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QUANTUM UNIVERSE

DESY.

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# QUANTUM UNIVERSE

## SMART

**Erika Garutti**

Hamburg, 23-25 Nov. 2025

# SMART Structures, Methods, Advanced Research Technologies

## SMART.3 Detectors, Quantum Sensors, and Accelerators

- Optimize detector concepts based on extreme spatial granularity and time resolution to operate at a circular e+/e- collider,

  (Garutti, Krüger, Nikolopoulos, Sefkow, Spannagel, Schwandt, Steinbrück)

- Qualify superconducting radio frequency (SRF) and quantum sensors for applications in DM and GW detectors

  (Garutti, Horns, Januschek, Lindner, Nikolopoulos, Reinhardt, Schnabel)

- Pursue acceleration technologies towards high-energy e+/e- linear colliders,

  (Grüner, Hillert, Moortgat-Pick, Wenskat)

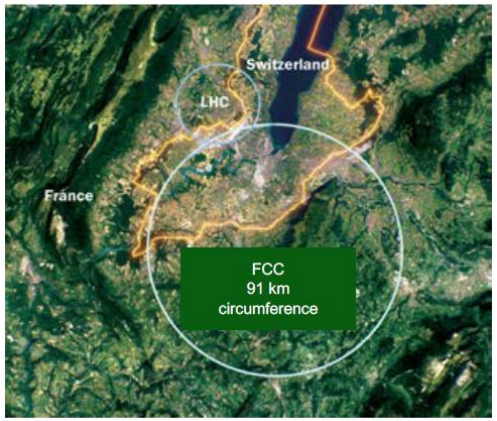
# SMART: Detectors for particle physics

➔ European Strategy for Particle Physics 2026 ongoing

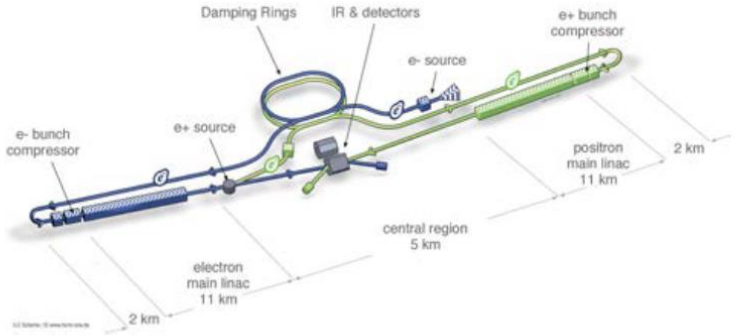
➔ Decision for the next flagship project for CERN to be taken in 2028

$e^+e^-$ colliders
("Higgs factories")

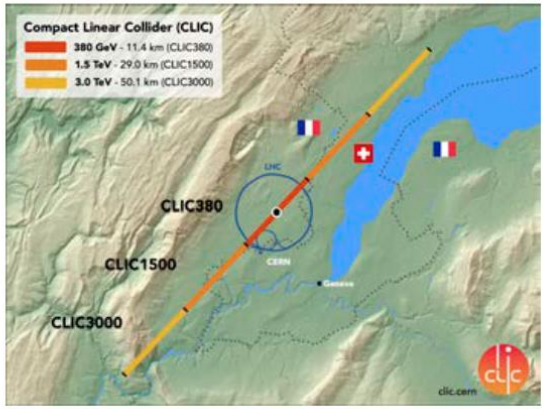
**FCC-ee** ($e^+e^-$, circular, 91 – 365 GeV)




