Measurement of Cosmic Ray spectra with DAMPE and future prospects with the HERD space mission

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on behalf of the DAMPE and HERD collaborations

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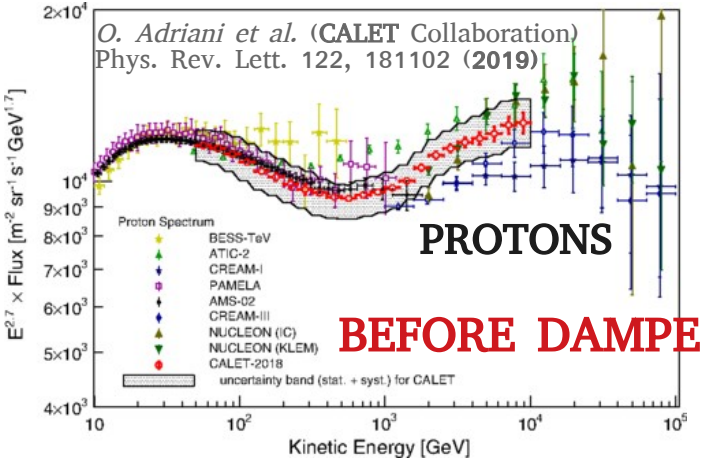
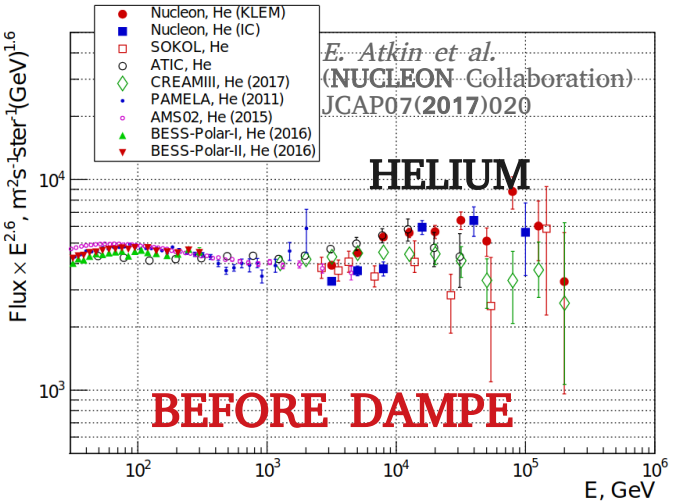
Vulcano Workshop 2022

FRONTIER OBJECTS IN ASTROPHYSICS AND PARTICLE PHYSICS

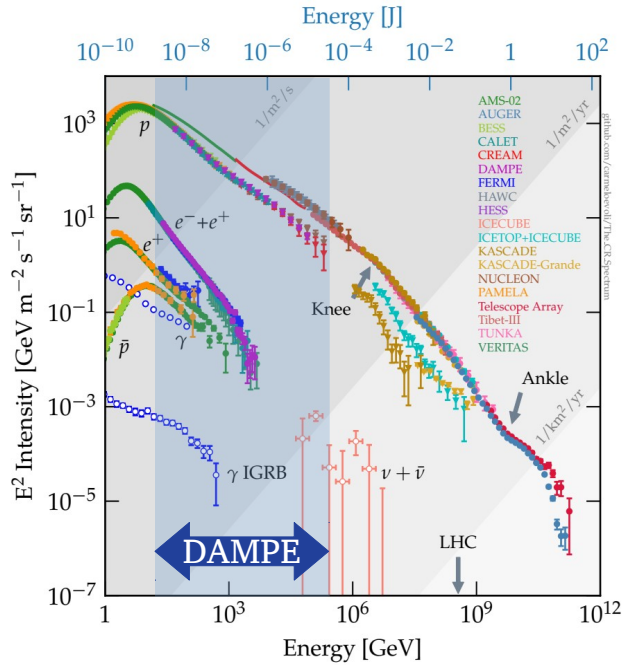
Study of CR spectra: motivations





Several measurements:
- spectral **hardening** at few hundreds GeV
- hints of a **softening** above ~10 TeV?

- Nearby **sources**?
- **Acceleration** mechanisms?
- **Propagation** effects?



Energy range:
5 GeV – 10 TeV e/γ
50 GeV – 300 TeV protons and nuclei

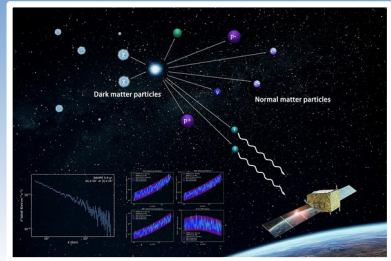
The DAMPE space mission

The **DA**rk **M**atter **P**article **E**xplorer (DAMPE) is a satellite-based experiment

DAMPE was successfully launched on **December 17th 2015** from the Jiuquan Satellite Launch Center

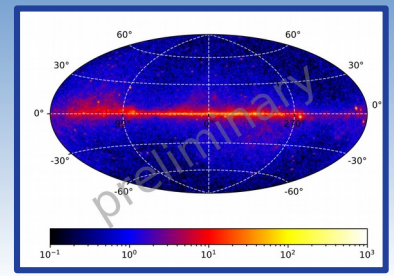
- ORBIT: Sun-synchronous
- ALTITUDE: 500 km
- INCLINATION: 97°
- PERIOD: 95 minutes

The DAMPE collaboration involves several institutes in China and Europe



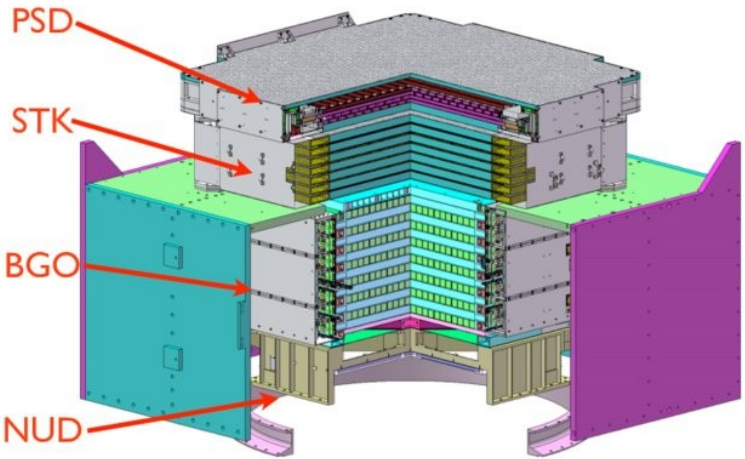
The main objectives of the DAMPE mission are:

- Study of galactic **cosmic-ray** physics
- **Dark matter** searches
- High-energy **gamma-ray** astronomy

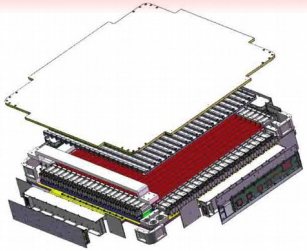


Detector structure

J. Chang et al., Astrop. Phys. 95(2017)6-24

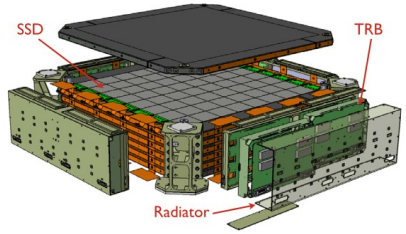


Plastic Scintillator Detector (PSD)



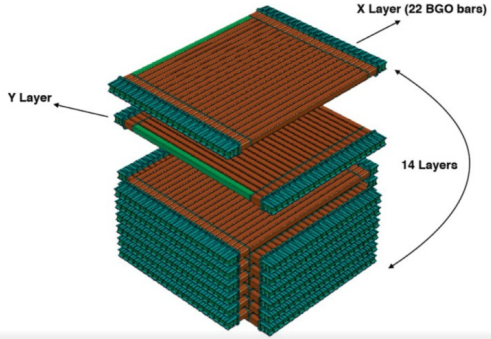
Charge measurement + identification of electrons and gamma-rays

Silicon-Tungsten tracKer (STK)



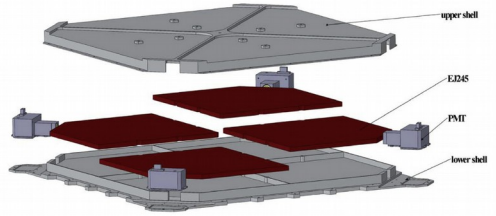
Silicon strips (precise tracking) + tungsten converter (pair production)

BGO Calorimeter (BGO)



Energy measurement + e/p separation

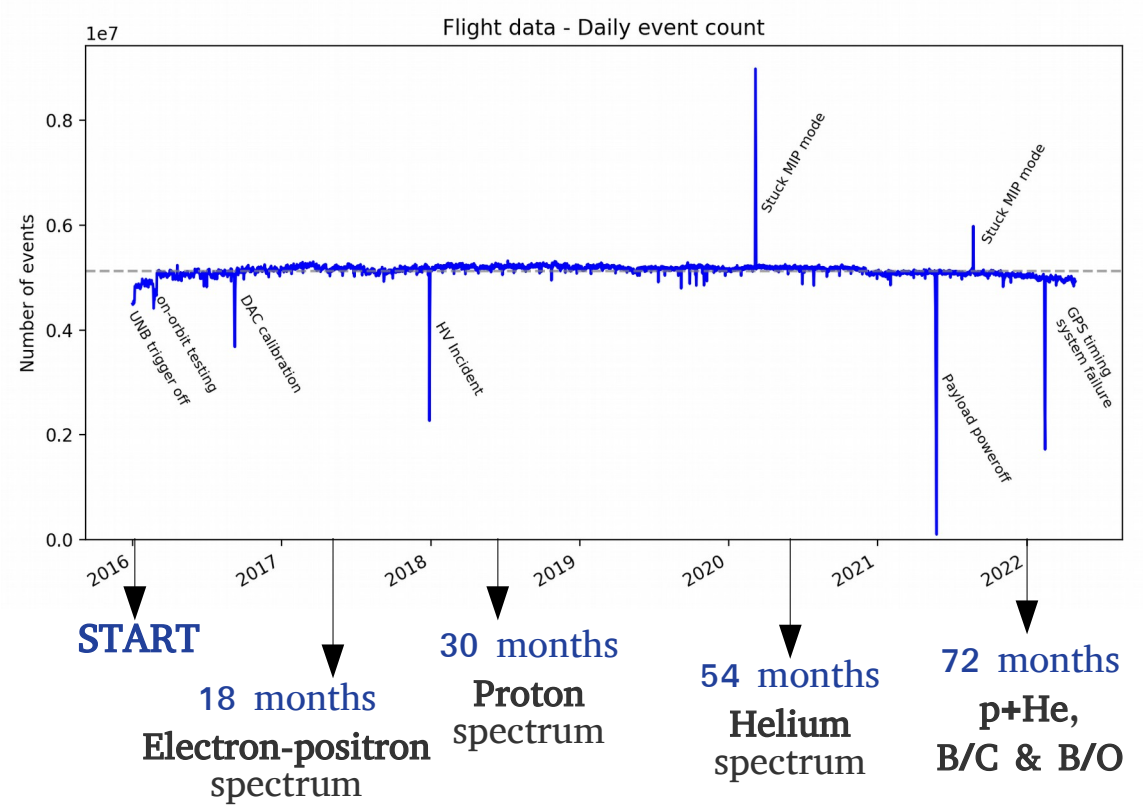
NeUtron Detector (NUD)



