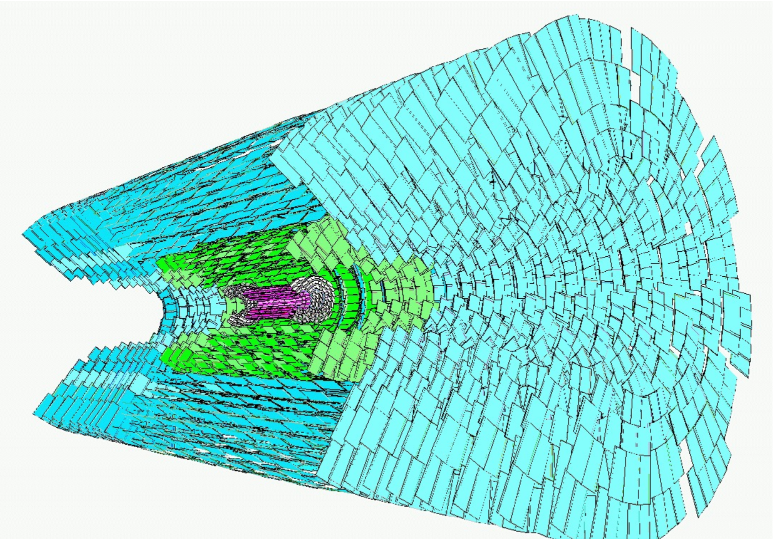
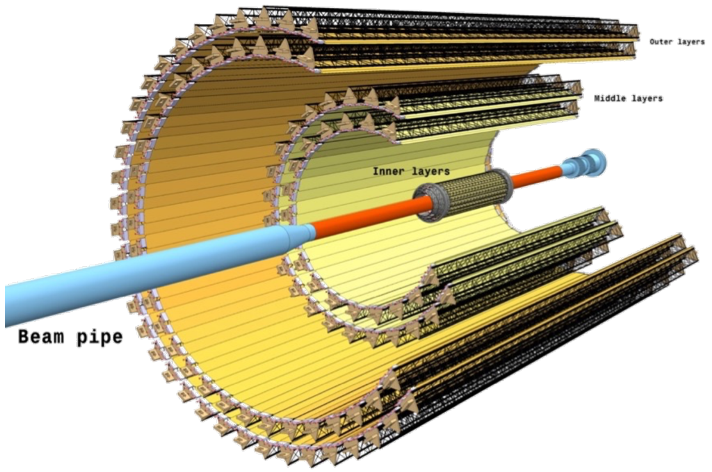
Silicon Trackers for High Energy Physics

EIRO Forum School 2021 – Duccio Abbaneo





Acknowledgements: Doris Eckstein, Petra Riedler, Michael Moll, and many others…

Outline

- What is a tracker?
- Silicon sensors
- The ingredients of a Silicon Tracker for HEP
- Examples of present and future solutions

A particle detector

Exploit interactions of particles with matter, in the right sequence!

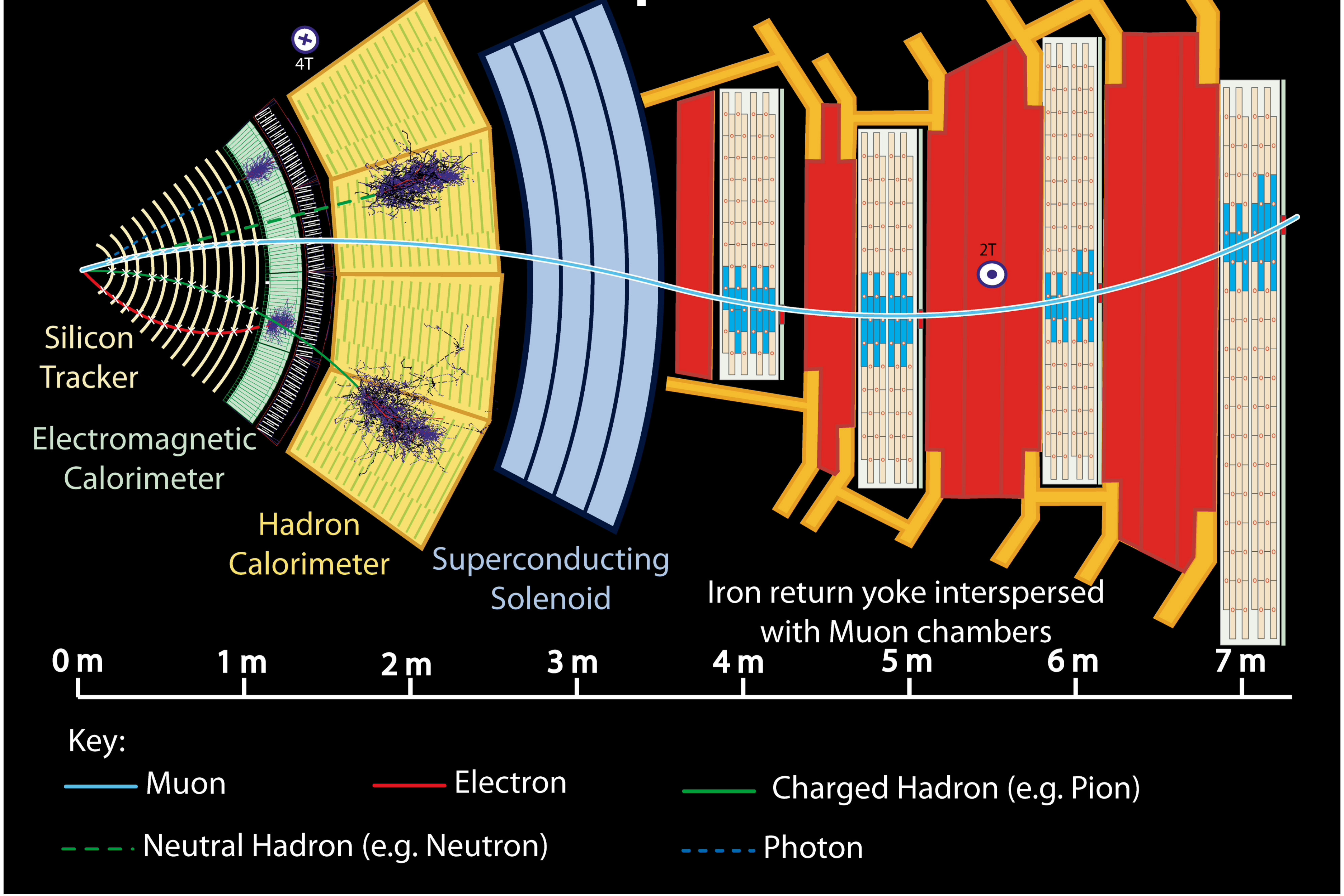
Ionisation in a high-granularity detector
In magnetic field, to measure momentum
Minimize amount of material
Reconstruct trajectories of charged particles
The TRACKER

Bremsstrahlung and photon conversions
Absorb electrons and photons with high Z materials
Measure energy: ELECTROMAGNETIC CALORIMETER
Hadronic showers start, but are not contained ($\lambda_I >> X_0$)

Absorb all hadrons and measure their energy
HADRON CALORIMETER
Large depth (1-2 m) of heavy material

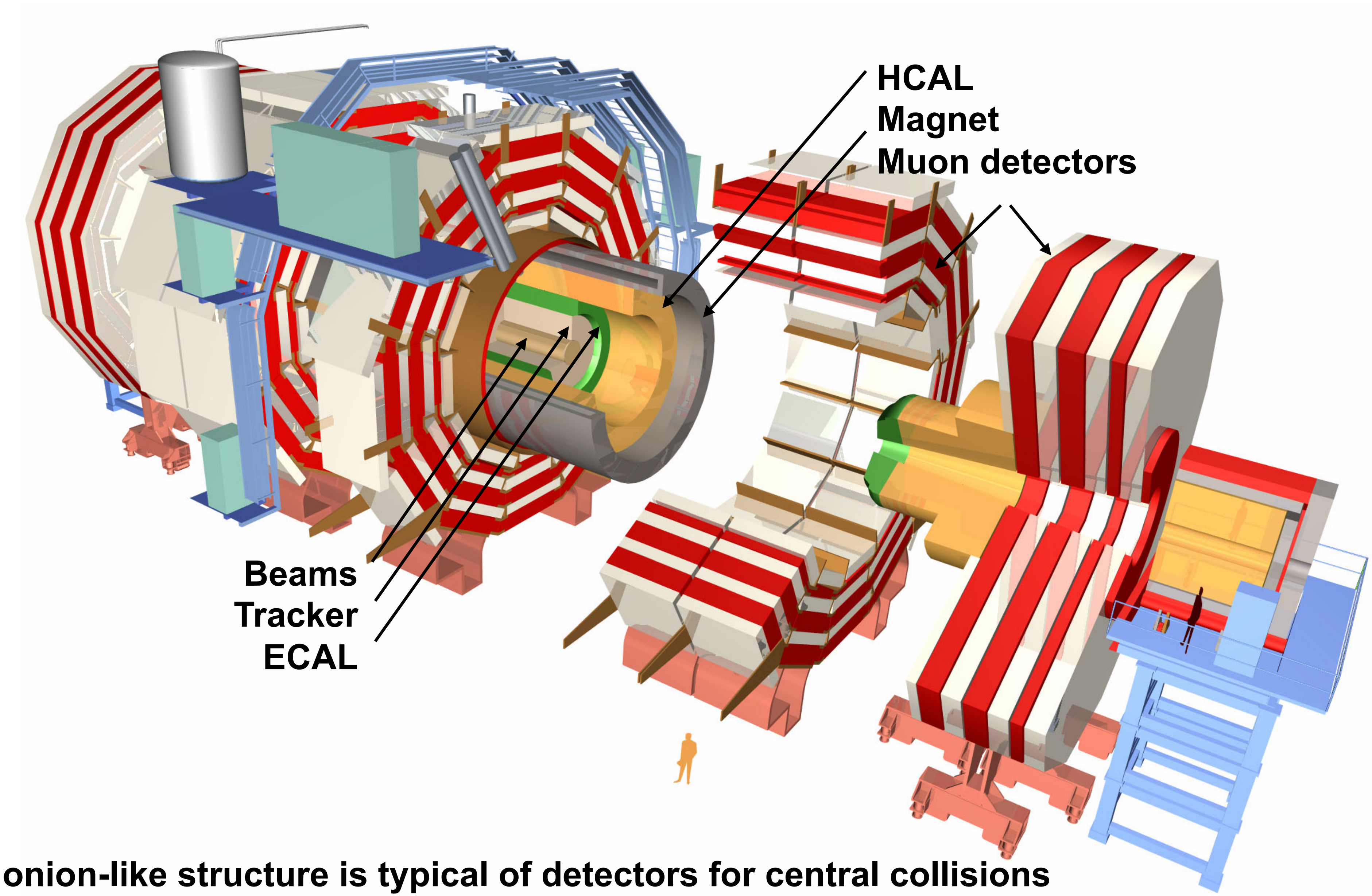
External detectors for outgoing muons
MUON DETECTORS
Often large-area gas detectors (ionisation)
Sometimes interleaved with iron to contain the magnetic field

Example: CMS



Dimensions are dictated by the energy of the particles that we want to measure, and the required precision

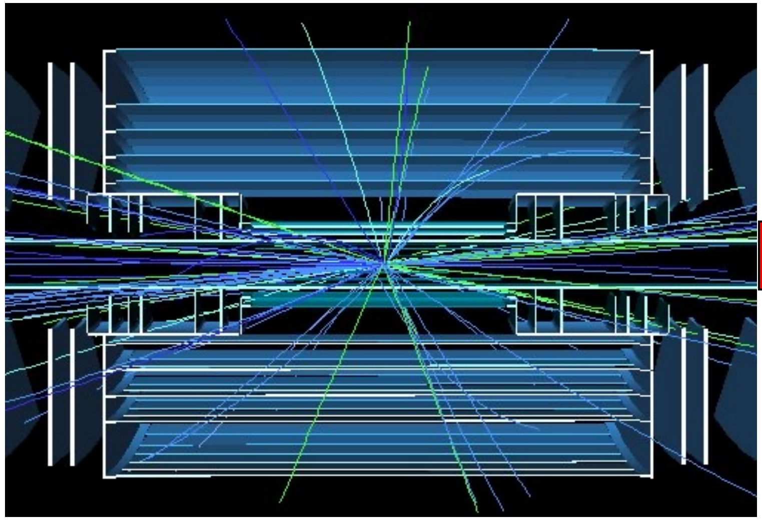
CMS 3D model



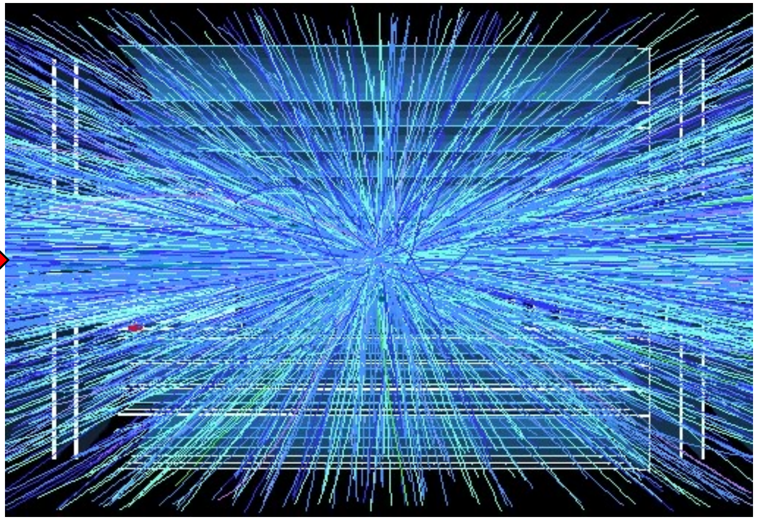
The onion-like structure is typical of detectors for central collisions

What a Tracker does

- **Find <u>the tracks</u>**
  - Extremely challenging in high-density environment
  - Huge combinatorics of coordinates to handle
  - Requires high granularity



HLC



High-Luminosity LHC

What a Tracker does

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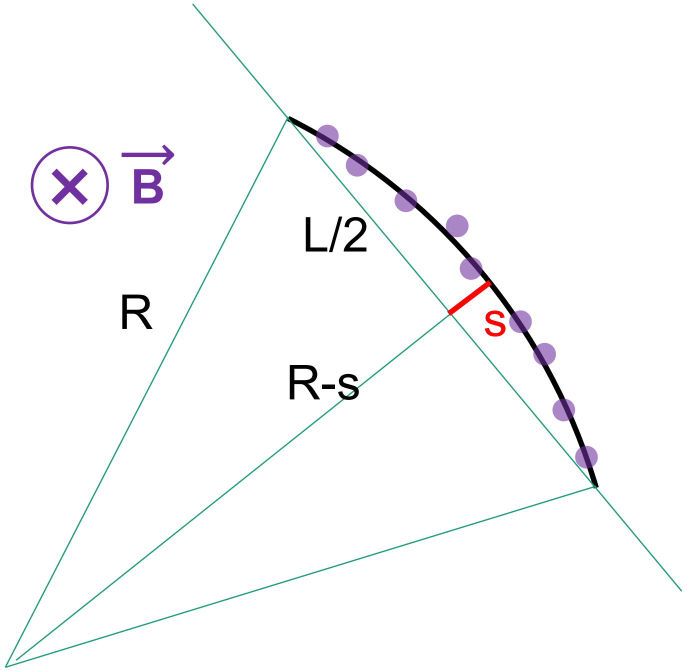
- **Fit the trajectories to measure momentum**
  - Measure the **sagitta** of the trajectory in the plan orthogonal to the B field



p_T [GeV/c] = 0.3 B [T] R [m]

$R \approx L^2 / 8s$

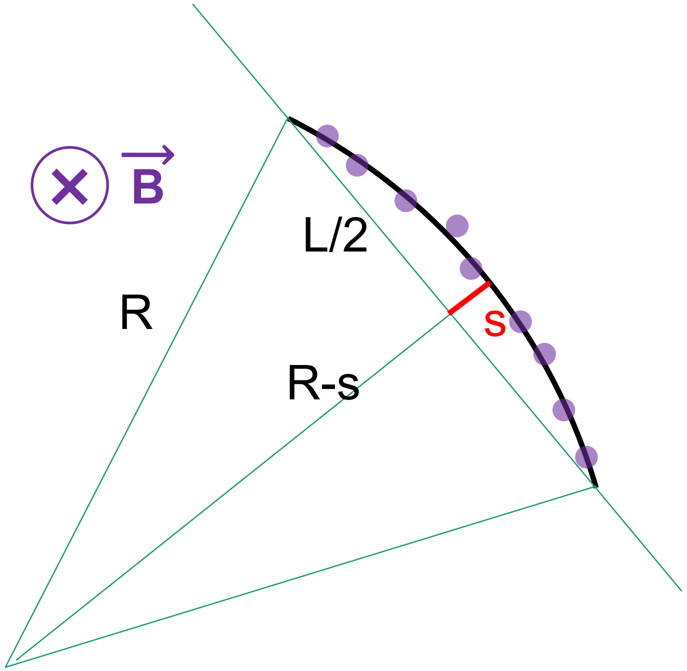
$p_T = \kappa\, B\, L^2/s \qquad \kappa = 3/80$

$\Delta p_T = \kappa\, B\, L^2\ \Delta s/s^2$

$\mathbf{\Delta p_T / p_T = p_T\ / (\kappa\, B\, L^2)\ \Delta s}$

Magnetic field
Size
Resolution

What a Tracker does



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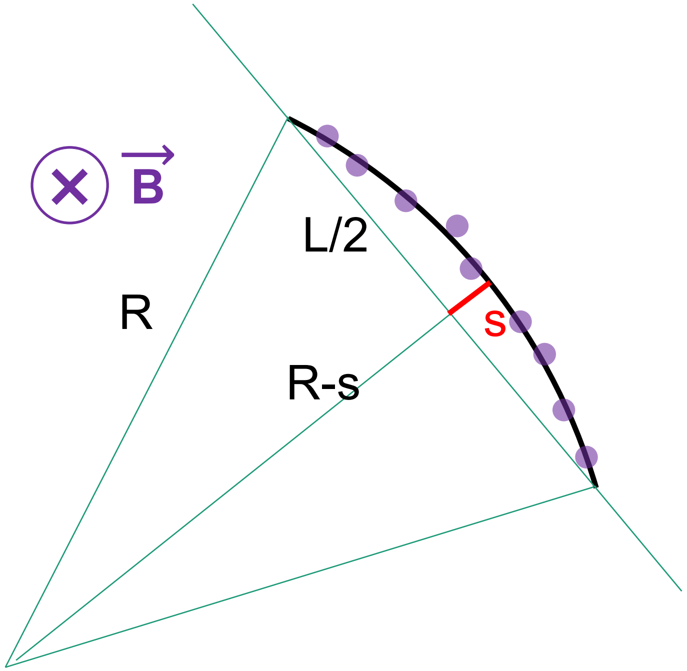
Example:
$\Delta p_T / p_T$ = 2% @ p_T =100 GeV
With a Tracker where **$B L^2 \approx 4$ Tm^2** (CMS)
Need **$\Delta s = 30\ \mu m$**

