Coding for X-ray Diffraction Imaging

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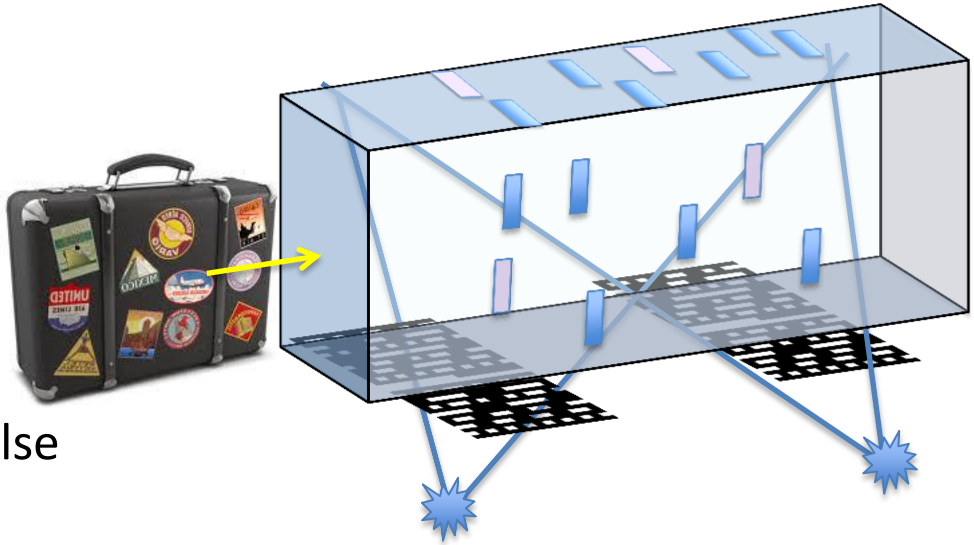
Introduction

- **Goal:** detect presence of threat substances in carry-on baggage

- **Primary constraints/challenges:**
  - Fast scan time (< 5s/bag) for high throughput
  - Good specificity and sensitivity to broaden threat space and reduce false alarm rate



- **Approach:** compressively acquire and combine transmission and coherent scatter signals to obtain material-specific signature at each voxel

- **Results**: structured illumination + energy-sensitive detection make real-time imaging possible

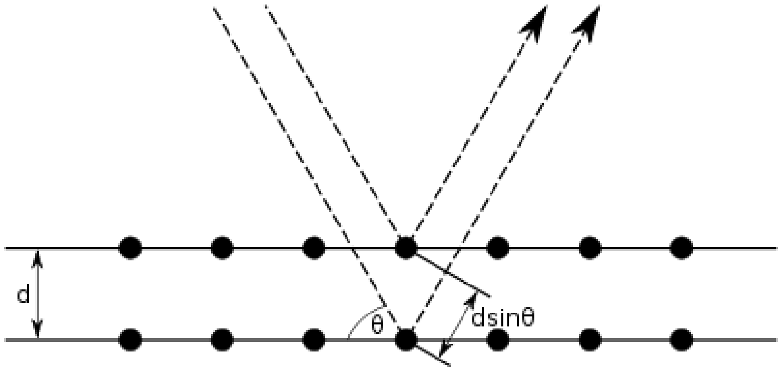
Background

Coherent x-ray scatter

Bragg's law

$$q = \frac{E}{hc}\sin\left(q/2\right)$$

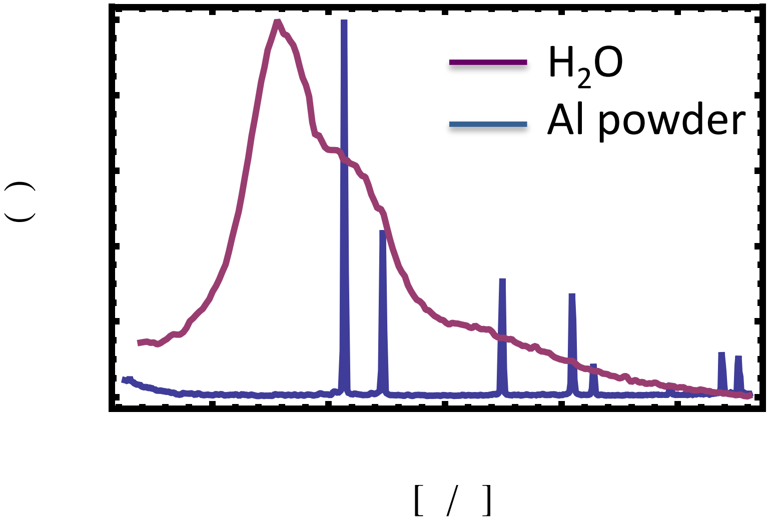
q=1/2d: momentum transfer
θ: scatter angle
E: x-ray energy



Differential cross section

$$\frac{ds}{dW} \propto \left[1+\cos(q)^2\right] f(q,\boldsymbol{r})$$

f(q,r): position-dependent form factor



Techniques to measure f(q)

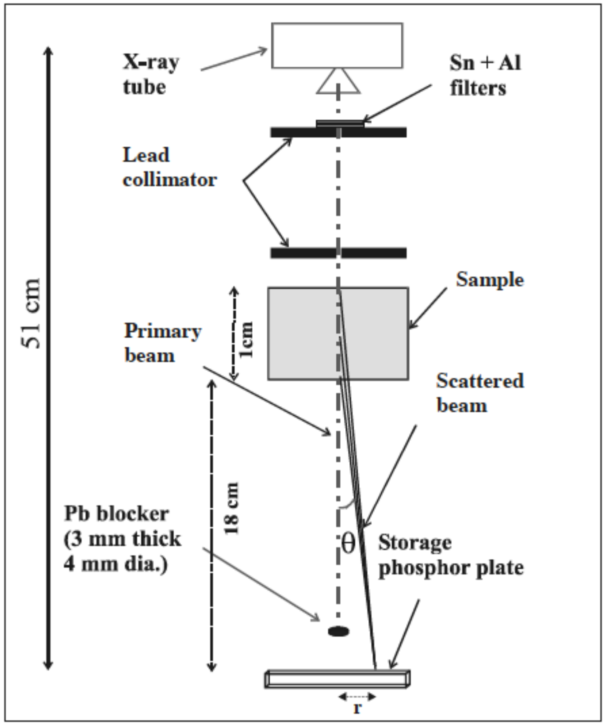
$$q = \frac{E}{hc}\sin\left(q/2\right)$$

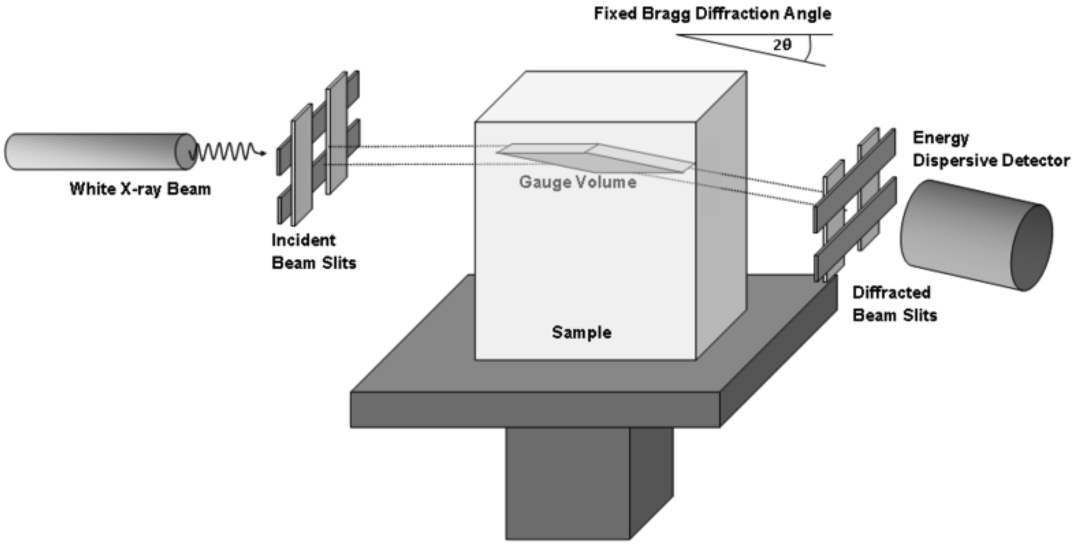
Angle-dispersive

- Study θ dependence of scatter for fixed E

Energy-dispersive

- Study energy dependence of scatter for fixed θ

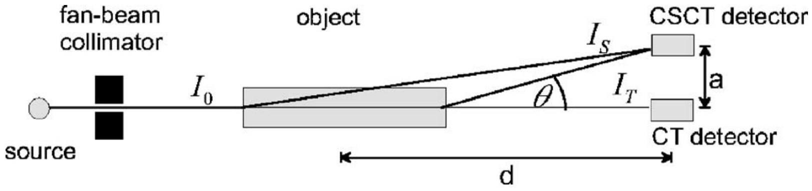




Coherent scatter imaging

<u>Coherent scatter computed tomography (CSCT)</u>

- Rotate/translate object
- Multiplexed
- State of the art: several minutes/2D slice



Delfs et al., Appl. Phys. Lett. 88, 243506 (2006)
Angew. Chem. Int. Ed. 50, 10148 (2011)
Harding et al., Phys. Med. Biol., Vol. 35, No 1, 33-41 (1990)
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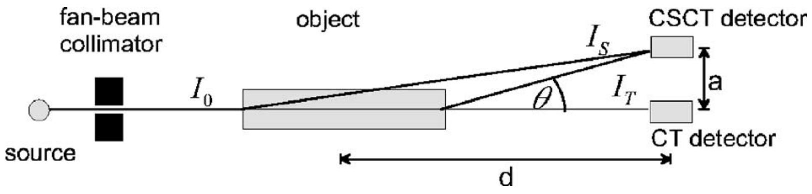
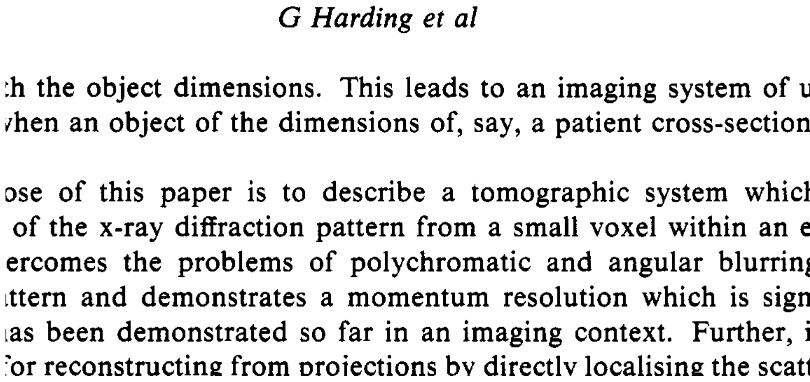


Selected volume tomography

- Scan object/collimators
- Non-multiplexed
- State of the art: several seconds/voxel



G Harding et al

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of the x-ray diffraction pattern from a small voxel within an e
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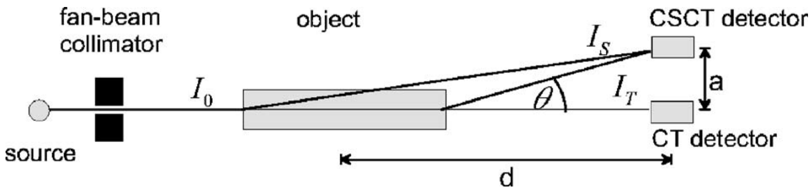
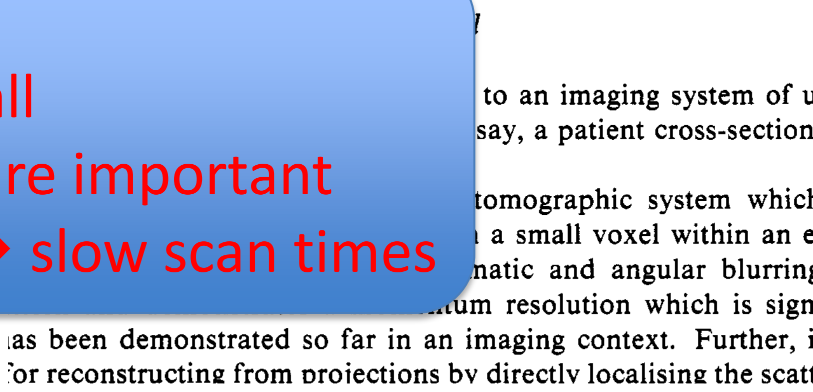


