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A system for 3D localization of gamma sources using Timepix3-based Compton cameras

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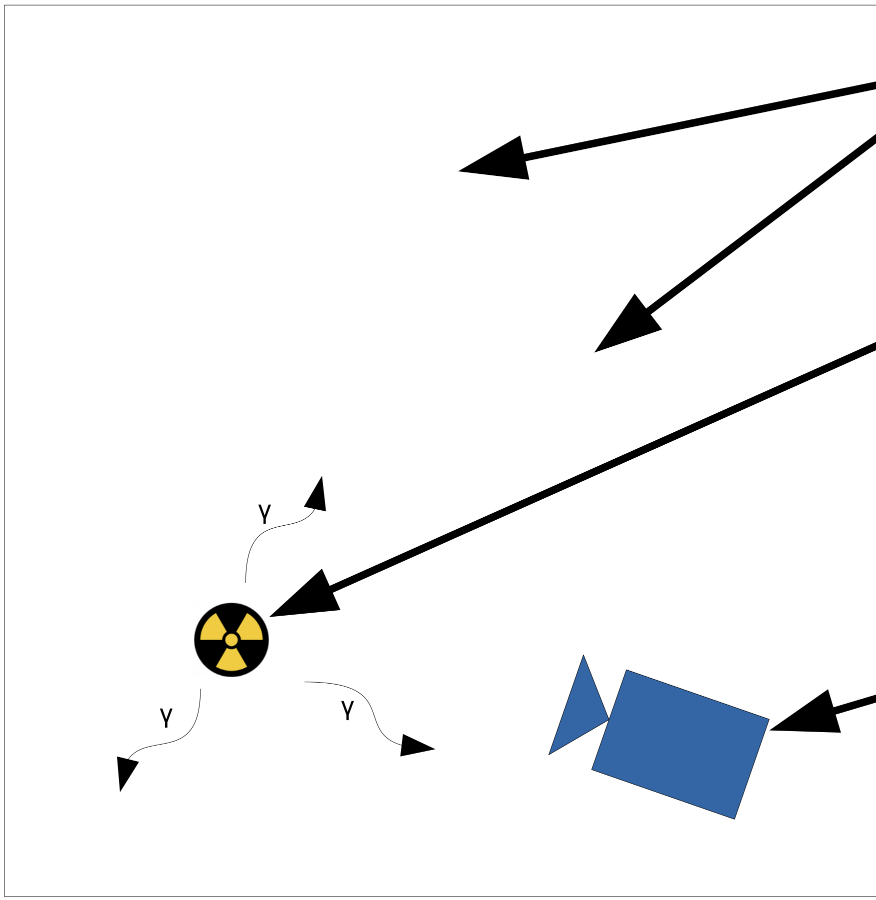
γ-camera



(1) Environment (domain)
- A well-defined set of locations

(2) Source
- Emits γ-radiation (ionizing photons)
- Its location is not fully known
  - ➔ <u>We want to find it</u>

(3) γ-camera
- Is sensitive to γ-photons
- Creates image of the environment (source receives large intensity)

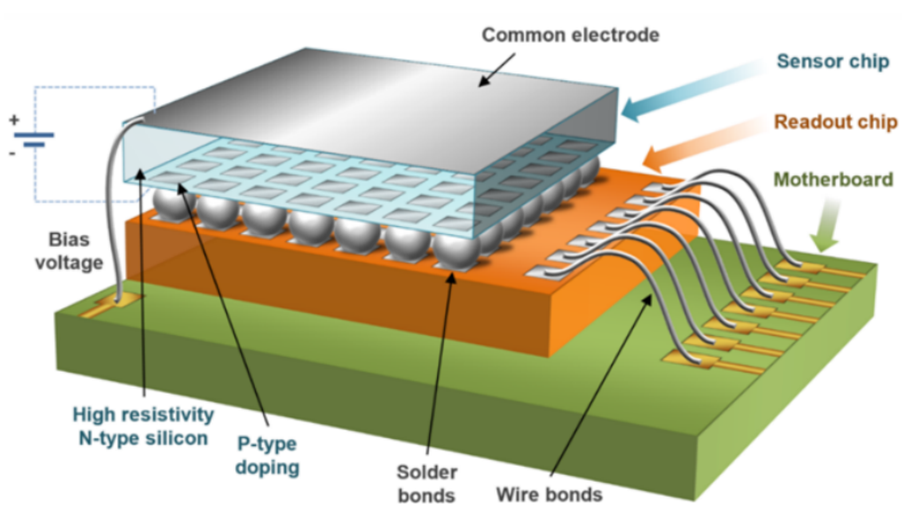
Ref.: *1959, Anger et al.*
1974, Todd et al.
1977, Everett et al.

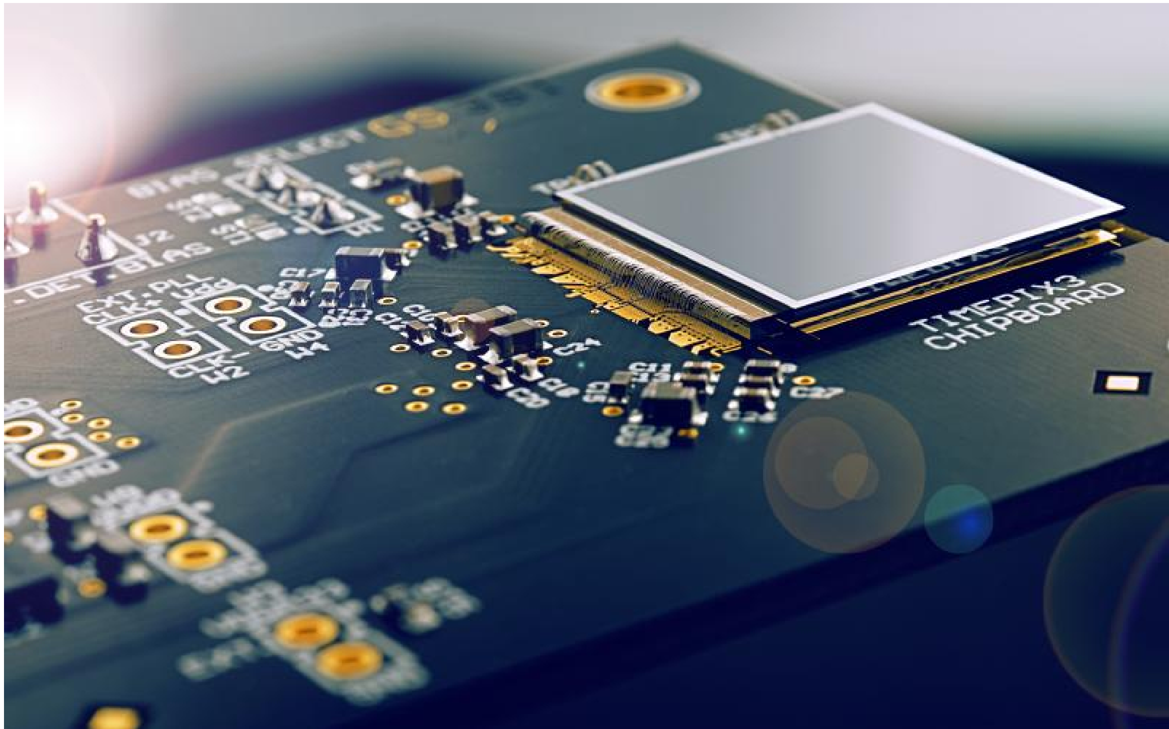
Timepix3

- Sensor: semiconductor layer < 1 mm (Si, GaAs, CdTe)
- 256 x 256 pixels with 55 μm pitch (~1.41 cm in total)
- Detector <u>runs continuously</u> a reports active pixels during measurement.
- Each pixel records:
  a) timestamp (± 1.25 ns),
  b) deposited energy.

→ **Erratic data flux spikes,**
→ **High volumes (units of GB/s)**

Ref.: *2014, Poikela et al.*





Thesis Structure

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Control program components:

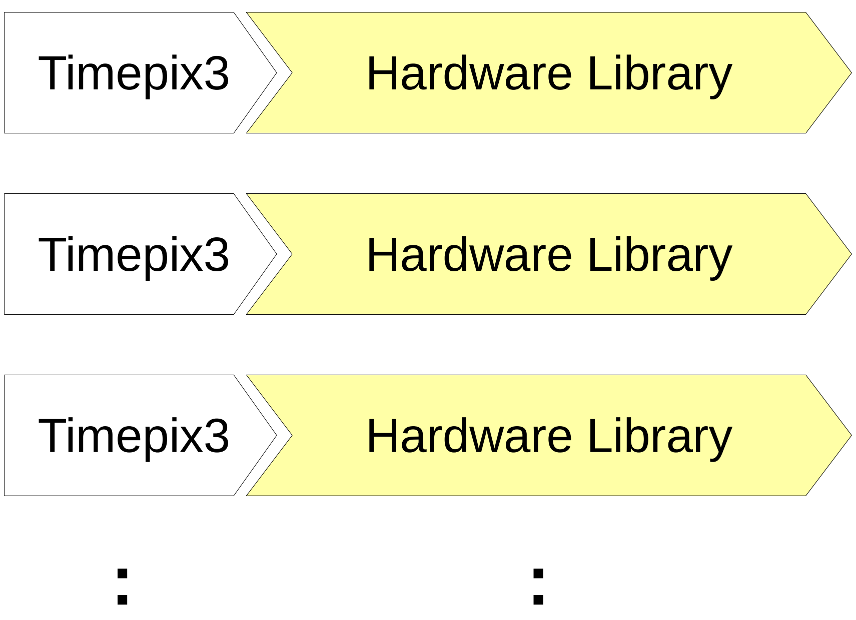
- Timepix3
- Timepix3
- Timepix3

⋮

Thesis Structure

1. Communication with Detector,

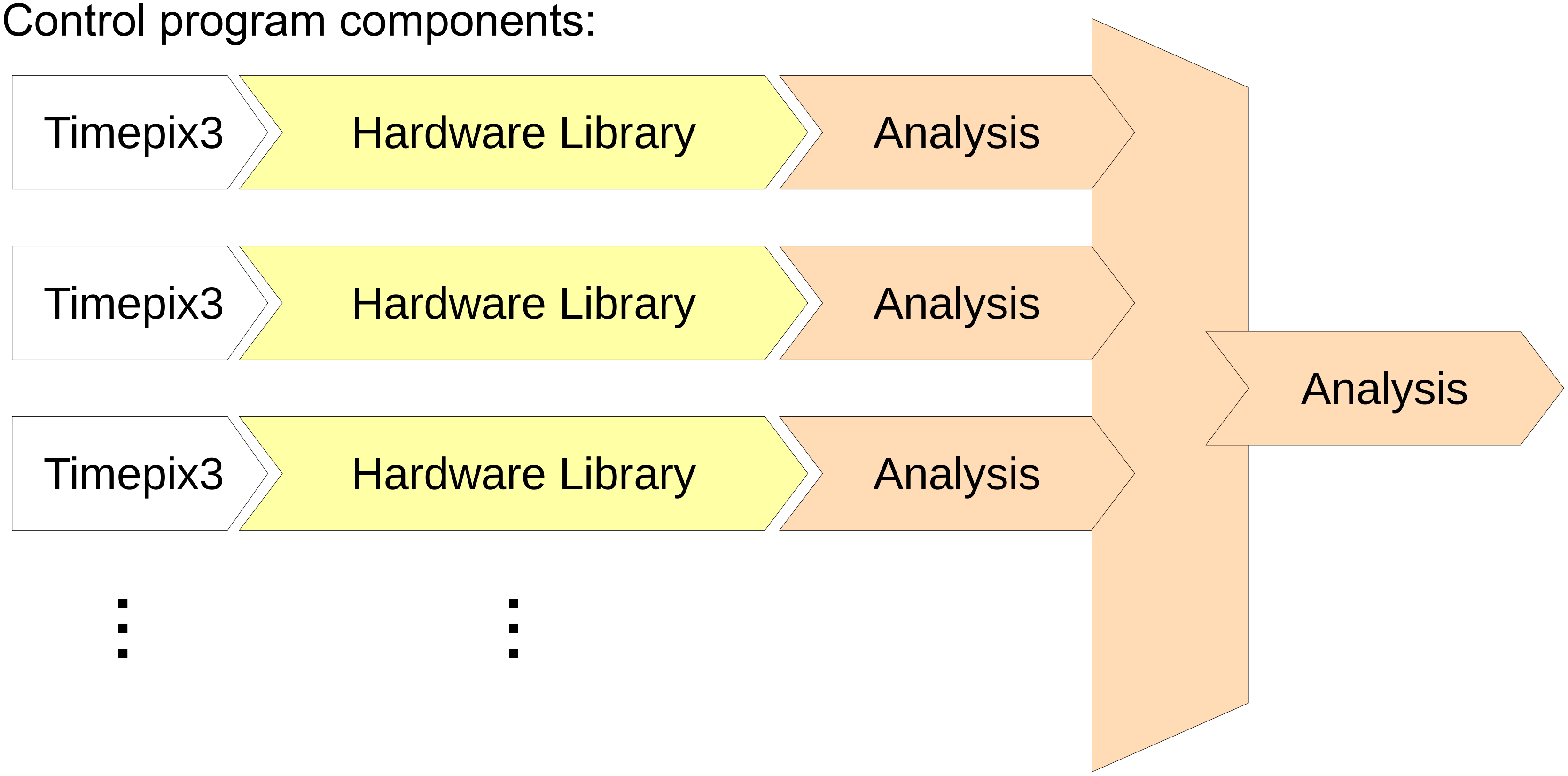
Control program components:



