APPLICATIONS OF THE MEDIPIX AND TIMEPIX ASICS

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[1] Honorary Professor at Glasgow University

Medipix2 (1999 ->)	Medipix3 (2005 ->)	Medipix4 (2016 ->)
Albert-Ludwig Universität Freiburg, Germany	Albert-Ludwig Universität Freiburg, Germany	CEA, Paris, France
CEA, Paris, France	AMOLF, Amsterdam, The Netherlands	CERN, Geneva, Switzerland
CERN, Geneva, Switzerland	Brazilian Light Source, Campinas, Brazil	DESY-Hamburg, Germany
Czech Academy of Sciences, Prague, Czechia	CEA, Paris, France	Diamond Light Source, England, UK
ESRF, Grenoble, France	CERN, Geneva, Switzerland	IEAP, Czech Technical University, Prague, Czeciah
IEAP, Czech Technical University, Prague, Czech Republic	DESY-Hamburg, Germany	IFAE, Barcelona, Spain
IFAE, Barcelona, Spain	Diamond Light Source, England, UK	JINR, Dubna, Russian Federation
Mid Sweden University, Sundsvall, Sweden	ESRF, Grenoble, France	NIKHEF, Amsterdam, The Netherlands
MRC-LMB Cambridge, England, UK	IEAP, Czech Technical University, Prague, Czech Republic	University of California, Berkeley, USA
NIKHEF, Amsterdam, The Netherlands	KIT/ANKA, Forschungszentrum Karlsruhe, Germany	University of Canterbury, Christchurch, New Zealand
University of California, Berkeley, USA	Mid Sweden University, Sundsvall, Sweden	University of Geneva, Switzerland
Universität Erlangen-Nurnberg, Erlangen, German	NIKHEF, Amsterdam, The Netherlands	University of Glasgow, Scotland, UK
University of Glasgow, Scotland, UK	Univesridad de los Andes, Bogota, Columbia	University of Houston, USA
University of Houston, USA	University of Bonn, Germany	University of Maastricht, The Netherlands
University and INFN Section of Cagliari, Italy	University of California, Berkeley, USA	University of Oxford, England, UK
University and INFN Section of Pisa, Italy	University of Canterbury, Christchurch, New Zealand	INFN, Italy
University and INFN Section of Napoli, Italy	Universität Erlangen-Nurnberg, Erlangen, German	
	University of Glasgow, Scotland, UK	
	University of Houston, USA	
	University of Leiden, The Netherlands	
	Technical University of Munich, Germany	
	VTT Information Technology, Espoo, Finland	

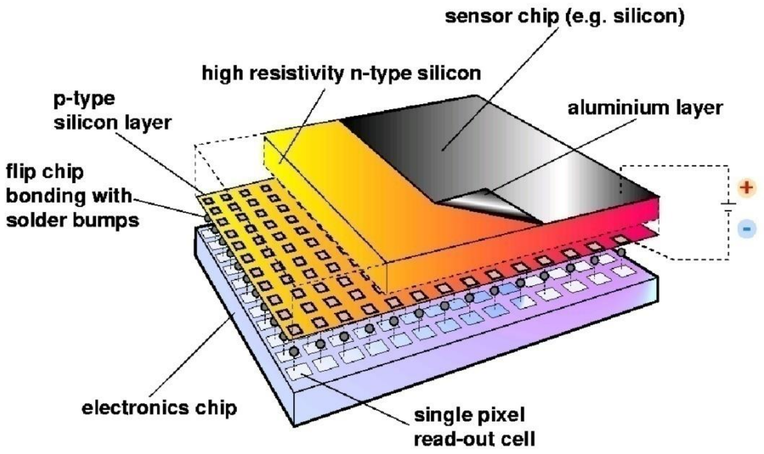
Acknowledgements – Commercial Partners

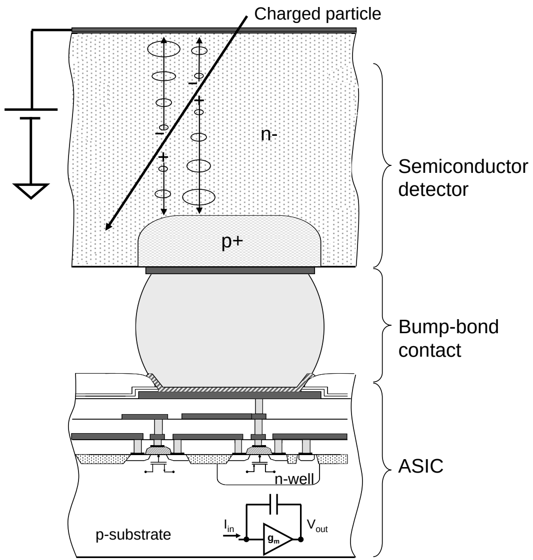
COLLABORATION NAME	Medipix2			Medipix3		Medipix4	
ASICS	**Medipix2**	**Timepix**	**Timepix2**	**Medipix3**	**Timepix3**	**Medipix4**	**Timepix4**
ADVACAM s.r.o., Czech Republic	X	X	X	X	X		X
Amsterdam Scientific Instruments, The Netherlands	X	X	X	X	X		X
Kromek, UK	X	X	X				
Malvern-Panalytical, The Netherlands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

Outline

- Introduction
- Spectroscopic X-ray imaging
  - Art authentication
  - Medical computed tomography
- Timepix3
  - Use in teaching
  - Thyropix Compton camera
  - Visible light detection and imaging
  - Neutrino physics
- Timepix4
- Some words on timing
- Summary and conclusions

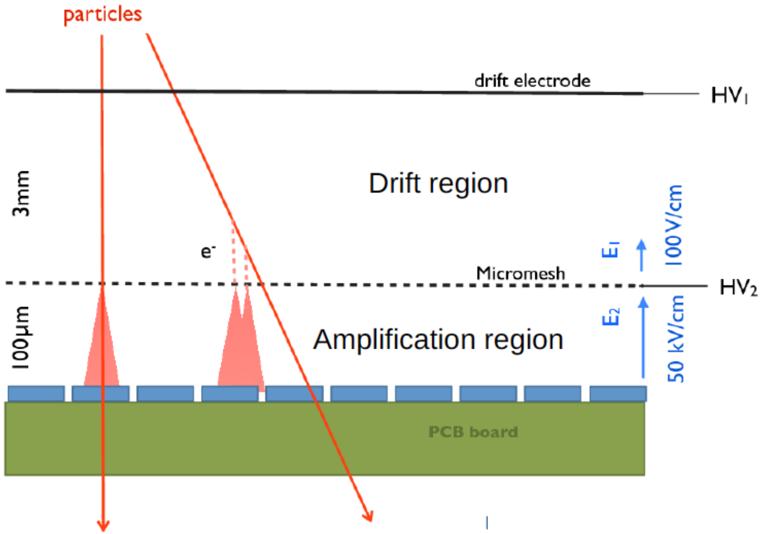
Hybrid Silicon Pixel Detectors

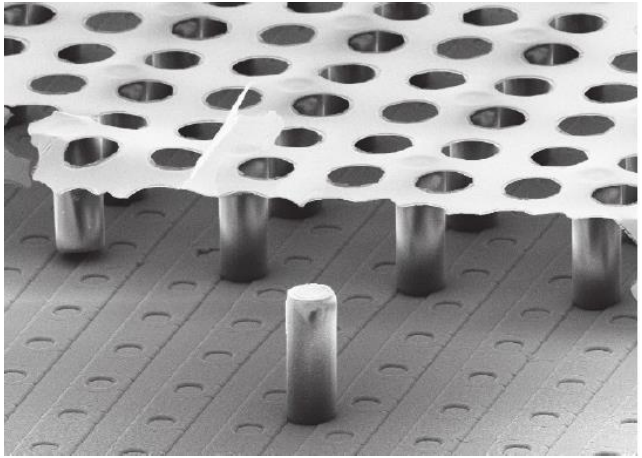




- Noise-hit free images possible (high ratio of threshold/noise)
- Standard CMOS can be used allowing on-pixel signal processing
- Sensor material can be changed (Si, GaAs, CdTe..)
- Semiconductor sensor can be replaced by a gas gain grid or MCP

Gas detector readout - InGrid





Semiconductor detector is replaced with charge amplification grid
Permits lower energy events to be detected

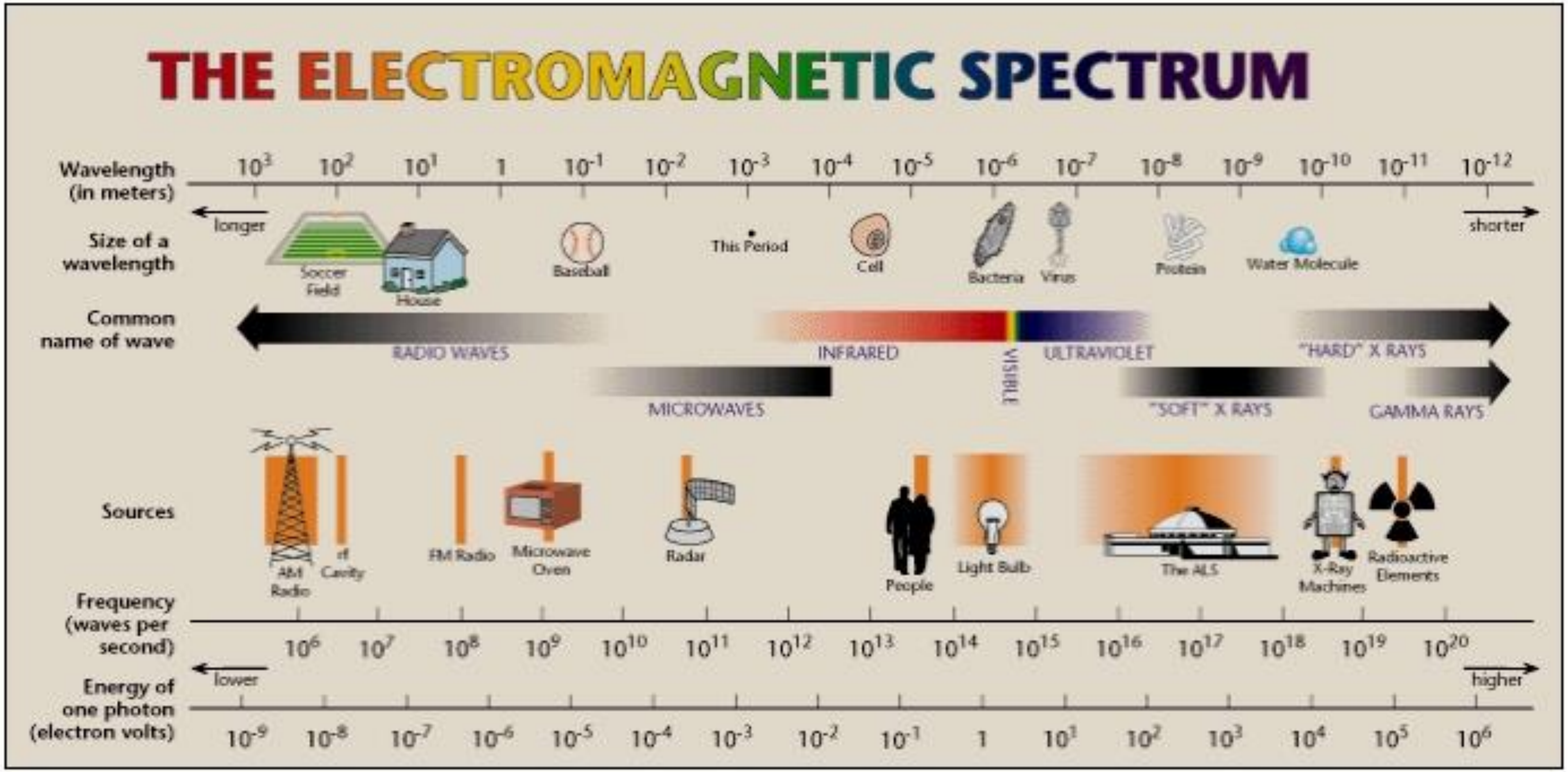
NB: GEM foils may be used in place of the InGrid foils

