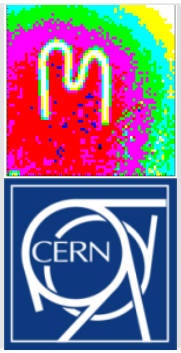
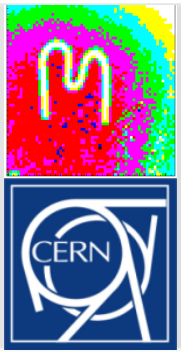


MEDIPIX: PIXEL DETECTORS FOR MEDICAL IMAGING AND OTHER APPLICATIONS

M. Campbell[1], J. Alozy, R. Ballabriga, E.H.M. Heijne, I. Kremastiotis, X. Llopart, T. Poikela, E. Santin, V. Sriskaran, L.Tlustos and W.Wong

CERN, PH Department
1211 Geneva 23
Switzerland

[1] Honorary Professor at Glasgow University



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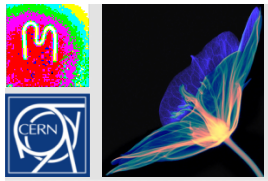
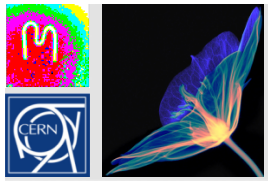


Medipix2 Collaboration

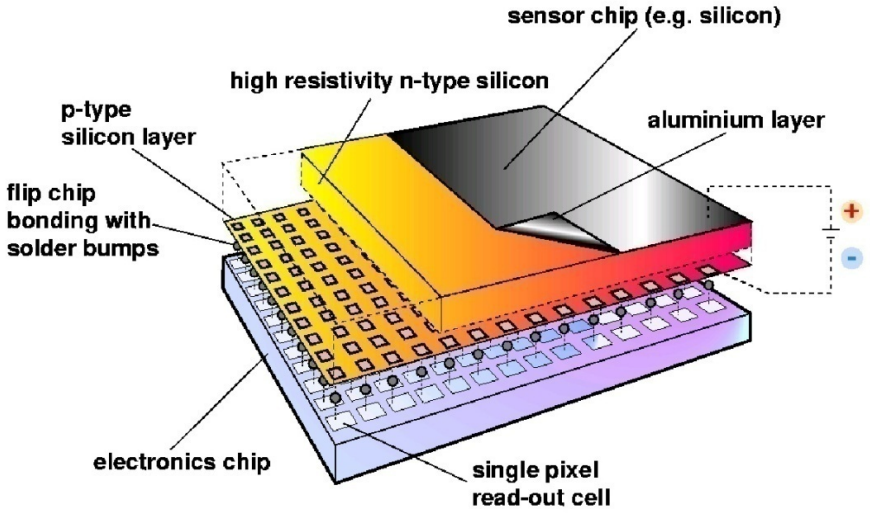
- University and INFN Cagliari, Italy
- CEA-LIST Saclay, France
- CERN, Geneva, Switzerland
- Friedrich-Alexander-University Erlangen-Nurnberg, Germany
- ESRF, Grenoble, France
- University of Freiburg, Germany
- University of Glasgow, UK
- IFAE Barcelona, Spain
- Mid-Sweden University, Sundsvall, Sweden
- MRC-LMB. Cambridge, UK
- University and INFN Napoli, Italy
- NIKHEF, Amsterdam, The Netherlands
- University and INFN Pisa, Italy
- FZU Czech Academy of Science, Prague, Czech Republic
- IEAP, Czech Technical University in Prague, Czech Republic
- Space Science Laboratory, UC Berkeley, USA

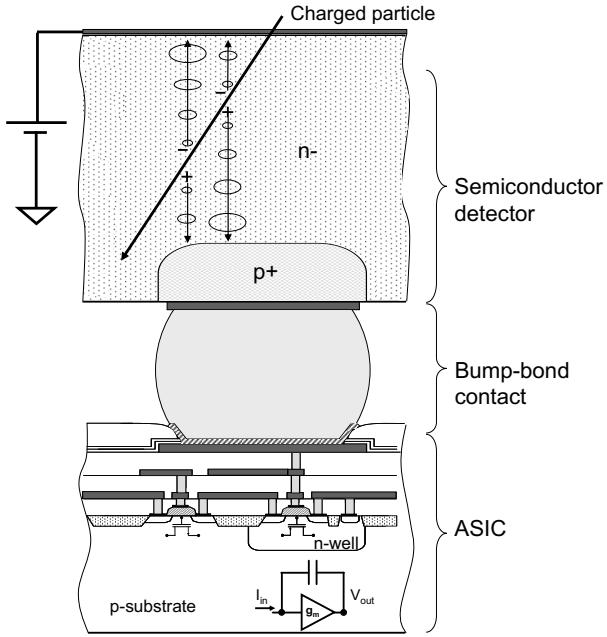


Medipix3 Collaboration

- University of Canterbury, Christchurch, New Zealand
- CEA, Paris, France
- CERN, Geneva, Switzerland,
- DESY-Hamburg, Germany
- Albert-Ludwigs-Universität Freiburg, Germany
- University of Glasgow, Scotland, UK
- Leiden University, The Netherlands
- NIKHEF, Amsterdam, The Netherlands
- Mid Sweden University, Sundsvall, Sweden
- IEAP, Czech Technical University, Prague, Czech Republic
- ESRF, Grenoble, France
- Universität Erlangen-Nurnberg, Erlangen, Germany
- University of California, Berkeley, USA
- VTT, Information Technology, Espoo, Finland
- KIT/ANKA, Forschungszentrum Karlsruhe, Germany
- University of Houston, USA
- Diamond Light Source, Oxfordshire, England, UK
- Universidad de los Andes, Bogota, Colombia
- University of Bonn, Germany
- AMOLF, Amsterdam, The Netherlands
- Technical University of Munich, Germany
- Brazilian Light Source, Campinas, Brazil

Hybrid Silicon Pixel Detectors

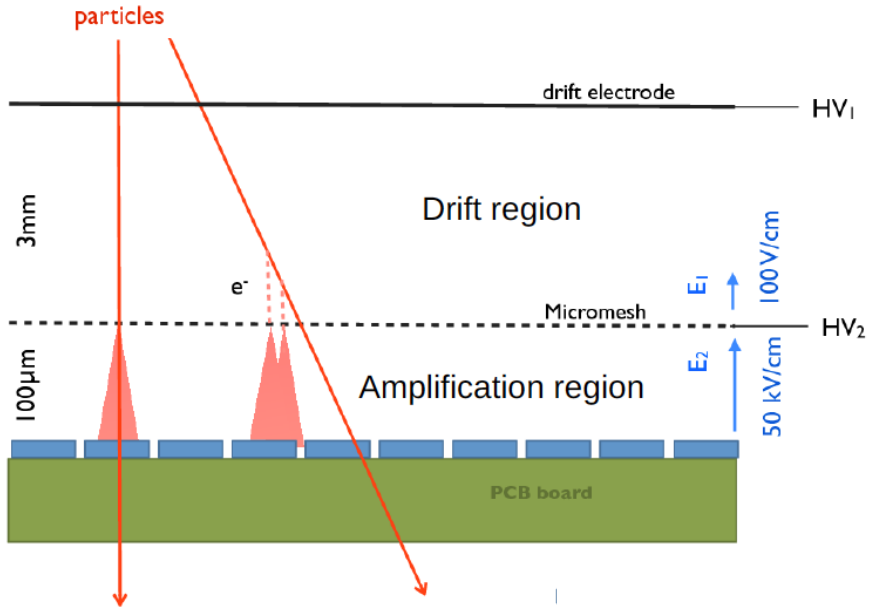


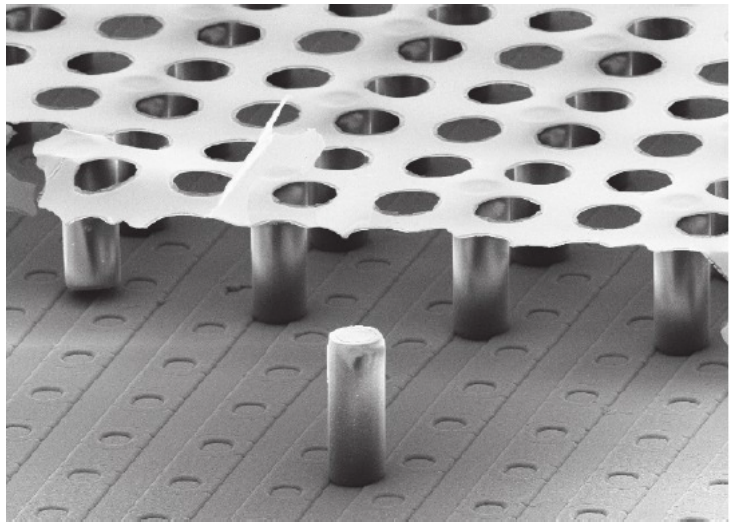


Standard CMOS can be used allowing on-pixel signal processing

Sensor material can be changed (Si, GaAs, CdTe..)

Gas detector readout - InGrid

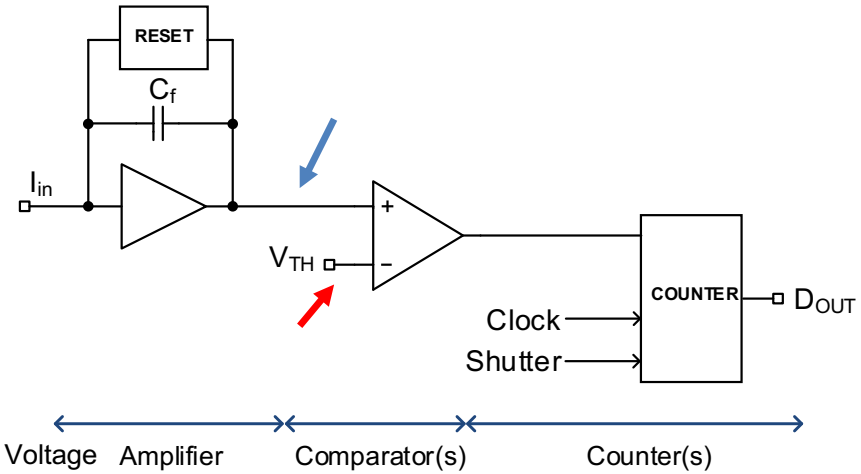


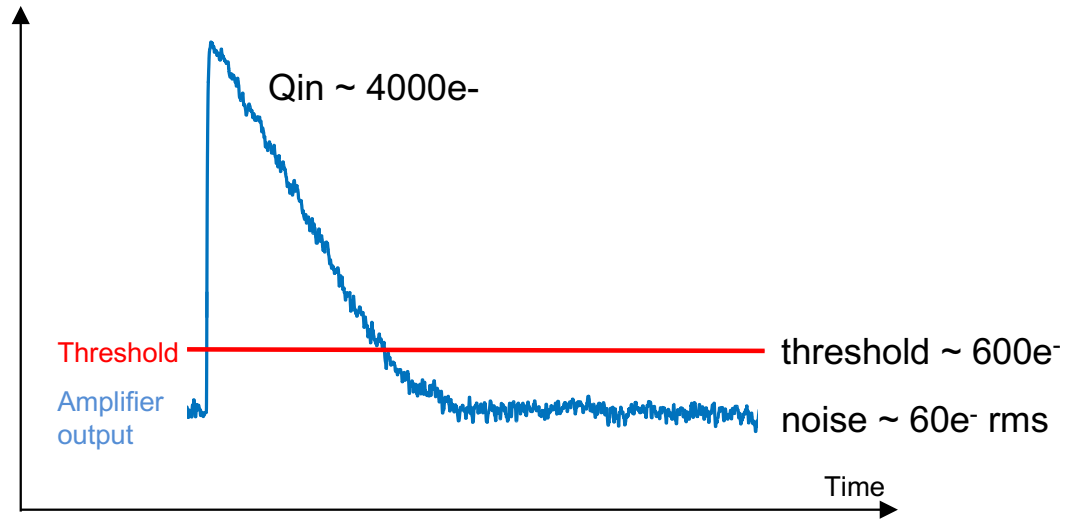


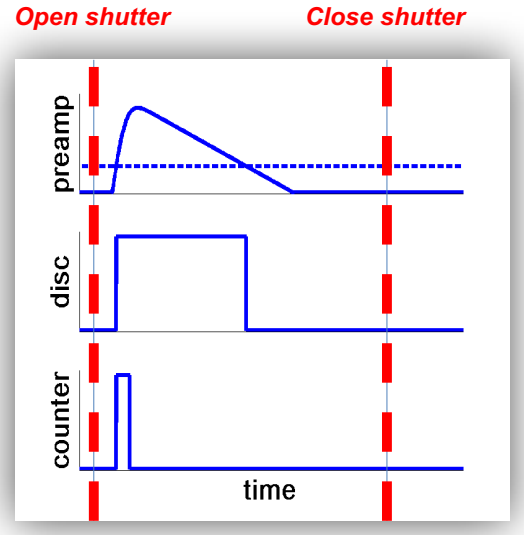
Semiconductor detector is replaced with charge amplification grid
Permits lower energy events to be detected

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

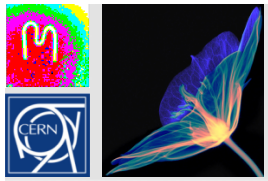
Hybrid Pixel Detector – Counting Electronics







→ Noise hit free imaging

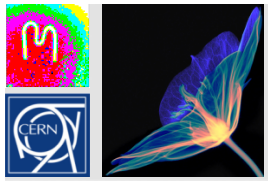


Hybrid pixel detectors

- Developed initially for LHC
- 3 large scale vertex detector systems (ALICE, ATLAS, CMS) operating smoothly
- One large RICH detector system (based on hybrid pixels in a photodetector tube) contributing to LHCb physics

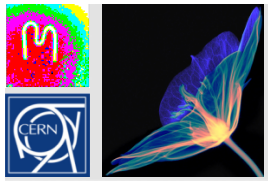
- In the Medipix2 and Medipix3 Collaborations we have taken the technology into many new fields

- This talk covers 3 readout chips and describes some applications



Outline

- The Timepix chip
  - Educational use
  - Space dosimetry and space weather
  - X-ray histology
  - Use in art
- The Medipix3 chip
  - X-ray imaging at synchrotrons
  - Spectroscopic X-ray imaging for medicine
- The Timepix3 chip
  - Silicon TPC
  - Anti matter research
- Medipix4 and Timepix4
- The Medipix cycle of Innovation
- Conclusions



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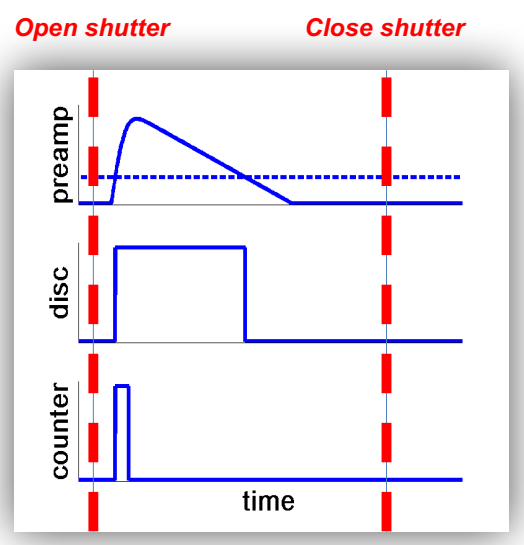
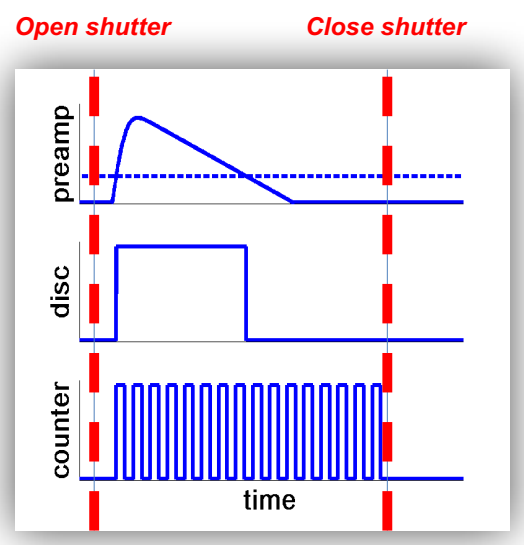
Timepix Pixel Operation Modes

