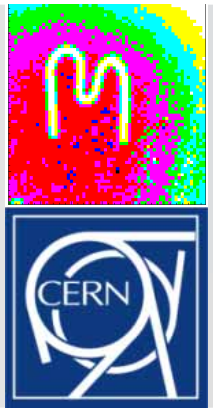
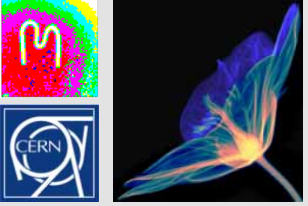


TIMEPIX AND MEDIPIX DETECTORS AND THEIR APPLICATIONS

M. Campbell[1], J. Alozy, R. Ballabriga, F. Bandi, P. Christodoulou, A. Dorda, S. Emiliani, E.H.M. Heijne, T. Hofmann, X. Llopart, M. Piller, V. Sriskaran, and L. Tlustos

CERN,
EP Department
1211 Geneva 23
Switzerland

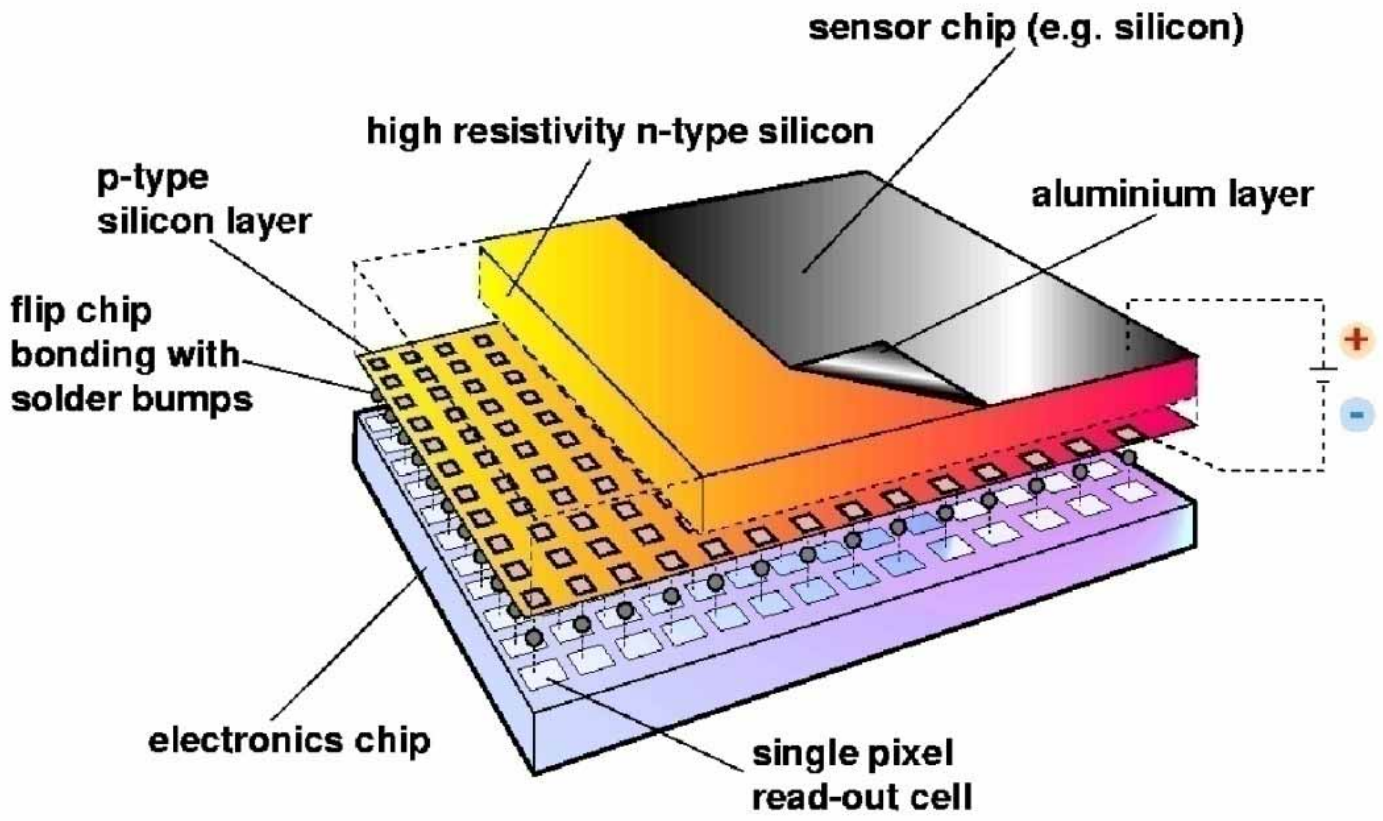
[1] Honorary Professor at Glasgow University

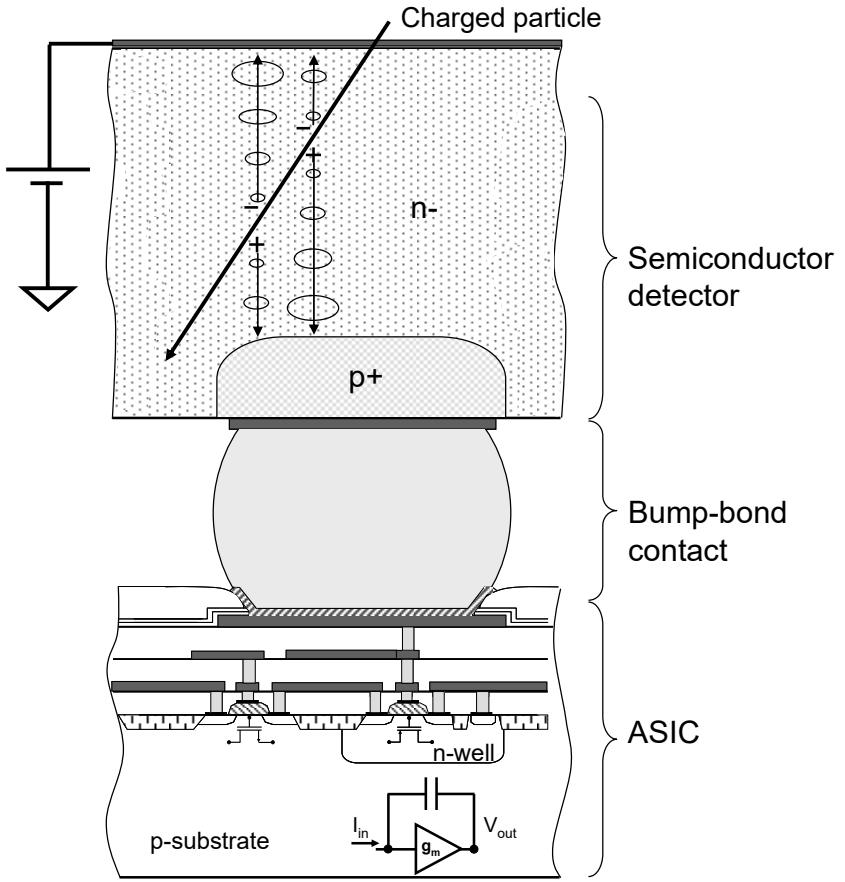


Outline

- Hybrid pixel detectors @ the LHC detectors
- Introduction to the Medipix/Timepix family
- The Timepix chip and some applications
- The Medipix3 chip and spectroscopic X-ray medical imaging
- The Timepix3 chip and the BGI beam monitoring system
- Status of Timepix4
- Conclusions

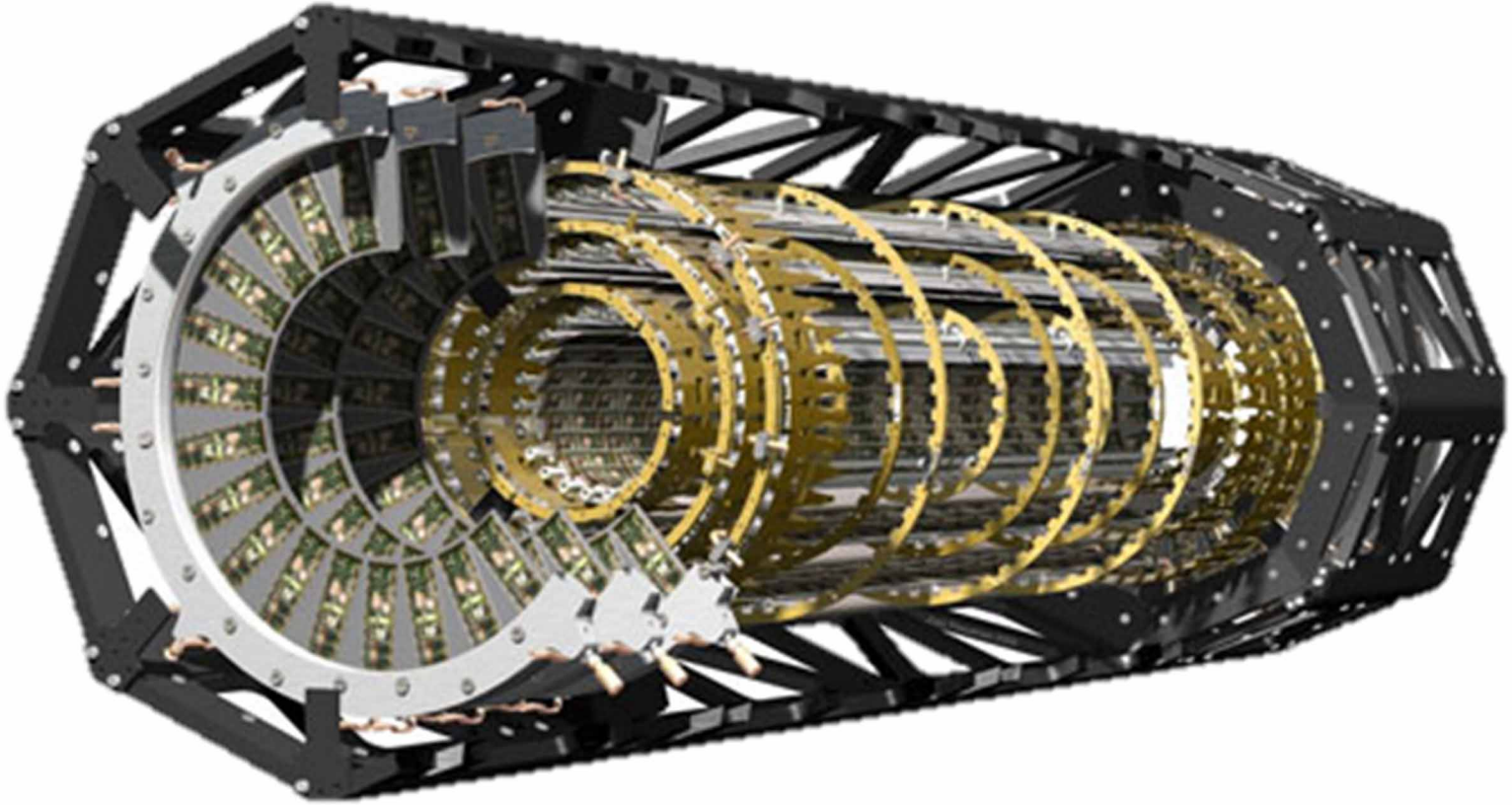
Hybrid Silicon Pixel Detectors





Standard CMOS can be used allowing on-pixel signal processing
Sensor material can be changed (Si, GaAs, CdTe..)
The close proximity of sensor and electronics permits noise hit free operation

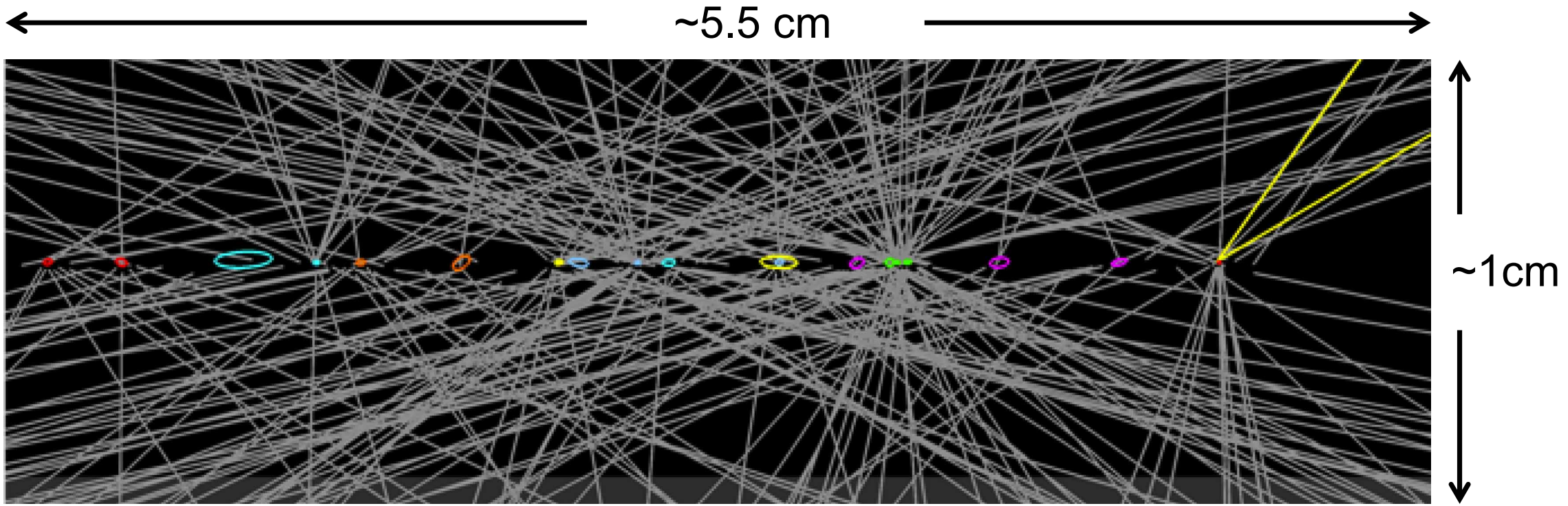
ATLAS Pixel detector – LHC Run 1



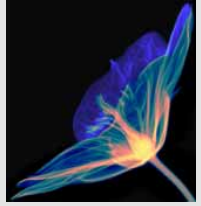
- 3 barrel layers at ~5, 9 and 12 cm from IP
- 3 disks on each side 9 ≤ r ≤ 15 cm
- Same module layout used everywhere
- Module size: 62.4 mm long X 21.4 mm wide
- Module read out by 16 FEI3 chips, each serving an array of 18 by 160 pixels
- An area of ~1.7 m2 for ~80M pixels

Module assembly for ATLAS pixel barrel

ATLAS high pile-up event – one 25ns 'frame'



About 10^{15} events had been accumulated before the Higgs boson discovery was announced, and only some 1000's were identified as Higgs boson decays

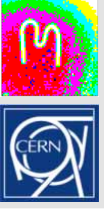


Hybrid pixel detectors

- Developed initially for LHC
- 2 large scale vertex detector systems (ATLAS, CMS) operating smoothly
- VELOpix (based on Timepix3) installed and running
- Upgrades for ATLAS and CMS (LS3) are ongoing

- In the Medipix2 and Medipix3 Collaborations we have taken the technology into many new fields

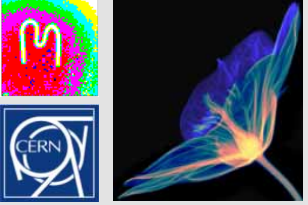
- This talk will now focus on the readout chips and describes some applications.



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	Chinese Spallation Neutron Source, Dongguan City,China
	University of Glasgow, Scotland, UK	Brazilian Light Source, Campinas, Brazil
	University of Houston, USA	
	University of Leiden, The Netherlands	
	Technical University of Munich, Germany	
	VTT Information Technology, Espoo, Finland	

Acknowledgements – Commercial and R and D 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			
MARS Bio Imaging, New Zealand				X			
PITEC, Brazil				X			X
Quantum Detectors, UK				X	X		X
Sydor Technologies, USA							X
Technologies de France, France					X		
X-ray Imaging Europe, Germany	X	X	X				
X-spectrum, Germany				X			X



The Medipix and Timepix ASICs - Timeline

Year	2003	2006	2013	2014	2017	2018	2020	2023
ASIC	Medipix2	Timepix	Medipix3	Timepix3		Timepix2	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
- Large interest inside and outside of CERN

The Medipix and Timepix ASICs - Timeline

1st large high resolution photon counting chip

Year	2003	2006	2013	2014	2017	2018	2020	2023
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The Medipix and Timepix ASICs - Timeline

1st large high resolution photon counting chip

Add possibility to measure time or energy

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The Medipix and Timepix ASICs - Timeline

1st chip with multiple energy bins

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The Medipix and Timepix ASICs - Timeline

1st chip with multiple energy bins

Data driven readout (timestamp 1.6ns)

Year	2003	2006	2013	2014	2017	2018	2020	2023
ASIC	Medipix2	Timepix	Medipix3	Timepix3		Timepix2	Timepix4	Medipix4

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The Medipix and Timepix ASICs - Timeline

Tileable on 4 sides (timestamp 200ps)

Year	2003	2006	2013	2014	2017	2018	2020	2023
ASIC	Medipix2	Timepix	Medipix3	Timepix3		Timepix2	Timepix4	Medipix4

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- Timepix chips are more oriented towards single particle detection
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The Medipix and Timepix ASICs - Timeline

Tileable on 4 sides (timestamp 200ps)

Tileable on 4 sides (8 energy bins)

Year	2003	2006	2013	2014	2017	2018	2020	2023
ASIC	Medipix2	Timepix	Medipix3	Timepix3		Timepix2	Timepix4	Medipix4

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The Medipix and Timepix ASICs - Timeline

Year	2003	2006	2013	2014	2017	2018	2020	2023	2025?
ASIC	Medipix2	Timepix	Medipix3	Timepix3		Timepix2	Timepix4	Medipix4	
LHCb					VELOpix				VELOpix2

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The Medipix and Timepix ASICs - Timeline

Add possibility to measure time or energy

Year	2003	2006	2013	2014	2017	2018	2020	2023	2025?
ASIC	Medipix2	Timepix	Medipix3	Timepix3		Timepix2	Timepix4	Medipix4	
LHCb					VELOpix				VELOpix2

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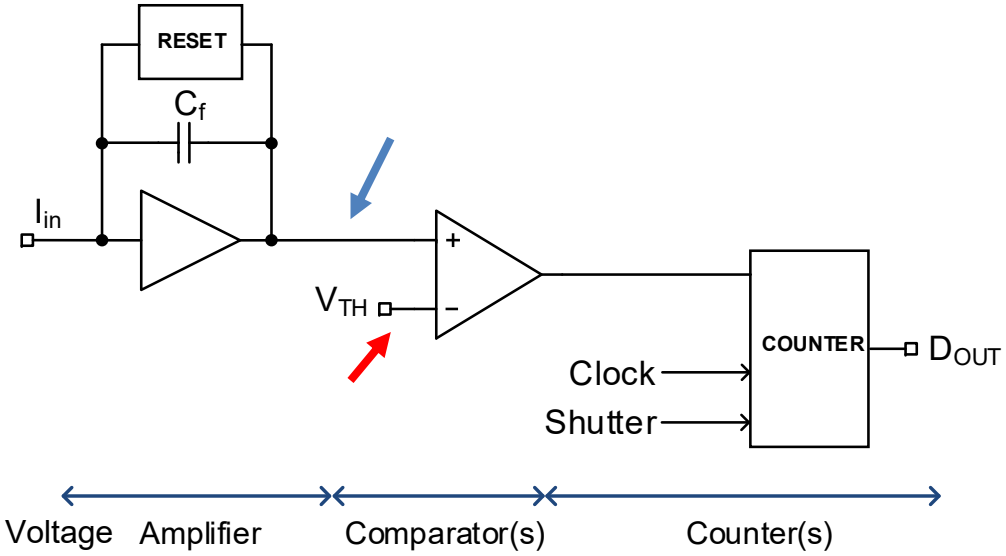
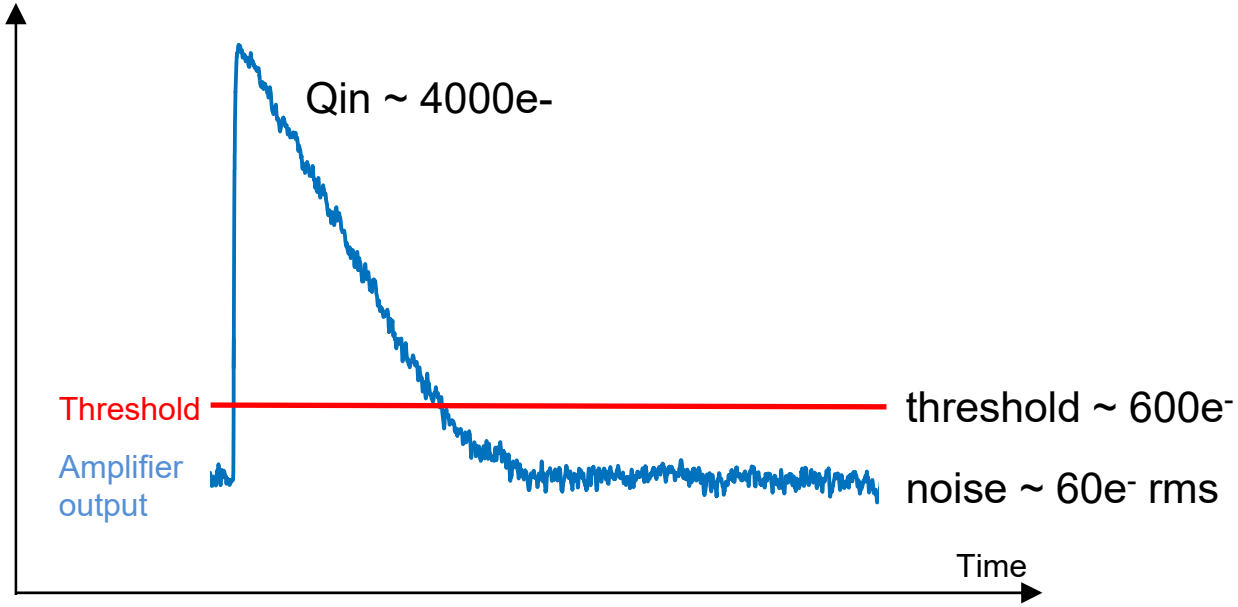
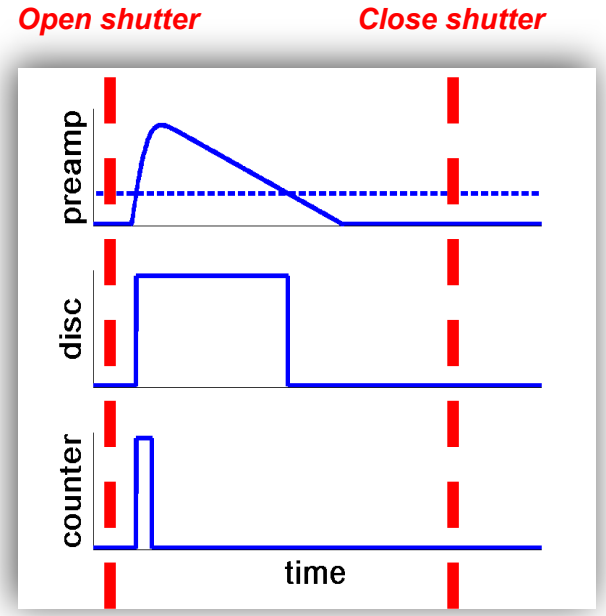
Hybrid Pixel Detector – Counting Electronics



