8th International Conference
on New Frontiers in Physics (ICNFP 2019)

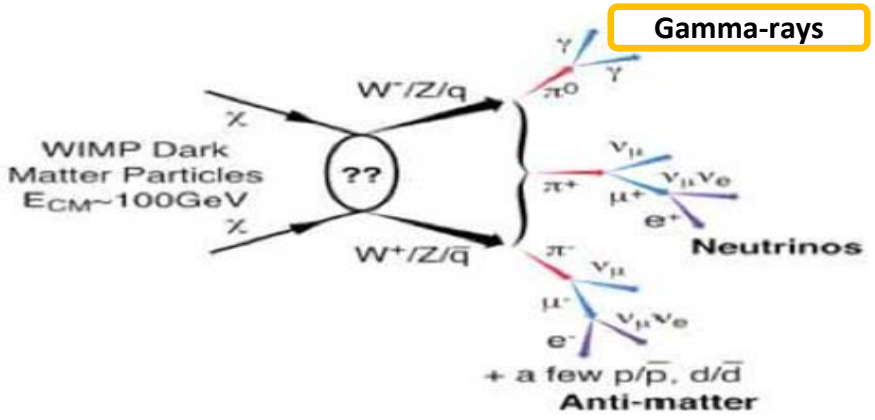
Main results of the DAMPE space detector in its 4th year in orbit

Piergiorgio Fusco
University and INFN Bari - Italy
on behalf of the DAMPE Collaboration

A few open questions in astroparticle physics

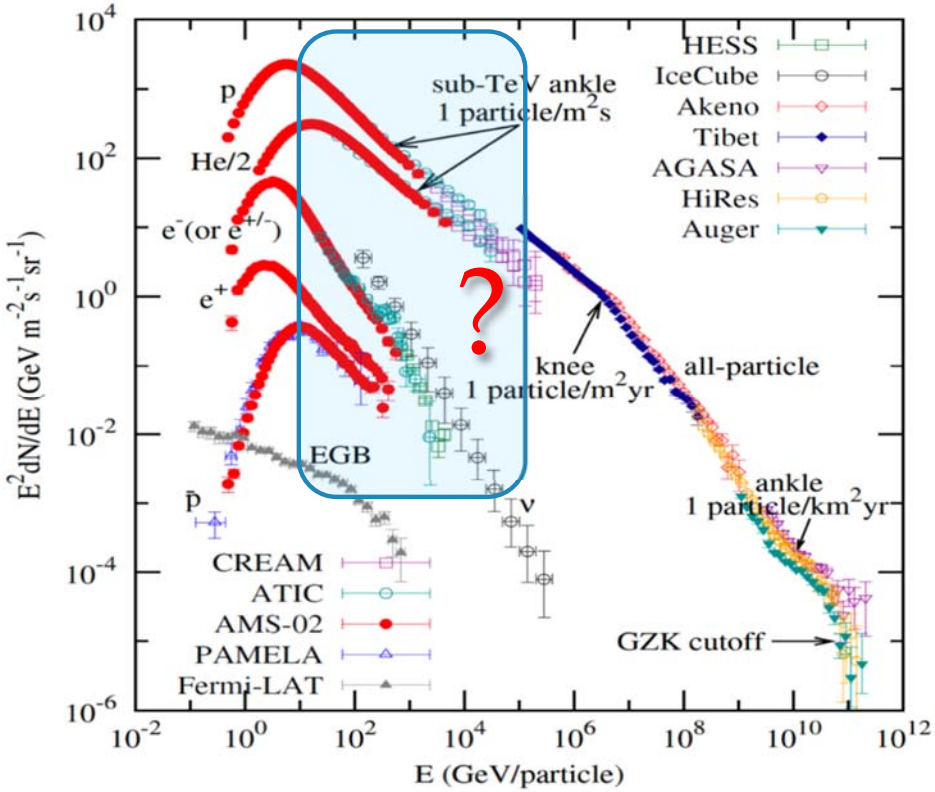
Dark Matter

nature, origin, abundance, properties



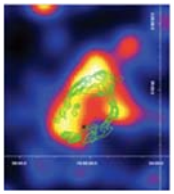
Cosmic rays

sources, acceleration, propagation

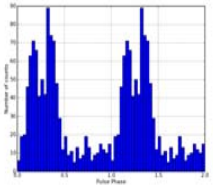


High-energy cosmic photons

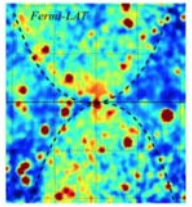
sources, interaction, non-thermal physics



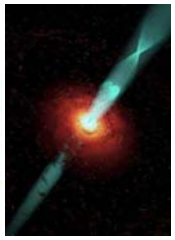
SNRs



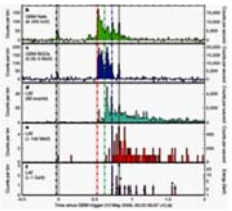
Pulsars



Galactic structures

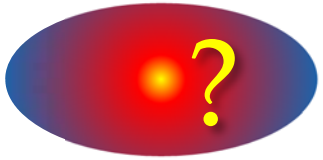


Blazars

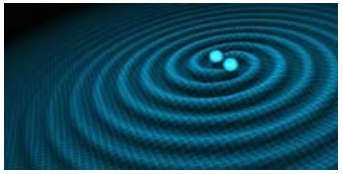


GRBs

Exotic particles



E.M. with GW



The DAMPE Collaboration

- 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

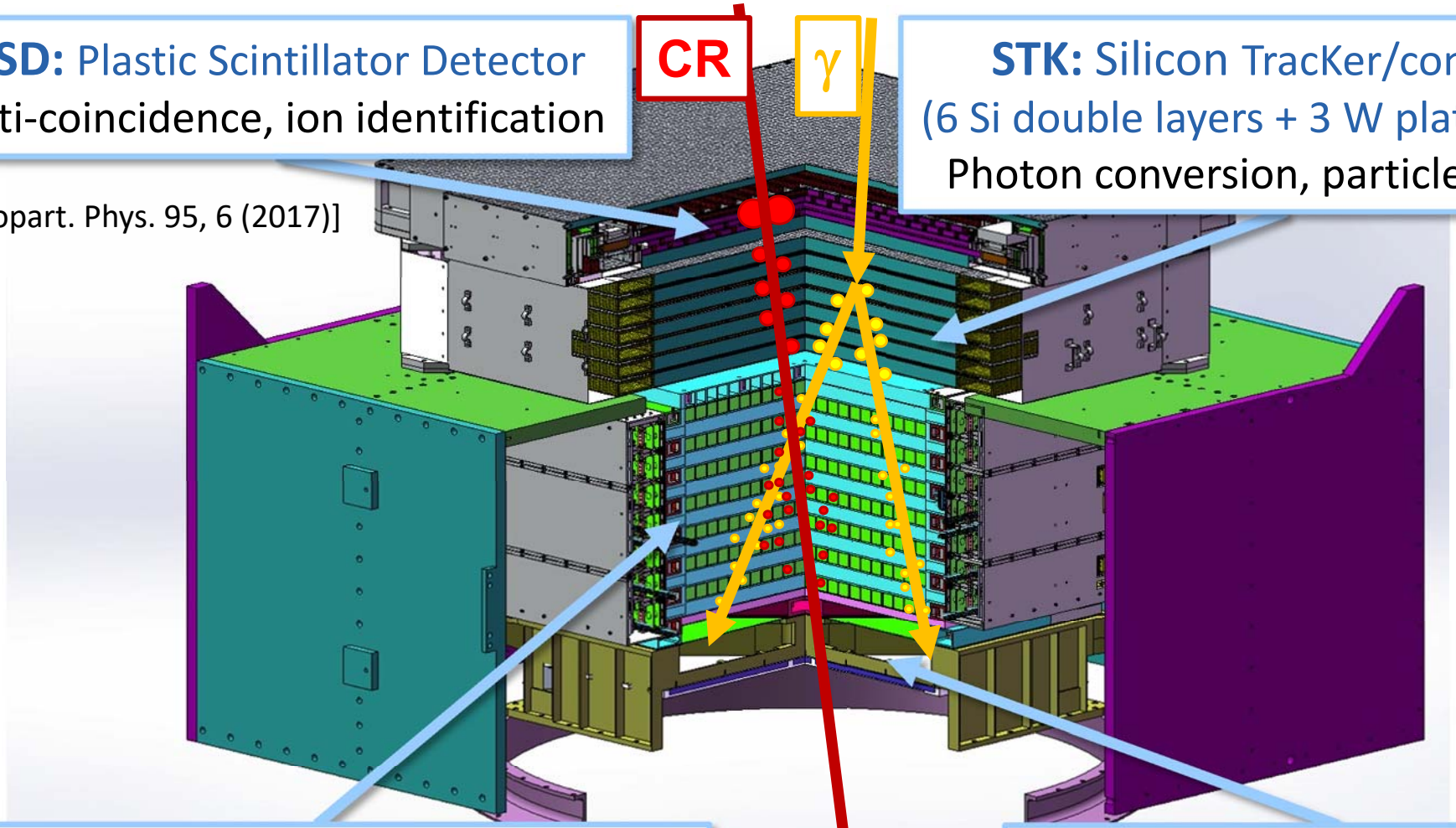
DAMPE scientific goals

- 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

The DAMPE instrument

PSD: Plastic Scintillator Detector
Anti-coincidence, ion identification

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

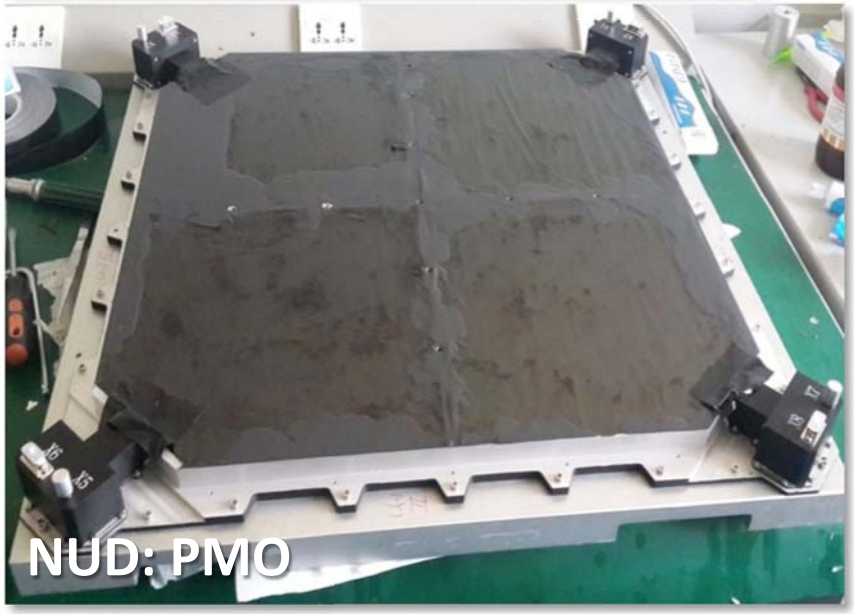


STK: Silicon TracKer/converter
(6 Si double layers + 3 W plates 1 mm)
Photon conversion, particle tracking

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

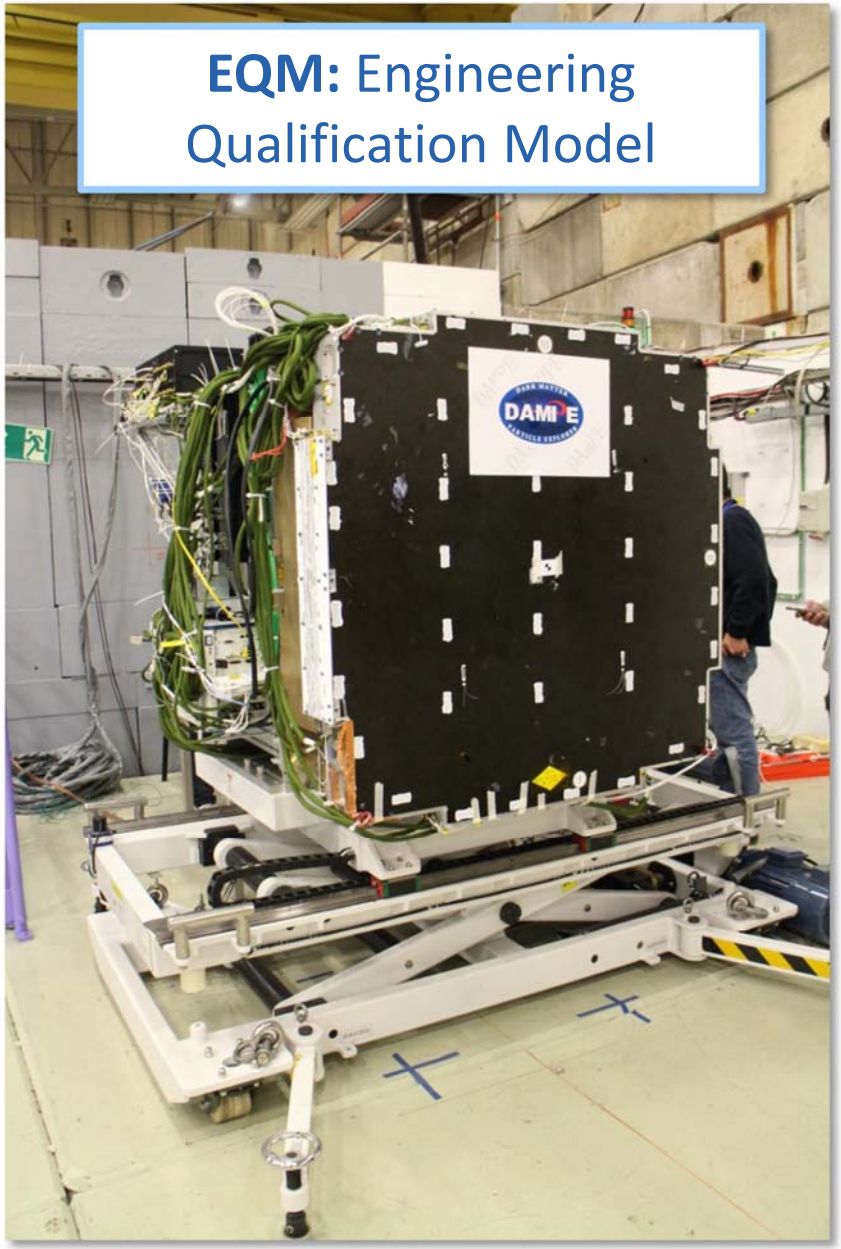
NUD: Neutron detector
(4 B-doped plastic scintillators)
Neutron showers measurement

The DAMPE sub-detectors



Beam tests at CERN

- 14 days @ PS, 29/10-11/11 2014
  - e @ 0.5, 1, 2, 3, 4, 5 GeV/c
  - p @ 3.5, 4, 5, 6, 8, 10 GeV/c
  - π^- @ 3, 10 G.eV/c
  - γ @ 0.5-3 GeV/c
- 8 days @ SPS, 12/11-19/11 2014
  - e @ 5, 10, 20, 50, 100, 150, 200, 250 GeV/c
  - p @ 400 GeV/c (SPS primary beam)
  - γ @ 3-20 GeV/c
  - μ @ 150 GeV/c,
- 17 days @ SPS, 16/03-10/04 2015
  - Fragments @ 66.67, 88.89, 166.67 GeV/c
  - Argon @ 30A, 40A, 75A GeV/c
  - p @ 30, 40 GeV/c
- 21 days @ SPS, 10/06-01/07 2015
  - p @ 400 GeV/c (SPS primary beam)
  - e @ 20, 100, 150 GeV/c
  - γ @ 50, 75 , 150 GeV/c
  - μ @ 150 GeV /c
  - π^+ @ 10, 20, 50, 100 GeV/c
- 6 days @ SPS, 20/11-25/11 2015
  - Pb @ 30A GeV/c (and fragments)

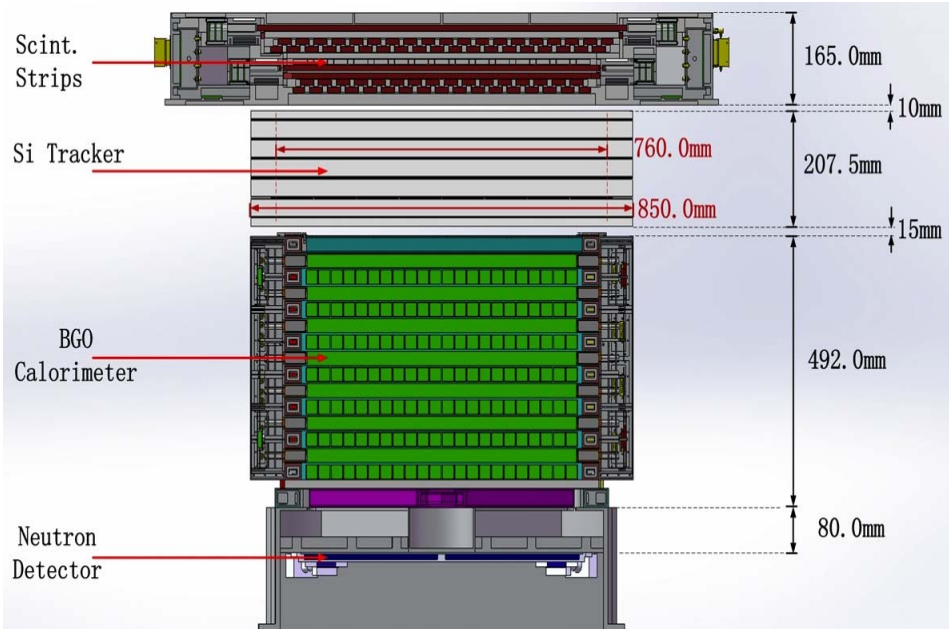


EQM: Engineering Qualification Model

DAMPE, AMS-02, Fermi LAT comparison

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

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

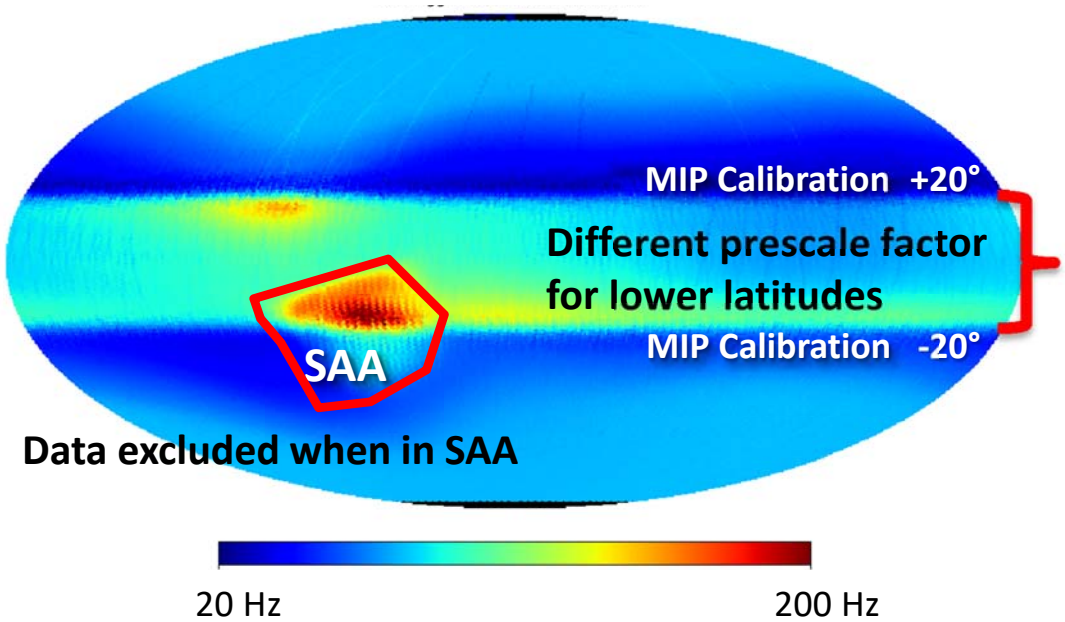


The launch

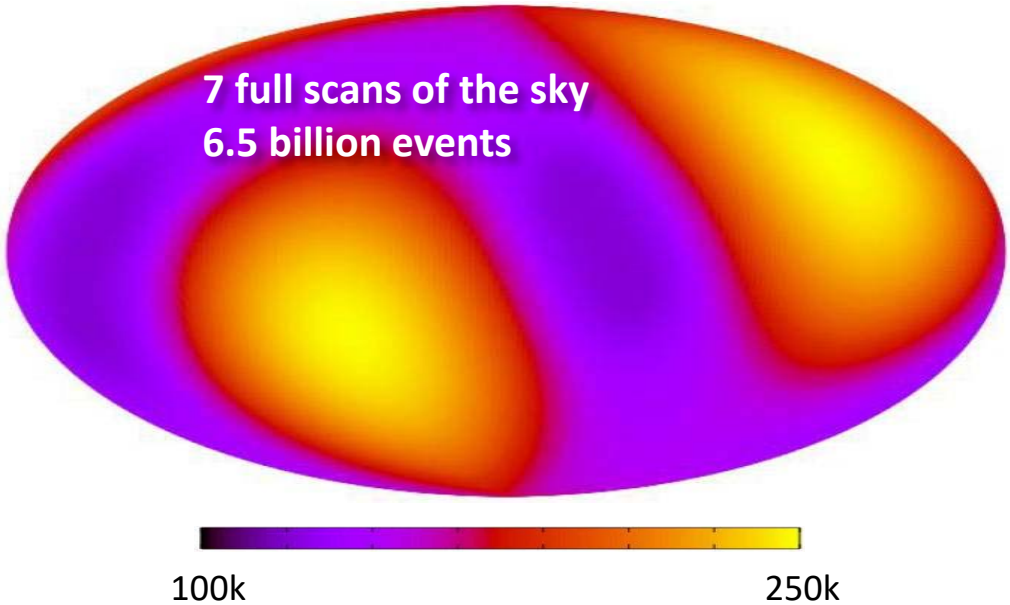
- **DAMPE was launched on Dec. 17, 2015**
  - **Launch site: Jiuquan Satellite Launch Center, Gobi desert, China**
  - **Orbit: 500 km altitude, 97° inclination, Sun-synchronous**

