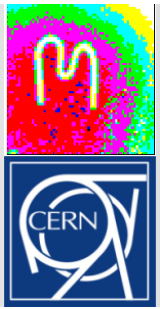
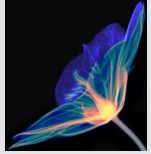


APPLICATIONS OF THE MEDIPIX AND TIMEPIX ASICS

M. Campbell[1], J. Alozy, R. Ballabriga, P. Christodoulou, A. Dorda, E.H.M. Heijne, I. Kremastiotis, X. Llopart, M. Piller, V. Sriskaran, and L.Tlustos

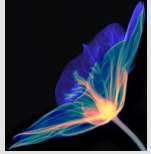
CERN, EP Department
1211 Geneva 23
Switzerland

[1] Honorary Professor at Glasgow University



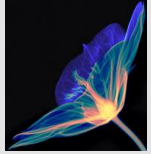
Acknowledgements – Collaboration Members

COLLABORATION NAME	Medipix2	Medipix3	Medipix4
ASICS	Medipix2 Timepix Timepix2	Medipix3 Timepix3	Medipix4 Timepix4
Albert-Ludwig Universität Freiburg, Germany	X	X	
AMOLF, Amsterdam, The Netherlands		X	
Brazilian Light Source, Campinas, Brazil		X	
CEA, Paris, France	X	X	X
CERN, Geneva, Switzerland	X	X	X
Czech Academy of Sciences, Prague, Czech Republic	X		
DESY-Hamburg, Germany		X	X
Diamond Light Source, England, UK		X	X
ESRF, Grenoble, France	X	X	
IEAP, Czech Technical University, Prague, Czech Republic	X	X	X



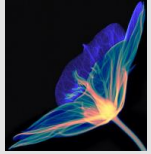
Acknowledgements – Collaboration Members

COLLABORATION NAME	Medipix2	Medipix3	Medipix4
ASICS	Medipix2 Timepix Timepix2	Medipix3 Timepix3	Medipix4 Timepix4
IFAE, Barcelona, Spain	X		X
KIT/ANKA, Forschungszentrum Karlsruhe, Germany		X	
Mid Sweden University, Sundsvall, Sweden	X	X	
JINR, Dubna, Russian Federation			X
MRC-LMB Cambridge, England, UK	X		
NIKHEF, Amsterdam, The Netherlands	X	X	X
Univesridad de los Andes, Bogota, Columbia		X	
University of Bonn, Germany		X	
University of California, Berkeley, USA	X	X	X
University of Canterbury, Christchurch, New Zealand		X	X
Universität Erlangen-Nurnberg, Erlangen, German		X	



Acknowledgements – Collaboration Members

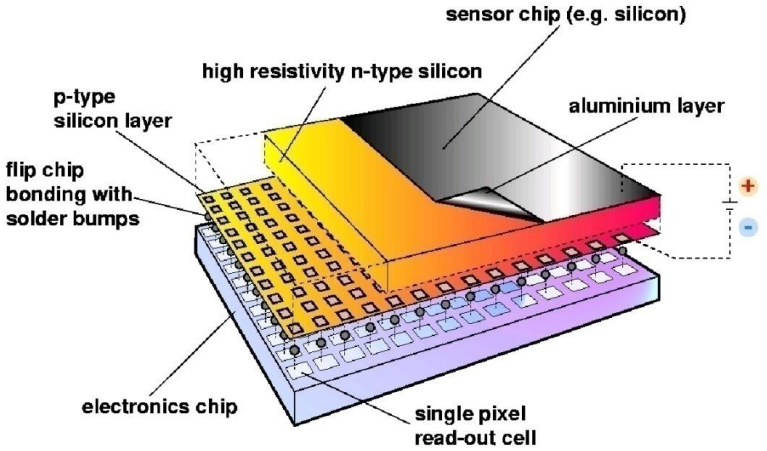
COLLABORATION NAME	Medipix2	Medipix3	Medipix4
ASICS	Medipix2 Timepix Timepix2	Medipix3 Timepix3	Medipix4 Timepix4
University of Geneva, Switzerland			X
University of Glasgow, Scotland, UK	X	X	X
University of Houston, USA	X	X	X
University of Leiden, The Netherlands		X	
University of Maastricht, The Netherlands		X	X
University of Oxford, England, UK			X
University and INFN Section of Cagliari, Italy	X		
University and INFN Section of Pisa, Italy	X		
University and INFN Section of Napoli, Italy	X		
Technical University of Munich, Germany		X	
VTT Information Technology, Espoo, Finland		X	

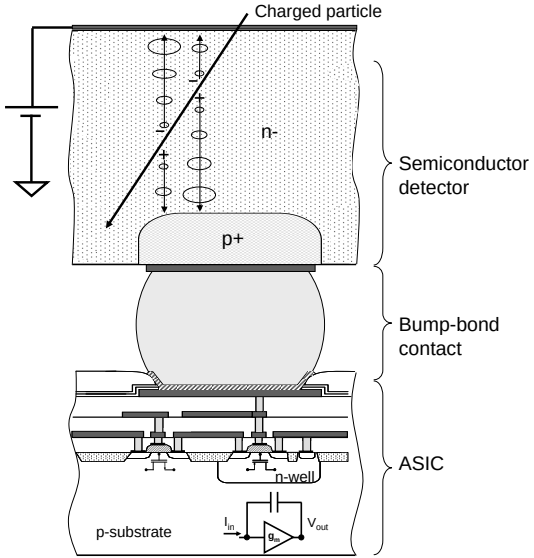



Acknowledgements – Commercial Partners

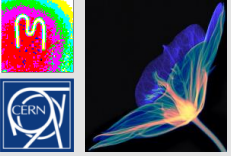
COLLABORATION NAME	Medipix2			Medipix3		Medipix4	
ASICS	**Medipix2**	**Timepix**	**Timepix2**	**Medipix3**	**Timepix3**	**Medipix4**	**Timepix4**
ADVACAM s.r.o., Czech Republic	X	X	X	X	X		
Amsterdam Scientific Instruments, The Netherlands	X	X	X	X	X		
Kromek, UK	X	X	X				
Malvern-Panalytical, The Netherlands	X	X	X	X			
MARS Bio Imaging, New Zealand				X			
Quantum Detectors, UK				X			
X-ray Imaging Europe, Germany	X	X	X				
X-spectrum, Germany				X			

Hybrid Silicon Pixel Detectors





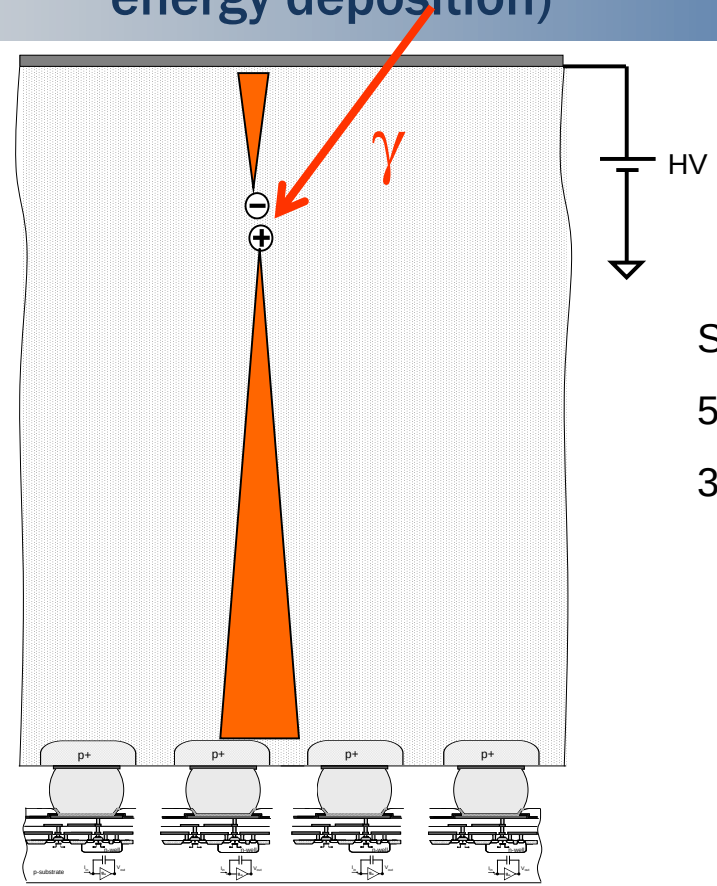
- Noise-hit free images possible (high ratio of threshold/noise)
- Standard CMOS can be used allowing on-pixel signal processing
- Sensor material can be changed (Si, GaAs, CdTe..)
- Semiconductor sensor can be replaced by a gas gain grid or MCP



Medipix readout chips – photon counting

	Medipix	Medipix2	Medipix3
Tech. node (nm)	1000	250	130
Year	1997	2003	2013
Pixel size (μm)	170	55	55 / 110
# pixels (x x y)	64 x 64	256 x 256	256 x 256 / 128 x 128
# thresholds(counters)	1(1)	2(1)	Up to 8 (up to 8)
Charge summing mode	No	No	Yes
Readout architecture (Frame based)	Sequential R/W	Sequential R/W	Sequential or continuous R/W
Number of sides for tiling	0	3	3

Cross section of a Hybrid Pixel Detector system (X-ray photon energy deposition)

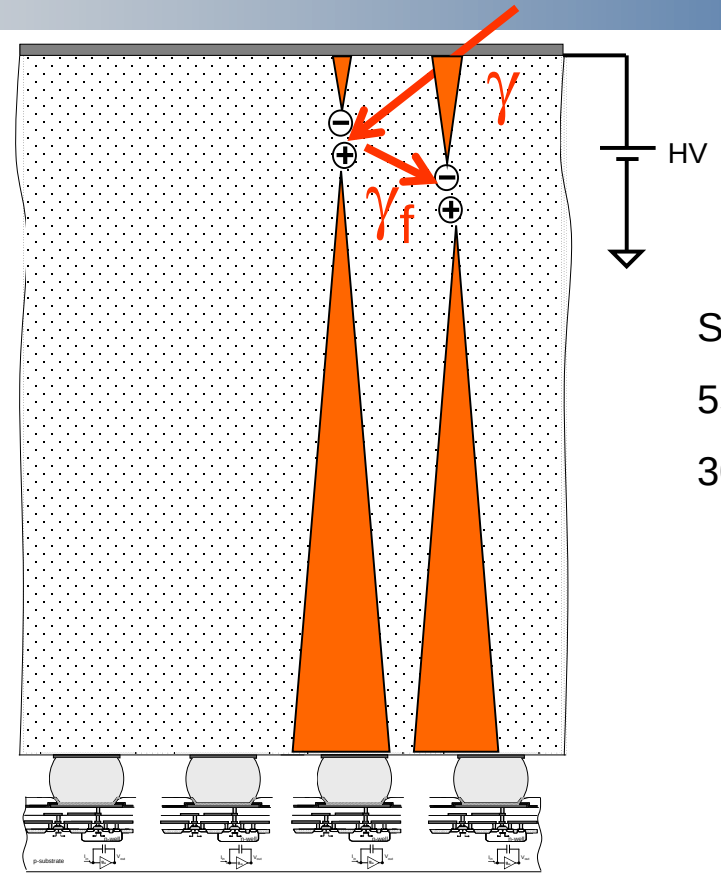


Sensor dimensions to scale:

55μm pixel pitch

300μm thick sensor

Fluorescence in high-Z materials



Sensor dimensions to scale:

55μm pixel pitch

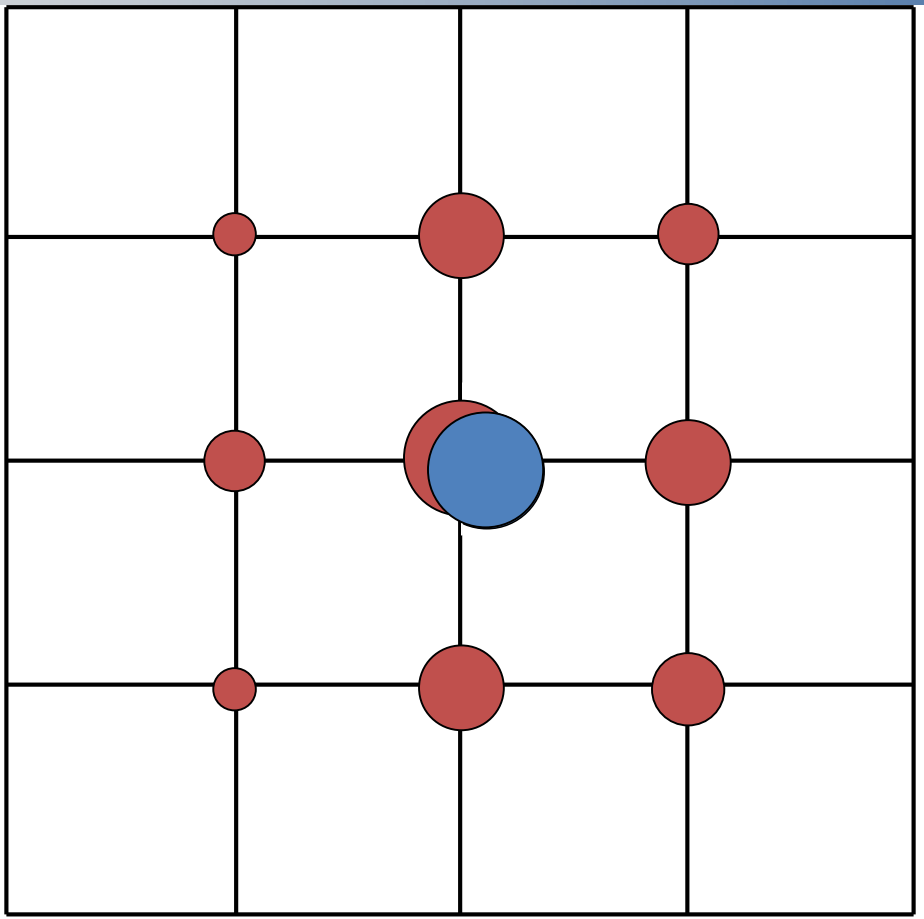
300μm thick sensor

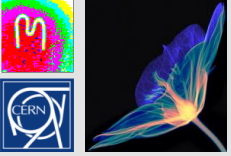
Fluorescence in high-Z detectors

	N	k-edge (keV)	Kα energy (keV)	dα (μm)	η [%]
Si	14	1.84	1.74	12	5
Ge	32	11.11	9.89	51	55
GaAs:					
Ga	31	10.38	9.25	42	51
As	33	11.87	10.54	16	57
CdTe:					
Cd	48	26.73	23.17	128	84
Te	52	31.82	27.47	64	87

Journal of Instrumentation Volume 6 June 2011
D Pennicard and H Graafsma 2011 *JINST* **6** P06007
doi:10.1088/1748-0221/6/06/P06007

