HV-MAPS Pixel Detectors for Particle Tracking and LiDAR: A Dual-Use Silicon R&D

Tianqi Gao

- Introduction to High Voltage Monolithic Active Pixel Sensor (HV-MAPS)

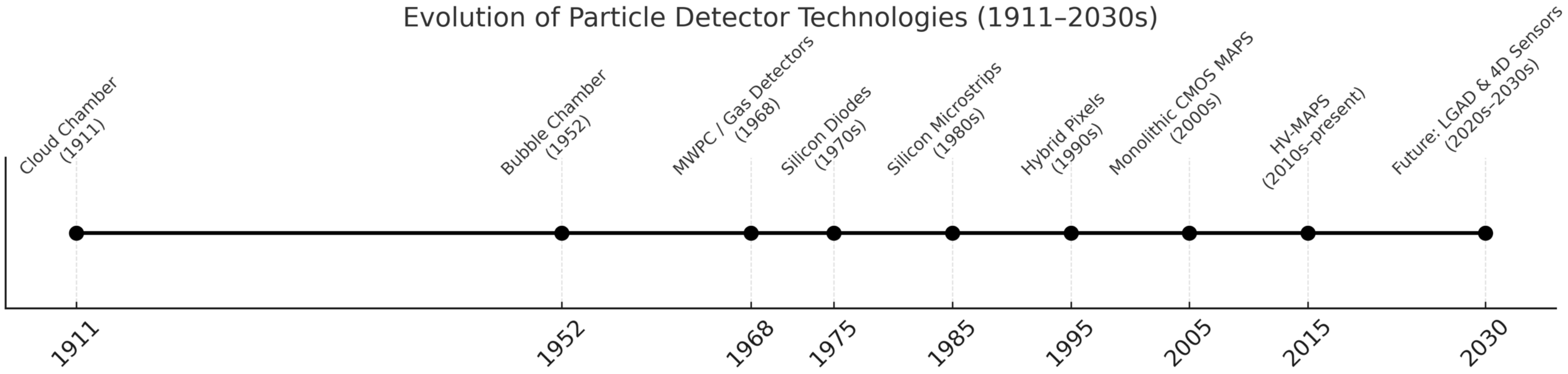
- Our latest results from Mightypix/Telepix2

- My early venture of HV MAPS application outside of HEP
  - HV-MAPS LiDAR
  - Astrophysics

- Future pipelines after the Mightypix project is done and dusted

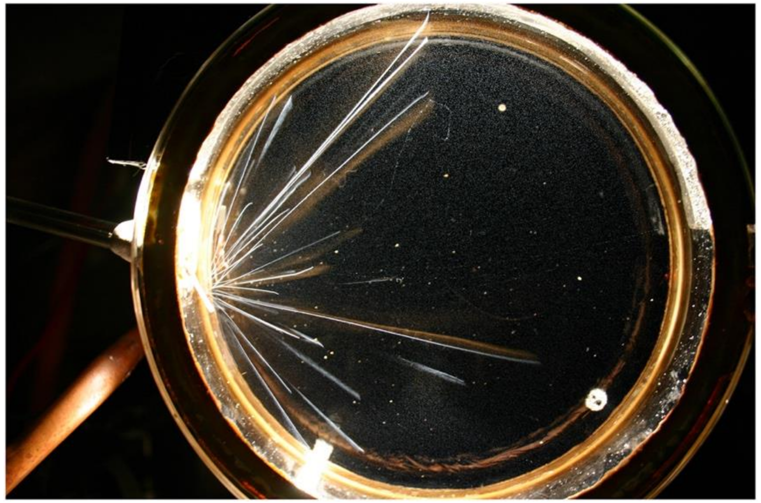
Section 1 - From Cloud Chambers to HV-MAPS

- Particle physics pushed from “see a single track” to “reconstruct 10^9 tracks per second” as accelerators got brighter and higher rate. This forced:
  - higher granularity,
  - faster readout,
  - better radiation tolerance.
- Early detectors were visual and offline (photographic); modern detectors are fully electronic, self-triggered, and radiation hard.
- All modern silicon tracking now aims for ~10 µm spatial resolution with ns-scale timing in high-rate environments such as the HL-LHC.



Cloud Chamber (Wilson 1911)

- Supersaturated vapour condenses along ionisation trails, making charged particle tracks directly visible as white lines.
- Used to observe and photograph cosmic rays and led to discoveries like the positron. (This is well documented historically in Cavendish and early cosmic-ray studies.)
- Purely passive and low-rate: every “event” is a single picture, not continuous data.



Tracks of beta particles from radium-226 obtained with a full-scale replica of Wilson's cloud chamber. Courtesy Wolfgang Engels.

Bubble Chamber (Glaser 1952)

- Superheated liquid (often liquid hydrogen) forms strings of bubbles along charged tracks.
- Produced millions of high-quality bubble photographs and enabled resonance discoveries in the 1950s–1970s.
- Still photographic, not electronic: analysis required scanning film, not real-time trigger logic.

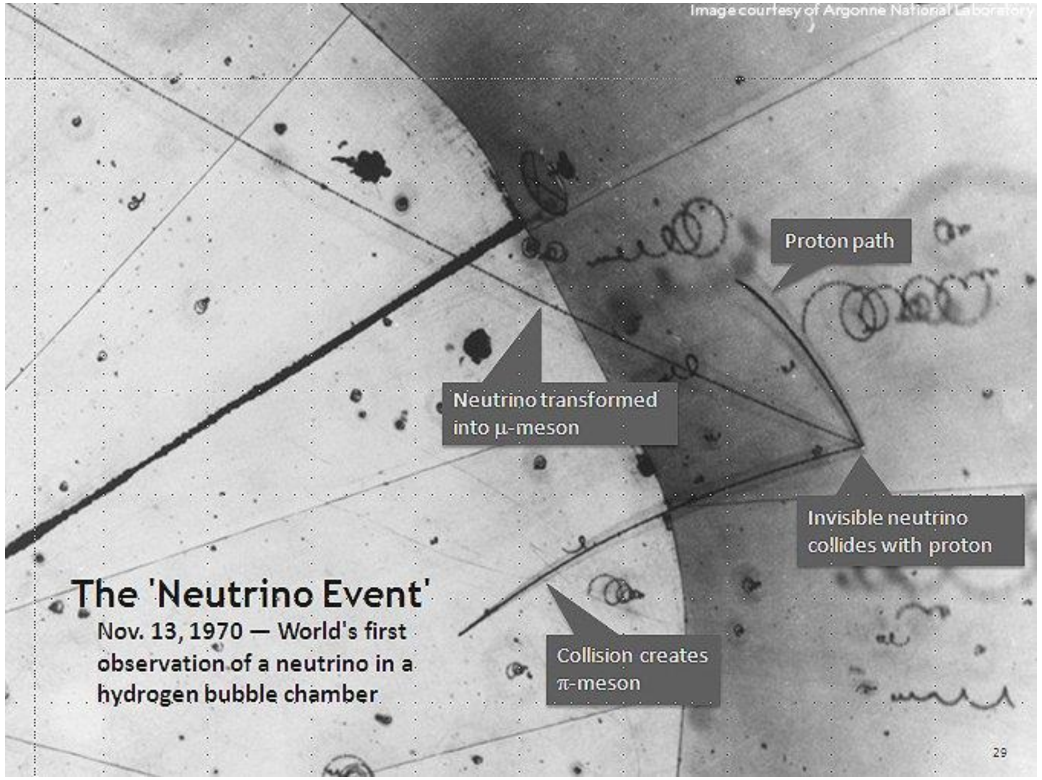


Image courtesy of Argonne National Laboratory

Proton path

Neutrino transformed into μ-meson

Invisible neutrino collides with proton

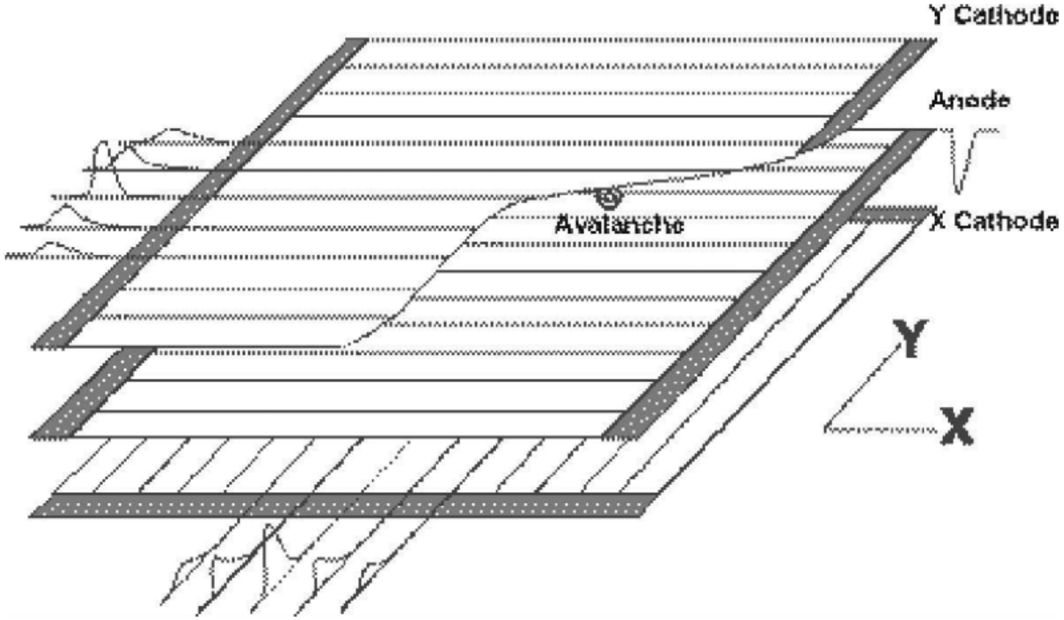
Collision creates π-meson

The 'Neutrino Event'

Nov. 13, 1970 — World's first observation of a neutrino in a hydrogen bubble chamber

Gas Detectors and the Multiwire Proportional Chamber (Charpak 1968)

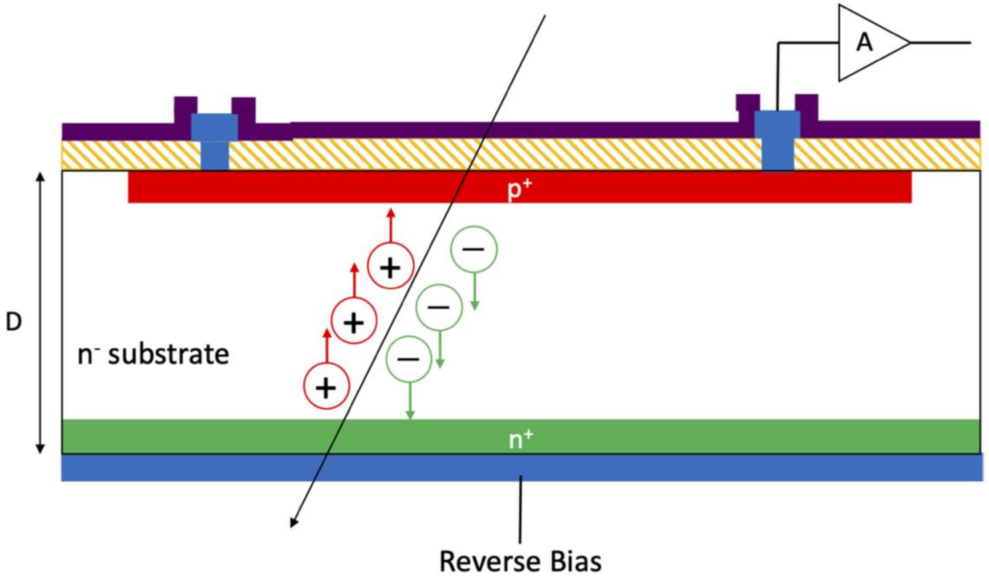
- Ionisation in gas is collected on many fine anode wires; signals are electronic, not photographic.
- The multiwire proportional chamber (MWPC) could localise hits in space, run at high rate, and be read out automatically.
- This step (Charpak, Nobel 1992) is widely viewed as the transition from photographic detectors to fully electronic tracking.



A 2D MWPC with segmented cathode planes. Signals induced on the two cathode planes are used to reconstruct the X-Y coordinates of the incident particle. S. Stapnes, Instrumentation for high-energy physics, (2006)

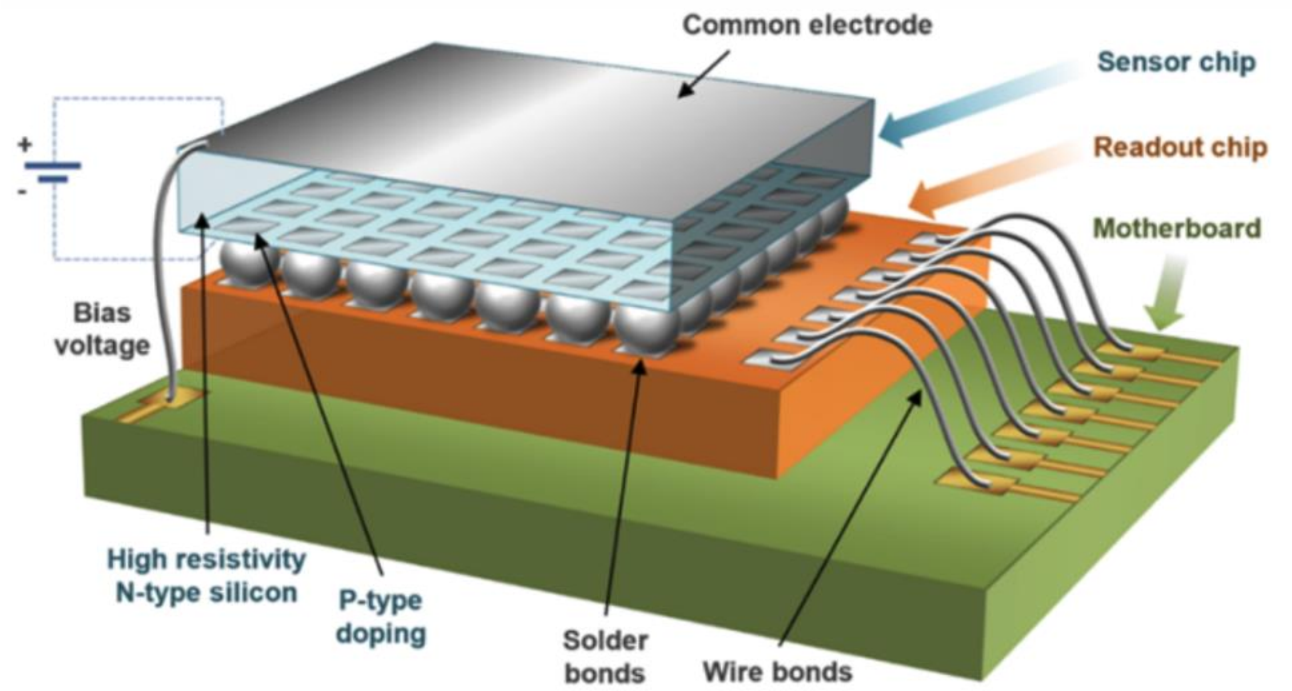
From Gas to Solid-State Silicon

- Silicon p–n junction detectors introduced in the 1970s gave much better spatial precision than gaseous trackers, and could be built very thin.
- Solid-state sensors enabled the first true precision vertex detectors at colliders by placing silicon very close to the interaction point.
- Silicon strip and pixel sensors became standard at LEP, Tevatron, and later the LHC.



