Application of pixel detectors

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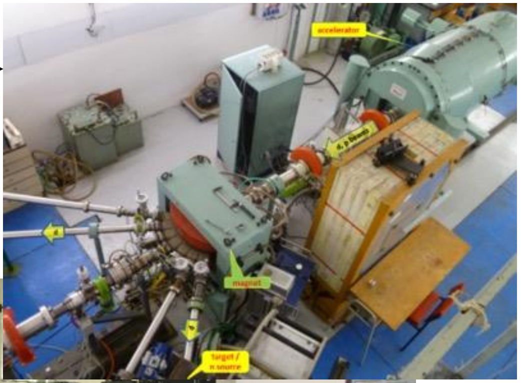
Main scientific programs in IEAP CTU:

- research infrastructure
- accelerator particle physics
- neutrino physics
- astroparticle physics
- applied nuclear spectroscopy
- R&D of detectors techniques

- applications of semiconductor pixel detectors

Research infrastructure of IEAP

- Van de Graaff accelerator



- Underground laboratory LSM in Modane, France
- Small underground laboratory in Prague in a nuclear shelter
- 2 electron microscopes
- Laboratory for high-resolution X-ray radiography, 3D X-ray tomography and neutronography in IEAP,

- Specialized laboratory for experimental imaging – common laboratory of IEAP and 3rd faculty of medicine of CU

- Radon laboratory (ultrasensitive measurement, radon-free chambers) – common laboratory of IEAP and the National Radiation Protection Institute;
- Tunable electron source and equipment for scintillators measurements – common laboratory of IEAP and the Nuvia company.

Research subjects:

(1) **LHC at CERN** – experiments ATLAS (shielding, ATLAS TPX – radiation field measurement, luminosity monitoring, theory, data processing), MoEDAL

(2) **Neutrino physics** – 2νEC/EC decay of ^{106}Cd (experiment TGV), detection of 0ν and 2νββ decay of ^{82}Se (experiment SuperNEMO), experiment LEGEND (USA/Germany – 0νββ decay of ^{76}Ge); detection of atmospheric neutrinos in experiment Baikal Gigaton Volume Detector (Baikal-GVD); detection of reactor antineutrinos in the nuclear power plant in Kalinin

(3) **Detection of dark matter** – experiment PICO in SNOLAB (Canada), detection of neutralino

(4) **Detection of high-energy cosmic rays** – detection of radiation from universe (6 Timepix detectors on ISS, NASA; Timepix detector on satellite Proba-V; future mission of RISESAT satellite; small unit VZLUSat), experiment GROND (γ ray burst, cooperation with MPI Germany, in Chile), experiment CZELTA (secondary cosmic rays, outreach, cooperation with secondary schools)

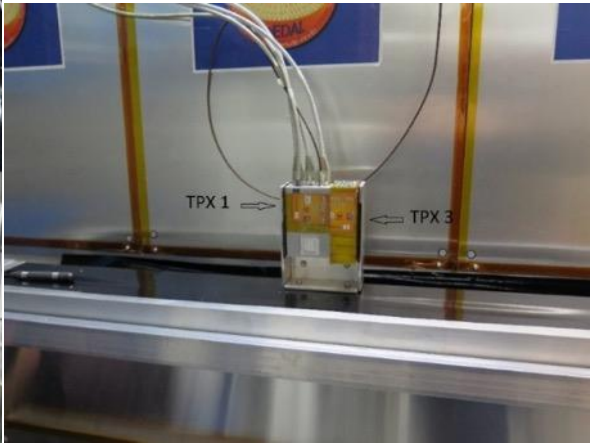
(5) **Structure of atomic nuclei and nuclear reactions** – fission, radioactive nuclei decay, super heavy nuclei, astrophysical reactions

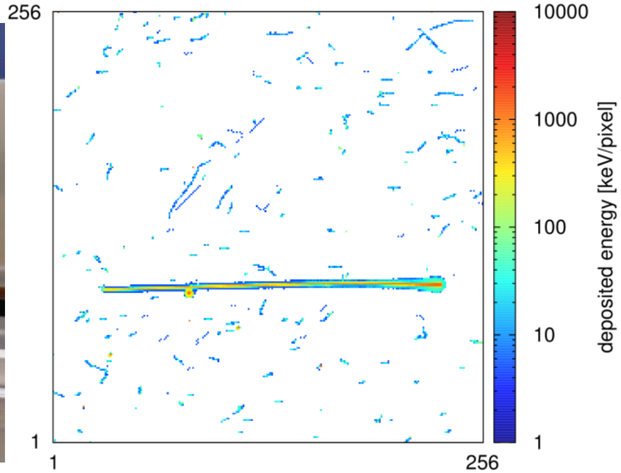
(6) **Applications –** pixel and strip detectors, imaging (X-rays and neutrons), biomedicine, hadron therapy, study of material…..

Experiment MoEDAL

- Detection of magnetic monopoles and other highly ionizing (pseudo-)stable massive particles.
- Consists of:
  - Passive nuclear track-etch detectors (CR 39 foils)
  - Trapping detectors (aluminium volumes)
  - MoEDAL-TPX array
    - Radiation monitor, capable of determining background of highly ionizing particles (alphas, protons,…).
    - Five TPX detectors, located at distances 1 m – 2 m around the IP

We need new detection technique based on hi-tech electronics (quick electronics, complex information about signals) => we need you

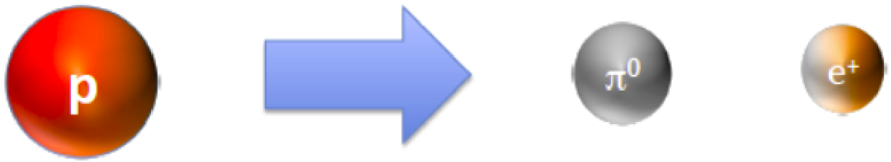


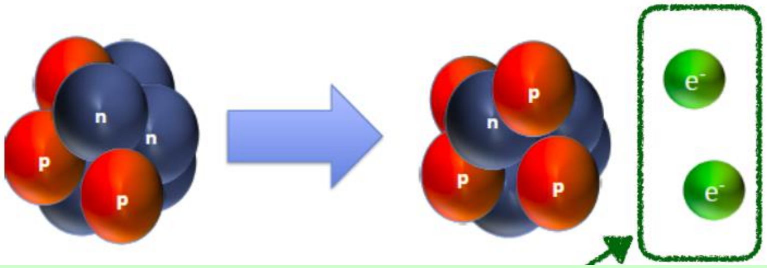


We are here because there is slight preference in our Universe of matter over anti-matter: No explanation in Standard Model, we need NEW PHYSICS

This “disbalance” is likely to be linked to the two processes:

- Proton decay (“disappearance” of nucleons)
- Neutrinoless double beta decay (“creation” of electrons)





Maria Goeppert-Mayer: two-neutrinos double beta decay (1935)

$(Z-2,A) \longrightarrow (Z,A)+2e^-+2\nu_e$ $(2\nu\beta^-\beta^-)$

Furry: neutrinoless double beta decay

$(Z-2,A) \longrightarrow (Z,A)+2e^-$ $(0\nu\beta^-\beta^-)$

The most important question: nature of neutrinos? Mass?

Long term study which need young people => we need you.

