https://www.desy.de/

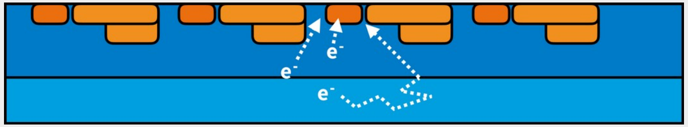
Monolithic Active Pixel Sensors

Bringing State-of-the-Art Technology to Today’s & Tomorrow’s Scientific Instruments

S. Spannagel
DESY-FH-ATLAS

Joint APC 13 & PRC 99 Meeting
08/04/2025, Zeuthen

Enabling Major Advances in Science



Monolithic Active Pixel Sensors

Evolution of Semiconductor Detector Technology

- Traditionally hybrid detectors or CCD sensor
- Technology improvements driven by consumer electronics
- Advanced technologies available:
- backside-illumination (BSI), stitching, 3D stacking, …
- Scientific applications on the rise

Technology enables major advances in our fields:

AP Astrophysics: low-power, high efficiency sensors

FH Particle Physics: high-precision, low-mass sensors for MIPs

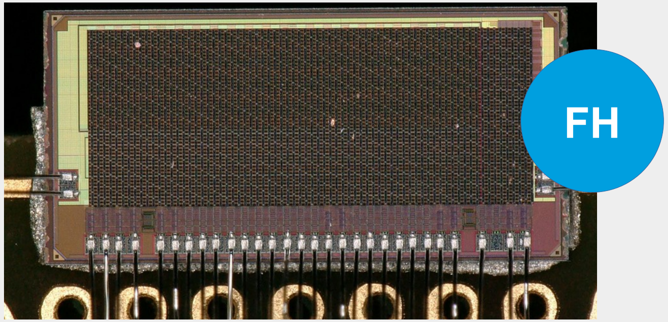
+ Low noise characteristics
+ Fast read-out speeds
+ Fully-integrated electronics
+ Reduced mass

− Smaller signal (MIPs)
− Intricate sensor design
− Limited to silicon
− **Complex R&D process:**
Fully integrated

Exploring the Full Range of MAPS Applications

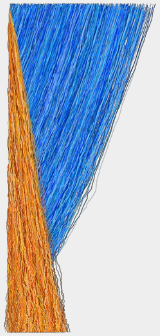
High-performance UV Imaging

ULTRASAT FPA



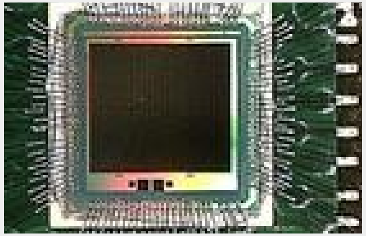
Next-gen High-precision Tracking Detectors

TANGERINE



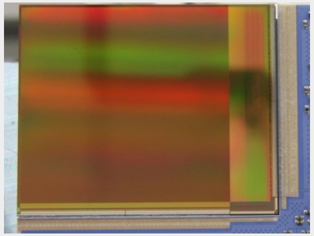
Semiconductor Monte-Carlo simulations

Allpix Squared



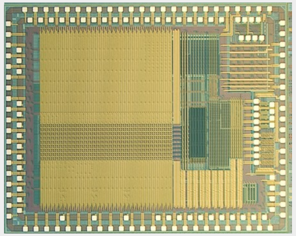
Pixels with Picosecond Time Resolution

Monolithic Digital SiPM



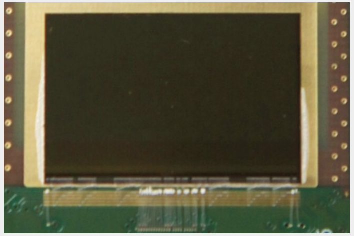
Megapixel Sensor for soft X-rays

Percival



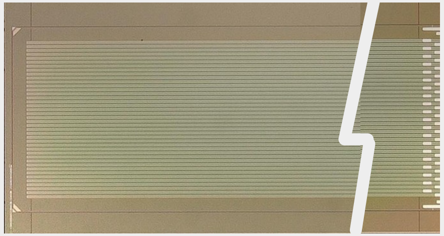
Radiation-hard Pixel Detector

MALTA



Flexible region-of-interest trigger

TelePix2 HV-MAPS



Cost-effective large-area instrumentation

CMOS Strip Sensors

ULTRASAT

SKYLIGHT TO SPACE

WEIZMANN INSTITUTE OF SCIENCE

Israel Space Agency

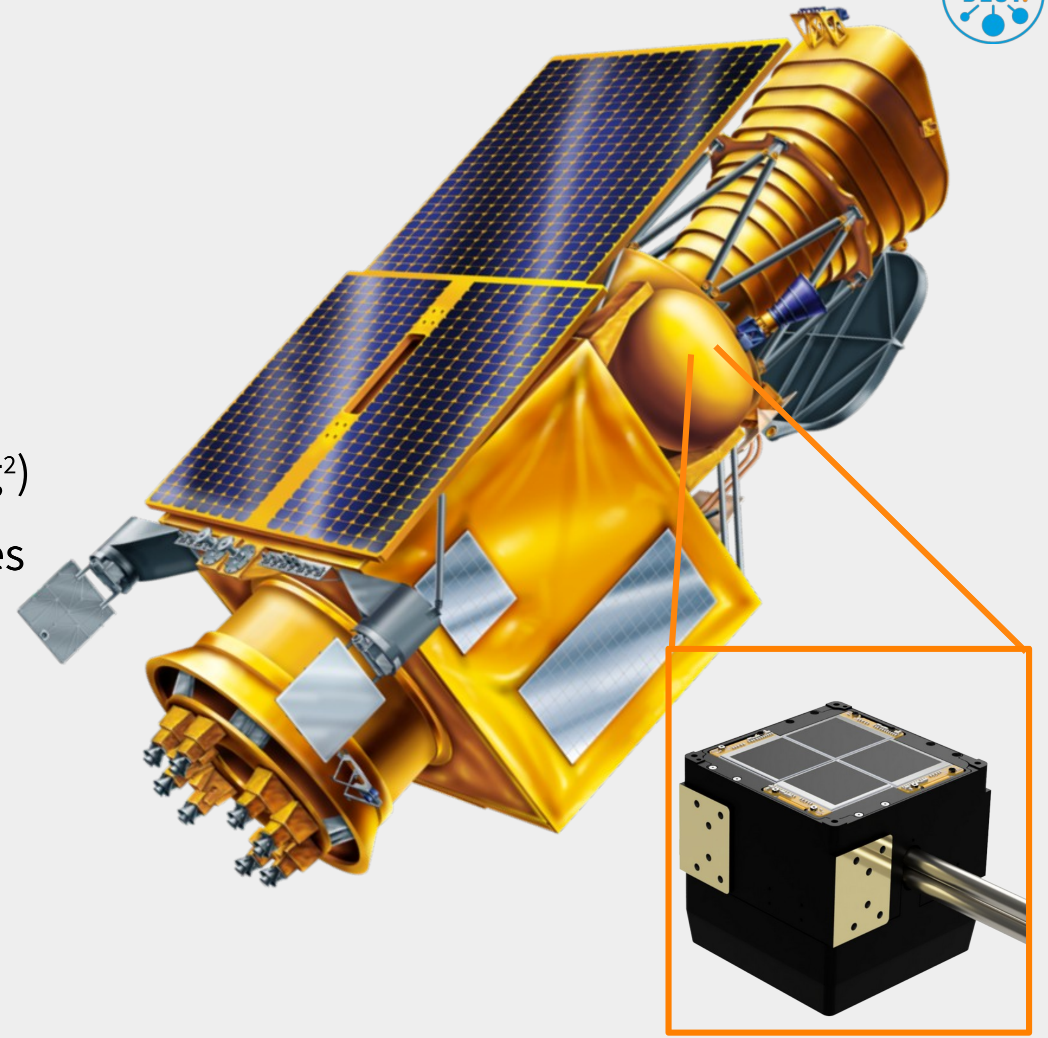
The ULTARSAT Camera

At the heart of the Israeli UV space telescope

- First scientific satellite mission led by Israel
- First DESY contribution to a satellite mission

