# Indirect Search for Dark Matter signatures in the Cosmic Rays as seen from Space

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# Outline

## Indirect DM Search and Signals
## Cosmic Messengers of DM

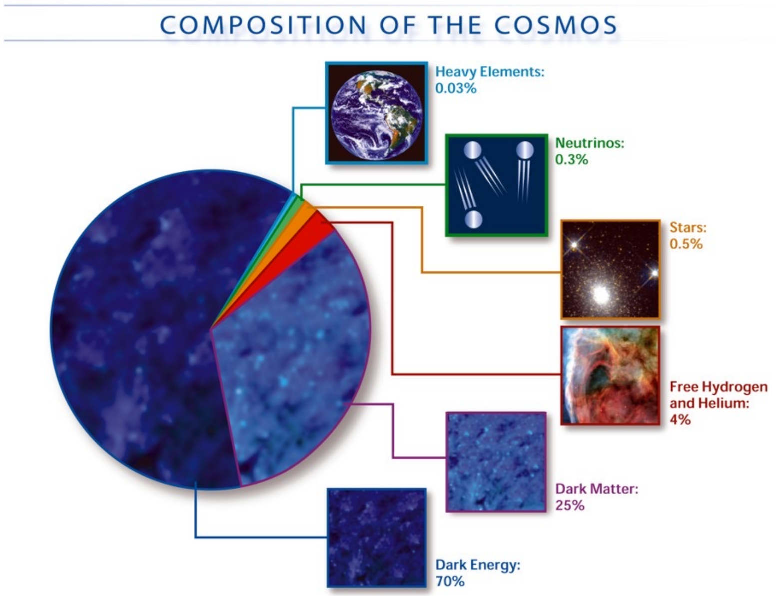
## Gamma Rays and DM

## Charged Cosmic rays

*Special thanks to:*
*Ivan De Mitri, Nicola Mazziotta, Roberta Sparvoli, Elena Vannuccini and Paolo Zuccon for providing material and bibliography.*

*Disclaimer: This is a review based on my personal knowledge.*
*Whatever omission, error, inaccuracy is my sole responsibility*

# Indirect DM search



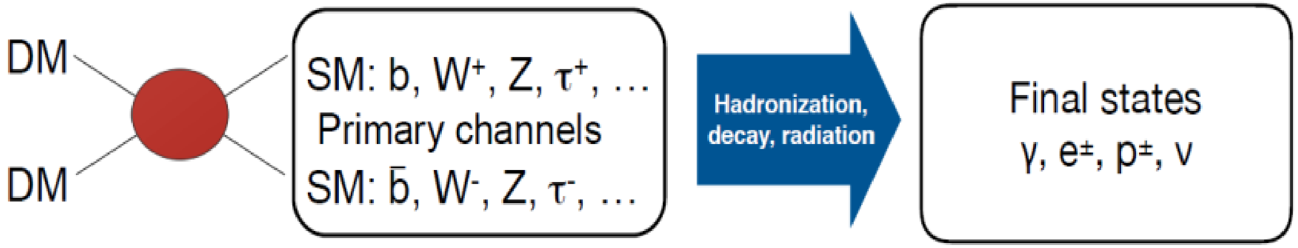

- ~1/4 of our Universe is composed of DM:
  - Weakly coupled to SM particles
  - Dynamically cold
  - No direct indication on the mass scale
    **GeV-TeV** well motivated range,
    → Weakly Interacting Massive Particle (**WIMP**)
- Current evidence of DM is purely of gravitational origin
- **Non-gravitational** signal is needed to understand its particle-physics nature

→ look for anomalies in the cosmic radiation ascribable to the presence of DM particles, from galactic to cosmological scale

→ Complementary approach to direct and collider searches

# Cosmic messengers of DM

Thermal relic from Big Bang, concentrated in galactic halos




→ Self-annihilation of DM particles into **visible products**

⊗ propagation along the way to the observer

⊕ background/foreground from conventional astrophysical processes

→ **Multi-messenger/multi-wavelength** approach to DM search

→ Available channels depend on DM mass and astrophysical background

# Indirect DM signal

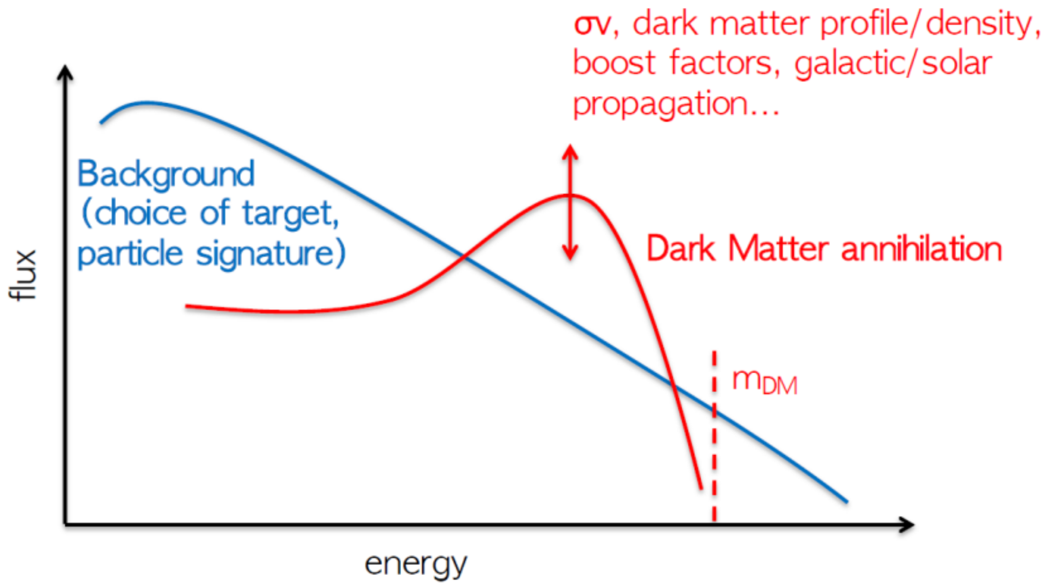
$$\frac{d\phi_m}{dE} \propto \frac{\Gamma}{m_{DM}^a} \cdot \sum_f B_f \left(\frac{dN_m}{dE}\right)_f \cdot \iiint dv\ \rho_{DM}{}^a$$

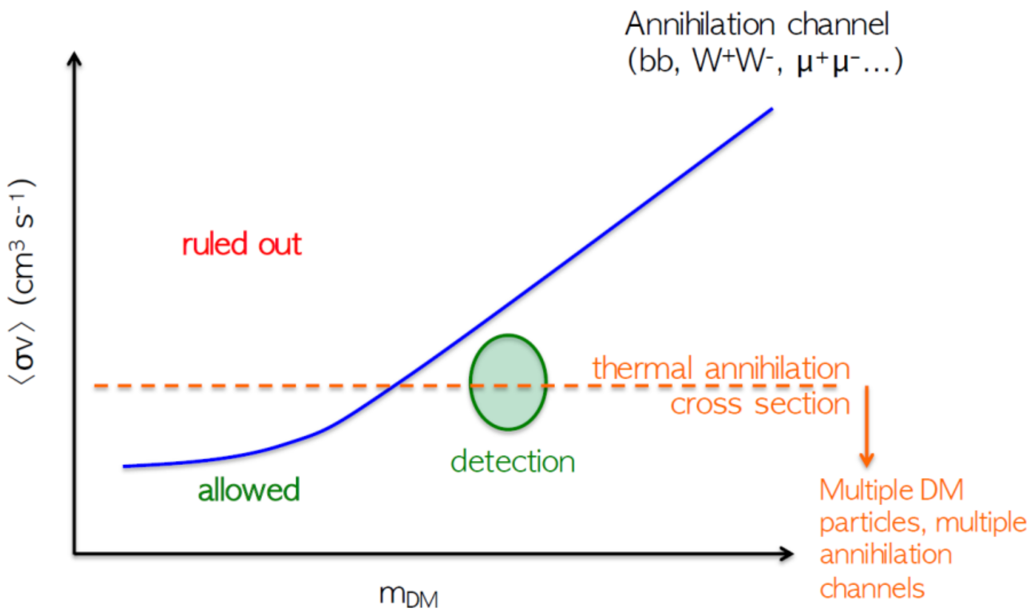
- Source term for particle $m$ ($\gamma, e^{\pm}, p^{\pm}, \nu, \ldots$) from annihilation (decay) of DM particle of mass $m_{DM}$
  - Terms in the equation:
    - Integral of the **DM density** to the power of $a = 2$ (1) for annihilation (decay)
    - Sum of the spectra from hadronization and decay of DM annihilation (decay) products over all the individual **annihilation (decay) modes** having probability $B_f$
    - Annihilation (decay) rate $\Gamma = \langle \sigma v \rangle / 2$ $(1/\tau)$

- Search for **excess** in the cosmic radiation allows to put constraints into the $\boldsymbol{\Gamma}$ $\boldsymbol{vs}$ $\boldsymbol{m_{DM}}$ parameter space

# Indirect DM signal

$$\frac{d\phi_m}{dE} \propto \frac{\Gamma}{m_{DM}^2} \cdot \sum_f B_f \left(\frac{dN_m}{dE}\right)_f \cdot \iiint dv\ \rho_{DM}{}^2$$



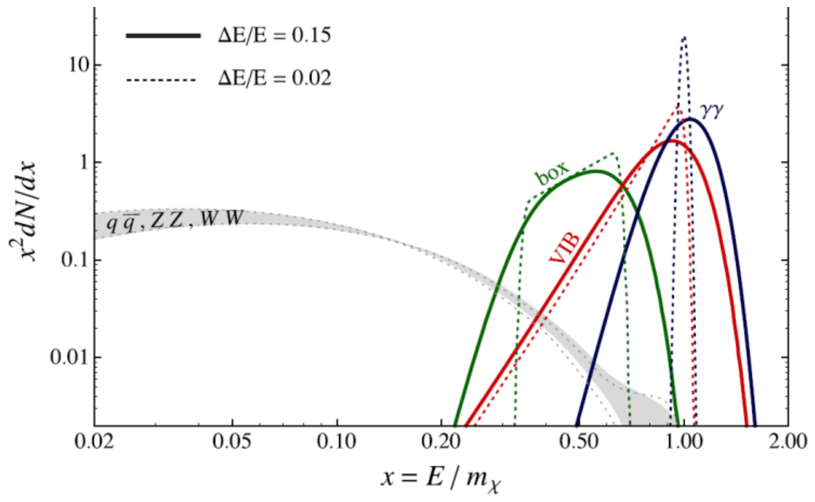




Credit: Perez APS-DPF Meeting 2019

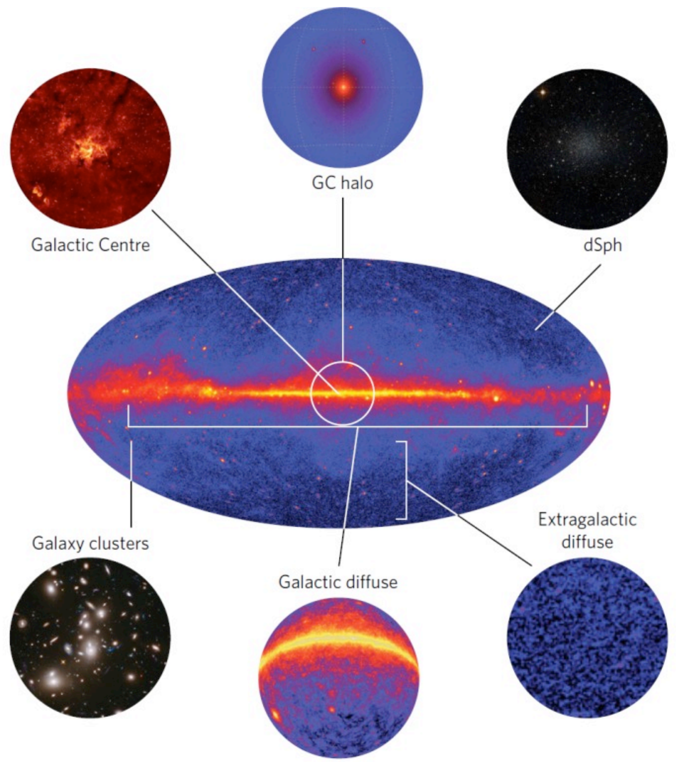
- Search for **excess** in the cosmic radiation allows to put constraints into the $\langle\sigma v\rangle$ $\boldsymbol{vs\ m_{DM}}$ parameter space

# Gamma-rays

- Produced as both primary and secondary products (from hadronization/decay of primary products)
  - Carry distinctive spectral features (e.g. lines!)
- Point back to the production sites
  - ~unaffected by energy losses (at non-cosmological scale)
  - Provide several DM search targets, that carry distinctive spatial features
- Suffer from significant astrophysical background



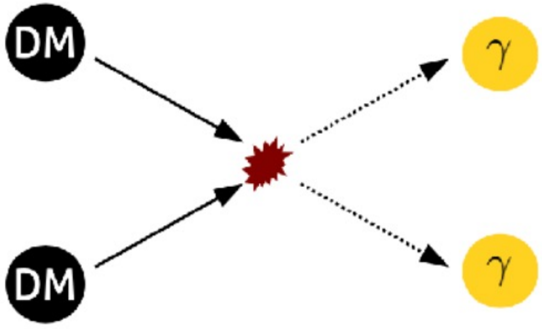

Bringmann-Weniger (2012)



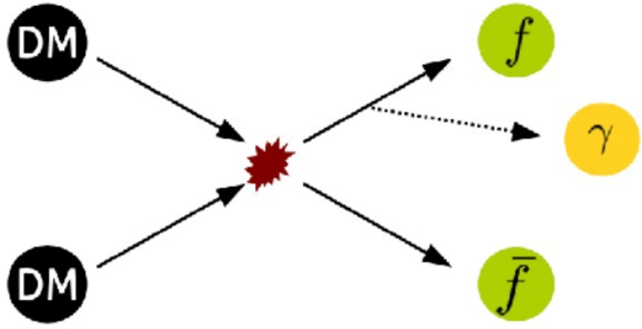

Conrad & Reimer (2017)

