INFN LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

Cosmic ray studies with the DAMPE and HERD space missions: light and heavy components

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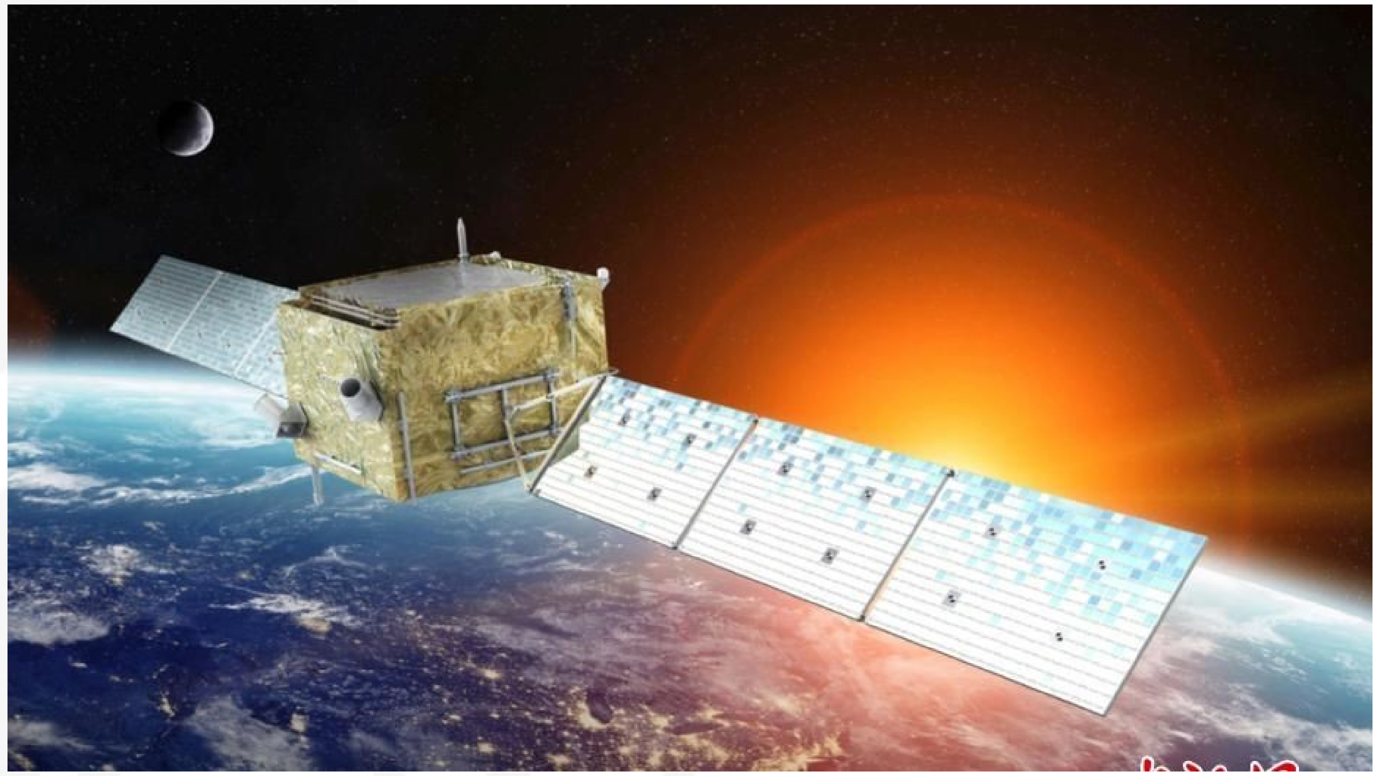
Supervisor: Prof. Ivan De Mitri

ADMISSION TO THE THIRD YEAR
PhD in Astroparticle Physics – XIV Cycle
13th October 2020



Overview

1. Introduction
2. Part 1: Cosmic Ray studies with the DAMPE experiment
3. Part 2: Cosmic Ray studies with the HERD space mission
4. Summary and Conclusions

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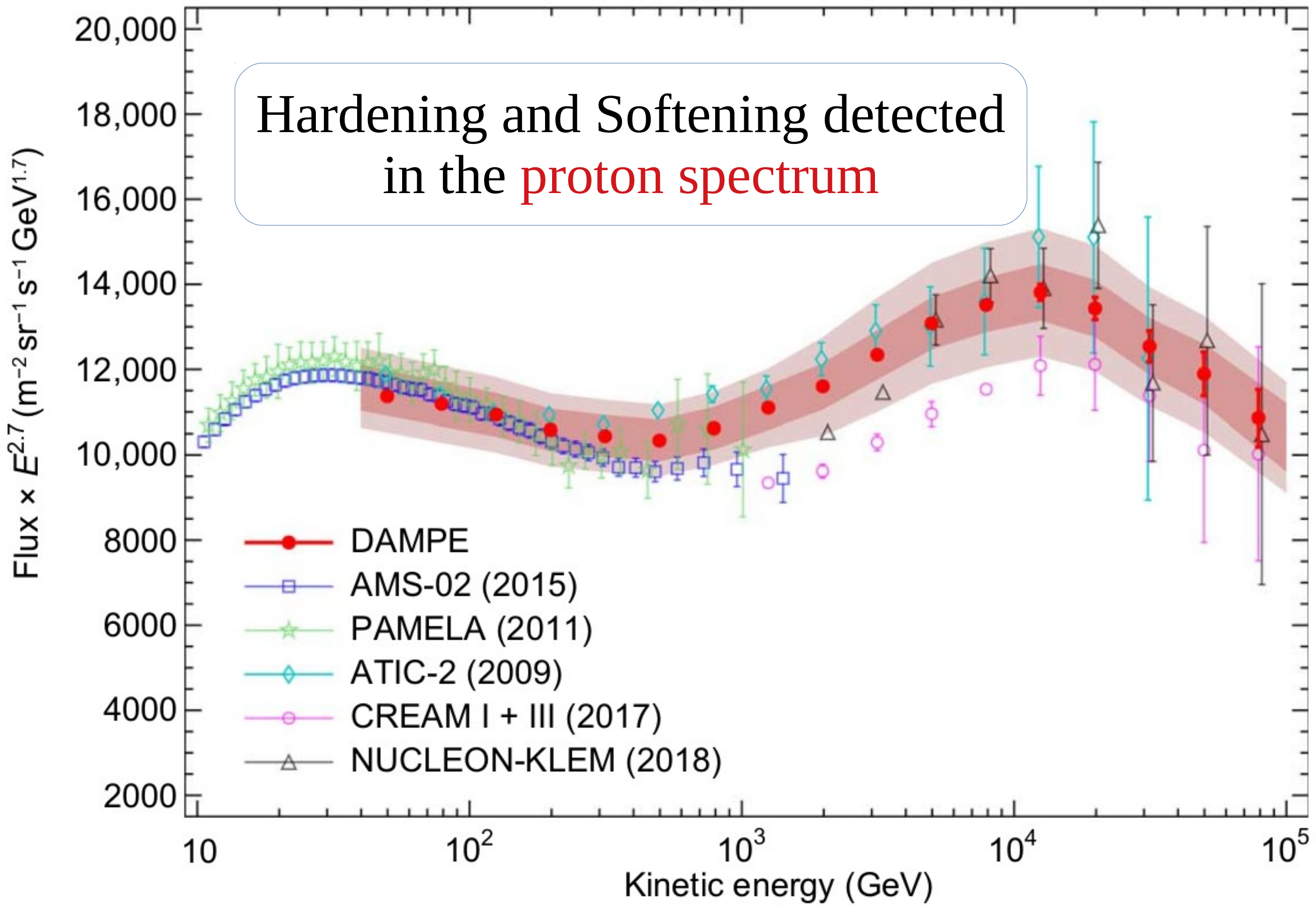
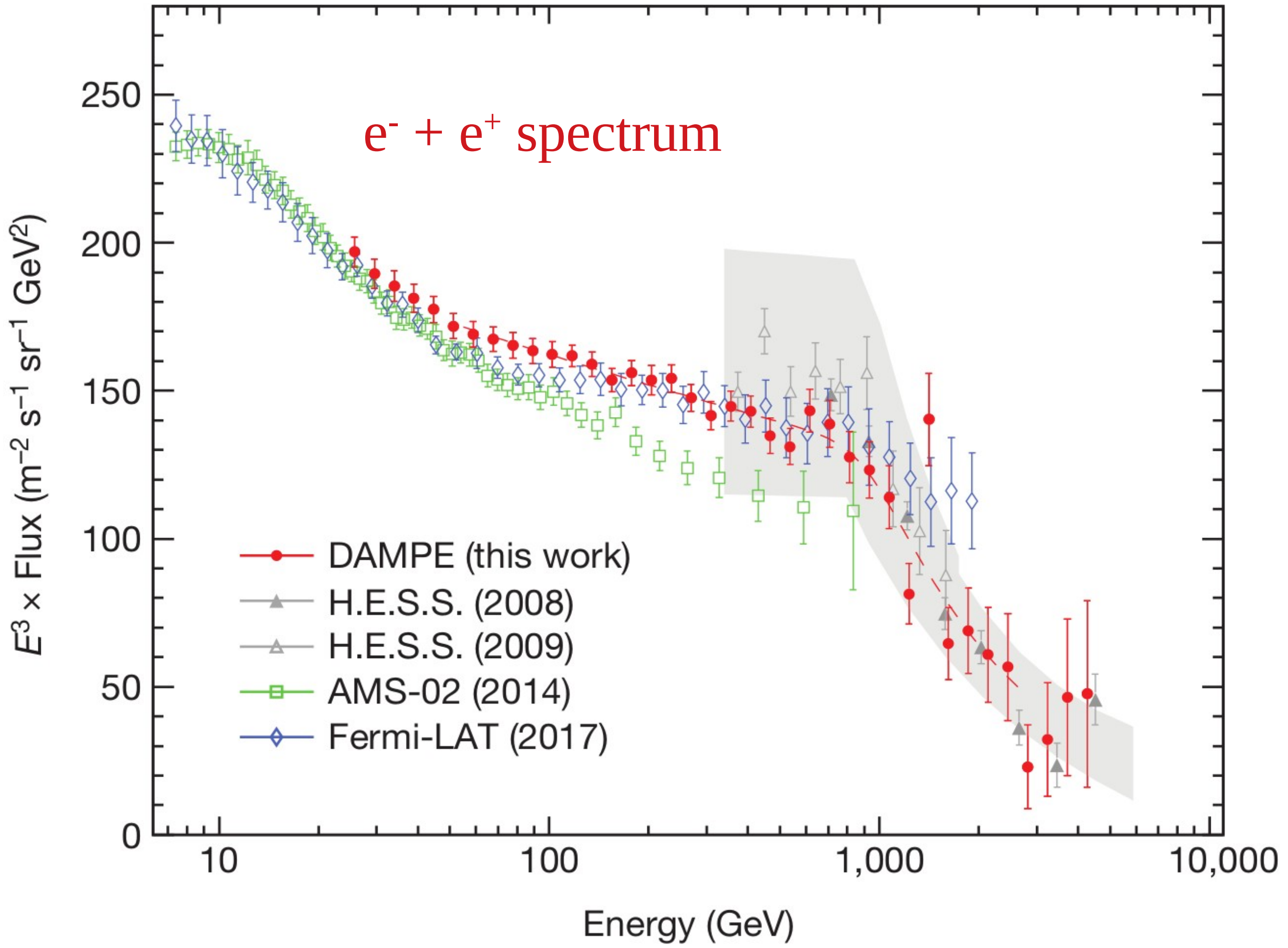
Introduction: Cosmic Ray physics in space

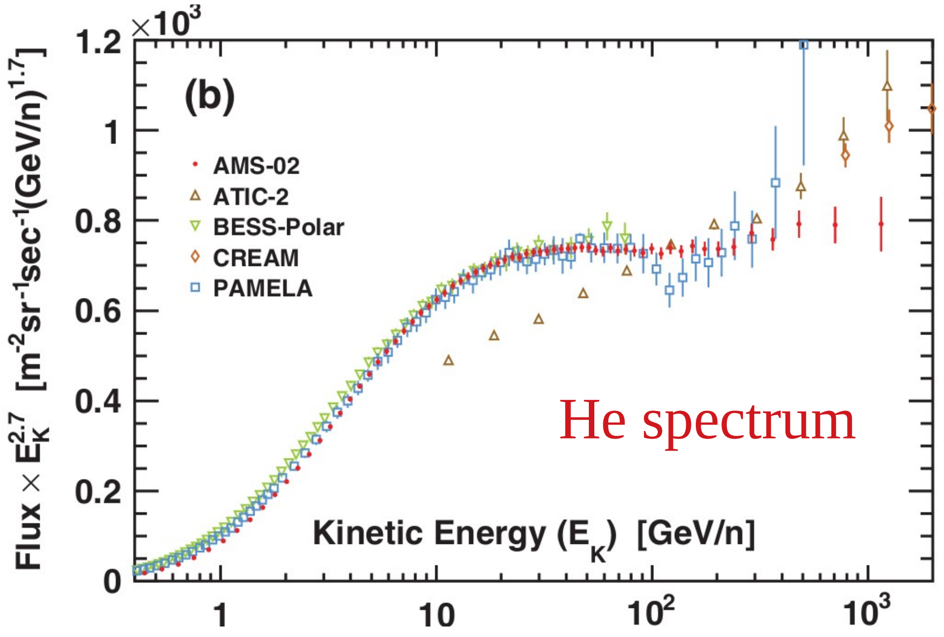


DAMPE Collaboration, Sci. Adv. 2019; 5 : eaax3793



DAMPE Collaboration, Nature 2017, doi:10.1038/nature24475

AMS-02 Collaboration, doi:10.1103/PhysRevLett.115.211101



What is needed:

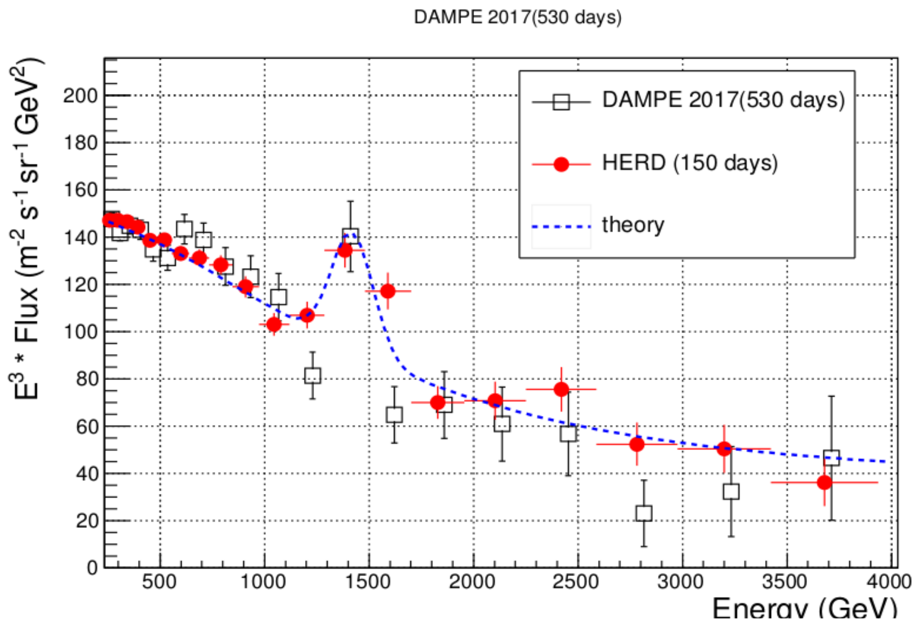
- Measurement of other nuclei spectra
- More accurate results
- Going to higher energy in space

Several open questions:

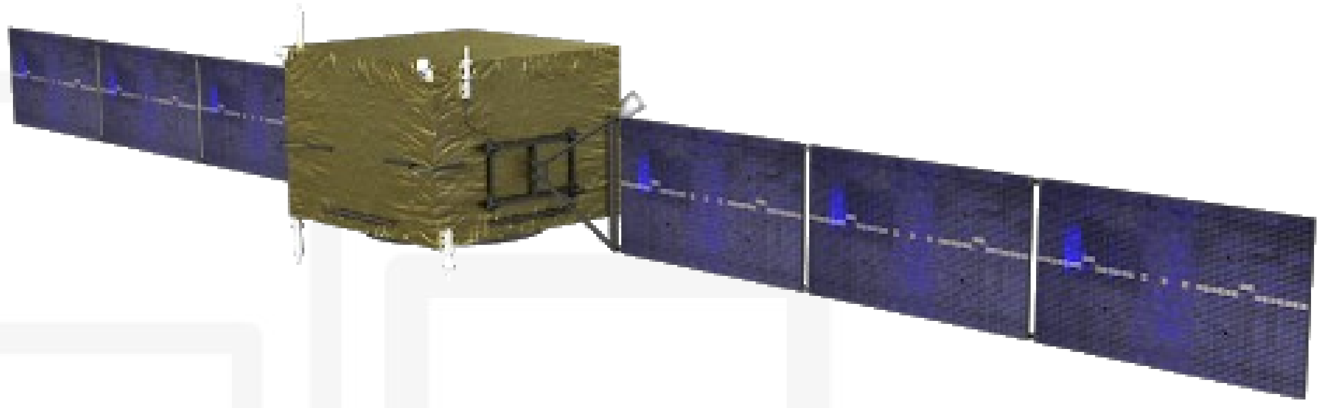
- Origin
- Acceleration
- Propagation

Several open questions:

- Nearby sources
- Dark matter signals



HERD Collaboration, HERD proposal, April 2018



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Part 1
Overview

1. The DAMPE experiment
2. Light component: p + He spectrum
3. Heavy component: Fe spectrum
4. Other contributions: Study of systematic uncertainties
5. Other contributions: Fit of the He spectrum

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Part 1
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1 **The DAMPE experiment**

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The DAMPE space mission

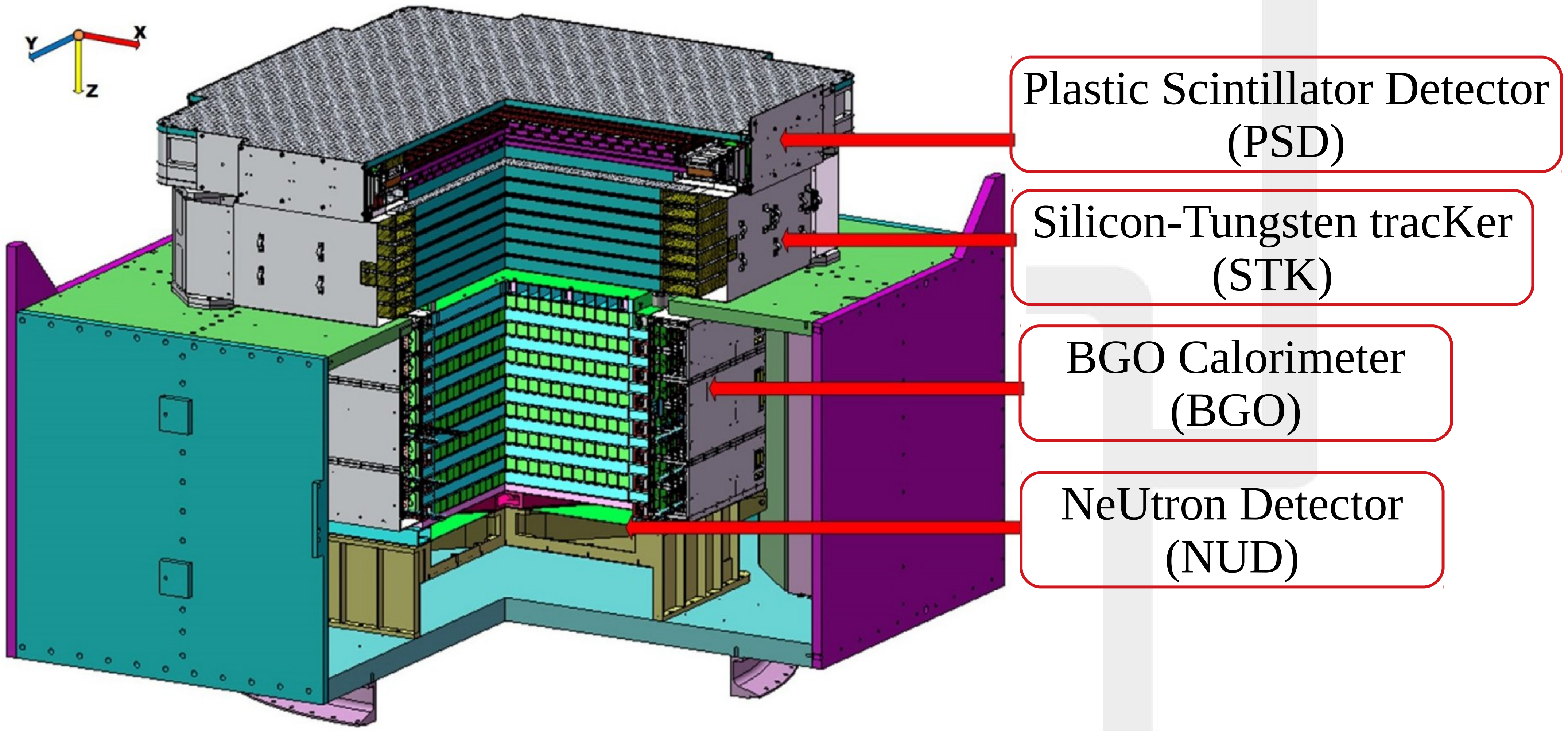
The DArk Matter Particle Explorer (DAMPE) is a high-energy particle detector

The main objectives of the DAMPE mission are:

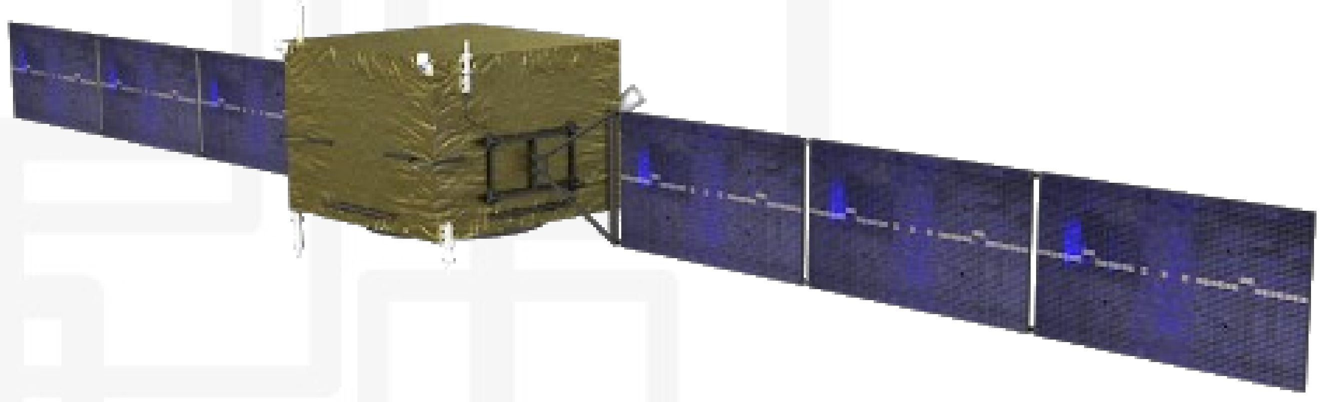
- Study of galactic cosmic-ray physics
- Dark matter searches
- High-energy gamma-ray astronomy

The DAMPE collaboration involves several institutes in China, Italy and Switzerland

DAMPE was successfully launched in a Sun-synchronous orbit on December 17th 2015 from the Jiuquan Satellite Launch Center



PSD → *Charge measurement + identification of electrons and gamma-rays*
STK → *Silicon strips (precise tracking) + tungsten converter (pair production)*
BGO → *Energy measurement + e/p separation*
NUD → *Hadrons rejection*