The algorithm for charge reconstruction and hit allocation: Charge Summing Mode





Medipix readout chips – photon counting

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Tech. node (nm)	1000	250	130
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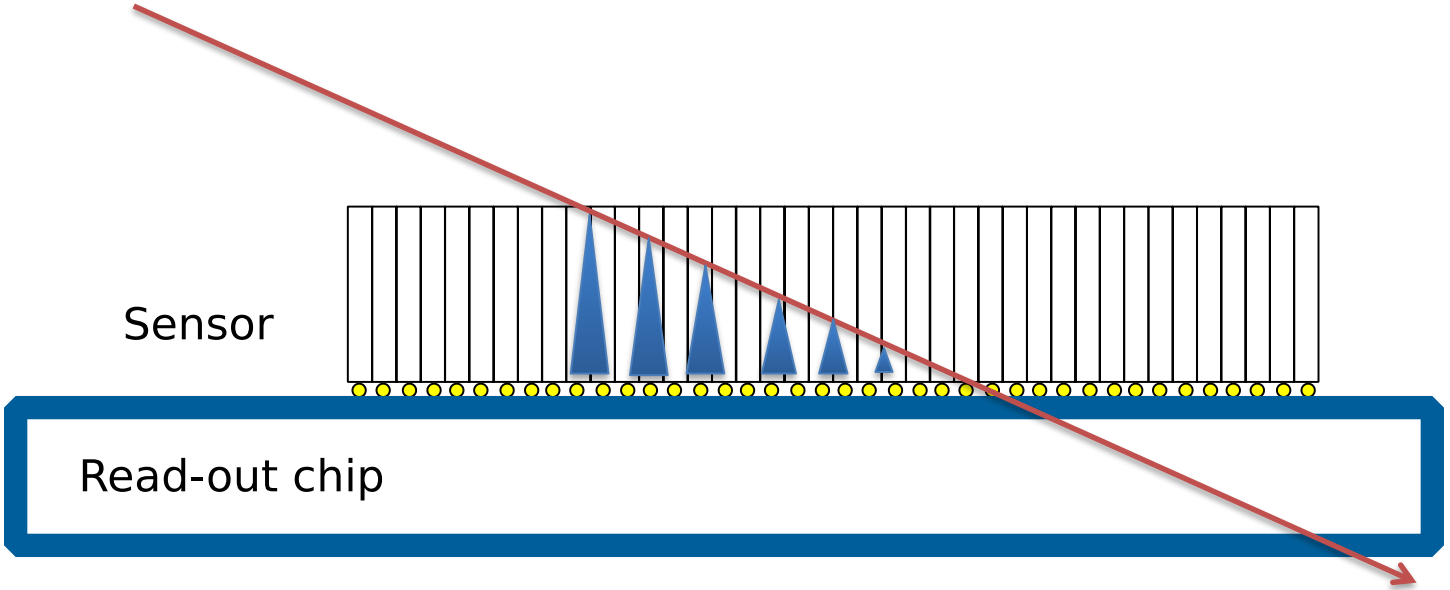
# pixels (x x y)	64 x 64	256 x 256	256 x 256 / 128 x 128
# thresholds(counters)	1(1)	2(1)	Up to 8 (up to 8)
Charge summing mode	No	No	Yes
Readout architecture (Frame based)	Sequential R/W	Sequential R/W	Sequential or continuous R/W
Number of sides for tiling	0	3	3

Timepix readout chips - single particle detection

	Timepix	Timepix2	Timepix3
Tech. node (nm)	250	130	130
Year	2005	2018	2014
Pixel size (μm)	55	55	55
# pixels (x x y)	256 x 256	256 x 256	256 x 256
Time bin (bin size in ns)	10	10	1.5
Readout architecture	Frame based (sequential R/W)	Frame based (sequential or continuous R/W)	Data driven or Frame based (sequential R/W)
Number of sides for tiling	3	3	3

Using charge collection time to track in a single Si layer



Timepix miniaturised readout

IEAP/CTU, Prague

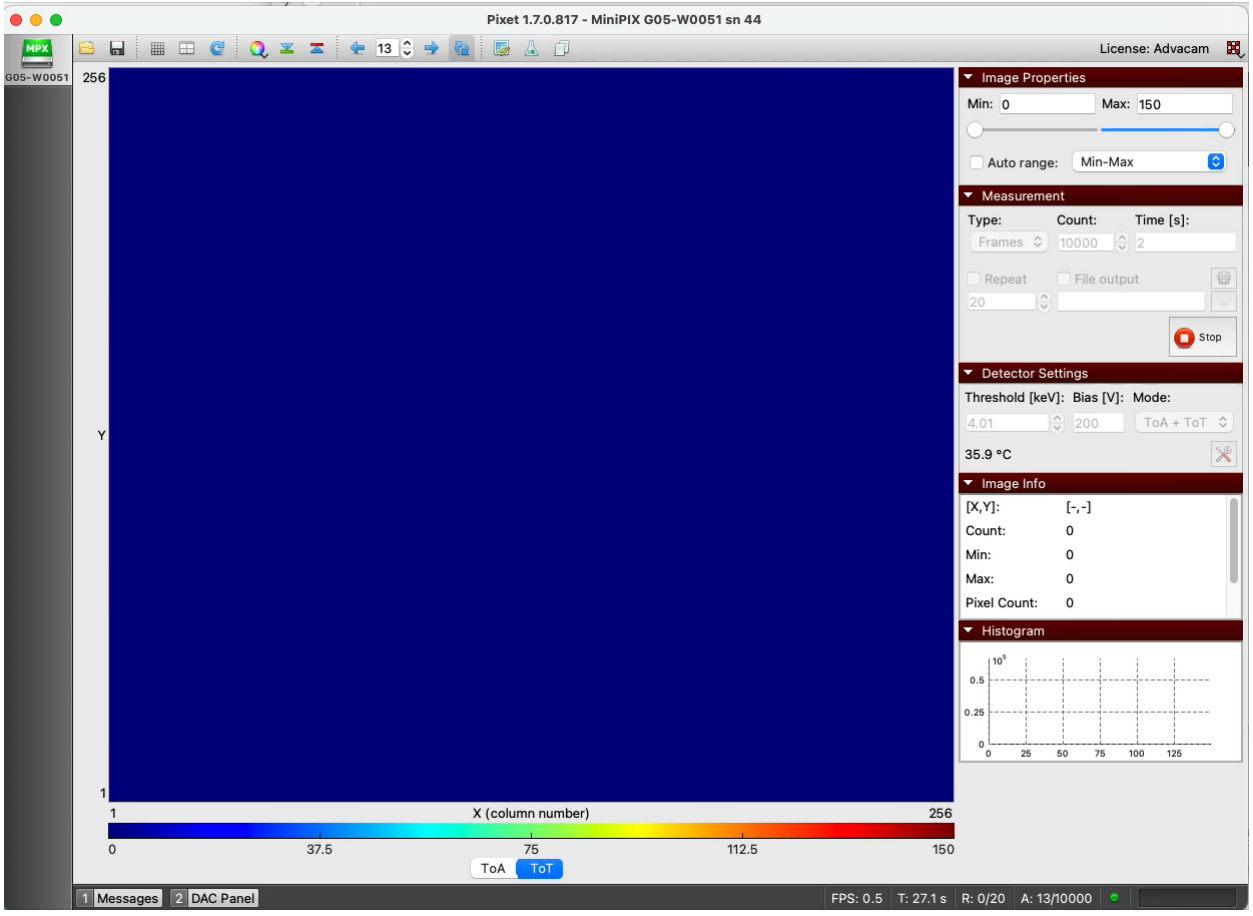
Timepix miniaturised readout

Advacam s.r.o., Prague

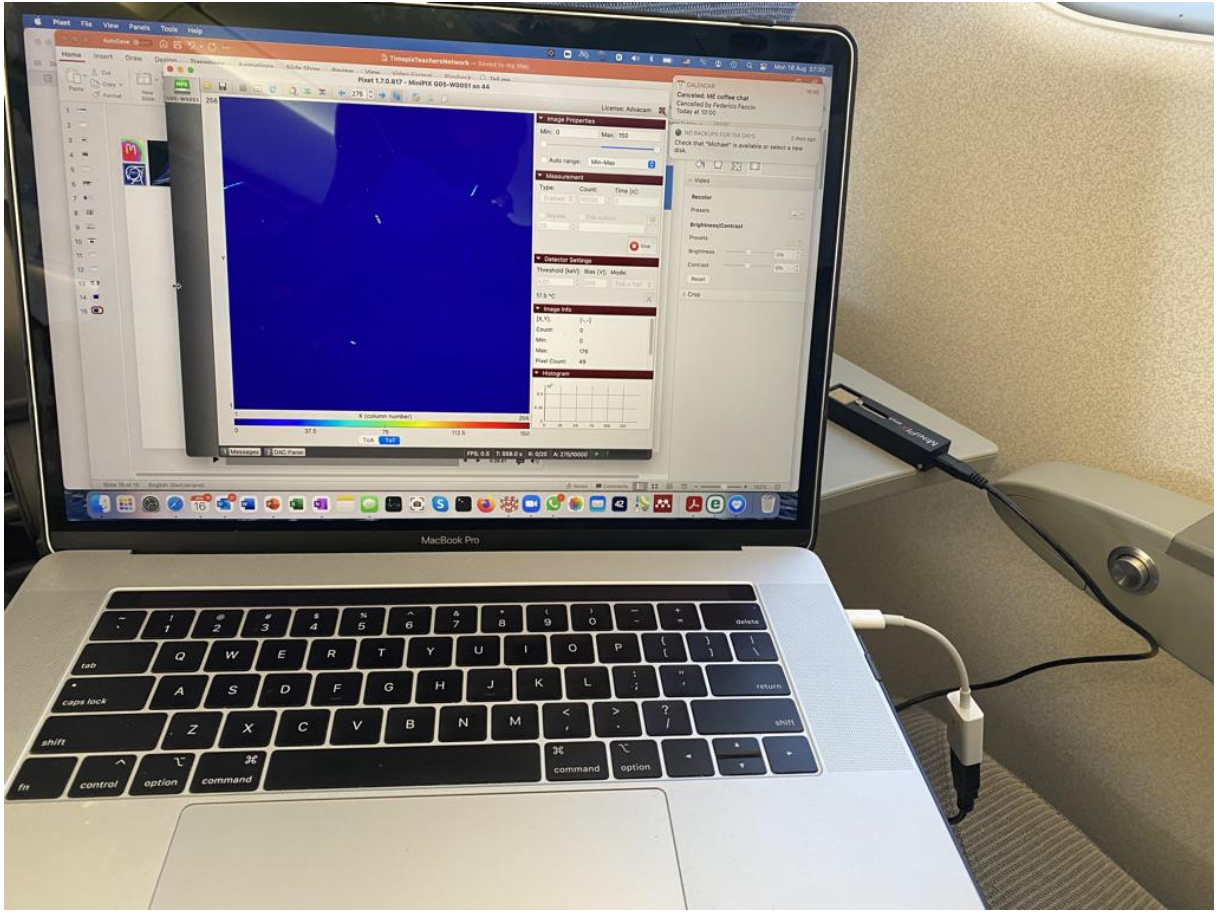
Timepix3 miniaturised readout

Advacam s.r.o., Prague

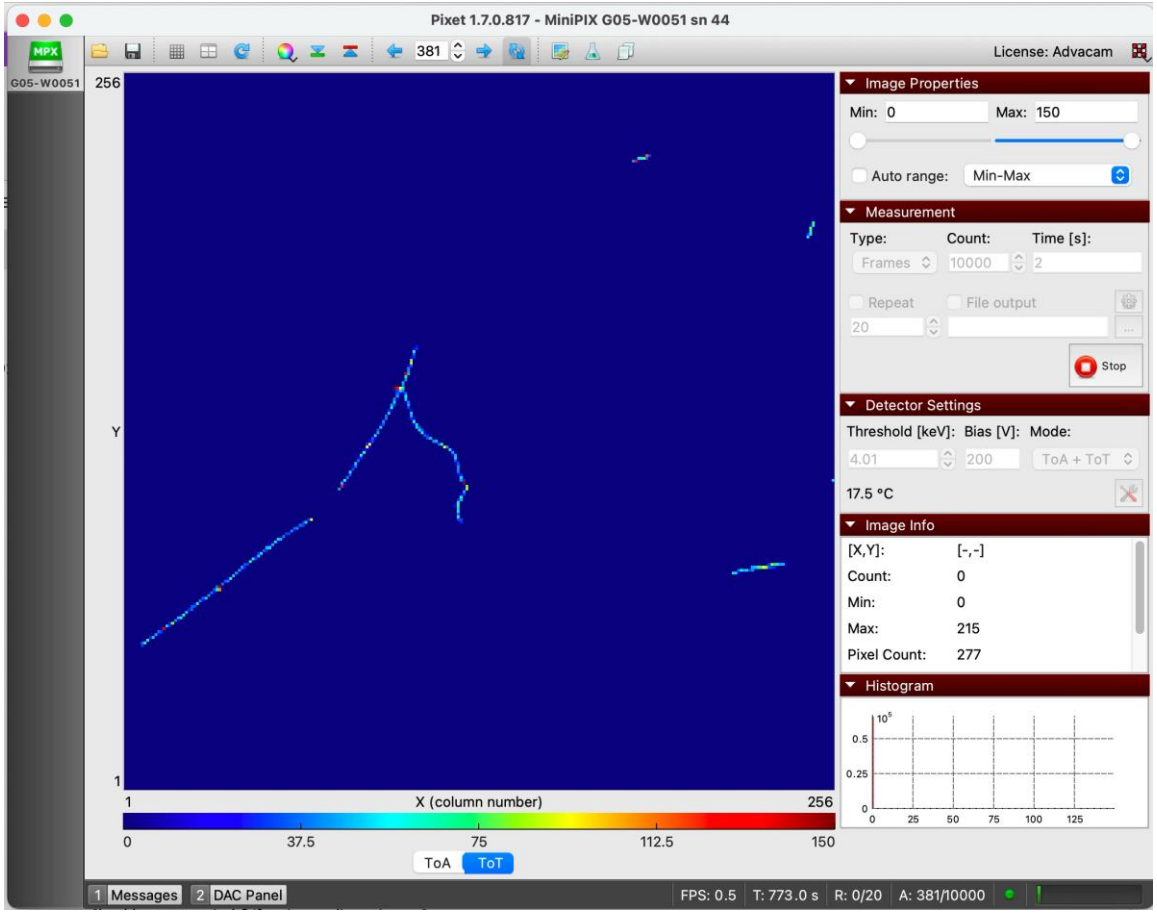
Home movie


Pixet 1.7.0.817 - MiniPIX G05-W0051 sn 44
G05-W0051
License: Advacam
256
Y
1
1
X (column number)
256
0
37.5
75
112.5
150
ToA
ToT
Image Properties
Min: 0
Max: 150
Auto range:
Min-Max
Measurement
Type:
Count:
Time [s]:
Frames
10000
2
Repeat
File output
20
Stop
Detector Settings
Threshold [keV]:
Bias [V]:
Mode:
4.01
200
ToA + ToT
35.9 °C
Image Info
[X,Y]: [-,-]
Count: 0
Min: 0
Max: 0
Pixel Count: 0
Histogram
1 Messages
2 DAC Panel
FPS: 0.5
T: 27.1 s
R: 0/20
A: 13/10000