Trigger rate and data transfer

Total trigger rate



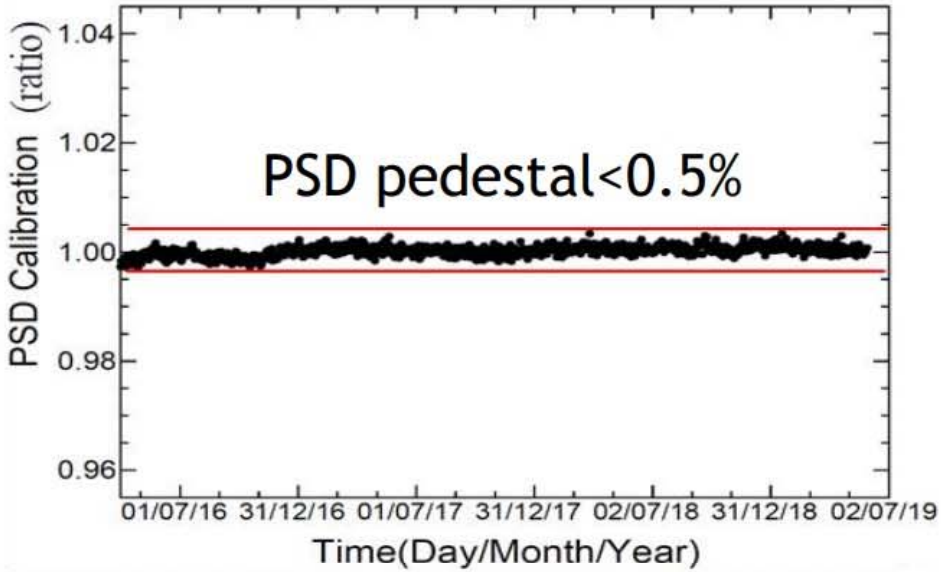
3.5 years exposure map

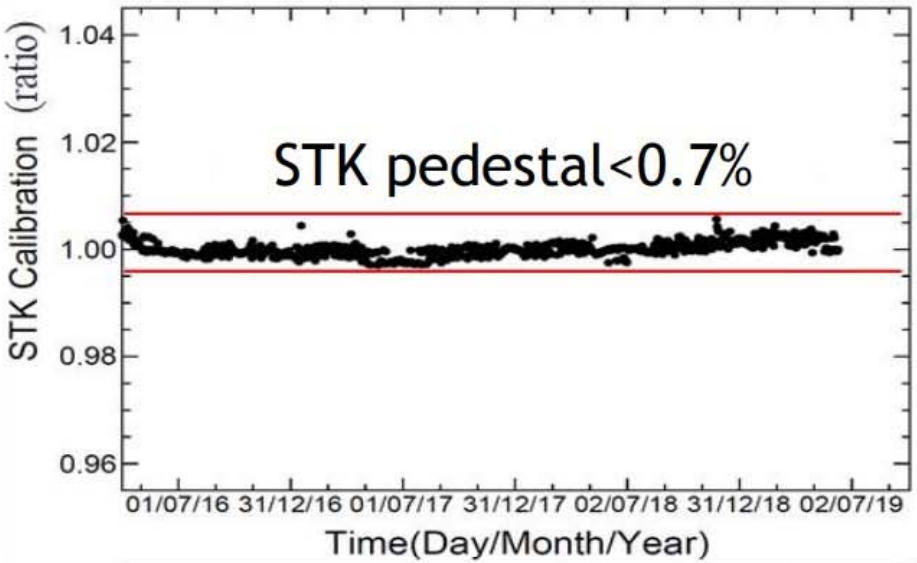


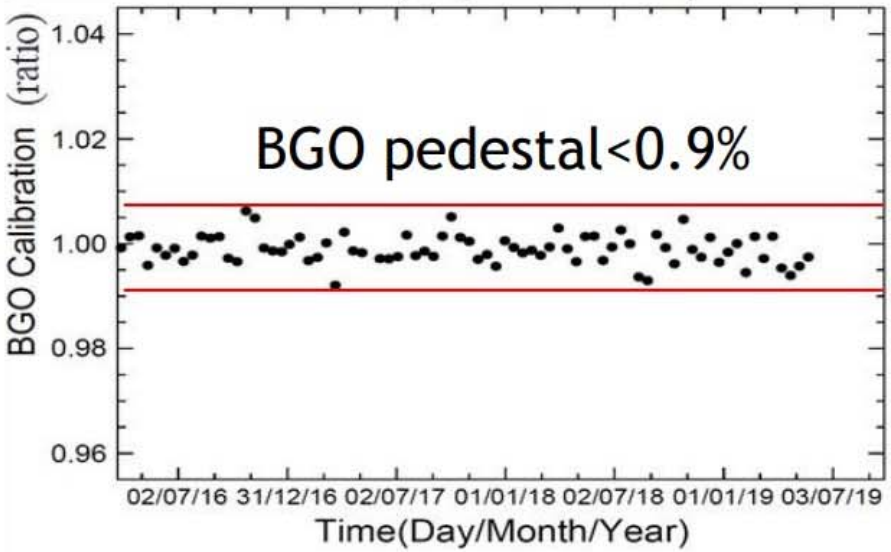
Acquisition rate	up to 200 Hz
High Energy (physics) trigger rate	up to 50 Hz
Raw data plus control data download	15 GB/day
Reconstructed data in ROOT format	85 GB/day
Total data per year	35 TB
Total events at 01/08/2019	6.5 billion

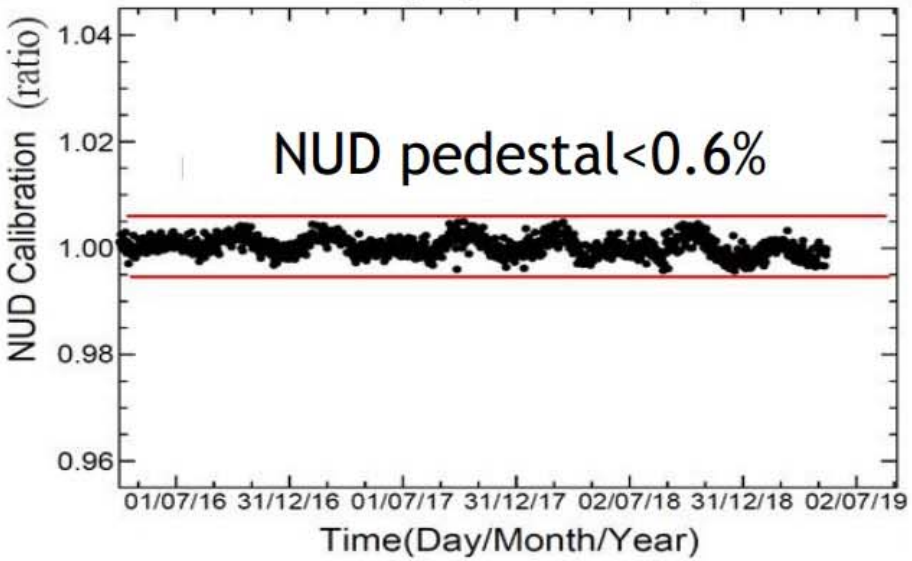
Detector stability

- PSD, STK, BGO and NUD pedestal fluctuation from 01/07/16 to 02/07/19



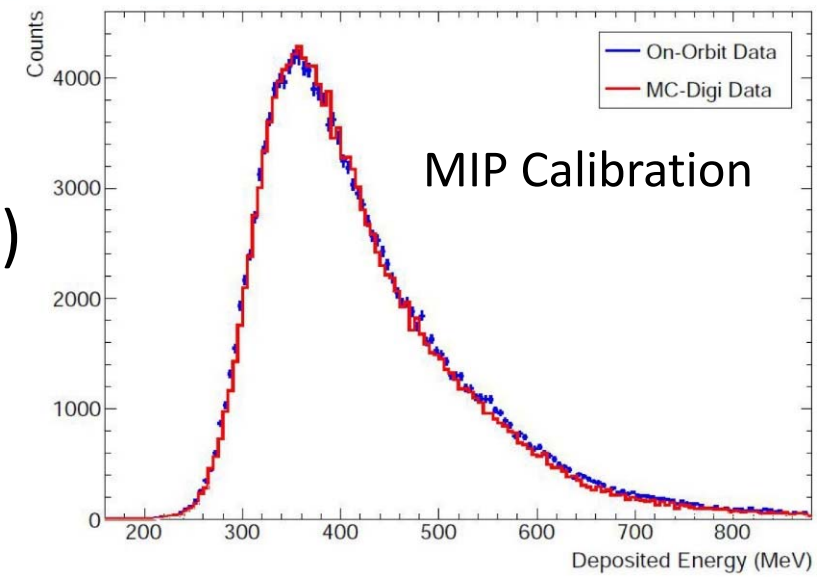


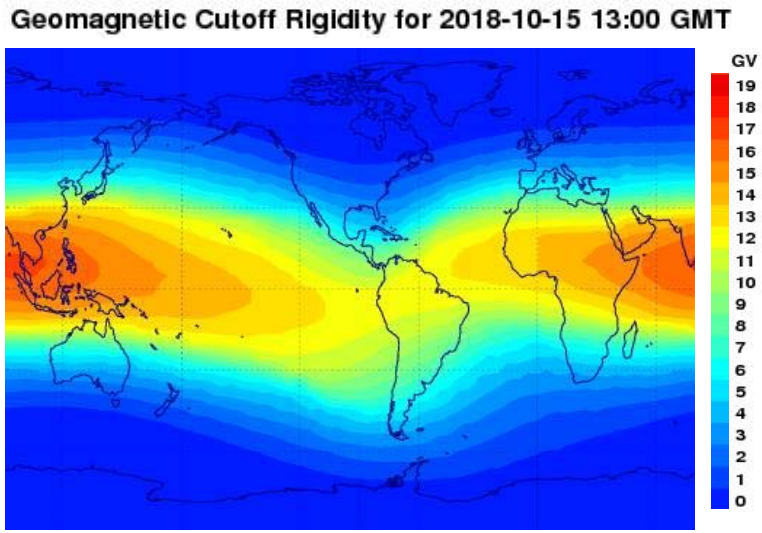


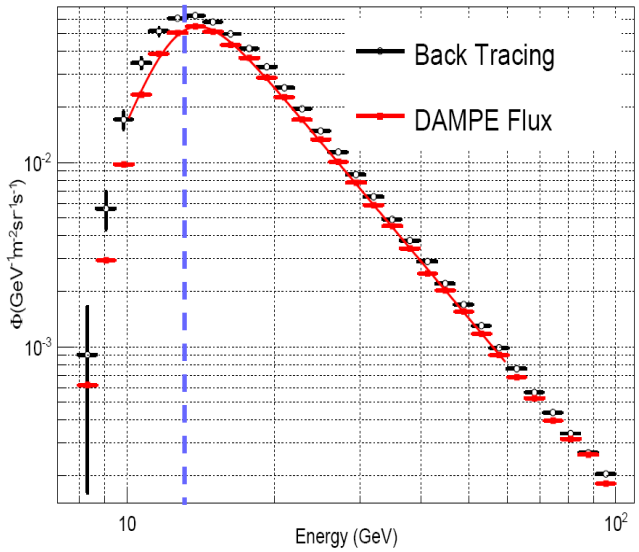


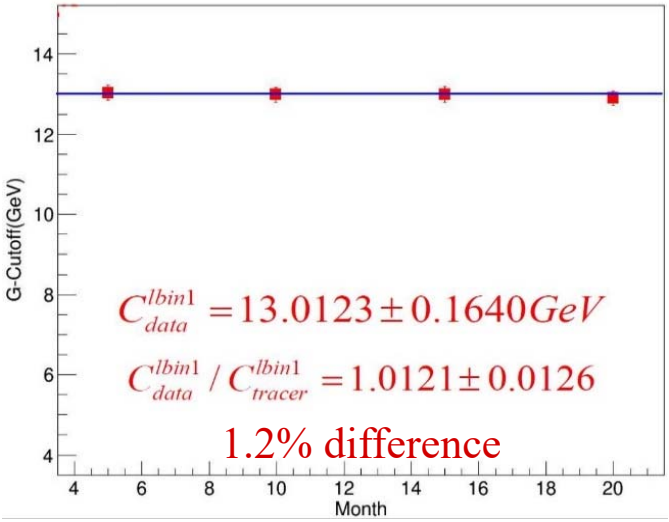
Energy calibration

- First level calibration at each orbit with MIPs
- Absolute calibration with the geomagnetic rigidity cut-off of Cosmic Ray Electrons (CREs)
  - cosmic ray electrons flux is measured in the low energy range 8 GeV – 100 GeV
  - flight and Monte Carlo data (with back-tracing in Earth magnetic field model IGRF12) are compared
  - expected cut-off: 13.0 GeV; DAMPE measured cut-off 13.2 GeV



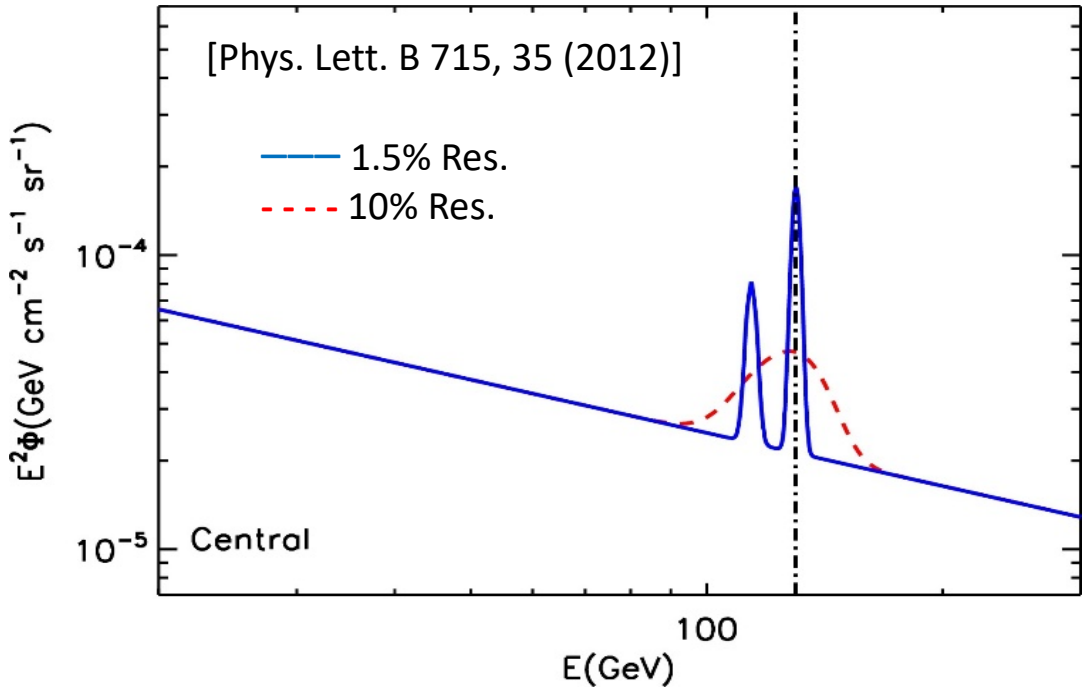


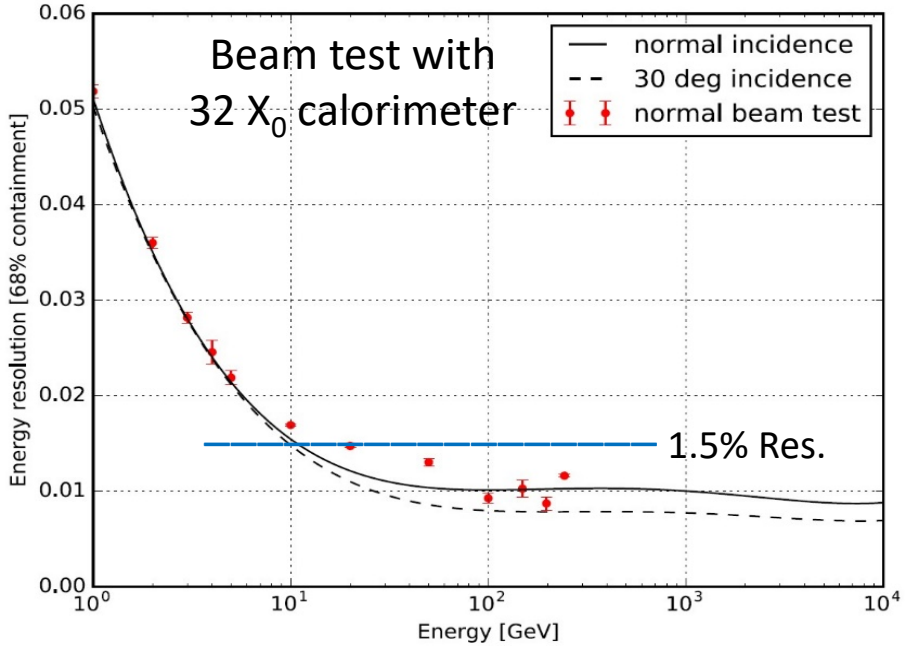




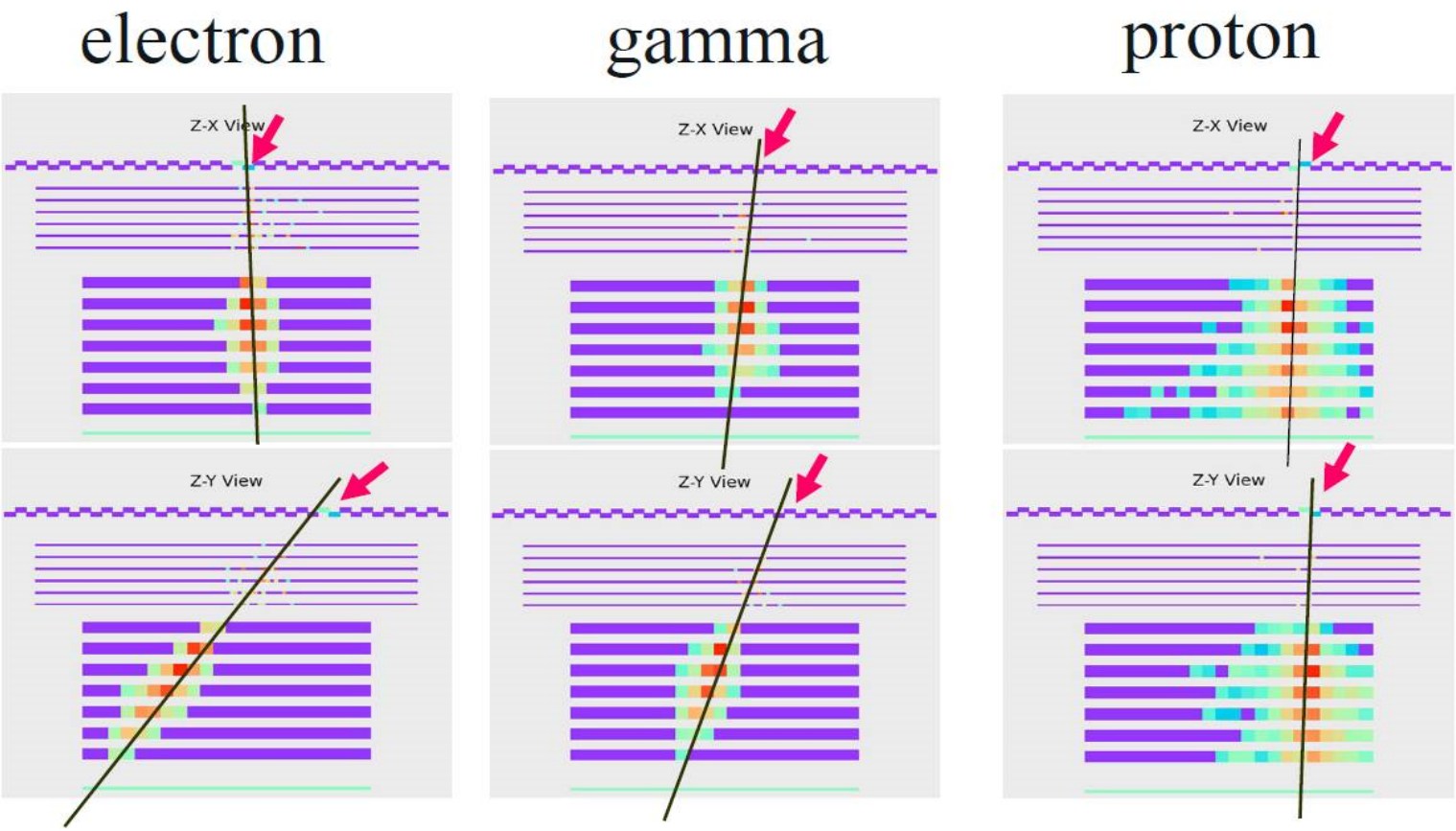
Detection and identification challenges

- 1) Particle identification
  - electrons/protons: 10^{-3} , photons/protons: 10^{-5} → high rejection capability
- 2) Dynamic range
  - e/γ energy: 1 GeV – 10 TeV → BGO bar range 2 MeV – 4 TeV
- 3) Energy resolution
  - sensitivity to DM line → 1.5% res. for e & γ



