Silicon pixel detectors application for low energy particle measurements: Mimosa, Timepix, SiPM matrices

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Project approach (a brief reminder)

- Two research directions
  - Scintillator Research – novel inorganic/organic materials
  - Signal processing – making sense of the readout
- Two development approaches:
  - Fully simulated system – physical processes, electronics, data processing (analysis)
    - allows for validation of the developed systems
    - allows generation of data for research into ML
  - Prototype studies
    - implement your model and feed it to your tools
    - see if it works half as well as your simulation

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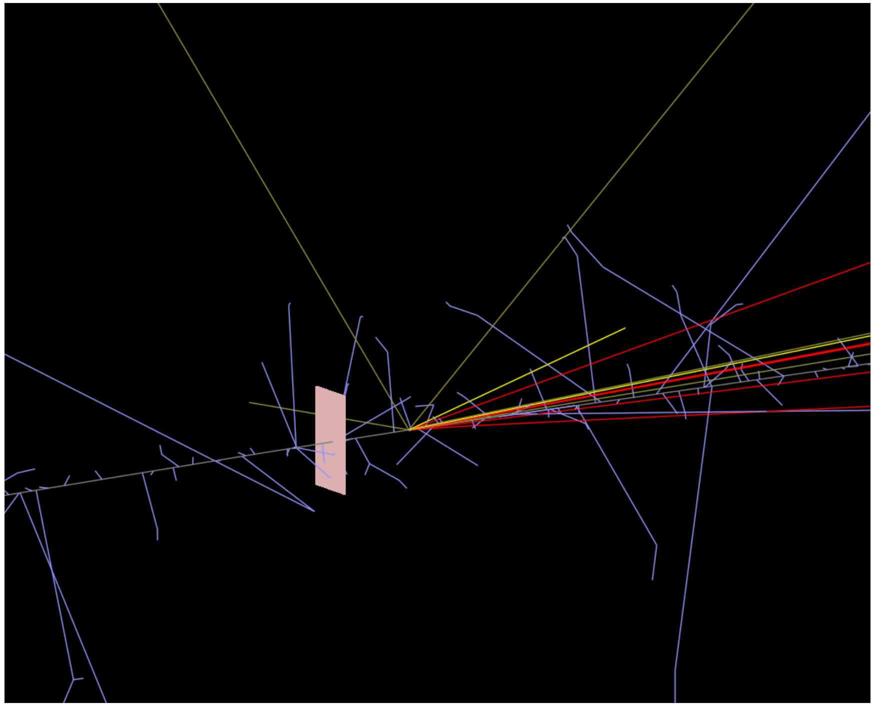
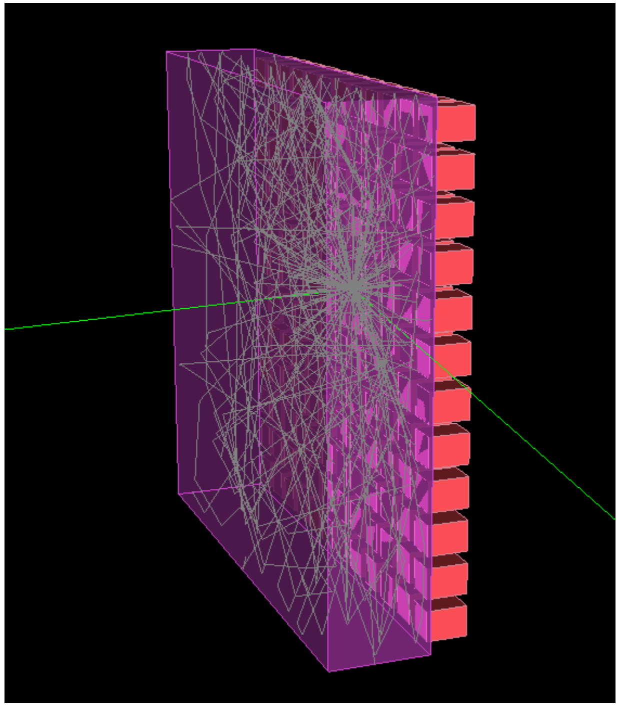
Particle Detection

- The basic idea of detection is simple and repetitive:
  - Deposited energy generates something we can measure - electric charge
  - We measure the charge and the way it has accumulated and try to guess what generated it.



