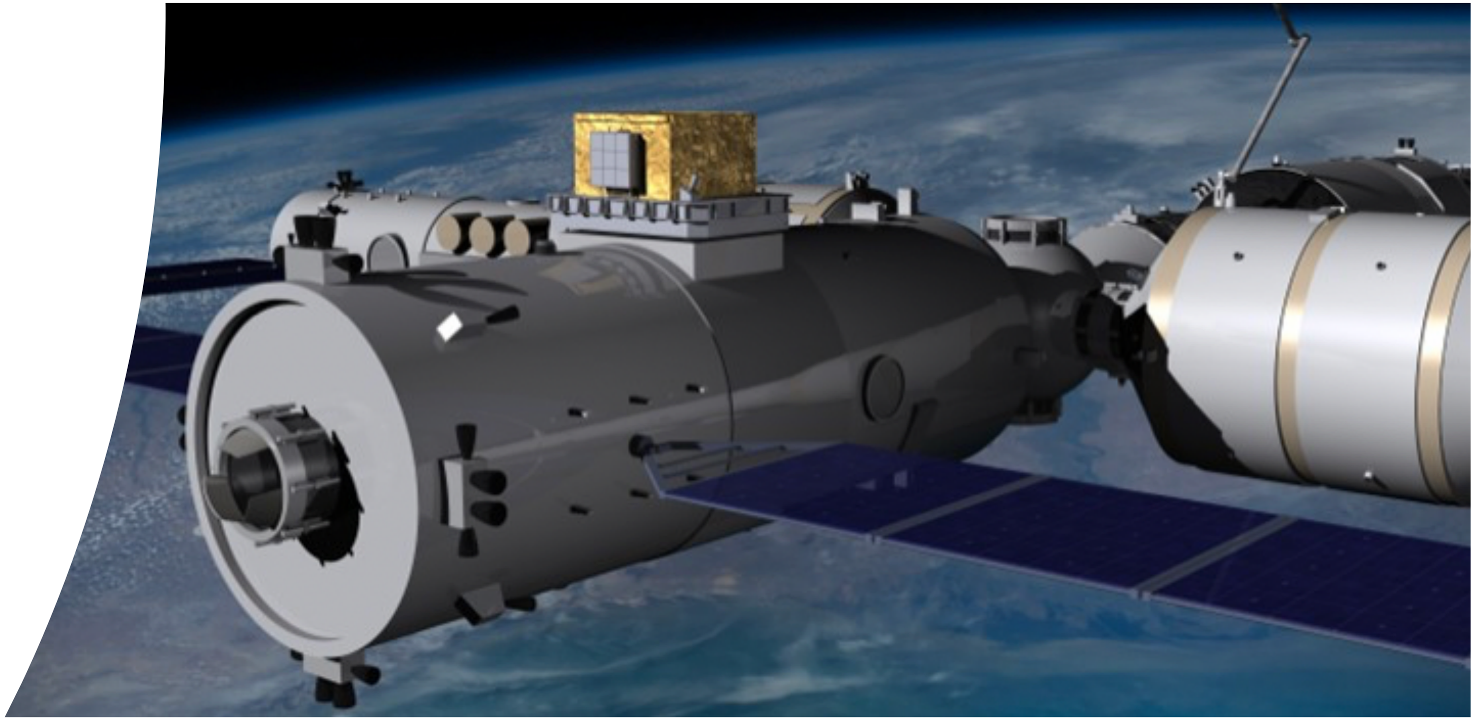
Attaining the PeV frontier of the cosmic ray spectrum in space with HERD

Chiara Perrina

on behalf of the HERD Collaboration

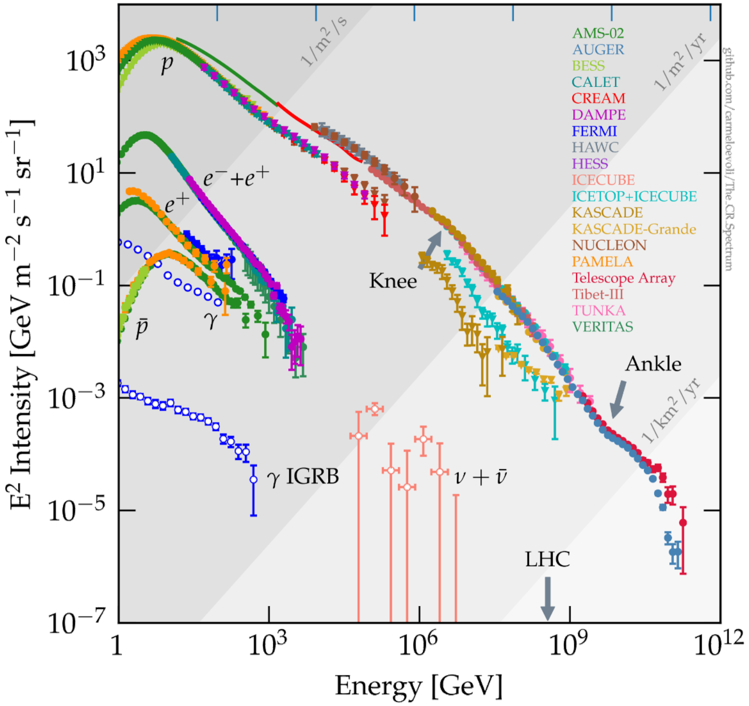
EPFL



Open questions in astroparticle physics

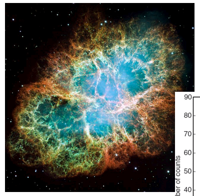
Cosmic rays

Sources, acceleration, propagation

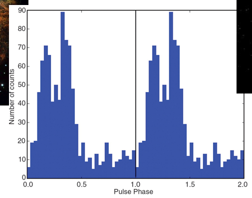


High energy cosmic photons

Sources, interactions, non-thermal physics

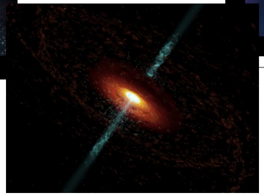


SNRs

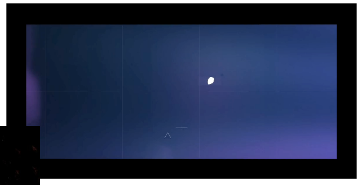


Pulsars

Galactic structures



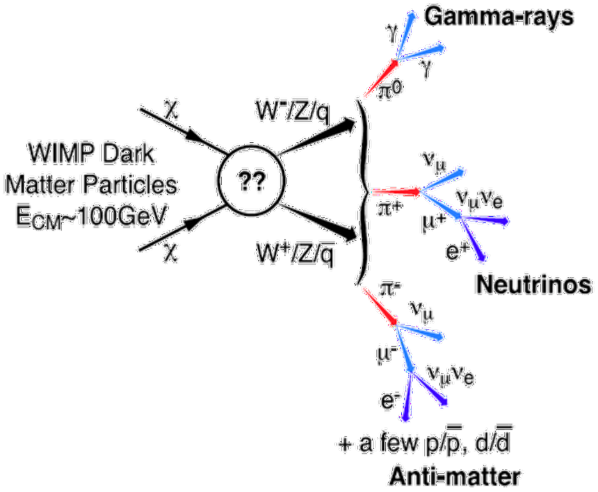
Blazars

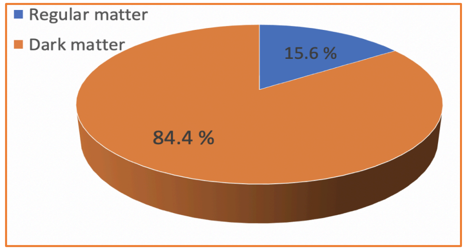


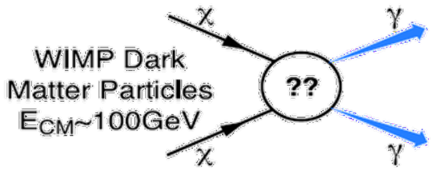
Tidal disruption events

Dark matter

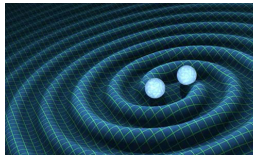
Nature, origin, properties



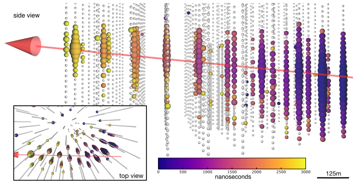




Multimessenger astrophysics

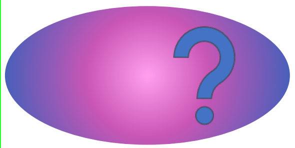


γ-ray counterpart of gravitational waves



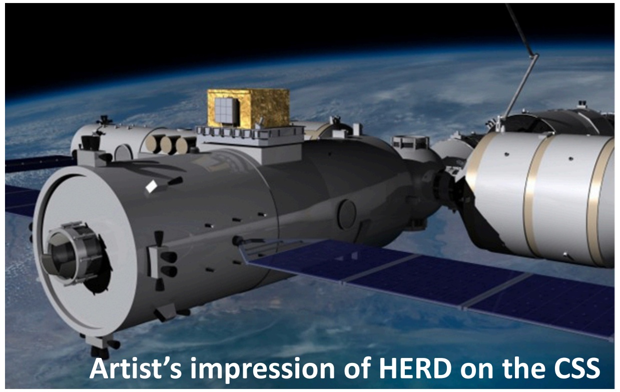
γ-ray counterpart of neutrinos

Exotic particles



HERD

- The **H**igh **E**nergy cosmic-**R**adiation **D**etection facility (HERD) is a space particle experiment and gamma ray observatory.
- HERD will be launched and installed onboard China's Space Station (CSS) in 2027, operational for at least 10 years.
- HERD is a space-borne calorimetric experiment.
- HERD is based on a **3D, homogeneous, isotropic and finely-segmented calorimeter** (55 X_0, 3 λ_I).

