# Image reconstruction in proton computed tomography*

for the Bergen Proton CT Collaboration

## Theory and Experiment in High Energy Physics
## V4-HEP, Warsaw
## 28-30/10/24

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*Gábor Bíró, Ákos Sudár, Zsófia Jólesz, Gábor Papp, Gergely Gábor Barnaföldi. Proton Computed Tomography Based on Richardson-Lucy Algorithm. ArXiv:2212.00126.

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# Motivation

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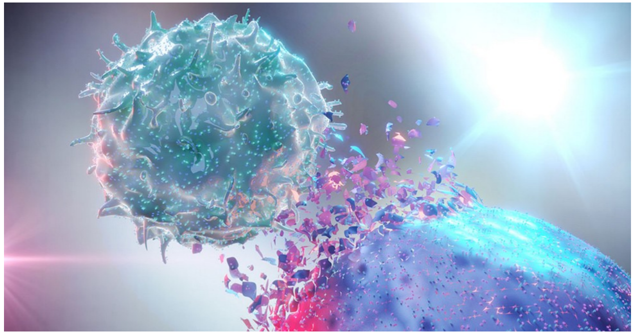
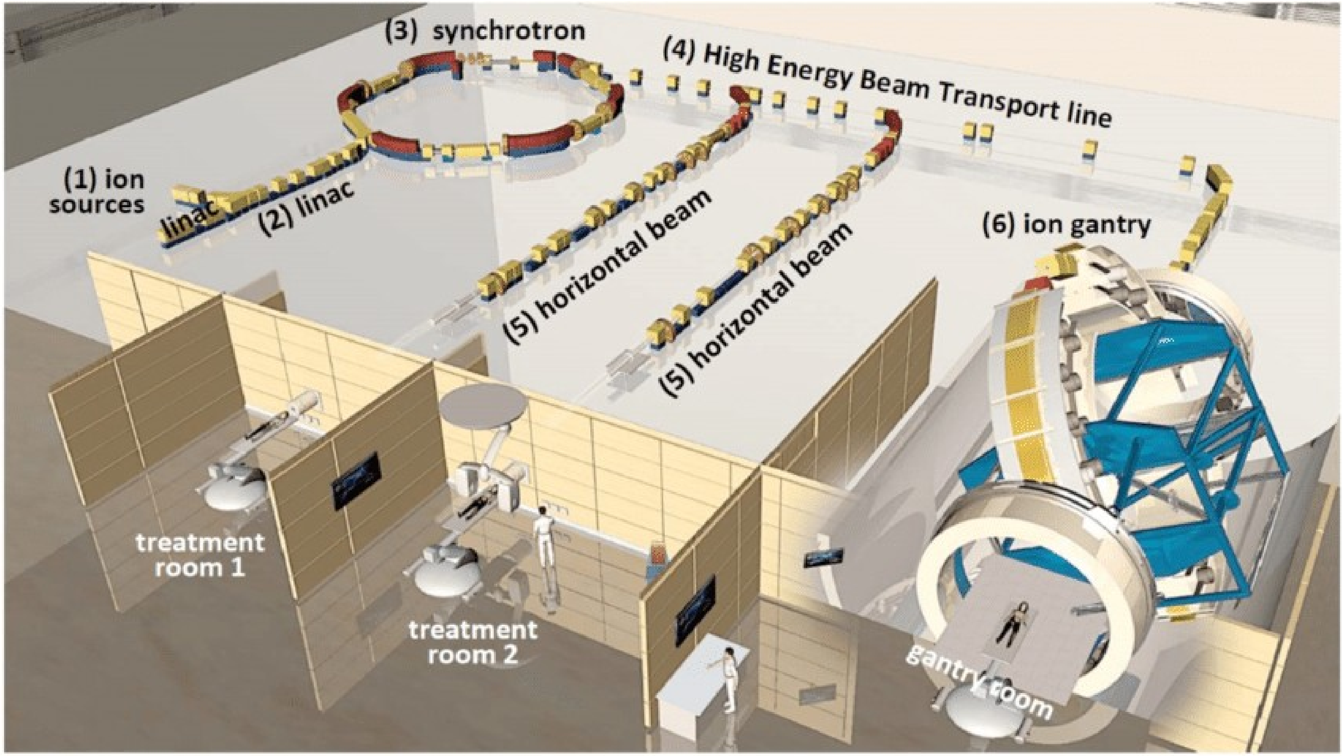


- Cancer treatment: surgery, chemotherapy, <u>radiotherapy</u>, immunotherapy
- Radiotherapy: uses ionizing particles

# Motivation

- Cancer treatment: surgery, chemotherapy, <u>radiotherapy</u>, immunotherapy
- Radiotherapy: uses ionizing particles
- What kind of particles?
  - Photons
  - <u>Protons</u>
  - Heavy ions

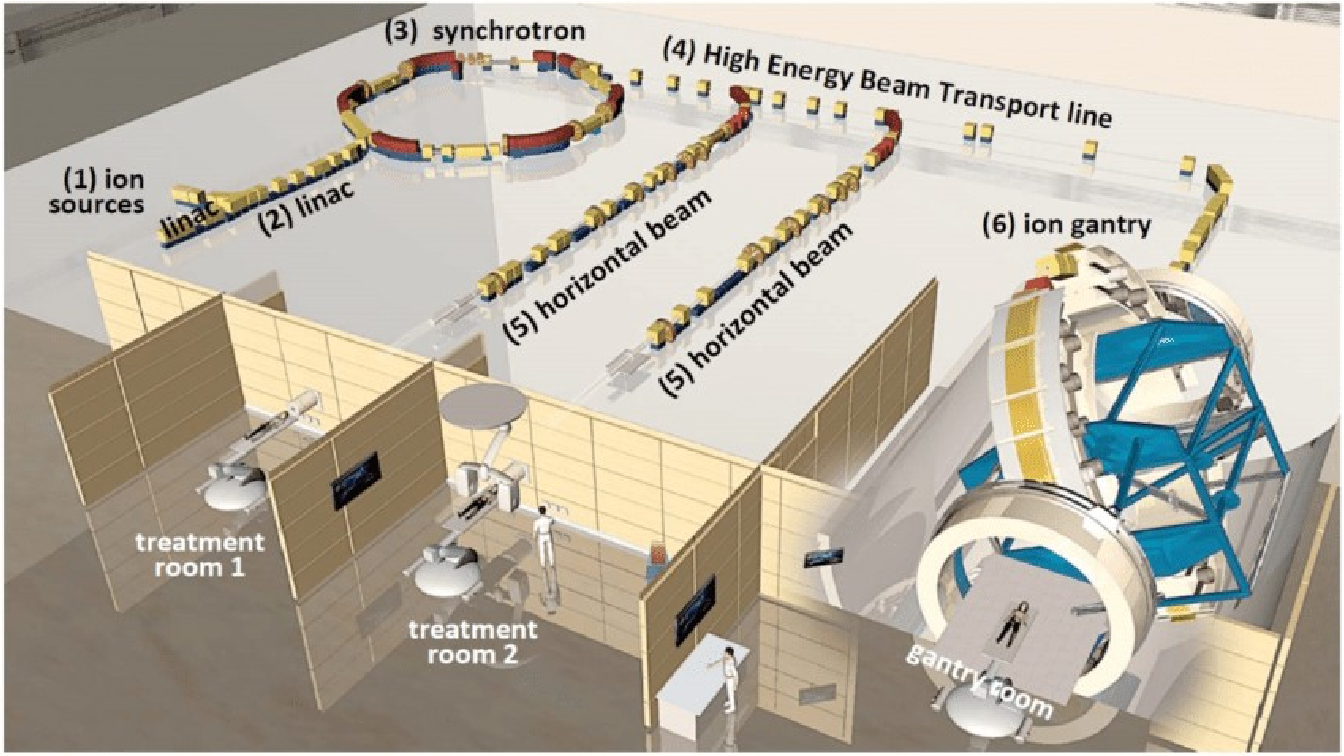



Layout figure of HIT Centre (Heidelberg)

# Hadron (proton) therapy

# Hadron therapy

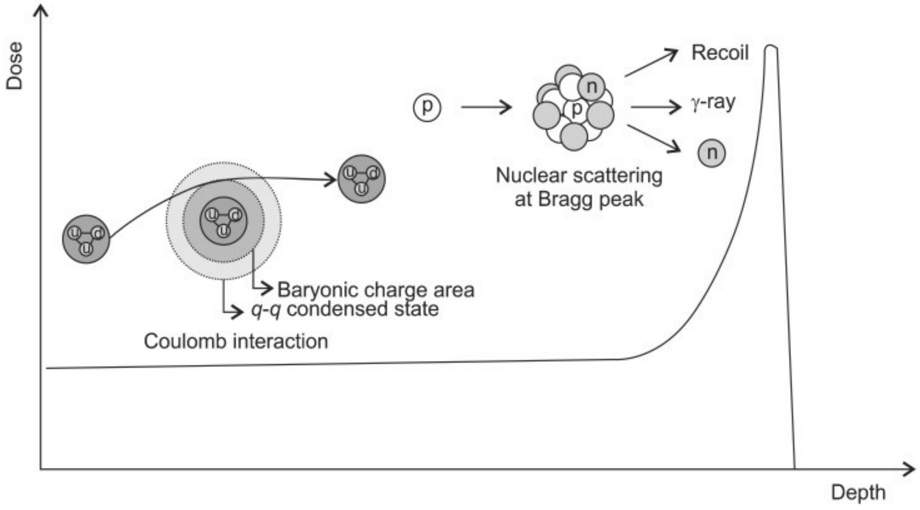
- 2024: 120 proton, 14 carbon ion centres in operation (more under construction)[1]
- End of 2022: >350000 patients treated[2]
- 5-year survival estimates: 19% for conventional radiotherapy, 40% for proton, 42% for carbon ion therapy[3]




Layout figure of HIT Centre (Heidelberg)

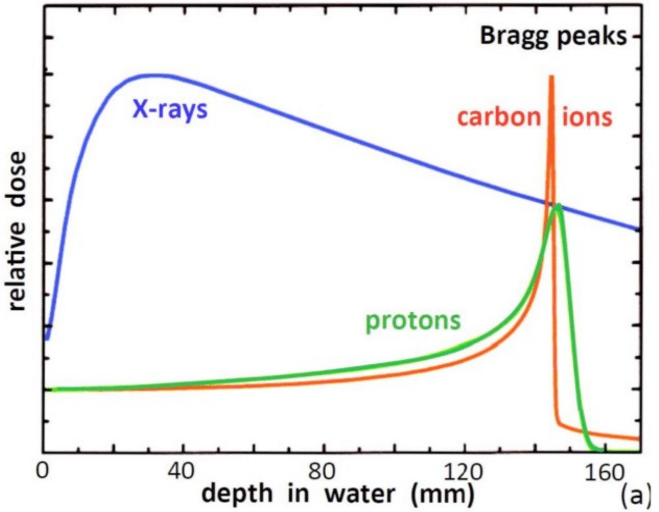
[1]PTCOG, Particle therapy facilities in operation. (2024).
[2]PTCOG, Patient statistics. (2022).
[3]Grutters, Janneke PC, et al. "Comparison of the effectiveness of radiotherapy with photons, protons and carbon-ions for non-small cell lung cancer: a meta-analysis." Radiotherapy and Oncology 95.1 (2010): 32-40.

