106° CONGRESSO NAZIONALE
SOCIETÀ ITALIANA DI FISICA
14-18 settembre 2020

Recent results on high-energy cosmic ray studies with DAMPE calorimetric spaceborne detector and perspectives for the future

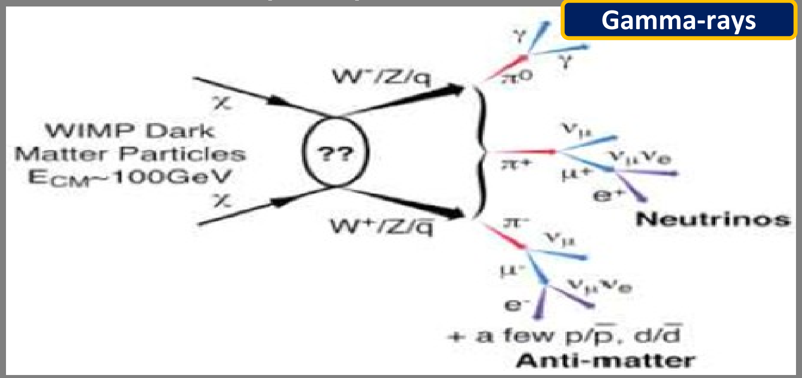
F. GARGANO ON BEHALF OF THE **DAMPE** AND **HERD** COLLABORATION

INFN BARI
Istituto Nazionale di Fisica Nucleare
Sezione di Bari

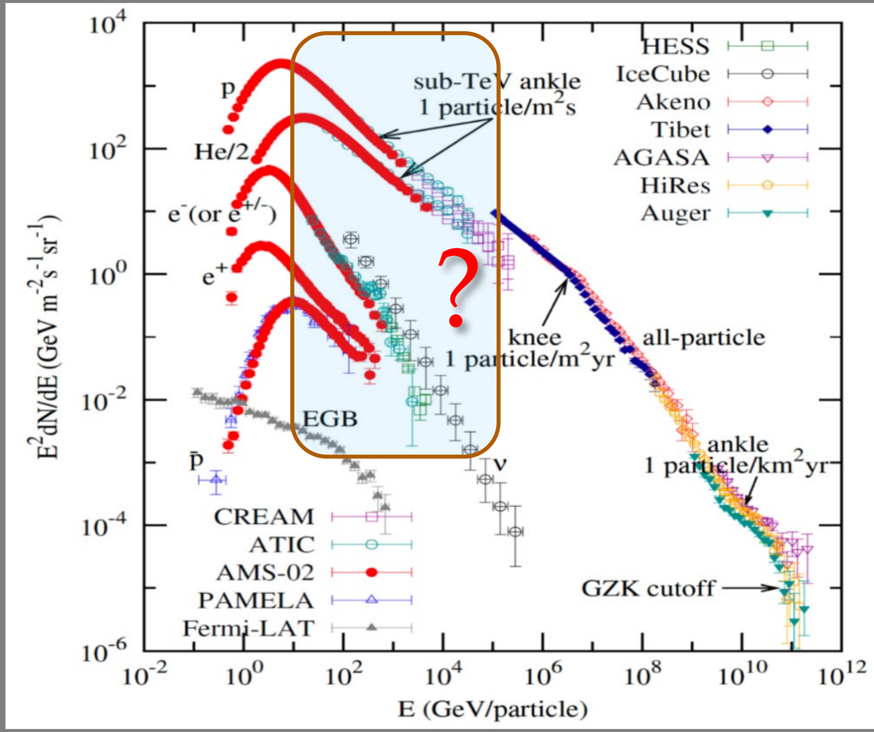
OUTLOOK

- DAMPE experiment
- DAMPE results and comparison with other experiments
- Perspective for the future: the HERD experiment

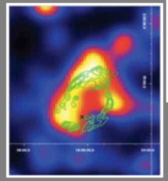
Dark Matter
nature, origin, abundance, properties

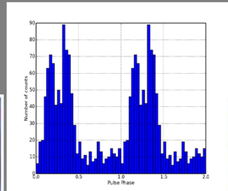


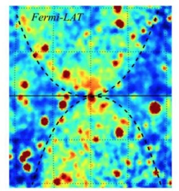
Cosmic rays
sources, acceleration, propagation



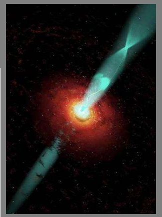
High-energy cosmic photons
sources, interaction, non-thermal physics

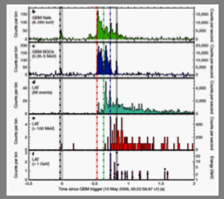

SNRs


Pulsars

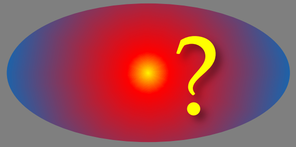


Galactic structures

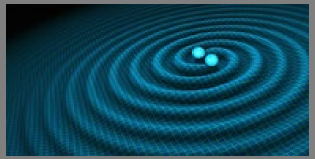

Blazars


GRBs

Exotic particles



E.M. with GW



- DAMPE – DArk Matter Particle Explorer – is a **space particle** and **photon detector** aimed to:
  - study **cosmic electrons** spectra
  - study **cosmic protons + nuclei** spectra and composition
  - astronomy with high-energy cosmic **gamma-rays**
  - search for **dark matter** signatures in **photon** and **lepton** spectra
  - search for **e.m. counterparts** of gravitational waves or neutrinos
  - quest for **exotic** particles and phenomena
- Excellent performance:
  - detection of 5 GeV – 10 TeV e/γ, 50 GeV – 100 TeV p and nuclei
  - energy resolution: < 1.5% for 100 GeV e/γ, < 40% for 800 GeV p
  - angular resolution: < 0.2° for 100 GeV γ
  - field of view: ~1 sr
  - effective area (normal incidence): 1200 cm^2 @ 100 GeV

CHINA

- Purple Mountain Observatory, CAS, Nanjing, *PI Prof. Jin Chang*
- Institute of High Energy Physics, CAS, Beijing
- National Space Science Center, CAS, Beijing
- University of Science and Technology of China, Hefei
- Institute of Modern Physics, CAS, Lanzhou

ITALY

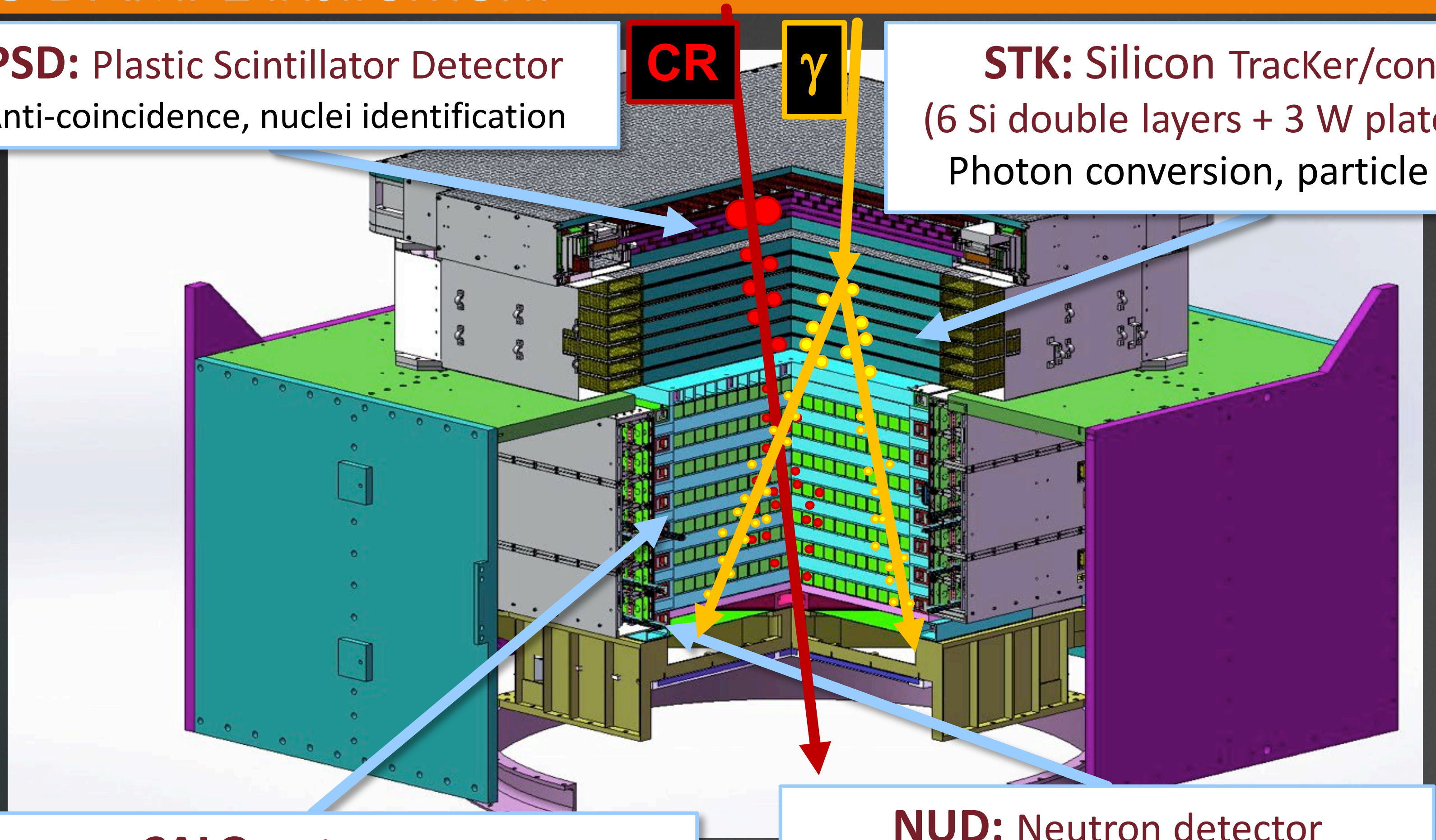
- INFN Perugia and University of Perugia
- INFN Bari and University of Bari
- INFN Lecce and University of Salento
- GSSI Gran Sasso Science Institute and INFN LNGS

SWITZERLAND

- University of Geneva

The DAMPE instrument

PSD: Plastic Scintillator Detector
Anti-coincidence, nuclei identification



STK: Silicon TracKer/converter
(6 Si double layers + 3 W plates 1 mm)
Photon conversion, particle tracking

CALO: Calorimeter
(14x22 hodoscopic BGO bars, 32 r.l.)
Energy deposition and profile, trigger

NUD: Neutron detector
(4 B-doped plastic scintillators)
Neutron showers measurement

DAMPE facts
Mass: 1400 kg
Power consumption: 400 W
Readout channels: > 75k
Data transfer: 16 Gbyte/day
Lifetime: >5 years

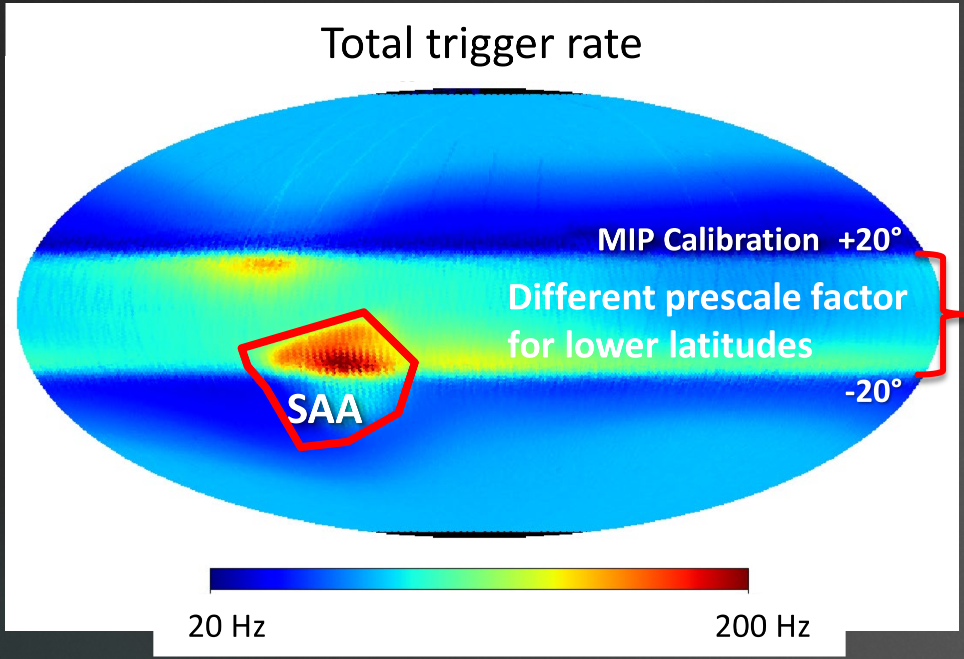
Performance	DAMPE
e/γ Energy resol. @100 GeV (%)	<1.5
e/γ Angular resol. @100 GeV (deg.)	<0.2
e/p discrimination	$>10^5$
Calorimeter thickness (X_0)	32
Geometrical acceptance ($m^2 sr$)	0.3

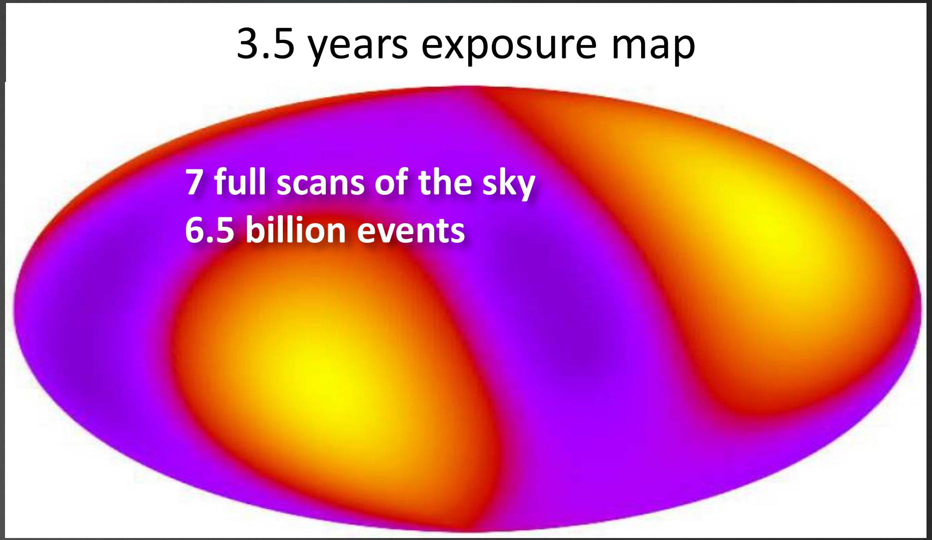
[Astropart. Phys. 95, 6 (2017)]

DAMPE was launched on Dec. 17th 2015

- Launch site: Jiuquan Satellite Launch Center, Gobi desert, China
- Orbit: 500 km altitude, 97° inclination, Sun-synchronous