- Unprecedentedly large field of view (204 deg^2)
- First wide-field survey of transient UV sources
- Unique multi-messenger science synergies

- Kick-off in 2019, launch planned for ≧ 2027
- We plan to deliver the flight camera by 2026



Sensor technology

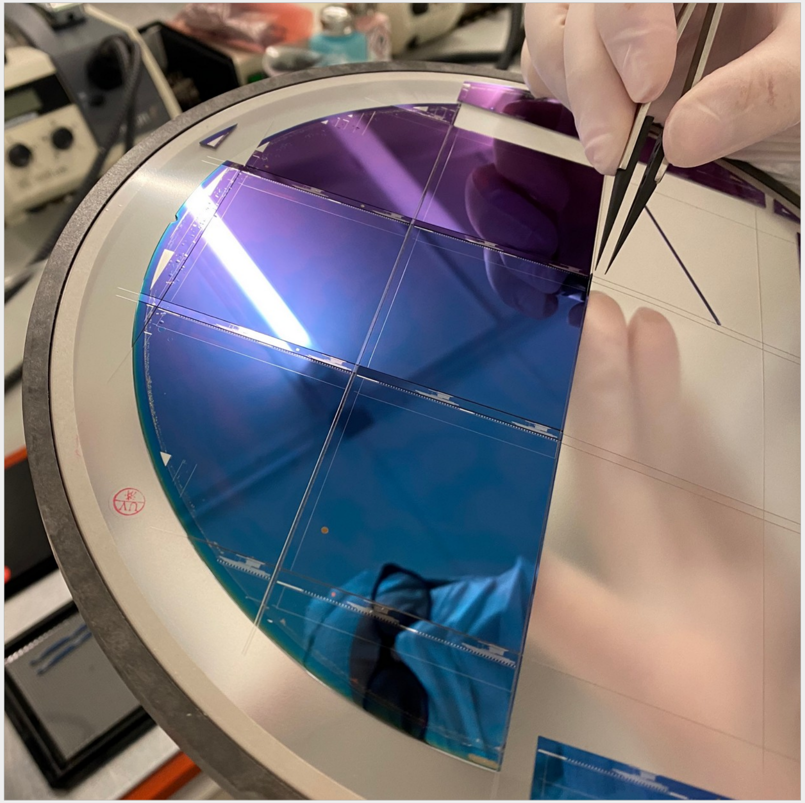
Exploiting state-of-the-art commercial technology for science instruments

The sensor

- 22.4 Mpixel, 45 mm x 45 mm active area
- Commercial 9.5 um^2 pixel of Tower Semiconductor
- Custom designed radiation tolerant a2d electronics
- We fly the first and only design of the sensor

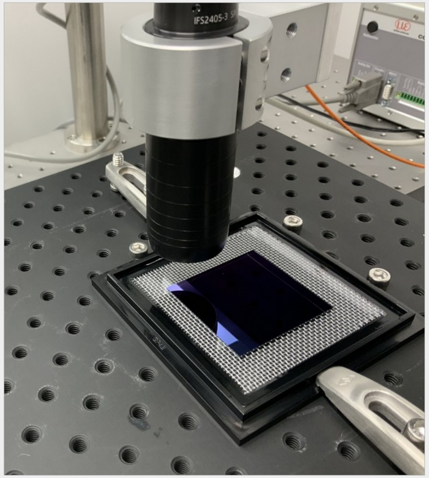
Development status

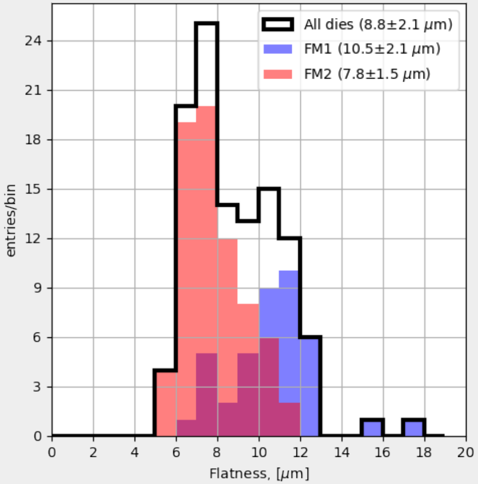
- Produced 3 wafer batches, tested on wafer level and diced
- Packaged sensors are characterized for optical performance
- SEL performance confirmed in two test campaigns
- First mosaic confirmed flatness can be realized

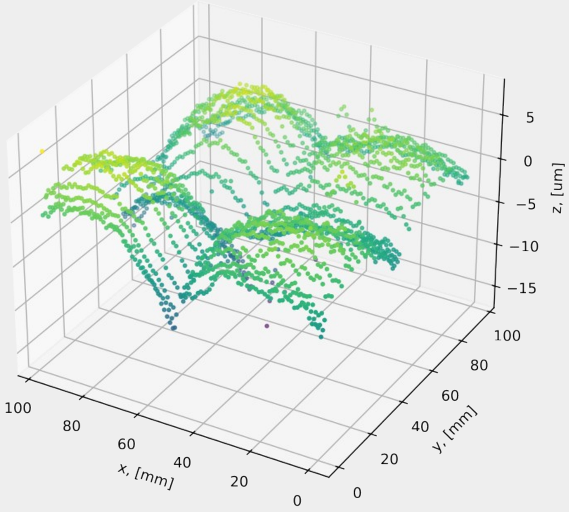


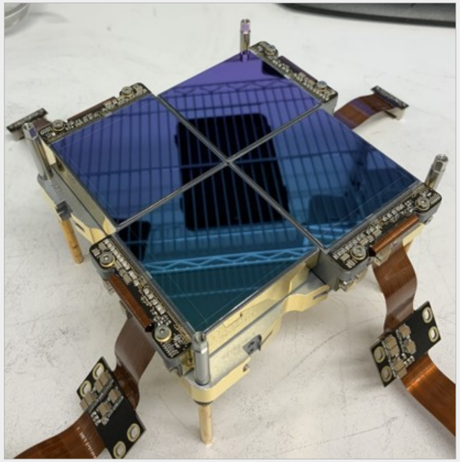
Mission-Specific Challenge: Flatness of the focal plane

- **Requirement of 20 um p2v flatness** for entire mosaic at operational temperature
- Diced **dies came out less flat** than the wafer specifications suggested
- Flatness became significant factor for flight dies selection, lowering yield
- First mosaic proves that **flatness budget can be realized** in room temperature
- Next step is measuring mosaic’s flatness at operational temperature





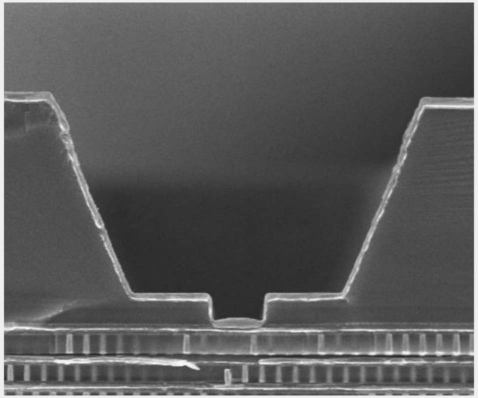




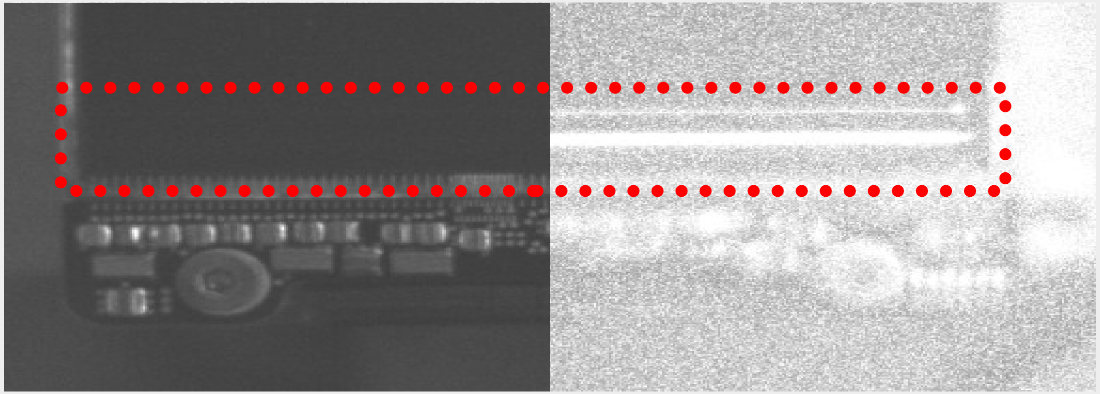
Mission-Specific Challenge: Infrared Glow