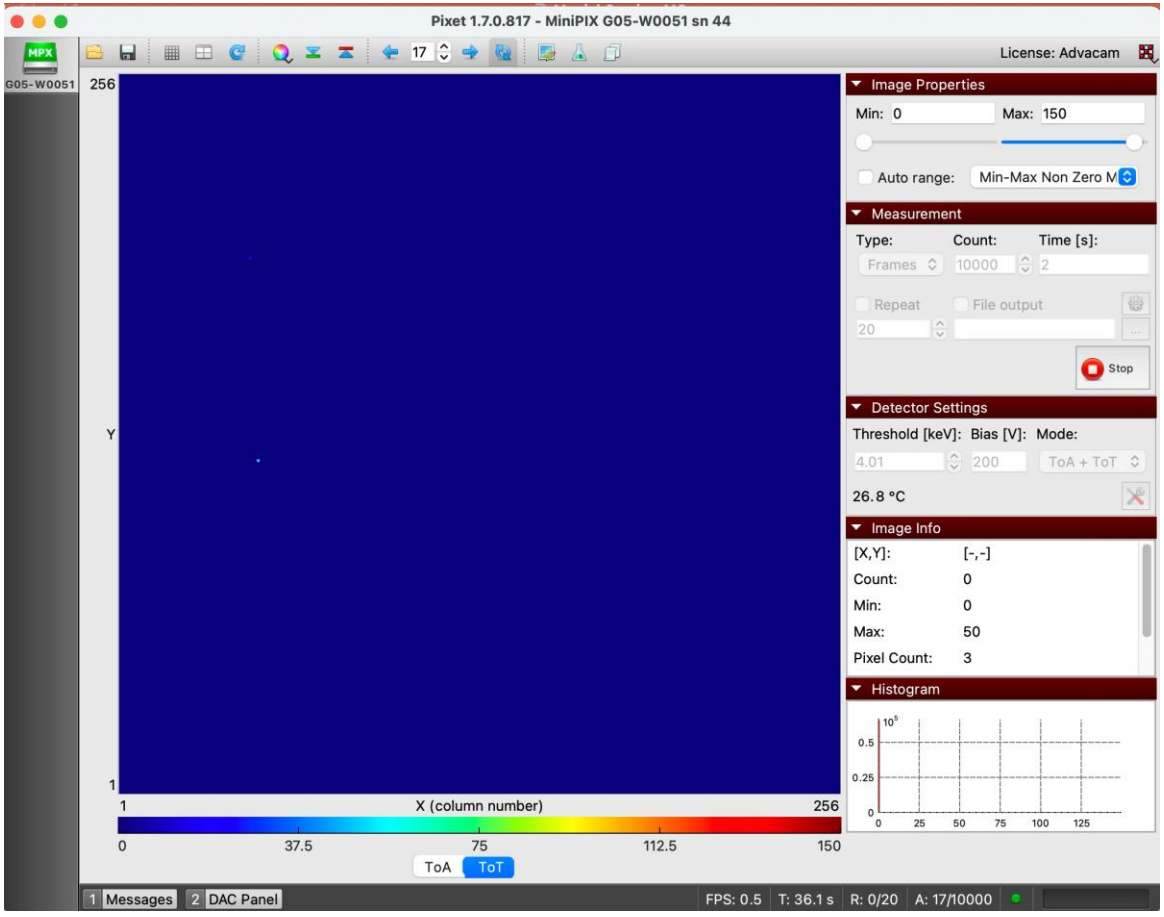
Airline movie



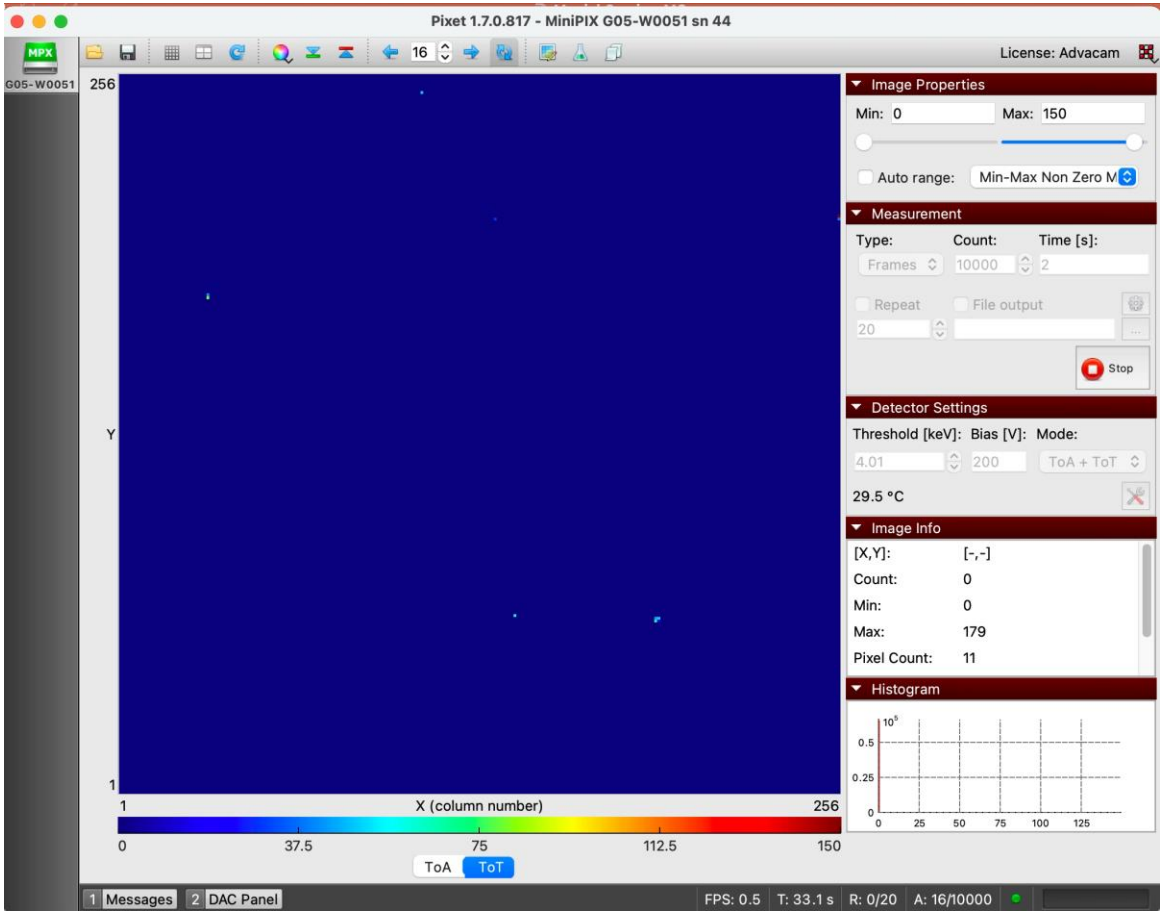
Airline movie



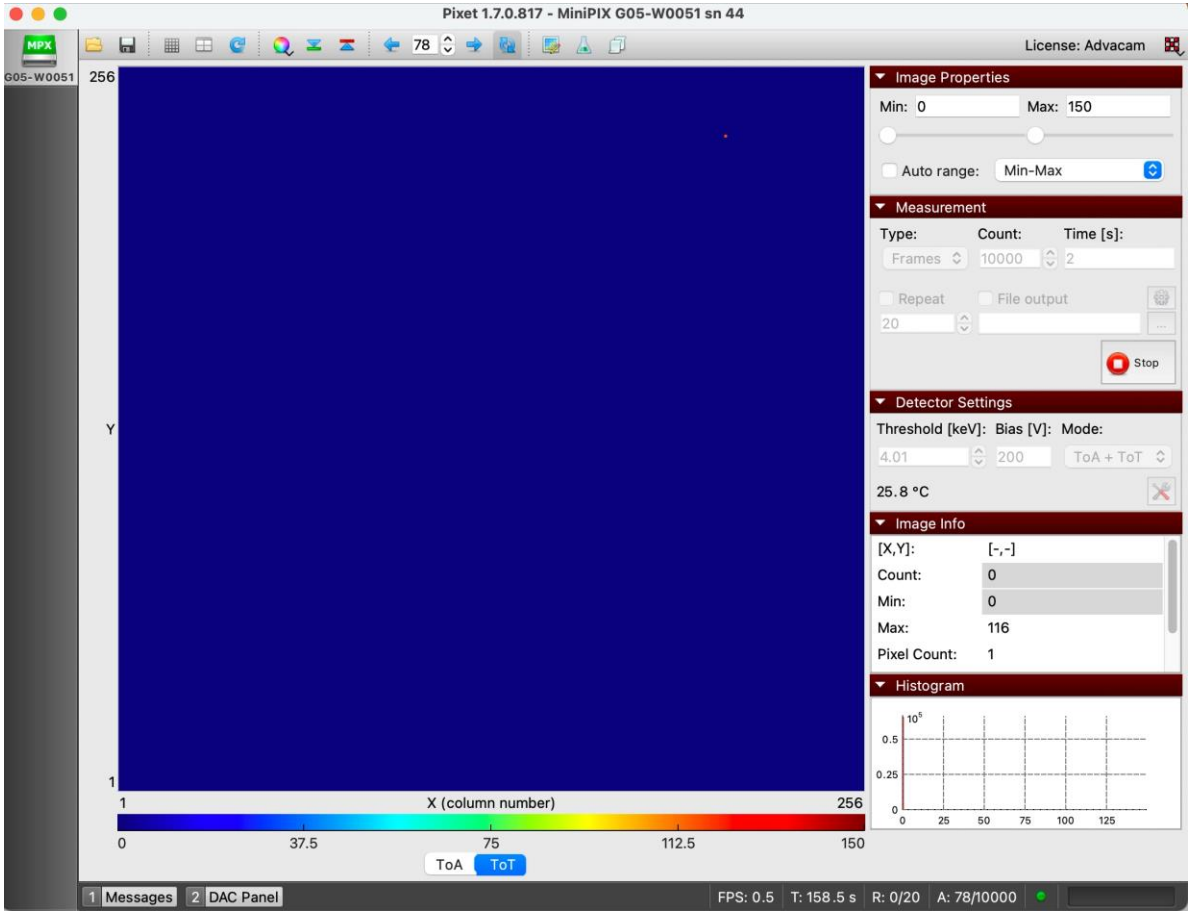
^{55}Fe in the lab



^{109}Cd in the lab

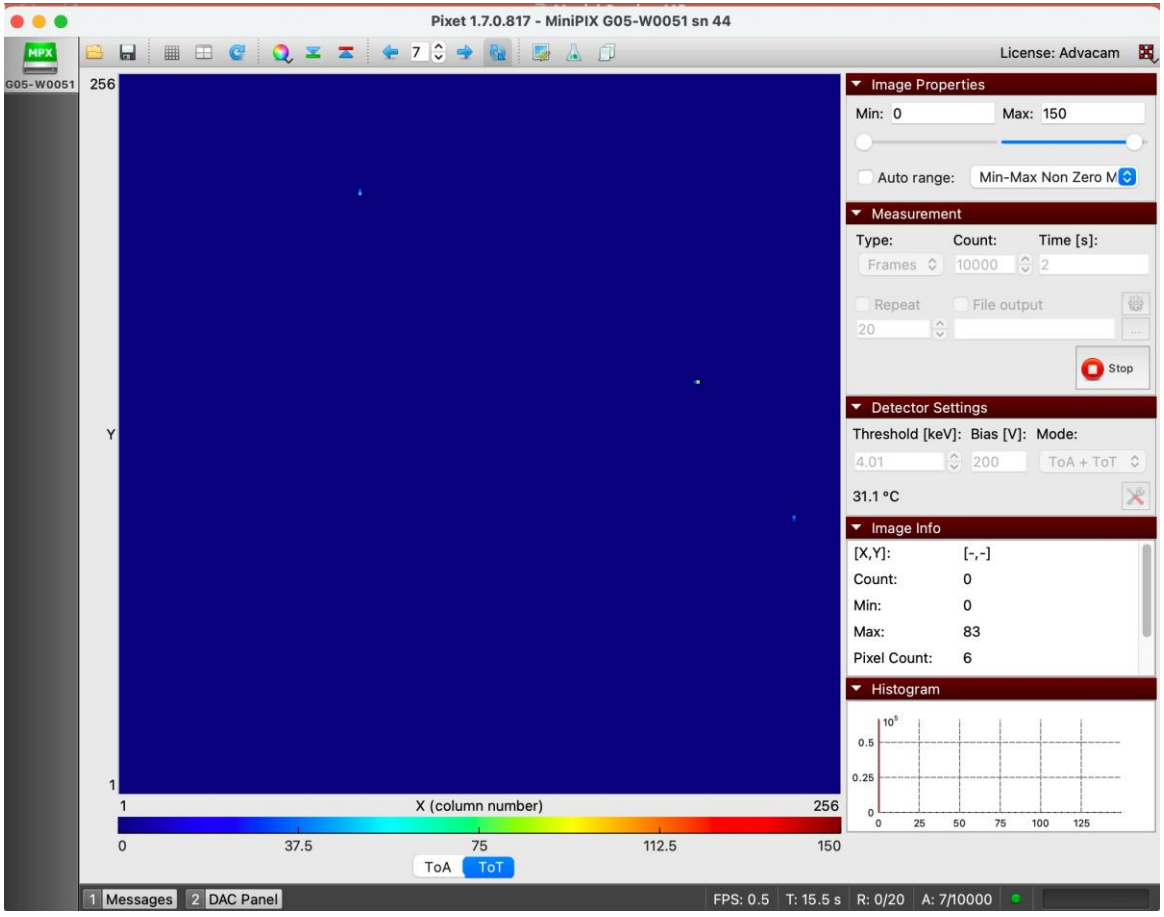


^{241}Am in the Lab



Sensor partly covered with paper

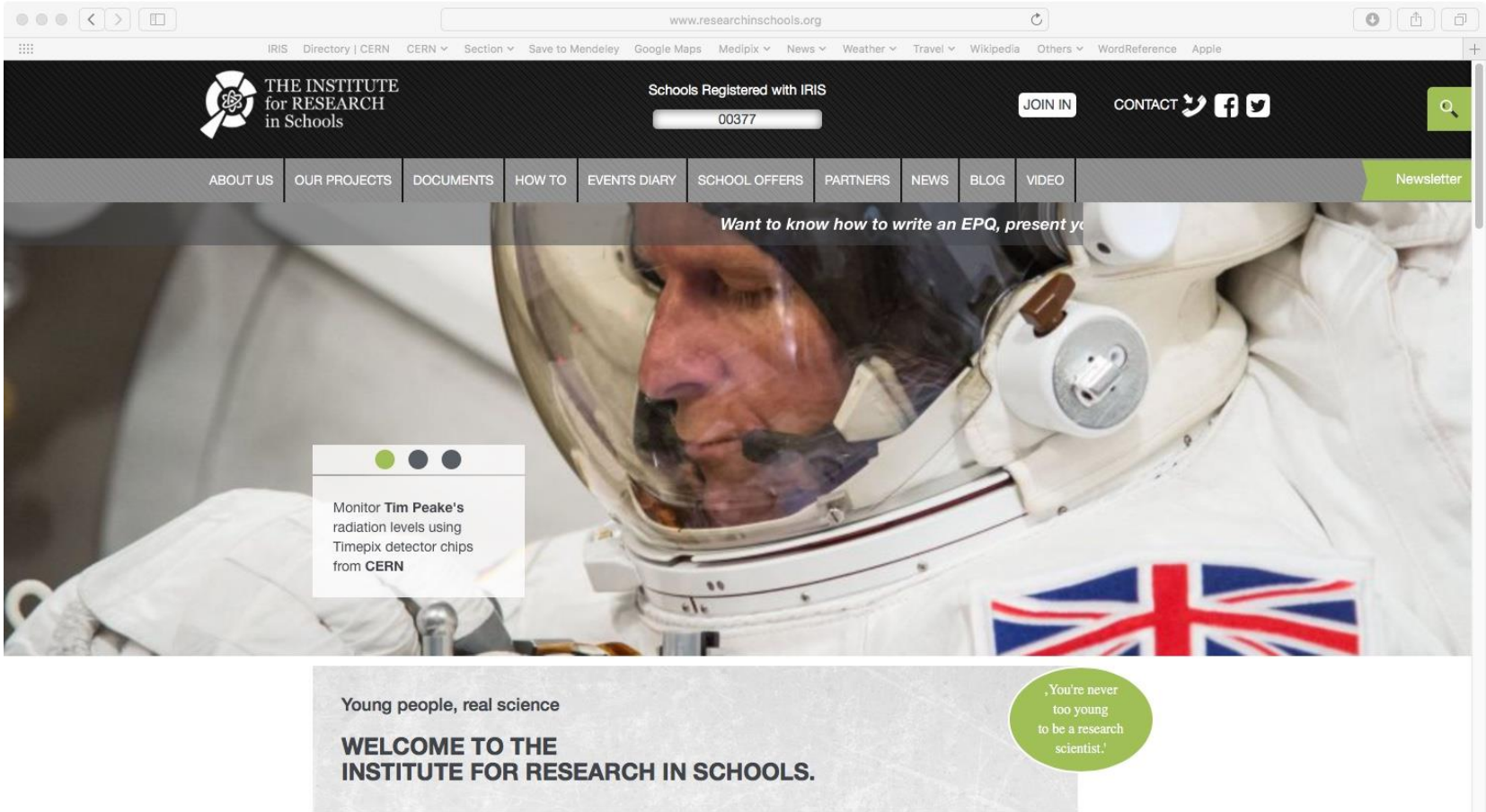
^{90}Sr in the lab



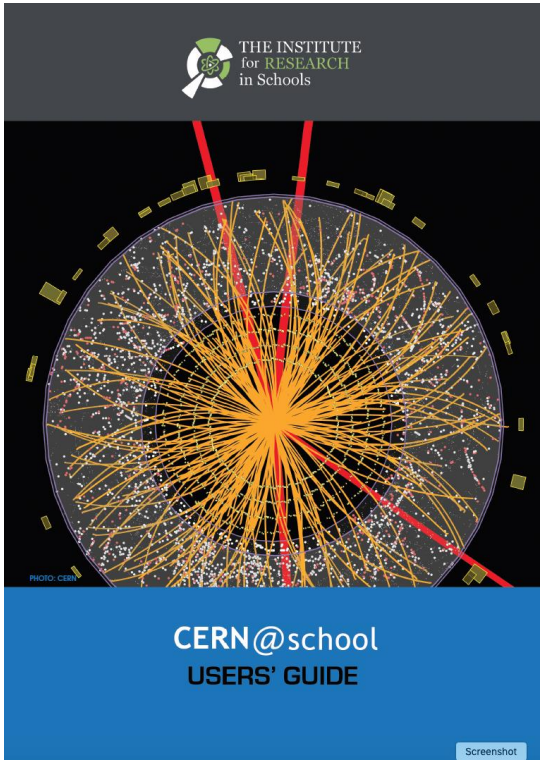
CERN@school

Simon Langton School, Canterbury, England

Institute for Research in Schools



Impact in UK schools



CERN@school Equipment loans			
School year	Number of loans	Average per school*	Total number of students engaged with detector*
2016-17	28	40	1120
2017-18	30	90	2700
2018-19	50	60	3000
		TOTAL	6820

*Based on post-loan survey responses

Location of CERN@school kits 2018-2019

Numbers of students going on to study Engineering

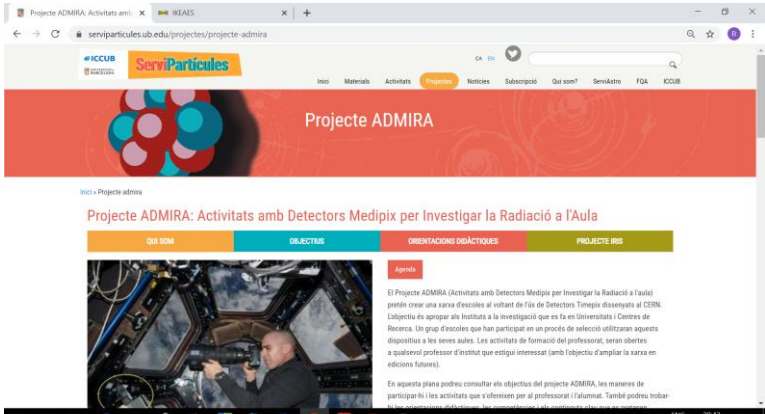
School type	male			female		
	2012/13	2015/16	% change	2012/13	2015/16	% change
ALL IRIS	235	325	38	20	60	200
Non IRIS - nationwide	15	10	-33	10	10	0

Citation: Dr. Lizzie Rushton The Institute for Research in Schools Report to the Trustees on Impact and Evaluation, September 2017.

ADMIRA

Activitats amb Detectors Medipix per Investigar la Radiació a l'Aula

- **ADMIRA:** Activitats amb Detectors Medipix per Investigar la Radiació a l'Aula
- **Goals (Essentially: bringing closer Research Centers, Universities and Schools)**
  - Build a network of schools that share 2 Timepix devices (courtesy of Microelectronics Section CERN)
  - Teachers share devices/experiences
  - Offer high quality training to teachers and students by experts (motivating teachers and students)