Trigger rate and data transfer



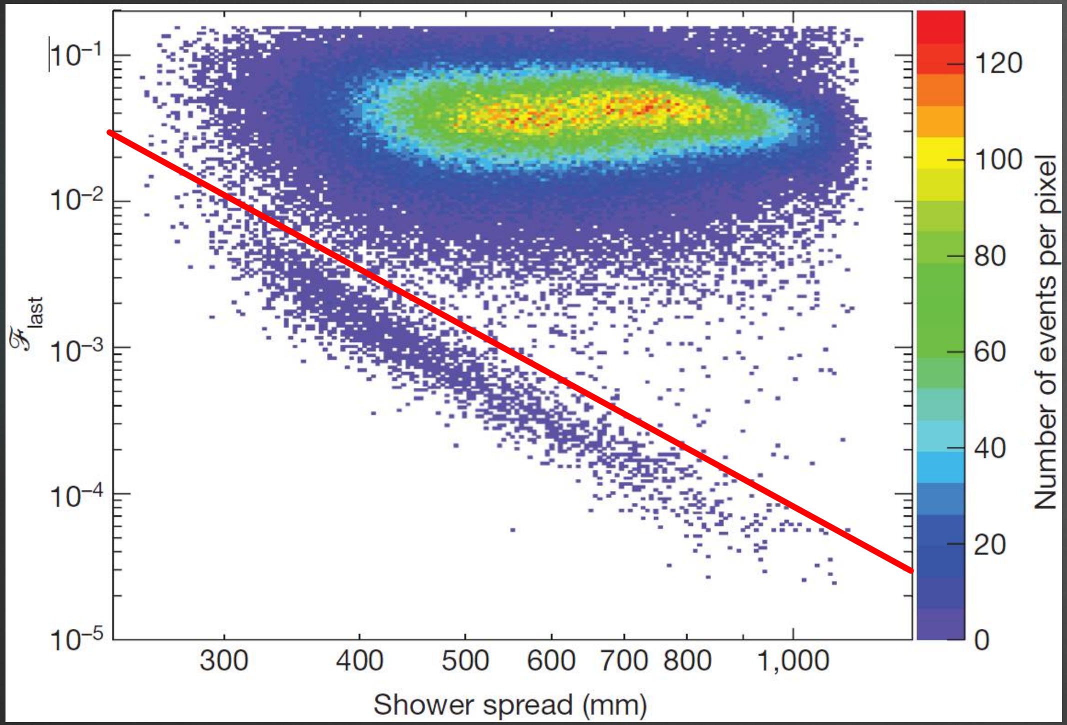


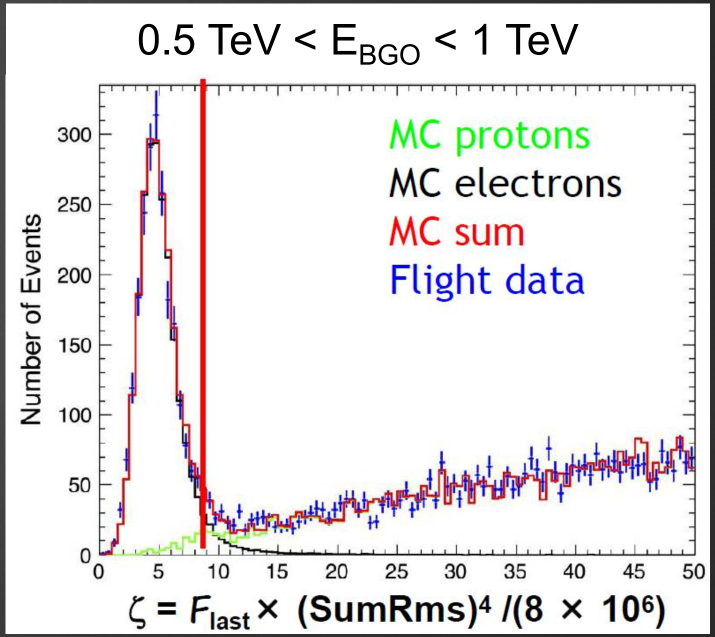
Two full scan of the sky every year

Acquisition rate	up to 200 Hz
High Energy (physics) trigger rate	up to 50 Hz
Raw data plus control data download	15 GB/day
Reconstructed data in ROOT format	85 GB/day
Total data per year	35 TB
Total events at 01/08/2020	>8 billion

Electron/proton separation

- The "ζ shower parameter" was computed from the lateral shower development in BGO and the energy deposition in the last layer
  - the cut $\zeta > 8.5$ was adopted to discriminate e^- (and e^+) from p
  - for 90% $e^\pm$ efficiency, p background ~2% @ 1 TeV, ~5% @ 2 TeV, ~10% @ 5 TeV





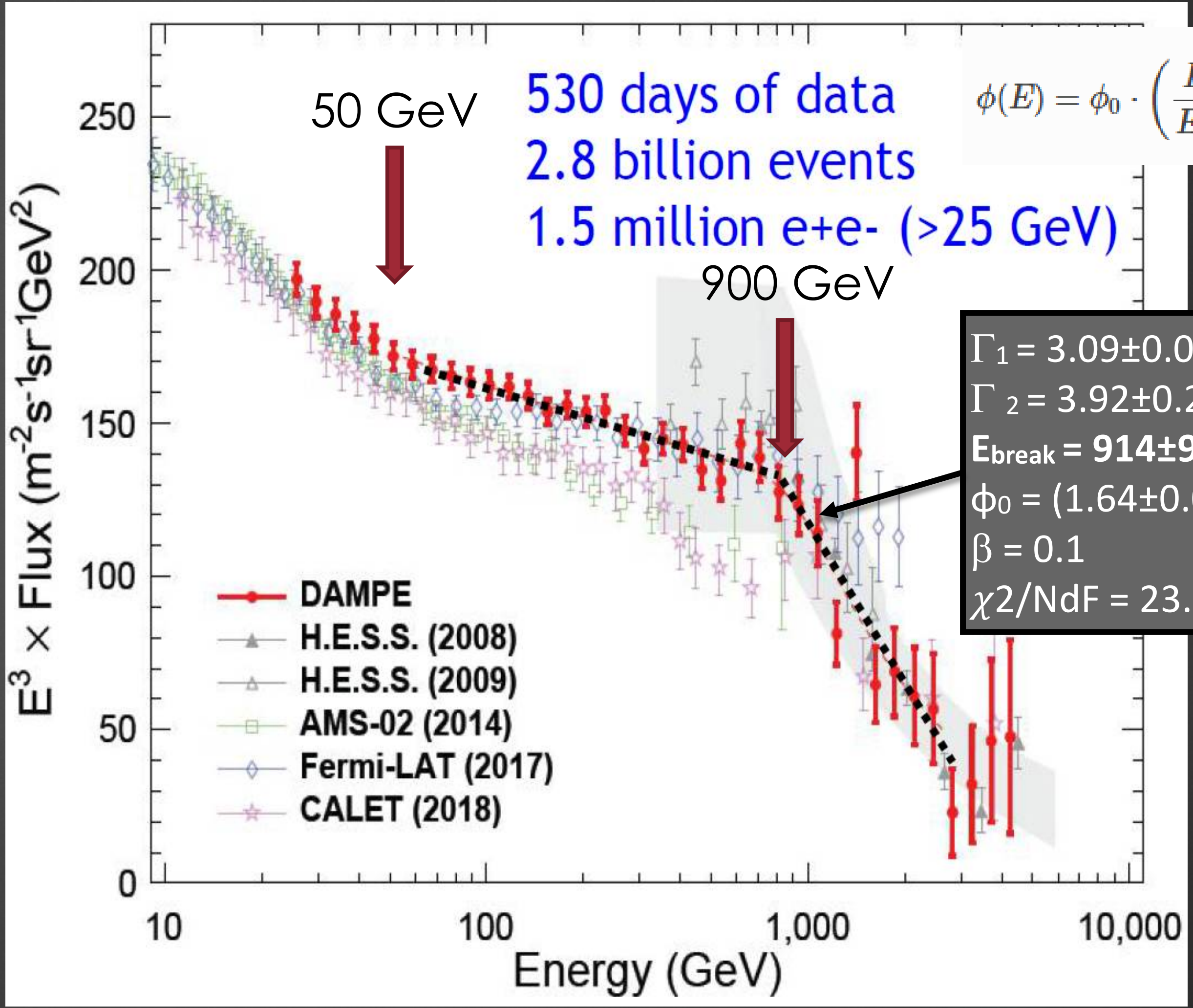
Cosmic-rays electrons and positrons from 20 GeV to ~5 TeV

[Nature 552, 63 (2017)]
+ CALET (2018)

- spectral hardening at 50 GeV
- direct detection of a spectral break at 0.9 TeV (6.6 σ c.l.)
- a smoothly broken power law fits data (γ = 3.1 → 3.9)

Tension in the data from different experiments

CALET data are consistent with a single power law without cutoff - PRL 120 (2018)



$$\phi(E) = \phi_0 \cdot \left(\frac{E}{E_0}\right)^{-\Gamma 1} \left(1 + \frac{E}{E_{break}}\right)^{\frac{\Gamma_2 - \Gamma_1}{\beta} \, -\beta}$$

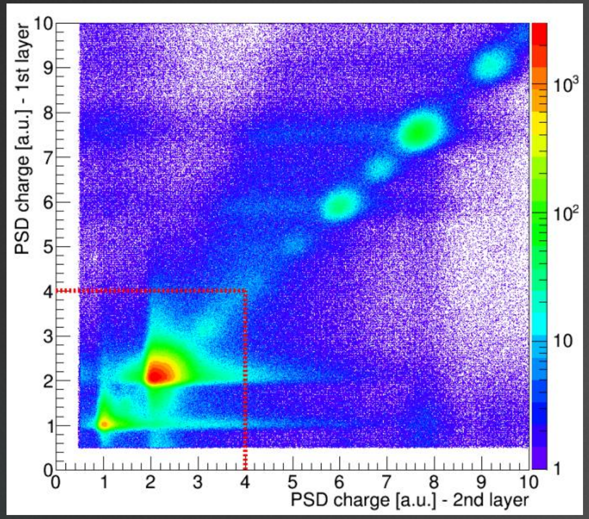
Γ_1 = 3.09±0.01
Γ_2 = 3.92±0.20
E_{break} = 914±98 GeV
ϕ_0 = (1.64±0.01) x 10^{-4} $m^{-2}s^{-1}sr^{-1}GeV^{-1}$
β = 0.1
χ2/NdF = 23.3/18 (6.6σ pref. over PL)

Shaded band shows the systematic uncertainties of the H.E.S.S. measurements

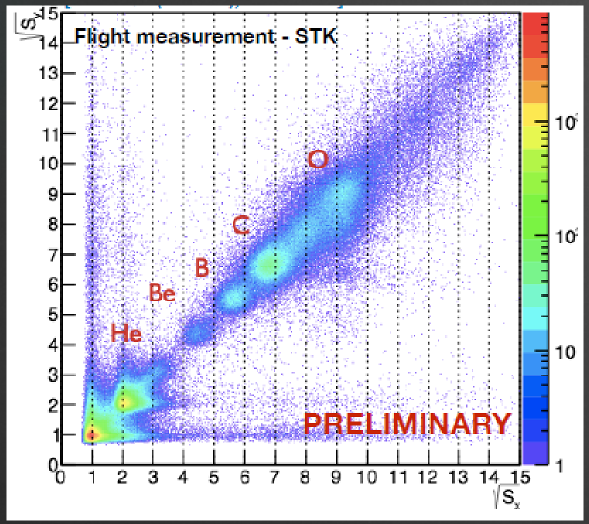
Study of cosmic nuclei charge

- Identifying protons and nuclei with PSD and STK
  - charge resolution: 0.1e for protons, 0.2e for CNO, 0.3e for Fe

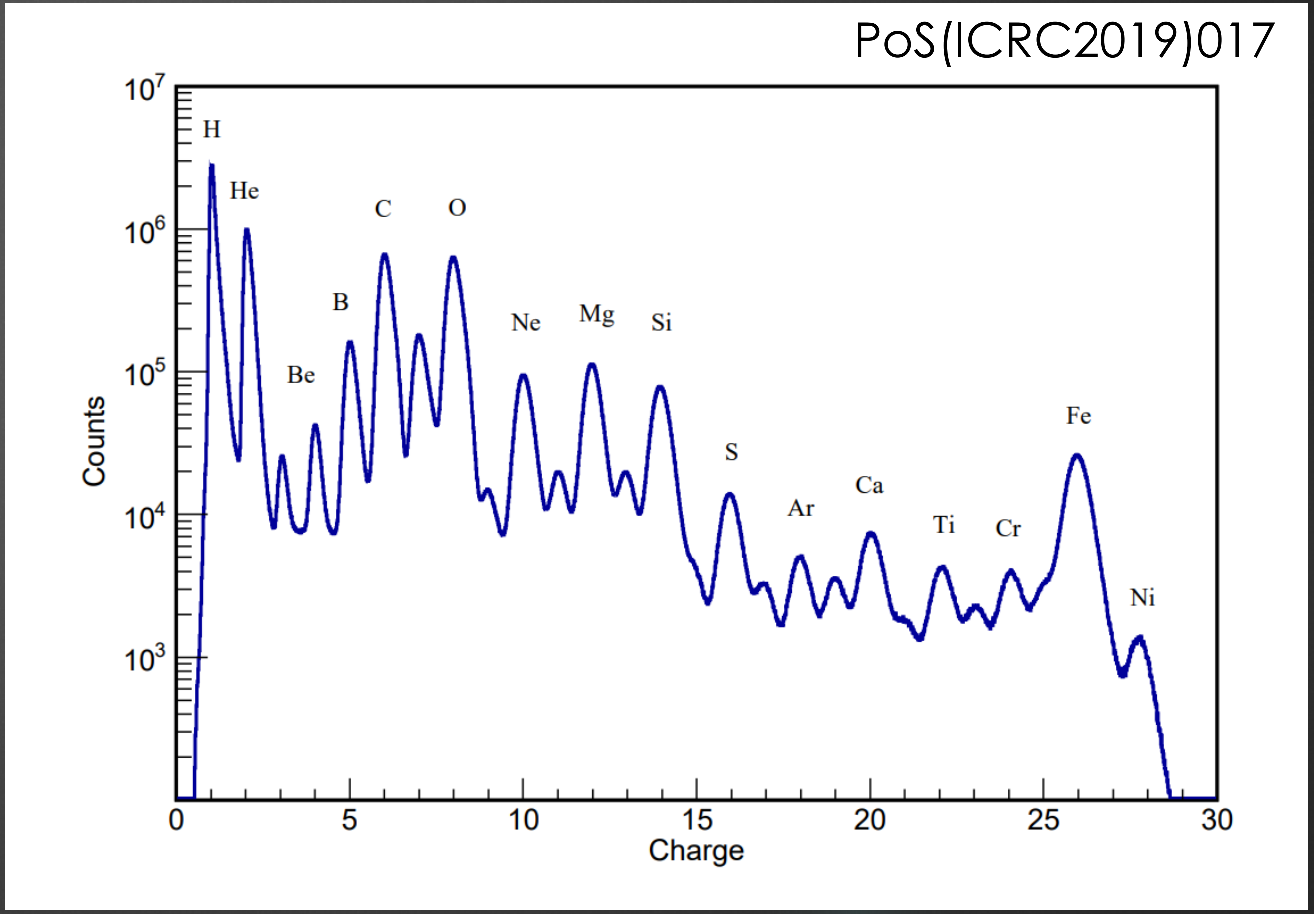
PSD



STK



Charge spectrum of cosmic nuclei
(2yr data)