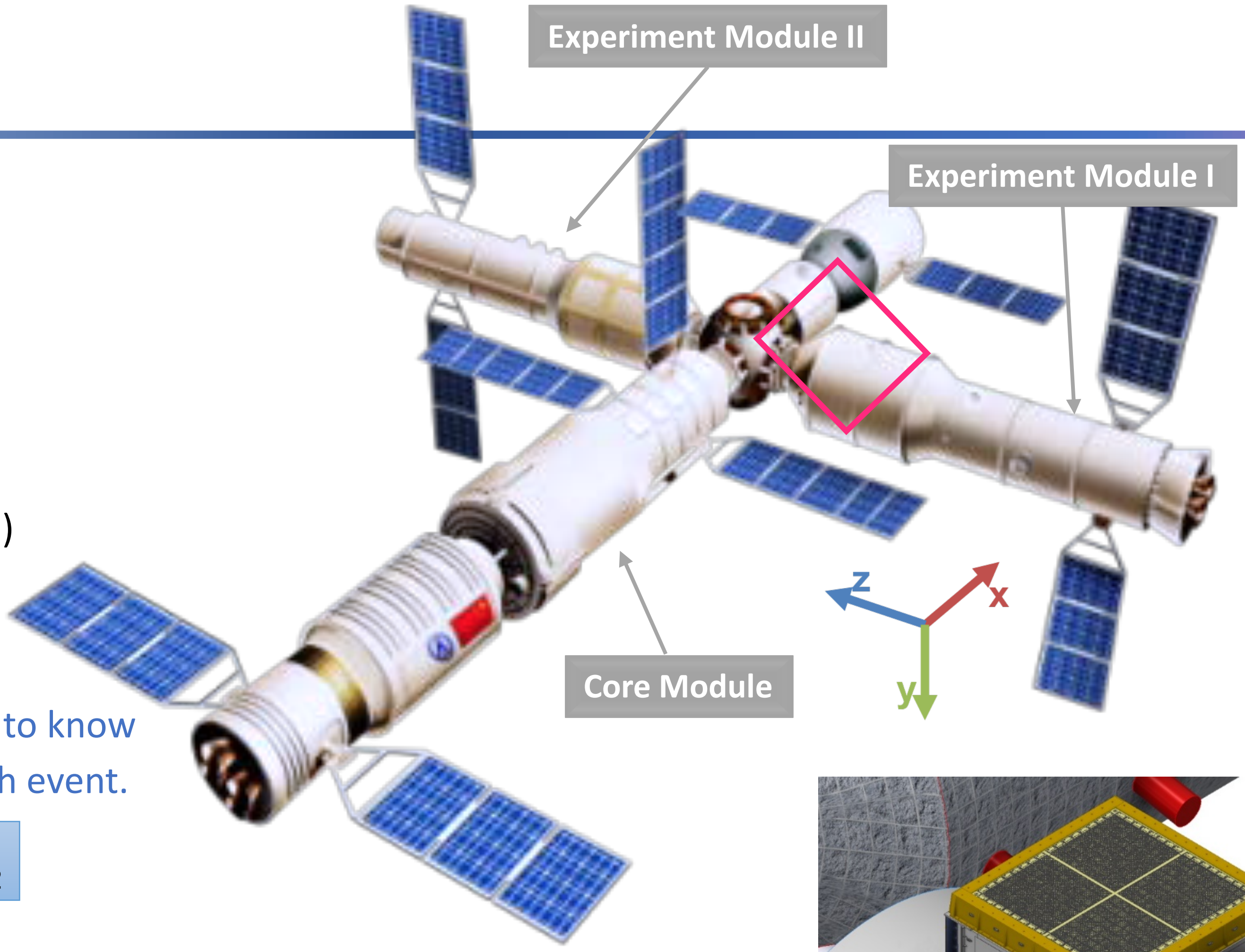

Artist's impression of HERD on the CSS

International scientific collaboration counting 180+ scientists from China and Europe.

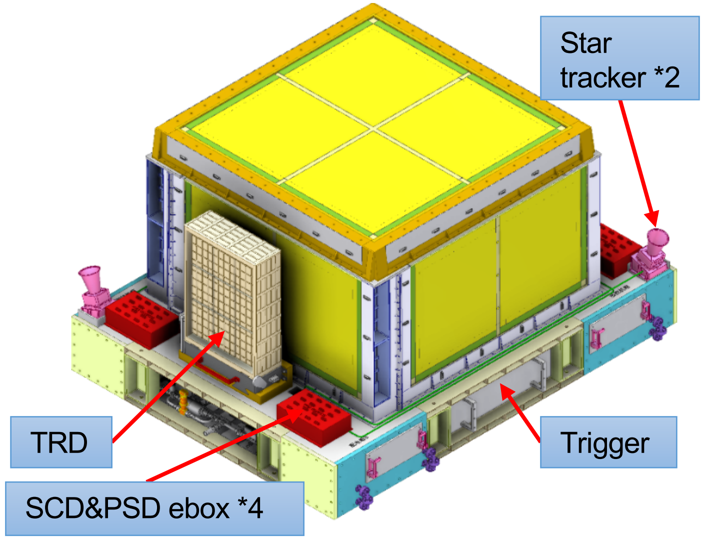
Lead by IHEP	University of Geneva EPFL - Lausanne
University and INFN of Bari, Firenze, Lecce, Napoli, Pavia, Perugia, Pisa, Roma2, Trieste, LNGS and GSSI.	CIEMAT – Madrid ICCUB – Barcelona IFAE - Barcelona

CSS parameters

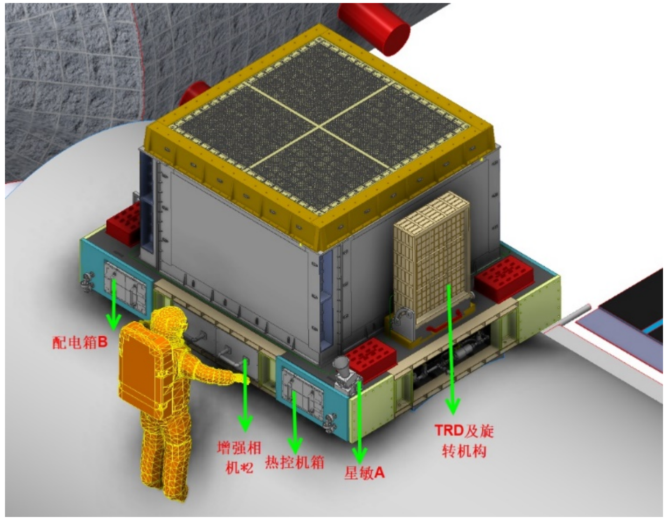
- **CSS** expected to be completed in 2022
- **Orbit**
  - Circular
  - Altitude: 340 km - 450 km
  - Inclination: 41° – 43°
- **Pointing**
  - To the Earth (three axis stabilized system)
  - Pointing accuracy ≤ 0.1° (3 σ)
  - Pointing stability ≤ 0.005°/s (3 σ)



