IBSim-4i

Hands-on training for the Core Imaging Library (CIL)

an open-source reconstruction platform for challenging and novel data.

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CIL Team

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Training School Program

Morning

9:00 Introduction to XCT and CIL
- CIL-Demos Notebook
- Exercise

10:30 Break

11:00 Pre-processing of XCT data
- CIL-Demos Notebook
- Exercise
- CIL GUI sneak preview

12:30 Lunch

Afternoon

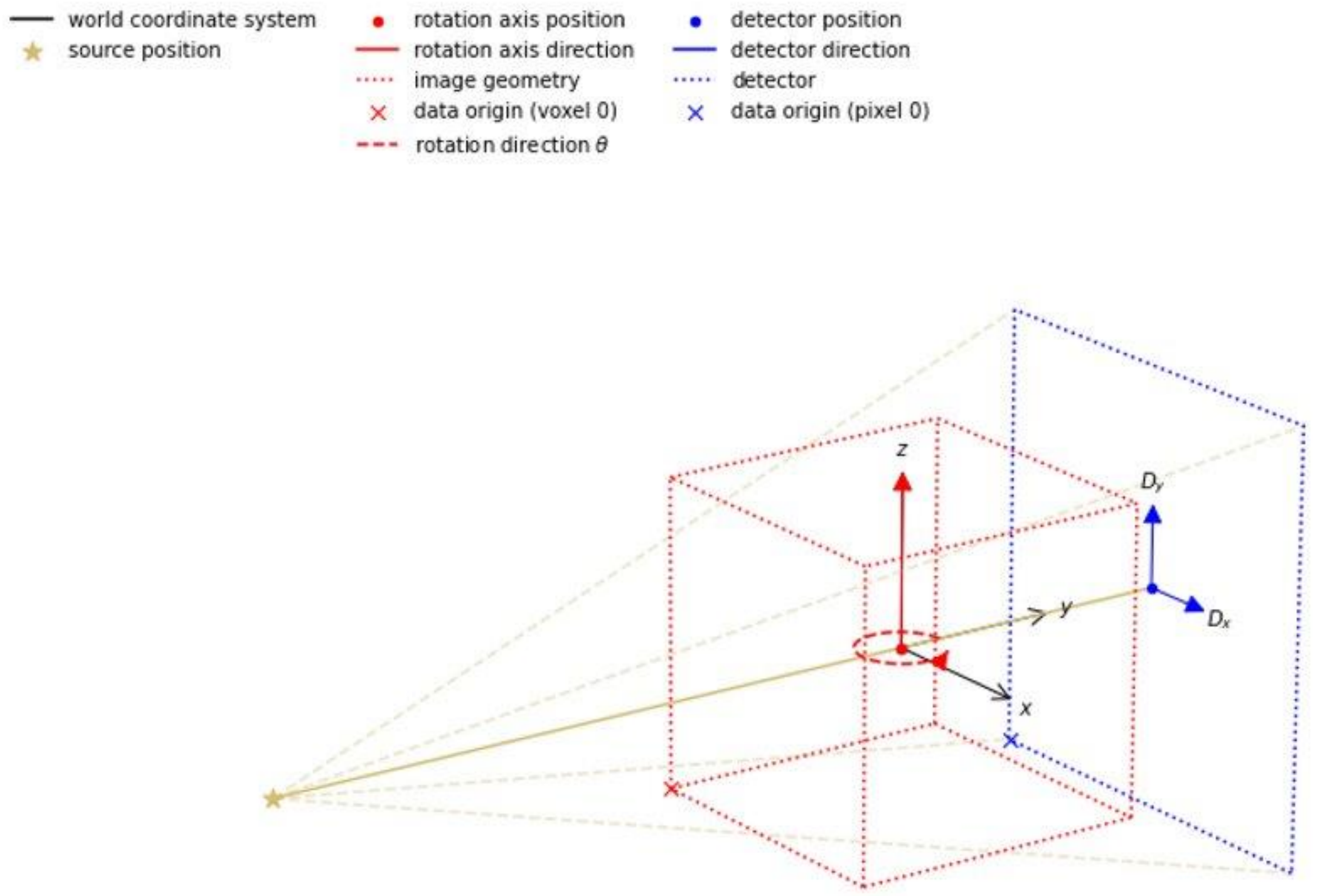
13:30 Introduction to iterative reconstruction methods for standard XCT data
- CIL-Demos Notebook
- Exercise

14:45 Break

15:15 Choose an exercise
- Reconstruct data from gxVR
- Hyperspectral XCT
- Laminography
- Reduced data

17:00 End of workshop

Tomography



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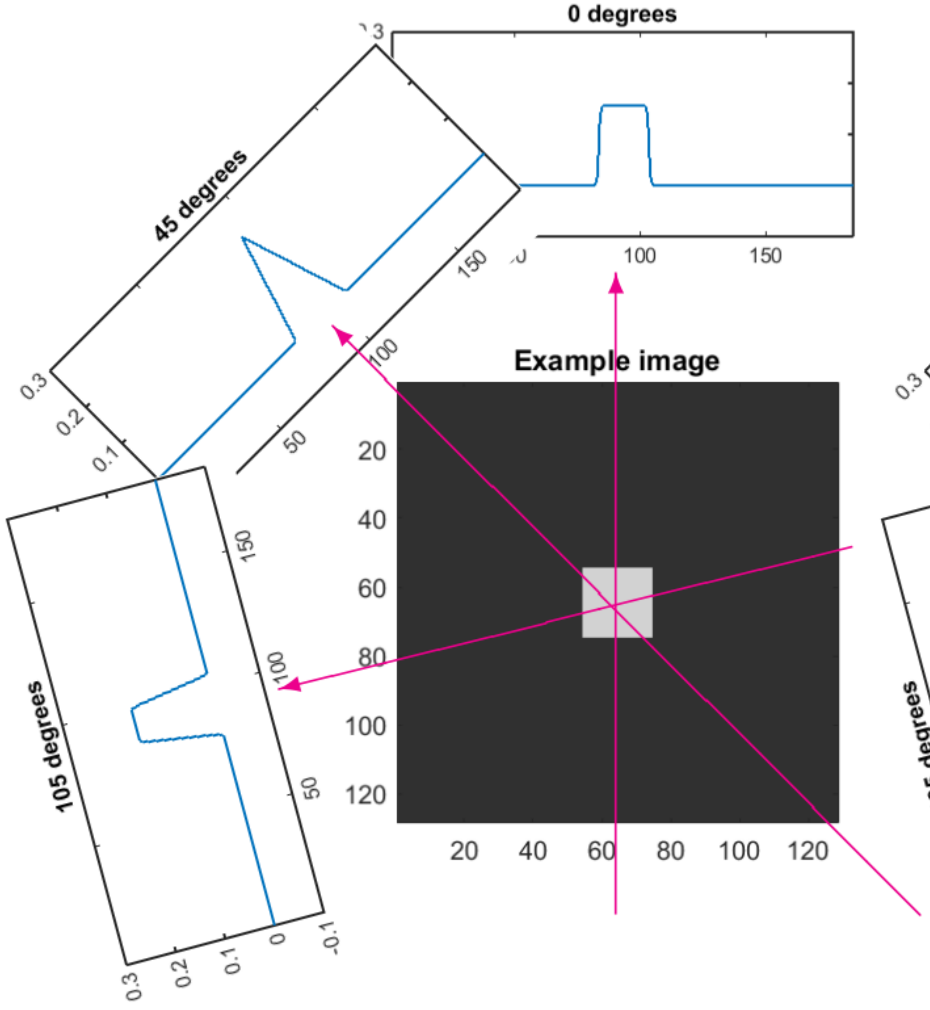
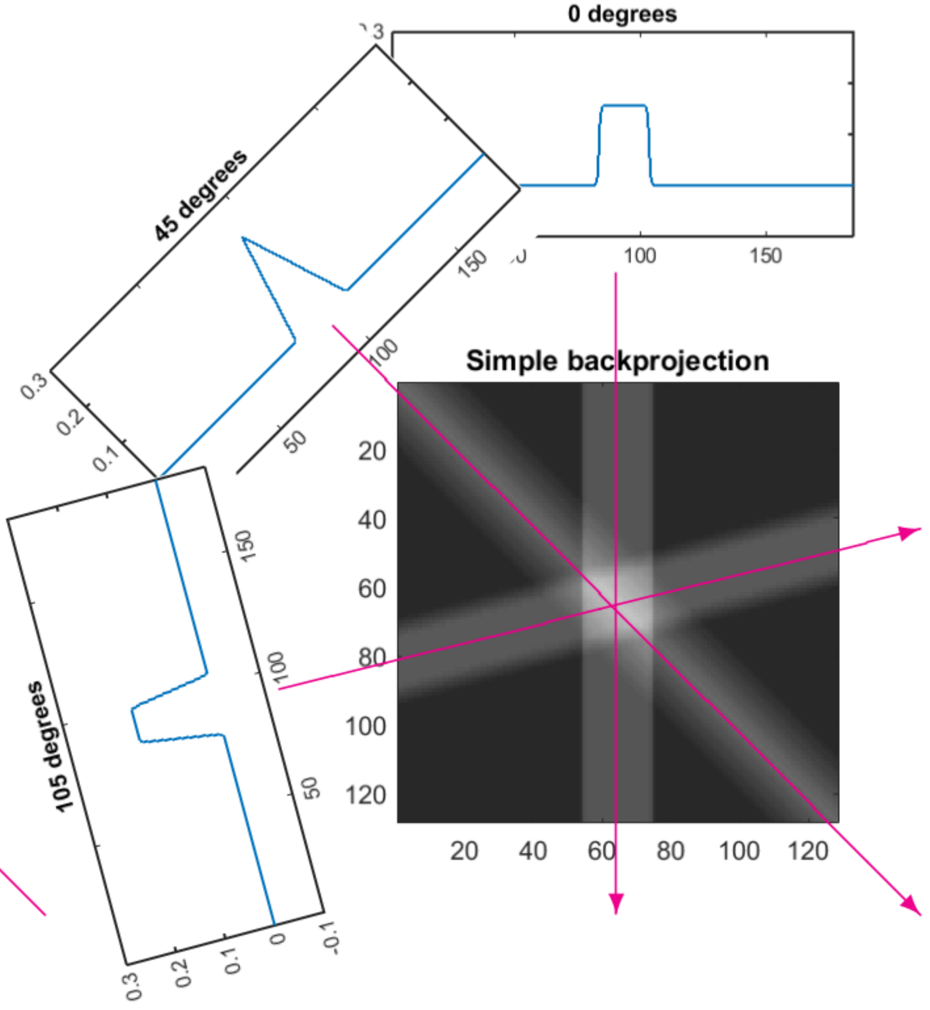
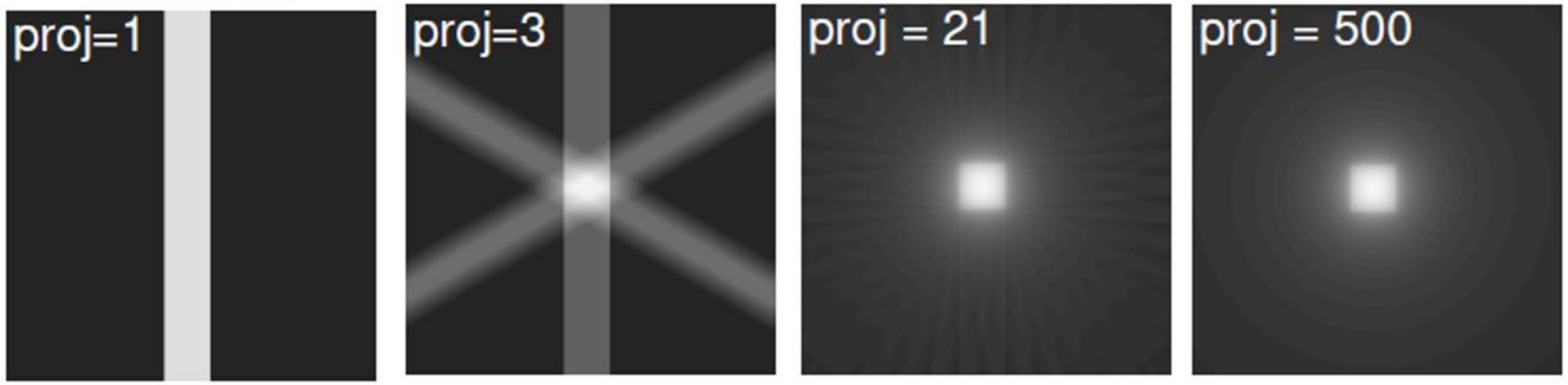
Filtered Back Projection (FBP)





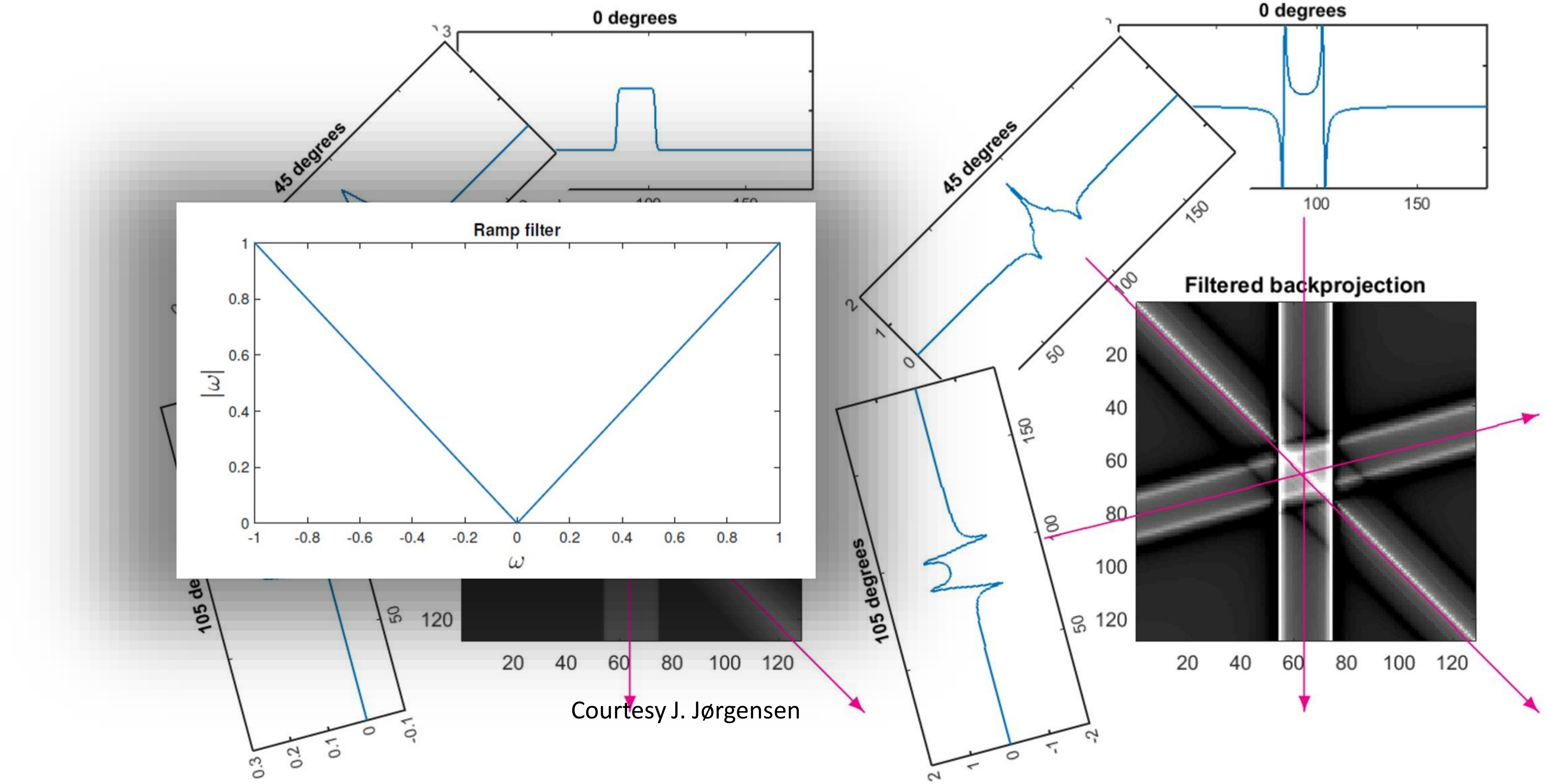
Filtered Back Projection (FBP)

