

Detectors for Particle Physics

Future Projects, Requirements, R&D

Ulrich Husemann, Karlsruhe Institute of Technology
Astroparticle/Particle Physics Workshop
Zeuthen, October 6–8, 2025



Image credit: CERN

Open Questions in Particle Physics

In 2025

What is the **structure of the vacuum**?

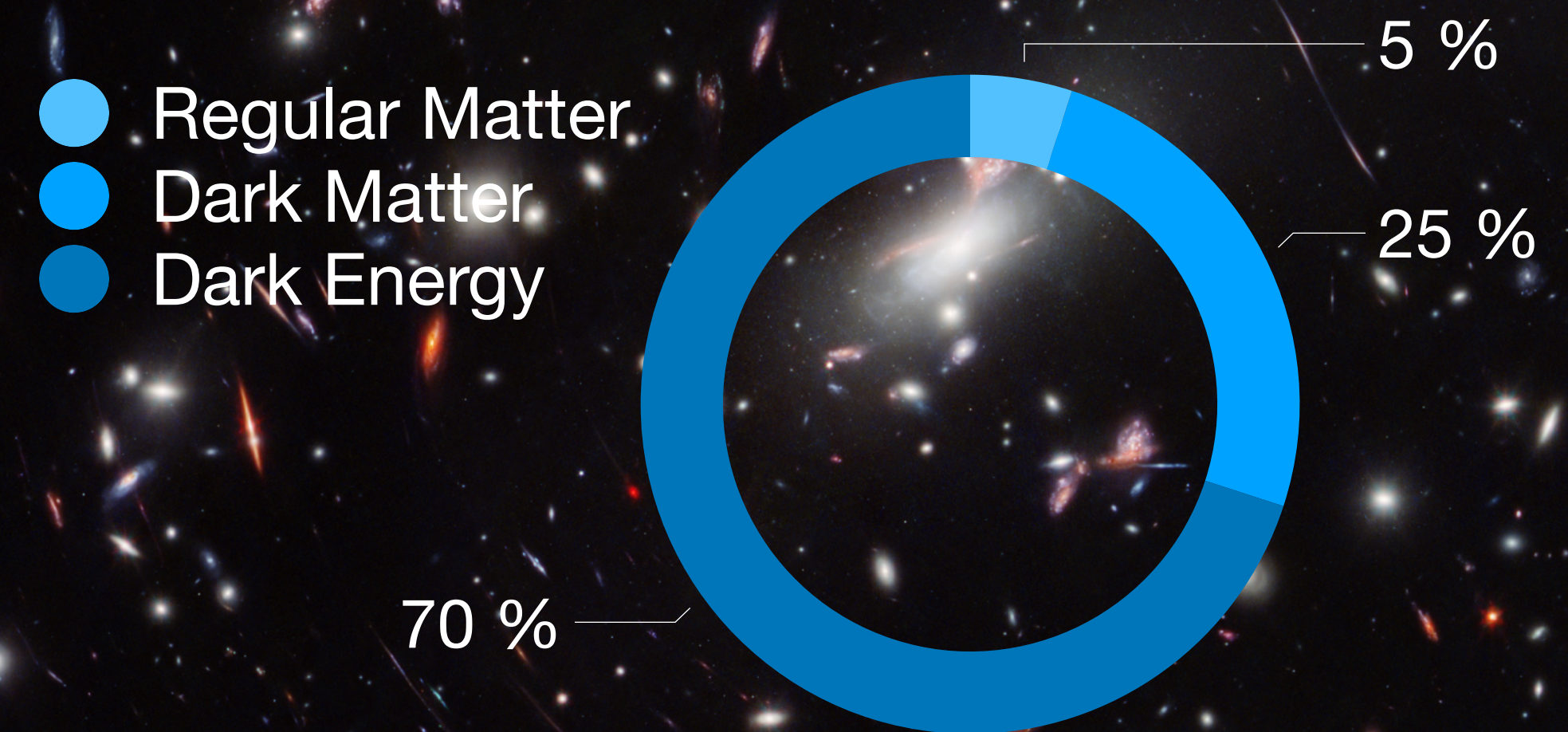
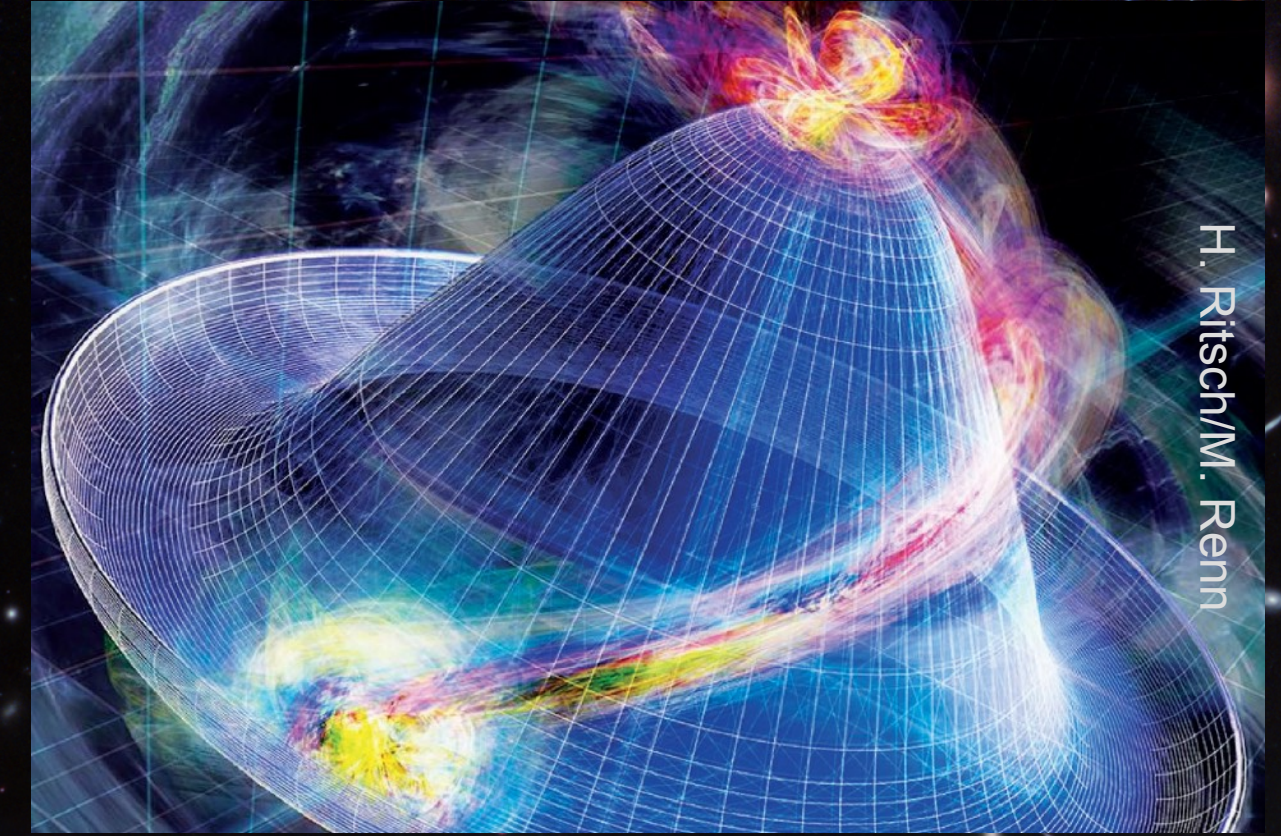
The Higgs potential.

What is the **energy content** of the universe?

Dark matter and dark energy.

Why is there so much **more matter than antimatter** in the universe?

Violation of the charge-parity (CP) symmetry.



Particle Physics – a Tool-Driven Scientific Field

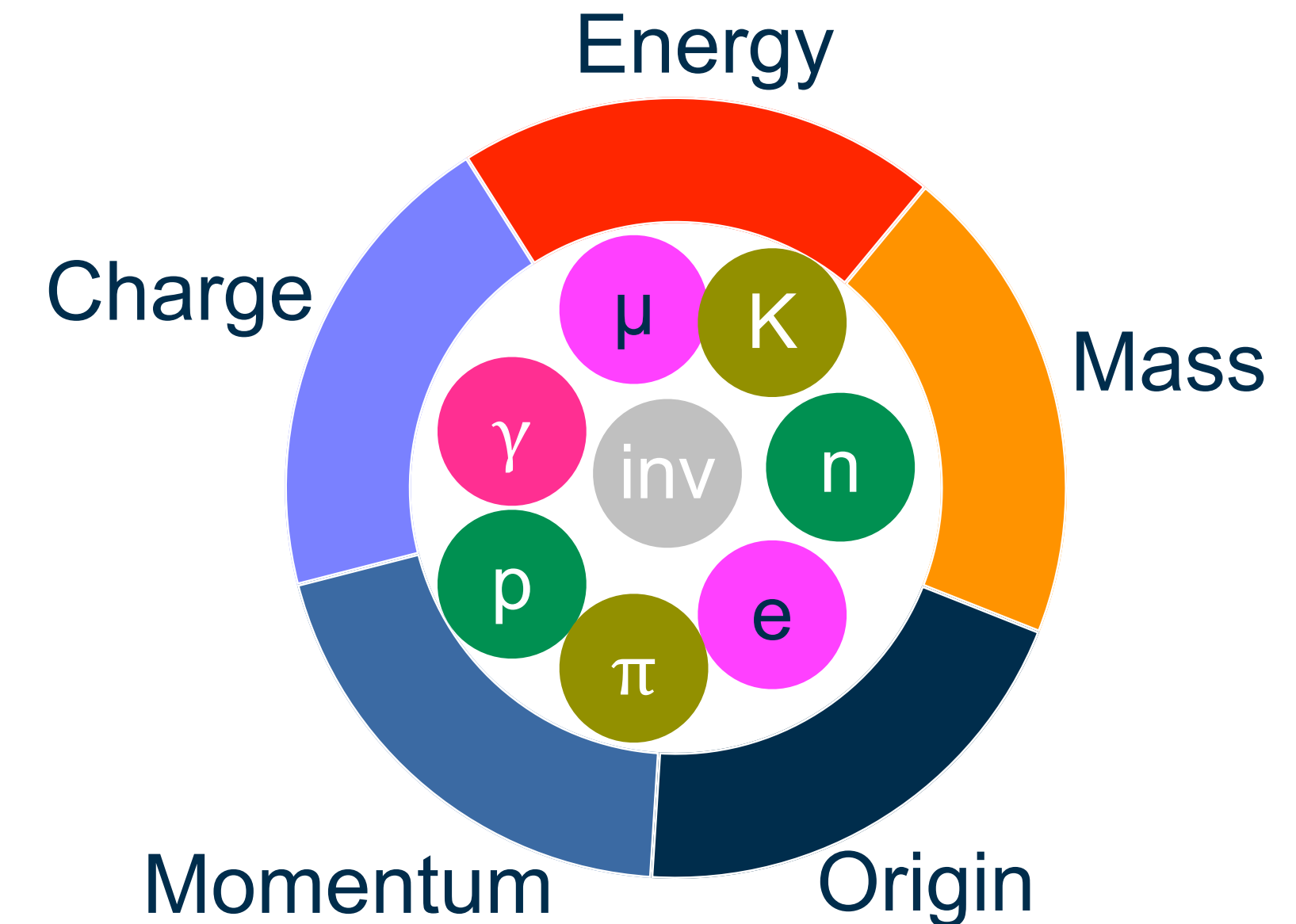
(See e.g. Galison: *Image and Logic*)

Unraveling the physics of elementary particles and their interactions: **sophisticated tools** required
→ **particle detectors, electronics and software/AI**

Basic detection task (seemingly) simple:
collect **full information** of **all** final state particles

A more detailed look reveals:

- Wide variety of technology **requirements**
- Very different **time scales** and technological **maturity**
- Widely varying **cost** and technology **dependencies**
- Very different availability of **skilled people** and **funding**



