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

Exotic particles

E.M. with GW

P. Fusco – Main results of the DAMPE space detector – ICNFP 2019 – August 22, 2019
The DAMPE Collaboration

**CHINA**
- Purple Mountain Observatory, CAS, Nanjing, *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 – 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 cm² @ 100 GeV
The DAMPE instrument

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

**STK:** Silicon Trakker/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

[Astropart. Phys. 95, 6 (2017)]
The DAMPE sub-detectors

PSD: IMP

STK: IHEP, UG, INFN Perugia

BGO: USTC & PMO

NUD: PMO
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
  - $\pi^-$ @ 3, 10 GeV/c
  - $\gamma$ @ 0.5-3 GeV/c

- **8 days @ SPS, 12/11-19/11 2014**
  - e @ 5, 10, 20, 50, 100, 200, 250 GeV/c
  - p @ 400 GeV/c (SPS primary beam)
  - $\gamma$ @ 3-20 GeV/c
  - $\mu$ @ 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
  - $\gamma$ @ 50, 75, 150 GeV/c
  - $\mu$ @ 150 GeV/c
  - $\pi^+$ @ 10, 20, 50, 100 GeV/c

- **6 days @ SPS, 20/11-25/11 2015**
  - Pb @ 30A GeV/c (and fragments)
# DAMPE, AMS-02, Fermi LAT comparison

<table>
<thead>
<tr>
<th>Performance</th>
<th>DAMPE</th>
<th>AMS-02</th>
<th>Fermi LAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>(e/\gamma) Energy resol. @100 GeV (%)</td>
<td>&lt;1.5</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>(e/\gamma) Angular resol. @100 GeV (deg.)</td>
<td>&lt;0.2</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>(e/p) discrimination</td>
<td>(&gt;10^5)</td>
<td>(10^5 - 10^6)</td>
<td>(10^3)</td>
</tr>
<tr>
<td>Calorimeter thickness ((X_0))</td>
<td>32</td>
<td>17</td>
<td>8.6</td>
</tr>
<tr>
<td>Geometrical acceptance (m(^2)sr)</td>
<td>0.3</td>
<td>0.09</td>
<td>1</td>
</tr>
</tbody>
</table>

## 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**

- 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

**3.5 years exposure map**

- Data excluded when in SAA
- Different prescale factor for lower latitudes
- SAA

**MIP Calibration**

- +20°
- -20°

**Total trigger rate map**

- 20 Hz to 200 Hz
- 100k to 250k
Detector stability

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

- PSD pedestal < 0.5%
- STK pedestal < 0.7%
- BGO pedestal < 0.9%
- NUD pedestal < 0.6%
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

P. Fusco – Main results of the DAMPE space detector – ICNFP 2019 – August 22, 2019
Detection and identification challenges

- **1) Particle identification**
  - electrons/protons: $10^{-3}$, photons/protons: $10^{-5}$ → high rejection capability

- **2) Dynamic range**
  - $e/\gamma$ energy: 1 GeV – 10 TeV → BGO bar range 2 MeV – 4 TeV

- **3) Energy resolution**
  - sensitivity to DM line → 1.5% res. for $e$ & $\gamma$

---


Beam test with 32 $X_0$ calorimeter
Several different PID methods used:

- Shape parameters
- Boosted Decision Trees
- Random Forest + Convolutional Neural Network
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± efficiency, p background ~2% @ 1 TeV, ~5% @ 2 TeV, ~10% @ 5 TeV

![Graph showing electron/proton separation](image)
The $\zeta$ 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 $\sim$5 TeV
  - spectral hardening at 50 GeV
  - 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: search for structures and anisotropies (nearby sources, pulsars, DM?)

\[ \gamma_1 = 3.09 \pm 0.01 \]
\[ \gamma_2 = 3.92 \pm 0.20 \]
\[ E_b = 914 \pm 98 \text{ GeV} \]
\[ \Phi_0 = (1.64 \pm 0.01) \times 10^{-4} \text{ m}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}^{-1} \]
\[ \Delta = 0.1 \]
\[ \chi^2/\text{NdF} = 23.3/18 \text{ (6.6$\sigma$ pref. over PL)} \]

530 days of data
2.8 billion events
1.5 million $e^+$-$e^-$ ($>25$ GeV)

[Nature 552, 63 (2017)]

(+ CALET)
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
Identifying protons and nuclei in space with PSD and STK

- charge resolution: 0.1e for protons, 0.2e for CNO, 0.3e for Fe
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 m²sr

p in PSD and He cut

He and e± contamination

Acceptance for protons

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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 \( \sim 400 \) GeV
  - softening at \( \sim 10 \) TeV
  - fitting with a smoothly broken power-law:
    \( \gamma = 2.60 \rightarrow 2.85 \) at 13.6 TeV

[C. Yue, ICRC 2019]
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 m²sr
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
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 $\sim 0.05 \text{ m}^2\text{sr}$ at $10^4 \text{ GeV}$

Preliminary

- $p+He$ 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

DAMPE total syst.