Unfiltered



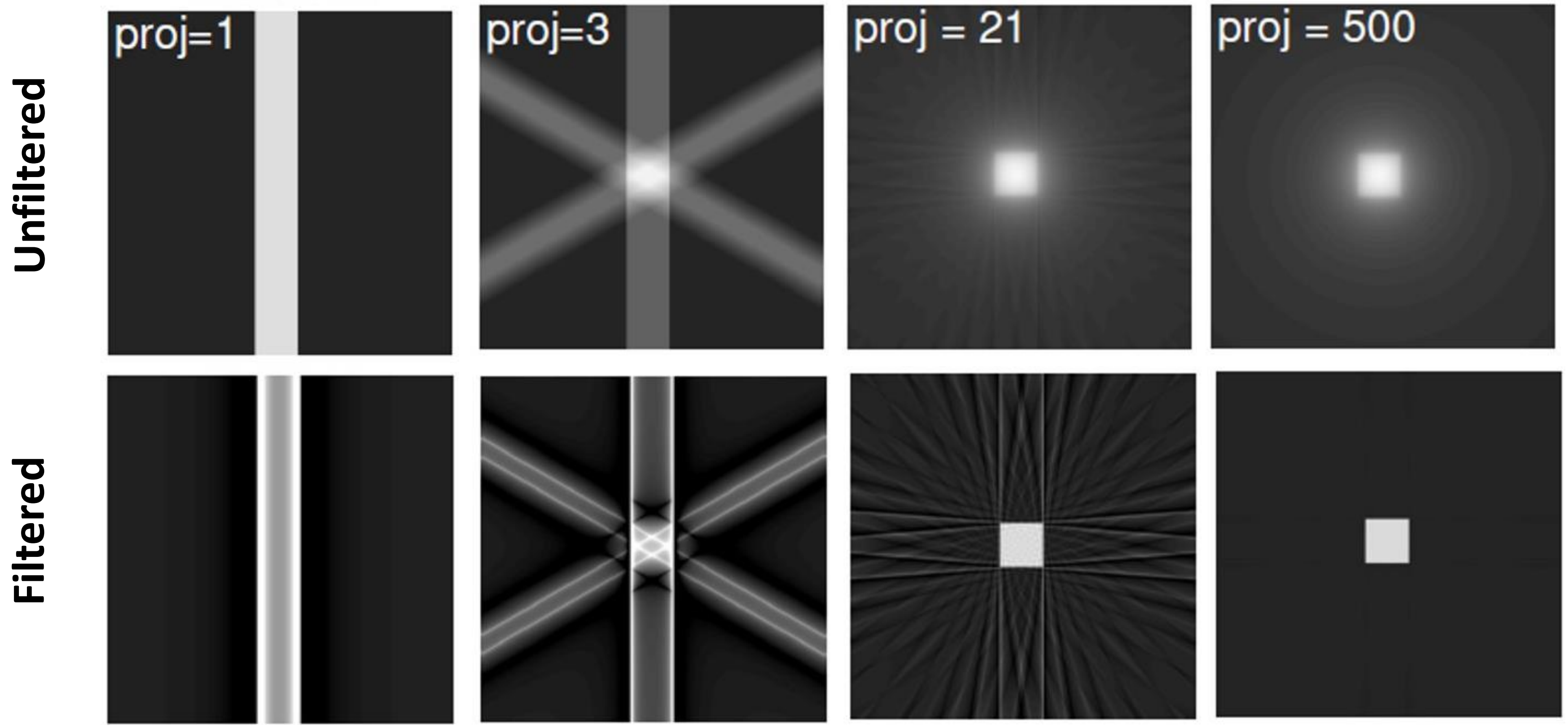
Courtesy J. Jørgensen

Filtered Back Projection (FBP)



Courtesy J. Jørgensen

Filtered Back Projection (FBP)



Courtesy J. Jørgensen

Filtered Back Projection (FBP)

Pros

- Fast as based on FFT and backprojection
- Few parameters
- Typically works very well
- Reconstruction behaviour well understood

What is the Core Imaging Library?

- A Python library for **processing** and **reconstruction** of tomography data.
- Optimised standard methods, such as **Filtered Back Projection**
- Special emphasis on *challenging data sets*: noisy, non-standard, incomplete, multi-channel, ...
- Highly modular to allow creation of bespoke pipelines.
- Apache v2 license.
- Actively developed on GitHub: https://github.com/TomographicImaging/CIL

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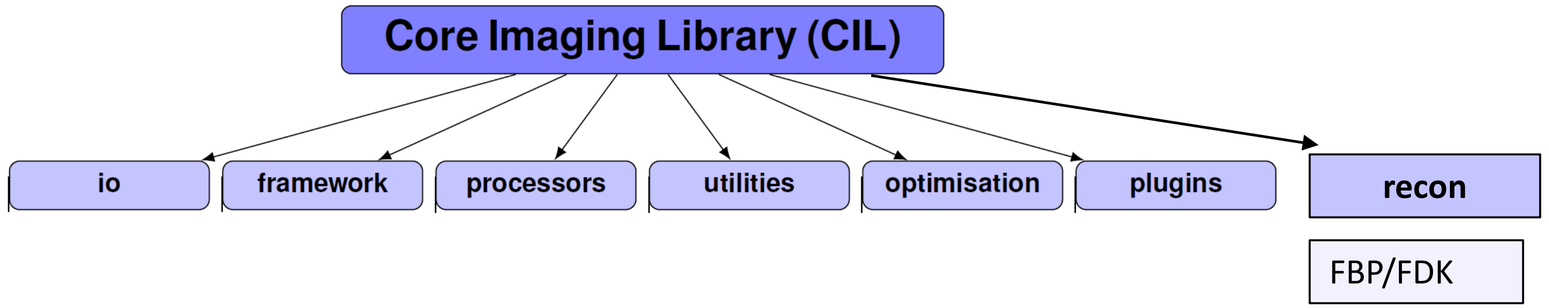
Who is CIL for?

- CT experimentalists
  - **Optimised** standard algorithms for large data
  - Batch processing
  - To utilise reconstruction algorithms for **poor data quality** or to handle novel imaging modalities
- image processing specialists
  - to easily implement new reconstruction algorithms
  - **assess** them against existing ones.

CIL Module Structure and Contents

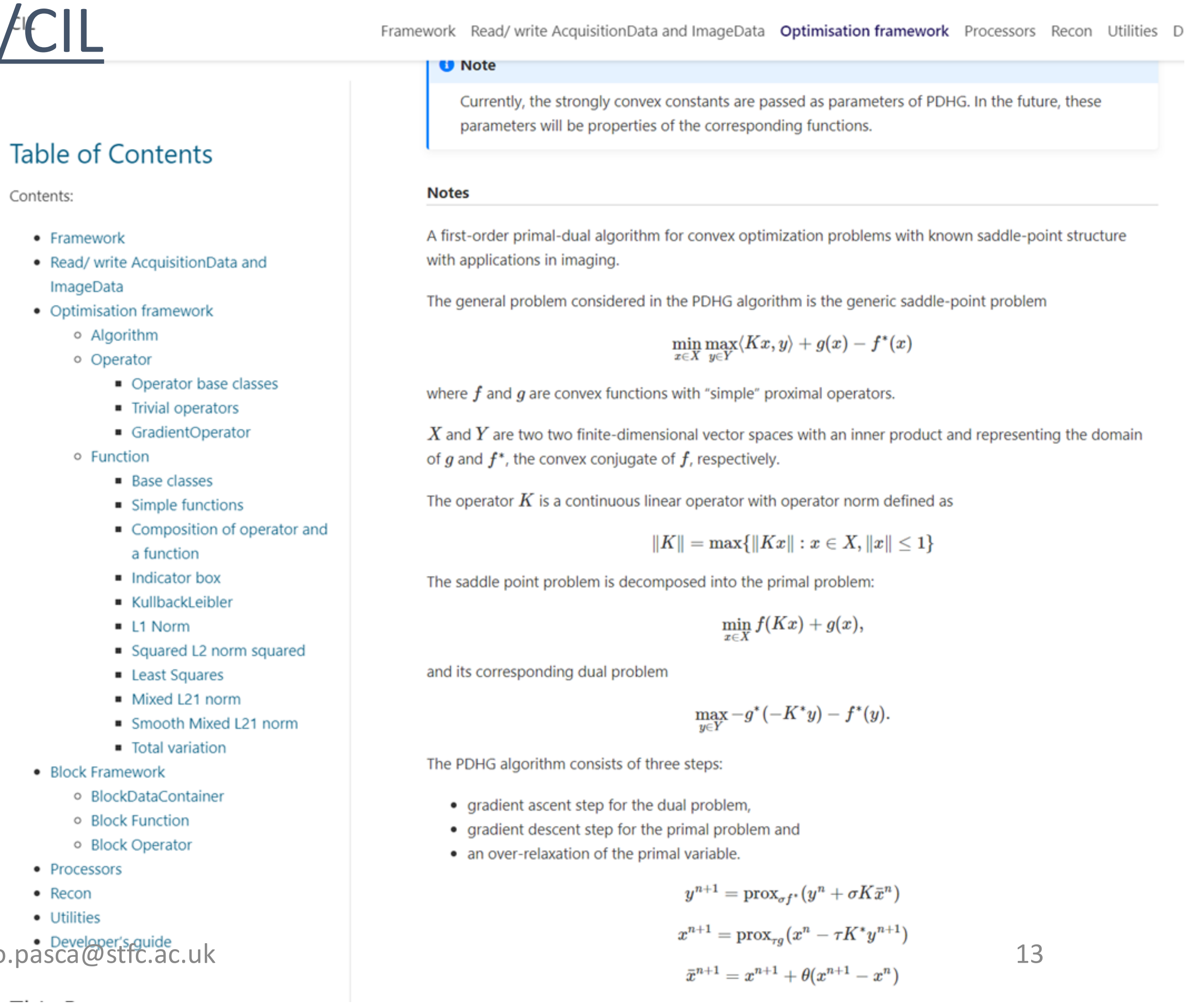


Jørgensen et al. 2021: *Core Imaging Library - Part I: a versatile Python framework for tomographic imaging,* Phil. Trans. R. Soc. A, **379**, 20200192: https://doi.org/10.1098/rsta.2020.0192

The **cil.plugins** module contains wrapper code for other software and third-party libraries that need to be installed separately to be used by CIL.

Documentation

https://tomographicimaging.github.io/CIL



Note

Currently, the strongly convex constants are passed as parameters of PDHG. In the future, these parameters will be properties of the corresponding functions.

Table of Contents

Contents:

Notes

A first-order primal-dual algorithm for convex optimization problems with known saddle-point structure with applications in imaging.

The general problem considered in the PDHG algorithm is the generic saddle-point problem

$$\min_{x\in X}\max_{y\in Y}\langle Kx, y\rangle + g(x) - f^{*}(x)$$

where f and g are convex functions with "simple" proximal operators.

X and Y are two two finite-dimensional vector spaces with an inner product and representing the domain of g and f^{*}, the convex conjugate of f, respectively.

The operator K is a continuous linear operator with operator norm defined as

$$\|K\| = \max\{\|Kx\| : x \in X, \|x\| \leq 1\}$$

The saddle point problem is decomposed into the primal problem:

$$\min_{x\in X} f(Kx) + g(x),$$

and its corresponding dual problem

$$\max_{y\in Y} -g^{*}(-K^{*}y) - f^{*}(y).$$

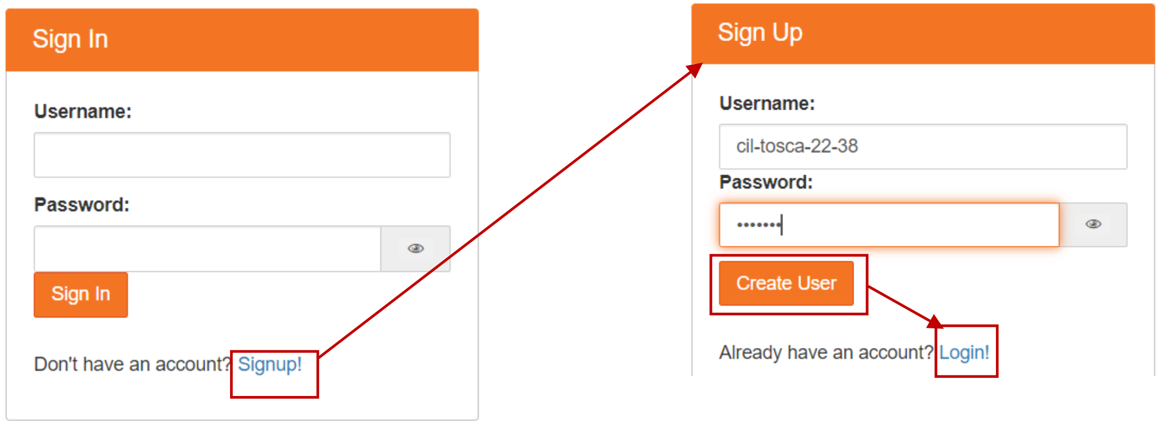
The PDHG algorithm consists of three steps:

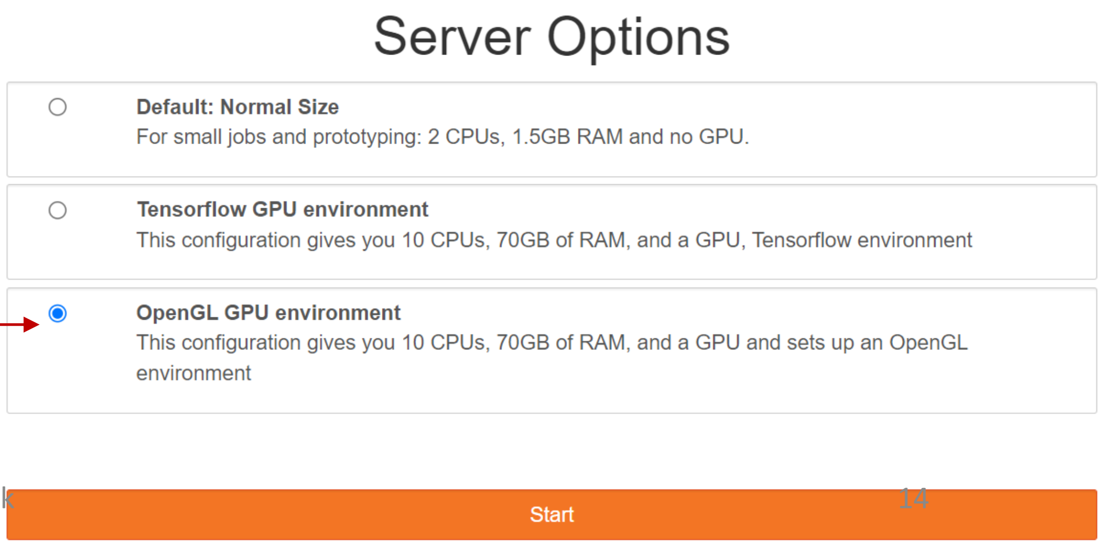
- gradient ascent step for the dual problem,
- gradient descent step for the primal problem and
- an over-relaxation of the primal variable.

$$y^{n+1} = \mathrm{prox}_{\sigma f^{*}}(y^{n} + \sigma K\bar{x}^{n})$$
$$x^{n+1} = \mathrm{prox}_{\tau g}(x^{n} - \tau K^{*}y^{n+1})$$
$$\bar{x}^{n+1} = x^{n+1} + \theta(x^{n+1} - x^{n})$$

Log in to JupyterHub

- Go to: https://ibsim.co.uk/training and write your name next to a username to claim it for the exercises
- Hands-on exercises at CIL Jupyter notebook server: https://training.jupyter.stfc.ac.uk/
- Sign up with the username you claimed and a password of your choice.
- No password reset option, so remember your password!
- Then log in with the username and password you set.
- Select the **OpenGL GPU environment** server and press "start":



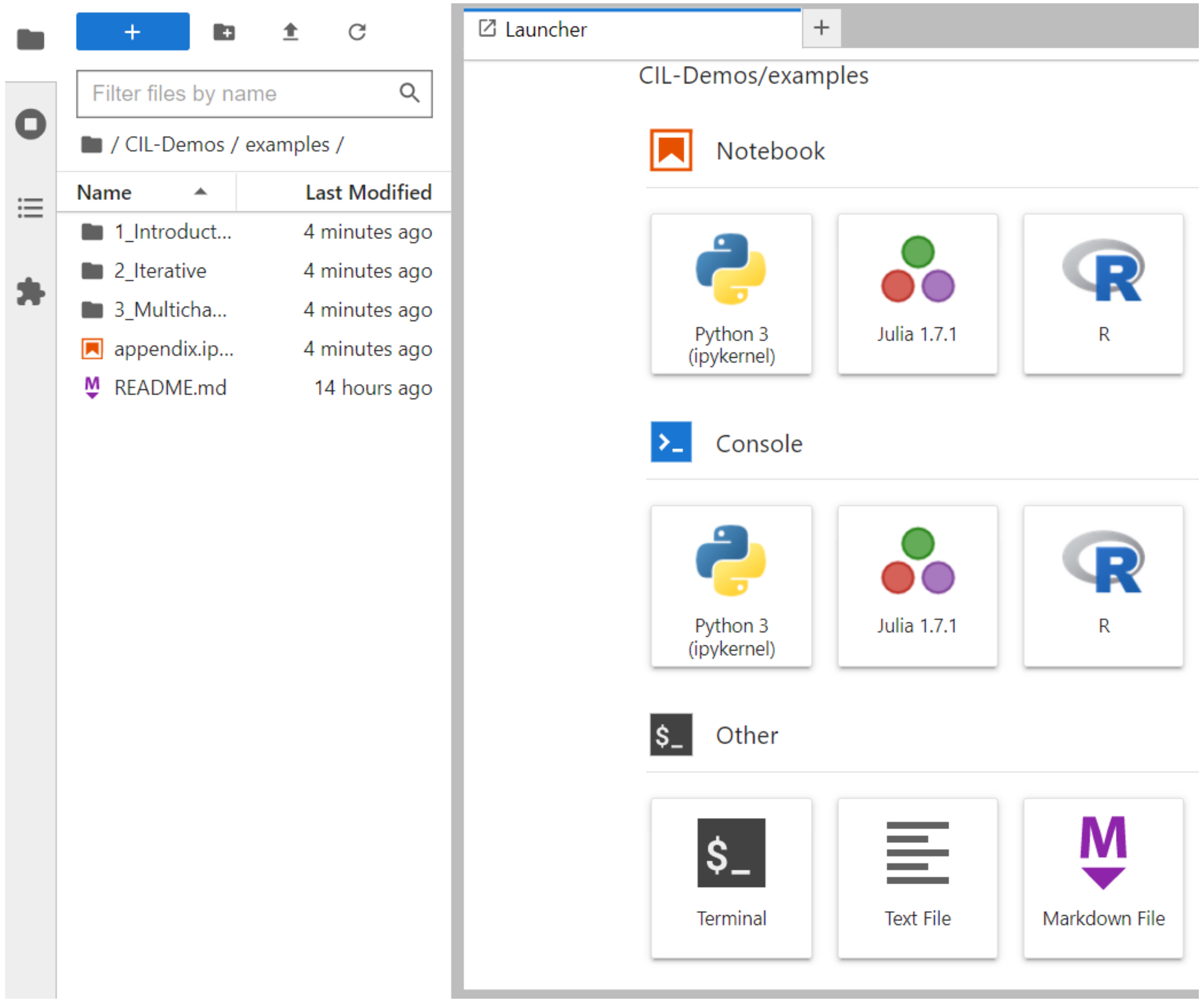

Server Options

( ) **Default: Normal Size**
For small jobs and prototyping: 2 CPUs, 1.5GB RAM and no GPU.