The Medipix and Timepix ASICs - Timeline

Collaboration	2003	2006	2013	2014	2017	2018	2020	2021	2025?
Medipix2	Medipix2	Timepix				Timepix2			
Medipix3			Medipix3	Timepix3					
Medipix4							Timepix4	Medipix4	

- Medipix chips aim at energy sensitive photon counting and typically use frame-based readout
- Timepix chips are more oriented towards single particle detection
- The Timepix3 design team developed the VELOpix chip for LHCb. Work has (just) started on an ASIC a future upgrade (~50ps time bin per pixel)

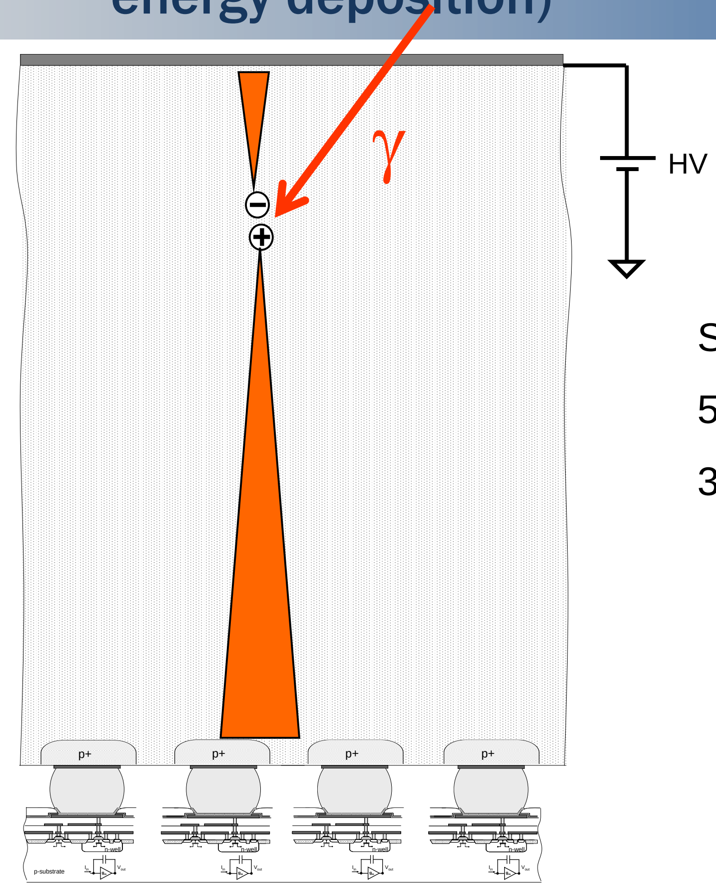
Spectroscopic X-ray imaging



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)

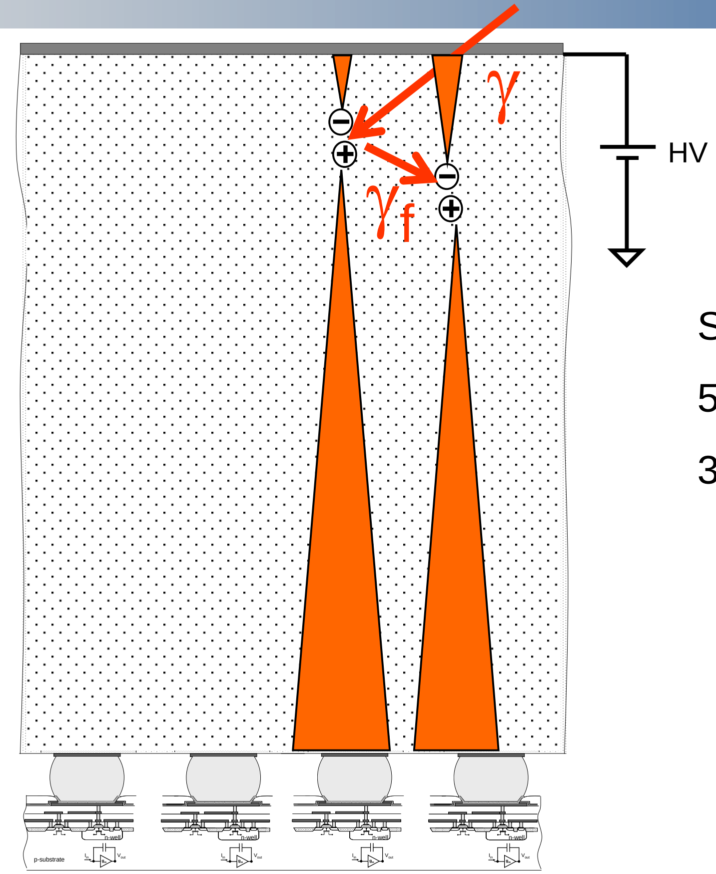


Sensor dimensions to scale:

55µm pixel pitch

300µm thick sensor

Fluorescence in high-Z materials



Sensor dimensions to scale:

55µm pixel pitch

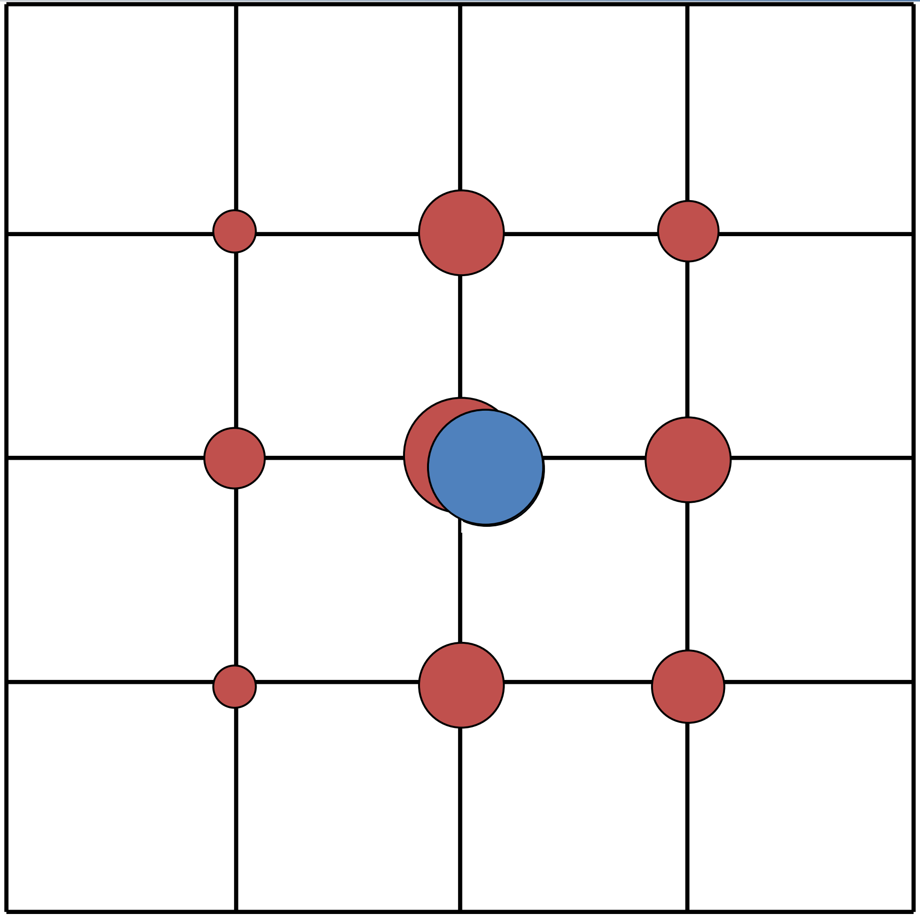
300µm thick sensor

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



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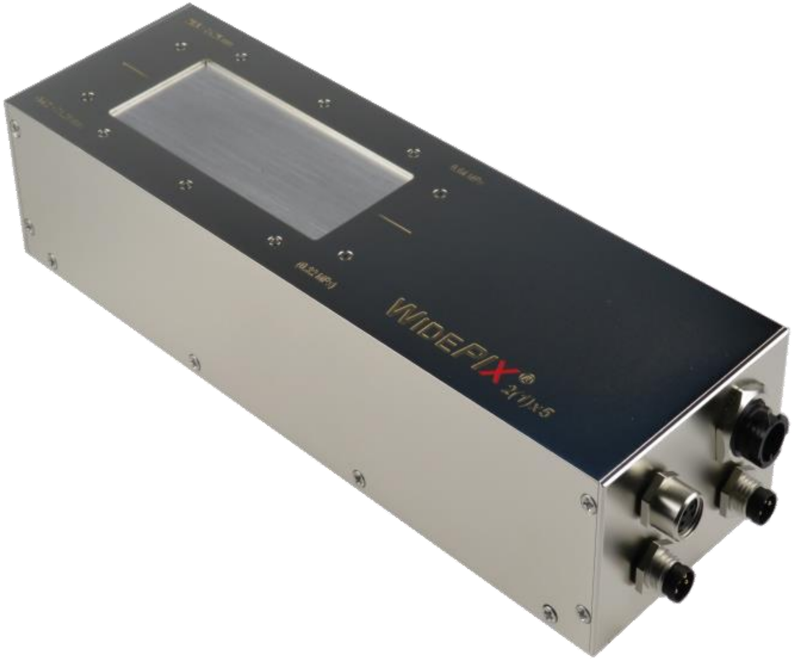
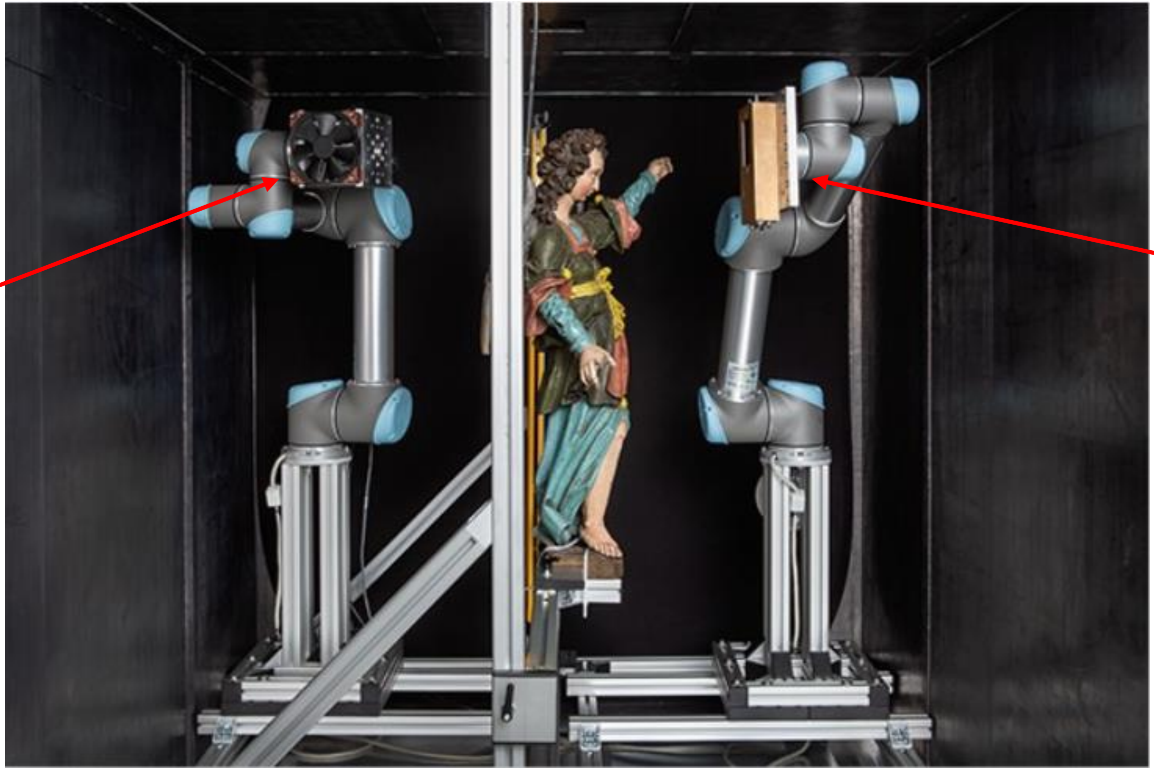
Large area detectors for Art inspection