Outline of the Presentation

Task and Guiding Questions

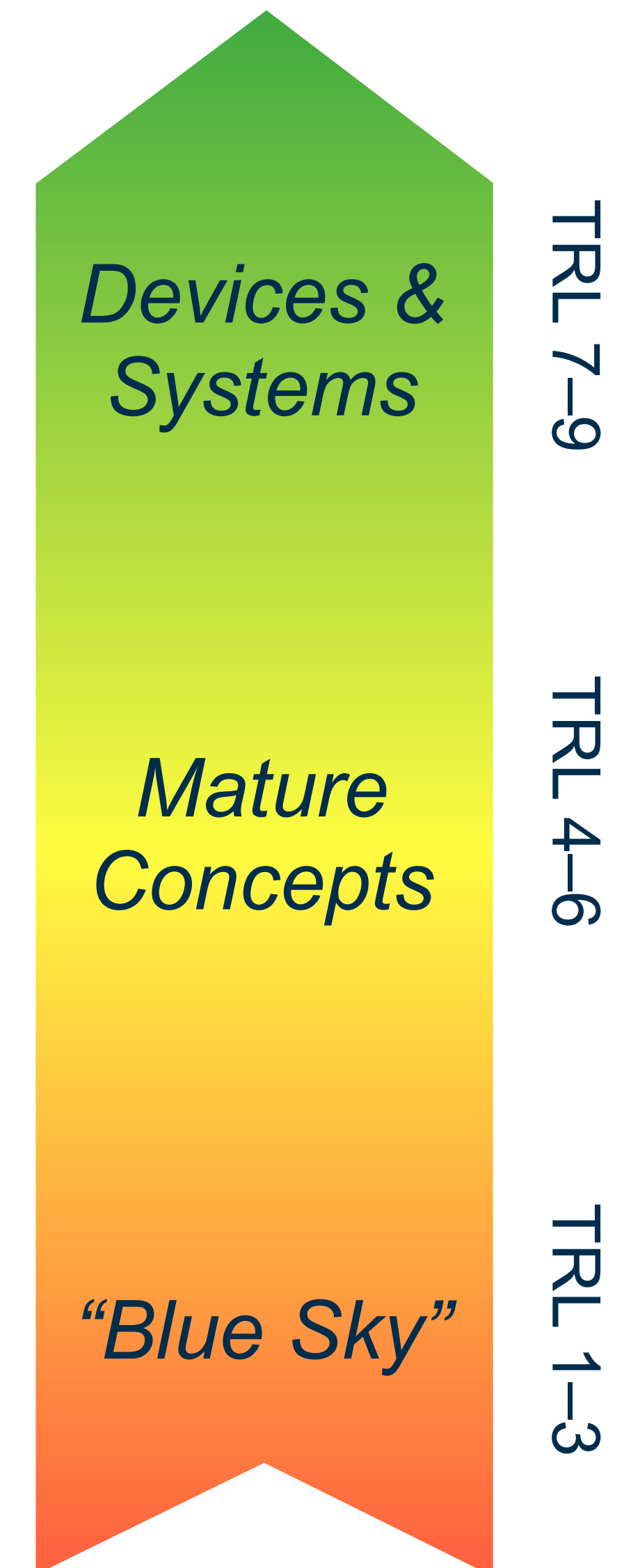
Task at hand: make sure we have the **right tools** at the **right time** to **answer open physics questions** (and possibly questions we have **not yet thought about**)

Guiding questions:

- Which **future projects drive** instrumentation development?
- Which **technologies** are **required** on which **timescale**?
- **Who will work** on instrumentation?

Detector physics is also physics!

Technology Readiness Levels (TRLs)



Collider Detectors Today

Example: CMS Experiment

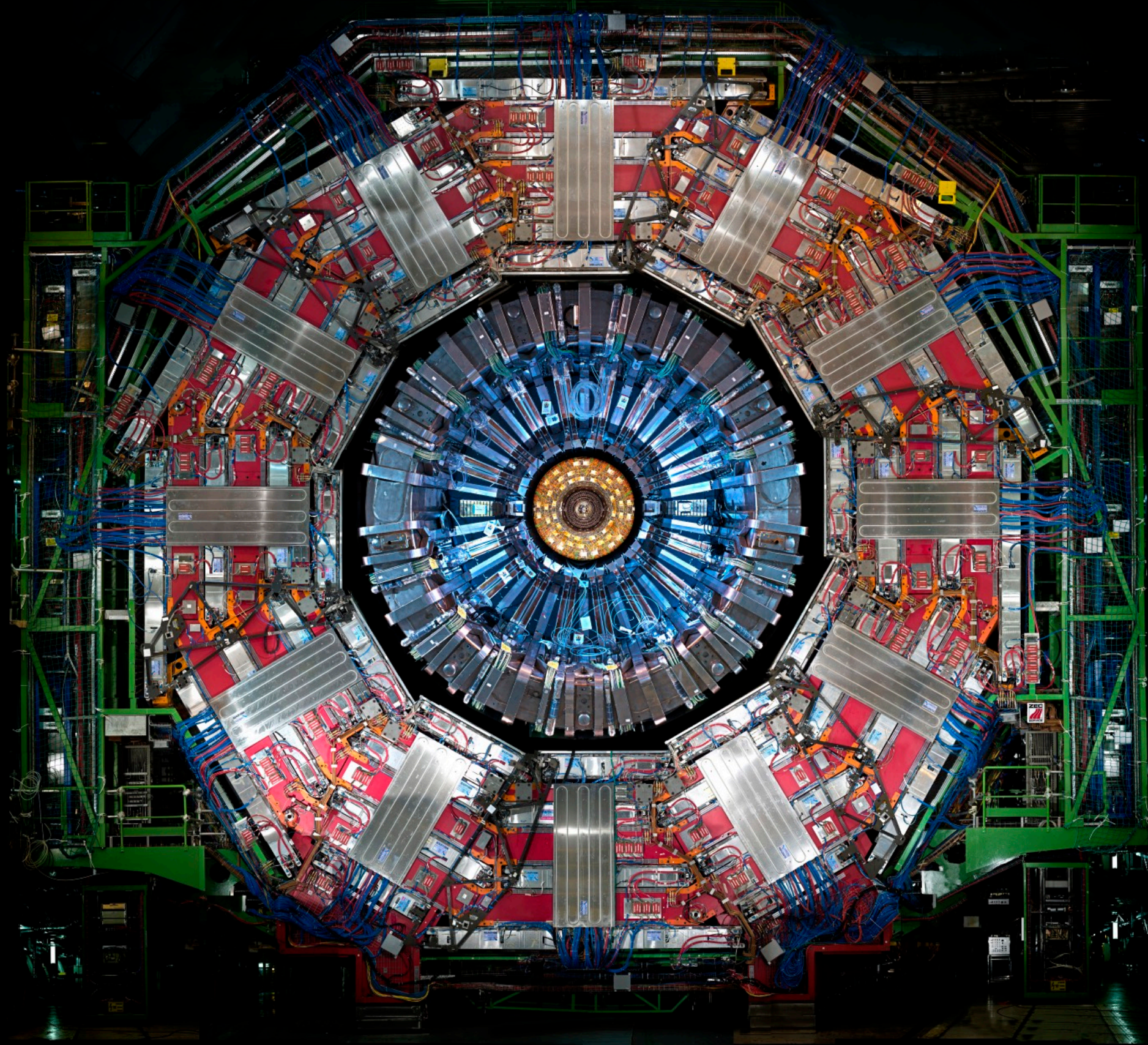
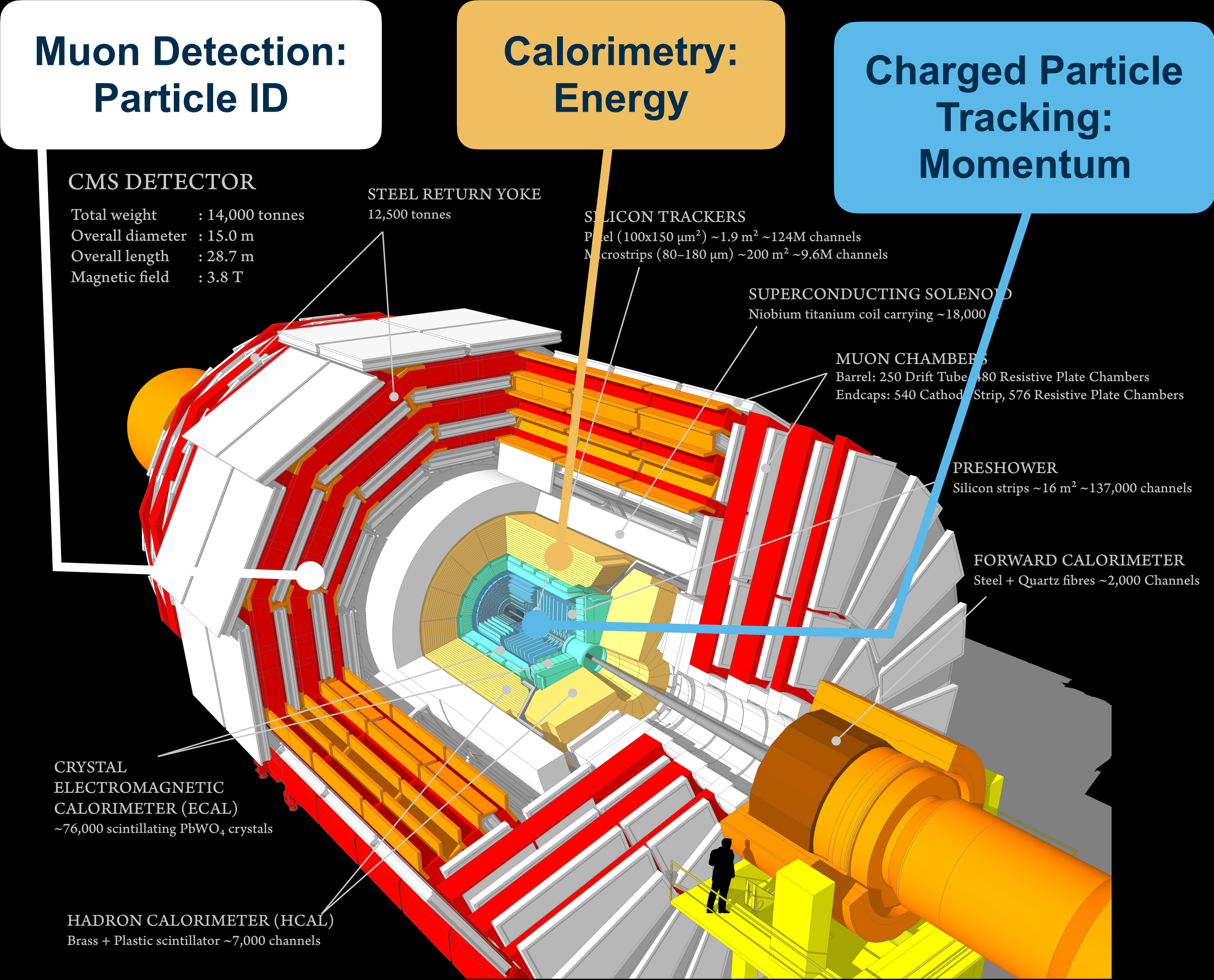


Image credit: CERN

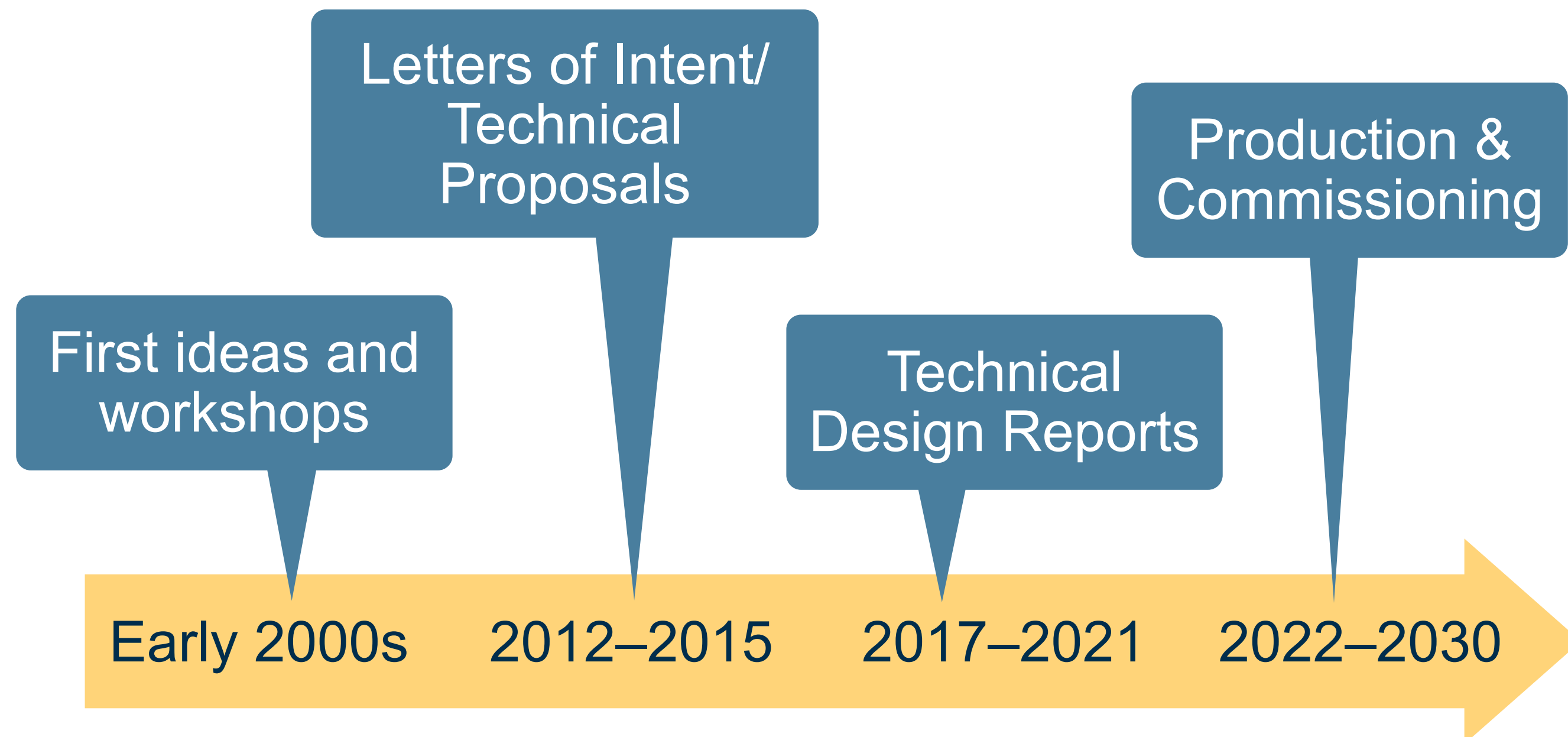


Based on [2014 J. Phys.: Conf. Ser. 513 \(2014\) 022032](#)