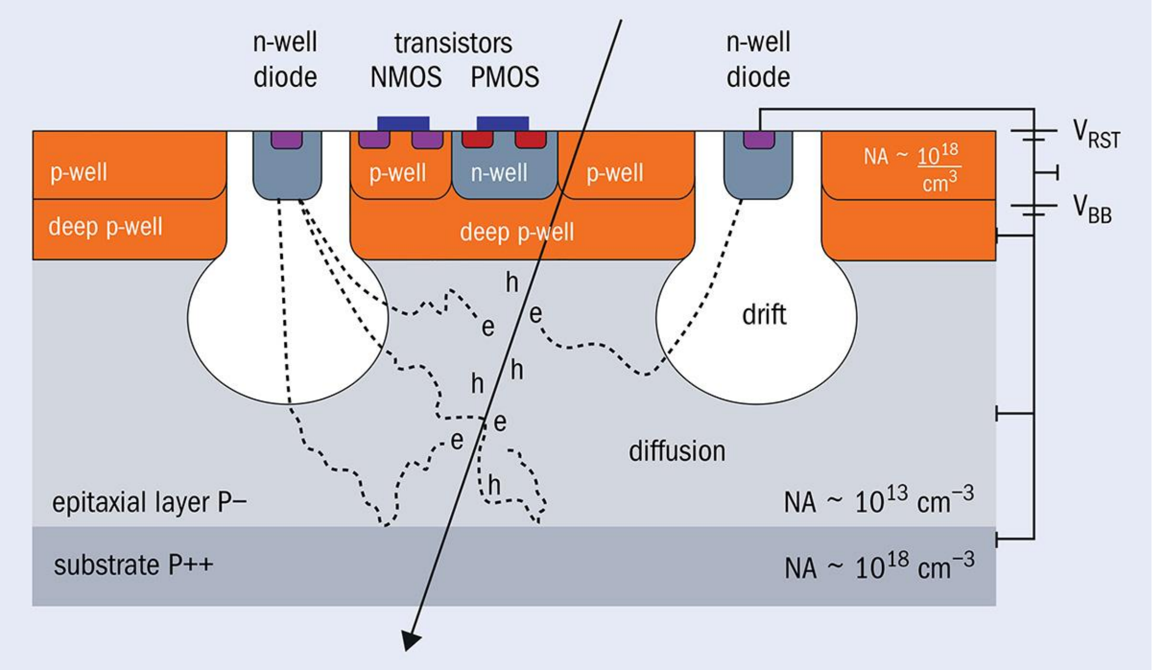
Silicon Microstrips → Hybrid Pixels

- Microstrip detectors give 1D position per layer; multiple layers reconstruct full 3D tracks with ~10–30 µm precision at hadron colliders.
- Hybrid pixels bond a separate sensor to a separate readout ASIC via bump bonds. This is used in ATLAS/CMS and allowed operation in extremely harsh radiation at the LHC.
- Drawbacks: thick material from sensor+ASIC+bumps+cooling; expensive fine-pitch bump bonding at scale.



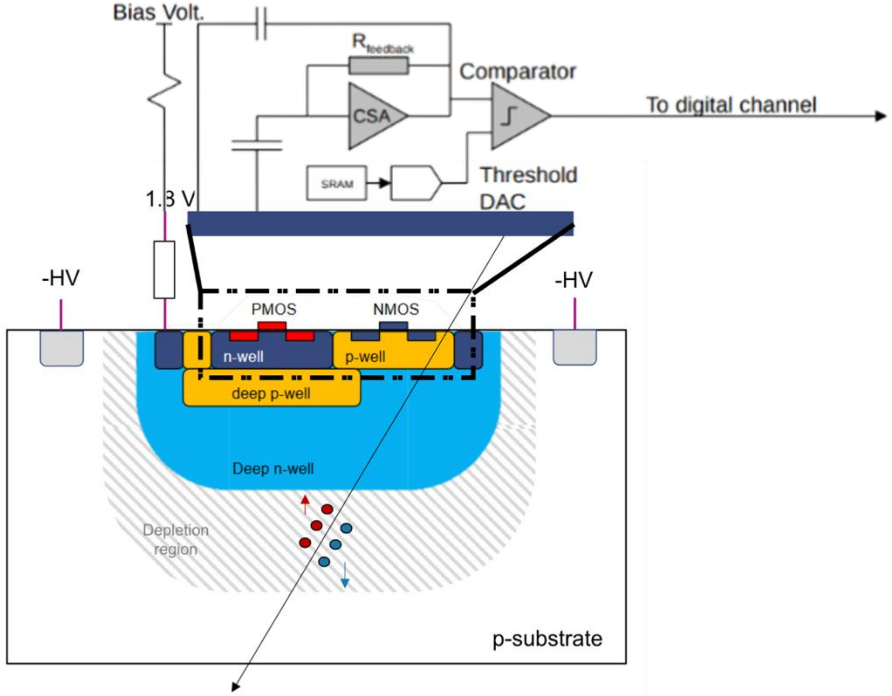
Monolithic CMOS MAPS

- Monolithic Active Pixel Sensors (MAPS) put the sensing diode and front-end electronics on the same wafer in commercial CMOS.
- ALICE ITS2 and other experiments now deploy large-area monolithic CMOS sensors: thin, low power, lower cost per cm² than hybrid pixels.
- Continuous, data-driven readout architectures (column-drain, priority scan) are designed for high hit rates.



High-Voltage MAPS (HV-MAPS)

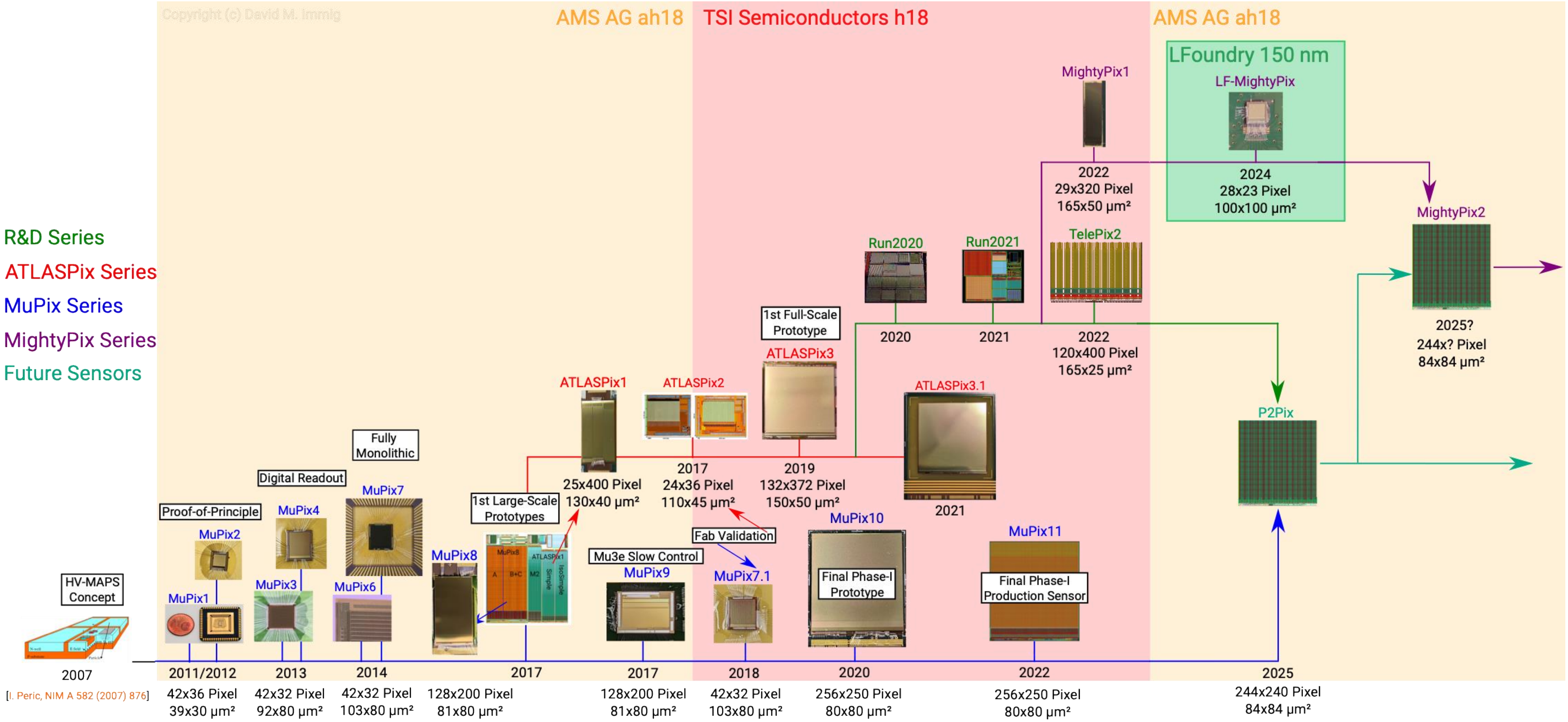
- HV-MAPS combine a depleted sensor with in-pixel amplification, discriminator, timing, and digital logic in a single CMOS die.
- HV-MAPS are a “depleted” variant of MAPS built in high-voltage CMOS: you bias the deep n-well at tens of volts so the sensitive volume is depleted, giving fast drift collection.
- Sensors can be thinned to ~50 µm, reaching per-layer material budgets down to around 0.1 % X_0, which is crucial for low-momentum tracking (Mu3e).



Working principle of HV-CMOS sensors.

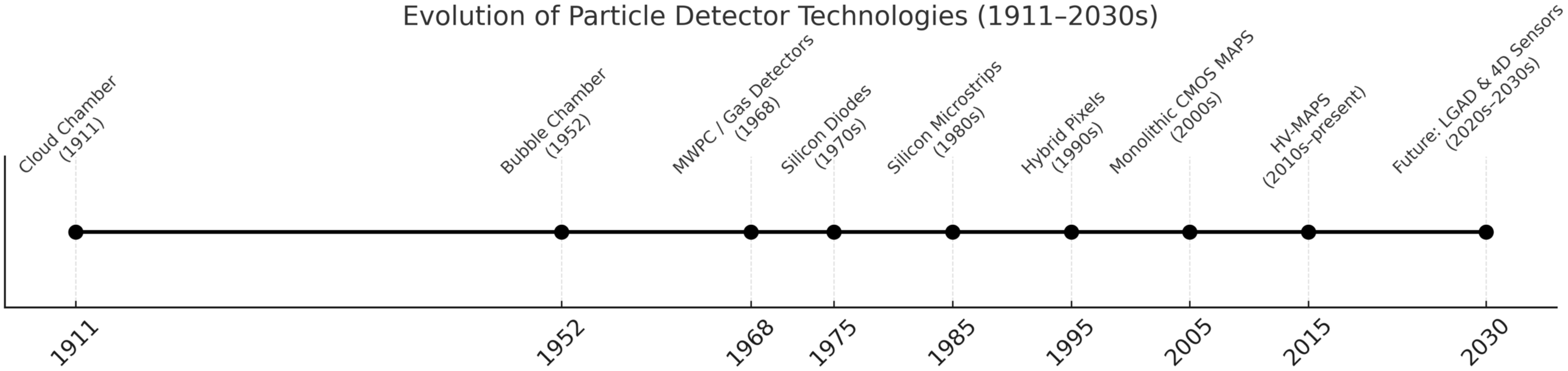
HV-MAPS Performance Milestones

- MuPix7/MuPix9/MuPix10 prototypes for Mu3e reach > 99 % efficiency and ~6–15 ns single-hit time resolution depending on generation and tuning.
- Output links run at O(1 Gbit/s) per chip and support high hit rates (tens of Mhits/s per chip).
- Radiation tolerance into the 10^{15} neq cm^{-2} range and doses O(10–40 MRad) is an explicit design target for HL-LHC style environments.



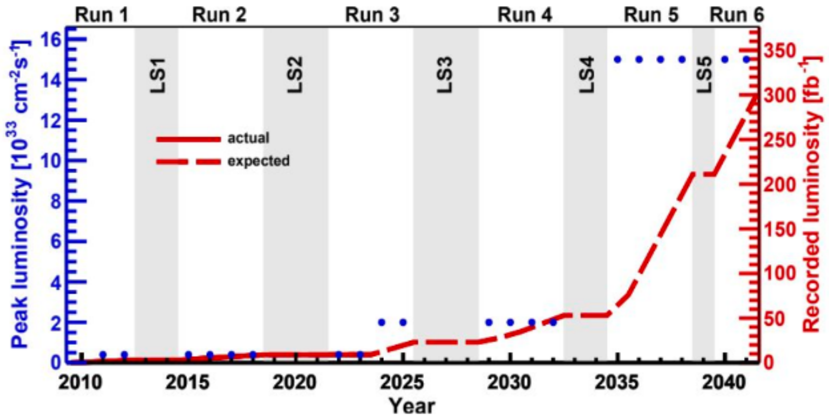
A Century of Progress

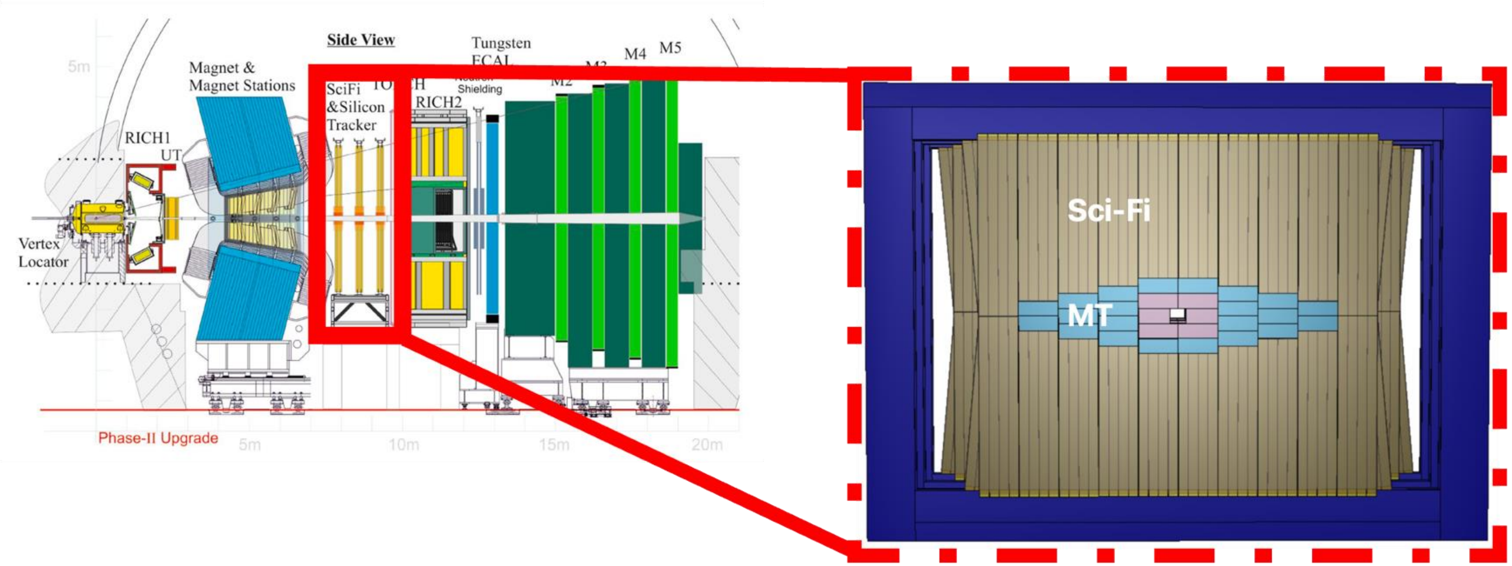
- The arc is: visual “track pictures” → electronic gas readout → silicon strip/pixel → monolithic CMOS → depleted high-voltage monolithic pixels.
- Every step drove down material, drove up timing precision, and made readout more local and parallel.
- Modern HV-MAPS are now thin, fast, self-triggered pixel planes designed for MHz/cm² particle rates.



Section 2 - LHCb Upgrade II and MightyPix Motivation

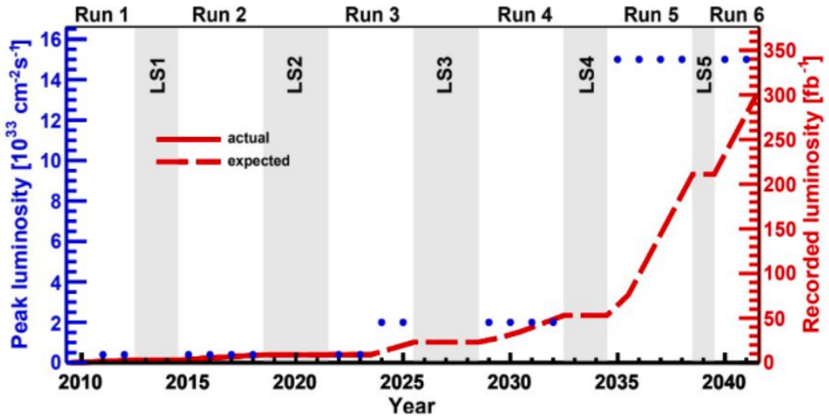
- LHCb after LS4 aims for instantaneous luminosity around $1.5 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ (≈ ten times higher than today), with corresponding high occupancies and radiation.
- The downstream tracking system (“Mighty Tracker”) will replace scintillating fibres in the central region with HV-MAPS pixel planes to survive that environment.
- MightyPix is the custom HV-MAPS line being developed to meet these conditions.