  - Promote CERN@School/IRIS activities to have secondary students do real science
  - 4 sessions of training scheduled in 2020, final student conference in December 2020
    - First session 10th January (~75 School teachers, ~50 secondary students)
- **Team:**
  - Lluís Casas, Rosa Maria Giralt (Institut Ciències de l'Educació-UB)
  - Eugeni Graugés, Marta Martín, Surinye Olarte, Esther Pallarès (Institut de Ciencies del Cosmos UB)
  - Daniel Parcerisas (Sagrada Família School Gavà)
  - Rafael Ballabriga (CERN)



ADMIRA project

Timepix-based detectors bring particle physics in the classroom

The ADMIRA project uses Timepix-based detectors to help students experiment with particle physics and contributes to transforming STEM education.

29 MARCH, 2021 | By Rafael Ballabriga & Antoine Le Gall

Xènia Turró, from INS Vilafant measuring natural radiation in Tapis (Maçanet de Cabrenys). She identified the various particles in the environment coming from different sources and compared the measured radiation dose with the recommendations from the International Commission on Radiological Protection.

Timepix on the ISS

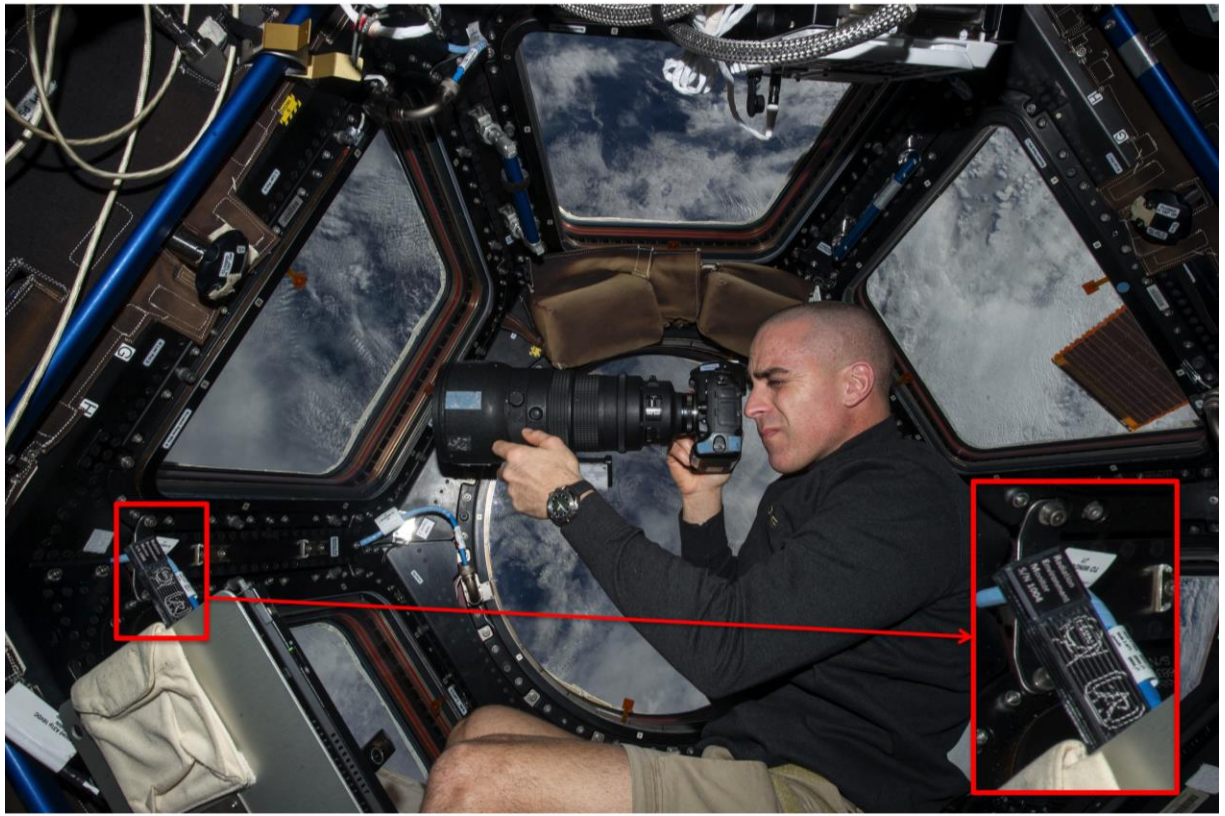
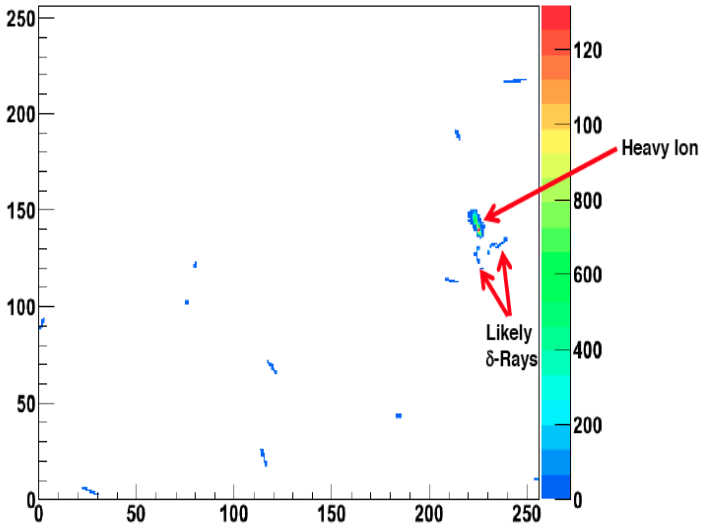
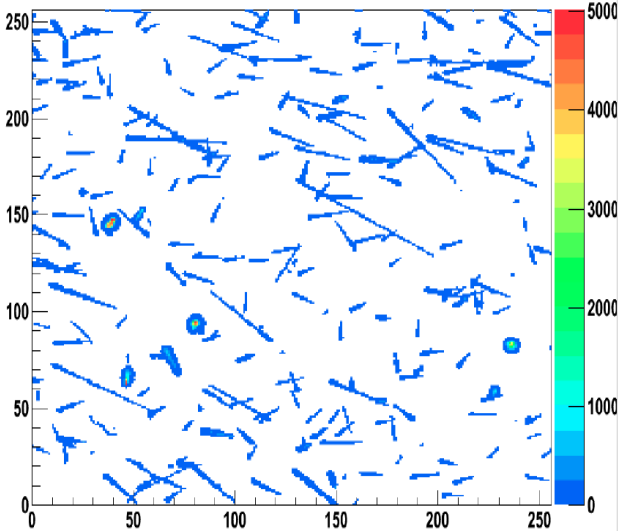


Image of the astronaut Chris Cassidy working near the Timepix USB on the International Space Station (Courtesy of NASA, photo ref. no. iss036e006175)

Timepix - 4s exposures



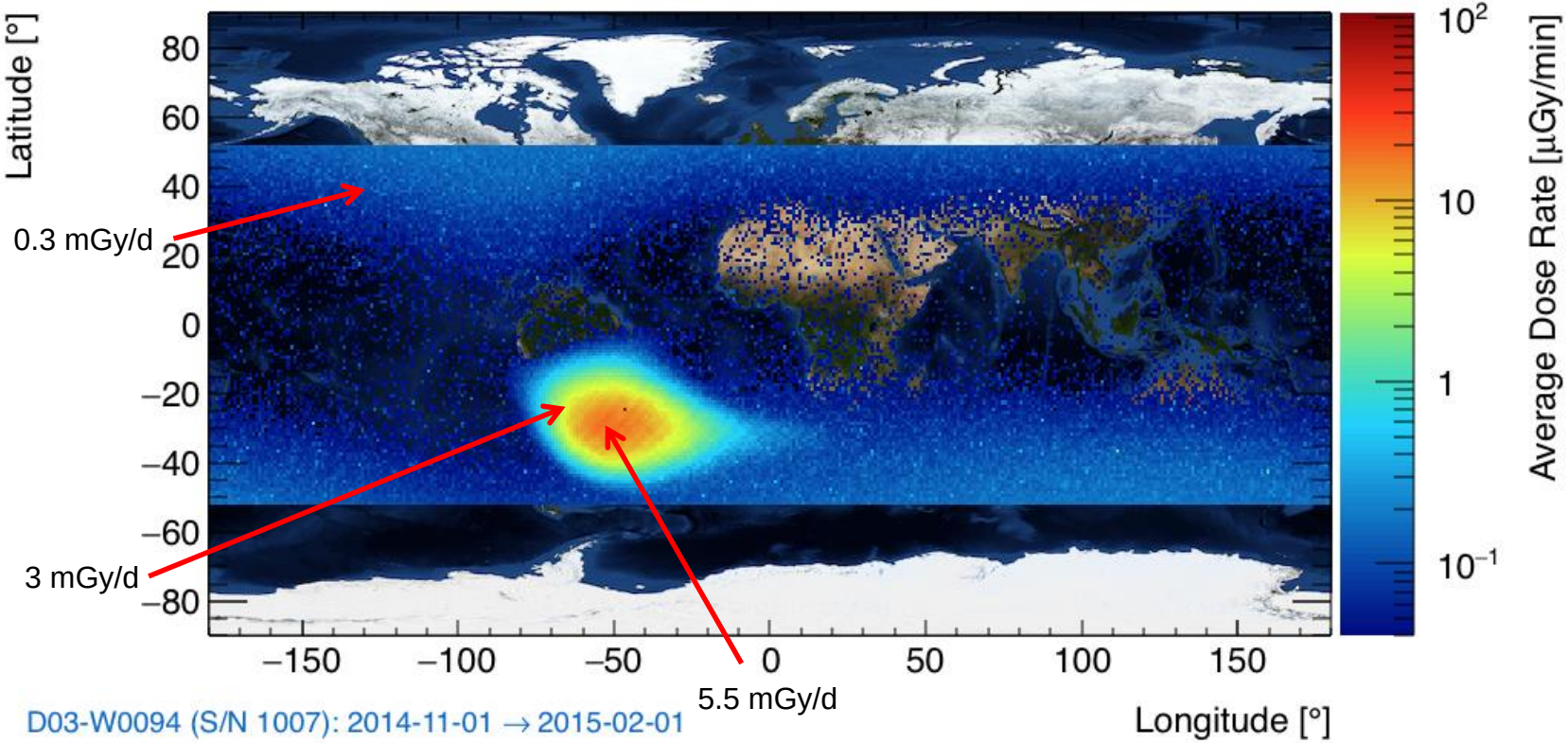
South China Sea



South Atlantic Anomaly

University of Houston, IEAP Prague, NASA

REM Dose Rate Data (μG/min)