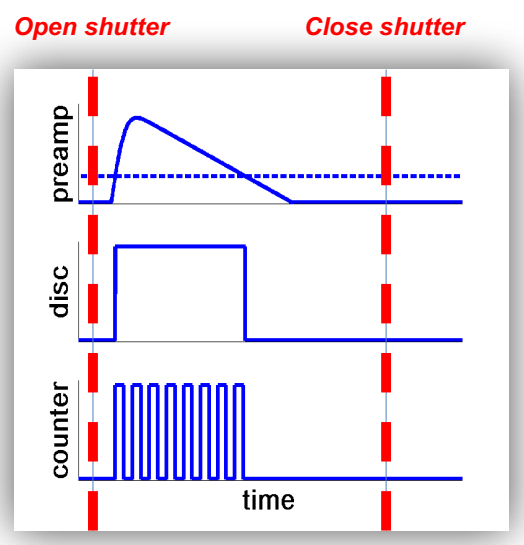
- Particle counting



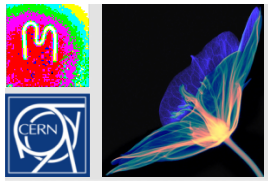
- Arrival Time*



- Time over threshold

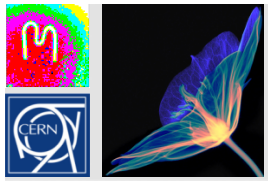


* Implemented at the request of the EUDet Collaboration



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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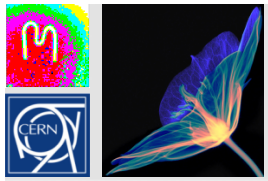

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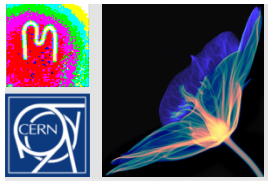

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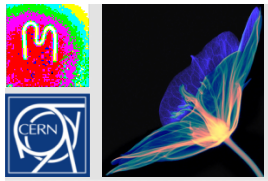

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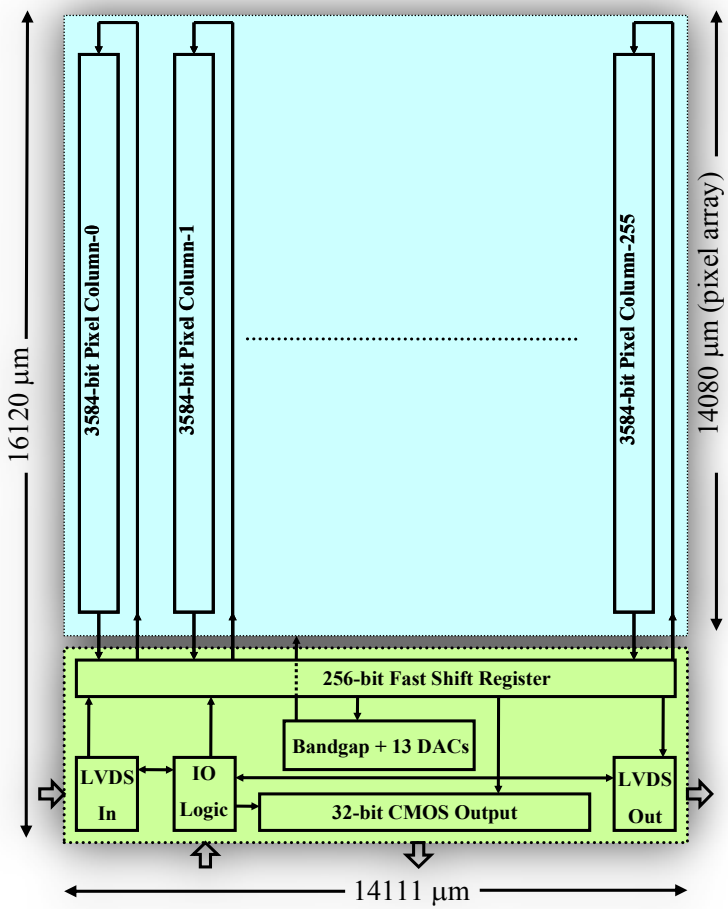
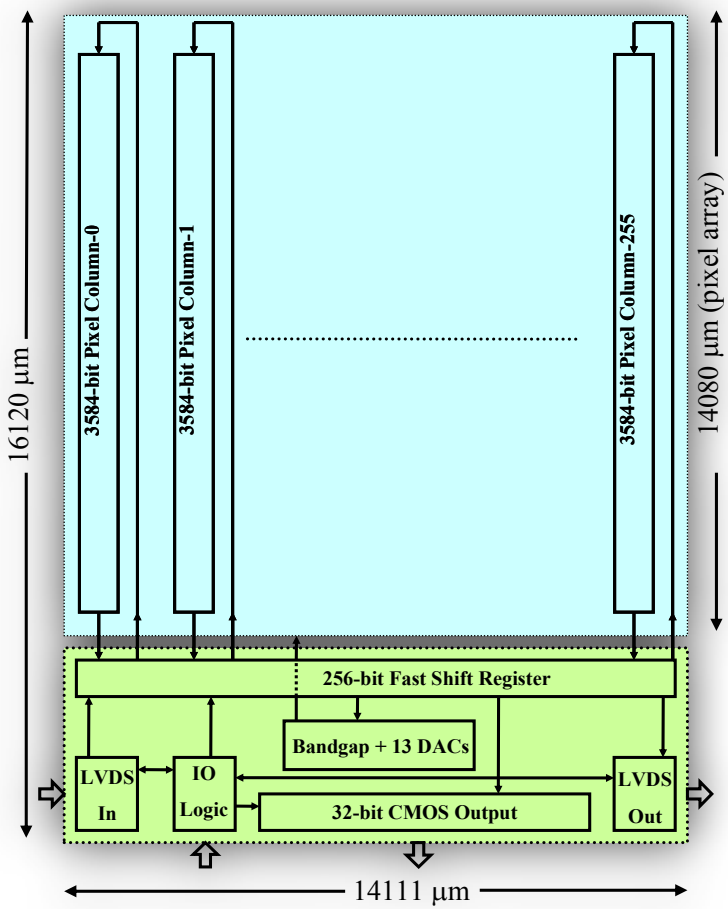
Timepix chip architecture



- 3-side Buttable floorplan
- In acquisition mode chip an external clock is used as a time reference (up to 100 MHz)
- 256x256 55µm square pixels
- Analog Power → 440mW
- Digital Power (Ref_Clk=50MHz) → 220mW
- > 36M Transistors
- System on chip design:
  - On-chip digital global biasing:
    - 14 DACs + Bandgap
  - Simple control logic
  - Serial readout (@100MHz) → 9.17 ms
  - Parallel readout (@100MHz) → 287 µs
  - Daisy-chain (serial only) for simple multiple chip readout

Timepix chip architecture



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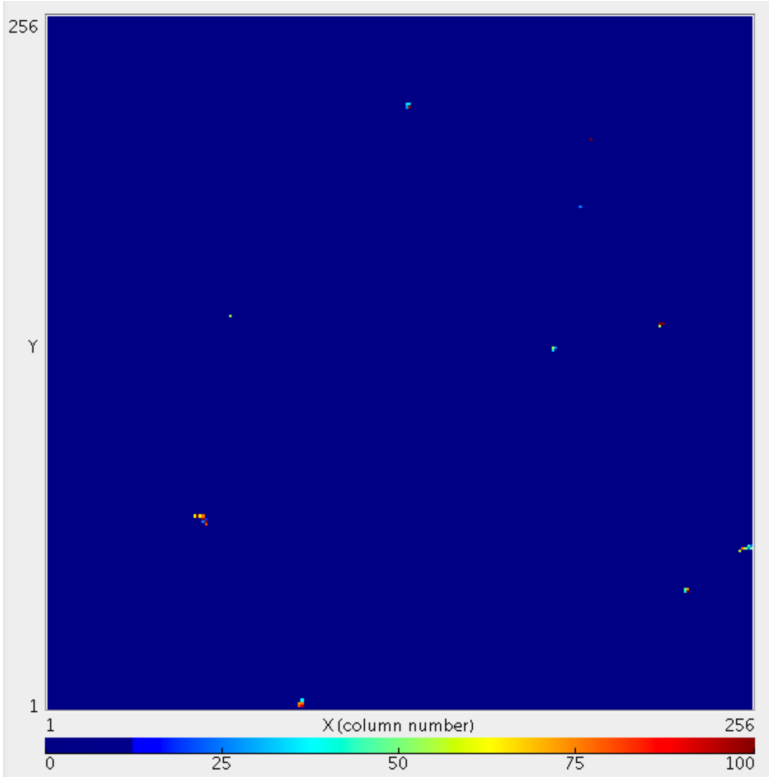
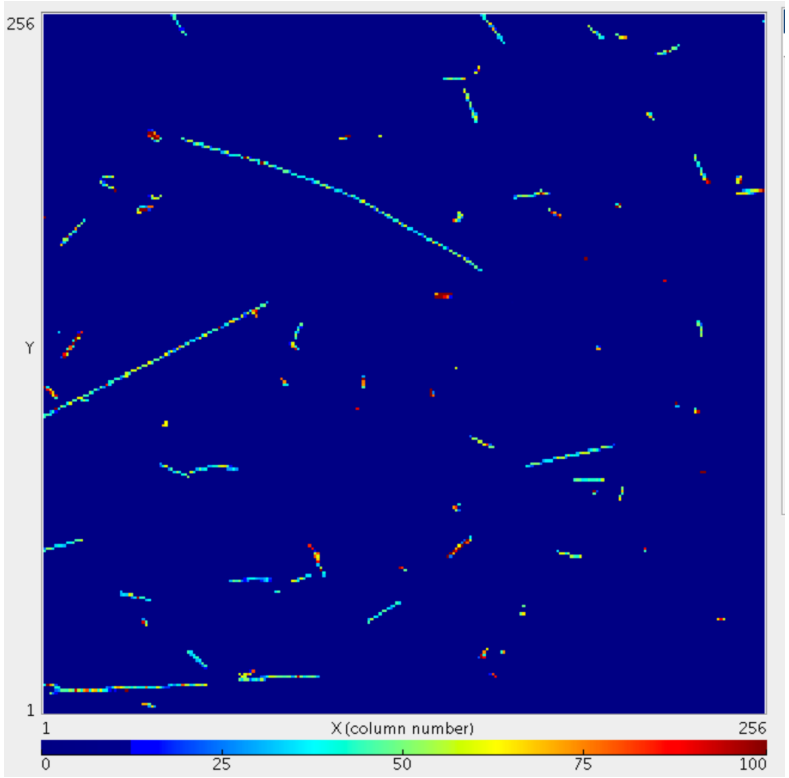
Timepix miniaturised readout

IEAP/CTU, Prague

Timepix chip – 60s exposures



Near sea level

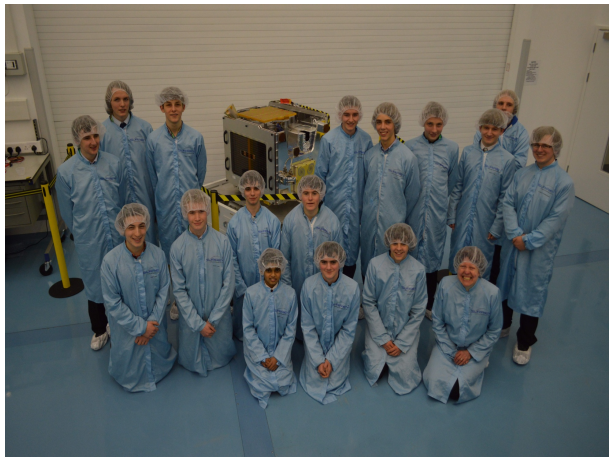


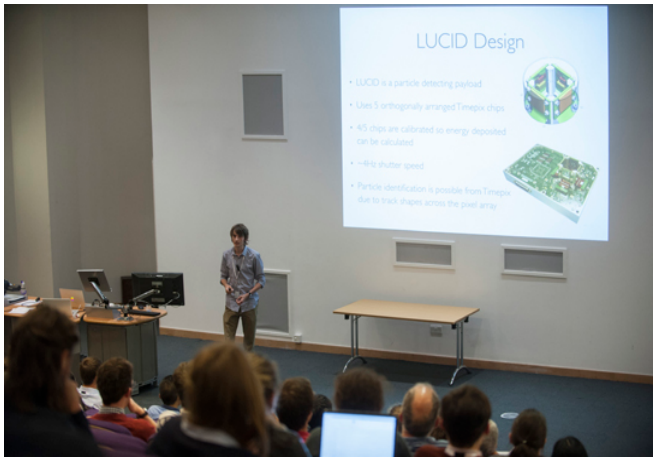
34 000 feet

CERN@school

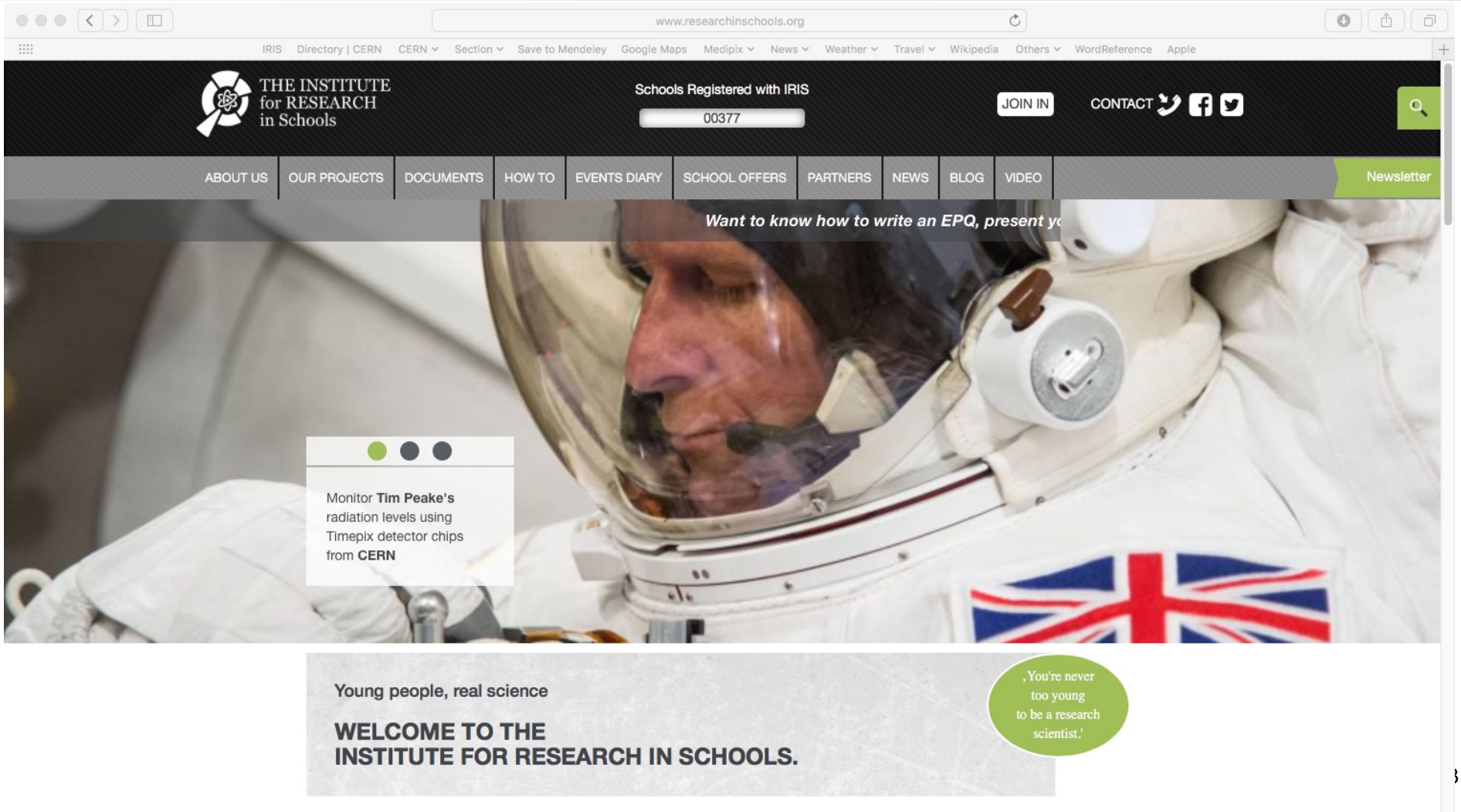
Simon Langton School, Canterbury, England