Additional hadrons rejection

CR data collected

DAMPE collects ~5 million CR events per day

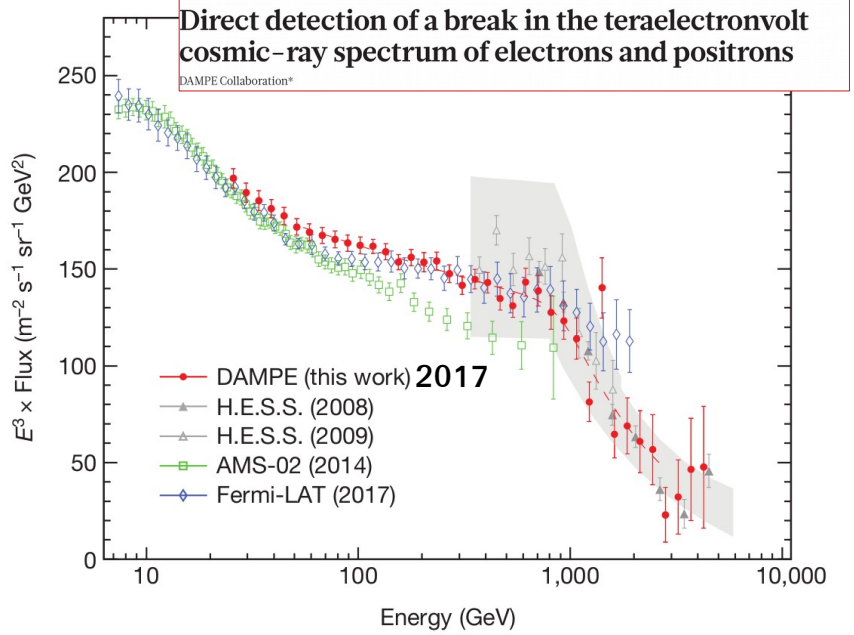


LETTER

doi:10.1038/nature24475

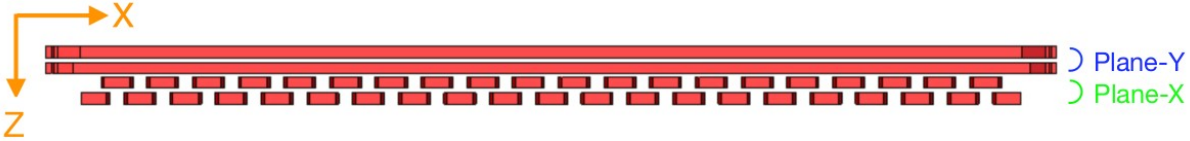
Direct detection of a break in the teraelectronvolt cosmic-ray spectrum of electrons and positrons

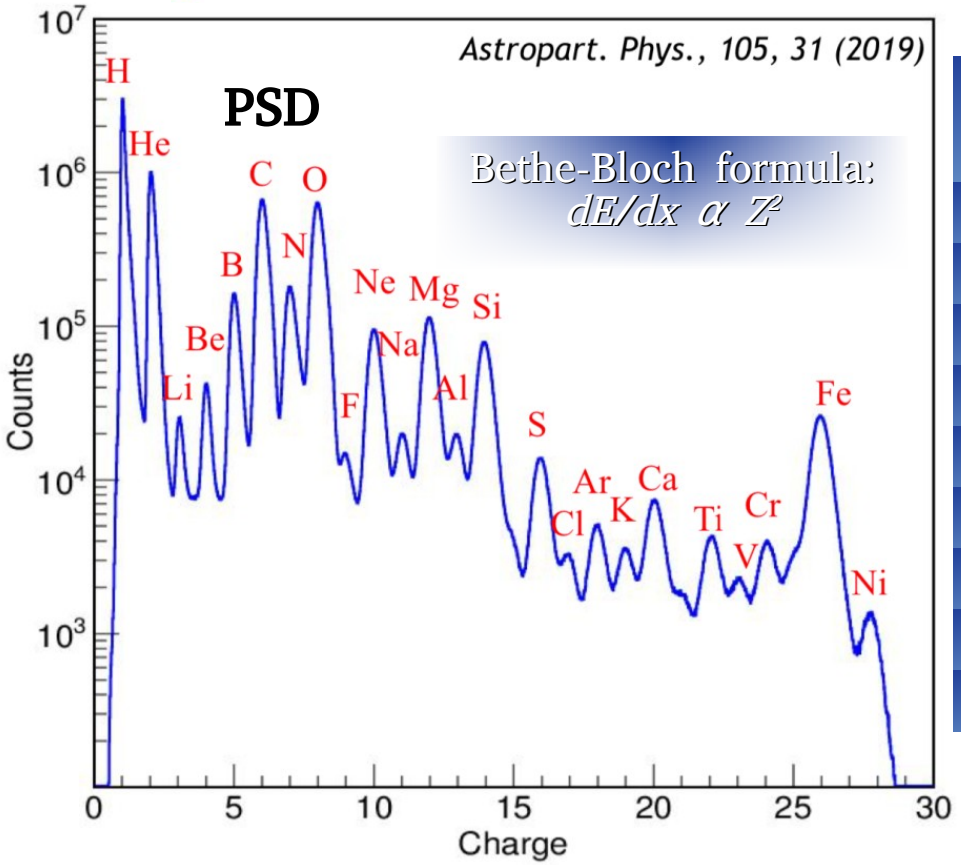
DAMPE Collaboration*



EVIDENCE OF A BREAK AT ~ 0.9 TeV with 6.6 σ significance

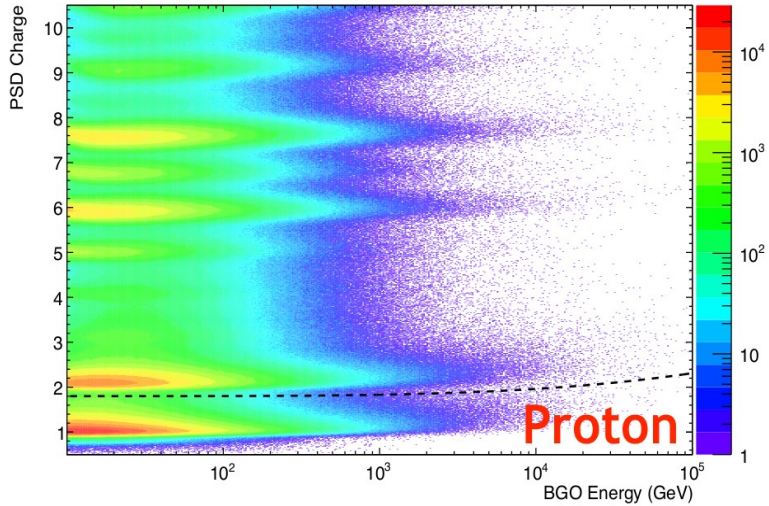
Identification of nuclei





Nuclei	Charge Resolution
p	0.13
He	0.12
Li	0.14
Be	0.21
B	0.17
C	0.18
N	0.21
O	0.21
Fe	0.32

Charge measurement also performed by STK and (with lower precision) by BGO bars

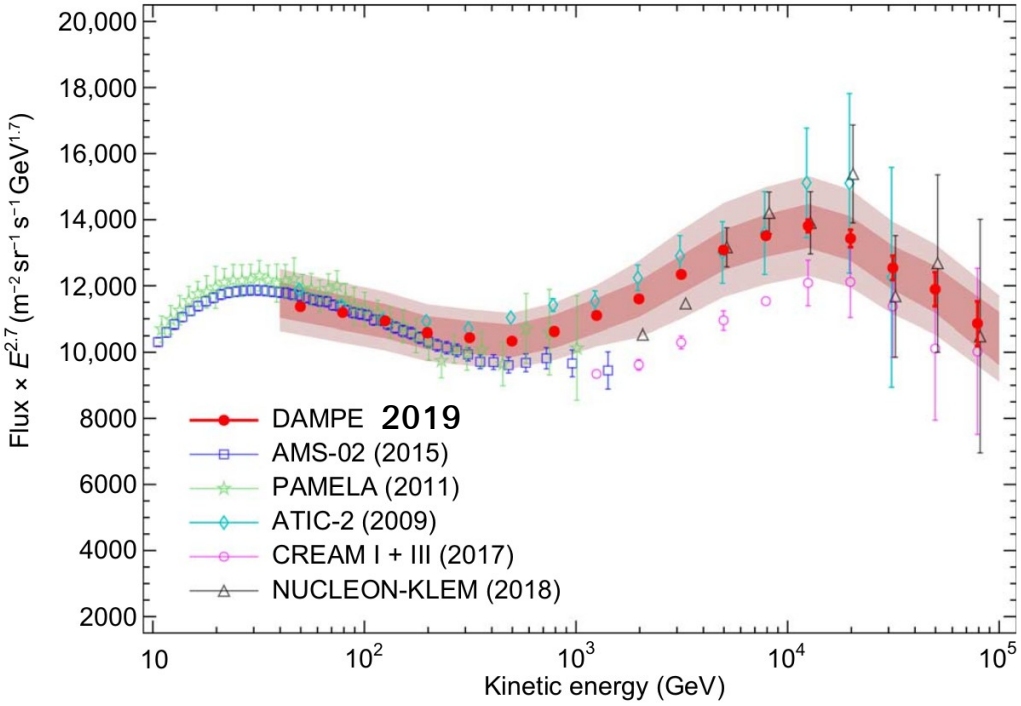


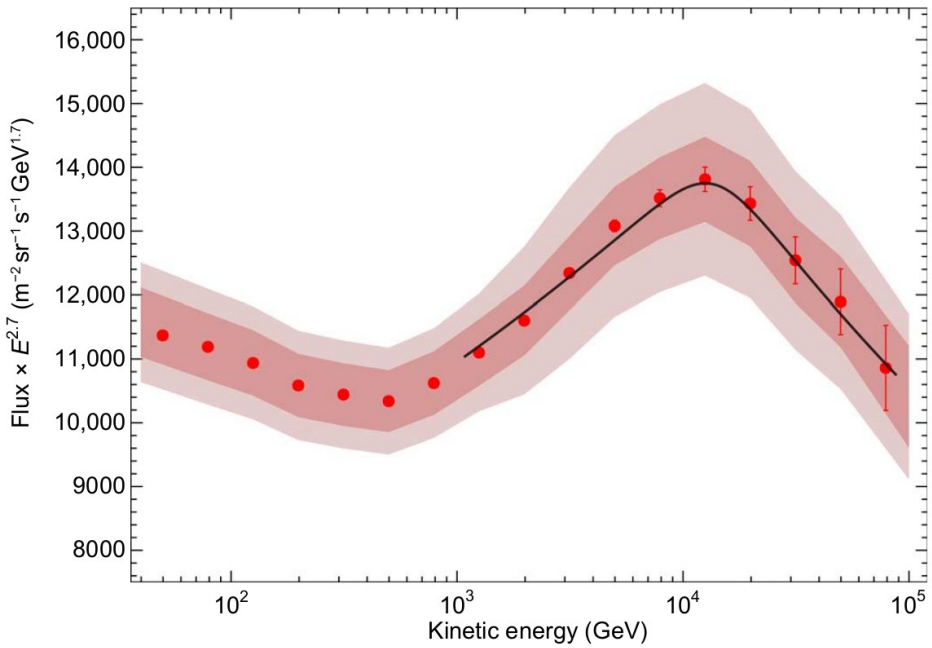
Proton spectrum

SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

Measurement of the cosmic ray proton spectrum from 40 GeV to 100 TeV with the DAMPE satellite





