Report on project

"New semiconductor detectors for fundamental and applied research" (04-2-1126-2015 / 2023)

At this stage of the project, the main task will be to research and create a new generation of energy-sensitive X-ray image detectors.

54th meeting of the PAC for Condensed Matter Physics
28 June 2021

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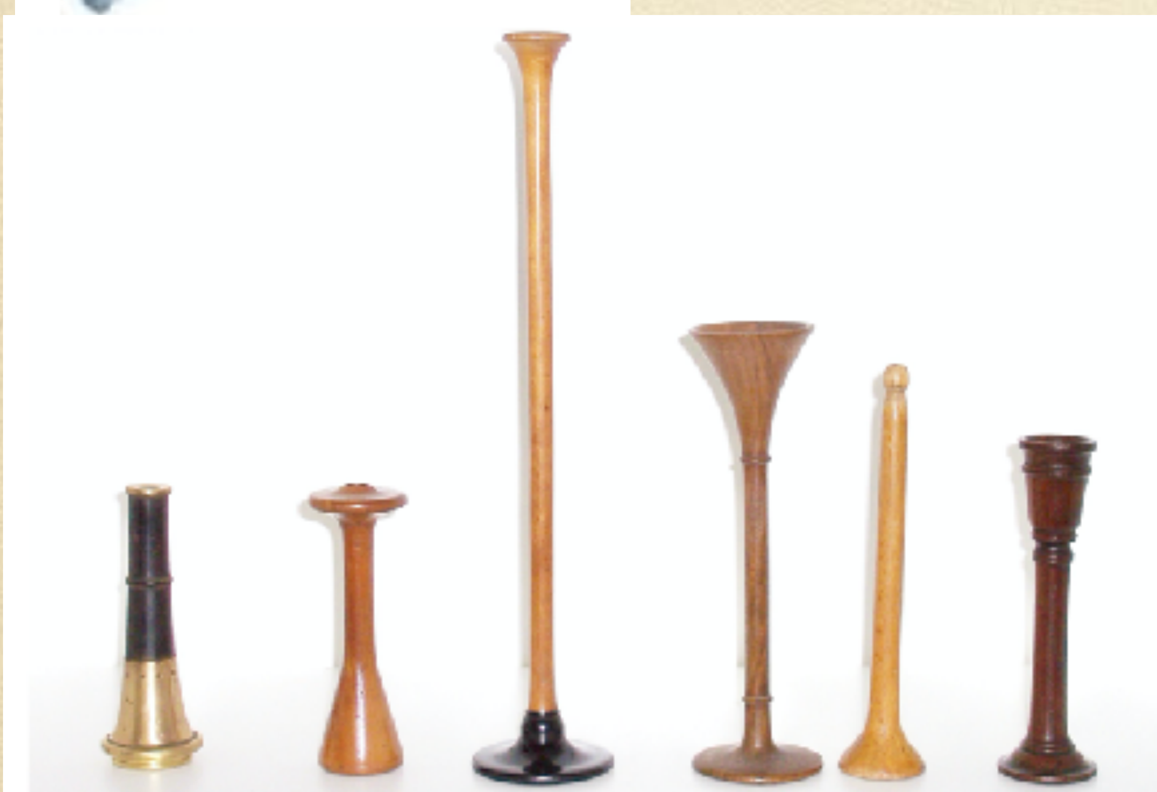
Current state of X-ray tomography (CT) devices

The 21st century will most likely be the century of rapid development of Genetics and Biology.

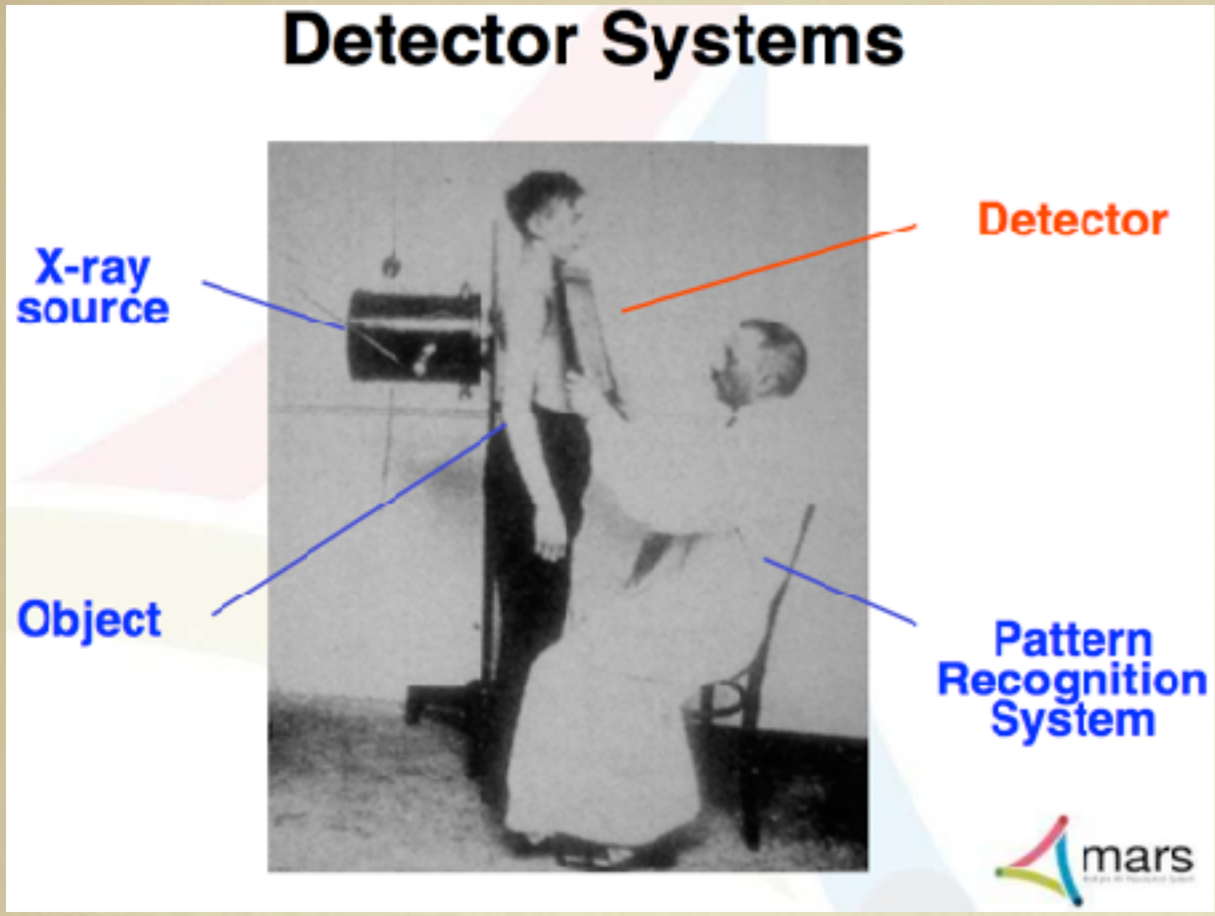
This leap was prepared by the equally rapid development of Physics and Technology in the previous XX century.

The main working tools of physicians and biologists at the beginning of the XX century.