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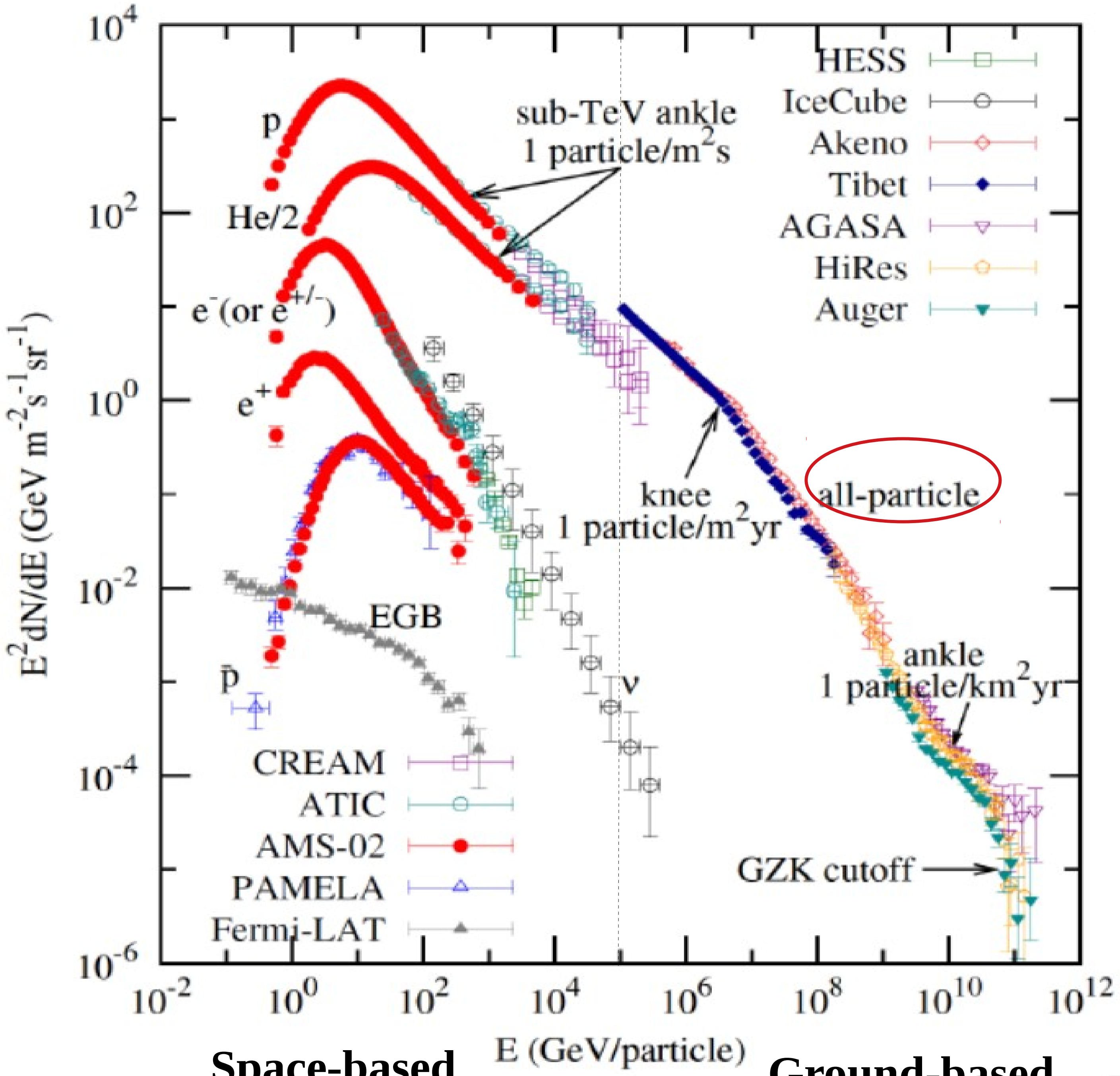
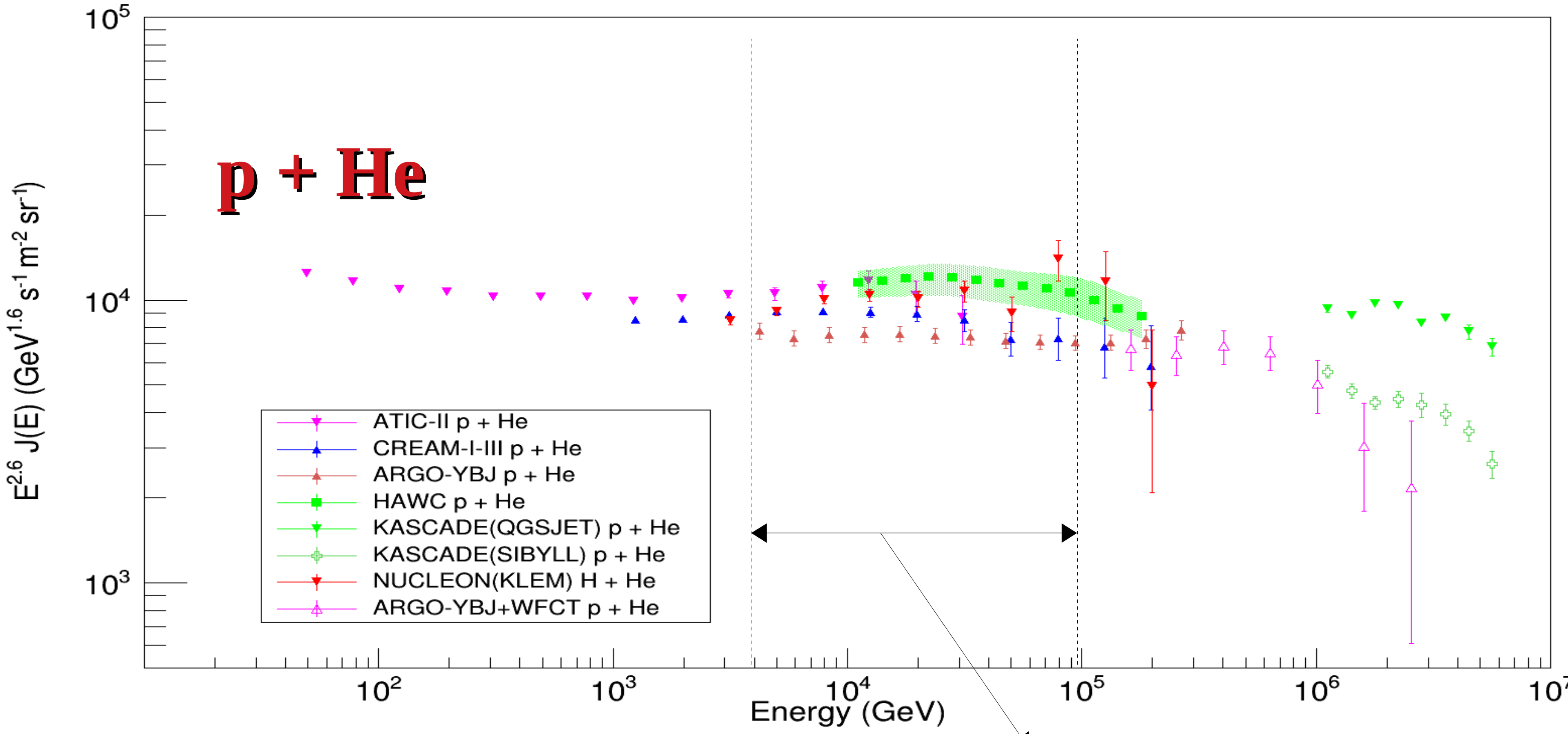
The light component: motivation

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)

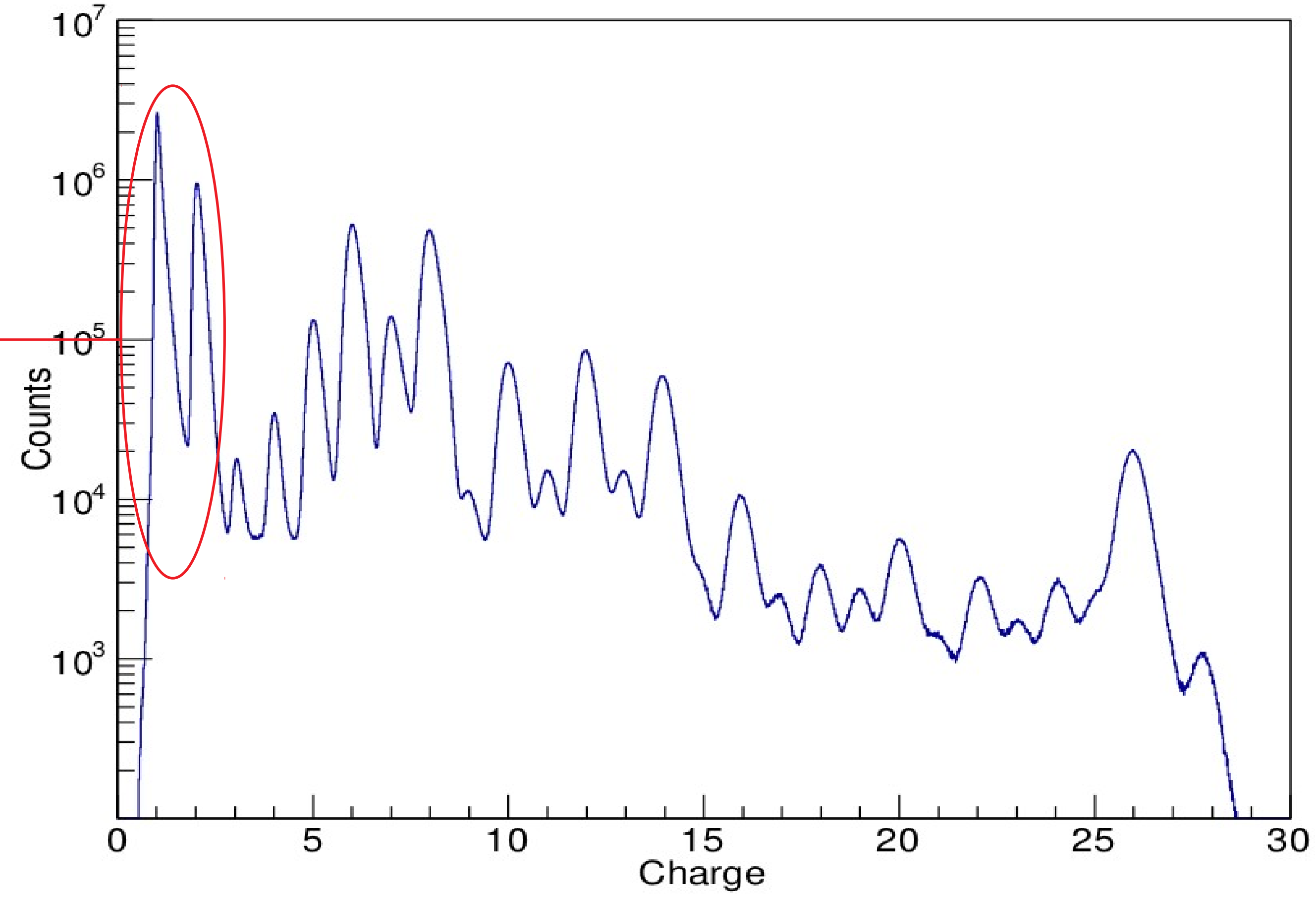


In this energy region direct and indirect spectra can be compared

Proton and Helium are well separated from other peaks

VERY LOW CONTAMINATION
(less than 0.1 %)

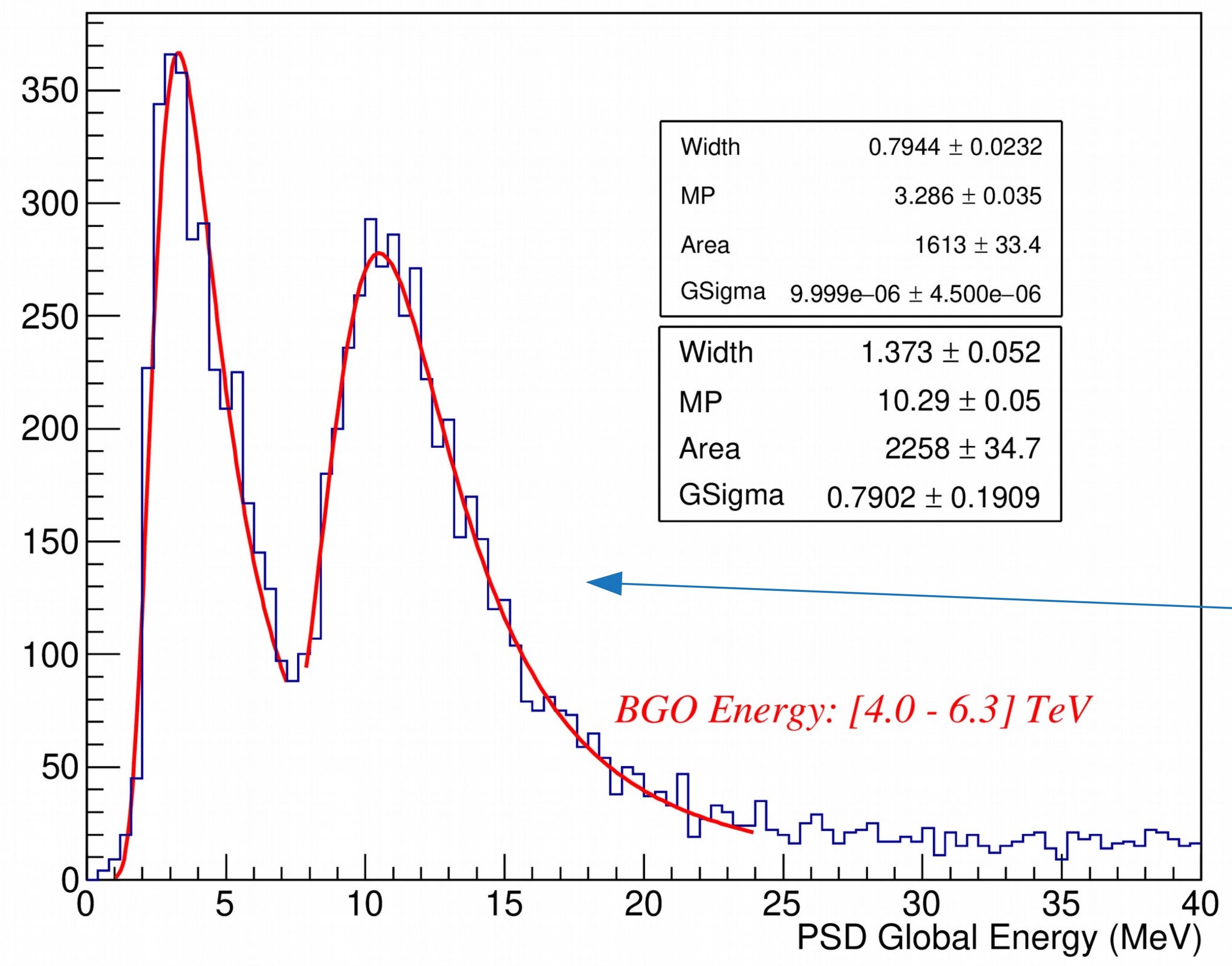
Looser cuts
Possibility to go to higher energy



Data sample and selection criteria

ORBITAL DATA (from the satellite):
44 months → January 2016 – August 2019

MONTE CARLO DATA (simulated):
- **Proton [1 GeV – 1 PeV]**
- **Helium [10 GeV – 200 TeV]**



Pre-selection:
Performed to eliminate events entering the detector from the side and to avoid the effect of geomagnetic rigidity cutoff

Trigger selection:
Events must activate the high energy trigger of DAMPE i.e. energy deposition in the top 4 BGO layers exceeding the threshold of ~ 10 MIPs in each hit BGO bar

Track selection:
To ensure that events have good quality of the reconstructed trajectories

Charge selection for p+He:
To reject CR nuclei with charge larger than 2 (Li, Be, B …)

Energy reconstruction

The nuclear interaction length of DAMPE is ~ 1.6, while the radiation length is 32.
Therefore, for protons and helium nuclei, a certain fraction of the primary energy is undetectable
The energy deposition for protons and helium nuclei in the BGO is only 35% - 40%

In order to obtain the primary energy of an entering event, a method based on the Bayes theorem is used

Using this formula, the primary spectrum can be obtained from the observed spectrum in the BGO calorimeter

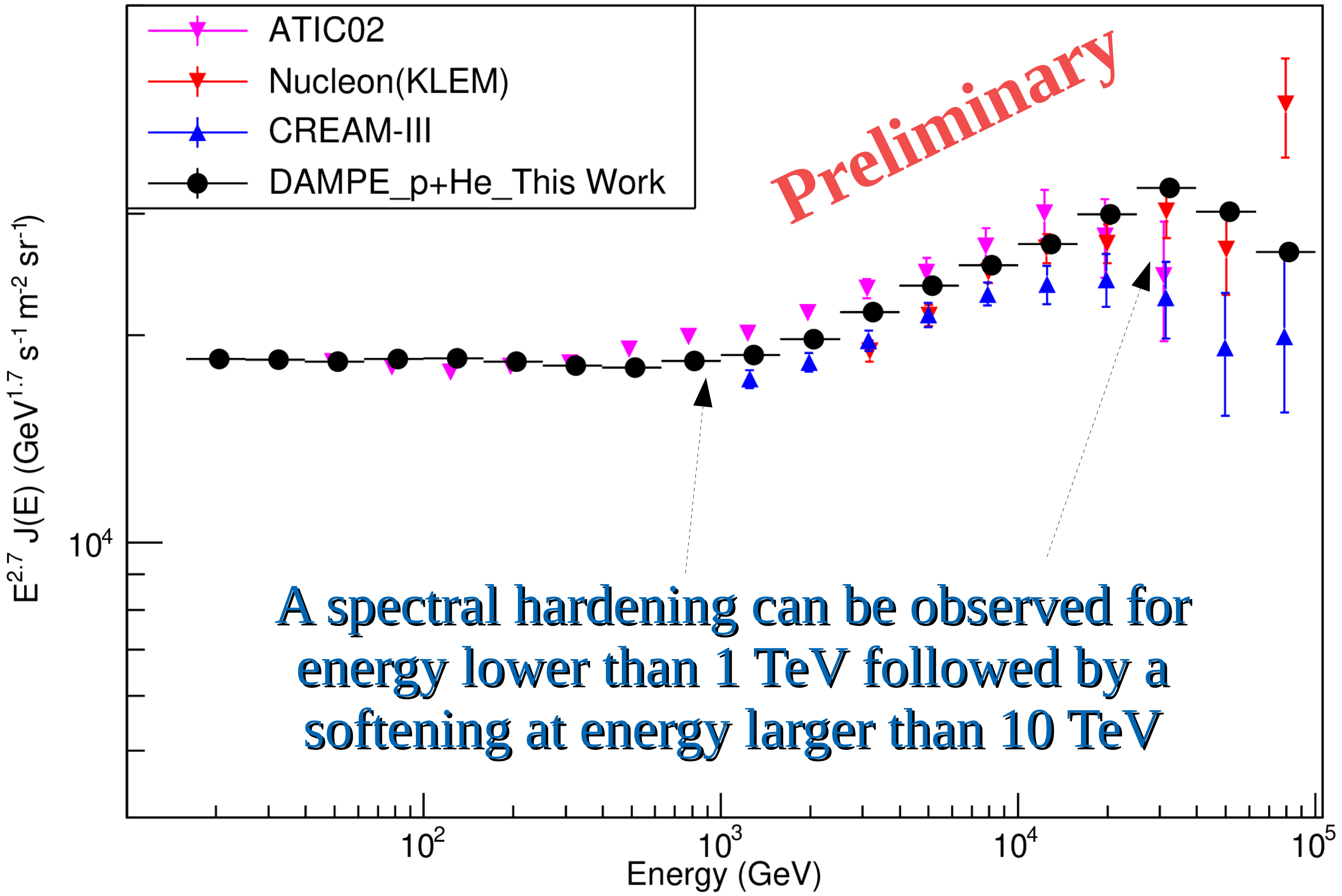
$$N(E_T^i) = \frac{1}{\varepsilon_i} \sum_{j=1}^{n} P\left(E_T^i \mid E_O^j\right) N\left(E_O^j\right)$$

$N(E_T^i)$ Primary spectrum

$N\left(E_O^j\right)$ Observed spectrum

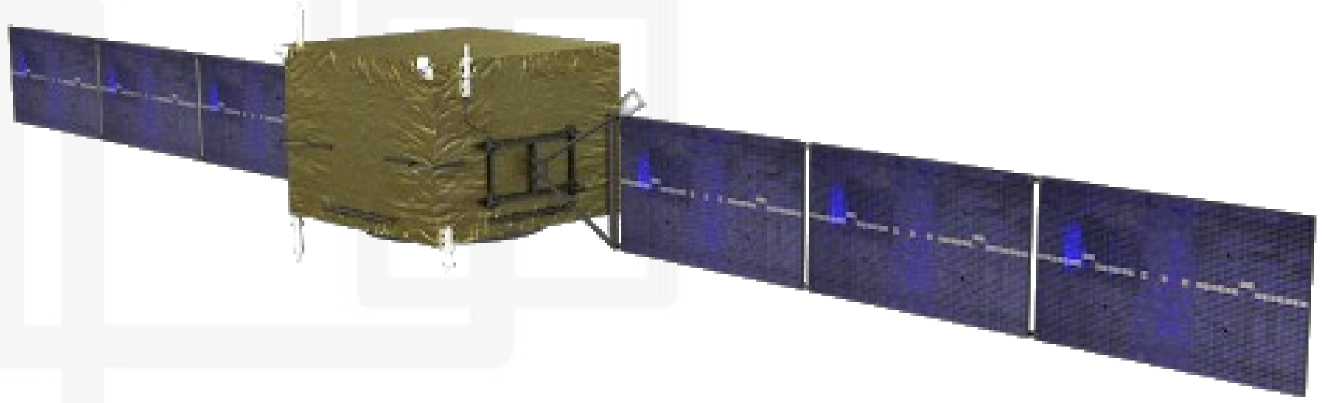
$P\left(E_T^i \mid E_O^j\right)$ Response matrix derived from MC using the Bayes theorem

ε_i Detection efficiency



Extend the flux above 100 TeV → need of MC samples
MC production **(work in progress)**:
Helium and Proton MC [100 TeV – 1 PeV]

Check the effect of saturation in the DAMPE calorimeter **(ONGOING)**



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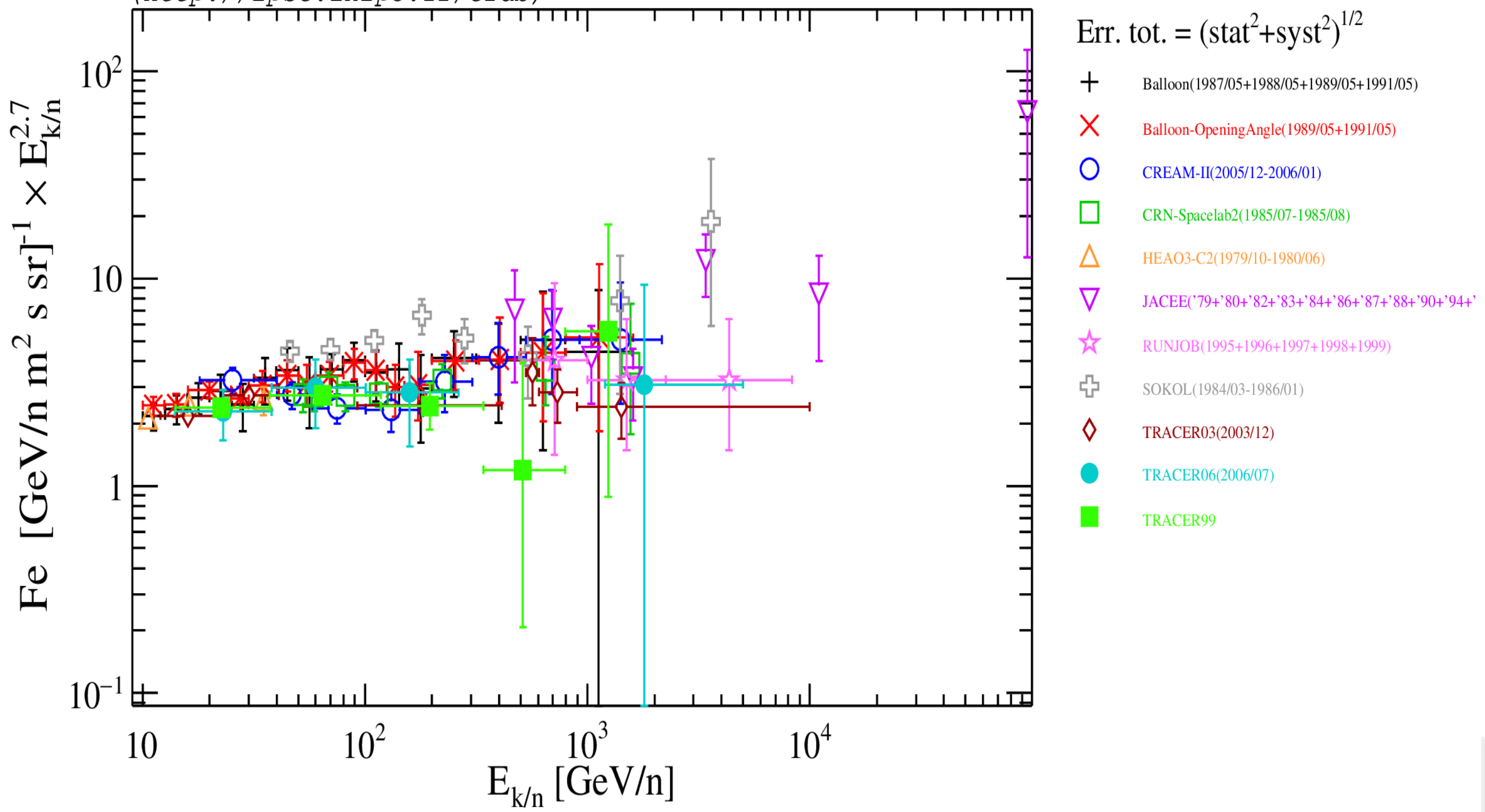
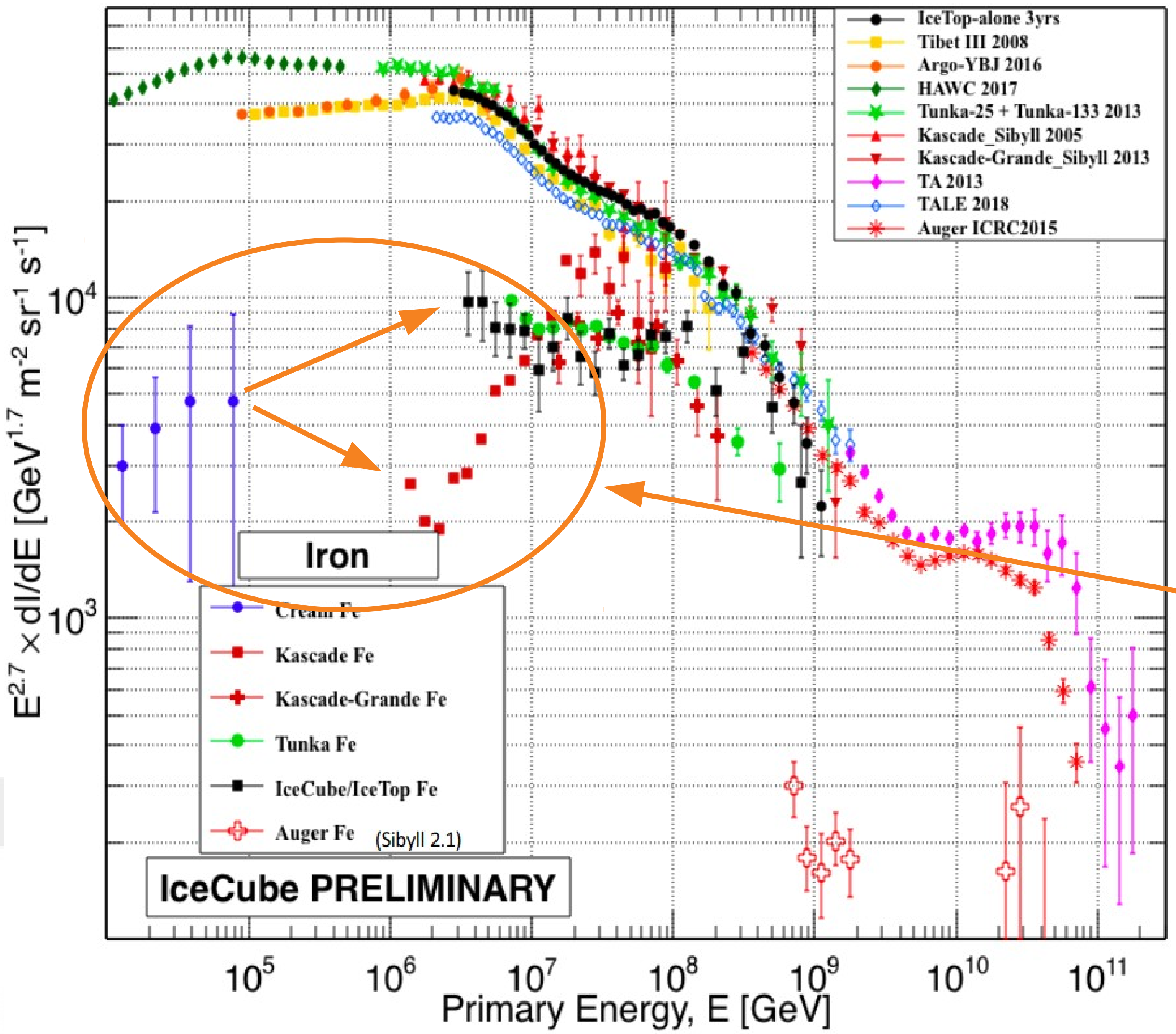
The Iron Sky & Fe spectrum measurement