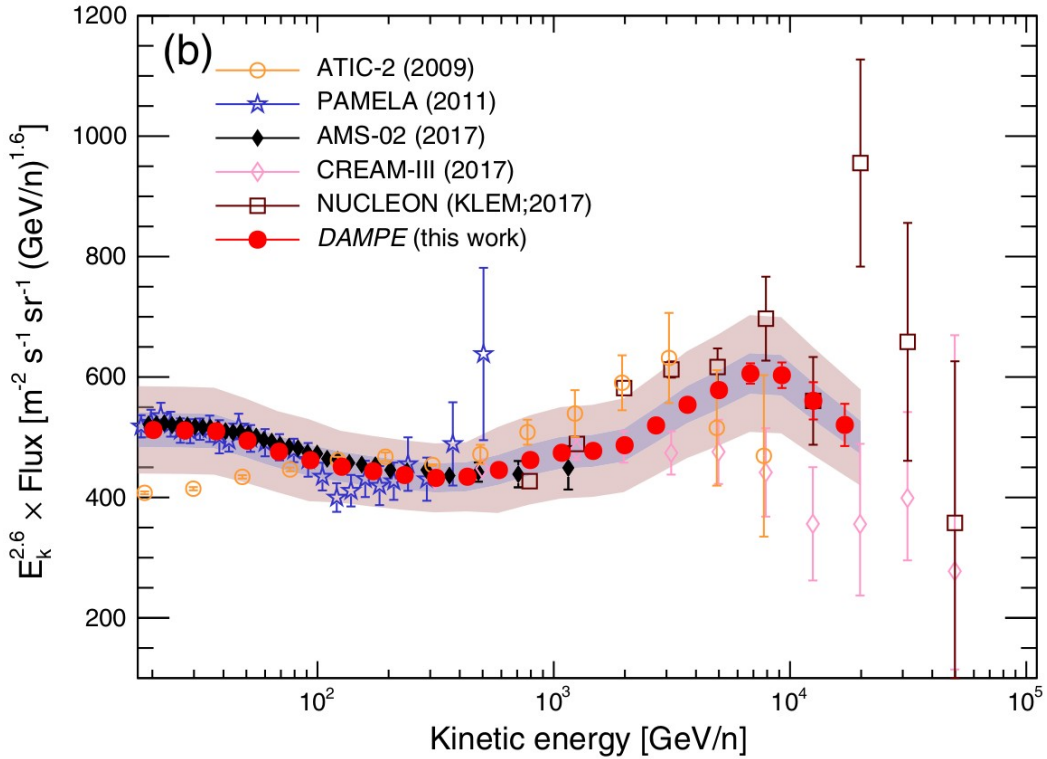
- Confirmation of a **hardening** structure at 480±10 GeV
- Detection of a **softening** at $13.6^{+4.1}_{-4.8}$ TeV with significance of ~4.7σ

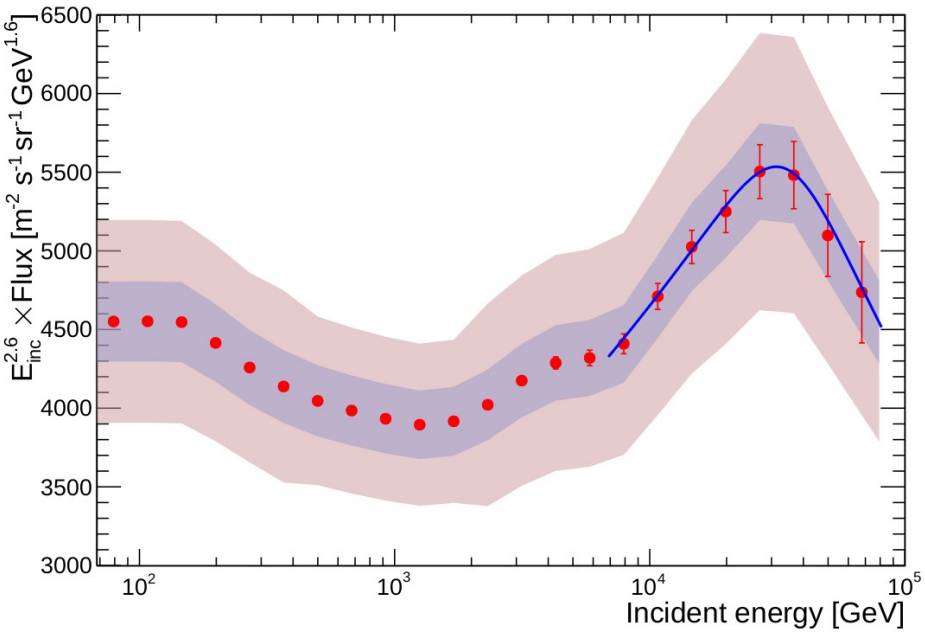
Helium spectrum

PHYSICAL REVIEW LETTERS **126,** 201102 (2021)

Editors' Suggestion | Featured in Physics

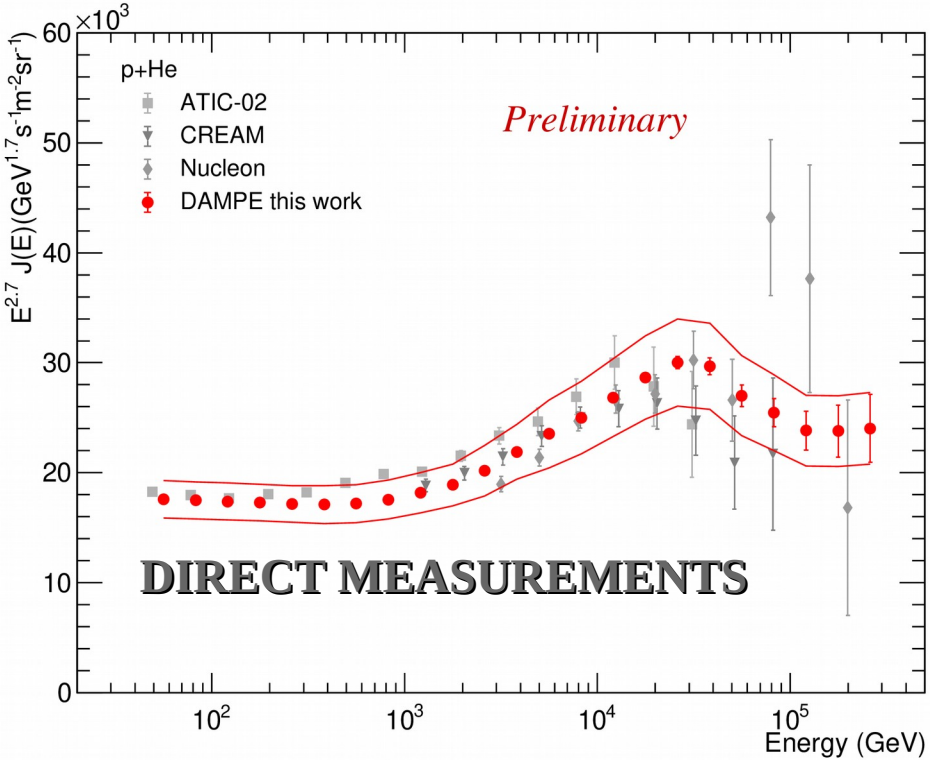
Measurement of the Cosmic Ray Helium Energy Spectrum from 70 GeV to 80 TeV with the DAMPE Space Mission

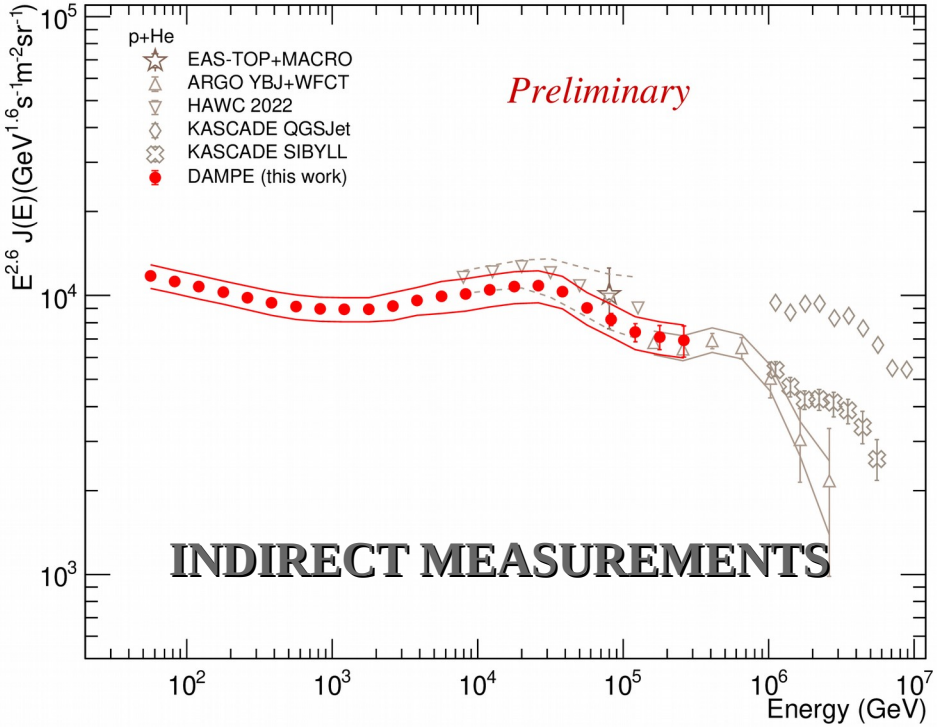




- First detection of a **softening** at 34.4$^{+6.7}_{-9.8}$ TeV with significance of ~4.3σ
- Suggesting a **charge dependent** feature

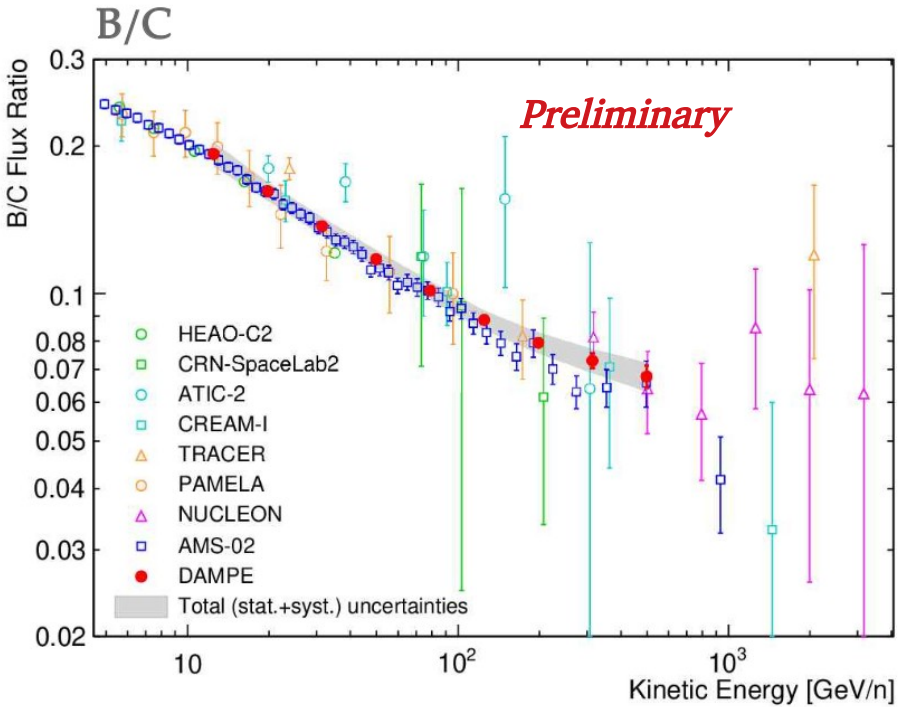
p+He spectrum

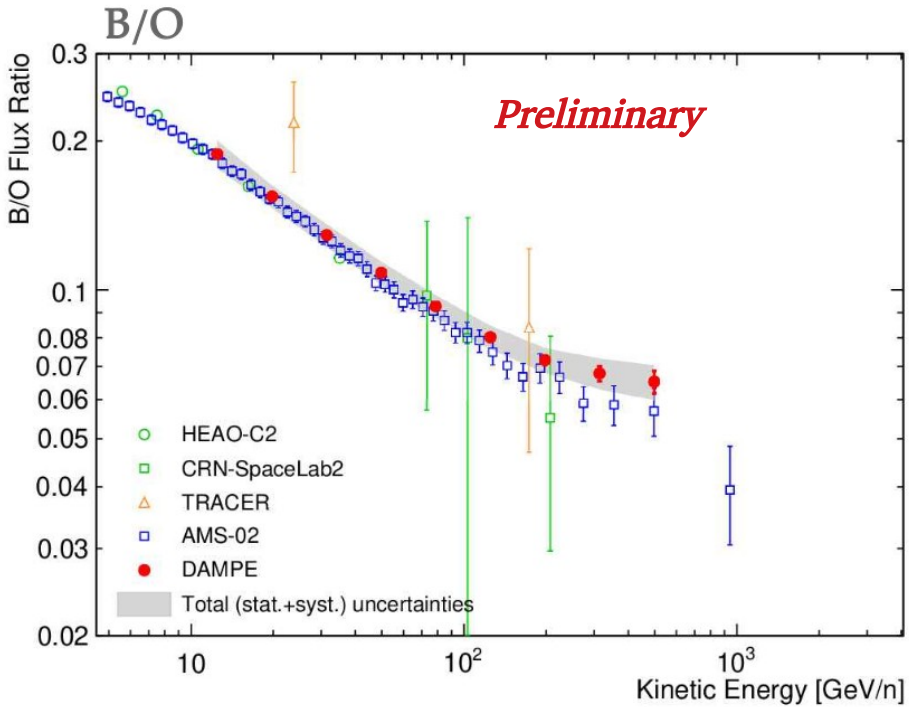




- General agreement with DAMPE proton and helium independent analyses
  - Evidence of the combined proton and helium softening at ~25 TeV
- Extension to higher energy (300 TeV) and comparison with ground-based experiments