What a Tracker does



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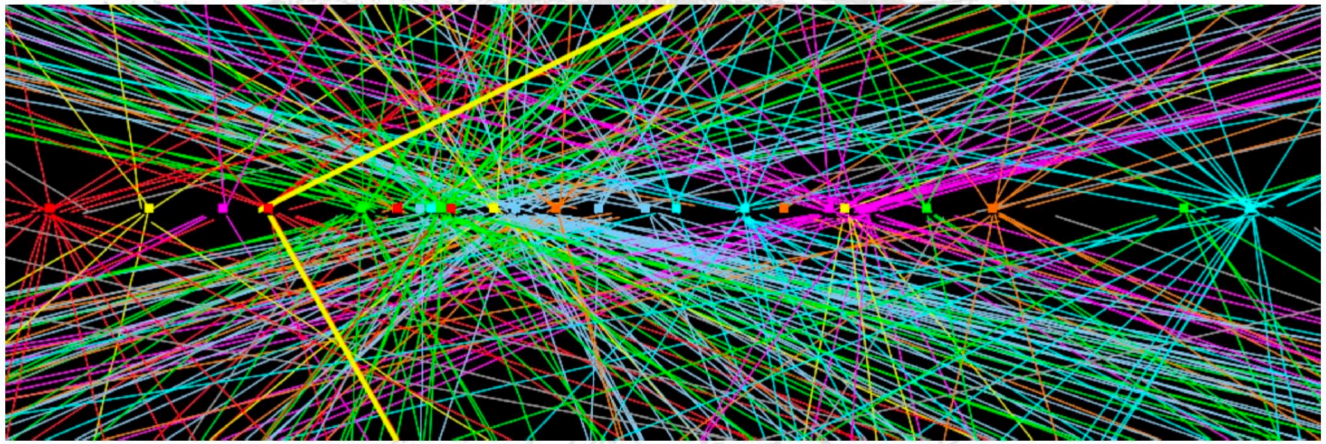
- **Reconstruct <u>primary vertices</u> and <u>secondary vertices</u>**
  - In case of multiple simultaneous collisions ("pile-up") it is **vital** to disentangle the products of the different collisions



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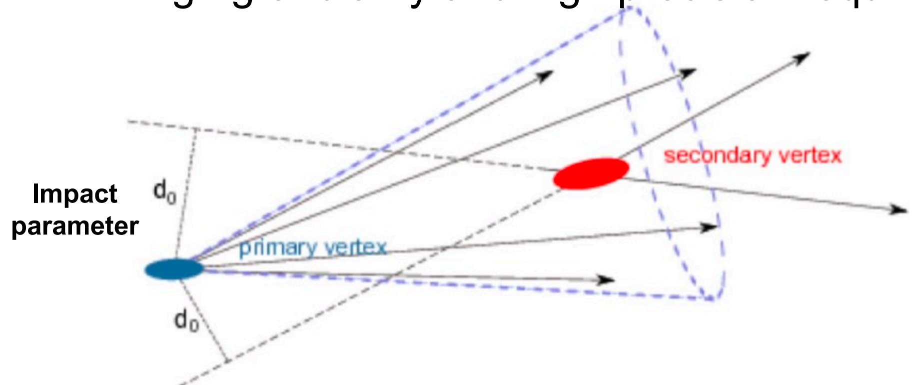
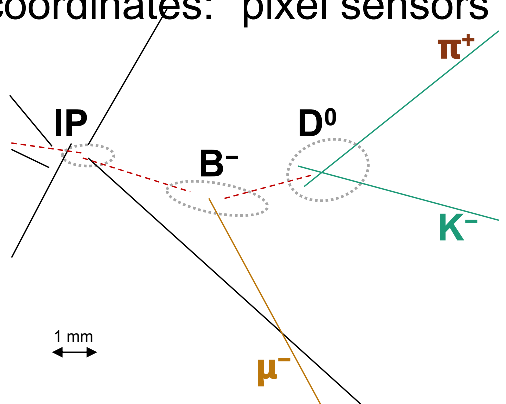
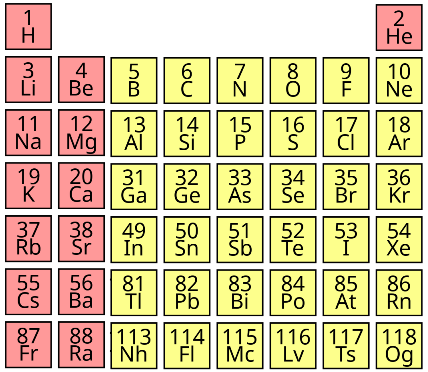
- **Reconstruct <u>primary vertices</u> and <u>secondary vertices</u>**
  - In case of multiple simultaneous collisions ("pile-up") it is **vital** to disentangle the products of the different collisions
  - Secondary (and tertiary) vertices are signatures of particles containing b and c quarks – essential for many physics channels
  - High granularity and high precision required in the first Tracker coordinates: "pixel sensors"



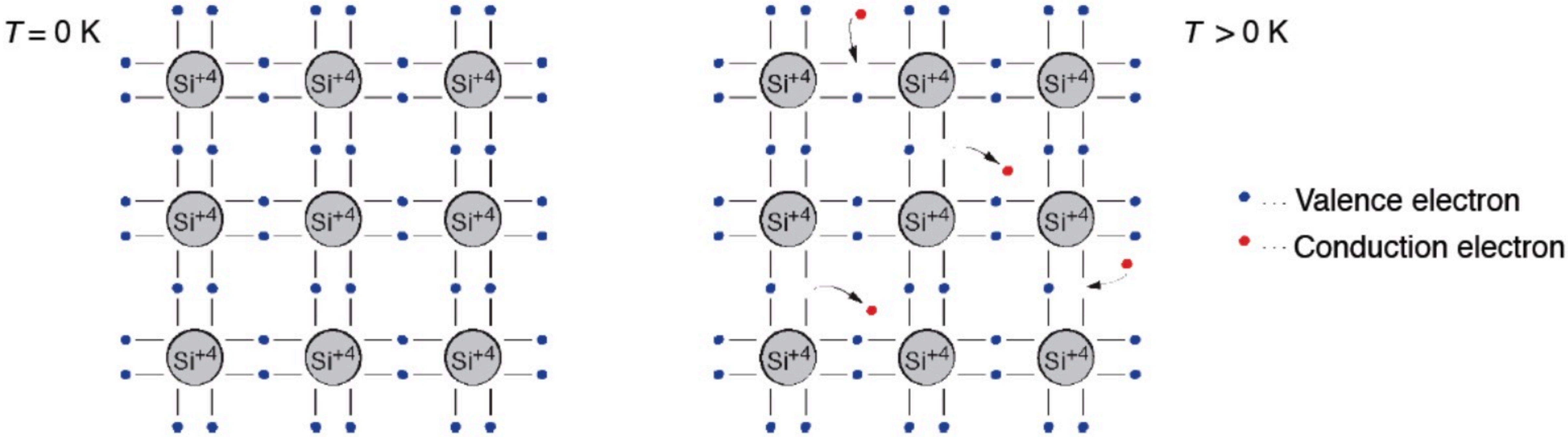


N.B. The first coordinate of the Tracker is typically a few cm away

Silicon sensors

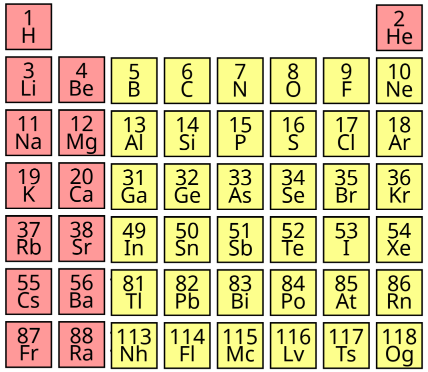


Silicon lattice:

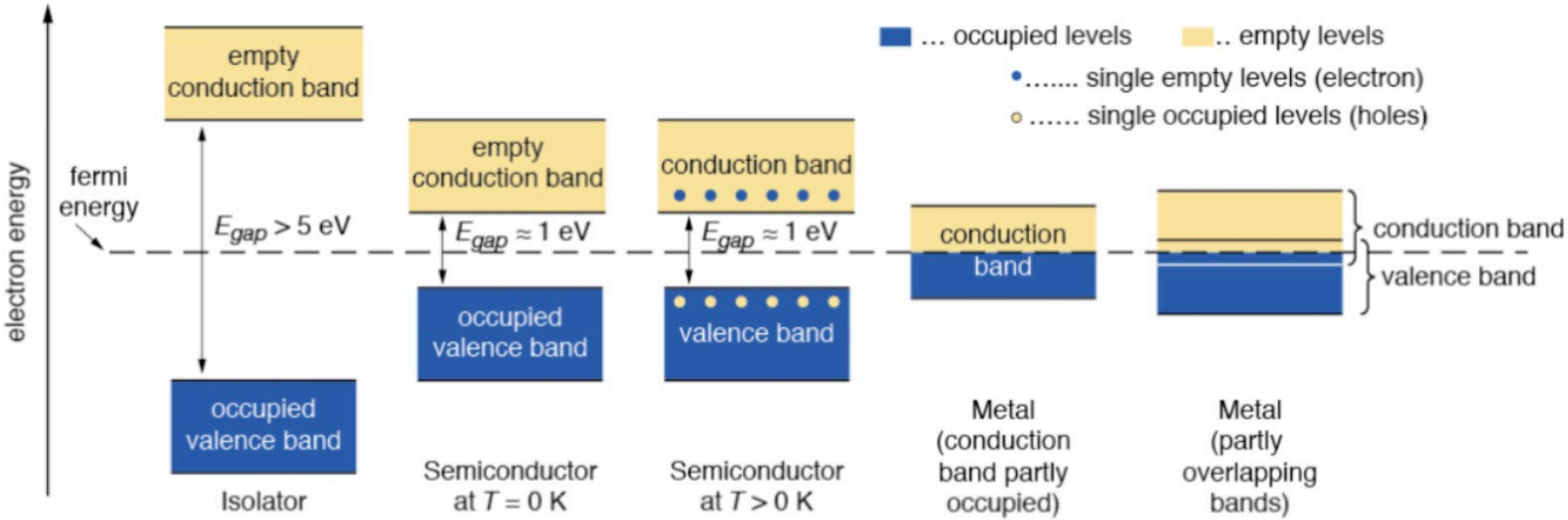


Si atoms have four electrons in the outer shells
In the reticle those four electrons are shared with the four closest atoms, to form covalent bonds
Thermal excitations can break valence bonds, creating “electron – hole” pairs ⟶ electrical conductivity

Energy bands



- In isolated atoms the **energy levels** of electrons are **discrete**
- In solid materials energy levels merge into **energy bands**
- In isolators and semiconductors the **conduction band** and the **valence band** are separated by a **band gap**



Making a particle detector

About 24,000 e-h pairs released by a Minimum Ionising Particle in 0.3 mm silicon

Mobility v [cm/s] = μ [cm^2/(Vs)] E [V/cm]

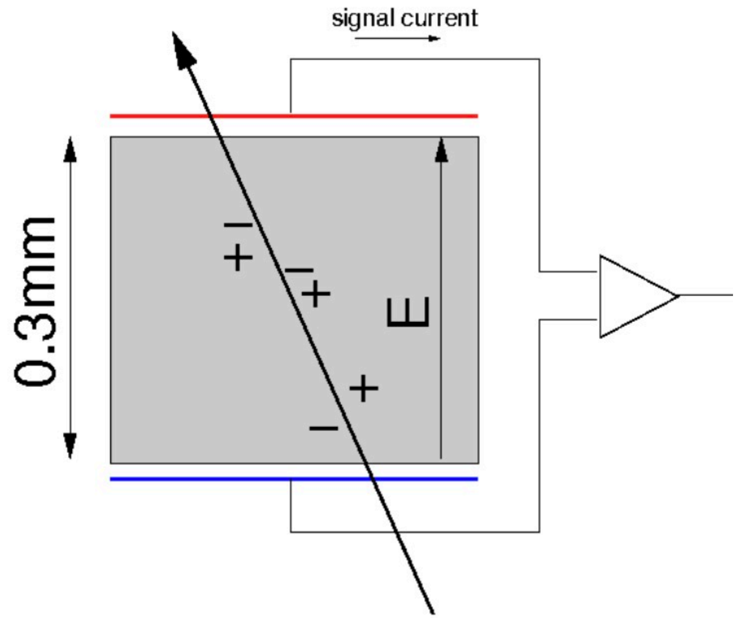
At 300 K:

$\mu_e \approx$ 1450 V/cm

$\mu_h \approx$ 450 V/cm

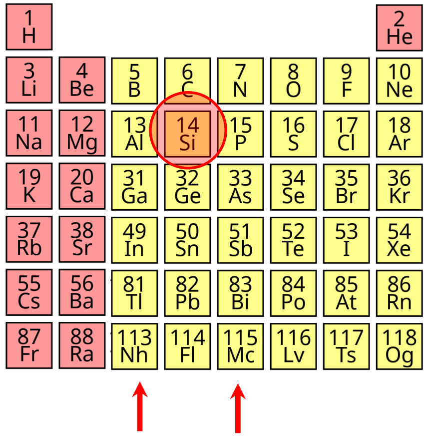
With 60 V, $v_e \approx 30\ \mu$m / ns

Charge collection in ~10 ns



BUT: Thermal charge carriers 3-4 orders of magnitude more numerous
Signal from traversing particle not detectable!

Doping

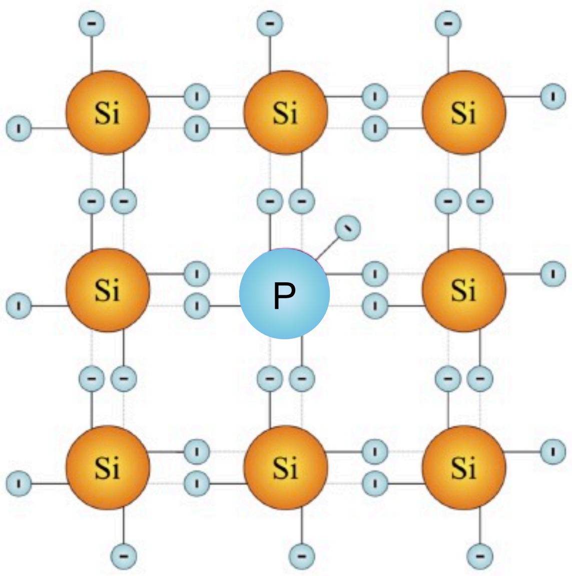


A small fraction of the atoms in the lattice are replaced with atoms from the neighbouring groups III or V

⟶ create energy levels within the bandgap

⟶ change conductivity

n-type silicon

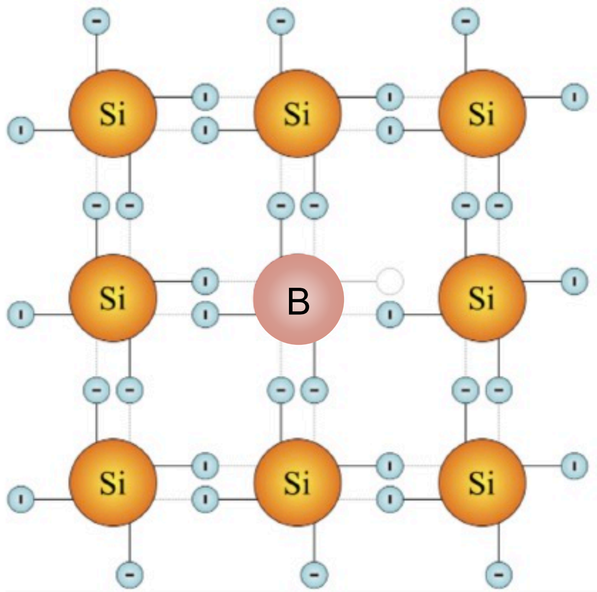


Dopant: element V atom (e.g. P)

Donor: 5th valence electron weakly bound

Majority carriers electrons

p-type silicon

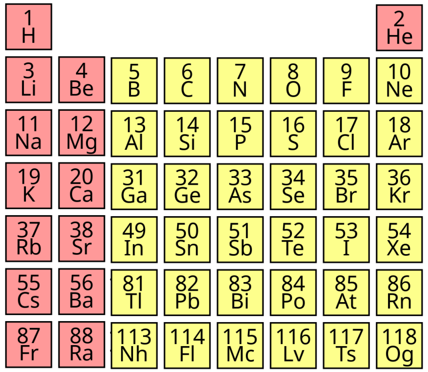


Dopant: element III atom (e.g. B)

Donor: one valence bond open
(attracts electrons for neighbour atoms)