# Gamma rays from dark matter annihilation

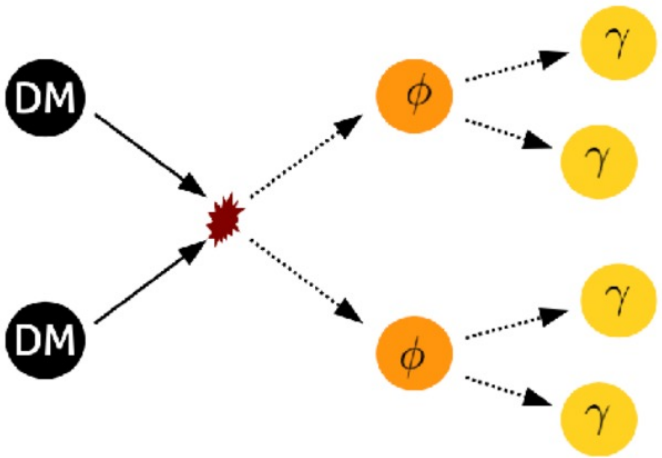
**Gamma-ray lines:**
Two-body annihilation into photons



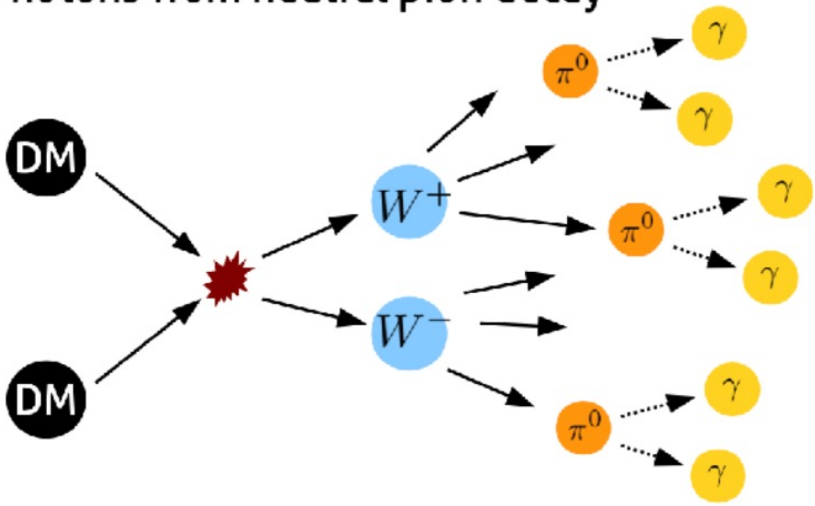

**Bremsstrahlung:**
Photon production in "hard process"



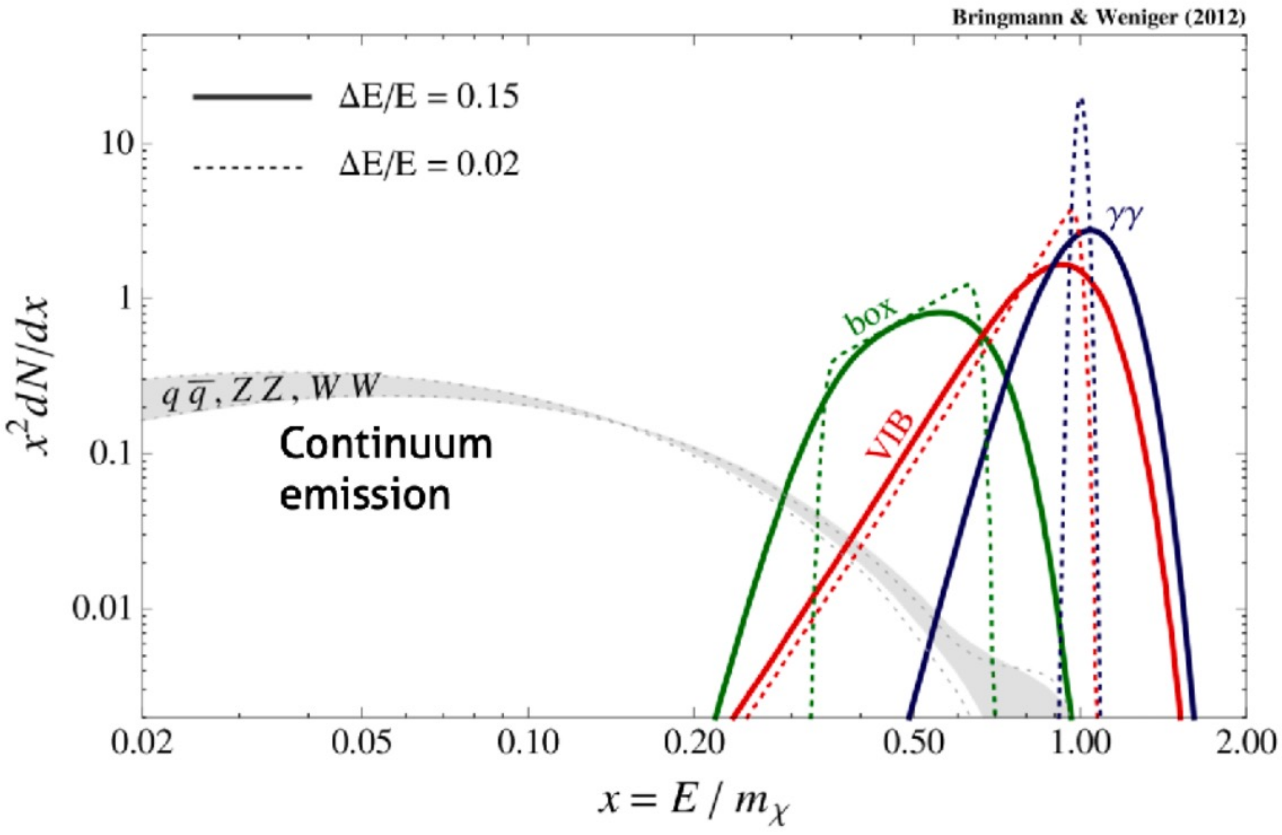

**Box-shaped spectra:**
Photons from cascade decay




**Continuum emission:** (Prompt)
Photons from neutral pion decay



# Gamma rays from dark matter annihilation




**Box-shaped spectra**

- Cascade-decay into monochromatic photons
- already at tree level

**Internal Bremsstrahlung (IB)**

- radiative correction to processes with charged final states
- Generically suppressed by O(α)

$$\chi\chi \to \bar{f} f \gamma$$

**Gamma-ray lines**

- from two-body annihilation into photons
- forbidden at tree-leve, generically suppressed by O(α²)

$$\chi\chi \to \gamma\gamma$$

# Gamma rays from dark matter annihilation

Velocity averaged annihilation cross-section

**Signal intensity:**
[photon flux per steradian per energy]

Photon energy spectrum per annihilation

$$\frac{d\phi}{d\Omega dE} = \frac{\langle \sigma v_{\rm rel} \rangle}{8\pi m_\chi^2} \frac{dN_\gamma}{dE} \times \int_{\rm l.o.s.} ds\ \rho(\vec{r}[s,\Omega])^2$$

Dark matter mass density

Dark matter mass

Line-of-sight integral

**Particle Physics**

**Astrophysics**

Characteristic **Energy Spectrum**

Characteristic **Morphology**
(point-like, extended or diffuse)

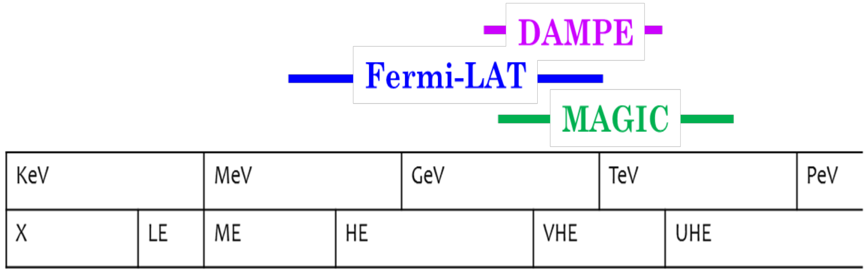
[review DM searches with gamma rays: Bringmann & Weniger (2012)]

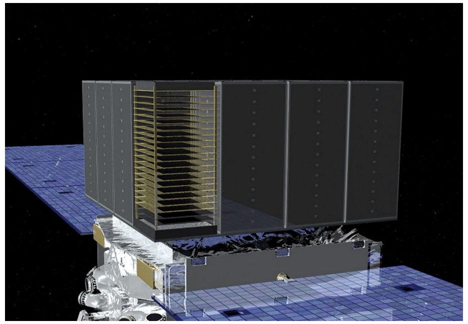
It is convenient to define a "J-value":

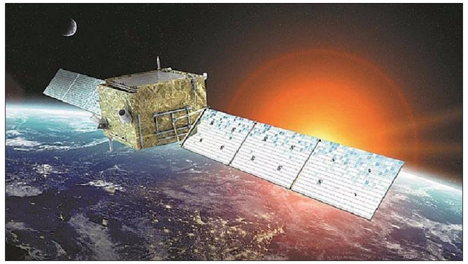
$$J_{\Delta\Omega} \equiv \int_{\Delta\Omega} d\Omega \int_{\rm l.o.s.} ds \rho(r[s, \vec{\Omega}])^2$$

# Running gamma-ray telescopes

- Proved detector technology
- Direct detection with pair conversion telescopes
  - tracker/converted + em calorimeter
    - Fermi-LAT, DAMPE, CALET
- Indirect detection of EASs (only mention)
  - Imaging Atmospheric Cherenkov Telescopes (IACT)s:
    - MAGIC, HESS, VERITAS
  - Water Cherenkov EAS array
    - HAWC

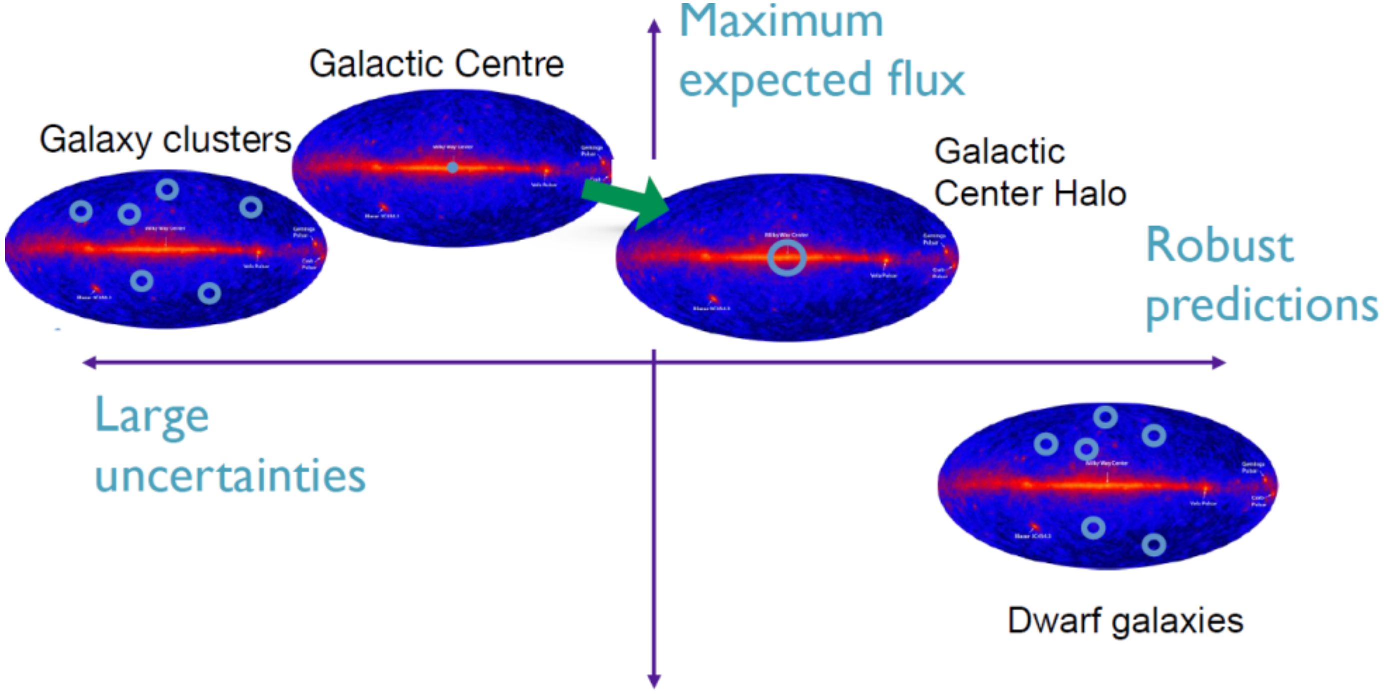




# Strategies and targets

- Relevant parameters for DM discovery:
  - DM quantity, concentration and distance
  - Signal prediction uncertainties
  - Astrophysical background
- Signal intensity and signal-to-bk pictures favors DM detection around the **Galactic Center region**
- Most robust predictions from **Dwarf Galaxies**




(Credits: Javier Rico)

Conrad & Reimer (2017)