B/C & B/O





- Preliminary DAMPE results in good agreement with other experiments
- Extension to ~5 TeV/n in progress

Summary – DAMPE

- The DArk Matter Particle Explorer, was launched in December 2015 and it is smoothly taking data since then
- Direct detection of a **break** at ~1 TeV in the **electrons and positrons** spectrum
- Detection of a **softening** at ~14 TeV in the **proton** spectrum
- First detection of a **softening** in the **helium** spectrum at ~34 TeV, suggesting a Z dependence
- Evidence of a combined proton and helium softening in the **p+He** spectrum at ~25 TeV
- Comparison between **space-based** and **ground-based** experiments
- Upcoming results on the **B/C** and **B/O** flux ratios
- Ongoing works on both primaries (C, O, Fe, …) and secondaries (Li, Be, B, …)

The HERD space mission

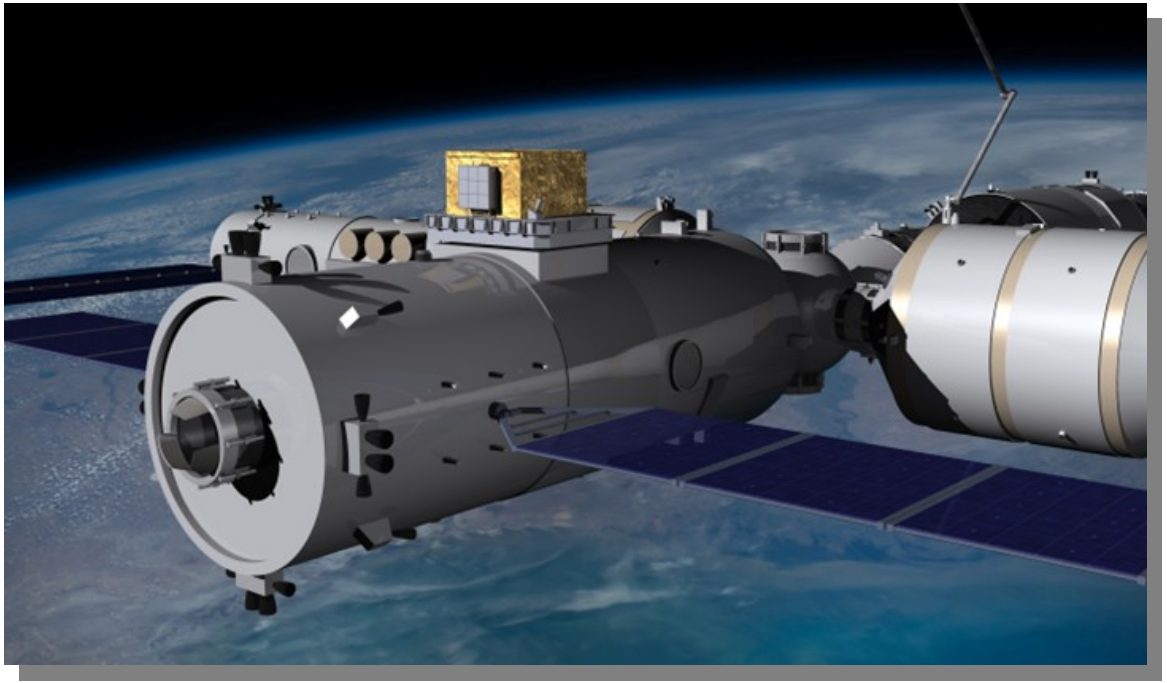
The High Energy cosmic Radiation Detection facility

Main scientific objectives:

- Galactic CR studies
- Dark Matter search
- Gamma-ray astronomy

International collaboration between China, Italy, Switzerland and Spain

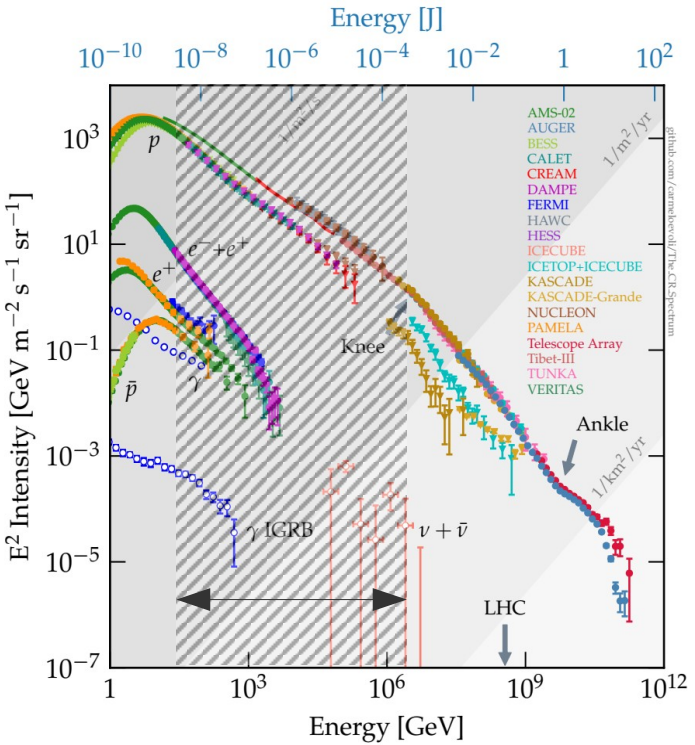
Planned to be installed onboard the China's Space Station
Expected lifetime ~10 years



Expected performance

	HERD	DAMPE	CALET
e/γ Energy res. @100 GeV (%)	<1	1.5	2
e/γ Angular res. @100 GeV (deg)	<0.1	0.1	0.2
e/p discrimination	$>10^6$	10^5	10^5
Calorimeter thickness (X_0)	55	32	27
Geometrical acceptance (m^2sr)	>3	0.29	0.12

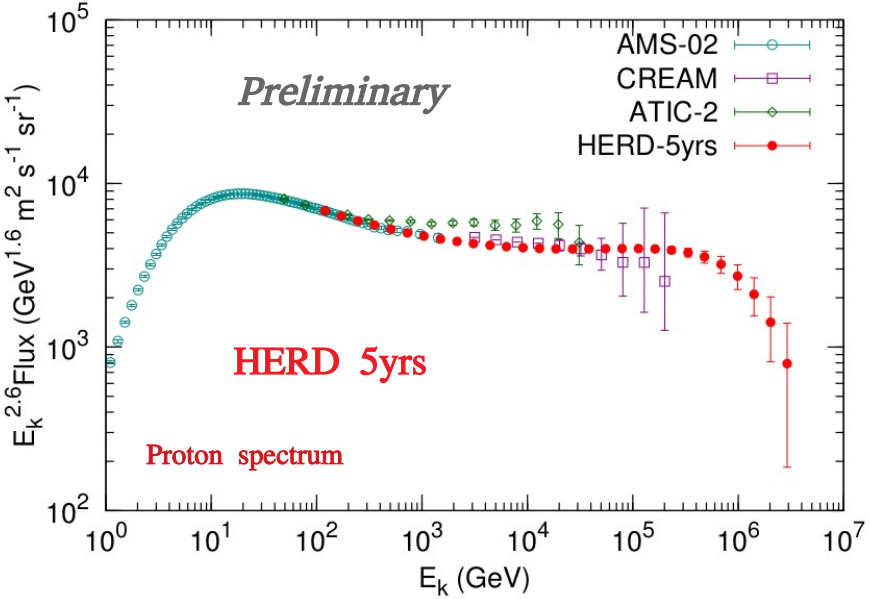
One order of magnitude upgrade in exposure wrt current generation CR experiments (~15 m² sr yr)



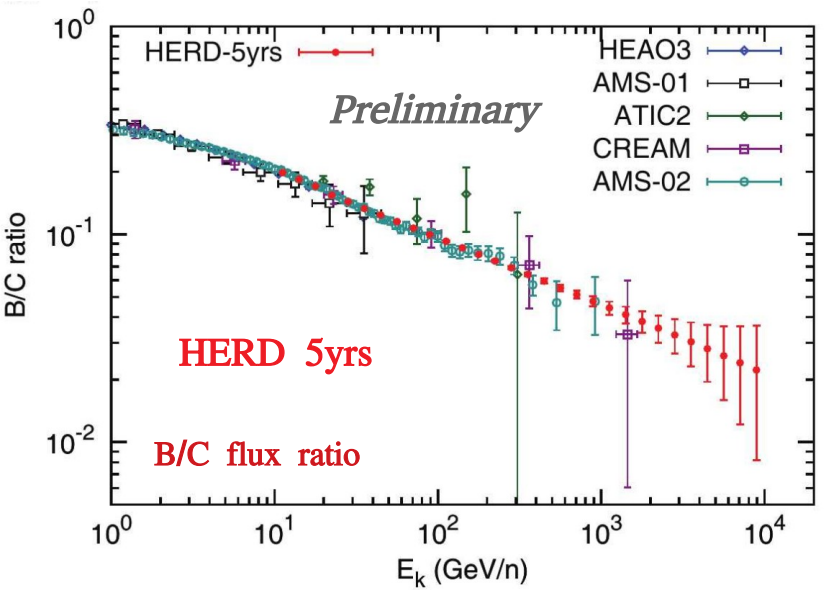
Energy range (e/γ)	10 GeV – tens of TeV (e); > 100 MeV (γ)
Energy range (CRs)	30 GeV – 3 PeV

Science with HERD

Galactic Cosmic Rays studies



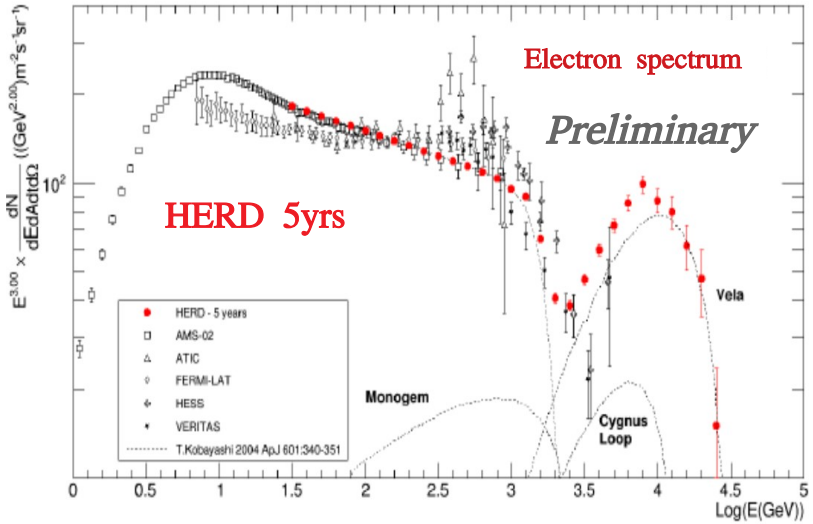
Exploring the CR knee from space



Clarifying propagation mechanisms

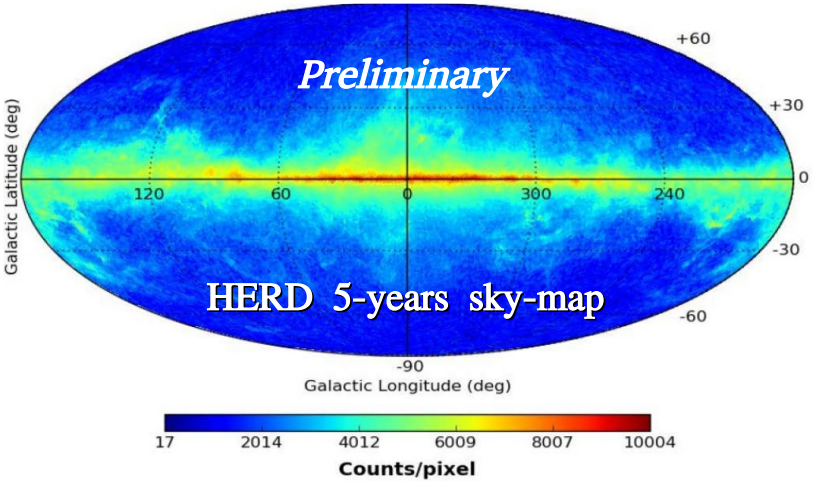
Science with HERD

All-electron spectrum



- Searching for nearby e^+-e^- sources
- Possible detection of a spectral cutoff at high energy

