NOW 2022

Session III - Multimessenger astrophysics

6th September 2022

Cosmic rays and gamma rays with DAMPE and HERD

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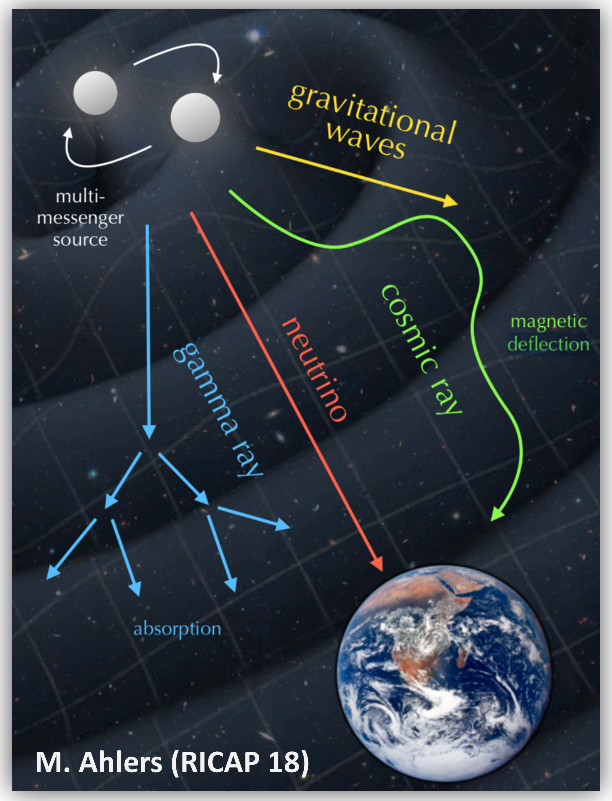
on behalf of the DAMPE and HERD Collaborations

Multimessenger astrophysics

- Multimessenger astrophysics is an extension of the multiwavelength astronomy.
- Multimessenger astrophysics provides unique insights into the properties and processes of the universe.
- These insights arise from the complementary information carried by different messengers: **photons**, neutrinos, (charged) **cosmic rays (CRs)** and gravitational waves.

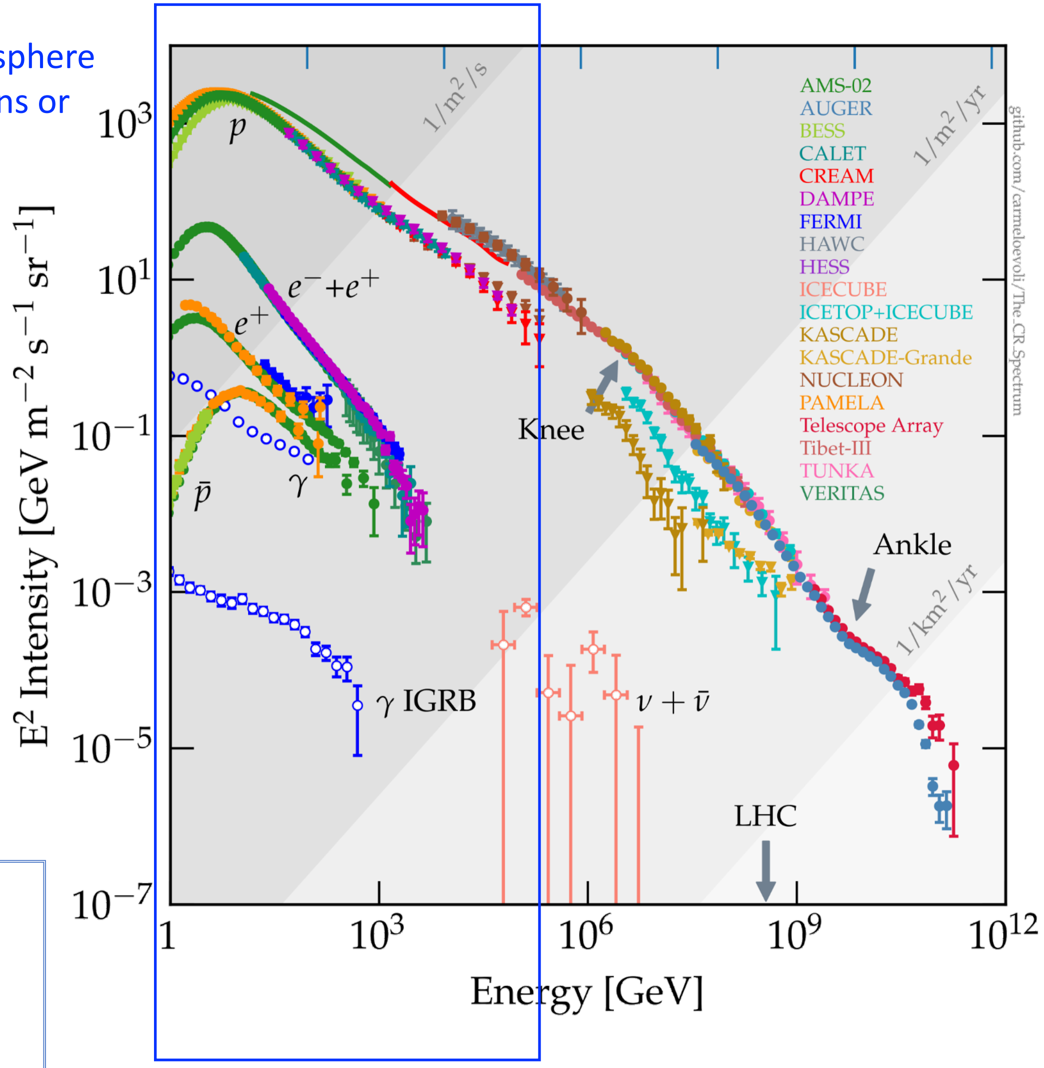
«The universe just talks to us in so many ways, and every time you find a new way of listening, you find something else.»

Ellen Zweibel



Direct vs. indirect detection of Cosmic Rays (NOW)

For energies up to 500 TeV:
→ Possible detection on top of the atmosphere (on balloons) or in space (on space stations or satellites)



For energies above 1 PeV:
→ Possible detection only on ground or underground.
→ detection on ground or underground possible also below 500 TeV (HAWC from 10 TeV)

When a cosmic ray (except neutrinos) interacts with a nucleus of the high atmosphere many energetic particles are produced.

These particles **interact** with other nuclei or **decay** and a cascade of particles is produced: an Extensive Air Shower (EAS).

Direct Detection
- With "space/balloon-borne" or direct detection experiments

- Fluxes of single components
- High precision
- Limited in energy (detector acceptance)

Indirect Detection
- With ground-based or indirect detection experiments or EAS arrays

- Highest energies
- Difficult composition measurements
- Larger systematics

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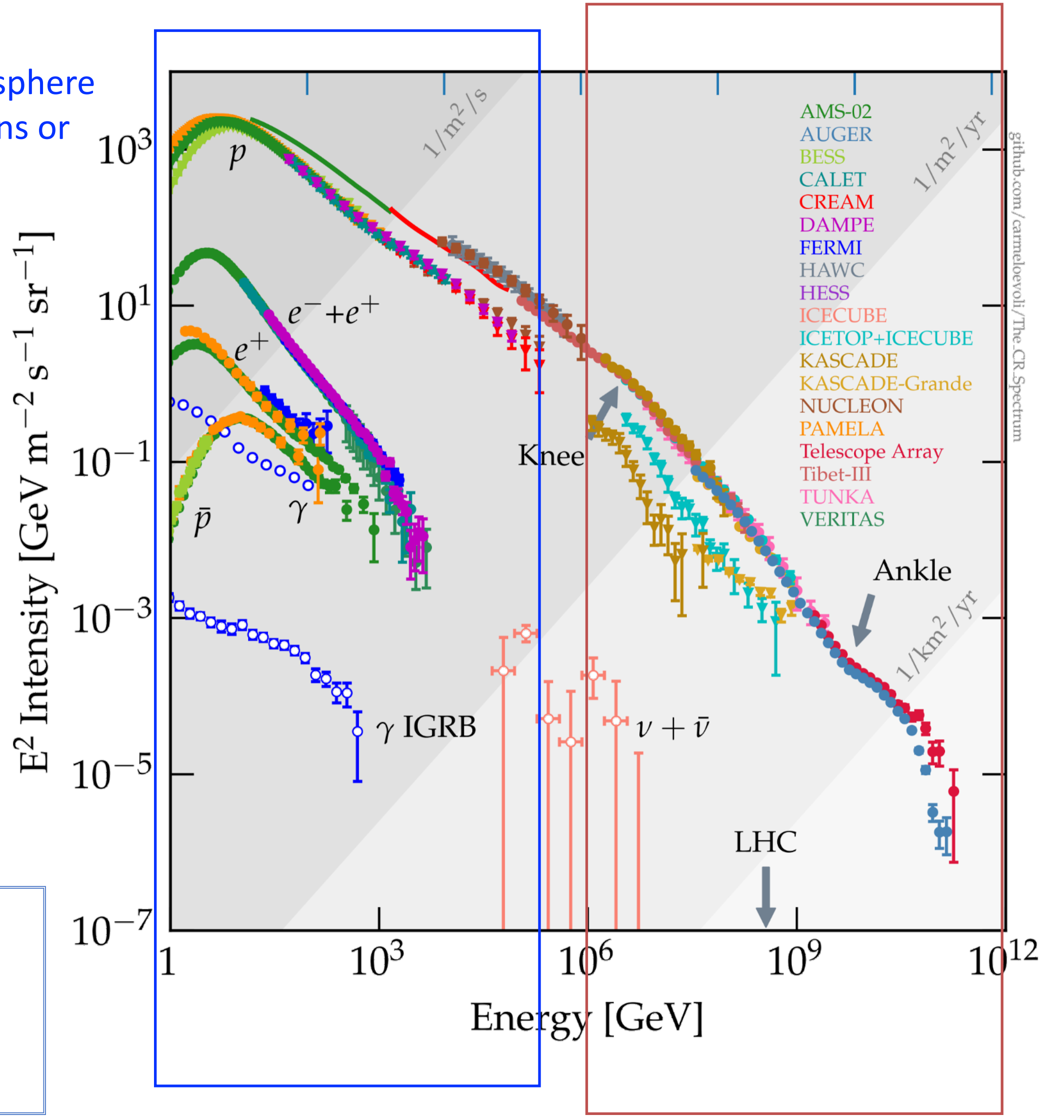

