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ADVANCED SEMICONDUCTOR DETECTORS FOR MEDICAL APPLICATIONS SYMPOSIUM

Small animal micro-CT[&] and mixed radiation field characterization in ion beam radiotherapy[#] and in outer space[*] with pixel detectors Timepix

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Czech Technical University in Prague

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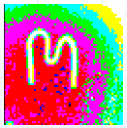
Research performed in frame of the CERN Medipix Collaboration

* Project funded by the European Space Agency



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spacecraft payload

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Basic Research

Astroparticle & non-accelerator physics
- Neutrino physics (NEMO3/SuperNEMO, TGV)
- Cosmic rays (CZELTA)
- Dark matter (PICASSO)

ATLAS at LHC
- SCT detection modules
- Neutron shielding
- Medipix radiation monitoring
- Higgs boson physics

Nuclear spectroscopy
- Fission fragment spectroscopy
- Laser induced nuclear excitation
- Ultra cold neutrons

Applied Research

Radiation imaging
- Medipix pixel detectors: SW, HW
- X-ray radiography and tomography
- Charged particle & neutron imaging
- Biomedical imaging
- Material science and defectoscopy

R&D of semiconductor detectors
- 3D and semi-3D detectors
- Thermal neutron detectors
- Room-temperature detectors
- Instrumentation for detector testing

Applied spectrometry
- Material analysis (CINAA, XRF, Radon)
- Particle tracking and spectroscopy
- Space: (gamma, neutron,micro-sensor,SATRAM payload)

Fundamental Experiments in the Physics of the Microworld

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Recent events

IEEE NPSS NSS MIC IEEE Conference
Seattle, USA
8-15 Nov 2014

NSS MIC IEEE Conference
Seoul, Korea
27 Oct - 2 Nov 2013

15th IWORID
Paris
23-27 June 2013

All.

IEAP, Horská 3a/22, 128 00 Praha 2, Tel: (+420) 22435 9290

Designed by Marte

2.5 MeV VdG accelerator at IEAP CTU in Prague

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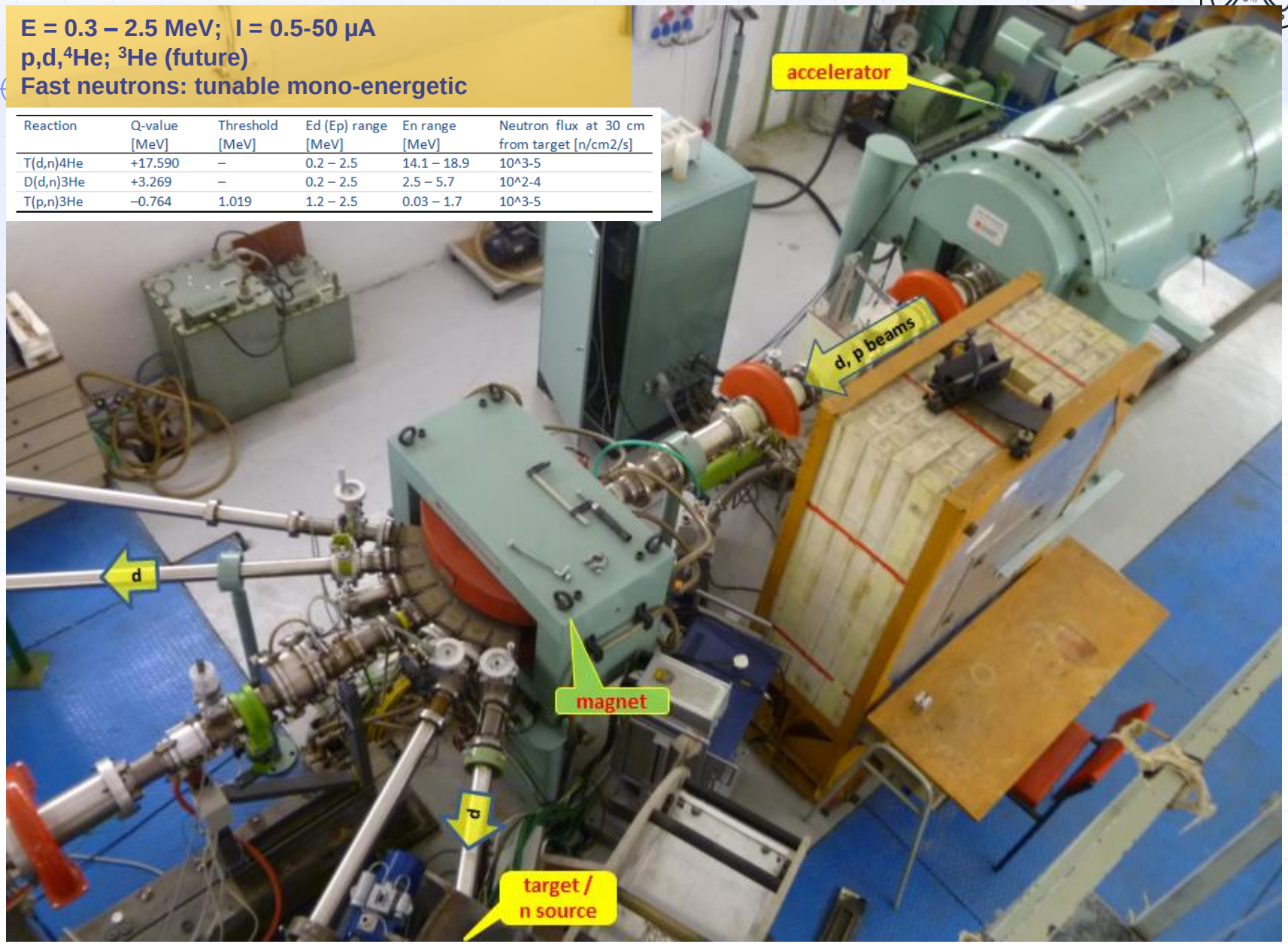
E = 0.3 – 2.5 MeV; I = 0.5-50 μA
p,d,^{4}He; ^{3}He (future)
Fast neutrons: tunable mono-energetic

Reaction	Q-value [MeV]	Threshold [MeV]	Ed (Ep) range [MeV]	En range [MeV]	Neutron flux at 30 cm from target [n/cm2/s]
T(d,n)4He	+17.590	–	0.2 – 2.5	14.1 – 18.9	10^3-5
D(d,n)3He	+3.269	–	0.2 – 2.5	2.5 – 5.7	10^2-4
T(p,n)3He	–0.764	1.019	1.2 – 2.5	0.03 – 1.7	10^3-5



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Small animal micro-CT& and mixed radiation field characterization in ion beam radiotherapy# and in outer space* with **pixel detectors Timepix**

Hybrid semiconductor pixel detectors Medipix/Timepix
Per–pixel signal readout electronics

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Hybrid architecture: sensor is bump-bonded to the readout ASIC chip. Different semiconductor sensors can be used:

- material (Si, CdTe, GaAs)
- thickness (e.g. 50, 300, 500, 700, 1000, 1500 μm).

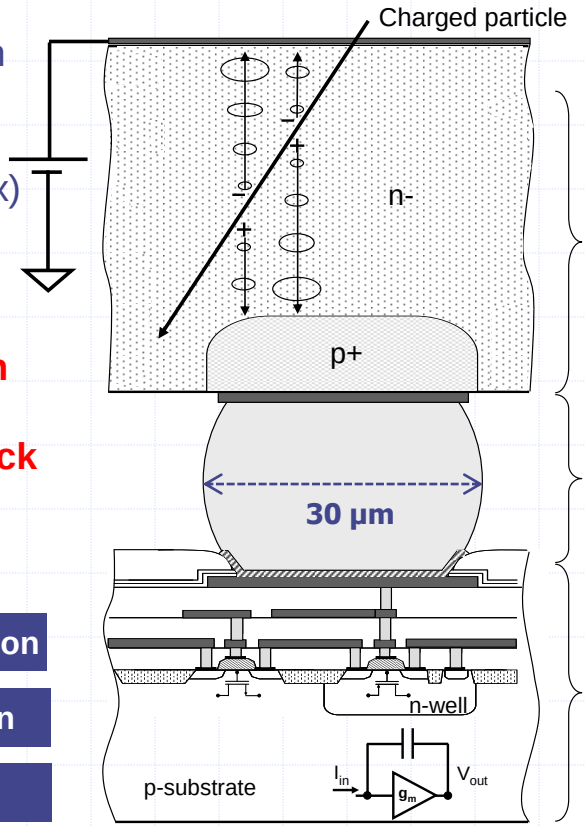
- high granularity
- sub-pixel & sub-μm spatial resolution
- per-pixel signal processing (13-bit/px)

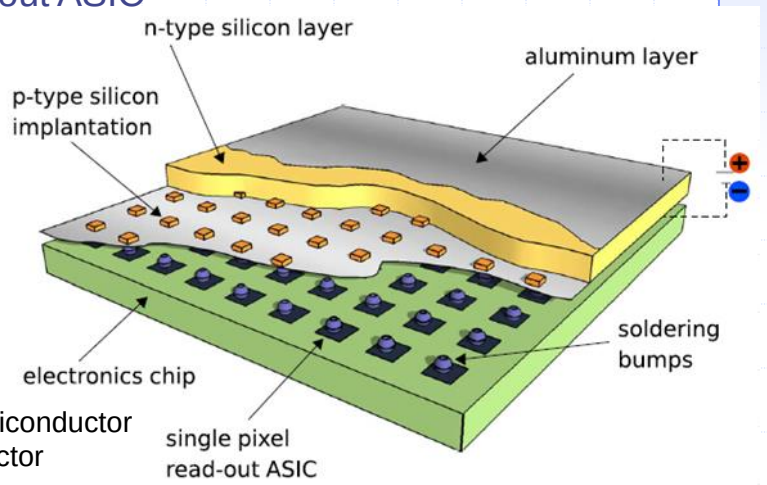
- dark-current free **noiseless detection**
- threshold ~ 4 keV
- **single-particle track visualization**

Quantum imaging detection

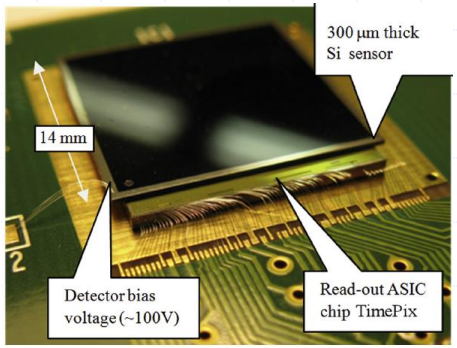
Active nuclear emulsion

Directional sensitivity



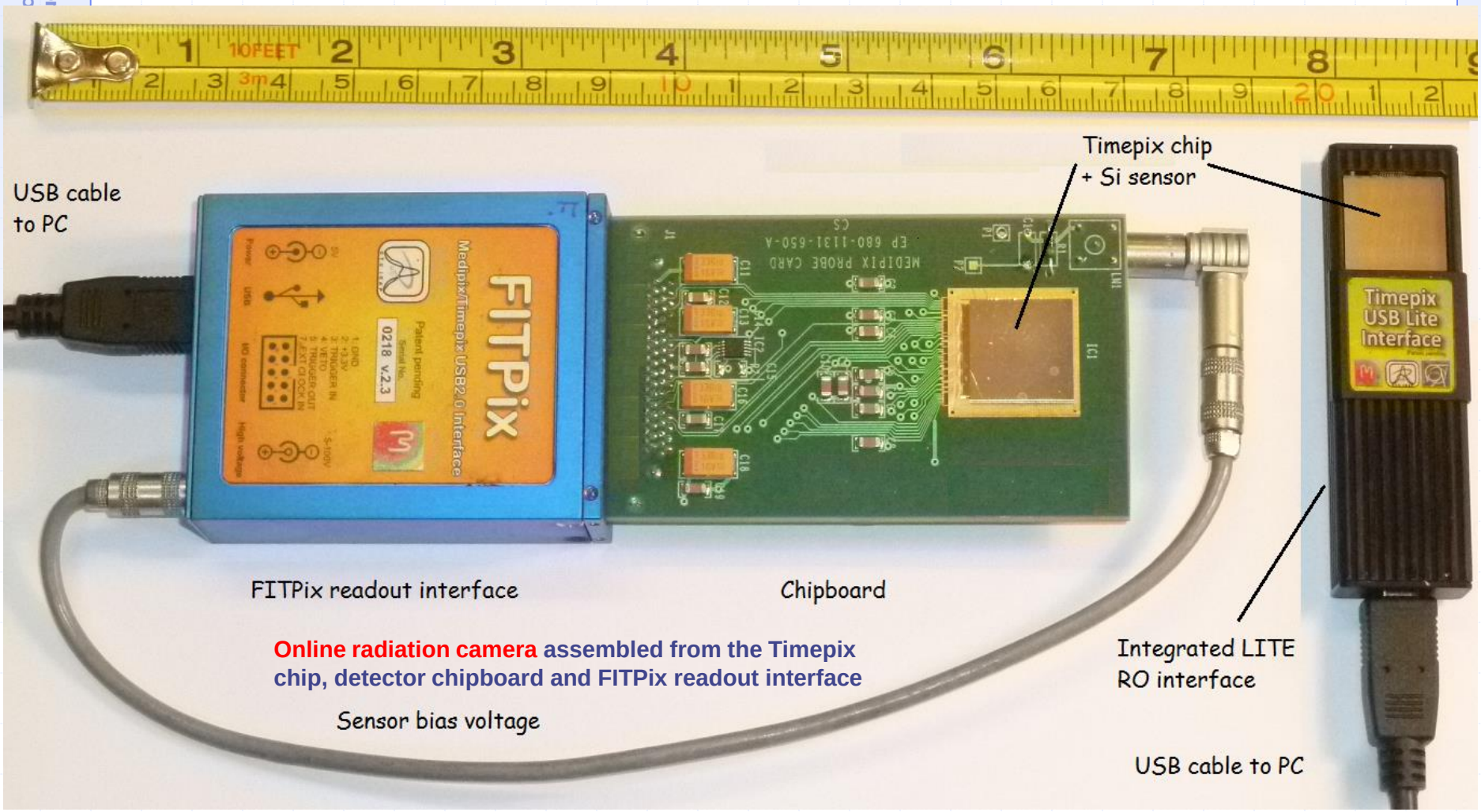


- 256 x 256 pixels (pitch 55 μm)
- 14mm x 14mm = 2 cm^2



Pixel detectors Medipix/Timepix + Integrated RO electronics + Online & data processing SW + Nuclear Physics know-how: Integrated Radiation Camera

www.cern.ch/medipix



Detector array architectures:
Miniaturization, stacking

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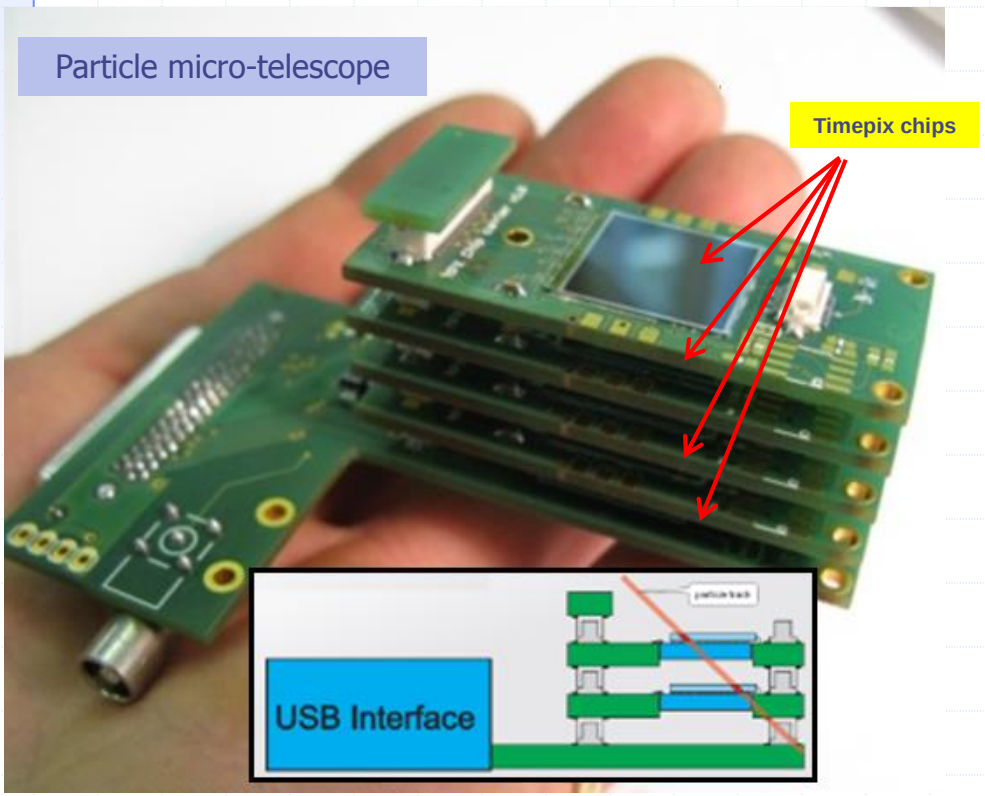
Enhanced particle tracker (high angular resolution)