( ) **Tensorflow GPU environment**
This configuration gives you 10 CPUs, 70GB of RAM, and a GPU, Tensorflow environment

[✓] **OpenGL GPU environment**
This configuration gives you 10 CPUs, 70GB of RAM, and a GPU and sets up an OpenGL environment

Once logged in …



Name	Last Modified
1_Introduct...	4 minutes ago
2_Iterative	4 minutes ago
3_Multicha...	4 minutes ago
appendix.ip...	4 minutes ago
README.md	14 hours ago

Let’s Try Out the Walnut Notebook!

Go to:
CIL-Demos/examples/1_Introduction /01_intro_walnut_conebeam.ipynb

Learning Objectives:

- Load and investigate a ZEISS data set.
- Apply CIL's TransmissionAbsorptionConverter.
- Compute FDK reconstruction using CIL and compare with a reconstruction made from fewer projections.
- Write out the reconstructed image to a TIFF stack.

- Go to: https://ibsim.co.uk/training - write your name next to a username to claim it for the exercises
- CIL Jupyter notebook server: https://training.jupyter.stfc.ac.uk/
- Sign up with the username you claimed and a password of your choice.

Questions?

Exercise 1

- Make your own reconstruction as the Walnut with a Nikon dataset

Questions?

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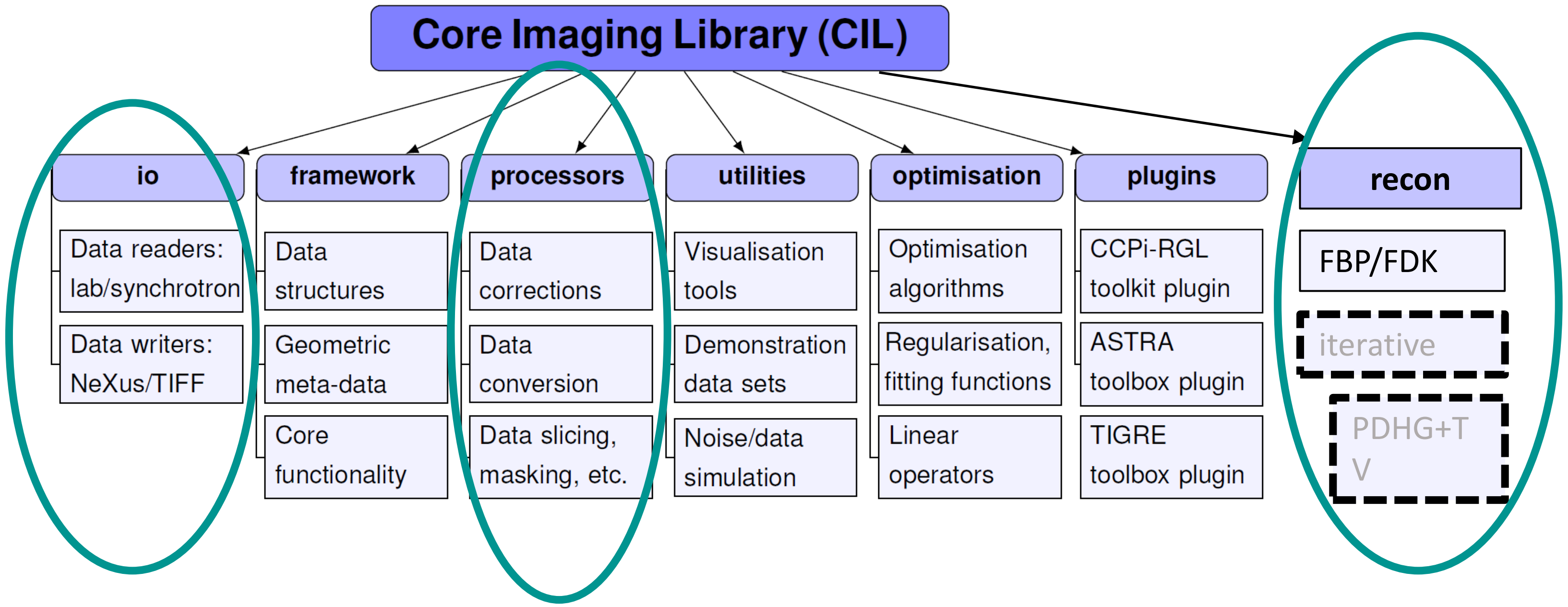
Session 2
Pre-processing of XCT data

CIL Module Structure and Contents



Jørgensen et al. 2021: *Core Imaging Library - Part I: a versatile Python framework for tomographic imaging,* Phil. Trans. R. Soc. A, **379**, 20200192: https://doi.org/10.1098/rsta.2020.0192

Typical XCT Data Pre-Processing

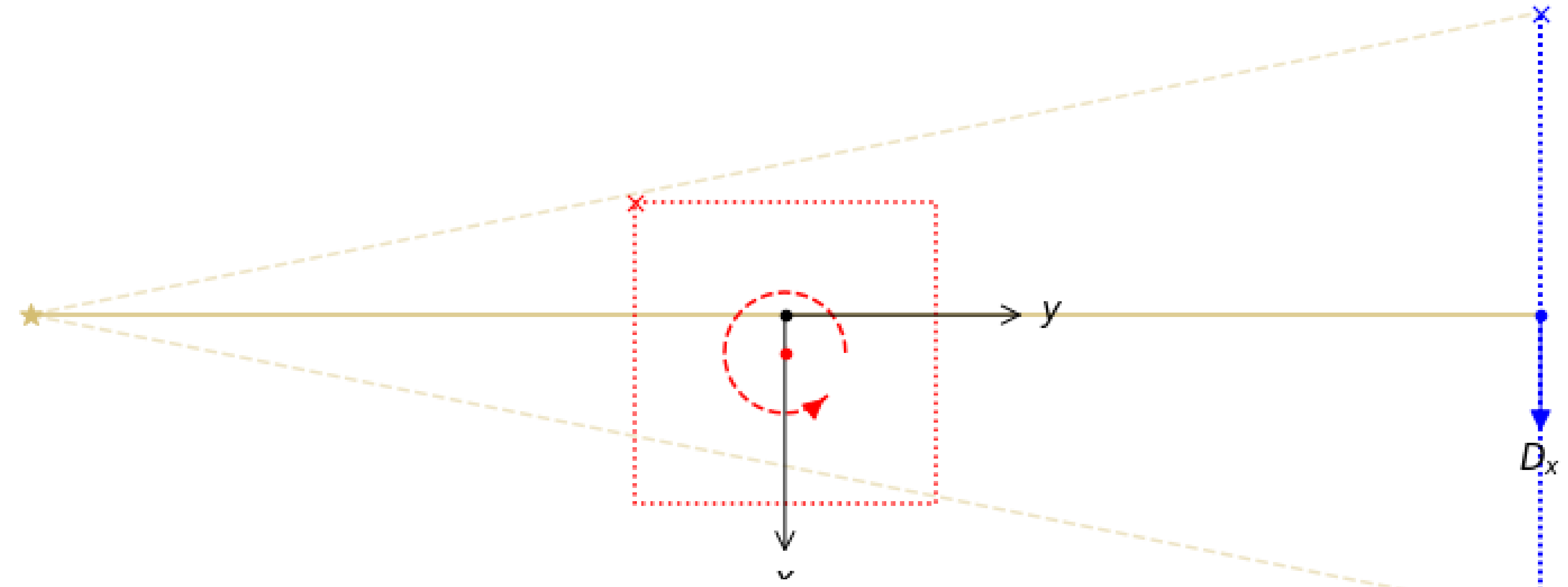
Data Manipulation

- Data Slicer
- Data Binner
- Data Padder
- Mask Generator from Data
- Data Masking

Pre-processors

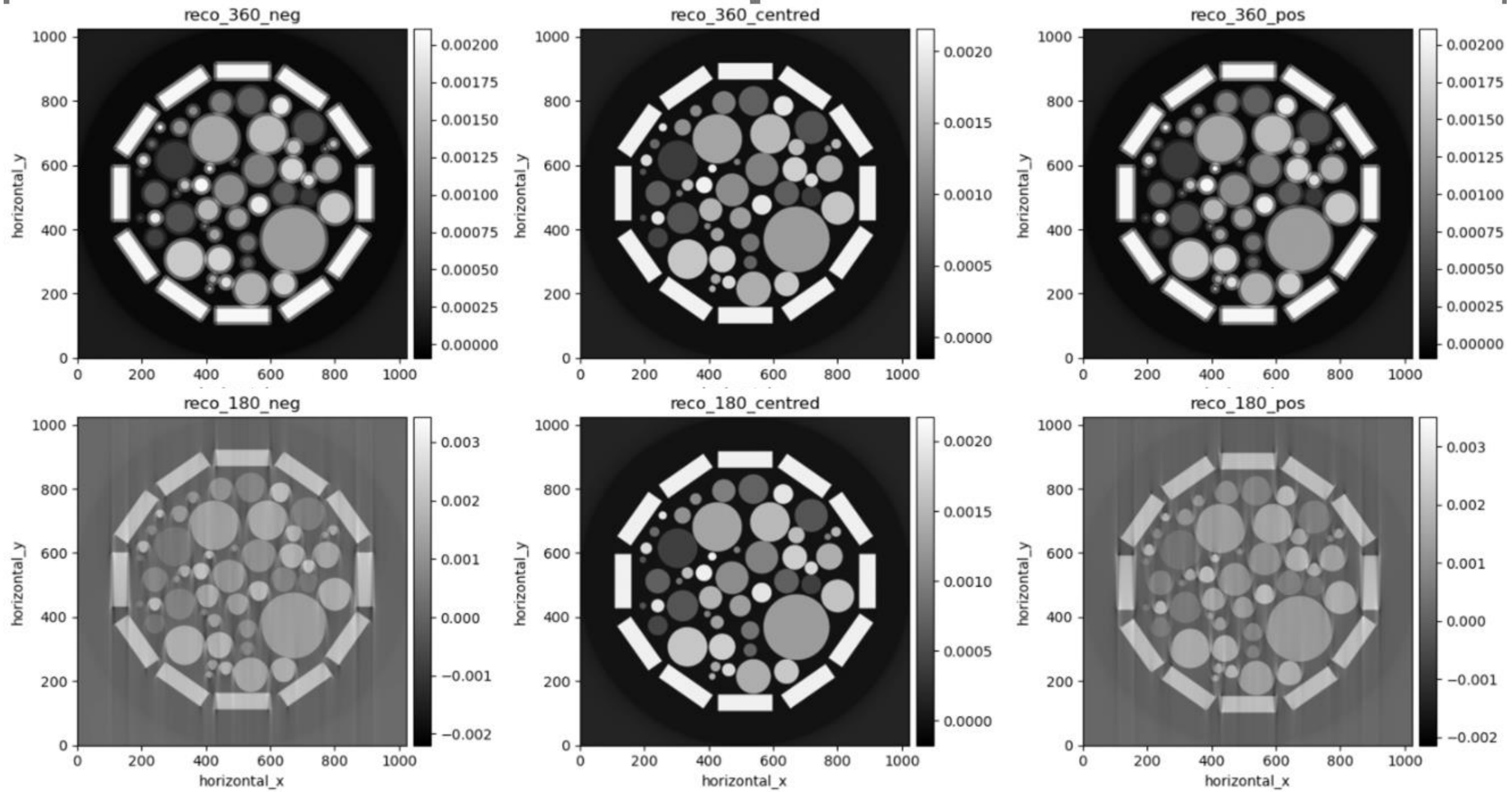
- Centre Of Rotation Correction
- Data Normaliser
- Transmission to Absorption Converter
- Absorption to Transmission Converter
- Ring Remover

Centre of Rotation



—	world coordinate system	●	rotation axis position	●	detector position
★	source position	—	rotation axis direction	—	detector direction
		·······	image geometry	·······	detector
		×	data origin (voxel 0)	×	data origin (pixel 0)
		----	rotation direction θ		

Centre of Rotation



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Let’s Pre-Process

Go to:
CIL-Demos/examples/1_Introduction /02_intro_sandstone_parallel_roi.ipynb

Learning Objectives:
- Load and investigate a real data set.
- Determine geometric information of the data and set up CIL data structures.
- Apply CIL processors to pre-process the data, including normalisation, negative log, region-of-interest and centre of rotation correction.
- Compute FBP reconstruction using CIL and compare with reconstruction provided.

- Go to: https://ibsim.co.uk/training - write your name next to a username to claim it for the exercises
- CIL Jupyter notebook server: https://training.jupyter.stfc.ac.uk/
- Sign up with the username you claimed and a password of your choice.

Questions?

Exercise 2

- As above, with different dataset from Nikon? (seeds in a box, uncentred?, centring? Slicer? Binner? Reconstruction volumes?, advanced exercise, do the same with a different dataset?
- GUI demo with seeds in the box

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Questions?

Session 3

Iterative reconstruction methods for standard XCT data

Filtered Back Projection (FBP)

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Pros

- Fast as based on FFT and backprojection
- Few parameters
- Typically works very well
- Reconstruction behaviour well understood

Cons

- Number of projections needed proportional to acquisition panel size
- Full angular range required (limited angle problem)
- Modest amount of noise tolerated
- Fixed scan geometries
- Cannot make use of prior knowledge such as non-negativity

Imaging model for iterative reconstruction

Beer-Lambert for ith ray (along line L_i):

$$\frac{I}{I_0} = \int e^{-\mu(x)} dx \qquad \int_{L_i} \mu \; ds = -\log \frac{I_i}{I_0} = b_i$$

Assume object constant in each pixel:

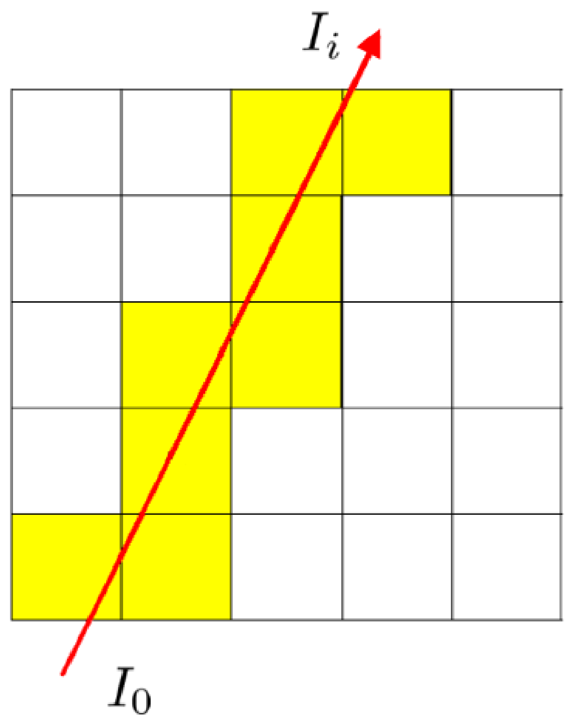
- u_j is the jth pixel value.
- a_{ij} is path length through jth pixel.