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



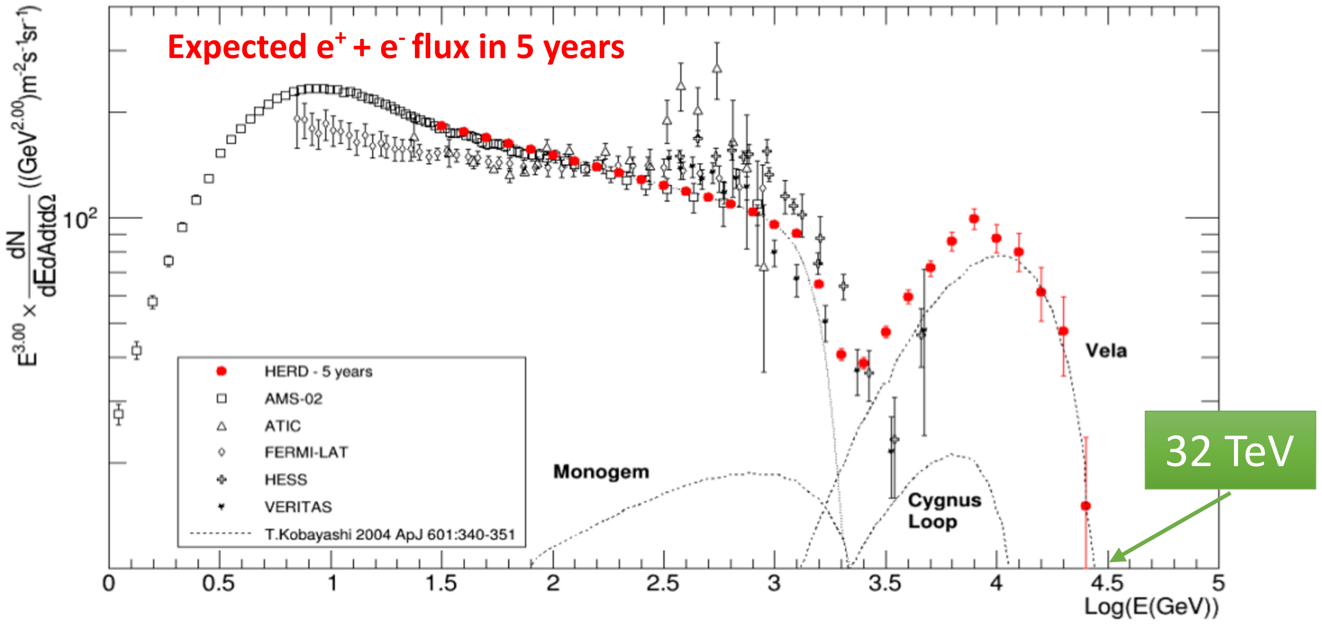
HERD will be a little bit off zenith to avoid interferences between antennas and star trackers.



HERD observables and physics goals (1/3)

Electrons + positrons up to some tens of TeV

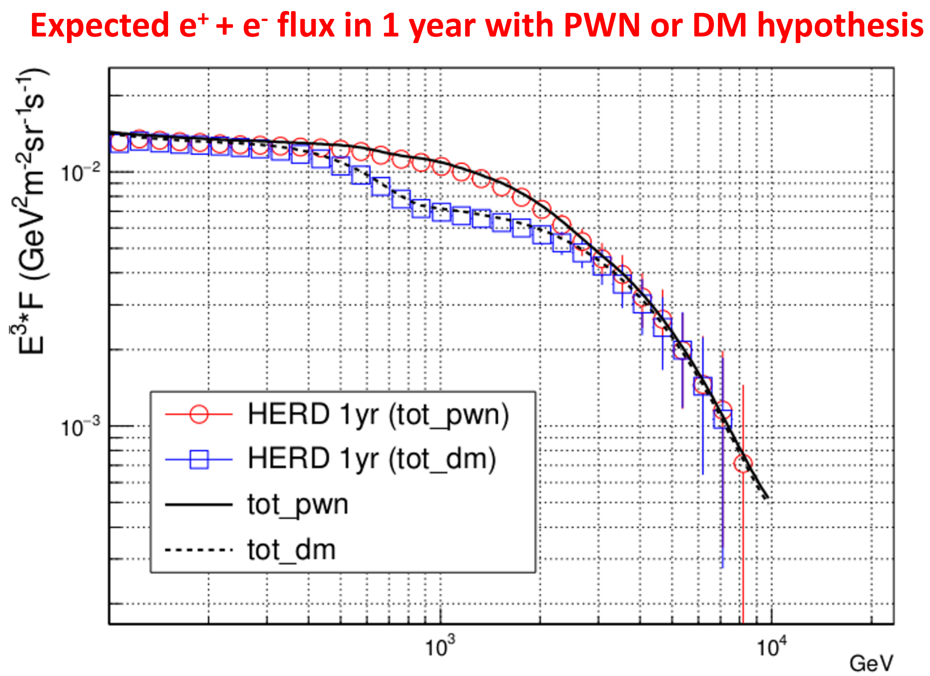
Acceleration and propagation studies



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

- spectral cutoff at high energy
- local nearby astrophysical sources of very high energy e^-
- additional information from anisotropy measurement…

Dark matter indirect searches

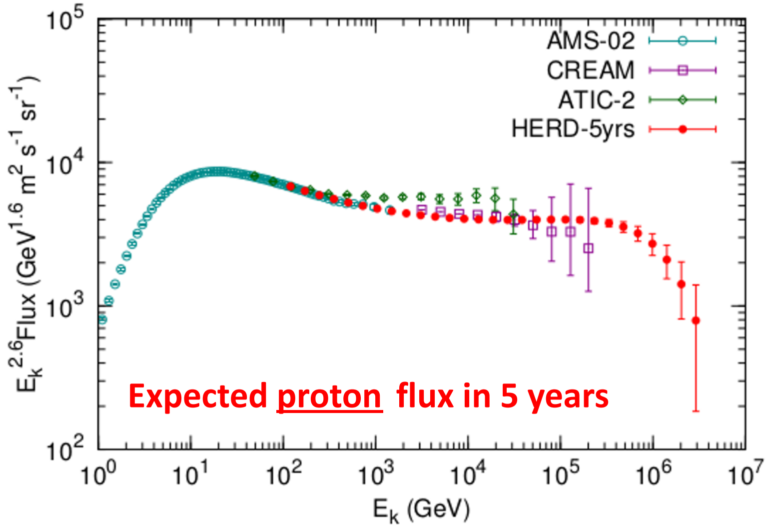


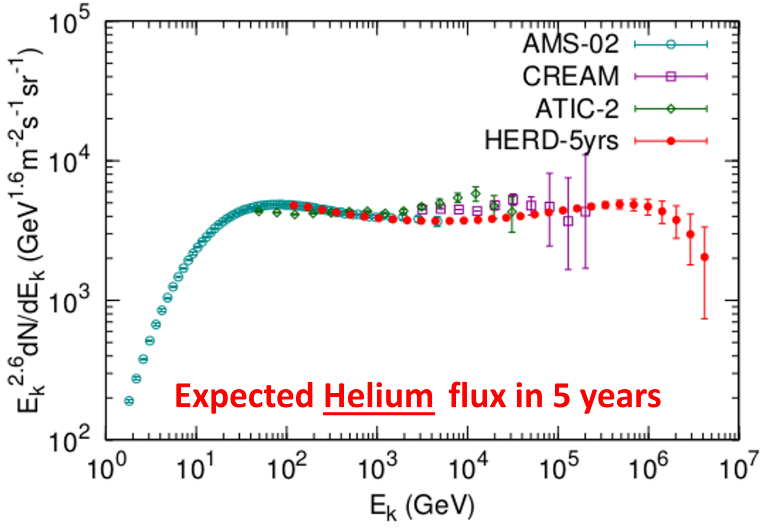
HERD will give important indications on the origin of the positron excess, i.e., to distinguish the dark matter origin of the excess from other astrophysical explanations, thanks to the precise measurement of the $e^+ + e^-$ flux.

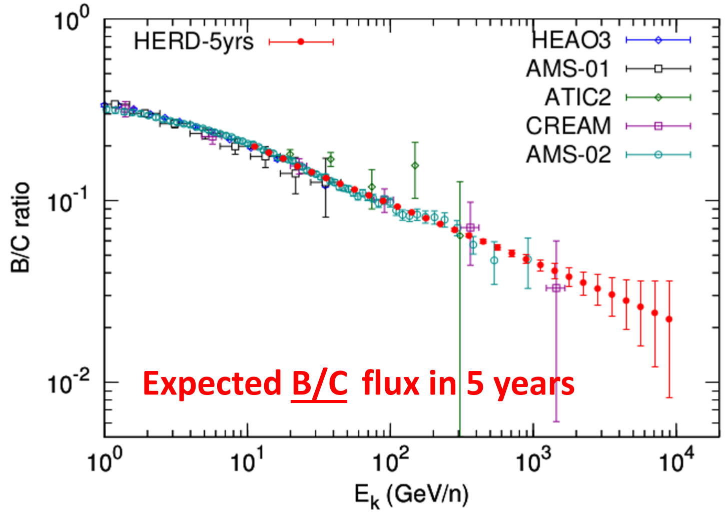
HERD observables and physics goals (2/3)

Hadrons up to the knee

Acceleration and propagation studies







HERD will measure the flux of nuclei:

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

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

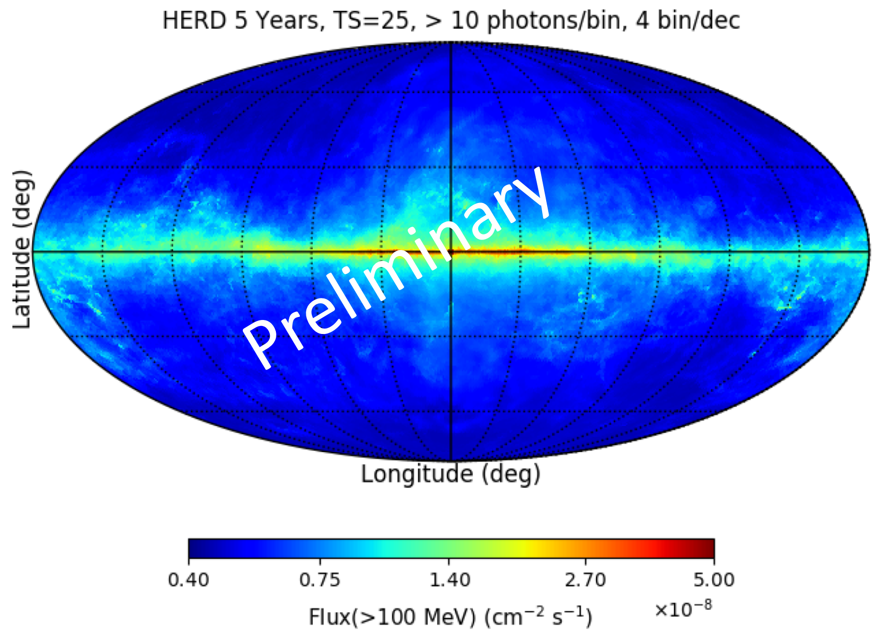
Extension of the B/C ratio to high energy will provide further insights into the propagation mechanisms of cosmic rays

HERD observables and physics goals (3/3)

Gamma rays from 100 MeV

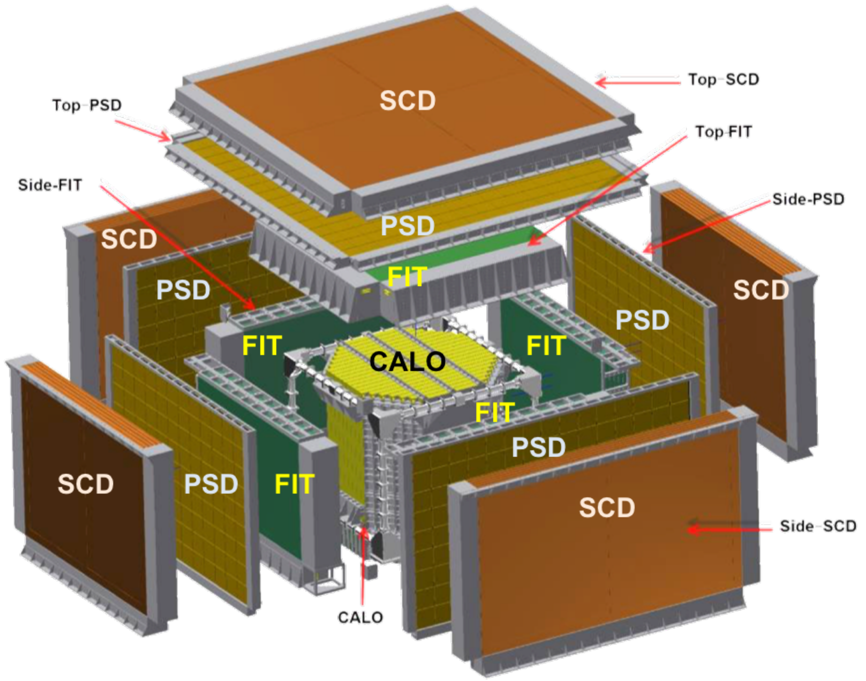
Thanks to its large acceptance and sensitivity, **HERD** will be able to perform a full gamma-ray sky survey in the energy range > 100 MeV

- study of galactic and extragalactic γ sources
- study of galactic and extragalactic γ diffuse emission
- detection of high energy gamma ray bursts
- extend Fermi-LAT catalog to higher energy (> 300 GeV)
- search for indirect dark matter signatures



The HERD detector

F. Gargano et al., POS (ICRC 2021) 026



CALO: CALOrimeter (55 X_0)

- Energy measurement
- Electron/proton separation

FIT: FIber Tracker (5 sides)

- Track reconstruction
- Low energy γ ray conversion ($\gamma \rightarrow e^+ e^-$)
- Charge measurement (|Z|)

PSD: Plastic Scintillator Detector (5 sides)

- Charge measurement (|Z|)
- γ ray identification

SCD: Silicon Charge Detector (5 sides)

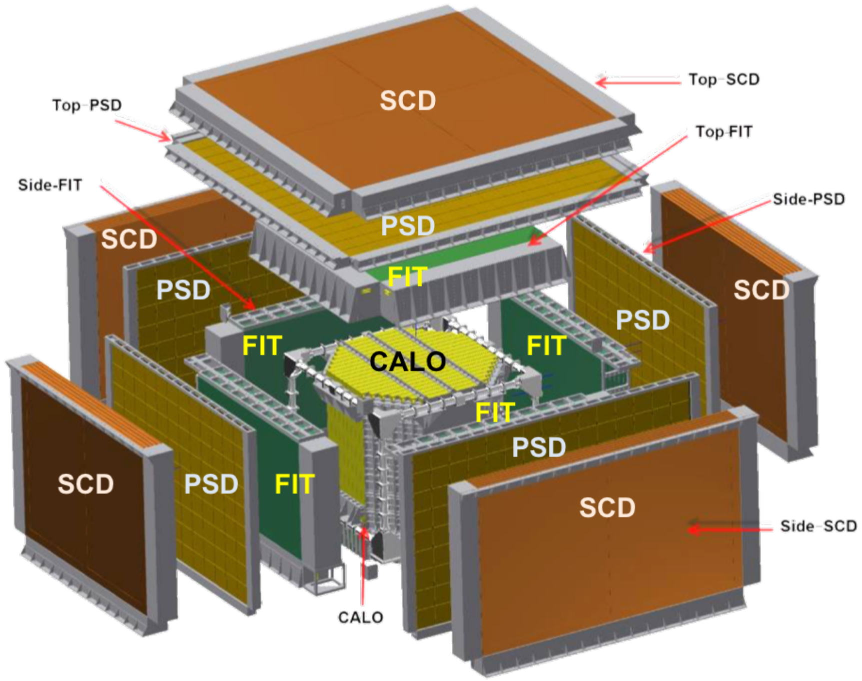
- Charge measurement (|Z|)

TRD: Transition Radiation Detector (1 side)

- Energy calibration of CALO for TeV nuclei

The HERD detector

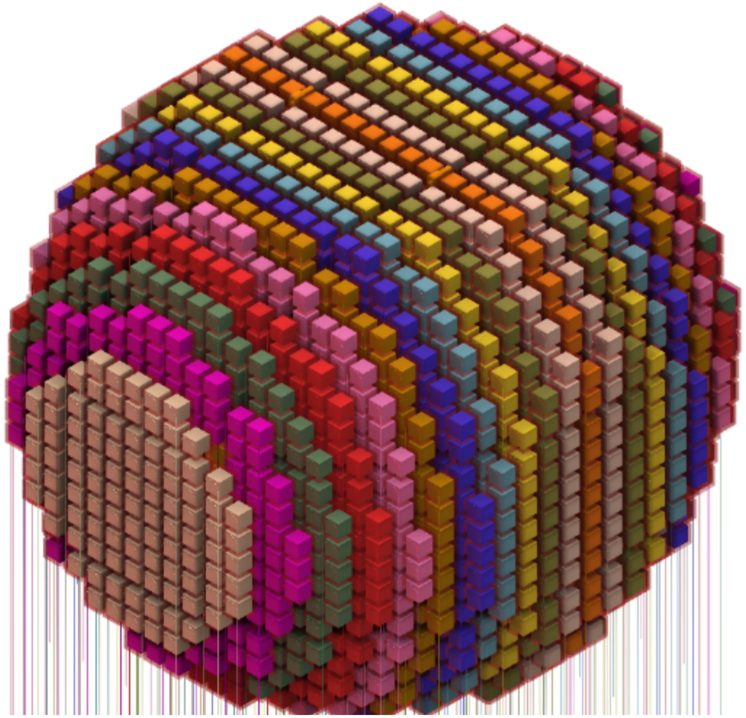
F. Gargano et al., POS (ICRC 2021) 026

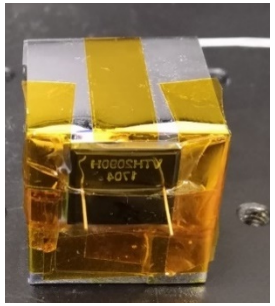


Mass	≤ 4000 kg
Envelope	~ 3.0 * 2.3 * 1.7 m^3
Field of view	+/- 90^o
Power	~ 1900 W
Telemetry	100 Mbps

- To maximize the acceptance: novel “isotropic” design with a 3D calorimeter + (FIT+PSD+SCD) on 5 sides
- To reduce systematics: double readout 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.

