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SPITZENFORSCHUNG FÜR
GROSSE HERAUSFORDERUNGEN

Status DTS

Marc Weber

MT Annual Meeting
March 2019, Jena

Outline

- DTS structure in PoF IV
- What has DTS achieved in the past years ?
- How has this helped “Matter“ ?
- What are the challenges for the next decade ?
- Glimpse at the *Distributed Detector Lab*

MT Annual Meeting 2018, HZB

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DTS in PoF-IV

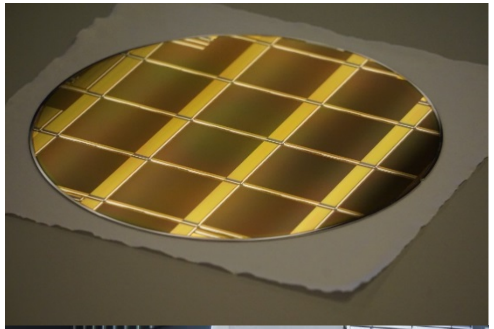
ST1: Detection and Measurement	ST2: System Technologies	ST3: Science Systems
Sensing	Advanced Data Transmission	Particle Physics, Hadrons & Nuclei
ASICs	Digital real-time data acquisition and processing systems	Photon Science
	Novel Engineering Techniques, Advanced Materials and Interconnects	Astroparticle Physics
		Beam Physics

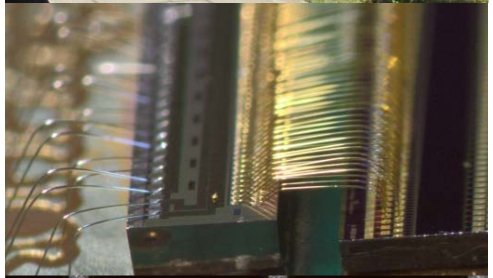
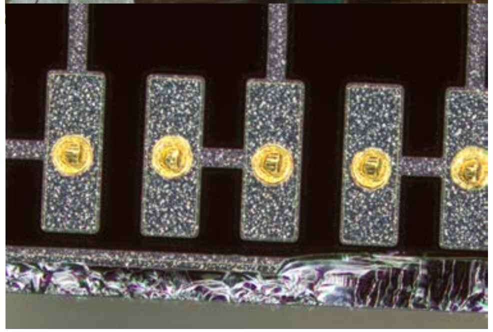
New DTS structure emphasizes links within “Matter“ even better. “Projects“ within application fields of ST3 relate to demonstrators and will be updated regularily.

What has DTS achieved in the past years ?

Achievements in sensors, ASICs and interconnects

- Monolithic HVCMOS sensors are ready for application in (particle physics) experiment
- Monolithic CMOS sensors are ready for application in photon science
- Provided sophisticated high-Z sensors for hard X-rays
- Much enhanced application-specific integrated circuit (ASIC) design competence
- Acquired world-level competence in interconnect and packaging technology for highest integration density



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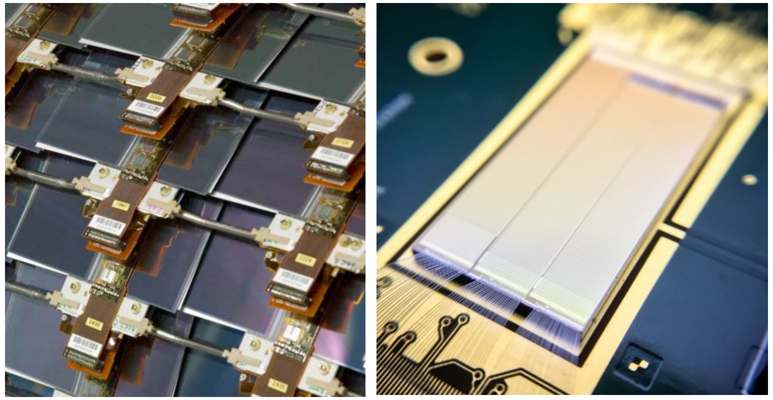
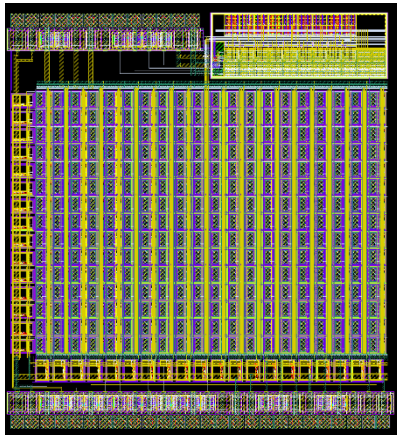
Monolithic HVCMOS sensors



Hybrid vs. monolithic sensors

HVCMOS advantages

- Very affordable, commercial process
- Much reduced material and thus good resolution
- Simplified detector system and module design



HVCMOS achievements

- Large-area, radiation-hard, fast and efficient sensors have been demonstrated
- HVCMOS is now a proven technology with a bright future

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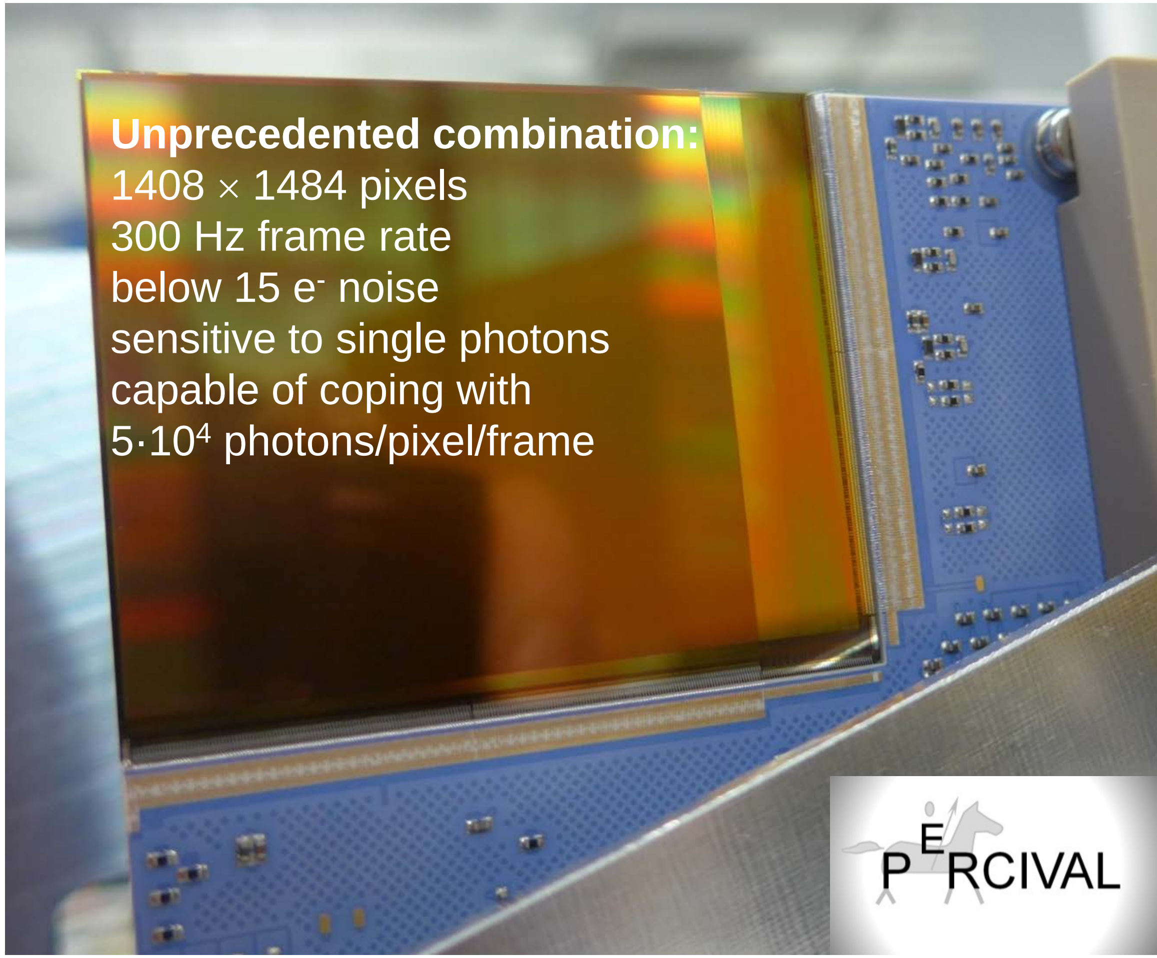
Monolithic CMOS images for soft X-ray

Back-thinned CMOS advantages

- Unique sensitivity to soft X-rays
- “Stitching” enables large-area detectors

CMOS achievements

- Fast megapixel camera (and more pixels to come)
- Large dynamic range, low noise
- Will find wide application in photon science and possibly elsewhere



Rutherford Appleton Lab / STFC

Elettra Sinchrotrone Trieste

Diamond Light Source

Pohang Accelerator Laboratory

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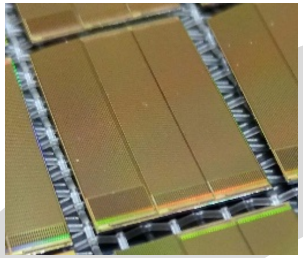
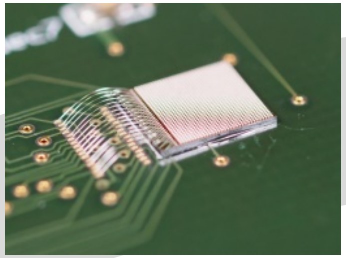
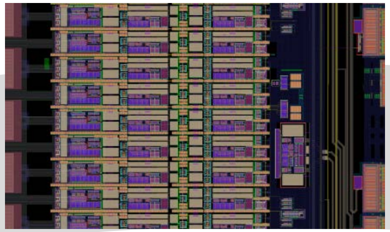
Selected ASIC submissions