**LCF** ($e^+e^-$, linear, 91 – 240, 550 GeV)




**CLIC** ($e^+e^-$, linear, 380 GeV, 1.5 TeV)



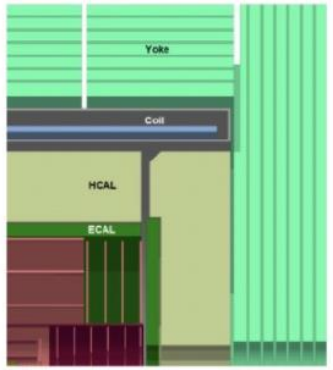

➔ The next large machine will likely be a $e^+e^-$ collider

# SMART: Detectors for particle physics

## FCC-ee concepts gaining momentum

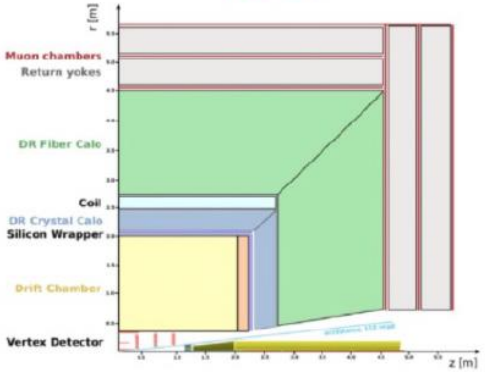
- excellent vertexing → **silicon detectors** (pitch < 25µm, < 0.1%$X_0$/layer, O(1ns) time resolution, power < 50mW/cm$^2$)
- excellent tracking → **gaseous trackers** (high rate capability, transparency, PID, continuous tracking)
- particle flow reco. → **high-granularity calorimeter**

