TECHNOLOGY AND INNOVATION GROUP
EUROPEAN PHYSICAL SOCIETY
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Quantum Dosimetry and Directional Visualization of Radiation in Space with Timepix Detectors

Carlos Granja

Institute of Experimental and Applied Physics
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Research carried out in frame of the CERN Medipix Collaboration
Work funded by the European Space Agency

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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
- Radiation in space (gamma, neutron, micro-sensor)

Space applications

Fundamental Experiments in the Physics of the Microworld

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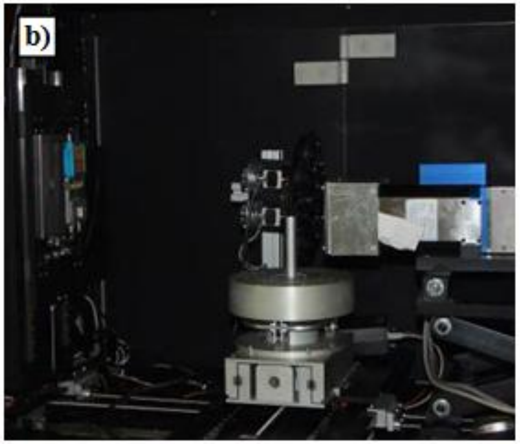
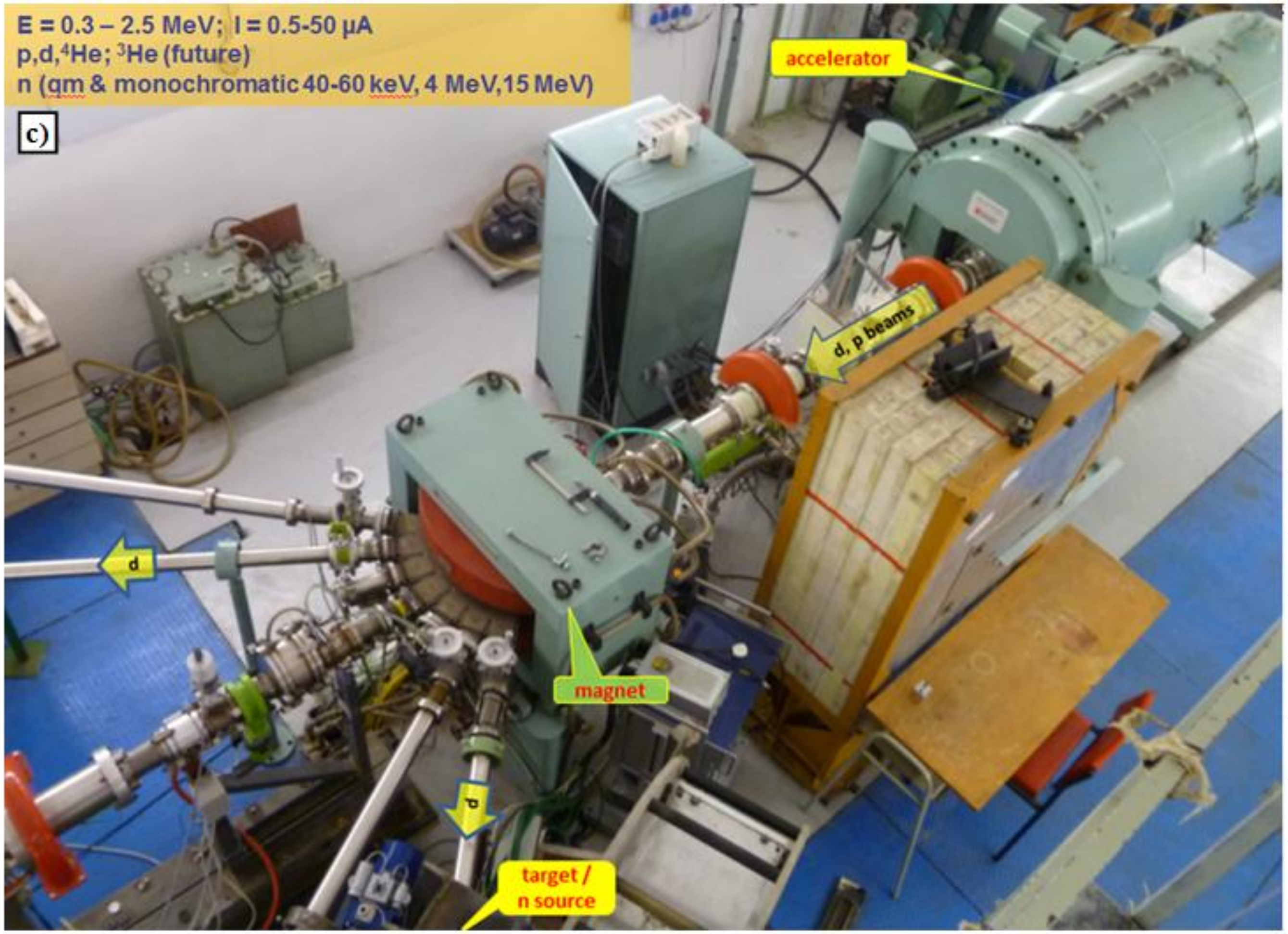
IEAP CTU in Prague

R&D Radiation Detectors, Radiation Spectroscopy, 2.5 MeV VdG ion accelerator

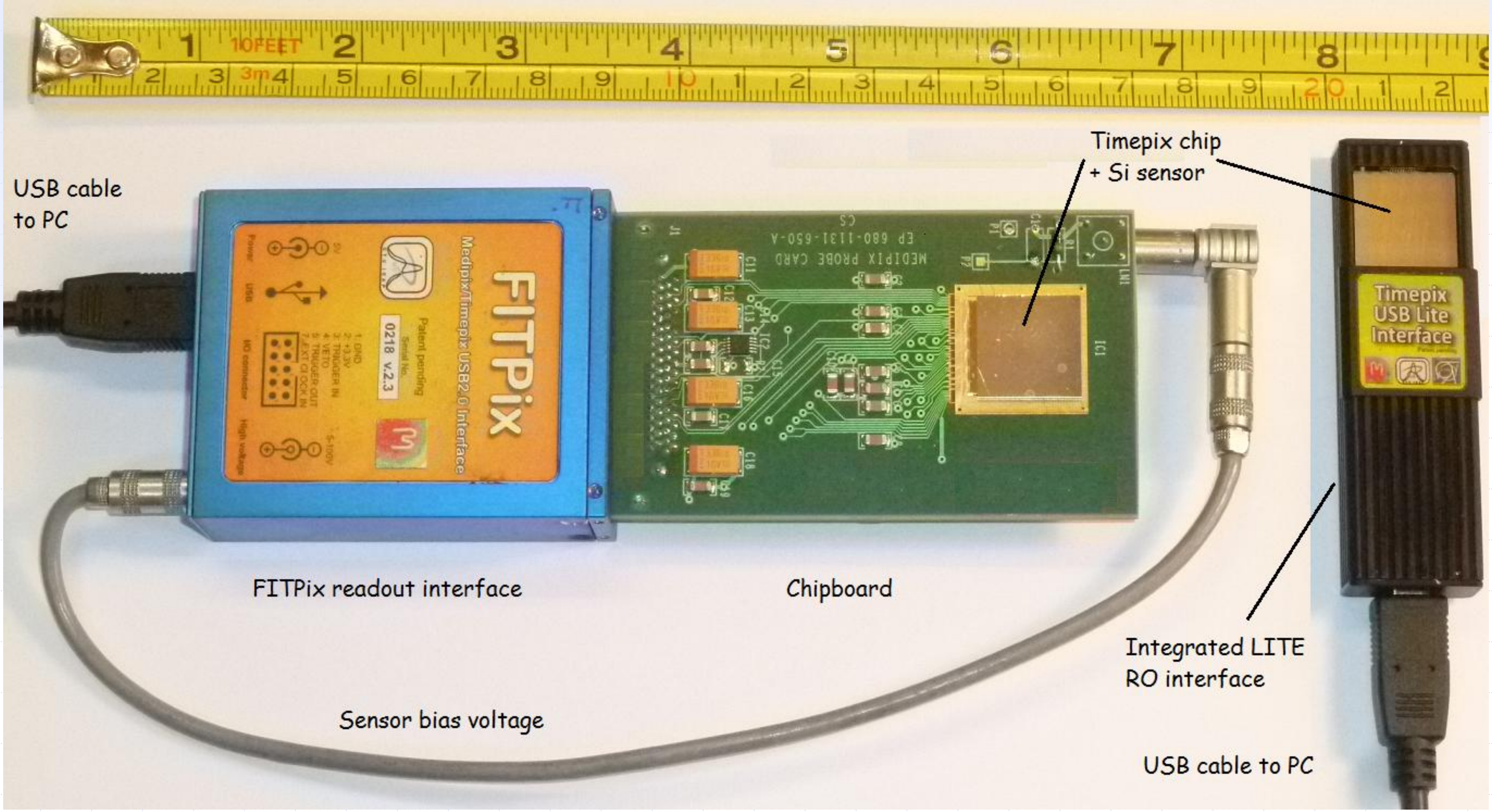




Clean room (a), X-ray micro-tomography unit and X-ray pencil beam test bench (b), Van de Graaff accelerator and beam guides (c).

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

www.cern.ch/medipix



Radiation camera assembled from the Timepix chip, detector chipboard and FITPix readout interface (left). Highly miniaturized Timepix LITE (right). Straightforward connection to PC via USB cable.

Timepix: Radiation Imaging
High resolution high contrast X-ray imaging

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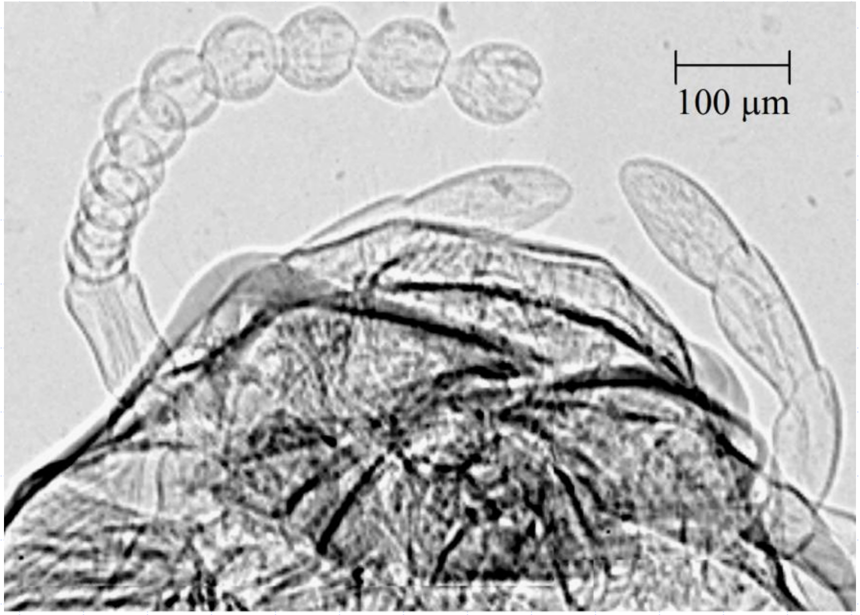
Living specimen, soft tissue contrast

X-ray transmission image of termite worker body (left) and detail of its head (bottom). Even fine internal structure of the antennae is recognized.

(Magnified 15x, time=30s, tube at 40kV and 70μA)



High resolution high contrast X-ray imaging
Living termites

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Images of a termite worker before (left) and after (right) its metamorphosis toward the soldier caste (5s exposure ~ 0.7mGy dose)

High resolution high contrast X-ray imaging
Living termites + X-ray phase contrast enhanced

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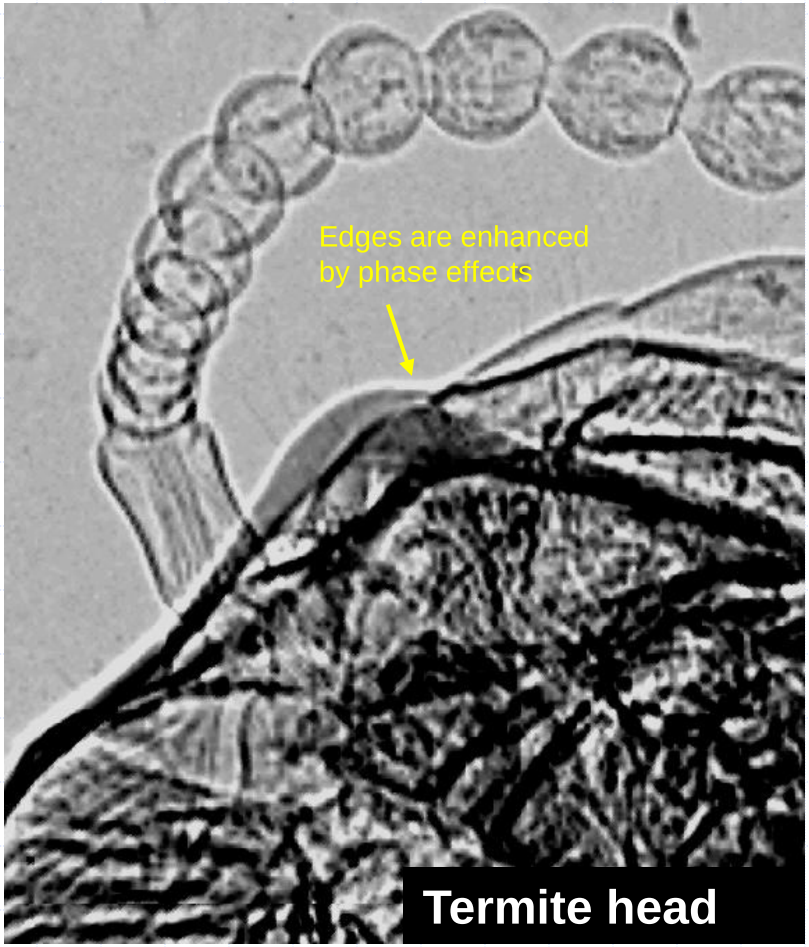
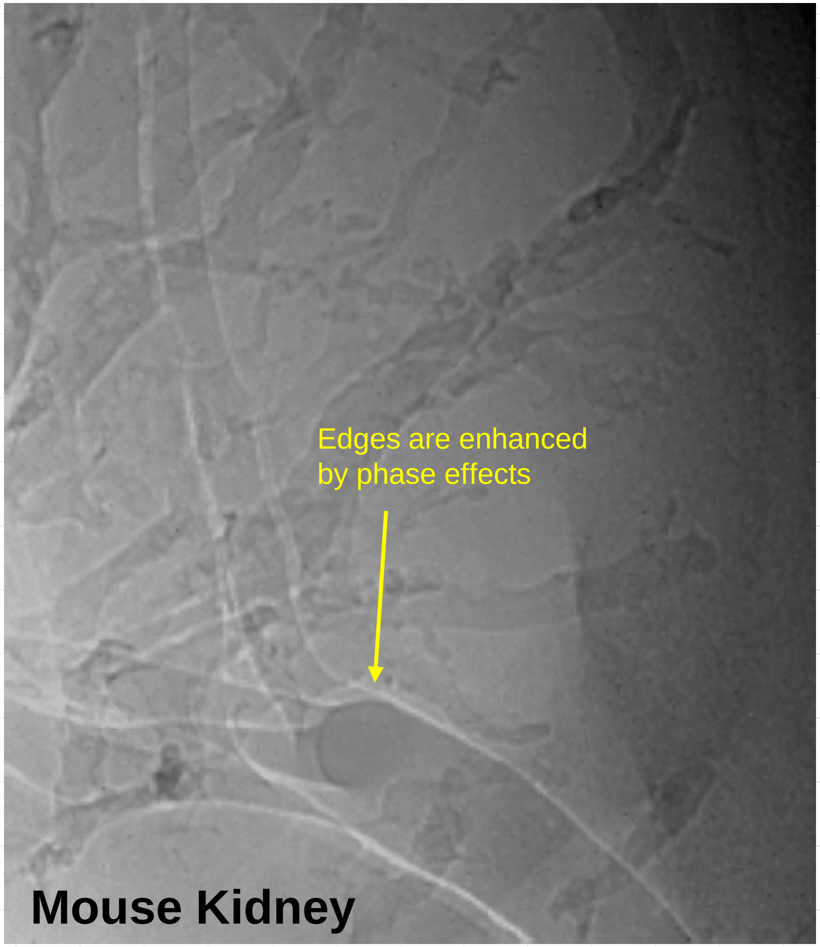
Edges are enhanced by phase effects





High resolution high contrast X-ray imaging
Leaf Miner – story

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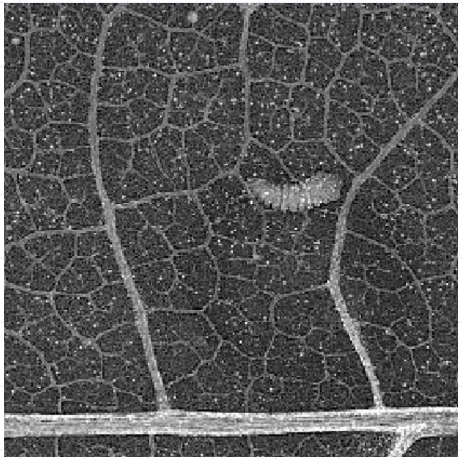
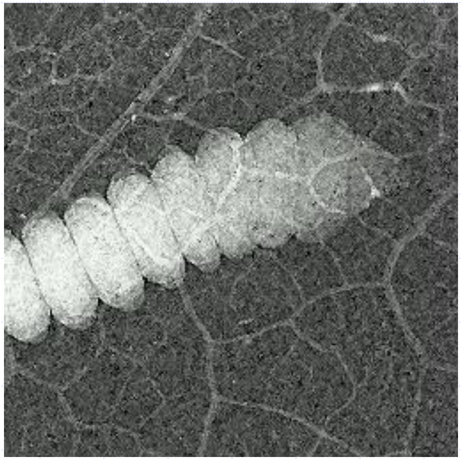
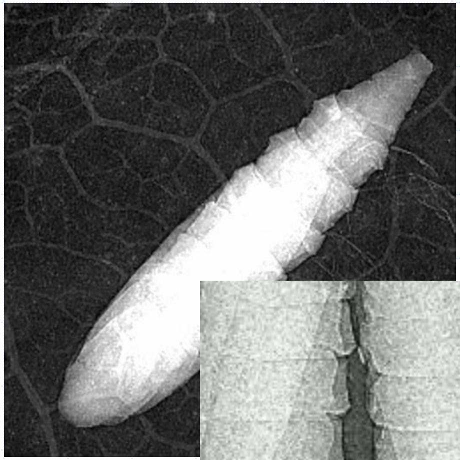
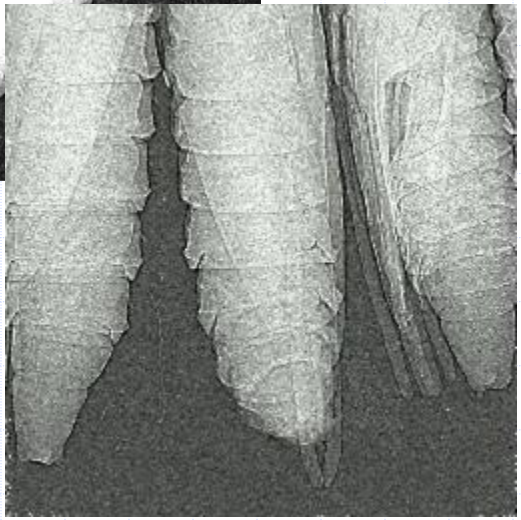
Worms are growing up and after three feeding instars larvae build-up a silken cocoon (pupae)

Several collected pupas

Stream imaging ⇨ observation of dynamic biological processes

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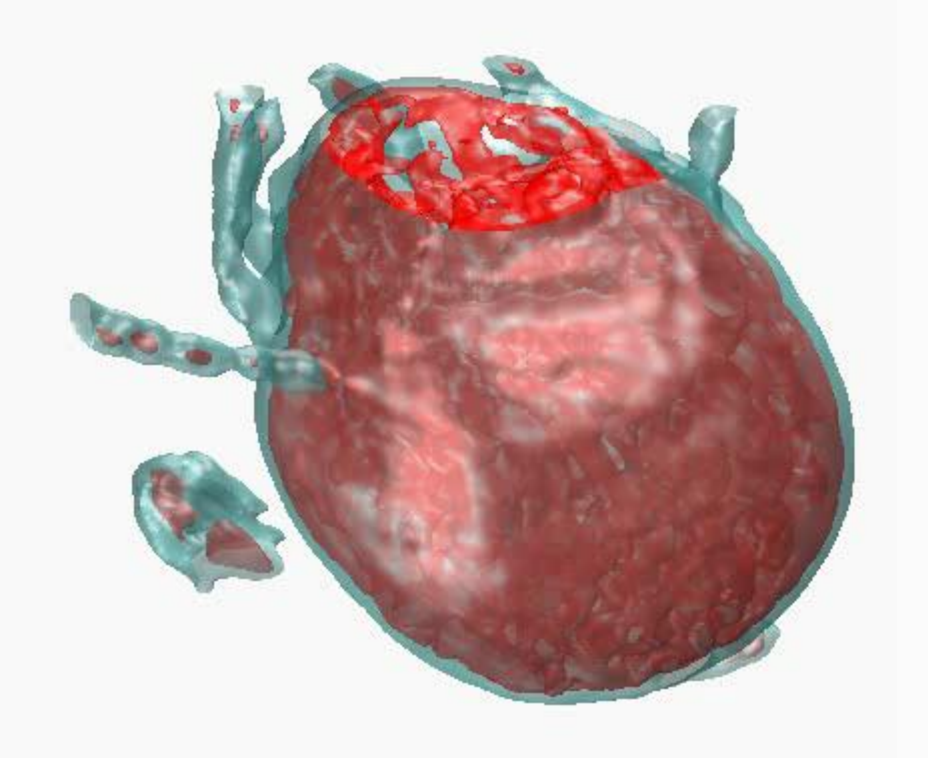
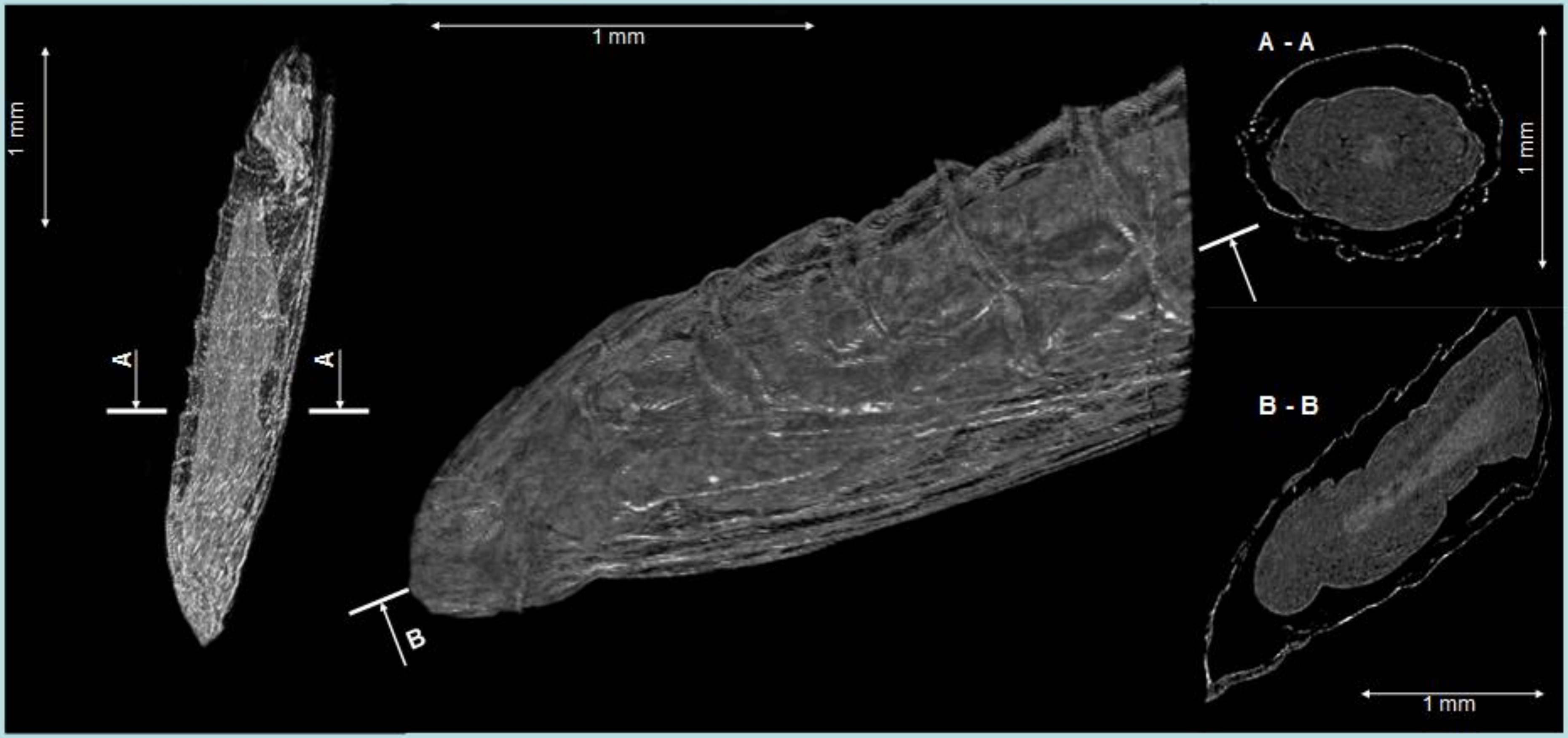
X-ray micro-CT:
Imaging of Living Termites



Tomographic reconstruction of the worker form of the same living termite individual.
Only 20 projections (5 seconds each) have been used for the reconstruction.

micro-CT of living biological specimen

3D of a pupa of entomoparasitoid inside a pupa of Cameraria



Few examples of tomographic reconstructions and cuts of a living pupa of entomoparasitoid inside a leaf miner pupa.

