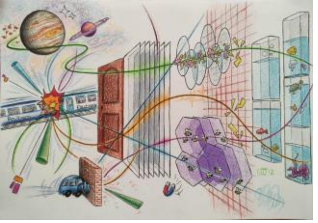


DRD3

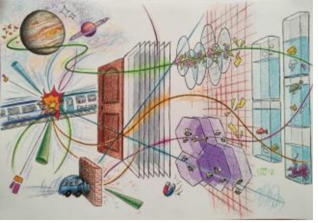
Future Perspectives on Solid State Detectors and DRD3 R&D Program

Gregor Kramberger

Jožef Stefan Institute, Slovenia

JSI
Ljubljana
Slovenia

Slovenian
Research
Agency



Motivation & Outline

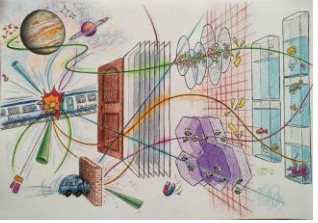
Presentation of the DRD3 as a platform for collaborative R&D on semiconductor sensors for future experiments

A flash-review of where we are, what we do and where future R&D will likely go.

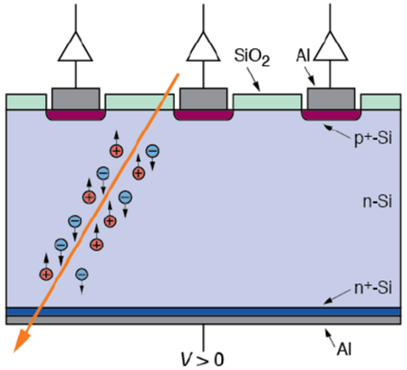
Outline:

- Semiconductor detectors in particle physics
- DRD3 Collaboration
- LGAD and 3D (WG2)
- CMOS (WG1)
- Simulations and defect characterization (WG3,4)
- WBG materials (WG6)
- Facilities and techniques (WG5)
- Interconnections (WG7)
- Conclusions

R&D Evolution



1980



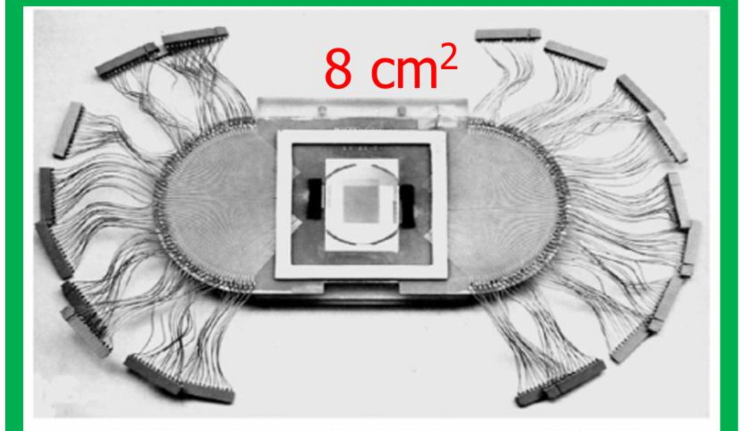


Fig. 3. Silicon strip detector assembly used in NA11 experiment at CERN [14-16].

(Detectors and Experiments for the Superconducting Super Collider, pg. 491, Snowmass 1984

	Luminosity			
Detector Element	10^{30}	10^{31}	10^{32}	10^{33}
Vertex Detection	Yes	Hard	Maybe	No
Central Tracking	Yes	Yes	Yes	Hard
Forward Tracking	Yes	Yes	Yes	Hard
Calorimetry	Yes	Yes	Yes	Yes
Electron I.D.	Yes	Yes	Yes	Hard
Muon I.D.	Yes	Yes	Yes	Yes
Triggering	Yes	Yes	Yes	Hard
Data Acquisition	Yes	Yes	Yes	Hard
Data Processing	Yes	Yes	Yes	Yes

Yes > Hard > Maybe > No

"Silicon strip detectors (near the beam pipe) appear to be limited to…≤ 10^{32}....the 10^{32} limit could be optimistic." (PSSC Summary Report pg. 130, 1984)

1984

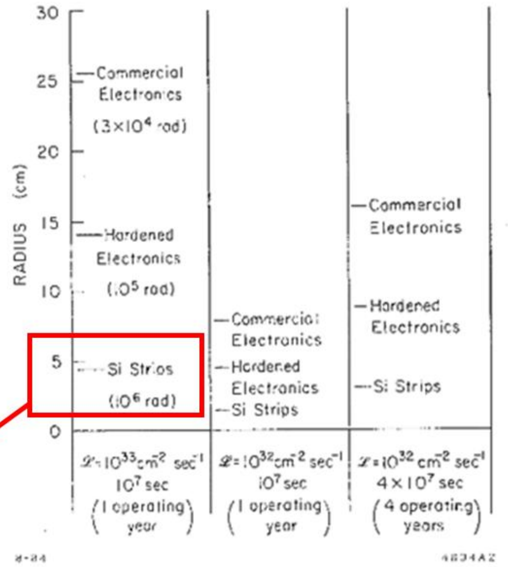


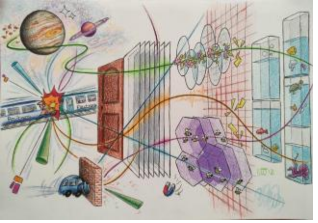
Fig. 1 Minimum component radii for radiation damage at luminosities of 10^{32} and 10^{33} cm^{-2} sec^{-1}.

1992-2001

RD2/RD48 – proved silicon detectors as solution for LHC (defect and device engineering were born – Oxygenated Si)

2003-2023

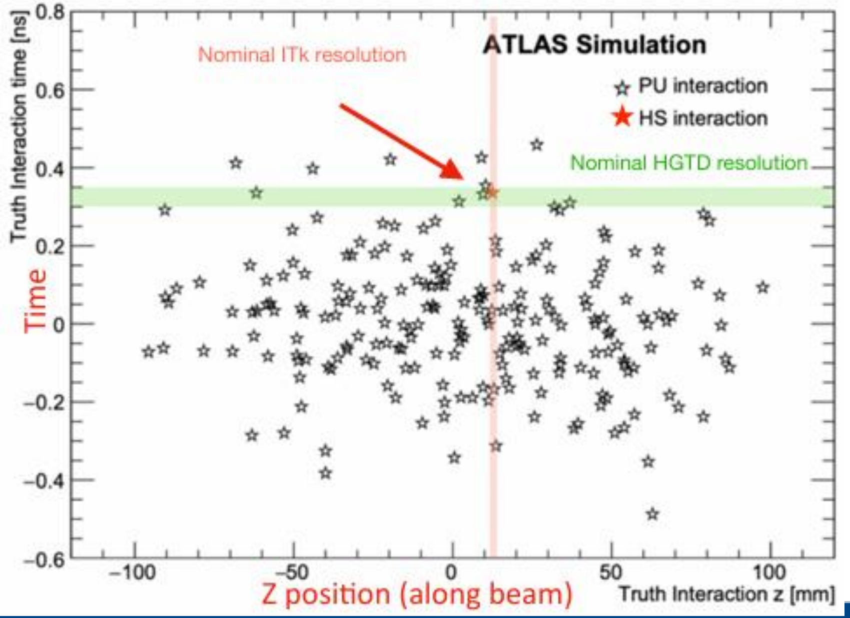
RD50 (silicon) and RD42 (diamond) solutions for **for HL-LHC** (p-type, 3D detectors, Low Gain Avalanche detectors)



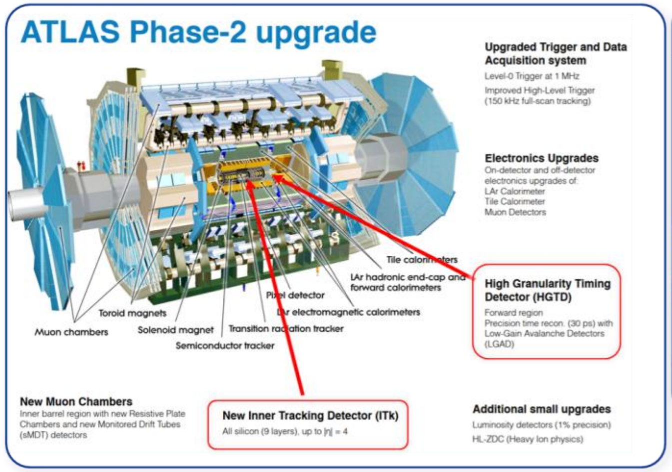
Silicon detectors

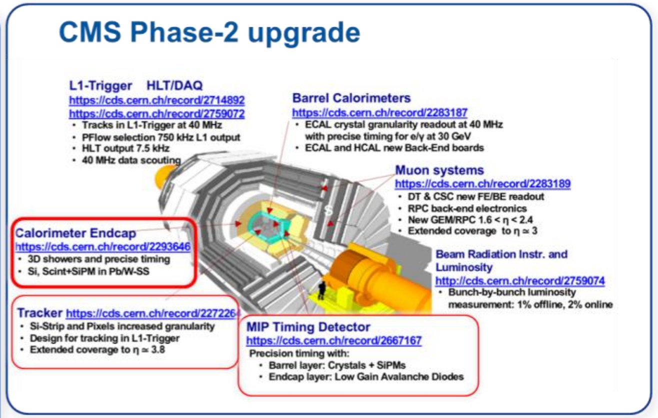
Remarkable challenges were over come in the last decade for the LHC upgrade!

- **Radiation hardness** at levels not imagined decades ago (few 10^{16} n cm^{-2}, tens of MGy) - 25x100, 50x50 μm^2 cells
- Not only the position but precise timing (~30 ps) should be measured for the mip particles - **Endcap Timing detectors** for ATLAS and CMS (4D tracking)
- **Superb spatial resolution at low mass** (ALICE ITS)



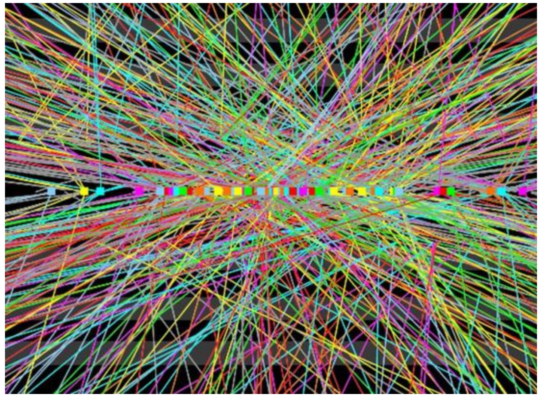
Coming after the accelerator upgrade in **2030**

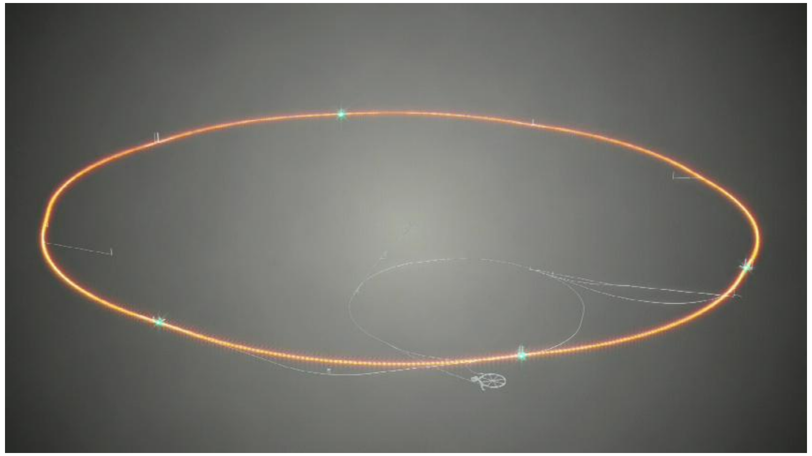


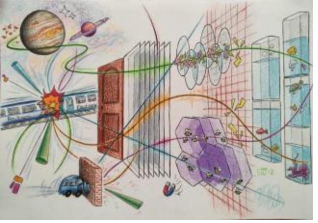


…also very close collaboration with LHCb!

200 pp collisions - pileup







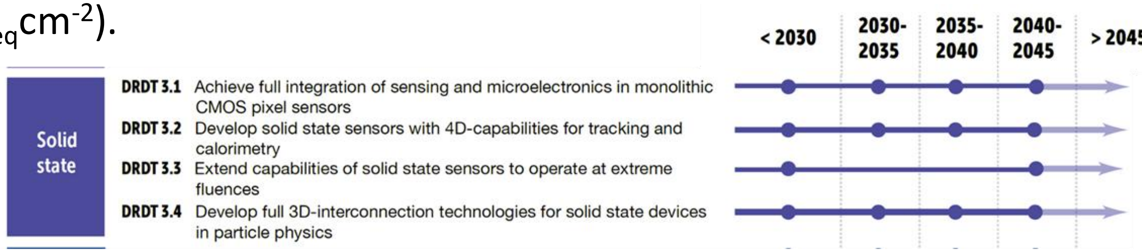
Semiconductor detectors …

New Major Challenges for the future **beyond 2030….**

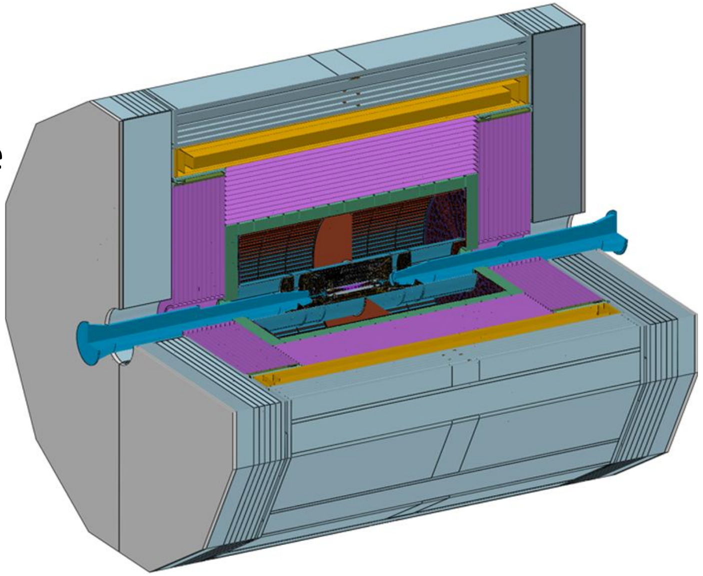
- FCC-ee/CEPC: Vertex detectors with low mass, high resolution (Target per layer spatial resolution of ≤ 3 µm and X/X_0≤ 0.05%)
- FCC-hh/SppC: low power and high radiation hardness (up to $8{\cdot}10^{17}$ $n_{eq}cm^{-2}$). Resolving many pp hits in a bunch by ultra-fast timing in O(10 ps)
- Full integration with electronics, mechanics, services
- Large area sensors at low cost for calorimetry

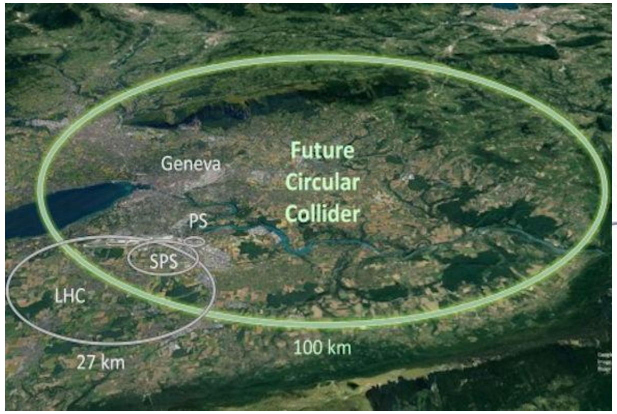
European Commission for Future Accelerators Road map document on sensors

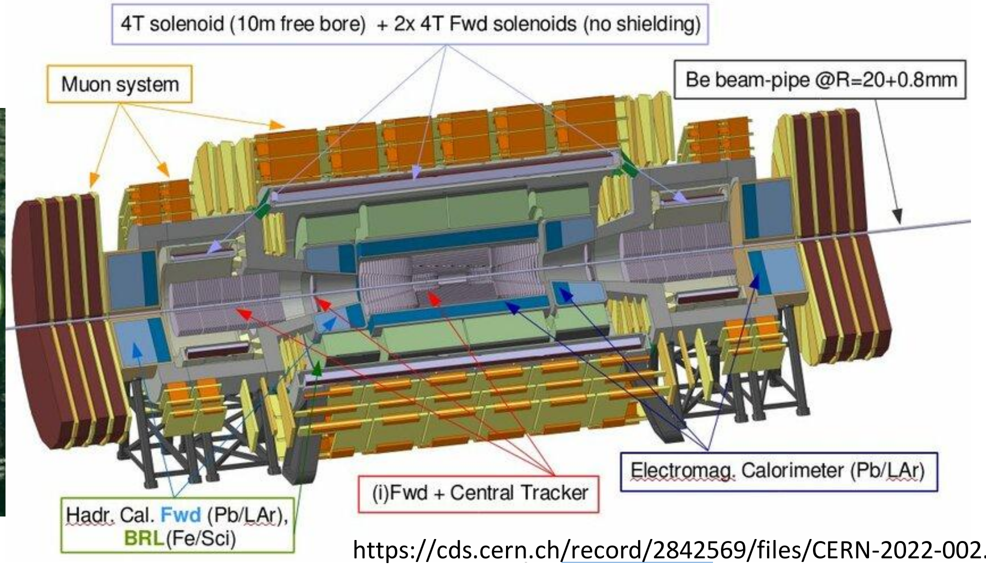
https://cds.cern.ch/record/2784893/files/ECFA%20Detector%20R&D%20Roadmap.pdf



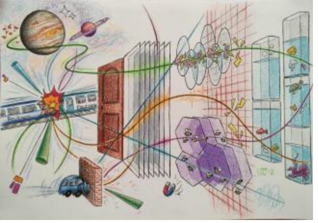
CEPC reference detector







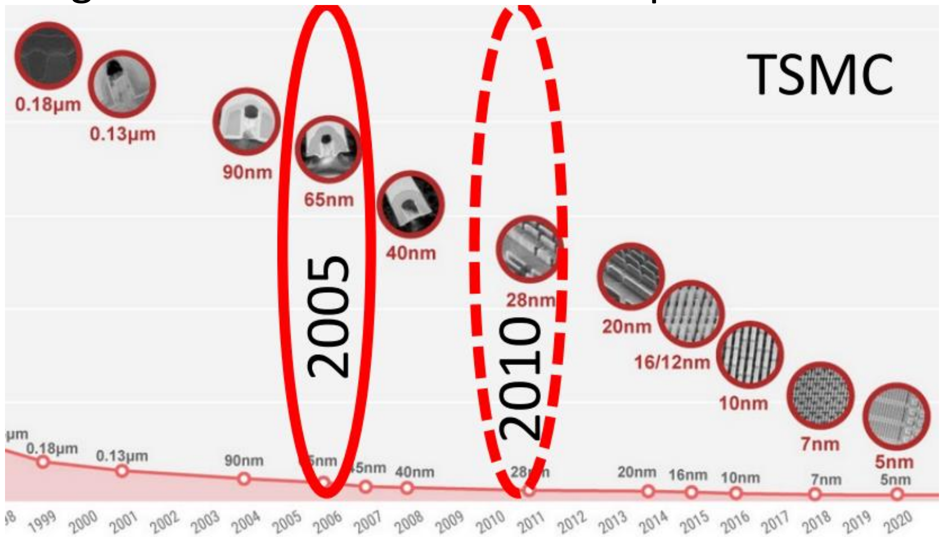
https://cds.cern.ch/record/2842569/files/CERN-2022-002.pdf

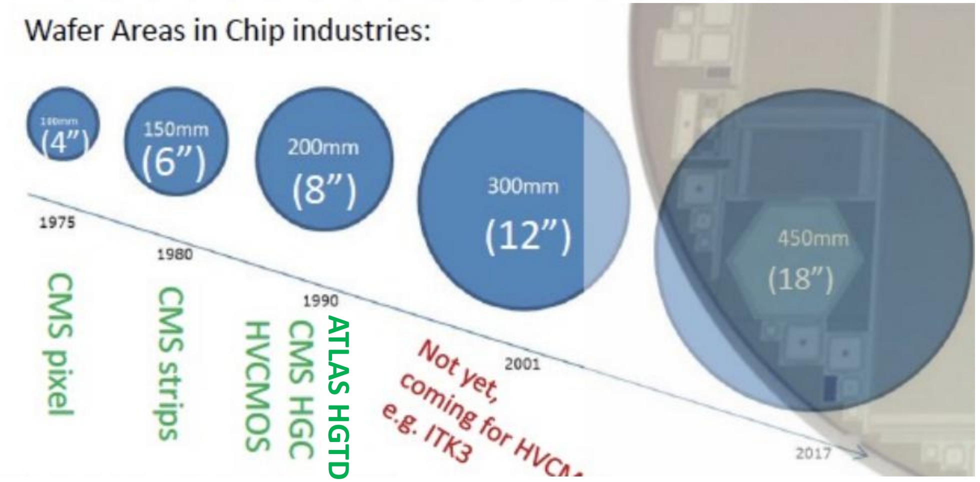


Evolution of Si particle sensors

DRD3

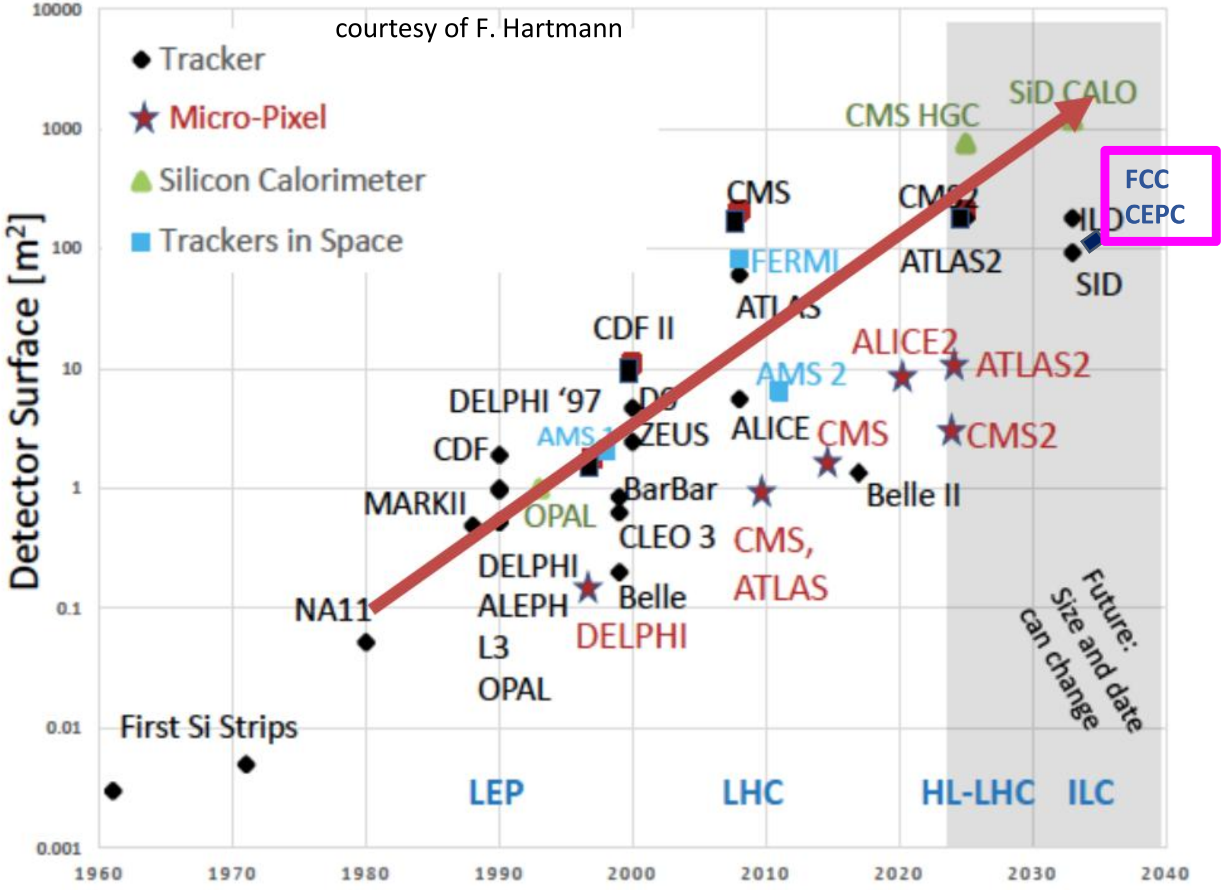
Remarkable success in HEP was enabled by the significant advancements in chip industries.