Selected volum

- Scan ob
- Non-mu
- State o



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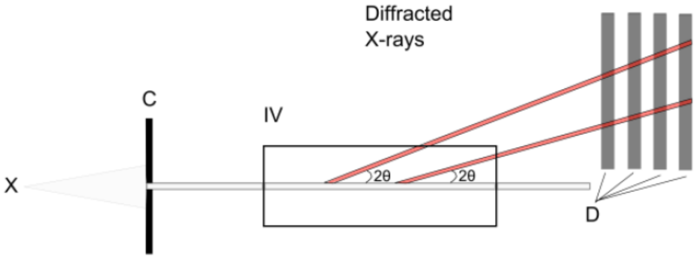
Primary challenges:

- scatter rates are small
- attenuation effects are important

Poor photon efficiency → slow scan times

Kinetic Depth Effect X-ray diffraction (KDEXRD)

- Move detector
- Multiplexed
- State of the art: 10 min/voxel



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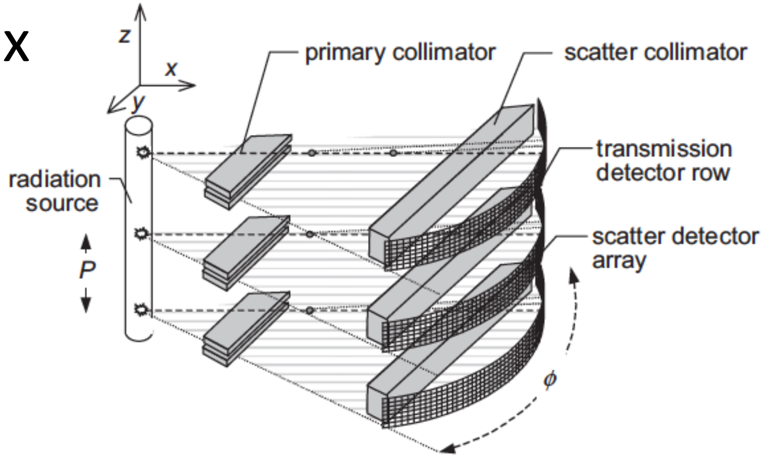
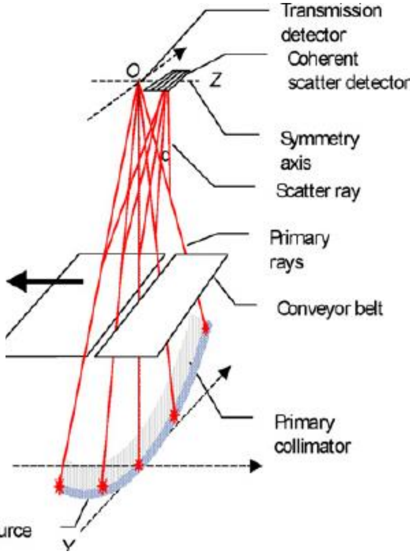
Speeding things up

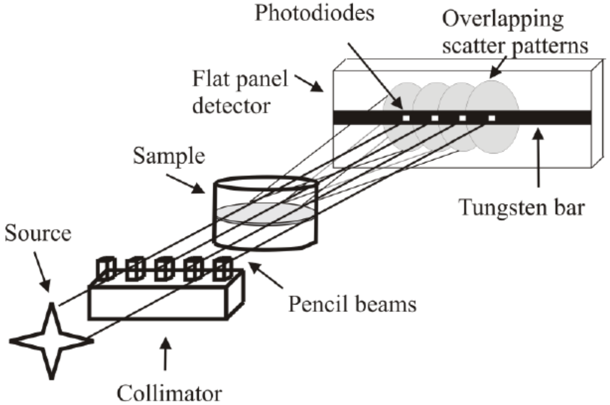
- Increase incident x-ray flux
  - - more current
  - - less filtering

- Use multiple beams
  - - in series
  - - in parallel (non-multiplexed)
  - - in parallel (multiplexed)

- Focus scatter
  - - multiple sources
  - - shaped sources







Harding et al., Applied. Rad. And Isotopes, 67, 287 (2009)

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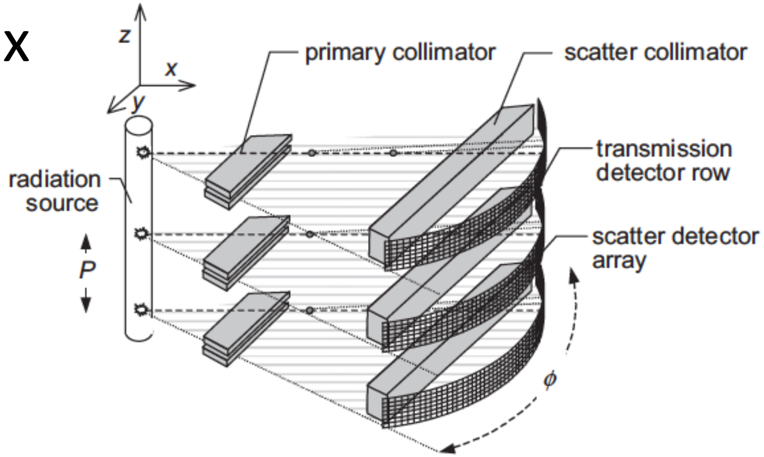

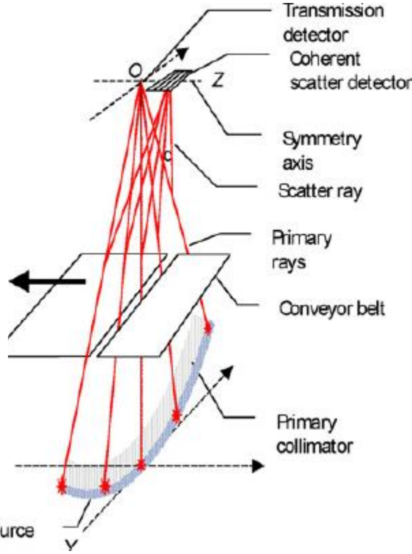

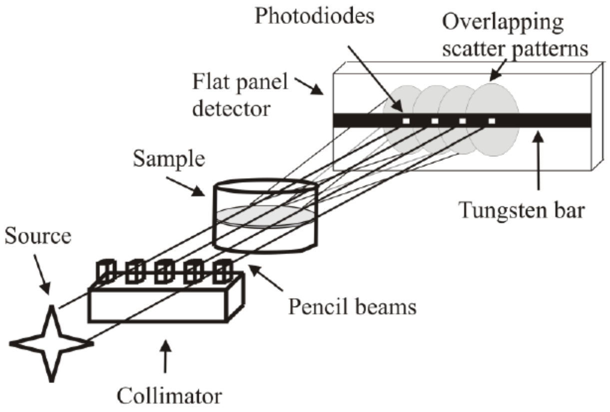

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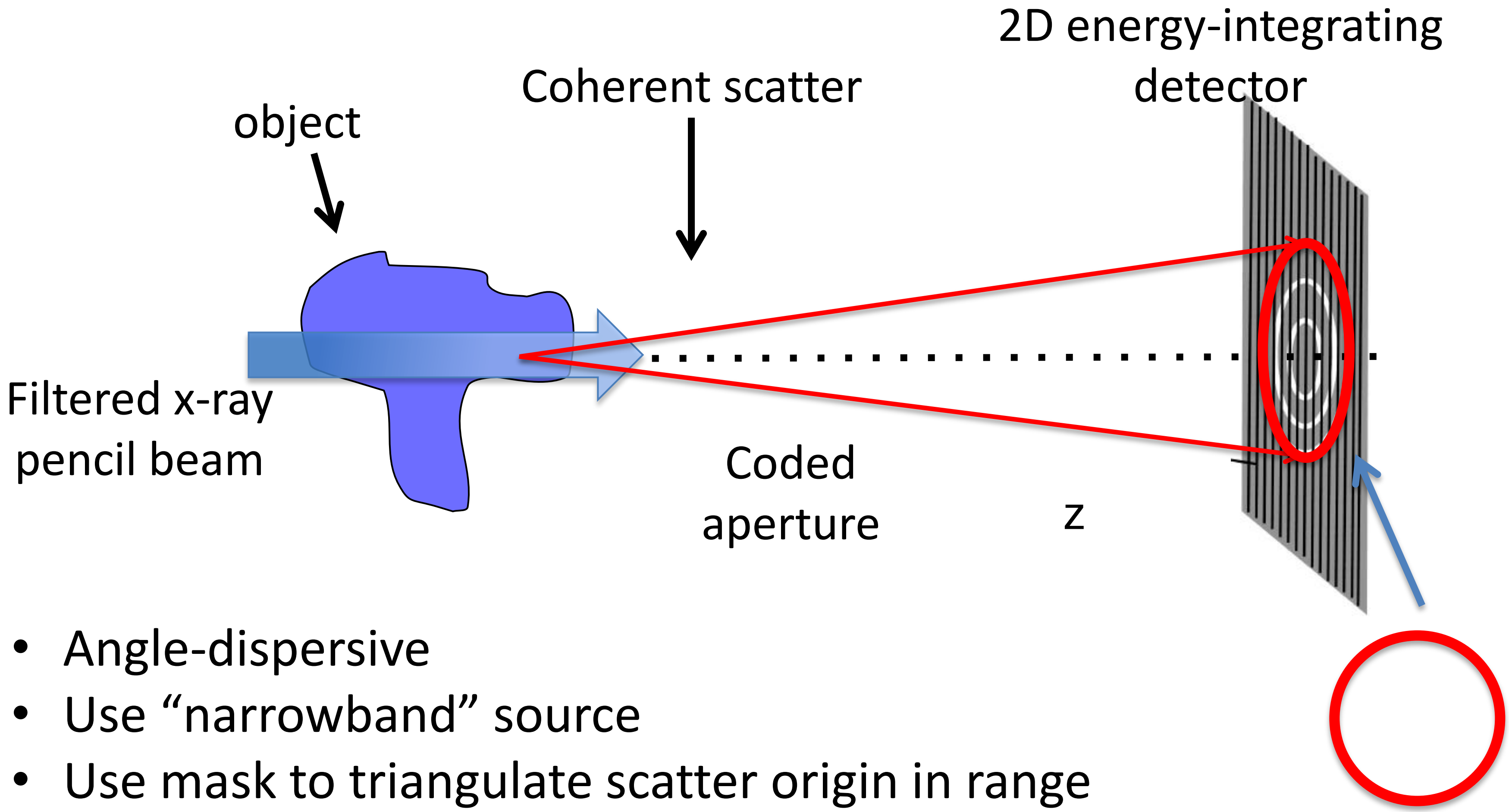
Coded aperture x-ray scatter imaging (CAXSI)

Pencil beam coded aperture x-ray scatter imaging (CAXSI)