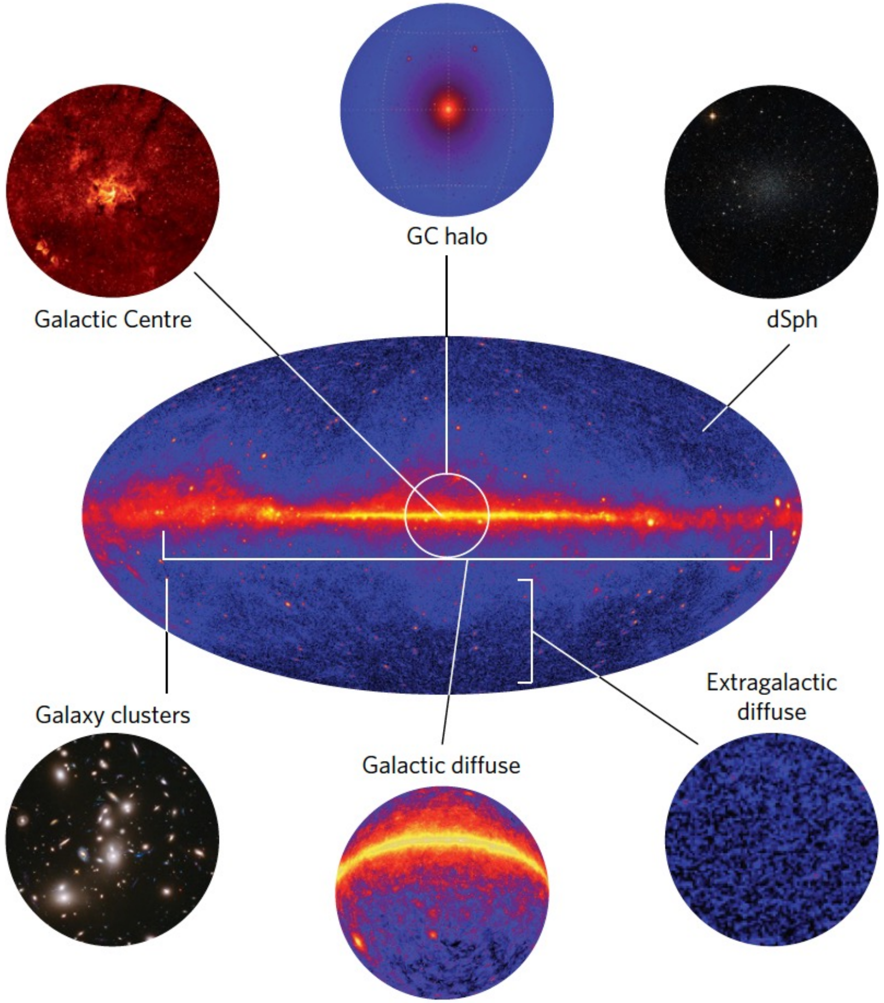
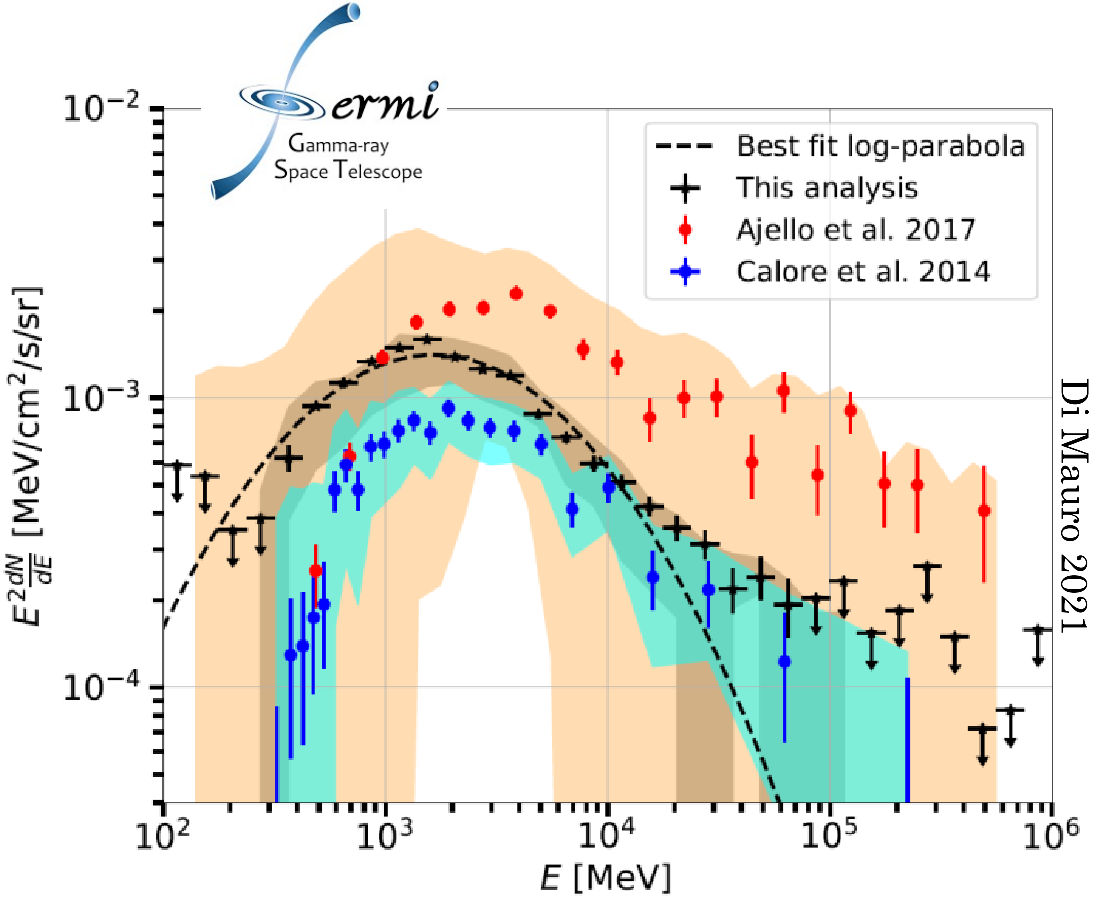



**Figure 2 | Targets for indirect dark matter searches in the gamma-ray sky.** The central Fermi-LAT skymap indicates the celestial distribution of high-energy photons. Symbolizing one or more specific characteristics of a respective search location, the most popular targets are emphasized in auxiliary pictures and discussed in the text. By GC we denote the Galactic Centre and by dSph dwarf spheroidal galaxy. Image credit: NASA/ESA/Q.D. Wang (University of Massachusetts, Amherst) (Galactic Centre); ref. 98, APS (GC halo); ESO/Digitized Sky Survey 2 (dSph); NASA/DOE/Fermi LAT Collaboration (galactic diffuse, extragalactic diffuse and main image); NASA/ESA/STScI (galaxy clusters).

# Galactic Center Excess (GCE)

- Signal excess (~30%) from the GC
  - Spatially extended ($\theta_{1/2} \sim 10^o$)
  - Observed by EGRET in 1997, confirmed by Fermi-LAT in 2009
  - Main difficulty is modeling the GC region
- Updated measurement of GCE with 11-years of Fermi-LAT data (2× previous statistics)
  - Spherical symmetric morphology, centered at GC, independent on energy
  - Consistent with DM of ~40 GeV mass
- DM interpretation degenerate with astrophysical models
  - sub-threshold unresolved source population, like MSPs
  - CR inhomogeneities

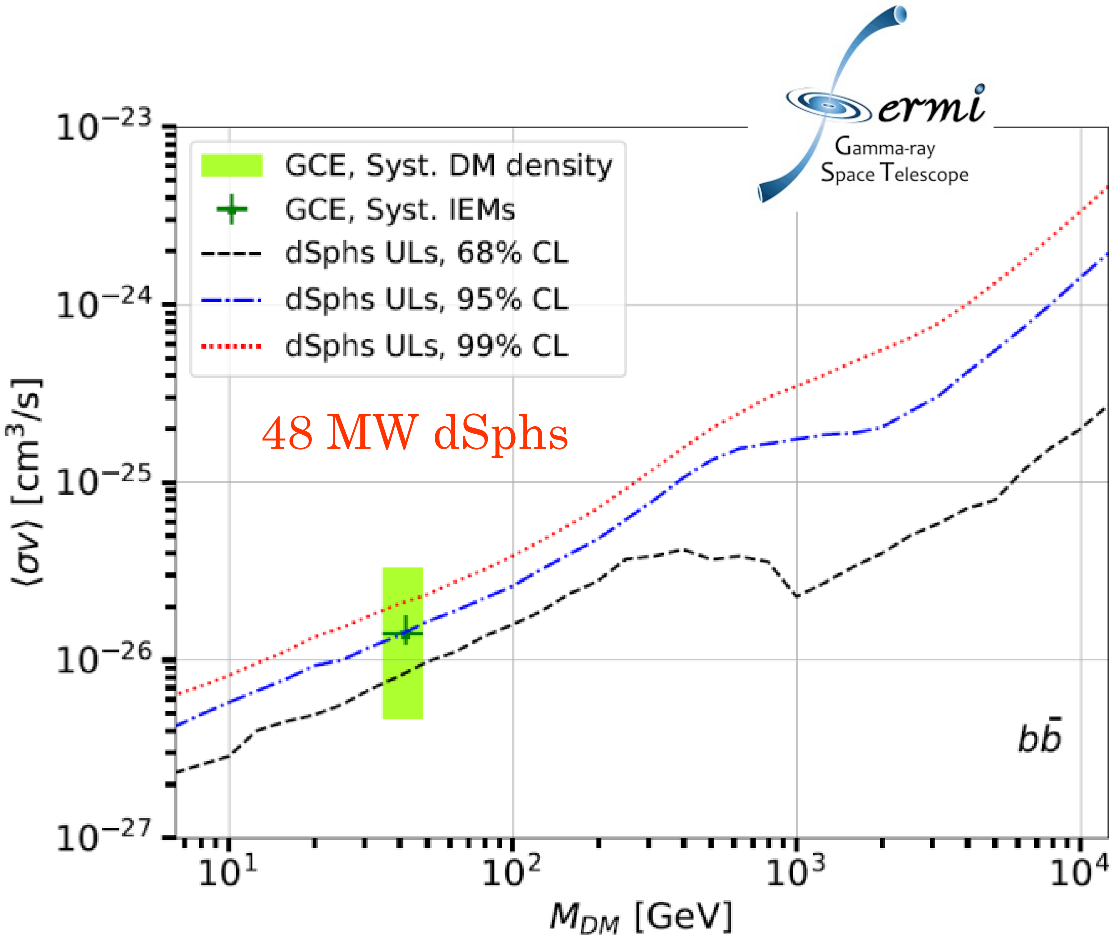



Di Mauro 2021

(Envelope of the GCE SEDs using different IEMs, data selections and analysis techniques)

# Dwarf spheroidal galaxies (dSph)

- Satellites of the Milky Way, most DM-dominated among galaxies
  - Mass well constrained via observation of star dynamics
  - No conventional gamma ray emission
- Low signal expected → more sources stacked to increase signal-to-bkg
- Several analysis published with different dSph Fermi-LAT samples, exposures and techniques
  - No significant excess detected
  - Most stringent limit to DM so far
  - Limits compatible with GCE, within the uncertainties




Di Mauro - Wingler (2021)

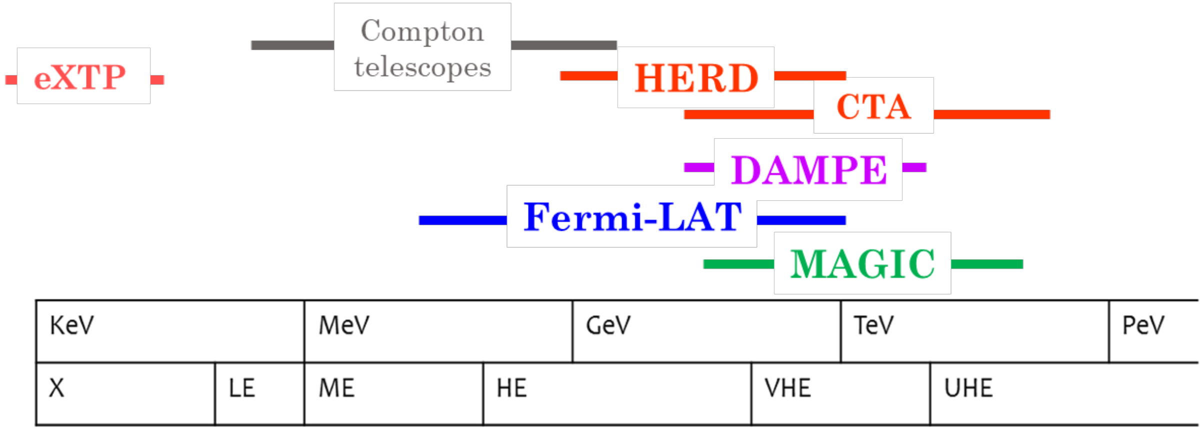
# Other DM searches with γ-rays

- DM annihilation/decay from different targets
  - Galaxy clusters (decaying DM)
  - Globular clusters
  - Sun (DM annihilation into long-lived mediators) (Fermi)
  - Unidentified Fermi sources (possible MW DM sub-halos)
  - …
- ALPs (Axion Like Particles)
  - Observational effects due to $\gamma \leftrightarrow$ ALP oscillation in the presence of magnetic fields.
    - transparency of the Universe to γ-rays: γ from distant AGNs might oscillate into ALP in intergalactic magnetic field
    - prompt γ-rays from core-collapse galactic and extragalact SNe
    - altered emission from galactic pulsars
    - …

# Future perspectives

- Running experiments
  - Fermi-LAT will run until 2022 (extension to 2025 after NASA review)
    - Better understanding of GC bk from multi-wavelength observations
    - Increasing number of dSps from optical survey (e.g. DES)
  - Ongoing effort for multi-target, multi-instrument joint analysis of dSphs will increase sensitivity

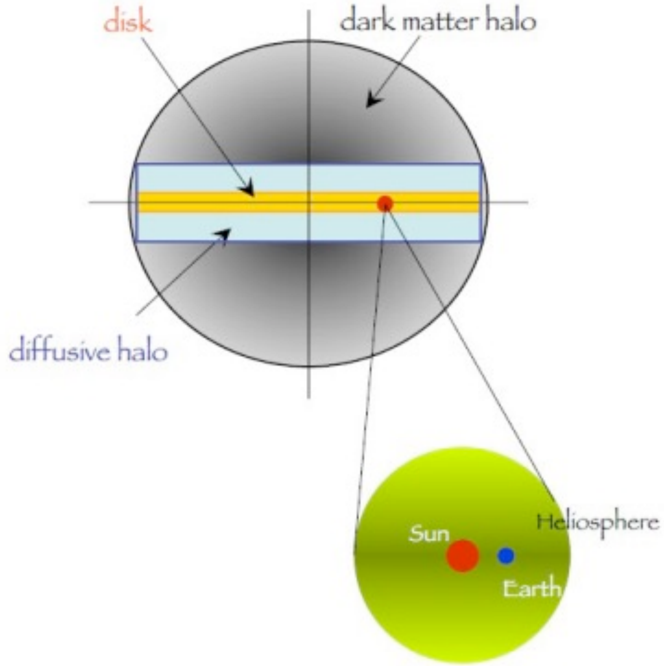
- Future missions: eXTP*, HERD, CTA
  - *eXTP-WFM instrument (FOV 4 sr, 2÷50keV, 0.3keV energy resolution ~Chandra) will provide an unprecedented high-signal measure of DM photons. WFM very sensitive to the candidate 3.5 keV line (possible decaying sterile neutrino signature)