Majority carriers holes

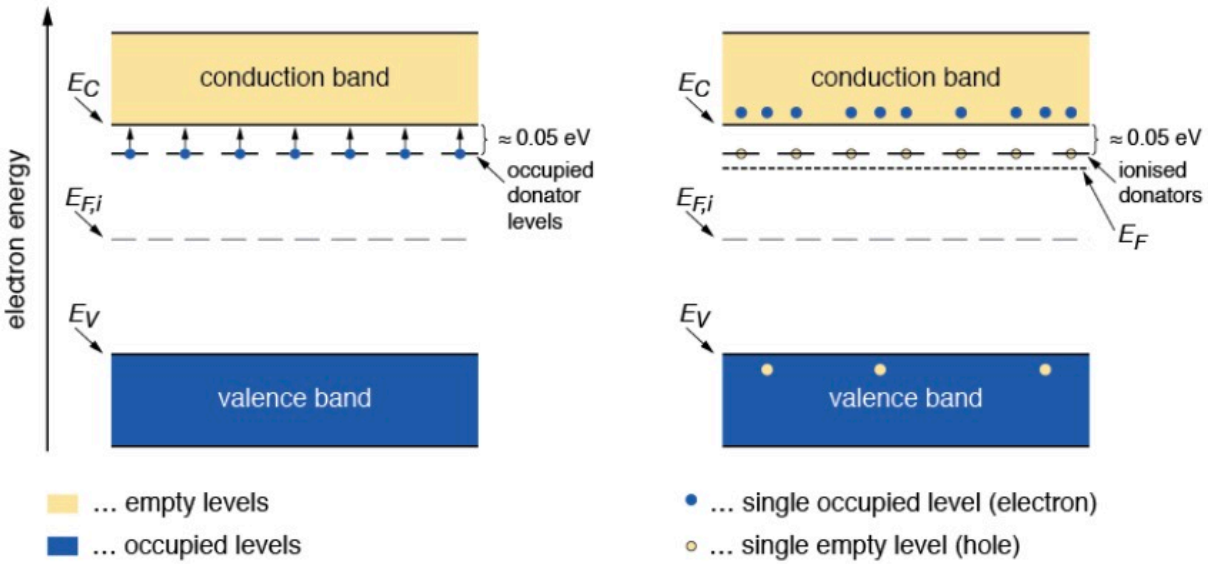
Doping – energy levels



n-type silicon

Energy level of donor just below the conduction band

With thermal excitation electrons move to the conduction band

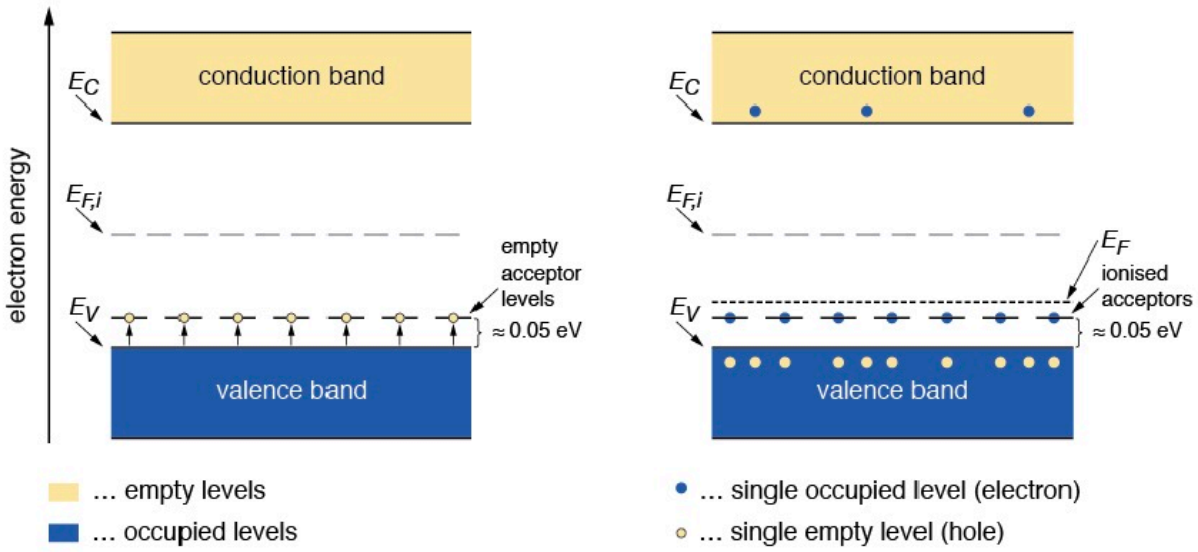


p-type silicon

Energy level of acceptor just above the valence band

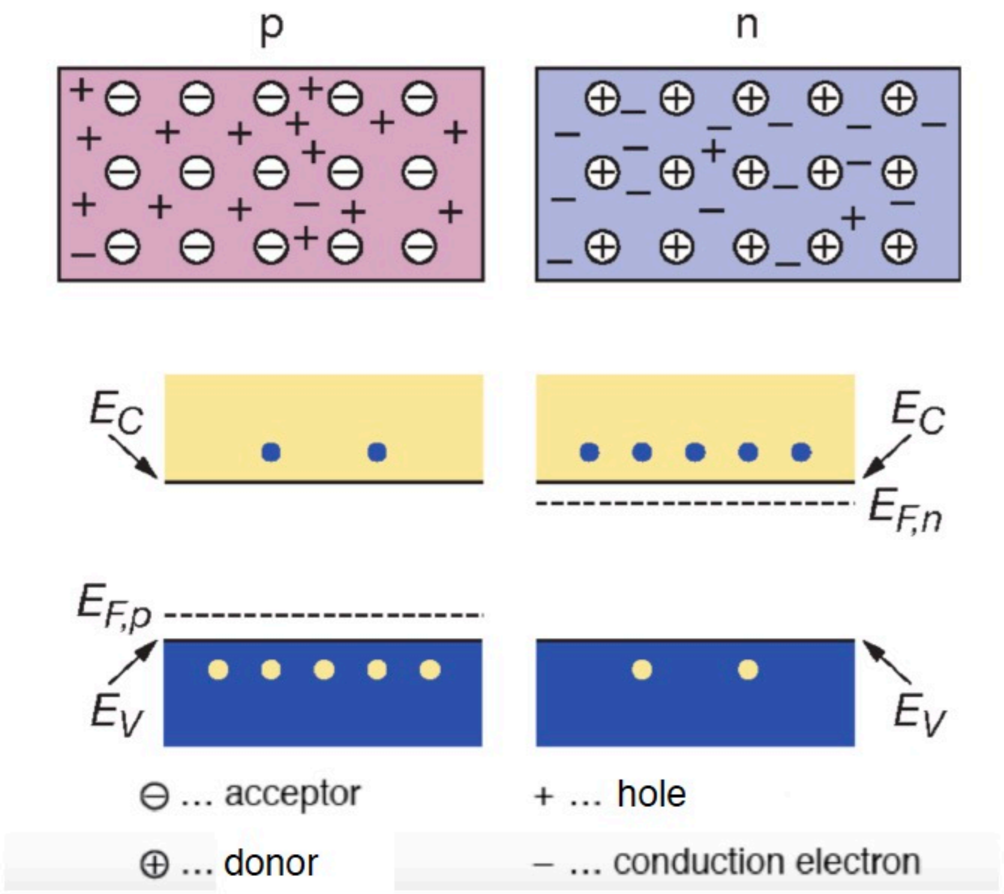
Electrons move from the valence band to the acceptor

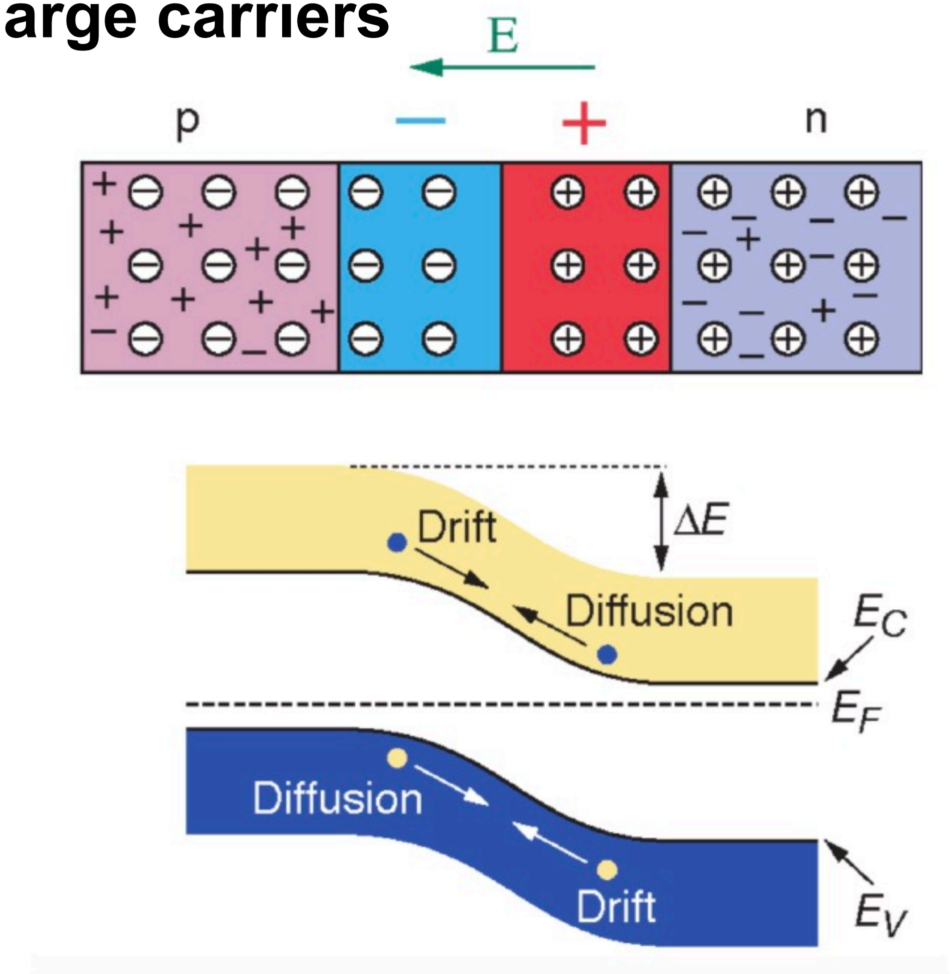
Holes are left in the valence band



The p-n junction

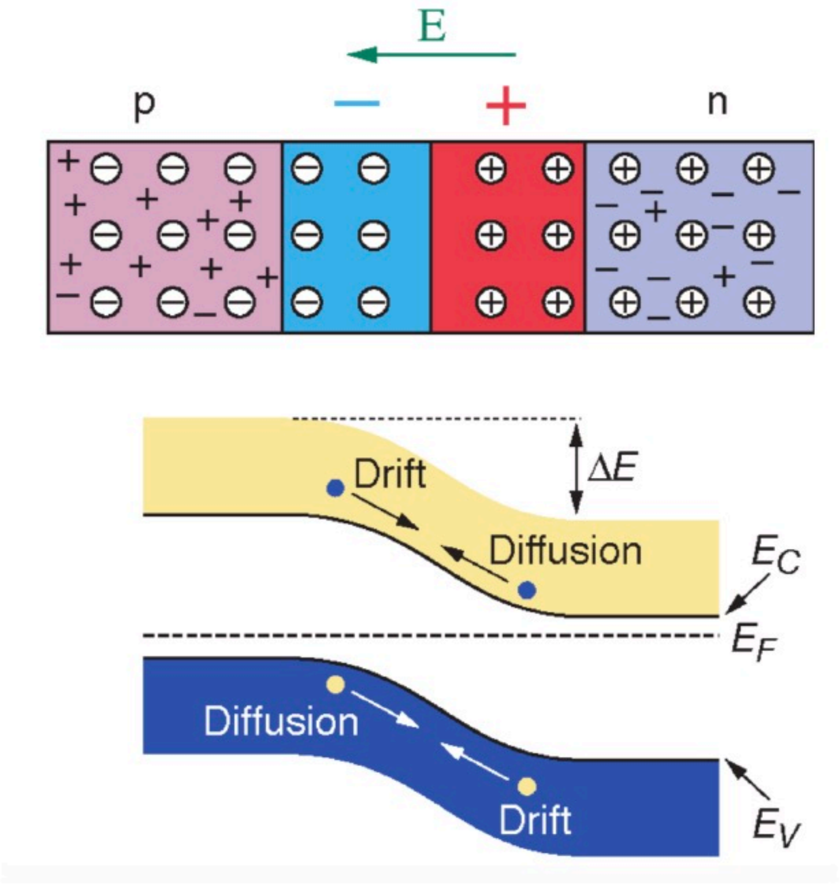
Majority carriers **diffuse across the junction**
Until the resulting **electric field** stops further diffusion
The region around the junction is **depleted of charge carriers**

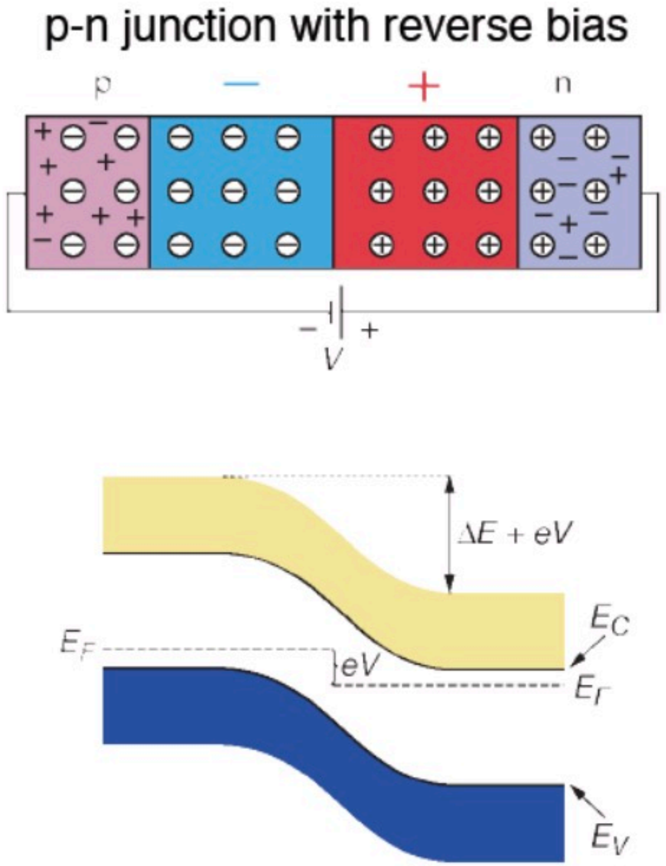




The p-n junction with reverse bias

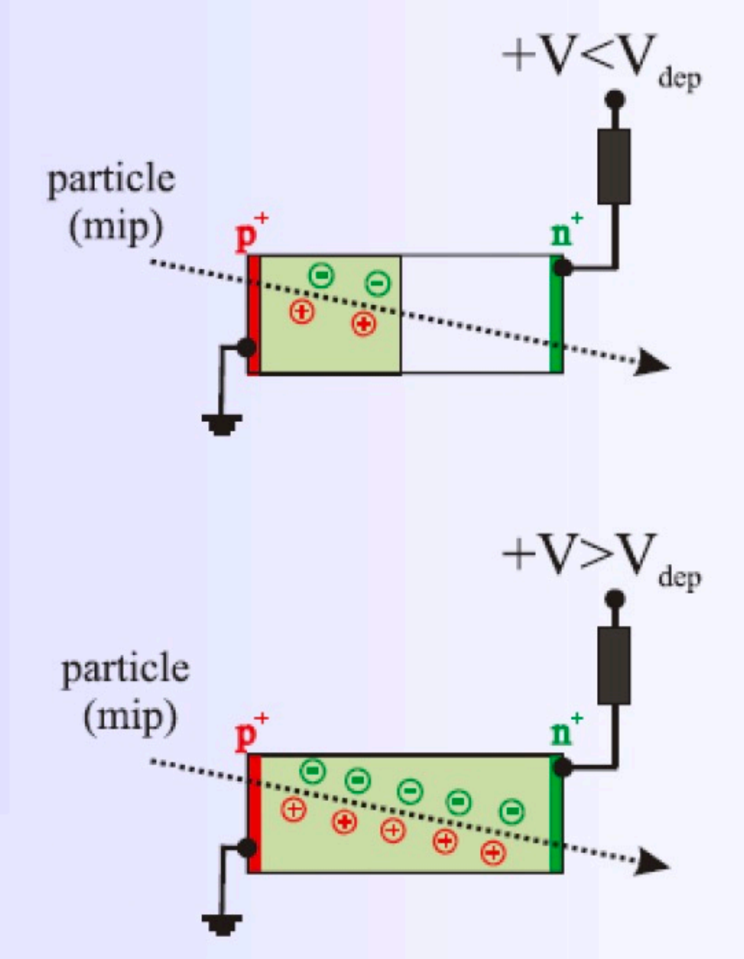
External voltage V, negative to p-type and positive to n-type
Electrons and holes are pulled out of the depletion zone
The depletion zone is extended
It can be used as a particle detector!

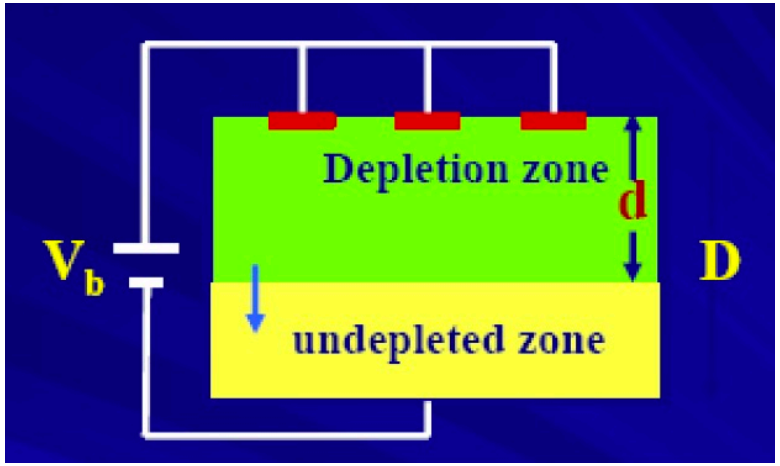


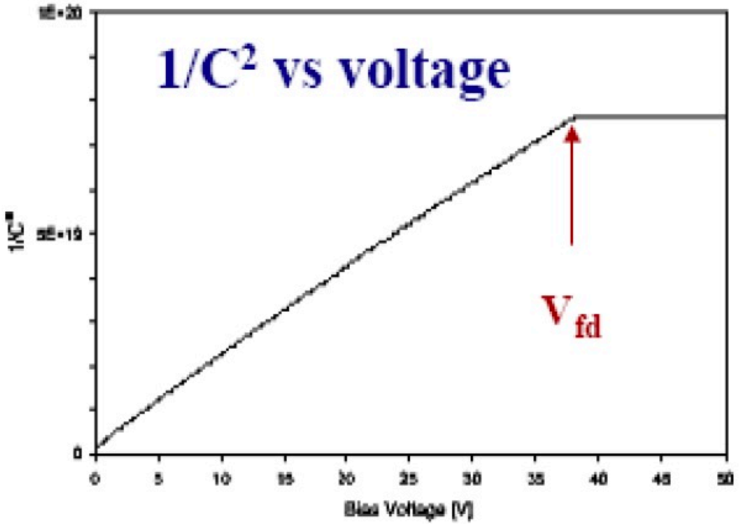


Depletion zone

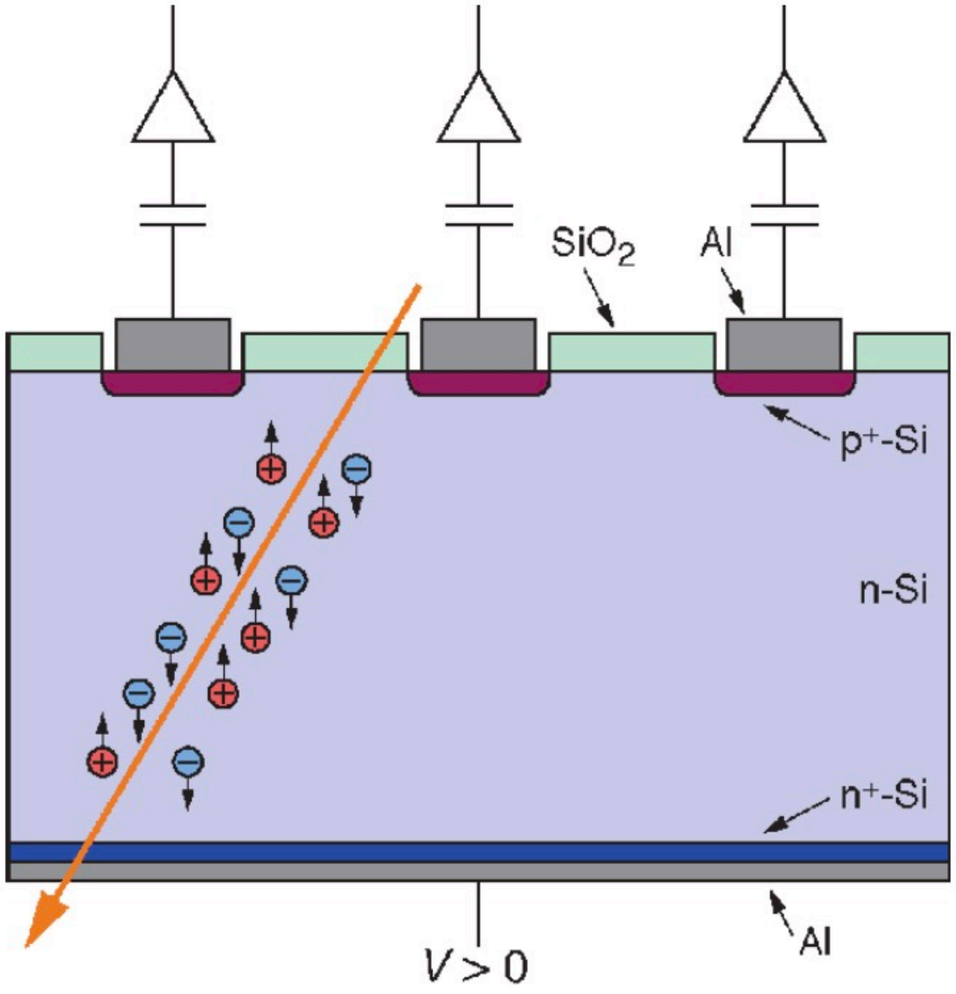
- ➢ **Grows with applied reverse bias voltage**
- ➢ **Only charges generated inside the depleted volume are collected**
  - In the undepleted volume there is no electric field – charges recombine
- ➢ **<u>Full depletion required for full charge collection</u>**
- The depletion voltage can be determined by measuring the capacitance vs reverse bias voltage
- The capacitance is the parallel plate capacity of the depletion zone







A (simple) silicon sensor



- Segmenting the implant
  —> one-dimensional position of the traversing particle