2D energy-integrating detector

Coherent scatter

object

Filtered x-ray pencil beam

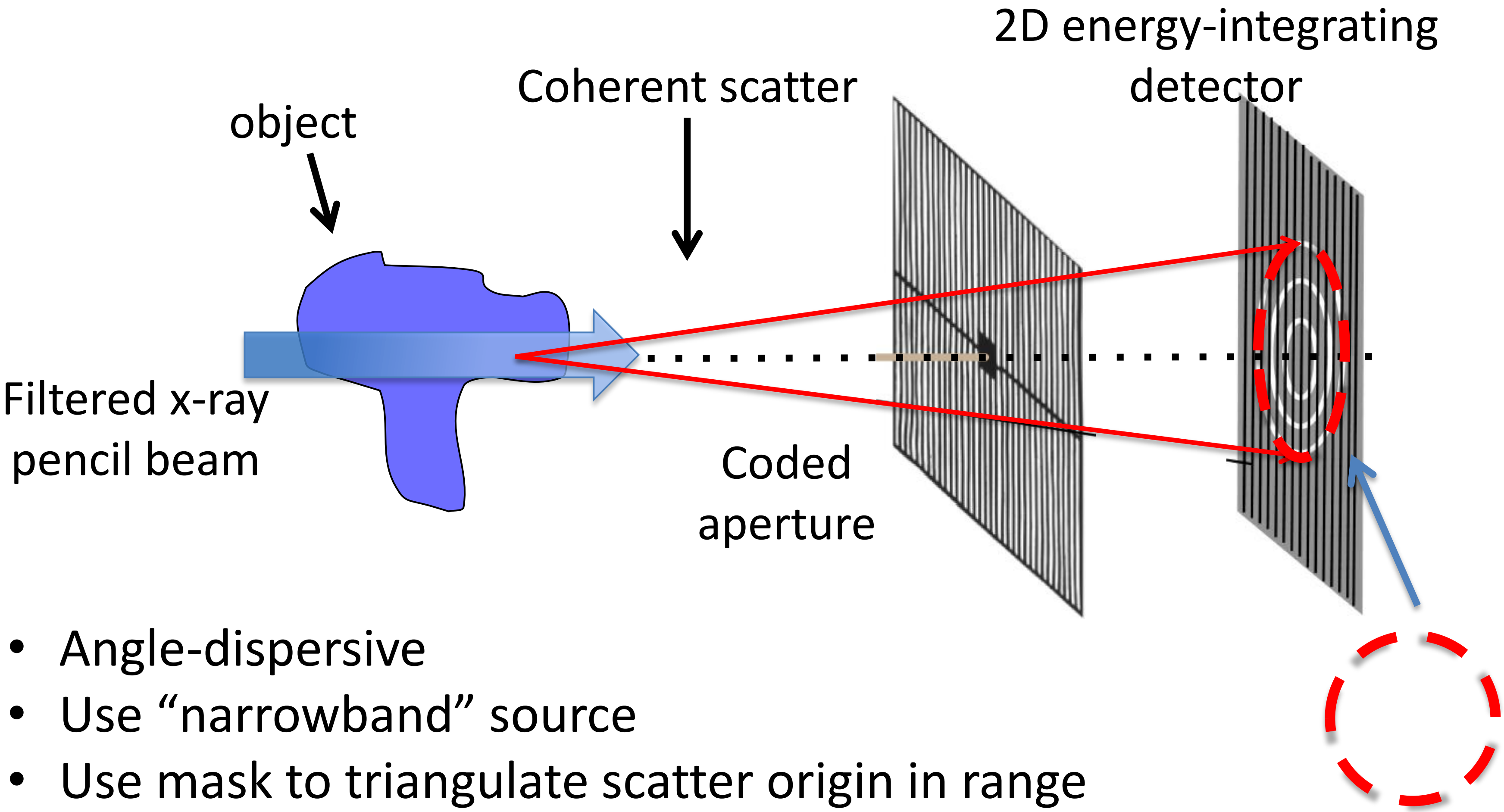
Coded aperture

z

- Angle-dispersive
- Use “narrowband” source
- Use mask to triangulate scatter origin in range
- Snapshot acquisition

MacCabe et al., Opt. Exp. 20, 16310 (2012)

Pencil beam coded aperture x-ray scatter imaging (CAXSI)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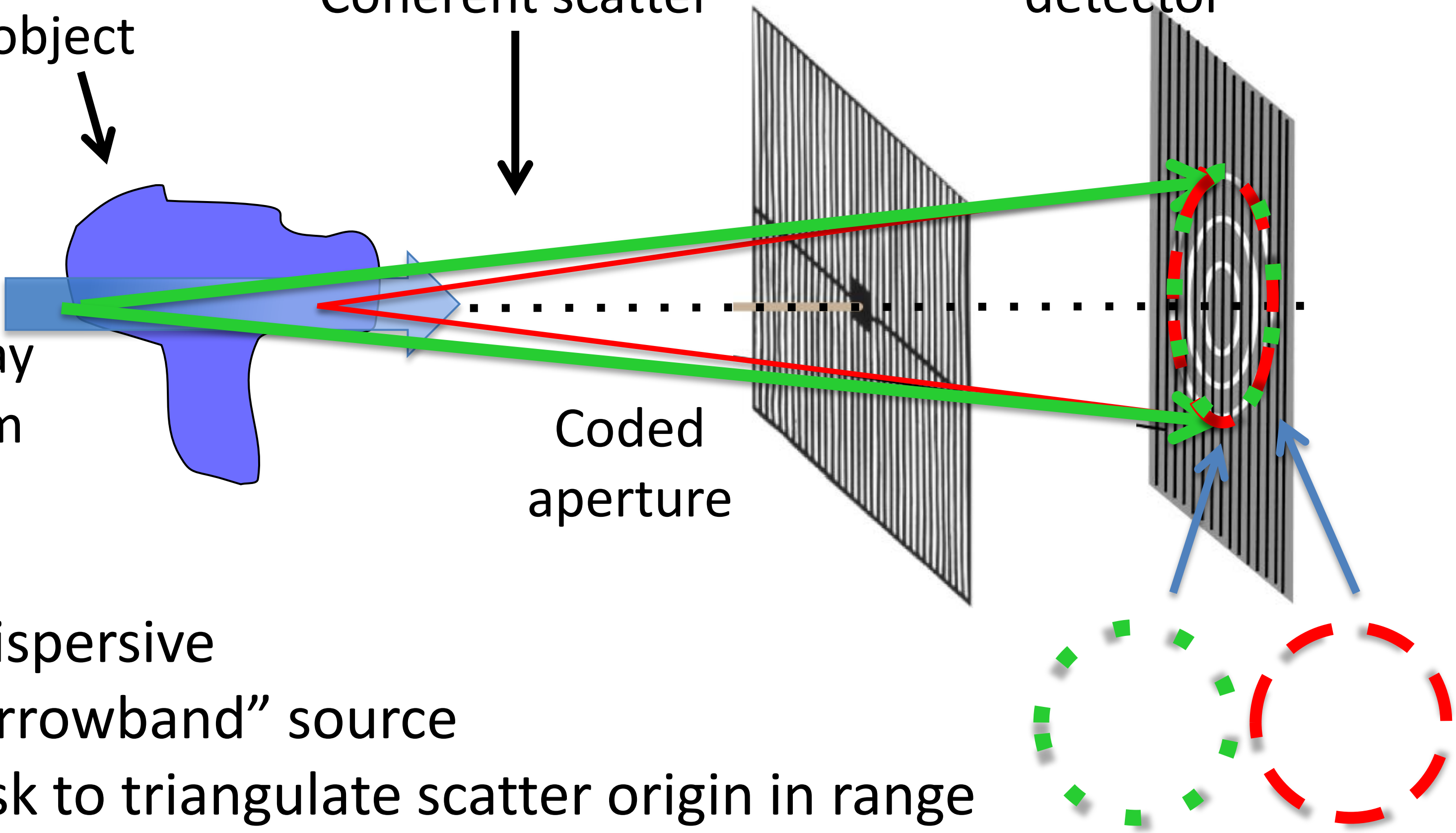

2D energy-integrating detector

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- Angle-dispersive
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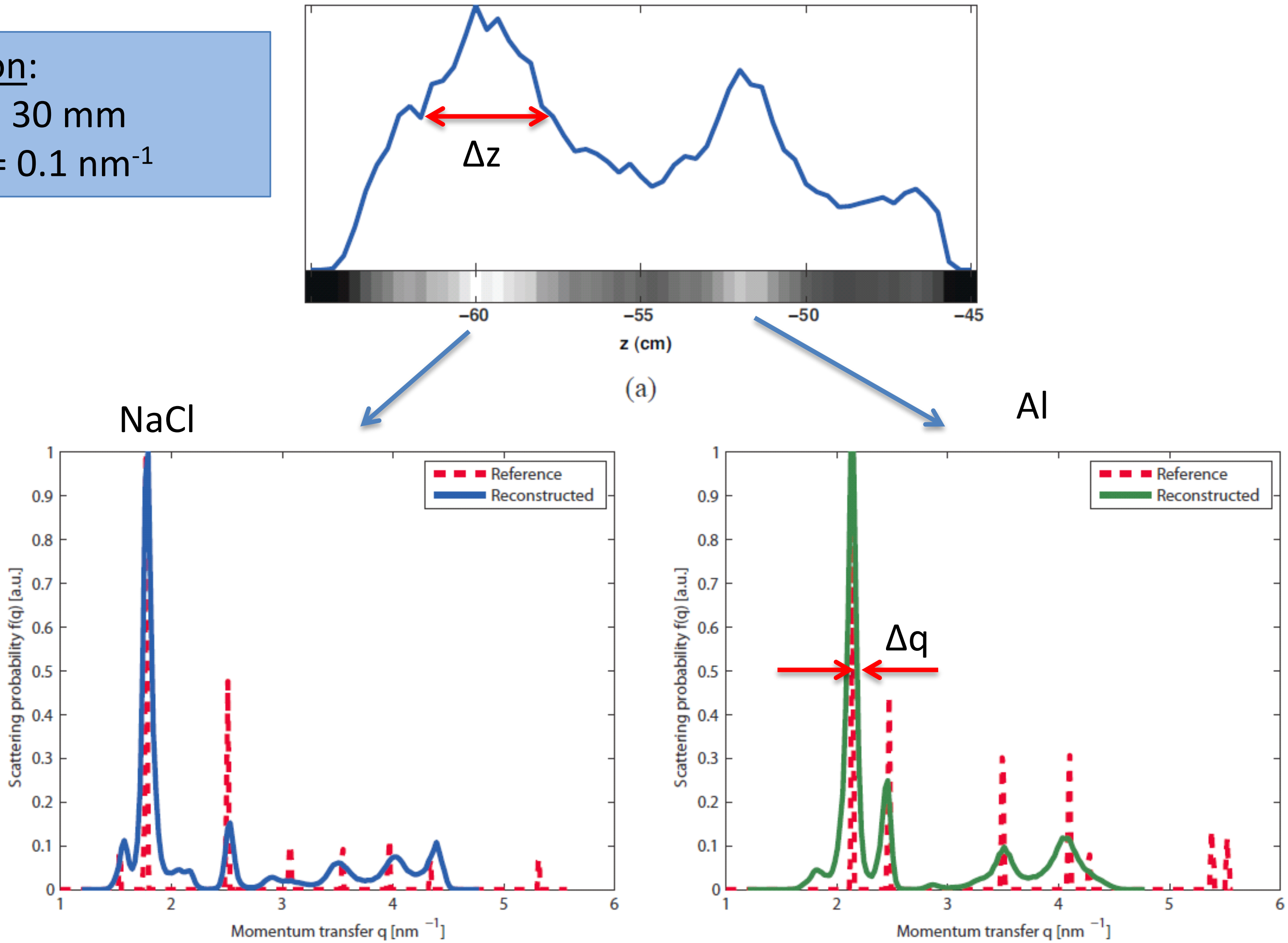
MacCabe et al., Opt. Exp. 20, 16310 (2012)

Imaging results

Resolution:

Δz = 30 mm

$\Delta q = 0.1\ \mathrm{nm}^{-1}$



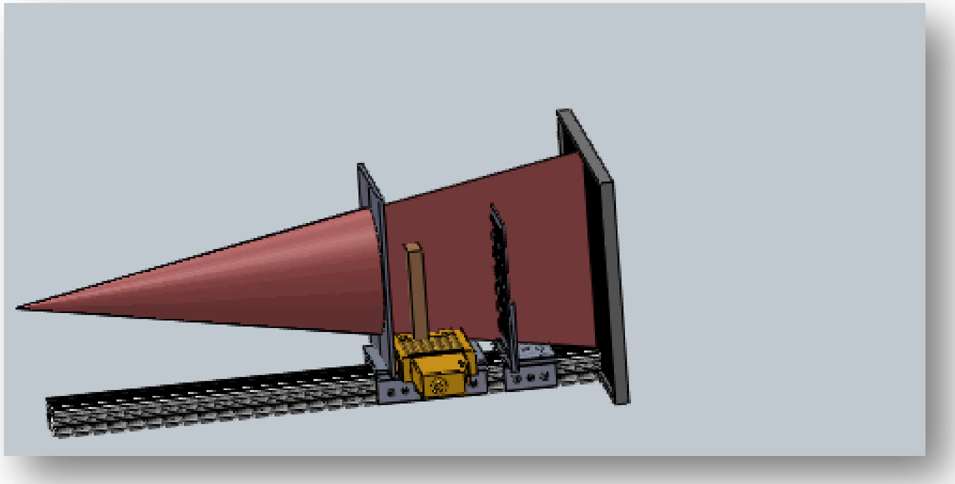
MacCabe et al., Opt. Exp. 20, 16310 (2012)