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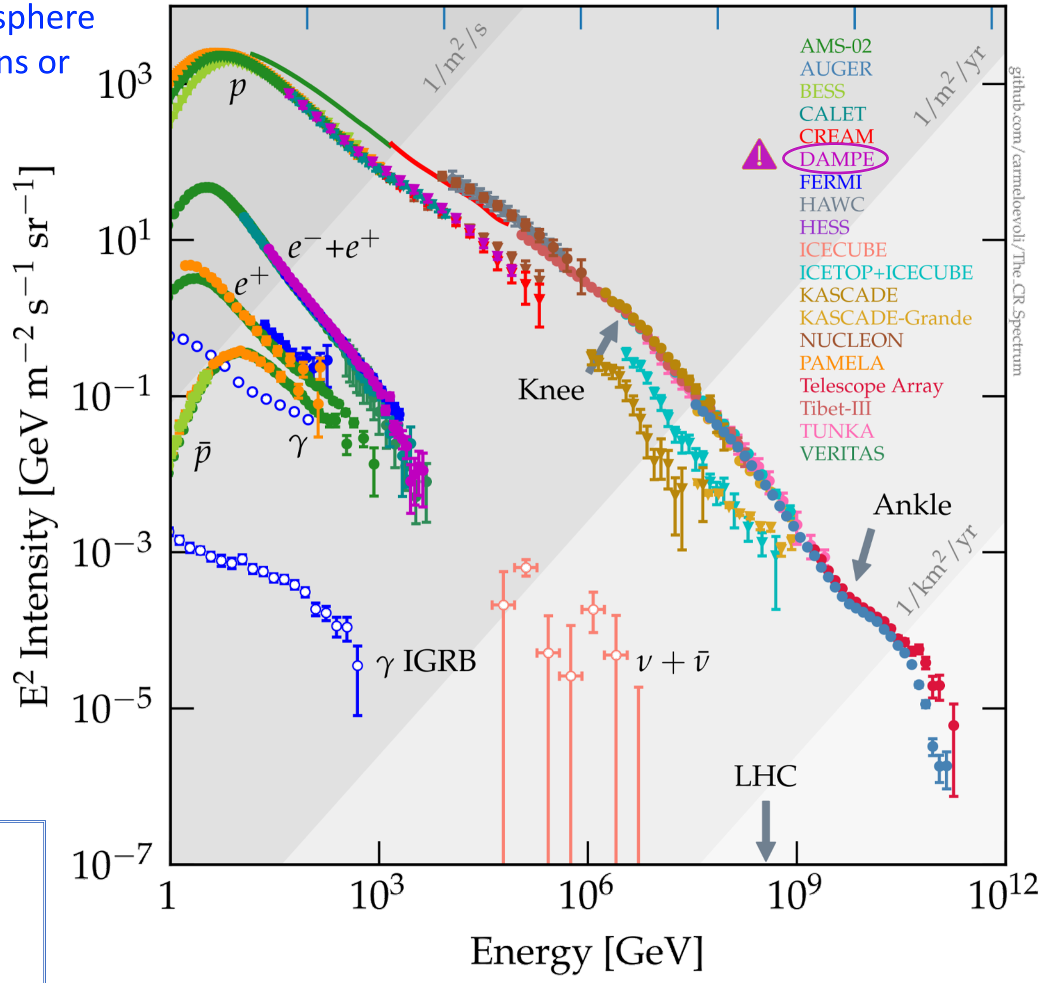

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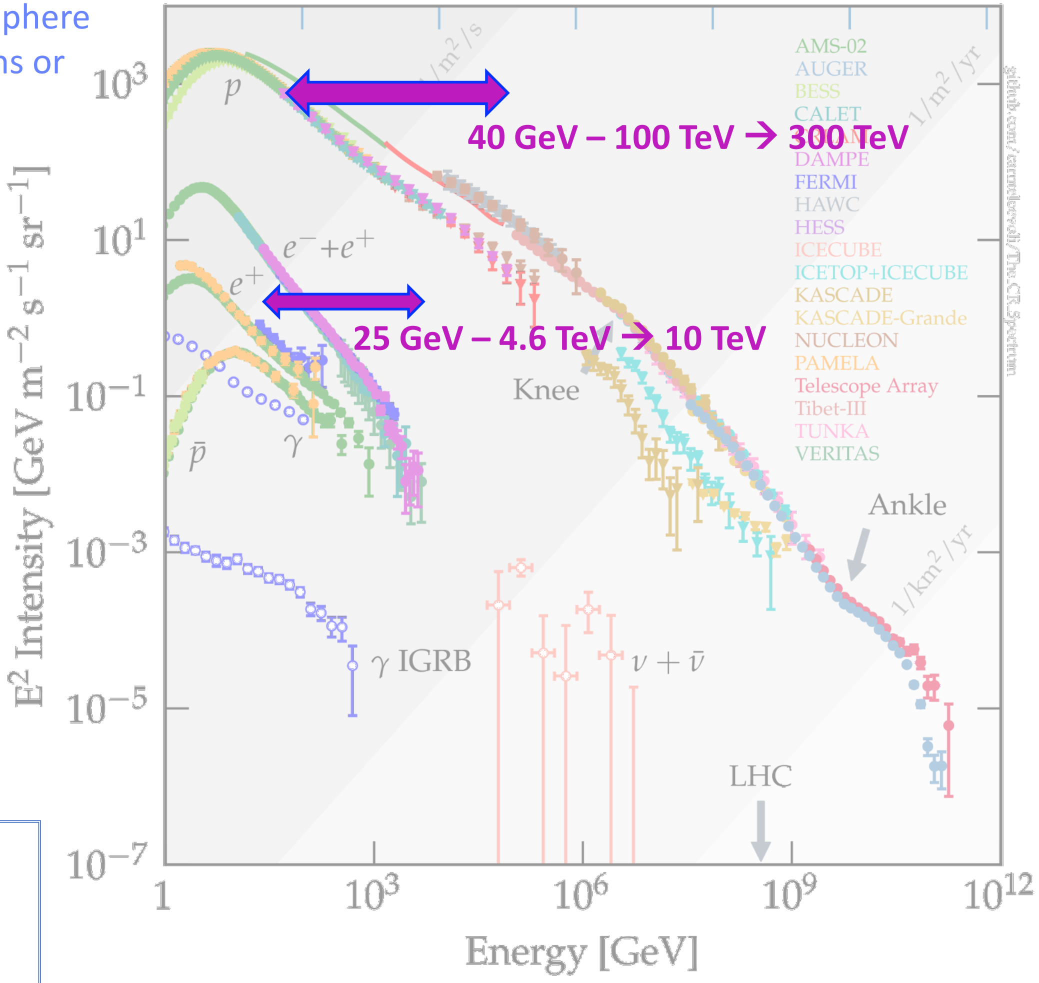

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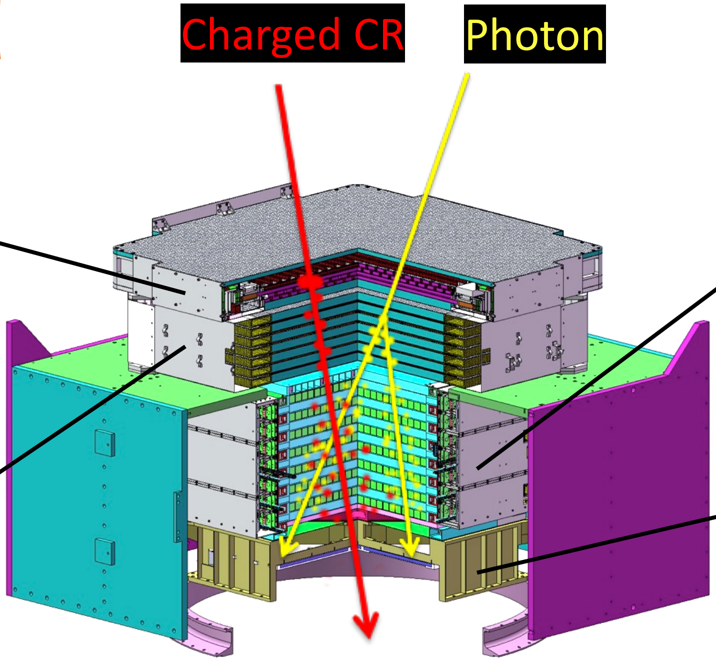
DAMPE: DArk Matter Particle Explorer

Goals:
- Search for signatures of annihilation/decay products of **dark matter** in the electrons + positrons and gamma-ray energy spectra
- Study of cosmic ray spectra (electrons + positrons, protons and heavier nuclei)
- Gamma ray astronomy
- Exotica and “unexpected” , e.g., electromagnetic counterpart of Gravitational waves

Needed: particle identification, energy and direction measurements.



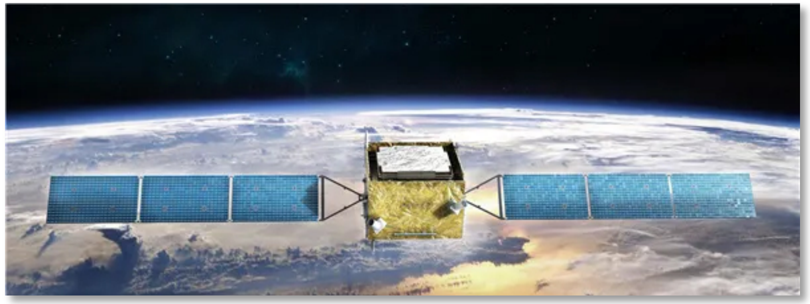
PSD: Plastic Scintillator Detector
- Anti-coincidence charged/neutral particles
- Charge measurement (|Z|)

STK: Silicon-Tungsten tracKer-converter
- Track reconstruction
- Photon conversion ($\gamma \rightarrow e^+ e^-$)
- Charge measurement (|Z|)

BGO: Bismuth Germanium Oxide calorimeter
- Energy measurement
- Electron/proton separation

NUD: NeUtron Detector
- Delayed neutrons coming from the hadronic interactions
- Electron/proton separation

The DAMPE satellite



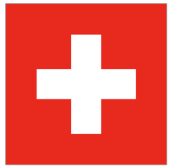
Orbit: polar, sun synchronous
Altitude: 500 km (LEO)
Inclination: 97°
Period: 95 minutes

Mass: 1850 kg (scientific payload: 1400 kg)
Power : 640 W (scientific payload: 400 W)
Downlink: 12 GB / day
Lifetime: December 17, 2015 -- present