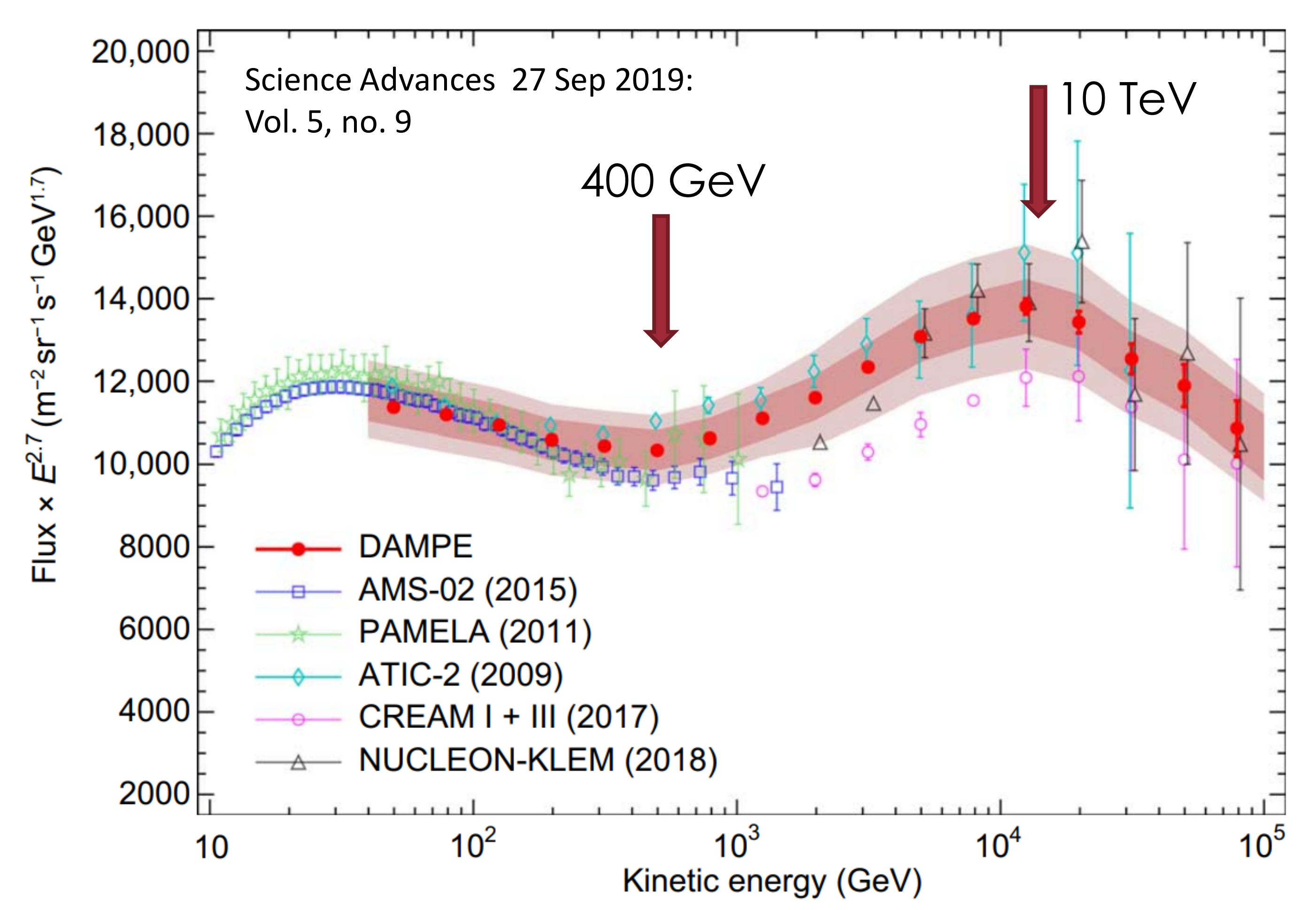


Cosmic ray protons flux

Protons flux

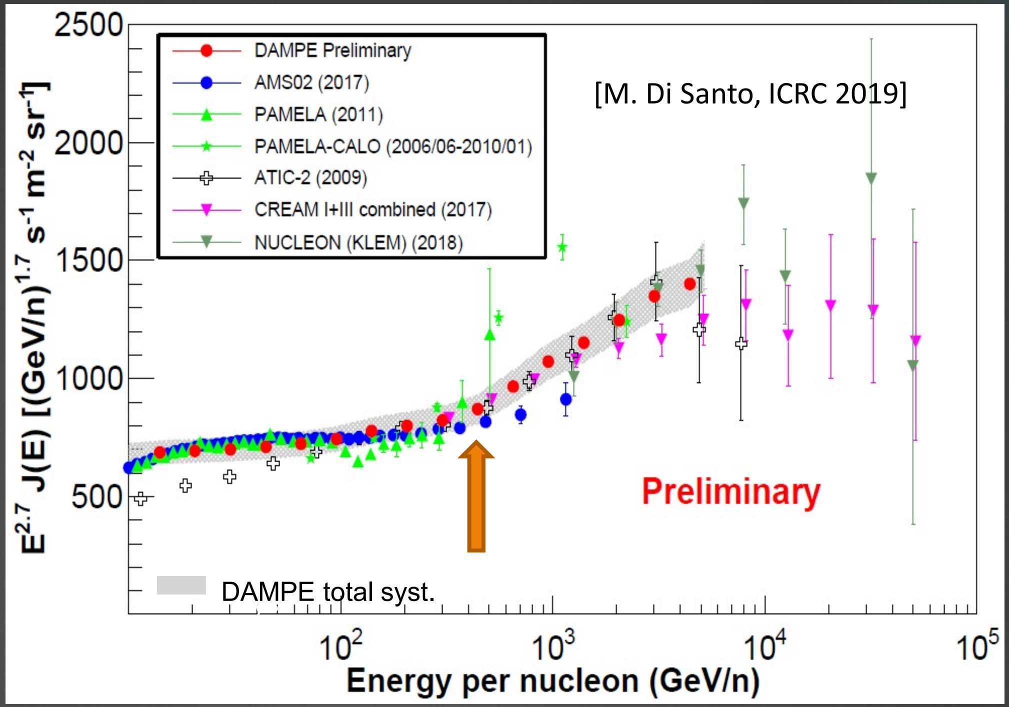
- from 40 GeV to 100 TeV
- 30 months of data (01/01/2016 – 30/06/2018)
- 4.68 billion events
- spectral hardening at ~**400 GeV**
- softening at ~**10 TeV**
- fitting with a smoothly broken power-law: $\gamma = 2.60 \rightarrow 2.85$ at **13.6 TeV**

The CALET collaboration reported new measurements of the proton spectrum from 50 GeV to 10 TeV and confirmed the spectral hardening feature



The red error bars show the statistical uncertainties, the inner shaded band shows the estimated systematic uncertainties due to the analysis procedure, and the outer band shows the total systematic uncertainties including also those from the hadronic models.

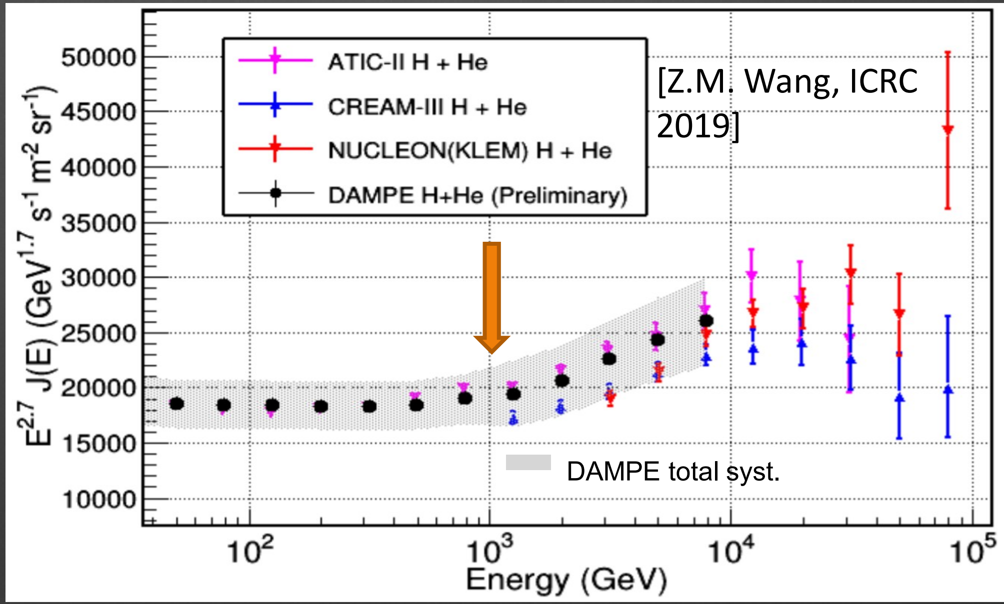
- **Helium flux**
  - from 10 GeV/n to ~5 TeV/n
  - spectral hardening at ~**400 GeV/n**
  - analysis ongoing at higher energies



39 months of data (01/01/2016 – 31/03/2019)

38 million events

- **p+He flux**
  - from 50 GeV to ~7 TeV
  - spectral hardening below ~**1 TeV/n**
  - analysis ongoing up to 100 TeV, new results expected



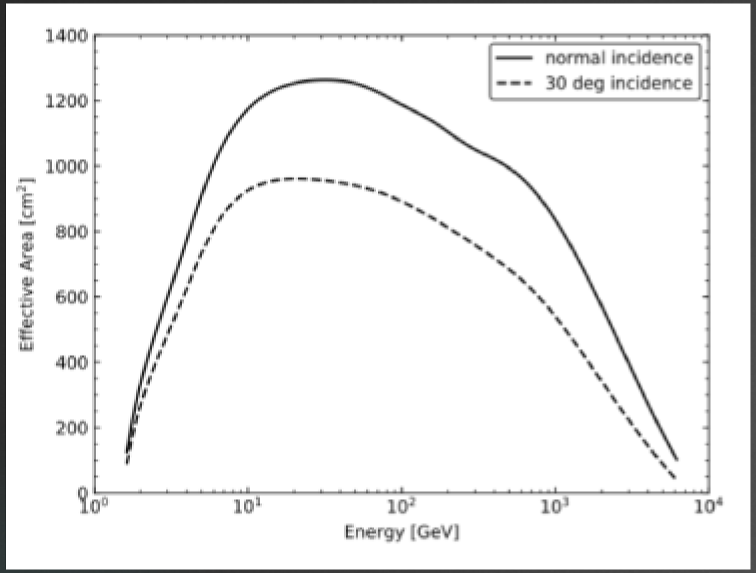
Focused talk @ SIF2020

Study of the cosmic B, C, N and O nuclei with the DAMPE space mission
Dimitrios Kyratzis

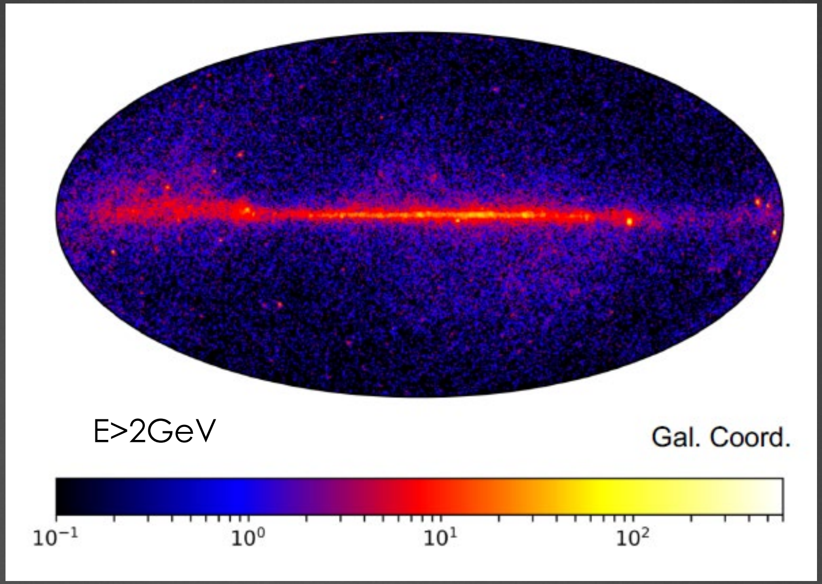
Measuring light elements in space with the DAMPE mission
Francesca Alemanno

Gamma-ray studies

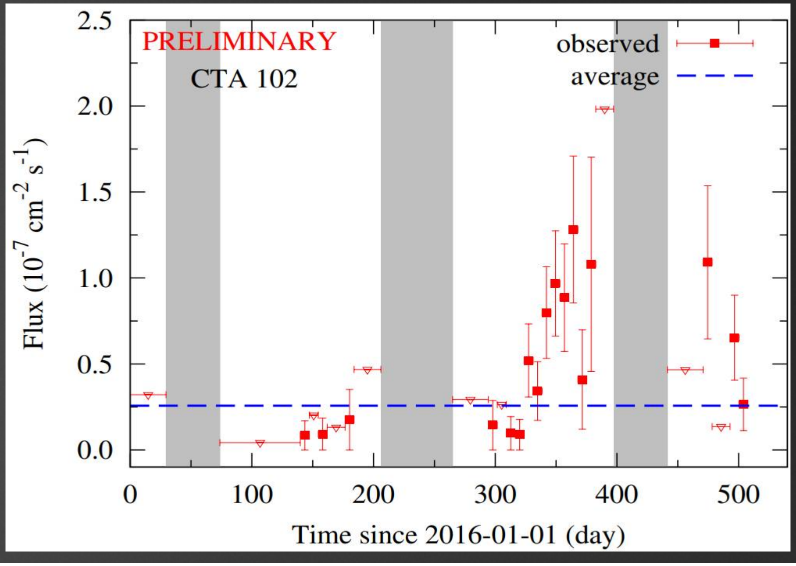
Effective area



6 full sky scan – Count map



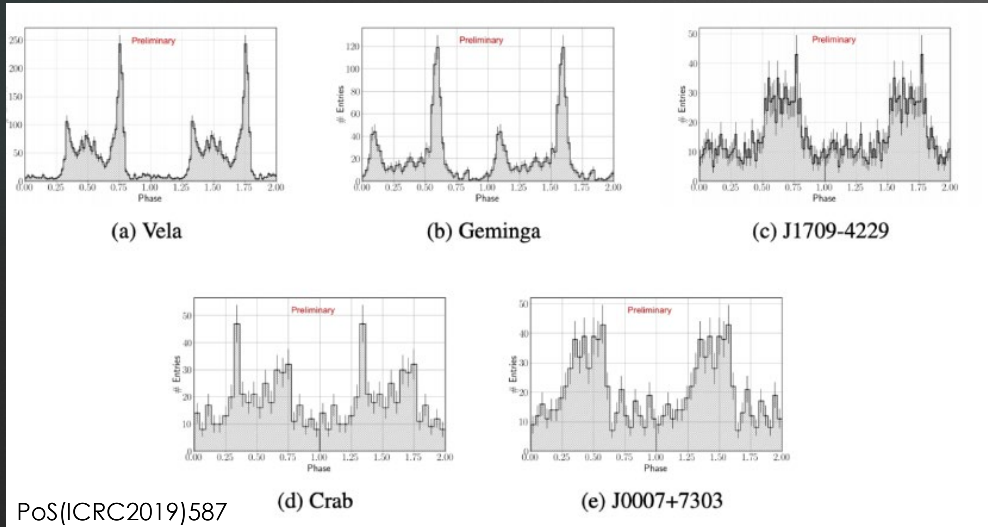
Blazar flare detection



DAMPE detection of variable GeV gamma-ray emission from blazar CTA 102

ATel #9901; *Zun-Lei Xu (PMO), Micaela Caragiulo (Bari), Jin Chang (PMO), Kai-Kai Duan (PMO), Yi-Zhong Fan (PMO), Fabio Gargano (Bari), Shi-Jun Lei (PMO), Xiang Li (PMO), Yun-Feng Liang (PMO), M. Nicola Mazziotta (Bari), Zhao-Qiang Shen (PMO), Meng Su (HKU/PMO), Andrii Tykhonov (Geneva), Qiang Yuan (PMO), Stephan Zimmer (Geneva), on behalf of the DAMPE collaboration, and Bin Li (PMO) and Hai-Bin Zhao (PMO) on behalf of the CNEOST group.*
on ***27 Dec 2016; 01:02 UT***
Credential Certification: Zun-Lei Xu (xuzl@pmo.ac.cn)

5 bright pulsars seen by DAMPE



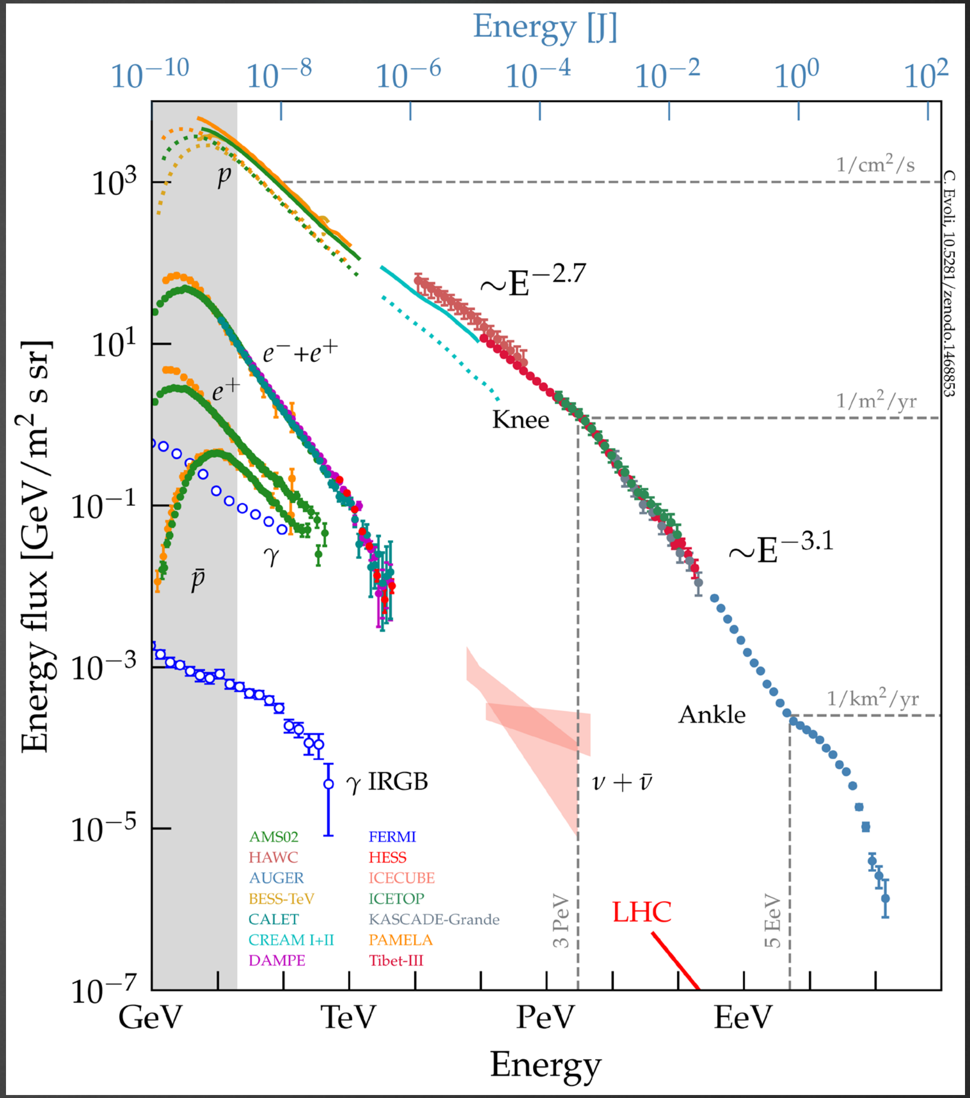
PoS(ICRC2019)587

DAMPE summary Towards the future

- DAMPE is working extremely well since ~5 years
- $e^{-}+e^{+}$ spectrum precisely measured up to TeV energies
  - a clear spectral break has been directly measured at ~1 TeV
- Proton spectrum measured
  - hardening at ~400 GeV, softening at ~10 TeV
- Helium spectrum measured
  - hardening at ~400 GeV/n
- Protons + Helium nuclei spectrum measured
- Heavier nuclei, chemical composition, etc. measurements ongoing

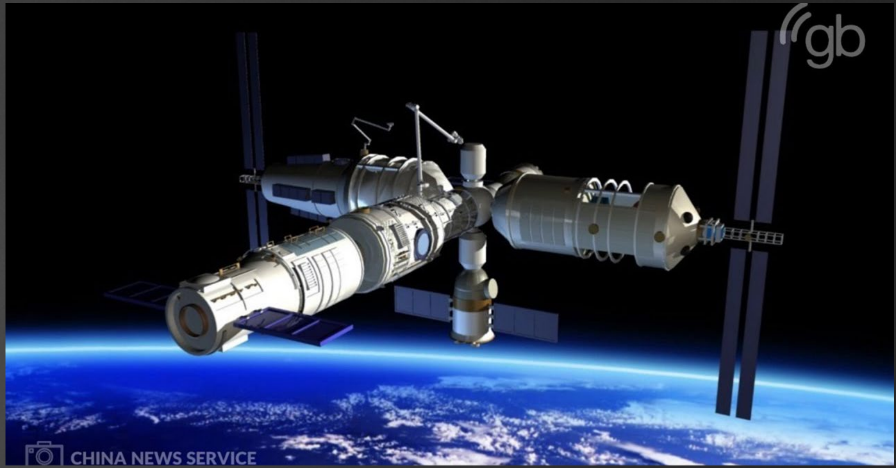
Towards the future

- A new space borne detector is needed in the next years to extend the measurements up to the PeV energy for charged particles in order to confirm (or not) the actual measurements from DAMPE, CALET, NUCLEON, (ISS) CREAM and to give an answer to still open questions in astroparticle physics
- This detector should have the capability to make direct measurement up to the knee of the cosmic rays spectrum
- This detector could be also very useful in gamma astrophysics since it can work togheter with ground-based Cherenkov detectors (MAGIC, HESS, CTA) with a good energy overlap



The **High Energy cosmic-Radiation Detection** (HERD) facility is a China-led international space mission that will start operation around 2026.