From R&D to Large Detectors

Typical Development Cycles: 20–30 Years

Example: **Phase-2 upgrades** of the ATLAS and CMS detectors for the **high-luminosity phase** of the LHC (HL-LHC)



Smaller-scale experiments: **shorter** development cycles, more **agile**

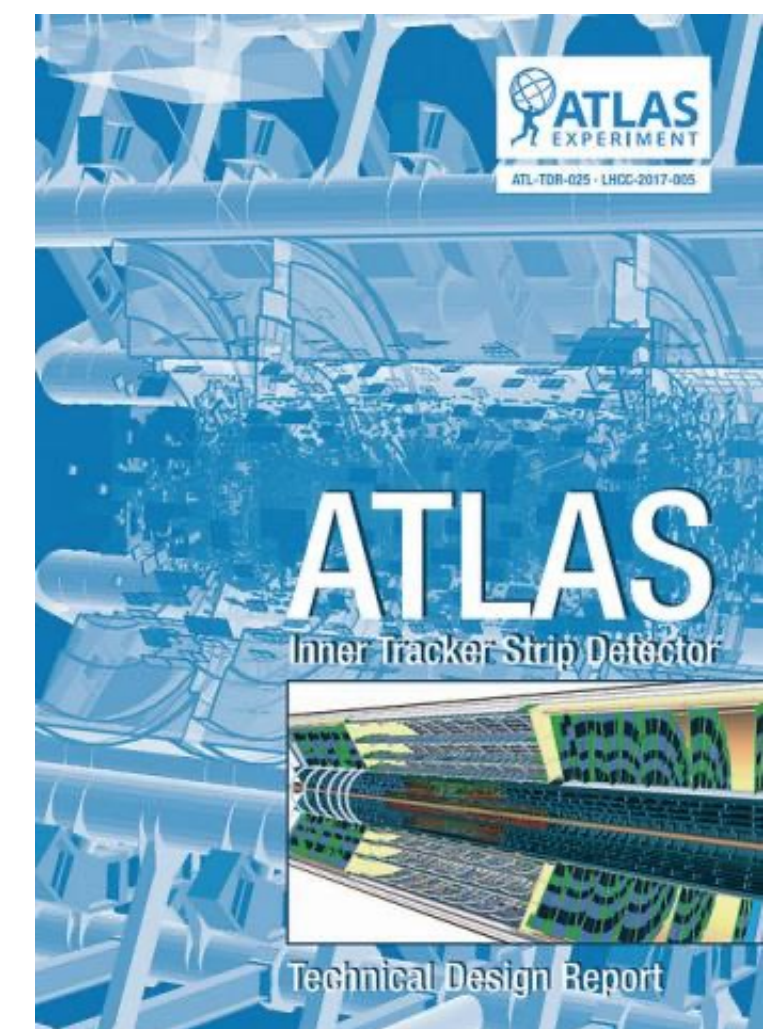
The world is **changing fast** around us new, e.g. materials science, quantum technologies, AI

Eur. Phys. J. C 39, 293–333 (2005)
Digital Object Identifier (DOI) 10.1140/epjc/s2004-02061-6

THE EUROPEAN
PHYSICAL JOURNAL C

Physics potential and experimental challenges of the LHC luminosity upgrade

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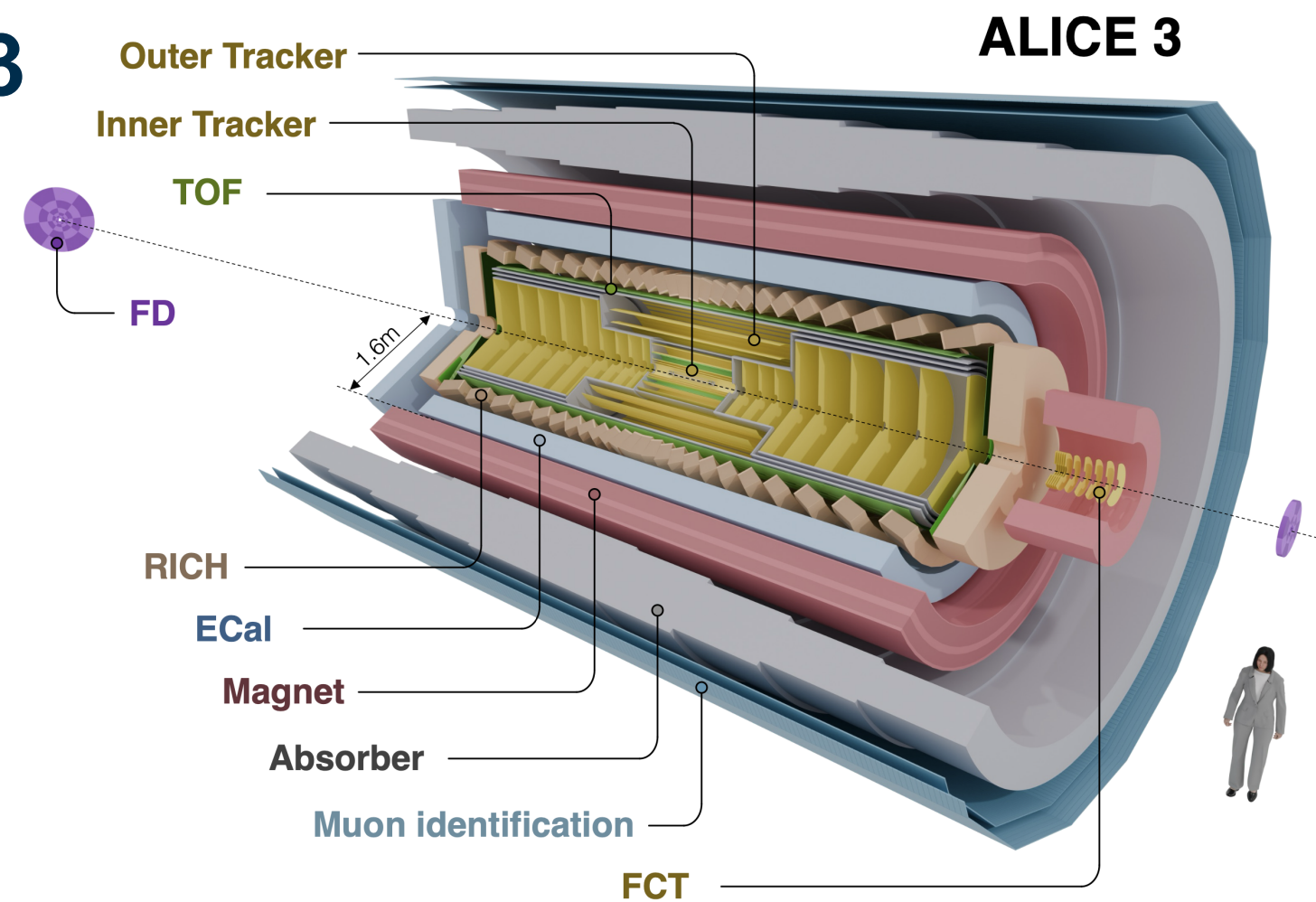


