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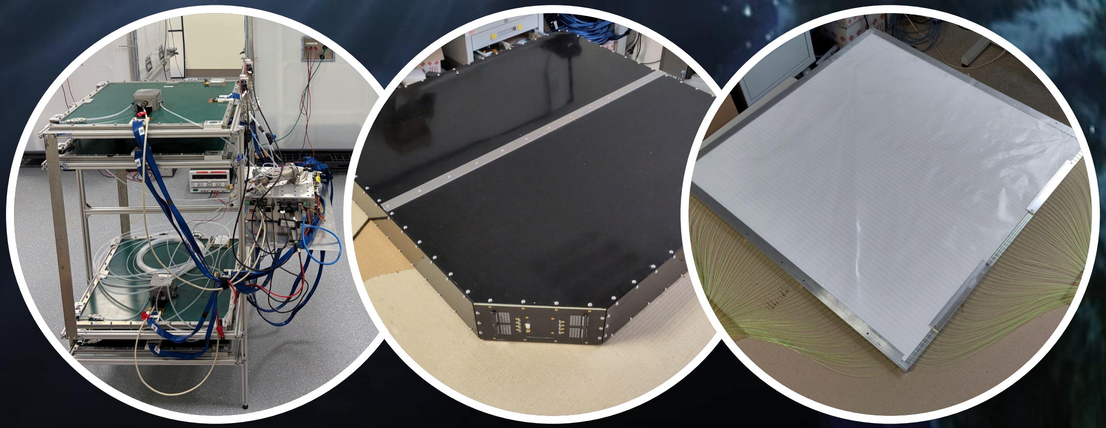
Industrialised strategies for centimetre precision muon scattering muography



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- Quick review on muon scattering tomography
- Scintillator detectors: applicability to scattering tomography
- Examples:
  - Lab experiment of small iron objects
  - Industrial client
- Software framework considerations
- Future pathways at Muodim.

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Who am I ?

Hi,

- My name is Fabio Dogliotti.
- PhD in High Energy Physics.
- Scientist at Muodim since 2023.
- I work on mathematical methods and algorithms for muography.
- I do a lot of C++ / Python / GPU programming.
- I am developing the software tools needed at Muodim.
- Come have a chat if you are interested in any of the above !

Muon scattering tomography

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Core Principles of MCS

Multiple Coulomb Scattering (MCS) occurs as muons deflect off nuclei. The angular distribution is approximately Gaussian:

$$P(\theta) = \frac{1}{\sqrt{2\pi}\theta_0} \exp\left(-\frac{\theta^2}{2\theta_0^2}\right)$$

The scattering standard deviation relates to material properties:

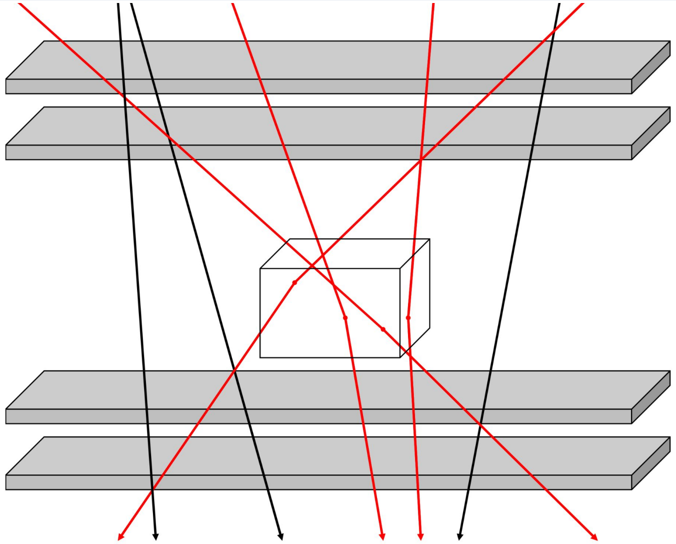
$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right]$$

- p: Momentum of the incident muon (in MeV/c)
- □: Velocity of the muon
- z: Charge number of the incident particle
- x: Opacity of the material the muon travels through
- X_0: Radiation length of the target material

L. J. Schultz Dissertation (2003)

Key contributions to muon scattering tomography:

- Established the **PoCA (Point of Closest Approach)** algorithm for 3D reconstruction
- Proposed the **MLSD (Maximum Likelihood Scattering and Displacement)** algorithm for higher quality reconstruction
- Demonstrated material segregation (High-Z vs Low-Z) using multiple Coulomb scattering



Source: L.J Shultz Phd

Scintillator detectors in muon tomography

Affordable & Robust Detection

- Plastic scintillator bars or slabs provide a cost-effective alternative to gaseous detectors.
- Solid-state Silicon Photomultipliers (SiPMs) or Photo-multiplier Tubes (PMTs) allow for the detection of a small number of photons via optical fibers.
- The modular design consists of perpendicular layers forming tracking panels.
- The plastic nature of the detectors make them highly stable for long data acquisition.