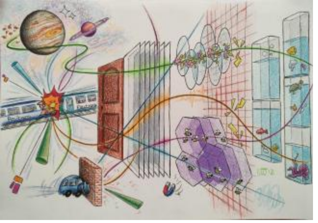




Huge growth of semiconductor particle detectors in various fields

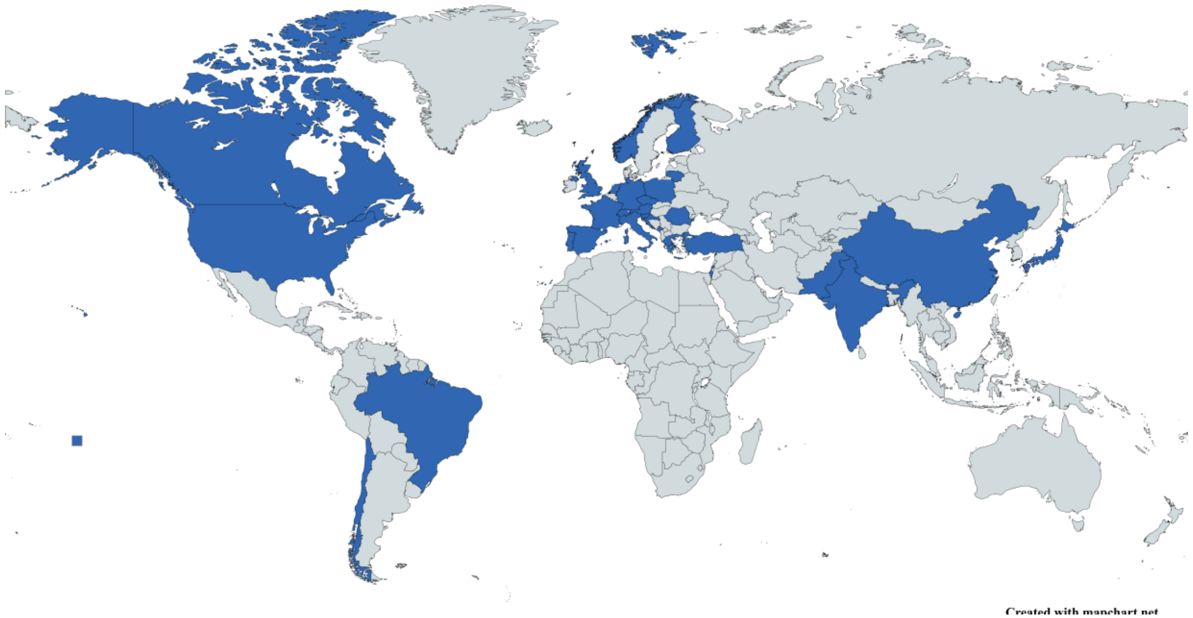
Detector area increased by one order of magnitude each decade (1 m^2 → 10 m^2 → 200 m^2 → 600 m^2)

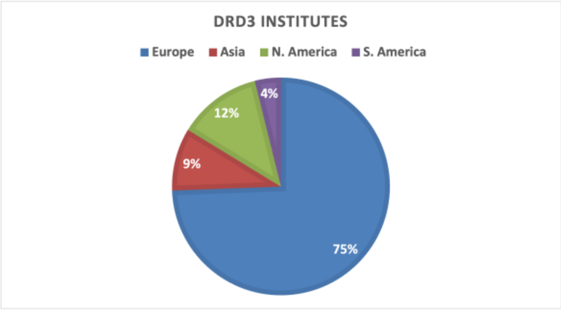


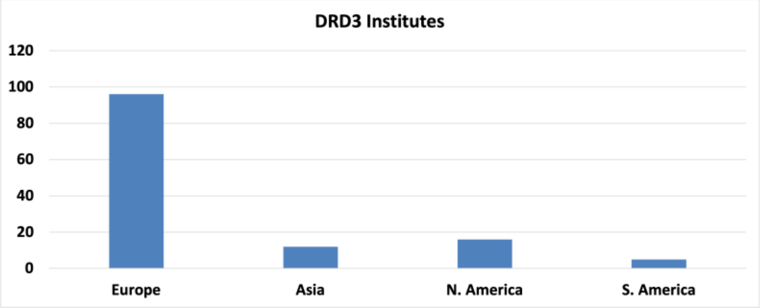


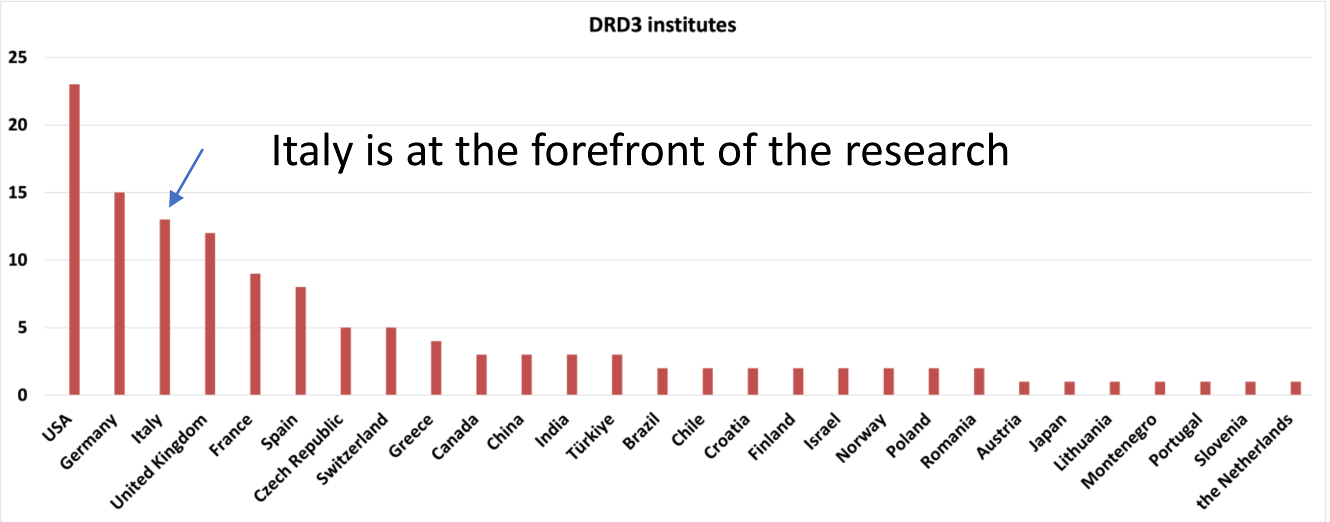
The DRD3 collaboration

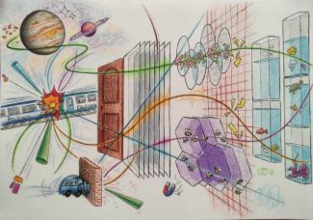
A large collaboration on semiconductor has been formed at CERN to guide and steer the developments of semiconductor sensor developments in the next decades. **143 Institutes currently involved with 700+ people**





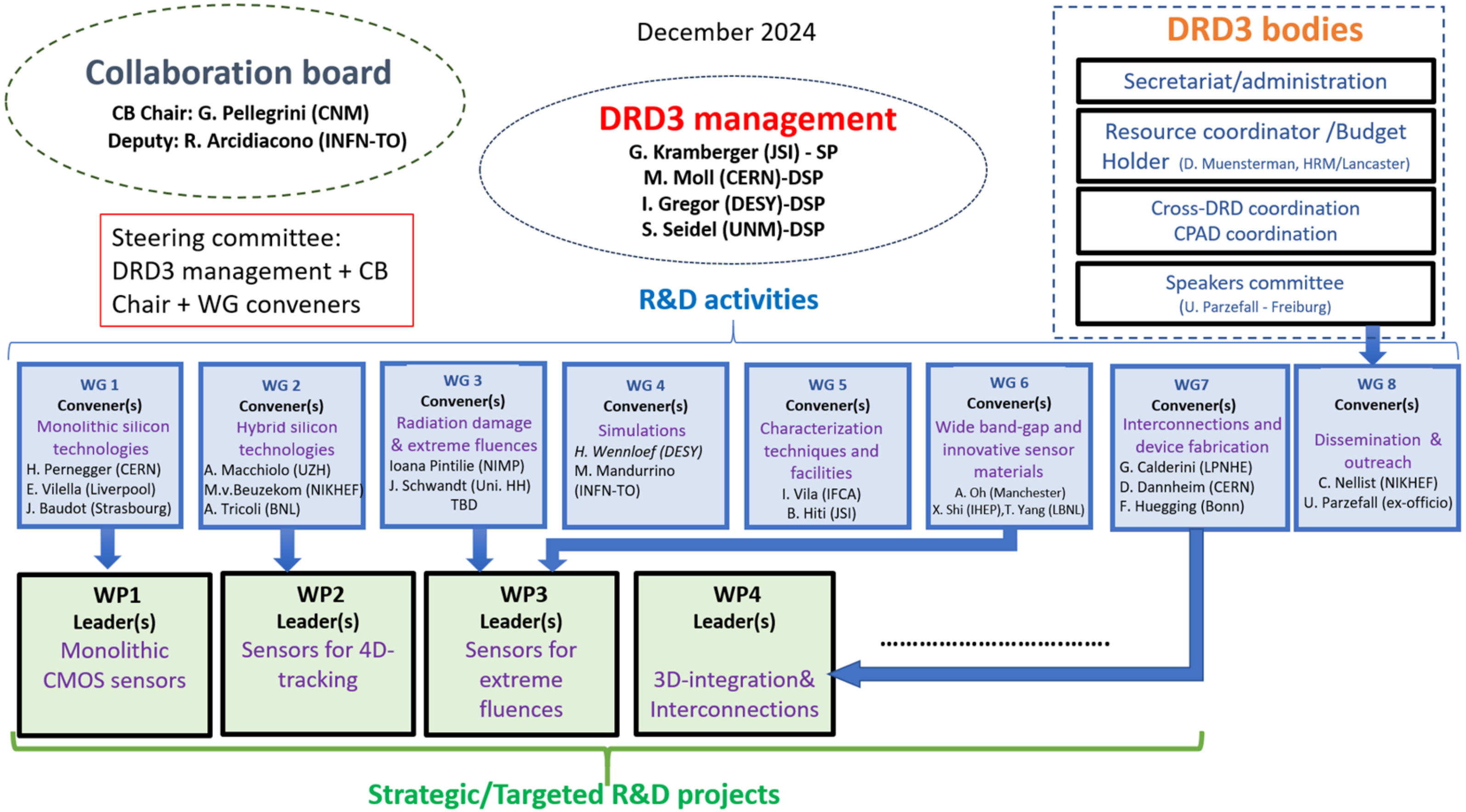






Organizational structure

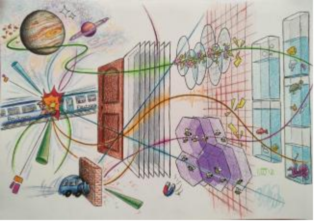
DRD3



Status of Collaboration – timeline:

- 12-2023 - provisional approval
- 01-2024 - formation of CB
- 03-2024 - election of SP
- 05-2024 - formation of WG-WPs
- 06-2024 - approval (sci proposal)
- 06-2024 - first DRD3 week
- 07-2024 - start of scientific meetings and preparation of WP projects
- 10-2024 - approval of the DRD3 rules
- 12-2024 - second DRD3 week
- 01-2025 - finalization of WP projects (adjustment to funding reality)
- 02-2025 - first DRDC review

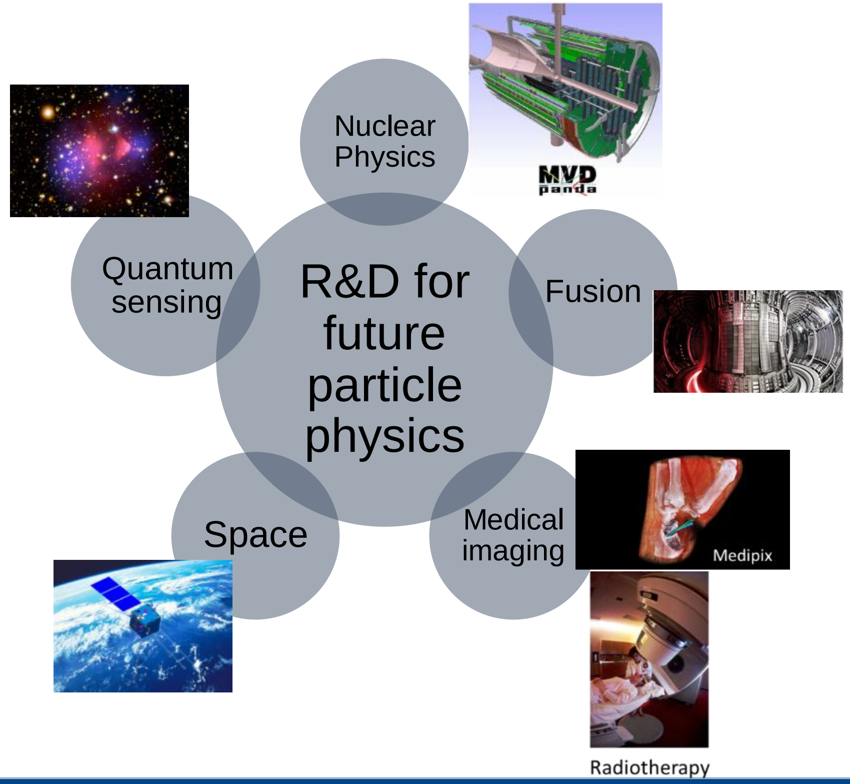
Work Package (WP) = strategic R&D activity and is linked to Tasks in the roadmap document. It should pursue the goals listed there.
o WPs gather a subset of DRD3 institutions, are resource loaded with clear milestones and deliverables and (at least partially) funded
o WPs reviewed/approved by DRD3 and appended to MoU annex
o WPs will be shaped and optimized (synergies with similar projects, sharing runs…)

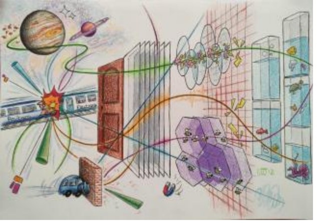


Objectives of the collaboration

We want mass-less detector, with superb time and position resolution with high rate capability with no power consumption and it must be very cheap, of course.

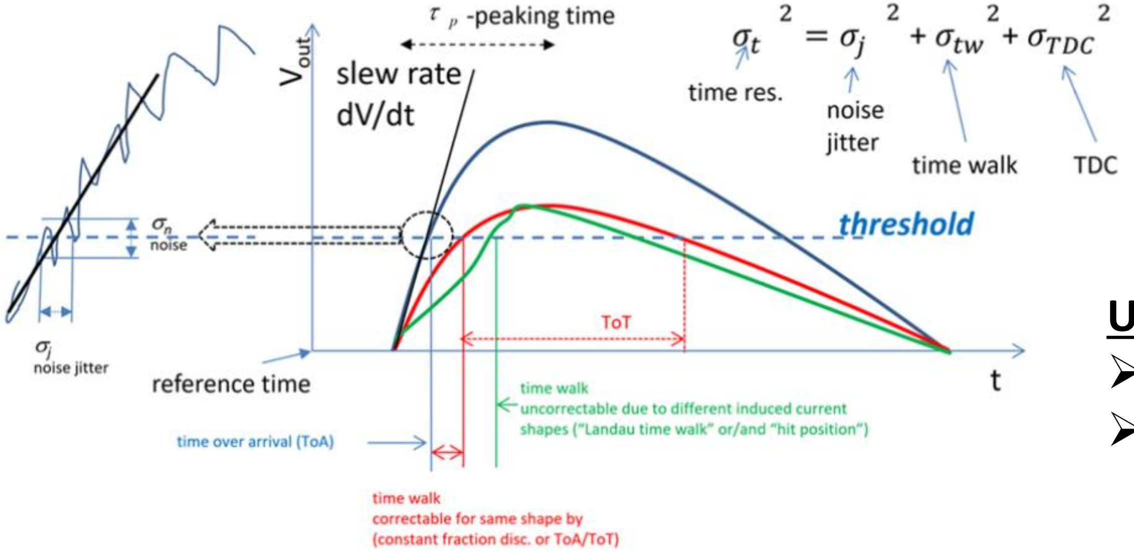
The DRD3 collaboration has the dual purpose of pursuing the realization of the **strategic developments** outlined in the ECFA road map and **promoting blue-sky R&D** in the field of solid-state detectors including the synergies with other fields of science where charged particle detection is a key ingredient.