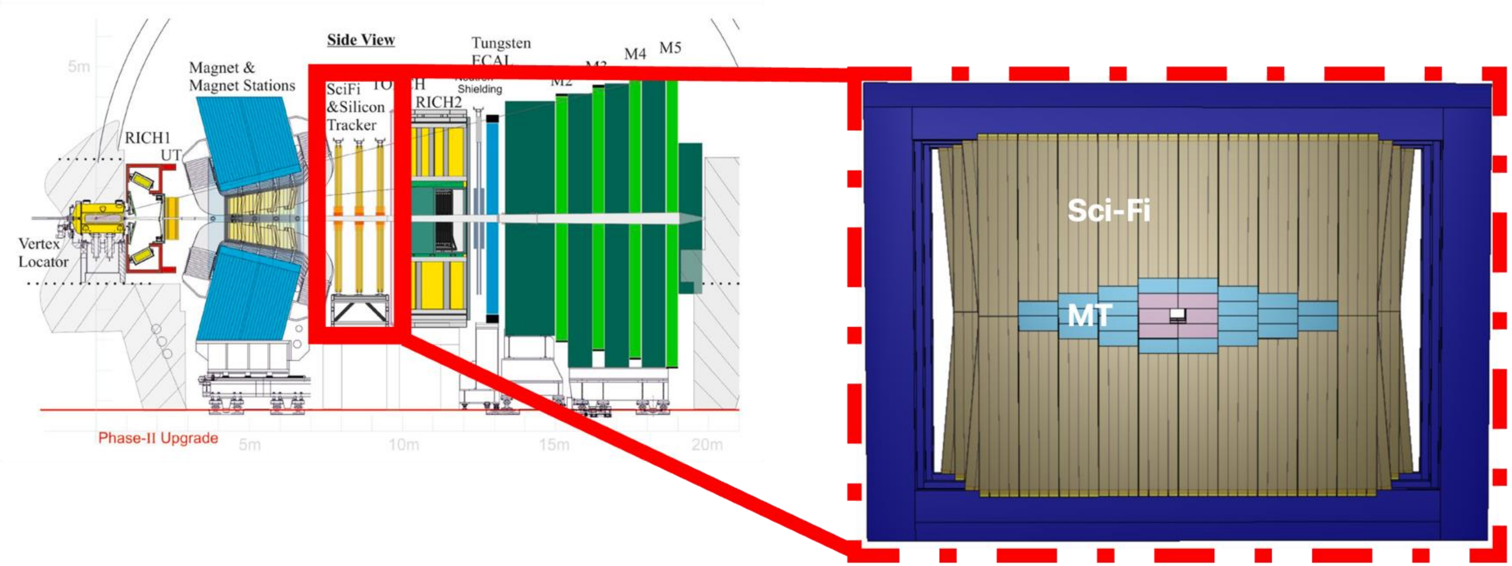




HV-MAPS in HEP: The LHCb MightyPix Project

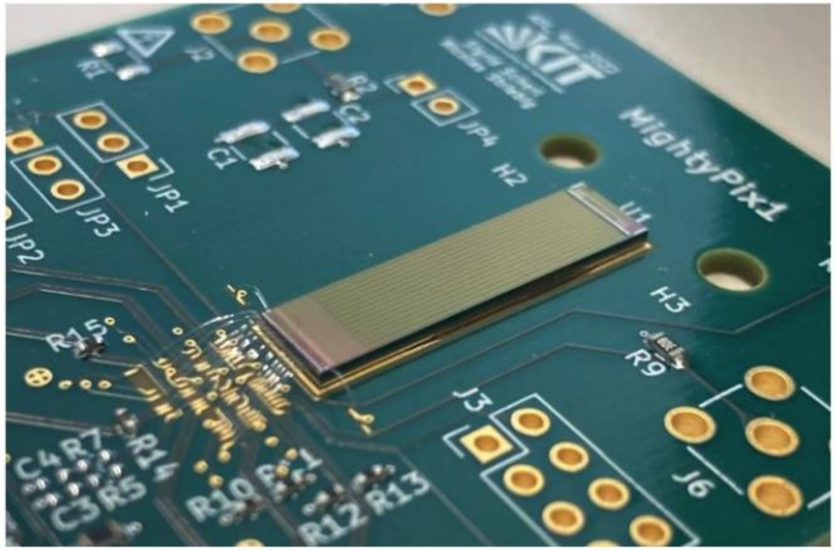
- They can be thinned to ~50 µm, reducing material to the order of (0.1 % X_0 per layer), which keeps multiple scattering under control in low-momentum tracking.
- They support continuous, triggerless readout at high hit rates - exactly what LHCb wants at high luminosity.
- Per-hit timestamps and ToT are used to correct timewalk and achieve ≤ 3 ns timing.

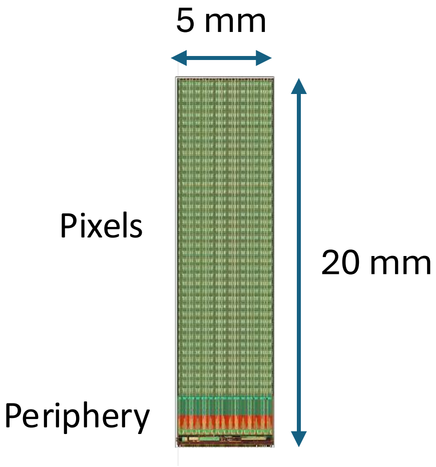




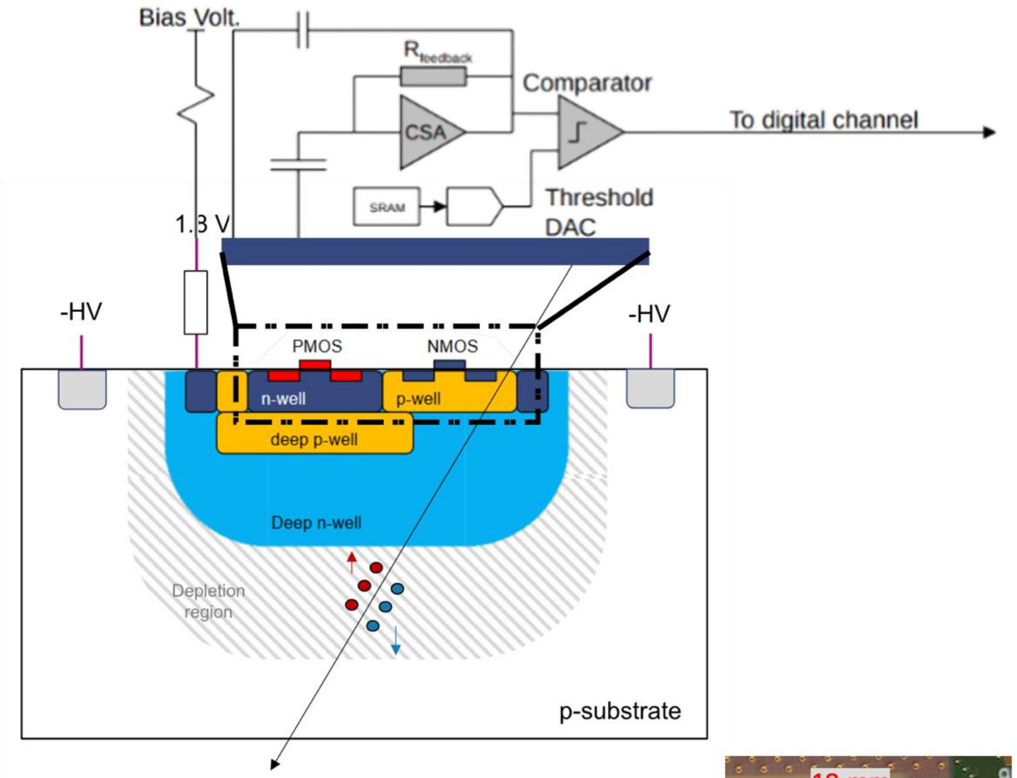
MightyPix Development Stages

- MightyPix1 (MP1): first full monolithic HV-MAPS prototype compatible with LHCb readout (lpGBT, etc.)
  - Config bit was connected to ground instead of DAC register in the design. 16 samples repaired by FIB
  - Two columns share the same digital output shielding, a digital signal from 1 pixel induces an analogue signal in its neighbour. Not repairable.
- MightyPix2 (MP2): adds timing refinements, radiation studies, portability across foundries (e.g. AMS vs LFoundry) as de-risking. Just submitted to AMS Foundry, due 2026
- MightyPix3 / production direction: aims at final sensor geometry and data format for installation in Run 5 / Upgrade II era. Planned submission late 2026, due 2027.

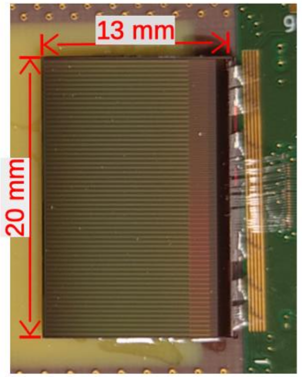




~~Mighty~~ Telepix2 Pixel Matrix Architecture

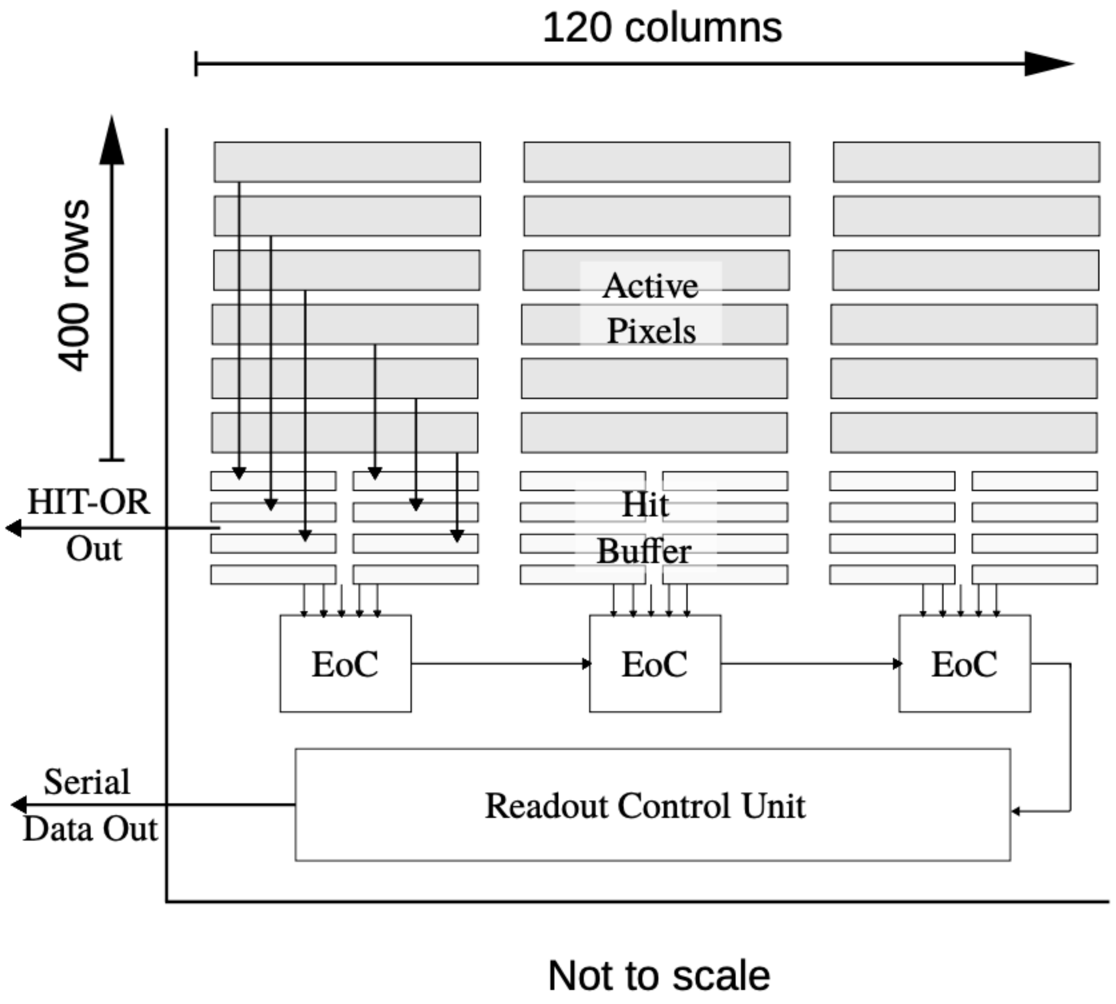


Working principle of HV-CMOS sensors.



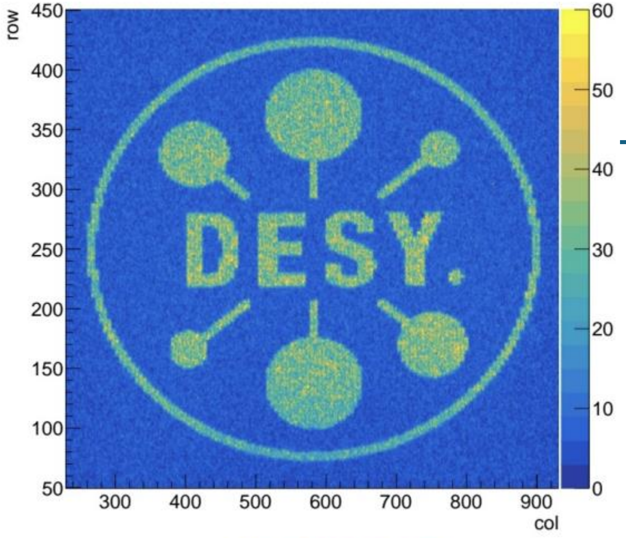
- Designed as a fast timing and triggering plane for beam telescopes
- Very similar to Mightypix pixel architecture design.
- Fabricated by TSI 180 nm HV-CMOS
- Pixel size 165 × 25 µm² - Mightypix is 165 × 50 µm²
- 200 – 400 Ωcm Cz p-substrate
- 130 V reverse bias ≈ 70 µm depletion zone
- In-pixel Charge sensitive amplifier, CMOS comparator, 3 bit threshold trimming, injection.