Snapshot fan-beam tomography

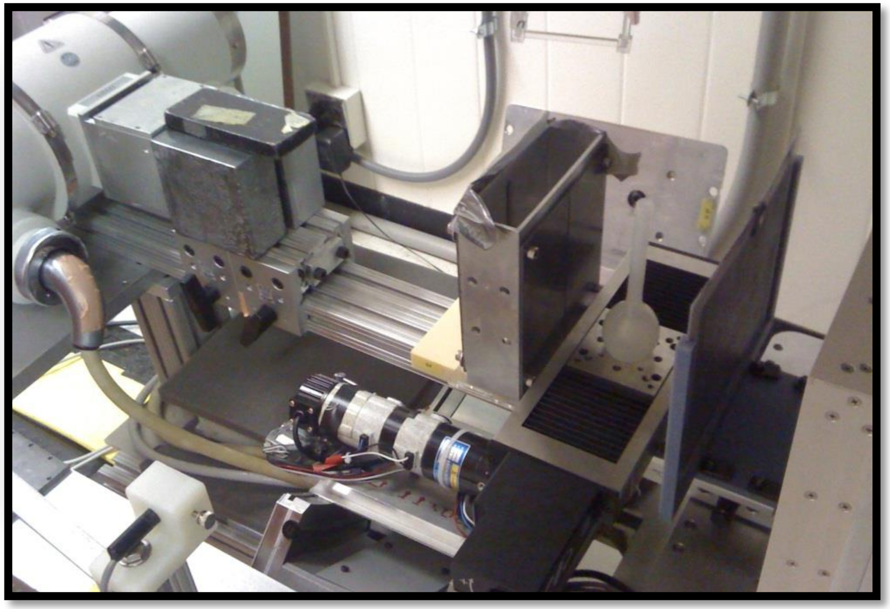
Extend results to fan-beam geometry

- Get range, cross-range, and angular scattering profile

Animation of experimental assembly

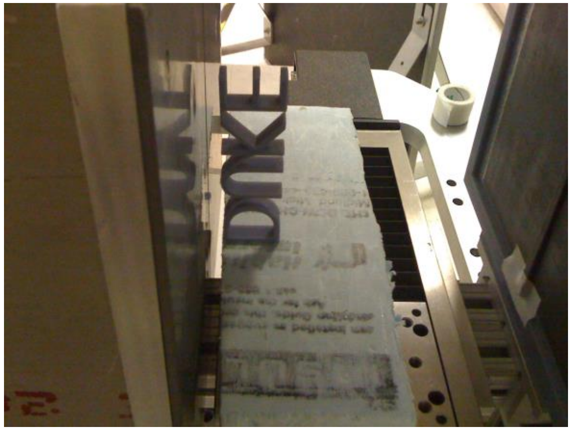


Experimental Setup at Duke MMIL

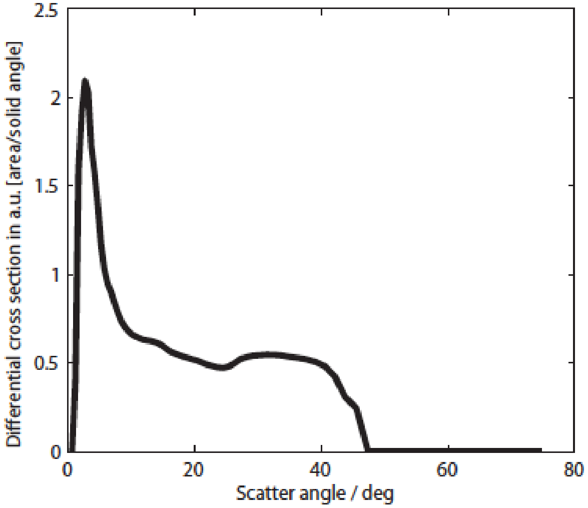


K. MacCabe, A. Holmgren, M. Tornai, and D. Brady, "Snapshot 2D tomography via coded aperture x-ray scatter imaging," Appl. Opt. 52, 4582-4589 (2013).

Snapshot fan-beam tomography



DUKE letters (plastic)
Single snapshot



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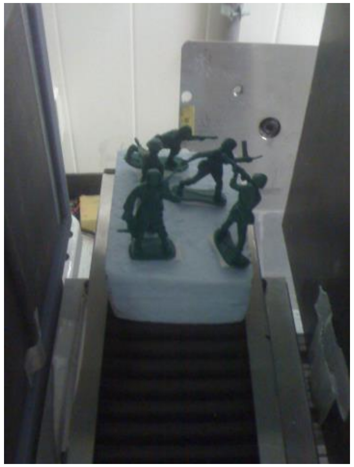
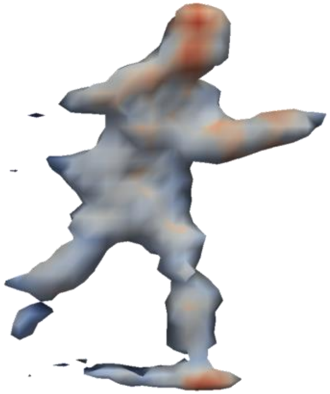
Multi-shot fan-beam tomography

Photo of object

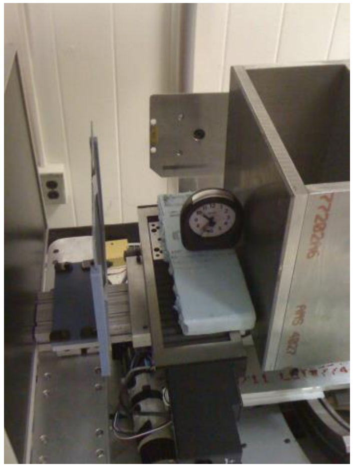
Volume reconstruction

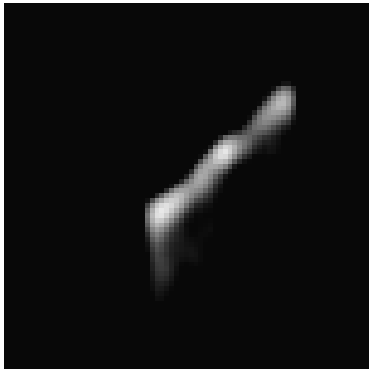
Toy army man
(3 spatial + 1 material)





Ticking clock
(2 spatial + 1 temporal + 1 material)



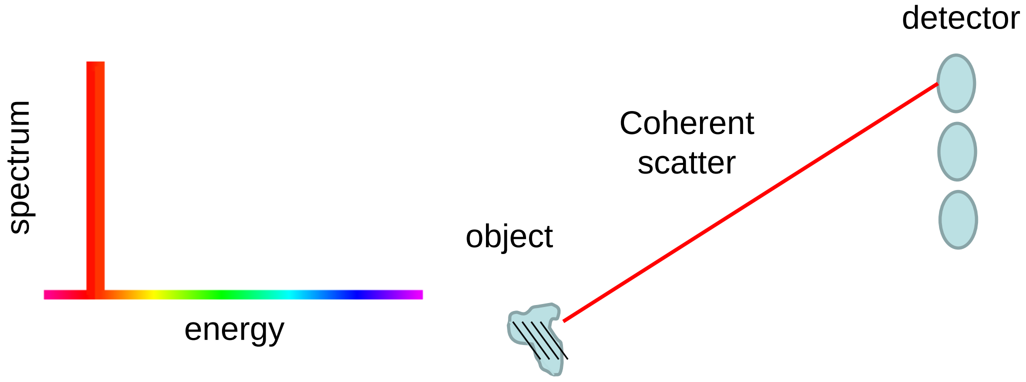


K. MacCabe, A. Holmgren, M. Tornai, and D. Brady, "Snapshot 2D tomography via coded aperture x-ray scatter imaging," Appl. Opt. 52, 4582-4589 (2013).

Coded aperture coherent scatter spectral imaging (CACSSI)

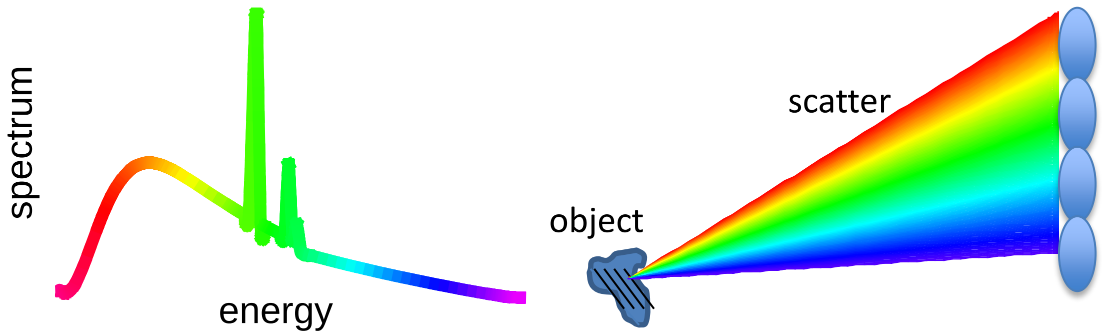
Broadband illumination

Monochromatic source



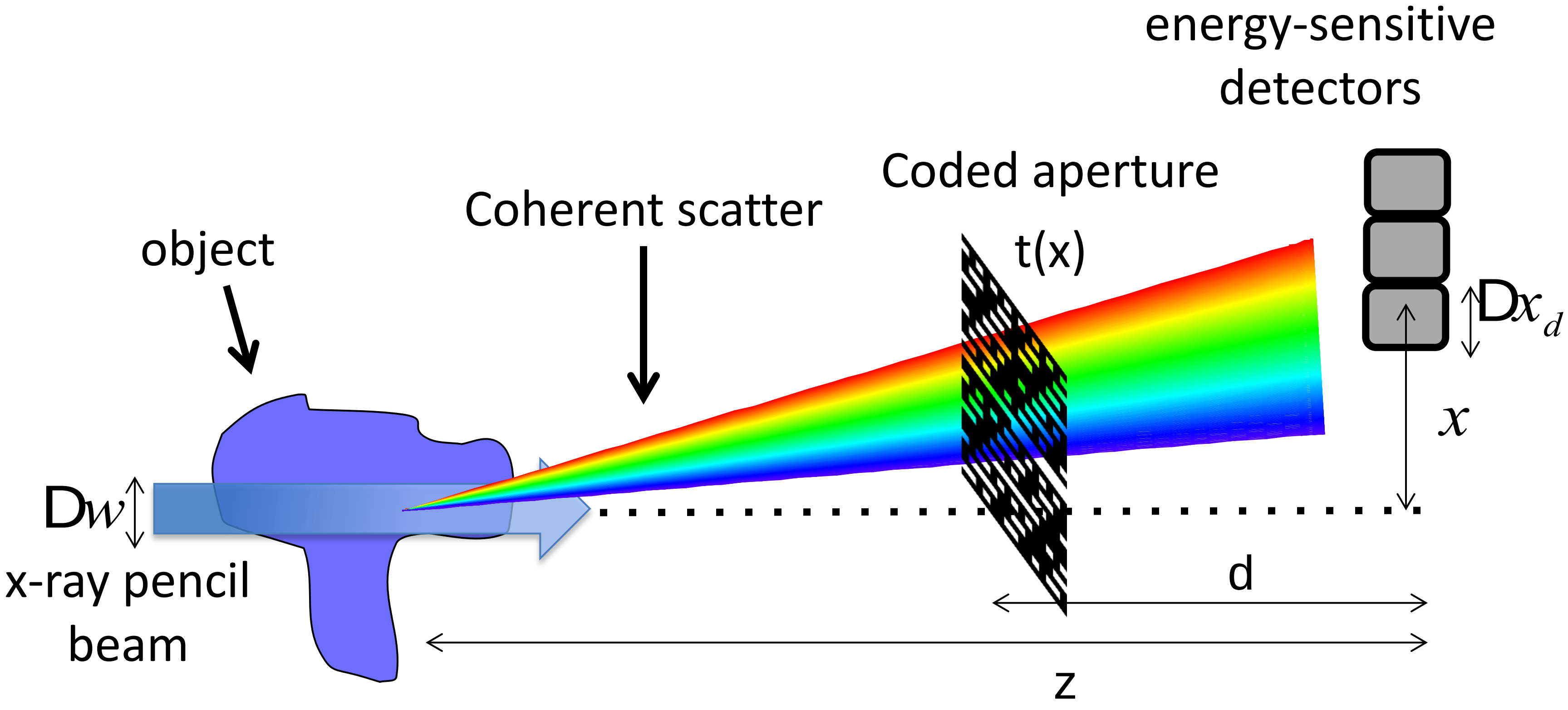
- Many photons thrown away
- Specific detector locations required