- Jiuquan Satellite Launch Center, Gobi desert (China)
- Long March-2D rocket

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

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



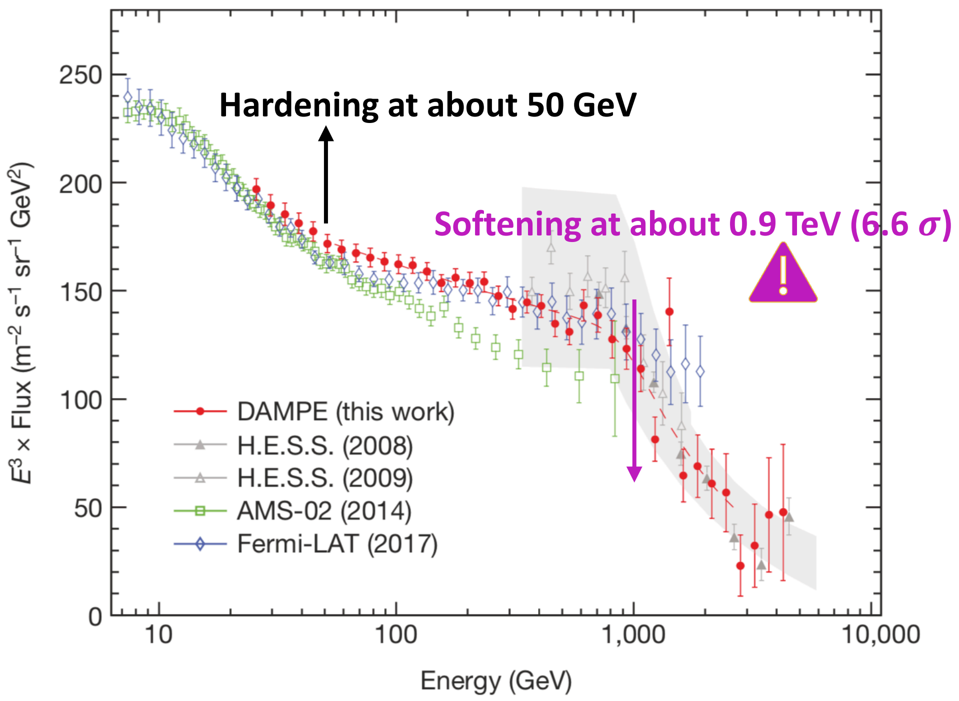
- University of Geneva
  - EPFL – Lausanne (visitor since 2021)

e/γ Energy range	GeV – 10 TeV
p Energy range	40 GeV – 300 TeV
e/γ Energy resolution at 100 GeV	< 1.5 %
p Energy resolution at 800 GeV	< 40 %
e/γ Angular resolution at 100 GeV	< 0.2°
e/p separation	> 10^5
Calorimeter thickness	32 X_0, 1.6 λ_I
Geometrical acceptance	0.3 m^2 sr

First measurements

DAMPE Collaboration, Nature volume 552, 63–66 (2017)

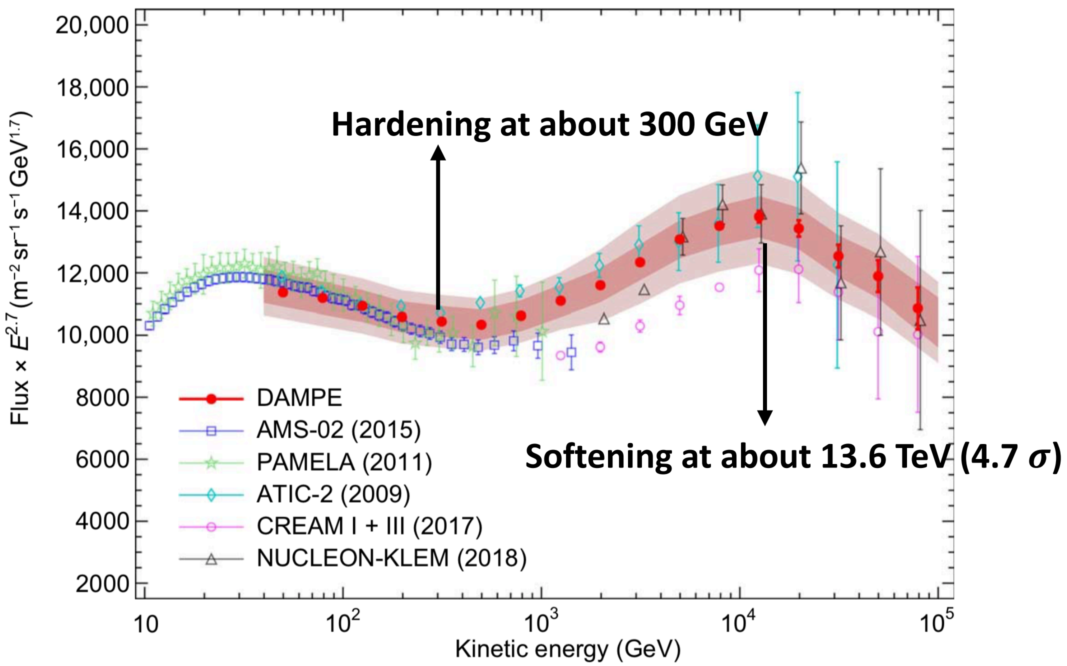
Electron + positron spectrum (25 GeV – 4.6 TeV)



18 months of data

DAMPE Collaboration, Science Adv. 5 (9) eaax3793 (2019)

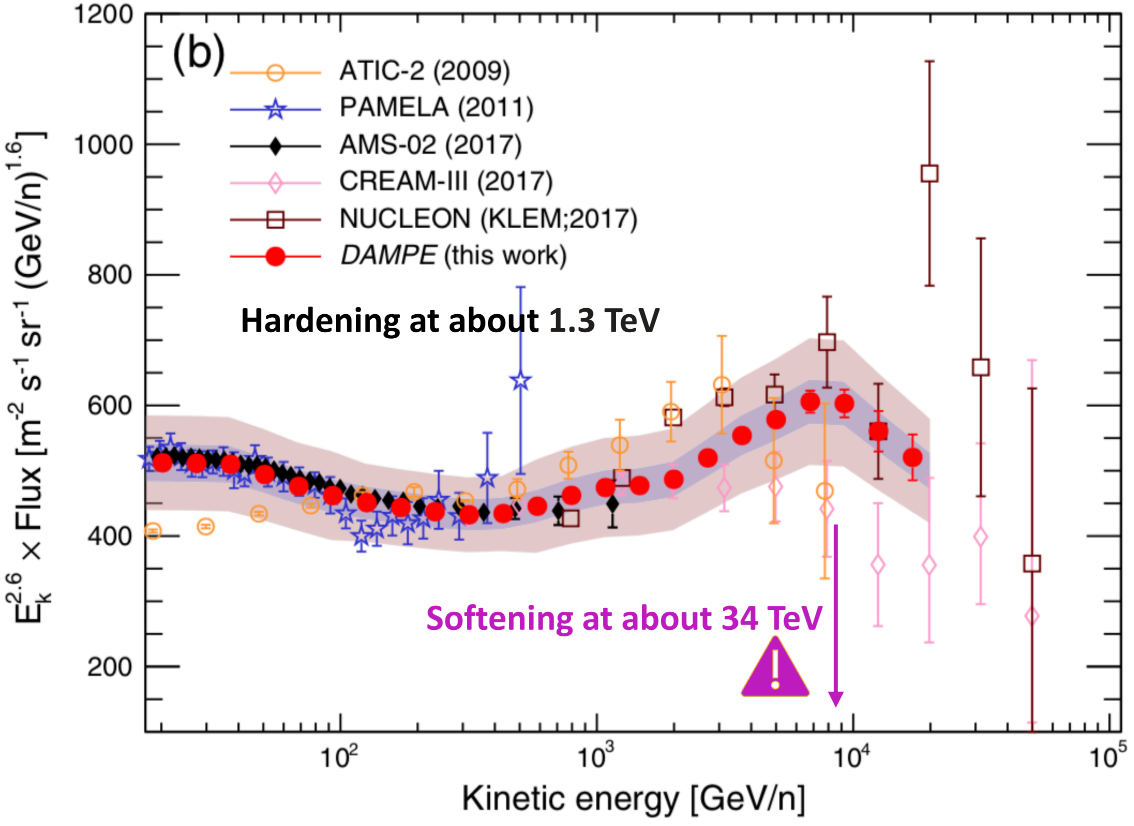
Proton spectrum (40 GeV – 100 TeV)

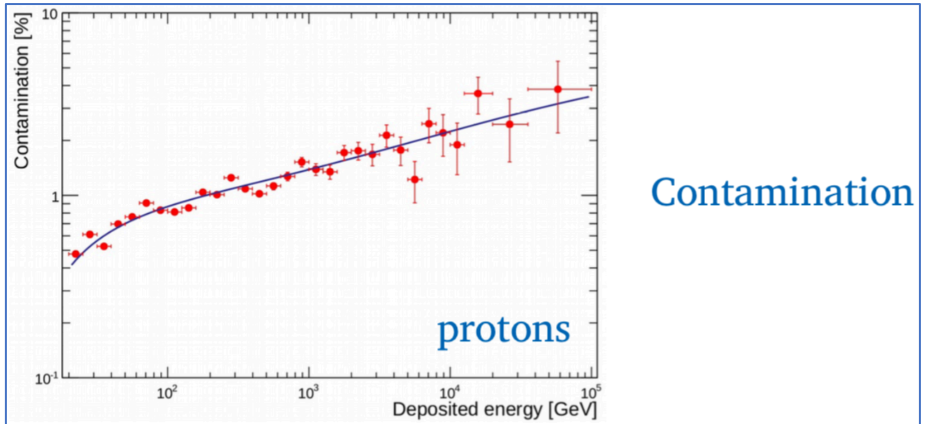


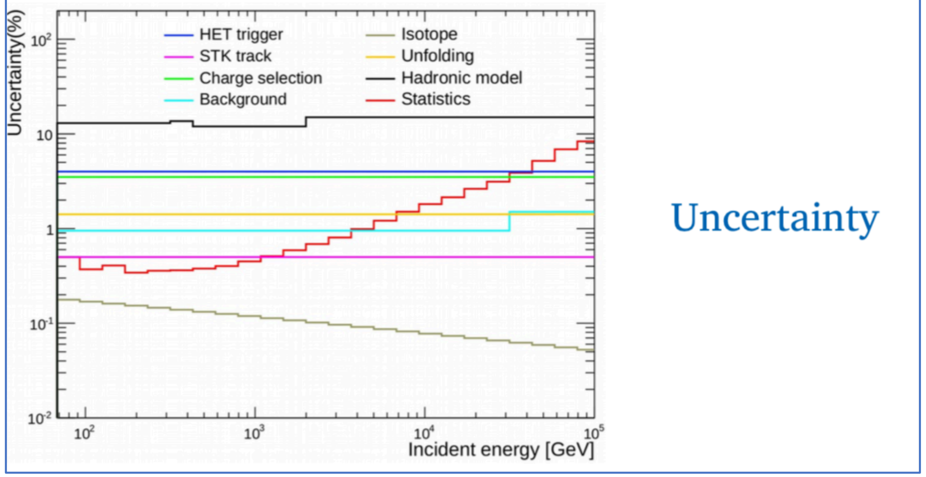
30 months of data

Helium spectrum (70 GeV – 80 TeV)

[DAMPE Collaboration, PHYSICAL REVIEW LETTERS 126, 201102 (2021)]