- Infrared light emitted from CMOS sensor's readout electronics is a known issue
- Sensor design includes metalized trench between pixel matrix and readout electronics
  - Tests at DESY proved that IR photons are effectively blocked from entering pixel matrix
- IR photons emitted out of sensor would be reflected at filter 0.55 mm above the sensors
  - Coating all non-sensitive sensor surface with Acktar to block IR photons
  - Testing of the coating process is currently ongoing

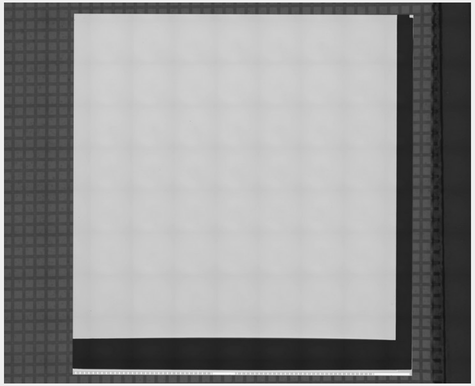
Optical trench / SEM image

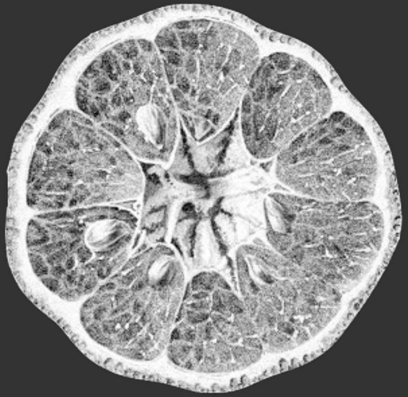


Optical / IR image of sensor exhibiting low



Sensor with Aktar coating





Tangerine

Towards next generation silicon detectors
A Helmholtz Innovation Pool Project

The Tangerine Project

Towards the Next Generation of Silicon Detectors

> “ Developments of Monolithic Active Pixel Sensors (MAPS) should achieve very high spatial resolution and very low mass […] To achieve low mass in vertex and tracking detectors, thin and large area sensors will be crucial.
>
> *ECFA Detector R&D Roadmap, Research Goal DRDT 3.1*

- Explore MAPS technologies as candidates for **vertex detector sensors at future lepton colliders**
- Develop **simulation approach for MAPS** to allow predictive studies on sensor layouts
- **Design & characterize prototypes** with fast front-ends and full digital integration

ECFA DRD Roadmap, 2020

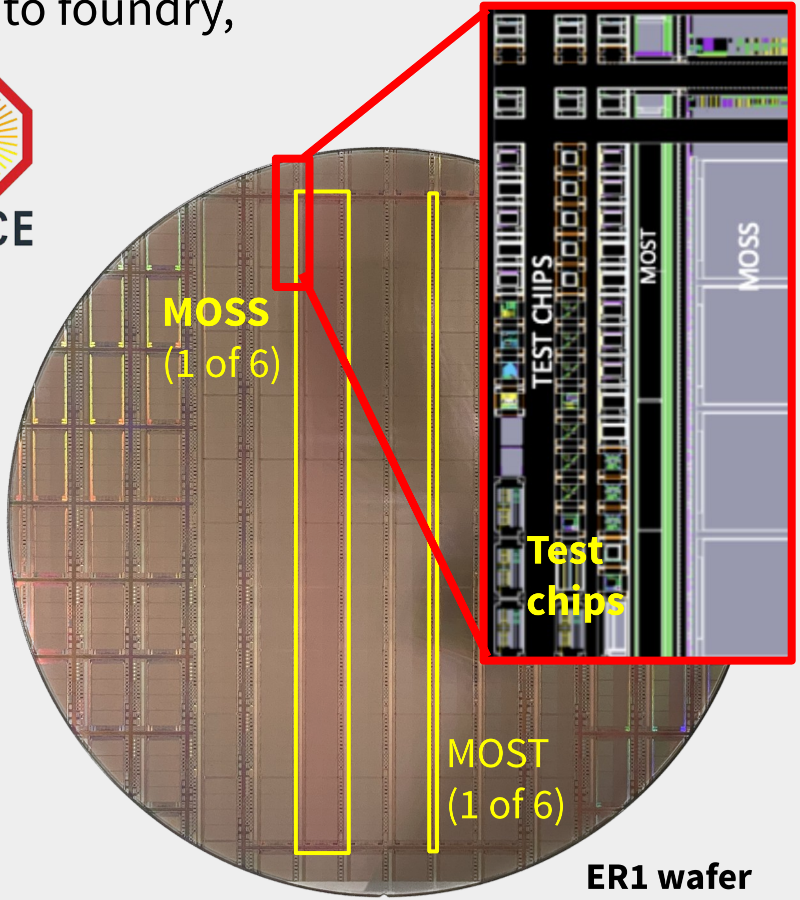
Vertex detector[2)]	DRDT	ILC 2035-2040	FCC-ee 2040-204	CLIC
Position precision	3.1,3.4			
Low X/X_0	3.1,3.4			
Low power	3.1,3.4			
High rates	3.1,3.4			
Large area wafers[3)]	3.1,3.4			
Ultrafast timing[4)]	3.2			
Radiation tolerance NIEL	3.3			
Radiation tolerance TID	3.3			

Technology: 65nm CMOS Imaging Process

submissions supported by

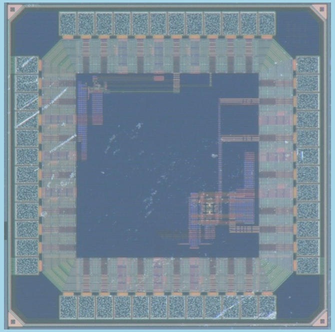
- International collaboration for common submissions to foundry, organized through CERN EP R&D programme
  - Strongly driven by ALICE ITS3 collaboration
  - First application in HEP
  - Two submissions received back & tested

- Goal: explore new technology in terms of
  - Performance: efficiency, …
  - Scalability: wafer-scale sensors, stitching
  - Timing: sensor layout optimization



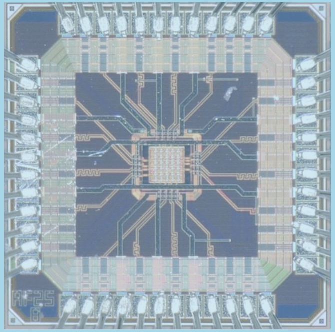
ER1 wafer

Investigated Chips within Tangerine



V1 MLR1

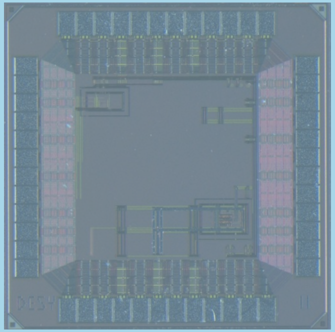
- Test chip for fast CSA front-end
- 2 x 2 pixels + test circuits