# Why is proton therapy so outstanding?




[Seo Hyun Park and Jin Oh Kang. Basics of particle therapy i: physics. Radiation oncology Journal, 29(3):135, 2011.]

Interactions of proton in a medium

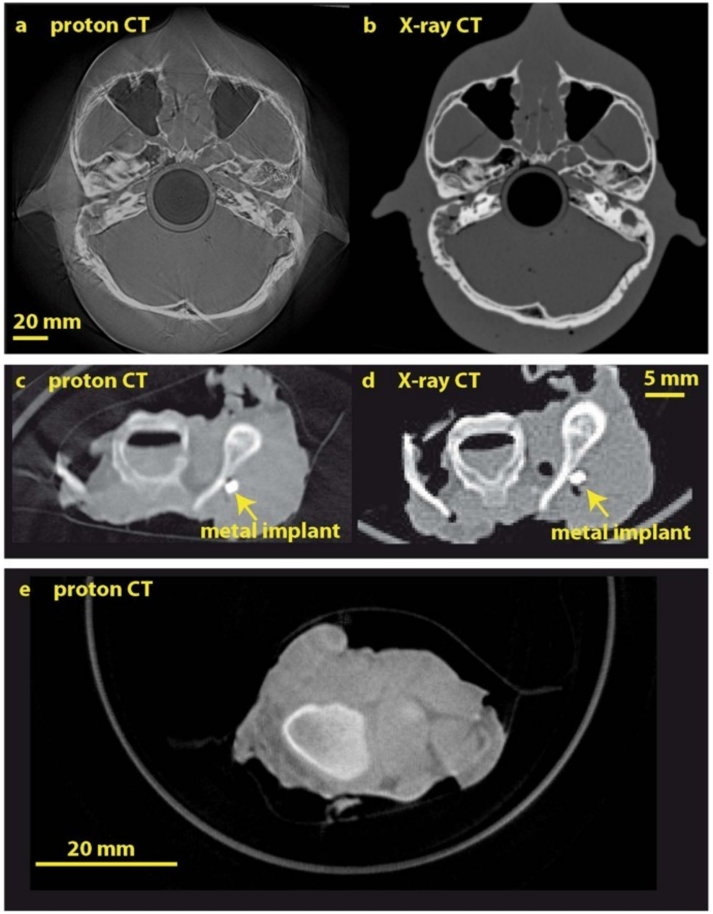



[Ugo Amaldi, Manjit Dosanjh, Jacques Balosso, Jens Overgaard, and Brita Sørensen. A facility for tumour therapy and biomedical research in south-eastern europe. 09 2019.]

Dose deposit characteristics → less radiation for healthy tissues

Energy loss in matter: $$-\frac{dE}{dx} = \frac{4\pi e^4 z^2 NZ}{(4\pi\varepsilon_0)^2 M_e v^2}\left[\ln\left(\frac{2M_e v^2}{I}\right) - \ln(1-\beta^2) - \beta^2\right]$$

# Problems with imaging – and the solution




X-ray CT vs. proton CT

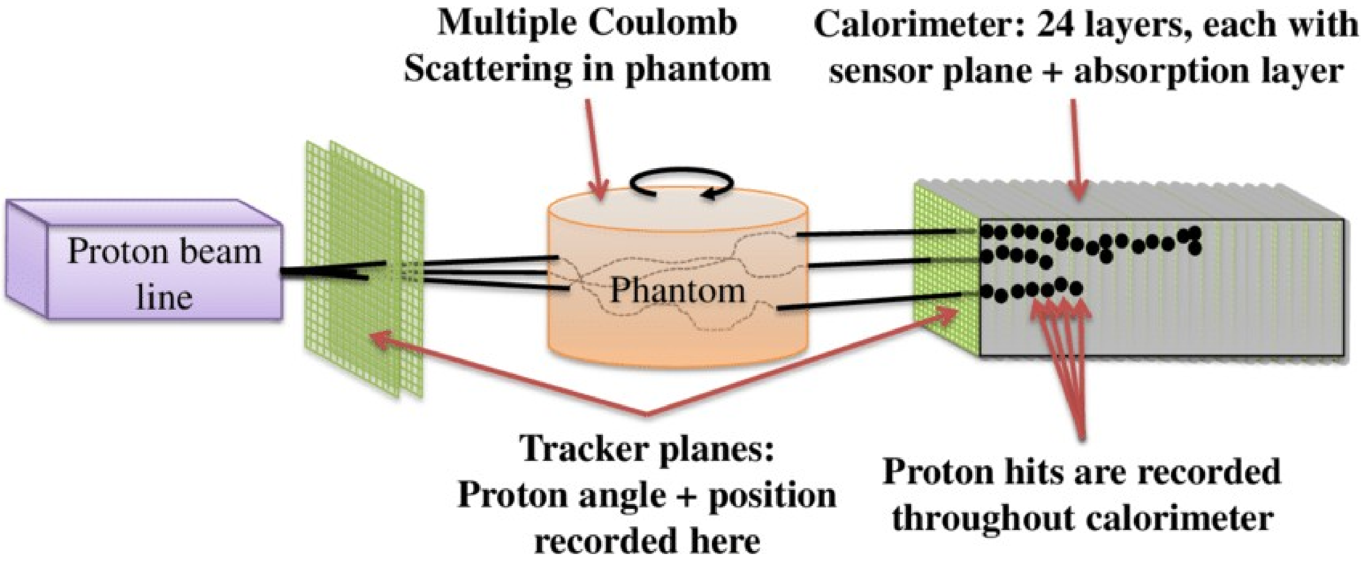
- Today X-ray CT is used
- We need to know the range of the protons → Relative Stopping Power (RSP): how much does it slow down in a material compared to water
- Difference between the absorption of photons and the energy loss of protons → conversion is not accurate between Hounsfield units* and RSP
- Solution: let's do the imaging with protons! → proton CT

*The quantitative scale of X-ray absorption

# Proton computed tomography

# What is proton CT?

- Cross-sectional images → information about energy absorption
- What do we need?
  - Proton beam
  - Tracker detector(s)
  - Calorimeter
- Very promising results: RMSE of estimation of the RSP was 0.2-0.5%*



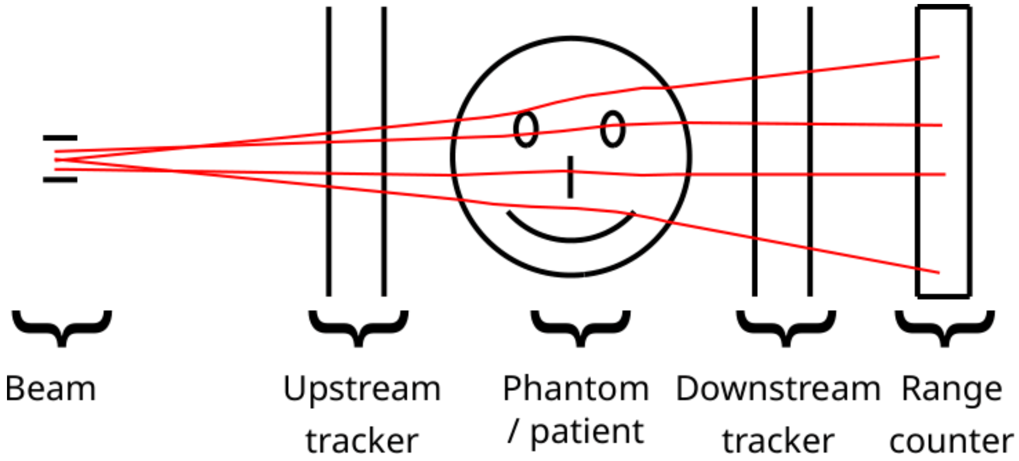

Pettersen, Helge Egil Seime. (2018). A Digital Tracking Calorimeter for Proton Computed Tomography.

David C Hansen et al. Acta oncologica, 54(9):1638–1642, 2015.

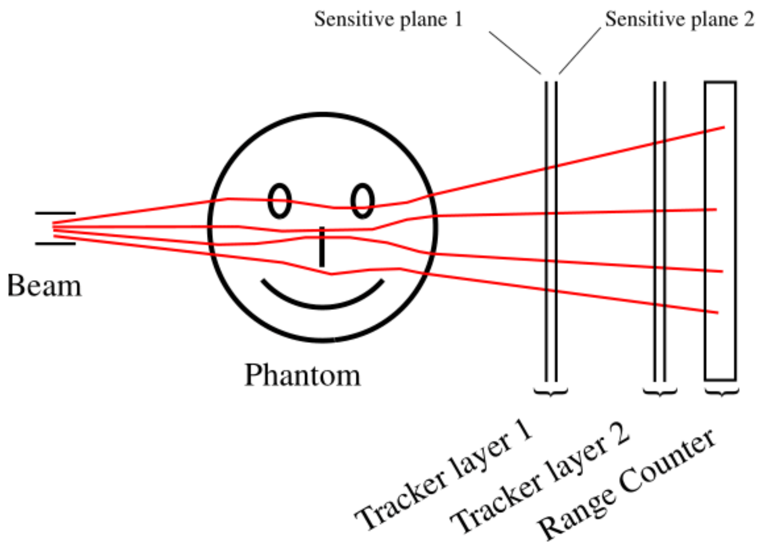
# What is proton CT?