Readout Architecture

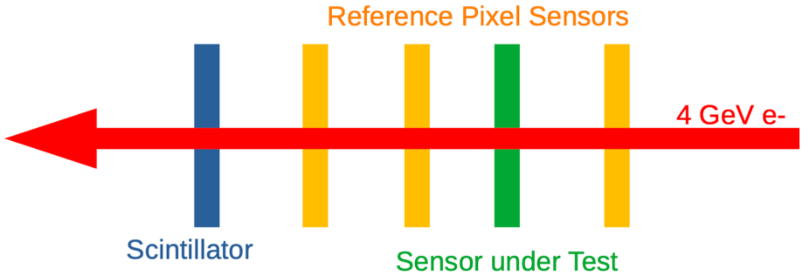


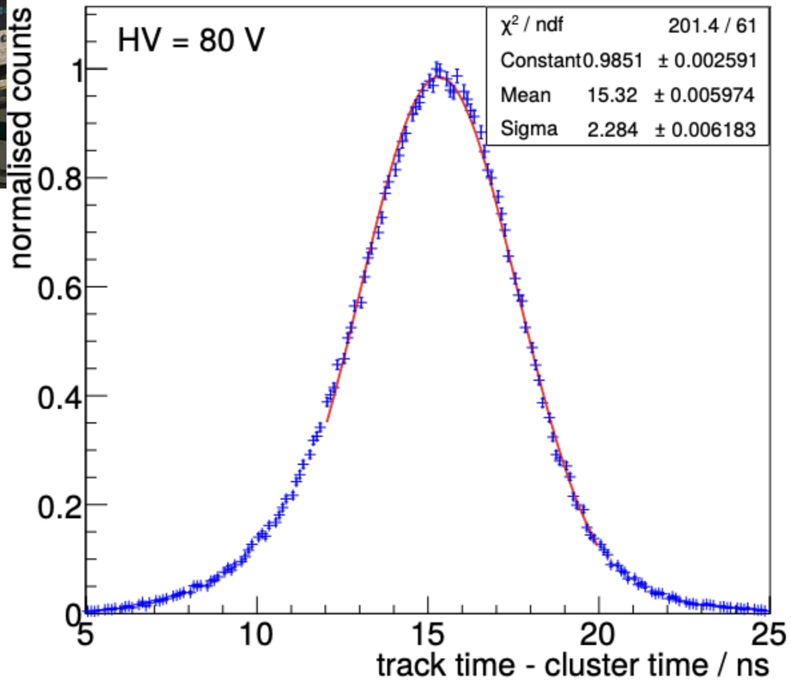
- 4 ns Time-of-Arrival sampling
- Address, timestamp, and time-over-threshold (ToT) info are buffered locally and moved via a column-drain / priority logic scheme for fast readout.
- Hit driven column drain readout at 1.25 Gbit/s
- Configurable trigger output (analogue Hit-OR)

Testbeam Characterisation



[arXiv:2503.08177]





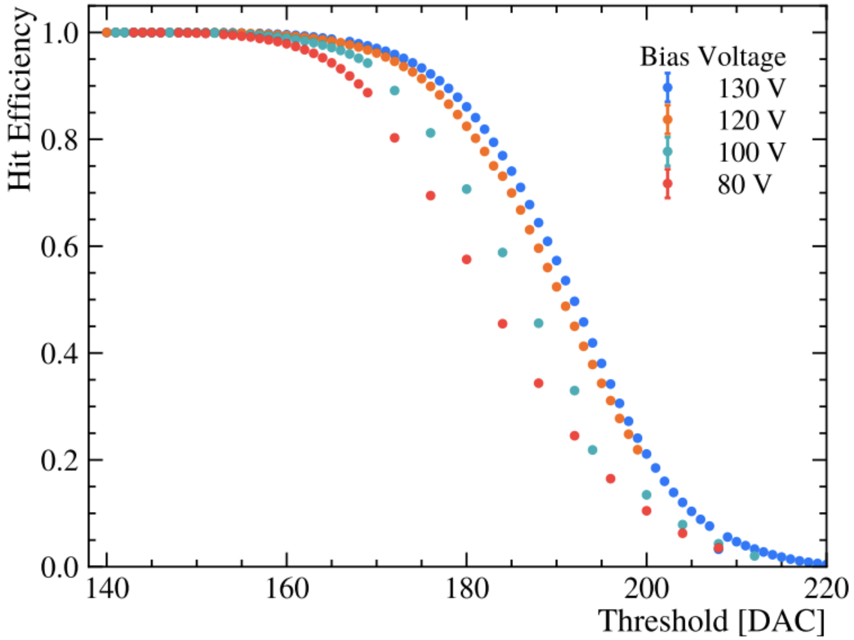
[arXiv:2503.08177]

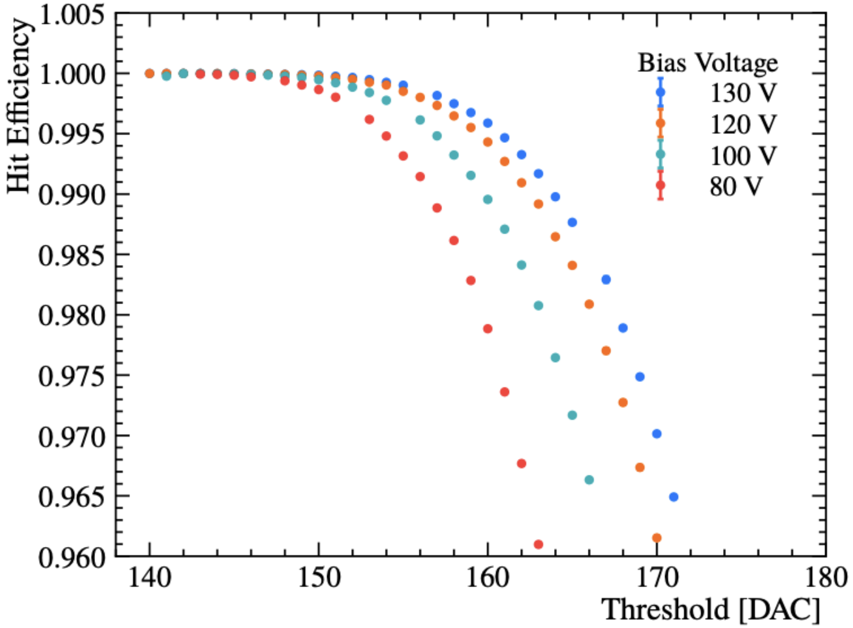
- Validation of optimisation with multiple test beams at DESY
- 4 GeV electrons
- 6 layers Adenium (DESY) telescope
- 3 layers Mupix11 telescope
- Mudaq1 readout system
- Analysis with Corryvreckan2
- σ = 2.284 ns ~ 3 ns as designed

All plots from Lucas Dittmann

Testbeam Characterisation Cont.

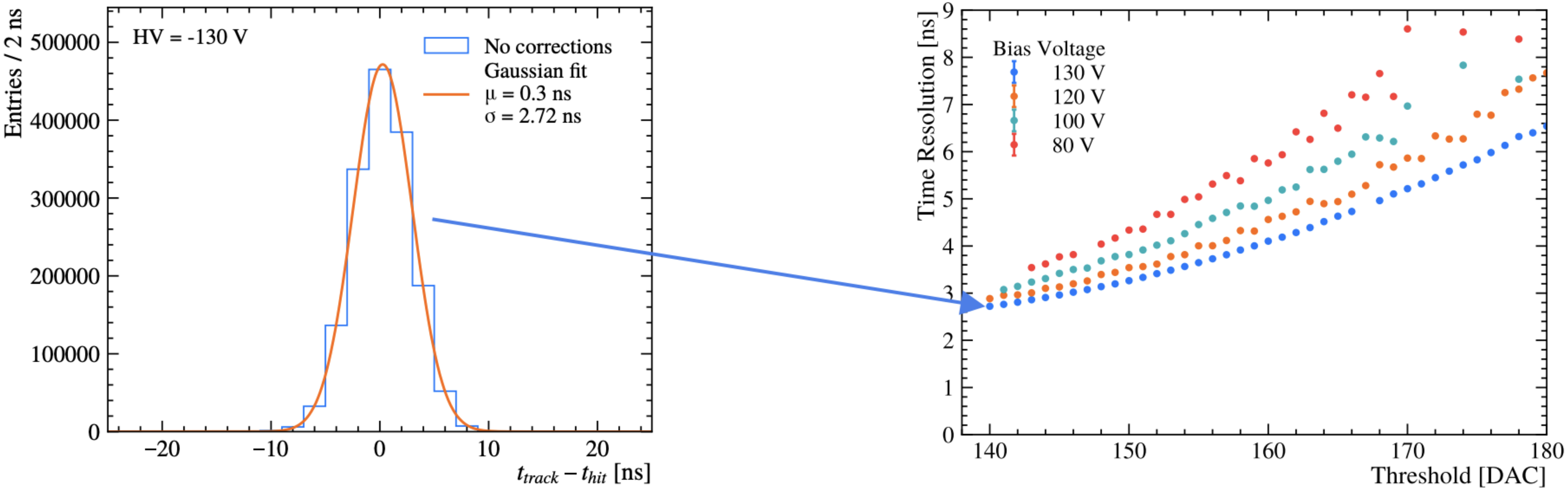
- As expected, the hit efficiency is proportional to:
  - Bias
  - Threshold





Testbeam Characterisation Cont.

- Time resolution < 2.7 ns @ 130 V (Includes reference system)
- HV-bias has a significant effect on time resolution
- Timewalk is negligible at a low threshold



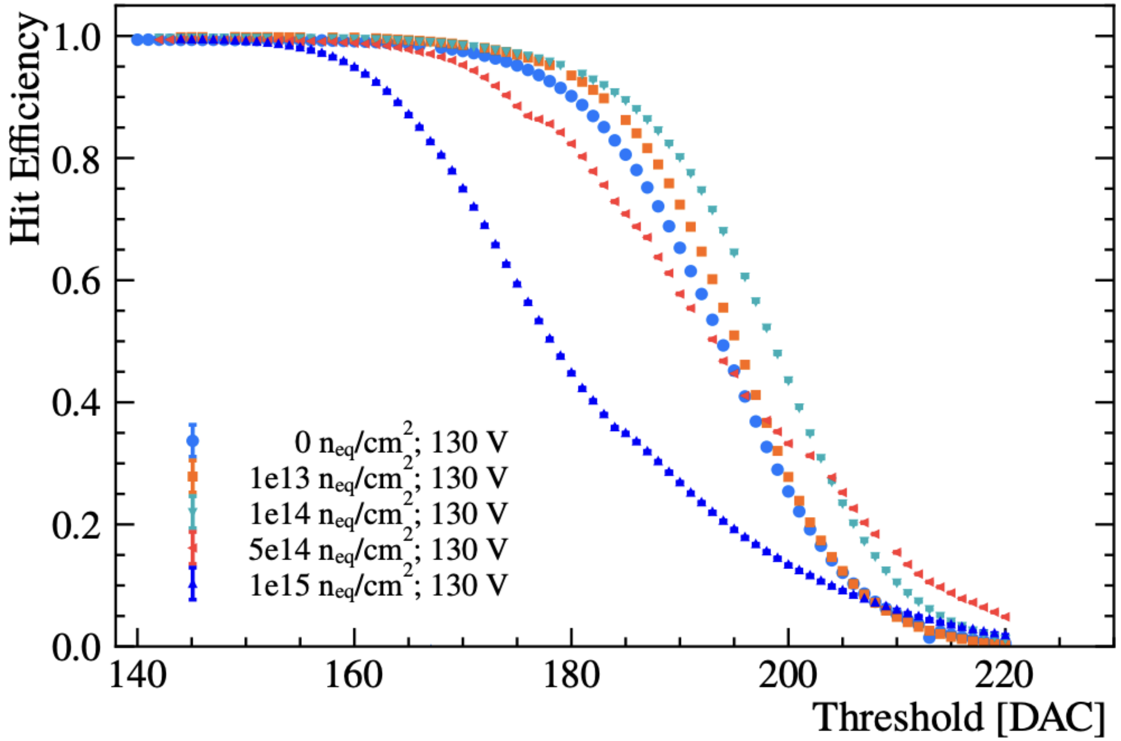
Radiation Hardness and Results

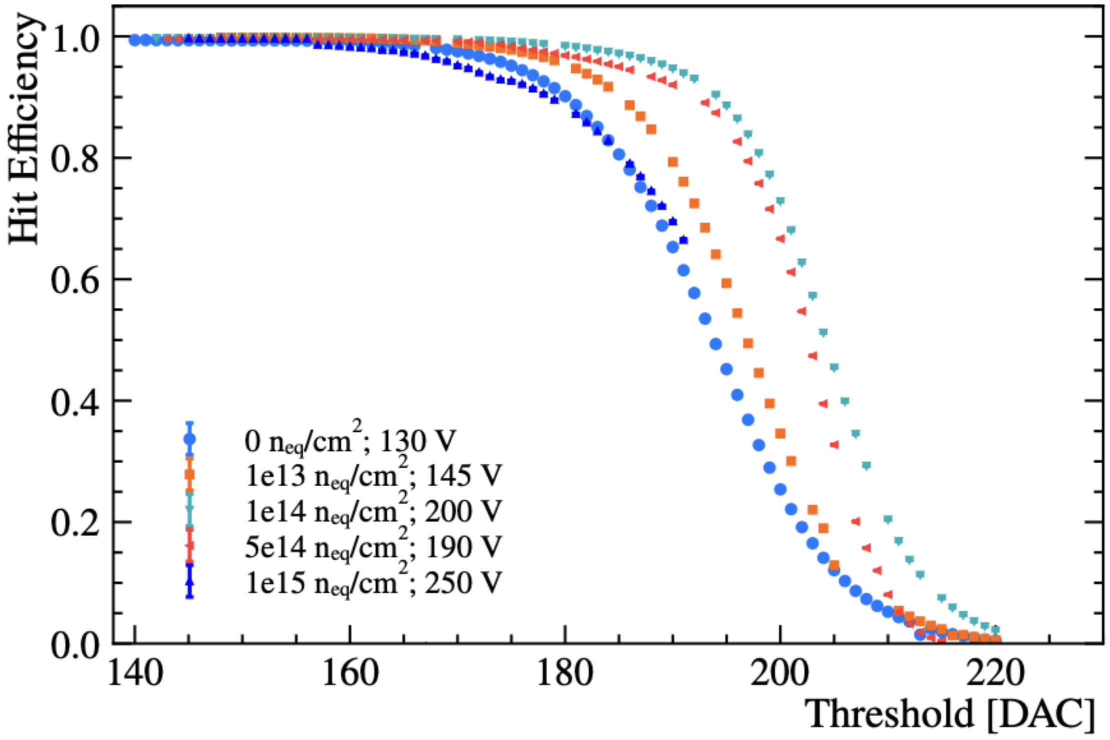
- ~~MightyPix~~ Telepix2 is designed to tolerate fluences of LHCb Run 5 downstream-tracker expectations.
- Requirements on HV-MAPS technology
  - 99 % hit efficiency within 25 ns (bunch crossing)
  - Radiation tolerance up to 3×10^{14} neq cm^{-2}
  - Noise rate < 400 kHz/cm^2
  - Now increased to around 3×10^{15} neq cm^{-2} due to the possible UP tracker using it.

NIEL	Irradiation Facility	Sensor Thickness
0	-	200 µm
1e13 n_{eq}/cm^2	JSI Ljubljana	100 µm
1e14 n_{eq}/cm^2	JSI Ljubljana	100 µm
1e14 n_{eq}/cm^2	JGU Mainz	200 µm
5e14 n_{eq}/cm^2	JGU Mainz	200 µm
1e15 n_{eq}/cm^2	JSI Ljubljana	100 µm

Radiation Hardness and Results Cont.

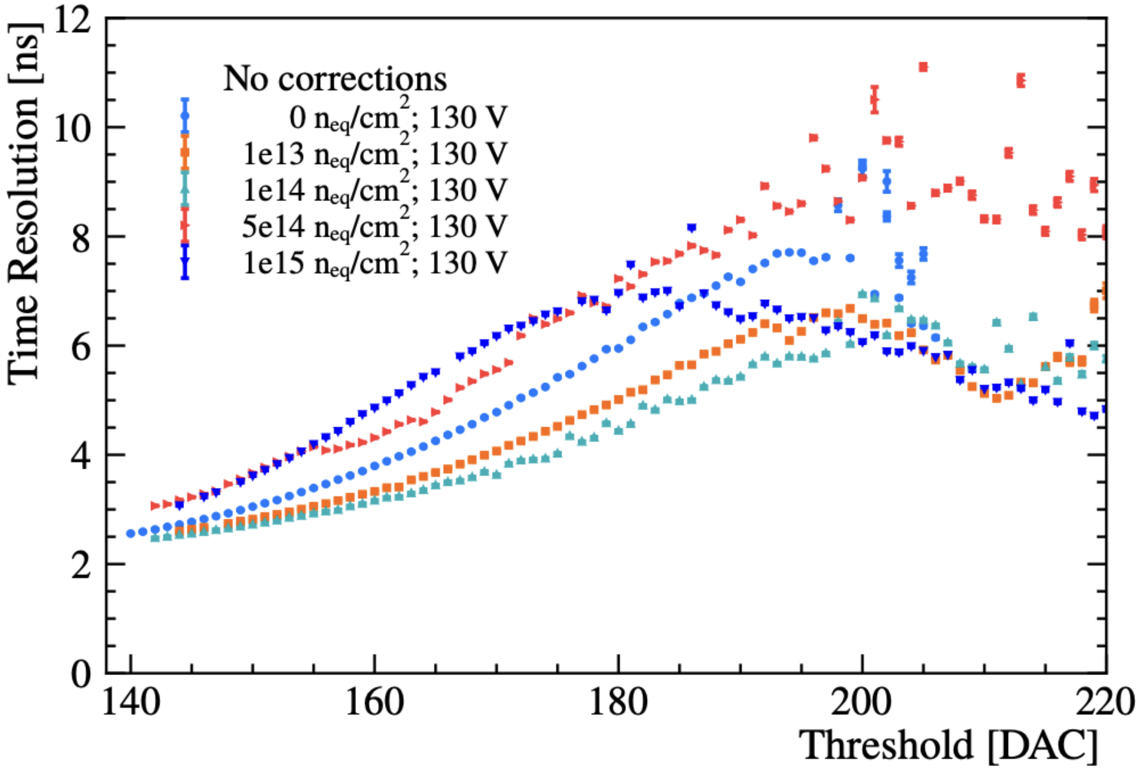
- Cooled between -10 to -30 °C
- After irradiation, HV-MAPS prototypes still show efficiencies > 99 % for minimum ionising particles and maintain multi-ns timing at suitable thresholds.
- After some light irradiation, up to 1 × 10^{14} neq cm^{-2}, the sensor can be pushed to a higher threshold.
- Efficiencies at higher bias allow us to push the Threshold if needed.
- Higher bias counteracts the radiation damage on detector performance.