A quick glance at the history of radiography

~ 1900 год



~ 2020 год

About 50 years have passed since the creation of the first CT scanner in 1971.
The schematic diagram remains the same:

- X-ray tube;
- X-ray detector;
- movement mechanics unit;
- data processing system.

In this report, we will discuss the situation with an X-ray image detectors.

What is a modern detector for registration of X-ray

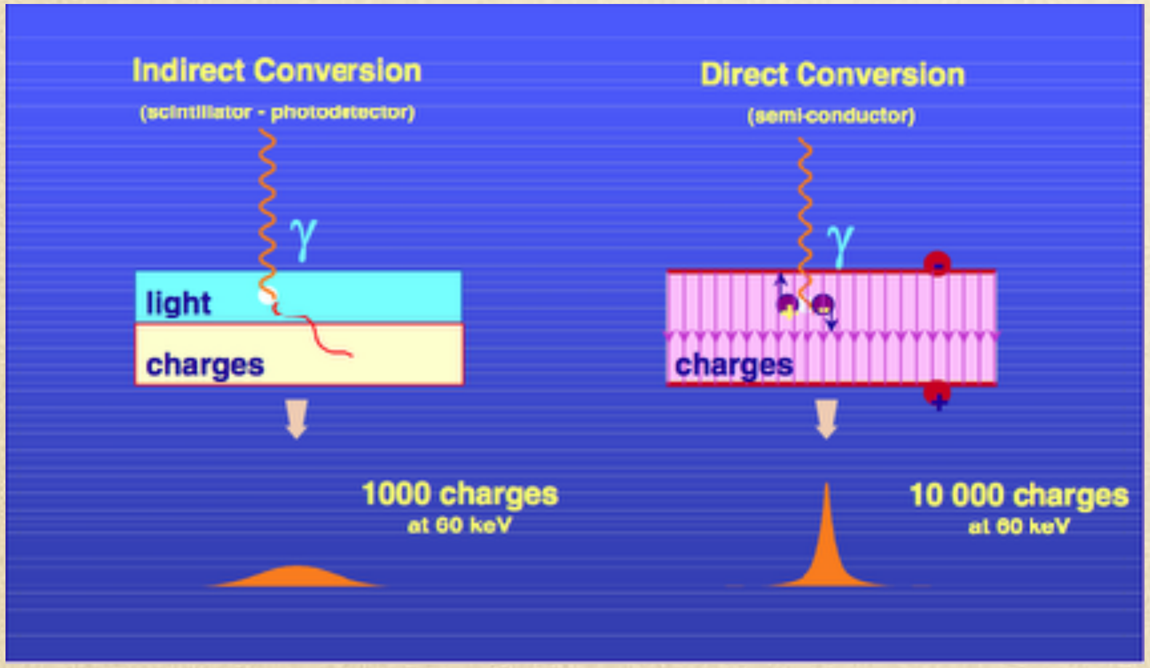
What are the features / difficulties of X-ray image registration?

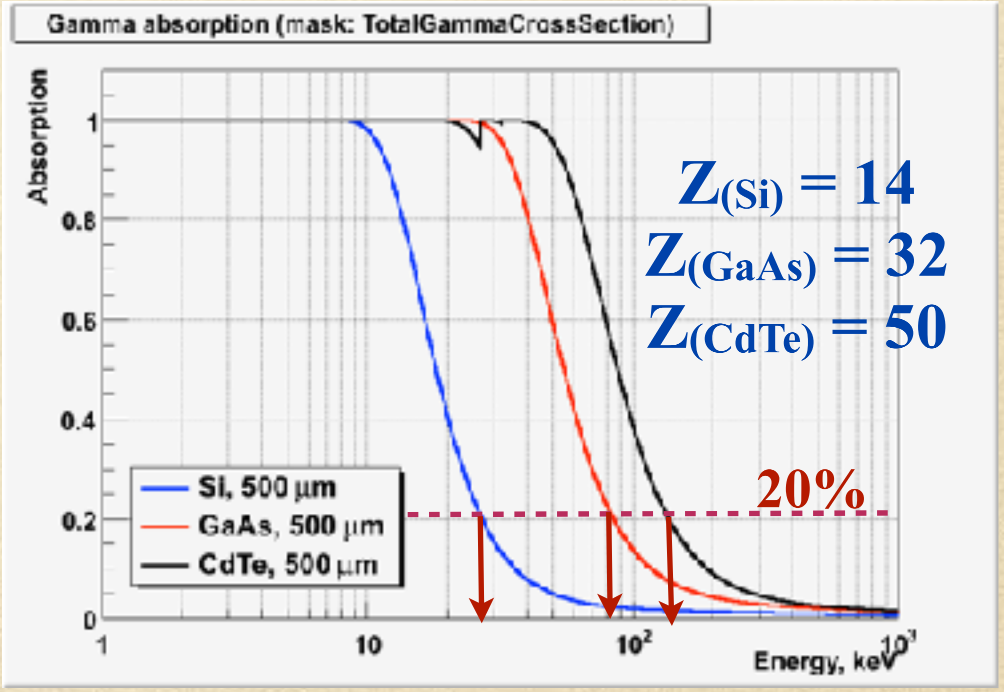
An ideal image detector should be opaque for the type of radiation it detects (black body). That is, to absorb it entirely.

Examples for visible light: the retina of the eye, photographic films, CCD.

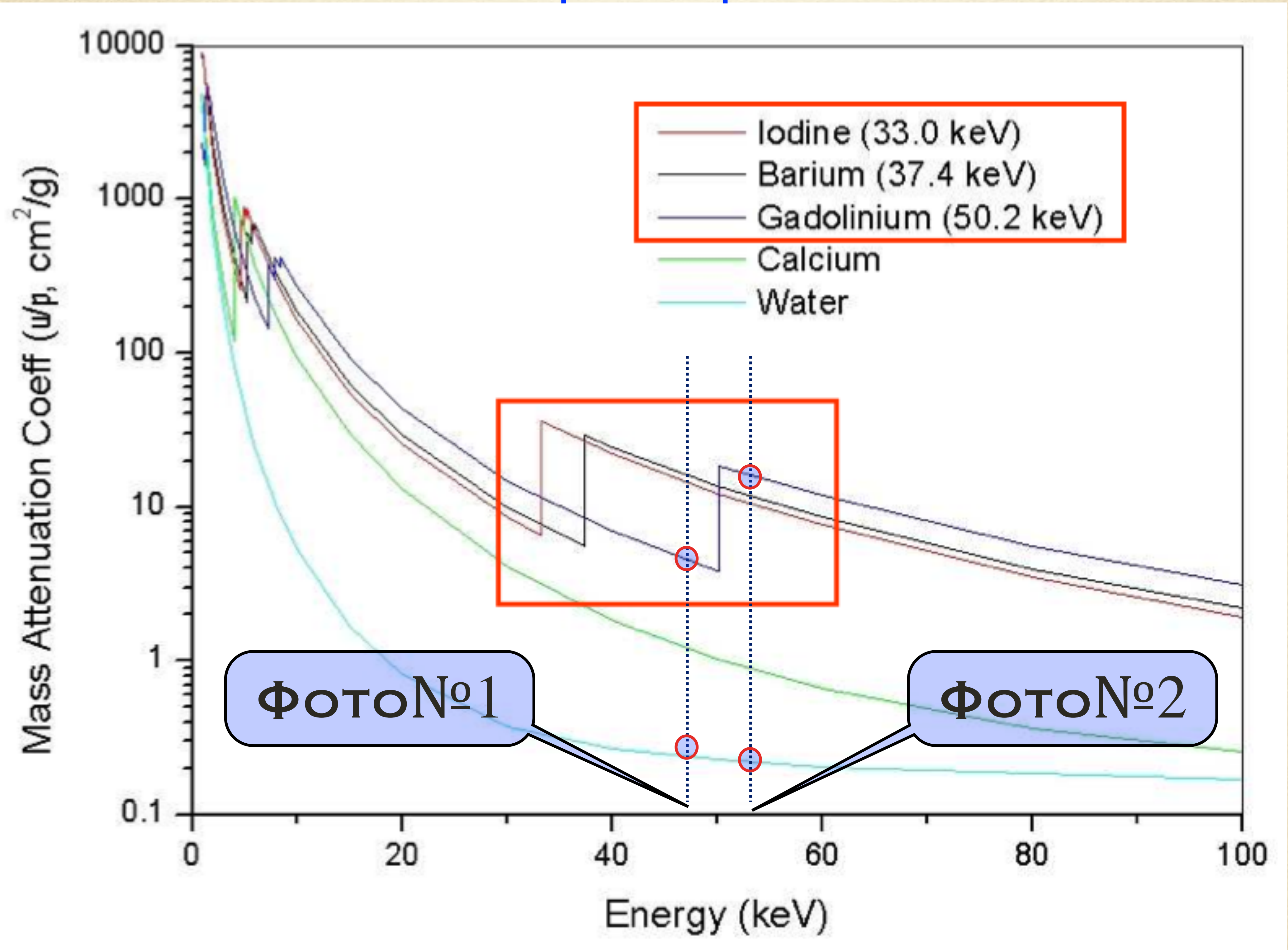
CCD matrices (made from silicon) in modern gadgets.

