Observation of high-energy cosmic photons with new-generation space telescopes

Piergiorgio Fusco
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on behalf of the DAMPE and HERD Collaborations
High-energy cosmic photons

- Cosmic photons from a few 100 keV to ~1 PeV = gamma rays
- Origin in non-thermal processes:
  - decay or de-excitation of nuclei;
  - decay of particles or their annihilation with antiparticles;
  - interaction of high energy particles with photons and matter.
- Emission features:
  - mono-energetic photons;
  - broad-band continuum spectrum.
- Pros and cons of cosmic gamma rays:
  - free from concurrent thermal radiation;
  - good galactic and extra-galactic transparency;
  - interact with Earth's atmosphere.
- Cosmic gamma rays provide a clear view onto the non-thermal physics in the Universe
Sources of high-energy cosmic photons

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

- Dark Matter
- TGFs
- GRBs
- Novae
- SNRs
- PWN
- Starburst Galaxies
- Globular Clusters
- Blazars
- Radio Galaxies
- EM and GW
- Galactic structures
- Sun
- Pulsars
- Moon
- TGFs
- Galactic
- Unidentified Sources

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Cosmic photons production and interaction

hadronic

- proton synchrotron
- Bethe-Heitler pair production
- photopion ($n^+$ component)
- photopion ($n^-$ component)
- photopion ($n^0$ component)

leptonic

- electron synchrotron
- Inverse Compton scattering
- photon-photon pair production
- electron-positron annihilation
Cosmic rays

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

**sources**  
**hadronic interactions**  
**leptonic interactions**

- production of $\pi^0$'s, etc.  
- decay of $\pi^0$'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

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Dark Matter

- **Evidence for missing mass**
  - rotation curves of galaxies
  - colliding clusters
  - cosmological probes ($\Omega_{dm} h^2 \approx 0.1$)

- **Observational indications**
  - non-baryonic
  - (almost totally) neutral
  - (almost totally) collisionless

- **Candidates**
  - WIMPs: continuum or line gamma-ray emission in GeV-TeV
  - ALPs, sterile neutrinos, etc.
  - modifications to gravity
  - …
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
"Kifune plot" by S. Fegan
(sfegan@llr.in2p3.fr)
Fermi 9 years gamma-ray sky
Fermi LAT 3rd Source Catalog

3034 sources > 100 MeV  95% extragalactic  21% BL Lacs
16% Flat Spectrum Radio Quasars
19% unclassified blazars
22% unassociated high latitude

3FGL Catalog
The DAMPE Experiment

- **CHINA**
  - Purple Mountain Observatory, CAS, Nanjing, *Pl 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

- **SWITZERLAND**
  - University of Geneva
DAMPE scientific goals

- DAMPE – DArk Matter Particle Explorer – is a \textit{space particle} and \textit{photon detector} aimed to:
  - study \textit{cosmic electrons} spectra
  - study \textit{cosmic protons + nuclei} spectrum and composition
  - astronomy with high-energy cosmic \textit{gamma-rays}
  - search for \textit{dark matter} signatures in \textit{photon} and lepton spectra
  - search for \textit{e.m. counterparts} of gravitational waves or neutrinos
  - quest for \textit{exotic} particles and phenomena

- \textbf{Excellent performance}:
  - detection of 5 GeV – 10 TeV $e/\gamma$, 50 GeV – 100 TeV $p$ and nuclei
  - energy resolution: $< 1.5\%$ for 100 GeV $e/\gamma$, $< 40\%$ for 800 GeV $p$
  - angular resolution: $< 0.2^\circ$ for 100 GeV $\gamma$
  - field of view: $\sim 1 \text{ sr}$
  - effective area (normal incidence): 1200 cm$^2$ @ 100 GeV
The DAMPE instrument

**PSD:** Plastic Scintillator Detector
Anti-coincidence, ion identification

**STK:** Silicon TracKer/ converter
(6 Si double layers + 3 1 mm W plates)
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

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DAMPE launch

- DAMPE was launched on Dec. 17\textsuperscript{th} 2015
  - Launch site: Jiuquan Satellite Launch Center, Gobi desert, China
  - Orbit: 500 km altitude, 97°, Sun synchronous
Trigger rate and data transfer

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
The geomagnetic rigidity cut-off of cosmic-ray electrons (CRE) spectrum provides a reference for absolute energy calibration

- low energy CRE flux is measured in the range $8 \text{ GeV} < E < 100 \text{ GeV}$
- flight data and Monte Carlo data (with back-tracing in Earth magnetic field model IGRF12) are compared
- expected cut-off: $13.0 \text{ GeV}$; DAMPE measured cut-off $13.2 \text{ GeV}$
- stable with time - slight decrease due to solar modulation of primary electrons
Several different PID methods used (Shape parameters; Boosted Decision Trees; Random Forest + Convolutional Neural Network)
A cosmic electron ($\sim$5 TeV)
- Cosmic-rays electrons and positrons from 20 GeV to ~5 TeV
  [Nature 552, 63 (2017)]
- Direct detection of a spectral break at 0.9 TeV (6.6 $\sigma$ c.l.)
- A smoothly broken power law fits data ($\gamma = 3.1 \rightarrow 3.9$)
- Next step: search for structures and anisotropies (nearby sources, pulsars, DM?)

