The High-Energy cosmic-Radiation Detection (HERD) facility for direct cosmic-ray measurements

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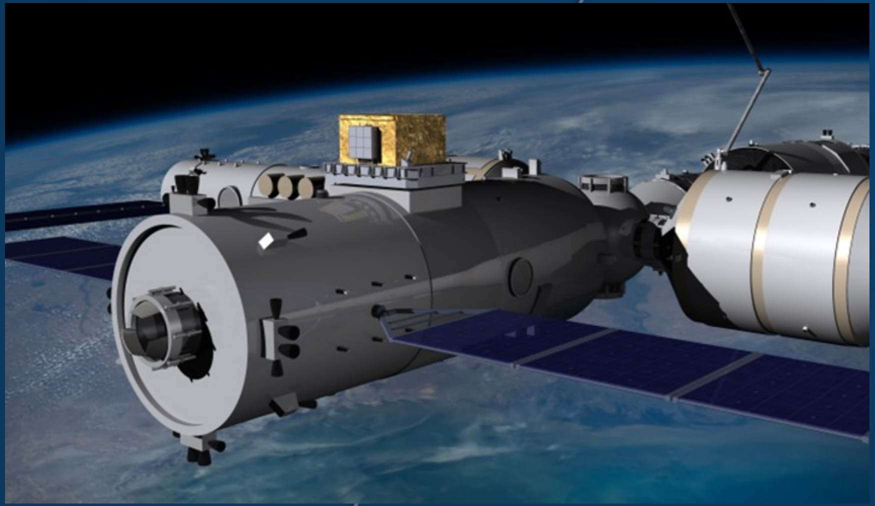
Introduction

- The HERD detector is aimed at direct measurements of cosmic rays from space. It will be installed on the future Chinese Space Station (CSS) in 2027

- Main observative and physics goals:
  - Hadron spectra up to the knee (~ PeV/n)
    - Acceleration and propagation studies
  - Electron+positron spectra up to some tens of TeV
    - Dark matter indirect searches
    - Search for nearby astrophysical sources (anisotropies)
  - Observation of gamma-ray sky above 100 MeV
    - Dark matter indirect searches
    - Galactic and extragalactic sources and diffuse emission
    - Detection of high-energy gamma-ray bursts



Artist's impression of HERD on the CSS

CHINA

Institute of High Energy Physics, CAS (IHEP)
Xi'an Institute of Optical and Precision Mechanics, CAS (XIOPM)
Guangxi University (GXU)
Shandong University (SDU)
Southwest Jiaotong University (SWJTU)
Purple Mountain Observatory, CAS (PMO)
University of Science and Technology of China (USTC)
Yunnan Observatories (YNAO)
North Night Vision Technology (NVT)
University of Hong Kong (HKU)

SPAIN

CIEMAT - Madrid
ICCUB – Barcellona
IFAE – Barcellona

ITALY

INFN Bari and Bari University
INFN Firenze and Firenze University
INFN Pavia and Pavia University
INFN Perugia and Perugia University
INFN Pisa and Pisa University
INFN Laboratori Nazionali del Gran Sasso and GSSI Gran Sasso Science Institute
INFN Lecce and Napoli University
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INFN Roma2 and Tor Vergata University
INFN Trieste and Trieste University

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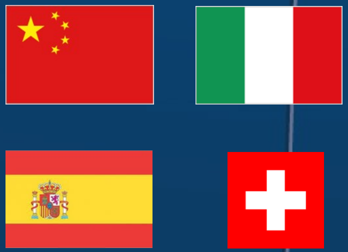
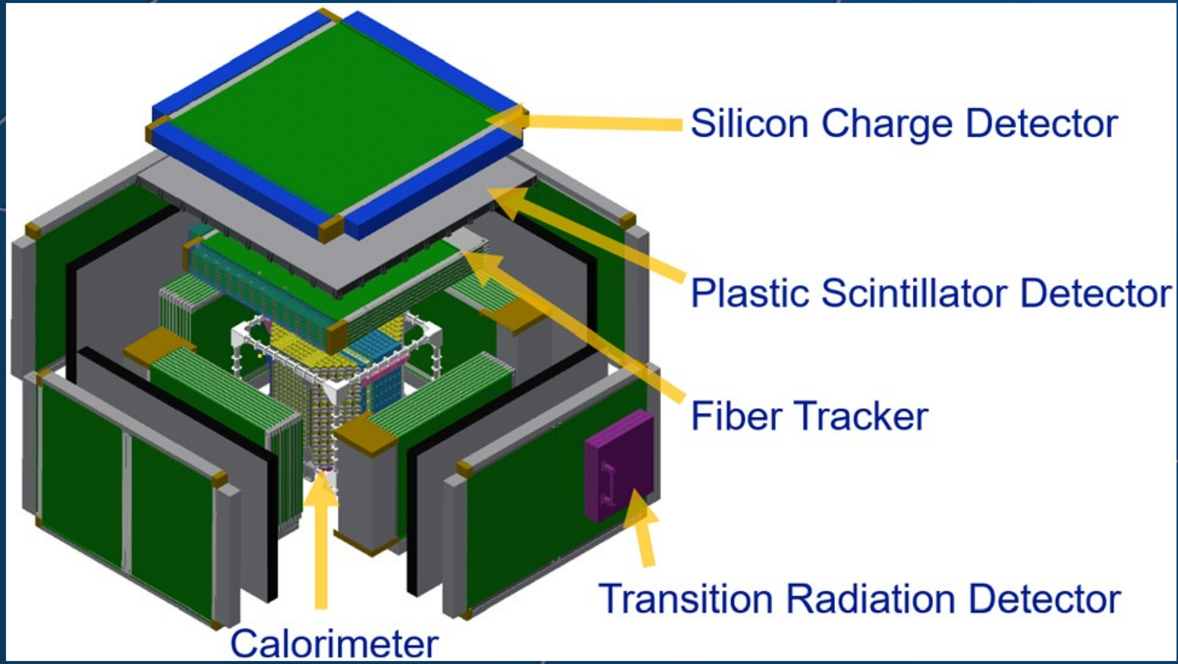


Xi'an (CN), 16-18 Dec 2019

Introduction

- Detector overview



SCD	Charge identification Trajectory reconstruction
PSD	γ Identification Charge reconstruction
FIT	Trajectory reconstruction Charge identification
CALO	Energy reconstruction e/p discrimination
TRD	Calibration of CALO response for TeV protons

Main requirements

	γ	**e**	**hadrons**
Energy range	>100MeV	10 GeV - 100 TeV	30 GeV - 3 PeV
Energy resolution	1% @ 200 GeV	1% @ 200 GeV	20% @ 100 GeV -1 PeV
Effective geometric factor	>0.2 m^2sr @ 200 GeV	>3 m^2sr @ 200 GeV	>2 m^2sr @ 100 TeV