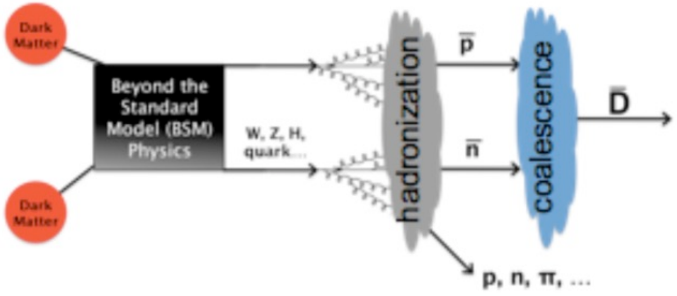



# Charged Cosmic Rays

# Charged (anti)particles

- Produced in the DM Halo mainly from hadronization of primary annihilation/decay products
  - Experience significant diffusion-loss processes while propagating through the diffusive Halo (and the Heliosphere)
  - Probe Milky Way Halo DM
- Background from secondary GCRs and close-by astrophysical sources
  - Antiparticles are the most promising channels due to reduced bkg from GCR collisions
  - Additional uncertainties for antinuclei from nuclear coalescence
  - Need excellent particle identification capabilities

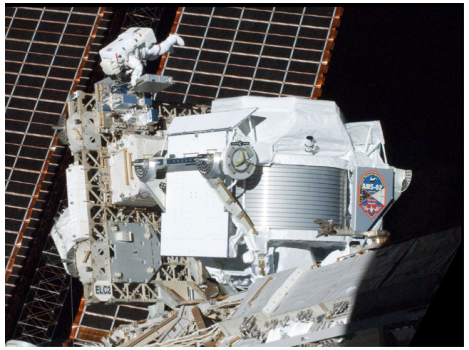
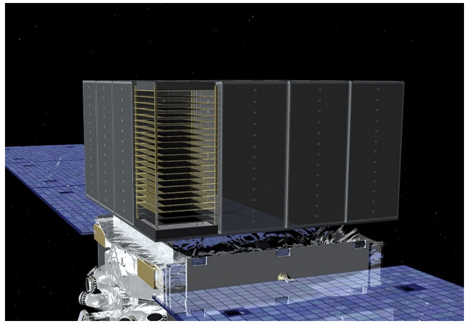
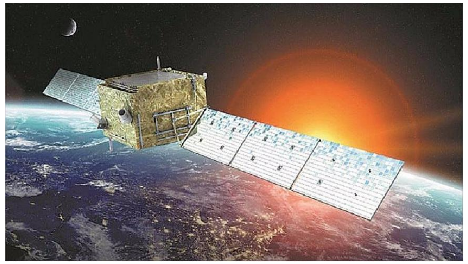


# Running CR experiments

- Direct CR detection from space
- **Magnetic spectrometers**
  - Provide most powerful particle discrimination capabilities over the widest energy range → antimatter identification
  - (PAMELA until 2016), BESS, AMS-02 (MDR ~ 2 TV)
- **Calorimeters**
  - Inclusive all-electron spectra
  - Fermi-LAT, CALET, DAMPE

| Experiment | Calorimeter | $X_0$ | Resolution |
|---|---|---|---|
| AMS-02 | SF/Pb | 17 | 1% > 10GeV |
| Fermi-LAT | CsI(Tl) | 8.6 | 6% @10GeV |
| DAMPE | BGO | 31 | 1% @200GeV |
| HERD | LYSO | 55 | 1÷2% @200GeV |

# Cosmic Ray Space Missions

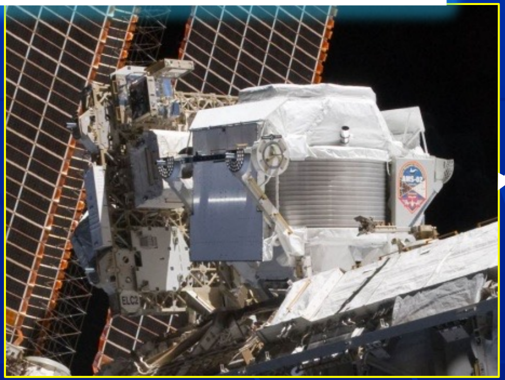
**PAMELA**
**15-06-2006**

**Fermi**
**11-6-2008**

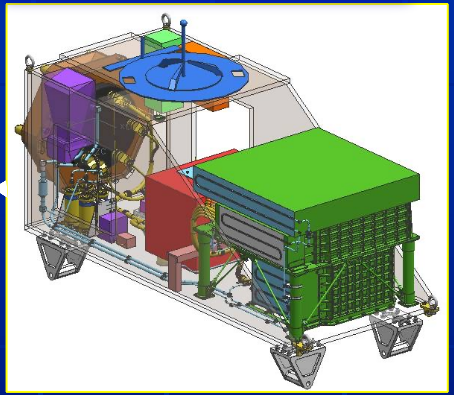
**DAMPE**
**17/12/2015**

ISS

**AMS**
**16-05-2011**

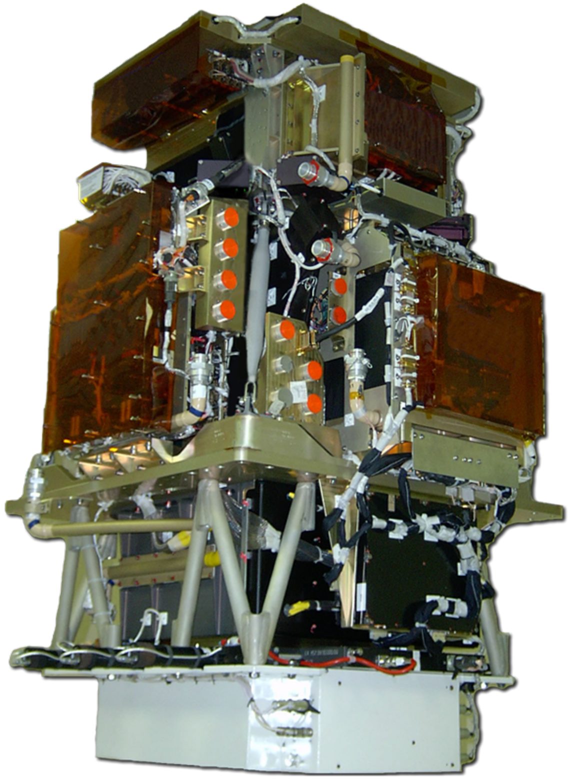


**CALET**
**19-08-2015**



# Magnetic Spectrometers

PAMELA 2006



$130x70x70\ cm^3$

470 Kg

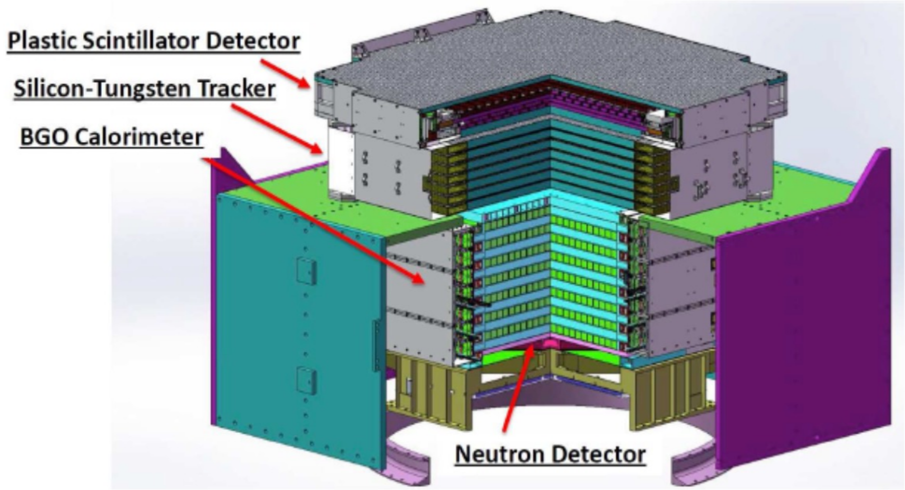
AMS-02 2011


5m x 4m x 3m

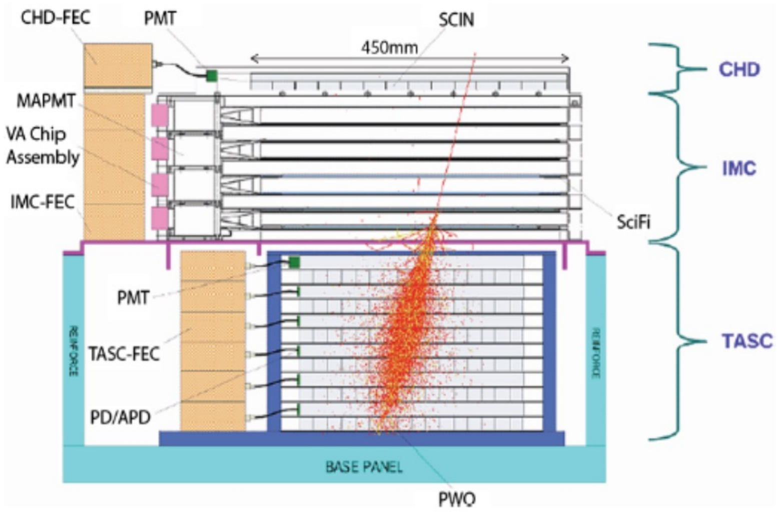
7.5 tons

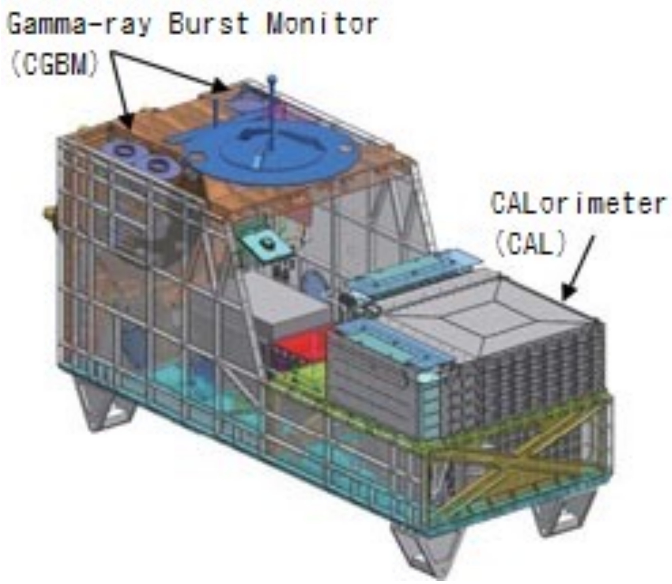
# Calorimetric Instruments

DAMPE



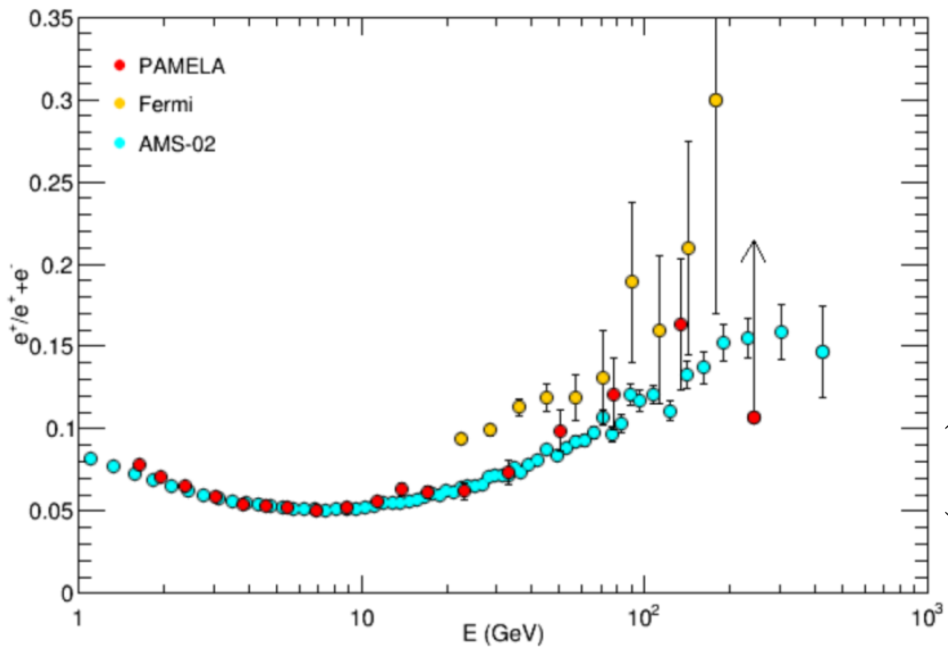

CALET



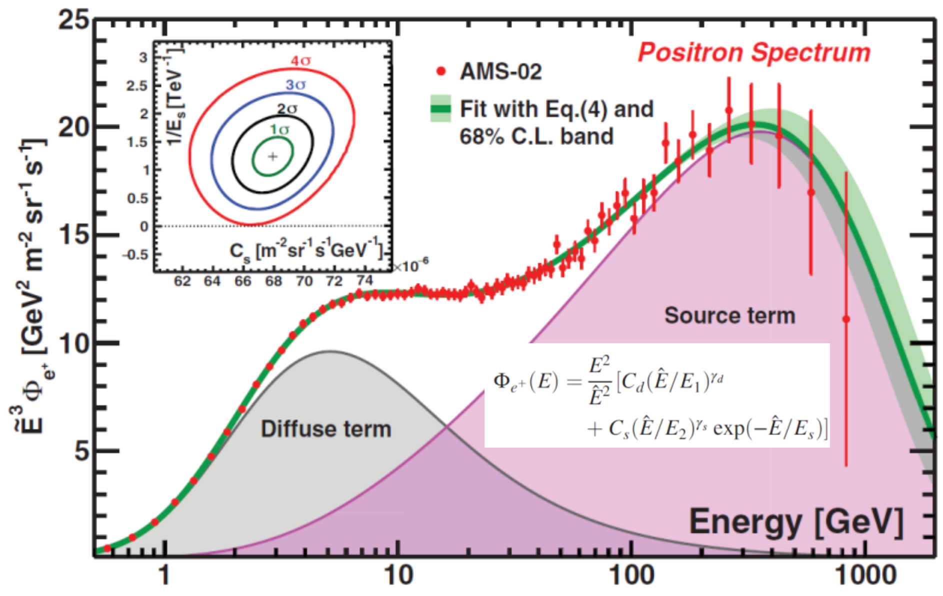



# Positrons

- Excess above 10 GeV
  - Observed by PAMELA in 2008, confirmed by AMS-02 in 2013
  - Secondary origin strongly disfavoured
- Updated measurement from AMS-02 in 2019
  - Significant cutoff at 810 GeV
  - Anisotropy limit set to δ<0.0XX



