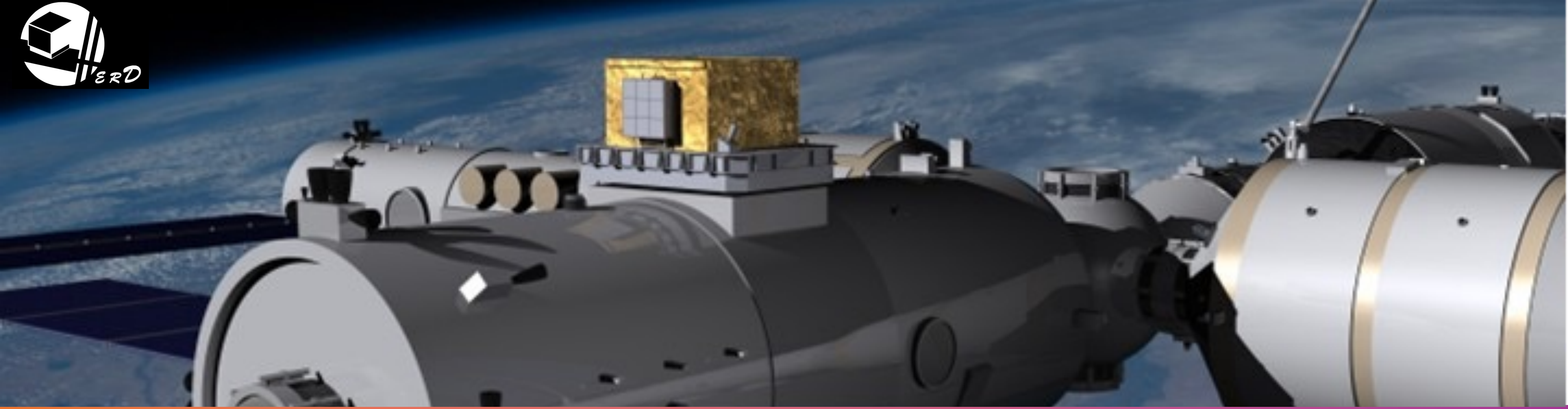


Progressing our understanding of cosmic rays with the HERD space-borne experiment

Chiara Perrina on behalf of the HERD Collaboration (Chiara.Perrina@epfl.ch)

September 27, 2024

HERD

The High Energy cosmic-Radiation Detection facility (HERD) will be the next experiment for the detection of cosmic rays in space.

HERD will be launched and installed onboard the China Space Station (CSS) in 2027, operational for at least 10 years.

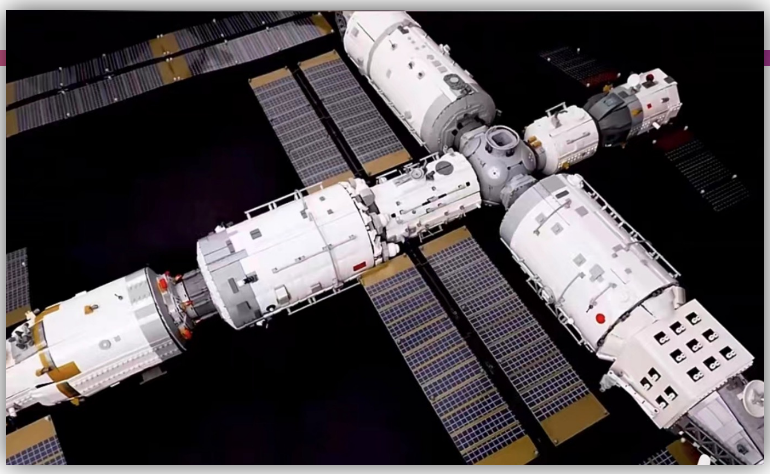
International scientific collaboration
of 270+ scientists from China and Europe

IHEP, XIOPM, GXU, SDU, SWJTU,CCNUU, SDU, PMO, USTC, YNAO, NVT, HKU

University of Geneva
EPFL - Lausanne

University and INFN of Bari, Firenze, Lecce, Napoli, Pavia, Perugia, Pisa, Roma2, Trieste, LNGS and GSSI.

CIEMAT – Madrid
ICCUB – Barcelona
IFAE - Barcelona



CSS:

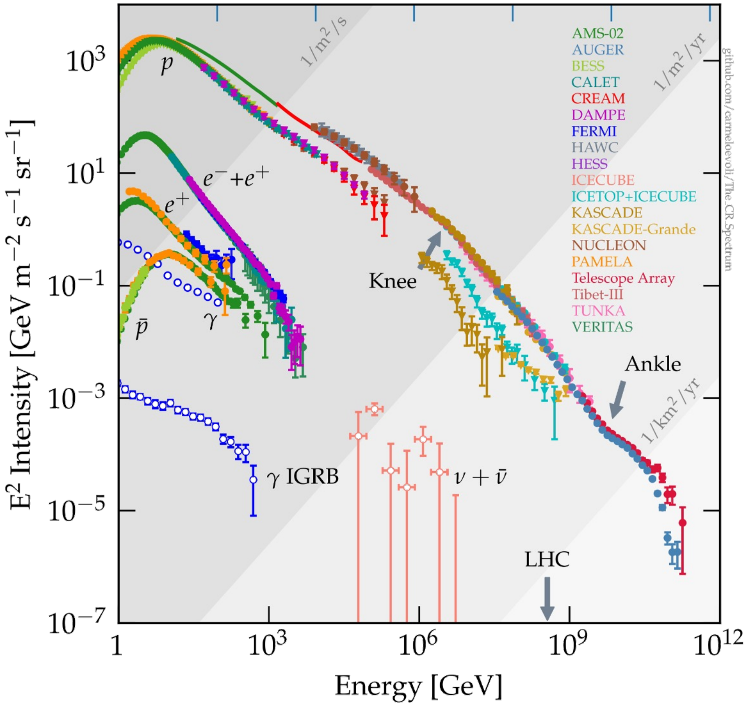
- Completed in 2022
- **Circular Orbit**
  - Altitude: 340 km – 450 km (LEO)
  - Inclination: 41° – 43°
- **Pointing**
  - To the Earth (three axis stabilized system)
  - Pointing accuracy ≤ 0.1° (3 σ)
  - Pointing stability ≤ 0.005°/s (3 σ)

HERD will be equipped with two **star trackers** to know the correct pointing of the instrument for each event.

Why do we need HERD?