- Deep homogeneous calorimeter (55 X_0, 3 λ_I) → High energy and good energy resolution
- Isotropic 3D geometry → Large geometric factor (top + lateral faces)
- Shower imaging with 3D segmentation → Good e/p discrimination, identification of shower starting point and shower axis

Each cube is readout by 2 systems. The double read-out system allows for **redundancy, independent trigger, and cross calibration** in order to reduce the systematic uncertainties (especially on the absolute energy scale).

CALO read-out #1: Intensified scientific CMOS (IsCMOS)

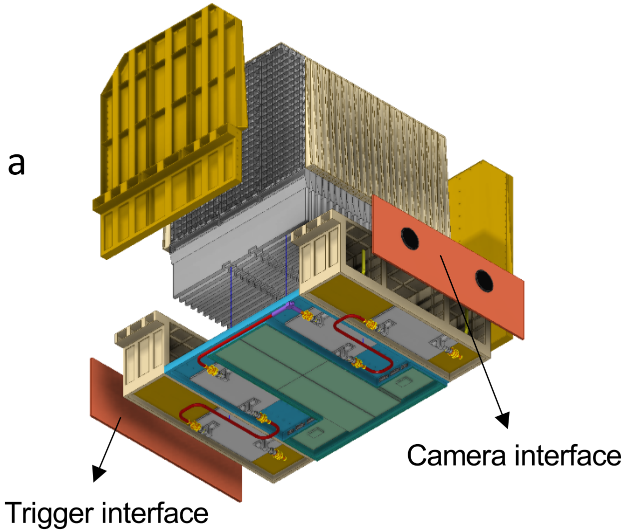
Encapsulation of WLSF with optical cement

WLSF coupled to LYSO and covered by a reflector

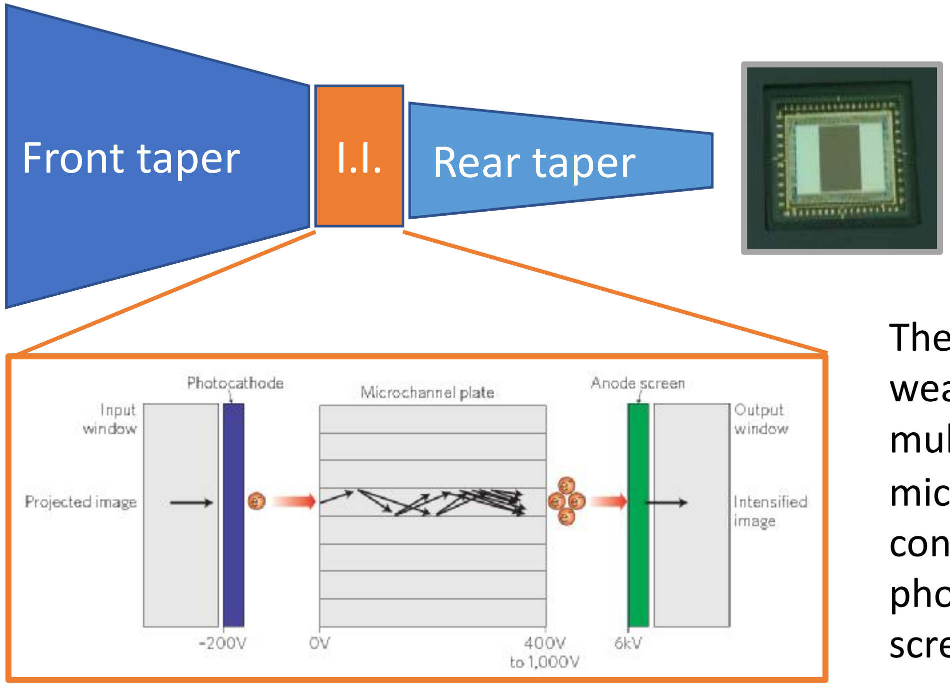
Wavelength shifting fibers (WLS) read-out

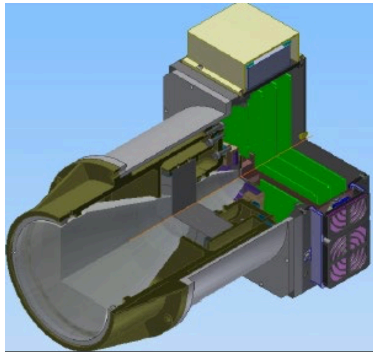
- Each cube is read-out by 3 WLS fibers.
- One fiber is used for triggering and the light signal is readout by a fast PMT.
- The signal from the other two fibers is amplified by an Image Intensifier (two gains) and readout by a IsCMOS camera

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.

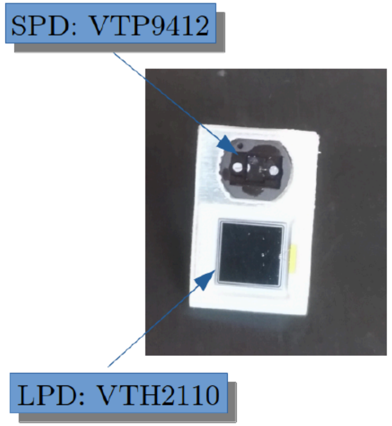




The **image intensifier** converts weak light signals into electrons, multiplies the electrons using a micro-channel plate, and then converts the electrons back into photons using a phosphor screen.

CALO read-out #2: photo-diode

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



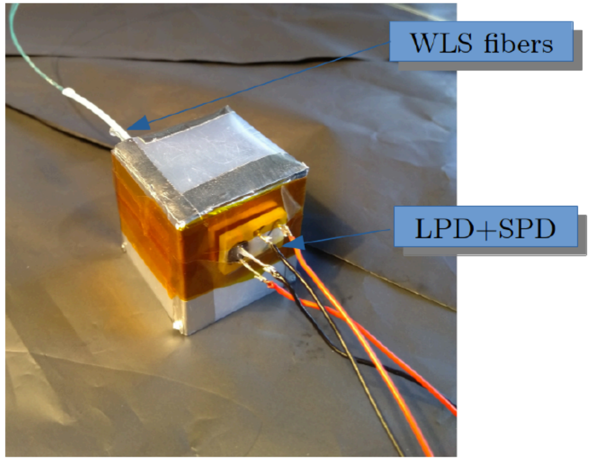
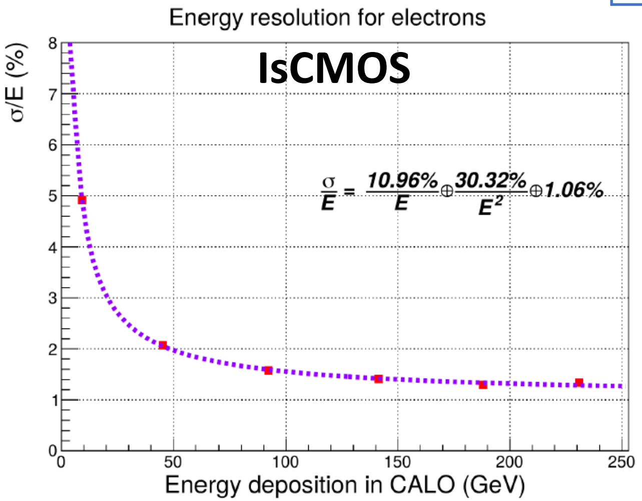
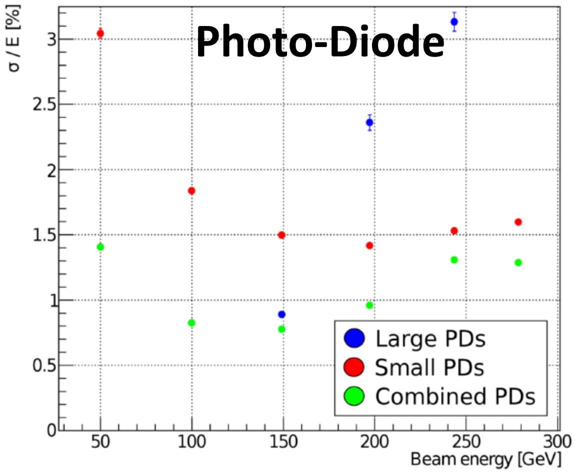