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

Combined with robots

Micro-focus X-ray soucre



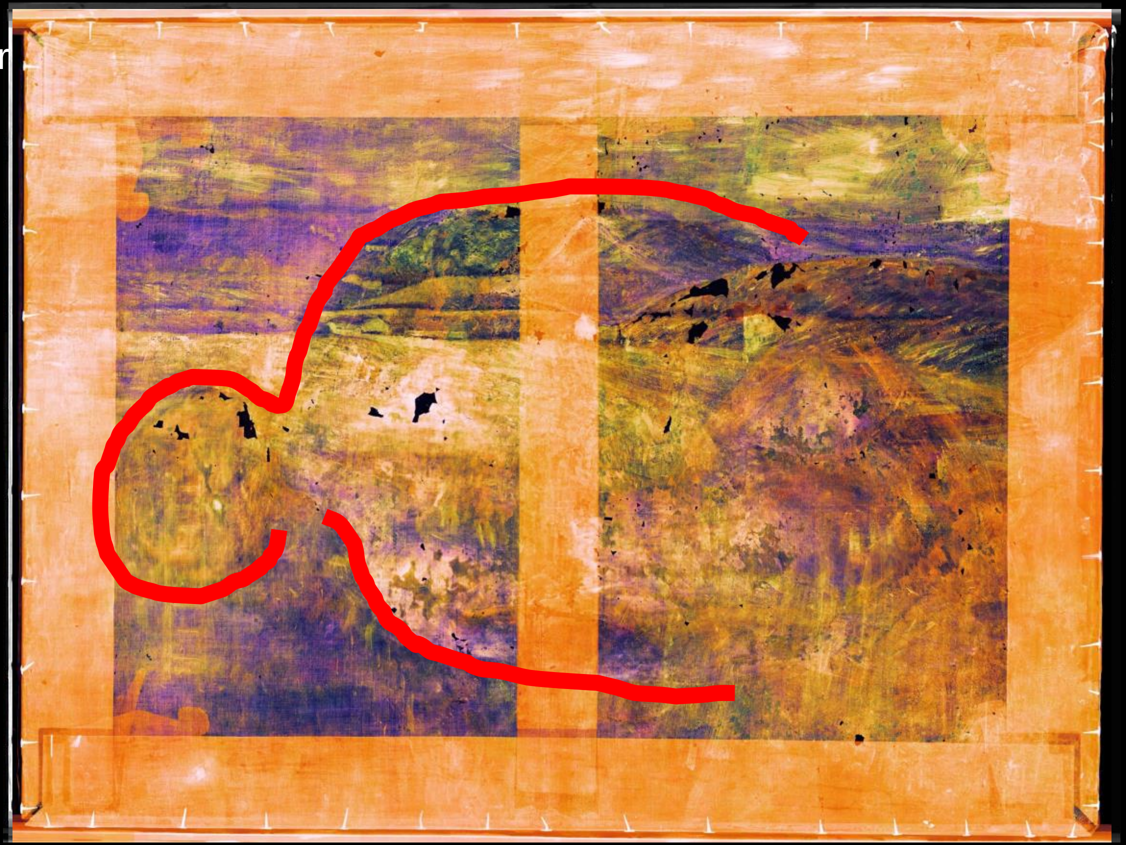
Timepix/Medipix3 spectroscopic imaging camera

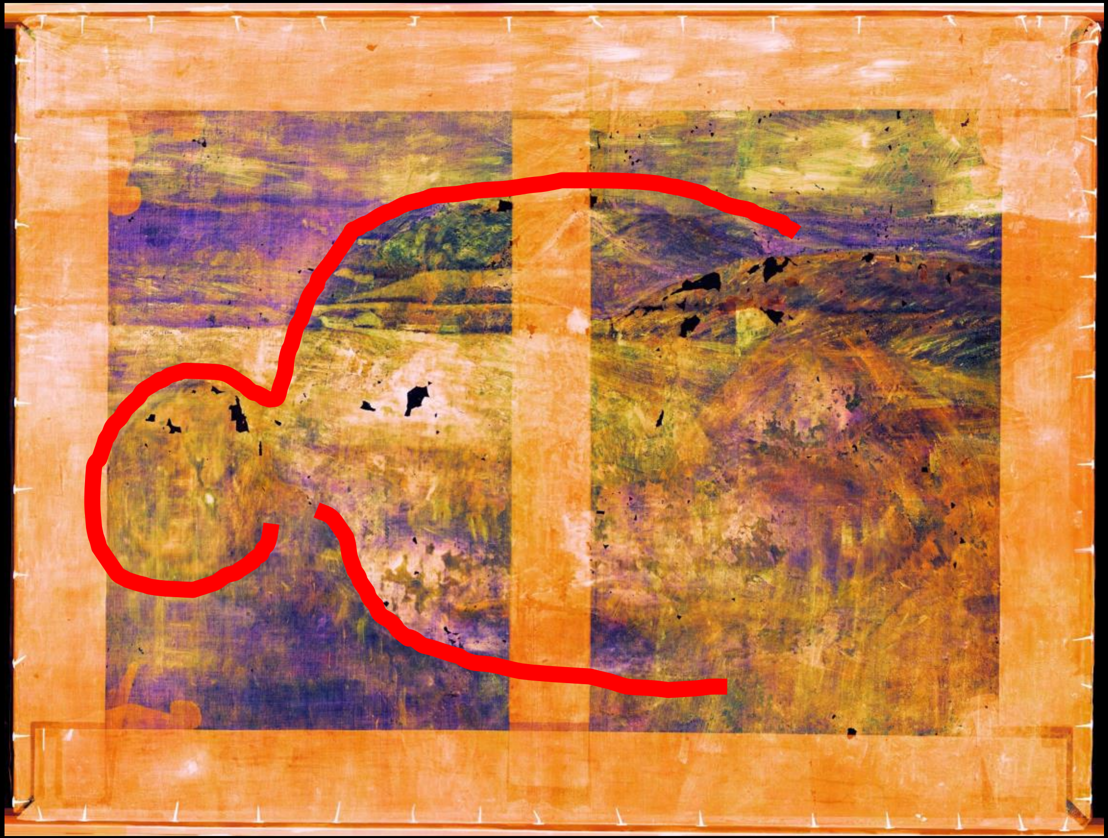
Source InsightART (insightart.eu)

Signed
Vincent van Gogh

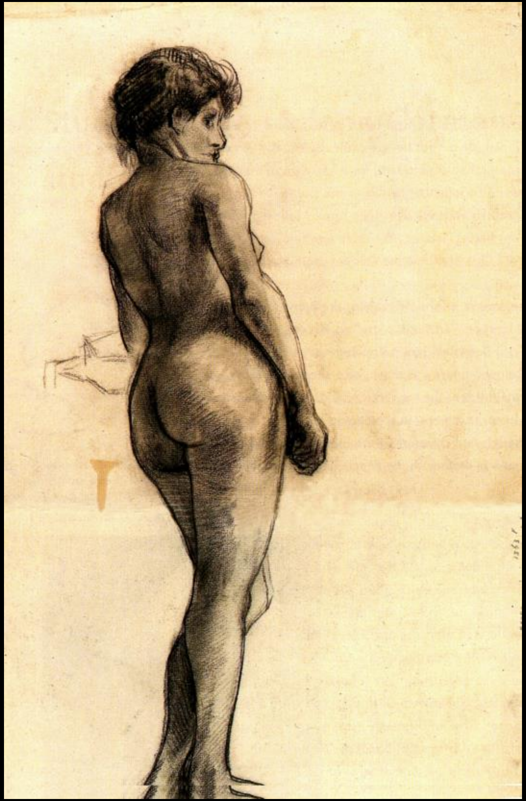
La Crau with Montmajour
in the backgroud