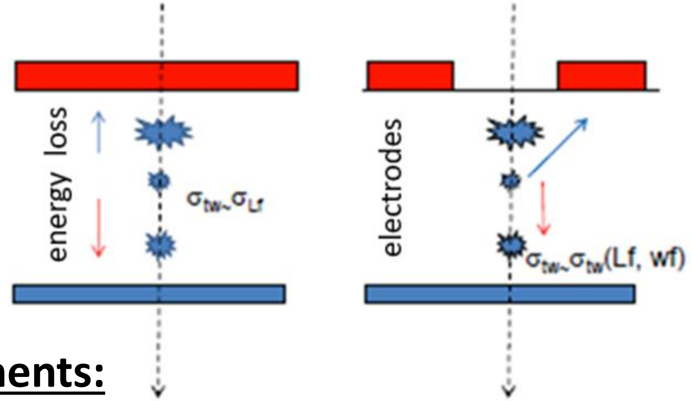


Timing and position resolution

TIME RESOLUTION



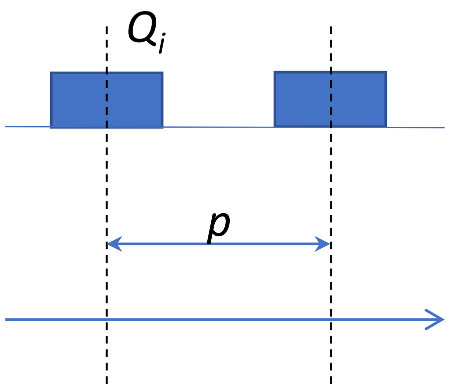
$$\boxed{\sigma_j = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|} \approx \frac{\sigma_n}{\left|\frac{S}{\tau_p}\right|} = \frac{\tau_p}{S/N}}$$



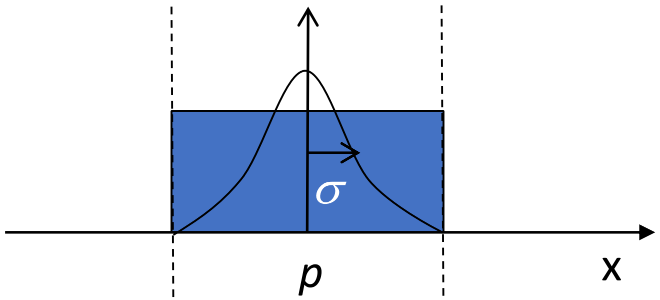
Un-correctable time walk components:

- ➢ variation of ionization pattern – Landau fluctuations
- ➢ variation of the drift paths – weighting field/distortion component

POSITION RESOLUTION



BINARY READ OUT



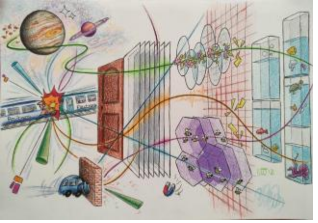
$$\sigma^2 = \frac{1}{p}\int_{-p/2}^{p/2} x^2 dx = \frac{p^2}{12} \Rightarrow \sigma = \frac{p}{\sqrt{12}}$$

ANALOG/DIGITAL READ OUT

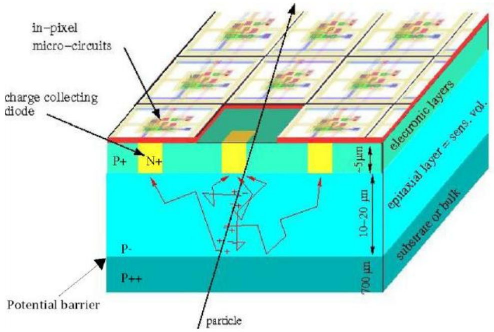
$$x_{hit} = \frac{\sum_{strips} x_i Q_i}{\sum_{strips} Q_i}$$

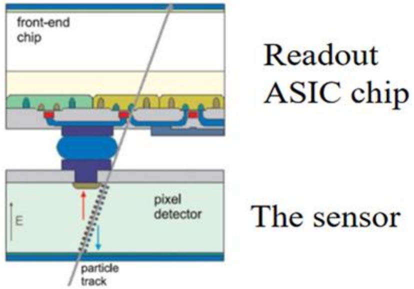
$$\sigma \propto \frac{p}{S/N}$$

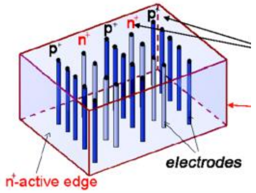
Centre of gravity on any other calibrated Look-Up-Table



Paths of present R&D

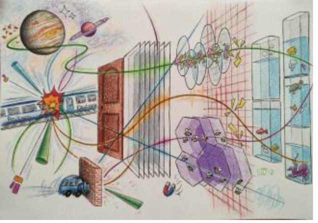






- Monolithic devices (all in one) – CMOS 55-180 nm processes
  - smaller "node" → Small electrode device
    - MAPS
    - with gain
    - without Gain → Optimized for rates/power/position resolution
  - larger "node" → Large electrode device
    - without Gain → Optimized for radhard/timing
    - with gain
    - Large area passive devices (strip)
- Hybrid devices
  - Planar
    - Large area passive devices (strip)
    - With Gain (LGADs)
  - 3D devices
    - Trench 3D
    - Column 3D → With Gain?

Legend:
- ideas
- recent research
- Proven/demonstrated

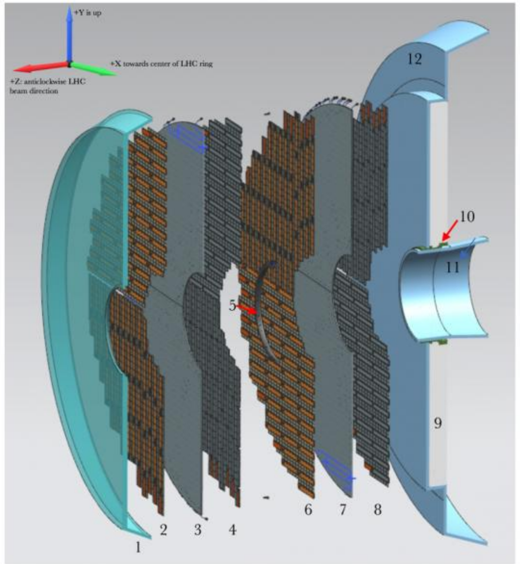


Hybrid silicon technologies and 4D tracking (WG2)

By “4D tracking” we mean the process of assigning a space and a time coordinate to a hit - ~10-30 μm position **and ~10-30 ps time resolution** – simultaneously (many benefits in dense particle environment for tracking and PID)

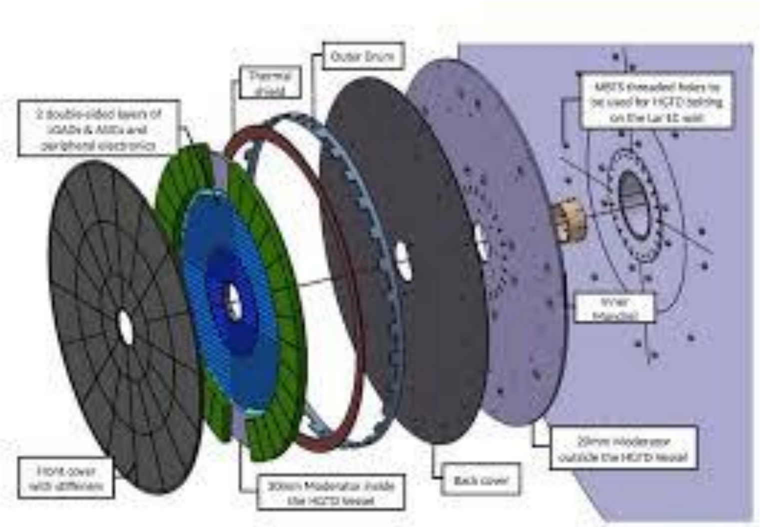
Track timing
(separate points for position and for time – in making at ATLAS/CMS)

CMS - ETL



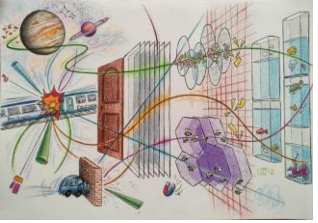
1: ETL Thermal Screen
2: Disk 1, Face 1
3: Disk 1 Support Plate
4: Disk 1, Face 2
5: ETL Mounting Bracket
6: Disk 2, Face 1
7: Disk 2 Support Plate
8: Disk 2, Face 2
9: HGCal Neutron Moderat
10: ETL Support Cone
11: Support cone insulation
12: HGCal Thermal Screen

ATLAS - HGTD

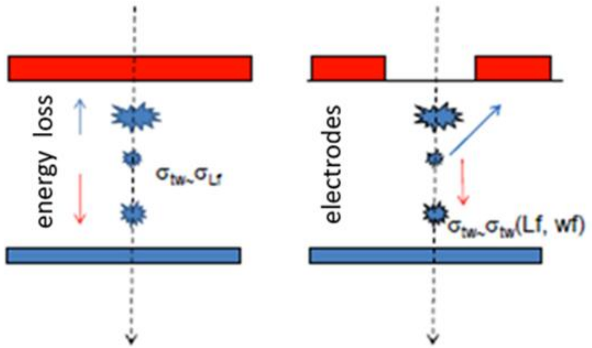


Real 4D timing – goal for the futute (each point with 4D)

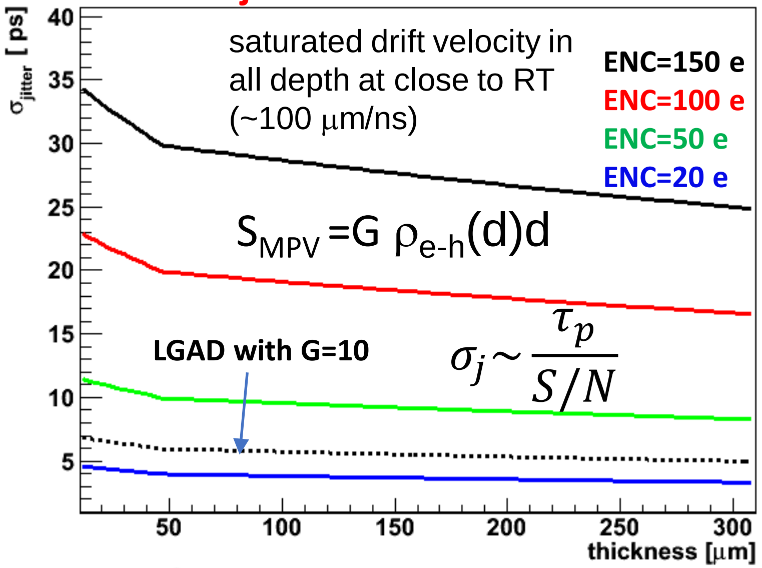
- much better/simpler pattern recognition, ghost rate reduction
- better and faster tracks/physics reconstruction, better tracking algorithms
- less CPU power (improved cost and energy efficiency)
- effectively more luminosity



Hybrid silicon technologies and 4D tracking (WG2)

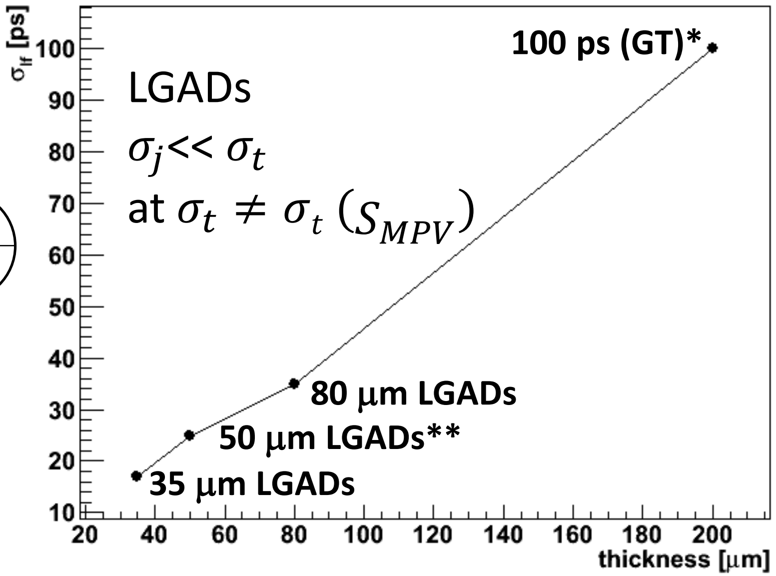


σ_j - Jitter (τ_p= $t_{collection}$)

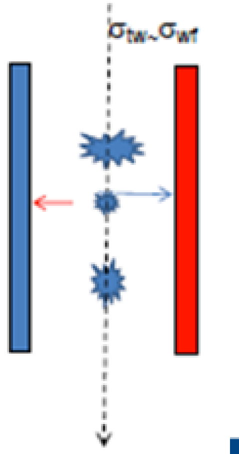


$\oplus$

σ_{lf} - Landau fluctuations



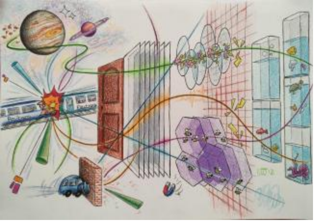
$\oplus$ **σ_{wf}** (segmentation pitch/thickness) $\approx$ **~10 ps** is (almost?) impossible in Si planar technology



So far this requirements lead to two solutions for 4D tracking:

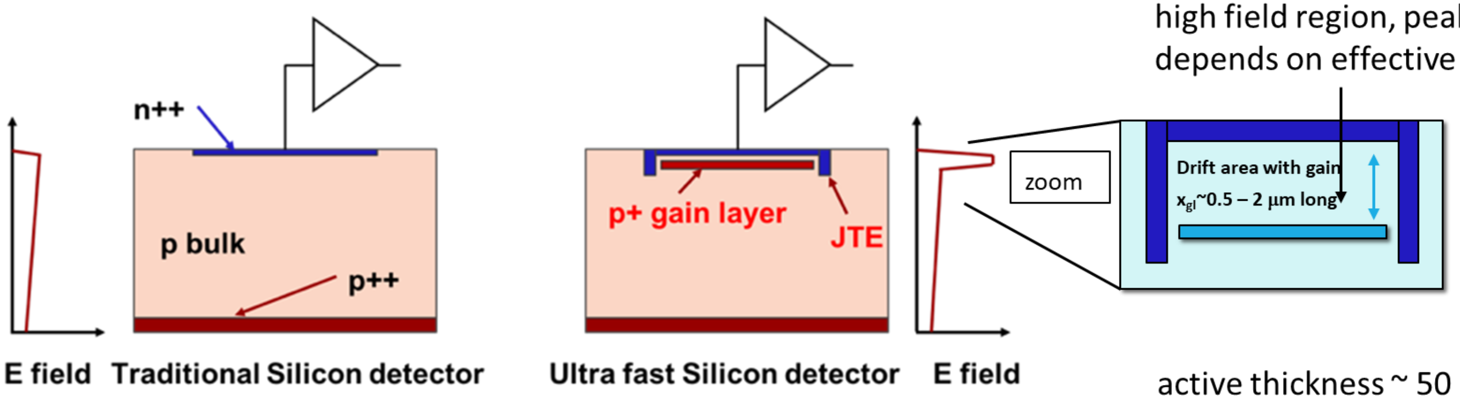
- planar with gain - **LGAD detectors**
- 3D detectors where drift time/rise time and signal size (thickness) are decoupled

	WG2 research goals <2027
	Description
RG 2.1	Reduction of pixel cell size for 3D sensors
RG 2.2	3D sensors for timing (50 × 50 μm, < 50 ps)
RG 2.3	LGAD for 4D tracking < 10 μm, < 30 ps, wafer 6" and 8"
RG 2.4	RSD for ToF (Large area, < 30 μm, < 30 ps)



LGAD – silicon detectors with gain

high field region, peak field depends on effective doping level

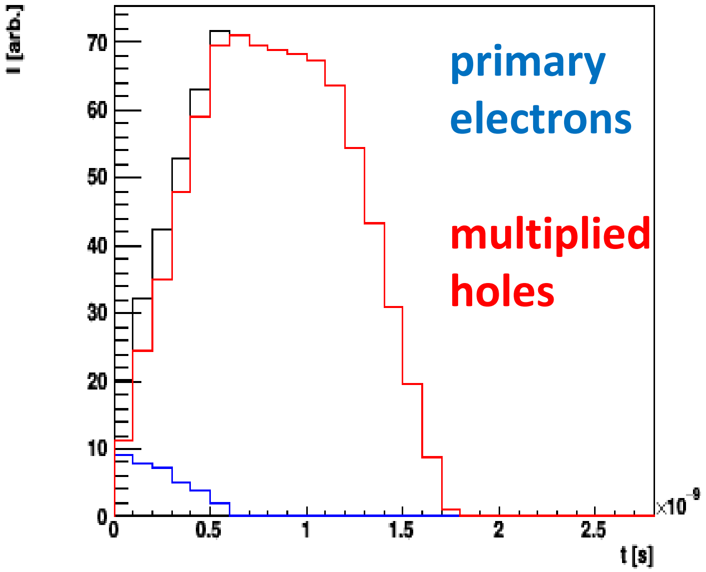


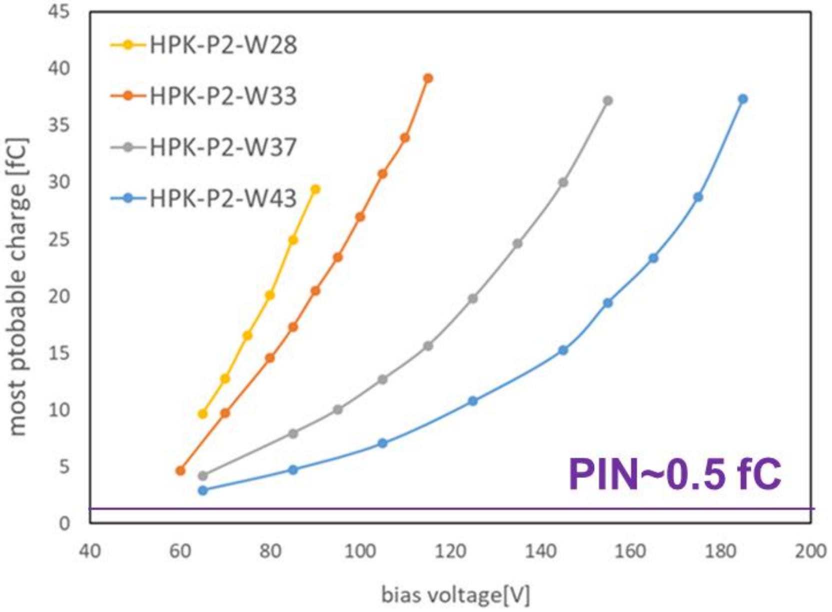
active thickness ~ 50 μm

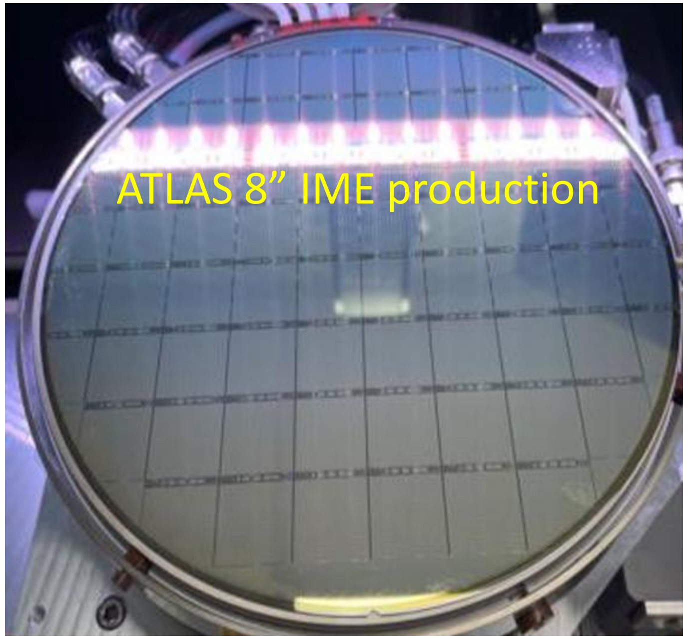
Typically 20-55 μm thick with signals of 20fC (G~40)

Limitations for conventional LGADs:

- Fill factor (large cell devices) due to JTE
- Radiation harness – **currently to ~3e15 cm^{-2}**