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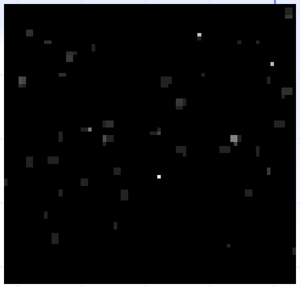
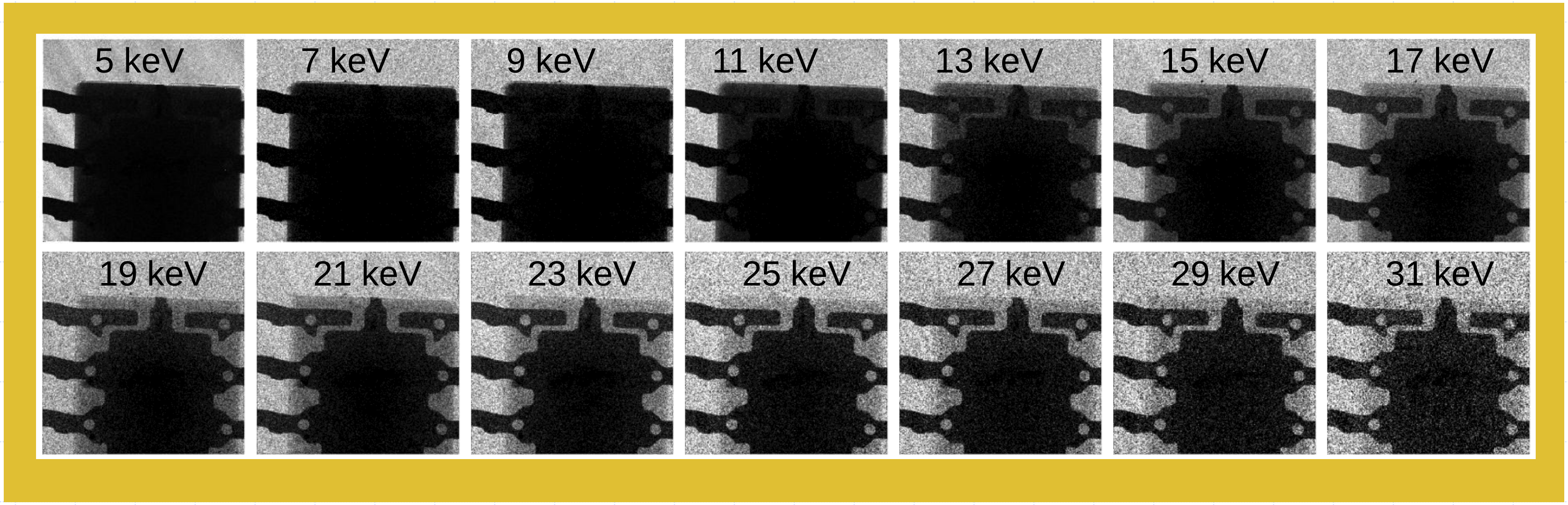
Timepix: Color radiography

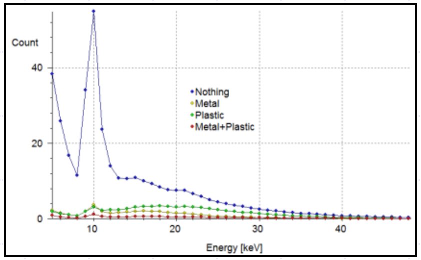
Event by event imaging



- Exposure time reduced to avoid overlapping clusters
- Clusters in each frame identified, energy determined by summation
- Many frames taken (14 000 000 clusters analyzed) in 2 hours



- Per pixel spectra determined
- Allows material reconstruction (many methods exist so far)



Timepix: Ion Radiography
Biological sample

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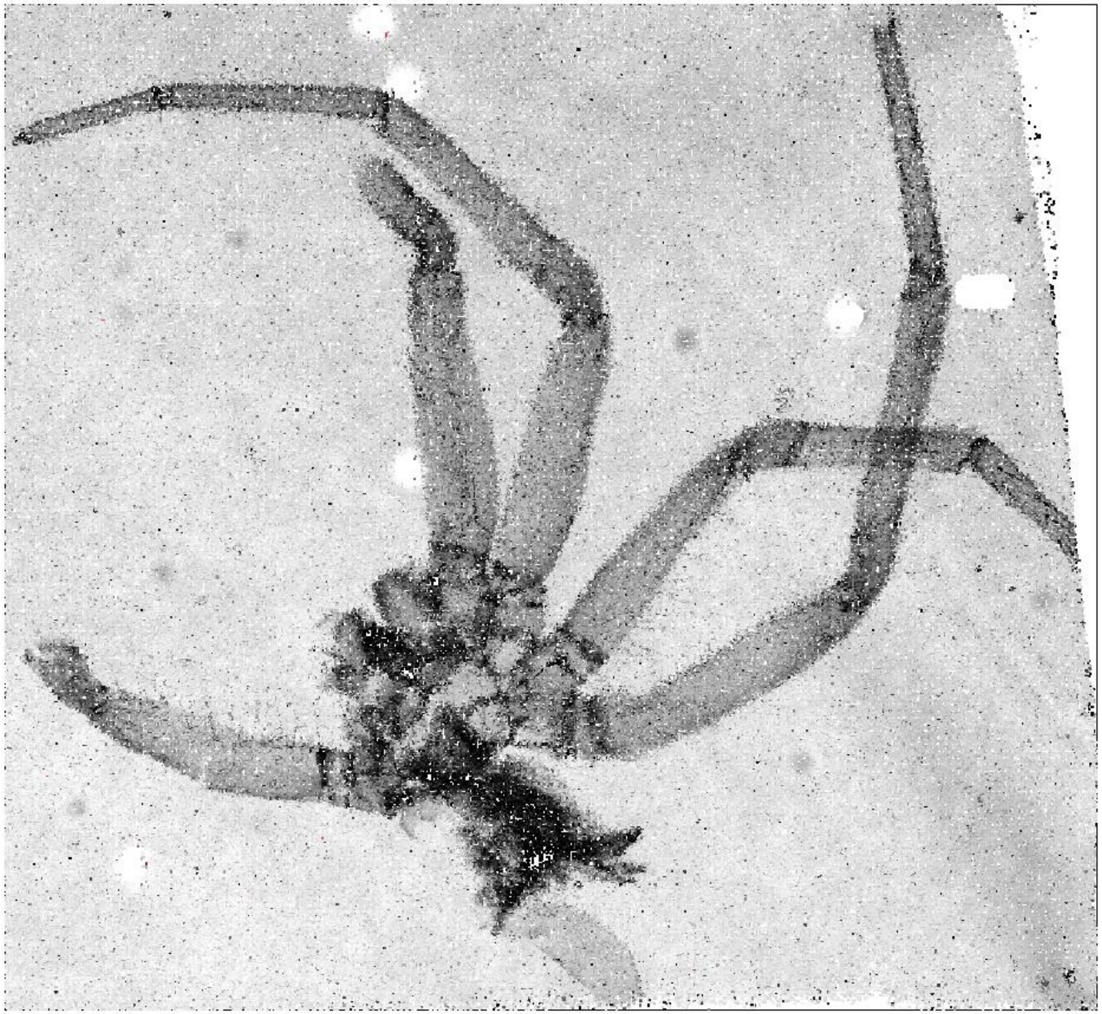


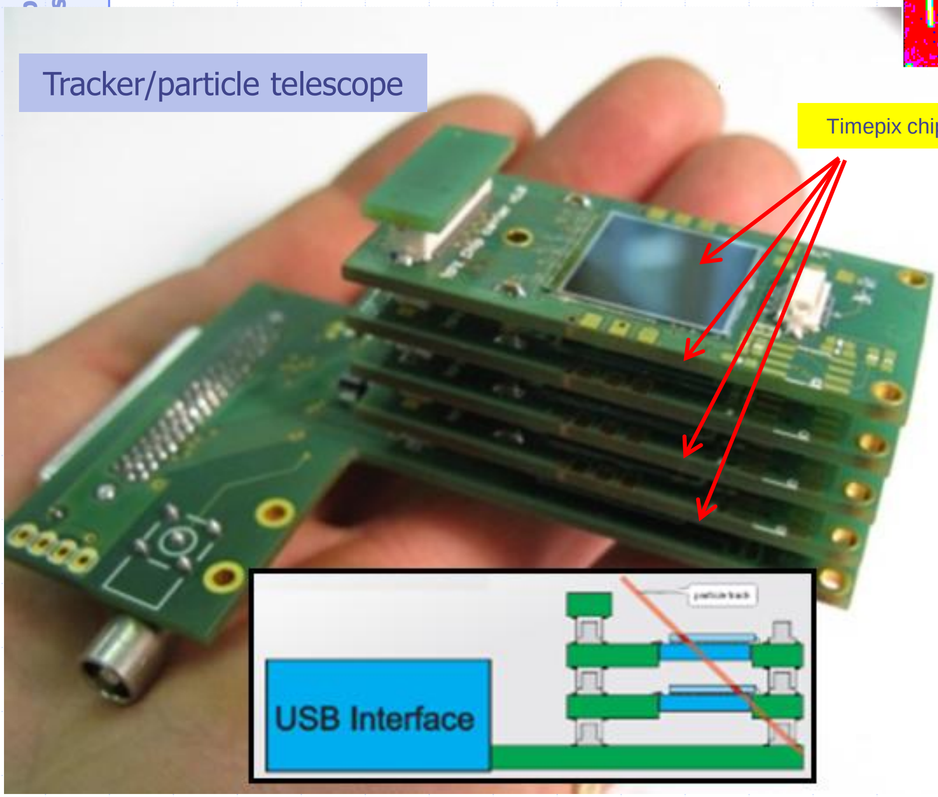
16 x

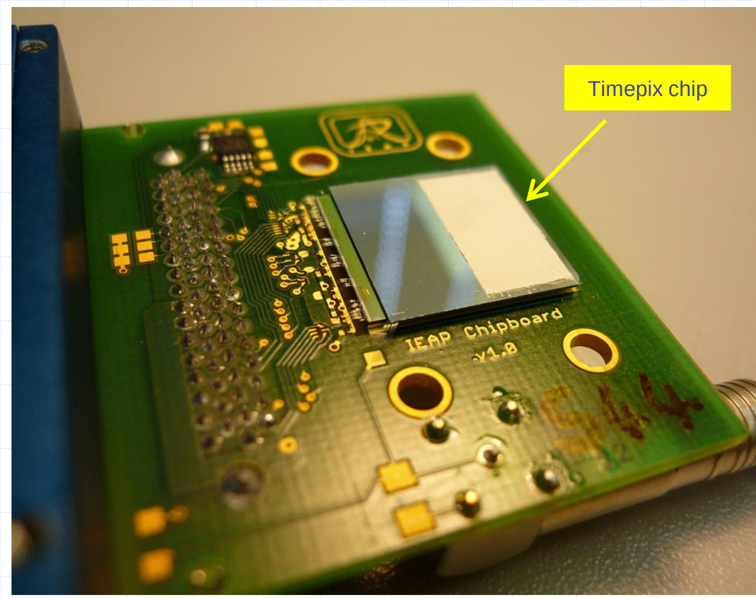
(1 Mpixels)

~0.7 particles per pixel

Detector array architectures: Miniaturization, stacking

R&D Radiation Detectors, highly integrated, high sensitivity, quantum detection





Highly miniaturized Timepix LITE (top right), Timepix chip on IEAP CTU Prague chipboard (bottom right) and particle tracker/telescope assembled/stacked from several Timepix devices (left)

Detector array architectures: Large/increased area

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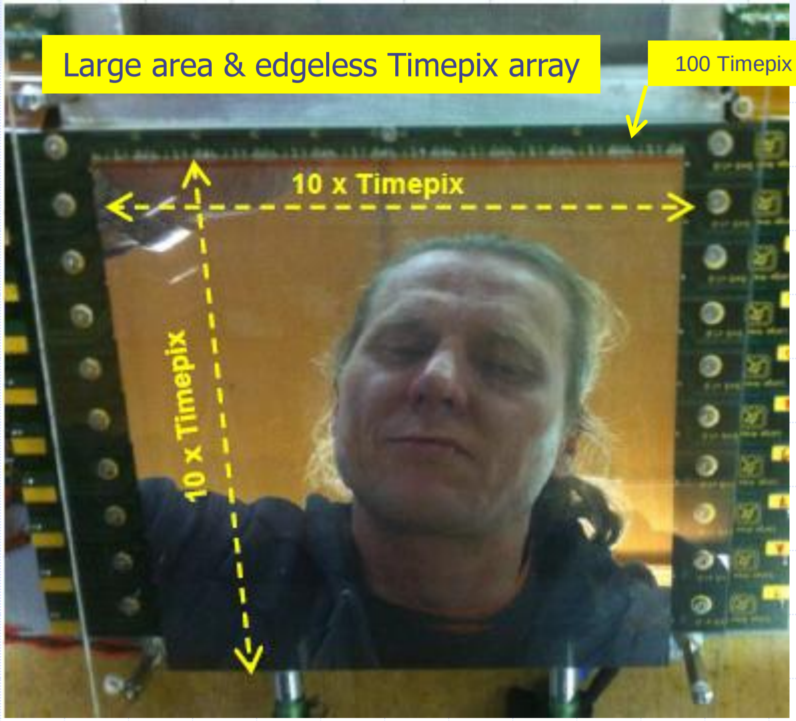
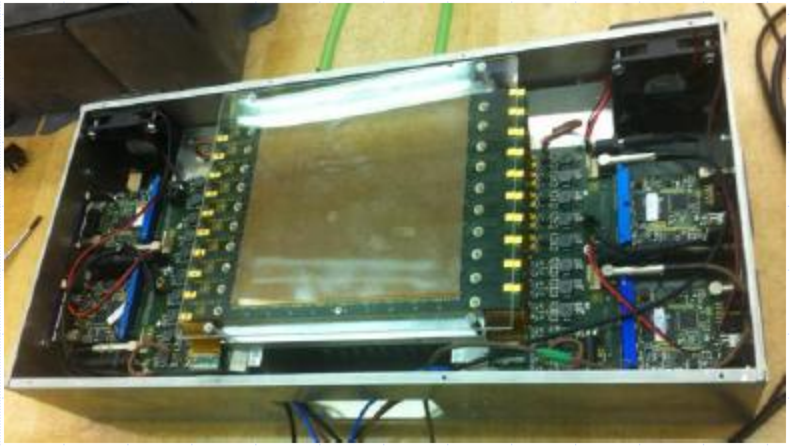
WidePIX 10x10 imager consists of an array of 10x10 of one-hundred Timepix detectors developed by the Medipix Collaboration based at CERN. The technology allowing coverage of large area is based on application of edgeless silicon sensors developed in VTT Finland and fabricated by ADVACAM Oy. The whole **WidePIX 10x10** device was designed, developed and constructed at the IEAP CTU Prague.

Features:

- Superior image quality without instrumental noise,
- 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,
- Support for major operating systems: Windows, Mac OS, Linux





WidePIX - Sample images:
Ground beetle: X-rays

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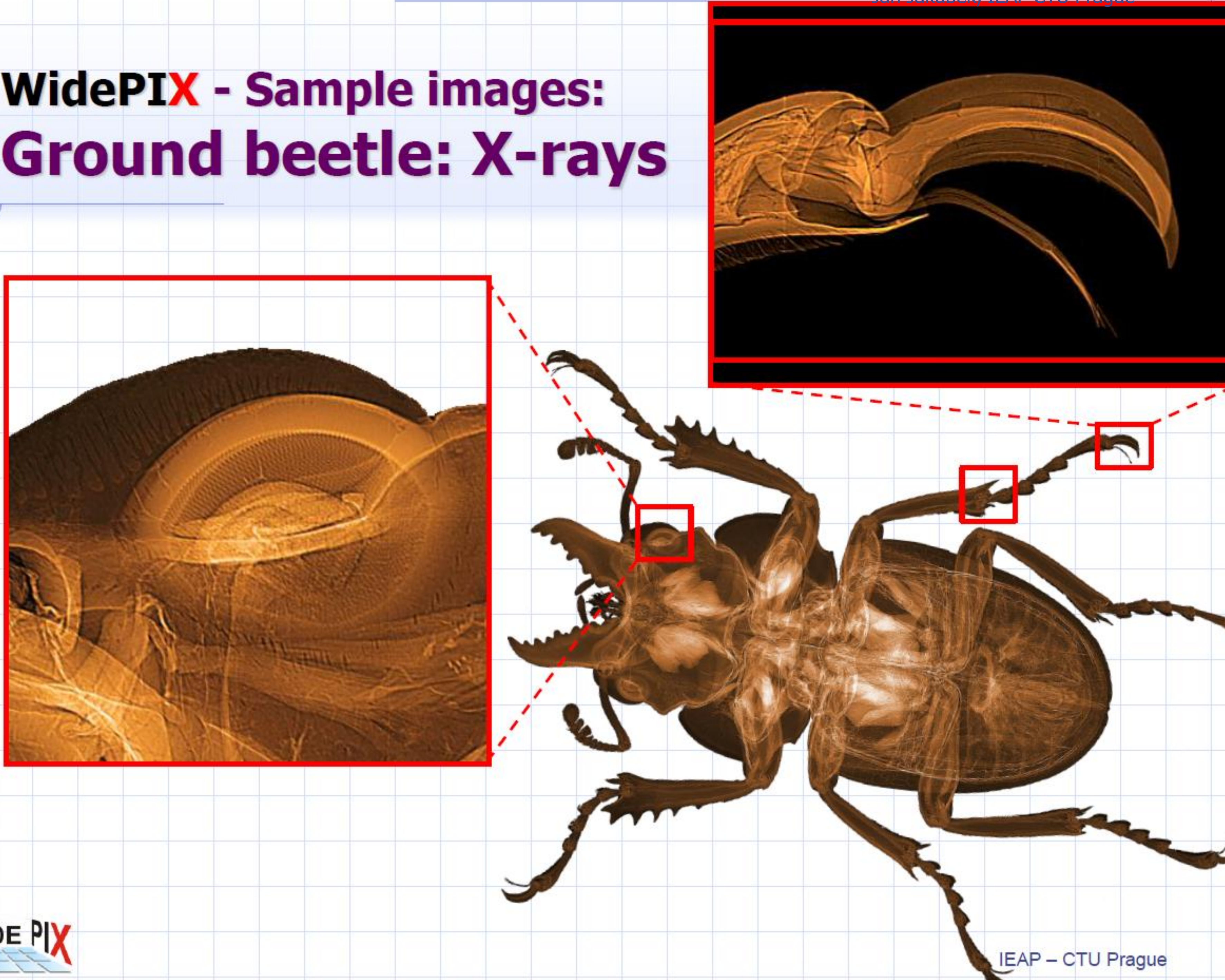

WidePIX - Sample images: Cockroach with parasite

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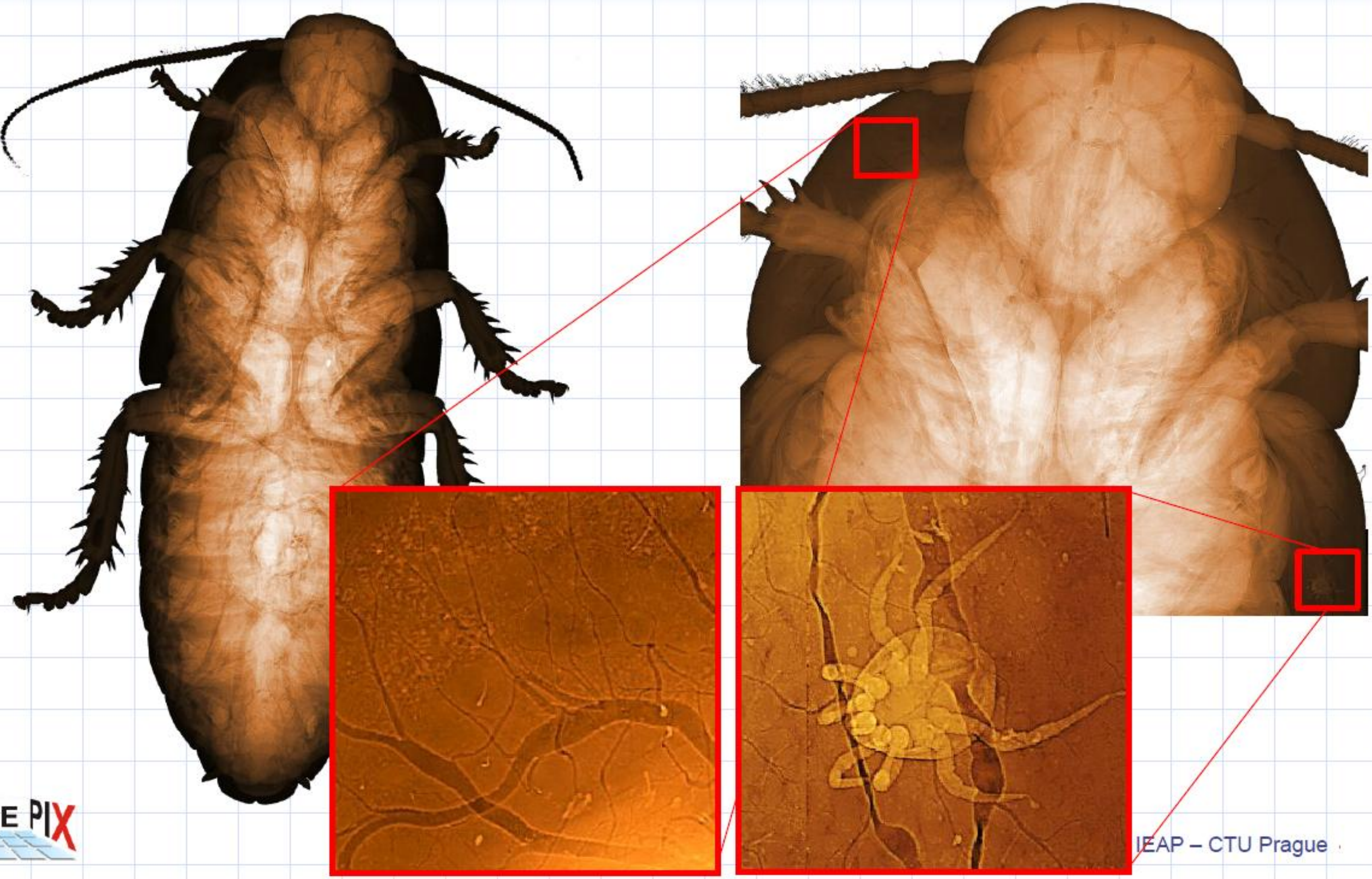

Detector array architectures:
Large area neutron imager

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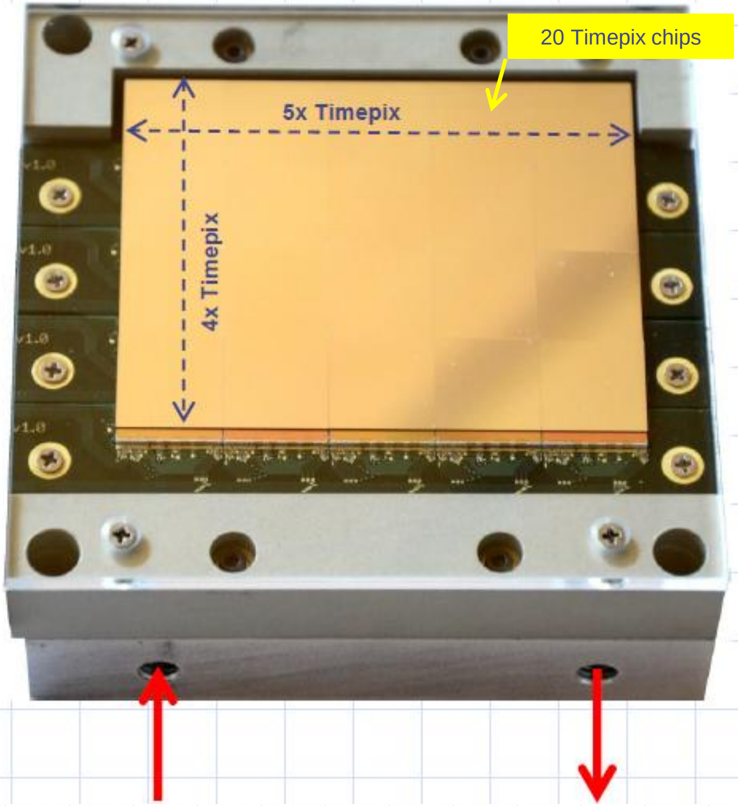
Compact design:

Cooling system integrated



Detector array architectures: Large/increased area

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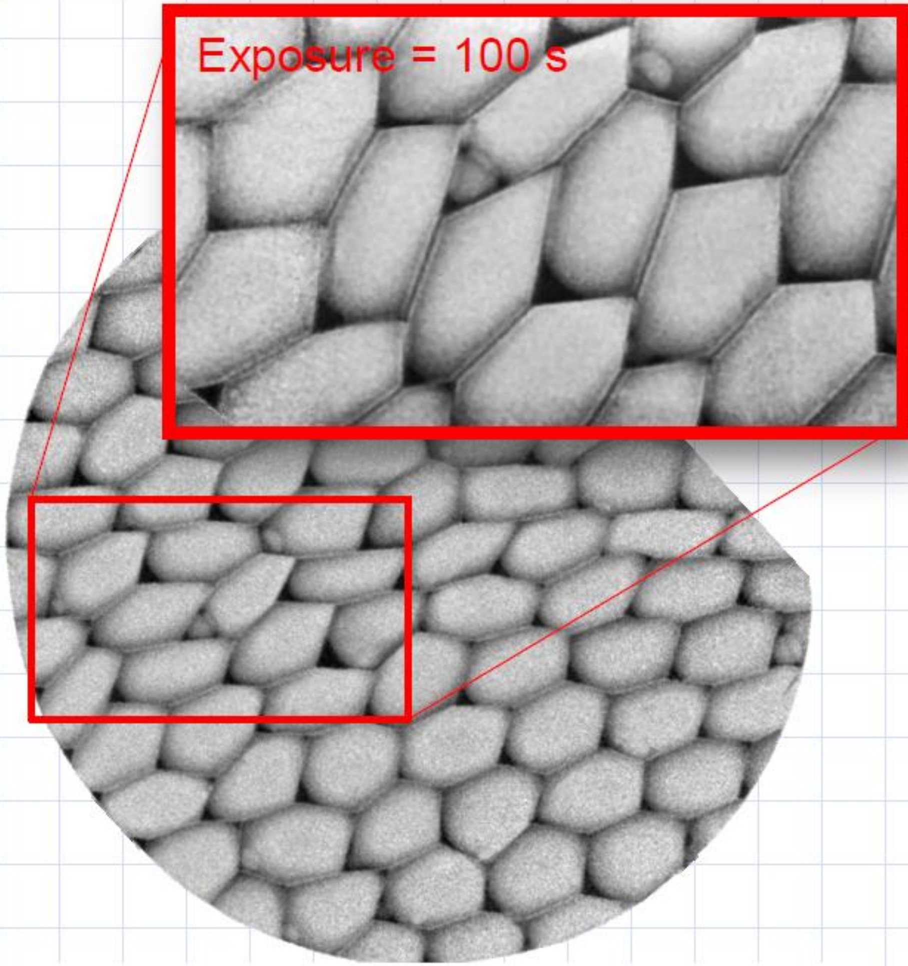
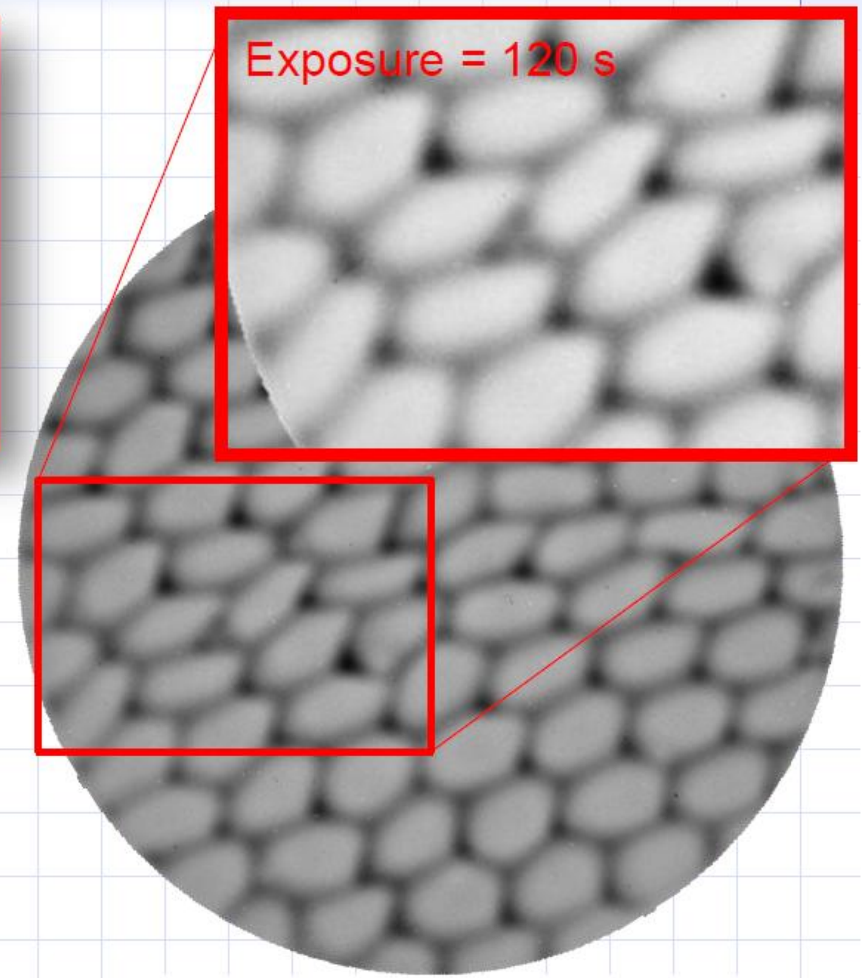
Neutron radiographs (in cooperation with ILL Grenoble**)**