LUCID detector





Institute for Research in Schools



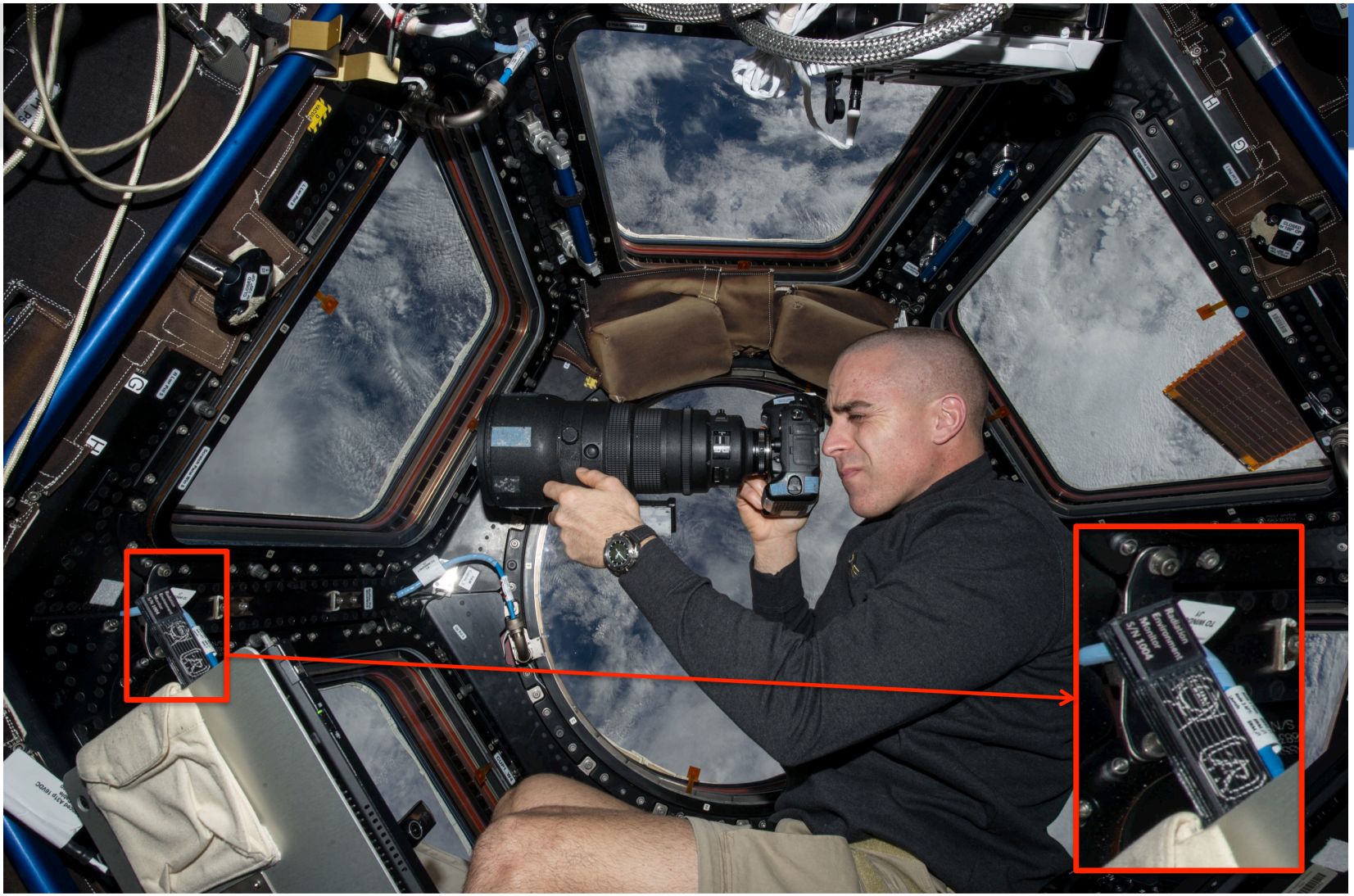
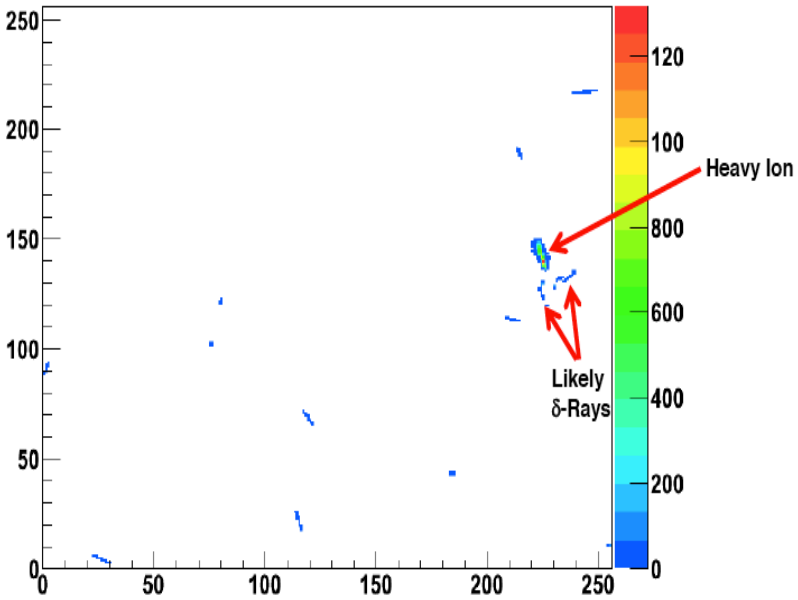
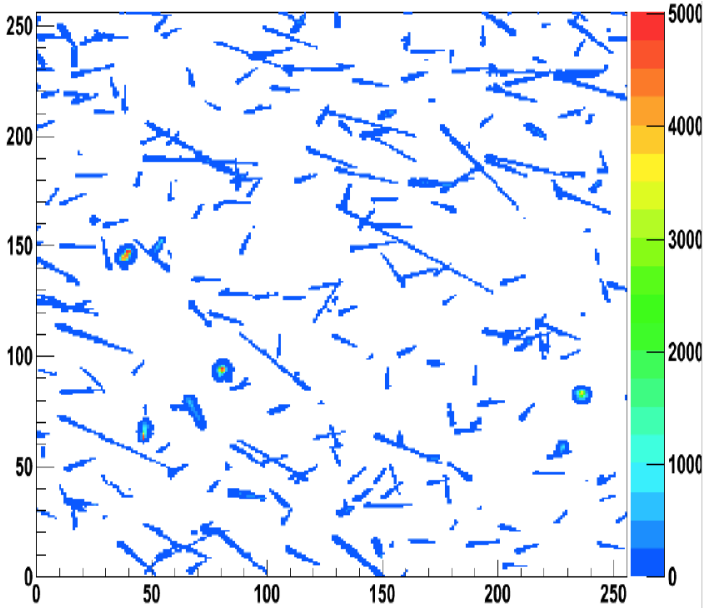


Image of the astronaut Chris Cassidy working near the Timepix USB on the International Space Station (Courtesy of NASA, photo ref. no. iss036e006175)

Timepix - 4s exposures



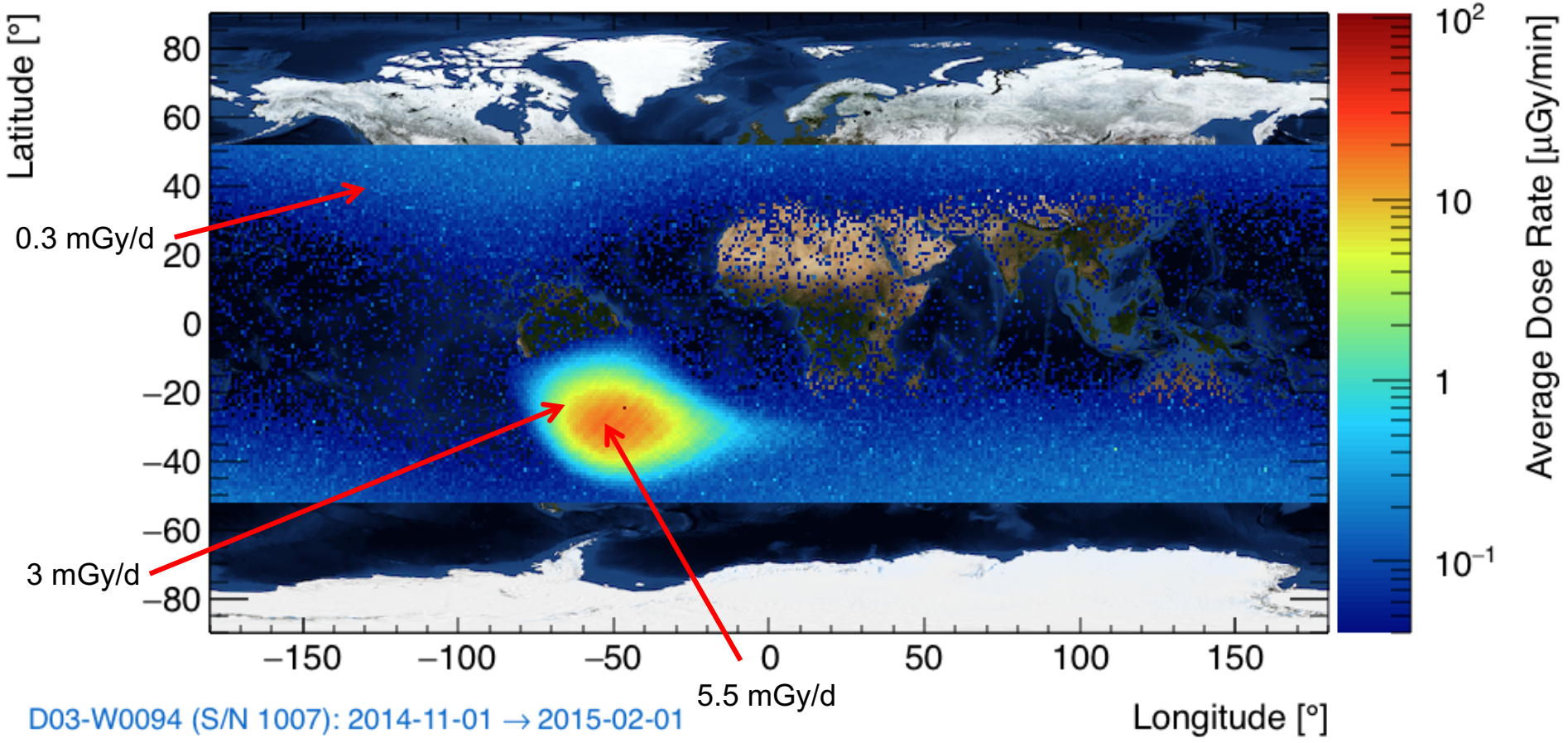
South China Sea



South Atlantic Anomaly

University of Houston, IEAP Prague, NASA

REM Dose Rate Data (μG/min)

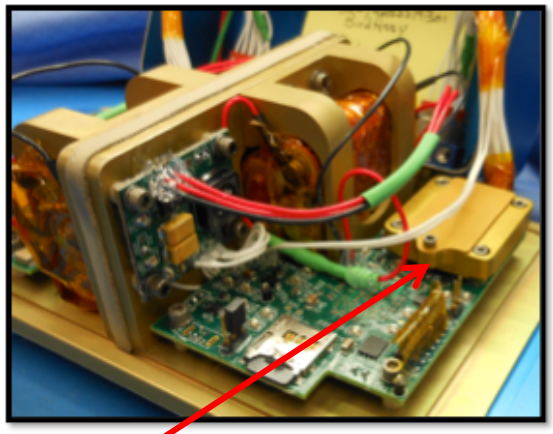


University of Houston, IEAP Prague, NASA

ORION test flight

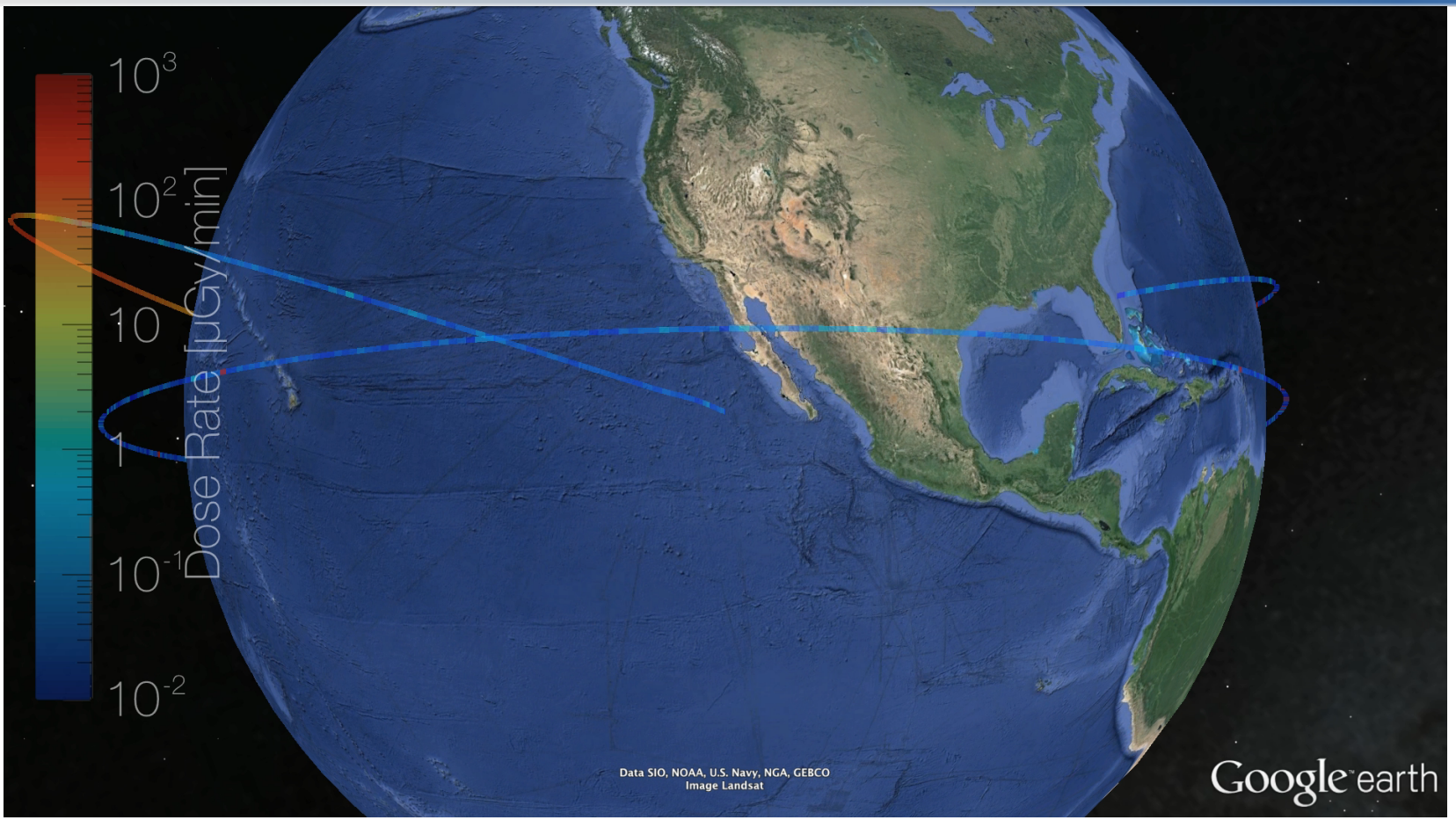
2 TIMEPIX chips inside the BIRD (Battery-operated Independent Radiation Detecto