Approximate line integral by sum:

$$\sum_j a_{ij} u_j = b_i$$

Extremely large set of linear equations:

$$Au = b$$



Operator *A*:

- Direct *Au*: Projection
- Adjoint *A*^{T}*b*: Backprojection

Iterative reconstruction is based on optimisation problems and algorithms

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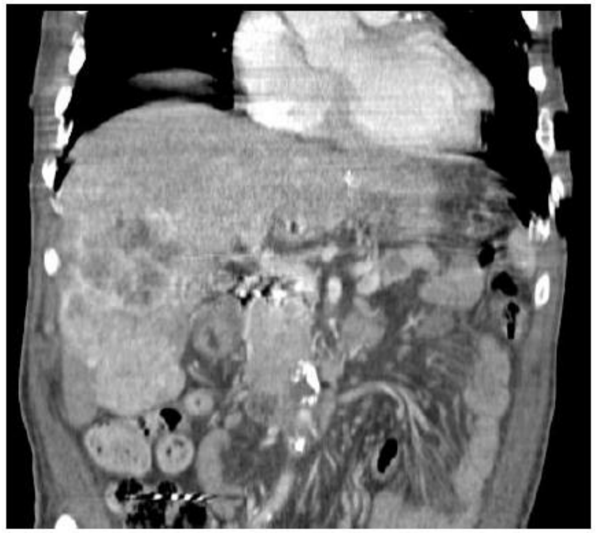
Discrete imaging model:

$$Au = b$$

Typical CT images:

- Regions of homogeneous tissue.
- Separated by sharp boundaries.

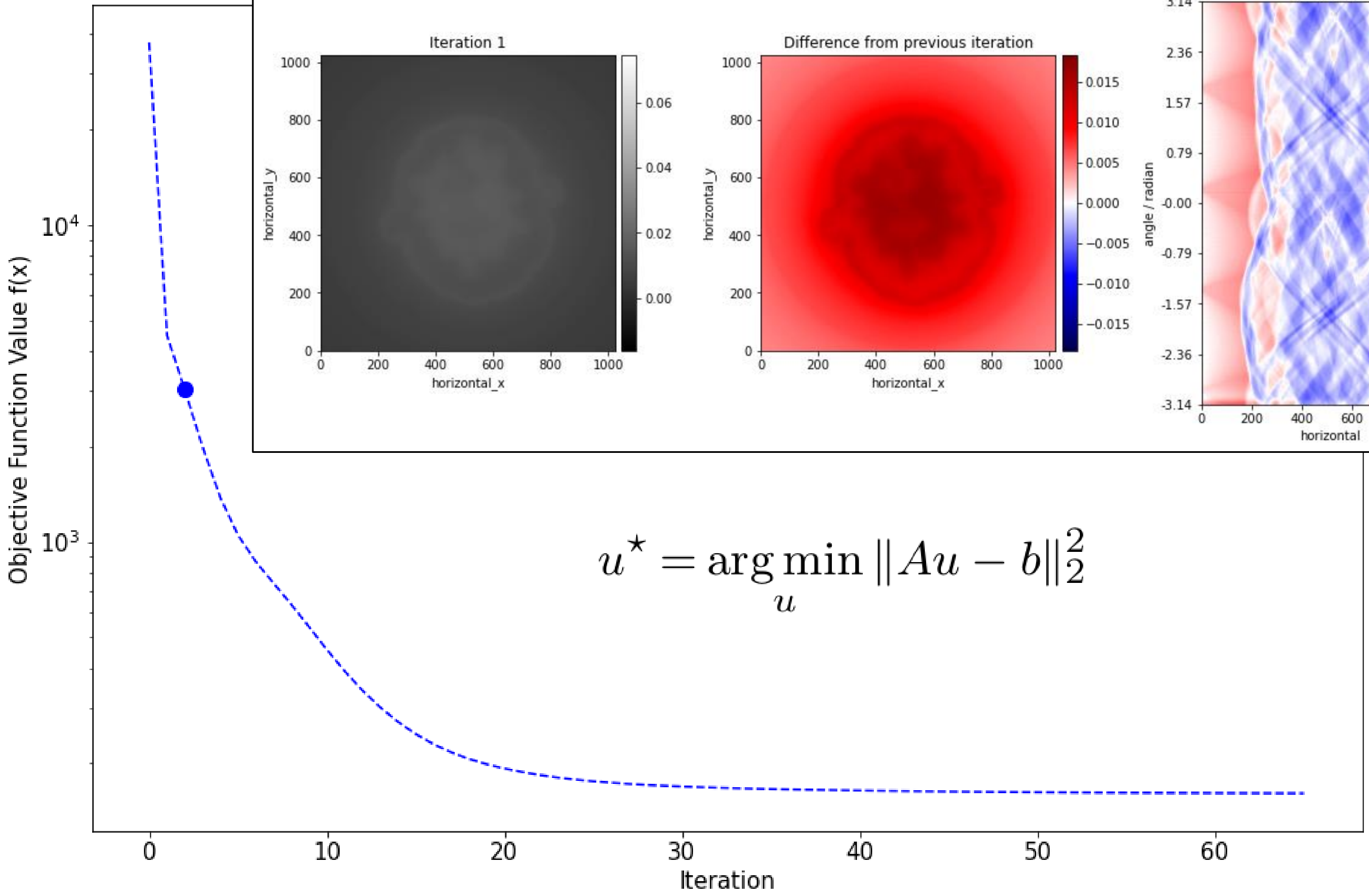


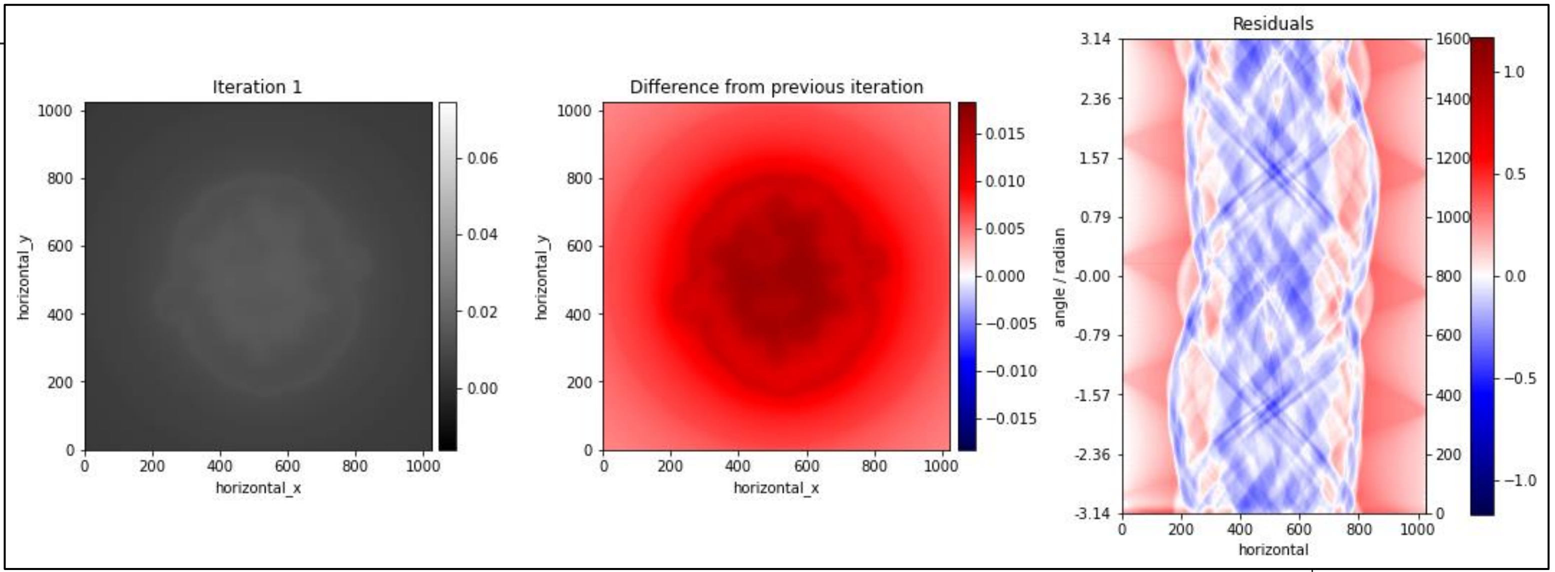
Reconstruction

$$u^\star = \underset{u}{\operatorname{argmin}} \{\mathcal{D}(Au, b) \qquad\qquad\qquad \}$$

$$u^\star = \underset{u}{\arg\min} \|Au - b\|_2^2 \quad = \sum_i ((Au)_i - b_i)^2$$