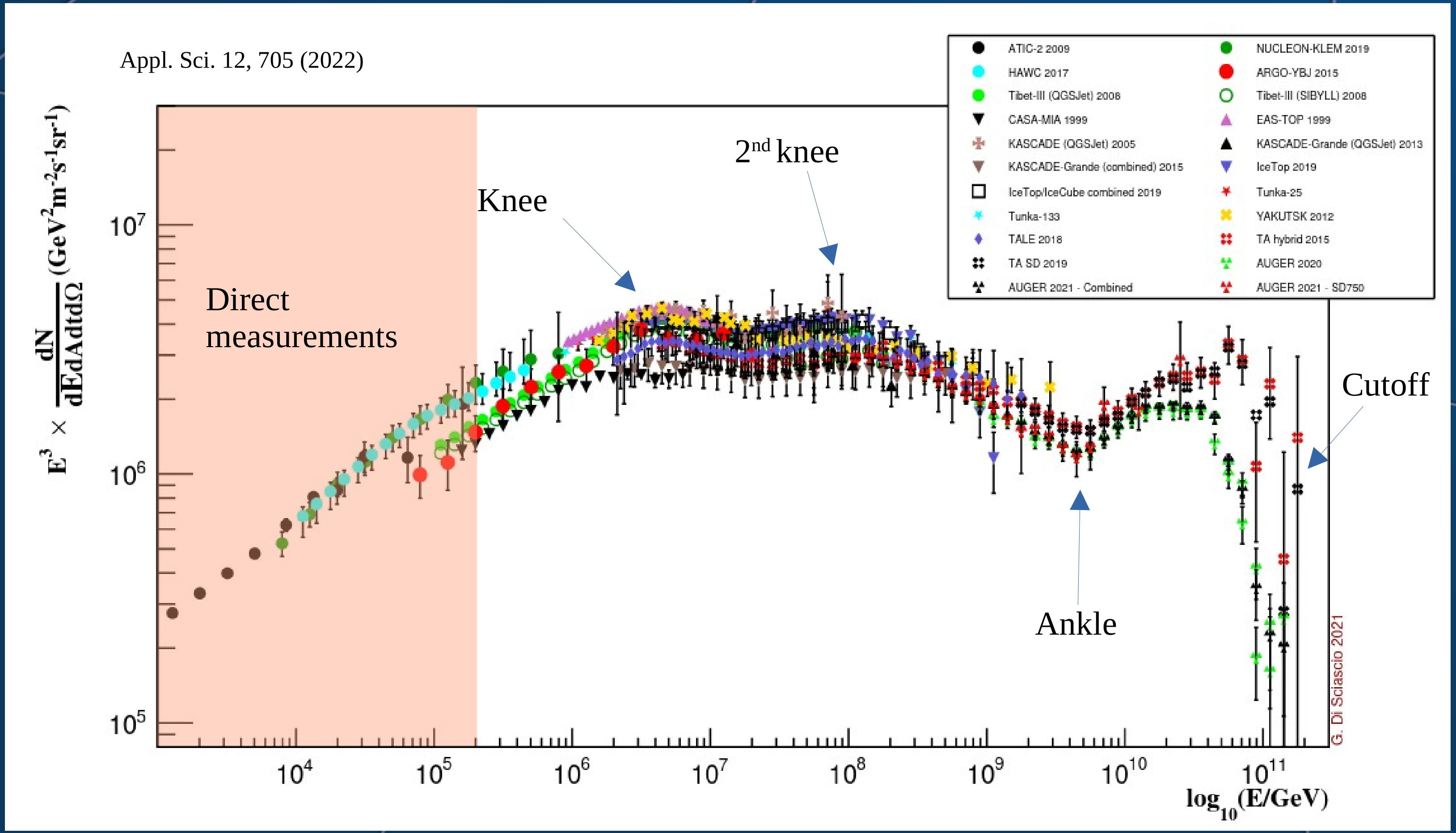
Innovative “isotropic” design for maximizing the acceptance

Special design focus on control over systematic effects

HERD physics: all-particle spectrum

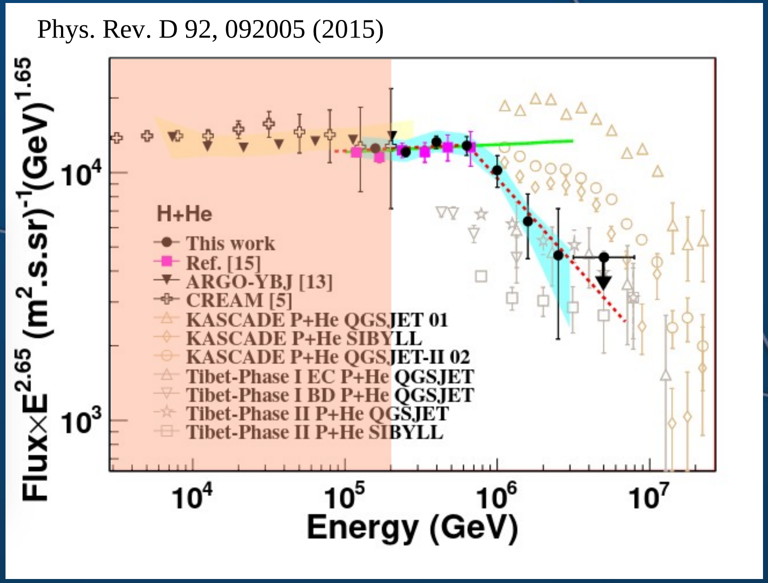
Evident features (→ physics) in the inclusive spectrum

Large systematics due to indirect detection techniques



Indications for particle-dependent knee energy

Direct measurement of the knee for light particles might be within the HERD reach



HERD physics: hadrons

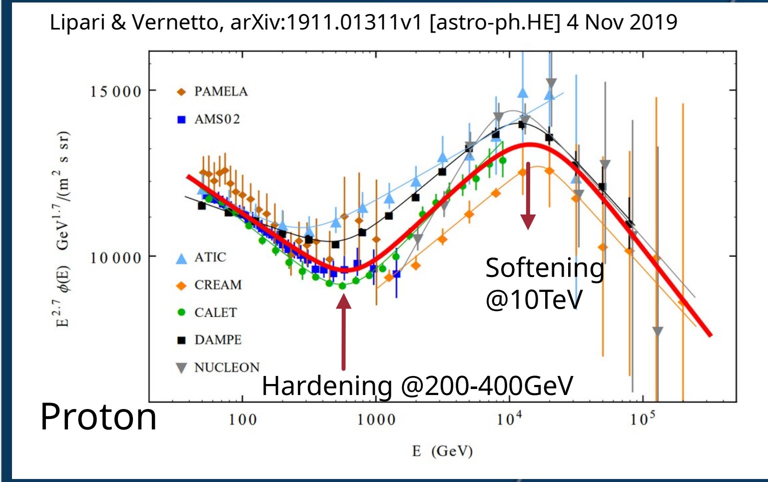
- Proton and helium

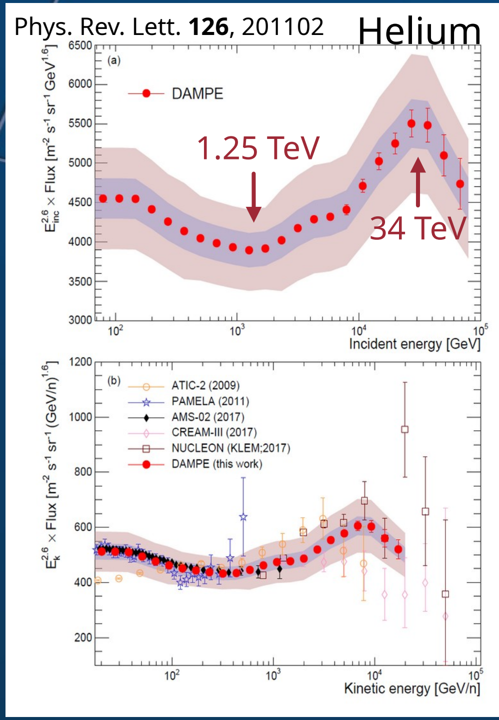
Feature-rich spectra emerged from power-law behavior thanks to recent accurate, statistically significant measurements:

- Hardening at 200-400 GeV (PAMELA, AMS)

- Softening in the 10-30 TeV region (DAMPE, CALET)