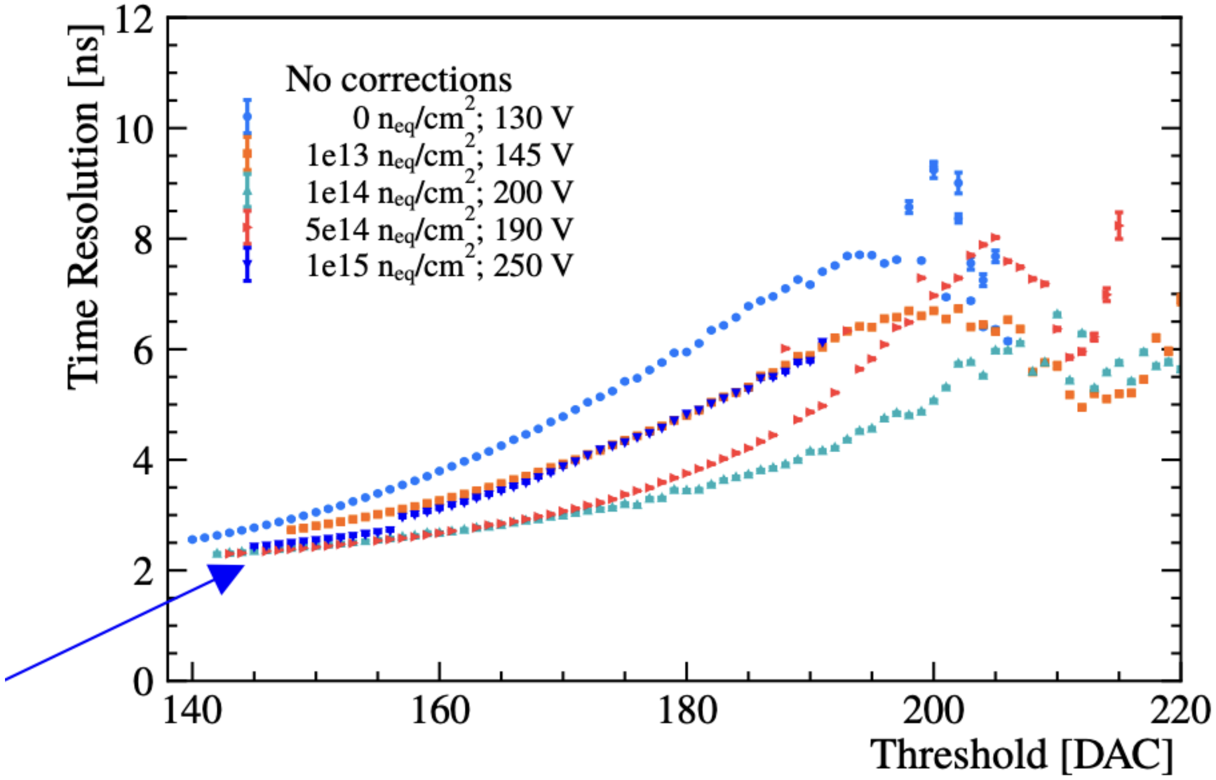




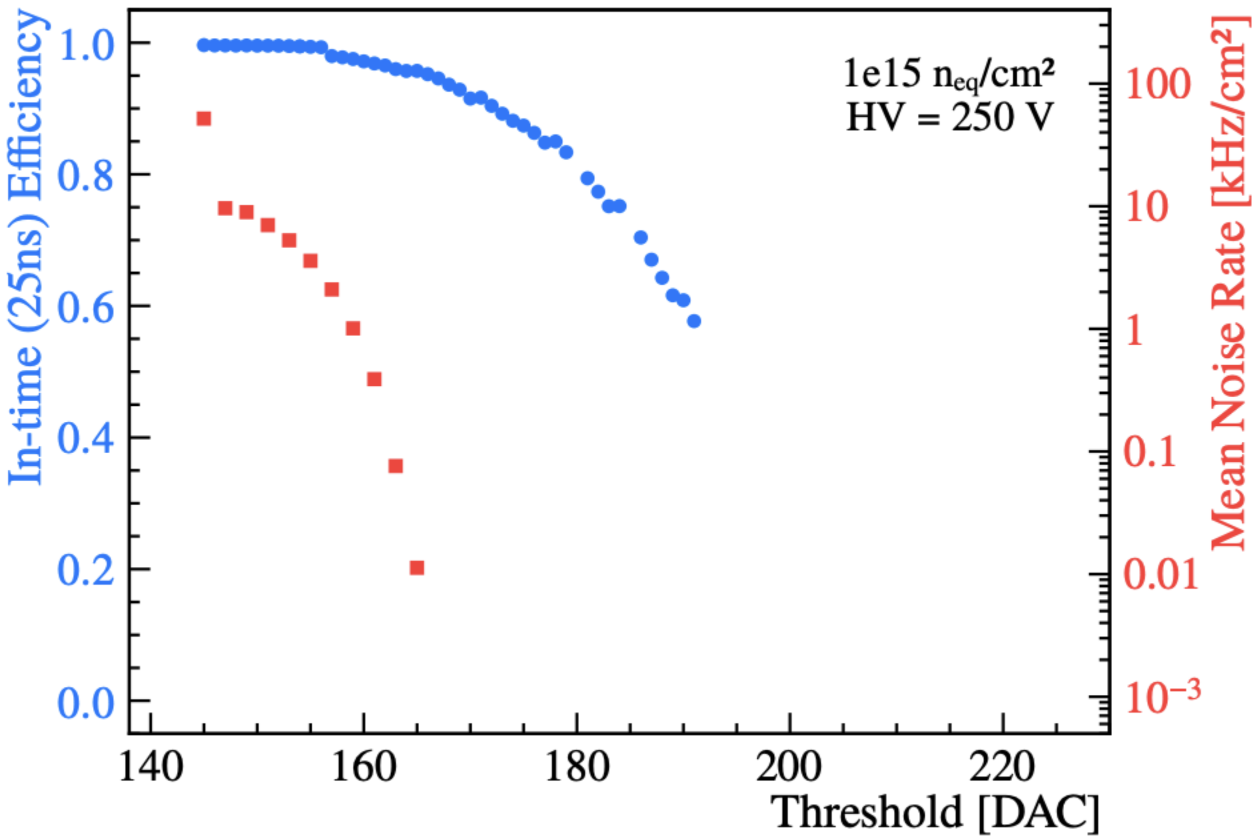
Radiation Hardness and Results Cont.

- Time resolution < 3 ns for all fluences (Includes reference system)
- The depth of the depletion zone has an impact on the collected charge and detector capacity
- Higher bias lowers time resolution





Radiation Hardness and Results Cont.



$$\text{In-time efficiency} = \frac{\text{Detected tracks within 25 ns}}{\text{All tracks}}$$

- In-time efficiency is the number of hits within a 25 ns time window

- After irradiation higher bias gives:
  - Better time resolution
  - Better efficiency
  - Lowers noise

Beam Tests and Validation for LHCb Use

- Time resolution < 2.4 ns @ 80 V bias
- Time resolution of 2.7 ns @ 130 V bias
- Hit efficiency > 99 %
- TelePix2 is radiation-tolerant up to 1 × 10^{15} neq/cm², after irradiation,
  - In-time efficiency > 99.5 %
  - Time resolution < 3 ns
  - Efficiency > 99.9% with longer ranges of bias and threshold
  - Noise rate < 400 kHz/cm²
- HV-MAPS technology is sufficiently radiation-tolerant for use cases such as LHCb Upgrade 2

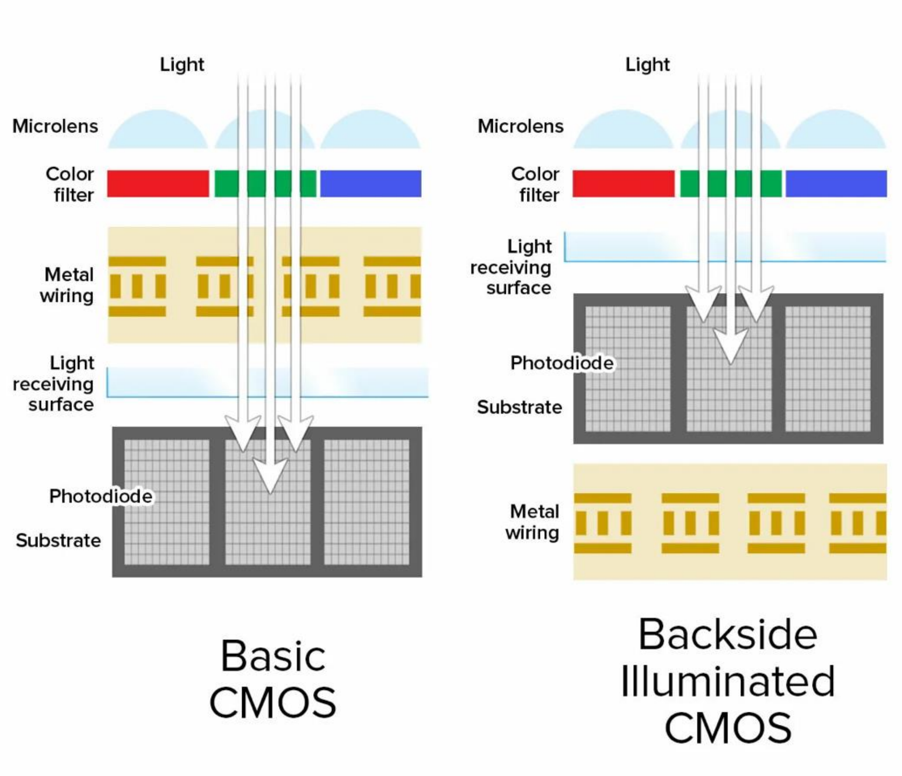
Challenges and Ongoing Improvements

- Need to test the radiation tolerance of Mightypix

- Power density and cooling: thin sensors + minimal material imply low-mass cooling concepts must be proven scalable.

- Higher radiation tolerance demand, needs to test
  - The bulk from AMS
  - The 180 nm CMOS circuits
- After both neutron and ionising irradiation

Section 3 – Adapting HV-MAPS for LiDAR

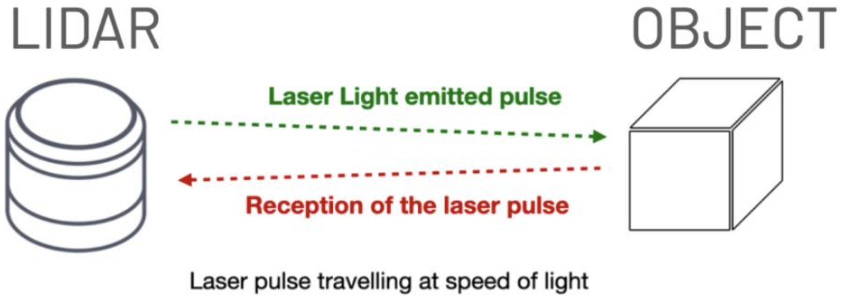


Camera CMOS sensors and HV MAPS are very similar

- Both are CMOS pixel arrays: each pixel senses charge, amplifies it, and sends digital data off-chip.
- Camera pixel: detects visible/IR photons → integrates intensity over exposure time (ToT).
- HV-MAPS pixel: detects ionisation charge → records time (ToA) + integrates signal amplitude per event (ToT).
- Common building blocks: diode → amplifier → logic → readout, all in CMOS.
- Difference: integration mode vs. time-stamping & integration dual mode.

- Time-stamping -> LiDAR
- Photon-integration -> Camera
- HV-MAPS is a compromised combination of both.

LiDAR 101



$$distance = \frac{c \times t}{2}$$

- Types of LiDAR
  - Scanning LiDAR
  - **Flash LiDAR (need lower time resolution, ~500 ps)**
  - FMCW LiDAR (Frequency-Modulated Continuous Wave)
  - Indirect ToF (iToF) / Phase Measurement
  - **Structured light (favours spatial resolution, 1–6 µm)**

- Flash LiDAR works like a “camera + stopwatch per pixel”: illuminate, wait for return, timestamp photons.

- Needs ns-scale timing and pixel-parallel readout - identical requirements to HEP pixels.

- HV-MAPS already have: fast amplifier, discriminator, timestamp, and serial output.

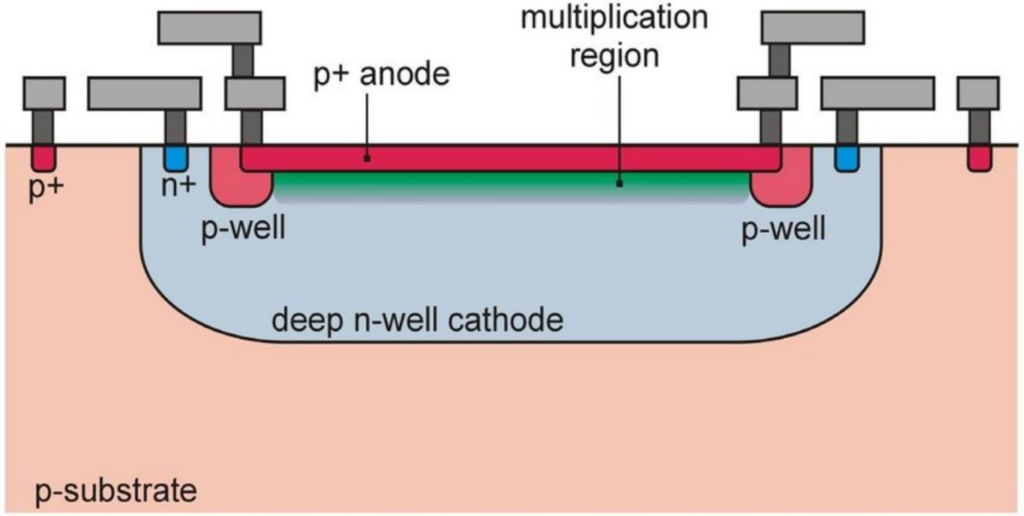
- Therefore adaptation is architectural, not conceptual. Two ways to go about it,
  - Optimise time resolution
  - Minimise pixel pitch

Timing Requirements for Automotive and Robotic LiDAR

System type	**Timing jitter / binning**	**Typical range precision**	**Range capability**
Mechanical / scanning	200–400 ps	2–5 cm	100–250 m
Flash / solid-state LiDAR	100–300 ps	1–3 cm	200–300 m
SPAD arrays	50–150 ps per-pixel	1–5 cm	10–100 m (scene-limited)
Indirect ToF	Equivalent of 100–500 ps	1–5 mm	< 10 m (short-range)

- Automotive and robotic LiDAR target 1–10 cm depth accuracy → 100–700 ps timing precision.
- Commercial SPAD and scanning systems already operate in this regime.
- HV-MAPS chips currently reach ~2 ns, and sub-ns timing is realistic with minor PLL/DLL upgrades.
- ⇒ HEP-grade timing already approaches LiDAR requirements.
    - ~2 ns to ~ 500 ps is absolutely doable.

Why Replace SPAD LiDAR?



SPAD is the standard of best-in-class LiDAR performance

- SPAD advantages: single-photon sensitivity, 10–100 ps intrinsic timing.