- Use all incident photons
- Range of available detector locations



J. A. Greenberg et al., Snapshot molecular imaging using coded energy-sensitive detection (2013)

Pencil beam geometry



J. A. Greenberg et al., Snapshot molecular imaging using coded energy-sensitive detection (2013) [under review]

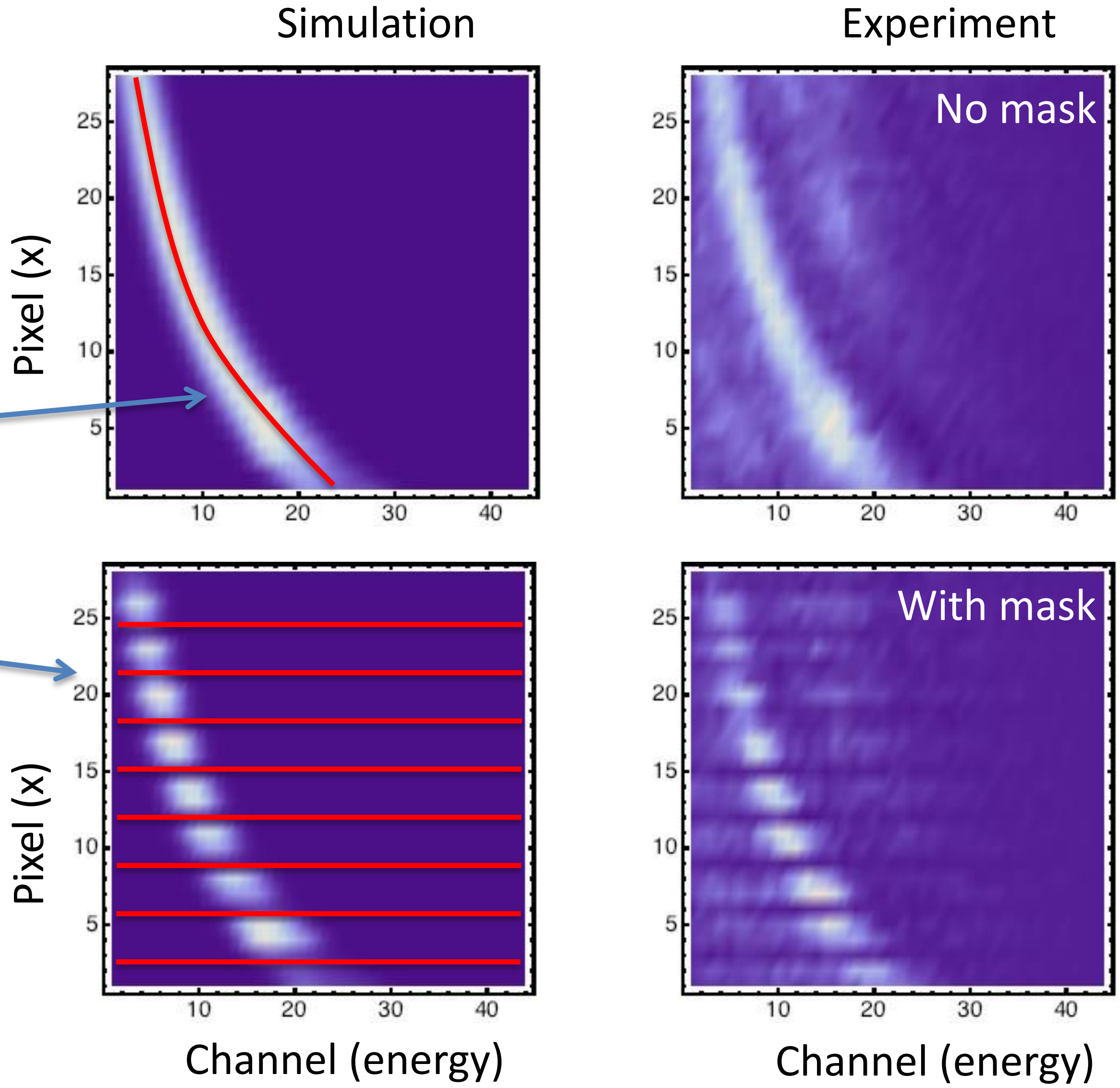
Raw measurements

Bragg's law

$x = 2 h c q z / E$

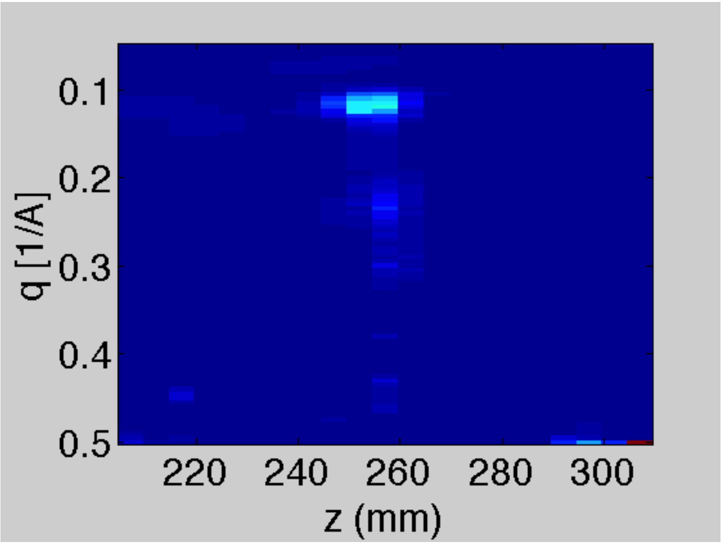
Coded aperture

$I_s \approx t[x(1-d/z)]$

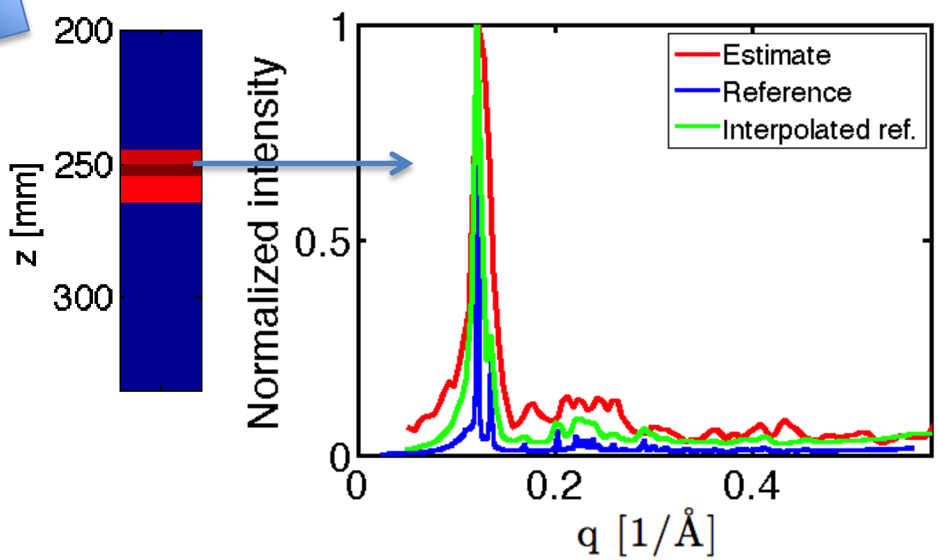


J. A. Greenberg et al., Snapshot molecular imaging using coded energy-sensitive detection (2013) [under review]

Single object reconstruction

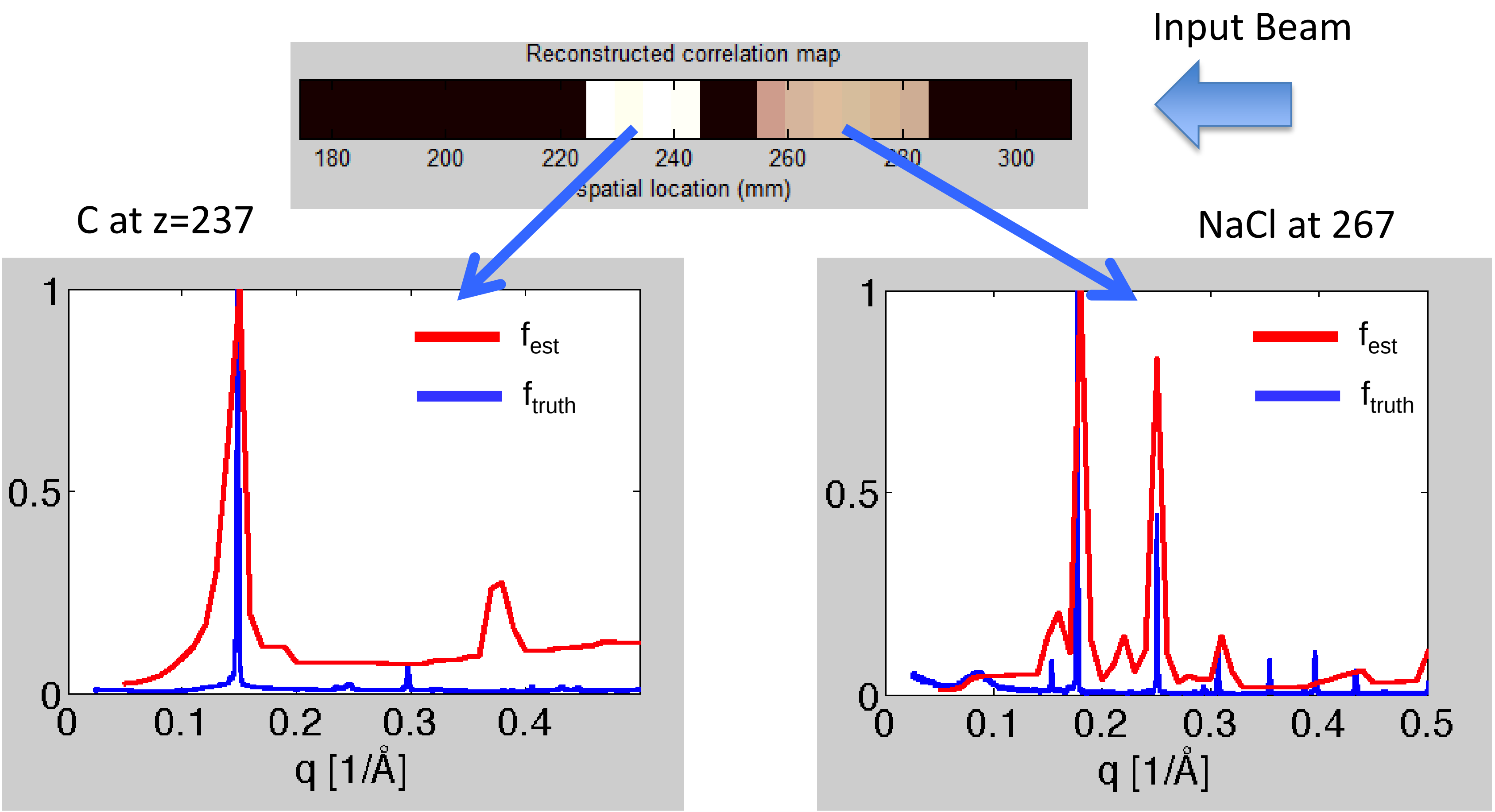

HDPE at z=252 mm

Converting to correlation map



J. A. Greenberg et al., Snapshot molecular imaging using coded energy-sensitive detection (2013)

Multi-object reconstruction



Input Beam

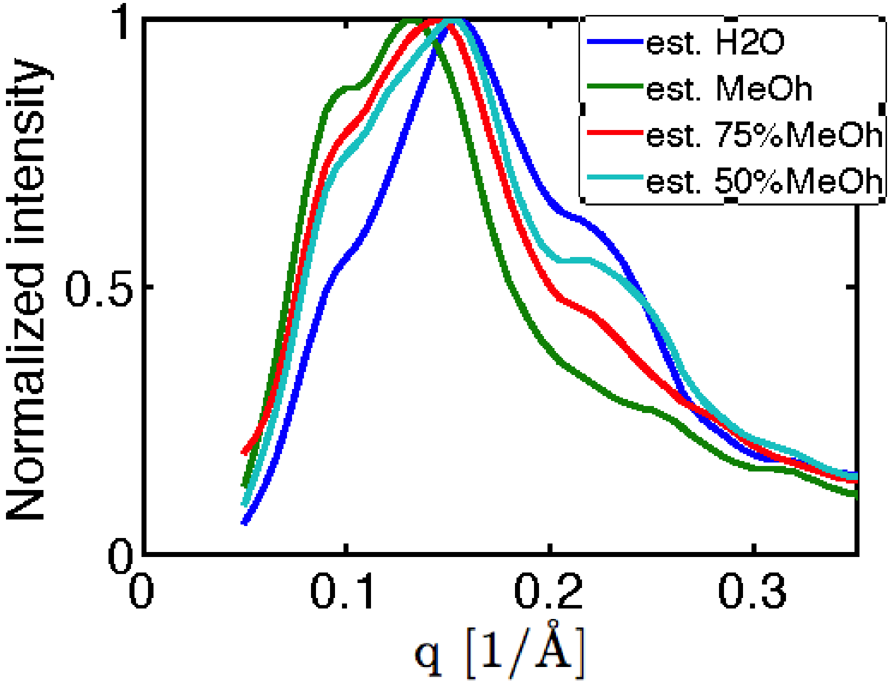
C at z=237