A Simplified Timeline

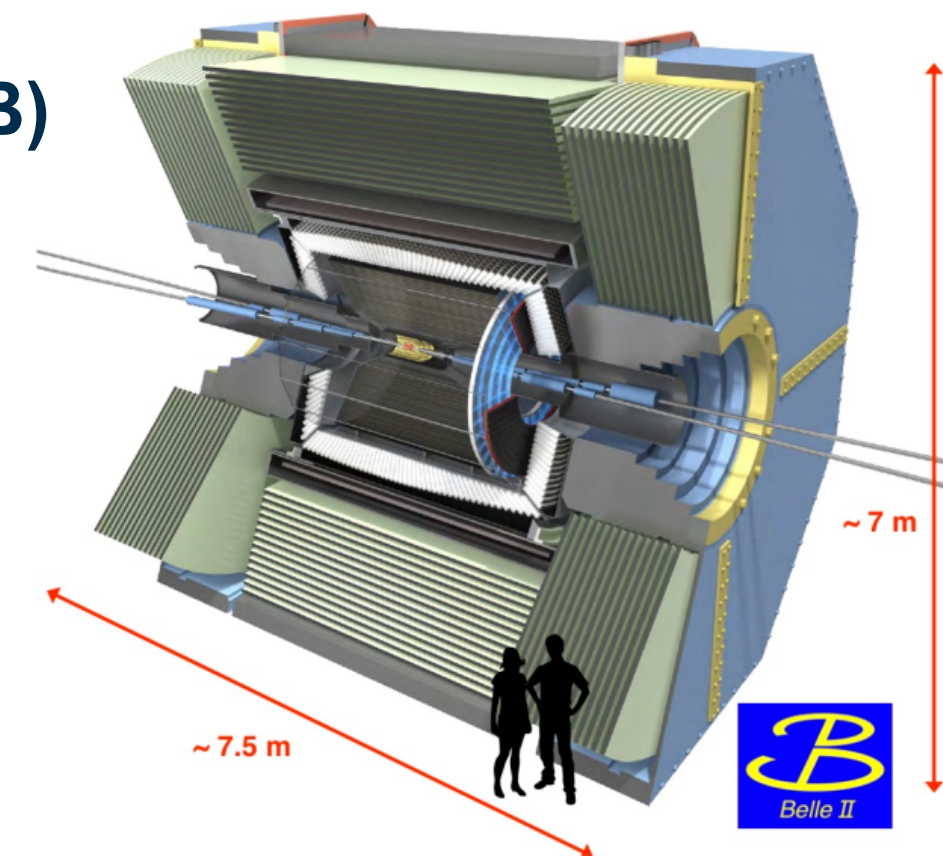
Proposed Key Collider Projects

■ Era 1: ALICE 3, LHCb Upgrade II, Belle II, ePIC

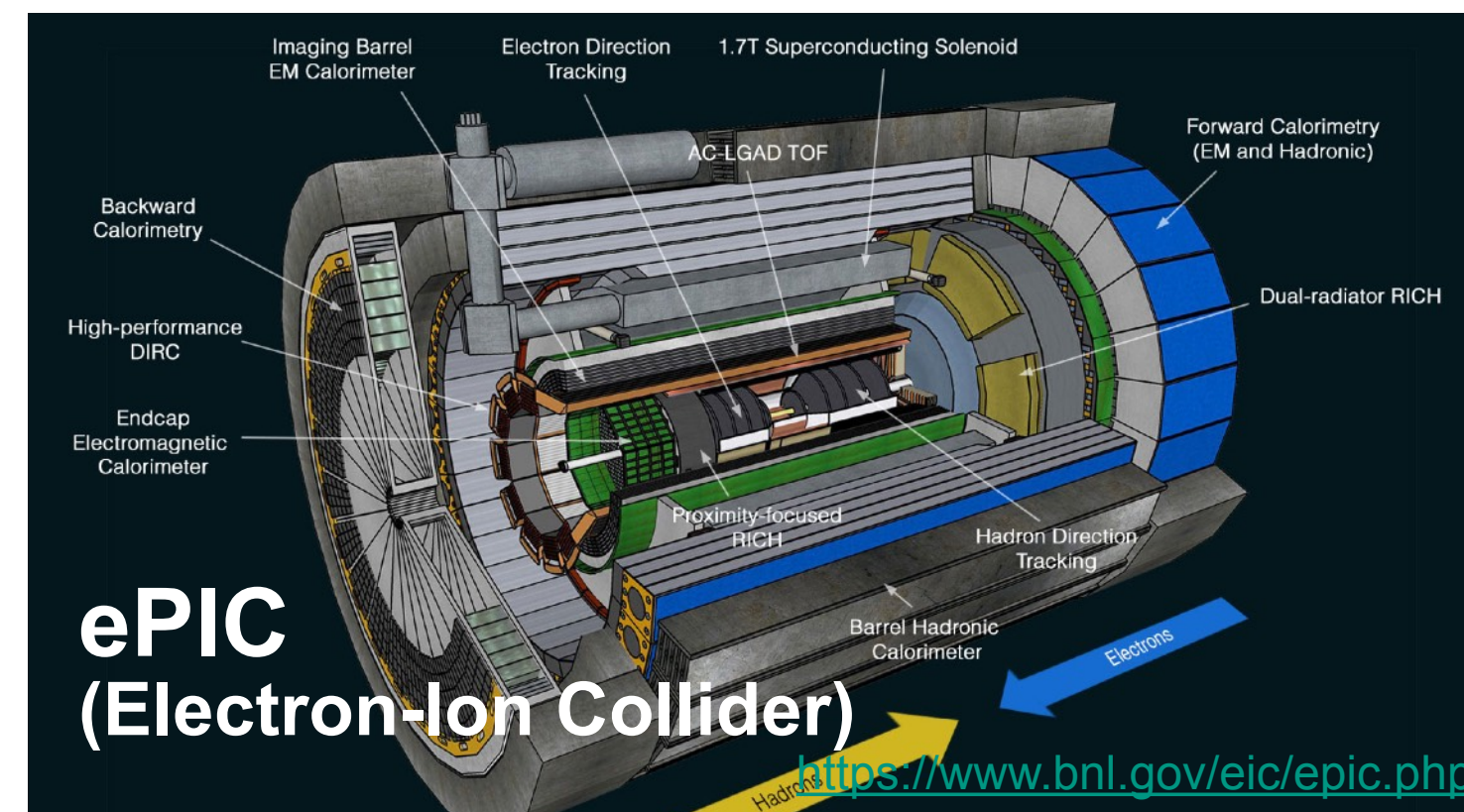
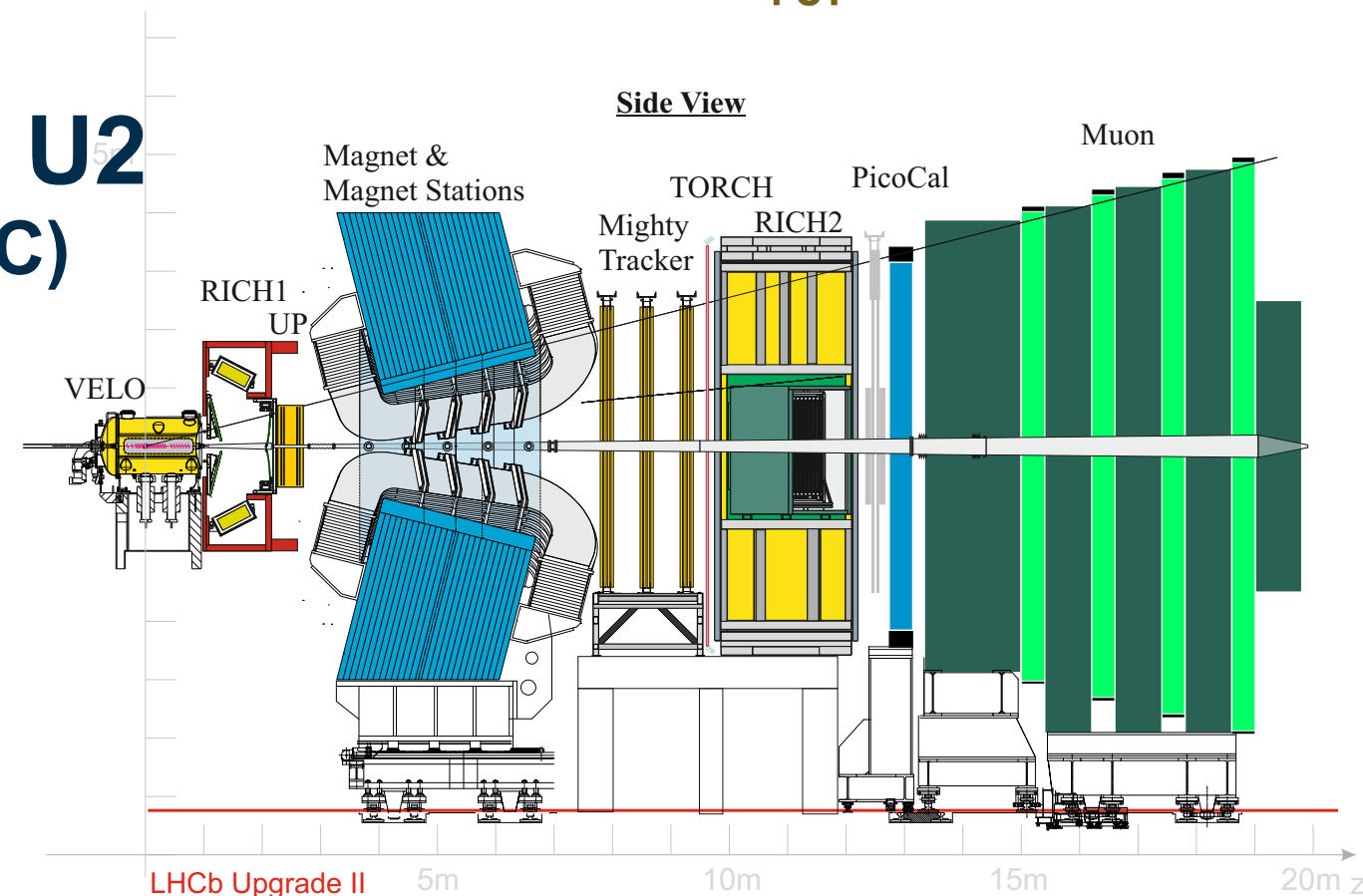
ALICE 3 (HL-LHC)



Belle II (SuperKEKB)



LHCb U2 (HL-LHC)



Today

1: HL-LHC & EIC

A Simplified Timeline

Proposed Key Collider Projects

- Era 1: ALICE 3, LHCb Upgrade II, Belle II, ePIC
- Era 2: Higgs/Electroweak/Top (HET) factory

Today

1: HL-LHC & EIC

2: HET Factory

First ECFA WORKSHOP.
on e^+e^- Higgs / Electroweak / Top Factories
5-7 October 2022, DESY / Hamburg

Topics:

- Physics potential of future Higgs and electroweak/top factories
- Required precision (experimental and theoretical)
- EFT (global) interpretation of Higgs factory measurements
- Reconstruction and simulation
- Software
- Detector R&D

The European Committee for Future Accelerators (ECFA) organises a series of workshops on physics studies, experiment design and detector technologies towards a future electron-positron Higgs/Electroweak/Top factory.

The aim is to bring together the efforts of various e^+e^- projects, to share challenges and expertise, to explore synergies, and to respond coherently to this high-priority item of the European Strategy for Particle Physics

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<http://www.desy.de/ecfa2022>

SECOND ECFA WORKSHOP
on e^+e^- Higgs / Electroweak / Top Factories
11-13 October 2023
Paestum / Salerno / Italy

Topics:

- Physics potential of future Higgs and electroweak/top factories
- Required precision (experimental and theoretical)
- EFT (global) interpretation of Higgs factory measurements
- Reconstruction and simulation
- Software
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<https://agenda.infn.it/event/ecfa2023>

3rd ECFA workshop on e^+e^- Higgs, Top & ElectroWeak Factories
9-11 October 2024
Sorbonne Université, Campus des Cordeliers, Paris

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• Physics Studies (DESY)
• Detector R&D (CERN)
• Reconstruction (BNP)
• Software (DESY)
• EFT (Munich)
• Higgs (Glasgow)
• Top (Munich MPE)
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<https://indico.in2p3.fr/e/ecfa2024>

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NUCLÉAIRE & PARTICULES

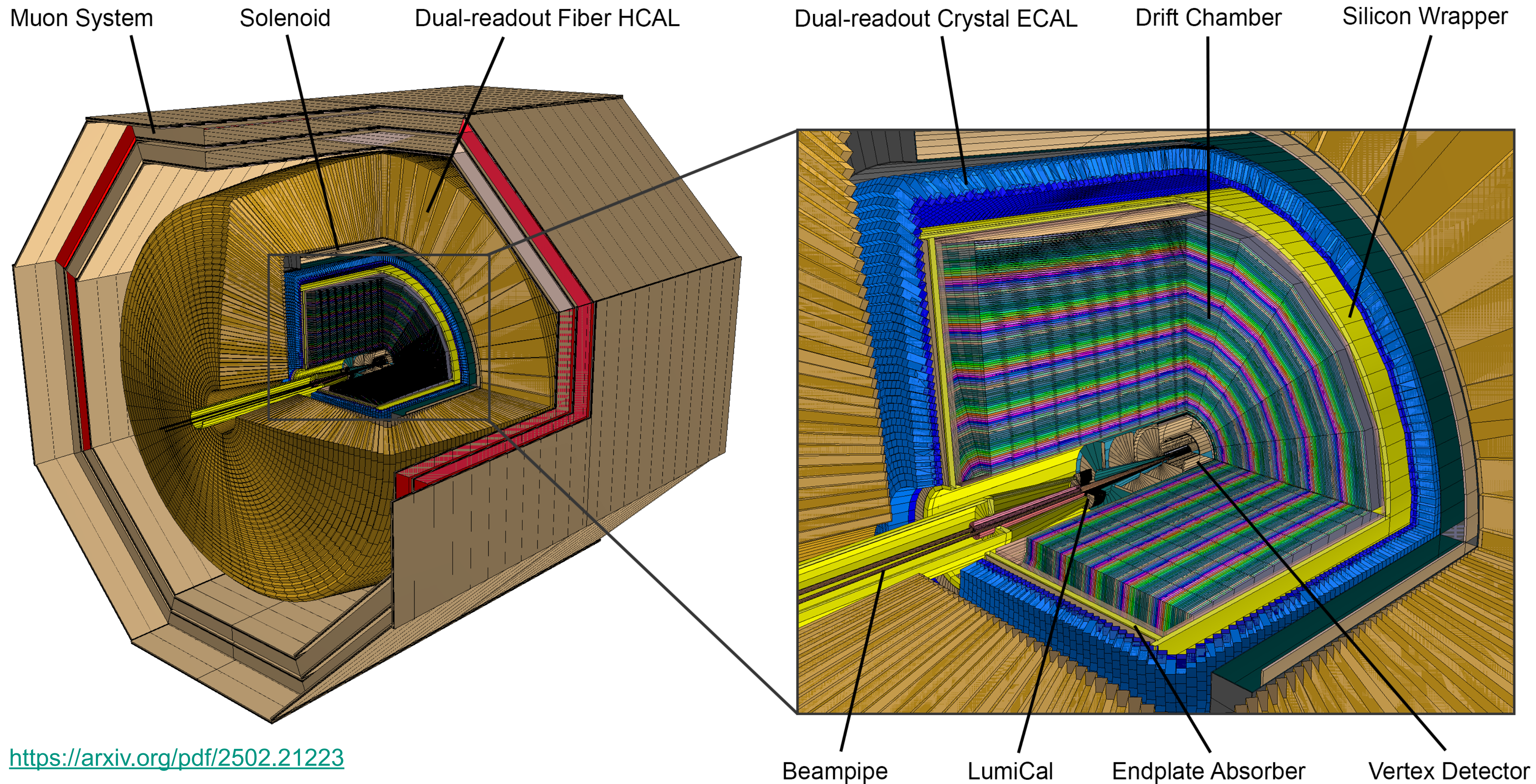
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Université Paris-Saclay