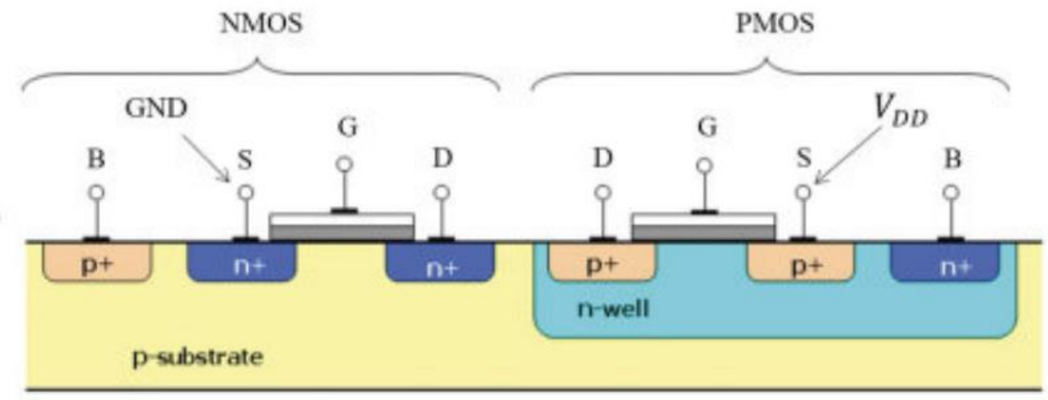
- SPAD limitations:
    - Binary response/Geiger mode → no intensity information.
    - Dead time and pile-up.
    - High bias voltage, power, and cost.

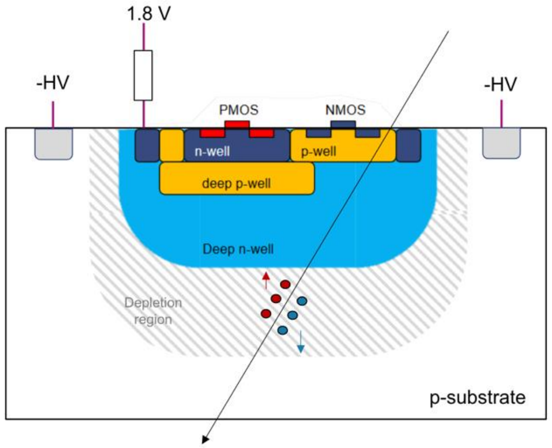
- HV-MAPS advantages:
    - Linear response → depth + intensity in same pixel.
    - Monolithic CMOS → low-cost, scalable.
    - ns-class timing sufficient for cm-scale ranging.

- HV-MAPS yield greyscale intensity + depth = richer scene information.

HV-MAPS: Mature CMOS Technology, Fabricated Like a CPU

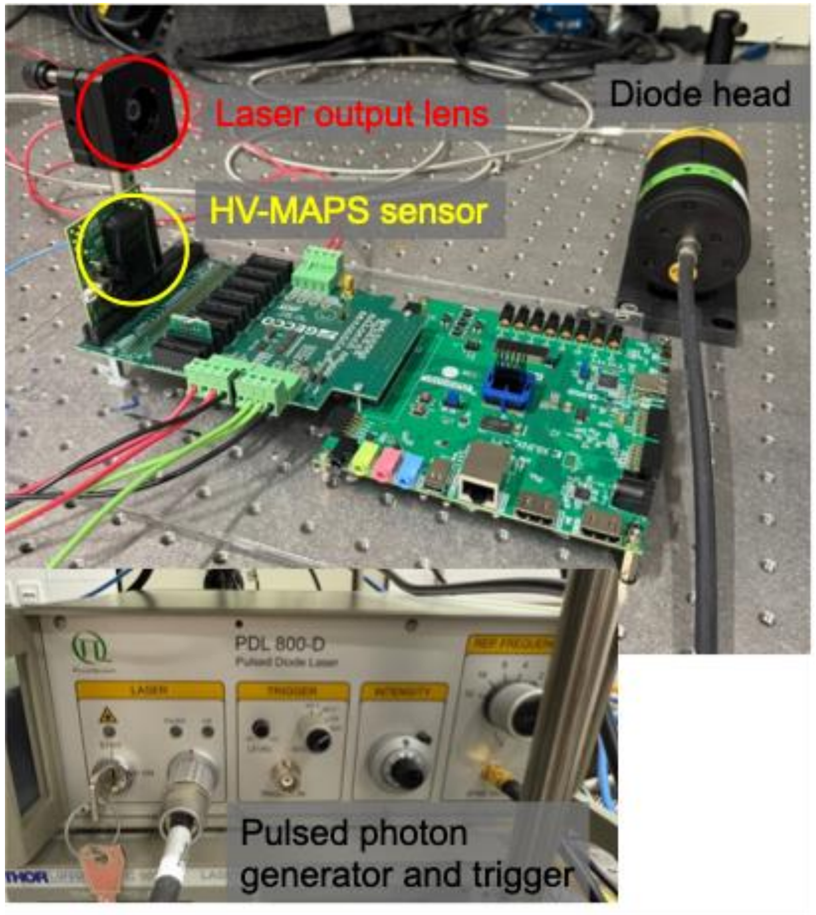
- Built entirely in **commercial high-voltage CMOS processes** (e.g. AMS 180 nm, TSI 180 nm, TowerJazz 65 nm).
- Uses **standard industrial toolchains** — the same lithography, doping, and metal stacks used for logic and imaging ICs.
- **No exotic materials** or post-processing: all front-end and sensor layers formed in a single wafer run.
- Wafer-level **yield** and packaging are **well understood** → can use standard dicing, thinning, bump-bonding, and encapsulation lines.
- Multi-Project Wafer (MPW) availability: **inexpensive prototyping path** (~€10 - 40 k per design) enables rapid iteration.
- **CMOS ecosystem** provides decades of reliability data, radiation models, and scalable foundry capacity.
- Architecturally, an HV-MAPS pixel array resembles a system-on-chip (SoC) more than a camera sensor — amplifiers, discriminators, and logic all monolithically integrated.





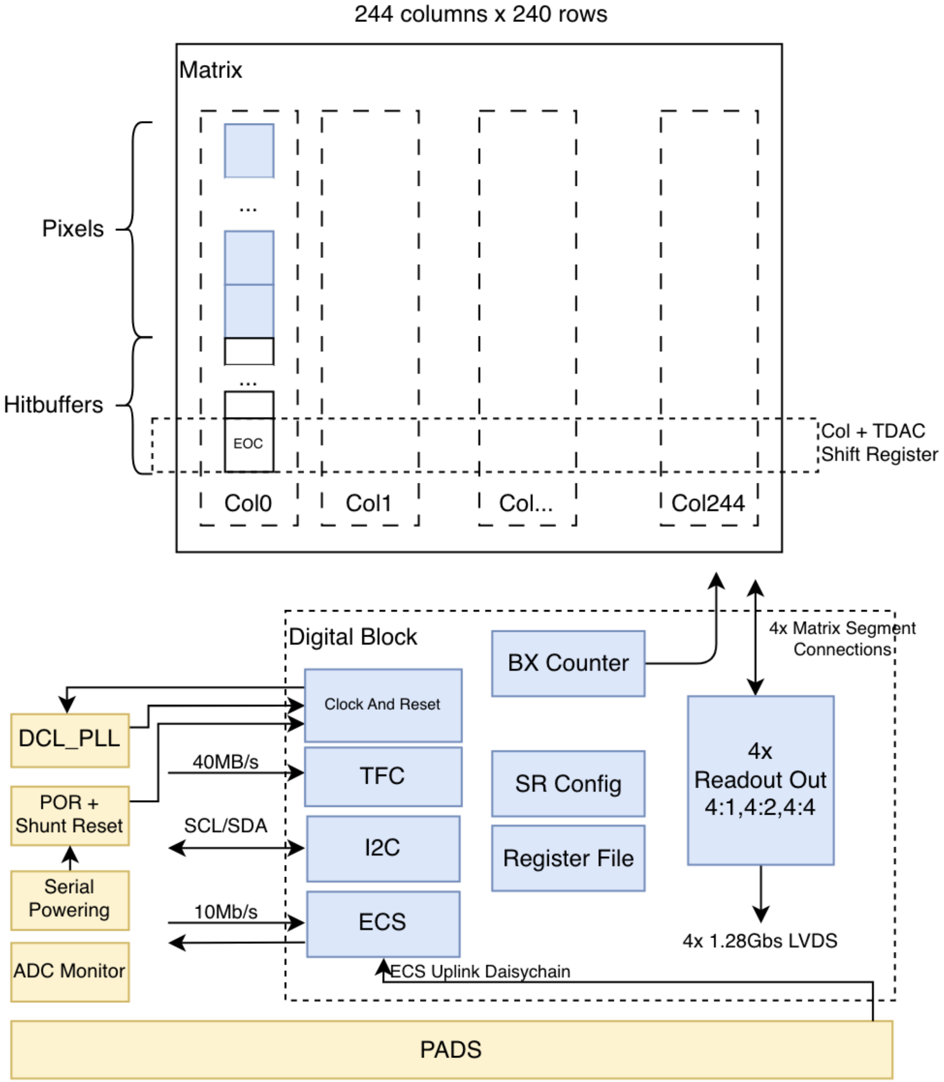
Working principle of HV-CMOS sensors.

Current Progress – HV-MAPS LiDAR Adaptation



- Setup:
  - PDL 800-D driver
    - ~ ns pulse width
    - Single to 80 MHz repetition rate
    - < 100 ps trigger jitter
  - 905 nm pulsed laser head
  - HV-MAPS with GECCO readout
  - PDL 800-D triggered measurements
- Objective:
  - First ToF measurement using a HEP HV-MAPS chip.
  - Depth resolution/range precision.
  - Different materials.
  - Extract first timing S-curves and correlation histograms.
- Next:
  - Establish a stable experiment setup and analysis chain.
  - Try with a floodlight laser for flash LiDAR testing.

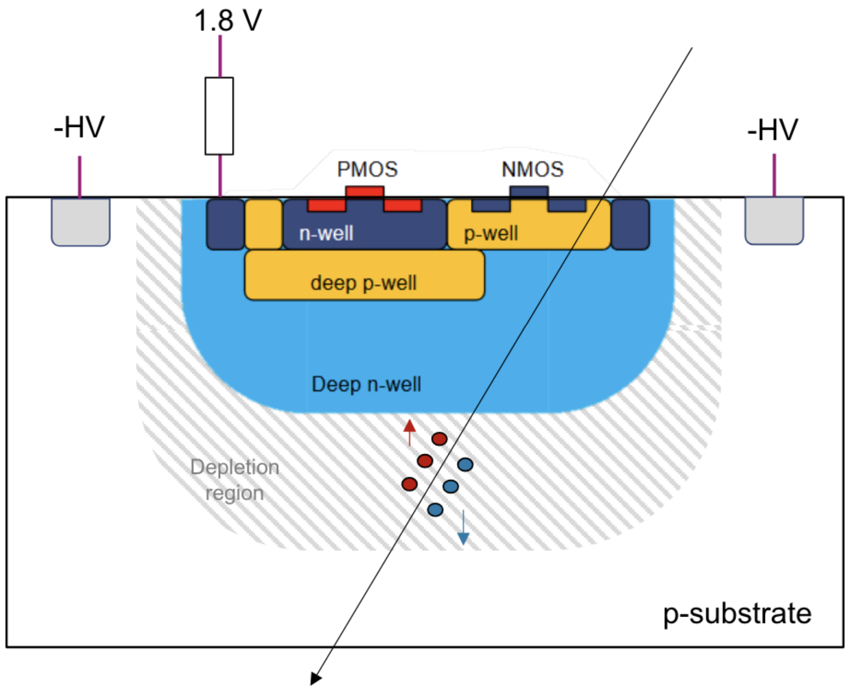
Architectural Adaptations Needed



Some basic examples of the modifications to achieve ~ 500 ps time resolution and better quantum efficiency.

- ASIC-level modifications:
  - Replace triggerless priority logic with frame-gated, direct ToF readout architecture.
  - Implement clean PLL and DLL clock structures to cut timing uncertainty from ns to ps scale.
  - Double-stack / 3D integration. → allows small pitch
  - Minimal-electronics HV-MAPS pixel: Strip timing logic, keep only diode + SF → smaller pitch
- Silicon-stack enhancements:
  - Introduce backside illumination with wafer thinning for higher photon collection efficiency.
  - Add surface passivation to minimise interface traps and dark noise.
  - Integrate a 905 nm band-pass filter to boost near-infrared quantum efficiency and suppress daylight background.

Architectural Adaptations Needed



Working principle of HV-CMOS sensors.

Some basic examples of the modifications to achieve ~ 500 ps time resolution and better quantum efficiency.

- ASIC-level modifications:
  - Replace triggerless priority logic with frame-gated, direct ToF readout architecture.
  - Implement clean PLL and DLL clock structures to cut timing uncertainty from ns to ps scale.
  - Double-stack / 3D integration. → allows small pitch
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Why LiDAR for Robotic Perception

- LiDAR gives absolute depth directly; cameras capture only brightness/colour and must infer distance computationally.

- A camera-based robot must compute in real time all this via stereo correlation, optical flow, segmentation & AI inference — billions of operations per frame. :
  - Stereopsis / Disparity – match left/right views pixel-by-pixel.
  - Convergence & Accommodation – eye-angle + lens-focus sensing for near-field range.
  - Motion Parallax – track apparent motion with viewpoint change.
  - Perspective, Shading & Occlusion – learn geometry from context.
  - Aerial Perspective – use haze/colour shift with distance.

- LiDAR bypasses all that: one laser pulse → time-of-flight → direct 3D distance in hardware.

Why LiDAR for Robotic Perception

- LiDAR give
- A camera-
  inference
  - Stere
  - Conv
  - Moti
  - Persp
  - Aeria
- LiDAR byp

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Why LiDAR for Robotic Perception

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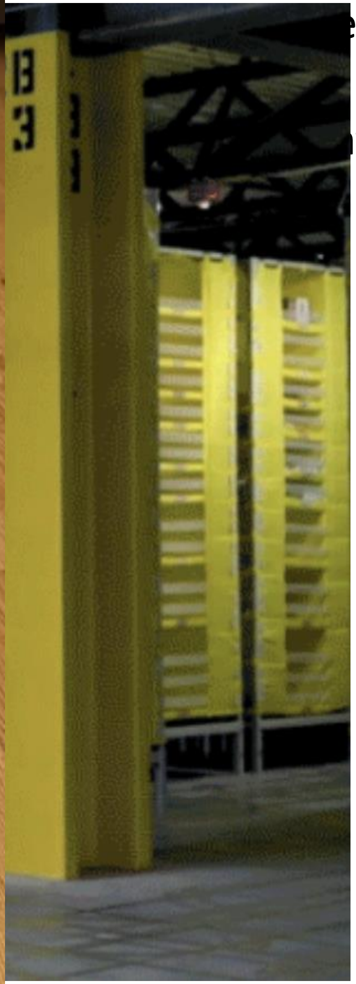

Why LiDAR for Rob

- LiDAR give
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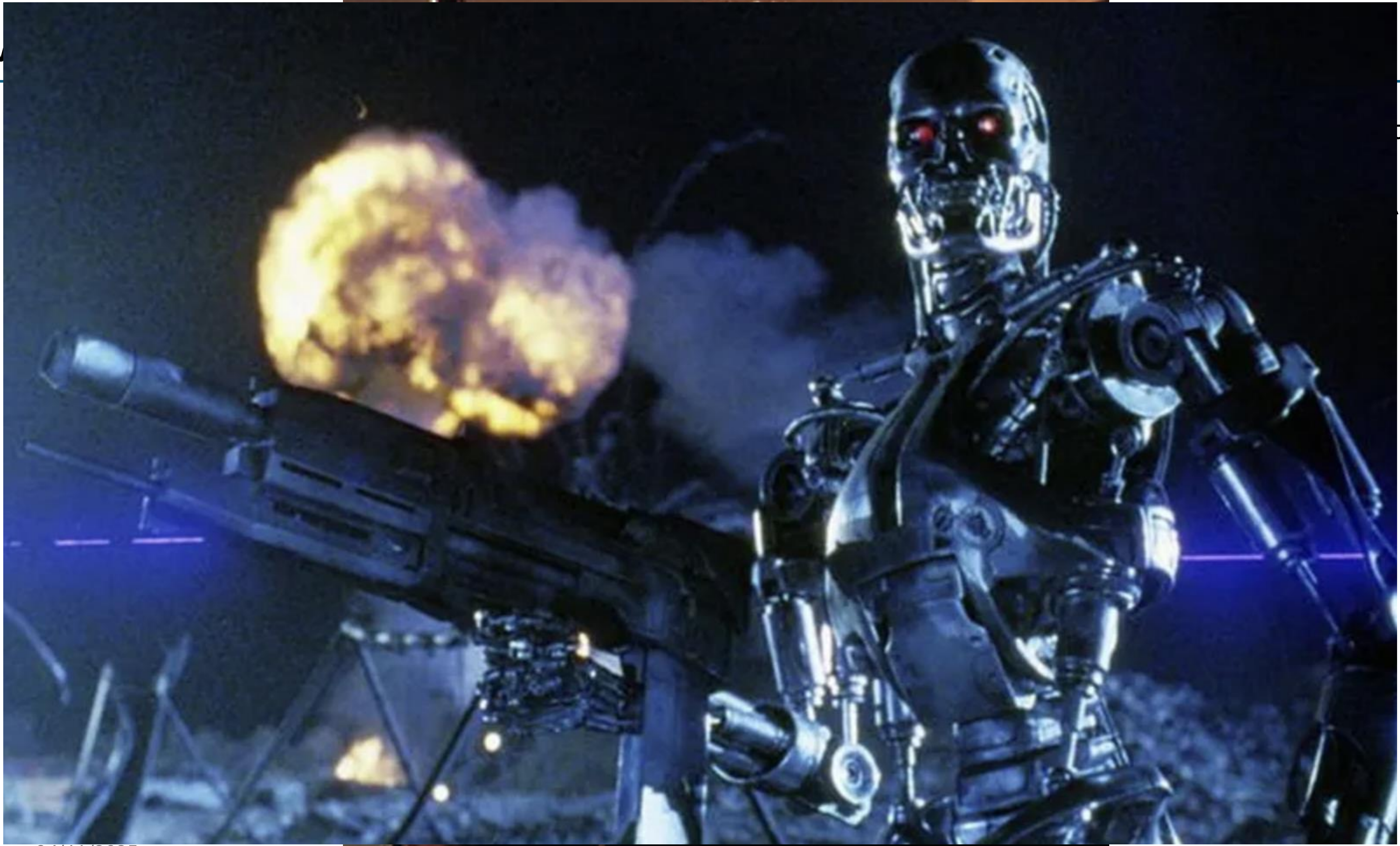


Why Tesla Says “No LiDAR” – and Why HV-MAPS Change That

- Elon Musk: “Humans drive with vision, not LiDAR” → claims extra sensors add cost and fusion ambiguity.