2 main types of detector designs

Double-sided scanner design




Single-sided scanner design

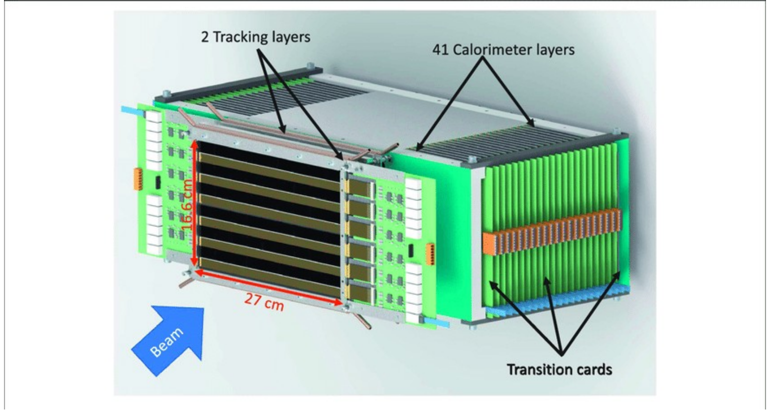


# The Bergen pCT Collaboration

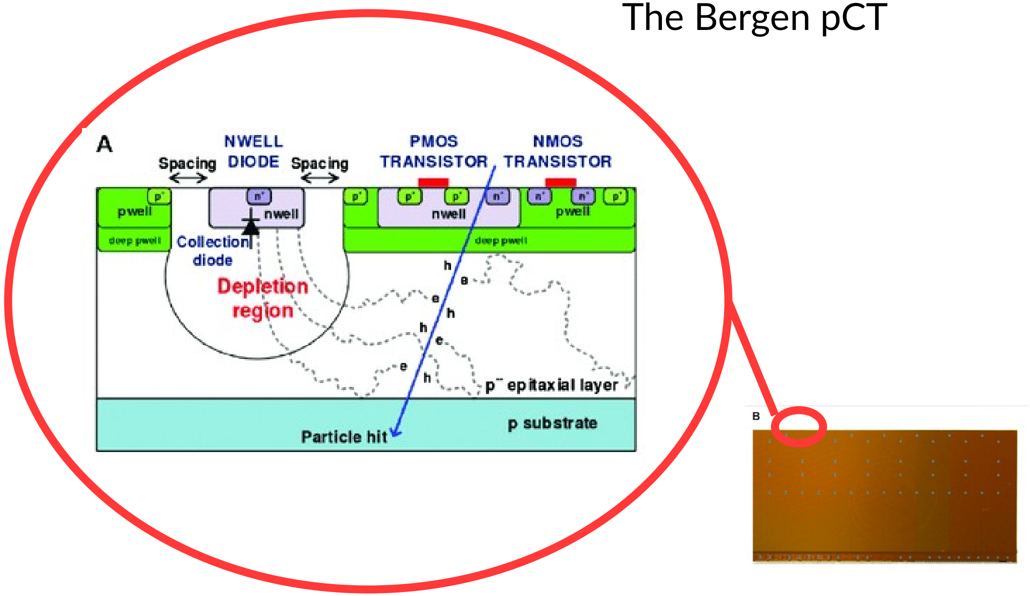
# The Bergen pCT Collaboration

- Goal: to build a proton CT based on the high-energy particle detectors used in the CERN ALICE collaboration (technology transfer)
- The detector system is based on the **ALPIDE chip**

→ Monolithic Active Pixel Sensor (MAPS)
→ Sensors are on the same layer with readout electronics




The Bergen pCT

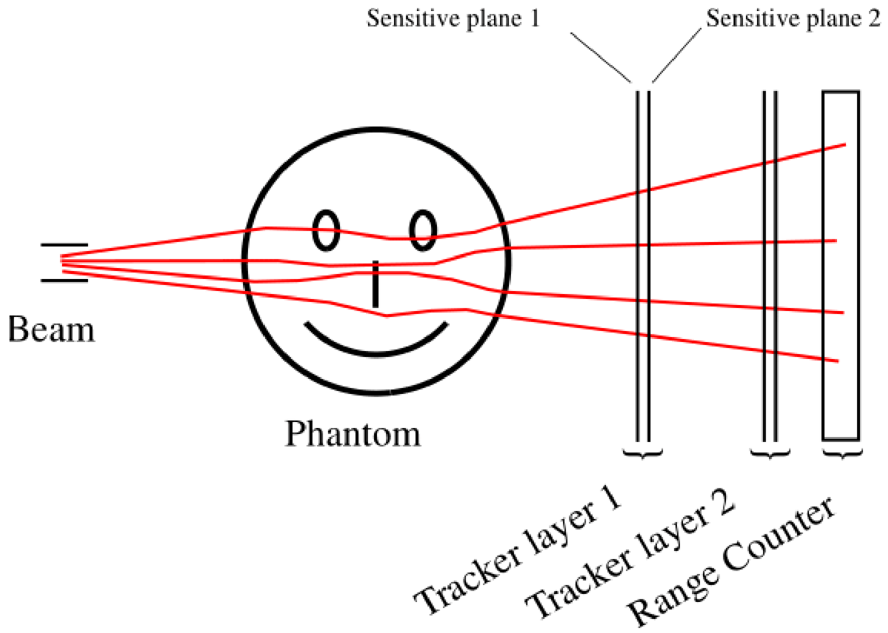



The cross-sectional image (A) and the photograph (B) of the ALPIDE chip

# The Bergen pCT Collaboration

- Avoids pairing problem → we can measure more tracks
- 4% accuracy in water equivalent thickness (WET) measurements
- $10^6$ protons/sec
- Goals: further optimized detector
  - 2 tracking layers and 41 alternating aluminium absorbing and tracking layers
  - $10^7$ protons/sec
  - using ALPIDE

**Single-sided scanner design**



# The Bergen pCT Collaboration

Irradiating the phantom with high energy (~100 MeV) protons

Detector system senses the signals

Processing the signals

Reconstructing the image

Currently: Monte Carlo simulations

Tasks:
- Reconstruct trajectories from hits
- Predict energies

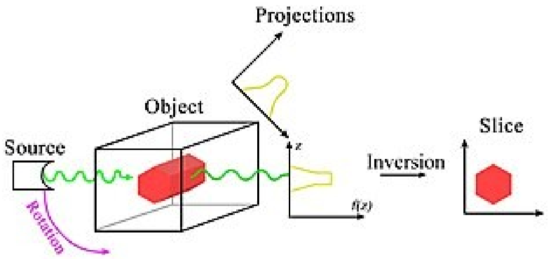
Tasks:
- Determine RSP distribution
- Develop the framework
- Test it on phantoms

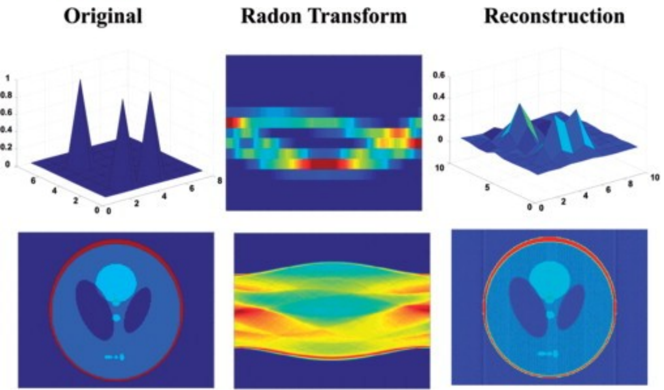
# Image reconstruction

# Image reconstruction techniques

Integral transformations → Radon, Inverse Radon

- Cannot be used for proton CT (due to nuclear scattering of protons)




Iterative reconstruction techniques

- Model the problem as a linear equation system

$$\boldsymbol{A} \cdot \color{red}{x} = y$$

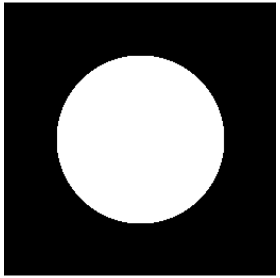
Matrix that contains interaction coefficients between protons and pixels/voxels

Vector that contains estimated proton RSP values

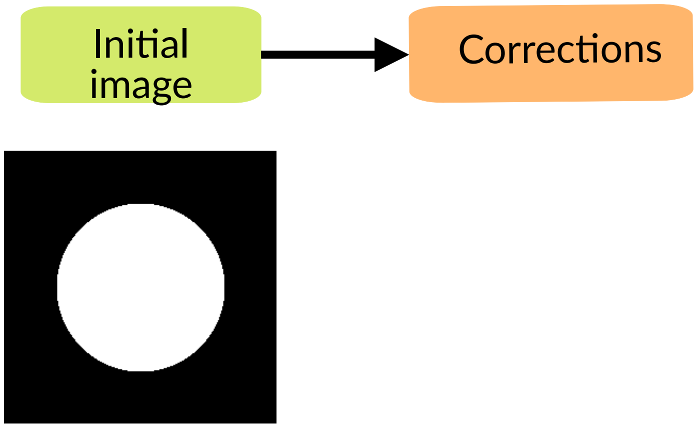
Vector that contains the known WEPL values of the protons