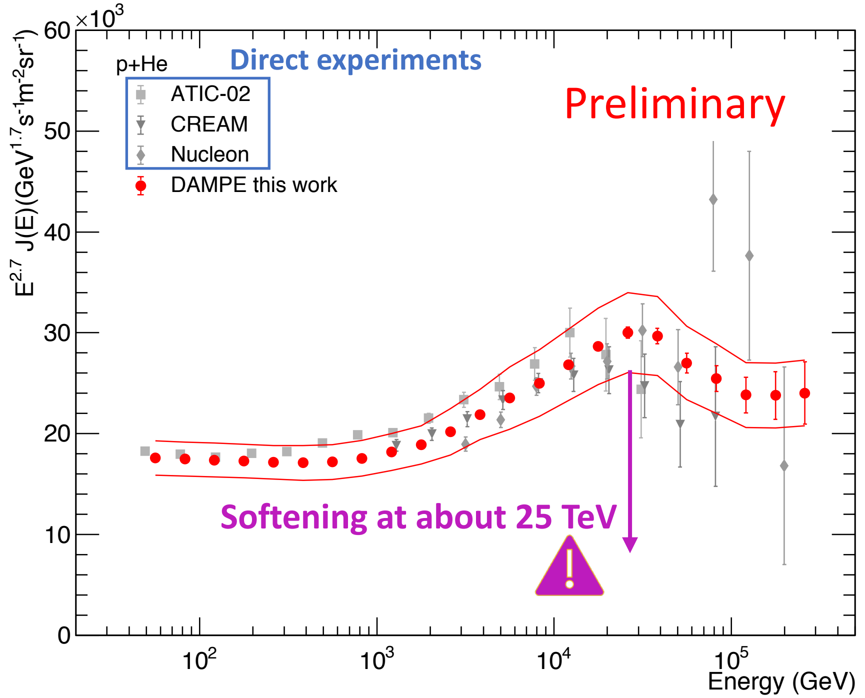


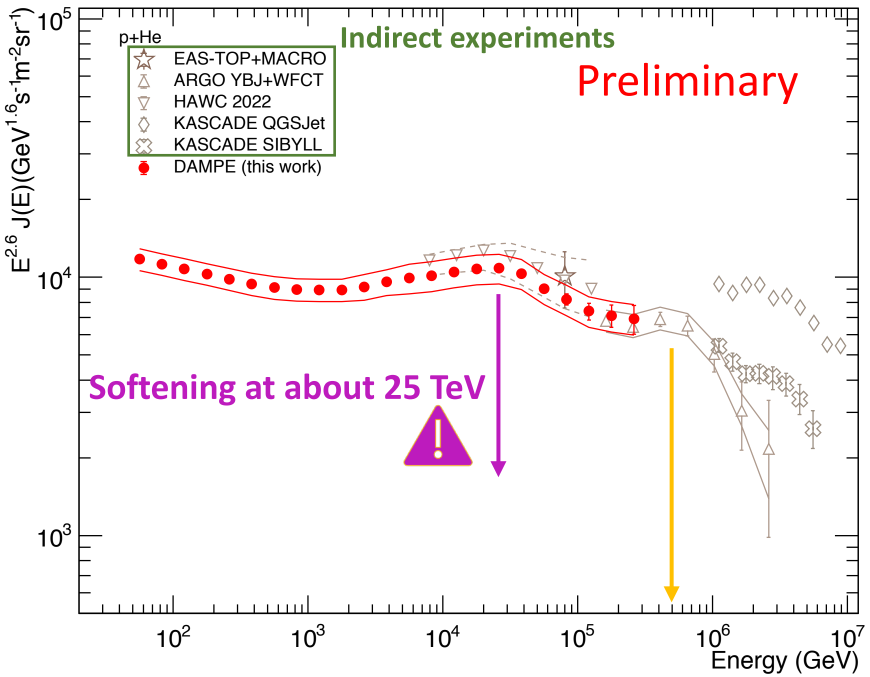


- Measured a softening at about 34 TeV, for the first time with large statistics and well controlled systematic uncertainties, with an overall significance of 4.3 σ.
  - Suggesting a Z dependent softening energy (~ 14 TeV for protons)

Proton + Helium spectrum (in preparation…)

Larger acceptance w.r.t. proton and helium independent analyses
=> flux measurement extension to higher energy (300 TeV) and comparison with ground-based experiments





- General agreement with DAMPE proton and helium independent analyses
  - Confirmation of the softening at about 25 TeV due to the combination of p (14 TeV) and He (34 TeV) spectra

- Another spectral break is suggested by ground based experiments at about 0.5 PeV.
  - Will we see it with DAMPE?

Proton and Helium towards PeV

Challenge #1: **Track reconstruction**

Conventional DAMPE track reconstruction:

- Shower axis from CALO as a seed
- Kalman fitting (Combinatorial track finding with XZ and YZ fitted separately)

→ 3D tracks

Problems:

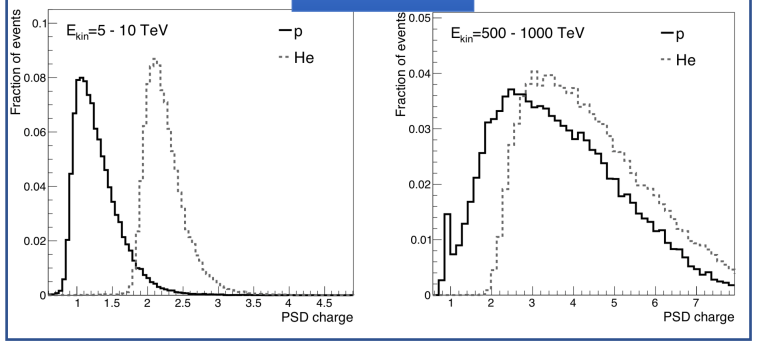
1. Selection needed to find the right track
2. Efficiency drops with high hit multiplicity

At TeV— PeV: hit multiplicity increases dramatically

Challenge #2: **Charge identification**

Normally done with PSD

PSD reco



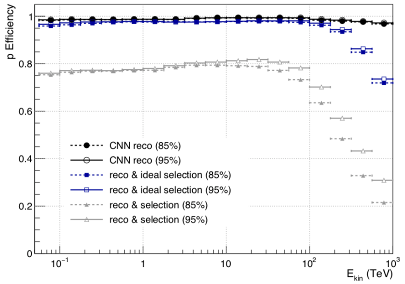
p and He peaks washed out at high energies

Solution: **Convolutional Neural Networks (CNNs)**

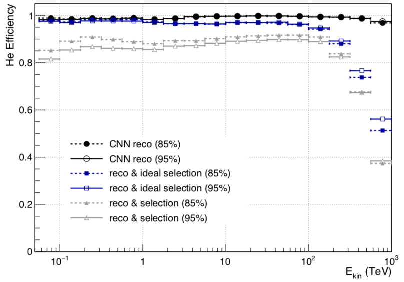
A.Tykhonov et al.

Input: CALO & Tracker "images".
Output: particle direction.

Protons



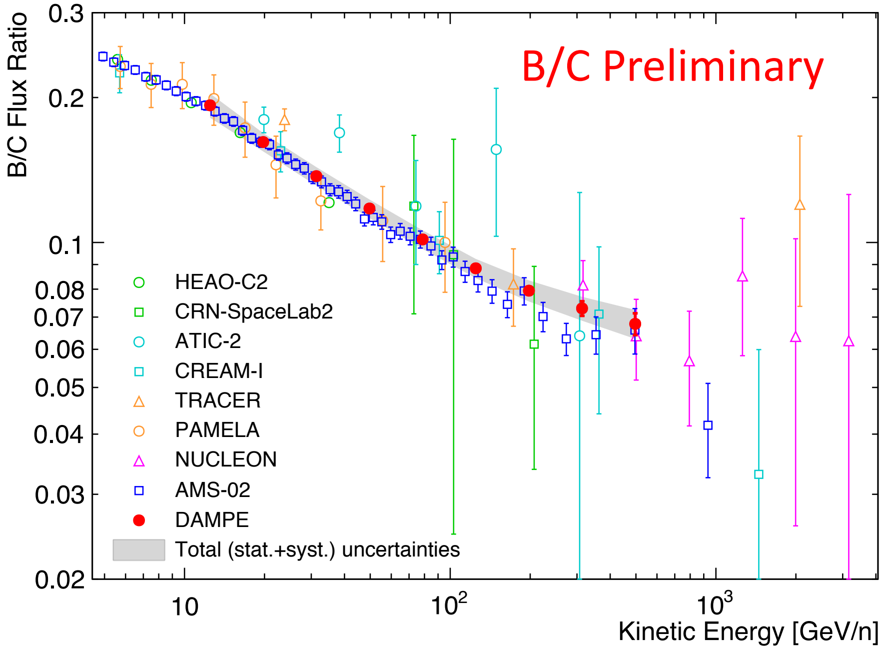
Helium

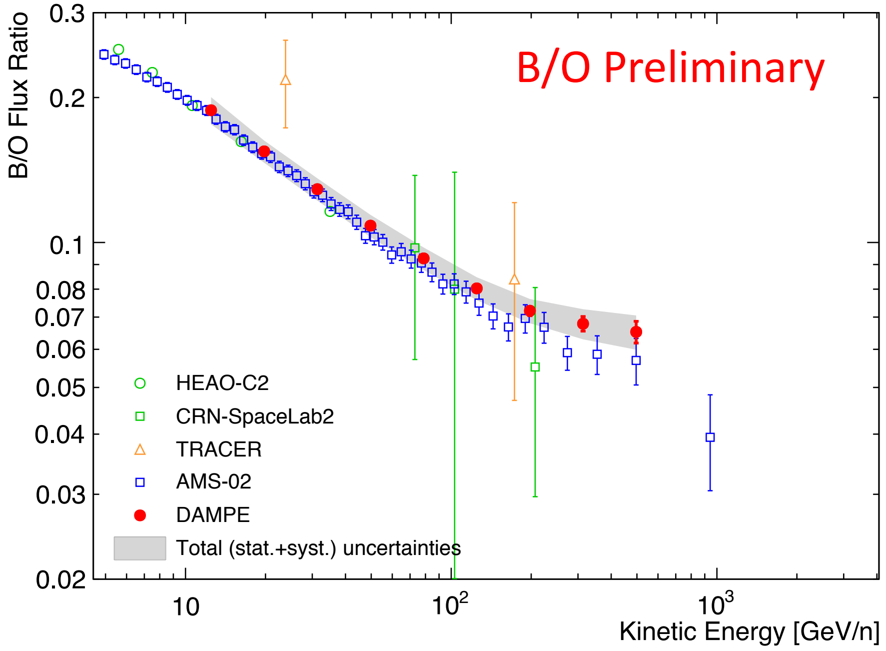


CNN tracking efficiency:
98% - 99% up to 500 TeV
> **96%** @ PeV

B/C and B/O fluxes (submitted…)

- Several independent analyses are ongoing for $_{3}$Li, Be, B, C, N, O, Ne, Mg, Si and $_{26}$Fe.
  - Different selection criteria to reject other nuclei and avoid charge misidentification.
  - Different approaches to limit and better evaluate the systematics.