- Implications for acceleration and propagation



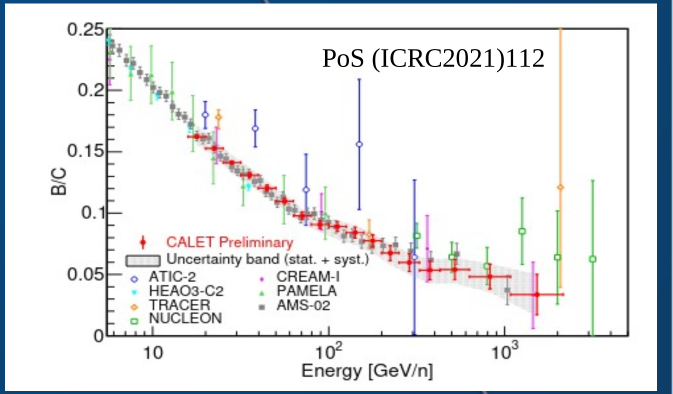


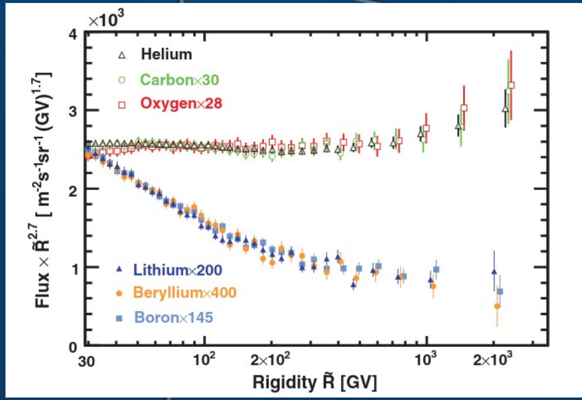
- B/C and heavy nuclei

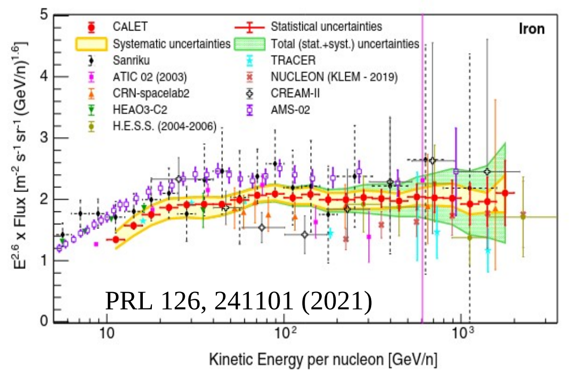
Distinct behavior of primaries and secondaries, albeit with similar features (e.g. break at 200-400 GV rigidity)

B/C is the “standard probe” for propagation models

Current measurements limited to the ~ TeV/n region due to low statistics (calorimeters) or instrumental limits (spectrometers)





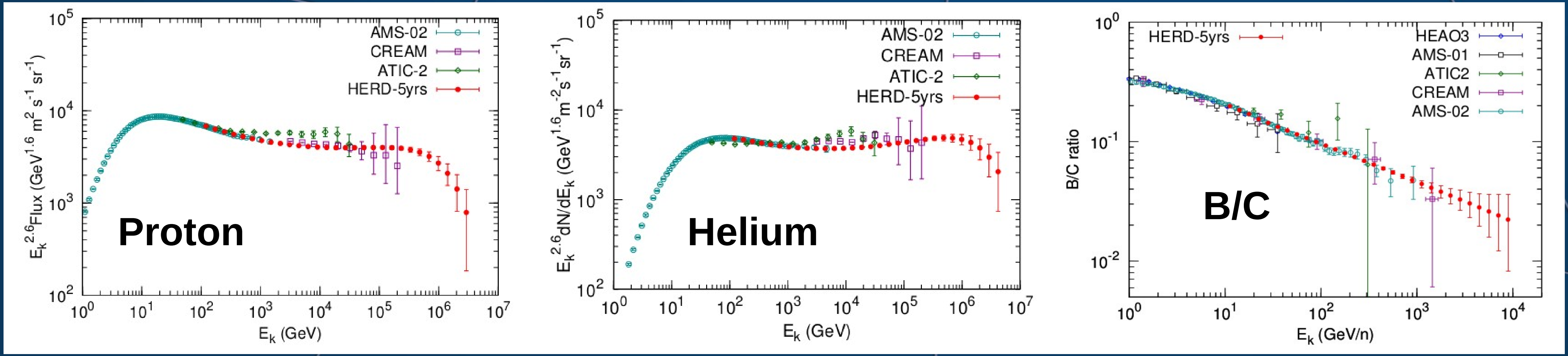


HERD physics: hadrons

- Expected performance in 5 years

The knee of light hadrons could be clearly seen

The energy ranges of measured spectra will be significantly extended towards high energies



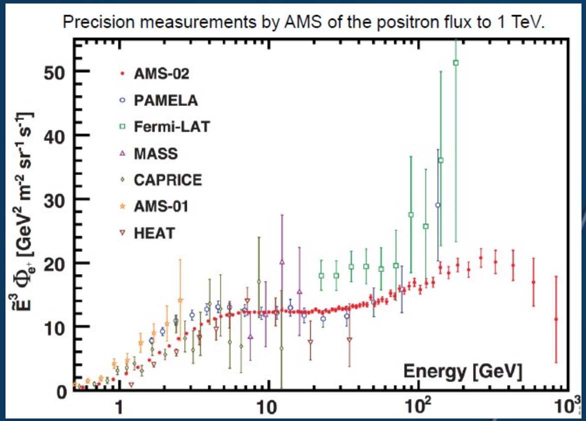
HERD physics: electrons and positrons

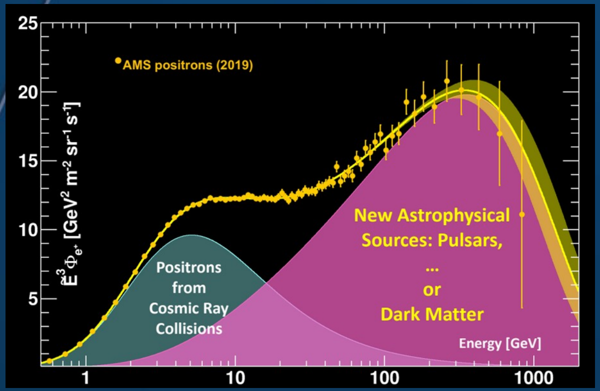
- ## Positrons

A “primary” component in positron spectrum has been firmly established (PAMELA, AMS)

Current measurements do not unequivocally identify its nature

Complementary measurements (gamma-ray emission from pulsars, anisotropy studies, antiproton spectrum, …) are needed





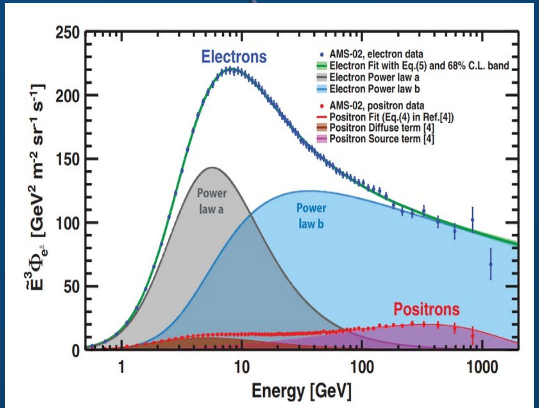
- ## All-electron

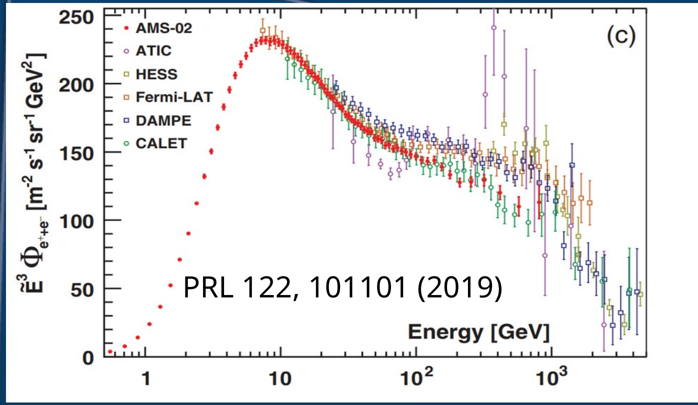
Significant discrepancies in current measurements (→ systematics)