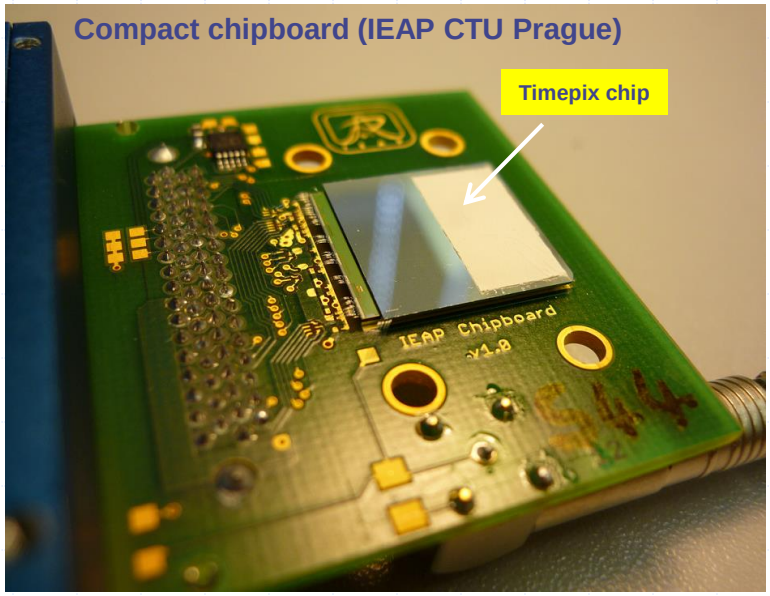
Particle micro-telescope



Particle tracker/telescope assembled/stacked from four Timepix devices

Highly miniaturized Timepix LITE

Compact chipboard (IEAP CTU Prague)



Detector array architectures:
Large sensitive area

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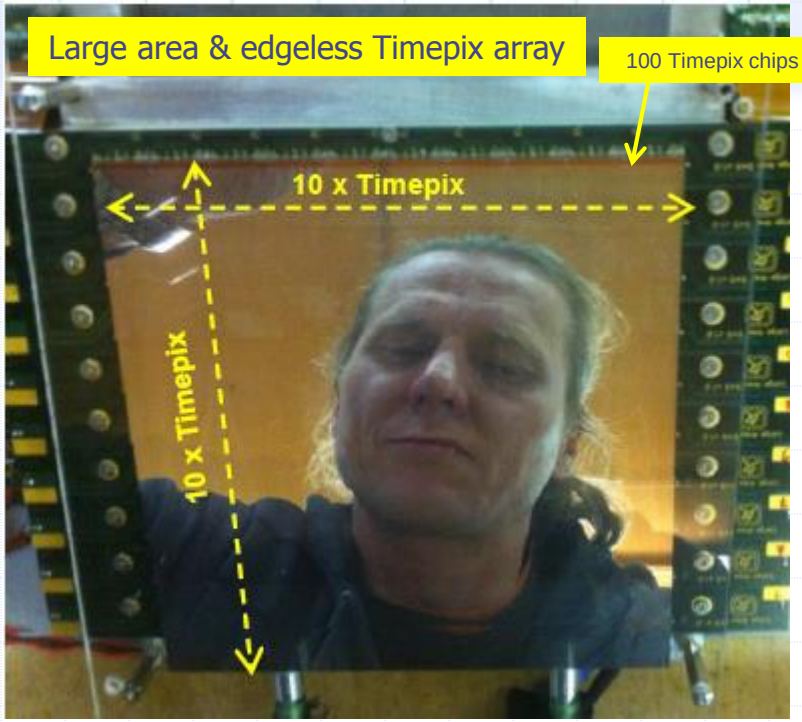
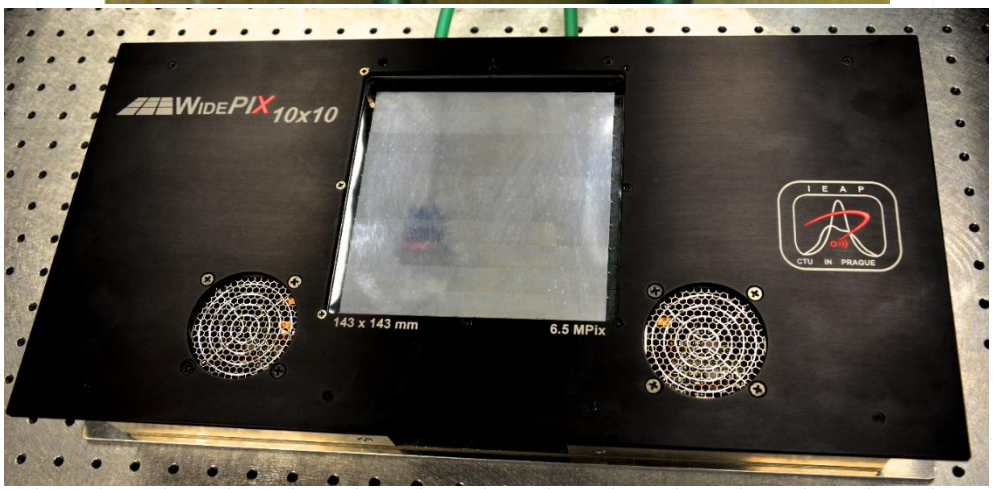
- **WidePIX 10x10 Timepix imager** consists of an array of 100 **edgeless** Timepix detectors (developed in VTT Finland and fabricated by ADVACAM Oy).
- The whole device was designed, developed and constructed at the IEAP CTU Prague
- Custom readout electronics + control software tool (Pixelman based)
- Versions: 10x10, 10x5, 5x4, 10x1, 5x1 chips



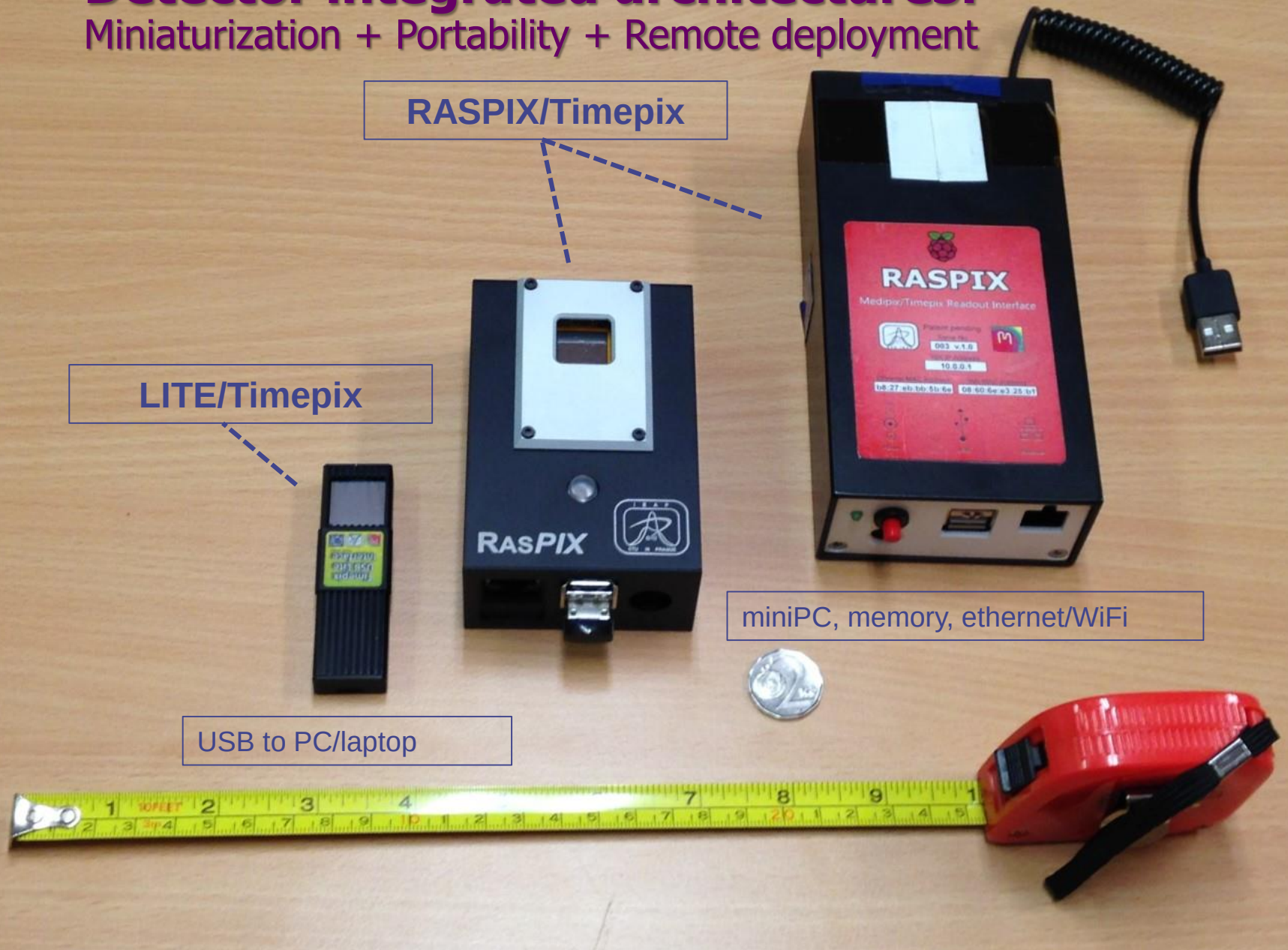
Features:

- Superior image quality without instrumental noise (particle counting)
- Large (14 cm x 14 cm) **fully sensitive area** with **no gaps** between sensor chips
- Fully digital detection with **ultra-high contrast** even for light objects (e.g. plastic or soft tissue)
- Energy discrimination allowing “color” radiography,
- Compact size and portability (1x PC)
- Support for major operating systems: Windows, Mac OS, Linux



Detector integrated architectures:

Miniaturization + Portability + Remote deployment



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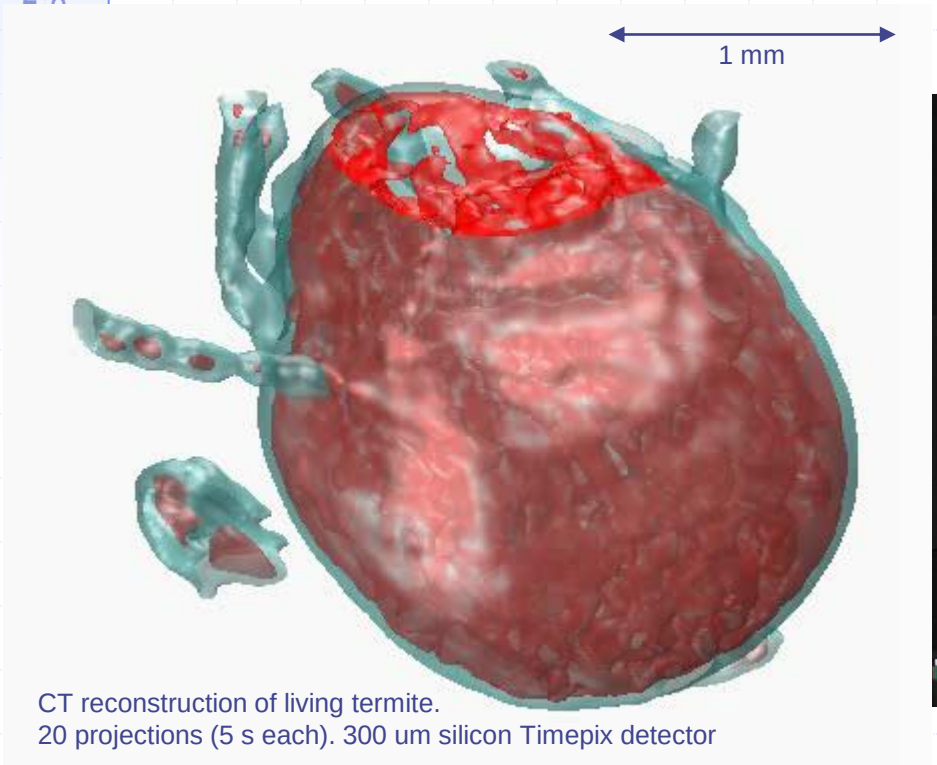
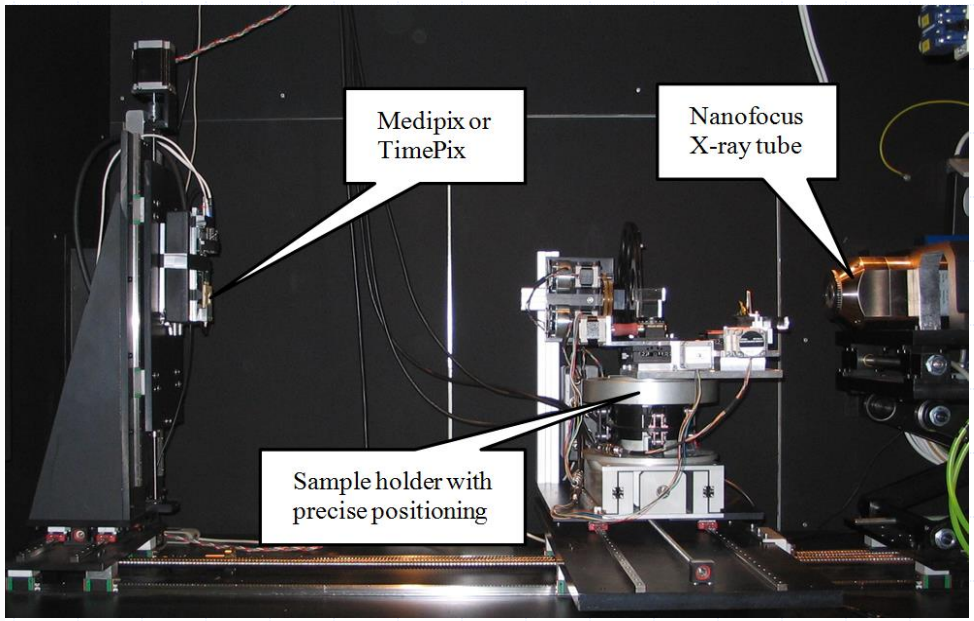
Small animal micro-CT& and mixed radiation field characterization in ion beam radiotherapy# and in outer space* with pixel detectors Timepix