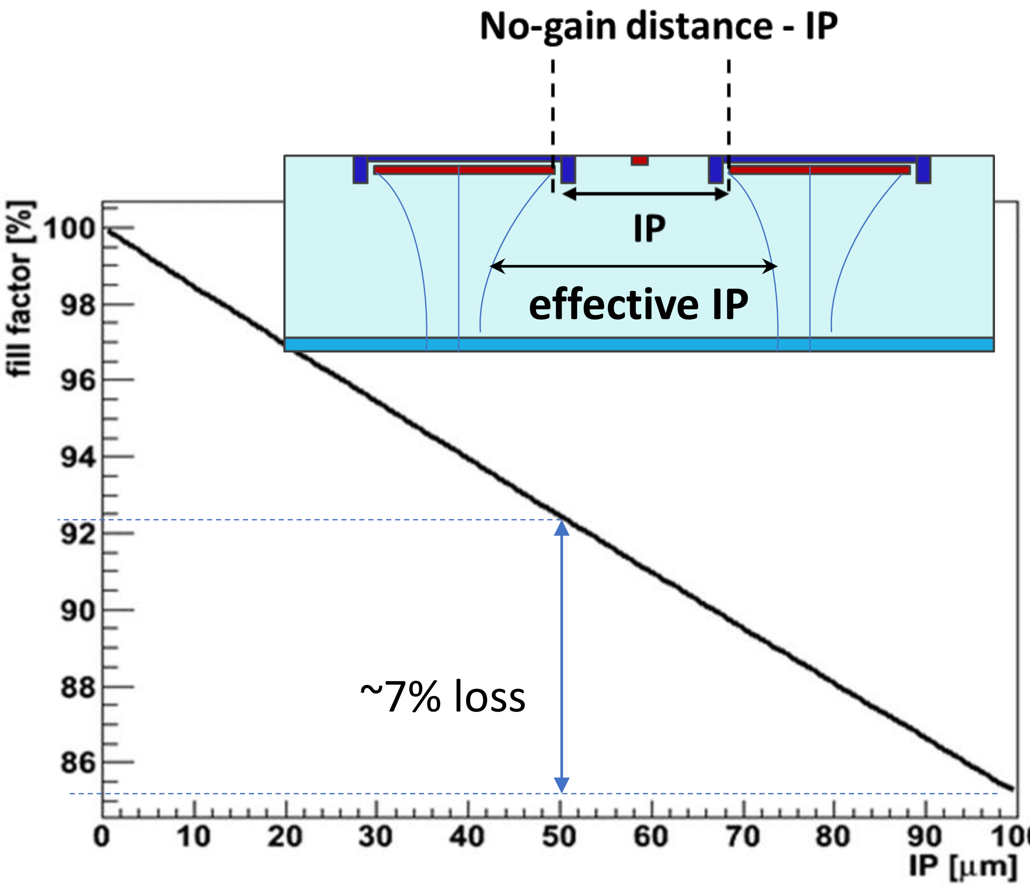


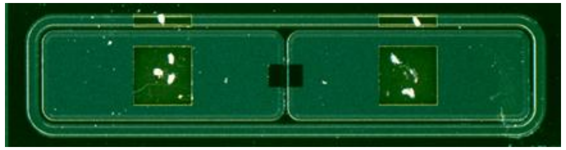


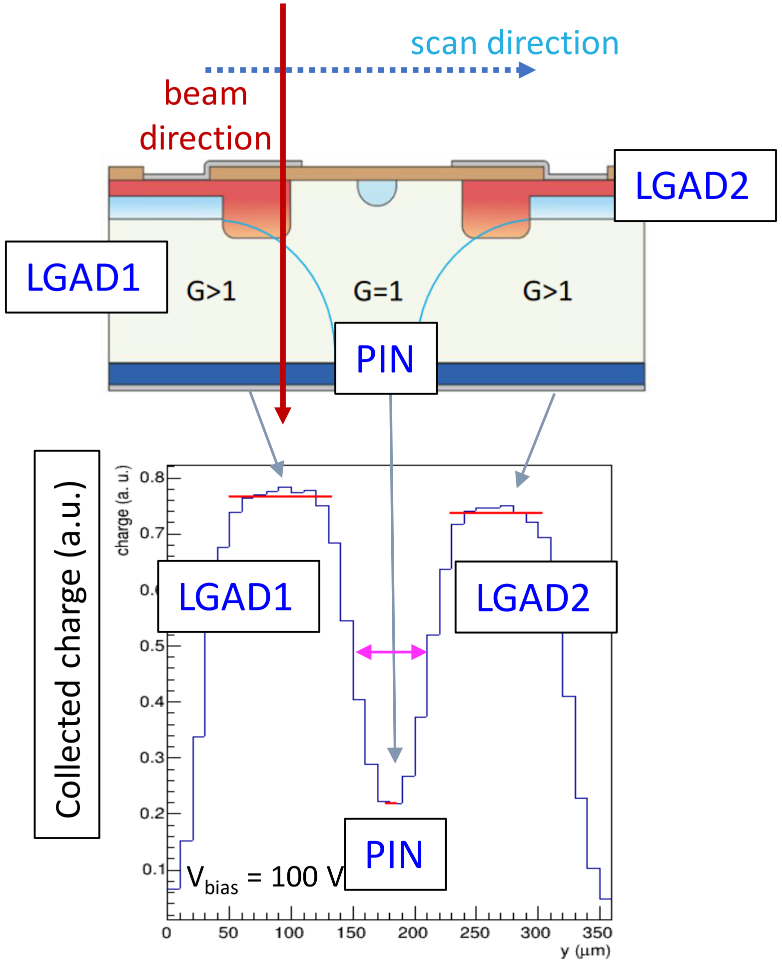


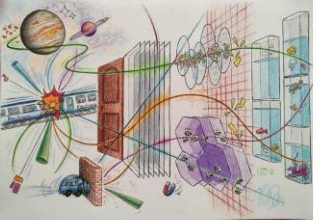
LGAD - Fill factor

Conventional LGADs – limited by the fill factor to ~1 mm^2 pixels



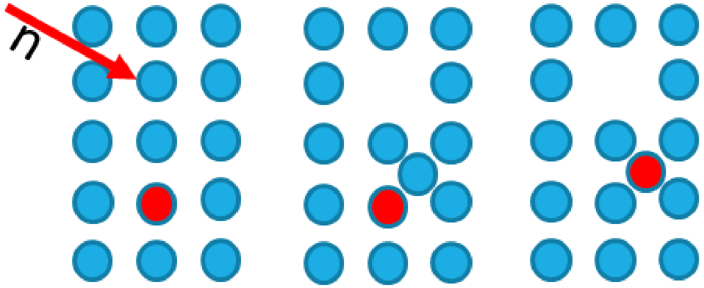






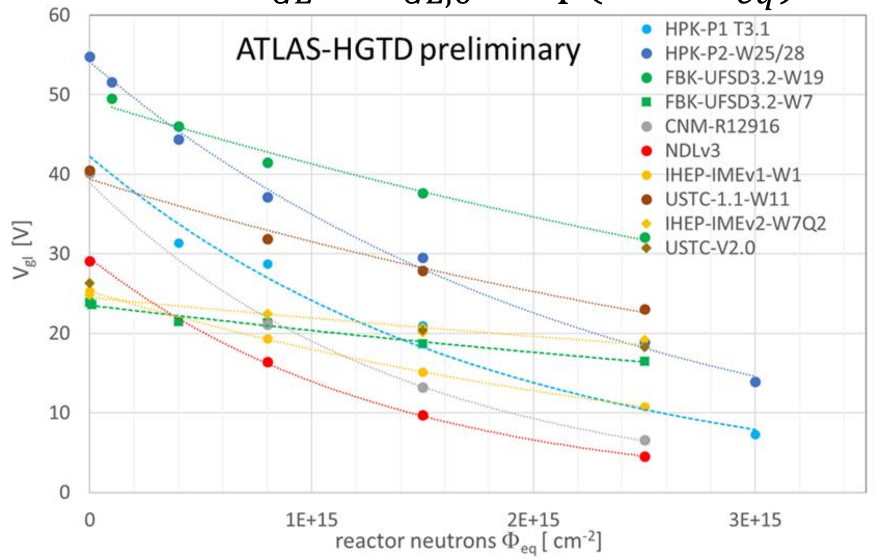
Radiation hardness of LGADs

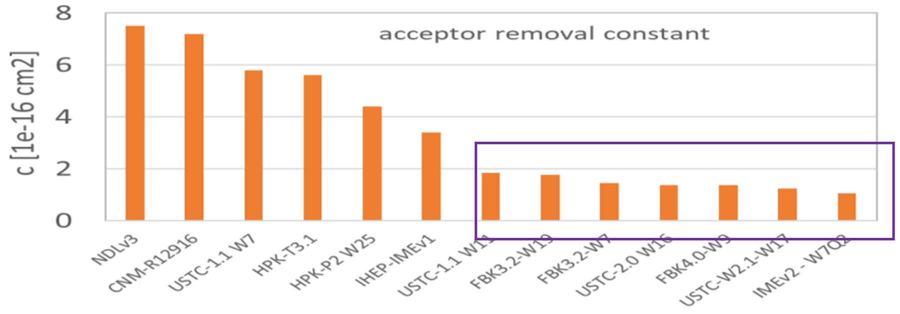
Dopant removal



Reduction of the doping concentration of gain layer due to irradiation reduces the gain.

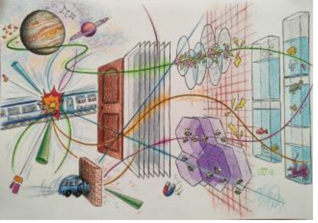
$$V_{GL} = V_{GL,0} \cdot \exp(-c \cdot \Phi_{eq})$$





huge improvement for the C-enriched GL

- C-enrichment of the gain layer (prevention of Boron removal and by that the reduction of the field) – FBK and IME have mastered the process– is there still room for improvement?
- Compensated LGADs – use of compensated p+ silicon in gain layer which if carefully tuned would not suffer from reduction of negative space charge with irradiation (both P and B are removed)
- Introduction of different dopants (Ga – 1st attempt not successful)
- Thermal treatment >200^{o}C re-activation of space charge



LGADs and fill factor

Several technologies were proposed and are investigated to overcome fill factor problem:

iLGAD – segment the side without multiplication no p-stop, JTE at the bottom (**complex processing, radiation hardness, hole collection**, ideal for high rate)

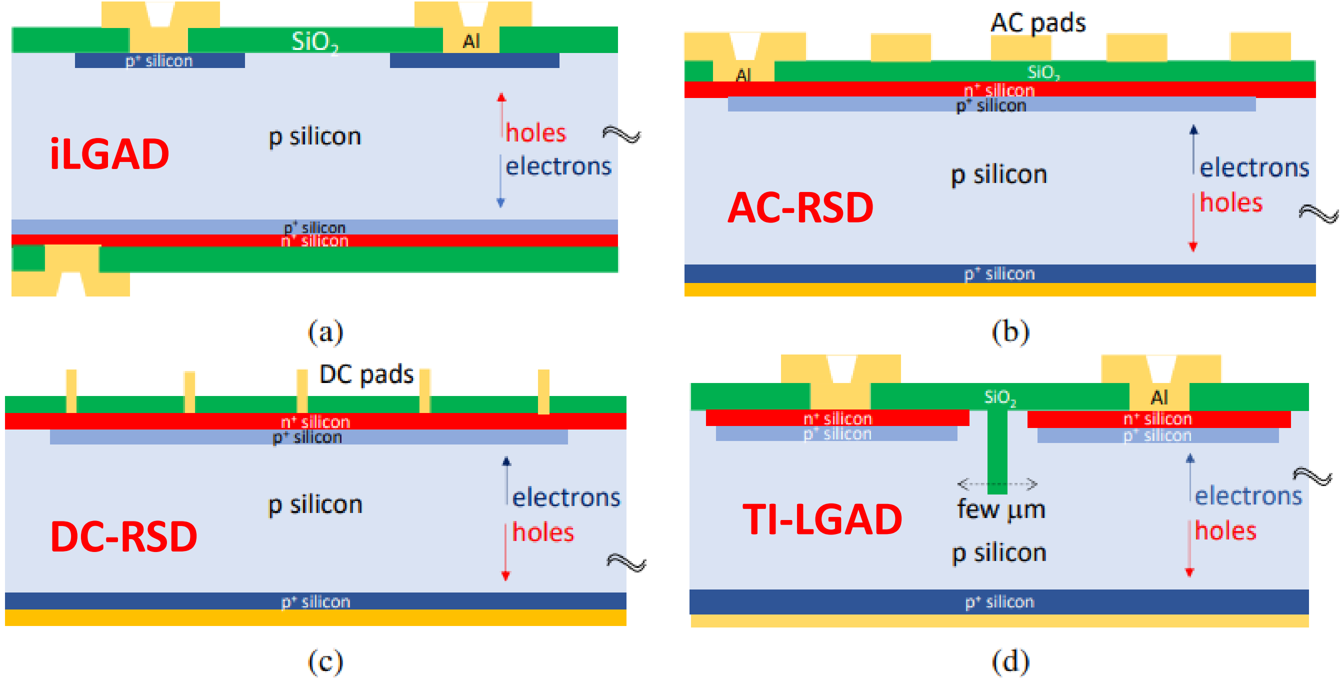
TI-LGAD – use SiO_2 trenches to isolate the pads, reducing the gap by an order of magnitude (C-enriched produced)

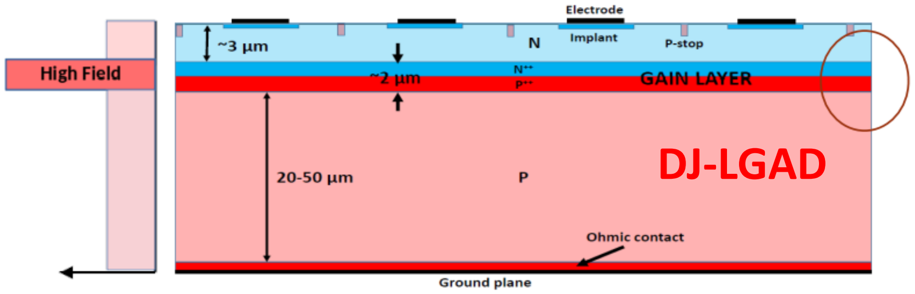
DC-RSD/AC-RSD (AC-LGAD) use AC coupling – bipolar signals:

- superb spatial and time resolution (up to ~5% of the pitch)
- **rate limited, radiation hardness**

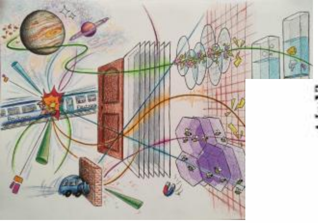
Very promising DC-RSD with Trench isolation – restriction of charge flow

DJ-LGAD





LGADs are the only planar technology good enough for precise timing (<50ps), but excellent electronics is needed. **(marriage of LGAD + CMOS looks promising – DJ-LGAD, MONOLITH)**

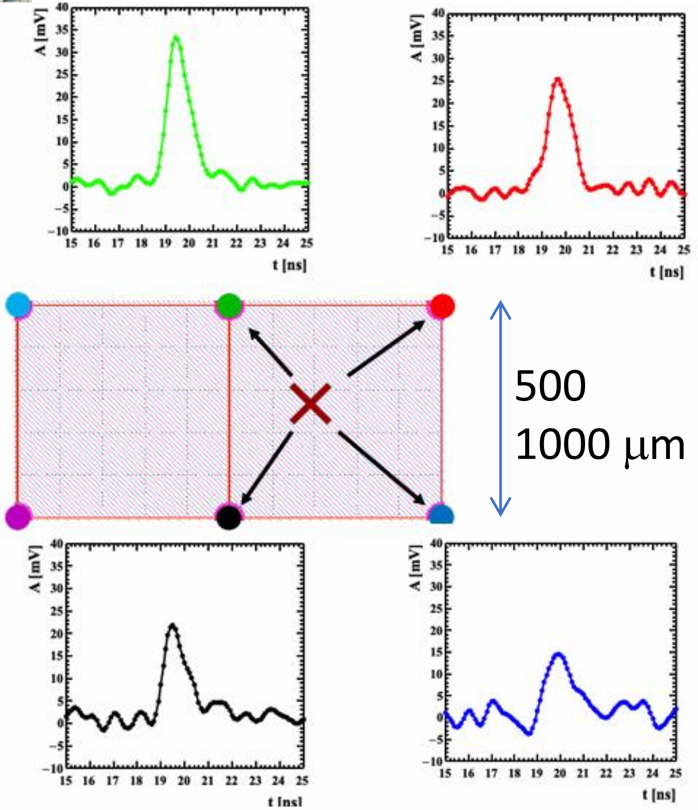


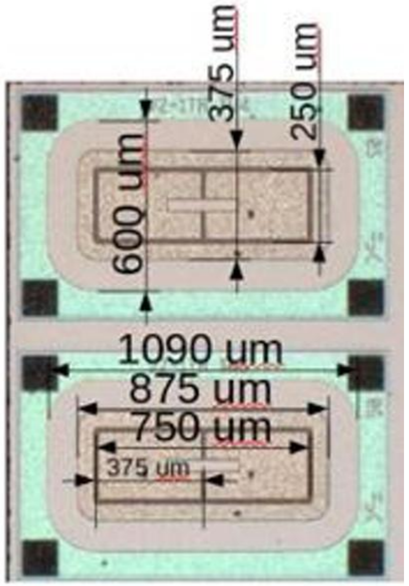
LGAD – recent

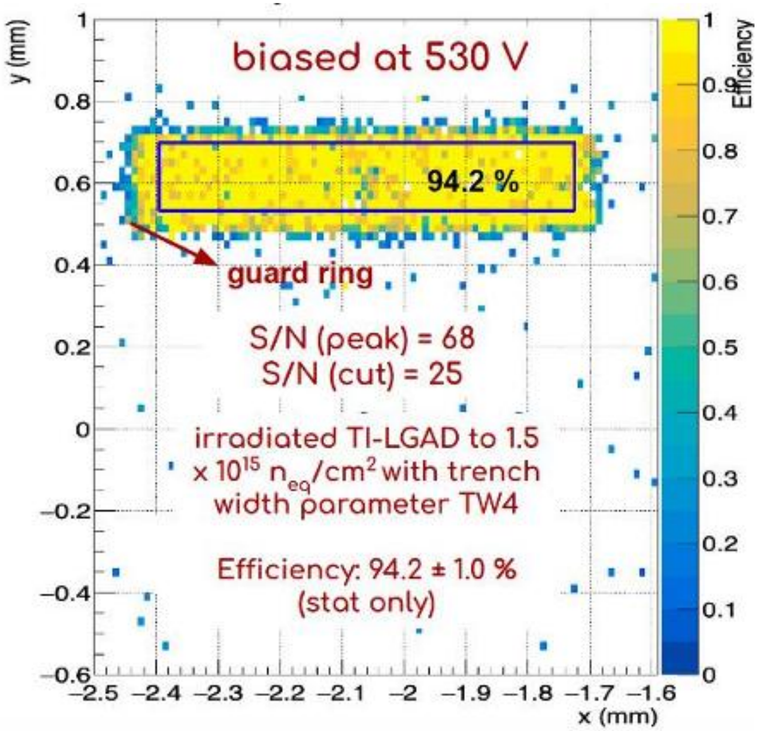
DRD3

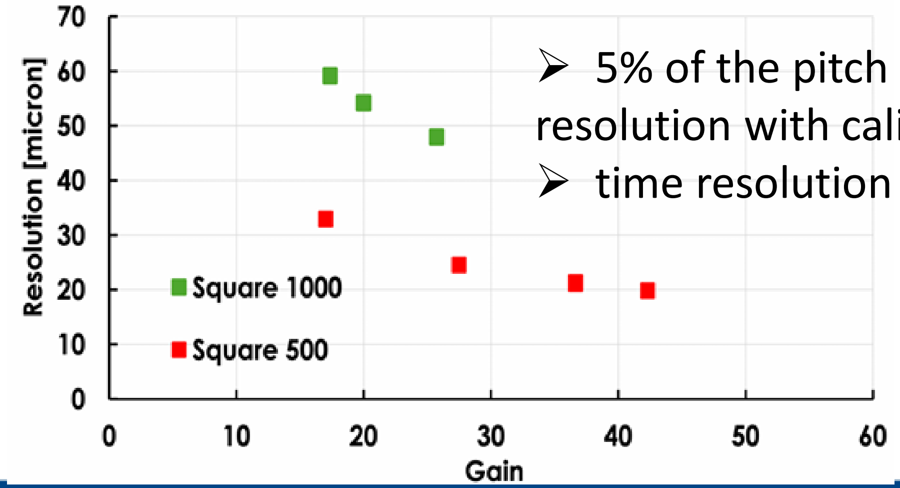
RSD-LGAD with trench electrode isolation

N. Cartiglia TREDI 2025

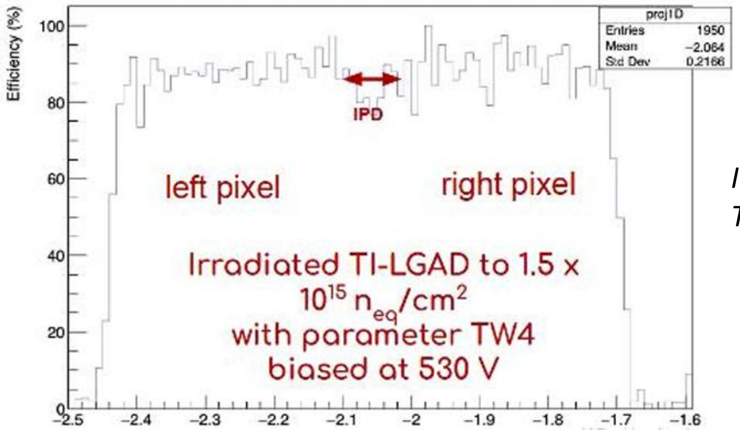




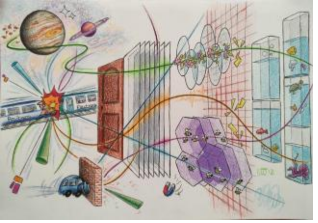




- 5% of the pitch is the position resolution with calibrated Look-up-Table
- time resolution likely to be ~30 ps



I. Velkovska TREDI 2025

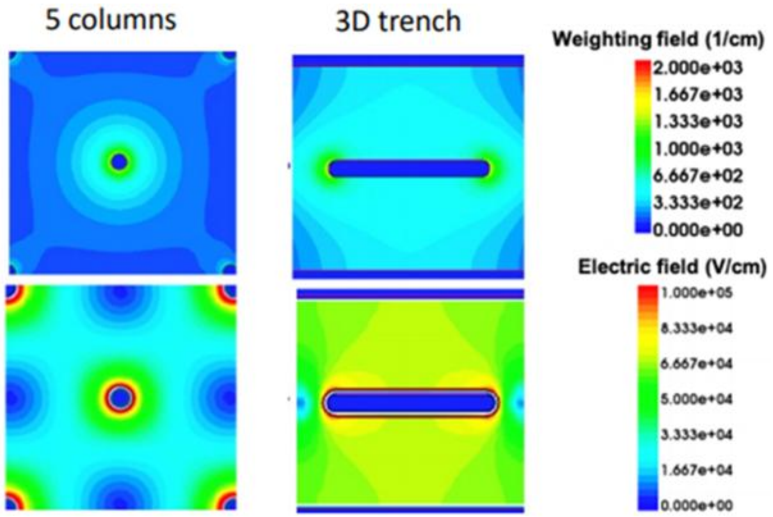


3D detectors

3D technology as timing detectors:

- They have fill factor ~100% (inclined tracks)
- They are fast (small distance) and can be thick (LF less important)
- The radiation tolerance of small cell size devices is large (for signal) and allows operation at higher bias voltages – shown up to ~1e17 cm^{-2}
- Technology is already mature-latest 3D detectors are done in single sided processing!

$$i = q\,\vec{E}_w \cdot \vec{v}_d$$



(web.infn.it/timespot/)

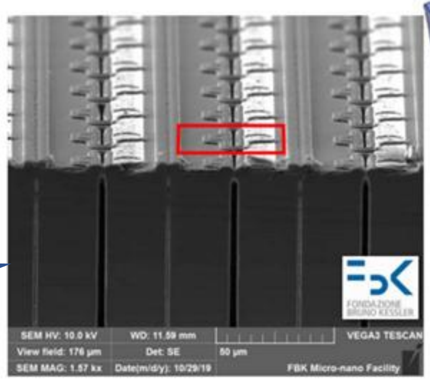
TCAD simulation

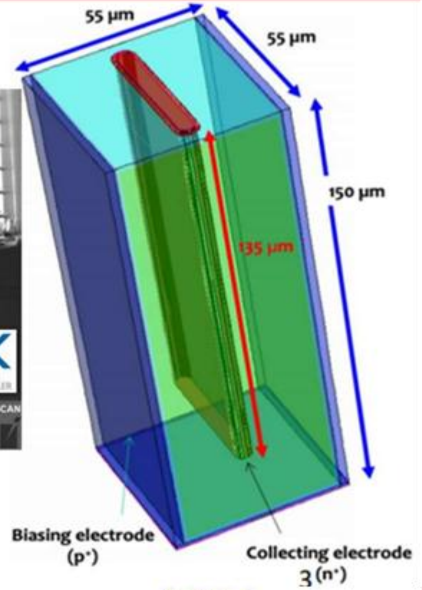
Trench 3D

(INFN – FBK)