It is task for future Nobel price winners

Paul Dirac

$$\nu \neq \nu^c$$

Ettore Majorana

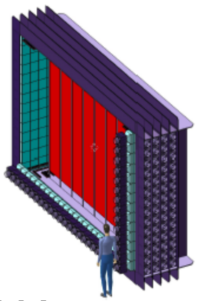
$$\nu = \nu^c = C\overline{\nu}^T$$

Neutrino physics in underground experiments

- Experiments for the measurement of double beta decay in the LSM underground laboratory in Modane, France – shielding 4 800 m w.e.
- low background technologies (Rn suppression ~1 mBq/m^3)

- Muon flux: $4 \times 10^{-5}\ \mu.m^{-2}.s^{-1}$
- Neutron flux: $4 \times 10^{-2}\ n.m^{-2}.s^{-1}$(fast); $1.6 \times 10^{-2}\ n.m^{-2}.s^{-1}$ (thermal)
- Radon: 15 $Bq.m^{-3}$

Background reduction and **rejection**



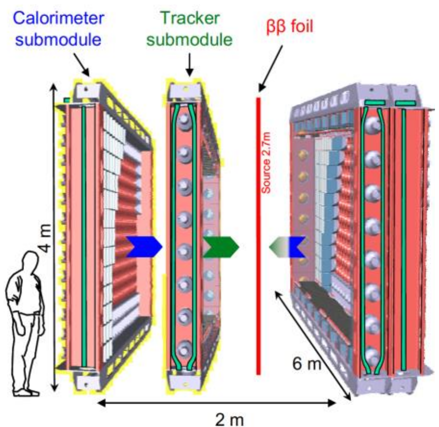
SuperNEMO Demonstrator Module
35 tons

= 1kg of bananas

= 100 Bq (decays/sec)

SuperNEMO
^{82}Se (^{150}Nd or ^{48}Ca)
100 - 200 kg
> 30 %
^{208}Tl ~ 2 μBq/kg ^{214}Bi < 10 μBq/kg Rn ≤ 0.2 mBq/kg
~ 8 % @ 1 MeV
$T_{1/2}(0\nu\beta\beta) > 1 \times 10^{26}$ y $\langle m_\nu \rangle < (0.04 - 0.11)$ eV

We are approaching to 1 ton experiments with many detectors; we need new detection technique based on hi-tech electronics => we need you



Detector "Obelix" (JINR/IEAP CTU/LSM)

P type coaxial HPGe detector (U-type ultra low background cryostat located at LSM (4800 m w.e.)

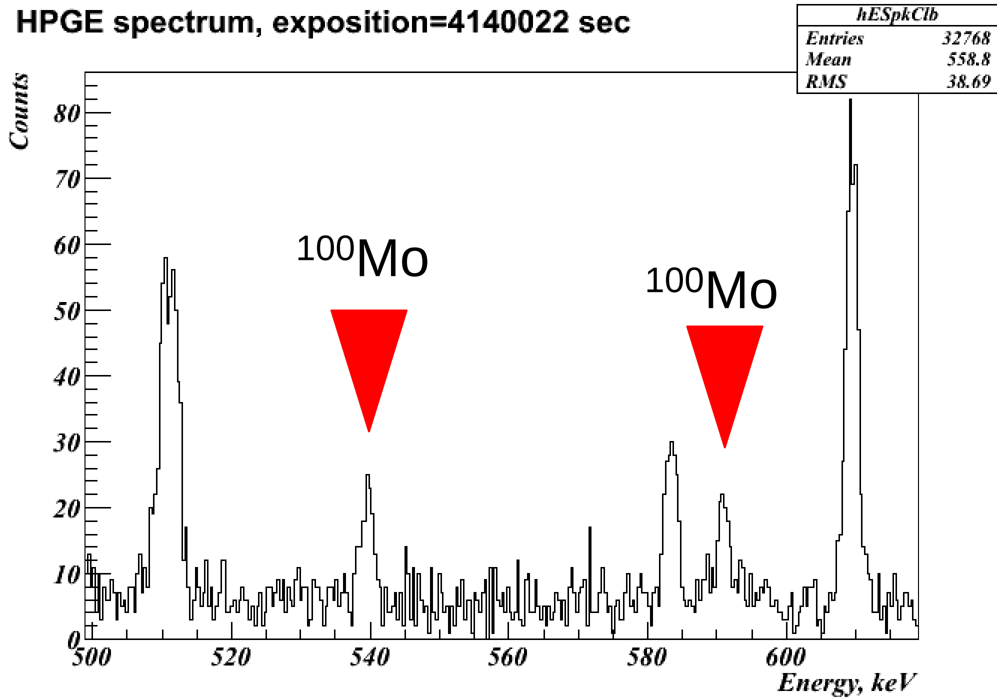
Sensitive volume 600 cm^3 Efficiency 162%

Energy resolution ~1.2 keV at 122 keV (^{57}Co), ~2 keV at 1332 keV (^{60}Co)

12 cm of arch. Pb, 20 cm of low active Pb, Radon free air

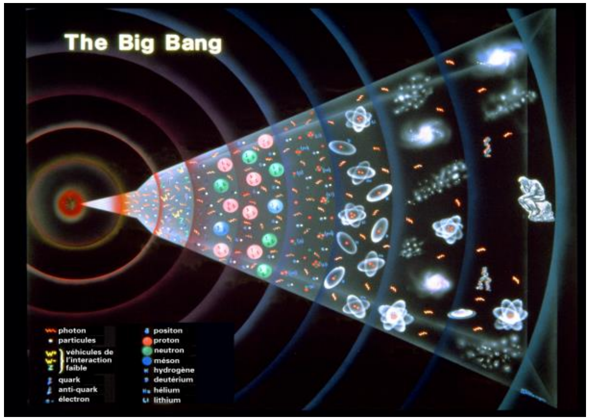
Process	$T_{1/2}$ [years]
$2\nu2\beta^-$ decay to 0^+_1 [1130 keV]	7.5×10^{20}
$2\nu2\beta^-$ decay to 2^+_1 [540 keV]	$> 2.5 \times 10^{21}$

- **Mass of ^{100}Mo – 2517,15 g**
- **Total measurement time – 2288 h**



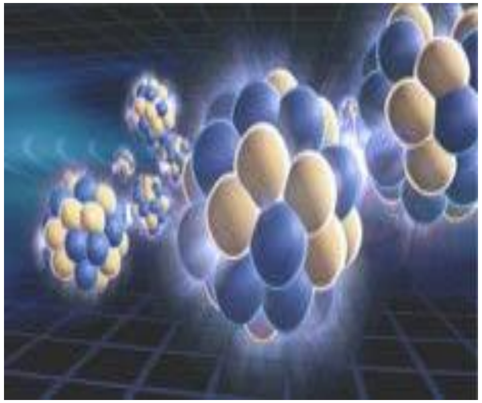
The price of such detector is 250 kEUROs => you need international cooperation

Scientific activities at LSM



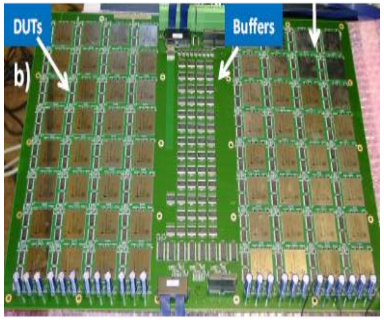
Neutrino physics
SuperNEMO, TGV,CUPID, R2D2

Search of dark matter
EDELWEISS, SEDINE, NEWS-G, MIMAC

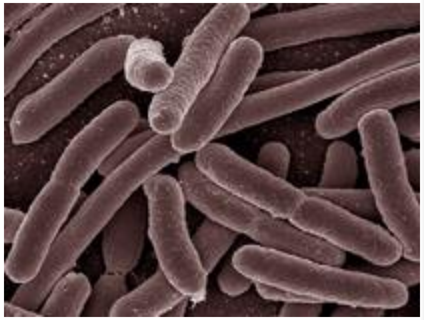


Nuclear physics
TGV, OBELIX, SHIN

Environmental sciences



Nano-electronics



Biology

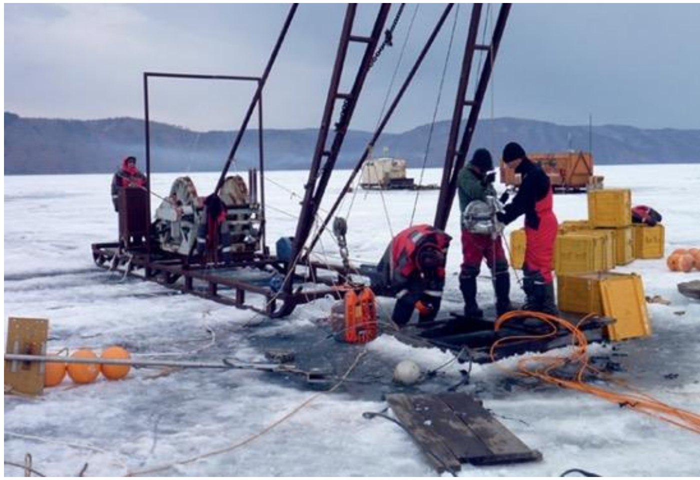
Applications

climatology, oceanography, effects of human activity on the environment, glaciology, archaeology,....