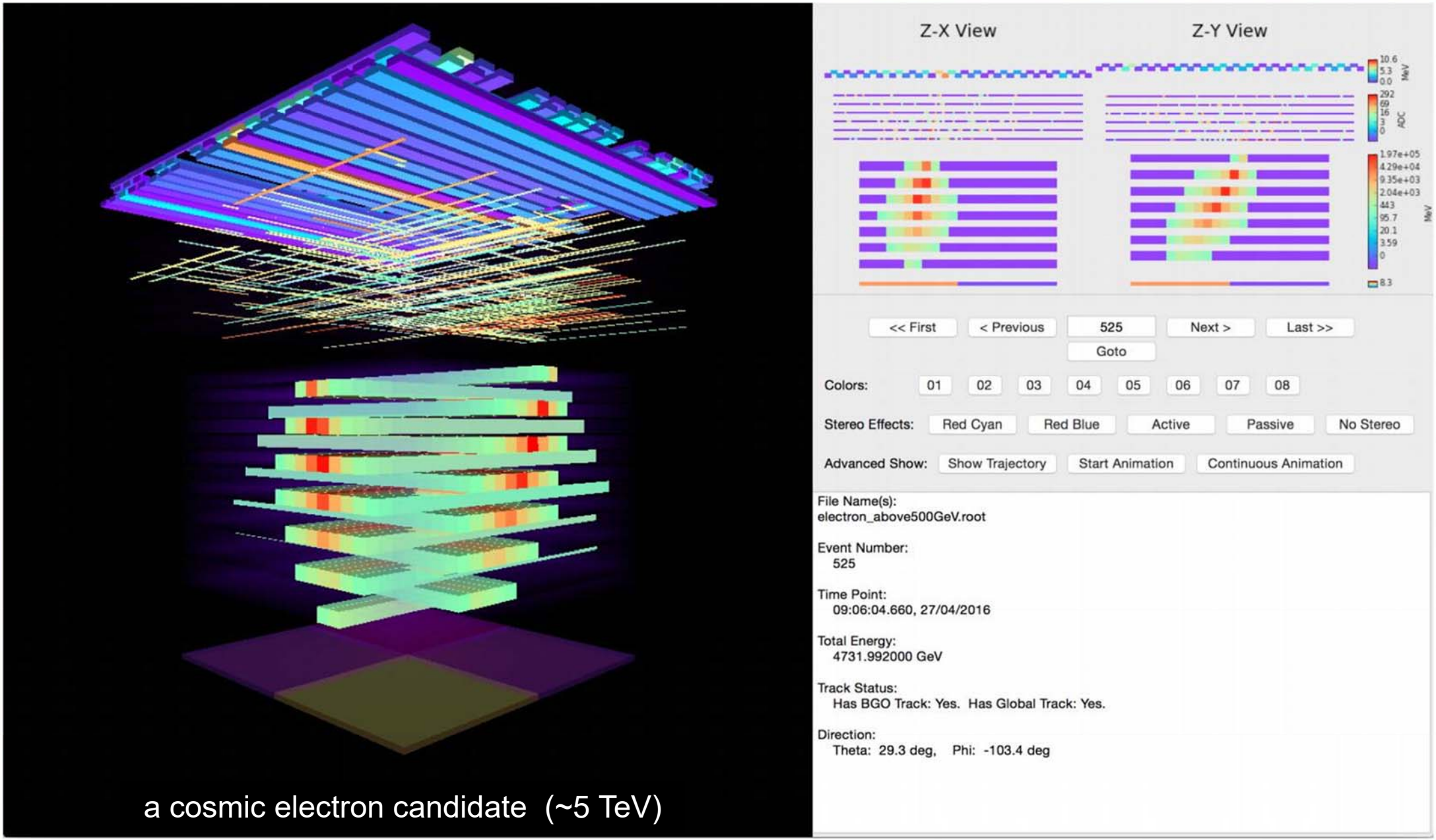


Particle identification



- Several different PID methods used:
  - Shape parameters
  - Boosted Decision Trees
  - Random Forest + Convolutional Neural Network

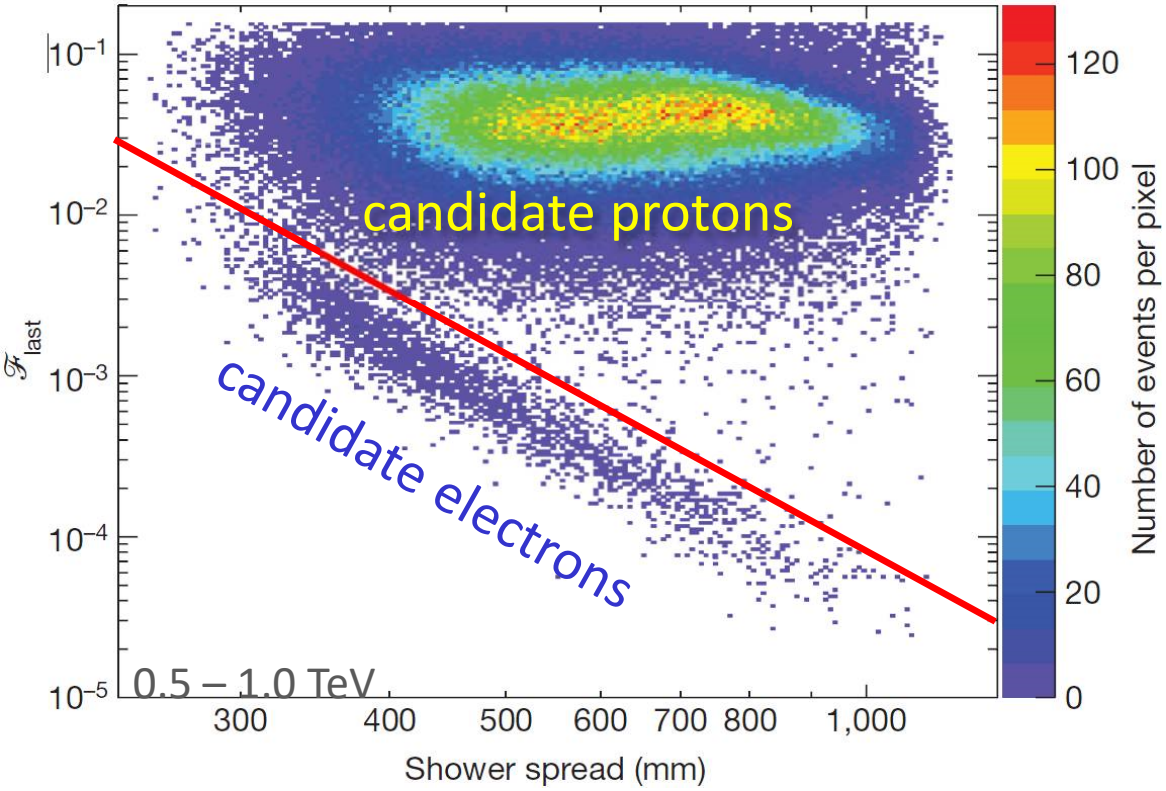
Study of cosmic electrons and positrons (CREs)

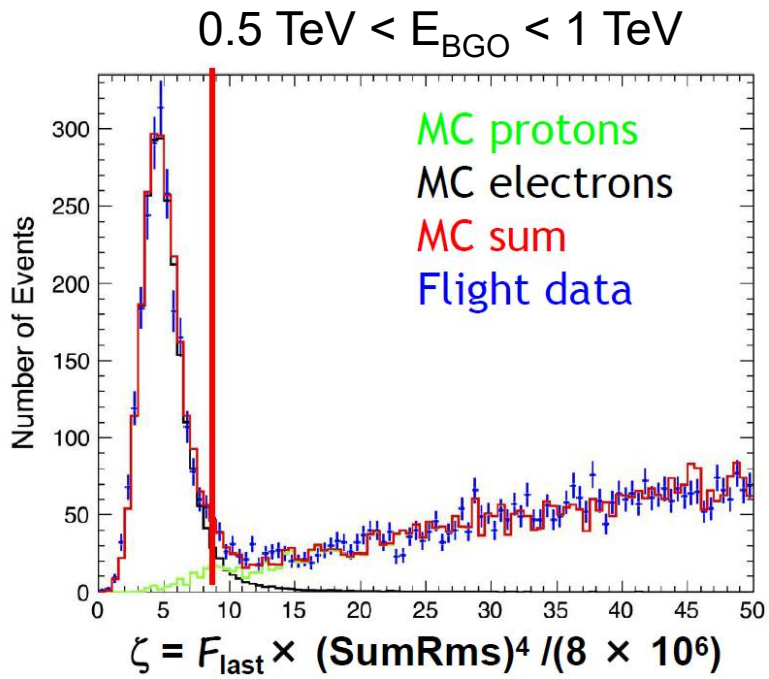


a cosmic electron candidate (~5 TeV)

Electron/proton separation

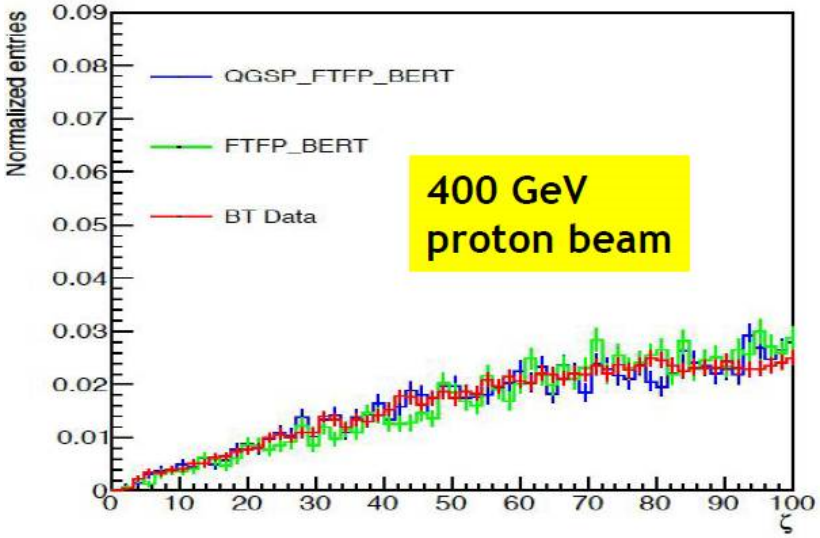
- The "ζ shower parameter" was computed from the lateral shower development in BGO and the energy deposition in the last layer
  - the cut ζ > 8.5 was adopted to discriminate e^- (and e^+) from p
  - for 90% $e^\pm$ efficiency, p background ~2% @ 1 TeV, ~5% @ 2 TeV, ~10% @ 5 TeV

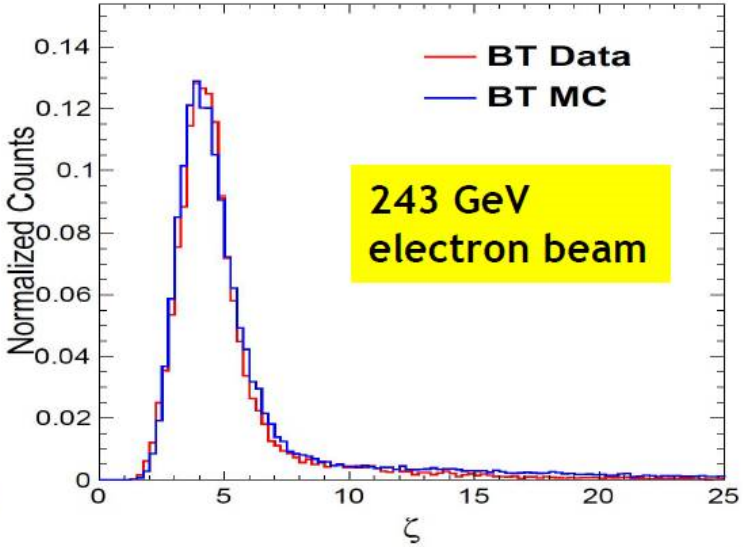


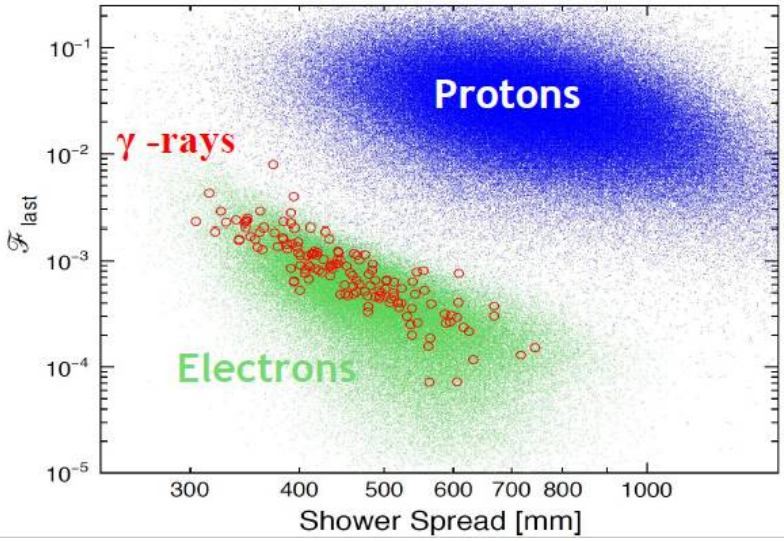


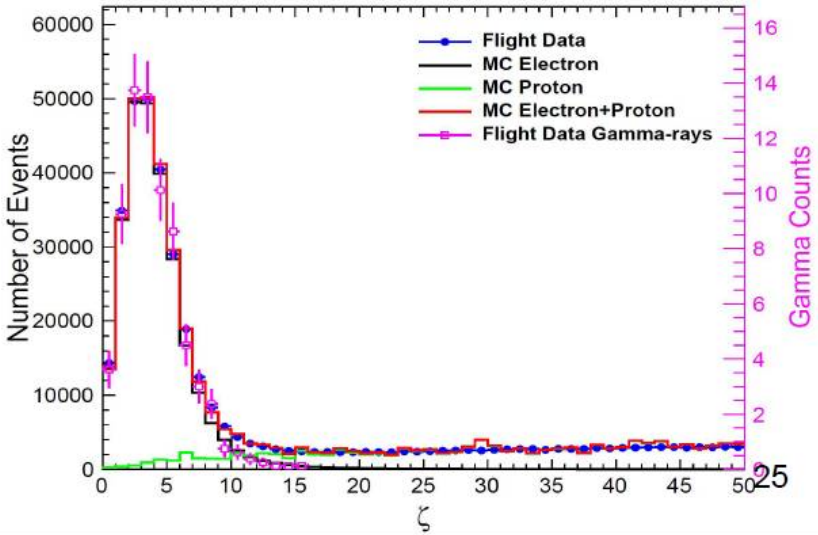
Validation of the ζ parameter

- The ζ parameter was validated with beam tests and with photons
  - different PID methods give consistent results







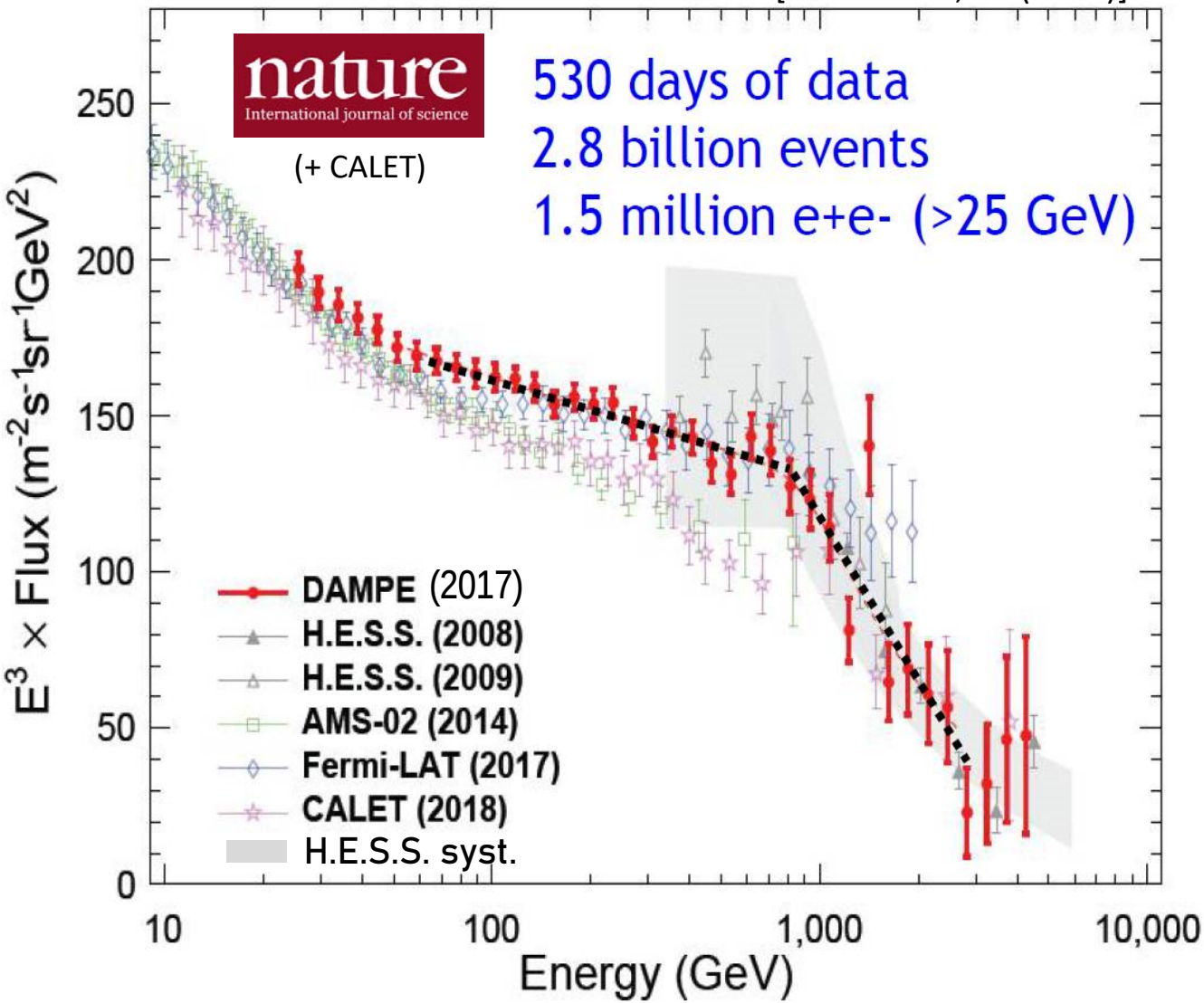


The e^++e^- spectrum

- Cosmic-rays electrons and positrons from 20 GeV to ~5 TeV
  - 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)
  - next: search for structures and anisotropies (nearby sources, pulsars, DM?)