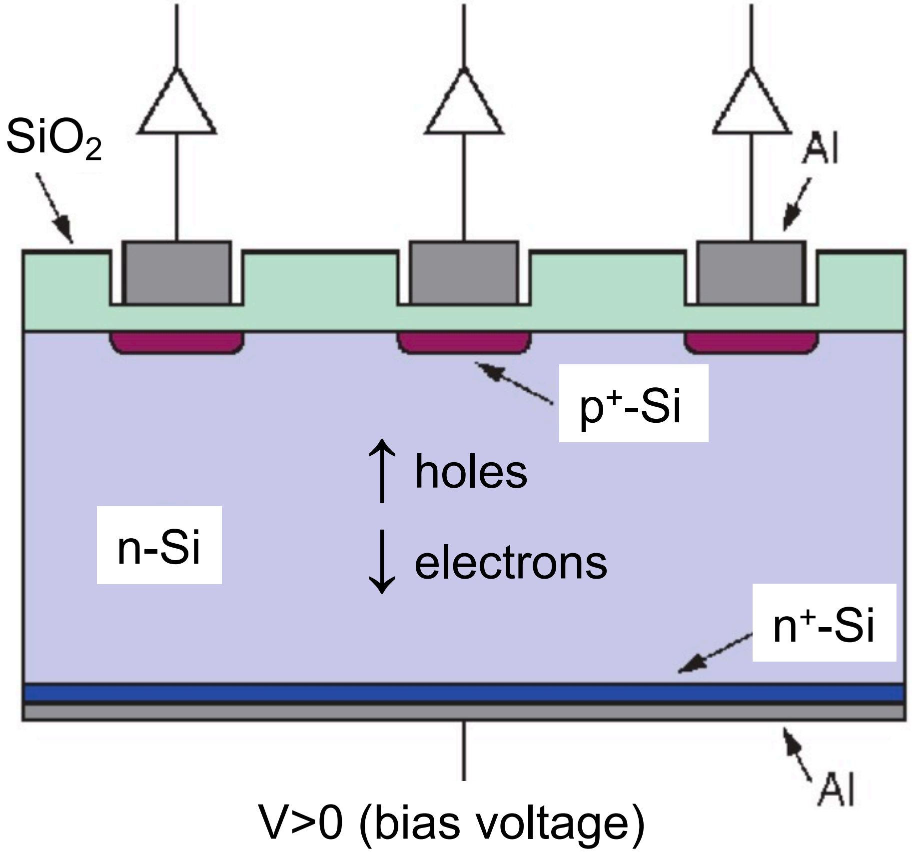
- Simplest version: **DC-coupled** strip detector

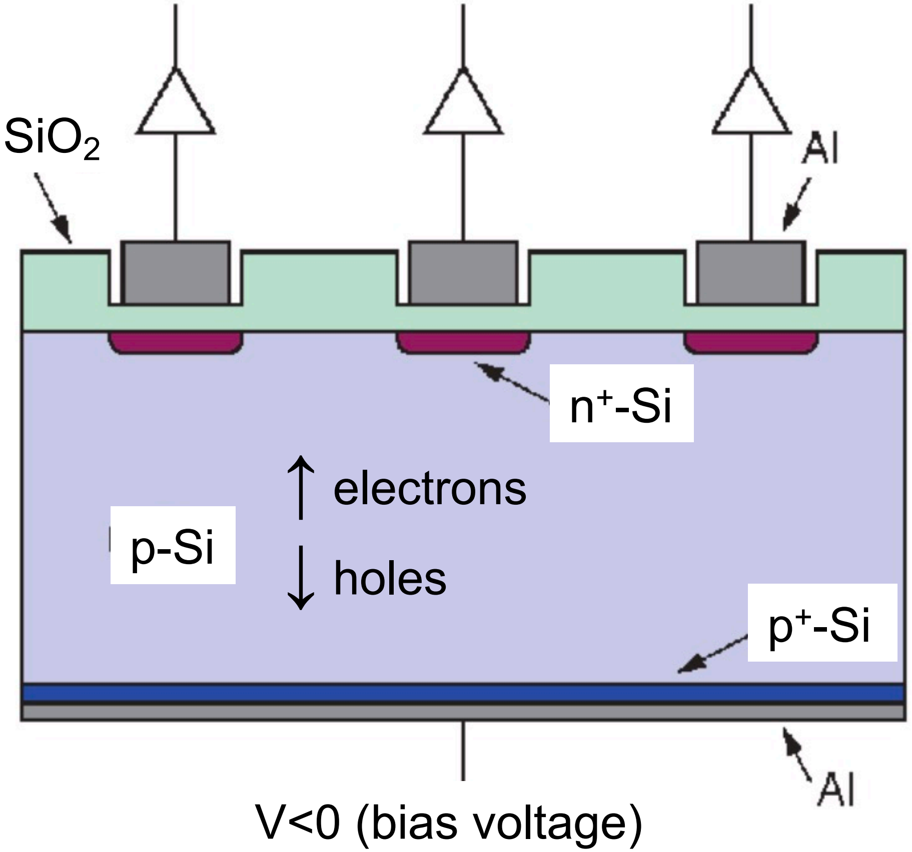
- **p-in-n** sensor:
  - Strips are Boron implants (p+)
  - Substrate is Phosphorous doped (~2-10 kΩcm)
- Thickness ~300μm
- $V_{dep} < 200$V

- Backside Phosphorous implant (n+) to establish ohmic contact and to prevent early breakdown

- Highest field close to the collecting electrodes where most of the signal is induced

Other designs



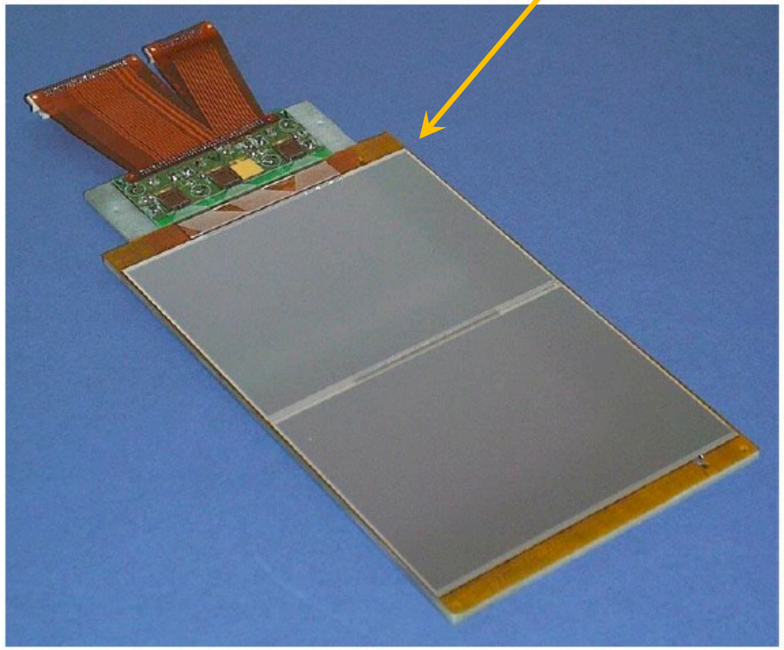


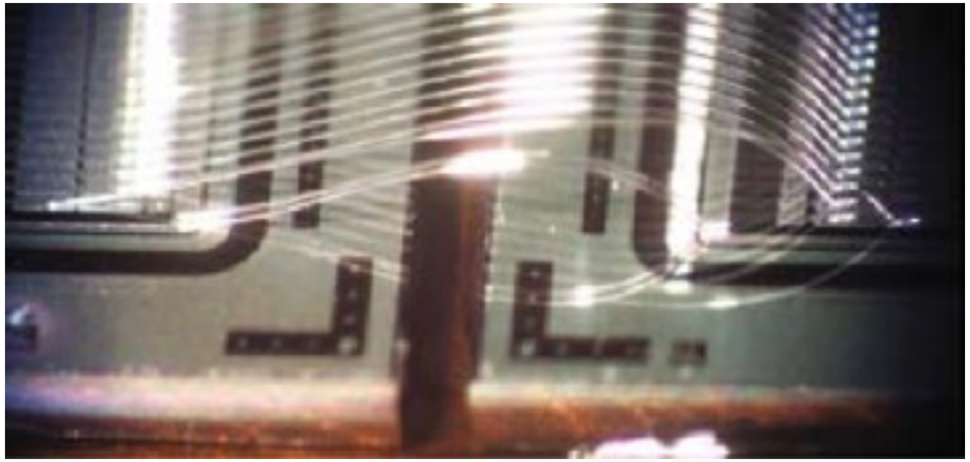
p-in-n, AC coupled

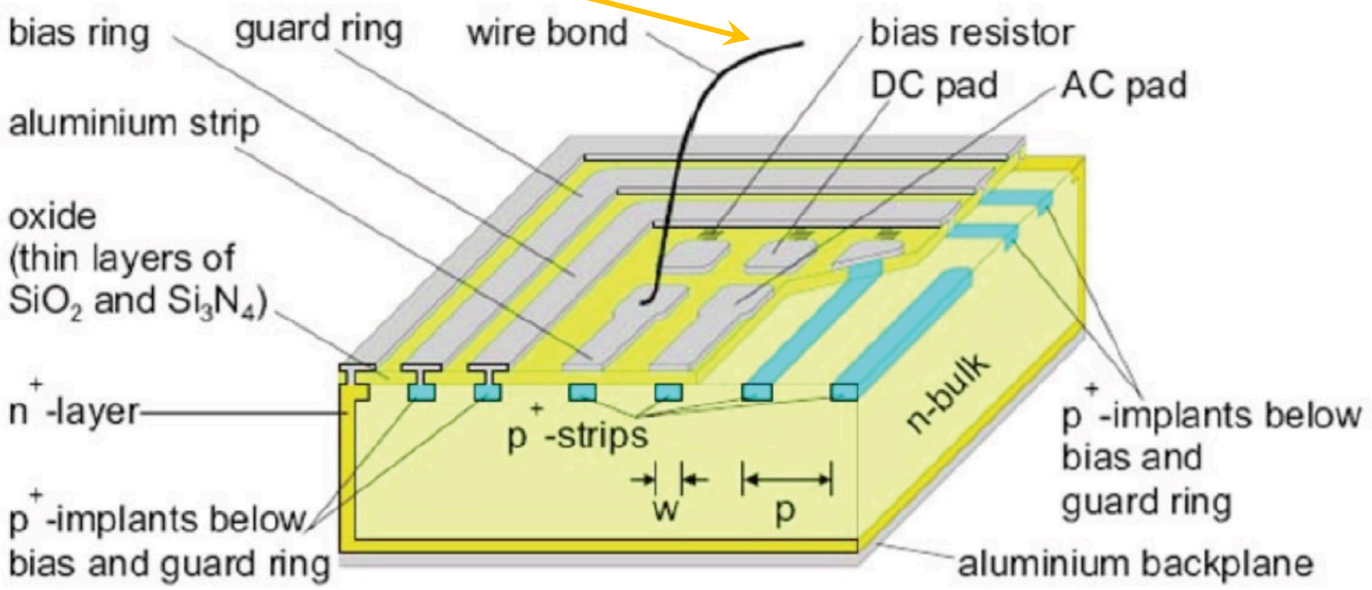
n-in-p sensors

Micro-strip detectors

Micro wirebonds connect the strips to the readout chips



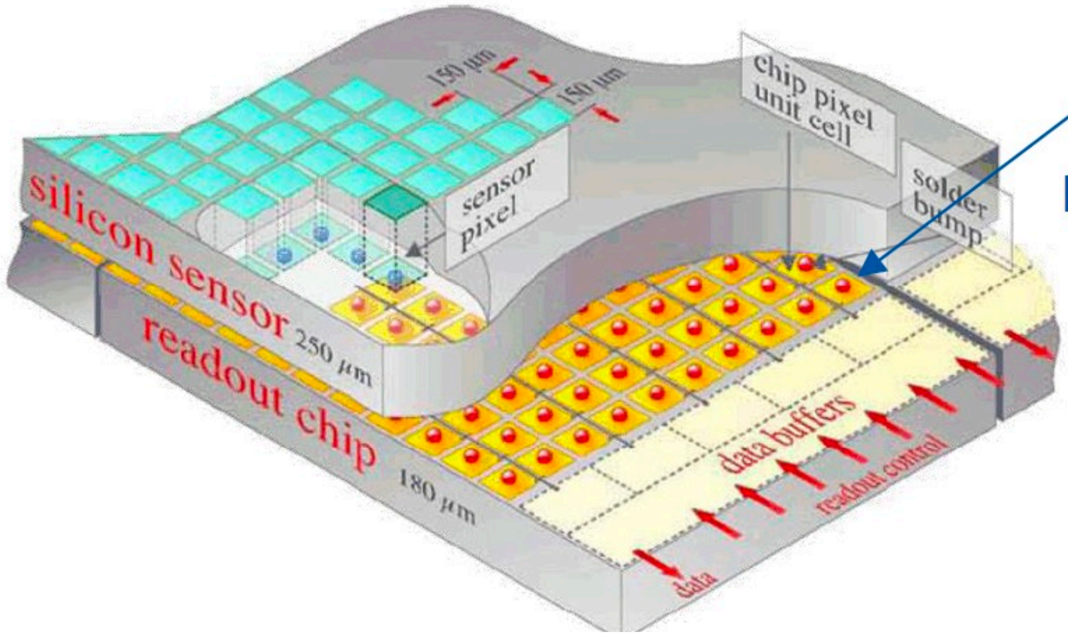




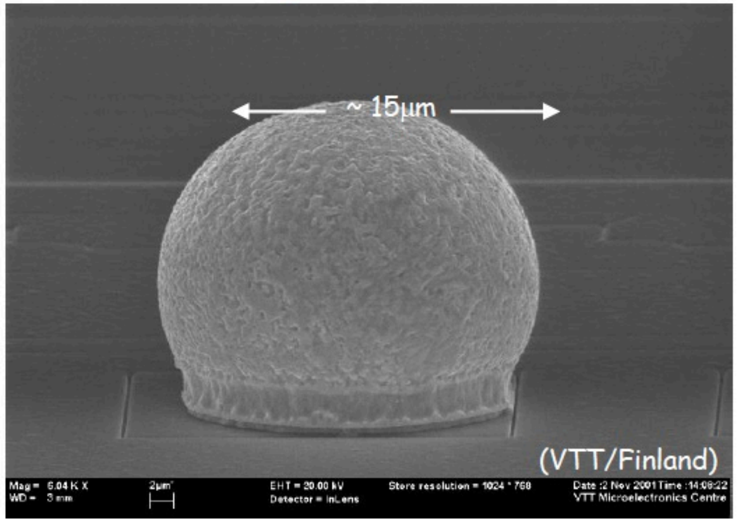
Pixellated detectors

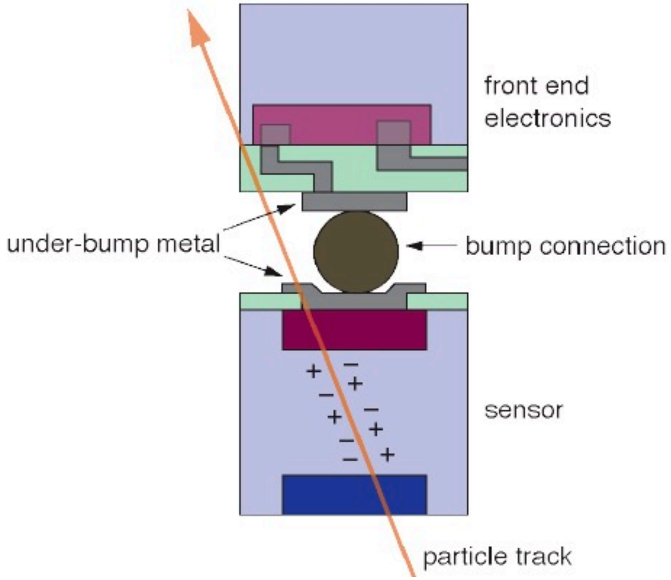
Every cell on the sensor is connected to a pixel in the readout chip

Connection by "bump bonding"



Flip-chip technique





Radiation damage

Particles traversing the silicon interact with the material and deposit energy

Two types of interactions:

- **Interactions with the electrons of the material: Ionising Energy Losess**
  - Caused by photons and all charged particles
  - May deposit charges on the insulating layers
  - Fast recombination in the silicon bulk (no damage)
- **Hadronic interactions with the nuclei: Non-Ionising Energy Losses**
  - Displacement of atoms in the lattice: **bulk damage**
  - Caused by pions, protons, neutrons

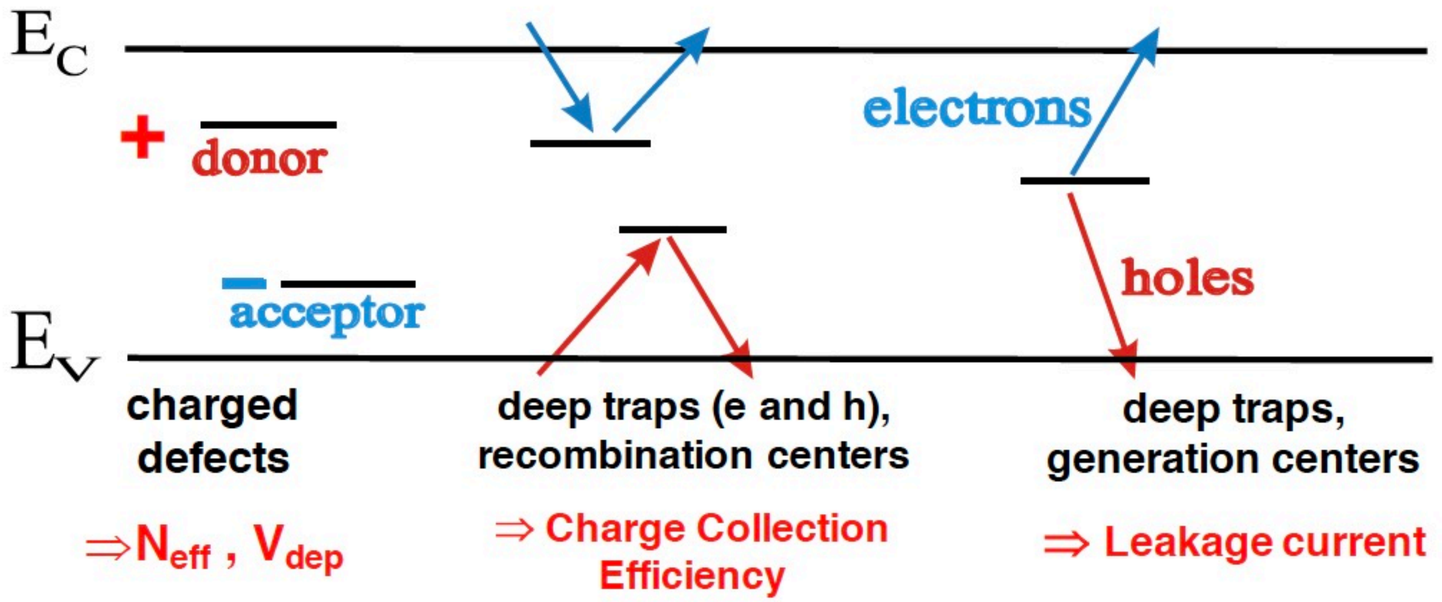
Electromagnetic damage is to first order not relevant
It is relevant for the readout chips