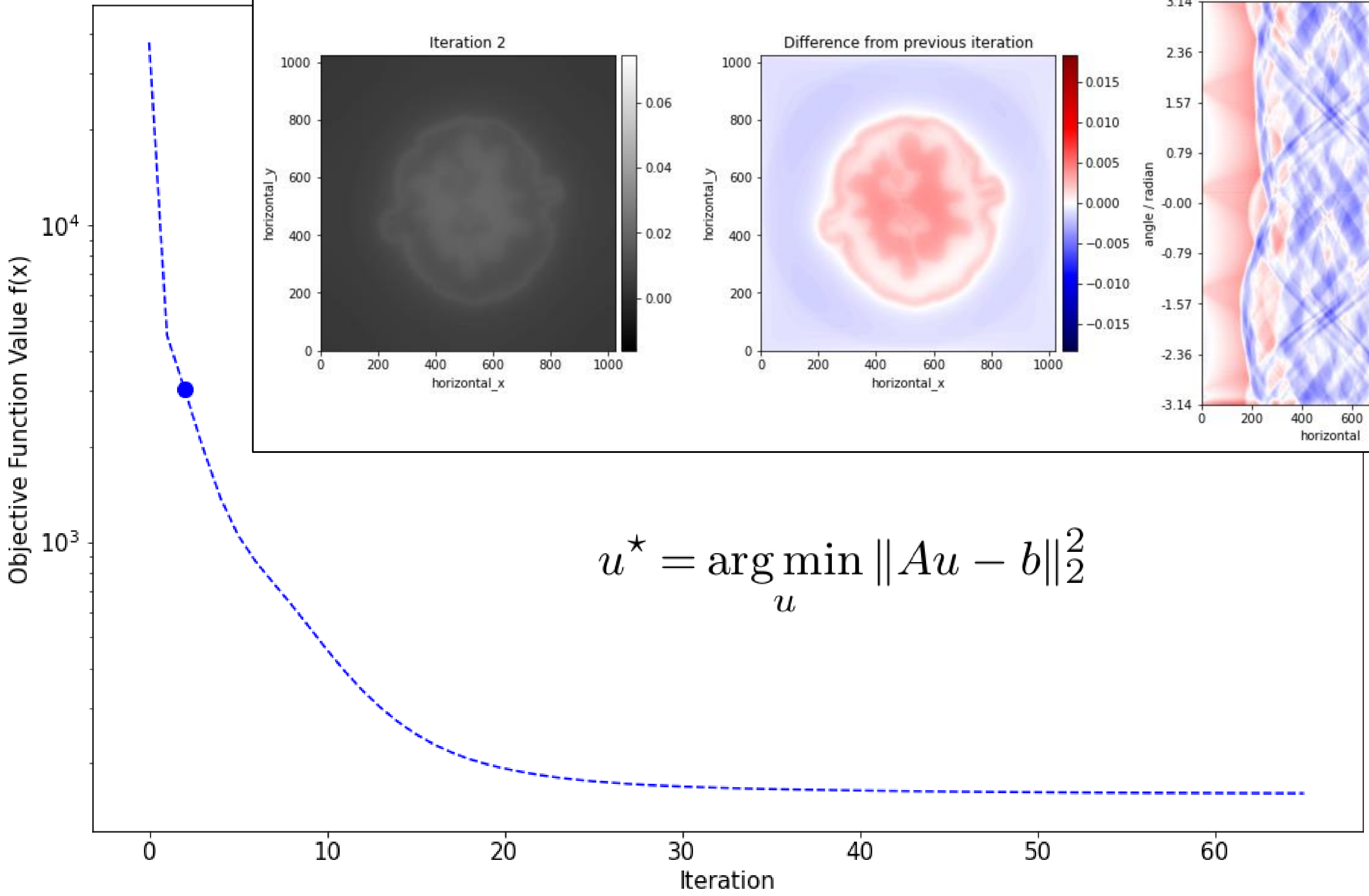
Solve optimisation problem iteratively

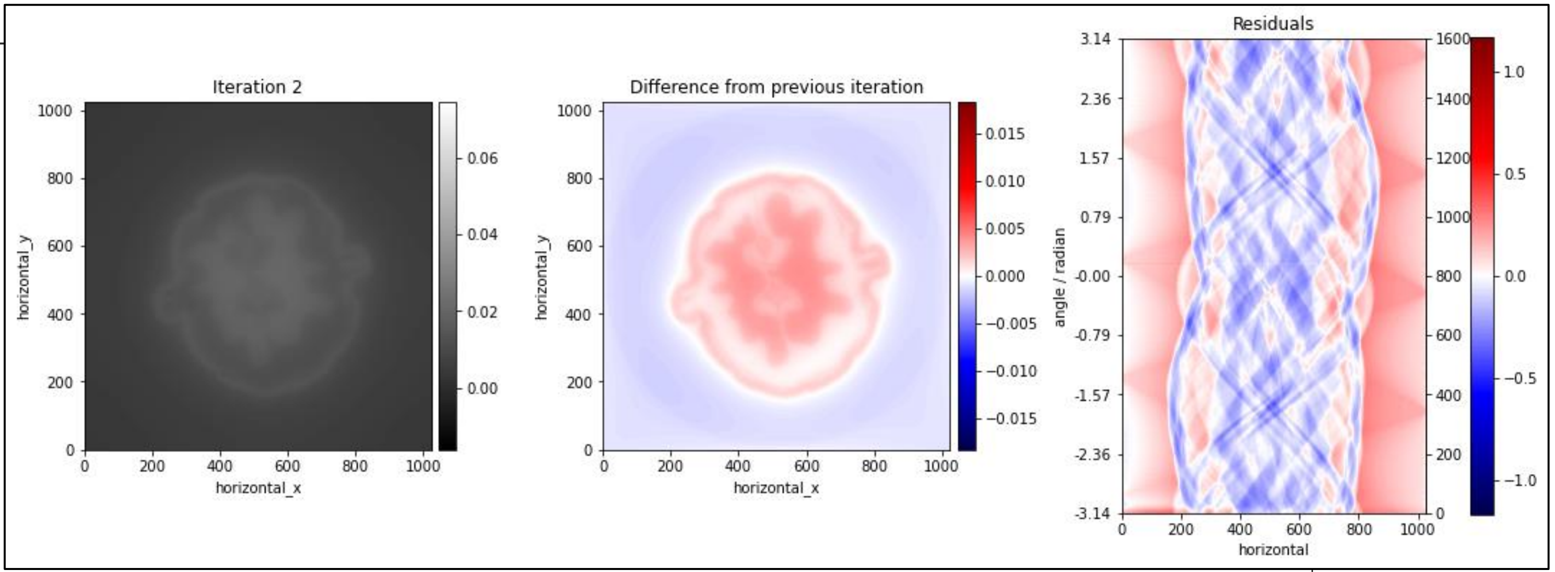




$$u^{\star} = \arg\min_{u} \|Au - b\|_2^2$$

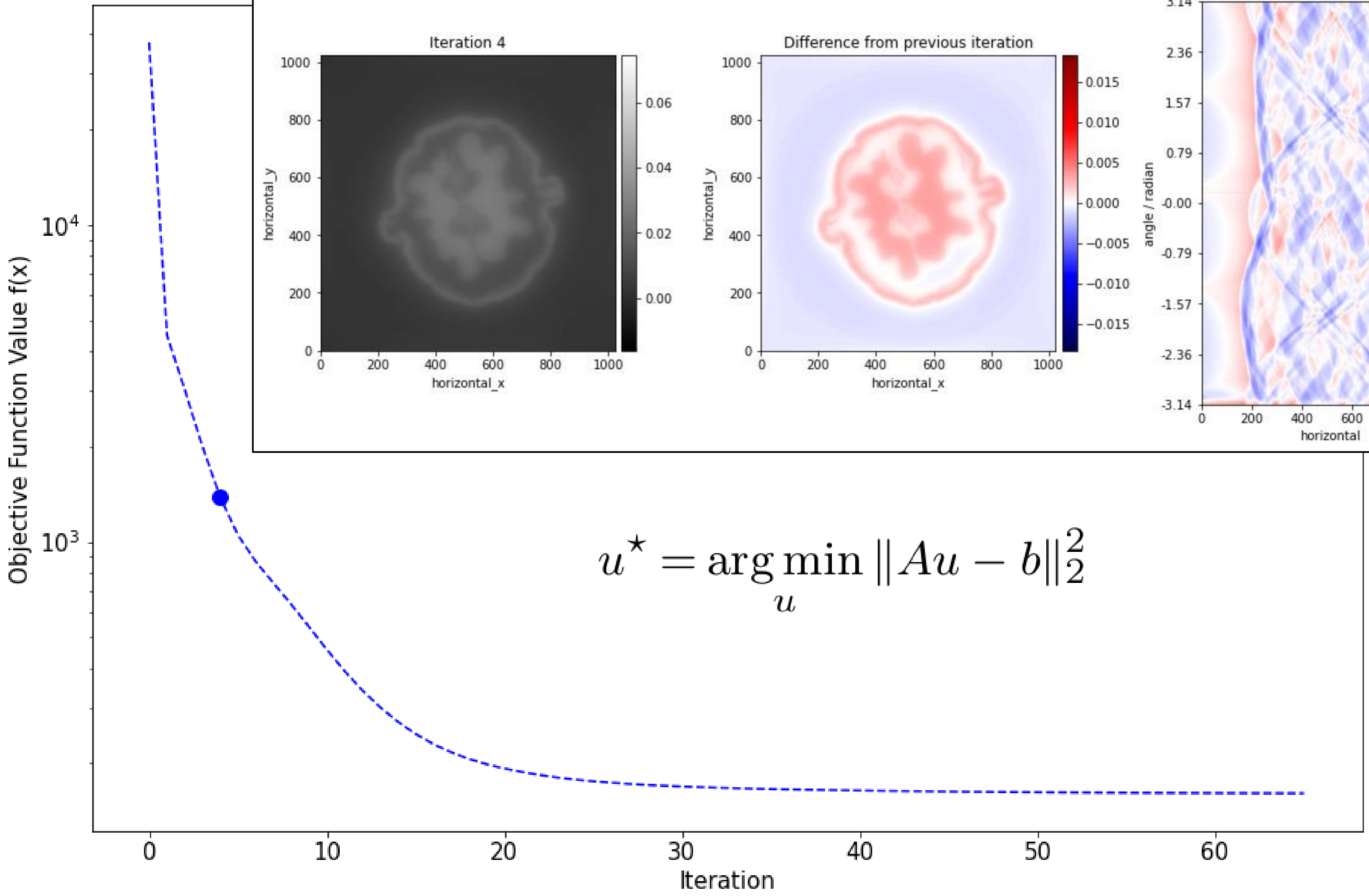
Solve optimisation problem iteratively

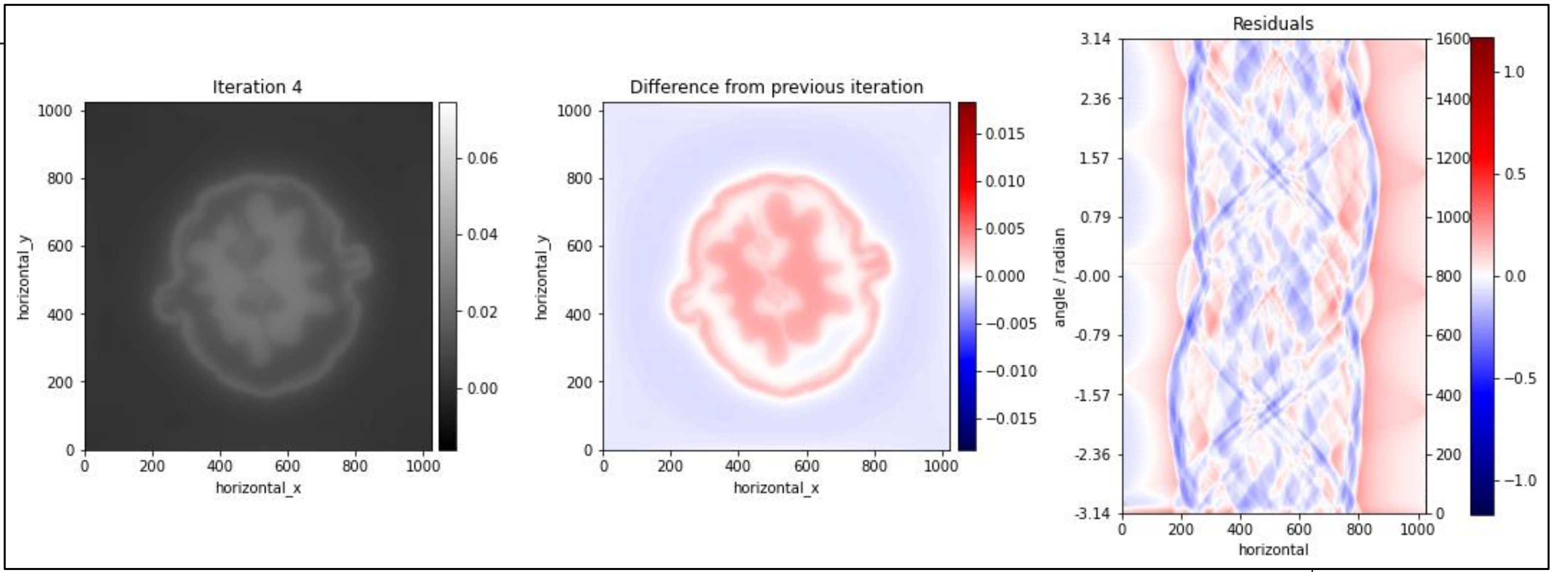




$$u^\star = \underset{u}{\arg\min} \|Au - b\|_2^2$$

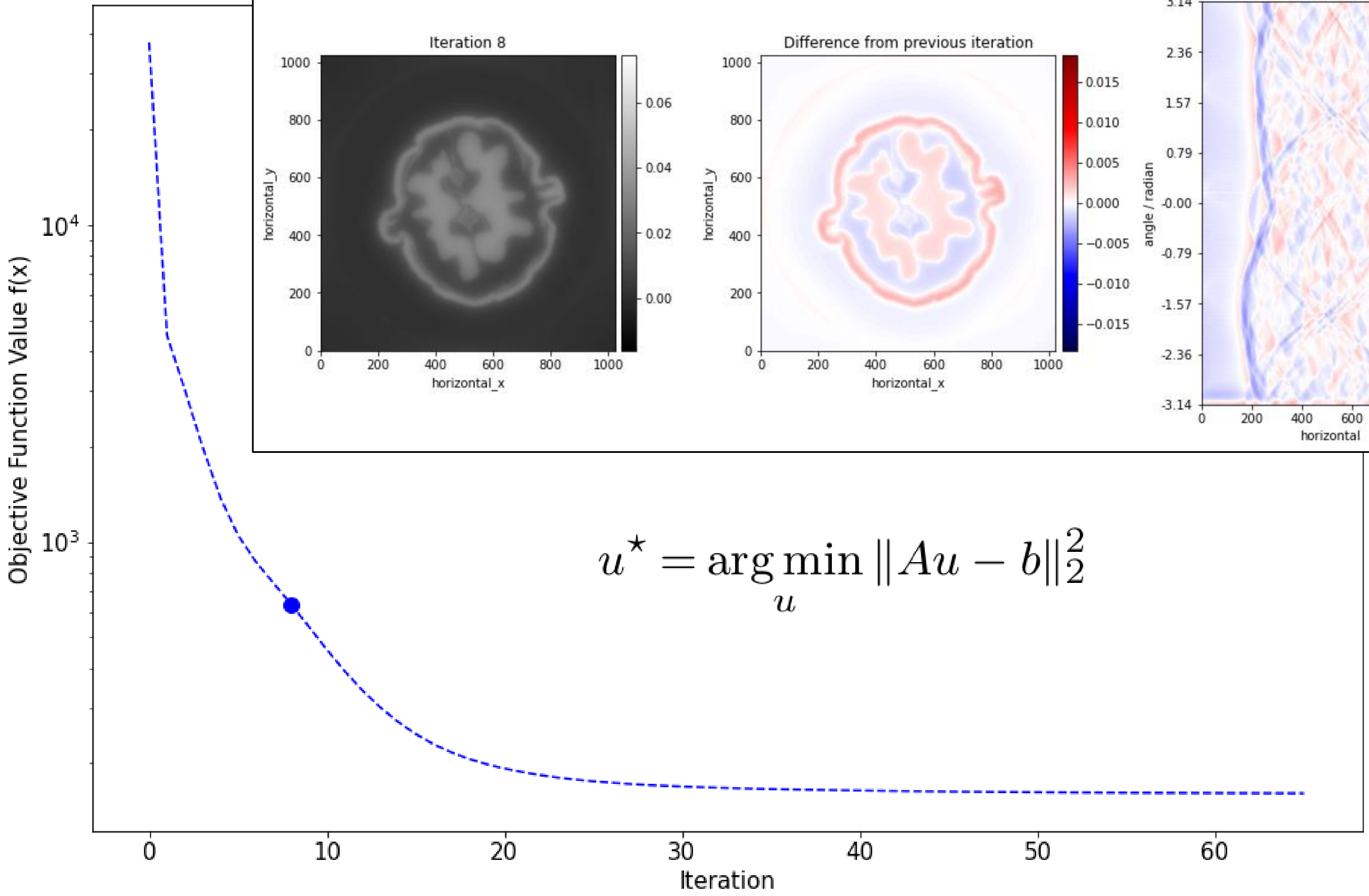
Solve optimisation problem iteratively

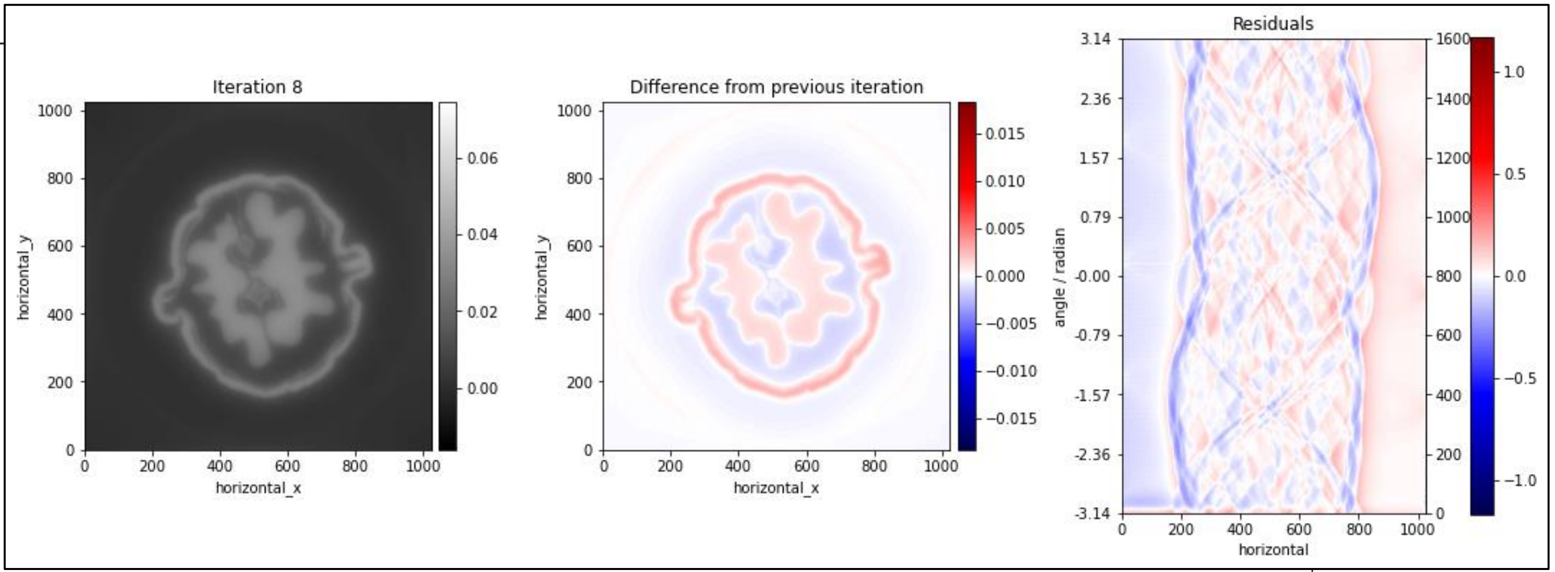




$$u^\star = \arg\min_u \|Au - b\|_2^2$$

Solve optimisation problem iteratively





$$u^\star = \underset{u}{\arg\min} \, \|Au - b\|_2^2$$

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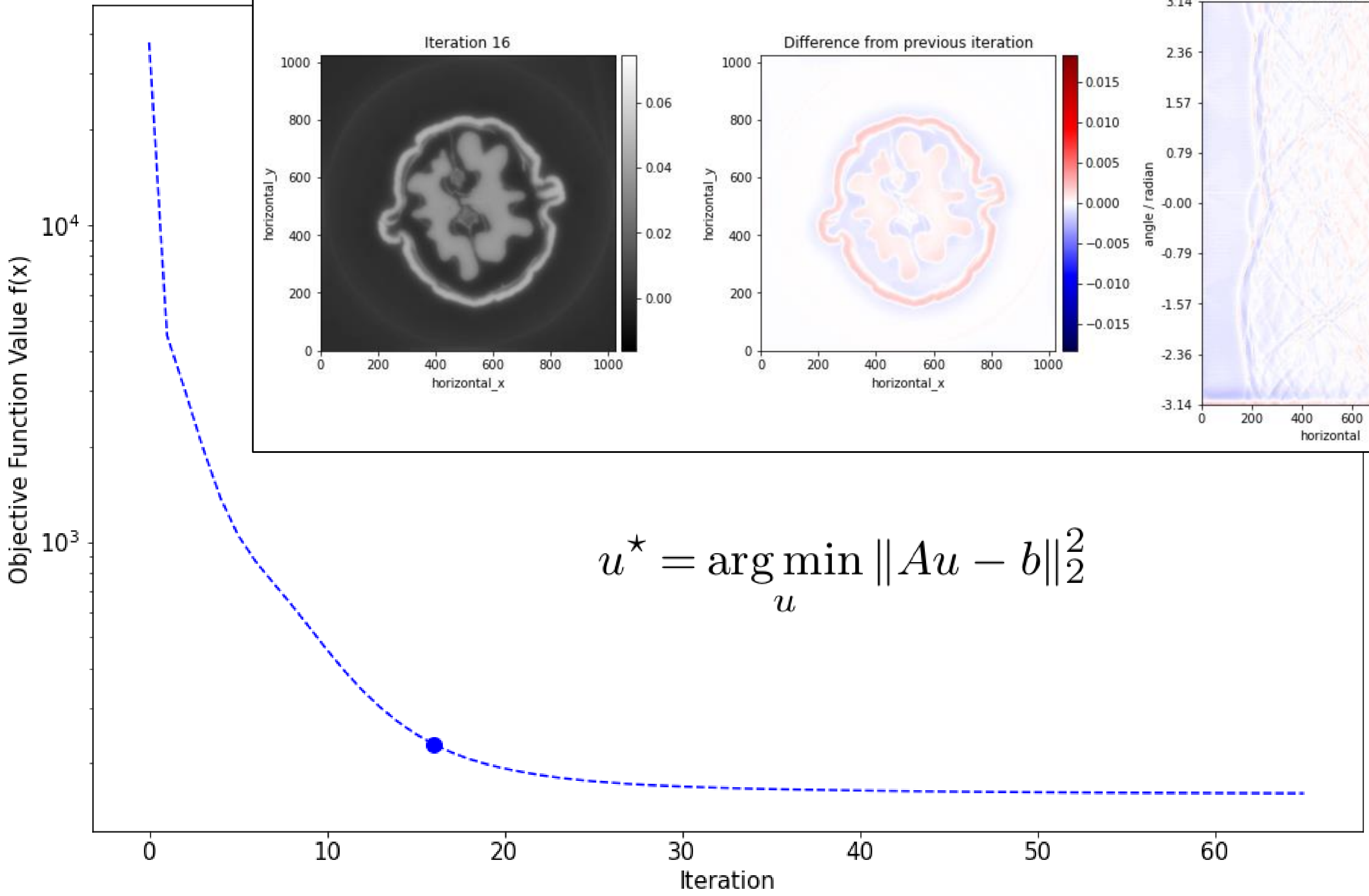
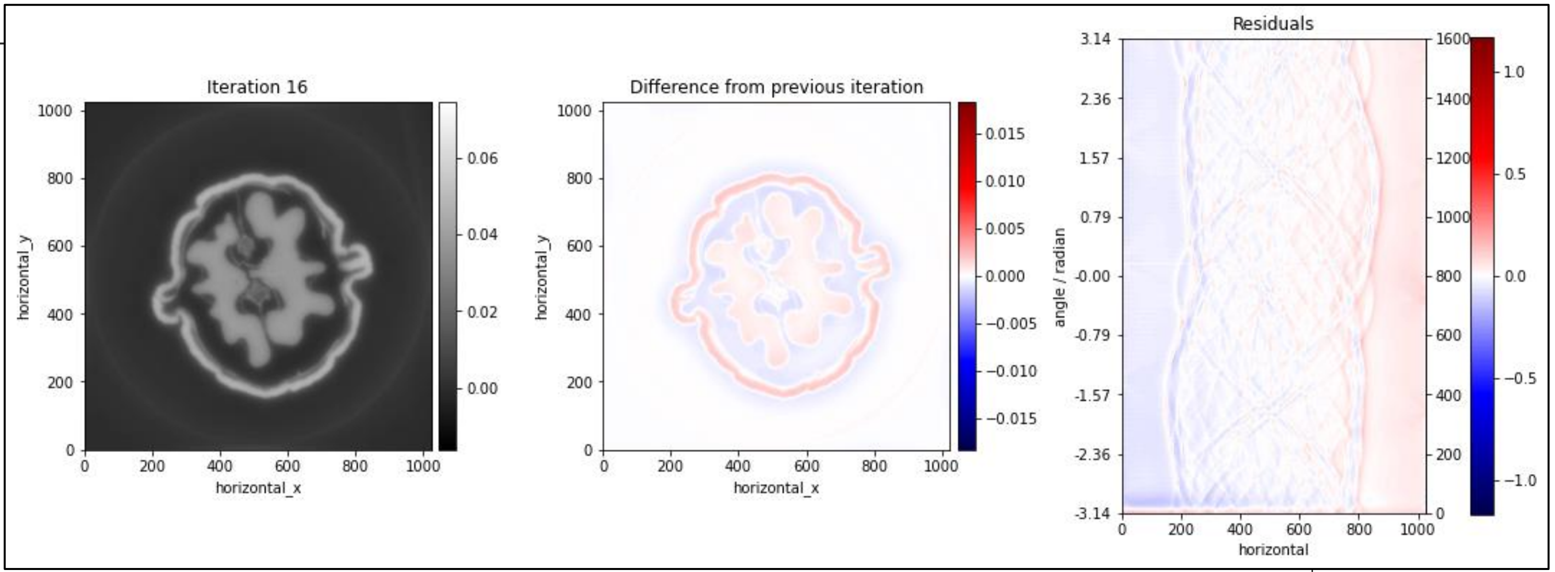
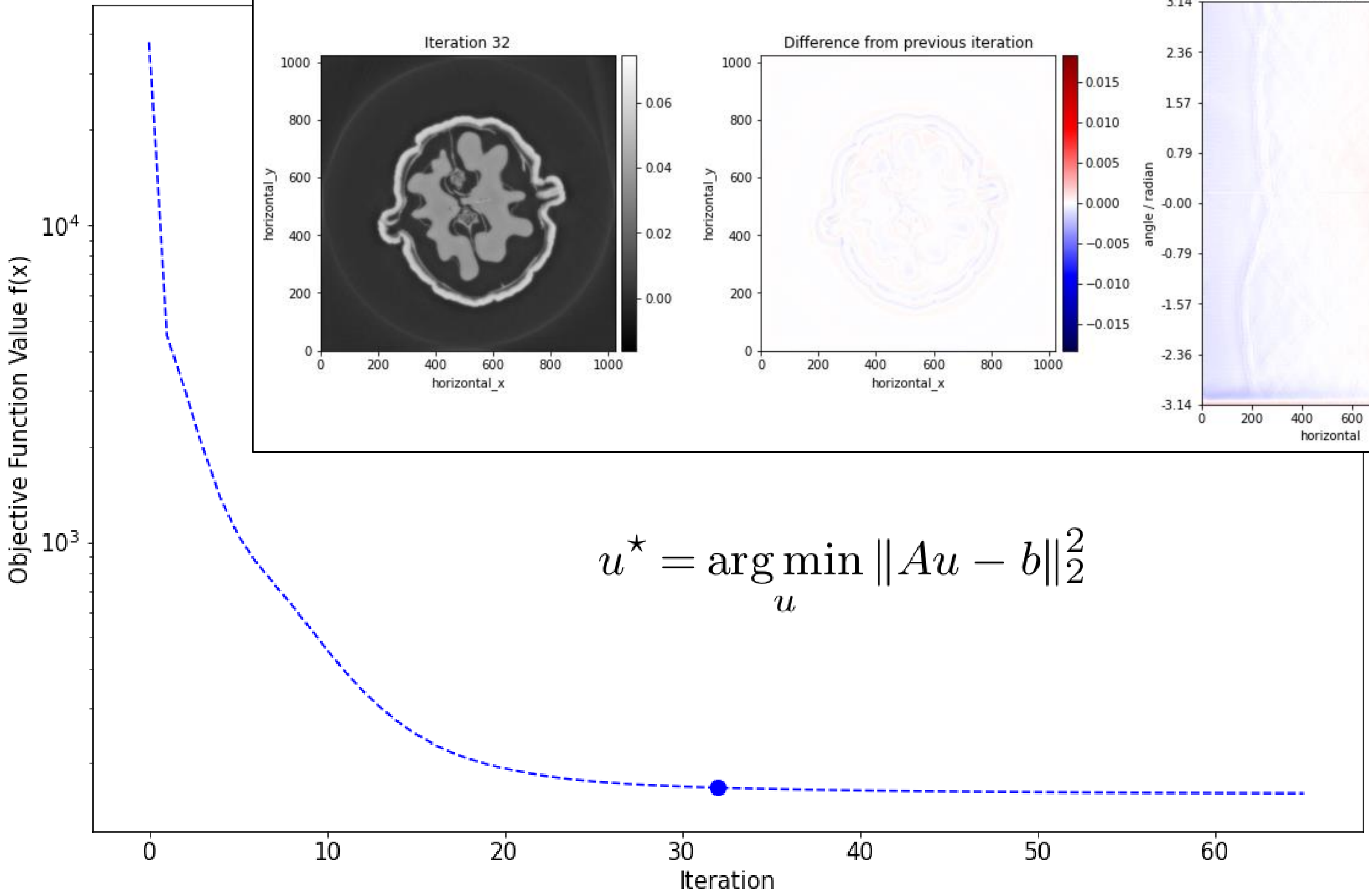
Solve optimisation problem iteratively