Aglieri et al, 2024

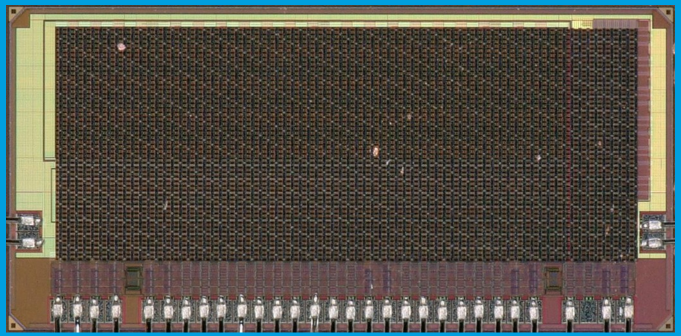
APTS

- Analog test chip
- 4 x 4 pixels
- Different pitches, layouts & front-ends



V2 ER1

- FE test chip for H2M
- 2 x 2 pixels
- Improved CSA front-end



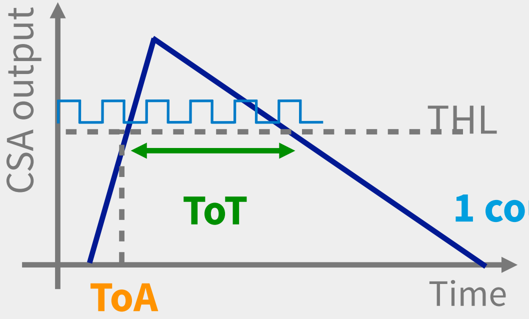
H2M

- 3 x 1.5 mm^2 chip area
- 64 x 16 square pixels, 35 um pitch
- Krummenacher-type CSA front-end
- Full digitization

all design supported by EP R&D

Hybrid-2-Monolithic: Integrated Digital-on-Top Design

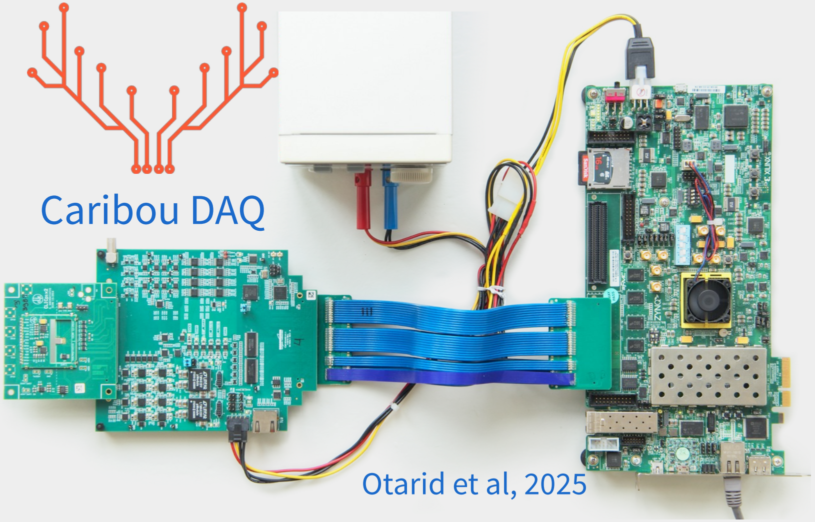
- Ports a **hybrid pixel detector architecture**
- **Digital-on-top** design workflow



- **Timepix-like 4 acquisition modes**:
  - 8 bit ToT,
  - 8 bit ToA (100 MHz clock - 10 ns binning),
  - photon counting (number of hits above threshold),
  - triggered (binary readout after hit validated by ext. trigger)

Integrated into the **Caribou DAQ system**

- Re-usable hardware, firmware and software
- Supports ~20 different prototypes



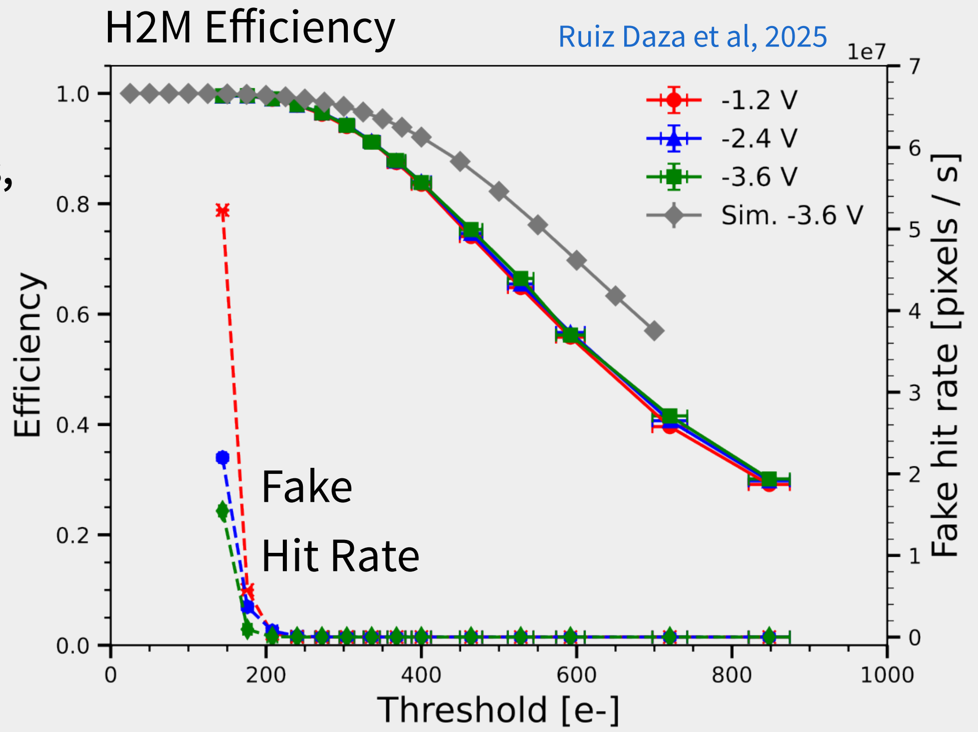
Otarid et al, 2025

Testbeam Performance of H2M

- Measurements performed at DESY II Testbeam Facility
- Crucial facility for detector R&D

- **Corryvreckan** Testbeam Data Analysis Tool
- Developed & maintained at DESY
- **Standard tool used by all LHC experiments, future collider studies & beyond**

- H2M prototype is fully efficient at threshold 144 e-, bias -3.6 V
- Higher efficiency was expected from preliminary simulations…



Allpix Squared

The Semiconductor Detector
Monte Carlo Simulation Framework

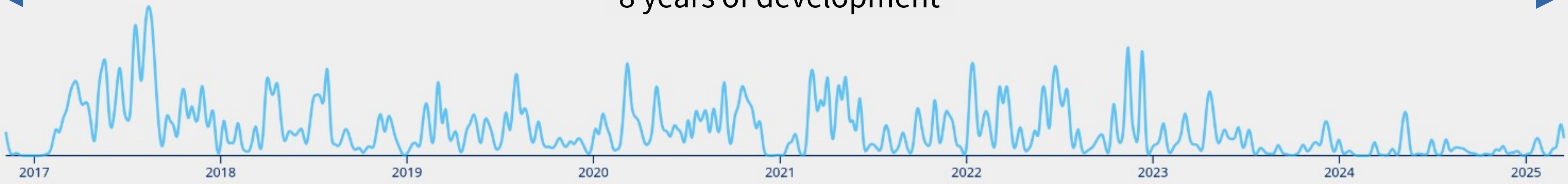
… I spare you the logos of
> 35 collaborating institutes &
> 70 contributors

The Allpix² Framework

- **Leading Monte Carlo simulator for semiconductor detectors**
- Now > 8 years of development with
  - 53 releases, current version 3.1.2
  - More than 70 code contributors
  - More than 160 citations
- **Development & maintenance: DESY, Nikhef**

Yearly User Workshops, soon in Amsterdam:

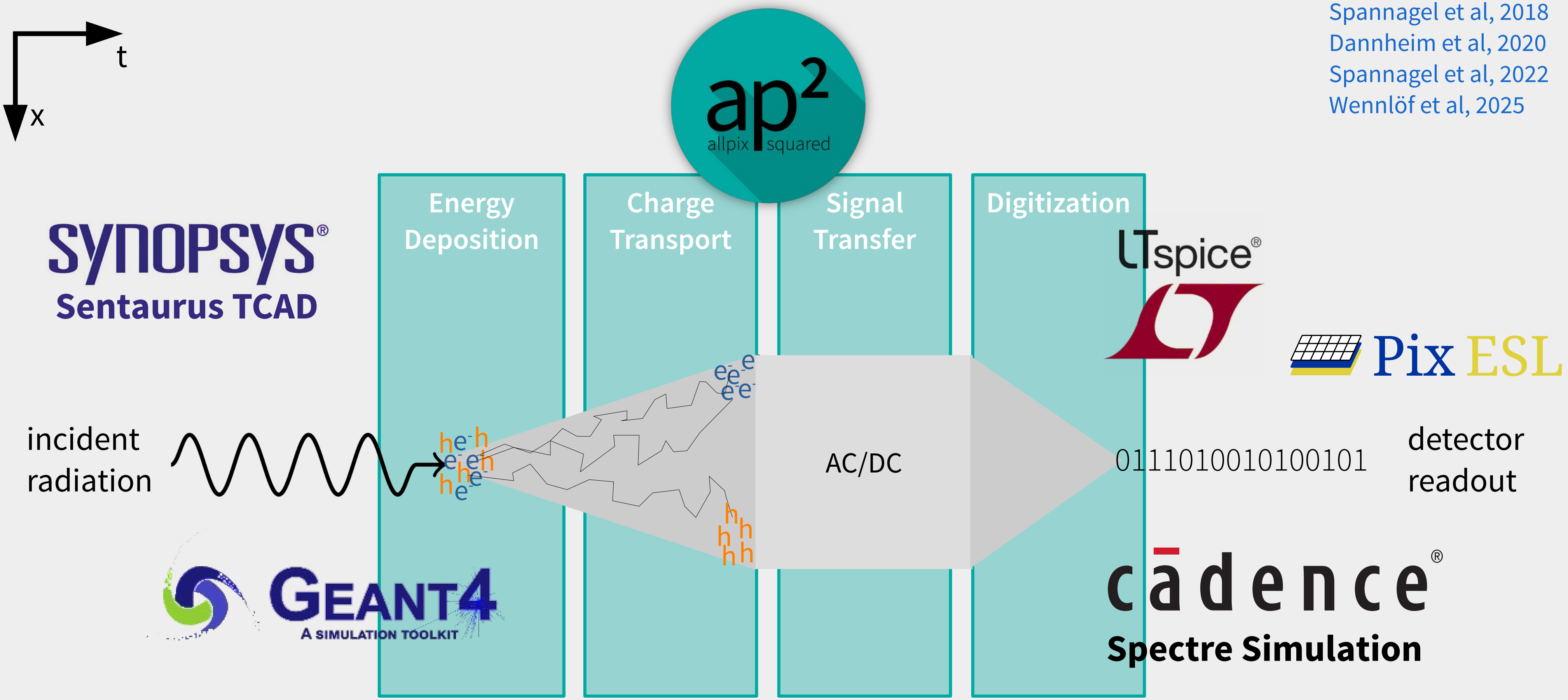
8 years of development



9079 commits | Last commit ≈ 2 weeks ago | 26 stars | 94 forks

Combining Tools for Full End-to-End Simulations

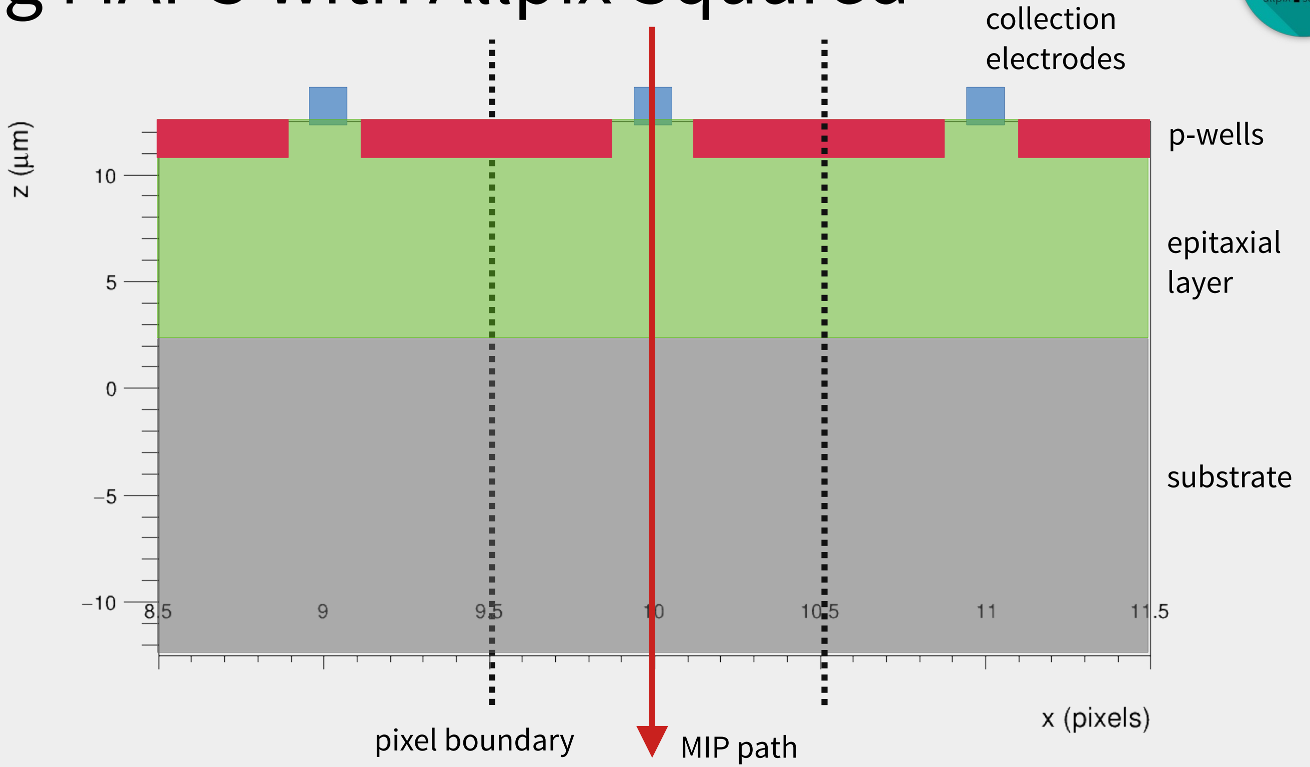
Spannagel et al, 2018
Dannheim et al, 2020
Spannagel et al, 2022
Wennlöf et al, 2025



Example: Simulating MAPS with Allpix Squared

Structure of simulated sensor:

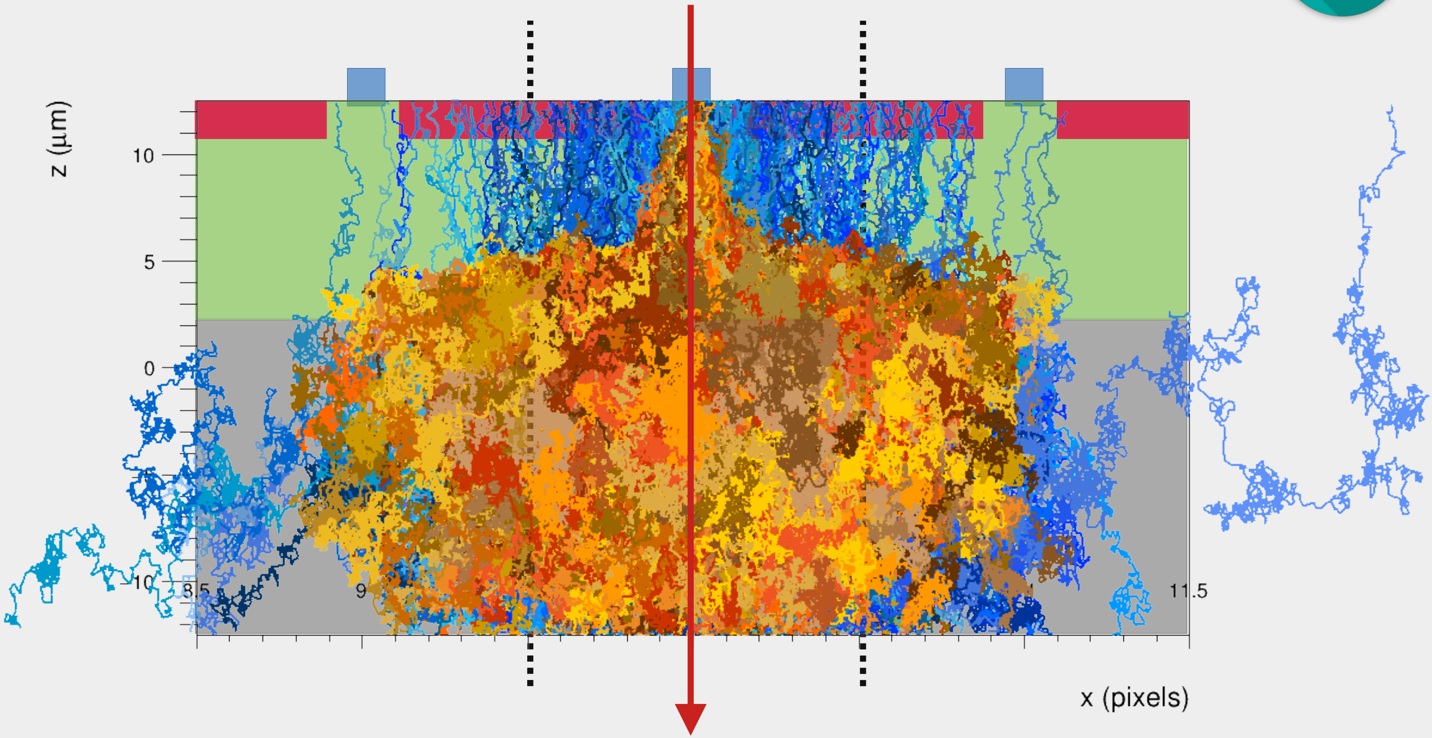
- Small-electrode sensor
- High-resistivity epi layer, electronics-grade substrate
- Deep wells protect circuit from field in sensor