Direct charge deposition



Scintillation

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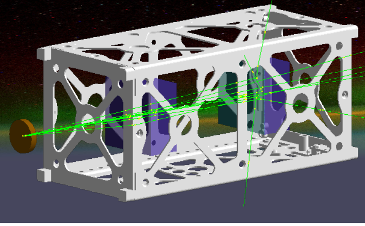

Particle Detection

- Technology overview I
  - Multipixel silicon sensors
    - Thin layer of semiconductor
    - A matrix of diode structures, where charge is collected
    - Integrated biasing, amplification, signal shaping and readout
    - Benefits
      - High efficiency for some particle types (x-rays, light charged particles) and low energy ranges
      - Good energy resolution and excellent time and positional resolution characteristics
      - Small, lightweight, low power compared to competing technologies
    - Challenges
      - Low efficiency for many particle types and energy ranges due to thin sensor
      - Small size, which precludes use in many scenarios
      - High cost in large volumes
      - Very high heat dissipation requirements
      - Calibration issues
      - Generate very high volumes of data, which are difficult to process

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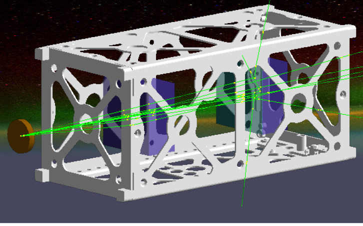

Particle Detection

- Technology overview II
  - Scintillation
    - Classically,
      - a large inorganic crystal, with lower time and energy resolution
      - readout via PMT – a large glass tube with complex internal structure
      - complex readout electronics
      - high voltage (kV) supply required
      - impossible to use in magnetic fields
    - Modern scintillator detectors are much more capable
      - new readout technology – silicon photomultipliers
      - new scintillating materials – faster, efficient, high-yield “bulk” scintillators, both organic and inorganic; nanoparticle-based organic scintillators with even better properties
      - in combination, the developments provide an excellent alternative to the silicon sensors in many common application scenarios
      - irreplaceable where the alternatives don’t work

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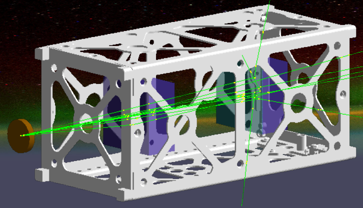
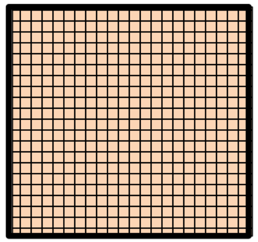
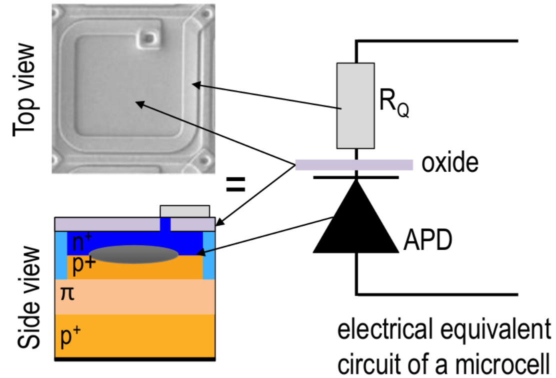


Sensor technology overview

- SiPM and SiPM matrices – passive pixel sensors
  - A single SiPM is a matrix of many “microcells
  - Every “microcell” is an avalanche photodiode reacting to one impacting photon
  - The device produces charge, proportional to the photon current
  - Operates similar to PMT, but smaller, lower power requirements, needs much smaller bias voltages, and can operate in environments with magnetic fields
  - Coupled to scintillators, cannot detect radiation on its own
  - Key characteristics:
    - breakdown voltage
    - quantum yield
    - cross-talk and dark current
  - A SiPM matrix can provide positional sensitivity
    - submillimeter resolution