JRC Lab

Detector Concepts for a Higgs/EW/Top Factory

Example: IDEA – Dual Readout Calorimetry for the FCC-ee

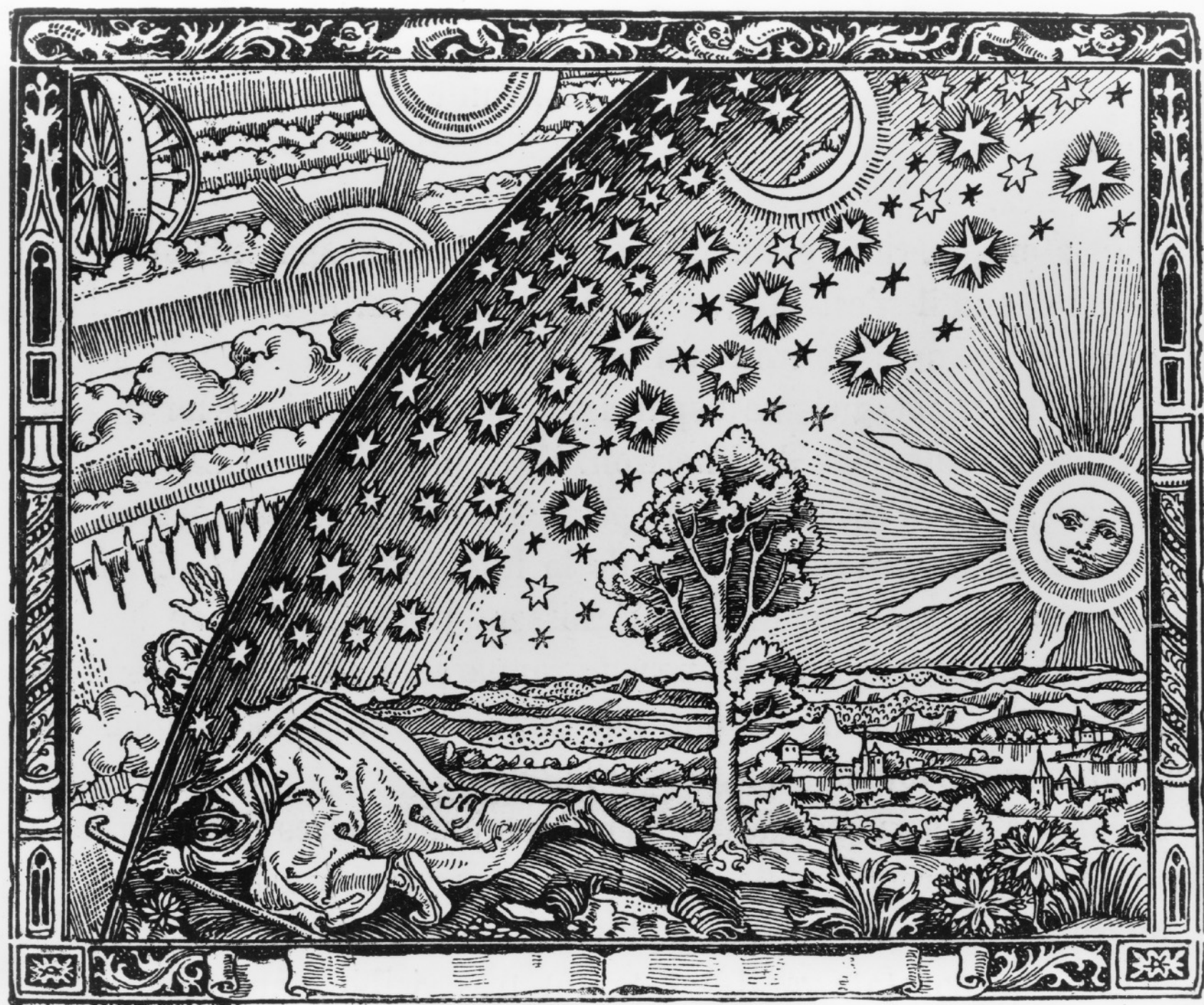


<https://arxiv.org/pdf/2502.21223>

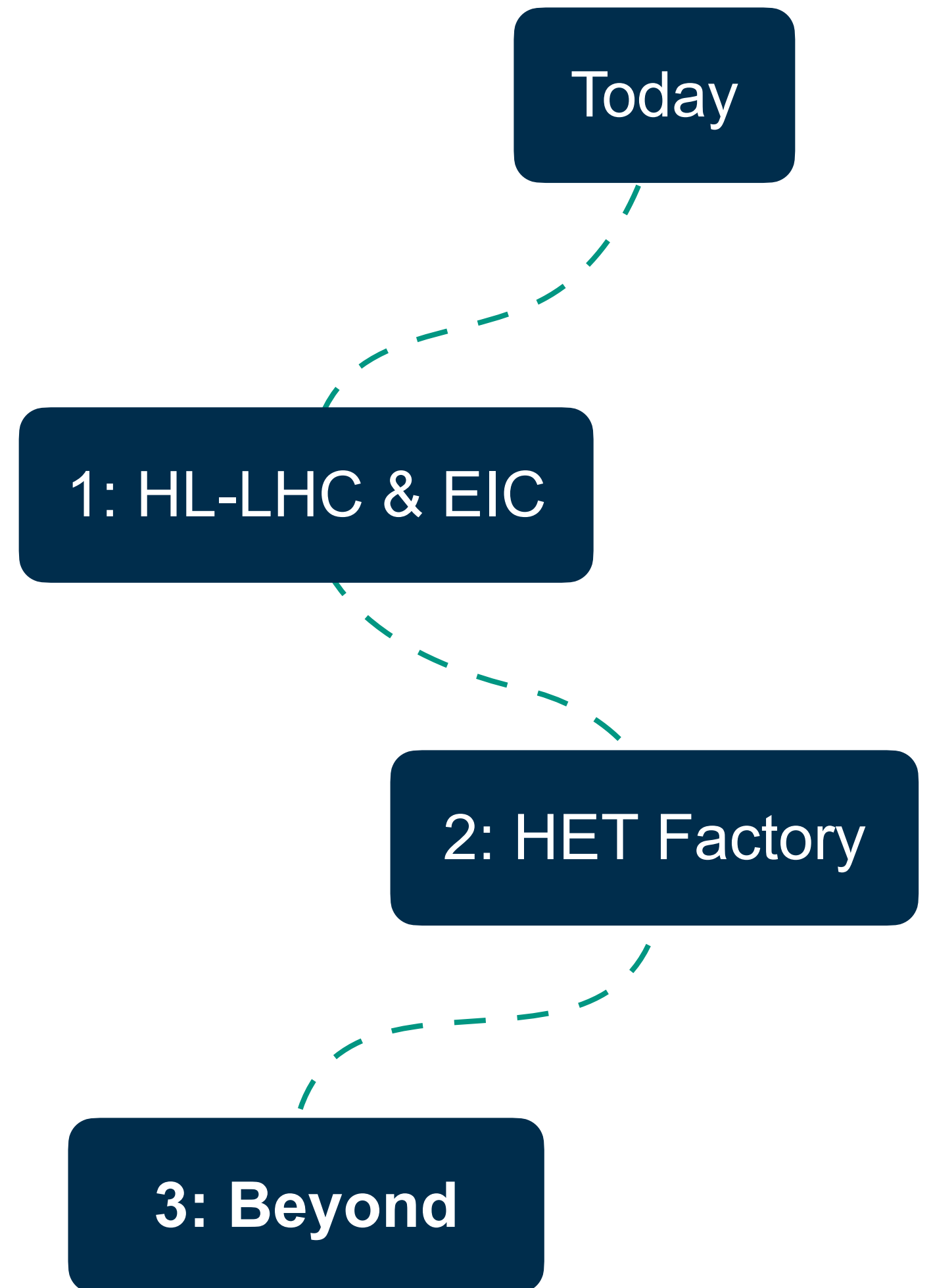
A Simplified Timeline

Proposed Key Collider Projects

- Era 1: ALICE 3, LHCb Upgrade II, Belle II, ePIC
- Era 2: Higgs/Electroweak/Top (HET) factory
- **Era 3: Beyond** – 10 TeV partonic center-of-mass energy



C. Flammarion, *L'atmosphère : météorologie populaire*

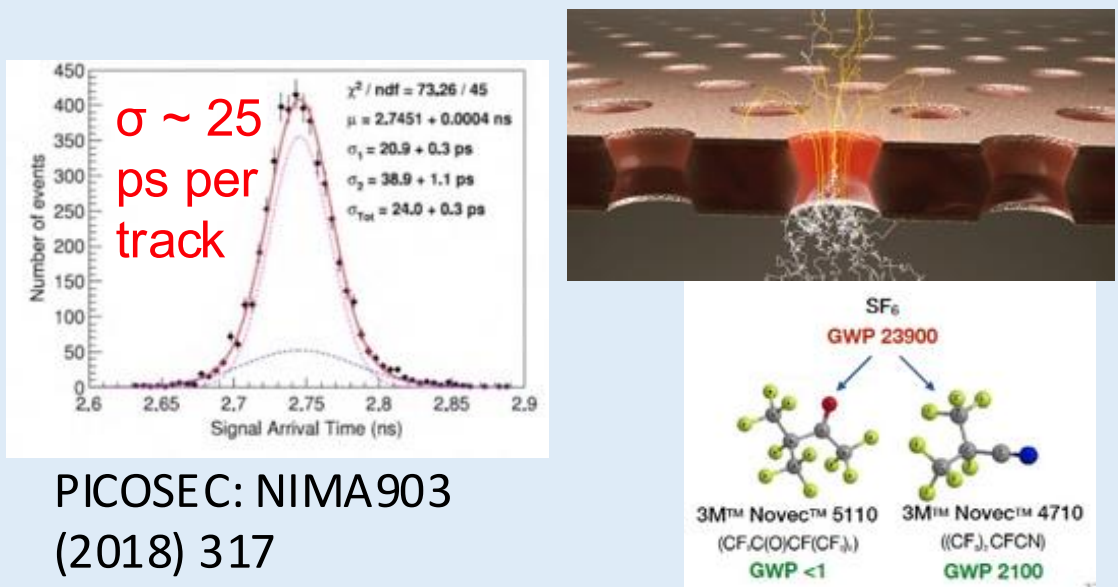


Strategic R&D: Detector R&D Collaborations (DRDs)

+ close collaboration and efforts in the US, Japan, and China

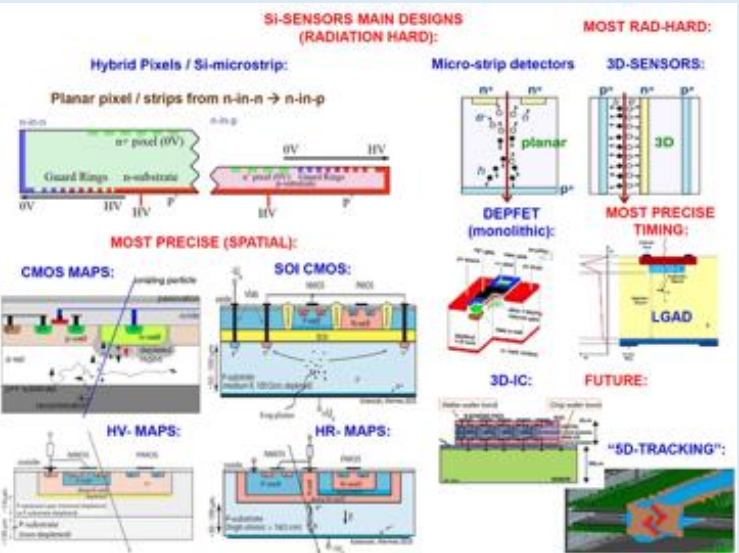
DRD1: Gaseous Detectors

Large · Fast · eco-friendly
gases · MPGD, e.g. GEMs



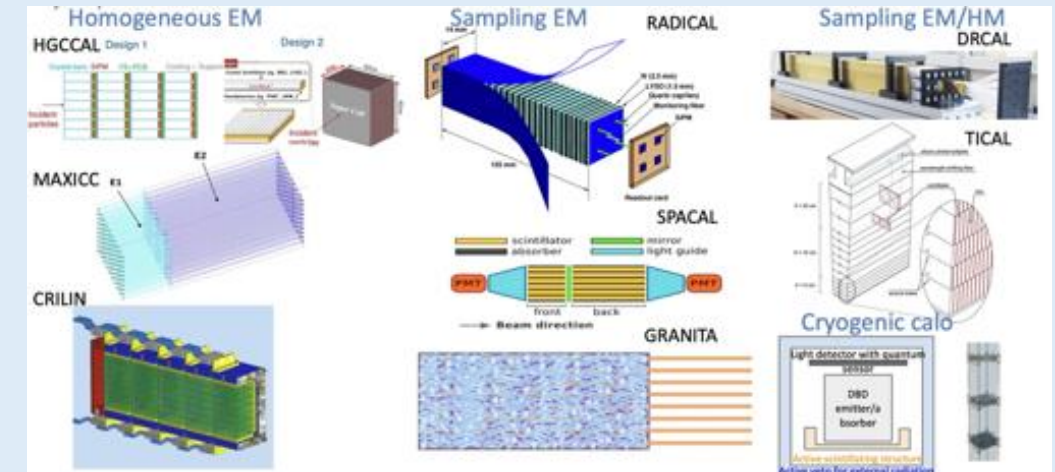
DRD3: Semiconductor Det.

Monolithic CMOS · LGADs ·
radiation hardness · interconns.