July 2018
ATLASPIX2_TSI
Project: ATLAS

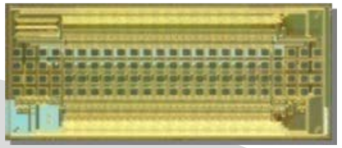




August 2018
PhotonV2
Project: Multi-purpose ROC

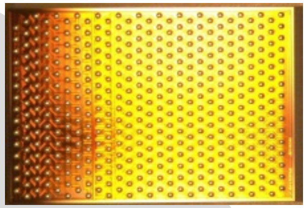


Mid 2019
Gotthard-HR (with PSI)
Project: KALYPSO



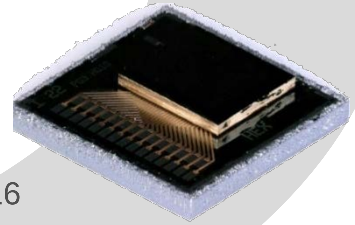
August 2015
SwitcherBGv2
Project: Belle II

November 2015
Edet DCD
Project: EDET

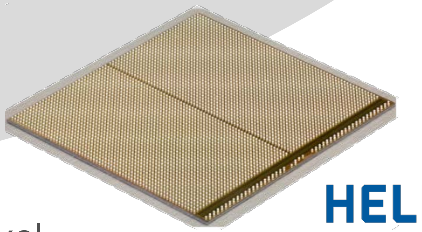


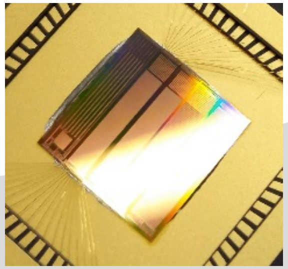
April 2018
MuPix_TSI
Project: Mu3e

November 2016
DSiPM
Project: Medical imaging, particle and astroparticle physics



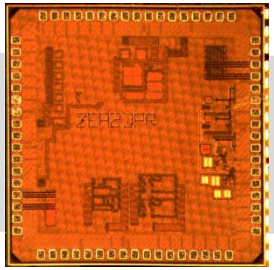
March 2016
DSSC
Project: XFEL



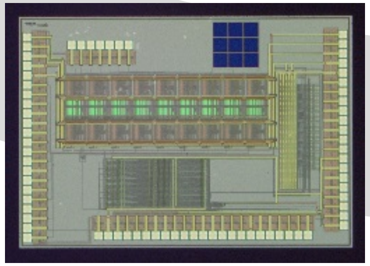


August 2016
ALPHA
Project: HVCMOS Pixel

2016
JuMPAR
Project: JUNO



2016
PhotonV2
Project: Multi-purpose ROC

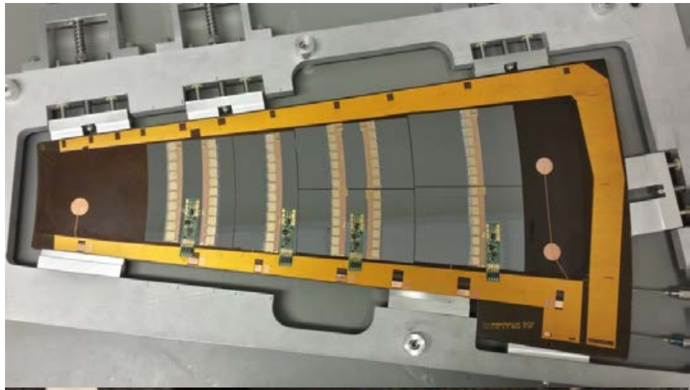


November 2017
AGIPD0.6
Project: XFEL

Achievements in advanced materials and engineering techniques

The best sensors and ASICs do not yet make a functional detector system

- We build light-weight large (CF) support structures
- We design cutting-edge thermo-mechanical-electrical modules and staves
- We have made much progress in automated assembly methods
- All this requires world-level competence in advanced materials, simulations and innovative engineering techniques

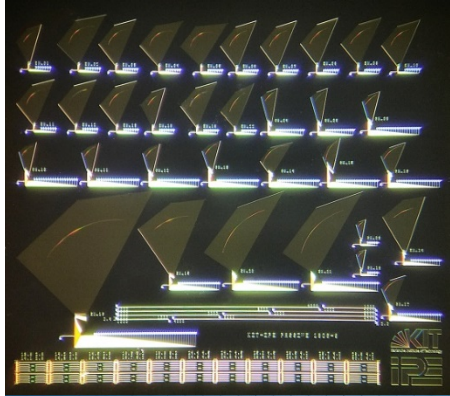


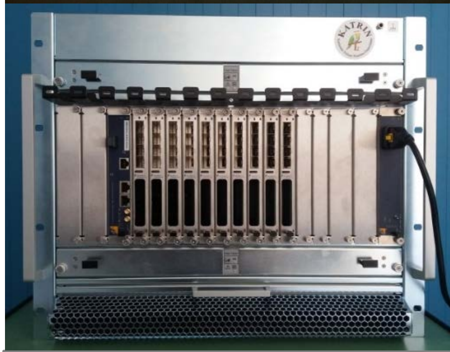
DTS achievements in data acquisition

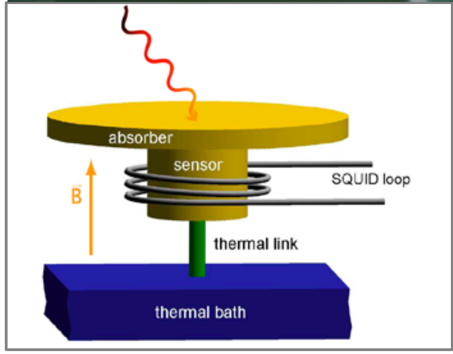
- Pioneering silicon photonics in detector instrumentation. Goal: Tb/s on one fiber
- Accelerating scientific computing by orders of magnitudes with GPUs
- Word-level competence in read-out of many-pixel superconducting sensors

DAQ Platform

- Providing a versatile µTCA DAQ platform
- Creating strong competence in very high-end trigger and data acquisition systems
- Modular smart scientific camera platform (UFO camera) for photon science







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DTS DAQ platform: components & features

FPGA Features

- Fast parallel preprocessing
- x Gb/s transceivers
- High flexibility

Micro TCA / AMC Features

- High-performance digital systems
- Scalable
- Communication fabric
- Hot swap, in-built diagnostics

Communication Features

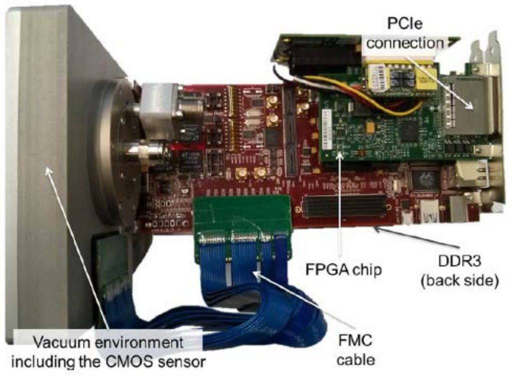
- PCIe, Ethernet

UFO DAQ Framework

Configuration layer

- Scale communication
- Scale computation

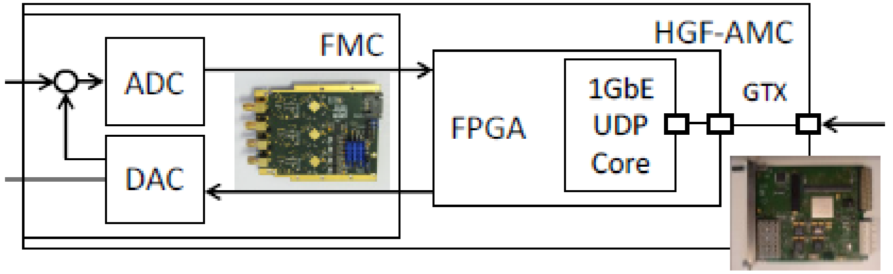
UFO DAQ Framework



Micro TCA for physics

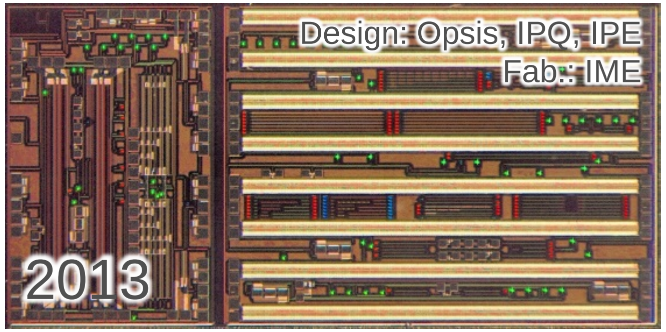
HGF AMC

Onboard FPGA

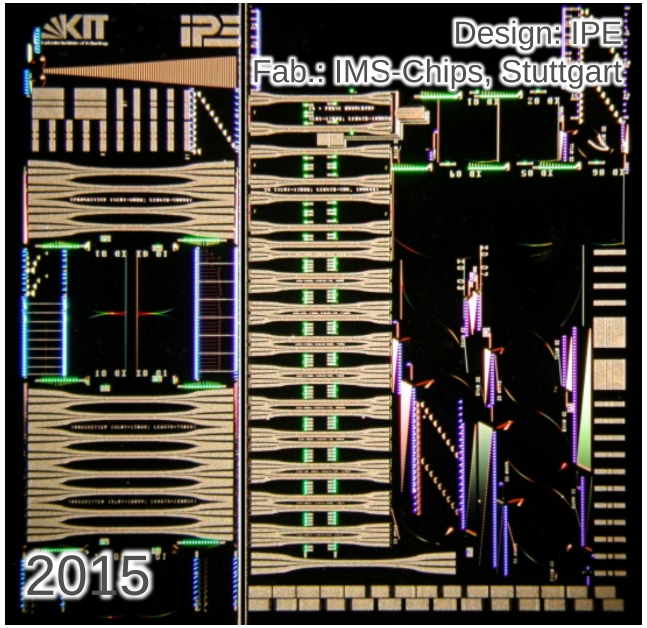


Silicon photonic chips

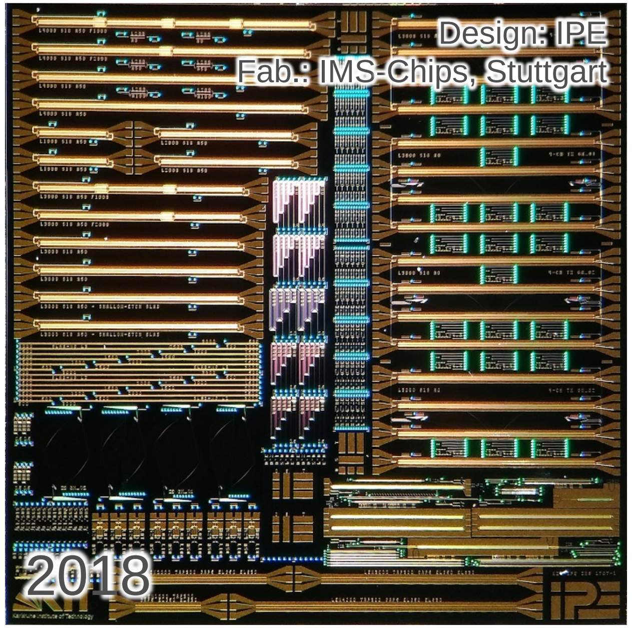
- Started from scratch
- Photonic chip design is challenging: few comprehensive tools, few standard processes
- Many functional designs
- Innovative and world-best features
- Compact WDM systems
- Major progress in developing design and simulation tools