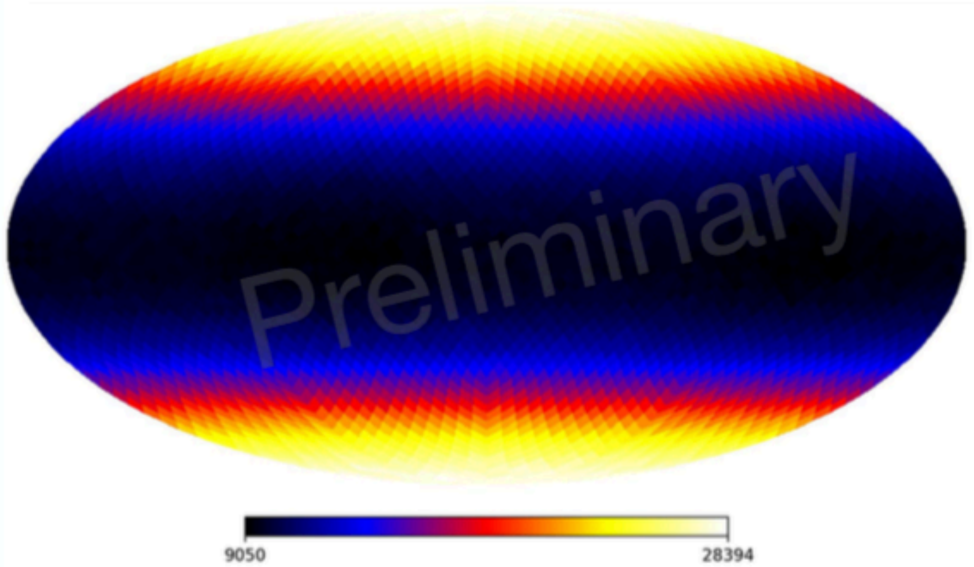




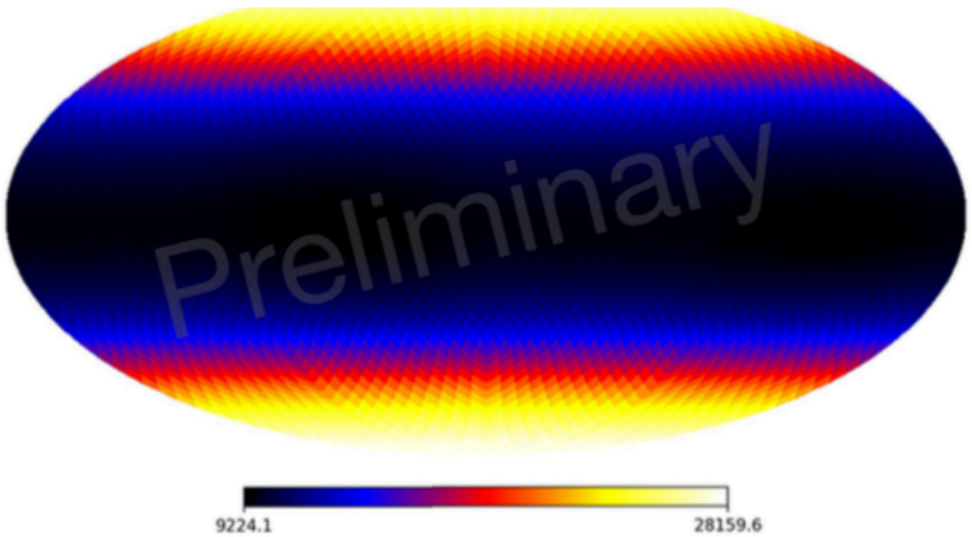
- Overall agreement with AMS-02 measurement + “hint” of a spectral hardening at about 100 GeV/n.
  - New measurements in the TeV/n region submitted for publication.

Cosmic ray anisotropy (work in progress…)

- CRs are highly isotropic.
- Small anisotropies measured with ground-based experiments
- So far no anisotropy found with direct experiments (lower acceptance) but worth trying



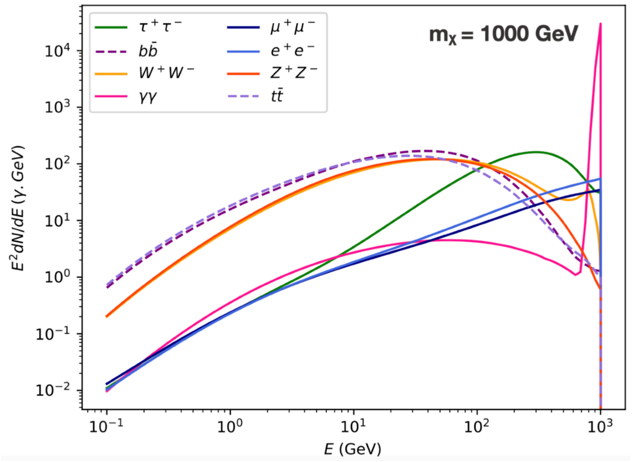
Map in equatorial coordinates of the **observed** incoming CR directions



Map in equatorial coordinates of the **expected** directions for an isotropic distribution of CRs

The two maps are consistent → no anisotropy found

Indirect dark matter (DM) search in the **gamma-ray** spectrum



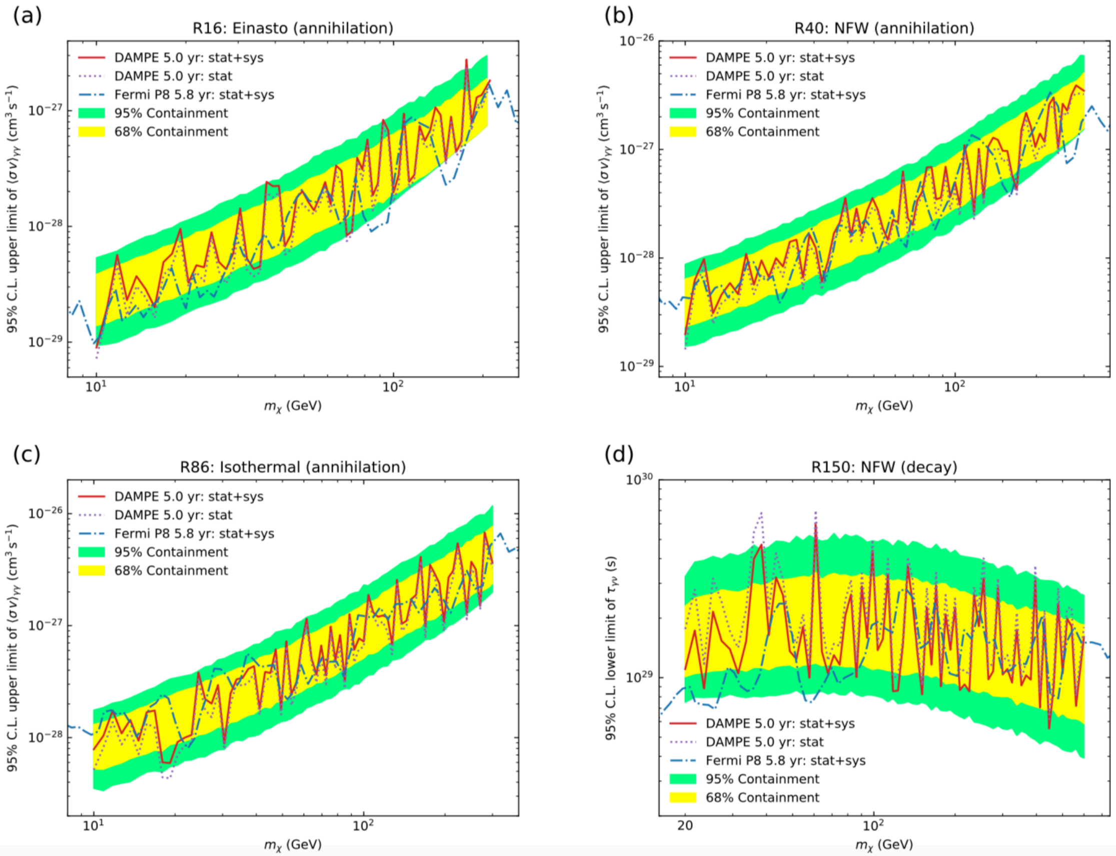
- The weakly interacting massive particles (WIMPs) are leading candidates for cold DM, since they provide a natural explanation for the observed DM relic density.

- The neutralino annihilation $\chi\overline{\chi} \rightarrow \gamma X$ where $X = \gamma, Z, H$ and the gravitino decay $\tilde{G} \rightarrow \gamma\nu$ with R parity violation, lead to a monoenergetic gamma-ray emission corresponding to a narrow peak in the gamma-ray energy spectrum.

DAMPE Collaboration, Science Bulletin 67 (2022) 679–684

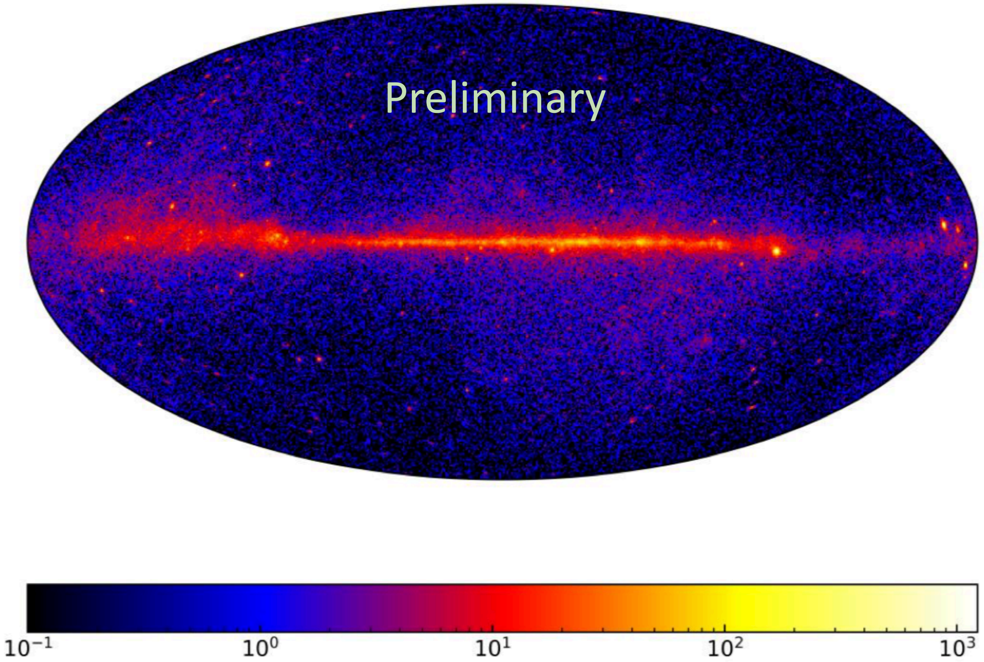
- No line signals in the gamma-ray spectrum are found between 10 GeV and 300 GeV in the Galaxy. The constraints on the velocity-averaged cross section for $\chi\overline{\chi} \rightarrow \gamma\gamma$ and the decay lifetime for $\tilde{G} \rightarrow \gamma\nu$, both at 95% confidence level, were calculated.