Scintillator detectors in muon tomography

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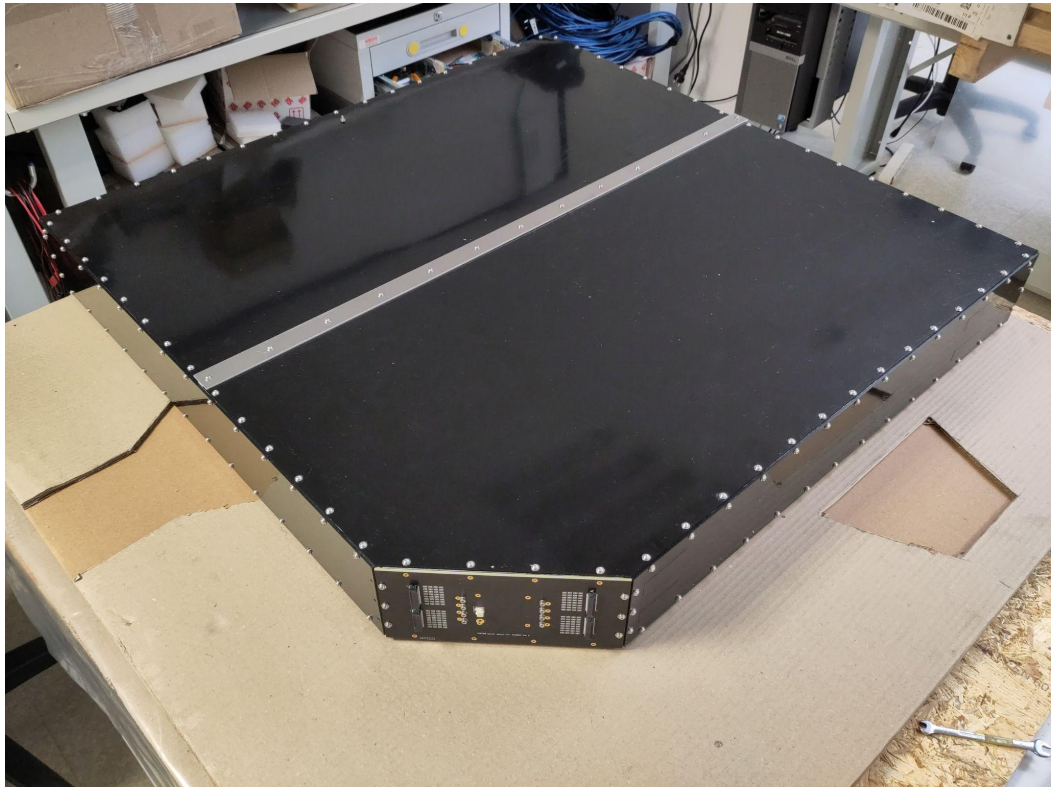
Limited resolution

- Plastic scintillator bars are typically 1cm wide and are limited in size due to mechanical and light transport considerations.
- The spatial resolution for these detectors is on the order the centimeter.
- This resolution is low compared to other technologies like Micromegas and RPCs.
- But these other options require gas to function, making them not well suited for industrial applications. They are also sensitive to temperature.