2.4×4.9 mm²



10×10 mm²



9.3×9.3 mm²

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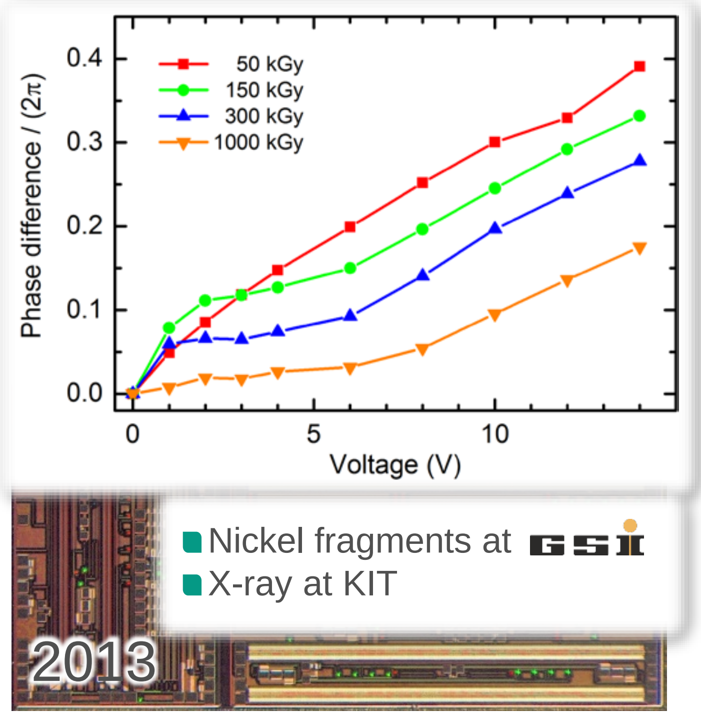
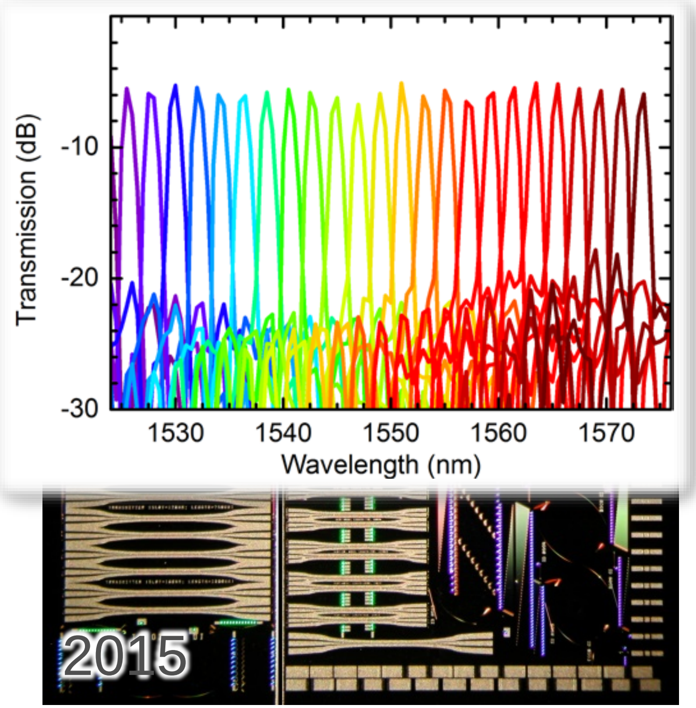
Silicon photonic chips

Highest measured radiation hardness of pn-modulators



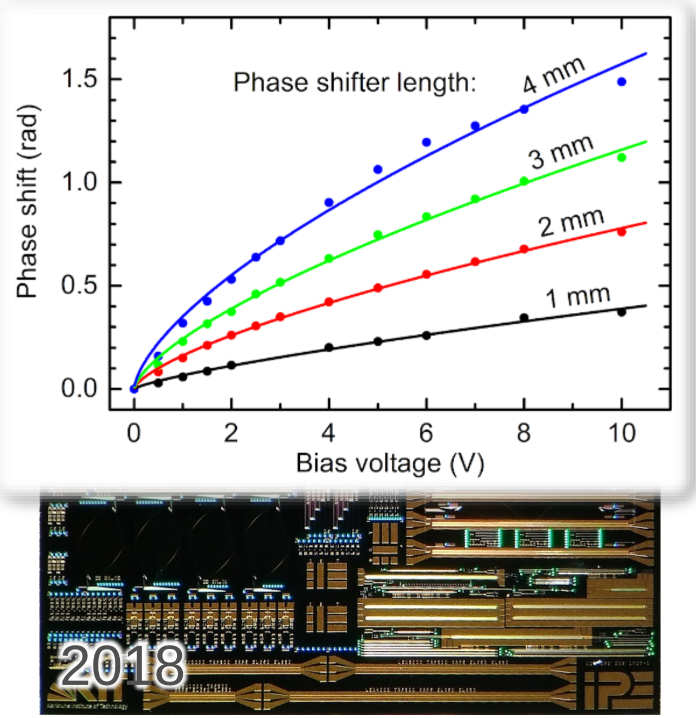
2.4 × 4.9 mm²

Fast modulators and excellent (de-)multiplexers



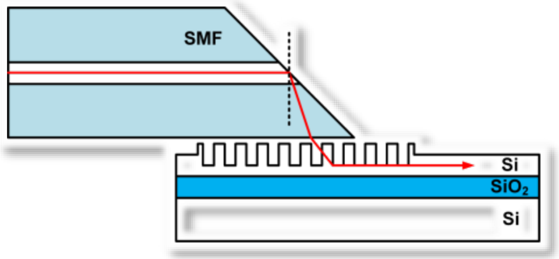
10 × 10 mm²

All-silicon monolithically integrated WDM systems

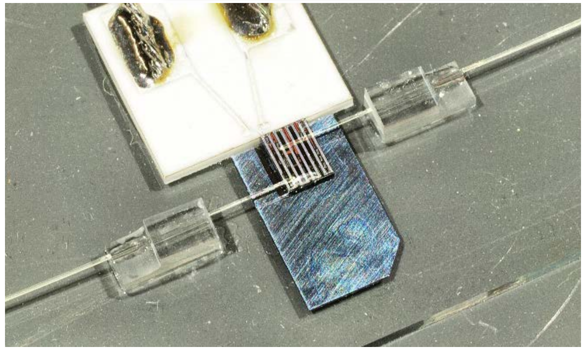


9.3 × 9.3 mm²

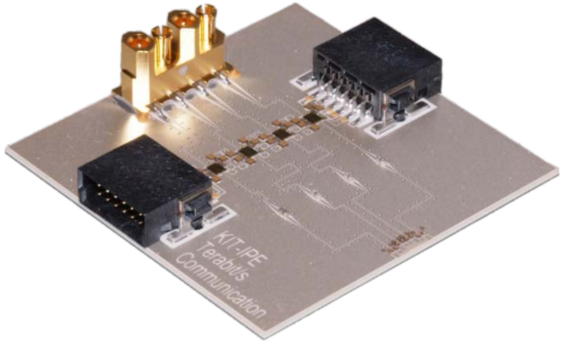
Data transmission status and vision



- **40 Gb/s demonstrator** near completion
- Concept allows scaling to **5 Tb/s** on one fiber
- Huge scope for improvements (e.g. monolithically integrated Ge photodiodes, higher modulation formats for higher rate, etc.)
- “Holy grail” could be **monolithic integration** of sensors, ASICs, photonics



fiber-chip-coupling with angle-polished fibers



miniaturized drivers

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How has this helped “Matter“ ?

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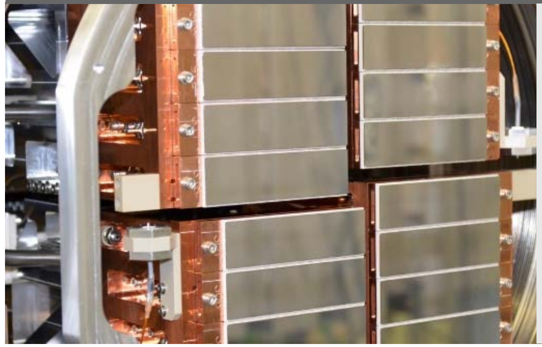
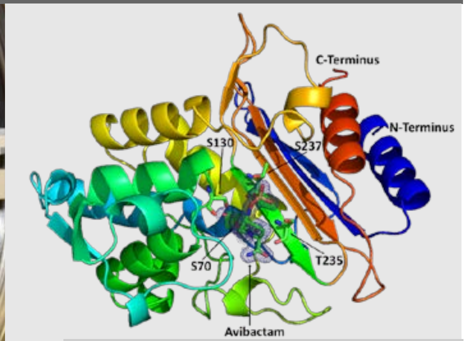
Detector systems for photon science