- Counter-view: modern LiDAR is cheap (< $500 units) and outperforms cameras in darkness, fog & glare.

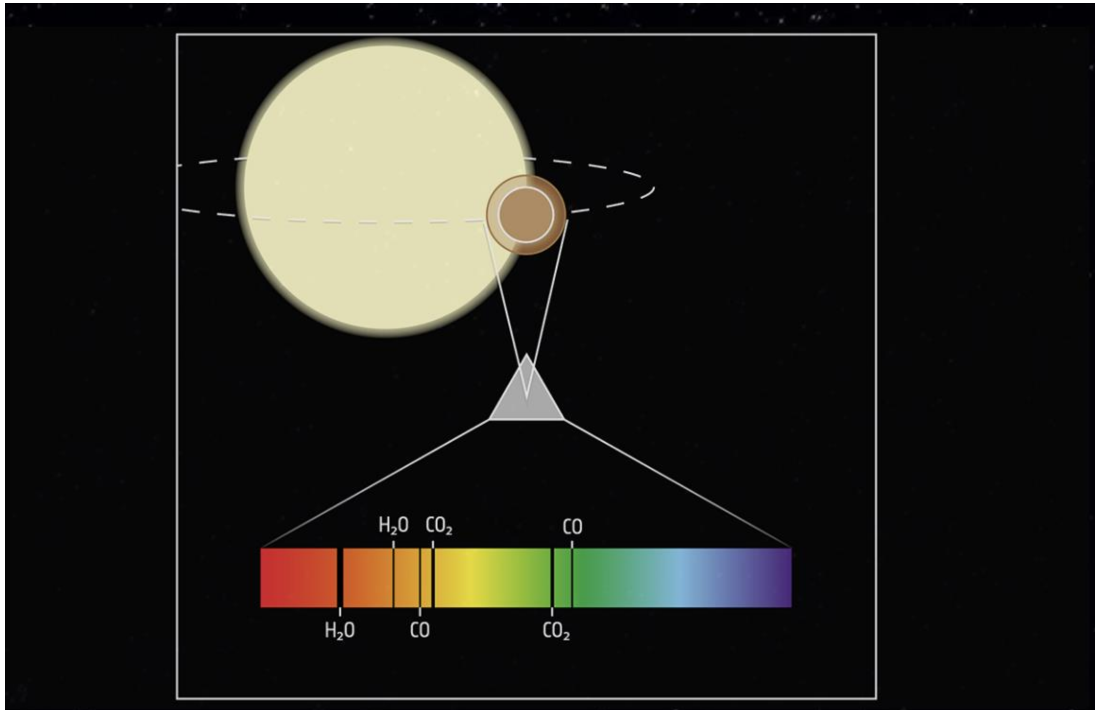
- HV-MAPS dual-mode operation:
  - Every 10 ms frame: first 400 ns (0.004%) → ToF burst for depth.
  - Remaining 9.9996 ms (99.996%) → camera mode for intensity imaging.

- Same pixels → same optics → no sensor fusion problem. true fusion in silicon.
- A.I. + Robotics + cars → economy of scale → no added cost problem.

Other Applications of ToF Detectors

- Automotive ADAS: collision avoidance, lane keeping, blind-spot detection.
- Robotics: warehouse navigation, pick-and-place, human-safety zoning.
- Drones / UAVs: terrain following, obstacle avoidance.
- AR / VR: gesture and room mapping (Apple LiDAR, Kinect).
- Space LiDAR: surface and atmospheric profiling (ICESat-2, GEDI).

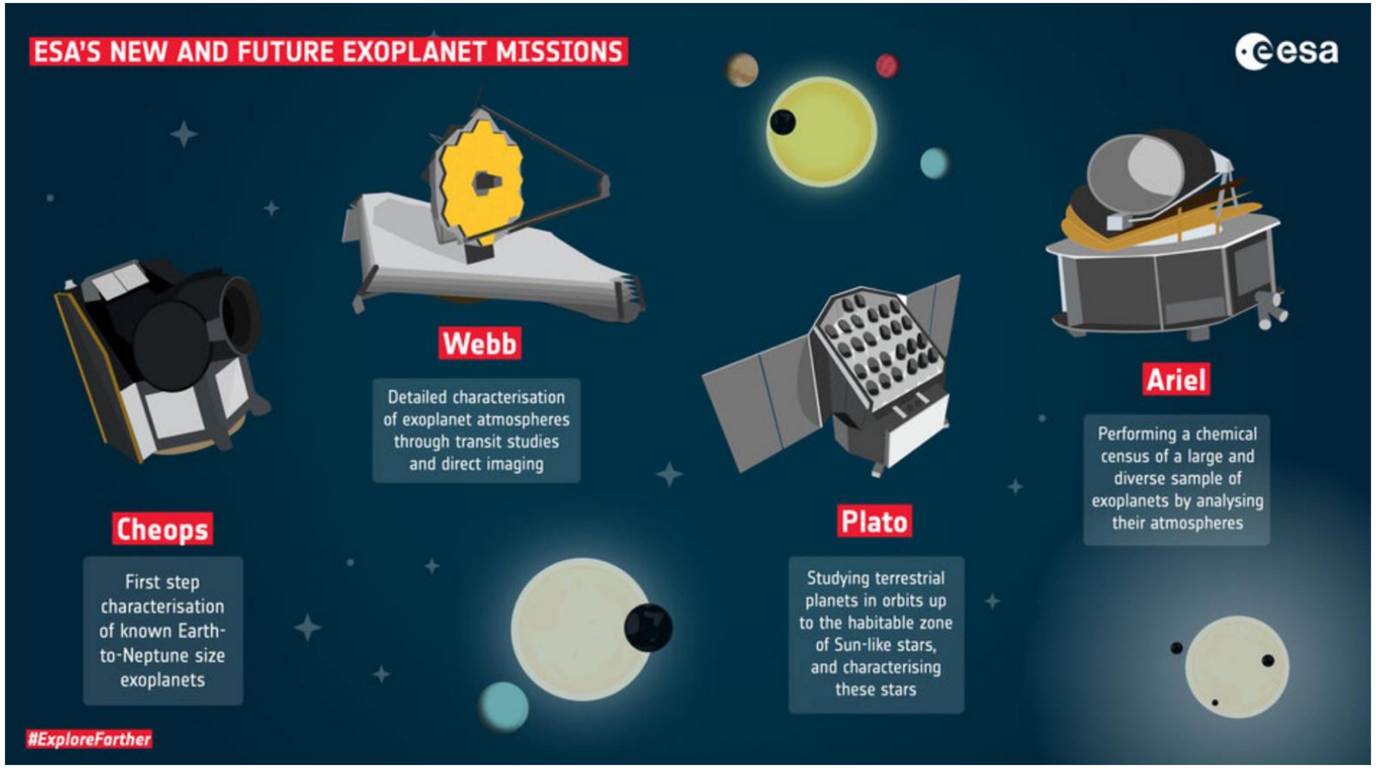
Section 4 – From HEP to Astrophysics - Ultra–Low-Light Imaging



Transmission spectroscopy reveals the composition of an exoplanet atmosphere by analyzing how the starlight is attenuated as it passes through the atmosphere. NASA's James Webb Space Telescope uses this technique to identify atmospheric components. Credit: NASA.

- HV-MAPS concept: high-gain, low-noise, fast timing pixel arrays
- Exoplanet spectroscopy demands 10–100 ppm photometric stability and ultra-low noise over hours.
- Same strengths needed for faint-photon astronomy and quantum imaging
- HV-MAPS architectures can be repurposed for photon-timestamping and gain-stabilised detection at low flux.
- Core idea → reuse LiDAR and HEP-optimised sensor for ultra-low-signal photon detection

Scientific Motivation: Exoplanet Spectroscopy and Biosignatures



Cheops

First step characterisation of known Earth-to-Neptune size exoplanets

Webb

Detailed characterisation of exoplanet atmospheres through transit studies and direct imaging

Plato

Studying terrestrial planets in orbits up to the habitable zone of Sun-like stars, and characterising these stars

Ariel

Performing a chemical census of a large and diverse sample of exoplanets by analysing their atmospheres

#ExploreFurther

- Photon-starved domains: exoplanet transits, faint galaxies, transients. Require:
  - Sub-electron noise,
  - ns–ps timing for coincidence or drift correction,
  - ppm-level gain stability.
- Current detectors (sCMOS, HgCdTe) limited by drift, crosstalk, slow readout.
- MIRI and NIRSpec measured atmospheric features (H_2O, CO_2, CH_4,) in transmission spectra down to ~50 ppm precision.
- Ariel at L2 explicitly target 10–100 ppm stability to detect atmospheric chemistry of warm exoplanets.

Key Sensor-Level Modifications for Astronomy

HV-MAPS Advantages

- Monolithic CMOS → low mass, high reliability, radiation tolerant.
- Fast timing + linear gain → intensity + timestamp per photon.
- Self-monitoring pixels allow continuous calibration and drift correction.
- Same readout philosophy as HL-LHC → proven scalability.

Adaptations for Faint-Photon Detection

- Lower front-end thresholds → sub-ke$^-$ sensitivity.
- Larger deep-nwell → higher charge-collection efficiency.
- Add anti-reflection coating or NIR-tuned backside layer (900–1700 nm).
- Integrate correlated-double-sampling (CDS) to suppress 1/f noise.

HgCdTe Mercury cadmium telluride avalanche photodiode (APD / e-APD) arrays:

- Linear-mode gain with > 60–70 % quantum efficiency from 0.9–4 µm.
- Near single-photon sensitivity, sub-e$^-$ effective noise, and dark current $< 10^{-4}$ e$^-$ / pixel / s.
- Already deployed in space LiDAR and planetary / atmospheric sensors – same “timing + gain + IR” principles as HV-MAPS.
- Can adapt RCU to read out HgCdTe as a hybrid detector.

Cross-Disciplinary Applications for HV-MAPS

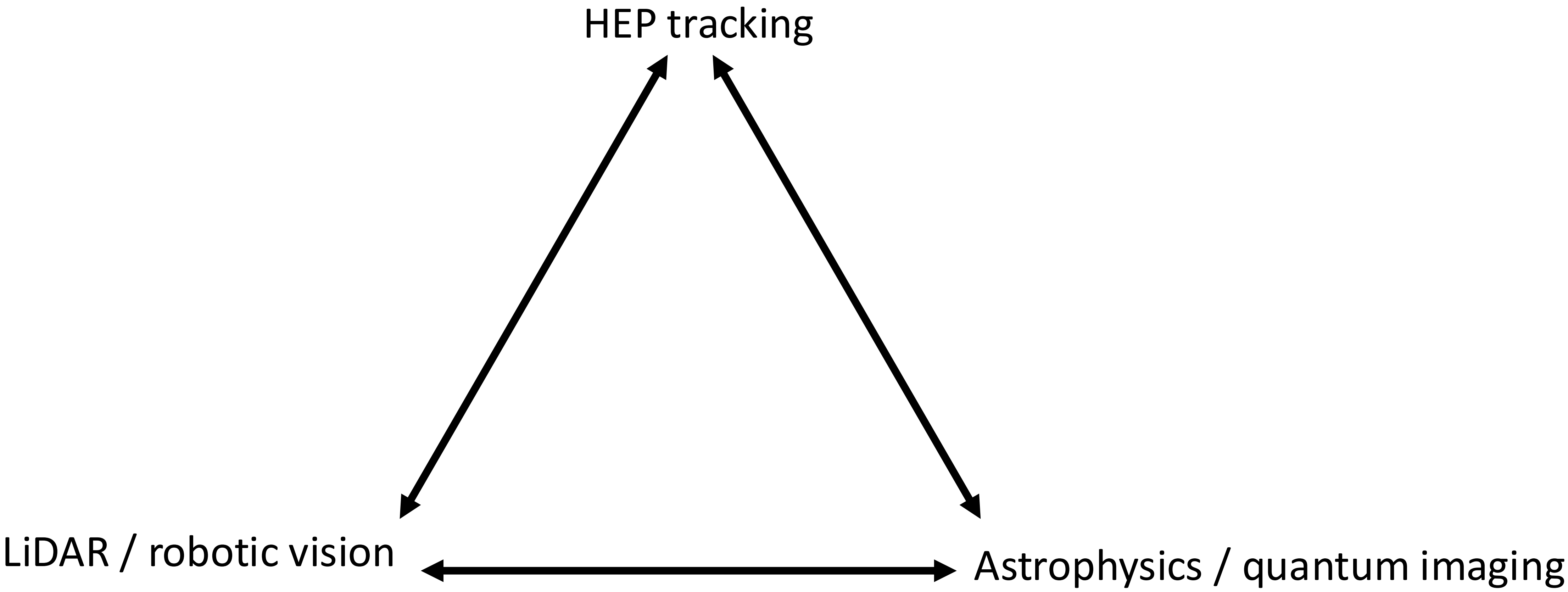
- Common R&D thread: HL-LHC → LiDAR + Astrophysics.

- Aligns with CERN DRD roadmap and non-accelerator instrumentation.

- One detector family, three frontiers:
    - HEP tracking
    - LiDAR / robotic vision
    - Astrophysics / quantum imaging

- Converging goals: ultra-fast timing, ultra-low noise, ppm-level stability, and intelligent on-sensor readout.