The problem is that silicon (Si) perfectly absorbs visible light, but is virtually transparent to X-rays.
That is why the currently widespread X-ray image detectors use a two-stage registration principle:
X-rays are converted to light in heavy scintillator crystals (CsJ, …); and this light is detected in Si-based photodetectors.
The main disadvantage of this scheme is that the possibility of measuring the energy of the absorbed X-ray quantum is lost.

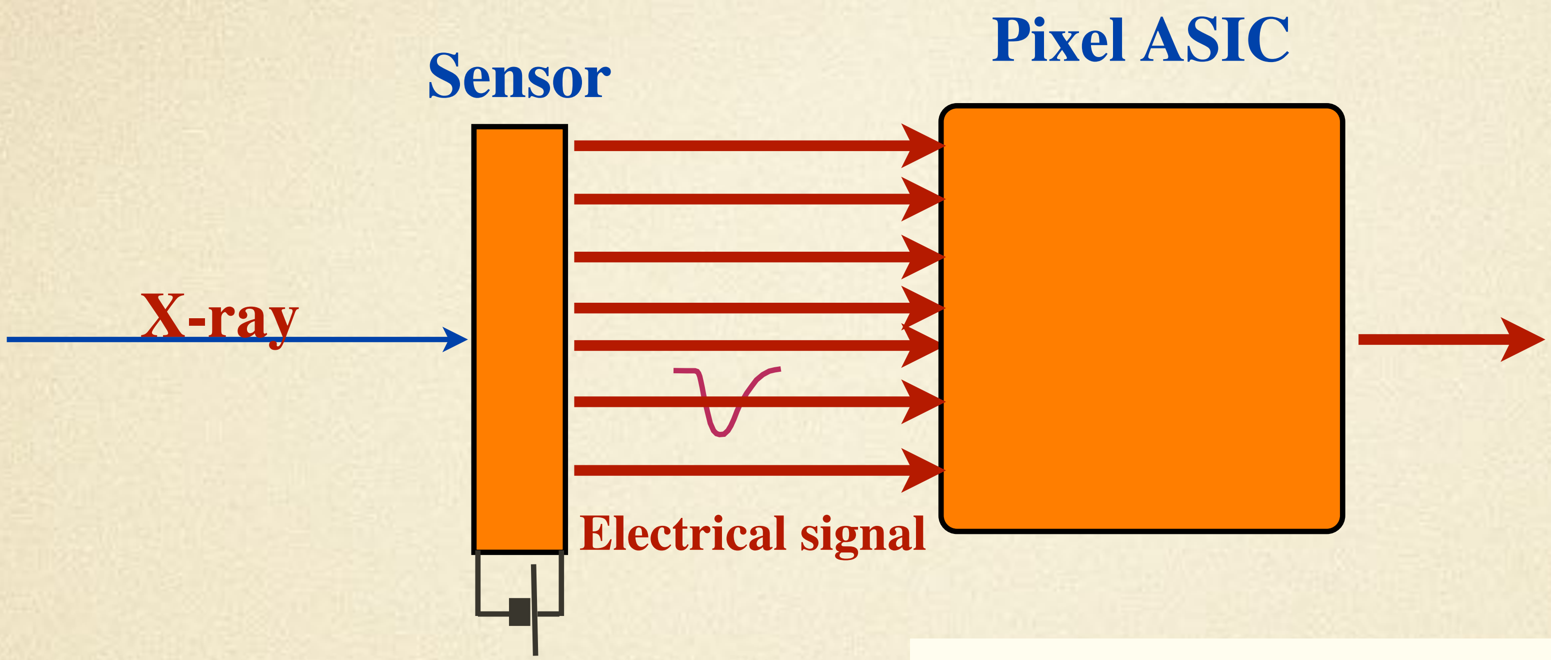


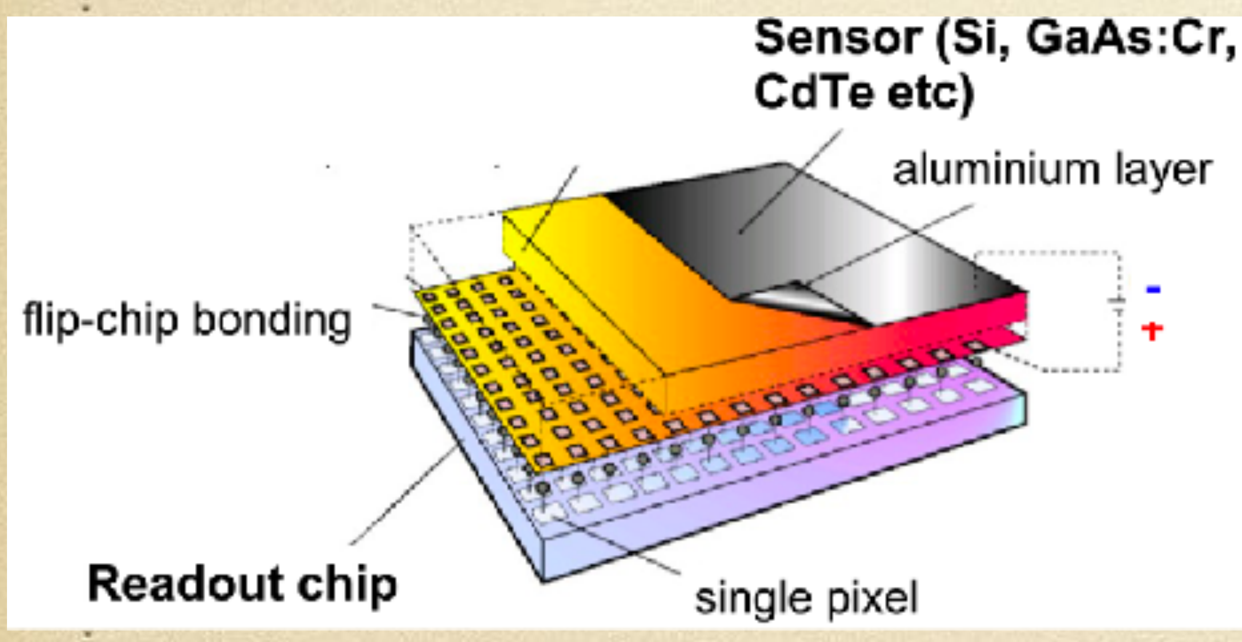


Measurement of the γ-quantum energy provides a unique opportunity to identify a material by the K-line in the X-ray absorption spectrum.