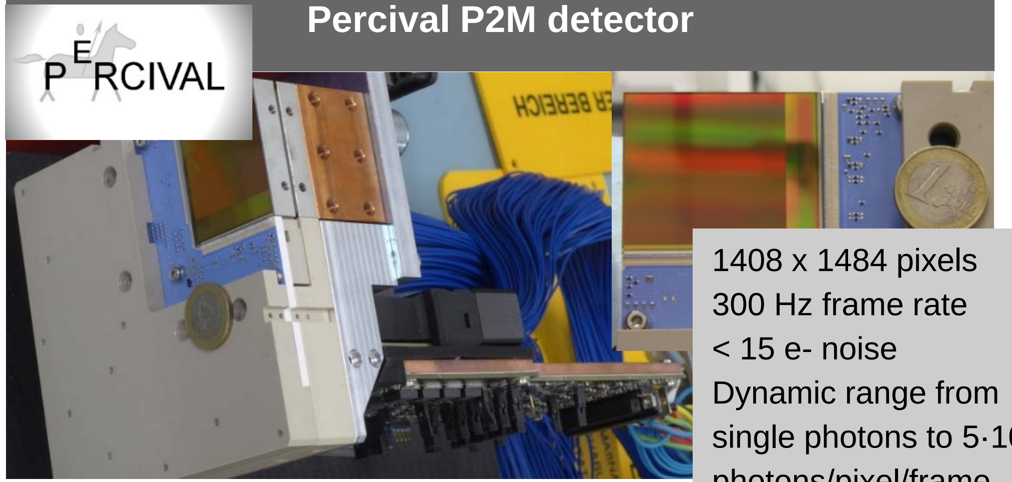
AGIPD detector for XFEL





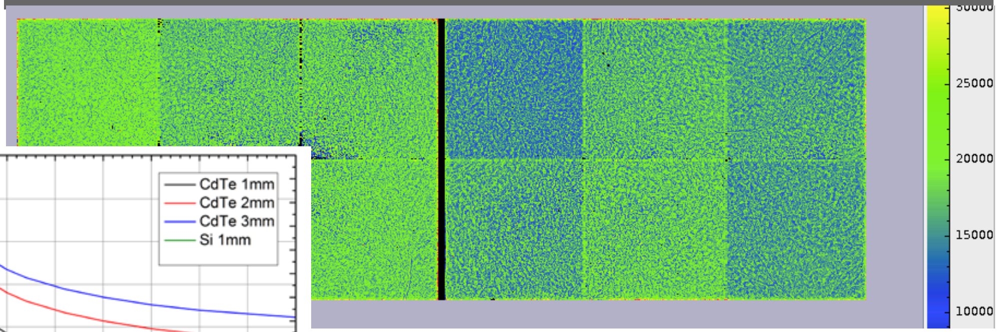
Resolved structure of
CTX-M-14 β-lactamase

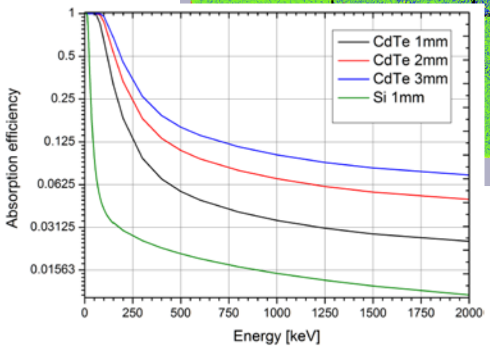
Percival P2M detector



1408 x 1484 pixels
300 Hz frame rate
< 15 e- noise
Dynamic range from single photons to $5 \cdot 10^4$ photons/pixel/frame

Large high-Z sensors Double-Hexa GaAs





Spin-off company X-Spectrum

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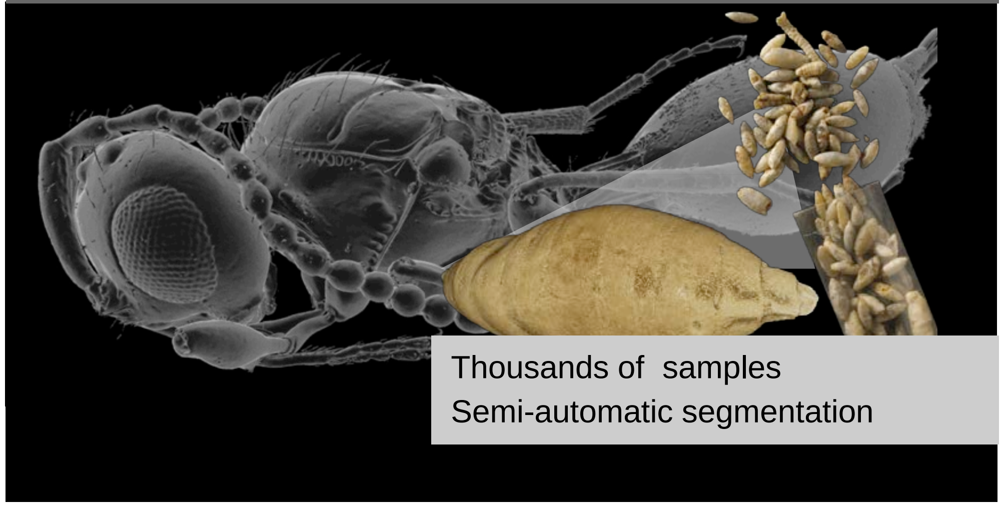
Online data processing – tomography

High throughput X-ray tomography

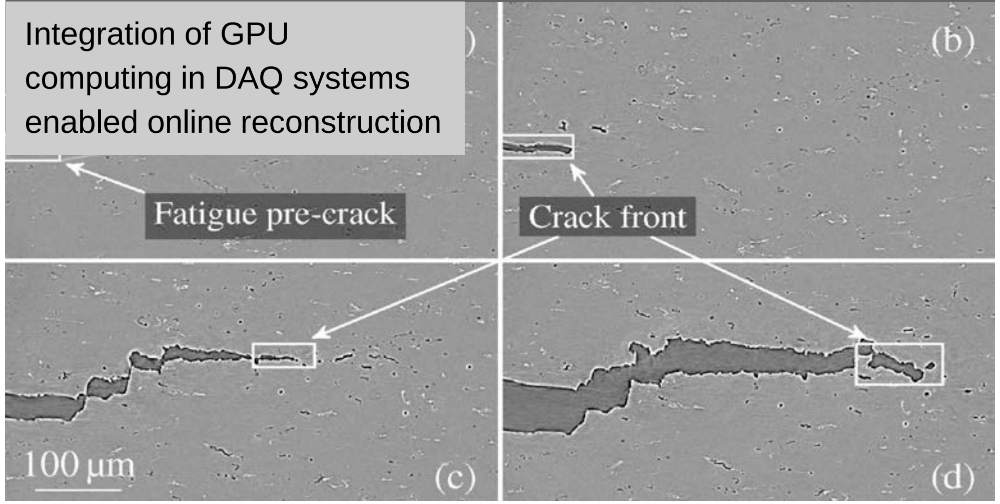


Thousands of samples
Semi-automatic segmentation

Nature Communications 9, 3325 (2018), Rendering: Th. van de Kamp, KIT

Ultrafast 4D X-ray tomography

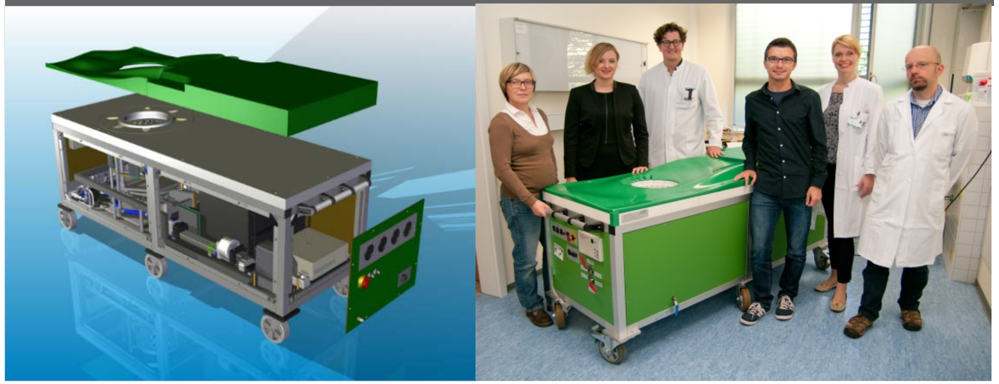
Integration of GPU
computing in DAQ systems
enabled online reconstruction



Grating-based phase contrast X-ray tomography

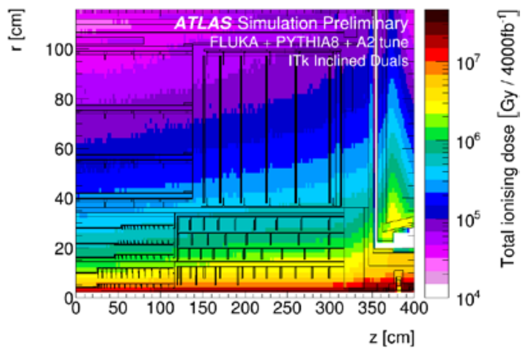
Modular programmable scientific camera
in operation at PETRA III P07