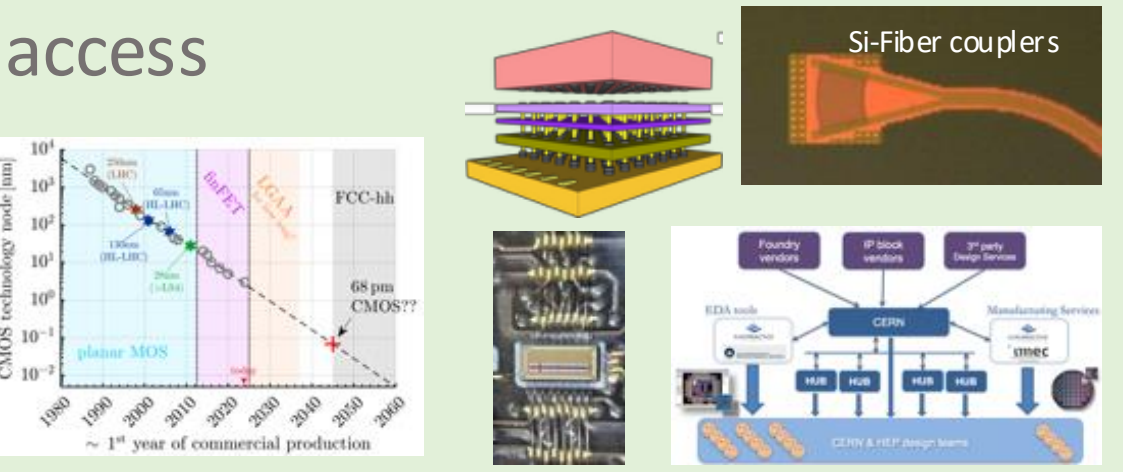
DRD6: Calorimetry

Energy resolution · High
granularity · dual readout ·
particle flow · sandwich · optical



DRD7: Electronics

ADC/TDC IP Blocks · Opto-
electronics · packaging · power ·
extreme environments · COTS ·
intelligence on detector · foundry
access

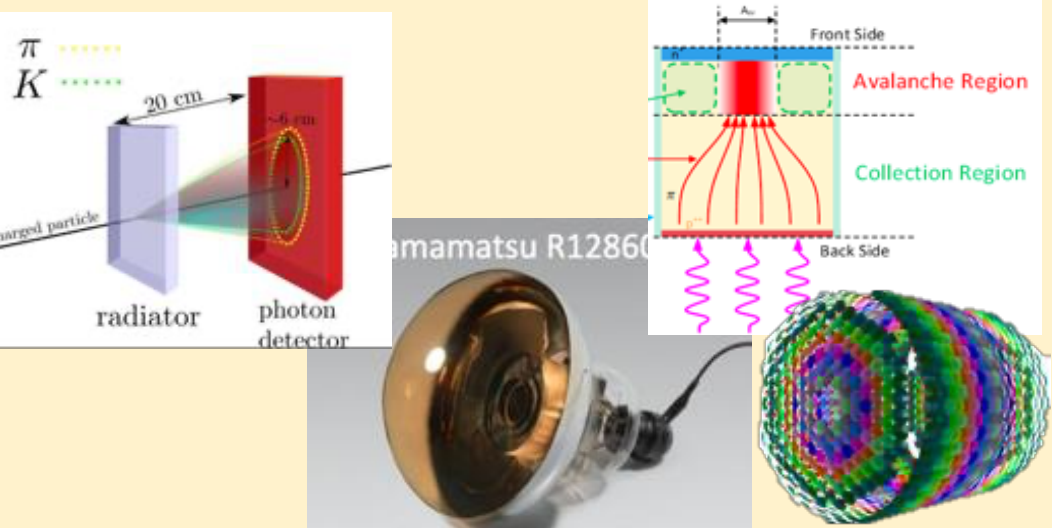


DRD2: Liquid Detectors for Neutrinos · Dark Matter · 0vbb

Noble Elements	Liquid Scintillators	Water Cherenkov
- Argon & Xenon - Ionisation charge & transport - VUV Scintillation, light propagation & detection	- Visible Scintillation, light propagation - Scintillator properties - Isotope loading	- Cherenkov light, light propagation - Doping for n-capture

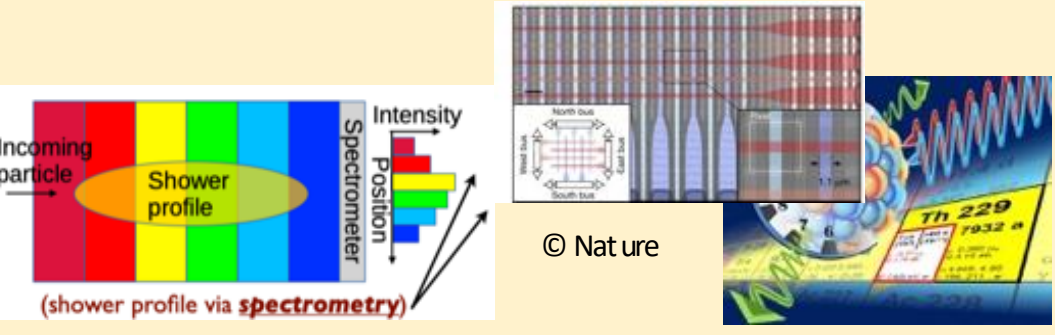
DRD4: Photon detectors

vacuum, solid-state (SiPM), hybrid
single-photon and SciFi detectors ·
applications in PID, RICH, tracking



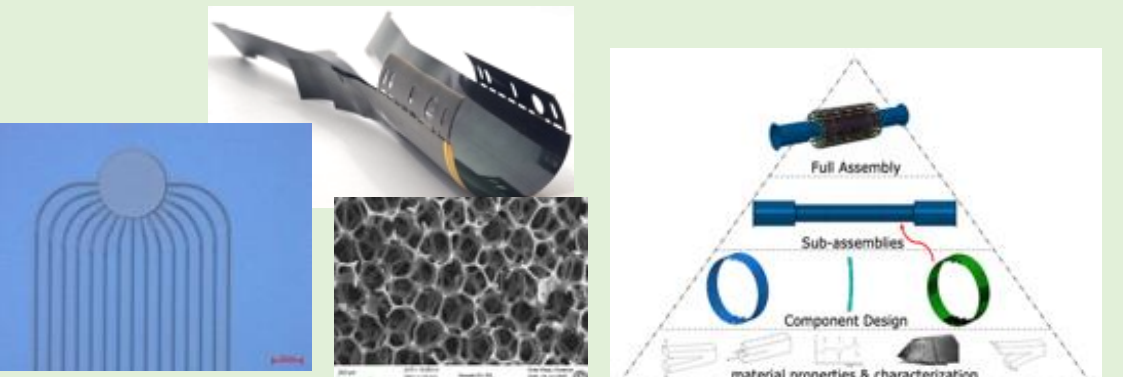
DRD5: Quantum Sensors

Quantum dots · superconduct.
nanowires · bolometers · TES ·
MMC · nuclear clocks
Applications in LEPP, first
projects in HEPP happening



DRD8: Mechanics

Ultra-thin beam pipes · CF foam and
new materials · curved, retractable
sensors · air & micro-channel cooling
· eco-friendly cooling fluids · robots ·
augmented reality



Semiconductor Detectors

Workhorse for Tracking, Vertexing, Calorimetry

Physics: **pn junction** in doped semiconductors
→ space-charge region sensitive to **ionization**

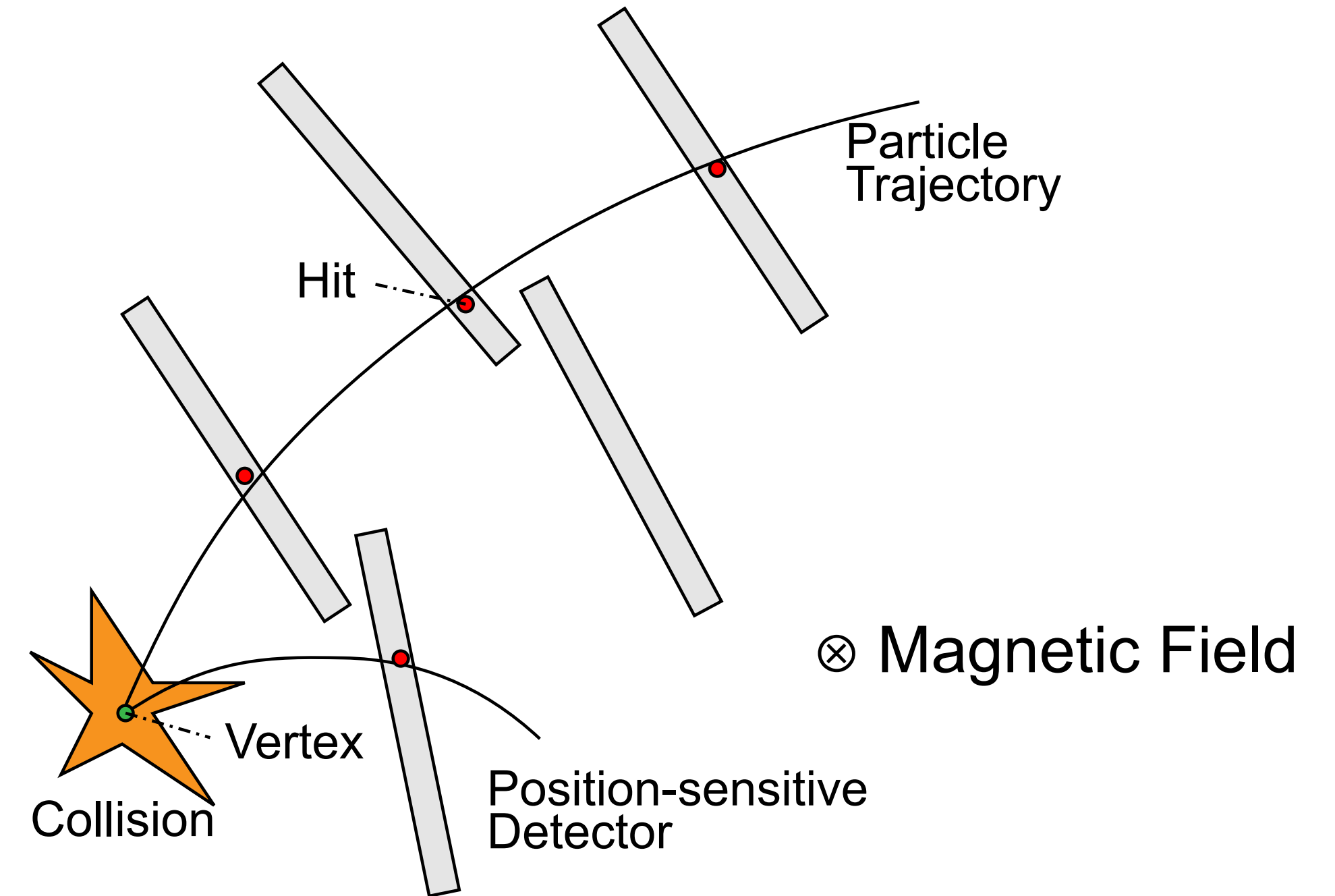
Selected semiconductor **properties**:

- **Pro**: Large signal, fast, thin, radiation-hard, ~industrial process, scalable
- **Con**: rather expensive

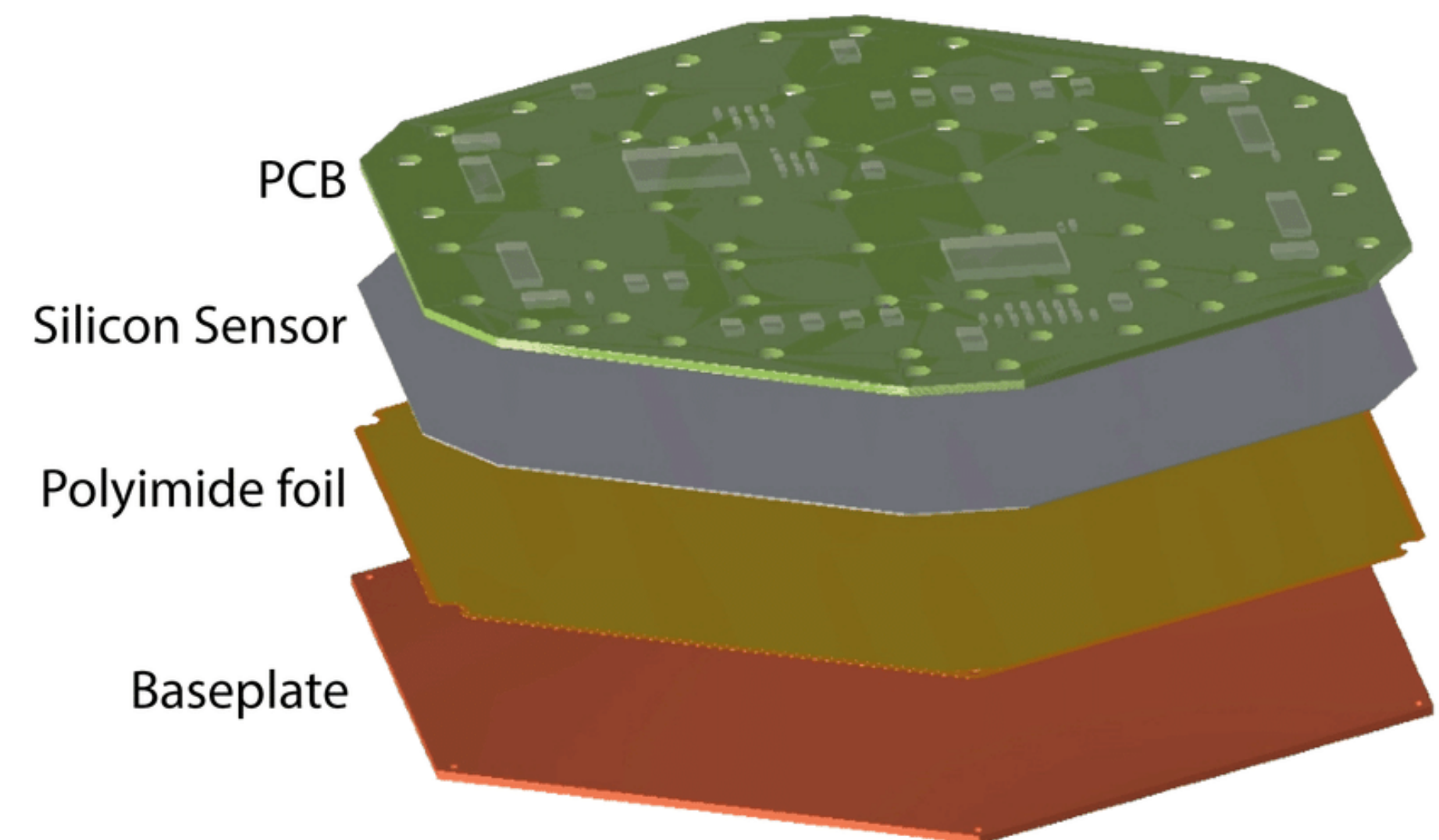
Tracking and vertexing of charged particles:
layers of position-sensitive detectors