### CLD



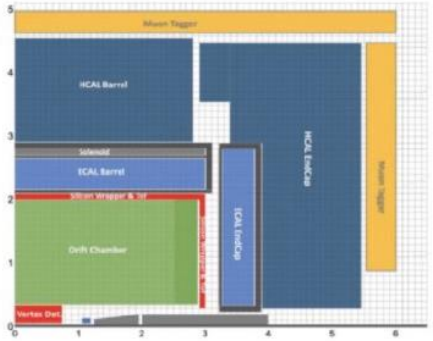

Full Si tracker
CALICE-like calo

### IDEA



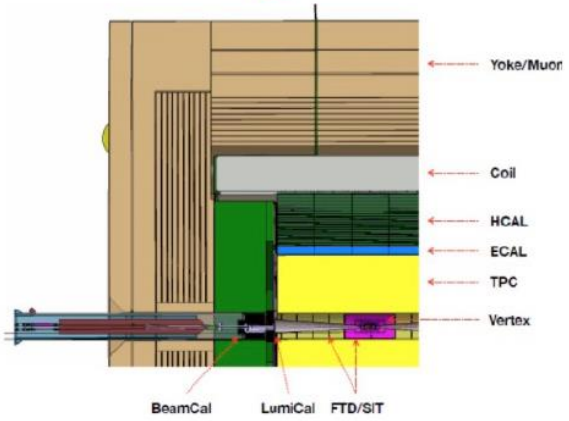

Ultra-light drift chamber
Crystal ECAL
Dual readout fibre calo

### ALLEGRO




In early design phase
Noble liquid ECAL

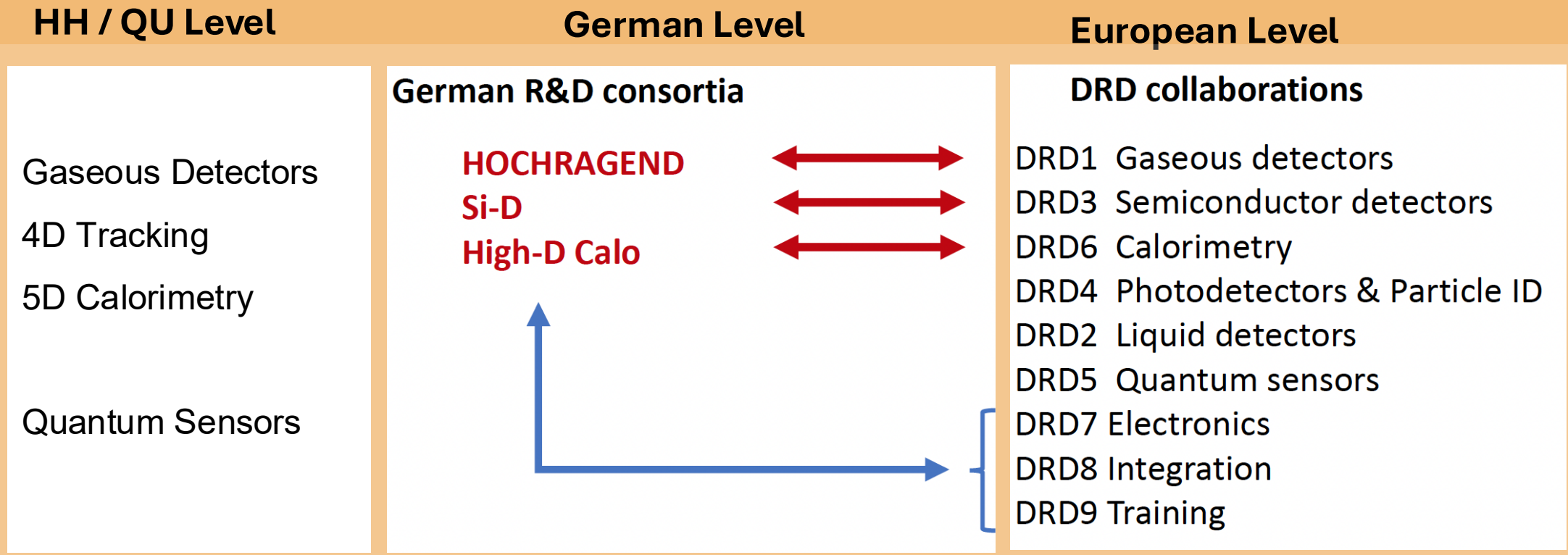
### ILD




Ported from ILC
Large volume TPC

# SMART : Detectors for particle physics

## The landscape

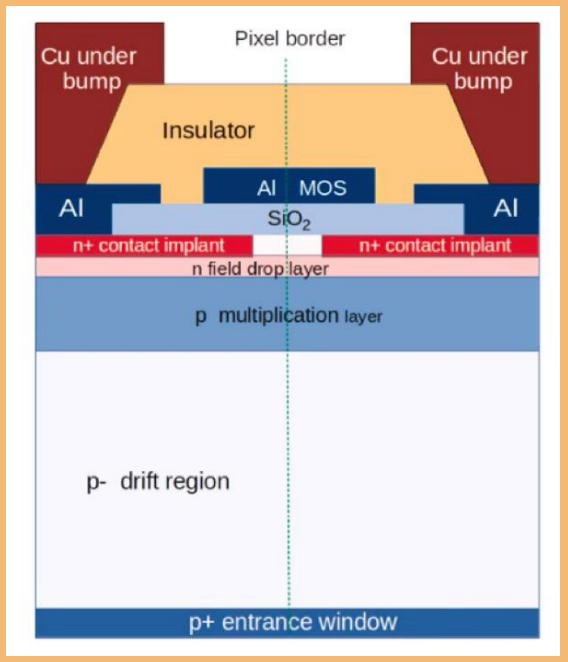



➔ QU supports the international effort to prepare for a future $e^+e^-$ collider

# SMART : 4D Tracking

## High resolution tracking detectors with ps time resolution

Position resolution: ~ **10 µm** ~ 5% of electrodes distance
Time resolution: ~ **25 ps** for 50 µm thick sensors
Radiation Hardness up to ~ 2 x $10^{15}$ $cm^{-2}$