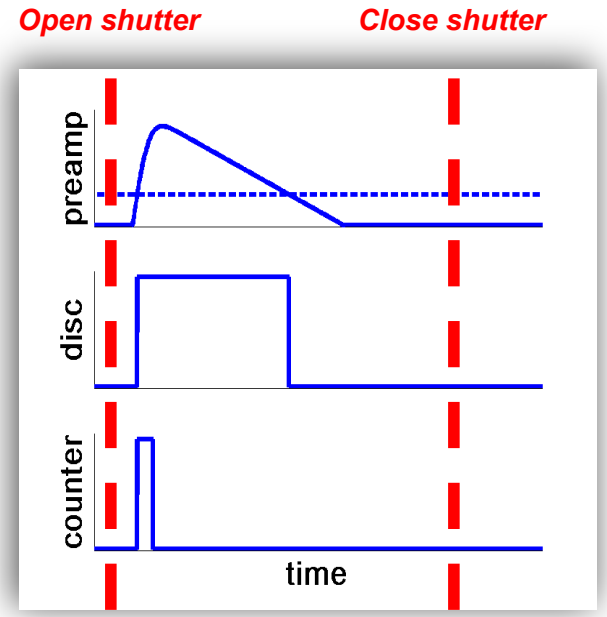




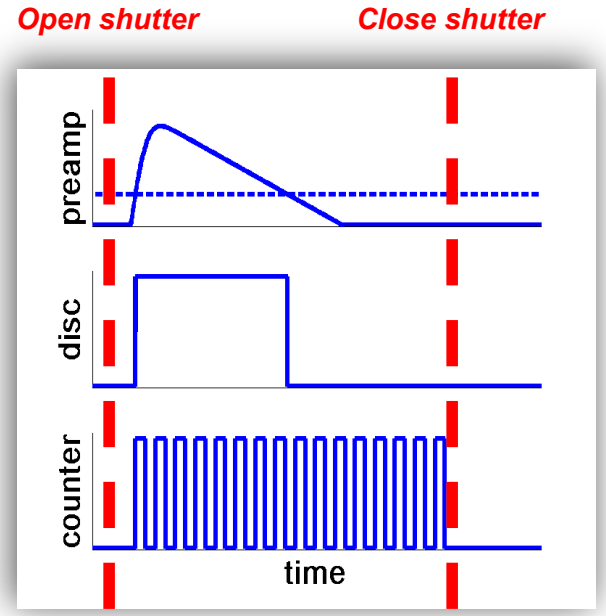
→ Noise hit free imaging

Timepix Pixel Operation Modes

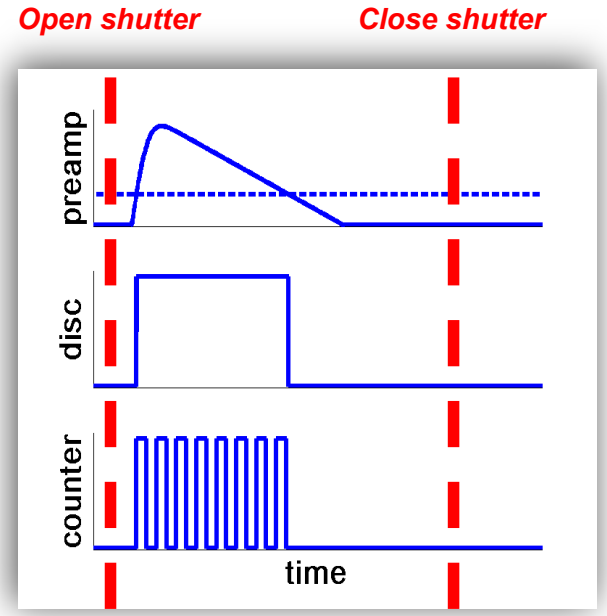
- Particle counting



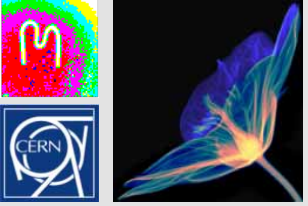
- Arrival Time*



- Time over threshold

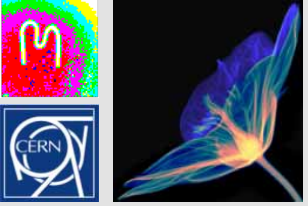


* Implemented at the request of the EUDet Collaboration



Timepix Specs

CMOS node	250nm
Pixel Array	256 x 256
Pixel pitch	55μm
Charge collection	e^-, h^+
Pixel functionality	PC (Particle Counting), TOT (Energy) or TOA (Arrival time)
Preamp Gain	~16.5mV/ke^-
ENC	~100e^-
FE Linearity	Up to 50ke^-
TOT linearity (resolution)	Up to 200ke^- (<5%)
TOA resolution	Up to 10ns (@ 100 MHz)
Time-walk	<50ns
Minimum detectable charge	~700e^- → 2.5 KeV (Si Sensor)
Counter Depth/Overflow	14-bits(11810)/Yes
Max Analog power (2.2V)	6.5μW/pix 190mA/chip
Static Digital Power (2.2V)	~500mW@100MHz/chip
Readout (@ 100 MHz)	Serial readout → 9.17 ms 32-bit Parallel readout → 287 μs



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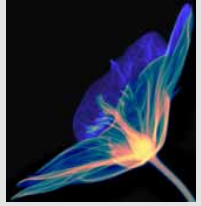

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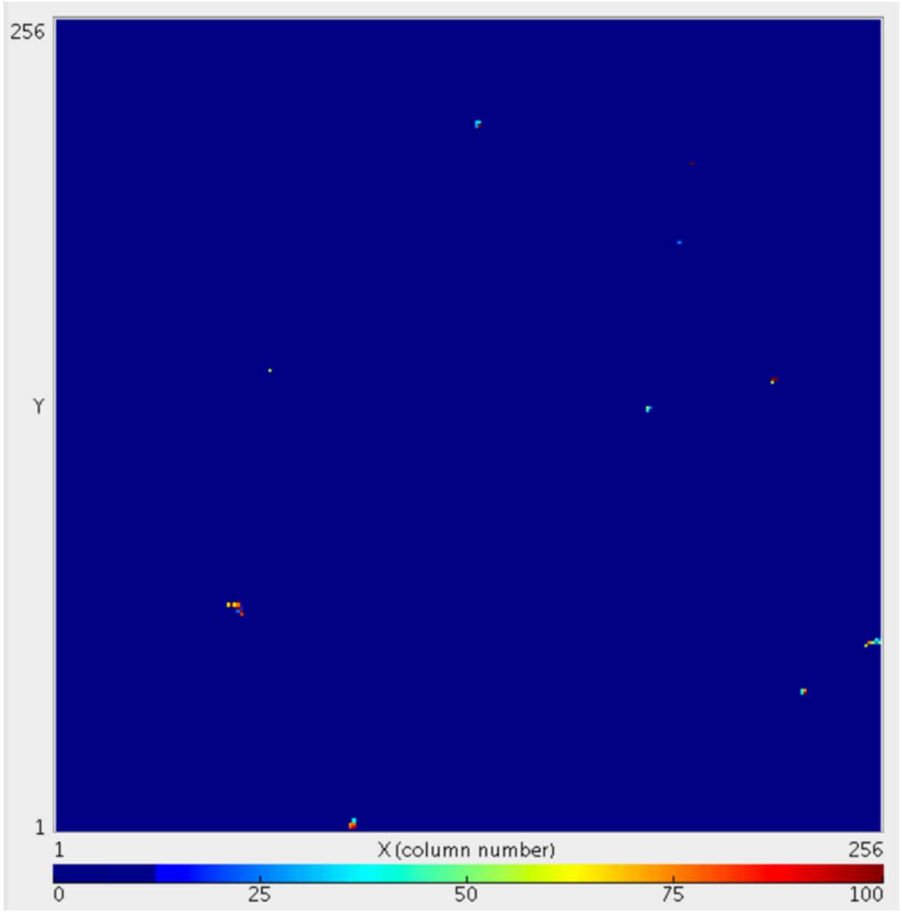
Timepix miniaturised readout

IEAP/CTU, Prague

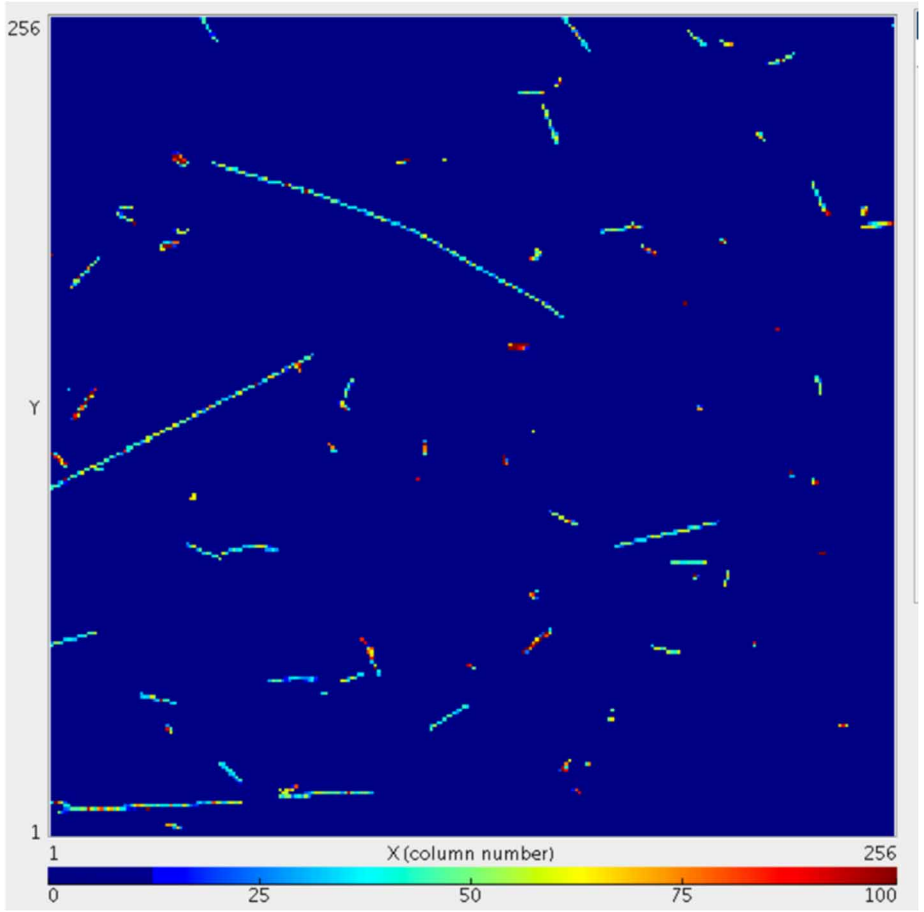
Timepix for schools

Advacam s.r.o., Prague

Timepix chip – 60s exposures



Near sea level



34 000 feet

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.

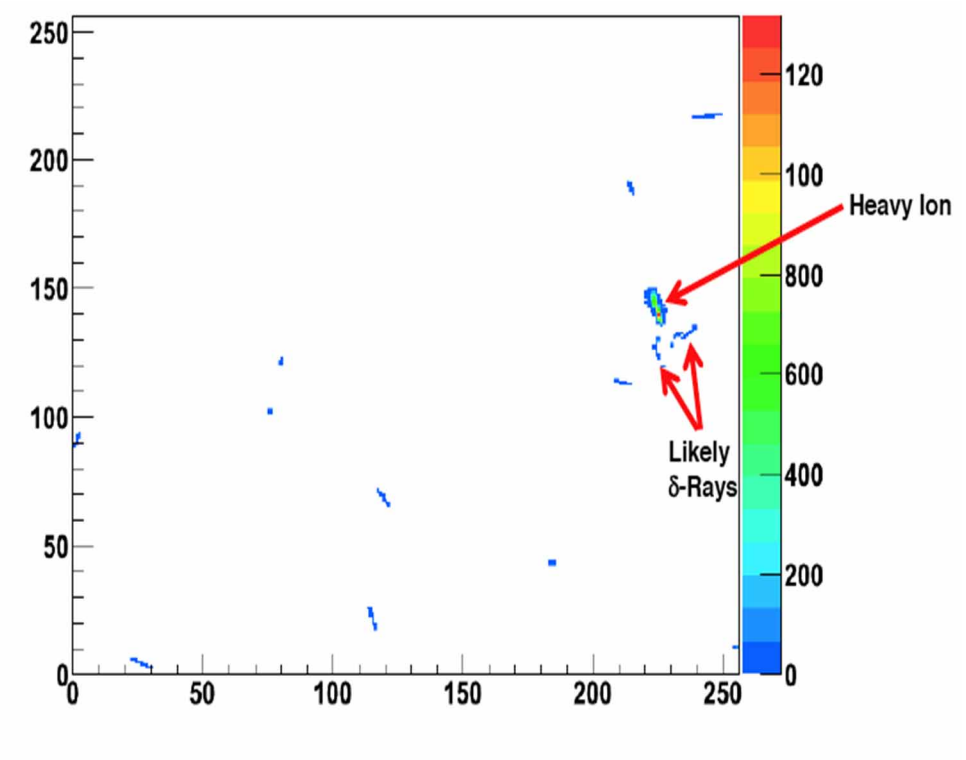
29 MARCH, 2021 | By Rafael Ballabriga & Antoine Le Gall

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.

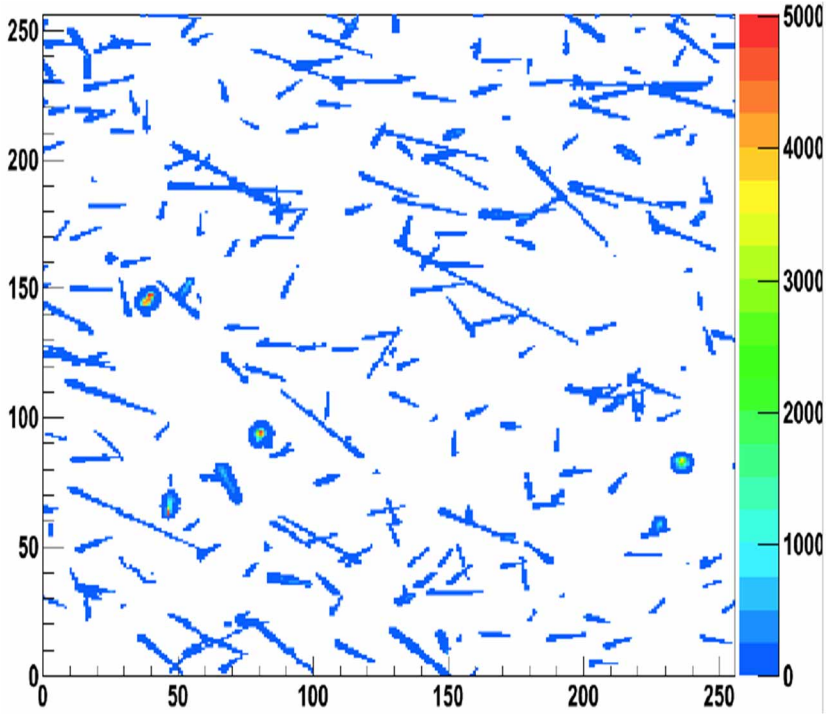
Prize-winning initiative in Spain

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



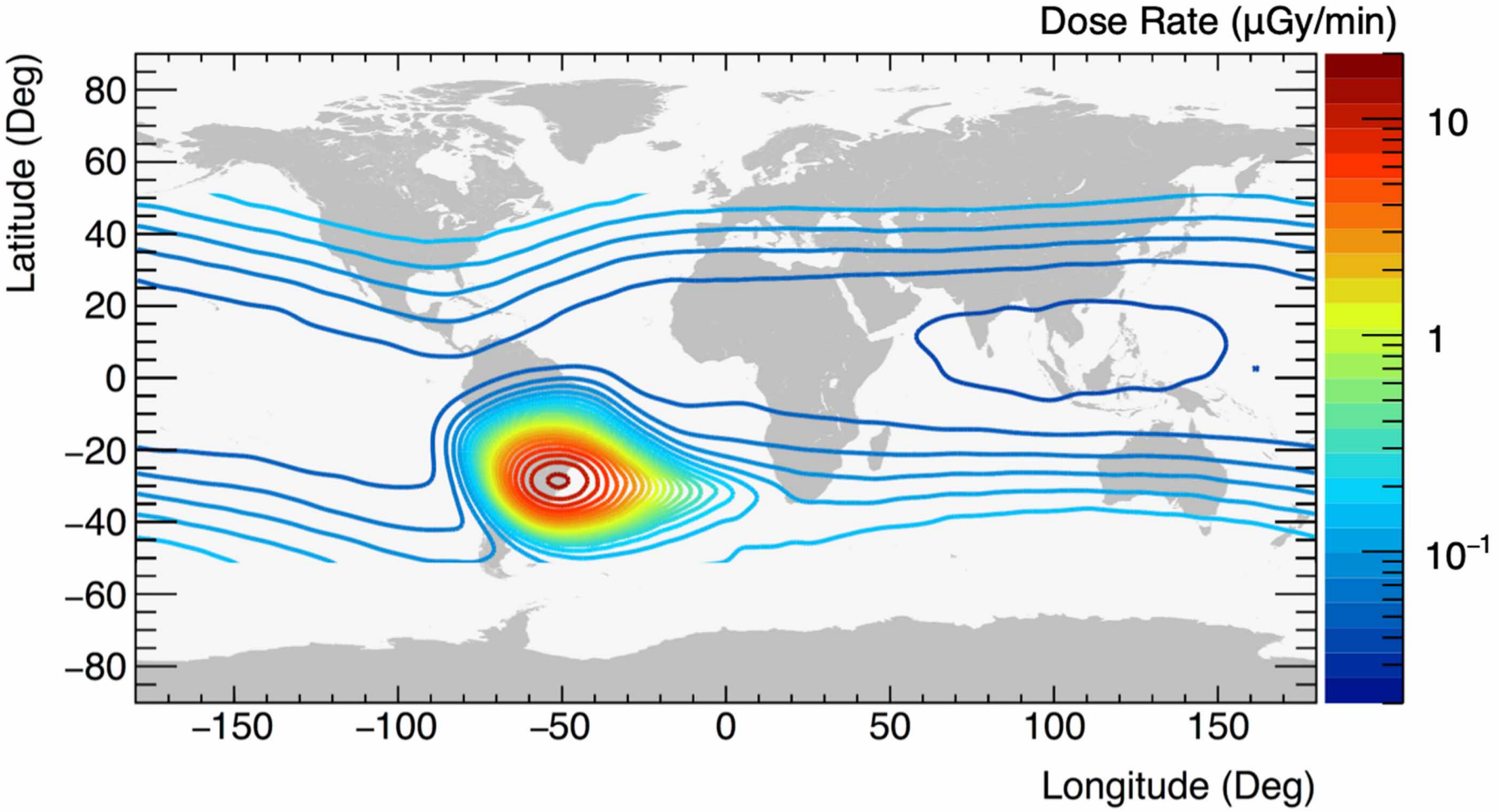
South China Sea



South Atlantic Anomaly

University of Houston, IEAP Prague, NASA

REM Dose Rate Data (μG/min)

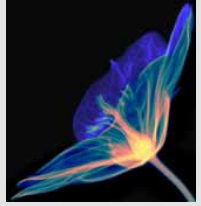


Timepix dose rates measured in 2014 on ISS

University of Houston, IEAP Prague, NASA

Timepix on Artemis 1

- Artemis 1 launch Wednesday Nov 16 2022
- Carrying 4 Timepix detectors from the Medipix2 collaboration at CERN on board to measure radiation
- Part of a larger program at NASA using Timepix based instruments for radiation measurement
- 3 devices part of HERA radiation dose monitoring hardware. Successful operation from just after launch to just before splashdown
- 4th device no board Biosentinal cubesat (now at >> 2Mkm from earth