NaCl at 267

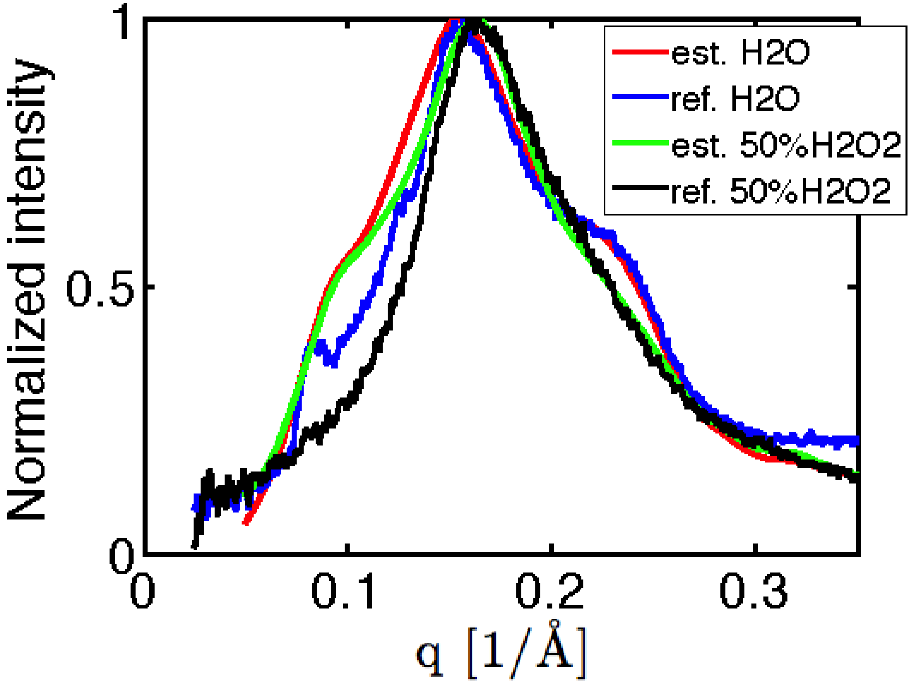
J. A. Greenberg et al., Snapshot molecular imaging using coded energy-sensitive detection (2013)

Water-like object discrimination

Different concentrations of H_20 + Methanol



H_20 + vs 50% H_2O_2



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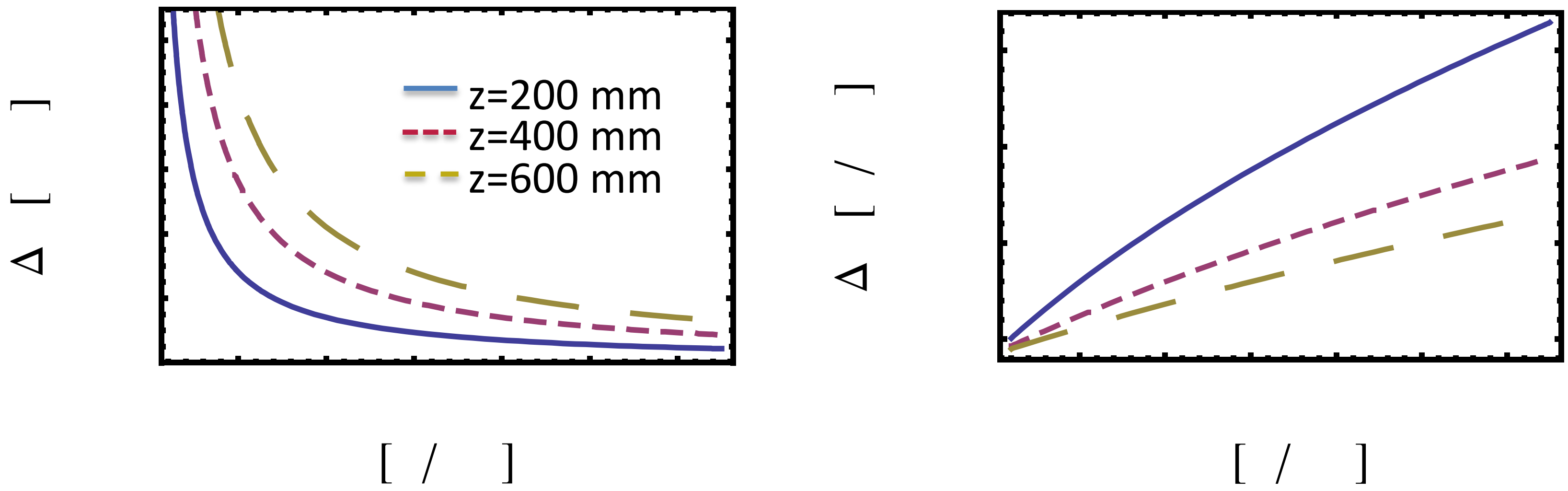
CACSSI resolution

Predictions



Observations

Δz~5 mm with

Δq<0.02 1/Å

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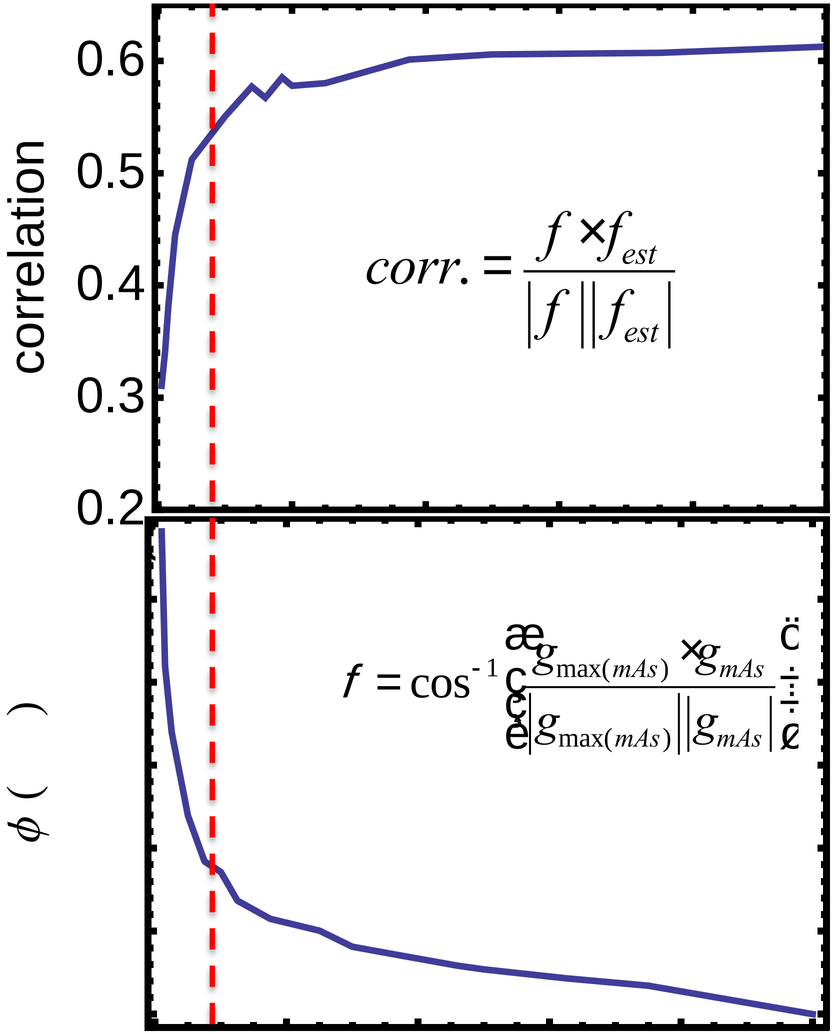
Dependence on mAs



Only ~100 mAs required to identify a range of materials with < 1% of total scatter signal collected

Lingering issues

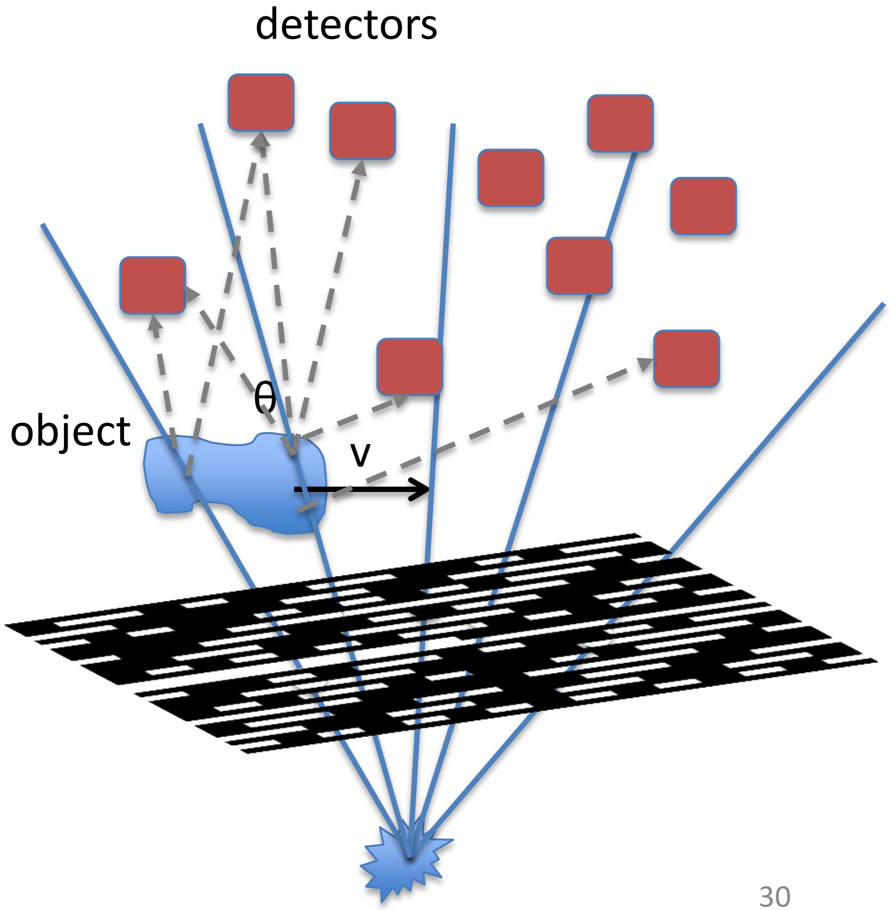
- Bulky
  - Detectors should be object thickness away from mask
- Difficult to scale to full 4D data cube
  - hard to code all dimensions
  - need higher-dimensional detector arrays ($)
- Bottom line: still too slow
  - Need more efficient use of source photons