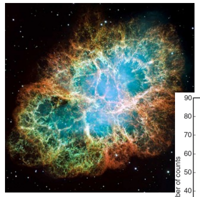
Charged cosmic rays

Sources, acceleration, propagation

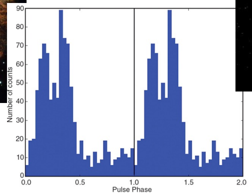


High-energy cosmic photons

Sources, interactions, non-thermal physics

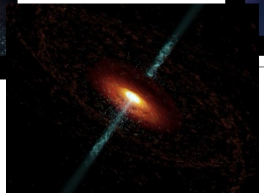


SNRs

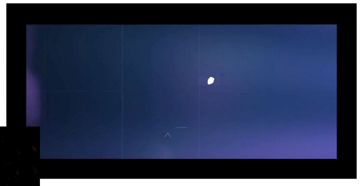


Pulsars

Galactic structures



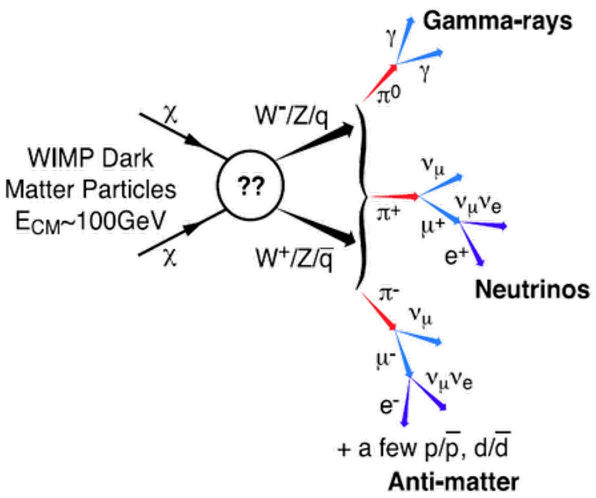
Blazars

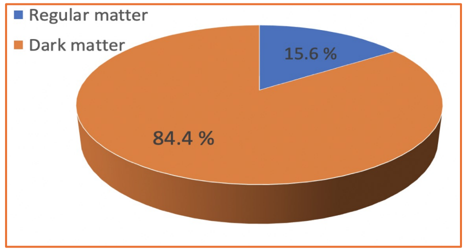


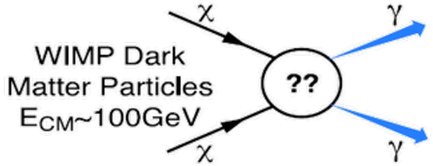
Tidal disruption events

Dark matter

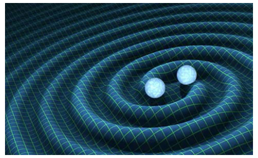
Nature, origin, properties



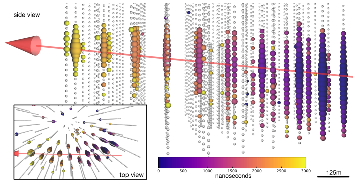




Multimessenger astrophysics

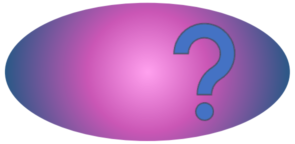


γ-ray counterpart of gravitational waves



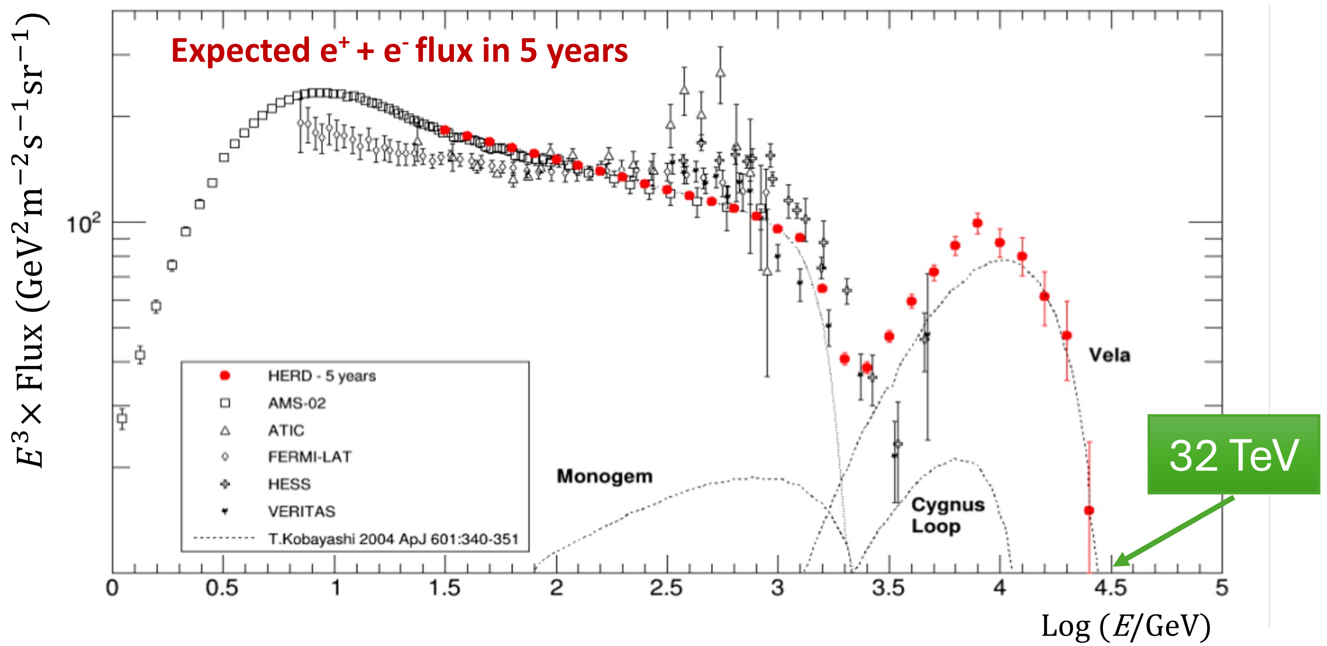
γ-ray counterpart of neutrinos

Exotic particles



HERD observables: electrons + positrons

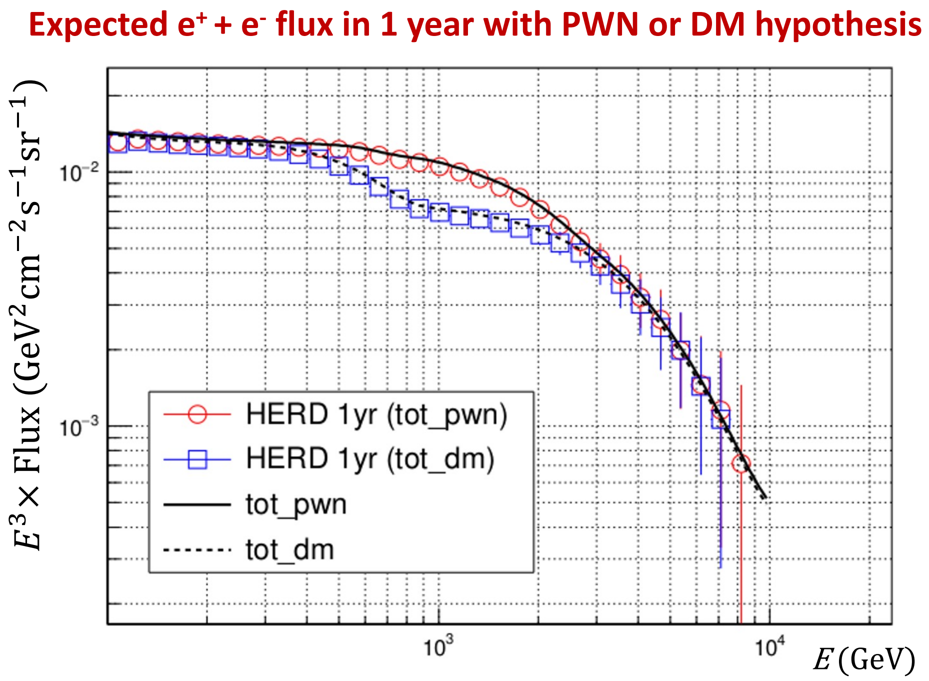
Acceleration and propagation studies



HERD will measure the all-electron flux up to several tens of TeV to detect:

- spectral cutoff at high energy
- local nearby astrophysical sources
- additional information from anisotropy measurements

Dark matter indirect searches

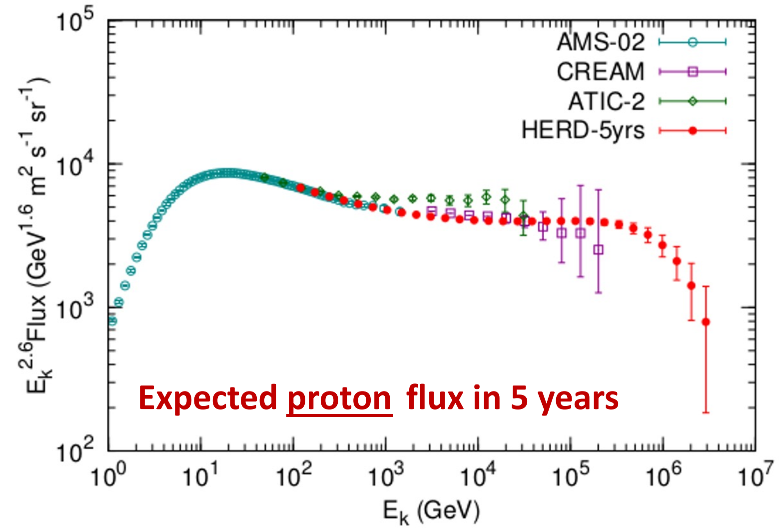


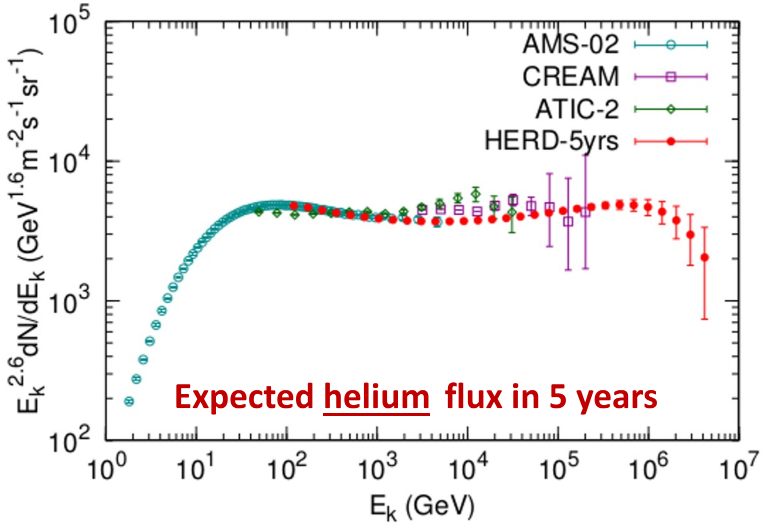
Thanks to the precise measurement of the $e^+ + e^-$ flux, HERD will provide insights into the origin of the positron excess. Is it due to:

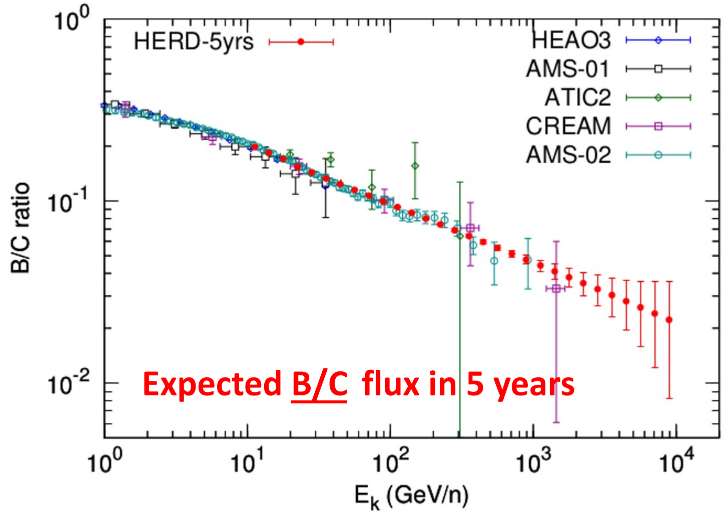
- ❑ Astrophysical sources (pulsars)?
- ❑ Dark-matter particle annihilation?