3D silicon detectors

<30 ps mips

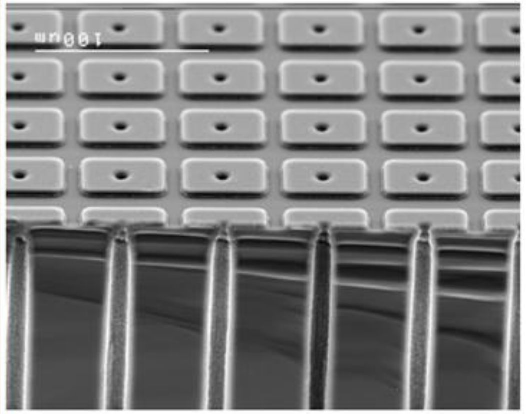


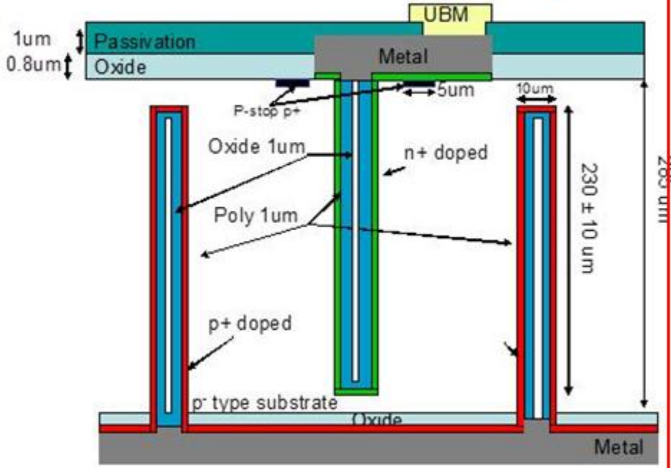


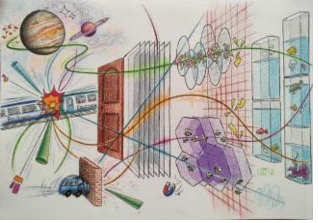
TimeSPOT

Column 3D

(CNM/FBK/Sintef/IME…)





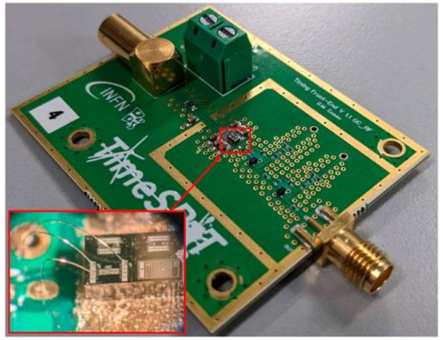


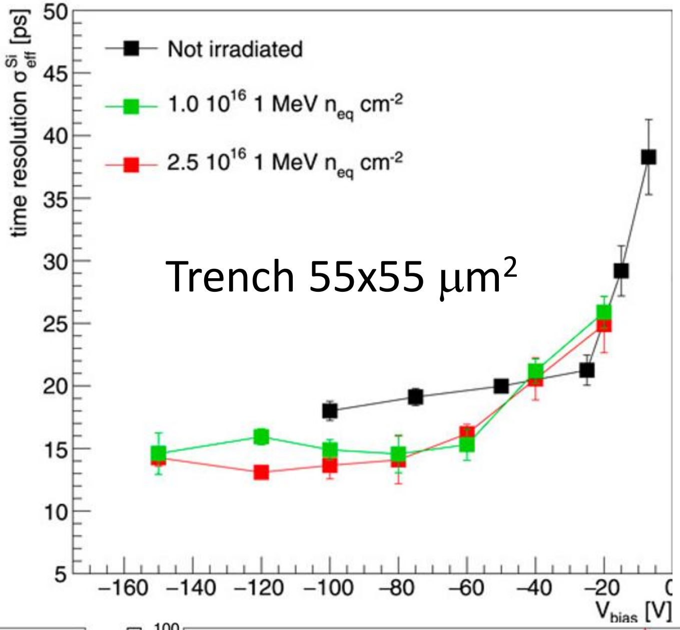
3D detectors - recent

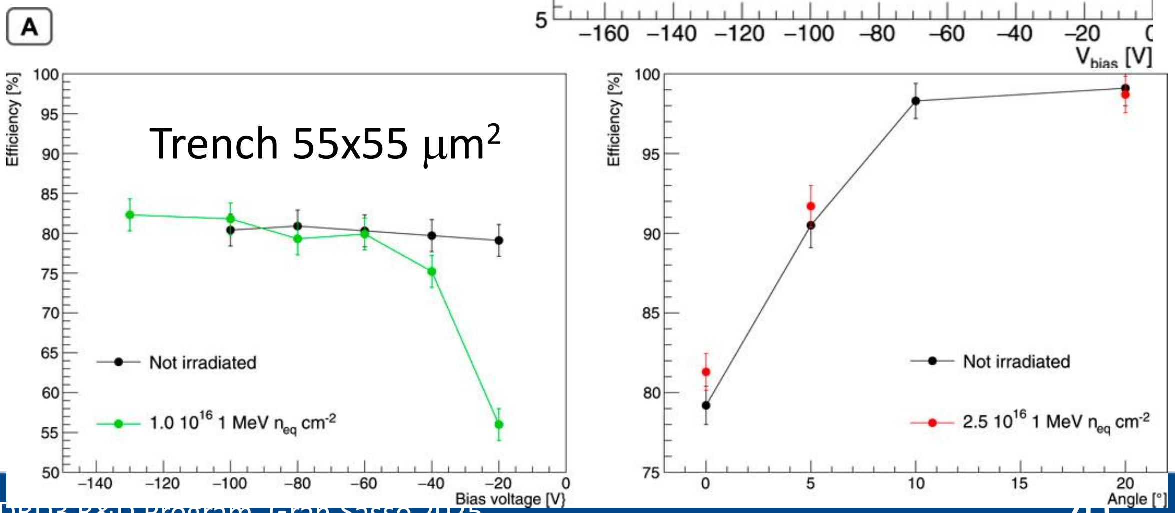
Challenges:

- the capacitance will be much larger (hence noise and the jitter) particularly for thick sensors with large signals (very narrow columns/trenches -> 100:1 at IME) – noise and jitter
- scalability of the processing -> 8”
- clustering issues for small cells
- Both column and trench perform well as prototypes!

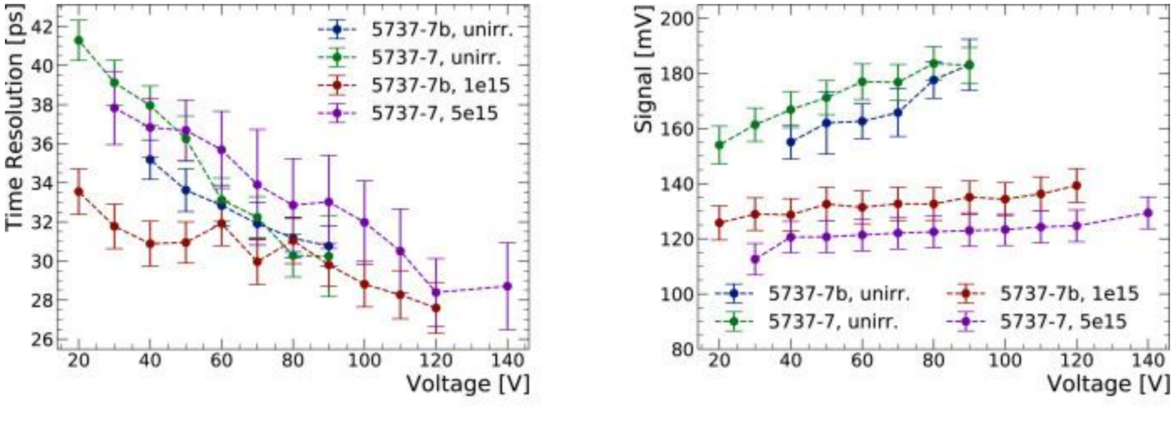
Front. Phys. , 22 April 2024
Sec. Radiation Detectors and Imaging
Volume 12 - 2024 | https://doi.org/10.3389/fphy.2024.1393019



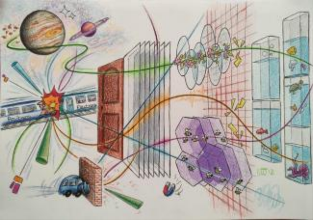




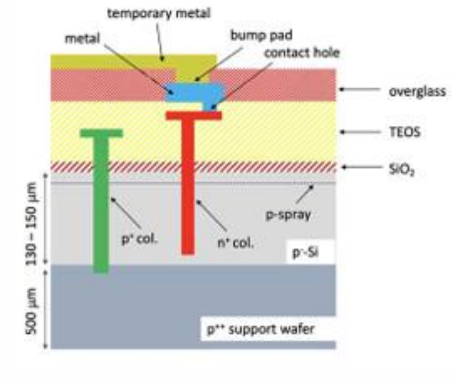
Column 50x50 μm^2

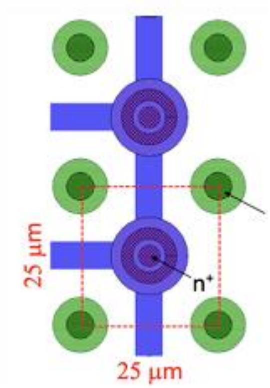


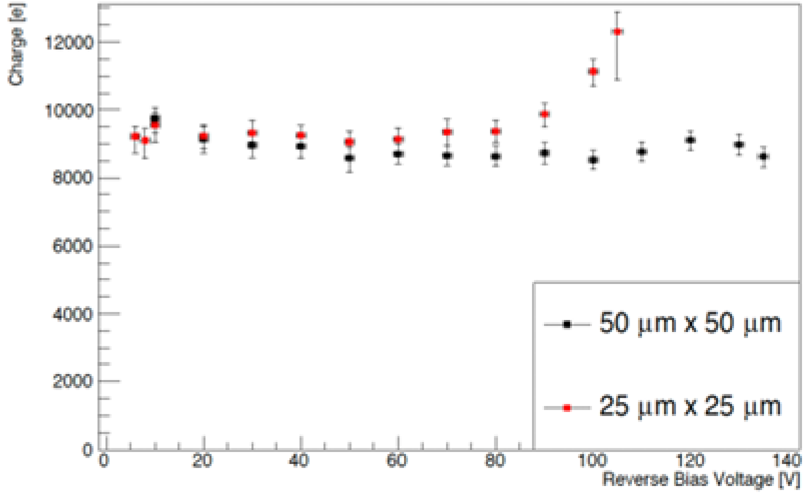
(a) Time resolution (b) Signal



3D with gain – future?





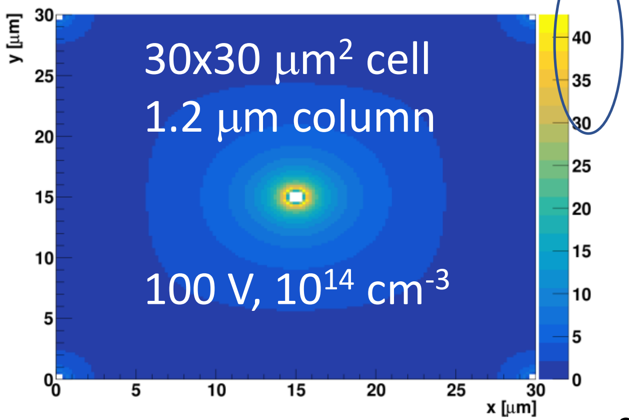


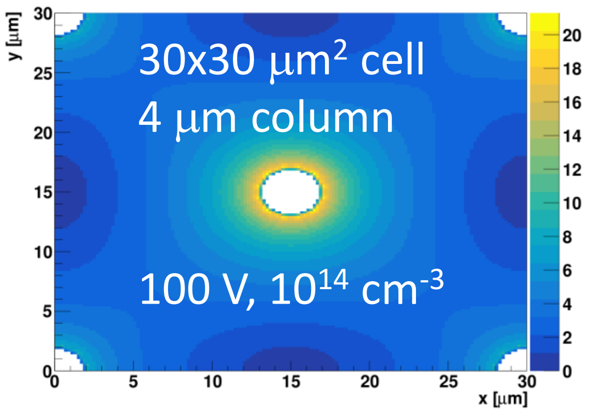
First observation of possible gain at high bias voltages in **FBK** 25x25 μm^2, with 4 μm wide columns

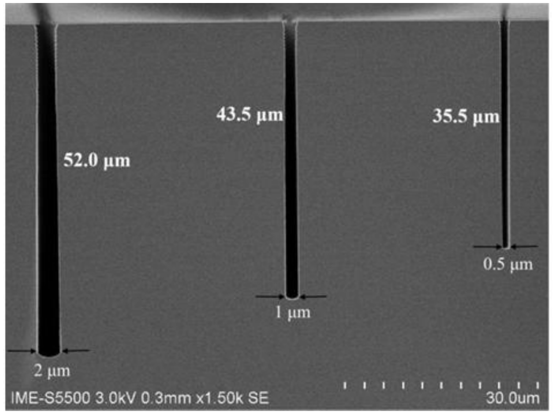
Devices with gain are possible with narrow columns allows use of small cell sizes and thin devices with much less capacitance and dead area. With being thin cluster reconstruction is simpler.

IDEAL DEVICES FOR TIMING

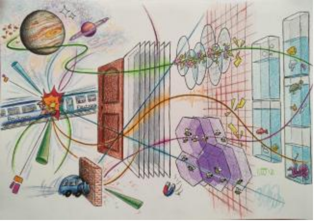
IMECAS - 8" CMOS process with aspect ratio of **>70**







Simulation of 30x30 μm^2 cell with 1.2 μm column

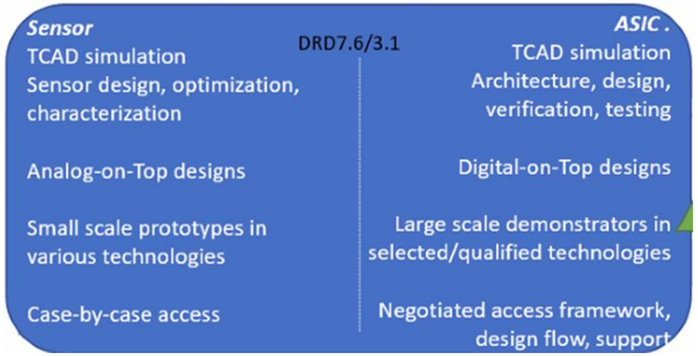


Monolithic silicon sensors (WG1)

<u>Aim</u> is to advance the performance of monolithic CMOS, combining sensing and readout elements, for future tracking applications, tackling the challenges of:

- very high spatial resolution;
- high data rate;
- high radiation tolerance;
- low mass;
- covering large areas;
- reducing power;
- keeping an affordable cost;
- **and ultimately combining these requirements in one single sensor device**.

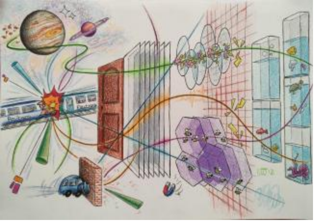
Program shared between DRD3/7



WG1 research goals <2027	
	Description
RG 1.1	Spatial resolution: ≤3 µm position resolution
RG 2.2	Timing resolution: towards 20 ps timing precision
RG 1.3	Readout architectures: towards 100 MHz/cm^2, 1 GHz/cm^2 with 3D stacked monolithic sensors, and on-chip reconfigurability
RG 1.4	Radiation tolerance: towards 10^{16} n_{eq}/cm^2 NIEL and 500 MRad
RG 1.5	Low-cost large-area CMOS sensors

We will have several MPW and engineering runs in 65-180 nm technologies (LF, Tower, AMS, TPSCo)

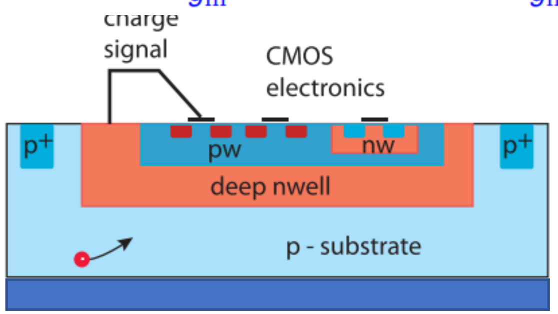
Maurice Garcia-Sciveres and Norbert Wermes 2018 Rep. Prog. Phys. 81 066101
Peric I 2007 , Nucl. Instrum. Methods A 582 876–85

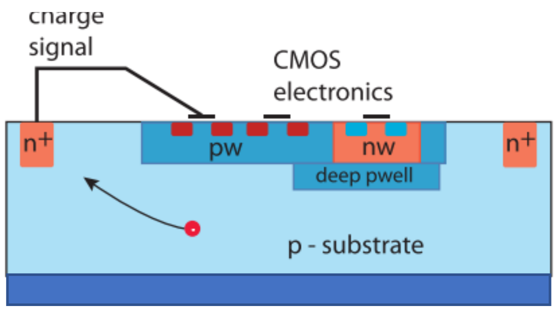


WG1/WP1 – main challenges

LARGE ELECTRODE DESIGN **SMALL ELECTRODE DESIGN**

$\tau \propto \frac{C}{g_m}$, $ENC_{\mathrm{thermal}} \propto \frac{kTC}{g_m}$ compensated by power (g_m)





taken from N. Wermes

- Large electrode: $C \approx 300\,\mathrm{fF}$
- Strong drift field, short drift paths, large depletion depth
- Higher power, slower
- Threshold $\sim 2000\,\mathrm{e}^-$

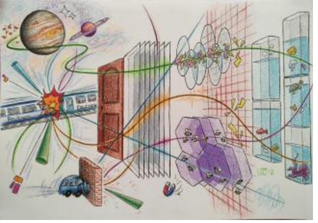
Timing: large jitter and small distortion component - ~100 ps

- Small electrode: $C \approx 3\,\mathrm{fF}$
- Low analogue power
- Faster at given power
- Difficult lateral depletion, process modifications for radiation hardness
- Threshold $\sim 300\,\mathrm{e}^-$

Timing: small jitter and large distortion/landau component ~ 1ns

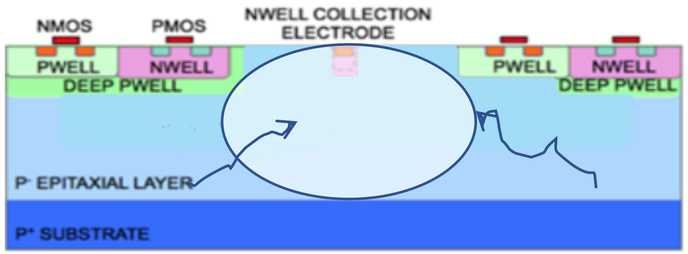
Main challenges (from DRD3 point):

- availability of the active volume (60-80 e-h/μm)
  - epitaxial layer decreases with smaller node processes (350 nm->28 nm). Also, the lateral drift becomes even bigger problem for thin epitaxial layers.
  - few foundries are/will be open to use high resistivity substrate wafer
- costs increase rapidly with the smaller node (MPW runs may not be available)
- allocating the vendors that are open to our needs
  - minimum information about the process which allows for simulation of particle detection in the devices.
  - adaptation of the process
- accessibility to the processes – licensing (process development kits - PDK)
- requirements of additional processing (back side processing), back side metallization …

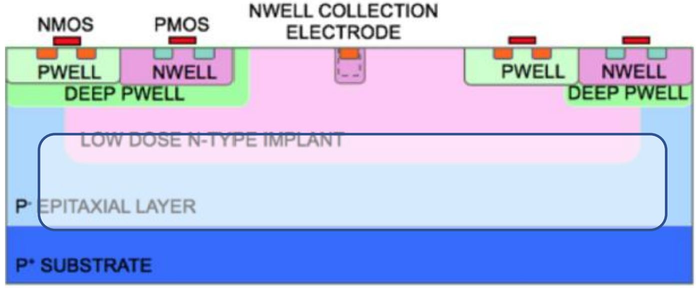


An example of advances in the design MALTA (Tower Jazz 180 nm process)

W. Snoeys et al., Nucl. Instrum. Meth. A 871 (2017) 90.
H. Pernegger et al 2023 JINST 18 P09018

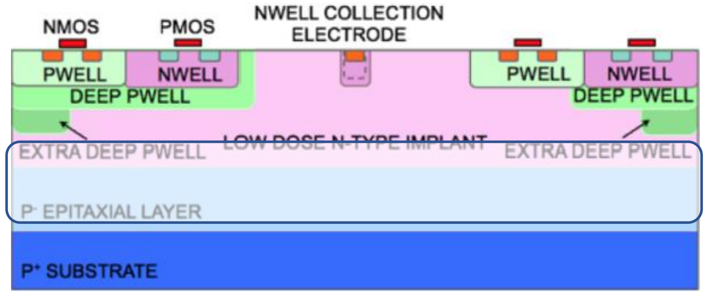


Standard (few V)