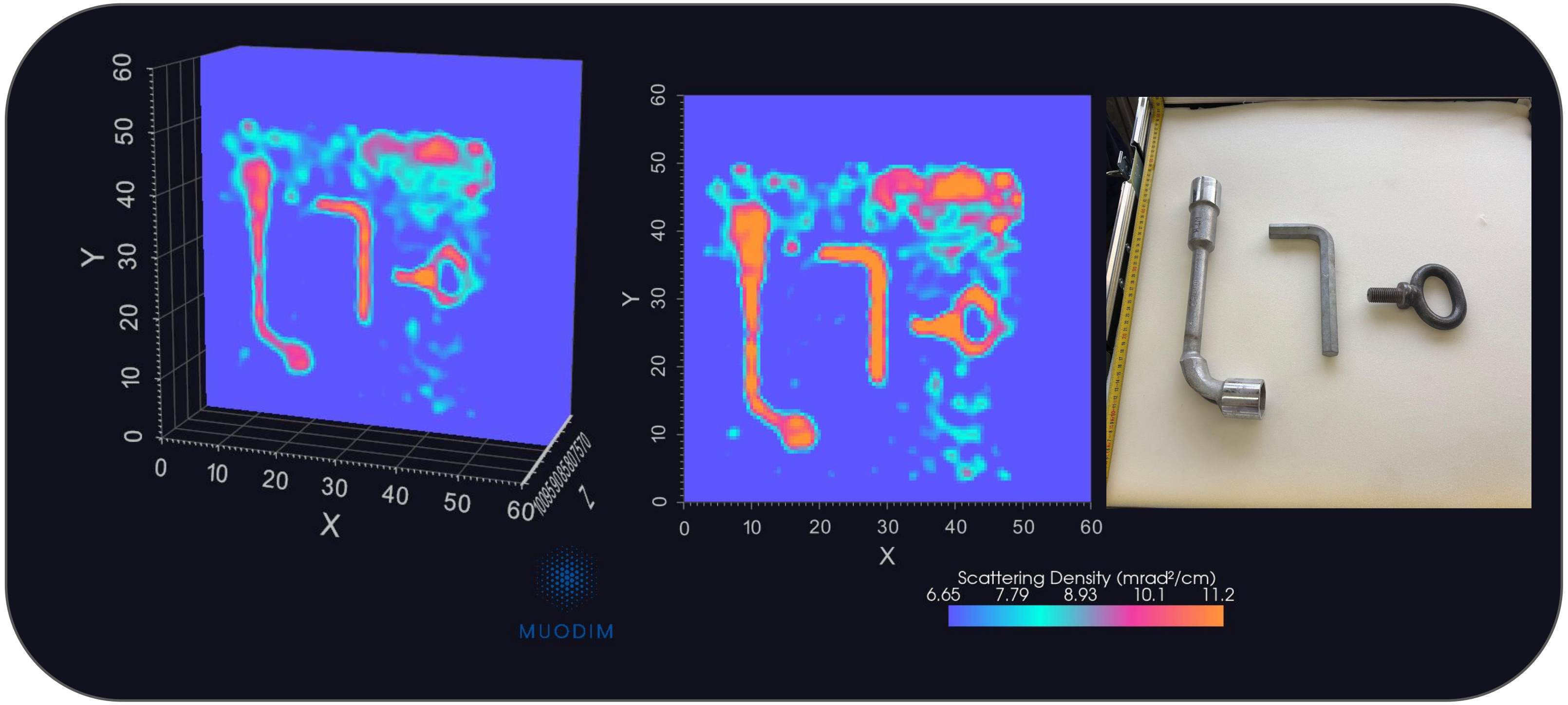
Scintillators have been successfully used for absorption muography, but, to our knowledge, never for scattering muography.

➡ We investigated the feasibility of using plastic scintillators for centimeter precision scattering muography.

In lab experiment

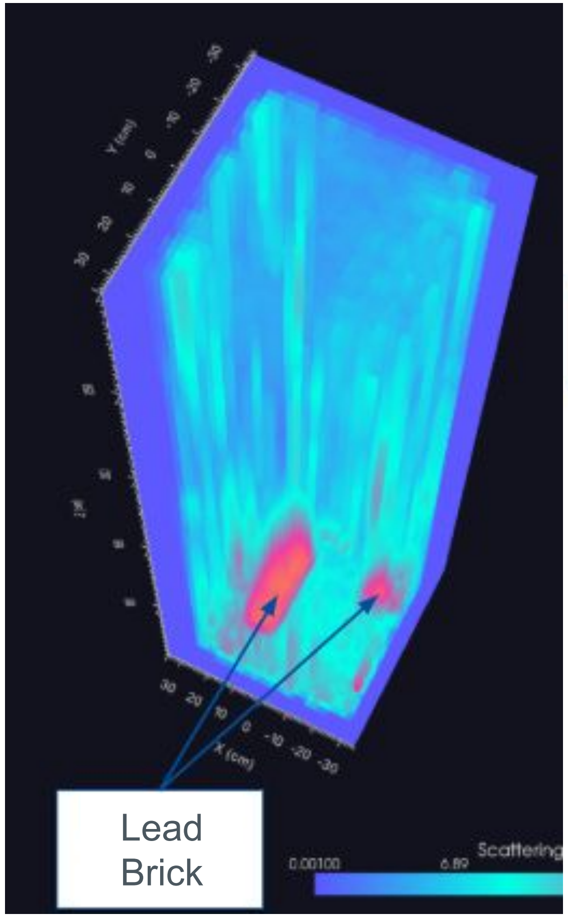
Experimental setup:

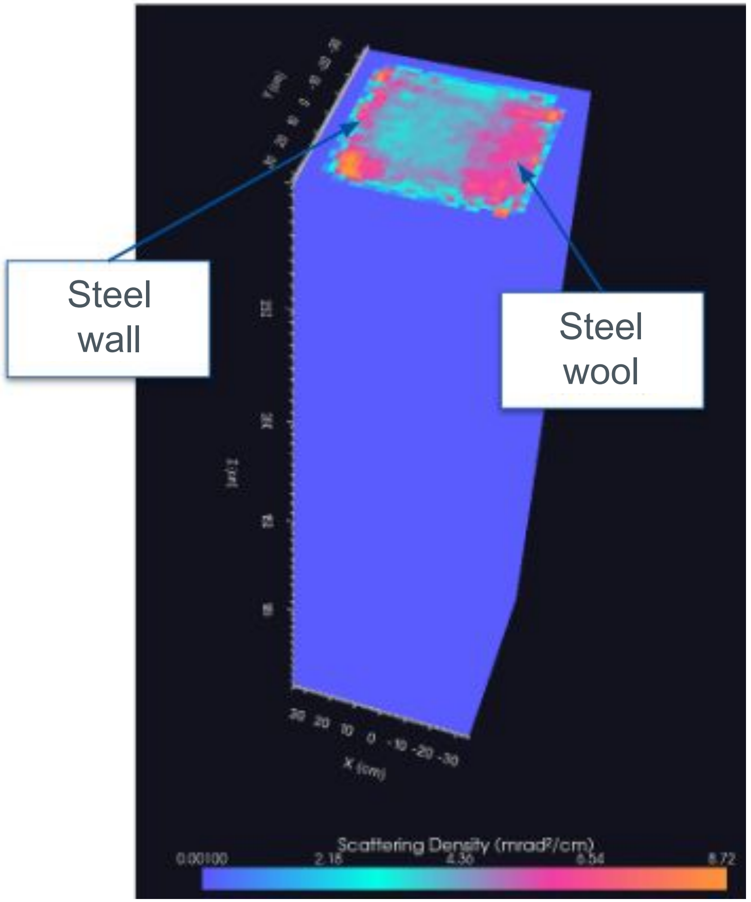
- Plastic scintillator bars (~1 cm).
- Detector panels are approximately 50 x 50 cm.
- Exposure period: 20 days (real time).
- Images are exploitable after about 10 days.
- Efficient data processing via in-house toolchain (in minutes). More on this later.