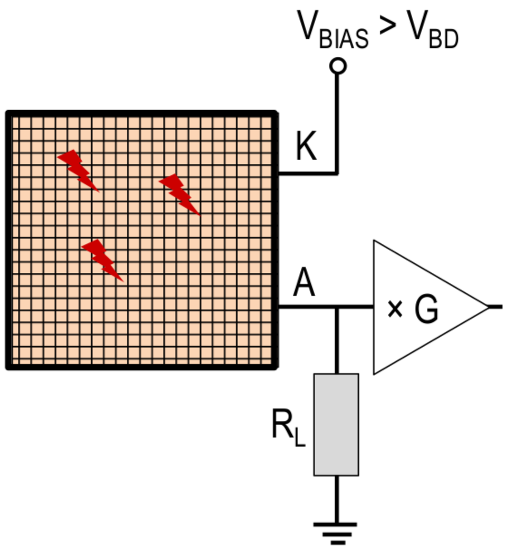


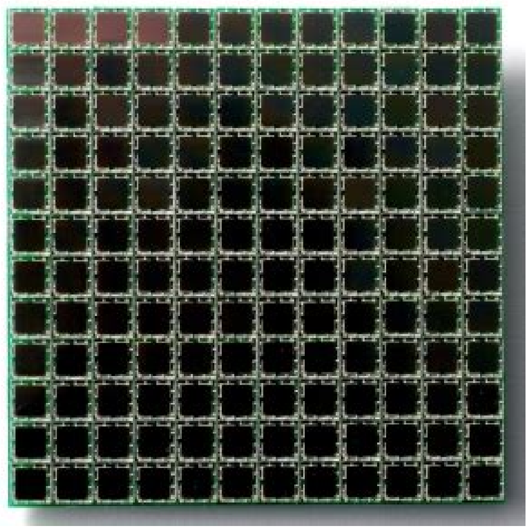
SiPM is an array of microcells



Single microcell

electrical equivalent circuit of a microcell





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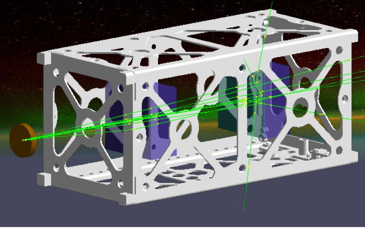
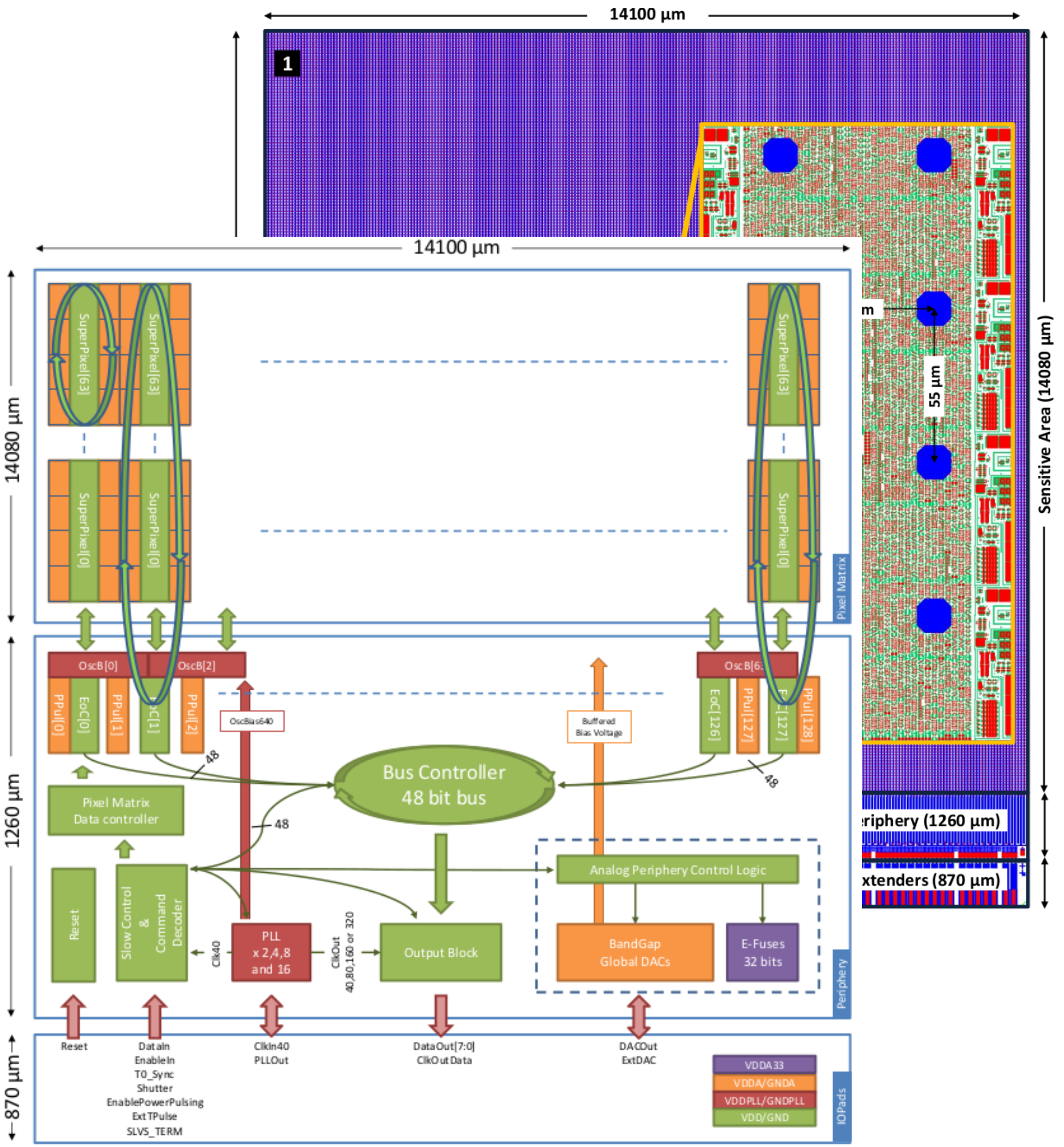


