EPFL Center for Imaging

Pyxu: a Modular Approach to Imaging across Domains and Scales

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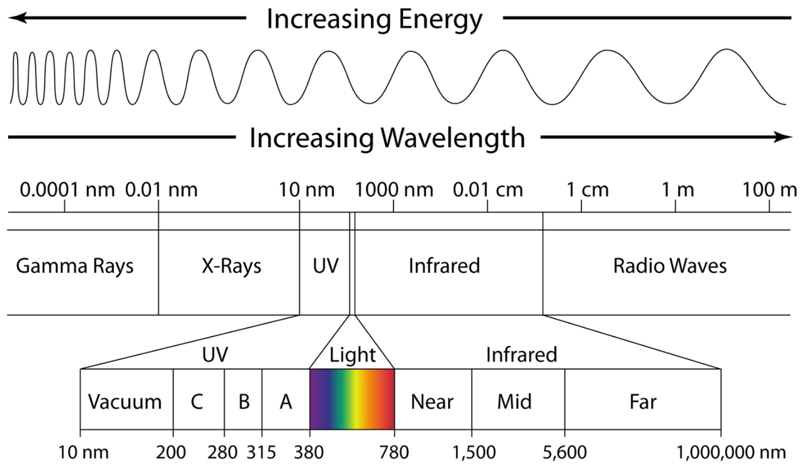
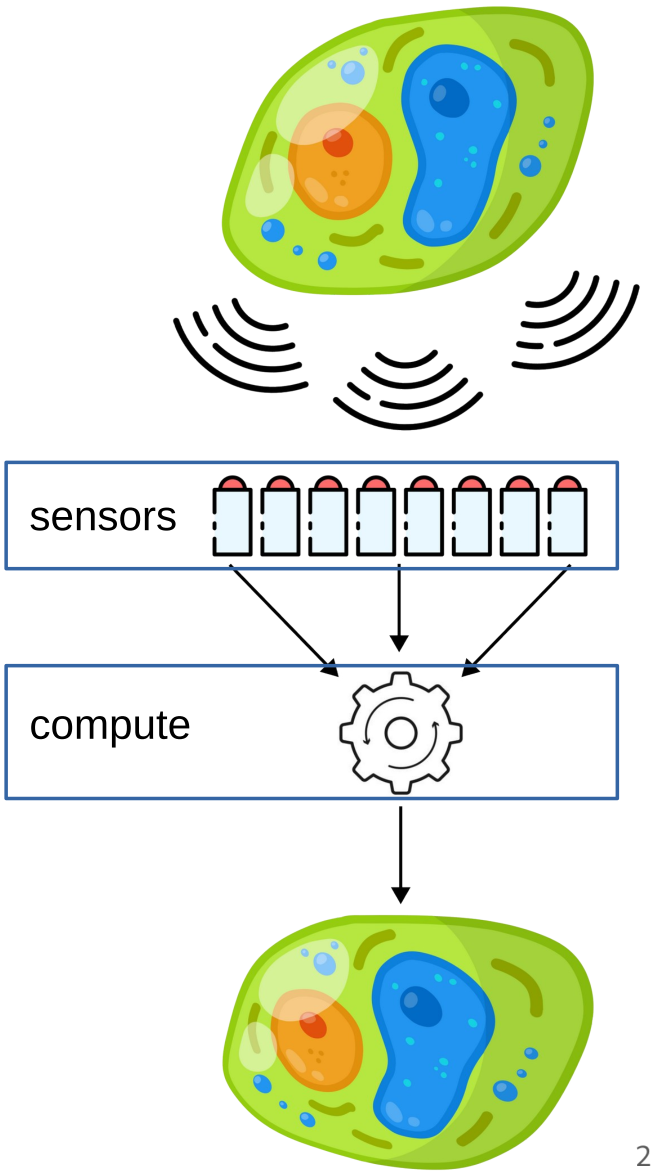
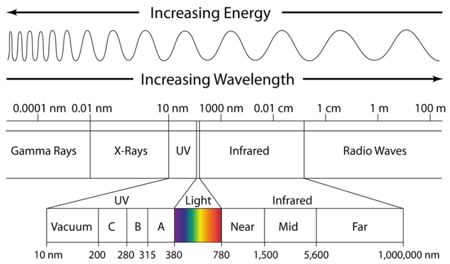
Computational Imaging (CI)

- Inverse problem involving **image**-like quantities
  - Capture signals from real world with sensors
  - Infer something about quantity of interest via **computation**

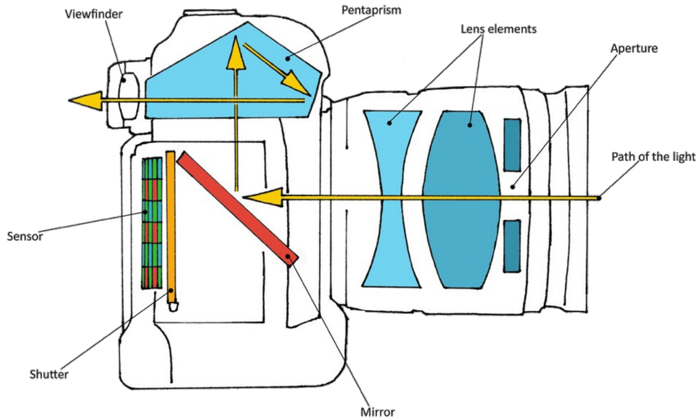




CI: Optical Imaging



- Capture scene radiance
  - Visible light enters camera
  - Recorded on pixel detector