Timepix-based flight hardware

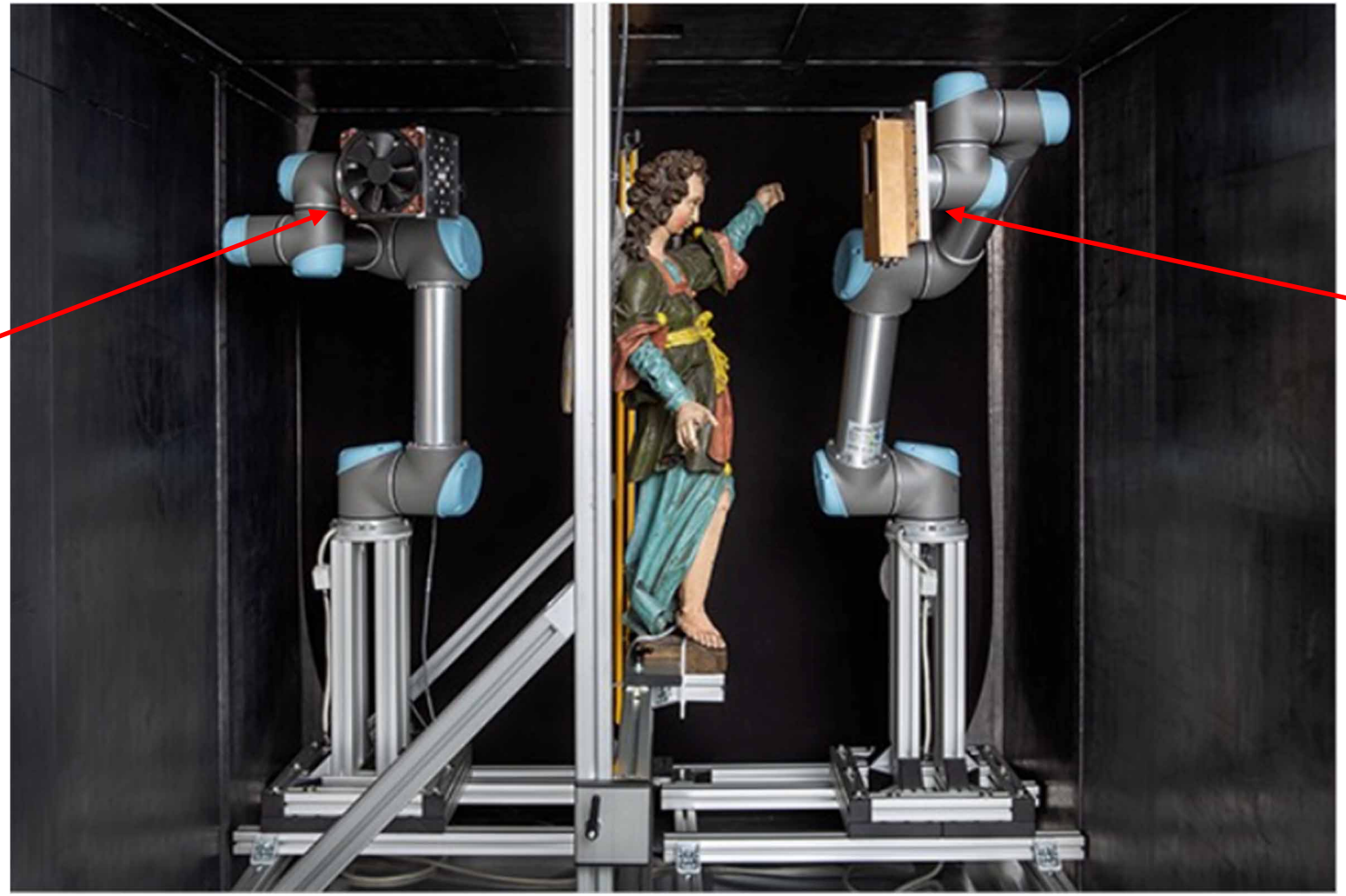
Name	Date Flown	Mission	Location	Objective	Vehicle	Number TPX
REM	2012	ISS	LEO	Demo	ISS	5
BIRD	2014	Orion EFT-1	LEO/MEO	Demo/Science	Orion	2
REM2	2018	ISS	LEO	Ops	ISS	7
MPT	2017	ISS	LEO	Science	ISS	2
Biosentinel	2020	ISS	LEO	Science	ISS	1
ISS-HERA	2018	ISS	LEO	Demo	ISS	3
AHOSS	2020	ISS	LEO	Demo/Ops	ISS	3
LETS(1)	2023	Astrobotic 1	Lunar Surface	Science	Peregrine	1
LETS(2)	2024/5	Berensheet 2*	Lunar Surface	Science	Berensheet 2	1
HERA	2022	Artemis 1	Lunar Orbit	Ops	Orion	3
Biosentinel	2022	Artemis 1	Solar Orbit	Science	Cubesat	1
HERA	2023	Polaris Dawn	MEO	Science	Crew Dragon	1
HERA	2024	Artemis 2	Lunar Orbit	Ops	Orion	6
HERA	2025	Artemis 3	Lunar Orbit	Ops	Orion	6
ARES	2025	Artemis 3	Lunar Surface	Ops	Starship	>=1
LEIA	~~2024	CLPS Lander	Lunar Surface	Science	TBS Lander	1
ARES	2026	Artemis	Lunar Orbit	Ops	Lunar Gateway	2

***Evaluating mission possibility**

7 missions flown, 4 missions next six months, 6 missions manifested, > 23 Timepix in Space to date

S. George (NASA) 10 Years of Timepix in Space – How CERN Detectors are supporting Human Spaceflight https://indico.cern.ch/event/1218130/

Combined with robots



Micro-focus X-ray soucre

Medipix3/Timepix spectroscopic imaging camera

Source InsightART (insightart.eu)

Signed

Vincent van Gogh

La Crau with Montmajour in the backgroud

~1888

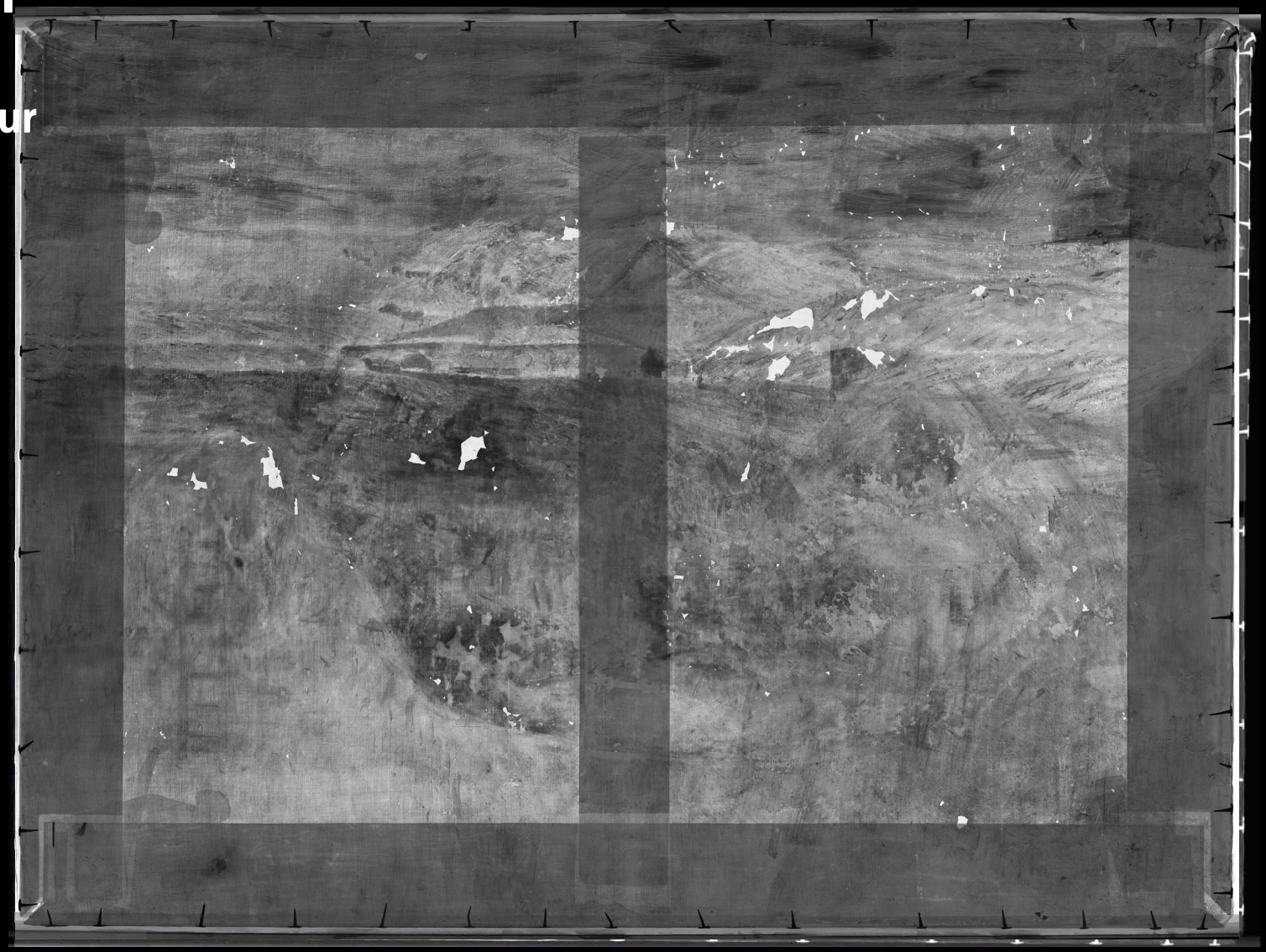
INSIGHTART

Signed

Vincent van Gogh

La Crau with Montmajour in the backgroud

~1888



INSIGHTART

Signed

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La Crau with Montmajour in the backgroud

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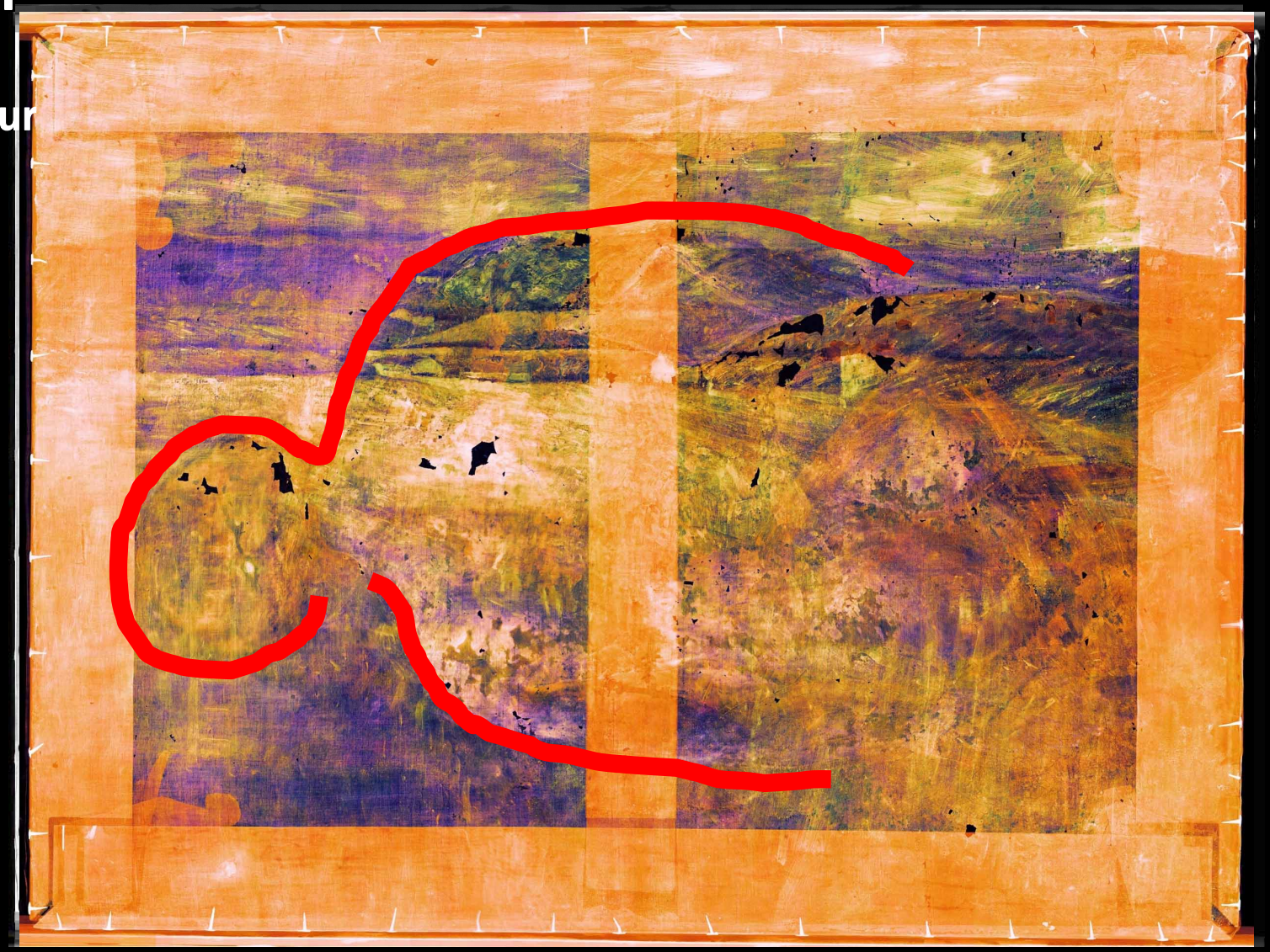
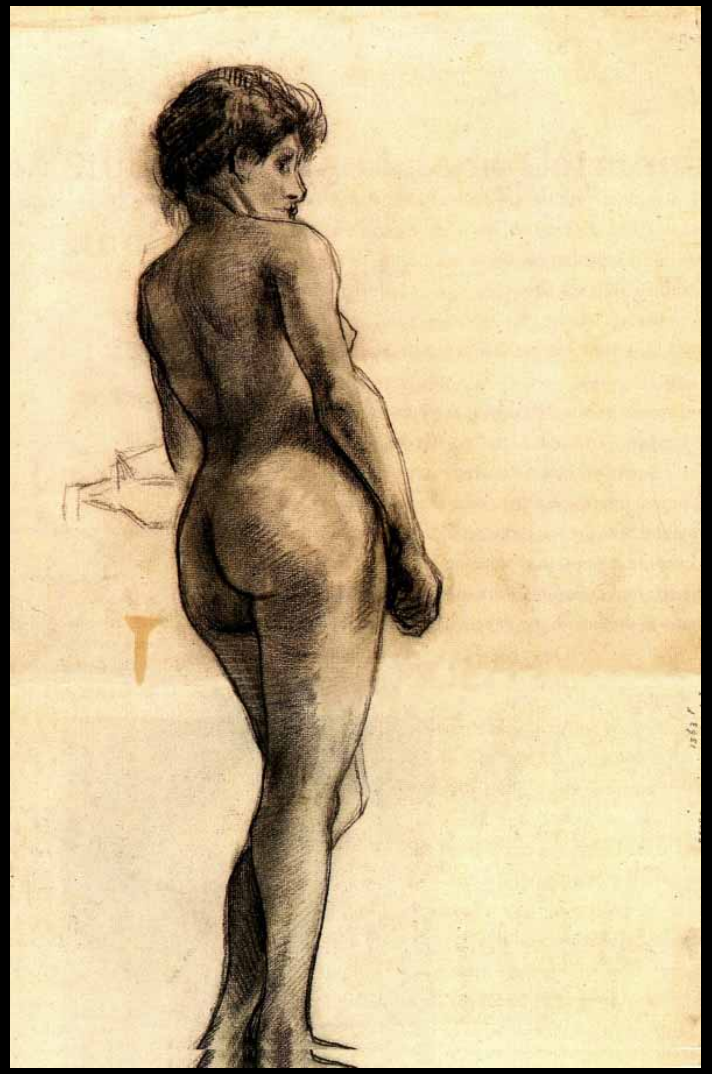


INSIGHTART



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1st chip with multiple energy bins

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LHCb					VELOpix				VELOpix2

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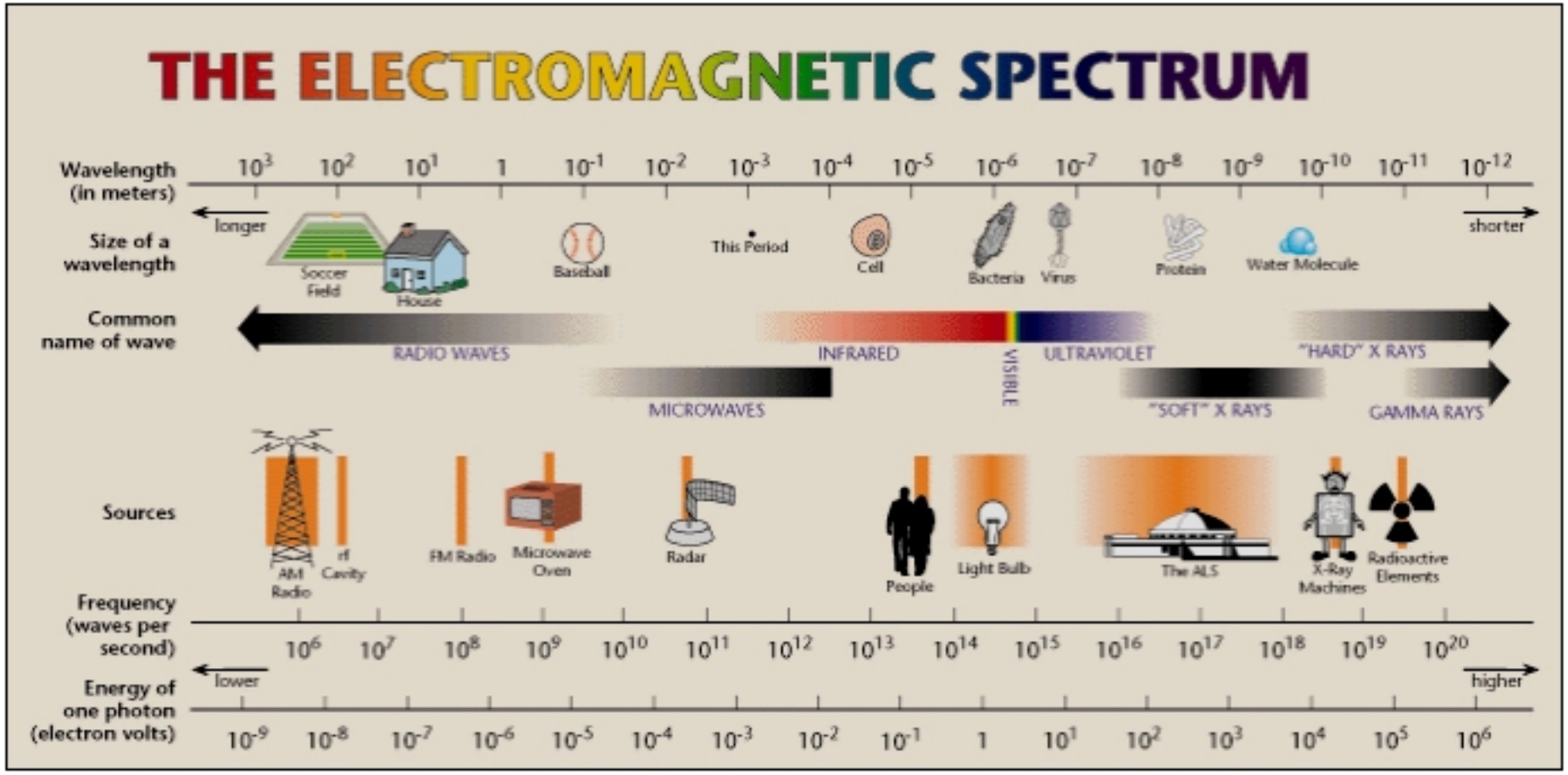
- Timepix chips are more oriented towards single particle detection
- Large interest inside and outside of CERN