Photo-diode (PD) read-out

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

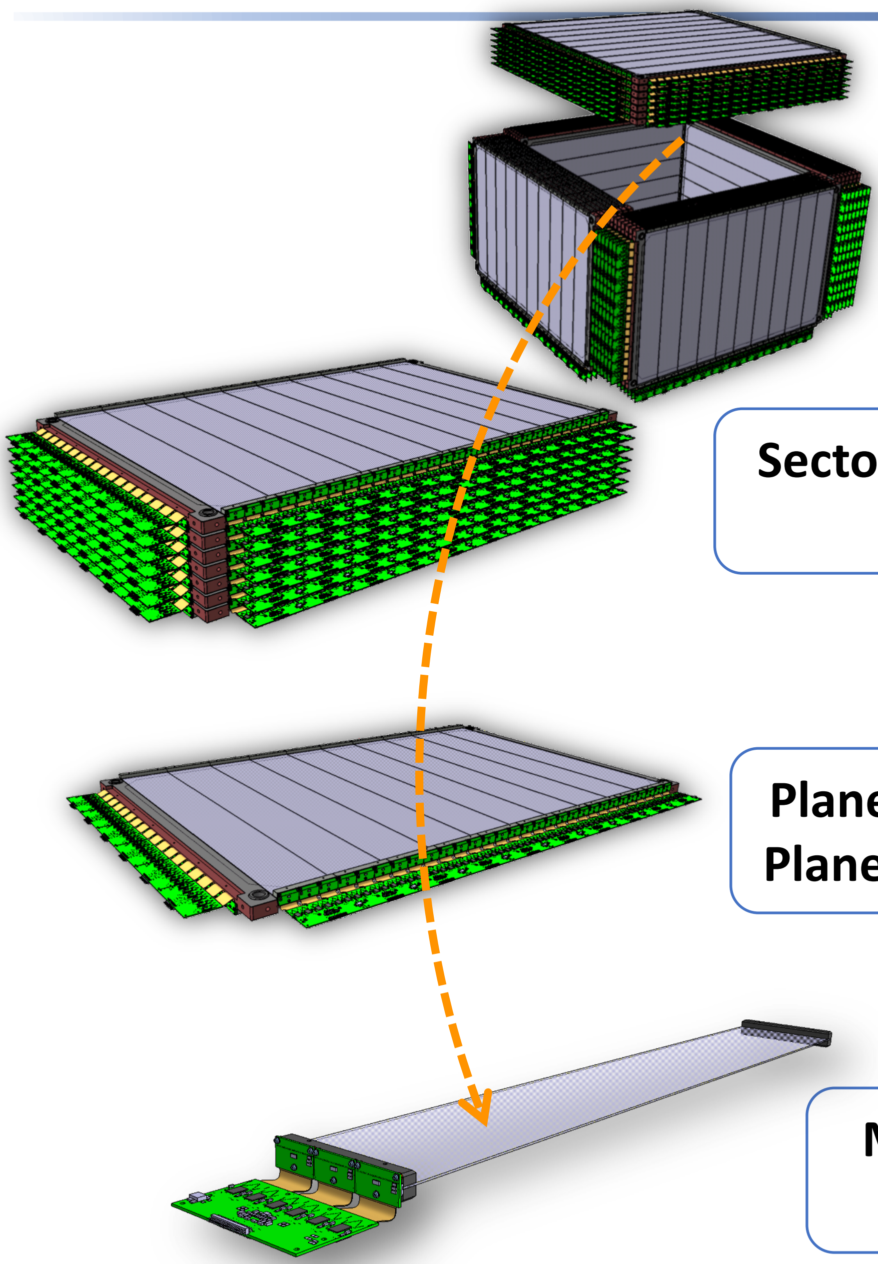
Energy resolution
Beam test **electrons**





L. Pacini *et al*, POS (ICRC 2021) 066

FIber Tracker (FIT)



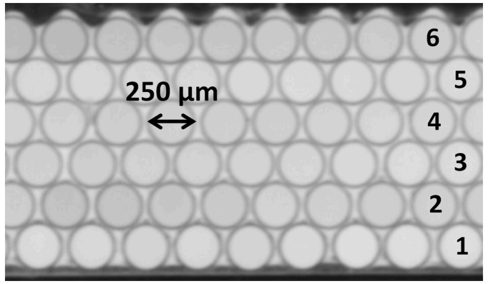
FIT = 5 sectors

Sector = 7 x-y tracking planes on 7 support trays

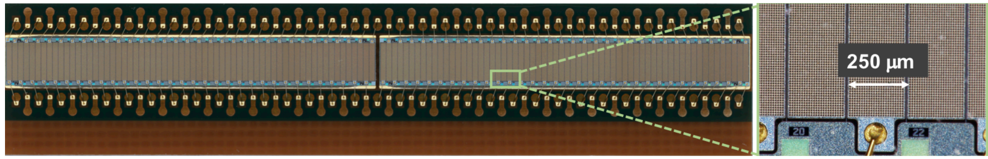
Plane (side) = 6x + 10y modules
Plane (top) = 10x + 10y modules

Module = 1 fiber mat + 3 SiPM arrays

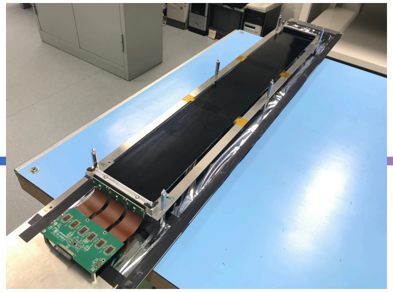
- Fiber mat: 6 layers of fibers
- Fiber type: **KURARAY SCSF-78MJ**
    - round section with, diameter = 250 μm
- Mat width ≅ 97.80 mm to match 3 SiPM arrays



- SiPM array (S13552-10): 2 chips with 64 channels
- Channel size: 230 μm × 1630 μm
- Pixel size: 10 μm × 10 μm
- 23 x 163 pixels/channel
- Gap between channels: 20 μm → pitch: 250 μm
- Gap between chips: 220 μm

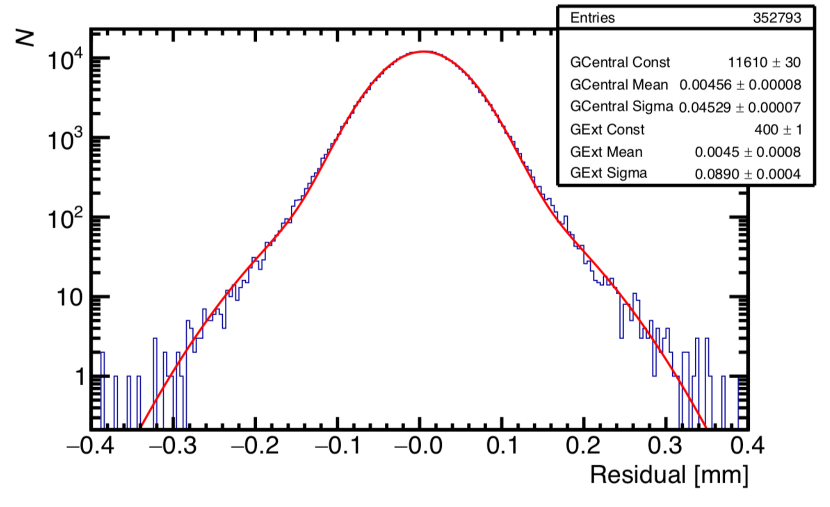


Performance of the FIT module



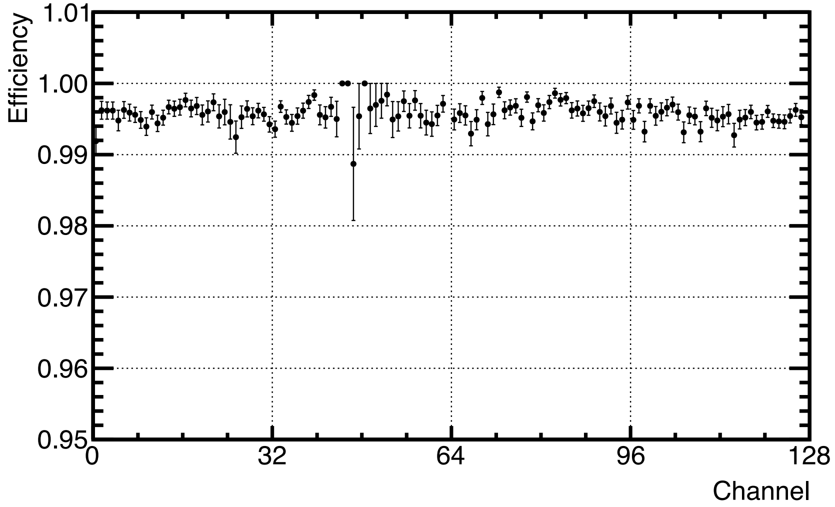
Proton beam test results

Position residual distribution:



Spatial resolution = (45.0 ± 0.1) μm
(considering the external beam telescope resolution)

Hit detection efficiency



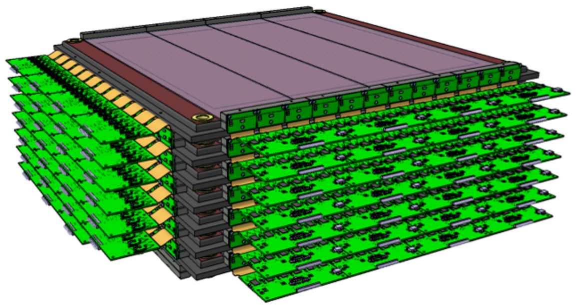
Mean efficiency = 99.6 %

Nuclei beam test results

Charge resolution for nuclei heavier than p (Preliminary)