DAMPE energy range ~ CREAM energy range

Difference: larger exposure → smaller error bars

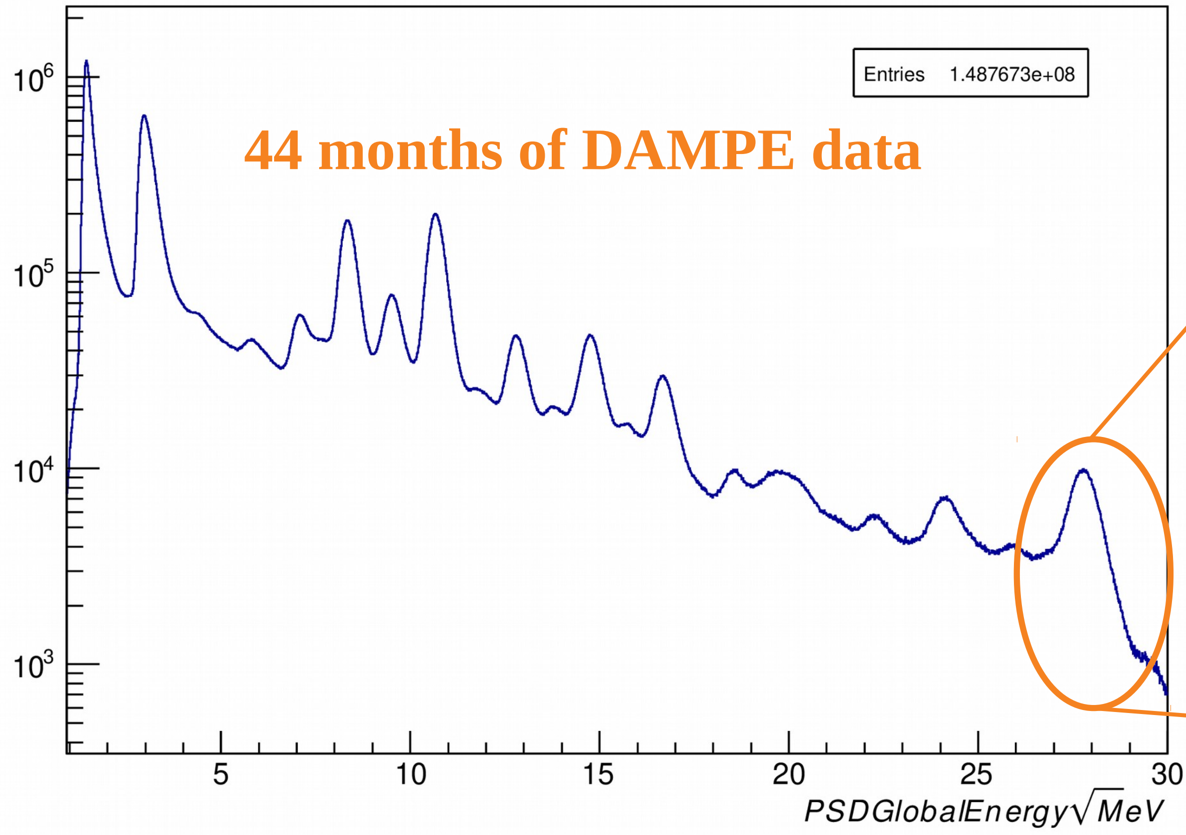
(http://lpsc.in2p3.fr/crdb)

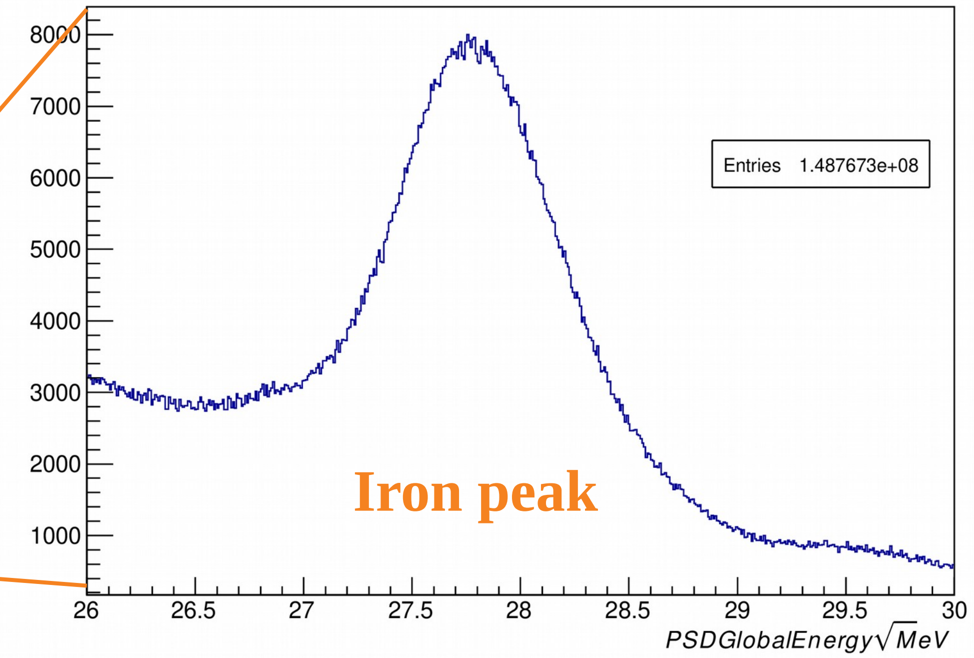




http://www.apc.univ-paris7.fr/~semikoz/CosmicRays2018/DEC11/Plum_APC_v1.pdf

Important contribution in link between direct and indirect measurement





Setup of an analysis chain for the measurement of the Fe spectrum

Production of Fe MC samples started recently

The implementation of preliminary cuts in order to identify the Fe nuclei in the DAMPE data is ongoing

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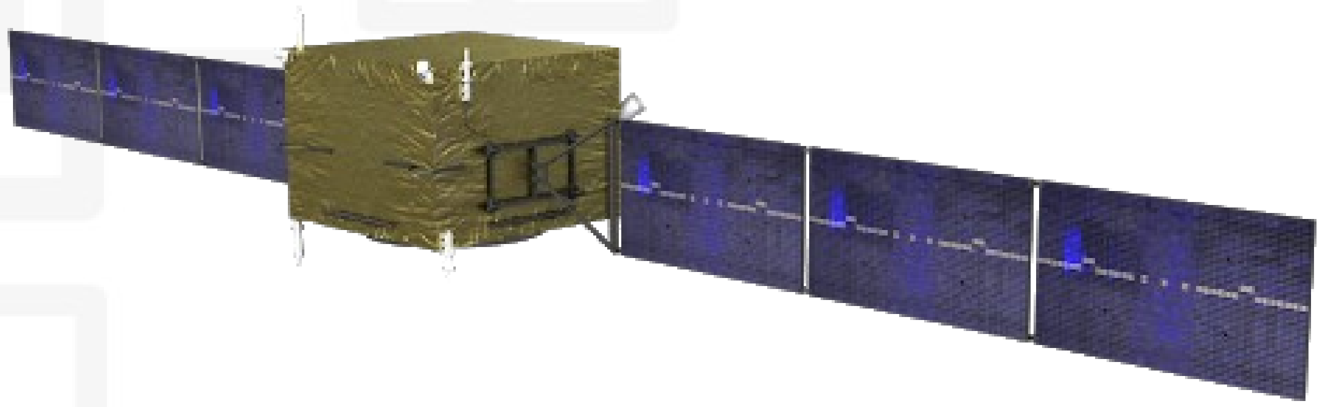
Part 1
Overview



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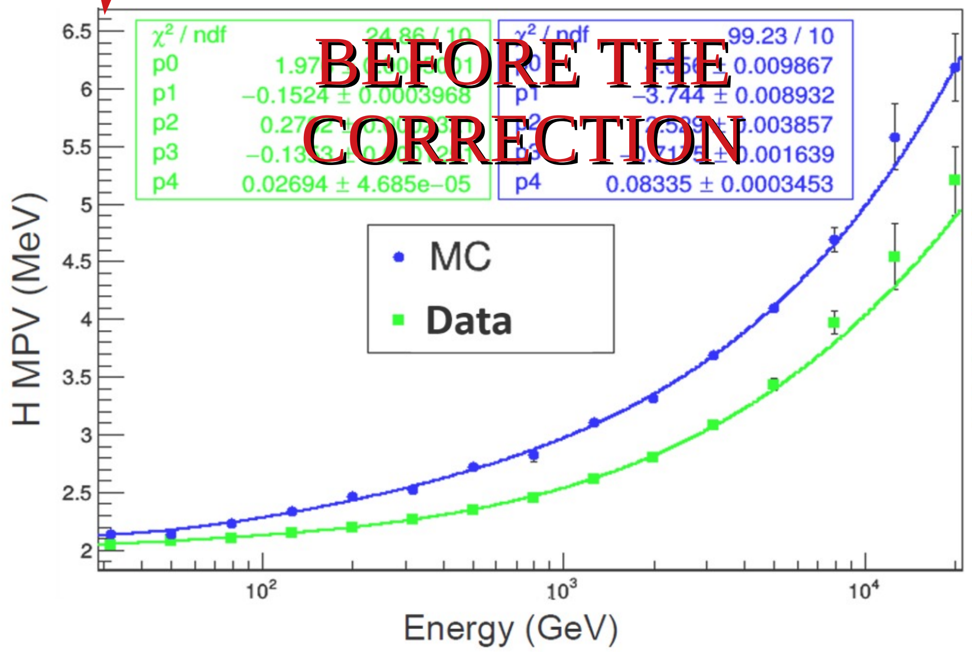
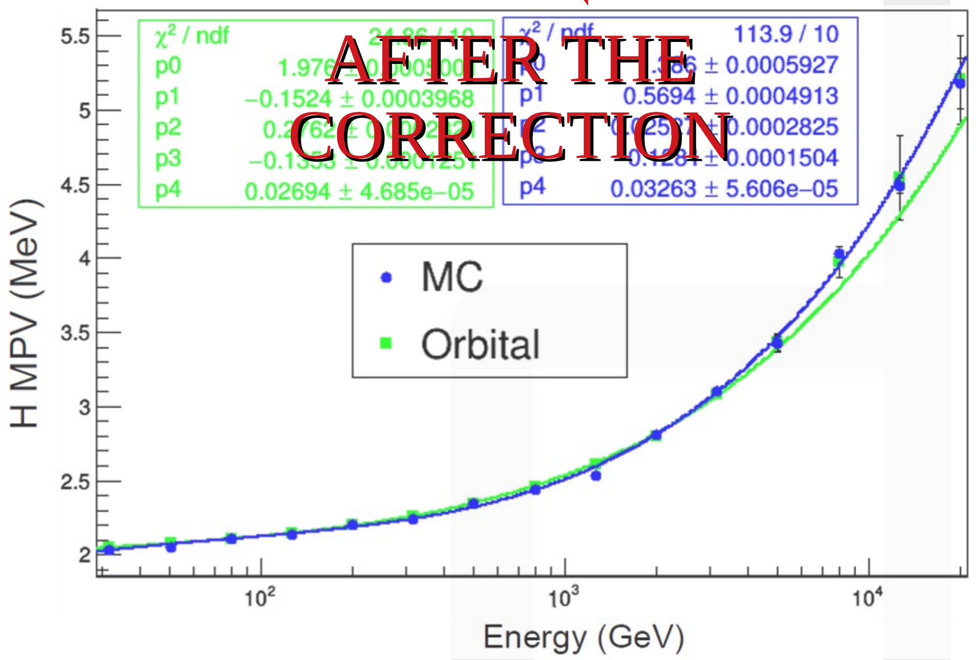
Backscattering study

From the p+He analysis:

- Disagreement between MC and data in all the charge selection's parameters (MPV, σ_{Gaus}, σ_{Landau}) for both hydrogen and helium
- Correction performed on the MC PSD charge selection
- Source of systematic uncertainty
- Possible explanation: MC overestimating the fraction of back-scattered particles





RESULTS:

- Number of backscattered particles increasing with energy of the primary
  - The backscattered particles are mainly: protons, pi+ and pi-
    - Energy released of ~ hundreds of MeV

NEXT STEPS:

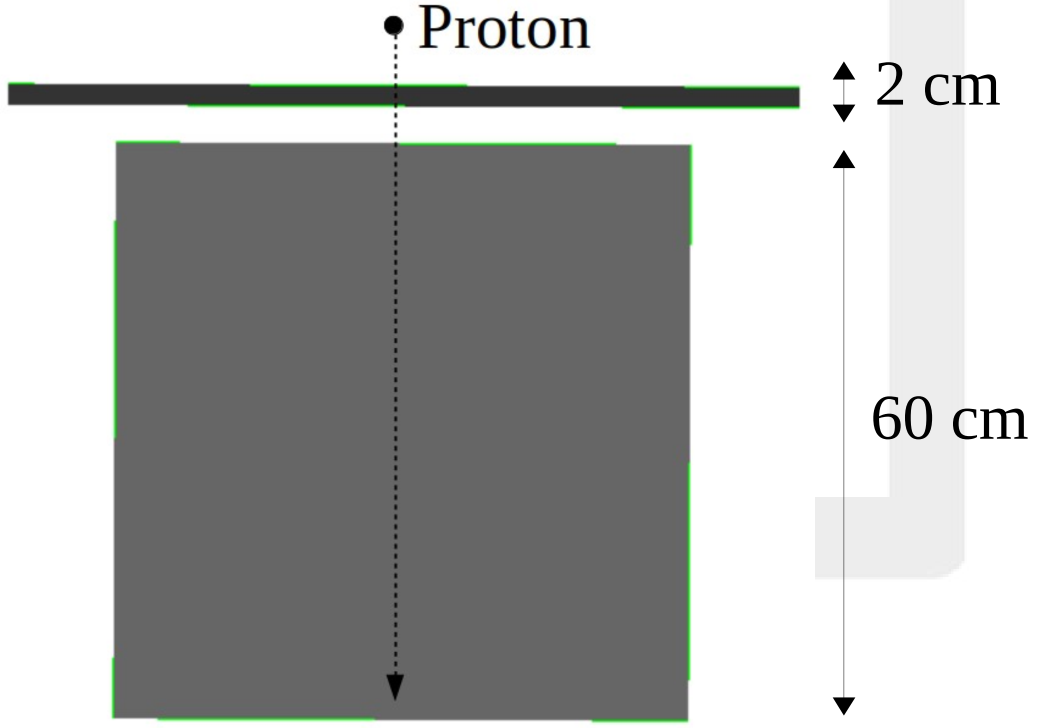
→ Extend the study to other nuclei (important for Fe analysis)

→ Check different hadronic models

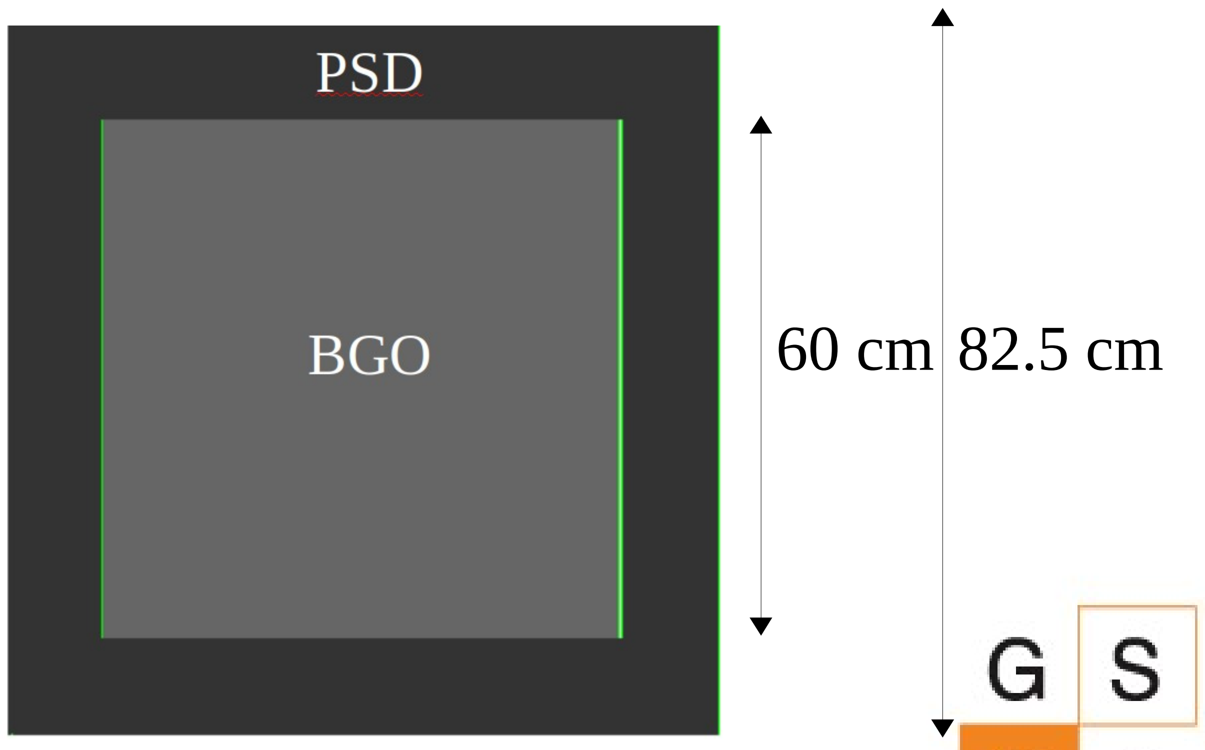
Backscattering effect studied

GEANT-4 based simulation - Simplified geometry

SIDE VIEW



BOTTOM VIEW



Distance PSD – BGO: 4 cm of G4_Galactic

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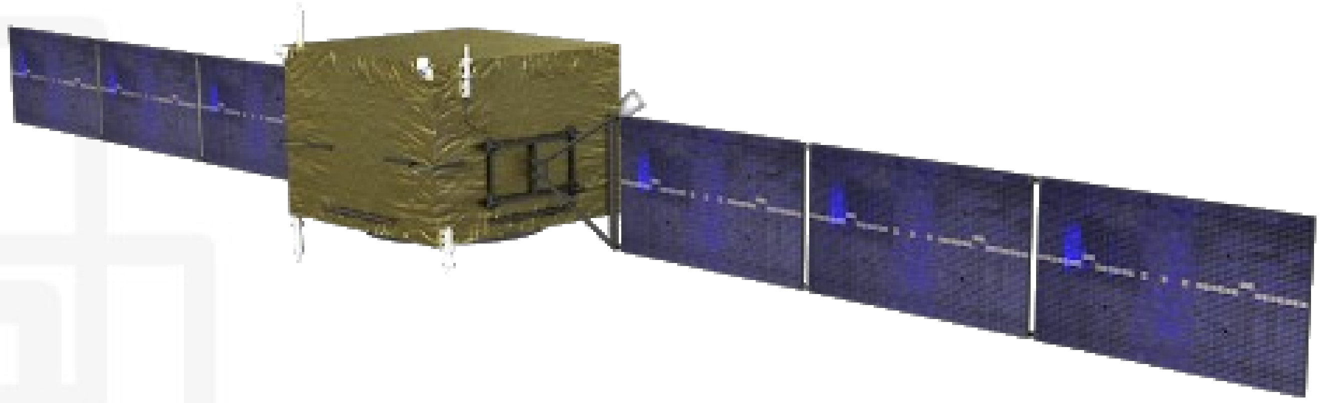


Smoothly Broken Power Law model(*)

22 points - energy range [30 GeV – 20 TeV]

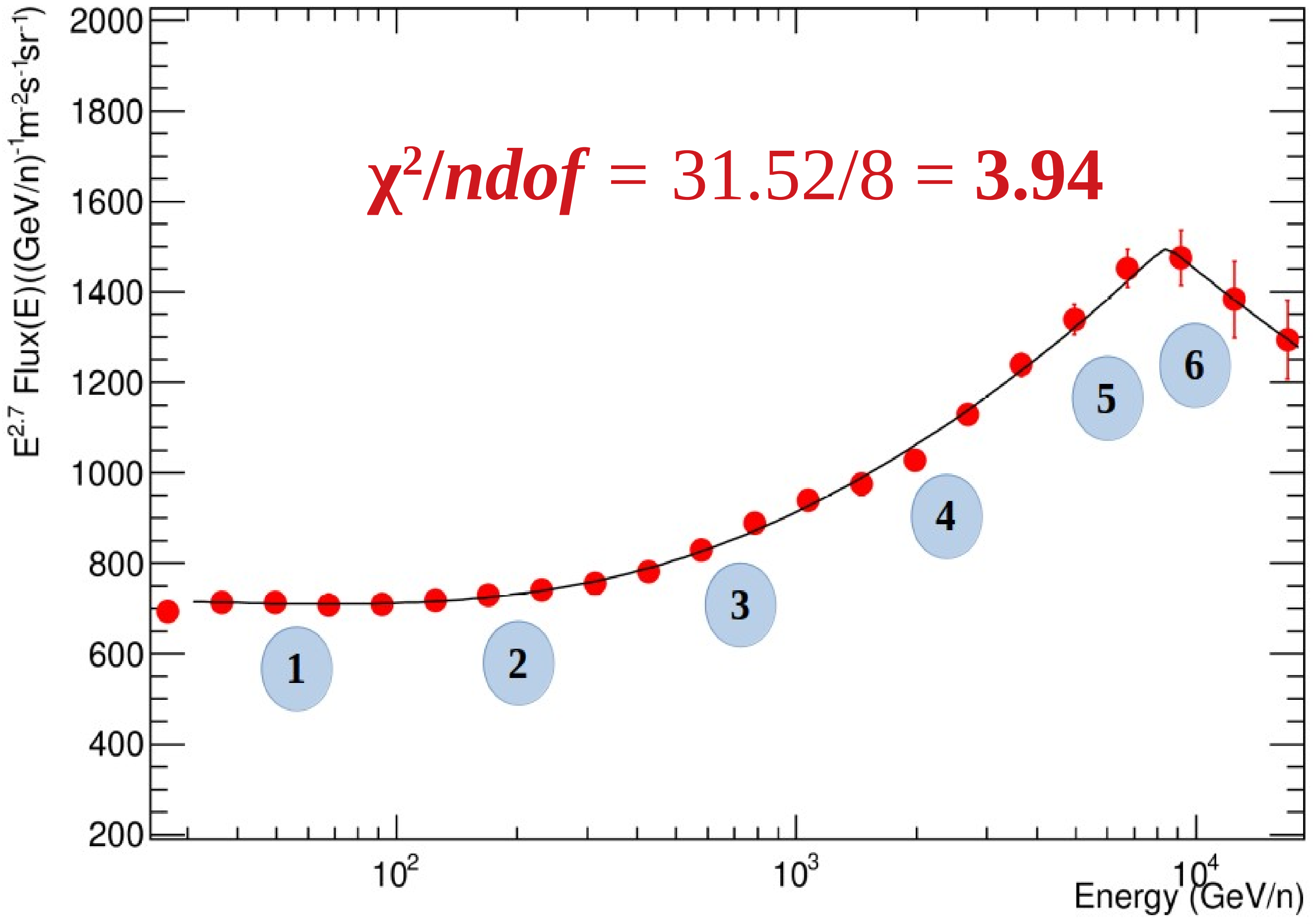
$$\phi(E) = K\left(\frac{E}{E_0}\right)^{-\alpha_1}\left[1+\left(\frac{E}{E_b}\right)^{1/w}\right]^{-(\Delta\alpha)w}\left[1+\left(\frac{E}{E_b'}\right)^{1/w'}\right]^{-(\Delta\alpha')w'}$$

$$\chi^2 = \sum_{i=1}^{22}\left[\frac{\Phi(\mathrm{E_i})S(\mathrm{E_i};\mathrm{n}) - \Phi_i}{\sigma_{\mathrm{stat}\,,i}}\right]^2 + \sum_{j=1}^{m}\left(\frac{1-n_j}{\tilde{\sigma}_{\mathrm{sys.}\,j}}\right)^2$$