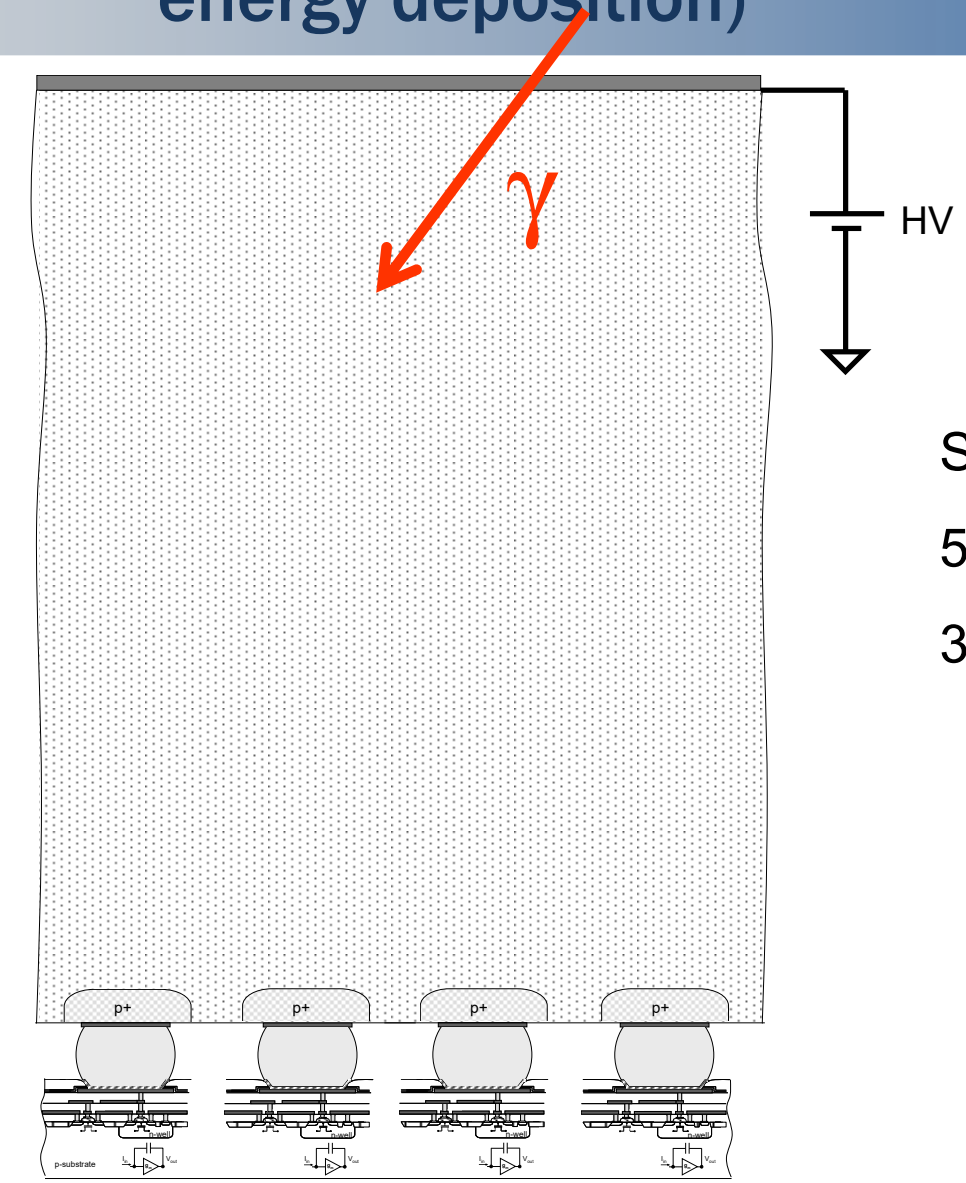
‘Colour’ X-ray imaging



Medipix3 Motivation

- Access to spectroscopic information opens a new dimension in X-ray imaging
- Retaining the energy information in X-ray radiography extracts more information from a given deposited dose
- Contrast agents (with metal nanoparticles) attached to bio markers could open the field of functional imaging using X-rays
- But several technical challenged remain:
  - Charges sharing in the sensor reduces (or destroys) spectral fidelity
  - High photon fluxes prohibit the use of data driven architectures

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

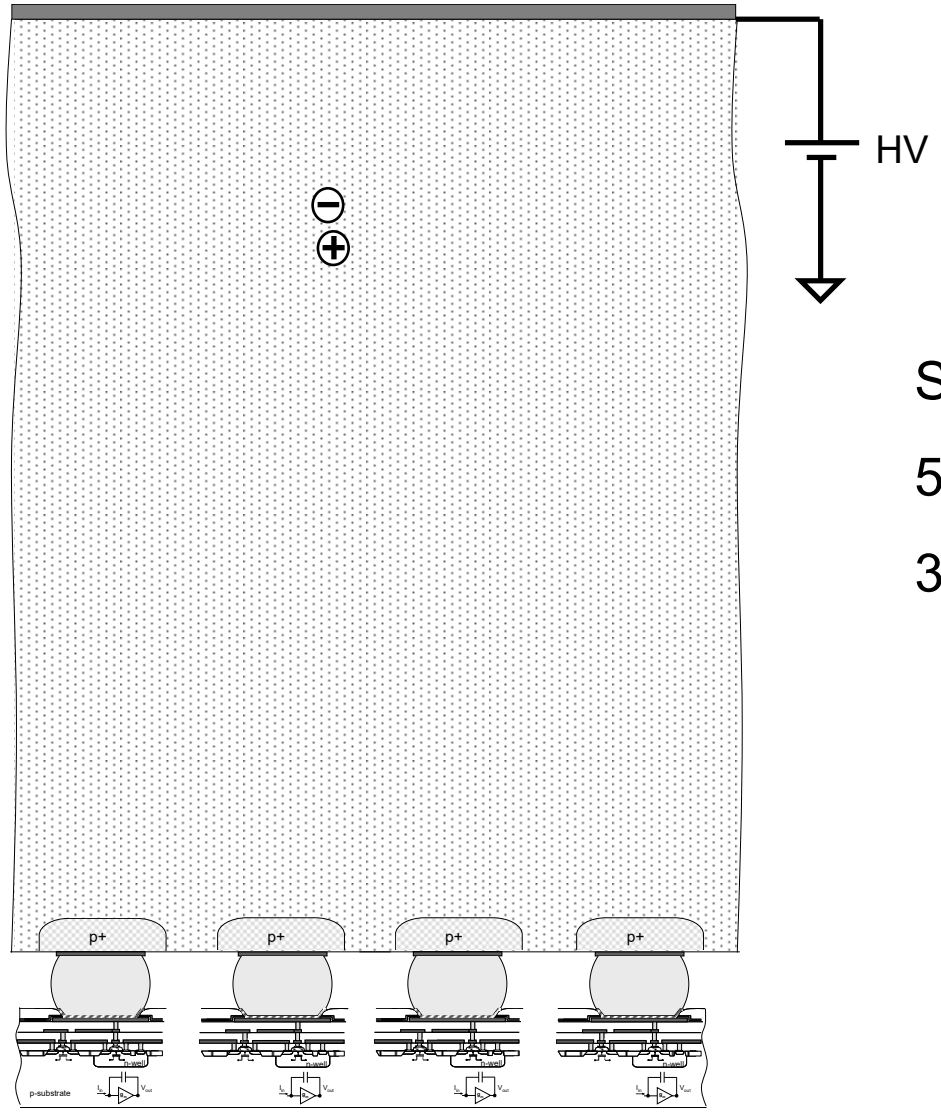


Sensor dimensions to scale:

55µm pixel pitch

300µm thick sensor

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



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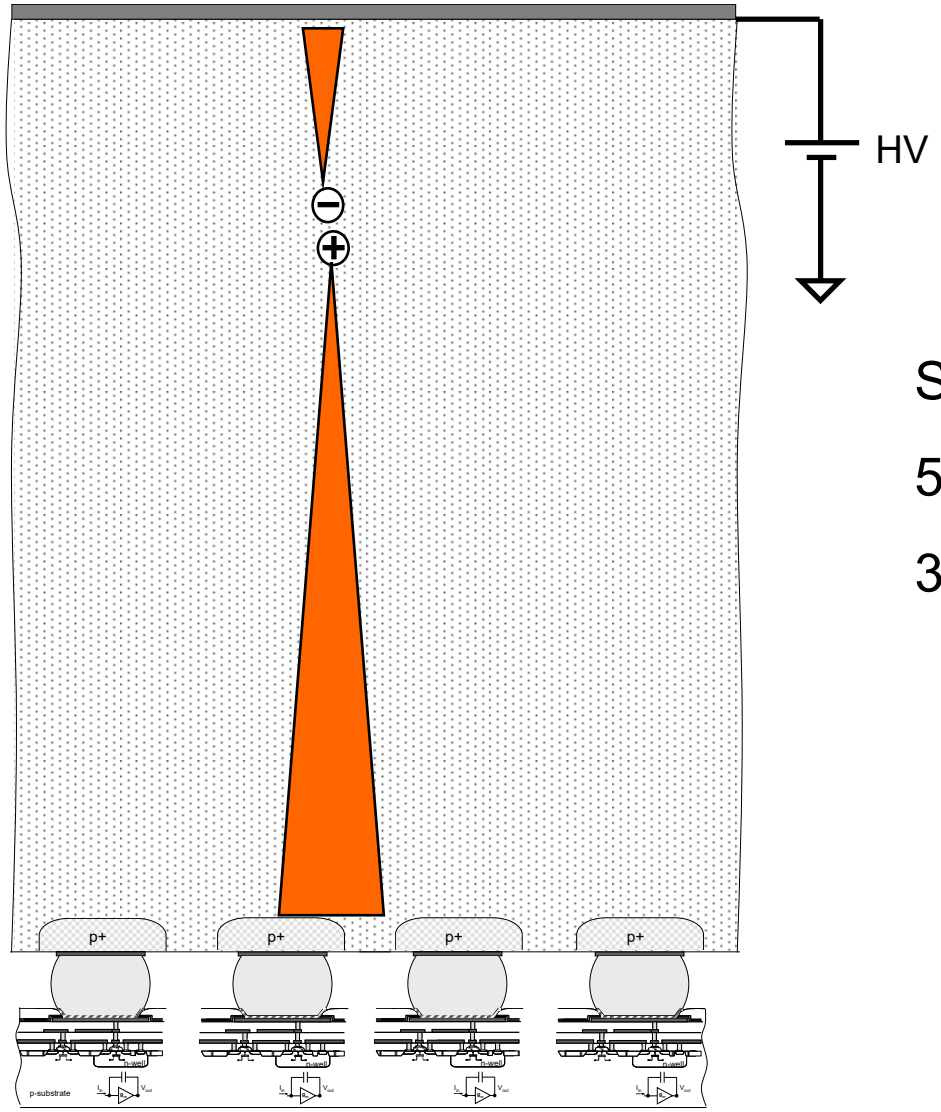
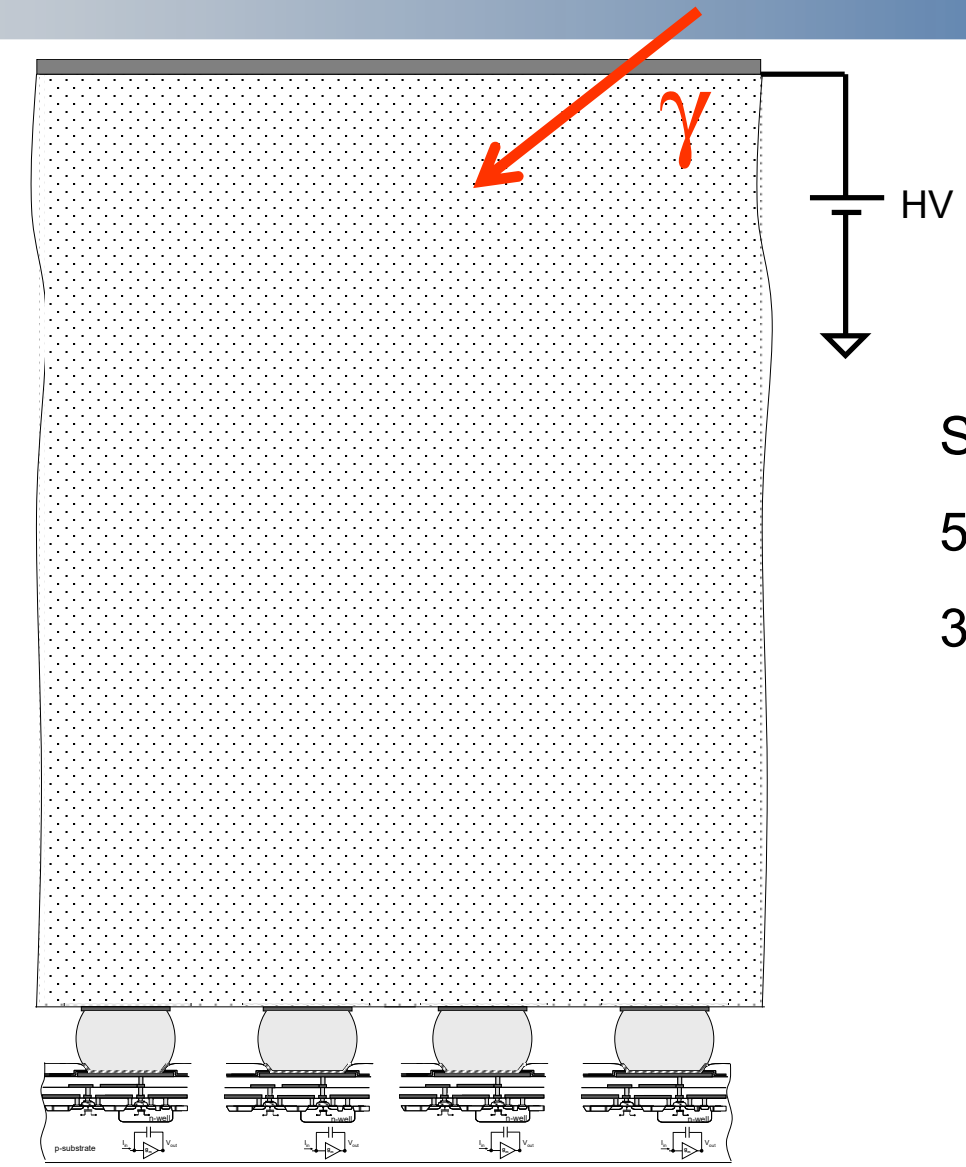


Sensor dimensions to scale:

55µm pixel pitch

300µm thick sensor

Fluorescence in high-Z materials

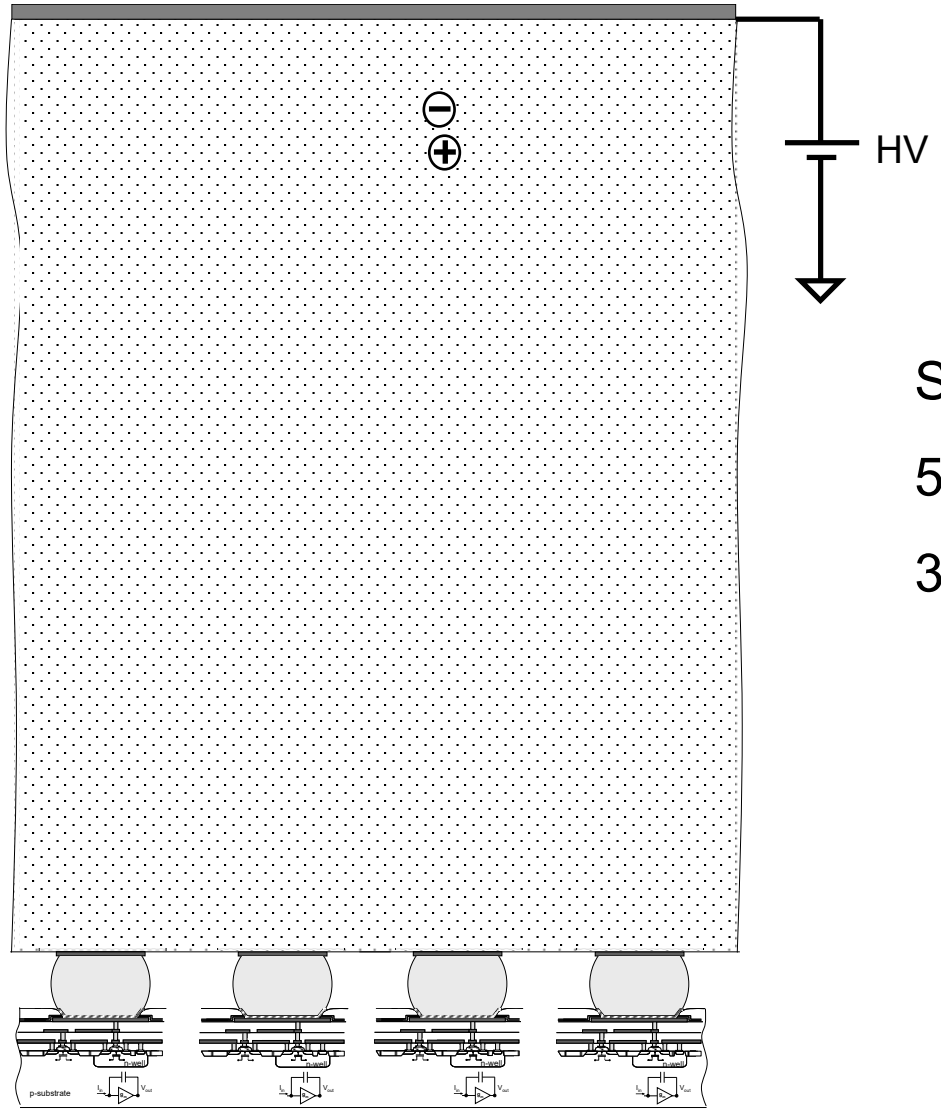


Sensor dimensions to scale:

55µm pixel pitch

300µm thick sensor

Fluorescence in high-Z materials



Sensor dimensions to scale:

55µm pixel pitch

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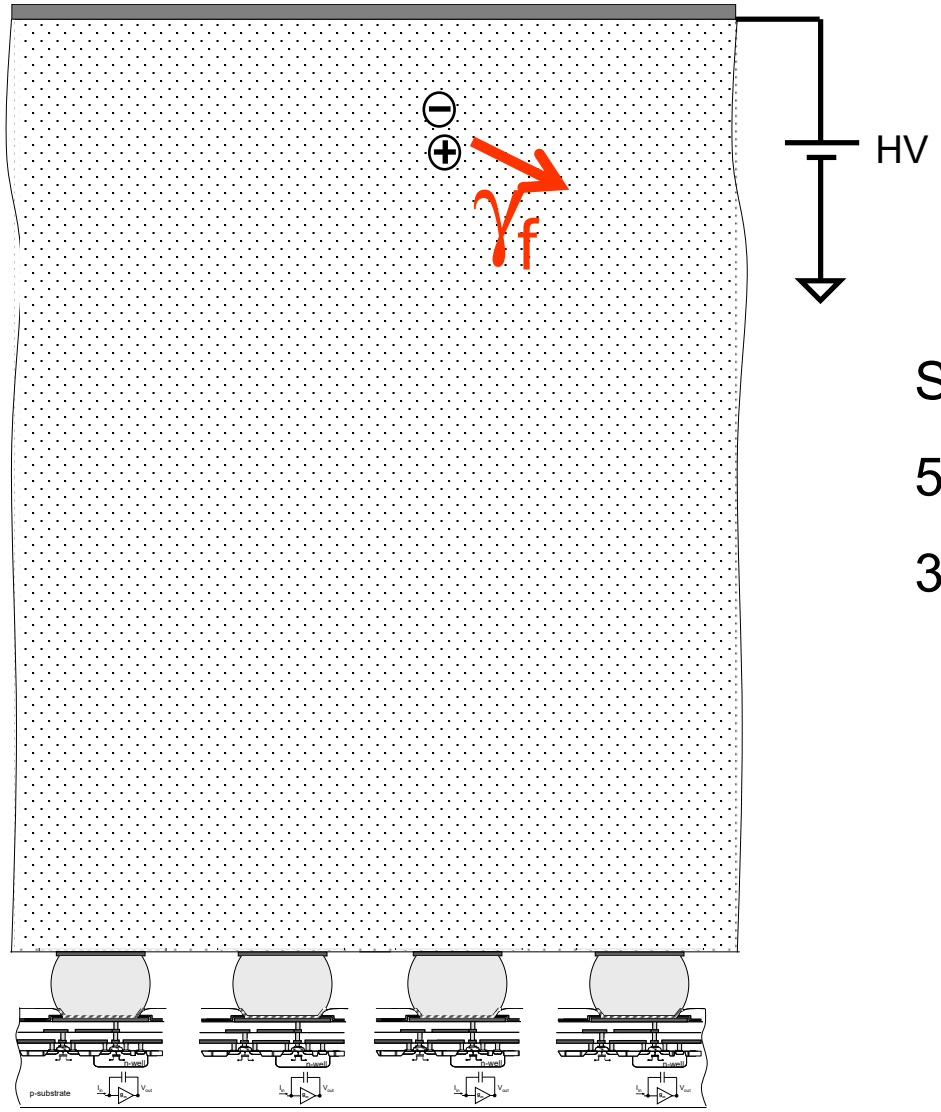

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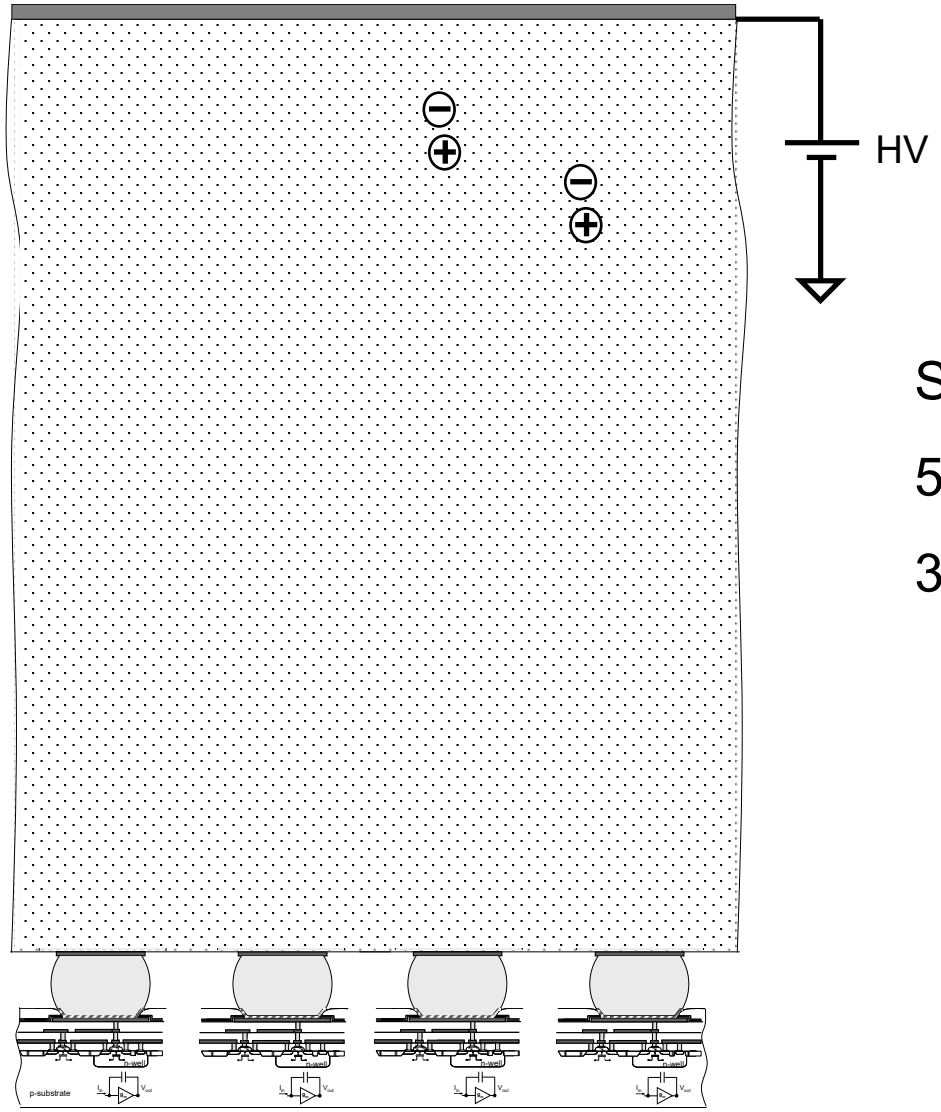