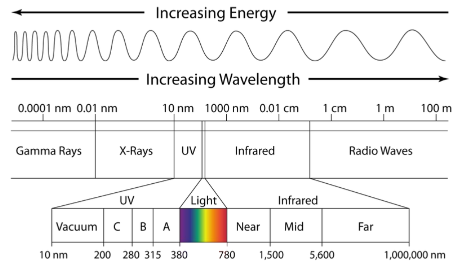
scene

measurement

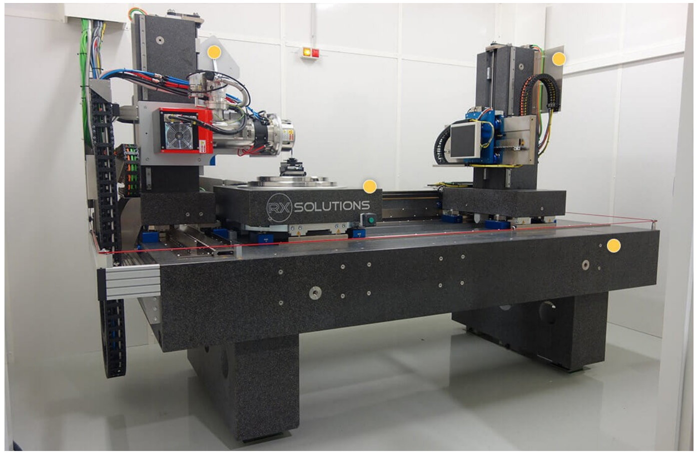
computation

sensor recording

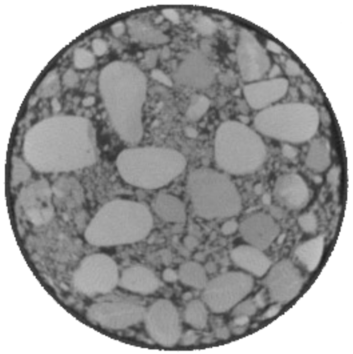
CI: Tomography



- Determine volume absorption profile
  - Project X-rays through object
  - Record shadows from different directions



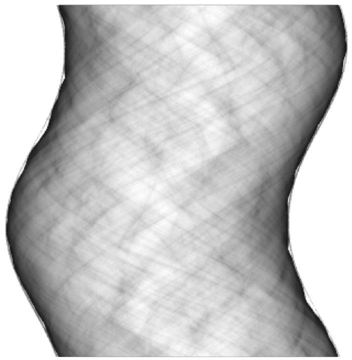
3D volume



measurement →

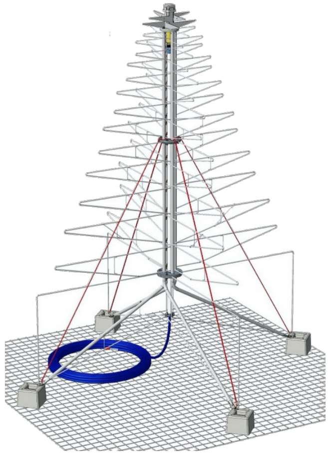
← computation

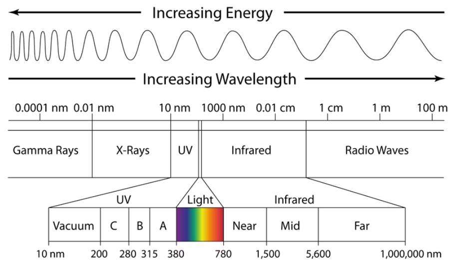
2D projections



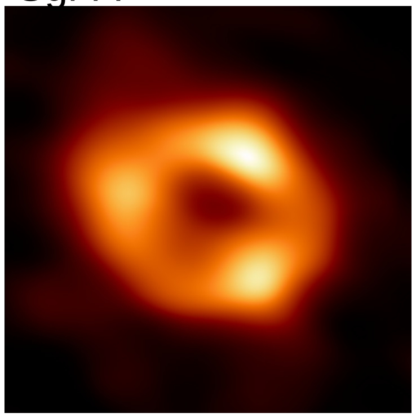
CI: Radio-Interferometry

- Determine sky brightness distribution
  - Stars emit radio emissions (among other things)
  - Recorded on Earth with antennas





Sgr A*



measurement

computation

antenna time series

Solving CI Inverse Problems

- Relate quantity of interest with measurements

$$\mathbf{y} = [\mathcal{A}_Q \circ \cdots \circ \mathcal{A}_1]\, \mathbf{f} + \mathbf{n}$$

- Typical forward models A encountered in imaging (after discretization):