530 days of data
2.8 billion events
1.5 million e+e- (>25 GeV)
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
PSD + BGO profile + NUD: rejection > $10^7$ for hadrons

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

- Event topology
- Random Forest + Convolutional Neural Networks
After application of selection criteria to reject protons and electrons

- Convolutional Neural Networks + Random Forest
- 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

- Pulsar phase profiles

Geminga, IC443 and Crab pulsars
Selection, count maps, phase maps, SEDs

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by M. Munoz (preliminary)
Sources: counts maps and SEDs

Vela
Geminga
Crab

by M. Munoz (preliminary)
DAMPE detection of gamma-ray variable emission in extragalactic sources:

- CTA 102 blazar; Atel #9905
- 3C 454.3 blazar
- 3C 279 blazar; Atel #11246
- S4 1800+44 FSRQ; Atel #12562
- PKS 1830-211 FRSQ; 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 (xzl@pmo.ac.cn)

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Participation to multi-messenger searches

- Detection of gamma-ray source TXS 0506+056
  - 5.7 Gly, associated with the 290 TeV $\nu_\mu$ 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
- A number of results on $e^-+e^+$, protons, nuclei and other items have been obtained or are ongoing
- Significant contribution to photon detection and analysis:
  - excellent energy resolution
  - many different sources and items studied
  - substantial statistics is being accumulated
The HERD experiment

- **CHINA**
  Institute of High Energy Physics, Purple Mountain Observatory, Xi'an Institute of Optical and Precision Mechanics, University of Science and Technology of China, Nanjing University, Beijing University, Yunnan University, China University of Geosciences, Ningbo University, Guangxi University

- **ITALY**
  Pisa University and INFN, Florence University and INFN, Perugia University and INFN, Bari University and INFN, Salento University, Lecce INFN, Pavia University and INFN, Gran Sasso Science Institute

- **SPAIN**
  CIEMAT

- **SWEDEN**
  KTH

- **SWITZERLAND**
  University of Geneva
HERD scientific goals

- **Search for Dark Matter with unprecedented sensitivity**
  - cosmic electron spectrum: fine structure, contribution for nearby sources, anisotropy, DAMPE spectral break and other features; **gamma-ray line signature**

- **Study the origin and features of cosmic rays**
  - proton, helium and other nuclei spectra and abundances

- **Study the gamma-ray sky with the highest sensitivity:**
  - local, galactic and extragalactic sources
  - galactic and extragalactic diffuse emissions
  - origin of cosmic rays
  - galactic winds and Fermi bubbles
  - GC region
  - gamma-ray pulsars and pulsar wind nebulae
  - monitoring of pulsars, blazars, GRBs and other transients
  - multi-messenger astronomy
HERD performance

- Deep, 3D and large acceptance calorimeter
- High-precision silicon tracker
- Efficient and low noise plastic scintillators
- Large exposure (about 10-15 m² sr yr, i.e. 10 times wrt other exps)
- High statistics measurements of e/γ 100 GeV – 10 TeV (DM)
- Better spectral and composition measurements of CRs 300 GeV – PeV with large geometrical factor (CR origin)
- Highest gamma-ray sensitivity
The Chinese Space Station

- Launch: 2025
- Lifetime: > 10 years
- Orbit: 350-450 km, 41-43 deg
- TC/TM: 500-1100 (DL), 3-9 (UL) Mbps
- Maintenance: Manned
HERD onboard the Chinese Space Station

- Weight and space constraints to be balanced among sub-detectors while optimizing fulfillment of physics goals
- Supply of power, liquid coolant, etc.
- Astronauts' maintenance possible (e.g. IsCMOS replacement)
The HERD instrument

- PSD, six sides
- LE Gamma identification
- Charge
- STK(SSID), five sides
- Trajectory
- Gamma tracking
- Charge
- TRD
- TeV proton calibration

- LYSO array
- Trigger sub-system
- ISCMOS sub-system

- CALO, 3-d e/G/CR energy
- e/p discrimination thickness 55 $X_0$
## HERD sub-detectors specifications

<table>
<thead>
<tr>
<th>Component</th>
<th>Technology</th>
<th>Size (cm)</th>
<th>Depth</th>
<th>Main functions</th>
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<tbody>
<tr>
<td></td>
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<td>Unit type</td>
<td></td>
<td></td>
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<tr>
<td>Tracker (top)</td>
<td>Si strips</td>
<td>70×70</td>
<td>2 $X_0$</td>
<td>charge, shower, tracking</td>
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<tr>
<td></td>
<td>W foils</td>
<td>7 x-y</td>
<td></td>
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<tr>
<td>Tracker (side)</td>
<td>Si strips</td>
<td>65×65</td>
<td>2 $X_0$</td>
<td>charge, shower, tracking</td>
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<tr>
<td></td>
<td>W foils</td>
<td>7 x-y</td>
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<td>CALO</td>
<td>~7500 LYSO crystals</td>
<td>63×63×63 cubes</td>
<td>55 $X_0$</td>
<td>e, g, nucleon energy, e/p separation</td>
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<td></td>
<td></td>
<td>3×3×3 cubes</td>
<td>3 $\lambda_i$</td>
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<td>PSD</td>
<td>plastic scintillator</td>
<td>120/170×12×1</td>
<td>0.1 $X_0$</td>
<td>anticoincidence, trigger, charge</td>
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<tr>
<td>TRD</td>
<td>PP foils</td>
<td>TBD</td>
<td>N/A</td>
<td>high energy calibration</td>
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</table>
HERD tracker