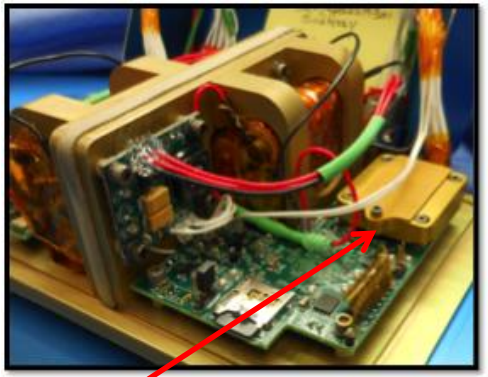


University of Houston, IEAP Prague, NASA

ORION test flight

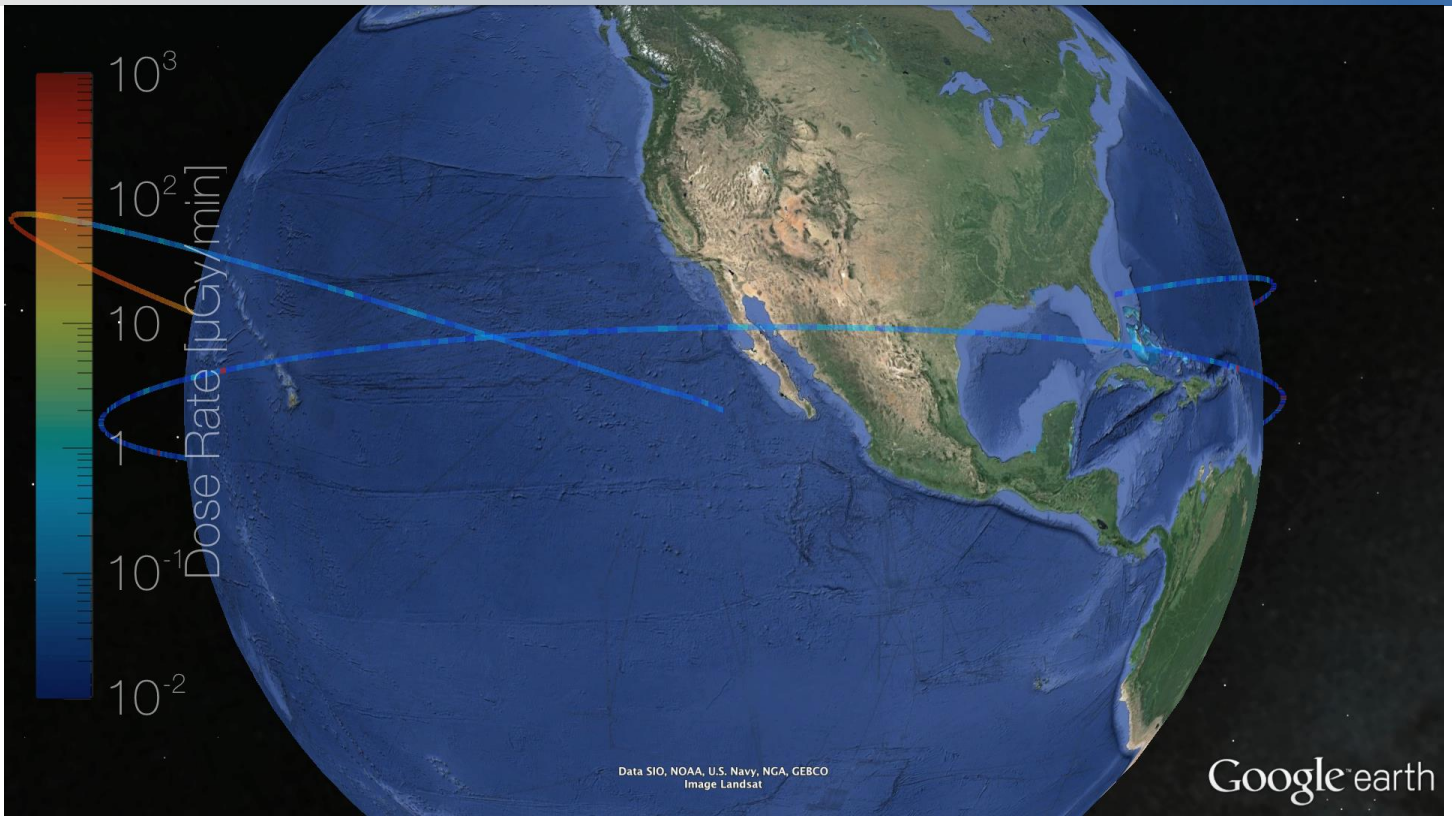
2 TIMEPIX chips inside the BIRD (Battery-operated Independent Radiation Detector)

5 December 2014



Timepix chip

EFT-1 Dose-Rate (μG/min) Along Trajectory

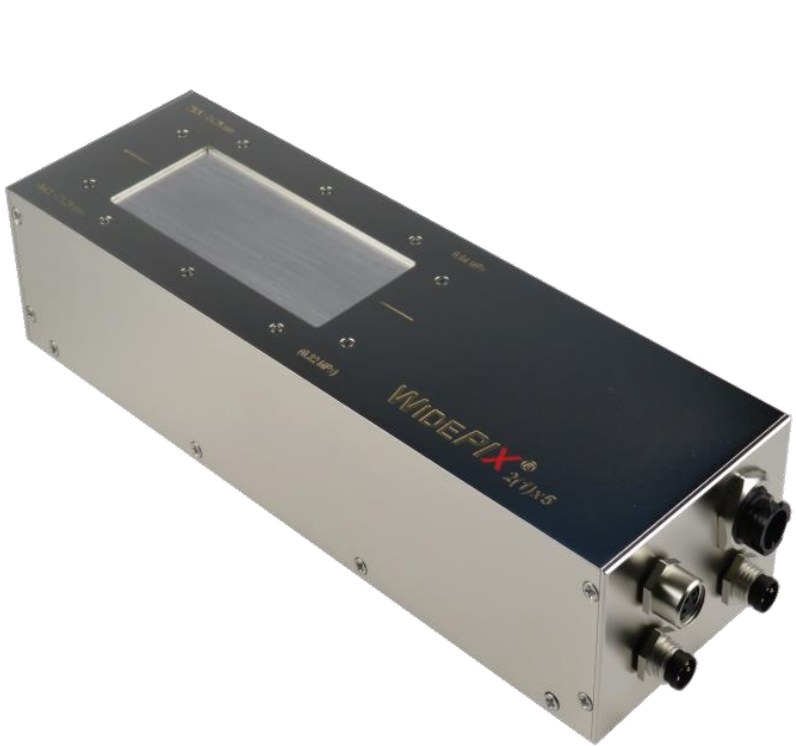


Courtesy of Ryan Rios, NASA, JSCSpace Radiation Analysis Group

Timepix3 will go to the moon next…

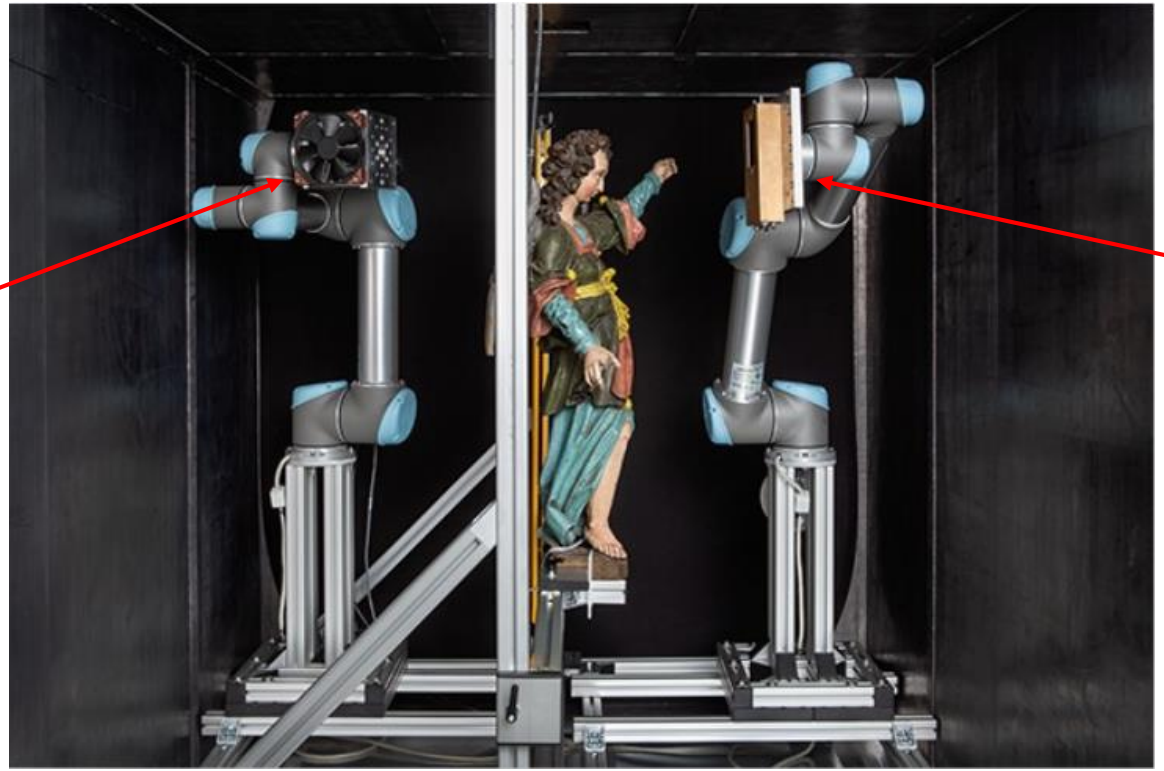
Advacam, Houston, IEAP, NASA

Large area detectors for Art inspection



WIDEPIX (now Advacam s.r.o.) is a spin-off of IEAP, Czech Technical University

Combined with robots



Micro-focus X-ray soucre

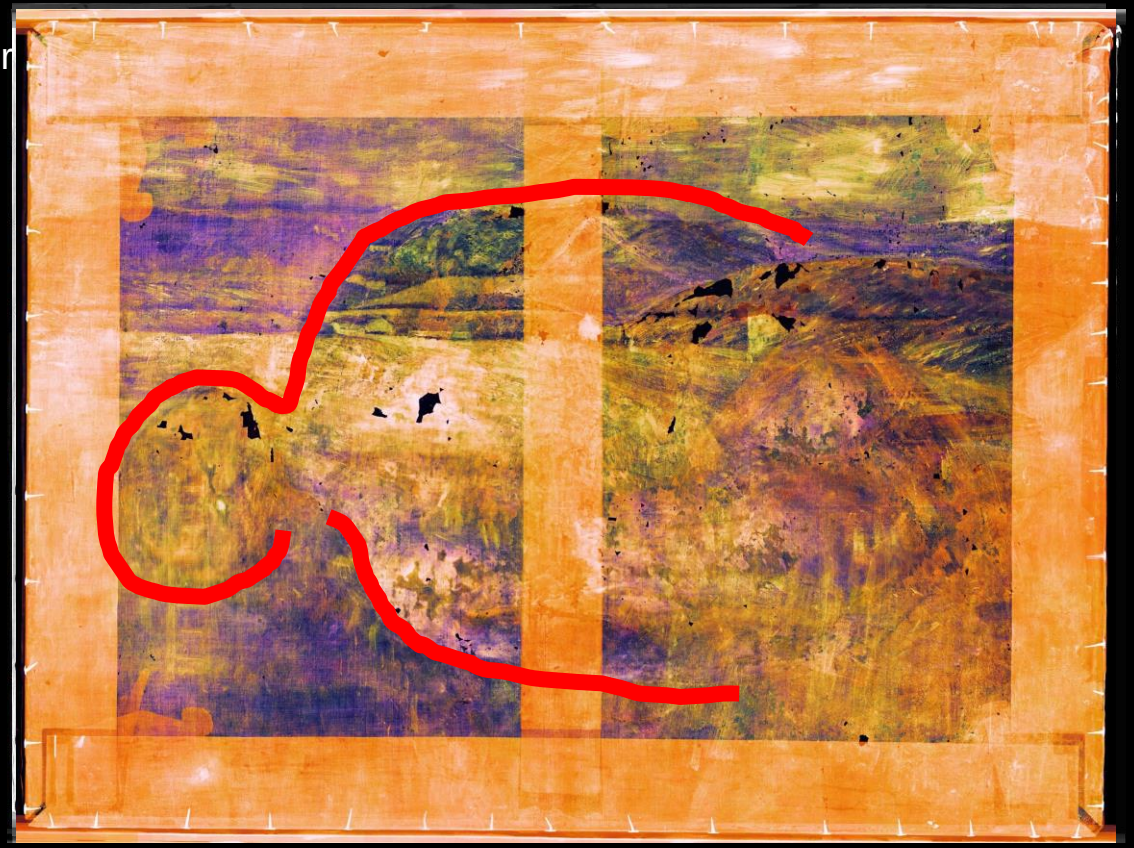
Timepix/Medipix3 spectroscopic imaging camera

Source InsightART (insightart.eu)