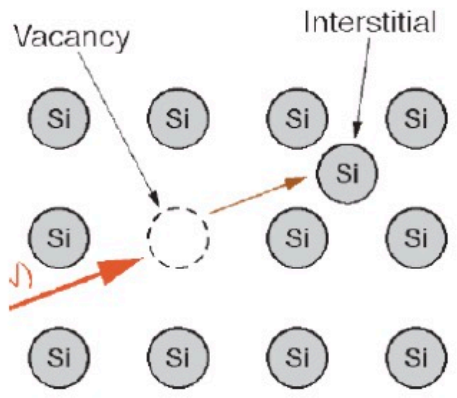
Non-ionising energy losses are responsible for the degradation of the sensor properties

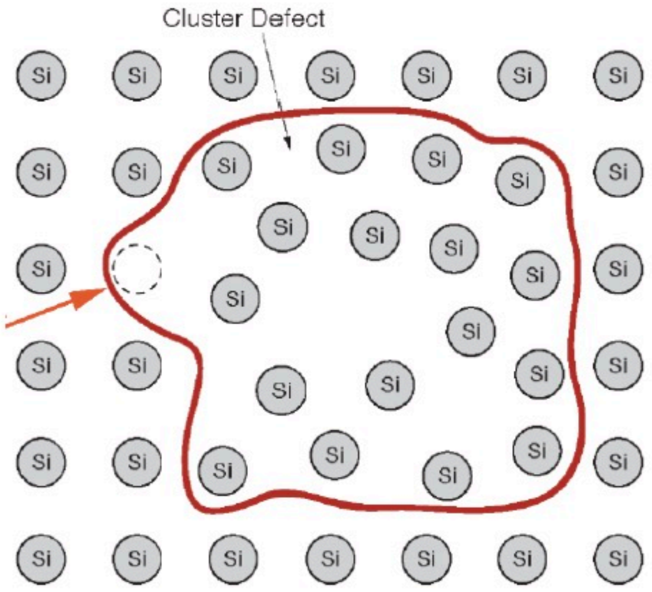
Radiation damage

Effects on sensor operation:

- **Loss of charge collection efficiency (charge trapping)**
- **Change in depletion voltage, distortion in internal E-field**
  - Eventually full depletion never really achieved
- **Leakage current**
  - Substantial power dissipated in the sensor



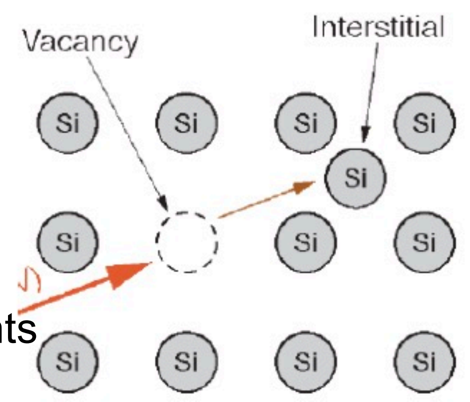




Radiation damage

Defects evolve with time, time constants exponential with temperature

- E.g. interstitials can move in the lattice and recombine with vacancies
- Other defects propagate in the lattice causing further damage – with longer time constants

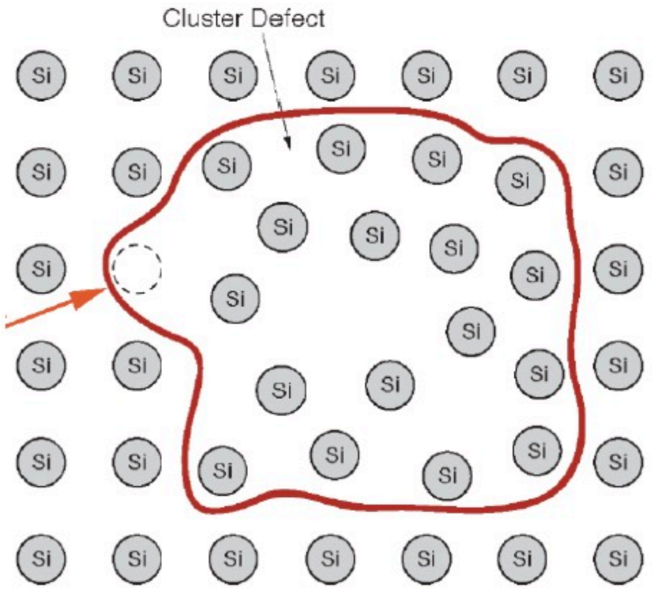


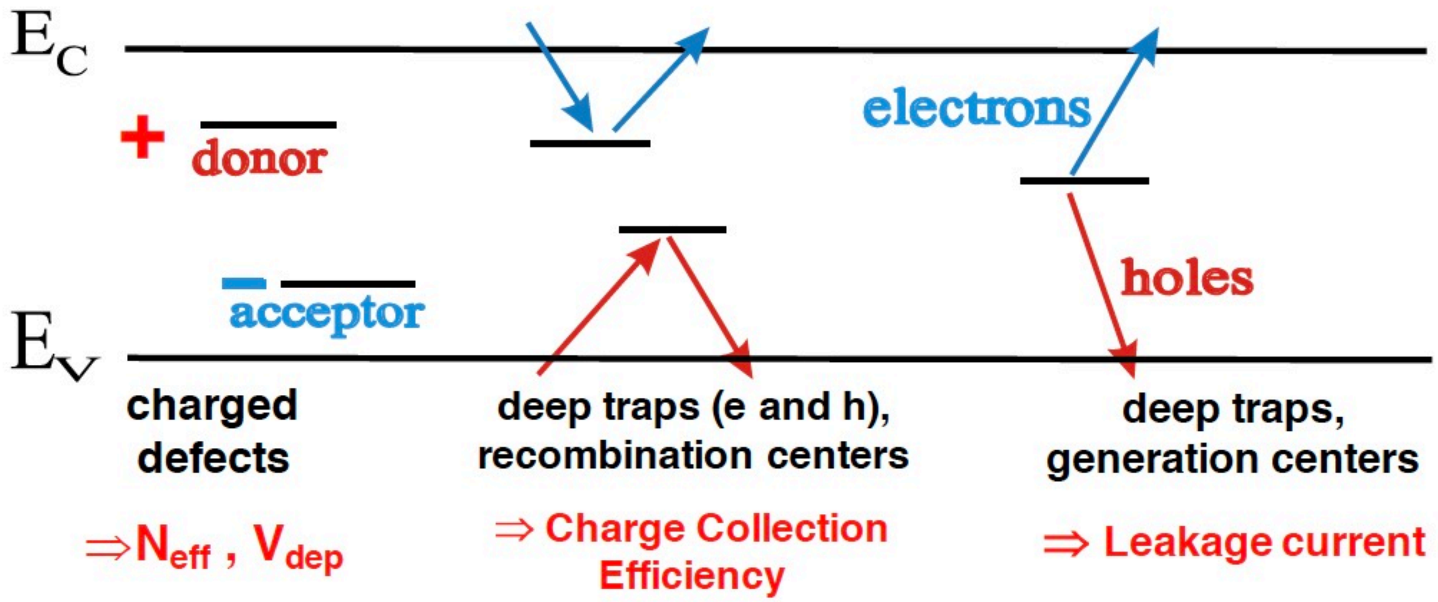
➢ **Short term: beneficial annealing**

- Reduce leakage current

➢ **Long term: reverse annealing**

- Further loss of charge collection efficiency





Radiation damage mitigation

(1) Avoid reverse annealing: keep sensors at cold temperature all the time (even when unused)

- At T< 0°C reverse annealing is "frozen"

(2) Exploit beneficial annealing: <u>short</u> periods at "warm" temperature

- E.g. 1-2 weeks / year at room T considered for ATLAS/CMS
- Notably it mitigates leakage current

(3) Mitigate reduction of charge collection efficiency: operate at high V_{bias}

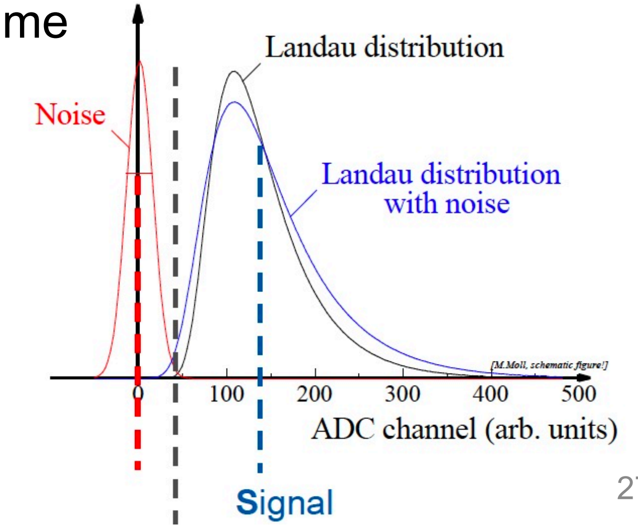
- High E-field in the sensor mitigates charge trapping
- Operate sensors substantially overdepleted
- N.B. High V_{bias} aggravates the effect of leakage current!

(4) Mitigate reduction of charge collection efficiency: design with large margin in S/N

- E.g. in ATLAS/CMS start with S/N ~ 20, to maintain S/N >10 at the end of lifetime

(5) Mitigate leakage current: operate the detector (very) cold

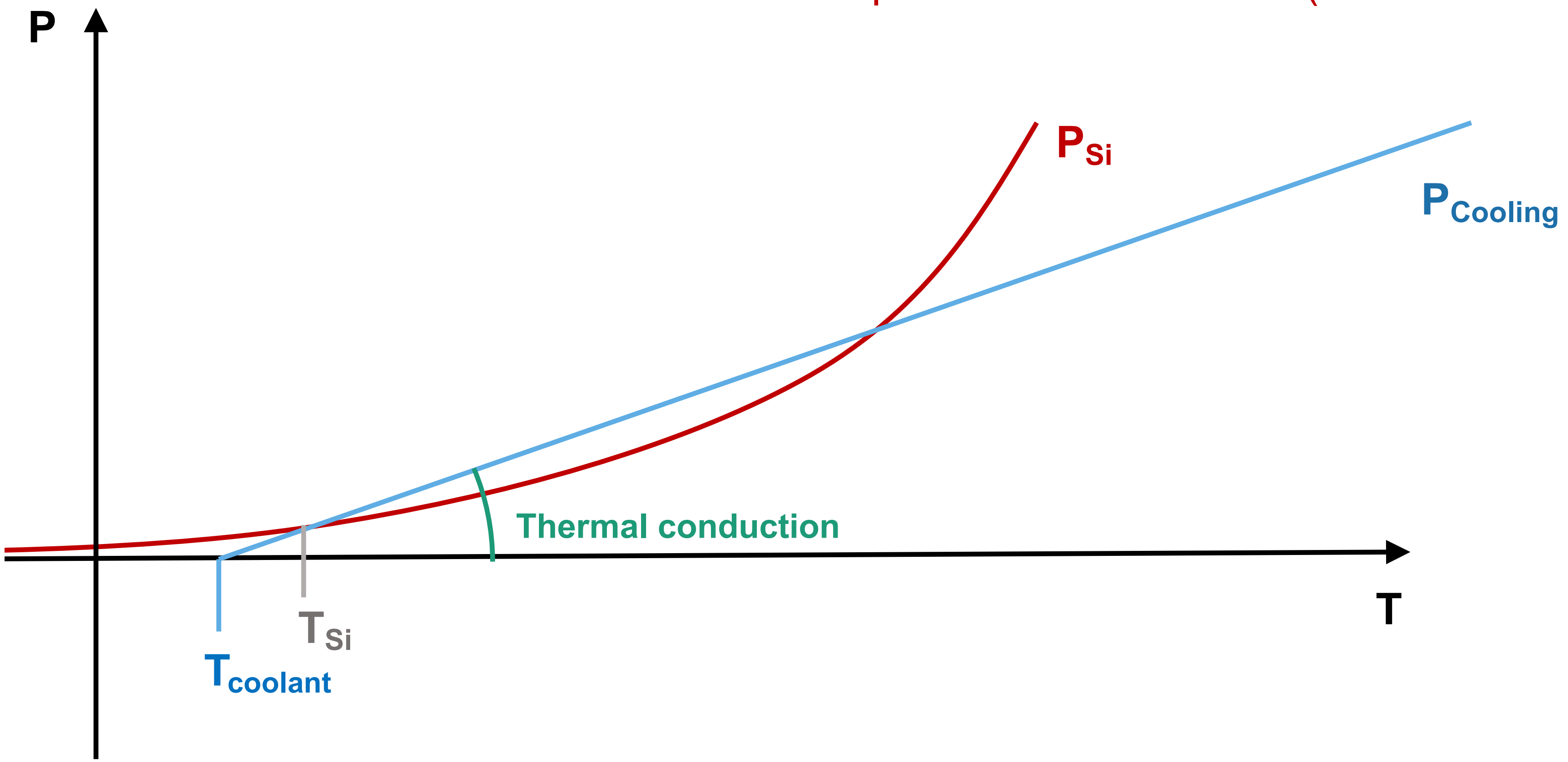
- Thermally generated e-h pairs: exponential with T



Leakage current and cooling

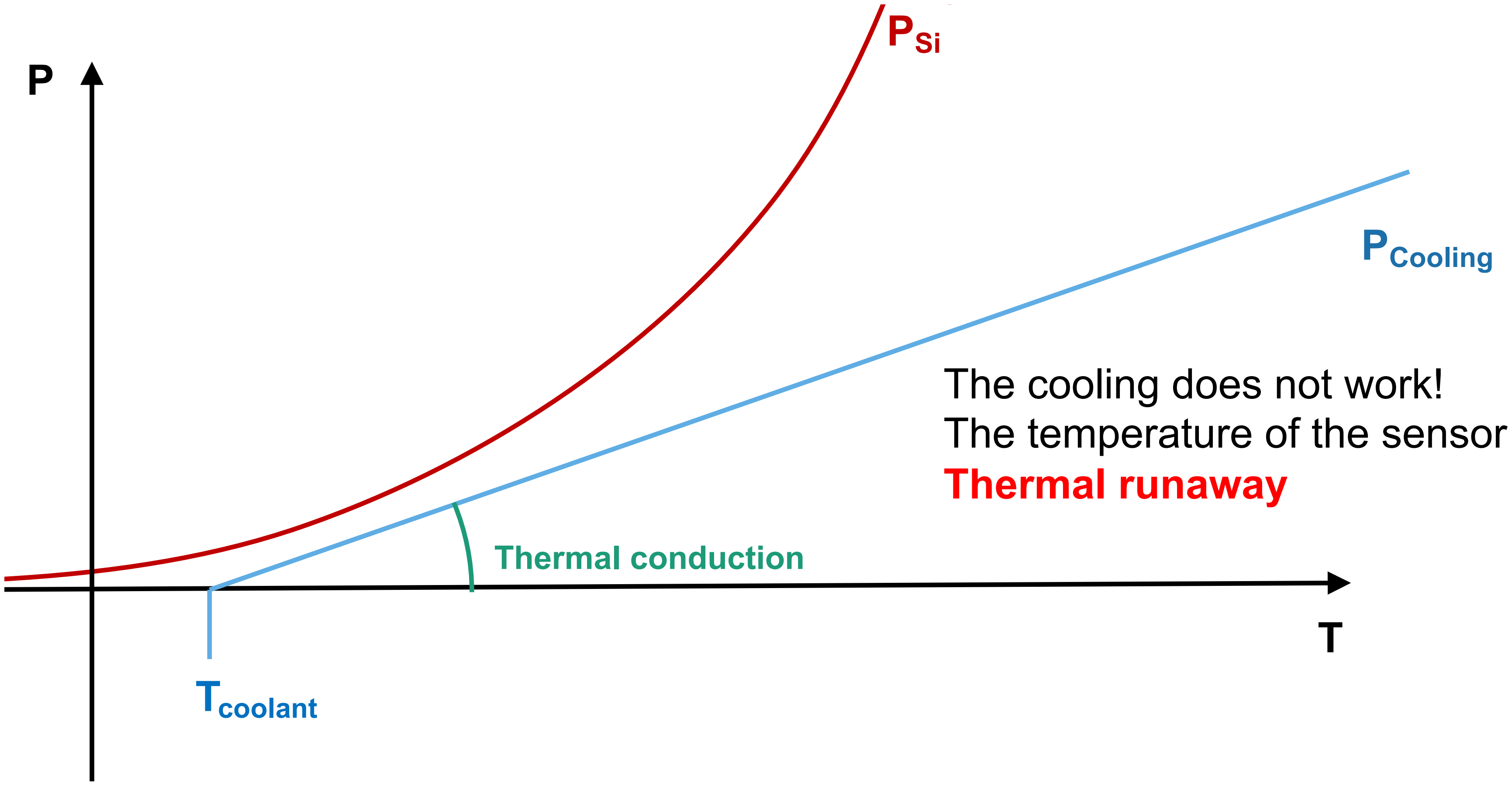
$$P(r,T) = U_{bias}(\phi(r) \cdot \alpha_0 \cdot V)\frac{T^2}{T_0^2}\exp\left(-\frac{\Delta E}{2k_b}\left(\frac{1}{T}-\frac{1}{T_0}\right)\right)$$

Proportional to irradiation (hadron fluence)



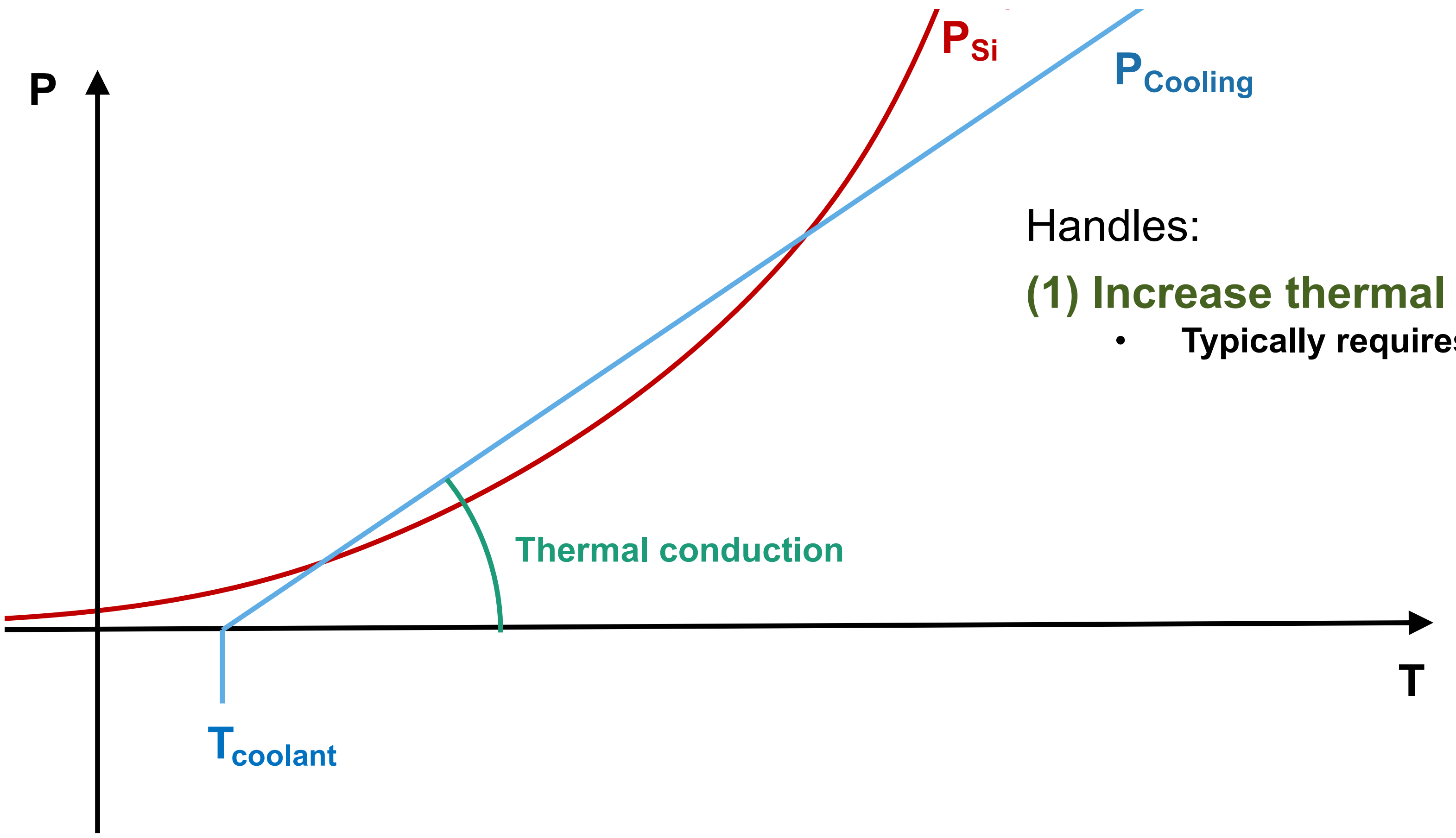
Now we increase the irradiation…

Leakage current and cooling



The cooling does not work!
The temperature of the sensor is not limited
Thermal runaway