HERD observables: hadrons

Acceleration and propagation studies







HERD will measure the flux of nuclei:

- p and He up to a few PeV
- heavier nuclei with (|Z| <= 28) up to a few hundreds of TeV/nucleon

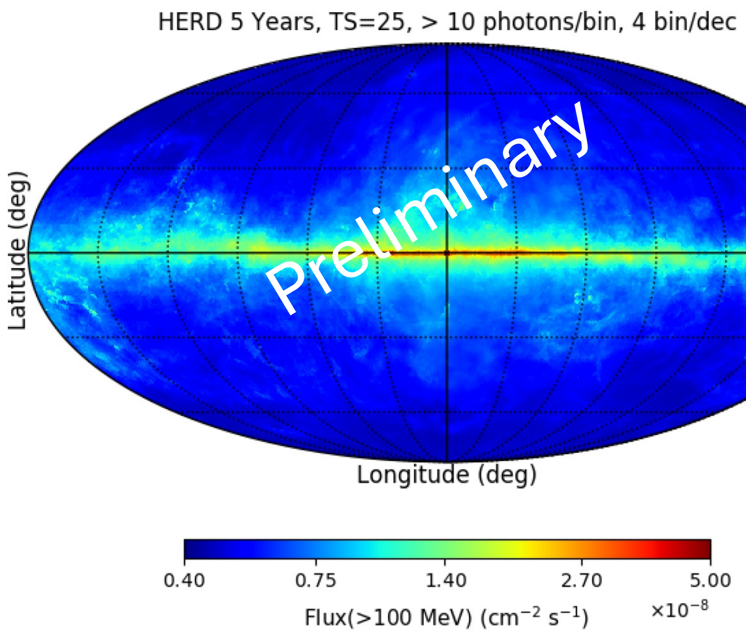
- **First direct measurement of p and He knees** will shed light on our understanding of the knee origin.

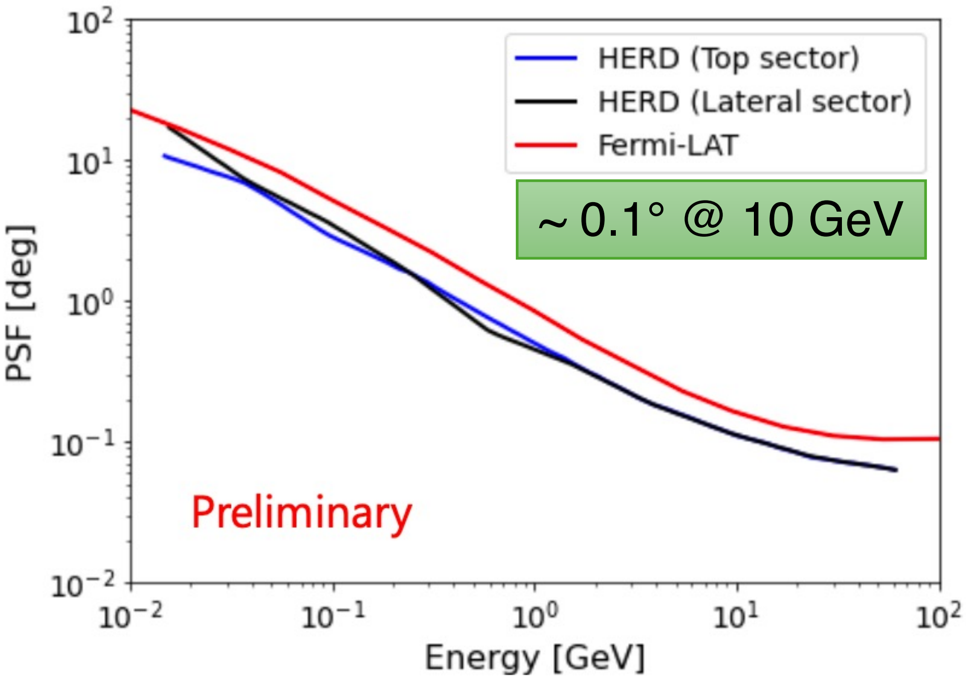
Extension of the B/C ratio to high energy will provide further insights into the propagation mechanisms of cosmic rays

HERD observables: gamma rays

Thanks to its large acceptance and sensitivity, **HERD** will be able to perform a full gamma-ray sky survey in the energy range > 100 MeV

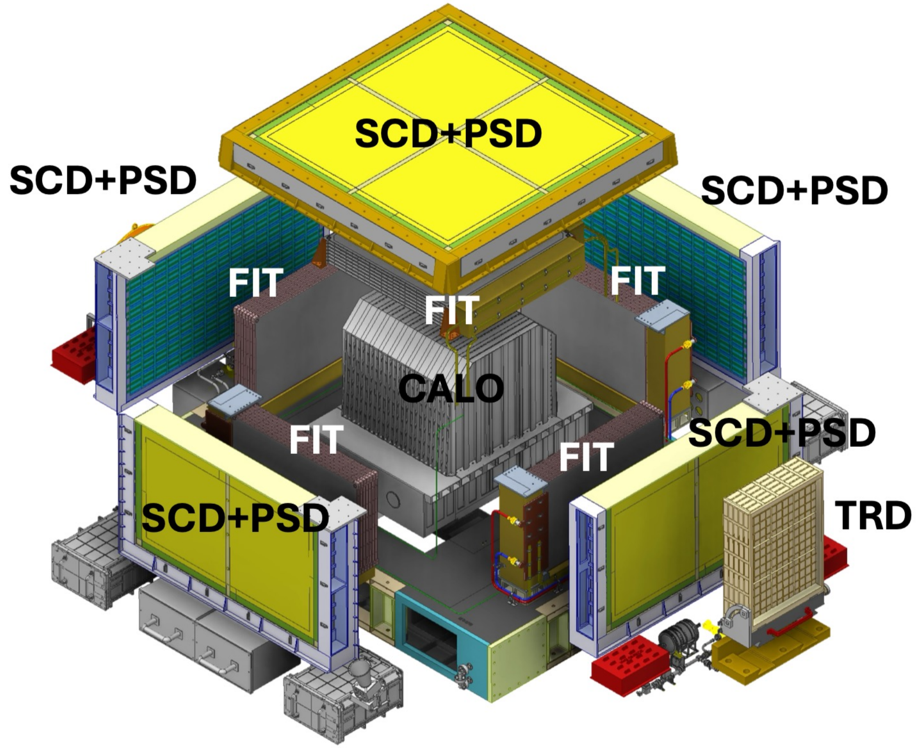
- **Study of galactic and extragalactic gamma-ray sources**
- **Study of galactic and extragalactic gamma-ray diffuse emission**
- **Search for indirect dark-matter signatures**
- **Extend Fermi-LAT catalog to higher energy (> 300 GeV)**





The HERD detector

→ Extend the energy range: **nuclei to PeV, $e^- + e^+$ and γ rays to 100 TeV**
- ○ Deep calorimeter: 55 X_0 (current max: 31 X_0 of DAMPE)
- ○ **Large acceptance:** electrons: > 3 $\mathrm{m^2sr}$ (DAMPE: 0.3 $\mathrm{m^2sr}$)
  protons: > 2 $\mathrm{m^2sr}$ (DAMPE: 0.03 $\mathrm{m^2sr}$)
  - ▪ "Isotropic" design with a central 3D calorimeter + other subdetectors on 5 sides.



https://doi.org/10.1051/epjconf/202328001008

Needed: **particle identification**, **energy** and **direction** measurements.

CALO: CALOrimeter (55 X_0)
- Energy measurement
- E.m./hadron separation

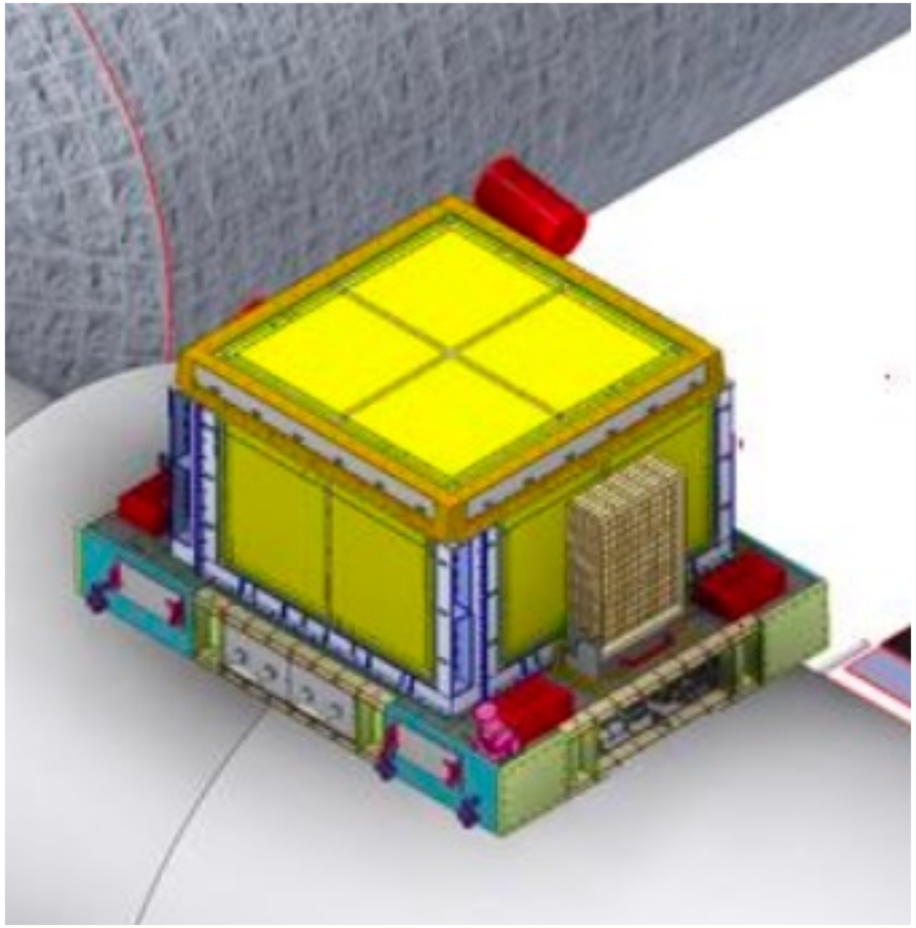
FIT: FIber Tracker (5 sides)
- Track reconstruction
- Charge measurement (|Z|)
- Low-energy γ–ray conversion (γ → $e^+ e^-$)