X-ray μCT: high resolution, soft tissue contrast
In-house laboratory scale system

- With source-detector distance → high magnification + spatial resolution down to 1 μm.
- The spatial resolution is currently limited by the X-ray tube focal spot diameter
- The detector and the X-ray tube are fixed + integrated SW tool
- Sample placed on the top of a precise multi-axial motorized stage
- Living specimen + high contrast of soft-tissue samples

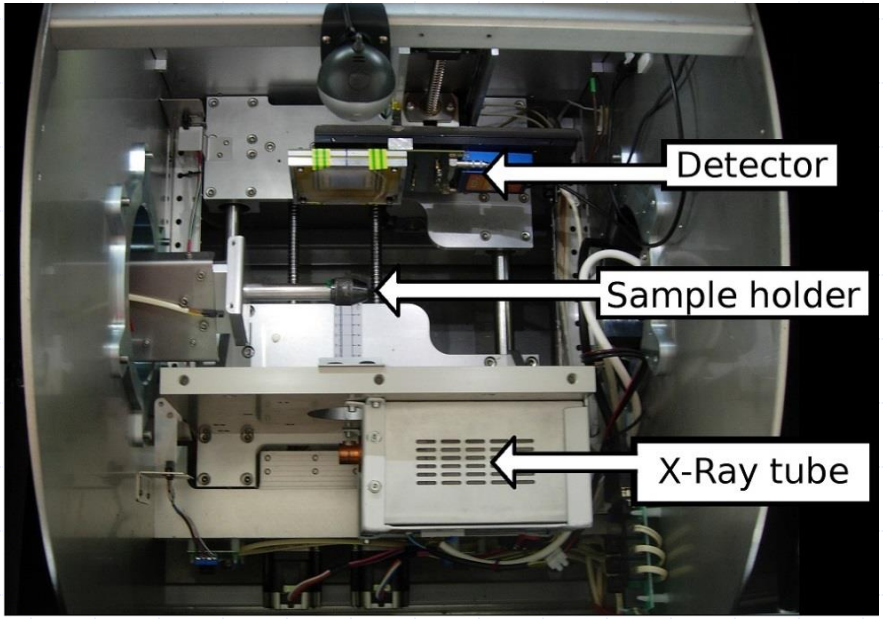


CT reconstruction of living termite.
20 projections (5 s each). 300 um silicon Timepix detector



X-ray μCT: high resolution, soft tissue contrast
Small animal CT scanner

- Sample fixed at the center of the rotating gantry → avoid undesirable movement of biological sample and position uncertainties
- Built-in house CT system:
  - Timepix Quad detector (512 × 512 pixels)
  - FITPix interface + processing SW Pixelman
  - KEVEX™ PXS11 X-ray tube μ-focus
  - Custom developed user SW interface
  - Highest achievable spatial resolution 28 μm



CT scanner rotating gantry: detector, sample holder and radiation source

Assembled small animal micro-CT scanner

High resolution high contrast X-ray µCT
Organic samples with micro-structures

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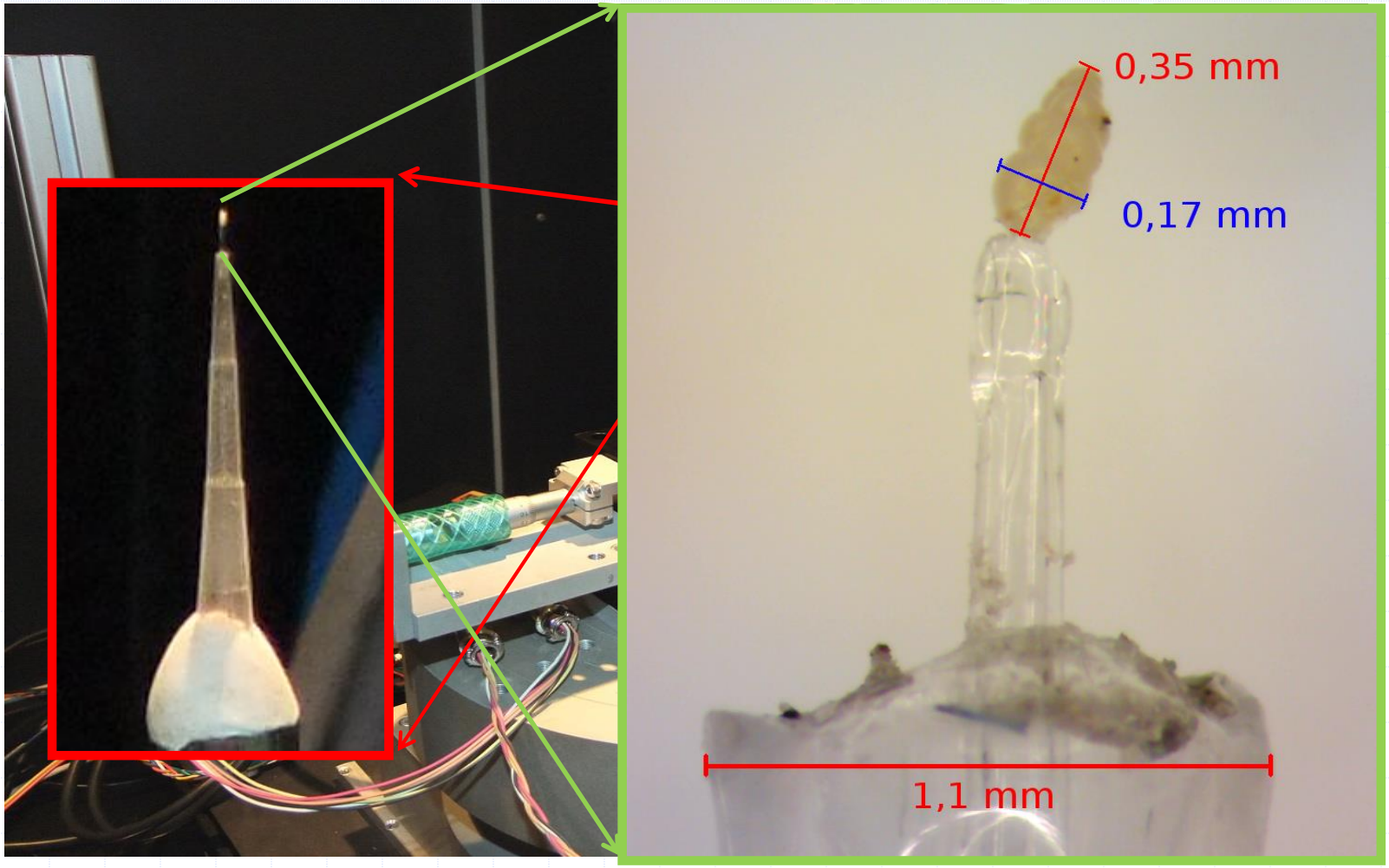
- Radiography of sea microfossils (foraminifera)



High resolution high contrast X-ray µCT
Organic samples with micro-structures

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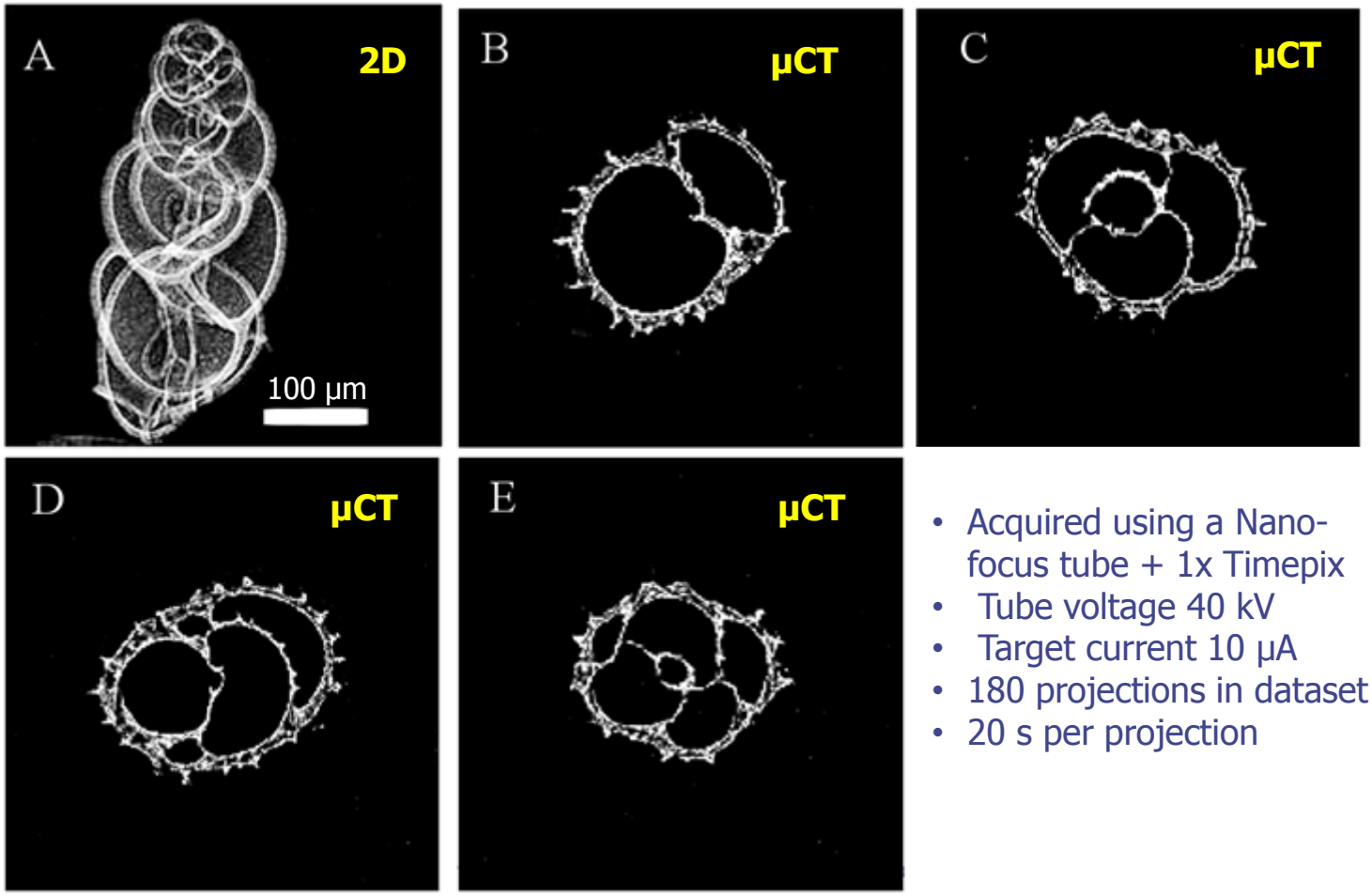
- A) Example of radiographic projection; B – E) Virtual sections through the reconstructed voxel model



- Acquired using a Nano-focus tube + 1x Timepix
- Tube voltage 40 kV
- Target current 10 µA
- 180 projections in dataset
- 20 s per projection

High resolution high contrast X-ray µCT
Soft tissue phantom + density resolving power

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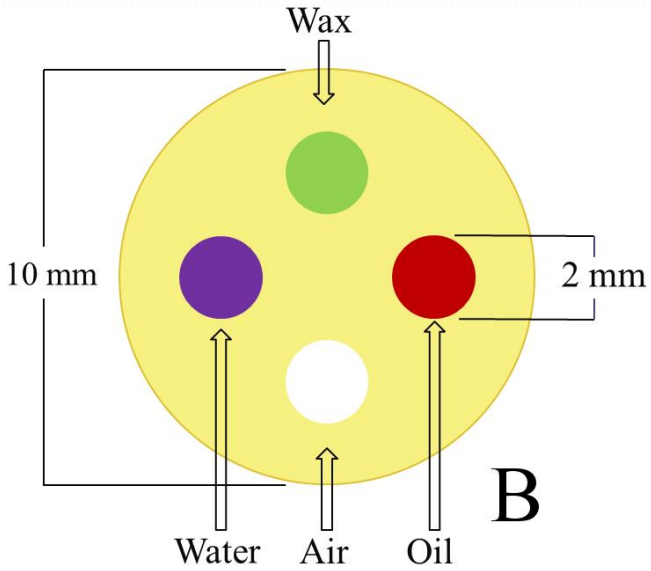
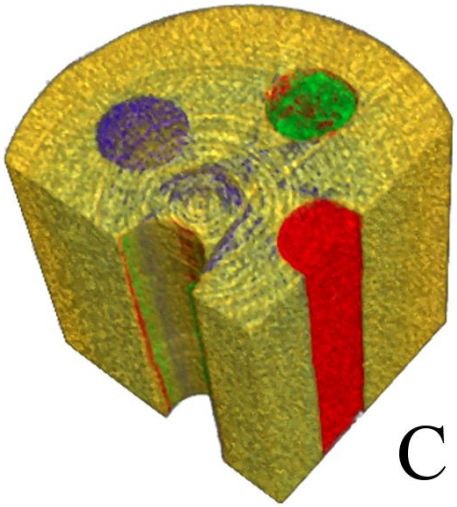
- Small animal uCT
- QUAD Timepix
- Tube voltage 60 kV
- Tube current 100 µA
- 180 projections
- 20 s per projection

- A: optical photo
- B: scheme layout
- C: volume rendering
- D: relative density histogram

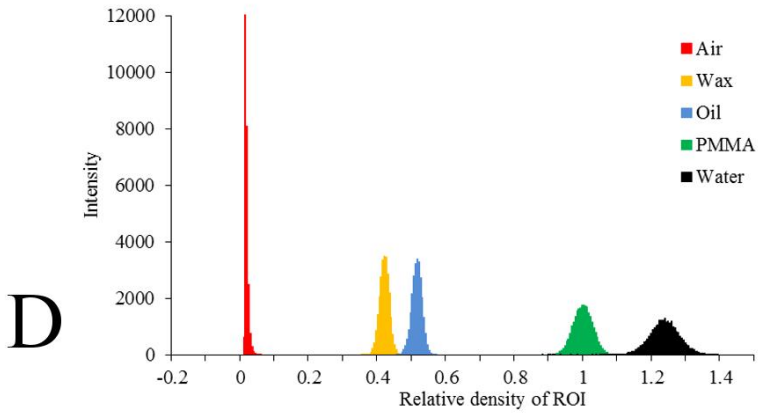
A



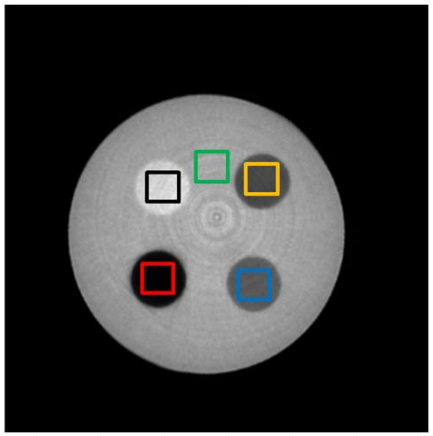
B



C



D



µCT slice

High resolution high contrast X-ray µCT
Soft tissue imaging of complex biological objects