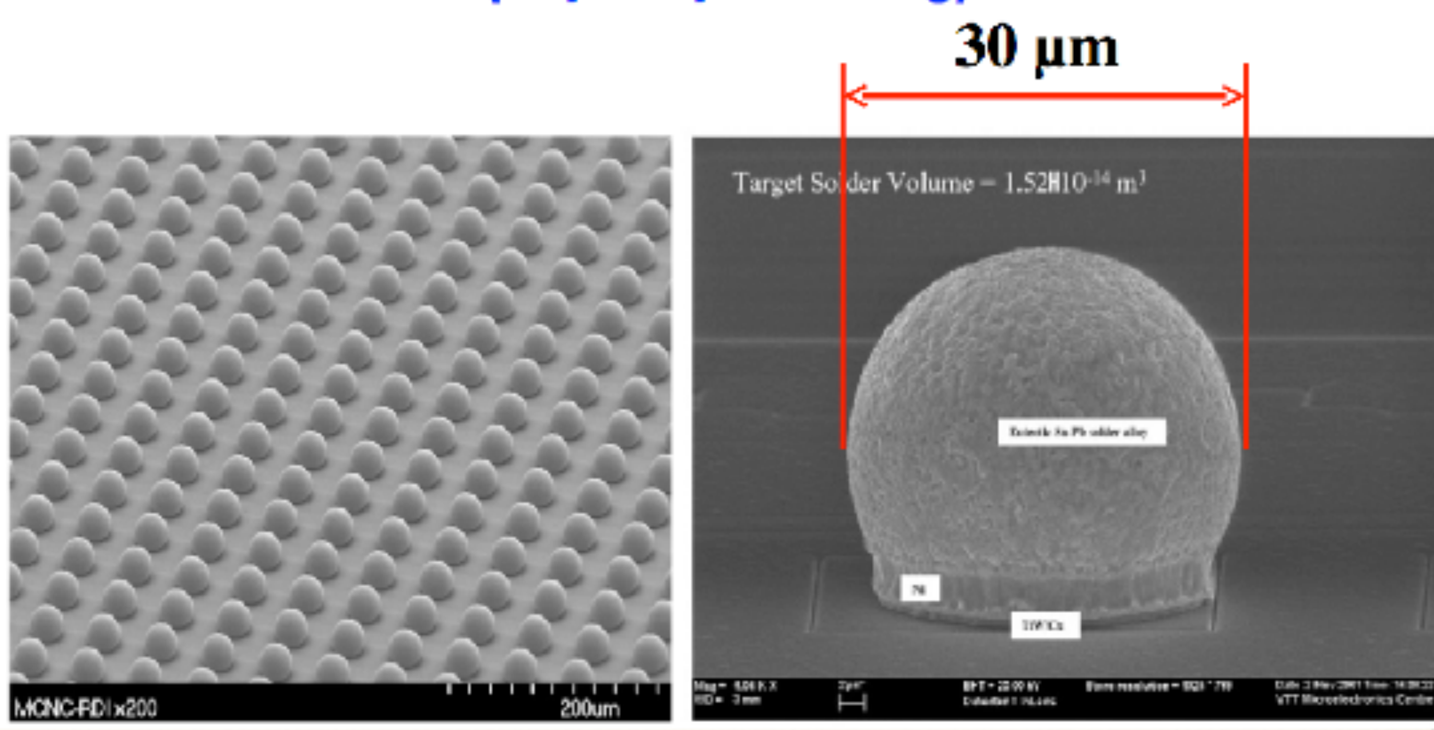


Block diagram of a hybrid pixel semiconductor detector

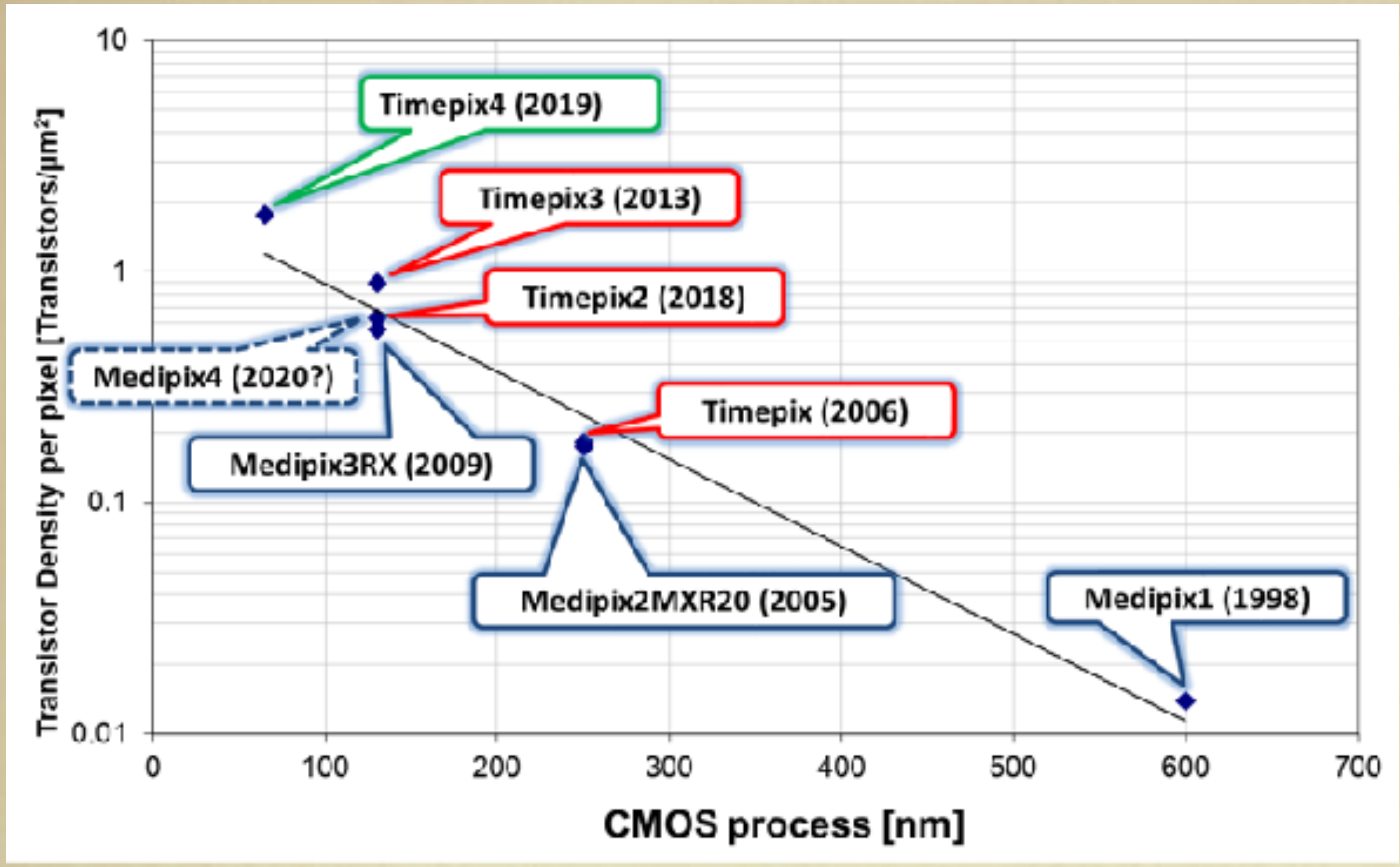




Connecting Sensor Pixels to Readout Chip Pixels
(Flip chip bonding)



The result of 20 years of work of the Medipix collaboration (data of 2019)



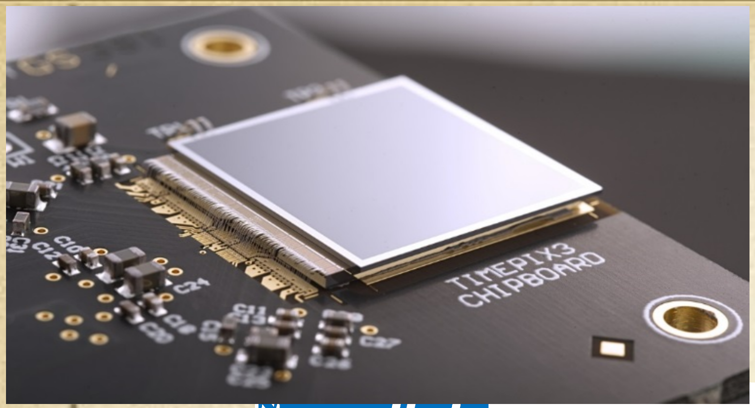
- CEA, Paris, France
- CERN, Geneva, Switzerland,
- DESY-Hamburg, Germany
- Diamond Light Source, Oxfordshire, England, UK
- IEAP, Czech Technical University, Prague, Czech Republic
- JINR, Dubna, Russian Federation
- NIKHEF, Amsterdam, The Netherlands
- University of California, Berkeley, USA
- University of Houston, USA
- University of Maastricht, The Netherlands
- University of Canterbury, New Zealand
- University of Oxford, England, UK
- University of Geneva, Switzerland
- IFAE, Barcelona, Spain
- University of Glasgow, UK

Timepix4: A 4-side tillable large single threshold particle tracking detector chip with improved energy and time resolution and with high-rate imaging capabilities

In 2016, the JINR group paid an entrance fee of 250 kCHF (50% of the JINR budget and 50% of the grant from the Ministry of Science of the Russian Federation) and became a full member of the new collaboration Timepix-4.