Energy measurement in calorimeters:
sensitive elements in sampling calorimeters

Charged Particle Tracking & Vertexing



CMS High-Granularity Calorimeter (HGCAL)



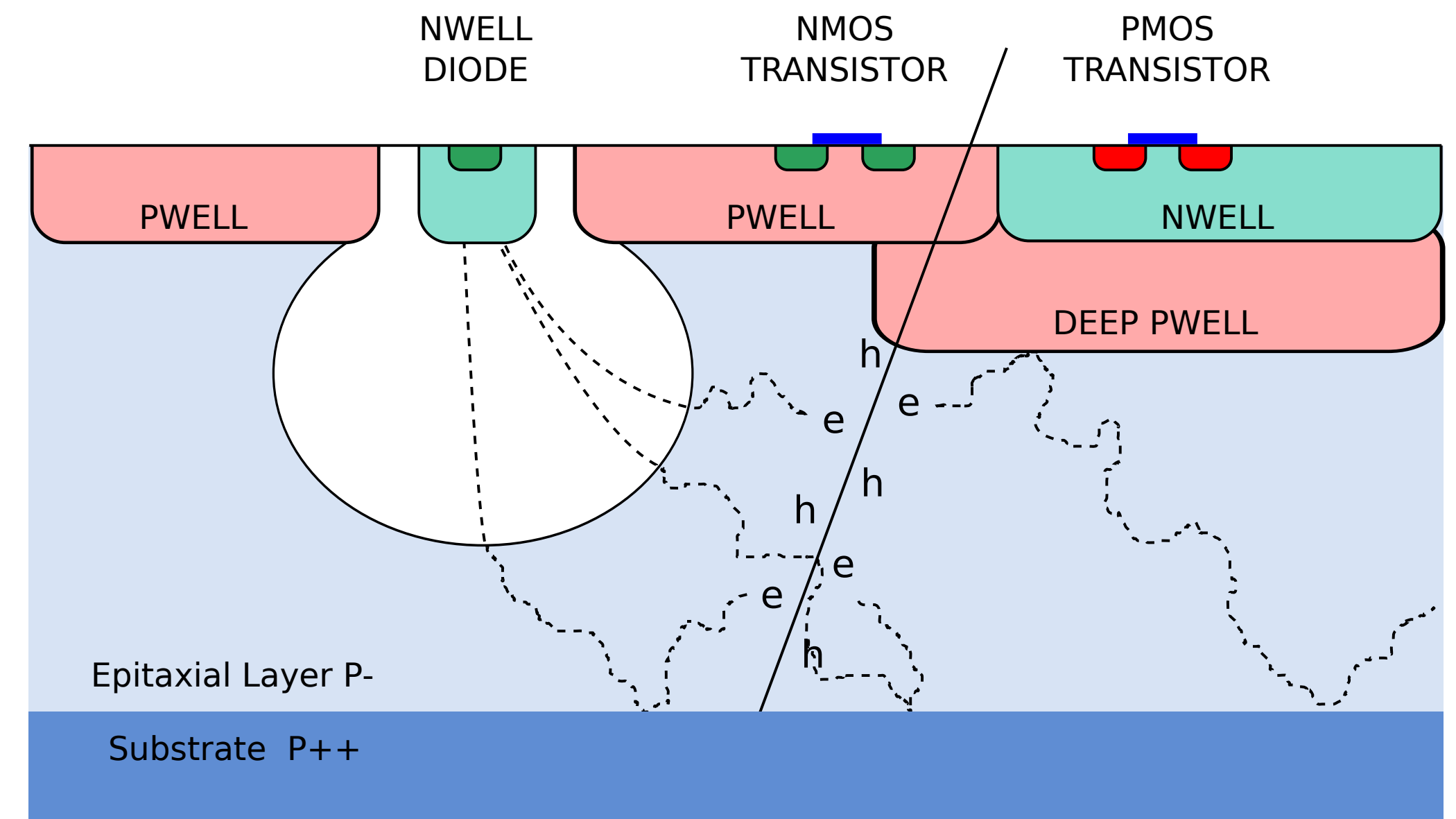
MAPS: Monolithic Active Pixel Sensors

Prime Choice for Future Vertex Detectors

Guiding idea: integrate particle **detection** and first **signal amplification** stage in a **single device** → **monolithic active pixel sensors (MAPS)**

Most commonly used: **CMOS sensors**

- **Microelectronics standard:**
widely available (digital cameras, ...),
more affordable and more power
efficient than hybrid detectors
(sensor + separate readoutchip)
- **No/small bias voltage:** particle
detection in epitaxial layer ($20\text{ }\mu\text{m}$)
→ **diffusion** to shallow depletion zone
- **Small signals** but also **small noise**



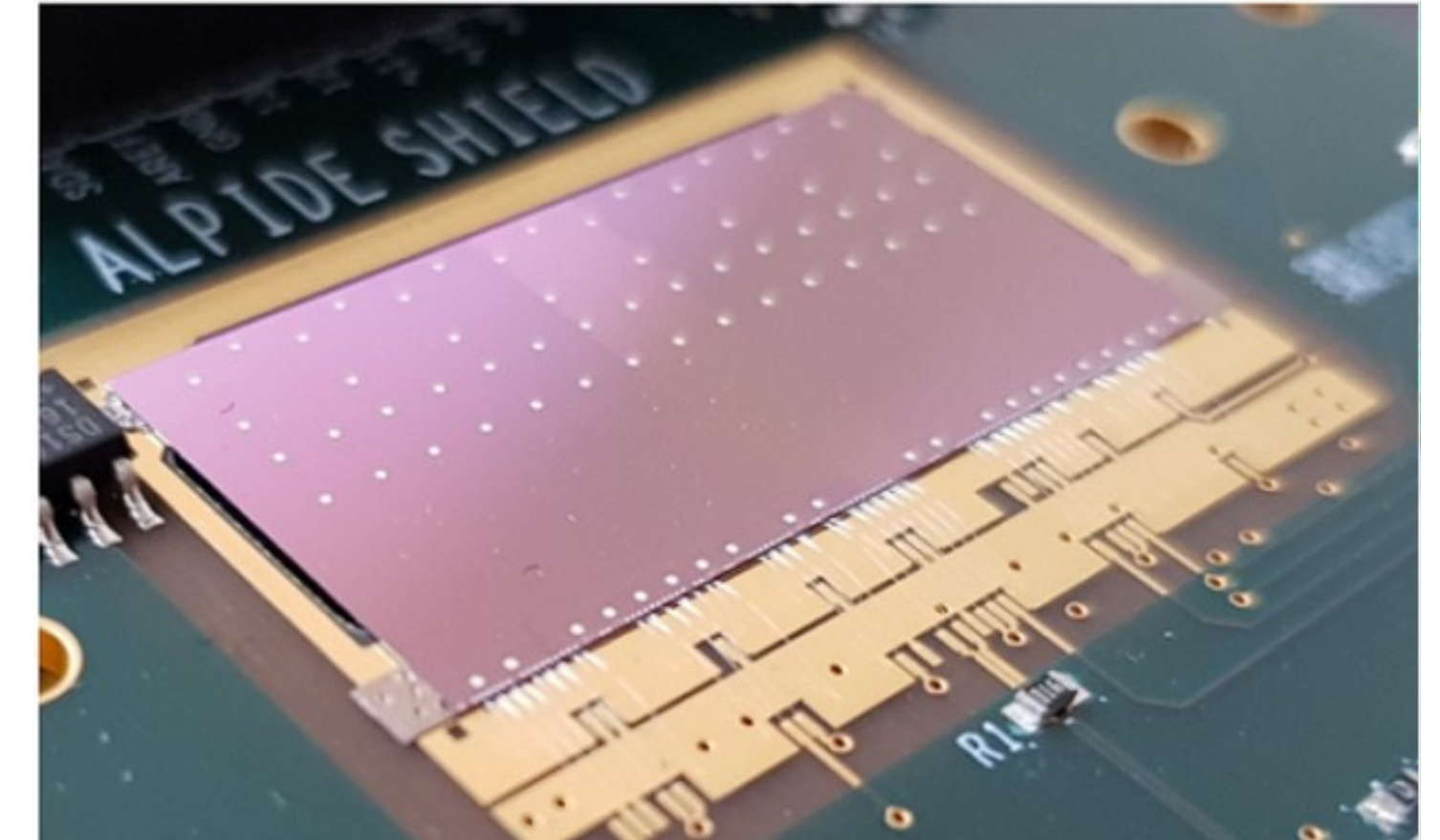
Example: TowerJazz 180-nm process, from [J. Phys. G41 \(2014\) 087002](#)

MAPS: Monolithic Active Pixel Sensors

Examples

Example: **ALPIDE**

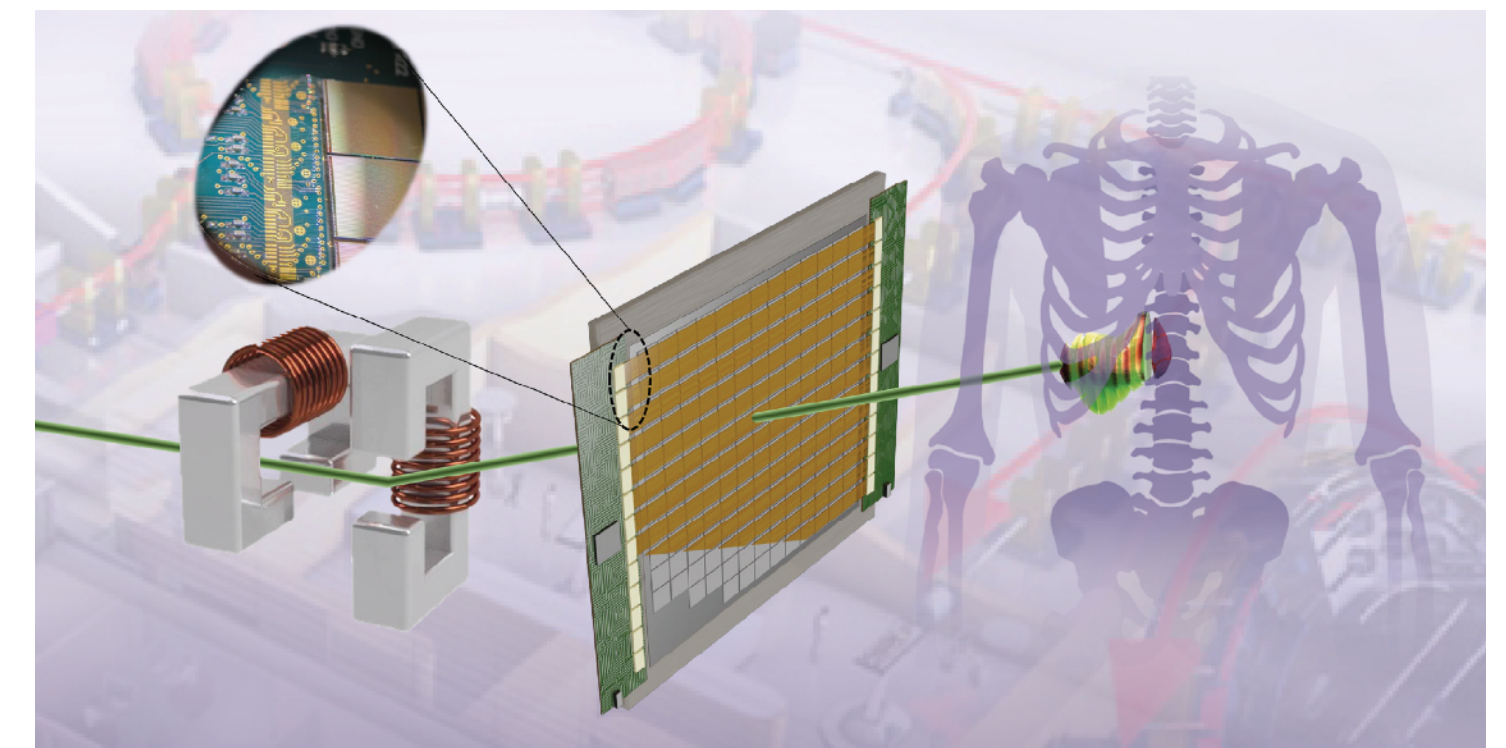
- Developed for ALICE experiment at the LHC: low power, low material, fast
- Transfer to medical applications: proton radiography, secondary ion tracking in ion beam therapy