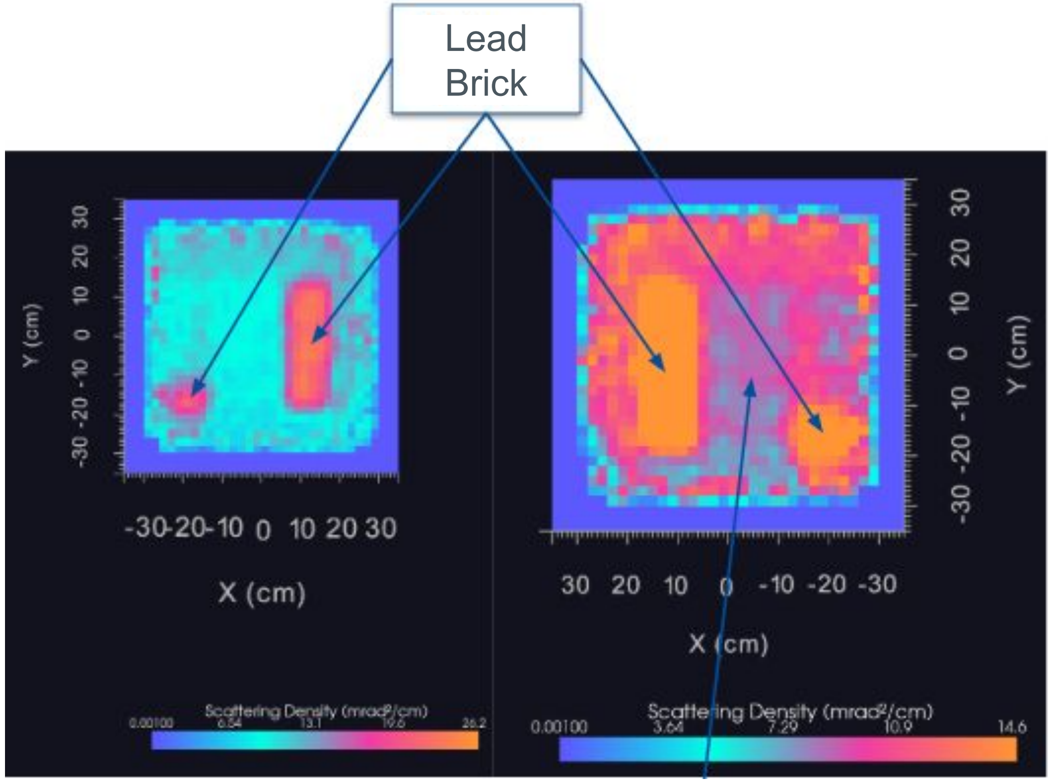


On site experiment

Client experiment

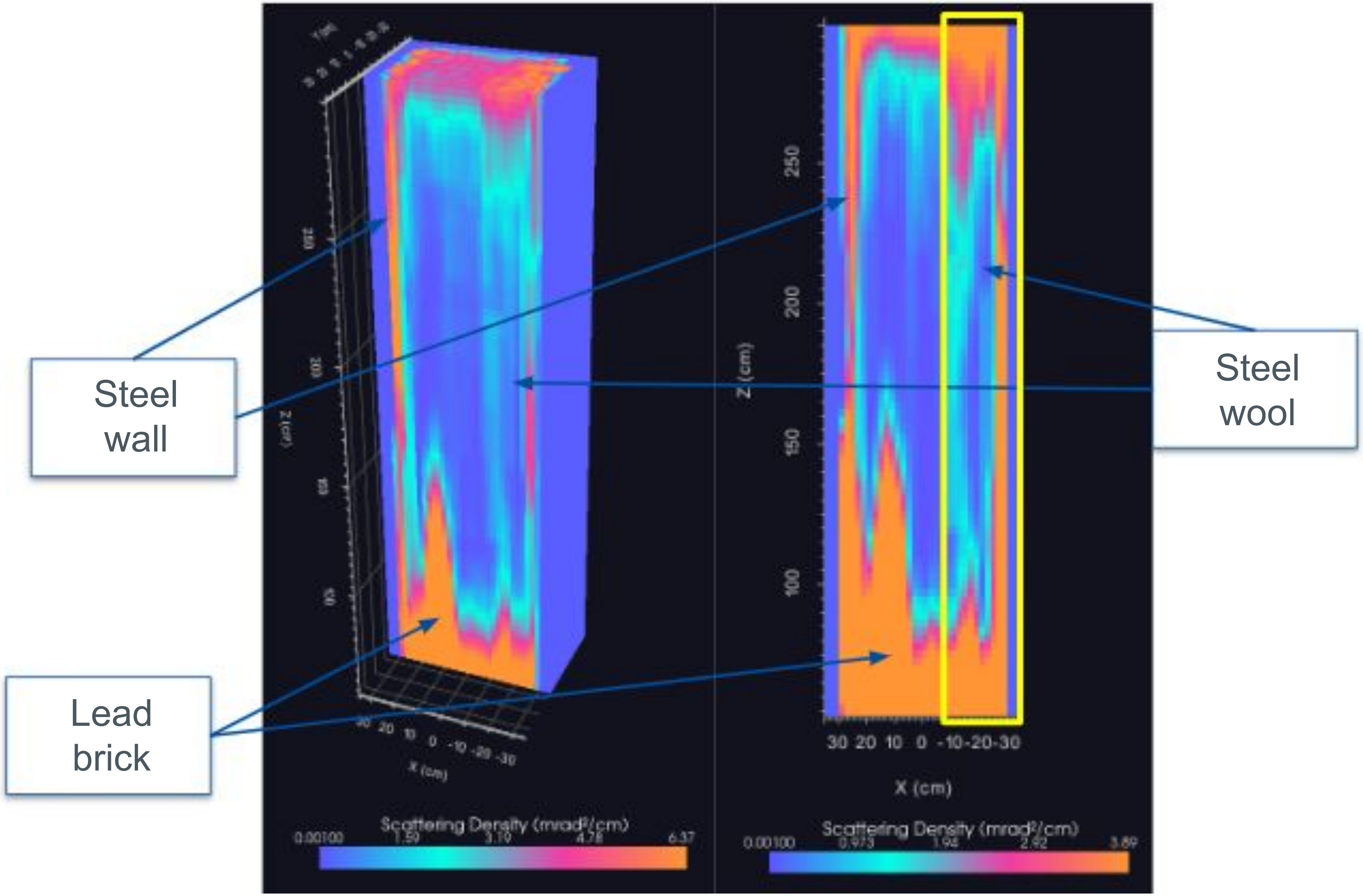






On site experiment

Client experiment



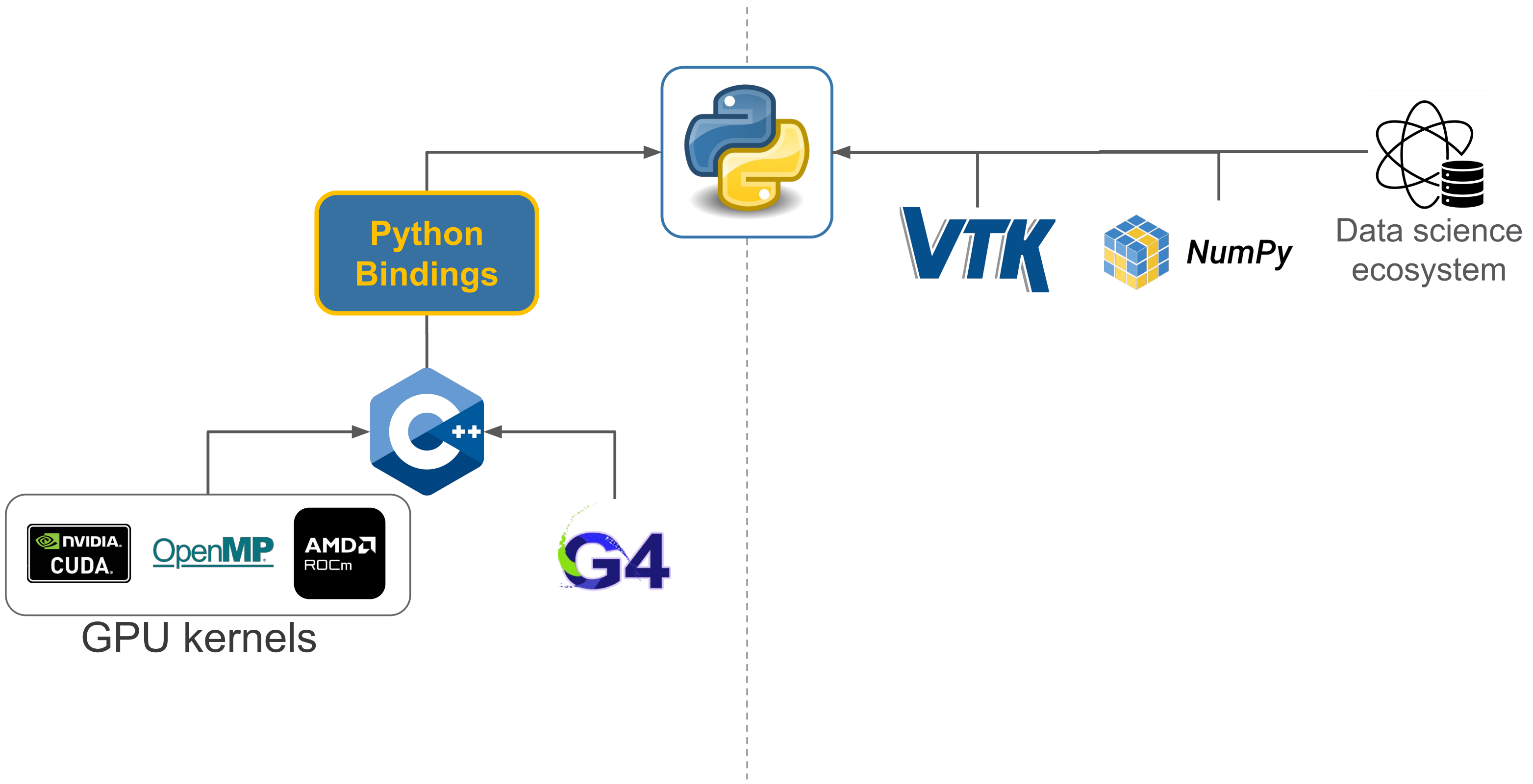
An Efficient Framework

Key ideas:

- The scientific community mainly uses Python.
- Pure Python implementations are slow by nature, but Python has a very rich ecosystem of data science libraries written in C / C++ / Rust / ....
- Through bindings, we can get the best of both worlds and use C++ / GPU kernels when appropriate.