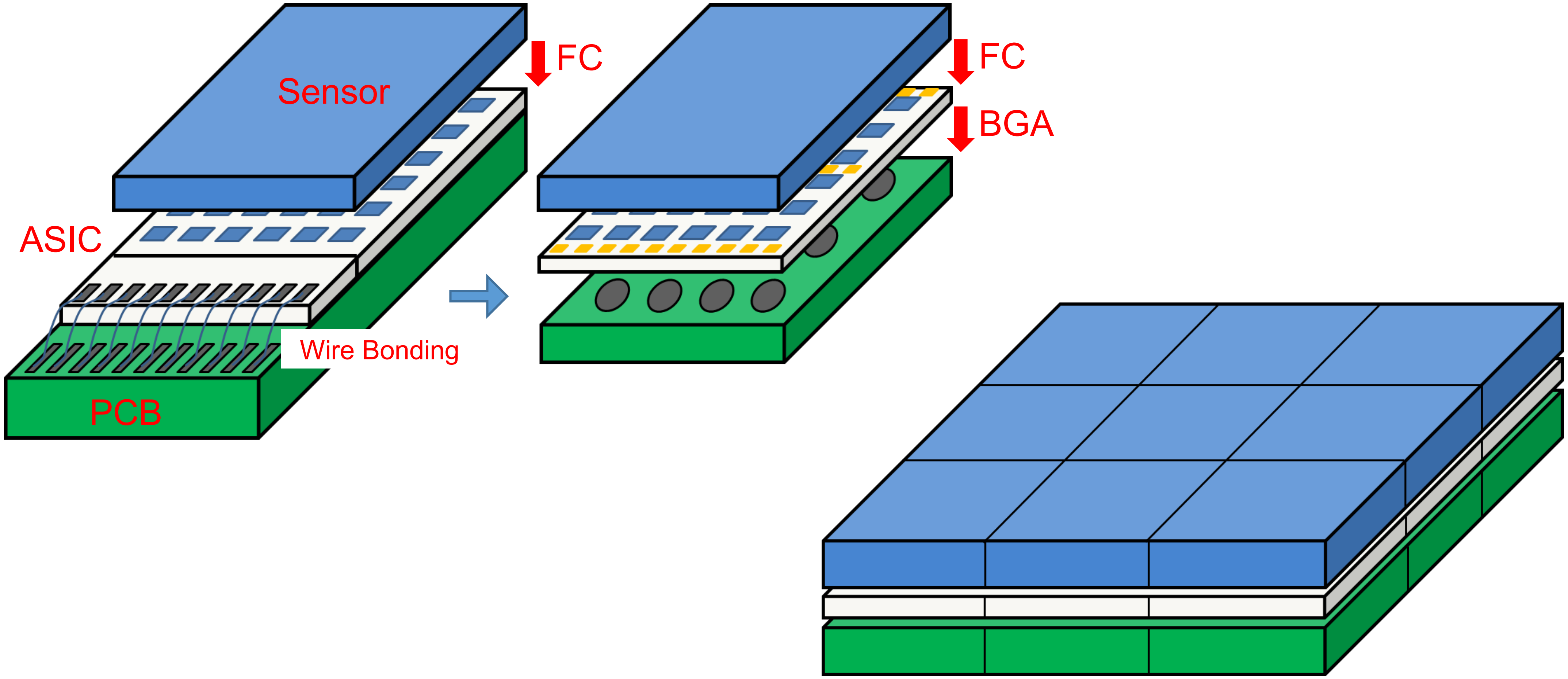
Timepix3 → Timepix4

			Timepix3 (2013)	Timepix4 (2019)	
Technology			130nm – 8 metal	65nm – 10 metal	
Pixel Size			55 x 55 µm	55 x 55 µm	
Pixel arrangement			3-side buttable 256 x 256	4-side buttable 512 x 448	3.5x
Sensitive area			1.98 cm^2	**6.94 cm^2**	
Readout Modes	Data driven (Tracking)	Mode	TOT and TOA		
		Event Packet	48-bit	64-bit	33%
		Max rate	0.43×10^6 hits/mm^2/s	**3.58×10^6 hits/mm^2/s**	8x
		Max Pix rate	1.3 KHz/pixel	**10.8 KHz/pixel**	
	Frame based (Imaging)	Mode	PC (10-bit) and iTOT (14-bit)	CRW: PC (8 or 16-bit)	
		Frame	Zero-suppressed (with pixel addr)	Full Frame (without pixel addr)	
		Max count rate	~0.82 x 10^9 hits/mm^2/s	~5 x 10^9 hits/mm^2/s	5x
TOT energy resolution			< 2KeV	**< 1Kev**	2x
TOA binning resolution			1.56ns	**195ps**	8x
TOA dynamic range			409.6 µs (14-bits @ 40MHz)	**1.6384 ms** (16-bits @ 40MHz)	4x
Readout bandwidth			≤5.12Gb (8x SLVS@640 Mbps)	**≤163.84 Gbps (16x @10.24 Gbps)**	32x