The experiment is based on a **3D, homogeneous, isotropic and finely-segmented calorimeter** that fulfills the following requirements and goals



Main requirements

	γ	e	p, nuclei
Energy Range	0.5 GeV 100 TeV	10 GeV 100 TeV	30 GeV 3 PeV
Energy resolution	1% @ 200 GeV	1% @ 200 GeV	20% @ 100 GeV -1 PeV
Effective Geometric Factor	>1 m^2sr @ 200 GeV	>3 m^2sr @ 200 GeV	>2 m^2sr @ 100 TeV

Main Scientific goals
Direct measurement of cosmic rays flux and composition up to the knee region
Gamma-ray monitoring and full sky survey
Indirect dark matter search (e^++e^-, γ,...)

HERD-COLLABORATION

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)
Academia Sinica

ITALY

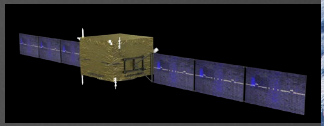
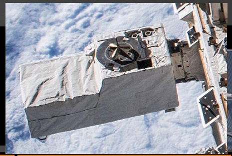
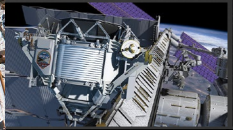
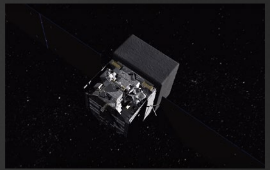
INFN Bari and Bari University
INFN Firenze and Firenze University
INFN Pavia and Pavia University
INFN Perugia and Perugia University
INFN Pisa and Pisa University
INFN Laboratori Nazionali del Gran Sasso and GSSI Gran Sasso Science Institute
INFN Lecce and Napoli University
INFN Napoli and Salento University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

SPAIN

CIEMAT - Madrid
ICCUB – Barcellona
IFAE – Barcellona

SWITZERLAND

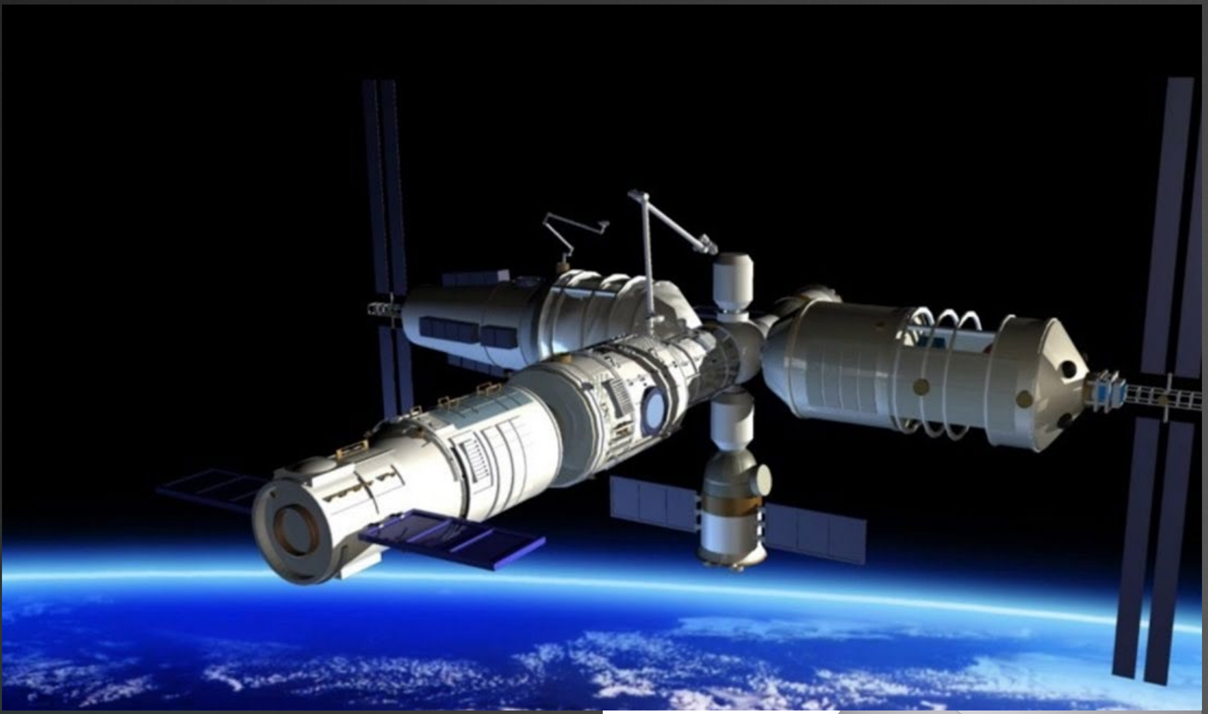
University of Geneva

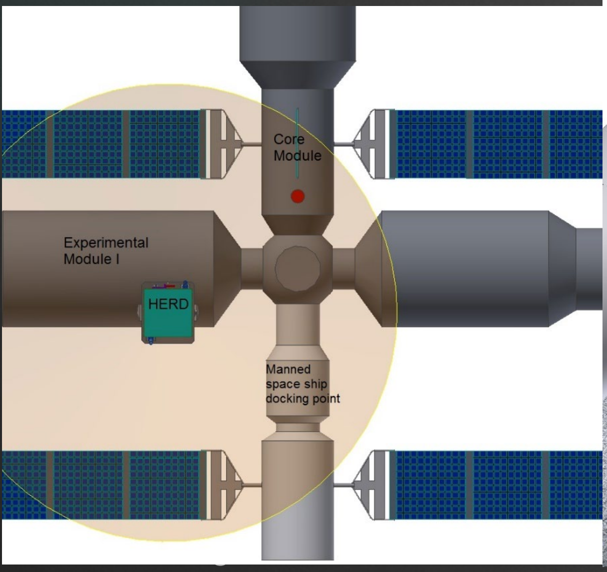





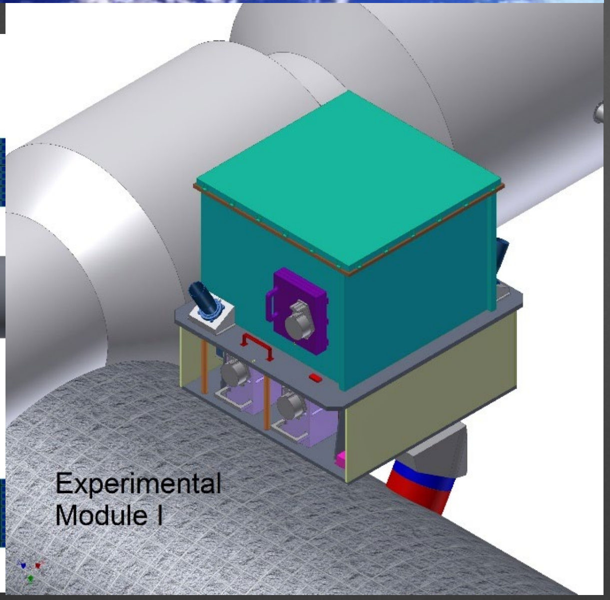
	HERD	DAMPE	CALET	AMS-02	Fermi LAT
e/γ Energy res.@100 GeV (%)	<1	<1.5	2	3	10
e/γ Angular res.@100 GeV (deg.)	< 0.1	<0.2	0.2	0.3	0.1
e/p discrimination	$>10^6$	$>10^5$	10^5	$10^5 - 10^6$	10^3
Calorimeter thickness (X_0)	55	32	27	17	8.6
Geometrical accep. (m^2sr)	>3	0.3	0.12	0.09*	1

*After analysis cuts for electrons

HERD on board CSS







CSS expected to be completed in 2025

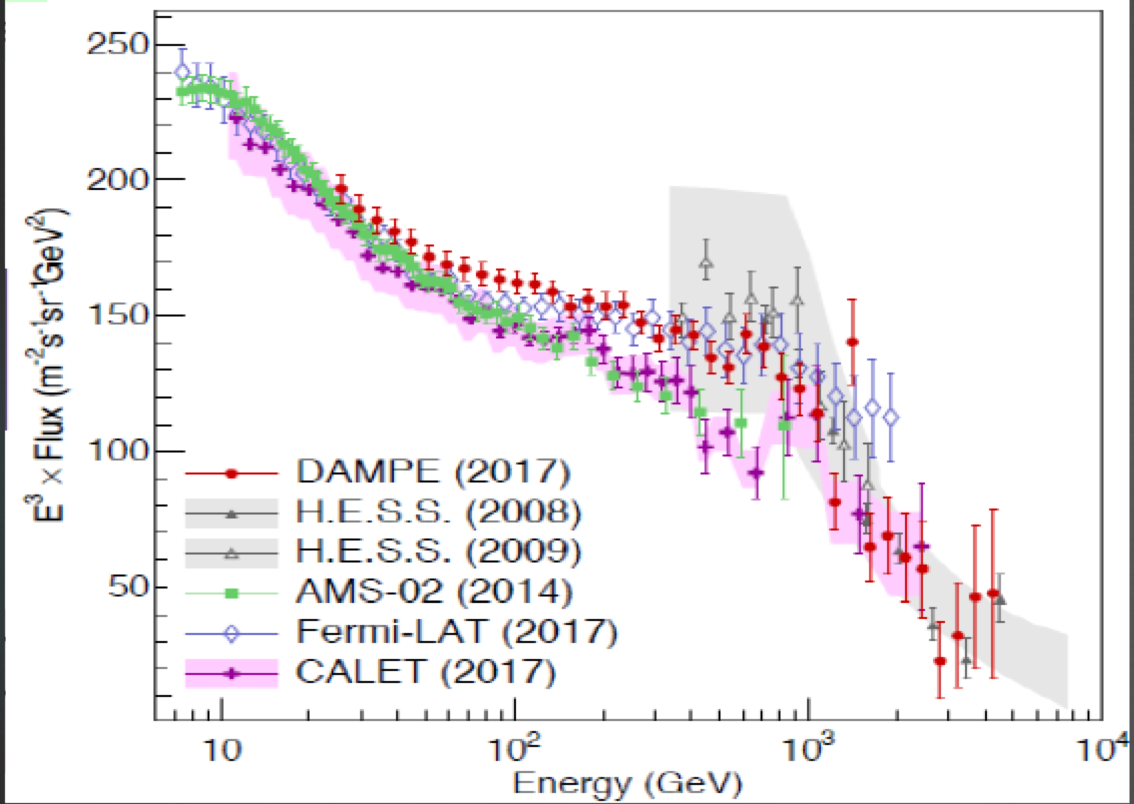
Life time	> 10y
Orbit	Circular LEO
Altitude	340-450 km
Inclination	42°

HERD expected to be installed around 2026

Life time	> 10y
FOV	+/- 70°
Power	< 1.5 kW
Mass	< 4 t

Electrons and Positrons (Fermi-LAT, DAMPE and CALET)

Recent calorimetric measurement of the $e^{+}+e^{-}$ flux (Fermi-LAT, CALET, DAMPE) lead to **very different results** and **no clear conclusion**

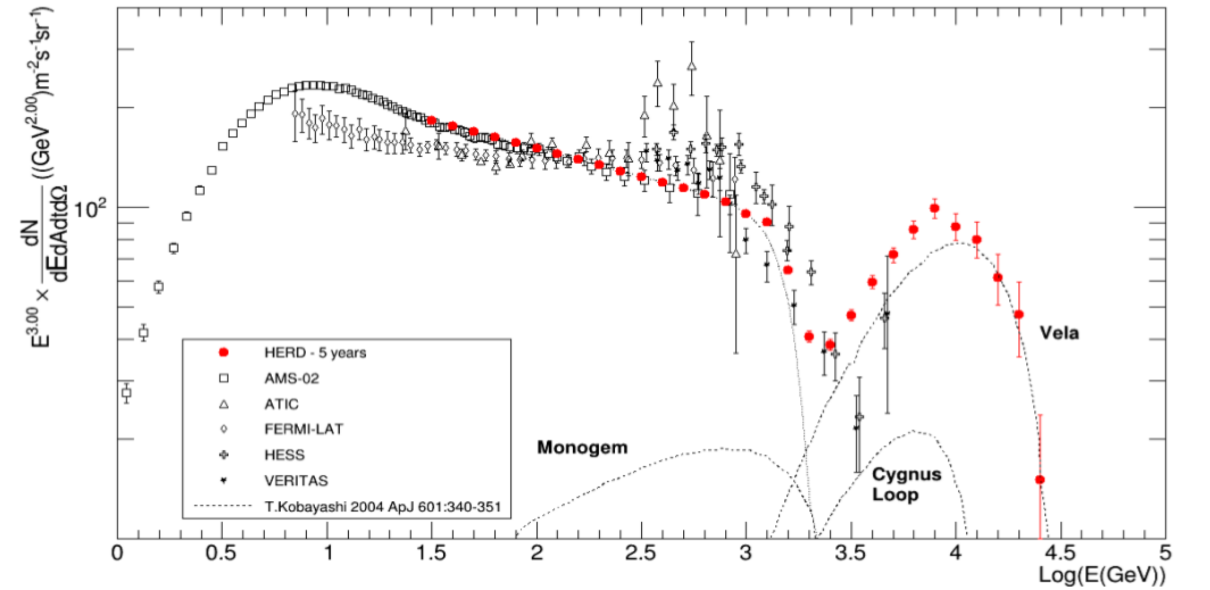


DAMPE data shows a cutoff at 1 TeV and a "sharp peak" at 1.4 TeV – NATURE 552 (2017)
CALET data are consistent with a single power law without cutoff - PRL 120 (2018)

HERD could help in resolving the "conflict" between different measurements:
improving the precision of the measurement
extending the measurement to higher energy

Electrons and Positrons (**HERD**)

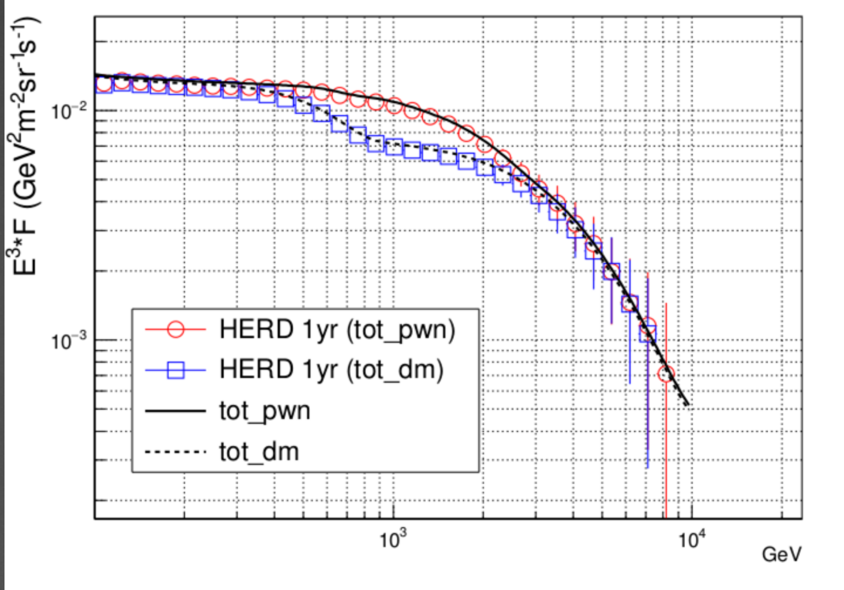
Expected $e^{+}+e^{-}$ flux in 5 years



HERD will measure the flux up to several tens of TeV in order to detect:
spectral cutoff at high energy
local SNR sources of very high energy e^{-}