Sensor technology overview

- Timepix chip – a *hybrid pixel detector*
  - 256x256 pixels
  - All necessary electronics to manage each individual pixel
  - Power supply
  - Input and output pins
- Many configurable parameters: individual pixel bias, readout mode, detection treshold
- Many ways to read data
  - as a "picture"
  - as a stream of events
  - provides high resolution time-of-arrival, energy
  - can combine pixels into "super-pixels"
  - can provide data from less pixels than the full matrix
  - internal and external triggering



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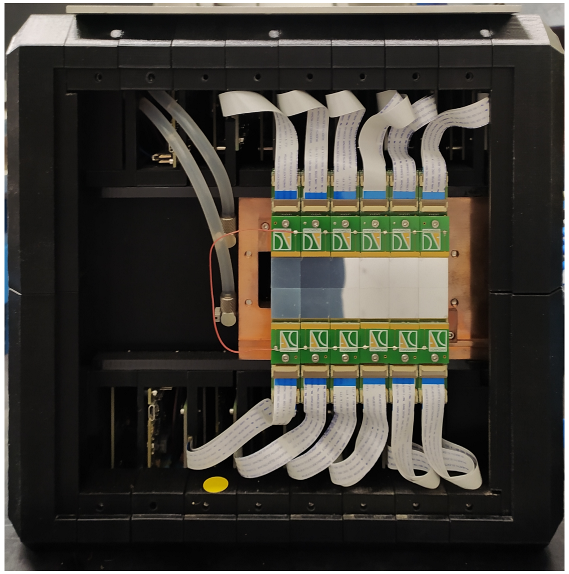
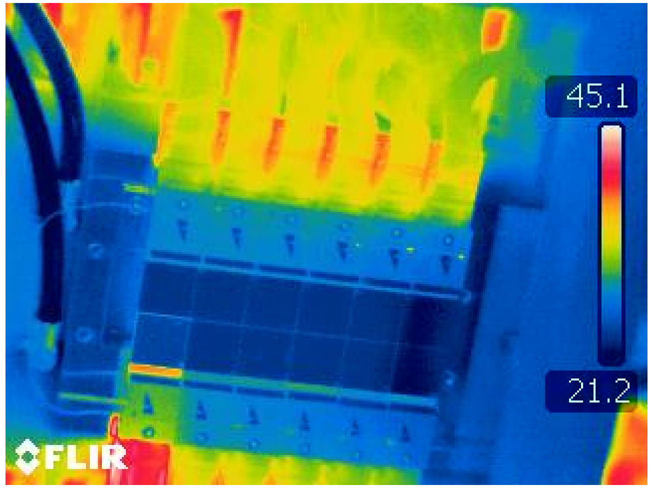
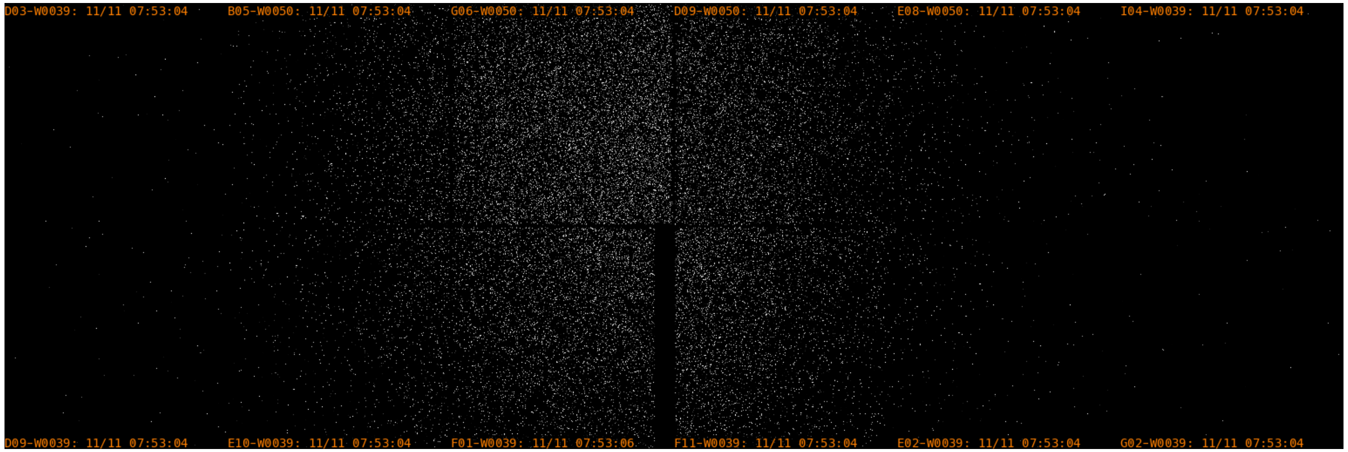
Sensor technology overview