Sensor dimensions to scale:

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300µm thick sensor

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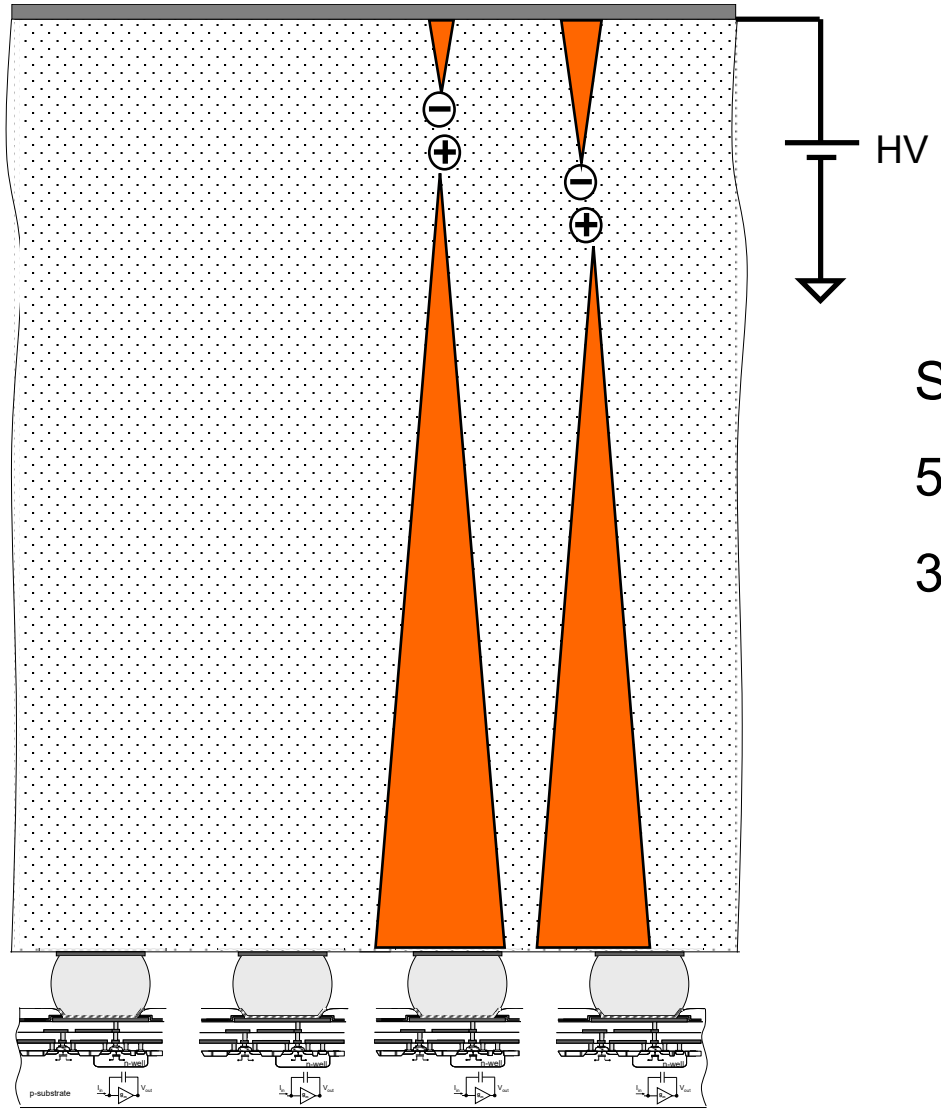

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55µm pixel pitch

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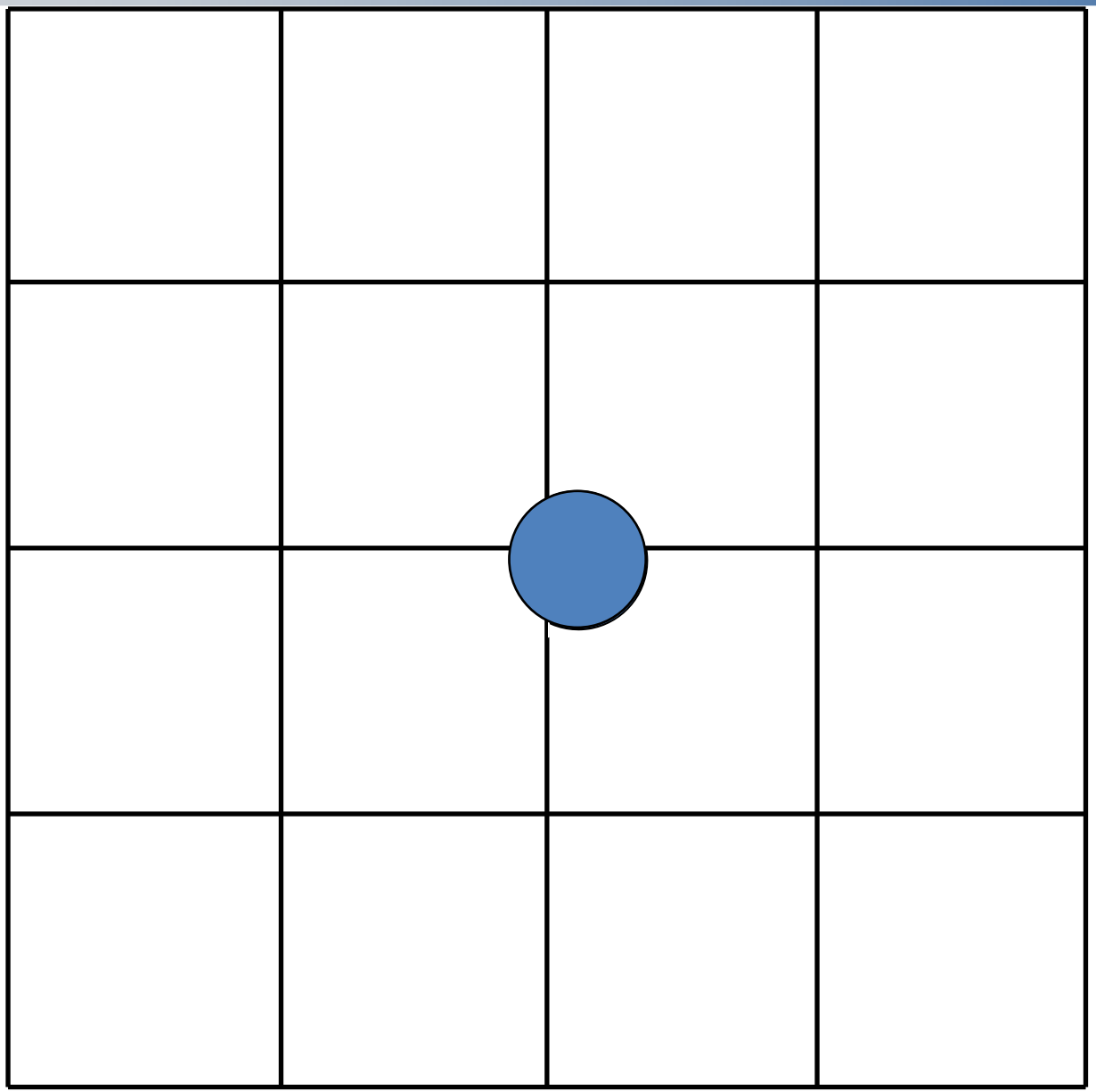
The algorithm for charge reconstruction and hit allocation: Charge Summing Mode



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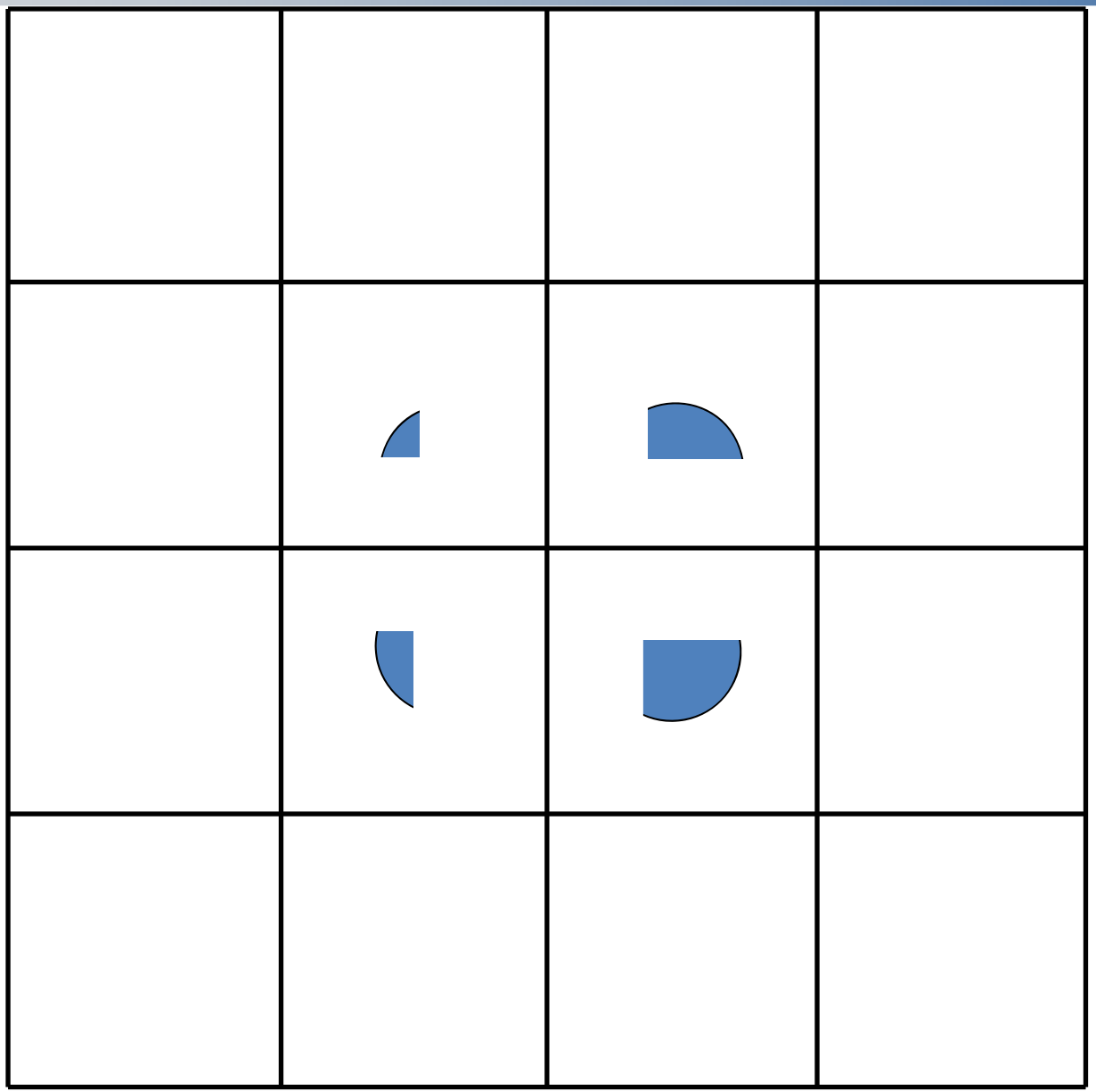

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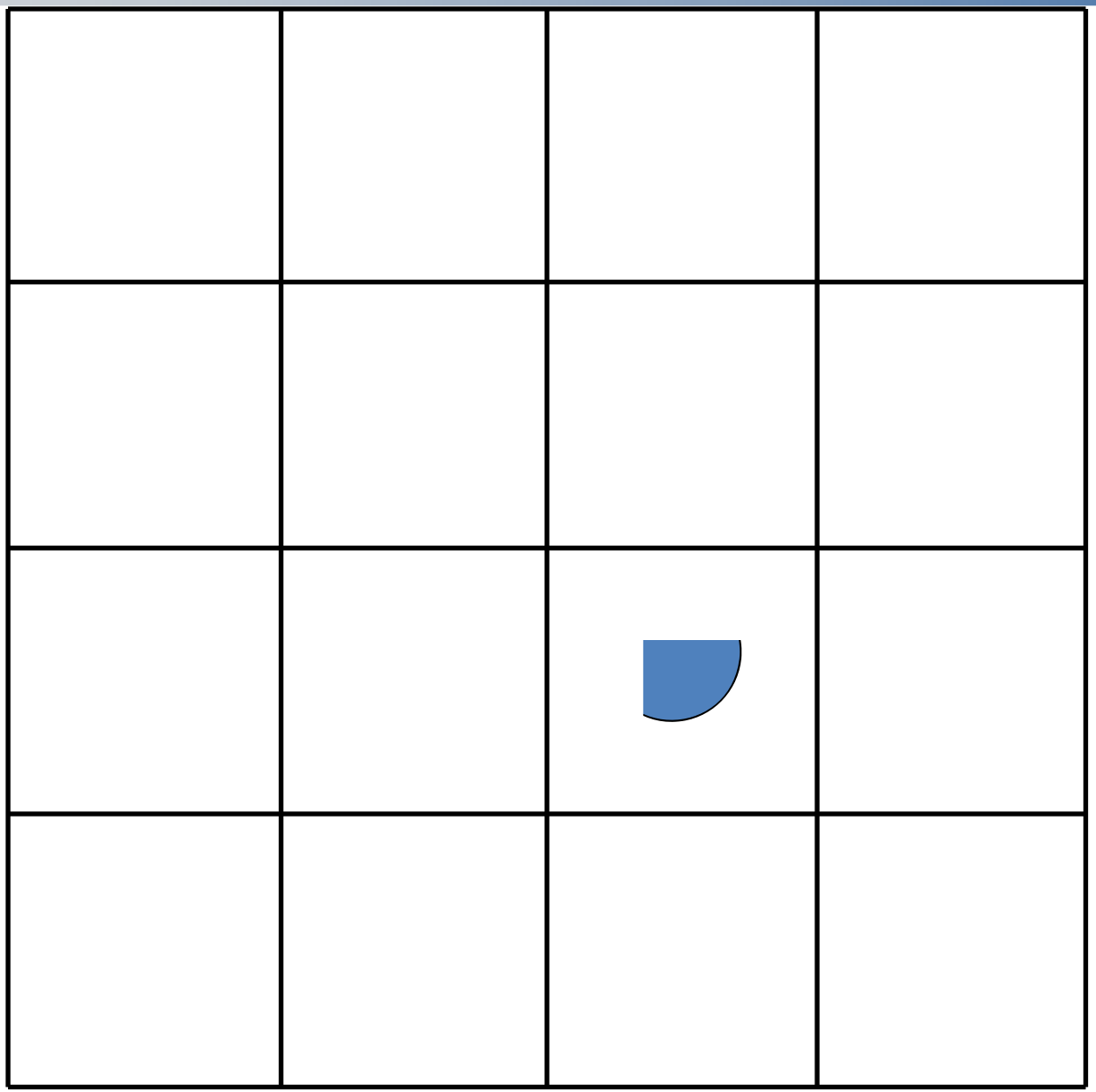

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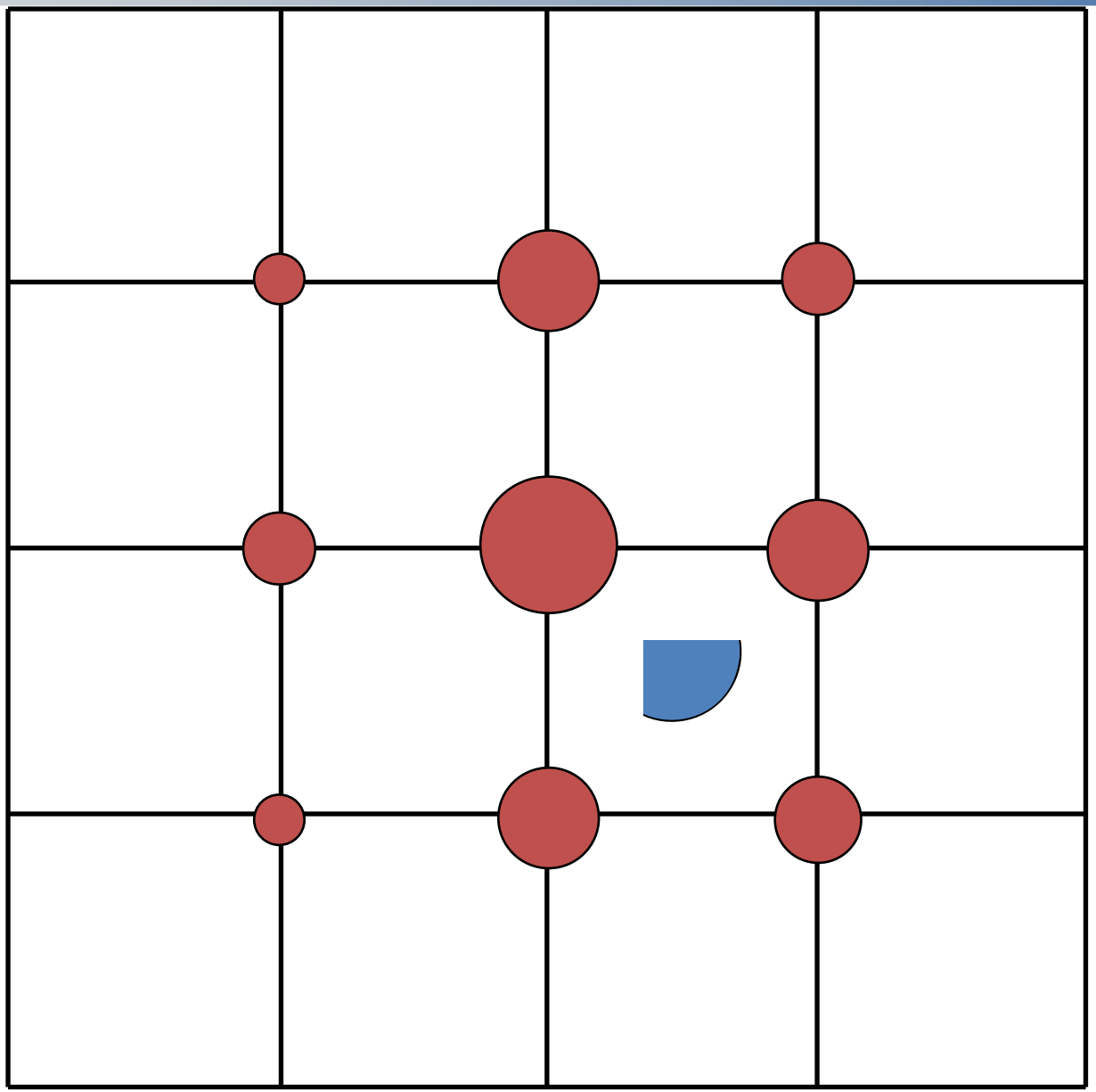