Piecewise function, defined as:
- Nuisance parameter 1, for interval 1
- Nuisance parameter 2, for interval 2
- Nuisance parameter 3, for interval 3

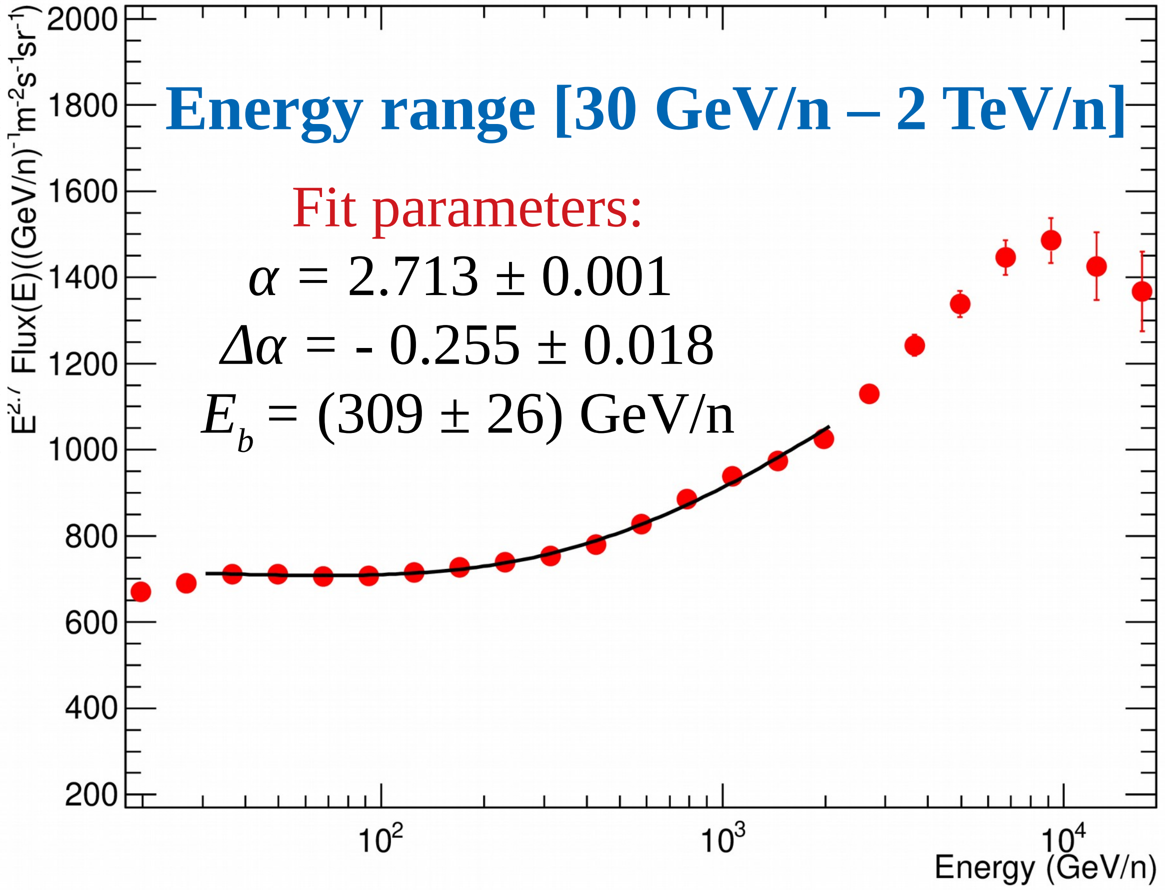
…

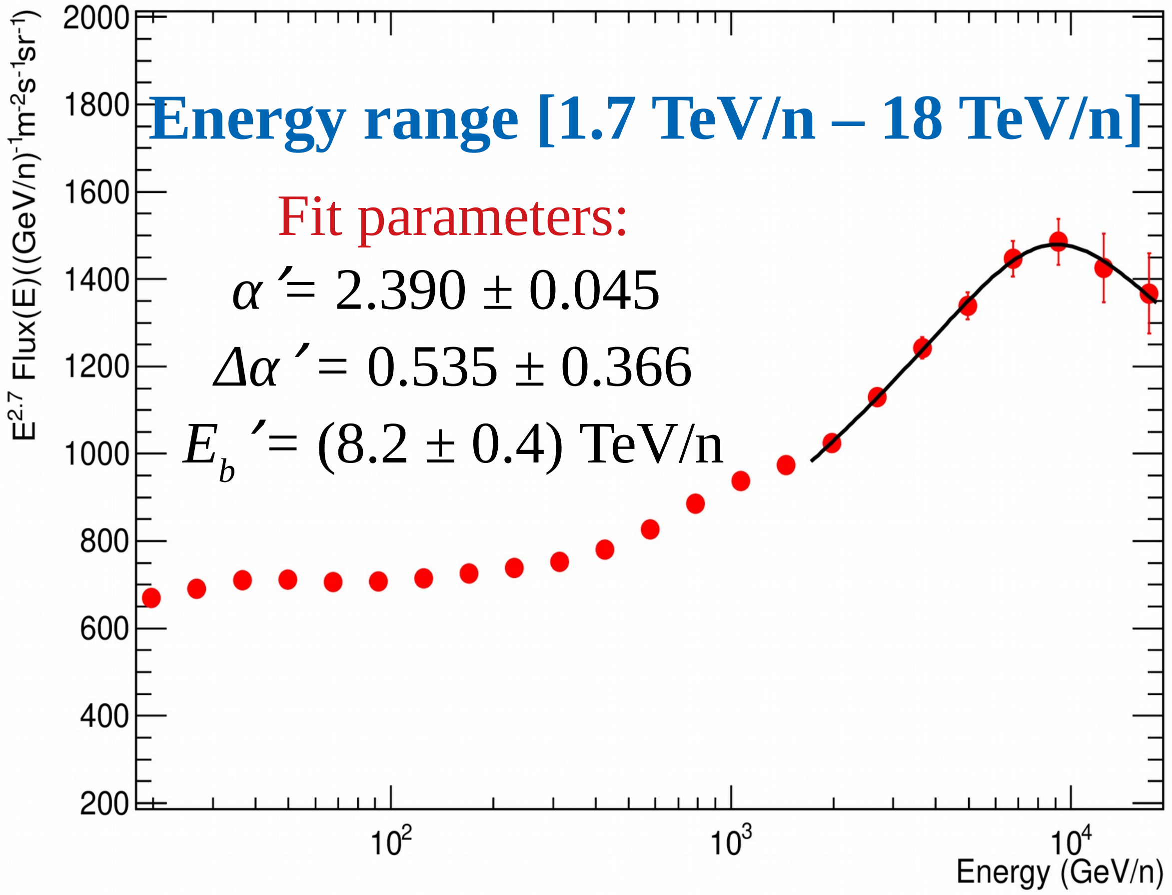
Number of nuisance parameters = 6



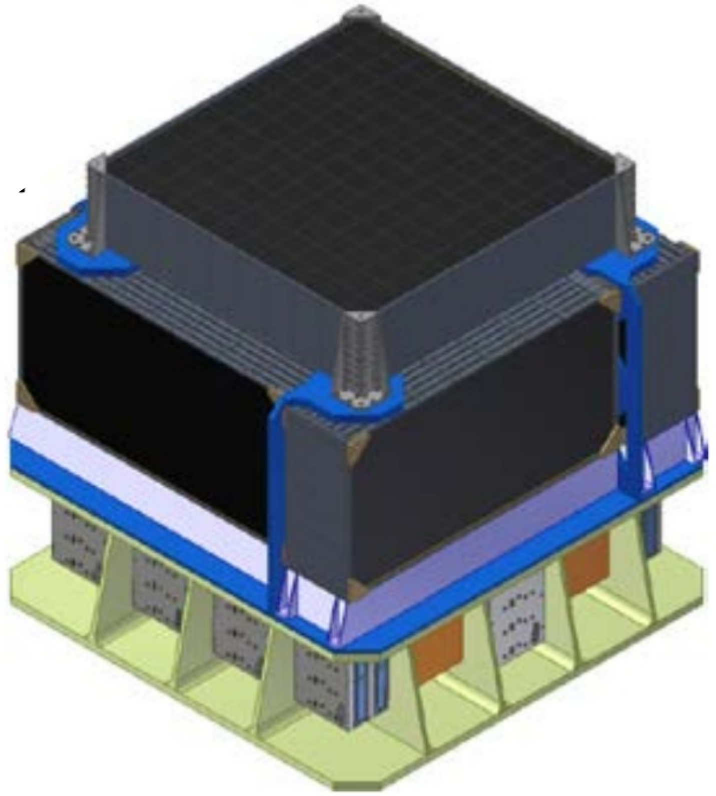
(*) **P. Lipari, S. Vernetto**, *The shape of the cosmic ray proton spectrum*, Astroparticle Physics 120 (2020) 102441

Fit done also with different m
No significant difference in the parameters





Good agreement between proton and helium DAMPE results and between DAMPE and other experiments



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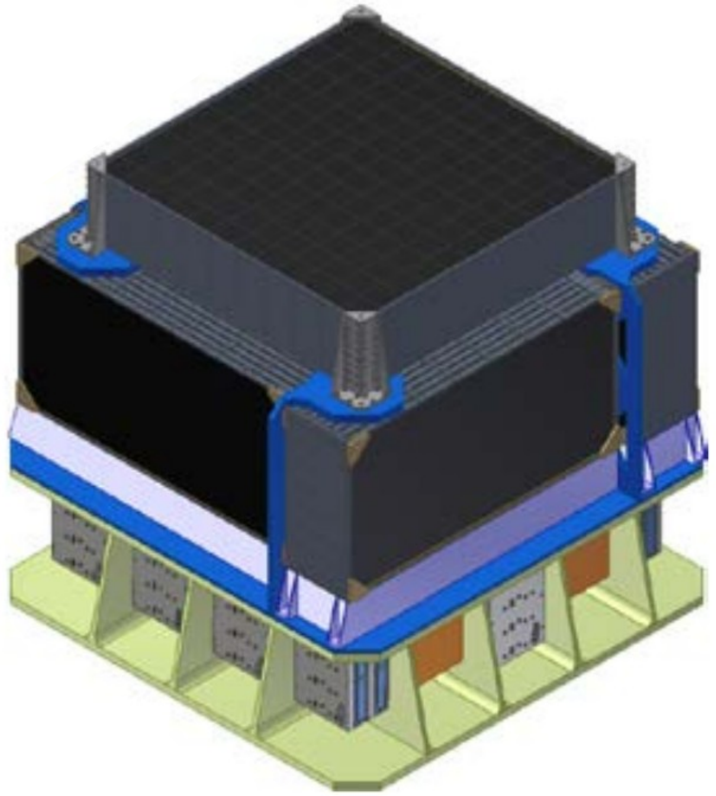
Overview

1. The HERD space mission
2. The PSD of HERD
3. Simulation results: Sr90 radioactive source and accelerated beams



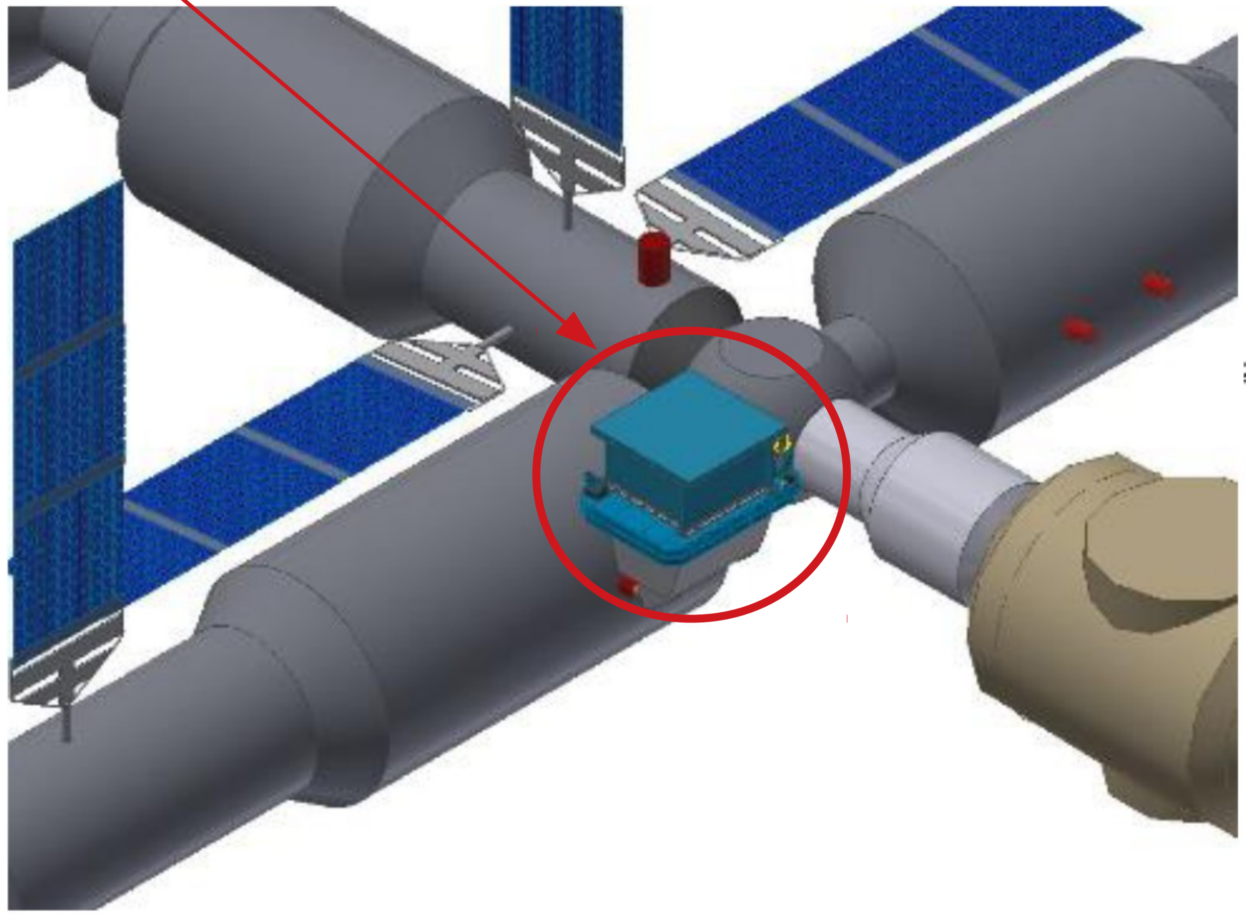
Part 2
Overview

1. **The HERD space mission**
2. The PSD of HERD
3. Simulation results: Sr90 radioactive source and accelerated beams

The HERD experiment

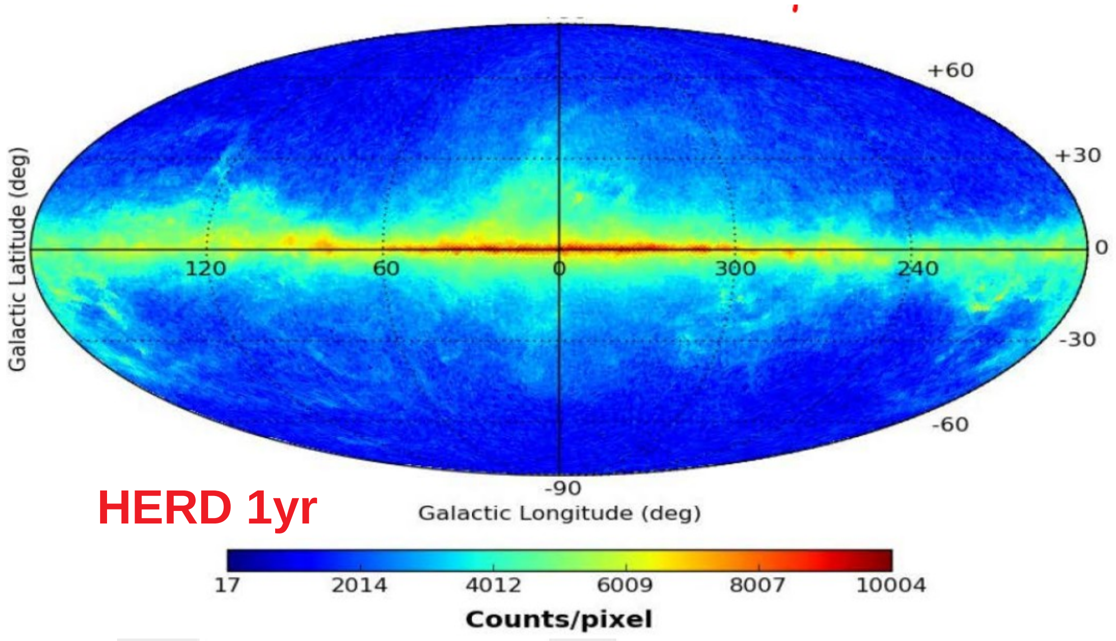
The High Energy cosmic Radiation Detection facility

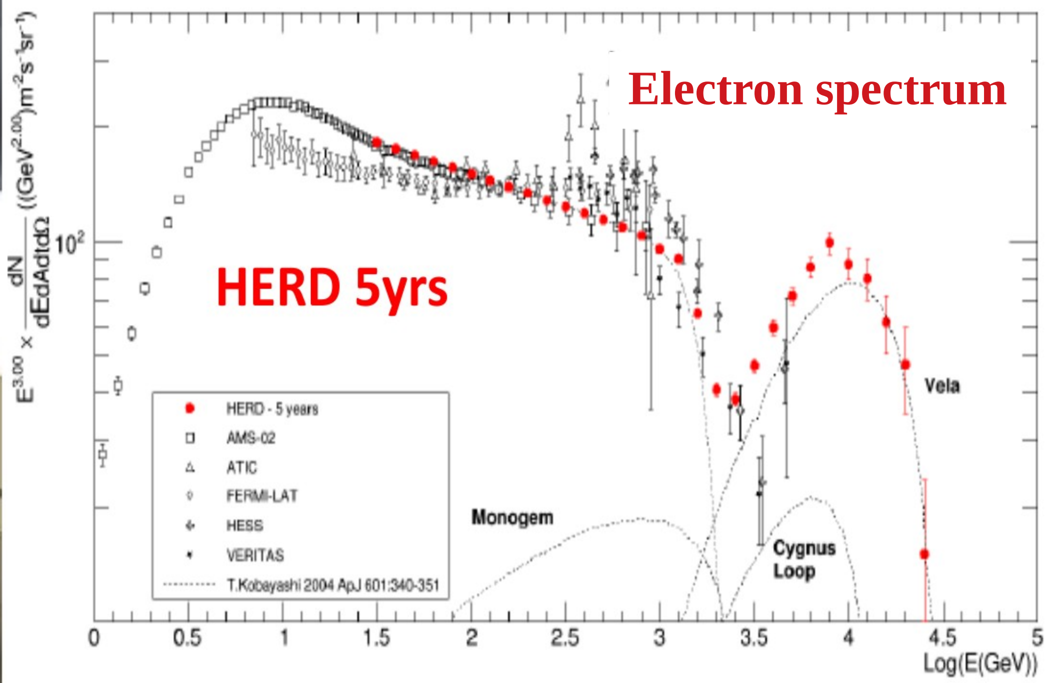
HERD is one of several space astronomy payloads planned to be on-board the China's Space Station

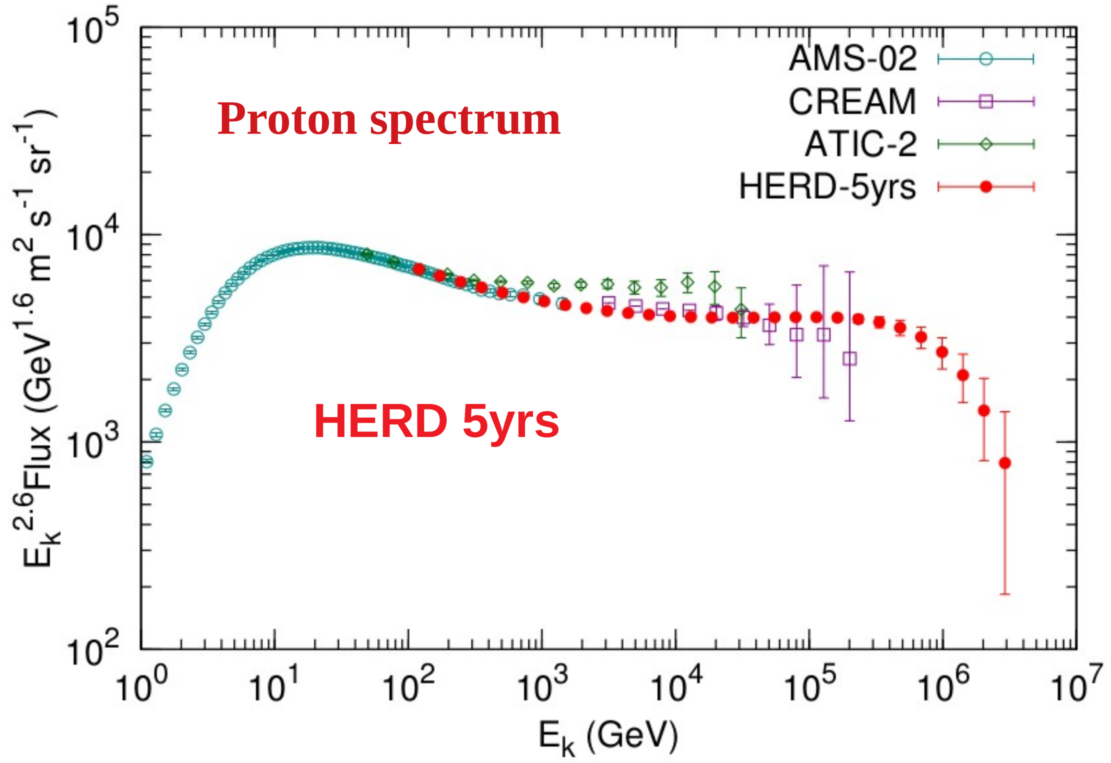


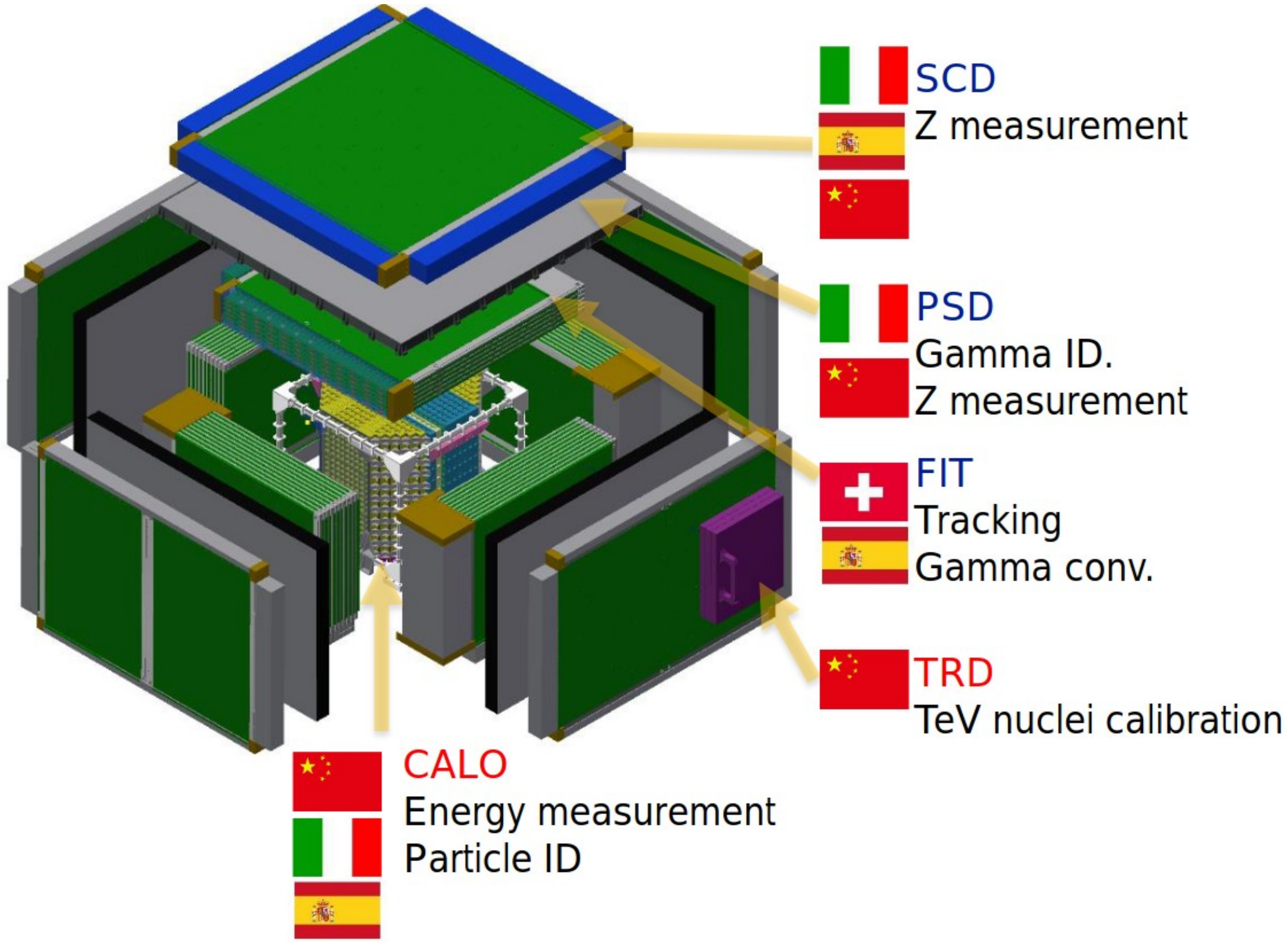
Scientific Objectives:

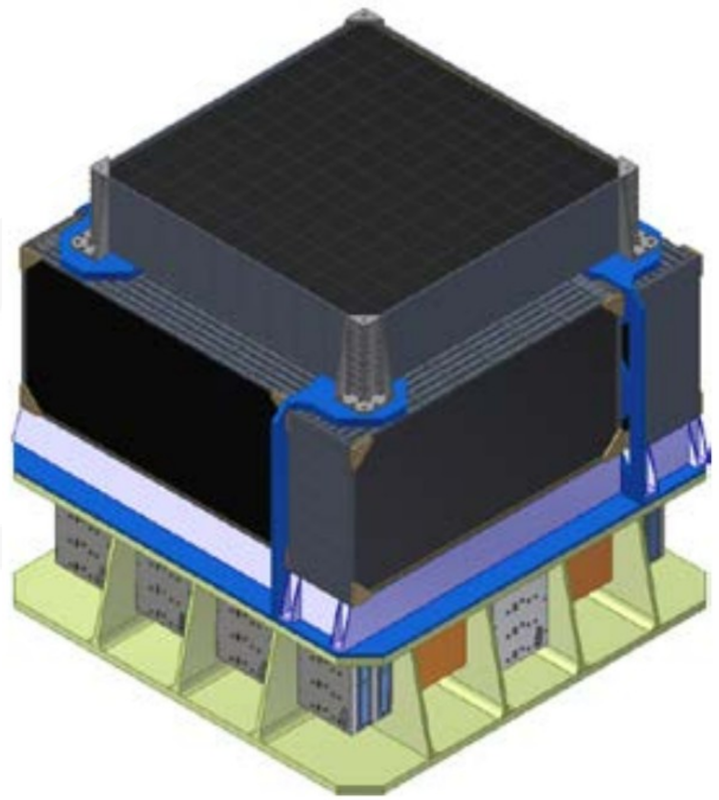
- Galactic Cosmic Rays studies
- Indirect Dark Matter searches
- High Energy Gamma Ray Astronomy











Part 2
Overview

1. The HERD space mission
2. **The PSD of HERD**
3. Simulation results: Sr90 radioactive source and accelerated beams

The Plastic Scintillator Detector (PSD)

Separation of γ-rays from charged particles, nuclei identification with Z from 1 to 26

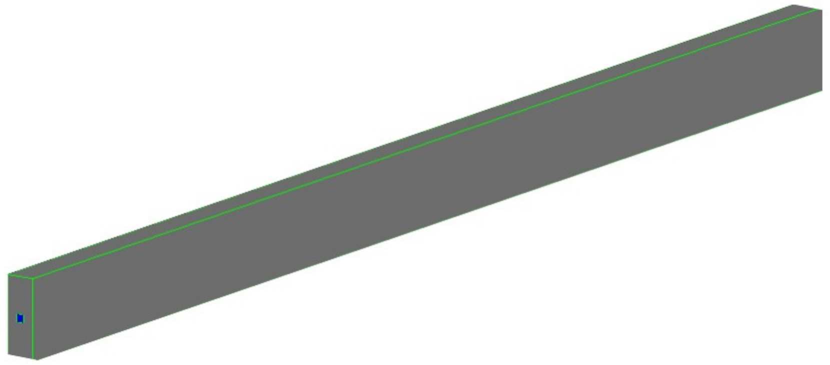
Two layout configurations under investigation – test in lab + simulation

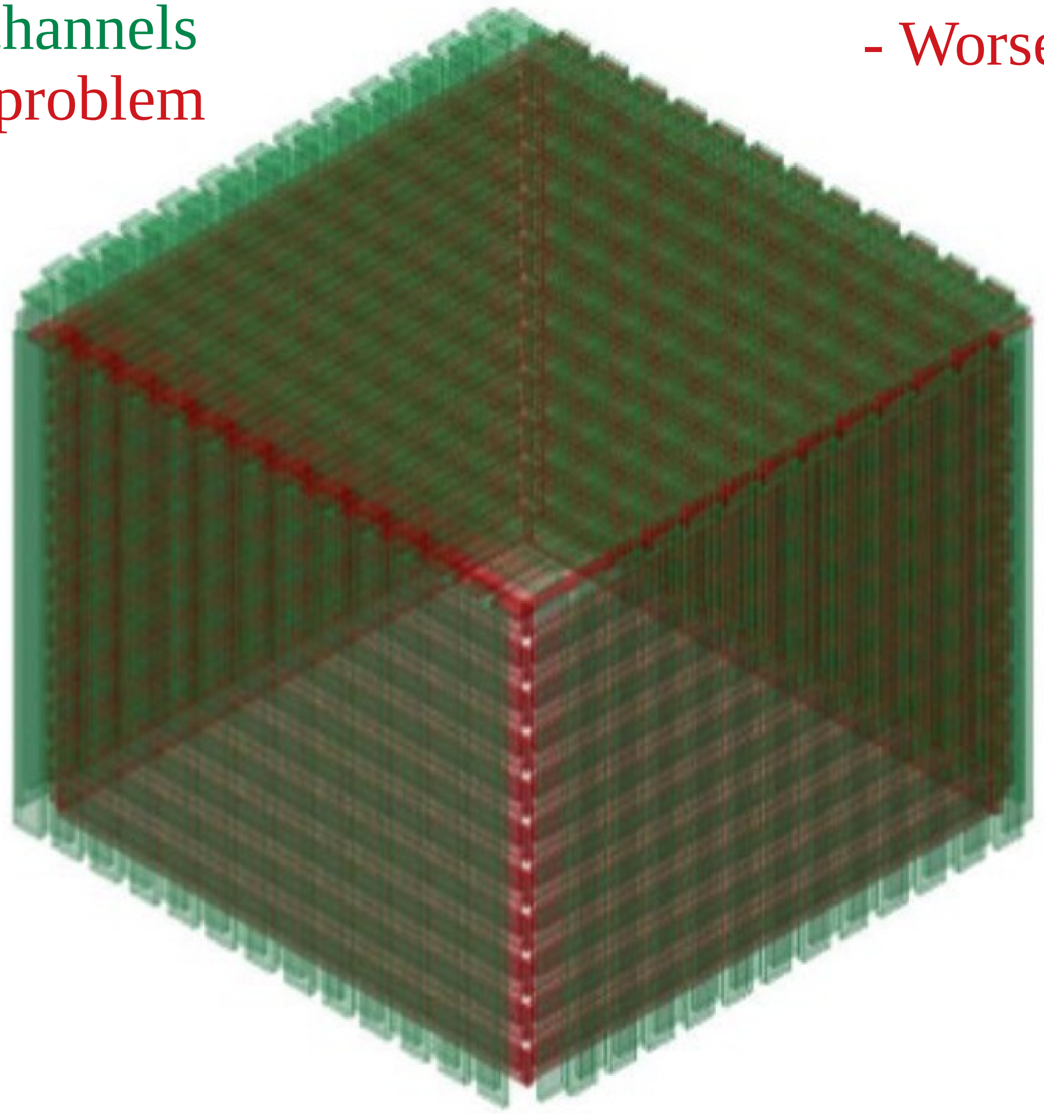
BAR option

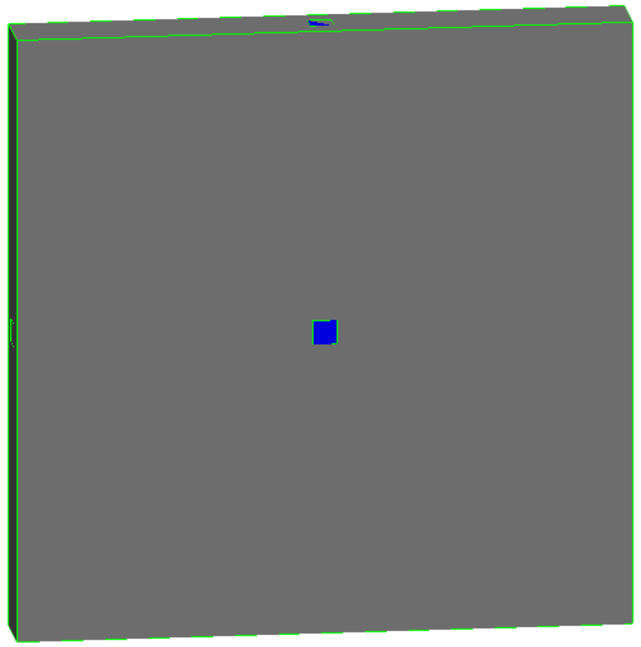
- Each layer made by two staggered sub-layers of long bars
- SiPM read-out at both ends of the bar (right and left) to reduce the light output non-uniformity along the bar itself
- Better option because of less number of read-out channels
- Worse option because of the higher backscattering problem

TILE option

- Two layers of small square tiles, read-out by 6 SiPMs
- Better option in order to reduce the backscattering problem
- Worse option for the large number of read-out channel







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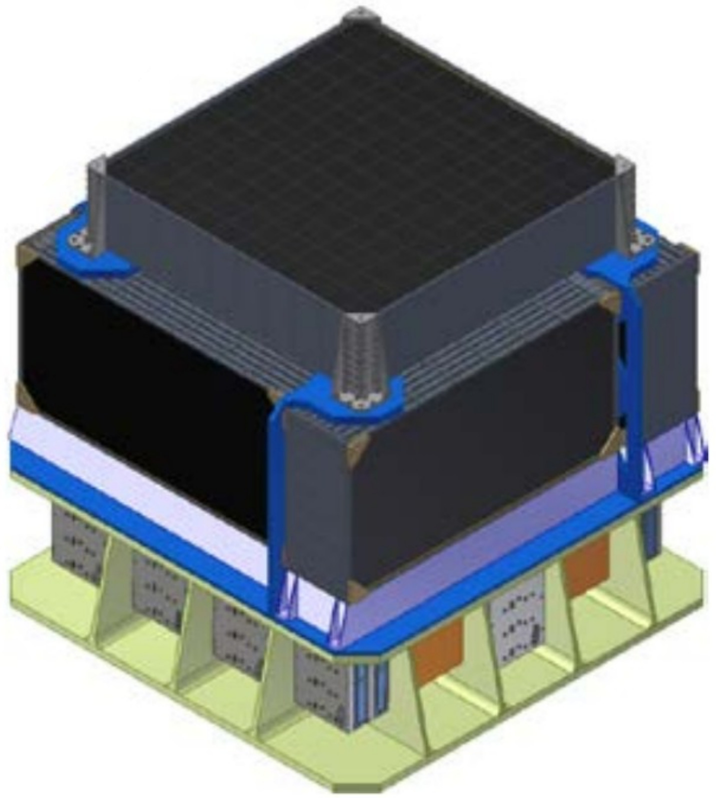
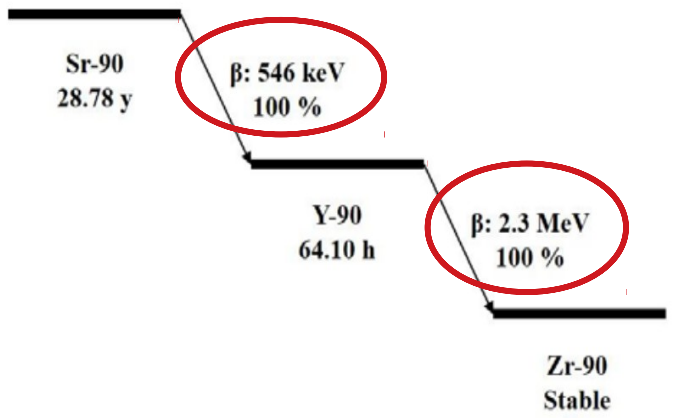
Part 2
Overview

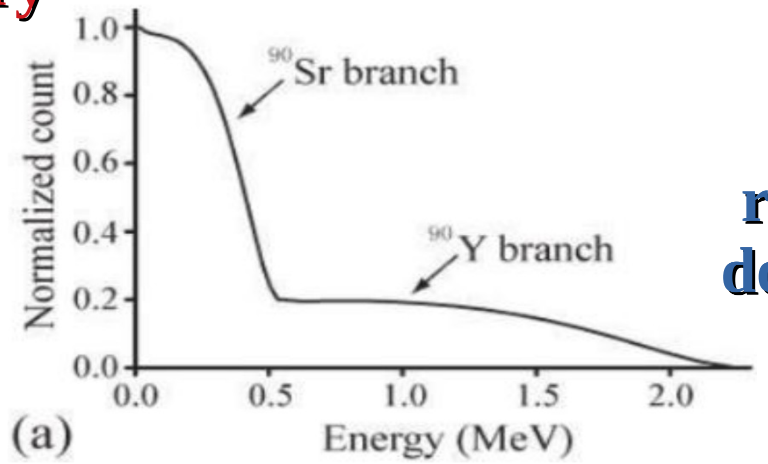


1. The HERD space mission
2. The PSD of HERD
3. **Simulation results: Sr90 radioactive source and accelerated beams**

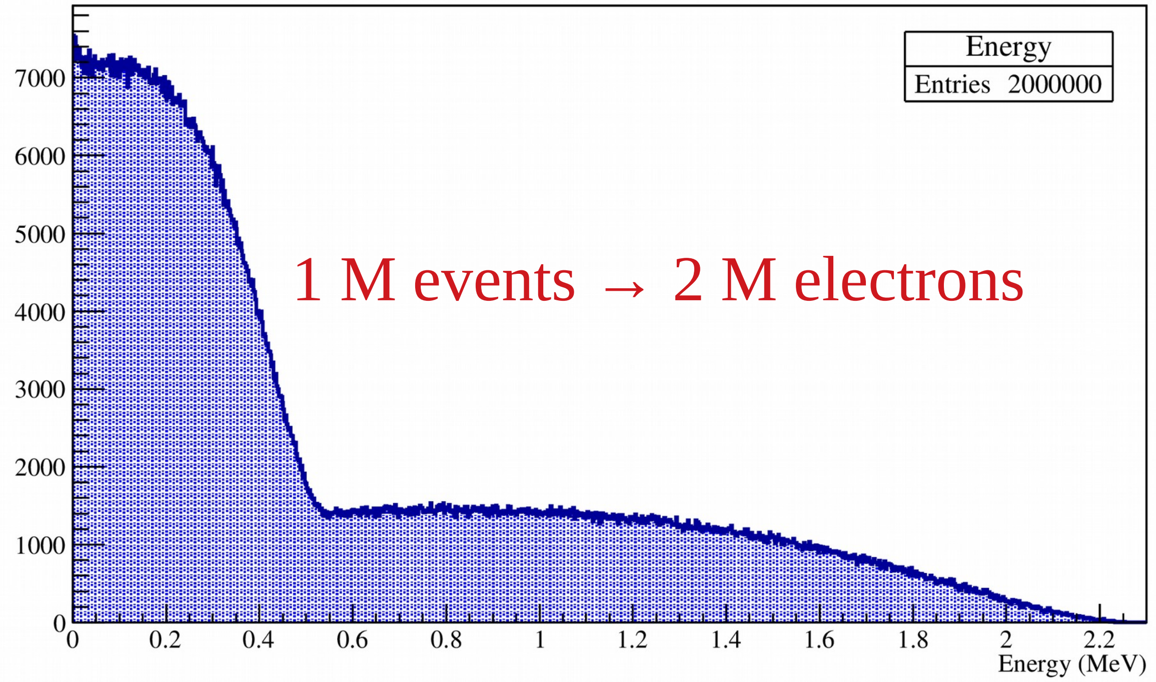
Sr90 radioactive source & test beam facilty

Theory

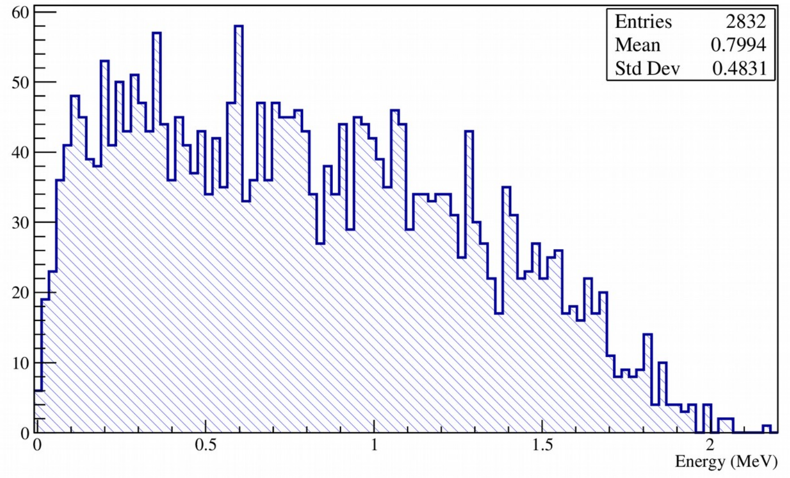




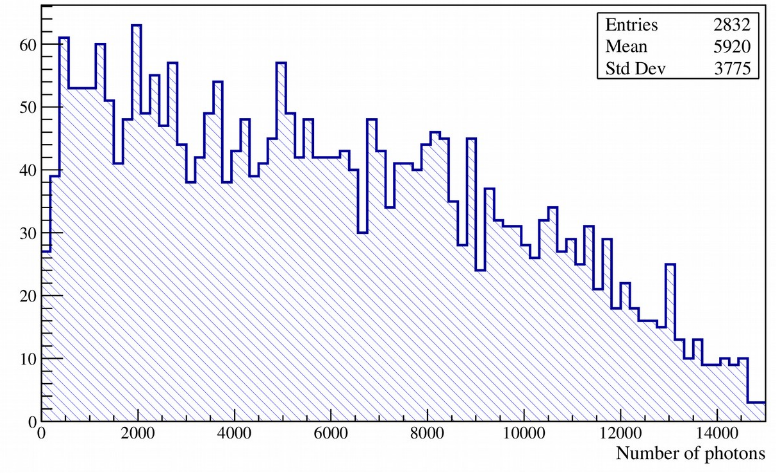
Simulation



Energy deposited by electrons in the bar



Number of scintillation photons produced by electrons in the bar

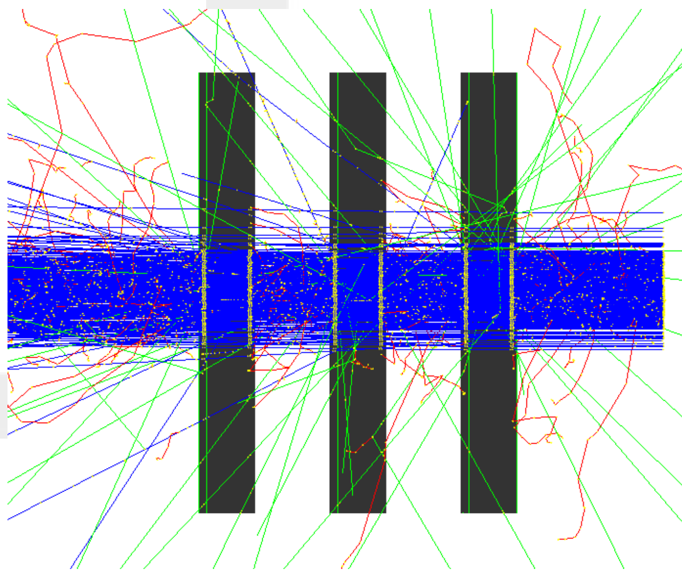


Simulation performed to reproduce hardware tests to be done at LNGS in the near future

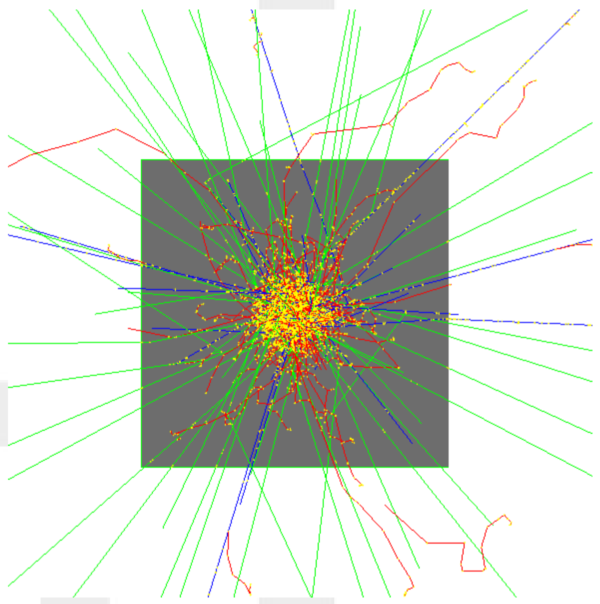
Studies for the test beam at CNAO with the Tile setup

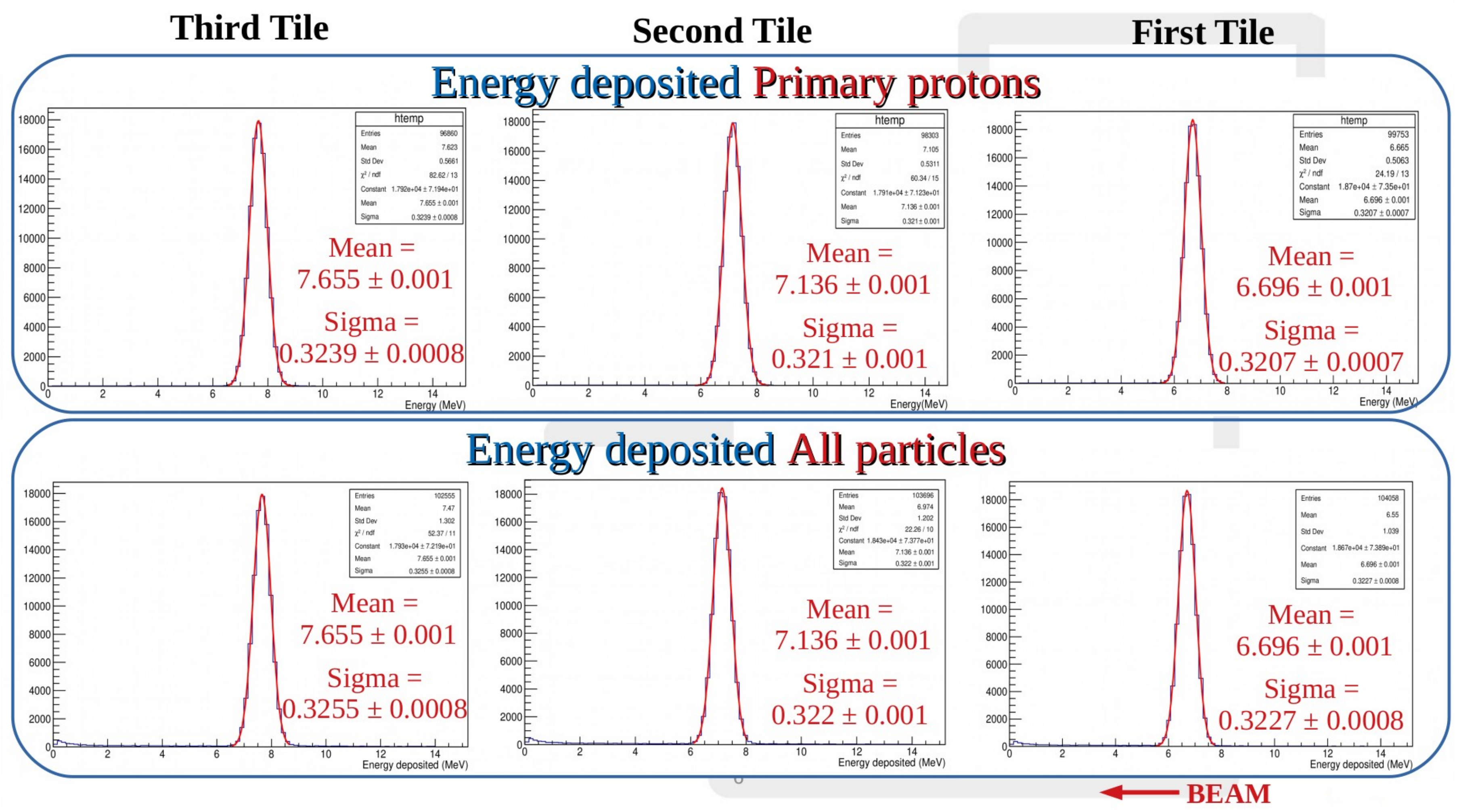
Ongoing simulation of the bar test beam setup