PSD: Plastic Scintillator Detector (5 sides)
- Charge measurement (|Z|)
- γ–ray identification (fast veto < 200 ns)

SCD: Silicon Charge Detector (5 sides)
- Charge measurement (|Z|)
- Track reconstruction

TRD: Transition Radiation Detector (1 side)
- Energy calibration of CALO for TeV nuclei

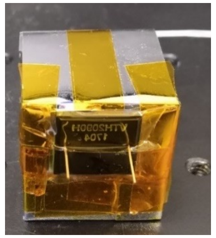
The HERD payload



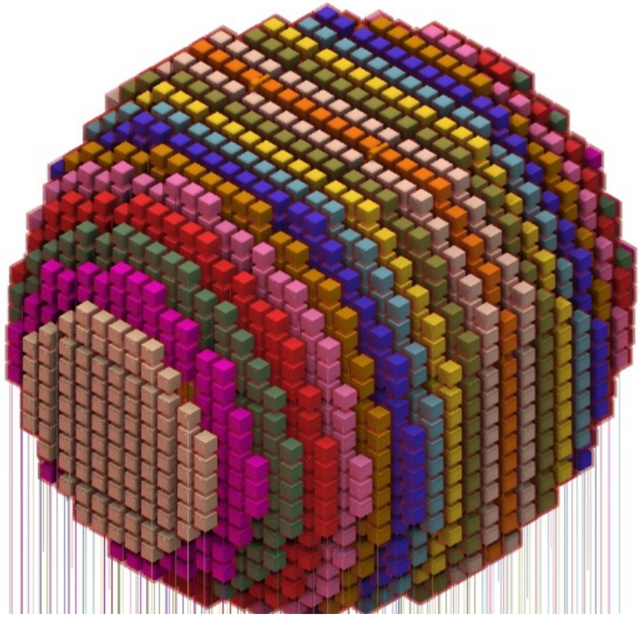
Mass	≤ 4000 kg
Envelope	~ 3.0 * 2.3 * 1.7 m^3
Field of view	+/- 90^o
Power	~ 1.9 kW
Telemetry	100 Mbps

- To maximize the acceptance: novel “isotropic” design with a 3D calorimeter + (FIT+PSD+SCD) on 5 sides
- To reduce systematics: double read-out system for CALO + in-flight calibration with TRD
- To control the nuclei fragmentation: charge detector as outermost detector

CALOrimeter (CALO)

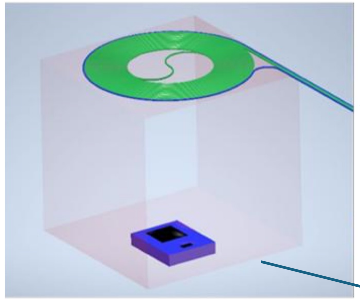


CALO consists of about **7500 LYSO cubes** with edge length of 3 cm arranged into a spherical shape.



Deep homogeneous calorimeter (55 X_0, 3 λ_I)	→	High energy and good energy resolution
Isotropic 3D geometry (top + lateral faces)	→	Large geometric factor
Finely segmented	→	Good e.m./hadronic discrimination, identification of shower starting point and axis

To reduce systematics (especially on the **absolute energy scale**), each cube is read out with 2 systems that allows for redundancy, independent trigger, and cross calibration.



Wavelength shifting (WLS) fibers read out by two Intensified scientific CMOS cameras

2 photodiodes (PD)

CALO readout #1: Intensified scientific CMOS (IsCMOS)

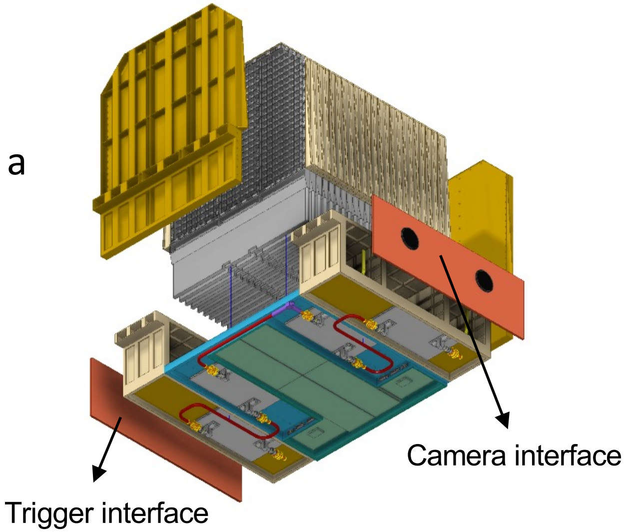
Encapsulation of WLSF with optical cement

WLSF coupled to LYSO and covered by a reflector

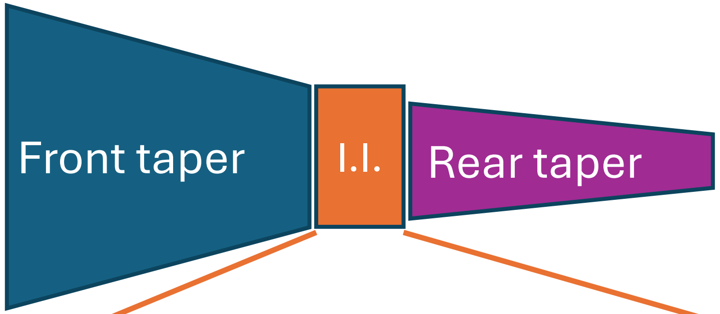
Wavelength shifting fibers (WLS) readout

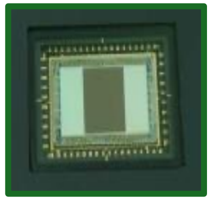
- Each cube is read out with 3 WLS fibers.
- One fiber is used for the trigger and the light signal is read out with a fast PMT.
- The signal from the other two fibers is amplified by an Image Intensifier (two gains) and read out by a IsCMOS camera

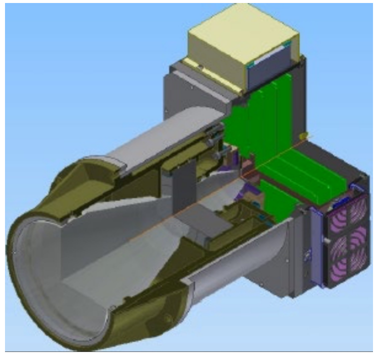
Dynamic range of the camera: **from 10 MeV** (1/3 MIP) **to 20 TeV** (created by a PeV hadronic shower). → 10^7 → 2 different image intensifiers

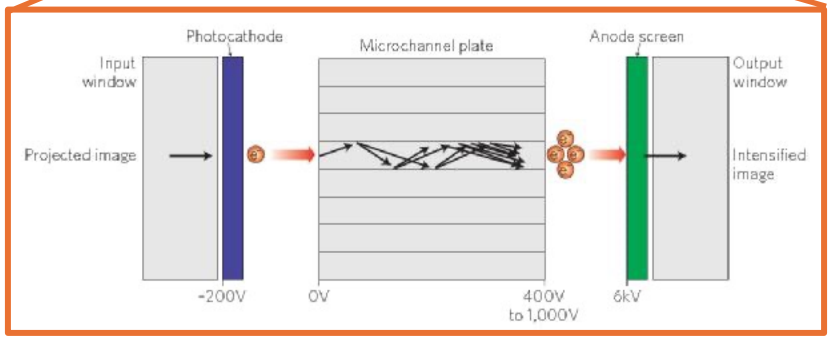


Each IsCMOS camera is composed of a **front taper**, an **image intensifier (I.I.)**, a **rear taper** and a **sCMOS** chip.







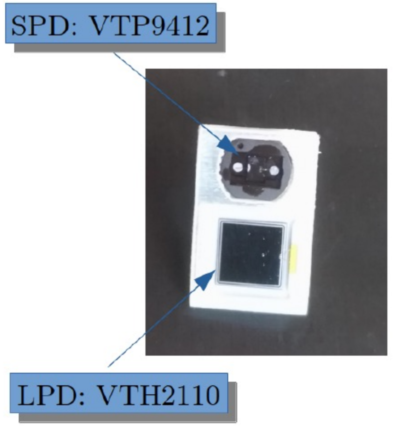


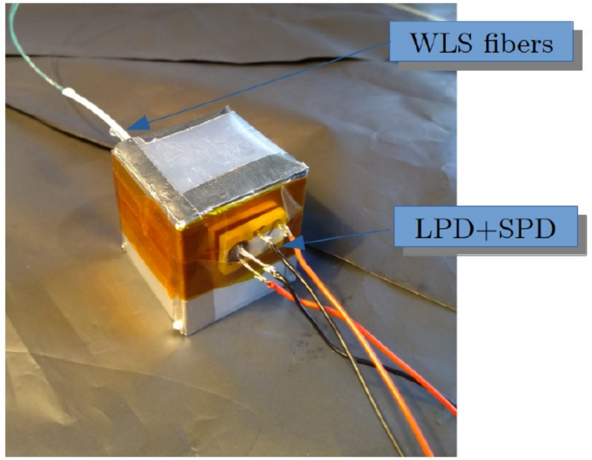
The **image intensifier** converts weak light signals into electrons, multiplies the electrons using a micro-channel plate, and then converts the electrons back into photons using a phosphor screen.