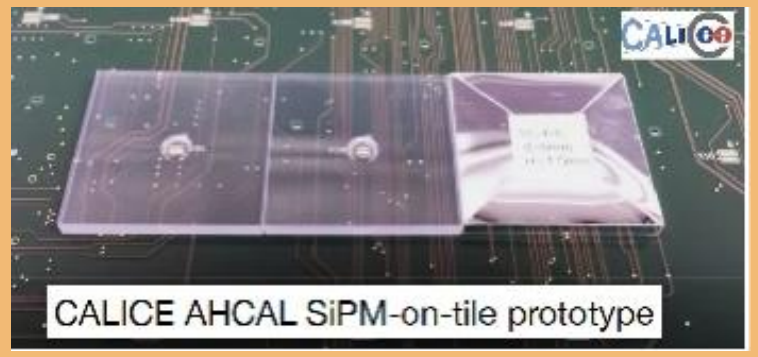

➔ **Establish Low Gain Avalanche Diode for timing layers instrumentation**

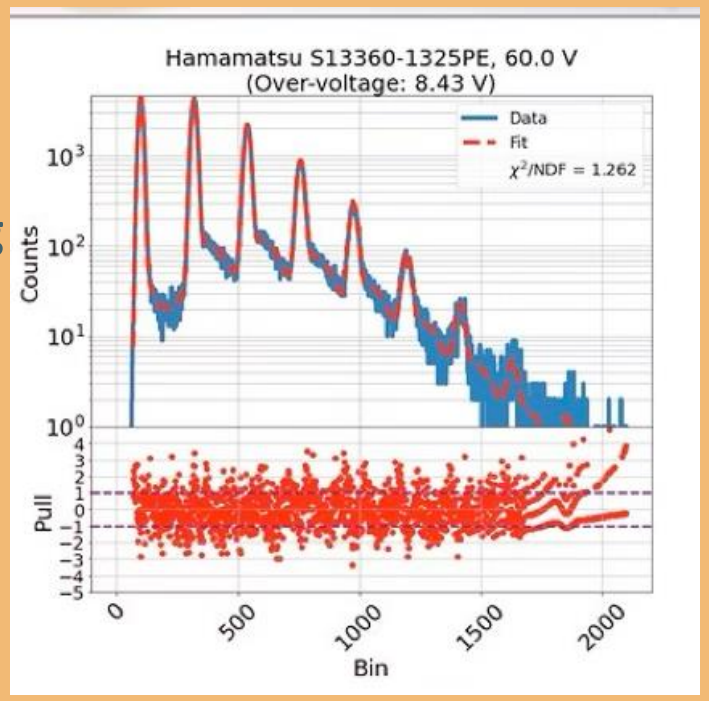
# SMART : 5D Calorimetry

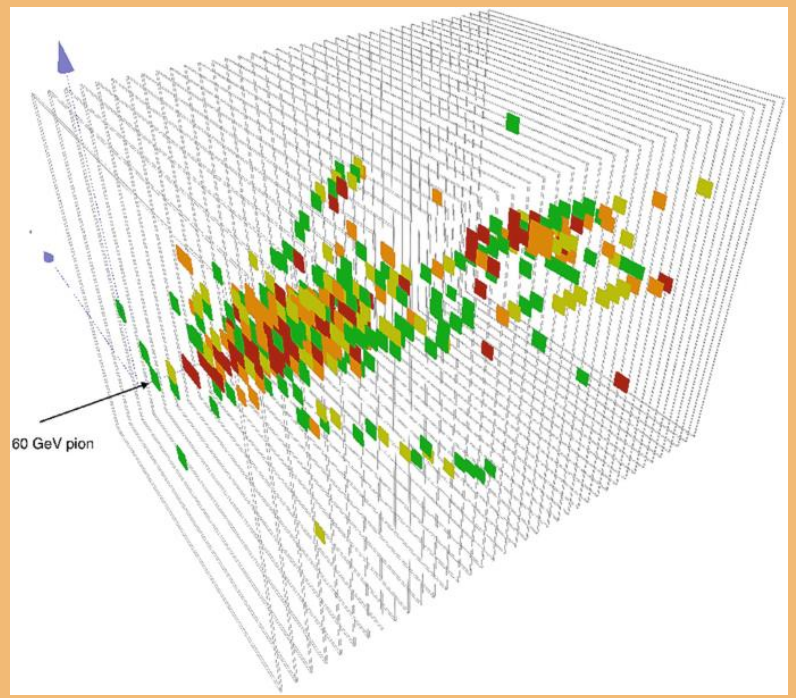
## High granular calorimeters with good energy and time resolution