γ_1 = 3.09±0.01
γ_2 = 3.92±0.20
E_b = 914±98 GeV
ϕ_0 = (1.64±0.01) x 10^{-4} $m^{-2}s^{-1}sr^{-1}GeV^{-1}$
Δ = 0.1
χ2/NdF = 23.3/18 (6.6σ pref. over PL)

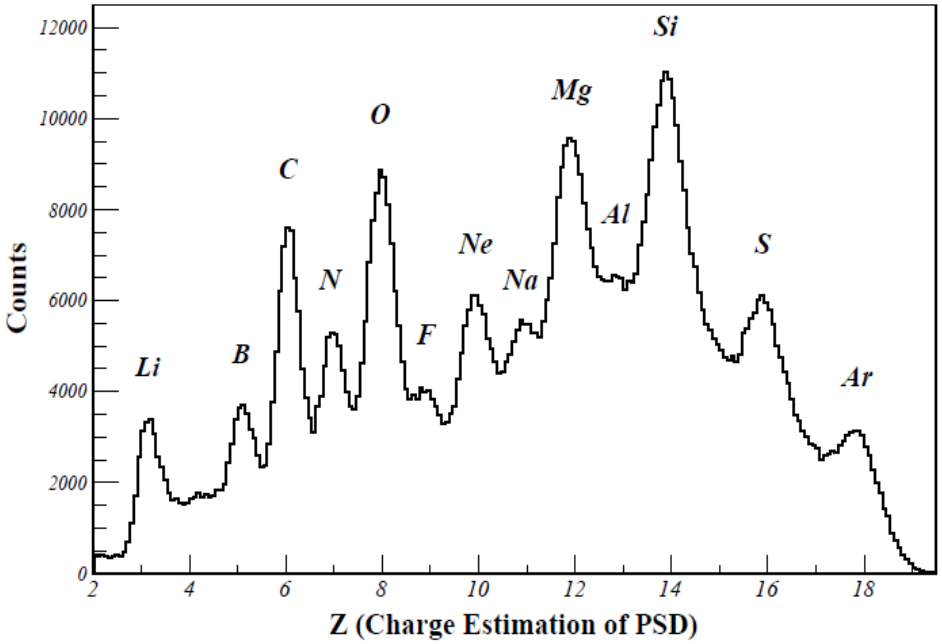
[Nature 552, 63 (2017)]



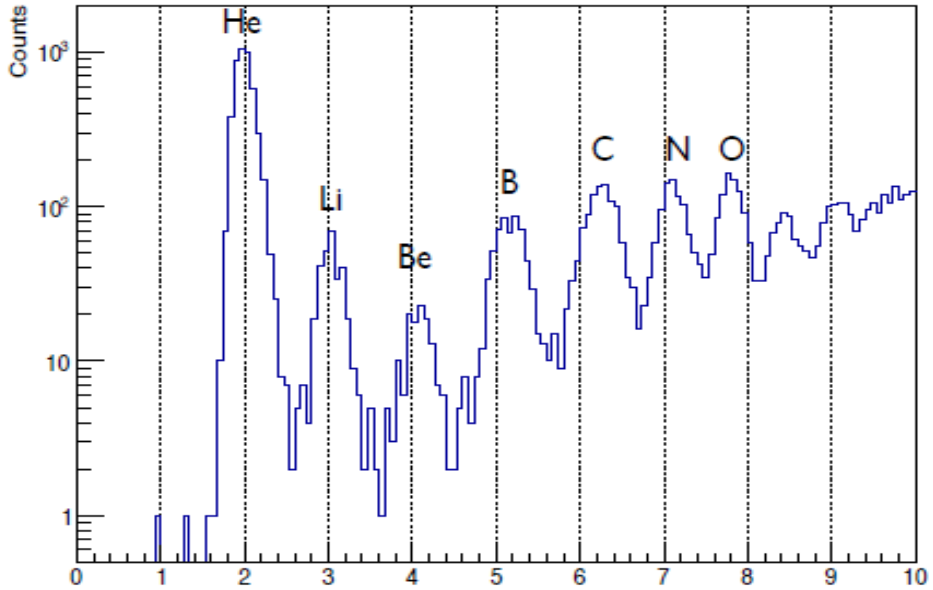
Study of cosmic nuclei charge: beam tests

- Identifying protons and nuclei with PSD and STK
  - charge measurement tested with ion beam tests at CERN SPS
  - PSD: up to Argon; STK: up to Oxygen
  - charge resolution depends on Z: from 0.06 for protons to 0.30 for Iron nuclei
  - more details in Astropart. Phys. 95, 6 (2017)

PSD – Argon beam 40 GeV/n



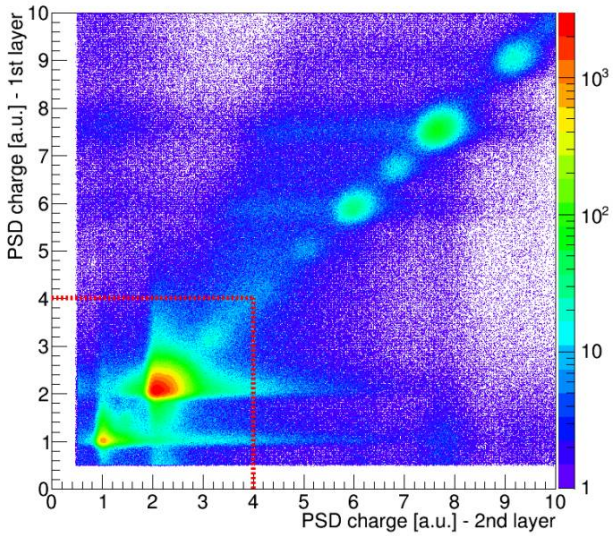
STK – Lead beam 40 GeV/n



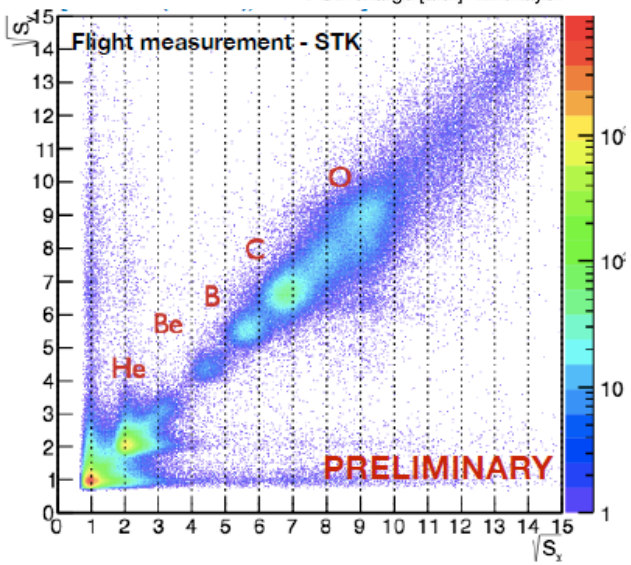
Cosmic nuclei: results

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

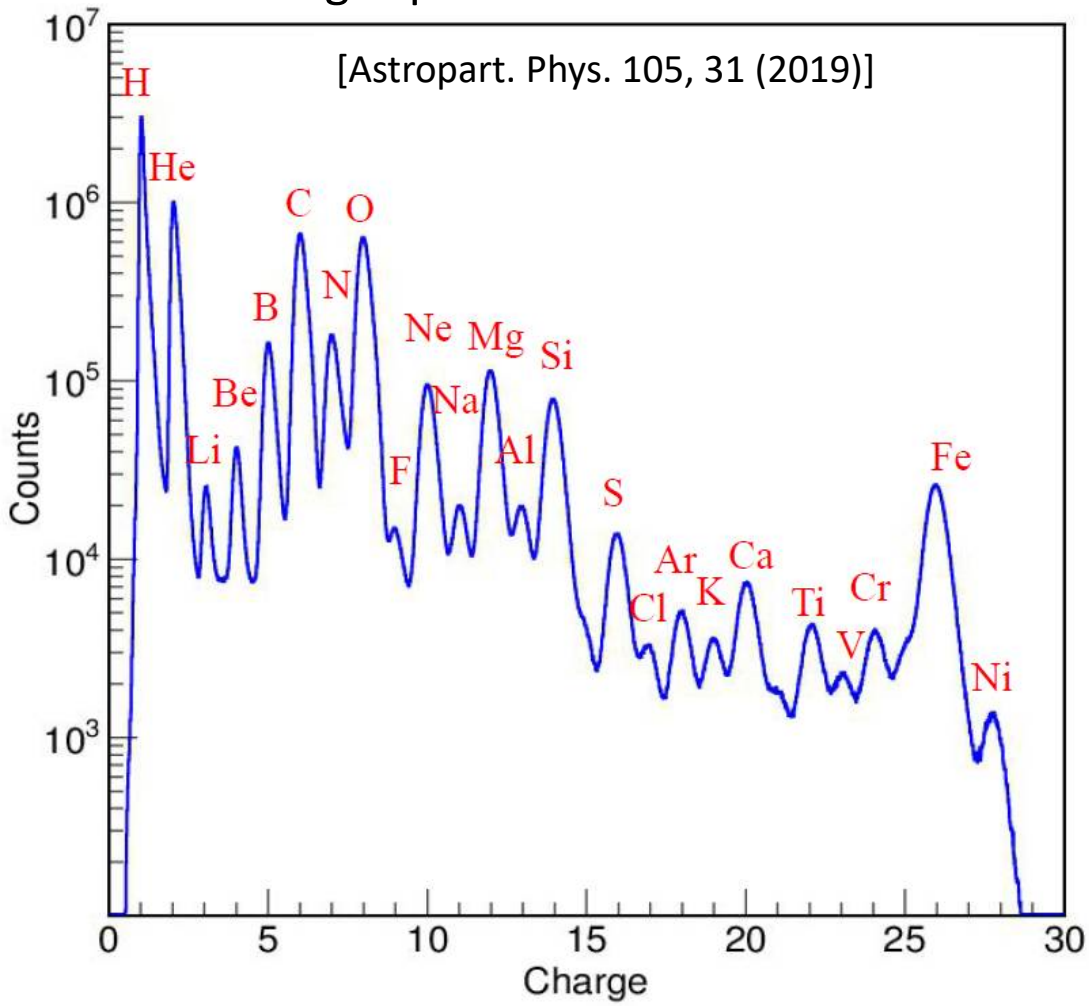
PSD



STK



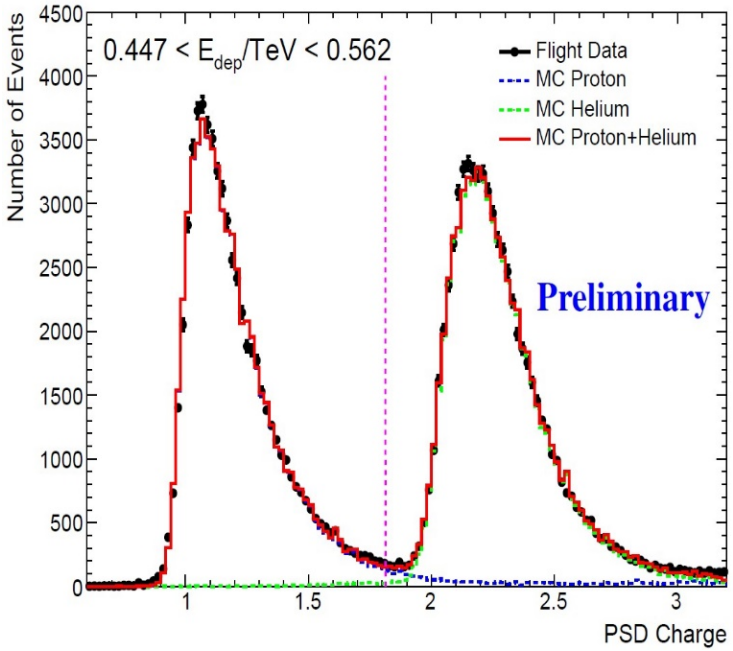
Charge spectrum of cosmic nuclei



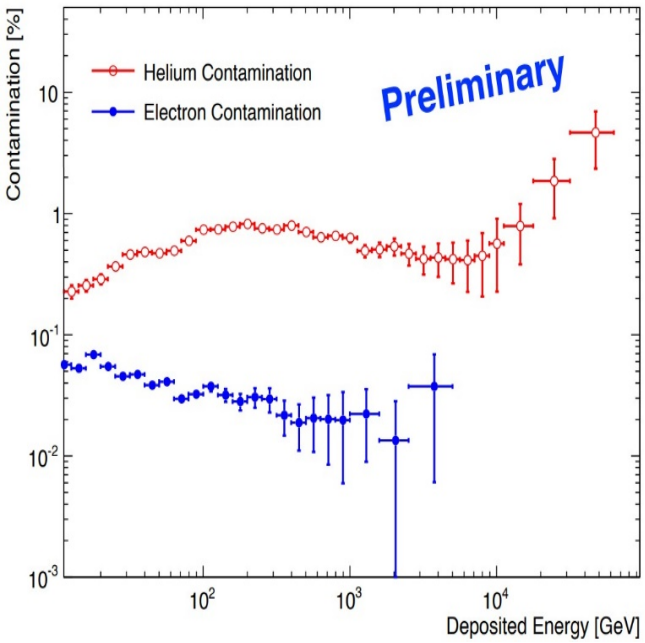
Study of cosmic protons: selection

- Protons selection
  - energy > 20 GeV in BGO + high energy trigger + STK, PSD, BGO track selection
  - Helium cut applied on PSD charge
  - Helium contamination <1% up to 10 TeV, 5% around 50 TeV
  - electron contamination very small thanks to high e/p discrimination of DAMPE
  - proton acceptance rises over 0.04 m^2sr

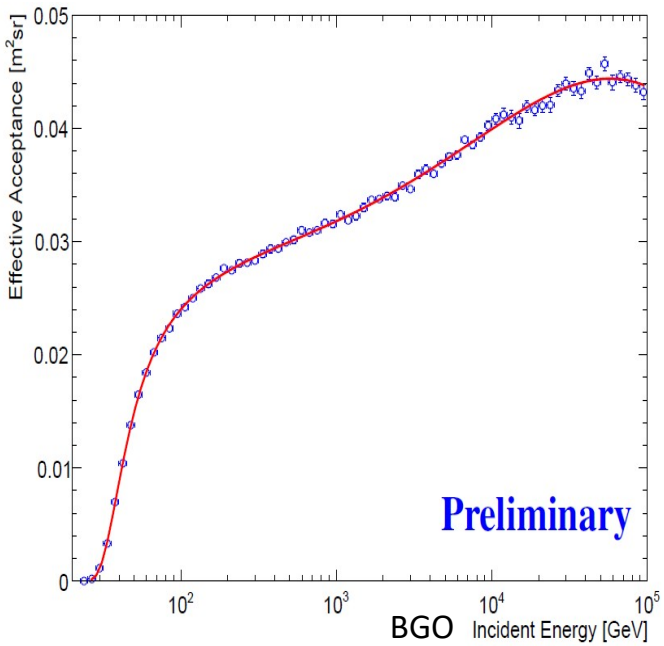
p in PSD and He cut



He and $e^{\pm}$ contamination

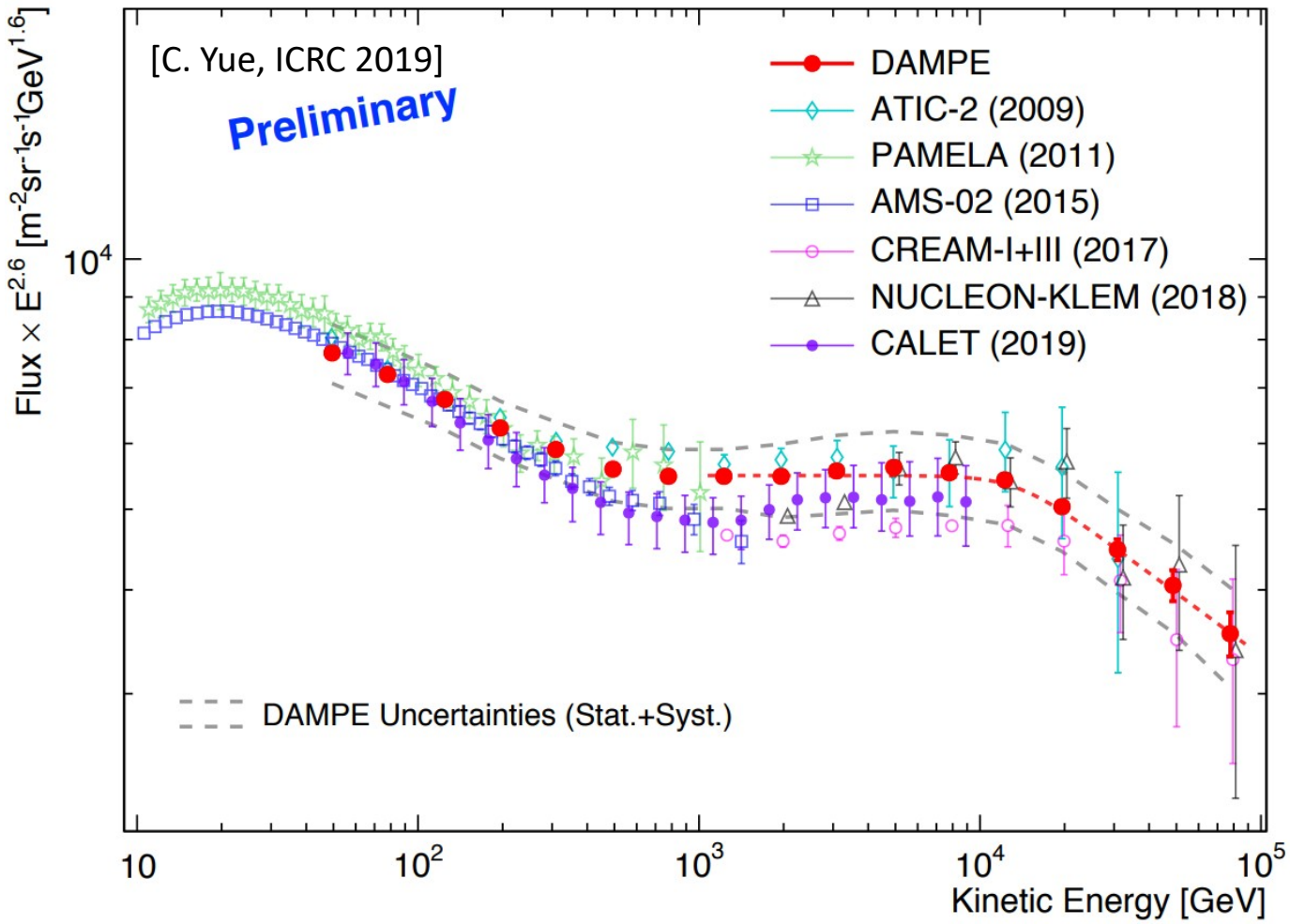


Acceptance for protons



Cosmic protons: results

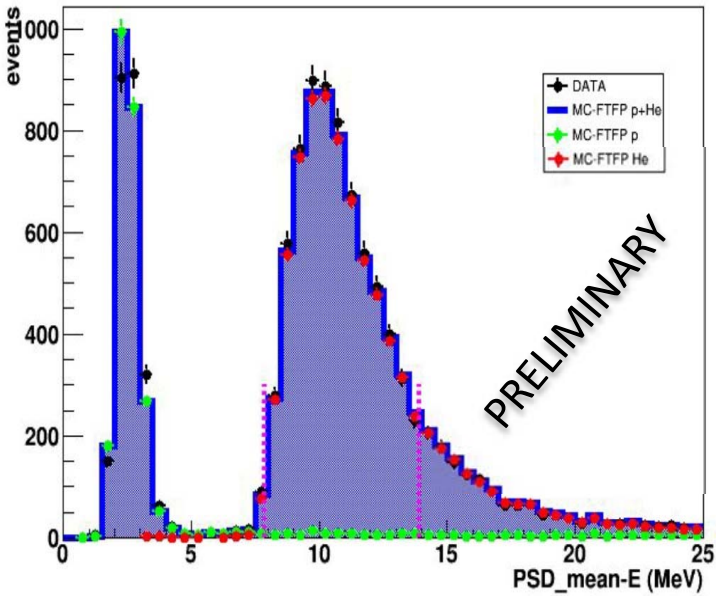
- Protons flux
  - from 40 GeV to 100 TeV
  - 30 months of data (01/01/2016 – 30/06/2018)
  - 4.68 billion events
  - spectral hardening at ~400 GeV
  - softening at ~10 TeV
  - fitting with a smoothly broken power-law: $\gamma = 2.60 \rightarrow 2.85$ at 13.6 TeV



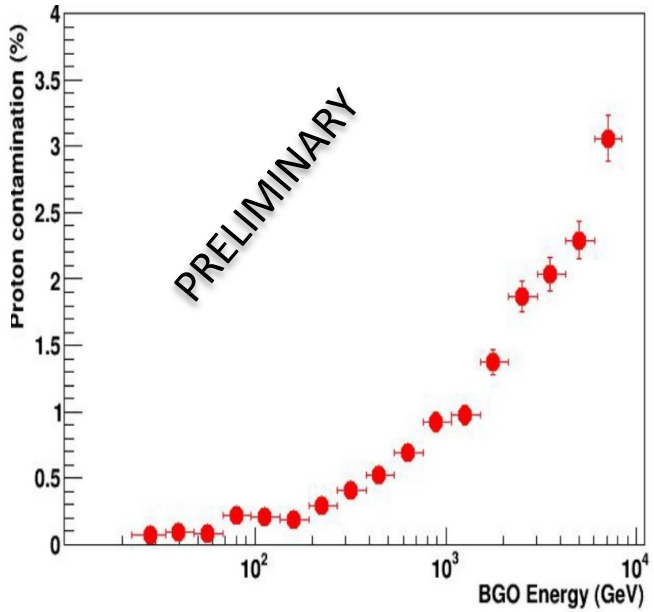
Study of Helium nuclei: selection

- Helium nuclei selection
  - energy > 20 GeV in BGO + high energy trigger + STK, PSD, BGO track conditions
  - charge measurement agreement in both PSD views and in STK 1st layer
  - protons cut based on MC
  - proton contamination <1% up to 1 TeV, 3% around 7 TeV
  - He nuclei acceptance rises over 0.035 m^2sr