5 December 2014



Timepix chip

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

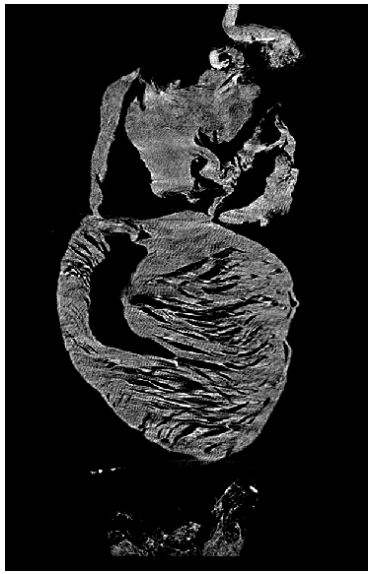


Courtesy of Ryan Rios, NASA, JSCSpace Radiation Analysis Group

Large area detectors

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

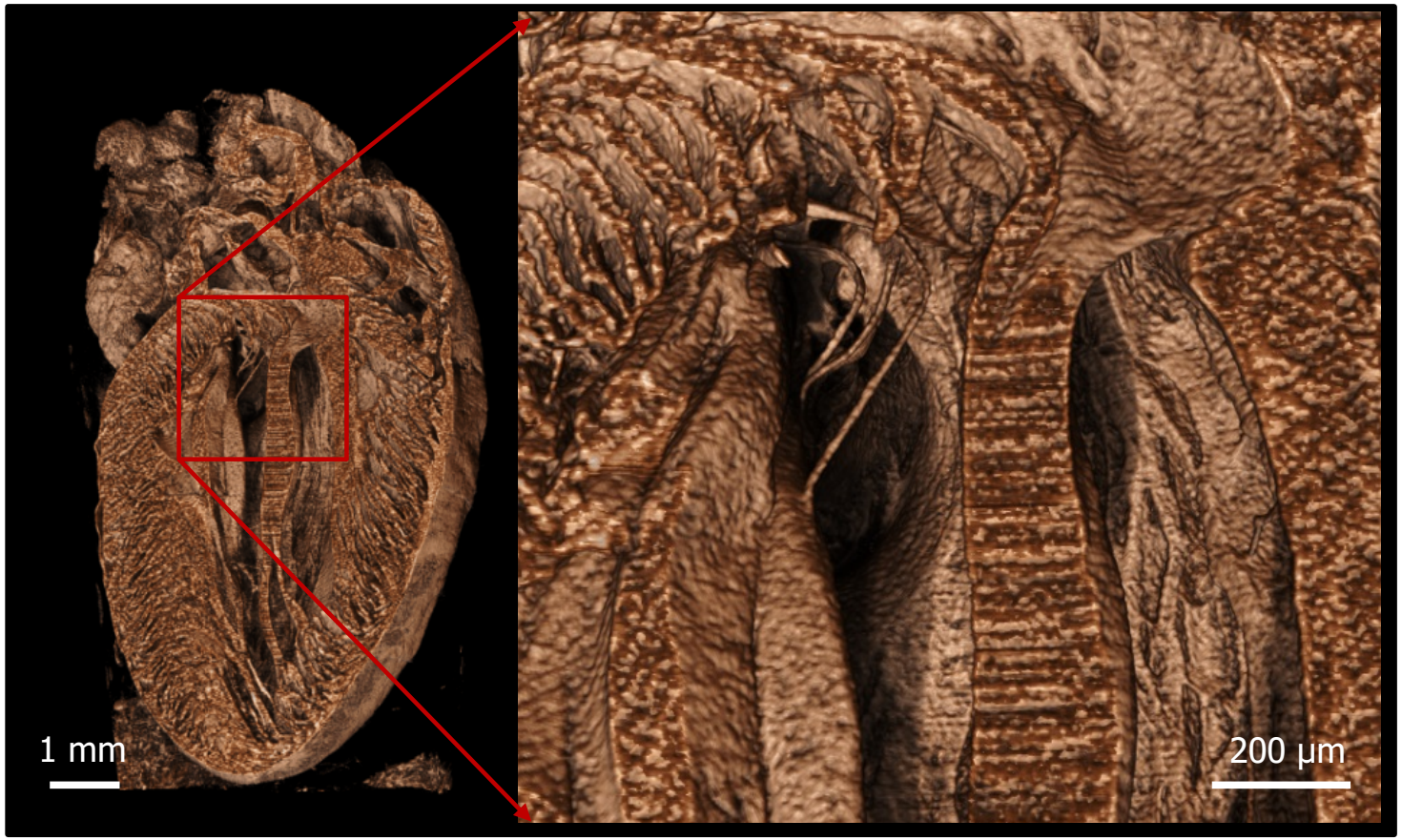
Micro-Computed Tomography scan of mouse heart



Ethanol-preserved mouse heart scanned using the WidePIX$_{10x5}$ detector
60 kVp tungsten spectrum
720 projections, 5 seconds per projection (one hours total)
Spatial resolution ca. 7 μm
Reconstructed using Volex, visualized using CTVox and Amide software

Slide courtesy of J. Dudak, IEAP, Czech Technical University

X-ray Histology



Slide courtesy of J. Dudak, IEAP, Czech Technical University

Understanding our cultural heritage

Painting from 1920's of Holy Family from US Embassy in Prague (85 cm x 65cm)

Understanding our cultural heritage

X-ray scan parameters:

624 tiles - total 5 hours

WIDEPIX 5 x 1 Timepix

Tube settings: 70kVp, 75 μA

Slide courtesy of
J. Zemlicka
IEAP, Czech Technical University

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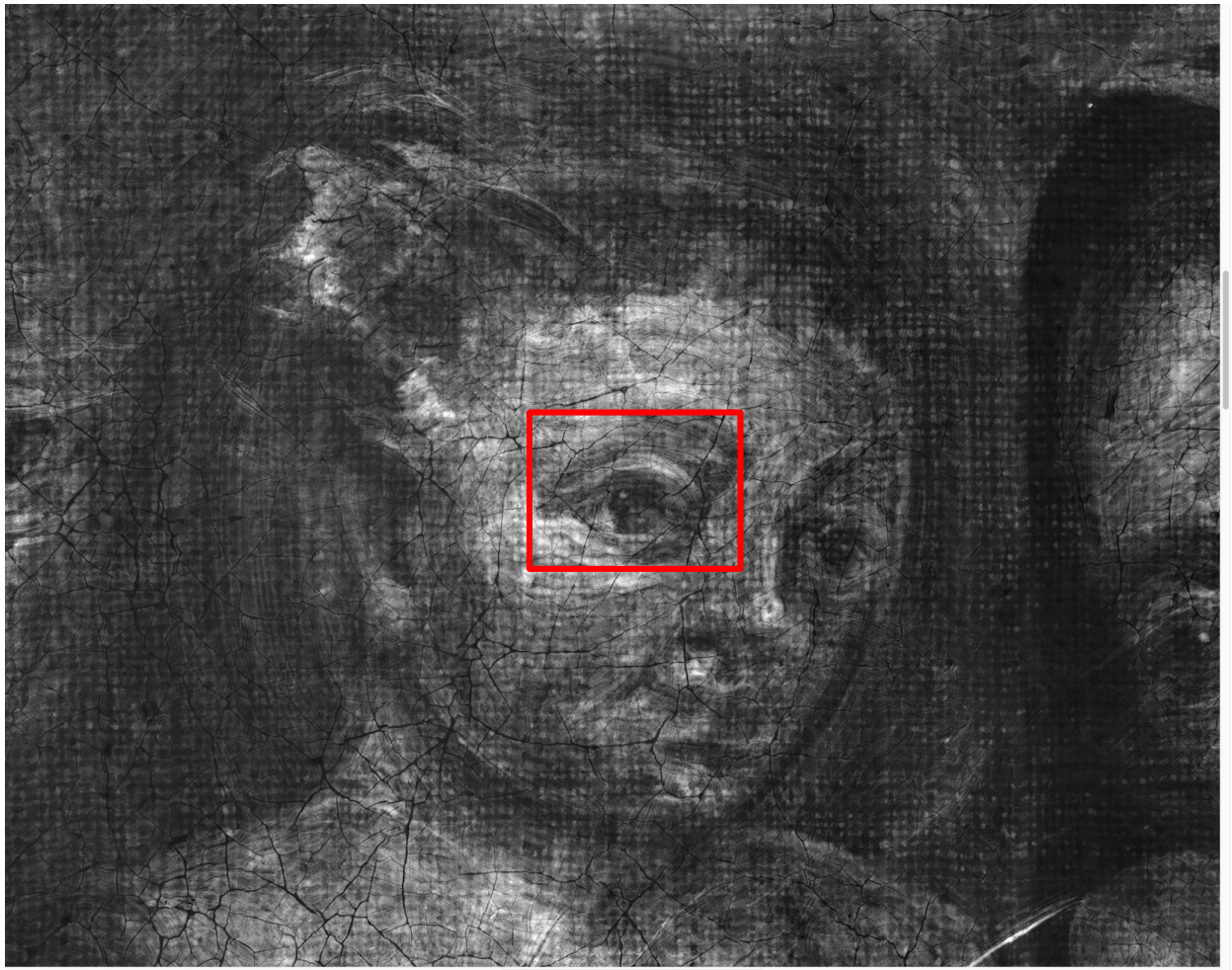


Slide courtesy of
J. Zemlicka
IEAP, Czech Technical University

Understanding our cultural heritage

X-ray scan parameters:

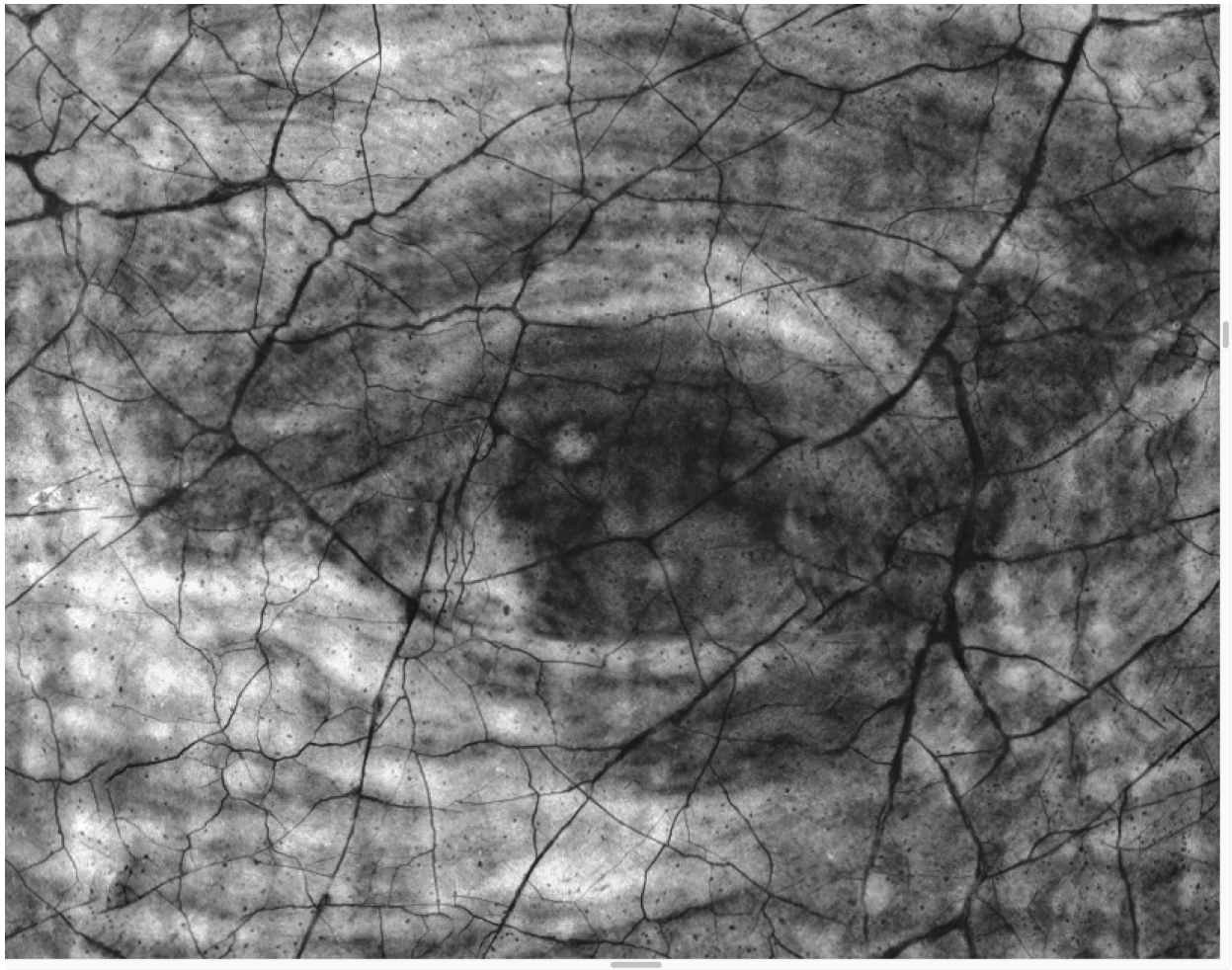
624 tiles - total 5 hours

WIDEPIX 5 x 1 Timepix

Tube settings: 70kVp, 75 μA

23 300 x 19 000 pixels

~450 Mpixels



Slide courtesy of
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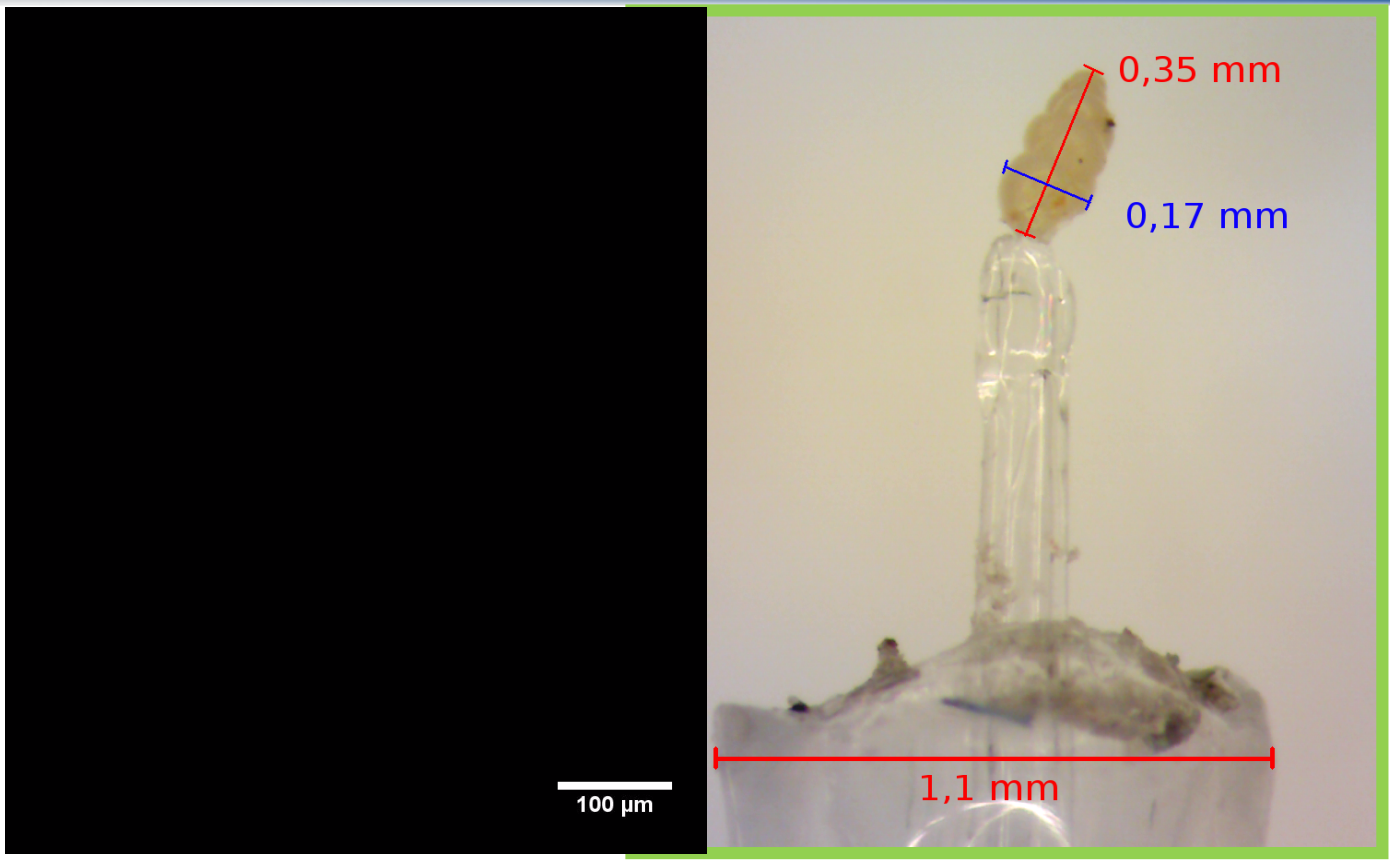
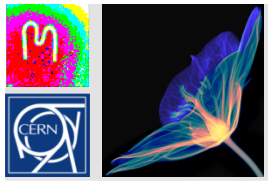
Understanding our natural environment