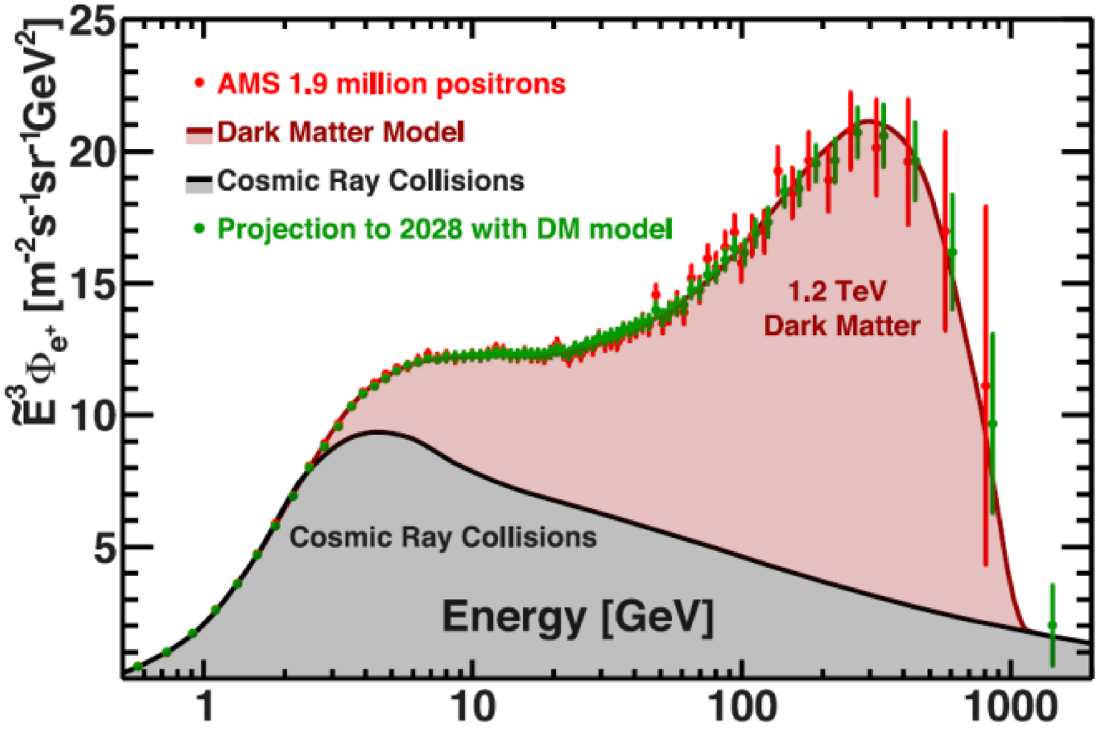

Adriani+ N.Cim. (2018)




Aguilar et al PRL 122 (2019)

# Origin of positron excess

- Positron excess consistent with TeV-mass DM annihilation
  - Severe constraints from γ-ray dSph and antiprotons observations
  - Large cross-section required $\langle \sigma v \rangle \sim 10^{-24}\ \mathrm{cm}^3/s$ to leptonic channels
- Possible standard astrophysical contribution from near-by pulsars
  - em cascading from electrons ejected from spinning neutron star

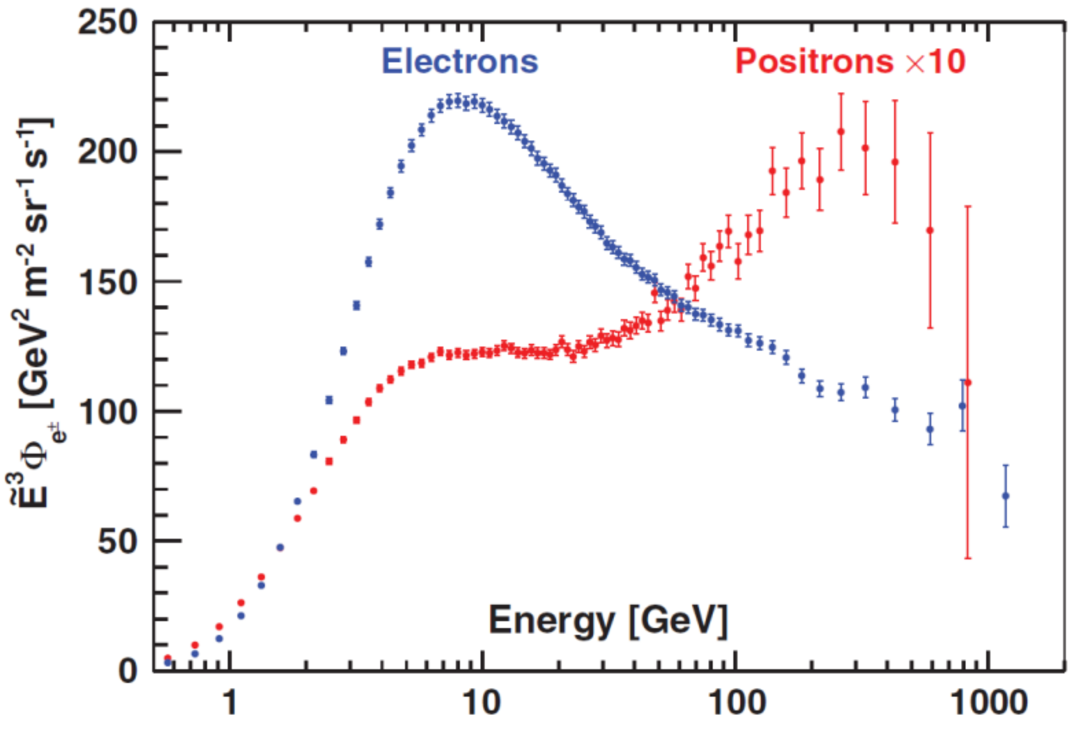



Aguilar+ PR (2021)
Kopp (2013)

# Electrons

- Distinctly different magnitude and energy dependency than positrons
  - Double power-law with no cut-off
  - Most high energy electrons originate from different sources than high energy positrons

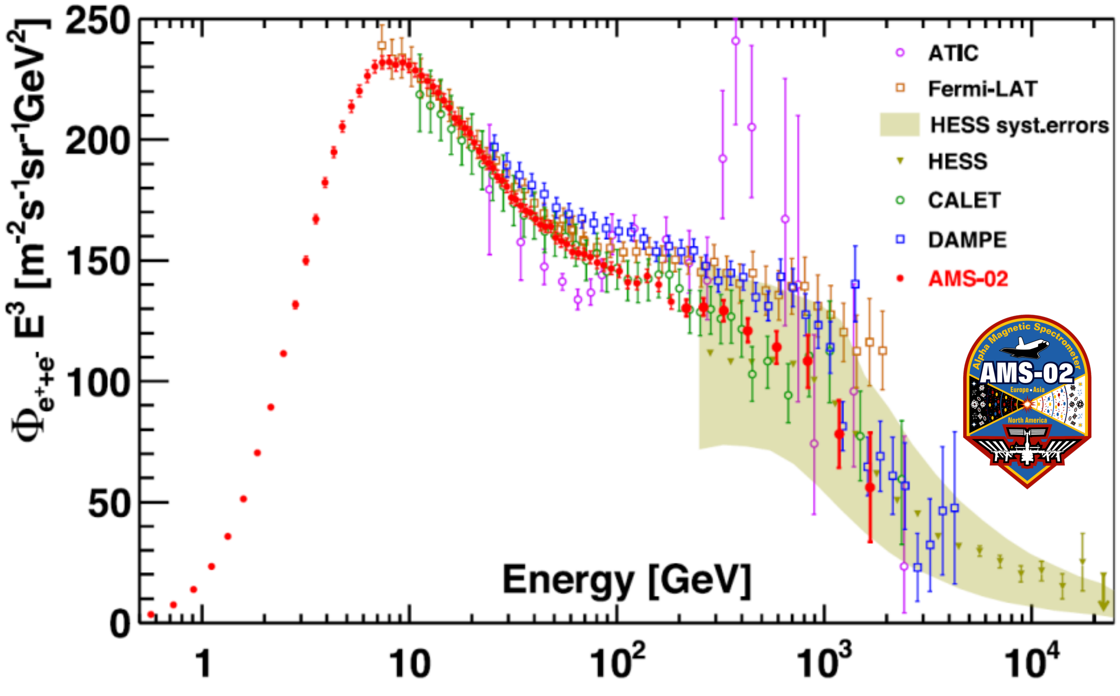
- Search for features in the electron spectrum
  - Data can accommodate an amount of electrons equal to the positron excess, but not statistically significant



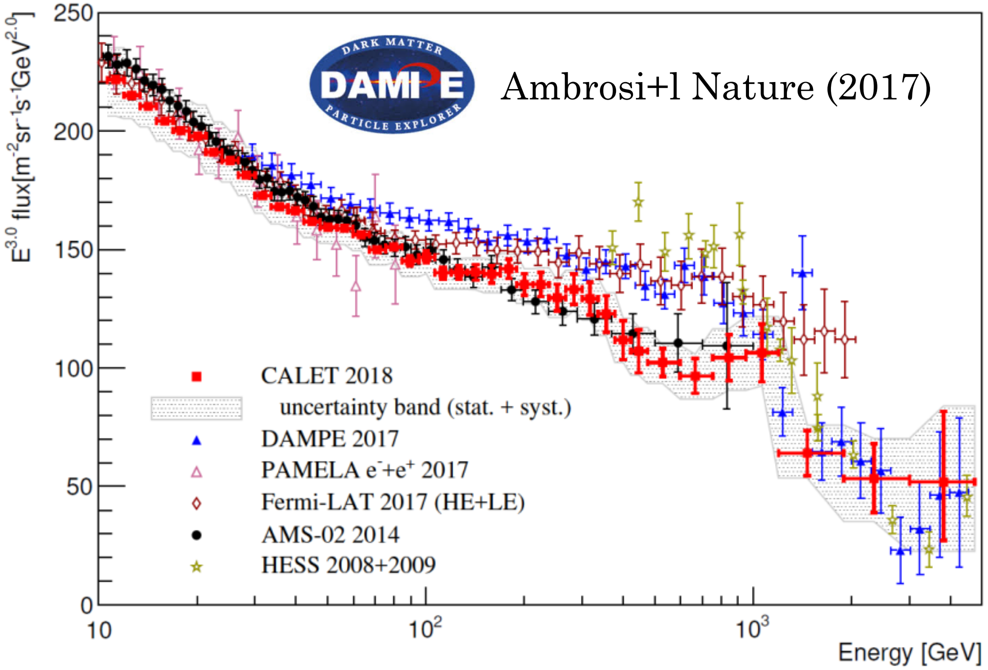

Aguilar+ PR (2021)

# Electron+positrons

- Search for features in the inclusive electron+positron spectrum
  - Search for lines (direct annihilation into $e^+e^-$) performed with AMS-02 and Fermi-LAT yield no evidence of features
  - Still very large discrepancy among different measurements



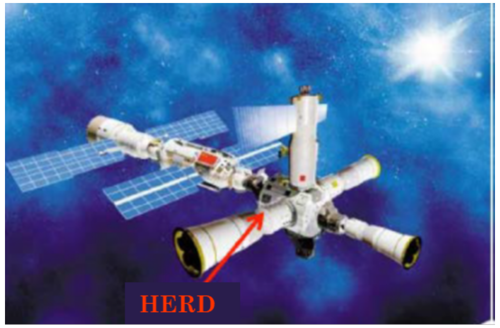

Aguilar+ PRL 122 (2019)

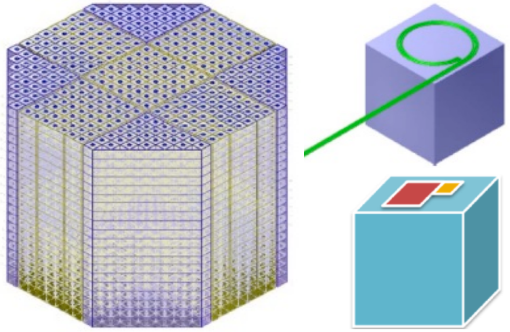



Adriani+ PRL 120 (2018)