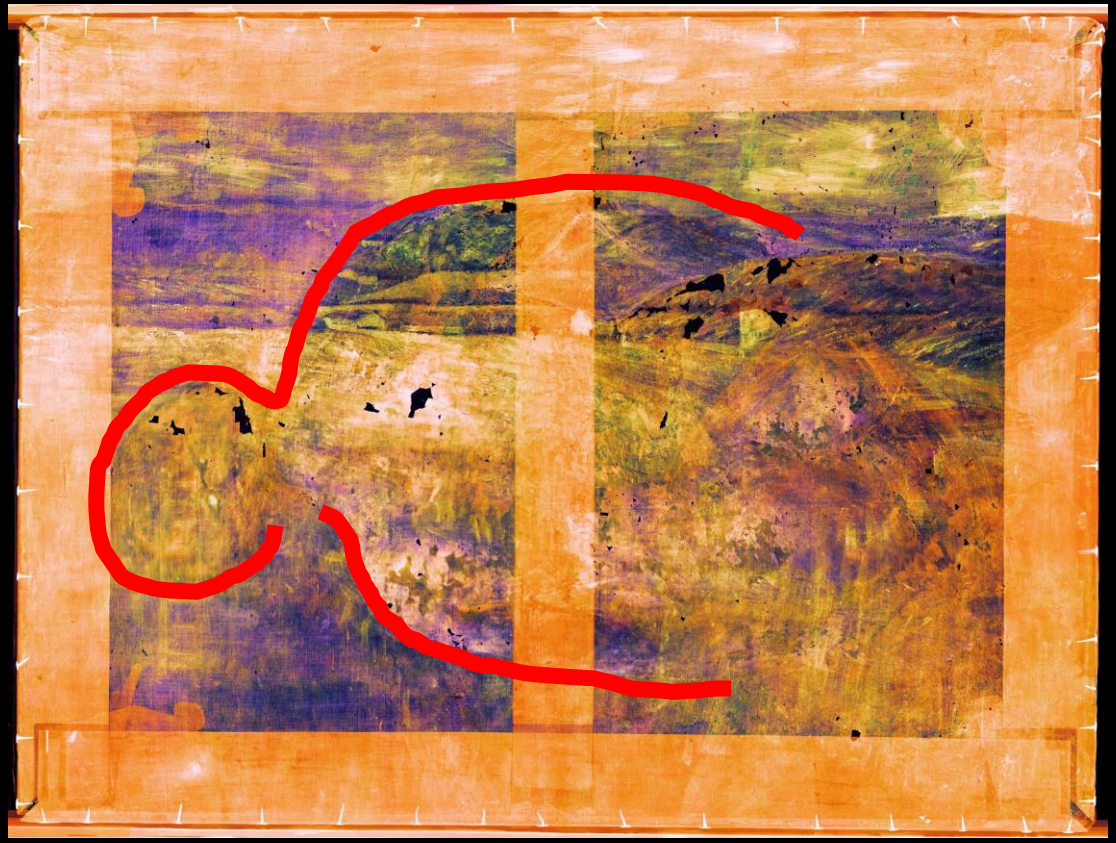
Signed
Vincent van Gogh

La Crau with Montmajour
in the backgroud

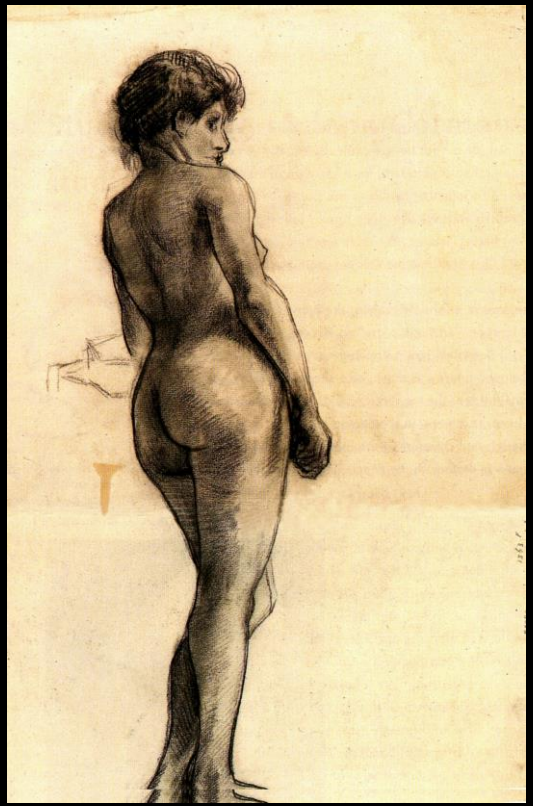
~1888



INSIGHTART



INSIGHTART



INSIGHTART

Raphael Santi: Madonna with Child

Signed:
RAPHAEL VRBINAS
PINGEBAT
(MDXVII, R O M A)

Madonna with child

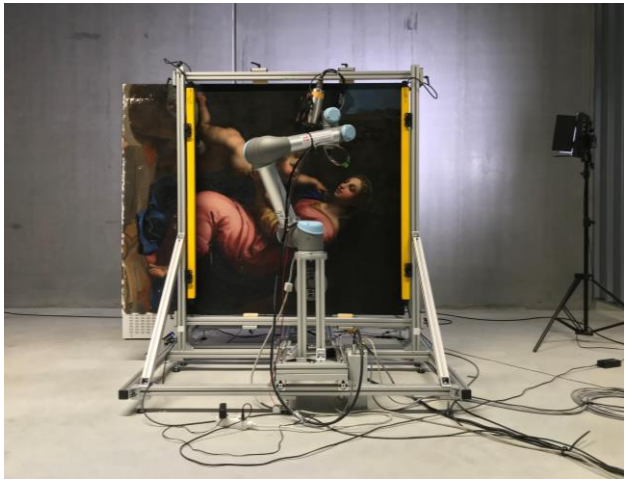
DATE
About 1517

TECHNIQUE
Oil on canvas

DIMENSIONS
157 x 127 cm

J. Uher, InsightArt, Prague, Czech Republic

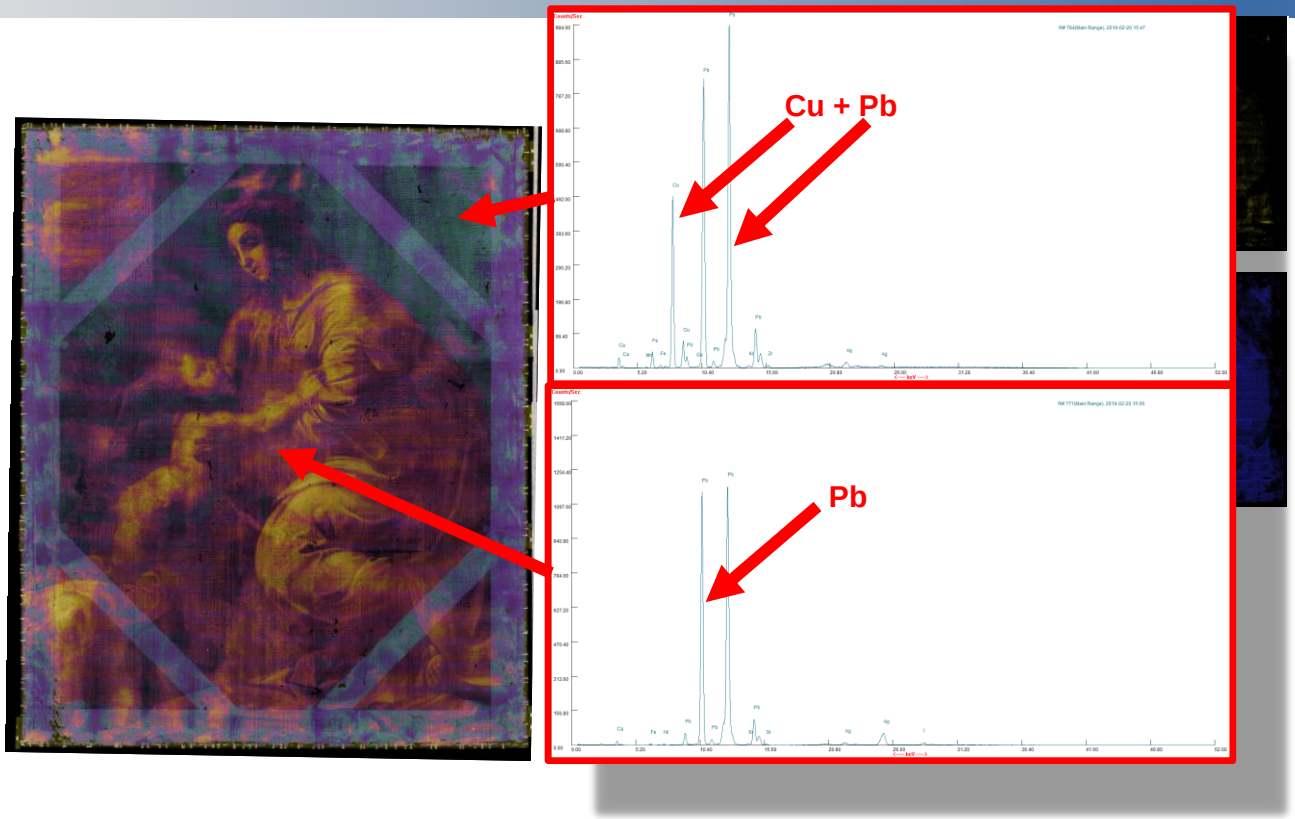
The most challenging scan we did



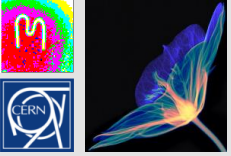
- Scanner transported to the storage
- Assembled
- All had to run on 100%

J. Uher, InsightArt, Prague, Czech Republic

Madonna with child



J. Uher, InsightArt, Prague, Czech Republic



Voir en français

CERN technology helps rediscover lost painting by Raphael

CERN's Timepix particle detectors, developed by the Medipix2 Collaboration, help unravel the secret of a long-lost painting by the great Renaissance master, Raphael

21 SEPTEMBER, 2020 | By Antoine Le Gall

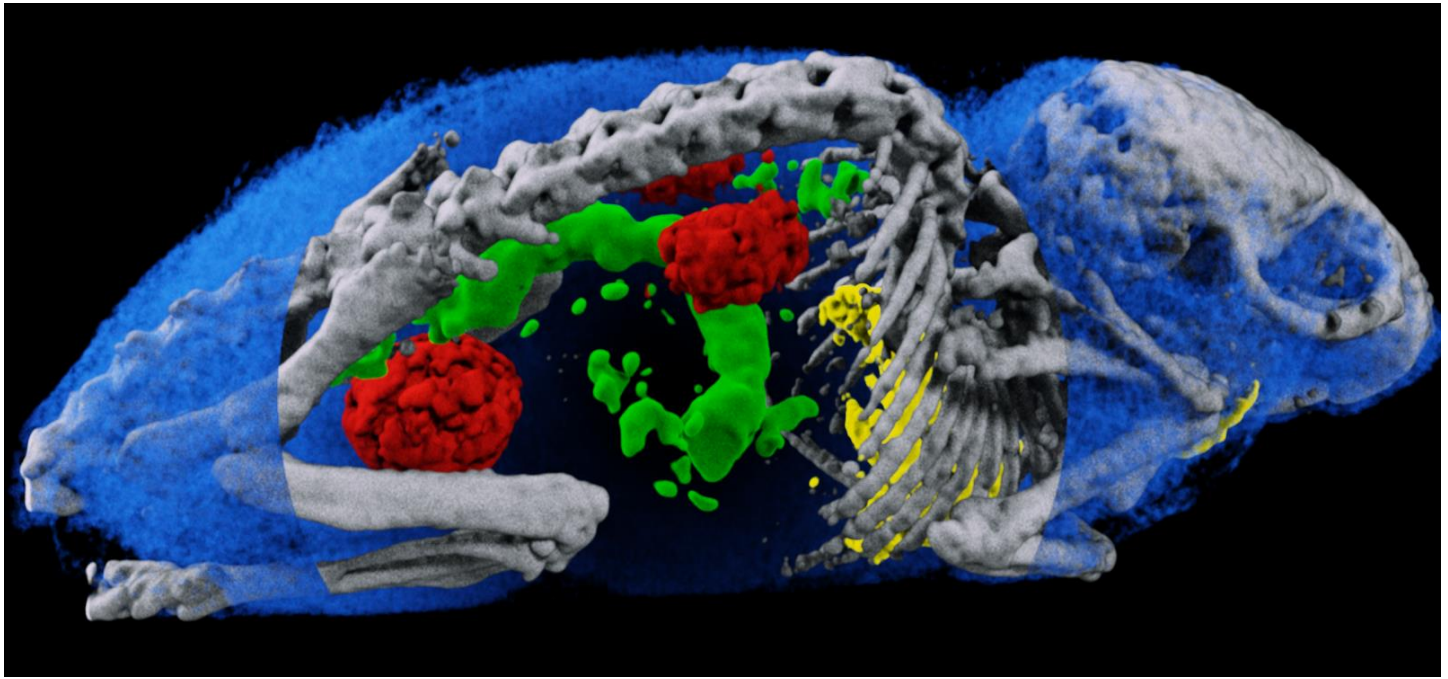
Left: Graphic combining energy spectra measured by RToo scanner (© InsightART, 2019); Right: RToo scanning the painting Madonna and Child (© Jiří Lauterkranc, 2019). (Image: CERN)

MARS Bio-scanner now commercial

Notre Dame imaging lab

Slide courtesy of A. Butler, University of Canterbury

Spectroscopic information permits material separation

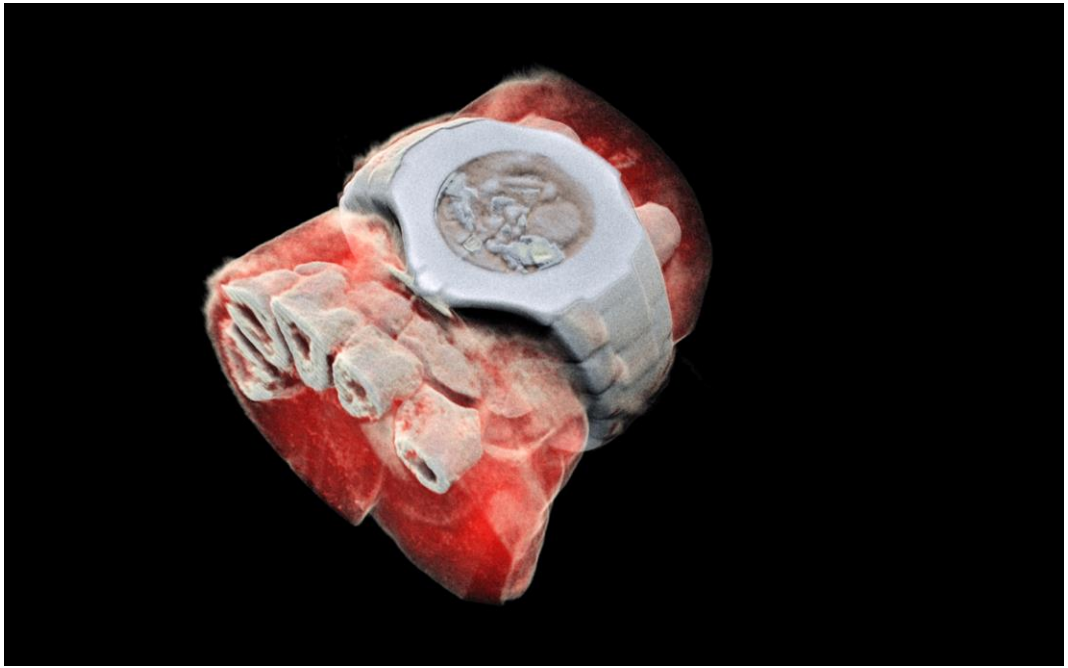


The water has been partly cut away to reveal the bone, gold, gadolinium and iodine

A. Butler, University of Canterbury

Images presented and the European Congress of Radiology, Vienna, March 2017.

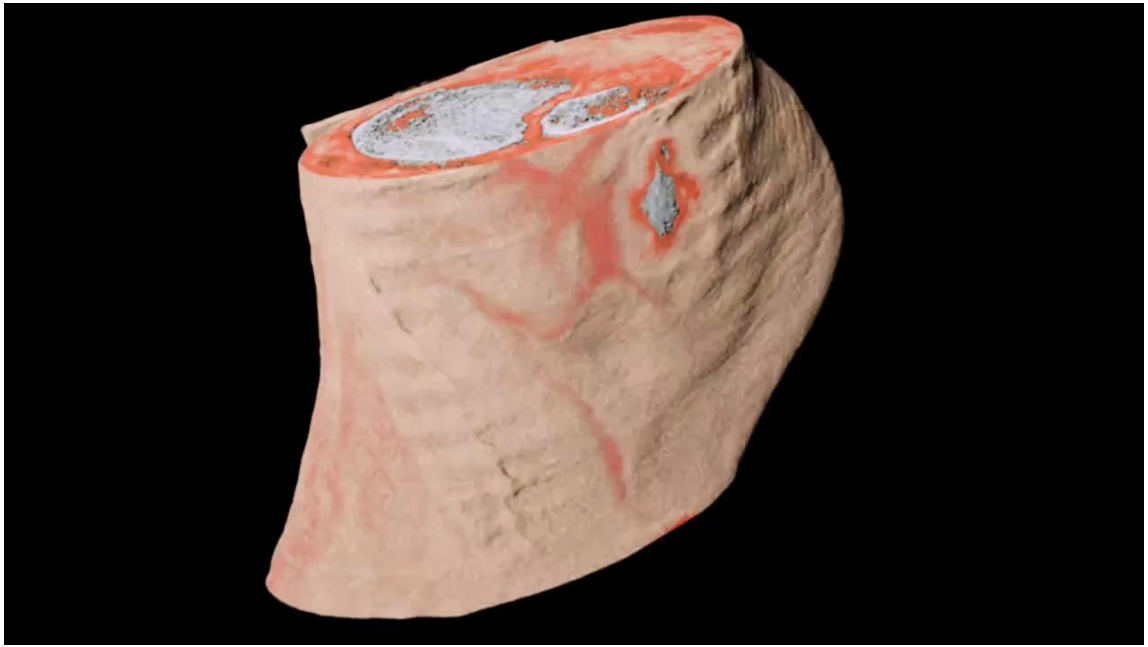
CT image of Phil Butler's wrist



World's first colour X-ray of live human body part

- Clearer images
- Less dose
- Material separation

Slice through of Phil Butler's Ankle



First European hospital receives 3D colour X-ray scanner using CERN technology

MARS Bioimaging's 3D colour X-ray scanner has arrived in Europe to undertake clinical trials that will lead to its medical use.