Thesis Structure

1. Communication with Detector,
2. Analysis of Measured Data,

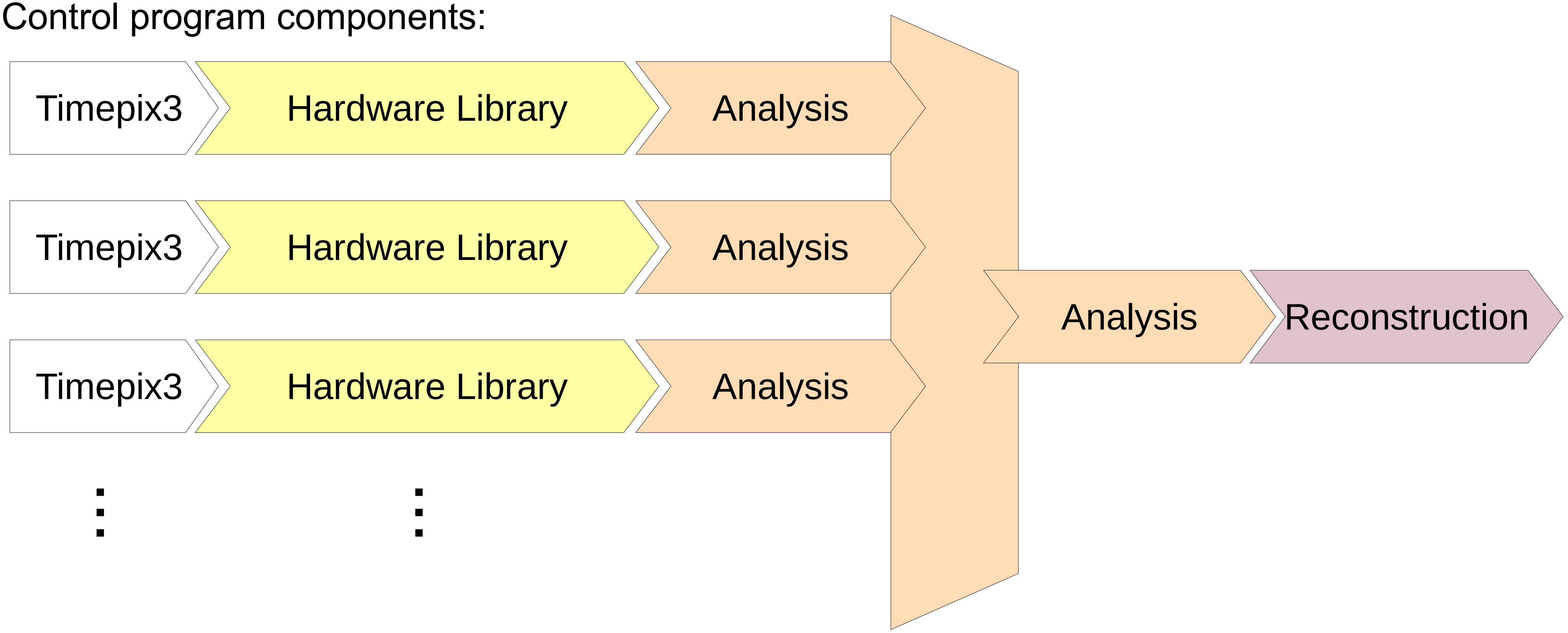
Control program components:



Thesis Structure

1. Communication with Detector,
2. Analysis of Measured Data,
3. 3D Image Reconstruction,

Control program components:

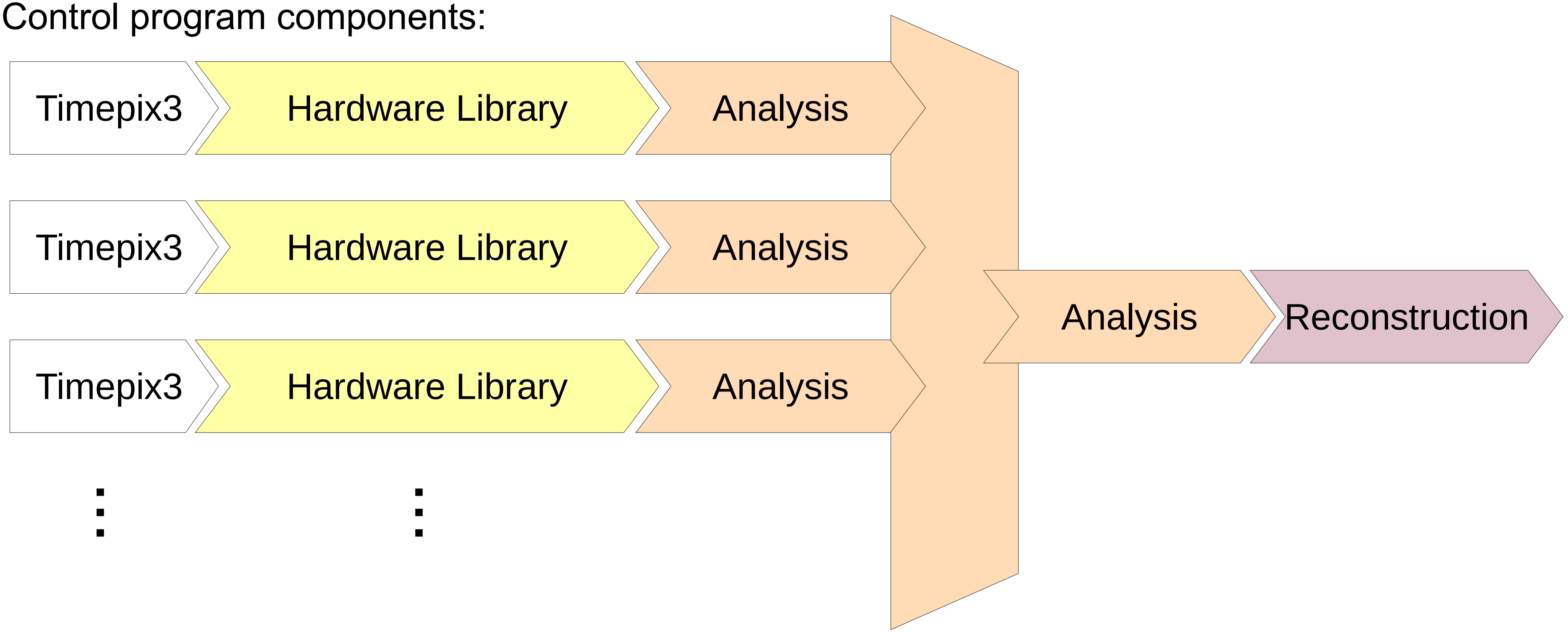


Thesis Structure

1. Communication with Detector,
2. Analysis of Measured Data,
3. 3D Image Reconstruction,

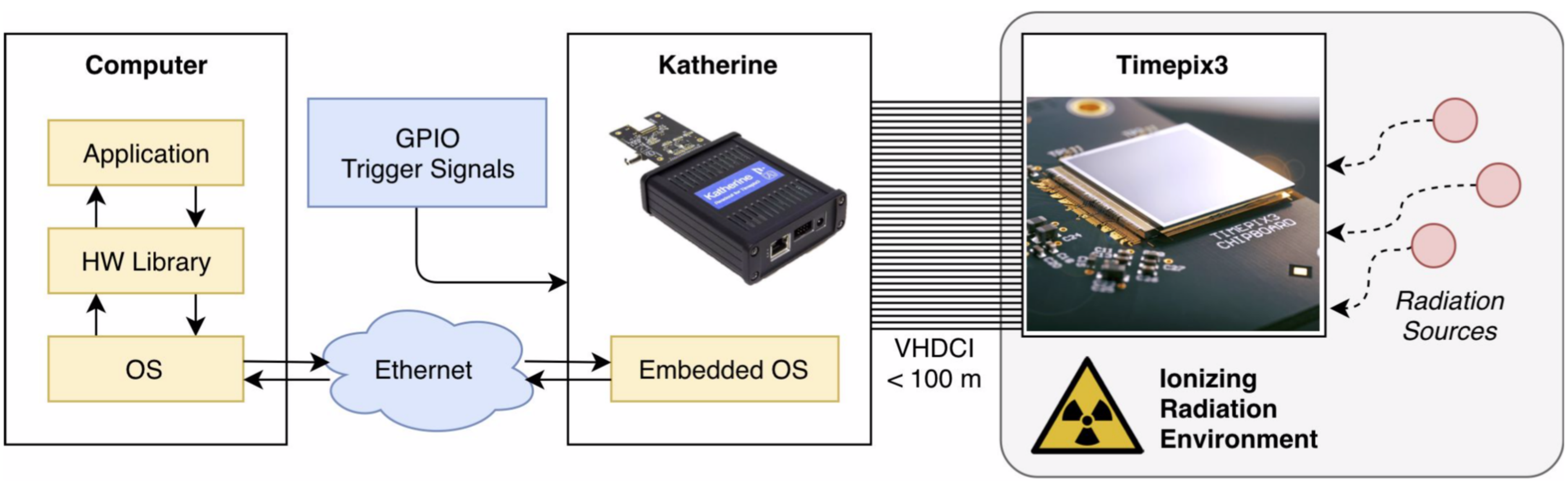
\+ 4. Experiments.

Control program components:



(1) Communication

- Control Program ↔ HW library ↔ Timepix3
- Implemented HW library for the Katherine readout (developed in Pilsen by UWB)
- Library supports:
    a) Detector configuration,
    b) Status monitoring and acquisition control,
    c) Fast asynchronous data processing (theoretically up to 15M px/s).



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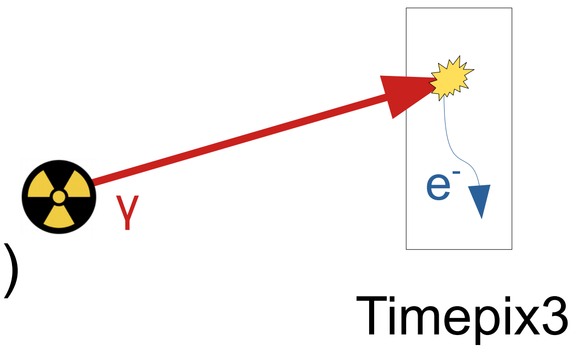
(2a) Data Analysis

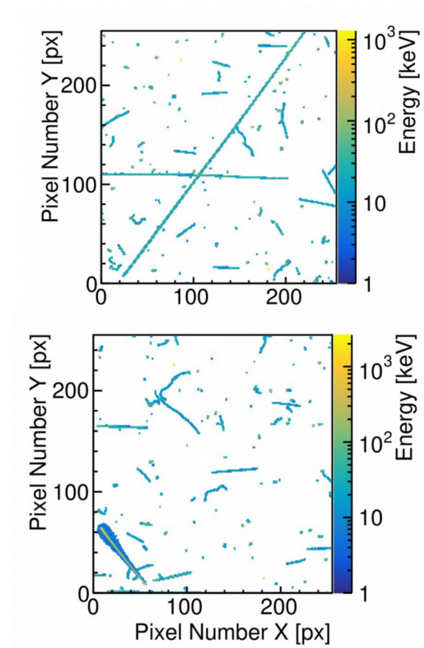
- Goal: observe electron ionized by a photon
- In the detector: electron ~ pixel cluster



- **Issue #1:** Detector only reports pixels.
  ➔ Morphological aggregation (group adjacent pixels)

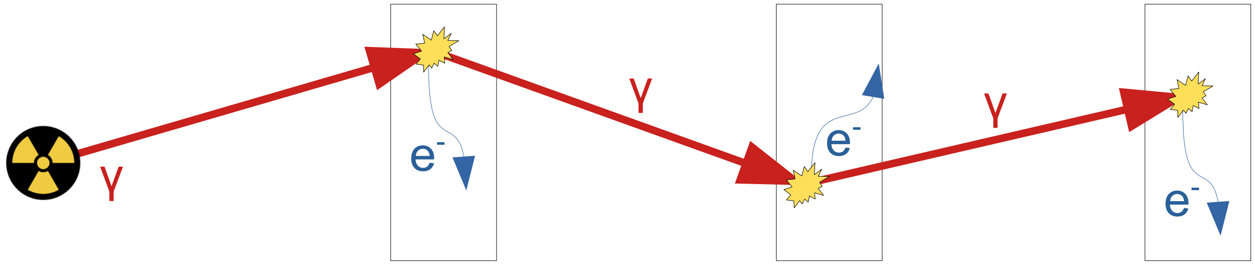
- **Issue #2:** Pixels may be reported out of order.
  ➔ Buffer incoming pixels before aggregating them.