Timepix WidePIX

Jan Jakubek

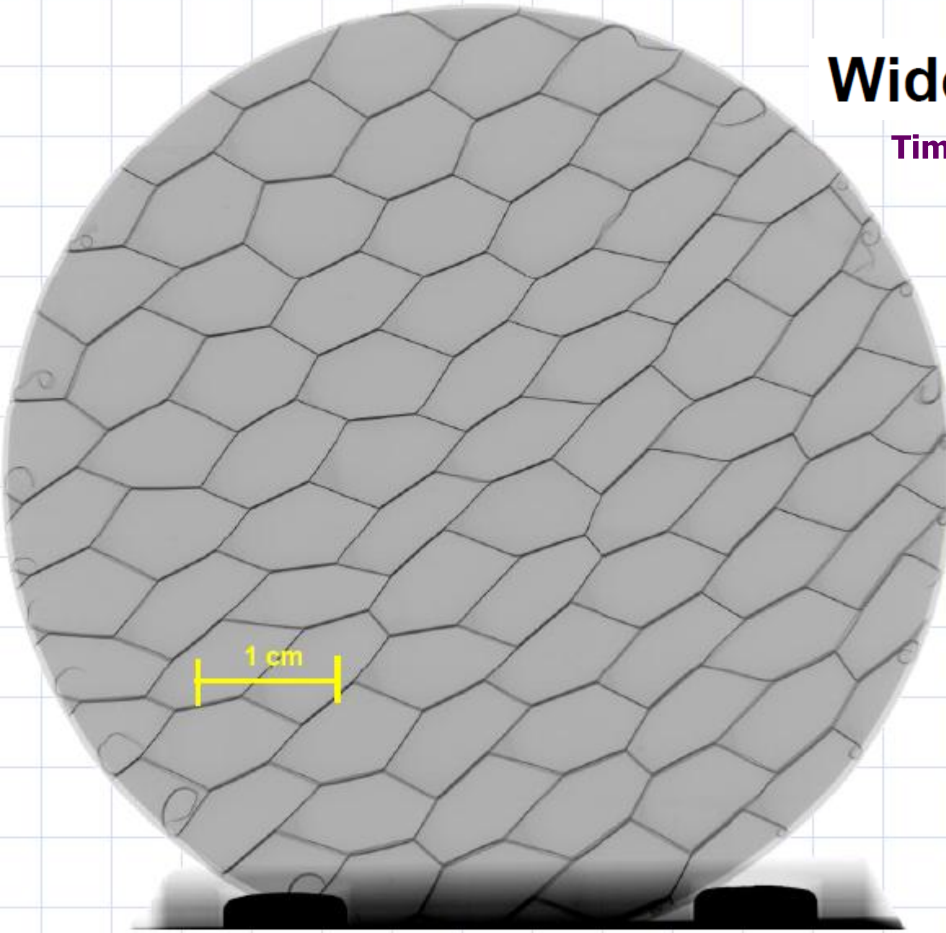
Scintillator Neutrograph

Detector array architectures:
Large/increased area

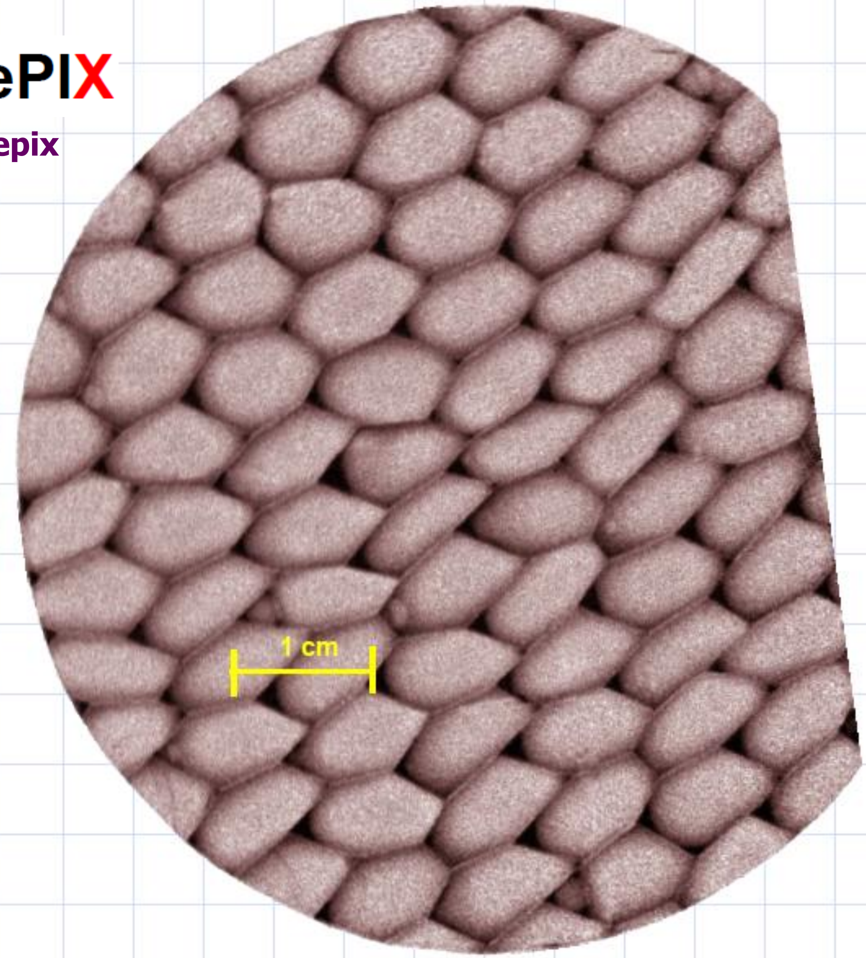
X-ray (left) & neutron (right) radiographs

WidePIX

Timepix



X-ray: Aluminum



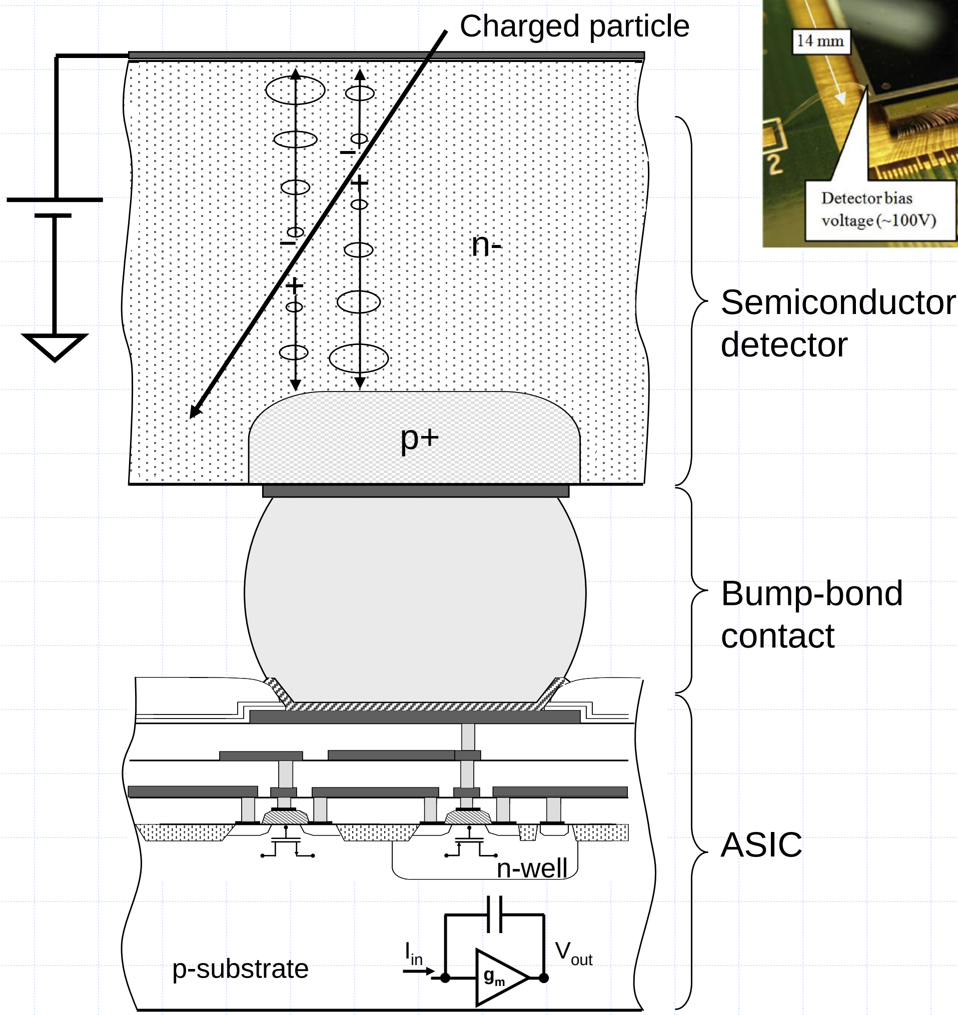
Neutrons: Glue

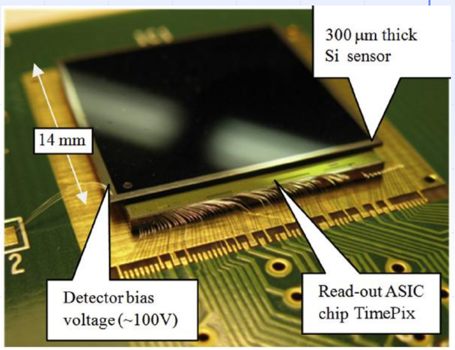
Jan Jakubek

IEAP – CTU Prague 10

Hybrid semiconductor pixel detector Medipix
Per–pixel signal readout electronics

- Core architecture of the hybrid pixel detectors where the sensor chip (top) is bump-bonded to the readout ASIC (bottom).
- Hybrid technology allows using semiconductor sensors of different
  - material (e.g, Si, CdTe, GaAs)
  - thickness (e.g. 300, 500, 700, 1000 um).
- Per-pixel pulse processing electronics provides simultaneously fast and dark-current free images of single particles (quantum counting).





In cooperation with JINR Dubna,
Nuclotron synchrotron ion accelerator

Timepix: Time-over-Threshold
Relativistic Heavy Charged Particles

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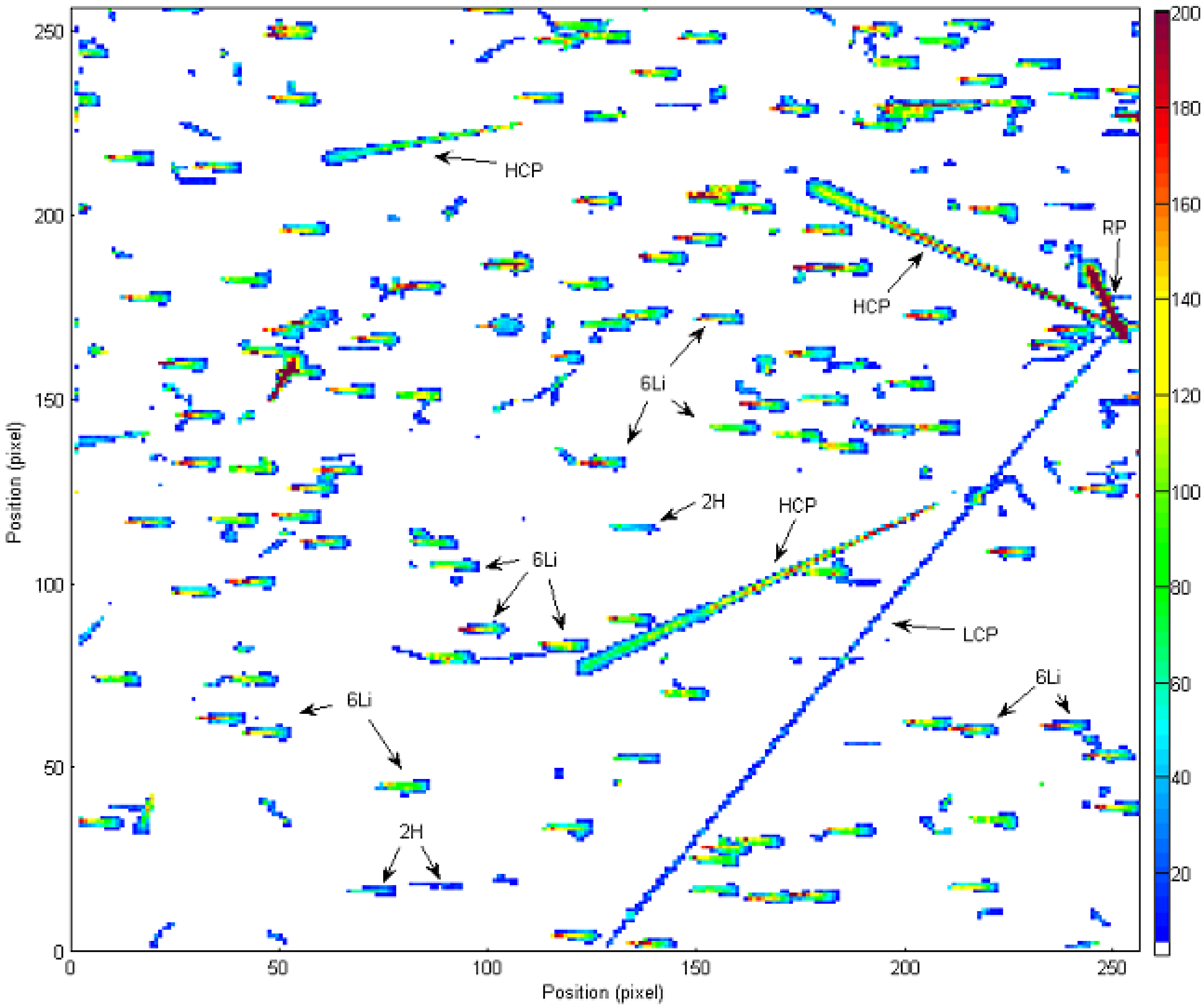
^{2}H, ^{6}Li 1.2 GeV ions @ 60 deg



ToT mode

In cooperation with JINR Dubna,
Nuclotron synchrotron ion accelerator

Timepix: Time-of-Arrival
Relativistic Heavy Charged Particles

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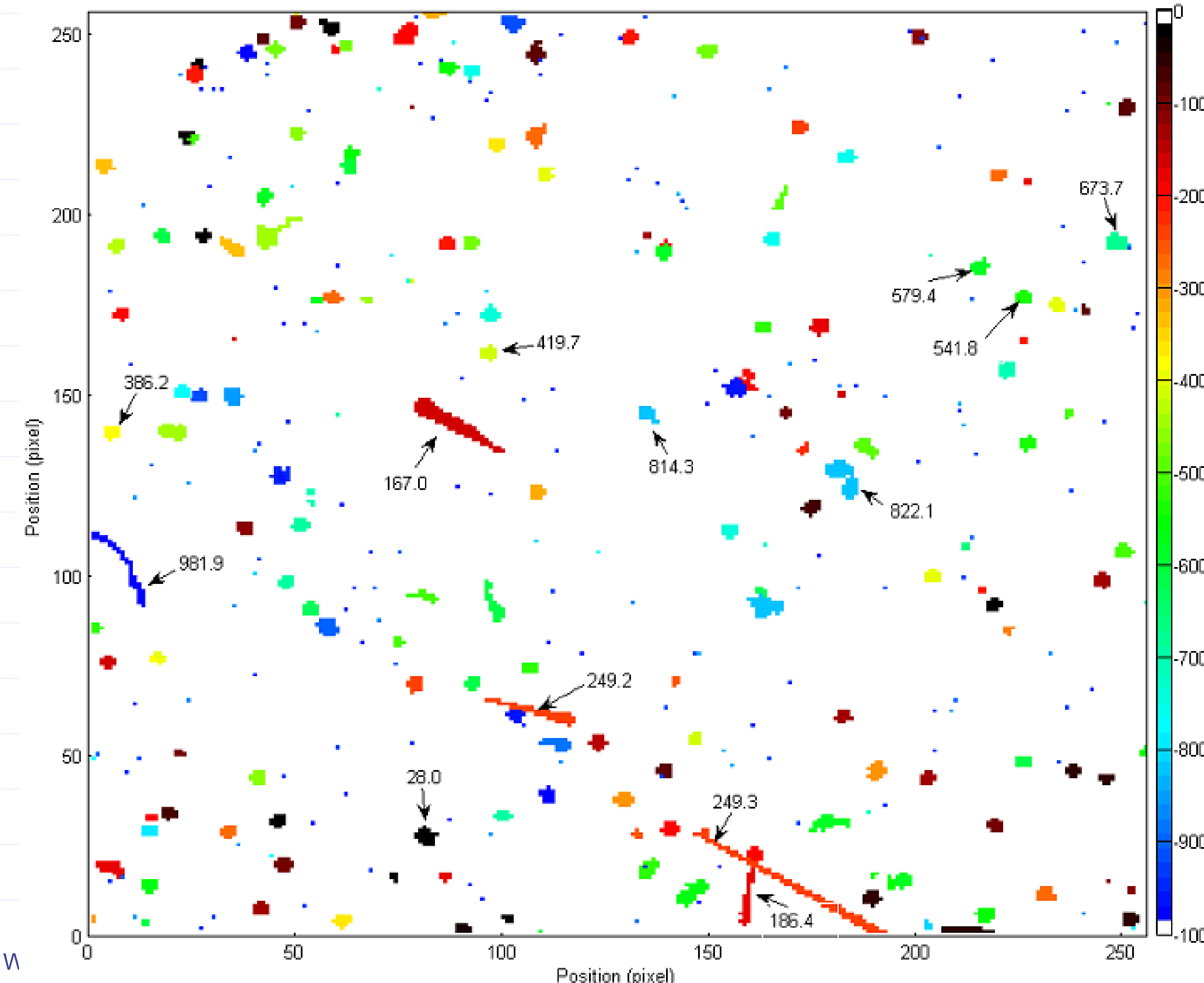
^{2}H, ^{6}Li 1.2 GeV ions @ 0 deg



ToA mode

Pixel detectors Medipix/Timepix + Integrated RO electronics + Online & data processing SW + Nuclear Physics/Radiation spectrometry: Space radiation

- Characterization and particle visualization of mixed radiation fields in space

sensitivity

- p, α, ions, e⁻, muons, neutrons, X-rays: particle species resolving power

tasks

- Detection, Radiation Monitoring, Quantum Imaging Dosimetry*
- Tracking , Visualization, Directional information (particle telescope)
- Spectrometry, Coincidence spectroscopy, reaction/fragmentation, ...

Capability, dynamic range

- Single-quantum sensitivity, noiseless detection, high signal-to-noise ratio
- Wide dynamic range (particle flux, particle energies, particle types)
- Linear-energy transfer (LET) measurement, low level threshold ≈ 4 keV
- High spatial resolution (sub-pixel resolution ≈ μm)
- Directional angular resolution: ≈ 1° (single sensor), ≈ 0.1° (stack telescope)
- Wide field-of-view: 2π, even 4π (no collimators, full sky mapping)

instrumentation

- Integrated electronics, no cryogenics

technical

- Light weight: e.g. launch cost for 1 g is 100 EUR
- Miniaturized size, low power

** Patent (E. Heijne, S. Pospisil)*

** S. Pospisil, E. Heijne*

Pixel detector Timepix
Active Nuclear Emulsion*

In cooperation with microtron accelerator, NPI Prague

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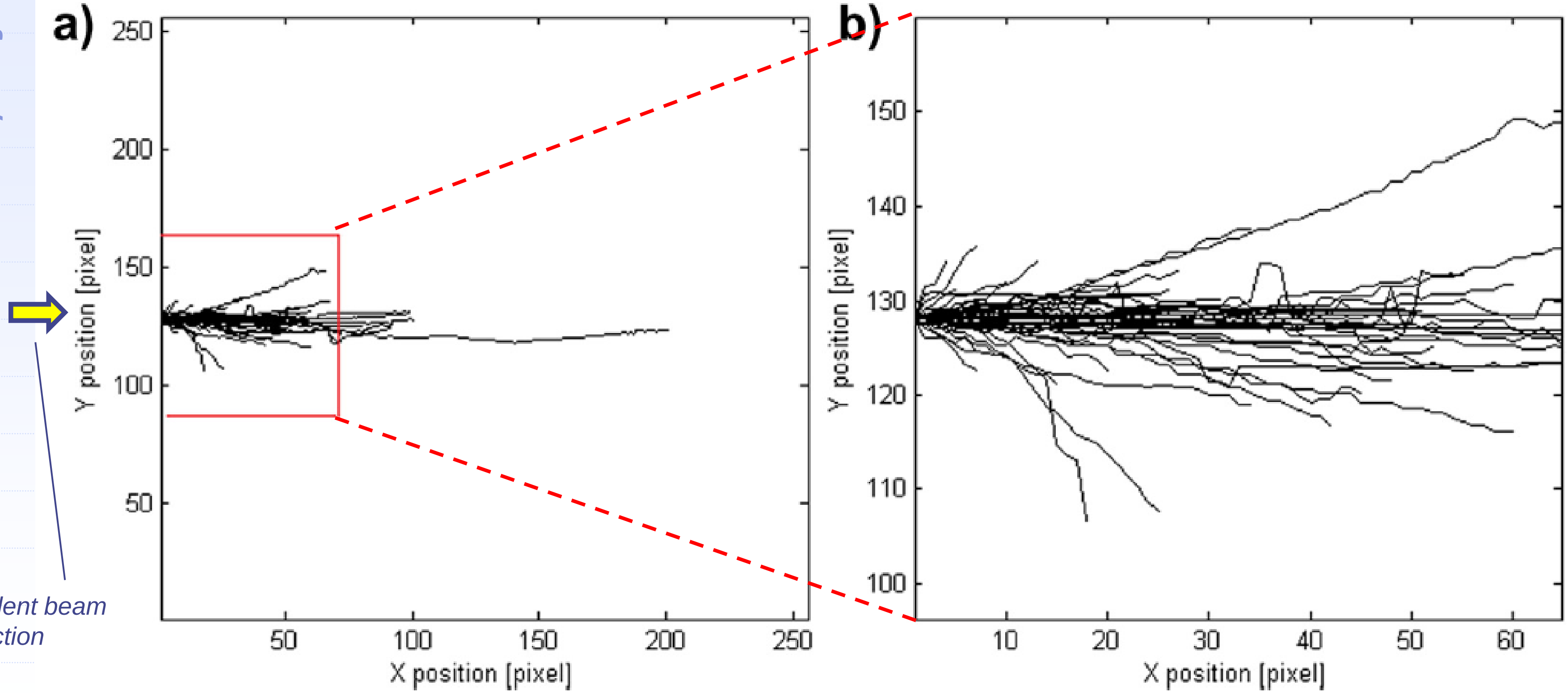

Incident beam direction

20 MeV electrons: visualization of beam path across silicon sensor (a), expanded view (b)

Radiation Measurements xxx (2013) 1–17

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Radiation Measurements

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Energy loss and online directional track visualization of fast electrons with the pixel detector Timepix

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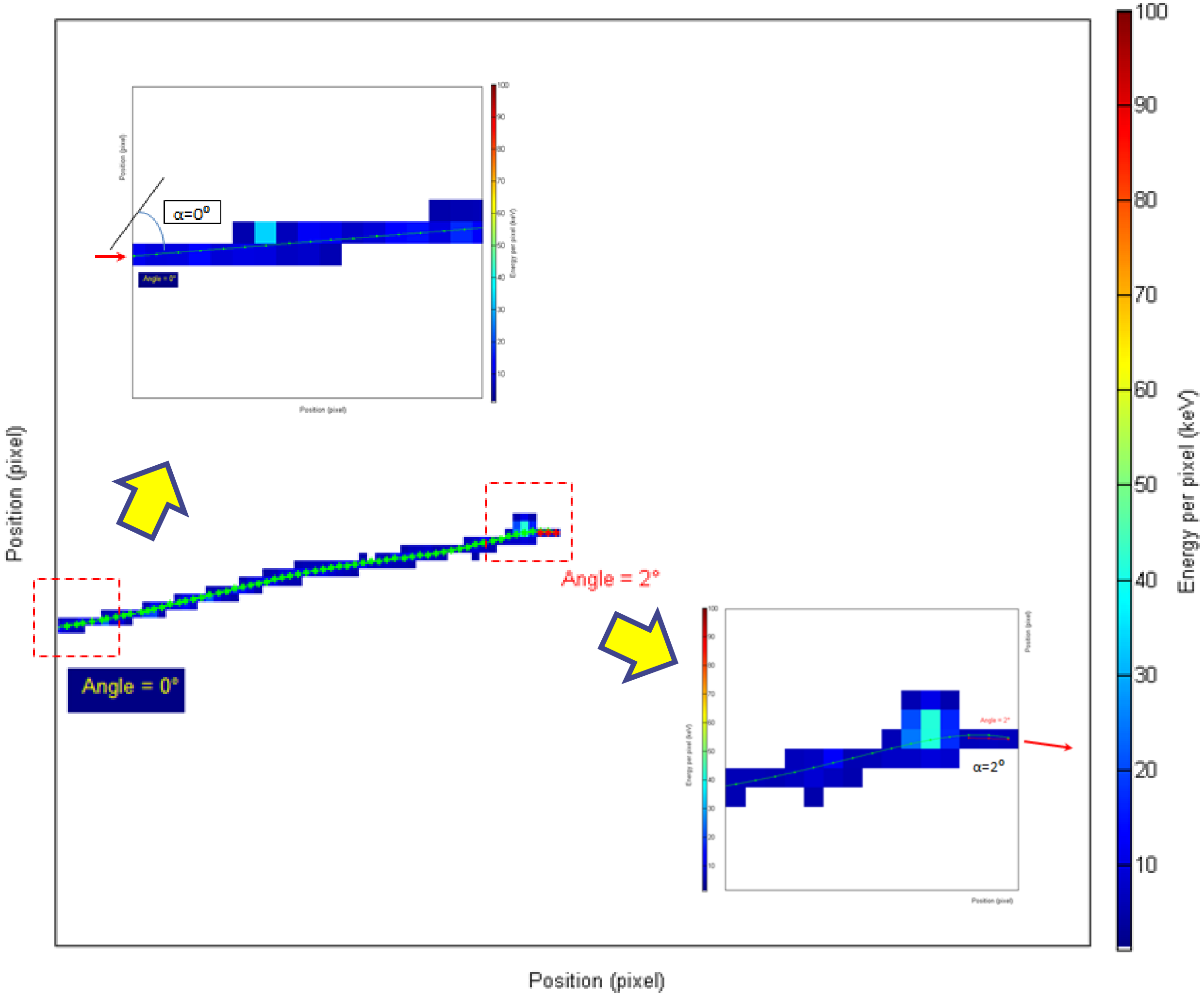
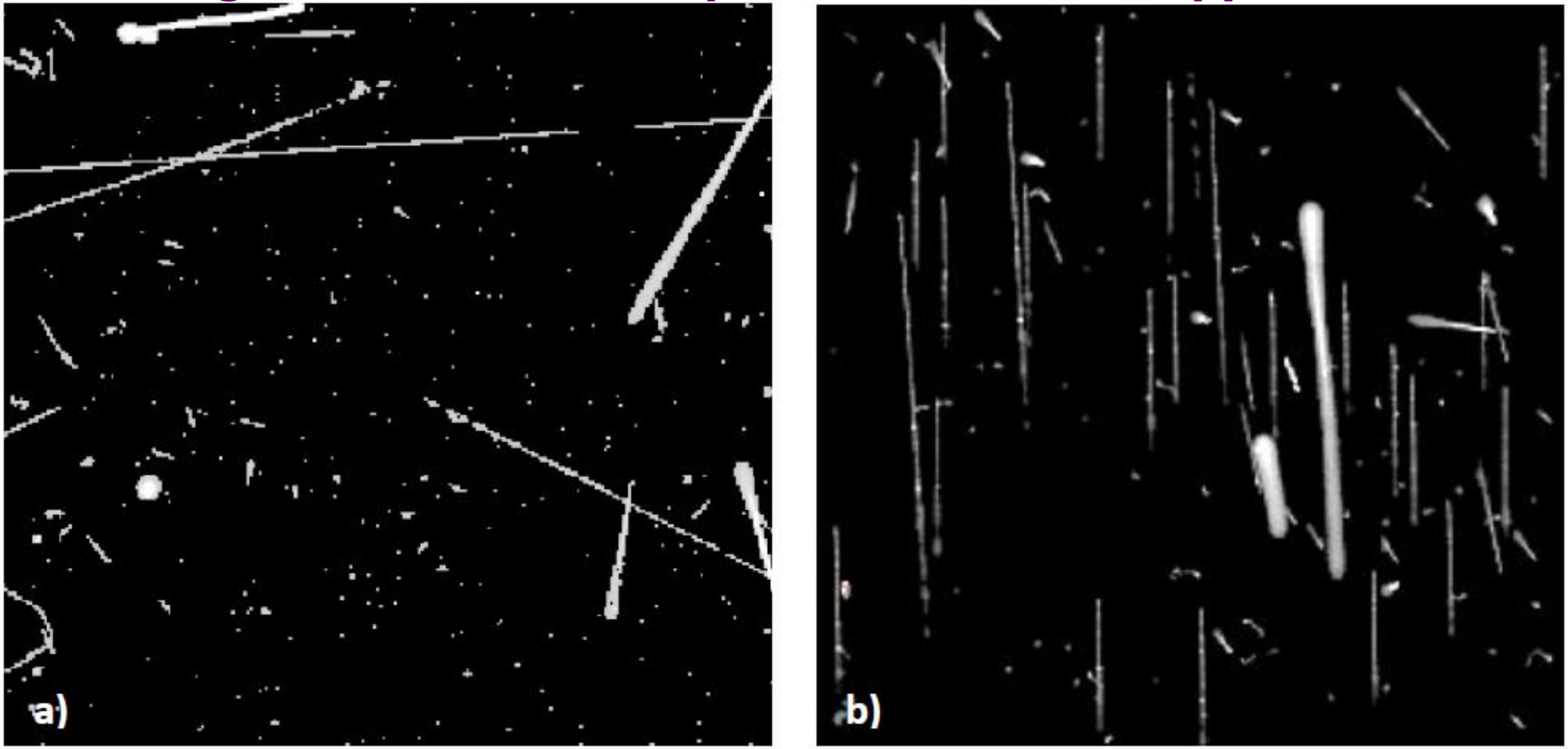
In cooperation with microtron accelerator, NPI Prague