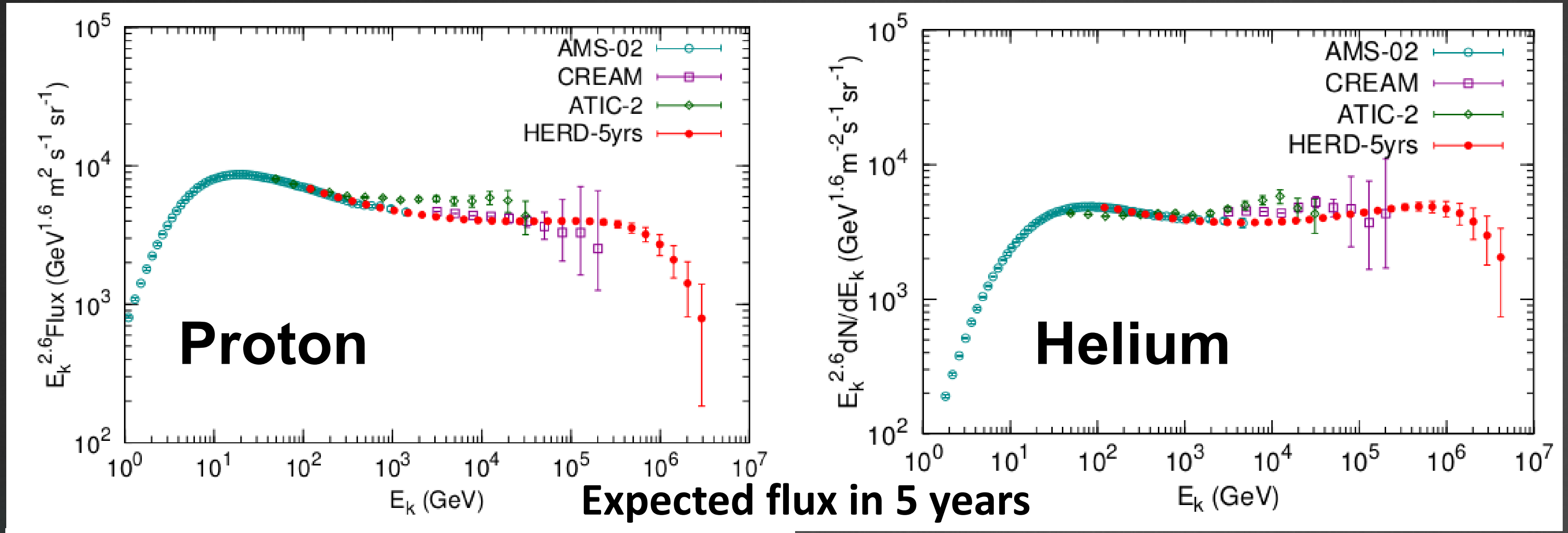
... and additional information from anisotropy measurement!

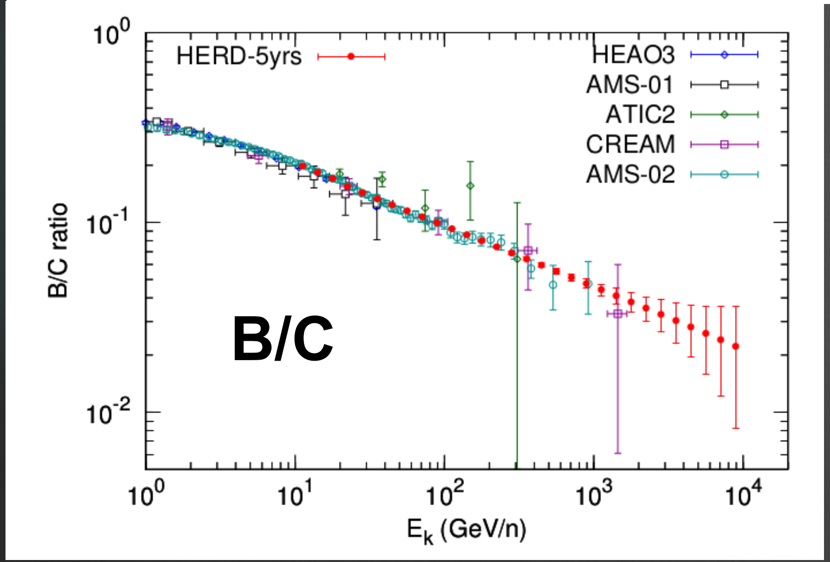
Expected $e^{+}+e^{-}$ flux in 1 year with PWN or DM sources



In case of additional PWN or DM production, **HERD** will give important indications on the two hypothesis thanks to precise measurement of the different spectral shape

Protons and Nuclei (**HERD**)





HERD will measure the flux of nuclei:

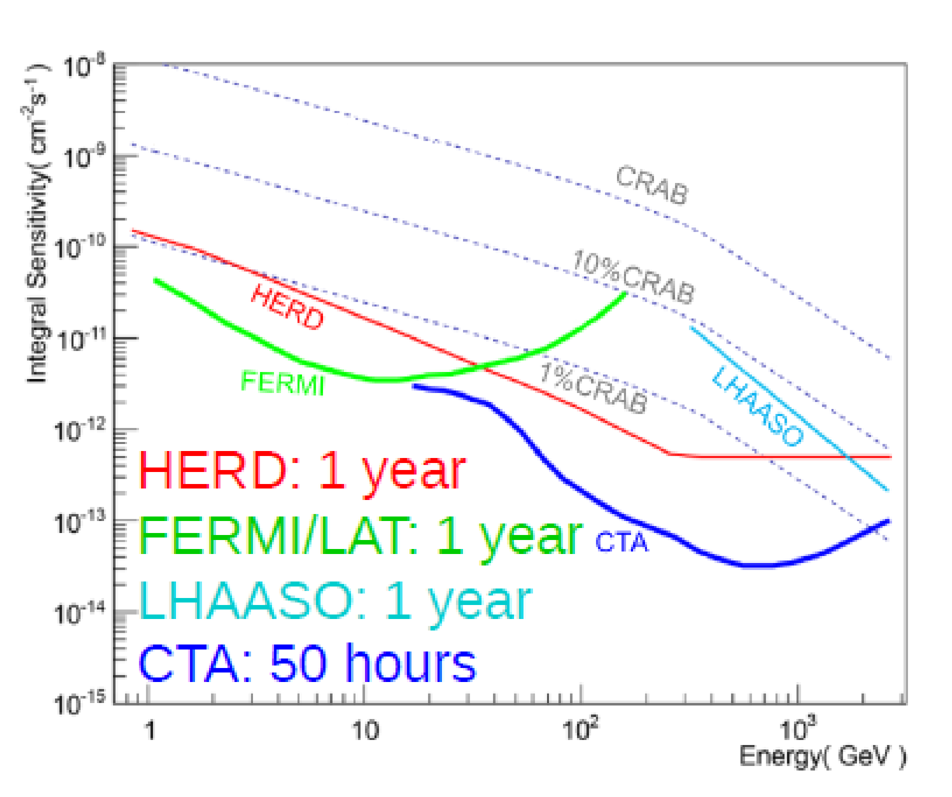
- p and He up to a few PeV
- nuclei up to a few hundreds of TeV/n

First direct measurement of p and He knees will provide a strong evidence for the knee structure as due to acceleration limit

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

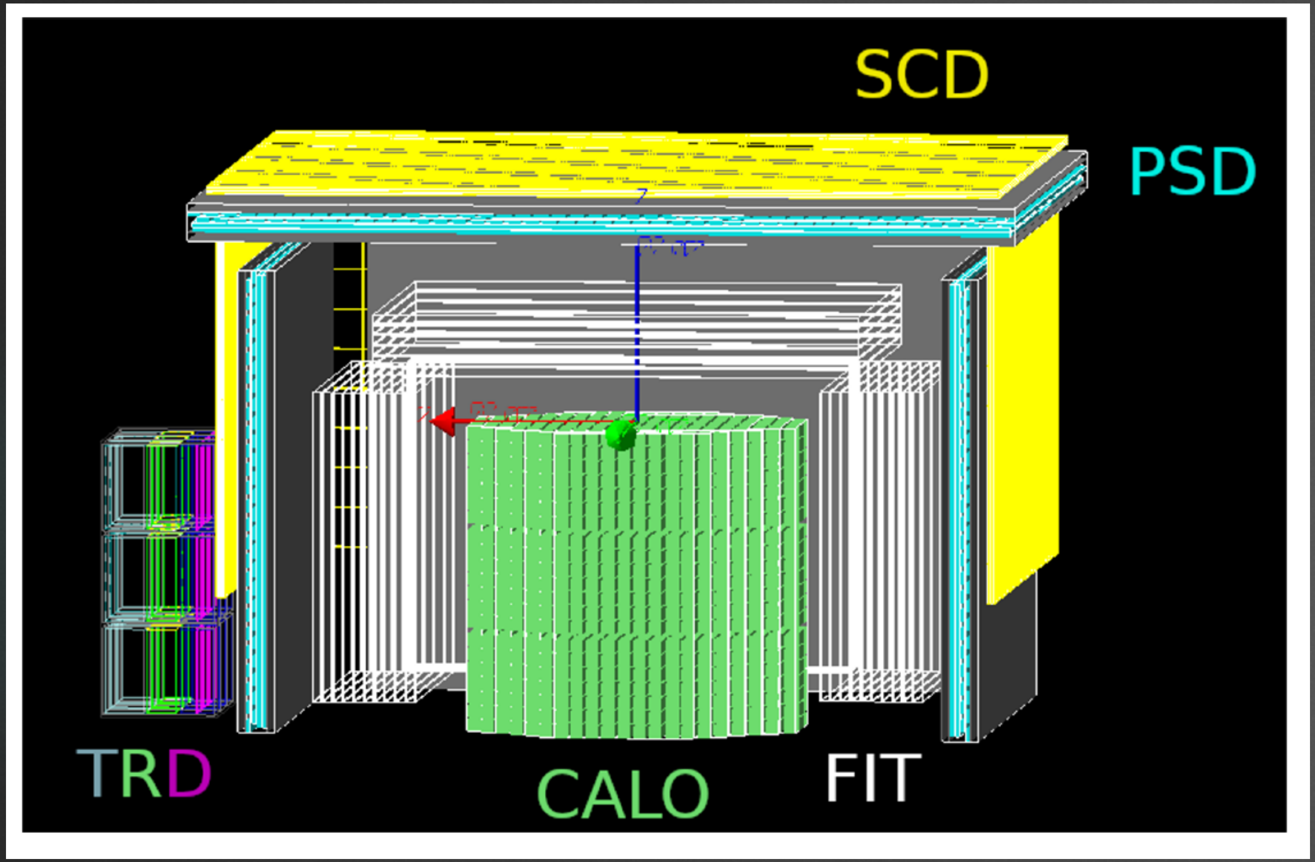
Gamma ray sky-survey (**HERD**)

Sky survey 5σ sensitivity



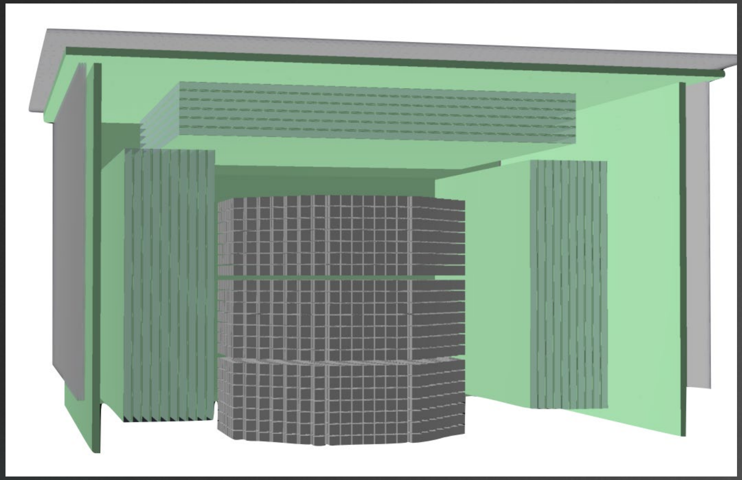
Multi-messenger astronomy
Possible synergy with other experiments designed for γ (CTA), ν (KM3, IceCube), GW (Ligo, Virgo)

- Thanks to its large acceptance and sensitivity, **HERD** will be able to:
  - improve Fermi-LAT measurements between 10 and 100 GeV
  - extend Fermi-LAT catalog to higher energy (between 0.1 and 100 TeV)
  - increase the chances to detect rare γ events
- **Targets of Gamma-Ray Sky Survey**:
  - search for dark matter signatures
  - study of galactic and extragalactic γ sources
  - study of galactic and extragalactic γ diffuse emission
  - detection of high energy γ Burst



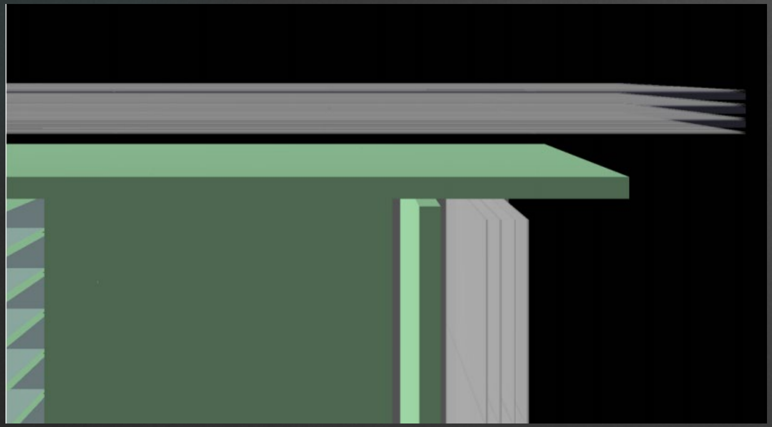
SCD	Charge Reconstruction
PSD	Charge Reconstruction γ Identification
FIT	Trajectory Reconstruction Charge Identification
CALO	Energy Reconstruction e/p Discrimination
TRD	Calibration of CALO response for TeV proton

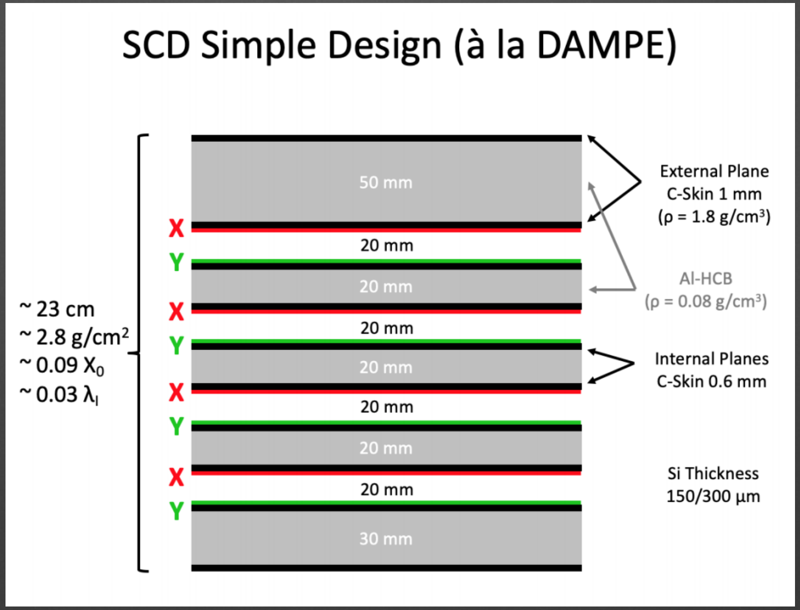
HERD Silicon Charge Detector (SCD)

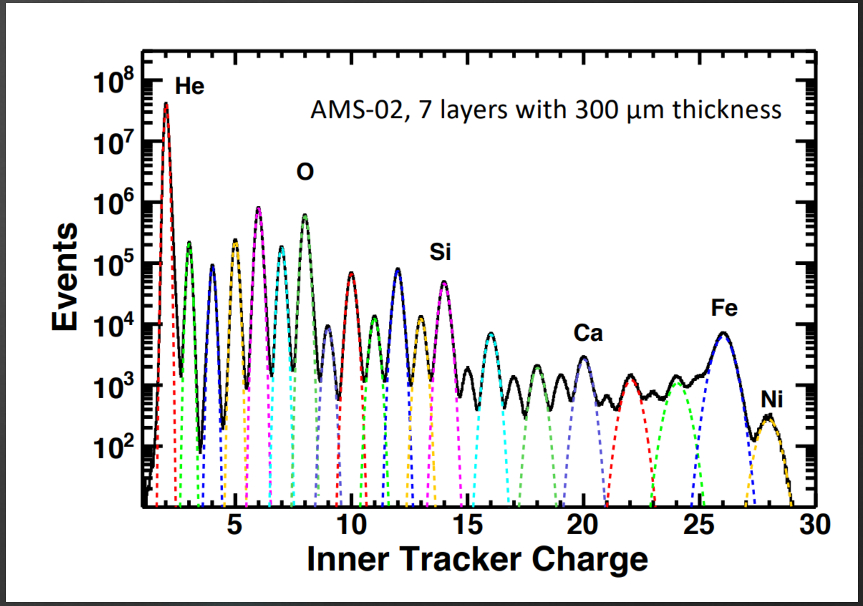


SCD is the outermost detector to identify the ions with high accuracy

9.5cm x 9.5cm x 150um silicon wafers
8 single sided top layers - 1.92m x 1.92m
8 single sided side layers - 1.72m x 0.86m
Carbon fiber support structures