Leakage current and cooling

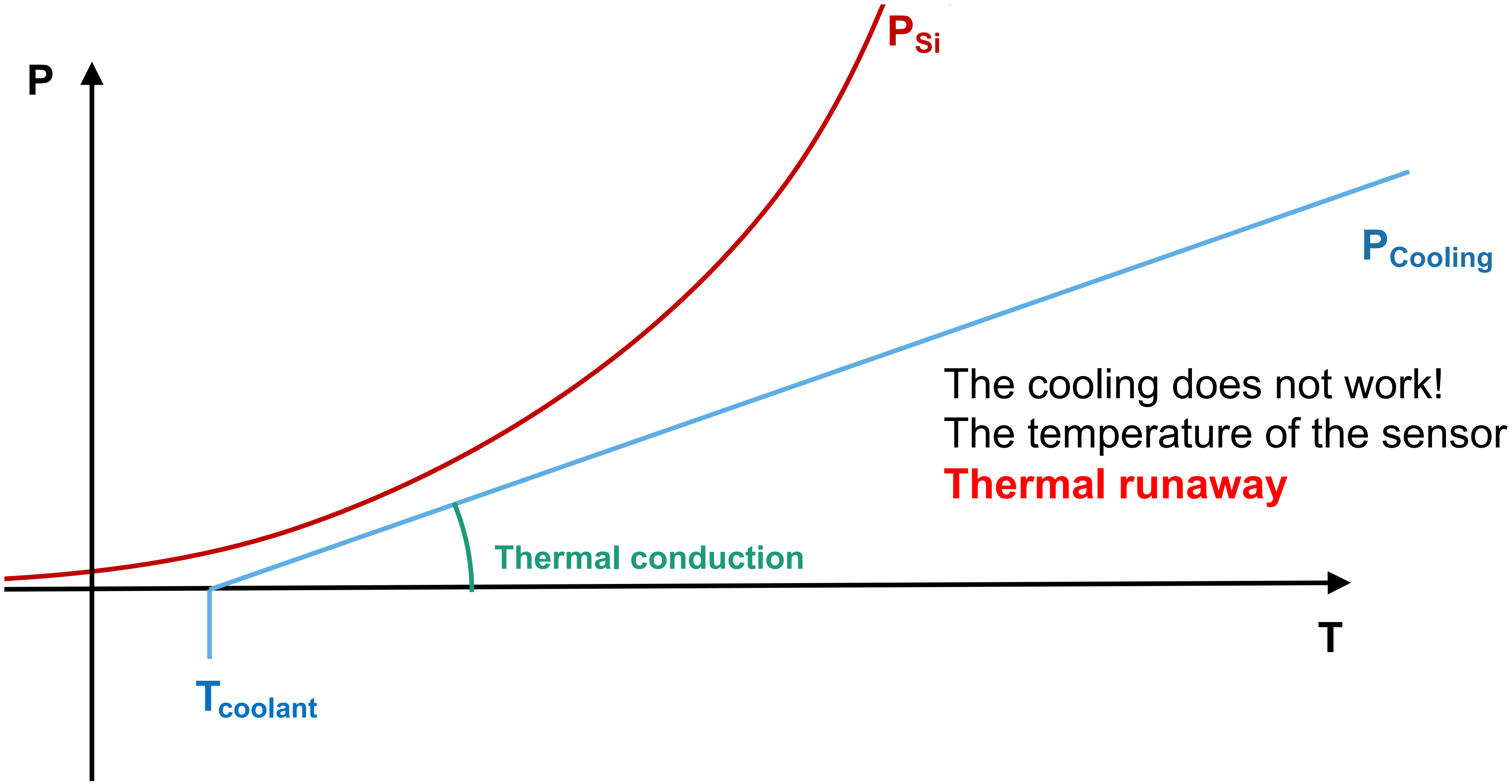


Handles:

(1) Increase thermal conduction

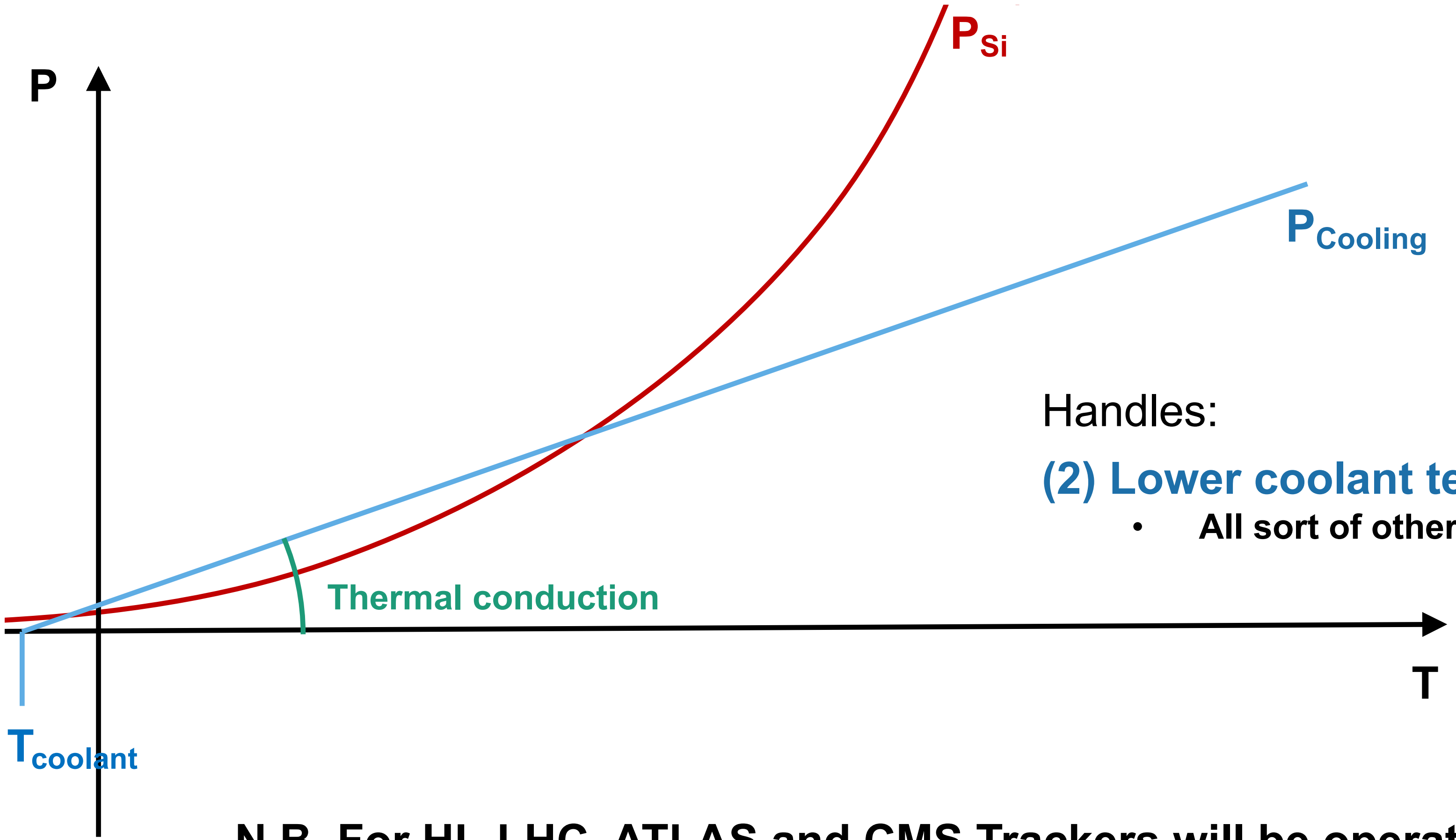
- **Typically requires adding substantial material**

Leakage current and cooling



The cooling does not work!
The temperature of the sensor is not limited
Thermal runaway

Leakage current and cooling



Handles:

(2) Lower coolant temperature

- **All sort of other complications…**

N.B. For HL-LHC, ATLAS and CMS Trackers will be operated with $T_{coolant} \approx -35°C$

Ingredients of a Silicon Tracker

Silicon sensors
- High-granularity pixellated sensors close to the interaction point
- Strip sensors adapted solutions for the outer regions
- Extreme requirements of rad hardness for the ATLAS and CMS Tracker inner regions

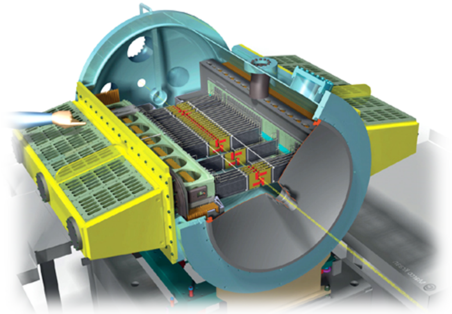
Readout electronics
- Extreme requirements of rad hardness and data rates for the ATLAS and CMS Tracker inner regions (not discussed)

Lightweight mechanical structures
- More stringent requirements for lower-energy applications (e.g. heavy ion physics in ALICE)

Efficient and lightweight cooling
- Cooling is most challenghing for the highest radiation environments
- Mass is most critical for low-energy applications

Low-mass power distribution and data links
- Minimize mass (and volume) of services
- Mass is most critical for low-energy applications
- Service routing is most challenging for trackers with nearly 4π coverage (ATLAS and CMS)

Example of solutions from the 4 LHC detector trackers



VELO

Active area: 0.12 m^2

NIEL ~ 8×10^{15} 1MeV n_{eq}/cm^2

Cooling: two-phase CO_2 @ −35° C

Forward geometry

Reconstruct B mesons
Detectors very close to the beam line

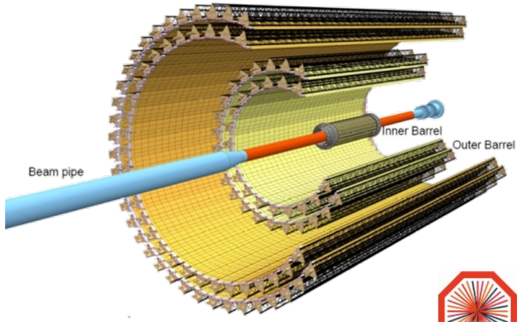
Active area: ~10 m^2

NIEL ~ 10^{13} 1MeV n_{eq}/cm^2

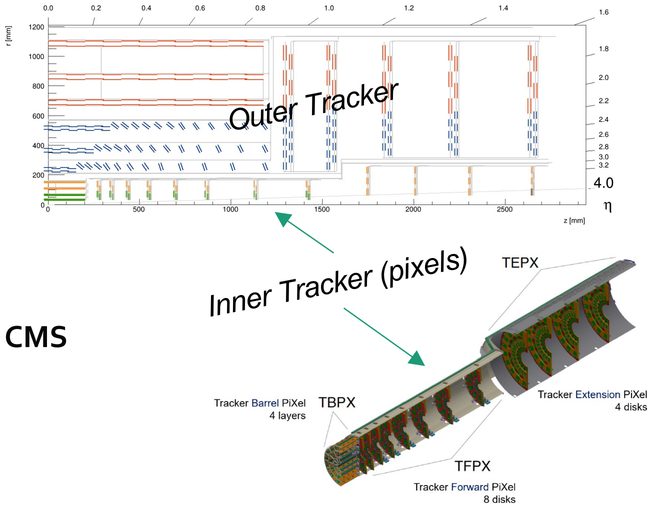
Cooling: water at 18° C

Barrel geometry

Heavy ion physics
Optimal performance down to low-pT



ITS



CMS

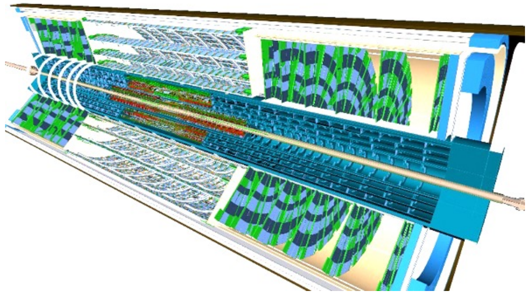
Active area: 5÷13 m^2 Inner Trackers
~200 m^2 Outer Trackers

NIEL ~ 2÷3 $\times10^{16}$ 1MeV n_{eq}/cm^2

Cooling: two-phase CO_2 < −35° C

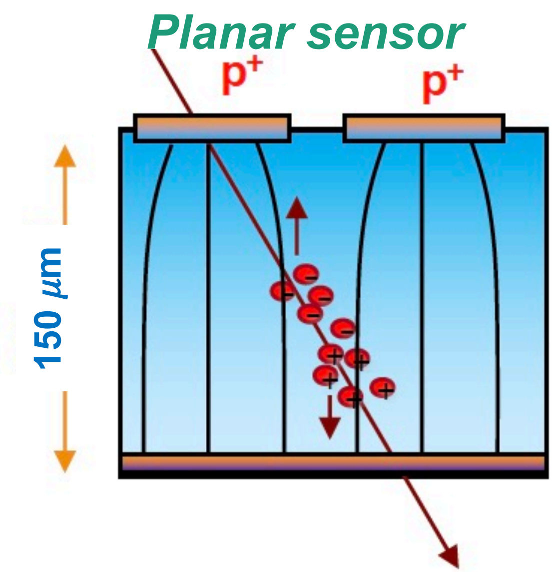
Full angular coverage

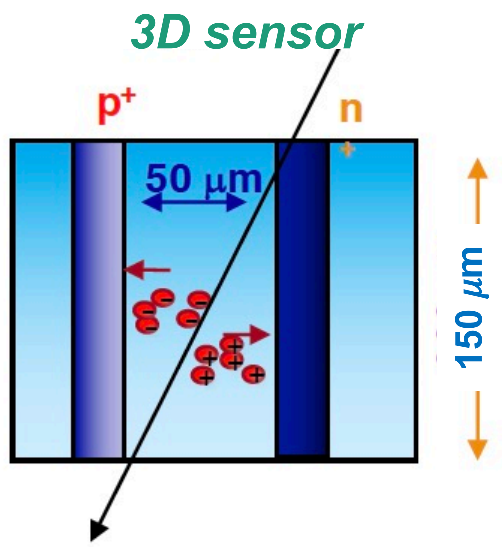
Omni-purpose detectors
Good performance in the whole energy range

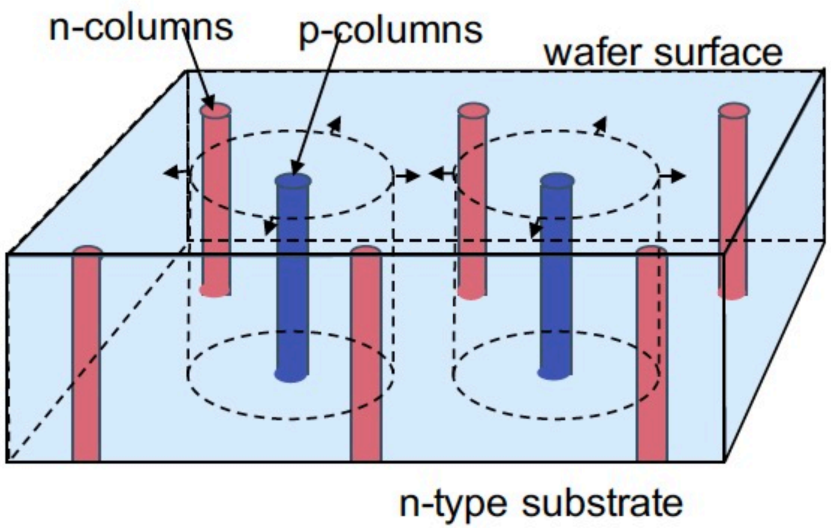


ITK
PIXEL

The highest radiation regions: 3D sensors







Drift path different from particle path (generating the signal)

Shorter drift path:

- **less prone to charge trapping – better charge collection efficiency after heavy irradiation**
- **depletion at much lower bias voltage – mitigate power dissipation from leakage current**

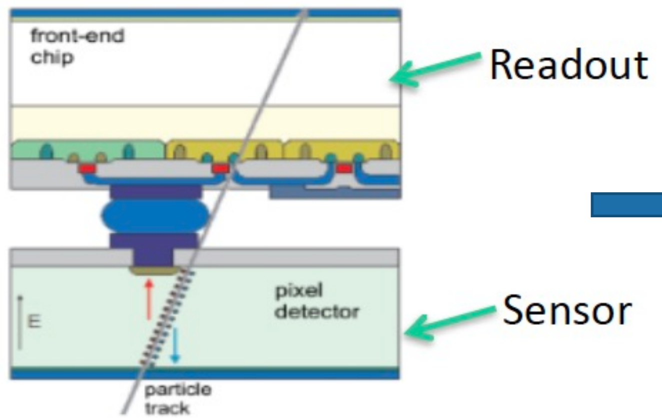
Some inefficiency for orthogonal particles

Complex fabrication, higher cost

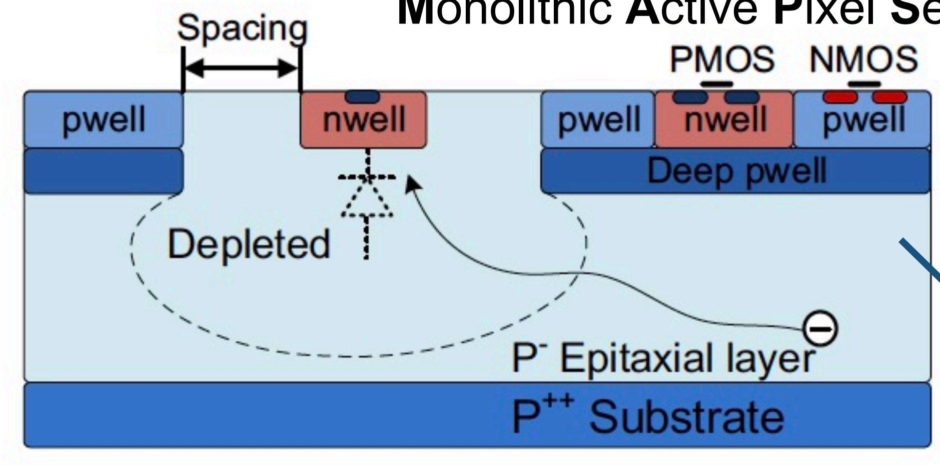
Baseline for the innermost layer(s) of the ATLAS and CMS Trackers