# Iterative methods for image reconstruction

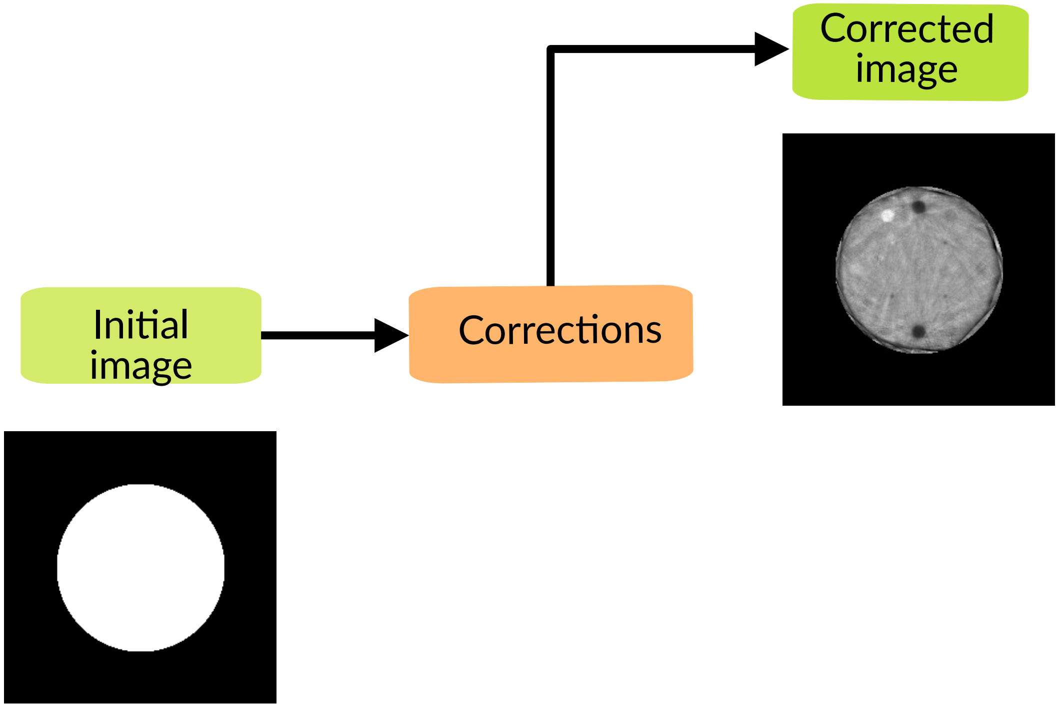
Initial image



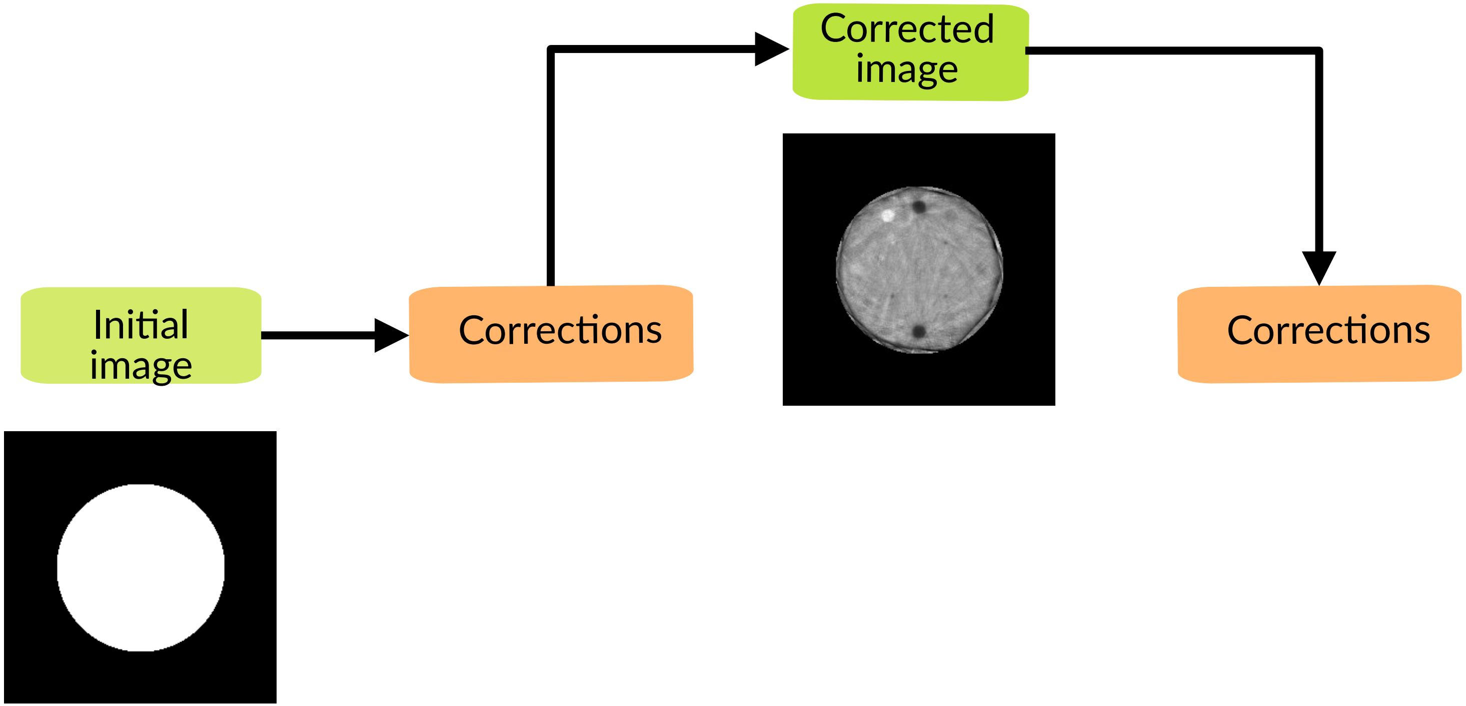
# Iterative methods for image reconstruction



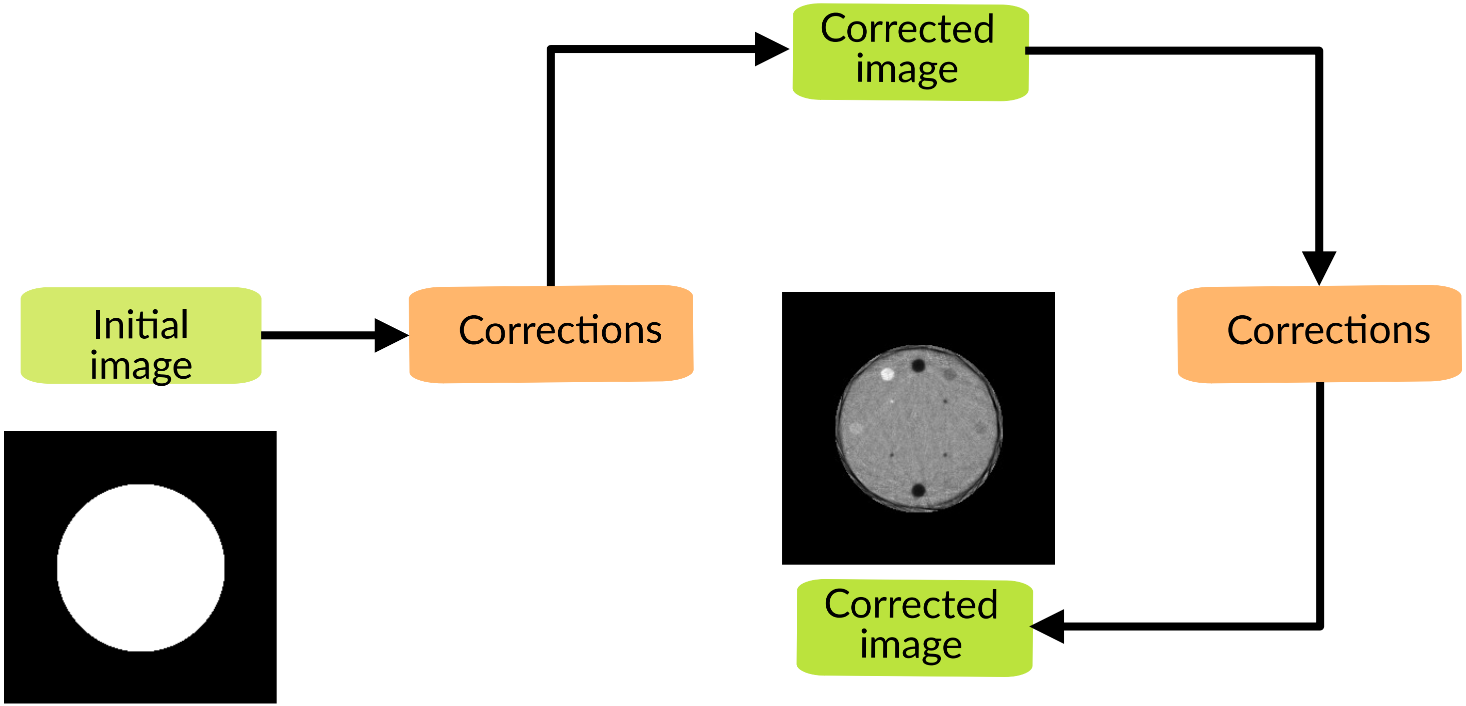
# Iterative methods for image reconstruction



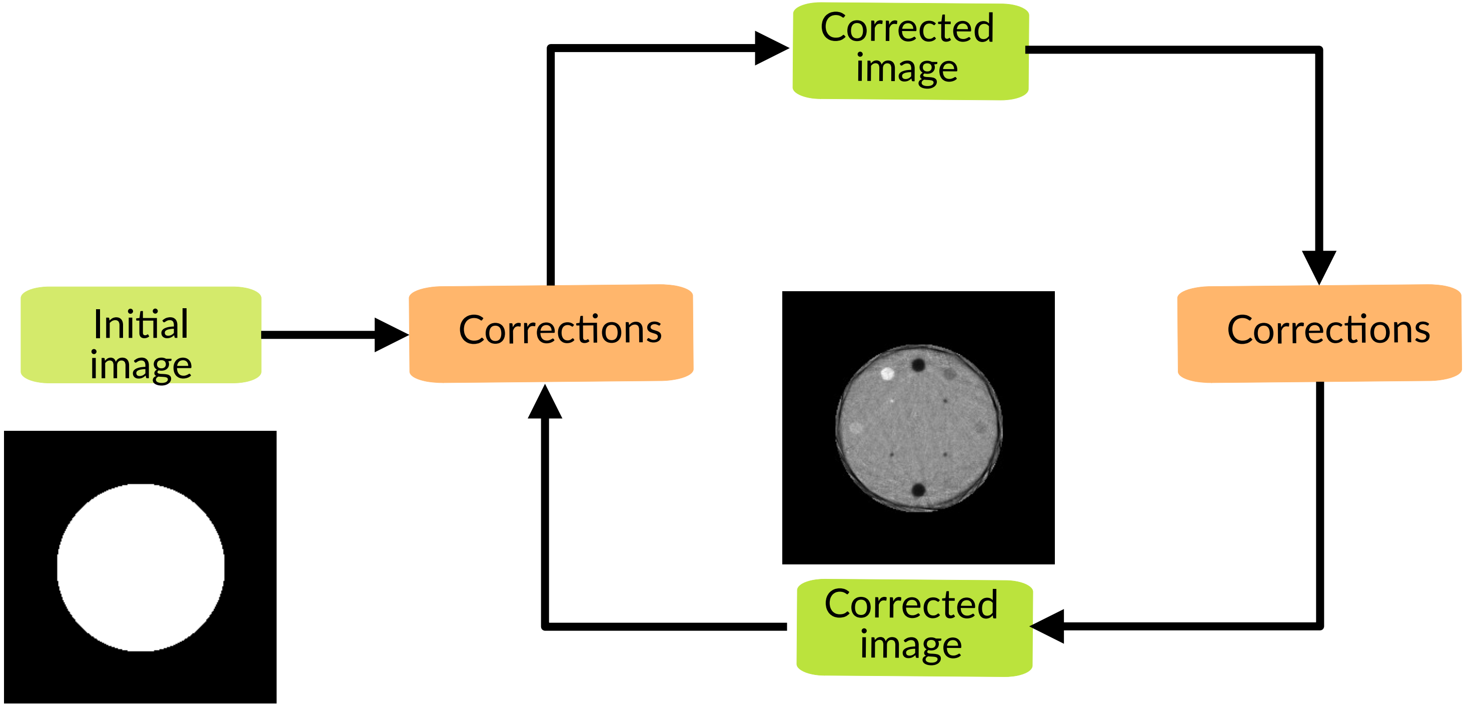
# Iterative methods for image reconstruction