- Bindings allow for a custom Python interface to Geant4 simulations.

But why the need for speed?

Python Framework



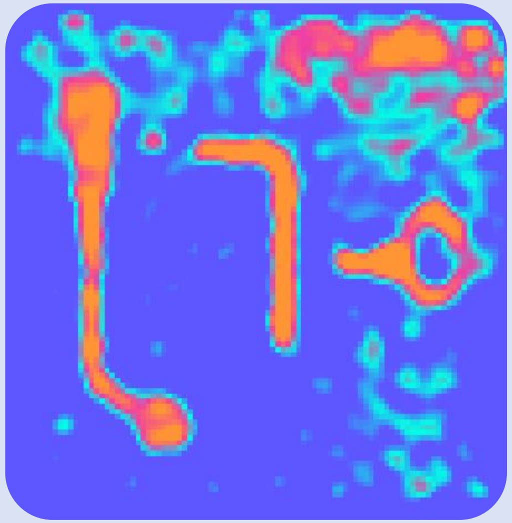
The software

When acquisition times are on the order of weeks, why is fast data processing important?

- Inversions are complex and usually contain many free parameters, scientists can iterate quickly through many different data processing methods and inversion parameters.
- Easier to develop intuition for each parameter in the processing if you can quickly run a few inversions.
- Opens the door for systematic “hyperparameter” search in a reasonable amount of time.
- Also, I like hearing my colleagues complain about not having time to make a cup of tea between runs anymore.

Our framework in numbers:

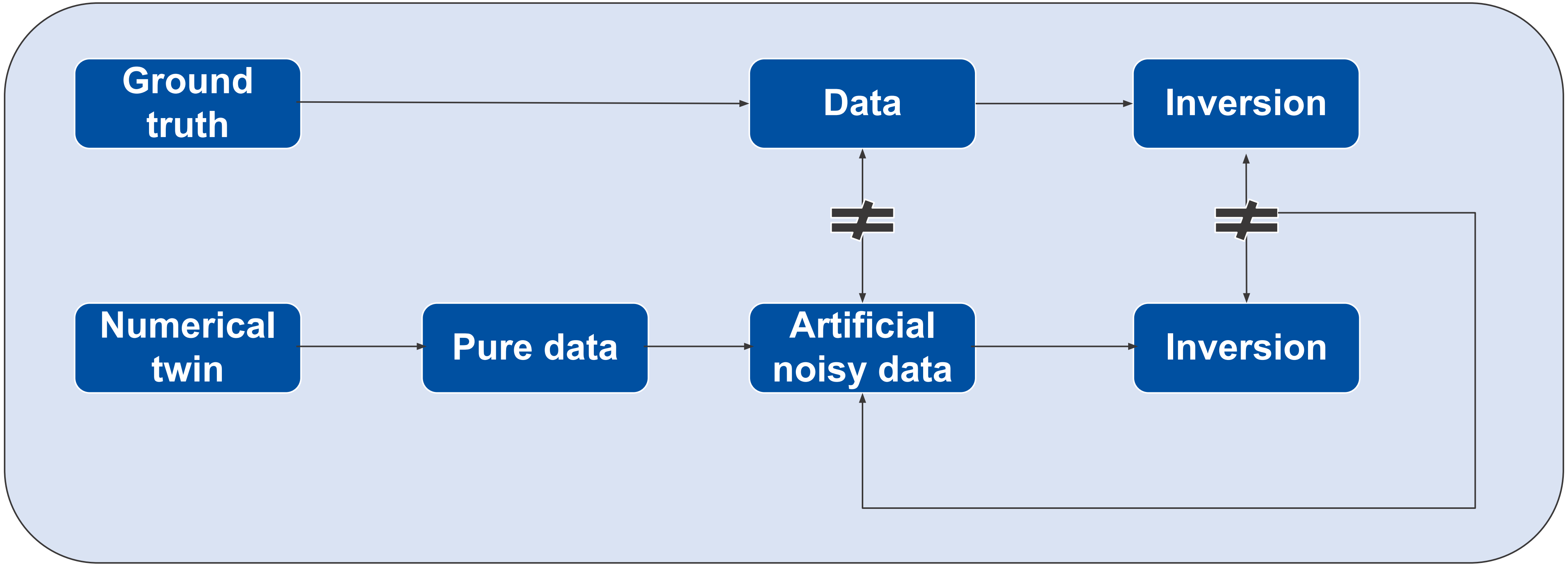
- ~ 1 millions voxels (120 x 120 x 68)
- ~ 1 million data points
- 600 iterations to convergence
- ~ 50 seconds on a 4GB laptop GPU