Spectral break at ~ 1 TeV (→ very low statistics at high energies)

Propagation makes high energies more sensitive to local sources and to anisotropies

Increasing positron fraction makes high energies potentially sensitive to positron physics





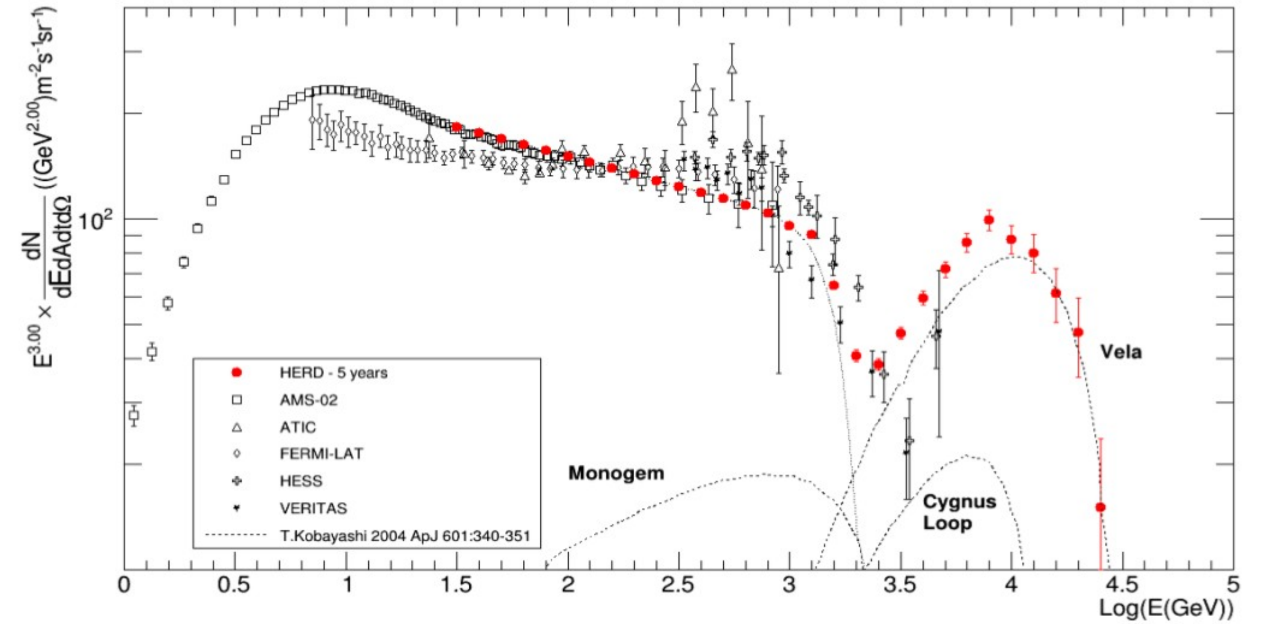
HERD physics: electrons and positrons

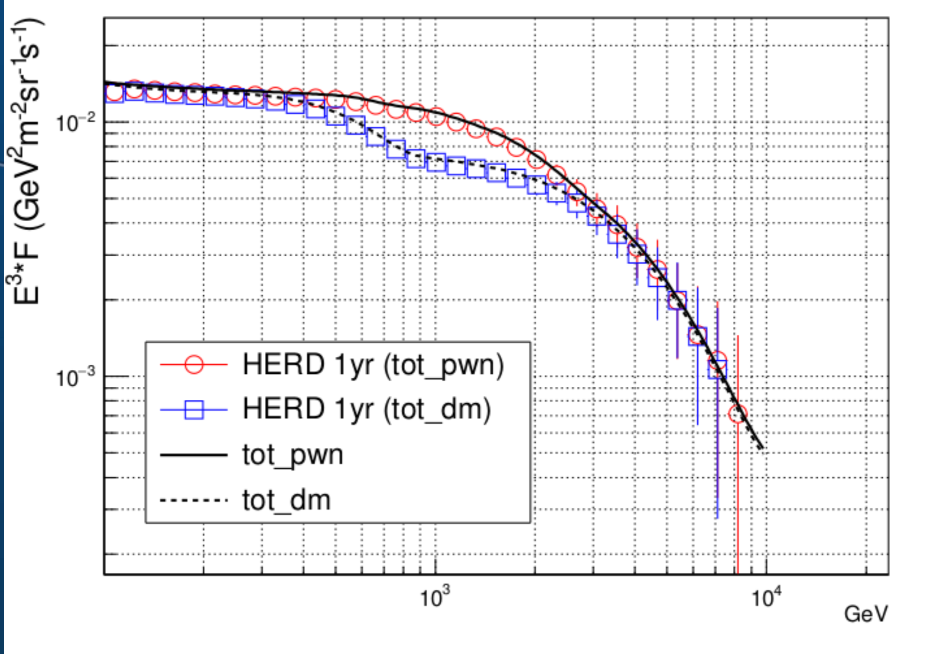
- Expected performance in 5 years

Detection of possible contributions from local sources

Detection of anisotropies

Indications of possible production from dark matter





HERD physics: gamma rays

Full gamma-ray sky survey in the energy range > 100MeV

- extend Fermi-LAT catalog to higher energy (> 300GeV)
- increase the chances to detect rare gamma events

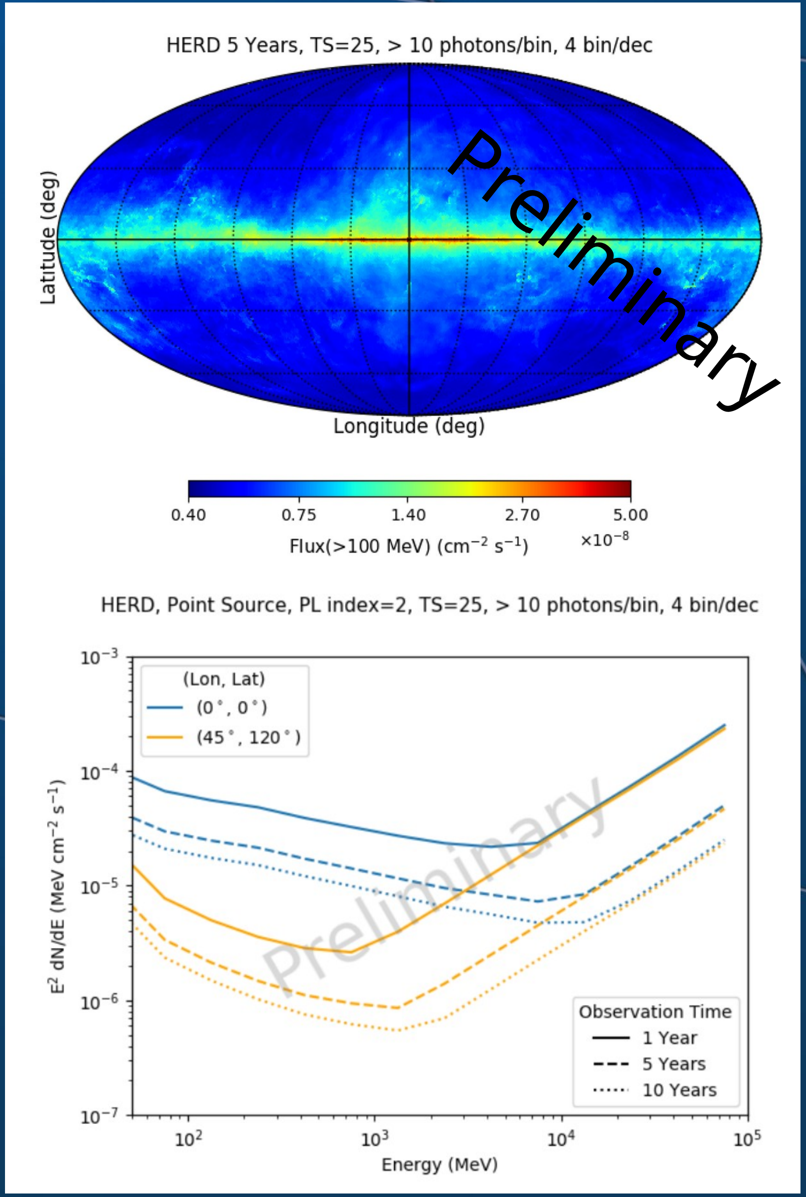
Targets of Gamma-Ray Sky Survey:

- search for dark matter signatures
- study of galactic and extragalactic gamma sources
- study of galactic and extragalactic gamma diffuse emission
- detection of high energy gamma bursts

Multi-messenger astronomy

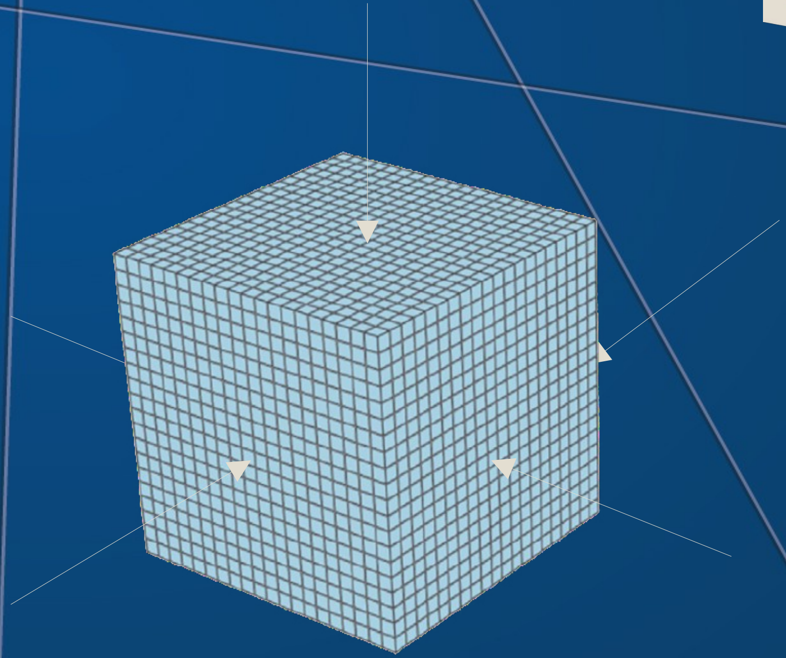
Possible synergy with other experiments designed for:

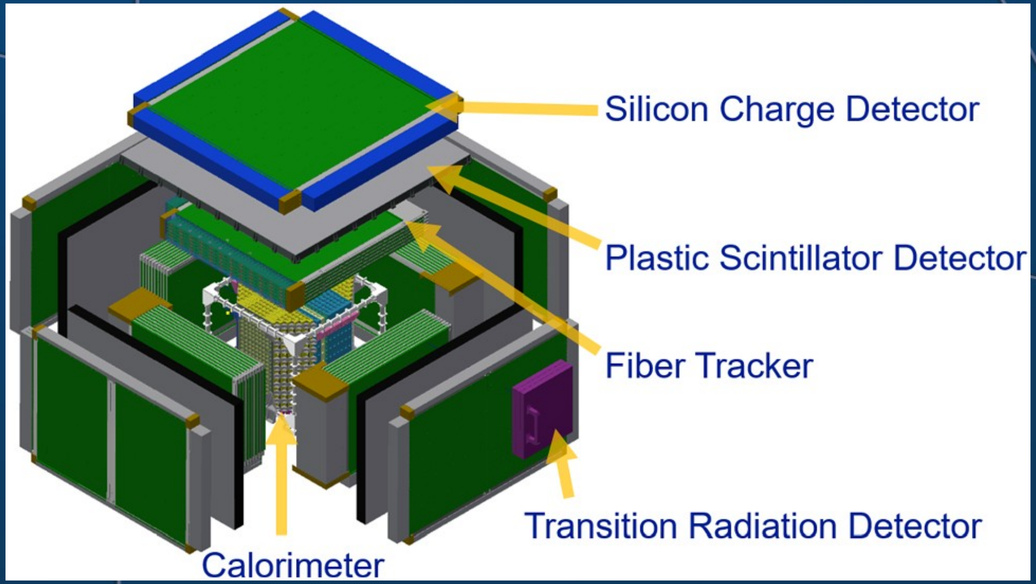
- photons (CTA, LHAASO, ...)
- neutrinos (KM3NeT, IceCube)
- gravitational waves (LIGO, Virgo)



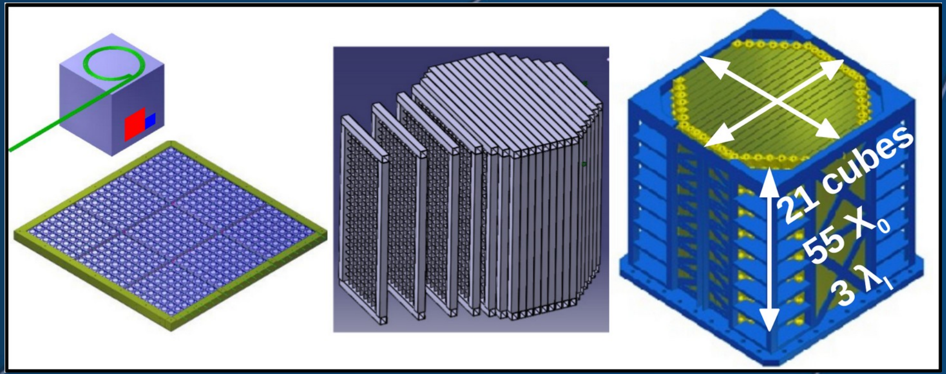
The HERD detector

- Main experimental issue: statistics at high energies
  - Cannot scale up conventional conventional calorimeter design due to mass&power budget of space-based experiments
  - Innovative design: “isotropic”, 3D-mesh calorimeter + subdetectors on 5 sides
- Control over systematics:
  - Absolute energy scale → CALO double readout system + in-flight calibration with TRD
  - Nuclei fragmentation → charge detector as outermost detector





The HERD detector: CALO

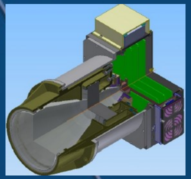


The effective geometrical factor is > 3 m^{2}sr for electrons and > 2 m^{2}sr protons

The design of the CALO consists of about **7500 LYSO cubes** with edge length of 3 cm, corresponding to about 2.6 X_0 and 1.4 Molière radii

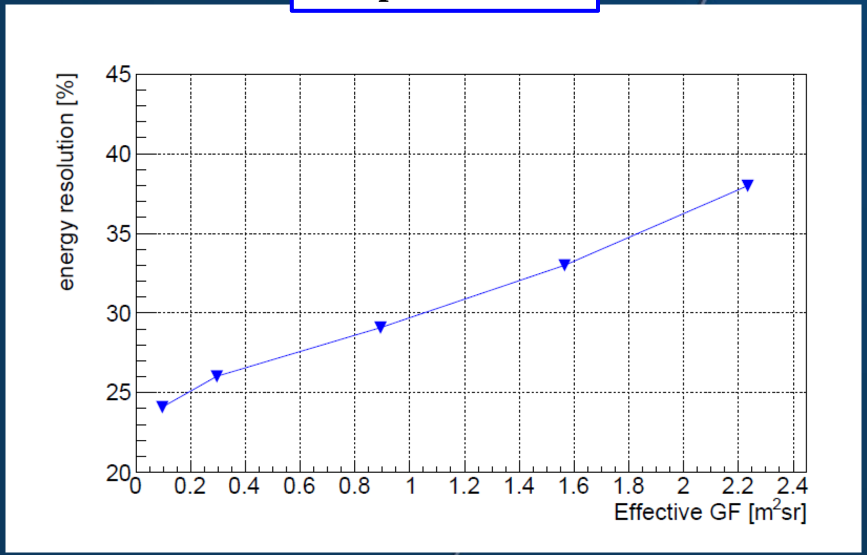
The scintillation light of each crystal is read-out by two independent systems:

1. WLS fibers coupled to image Intensified scientific CMOS (IsCMOS) cameras
2. pair of photo-diodes (PD) connected to custom front-end electronics (HIDRA)

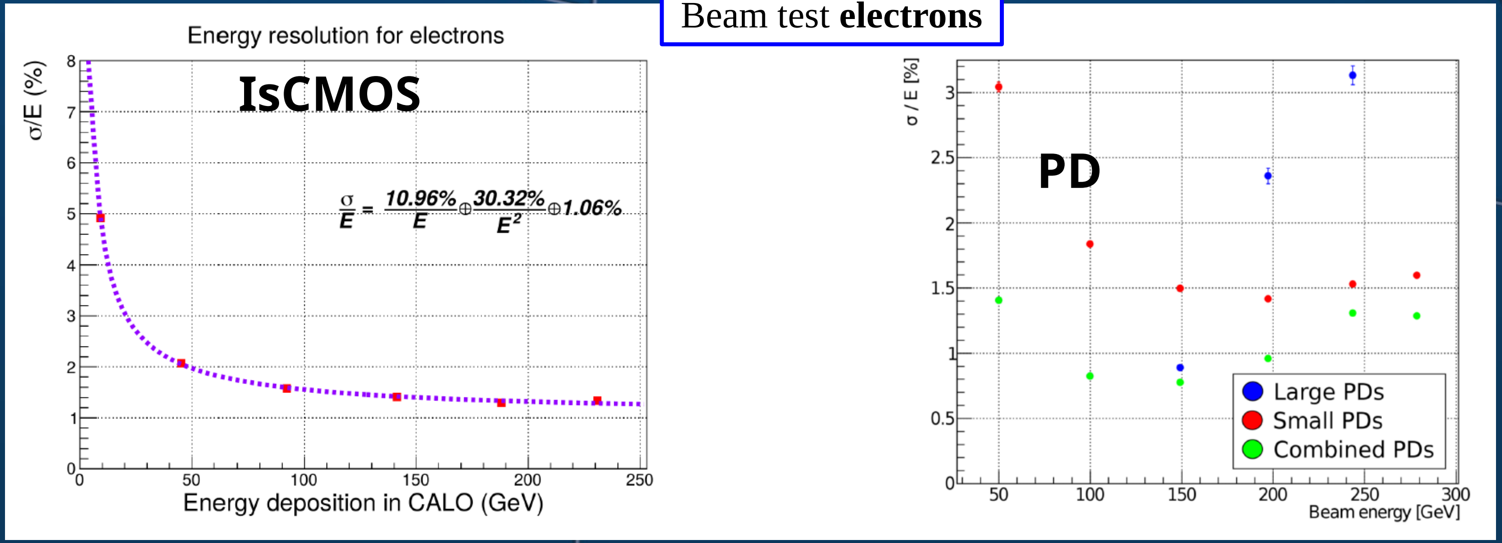


The ***double read-out system*** achieves the capability of cross-calibrating the scintillation light measurement and help in **reduce the systematic errors** and a **dynamic range > 10^7**

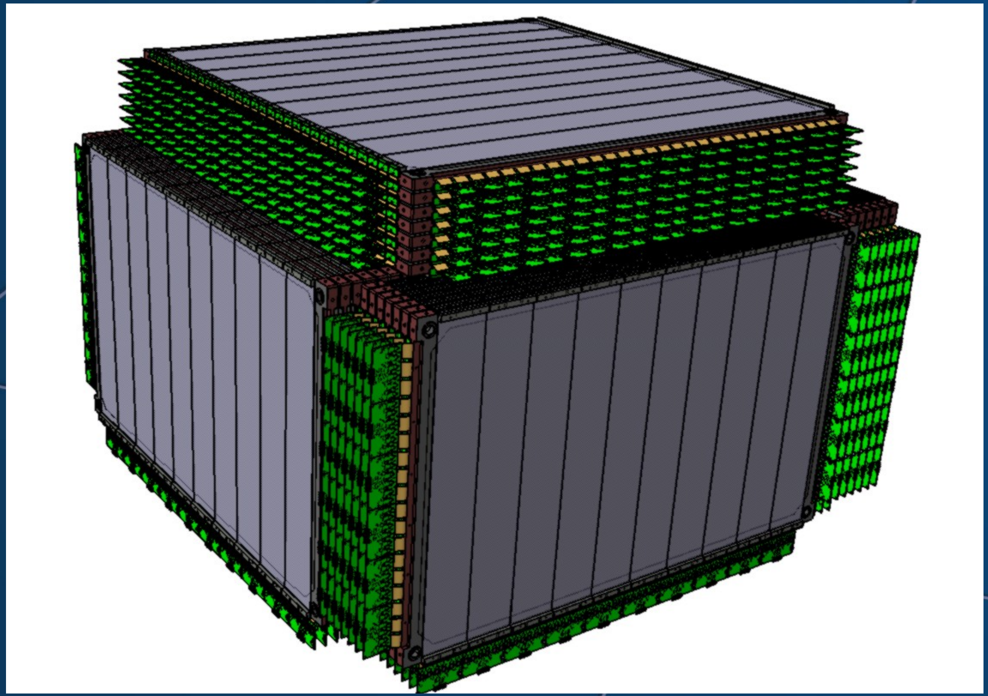
Energy resolution
MC **protons**



Energy resolution
Beam test **electrons**



The HERD detector: FIT



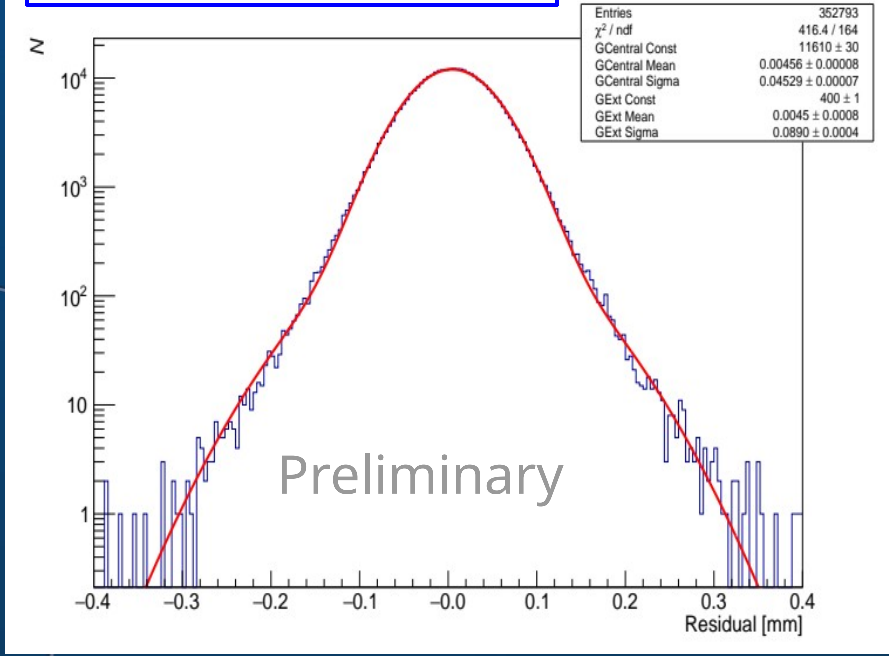
Charge resolution for nuclei heavier than p