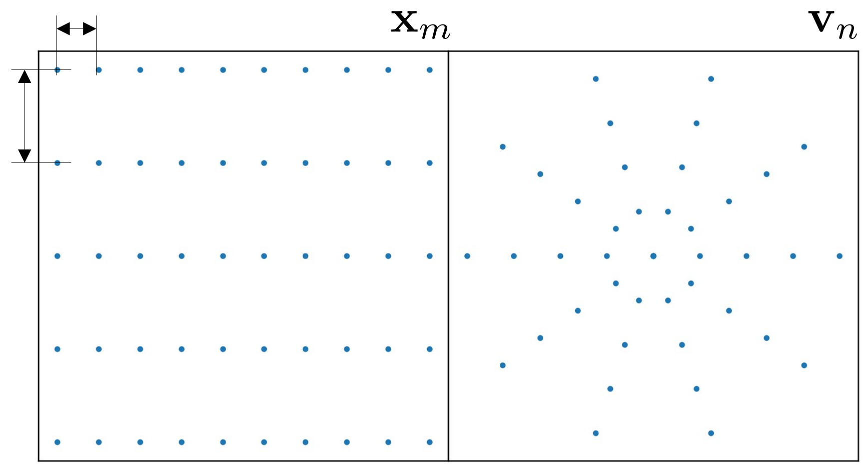
$\mathbb{R}^D$ knots

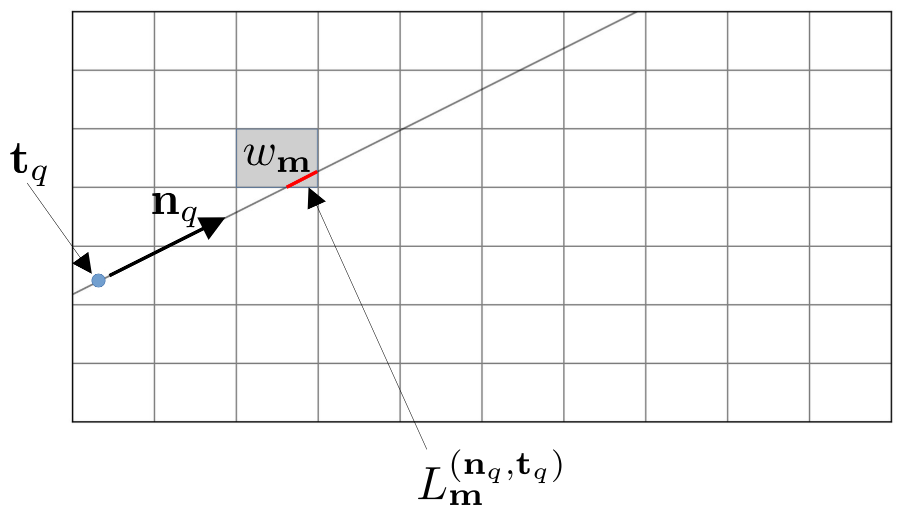
Fourier Sums

$$[\mathbf{z}_n]_{n=1}^{N} = \sum_{m=1}^{M} w_m e^{-j2\pi\langle \mathbf{x}_m, \mathbf{v}_n \rangle}$$

Line Integrals

$$\left[\mathbf{z}_{\mathbf{n}_q, \mathbf{t}_q}\right]_{q=1}^{Q} = \sum_{\mathbf{m} \subset \mathbb{Z}^D} w_{\mathbf{m}} L_{\mathbf{m}}^{(\mathbf{n}_q, \mathbf{t}_q)}$$



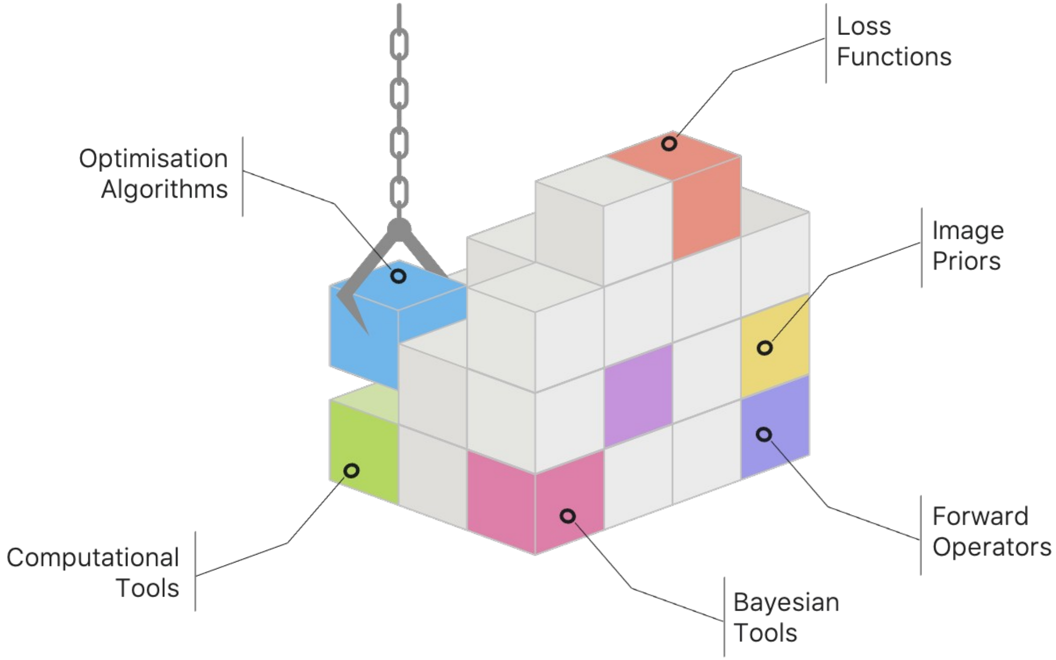


The CI Software Landscape

- Rich software tools for all types of imaging
  - Silo software: re-inventing the wheel
  - Slow dissemination across domains

https://pyxu-org.github.io/

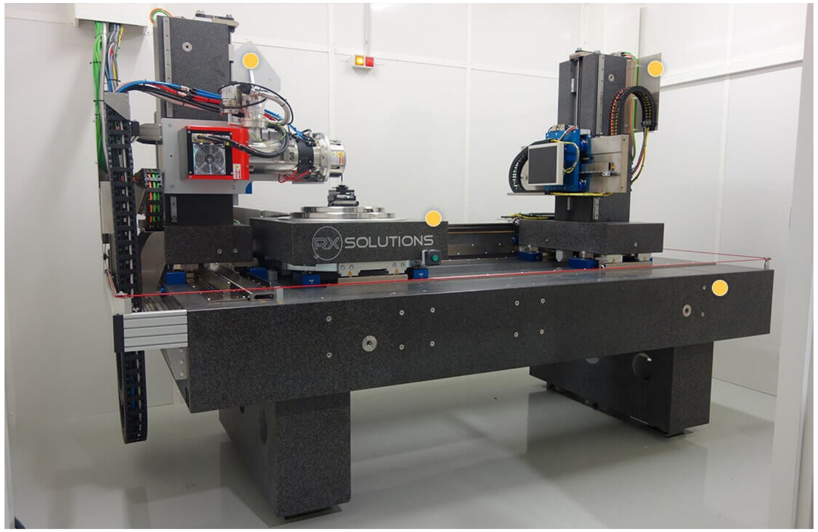
- Python library to design/deploy CI pipelines
  - CPU/GPU imaging operators (CT, Fourier, …)
  - Reconstruction algorithms
  - Strong interopability with ML ecosystem
  - Speed up R&D loop
- Share compute-part between domains and applications.



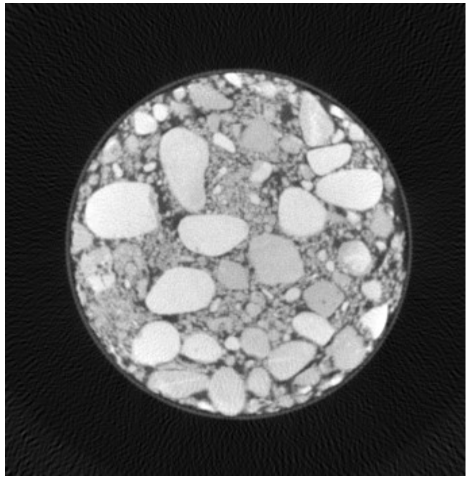
LenslessPiCam [Bezzam et al.]
Divergent X-ray tomography reconstruction and optimisation [Haouchat
An Angular Framework for Ultrasound Imaging [Hériard-Dubreuil]
Neural Manifolds Through the Lens of Connectome Spectral Analysis [Rué Queralt]
HVOX: Scalable Interferometric Synthesis and Analysis of Spherical Sky Maps [Kashani et al.]
PolyCLEAN: Atomic Optimization for Super-Resolution Imaging and Uncertainty Estimation in Radio Interferometry [Jarret et al.]