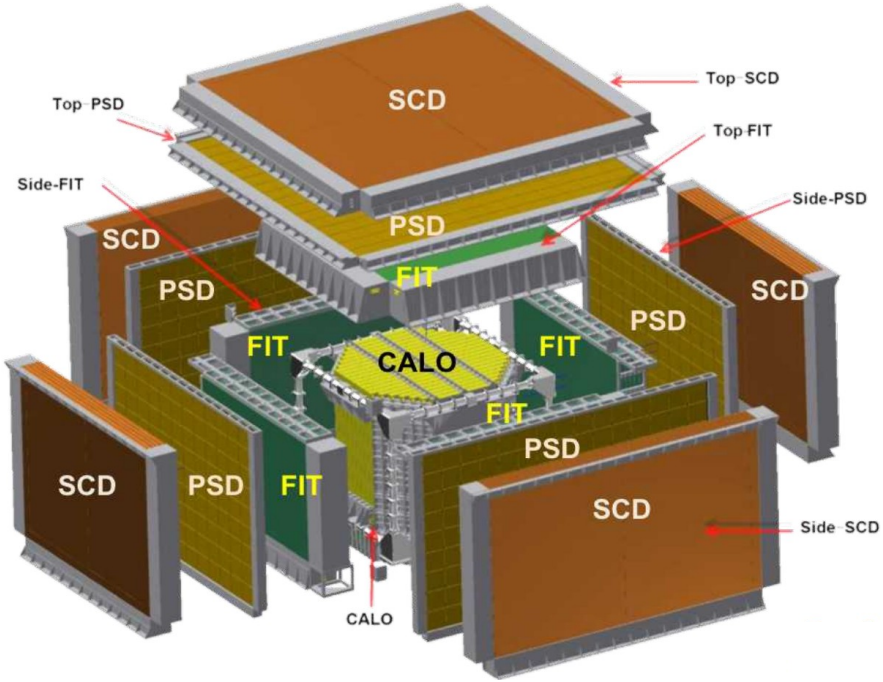
Gamma-rays from 100 MeV



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

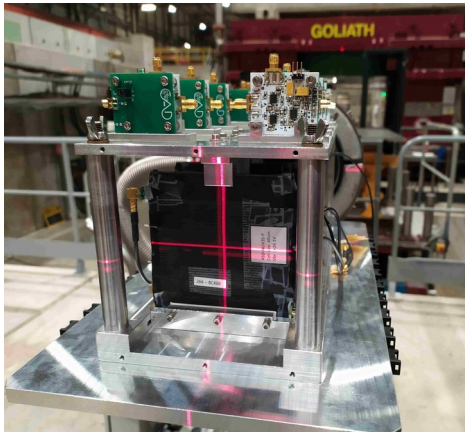
The HERD detector

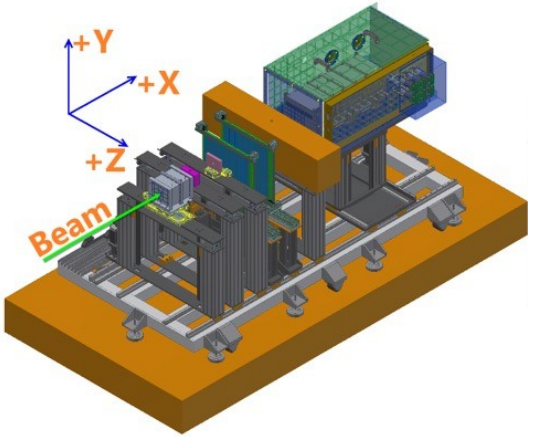
Accepting particles from the top **and** four lateral sides

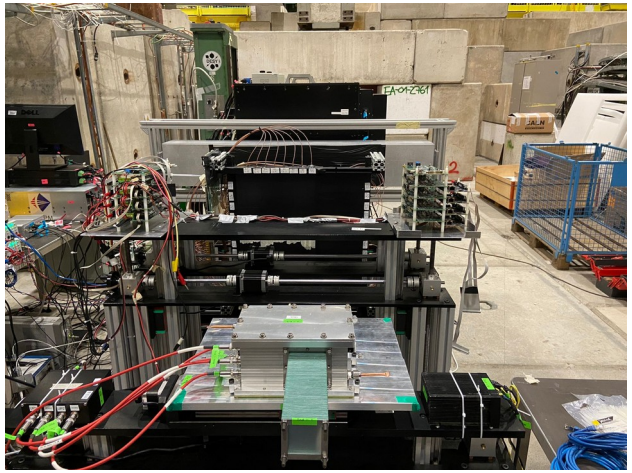


- **CALO:** deep 3D calorimeter. Energy measurement + e/p separation
- **FIT:** Fiber Tracker. Particle tracker.
- **PSD:** Plastic Scintillator Detector. Charge measurement + trigger for gamma-rays and charged particles
- **SCD:** Silicon Charge Detector. Additional charge measurement
- **TRD:** Transition Radiation Detector, on one of the lateral faces. Energy calibration of nuclei in the TeV region

HERD test beam campaigns @CERN







INFN-LNGS

Summary – HERD

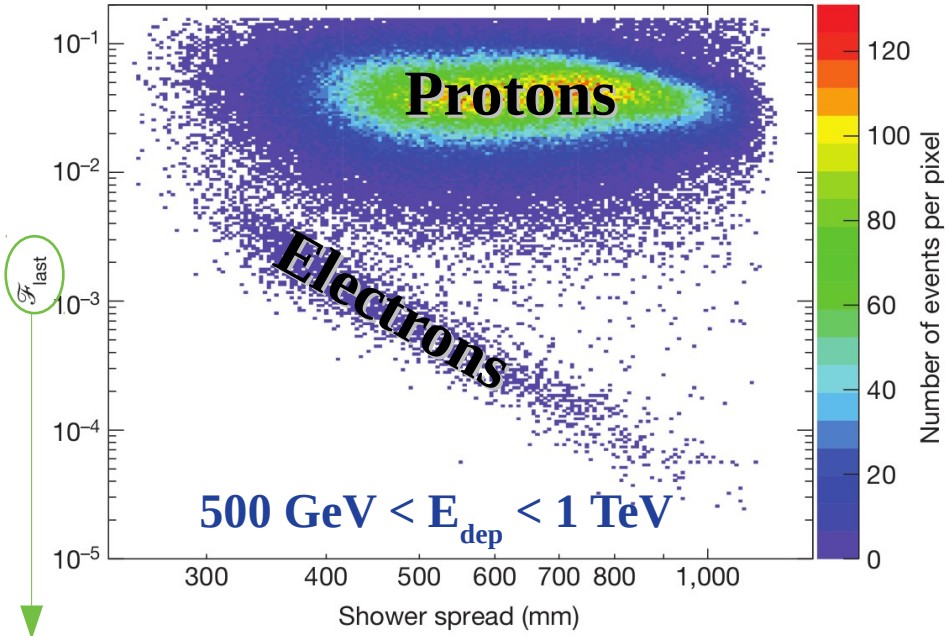
- HERD is a space-based experiment to be installed on board China's Space Station, and will operate for ~10 years
- HERD will give the possibility to reach the CR knee from space (~PeV), to search indirectly for dark matter signatures and to perform gamma-ray astronomy
- **One order of magnitude upgrade in exposure wrt current generation CR experiments**
- The full HERD prototype was tested at CERN in Autumn 2021 and Summer 2022
- Ongoing work includes hardware R&D and MC simulations, for further optimization of the detectors and definition of the final design

Thank you for the attention!


BACKUP

Electron IDentification

Discrimination between electrons and protons in the BGO

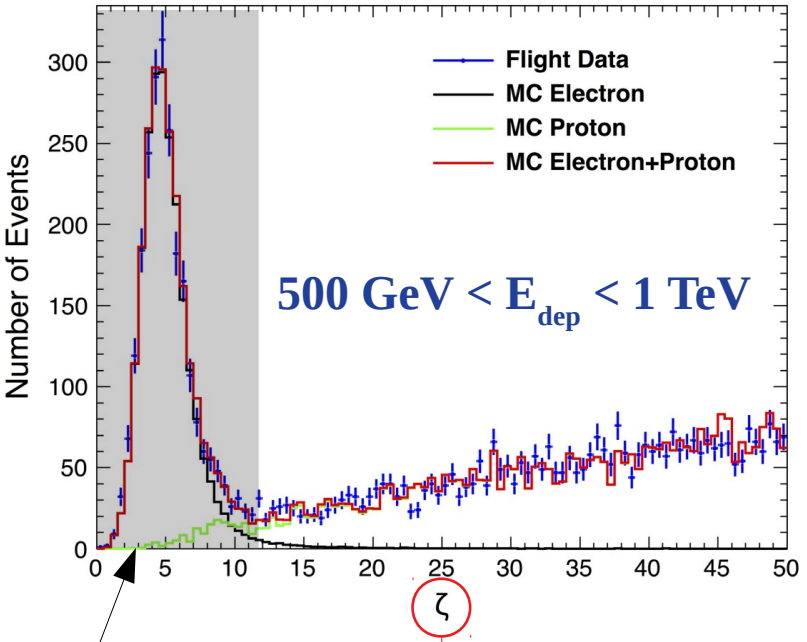


Ratio of energy deposited in the last BGO layer to the total energy deposited in the BGO calorimeter

$\Sigma_i RMS_i$

Sum of the energy-weighted shower dispersion of each layer

Comparison of flight data and MC simulations of the ζ distributions

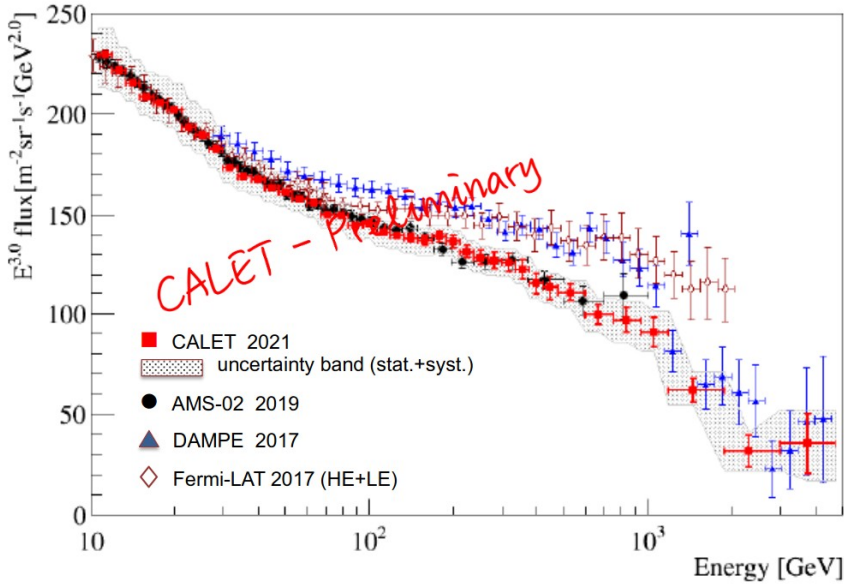


$$\zeta = \mathcal{F}_{\text{last}} \times \left(\Sigma_i RMS_i/\text{mm}\right)^4 / \left(8 \times 10^6\right)$$