~1888





INSIGHTART



INSIGHTART

Raphael Santi: Madonna with Child

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

Madonna with child

DATE
About 1517

TECHNIQUE
Oil on canvas

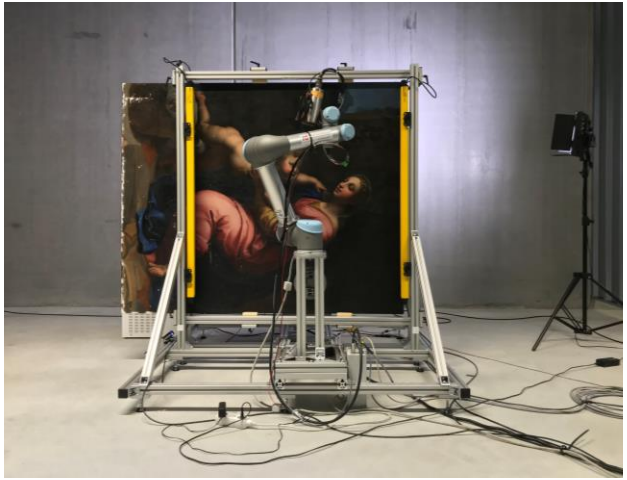
DIMENSIONS
157 x 127 cm

J. Uher, InsightArt, Prague, Czech Republic

The most challenging scan we did

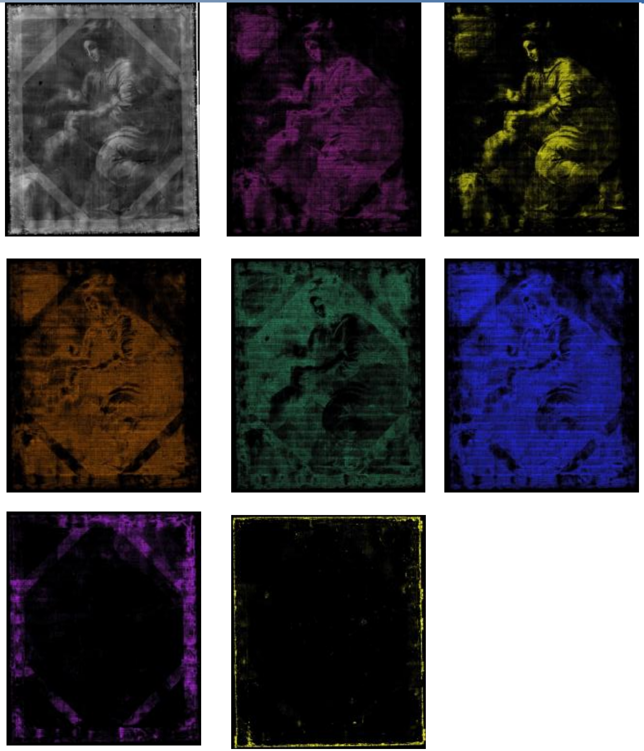
INSIGHTART

- 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

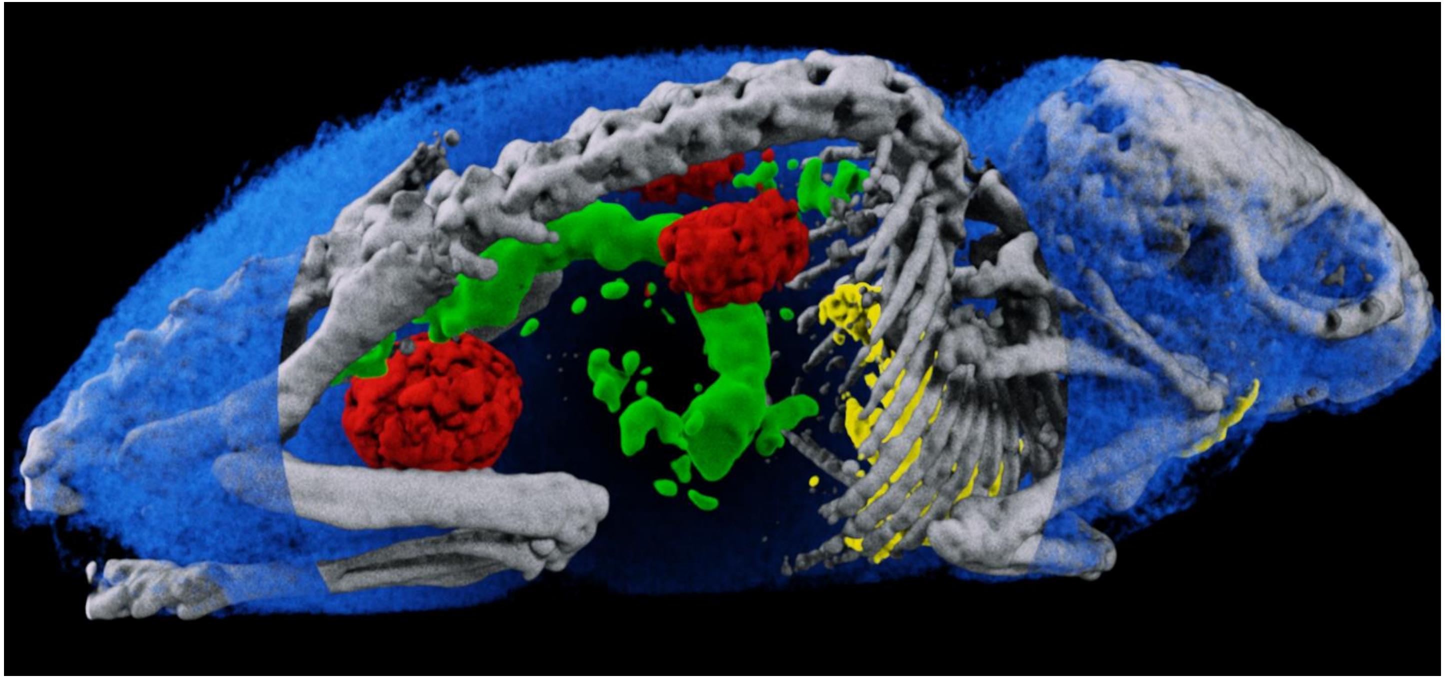
Left: Graphic combining energy spectra measured by RToo scanner (© InsightART, 2019); Right: RToo scanning the painting Madonna and Child (© Jiří Lauterkranc, 2019). (Image: CERN)

MARS Bio-scanner now commercial

Notre Dame imaging lab

Slide courtesy of A. Butler, University of Canterbury

Spectroscopic information permits material separation

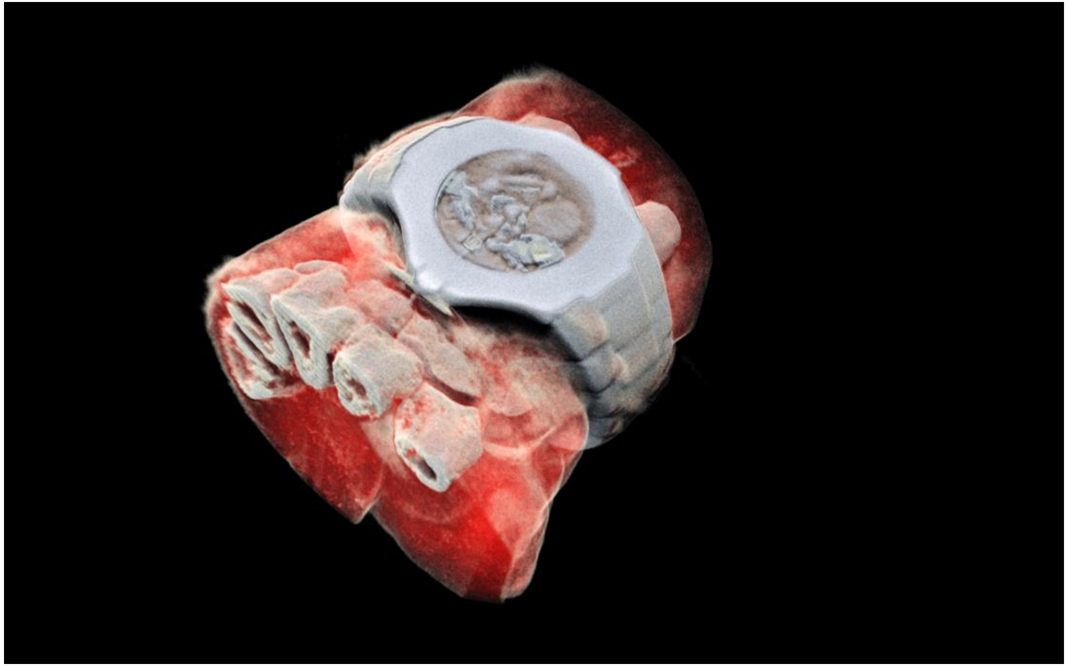


The water has been partly cut away to reveal the bone, gold, gadolinium and iodine

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 Phil's ankle

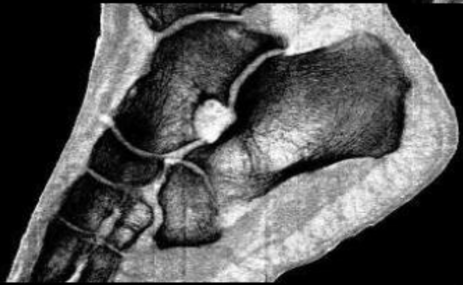
Library images:

CT

MRI

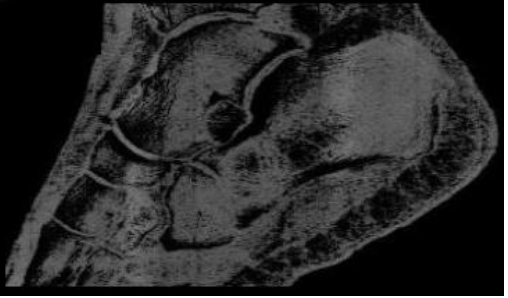
MARS images:

Calcium,
colour it white

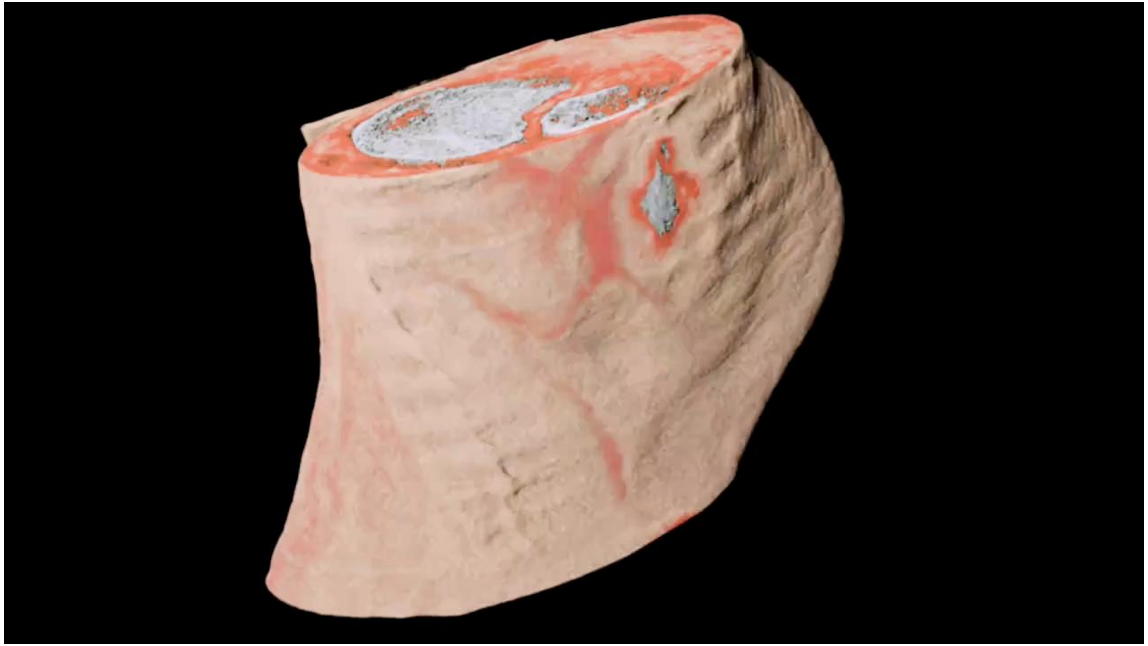


Fat,
colour it yellow

Water,
colour it red and
semi-transparent red



Slice through of Phil Butler's Ankle



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

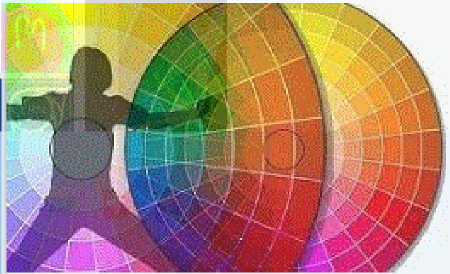
MARS Bioimaging's 3D colour X-ray scanner has arrived in Europe to undertake clinical trials that will lead to its medical use.