Example: CT Reconstruction

- High-resolution Cone-beam CT scanner.
- Goal: Speed up acquisition at equivalent reconstruction quality.

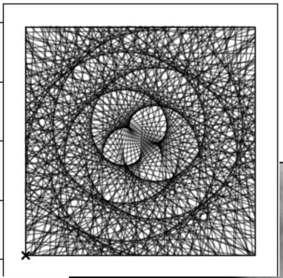


Device software

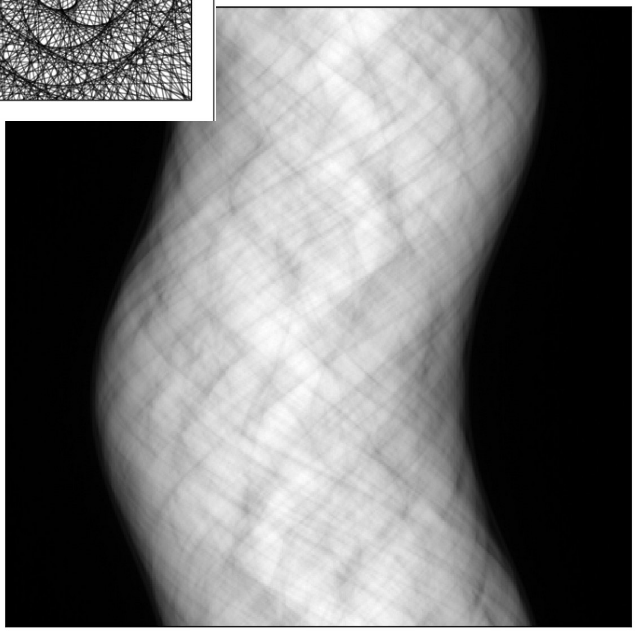


Match the device output 1

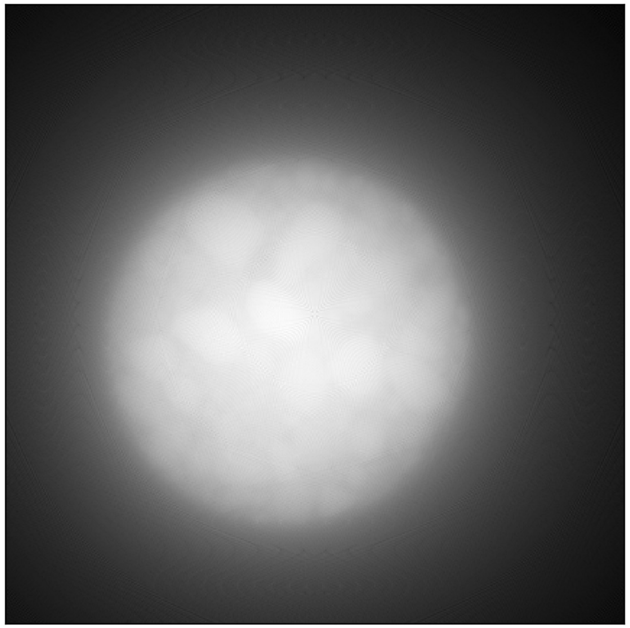
- Parse XML file → extract scan geometry.
- Build CT projector digital twin via Pyxu.