- Comparing to the previous Fermi-LAT results, similar constraints on the DM parameters are achieved and below 100 GeV the lower limits on the decay lifetime are even stronger.

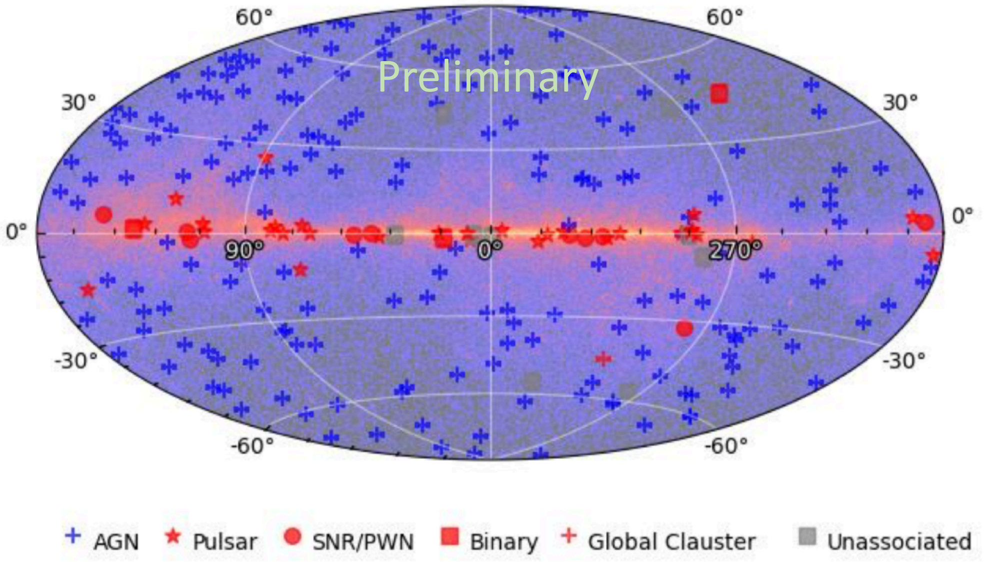


High energy gamma ray astronomy (work in progress...)

6-year count map
0.3 M photons (> 2 GeV)

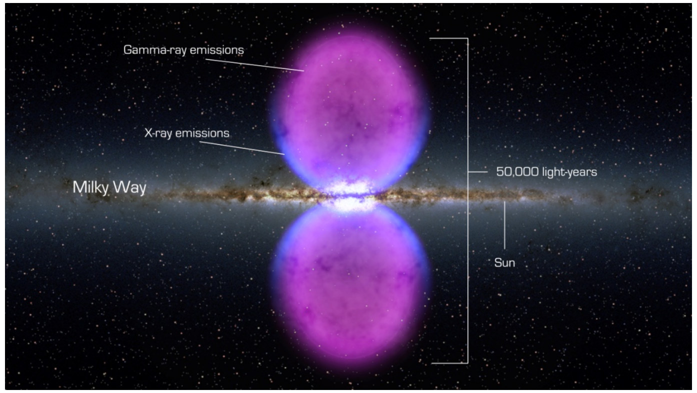


Source catalogue



Source Type	Number
AGN	188
Pulsar	30
SNR/PWN	10
Binary	3
Globular cluster	1
Unassociated	9
Total	260

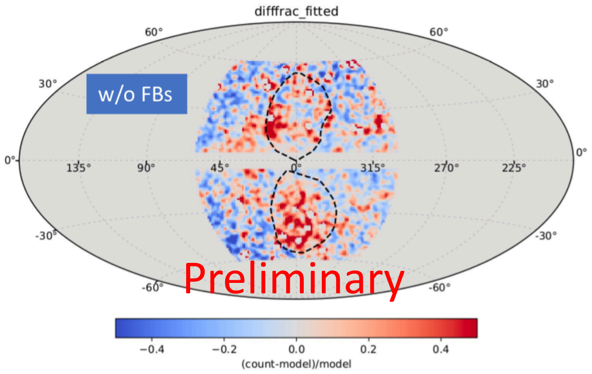
Fermi Bubbles (FB) (work in progress...)



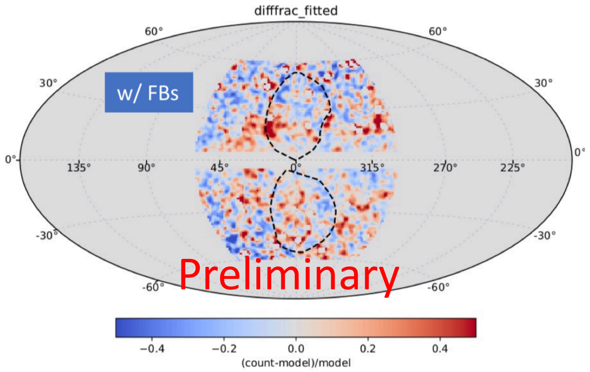
- Excess of gamma- (X-) rays, observed by the Fermi-LAT Collaboration, from two extended "bubble"-like regions above and below the Galactic Plane.
- The signal is characterized by
  - a homogeneous intensity over the whole bubble regions
  - a hard ($\propto E^{-2}$) spectrum with a probable cutoff at energies > 100 GeV.
- The origin is still debated. Some models propose hadronic mechanisms in which accelerated cosmic rays interact with the interstellar medium producing protons decaying in gammas and neutrinos.

[M. Ackermann et al. ApJ 793:64 (2014)]

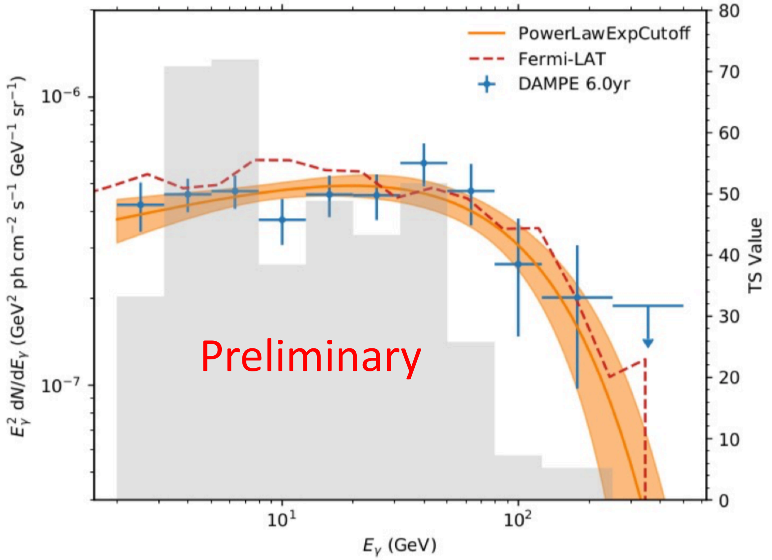
Data set: 6.0 years
Region of interest: $|l| < 60°$ and $5° < |b| < 60°$
Energy: 2 GeV – 500 GeV
Mask: 2° regions around point sources



FB significantly detected (> 17 σ)

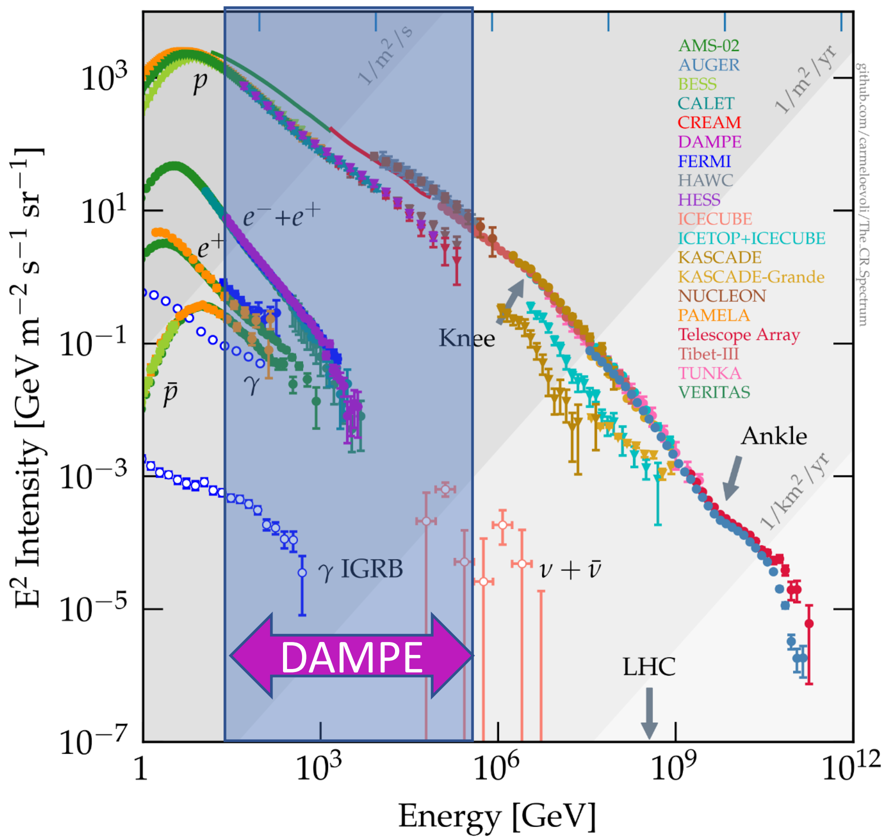


Most of excess removed if FB template included in the model → weak excess appears in the southern sky, is it due to the cocoon?