Preliminary [Z.M. Wang, ICRC 2019]
Charged particles are a massive background for photons

Protons vs $\gamma$:
- $10^5$ factor @ $E > 100$ GeV
- mainly rejected using the shower profile and the onboard trigger

Electrons vs $\gamma$:
- $10^3$ 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

- Event topology
- Random Forest Classifiers + Convolutional Neural Networks

**Proton**

Y [No. 32: 49.132GeV]

PSD + BGO profile + NUD: rejection up to $10^3$ for electrons

**Electron**

Y [No. 40: 5.034GeV]

PSD + STK: rejection up to $10^7$ for hadrons

**Photon**

Y [No. 61: 5.559GeV]

PSD + BGO profile + NUD: rejection > $10^7$ for hadrons
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
$E > 1 \text{ GeV}$

Angular resolution: $\sim 1^\circ$ @ 1 GeV, $\sim 0.1^\circ$ @ 100 GeV, $\sim 0.05^\circ$ @ 1 TeV
Photons: bright sources

- Algorithms to resolve gamma-rays from charged cosmic rays

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

- Pulsar phase profiles

  - Geminga (T~237 ms)
  - Vela X (T~89 ms)
  - PSR J0007+7303 (T~316 ms)
Photons: pulsars

- Selection, count maps, phase maps, SEDs

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<th>RA</th>
<th>DEC</th>
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<td>J0007+7303</td>
<td>1.756</td>
<td>73.052</td>
<td>315.892</td>
</tr>
</tbody>
</table>

by Maria Munoz Salinas (preliminary)
Gamma-ray sources: counts maps and SEDs

Vela

Geminga

Crab

preliminary

preliminary

preliminary

by Maria Munoz Salinas (preliminary)
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
- ...

Emission variation in extragalactic sources

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 Mazzotta (Bari), Zhao-Qiang Shen (PMO), Meng Su (HKU/PMO), Andriy 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 $\nu_\mu$ 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
- $\text{e}^-\text{e}^+$ 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
The Silicon TracKer (STK)

- 48 μm wide Si strips - 121 μm pitch
- 95×95×0.32 mm³ Silicon Strip Detectors (SSD) - 768 strips
- 1 ladder composed by 4 SSDs
- 16 ladders per layer (76×76 cm²)
- 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 cm³
  - Total depth ~32 $X_0$, ~1.6 $\lambda$

- 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 \((x \text{ and } y)\), 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

<table>
<thead>
<tr>
<th>Trigger Type</th>
<th>Logic</th>
<th>Energy Threshold</th>
<th>Pre-scale factor</th>
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</thead>
<tbody>
<tr>
<td>HE</td>
<td>L1_P_dy5 &amp; L2_P_dy5 &amp; L3_P_dy5 &amp; L4_N_dy8</td>
<td>~10 MIPs &amp; ~10 MIPs &amp; ~10 MIPs &amp; ~2 MIPs</td>
<td>1</td>
</tr>
<tr>
<td>MIPs (Type I)</td>
<td>L3_P_dy8 &amp; L11_P_dy8 &amp; L13_P_dy8</td>
<td>~0.4 MIPs &amp; ~0.4 MIPs &amp; ~0.4 MIPs</td>
<td>4 (low latitude(±20°))</td>
</tr>
<tr>
<td>MIPs (Type II)</td>
<td>L4_P_dy8 &amp; L12_P_dy8 &amp; L14_P_dy8</td>
<td>~0.4 MIPs &amp; ~0.4 MIPs &amp; ~0.4 MIPs</td>
<td>4 (low latitude(±20°))</td>
</tr>
<tr>
<td>LE</td>
<td>L1_N_dy8 &amp; L2_N_dy8 &amp; L3_N_dy8 &amp; L4_N_dy8</td>
<td>~0.4 MIPs &amp; ~0.4 MIPs &amp; ~2 MIPs &amp; ~2 MIPs</td>
<td>8 (low latitude(±20°))</td>
</tr>
<tr>
<td>Unbiased</td>
<td>(L1_P_dy8 &amp; L1_N_dy8)</td>
<td>~0.4 MIPs &amp; ~0.4 MIPs</td>
<td>512 (low latitude(±20°))</td>
</tr>
<tr>
<td></td>
<td>(L2_P_dy8 &amp; L2_N_dy8)</td>
<td>~0.4 MIPs &amp; ~0.4 MIPs</td>
<td>2048 (other region)</td>
</tr>
</tbody>
</table>
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.

Extragalactic

- Blazars
- Radio Galaxies
- Starburst Galaxies
- Globular Clusters
- SNRs
- PWN
- TGFs
- Pulsars
- γ-ray Binaries
- Galactic structures
- EM and GW
- GRBs

Galactic

- Sun
- Novae
- Moon
- Earth
- Globular Clusters
- SNRs
- PWN
- TGFs
- Pulsars
- γ-ray Binaries
- Galactic structures

Local

- Blazars
- Radio Galaxies
- Starburst Galaxies
- Globular Clusters
- SNRs
- PWN
- TGFs
- Pulsars
- γ-ray Binaries
- Galactic structures
- EM and GW
- GRBs

Unidentified Sources
Cosmic photons production and interaction

**hadronic**
- Proton synchrotron
- Bethe-Heitler pair production
- Photopion (n⁺ component)
- Photopion (n⁻ component)
- Photopion (n⁰ 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

<table>
<thead>
<tr>
<th>Categories</th>
<th>Details</th>
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<tbody>
<tr>
<td>Sources</td>
<td>hadronic interactions</td>
</tr>
<tr>
<td>Production</td>
<td>decay of $\pi^0$'s, etc. into photons</td>
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<tr>
<td>Interactions</td>
<td>observation of photons</td>
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<tr>
<td>Identification</td>
<td>features of sources</td>
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<tr>
<td>Acceleration</td>
<td>interaction with ISM</td>
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<tr>
<td>Solar Modulation</td>
<td>etc...</td>
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Latest measurements of CR spectrum