Pixel detector Timepix:
Tracking visualization: Directional information

20 MeV electron: track + angular determination of IN/OUT trajectory vectors



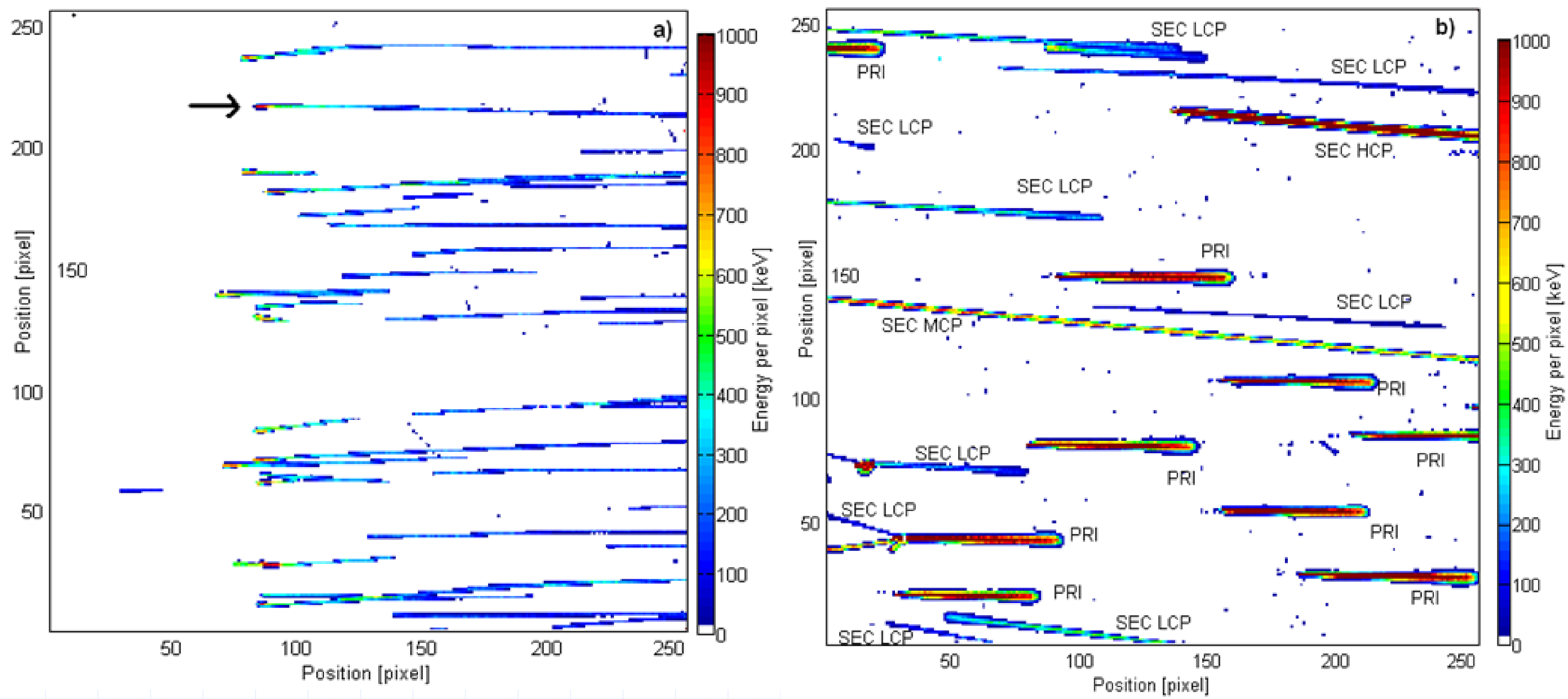
Timepix: Energetic Particle Tracking
Energetic radiation: Atmosphere & Hadron Therapy



Registration of atmospheric cosmic rays at 10 km (a) and 221 MeV synchrotron protons at grazing angle (b) by Timepix. The images correspond to the entire sensor area (14 mm × 14 mm) which consists of an array of 256 × 256 sq. pixels of pitch size 55 µm. The white depth is a measure of the energy deposited per pixel. Single particles are detected and distinguished by their characteristic tracks resolving electrons (fast, slow, delta), muons and energetic and recoiled ions. Directional information can be obtained with µm resolution.

In cooperation with DKFZ/HIT Heidelberg

Timepix ToT:
48 MeV protons (left) and 1.1 GeV ^{12}C ions (right)



Detection of 48 MeV protons (a) and 88 MeV/u ^{12}C ions (b) by Timepix operating in TOT mode (the energy deposited in each pixel is recorded and is shown by the vertical bar in color in keV). The beam was incident from right to left at 0° (i.e. parallel) and 5° to the sensor plane, respectively. The undeflected protons are fully stopped in the sensor. The ^{12}C ions cross the sensor volume. The event labeled with an arrow in (a) is shown in detail next. On figure (b) are indicated primary beam ^{12}C ions (PRI) as well as secondary particles (SEC) which can be grouped into light- (LCP), medium- (MCP) and heavy- (HCP) mass charged particles.

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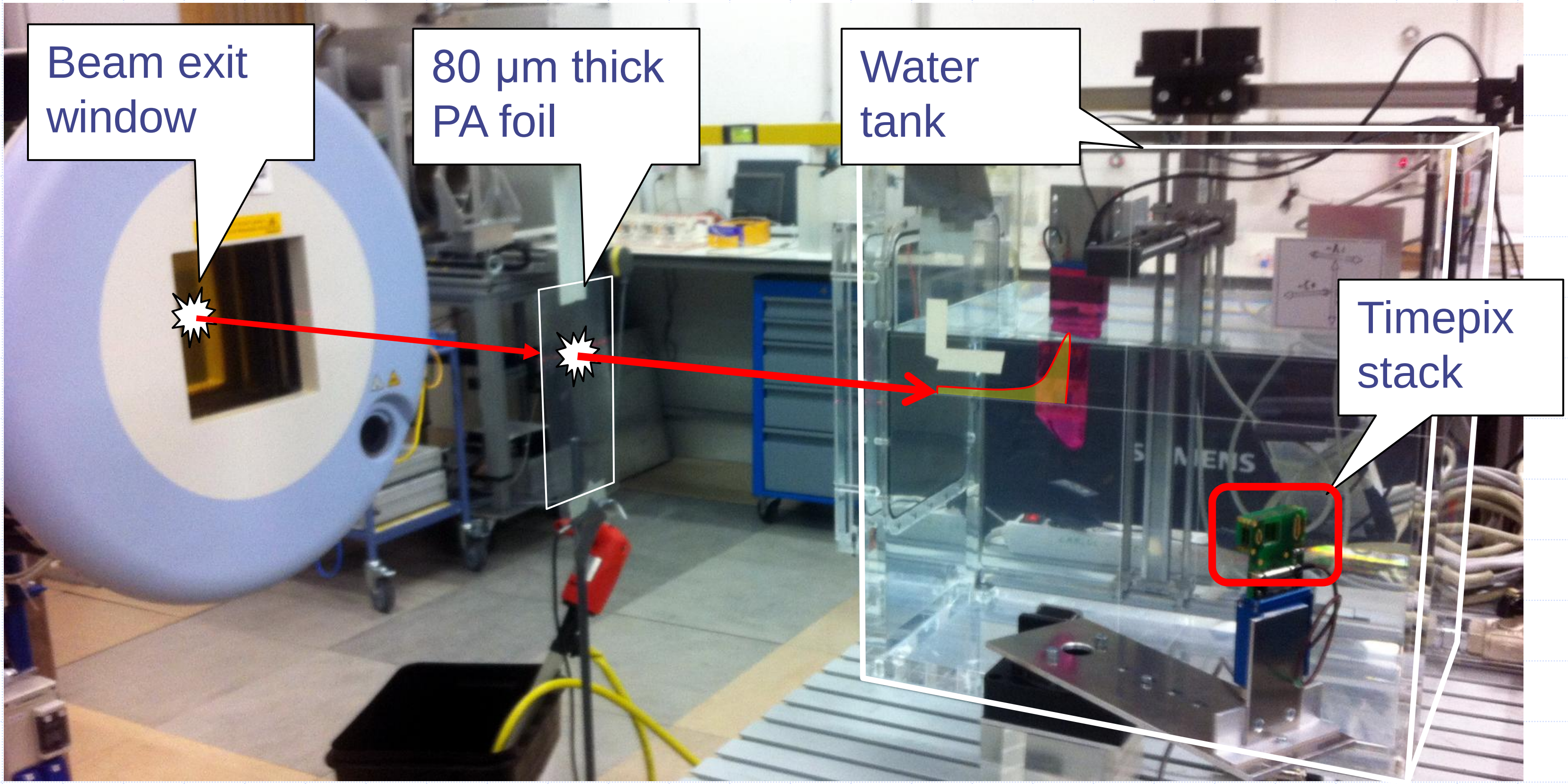
Beam path can be imaged

Remote Online visualization of particle beam



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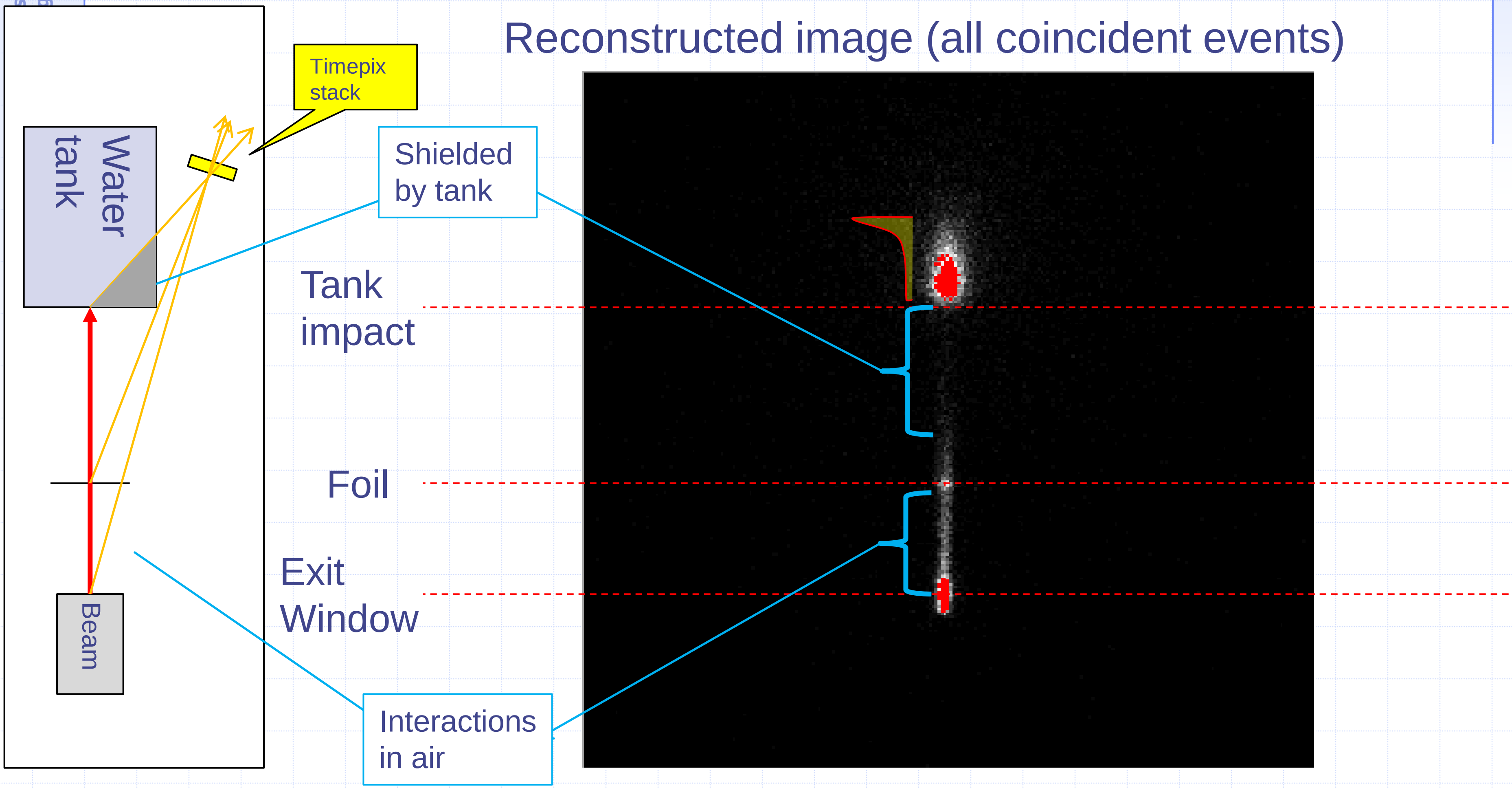
Beam path can be imaged

Remote Online visualization of particle beam

→ Online monitoring of beam spatial deposition

Reconstructed image (all coincident events)



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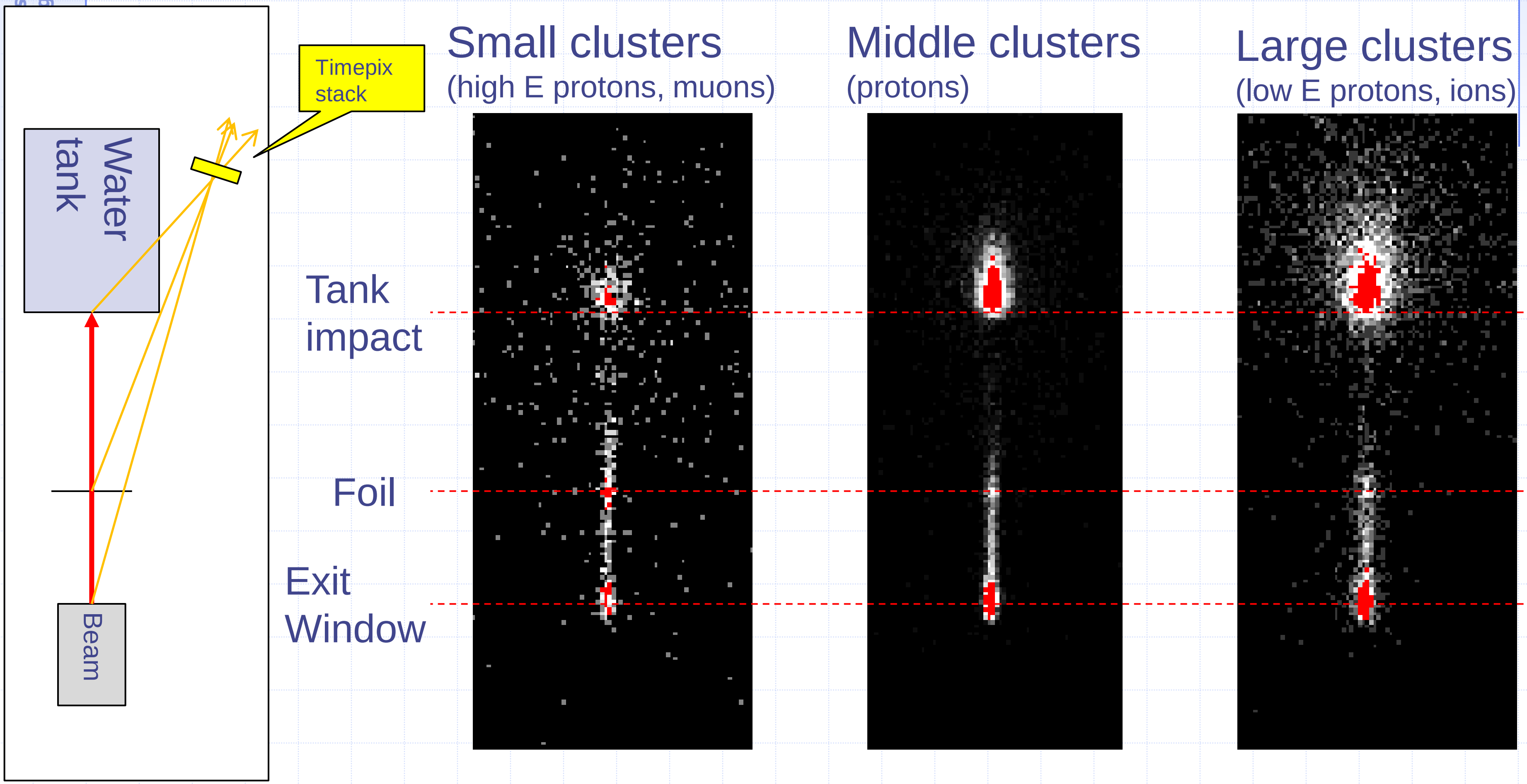
Beam path can be imaged

Remote Online visualization of particle beam

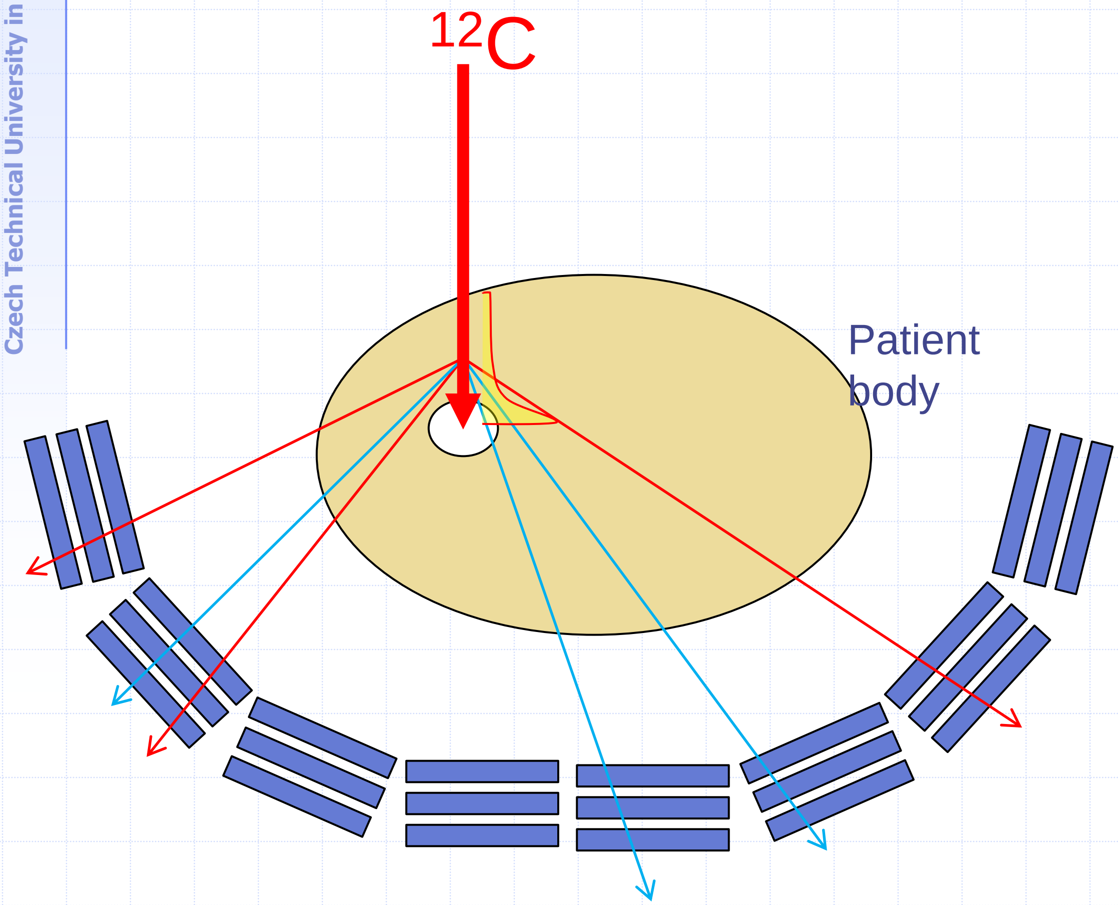
→ Online monitoring of beam spatial deposition



Geometrical efficiency = 10^{-5} (Sensor=2 cm^2, distance=140 cm), **time = 8 min**

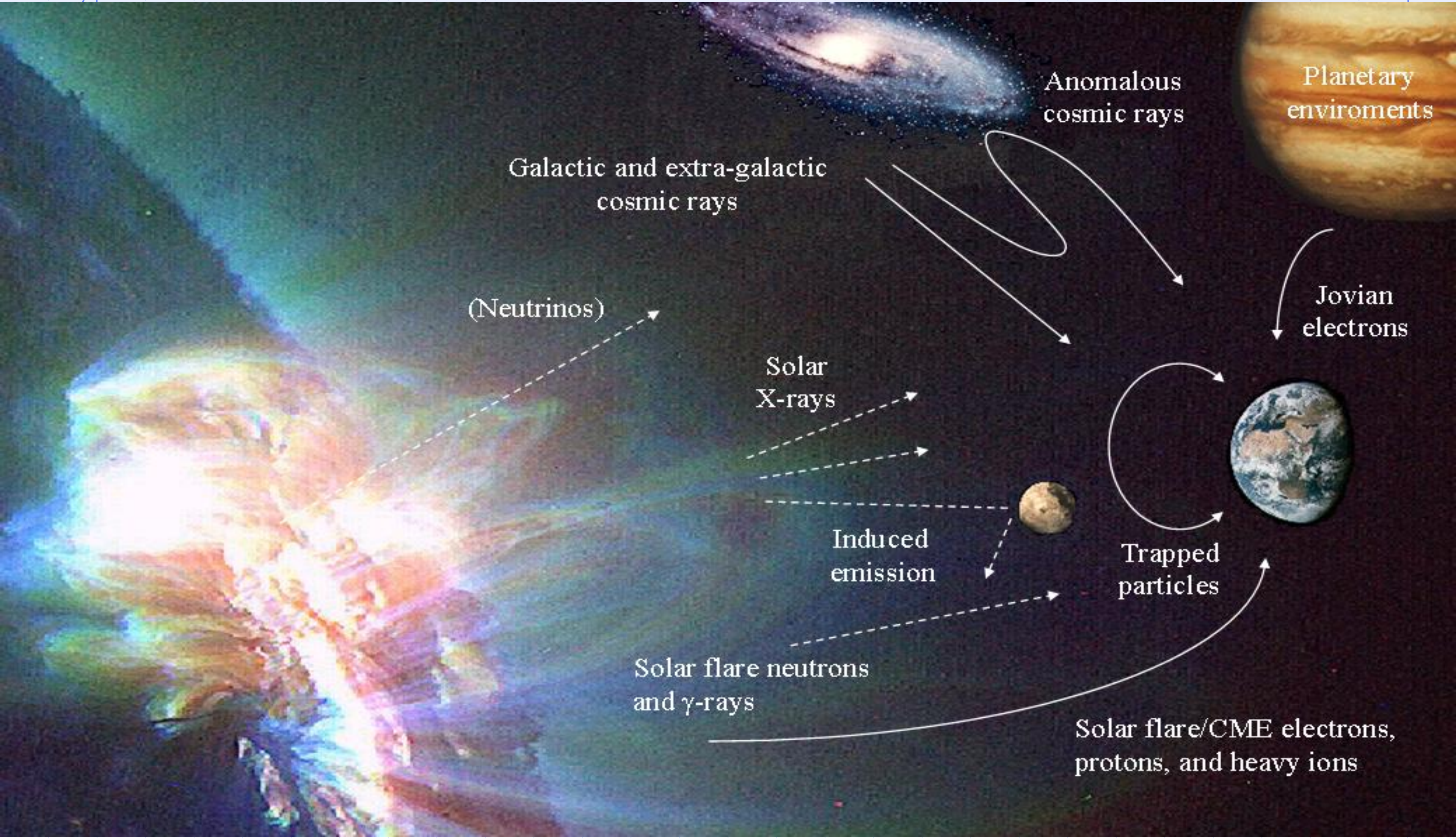
Imaging principle: Tracking of secondary particles

→ Online monitoring of beam spatial deposition



- The tracker would optimally surround the irradiated body.
- 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.

Space Radiation Environment



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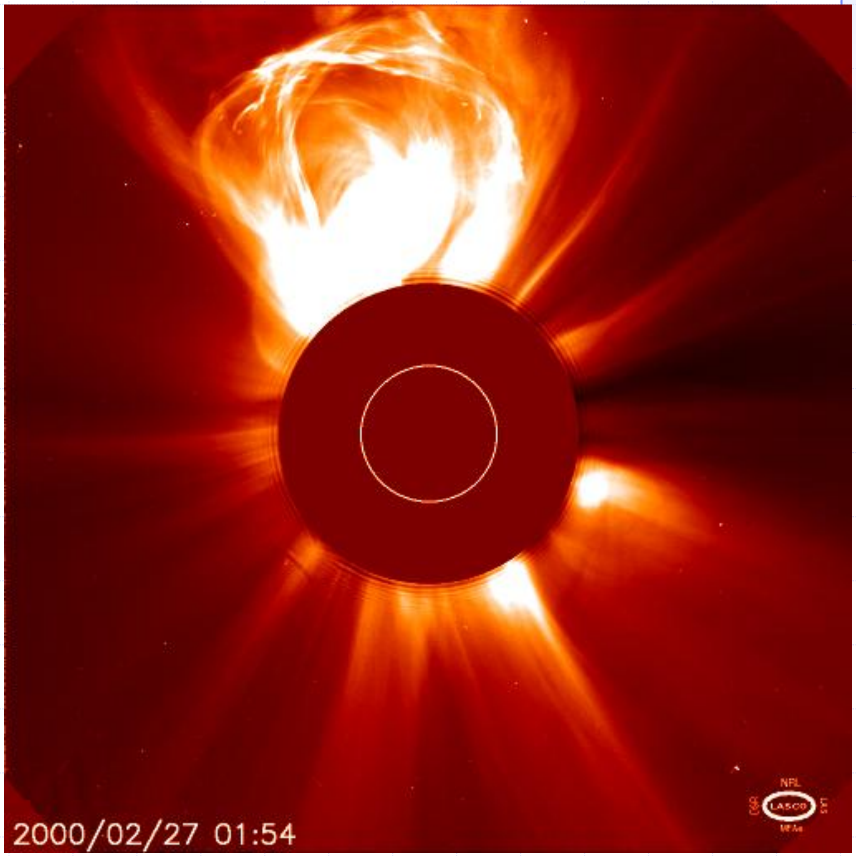
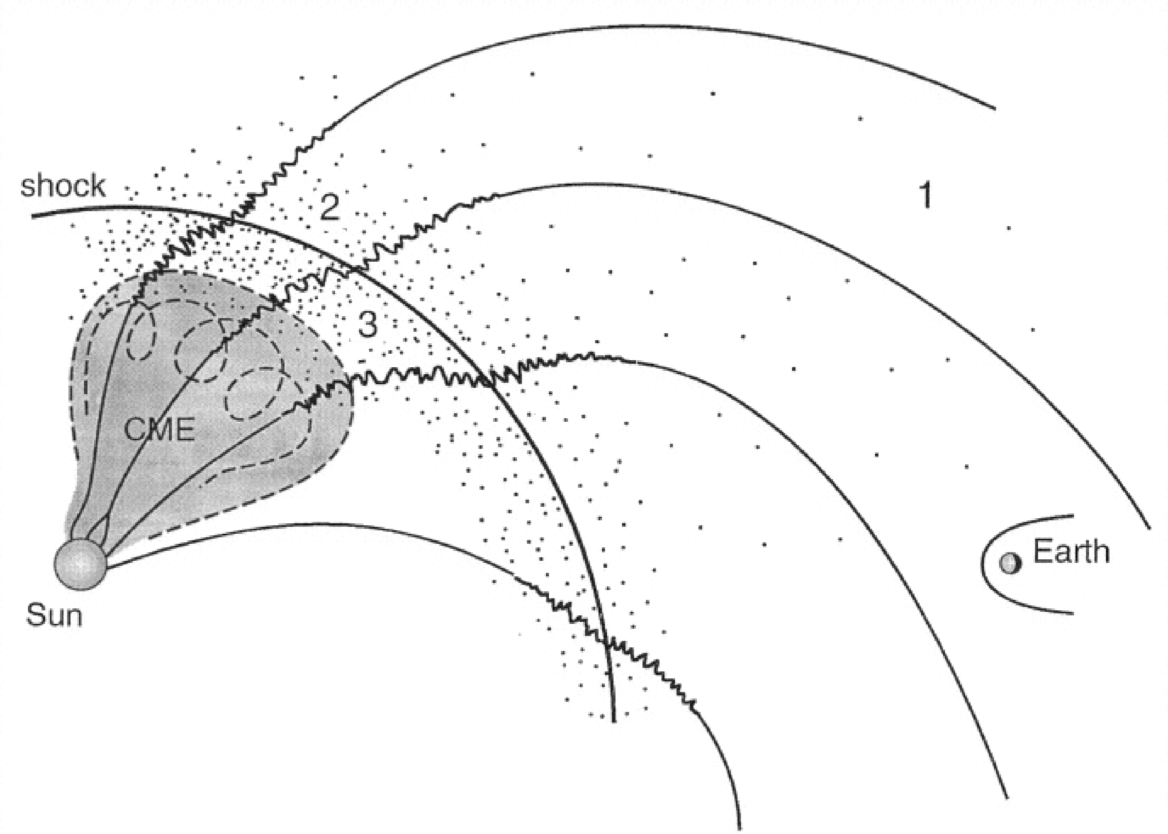
Coronal mass ejections – CMEs

CMEs are directional..!