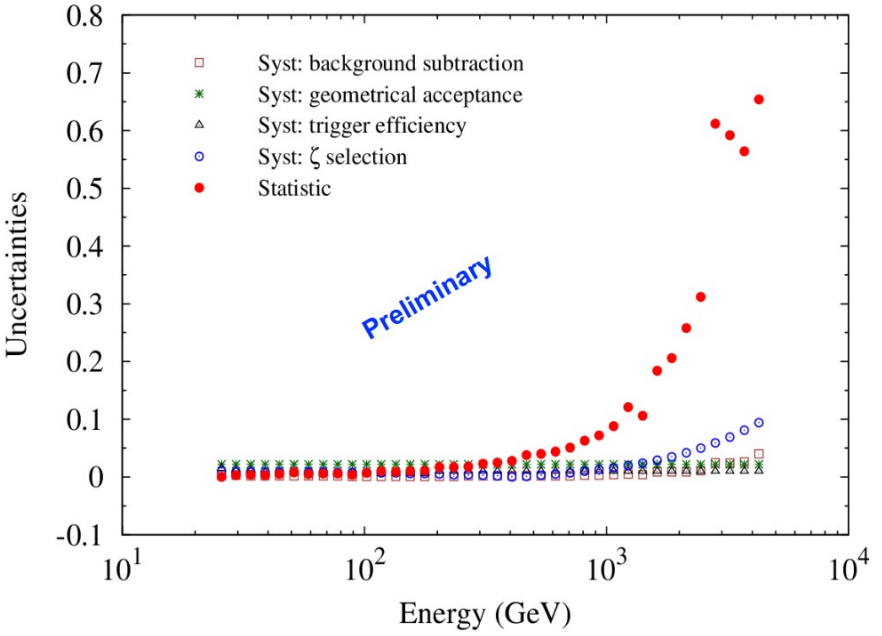
All-electron spectrum

All Electron Spectrum:
Comparison between Recent Direct Measurements

CALET Observations: Oct.13, 2015 - Sep.30, 2020 (for 1815 days)



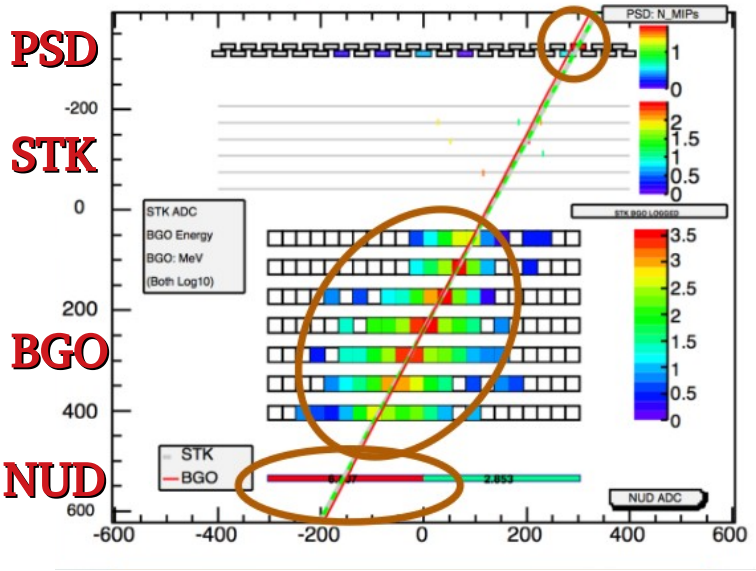
Errors of e^++e^- spectrum



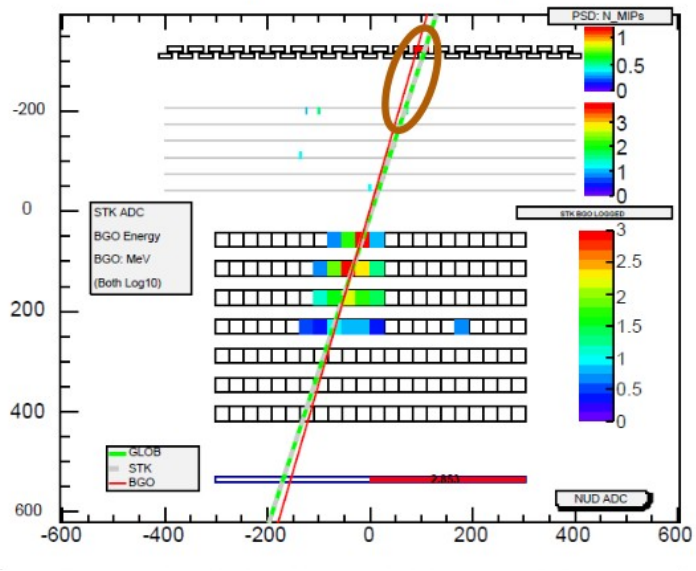
SLIDES TAKEN FROM ICRC 2021 –
Shoji Torii and *Yosui Akaike* for CALET and *Li Xiang* for DAMPE

Particle selection and identification

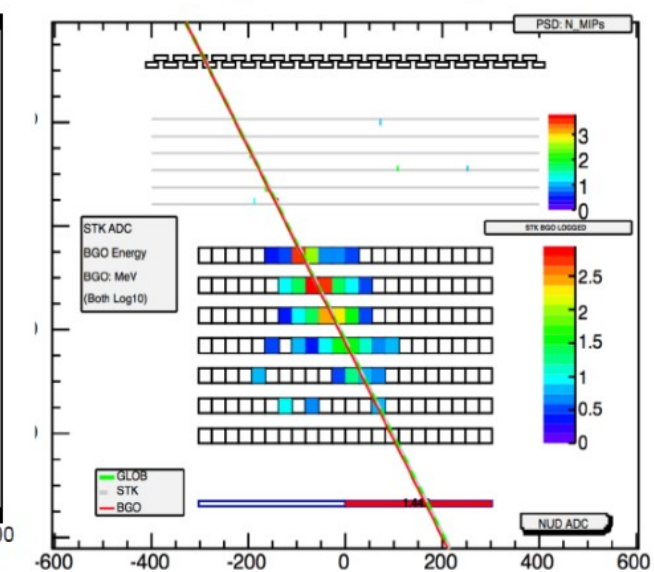
Proton



Electron



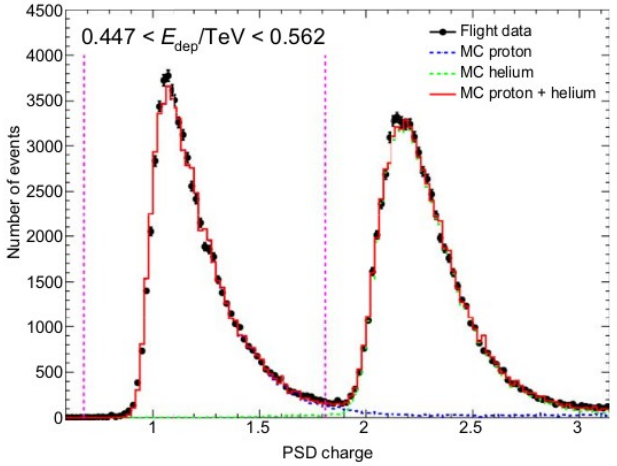
Gamma



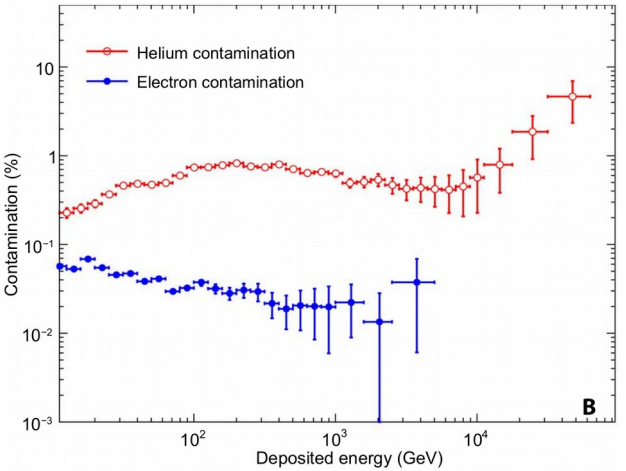
Plots from F. Gargano @MG15 ROME 2018

Proton spectrum

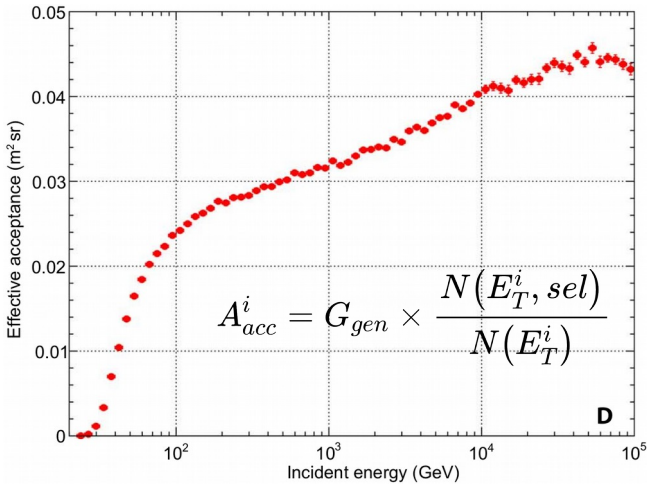
Charge selection



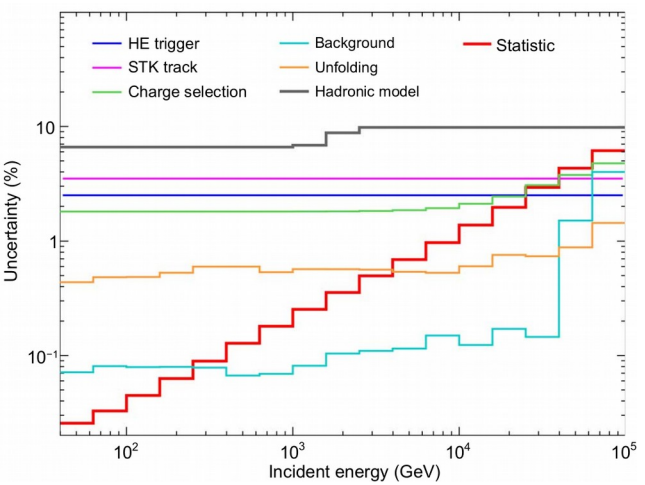
Contamination



Acceptance



Uncertainty



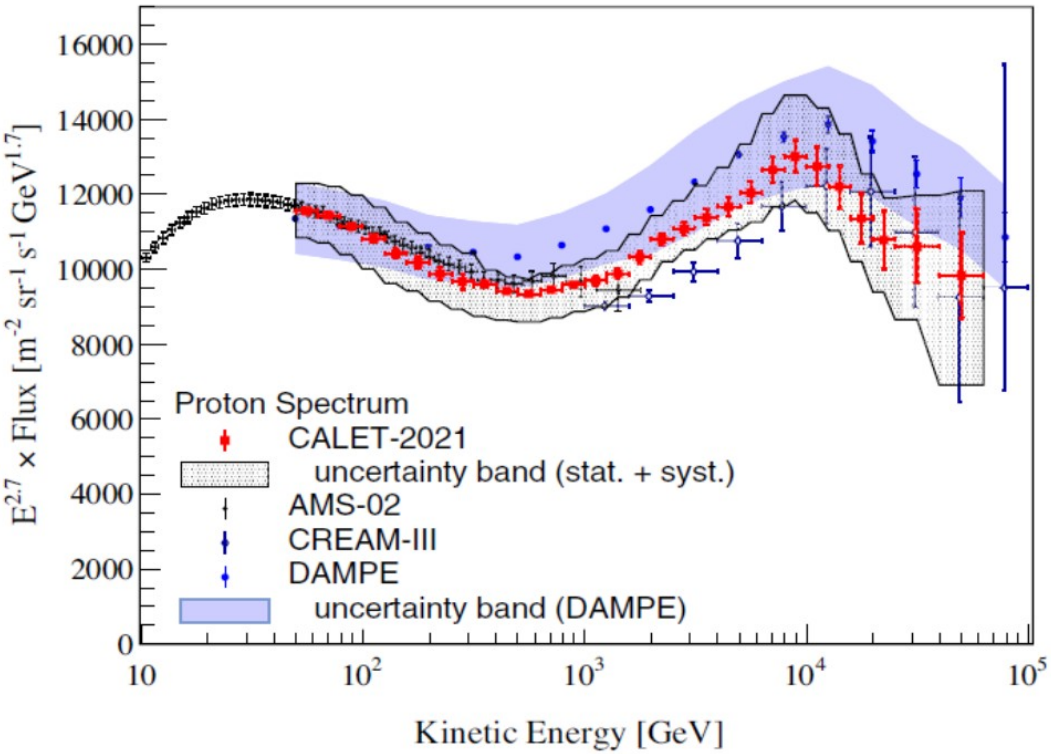
Proton spectrum

PHYSICAL REVIEW LETTERS **129,** 101102 (2022)