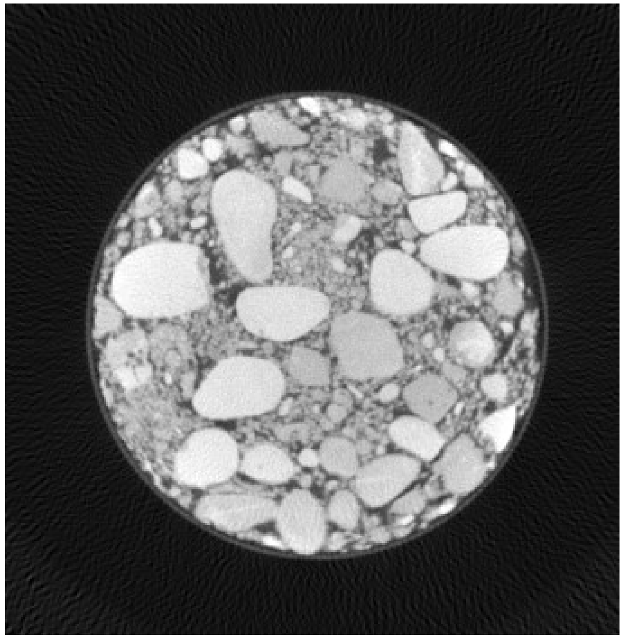
Raw data



$$\mathbf{x} = \mathbf{A}^* \mathbf{y}$$



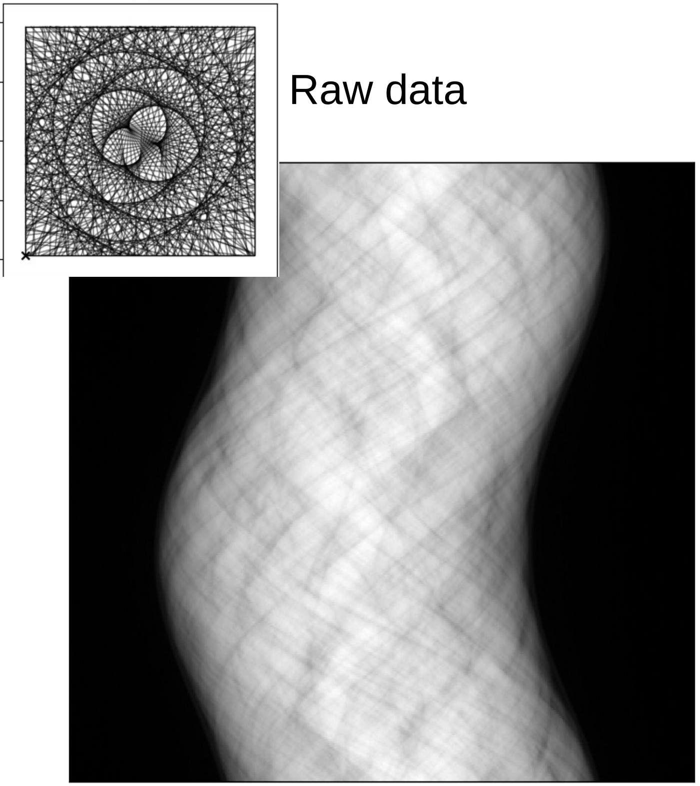
Device software



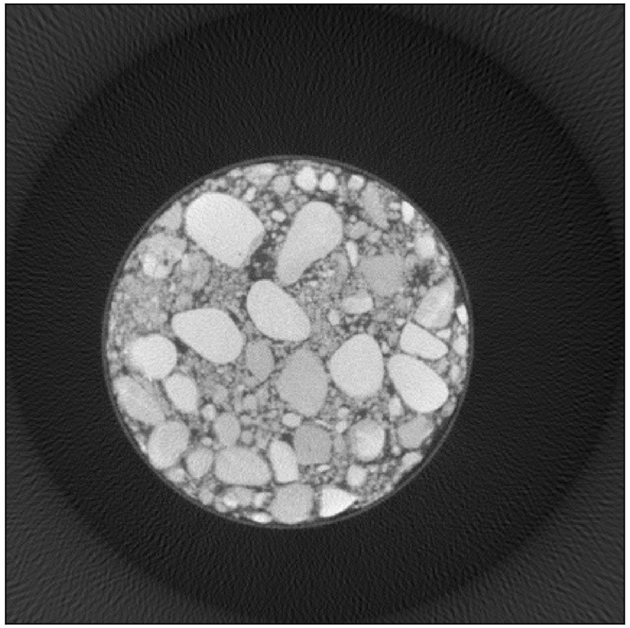
Match the device output 2

- Direct inversion: Filtered Back-Projection

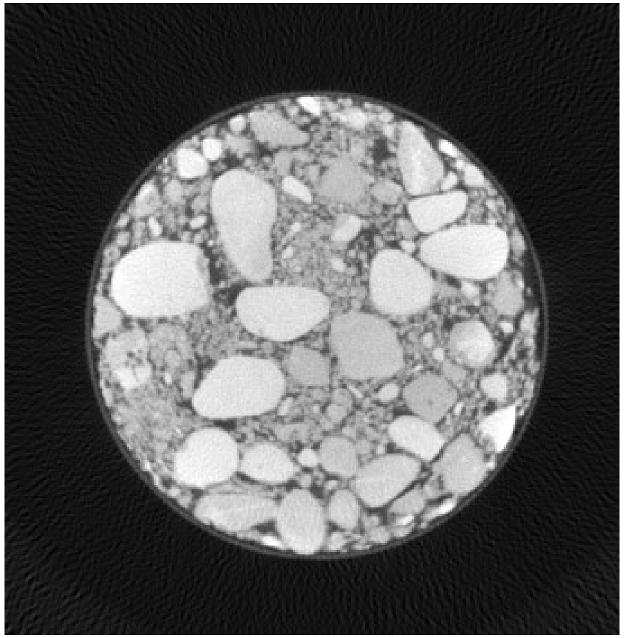
Raw data



$$\mathbf{x} = \mathbf{A}^{-1}\mathbf{y}$$

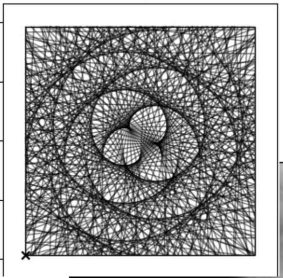


Device software

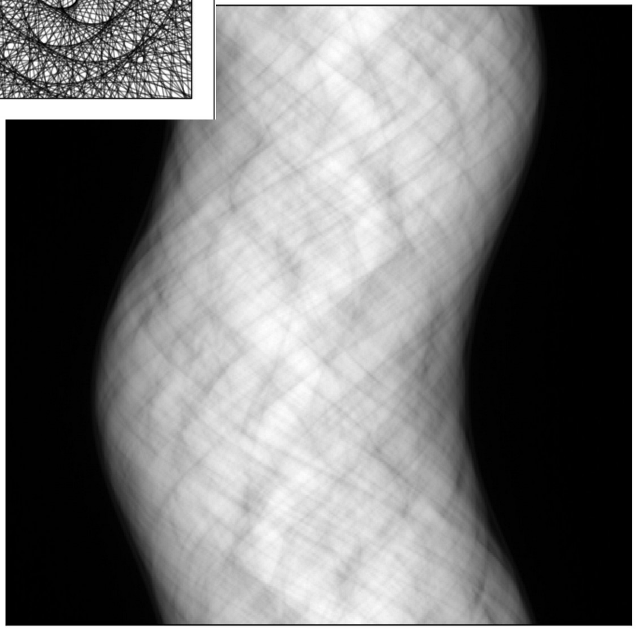


Direct Inversion with 25% data

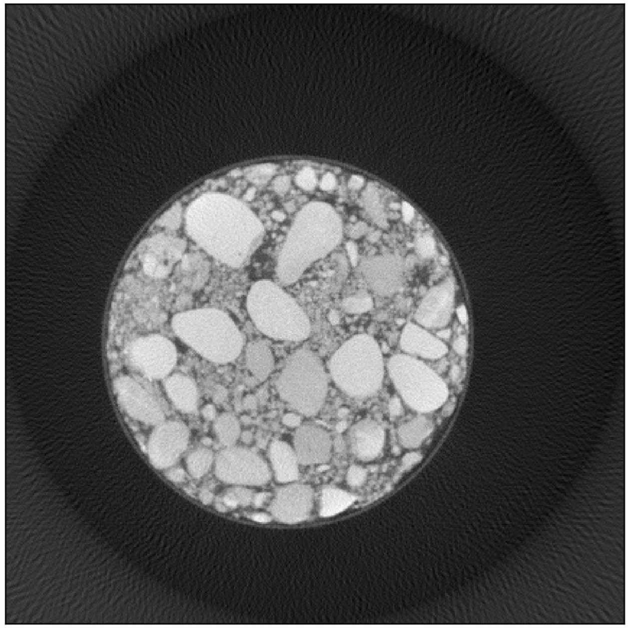
- Speeds up acquisition
- Direct inversion breaks down