- **Solution:** Novel clustering algorithm
  - Pixels are sorted by timestamps in a priority queue,
  - Adjacent pixels are then identified using geometric DS.



(2b) Data Analysis

- **Issue #3:** A single photon can ionize multiple electrons.
  ➔ Group time-coincident clusters from different detectors.

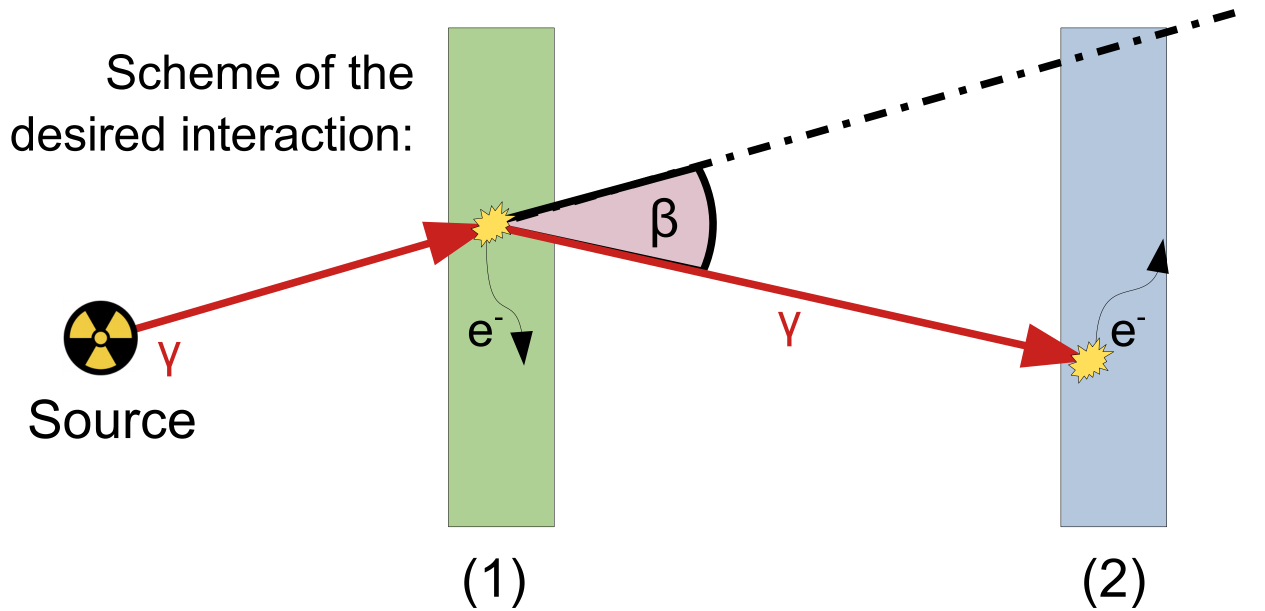


- **Solution:** Time synchronization + novel matching algorithm
  - Pixel aggregation runs simultaneously for all detectors,
  - Clusters are then matched based on theirtimestamps.

- Both new algorithms:
  - Scale well asymptotically (Katherine can measure up to 15M px/s),
  - Can run *online* → they can be composed into data pipeline,
  - Support cascade filtering → decrease complexity and memory usage.

(3a) Reconstruction

- Goal: localize the source
- We are looking for photons which ionized some electrons in both detectors.
- Deposited energies give the angle β of a conic surface.



(1) Compton Scattering

- γ-photon loses <u>some</u> of its energy
- Changes its velocity by the angle β

$$\cos\beta = 1 - m_e c^2 \left(\frac{1}{E'_\gamma} - \frac{1}{E_\gamma}\right)$$

(2) Photoelectric Absorption

- γ-photon loses <u>all</u> its energy
- Photon is absorbed and ceases to exist

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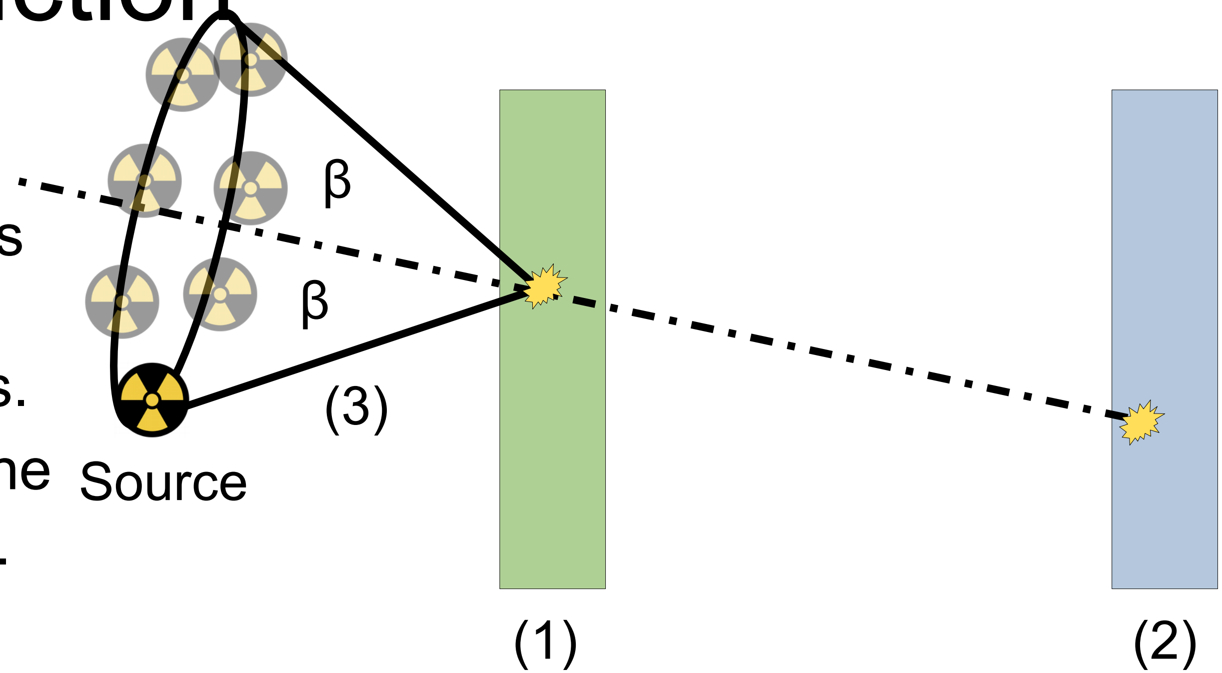
(3b) Reconstruction

- Goal: localize the source
- We are looking for photons which ionized some electrons in both detectors.
- Deposited energies give the angle β of a conic surface.



- The source lies *somewhere* on the cone mantle (3)
  - ➔ We need multiple cones,
  - ➔ N is corresponds to the desired accuracy

(1) Compton Scattering

- γ-photon loses <u>some</u> of its energy
- Changes its velocity by the angle β

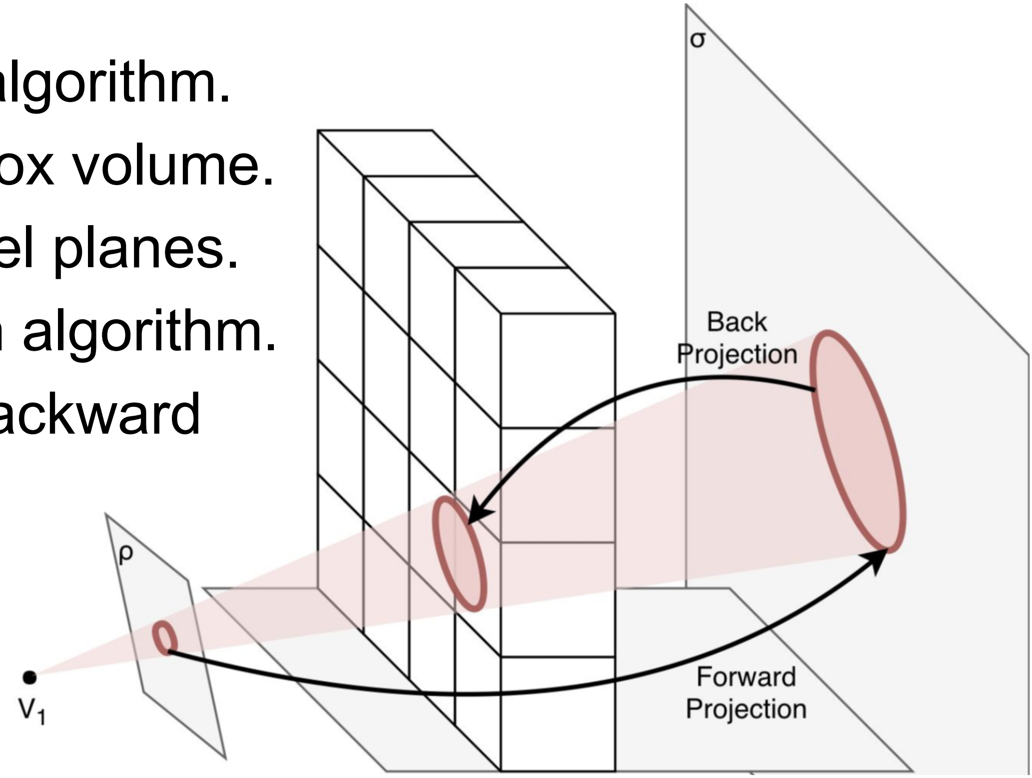
$$\cos\beta = 1 - m_e c^2 \left(\frac{1}{E'_\gamma} - \frac{1}{E_\gamma} \right)$$

(2) Photoelectric Absorption

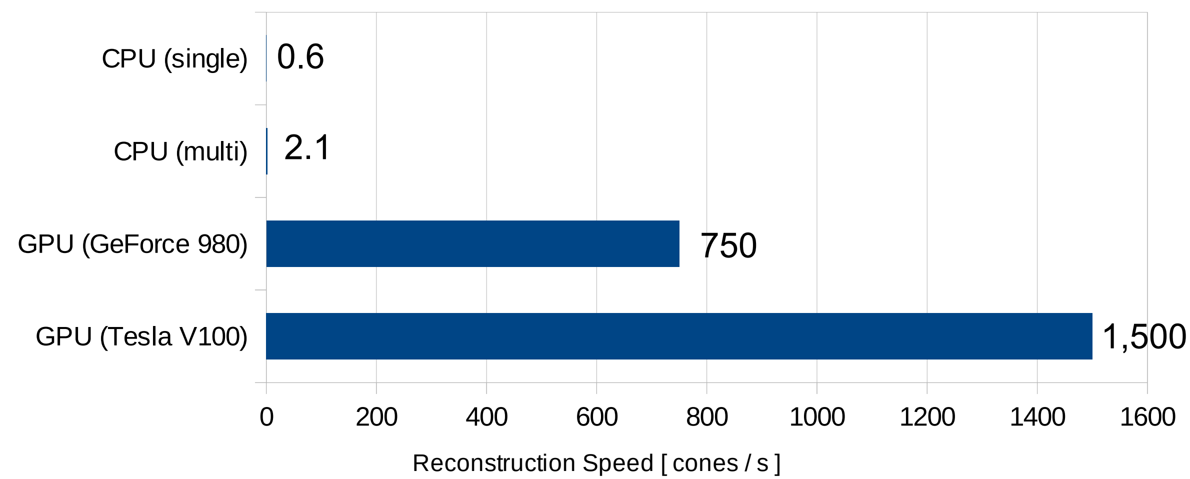
- γ-photon loses <u>all</u> its energy
- Photon is absorbed and ceases to exist