22 JUNE, 2021 | By Antoine Le Gall

MARS Bioimaging scanner at Lausanne University Hospital (CHUV). (Image: CHUV)

50

MARS scan of diseased carotid artery

Single Layer Compton Camera with MiniPIX TPX3

Compton camera principle

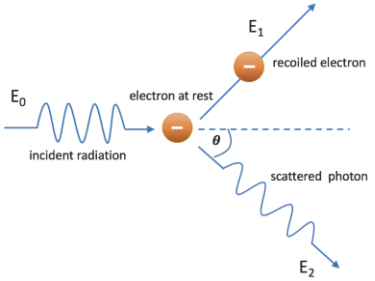
- Typical two detectors
- primary gamma is scattered in first detector (position and energy recorded), scattered gamma continues to second detector (absorbed, position and energy recorded)
- from energies - > scattering angle calculated
- from position and energies -> possible position of the source on the surface of a cone
- Multiple cones intersection - > source position

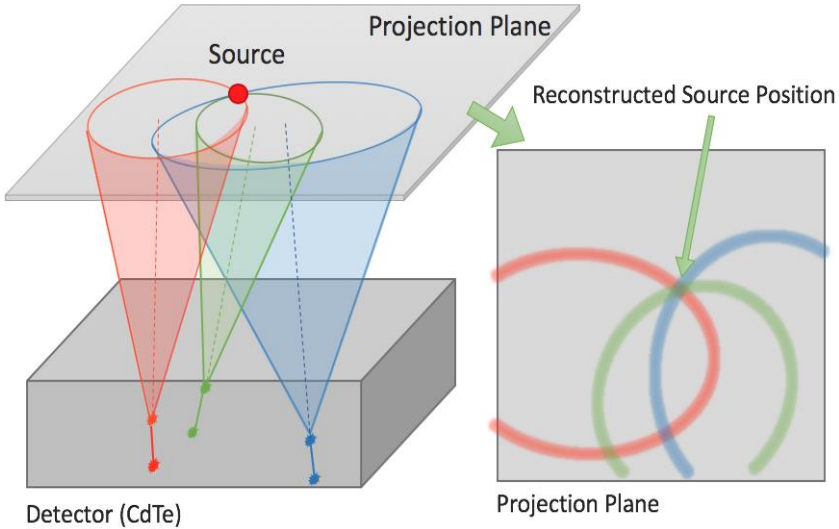
- Single Timepix3 layer camera
  - Instead of 2 detectors, only single TPX3
  - Using time of charge collection to determine relative depth

Courtesy of D. Turecek, Advacam s.r.o

$$\cos\theta = 1 - m_e c^2 \frac{E_1}{E_0(E_0 - E_1)}$$

$$E_0 = E_1 + E_2$$

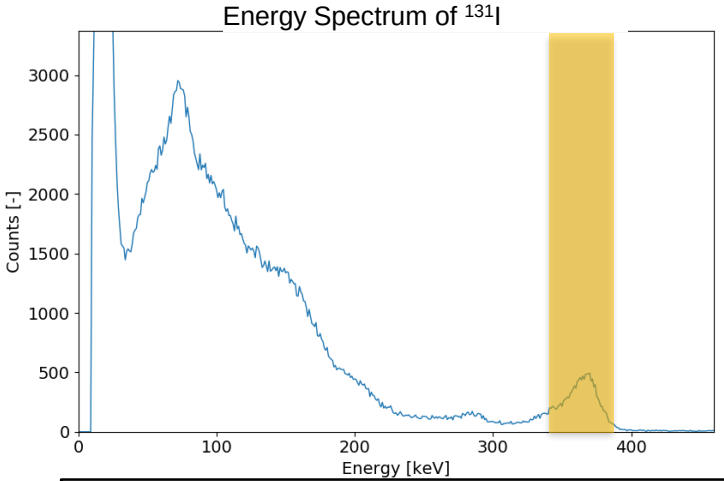




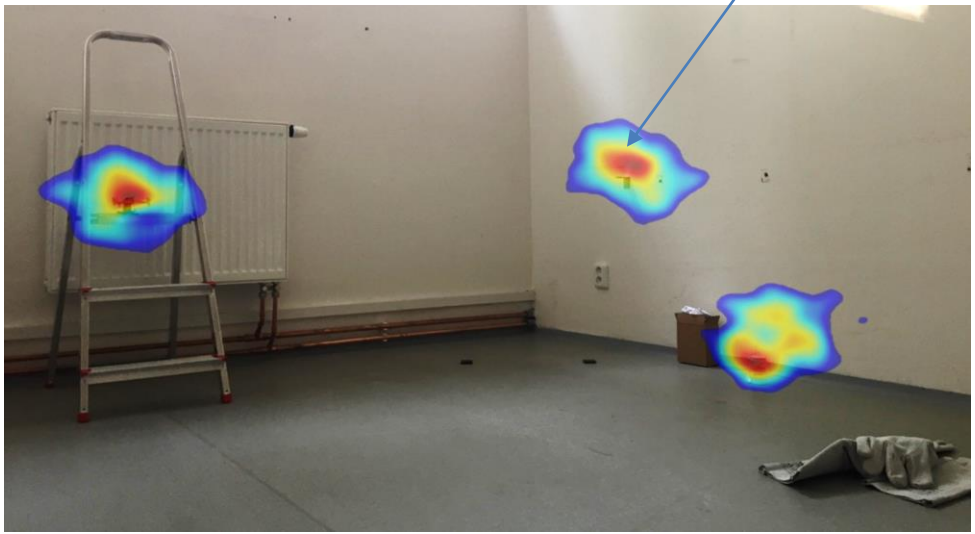
Single Layer Compton Camera with MiniPIX TPX3

^{131}Iodine gamma source

- 3 different Iodine solution in small bottles positioned in a room at different positions
- Distance from detector 3.5 m (activity 10's of MBq)
- Mapped on photograph of the room
- Sources located correctly within minutes
- Image took hours to collect



Courtesy of D. Turecek, Advacam s.r.o

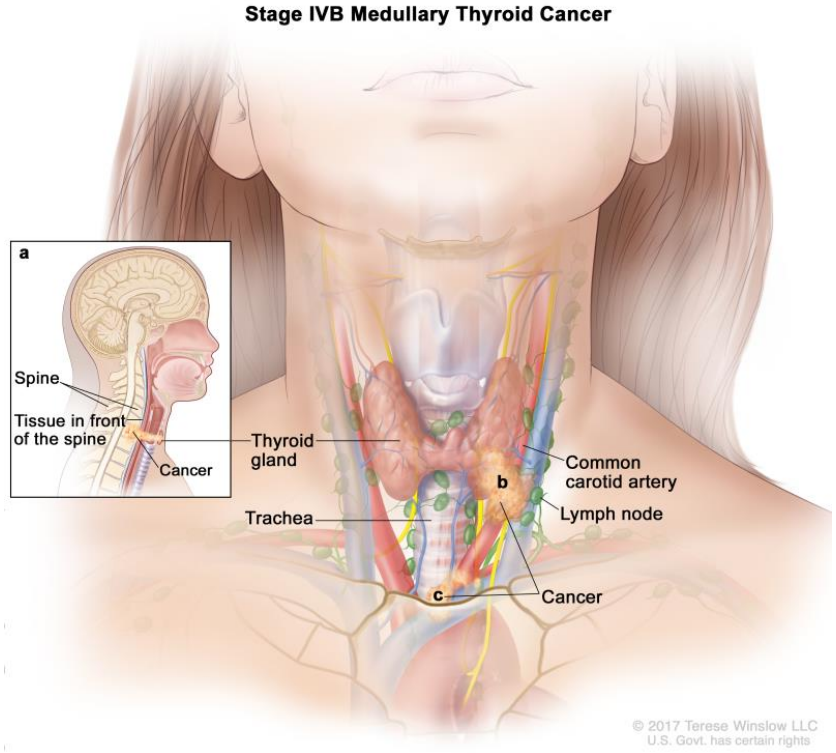


Reconstruction of position of three ^{131}I gamma sources (364 keV)

Gamma camera application: Thyroid diagnostics

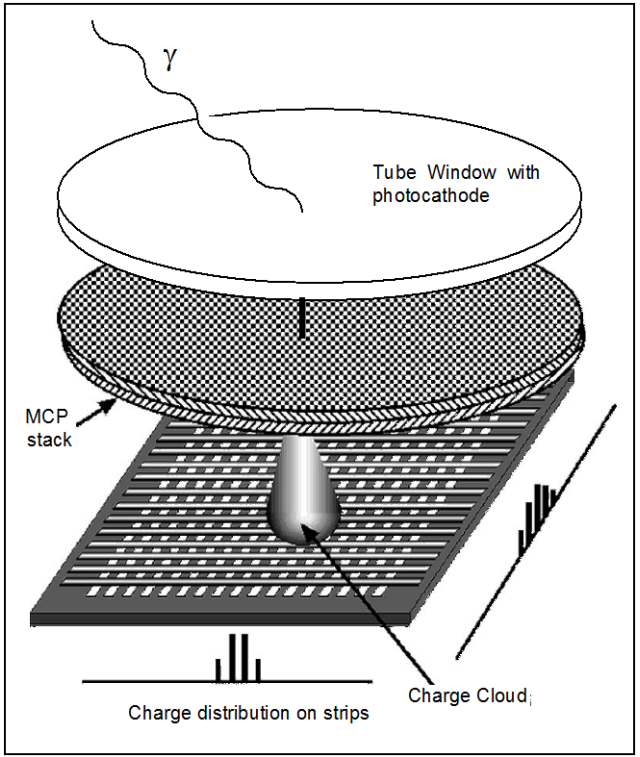
Thyroid cancer diagnostics and treatment monitoring:

- The second most frequent cancer for women (after breast cancer)
- Current imaging methods offer resolution of about 12 mm in 2D
- Our technology allows
  - 5 times better resolution and 3D (2.5 mm)
  - 4 times lower dose

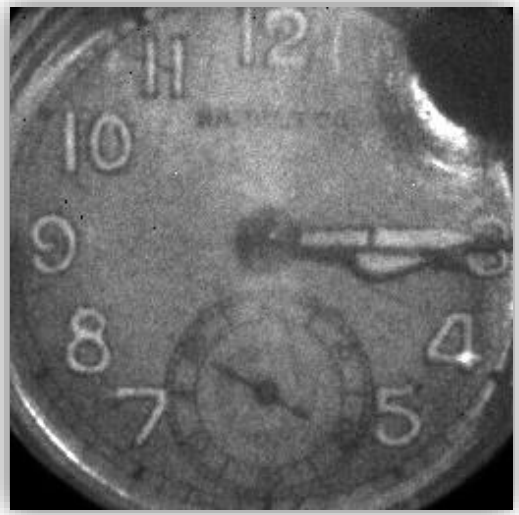


Courtesy of D. Turecek, Advacam s.r.o

Micro-channel plate readout



Optical MCP image tube using Medipix readout

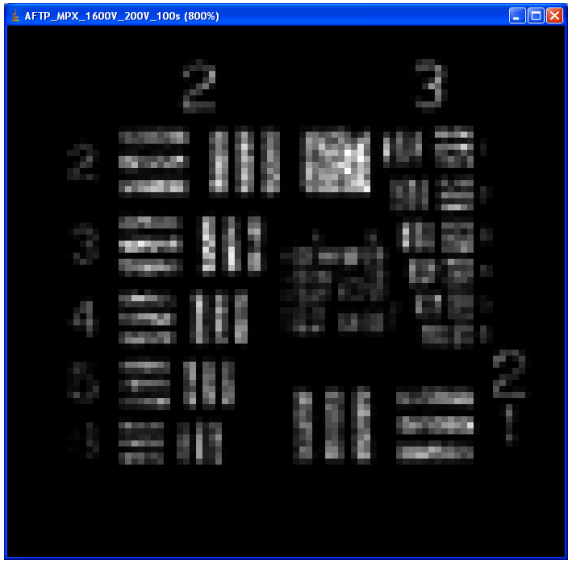


White light illumination
(90 MHz ct. rate)

Radium fluorescence
(100 cps)

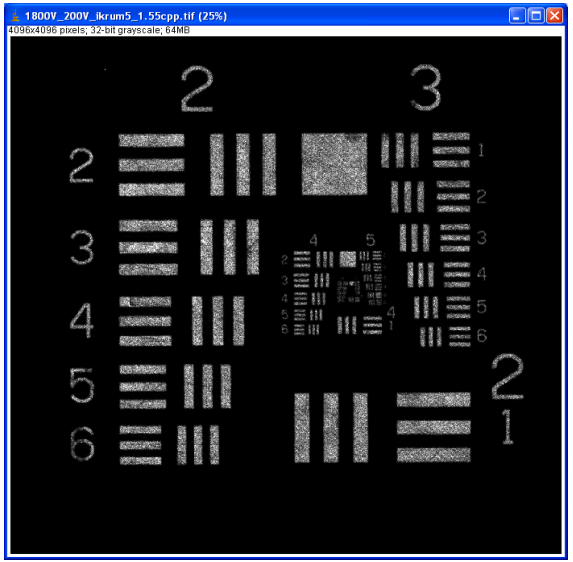
J. Vallerga and co-workers, UC Berkeley, USA

High spatial resolution using Timepix
“Time over Threshold” mode + center of gravity algorithm



9 lp/mm

Medipix2

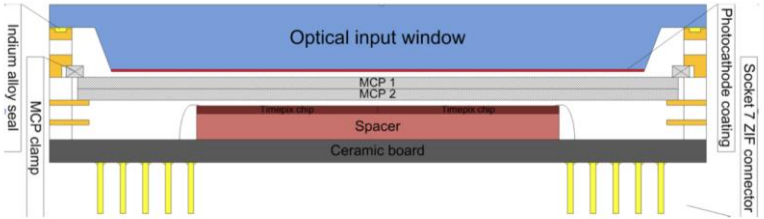


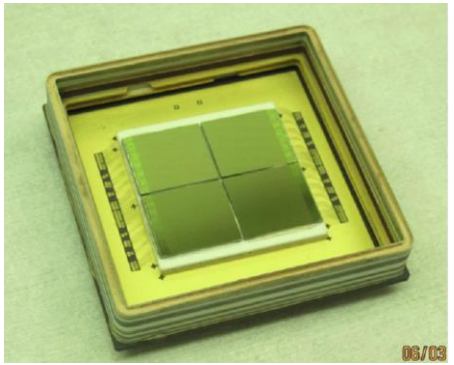
57 lp/mm

Timepix

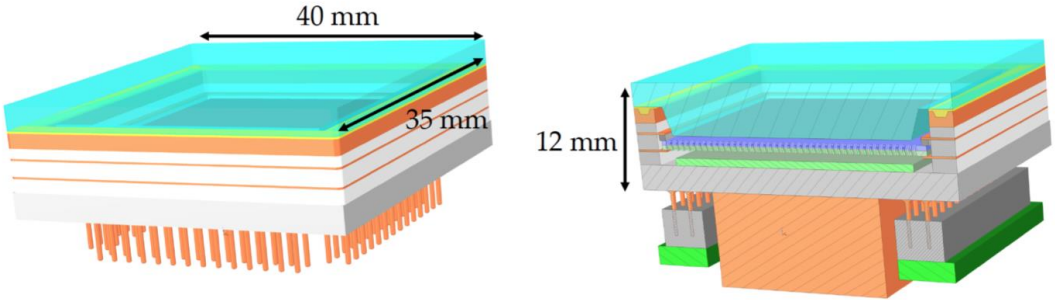
J. Vallerga and co-workers, UC Berkeley, USA