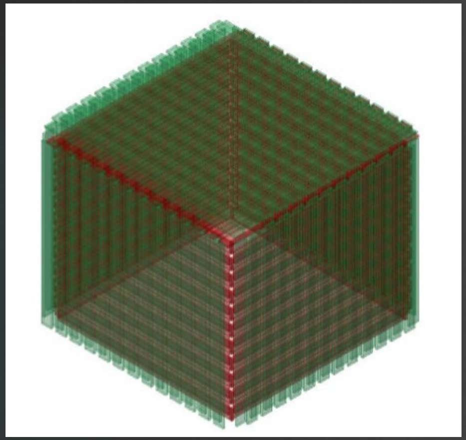


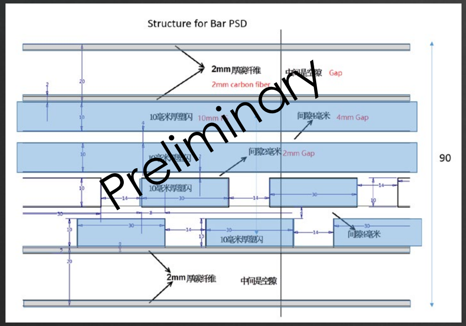


HERD Plastic Scintillator Detector (PSD)

- PSD provide γ **identification** (VETO of charged particles) and **nuclei identification** (energy loss $\propto Z^2$)
- PSD needs to have a very high efficiency in charged particles detection (>99,98%) to be used as veto, but also a very high dynamic range to identify nuclei at least up to iron
- Back-scattering can greatly degrade the PID performances

Two layout configuration are under investigation:



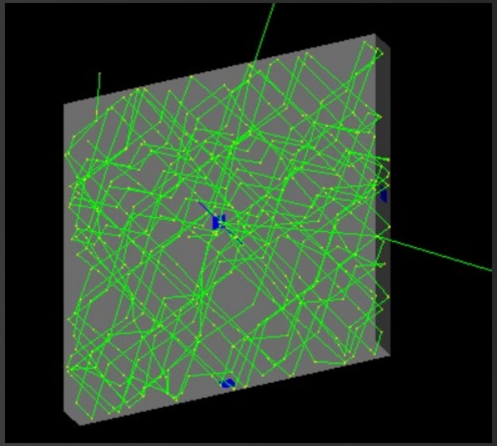


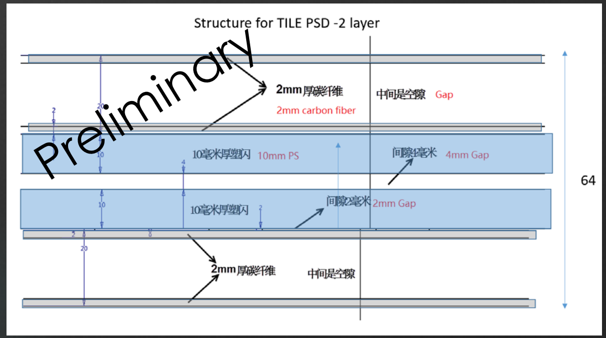
Bar - option

- Long bars 160x3x1 cm^3
- Each layer made by two staggered sub layer to increase hermeticity
- Read-out with 4 SiPM (two for each end)
- PRO
  - Less number of readout channel
- CONS
  - Higher Back-scattering problem

Tile - option

- Small square tile 10x10x1 cm^3
- Two layer of tiles to increase nuclei identification power
- Each tile is readout by 6 SiPM (three on two sides)
- PRO
  - Reduce back-scattering problem
- CONS
  - Higher number of readout channel

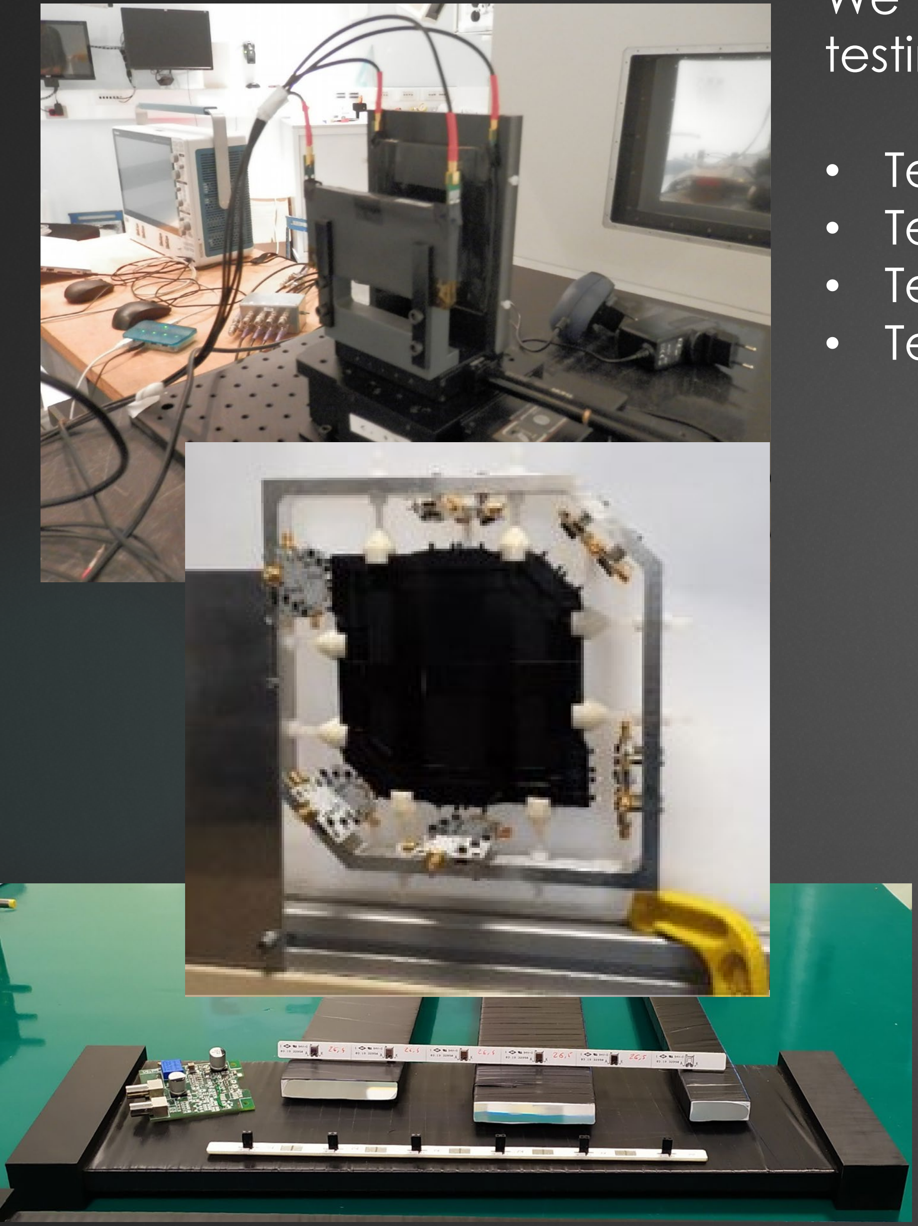


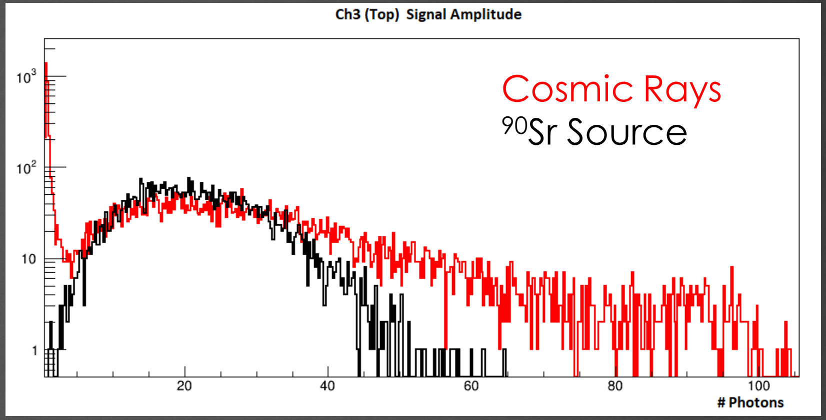


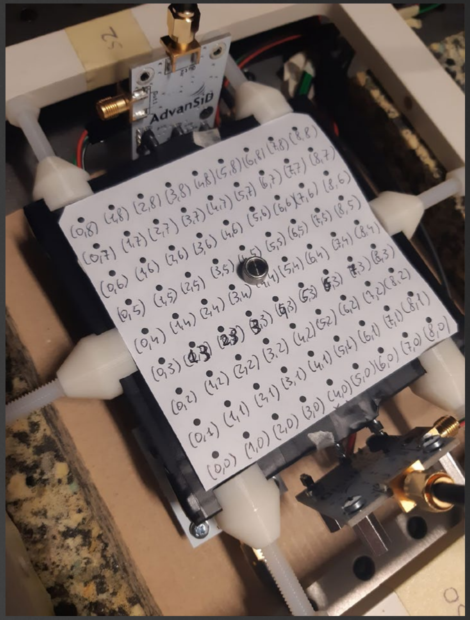
HERD Plastic Scintillator Detector (PSD)

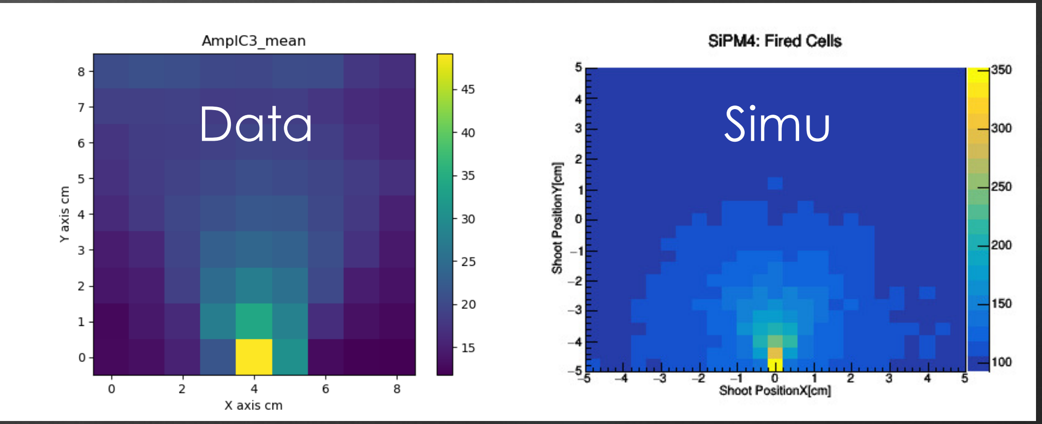
We have built different tile and bar prototypes and we are testing them in different configurations:

- Test with protons and ions @ CERN (2018-2019)
- Test with CR in labs
- Test with radioactive sources in labs
- Test with ions @ CNAO (PV)

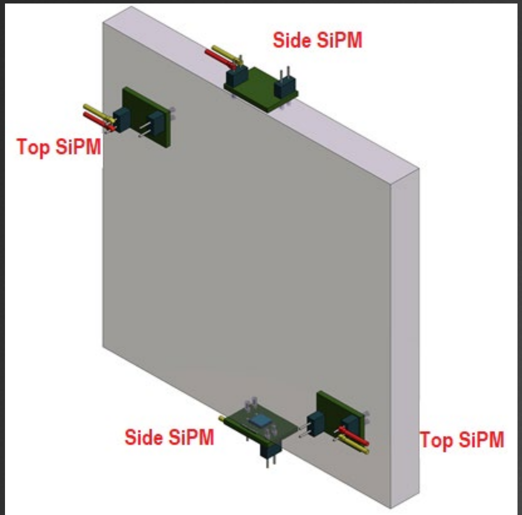




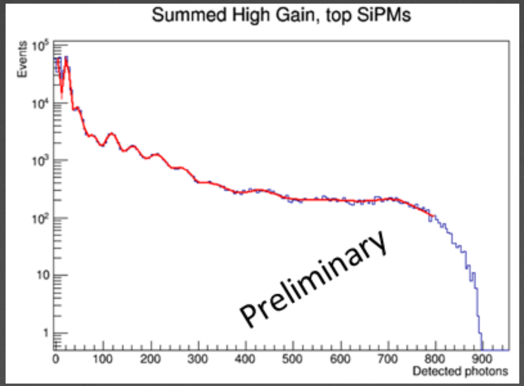


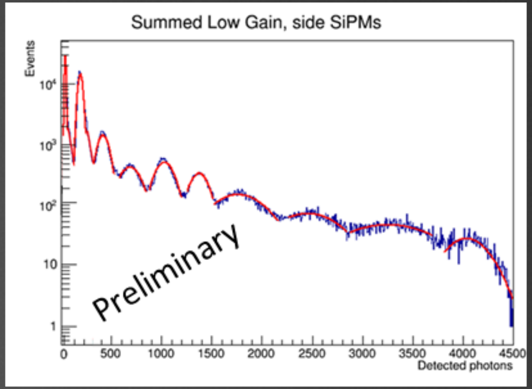


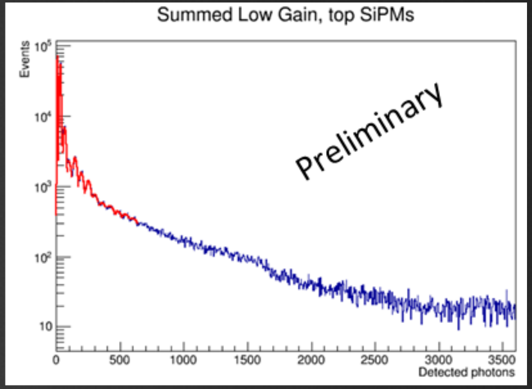
CERN beam test (2018-2019)

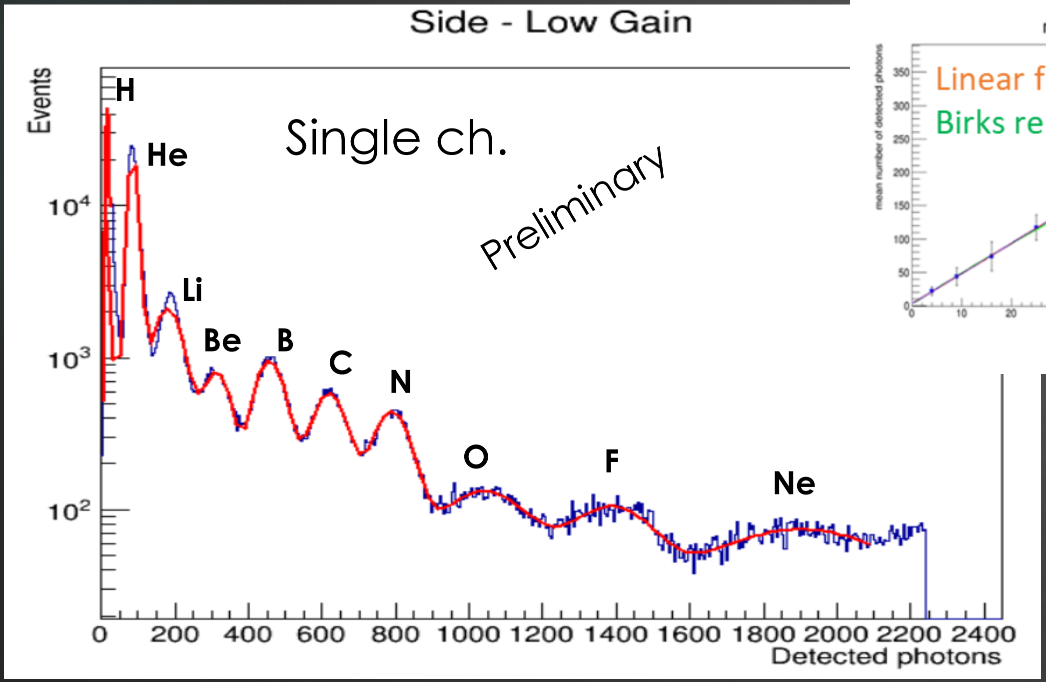


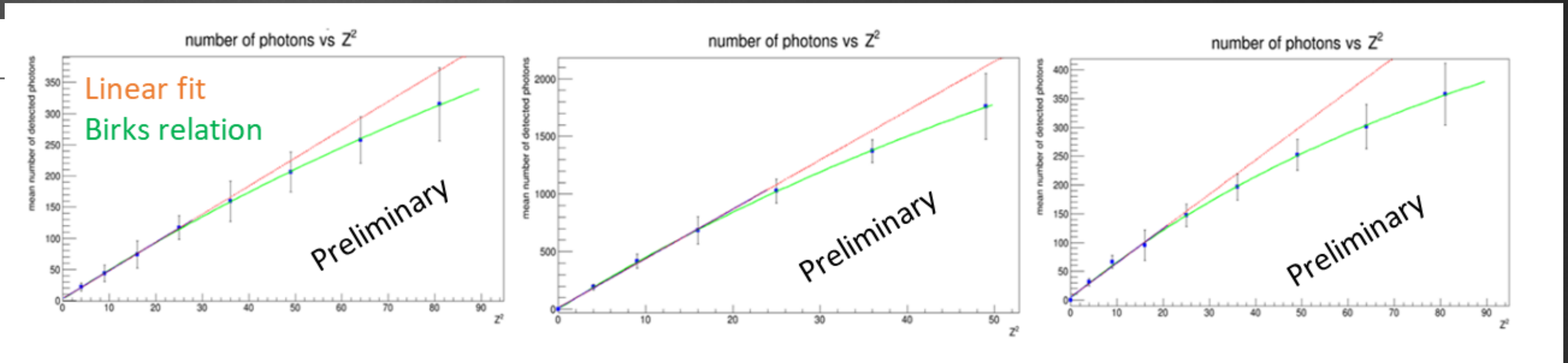
Improvement achieved if we sum together the signals from SiPMs