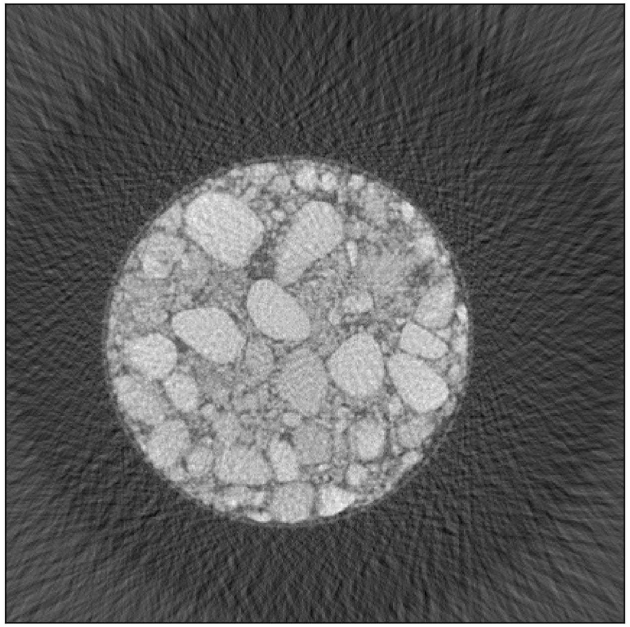
Raw data



$\mathbf{x} = \mathbf{A}^{-1}\mathbf{y}$ (full data)

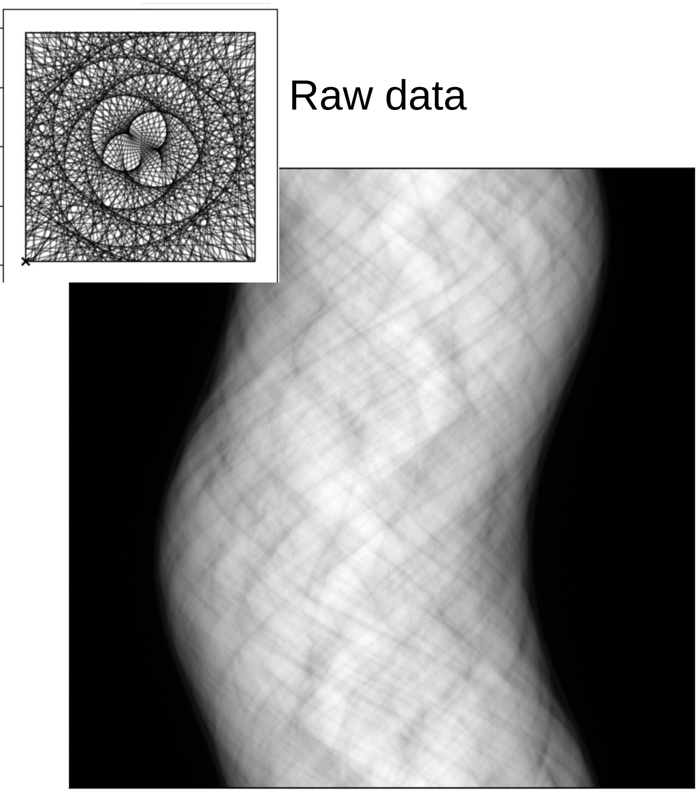


$\mathbf{x} = \mathbf{A}^{-1}\mathbf{y}$ (25% data)

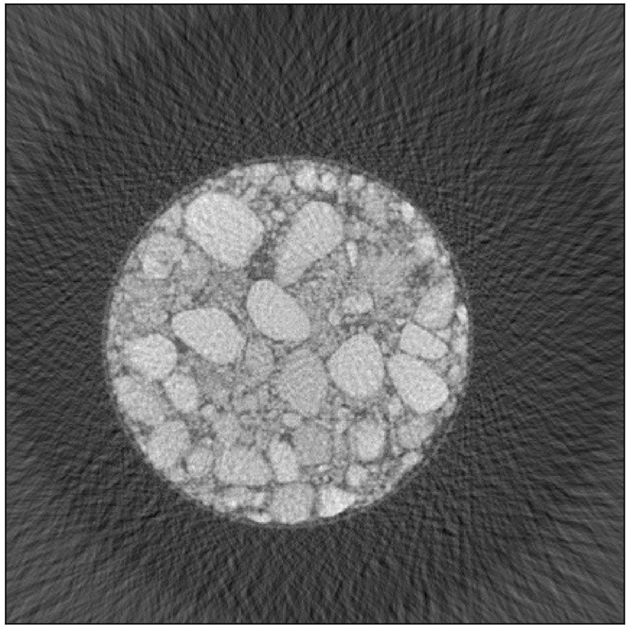


Model-Based Reconstruction 1

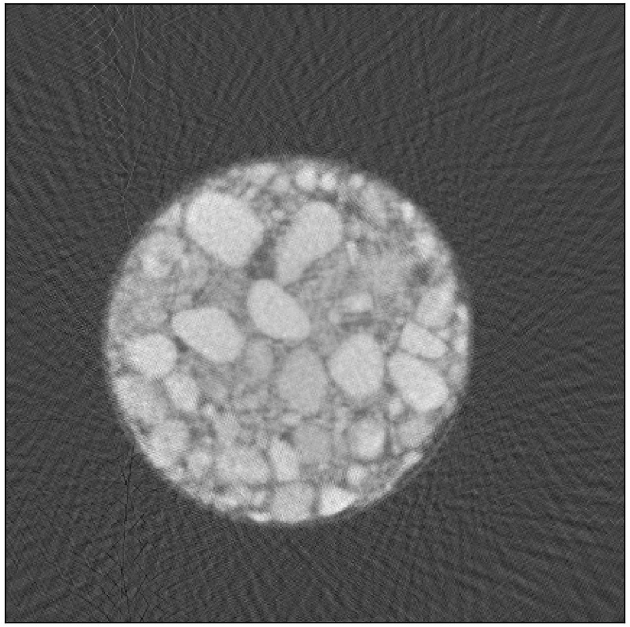
Raw data



$\mathbf{x} = \mathbf{A}^{-1}\mathbf{y}$ (25% data)