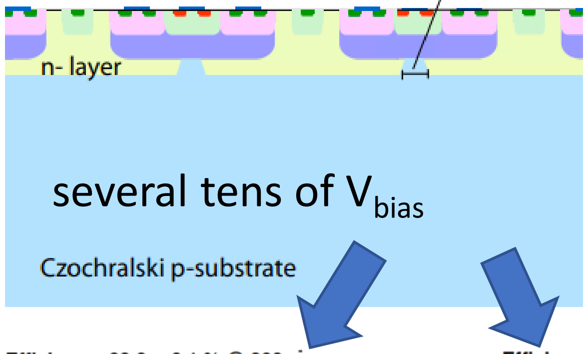
Modified implant (lateral collection)

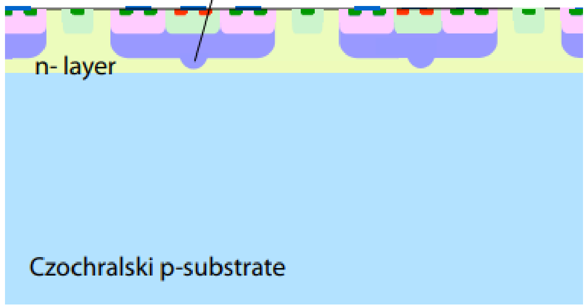
Figure 1. Improved pixel design with n-gap [8]

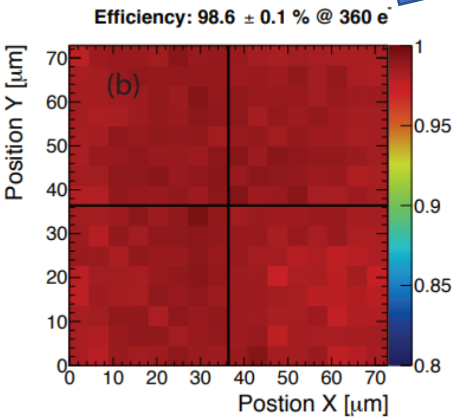


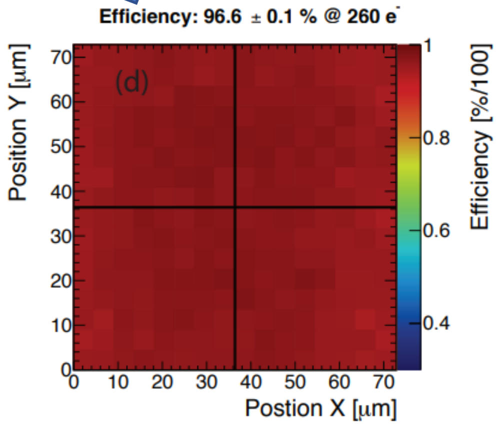
Modified implant – additional notch

MALTA-Cz – high resistivity substrate

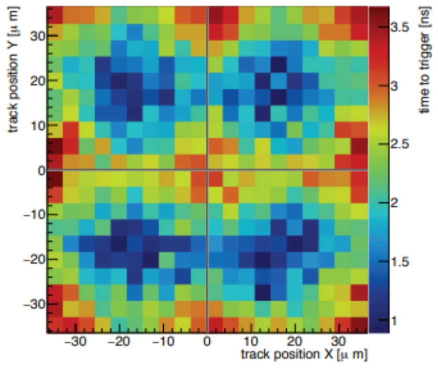




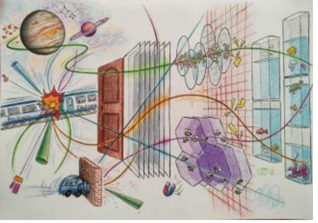




1x10^{15} neq/cm^2., Vsub= -50V, 260 e-



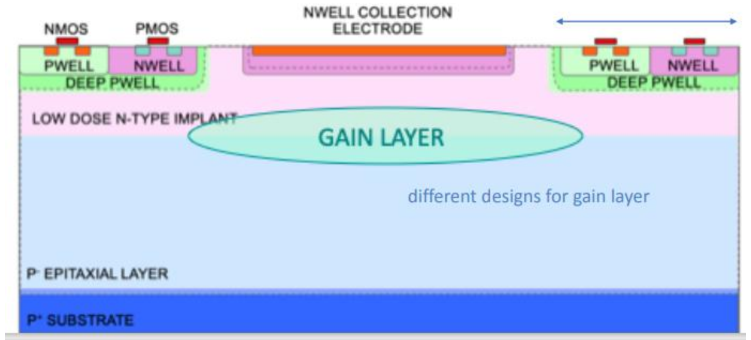
- good efficiency over the pixels even after 3e15 cm^{-2}
- ToA distribution shows differences in signal speed ~2 ns resolution



Future advances – CMOS with gain

- CMOS sensor with gain – can the process be modified in the way that you create an internal gain structure
  - **faster rise time and better S/N - better timing**
  - **better position resolution**
  - **less power consumption**
- Examples of different approaches to reach gain layer multiplication (small electrode design seems more suitable)

Cassia (DRD3 WP1 project)

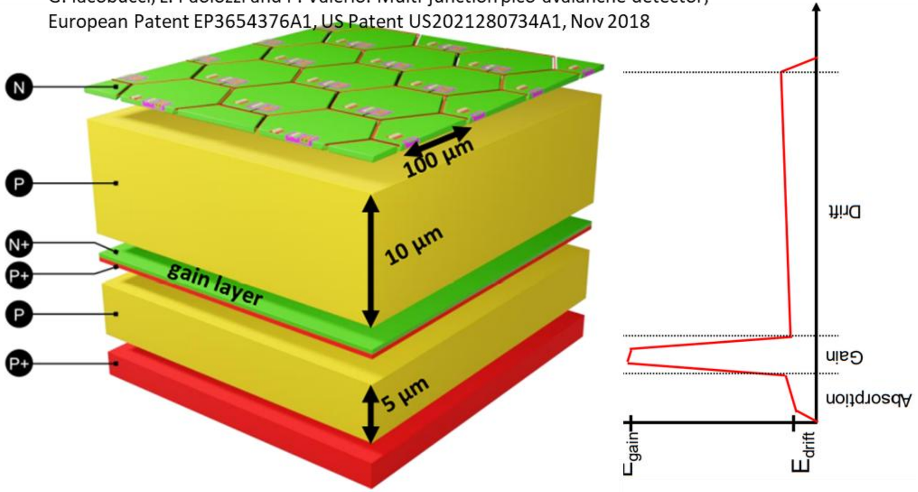


"deep junction" gain layer design

- TJ180 conventional LGAD

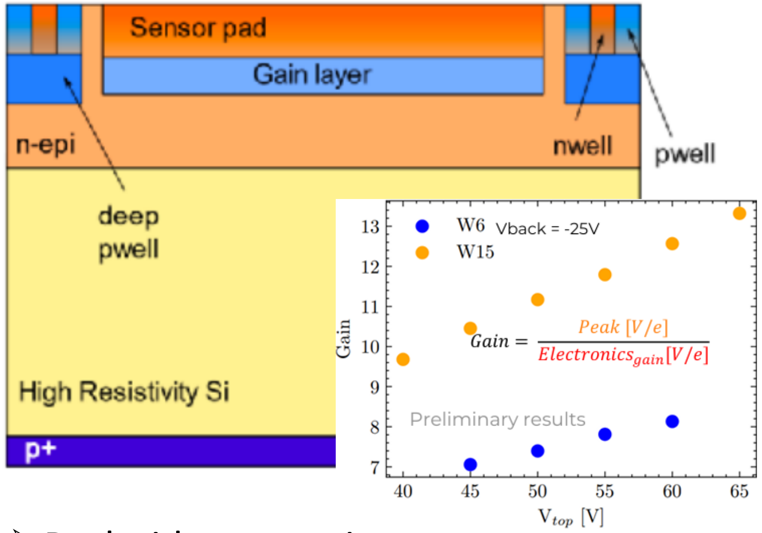
PicoAdd SiGe130 nm (Uni-Geneve)

G. Iacobucci, L. Paolozzi and P. Valerio. Multi-junction pico-avalanche detector; European Patent EP3654376A1, US Patent US2021280734A1, Nov 2018

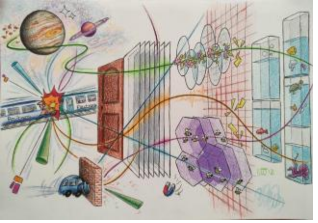


- SiGe bipolar amplifiers – fast (good timing)
- CMOS for digital electronics (monolithic)
- Gain-layer removed from the surface allowing very good spatial resolution without dead area

ARCADIA LF110 nm (DRD 3.1/7.6 – INFN-TO)

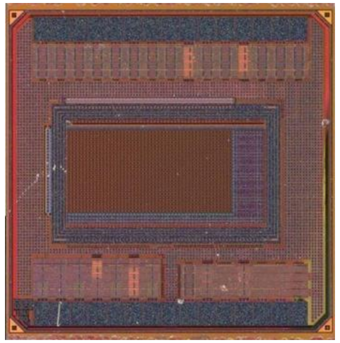


- Back side processing
- High-field grows from the back side – high drift field at the back.
- First results Gain 7-13 – more soon!

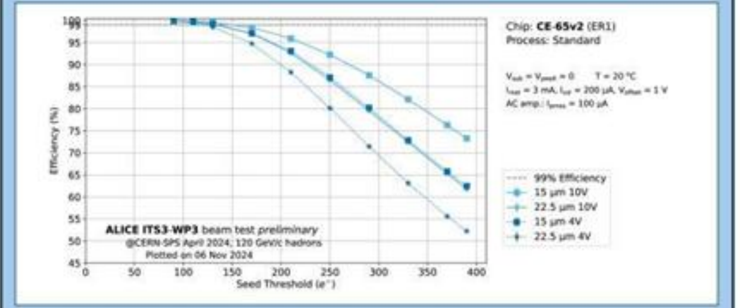


Recent achievements

- CE-65v2 (TPSco 65 nm)
  - 15 µm pixel pitch
  - For ALICE ITS-3

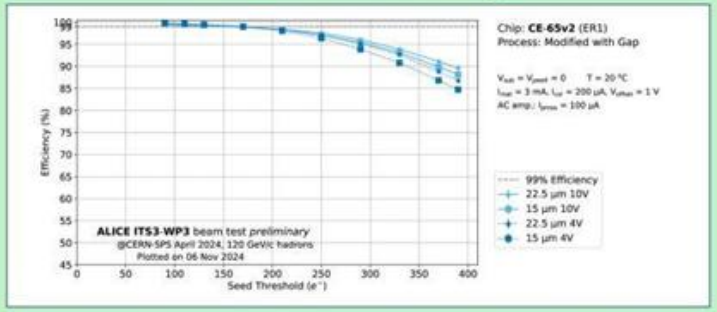


Standard



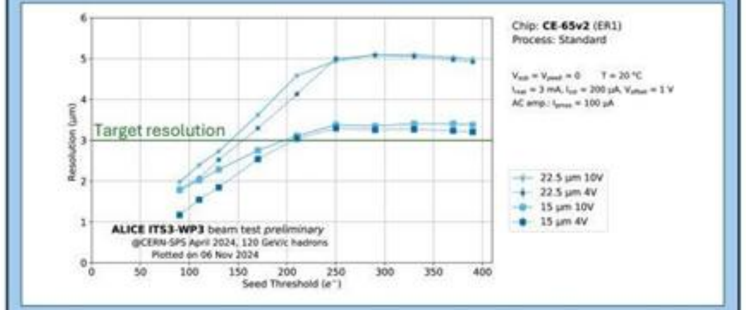
Better efficiency for 10V than 4V

Modified with Gap



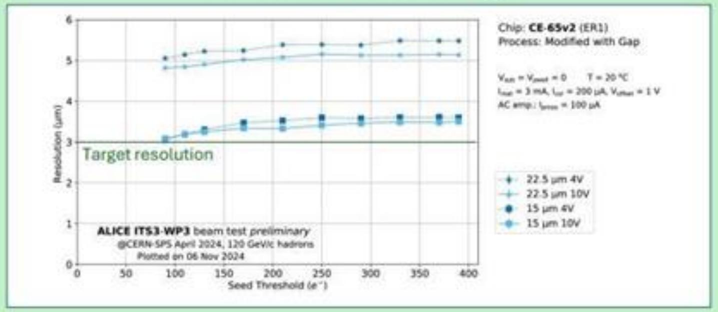
Negligible impact of higher voltage

Standard



< 2.5 µm and < 3.5 µm resolution for 15/22.5 µm pitch at efficiencies > 99%

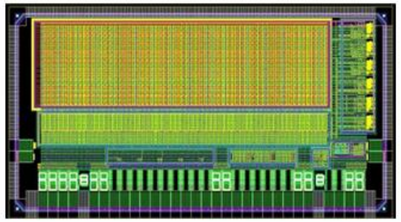
Modified with Gap

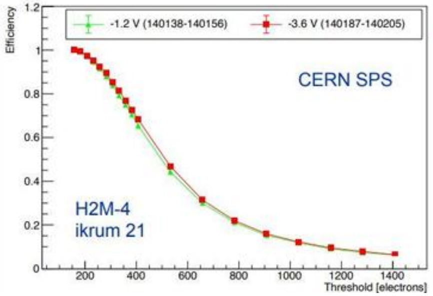


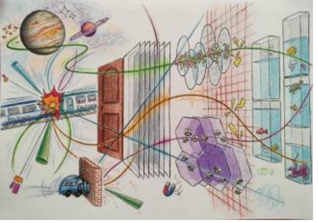
< 3.5 µm and < 5.5 µm resolution for 15/22.5 µm pitch at efficiencies > 99%

11

- H2M (Hybrid-to-monolithic) (TPSco 65 nm)
  - Efficiency 99.6% at a threshold of 144 e- (~5σ noise)
  - Spatial resolution 10.1 µm (expected from pitch)
  - Thinning down to 21 µm without performance loss

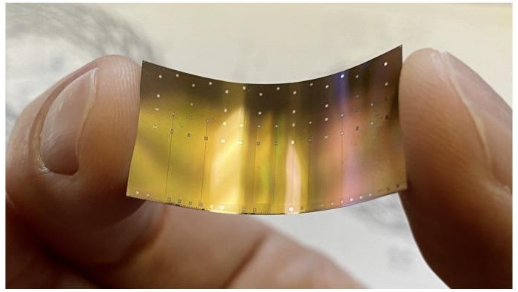


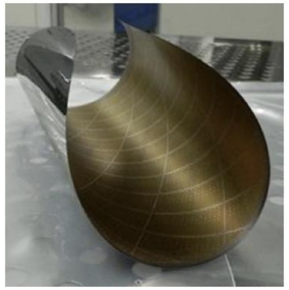


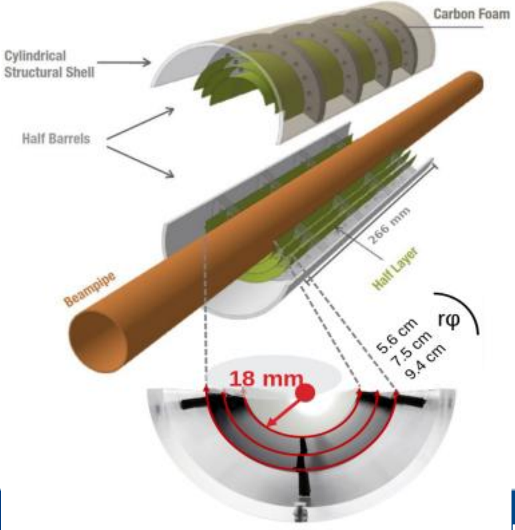


Future advances – scaling up

- Chip-Chip transmission and serial powering (Power&Space)
- Stacking up the wafers – better electronics
- **Large-scale reticle stitching of thinned foldable MAPS**

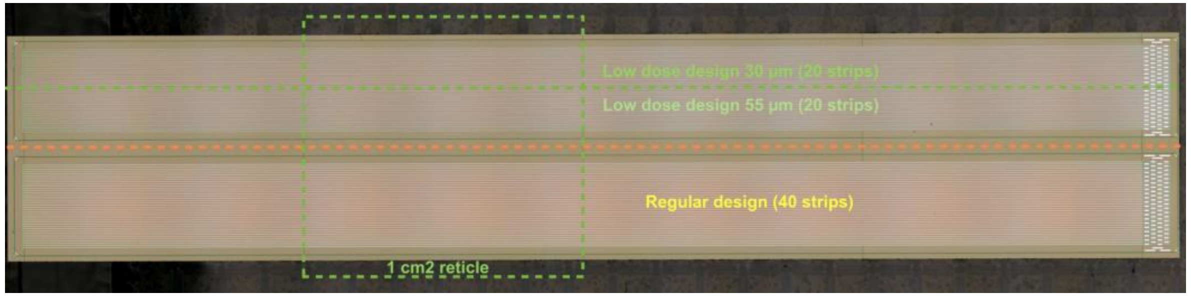




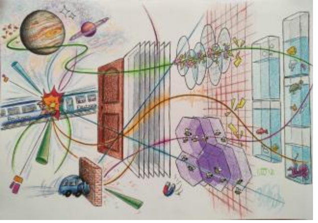


- **Large area strip sensors**
  - Reduced material budget
  - Easier integration
  - Potentially low cost and availability

Monolithic CMOS Strip Sensors for large area detectors (Dortmund, Freiburg, DESY, Bonn)
LFA150 nm - Resistivity of wafer: >2000 Ω·cm



Next step is implementation of the FEI4 like readout per strip



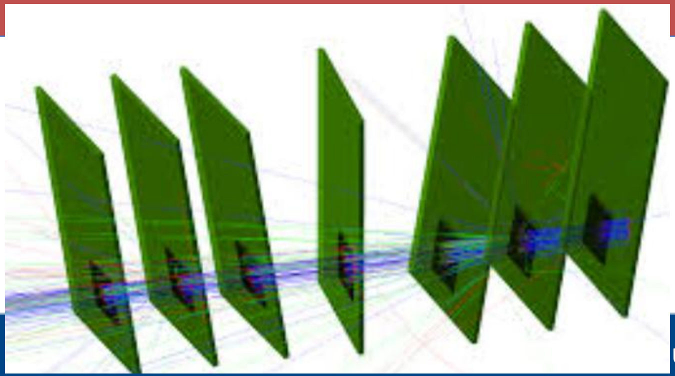
Simulations (WG4)

- Simulations are essential for planning, understanding the performance and designing of devices.
- Simulations WG will provide the tools that could be (easily) implemented to simulate any specific detector or measurement.

“Monte Carlo”
(predicting the performance of complex detector assemblies)

AllPix2 / Garfield++ as the main tool complement by other ones (KDetSim, WF2)

GOALS:
- Implementation of improved semiconductor models (e.g. mobility, impact ionization, trapping …)
- Adaptation of WBS sensors
- Adaptation of dynamic /adaptive E,E_w
- Implementation of common electronics/digitization



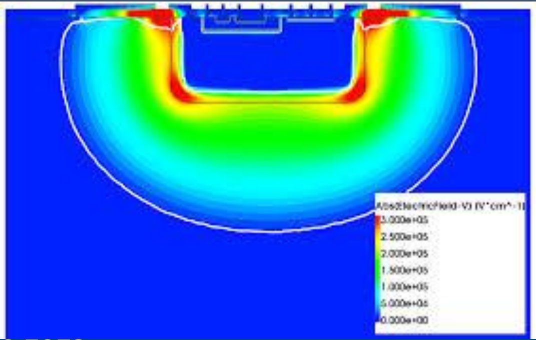
GEANT4

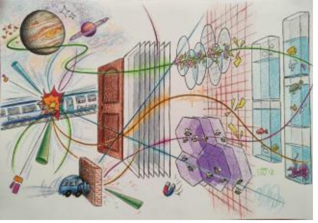
E,E_w

TCAD
(understanding the sensors)

Synopsis, Silvaco …

GOALS:
- Developing and verification of damage models (effective and defect based)
- Establish how to benchmark/evaluate the models against the measured properties (important milestone)
- Improving the TCAD with new findings (WBS, extreme fluences)
- Develop a flexible framework to simulate performance of different processes (CMOS)





Radiation damage characterization and sensor operation at extreme fluences (WG3)

DRD3

- WG covers 3 main areas around radiation hardening (see below)
- WG closely related to all other WGs

WG4: Simulations

Need for simulations in all areas

- on the material level
  Geant4, TRIM, NIEL, DFT, KMC, …
- on the device & system level
  TCAD, AP2, Signal & MC simulators, generic sensor parameter simulations (e.g. Hamburg model)
- extrapolation to extreme fluences
  do models still deliver reliable results?