CALO readout #2: photodiodes

Photodiode (PD) readout

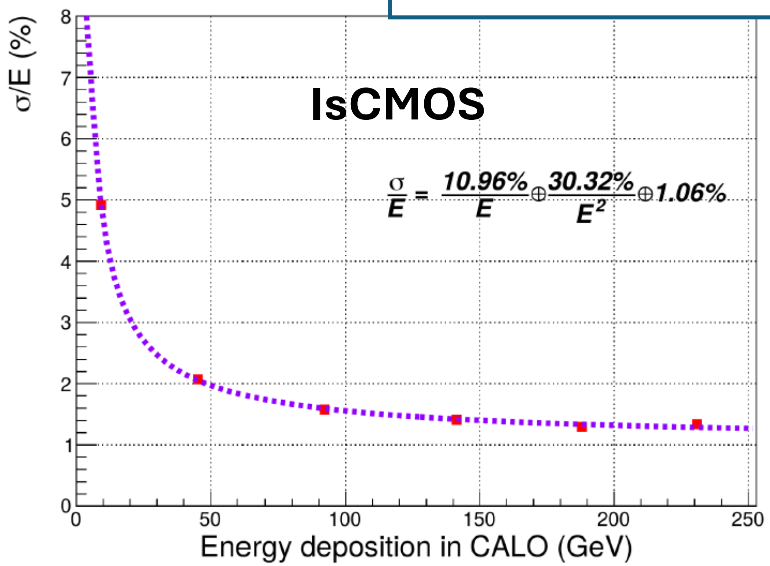
Each cube is read out with 2 PDs: the large PD (LPD, 25 mm^2) and the small PD (SPD, 1.6 mm^2) connected to HIDRA chips .

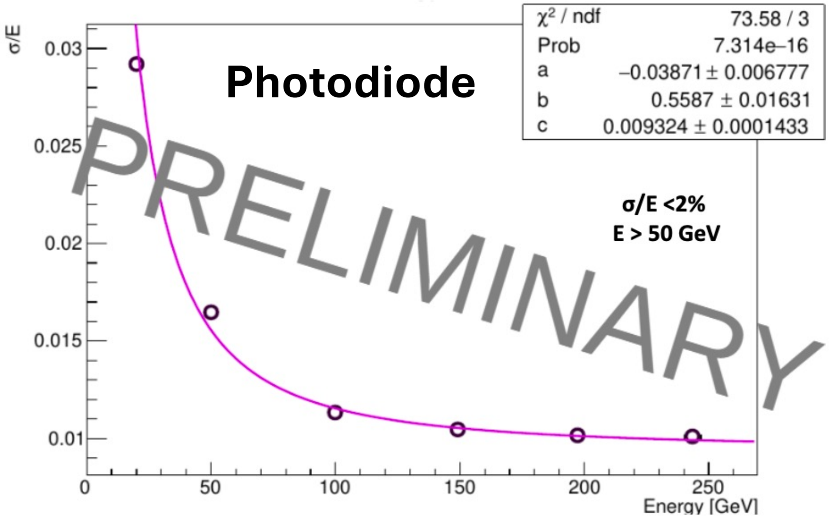




O. Adriani *et al* 2022 *JINST* **17** P09002

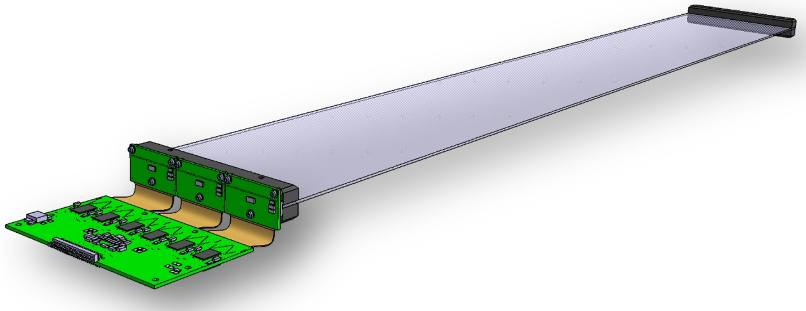
Energy resolution
Electron beam test



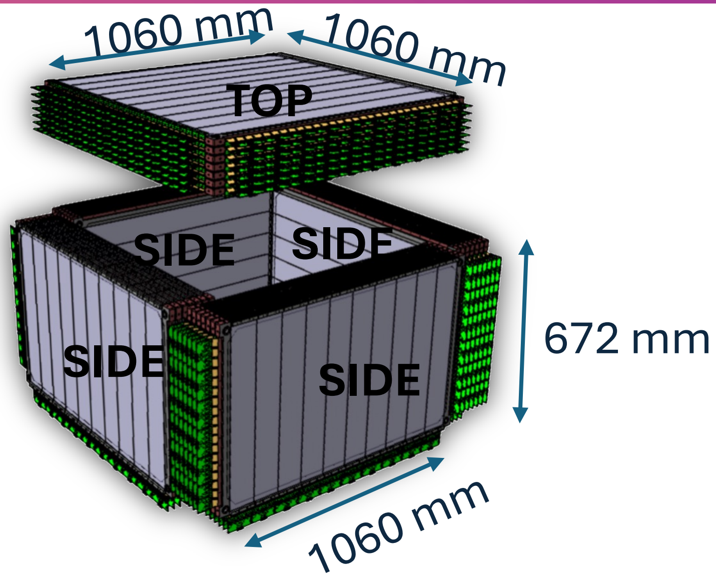


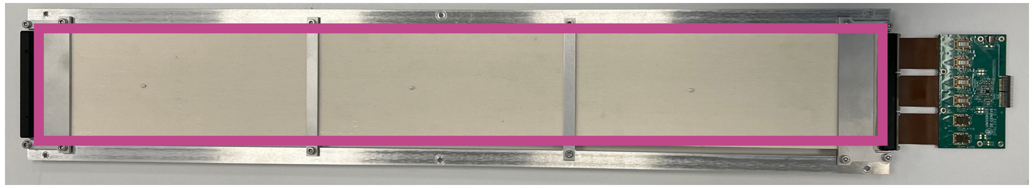
FIT: modular high-resolution tracker for application in space

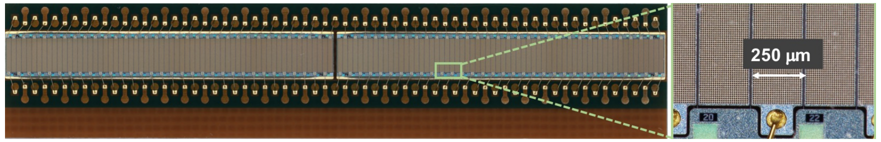
FIT Module = 1 fiber mat + FEB with 3 SiPM arrays



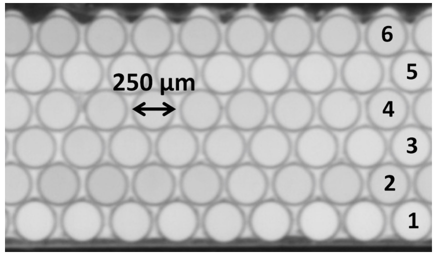
FIT = 5 sectors







- Fiber mat: **6 layers of fibers**
- Fiber type: KURARAY SCSF-78MJ
  - round section, diameter = **250 µm**
  - Peak at 450 nm
- Mat width ≅ 97.8 mm to match 3 SiPM arrays

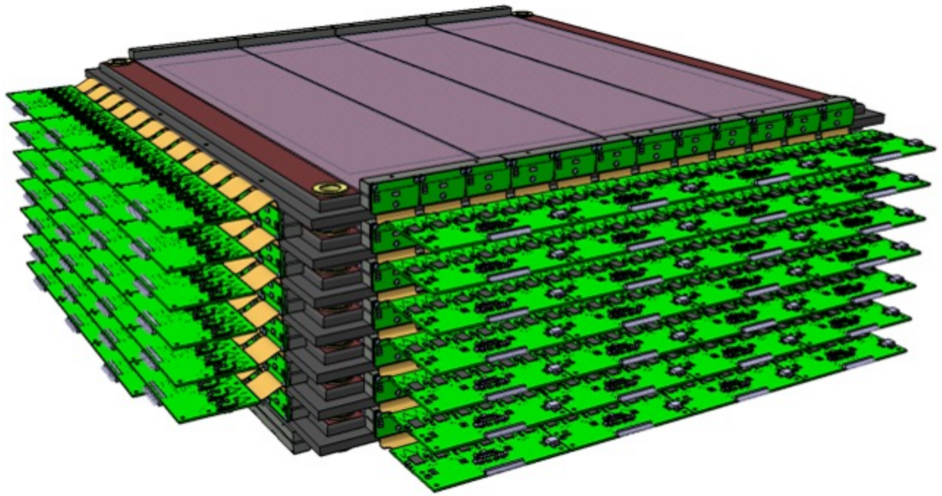


- Hamamatsu array: 2 chips with 64 SiPMs
- 23 x 163 pixels/SiPM
- **Pixel pitch: 10 µm**
- SiPM size: 230 µm × 1630 µm
- **SiPM pitch: 250 µm**

https://doi.org/10.22323/1.395.0067

MiniFIT

The miniature of a FIT sector.

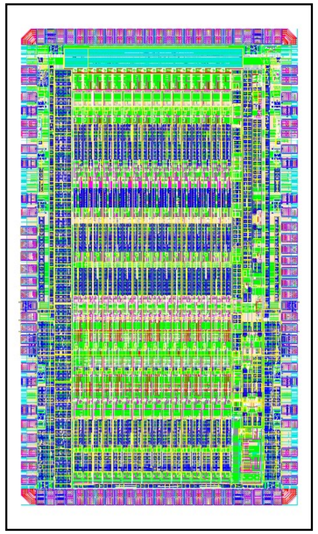


Layout:

- 7 x-y tracking planes
- 4 x + 4 y FIT modules per tray
- Fiber-mat length: 40 cm.