22 JUNE, 2021 | By Antoine Le Gall

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

29

MARS scan of diseased carotid artery



Workshop on Medical Applications of Spectroscopic X-ray Detectors

CERN, 13-16 May 2019

~120 invited participants of which ~50 were from industry

All large medical equipment suppliers represented: Canon, GE, Philips, Siemens

Also major research institutes present :Johns Hopkins, Massachusetts General Hospital, Mayo Clinic, Royal Marsden, TU Munich etc

Medipix Collaboration plays a ‘pathfinding’ role in this community

Timepix readout chips - single particle detection

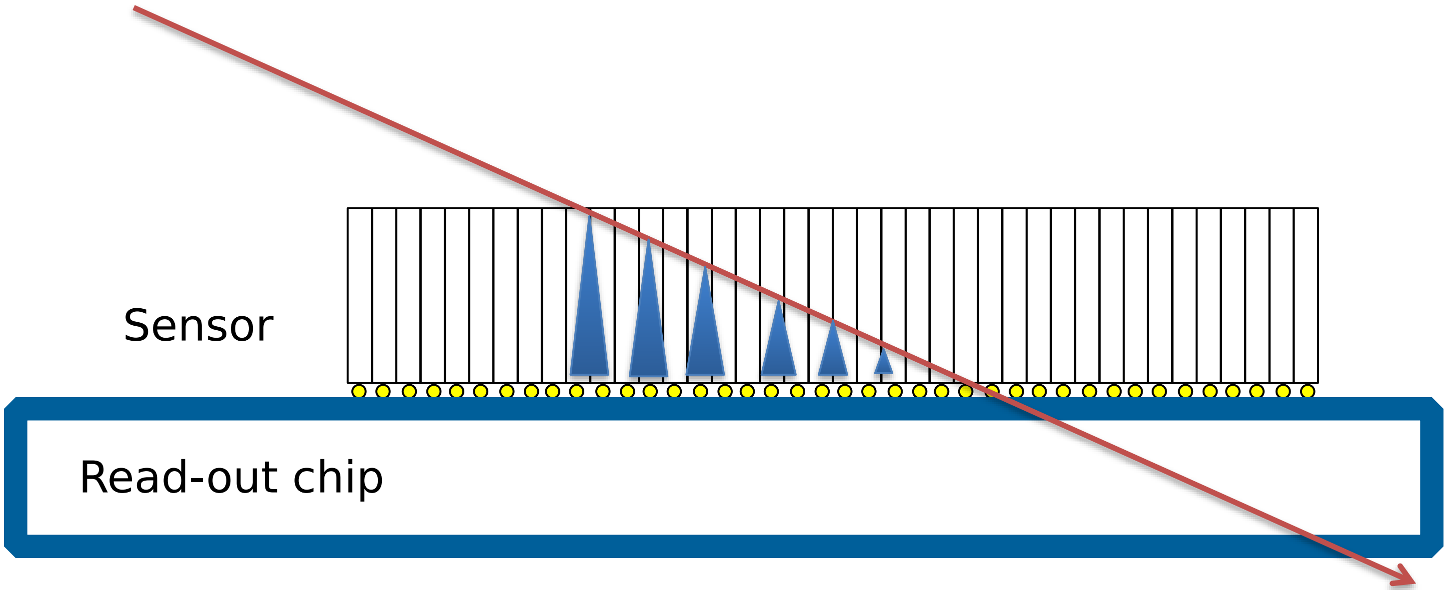
	Timepix	Timepix2	Timepix3
Tech. node (nm)	250	130	130
Year	2005	2018	2014
Pixel size (µm)	55	55	55
# pixels (x x y)	256 x 256	256 x 256	256 x 256
Time bin (bin size in ns)	10	10	1.5
Readout architecture	Frame based (sequential R/W)	Frame based (sequential or continuous R/W)	Data driven or Frame based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

Timepix3 miniaturised readout

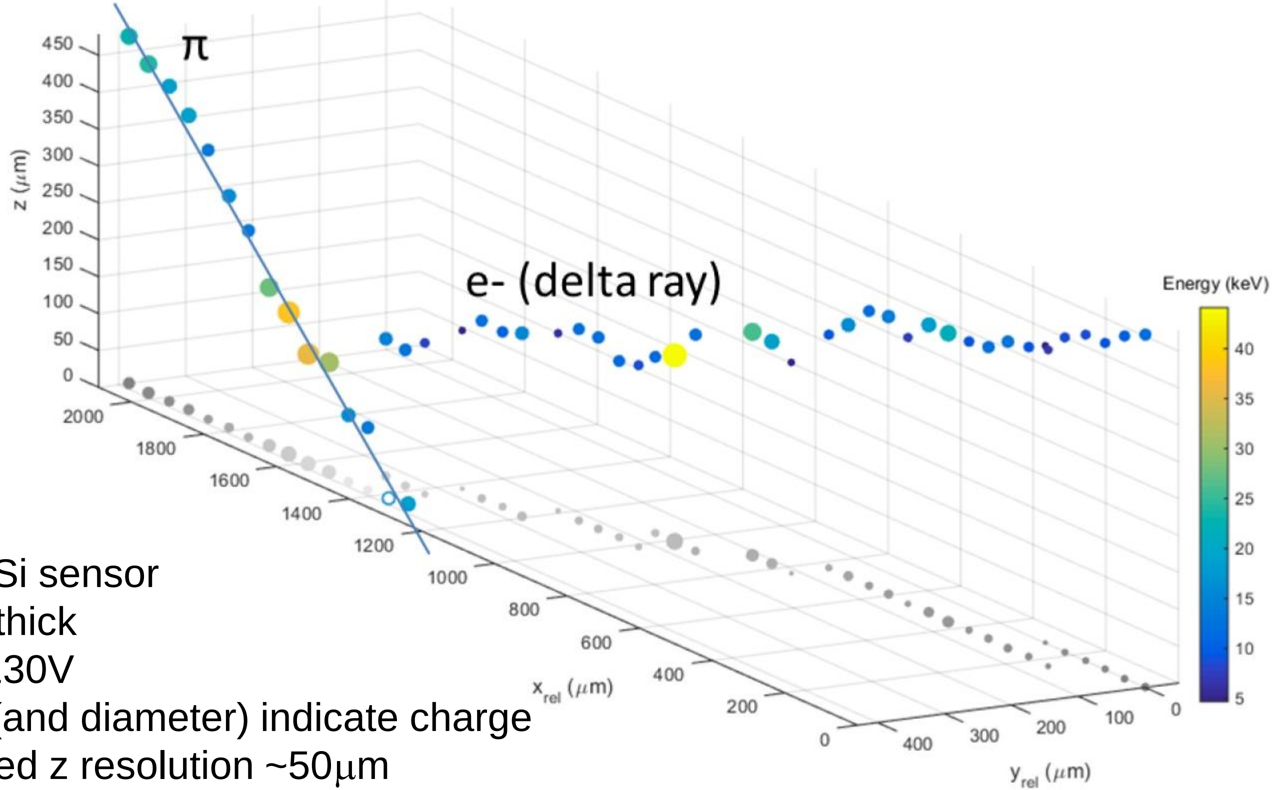
Advacam s.r.o., Prague

Demo Timepix3

Using charge collection time to track in a single Si layer



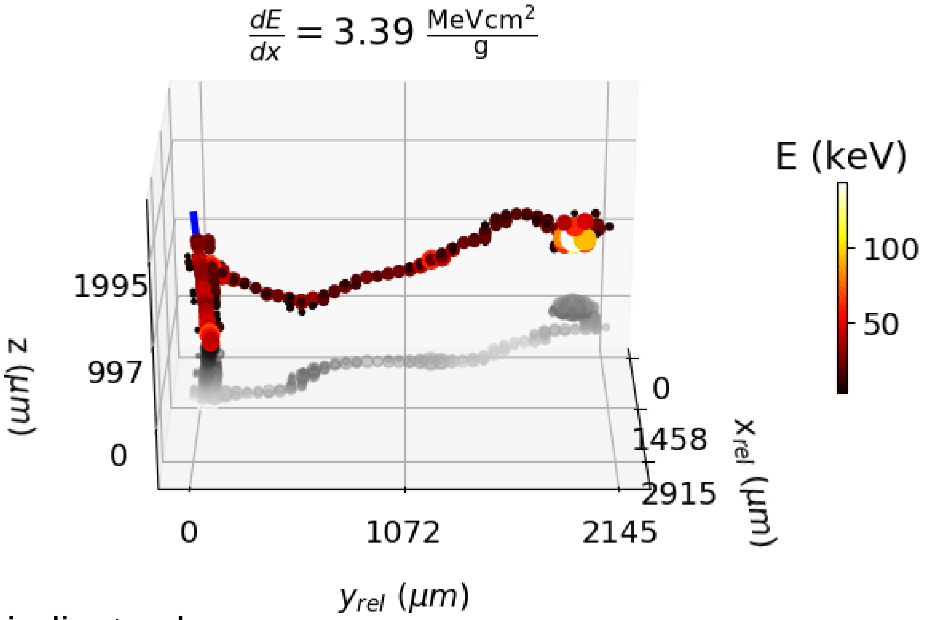
Test with 120GeV/c Pion Track



60 deg
p+ in n Si sensor
500μm thick
V_{bias} = 130V
Colour (and diameter) indicate charge
Measured z resolution ~50μm

Slide courtesy of B. Bergmann, S. Pospisil, IEAP, CTU, Prague

3D rendering of traversing particle with delta electron



45 deg
CdTe sensor
2mm thick
V_{bias} = 130V
Colour (and diameter) indicate charge

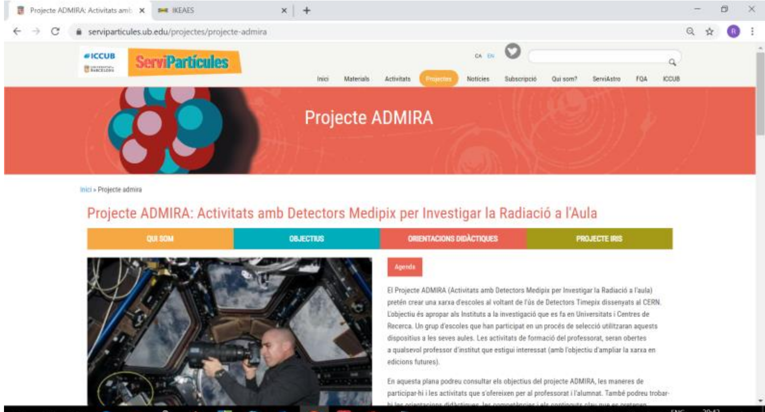
Slide courtesy of B. Bergmann, S. Pospisil, IEAP, CTU, Prague

CERN@school

Simon Langton School, Canterbury, England

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.

Single Layer Compton Camera with MiniPIX TPX3

Compton camera principle

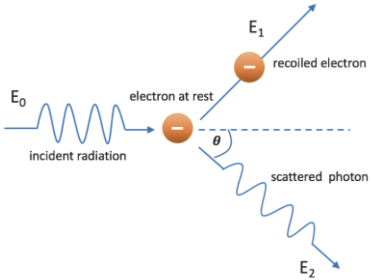
- Typical two detectors
- primary gamma is scattered in first detector (position and energy recorded), scattered gamma continues to second detector (absorbed, position and energy recorded)
- from energies - > scattering angle calculated
- from position and energies -> possible position of the source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

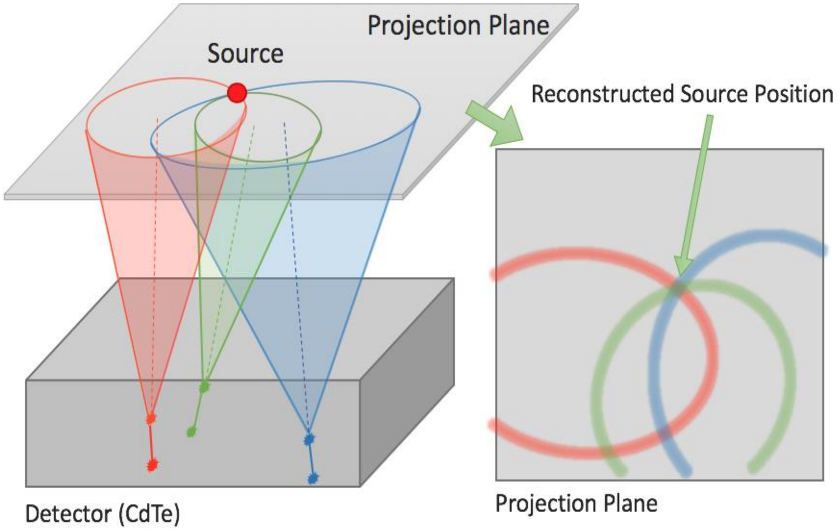
- Single Timepix3 layer camera
  - Instead of 2 detectors, only single TPX3
  - Using time of charge collection to determine relative depth