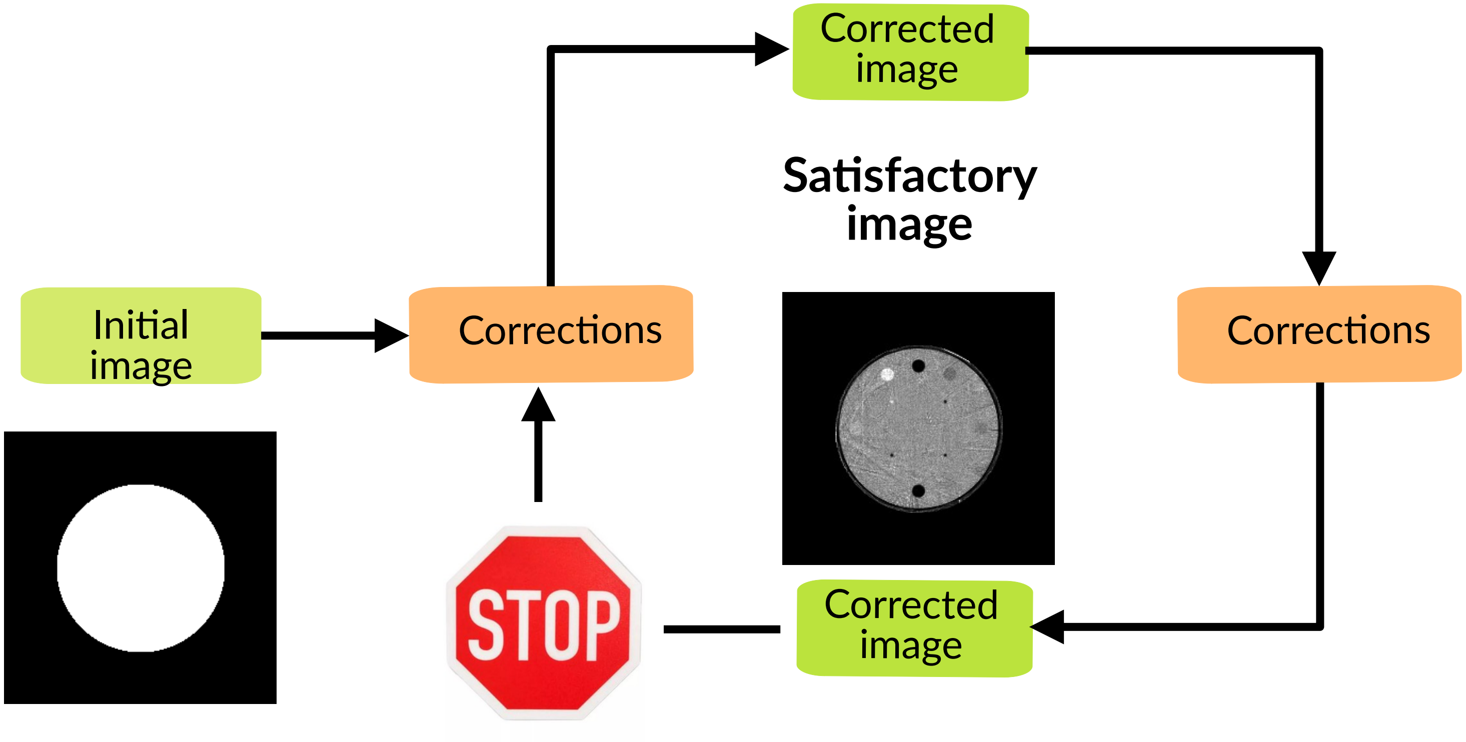
# Iterative methods for image reconstruction



# Iterative methods for image reconstruction



# Iterative methods for image reconstruction



# Development of the framework

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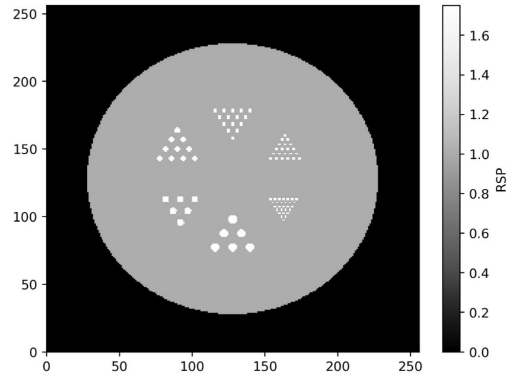
## Steps of the framework

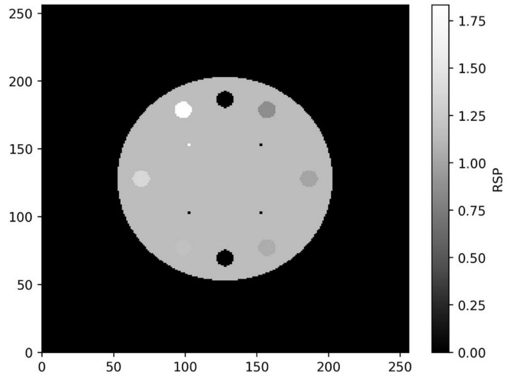
1. Generating data with Monte Carlo → Simulations with Geant4 & Gate → Very time-consuming! → Parallelization
2. Adding simulated measurement errors
3. 3-sigma filtering
4. MLP calculation
5. Calculating RSP distribution with Richardson-Lucy algorithm

**Derenzo**




- 200 mm diameter water cylinder with 6 sectors of 1.5-6 mm diameter aluminium rods
- Used for measuring spatial resolution

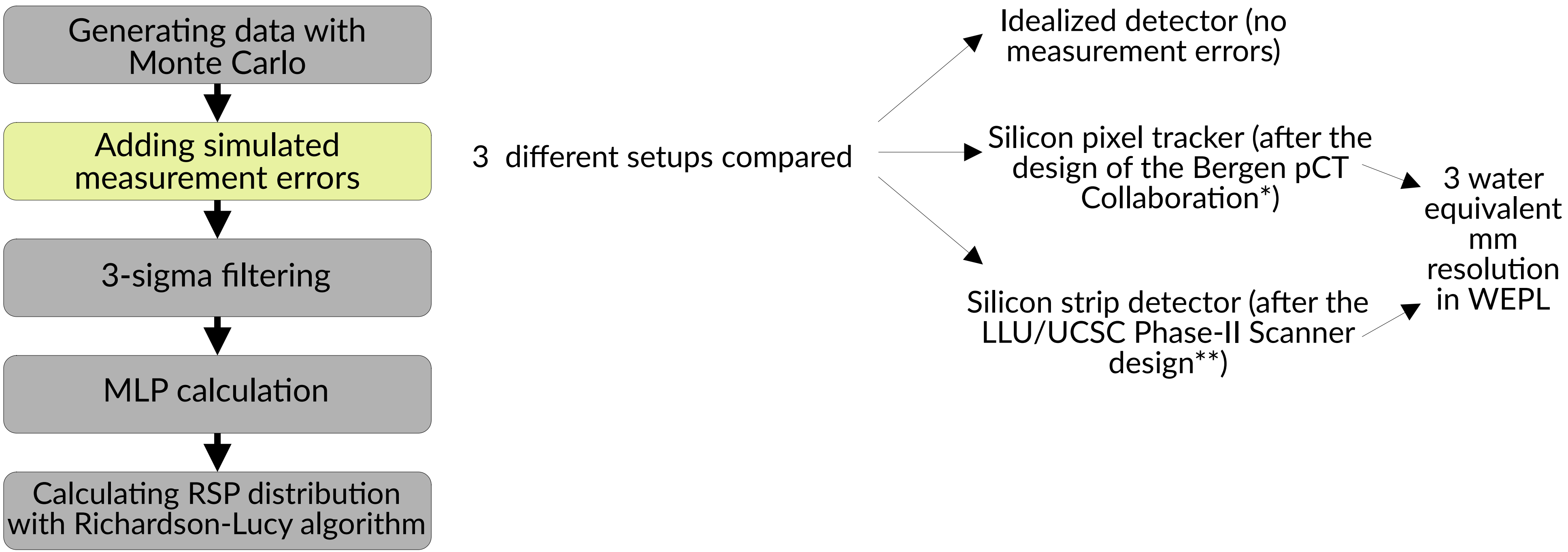
**CTP404**




- 150 mm diameter epoxy cylinder with 8 different material inserts with 12.2 mm diameter
- Used for measuring reconstruction accuracy for RSP