Coronal mass ejections – CMEs

CMEs are directional..!



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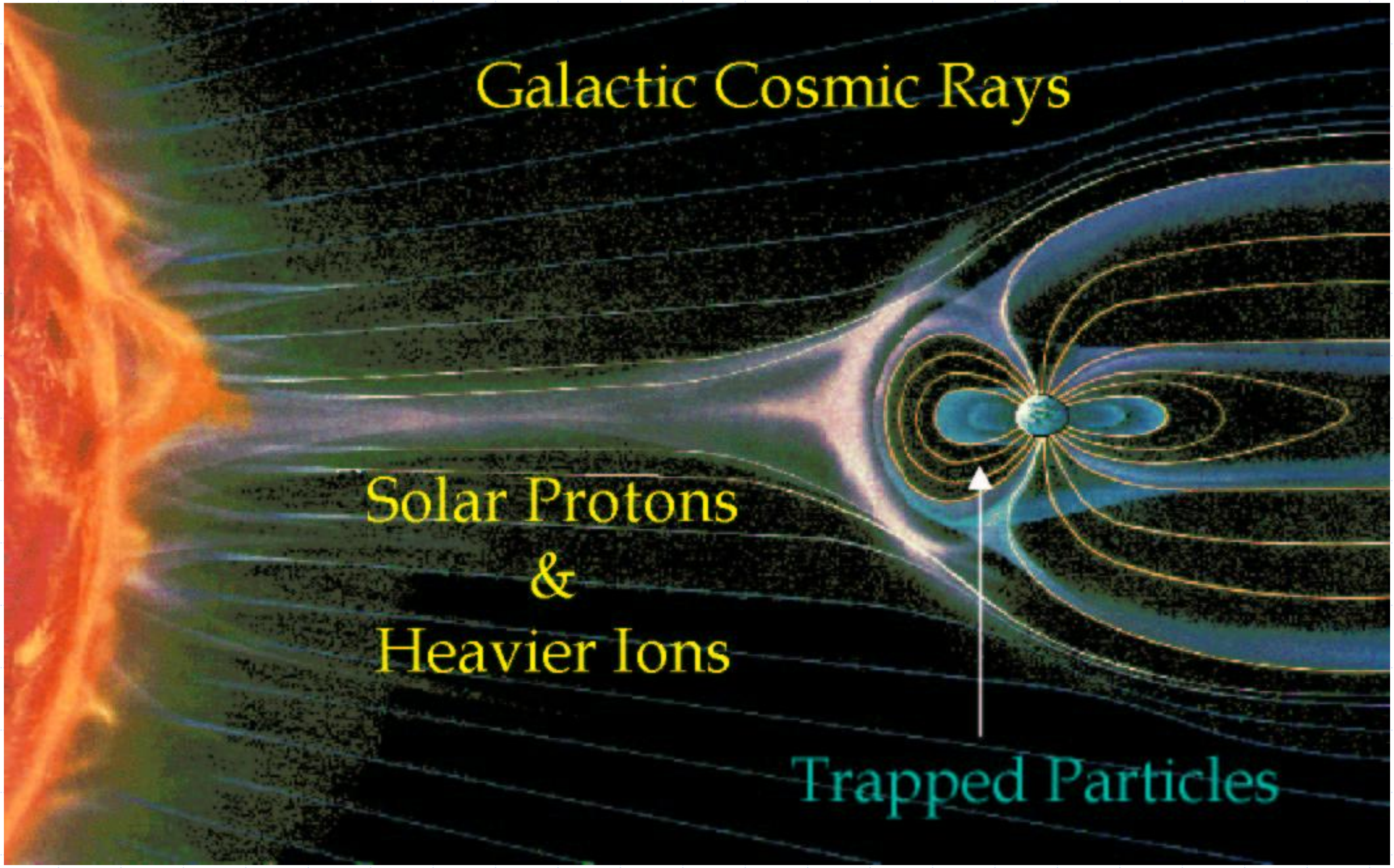
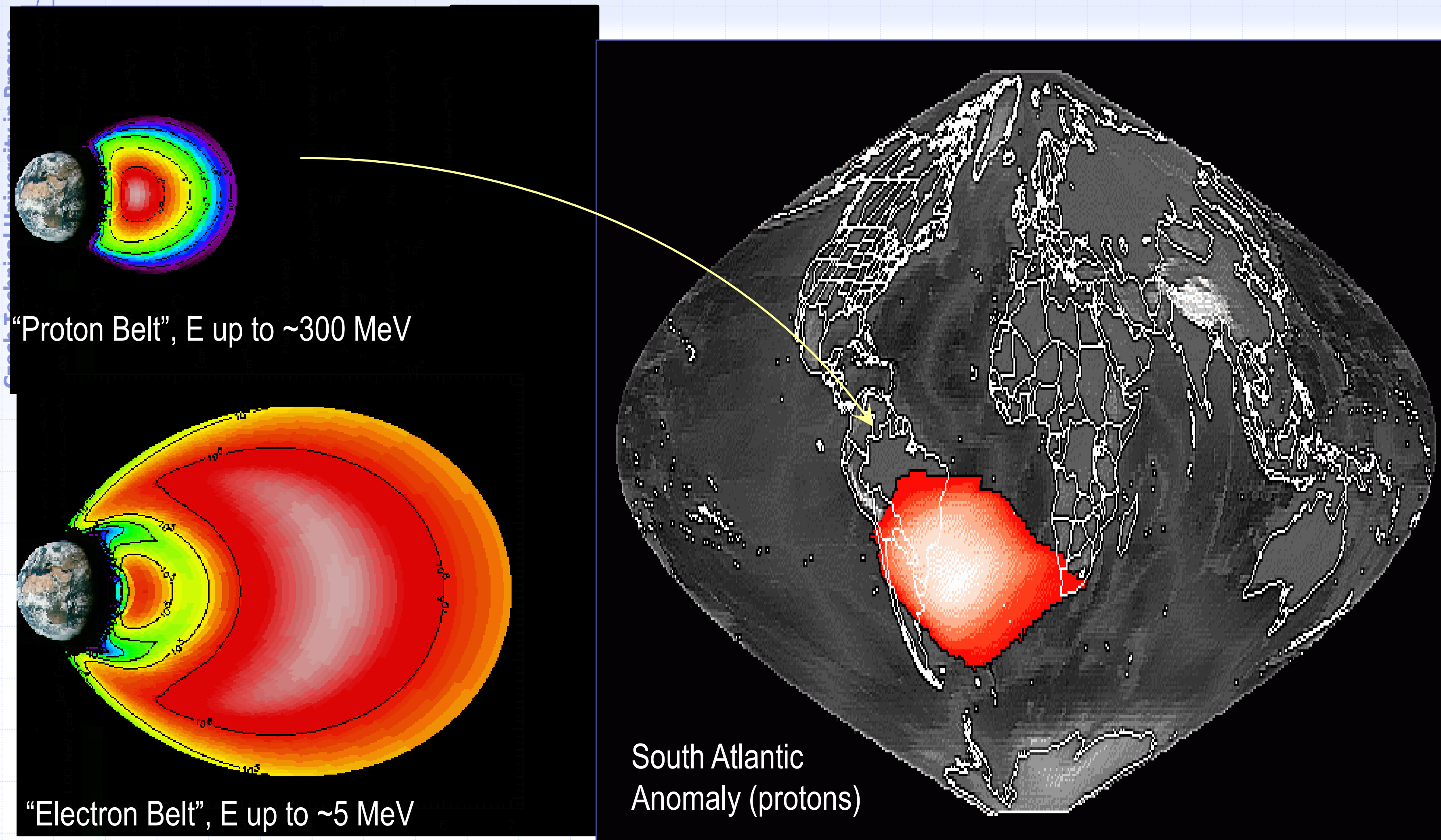
Space Radiation Environment & Earth



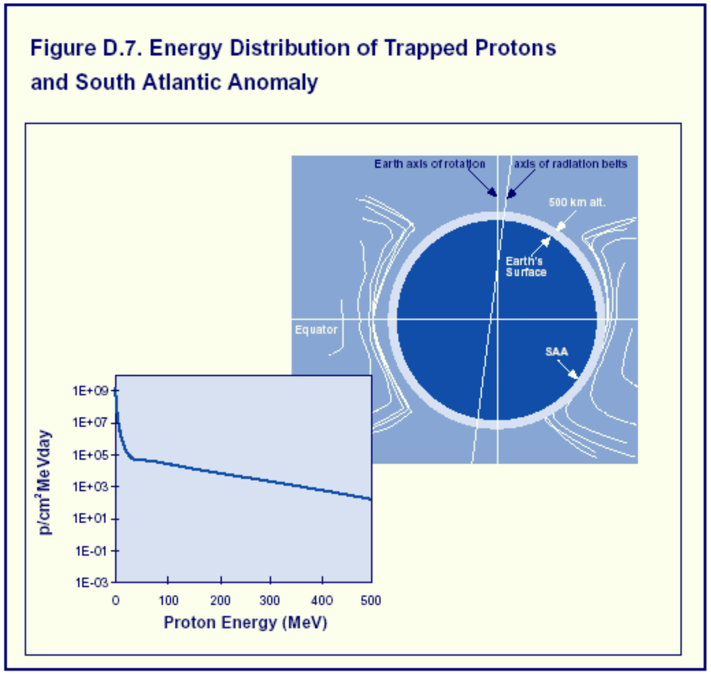
Earth radiation belts

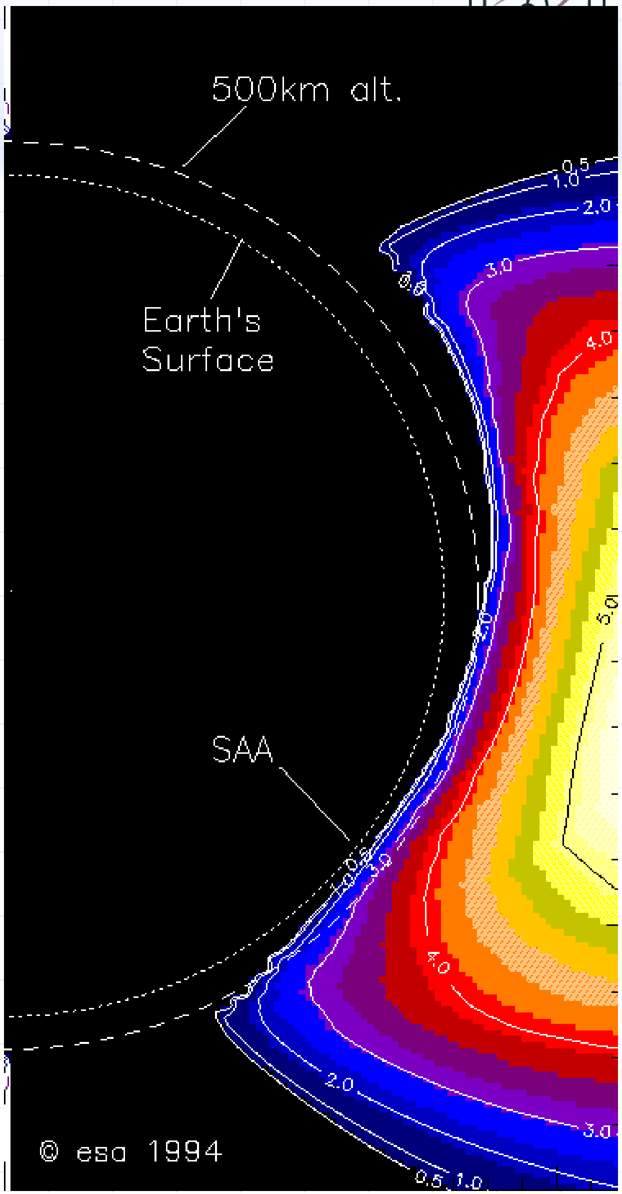
Institute of Experimental and Applied Physics

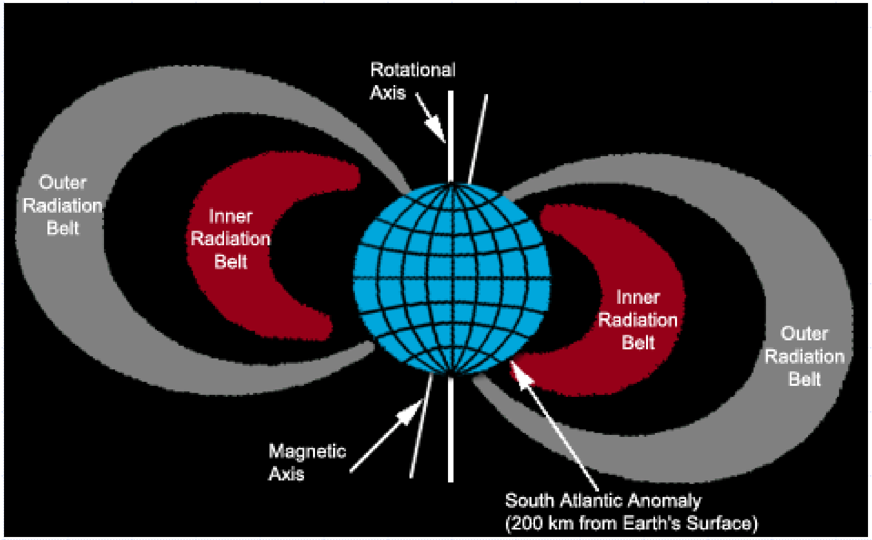


South Atlantic Anomaly

[SAA]







SPACE WEATHER

Where did all the electrons go?

Geomagnetic storms driven by the solar wind can cause the flux of high-energy electrons in the Earth's Van Allen belts to rapidly fall. Analysis of data obtained during one such event from multiple spacecraft located at different altitudes in the magnetosphere reveals just where these electrons go.

Mary K. Hudson

As the Sun's activity increases towards the peak of its approximately eleven-year cycle, predicted to occur in 2013 (ref. 1), there will be increased attention paid to the resulting surges of high-energy electrons that are trapped by the Earth's magnetic field. These electrons — also known as killer electrons[2] — pose a direct hazard to astronauts and spacecraft. The severest of these space weather events can even affect systems on the ground, including communications networks and power grids[3]. Yet, the relationship between these events and the solar activity that generates them is not as simple as one might expect. Indeed, weather satellites — often by many orders of magnitude in just a few hours. The mechanism that causes these 'flux dropouts' has never been clear. Yet, it is necessary to better understand this flux decrease at the beginning of storms if we are ever to understand, and better predict, the processes that drive subsequent increases that threaten the systems on which our modern society depends. The first step is to work out where these electrons go. Do they simply move somewhere else in the equatorial plane? Do they fall to Earth and get lost in its atmosphere? Or are they funnelled back out into space?

moderate geomagnetic storm that began on 6 January 2011. Figure 1 shows data collected during this event by the National Oceanic and Atmospheric Administration (NOAA)'s Geostationary Operational Environmental Satellites (GOES) located over the eastern and western United States. To build a complete picture of this event, the authors combined the GOES data with data that was simultaneously collected by NOAA's Polar Operational Environmental Satellites (POES) in low-altitude polar orbit, and by NASA's Time History of Events and Macroscale Interactions during Substorms (THEMIS) satellites in high-altitude,

NATURE PHYSICS | VOL 8 | MARCH 2012 | www.nature.com/naturephysics

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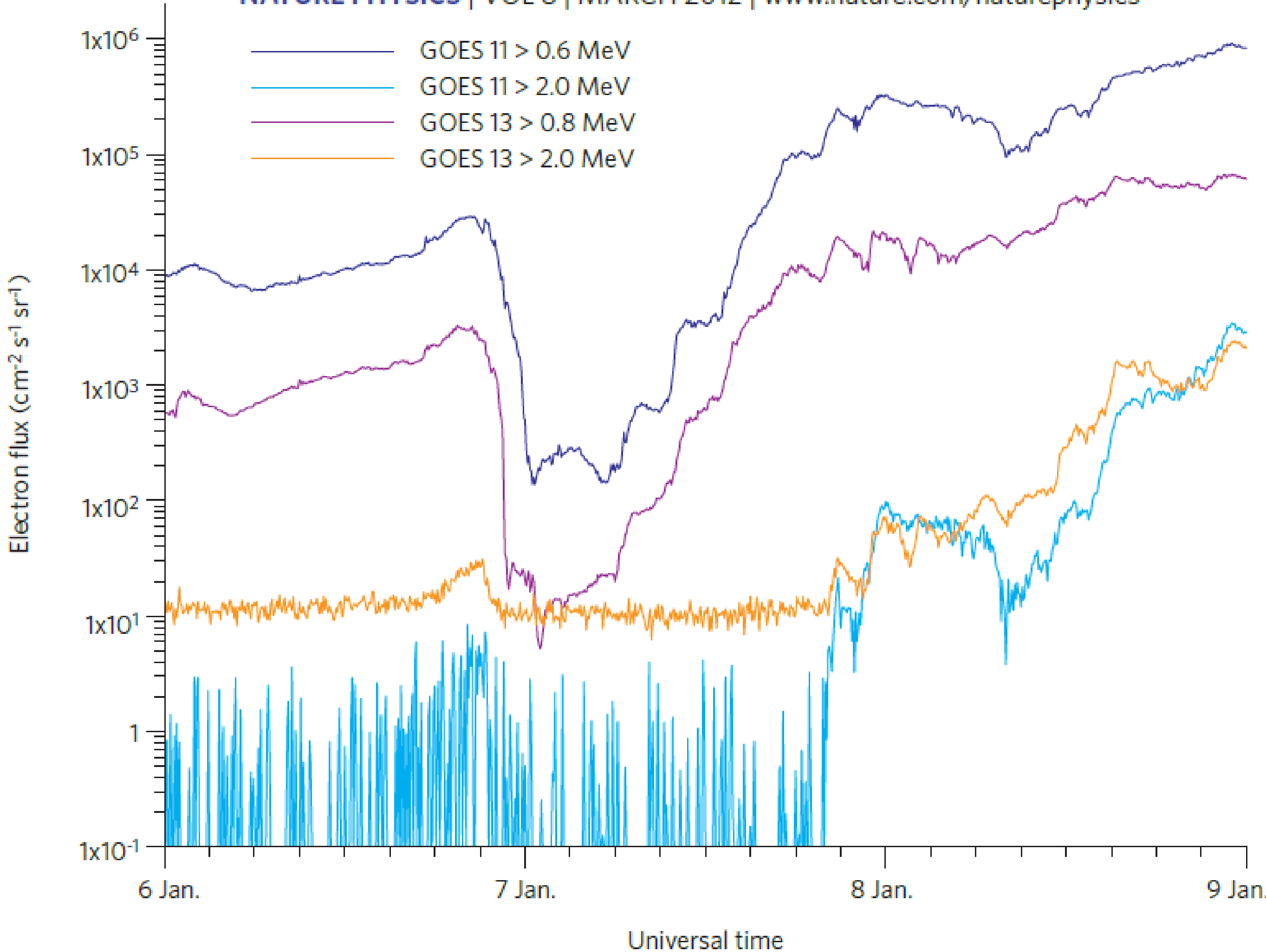

Figure 1 | High-energy electron flux measurements collected by NOAA GOES satellites 11 and 13 during a geomagnetic storm that began on 6 January 2011. Just before midnight of the eve of 6 January, the flux of electrons with energies above 0.6 and 0.8 MeV measured by satellites 11 and 13, respectively, decreased rapidly by over two orders of magnitude. Several hours later, the flux of these electrons recovered and was accompanied by an increase in the flux of higher-energy electrons above 2.0 MeV as the main phase of the storm took hold. Figure courtesy of Howard Singer, National Oceanic and Atmospheric Administration.

Timepix-based space instruments/payloads

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Czech Technical University in Prague

platform device — open space — Scientific payload

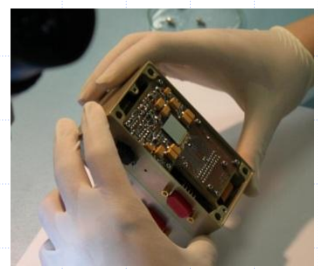
International Space Station

Deployed 3Q 2012 | 400 km

5 x Timepix devices

ESA Proba V satellite

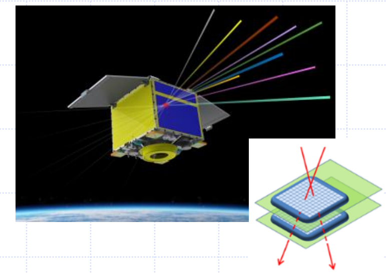
Launched 7th March 2013 | 800 km

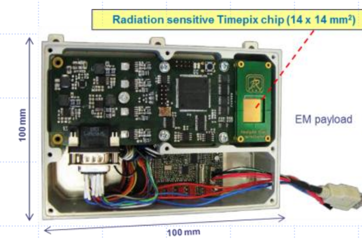


150 Kg

RISESAT satellite

Launch 2014/5





50 Kg

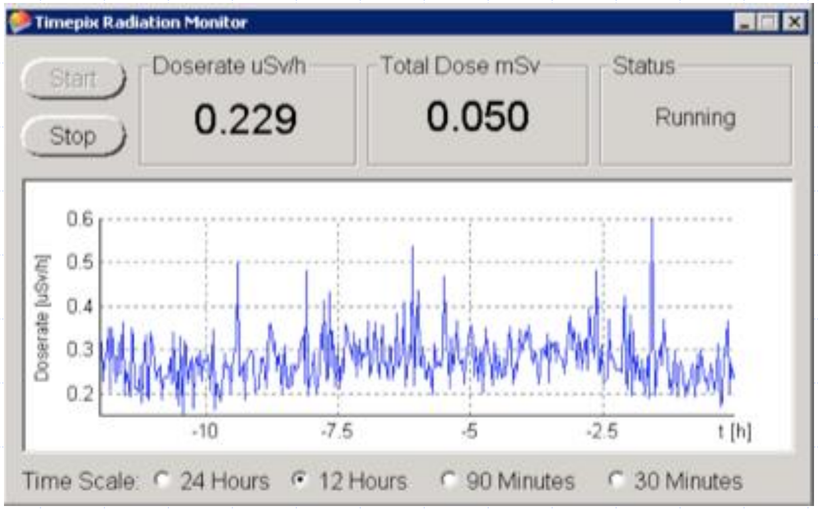
Type	Size (mass)
Minisatellite	100 – 200 Kg
Microsatellite	10 – 100 Kg
Nanosatellite	1 – 10 Kg
Picosatellite	< 1 Kg

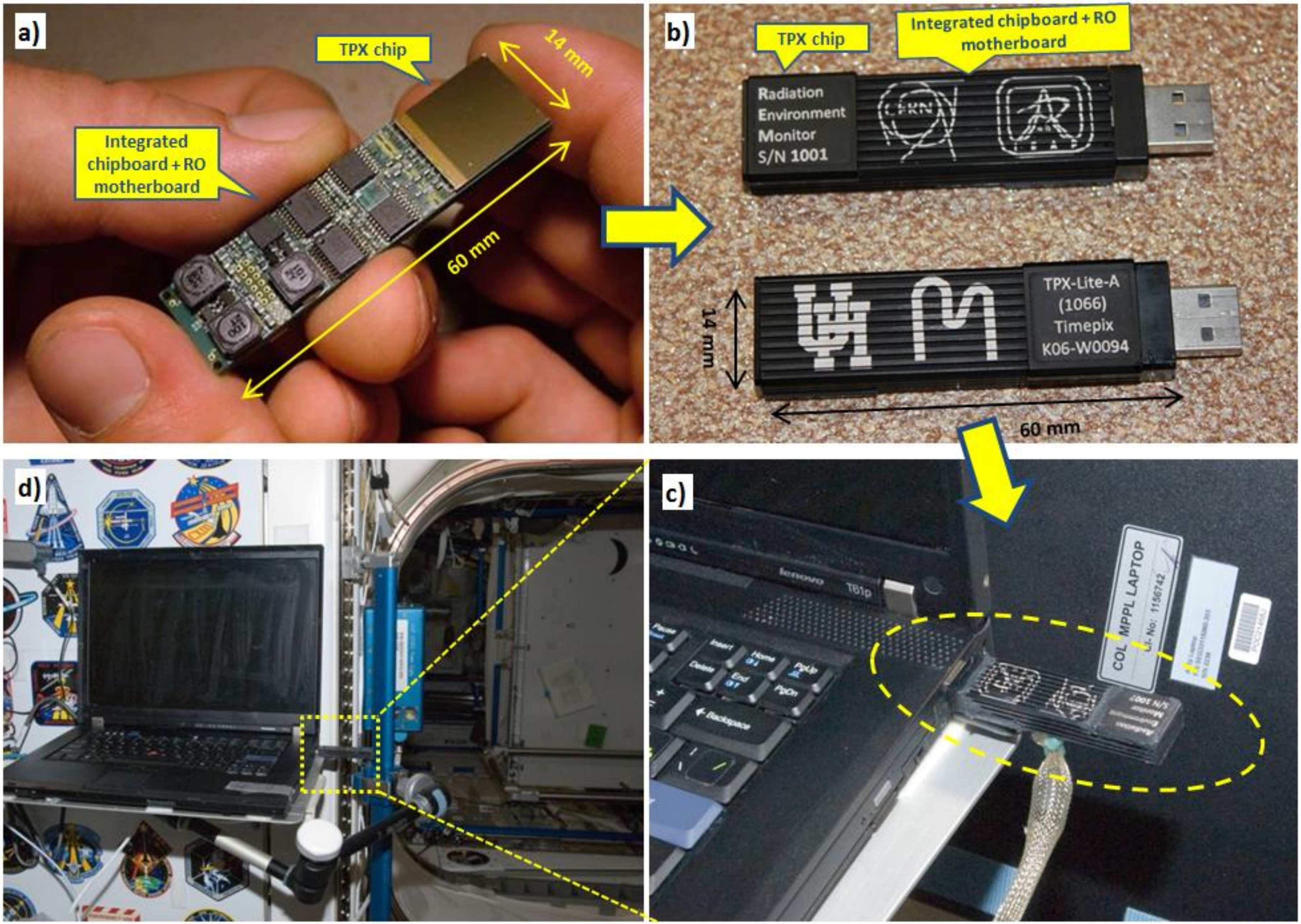
Online miniaturized Timepix Quantum Dosimeter
for the International Space Station (ISS)

Institute of Experimental and Applied Physics
Czech Technical University in Prague

5 independent detectors launched in space since 3Q 2012, all running, taking data

HW + Know-how + SW





Timepix detector in the highly miniaturized LITE architecture (a) customized for the ISS (b) as deployed with an on-board laptop via USB port (c) in a NASA Module at the ISS (d). Work done in cooperation with NASA and the University of Houston.