Target global minimum threshold			<500 e^-	<500 e^-	



Assembly of large area Timepix4 detectors

4-side buttable pixel arrangement



- Target to build **large area detectors** by combining smaller modules
- The through-silicon vias (TSVs) is the key technology for this paradigm shift

The main advantages of using Medipix type detectors in radiography.

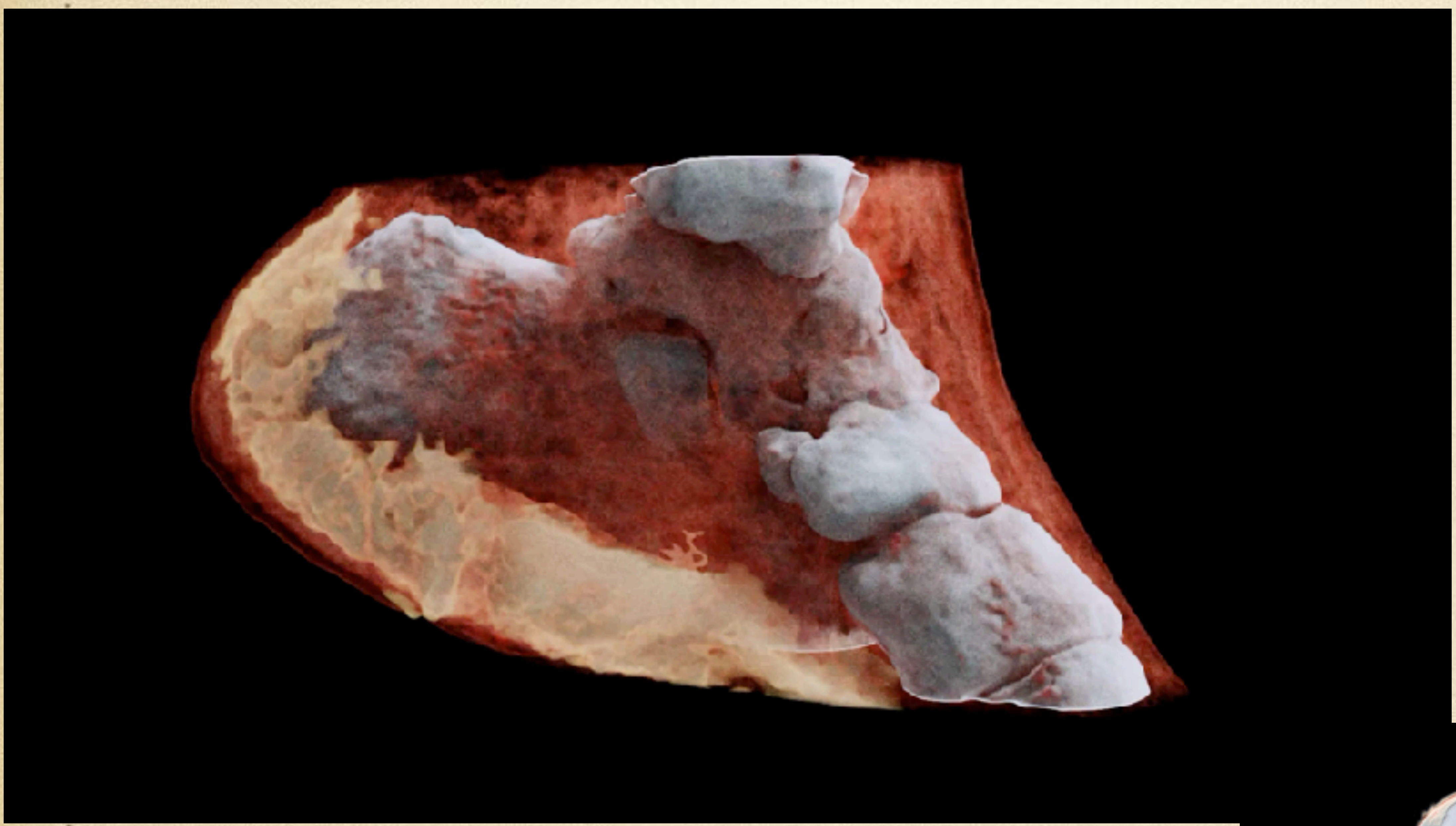
1. High efficiency of registration of γ-quanta (due to direct conversion γ -> e)

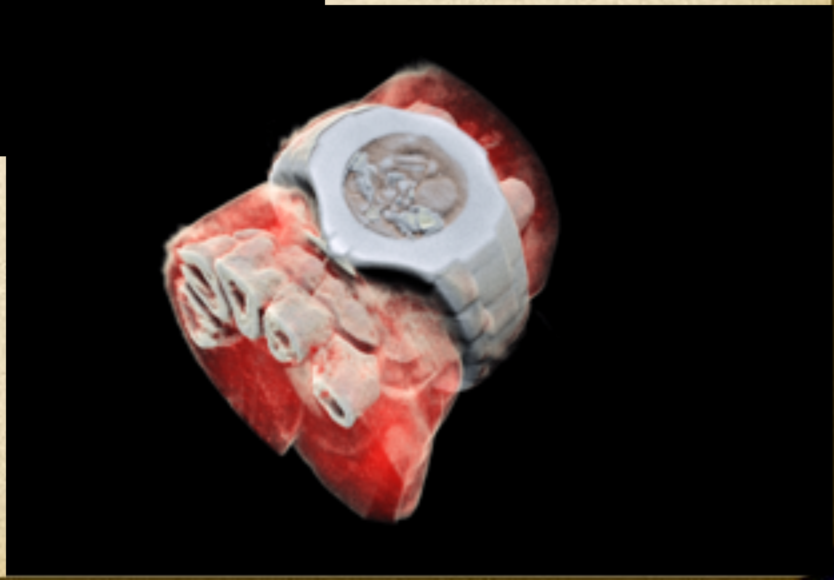
2. Low noise (Single Photon Counting) -> higher sharpness and contrast while maintaining radiation exposure -> higher image quality.

3. High spatial resolution (~ 60μm)

4. The ability to measure the energy of γ-quanta makes it possible to identify substances and contrasts.

Human foot CT obtained from the first full-scale tomograph with Medipix3-RX ASIC at Crischurch University in New Zealand.