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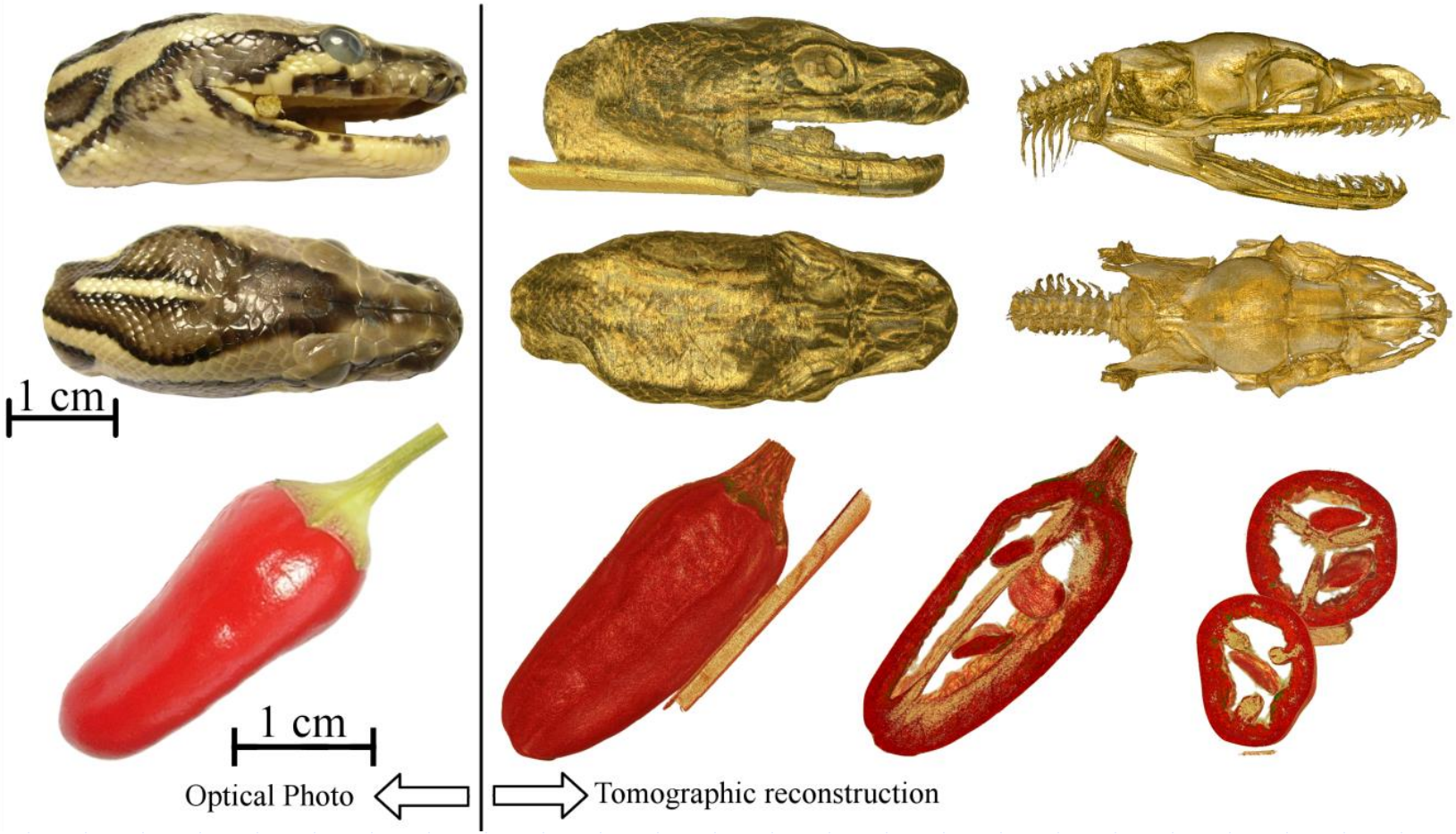

- Small animal µCT + Timepix QUAD (512 x 512 pixels), silicon 300 µm sensor
- X-ray tube voltage 60 kV, current 90 µA, 180 projections, 10 s per projection.

High resolution high contrast X-ray imaging
Soft tissue imaging of complex biological objects

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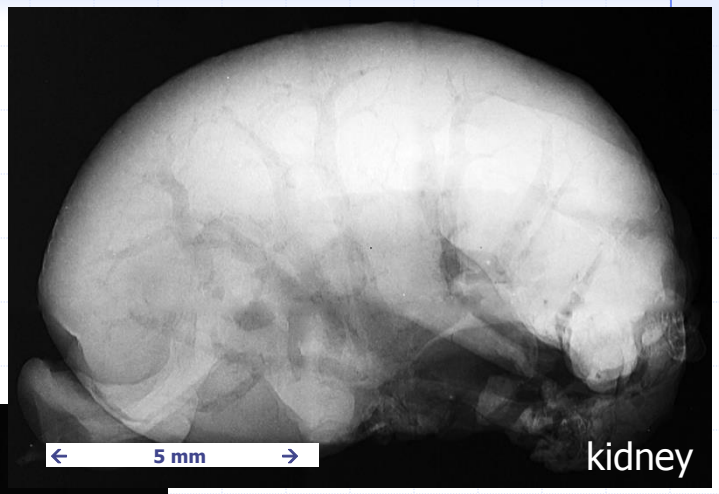
- 2D X-ray imaging of native and alcohol-fixed rat and mouse inner organs with the aim to study their anatomy and morphology
- Examples of alcohol-fixed mouse organs without any contrast agents



- Samples shown scanned with the small animal µCT scanner
- Timepix Quad detector
- Spatial resolution 28 µm
- Acquisition parameters: Tube voltage 60kV, current 100 µA, 45 s/acq

High resolution high contrast X-ray imaging
Imaging of biological objects + contrast agents

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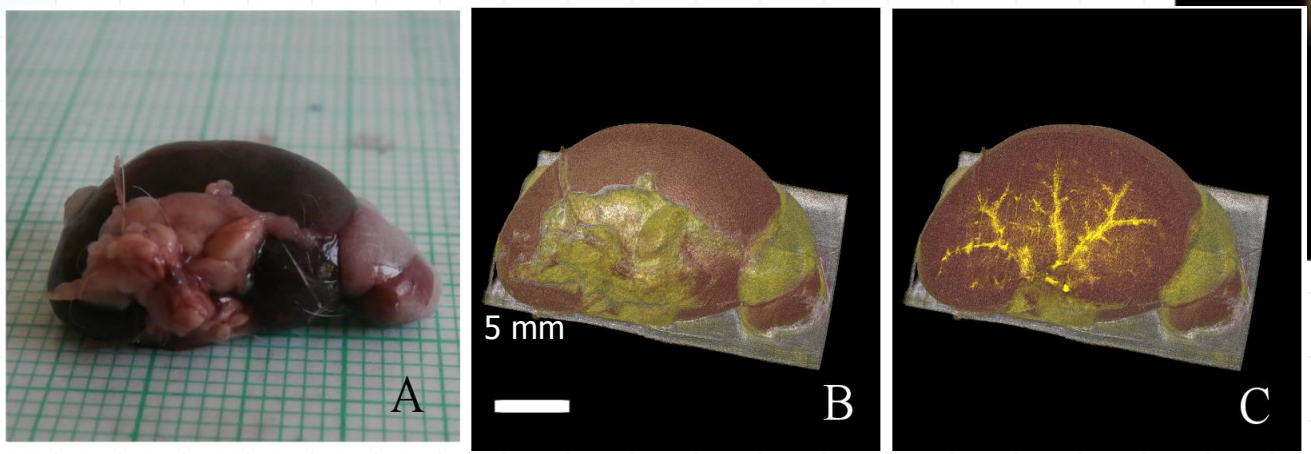
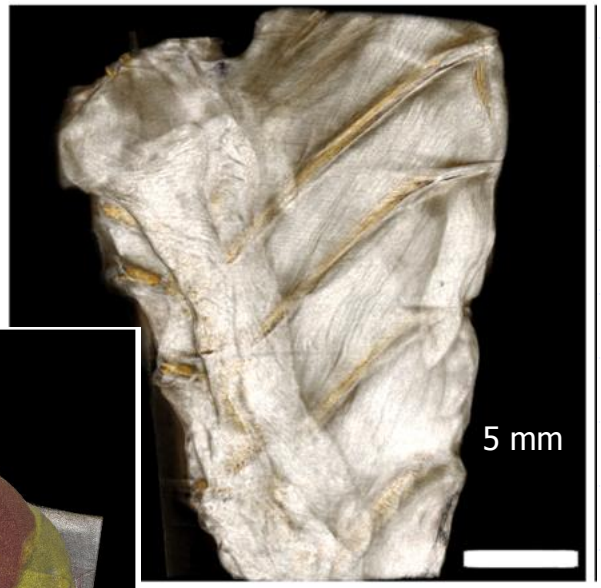
- Different available contrast staining methods and commercially available in vivo dedicated contrast agents are tested
  - Iodine based staining
  - $BaSO_4$
  - Aurovist™
- small animal μCT scanner + Timepix Quad detector

Volume rendering of a rat kidney with contrast enhanced by Aurovist™: A) Optical photo of the sample; B) Volume rendering of the tomographic reconstruction; C) A virtual section through rendered volume revealing enhanced contrast enhancement of cavities.





Volume rendering of a part of laboratory rat chest stained with Lugol's solution reveals the fibrous muscle structure.

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Small animal micro-CT& and mixed radiation field characterization in ion beam radiotherapy# and in outer space* with pixel detectors Timepix

Ion beam radiotherapy
Imaging of secondary radiation

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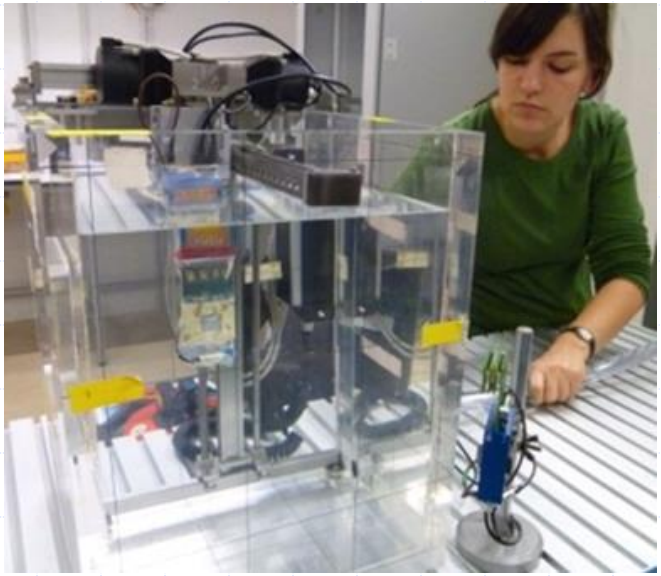
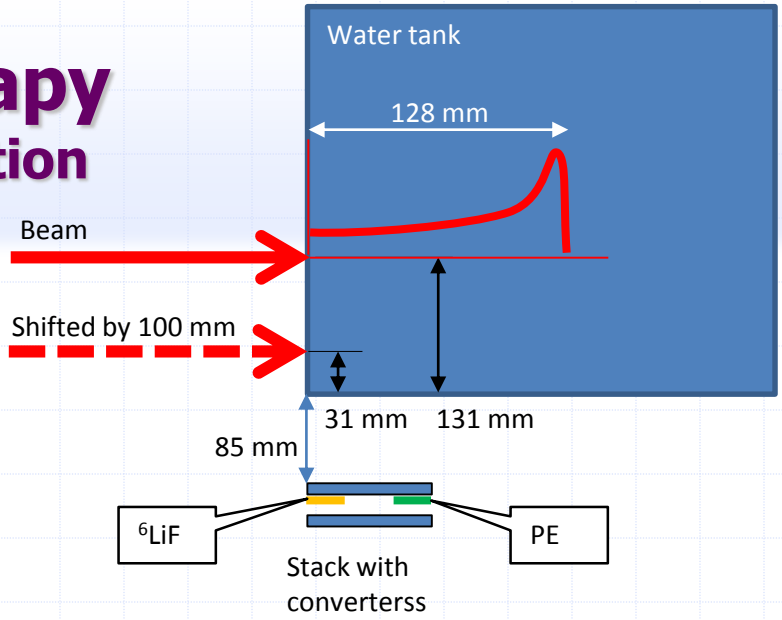
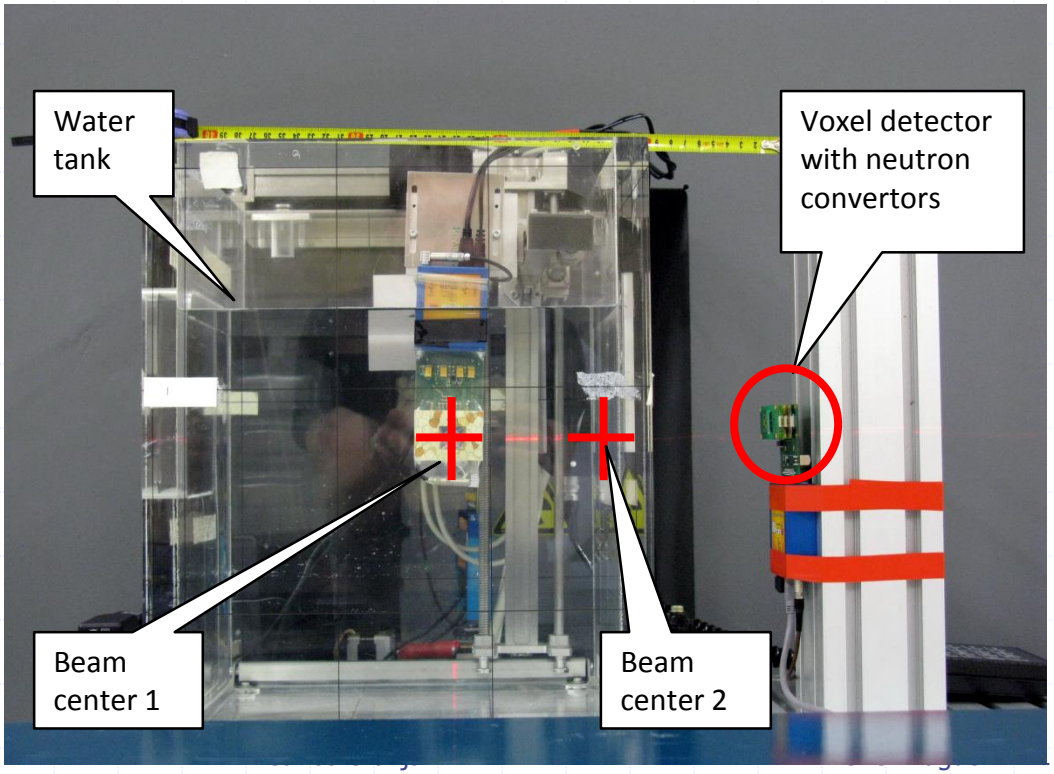