Editors' Suggestion

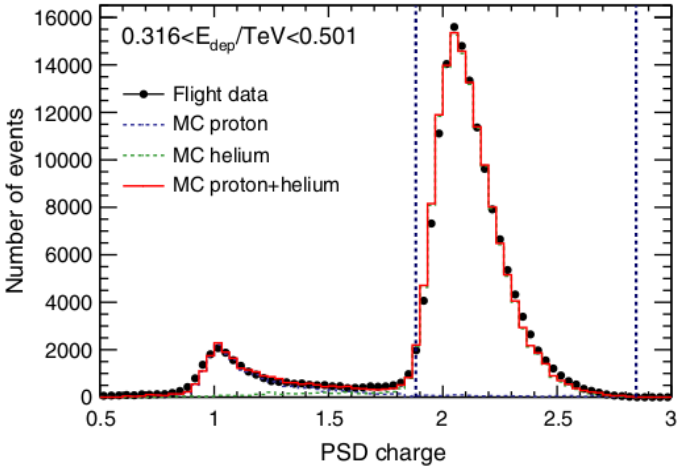
September 1, 2022

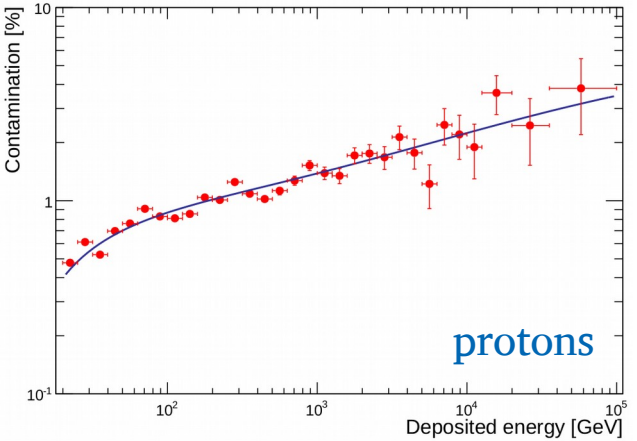
Observation of Spectral Structures in the Flux of Cosmic-Ray Protons from 50 GeV to 60 TeV with the Calorimetric Electron Telescope on the International Space Station



Helium spectrum

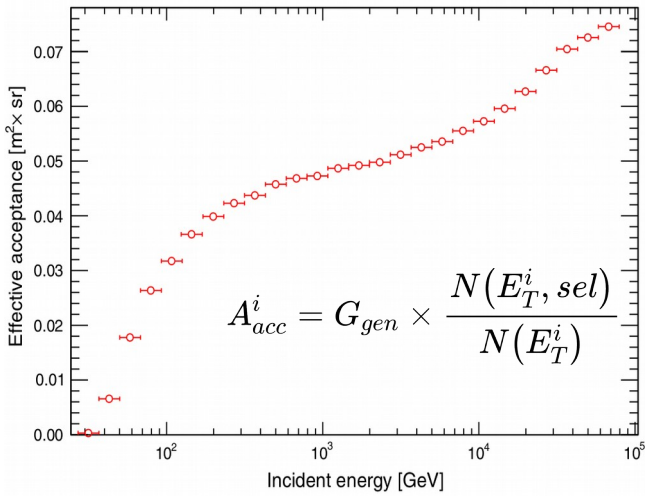
Charge selection

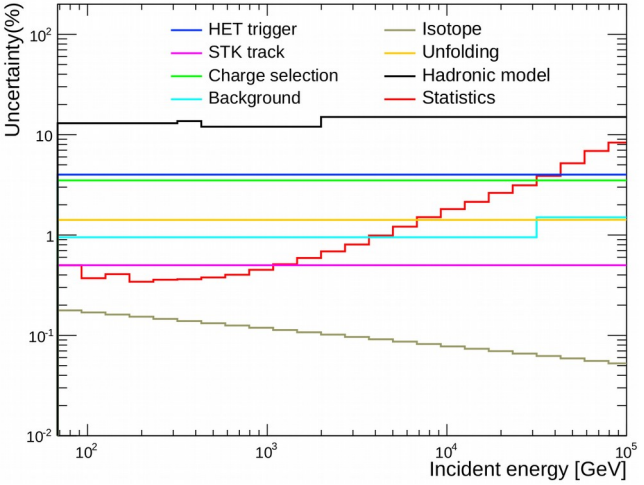




Contamination

Acceptance

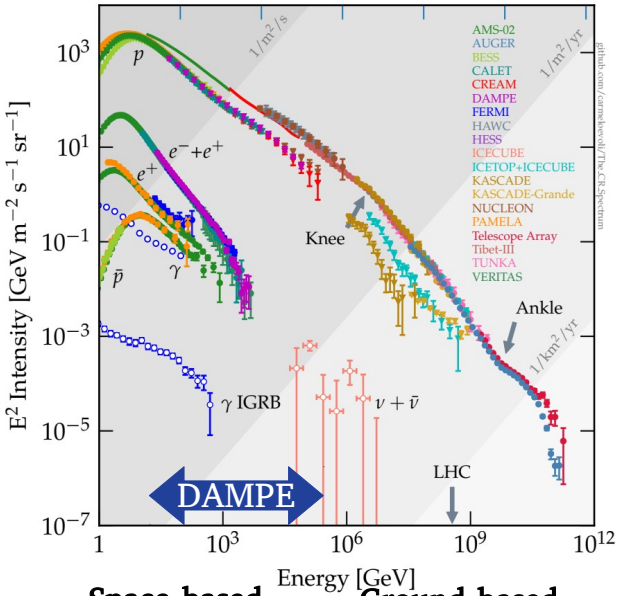




Uncertainty

Study of light (p+He) CR component: motivations

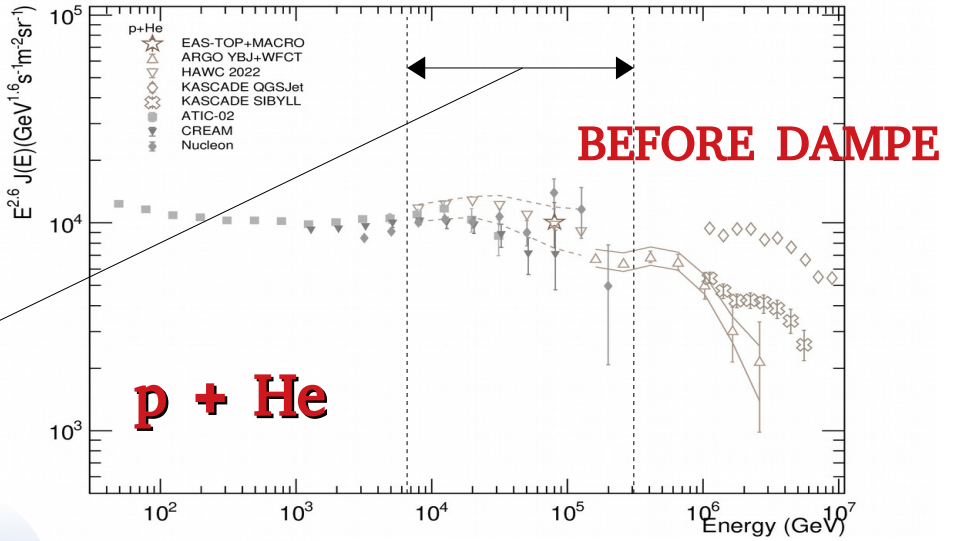
Measuring light elements in space (i.e. proton + helium spectrum) gives the **possibility to compare results between direct and indirect experiments**



Space-based experiments (direct measurements)

Ground-based experiments (indirect measurements)

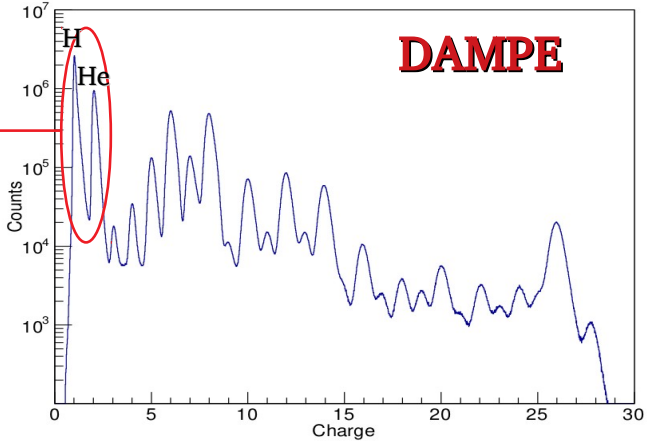
In this energy region direct and indirect spectra can be compared



Proton and Helium are well separated from other peaks

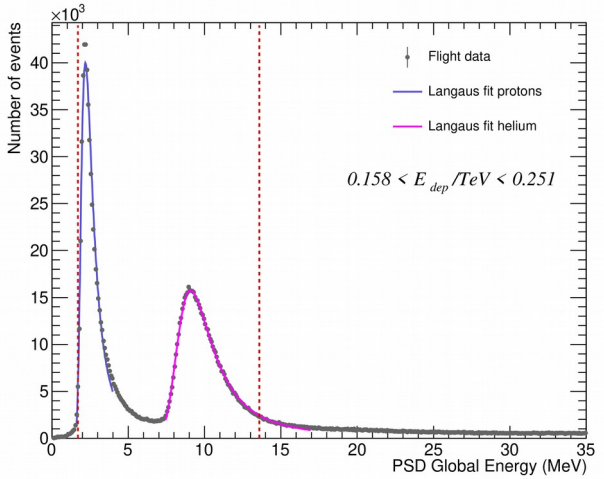
VERY LOW CONTAMINATION (less than 0.1%)