- Larger Timepix configurations
  - timepix chips can be combined in larger configurations
  - “widepix” is a product with 5 chips in one row
  - super-”widepix”, used in the PADME experiment consists of 6 chips in 2 rows, giving a very large area of detection.
  - huge volumes of data to process
  - serious challenge for synchronization, readout software, even cooling
  - complex infrastructure around the sensors
  - complex external triggering







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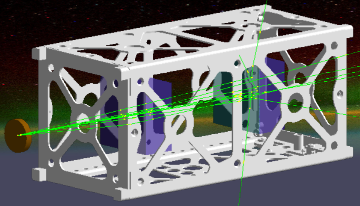
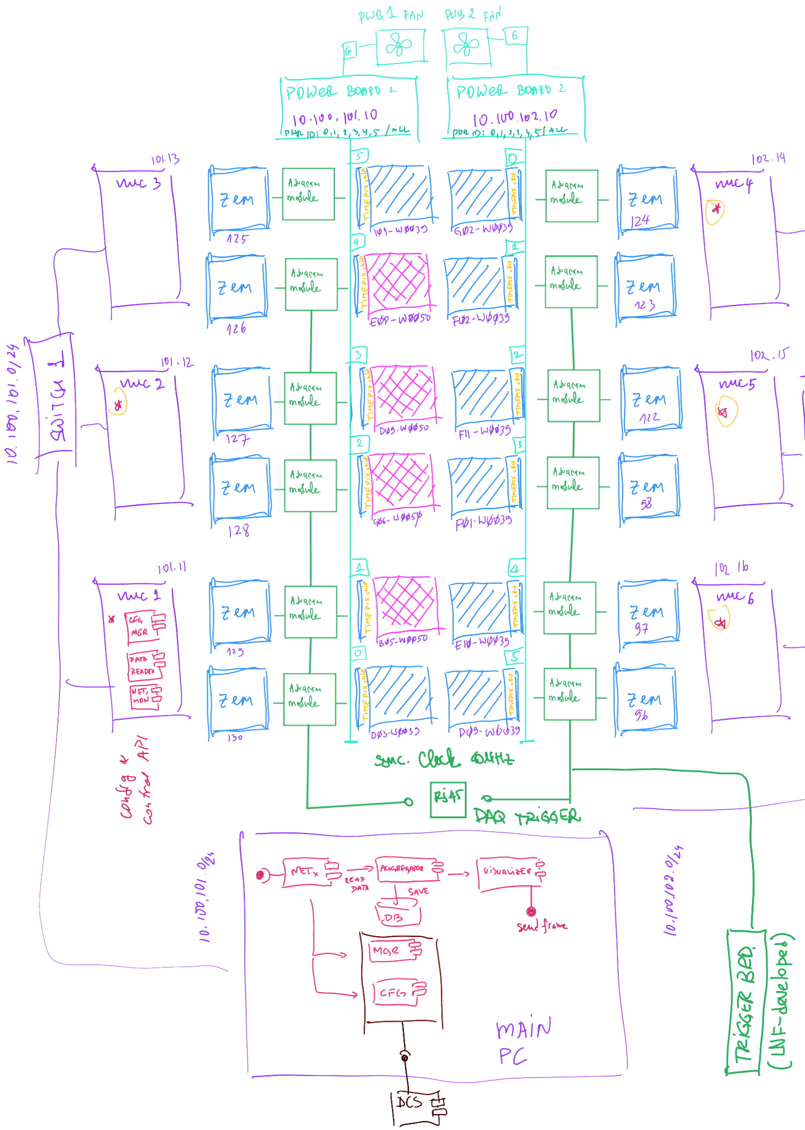
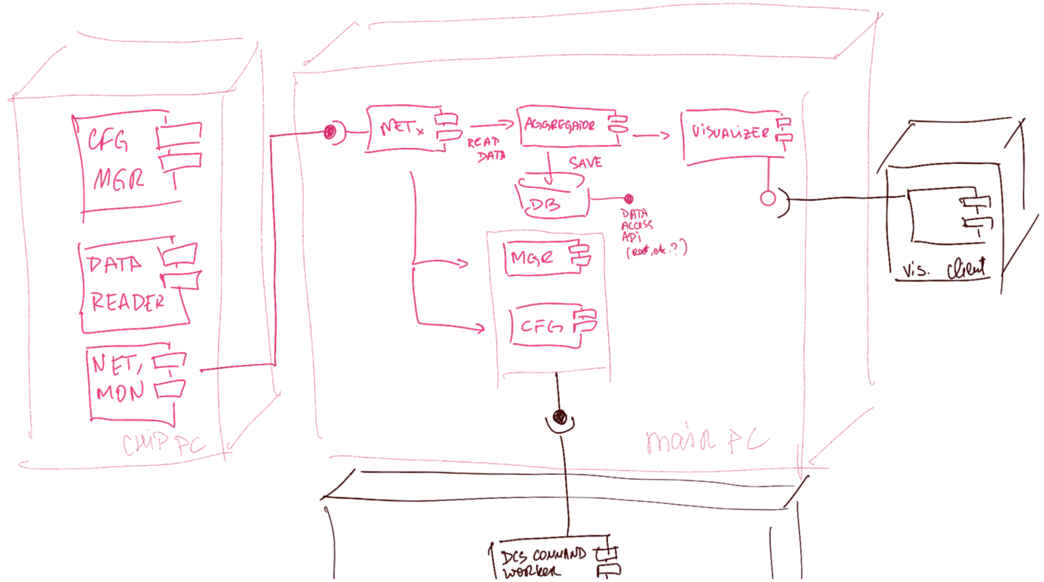


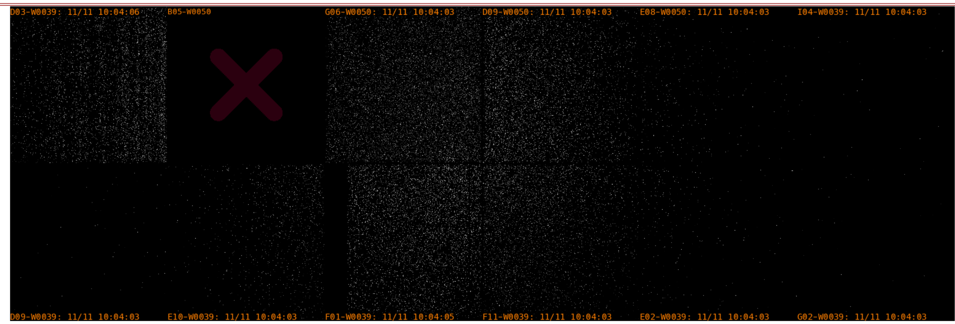
Example in complexity – widepix hw and sw





Visual timepixen

frame acquisiton hw manager



Check acquisition state	Acquisition status:
	start/stop acquisition
1 [s]	time length of a single frame in seconds, must be more than 0, too long a frame will result in slow update be an integer/float
50 [keV]	energy threshold of detected particles, maybe in keVs. Integer/float

Data acquisition.