Goals:

- Test the **tracking** capability of FIT
- Test the **charge measurement** capability of FIT
- Test the BETA ASIC



- ✓ Channels: 64 (PSD version: 16 ch)
- ✓ Event rate: 10 kHz with ADC @ 50 MHz
- ✓ Configurable preamplifer gain: 4 bits
- ✓ Tunable shaping time: 230 ns to 1.5 us
- ✓ Trigger output: < 250 ps time resolution

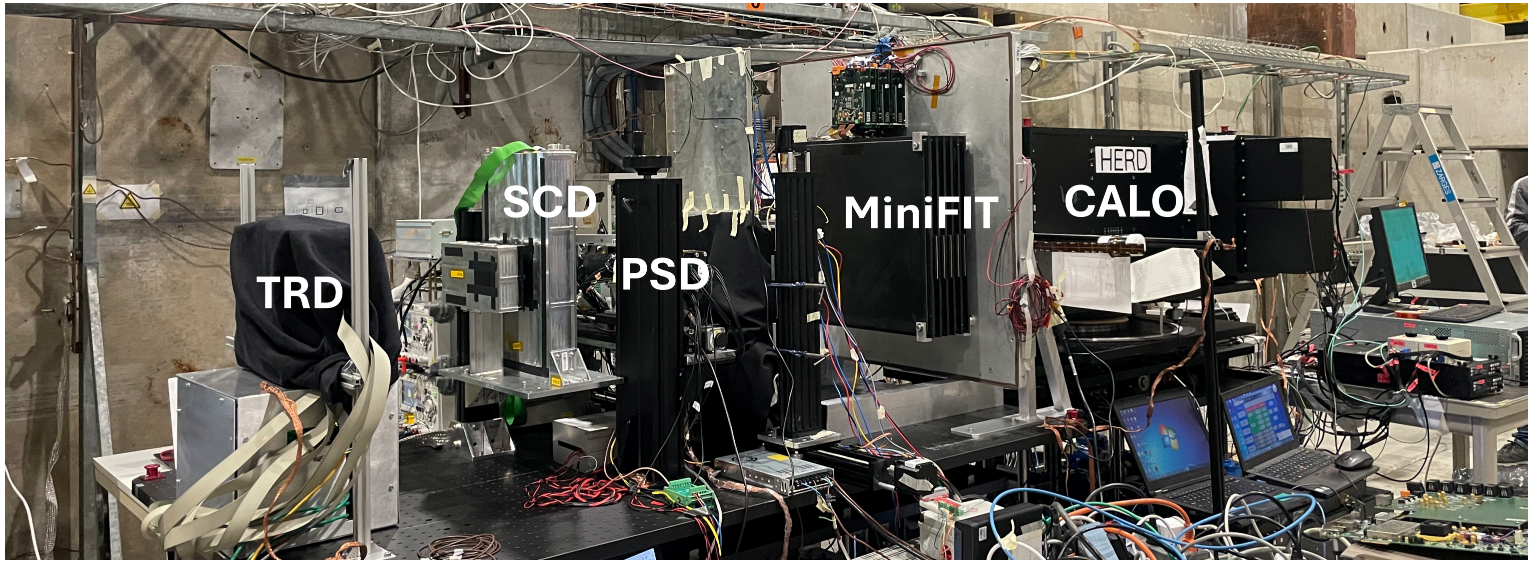
- ✓ **Single photon resolution: SNR >5 for 10 µm pixel**
- ✓ On chip ADC: Wilkinson 11 bit + 1bit (path sel)
- ✓ **High Dynamic Range: 15 bit (no saturation for > 3800 fired pixels)**
- ✓ **Dual path: automatic gain switching**
- ✓ Slow Digital Control : I2C
- ✓ **Power Budget : < 1 mW/ch**

https://doi.org/10.22323/1.444.0085

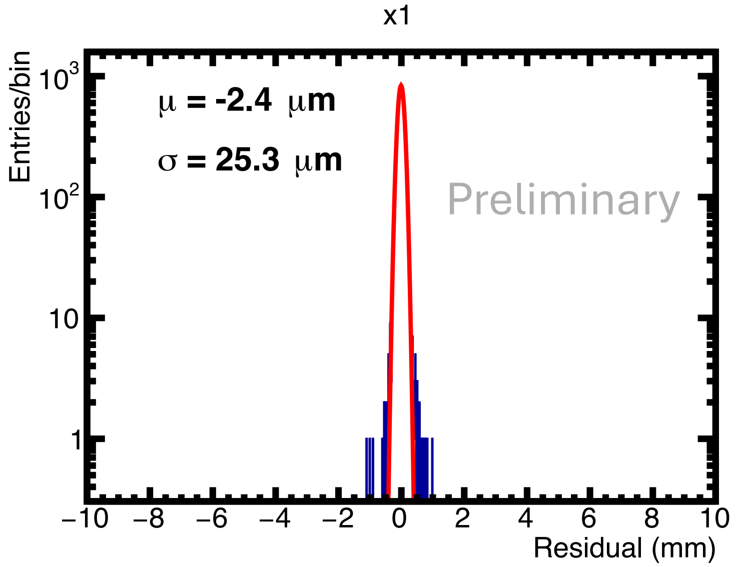
MiniFIT performance

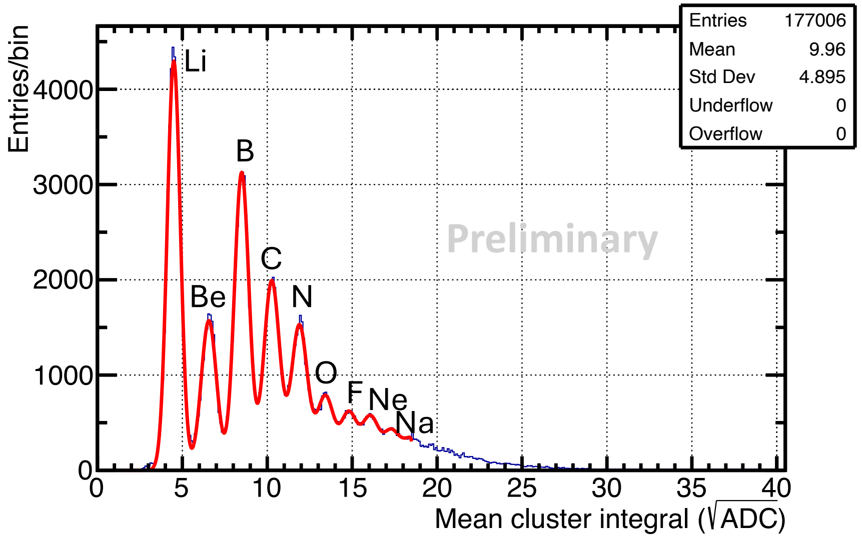
MiniFIT @CERN SPS, Fall 2023

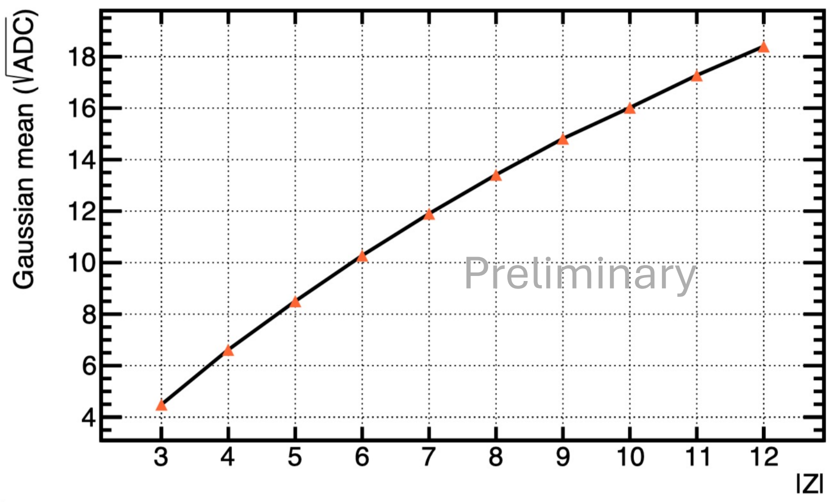
- **Fragmentation ion beam** (330 GV/c) created with a beam of lead nuclei (379 GV/c) hitting a 40 mm thick beryllium target.



Carbon (Z = 6)

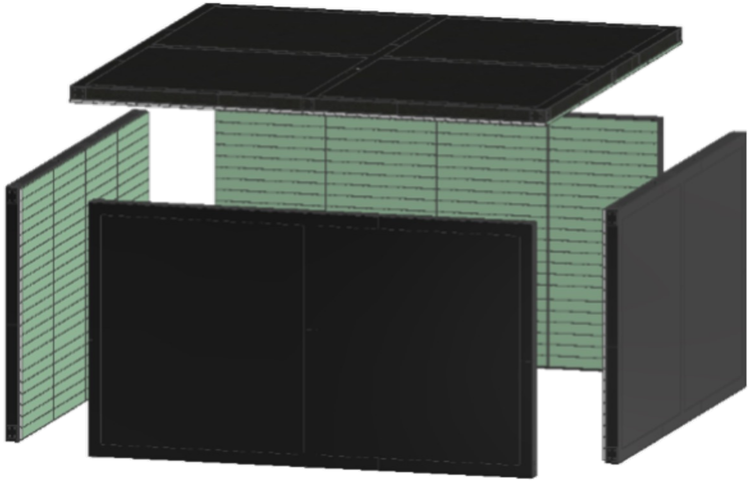






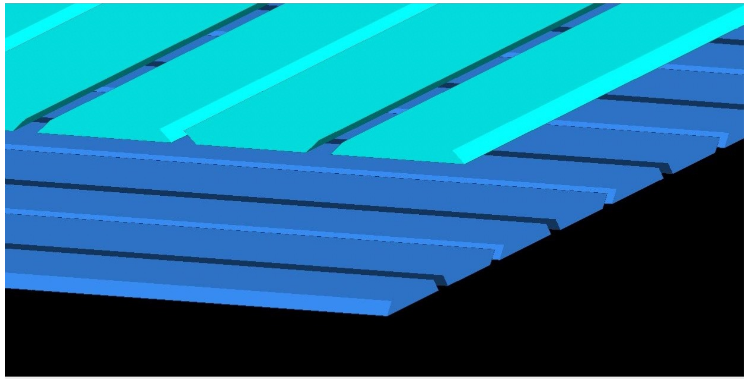
Plastic Scintillator Detector (PSD)