JINR group has been actively cooperating with the MEDIPIX collaboration since ~ 2008.

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Characterisation of a GaAs(Cr) Medipix2 hybrid pixel detector

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The JINR group took part in the development of the terms of reference for the new MEDIPIX-4 microcircuit and became a full member of this collaboration since 2016.

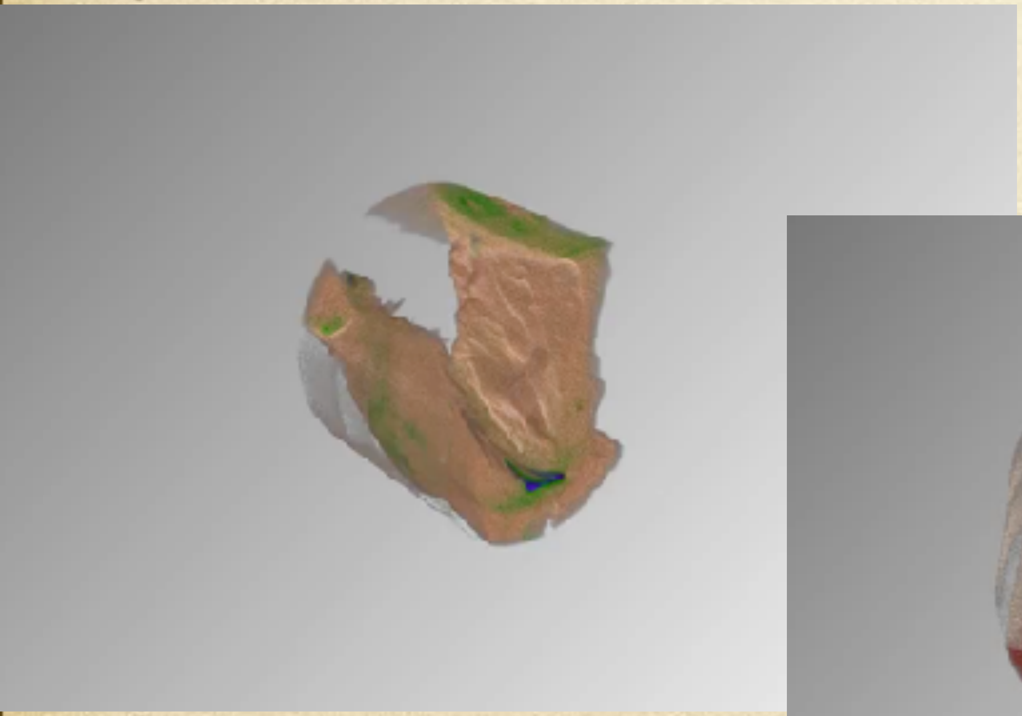
Only now we got access to all the documentation needed to develop our own devices using MEDIPIX-4

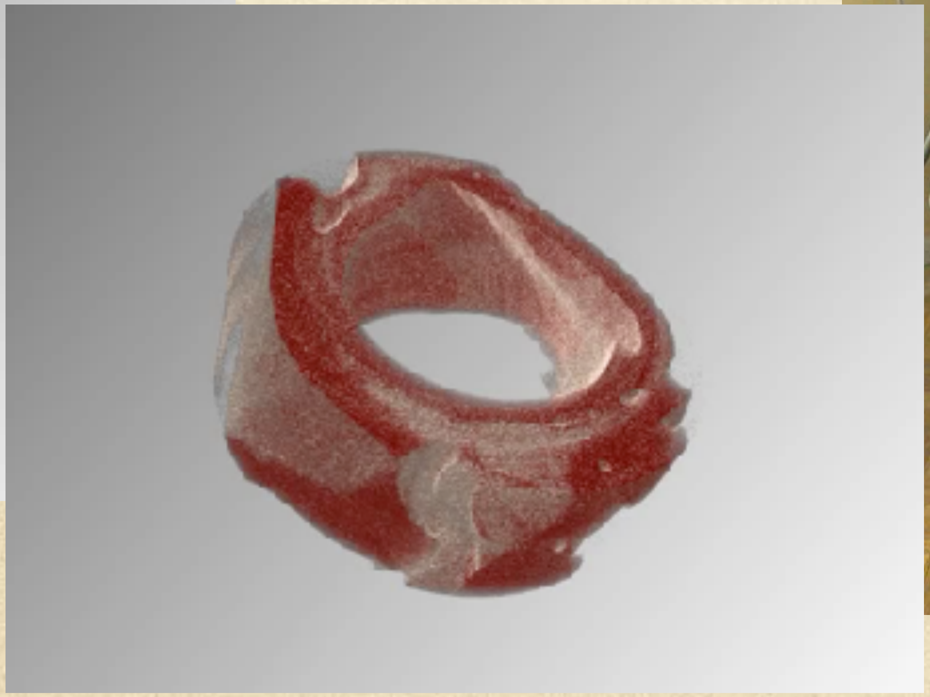
Timepix detectors with GaAs: Cr sensor, <u>purchased</u> by JINR.

In 2013, the JINR group bought a MARS μ-tomograph from our colleagues from New Zealand, mastered the scanning and processing technology and gained significant experience in scanning mice, medical and geological samples.

Based on the materials of this research, two Ph.D. theses were successfully defended.

At the moment, an agreement has been reached to create a joint group with MIPT and Moscow State University at the Faculty of Molecular and Biological Physics of MIPT for more efficient use of the equipment available to these groups (CT and MRI μ-tomographs).