Refresh latest

Commands	Run	Frame counter	Working devices	Min db time	Max db time	Min chip ts	Max chip ts	Highest temp (C)
ToA frame ToT frame	dbe746a16d324b7b8d3dea0ac8999879	3	6	2022-11-11 10:04:05	2022-11-11 10:04:06	1668161044.7025511	1668161044.8499491	21.01
ToA frame ToT frame	dbe746a16d324b7b8d3dea0ac8999879	2	9	2022-11-11 10:04:04	2022-11-11 10:04:05	1668161043.544787	1668161043.838138	22.09
ToA frame ToT frame	dbe746a16d324b7b8d3dea0ac8999879	1	11	2022-11-11 10:04:03	2022-11-11 10:04:06	1656305467.3357038	1668161042.416331	22.31

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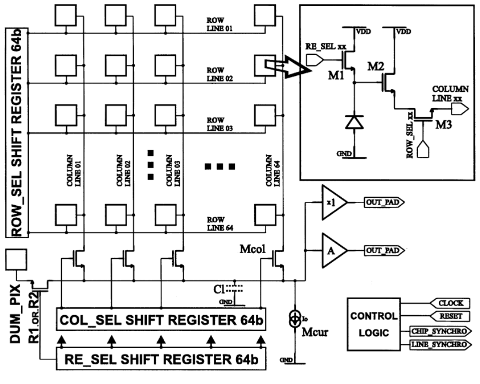
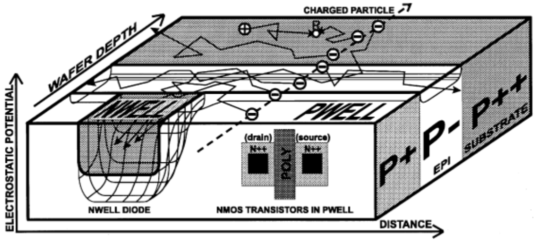
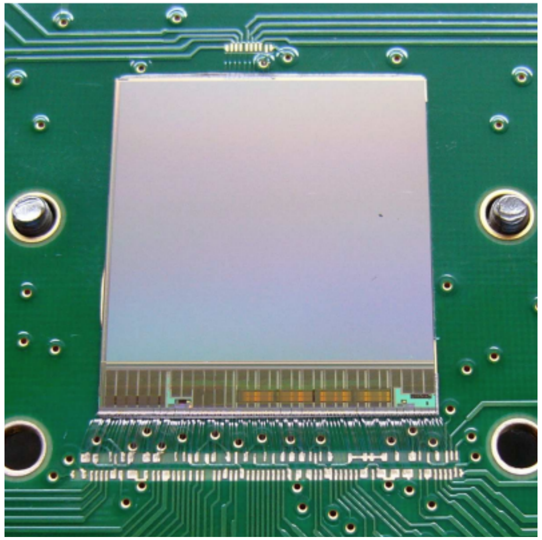
Sensor technology overview

- Mimosa – a *MAPS*
  - monolythic active pixel sensor
  - sensor and sensor electronics are produced together
  - lower costs
  - better integration
  - better performance
- Some “downsides”
  - still high thermal dissipation and cooling requirements
  - smaller pixels, larger size than hybrid senors – even more data to process, requires very large processing capacity, often unavailable in space