Today`s science is multidisciplinary => you can find application of your knowledge in different fields

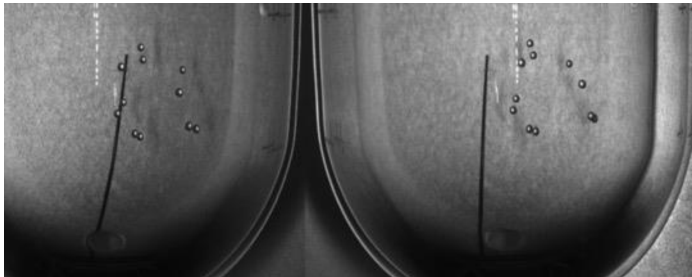
Other neutrino and astroparticle experiments

- S3 - detector of reactor (anti)neutrinos
  - Collaboration with JINR Dubna (South Africa is associated member)
  - Detection of sterile neutrinos in low-distance oscillations.
  - Compact detector made from plastic scintillators.



- BAIKAL-GVD experiment (Baikal Gigaton Volume Detector)
  - 1.5 km^3 of water in the Baikal lake as a neutrino detector.
- PICASSO, PICO experiment
  - SNOLAB underground laboratory.
  - Detection of neutralinos as dark matter candidates using a bubble detector.

If you like real winter, tell me and you can go to Bajkal lake during Russian winter (2 meters of snow, 1 meter of ice and -30 degrees) => sometimes science is difficult



Detector of reactor antineutrinos (S^3)

Nuclear power reactor is the most intense artificial source of antineutrinos on Earth (the neutron-rich fission fragments are produced, further undergoing β-decays producing about 6 $\bar{\nu}_e$ per one fission). A typical 3 GW_{th} industrial power reactor emits about 10^{21} $\bar{\nu}_e/s/4\pi$.

<u>The purpose of such detector:</u>

- Online monitoring of the reactor power (proportional to number of fissions)
- Isotopical composition of the reactor fuel (each isotop in the reactor has different antineutrino spectrum)
- Investigation of short range neutrino oscillations (sterile neutrino hypothesis)

<u>Inverse beta decay</u>

$$\widetilde{\nu_e} + p \rightarrow e^+ + n$$

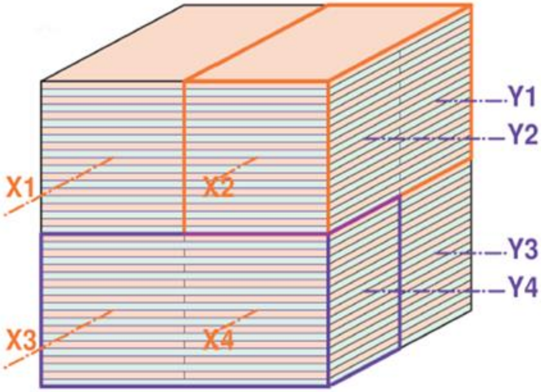
followed by positron annihilation

$$e^+ + e^- \rightarrow 2\gamma$$

and by neutron capture:

$^{157}Gd(n,\gamma)$ $\Sigma E_\gamma = 8$ MeV $\sigma = 255\ 000$ b

You need to be familiar with different detection techniques, you need to know physics (you know how it works, but physics tells you why it works (or not).



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R. Ballabriga[2], B. Bergmann[1], P. Burian[1,12], I. Caicedo[1], M. Campbell[2], J. Dammer[1], C. DaVia[8], J. Dudák[1], C. Froejdh[9], E. Froejdh[2], V. Georgiev[12], C. Granja[1], E. Heijne[1,2], M. Holík[1,12], R. Hall-Wilton[10], M. Holík[12], T. Holý[1], J. Jakůbek[1], M. Jakůbek[1], J. Kirstead[7], V. Kraus[1,12], F. Krejčí[1], E. Lehmann[11], C. Leroy[4], X. Llopart[2], J. M. O'Donnel[3], R. Nelson[3], M. Nessi[2], A. Owens[5], L. Pinsky[6], S. Petersson[9], S. Pospíšil[1], M. Platkevič[1], K. Smith[13], T. Slavíček[1], P. Soukup[1], M. Suk[1], J. Šolc[1], H. Takai[7], G. Thungstroem[9], D. Tureček[1], J. Uher[1], D.Vavřík[1], Z.Vykydal[1], S. Wender[7], J. Žemlička[1]

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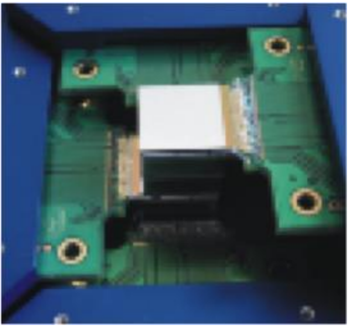
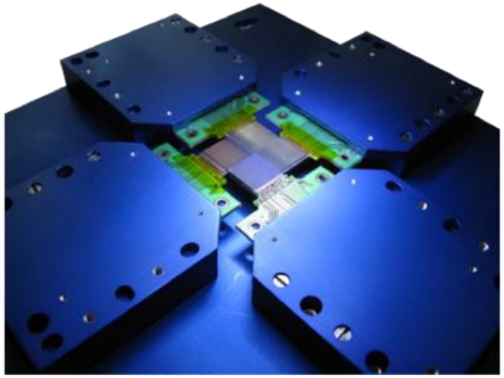
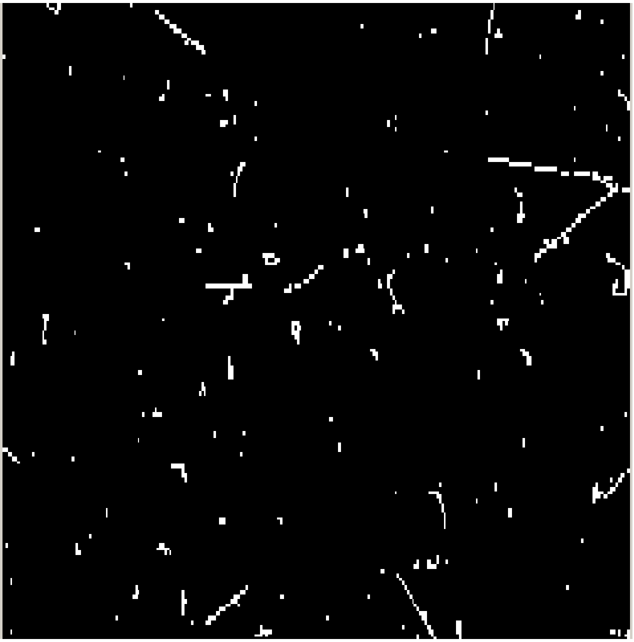
[8] Manchester University, UK
[9] MidSweden University, Sundsvall, Sweden
[10] ESS, Sweden
[11] PSI, Switzerland
[12] WBU Pilsen, Czech Republic
[13] Glasgow University

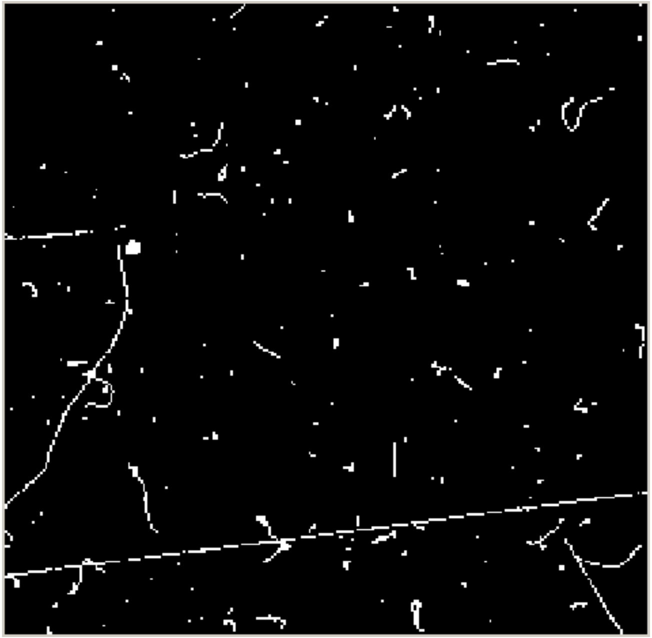
Timepix based devices developed and tested in IEAP CTU