Beams: 1H, 4He, 12O, 16O
E: 50-400 MeV/u



Ion beam radiotherapy

Particle tracking with pixel detectors Timepix

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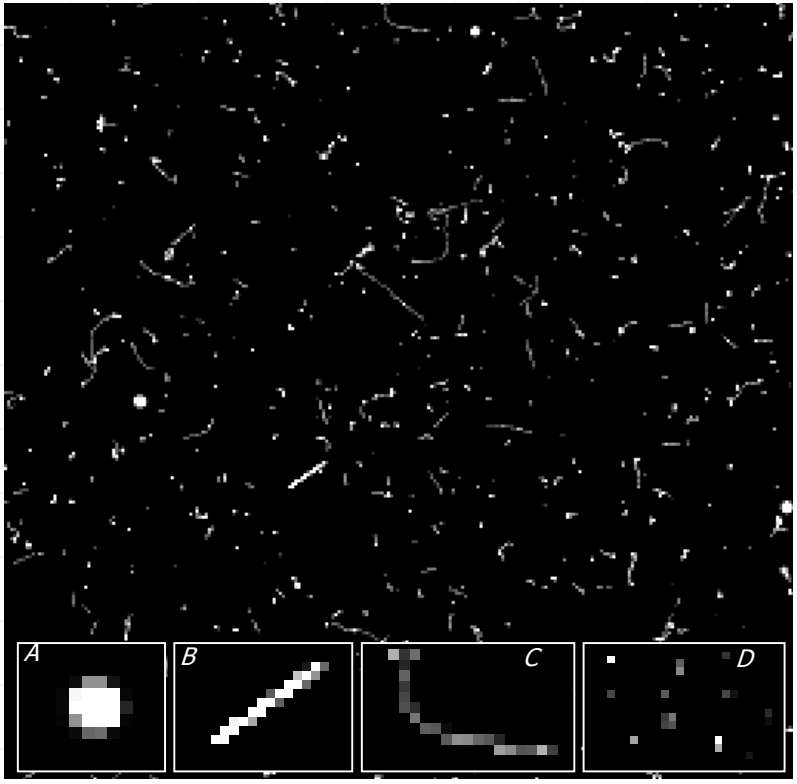
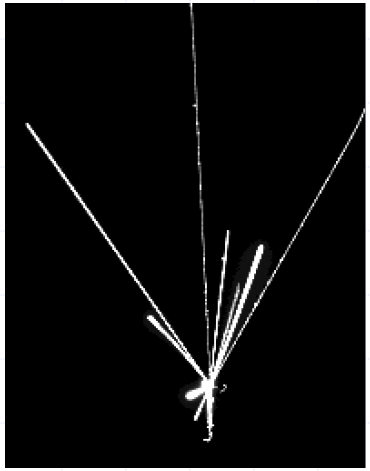
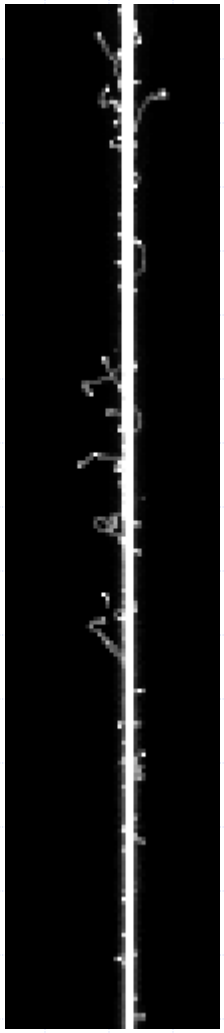


Lab radioactive source + cosmic ray background + long exposure



HIT: 430 MeV/u 12C primary beam: high LET interaction



HIT: 430 MeV/u 12C primary beam: energetic/delta electrons

Proton track

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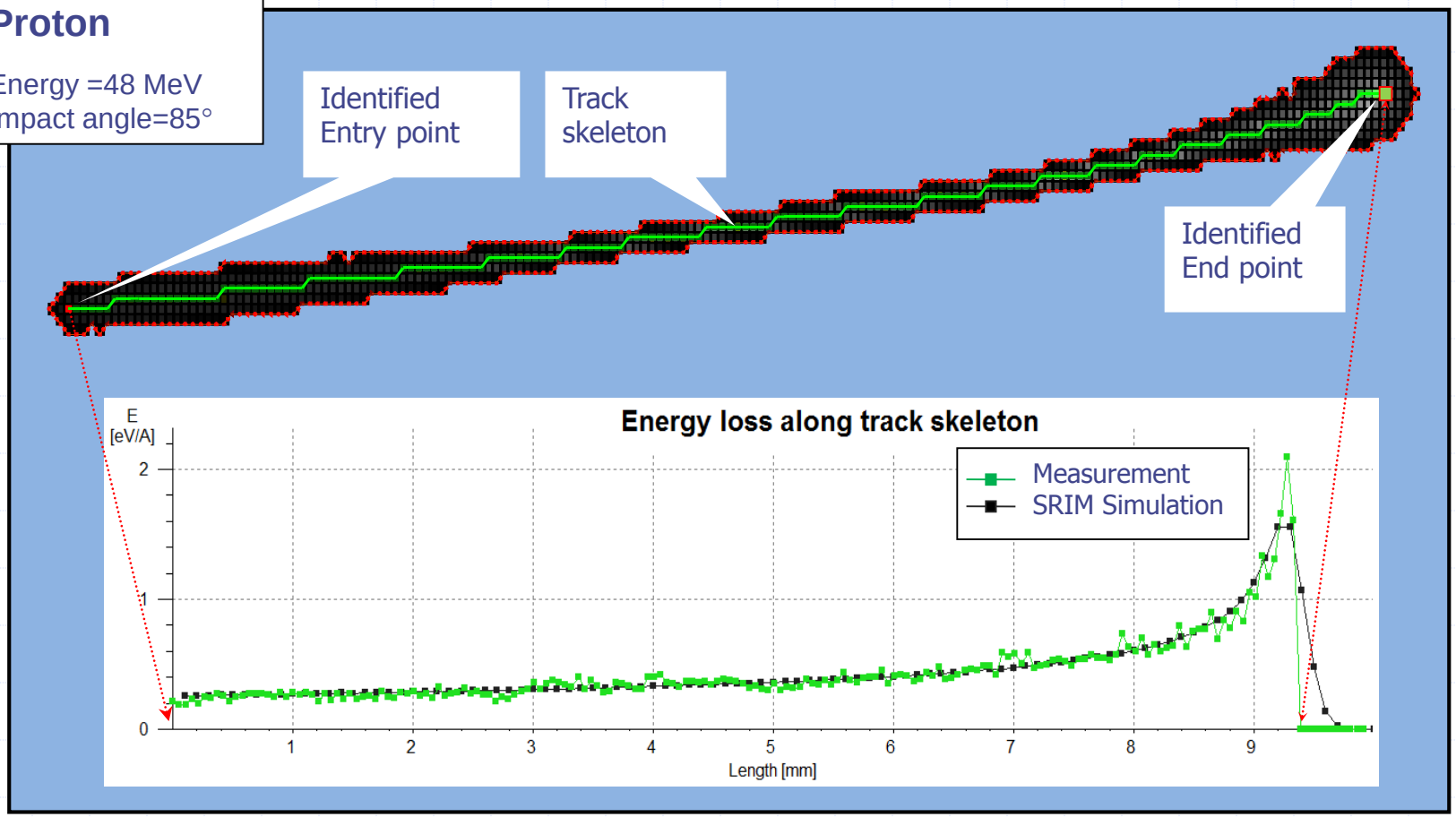
HIT: 48 MeV proton primary beam

Proton

Energy =48 MeV
Impact angle=85°



Calculation LET

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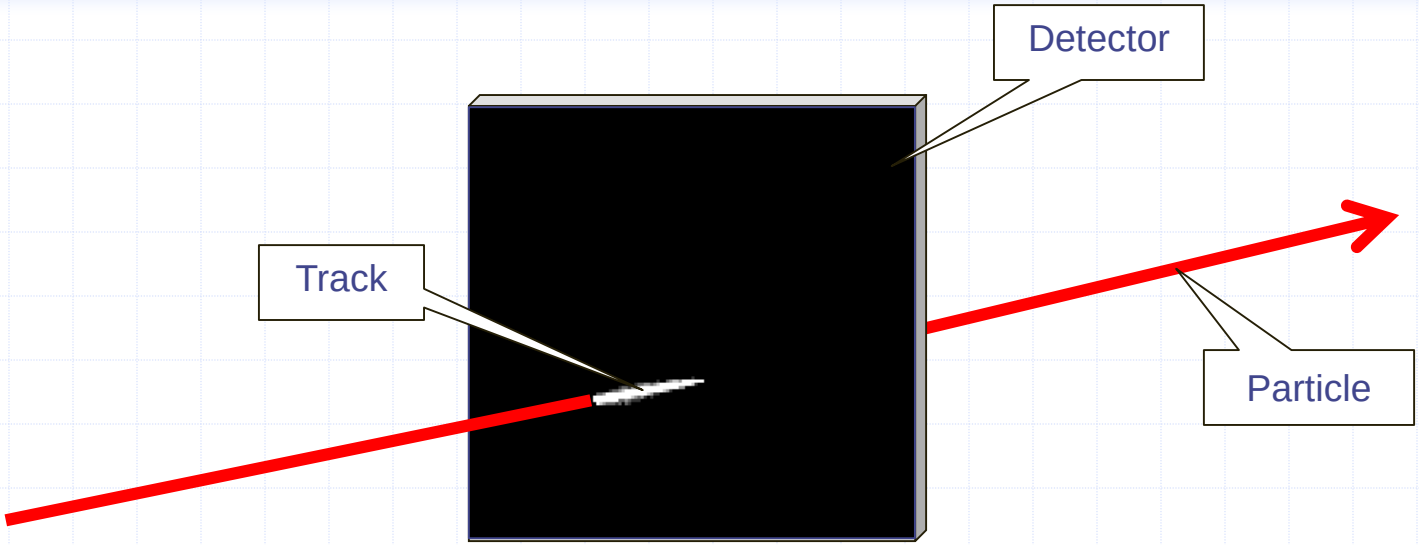

- LET calculated as the ratio of total deposited energy (integral of energies in all pixels of the cluster) and path length across of the particle through the sensor volume.

$$LET = \frac{dE}{dx}$$

- This calculation is affected of the path length which is better for long clusters.

Ion beam radiotherapy
Imaging + setup of measurements

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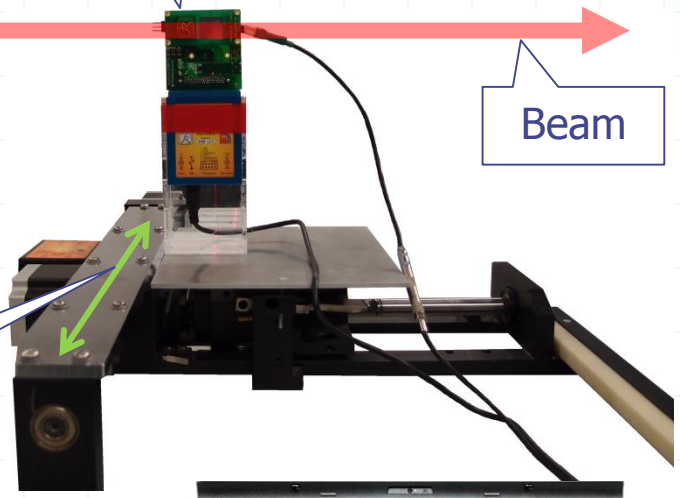
Exit window

Detector Timepix

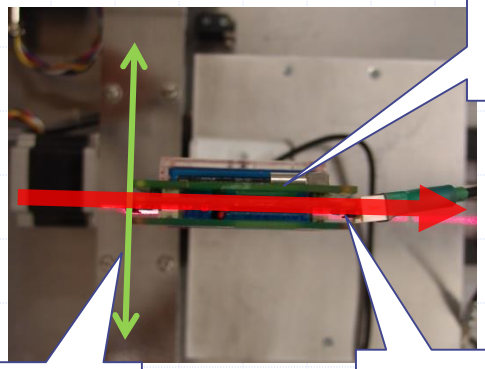
Beam

- Parameters of beam
  - Type : ^{12}C
  - Energy: 430 MeV/u (5120 MeV)
  - FWHM: 9.8 mm



Position system

View from the top



Detector Timepix

Position system

Beam

- Parameters of detector
  - Silicon detector
  - 1000 μm thickness
  - BIAS: 450 V
  - TOT mode
  - Event by event

Setup of measurement

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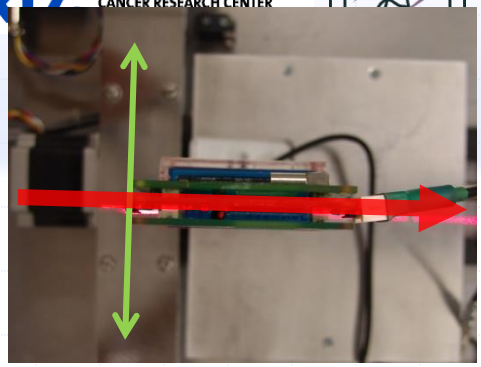
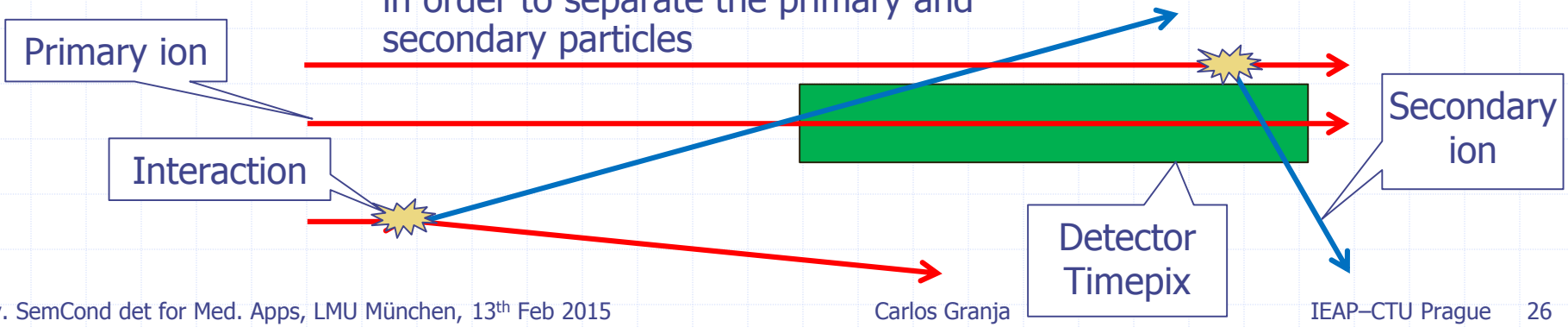


View from the top

- The detector orientation was parallel with respect to the beam axis.
- 8 different positions

- Detection of the primary ions
- Orientation of the detector was chosen in order to separate the primary and secondary particles