Foraminifera – single-cell sea organisms living in benthos or plankton.
The sample kindly provided by dr. Katarina Holcova, Faculty of Science, Charles Univ.
Holes through the shell are ca. 1 – 3 micrometers in diameter

Slide courtesy of J. Dudak, IEAP, Czech Technical University



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  - Investigating art and the natural environment
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  - X-ray imaging at synchrotrons
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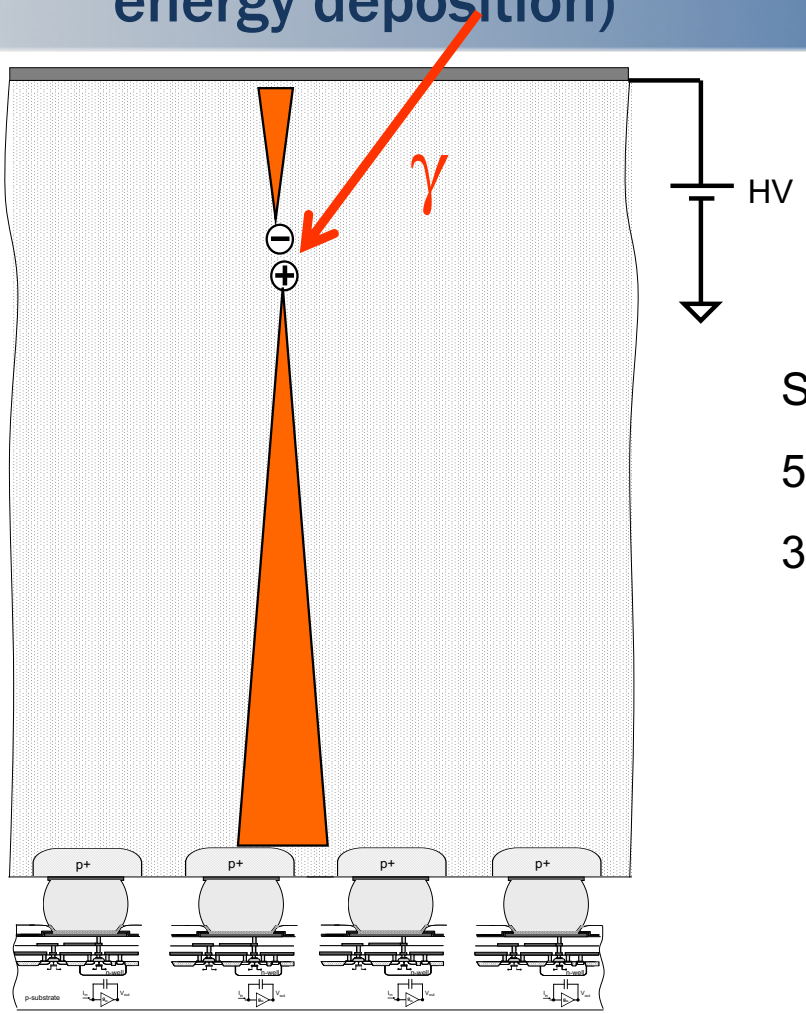
  - Silicon TPC
  - Anti matter research
- Medipix4 and Timepix4
- The Medipix cycle of Innovation
- Conclusions

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

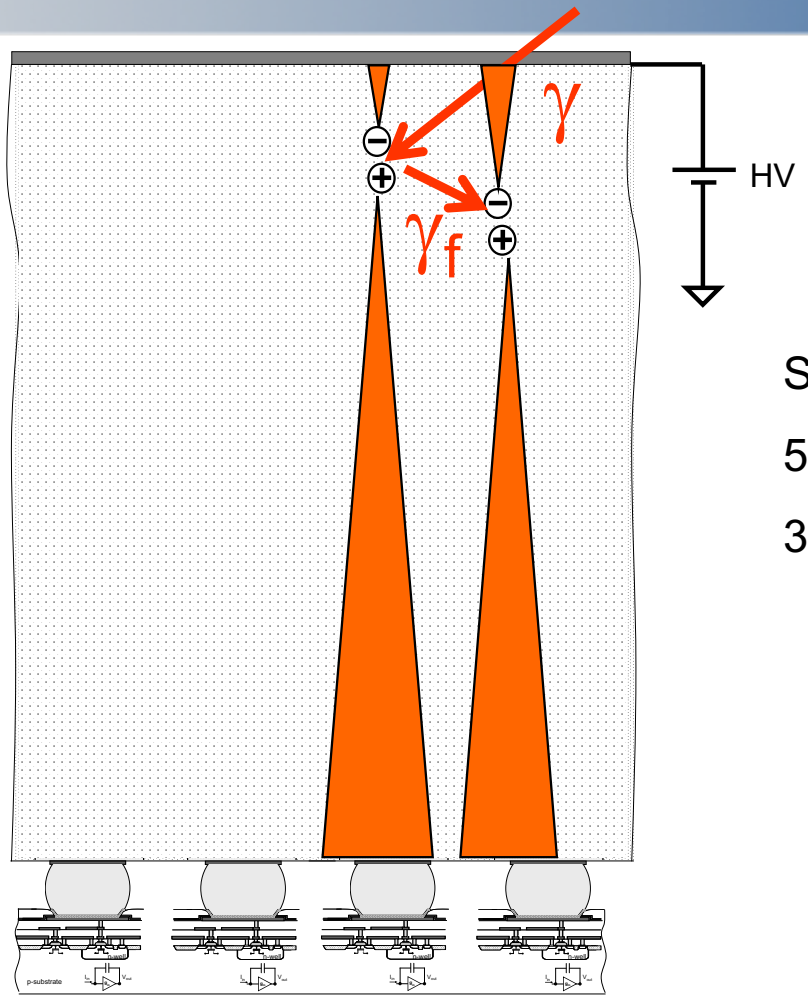


Sensor dimensions to scale:

55μm pixel pitch

300μm thick sensor

Fluorescence in high-Z materials



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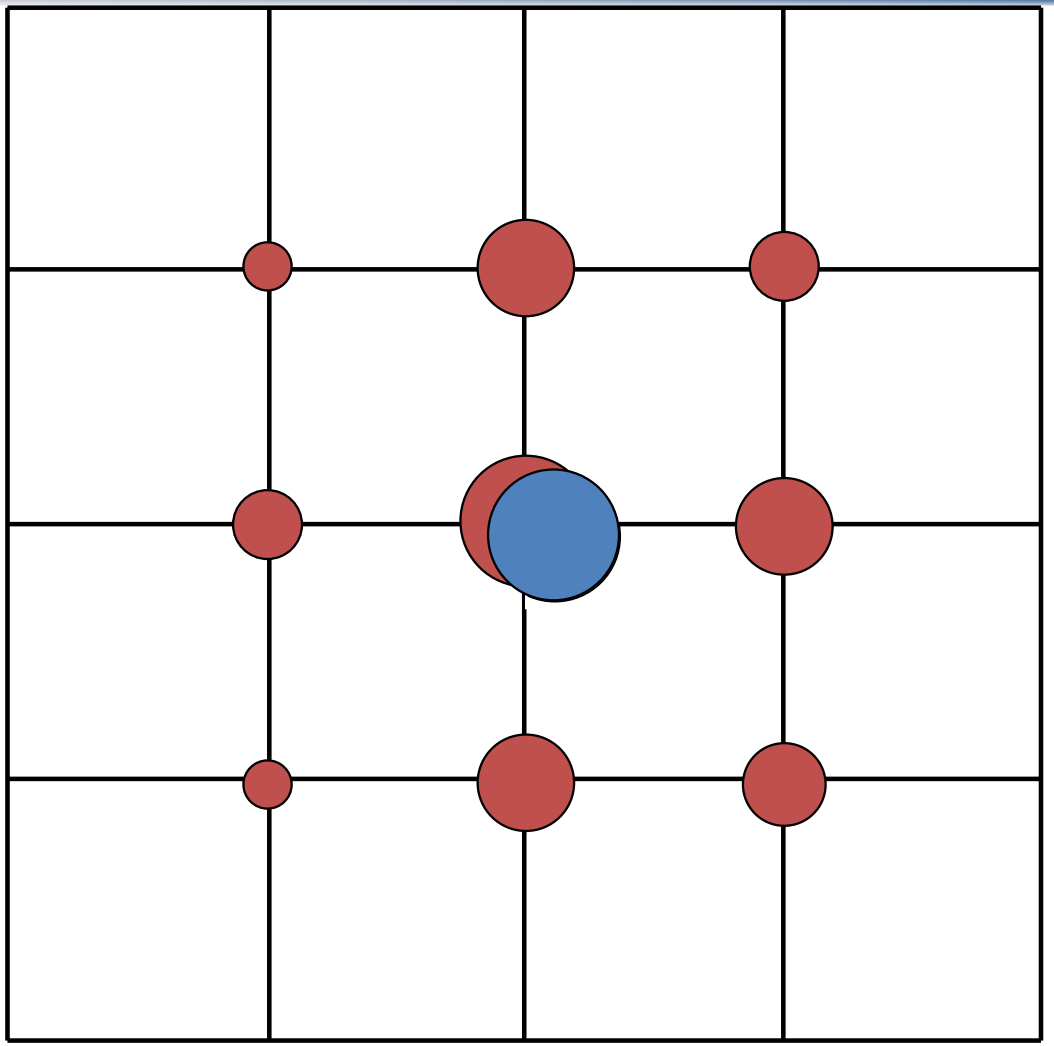
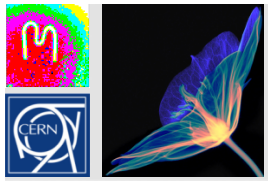
300μm thick sensor

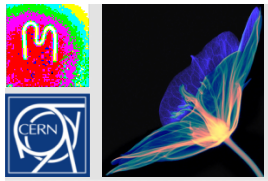
The algorithm for charge reconstruction and hit allocation: Charge Summing Mode





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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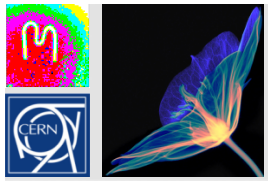

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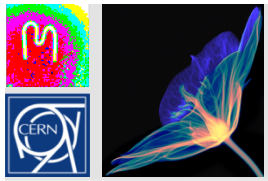

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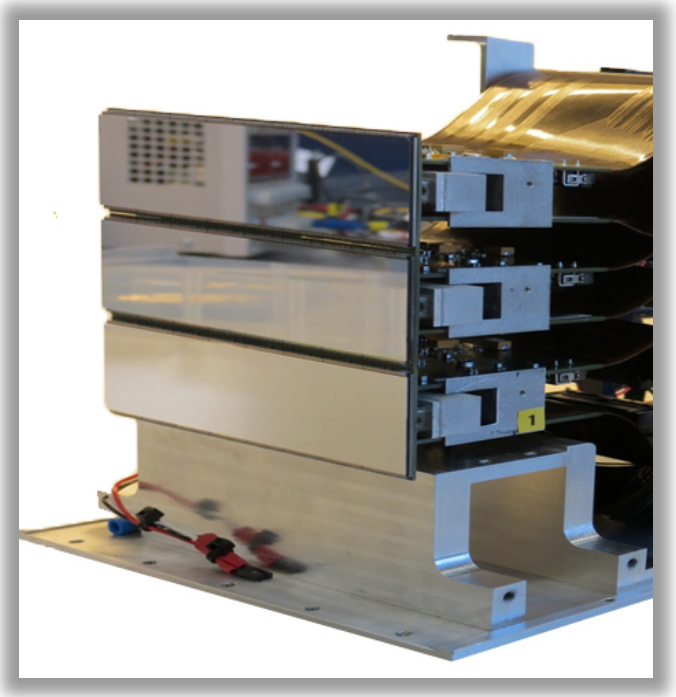
Science & Technology Facilities Council
Technology

Excalibur Detector

- 48 Medipix3 readout chips
- 3 Mpixels @55 microns pitch
- 1 kHz frame rate



3x16 ASIC units of 256x256 pixels

diamond

Science & Technology Facilities Council

Lambda detector from X-Spectrum (DESY)

lambda

Large Area **Medipix3** Based Detector Array

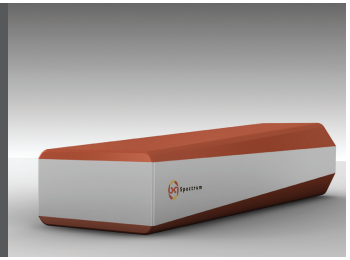
Spectrum

a DESY spinoff company

LAMBDA detector

The LAMBDA pixel detector is designed for high-end X-ray experiments, particularly at synchrotron sources. Using the Medipix3 chip, it achieves an extremely high image quality by combining effectively noise-free photon-counting operation with a small pixel size of 55µm.

For fast and time-resolved experiments, LAMBDA can be read out at up to 2000 frames per second with no time gap between images.



Silicon LAMBDA specifications	
Pixel size:	$(55\mu m)^2$
Detector layout:	1536 x 512 pixels (780k pixels)
Sensor area:	85mm x 28mm
Max frame rate:	2000 frames per second, no time gap
Noise:	Photon counting – noise free at 5keV
Sensor:	300µm-thick silicon
Quantum efficiency:	90% at 10keV
Max. count rate:	10^8 counts/mm²/s
Counter depth:	12 bit with zero time gap between images 24 bit with 1ms time gap between images
Energy binning:	Up to 2 thresholds - see www.x-spectrum.de
External trigger:	5V TTL

LAMBDA with high-Z sensors

The LAMBDA pixel detector is available with different sensor layers for different X-ray energy ranges. For hard X-ray detection, the GaAs and CdTe LAMBDA systems replace the standard silicon sensor layer in LAMBDA with a "high-Z" (high atomic number) sensor. This provides high quantum efficiency at high X-ray energies (75% at 40keV for GaAs, and 75% at 80keV for CdTe), while retaining single-photon-counting performance and a frame rate over 100 times higher than a standard flat-panel hard X-ray detector.

These detectors are available in two variants. The high-resolution system retains a fine pixel size of 55µm. The colour mode system can divide photon hits into up to 8 energy bins, using the "colour imaging" feature of the **Medipix3** chip. This can make it possible, for example, to distinguish different elements in a sample. In addition to the full-size modules described below, these systems are also available with smaller sensor areas (42mm by 28mm).