Preliminary results

Z	μ_Z	σ_Z	σ_Z/μ_Z
2	1.99	0.31	15 %
3	3.07	0.40	13 %
4	4.01	0.51	12 %

- FIber Tracker made of scintillating fibers read by SiPMs
- 7 x-y tracking planes in each sector
- Module = 1 fiber mat + 3 silicon photomultiplier (SiPM) arrays

Proton beam test results

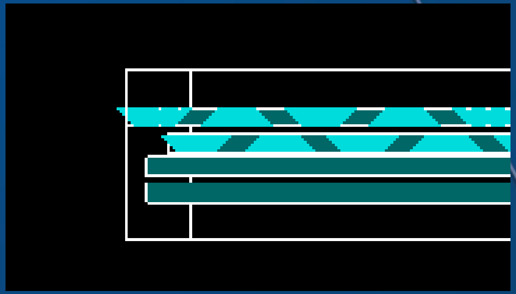


$$\sigma_{\mathrm{FIT}} = (45.0 \pm 0.1)\ \mu\mathrm{m}$$

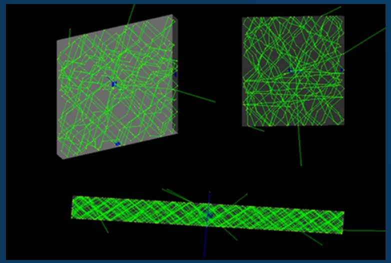
Takes into account the external tracker resolution

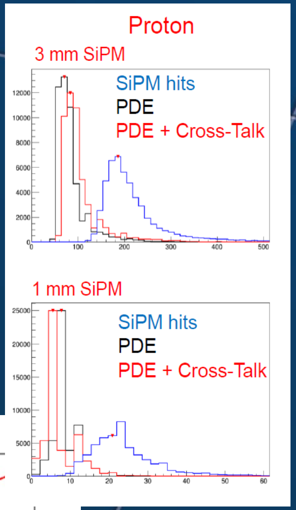
The HERD detector: PSD

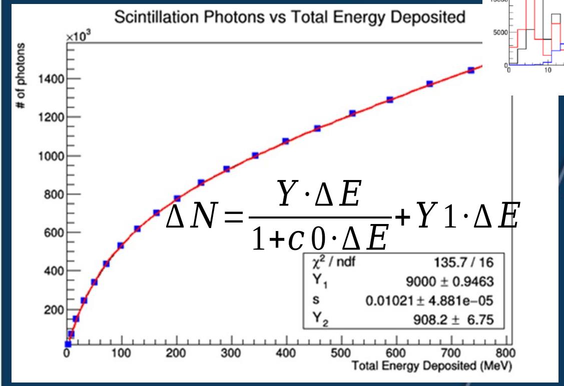
- PSD provide **γ identification** (VETO of charged particles) and **nuclei identification** (energy loss ∝ Z^2)
- Requirements:
  - high efficiency in charged particles detection (>99,98%)
  - high dynamic range to identify nuclei at least up to iron
  - segmented to reduce the back-scattering contribution from the CALO
- Sensitive element: rectangular tile with trapezoidal profile
- Readout: SiPMs



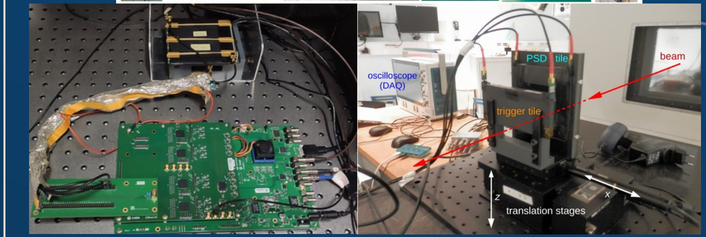
Simulations

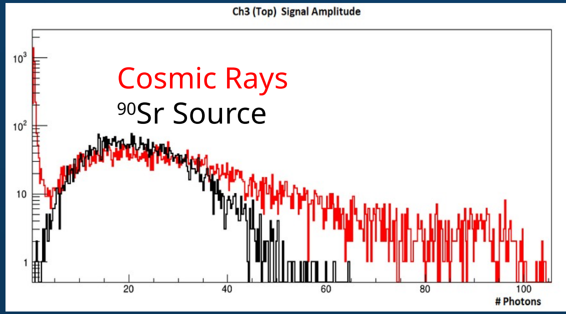




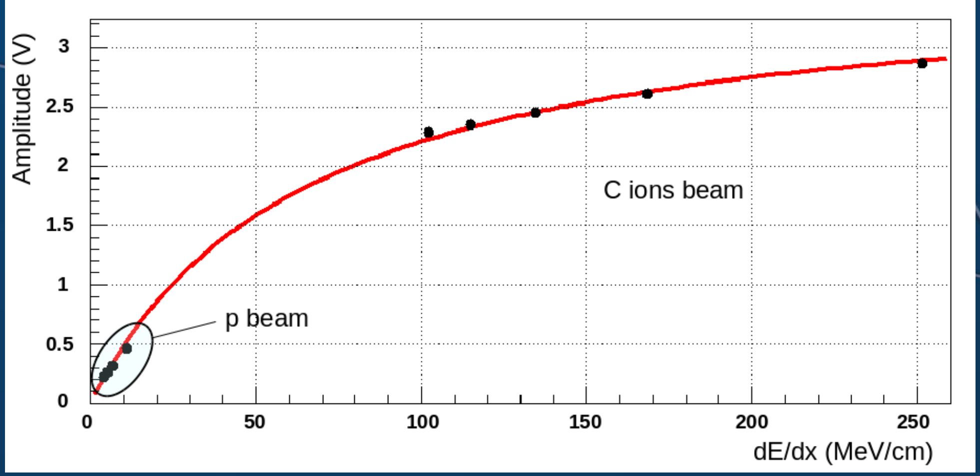


Lab. and Beam test



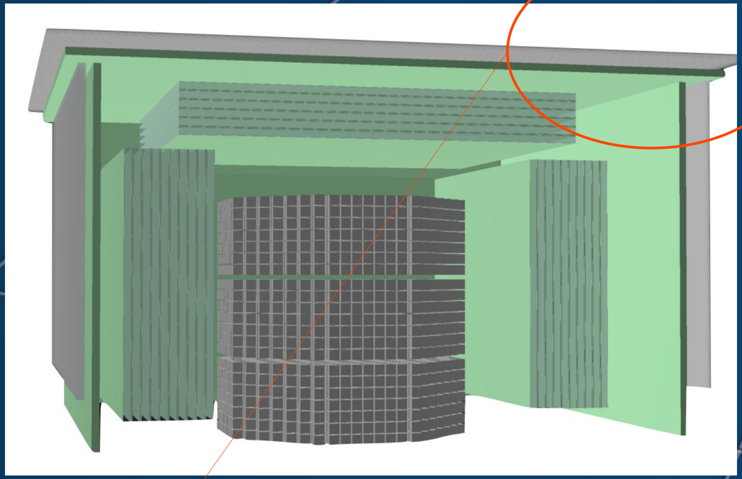


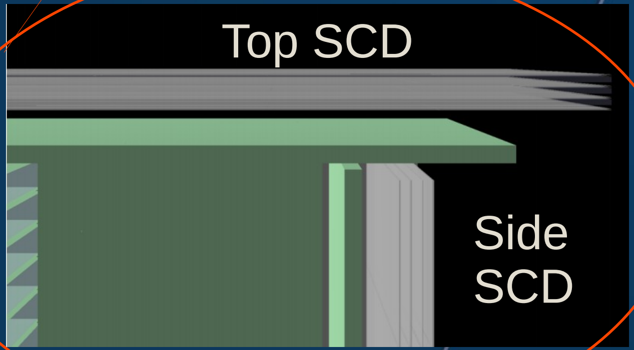
Birks saturation effect tested with low momenta nuclei @ CNAO