# Development of the framework

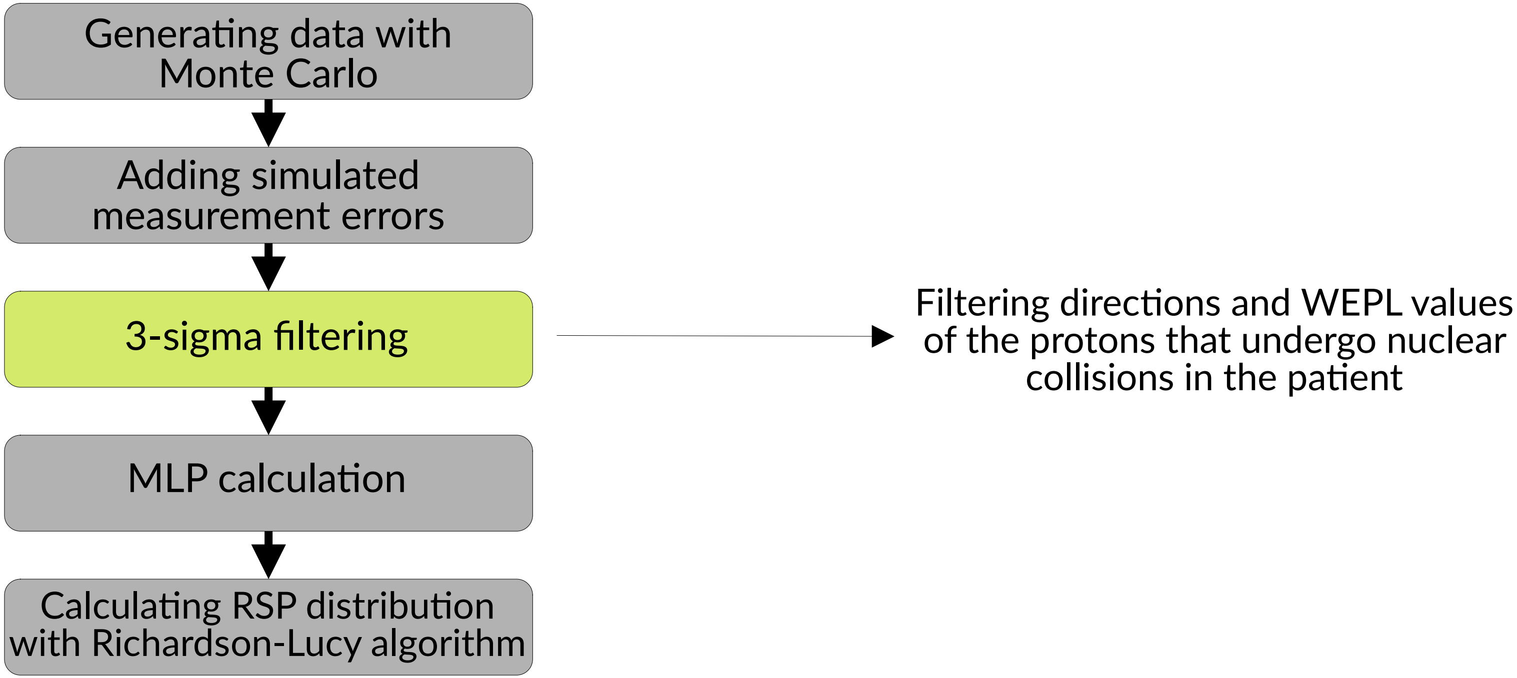
## Steps of the framework




*Pettersen et al., 2019; Alme et al., 2020
**Johnson et al., 2016

# Development of the framework

### Steps of the framework



# Development of the framework

## Steps of the framework

Generating data with Monte Carlo

↓

Adding simulated measurement errors

↓

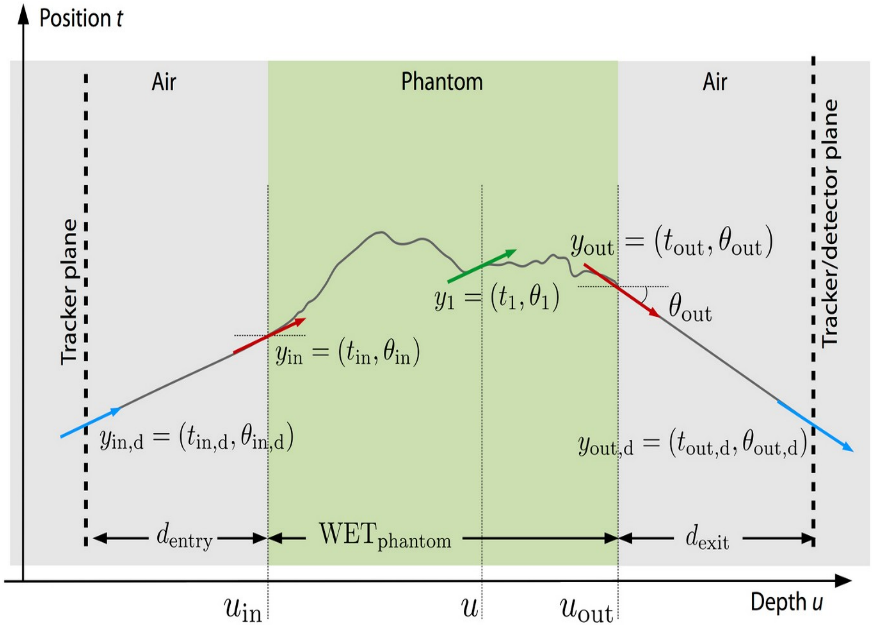
3-sigma filtering

↓

**MLP calculation** → Calculating the most likely position of protons going in and coming out of the cylinder around the phantom*

↓

Calculating RSP distribution with Richardson-Lucy algorithm




Compromise is needed between runtime and accuracy!

*Krah et al., 2018.
Schulte et al., 2008.
Williams, 2004.

# Development of the framework

## Steps of the framework

Generating data with Monte Carlo

↓

Adding simulated measurement errors

↓

3-sigma filtering

↓

MLP calculation

↓

Calculating RSP distribution with Richardson-Lucy algorithm

$$x_i^{k+1} = x_i^k \frac{1}{\sum_j A_{i,j}} \sum_j \frac{y_j}{\sum_l A_{l,j} x_l^k} A_{i,j}$$

Number of iterations

Vector containing WEPL values

Matrix containing interaction coefficients between proton trajectories and voxels

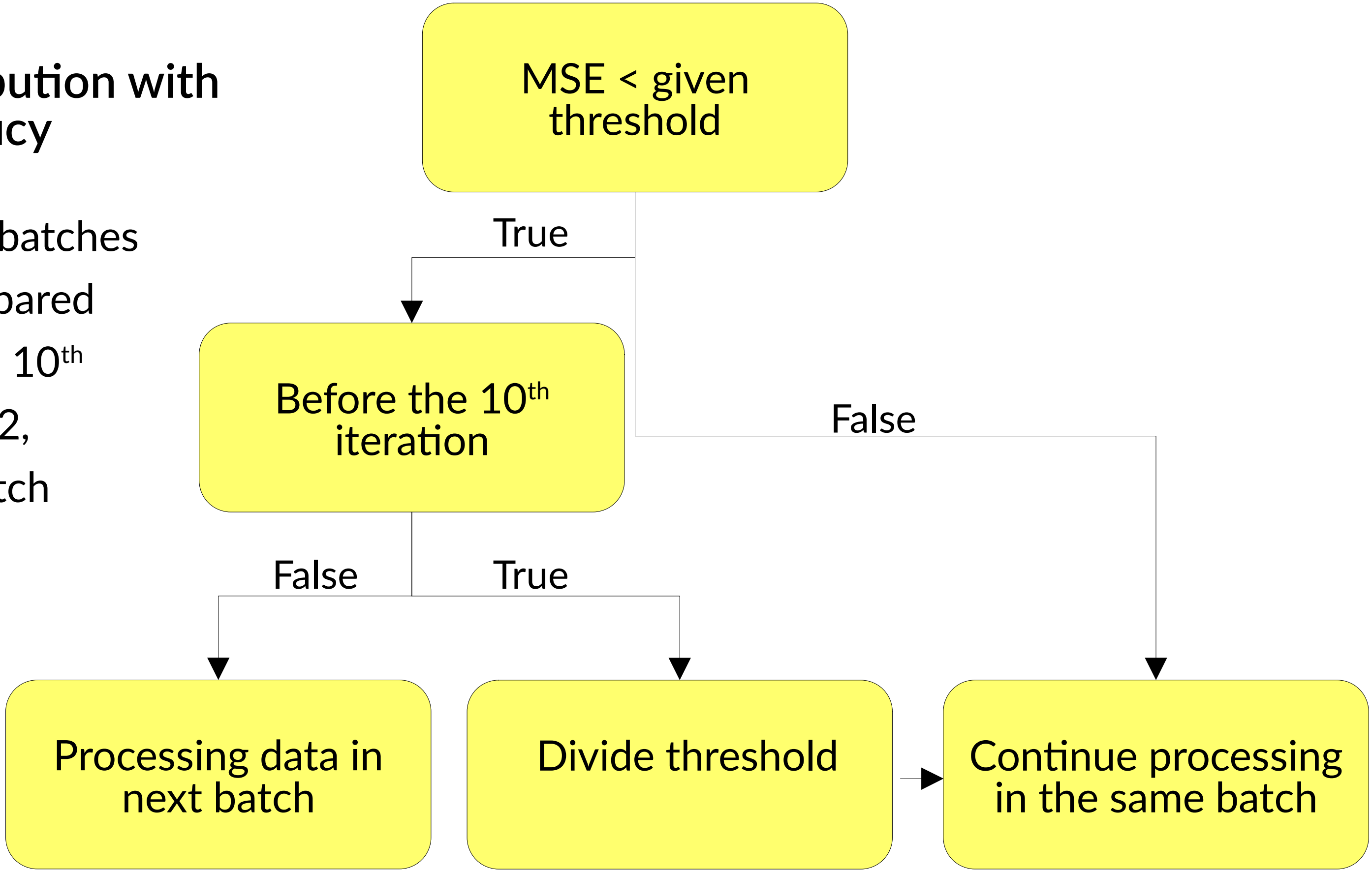
Vector containing RSP values

- Statistical iterative algorithm
- Maximum Likelihood - Expectation Maximization (ML-EM)
- Originally used in optics
- Very difficult technically (~millions of proton trajectories)
- Using GPU (CUDA): C++ code: different parts run in the GPU kernels (WSCLAB) → Nvidia GTX 1080 Ti GPU, 32 GB RAM
  - Goal: Finding optimization regarding the number of iterations and protons

# Development of the framework

## Calculating RSP distribution with Richardson-Lucy

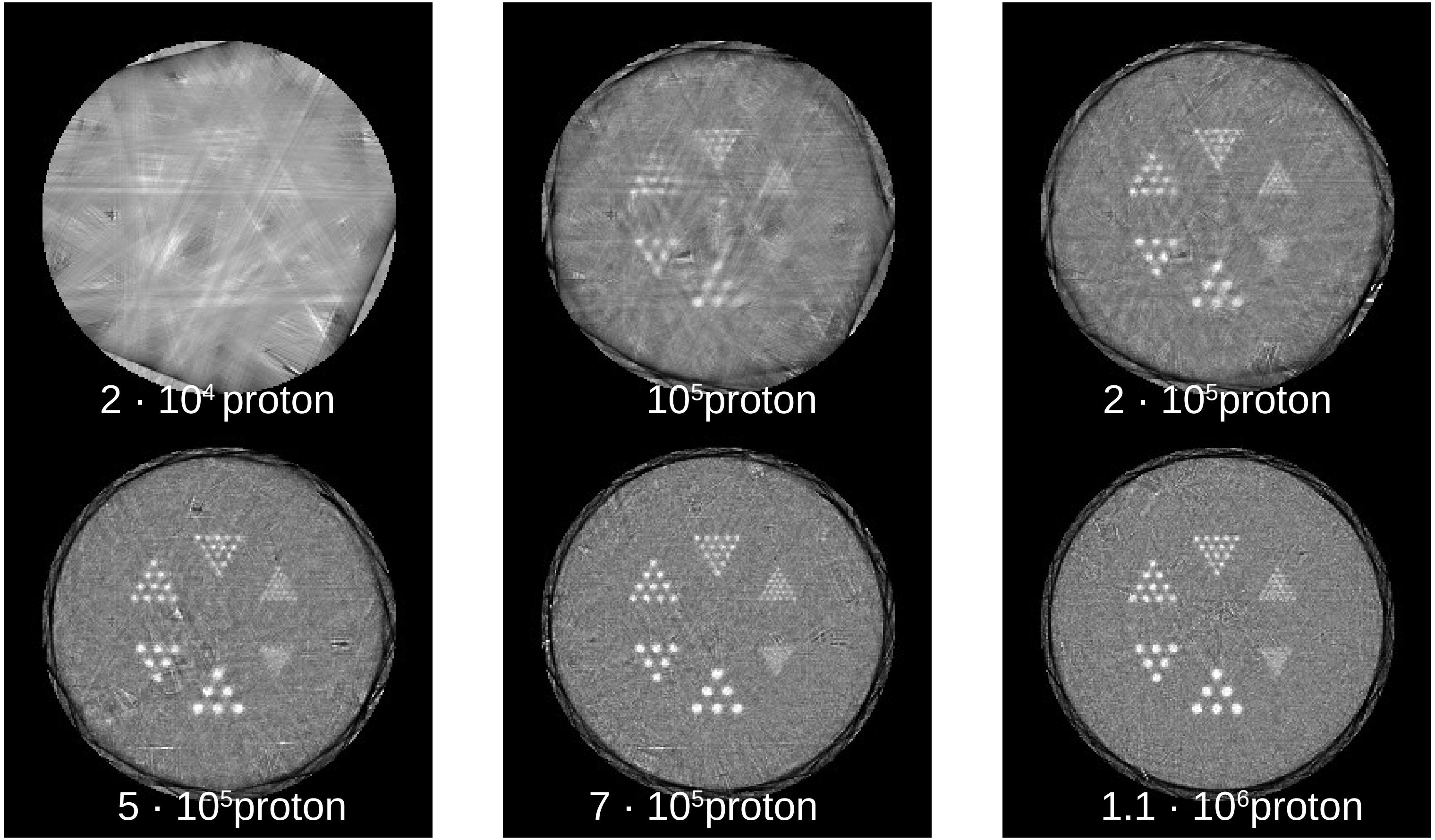
- Data to be processed is grouped in batches
- The consecutive iterations are compared
- If MSE < given threshold before the $10^{th}$ iteration, threshold gets divided by 2, otherwise iterations stop in that batch