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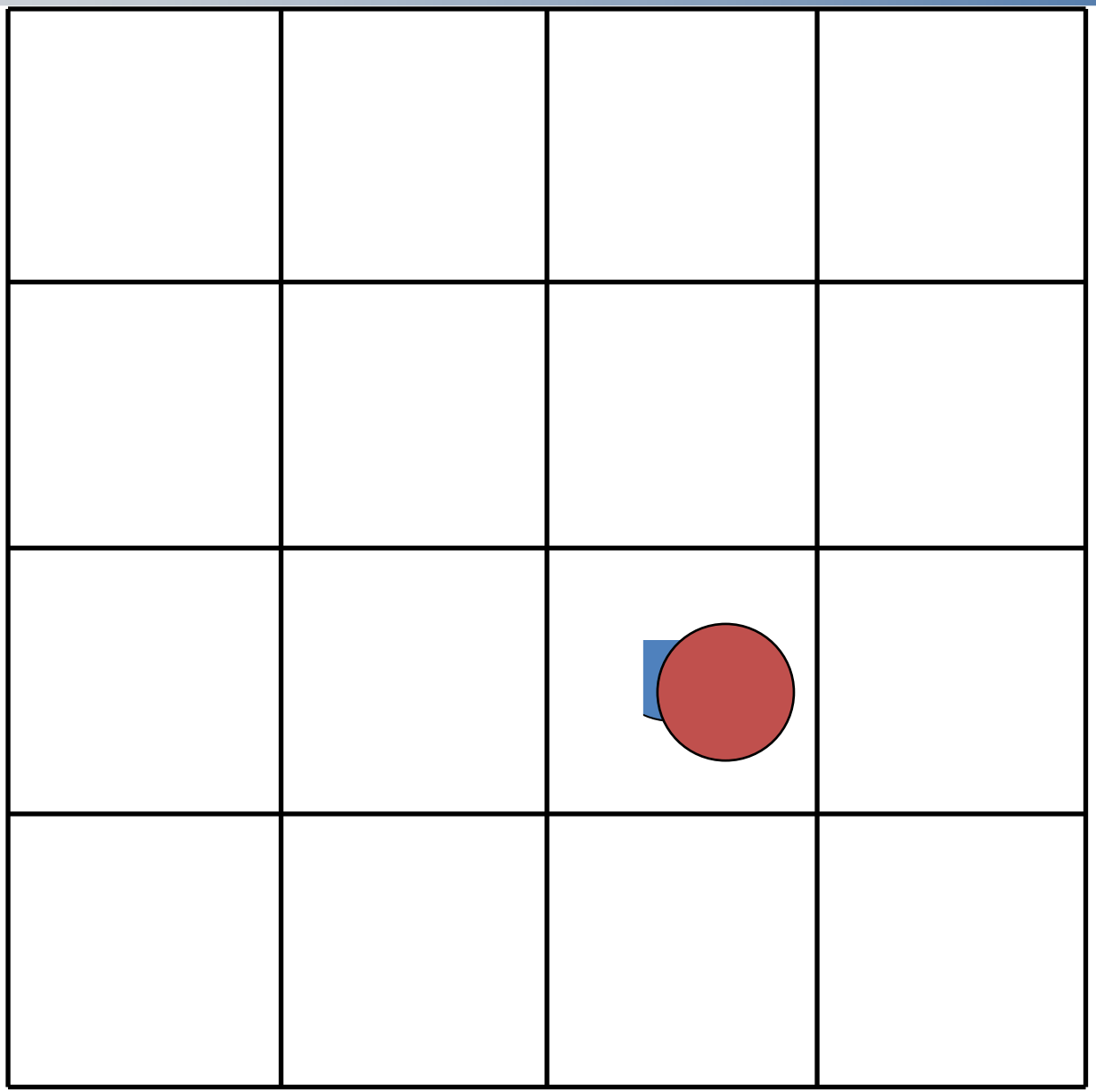
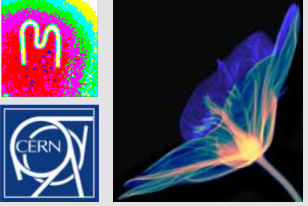
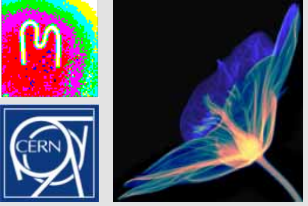




Medipix3 Specs

CMOS node	130nm
Pixel Array	256 x 256 / 128 x 128
Pixel pitch	55µm or 110µm
Charge collection	e^-, h^+
Pixel functionality	Energy selective photon counting With or Without Charge Summing
Preamp Gain	~22mV/ke^-
ENC	80e^-/174e^-
Number of counters	2/4/8
Minimum detectable charge	~500e^- /1000e^-
Counter Depth/Overflow	2/6/12/24
Max Analog power (1.5V)	6.5µW/pix 190mA/chip
Digital Power (1.5V)	~200mA@2z00MHz/chip
Readout (@ 100 MHz)	Frame-based, continuous R/W



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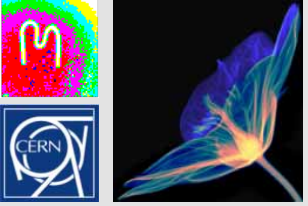

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First living human scan…

Phil Butler, CEO of MARS Bio Imaging

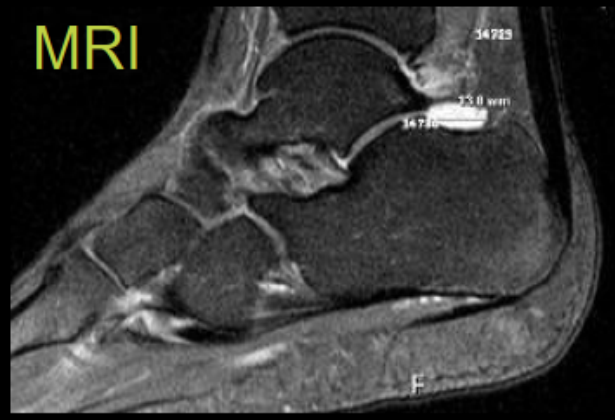
Movie Slice through Phil's ankle

Slice through Phil's ankle

Conventional imagers

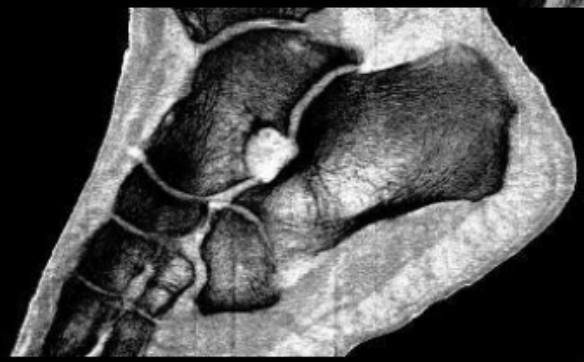
CT

MRI

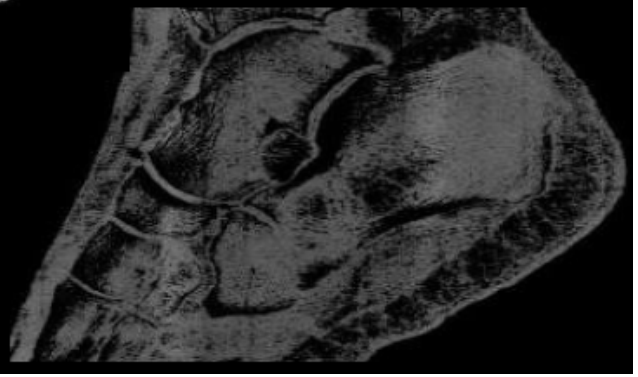


MARS CT

Calcium,
colour it white



Fat,
colour it yellow



Water,
colour it red and
semi-transparent red

Press Impact

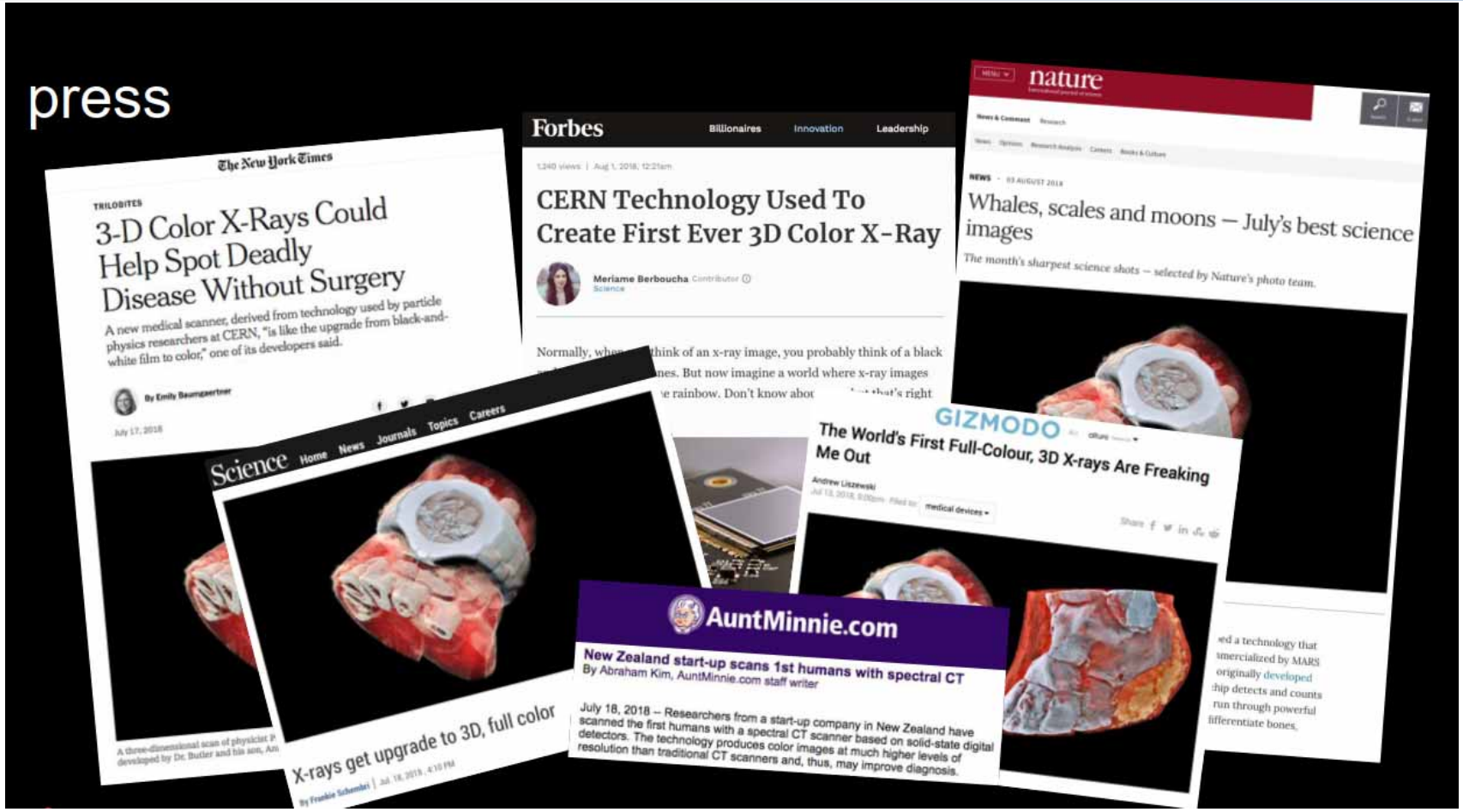


Image viewed over 40 M times on Twitter

Highest number of hits on CERN website since the Higgs announcement

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

In 2022 we marked the first FDA-approved photon counting CT system for regular clinical use.

Medipix highlights: Specxray workshop

Conclusion

I am convinced, that institutions like CERN play an important role for continuous innovations in medical imaging. Communities like the Medipix Collaboration and the SpecXray Workshop are essential instruments of our society, connecting and affirming researchers in academia and industry during the maturation and commercialization processes of disruptive detector technologies for medicine.

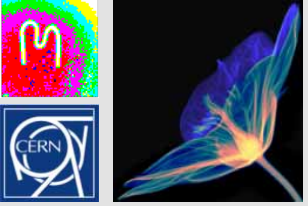
Stephan Kappler, Scientific committee

The Medipix and Timepix ASICs - Timeline

Data driven readout (timestamp 1.6ns)

Year	2003	2006	2013	2014	2017	2018	2020	2023	2025?
ASIC	Medipix2	Timepix	Medipix3	Timepix3		Timepix2	Timepix4	Medipix4	
LHCb					VELOpix				VELOpix2

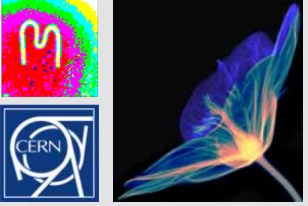
- Medipix chips aim at energy sensitive photon counting and typically use frame-based readout
- Timepix chips are more oriented towards single particle detection
- Large interest inside and outside of CERN



Timepix3 Specs

CMOS node	130nm
Pixel Array	256 x 256
Pixel pitch	55μm
Charge collection	e^-, h^+
Pixel functionality	TOT (Energy) and TOA (Arrival time)
Preamp Gain	~47mV/ke^-
ENC	~60e^-
FE Linearity	Up to 12ke^-
TOT linearity (resolution)	Up to 200ke^- (<5%)
TOA resolution*	Up to 1.6ns
Time-walk	<20ns
Minimum detectable charge	~500e^- → 2 KeV (Si Sensor)
Max Analog power (1.5V)	500 mA/chip
Digital Power (1.5V)	~400mA data driven
Maximum hit rate	80Mhits/sec (in data driven)
Readout	Data driven (44-bits/hit @ 5Gbps)

* Thanks to V. Gromov, et al. Nikhef, C. Brezina et al., Bonn



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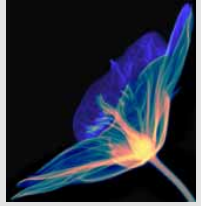

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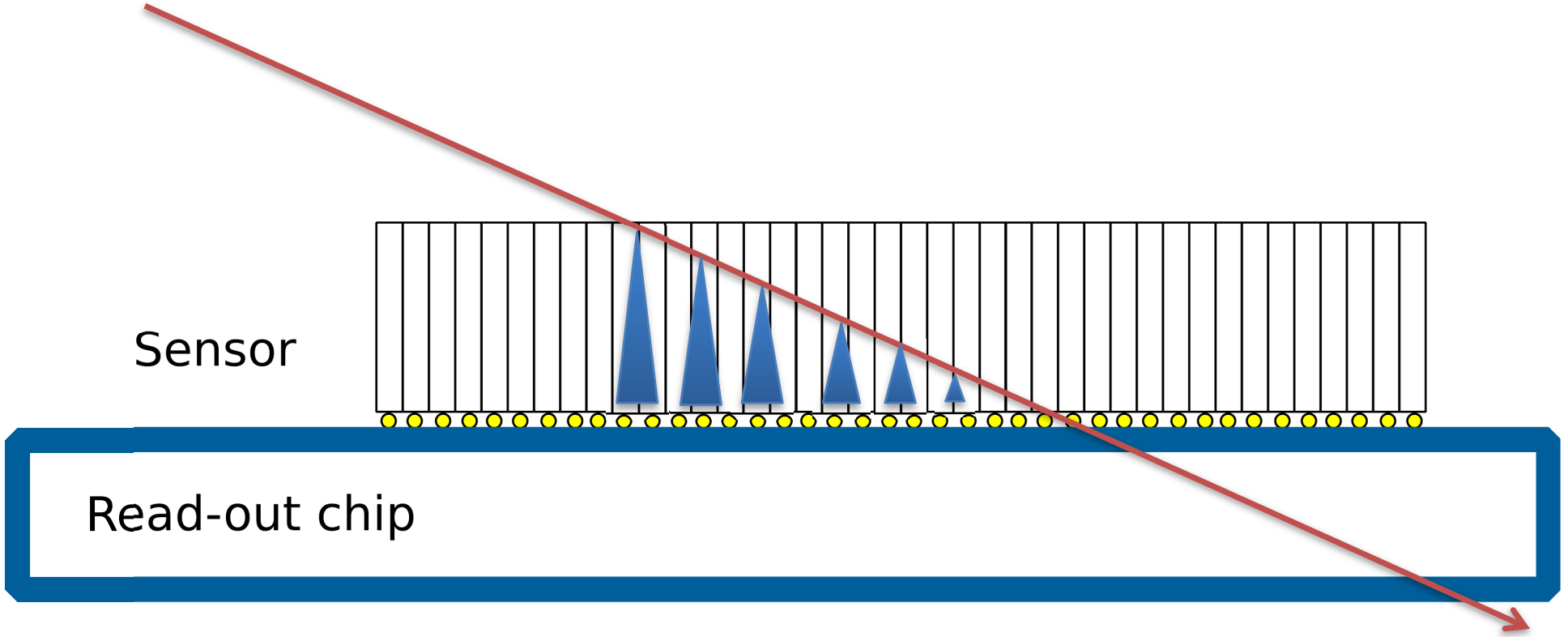
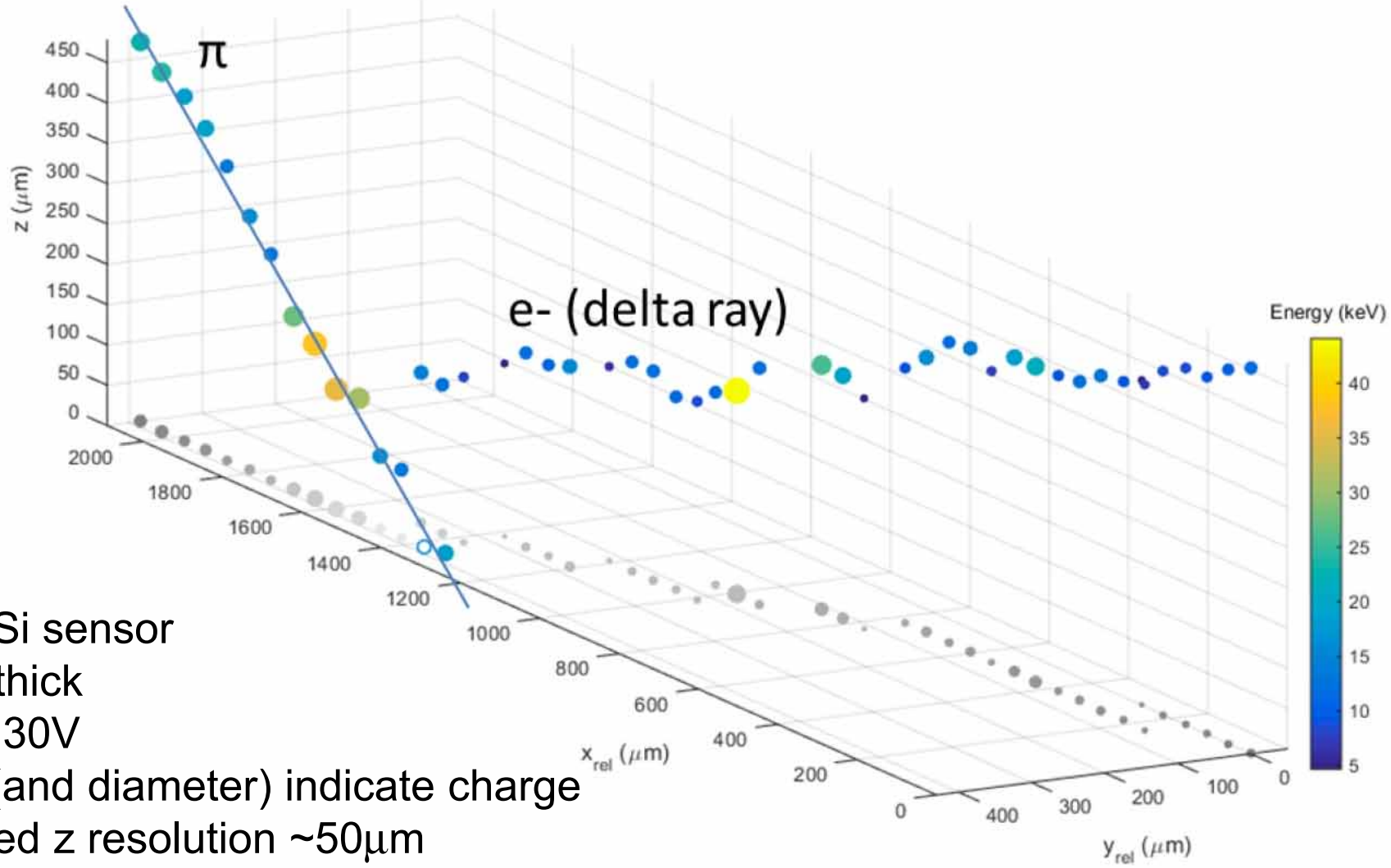
Tracking in a single Si layer



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

Ionisation electron detector based on Timepix3 HPD

Ionisation electron detector requirements

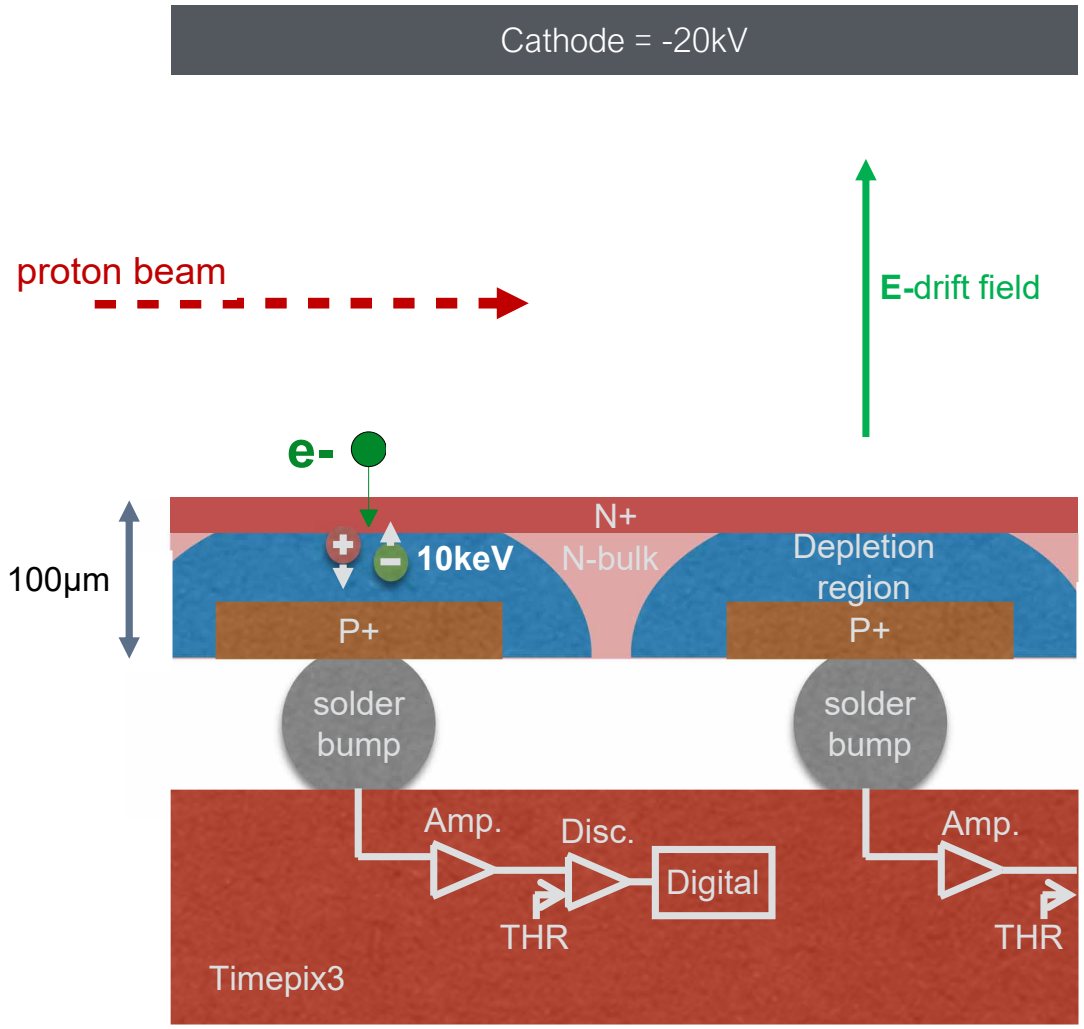
- Detect 10keV electrons (penetration depth in silicon = 1.5μm)
- Detect each electron with time resolution < 25ns & spatial resolution < 100μm
- Meet outgassing requirements for installation in the UHV of the PS beam pipe
- Operate during the acceleration cycle