(3c) Reconstruction

- Implemented the forward projection algorithm.
  - ➔ Projects cones into a discretized box volume.
- Speed can be increased using parallel planes.
  - ➔ Derived faster backward projection algorithm.
  - ➔ 1 cone projection: 1 forward + N backward
- Total cell count increases fast with N.
- N = 300 → 27M cells (~100 MB)



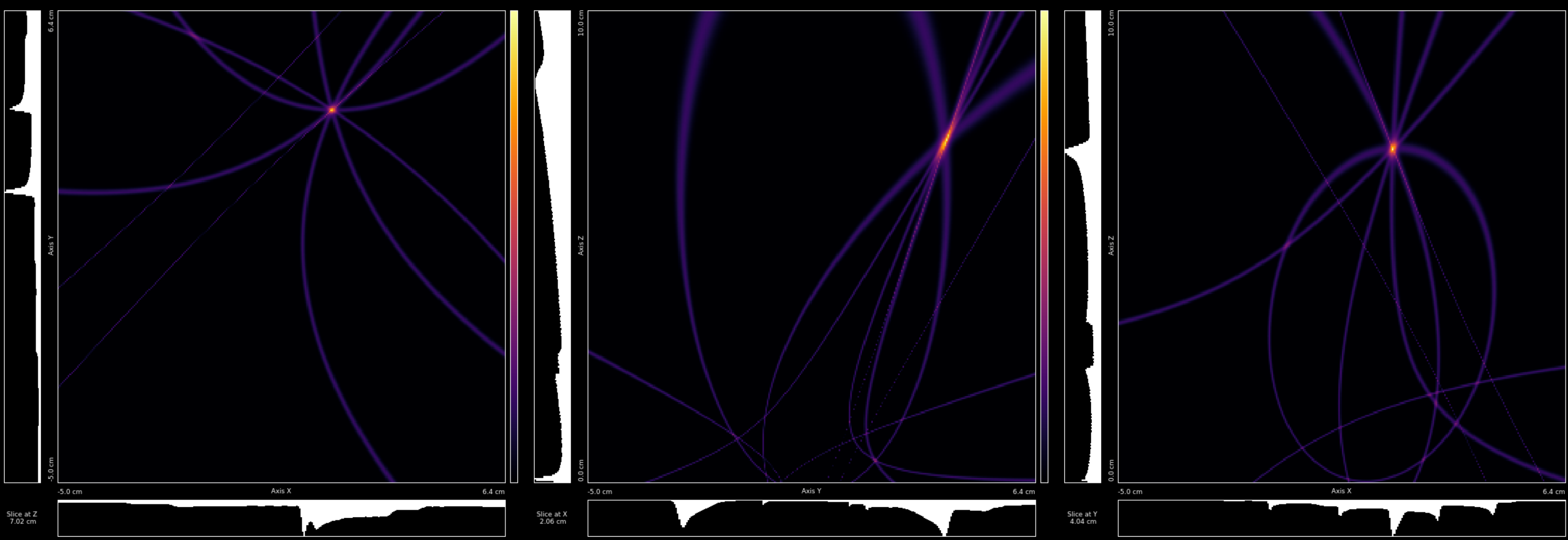
- Further performance improvements:
  - ➔ Parallel implementation,
  - ➔ Look-up tables,
  - ➔ Interpolation,
  - ➔ Graphics Cards (CUDA).



Ref.: *1984, Dudgeon et al.*
2009, Herman

(3d) Reconstruction

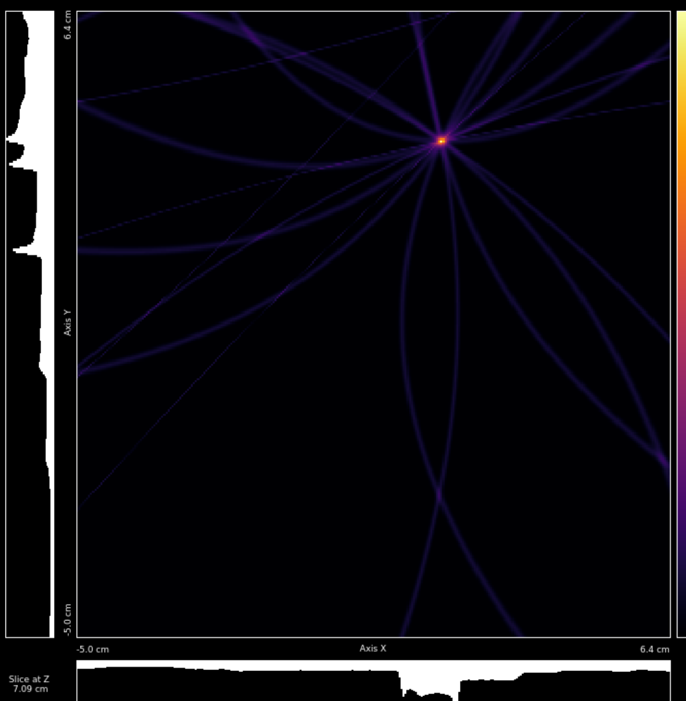
Front view (XY) Side view (YZ) Top view (XZ)



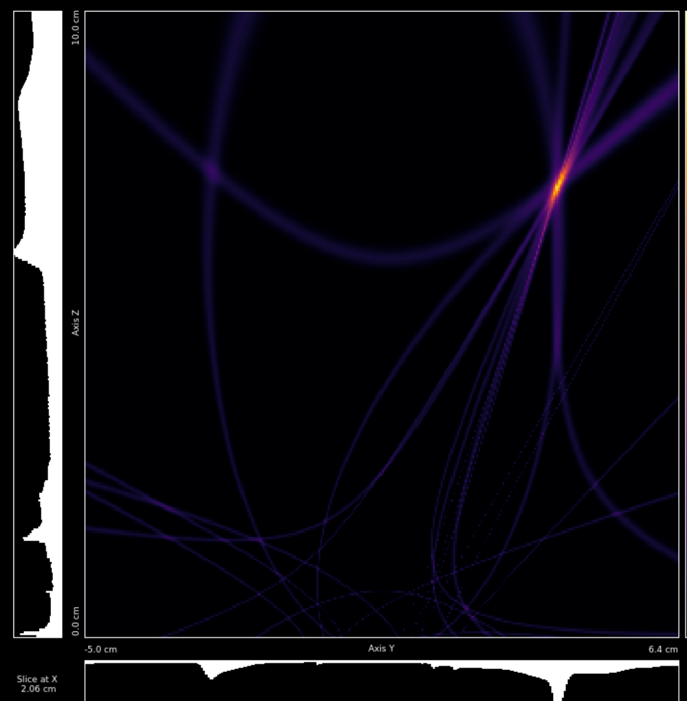
N = 5 cones

(3d) Reconstruction

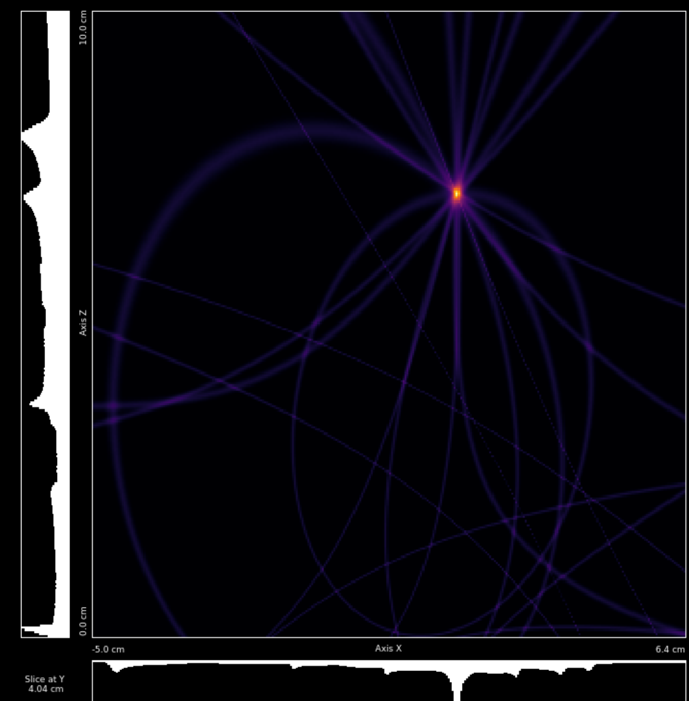
Front view (XY)



Side view (YZ)



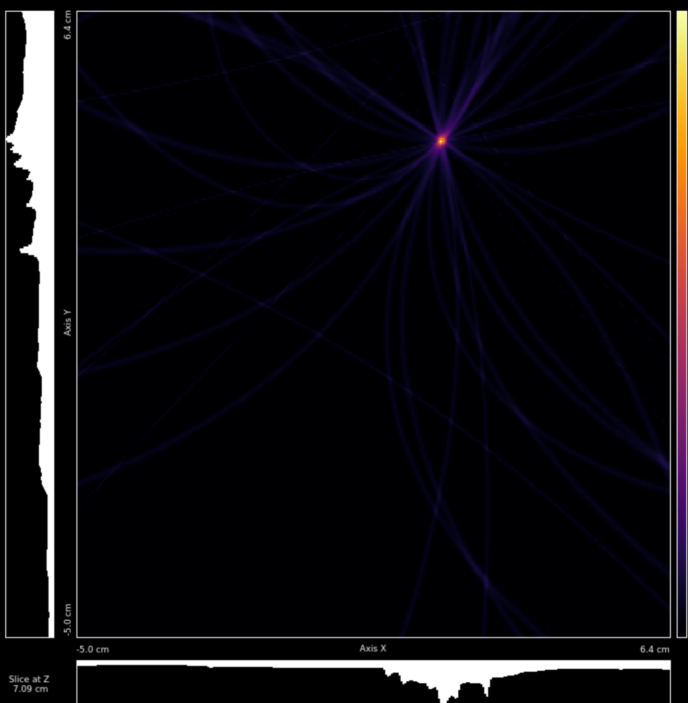
Top view (XZ)



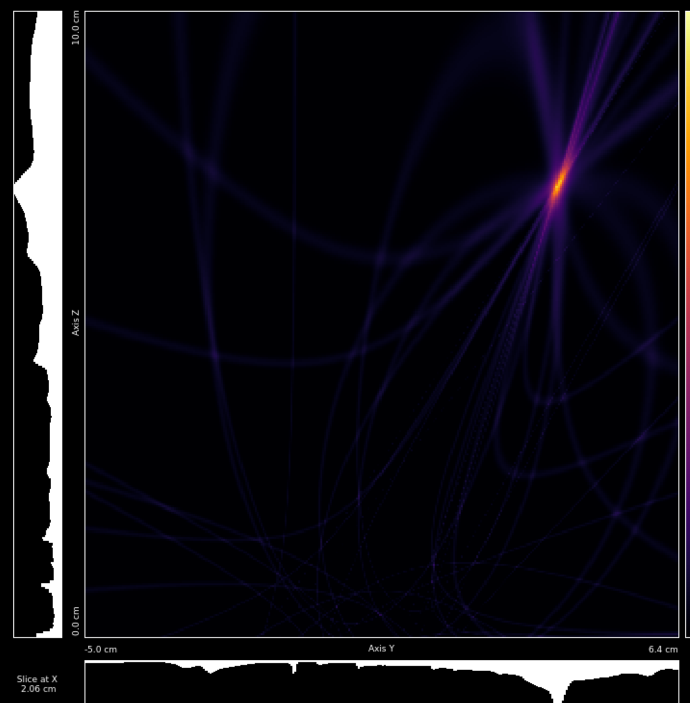
N = 10 cones

(3d) Reconstruction

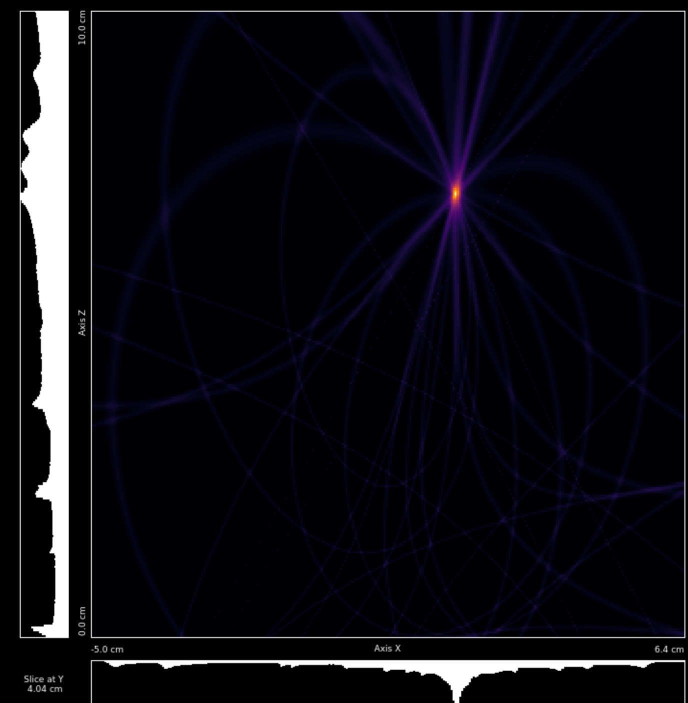
Front view (XY)