WG5: Characterization techniques

Need for tools in all areas

- on the material level
  EPR, FTIR, PL, DLTS, TSC, …
- on the device & system level
  TCT, CV, IV, IBIC, test-beams, ….
- extrapolation to extreme fluences
  which tools still deliver reliable results?
  radiation facilities,…

WG3: Radiation Hardening

Radiation hardening of material
understand fundamental damage process, defect formation, impact of defects on device performance (also non-silicon!), material and defect engineering

Radiation hardening of devices and systems
understand device operation with radiation damage, device engineering

Extreme fluences
understand physics, possibilities for operation of detectors

WG6: Non-silicon based detectors

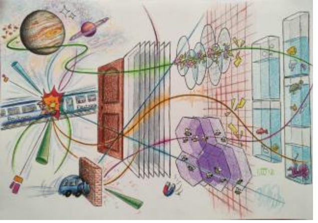
- Material & devices to be studied and understood as silicon in terms of radiation damage in all areas (simulations, material/sensor characterization, tool development)
- Developments for extreme fluence

WG1 & WG2: Silicon based detectors

- Radiation hardness evaluation of all sensors with exposure to radiation (existing and newly developed sensors/sensor concepts)
- Developments for extreme fluence

Synergies with other application areas in radiation fields

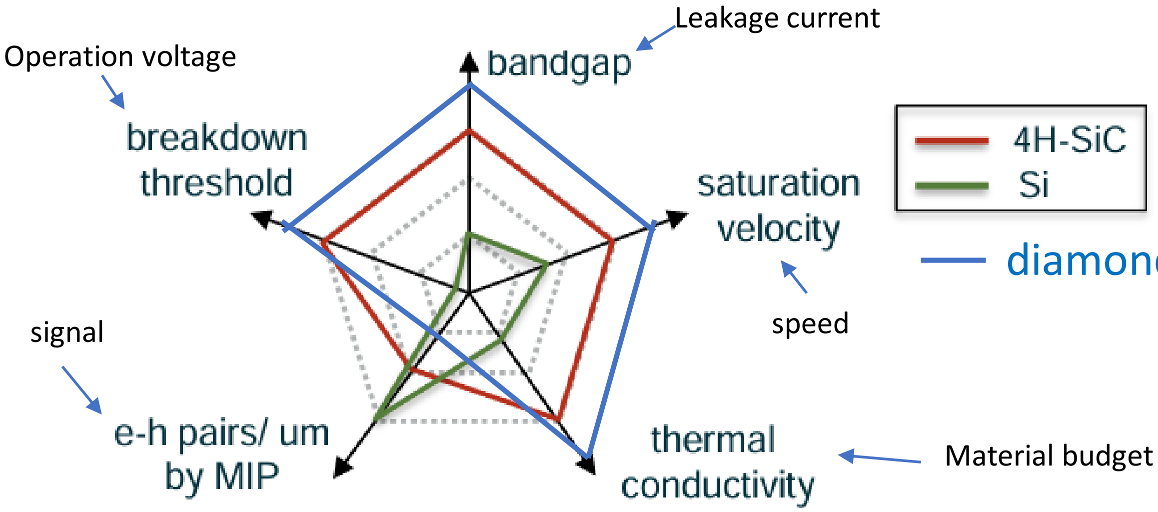
- Detectors for nuclear physics, space applications, fusion, medical applications, …



Other materials – non silicon (WG6)

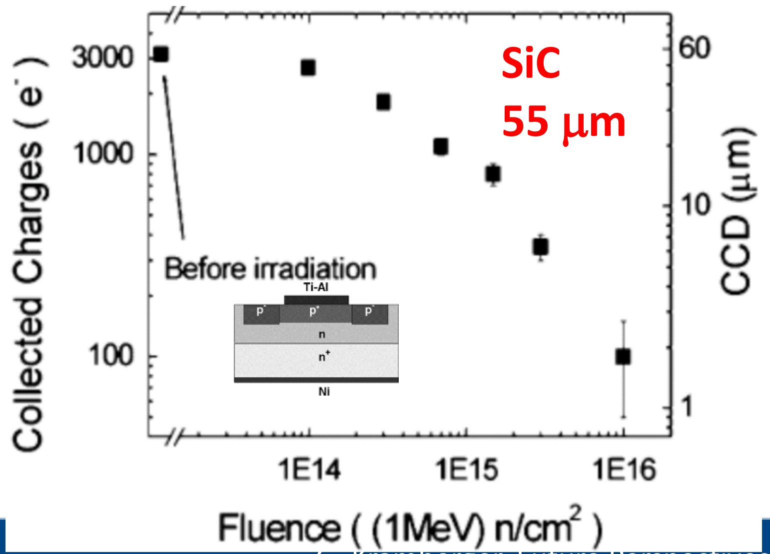
DRD3

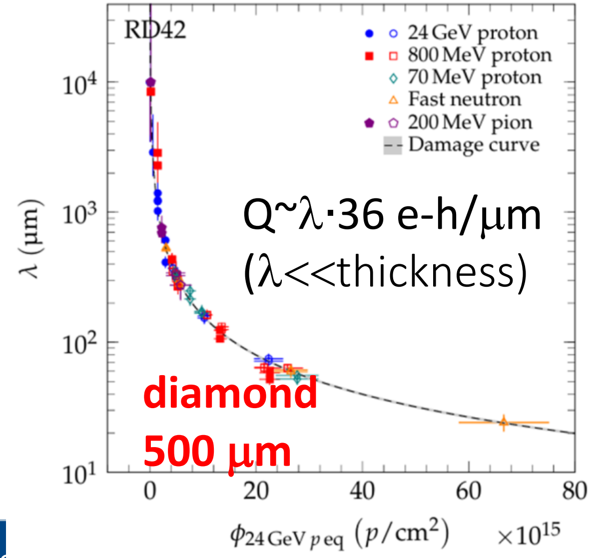
Property	Diamond	GaN	4H SiC	Si
E_g [eV]	**5.5**	**3.39**	**3.26**	**1.12**
$E_{breakdown}$ [V/cm]	10^7	$4\cdot10^6$	$2.2\cdot10^6$	$3\cdot10^5$
μ_e [cm^2/Vs]	1800	1000	800	1450
μ_h [cm^2/Vs]	1200	30	115	450
v_{sat} [cm/s]	$2.2\cdot10^7$	-	$2\cdot10^7$	$0.8\cdot10^7$
Z	6	31/7	14/6	14
ε_r	5.7	9.6	9.7	11.9
e-h energy [eV]	**13**	**8.9**	**7.6-8.4**	**3.6**
Density [g/cm3]	3.515	6.15	3.22	2.33
Displacem. [eV]	**43**	20	**25**	**13-20**



Charge collection for SiC and diamond:

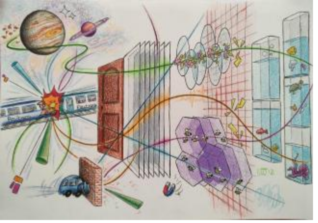
IEEE Transactions on Nuclear Science 53(3):1557 - 1563
DOI:10.1109/TNS.2006.872202





Particle Species	κ
24 GeV protons	1.0
800 MeV protons	1.67 ± 0.09
70 MeV protons	2.60 ± 0.29
25 MeV protons	4.4 ± 1.2
Fast neutrons	4.3 ± 0.4
200 MeV pions	3.2 ± 0.8

Diamond: ~2000-4000 e@10^{16} cm^{-2}
SiC: few 100 e @10^{16} cm^{-2}



Other materials – non silicon

DRD3

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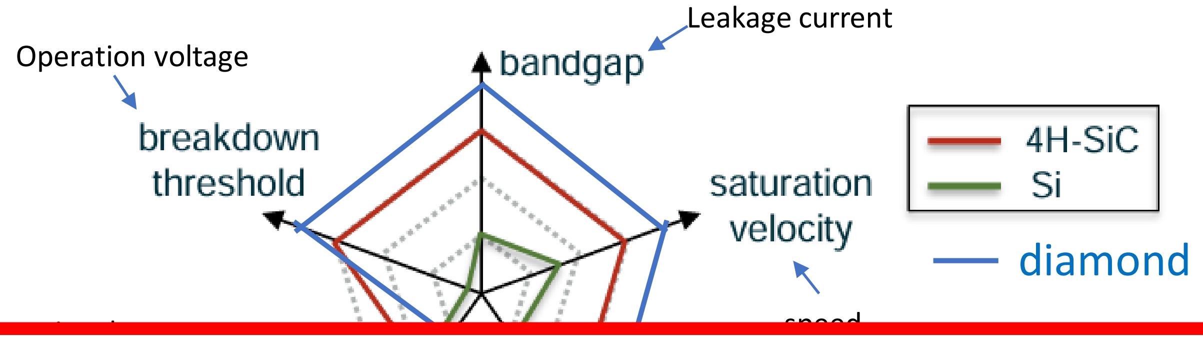
v_{sat} [cm/s]	$2.2\cdot10^7$	-	$2\cdot10^7$	$0.8\cdot10^7$
Z	6	31/7	14/6	14

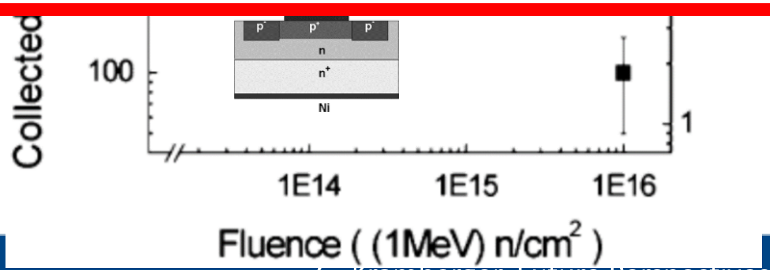


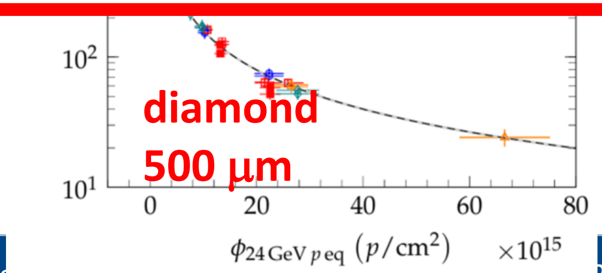
Other semiconductor materials **are not more radiation hard in terms of charge collection**. Due to band-gap, however, they have low leakage current.

Why are they still considered for high radiation environments?

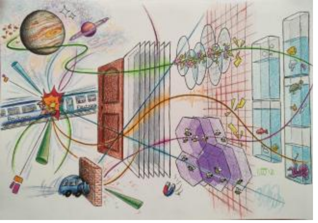
- Device engineering – 3D diamond sensors !
- Gain devices – SiC LGAD with possibly lower dopant removal!

IEEE Transactions on Nuclear Science 53(3):155
DOI:10.1109/TNS





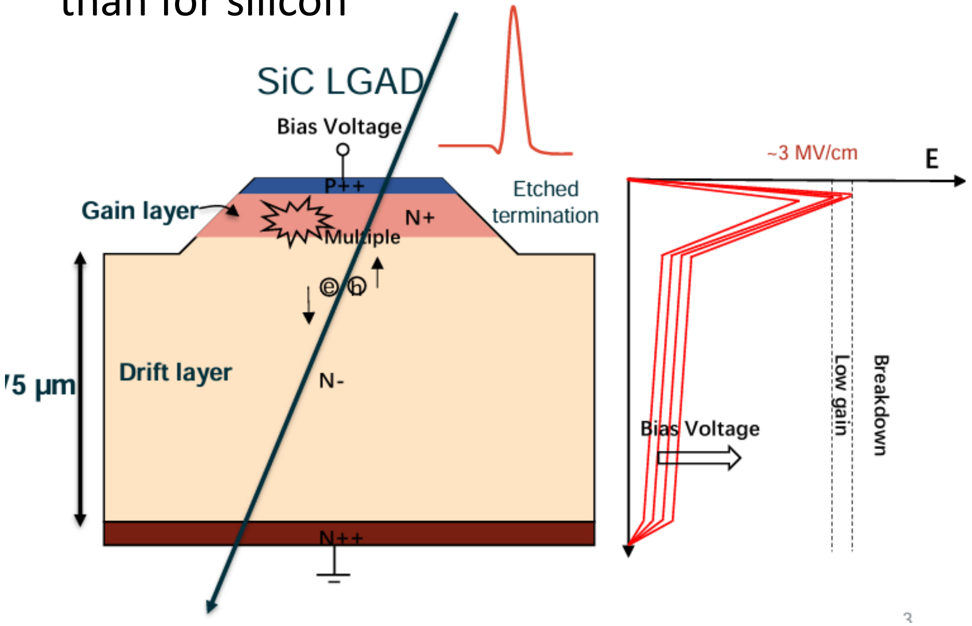
Diamond: ~2000-4000 e@10^{16} cm^{-2}
SiC: few 100 e @10^{16} cm^{-2}

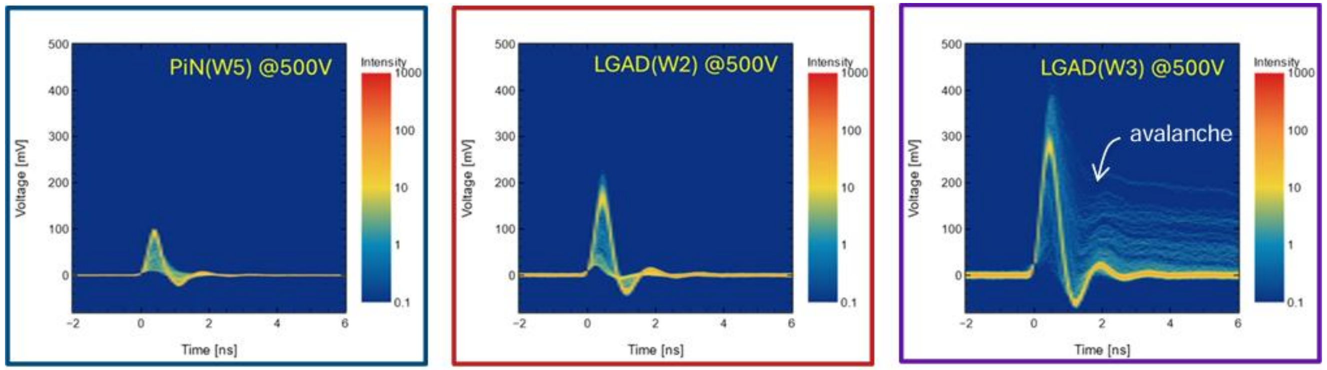


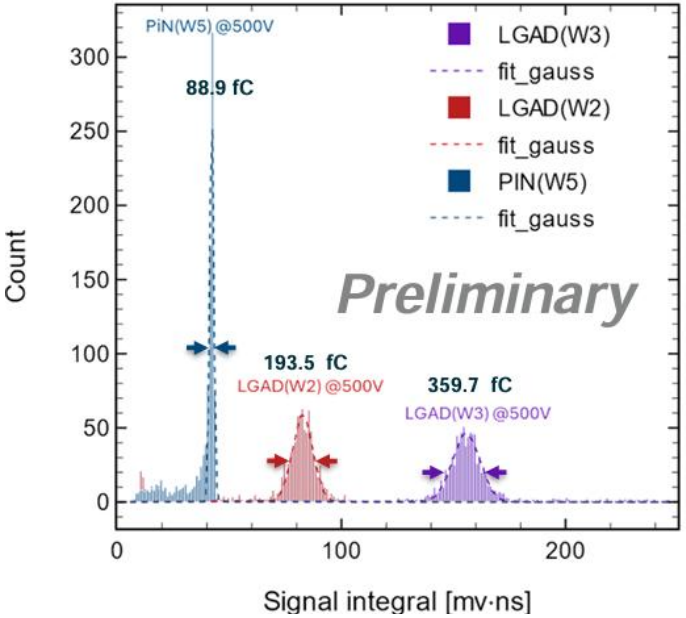
Silicon Carbide LGADs

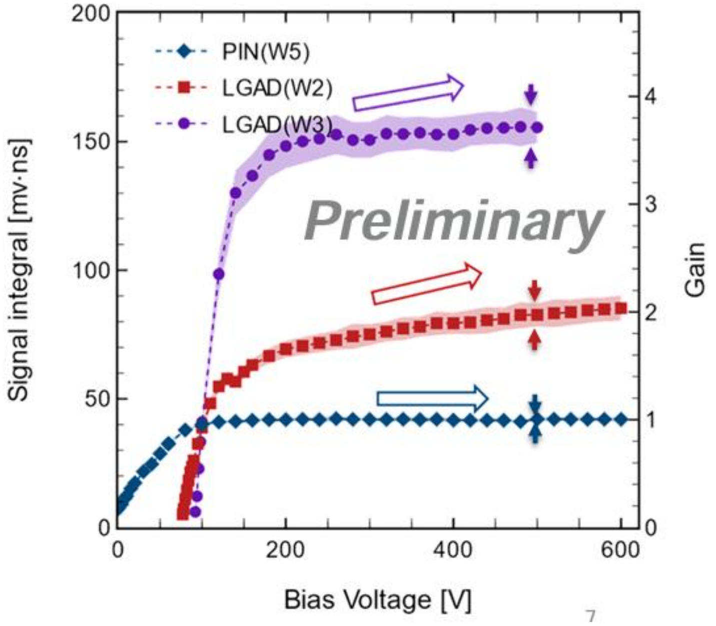
LBNL & NCSU

Quite different processing – but wafers are available
- not the same implant depth as for Si)
- Apart from JTE and **bevel-ed** edge termination
- Doping levels of gain layer an order of magnitude higher than for silicon





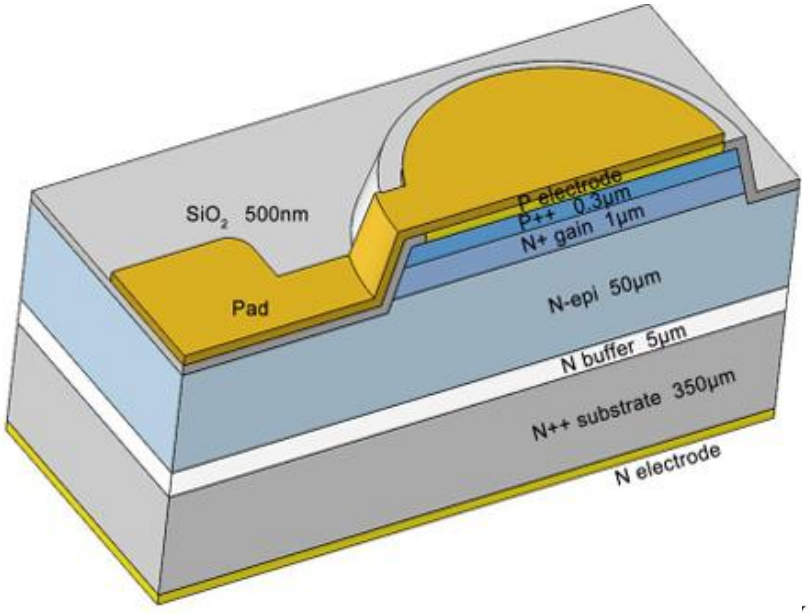


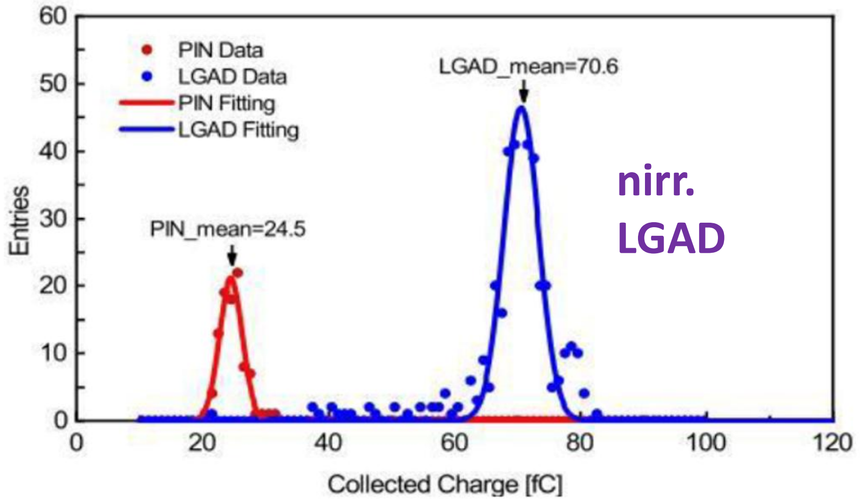


Note – impact ionization is larger for holes than for electrons in SiC (p^{++}-n^{+}-n device)

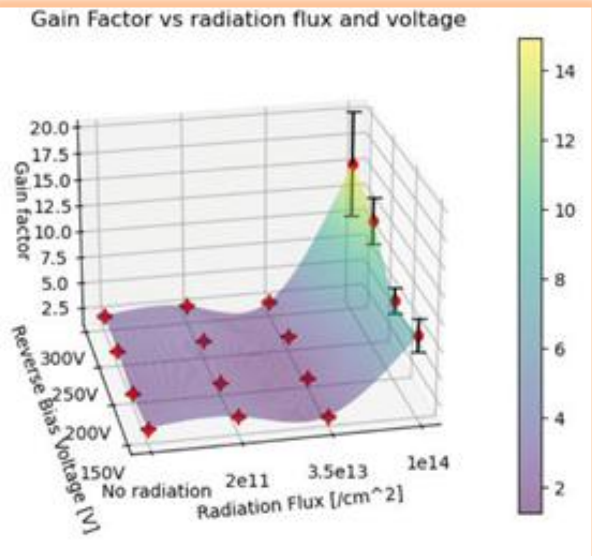
SiC - irradiated sensors

Similar results obtained for SICAR – production It seems that the irradiation **increases the dopant concentration in gain layer!**



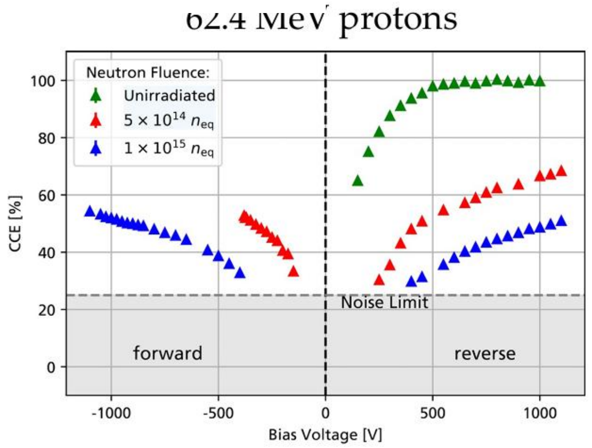


10.1109/TNS.2024.3471863

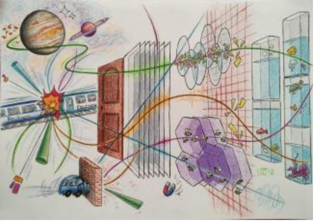


Gain increase with irradiations!