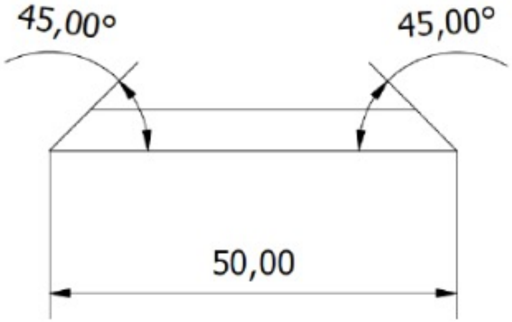
- PSD provide **gamma-ray identification** (VETO of charged particles) and **nuclei identification** (energy loss $\propto Z^2$)
- Requirements:
  - High **efficiency** in charged-particle detection (> 99.98%) to be used as veto
  - High **dynamic range** to identify nuclei at least up to iron
  - **Segmented design** to reduce the self VETO due to the charged secobdary particles back scattered from the CALO



1 TOP plane and 4 SIDE planes

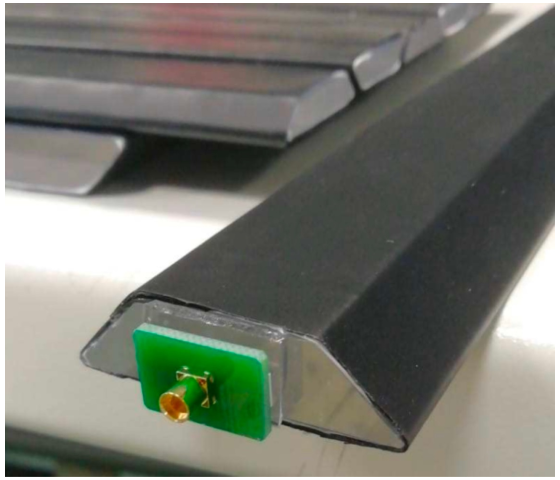
A plane is made of two orthogonal **layers of** trapezoidal plastic scintillating tiles (40 cm long) to increase the hermeticity and the VETO efficiency.





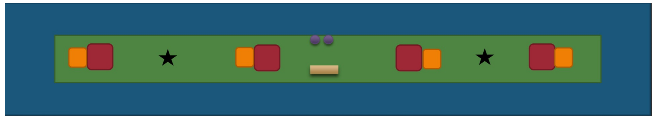
TOP: 180 cm x 180 cm, ~400 tiles
SIDE: 170 cm x 95 cm, ~160 tiles
Total number of tiles: ~1000

PSD readout and performance



Readout: 2 sets of SiPMs (low-Z/high-Z) + BETA ASIC, ensuring:

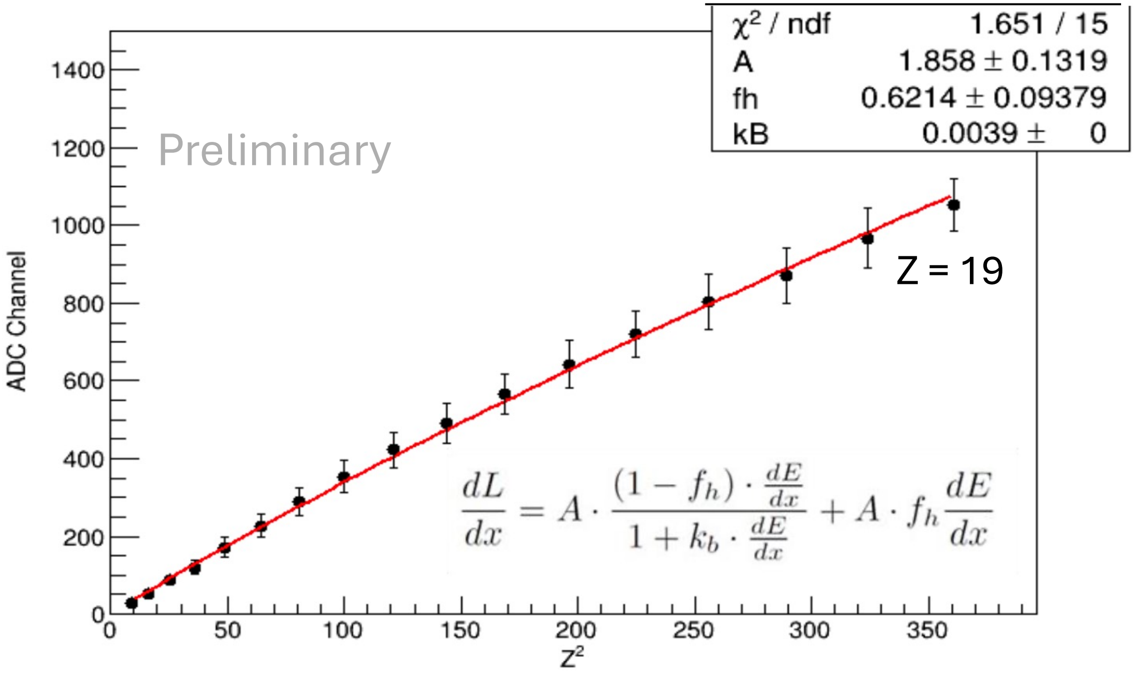
- high triggering efficiency;
- wide dynamic range.



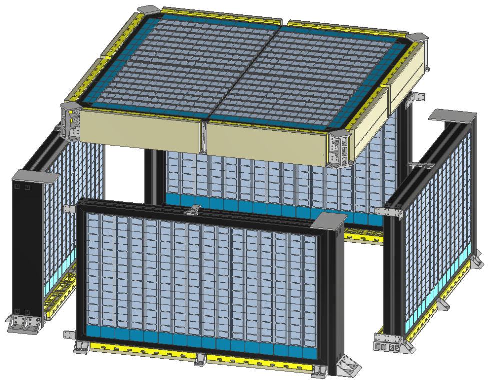
Low-Z SiPM
3 mm x 3 mm channel
50 mm x 50 mm pixel

High-Z SiPM
1.3 mm x 1.3 mm channel
15 mm x 15 mm pixel

PSD prototype:
4 X– 4 Y tiles

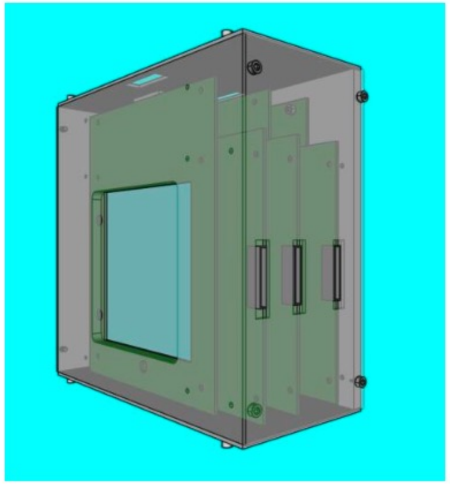


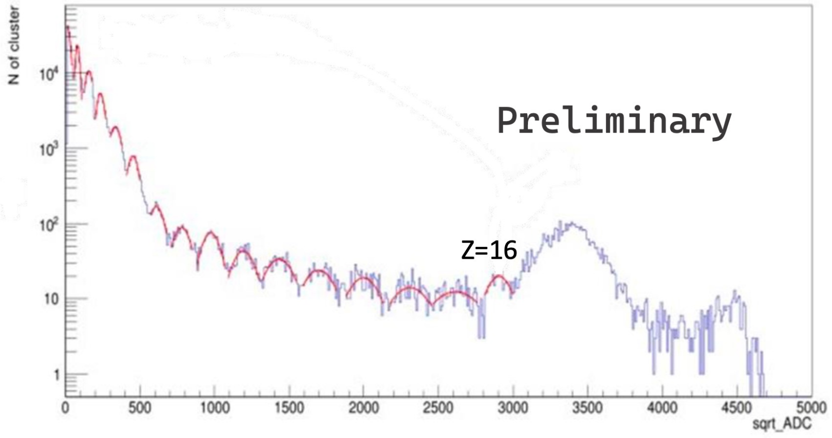
Silicon Charge Detector (SCD)

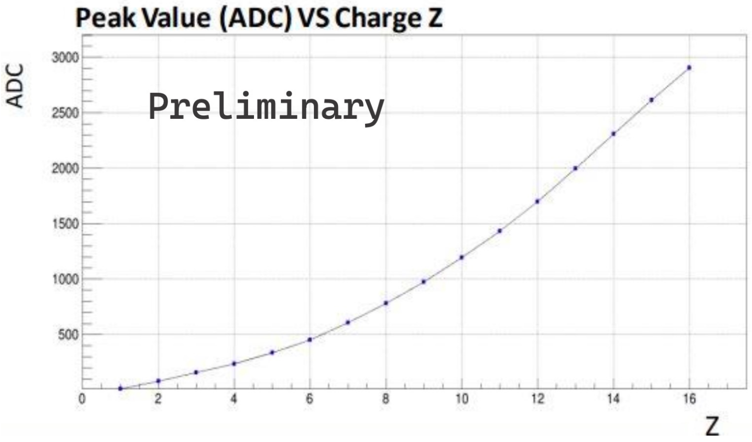


- SCD is a **silicon micro-strip** detector (SSD) that will measure with precision the impinging particle charge |Z|
- 4 X-Y layers of single sided SSD for each of the five sectors → 8 independent ionization measurements per sector → Z =1 to 28
- It is the **outermost** detector to avoid early charge-change interactions in the PSD and to reduce the systematic uncertainty on the reconstructed charge due to fragmentation
- It is highly **segmented** to minimize the unavoidable backscattered secondary particles coming from the CALO

SCD prototype: 3 X-Y single SSDs, Si thickness: 150 µm, active area 96 mm x 96 mm