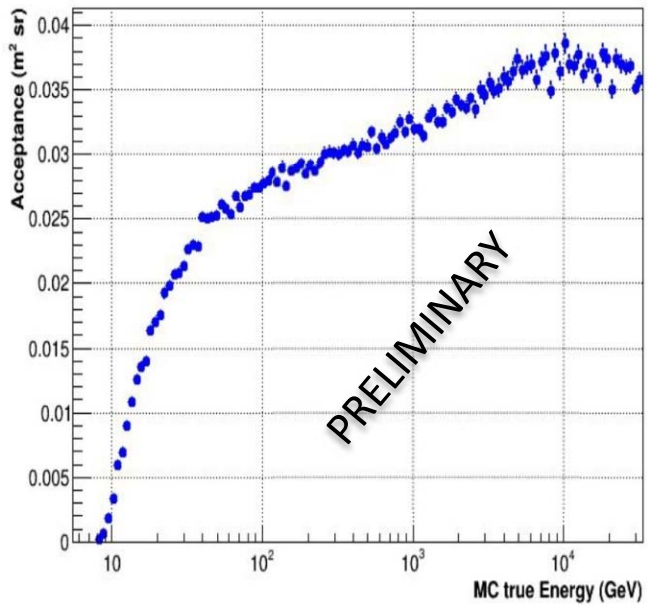
He in PSD (BGO 1.5-2.1 TeV)



proton contamination

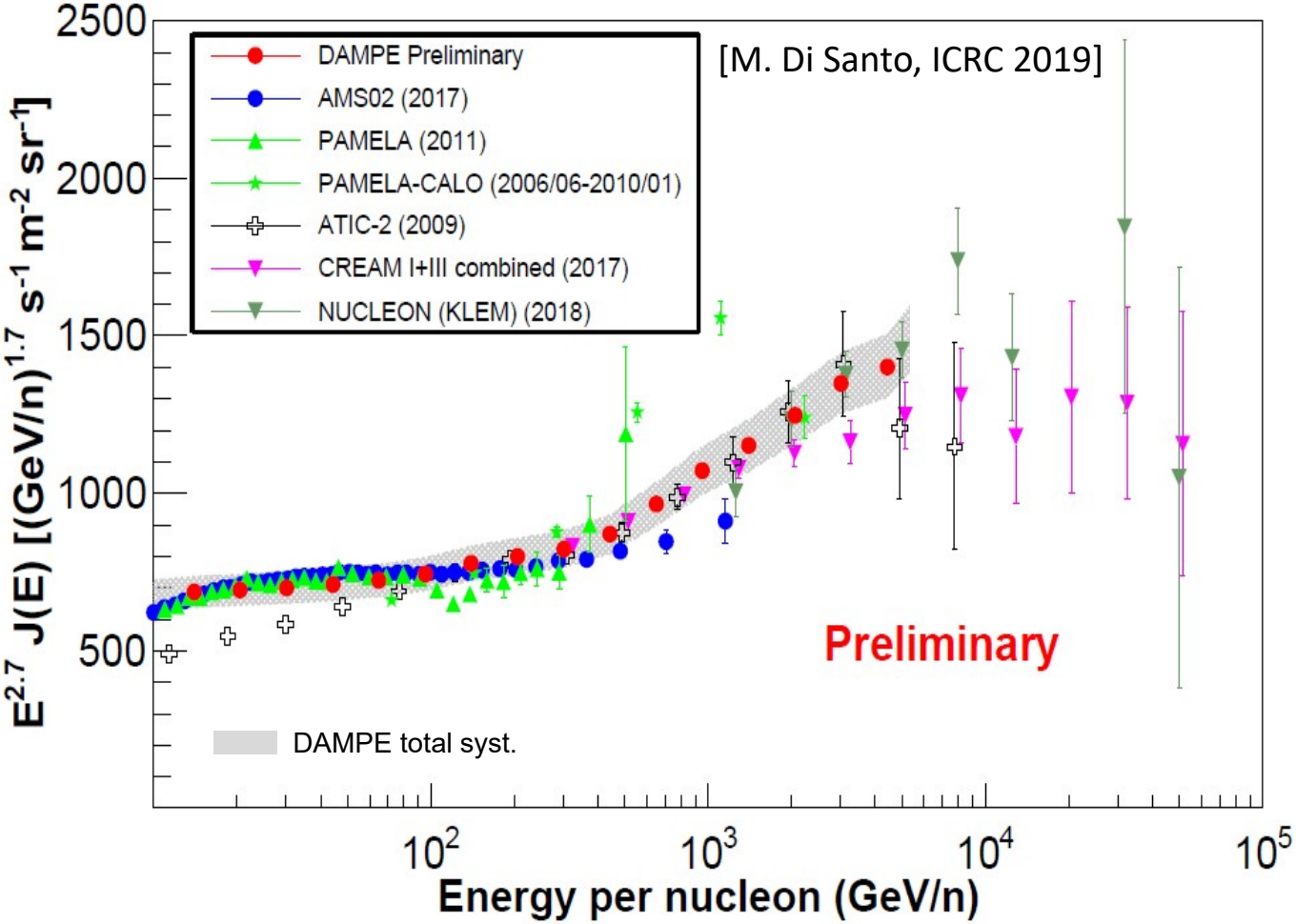


Acceptance for He nuclei



Helium nuclei: results

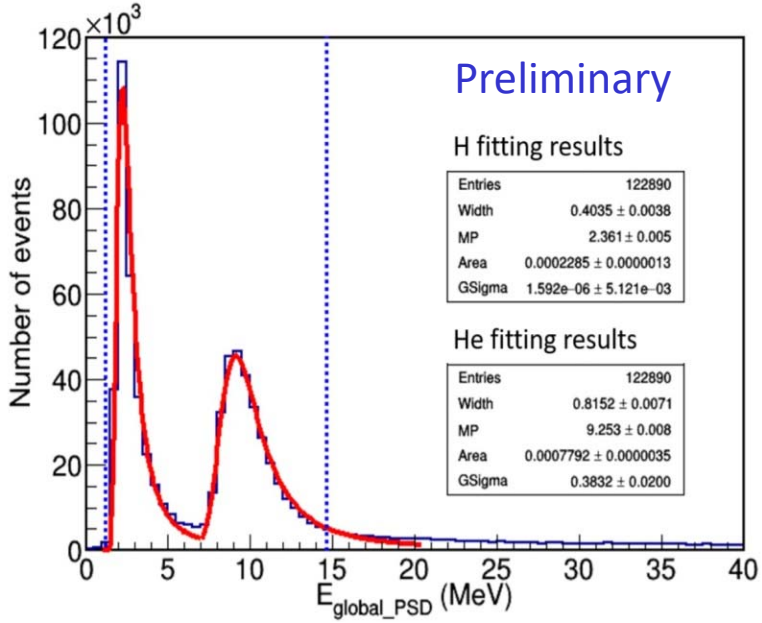
- Helium flux
  - from 10 GeV/n to ~5 TeV/n
  - 39 months of data (01/01/2016 – 31/03/2019)
  - spectral hardening at ~400 GeV/n
  - analysis ongoing at higher energies



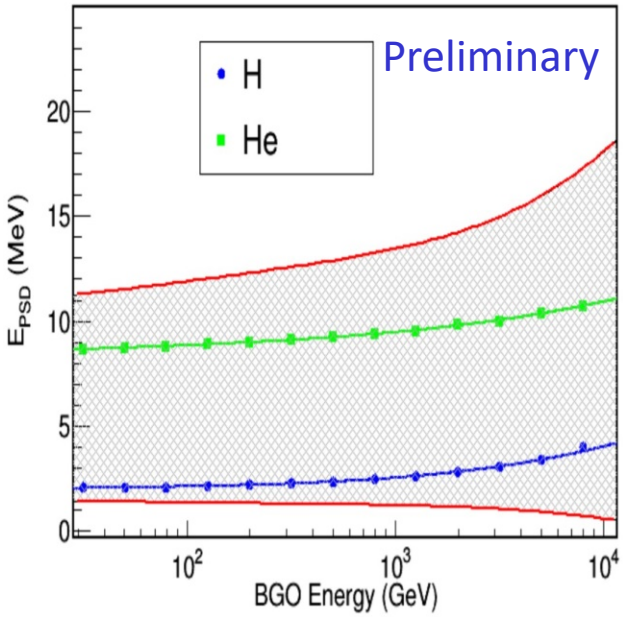
Study of protons + Helium nuclei

- PSD selection with high purity (background < 0.1%): crosscheck with H and He spectra, link with CRs up to 100 TeV, useful in indirect studies
- Protons + Helium nuclei selection
  - energy > 20 GeV in BGO + energy conditions + STK, PSD, BGO track conditions
  - energy measured in both PSD views and proportional to Z^2
  - p+He acceptance ~0.05 m^2sr at 10^4 GeV

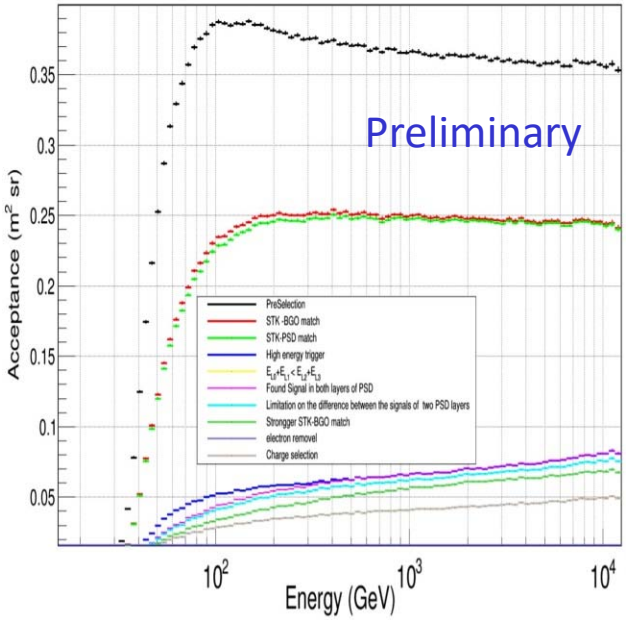
p+He in PSD (BGO 400-630 GeV)



PSD range vs BGO energy

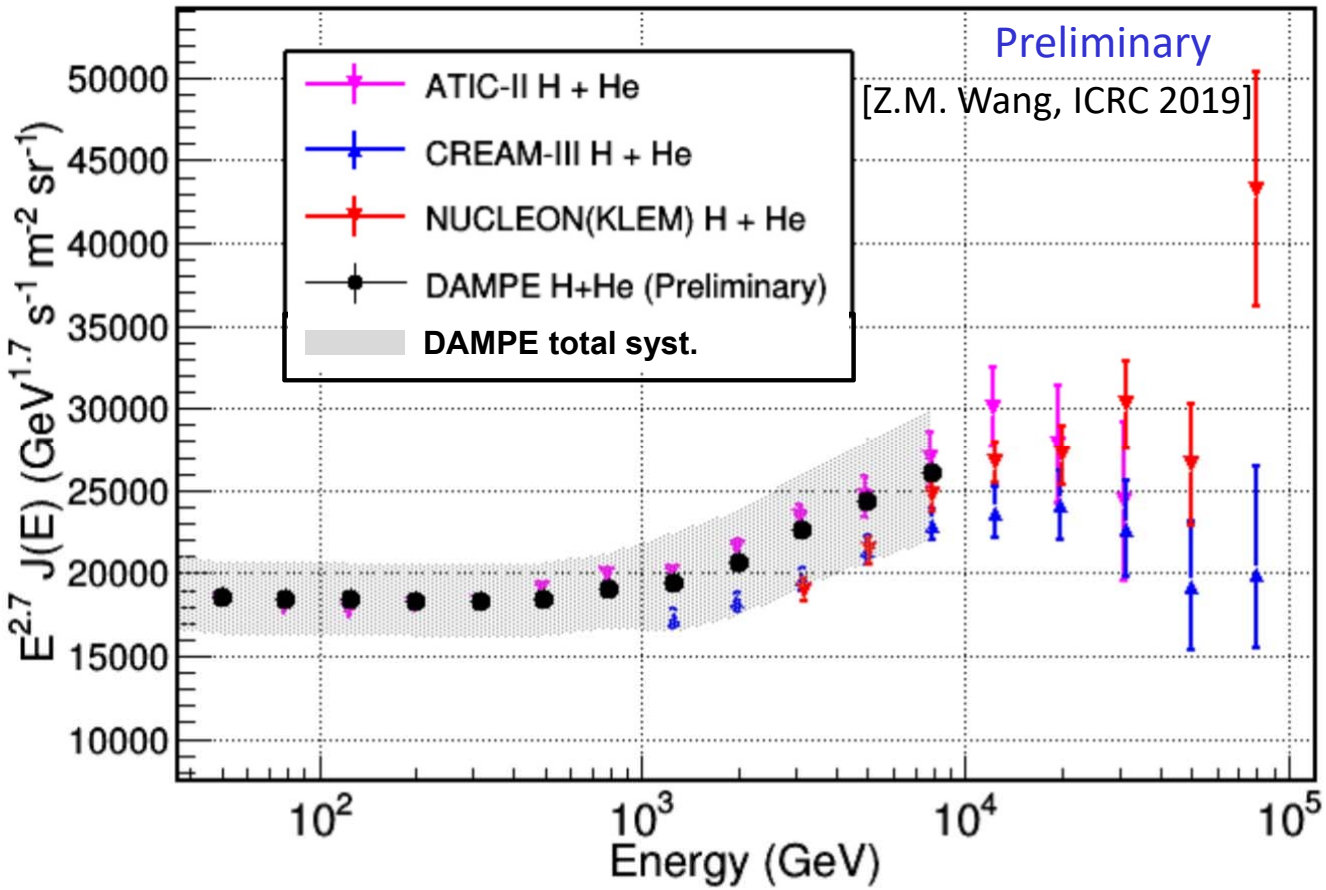


Acceptance p + He nuclei



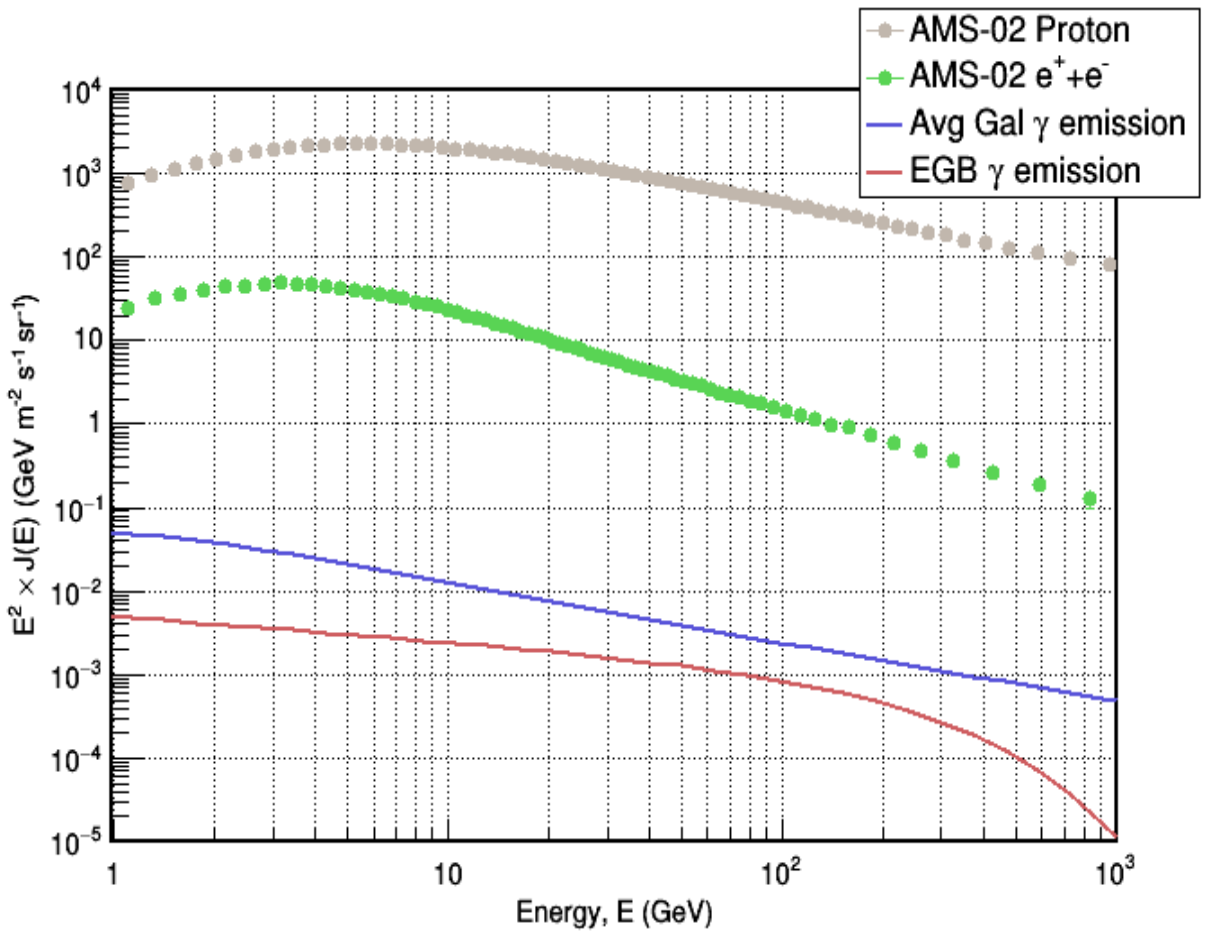
Protons + Helium nuclei: results

- p+He flux
  - from 50 GeV to ~7 TeV
  - 39 months of data (01/01/2016 – 31/03/2019)
  - 38 million events
  - spectral hardening below ~1 TeV/n
  - analysis ongoing up to 100 TeV, new results expected



Study of cosmic photons: background

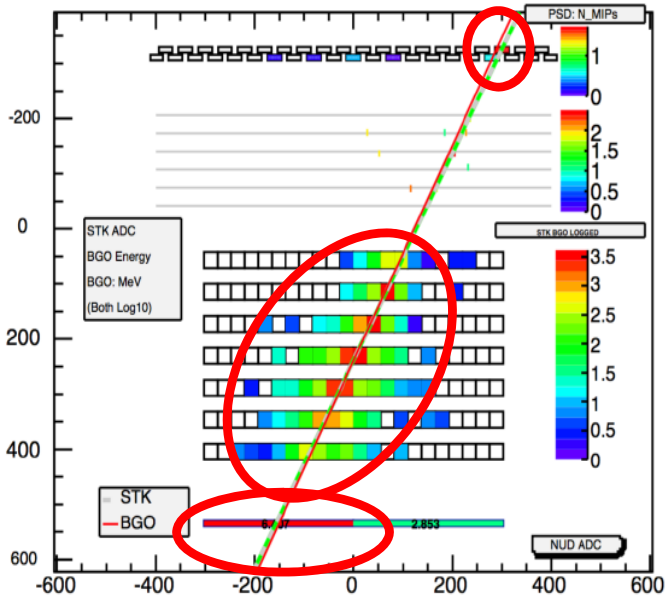
- Charged particles are a massive background for photons
- Protons vs γ:
  - 10^5 factor @ E > 100 GeV
  - mainly rejected using the shower profile and the onboard trigger
- Electrons vs γ:
  - 10^3 factor @ E > 100 GeV
  - mainly rejected using the PSD and the 1st layer of STK
  - key problem is the back scattering at high energy



Photons: selection

proton

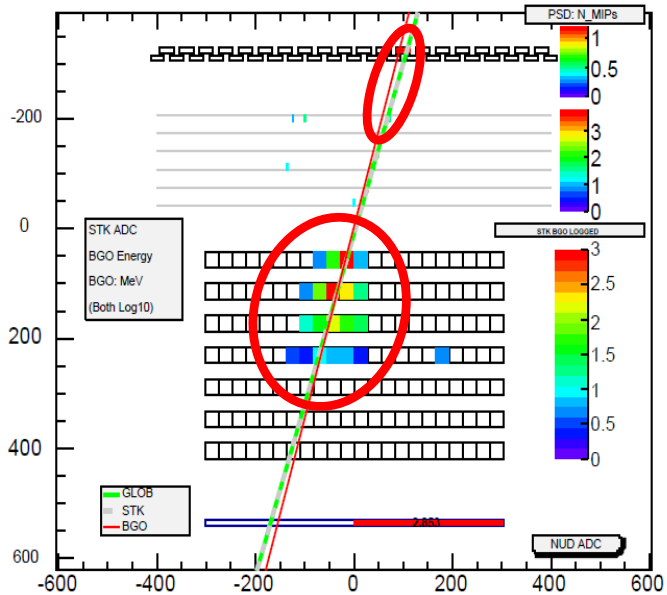
Y [No. 32: 49.132GeV]



PSD + BGO profile + NUD: rejection > 10^7 for hadrons

electron

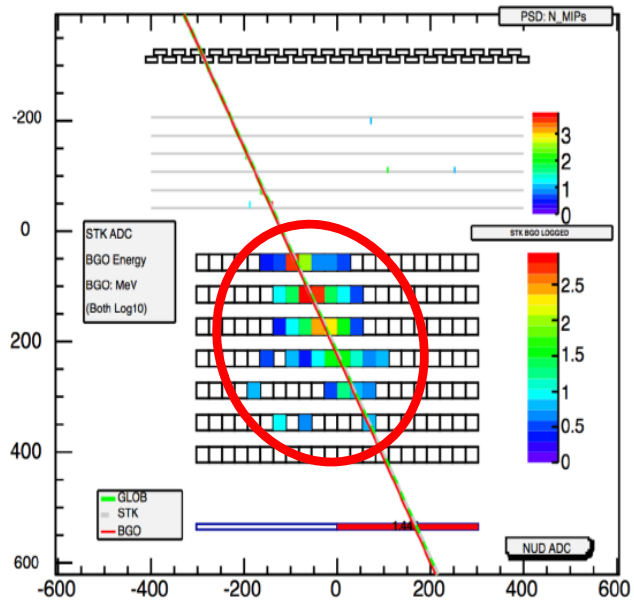
Y [No. 40: 5.034GeV]



PSD + STK: rejection up to 10^3 for electrons

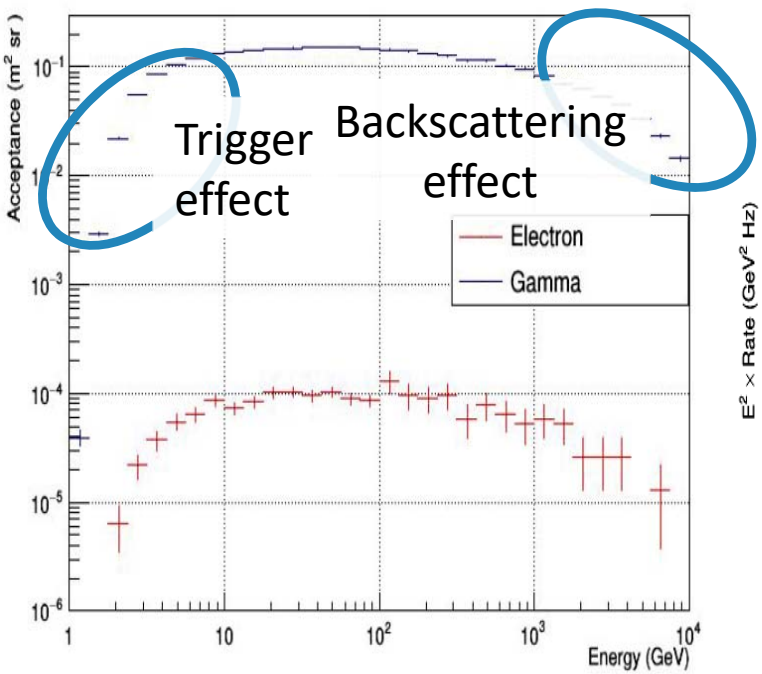
photon

Y [No. 61: 5.559GeV]