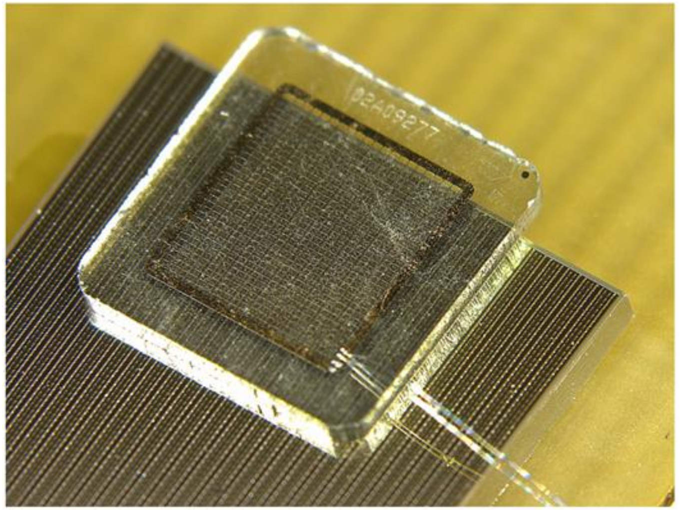
Forward operation possible – but still lower CCE (not LGAD)



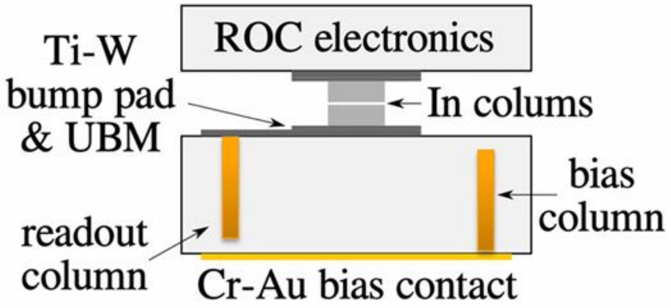
Charge multiplication also observed after operation in forward bias in irradiated SiC detector (not LGADs).
Lots to be understood, but very encouraging first results!

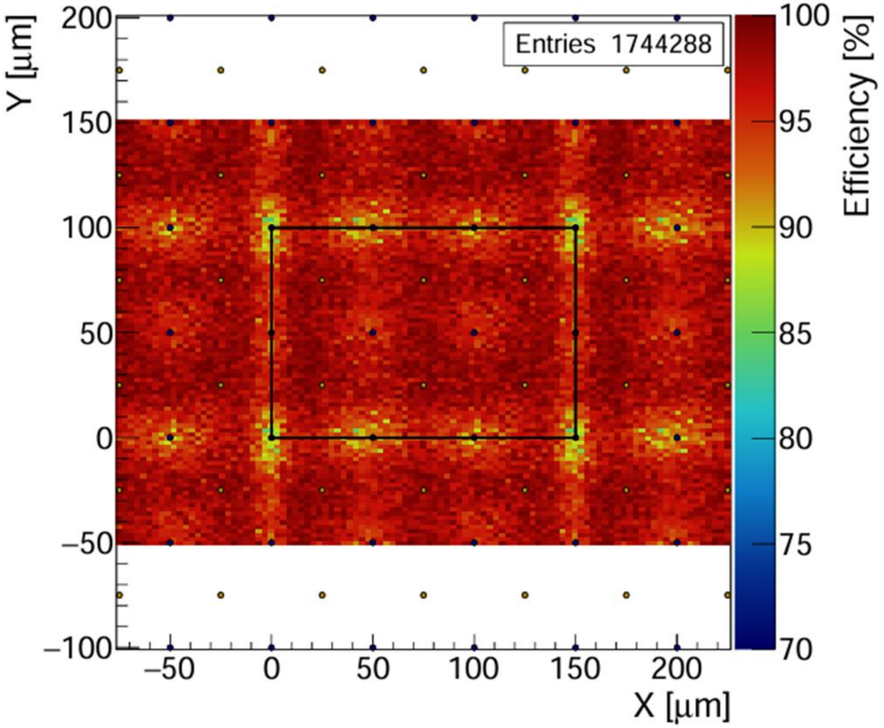


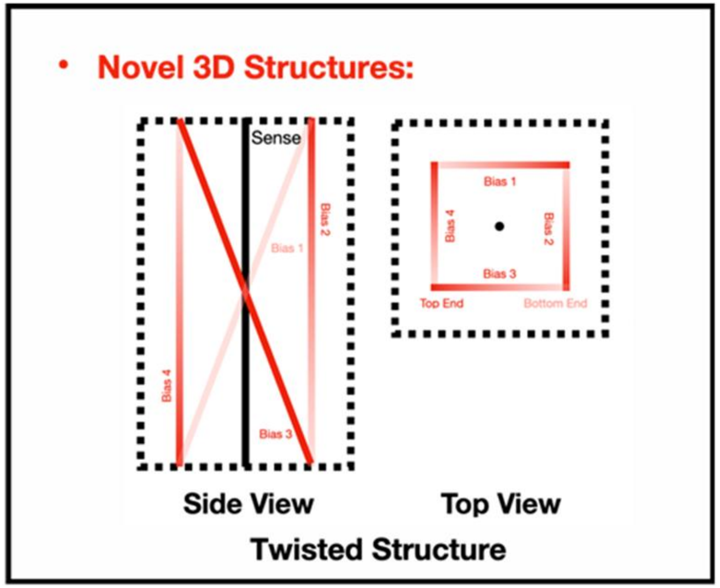
Diamond – 3D detectors

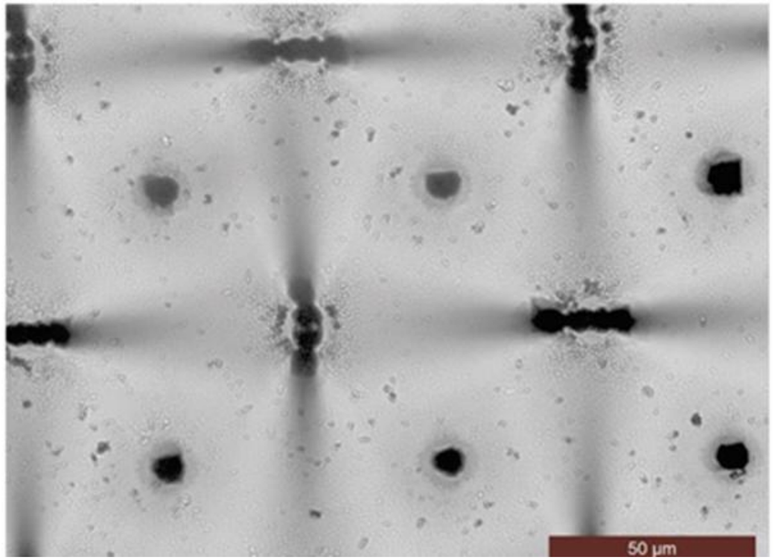


3D diamond detector connected to CMS pixel ASIC



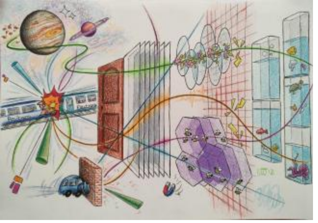






3D electrodes made with laser (graphitization when focused light pulls through the diamond – slow)

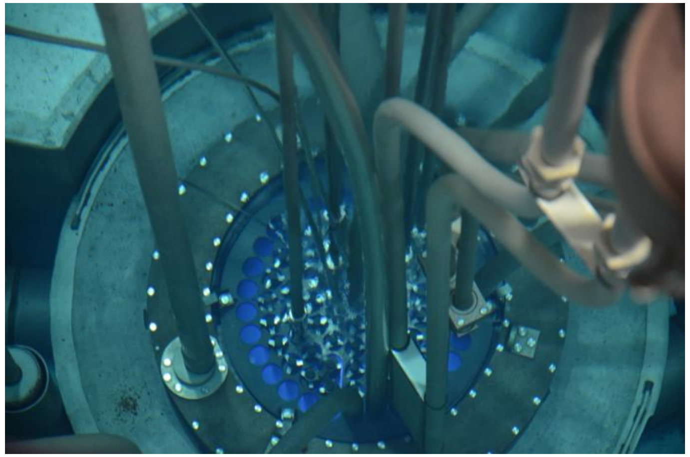
Twisted structure would improve timing performance and reduce the impact of the pCVD grains.



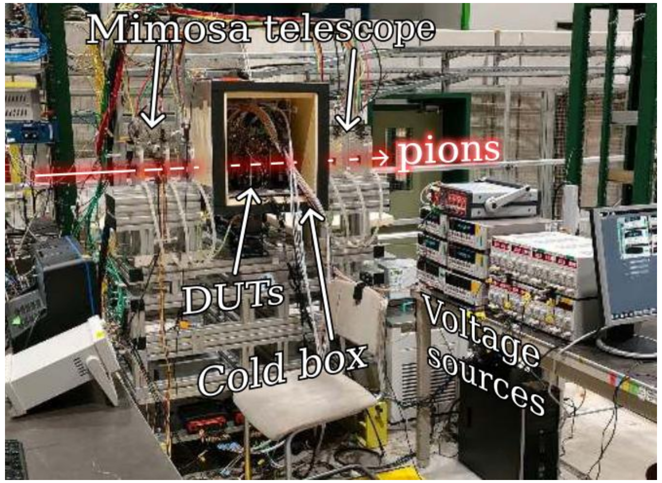
New techniques, common infrastructures, and characterization facilities (WG5)

- **WG lines of actions:**
  - Development/improvement/diffusion of **methods and techniques for characterizing sensors** (those for defects spectroscopy DLTS,TSC, EPR…. as well those for characterization TCT, Beta-scope…)
  - Joint research activities for the **delivery of common infrastructures for sensor testing** (common sensor readers, jigs, test fixtures,…)
  - Promoting the **use of unique characterization facilities.**

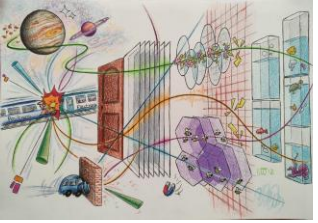
Irradiation facilities (e.g. JSI reactor)



Test beam activities (CERN/DESY)



fs high intensity laser facilities (ELI Prague, SGIKER Bilbao…)



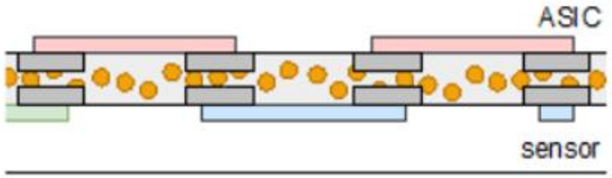
Interconnections (WG7)

WG Scope: Sensor mechanical and electrical integration to **low-mass tracking + vertexing systems:**

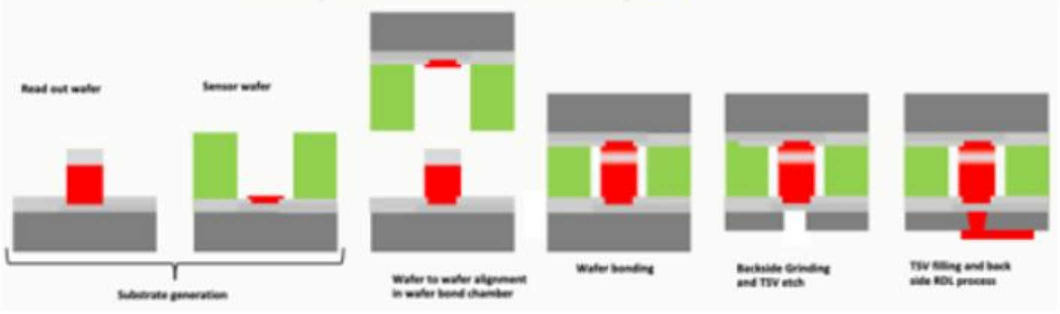
- **Post-processing** (plating/UBM)
- Sensor to frontend **hybridisation**
    - **In-house single-die**
    - **3d integration (wafer-to-wafer)**
- **low-mass flex PCBs / module integration**

Plating

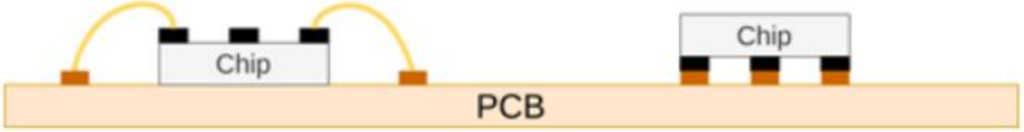
In-house hybridisation

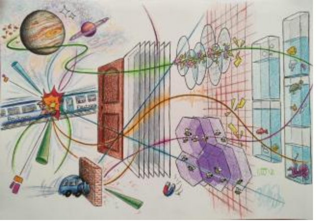


Wafer-to-wafer bonding



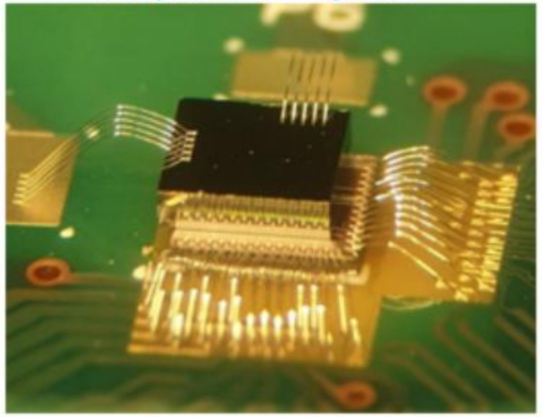
Module integration



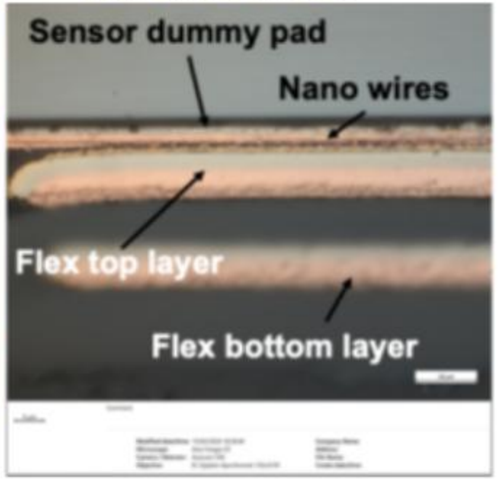


In house bonding and wafer-wafer (WG7)

Timespot1 ACF hybrid



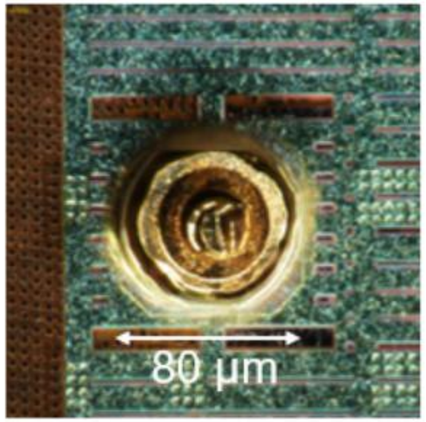
Nanowires on flex



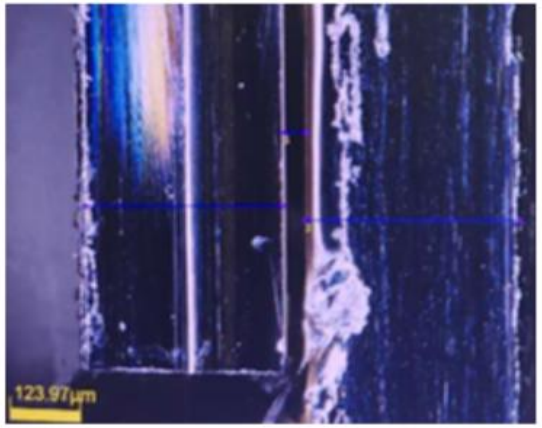
In-house hybridization, module integration

- Exploring innovative **bonding** methods, adapted to the requirements of various projects
  - **Conductive adhesives (ACF / ACP)**
    → good results for <1cm^2 devices and >~50 μm pitch
  - **Nano wires**
    → successful bonding of MALTA2 to flex
  - **Gold studs** + epoxy
    → successfully used for large (>100 μm) pitch
    → developed **low-temperature bonding process** suitable for **irradiated samples**

Gold-stud on ALTIROCA



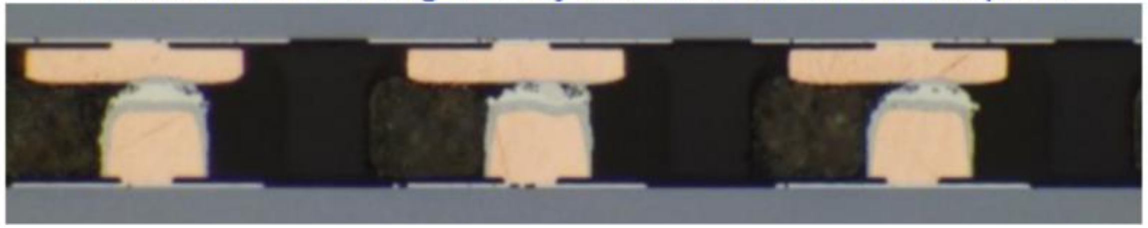
ALTIROCA + irradiated LGAD

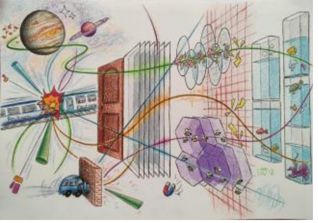


Wafer-to-wafer bonding

- Target: ultra-thin hybrid detectors with TSV
- Pilot project U Bonn / IZM: passive CMOS sensors + Timepix3

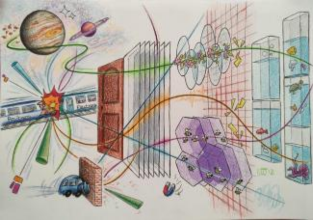
Wafer-to-wafer bonding of daisy-chain test wafers with Cu pillars





Conclusions

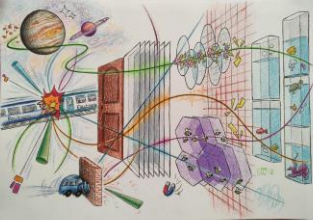
- DRD3 is a large collaboration under which umbrella future R&D on semiconductor particle detectors will take place.
  - The **strategic funding of the activities (HEP detector R&D) should be** supported by funding agencies – that is yet to materialize
  - WP project proposals are being formed and shaped – lots of interesting projects
  - The collaboration will have common fund from which many smaller R&D projects will be supported also for synergies with other fields and Blu-Sky R&D
  - More information can be found on drd3.web.cern.ch
- CMOS is going to dominate the large scale applications in the future
  - CMOS **with gain** is likely to become the dominant field of research
  - A way to mitigate the distortion/weighting field component to time resolution will be critical to reach simultaneously superb position and timing resolution
  - One of the main obstacles will be availability of epitaxial (active) layer for small node processes
  - Large scale passive sensors are choice for large area strip & pad detectors



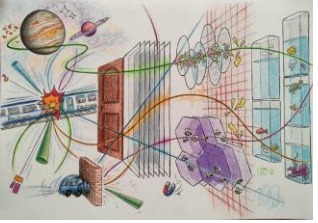
Conclusions

DRD3

- Hybrid detectors
  - Trench and Column 3D detectors remain the choice for superb time and position resolution for the most radiation harsh environments
  - LGADs are the choice for moderate fluences and increase of radiation hardness remains the task for the future
  - LGADs will dominate the conventional strip detectors
  - 3D sensors with gain may be the ultimate solution for superb position and time resolution
- WBS semiconductor detectors
  - SiC LGADs may be a solution for high radiation environments if the gain layer doesn’t disappear inspite of large trapping of charge carriers
  - 3D diamond detector can be choice for niche applications in high radiation hard environments. New design with inclined electrodes can offer improved performance.
  - GaN is also progressing – first runs are expected
- Interconnections and new characterization techniques



Backup/additional slides



WG8- Dissemination and outreach activities

Disseminating knowledge on solid-state detectors:

Organize DRD3 schools for young post-doc and Ph.D. in:
- TCAD, FPGA, GEANT
- Laboratory measurements, TCT

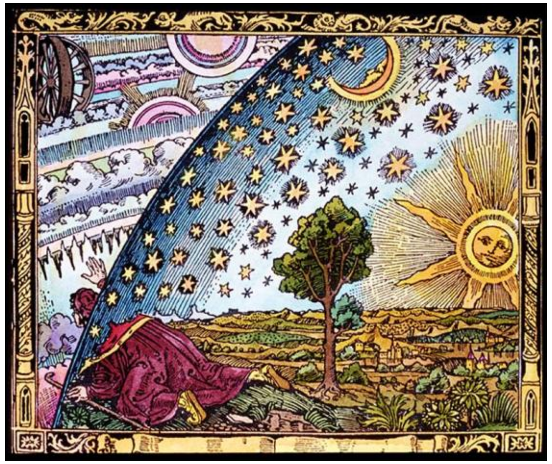
Participation to instrumentation schools
- In specific locations (CERN, FNAL…)
- On specific topics (Allpix2, TCAD, setups..)

Share knowledge of measurement techniques
- Device characterizations, such as IV, CV
- Transient studies using TCT, beta telescopes
- Handling and measurements of irradiated sensors
- Intra-DRD3 groups training

Dissemination of the DRD3 activities:

Organize the DRD3 website (drd3.web.cern.ch)
- Point of entry to DRD3
- Link to results, meeting, etc
- Opportunities: conferences, stages
- Documentation (how to do XYZ…)

Present DRD3 work at conferences
- Opportunity for young researchers
- DRD3 activities documented in printed papers



TPA – 3D diamond