3D - Ultrasound computer tomography for breast cancer diagnosis

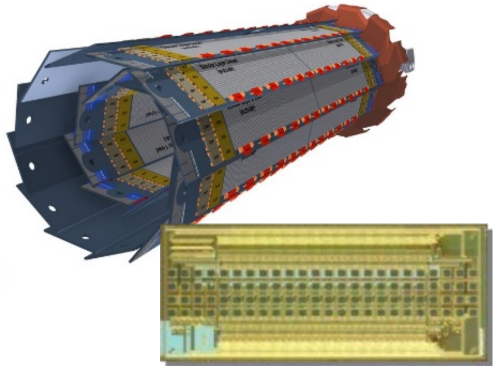


Particle and heavy-ion physics

Radiation-hard sensors for LHC upgrades

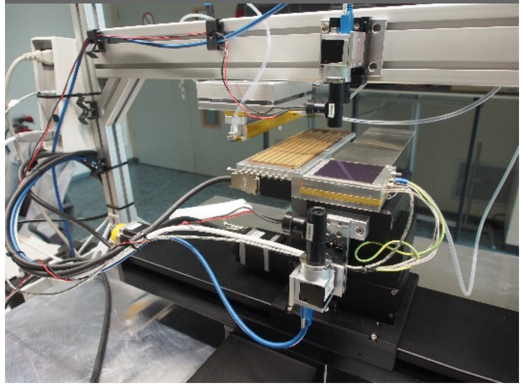


Readout ASICs for Belle II

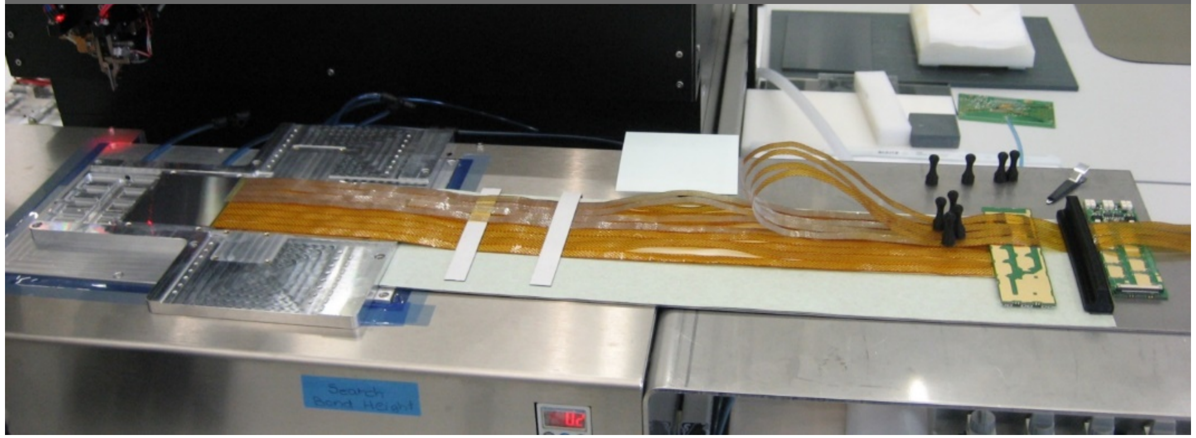


Flip-chip processes for CMS pixel bare modules

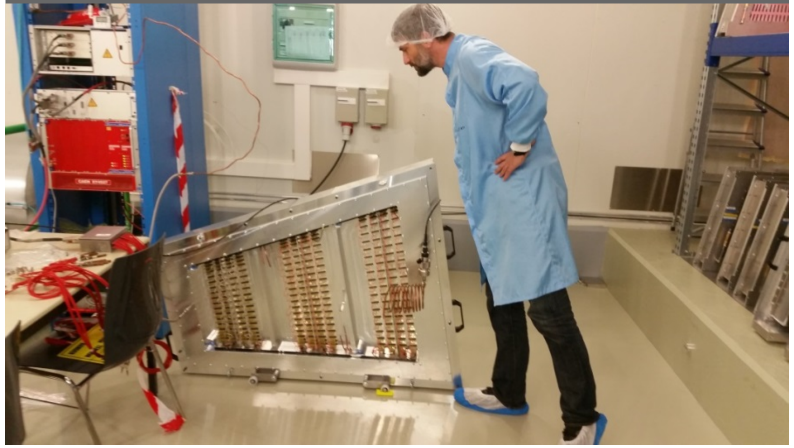
Automated module assembly



TAB-bonding of CBM microcables to silicon sensors



ALICE TPC-U readout chambers



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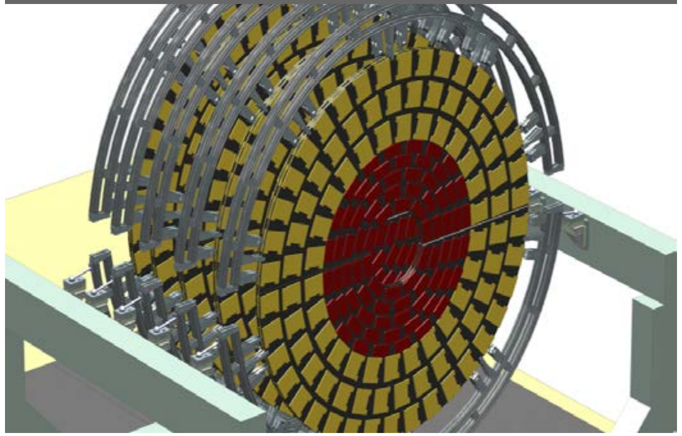
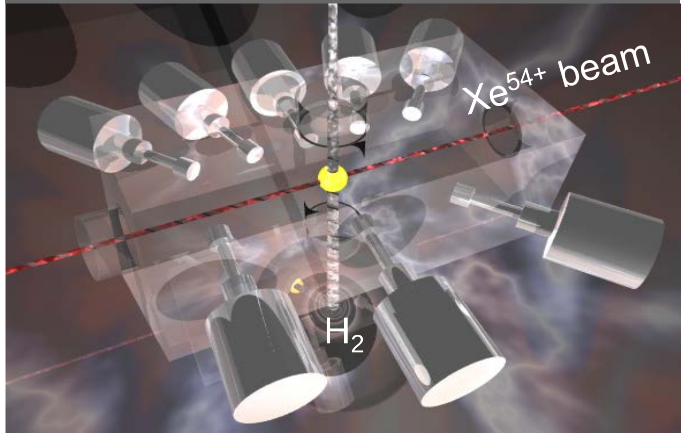
Particle and heavy-ion physics

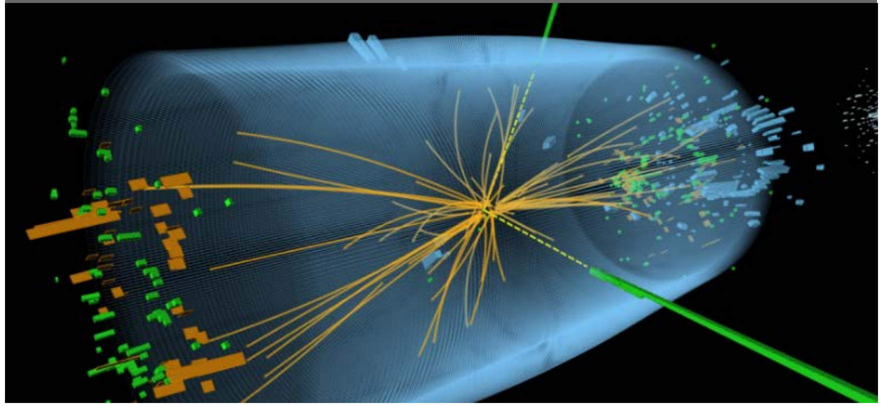
CMS silicon endcap integration



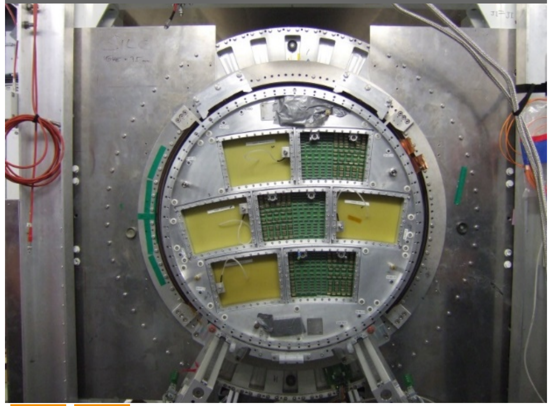
Radiative Electron Capture: Xe^{54+} + H_2 @ 31 MeV/u



CMS high-luminosity track trigger



TPC in DESY test beam



Digital silicon data acquisition system

Commercial artificial diamonds

Augsburg Diamond Technology GmbH

Quench detection

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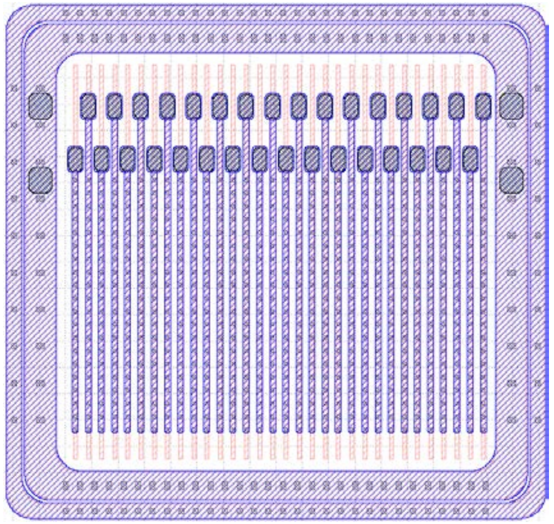
Single-shot beam diagnostics

LGAD sensor for photon science



32 strips at 50 µm pitch

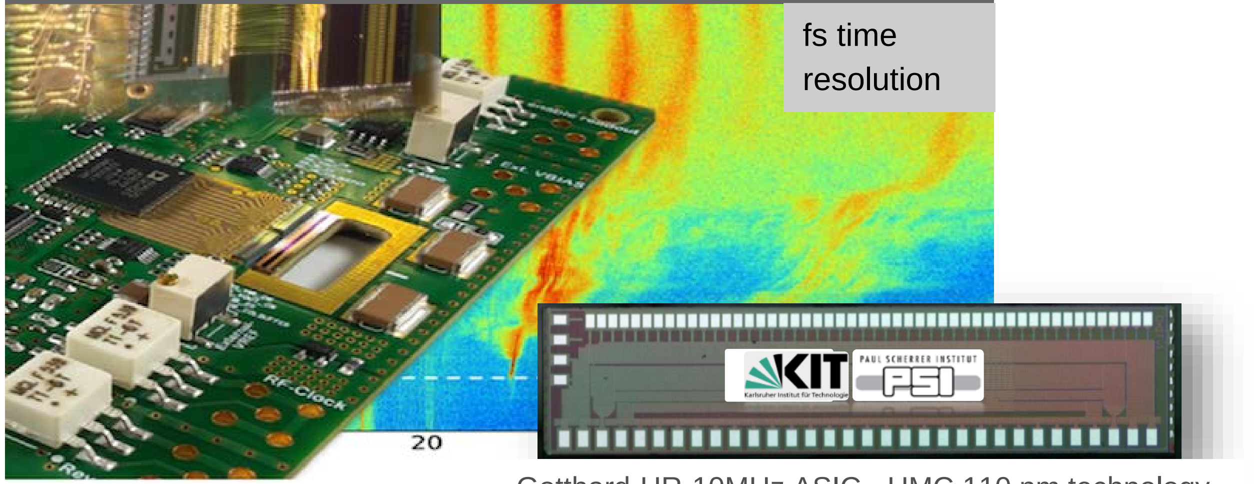
Enable shutter-less measurements beyond 200 MHz