Online miniaturized Timepix Quantum Dosimeter
Single particle visualization & tracking

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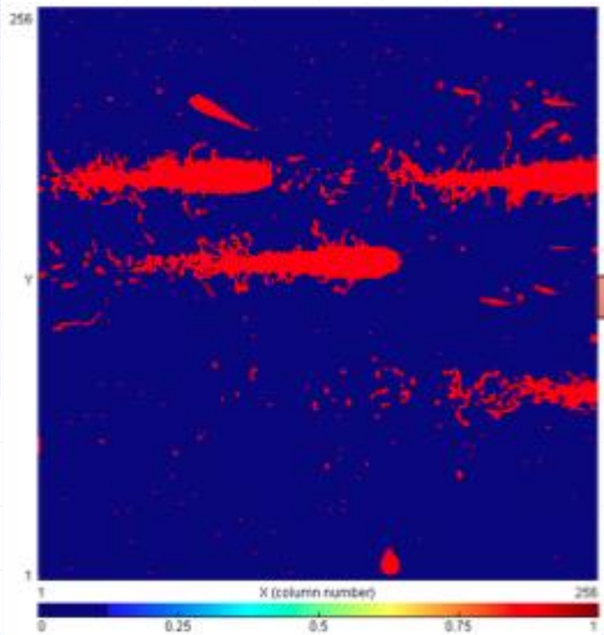
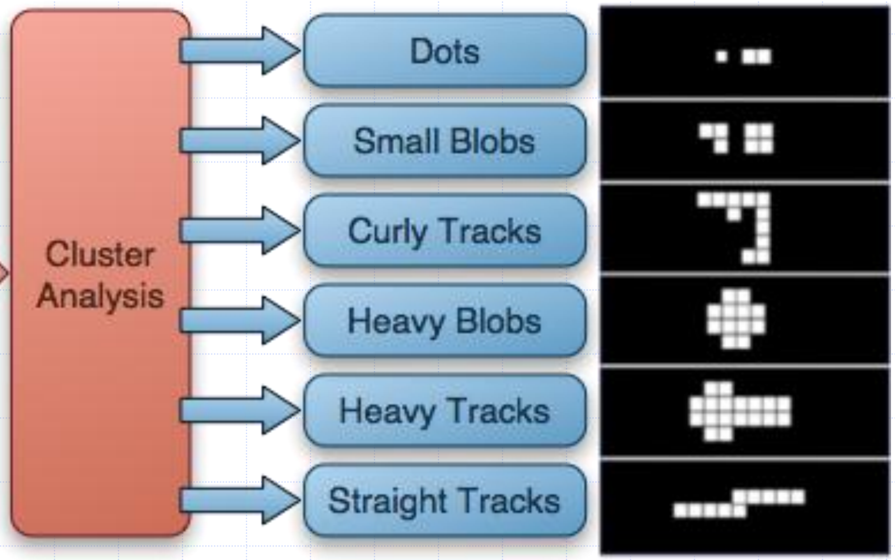
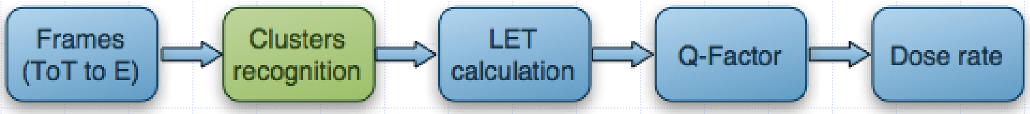
Czech Technical University in Prague



Frame containing 400 MeV 56Fe, 85°, measured at HIMAC, Japan

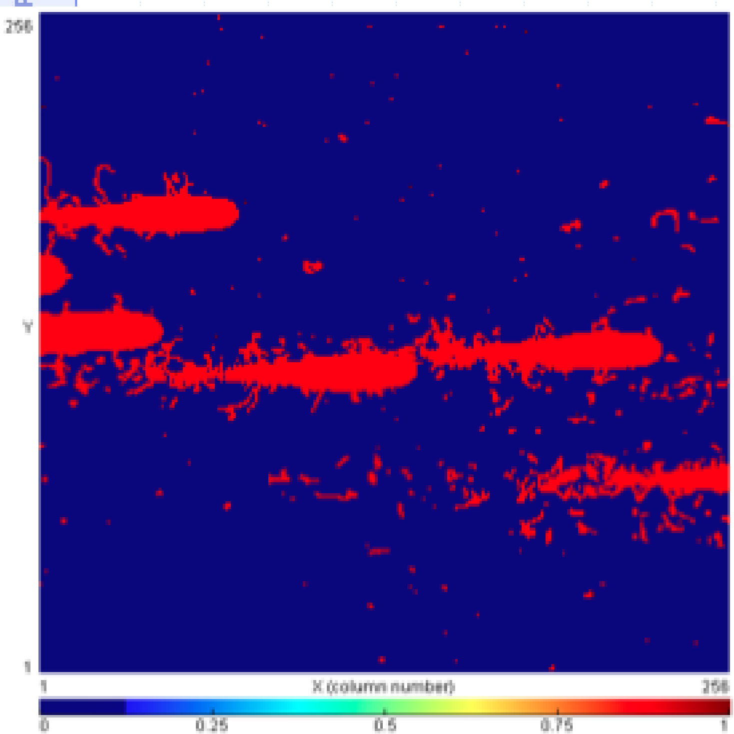


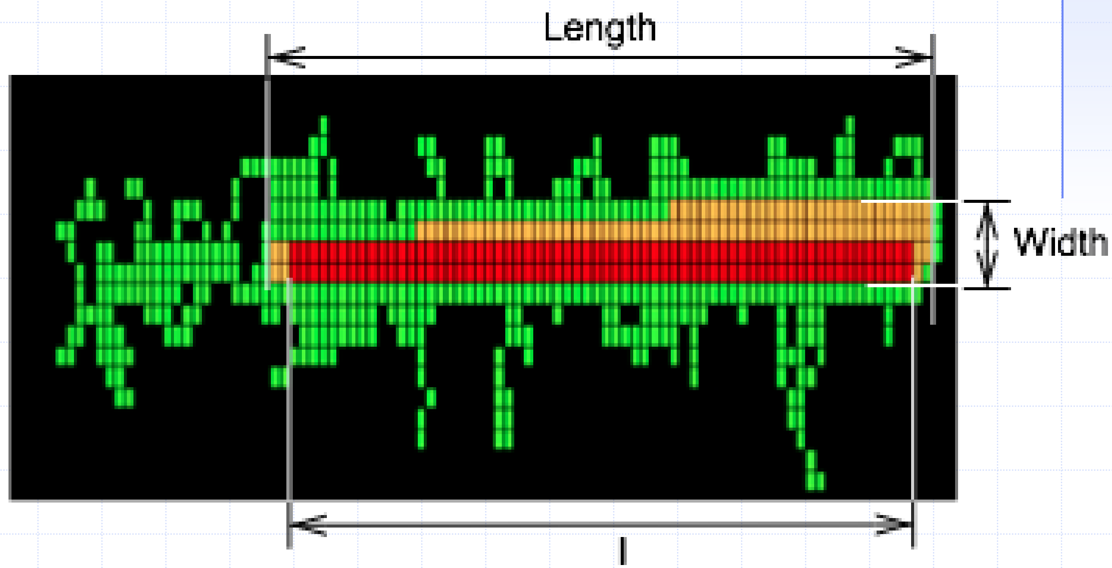
Cluster analysis algorithm is successfully working in ATLAS-MPX network

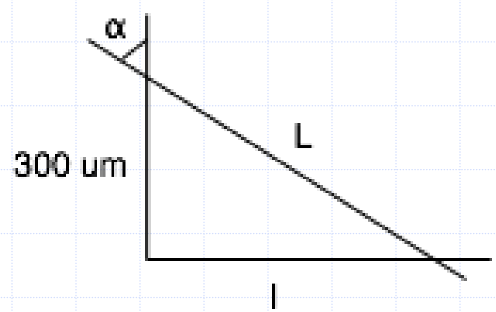


Online miniaturized Timepix Quantum Dosimeter

Single particle determination of linear energy transfer LET







$$l = Length - Width$$

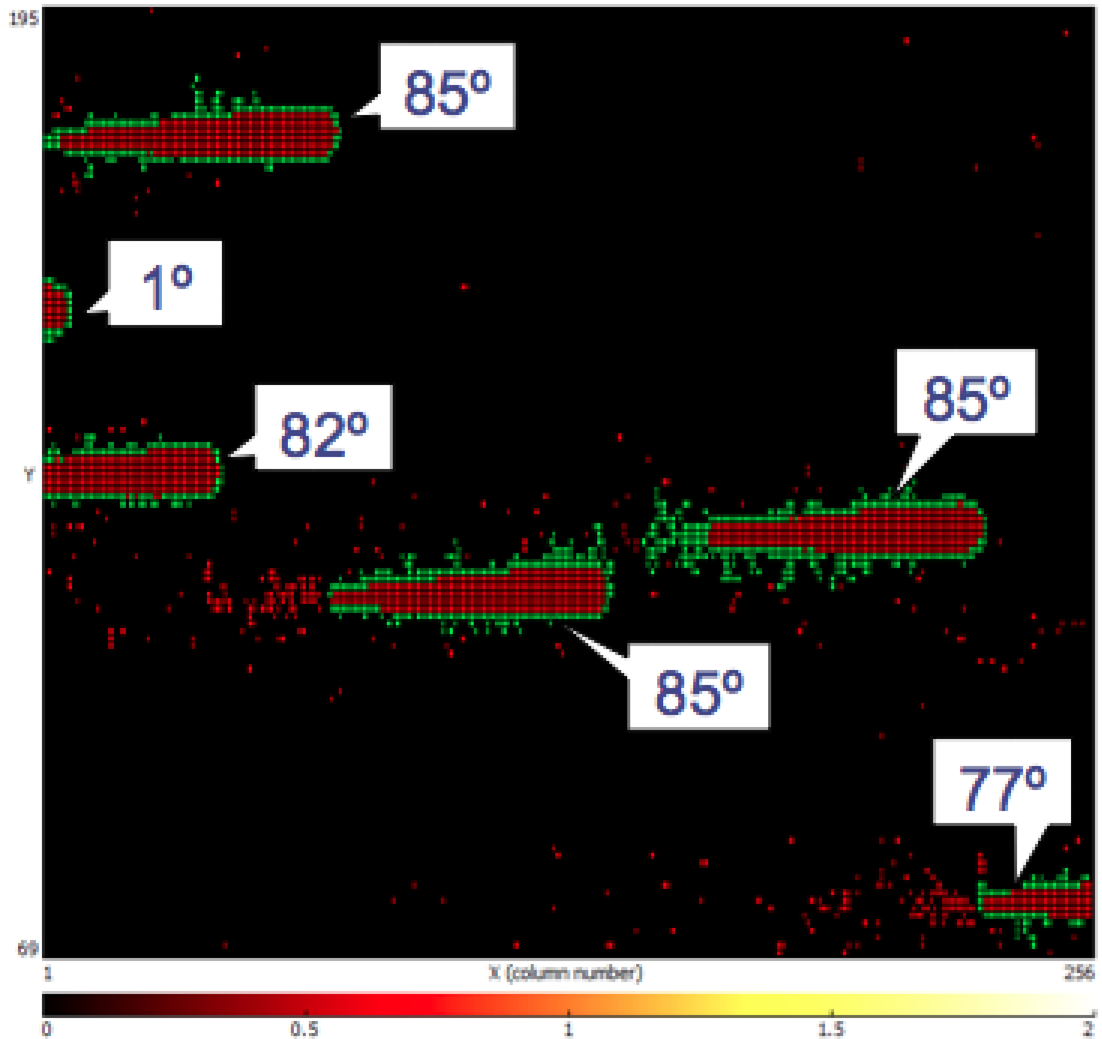
$$L = \sqrt{l^2 + 300^2}$$

$$LET = \frac{E}{L}$$

Frames (ToT to E) → Clusters recognition → LET calculation → Q-Factor → Dose rate

Online miniaturized Timepix Quantum Dosimeter

Single particle directional information in 3D



- In addition to the intrinsic 2D spatial information, detailed analysis of the characteristic tracks can give also the angle of incidence to the plane of the pixelated sensor.
- Custom-made plug-in SW packages automatically distinguishes and evaluates single particles and determines their direction in 3D

Timepix onboard the ISS
Time-correlated flux of charged particles

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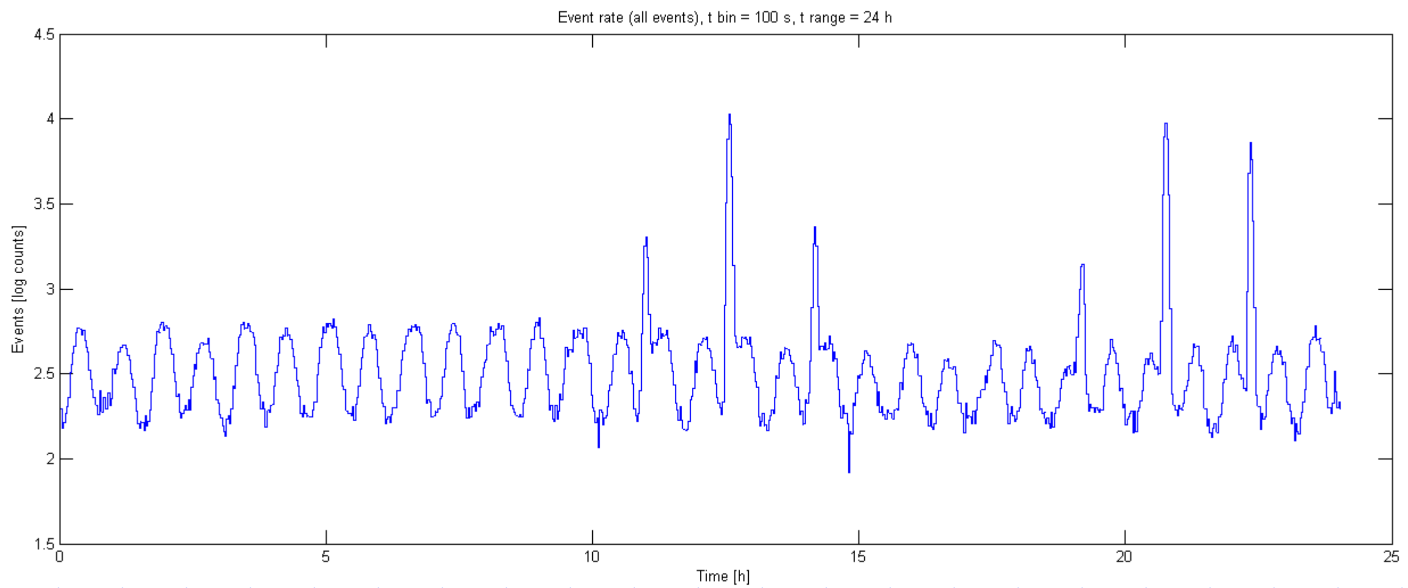
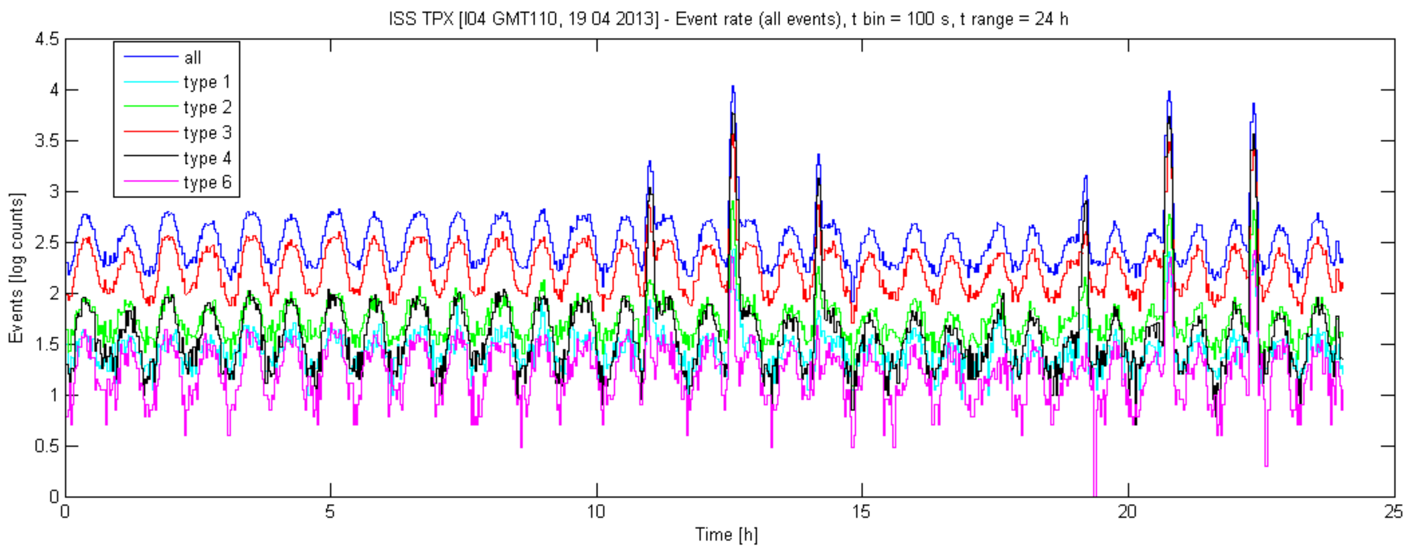
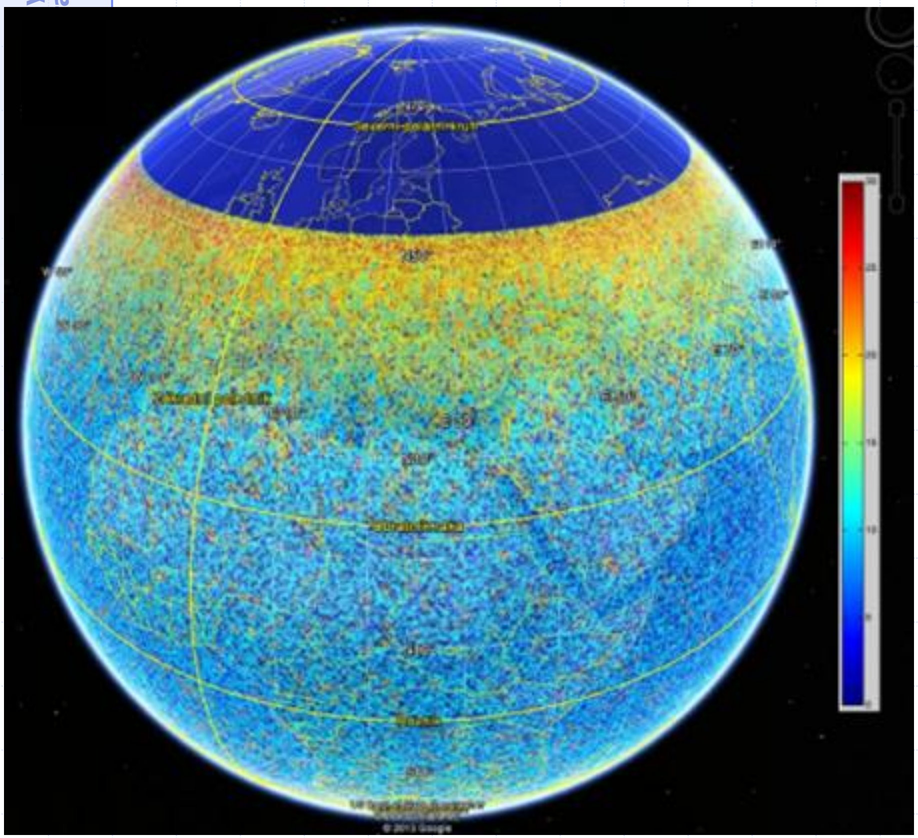
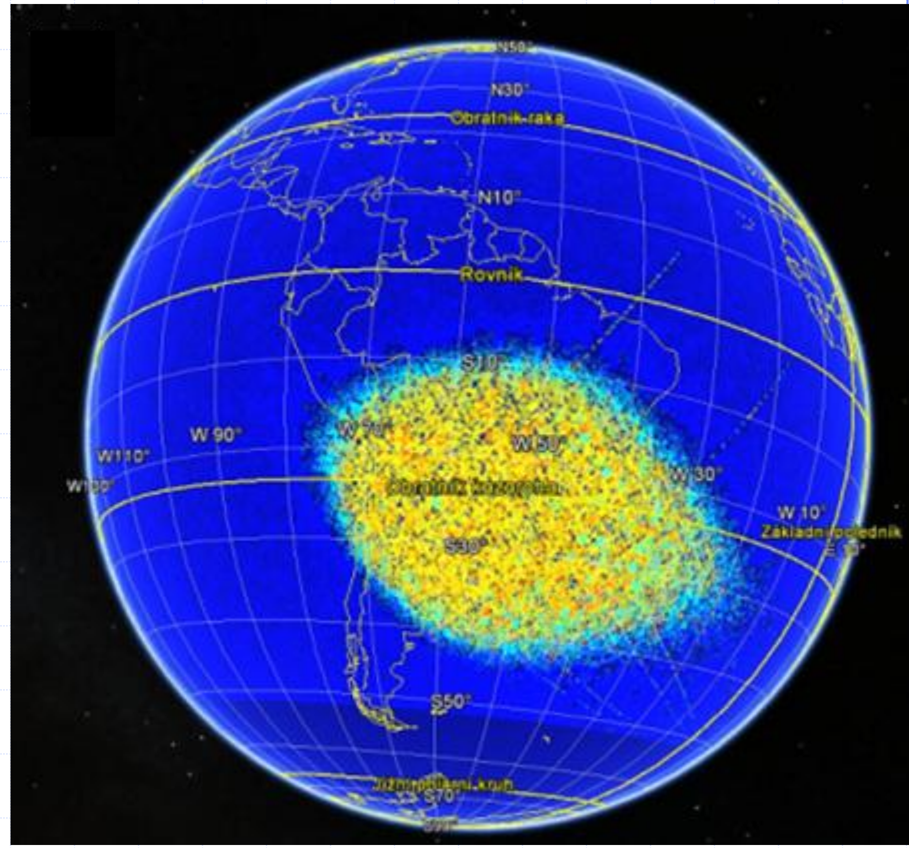




Timepix onboard the ISS

Spatial-correlated flux of charged particles





Detection and distribution of energetic radiation at the ISS measured by Timepix. Display on Earth position coordinates showing the Northern (left) and Southern (right) hemispheres.

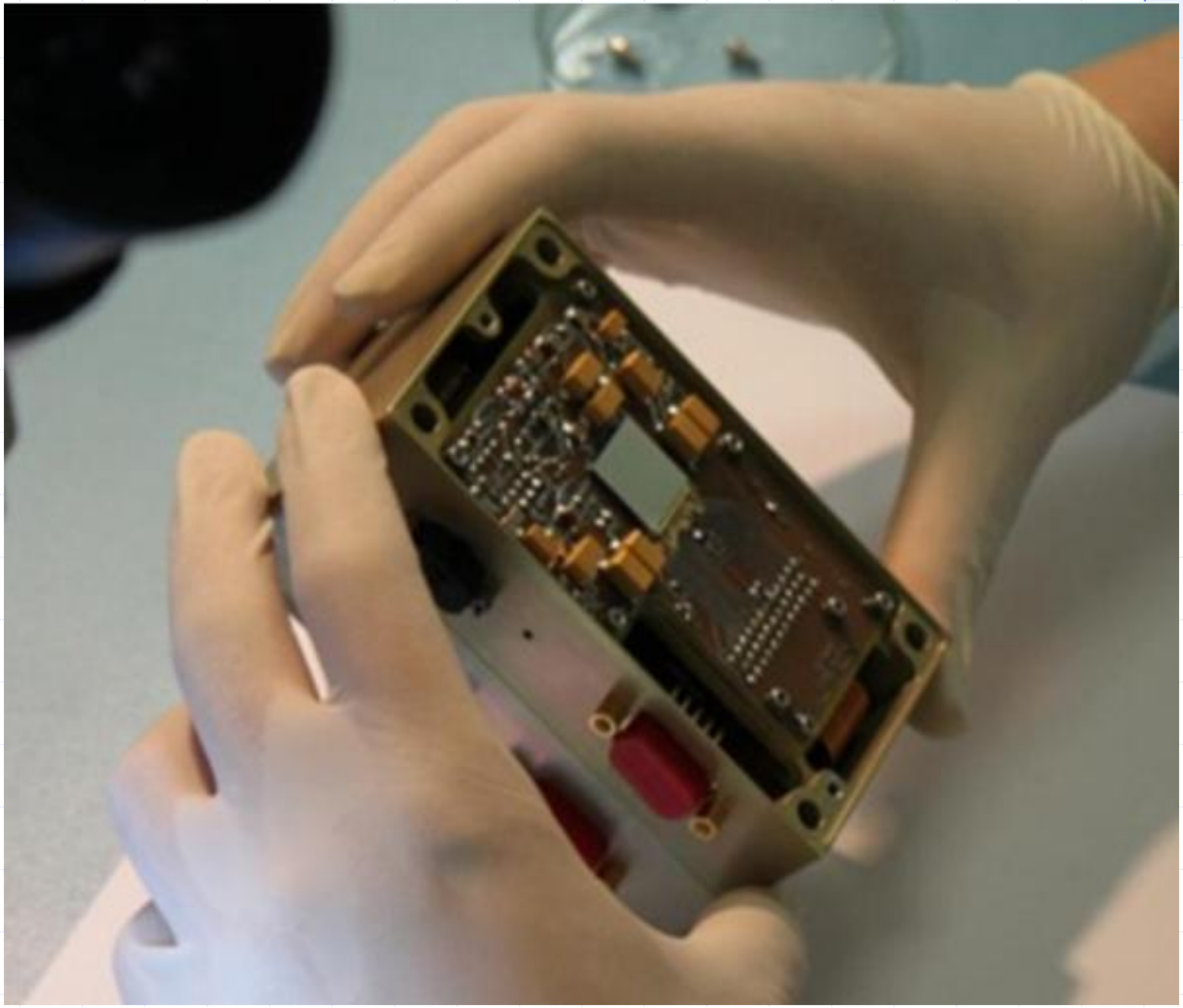
Timepix SATRAM Payload
ESA Proba-V satellite

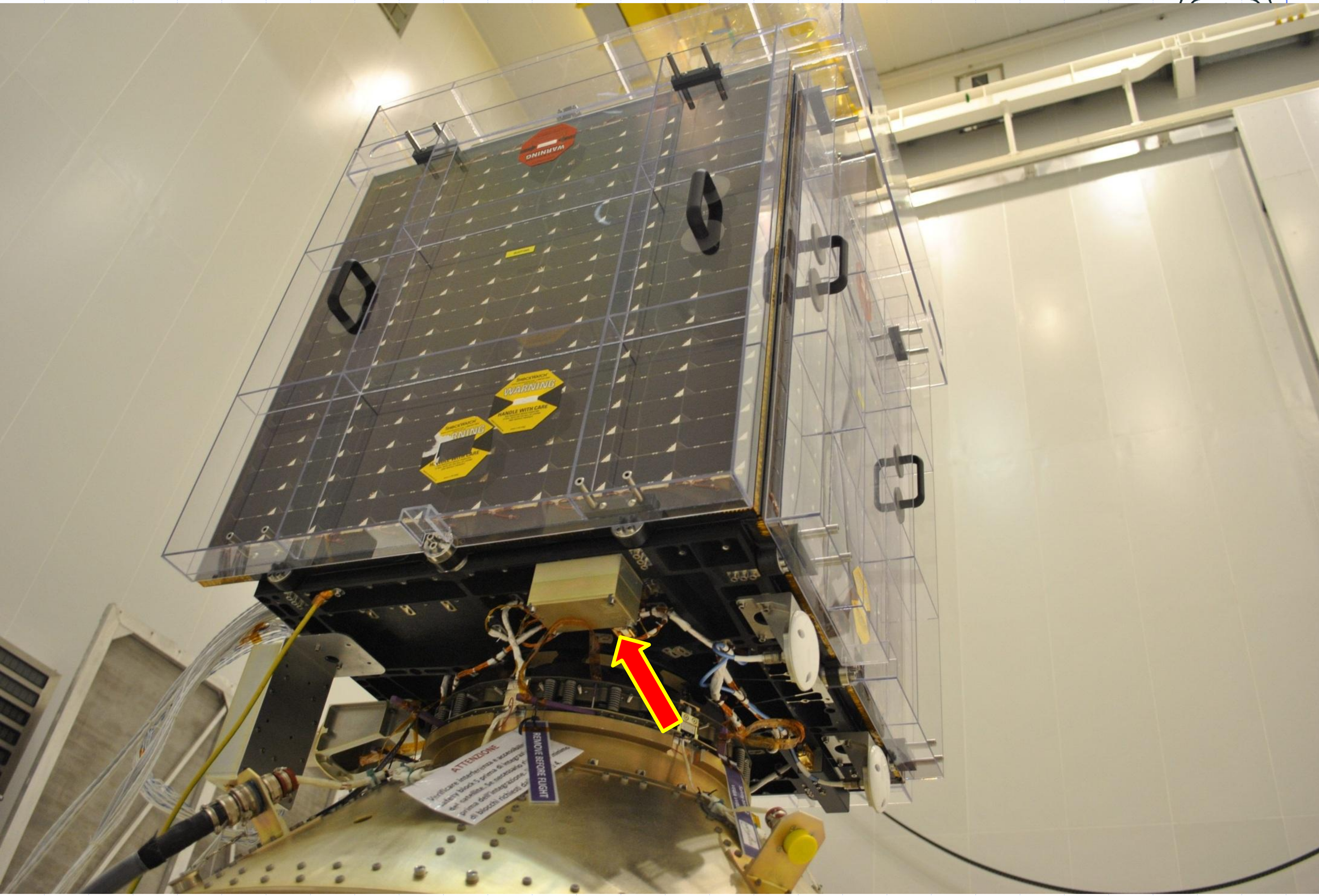
Institute of Experimental and Applied Physics
Czech Technical University in Prague