Simulating response to minimum ionizing particle incident perpendicular to surface

A Simplistic Approach

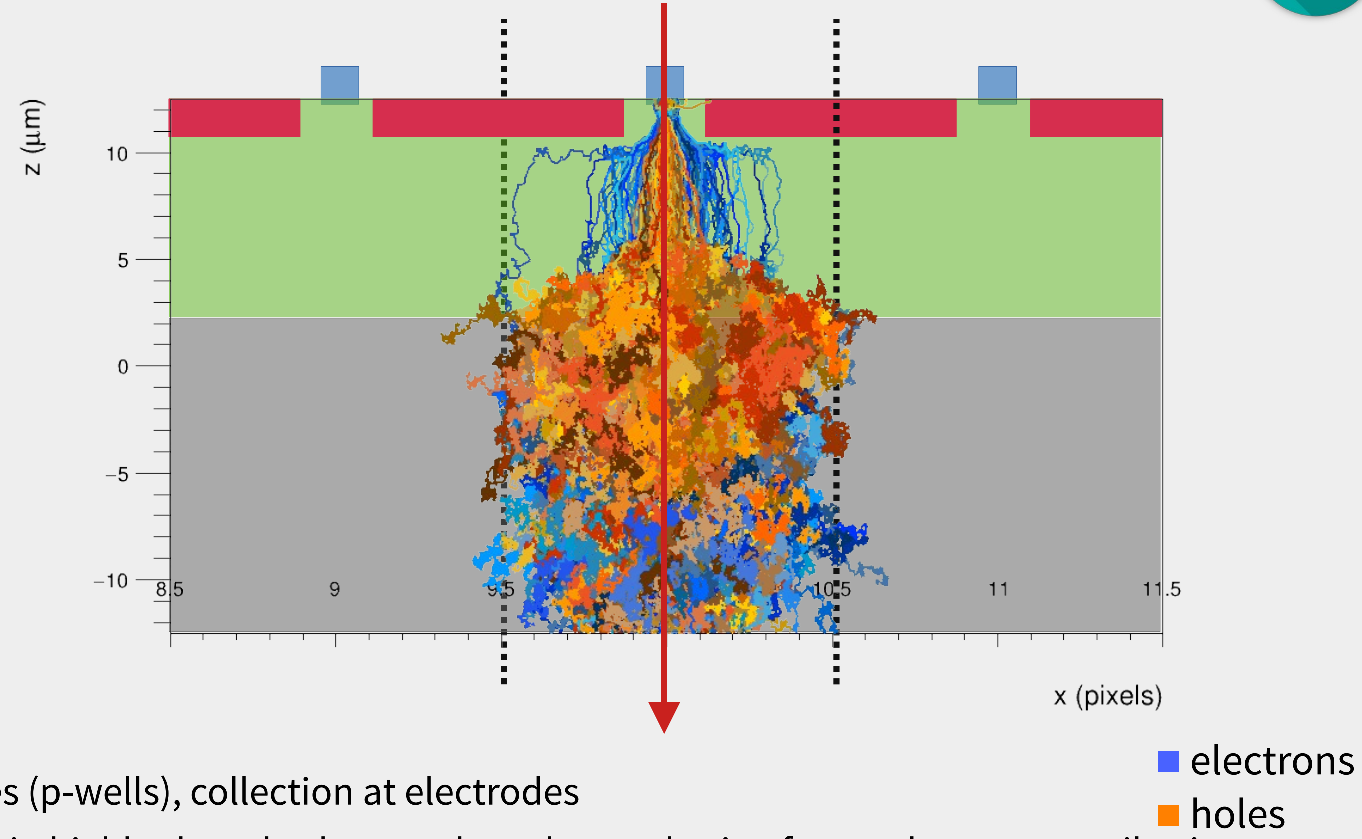
- Applying linear electric field
  - Bias voltage -1.2 V
  - Depletion depth 10 µm
- Carrier mobility:
  - Standard Canali model (doping-independent)



- Diffusion dominant in undepleted volume
- Linear drift of charge carriers towards sensor surface, no drift to electrodes
- Large charge cloud & cluster size, significant signal contribution from substrate

Realistic Simulation Requires More Information

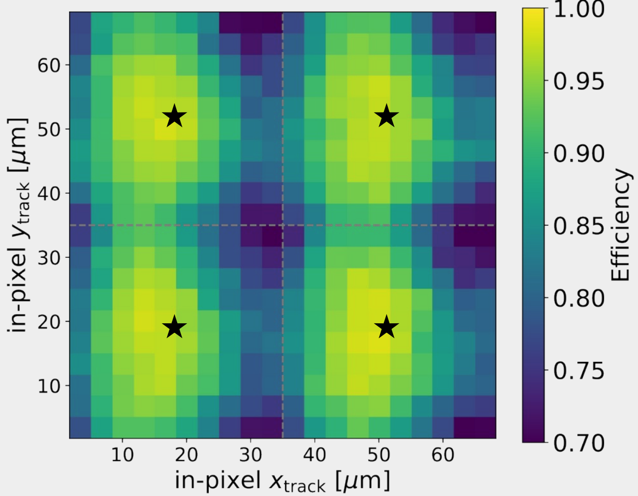
- Applying **TCAD electric field**
  - Bias voltage -1.2 V
  - Depletion depth 10 µm
- Setting **doping for epi & subs.**
- Carrier mobility:
  - **Masetti-Canali** model (doping dependent)
- Recombination:
  combined SRH-Auger model



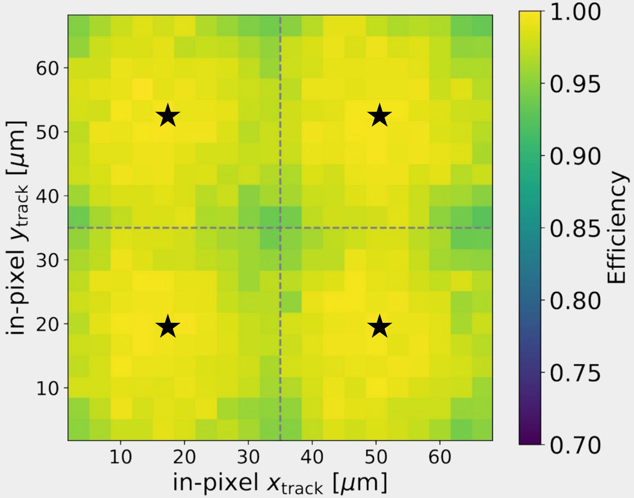
- Carrier drift obeys sensor features (p-wells), collection at electrodes
- Significant reduction of diffusion in highly-doped substrate, less charge sharing from substrate contributions
- Significant reduction of substrate contributions due to short lifetime in high-doping volume