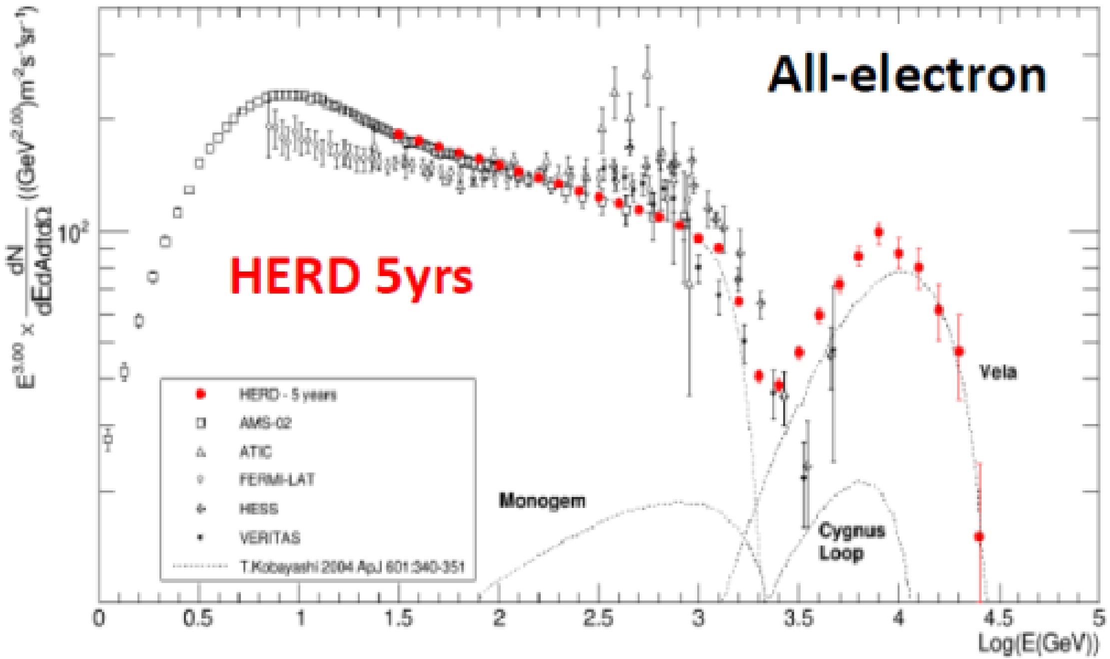
# Outlook

- AMS-02 and DAMPE will continue operations
  - Measure positrons excess end-point (2×statistics in 2018)
  - Ascertain existence of positron source term in the electron spectrum
  - Improved inclusive electron+positrons spectrum



- Future HERD mission
  - Inclusive electron+positron spectrum up to 10s TeV
  - Better control of systematics,
    - cubic calorimeter with redundant redout system + TRD




De Mitri CRATER 2018

# Antiprotons

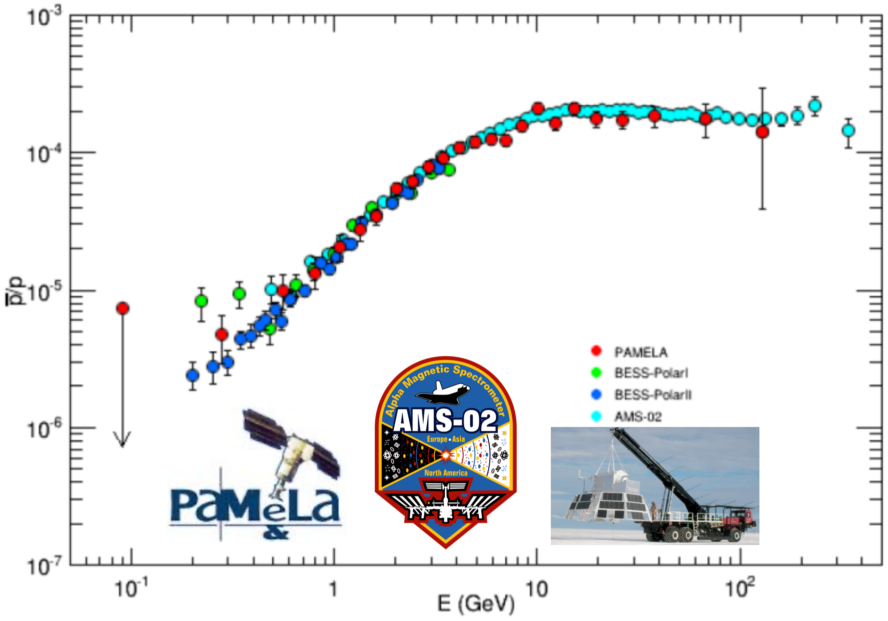
- Extensively measured with magnetic spectrometers from 200 MeV up to 450 GeV

- Backgoround from secondary $\bar{p}$
  - Produced in the disk by GCR interaction

$$p_{CR} + p_{ISM} \rightarrow \bar{p} + ppp$$

  - Propagate in the diffusive halo
  - Kinematically suppressed at low energy

- No pronounced deviations from secondary GCR background
  - Interpretation limited by theoretical uncertainties on interstellar/heliospheric propagation parameters and $\bar{p}$ production cross sections

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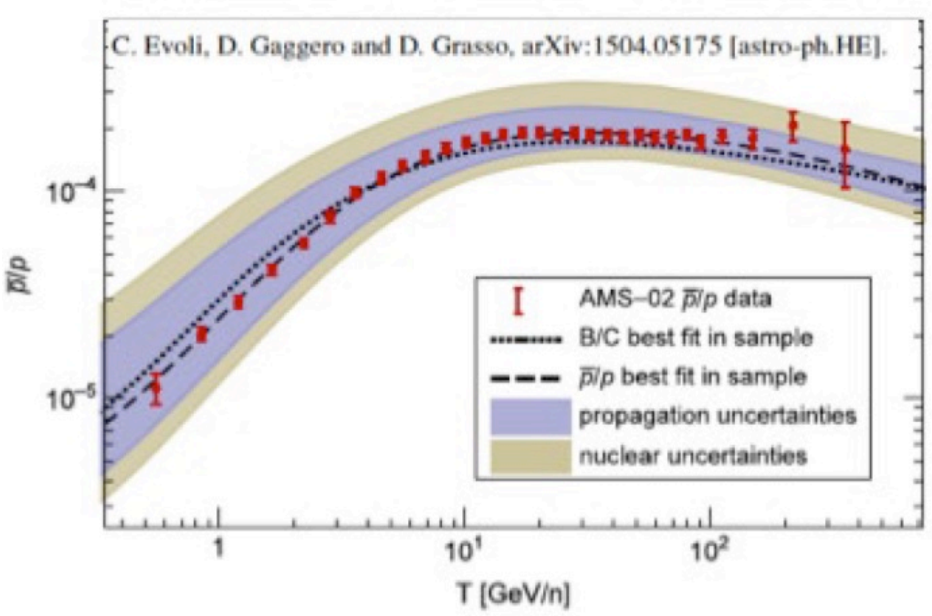
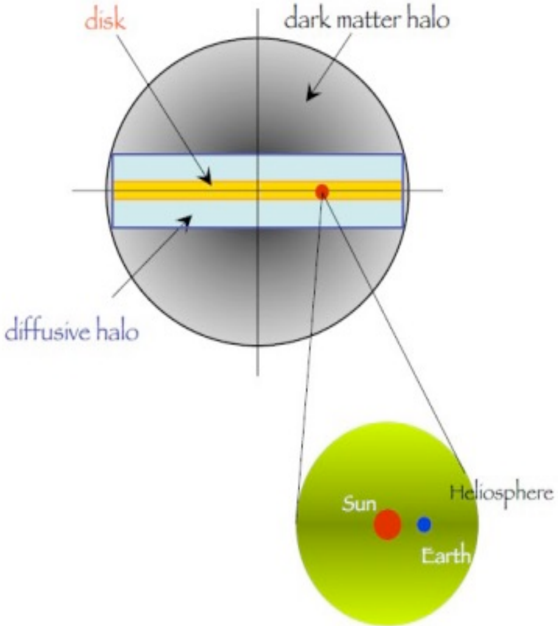
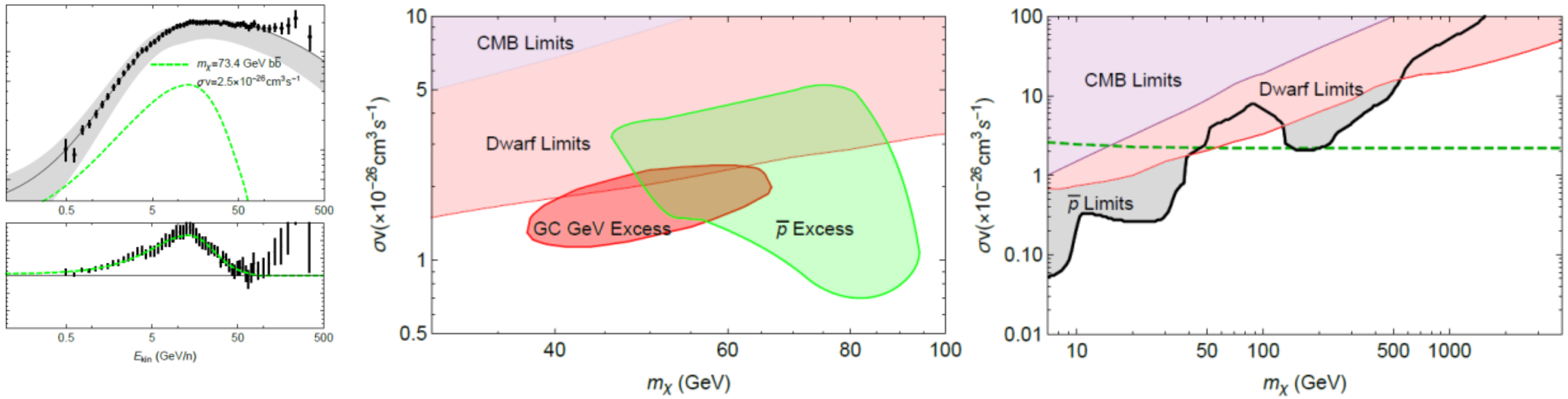


# Antiproton from DM




- Produced in DM halo from hadronization of DM annihilation products, propagate in the diffusive halo
- Provide robust upper to DM annihilation cross-section
  - Competitive with dSph limits for many annihilation channels
  - Less sensitive to DM density profile
- Many works indicate a possible excess (~10%) at  in AMS-02 data at low energy
  - Consistent with GCE interpretation in terms of DM
  - Sys. uncertainties (e.g. energy correlation) could affect significance of narrow spectral features




Cholis-Linden-Hooper PRD (2019)

# Antinuclei

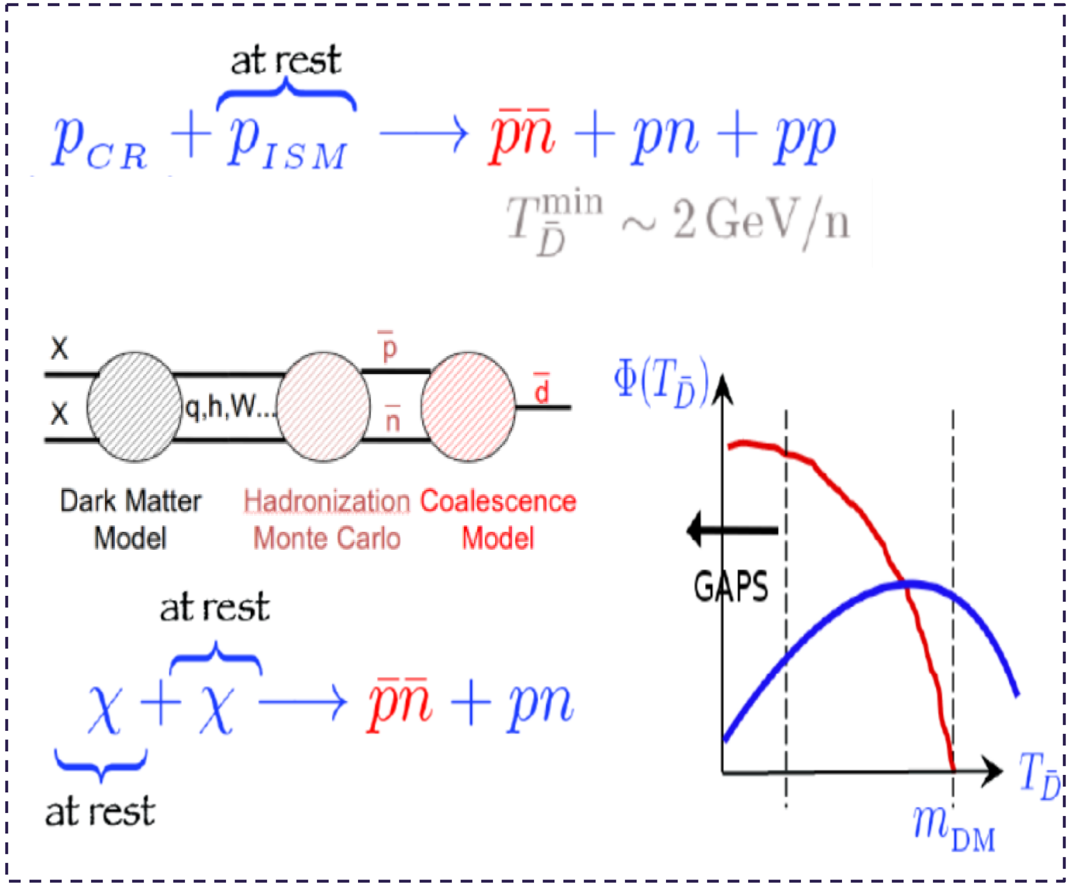
- Background free DM search
  - Secondary antinuclei formation in the ISM requires:
    - additional antinucleons (yield reduced by ~10^3 each)
    - coalscence

  → Bkg strongly kinematically suppressed at low energies

  → Favorable S/N for DM search

- Formation of heavier antinuclei progressively suppressed

  → Antideuterons most promising target



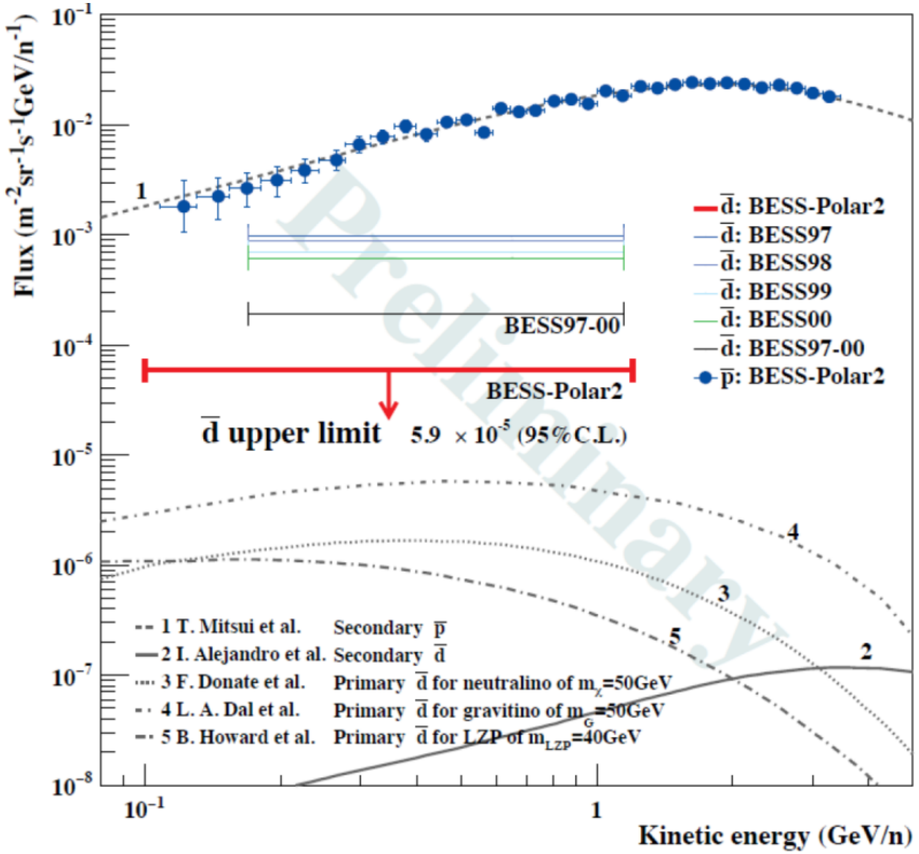

(Credits: Fornengo)

# Antinuclei

- Antideuteron search conducted by magnetic spectrometers BESS and AMS-02
  - Isotopic separation based on β vs rigidity measurement

- **Antideuterium**
  - Critical for AMS-02 (work-in-progress)
  - Best upper limit provided by BESS

- **Antihelium**
  - $8\times\overline{\mathrm{He}}$ candidates found by AMS-02 below 50 GeV ($6\times\,^3\overline{\mathrm{He}} + 2\times\,^4\overline{\mathrm{He}}$)
  - $^3\overline{\mathrm{He}}$ could be within sensitivity
    - requires optimistic coalescence scenario
    - DM origin in tension with other constraints
  - $^4\overline{\mathrm{He}}$ challenging to explain in terms of known physics
    - If confirmed, breakthrough discovery (local antimatter over-densities??)