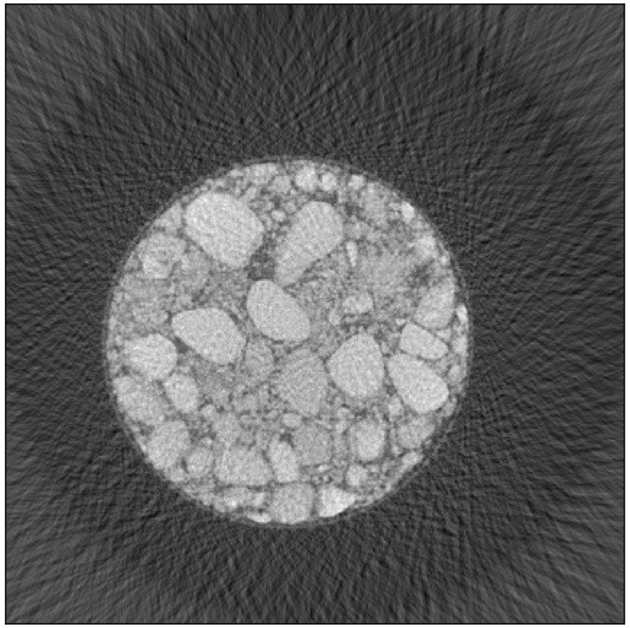


$\arg\min_{\mathbf{z}} \|\mathbf{y} - \mathbf{A}\mathbf{z}\|_2^2 + \lambda \|\mathbf{z}\|_2^2$

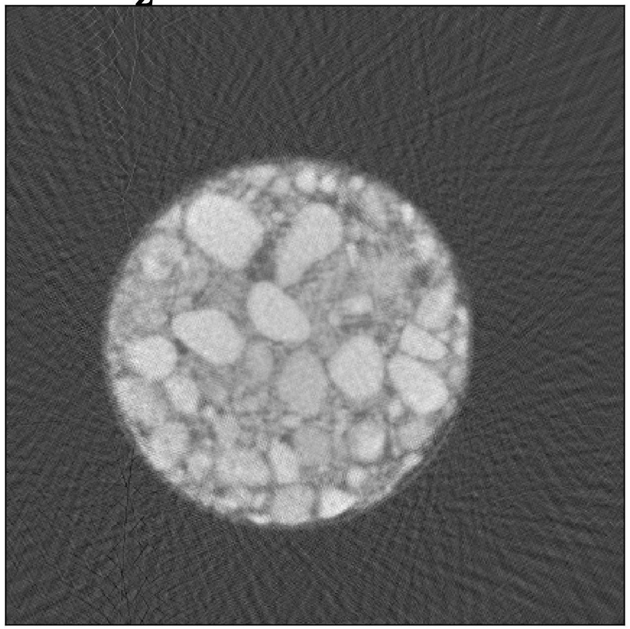


Model-Based Reconstruction 2

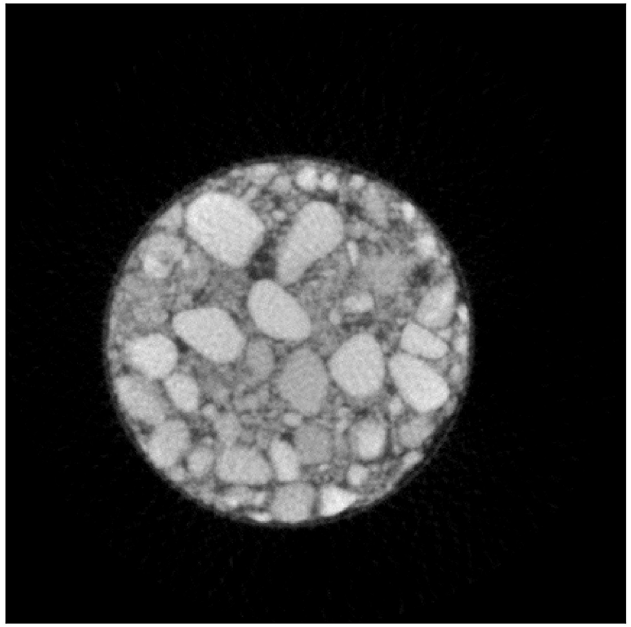
$\mathbf{x} = \mathbf{A}^{-1}\mathbf{y}$ (25% data)



$\arg\min_{\mathbf{z}} \|\mathbf{y} - \mathbf{A}\mathbf{z}\|_2^2 + \lambda \|\mathbf{z}\|_2^2$