Significant speed-up in runtime
(hours → minutes)
(~$10^6$ protons)

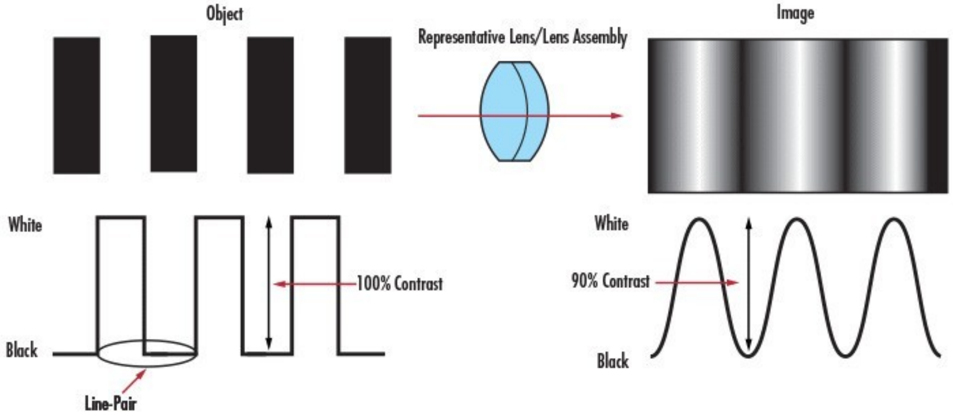
# Evaluation of the framework

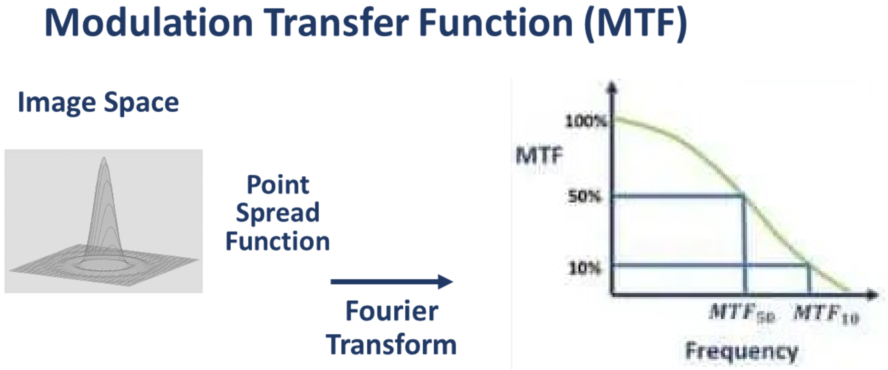
# Spatial resolution with Derenzo phantom



# Spatial resolution with Derenzo phantom

Good measure for spatial resolution: **Modulation Transfer Function** [lp/mm] → how well can we differentiate between two objects on an image

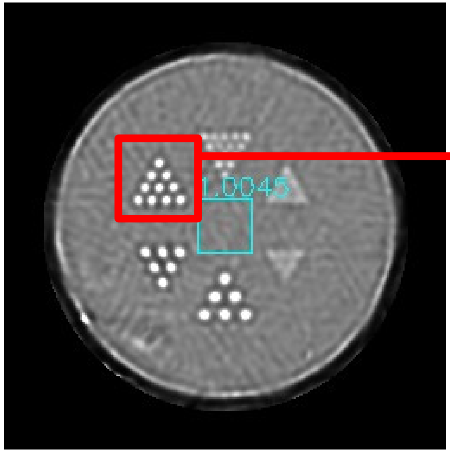



The more linepairs we can differentiate, the better the resolution is

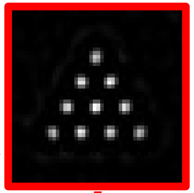
# Spatial resolution with Derenzo phantom

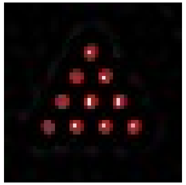
(i)




Subtract the mean background

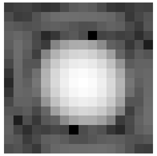
(ii)

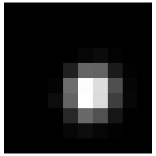




Find individual rods from each sector

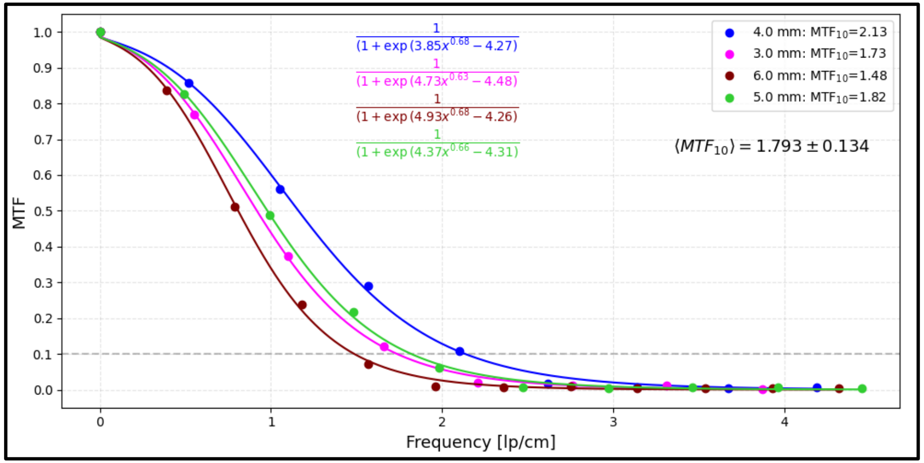
(iii)





Average them → Point Spread Function

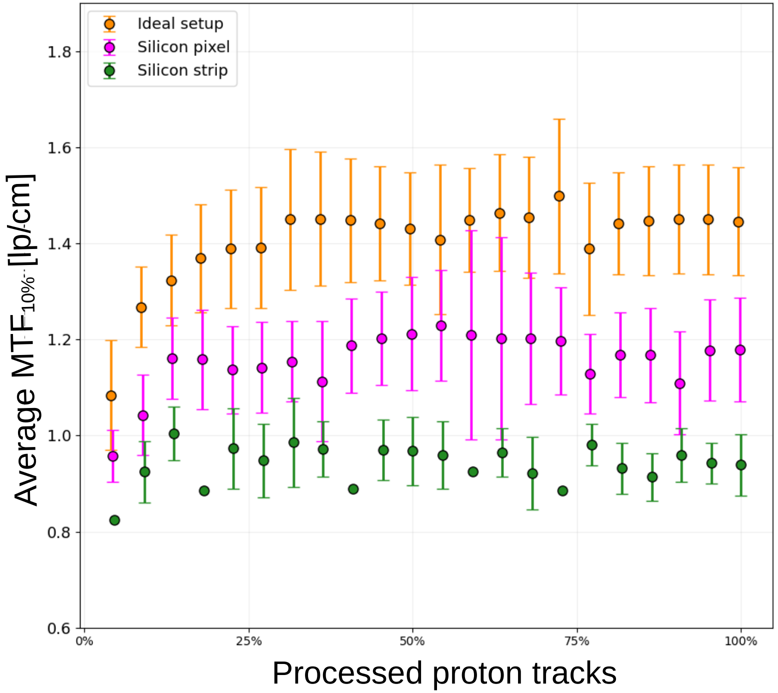
(iv)-(v)




- 2D Fourier transform PSF → Modulation Transfer Function (MTF)
- MTF10% averaged for the sections represents spatial resolution

# Spatial resolution with Derenzo phantom

| | Ideal | Reference - ideal | Realistic | Reference - realistic |
|---|---|---|---|---|
| MTF10% [lp/cm] | 1.43 | 3.8 | 1.17 (pixel) 0.94 (strip) | 3.2 |