Typical response of Medipix2/Timepix device to natural background radiation

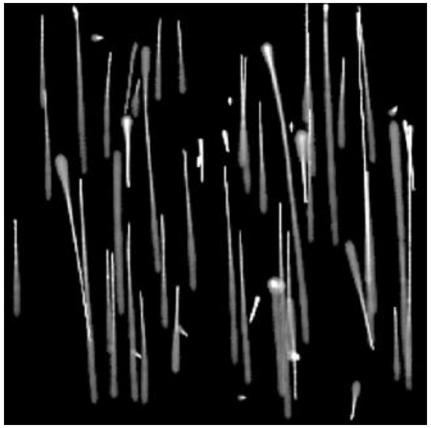




Clearly recognizable tracks and traces of
- X-rays
- electrons generated mostly by gamma rays
- alpha particles
- muon
- electron-positron pair, … .

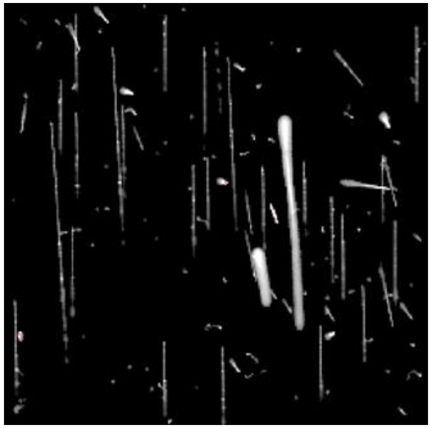
Typical observed tracks of particles used for hadron therapy beam

Protons 48 MeV



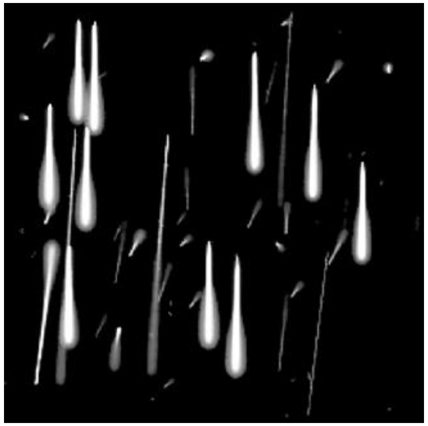
Only protons and their scattering, no secondaries.

Protons 221 MeV



Many secondaries, (delta electrons fragments).

Carbons 89 MeV/u

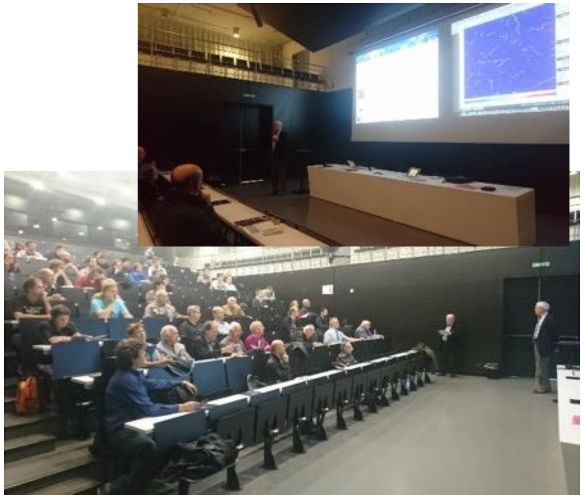


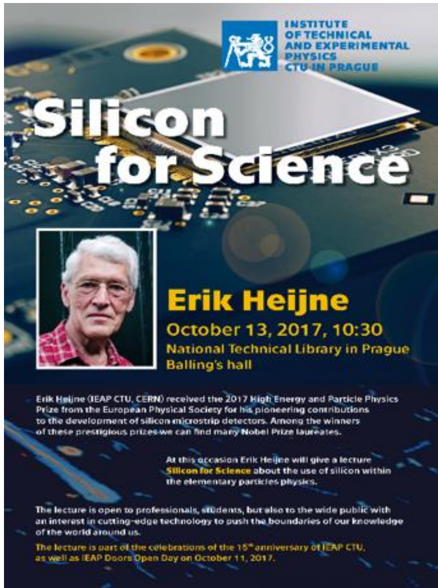
Carbons and protons and their scattering, no secondaries.

Carbons 430 MeV/u

Carbons and many secondaries.

Erik Heijne received the 2017 High Energy and Particle Physics Prize from the European Physical Society for his pioneering contributions to the development of silicon microstrip detectors. At this occasion (and as a part of the celebrations of the 15th anniversary of IEAP CTU) he gave a lecture for wide public about the use of silicon within the elementary particles physics.