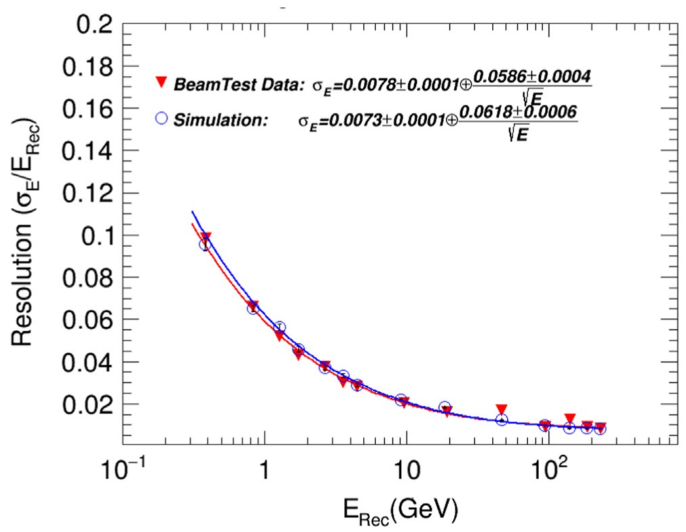
DAMPE spectrum well consistent with Fermi-LAT spectrum

DAMPE perspectives



Energy range:
- GeV – 10 TeV (e/γ)
- 40 GeV – 300 TeV (p and nuclei)

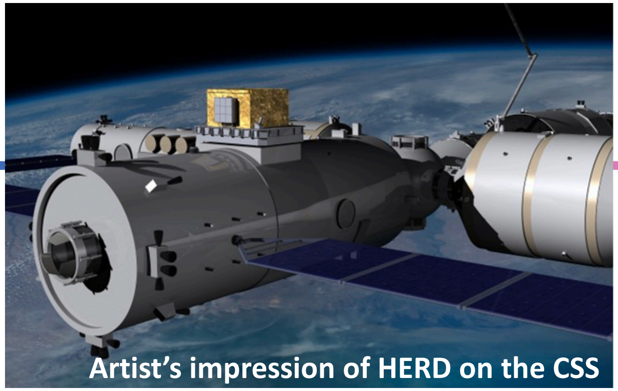
Z. Zhang et al., NIM A 836 (2016) 98–104



- The **calorimeter energy resolution improves with energy:** $\sigma(E)/E \propto 1/\mathrm{sqrt}(E)$, but at high energies it becomes difficult to contain the shower.

Solution: larger calorimeter

Future calorimeter experiment: HERD

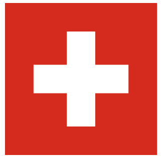


Artist's impression of HERD on the CSS

- The **H**igh **E**nergy cosmic-**R**adiation **D**etection facility (HERD) is an international space particle experiment and gamma ray observatory.
- One of the two flagship scientific experiments onboard China's Space Station (CSS).
- HERD is based on a **3D, homogeneous, isotropic and finely-segmented calorimeter** (55 X_0, 3 λ_I).

International scientific collaboration:

Lead by IHEP



University of Geneva
EPFL - Lausanne

University and INFN of Bari, Firenze, Lecce, Napoli, Pavia, Perugia, Pisa, Roma2, Trieste, LNGS and GSSI.

CIEMAT – Madrid
ICCUB – Barcelona
IFAE - Barcelona

CSS expected to be completed in 2022

Orbit	Circular LEO
Altitude	340 - 450 km
Inclination	42°

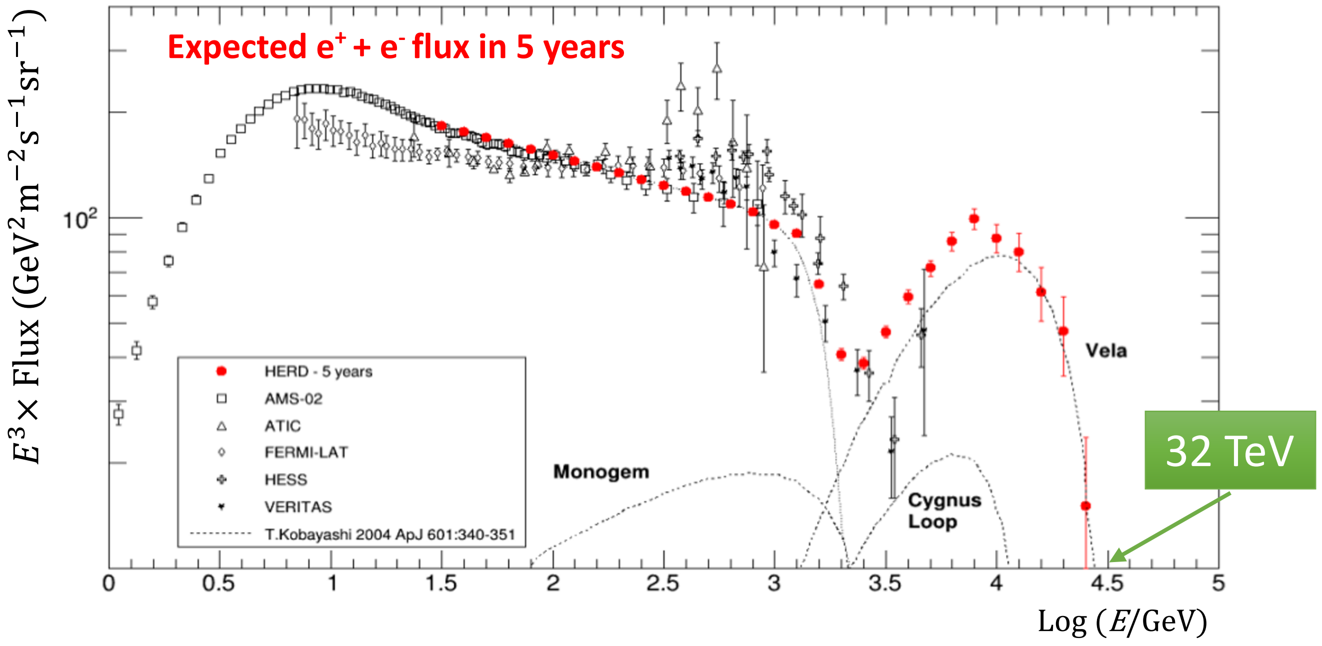
HERD planned to be operational from 2027 for at least 10 years

Mass	≤ 4000 kg
Envelope	~ 3.0 * 2.3 * 1.7 m^3
Field of view	+/- 90°
Power	~ 1900 W
Telemetry	100 Mbps

HERD observables and physics goals (1/3)

Electrons + positrons up to some tens of TeV

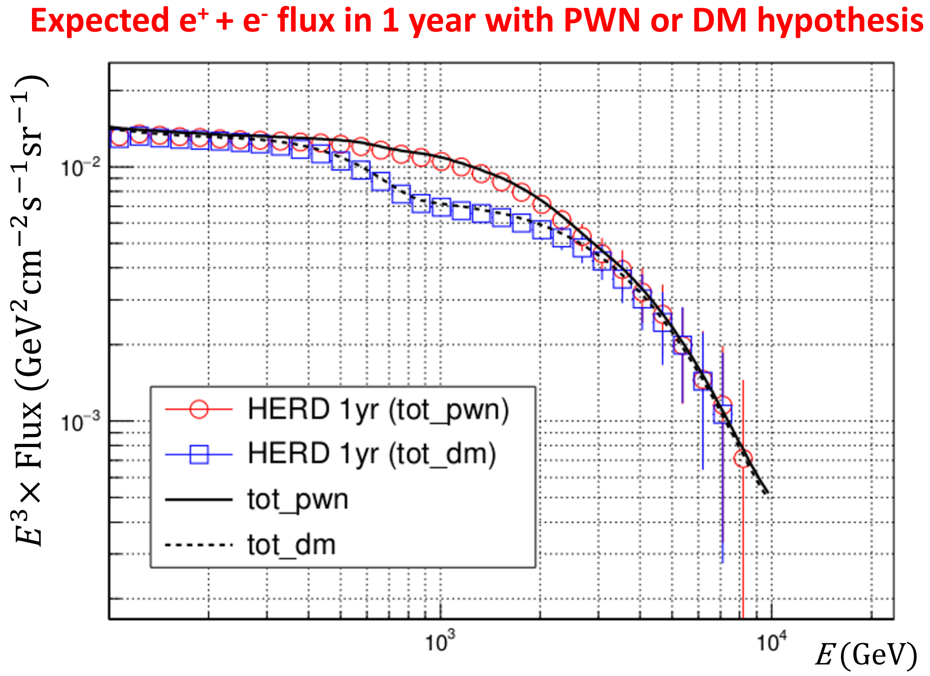
Acceleration and propagation studies



HERD will measure the all-electron flux up to several tens of TeV in order to detect:

- spectral cutoff at high energy
- local nearby astrophysical sources of very high energy e-
- additional information from anisotropy measurement…

Dark matter indirect searches

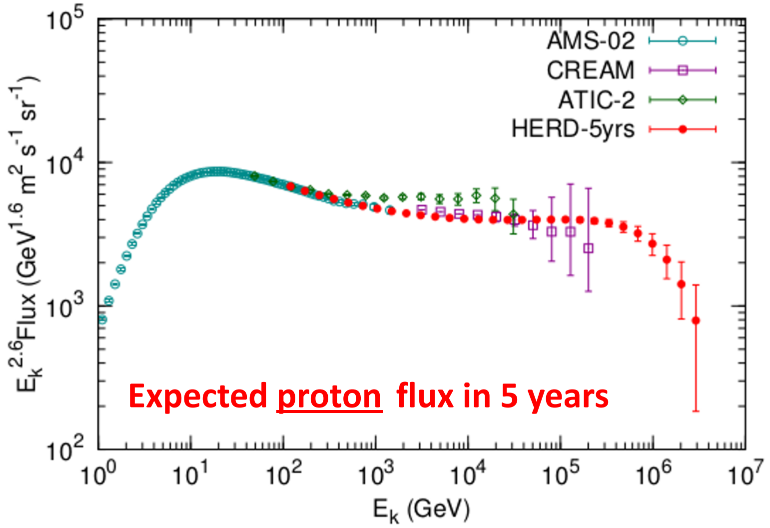


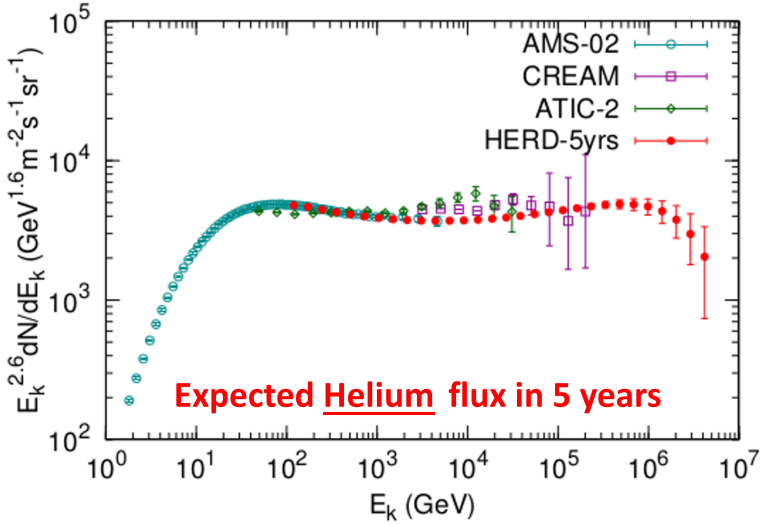
HERD will give important indications on the origin of the positron excess, i.e., to distinguish the dark matter origin of the excess from other astrophysical explanations, thanks to the precise measurement of the e+ + e- flux.