Structured illumination coherent scatter imaging (SICSI)

Structured illumination

Measurement strategy

- Use code to modulate illumination before object
- Object moves through beams
- Acquire many spectra at different times using energy-sensitive pixels: g(E, t, x, y)



J. A. Greenberg et al., Structured illumination for tomographic molecular imaging (2013) [under review]

Structured illumination

Measurement strategy

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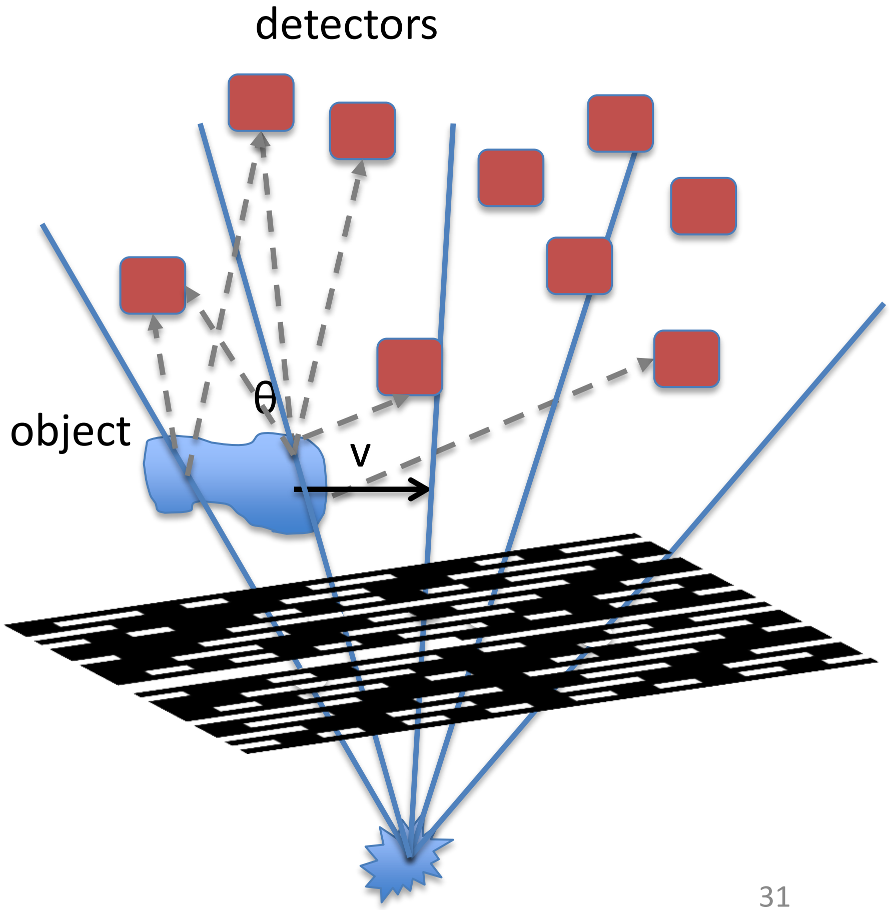
- Acquire many spectra at different times using energy-sensitive pixels: g(E, t, x, y)

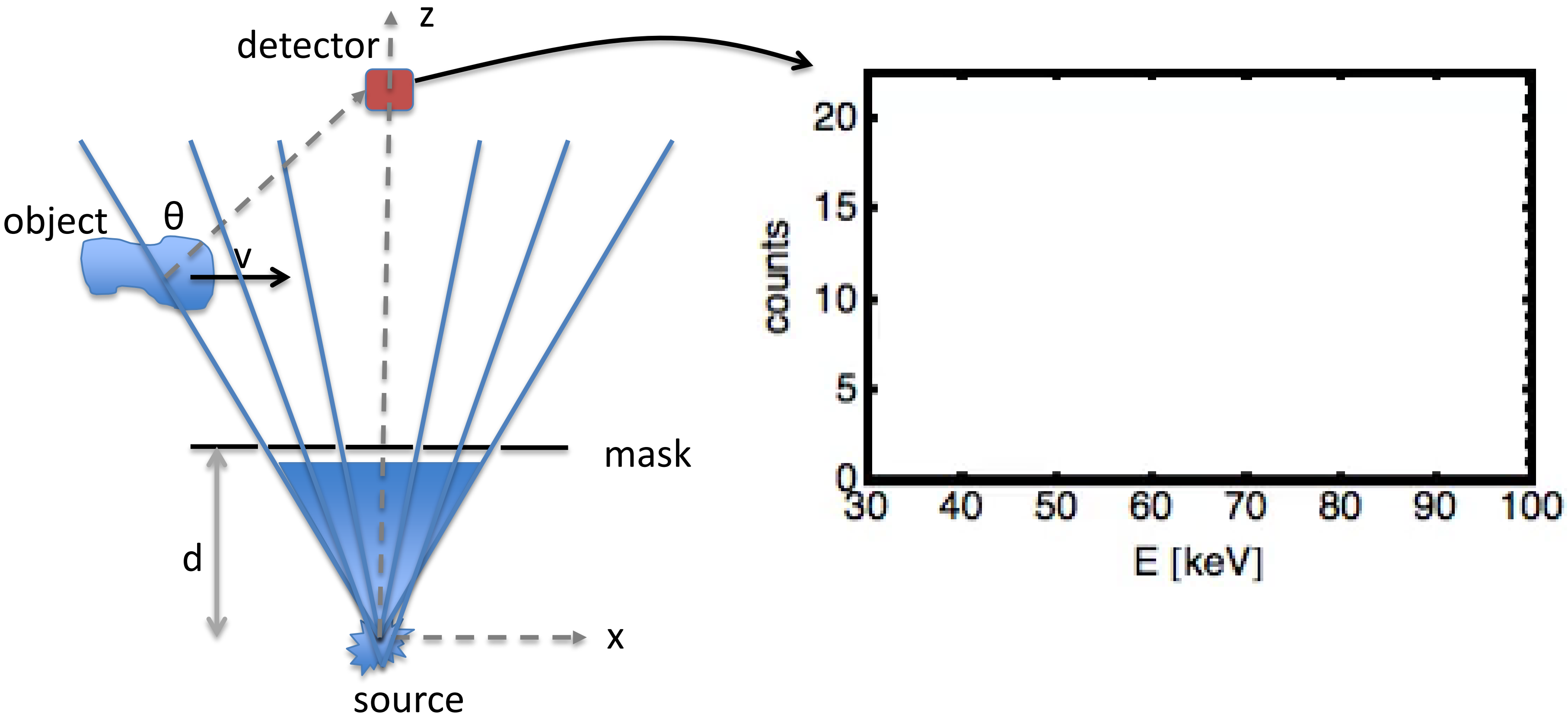
Advantages

- Optimal use of source photons (no spectral/minimal spatial filtering)
- Scales easily up to 4D
- Fewer detectors needed (sparse array only)
- Allows for simultaneous tomosynthesis
- Compatible with multiple sources
- Allows for adaptive implementation
- Simple modification to existing machines
  - Open up collimation
  - Add scatter detectors



Example: modulated fan beam

- Source: conventional x-ray tube
- Mask: periodic series of holes along a line t(x) = (1+sign[sin(u x)])/2
- Detector: Single, energy sensitive pixel



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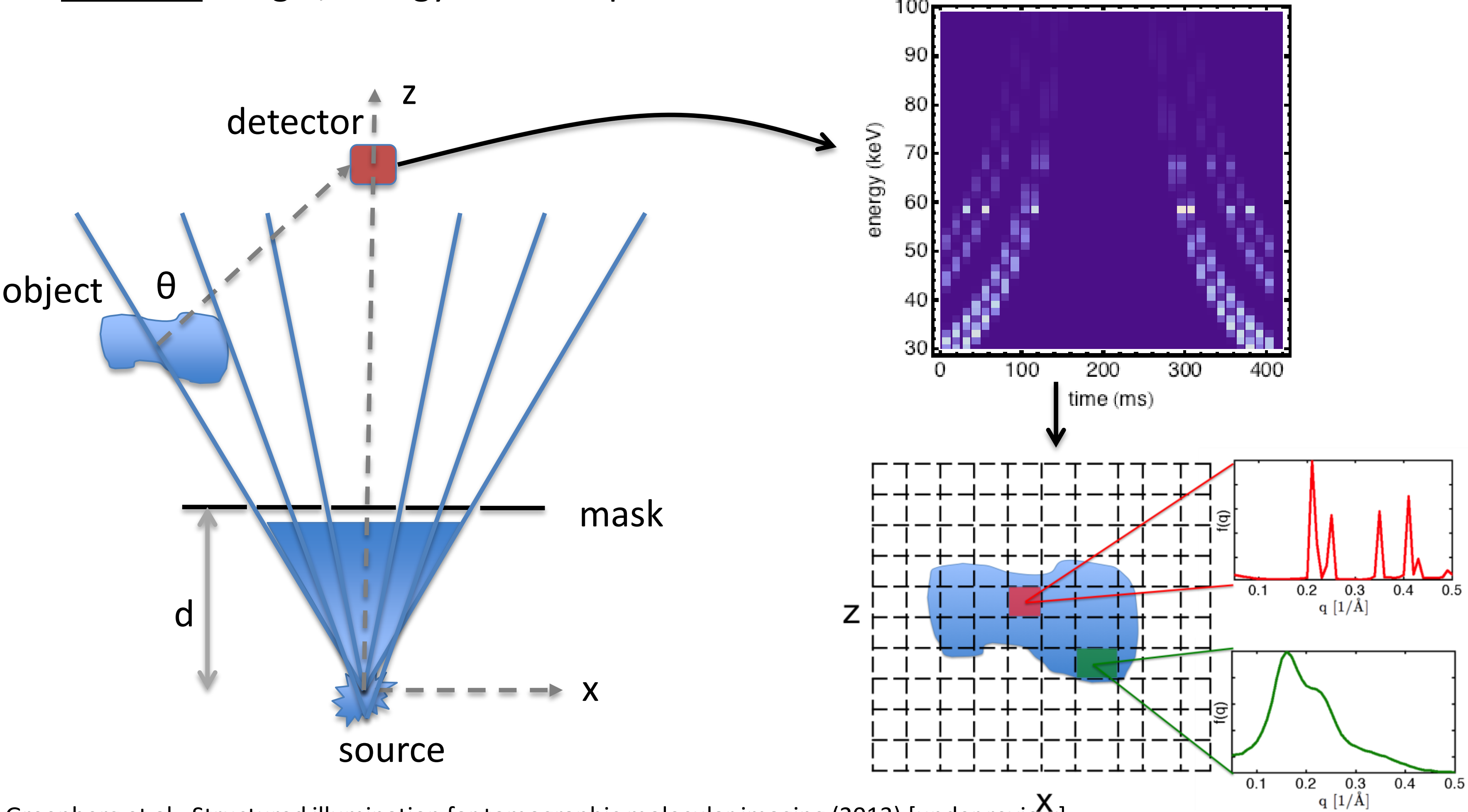