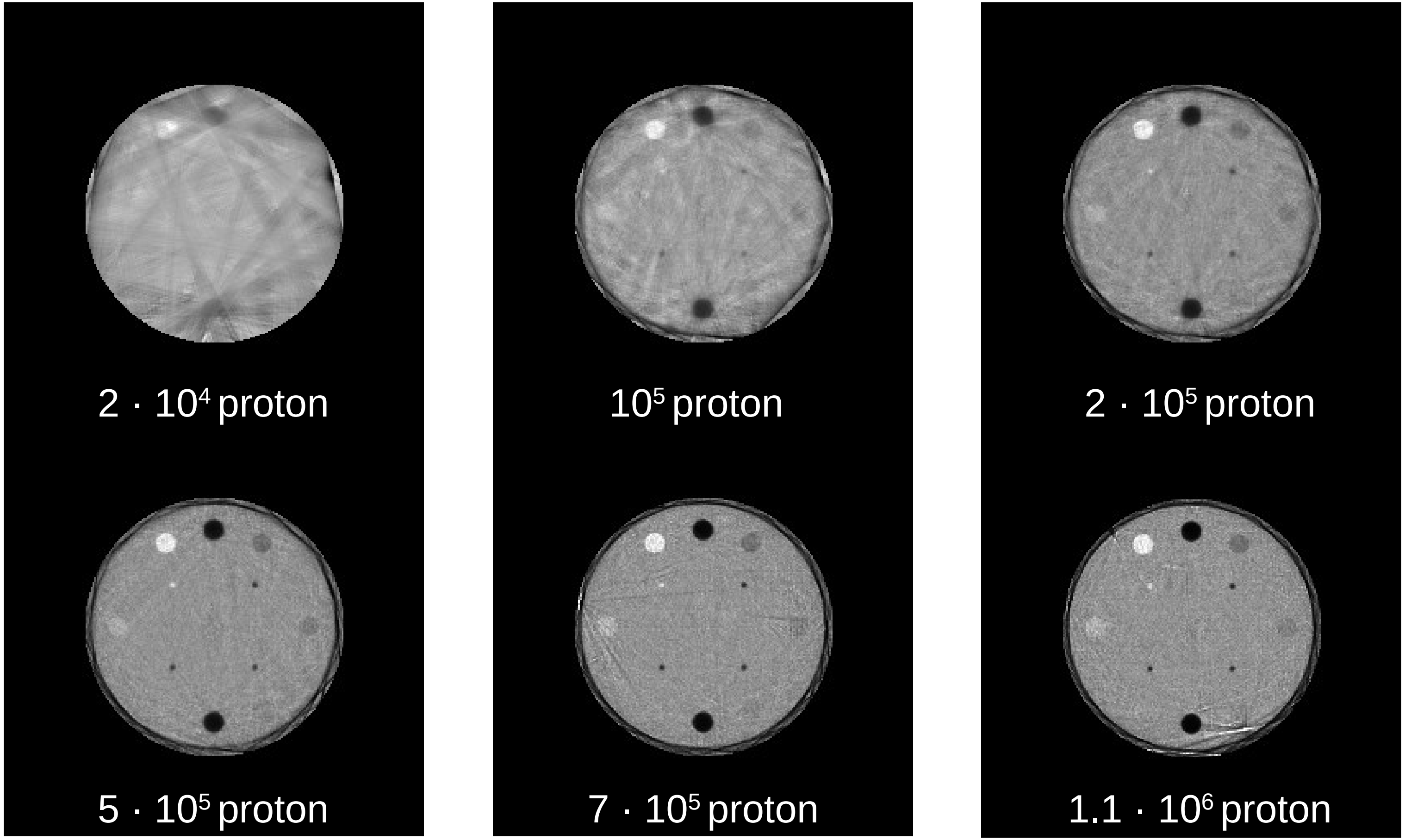



Results compared to literature: promising, but still need development

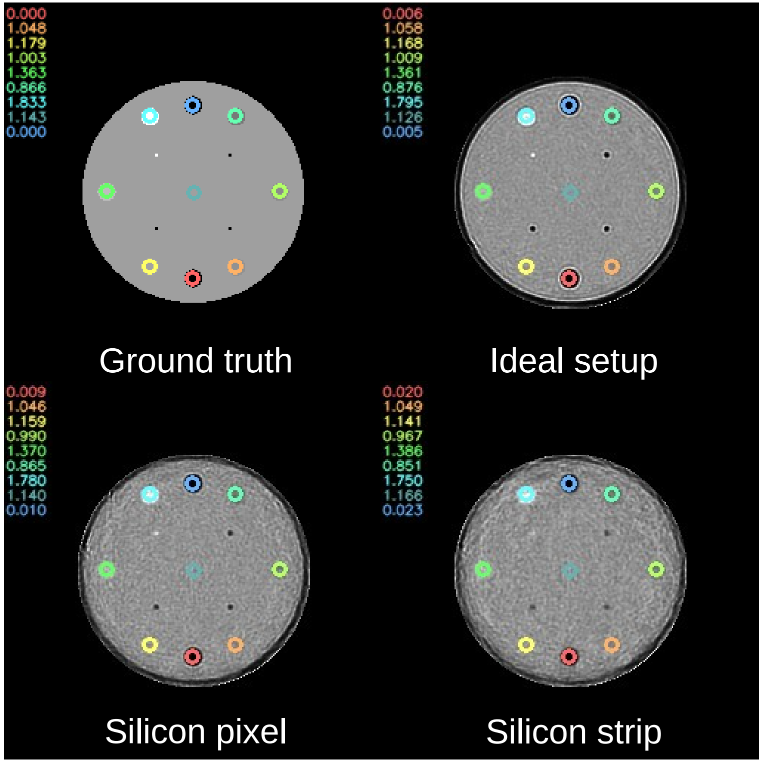
Sølie et al., 2020

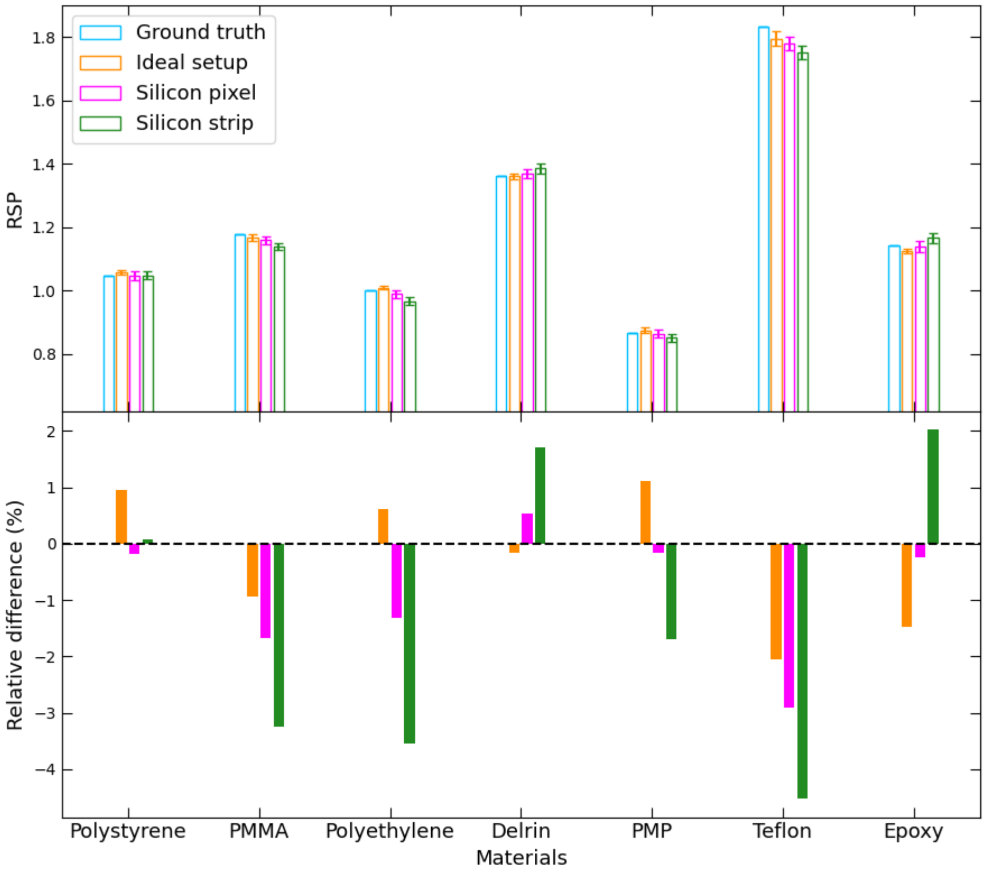
Gábor Bíró, Ákos Sudár, Zsófia Jólesz, Gábor Papp, Gergely Gábor Barnaföldi. Proton Computed Tomography Based on Richardson-Lucy Algorithm. ArXiv:2212.00126.

# RSP reconstruction accuracy with CTP404 phantom



# RSP reconstruction accuracy with CTP404 phantom




- ~1% for Wang et al., 2010, runtime is more (Bayesian interference-based proton path probability map for MLP calculation)
- ~-4% for our research

Gábor Bíró, Ákos Sudár, Zsófia Jólesz, Gábor Papp, Gergely Gábor Barnaföldi. Proton Computed Tomography Based on Richardson-Lucy Algorithm. ArXiv:2212.00126.

# Summary of achievements and future plans

- Richardson-Lucy algorithm used for the first time in medical imaging*
- Promising results (using ~$10^6$ protons), comparable with other used algorithms
- But still needs further developments for clinical usability → Using Machine Learning for noise filtering, MLP calculation, realistic phantoms, etc.; achieving shorter runtime

*Gábor Bíró, Ákos Sudár, Zsófia Jólesz, Gábor Papp, Gergely Gábor Barnaföldi. Proton Computed Tomography Based on Richardson-Lucy Algorithm. ArXiv:2212.00126.

# Thank you for your attention!

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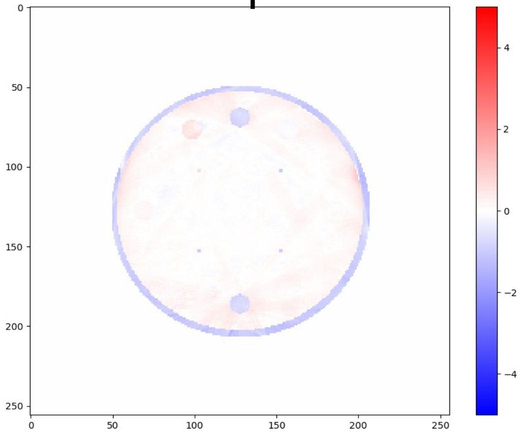
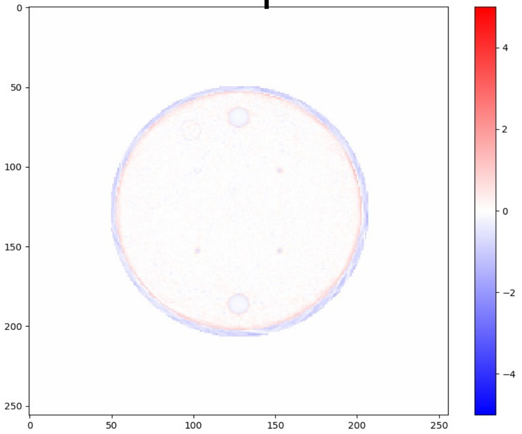
# Backup - Differences between the RSP values

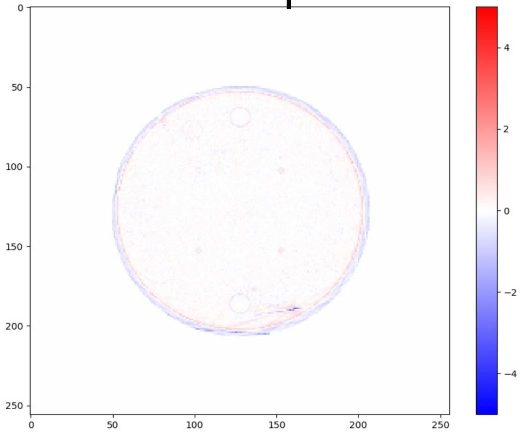
$2 \cdot 10^4$ proton




$3.4 \cdot 10^5$ proton




$1.14 \cdot 10^6$ proton




$1.5 \cdot 10^6$ proton