SATRAM: **Space Application of Timepix Radiation Monitor**

Characterization of space radiation at the Low Earth Orbit (LEO) on ESA PROBA-V satellite

- Altitude ~ 820 km
- Timepix for the first time in open space – currently TRL 9
- Launched March 2013



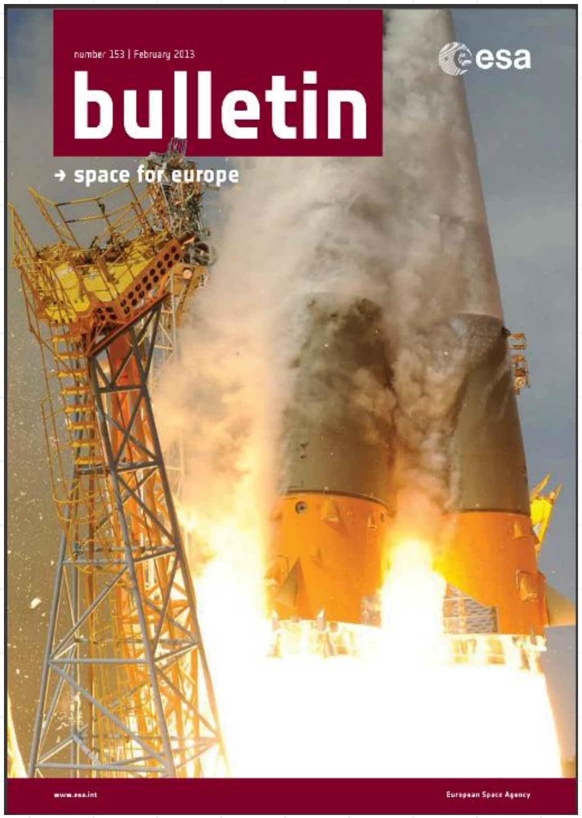

WARNING
HANDLE WITH CARE
ATTENZIONE
REMOVE BEFORE FLIGHT


esa
proba
VEGETATION
QinetiQ
VNREDSat-1 VAST
ASTRIUM
ESTCUBE
arianespace
service & solutions

esa
proba
VEGETATION
QinetiQ
arianespace

Timepix
SATRAM – ESA Proba V satellite

ESA Bulletin No. 153, Feb 2013, pg. 19

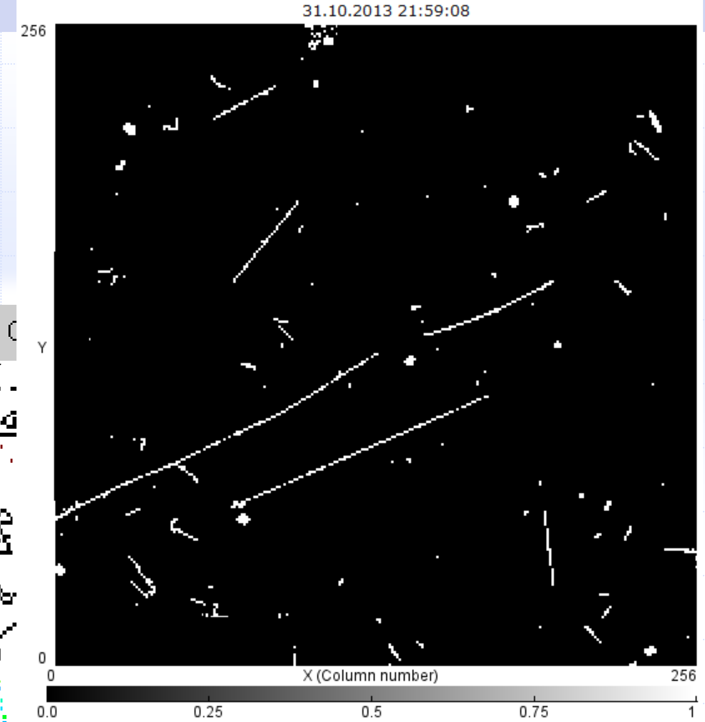


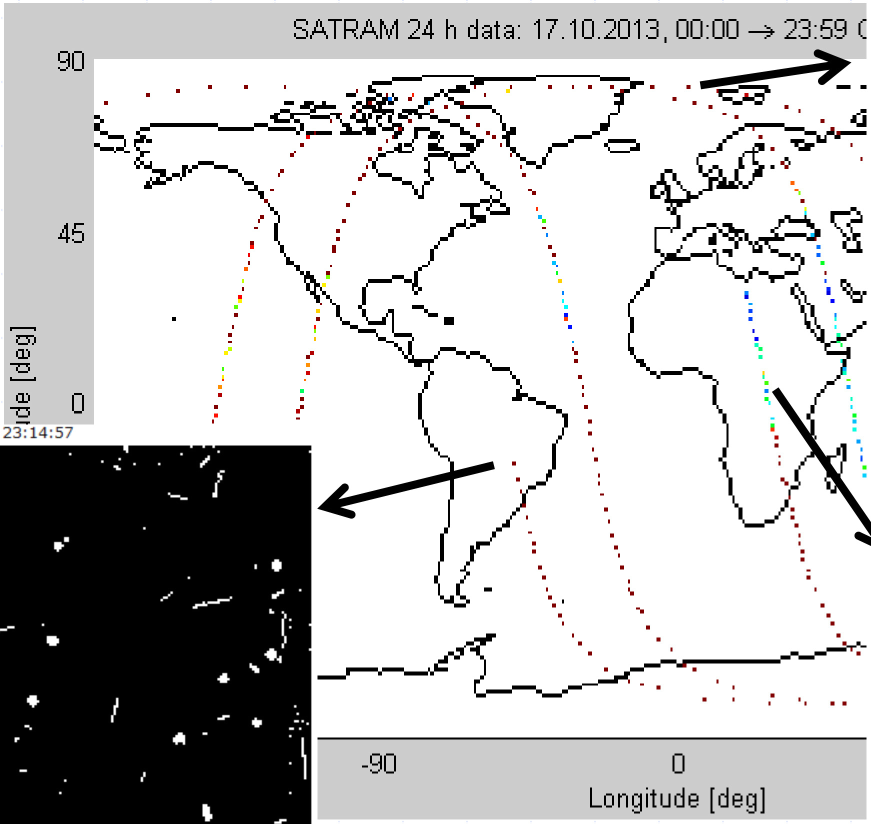
http://esamultimedia.esa.int/multimedia/publications/ESA-Bulletin-153/

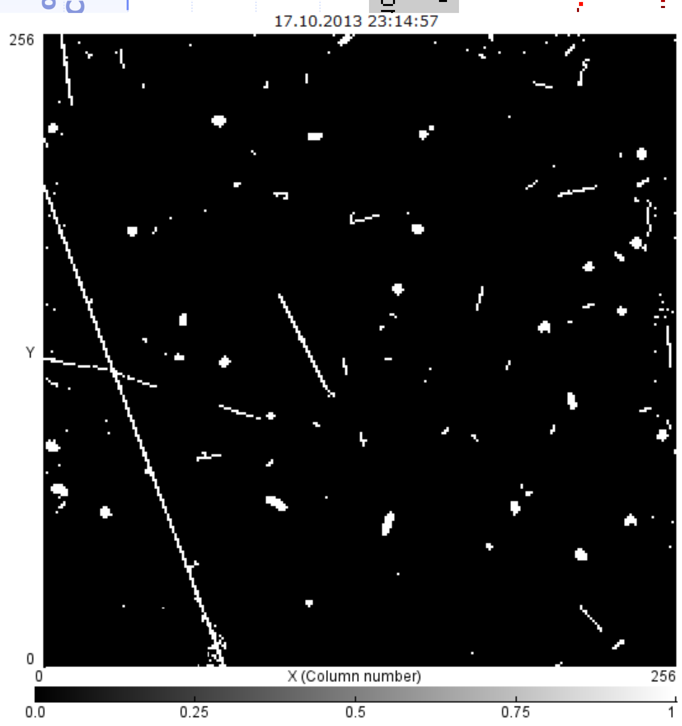
ESA Vega rocket, launched 7th March 2013

Timepix/ESA Proba-V:
LEO space radiation @ 800 km

of Experimental and Applied Physics
Czech Technical University in Prague

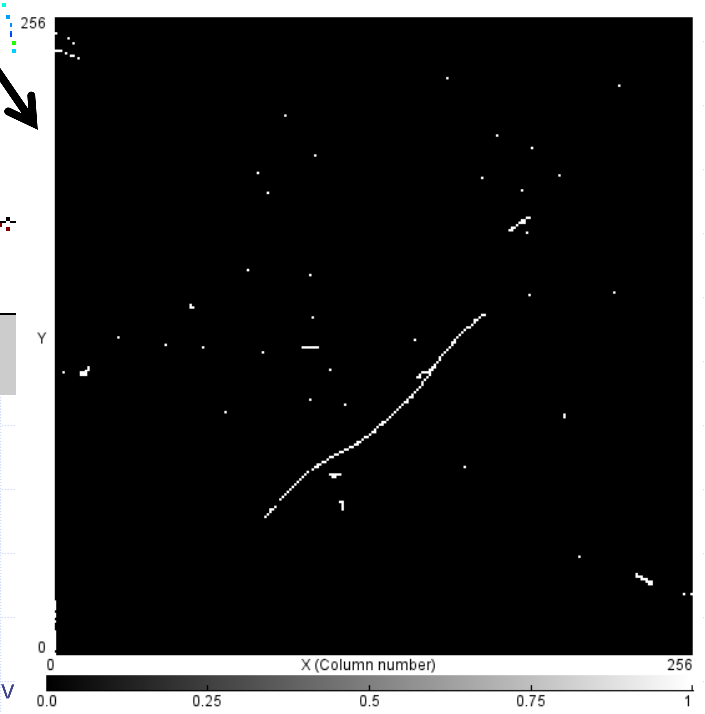






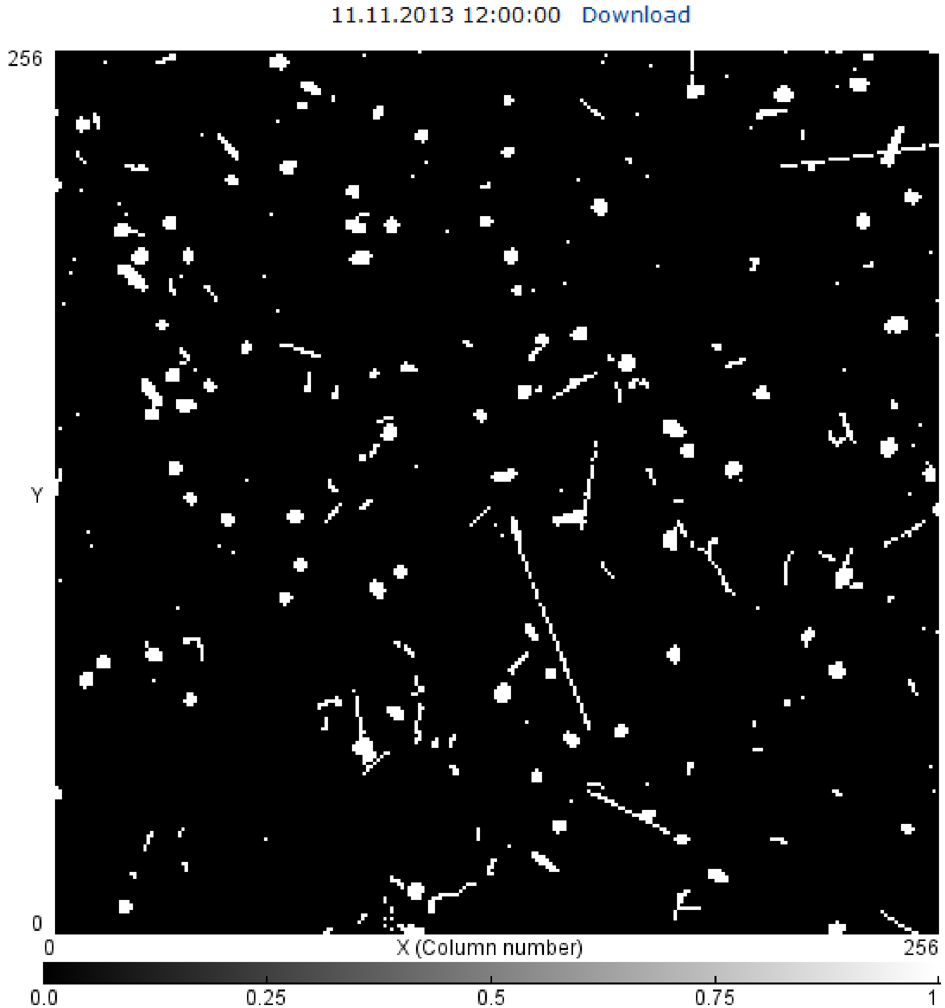
1 orbit: 1 h 40 min, acq t = 5 s

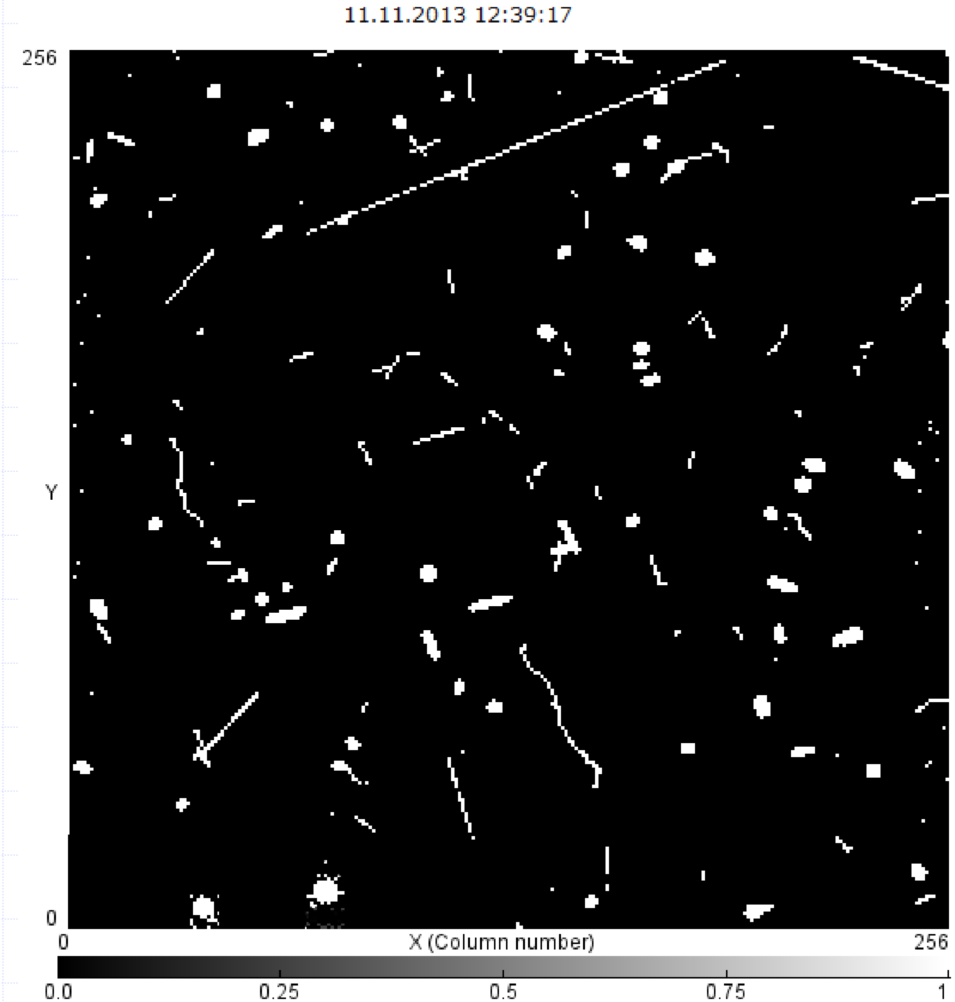
v = 26870 km/h = 450 km/h = 7.5 km/s



Timepix/ESA Proba-V:
LEO space radiation @ 800 km

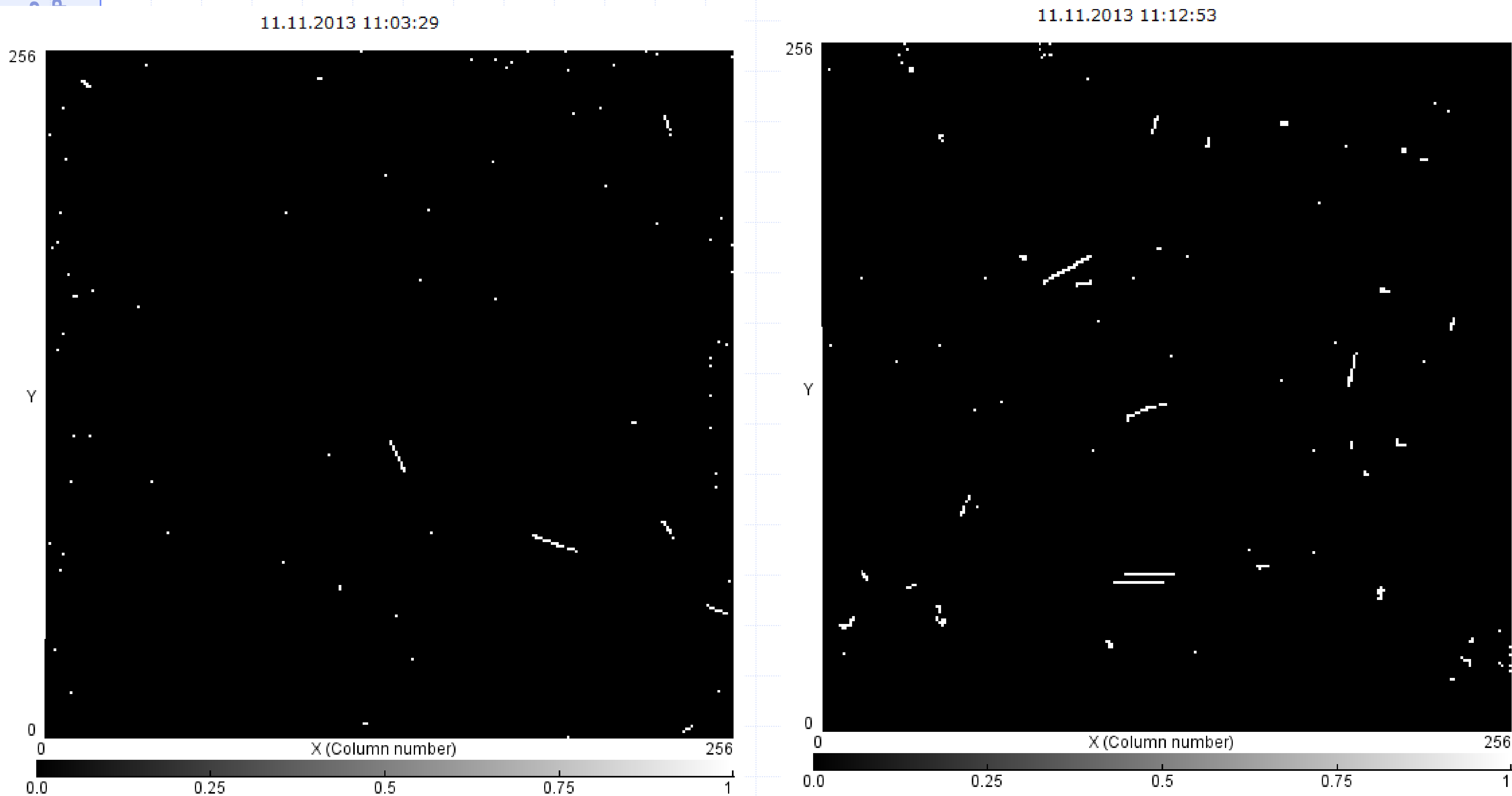
High radiation regions & heavy charged particles (p's)





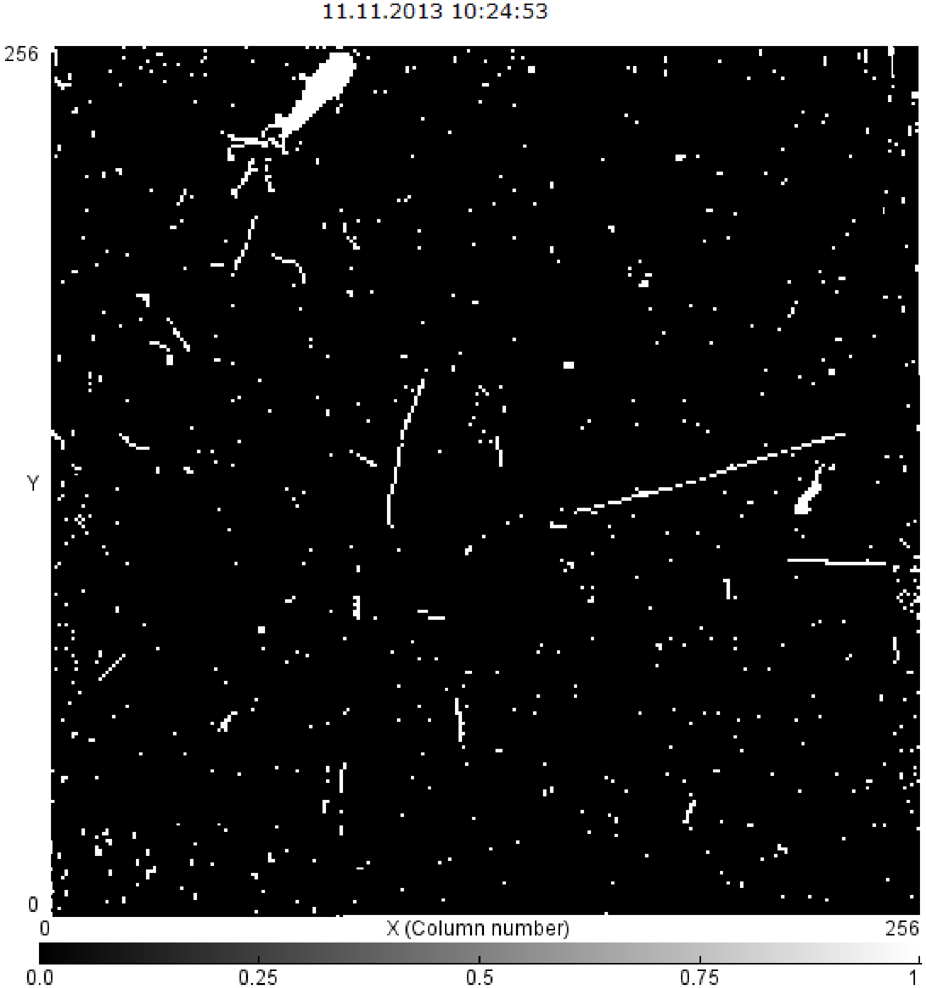
Timepix/ESA Proba-V:
LEO space radiation @ 800 km

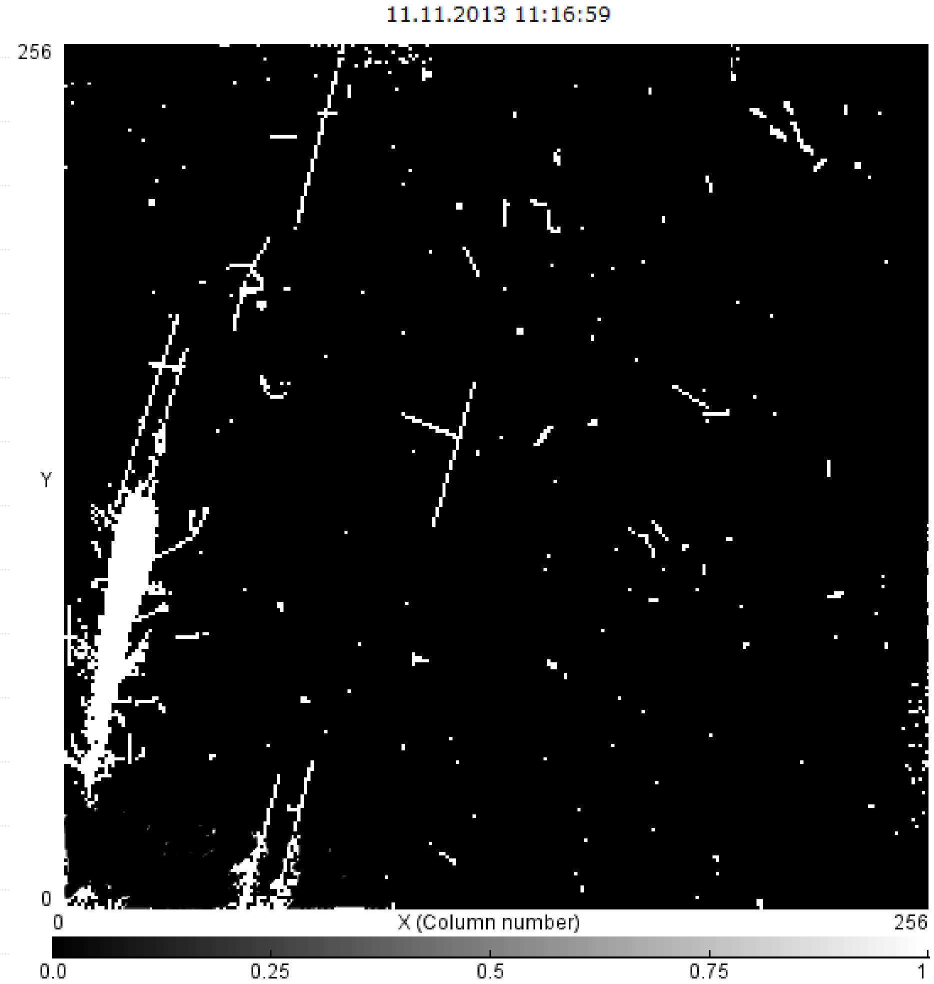
Low radiation regions & light charged particles (p's)



Timepix/ESA Proba-V:
LEO space radiation @ 800 km

Energetic heavy charged particles (ions)





Data visualization and evaluation:
Web-portal display & time-distributions

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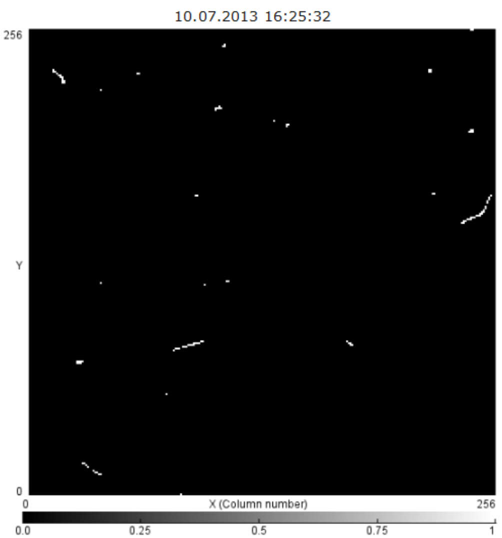
Czech Technical University in Prague

Medipix Radiation Monitor at Institute of Experimental and Applied Physics

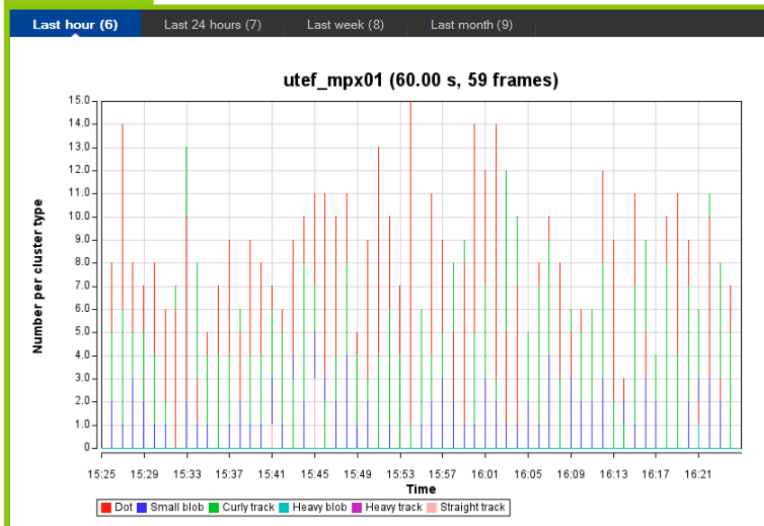
UTEF | ZCU | VDG | MOEDAL | SURO | REZ | ISS

mpx01

Last Frame



Cluster Time Plot



User Manual

Change location
- 1 ... move to previous location
- 2 ... move to next location

Change plot time range
- 6 ... 1 hour
- 7 ... 24 hours
- 8 ... last week
- 9 ... last month