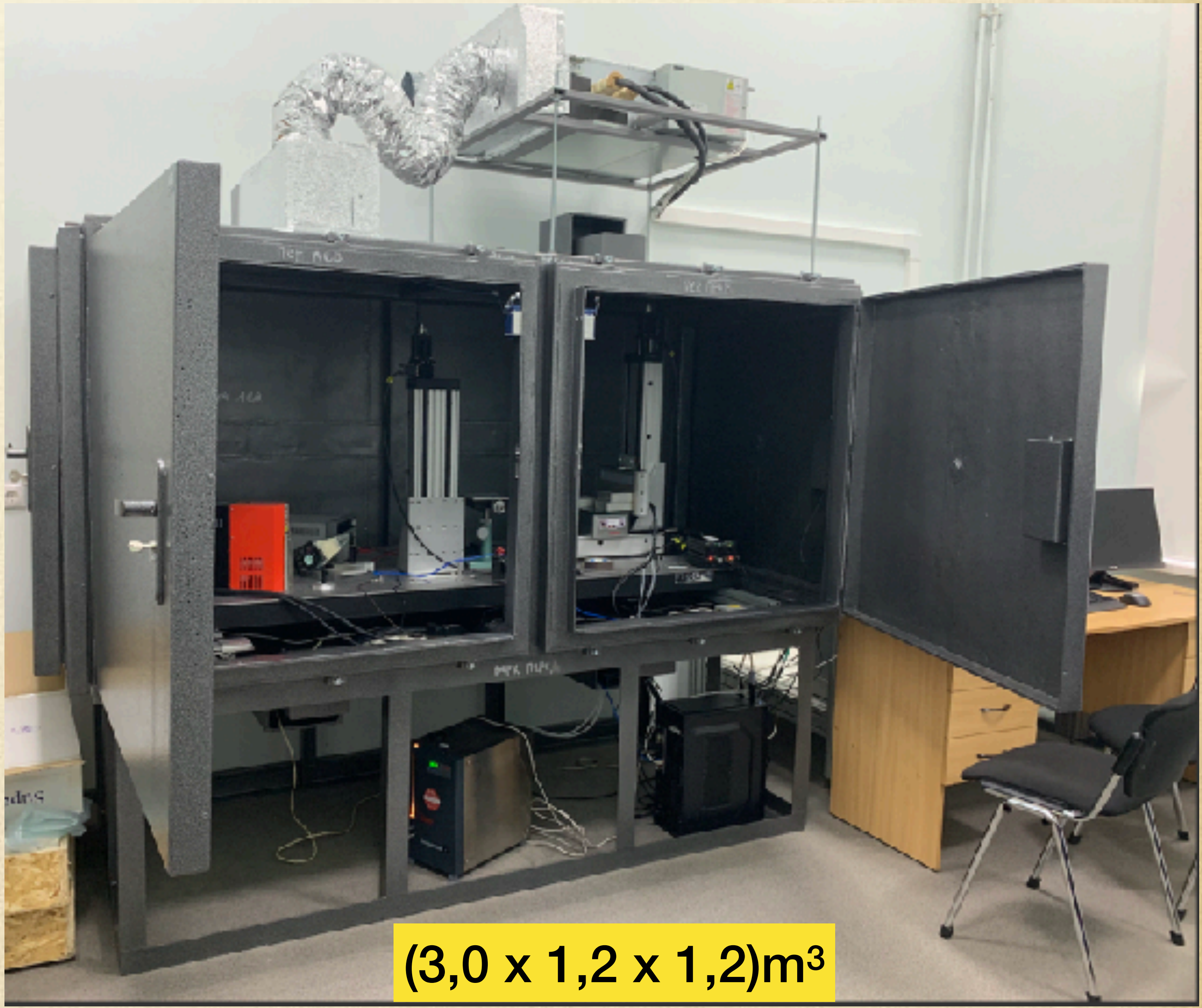




Work plans in 2021-2023

A Kalan-4 μ-tomograph with a rotating sample (without a gantry) was created to carry out research work in the field of multi-energy CT at the NEOVP DLNP.

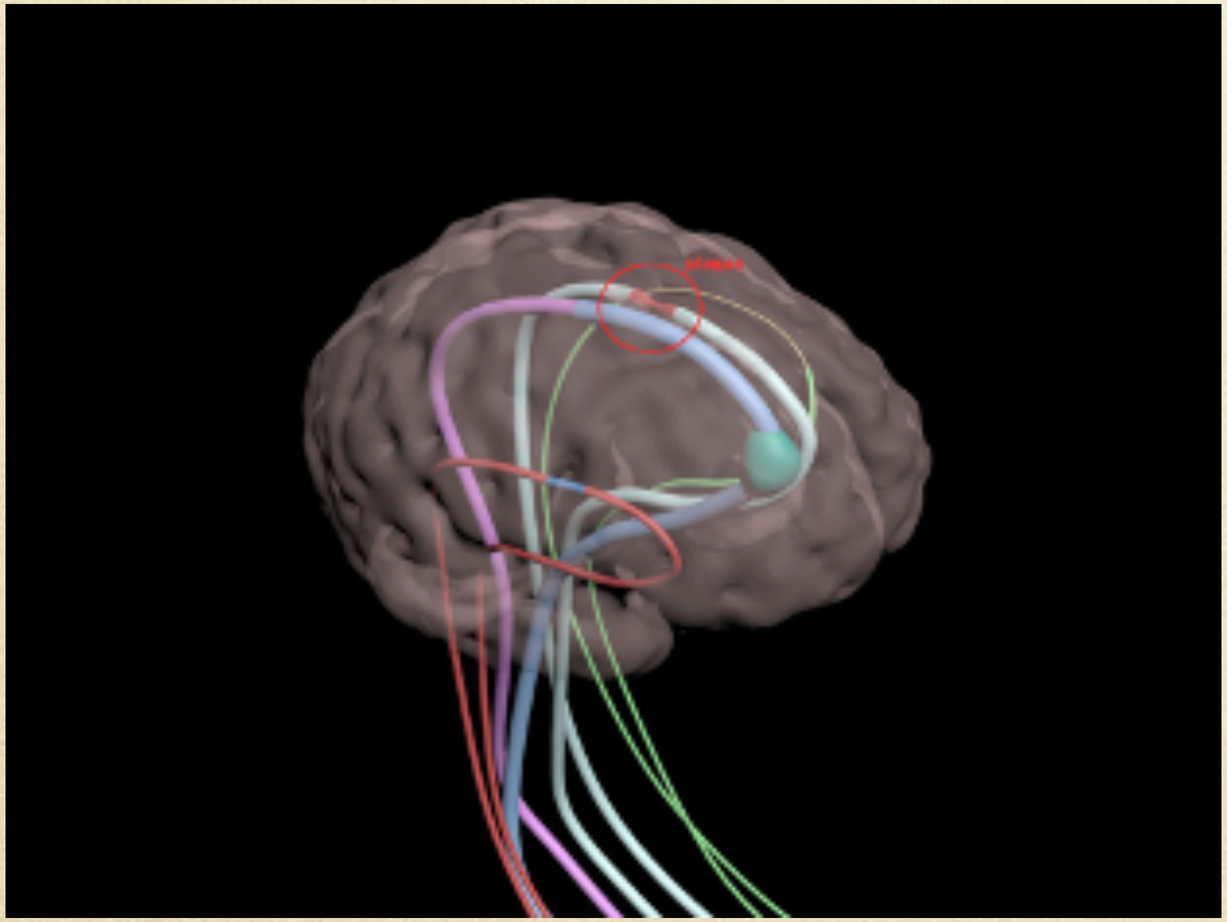
Such a scheme provides more opportunities for R&D and the implementation of various types of CT: the use of various X-ray tubes, detectors, changes in the geometric magnification.



After the hardware configuration is complete the main tasks will be:

- **creation of our own program for conducting and restoring 3D CT;**
- **creation of a working laboratory sample of the “head” CT scan.**

For this purpose, a phantom of a human head was purchased with built-in “vessels” of various diameters (from 0.5 to 5) mm.



Conclusion

- A new generation of X-ray image detectors is being developed in many countries around the world.
- The key task is to create pixel detectors based on ASIC capable of measuring the energy of each individual γ-quantum.
- The most advanced ASIC in which these requirements are implemented are being developed by the international Medipix collaboration.
- JINR is the full member of the Medipix4 collaboration and has experience and all necessary information to create new devices using these ASIC.

Cost estimates for the Project

For the program implementation in 2021-2023 the next JINR resources are needed:

- 180 k$ - the TPX4 chips purchase, creation of detector prototypes, conclusion of contracts to carry out R&D works.
- 110 k$ - creation of working prototype of the “head” scanner, computing infrastructure.
- 200 k$ - microfocus X-ray tube, microfocus scanner prototype.
- 40 k$ - measuring equipment.
- 60 k$ - semiconductor sensors.
- 90 K$ - participation in test beams, meetings and conferences.

———————

Sum 680 k$

Thanks for your attention.