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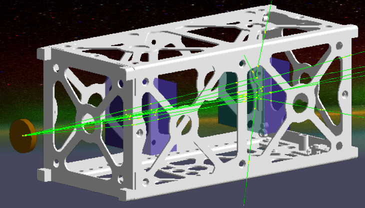
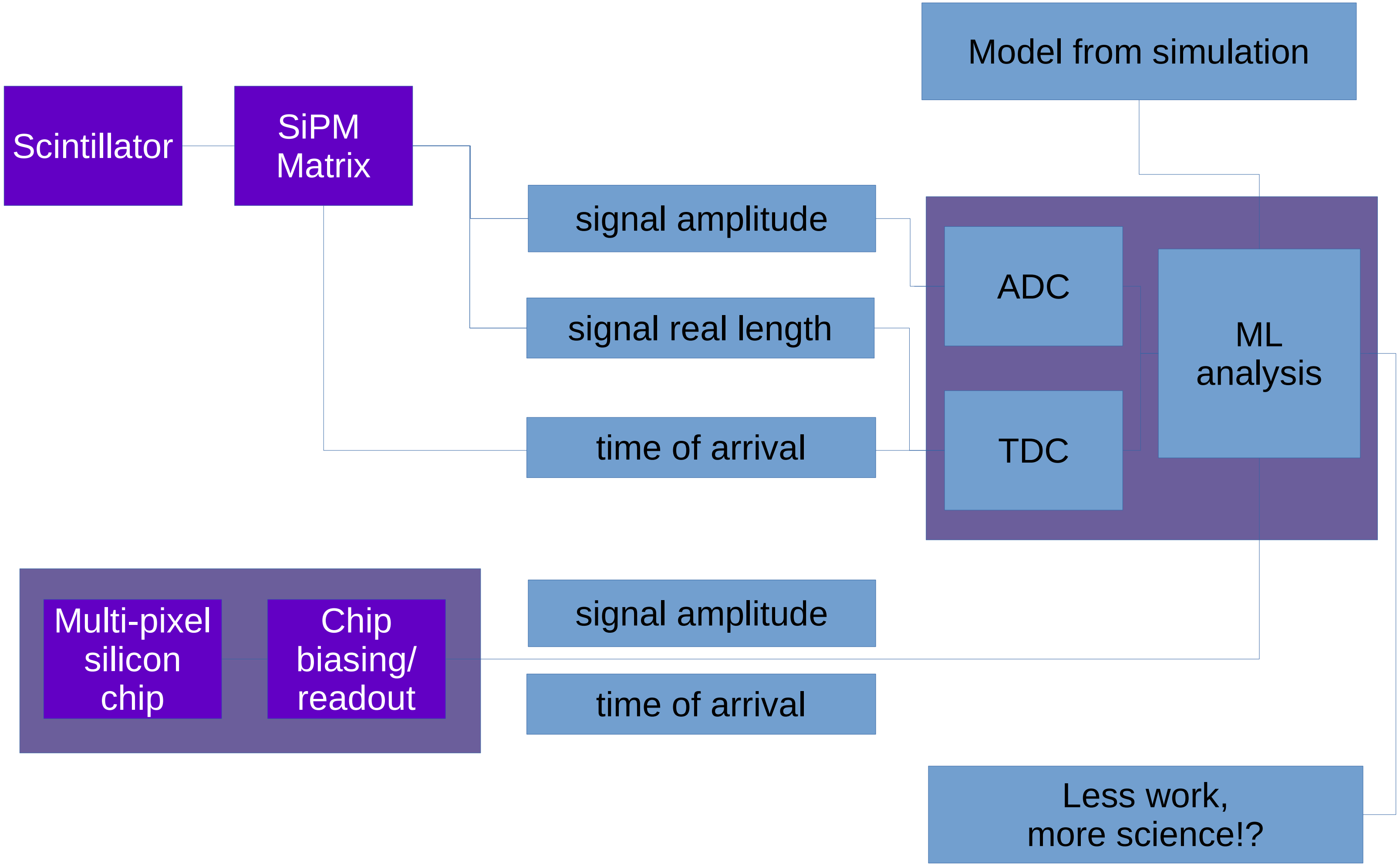


Data Acquisition and Analysis Approach

Old and busted

New hotness



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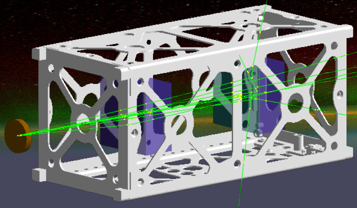

Where are we now?

- Successfully model complex systems
  - we can model both physical processes and electronics response
- Can train and verify several types of ML models
  - Classification
  - Clustering
  - Parameter estimation
- Already using our methodology to process data from scintillator/SiPM matrices with different geometries:
  - Scintillators for spectrum measurements (typically cylinders or rectangular prisms)
  - Enclosures for 4π measurements, e.g.
  - Sheet and rod organic scintillators for positional and timing characteristics
- No “by-hand” analysis required – ML methods combine data to produce calibration, measurements of deposited energy and event reconstruction
- Work is on-going to apply the method for use with the multipixel silicon sensors

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Conclusions

- Space applications potential
  - Passive sensor (SiPM) applications – larger, low positional resolution, but much lower power requirements, easier to read out and can accommodate very complex detector geometries and larger sizes. Good choice for most current space applications.
  - Hybrid active sensors (Timepix) – small, high positional resolution, poorer energy resolution, serious thermal dissipation requirements. Very complex readout and analysis. A serious overkill in the known current space application – dosimetry.
  - Monolithic active sensors (Mimosa) – lower cost and possible better performance than the hybrid sensors, especially in terms of energy resolution. Very complex readout and analysis in the advanced usage scenarios. Most likely the future.

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