Side view (YZ)



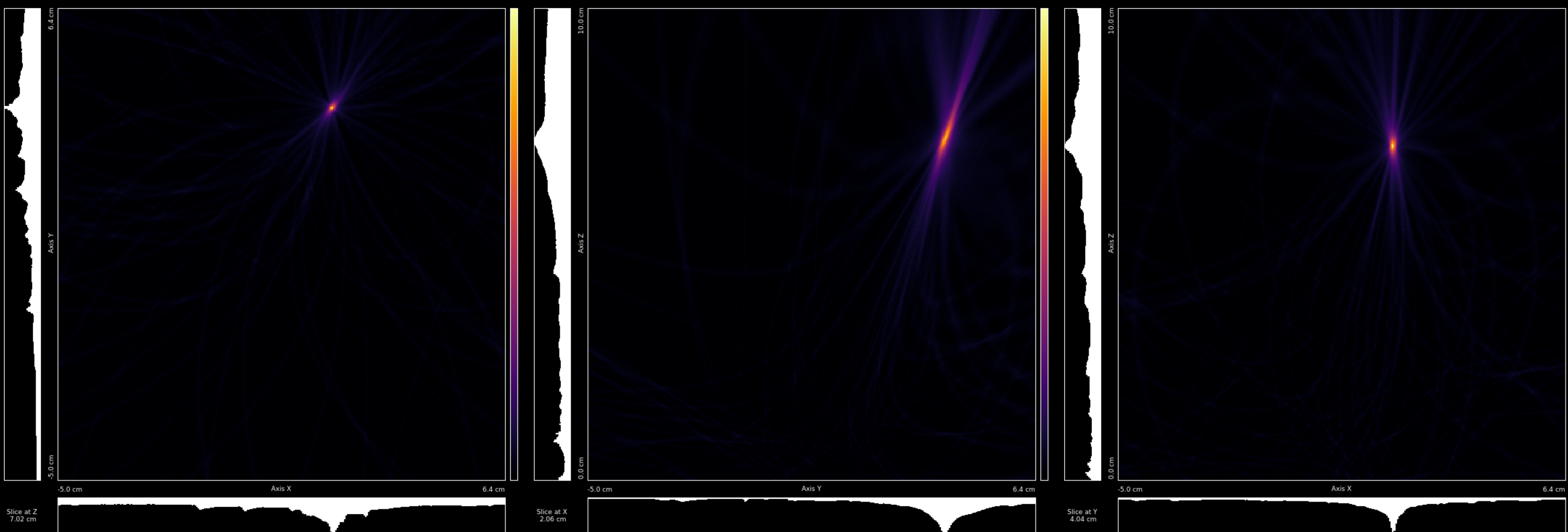
Top view (XZ)



N = 20 cones

(3d) Reconstruction

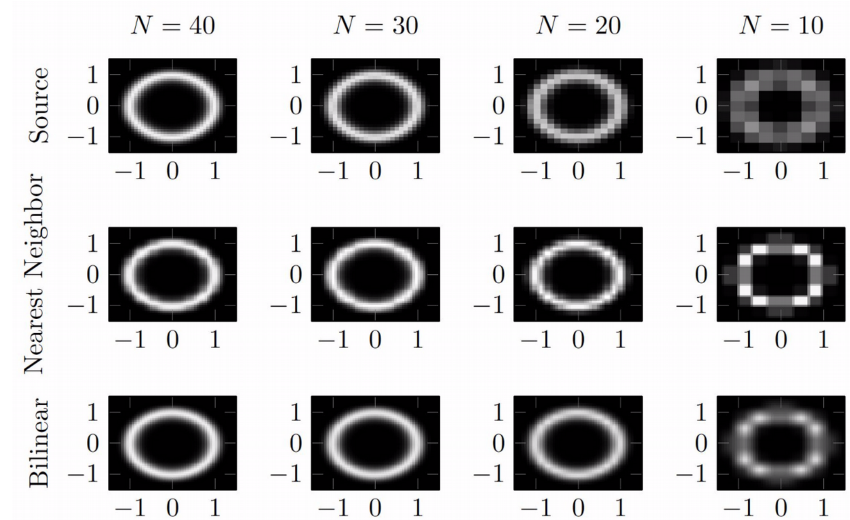
Front view (XY) | Side view (YZ) | Top view (XZ)

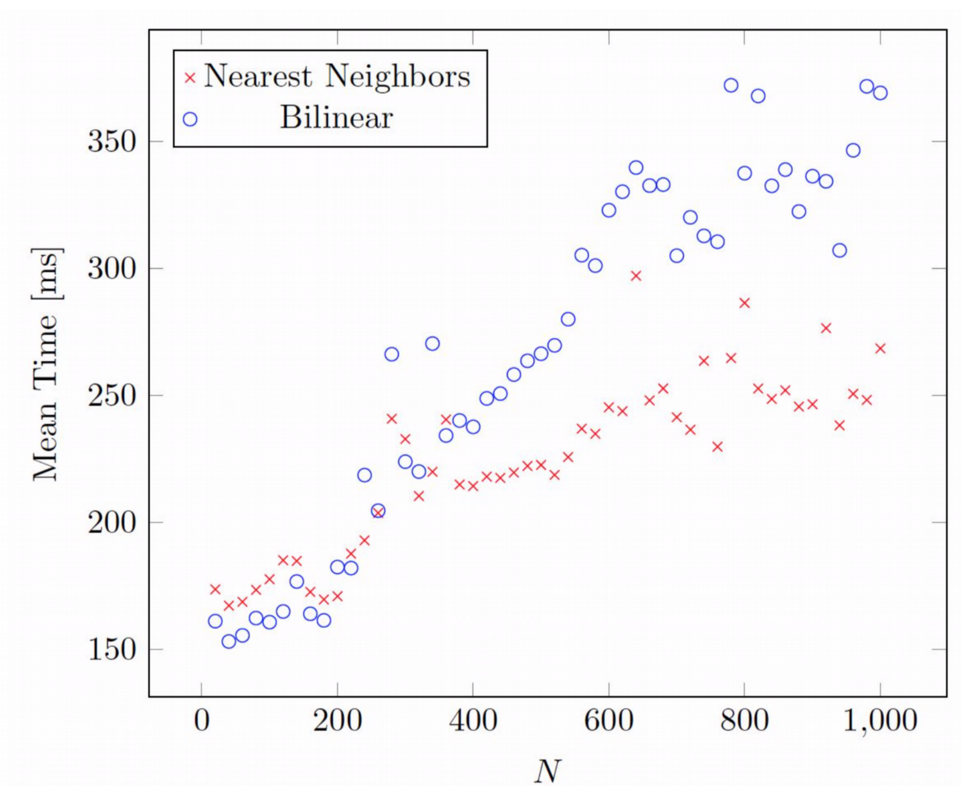


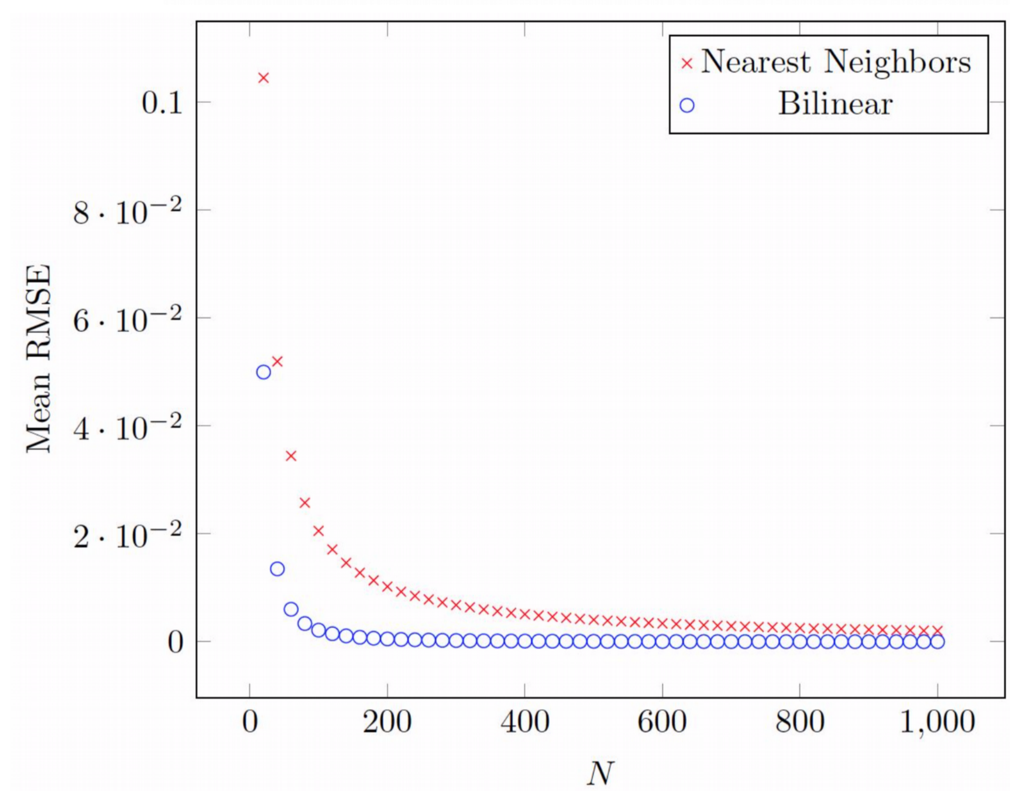
N = 50 cones

(4a) Experiments

- Interpolation error evaluation,



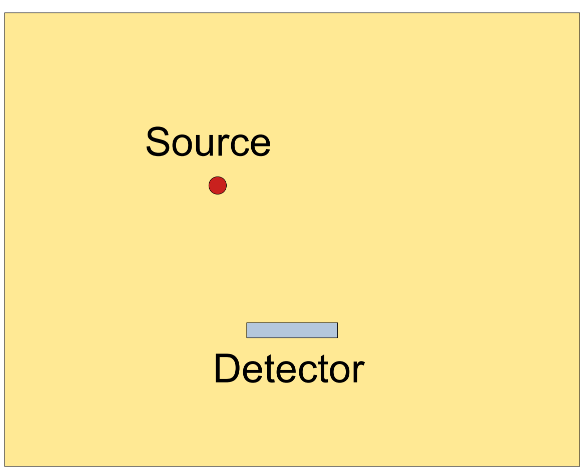




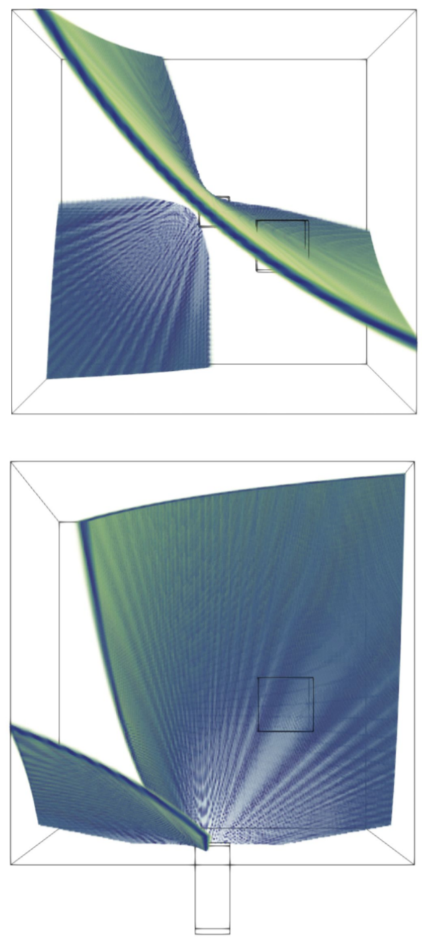
(4b) Experiments

- Interpolation error evaluation,
- Reconstruction of a simulated point source,

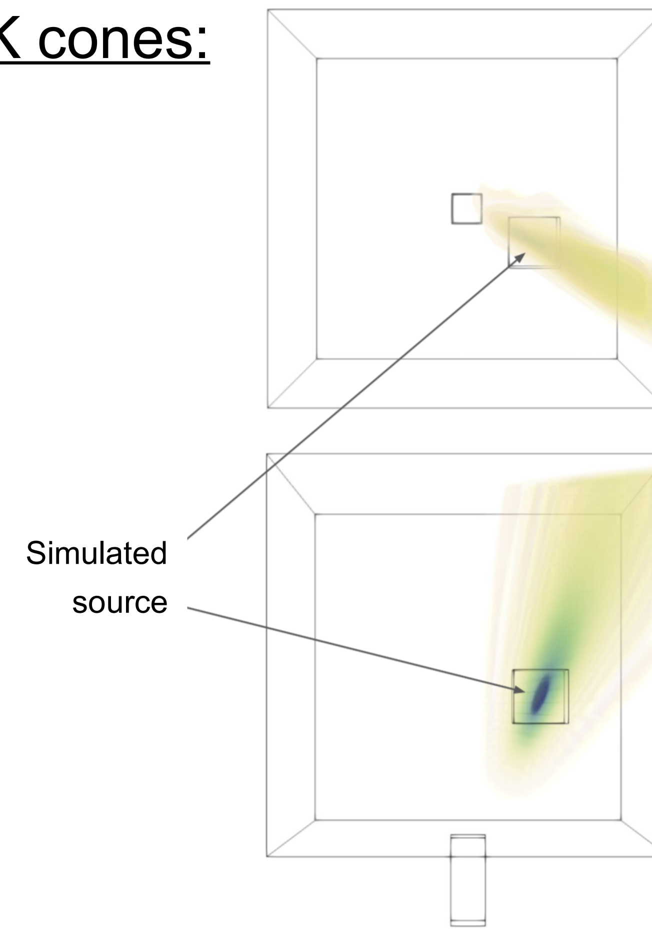
Simulated setup



1 cone:



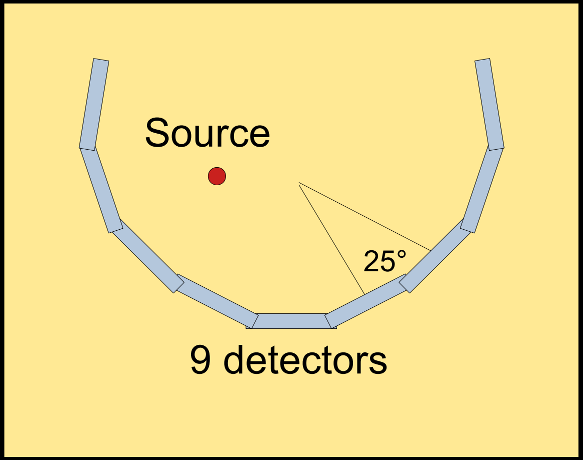
5K cones:

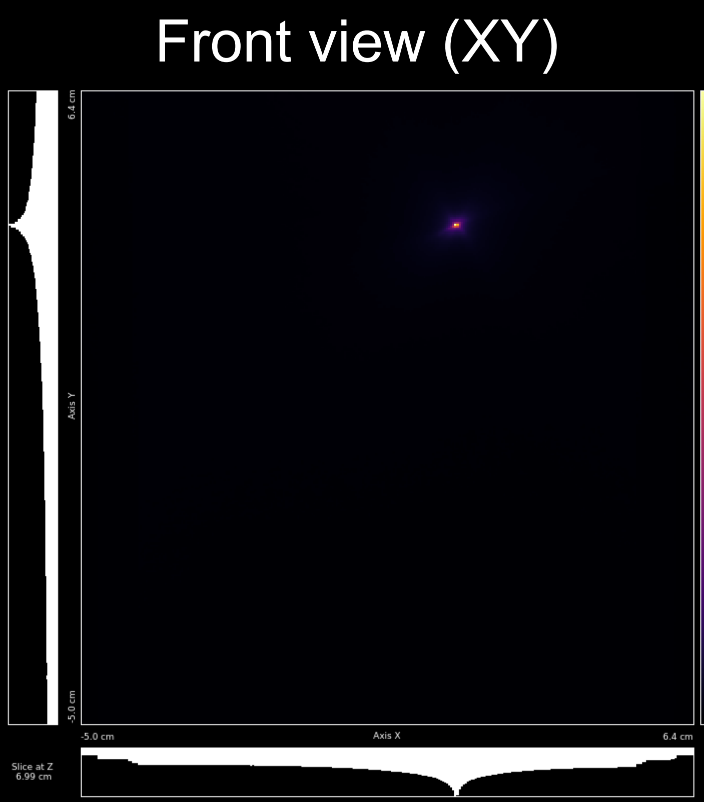


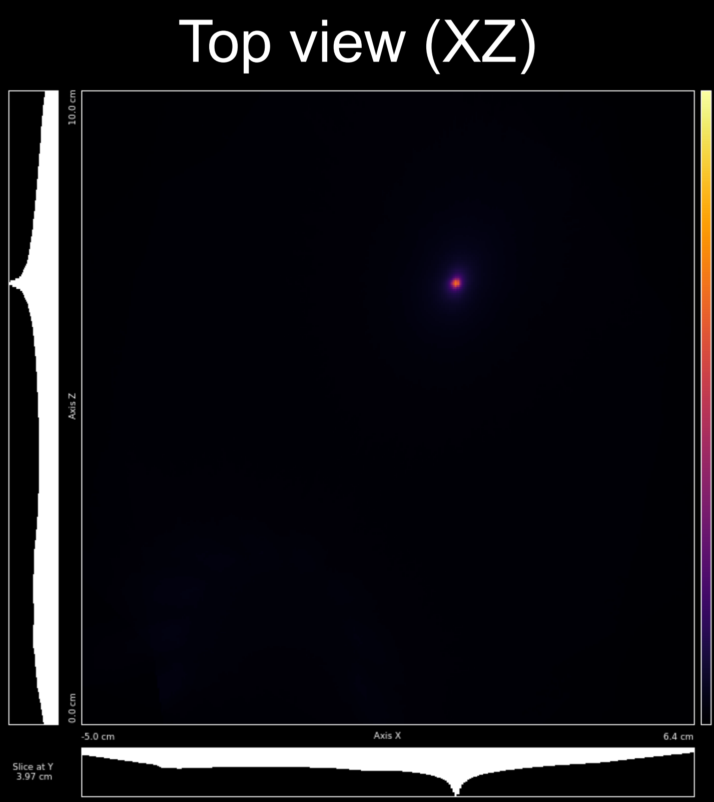
(4c) Experiments

- Interpolation error evaluation,
- Reconstruction of a simulated point source,
- Reconstruction of a simulated point source with multiple viewpoints,

Simulated setup



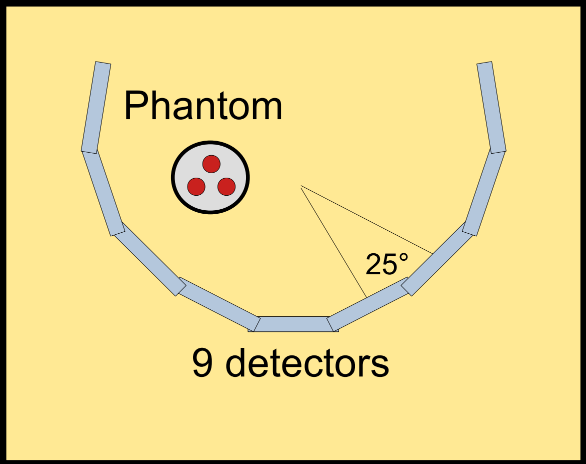




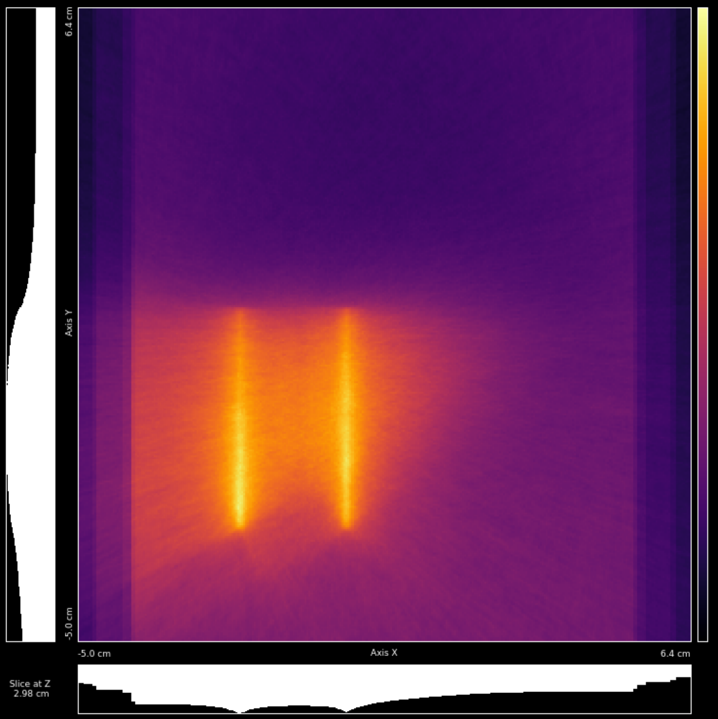
(4d) Experiments

- Interpolation error evaluation,
- Reconstruction of a simulated point source,
- Reconstruction of a simulated point source with multiple viewpoints,
- Reconstruction of a simulated phantom with multiple capilaries,

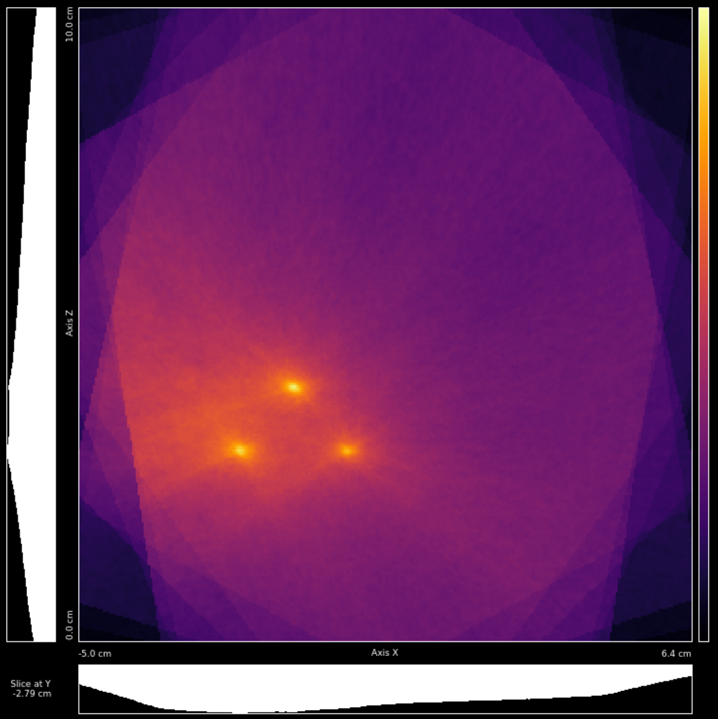
Simulated setup



Front view (XY)



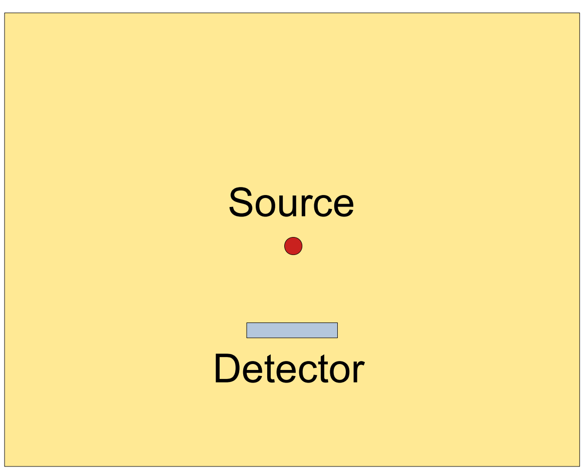
Top view (XZ)