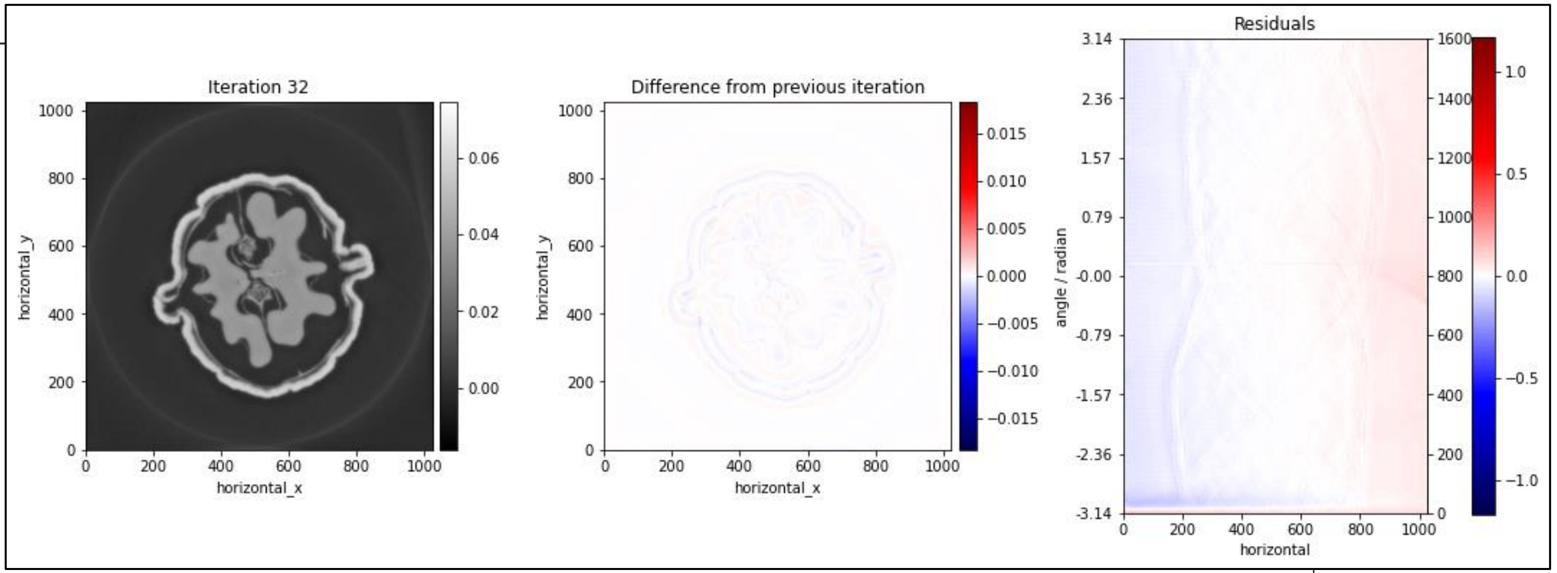




$$u^{\star} = \underset{u}{\arg\min} \|Au - b\|_2^2$$

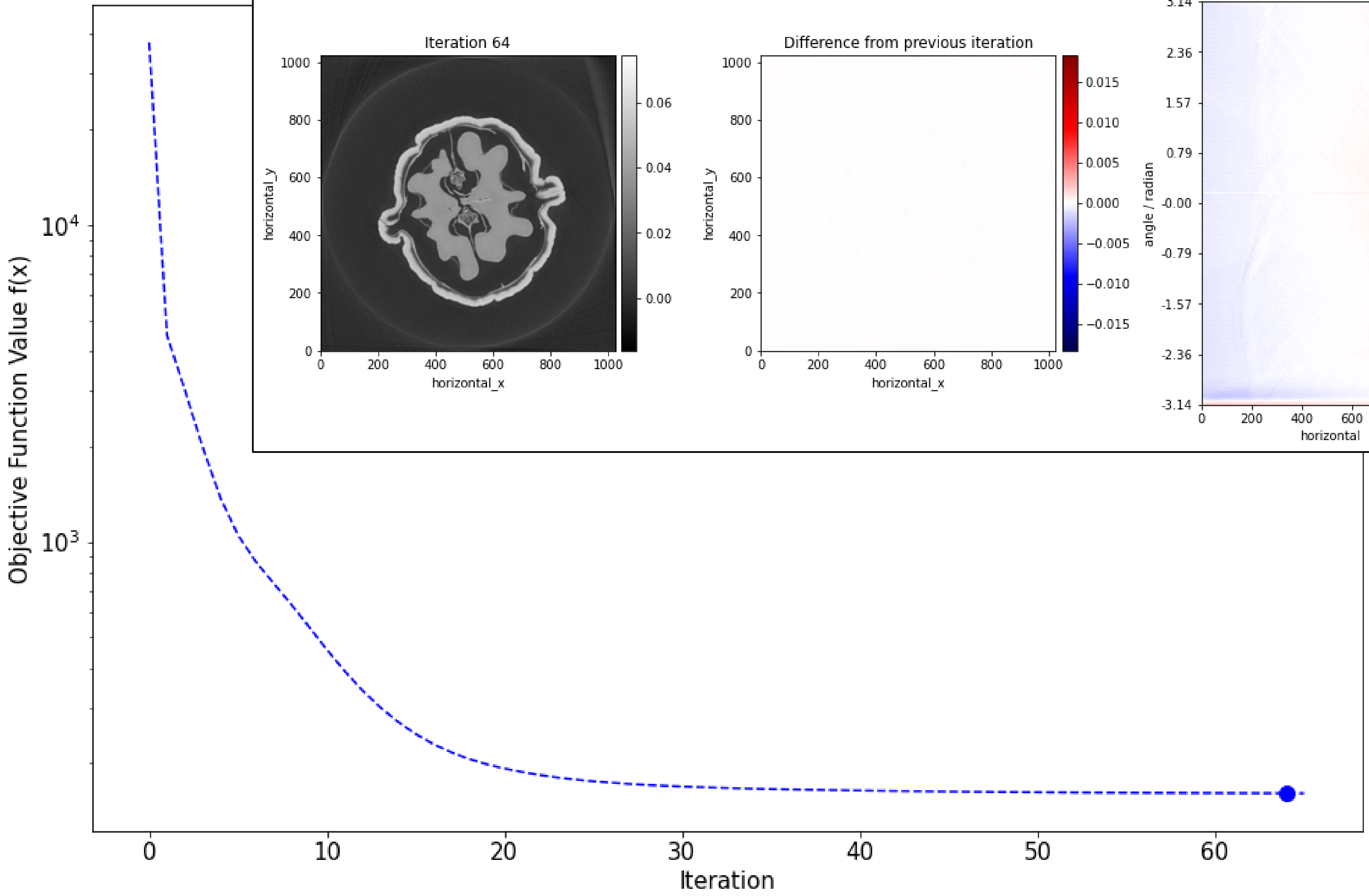
Solve optimisation problem iteratively

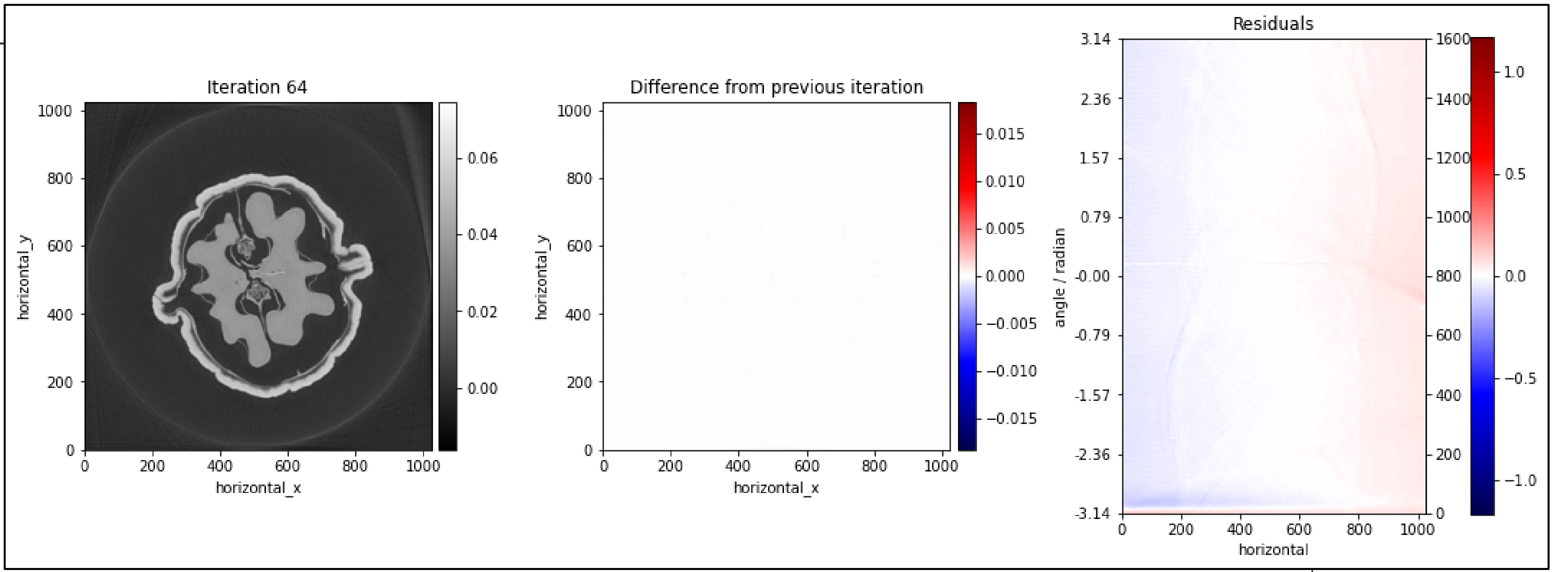




$$u^\star = \arg\min_u \|Au - b\|_2^2$$

Solve optimisation problem iteratively





Let's Get Iterative!

Go to:
CIL-Demos/examples/1_Introduction/04_FBP_CGLS_SIRT.ipynb

Learning Objectives:

- formulate CT reconstruction as an optimisation problem and solve it iteratively
- introduce constraints in the optimisation problem
- visualise final and intermediate reconstruction results
- get familiar with the CIL `Algorithm` and `Operator` classes
- Use of the CGLS, SIRT algorithms

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Questions?

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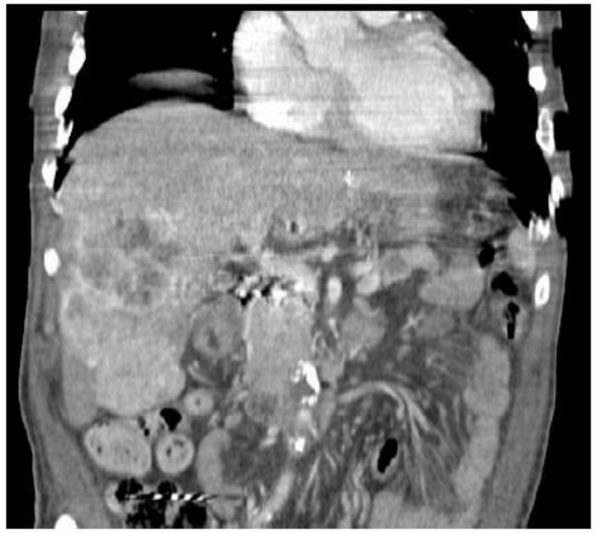
Iterative reconstruction with Regularisation

Discrete imaging model:

$$Au = b$$

Typical CT images:

- Regions of homogeneous tissue.
- Separated by sharp boundaries.