Position resolution: ~ **3 cm**
Time resolution: ~ **1 ns**

**Characterization and modeling of SiPM response**



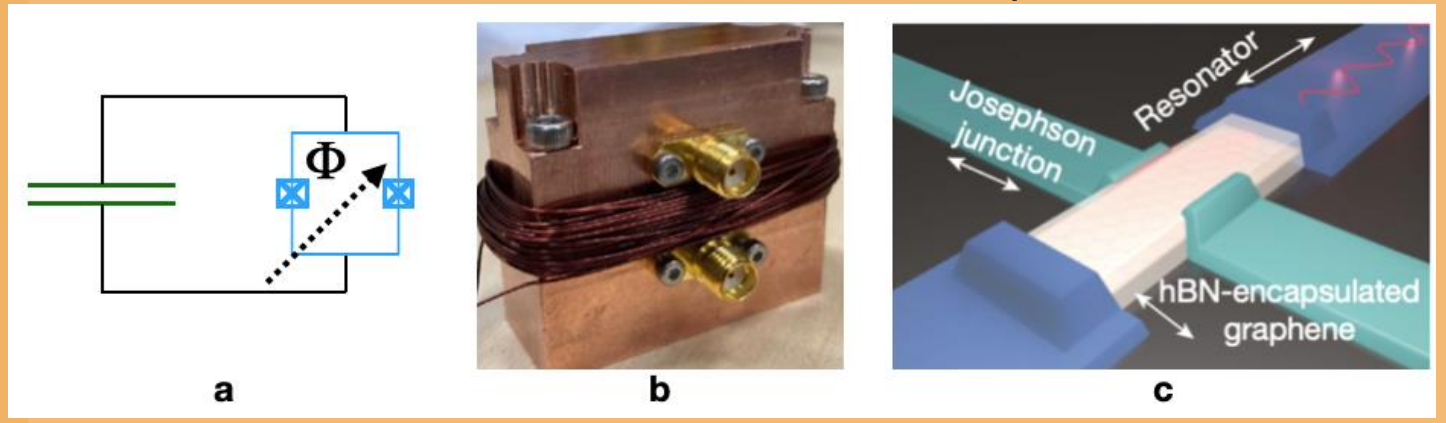




➔ **Optimize particle flow calorimetry design for FCC-ee**

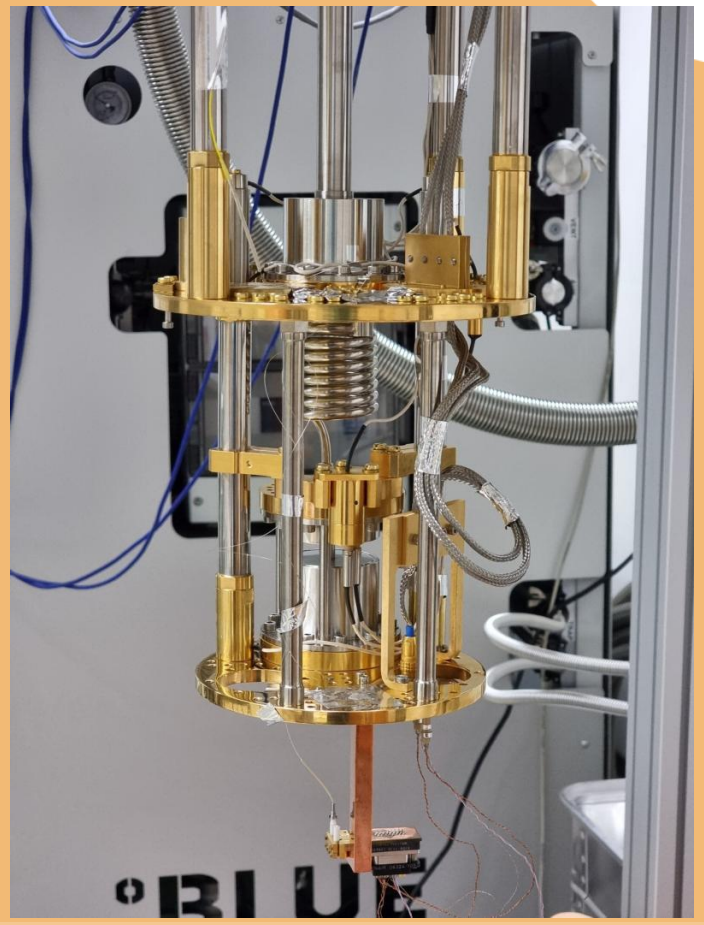
# SMART : Quantum Sensors

Transmon QBit

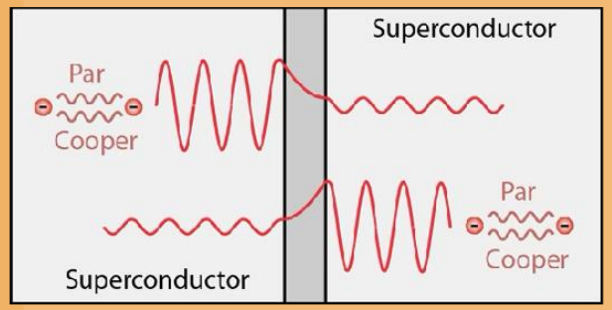


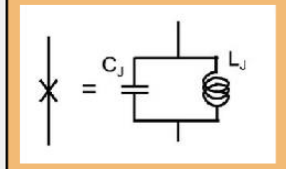

Graphene JJ bolometer



Josephson Junction (JJ)

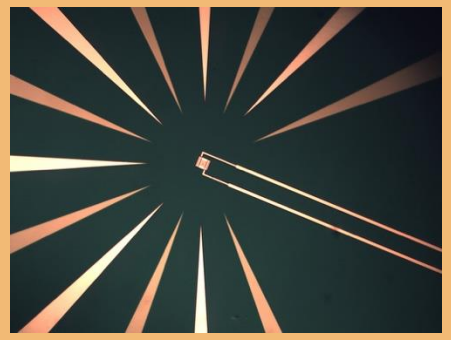



JJ symbol and electrical model

Discovered by Brian Josephson in 1962. Application in SQUIDs, superconducting qubits, and amplifiers.

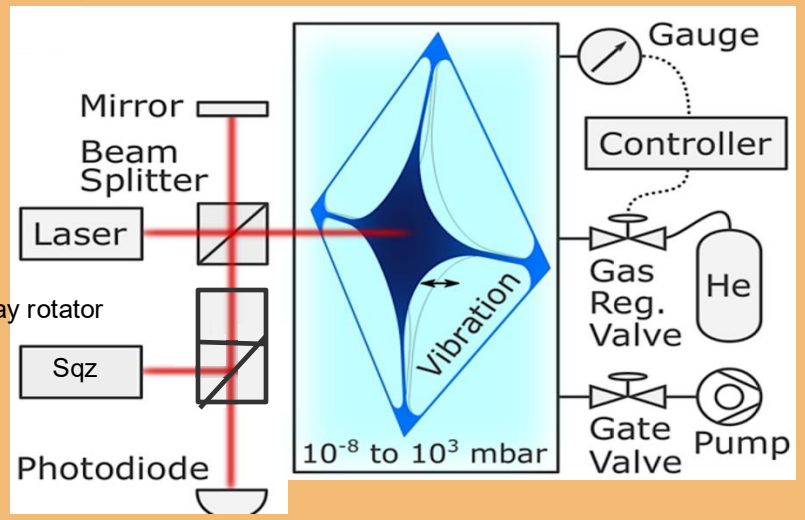
Transition Edge Sensors



Based

➔ Improve sensitivity of dark matter experiments

# SMART : Quantum Sensors




"Squeeze Laser" for squeezed vacuum states at 1550 nm built by the group of R. Schnabel in 2020, financed by BMBF.
The UHH spin-off *Noisy Labs GmbH* was founded in 2023.
First commercial company to sell squeeze lasers.

Our membrane pressure sensor can be used at arbitrarily low temperatures, just limited by the heating of the readout laser.

The 10dB squeezing enables a tenfold reduction in light power/heating without loss of S/N.

1 PhD Proof of concept and transfer of opto-mechanical gas pressure sensing [Lindner/Reinhardt]

➔ **Improve sensitivity gravitational wave experiments**

# SMART Structures, Methods, Advanced Research Technologies

Cooperation between physics & informatics

## SMART.2 Artificial Intelligence

- Develop innovative and competitive AI technologies, including novel **foundation models** and **generative AI** models, with a wide range of applications in all areas of the Cluster and beyond,