Cross-Disciplinary Applications for HV-MAPS

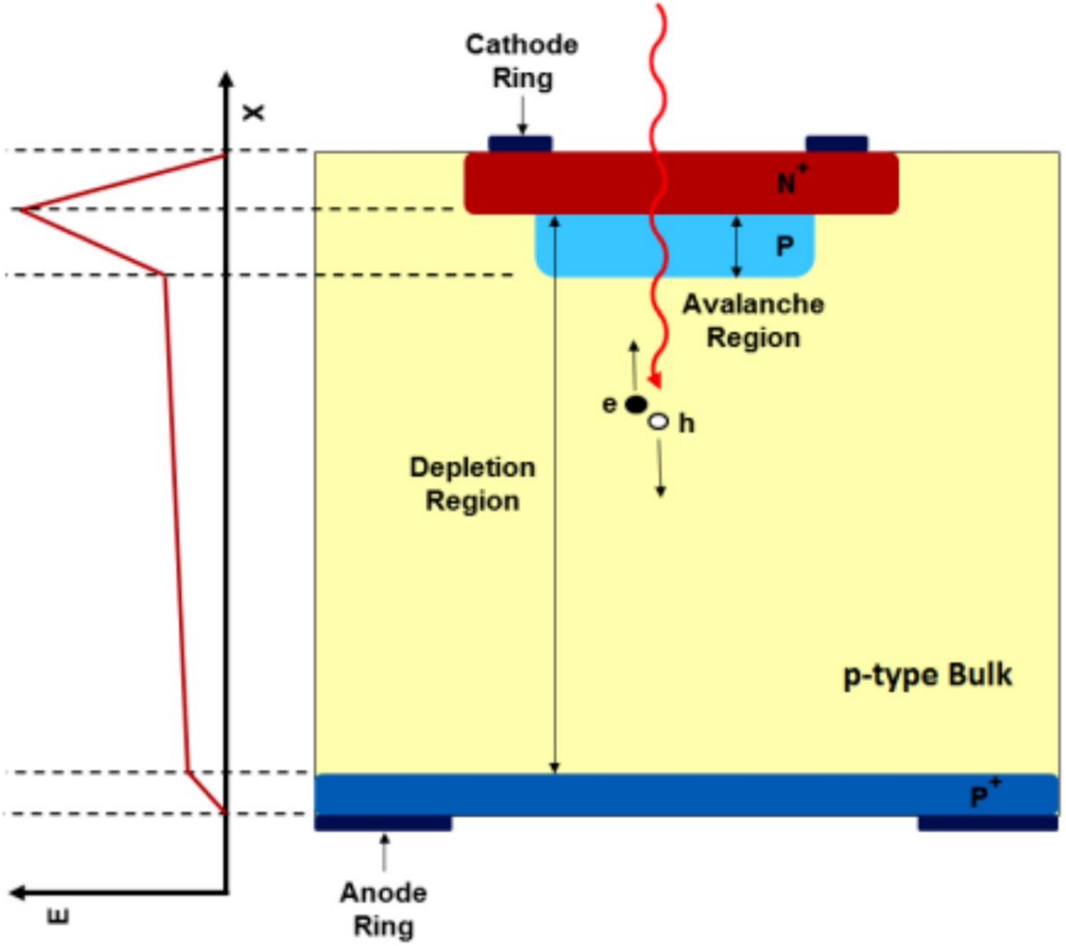


HEP tracking

LiDAR / robotic vision

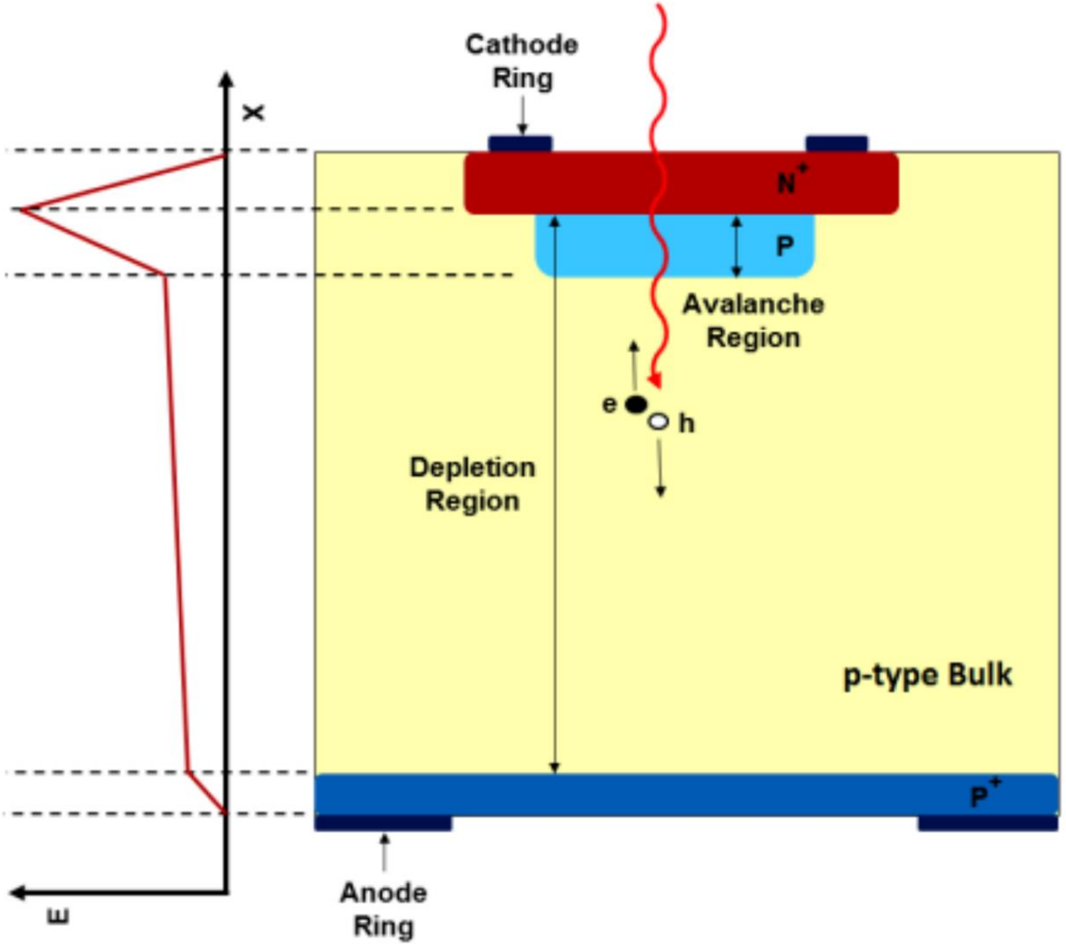
Astrophysics / quantum imaging

Section 5 – Future Pipelines: LGAD and Multi-Use Integration



- HV-MAPS: monolithic CMOS → low cost, integration, moderate timing (~ns).
- LGADs: segmented avalanche diodes → sub-50 ps timing, mature in HEP.
- Complementary technologies:
  - HV-MAPS → high granularity, full integration.
  - LGADs → precision timing, higher S/N.
- Major Variants include
  - DC-LGAD (segmented implants),
  - AC-LGAD (capacitive coupling for continuous 2D readout)
  - monolithic LGAD concepts that merge sensor and readout.

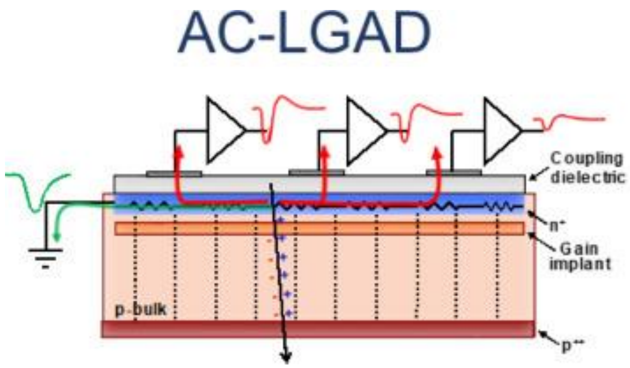
Operating Principle of LGADs



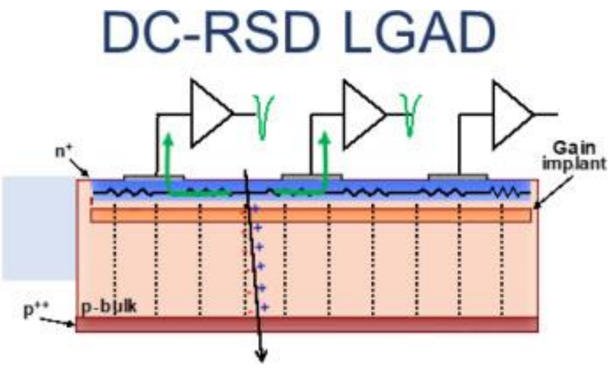
- Thin p+ gain layer induces controlled avalanche → internal gain ≈ 10–30.
- Fast signal rise (< 1 ns) → timing resolution 20–40 ps.
- Spatial resolutions possible at ~10 µm level.
- Radiation tolerant with proper gain layer engineering (Carbon co-implant, N-in-P design).
- Gain is high to beat frontend noise but still linear enough to preserve **limited** amplitude info.
- Deploying in ATLAS & CMS Timing Layers (HL-LHC).

Design Variants: DC, AC, Monolithic

AC-LGAD



DC-RSD LGAD

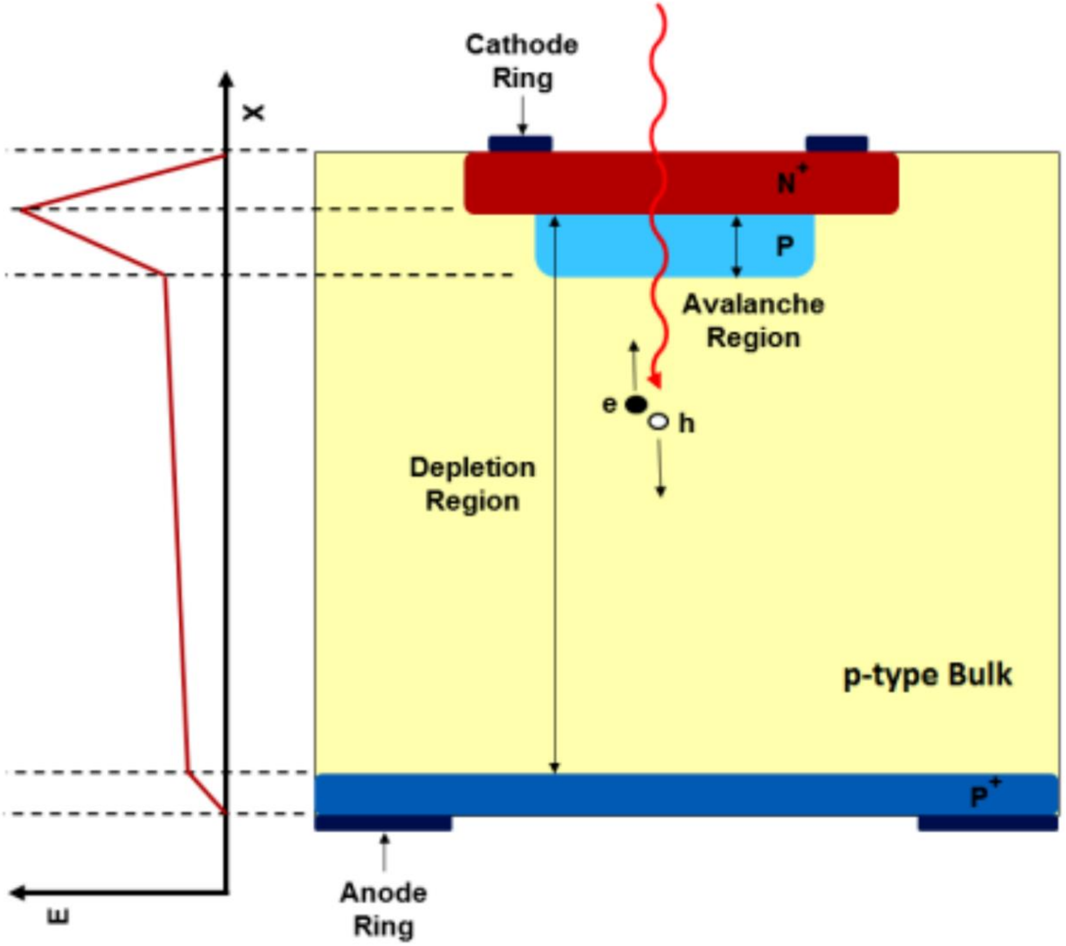


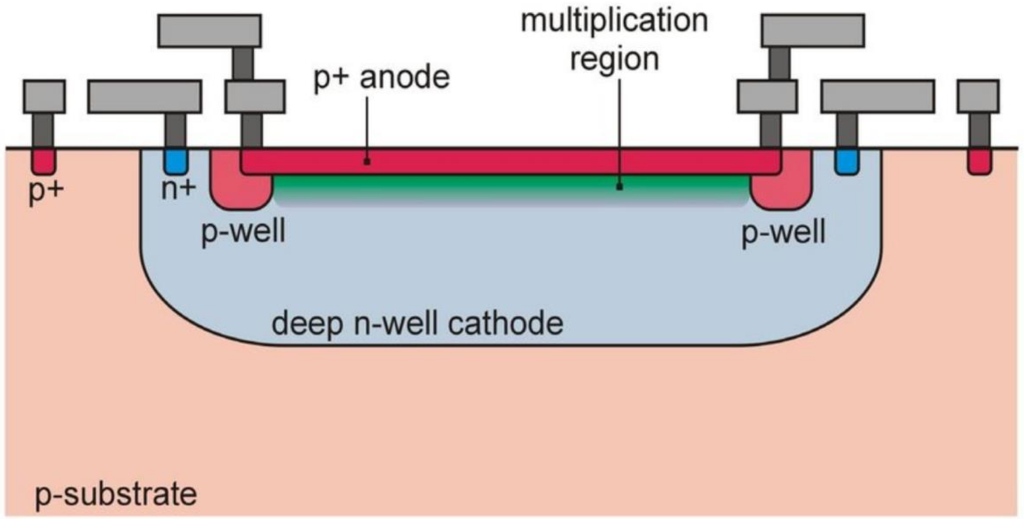
DC-LGAD
- ✅ Excellent timing (~20–30 ps)
- ✅ Simple segmented pad readout
- ❌ Gaps between pads → incomplete fill factor
- ❌ Coarse spatial resolution (> 100 μm)

AC-LGAD
- ✅ Continuous resistive n-layer → full fill factor
- ✅ Fine spatial resolution (~10 μm) with ~30 ps timing
- ❌ More complex fabrication, signal sharing
- ❌ Slightly lower S/N, needs reconstruction

Monolithic LGAD
- ✅ Gain + readout on one die (true integration)
- ✅ Compact, CMOS-compatible, radiation-hard
- ✅ Potential for most linear response.
- ❌ Still early R&D; gain uniformity and noise control challenging
- ❌ Hard to balance ps timing with low noise

Core R&D Challenges and CERN Support





Core R&D Challenges and CERN Support

- Technical challenges
    - Gain uniformity: keeping avalanche gain stable while avoiding premature breakdown, especially after irradiation.
    - Design limits: achieving both ~10 µm spatial pitch and ps-class timing stretches AC-LGAD layout and metallisation capabilities.
    - System integration: combining sensors with low-mass cooling, high-bandwidth readout, and trigger architectures for HL-LHC and beyond.
    - Low radiation tolerance

- CERN coordination and support
    - DRD3 – Solid-State Detectors Collaboration:
        - Strategic work packages
        - Links HL-LHC timing layers, future colliders, and applied domains (medical imaging, beam monitoring).
    - Establishes LGAD + HV-MAPS as a pan-CERN technology stack, not experiment-specific.

Multi-Use Applications of LGAD Technology

What HV-MAP can be envisaged to do, LGAD can most likely do it better based on current lab performances.

- **Automotive LiDAR: 50 ps timing → cm-level depth @ > 200 m.**
- Quantum optics / photon correlation detectors.
- **Space & atmospheric sensing: single photon capable.**
- Medical imaging & proton therapy: time-of-flight dosimetry.

Summary and Outlook

HV-MAPS

- Fully monolithic CMOS sensors delivering fine granularity, low noise, and ns-scale timing.
- Proven architecture for LHCb MightyPix and next-generation HEP tracking.
- Mature, CMOS-compatible process → ideal platform for applied sensor adaptation.

LiDAR adaptation

- HV-MAPS can operate as dual-mode sensors, imaging and time-of-flight.
- Enable flash LiDAR with centimetre-scale ranging and full-intensity readout.
- Bridge between HEP detector electronics and robotic / automotive vision.

Astrophysics and quantum imaging

- Same drive for low noise, gain stability, and fast timing supports exoplanet spectroscopy and faint-photon detection.
- HV-MAPS and e-APD principles converge toward photon-timestamping detectors.
- Dual-use R&D aligns HEP and space-instrumentation needs.

LGAD and beyond

- LGAD / AC-LGAD deliver sub-50 ps timing and are merging with HV-MAPS readout concepts.
- Future sensors: 4D monolithic CMOS with gain, integrating spatial precision and ps-class timing.
- CERN DRD3 provides the framework linking collider timing layers, LiDAR, and astrophysics instrumentation.

Outlook

- Unified goal: extend HV-MAPS intelligence and integration into the picosecond regime.
- One technology continuum:
  HV-MAPS → LiDAR → Astrophysics → LGAD.