Charge collection time: < 3 ns

Built-in gain: ~10-30

KALYPSO line camera for electro-optical modulation

fs time resolution



Gotthard-HR-10MHz ASIC - UMC 110 nm technology

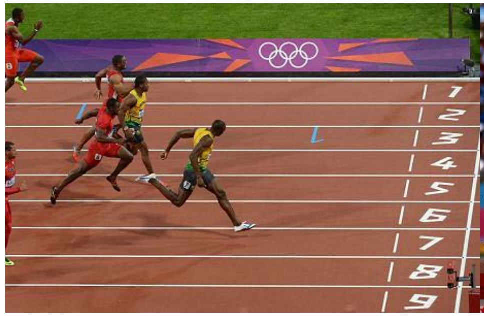
KAPTURE ultrafast continuous sampling

8 channels with programmable ps delays

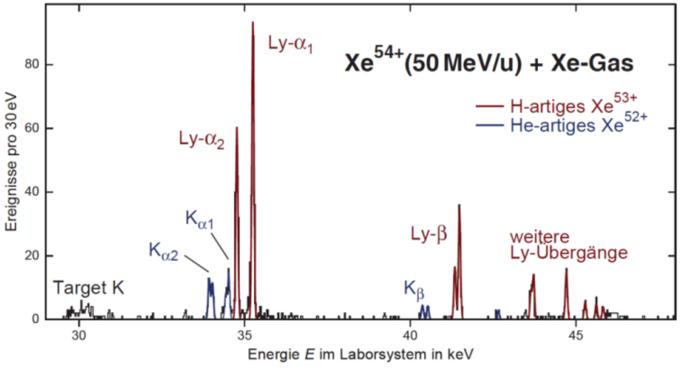
Applications of KAPTURE & KALYPSO

What are the challenges for the next decade and PoF IV?

- The citius-altius-fortius challenge

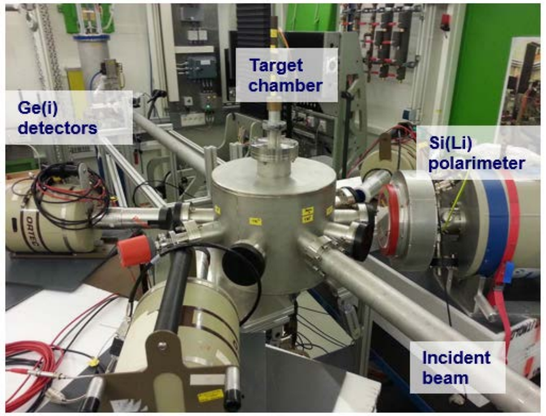


- The ultimate-resolution, highest-efficiency challenge



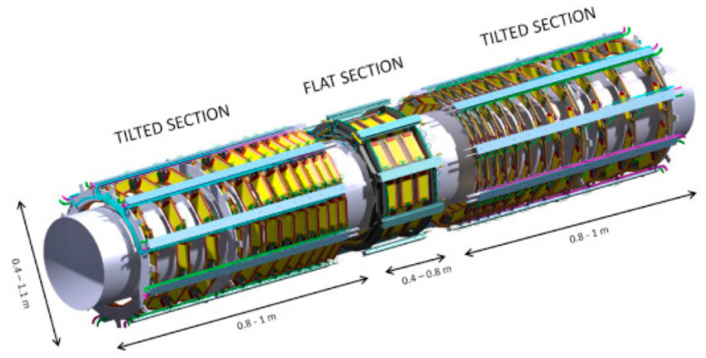
- The complexity challenge

Experimental set-up at P07 beamline at PETRA III



Citius, altius, fortius

- Ever more pixels and ever larger detector area
  camera systems with tens of millions of pixels in photon science
  ~500 million pixel/strip systems in particle physics



CMS inner tracker for high-luminosity upgrade

- Pixel number, resolution and frame rate all increase
  1- 1000 million pixels
  1-14 bit resolution
  kHz – GHz frame rates
  } *imply data streams of up to 100 Tb/s*

- Need to zero-suppress, compress, filter and process these data on and off the detector
  → *smart ASICs on detector*
  → *capable data transmission of >> Terabit/second*
  → *powerfull trigger, data processing, visualisation and management systems*

Highflex board version 1

MATTER AND TECHNOLOGIES

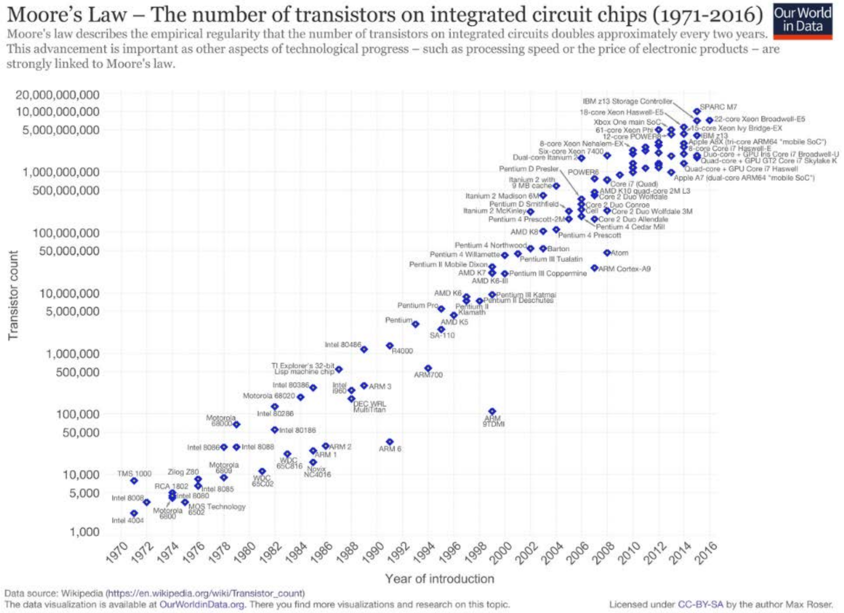
Sensors – a huge market

Applications and global market forecast 2023*

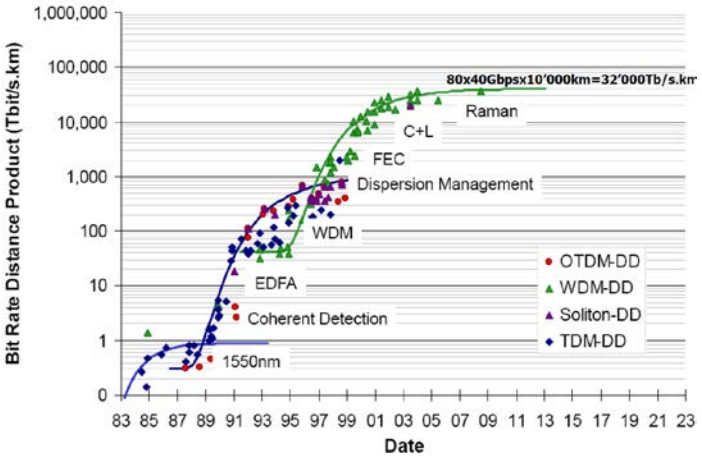
*) Source: Yole Status of the MEMS Industry Report 2018

Sensors – The heart of multiple applications and a global billion-dollar market

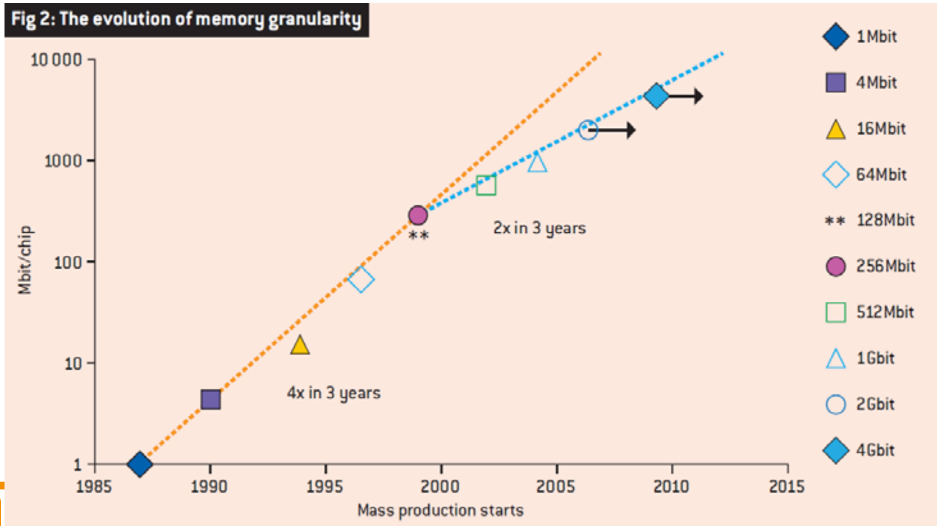
So far commercial nanoelectronics has been working for us



Transmission capacity in optical fibers



http://www.nature.com/nphoton/journal/v7/n5/full/nphoton.2013.94.html



Exponential progress with time

- Single fiber bandwidth: 10x every 4 years
- Processor transistor count: 4x every 3 years
- Memory size: 2x every 3 years

The times they are a-changing !