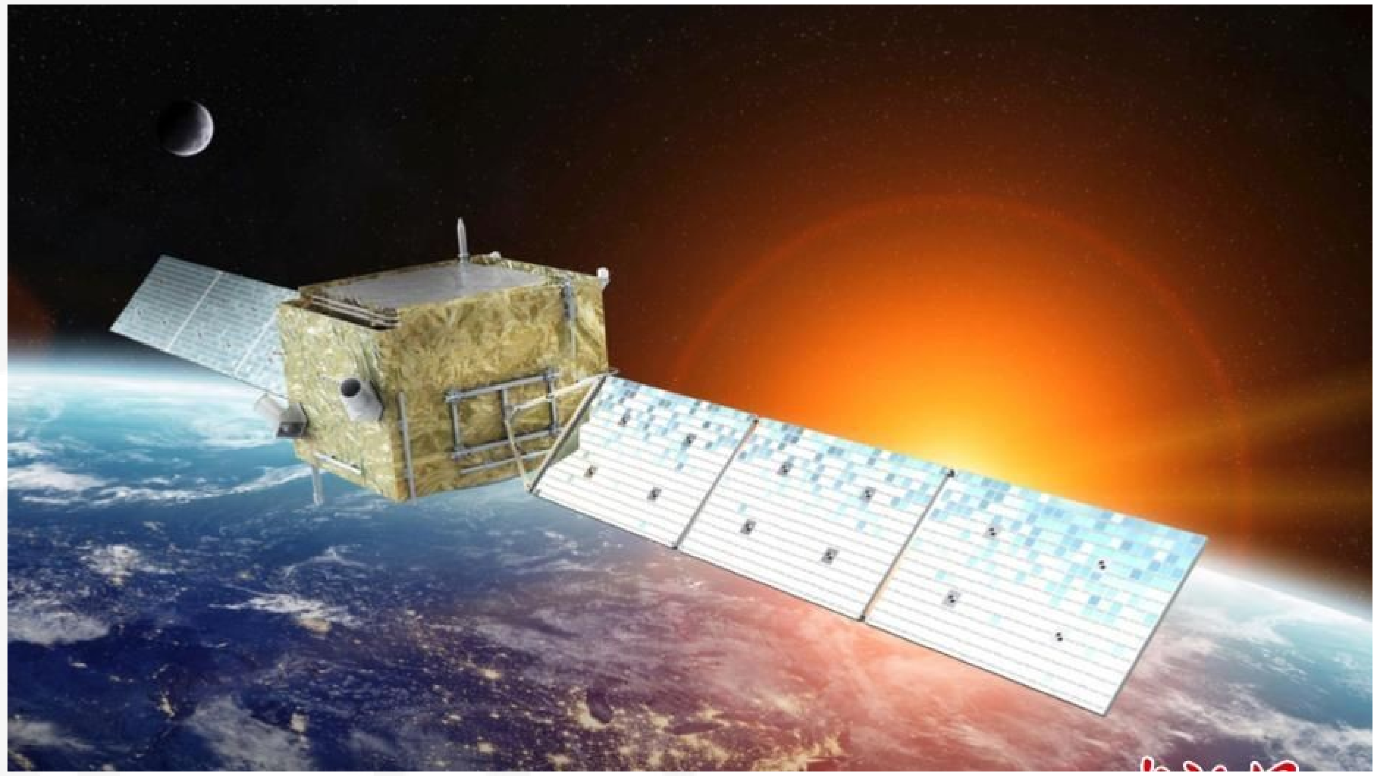
SIDE VIEW



FRONT VIEW







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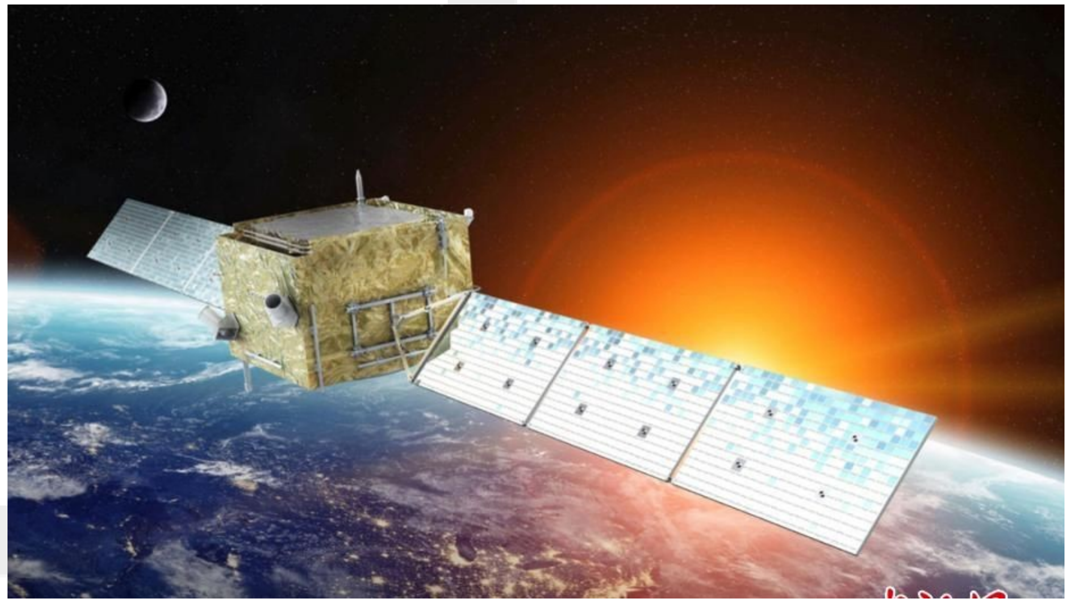
Summary and conclusions

- Light component (p+He) spectrum preliminary measured with the DAMPE experiment
- Ongoing extension of the spectrum to higher energy and correction for the saturation in DAMPE calorimeter
- Study towards the measurement of the heavy component (Fe)

- Evaluation of the systematic uncertainties due to backscattering effect
- Fit of the He spectrum

- GEANT4-based simulation of the Plastic Scintillator Detector
- Simulation to be compared with hardware tests
- I am participating in the definition of the final design for the future HERD space mission

Thank you for your attention!



WORKSHOPS/CONFERENCES/COLLABORATION MEETINGS

- 8th International DAMPE Workshop, L'Aquila, 10/12/2018 – 12/12/2018
- 105° Congresso Nazionale SIF, L'Aquila, 23/09/2019 – 27/09/2019.

Talk: *"Measurement of the cosmic-ray proton + helium spectrum with DAMPE"*

- SiPM workshop: from fundamental research to industrial applications, Bari, 2/10/2019 – 4/10/2019
- Cosmic Ray Anisotropy Workshop CRA2019, L'Aquila, 7/10/2019 – 11/10/2019
- HerdSoftware hands-on session, Bari, 16/10/2019 – 18/10/2019
- DAMPE simulation hands-on meeting, CERN (Geneva), 25/11/2019
- 8th HERD Workshop, Xi'an, China, 16/12/2019 – 17/12/2019.

Talk: *"GEANT4-based simulation of light production/propagation/detection in bar shaped PSD with SiPM readout @ GSSI"*

- CORSIKA Cosmic Ray Simulation Workshop [virtual], 22/06/2020 – 25/06/2020
- DAMPE-EU collaboration meeting [virtual], 16/07/2020

Talk: *"Update on the light element (p + He) analysis and studies towards the measurement of the heavy component (Fe)"*

- 106° Congresso Nazionale SIF [virtual], 14/09/2020 – 18/09/2020

Talk: *"Measuring light elements in space with the DAMPE mission"*

- **Several talks** during periodical working group online meetings of DAMPE and HERD.

OUTREACH ACTIVITIES

- Part of the scientific committee for "Premio Asimov", April 2019
- Outreach Cosmic Ray Activities (OCRA stage), L'Aquila, 15/04/2019 – 16/04/2019
- Volunteer in the SIF conference, L'Aquila, 23/09/2019 – 27/09/2019
- Participation in SHARPER (European Researcher's night) with a stand in Piazza Duomo, L'Aquila, 27/09/2019
- ICD International Cosmic Day, L'Aquila, 6/11/2019
- Part of the scientific committee for "Premio Asimov", April 2020

SCHOOLS

- Joint 9th IDPASC SCHOOL and XXXI INTERNATIONAL SEMINAR of NUCLEAR and SUBNUCLEAR PHYSICS “Francesco Romano”, Otranto, 27/05/2019 – 4/06/2019

- VIII International Geant4 School, Belgrade, 17/11/2019 – 22/11/2019

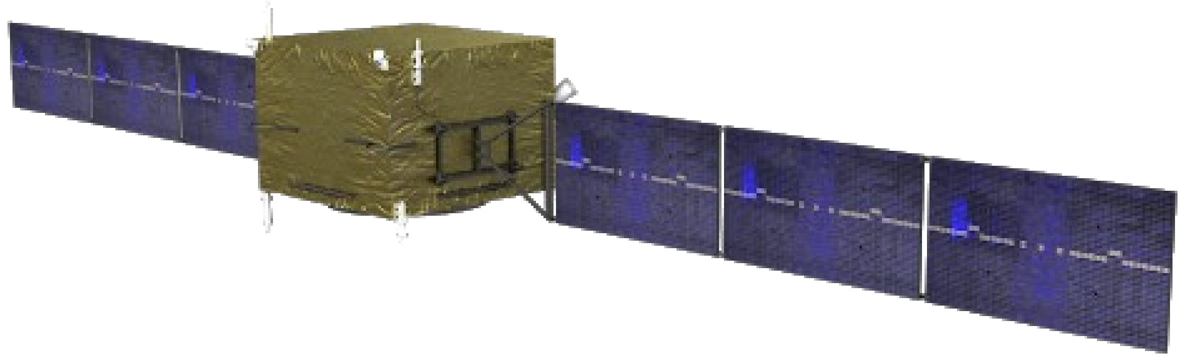
SCIENTIFIC PUBLICATIONS

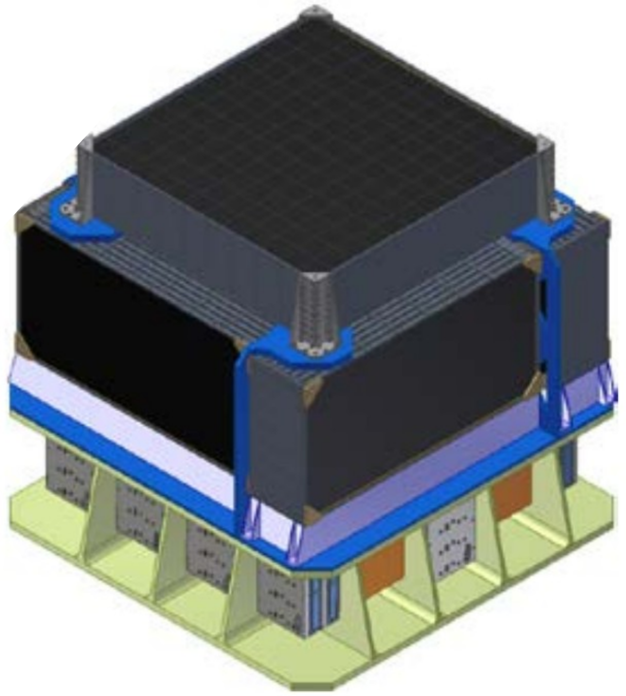
- **PUBLISHED:** Y. Wei, Y. Zhang, Z. Zhang, L. Wu, H. Dai, C. Liu, C. Zhao, Y. Wang, Y. Zhao, P. Jiang, Y. Wang, F. Alemanno, M. Di Santo, E. Catanzani, X. Wang, Z. Xu, G. Huang, “The Quenching Effect of BGO Crystals on Relativistic Heavy Ions in the DAMPE Experiment”, in *IEEE Transactions on Nuclear Science*, vol. 67, no. 6, pp. 939-945, June 2020, doi: 10.1109/TNS.2020.2989191.

- **PUBLISHED:** C. Yue, P. Ma, M. Di Santo, L. Wu, F. Alemanno, P. Bernardini, D. Kyratzis, G. Yuan, Q. Yuan, Y. Zhang, “Correction Method for the Readout Saturation of the DAMPE Calorimeter”, in *Nuclear Inst. and Methods in Physics Research A*, September 2020. https://doi.org/10.1016/j.nima.2020.164645

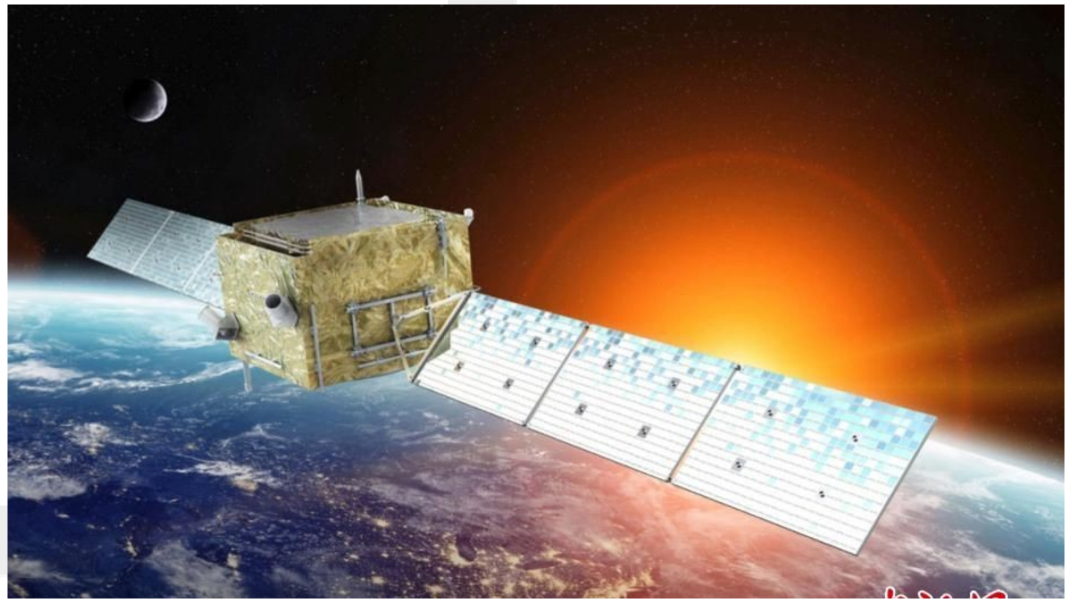
- **ACCEPTED FOR PUBLICATION:** W. Jiang, C. Yue, M. Cui, X. Li, Q. Yuan, F. Alemanno, P. Bernardini, Z. Chen, T. Dong, G. Donvito, D. F. Droz, P. Fusco, F. Gargano, D. Guo, D. Kyratzis, S. Lei, Y. Liu, F. Loparco, P. Ma, G. Marsella, M. N. Mazziotta, I. De Mitri, X. Pan, W. Peng, A. Surdo, A. Tykhonov, Y. Wei, Y. Yu, J. Zang, Y.-P. Zhang, Y.-J. Zhang, Y.-L. Zhang, “Comparison of proton shower developments in the BGO calorimeter of the Dark Matter Particle Explorer between GEANT4 and FLUKA simulations”, in *Chinese Physics Letters*, September 2020. http://arxiv.org/abs/2009.13036

- **TO BE SUBMITTED:** F. Alemanno, D. Kyratzis, et al., “Outreach Cosmic Ray Activities (OCRA): measurement of muon flux at various altitude”, September 2020.

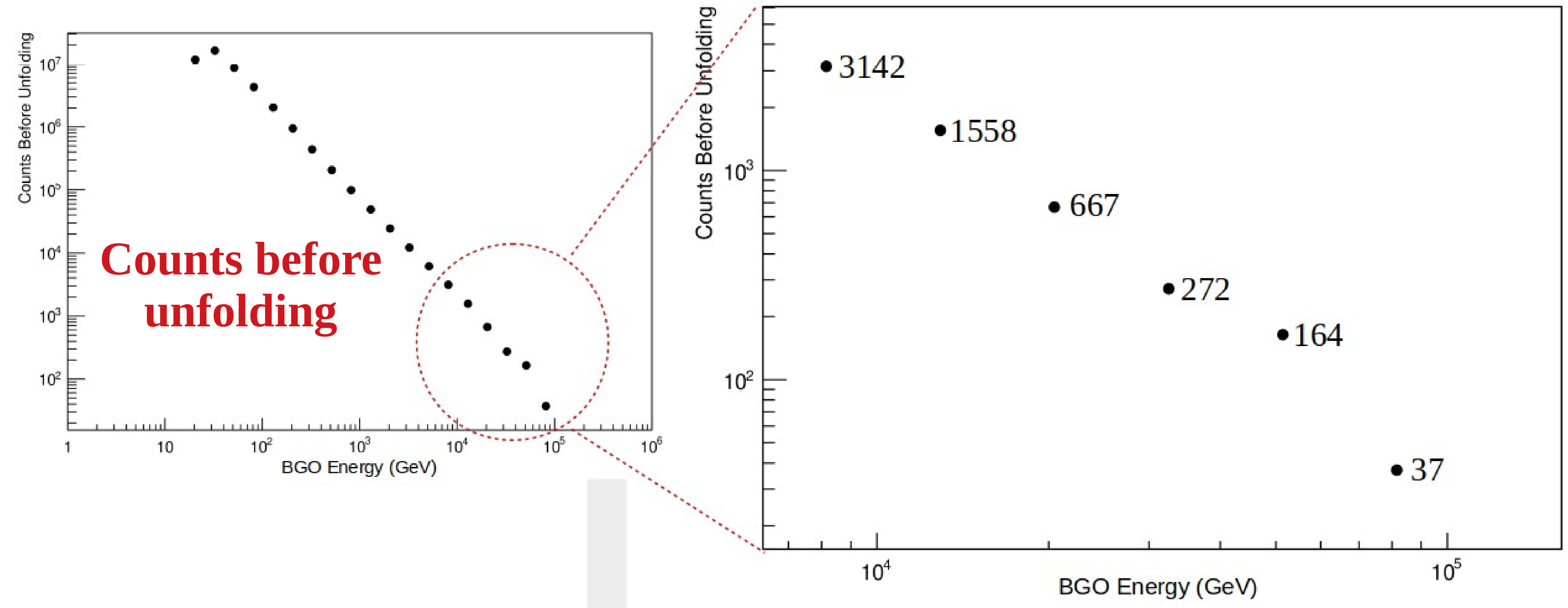


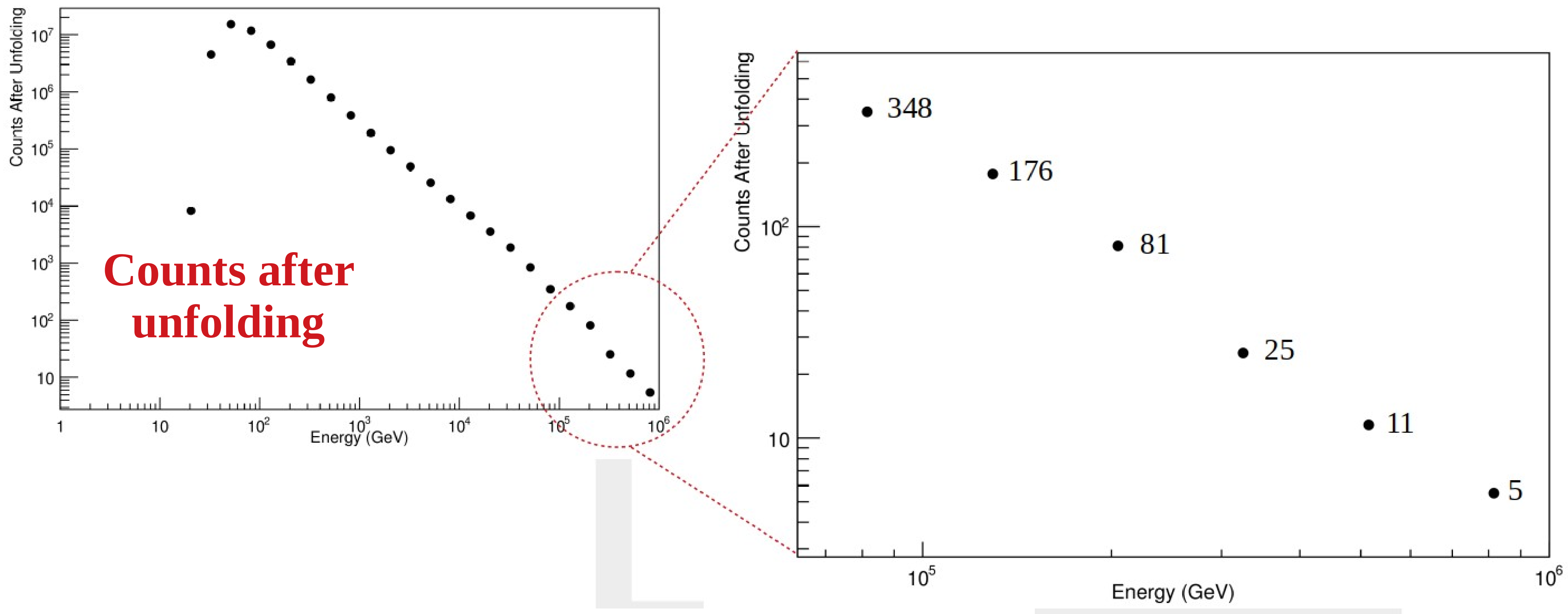


BACKUP SLIDES

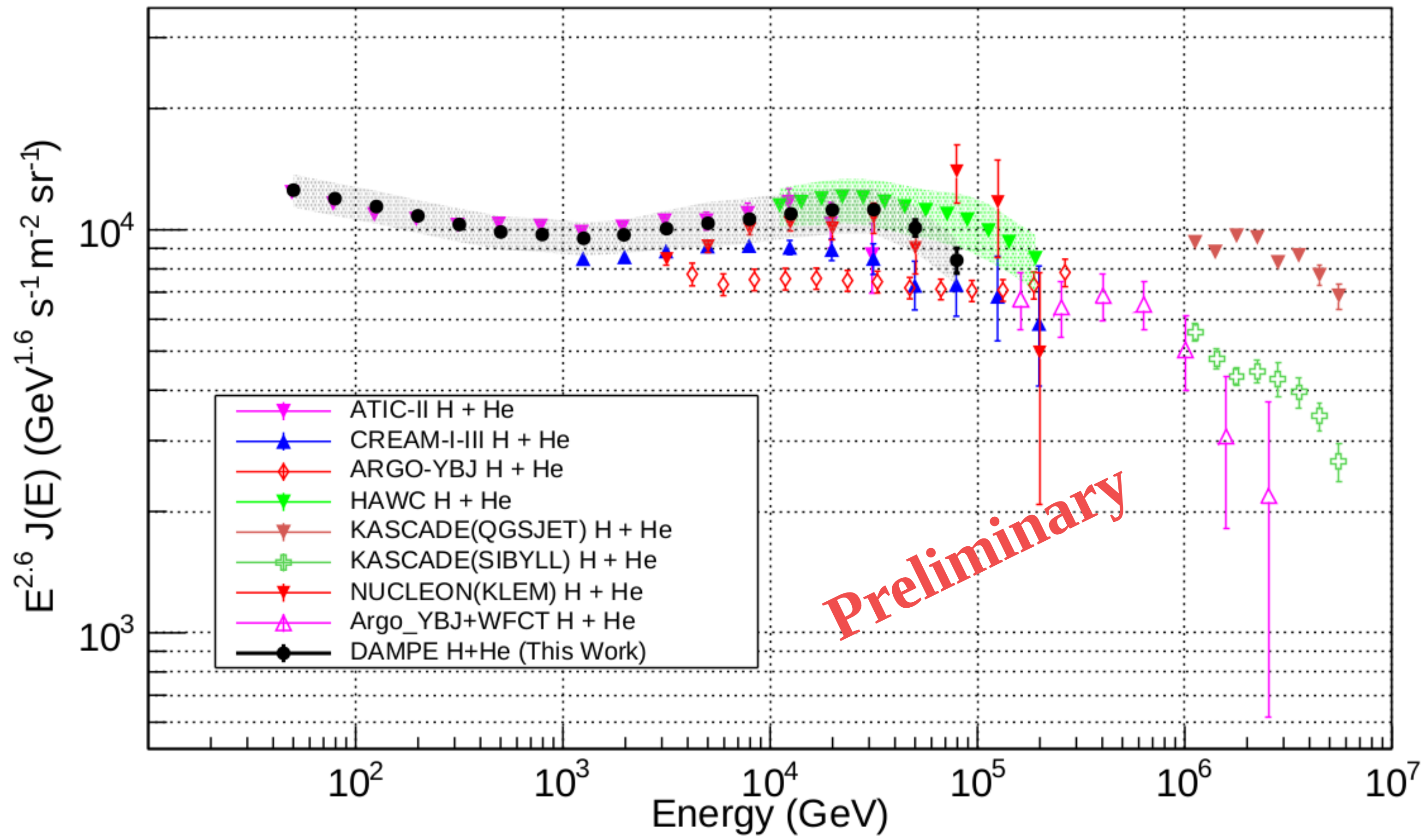


Is it worth to extend the p + He spectrum to higher energy





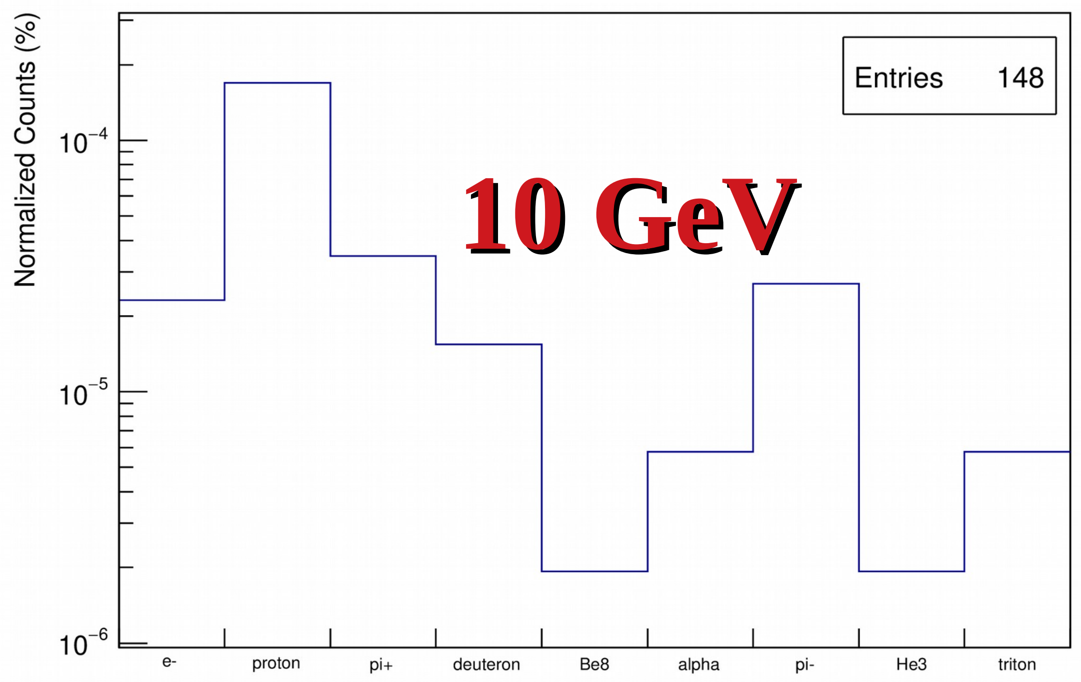
High energy region important for comparison with indirect detection experiments