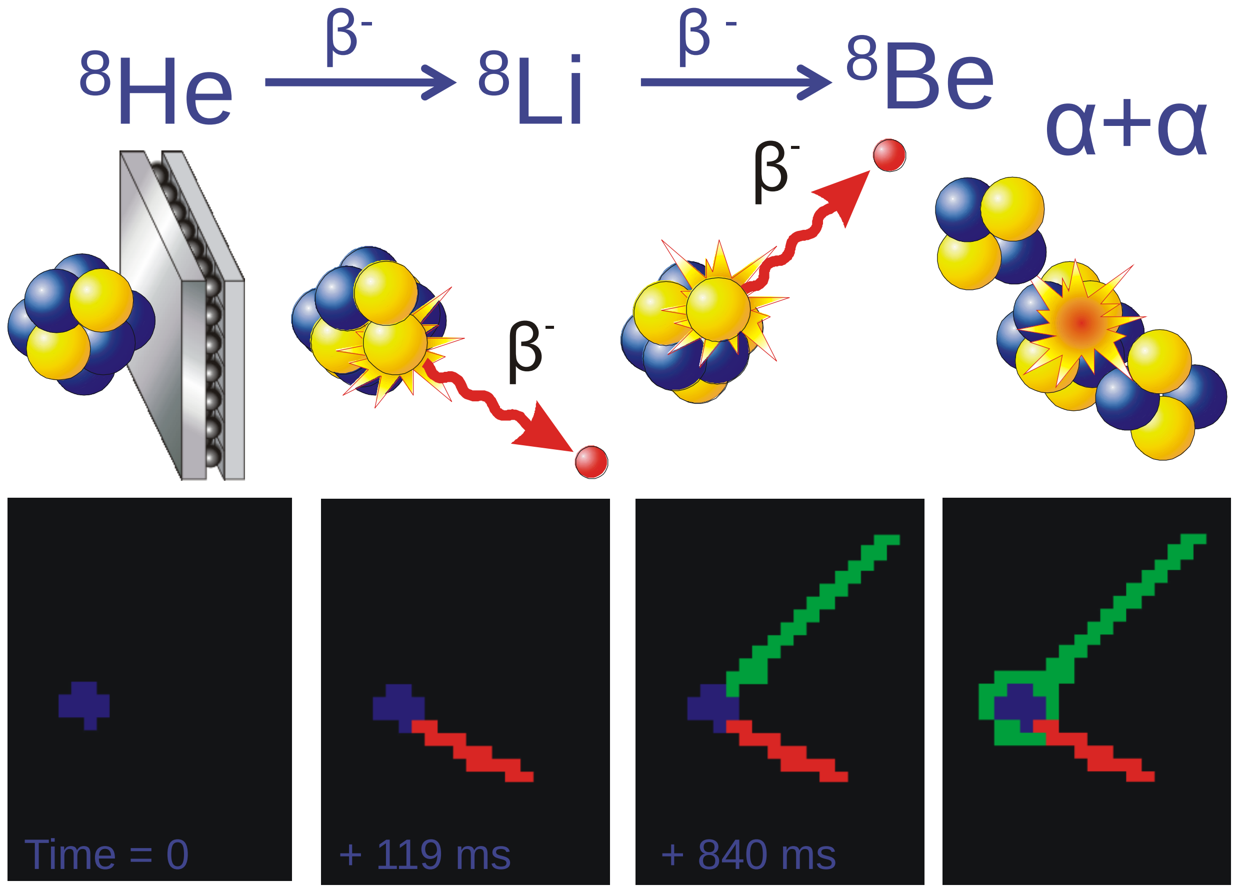




Single ^{8}He ion decay sequence recorded by Timepix operating in ToA mode

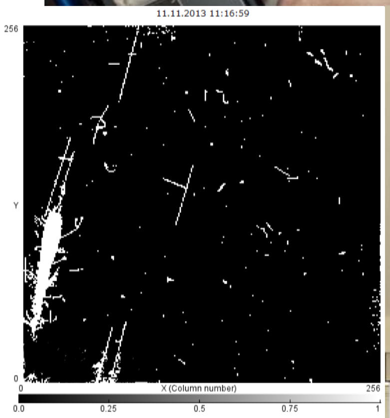
^{8}He ion hits the Timepix sensor where undergoes β-decay

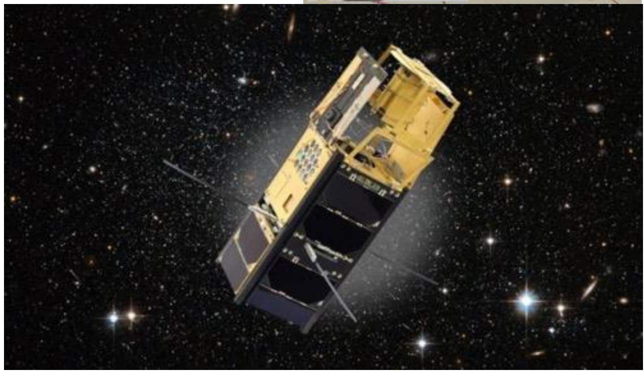
Subsequent decays of the daughter nuclei by emission of one beta and two alpha particles follow



Astroparticle physics in space

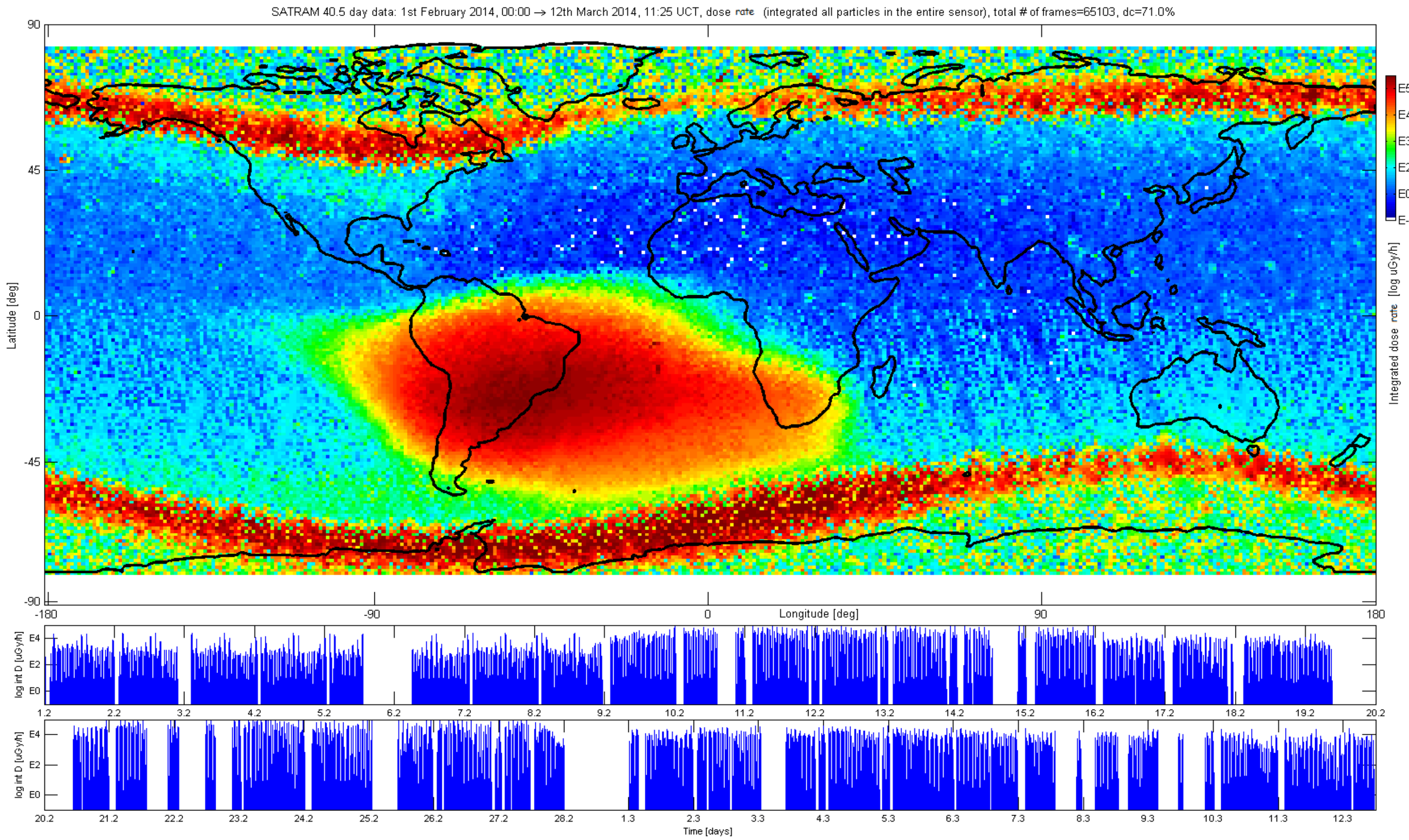
- Measurement of cosmic rays in space
  - Equipments based on the Medipix/Timepix semiconductor pixel detectors
  - Dosimeters in Interantional Space Station (NASA)
  - Equipment for the measurement of cosmic rays in outer space in Proba-V satellite (ESA)
  - In preparation: RISESAT (Japan Space Agency)
- Pixel detectors in X-ray telescopes
  - VZLUSAT-1 nanosatellite with the novel concept of X-ray telescope (wide-field optical system "Lobster Eye") – launched in June 2017
  - X-ray telescope test with ballistic missile (NASA)





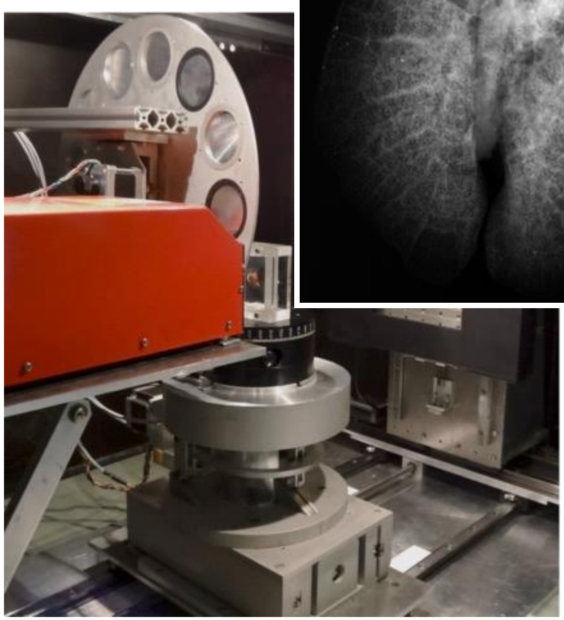
Measured radiation map by Satram device in orbit

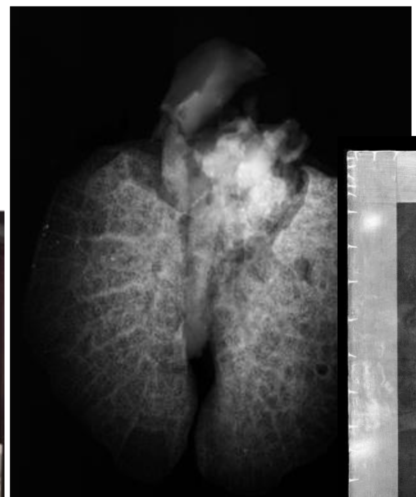
around the Earth at an altitude of 820 km from the earth's surface obtained within 36 days from January 1, 2014 to February 7, 2014 logarithmic scale in μG/hr.