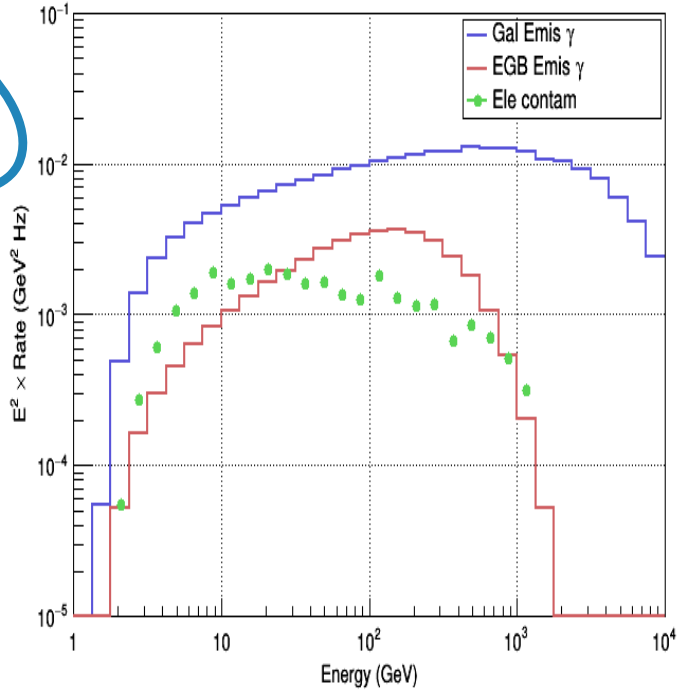


- Event topology
- Random Forest Classifiers + Convolutional Neural Networks

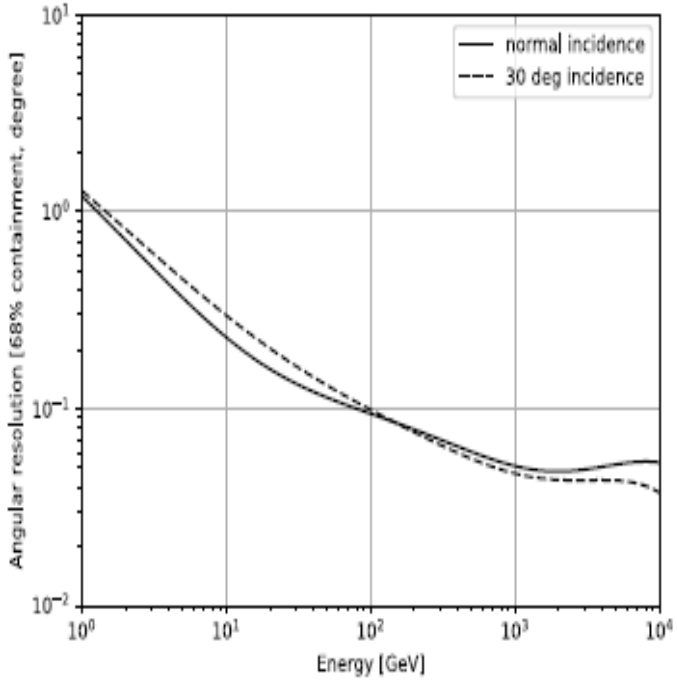
Photons: acceptance, rates, resolution



Acceptance



Rate

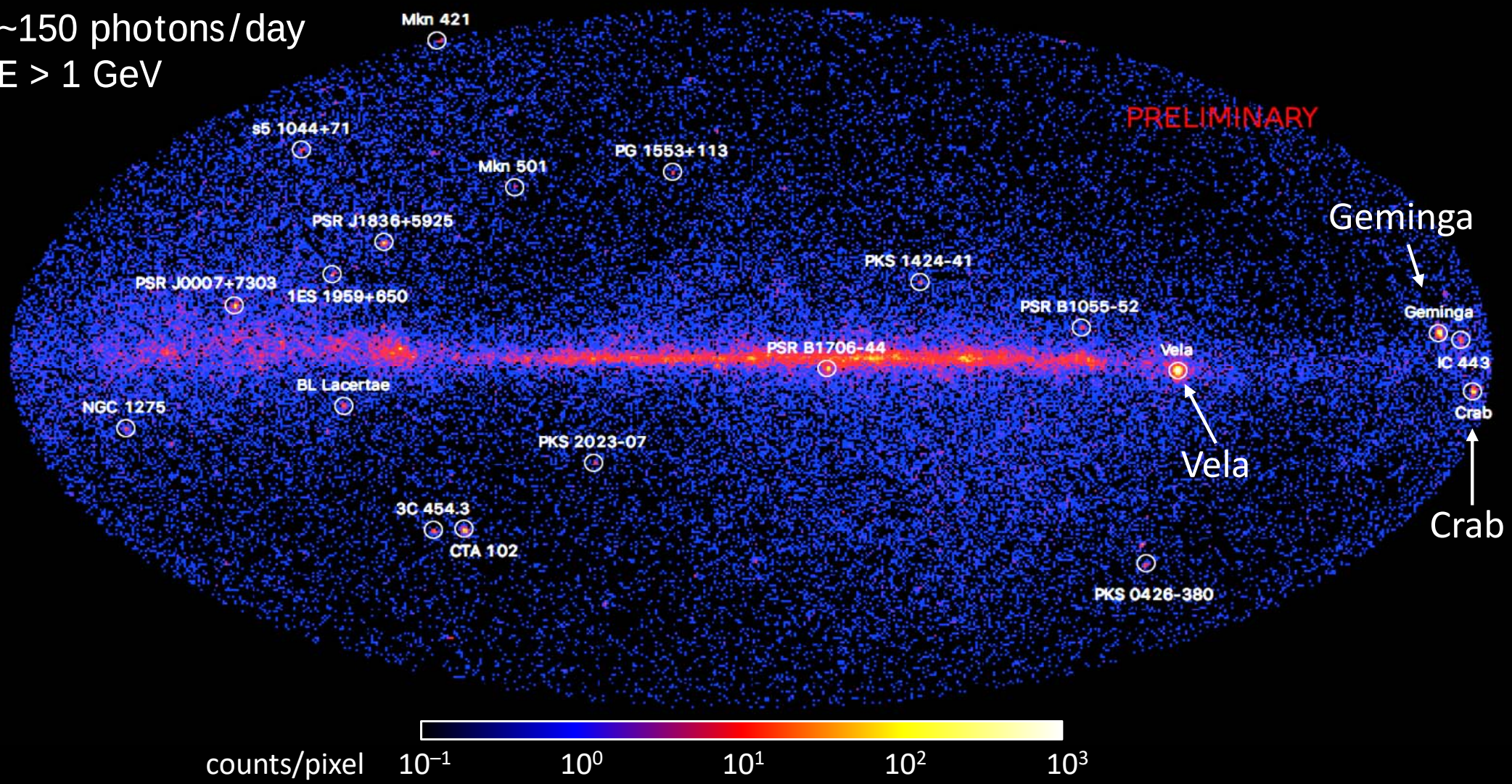


Angular Resolution

- After application of selection criteria to reject protons and electrons
  - Convolutional Neural Networks + Random Forest Classifiers
  - Other PID algorithms to decrease the contamination from electrons below the Extra Galactic Background emission

The DAMPE gamma-ray sky

~150 photons/day
E > 1 GeV

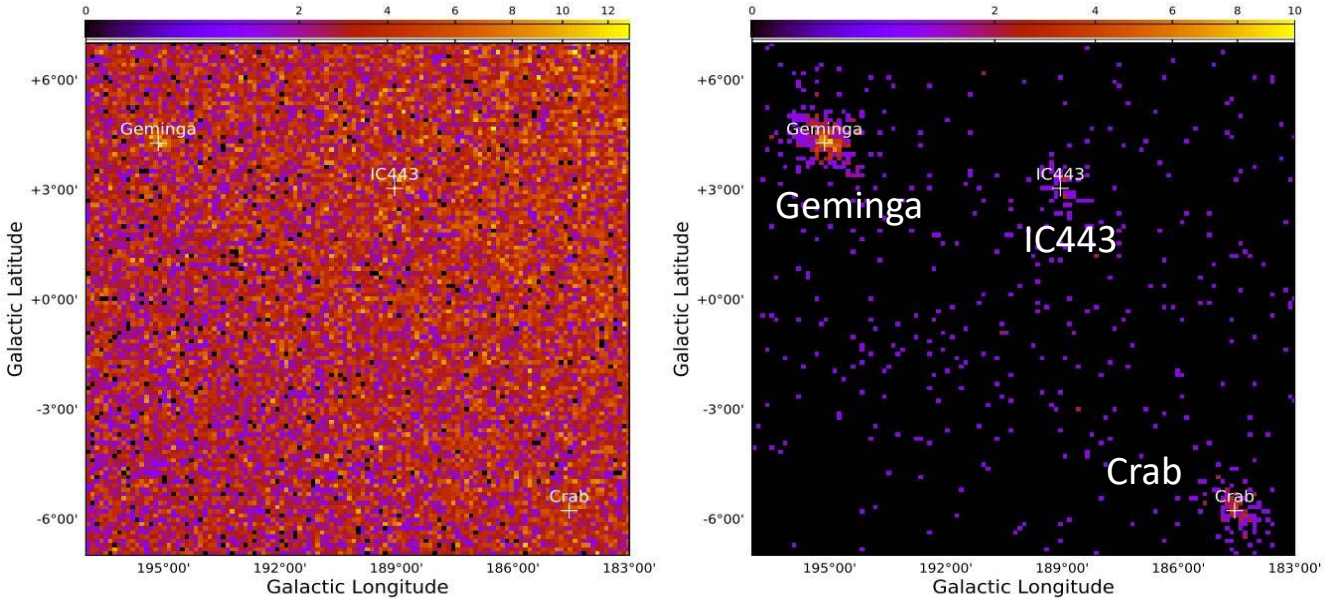


Angular resolution: ~1° @ 1 GeV, ~0.1° @ 100 GeV, ~0.05° @ 1 TeV

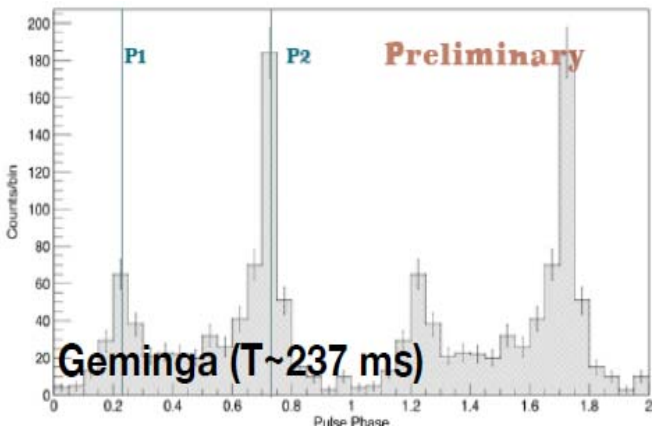
Photons: bright sources

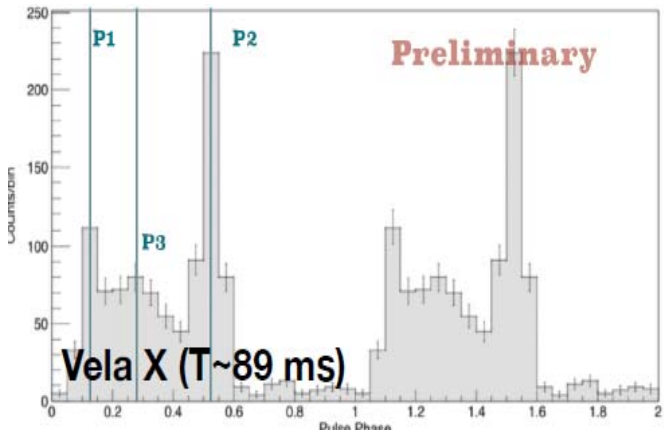
- Algorithms to resolve gamma-rays from charged cosmic rays

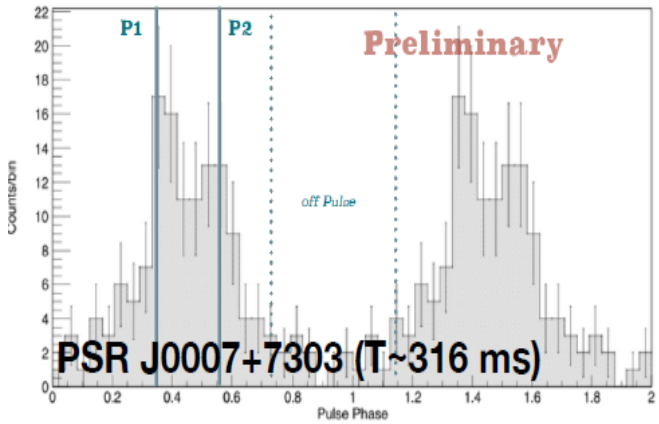
[Res. Astron. Astrophys 18, 3, 27 (2018)]



- Pulsar phase profiles



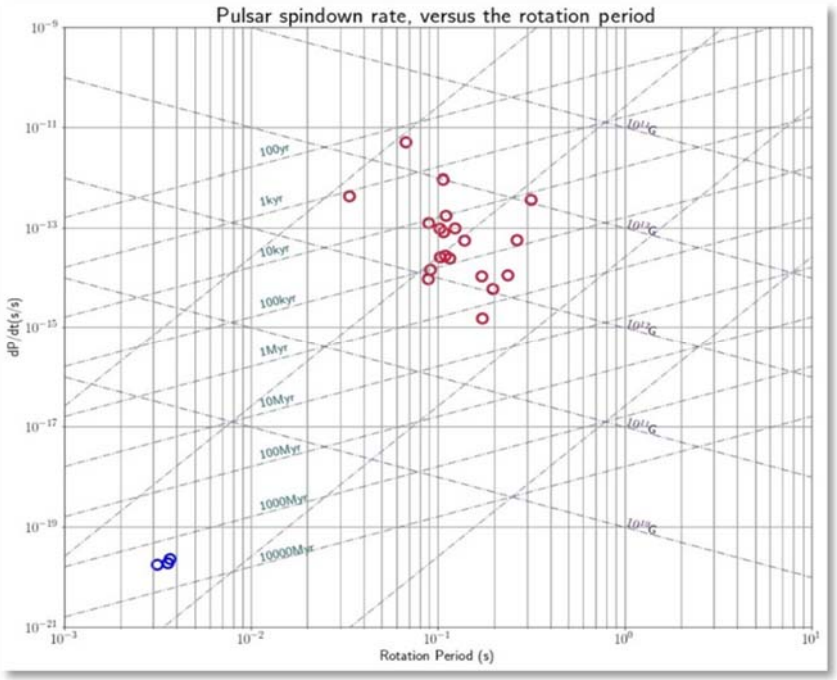




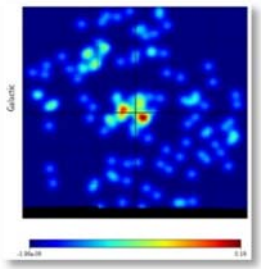
Photons: pulsars

- Selection, count maps, phase maps, SEDs

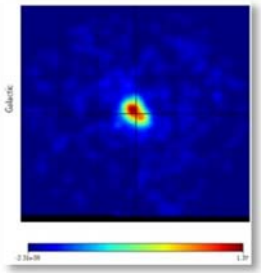
NAME	RA	DEC	PERIOD [ms]
J0614-3329	93.543	-33.498	3.149
J1514-4946	228.58	-49.771	3.589
J1231-1411	187.797	-14.195	3.684
J0534+2200	83.633	22.014	33.651
J1420-6048	215.034	-60.805	67.47
J1509-5850	227.363	-58.849	88.925
J0835-4510	128.836	-45.176	89.371
J1028-5819	157.116	-58.318	91.404
J1709-4429	257.428	-44.486	102.504
J1459-6053	224.876	-60.889	103.152
J0908-4913	137.148	-49.218	106.694
J1016-5857	154.088	-58.953	107.405
J1413-6205	213.376	-62.094	109.743
J1418-6058	214.678	-60.967	110.583
J1429-5911	217.494	-59.193	115.844
J1048-5832	162.053	-58.534	123.708
J1044-5737	161.137	-57.622	139.032
J1620-4927	245.173	-49.46	171.935
J1836+5925	279.057	59.425	173.264
J1057-5226	164.496	-52.449	197.114
J0633+1746	98.476	17.77	237.104
J2021+4026	305.378	40.446	265.321
J0007+7303	1.756	73.052	315.892



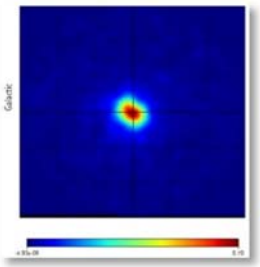
by Maria Munoz Salinas (preliminary)