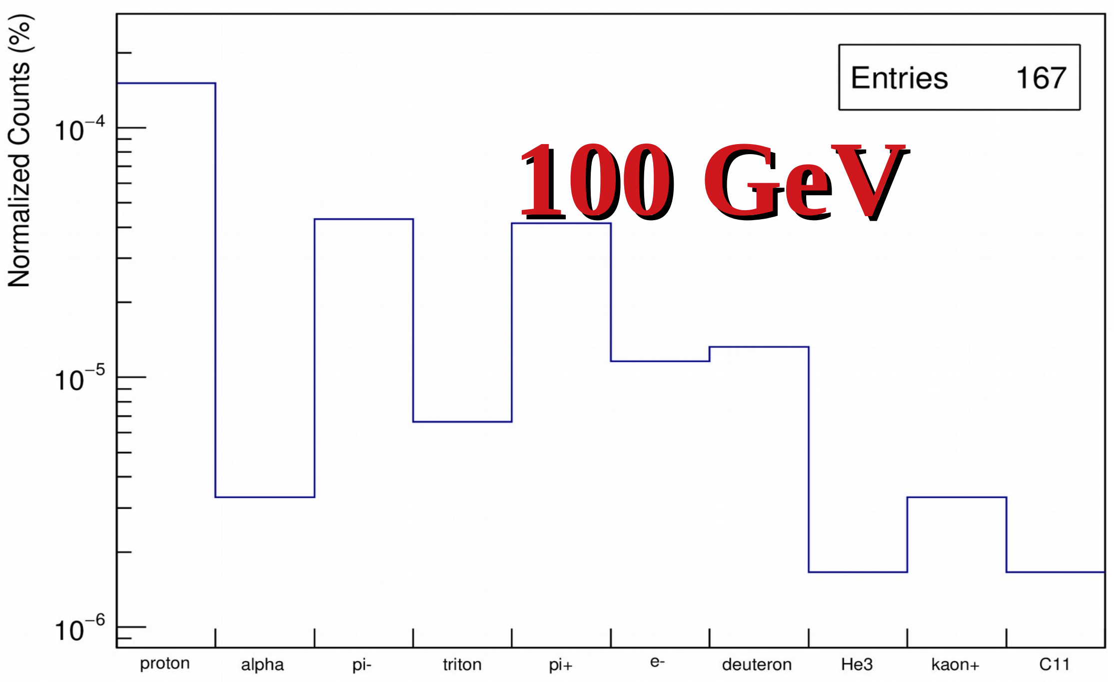


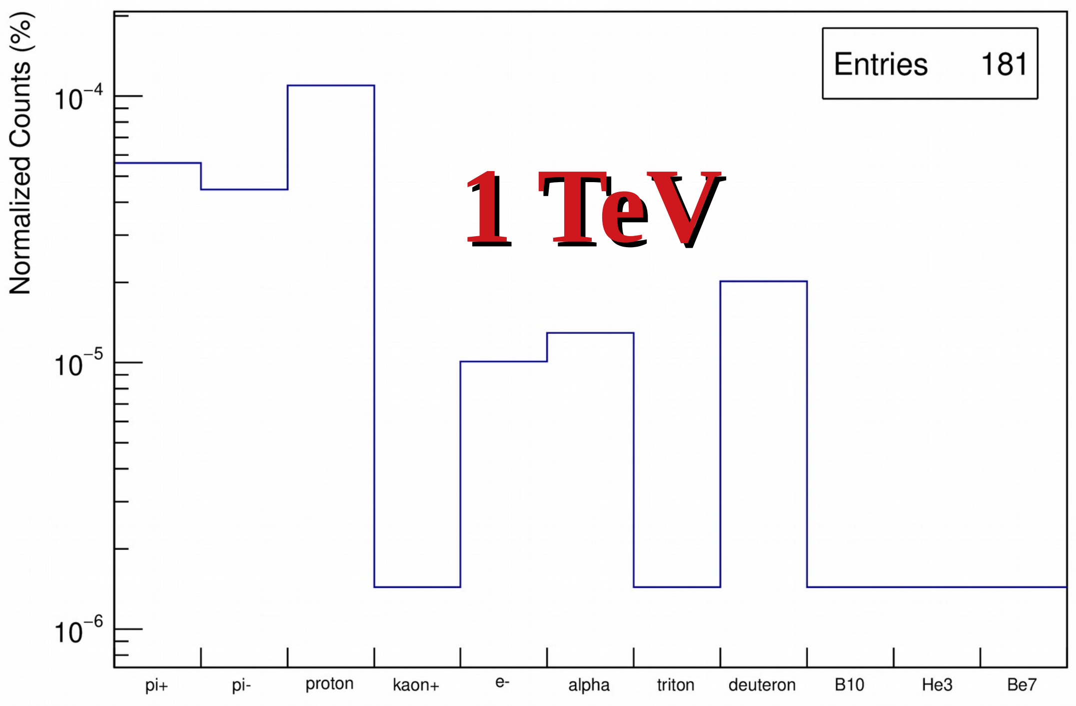
Extend the flux above 100 TeV → need of MC samples
MC production (work in progress):
Helium and Proton MC [100 TeV – 1 PeV]

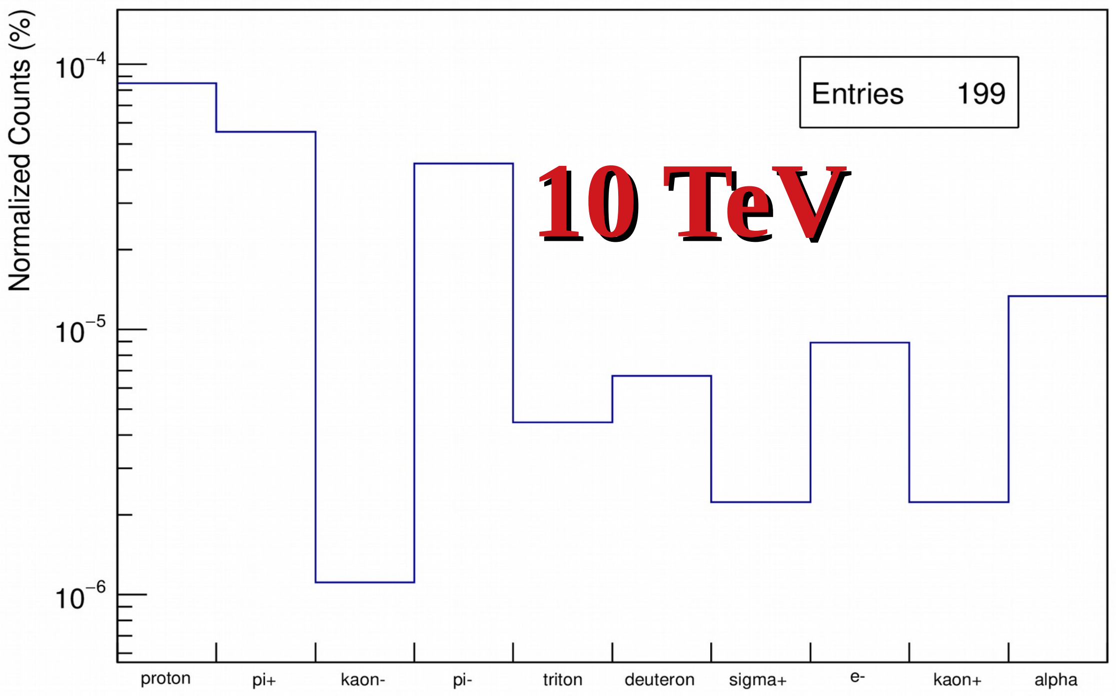
GSSI

Backscattered particles in the PSD









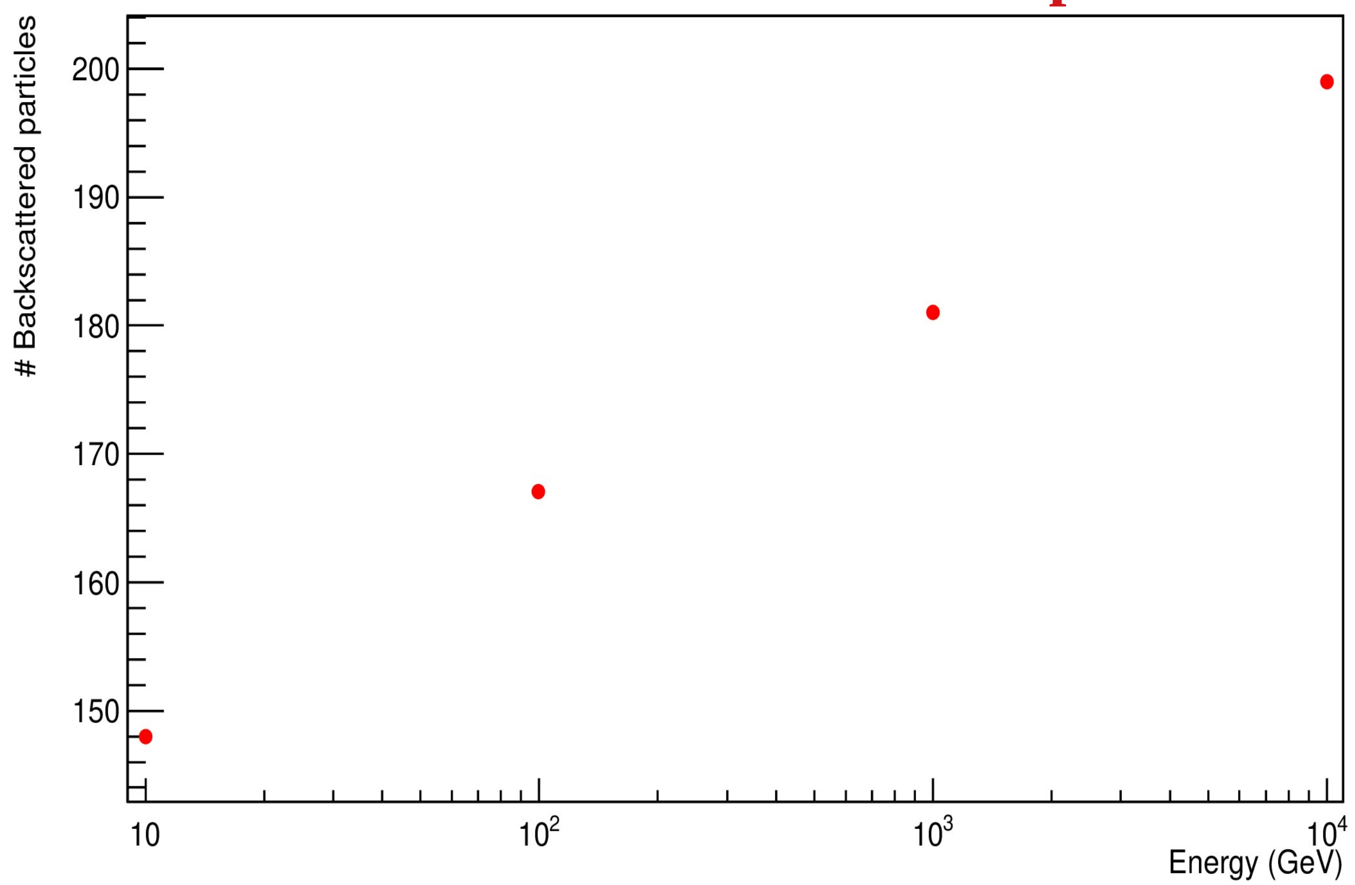
Primary particles: Protons

Number of events: 1000 per energy value

Energy of the incoming particle:

10 GeV, 100 GeV, 1 TeV, 10 TeV

Total number of backscattered particles



The backscattered particles are mainly: protons, pi+ and pi- releasing energy of ~ hundreds of MeV

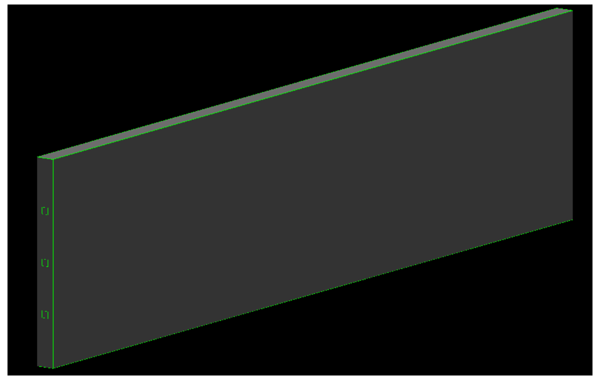
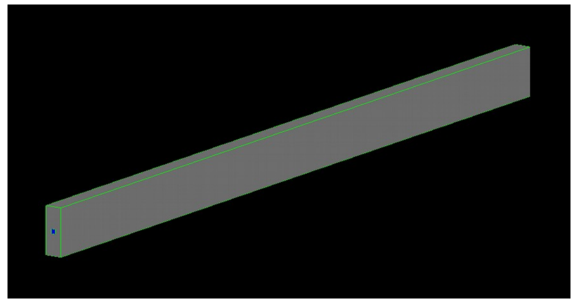
NEXT STEPS:

- **Extend the study to other nuclei (important for Fe analysis)**
- **Check different hadronic models**

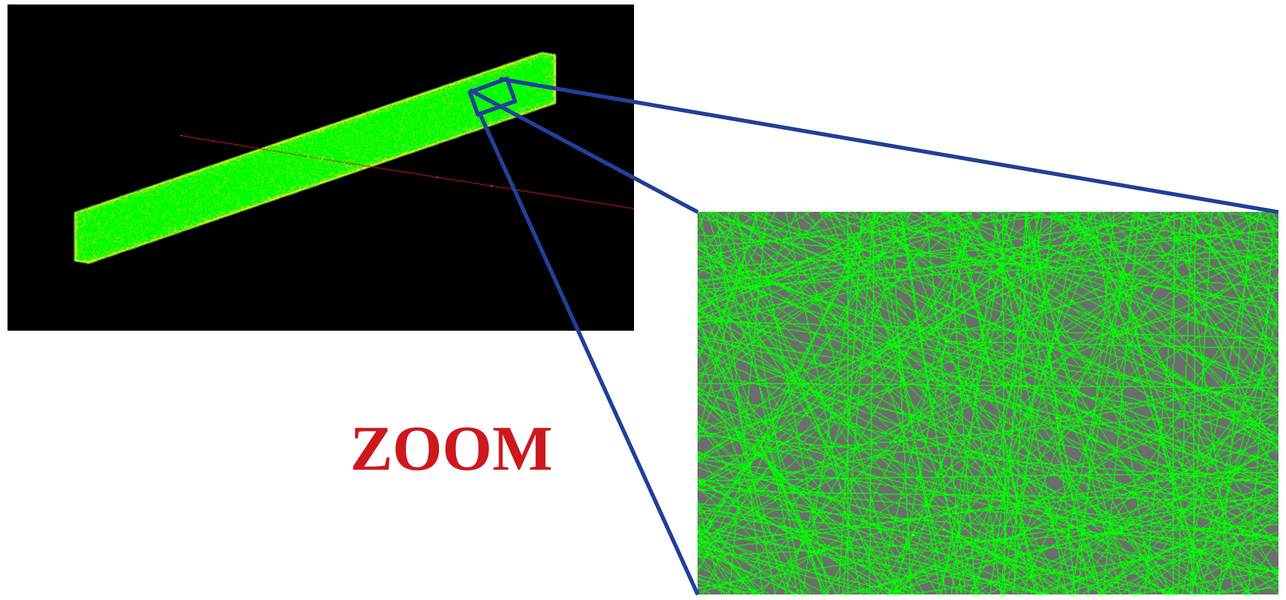
GEANT-4 based simulation of the PSD

The user can:

Modify the geometry:
- scintillator shape, size, material
- wrapping thickness and material
- SiPMs size, dimension, position

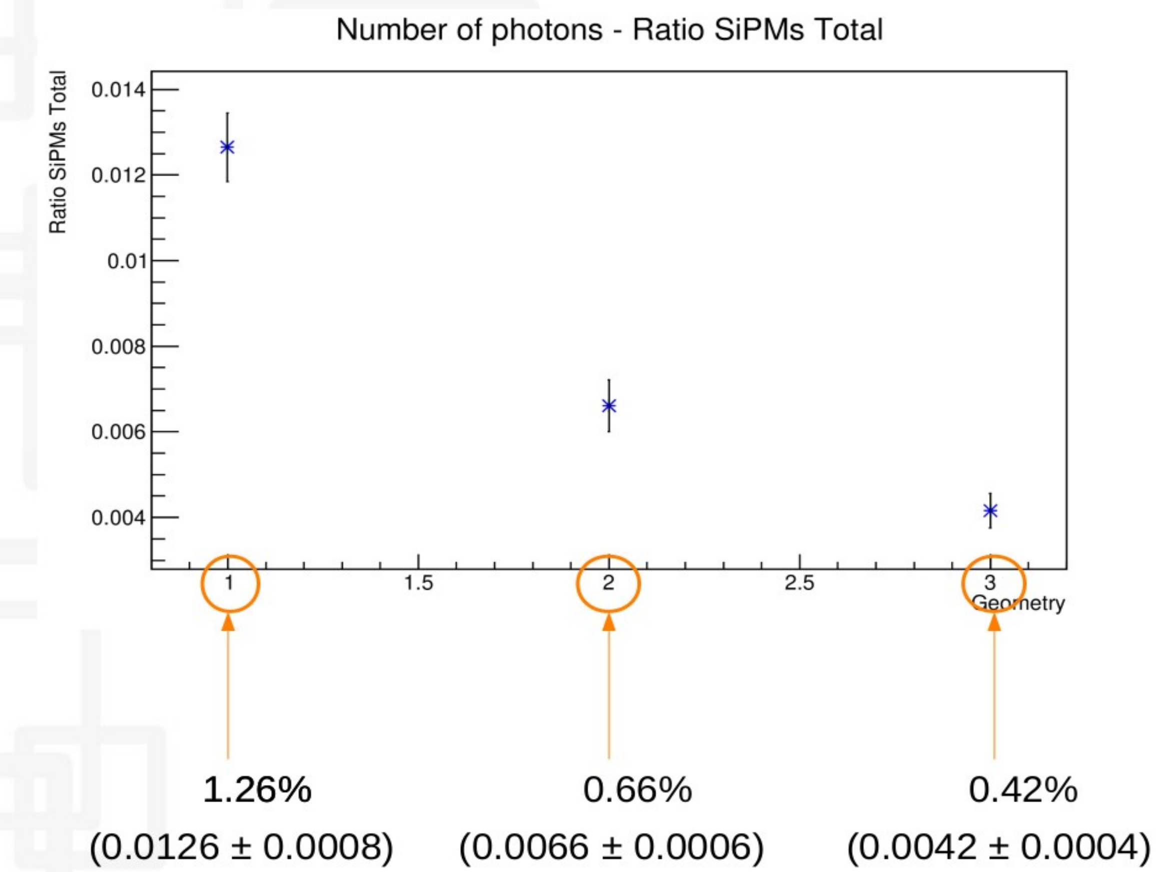
The user can:
- Turn ON/OFF Cherenkov/Scintillation photon production
- Set the optical properties of the detector: light yield and attenuation length of the scintillator material, refractive index etc.



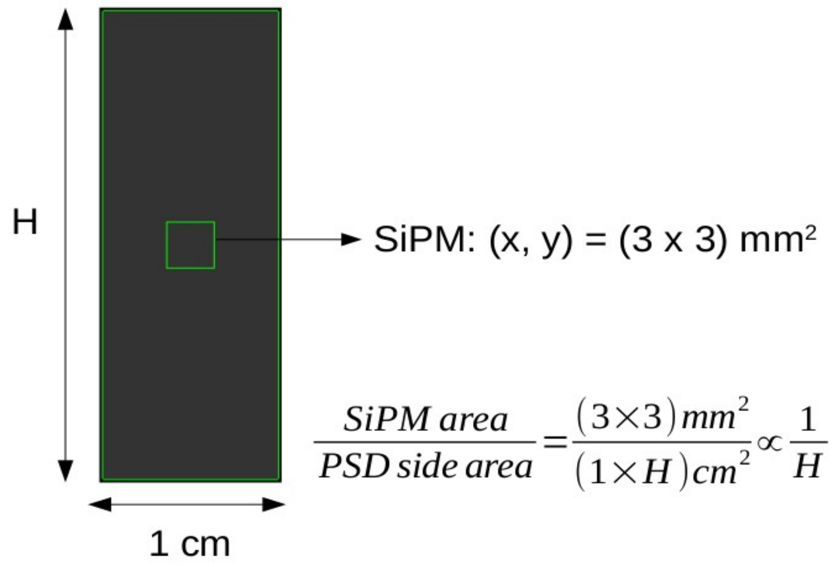
ZOOM

Ratio between number of photons at the SiPMs and total number of photons in the bar

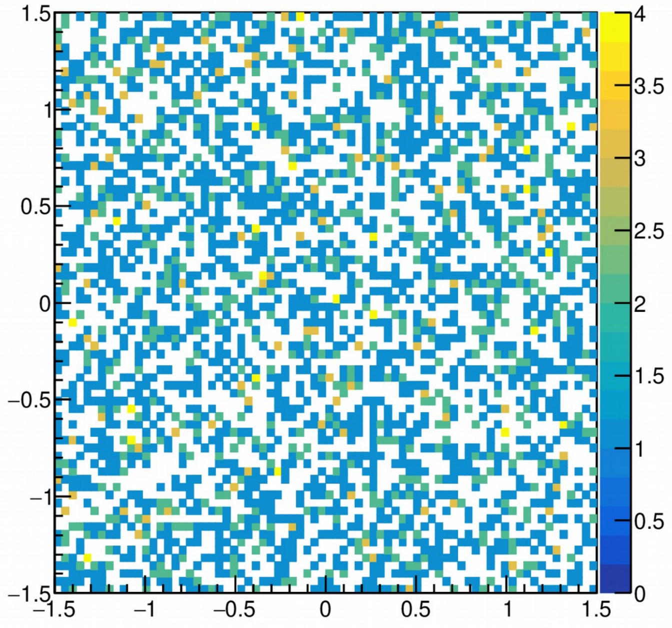
COMPARISON



Geometry 1: (x, y, z) = (1, 1, 50) cm
Geometry 2: (x, y, z) = (1, 2, 50) cm
Geometry 3: (x, y, z) = (1, 3, 50) cm