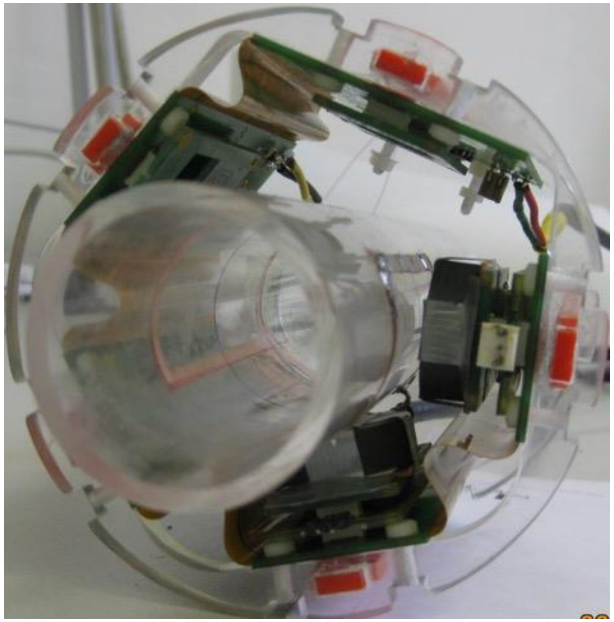


Applications of pixel detectors in imaging

- X-ray radiography and tomography
  - ➢ Imaging of different samples (materials, biology, medicine….)
  - ➢ Applications in art
- Neutron radiography
- MRI-SPECT

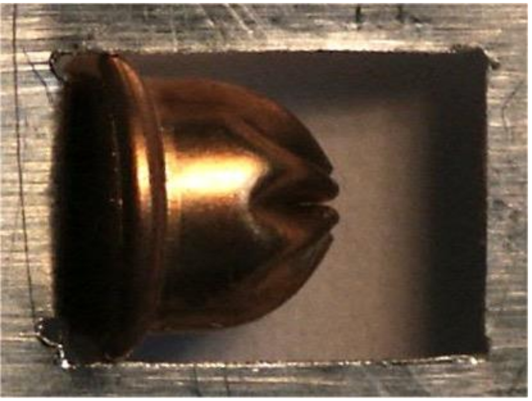




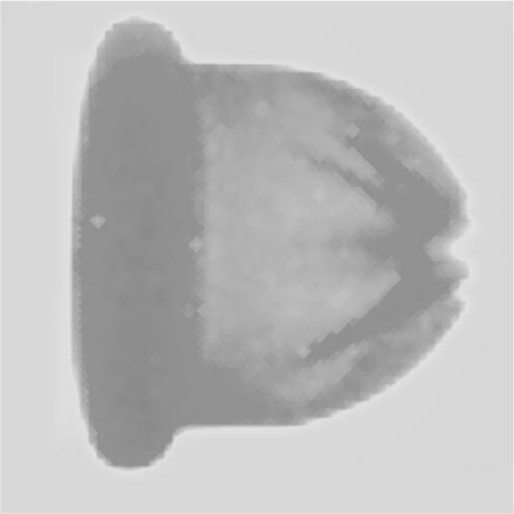


Medipix with neutron converter: Visualization of explosive encapsulated in a copper cartridge

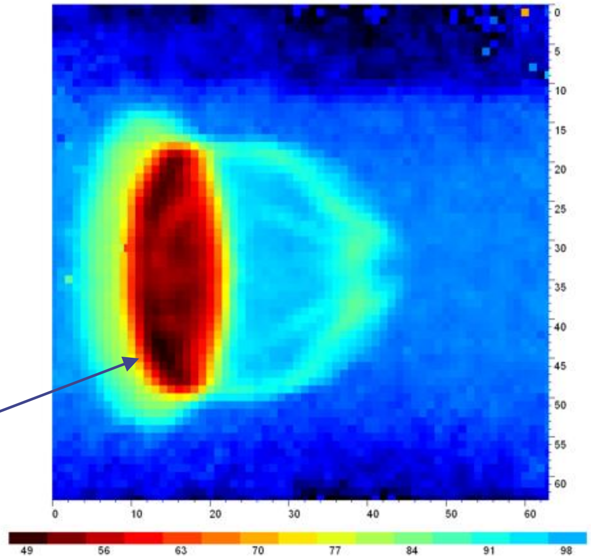
Photography



Roentgenogram

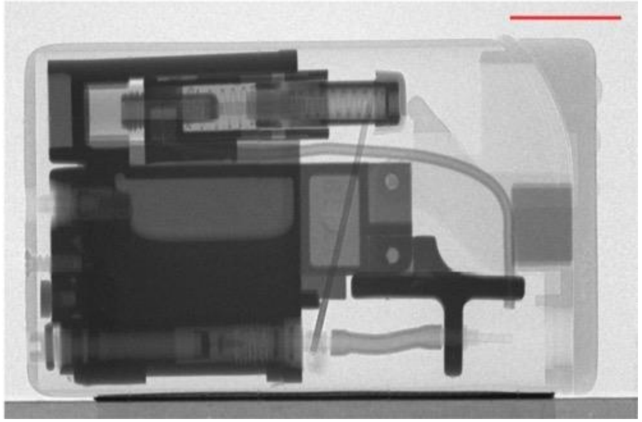


Neutronogram

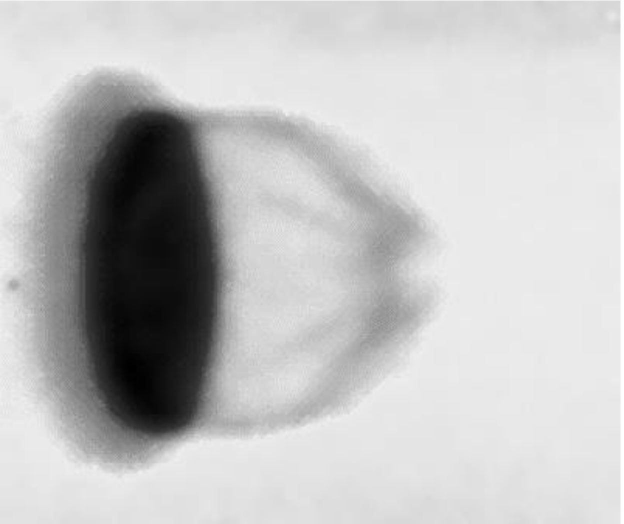


Blank shell (cartridge)