Perspectives

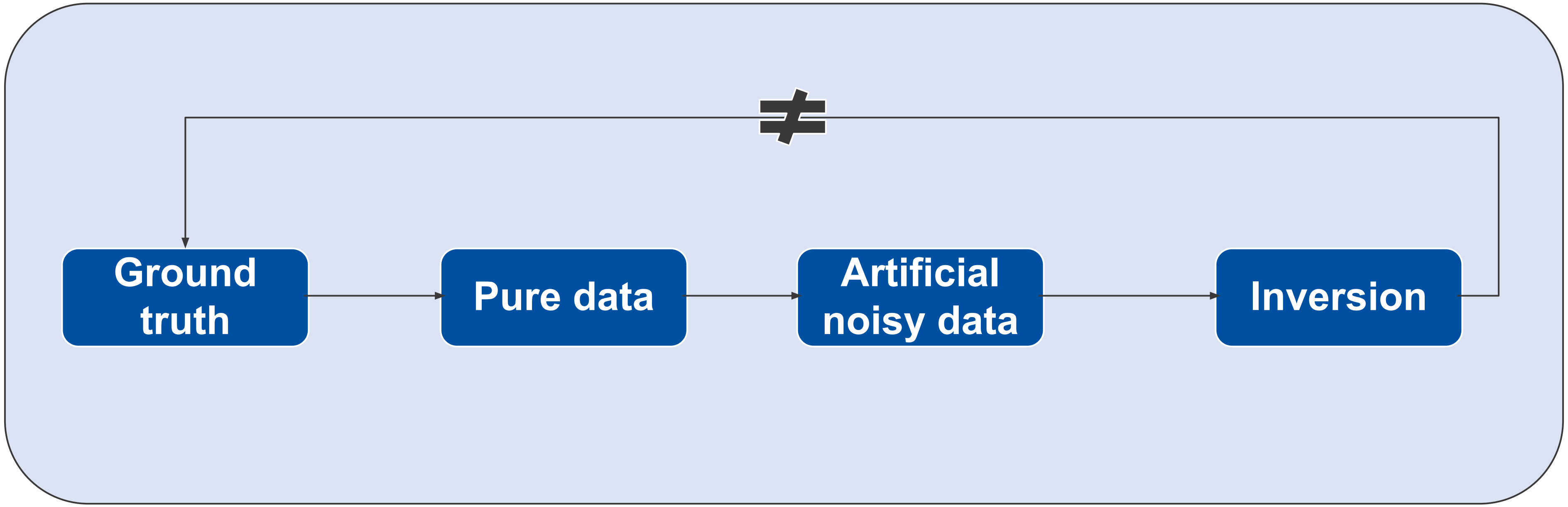
➡ **To improve the quality of reconstructions, we need both high quality simulated data and fine tuned inversion algorithms.**

Generating realistic data



Perspectives

High fidelity inversions



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Thank you for your attention

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