Integrate Timepix4 in a photo tube



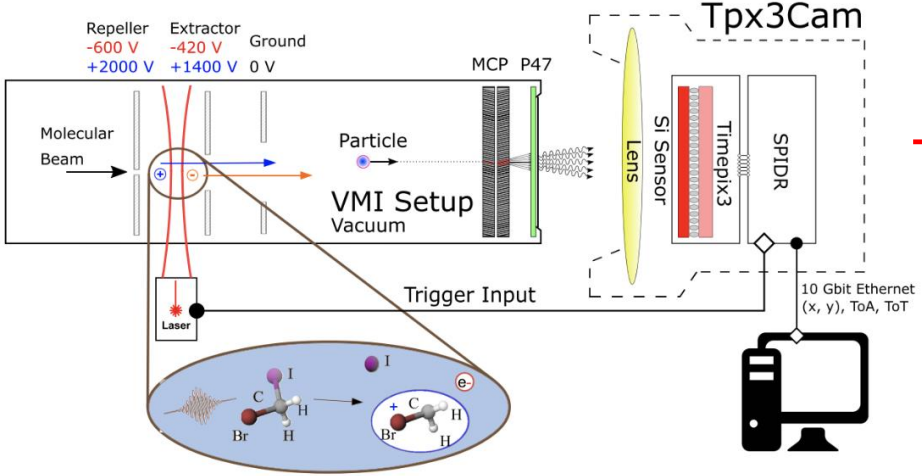


Concept already proven with 4 Timepix chips
See: J Vallerga et al. https://iopscience.iop.org/article/10.1088/1748-0221/9/05/C05055



Ongoing effort with Timepix4 started
See: M. Fiorini et al. https://iopscience.iop.org/article/10.1088/1748-0221/13/12/C12005/pdf

Velocity Map Imaging - Timepix3CAM



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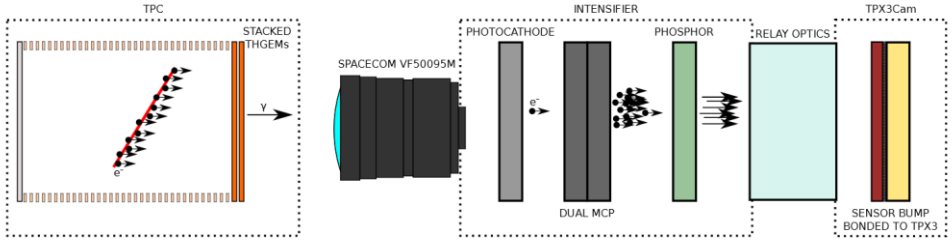
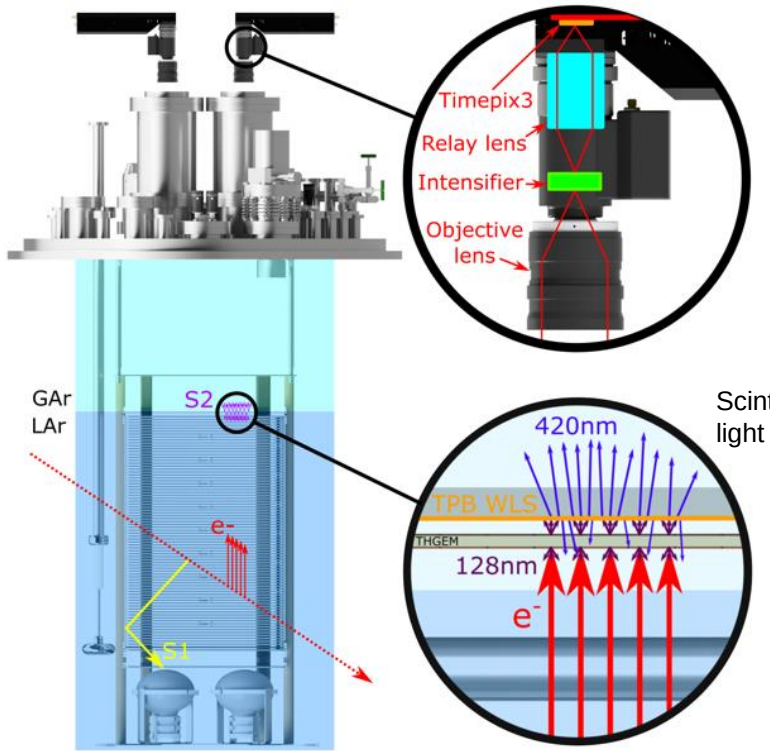
Setup TPIX3CAM test

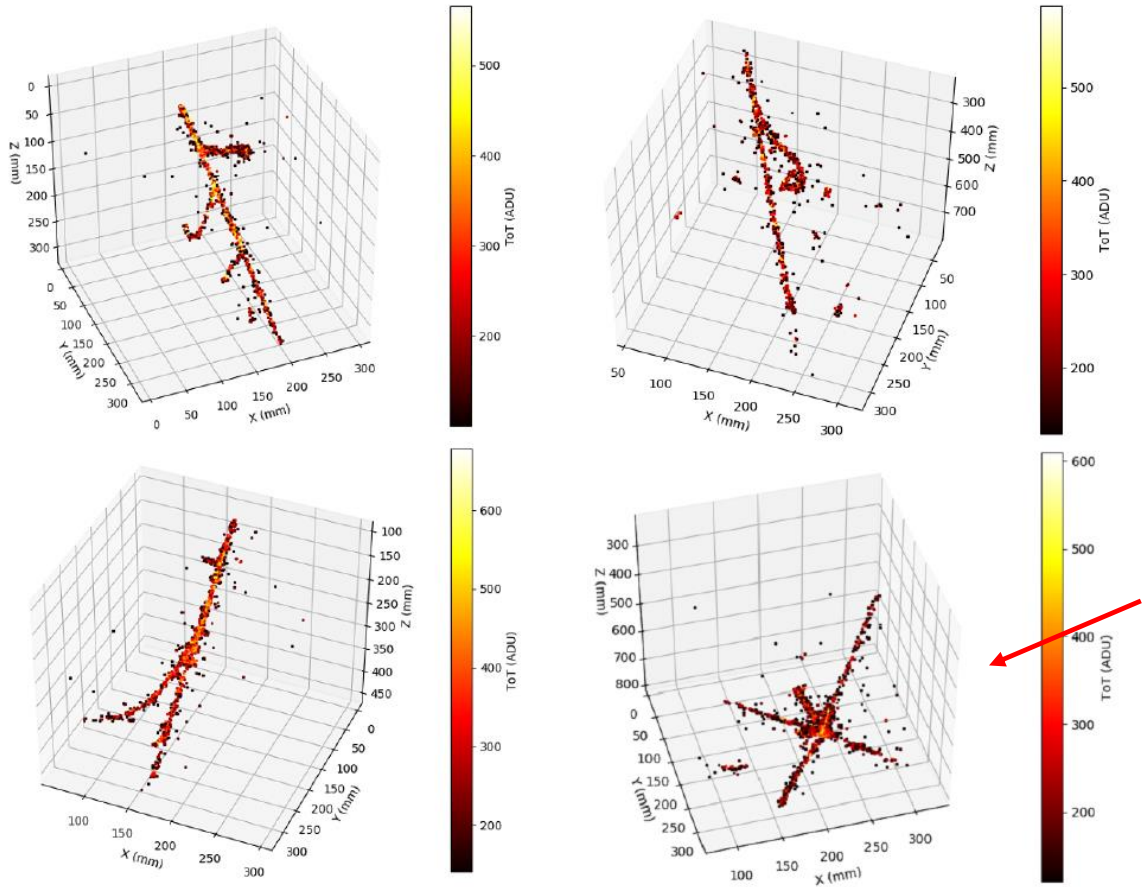


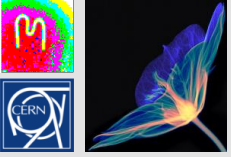


- A TimePix3 camera was mounted on the ARIADNE prototype TPC we have in Liverpool.
- The TPC was filled with 100mb CF4 and the detection/operation principle is the same like in ARIADNE. The light detection efficiency has been directly compared to the EMCCD camera and found to be very similar.
- 32 cm x 32 cm area read out by a single TPIX3Cam

Slide courtesy of K. Mavrokoridis

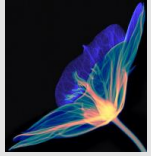
A selection of cosmic muon events ARIADNE TPIX3Cam





Timepix readout chips - single particle detection

	Timepix	Timepix2	Timepix3
Tech. node (nm)	250	130	130
Year	2005	2018	2014
Pixel size (μm)	55	55	55
# pixels (x x y)	256 x 256	256 x 256	256 x 256
Time bin (bin size in ns)	10	10	1.5
Readout architecture	Frame based (sequential R/W)	Frame based (sequential or continuous R/W)	Data driven or Frame based (sequential R/W)
Number of sides for tiling	3	3	3

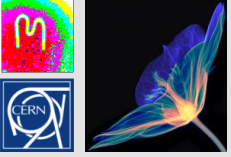



Timepix readout chips - single particle detection

	Timepix	Timepix2	Timepix3	Timepix4
Tech. node (nm)	250	130	130	65
Year	2005	2018	2014	2019
Pixel size (μm)	55	55	55	55
# pixels (x x y)	256 x 256	256 x 256	256 x 256	448 x 512
Time bin (bin size in ns)	10	10	1.5	200ps
Readout architecture	Frame based (sequential R/W)	Frame based (sequential or continuous R/W)	Data driven or Frame based (sequential R/W)	Data driven or Frame-base (sequential or continuous R/W)
Number of sides for tiling	3	3	3	4

Medipix readout chips – photon counting

	Medipix	Medipix2	Medipix3
Tech. node (nm)	1000	250	130
Year	1997	2003	2013
Pixel size (μm)	170	55	55 / 110
# pixels (x x y)	64 x 64	256 x 256	256 x 256 / 128 x 128
# thresholds(counters)	1(1)	2(1)	Up to 8 (up to 8)
Charge summing mode	No	No	Yes
Readout architecture (Frame based)	Sequential R/W	Sequential R/W	Sequential or continuous R/W
Number of sides for tiling	0	3	3



Medipix readout chips – photon counting

	Medipix	Medipix2	Medipix3	Medipix4
Tech. node (nm)	1000	250	130	130
Year	1997	2003	2013	2020
Pixel size (μm)	170	55	55 / 110	70/140
# pixels (x x y)	64 x 64	256 x 256	256 x 256 / 128 x 128	400 x 400/ 200 x 200
# thresholds(counters)	1(1)	2(1)	Up to 8 (up to 8)	>8
Charge summing mode	No	No	Yes	Yes
Readout architecture (Frame based)	Sequential R/W	Sequential R/W	Sequential or continuous R/W	Sequential or continuous R/W
Number of sides for tiling	0	3	3	4

Examples of other applications

- Large area X-ray cameras for synchrotrons
- X-ray materials analysis
- X-ray non-destructive testing
- X-ray dosimetry - dosepix chip development

- High resolution neutron detection and imaging

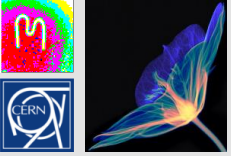
- Low Energy Electron Microscopy
- Electron Backscattering diffraction (EBSD)
- Transmission electron microscopy and cryo em

- Time-of-Flight mass spectrometry

- Dose deposition tracking in hadron therapy
- Gamma (and Compton) camera for power plant decommissioning and homeland security

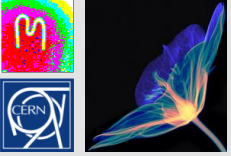
Applications for CERN/Physics

- LHCb VELOpix chip is directly derived from Timepix3
- LHCb Timepix3 telescope – 80 Mhits/cm^2/sec
- Sensor studies for CLIC/LHCb
- Background radiation monitoring at ATLAS and CMS
- Beam monitoring in UA9
- Positron annihilation in Aegis
- ASACUSA experiment
- Beam Gas Interaction real time monitor at SPS
- Breit-Wheeler experiment at RAL
- Beta particle channeling in ISOLDE
- Axion search at CAST (with InGrid)
- Large area TPC (with InGrid)
- Transition radiation measurements for ATLAS
- GEMPIX development for radiation therapy beam monitoring
- GEMPIX for ^{55}Fe waste management
- Developments for CLIC: CLICpix, CLICpix2, C3PD



Conclusions

- Hybrid pixel detectors were developed as tracking detectors of LHC and the Medipix2 and Medipix3 Collaborations have taken the technology into many other fields
- Timepix chips are actively detecting background radiation in school classrooms, in airplane, in labs and in space
- “Colour” X-ray imaging using Medipix3 has helped authenticate ancient art and has significant potential for medical diagnostic imaging
- The technology has permitted a number of high-tech start ups to develop in CERN member states and elsewhere.



Conclusions

- Many novel scientific applications and experiments have been made possible by the very generic architecture of the Timepix and Timepix3 chips. This helps contribute to a diverse physics programme.
- CERN experiments have benefitted directly from use of our chips and indirectly from the development of technologies and know-how which can be applied to HEP experiments.
- Technology transfer is not a one-way process and can actually stimulate innovation in HEP instrumentation
- The Medipix4 Collaboration is developing high resolution pixel readout chips which can be tiled on 4 sides.

Some references and links

“An introduction to the Medipix family ASICs,” R. Ballabriga, M. Campbell, X. Llopart, *Radiation Measurements* 136 (2020) 106271

“VeloPix: the pixel ASIC for the LHCb upgrade,” T. Poikela et al. *Journal of Instrumentation*, Volume 10, January 2015

MARS Bio-imaging

InsightArt

Advacam cameras

Diamond Light Source detector group

Admira project

“Development of a rest gas ionisation profile monitor for the CERN Proton Synchrotron based on a Timepix3 pixel detector,” S. Levasseur et al., *Journal of Instrumentation*, Volume 12, February 2017

“Optical Readout of the ARIADNE LArTPC Using a Timepix3-Based Camera,” Adam Lowe et al *Instruments* 2020, *4*(4), 35;

“Registration of the transition radiation with GaAs detector: Data/MC comparison,” J Alozy et al, 2020 J. Phys.: Conf. Ser. 1690 012041

3D reconstruction of particle tracks in a 2 mm thick CdTe hybrid pixel detector,” Bergmann, B., Burian, P., Manek, P. *et al. Eur. Phys. J. C* 79, 165 (2019).

Thank you for your attention!