- SSDs with tungsten foils
- 7 layers on top, 3 layers on sides
  - charge measurement
  - direction measurement
  - gamma-ray conversion and tracking
  - CALO showers backsplash rejection
- Optimization is ongoing
  - CR calorimetry requires shallow STK
  - multiple dE/dx requires many planes
  - $\gamma$-ray acceptance requires thick STK

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**HERD 3D imaging calorimeter**

- 7500 LYSO $3 \times 3 \times 3$ cm$^3$ crystals
  - high light output
  - quick decay time
  - excellent energy resolution
  - $55 \ X_0$ and $3 \ \lambda_i$
  - fluorescence linearity
  - full 3D reconstruction of showers
  - WLS fibers light collection
  - IsCMOS cameras light readout

**CALO array**

**CALO structure**

- WLS fibers on cube for signal readout

- Image Intensifier and IsCMOS camera
HERD calorimeter prototype tests

200 GeV electron

\[ \sigma/E \sim 2\% \]

400 GeV primary proton

Test
**HERD PSD**

- Scintillator elements read by SiPMs
  - veto for charged particles
  - gamma-ray selection
  - trigger for CRs
  - measurement of CR charge and Z

**PSD bars top and side views**

**PSD tiles**

**CR Z spectra with PSD**

- Optimization is ongoing
  - bars/tiles (backsplash minimization)
  - thickness
  - number of layers
HERD performance

Energy resolution

Calorimeter geometrical factor

Electrons < 1%

Protons 20 %

Photons

500 MeV-100 GeV result
DM annihilation line in HERD

- Non-relativistic DM particles:
  - pair annihilation $\rightarrow$ monochromatic photons
  - HERD unprecedented sensitivity
  - $5\sigma$ signal $\rightarrow$ line flux $> 2.8 \times 10^{-10}$ cm$^{-2}$ s$^{-1}$

Simulation of 1-year gamma-ray data from annihilation of 416 GeV DM
HERD summary

- The baseline detector is defined and fulfills the requirements
- Further improvements and optimization ongoing
- Calorimetric detector with unprecedented GF
- Its main scientific goals will be DM searches, CR physics above the PeV, high-energy (and maybe also sub-GeV) cosmic photons observations
- It will probably be the only high-energy gamma-ray detector operating in space in the next future – and with excellent performance
Thank you
Backup
Today and tomorrow

<table>
<thead>
<tr>
<th>Performance</th>
<th>Fermi LAT</th>
<th>DAMPE</th>
<th>HERD</th>
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<tbody>
<tr>
<td>Launch</td>
<td>2008</td>
<td>2015</td>
<td>2026</td>
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<tr>
<td>$e/\gamma$ Energy range</td>
<td>0.02 - 300</td>
<td>2 - $10^4$</td>
<td>0.1 - $10^4$</td>
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<td>$e/\gamma$ Energy resol. @100 GeV (%)</td>
<td>10</td>
<td>&lt;1.5</td>
<td>1</td>
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<tr>
<td>$e/\gamma$ Angular resol. @100 GeV (deg.)</td>
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<td>&lt;0.2</td>
<td>0.1</td>
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<tr>
<td>$e/p$ discrimination</td>
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<td>$&gt;10^5$</td>
<td>$&gt;10^5$</td>
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<tr>
<td>Calorimeter thickness ($X_0$)</td>
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<td>55</td>
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<tr>
<td>Geometrical acceptance ($m^2sr$)</td>
<td>2.5</td>
<td>0.3</td>
<td>3</td>
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</table>
Identifying protons and nuclei with PSD and STK

- charge measurement tested with ion beam tests at CERN
- PSD: up to Argon; STK: up to Oxygen
- charge resolution is dependent on Z and ranges from 0.2 to 0.4
- more details in Astropart. Phys. 95, 6 (2017)
DAMPE protons and nuclei: flight data

- Identifying protons and nuclei with PSD and STK

[Image of PSD and STK plots]

[Astropart. Phys. 105, 31 (2019)]
Agreement with other experiments

Protons: hardening at $E > 300$ GeV, softening at $E > 10$ TeV

Helium: hardening at 200 GeV

Analysis is being extended to higher energies
FIT with 10 double-layers
- better angular resolution than Fermi (unprecedented)
- competitive sub-GeV sensitivity
- simultaneous observations with eXTP, CTA, LIGO, LHAASO, ...
- wide FOV, continuous time coverage
- (polarization ?)