Explosive filling

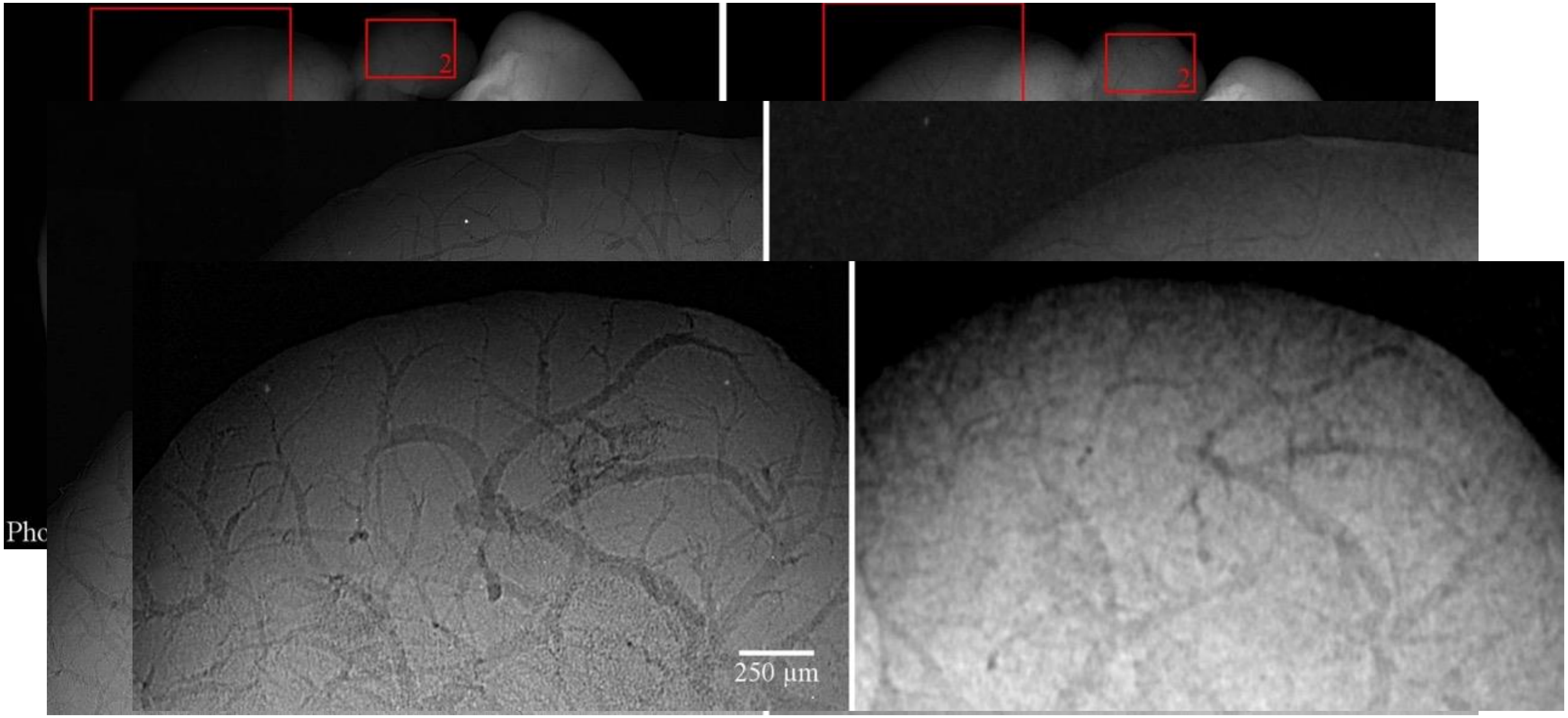


Neutron radiography of a lighter with a steel body; prepared in PSI, Switzerland.



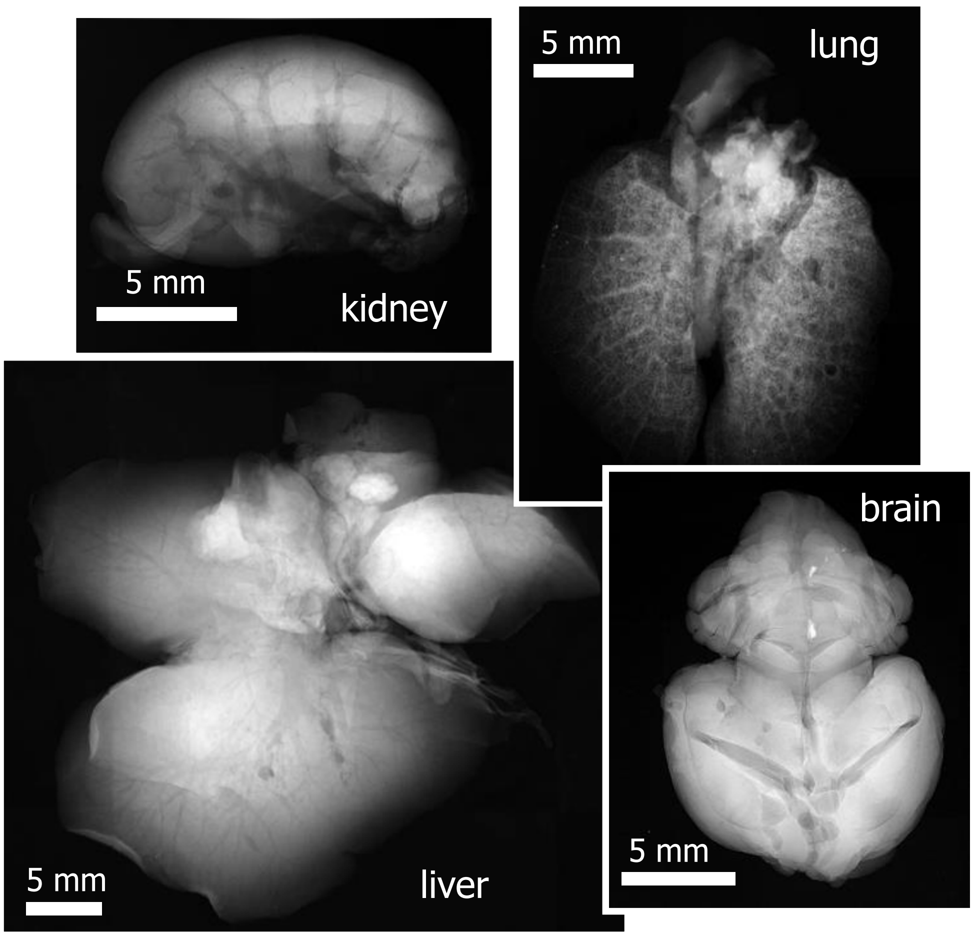
Imaging of biological samples

- High contrast, high resolution
- Energetically-sensitive detector response

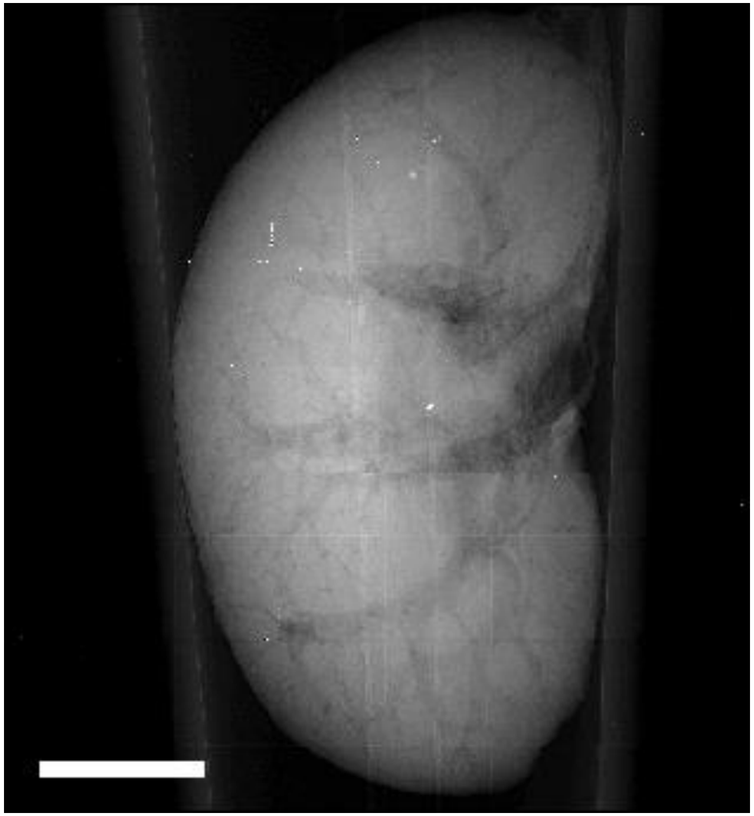


- Timepix detector - 55 µm pixel, 300 µm Si sensor
- CCD camera – 9 µm pixel, 22 µm Gadox scintillator