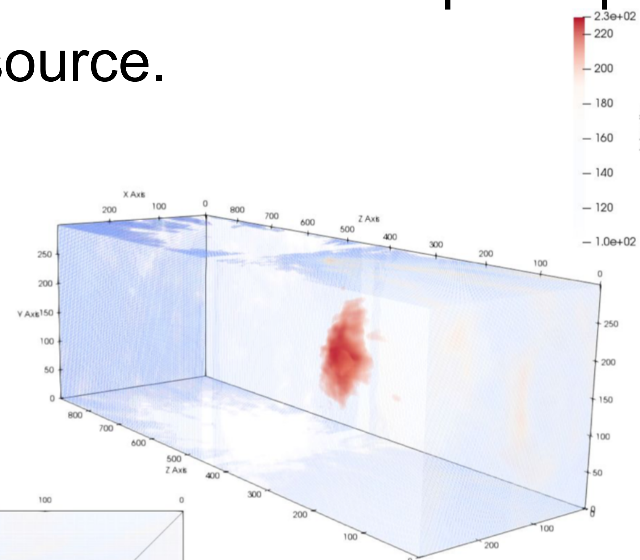


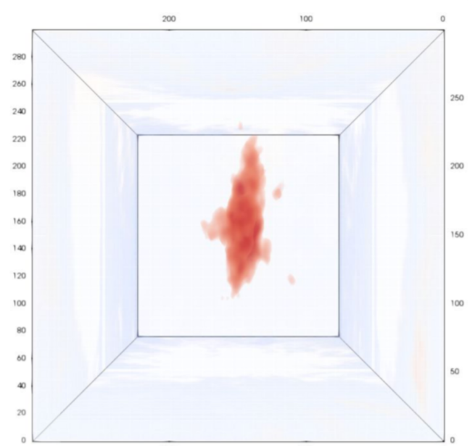
(4e) Experiments

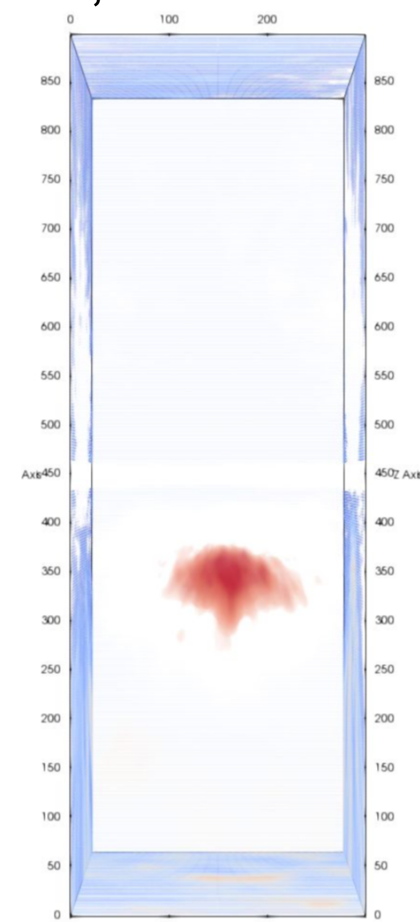
- Interpolation error evaluation,
- Reconstruction of a simulated point source,
- Reconstruction of a simulated point source with multiple viewpoints,
- Reconstruction of a simulated phantom with multiple capilaries,
- Reconstruction of a Am and Tc source.

Measurement setup









Preliminary results

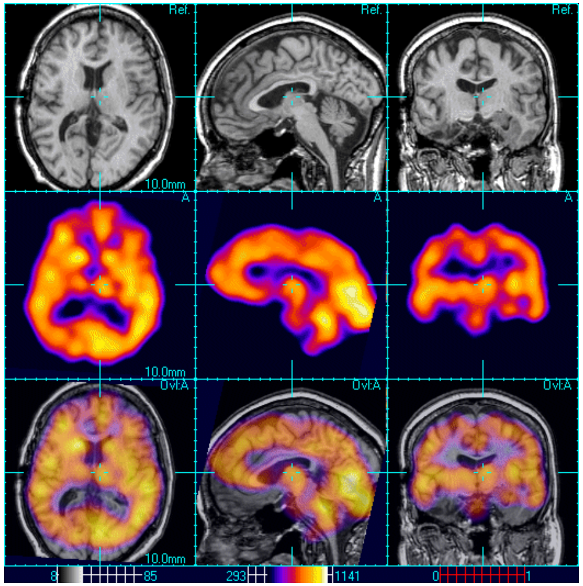
Conclusion

- Proposed novel γ-camera, capable of outperforming state-of-art solutions.
- In the thesis,
  - ➔ New Timepix3 readout SW was created (can be used in other apps.),
  - ➔ Fast reduction and aggregation algorithms were implemented,
  - ➔ 3D image reconstruction algorithms were derived and evaluated,
  - ➔ Multitude of experiments were conducted to verify corectness.

- Autumn 2018:
  - ➔ Constructed prototypes using Si-Si, Si-GaAs detectors,
  - ➔ All SW converted to parallel implementation (CPU i GPU),
  - ➔ Performed basic measurements in Prague and Freiburg.

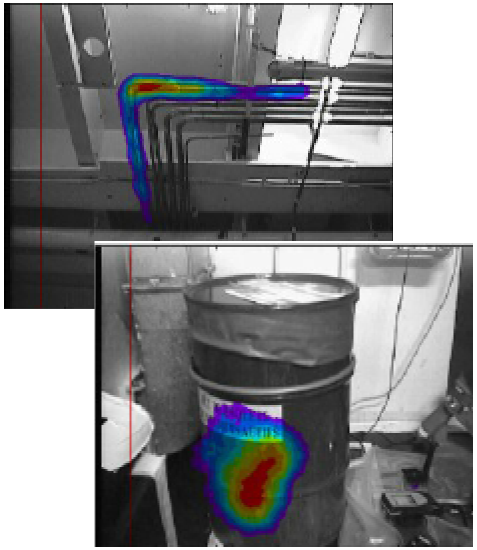
Camera doesn‘t require mechanical collimation → **smaller, lighter, more efficient,**
High energy resolution of Timepix3 → **lower angular error.**

Applications



(1) Medical Imaging (SPECT)
- Source: radioactive contrast material
- Exposure duration ~ damage to patient.

(2) Decontamination
- Source: radioactive material to eliminate
- Lower desired precision (direction is sufficient).



(3) Homeland Security (airports, military, etc.)
- Source: nuclear weapons, fuel, contraband
- Classification task: is the source present?

(4) Quality Control of Nuclear Fuel

Further Work

- Construct Si-CdTe prototype, use more layers, arc configuration
  - ➔ Increase measurement efficiency
- The LM-MLEM algorithm
  - ➔ Decrease time complexity, increase contrast (CNR)
- Benchmark using certified SPECT system
  - ➔ Objective comparison, study of response and resolution
  - ➔ Reconstruction of basic phantoms and small mammals
- Visible image overlay, miniaturization
  - ➔ Handheld measurement probe
- ROS integration for drones
  - ➔ Communication and power management
  - ➔ Autonomous mapping setup (using e.g. SLAM)

Thank you for your attention!

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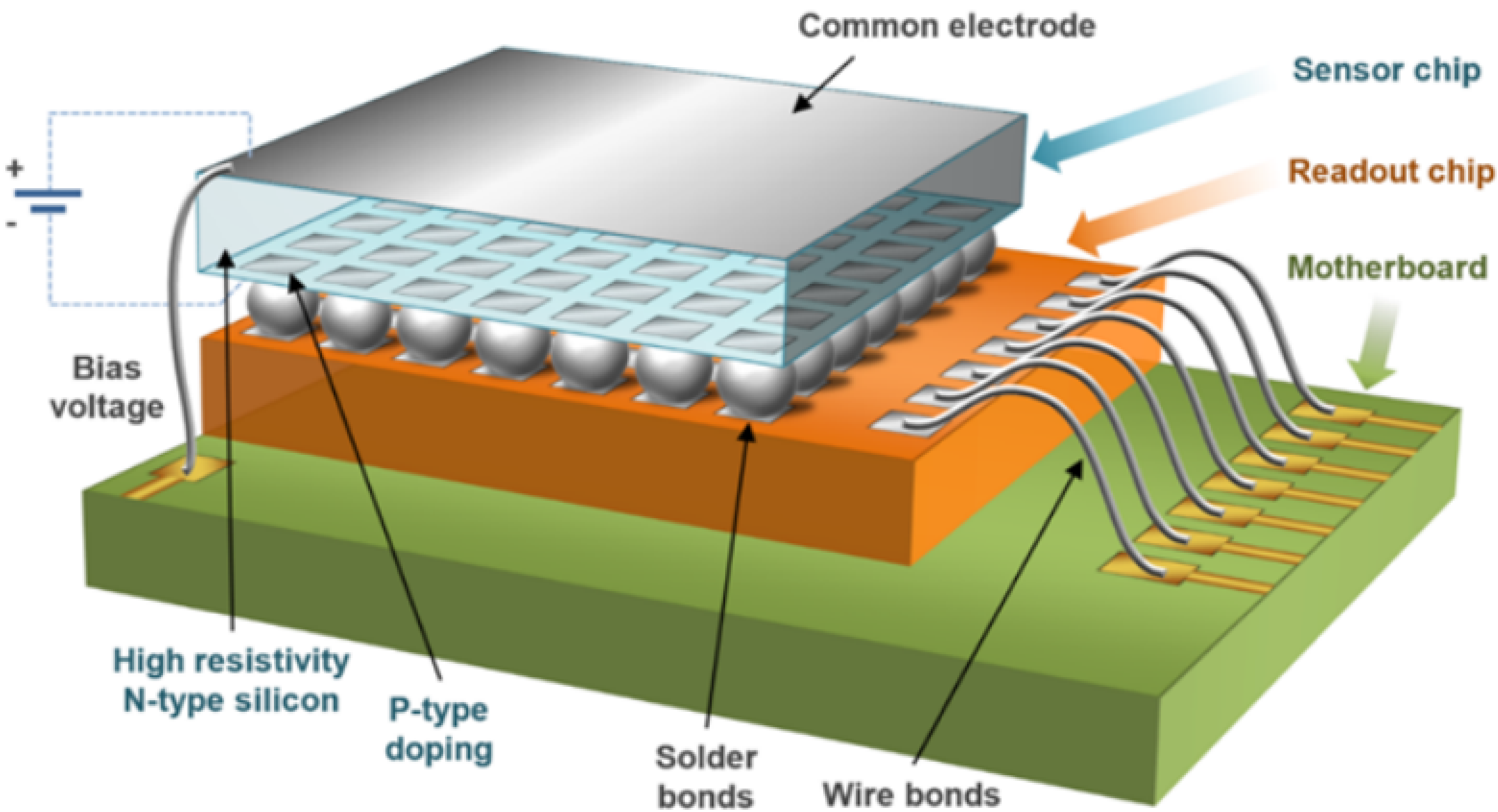
I would like to thank: Martin Pichotka, Benedikt Bergmann,
Moritz Weigt, Petr Burian, Martin Kruliš, Jakub Yaghob

Backup



Common electrode
Sensor chip
Readout chip
Motherboard
+
-
Bias voltage
High resistivity N-type silicon
P-type doping
Solder bonds
Wire bonds

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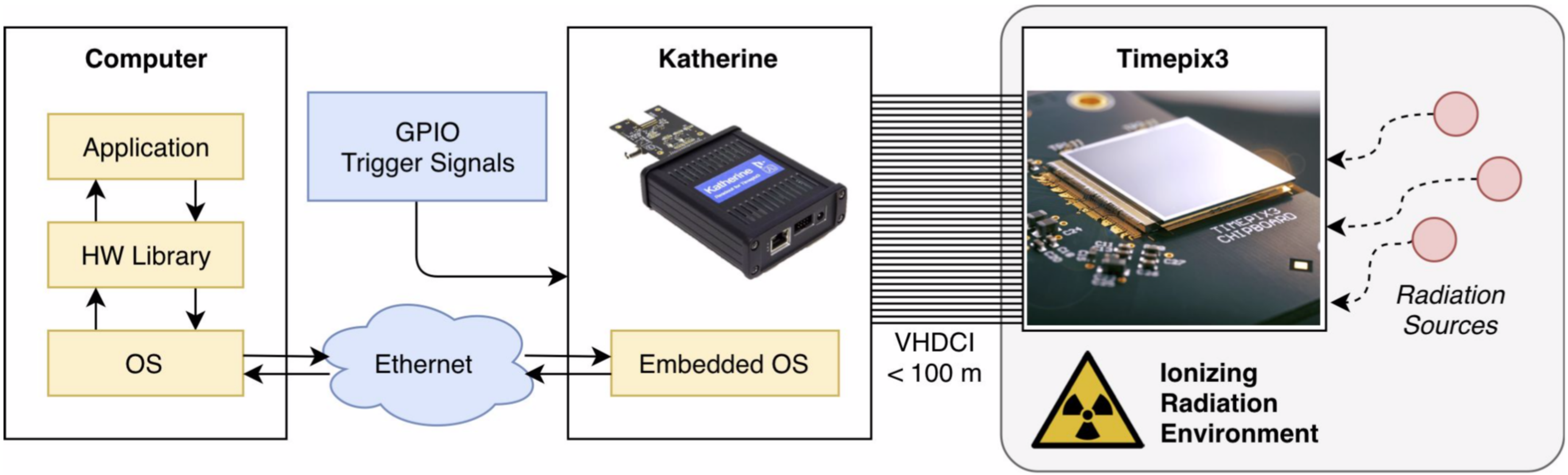