Sensor

- Non-metalized, p-in-n, 100m deep
- 256 x 256 array of PN-diodes
- Pixel size = 55um x 55um
- Sensor area = 14mm x 14mm

Timepix3 readout chip

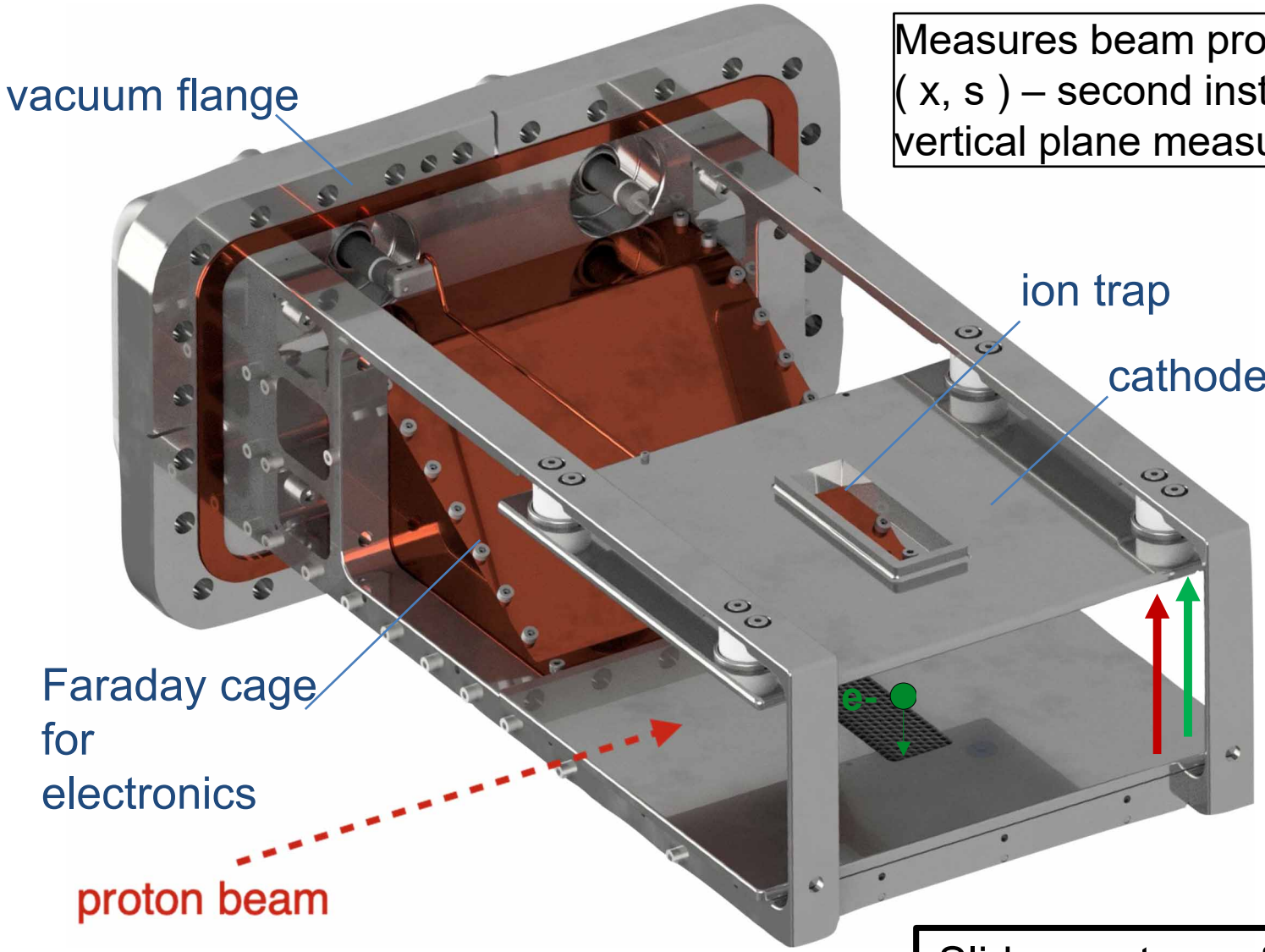
- Each sensor pixel is connected to an individual readout channel (pixel)



Slide courtesy of J. Storey, CERN

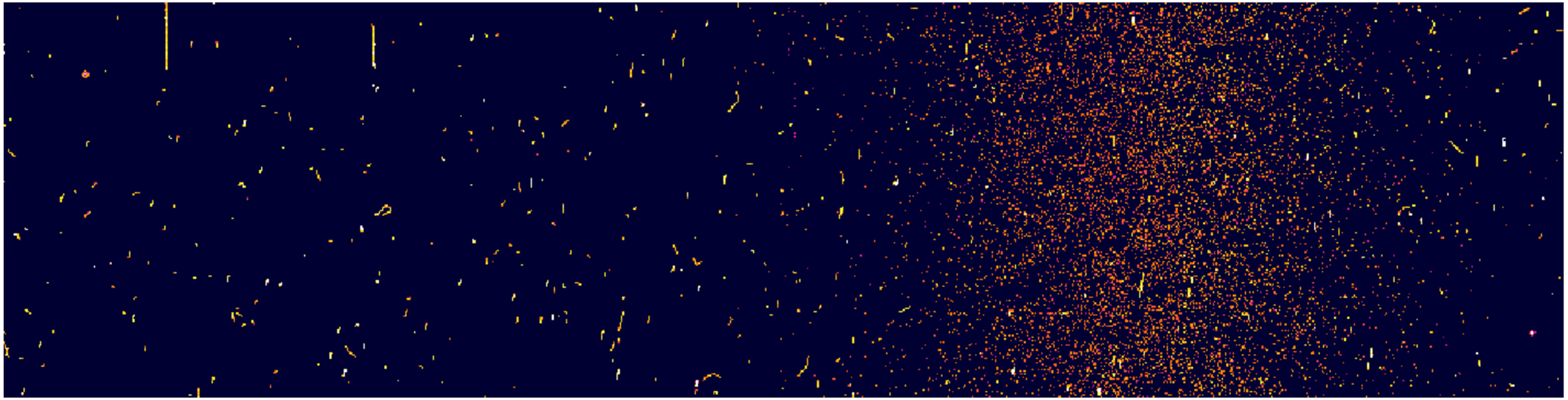
Instrument overview

Measures beam profile in horizontal plane (x, s) – second instrument design for vertical plane measurement



Slide courtesy of J. Storey, CERN

Slowed down movie of beam in the PS



- Timepix3 data-driven readout enables "live" display of the beam throughout the cycle
- 1.5 seconds in real time: slowed down here x30 for viewing purpose
- Not filtered: *background particles are interesting to look at!*
- LHC type beam, single bunch (I = 20×10^{10} p)

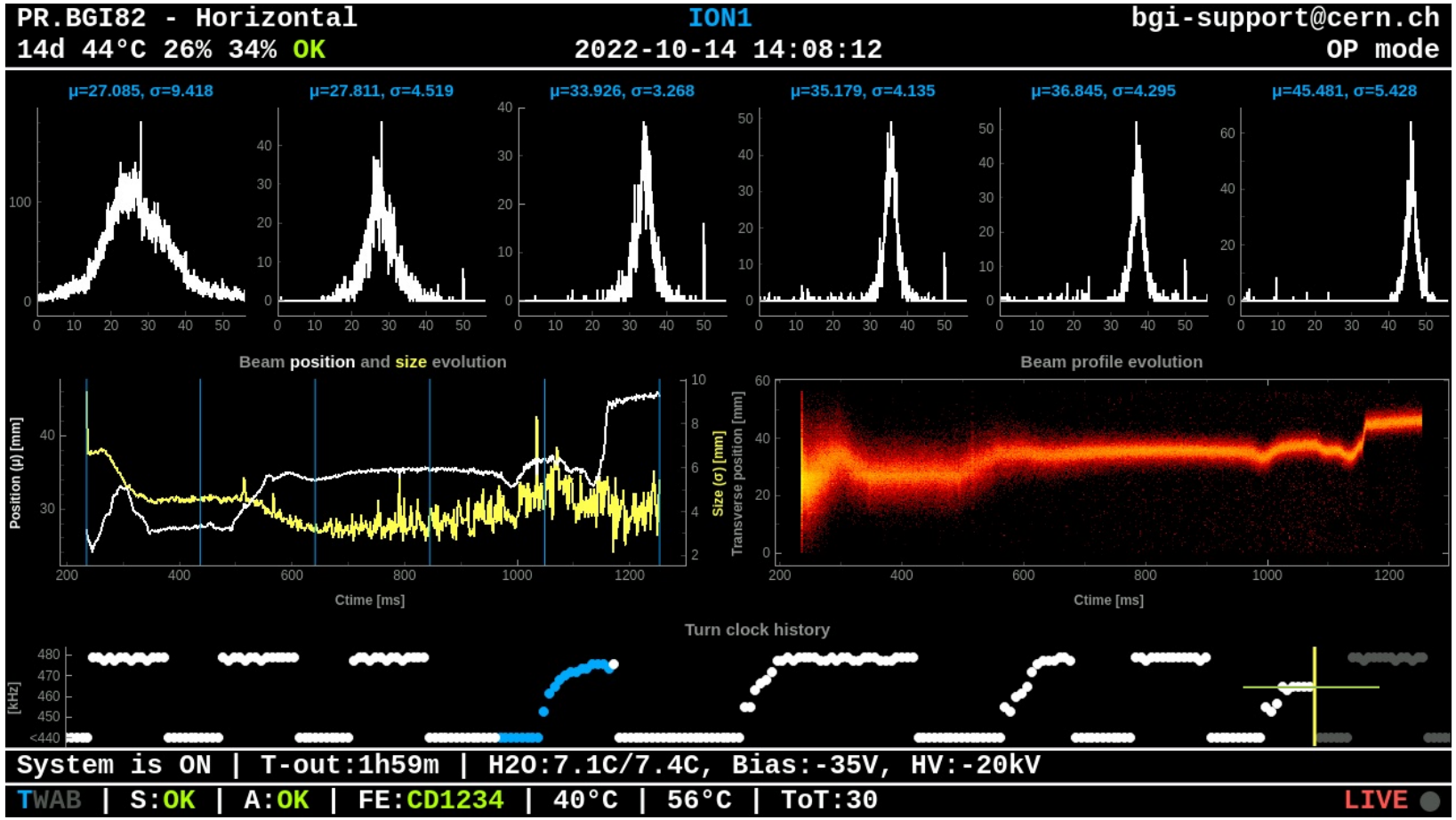
Slide courtesy of J. Storey, CERN

Software Vistar

Beam profiles distributed over the cycle

Beam position & size

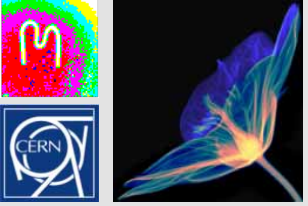
Instrument status



Waterfall plot (beam profile vs. cyle time)

Turn clock (blue active measurment)

Further details: PS-BGI Software Vistar, H.Sandberg, https://edms.cern.ch/document/2742171/1

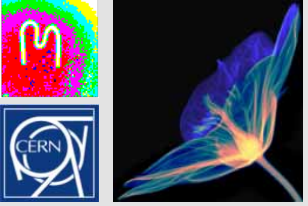


Status of BGI deployment

- PS-BGI horizontal working smoothly
- PS-BGI vertical has some issues (with background) which are being addressed

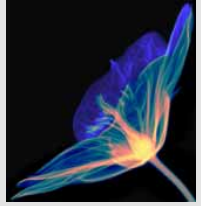
- SPS BGI 2 systems are being prepared for installation at YETS 23/24

- LHC BGI (will be based on Timepix4) under development



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	
		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^-



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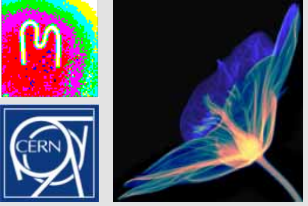

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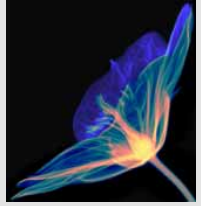
Readout Modes	Data driven (Tracking)	Mode	TOT and TOA	
		Event Packet	48-bit	64-bit
		Max rate	<80 Mhits/s	<365 $MHz/cm^2/s$
		Max pix rate	1.3kHz/pixel	10.6kHz/pixel
	Frame based (Imaging)	Mode	PC (10-bit) and iTOT (14-bit)	CRW: PC (8 or 16-bit)
		Frame	Zero-suppressed (with pixel addr)	Full Frame (without 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^-



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	
		Event Packet	48-bit	64-bit
		Max rate	<80 Mhits/s	<365 $MHz/cm^2/s$
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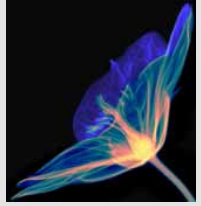

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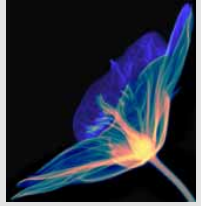

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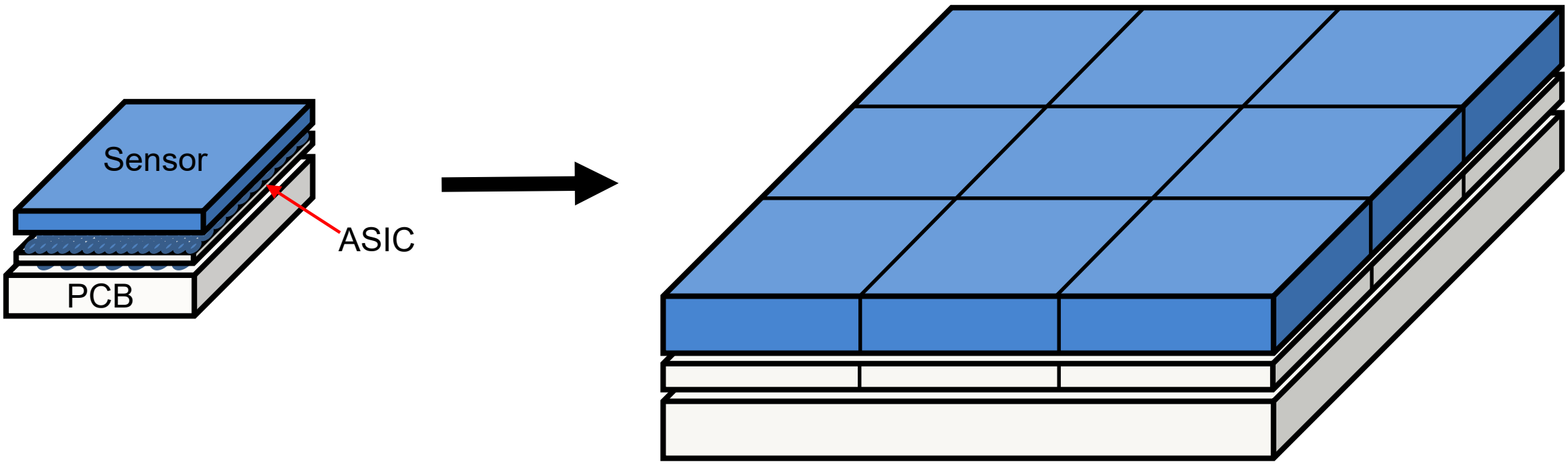
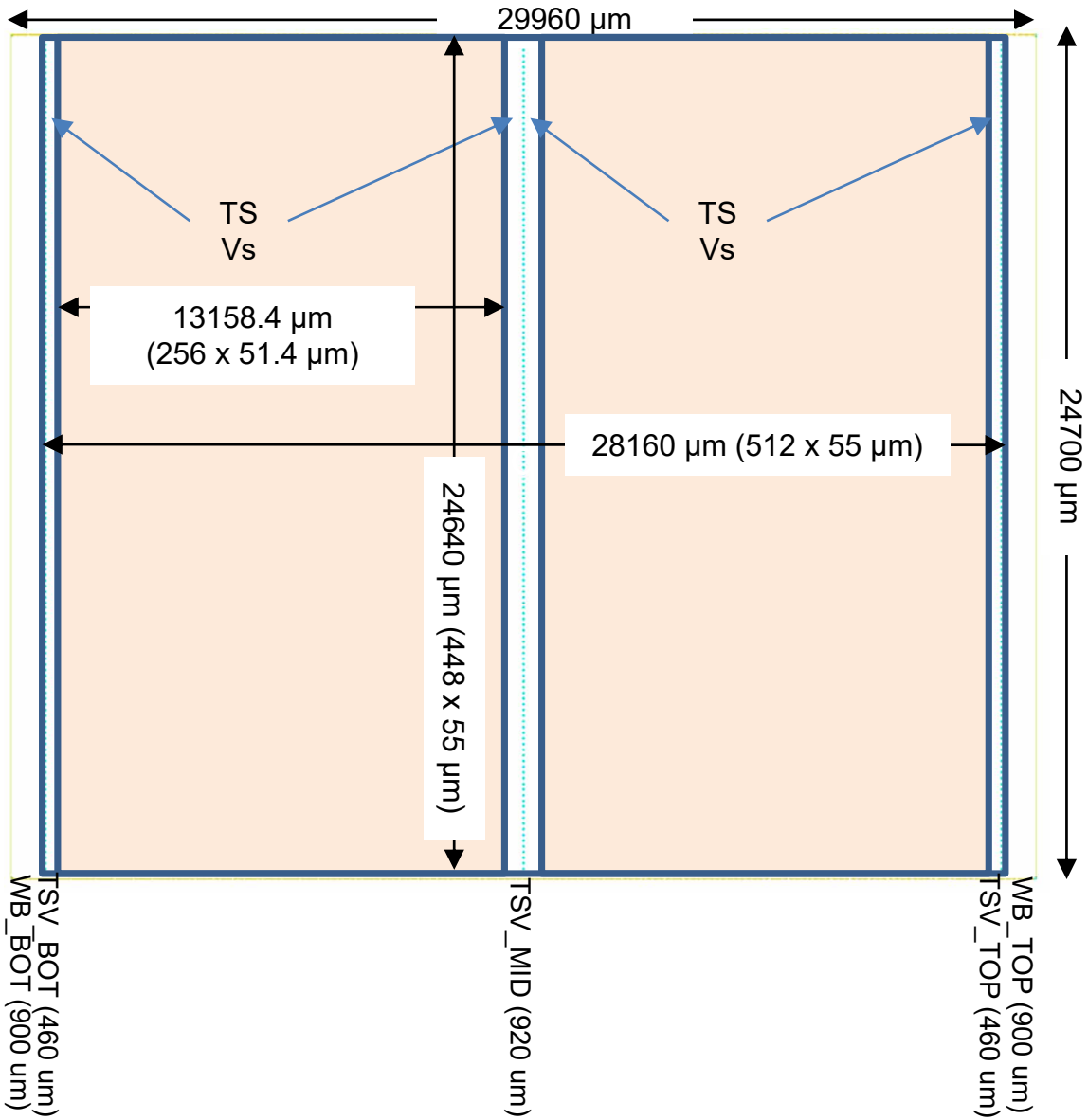
Tiling larger areas