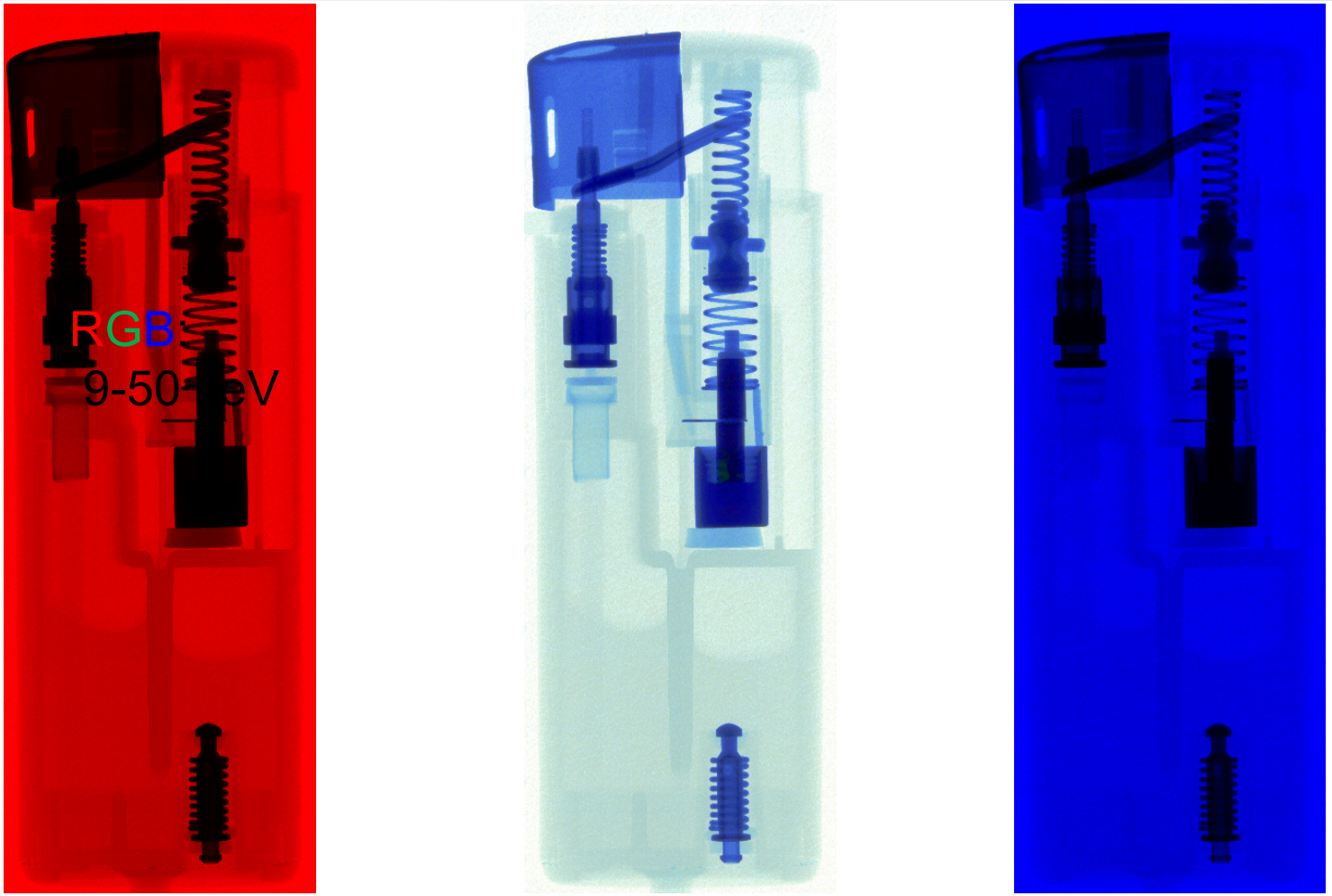
	High resolution module	Colour mode module
Pixel size:	$(55\mu m)^2$	$(110\mu m)^2$
Detector layout:	1528 x 512 pixels (780k pixels)	764 x 256 pixels (196k pixels)
Sensor area:	85mm x 28mm	85mm x 28mm
Max frame rate:	2000 frames per second, no time gap	2000 frames per second, no time gap
Noise:	Photon counting – noise free at 6keV	Photon counting – noise free at 6keV
Sensor:	1000µm-thick CdTe, or 500µm-thick GaAs	1000µm-thick CdTe, or 500µm-thick GaAs
Quantum efficiency:	75% at 40 keV (GaAs) or 75% at 80 keV (CdTe)	75% at 40keV (GaAs) or 75% at 80keV (CdTe)
Max. count rate:	10^8 counts/mm²/s	2.5×10^7 counts/mm²/s
Counter depth:	12 bit with zero time gap between images 24 bit with 1ms time gap between images	12 bit with zero time gap between images 24 bit with 1ms time gap between images
Energy binning:	Up to 2 thresholds	Up to 8 thresholds
External trigger:	5V TTL	5V TTL

X-Spectrum GmbH | www.x-spectrum.de

Indium flakes falling

60ms total time
X 67 slow motion
2000 fps

Colour x-ray of a lighter

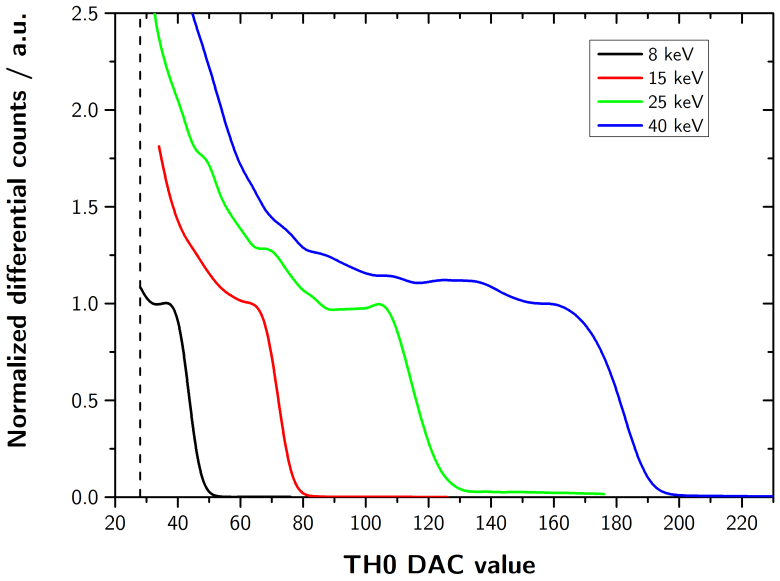


S. Procz et al.

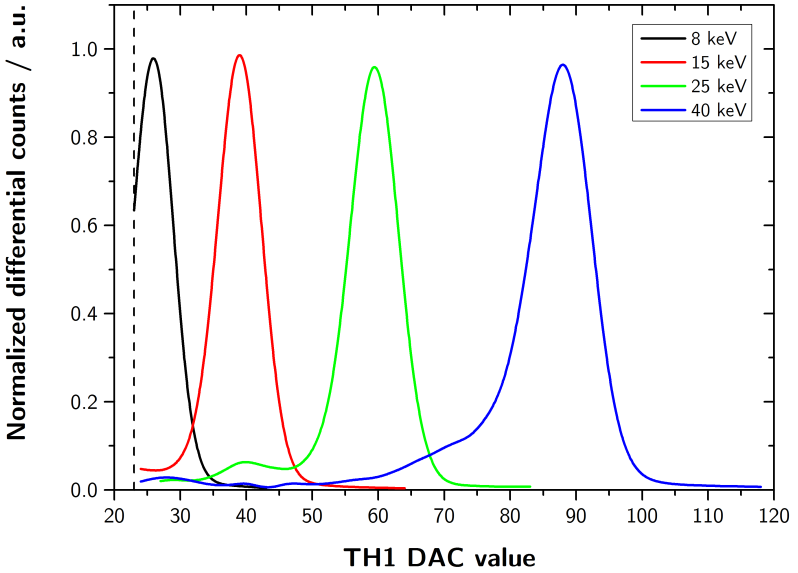
Energy calibration (GaAs 55μm/500μm)

Energy calibration with monochromatic synchrotron radiation (ANKA, KIT0

- 8, 15, 25 and 40 keV
- - 300V bias



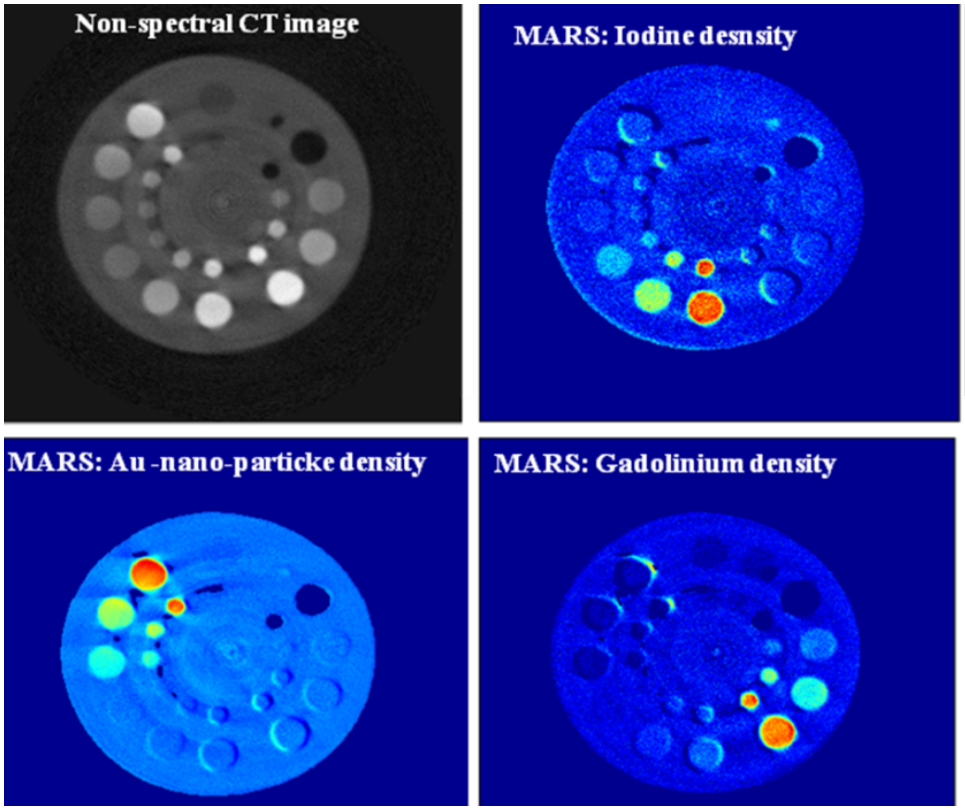
SPM



CSM

Slide courtesy of E. Hamann, KIT/ANKA:
"Characterization of High Resistivity GaAs as Sensor Material for Photon Counting Semiconductor Pixel Detectors", PhD thesis, University of Freiburg, 2013

The future: Functional labels for CT



Complex physiological markers can be made

These often have unique spectral response (contain heavy atoms)

We can measure the spectral response of nano-particle that target aggregated platelets.

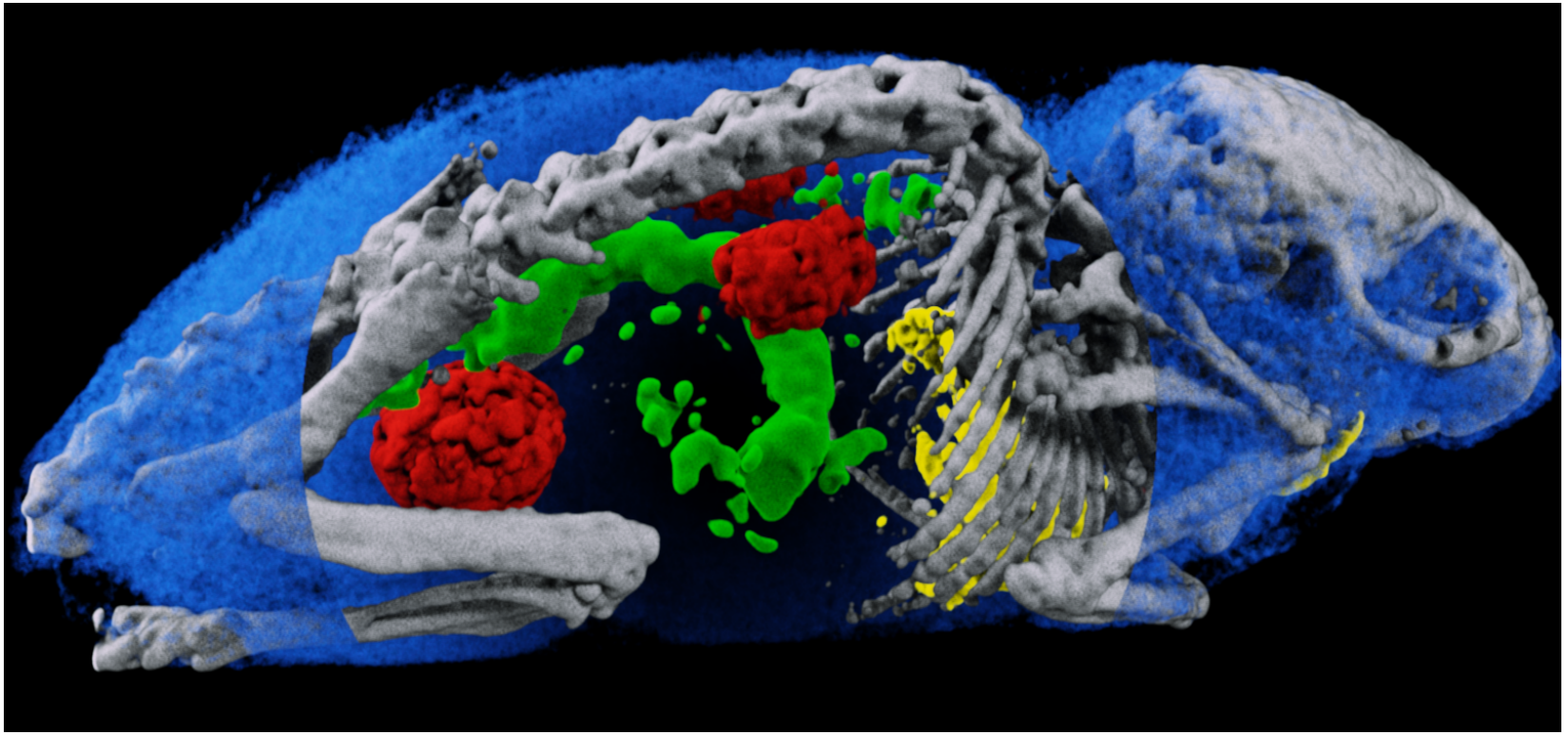
Slide courtesy of A. Butler, University of Canterbury

MARS Bio-scanner now commercial

Notre Dame imaging lab

Slide courtesy of A. Butler, University of Canterbury

Spectroscopic information permits material separation



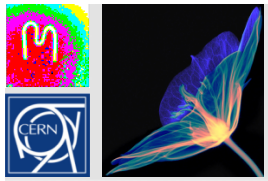
The water has been partly cut away to reveal the bone, gold, gadolinium and iodine

A. Butler, University of Canterbury

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

Workshop on
Medical Applications of Spectroscopic X-ray Detectors
CERN, 15-18 May 2017

- ~130 invited participants of which ~60 were from industry
- All large medical equipment suppliers represented: GE, Philips, Samsung, Siemens and Toshiba
- Also major research institutes present :Johns Hopkins, University of Massachusetts, Mayo Clinic, Royal Marsden, TU Munich etc



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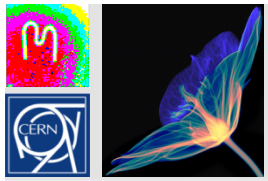
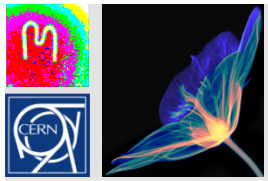


