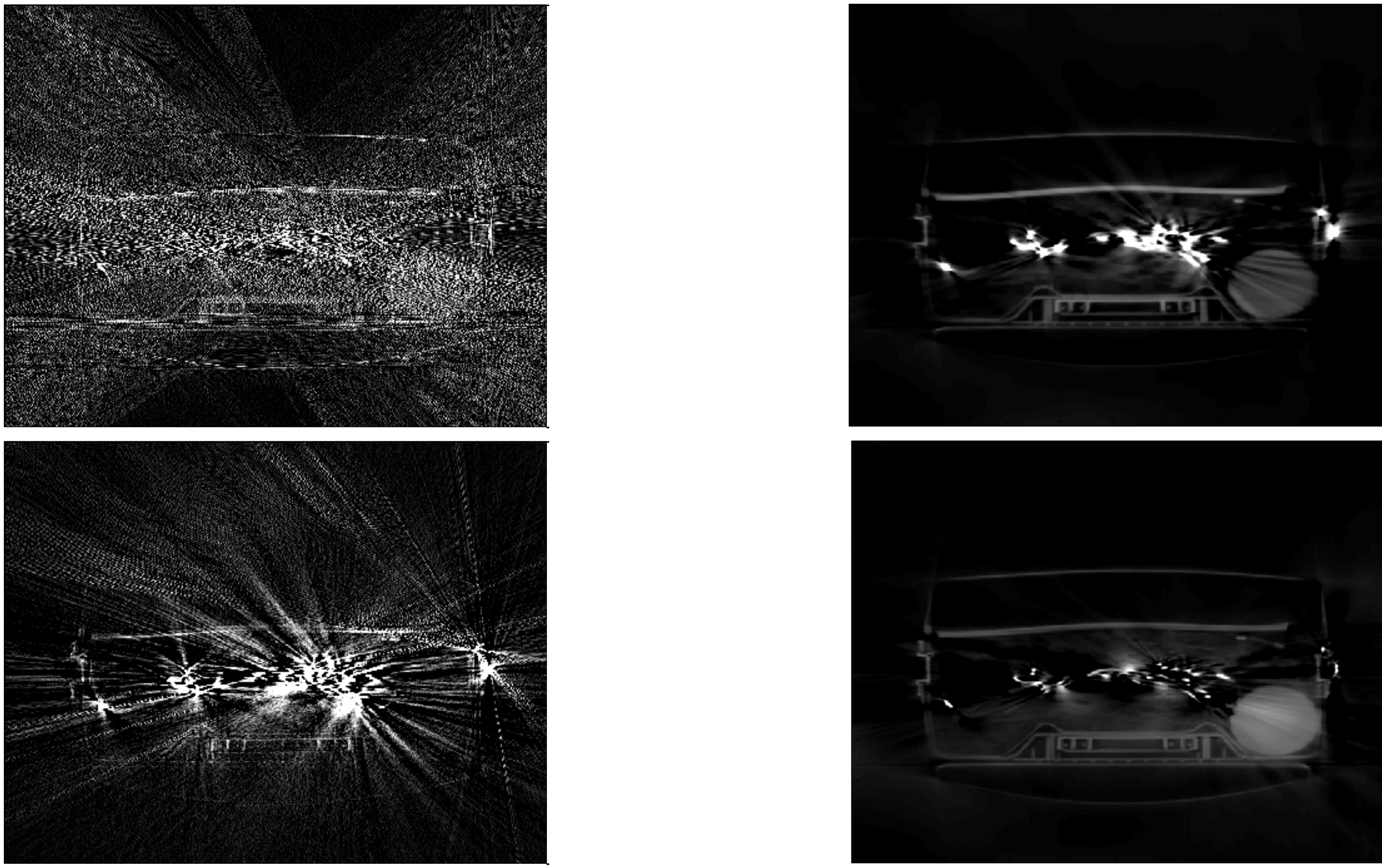


Image dynamic range:
Compton 0-0.5 1/cm; Photoelectric 0-4e4 KeV/cm

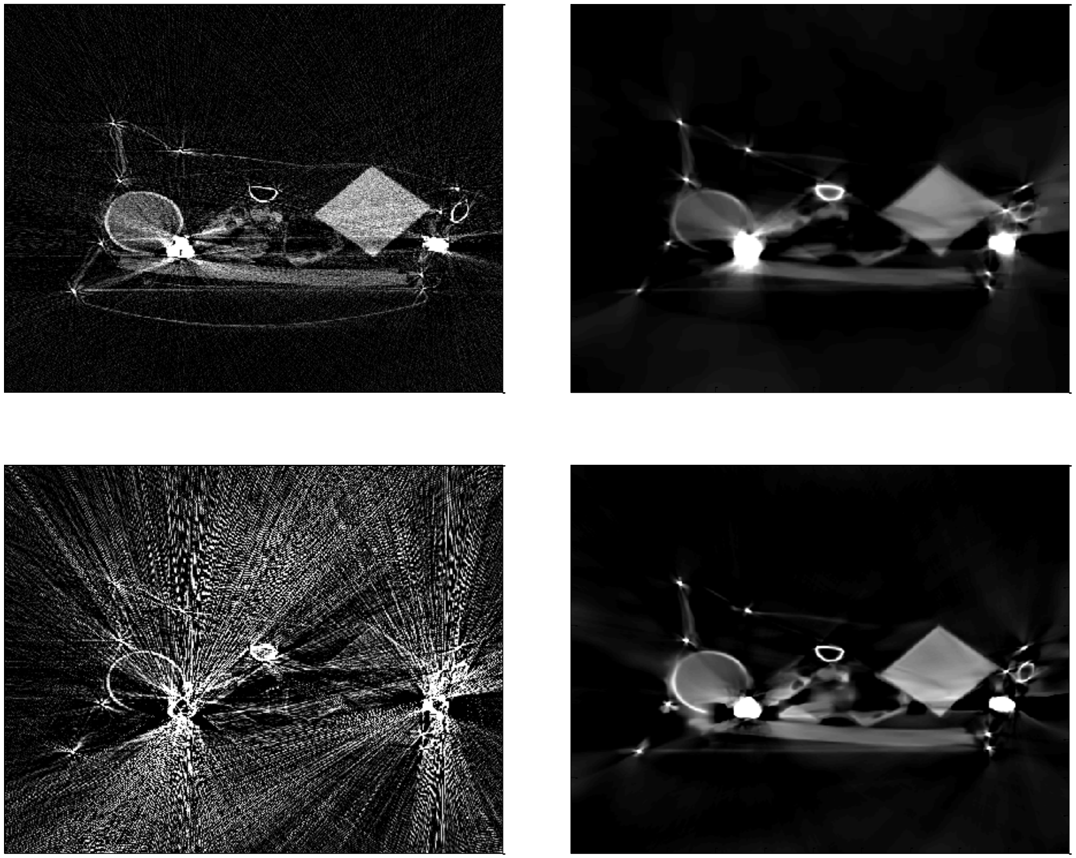
Problems with metal artifacts

Example: High Clutter 1, Slice 220

Legacy **Patch-regularized ADMM very high patch**

Compton

Photoelectric



- Can **partially** control Compton artifacts through regularization
  1) Use FBP image to <u>stabilize Compton</u> (patch-based)
  2) Use Total Variation

- However, need for additional metal artifact handling

Image dynamic range:
Compton 0-0.5 1/cm; Photoelectric 0-7e4 KeV/cm

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