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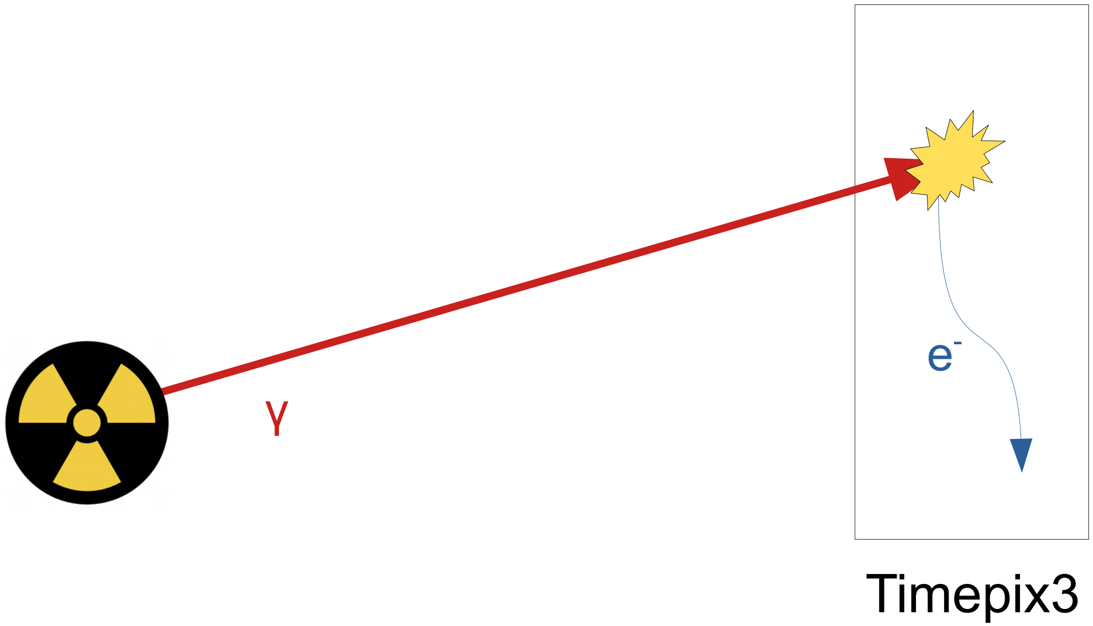

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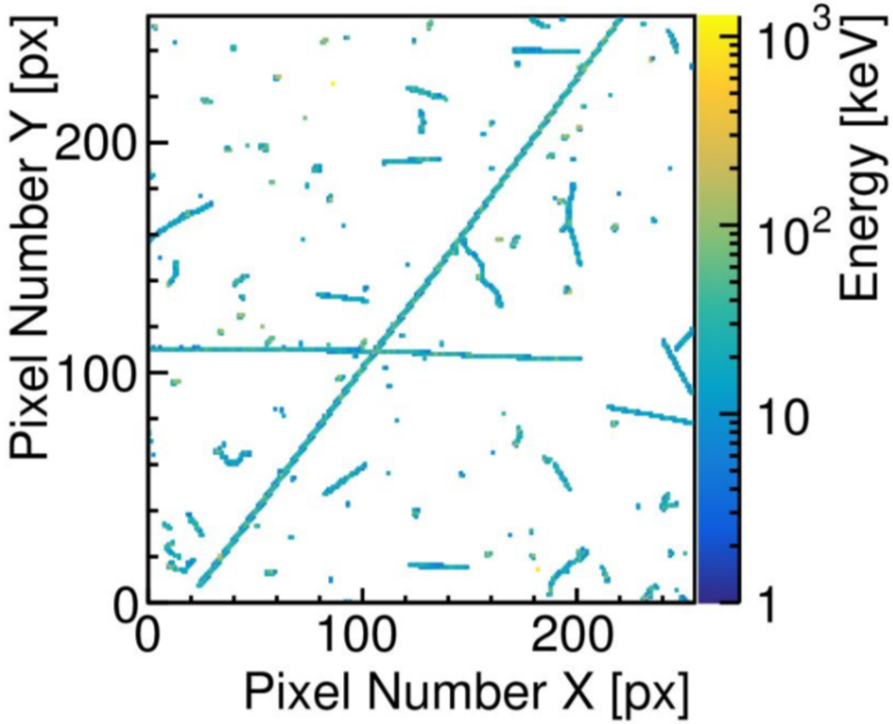
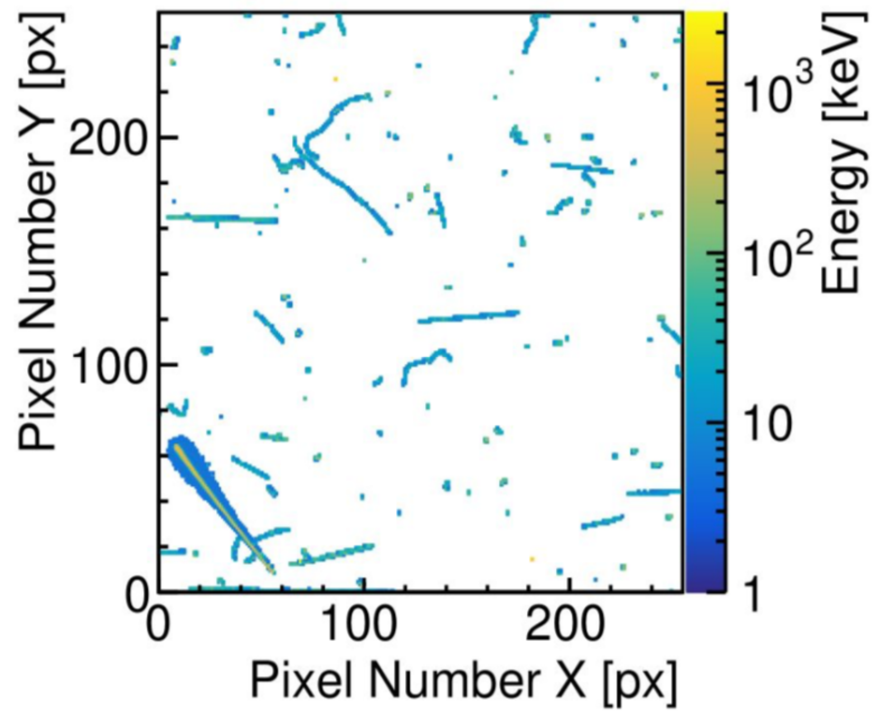

Pixel Number Y [px]
Pixel Number X [px]
Energy [keV]
0
100
200
1
10
10^2
10^3


Pixel Number Y [px]
Pixel Number X [px]
Energy [keV]
0
100
200
1
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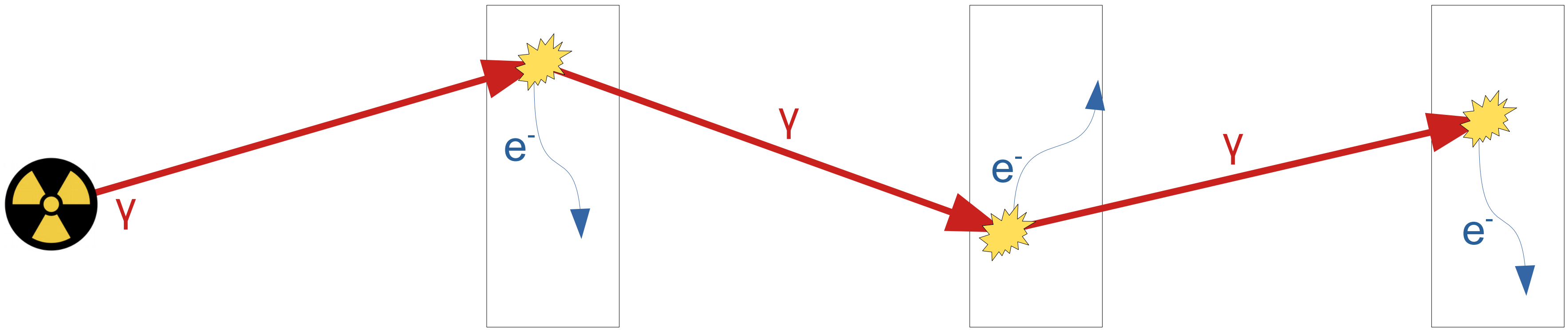
10^2
10^3

Backup



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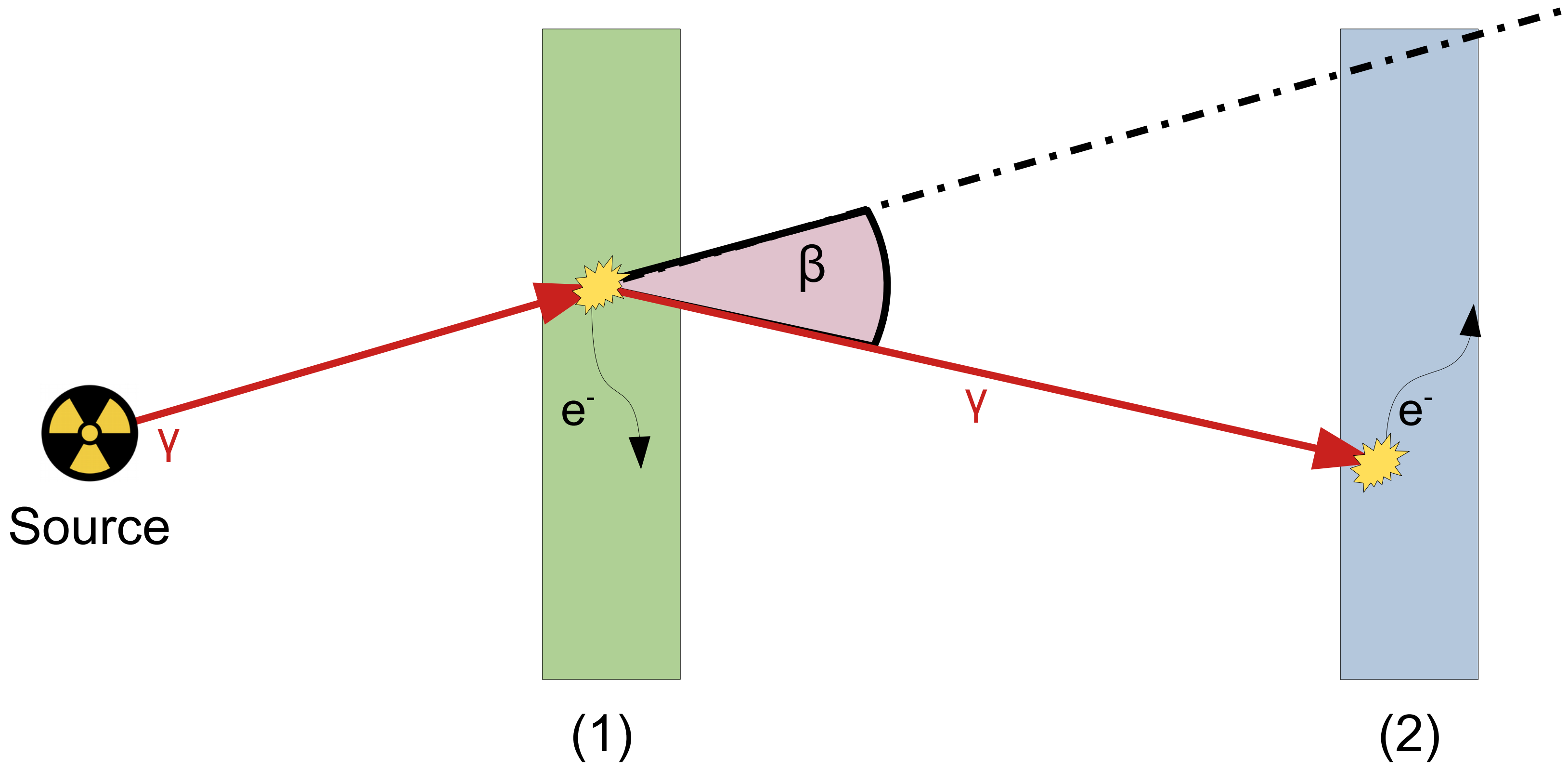

Backup

$$\cos\beta = 1 - m_e c^2 \left(\frac{1}{E'_\gamma} - \frac{1}{E_\gamma} \right)$$

Backup