Timepix3 Specs

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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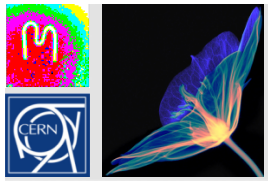

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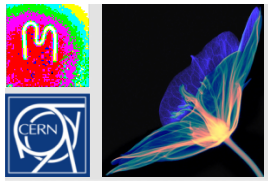

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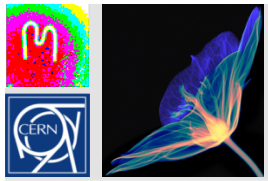

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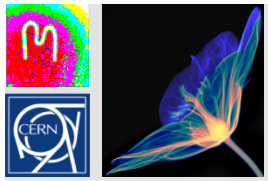

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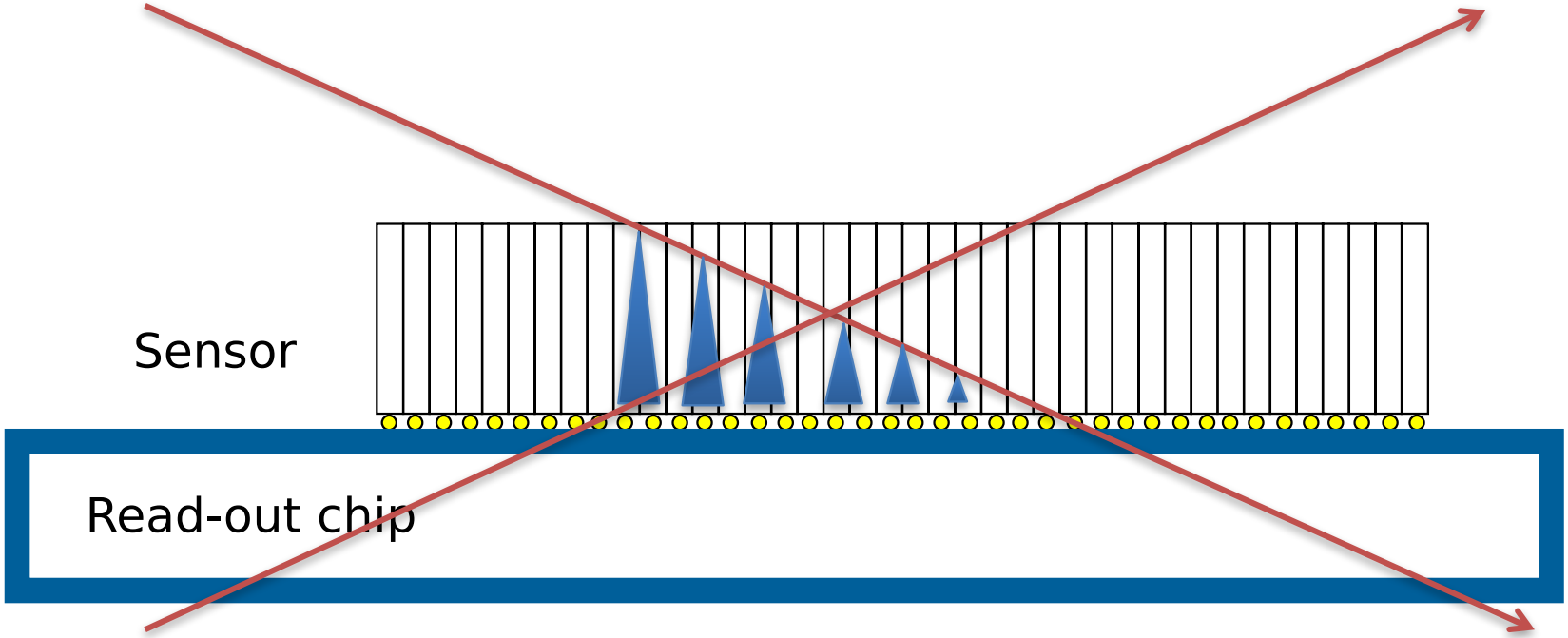
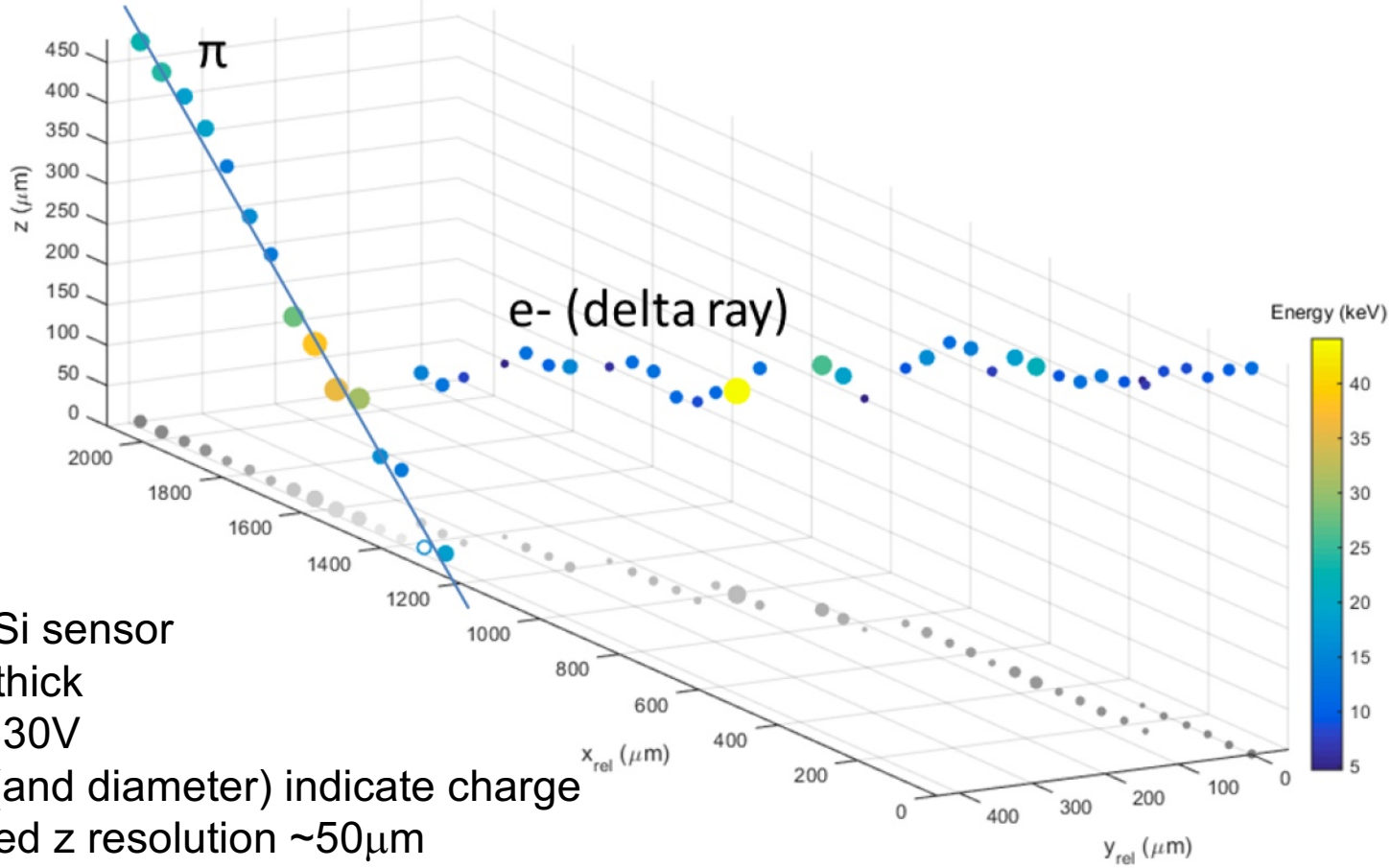
Tracking in a single Si layer

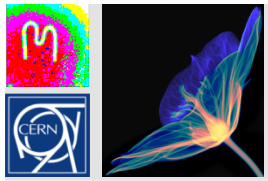


Test with 120GeV/c Pion Track



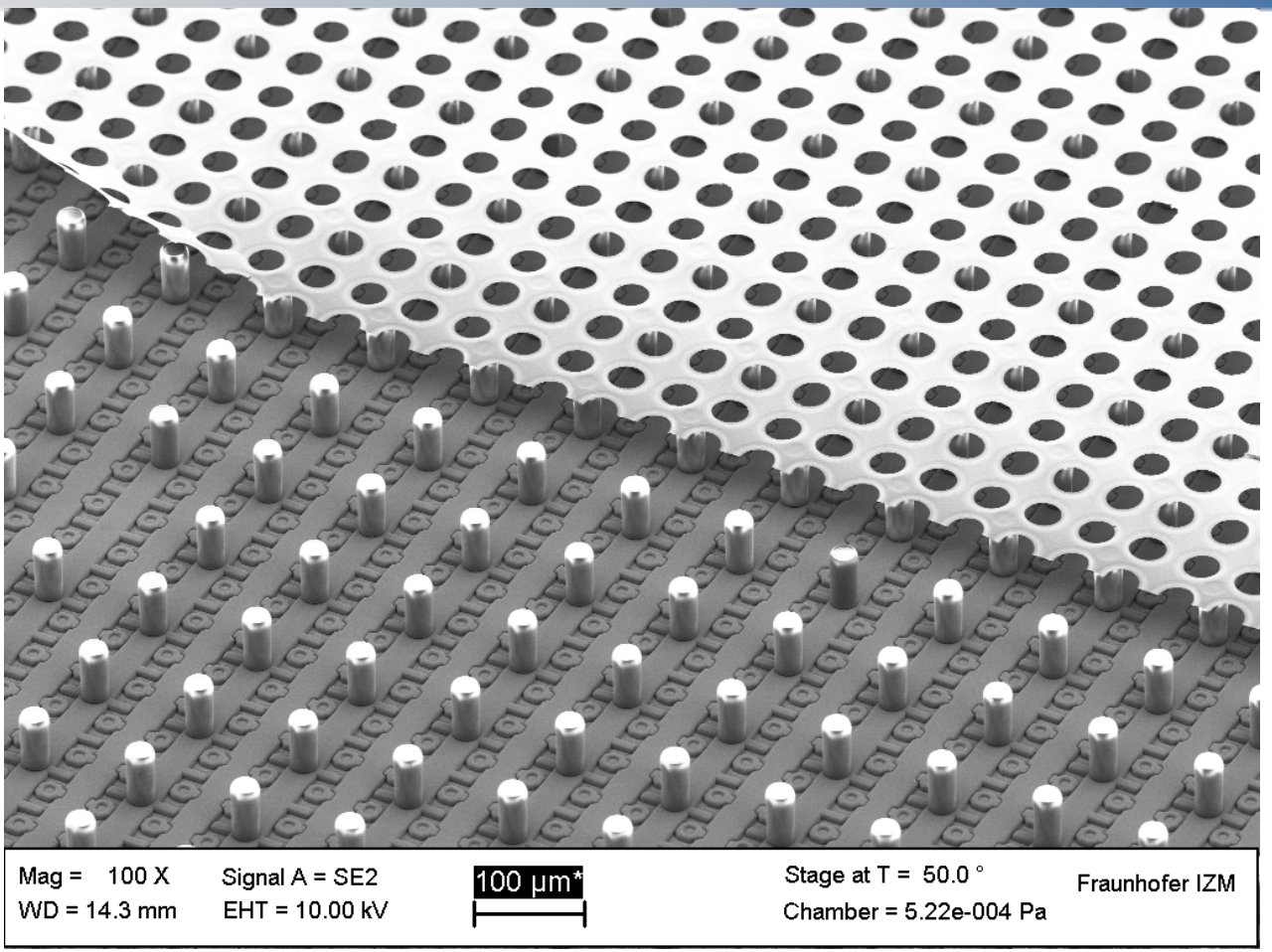
60 deg
p+ in n Si sensor
500μm thick
V_{bias} = 130V
Colour (and diameter) indicate charge
Measured z resolution ~50μm

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

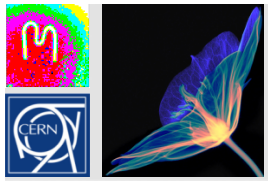


Timepix3 miniaturised readout

InGrid on Timepix3



Slide courtesy of K. Desch, Univ Bonn



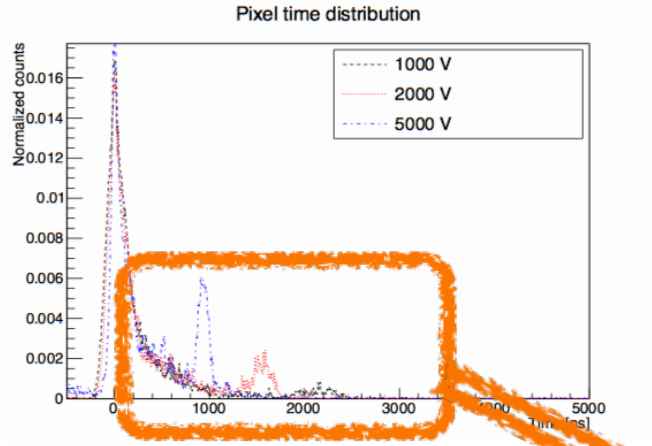
Anti-matter research

AEgIS experiment seeks to measure the pull of gravity on anti-hydrogen

Timepix3 used as ‘active bubble chamber’ to detect anti-proton annihilation

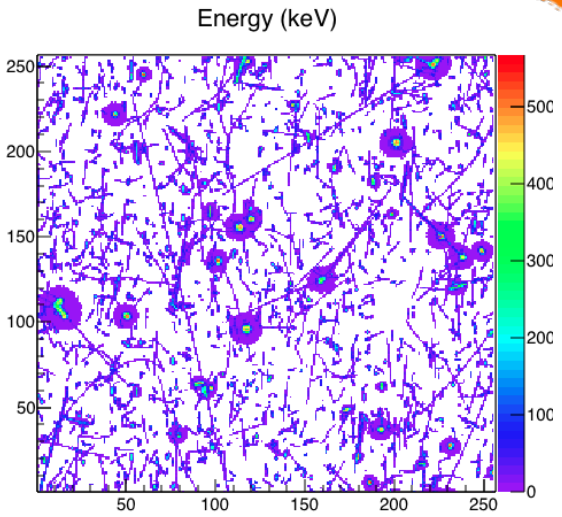
Continuing work to reduce operating temperature

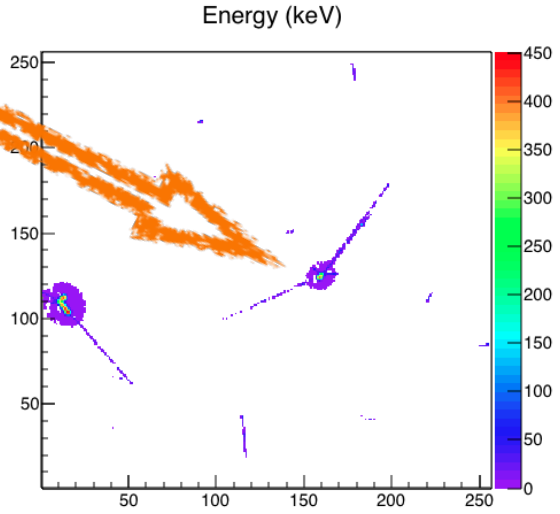
Time Topology



✳ Background (fast gaussian, pions and fast fragments from beam annihilations on chamber walls and moderators) is extinguished before the arrival of late antiprotons.