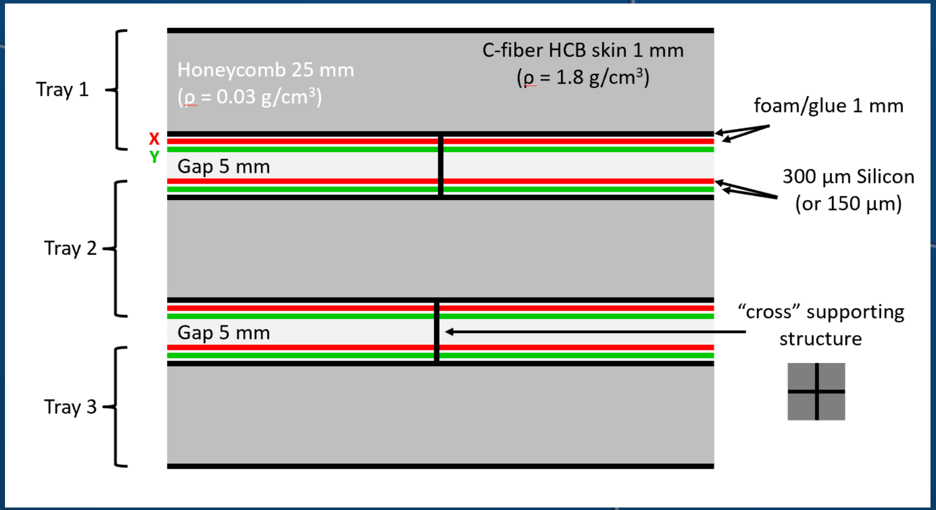


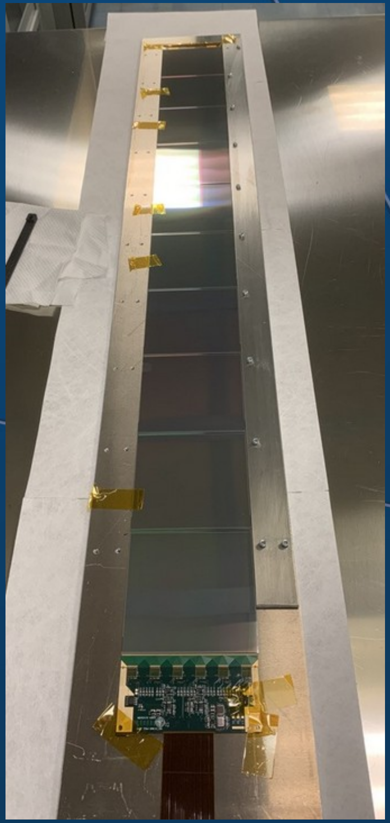
The HERD detector: SCD

- SCD is a **silicon micro-strip** detector that will measure with precision the impinging particle charge |Z| via ionization measurements and help with tracking
- 4 double X-Y layers for a total of 8 independent ionization measurements
- It is the **outermost** detector to avoid early charge-change interactions in the PSD and **reduce systematics in charge reconstruction**
- It is highly **segmented** to minimize the unavoidable backscattered secondary particles coming from the CALO



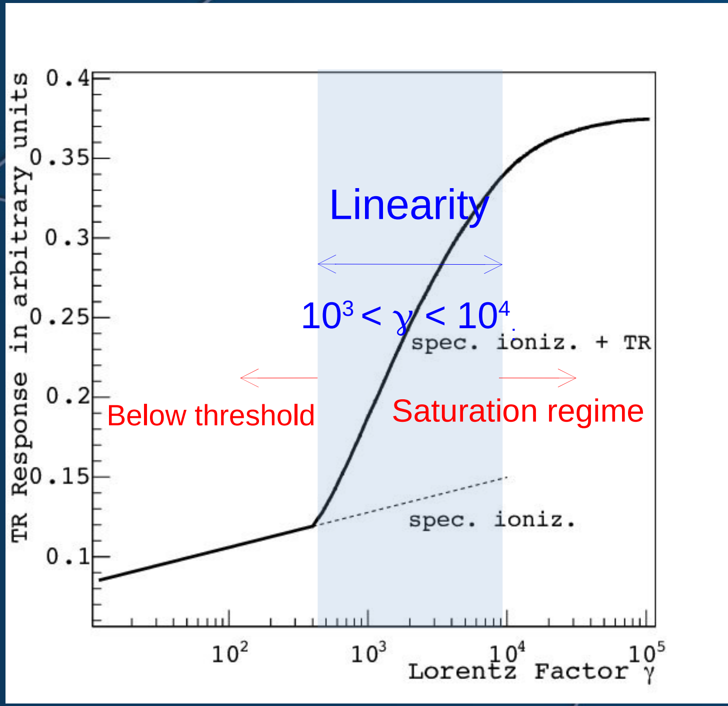






The HERD detector: TRD

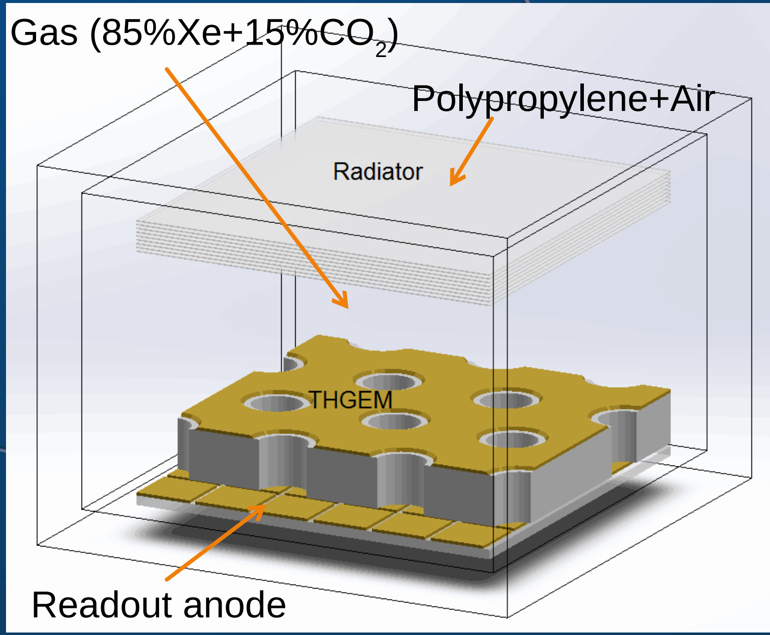
The TRD, installed on a lateral face of the detector, is needed to calibrate the response of the calorimeter to high energy hadronic showers



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

Electron 0.5 GeV < E < 5 GeV

Proton 1 TeV < E < 10 TeV



Calibration procedure:

- calibrate TRD response using [0.5 GeV, 5 GeV] electron beams on ground
- calibrate CALO response using [1 TeV, 10 TeV] protons from TRD (3 months data required)

Summary

- The HERD detector, set to operate from 2027 on the Chinese Space Station, will measure the spectra of charged cosmic rays at the highest-ever energies reached by a direct detection experiment, and monitor the gamma-ray sky for transient phenomena:
  - nuclei fluxes up to the knee region for probing propagation and acceleration models
  - e^+e^- fluxes up tens of TeV for testing the cutoff and the origin of positron excess (astrophysical vs. dark matter)
  - Monitor the gamma-ray sky above 100 MeV
- An innovative “isotropic” design maximizes the energy reach while respecting the mass&power budget of a space experiment
- Control over systematics has been a major design guideline, in order to significantly reduce uncertainties with respect to the current generation of space-borne calorimeters
  - Double readout system for CALO
  - TRD for in-fligth calibration of CALO
  - Charge detector on the outermost part