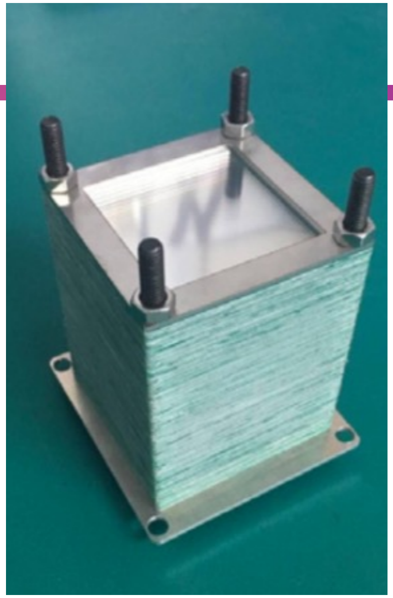




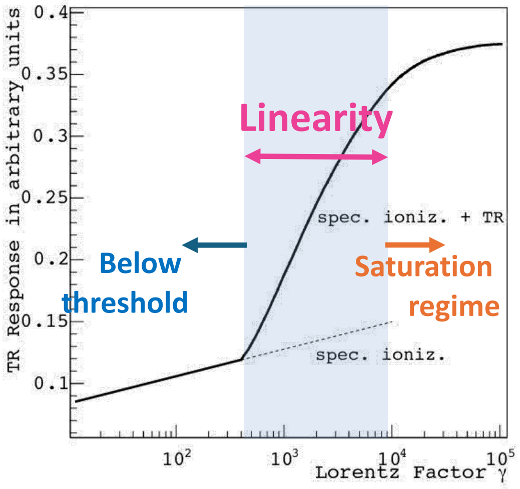


Charge resolution < 20%

Transition Radiation Detector (TRD)



The TRD, installed on one lateral face of the detector, is needed to **calibrate the response of the calorimeter to high-energy hadronic showers**.

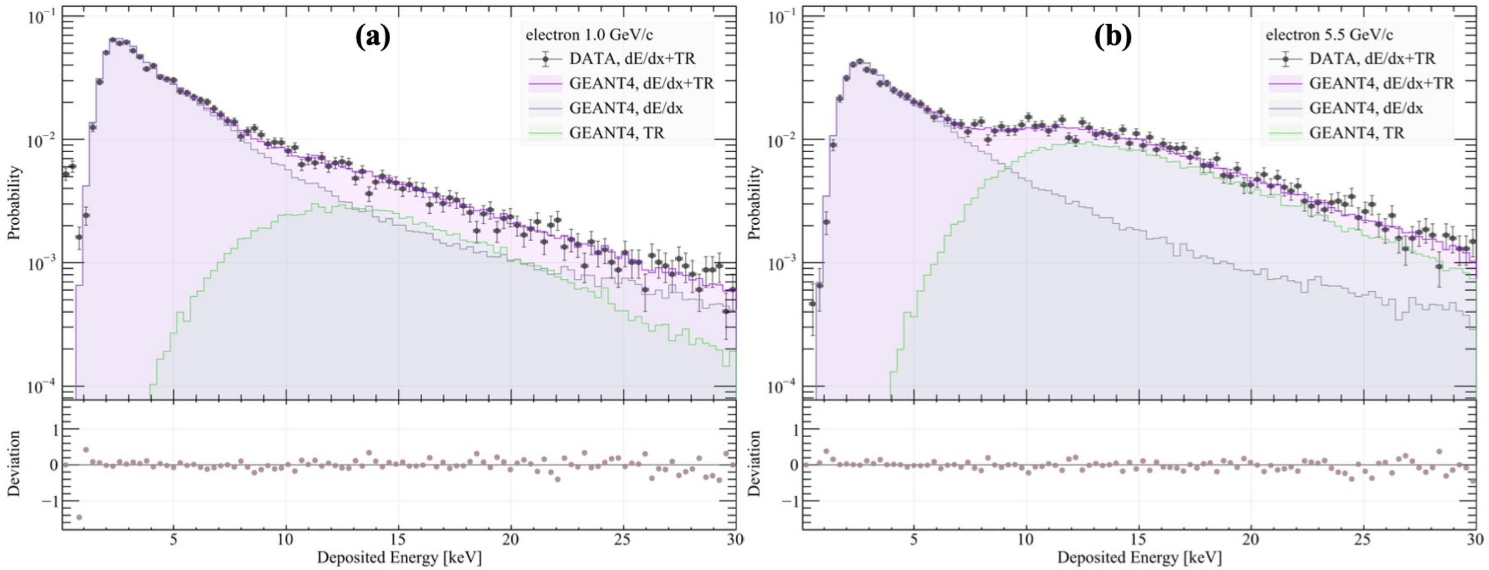


Linearity for $10^3 < \gamma < 10^4$

- Electrons: 0.5 GeV $< E_e <$ 5 GeV
- Protons: 1 TeV $< E_p <$ 10 TeV

Calibration procedure:

- calibrate TRD response using [0.5 GeV, 5 GeV] electrons in space (and beam test)
- calibrate CALO response using [1 TeV, 10 TeV] protons from TRD (3 months data required)



Radiator:

- multi-layer Polyimide thin foils

Detector:

- 1 atm Xe
- side-on THGEM (THick Gaseous Electron Multiplier)

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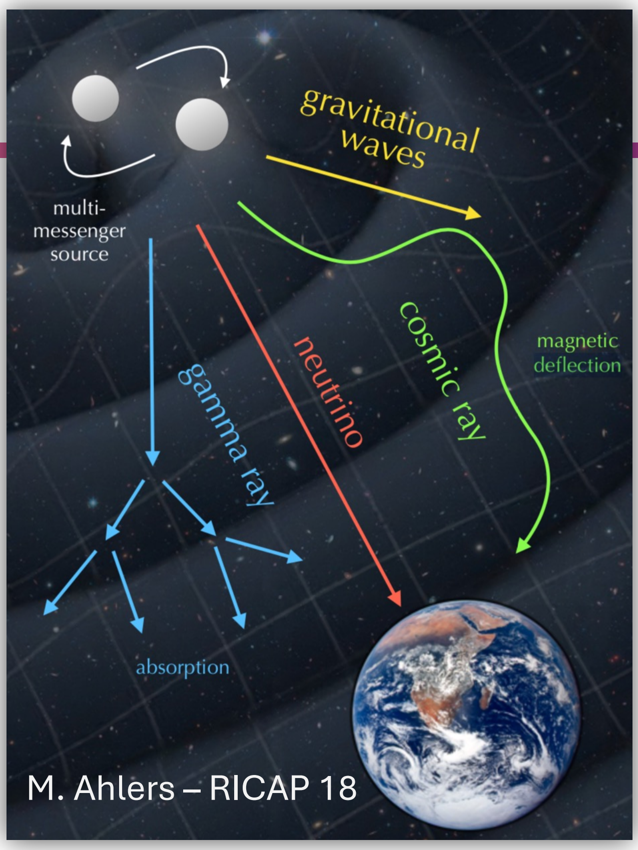
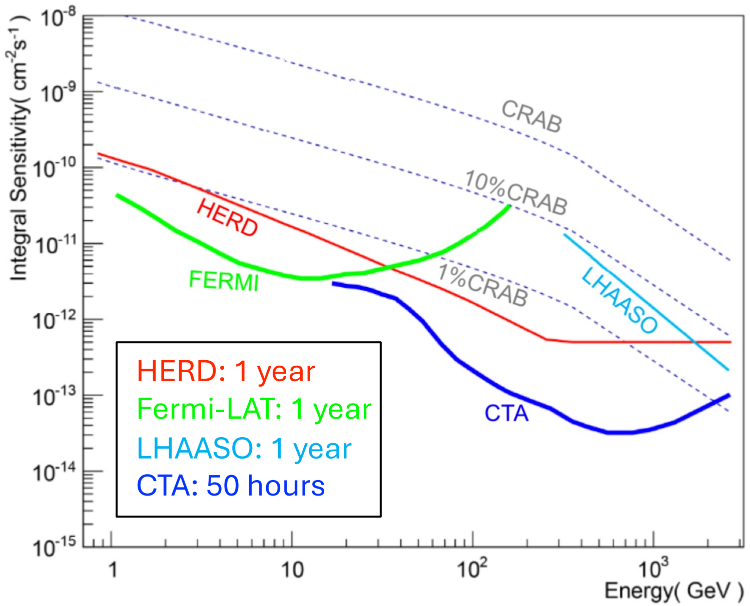
Multimessenger astronomy

- HERD with its unusual large **field of view** and unique **energy coverage** will play a unique and complementary role in
  - multi-wavelength studies across the electromagnetic spectrum with other space and ground telescopes involving radio, optical, X-ray, γ-ray emission
  - search for electromagnetic counterpart of gravitational waves and of neutrinos (IceCube, KM3Net).
- HERD will produce alerts: AGN, novae, binary systems, …





HERD + CTA + LHAASO

- Simultaneous coverage of the same sources from few GeV to 1 PeV
- Overlap of measured spectra
  - Distinguish diffuse emission from localized contributions, to disentangle acceleration and propagation mechanisms in SNRs, PWN, pulsars, and in more extended objects as the Fermi bubbles.
  - Study transient phenomena, which is crucial to analyse the properties of jets, and can help determining the extragalactic background light, intergalactic magnetic fields, and the validity of the Lorentz invariance.

Summary and outlook

- HERD will be a calorimetric detector with unprecedent acceptance, launched and installed on the CSS in 2027.
- HERD could become the only space-borne high-energy gamma-ray detector, once the Fermi satellite will stop its operations.
- Frontier scientific goals in cosmic-ray physics, gamma-ray astronomy, and dark-matter search.
- Performance of subdetector prototypes evaluated during several beam-test campaigns:
  - Additional beam tests in 2024 and 2025.
  - Moving toward the production of qualification models.

Thank you!