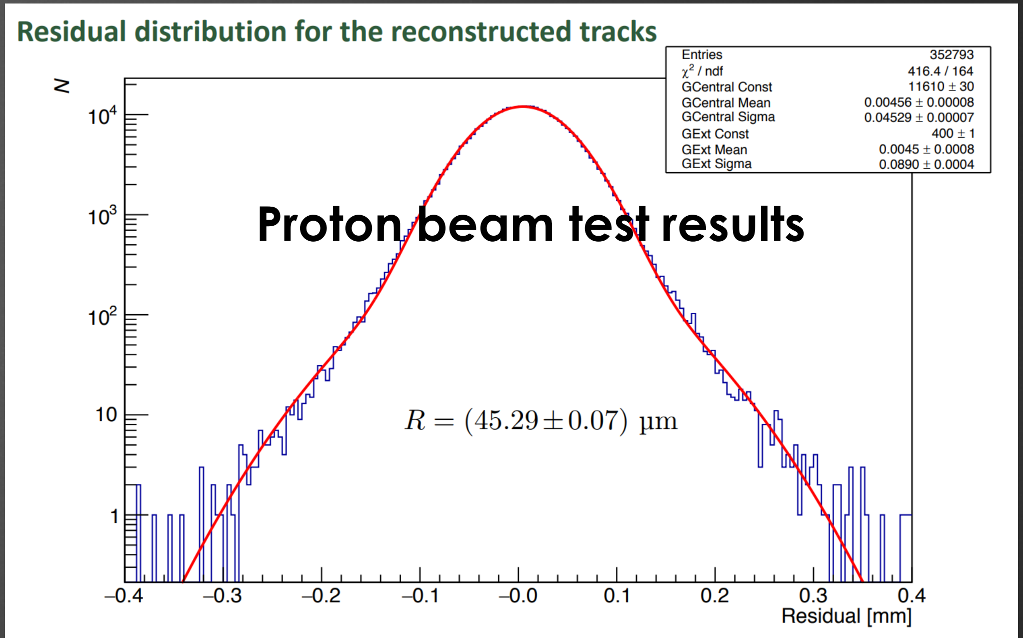




SIF2020
Characterization of plastic scintillator Detector prototypes for the HERD experiment
Davide Serini

HERD Fiber TracKer (FIT)

- 4 identical side sectors + 1 top sector
- 9 x-y planes in each side sector
- 5 x-y planes in the top sector
- 6 x modules (106 cm fiber length) in each x plane
- 10 y modules (77 cm fiber length) in each y plane
- 1 fiber mat + 3 silicon photomultiplier (SiPM) arrays



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

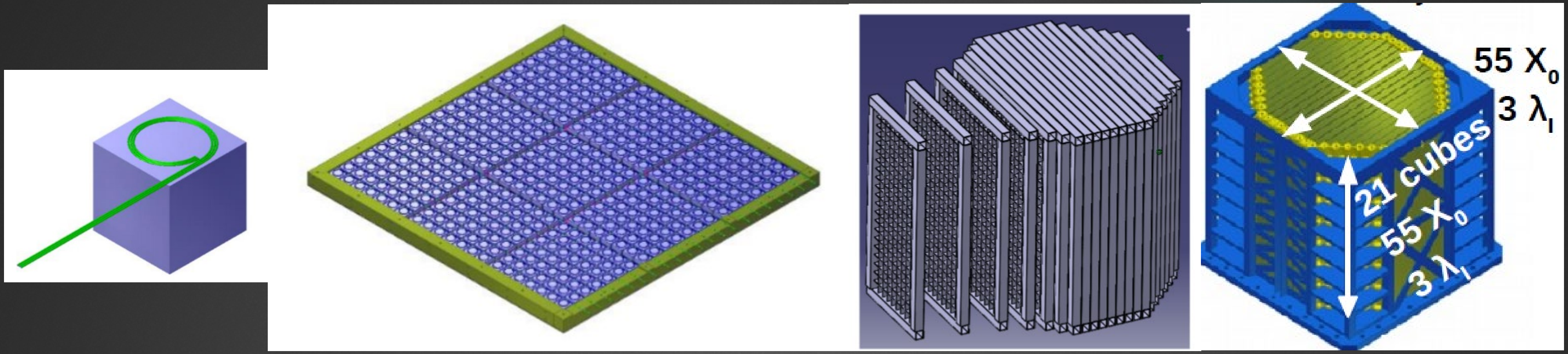
Takes into account the external tracker resolution

Ion identification capability
Very 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 %

Preliminary

HERD CALOrimeter (CALO)



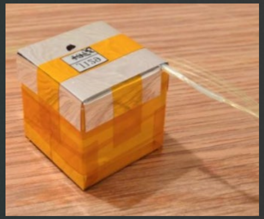
Octagonal Prism made of about 7500 LYSO cubic crystals (80x80x80 cm^3):
each crystal has 3 cm side

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

SIF2020
Progettazione, sviluppo e realizzazione del calorimetro dell'esperimento HERD
Eugenio Berti

Dynamic range of 10^7 is needed to detect from a MIP (~30 MeV released in a single crystal) to a PeV proton (~20 TeV released in a single crystal)

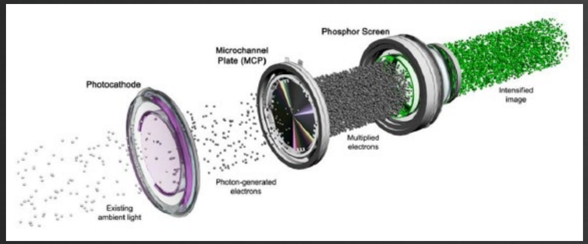
WLS read-out

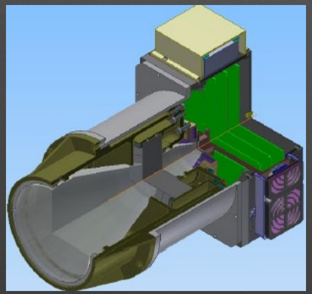


Each cube is read-out by 3 WLS fibers.

One of the fiber is used for triggering and the light signal is readout by a fast PMT

The light signal from the other two fibers is amplified by an Image Intensifier (two gains) and read-out by a IsCMOS camera

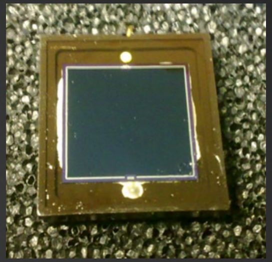


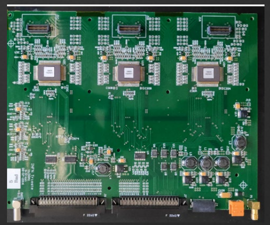


PIN-Diode read-out

Each cube is read-out by 2 PIN-Diode of different area (1:100 ratio)

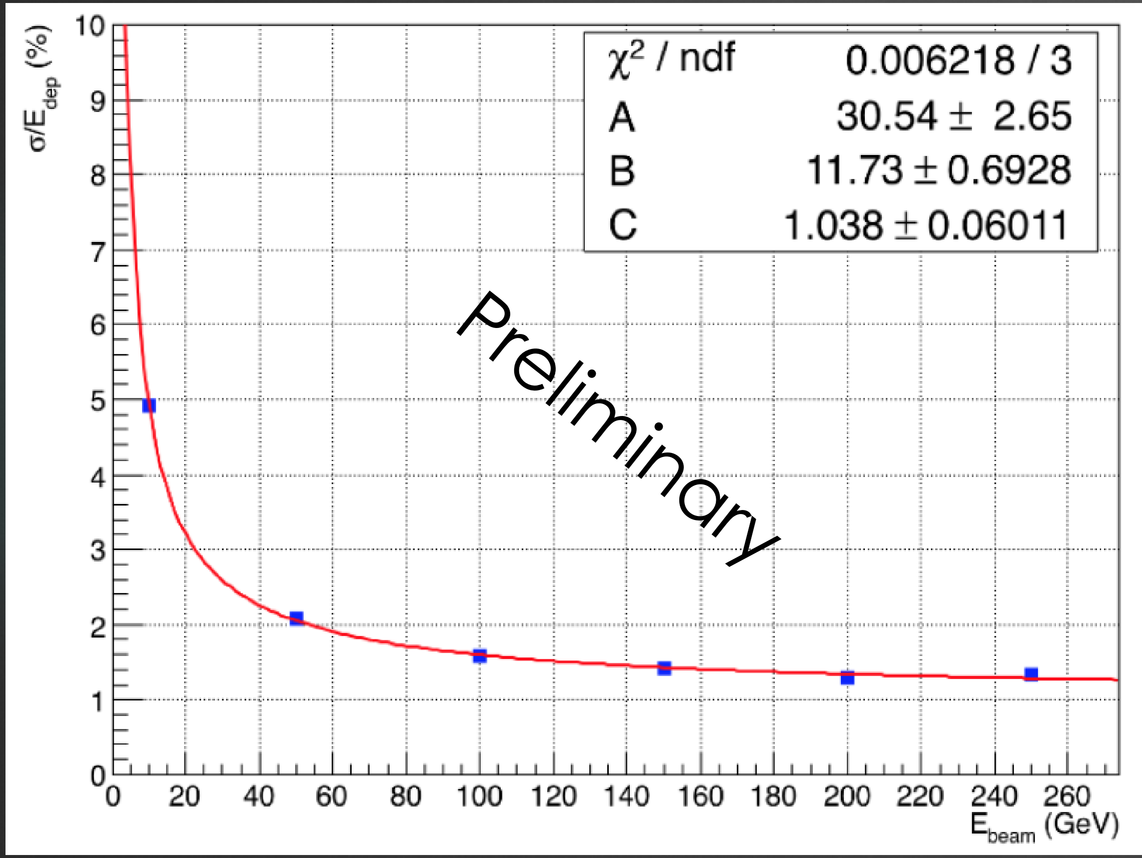
Each PIN-Diode is read-out by CASIS chip with two gains and trigger capability

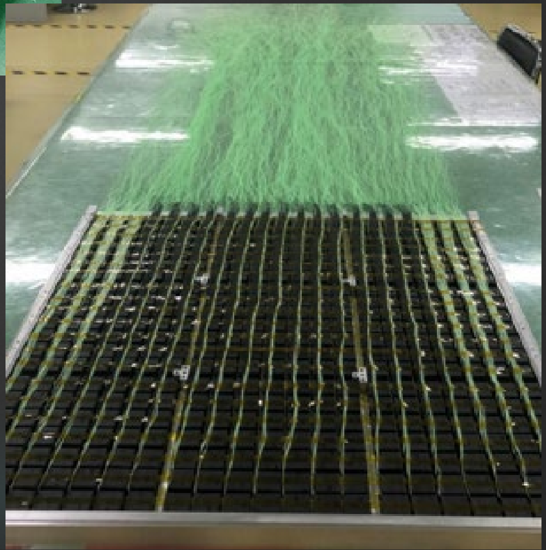




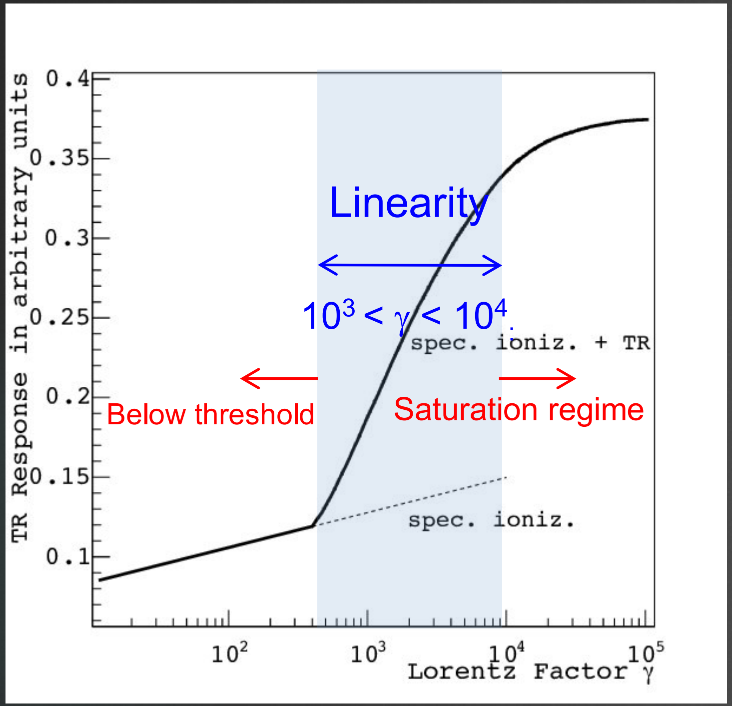
Beam Test at CERN – SPS (2017) with a prototype of 250 crystals with WLS read-out

Energy resolution < **1.3% at 200 GeV/c** (electrons)





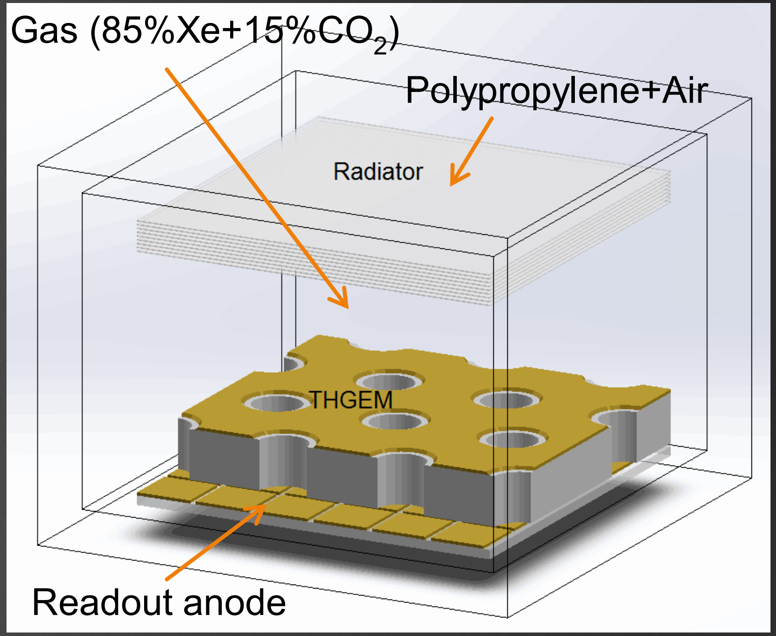
The TRD, installed on a lateral face of the detector, is needed to calibrate the response of the calorimeter to high energy hadronic showers



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] electrons in space (and at beam test)

calibrate CALO response using [1 TeV, 10 TeV] protons from TRD (3 months data required)

The **High Energy cosmic-Radiation Detection** facility is a China-led international space mission that will start its operation around 2026 on board the future China's Space Station.