Z	μ	σ	σ/μ
2	1.99	0.31	15 %
3	3.07	0.40	13 %
4	4.01	0.51	12 %

MiniFIT

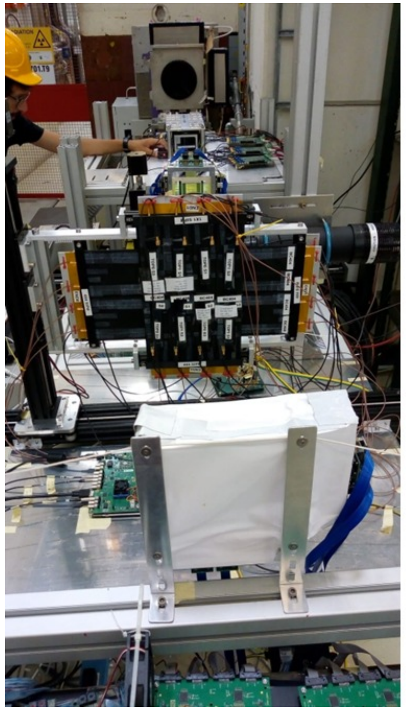


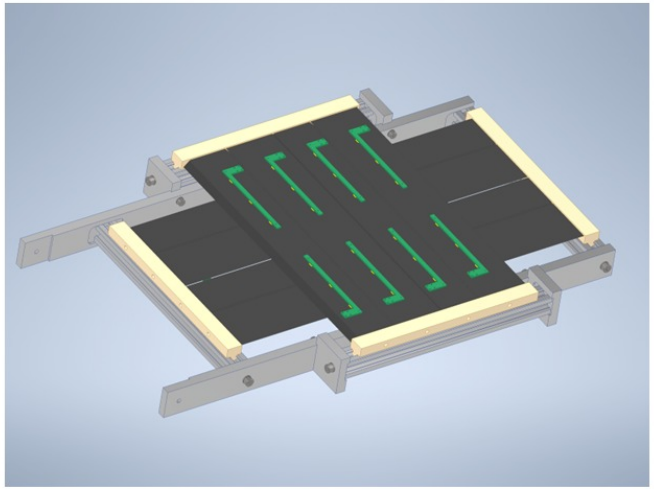
...will be assembled and tested soon

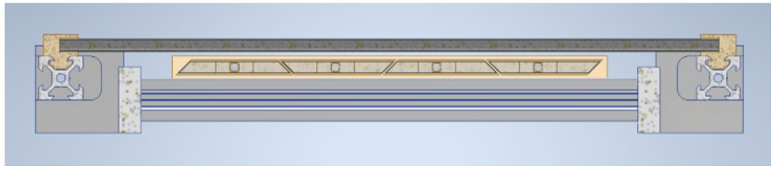
Plastic Scintillator Detector (PSD)

- PSD provide γ **identification** (VETO of charged particles) and **nuclei identification** (energy loss $\propto Z^2$)
- Requirements:
  - Very high efficiency in charged particles detection (> 99.98%) to be used as veto
  - high dynamic range to identify nuclei at least up to iron
  - segmented to reduce the back-scattering particles from the CALO

Beam test ongoing

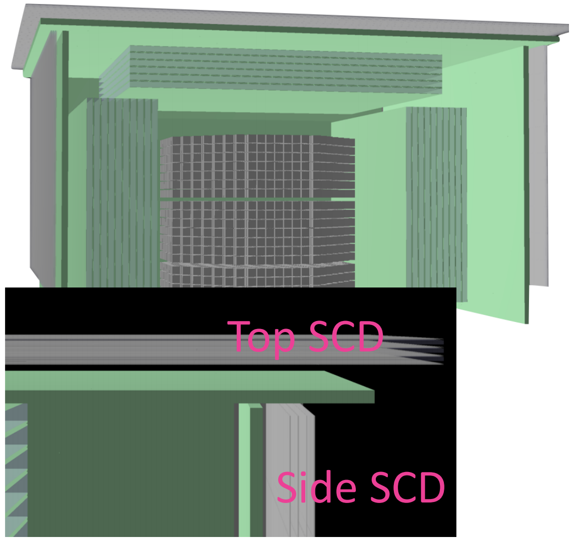




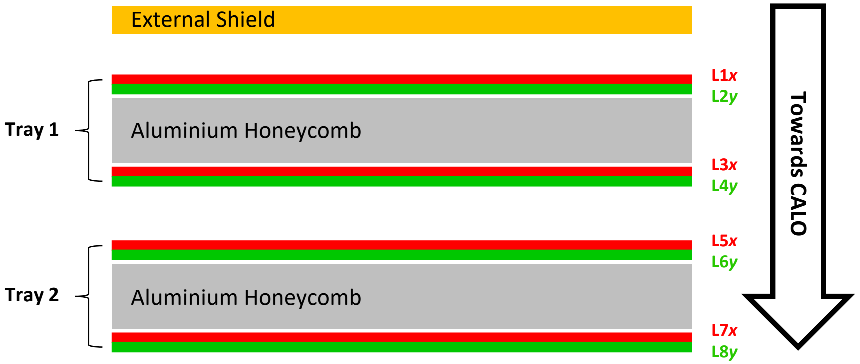


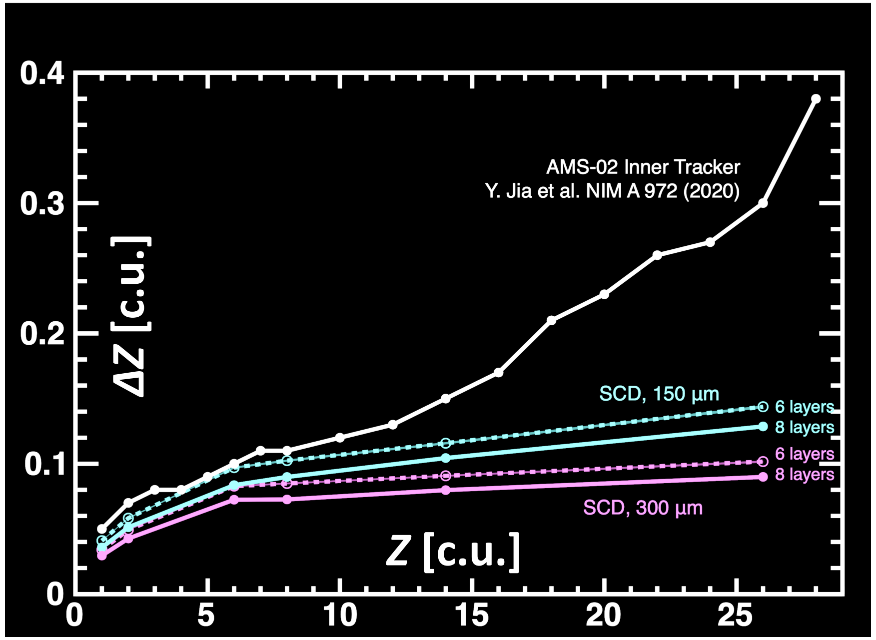
Scintillator: bar with trapezoidal face (30 cm and 40 cm long) readout by SiPMs (S14160-3050HS)

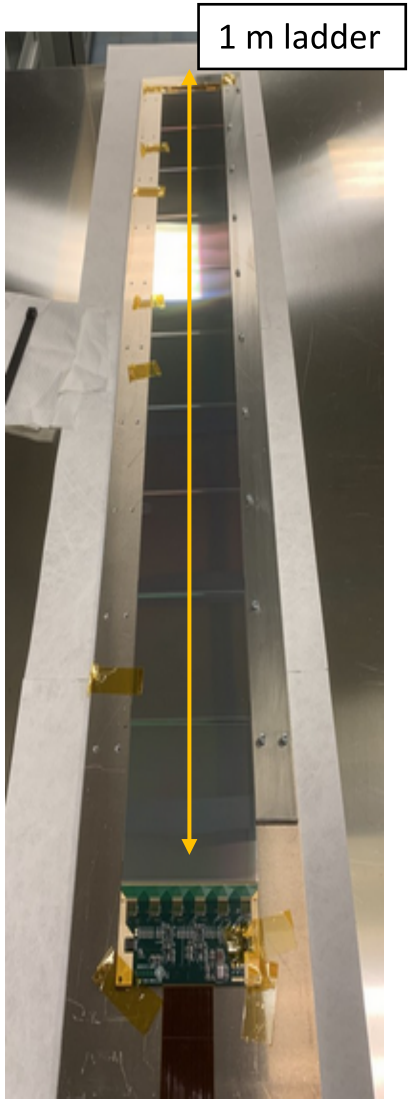
Silicon Charge Detector (SCD)