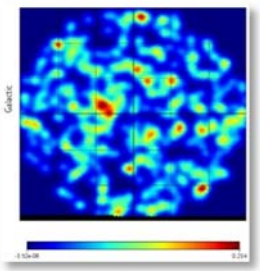
J 0614-3329 MSP



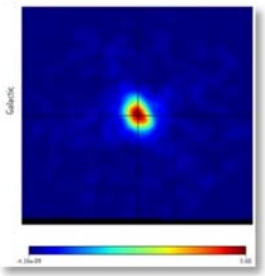
J 0534+2200



J 0835-4510

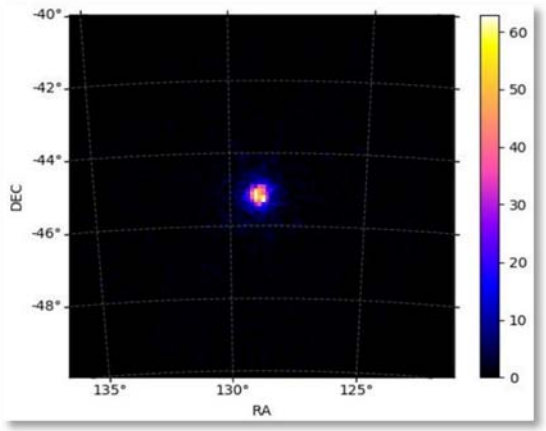


J 0908-4913

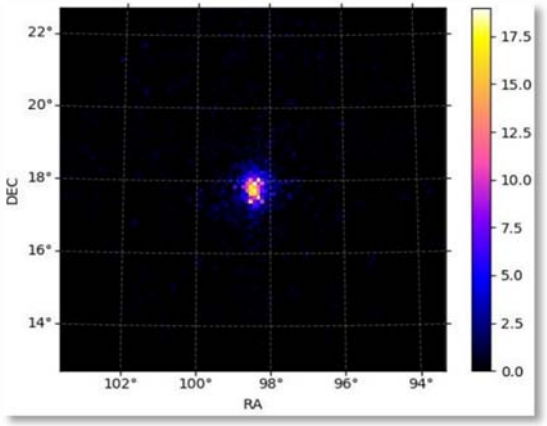


J 0633+1746

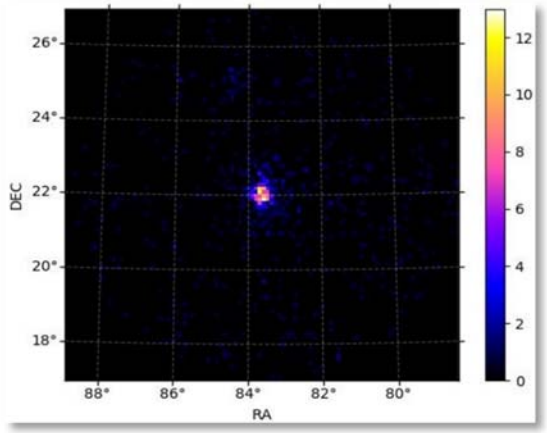
Gamma-ray sources: counts maps and SEDs



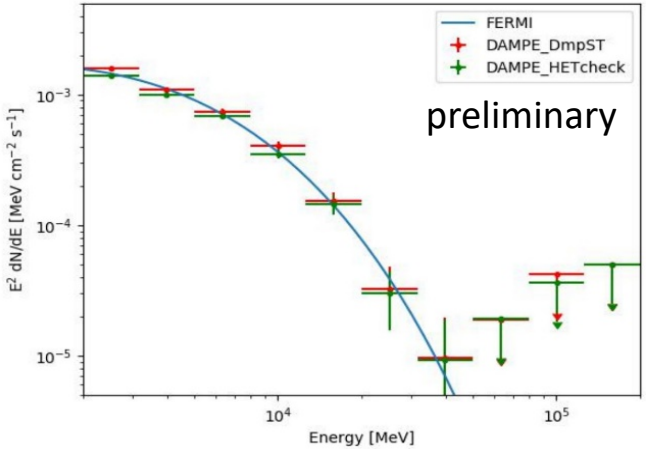
Vela

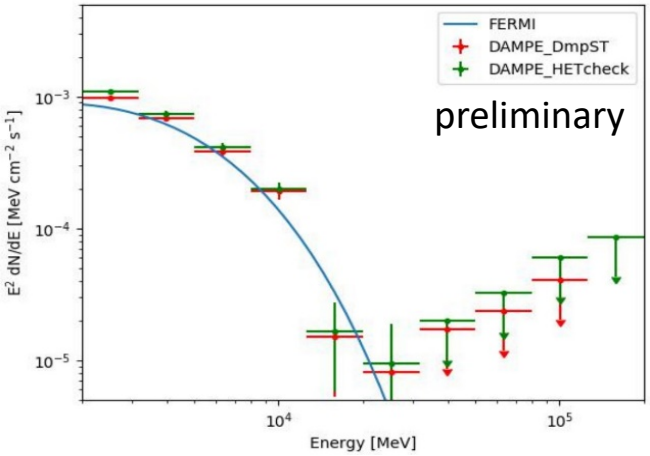


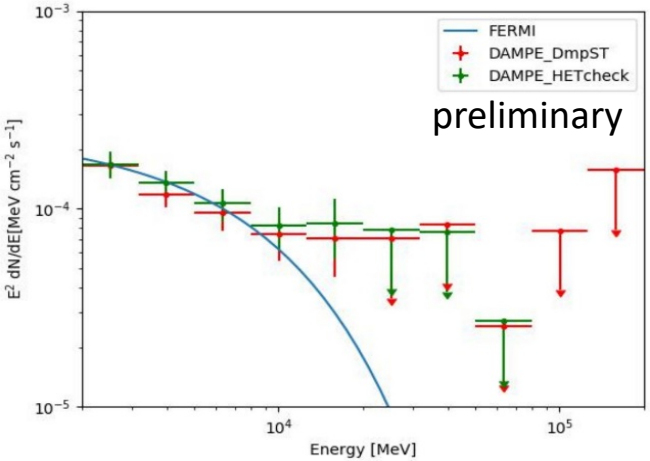
Geminga



Crab



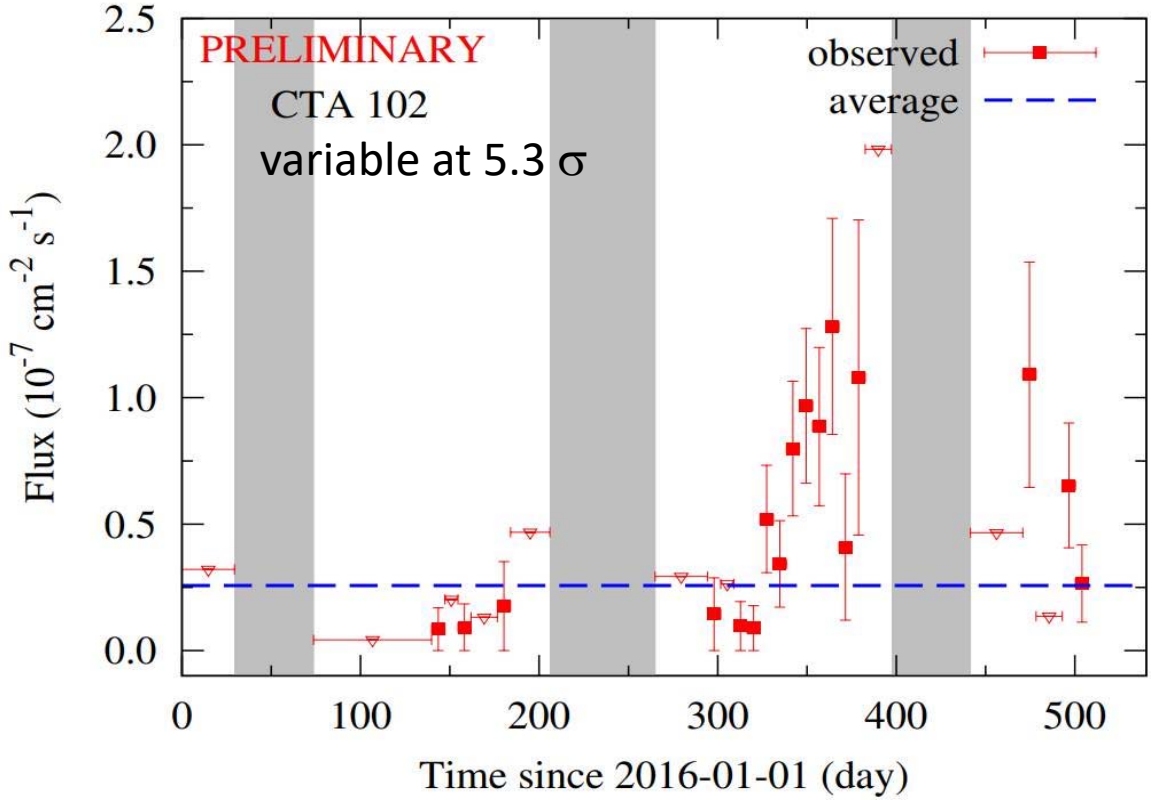




by Maria Munoz Salinas (preliminary)

Emission variation in extragalactic sources

- DAMPE detection of gamma-ray variable emission in extragalactic sources:
  - blazar CTA 102; Atel #9901
  - blazar 3C 454.3
  - blazar 3C 279; Atel #11246
  - FSRQ S4 1800+44; Atel #12562
  - FRSQ PKS 1830-211; Atel #12705
  - …

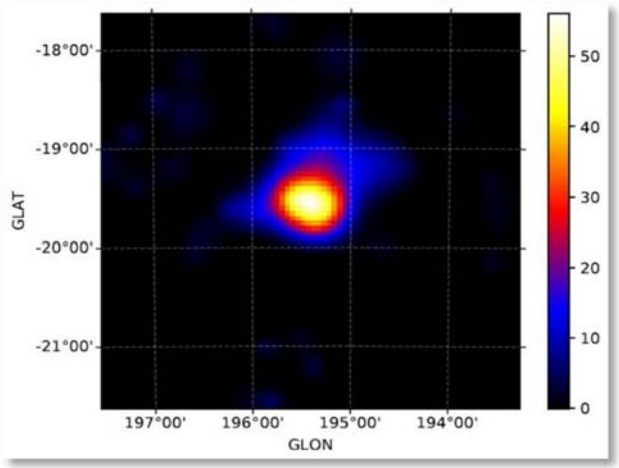


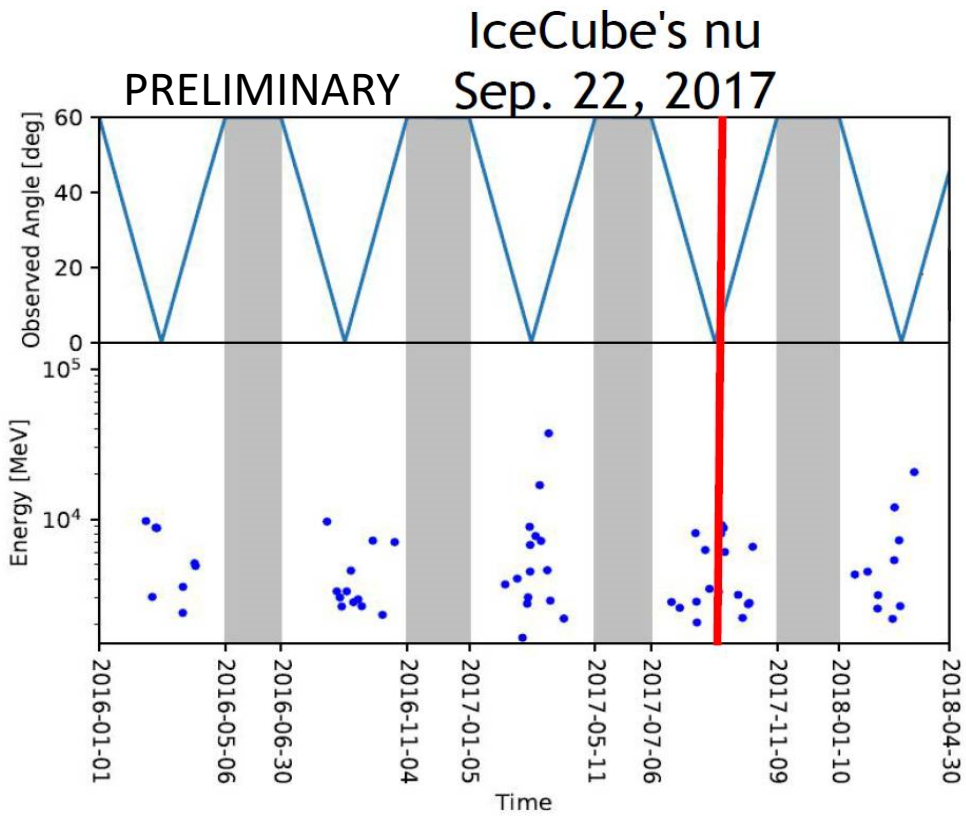
DAMPE detection of variable GeV gamma-ray emission from blazar CTA 102

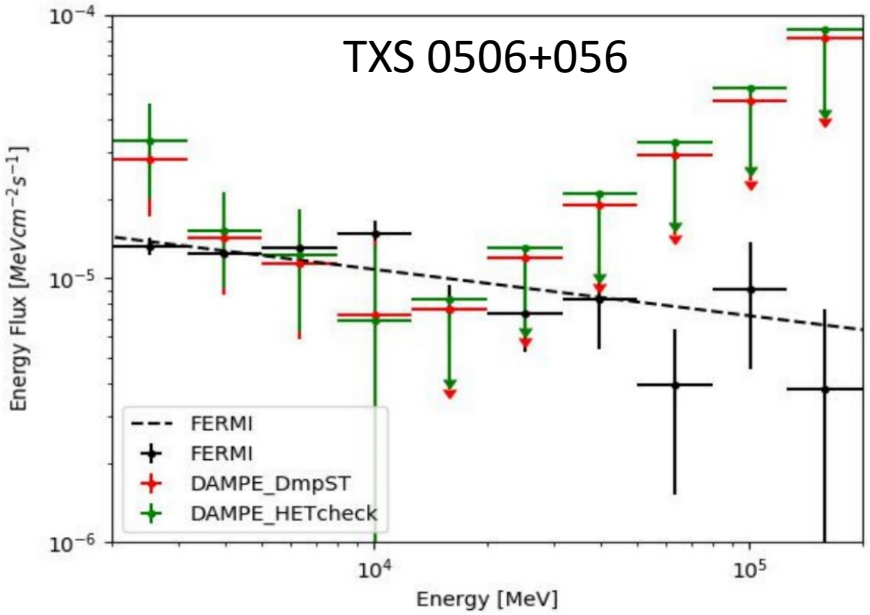
ATel #9901; *Zun-Lei Xu (PMO), Micaela Caragiulo (Bari), Jin Chang (PMO), Kai-Kai Duan (PMO), Yi-Zhong Fan (PMO), Fabio Gargano (Bari), Shi-Jun Lei (PMO), Xiang Li (PMO), Yun-Feng Liang (PMO), M. Nicola Mazziotta (Bari), Zhao-Qiang Shen (PMO), Meng Su (HKU/PMO), Andrii Tykhonov (Geneva), Qiang Yuan (PMO), 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)

Participation to multi-messenger searches

- Detection of gamma-ray source TXS 0506+056
  - 5.7 Gly, associated with the 290 TeV ν_μ IceCube-170922A
  - no clear variability detected due to limited statistics
  - ongoing monitoring of the source







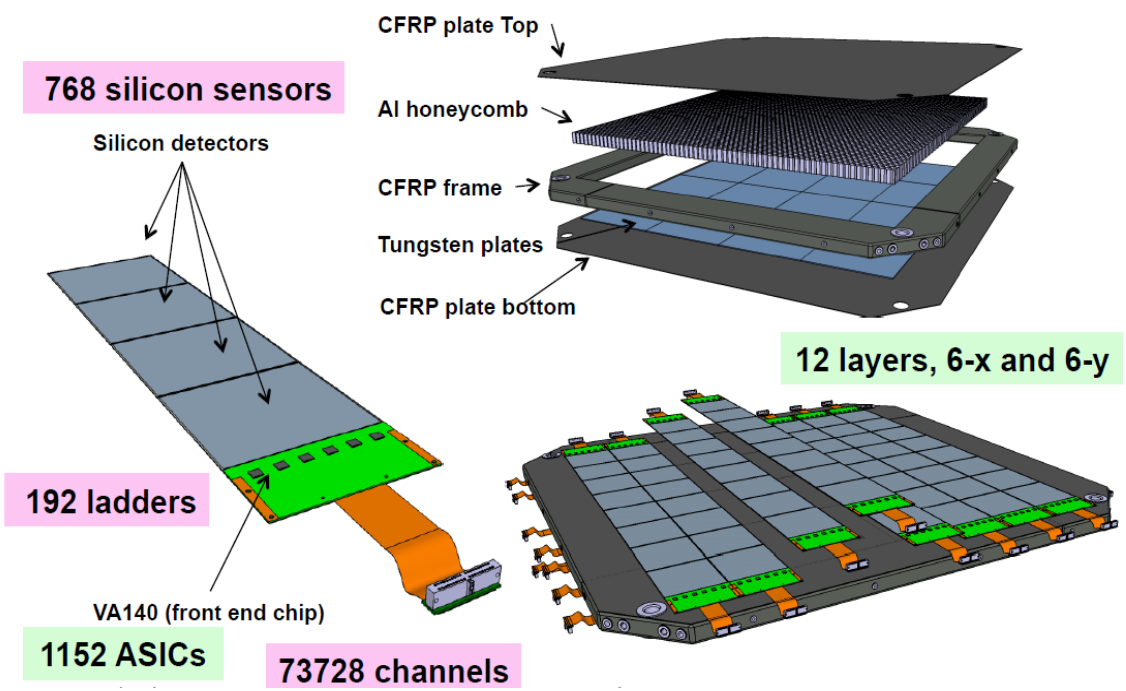
DAMPE summary

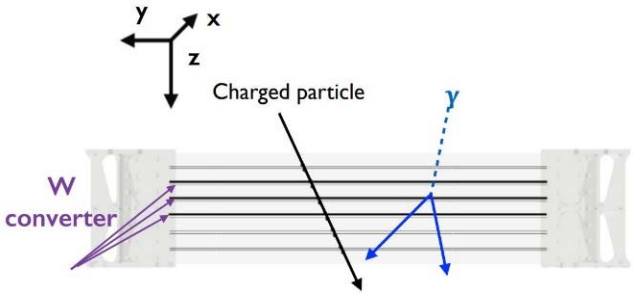
- DAMPE is working extremely well since ~4 years
- e^-+e^+ spectrum precisely measured up to TeV energies
  - a clear spectral break has been directly measured at ~1 TeV
  - improving precision on behavior and structures (nearby sources, anisotropies, DM?)
- Proton spectrum measured
  - hardening at ~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
- Contribution to photon detection and analysis
  - excellent energy resolution
  - many different sources and items studied
  - significant statistics is being accumulated

Thank you

Backup

The Silicon TracKer (STK)



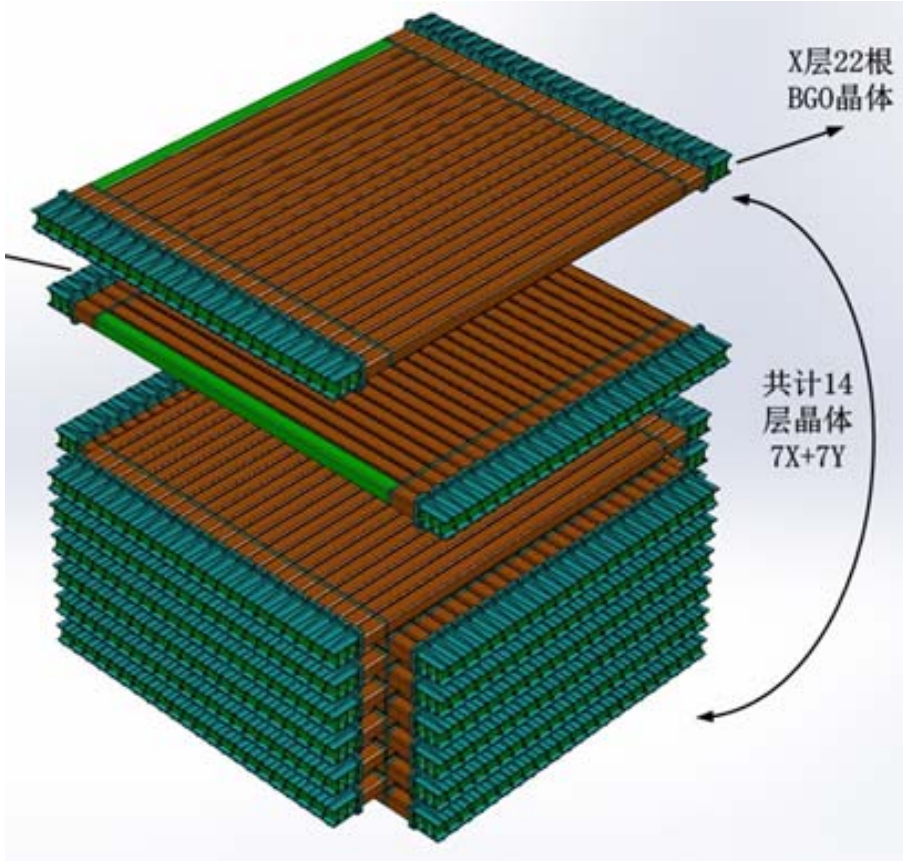


- 48 μm wide Si strips - 121 μm pitch
- 95×95×0.32 mm^3 Silicon Strip Detectors (SSD) - 768 strips
- 1 ladder composed by 4 SSDs
- 16 ladders per layer (76×76 cm^2)
- 12 layers (6x + 6y)

Analog Readout of each second strip:
384 channels / SSD- Ladder
Charge sharing

The CALOrimeter

- 14 alternate orthogonal layers,each of 22 BGO bars
  - Total 308 bars
  - Dimensions of a bar: 2.5×2.5×60 cm^3
  - Total depth ~32 X_0, ~1.6 λ

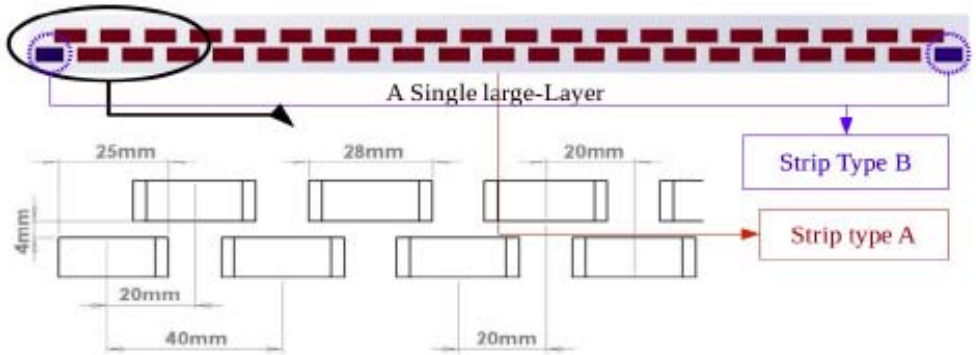


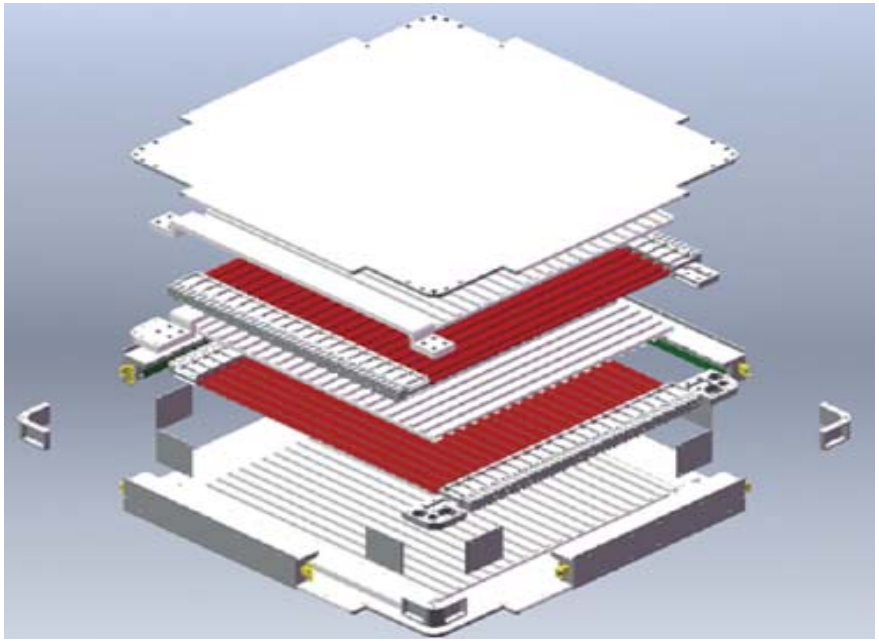
- One PMT at each BGO bar end
  - Two PMTs per bar, total 616 PMTs

- Electronics boards attached to each side of the module
- Deposited energy ranges: 2 MeV – 2 TeV and 10 MeV – 5 TeV

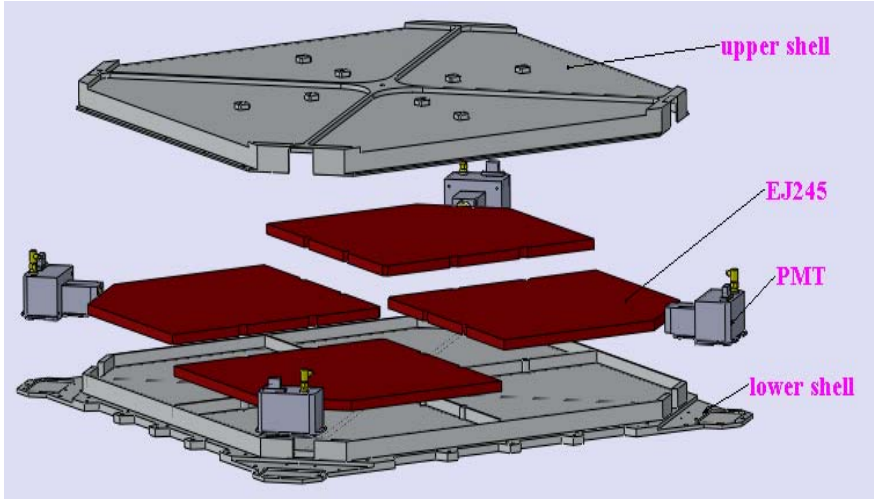
The PSD and the NUD

- PSD
  - 2 layers (*x* and *y*), each is 82×82 cm^2
  - 88×2.8×1 cm^3 scintillator bars
  - Staggered by 0.8 cm in each layer





- NUD
  - 4 large area boron-doped plastic scintillators, 30×30×1 cm^3 each
  - Wrapped in Al for photon reflection