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

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

$$E_0 = E_1 + E_2$$

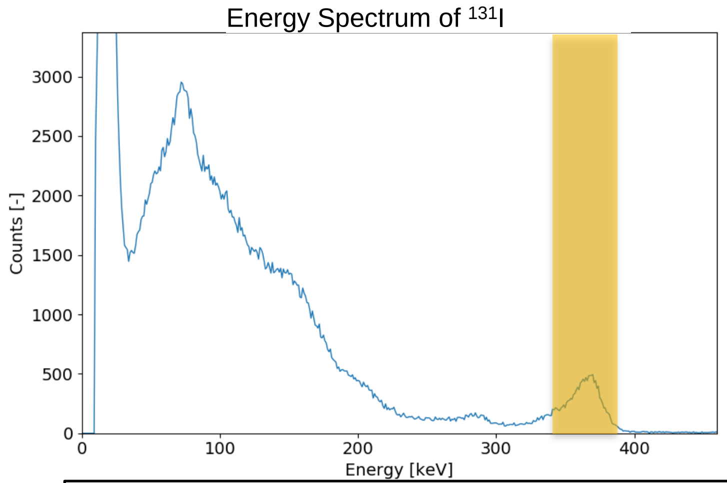




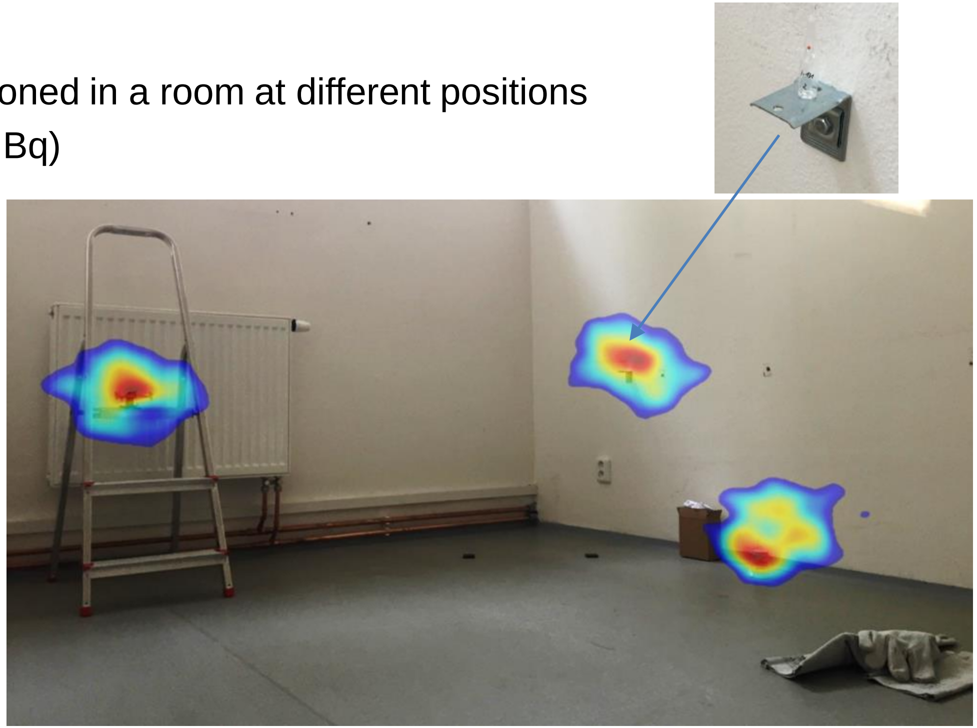
Single Layer Compton Camera with MiniPIX TPX3

^{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

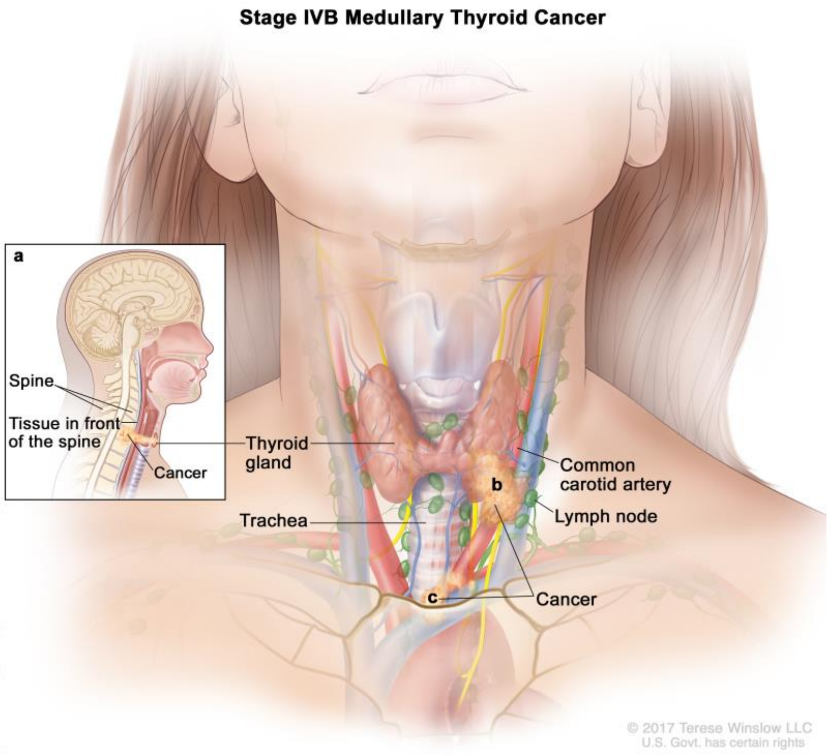


Reconstruction of position of three ^{131}I gamma sources (364 keV)

Gamma camera application: Thyroid diagnostics

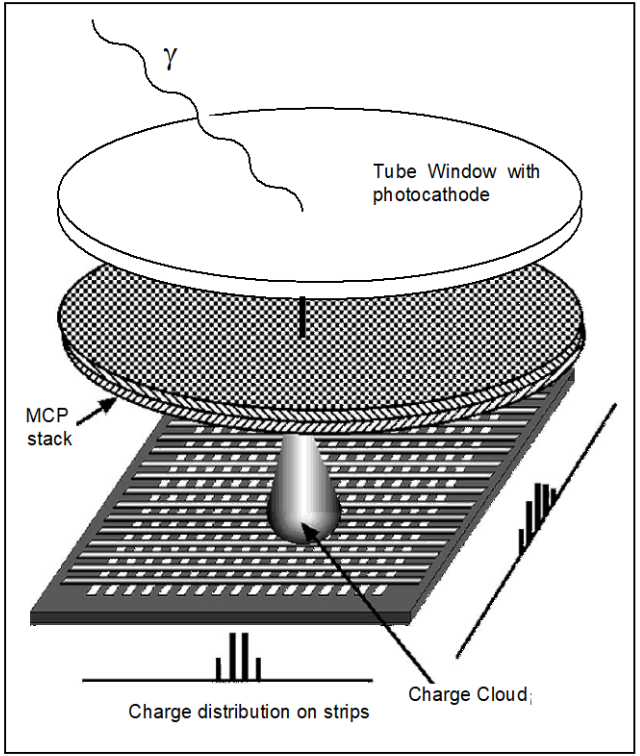
Thyroid cancer diagnostics and treatment monitoring:

- 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

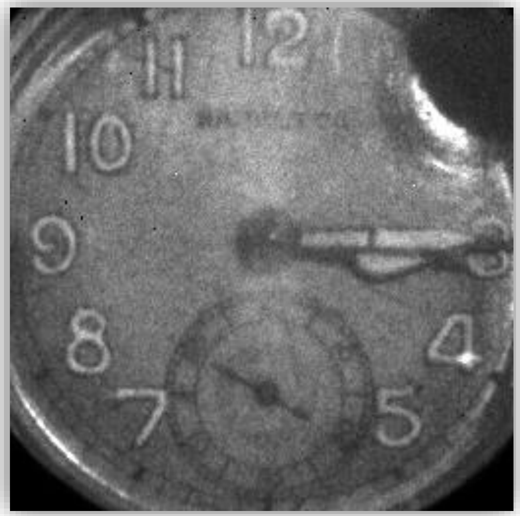


Courtesy of D. Turecek, Advacam s.r.o

Micro-channel plate readout



Optical MCP image tube using Medipix readout

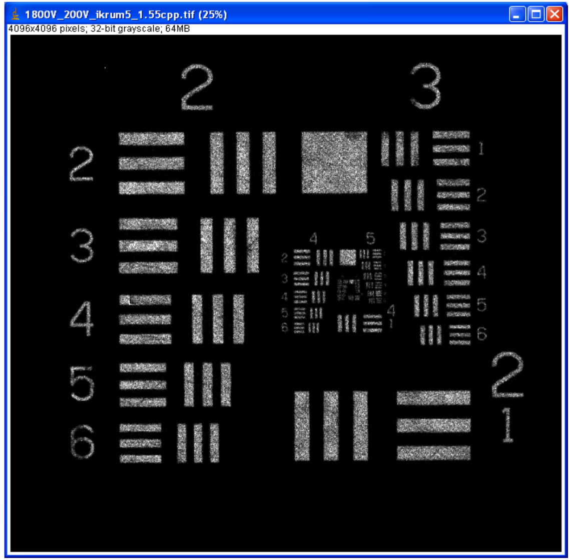


White light illumination
(90 MHz ct. rate)

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

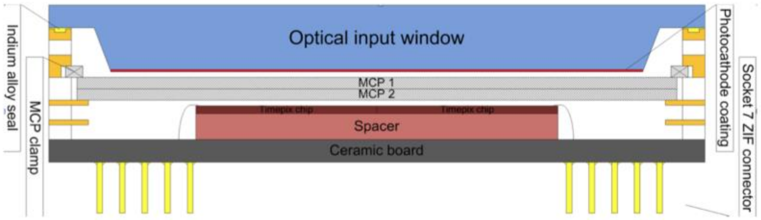
Medipix2

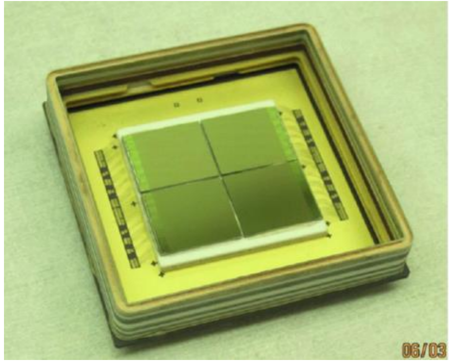
57 lp/mm

Timepix

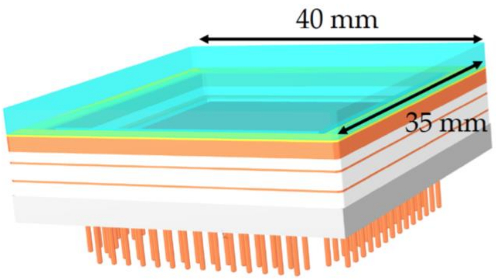
J. Vallerga and co-workers, UC Berkeley, USA