MATTER AND TECHNOLOGIES

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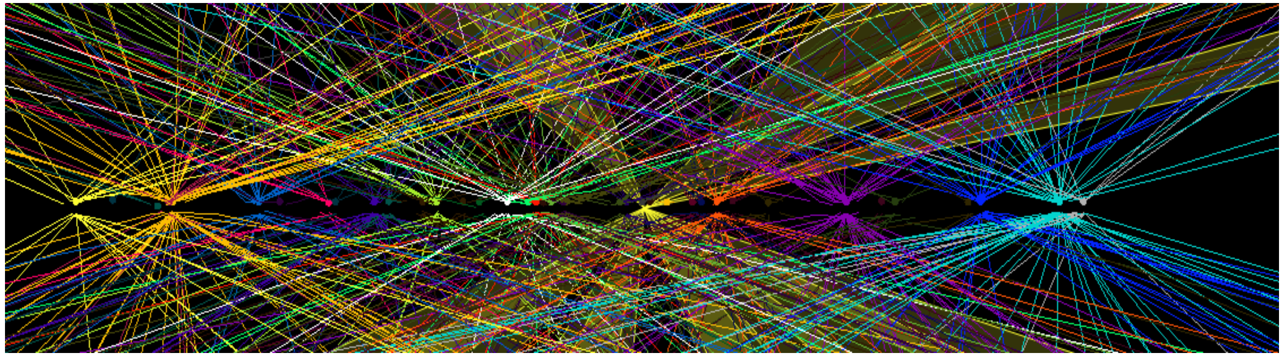
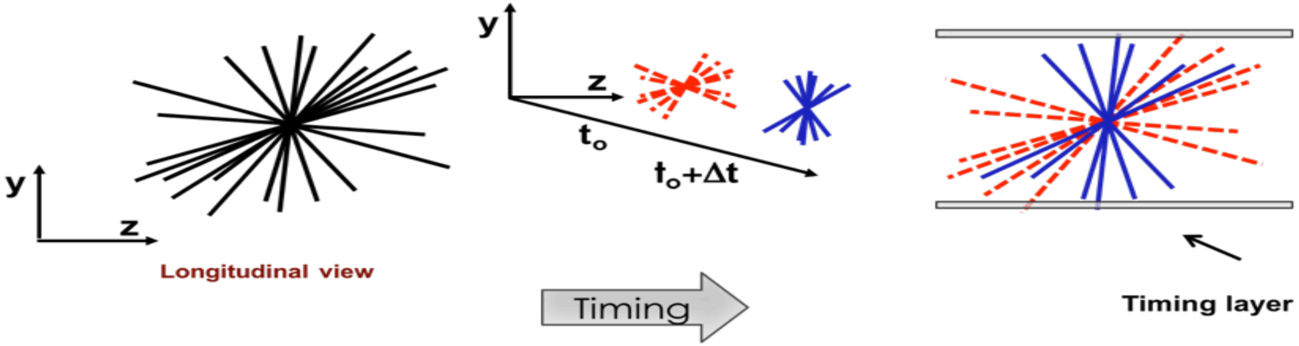
From 3D to 4D tracking: a paradigm change

- We can distinguish different vertices, if they are not overlapping

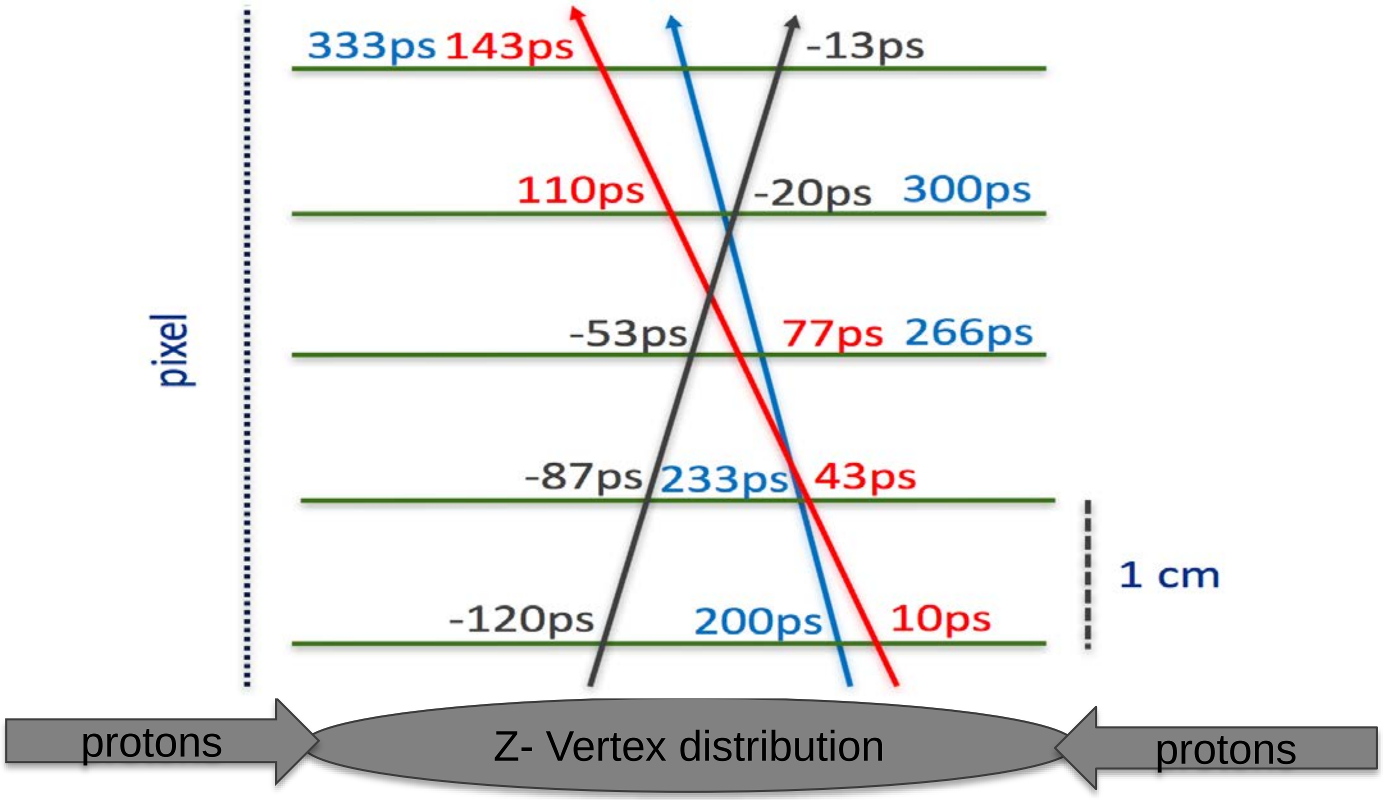


~200 collision vertices in 30 cm at high-luminosity LHC

- Just imagine we could precisely measure time as well!
- Timing would allow much better separation of overlapping events and offer great physics benefits



4D tracking would also revolutionize track fitting



Courtesy of Nicola Cartiglia (INFN Torino)

Can this be realized?

LGAD: Low-Gain Avalanche Detector

- LGADs combine position location of ~10 µm with ultra-fast timing resolution of ~10 ps

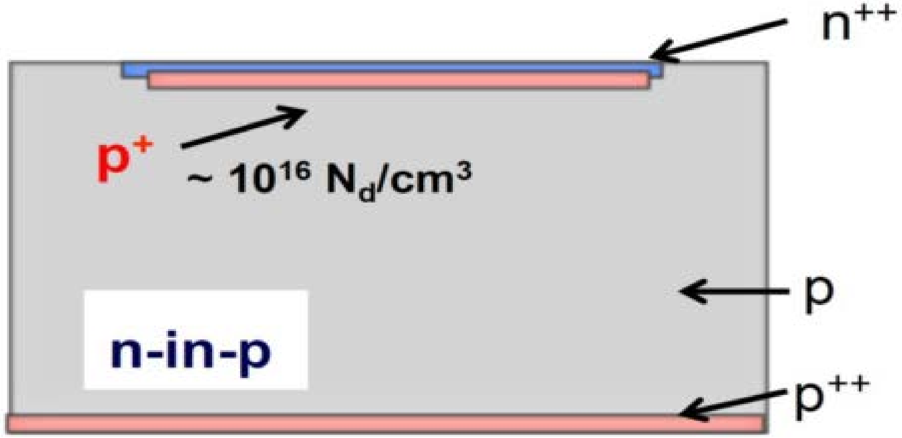
- How do they work?

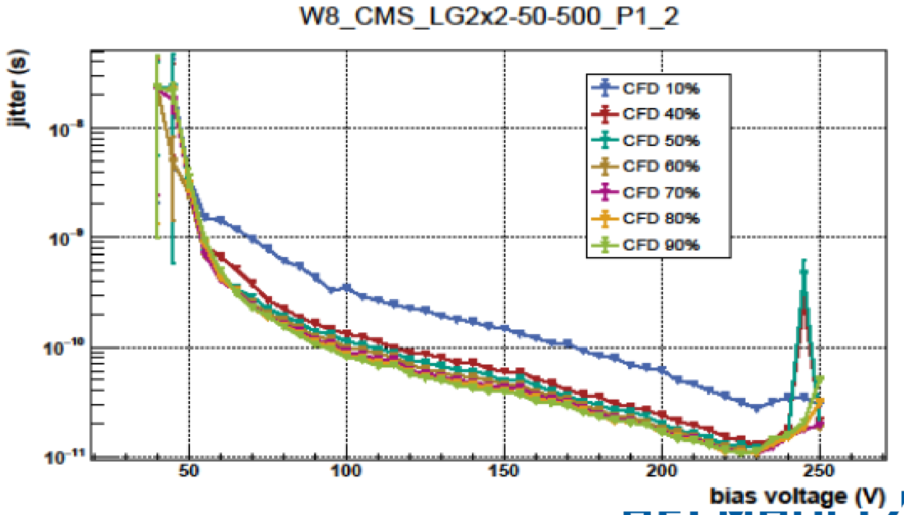
  Start with a thin sensor for fast charge collection, compensate low signal and corresponding large jitter by internal signal amplification through an avalanche

- LGAD have the potential of replacing standard silicon sensors in almost every application

- Gain of LGADs is ~ 10 - 20

- Jitter of 50 µm thin sensors is > 12 ps





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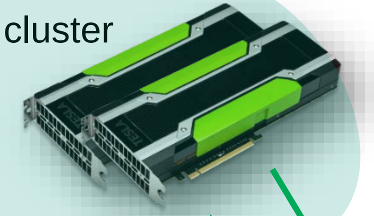
High-performance deep machine-learning

- Processing large data volumes in real-time by artificial intelligence algorithms will be a game changer
- Using heterogeneous FPGA-GPU platforms to combine the strengths of both technologies

FPGA: Low-latency, customized designs, high-perfomance memories resources, many interfaces, broader flexibility, etc.