Reconstruction

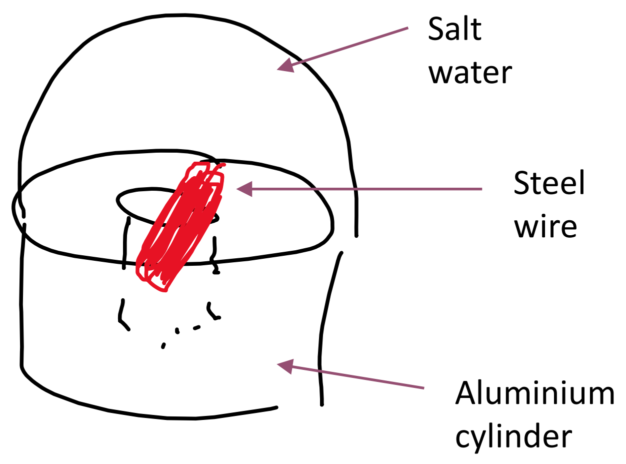
$$u^\star = \underset{u}{\operatorname{argmin}} \{\mathcal{D}(Au, b) + \alpha \cdot \mathcal{R}(u)\}$$

$$u^\star = \arg\min_u \|Au - b\|_2^2 \quad = \sum_i ((Au)_i - b_i)^2$$

Demonstration dataset

- 3D parallel-beam X-ray CT dataset from Beamline I13-2, Diamond Light Source.
- 0.5 mm aluminium cylinder with a piece of steel wire embedded in a small drilled hole. A droplet of salt water was placed on top, causing corrosion to form hydrogen bubbles.
- 160x135 15 projections over 180°

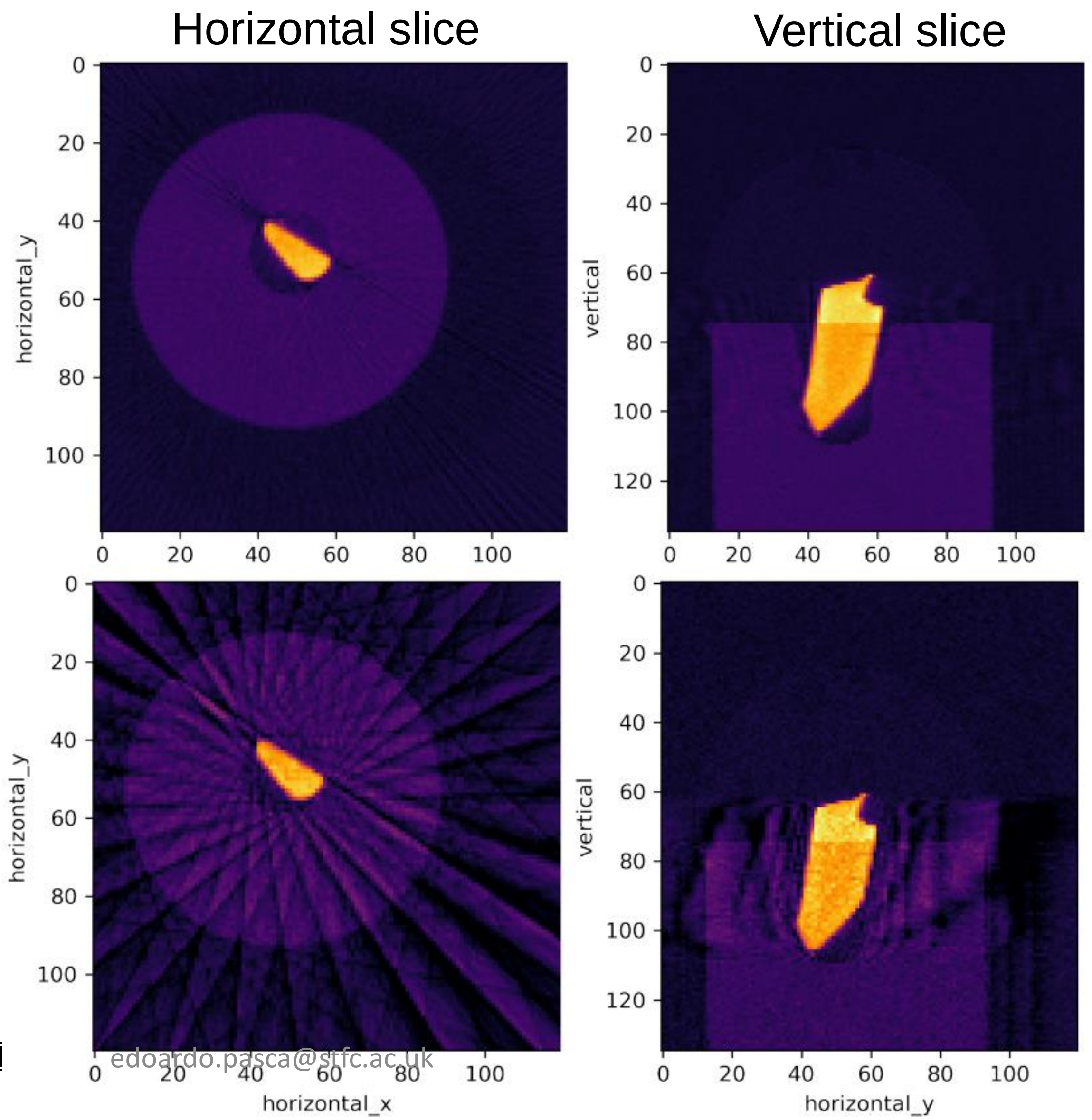
Jørgensen et al.: *Core Imaging Library - Part I: a versatile Python framework for tomographic imaging* Phil. Trans. R. Soc. A. **379** 20200192 (2021) DOI: [10.1098/rsta.2020.0192](https://doi.org/10.1098/rsta.2020.0192)



Demonstration dataset

90
projections

15
projections



Algebraic Iterative Methods

regularising by number of iterations

CGLS

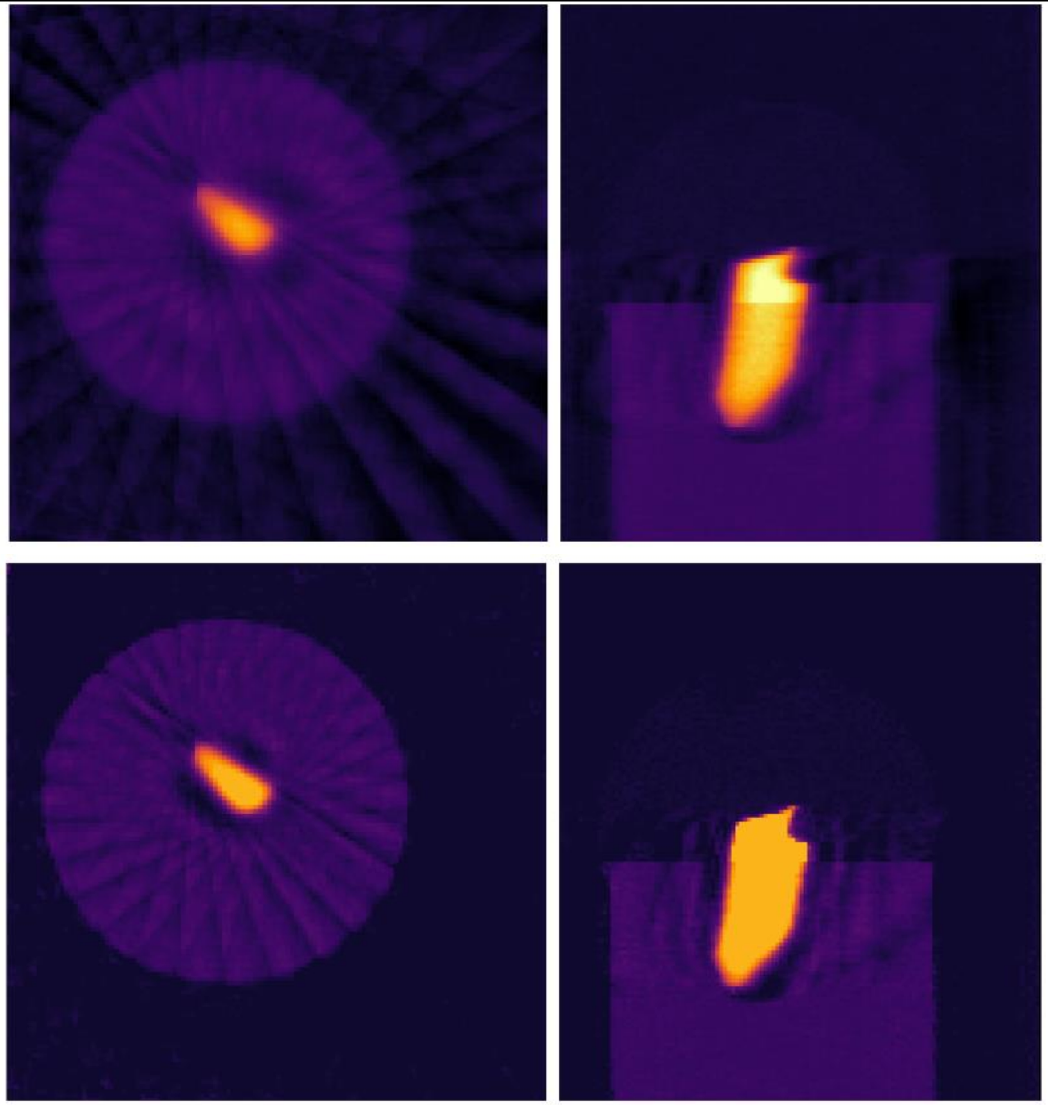
$$u^\star = \arg\min_u ||Au - b||_2^2$$

Typically 10s of iterations

SIRT

As above and allowing lower and upper bounds on pixel values, here Non-negative and <= 0.9

Typically 100s of iterations



Smooth Regularisation: Tikhonov

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$$u^{\star} = \arg\min_{u} \left\{ \|Au - b\|_2^2 + \alpha^2 \|Lu\|_2^2 \right\}$$

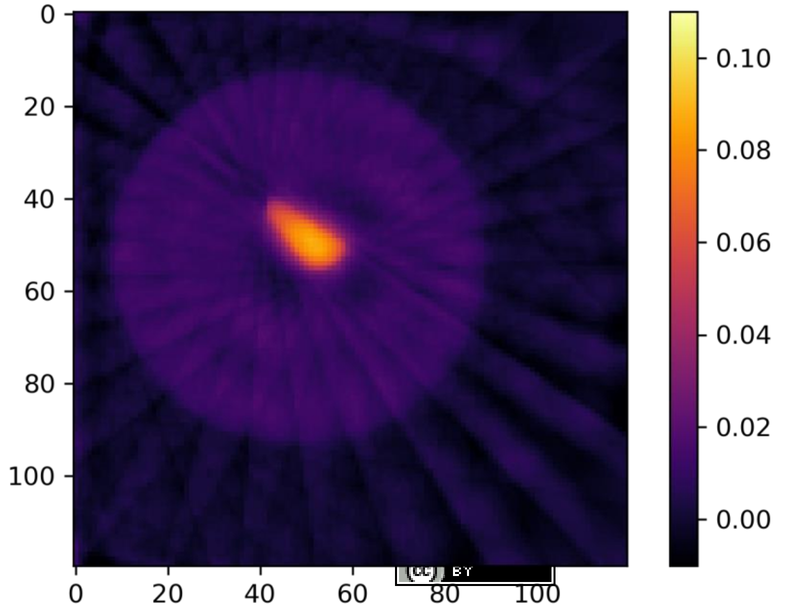
Data fidelity

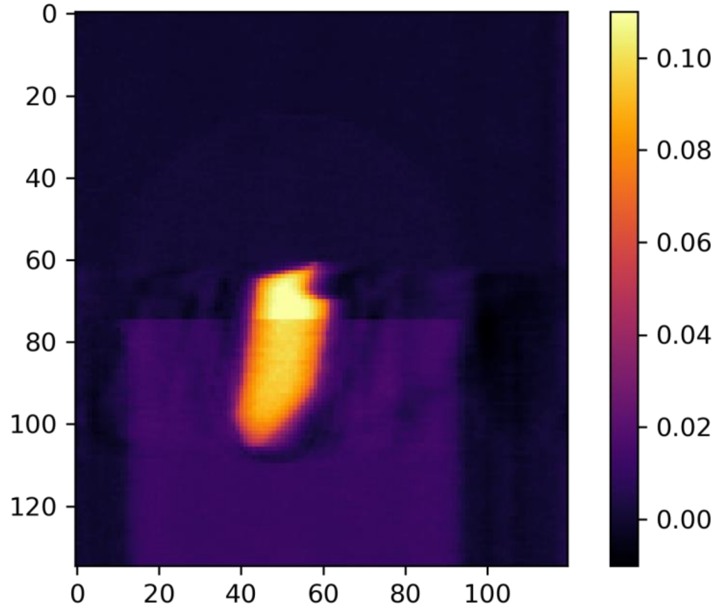
Regulariser

Minimiser: Solution image

Unknown image TBD

Regularisation parameter

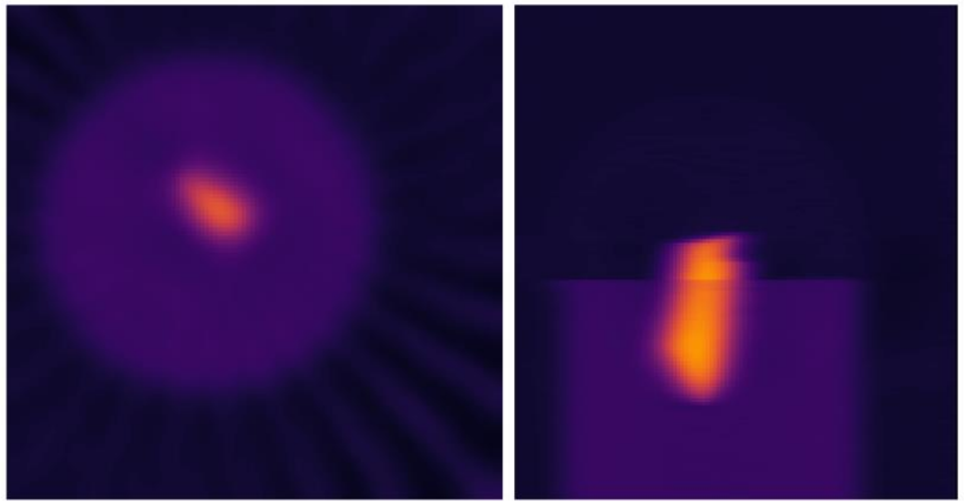




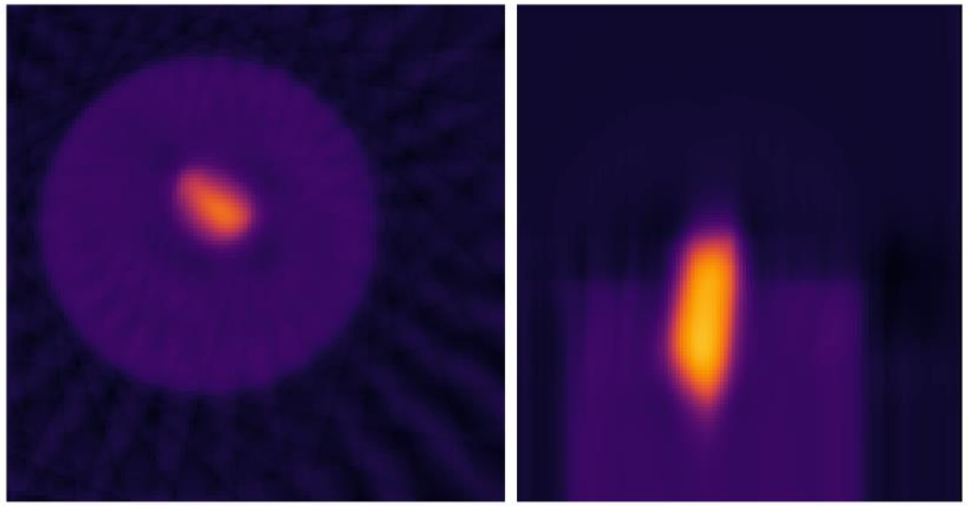
Smooth Regularisation: Anisotropic Tikhonov

$$u^\star = \underset{u}{\arg\min} \left\{ \|Au - b\|_2^2 + \alpha_x^2 \|L_x u\|_2^2 + \alpha_y^2 \|L_y u\|_2^2 + \alpha_z^2 \|L_z u\|_2^2 \right\}$$

**Large horizontal,
small vertical smoothing**



**Small horizontal,
large vertical smoothing**



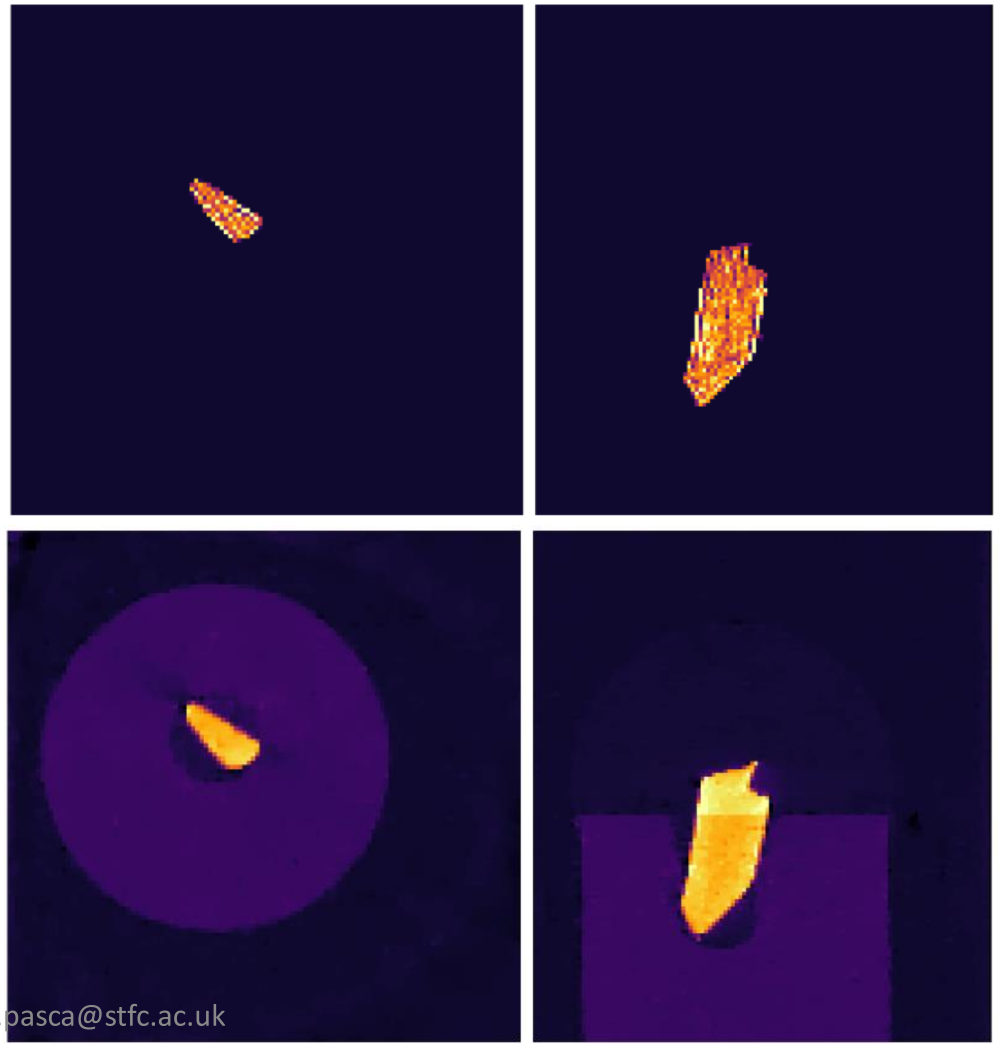
Sparsity and Total Variation Regularization