<https://ep-esf.web.cern.ch/project/alice-its>

Example: **HV-CMOS** pixel detectors

- Faster (drift instead of diffusion) and more radiation hard (high depletion voltage) than standard MAPS
- Application: new **beam monitor** for Heidelberg Ion Beam Therapy Center (HIT)



<https://www.mdpi.com/2410-390X/7/1>

Silicon Photomultipliers

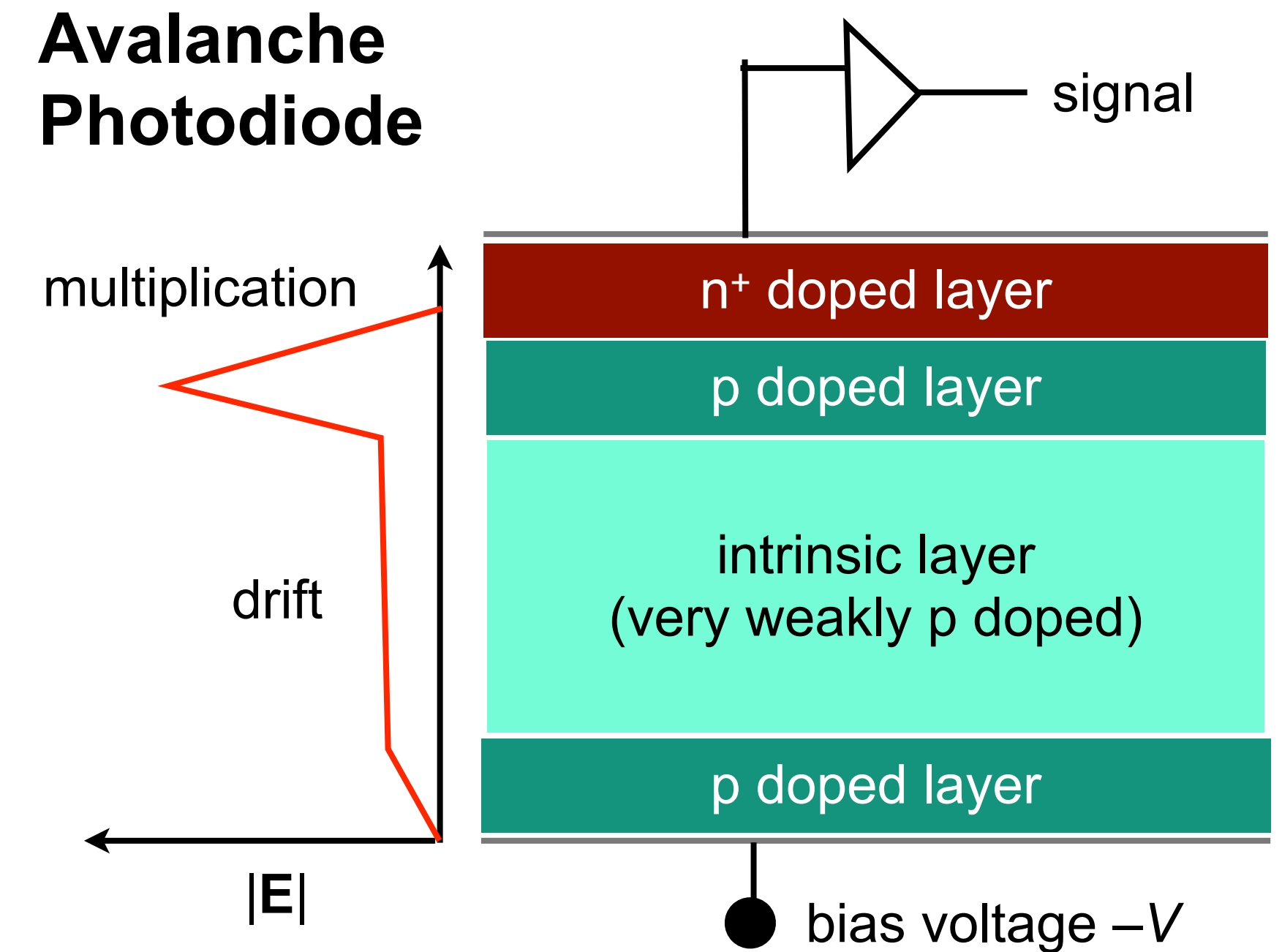
Workhorse for Photon Detection in Basic Science

Avalanche photodiode (APD):

- Photon absorption in intrinsic layer
→ electron **drift** into multiplication zone
- **Amplification** by impact ionization,
typical gains: $G = 100\text{--}1000$

Silicon photomultiplier (SiPM):

- **2D array of APDs** operated with voltage above breakdown voltage (“Geiger mode”)
→ discharge independent of light input (single-photon avalanche diode, **SPAD**)
- Single SPAD: **binary** device, intensity = sum of photons detected in all SPAD
- Performance similar to PMT, but: **very compact** design, **insensitive to magnetic fields**, **low afterpulsing** → replacement for traditional PMTs



Instrumentation for Future Experiments

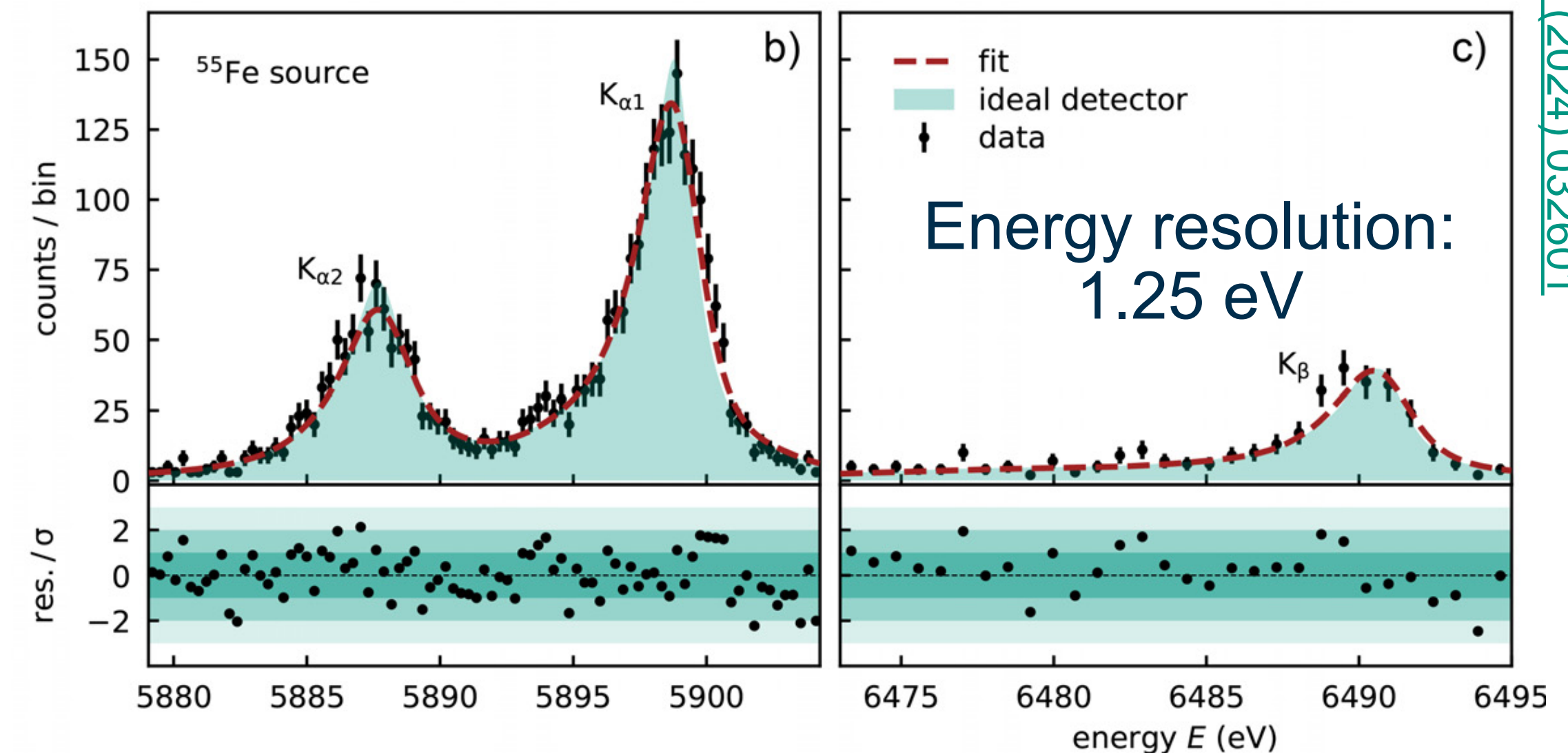
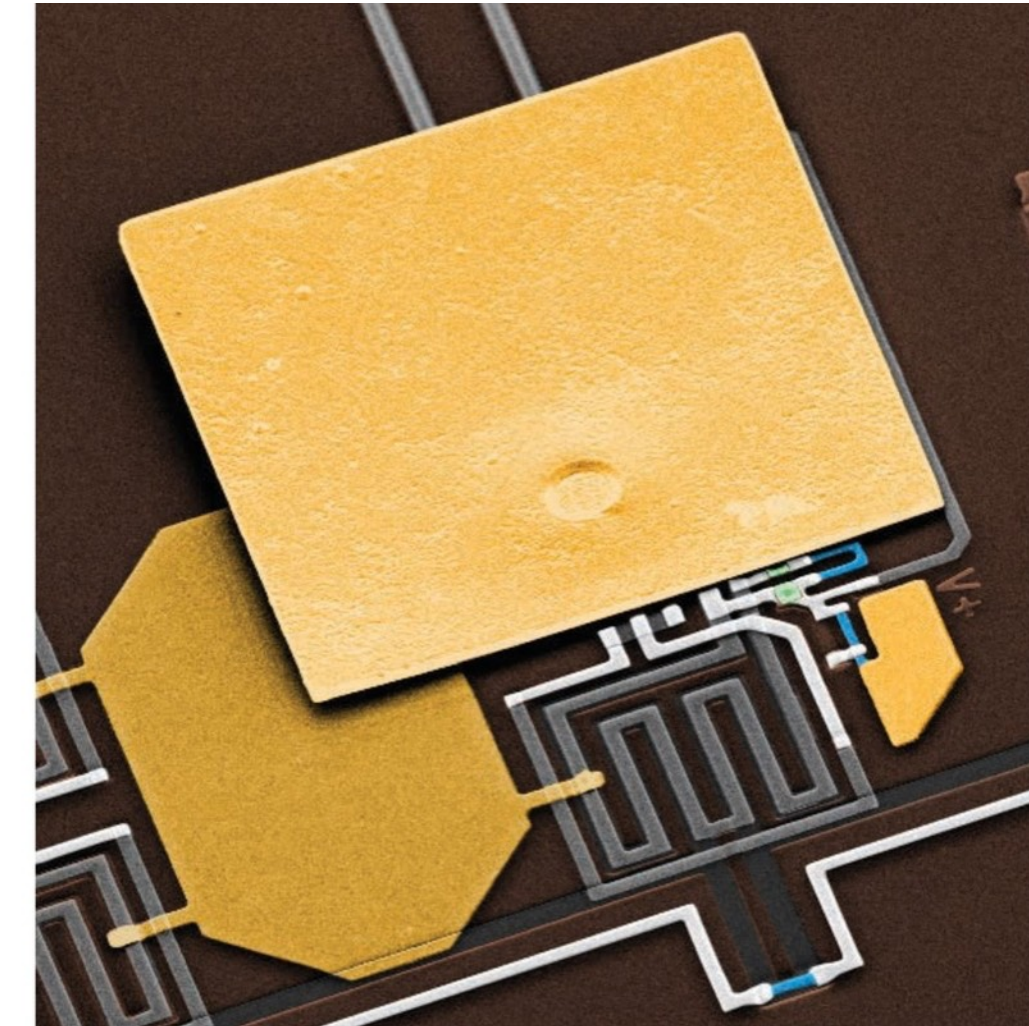
Major Challenges Ahead

Pushing **detector performance**: higher particle rates, higher resolution, lower noise, lower power, ultra-fast timing, ...

Incorporating the **latest technologies**: microelectronics, heterogeneous computing, AI, quantum sensing, materials science, additive manufacturing, ...

Keeping both **experienced experts** and **early-career researchers** in the field: challenging projects, attractive career paths, recognition ...

Quantum Sensor (MMC)



Instead of a Summary

Attempting to Answer Cigdem's Charge

What is the relevance of your research within your research field?

→ detector instrumentation: **enabler** and **driver** of new scientific projects

What is the relevance of your research for other fields?

→ **same/similar detectors** in neighboring fields (astroparticle physics, nuclear physics, ...), but often with **different requirements/challenges**

What theoretical/experimental input would benefit your work?

→ broad range of improved (microelectronics) and novel technologies (quantum, AI)

What methods are you using or developing that could be useful for others?

→ hardware & software for precision imaging & fast low-latency data processing