Change detector
- + ... move to next detector
- - ... move to previous detector

Cluster Statistics

Track type	Sum	Average [s-1]
All	25	0.417
Dots	11	0.000
Small blobs	3	0.000
Curly tracks	11	0.000
Heavy blobs	0	0.000
Heavy tracks	0	0.000
Straight tracks	0	0.000

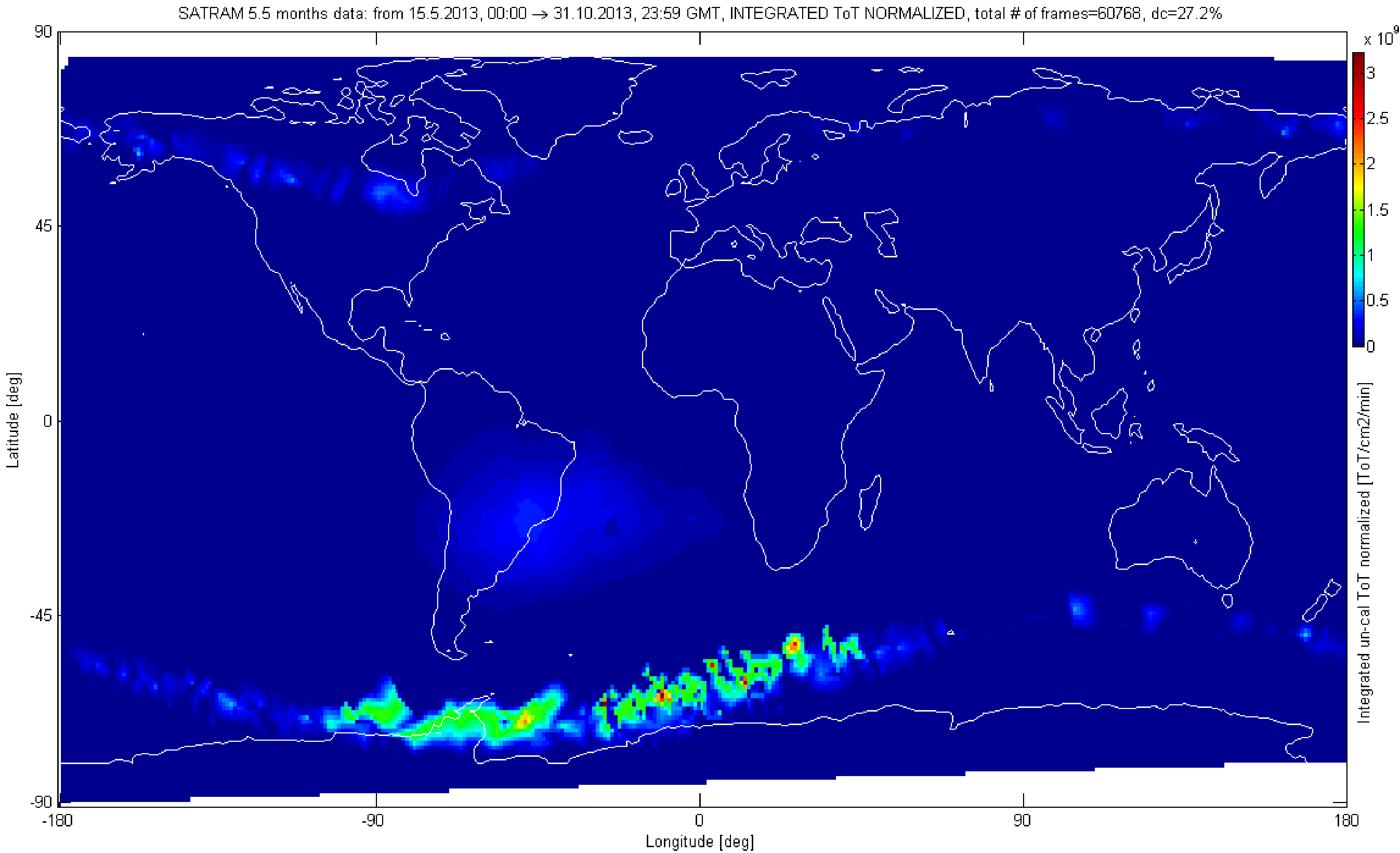
Energy Statistics

Track type	Sum	Average [s-1]
All	0	0.000
Dots	0	0.000
Small blobs	0	0.000
Curly tracks	0	0.000
Heavy blobs	0	0.000
Heavy tracks	0	0.000
Straight tracks	0	0.000

Cluster Statistics

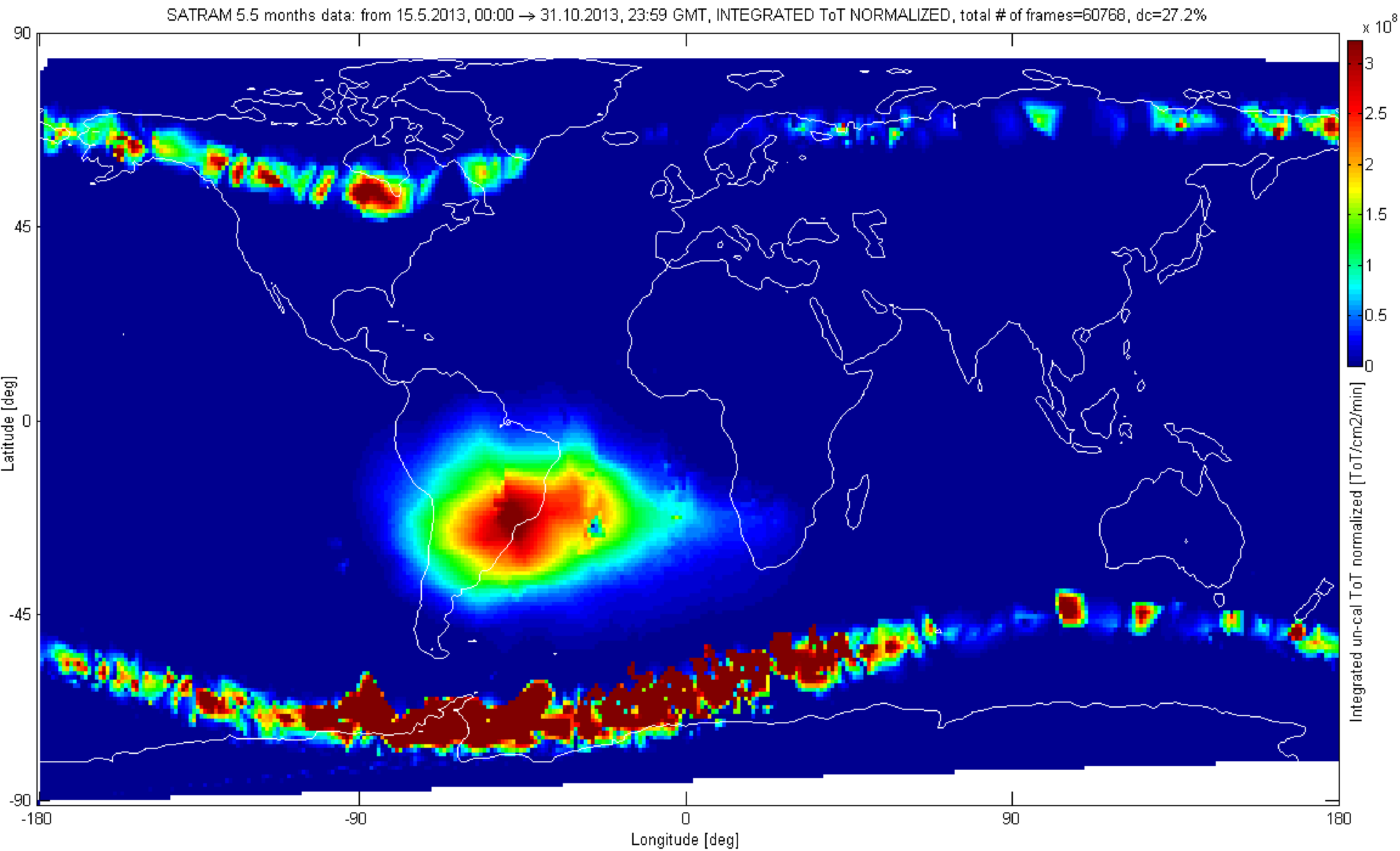
Track type	Sum	Average [s-1]
All	934	0.264
Dots	482	0.136
Small blobs	109	0.031
Curly tracks	336	0.095
Heavy blobs	1	0.000
Heavy tracks	0	0.000
Straight tracks	6	0.002

Timepix
SATRAM – ESA Proba-V satellite

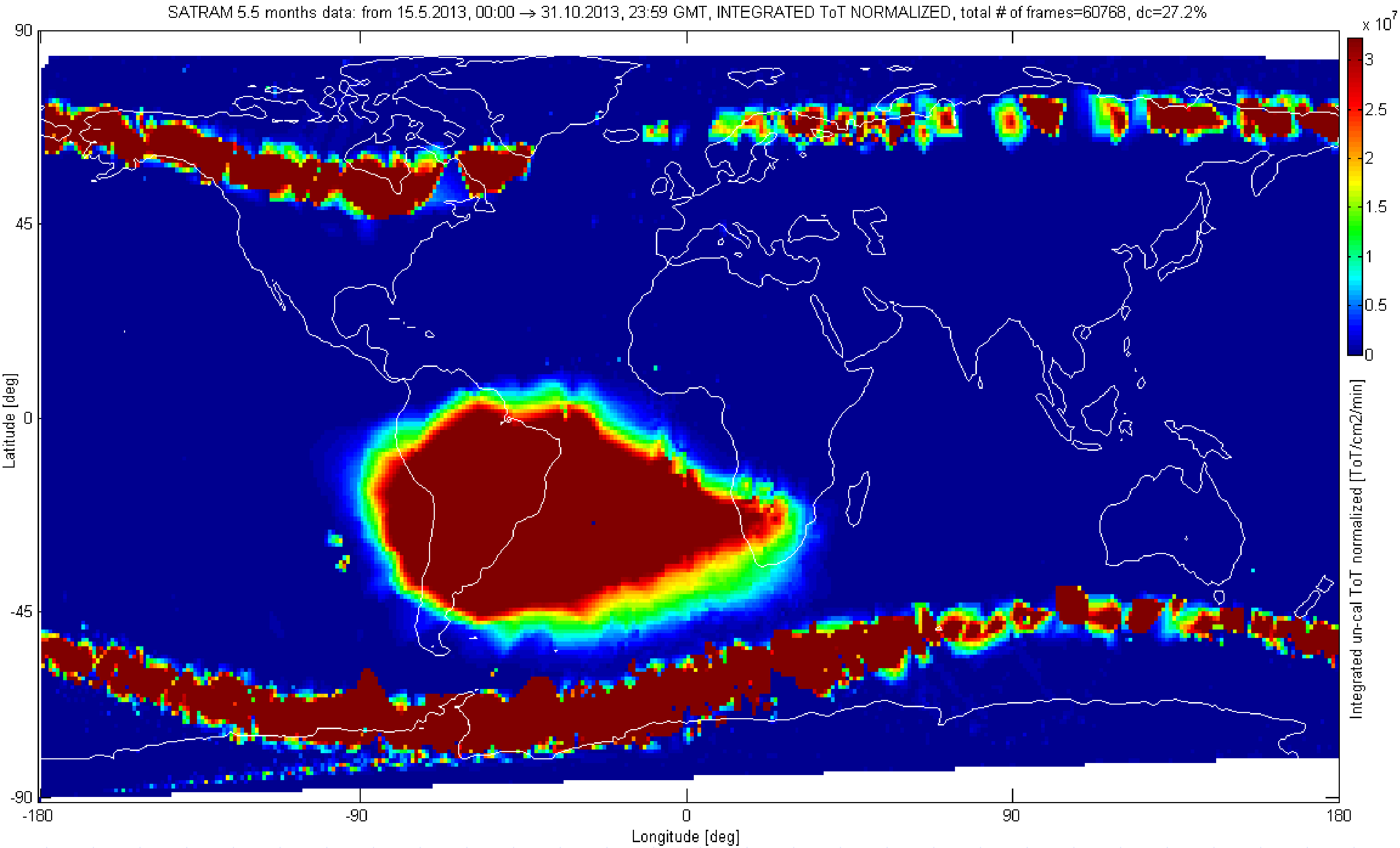


Timepix

SATRAM – ESA Proba-V satellite

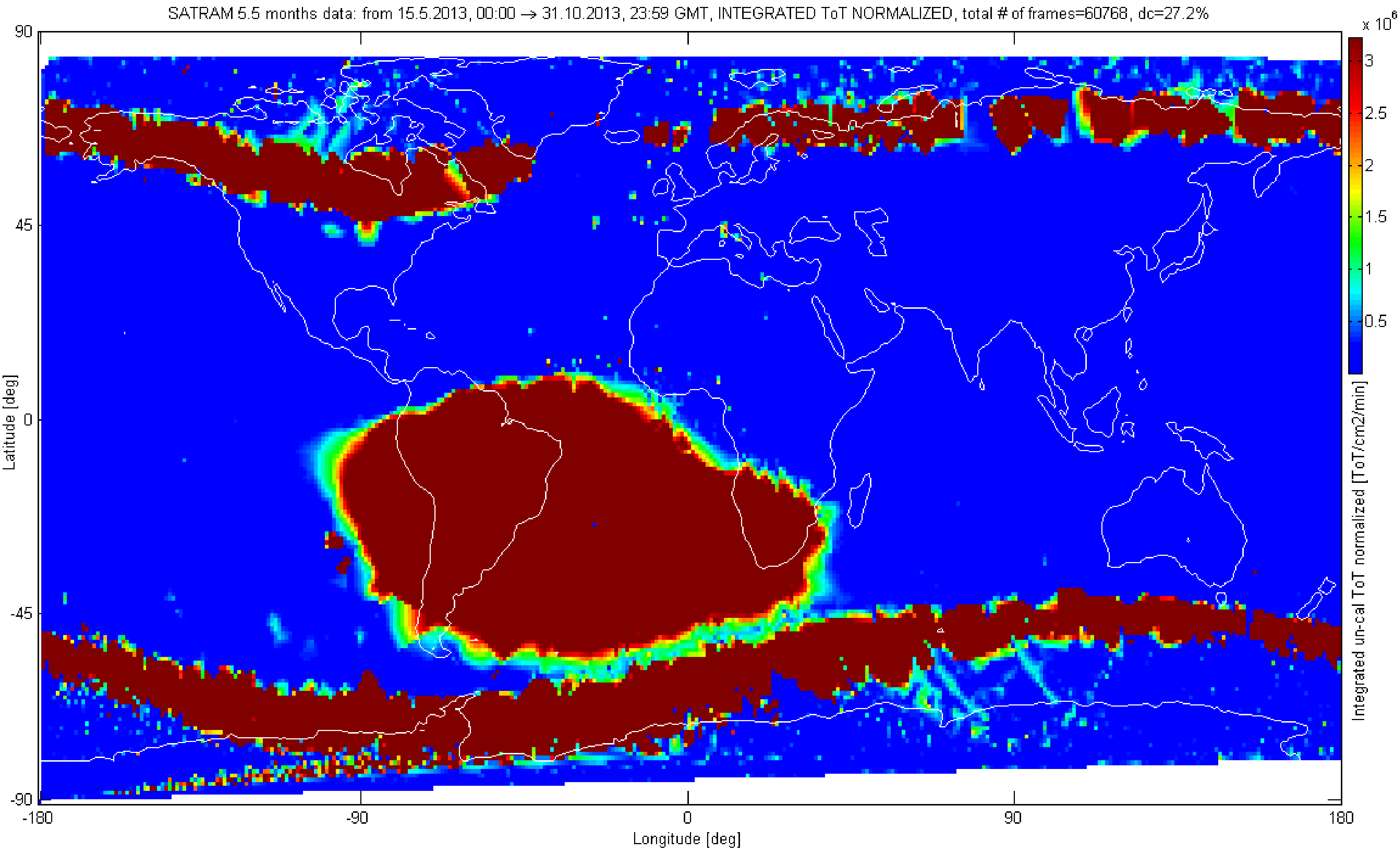


Timepix
SATRAM – ESA Proba-V satellite



Timepix

SATRAM – ESA Proba-V satellite



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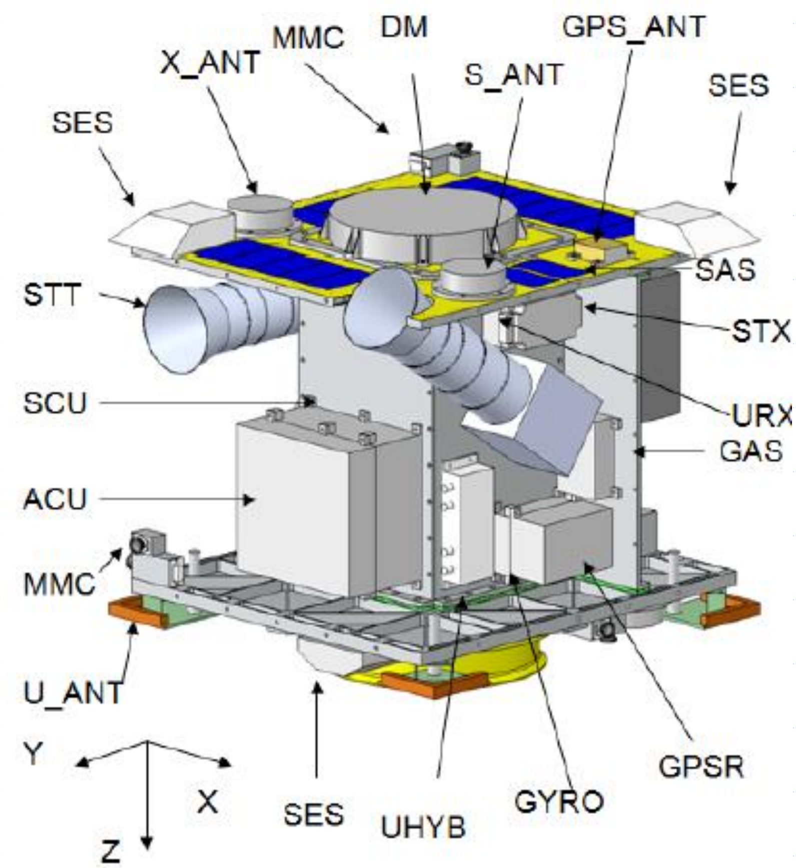
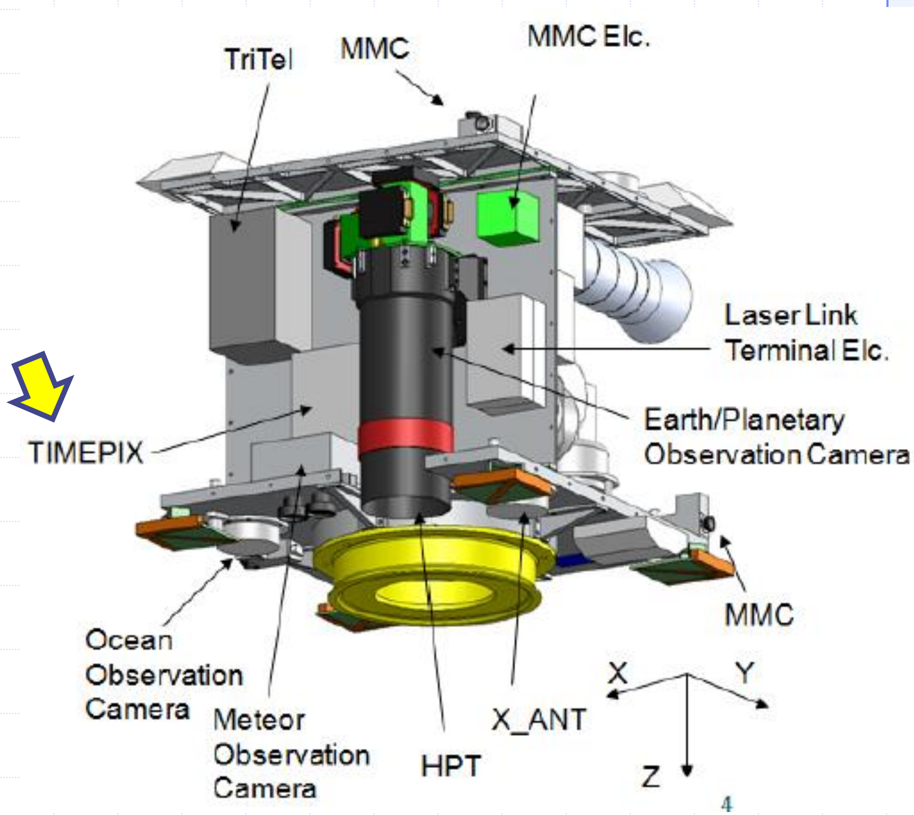
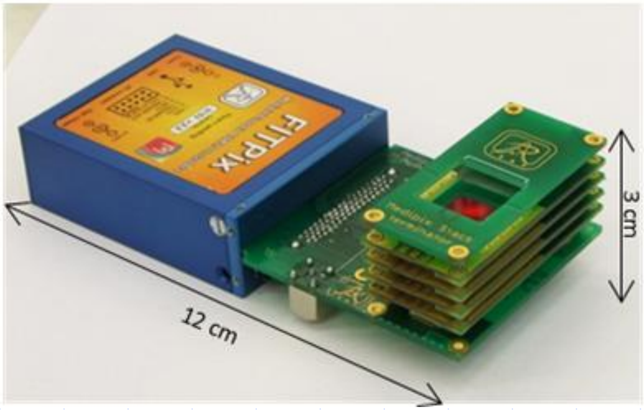
RISESAT
Rapid International Scientific Experimental Satellite

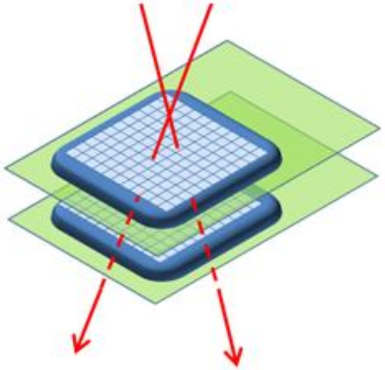
Institute of Experimental and Applied Physics
Czech Technical University in Prague

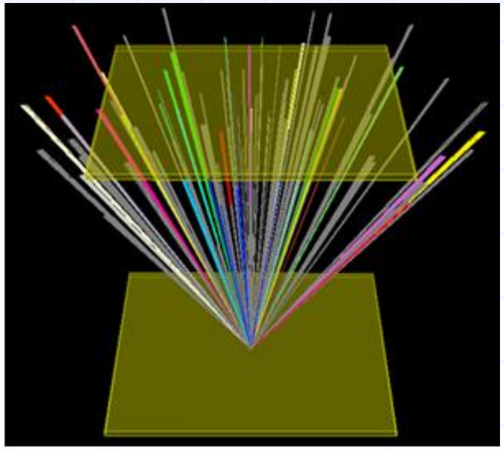




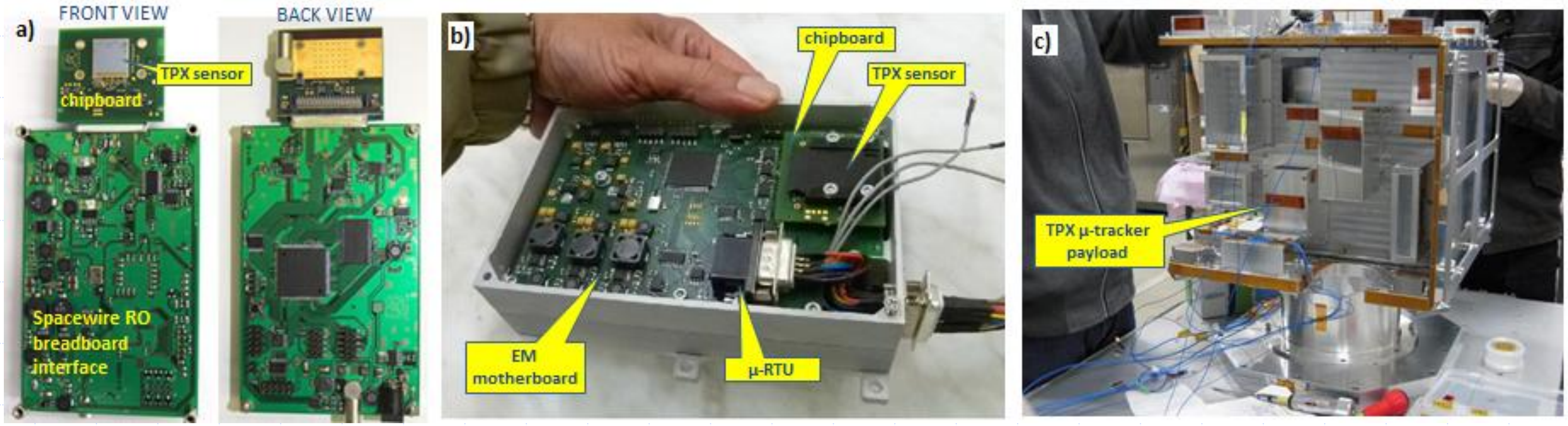
RISESAT
Timepix Micro-Tracker Particle Telescope







Particle micro-tracker of a stack of several Timepix detector chipboards with common motherboard and single integrated readout interface (left). Illustration of principle of particle telescope on two pixelated sensors determining the direction of trajectory of the particles (middle) providing direction information and spatial visualization of the origin of the particles (right).



Timepix μ-tracker for the RISESAT satellite consisting of two separate devices with synchronized operation. Spacewire prototype of one device (a), payload engineering model (b) and its position in the 50 Kg micro-satellite (c).

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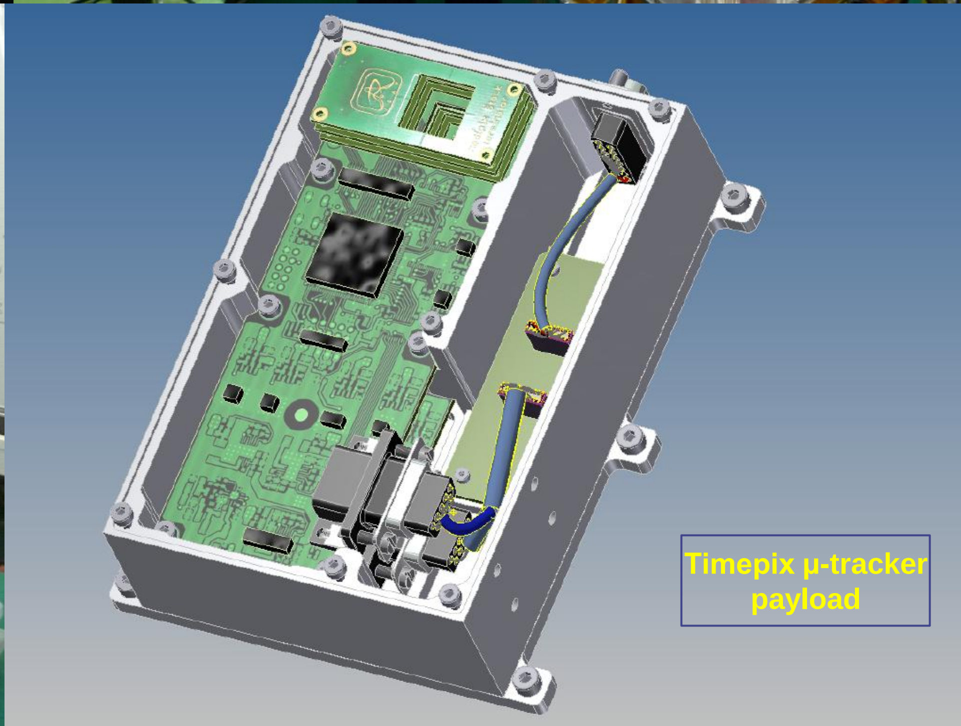
RISESAT satellite


Timepix μ-tracker
payload

Timepix-based space instruments/payloads
Technology Transfer & Industry Opportunity

Platform device/technology	Scientific instrument
❑ Technology demonstrator/platform device ▪ Spacecrew quantum dosimeter ▪ Spacecraft radiation monitor (potential for Galileo satellites, planetary missions)	❑ Mission-oriented customized payloads ▪ Planetary orbiter ▪ Search for water (n's) ▪ Particle telescope
→ Large-scale deployment	→ Small-scale deployment

Acknowledgment/special thanks to

- *EPS TIG & EPS/CERN Workshop Organizers*
- *E. Heijne, S. Pospisil, Z. Vykydal, M. Campbell et al & the Medipix Collaboration*
- *European Space Agency*