L1-norm regularisation:

$$\|u\|_1 = \sum_j |u_j|$$

Total variation regularisation:

$$\sum_j \|D_j u\|_2$$

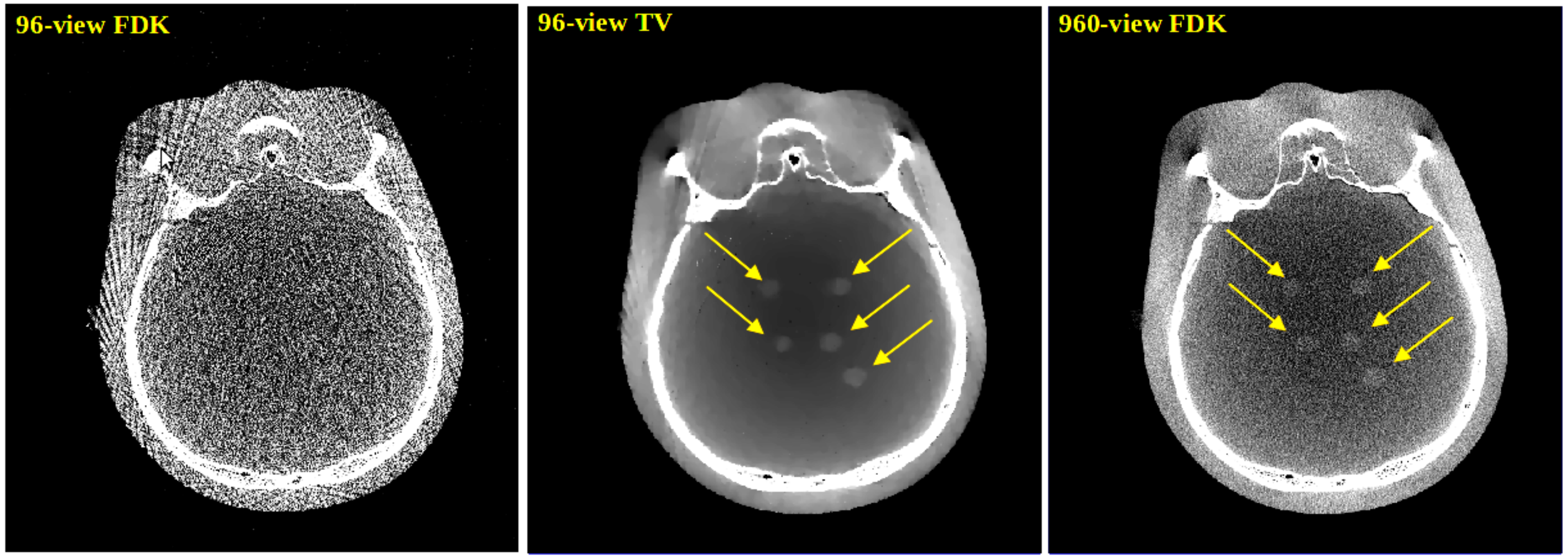


Total Variation (TV) Regularised Reconstruction

Total variation: Homogeneous regions with sharp boundaries.

$$\min_{u} \|Au - b\|_2^2 + \lambda \cdot \mathrm{TV}(u)$$

TV is an example of **sparsity-regularized reconstruction.**

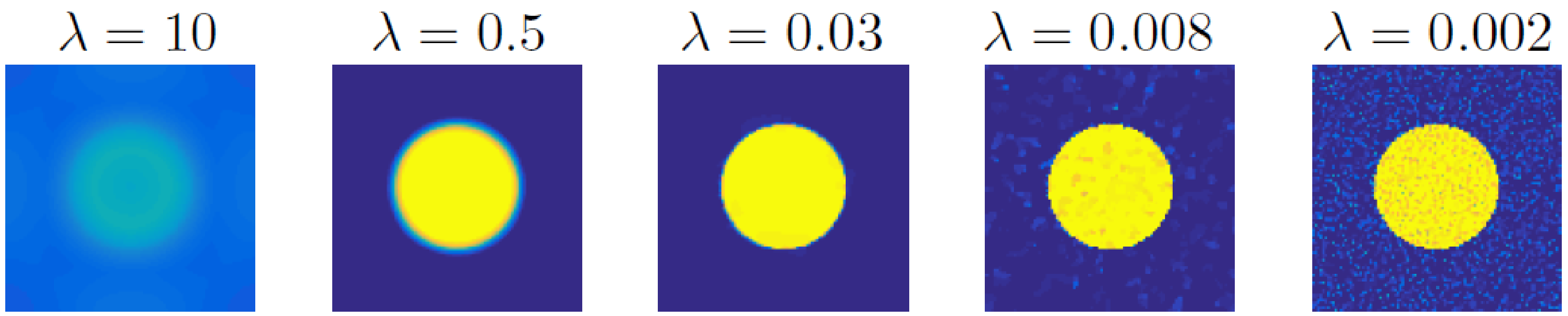


[Bian et al. 2010, Phys. Med. Biol. **55**, 6575–6599]. Courtesy: X. Pan, U. Chicago.

Effect of the Regularisation Parameter

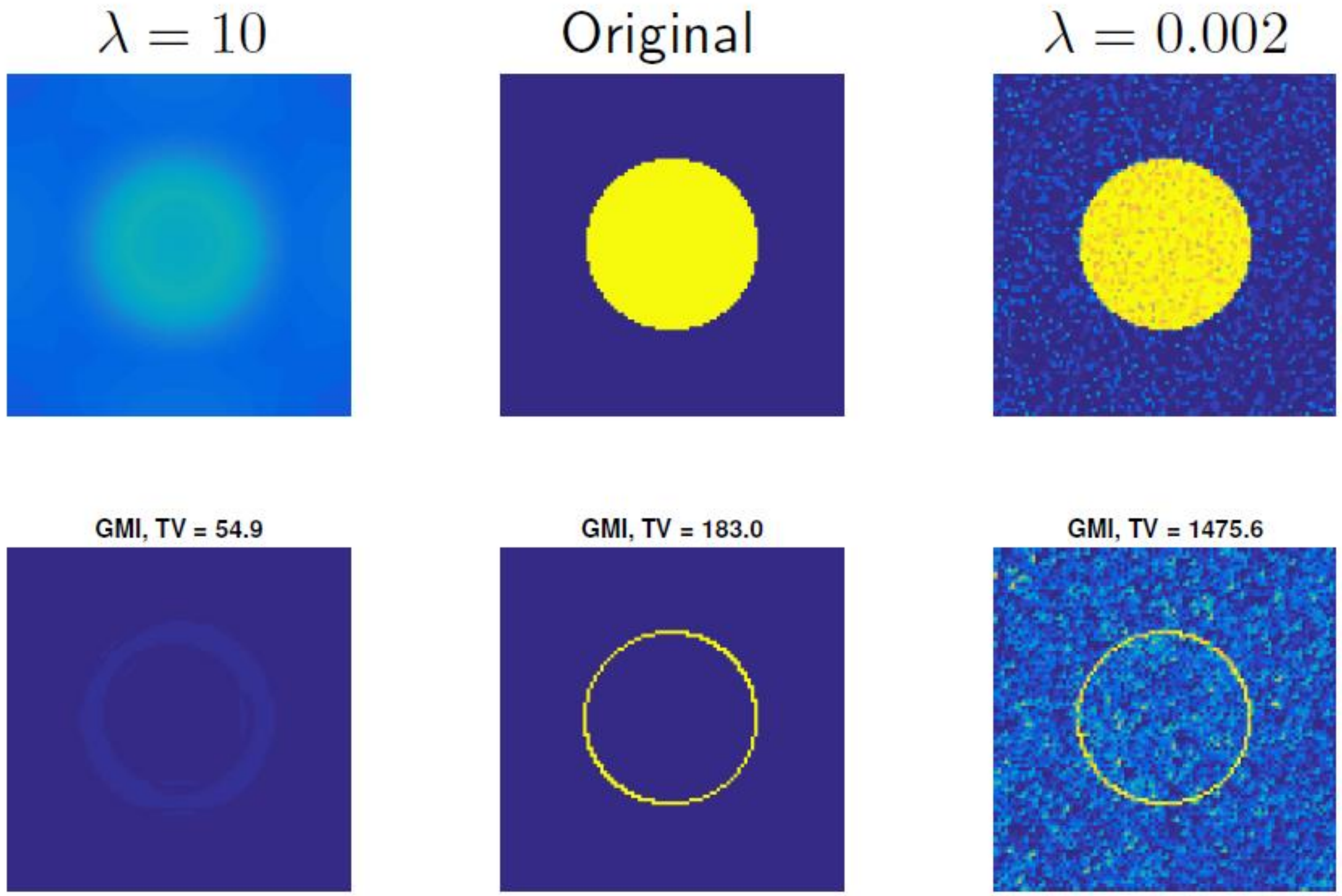
Total variation regularization:

$$\min_{u} \|Au - b\|_2^2 + \lambda \cdot \mathrm{TV}(u)$$



- Large λ: Almost only effect of regularizer. TV $\rightarrow$ Constant.
- Small λ: Almost just least-squares solution.
- Best trade-off?

What is TV?



- Measures variation of an image
- Sum of gradient magnitude image

$$\mathrm{TV}(u) = \sum_j \|D_j u\|_2$$

- Prior: few homogeneous regions with simple boundaries
- Quite successful in tomography, in particular for reduced data

Exercise 3

- Tomography: 2_Iterative /01_optimisation_gd_fista.ipynb

Questions?

Session 4
Choose one from

1. Reconstruction of data simulated from gVXR
2. Advanced iterative reconstruction with spectral XCT data
   - 3_Multichannel /03_Hyperspectral_reconstruction.ipynb
3. Advanced iterative reconstruction on laminography XCT data
   - 2_Iterative /05_Laminography_with_TV.ipynb
4. Reduced data reconstruction:
   - Use CIL processors (e.g. Slicer or Binner or Masker/MaskGenerator) to remove parts of or downsample data sets, for example to obtain a reduced number of projections, a limited angle problem, truncated projections (region of interest data), exterior problem, etc. Compare for example different regularised reconstruction methods at increasingly few projections.
5. Check in each folder for additional exercises and data resources

Questions?

CIL Publications

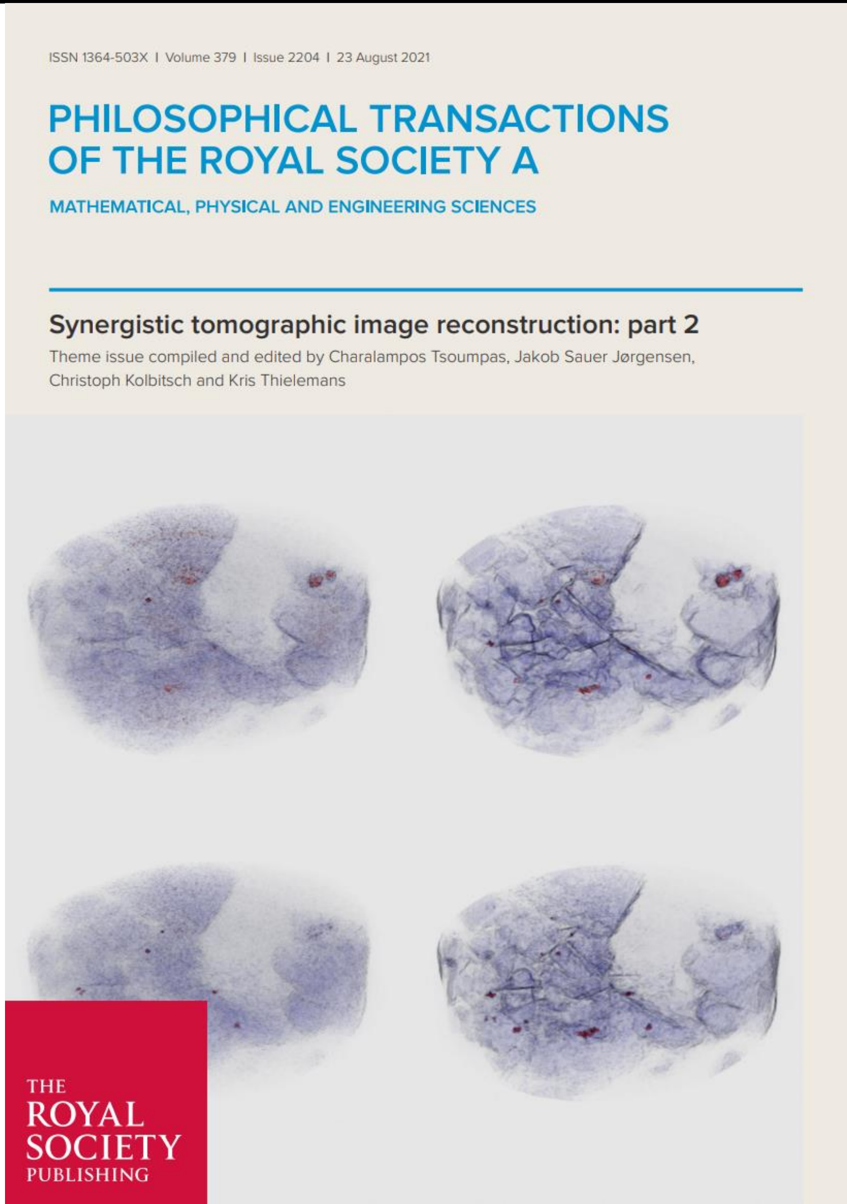
Jørgensen et al.: *Core Imaging Library - Part I: a versatile Python framework for tomographic imaging* Phil. Trans. R. Soc. A. **379** 20200192 (2021) DOI: 10.1098/rsta.2020.0192

Papoutsellis et al.: *Core Imaging Library - Part II: multichannel reconstruction for dynamic and spectral tomography* Phil. Trans. R. Soc. A.**379**20200193 (2021) DOI*:* 10.1098/rsta.2020.0193

Ametova et al.: *Crystalline phase discriminating neutron tomography using advanced reconstruction methods*, J. Phys. D: Appl. Phys. **54** 325502 (2021) DOI 10.1088/1361-6463/ac02f9

Warr R. et al.: *Enhanced hyperspectral tomography for bioimaging by spatiospectral reconstruction* Sci Rep **11,** 20818 (2021) DOI: 10.1038/s41598-021-00146-4

Brown R. et al: *Motion estimation and correction for simultaneous PET/MR using SIRF and CIL* Phil. Trans. R. Soc. A.**379** 20200208 (2021) DOI:10.1098/rsta.2020.0208



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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

MATHEMATICAL, PHYSICAL AND ENGINEERING SCIENCES

Synergistic tomographic image reconstruction: part 2

Theme issue compiled and edited by Charalampos Tsoumpas, Jakob Sauer Jørgensen, Christoph Kolbitsch and Kris Thielemans

THE ROYAL SOCIETY PUBLISHING

CCP*i* = CCP in Tomographic Imaging

- The Collaborative Computational Projects (CCPs)
- UK Network of expertise in key computational research fields
- CCP's foster exchange by organising workshop, training, conferences …
- Enable large-scale scientific software development, maintenance and distribution.
- Long term funding by EPSRC with a 5 years renewal cycle
- CCP's are supported by the Computational Science Centre for Research Communities (CoSeC).
- https://www.ccpi.ac.uk

Conclusion

- CIL is a Open Source mostly Python library for all your tomographic needs:
  - I/O
  - pre-processing
  - Reconstruction
  - visualisation
- Developer Support, user driven, long term funding
- Join the community Discord
- https://www.ccpi.ac.uk/CIL

Thank you!

Feedback form:

https://forms.office.com/r/2sHucKJeGV

Discord community:

https://discord.gg/ky7yCqRcYn

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