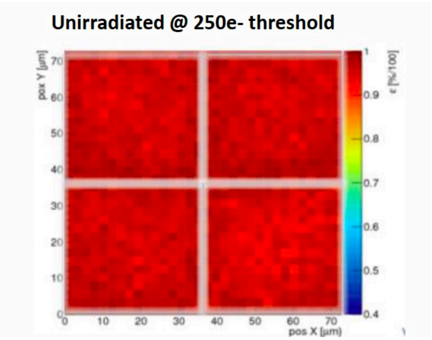
Lower radiation, lower rates, lowest mass: MAPS

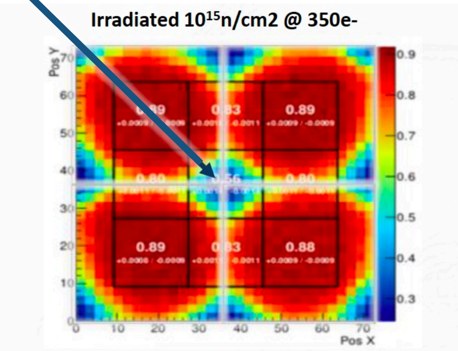
Hybrid detector



Monolithic Active Pixel Sensor







MAPS: sensor and readout integrated in the same silicon wafer (CMOS process)

Lower mass

Easier fabrication and testing

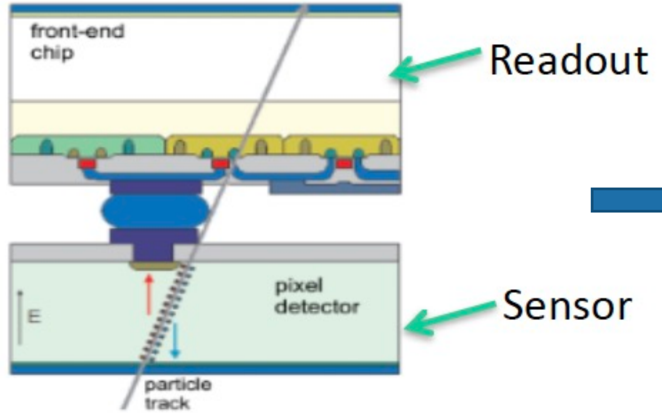
Constraints in the electronics design ⟶ limited rate capability

Limited depletion region ⟶ limited radiation tolerance

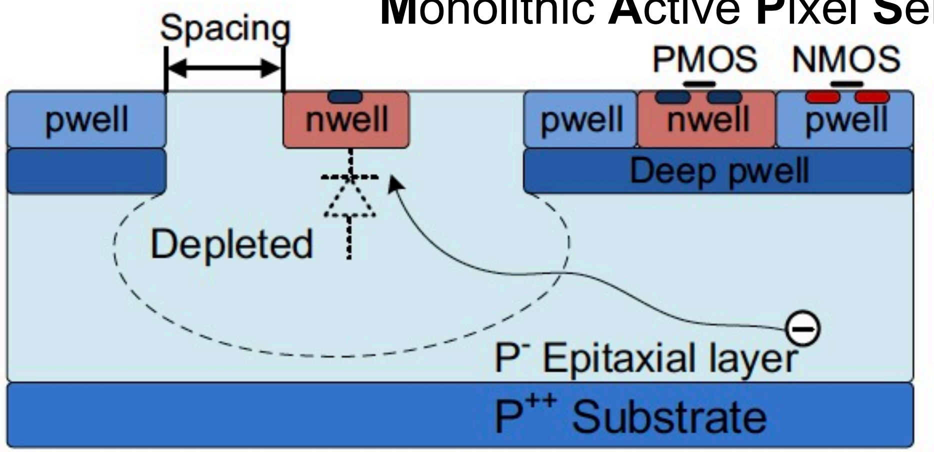
Technology used in the ALICE Tracker

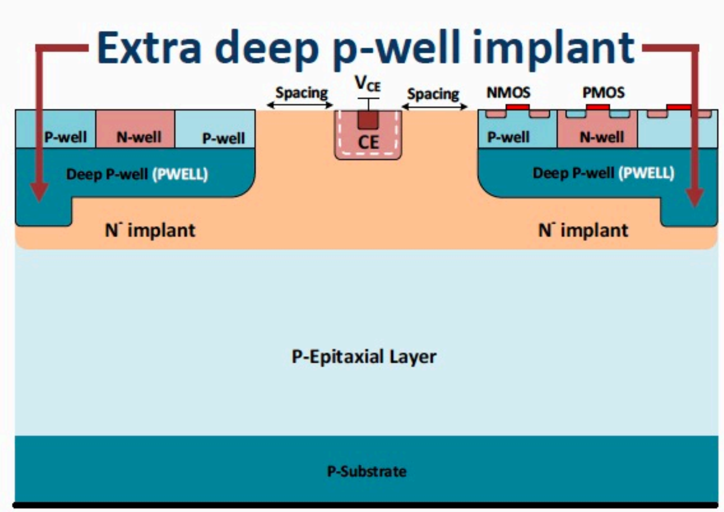
Lower radiation, lower rates, lowest mass: MAPS

Hybrid detector



Monolithic **A**ctive **P**ixel **S**ensor

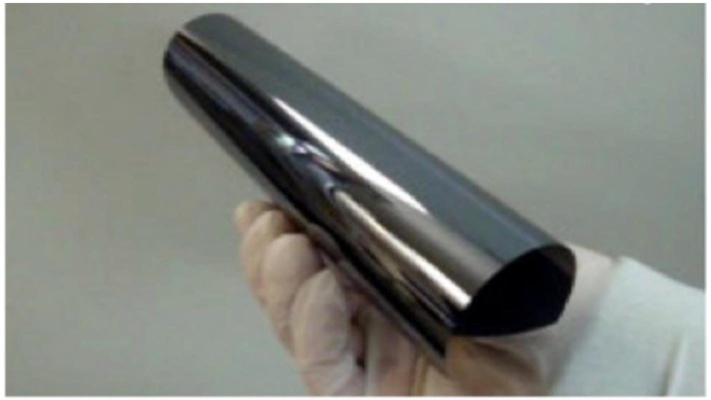




R&D ongoing to extend radiation tolerance

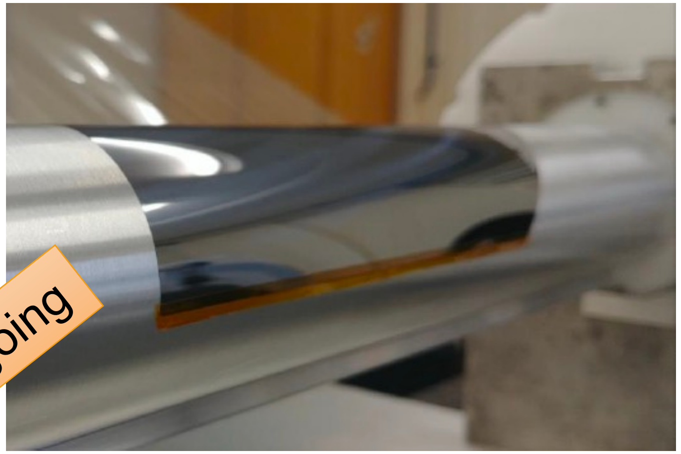
Requires process modifications

Beyond MAPS: curved MAPS!



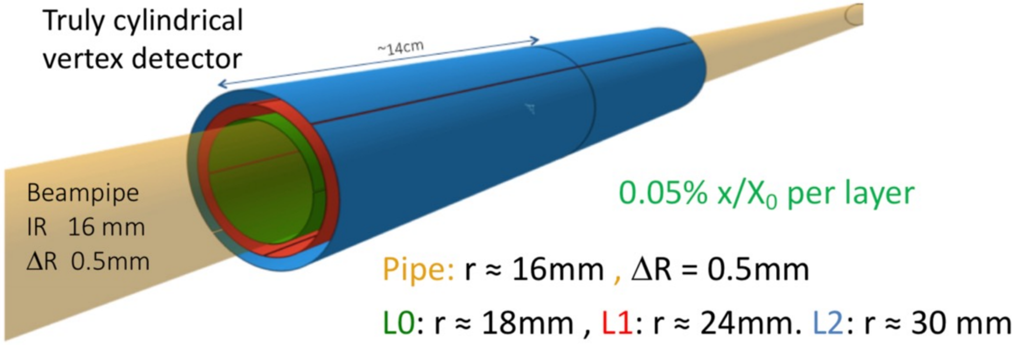
Very thin silicon wafers can be bent

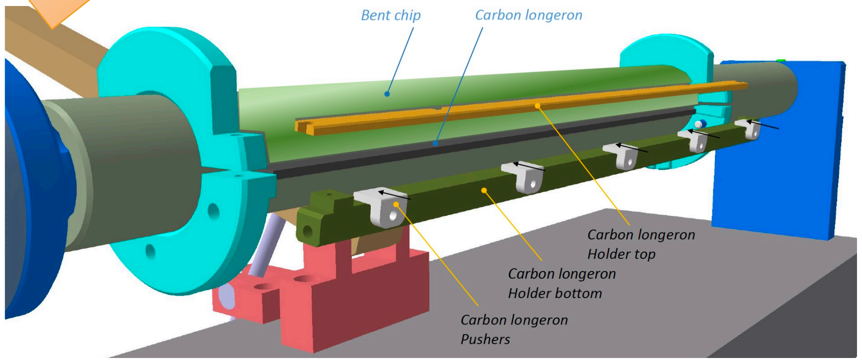
Possibility of ultra-light detecting layers with bent MAPS
Sensors thinned to ~ 30 μm can be bent with a radius of 10÷20 mm



R&D ongoing

Technology chosen for the next upgrade of the 3 inner layers of the ALICE Tracker





Mechanical structures

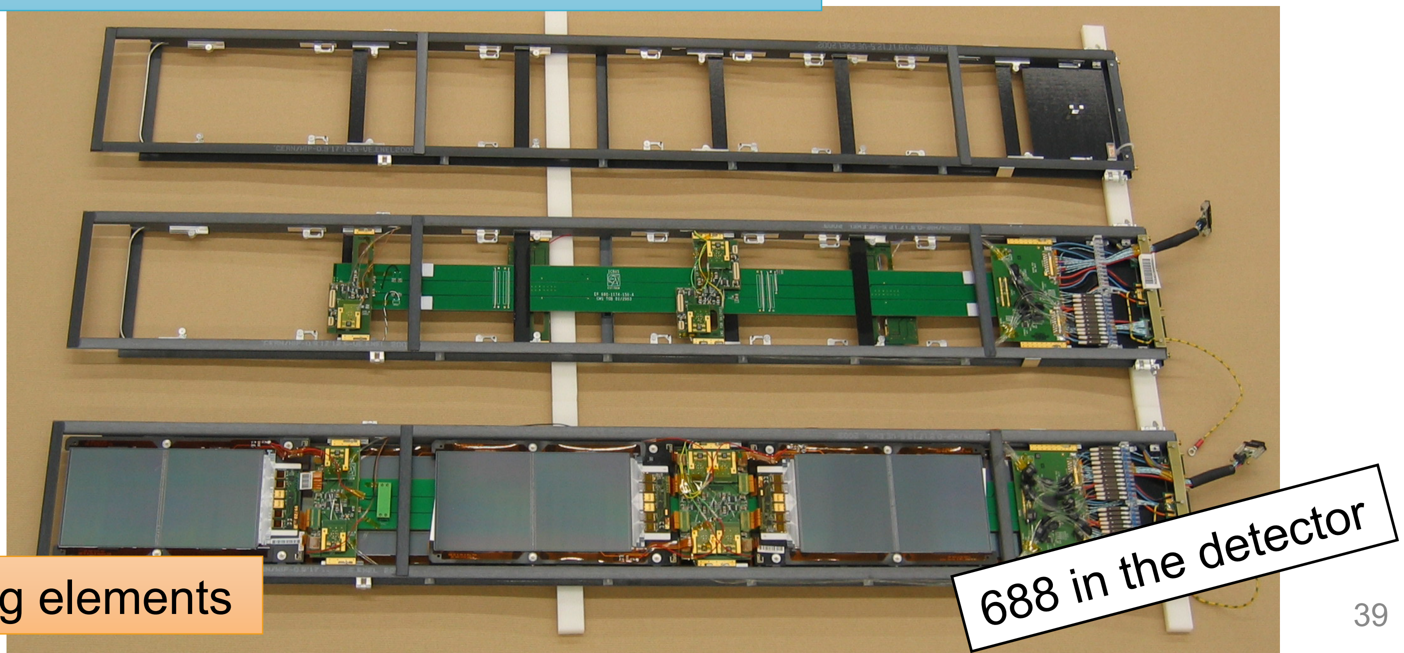
In a Tracker, mechanical structures contribute to the detector performance as much as sensors and readout electronics

- Minimize inactive material
- Provide required mechanical stability
- Provide cooling to sensors and electronics

Mechanics and cooling must be designed as an integrated concept

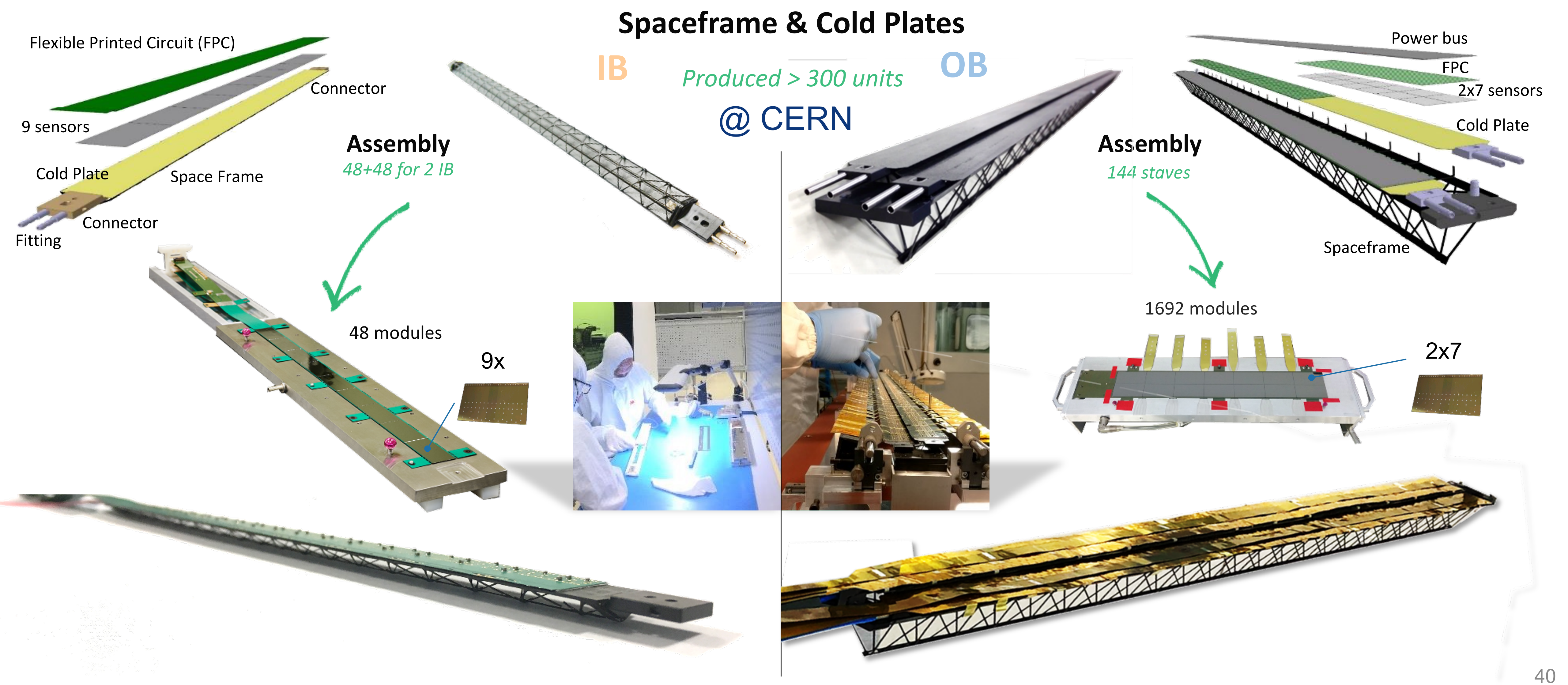
Assembly of CF profiles and Alu cooling elements

Example #1: the CMS Tracker Outer Barrel



Mechanical structures

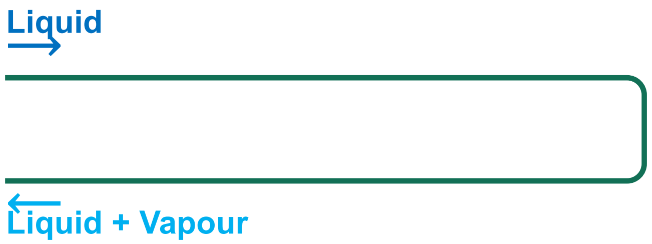
Example #2: the ALICE ITS

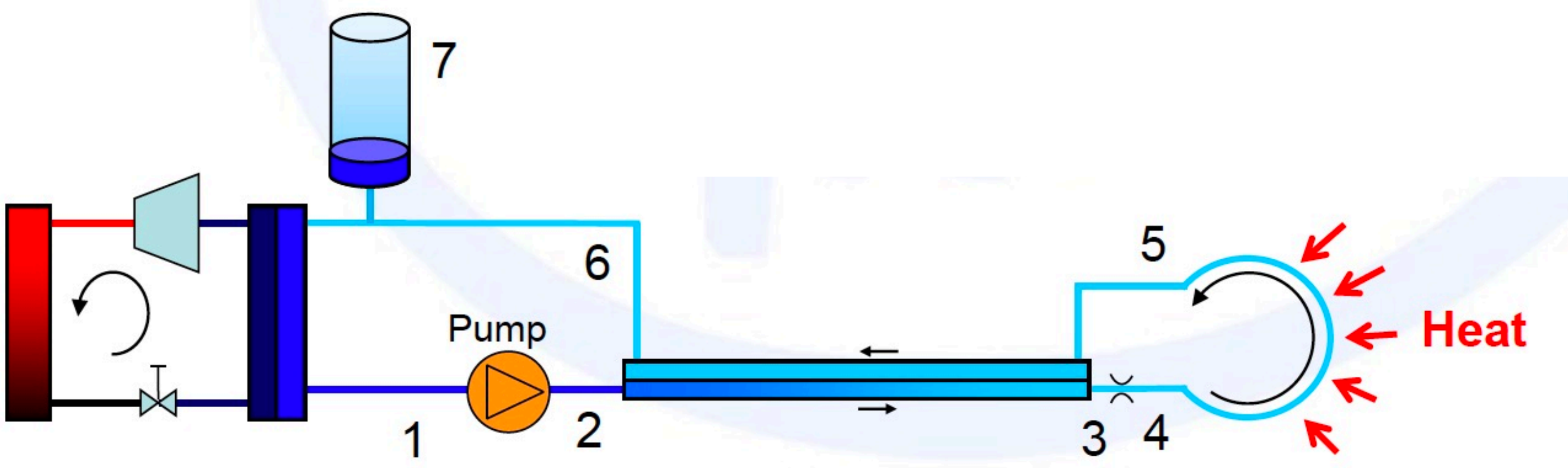


CO_2 evaporative cooling

Many present/past detectors:
low-temperature cooling with liquid fluorocarbon (e.g. C_6F_{14})

Some present and most future systems:
Two-phase CO_2





CO_2 evaporative cooling

Advantages:

- Large latent heat of evaporation ⟶ less fluid, smaller pipes
- Low liquid viscosity ⟶ small pipes
- High heat transfer coefficient ⟶ small thermal contacts
- High pressure ⟶ OK with high pressure drop, small pipes