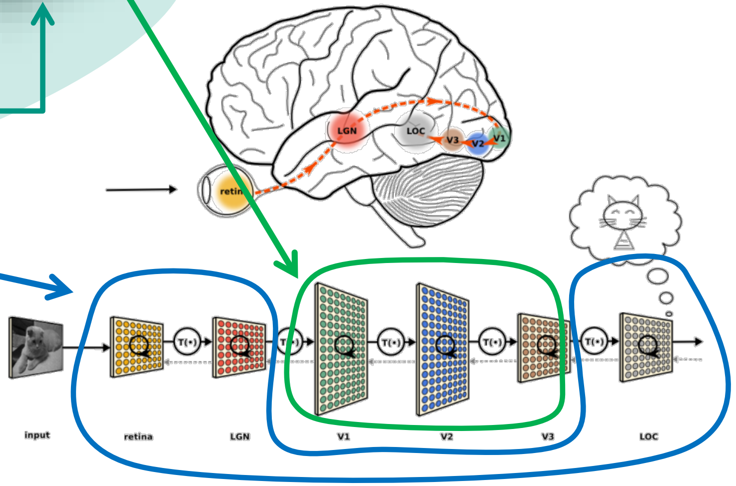
GPU: floating-point and large processing capabilities, easy to program, etc.

GPU cluster



Data source

heterogeneous



Fast feedback to experiment based on machine-learning

Mastering the ultimate-resolution challenge

Mega pixels

High rates

High dynamic range

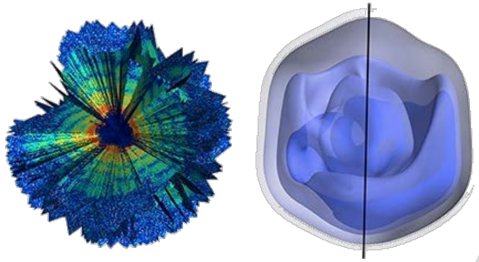
Low noise

Ultimate energy resolution

Good time resolution

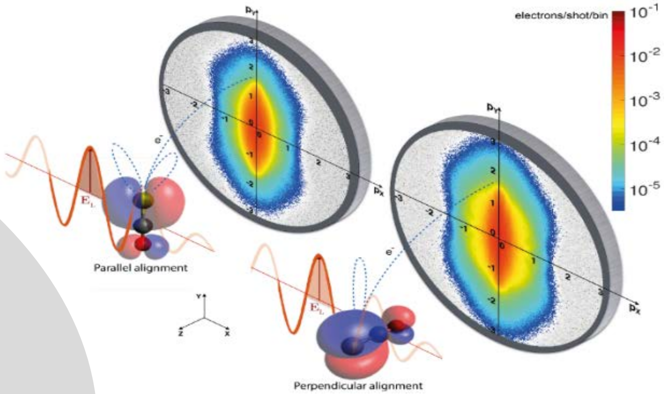
Low rates

Imaging bio-systems



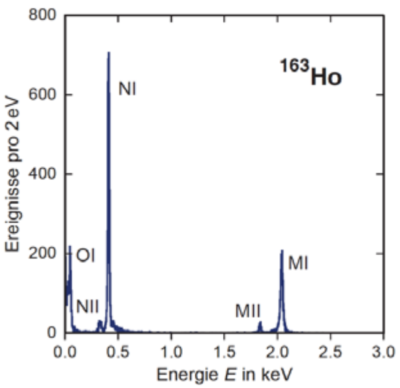
Soft X-rays

Molecular dynamics



~ keV electrons

Neutrino mass



keV X-rays and electrons

Dark Matter searches

eV photons

MT MATTER AND TECHNOLOGIES

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Why DDL?

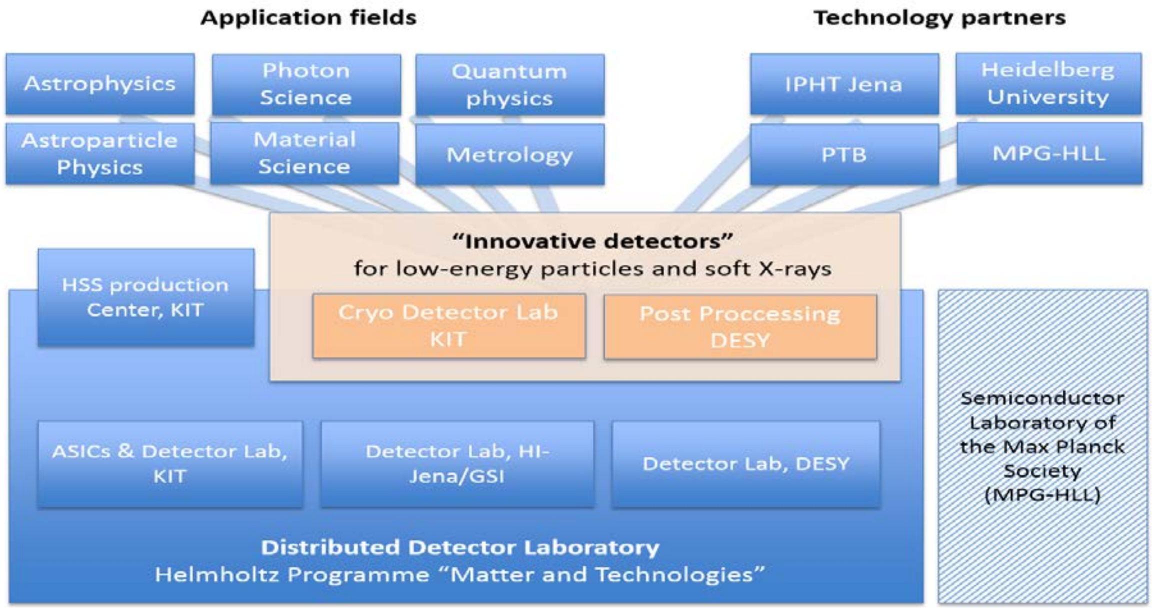
- We have seen that there are huge challenges and opportunities

- High-tech solutions demand high-tech infrastructure

- Need to provide custom, flexible and fast solutions for a diverse, broad and innovative science community

Distributed Detector Lab (DDL)

- Distributed infrastructure, competence center and hothouse of technology
- Partners from universities, Leibniz, MPG and PTB
- DDL will provide key technologies to “Matter” and university partners
- Application to the Helmholtz large-scale investment fund (> 15 M€)

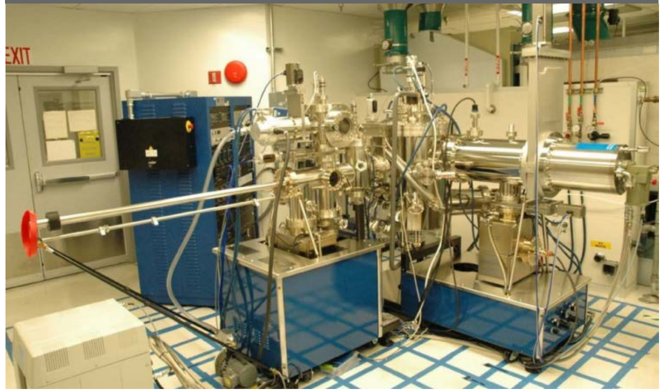


Conceptual view of a possible DDL implementation. Preliminary

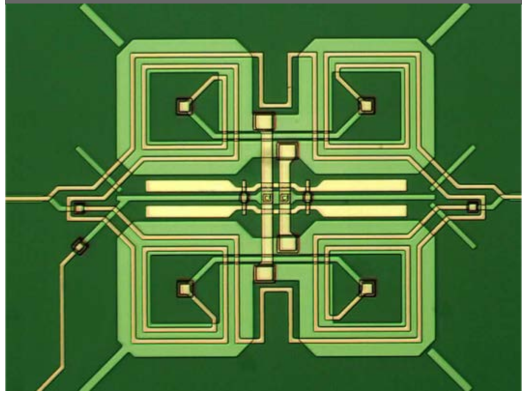
DDL has been strongly endorsed in all center evaluations.
We will follow up with a full proposal for PoF-IV strategic evaluation

Key elements of DDL

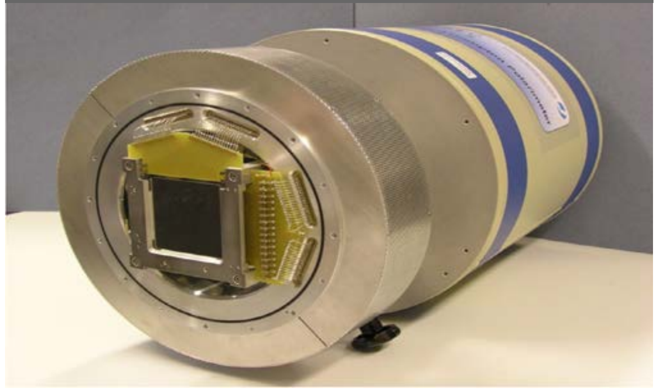
Post-processing of silicon sensors



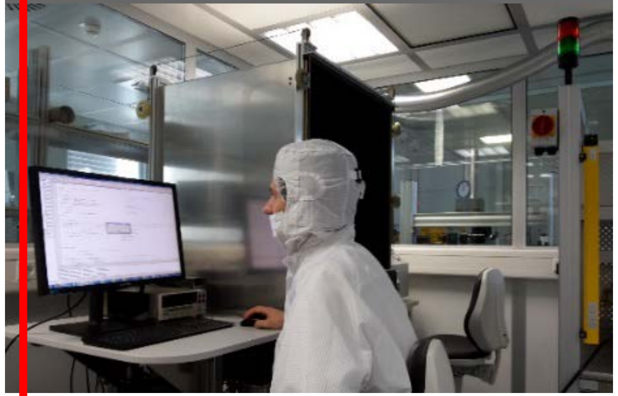
Fabrication of superconducting sensors



Preparation and 3D structuring of bulk semiconductor and high-Z sensors



Interconnect and packaging technologies



Cryogenic DAQ laboratory

Silicon photonics characterization

Test beam infrastructures

Competence centers

- Application-specific electronics (ASICs)
- Massive parallel processing (FPGA + GPU)
- System engineering

Summary

- DTS has been extremely active in the past few years
- Could only show a fraction of what we do (sorry!)

- DTS technology has proven to boost „Matter“ science

- PoF-IV is a great opportunity to be even better

- For one, the installation of the Distributed Detector Lab would strongly benefit “Matter“ science for decades to come

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