Requires an ASIC designed to permit tiling on all sides

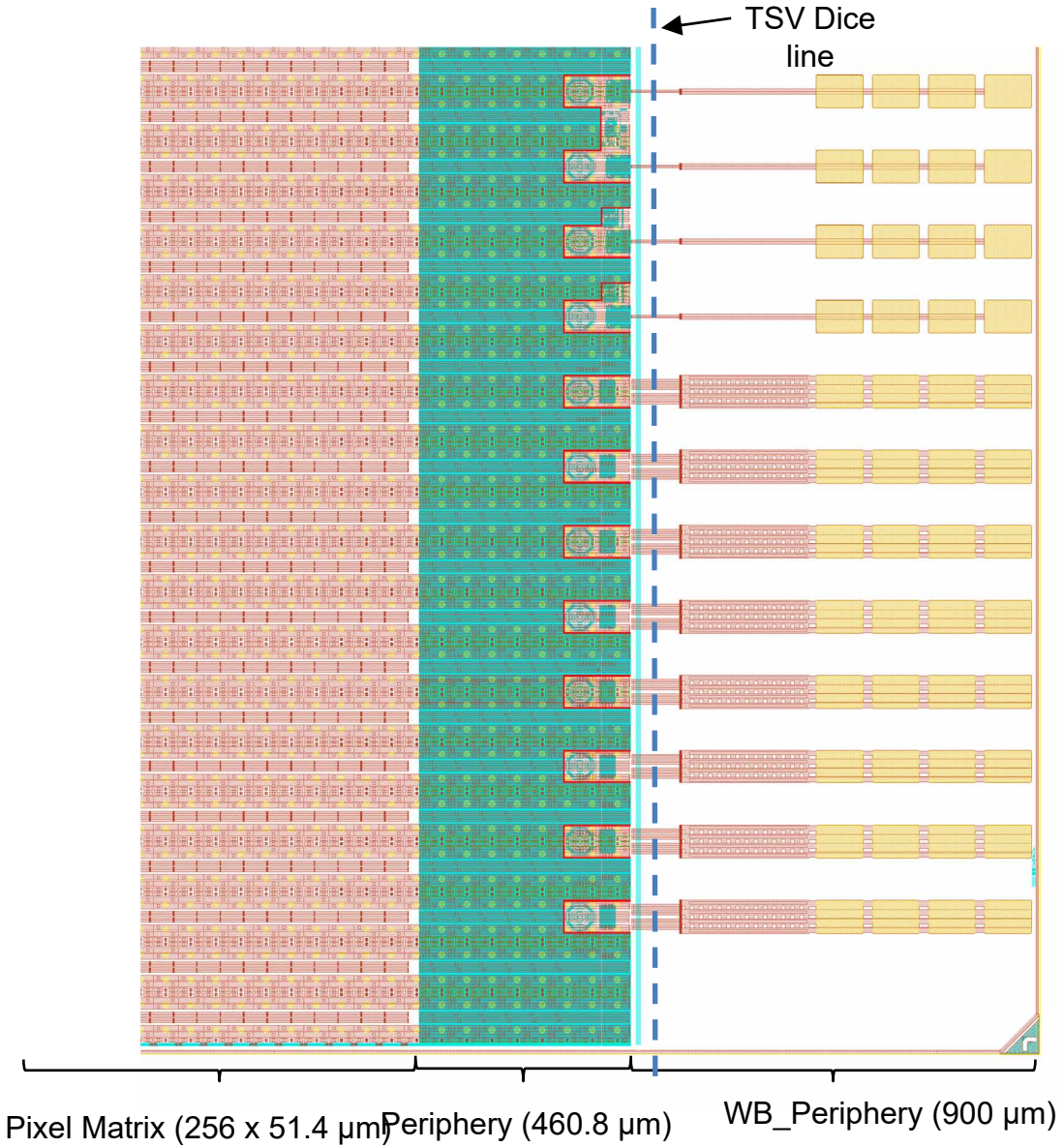
Timepix4 Floorplan



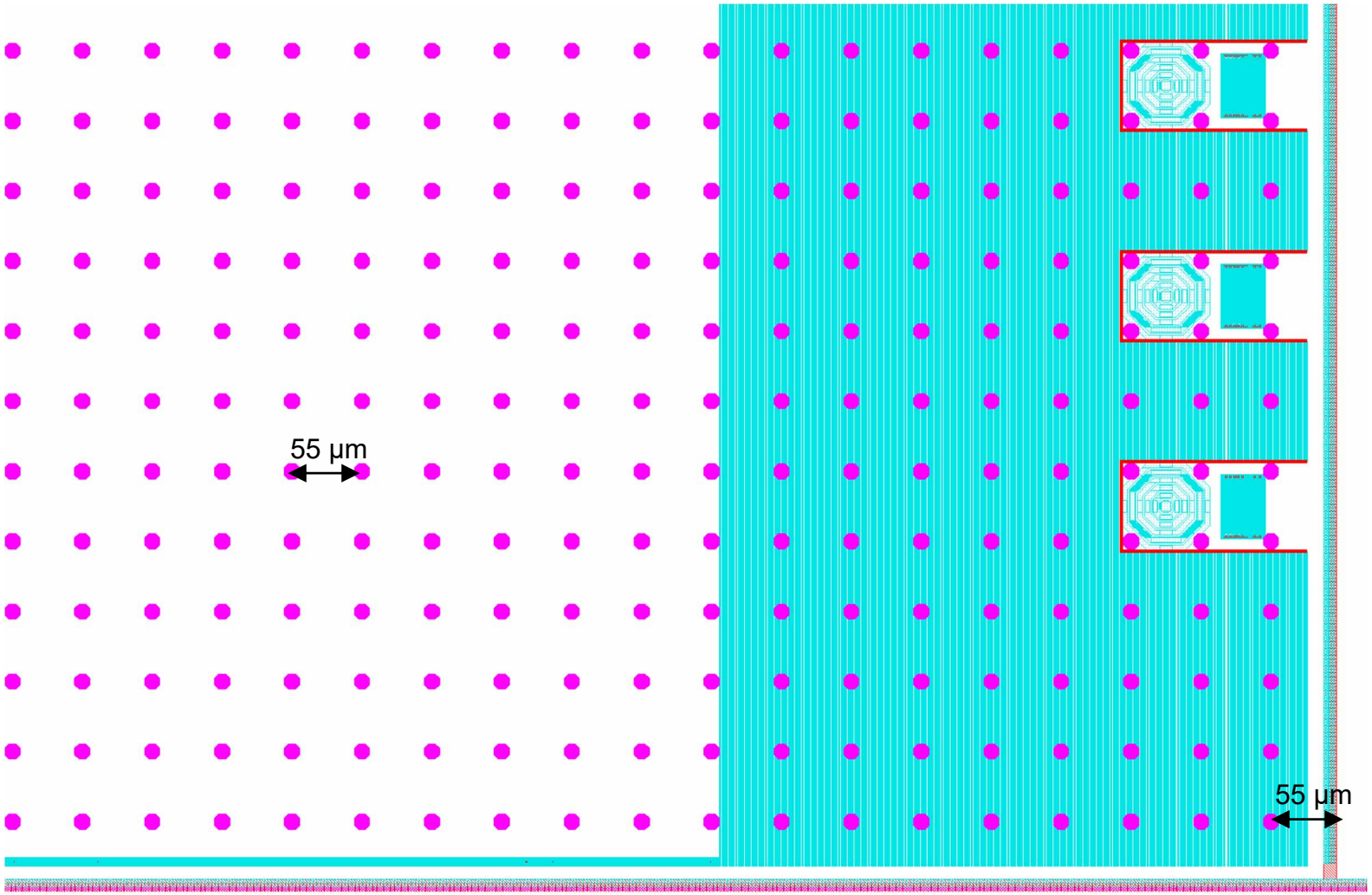
Edge periphery floorplan

- Digital on top design:
  - Default periphery size is 460.8 µm
  - Scripted to allow different periphery sizes
- WB openings 4x 100x70 µm
  - Multiple probing pads
- TSV M1 octagons of 69 µm

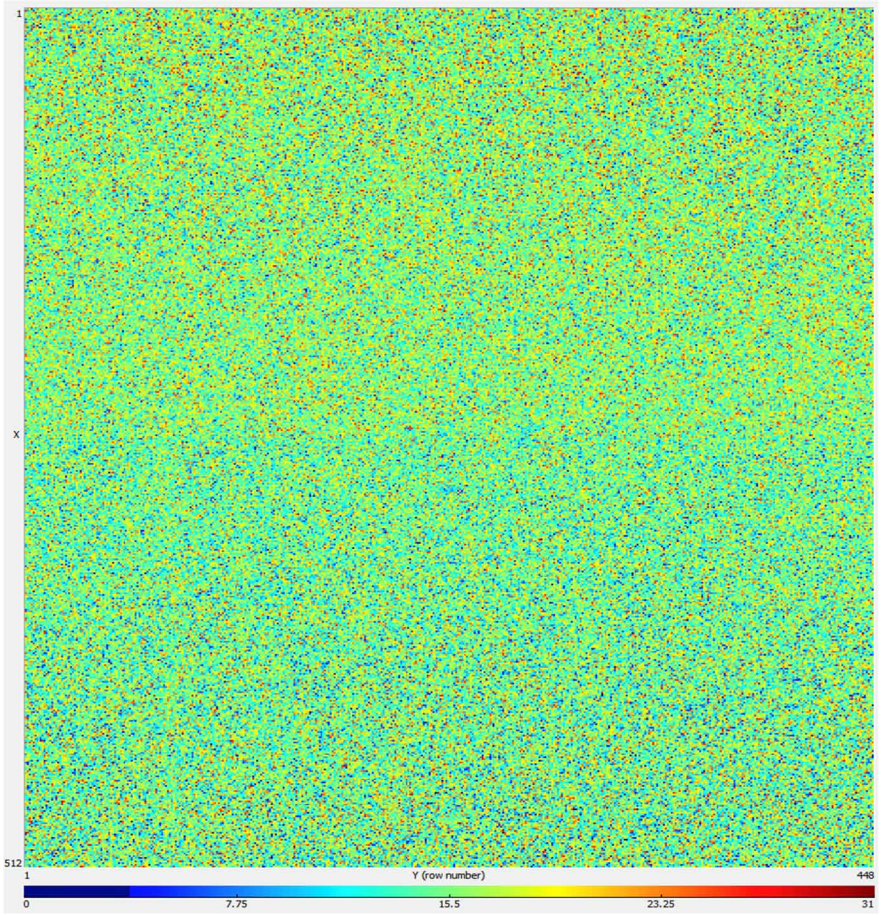
- First version of edge routing
  - 13158.4 x 5.4 µm
  - Buffer routing between peripheries



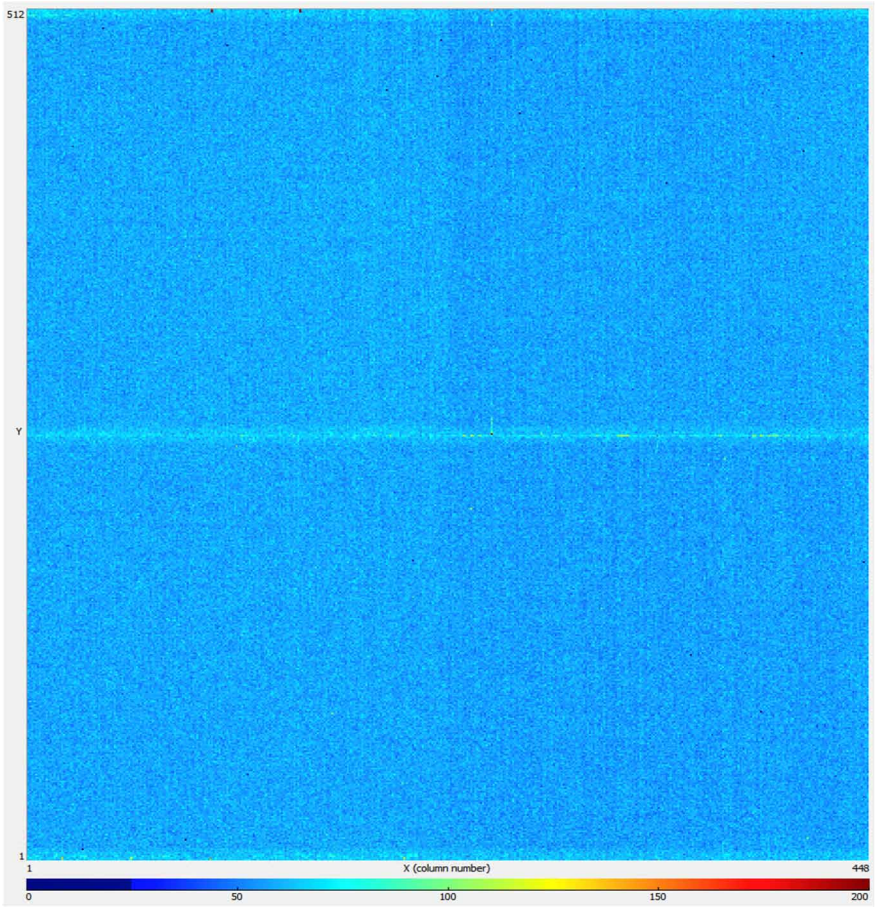
TSV (on M1) and BUMPs (on M10)



Uniformity of response Timepix4



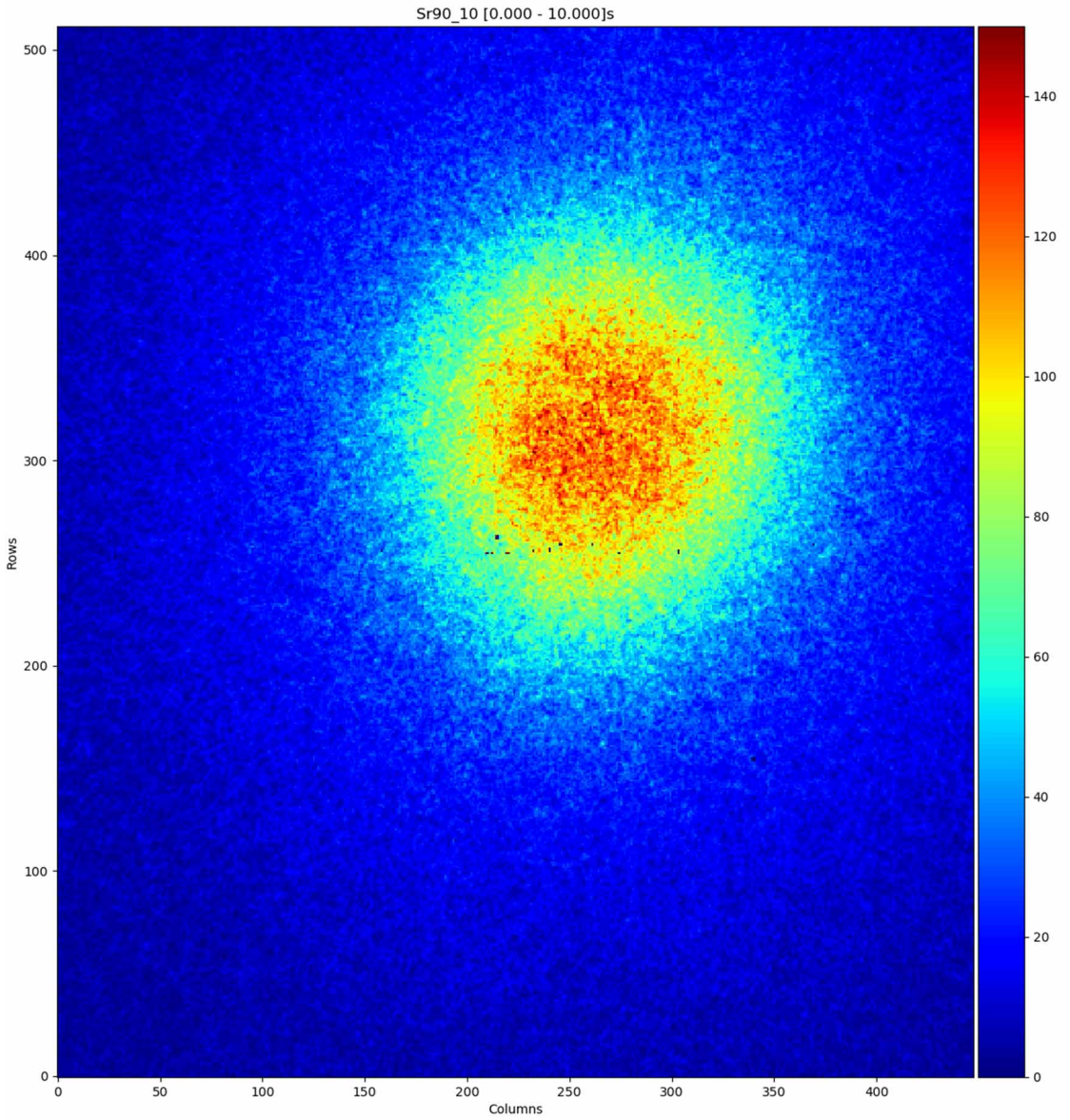
Threshold adjustment bits



Noise in e^- rms

Timepix4 assembly (300μm Si sensor)

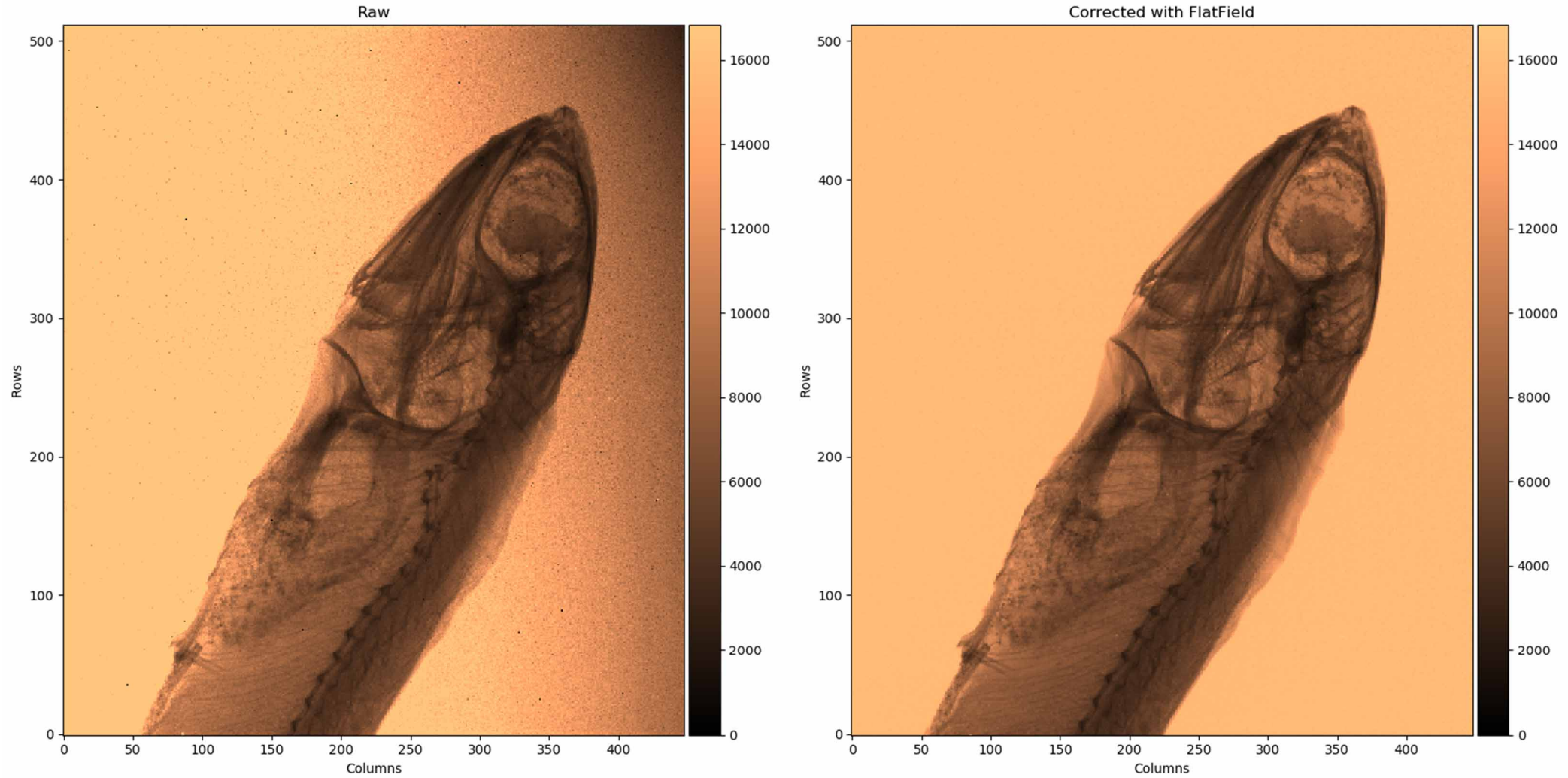
Timepix4 – works! ☺

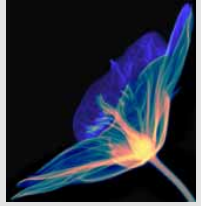


10s exp. ^{90}Sr

Threshold ~ 800e^-
6.1 M packets @ 5 Gbps

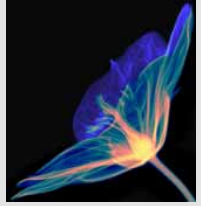
Photon counting image Timepix4





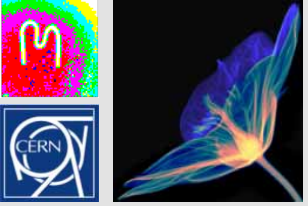
Examples of other applications

- Large area X-ray cameras for synchrotron light sources
- X-ray materials analysis with diffraction
- X-ray non-destructive testing
- X-ray dosimetry - dosepix chip development
- Neutron detection and imaging
- Low Energy Electron Microscopy
- Transmission Electron Microscopy
- Time-of-Flight mass spectrometry
- Dose deposition tracking in hadron therapy
- Numerous satellite systems dedicated to space weather observation



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
- Breit-Wheeler experiment at RAL
- Beta particle channeling in ISOLDE
- Background monitoring at Moedal experiment
- 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 made an important contribution to the Higgs boson discovery
- Hybrid pixels will continue to contribute to tracking systems in high luminosity environments going forward.
- The Medipix2, Medipix3 and Medipix4 Collaborations have taken the technology into many other fields
- Timepix chips are actively detecting background radiation in school classrooms and in space
- “Colour” X-ray imaging using Medipix3 has significant potential for medical diagnostic imaging
- Timepix3 is the basis of the PS and SPS BGI beam profile monitors
- Timepix4 tags hits to within 200ps and can be tiled on 4 sides

Thank you for your attention!

Medipix3RX images: S. Procz et al.