⟶ Large saving in material compared to liquid cooling

In addition:

- **Environmentally friendly. Does not get activated.**
- **Practical T range for detector applications -45^0C to $+25^0$C**

Difficulties:

High pressure (> 100 bar) requires strict QC on pipes and joints

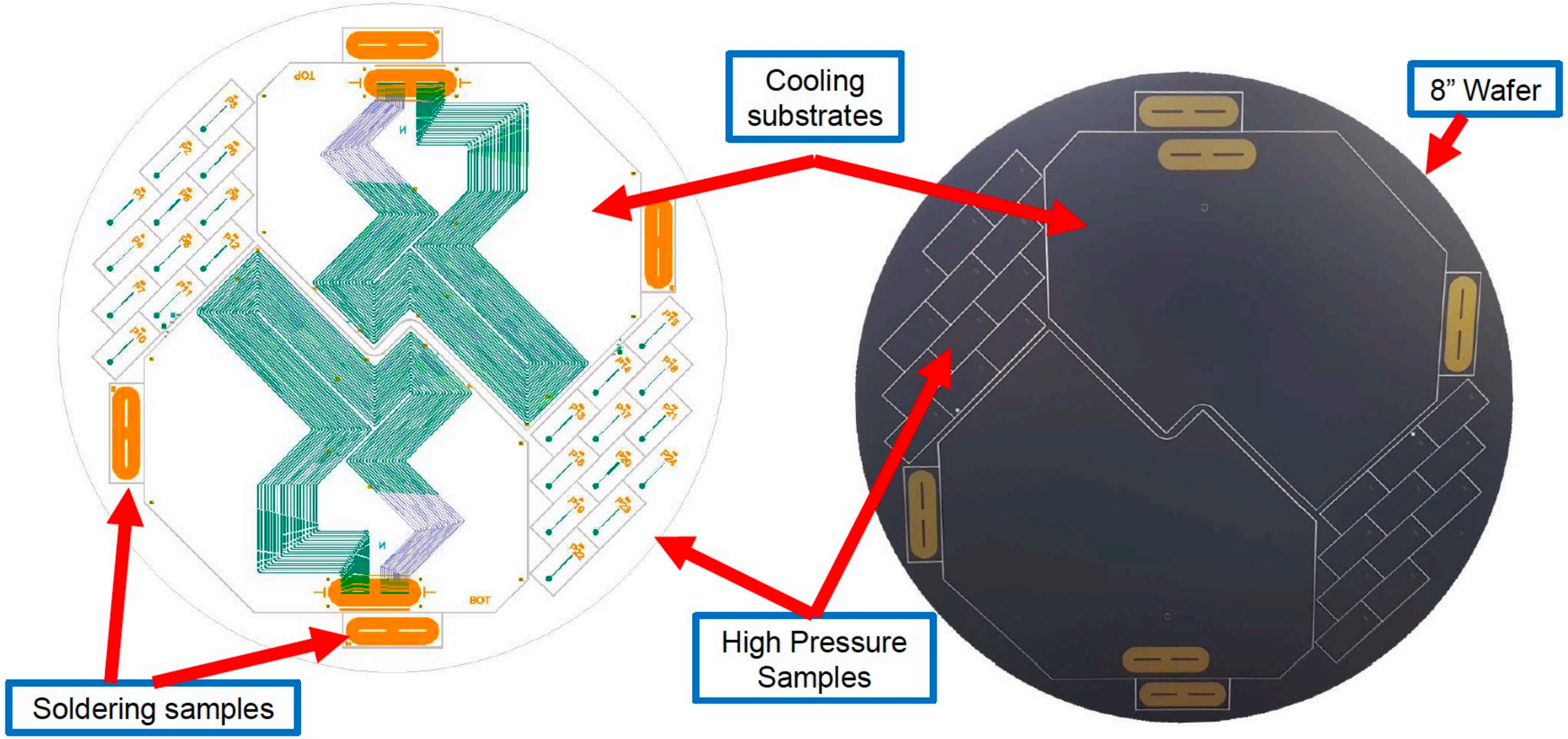
Much more complex controls than a liquid monophase system

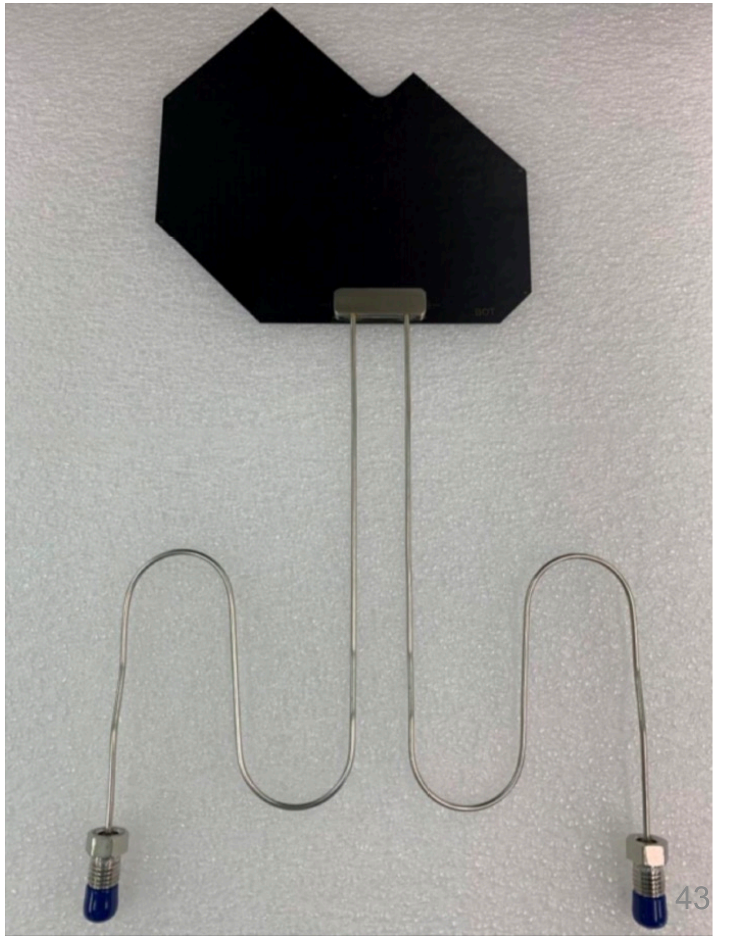
Ensure evaporation, avoid dry out, ensure flow balance in parallel lines…

LHCb: micro-channel cooling

Micro cooling channels realized in a silicon wafer for the LHCb Tracker upgrade
Technology similar to sensors and chips!

Qualified for high-pressure CO_2 operation





LHCb: micro-channel cooling

Micro cooling channels realized in a silicon wafer for the LHCb Tracker upgrade
Technology similar to sensors and chips!

Qualified for high-pressure CO_2 operation

Minimal material budget (500 μm silicon)
Ideal thermal contact to chips – with no CTE mismatch

Complex and expensive fabrication
Challenging connectivity

Perfect solution for the (relatively) small LHCb tracker!

Power distribution: DC-DC conversion

More advanced ASICs technologies require larger and larger current at lower voltage

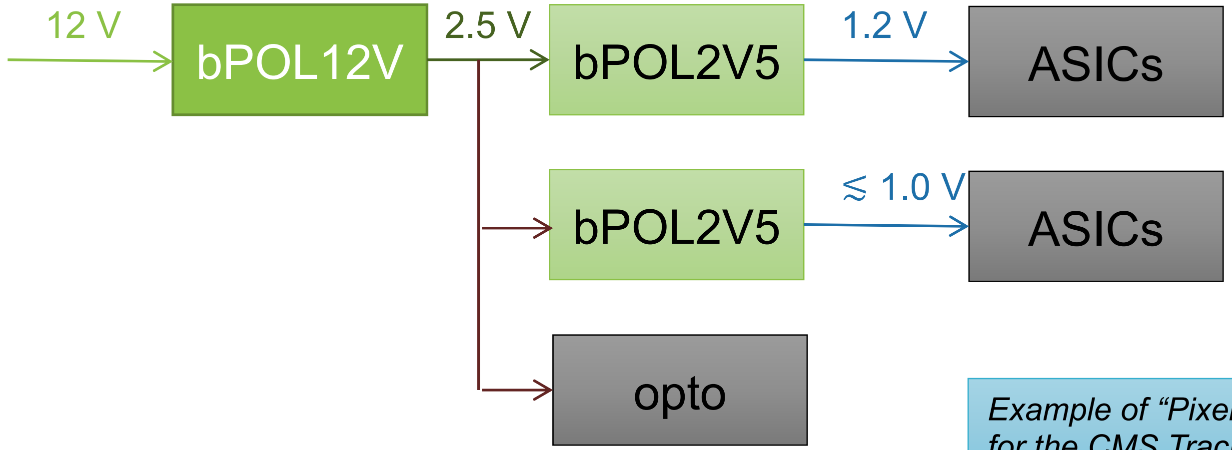
Direct powering over long cables is no longer an option – huge cross section of conductors

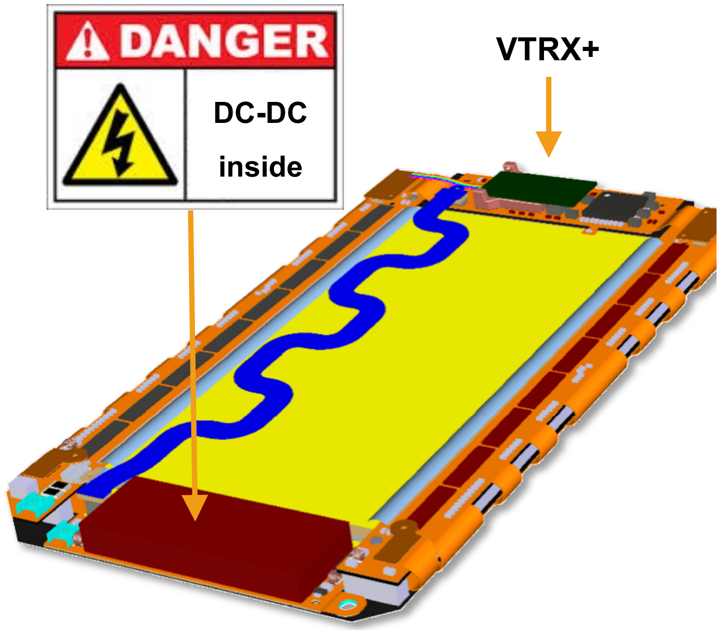
Point-Of-Load DC-DC converters enable to bring in current at higher voltage

Large saving in cross section of conductors

Some penalty in efficiency (70 ÷ 80%) and some added material inside the detector

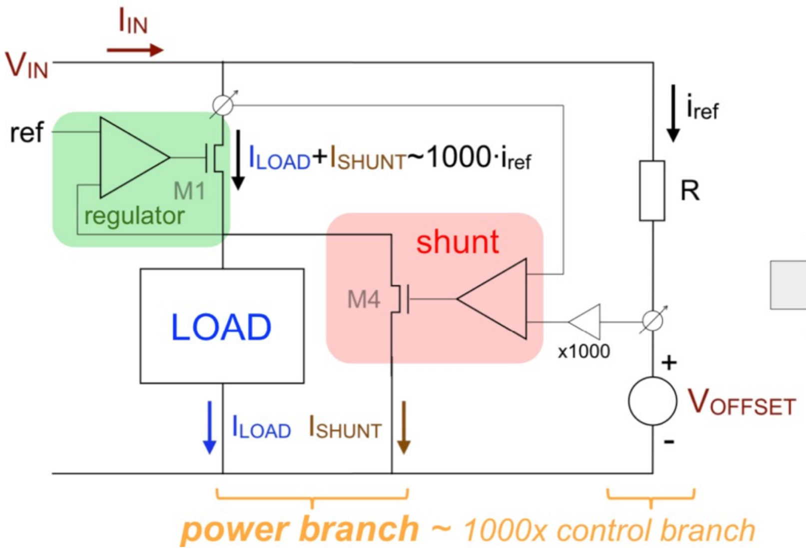
Limited radiation tolerance (not suitable for the innermost layers in ATLAS and CMS)

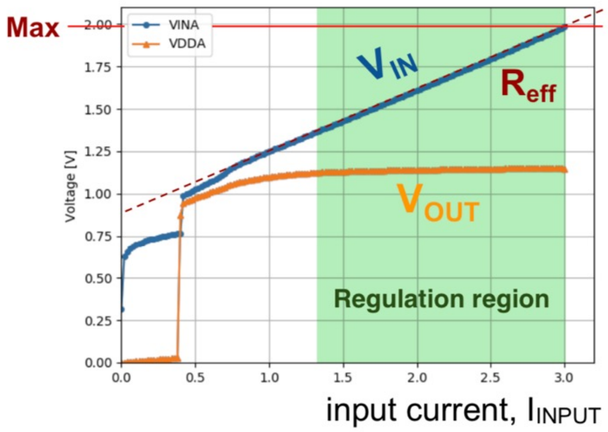




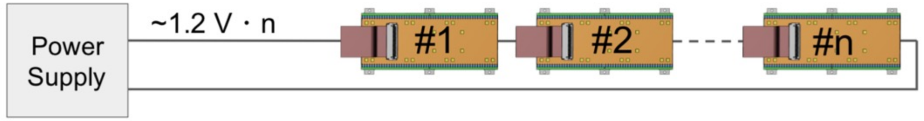
Example of "Pixel-Strip module" for the CMS Tracker upgrade

Power distribution: serial powering





For the upgrade of the ATLAS and CMS Inner Trackers

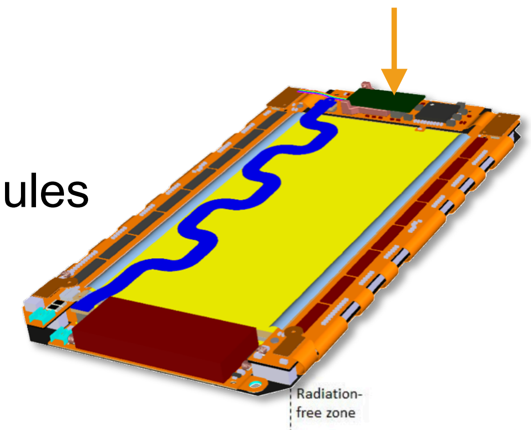


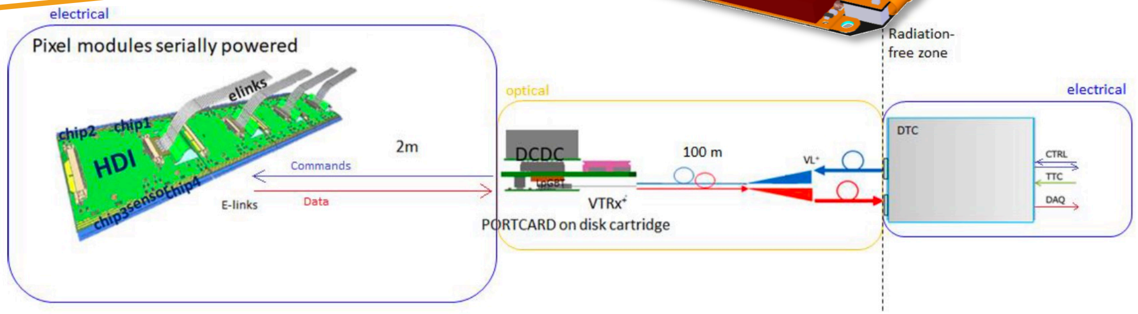
- **On-chip shunt-LDO regulator derives a constant voltage from a fixed input current**
- **Additional current flows through the shunt**
- **Requires voltage and current headroom (overall efficiency ~ 70%)**
- **Integrated on-chip solution – no additional components**
- **Radiation hard (as much as the chip…)**
- **Suitable for parallel applications (e.g. separate regulators for digital and analogue parts of the chip)**
- **Each module has a different ground level – novel system design!**

Current and future data links

Electro-optical transceiver (VTRX+) implemented "on-board" or relatively close to the modules
Limited radiation tolerance, additional components and powering infrastructure
E.g. CMS Tracker upgrade:

on-module optical conversion on the Outer Tracker
up to 2m electrical links in the Inner Tracker

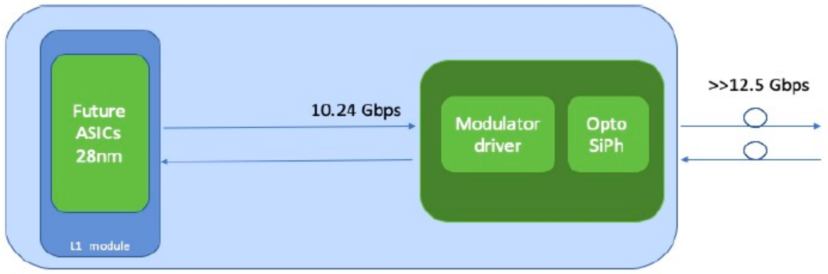


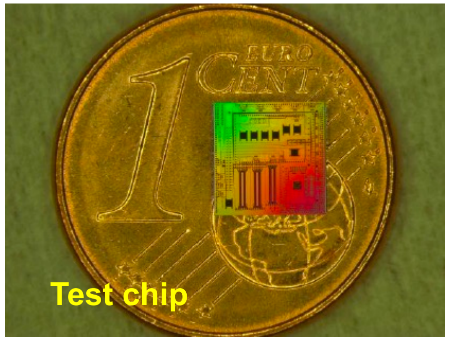


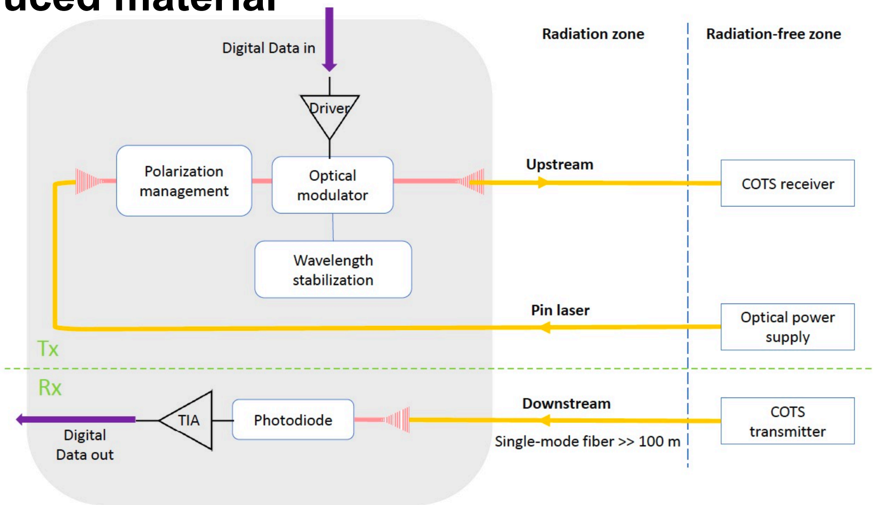
Future: silicon photonics

Light source in the back end
Optical modulator integrated on module
Target: higher radition hardness, higher bandwidth capability and reduced material

R&D ongoing!







Conclusions

Silicon detector technologies are more and more widely used in the design of tracking detectors for HEP
Not only in high-rate, high-radiation environments

Developing a state-of-the-art Tracker for HEP requires innovative solutions in many different domains

Sensors	**Mechanics**	**Readout electronics**
Cooling	**Data links**	**Power distribution**

There are many other interesting topics and novel developments that I did not cover
Tracking and alignment
Detector calibration
"Intelligent" modules with p_T filtering capability
Precision timing and "4D tracking"
….

A rich and fascinating research field!

Thank you for your attention