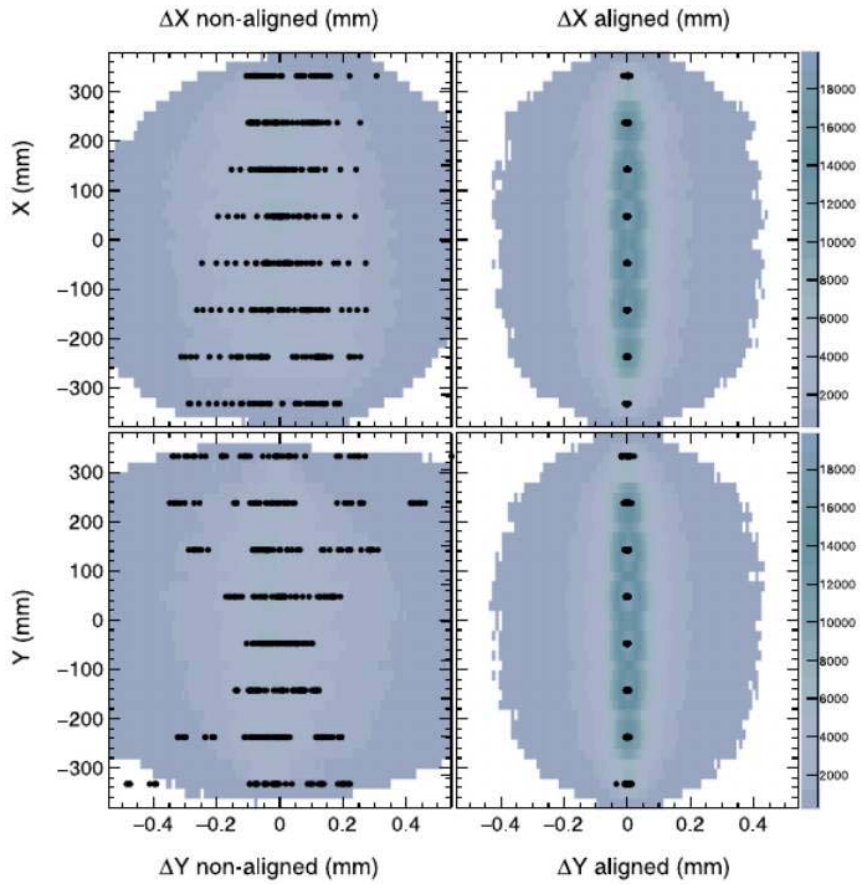


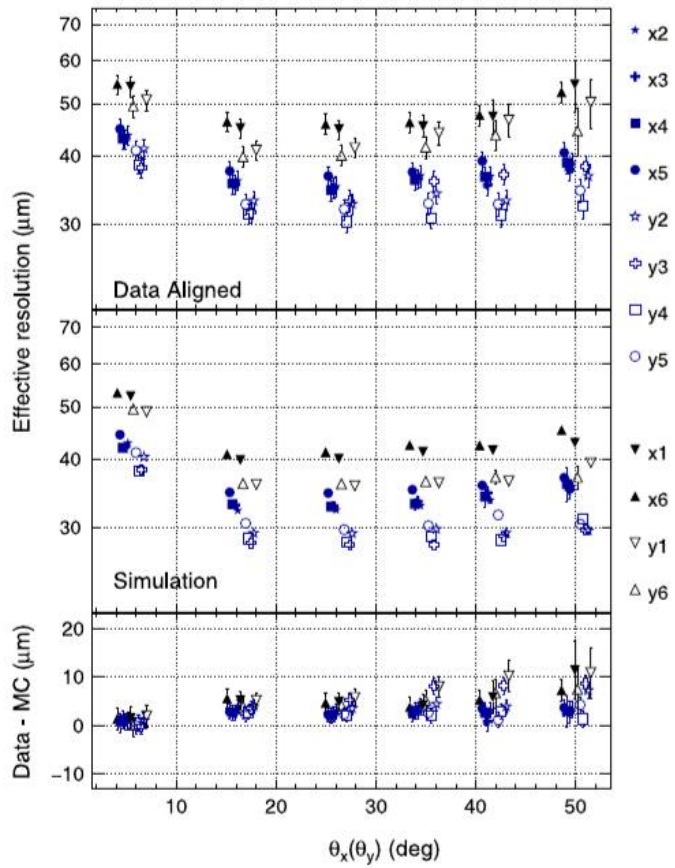
The DAMPE triggers

Trigger Type	Logic	Energy Threshold	Pre-scale factor
HE	L1_P_dy5	~10 MIPs	1
	& L2_P_dy5	~10 MIPs	
	& L3_P_dy5	~10 MIPs	
	& L4_N_dy8	~2 MIPs	
MIPs (Type I)	L3_P_dy8	~0.4 MIPs	4 (low latitude(±20°))
	& L11_P_dy8	~0.4 MIPs	
	& L13_P_dy8	~0.4 MIPs	Turn Off (other region)
MIPs (Type II)	L4_P_dy8	~0.4 MIPs	4 (low latitude(±20°))
	& L12_P_dy8	~0.4 MIPs	
	& L14_P_dy8	~0.4 MIPs	Turn Off (other region)
LE	L1_N_dy8	~0.4 MIPs	8 (low latitude(±20°))
	& L2_N_dy8	~0.4 MIPs	
	& L3_N_dy8	~2 MIPs	
	& L4_N_dy8	~2 MIPs	64 (other region)
Unbiased	(L1_P_dy8 & L1_N_dy8)	~0.4 MIPs ~0.4 MIPs	512 (low latitude(±20°))
	| (L2_P_dy8 & L2_N_dy8)	~0.4 MIPs ~0.4 MIPs	2048 (other region)

STK alignment

- STK alignment is performed once every two weeks
  - MIPs (non-showering particles) are used to correct the alignment
  - a spatial resolution < 40 μm on central STK planes is achieved





Dark Matter search targets

Satellite galaxies

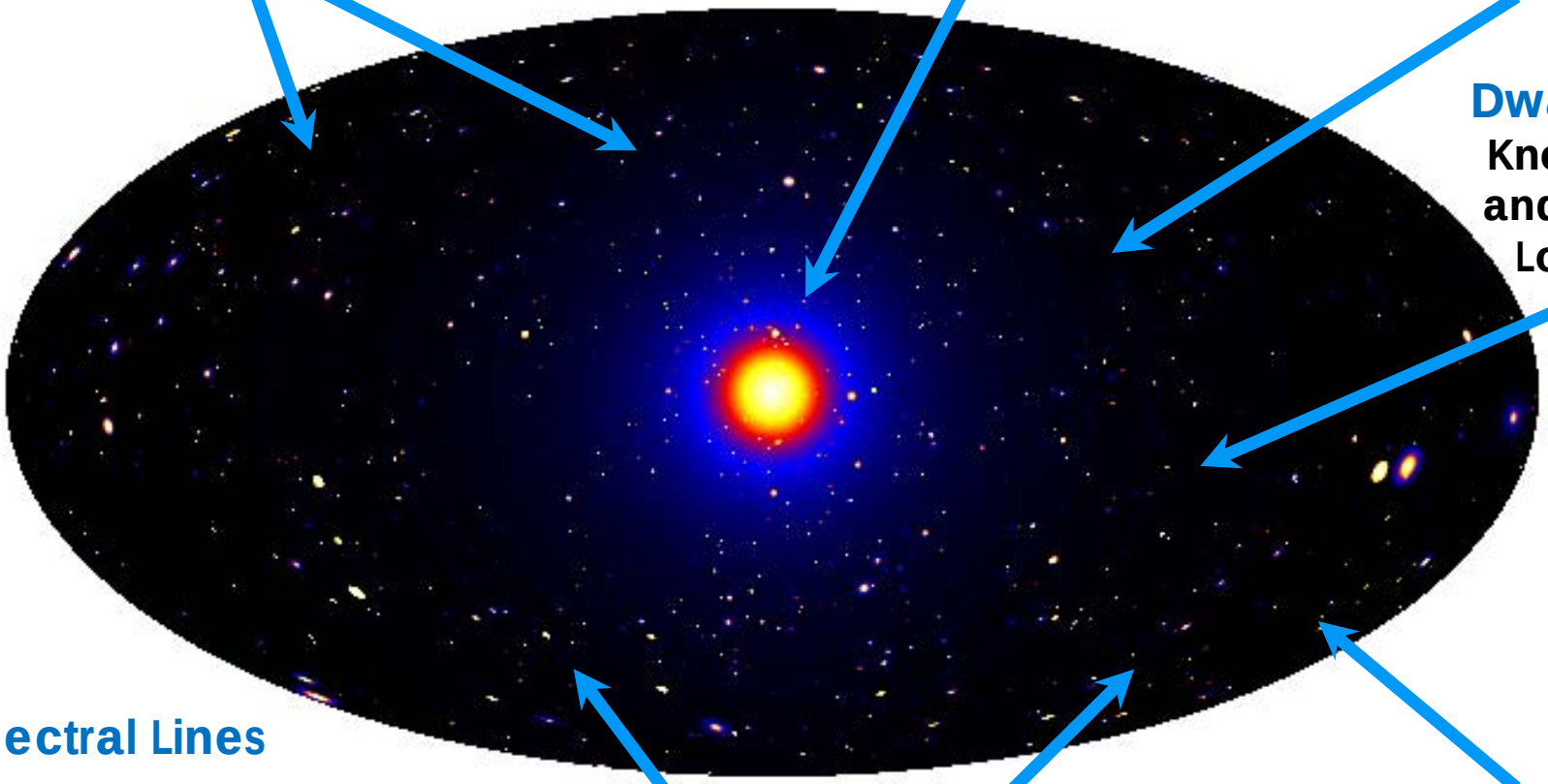
Low background and good source id, but low statistics

Galactic Center

good statistics, but source confusion/diffuse background

Milky Way Halo

Large statistics, but diffuse background



Dwarf Galaxies

Known location and DM content
Low statistics

Spectral Lines

Little or no astrophysical uncertainties, good source id, but low sensitivity because of expected small branching ratio

Galaxy Clusters

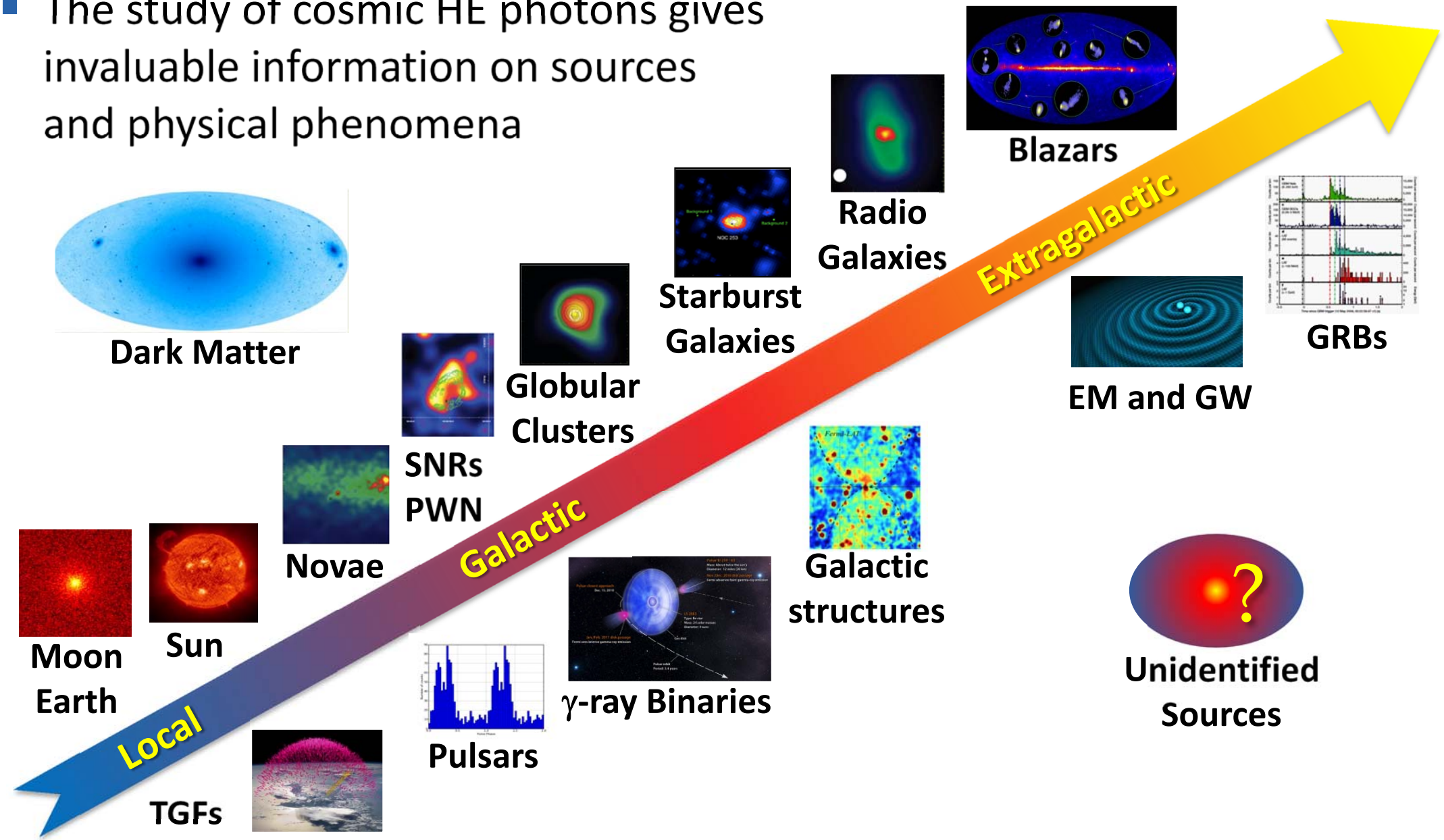
Low background, but low statistics

Isotropic contributions

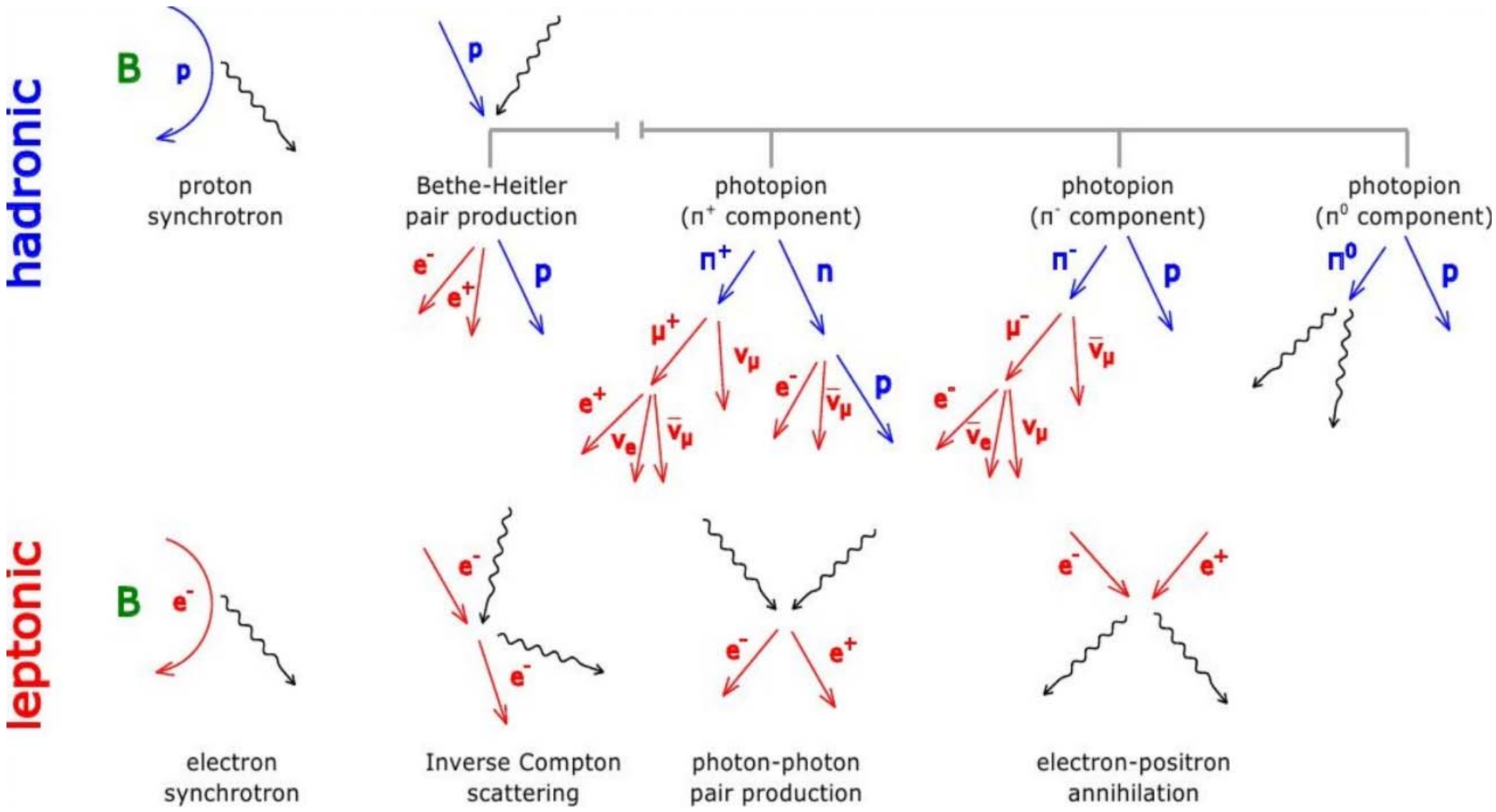
Large statistics, but galactic diffuse background

Sources of high-energy cosmic photons

- The study of cosmic HE photons gives invaluable information on sources and physical phenomena



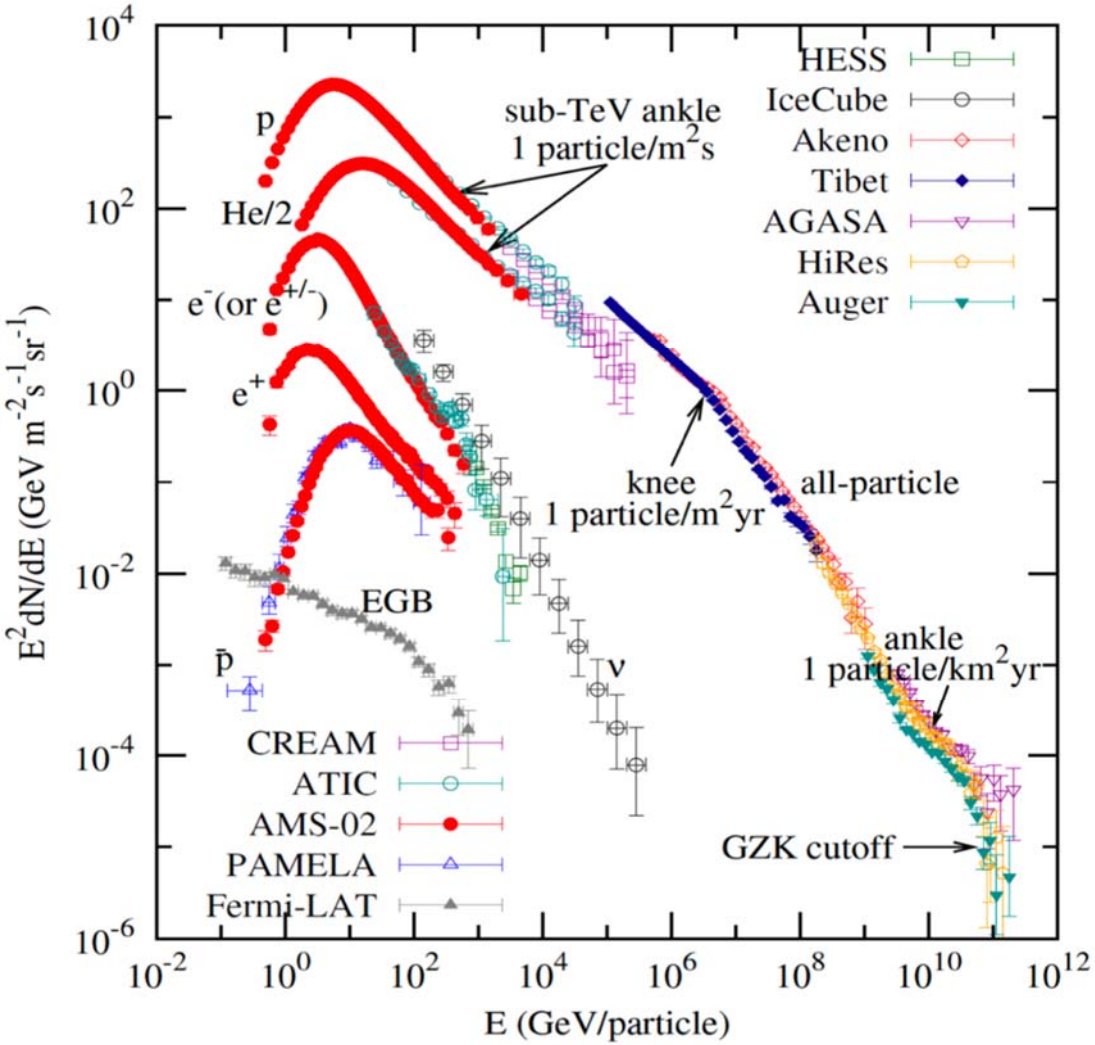
Cosmic photons production and interaction



Cosmic rays

- High-energy atomic nuclei and traces of e^-, e^+, $\bar{p}$
- Energies: ~10^8 eV → ~10^{20} eV

sources	hadronic interactions	leptonic interactions
production of π^0's, etc.	decay of π^0's, etc. into photons	
interaction of photons	observation of photons	
identification of sources	features of sources	
acceleration mechanisms	interaction with ISM	
solar modulation	etc…	



Latest measurements of CR spectrum