Ion groups sensitivity
LET spectrum

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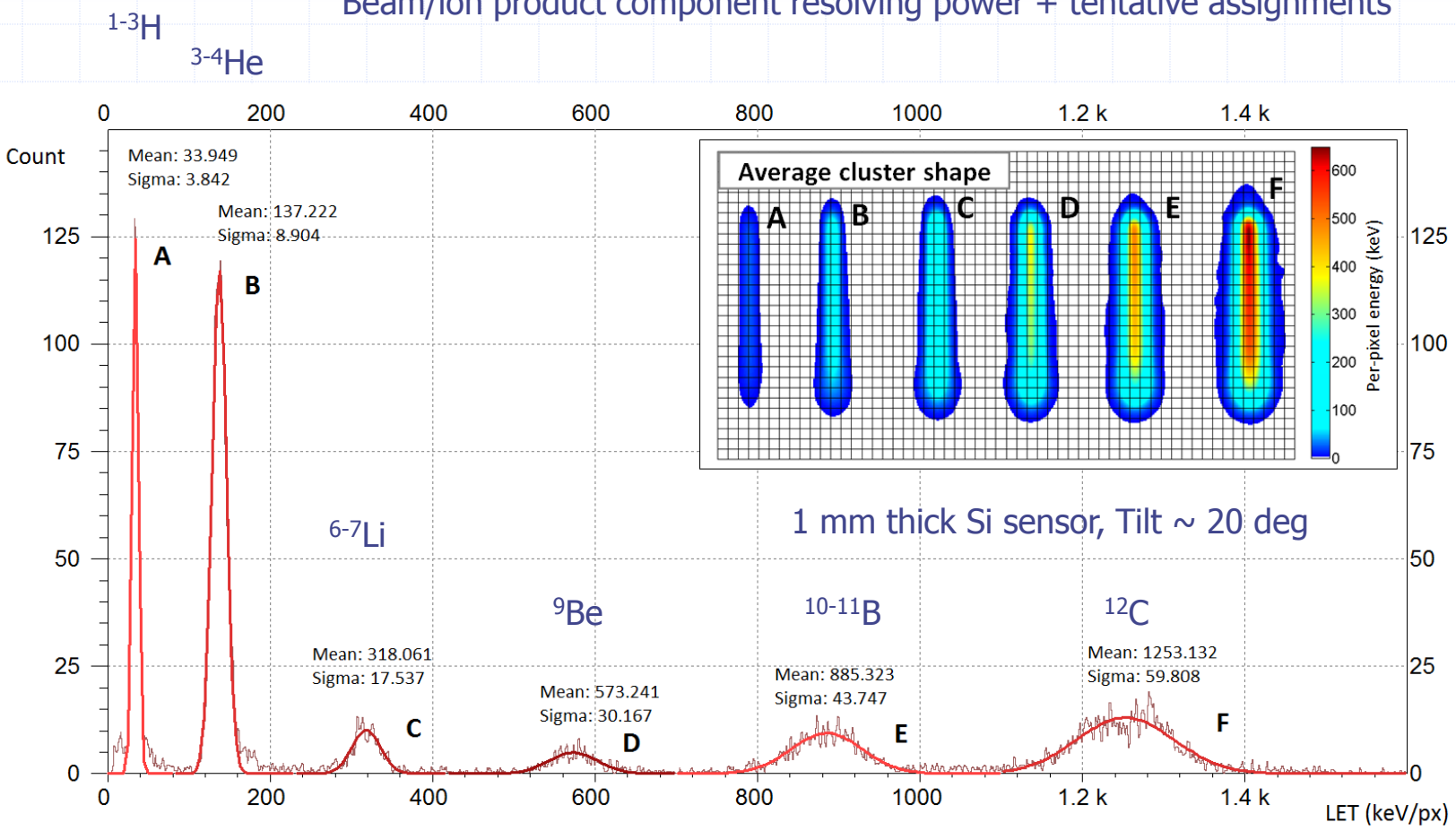
Beam/ion product component resolving power + tentative assignments



LET spectrum of particles detected 20 mm from the beam center.

Imaging for hadron therapy
Tracking of secondary particles & vertex visualization

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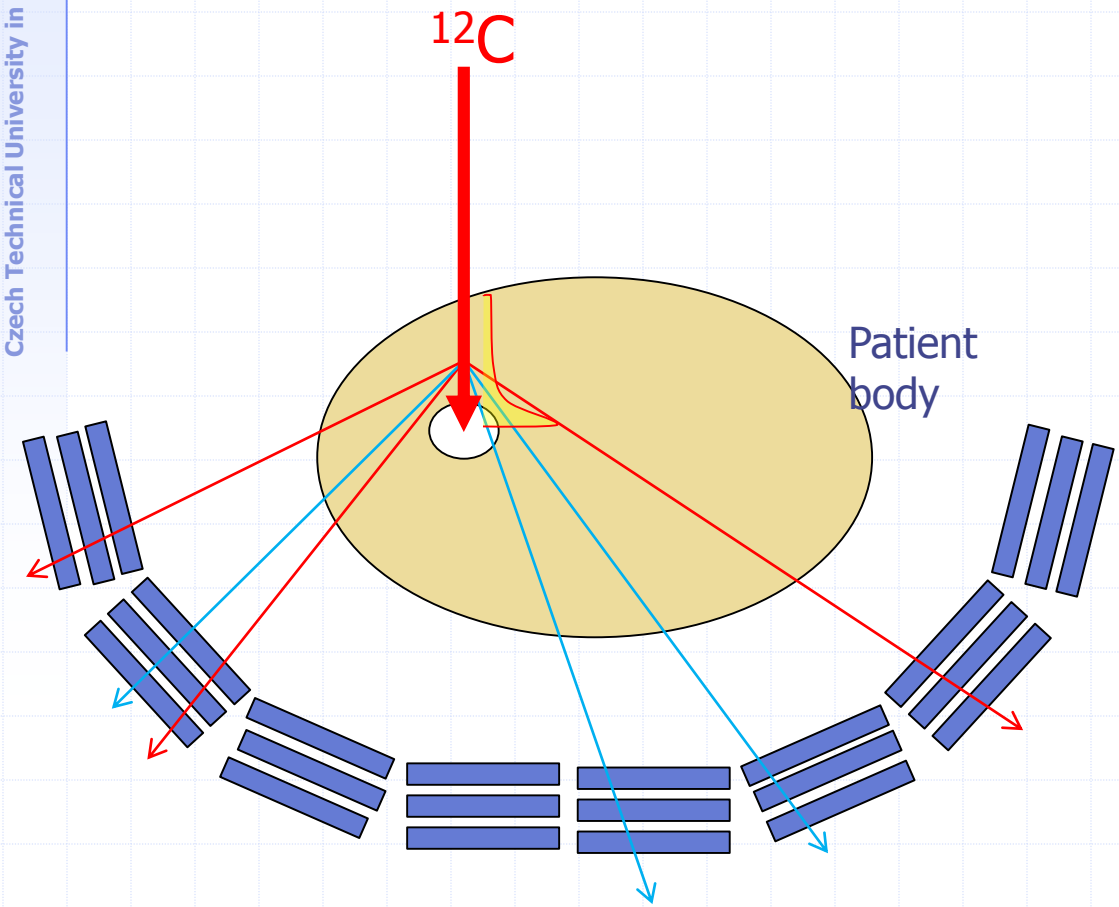

- The tracker can be scaled to surround the irradiated object.
- Tracker data can be back-projected to form an image of the beam path.
- Possibility to select particles with higher penetration power would improve quality.

Imaging for hadron therapy
Tracking of secondary particles & vertex visualization

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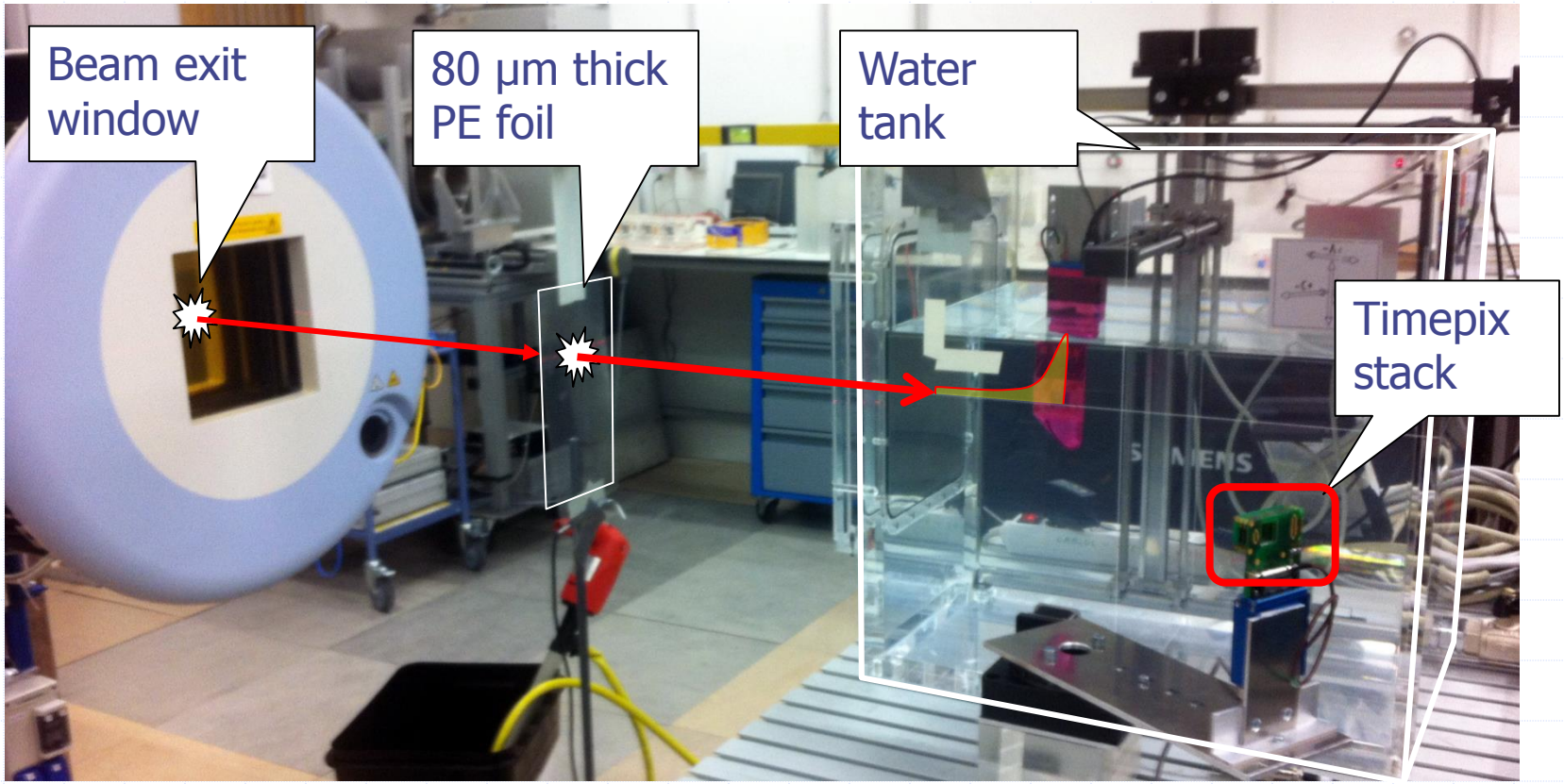
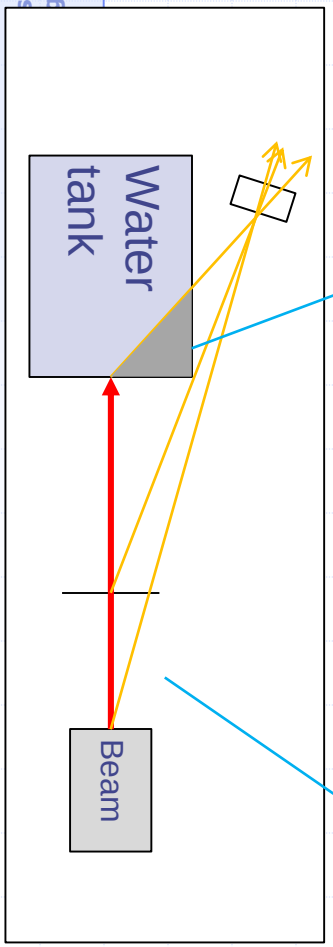
Timepix stack (voxel) detector + experimental setup

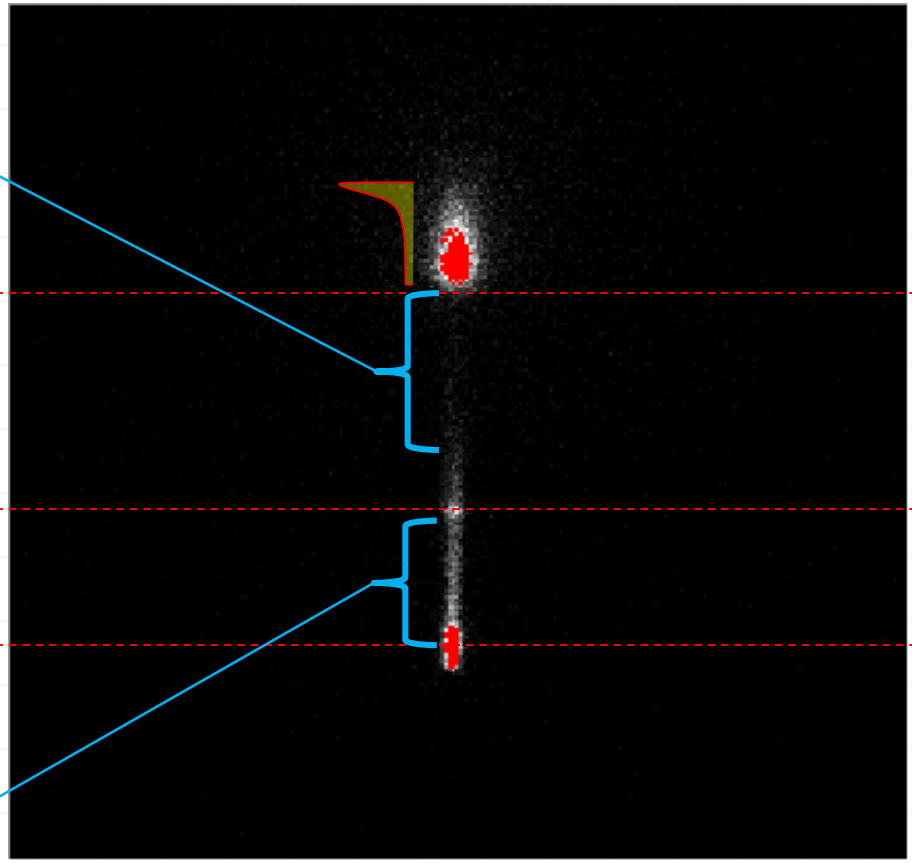


Vertex visualization

Beam line can be imaged



Reconstructed image (all coincident events)



Shielded by tank

Tank impact

Foil

Exit Window

Interaction s in air

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Small animal micro-CT& and mixed radiation field characterization in ion beam radiotherapy# and in outer space* with pixel detectors Timepix