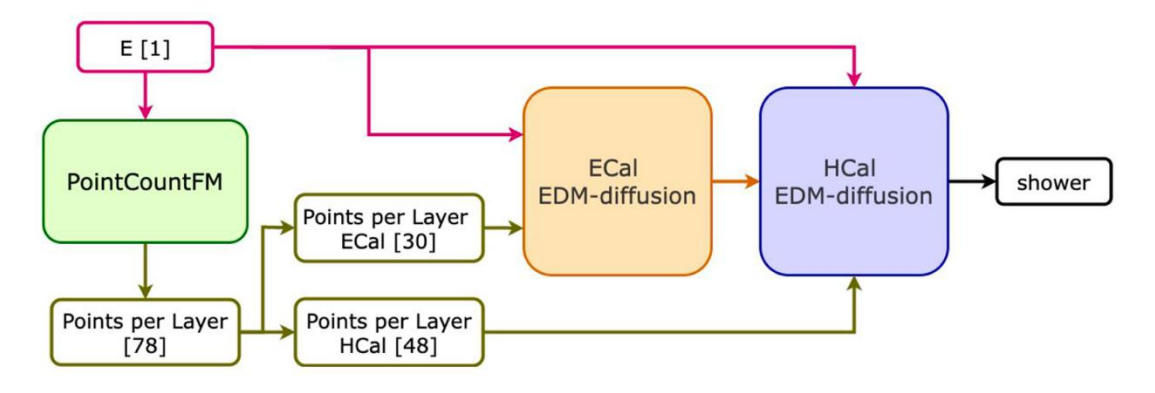
  (Blekman, Brüggen, Gerkmann, Heim, Kasieczka, Laue, Lucie-Smith, Krüger, Lederer, Neumann, Schindler, Schomerus, Weigand, Westphal)

- Create a hub for ultra-fast ML techniques with wide applications, such as collider physics and seismic noise control

  (Gaede, Gerberding, Haller, Kasieczka, Laue, Schröder)

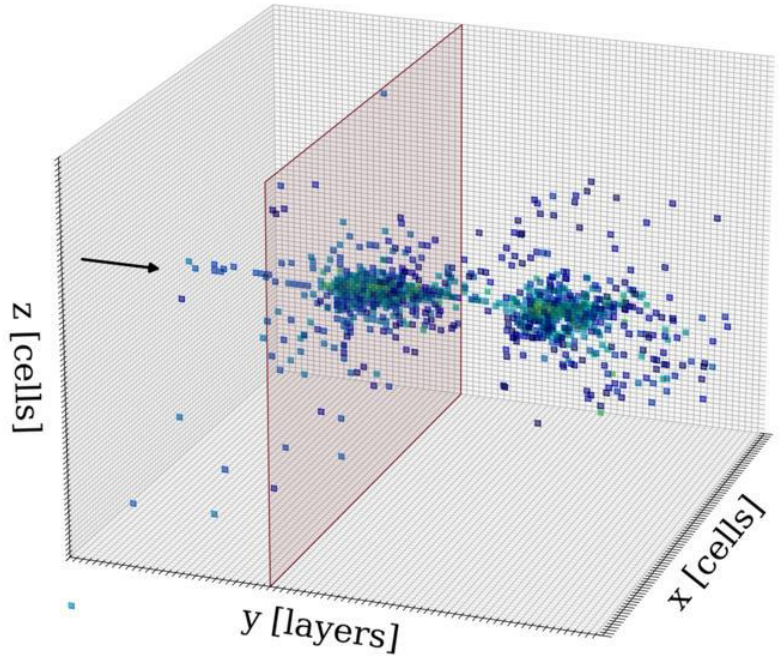
# SMART : Generative AI

## Simulation of high granular detectors via generative surrogates
## ➔ Speed-up




1 PhDs in Foundational models [Heim]

2 PhDs in Gernative AI [Brüggen / Kasieczka]




## ➔ Optimize detector design for FCC-ee

# SMART : Fast-ML Lab

**Examples of applications for fast ML-based trigger algorithms:**

1. **Applications of ML to decision-making in the CMS L1 trigger with microsecond latency**

1 PhD in Signature based triggers [Haller / Kasieczka]

2. **Real-time non-linear control for seismic isolation and suspension systems for future GW detectors, specifically the Einstein Telescope**

➔ **Optimization and fine-tuning for specific FPGA architectures**