Thanks to its **novel design**, based on a 3D, homogeneous, isotropic and finely-segmented calorimeter, HERD is expected to accomplish **important and frontier goals** relative to DM search, CR observations and Gamma-Ray astronomy:

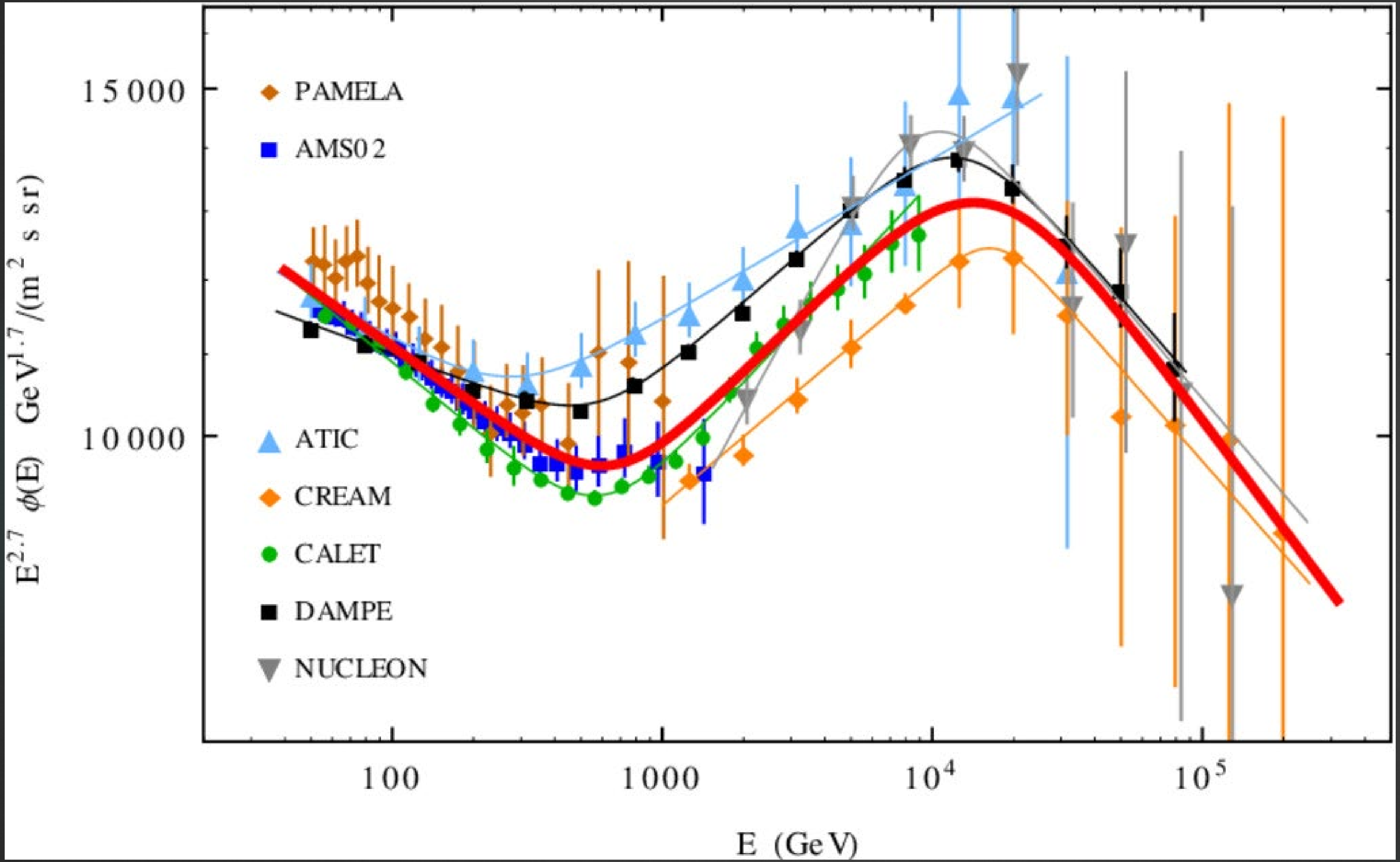
- extend the measurement of e^++e^- flux up to several tens of TeV
  - testing the hypothesis of the expected cutoff at high energy
  - distinguishing between DM or astrophysical origin of positron excess
- extend the measurement of p and He flux up to a few PeV
  - testing the theory of the knee structure as due to acceleration limit
- large acceptance, high sensitivity to γ up to several tens of TeV
  - searching for γ line associated to DM annihilation
  - accomplishing a γ sky survey up to very high energy

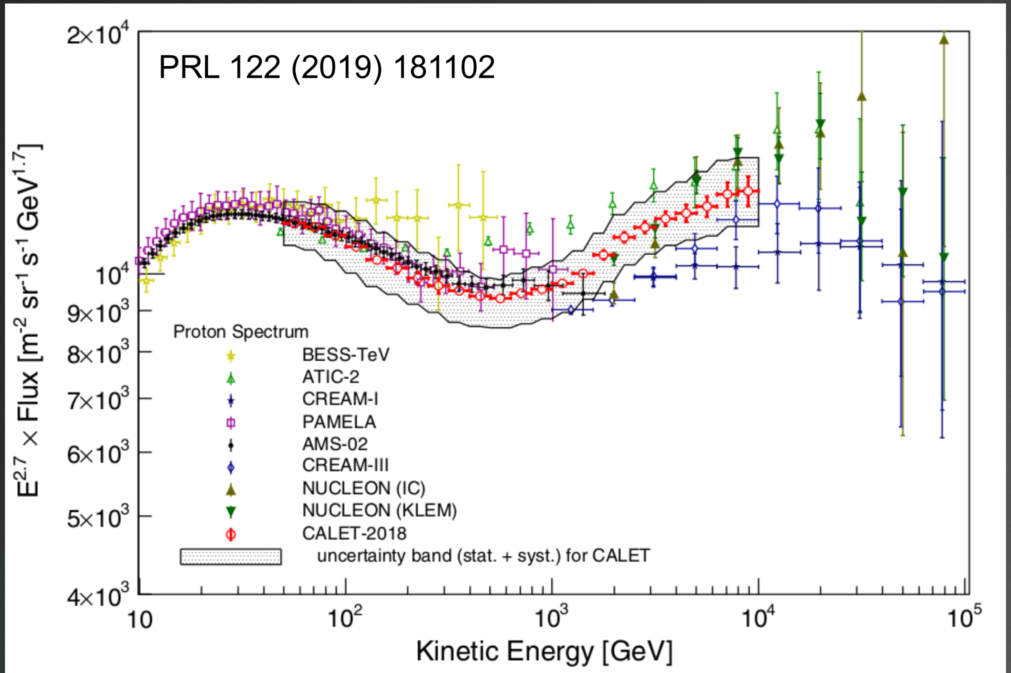
Thank you for your attention

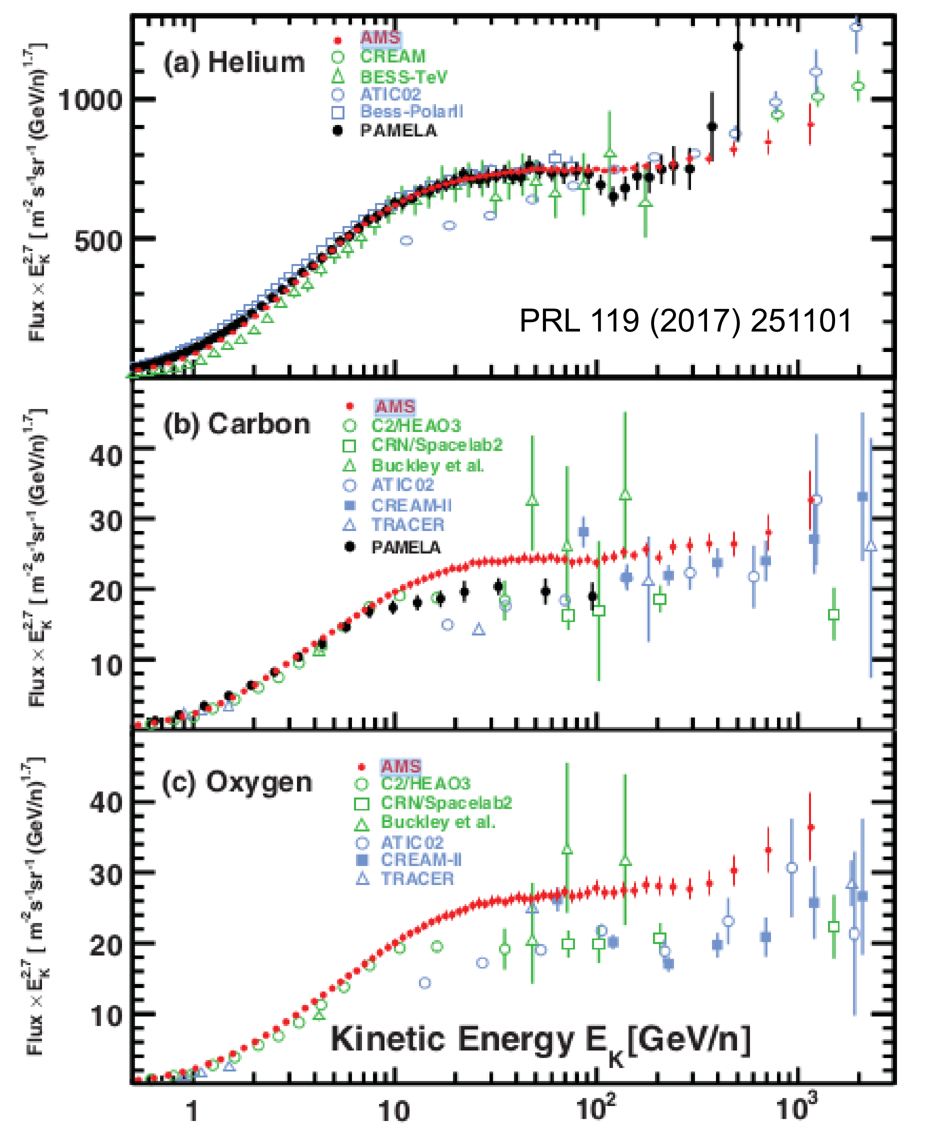
BACKUP

DAMPE - CALET Proton spectrum comparison

arXiv:1911.01311 **[astro-ph.HE]**



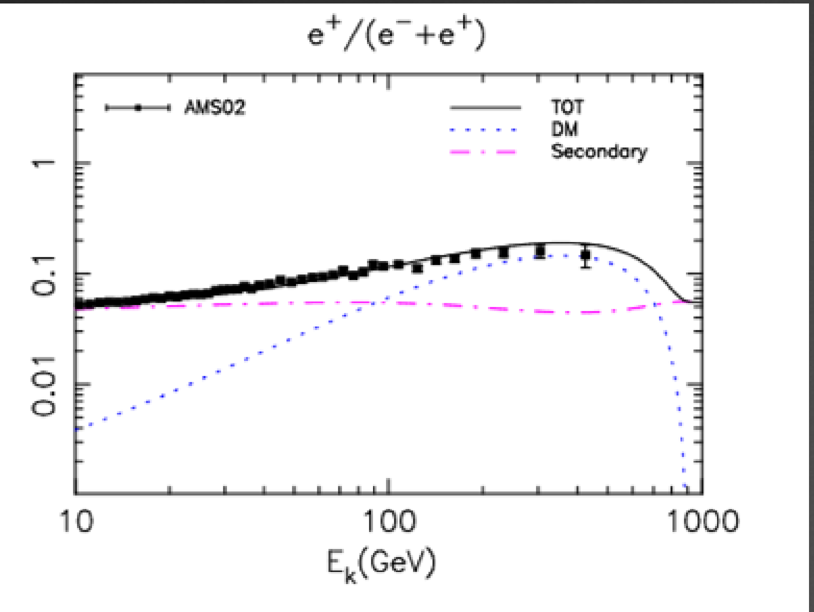


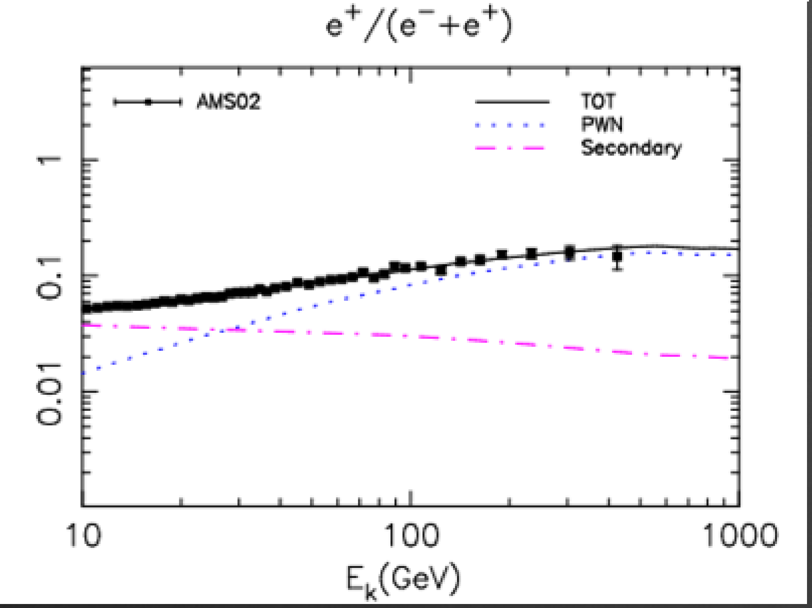


Proton flux measured up to 100 TeV but with large uncertainties:
spectral hardening at 200 GeV
spectral softening > 10 TeV
(DAMPE preliminary analysis)

Still no direct measurement of proton and helium knee
He spectral hardening > 100 Gev/n
(DAMPE preliminary analysis)

Electrons and Positrons (Pamela and AMS-02)



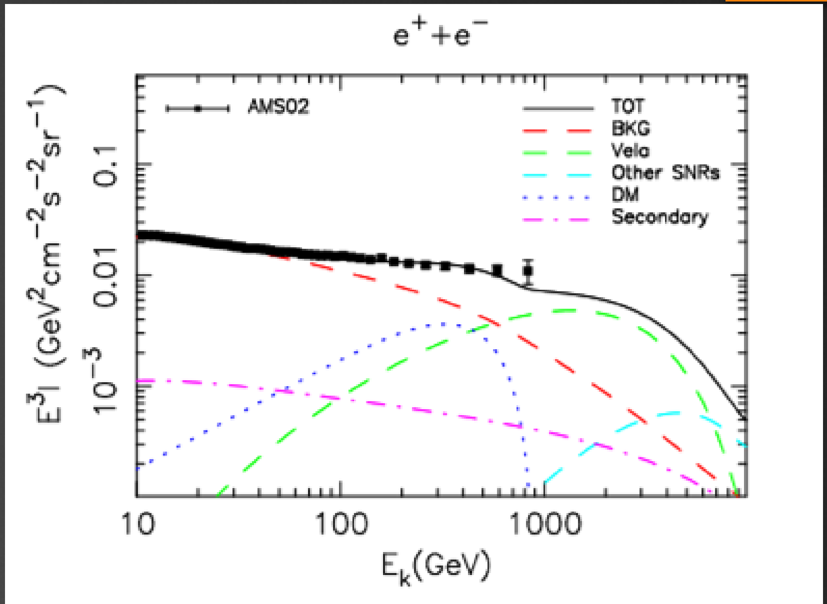


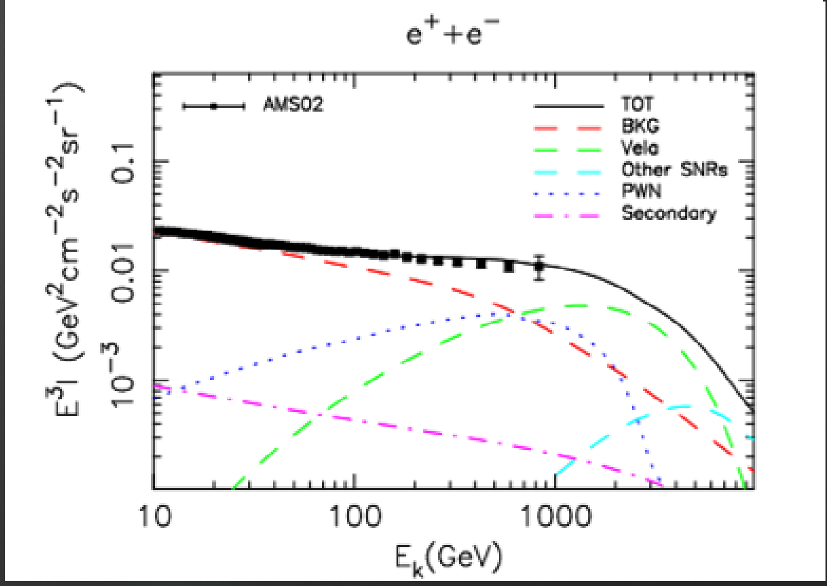
Positron excess respect to pure secondary production (PAMELA, AMS-02)

Two hypotheses
Dark Matter (DM) annihilation
Nearby Pulsar Wind Nebulae (PWN)

How to distinguish among them?

An important contribution to our understanding can be obtained by **high energy (calorimetric) measurement of the e^++e^- flux**





- 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)
  - Academia Sinica
- ITALY
  - INFN Bari and University of Bari
  - INFN Firenze and University of Firenze
  - INFN Pavia and University of Pavia
  - INFN Perugia and University of Perugia
  - INFN Pisa and University of Pisa
  - INFN Lecce and University of Salento
  - INFN Laboratori Nazionali del Gran Sasso and GSSI Gran Sasso Science Institute
  - INFN Roma2 and University of Tor Vergata
- SPAIN
  - CIEMAT - Madrid
  - ICCUB – Barcellona
  - IFAE – Barcellona
- SWITZERLAND
  - University of Geneva