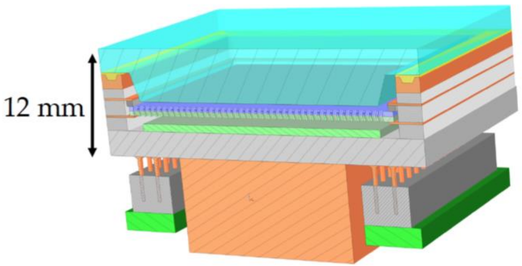
Integrate Timepix4 in a photo tube





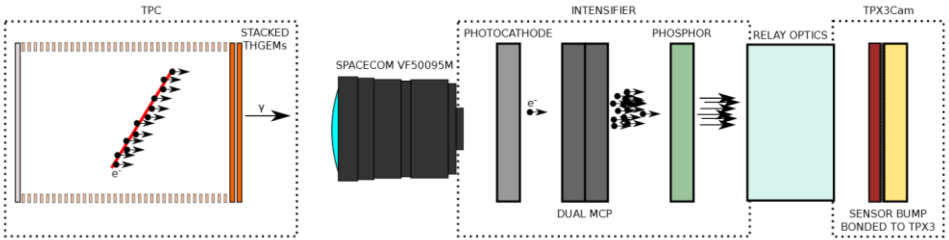
Concept already proven with 4 Timepix chips
See: J Vallerga et al. https://iopscience.iop.org/article/10.1088/1748-0221/9/05/C05055



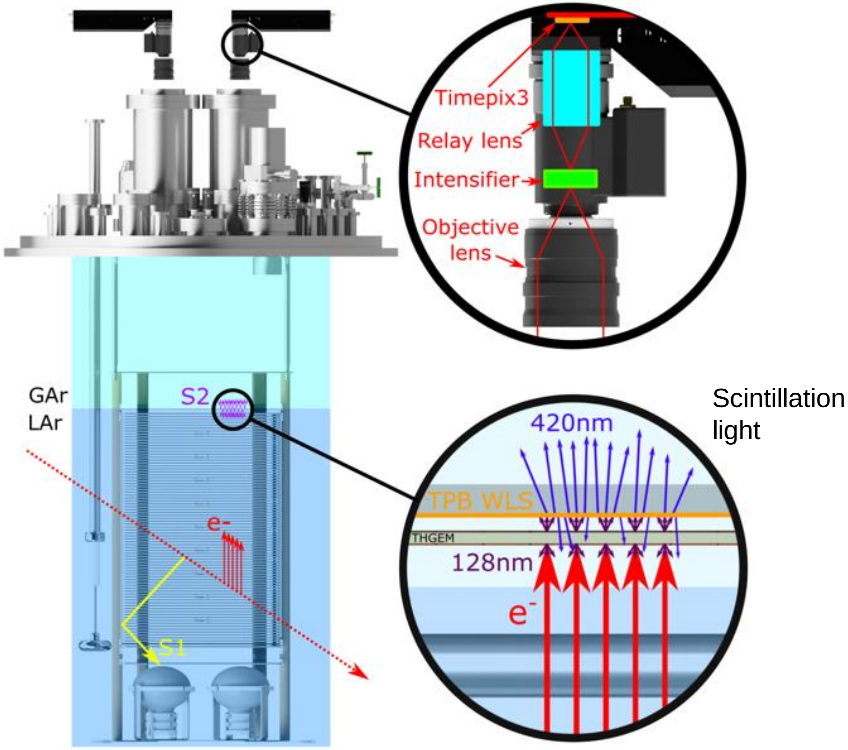


Ongoing effort with Timepix4 started
See: M. Fiorini et al. https://iopscience.iop.org/article/10.1088/1748-0221/13/12/C12005/pdf

Setup TPIX3CAM test

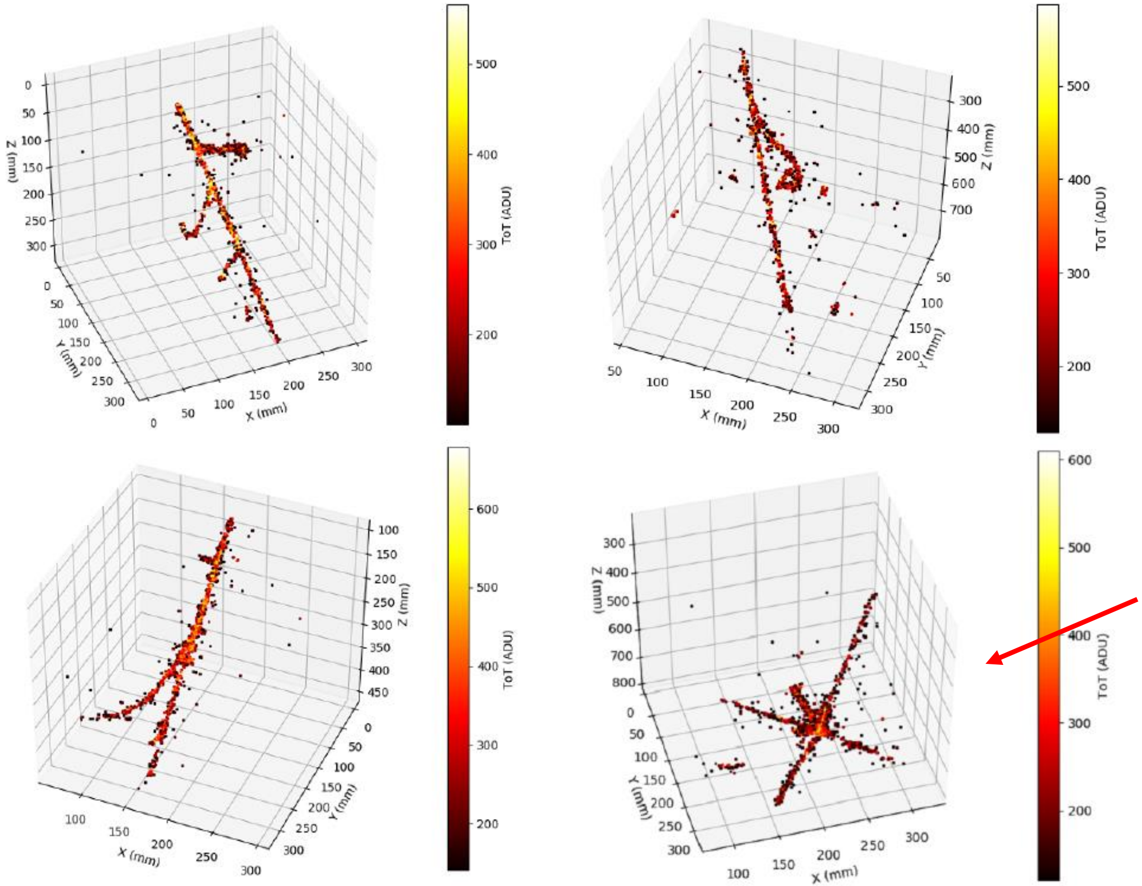


- A TimePix3 camera was mounted on the ARIADNE prototype TPC we have in Liverpool.
- The TPC was filled with 100mb CF_4 and the detection/operation principle is the same like in ARIADNE. The light detection efficiency has been directly compared to the EMCCD camera and found to be very similar.
- 32 cm x 32 cm area read out by a single TPIX3Cam



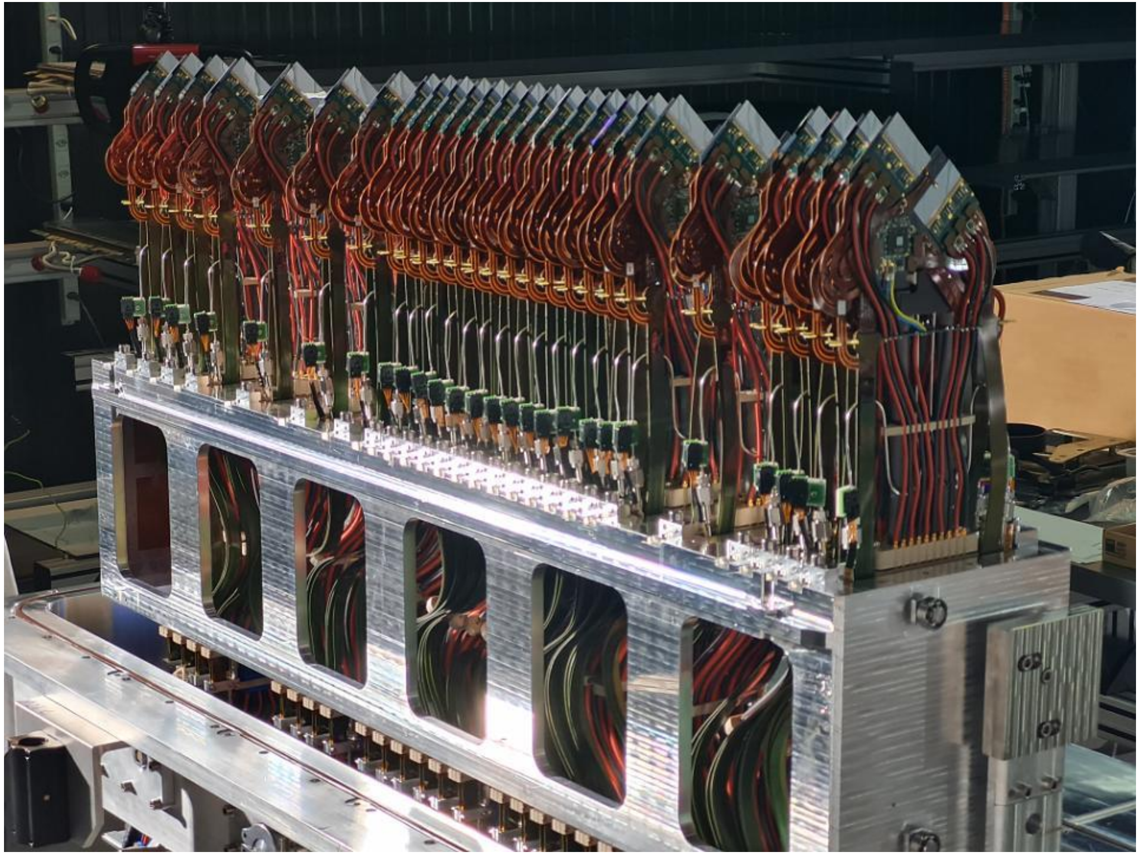
Slide courtesy of K. Mavrokoridis

A selection of cosmic muon events ARIADNE TPIX3Cam



antiproton?