Spacecraft Payload SATRAM
Space Application of Timepix Radiation Monitor

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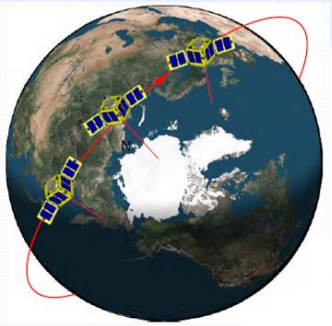
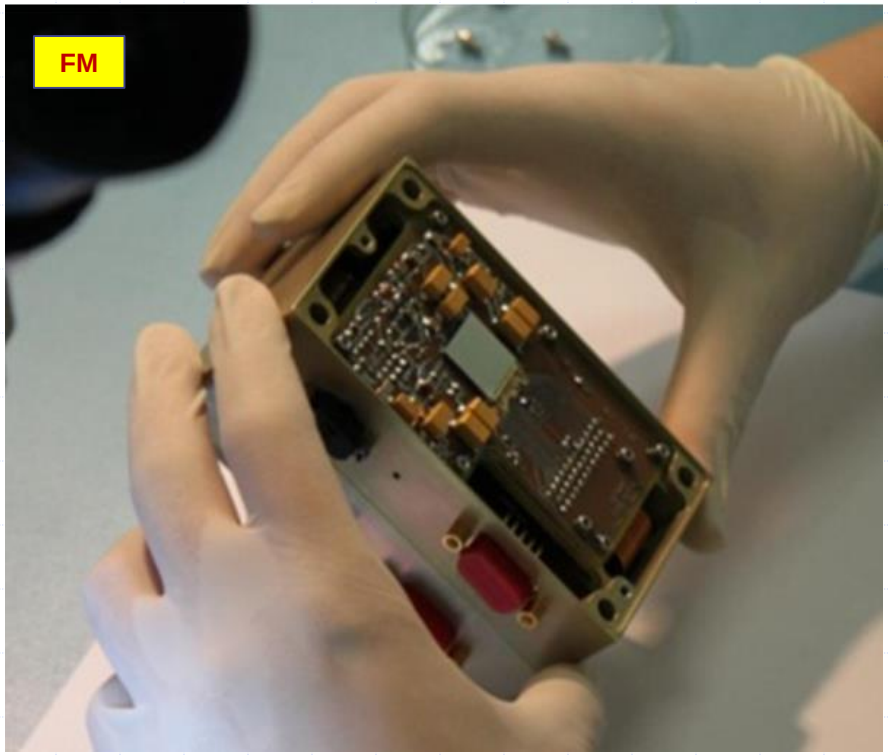


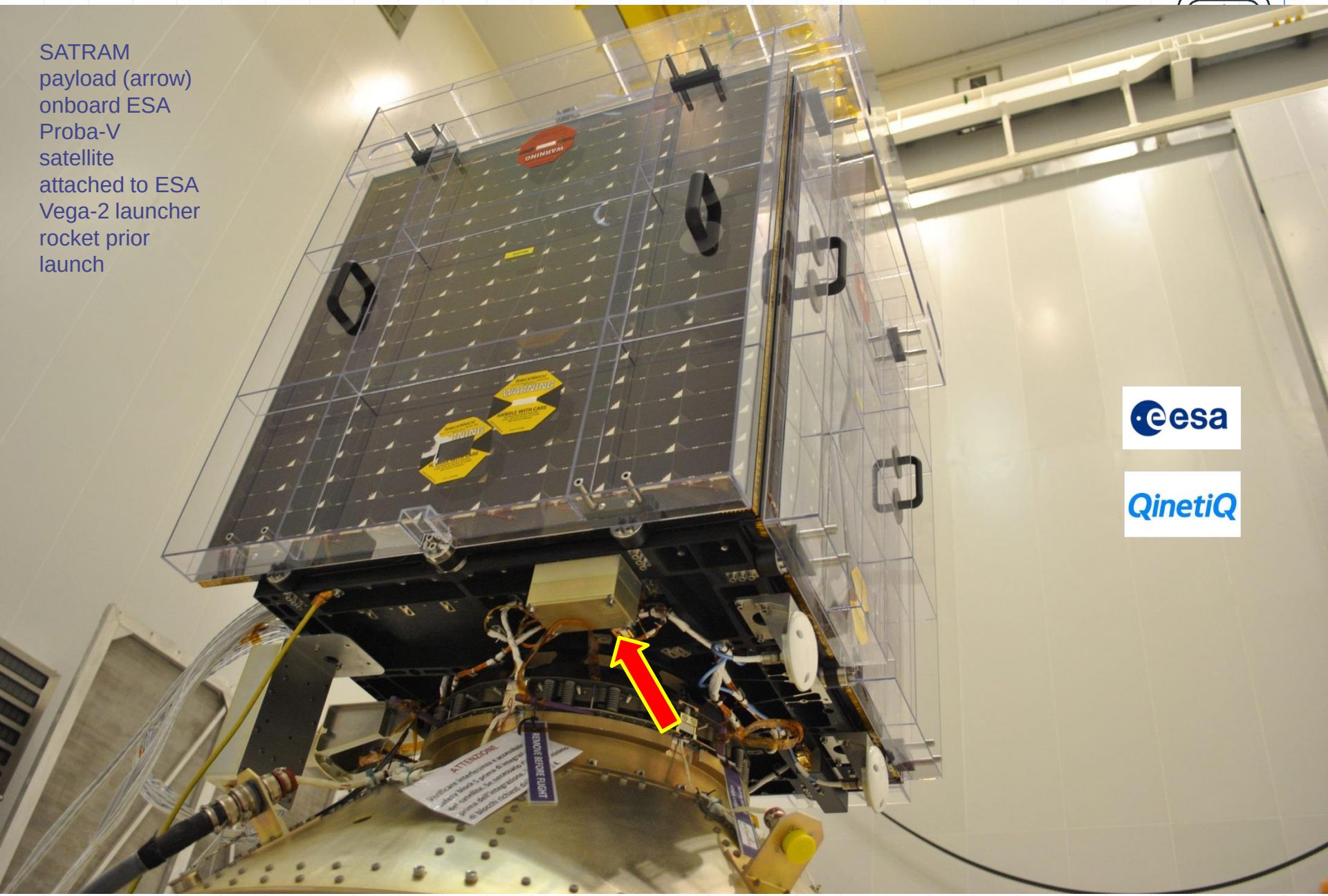
Characterization of space radiation in Low Earth Orbit (LEO) onboard ESA PROBA-V satellite

- Altitude ~ 820 km, polar sun synchronous orbit, 82° inclination
- Timepix for the first time in **open space** – currently TRL 9
- Launched 7th May 2013



Size: 10.8 cm × 6.3 cm × 5.6 cm, full mass 340 g

SATRAM payload (arrow) onboard ESA Proba-V satellite attached to ESA Vega-2 launcher rocket prior launch

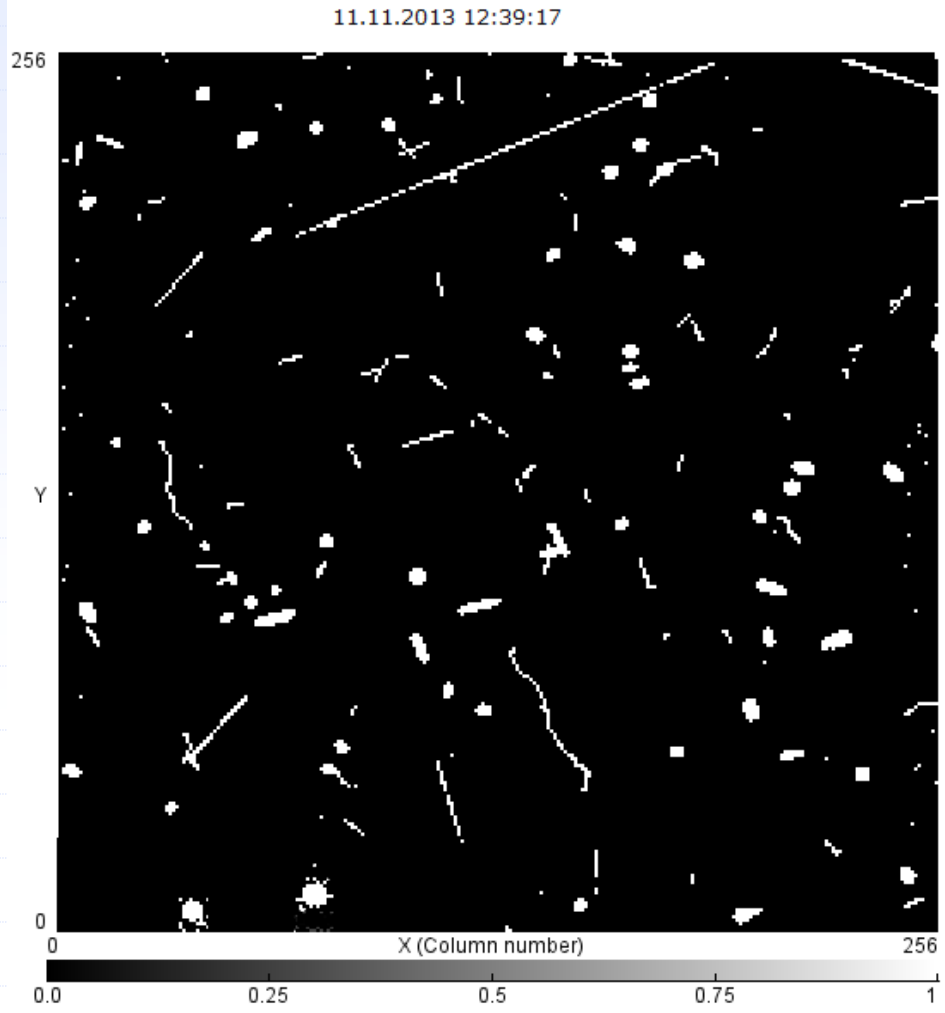


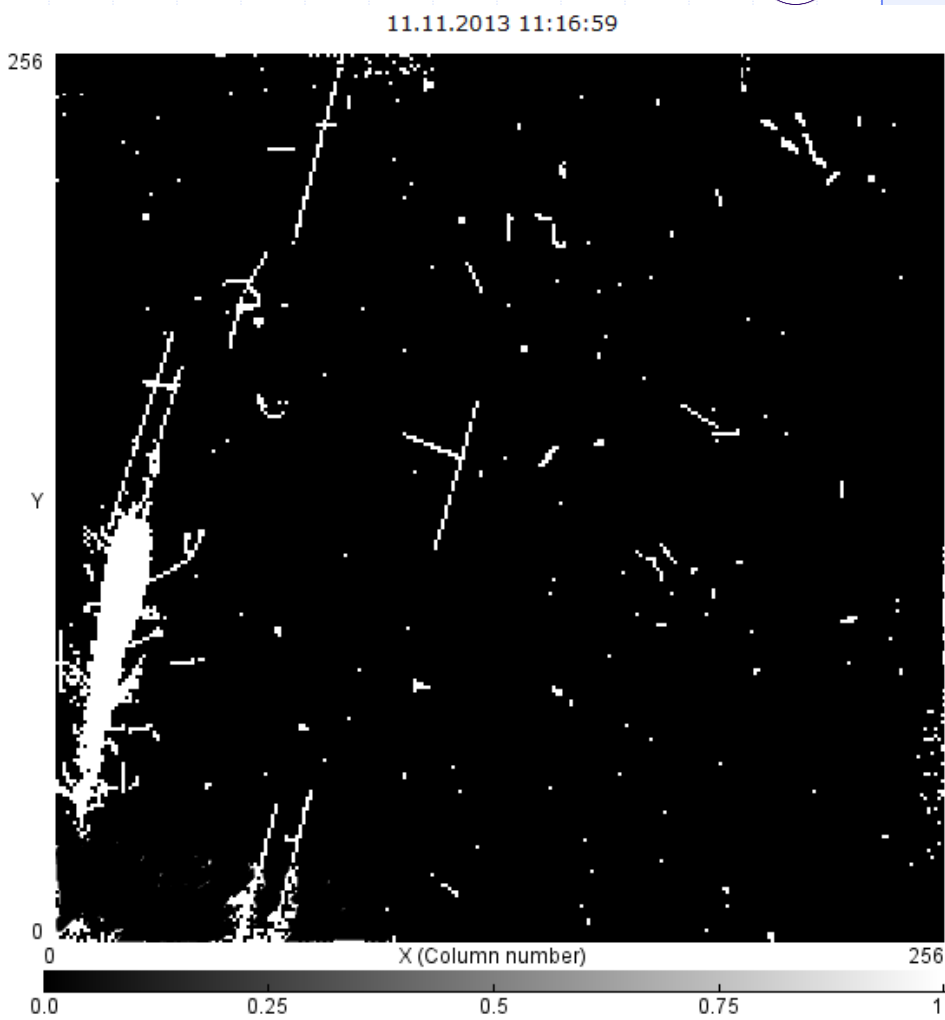
- SATRAM payload (arrow) onboard ESA Proba-V satellite.
- ESA Vega-2 launcher rocket upper stage

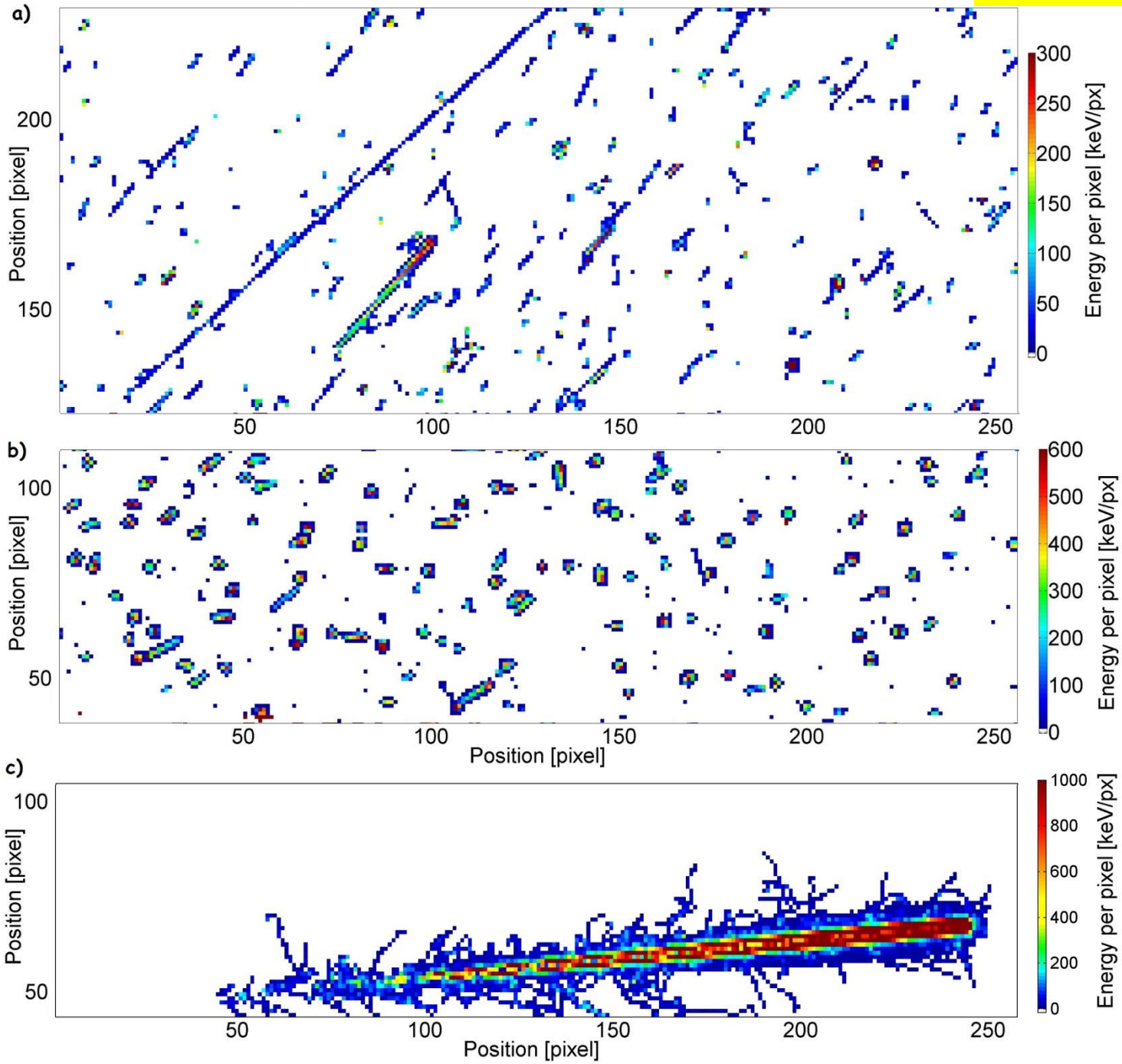
Timepix SATRAM/ESA Proba-V in Open Space