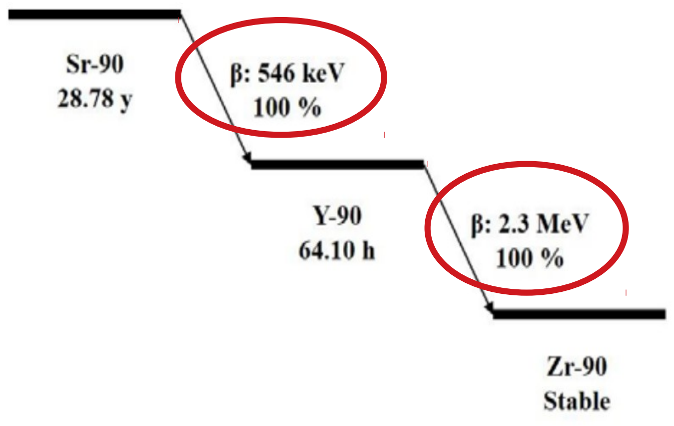


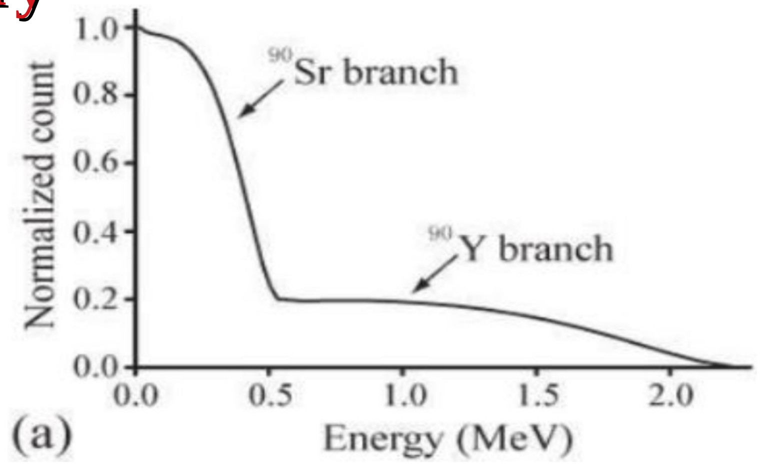
Study of the SiPMs cell occupancy
- AdvanSiD ASD – NUV3S
- 40 µm microcells pitch
- 43% PDE
- 250 MeV proton beam
- 100 protons central position



Simulation results: Sr90 radioactive source

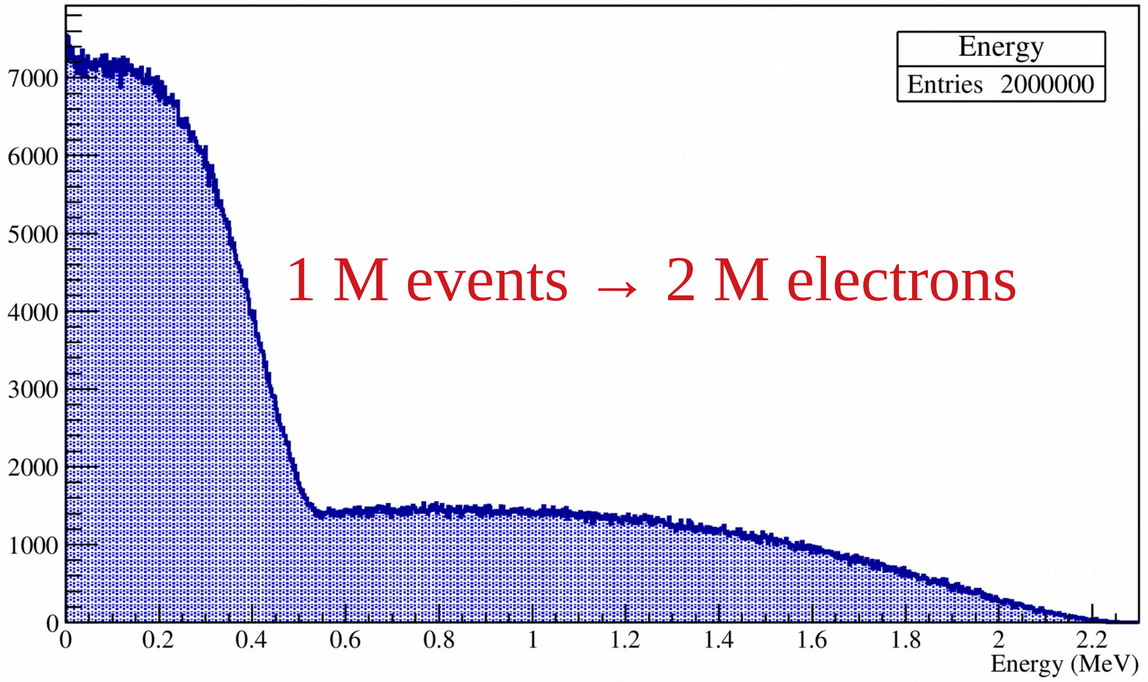
Theory



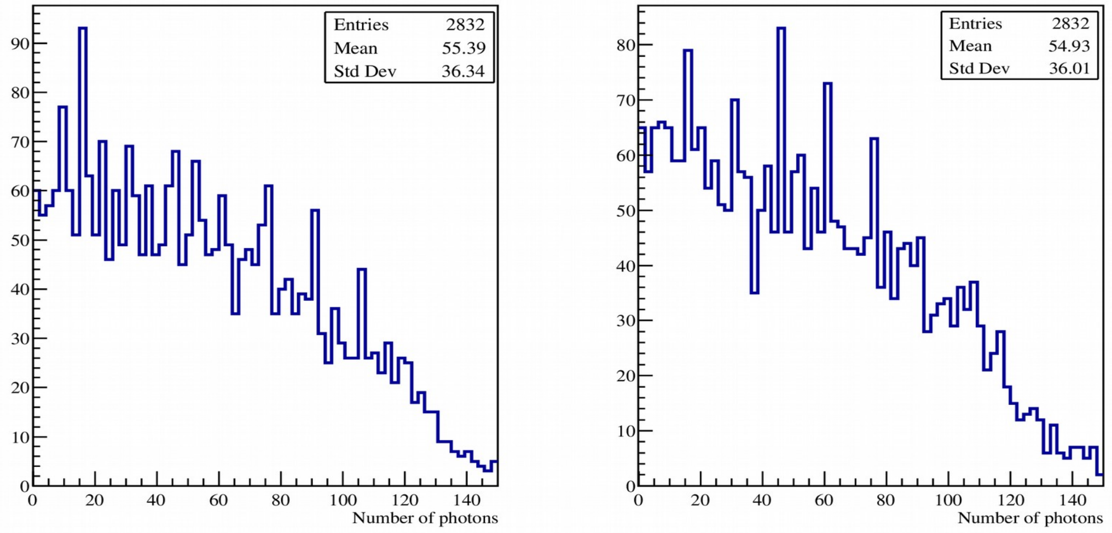


(a)

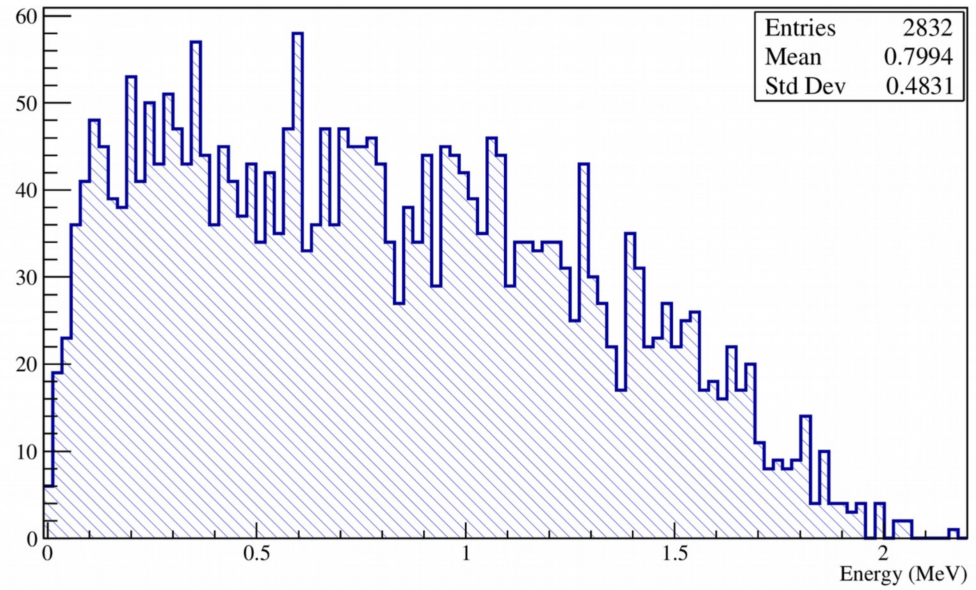
Simulation



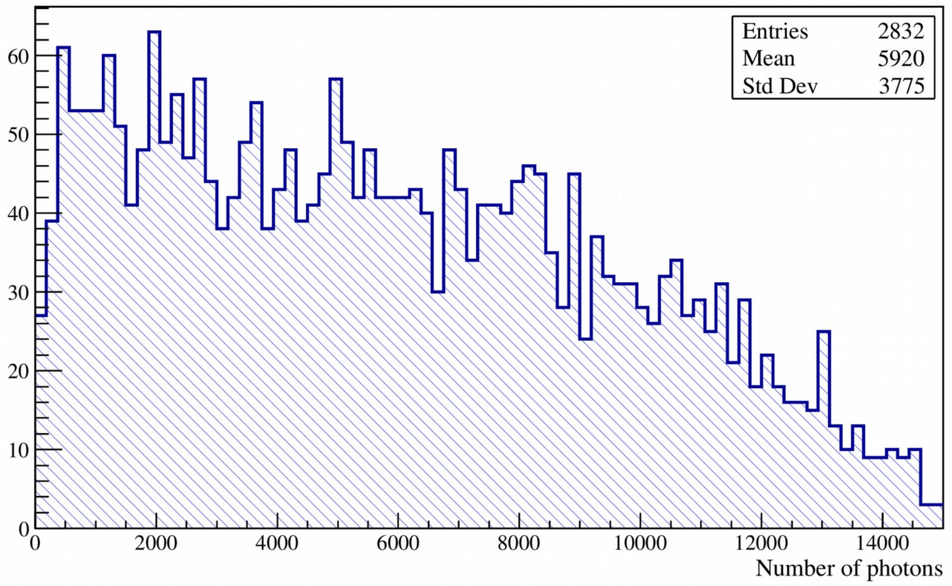
Number of photons at the SiPMs (Right and Left)



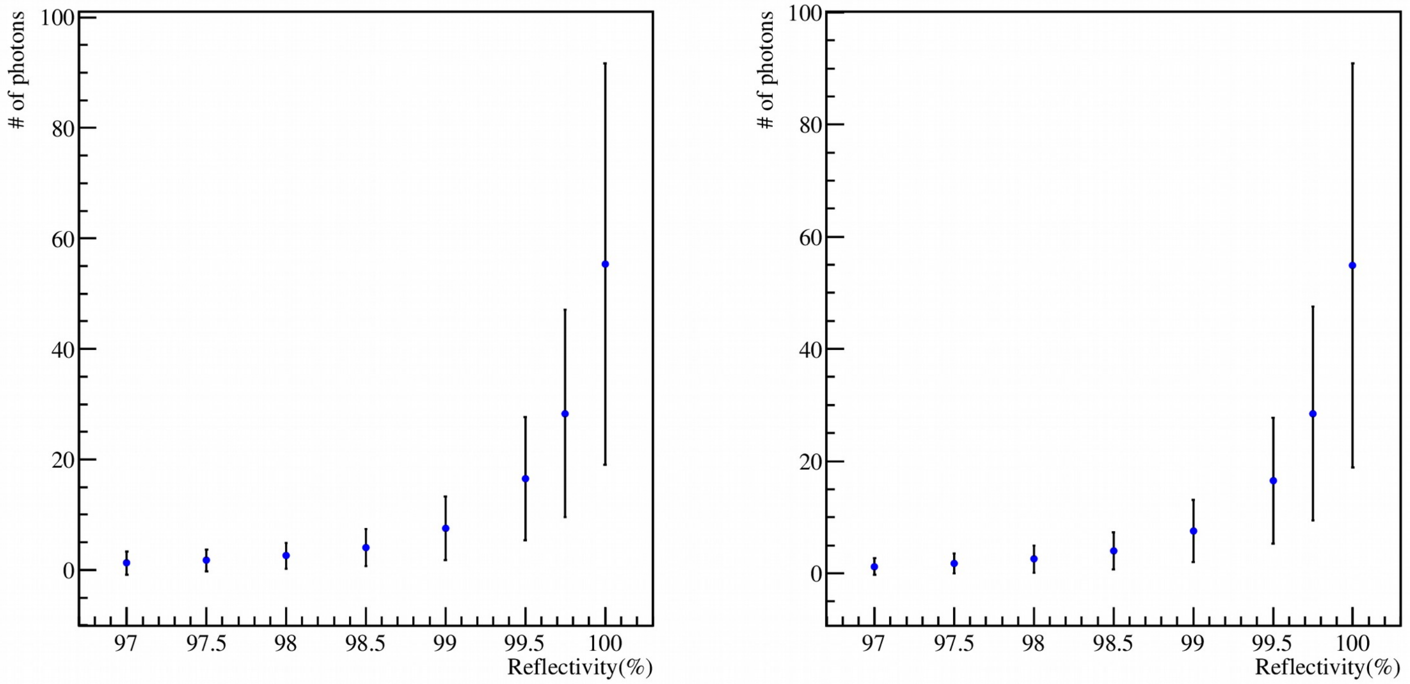
Energy deposited by electrons in the bar



Number of scintillation photons produced by electrons in the bar



Photons at the SiPMs vs Reflectivity of the wrapping

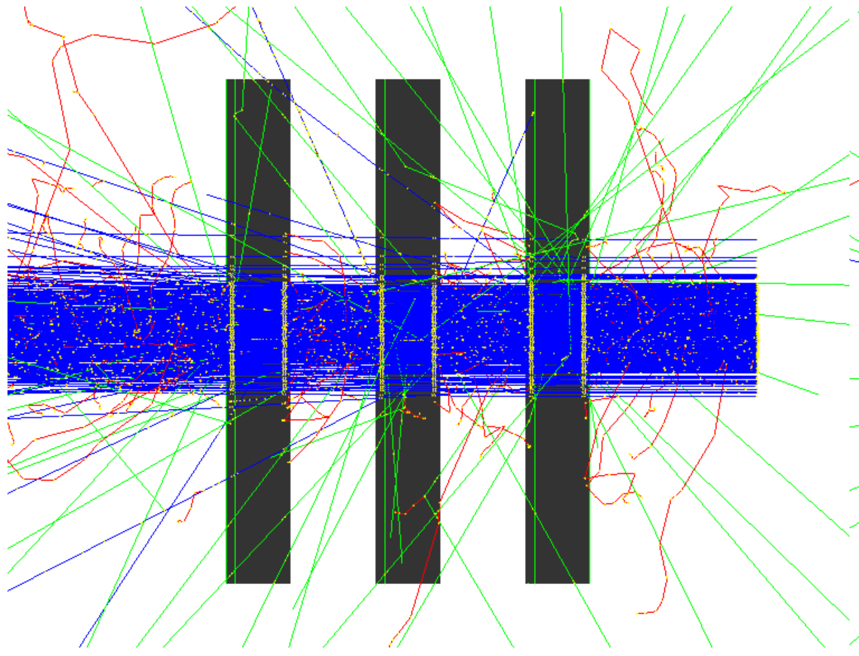


Simulation performed to reproduce hardware tests to be done at LNGS in the near future

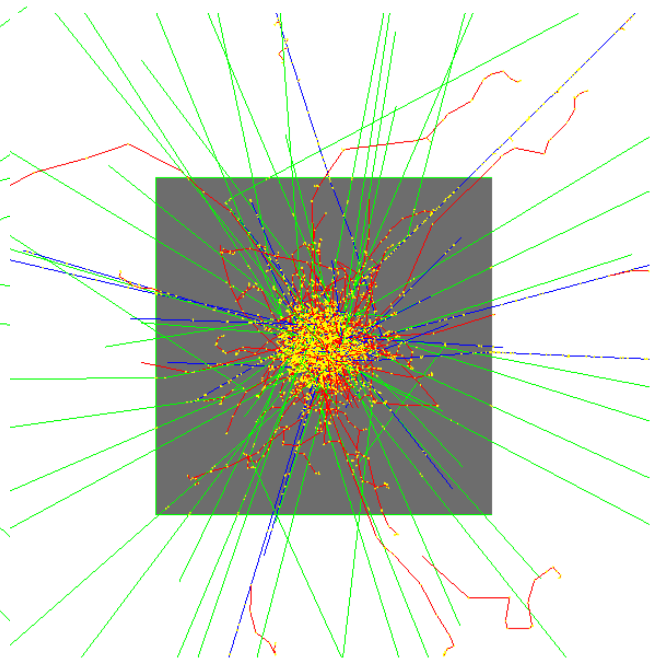
G S
S I

Simulation results: test beam facility

SIDE VIEW



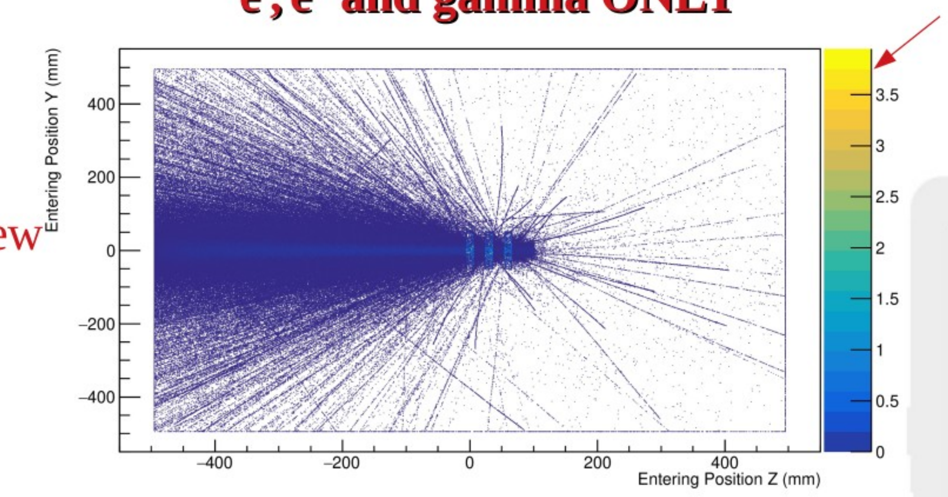
FRONT VIEW



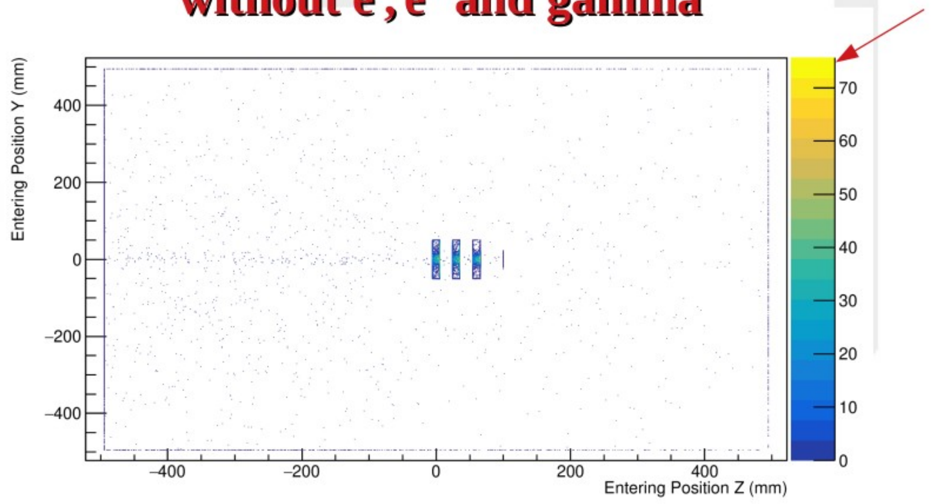
10^5 beam protons → ~ 4 x 10^6 secondary particles

e^-, e^+ and gamma ONLY

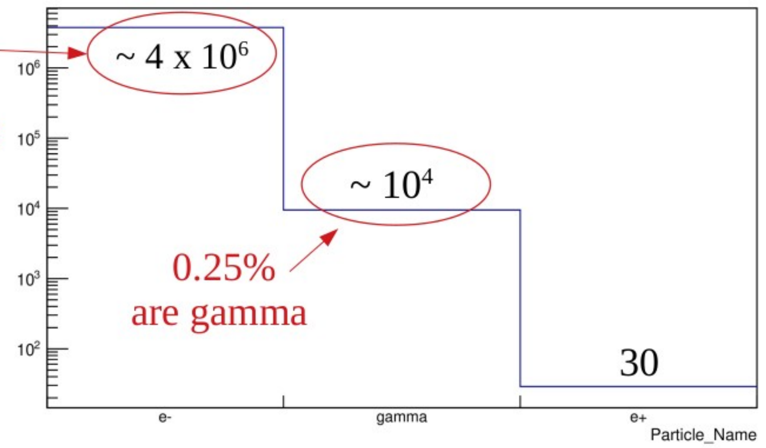
ZY View



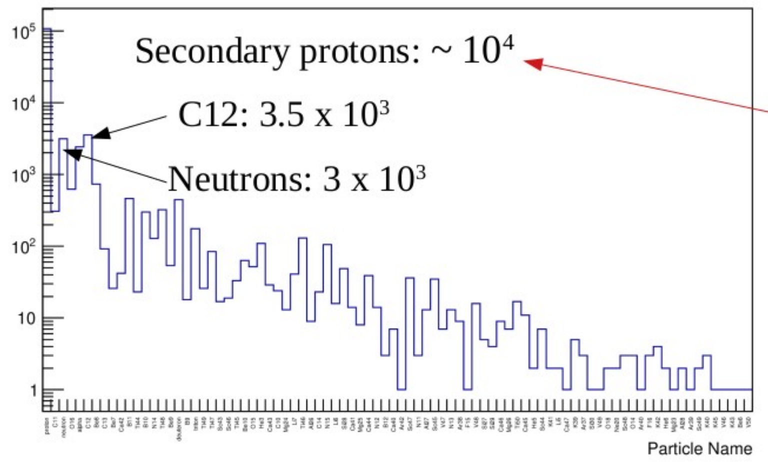
without e^-, e^+ and gamma



99% of secondary particles are electrons



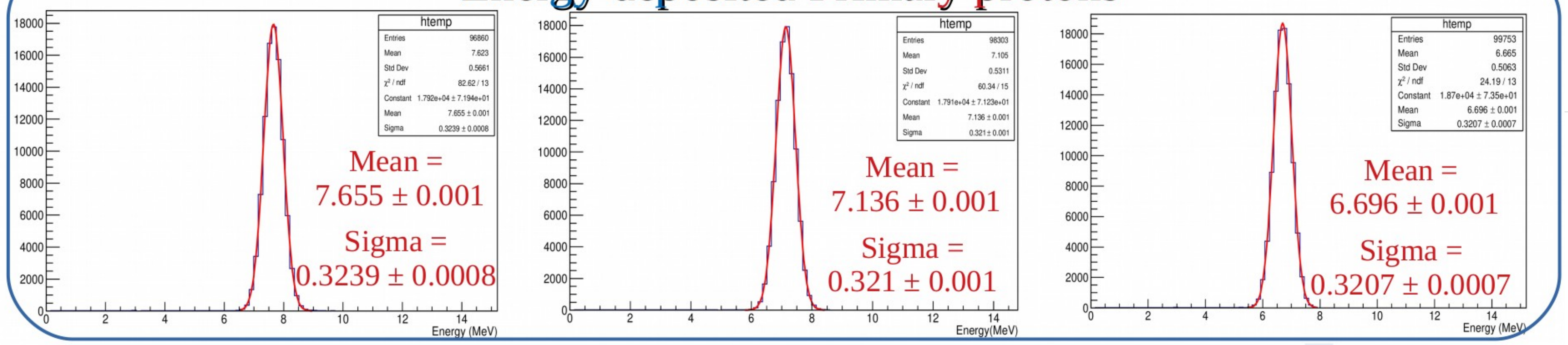
0.25% are gamma



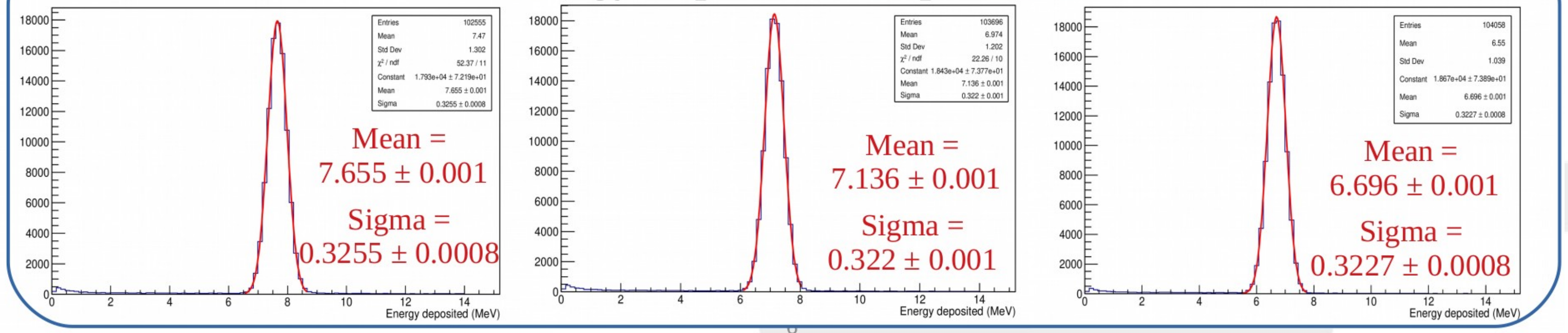
0.21% are secondary protons

Third Tile **Second Tile** **First Tile**

Energy deposited Primary protons



Energy deposited All particles



← BEAM

Studies for the test beam at CNAO with the Tile setup
The simulation of the bar setup is ongoing

	Contribution from beam protons	Contribution from secondaries
First Tile	~ 95 %	~ 5 %
Second Tile	~ 93 %	~ 7 %
Third Tile	~ 92.6 %	~ 7.4 %