Image of ½ of Velopix tracker for LHCb



April 2022

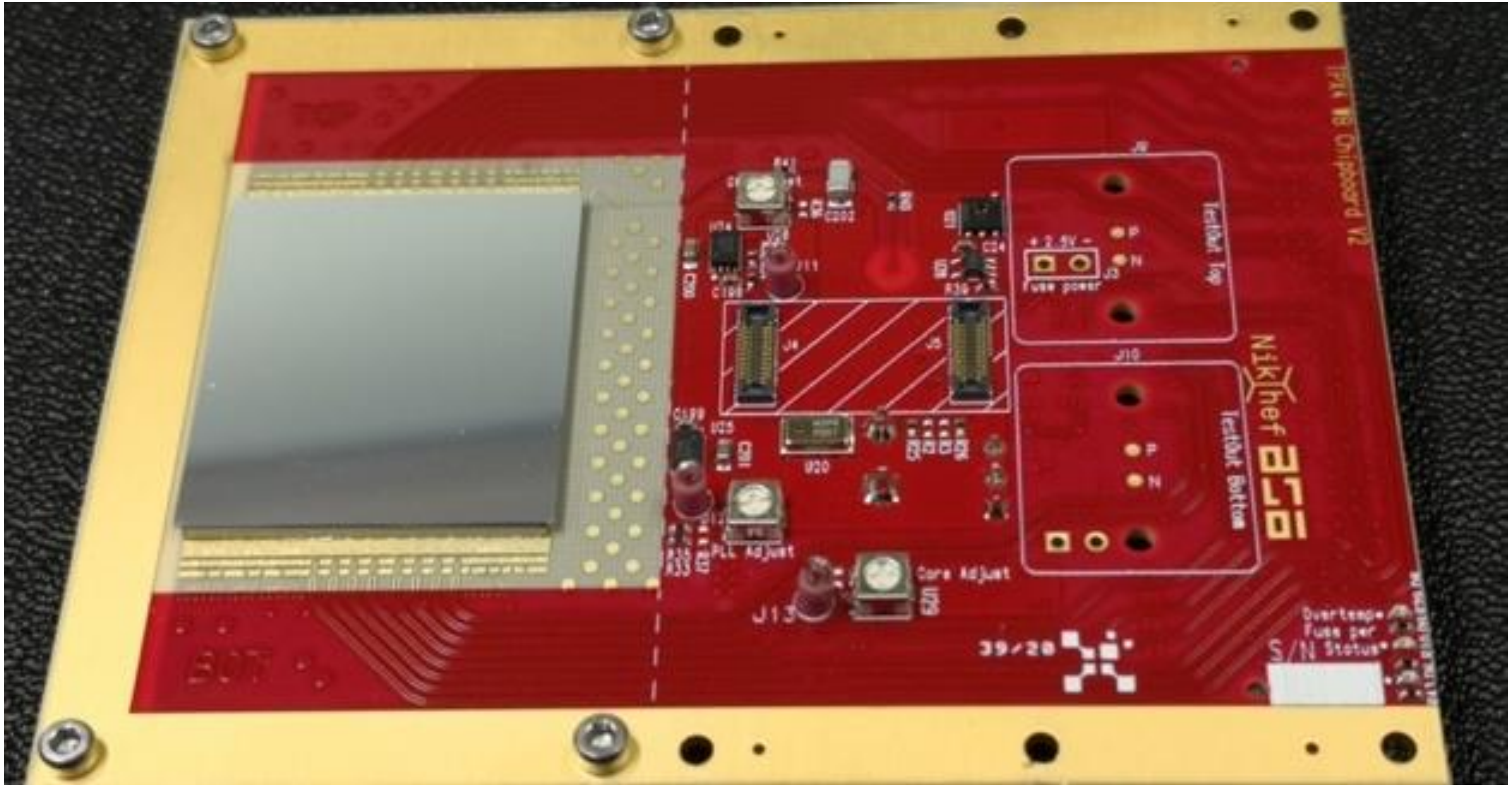
Timepix readout chips - single particle detection

	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

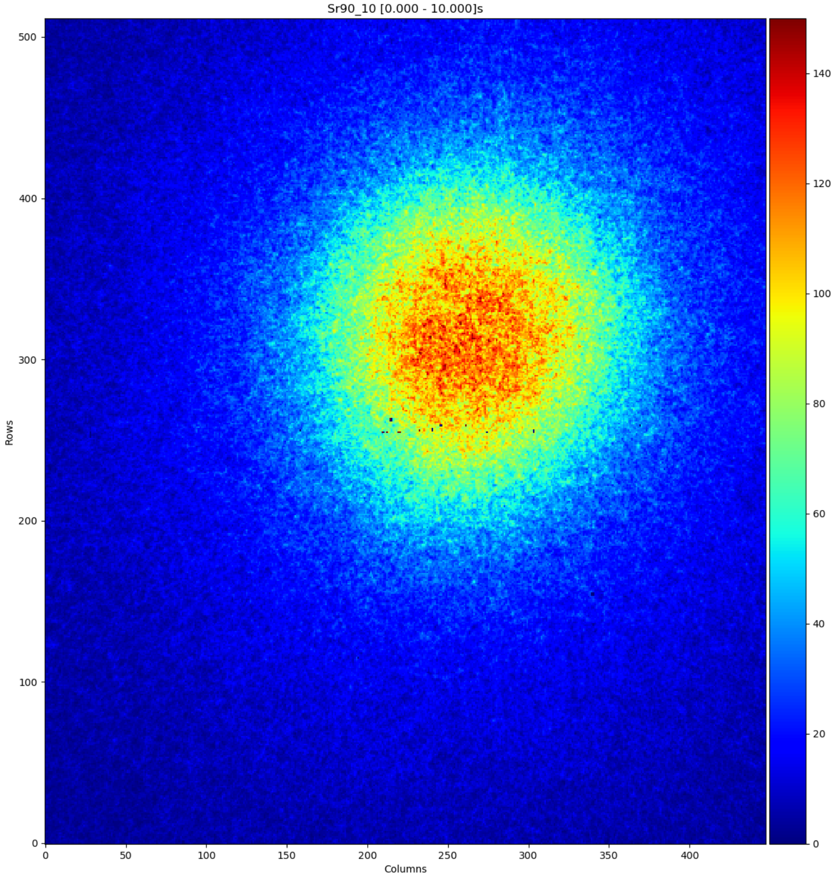
Timepix3 → Timepix4

			Timepix3 (2013)	Timepix4 (2018/19)
Technology			130nm – 8 metal	65nm – 10 metal
Pixel Size			55 x 55 µm	55 x 55 µm
Pixel arrangement			3-side buttable 256 x 256	4-side buttable 512 x 448
Sensitive area			1.98 cm^2	6.94 cm^2
Readout Modes	Data driven (Tracking)	Mode	TOT and TOA	TOT and TOA
		Event Packet	48-bit	64-bit
		Max rate	<80 Mhits/s	<365 $MHz/cm^2/s$
		Max pix rate	1.3kHz/pixel	10.6kHz/pixel
	Frame based (Imaging)	Mode	PC (10-bit) and iTOT (14-bit)	CRW: PC (8 or 16-bit)
		Frame	Zero-suppressed (with pixel addr)	Full Frame (without pixel addr) CRW (8-bit / 16-bit) Up to 44 KHz frame @8b
		Max count rate	82 $Ghits/cm^2/s$	~800 $Ghits/cm^2/s$
TOT energy resolution			< 2KeV	< 1Kev
Time resolution (bin size)			1.56ns	~200ps
Readout bandwidth			≤5.12Gb (8 x SLVS@640 Mbps)	≤163 Gbps (16 x 10.24 Gbps)
Target global minimum threshold			<500 e^-	<500 e^-

Timepix4 assembly (300μm Si sensor)



Timepix4 – works! ☺

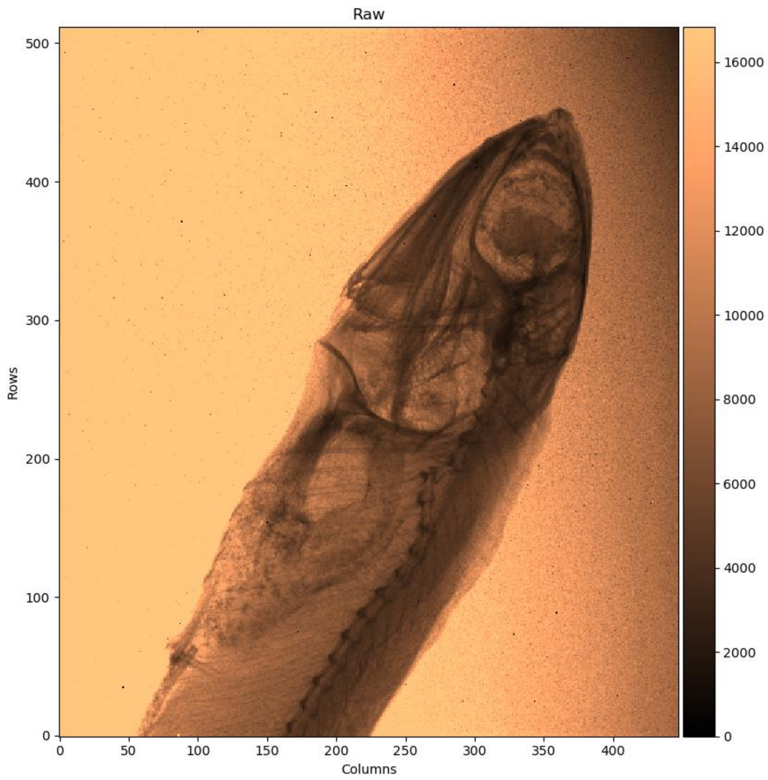


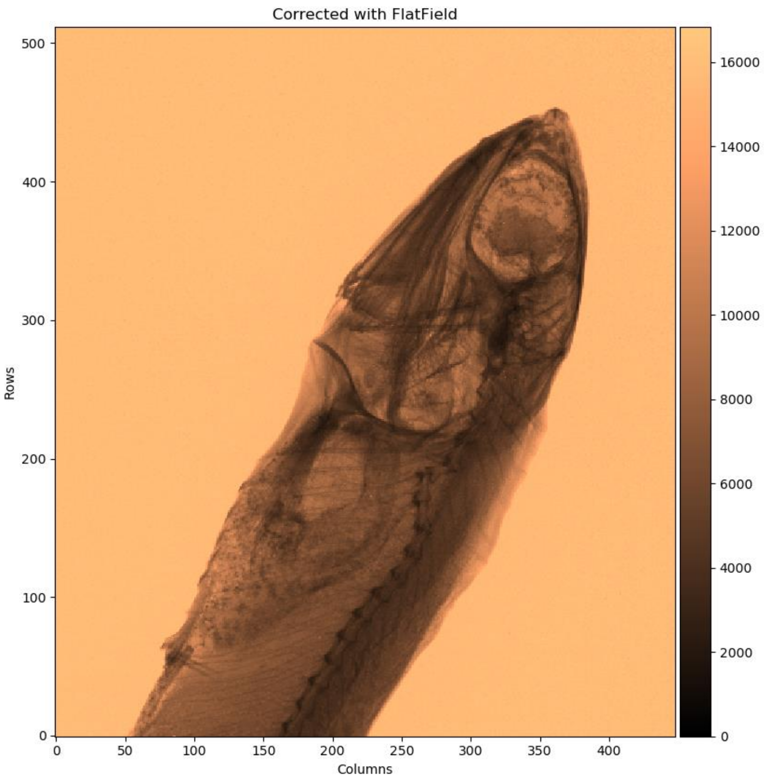
10s exp. ^{90}Sr

Threshold ~ $800e^-$

6.1 M packets @ 5 Gbps

Photon counting image Timepix4





Some words on time stamping

Analog front-end timing optimization

- maximize input charge (sensor with gain) BUT be careful of fill factor and uniformity
- maximize input transconductance BUT watch power density
- minimize C_{in} and C_{out} of prepamp

Time stamp distribution

- Every pixel should be referred to the same precisely distributed clock
- It is basically impossible to distribute high frequency clocks over a large pixel matrix because of power consumption
- Distribution of a single phase provokes power supply bounce
- In Timepix4 the clock edge 'seen' by each pixel is precisely controlled by a column-based DLL but the phase varies from pixel to pixel.

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

- Dosimetry and space weather (ISS and multiple satellites)

- 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 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 initially developed as tracking detectors of LHC and the Medipix Collaborations have taken the technology into many other fields
- Timepix chips are actively detecting background radiation in school classrooms, in airplanes, 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 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. Unique instruments for beam instrumentation have also been developed
- 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 (Timepix4 and Medipix4) 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!