Back to H2M: Non-Uniformity of In-Pixel Response

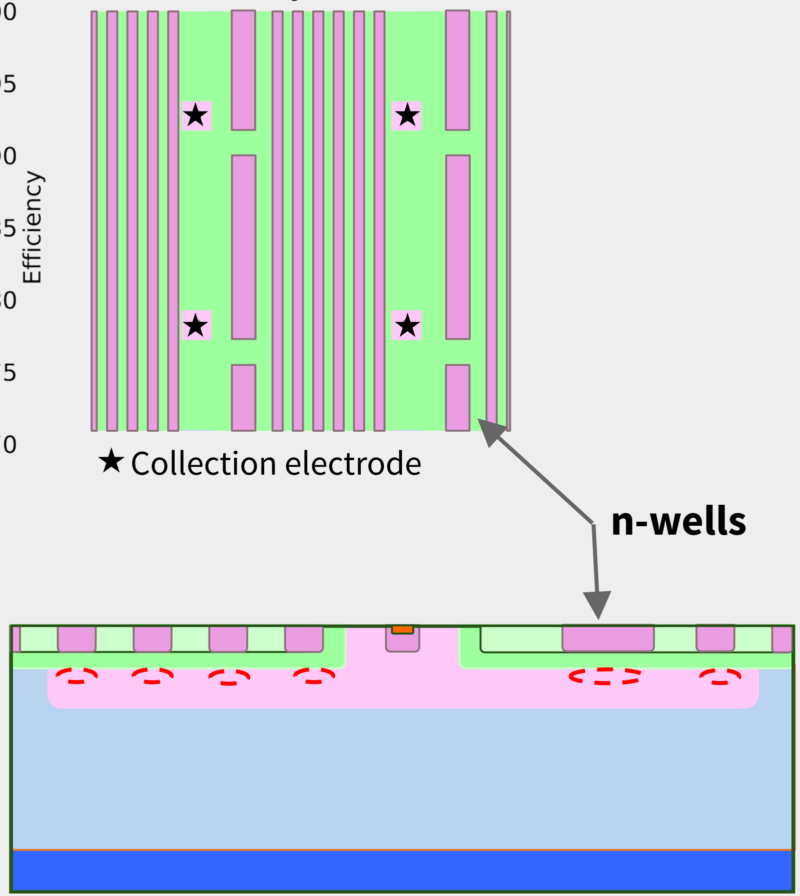
V_{bias} -1.2 V, ikrum 21, THL 332 e^-



V_{bias} -3.6 V, ikrum 10, THL 240 e^-

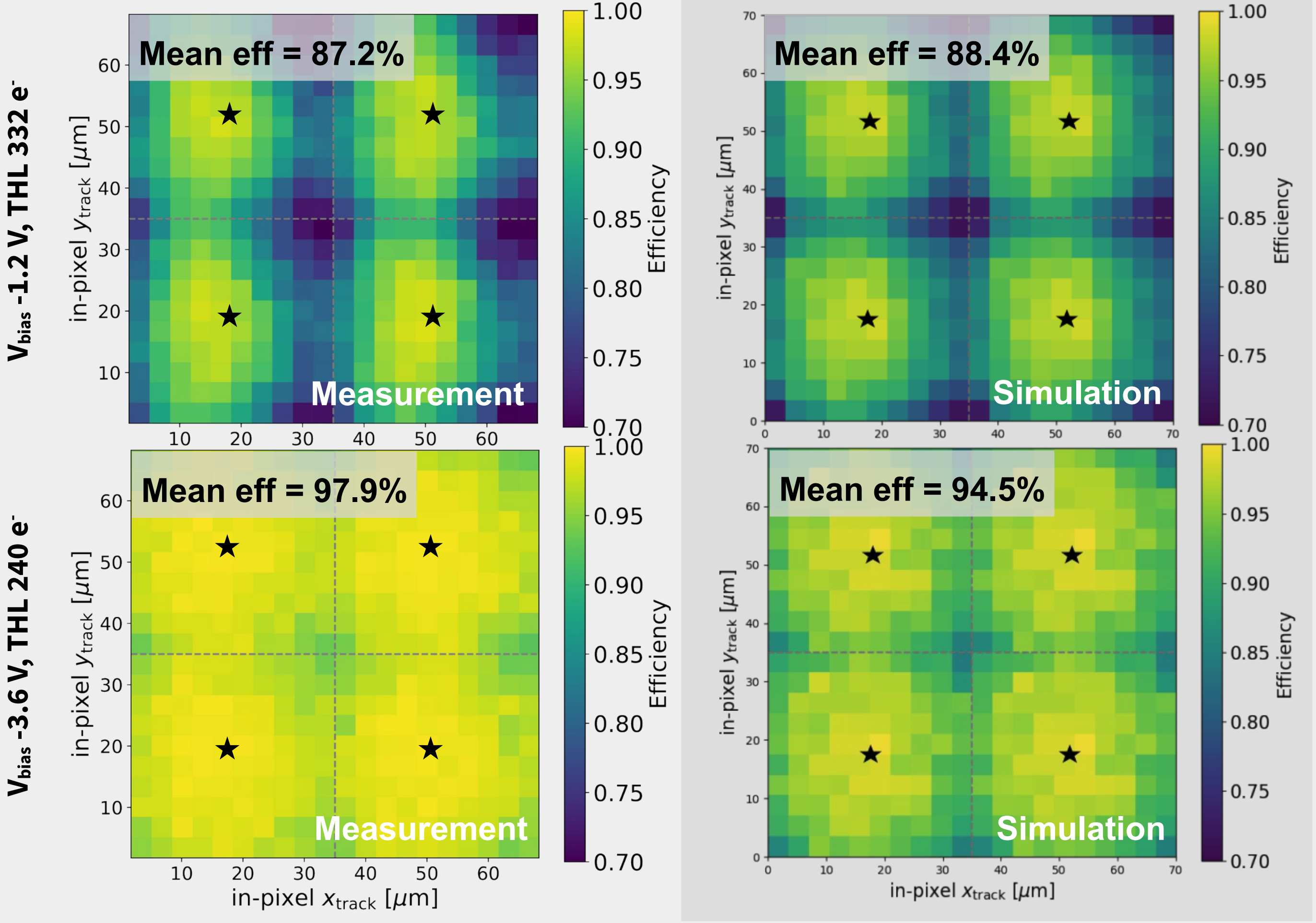


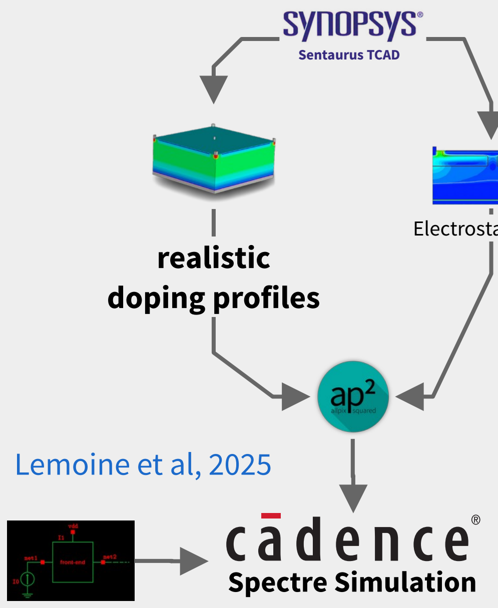
Layout



- Related to the **size and location of the n-wells** of the analog circuitry
  - Large n-well to house feedback capacitance for amplifier
  - N-wells of digital circuitry small & regular
- For future designs:
  investigating effects of relocating n-wells **with simulations**