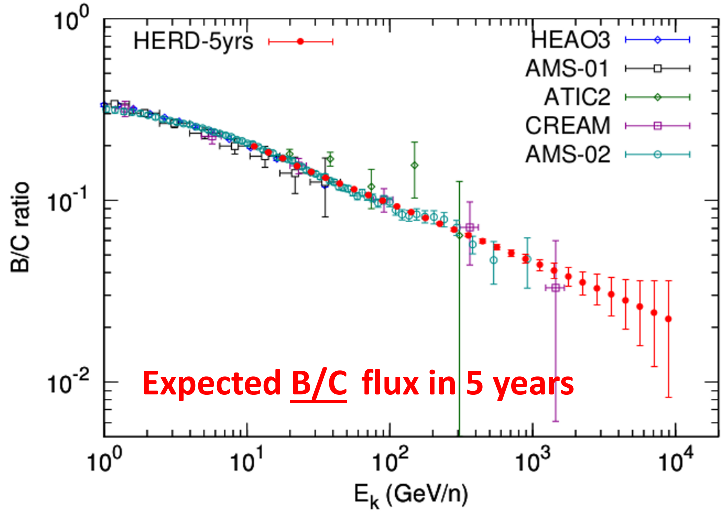
HERD observables and physics goals (2/3)

Hadrons up to the knee

Acceleration and propagation studies







HERD will measure the flux of nuclei:

- p and He up to a few PeV
- heavier nuclei (|Z| < 28) up to a few hundreds of TeV/n

First direct measurement of p and He knees will shed light on our understanding of the knee origin

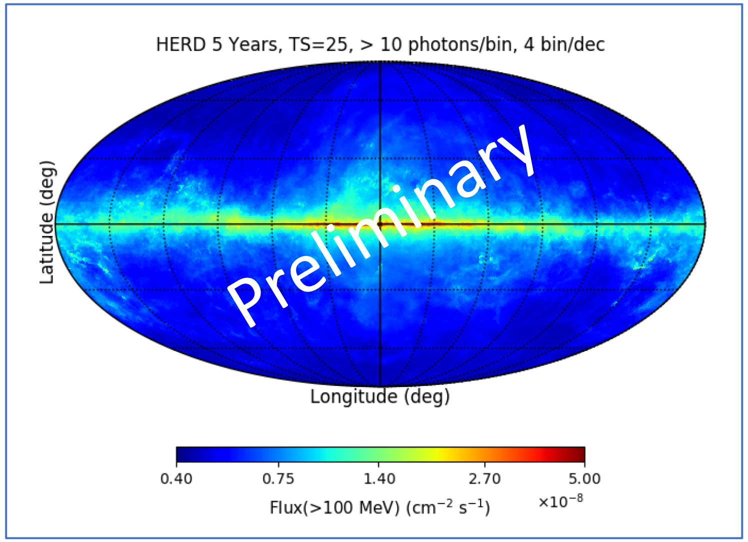
Extension of the B/C ratio to high energy will provide further insights into the propagation mechanisms of cosmic rays

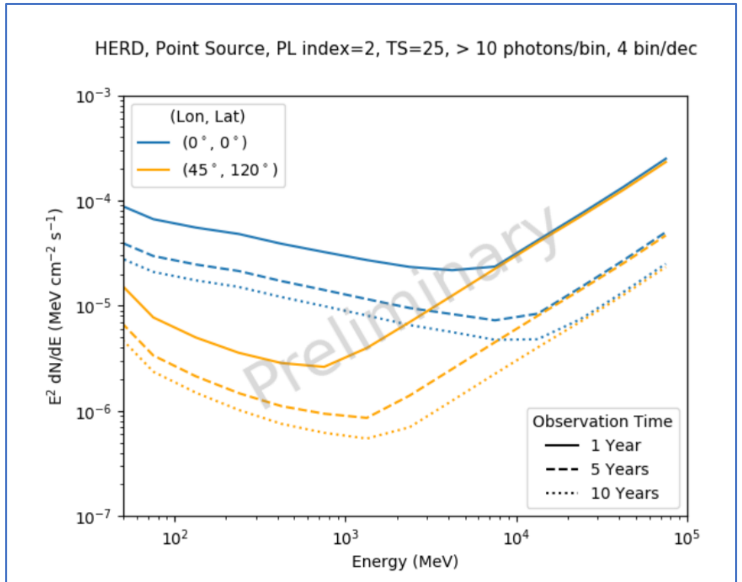
HERD observables and physics goals (3/3)

Gamma rays from 100 MeV

Thanks to its large acceptance and sensitivity, **HERD** will be able to perform a full gamma-ray sky survey in the energy range > 100 MeV

- study of galactic and extragalactic γ sources
- study of galactic and extragalactic γ diffuse emission
- detection of high energy γ bursts
- extend Fermi-LAT catalog to higher energy (> 300 GeV)
- increase the chances to detect rare γ events
- search for indirect dark matter signatures

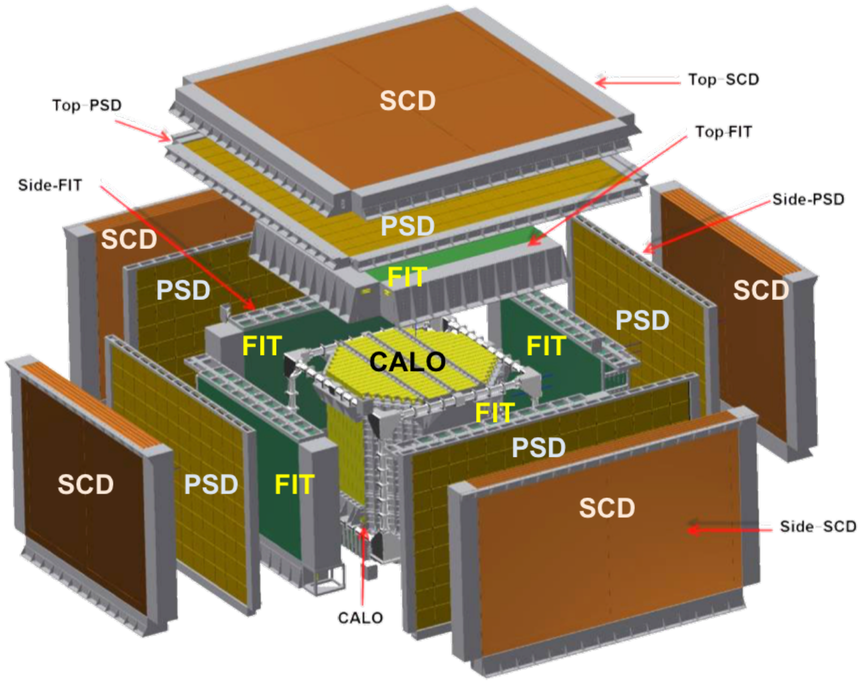




Multi-messenger astronomy
Possible synergy with other experiments designed for:
γ (CTA, LHAASO, …)
ν (KM3NeT, IceCube)
GW (Ligo, Virgo)

The HERD detector

- To maximize the acceptance: novel “isotropic” design with a 3D calorimeter + (FIT+PSD+SCD) on 5 sides under optimization
- To reduce systematics: double readout system for CALO + in-flight calibration with TRD
- To control the nuclei fragmentation → charge detector as outermost detector



F. Gargano et al., POS (ICRC 2021) 026

CALO: CALOrimeter (55 X_0)
- Energy measurement
- Electron/proton separation

FIT: FIber Tracker (5 sides)
- Track reconstruction
- Low energy γ ray conversion ($\gamma \rightarrow e^+ e^-$)
- Charge measurement (|Z|)

PSD: Plastic Scintillator Detector (5 sides)
- Charge measurement (|Z|)
- γ ray identification

SCD: Silicon Charge Detector (5 sides)
- Charge measurement (|Z|)

TRD: Transition Radiation Detector (1 side)
- Energy calibration of CALO for TeV nuclei

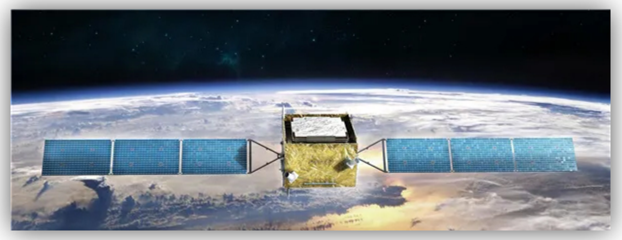
HERD vs. other experiments

HERD is a next generation experiment with much better performance in the direct detection of high energy electrons + positrons, protons, gamma-ray.

Experiment	Energy (e/γ)	Energy (p)	Calorimeter thickness (X_0)	$\Delta p/p$ (e/γ) @ 100 GeV	$\Delta p/p$ (protons) > 100 GeV	e/p ID	e acceptance (m^2sr) @ 200 GeV	p acceptance (m^2sr) @ 100 GeV
Fermi-LAT (2008)	1 GeV – 300 GeV	30 GeV – 10 TeV	8.6	10%	40%	10^3	0.9	< 0.28
AMS-02 (2011)	1 GeV – 1 TeV	1 GeV - 2 TeV	17	2%	20%	$10^4 – 10^5$	0.05	0.16
CALET (2015)	1 GeV – 10 TeV	50 GeV – 60 TeV	27	2%	30%	10^5	0.1	0.042
DAMPE (2015)	5 GeV – 10 TeV	40 GeV – 300 TeV	32	< 1.5%	25 - 35%	> 10^5	0.3	0.03
HERD (2027)	10 GeV – 100 TeV 0.5 GeV – 100 TeV (γ)	30 GeV - PeV	55	< 1%	20%	> 10^6	3	> 2

Summary

DAMPE = Present



- In-flight operation 2015 — now
- Excellent performance and stability
- Unique current CR detection direct experiment for tens TeV

- **Physics results:**
  - $e^+ + e^-$: first direct observation of TeV-break
  - p, He: enter TeV—PeV frontier
  - Ongoing works on Li, Be, B, C, N, O, Ne, Mg, Si and Fe
  - Interesting results on B/C and B/O are coming soon
  - Gamma-ray sky, Fermi Bubbles, DM search

HERD = Future

- International space mission starting operations in 2027 on board the future China's Space Station.

- **Novel** isotropic **design**, based on a 3D, homogeneous, isotropic and finely-segmented calorimeter
  - Maximizes the energy range while respecting the mass and power budget of a space experiment
  - Reduces systematics uncertainties with respect to the current generation space-borne calorimeters.

- **Rich and frontier physics program:** DM search, CR observations and gamma-ray astronomy.

Thank you!!