Looser cuts
Possibility to go to higher energy

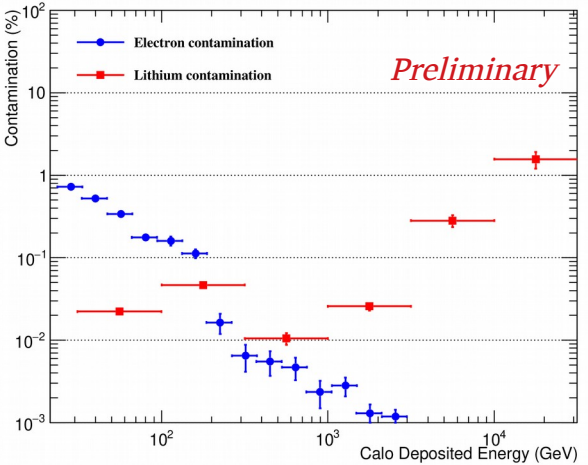


p+He spectrum

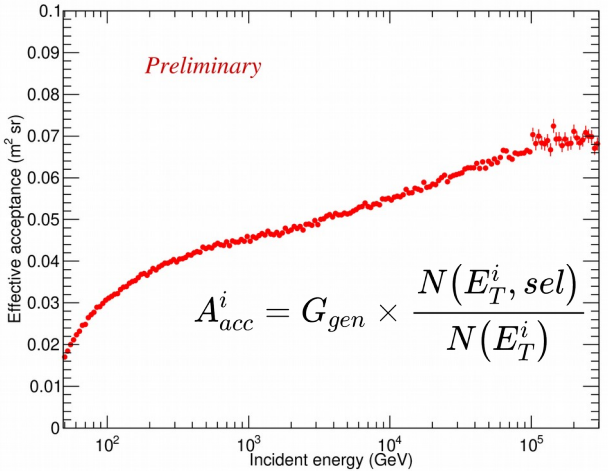
Charge selection



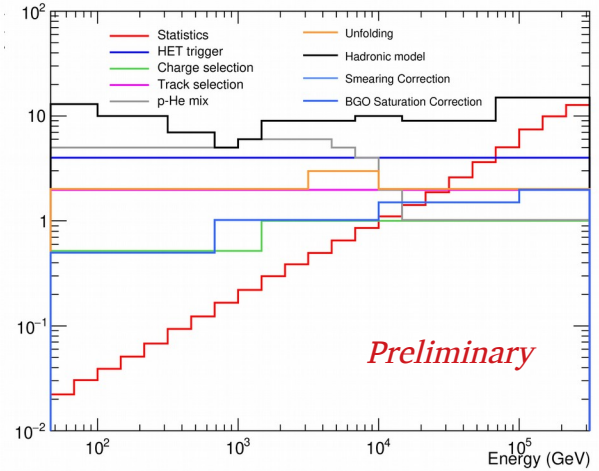
Contamination



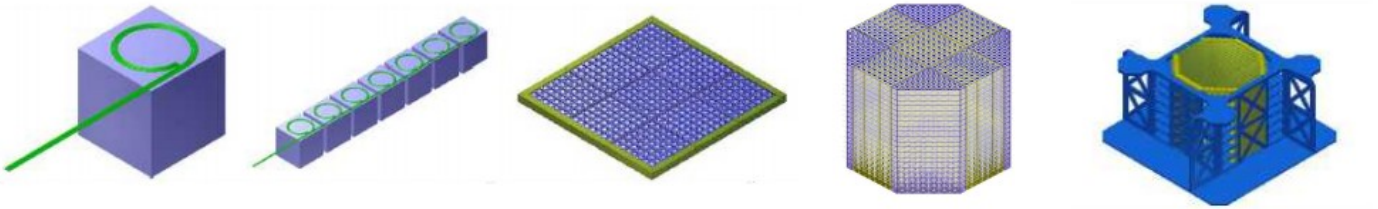
Acceptance



Uncertainty



HERD sub-detectors: Calorimeter (CALO)

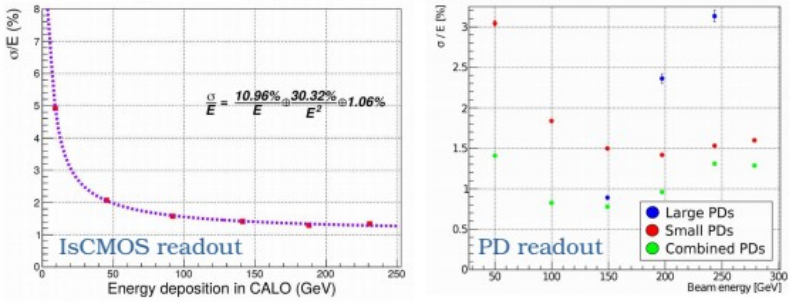


Item	Value
Type of crystal	LYSO
Nuclear interaction length	3 (55 X_0)
Number of crystals	~7500
Crystal dimension	3 x 3 x 3 cm³

Scintillation light is readout independently by:
1) WLS fibers coupled to IsCMOS cameras
2) Photodiodes connected to custom front-end electronics

Partial readout of crystals with PhotoDiodes (Calocube) for calibration extended dynamic range & reduced systematics.

Energy resolution for electrons



...from beam tests at CERN – SPS

L. Pacini et al, PoS, ICRC2021(2021) 066

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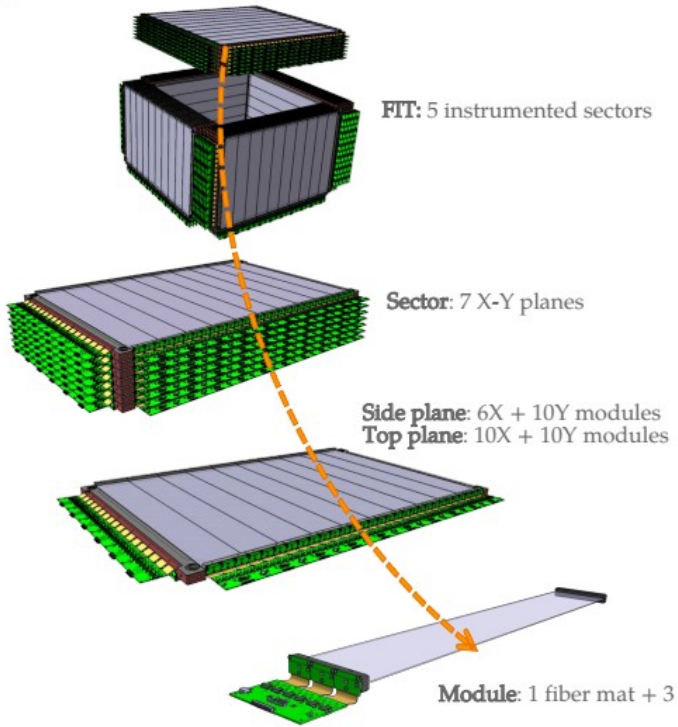
HERD sub-detectors: Fiber Tracker (FIT)



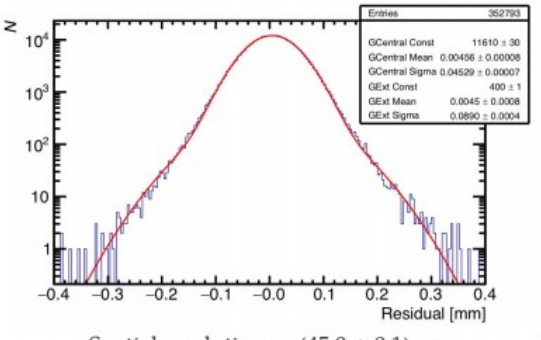
FIT: 5 instrumented sectors

Sector: 7 X-Y planes

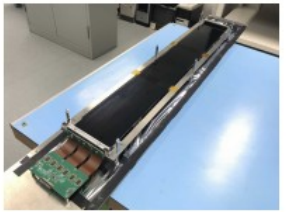
Side plane: 6X + 10Y modules
Top plane: 10X + 10Y modules

Module: 1 fiber mat + 3 SiPM arrays

Position residual distribution from proton beam tests



Spatial resolution = (45.0 ± 0.1) μm



Z	μ_Z	σ_Z	σ_Z/μ_Z [%]
2	1.99	0.31	15
3	3.07	0.4	13
4	4.01	0.51	12

Charge resolution for nuclei heavier than protons

C. Perrina et al, PoS, ICRC2021(2021) 067

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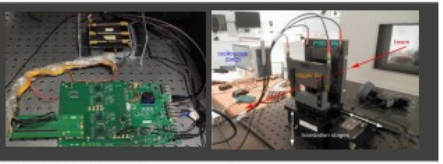
HERD sub-detectors: Plastic Scintillator Detector (PSD)

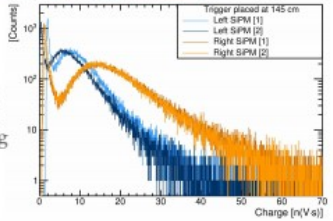
The PSD will provide **γ identification** (vetoing charged particles) w/ accurate **measurement of impinging charged particles**

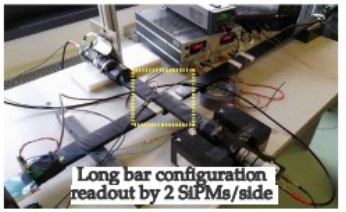
Two scintillator design layouts investigated:
one w/ long bars while the other w/ square tiles
both coupled with **SiPMs.**

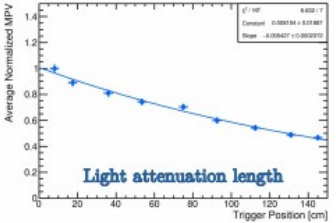
D. Kyratzis et al, PoS, ICRC2021(2021) 054



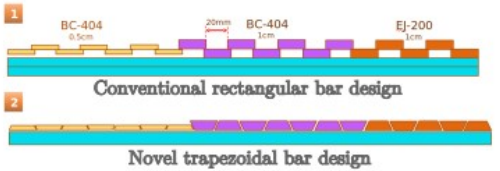
Cosmic ray muon **charge distributions** measured in various **trigger positions** along the bar







Measurement of **light attenuation length** extracted from all trigger positions



Hermeticity studies concerning the feasibility of **novel trapezoidal bars** (bottom) as opposed to default rectangular designs (top)

Additional info on this meeting's posters:

The Plastic Scintillation Detector for the HERD experiment
by Corrado Altomare

A tile prototype of the Plastic Scintillation Detector for HERD based on long Printed Circuit Boards: design and test with ion beams at CNAO
by Massimo Rossella

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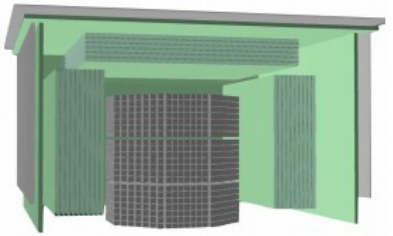
HERD sub-detectors: Silicon Charge Detector (SCD)

The SCD is a **silicon micro-strip** detector with the objective of precisely measuring the particle charge

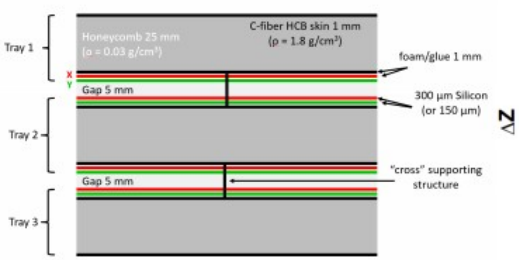
Additional info on this meeting's poster:

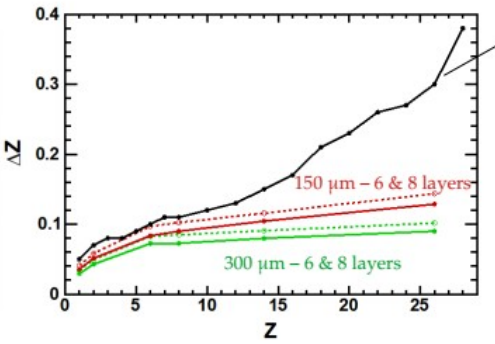
The Silicon Charge Detector of the High Energy Cosmic Radiation Detection facility by Matteo Duranti



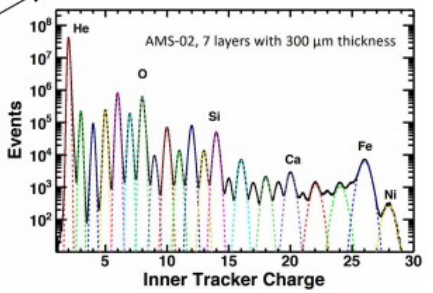
Being the **outermost** detector the SCD aims to avoid early charge – modifying interactions in the PSD

Highly segmented to minimize backsplash events moving upward from the CALO





Y. Jia et al. NIM A **972** (2020)



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