Confirmation by Simulation with N-Wells





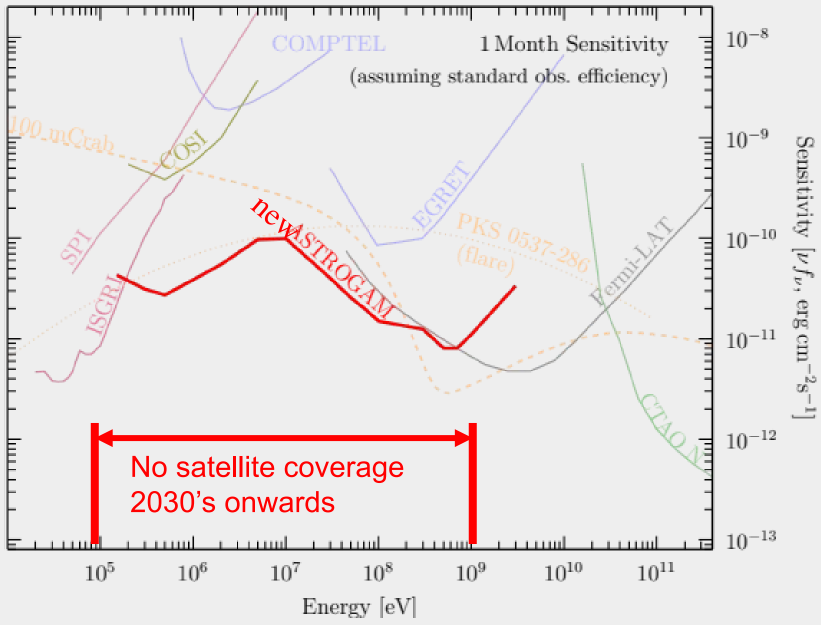
- Simulation with **realistic doping** profiles
- Includes n-well structure within p-well
- Simulation can qualitatively reproduce effect in **efficiency as well as ToA**
- **Slowing-down of charge carriers** traveling below large n-wells

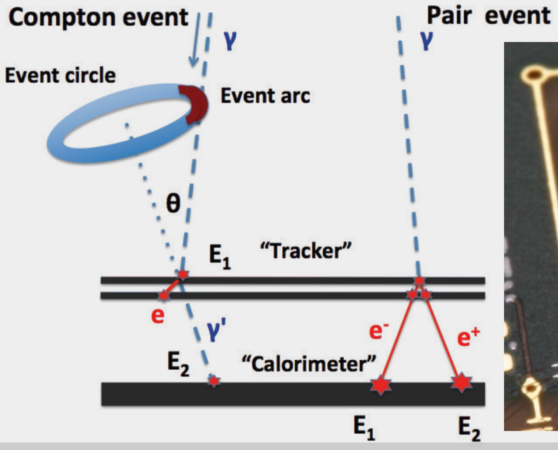
newASTROGAM

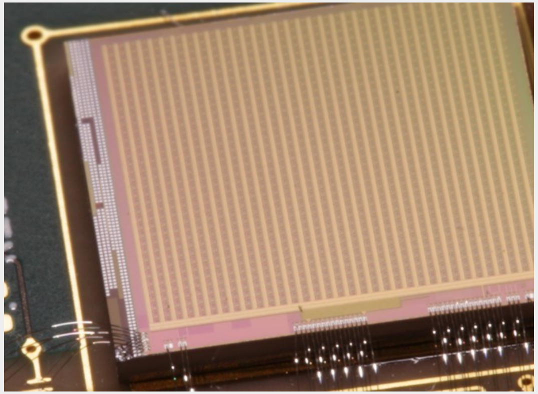
Proposal for ESA Call for Medium-Sized Missions (M8)

newASTROGAM

- ESA science program co-funds scientific satellite missions
  - Several proposal phases, possible launch ~2041
  - newASTROGAM: **Compton camera** satellite concept for MeV to GeV gamma rays
  - The 'MeV gap' impairs high-energy astrophysics & multimessenger astronomy
- Investigating pixel detector for tracker
- Collaboration with KIT, NASA: **AstroPix HV-MAPS prototype**
- Exploring synergies in MAPS detectors between Astroparticle & Particle Physics







OCTOPUS

Optimized CMOS Technology for Precision in Ultra-thin Silicon
A Project in the Framework fo the ECFA DRD3 Collaboration

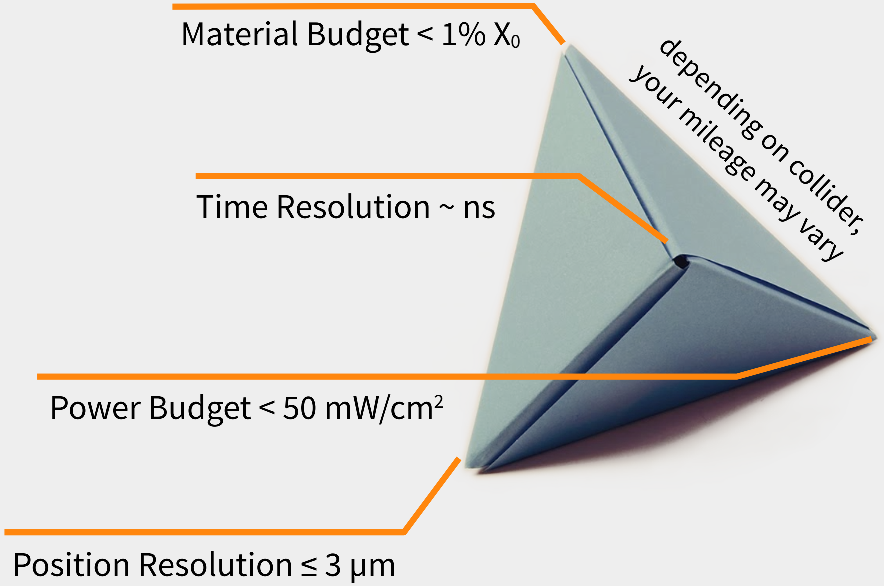
DRD3 Project OCTOPUS

The ECFA Detector R&D Collaborations

- Addressing challenges of future particle physics experiments
- DRD3 focusing on Solid State Detectors & Technologies

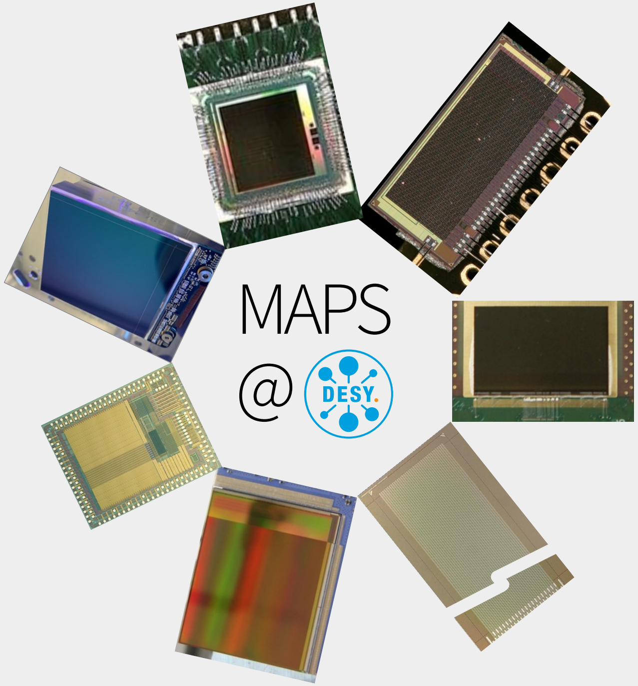
OCTOPUS – A Project for a Future Vertex Detector

- DRD goal: *"Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors"*
- Development of a **monolithic sensor prototype**
- **Staged approach:** further refinement of performance targets after conclusion of strategy update
- Intermediate target: Development of **high-resolution sensors for beam telescopes**



Summary

- MAPS enable major advances in imaging & particle detection
- DESY brings **state-of-the-art technology to scientific instruments**
- DESY **develops & maintains several tools** crucial to the MAPS R&D community
- DESY has accumulated **significant experience** in MAPS development:
    - Microelectronics design & simulation
    - Sensor design & signal formation simulation
    - Testing & characterization techniques



Tools by DESY.

DESY is ready to apply expertise to future projects
OCTOPUS, newASTROGAM, vertex detectors…

DESY.