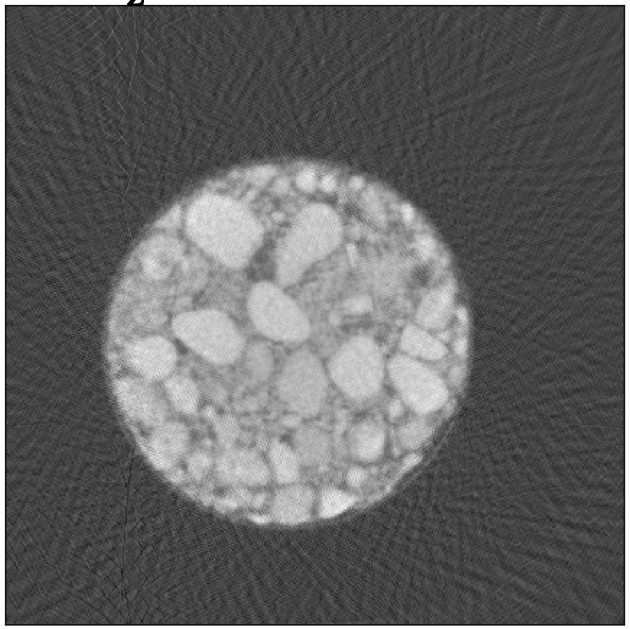


support constraint + positivity

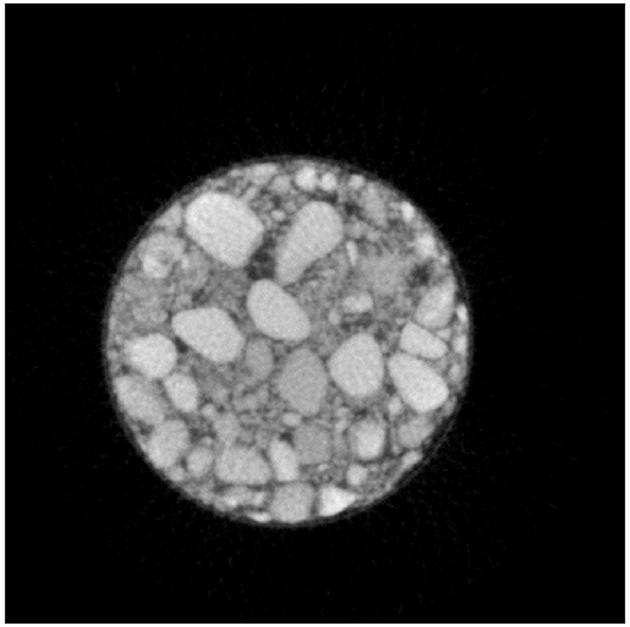


Model-Based Reconstruction 3

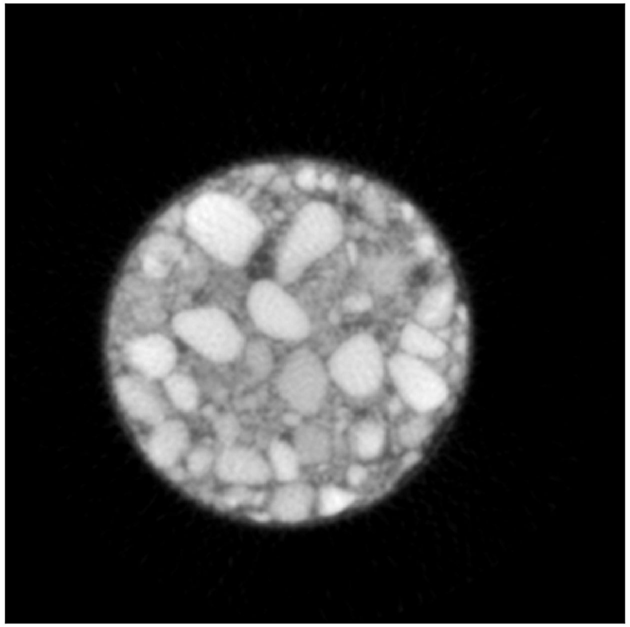
$$\arg\min_{\mathbf{z}} \|\mathbf{y} - \mathbf{A}\mathbf{z}\|_2^2 + \lambda \|\mathbf{z}\|_2^2$$



support constraint + positivity

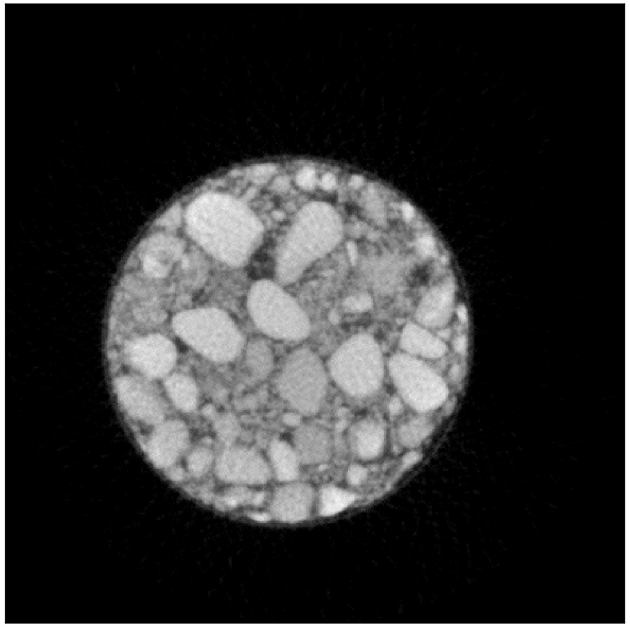


+ TV regularization

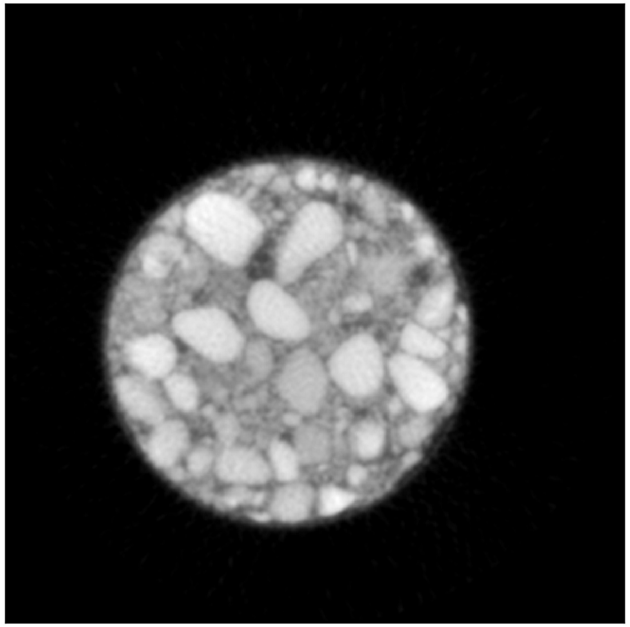


Model-Based Reconstruction 4

support constraint + positivity



+ TV regularization



+ Plug-and-play denoiser