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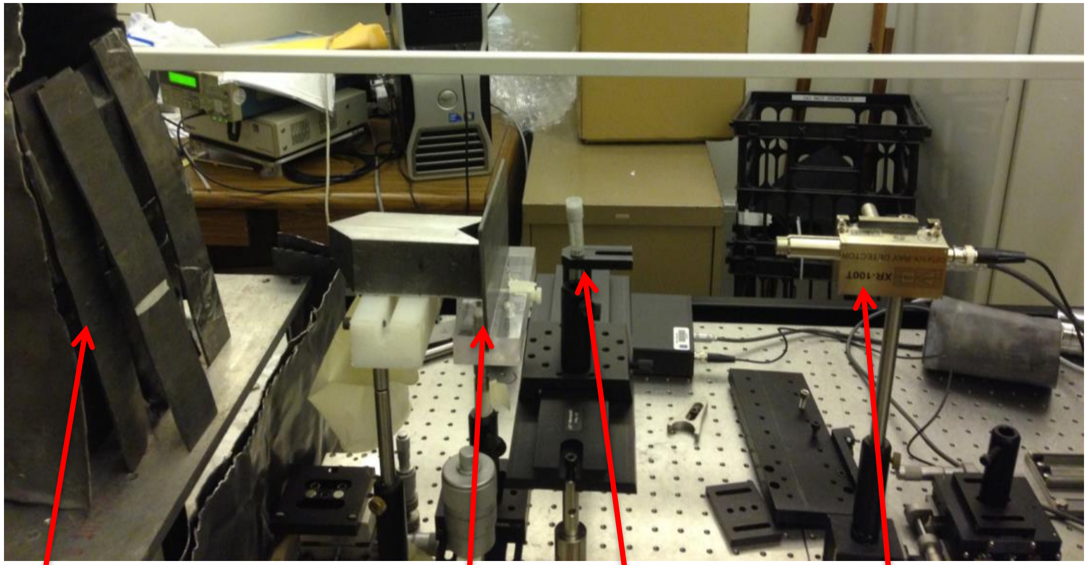
SICSI experiment



Source/collimation
(125 keV)

mask

(moving)
object

detector

Mask (x-ray image)

- 3 mm thick Pb
- 1.5 mm diameter holes
- 3 mm center-to-center spacing

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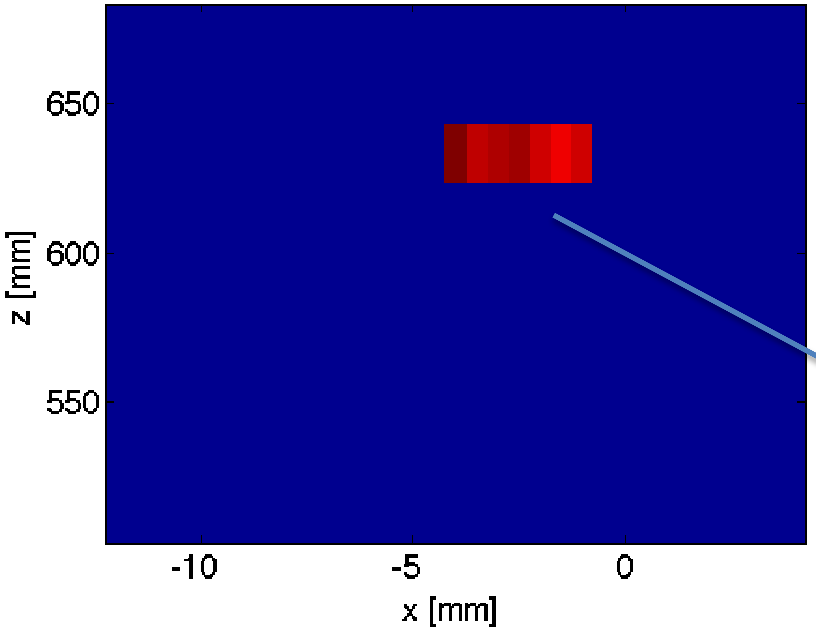
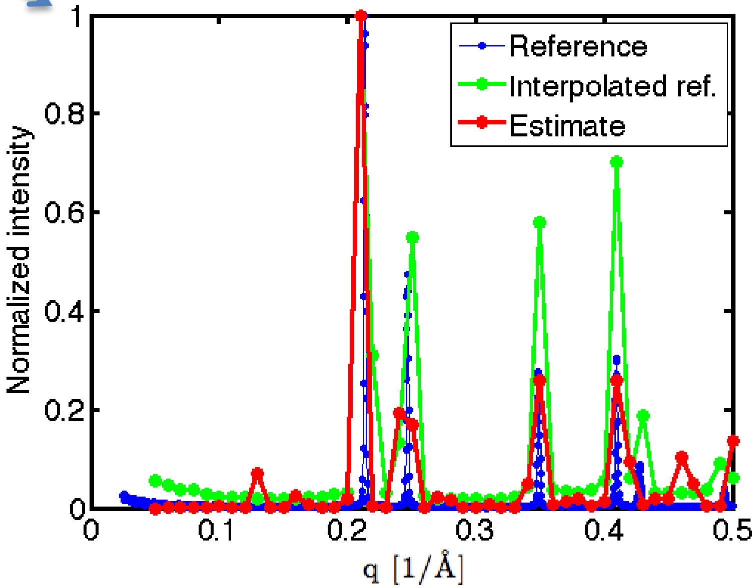
Single object reconstruction

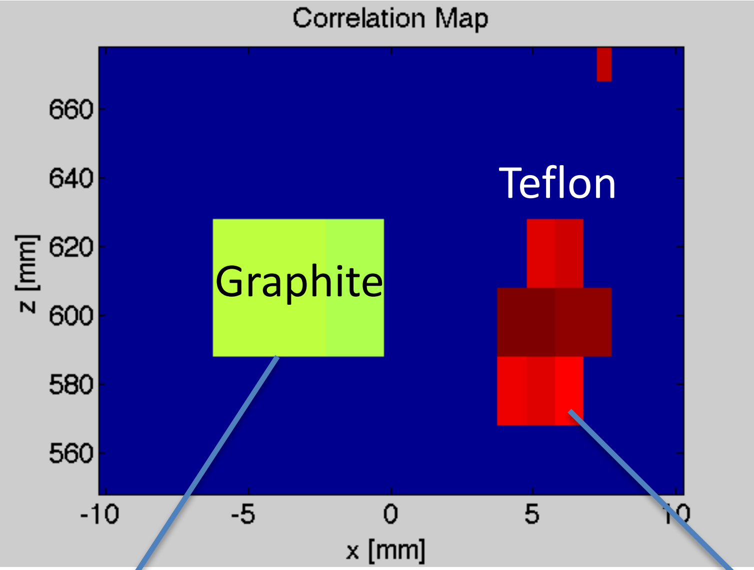


Al powder at z=640 mm, x=-3 mm

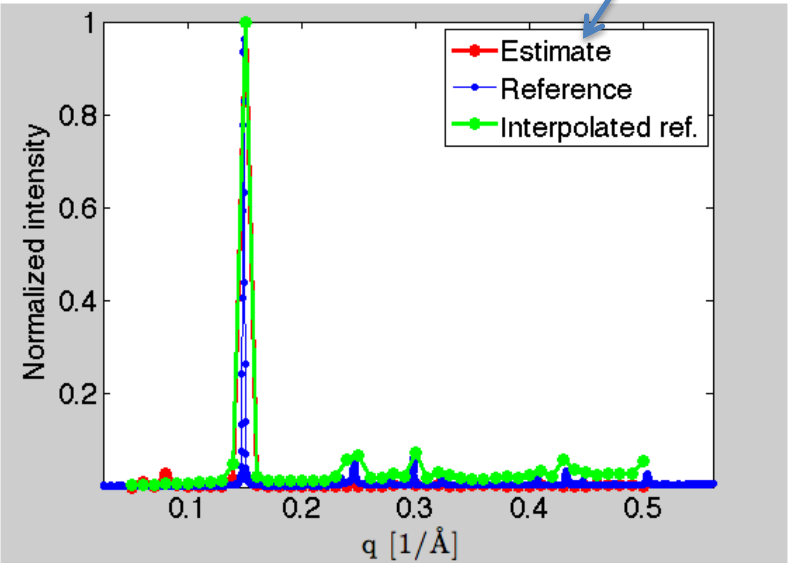


J. A. Greenberg et al., Structured illumination for tomographic molecular imaging (2013) [under review]

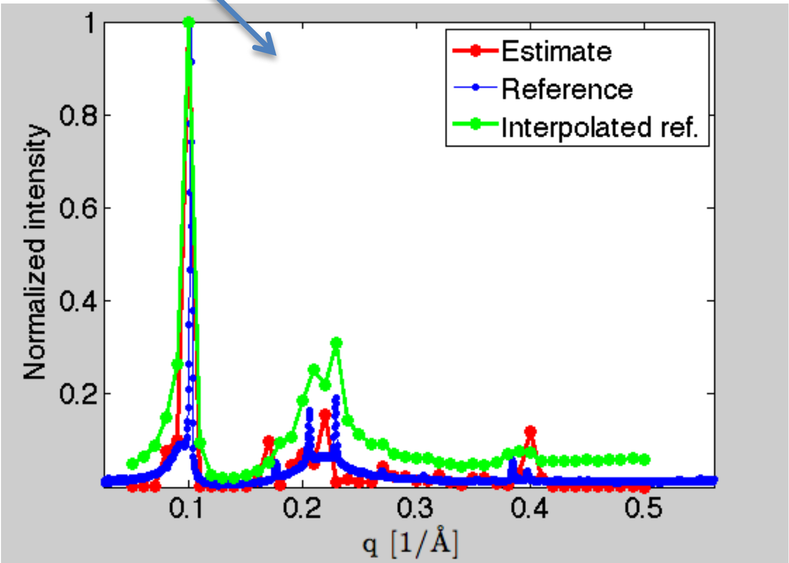
Multi-object classification



Graphite at x=-3, z=613



Teflon at x=5, z=593



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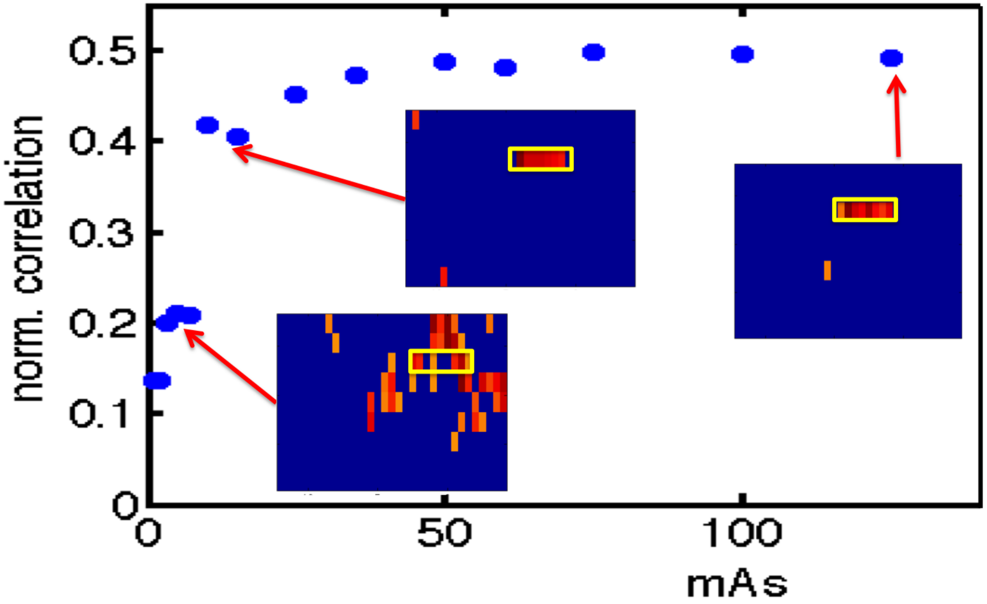
Dependence on mAs



Notes

- Only use 1 pixel
  - Collect ≈0.1% of scatter!
- Accurate results down to 5 mAs (defined per integration time)
  - Corresponds to ~1 cm/s belt speed with 10 mA source

Going forward

- Use more pixels
  - Collect more photons (e.g., 10-100x)
  - better conditioning (less compressive)
- Use higher mA/kV source (e.g., 160 kV at 90 mA)
- Combine with transmission-based tomosynthesis
- Use full cone beam

→ Real-time (>10 cm/s) operation with real suitcases

Summary

- Arrays of energy-sensitive detectors are crucial for real-time operation
- Minimal source filtering with structured illumination yields a drastic speed-up in required imaging time
- Integration of scatter and transmission is necessary
- Prototype construction is currently underway!

Acknowledgements

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