RTG imaging of soft tissues fixed by alcohol



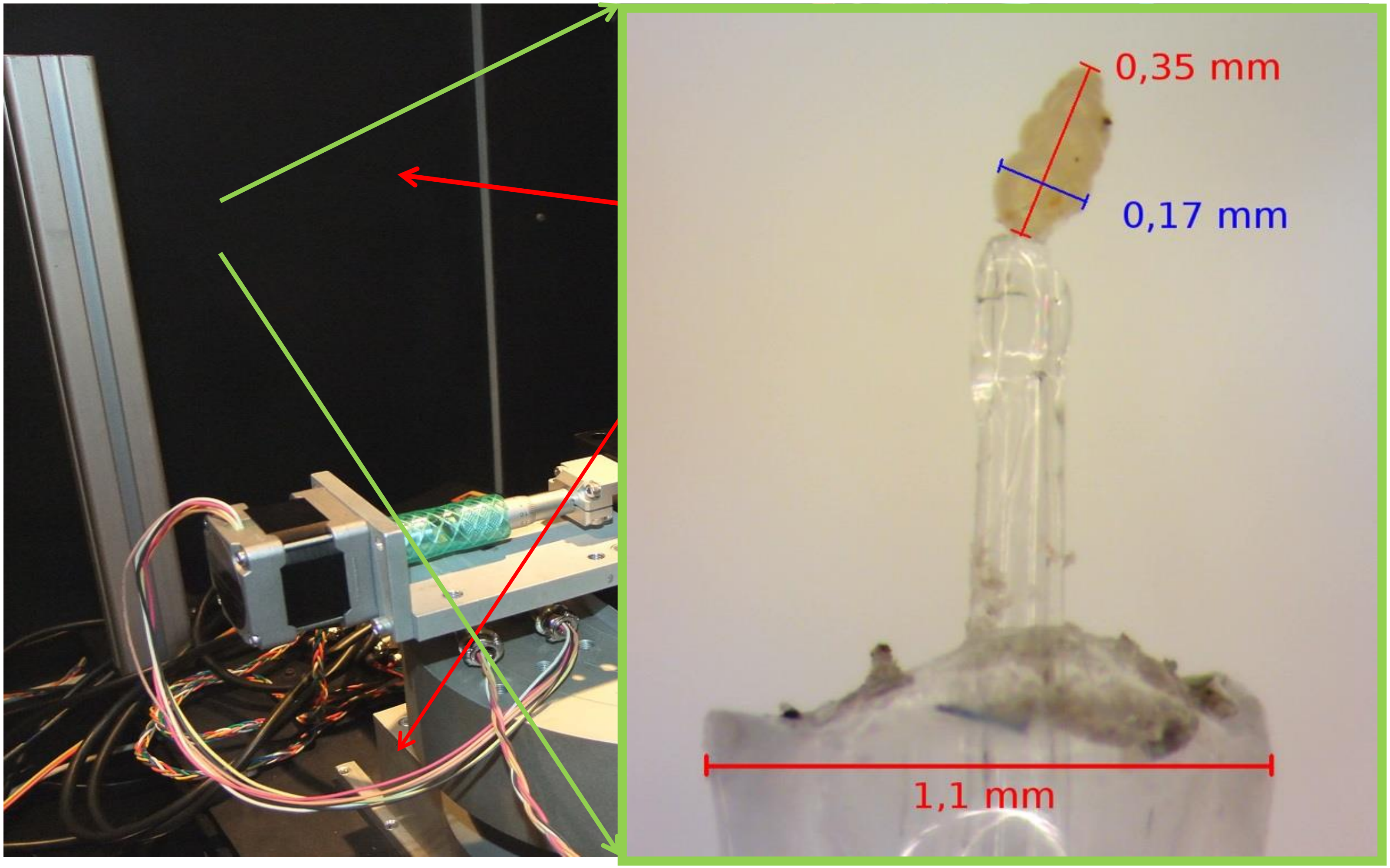
2D projections ex-vivo organs of a mouse.



A set of CT projections of a mouse kidney, resolution 4.5 μm, prepared with the detector WidePIX_{10x5}

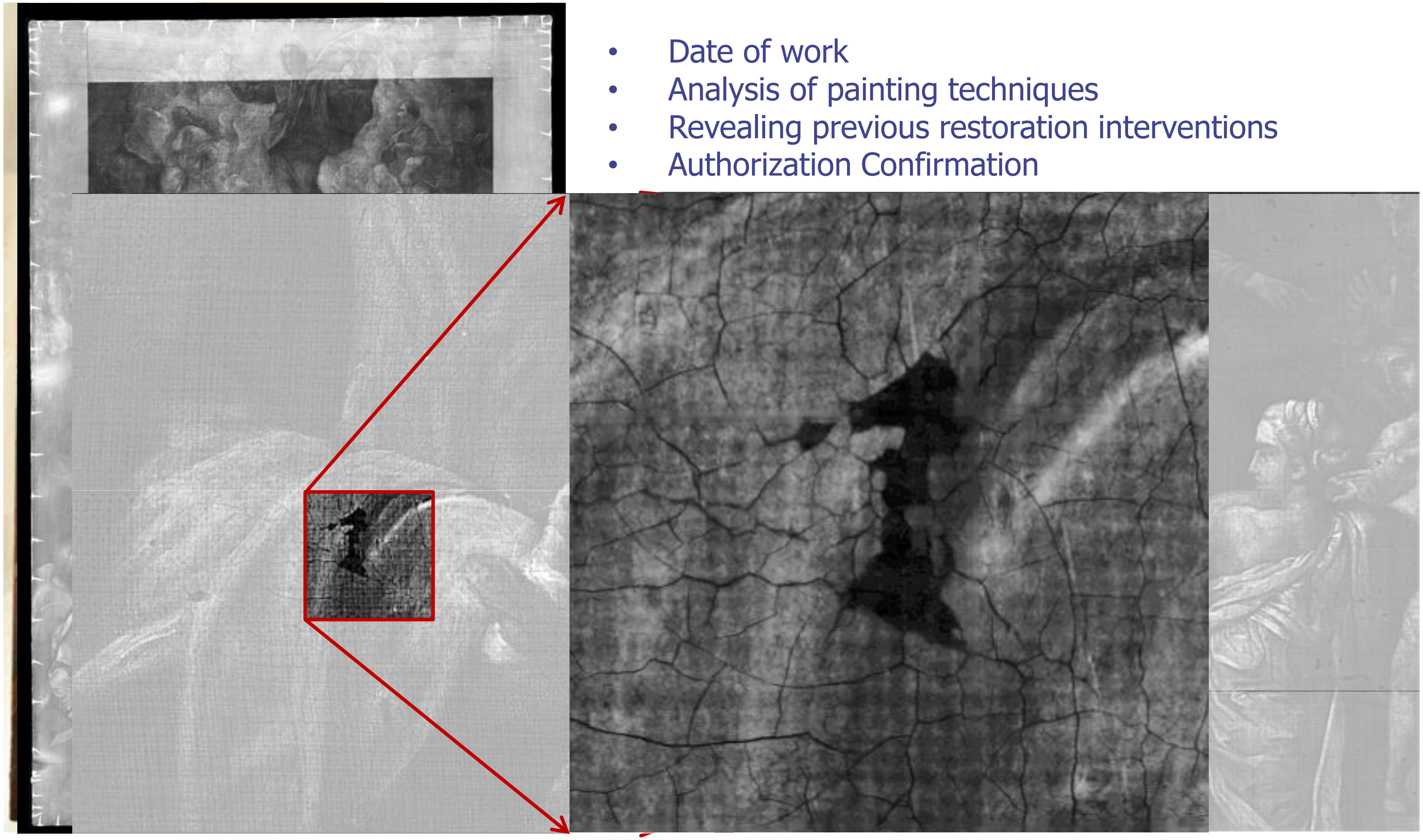
RTG imaging with sub-micron resolution

- Foraminifera – one-cell sea organism



Radiography of works of art

- **Transformation of Christ on the hill**
- Size 90 x 60 cm, 18400 x 12000 pixels (220 megapixels)



- Date of work
- Analysis of painting techniques
- Revealing previous restoration interventions
- Authorization Confirmation

Radiography of works of art

Conclusion:

- we need your expertise in hardware and software (huge amount of detectors of different types, huge amount of data, importance of data processing)

- a lot of questions in fundamental and applied science (nature of neutrino, DM, astrophysics, medicine, biology, art, electronics…)

- international cooperation, but develop your infrastructure in South Africa

I wish you success in your activities

Thanks a lot for your attention