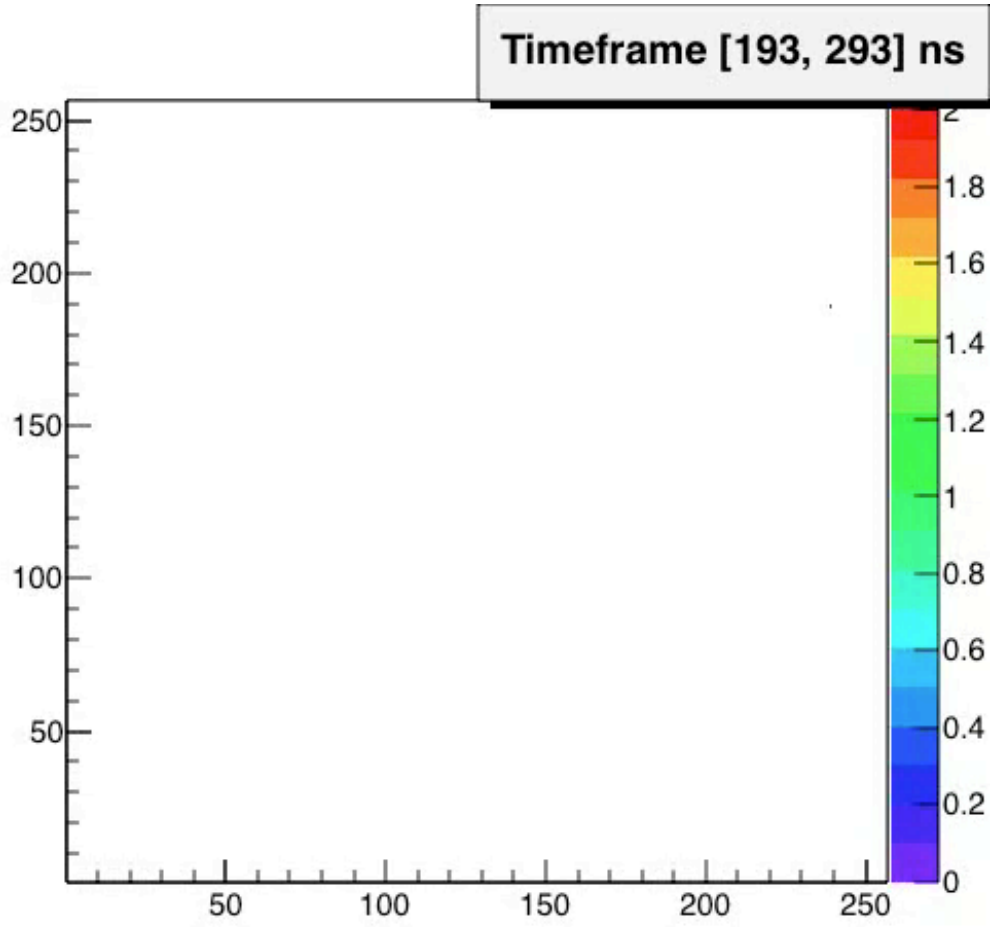
✳Time delay of slow antiprotons - indication for their energy. E.g. 500 ns delay - 40 keV; 1 us - 10 keV; 2 us - 2555 keV.





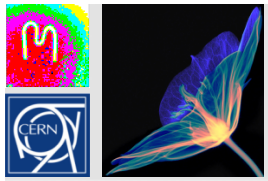
Slide courtesy of N. Pacifico, CERN

Movie of AEgIS test – ToT data using ToA window



Slide courtesy of N. Pacifico, CERN

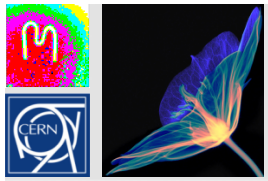
- 300-700 ns: main burst of secondaries coming from annihilation in the moderators
- 700-1200 ns: scattered antiprotons
- 1200-1500 ns: energy-selected antiprotons.



Other applications

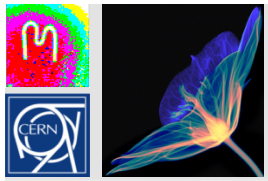
- X-ray materials analysis
- X-ray non-destructive testing
- Dosepix chip development
- Gamma camera
- Compton camera
- Low Energy Electron Microscopy
- Transmission electron microscopy
- Dose deposition tracking in hadron therapy
- High resolution neutron imaging
- Single (visible) photon imaging
- Time-of-Flight mass spectrometry

} combined with MCP



Applications for CERN/Physics

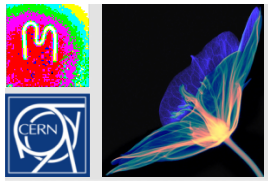
- LHCb VELOpix chip is directly derived from Timepix3
- LHCb Timepix3 telescope – 80 Mhits/sec
- Sensor studies for CLIC/LHCb
- Background radiation monitoring at ATLAS and CMS
- Beam monitoring in UA9
- Beam Gas Interaction monitor is operating at CERN PS
- ASACUSA experiment
- Beta particle channeling in ISOLDE
- Forward physics using Timepix3?
- 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



Industrial licensing of Medipix/Timepix chips

- 2 Medium Sized Enterprises
  - PANalytical (The Netherlands)
  - Kromek (UK)

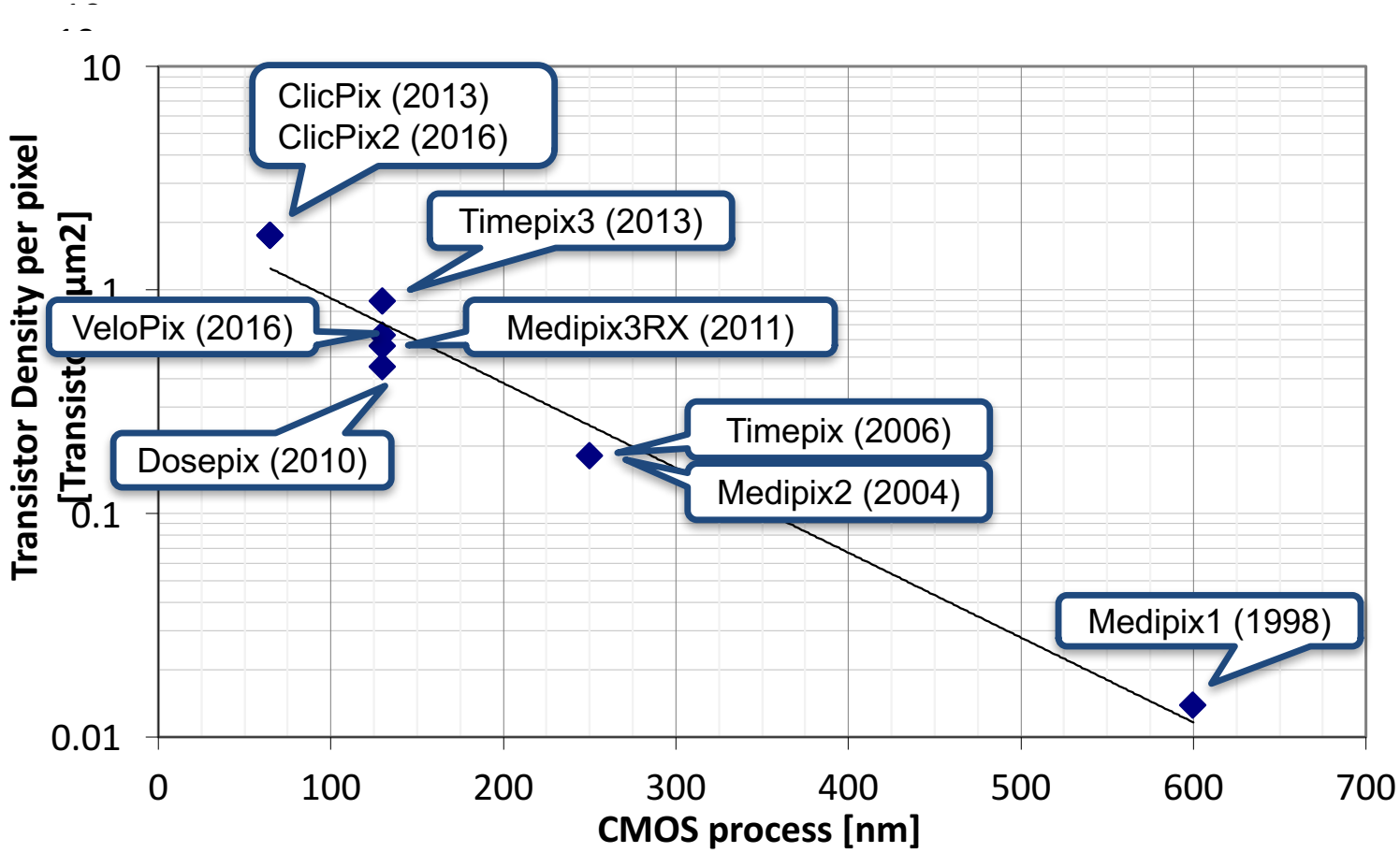
- 6 start-ups from Collaboration members:
  - Advacam s.r.o. (from IEAP, Czech Republic)
  - Amsterdam Scientific Instruments (from NIKHEF, The Netherlands)
  - MARS Bio-imaging (from University of Canterbury, New Zealand)
  - Quantum Detectors (from Diamond, UK)
  - X-ray Imaging Europe (from FMF, Germany)
  - X-Spectrum (from DESY, Germany)



Outline

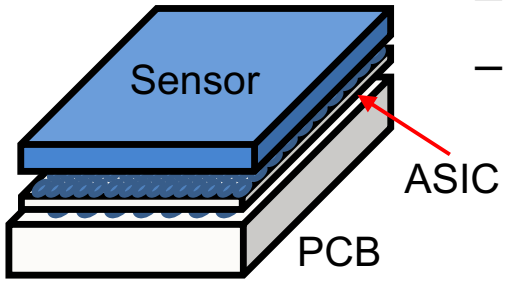
- The Timepix chip
  - Educational use
  - Space dosimetry and space weather
  - X-ray histology
  - Investigating art
- The Medipix3 chip
  - X-ray imaging at synchrotrons
  - Spectroscopic X-ray imaging for medicine
- The Timepix3 chip
  - Silicon TPC
  - Anti matter research
- Medipix4 and Timepix4
- The Medipix cycle of Innovation
- Conclusions

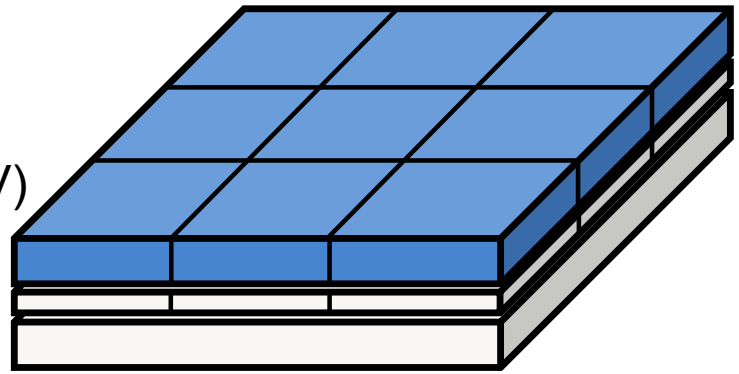
“Moore’s Law” of Medipix Family

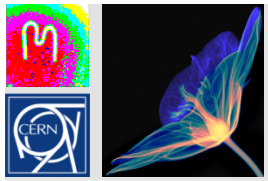


What's next?

- The Medipix4 Collaboration was started in March 2016
- Chips to be fully tile-able on 4-sides – use of Through Silicon Vias (TSV) for I/O
- Medipix4 Photon counting spectrometric chip
  - Will use charge summing and allocation scheme
  - Multiple thresholds
  - Pixel pitch varied to match sensor material
  - Better high count rate performance (aimed at human CT)
- Timepix4
  - Smaller pixel pitch?
  - Better timing resolution (~200ps)
  - Better high count rate performance (TSV)



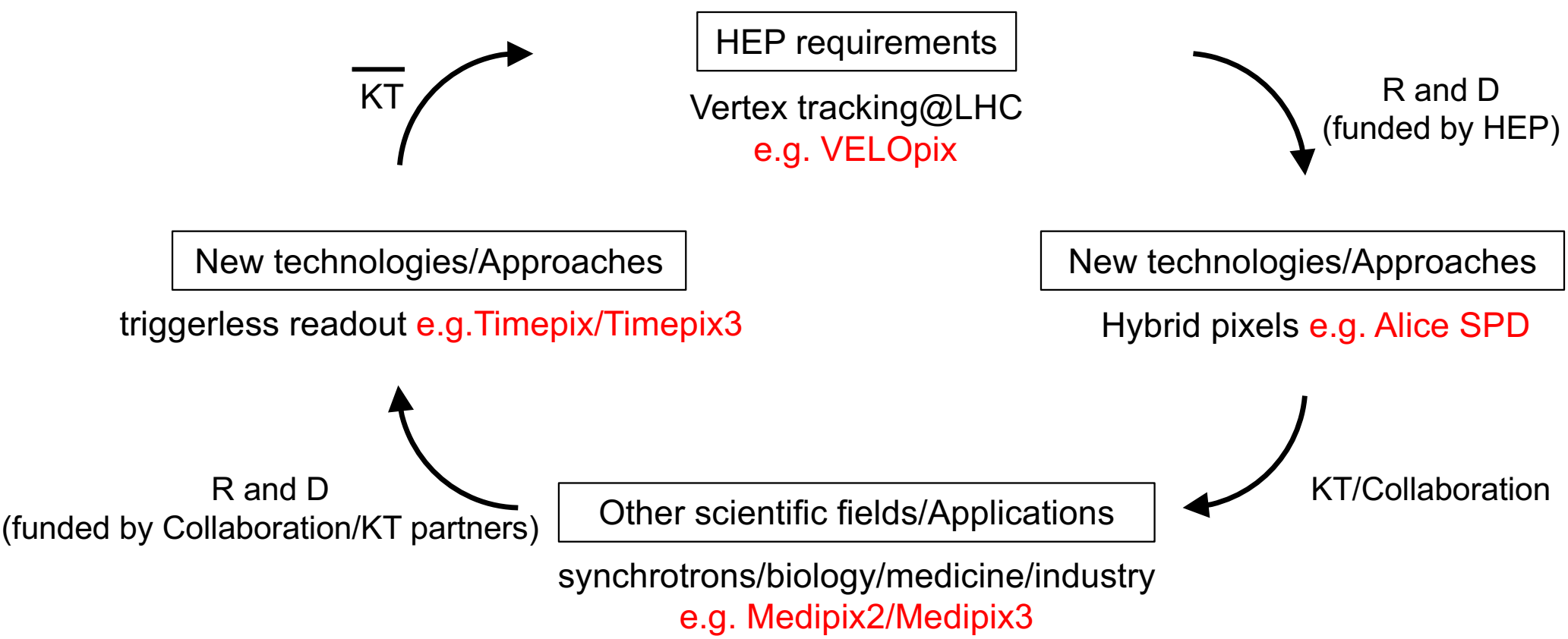


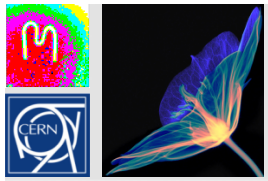


The Medipix4 Collaboration

- CEA, Paris, France
- CERN, Geneva, Switzerland,
- DESY-Hamburg, Germany
- Diamond Light Source, Oxfordshire, England, UK
- IEAP, Czech Technical University, Prague, Czech Republic
- IFAE, Barcelona, Spain
- JINR, Dubna, Russian Federation
- NIKHEF, Amsterdam, The Netherlands
- University of California, Berkeley, USA
- University of Houston, USA
- University of Maastricht, The Netherlands
- University of Canterbury, New Zealand
- University of Oxford, England, UK
- University of Geneva, Switzerland

Medipix Cycle of Innovation - enhanced by Knowledge Transfer



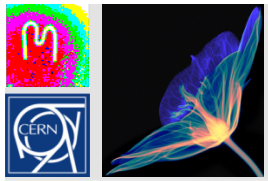


Conclusions

- Hybrid pixel detectors were developed as tracking detectors of LHC
- The Medipix2 and Medipix3 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 opening new possibilities with single layer tracking
- Spin-off activities spin back to physics

Thank you for your attention!

Medipix3RX images: S. Procz et al.



Backup slide

Moore's uncertain future