Quantum imaging detection/monitoring of space radiation

Low Earth Orbit (LEO), 820 km altitude





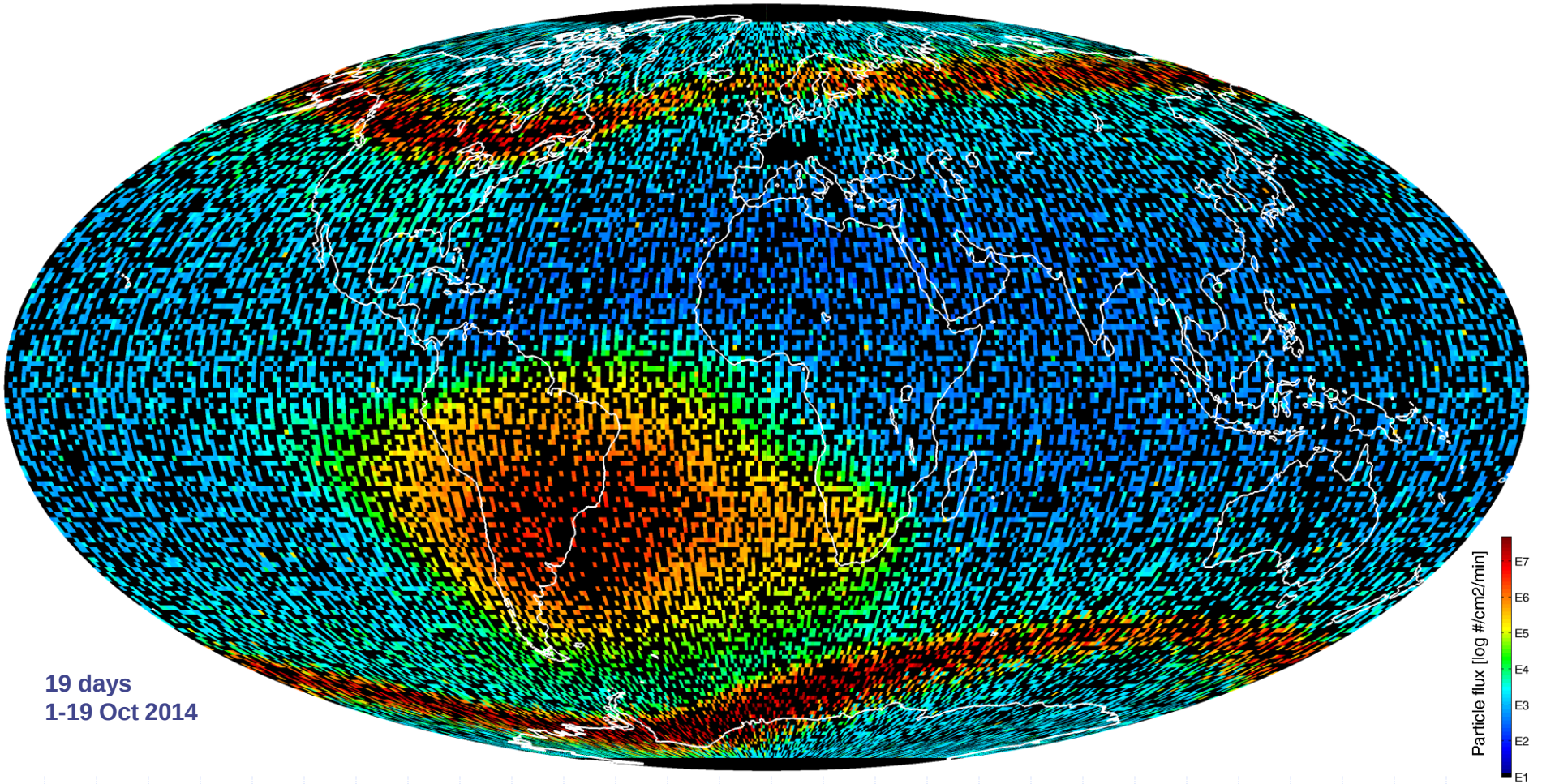


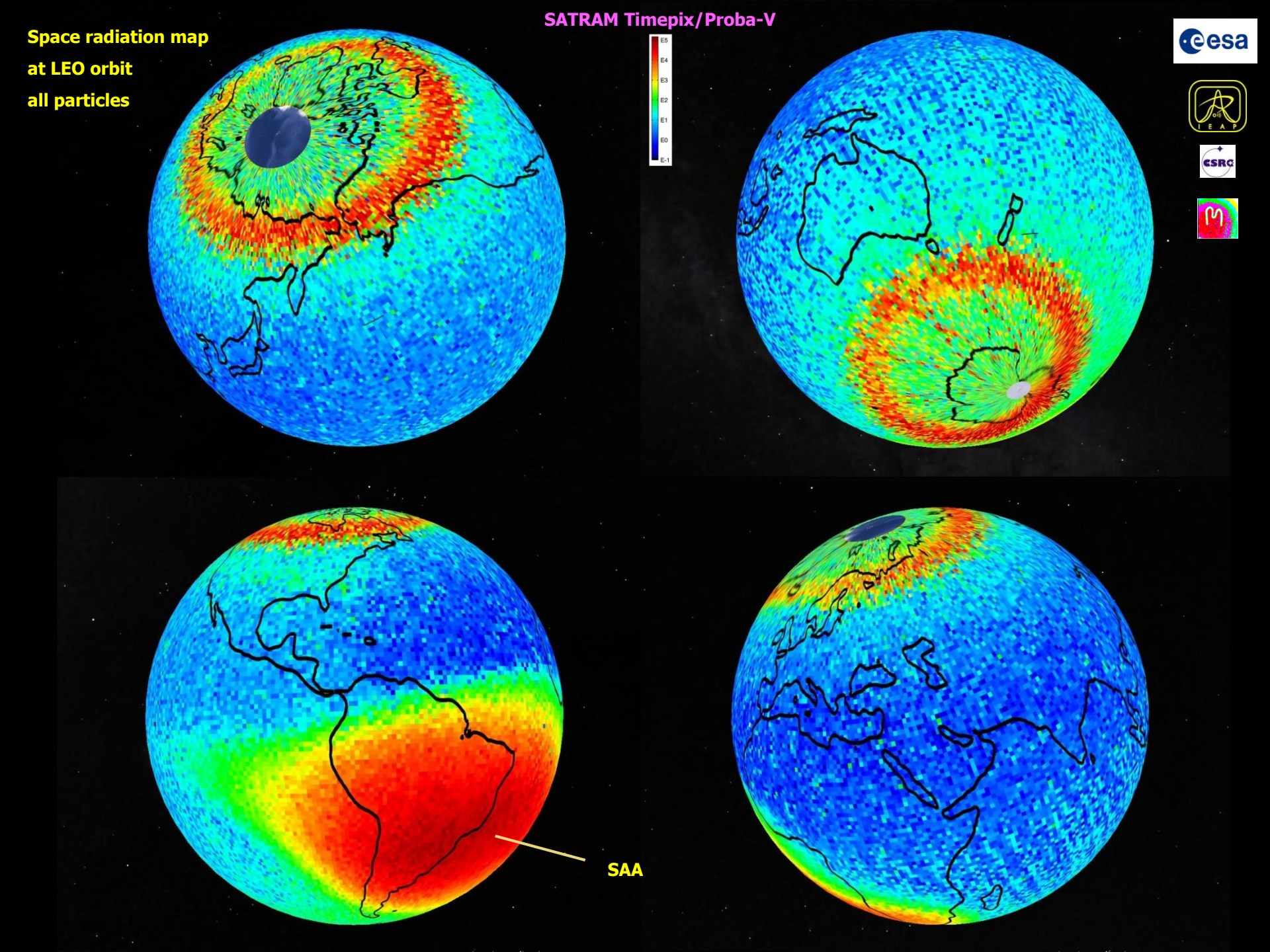
- Quantum imaging detection
- Resolving power radiation components
- directional sensitivity
- dE + track path → LET

Timepix SATRAM/ESA Proba-V in Open Space

Quantum imaging detection/monitoring of space radiation

Map: particle flux (all particles)



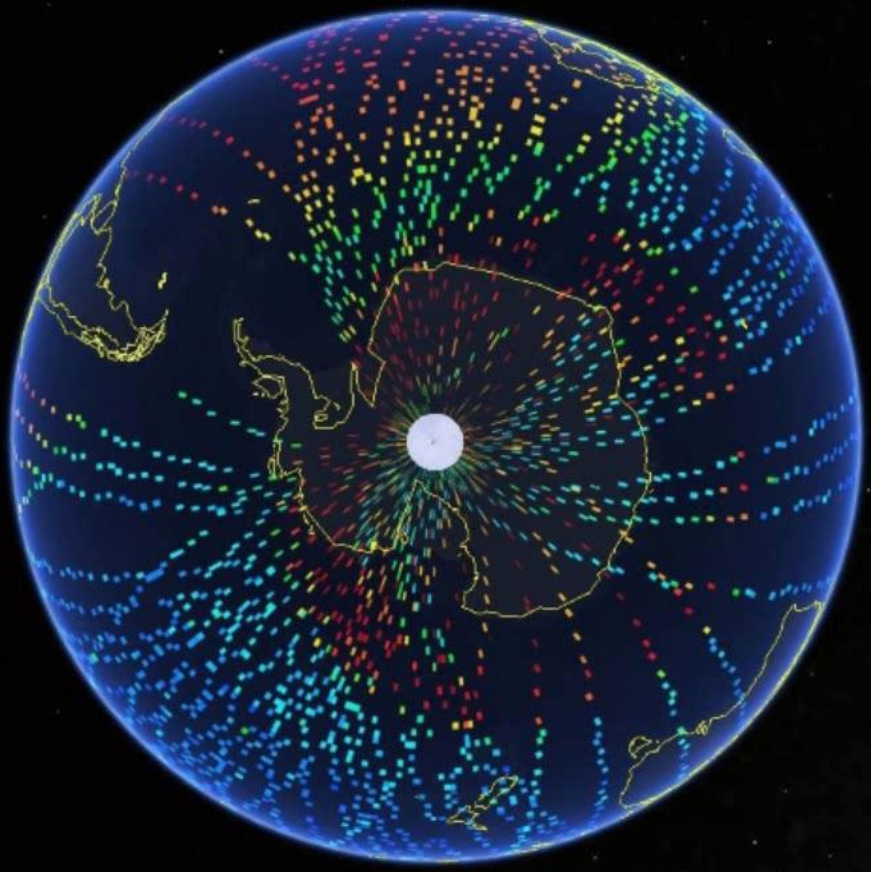

Space radiation map
at LEO orbit
all particles
SATRAM Timepix/Proba-V
E5
E4
E3
E2
E1
E0
E-1
esa
IEAP
CSRC
SAA

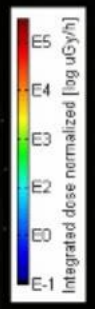
South Pole

Space radiation map at LEO orbit

SATRAM Timepix/Proba-V

3-9 Jan 2014





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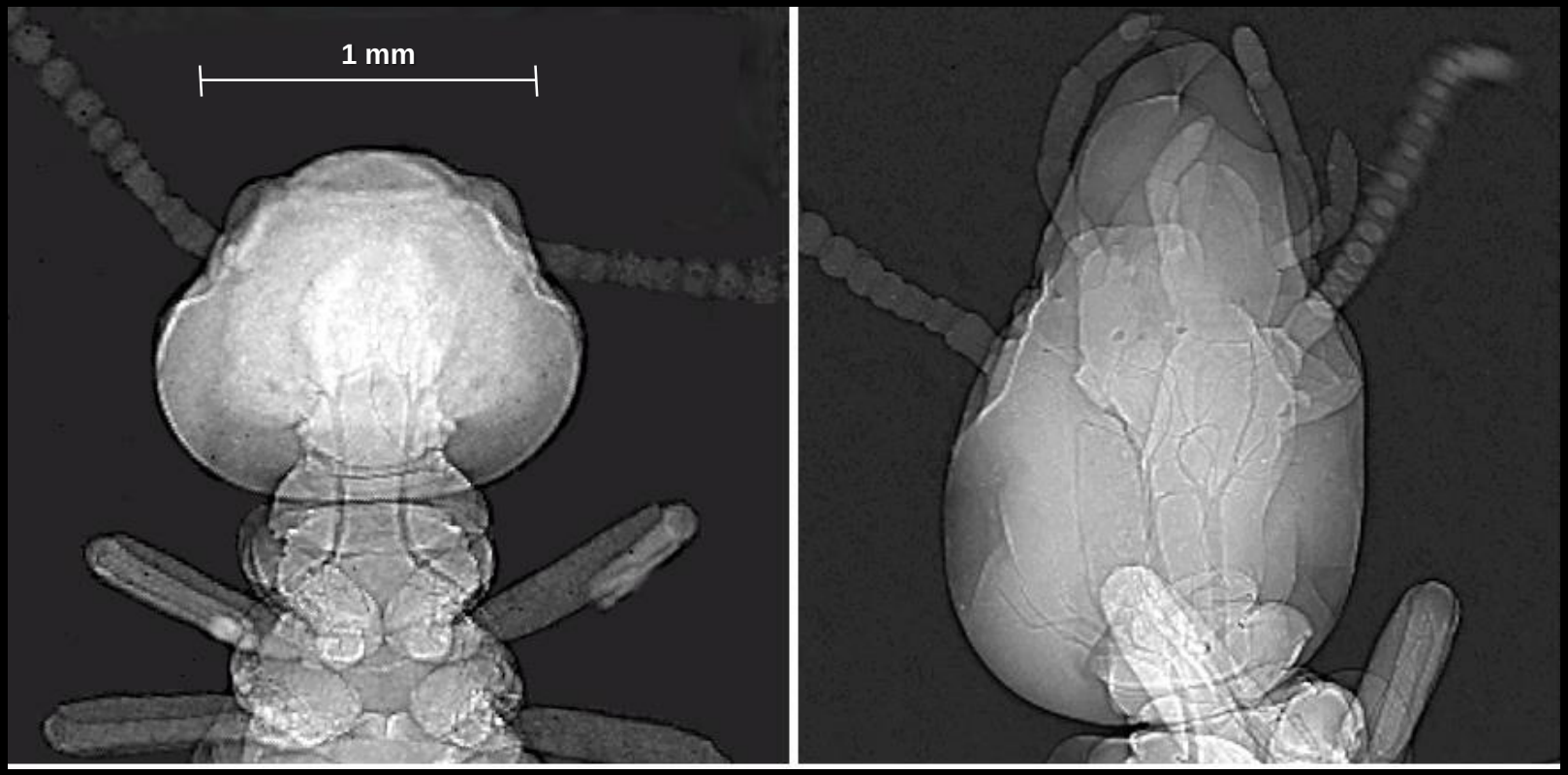
High resolution high contrast X-ray imaging

Living termites + observation of dynamic biological processes



Thanks to the organizers + audience

- X-ray radiographs of a termite worker before (left) and after 20 h (right) its metamorphosis toward the soldier caste (5s exposure ~ 0.7mGy dose)
- Micro-focus X-ray tube + Timepix detector
- Phase-contrast enhanced sensitivity