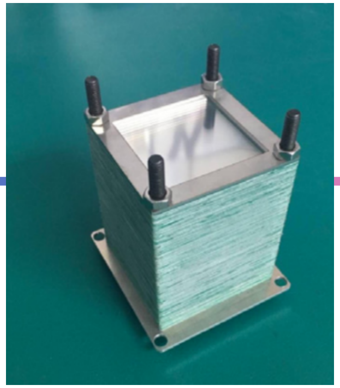
- SCD is a **silicon micro-strip** detector that will measure with precision the impinging particle charge |Z|
- 4 double X-Y layers for each of the five sectors → 8 independent ionization measurements per sector → Z =1 to 28
- It is the **outermost** detector to avoid early charge-change interactions 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



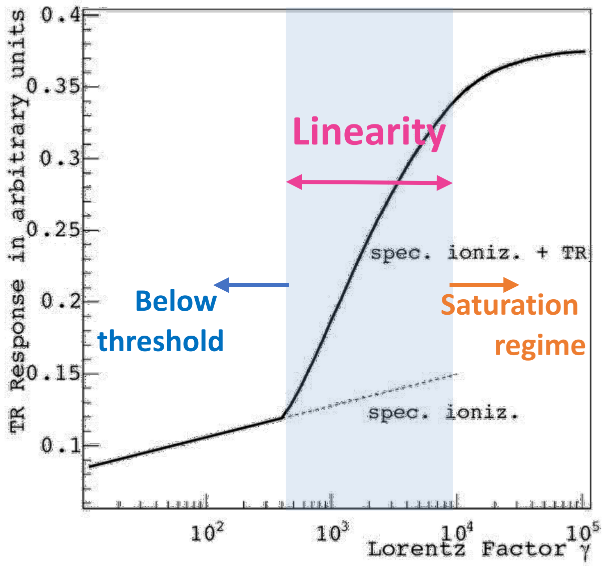




Transition Radiation Detector (TRD)

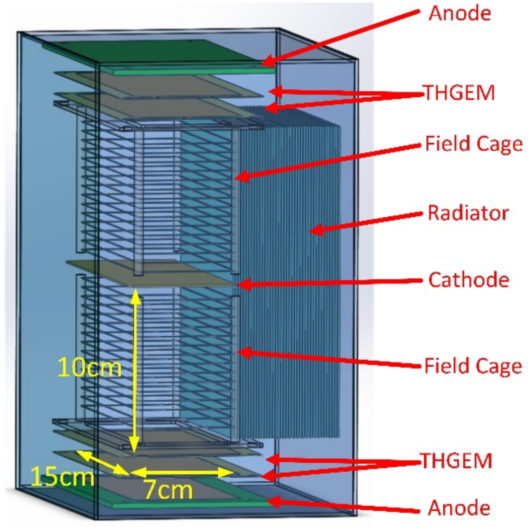


The TRD, installed on one lateral face of the detector, is needed to **calibrate the response of the calorimeter to high energy hadronic showers**.



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

- Electrons: $0.5\ \mathrm{GeV} < E_\mathrm{e} < 5\ \mathrm{GeV}$
- Protons: $1\ \mathrm{TeV} < E_\mathrm{p} < 10\ \mathrm{TeV}$



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)

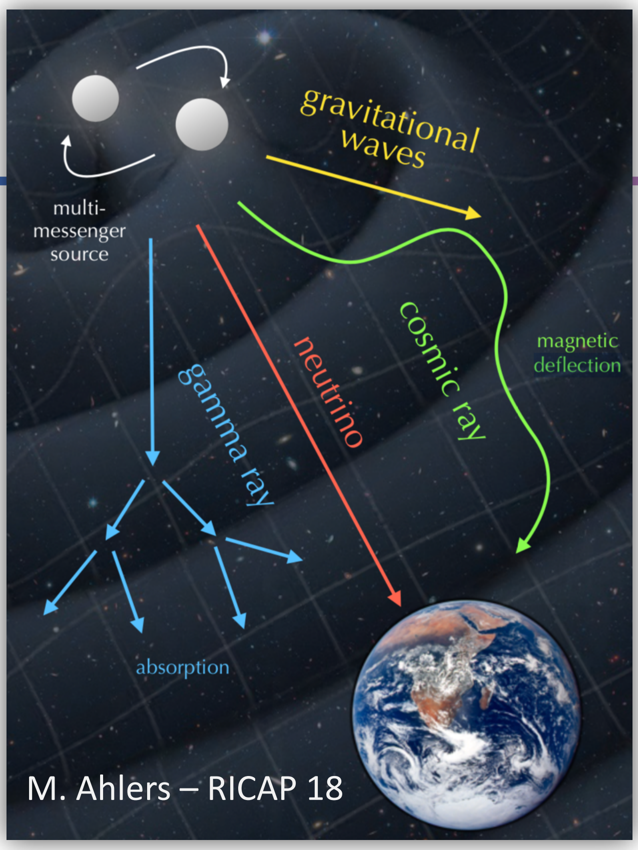
Radiator:

- multi-layer thin foils

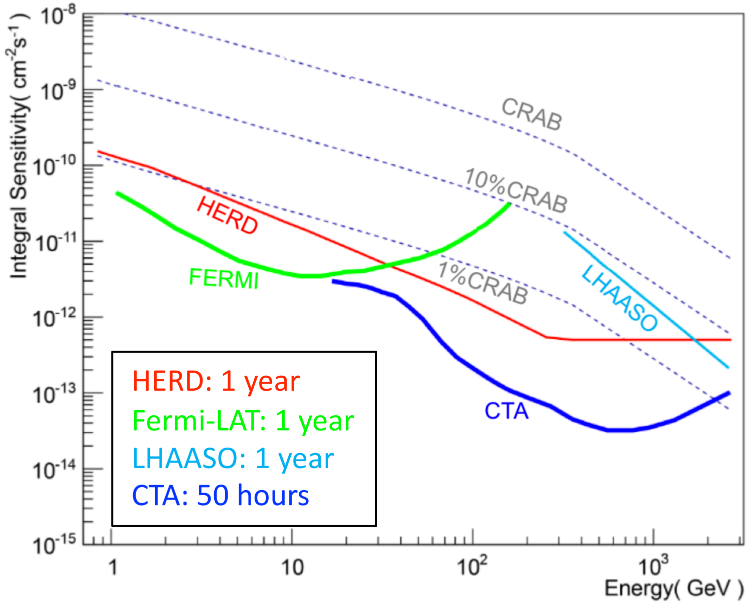
Detector:

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

Multi-messenger 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
  - search of electromagnetic counterpart of gravitational waves and for simultaneous flares in photons and neutrinos (IceCube, KM3Net).
- HERD will produce alerts: AGN, Crab, 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 mechanism 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.

HERD vs. other experiments

HERD is a next generation experiment with much better performance in the direct detection of high energy electrons + positrons, protons, gamma-ray.

Experiment	Energy (e/γ)	Energy (p)	Calorimeter thickness (X_0)	Angular res. @ 100 GeV (deg)	$\Delta p/p$ (e/γ) @ 100 GeV	$\Delta p/p$ (protons) > 100 GeV	e/p ID	e acceptance ($m^2 sr$) @ 200 GeV	p acceptance ($m^2 sr$) @ 100 GeV
Fermi-LAT (2008)	1 GeV – 300 GeV	30 GeV – 10 TeV	8.6	0.1	10%	40%	10^3	1	< 0.28
AMS-02 (2011)	1 GeV – 1 TeV	1 GeV - 2 TeV	17	0.3	2%	20%	$10^4 – 10^5$	0.05	0.16
CALET (2015)	1 GeV – 10 TeV	50 GeV – 60 TeV	27	< 0.2	2%	30%	10^5	0.1	0.042
DAMPE (2015)	5 GeV – 10 TeV	40 GeV – 300 TeV	32	0.2	< 1.5%	25 - 35%	> 10^5	0.3	0.03
HERD (2027)	10 GeV – 100 TeV 0.5 GeV – 100 TeV (γ)	30 GeV - PeV	55	0.1	< 1%	20%	> 10^6	3	> 2

Summary and outlook

- HERD will be a calorimetric detector with unprecedent acceptance , launched and installed on CSS in 2027
- It could become the only space-borne high energy gamma-ray detector, once the Fermi satellite will stop its operations.
- Important and frontier scientific in cosmic ray physics, gamma-ray astronomy, and dark matter search.
- Detailed designs are under study:
  - The baseline detector is defined and fulfills the requirements;
  - To optimise the detector geometry a dedicated Monte Carlo simulation is being developed;
  - There is still room for further improvements and optimization.

- 2022 & 2023: Phase B : Study of key technology and key components, Prototype for beam tests, EM, STM (partially) development
- 2024 & 2025: Phase C: Engineering Model, Space Traffic Management, Qualification Model
- 2026 & 2027: Phase D: Flight Model
- 2027: Launch
- Operation up to 2037+

http://herd.ihep.ac.cn

https://www.herd.cloud.infn.it/en

Thank you!!