Sakai (Dbar19)

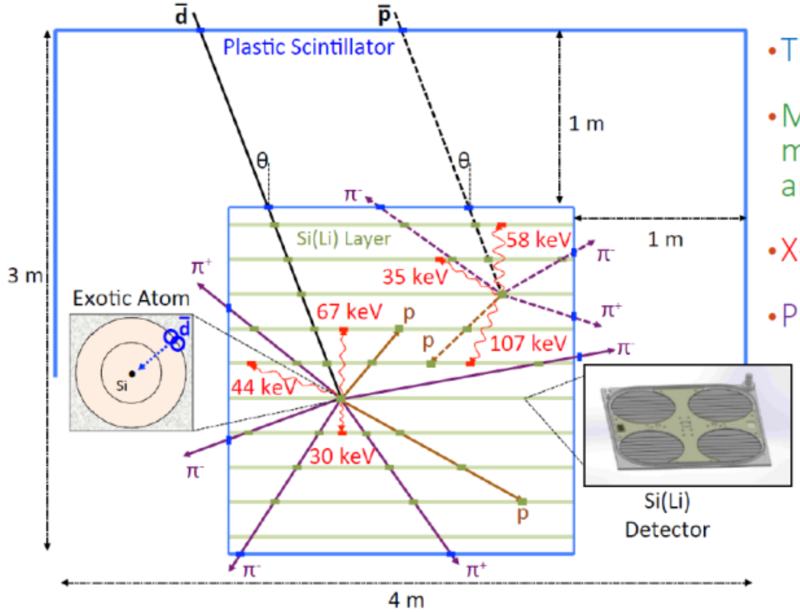
# Outlook

- AMS-02 will continue operations (2×statistics in 2018)
  - Possible confirmation of antihelium candidates
  - Improved $\bar{p}$ measurement
  - On-going effort to reduce uncertainties in secondary $\bar{p}$ predictions
    - Measuring p-bar production cross sections to improve AMS-02 data sensitivity to DM signals
    - Proposal of measuring p-He to p-bar with the AMBER (COMPASS) spectrometer using proton beam from SPS on Liquid Helium target
      - Cross-check p-p measurement of NA61, complement p-He measurement of LHCb

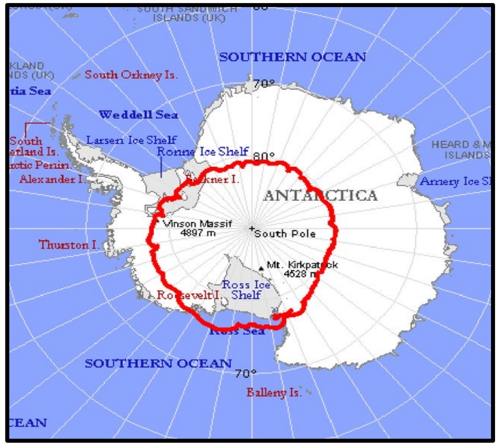
- Future missions
  - GAPS mission on LDB
  - HERD
  - Next generation spectrometers?
  - (ALADINO, AMS-100)

# GAPS (General AntiParticle Spectrometer)

- Specifically designed to search for $\overline{D}$
  - Novel antinuclei identification techniques, based on exotic atom formation and annihilation
  - Sensitive also to $\overline{He}$ nuclei
- Mission plan
  - First LDB flight already scheduled
    - 100× statistics of $\bar{p}$ below 250 MeV
  - Full $\overline{D}$ sensitivity after ~100 hours (~3×LDB flights)




- Time-of-light
- Multiple dE/dx measurements along antiparticle trajectory
- X-ray energies
- Pion/proton multiplicity



# GAPS detector

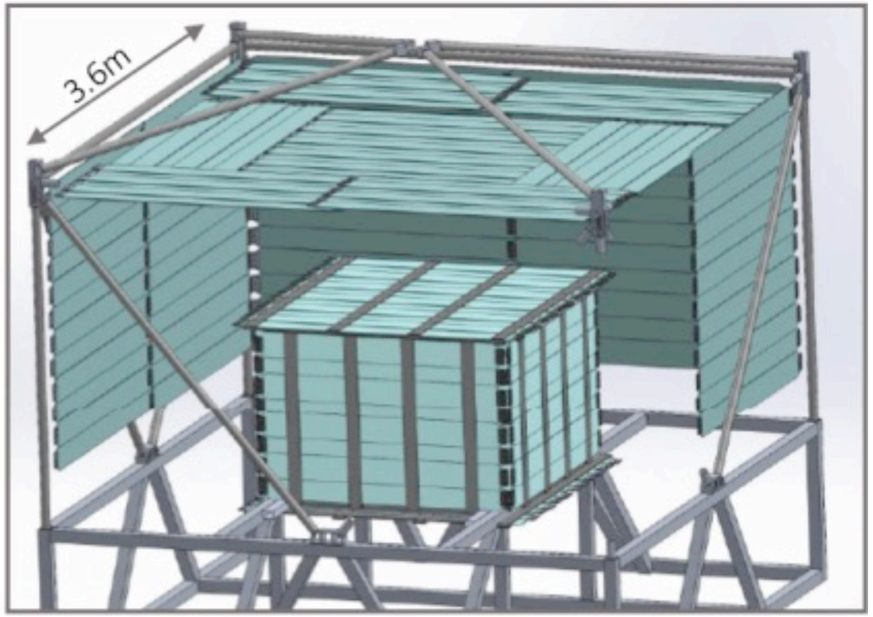
*Time-of-Flight system*

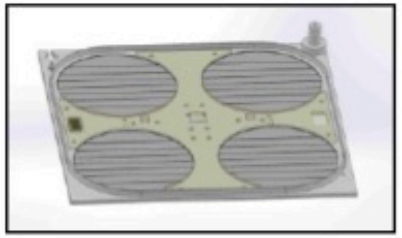
- 1 outer + 1 inner layers
  - Plastic scintillator, readout on each end by SiPMs
  - 1 m b/w outer and inner layers
  - < 500 ps resolution

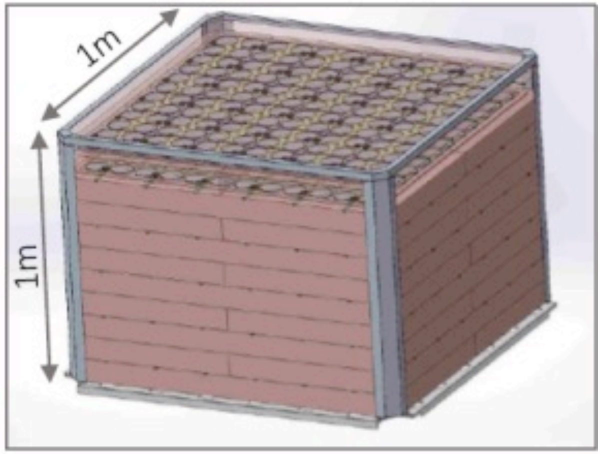
*Tracking system*

- 12×12 Si(Li) wafers
  - -48°C operation temperature
  - 10 cm ∅ × 2.5mm thickness
  - segmented into 8 strips
- 10 layers with 10 cm spacing
  → 3D particle tracking
- dual channel electronics
  - X-ray (20 - 80 keV)
  - charged particles (up to 50 MeV)
- 4 keV energy resolution

*Oscillating Heat Pipe (OHP) passive cooling system*



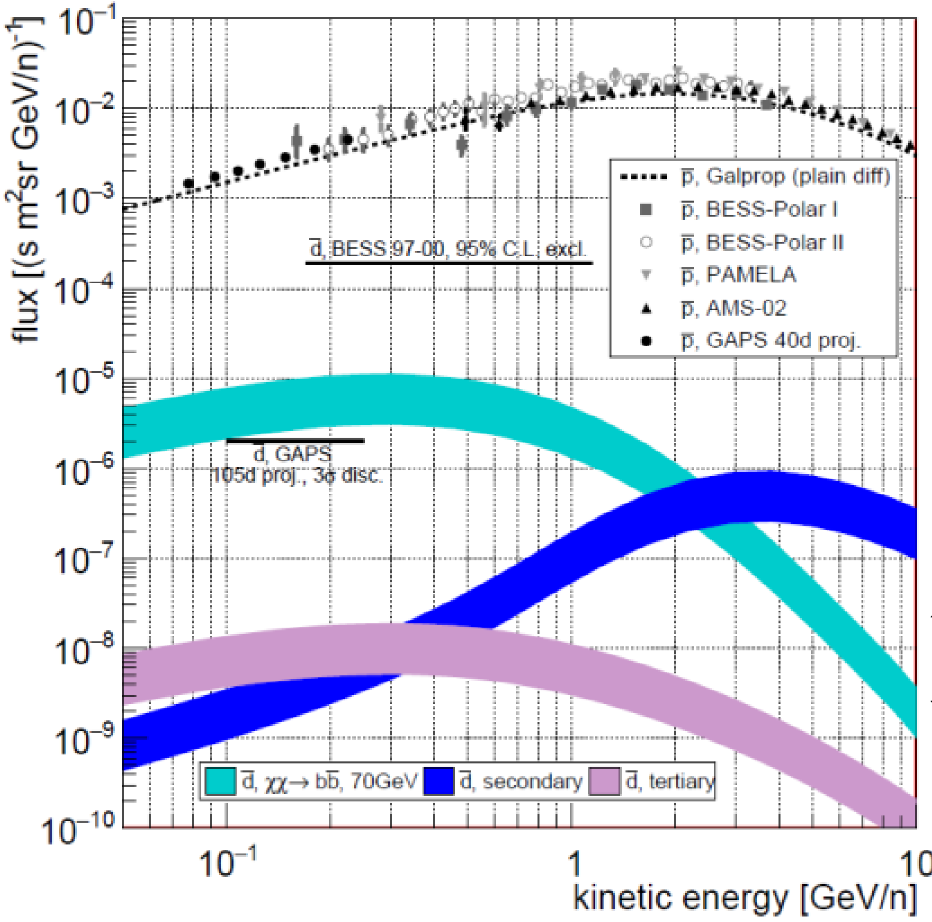






weight: 1700kg
power: 1.4kW

# GAPS sensitivity

- **Antiprotons**
  - energy region currently inaccessible to any experiment
  - probe light DM models and PBHs
  - sensitive studies of propagation in ISM and Heliosphere
- **Antideuterium**
  - Most direct option to cross check antiproton excess
- **Antihelium**
  - Crucial input to interpret the AMS-02 candidate events




vonDoetinchem+ JCAP (2021)

# HERD - **H**igh **E**nergy cosmic-**R**adiation **D**etection facility

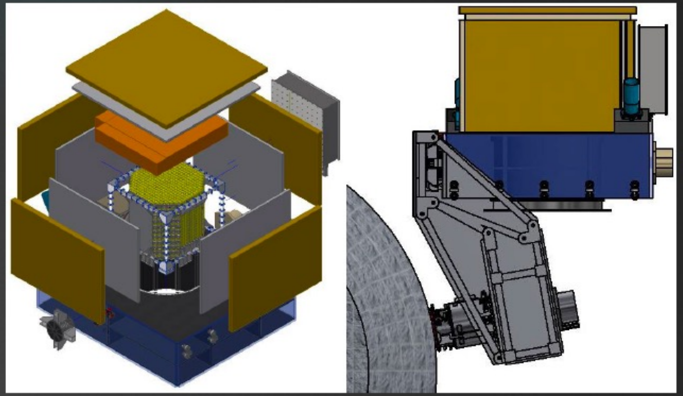
Herd is an international space mission that will start operation around **2026**

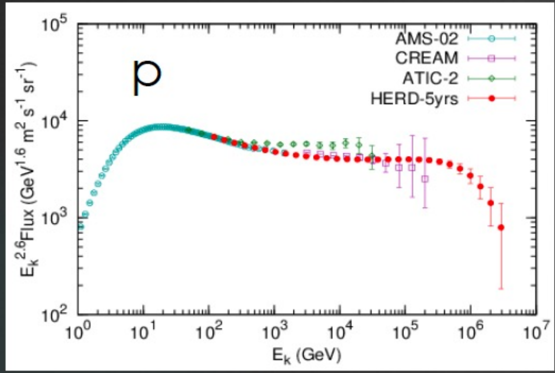
The experiment is based on a **3D, homogeneous, isotropic and finely-segmented calorimeter** that fulfills the following goals:

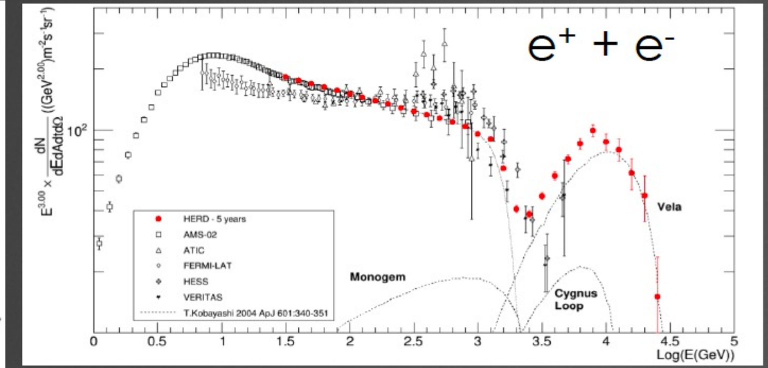
Direct measurement of cosmic rays flux and composition up to the knee region

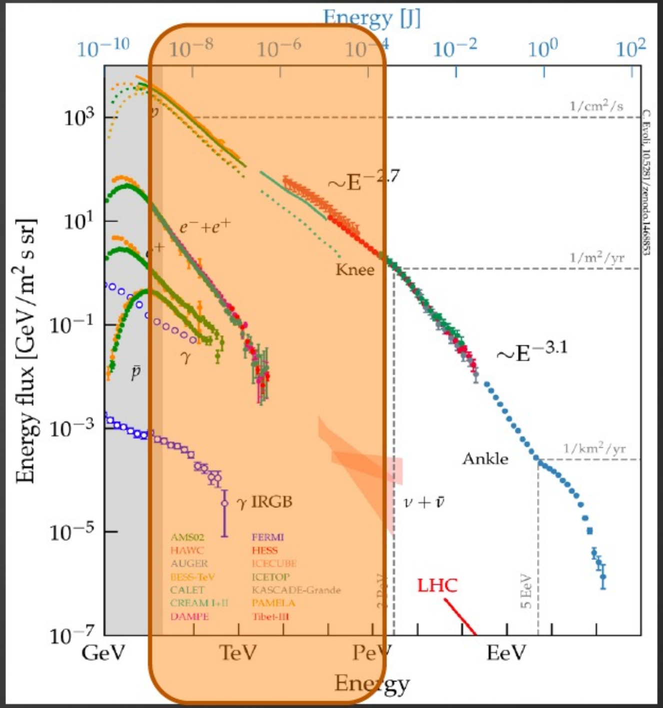
Indirect dark matter search ($e^+$+$e^-$, γ,... )

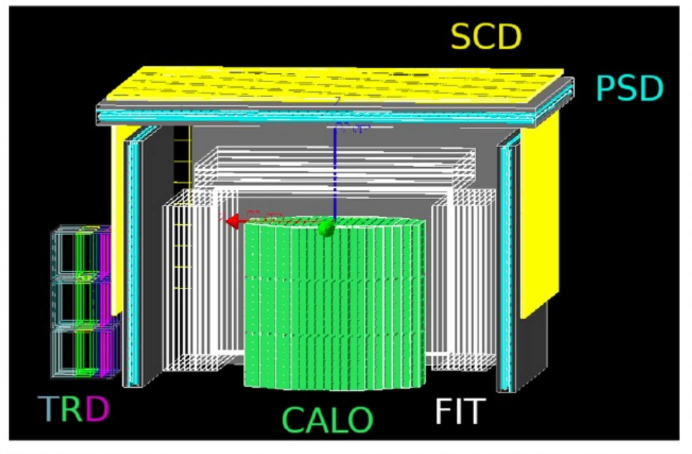
Gamma-ray monitoring and full sky survey for multimessenger astrophysics






| | |
|---|---|
| **SCD** | Charge Reconstruction |
| **PSD** | Charge Reconstruction<br>γ Identification |
| **FIT** | Trajectory Reconstruction<br>Charge Identification |
| **CALO** | Energy Reconstruction<br>e/p Discrimination |
| **TRD** | Calibration of CALO response for TeV protons |

| | γ | e | p, nuclei |
|---|---|---|---|
| **Energy Range** | 0.5 GeV<br>100 TeV | 10 GeV<br>100 TeV | 30 GeV<br>3 PeV |

# CONCLUSIONS

- Due to the increased sensitivity and performance of space detectors, indirect searches for Dark Matter signals are exciting now more than ever.

- In the center of our Galaxy, the excess of GeV gamma rays reported by Fermi-LAT might be Dark Matter. The leading alternate explanation is millisecond pulsars.

- Antiprotons are observed in excess at AMS-02, and while it is consistent with a dark matter origin (and consistent with the GCE), there are also arguments that it is consistent with cosmic-ray secondaries. Systematic correlation matrices, and better cosmic-ray propagation models, are needed here to definitively confirm or exclude explanations of this excess.

- Positrons exist in excess, as observed by PAMELA, AMS-02, and DAMPE. This signal is consistent with a TeV Dark Matter candidate. Nevertheless, astrophysical explanations, like near-by Pulsar origin or Supernova Remnants (SNR), remain still in place.

- Future balloon and space missions (GAPS, HERD) and the complementary fundamental role played by the next generation of ground telescopes (CTA) will – hopefully – try to shed new light and resolve the still present uncertainties

# SPARES

# Recent (2021) re-analysis of FERMI data

- The analysis of 11 years of Fermi data clearly shows that the excess of gamma rays is concentrated in the Galactic center, exactly what we would expect to find in the heart of the Milky Way if dark matter is in fact a new kind of particle

- The theoretical model demonstrates how the existence of dark matter particles is not disproven by other anomalies recorded in the astrophysical background. These include the excess of positrons measured by Pamela and AMS-02, if attributed to a surplus of dark matter

Mattia Di Mauro PRD and INFN News

| | Tracker/converter | $X_0$ | Calorimeter | $X_0$ | | | Aeff | FOV | PSF | |
|---|---|---|---|---|---|---|---|---|---|---|
| Fermi-LAT | 18×Si 16×W | 1.3 | CsI(Tl) | 8.6 | 20 MeV | 300 GeV | | 2.4 sr | 0.1° @10 GeV | 6% @10GeV |
| DAMPE | 6×Si 3×W | 0.9 | BGO | 31 | 2 GeV | 10 TeV | 1200 cm2 | | 0.1° @100 GeV | 1% @200GeV |
| HERD | 6×Si 3×W | 1 | LYSO | 55 | 0.5 GeV | 100 TeV | | ±70 deg | 0.1° @10 GeV | 1÷2% @200GeV |

# Fermi-LAT

## LAT Specifications & Performance

| Quantity | LAT (Minimim Spec.) | EGRET |
|---|---|---|
| Energy Range | 20 MeV - 300 GeV | 20 MeV - 30 GeV |
| Peak Effective Area [1] | > 8000 $cm^2$ | 1500 $cm^2$ |
| Field of View | > 2 sr | 0.5 sr |
| Angular Resolution [2] | < 3.5° (100 MeV)<br>< 0.15° (>10 GeV) | 5.8° (100 MeV) |
| Energy Resolution [3] | < 10% | 10% |
| Deadtime per Event | < 100 μs | 100 ms |
| Source Location Determination [4] | < 0.5' | 15' |
| Point Source Sensitivity [5] | < 6 x $10^{-9}$ $cm^{-2}$ $s^{-1}$ | ~ $10^{-7}$ $cm^{-2}$ $s^{-1}$ |

[1] After background rejection
[2] Single photon, 68% containment, on-axis
[3] 1-σ, on-axis
[4] 1-σ radius, flux $10^{-7}$ $cm^{-2}$ $s^{-1}$ (>100 MeV), high |*b*|
[5] > 100 MeV, at high |*b*|, for exposure of one-year all sky survey, photon spectral index -2

## LAT Characteristics

| Parameter | Value or Range |
|---|---|
| Energy Range | ~20 MeV to >300 GeV |
| Energy Resolution | <15% at energies >100 MeV |
| Effective Area | >8,000 $cm^2$ maximum effective area at normal incidence |
| Single Photon Angular Resolution | <0.15°, on-axis, 68% space angle containment radius for E > 10 GeV; < 3.5°, on-axis, 68% space angle containment radius for E = 100 MeV |
| Field of View | 2.4 sr |
| Source Location Determination | <0.5 arcmin for high-latitude source |
| Point Source Sensitivity | $<6 \times 10^{-9}$ ph $cm^{-2}$ $s^{-1}$ for E > 100 MeV, 5σ detection after 1 year sky survey |
| Time Accuracy | <10 microseconds, relative to spacecraft time |
| Background Rejection (after analysis) | <10% residual contamination of a high latitude diffuse sample for E = 100 MeV - 300 GeV. |
| Dead Time | <100 microseconds per event |

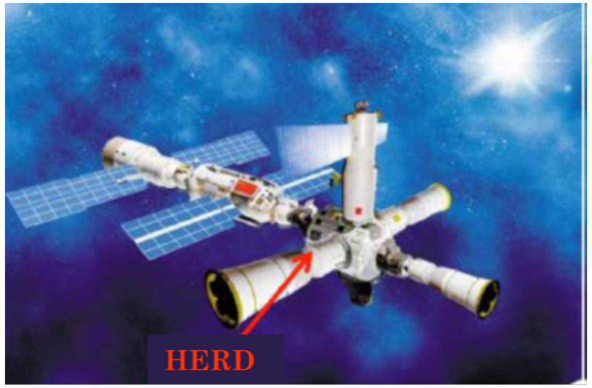
# DAMPE

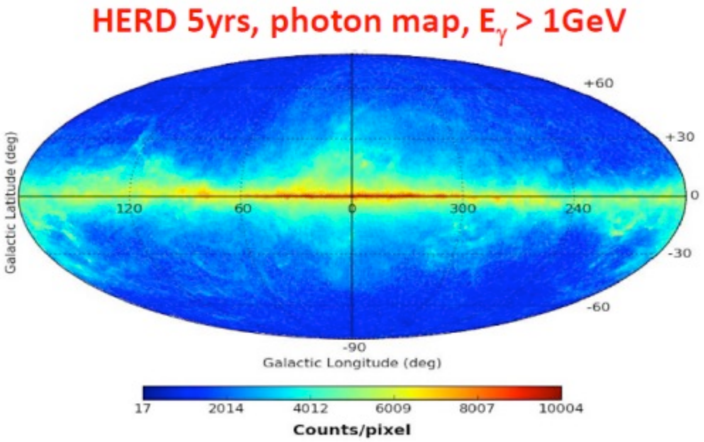
| | |
|---|---|
| Energy Range | 2 GeV - 10 TeV |
| Field of View | ~ 1 sr |
| Effective Area (normal incidence) | ~ 1200 cm^2 @ 100 GeV |
| Angular Resolution (normal incidence) | 0.1°@ 100GeV |
| Energy Dispersion (normal incidence) | ~1% @ 100 GeV |

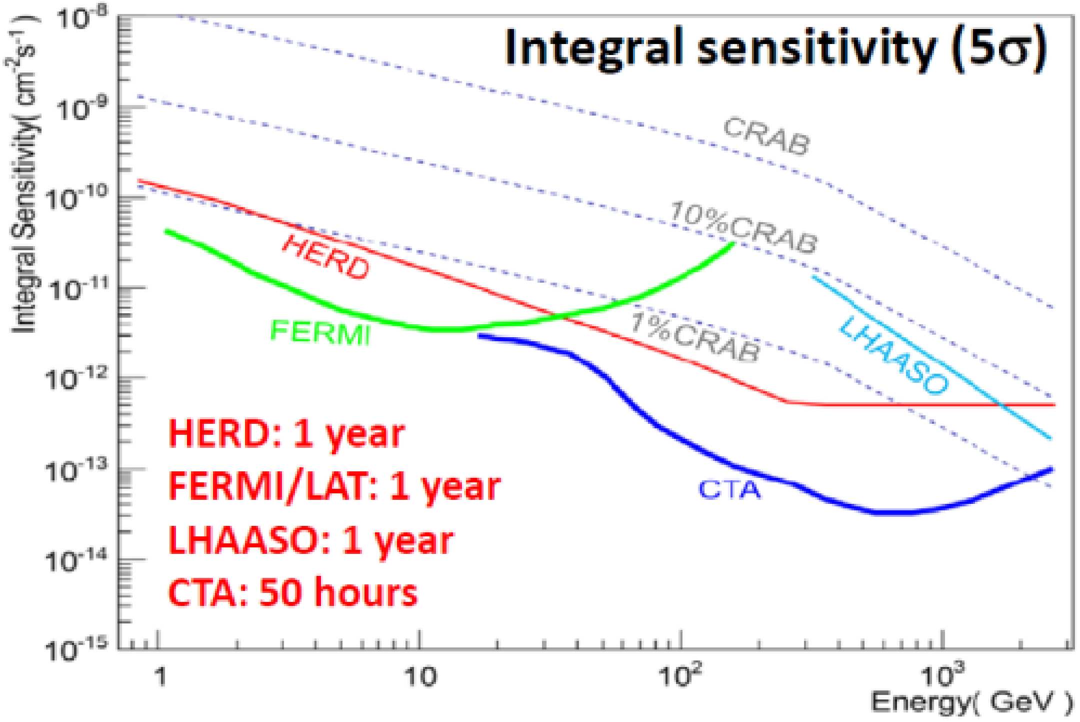
Li Xiang ICRC 2019

# HERD

- Will continue sky-survey after Fermi-LAT, with ~comparable performances




De Mitri CRATER 2019

# HERD specifications

| Item | Value |
|---|---|
| Energy range (e/γ) | 10 GeV-100 TeV(e); 0.5 GeV-100 TeV (γ) |
| Energy range (CR) | 30 GeV—3 PeV |
| Angle resolution | 0.1 deg.@10 GeV |
| Charge measurement resolution | 0.15-0.2 c.u |
| Energy resolution (e) | 1-2%@200 GeV |
| Energy resolution (p) | 20-30%@100 GeV – PeV |
| e/p separation | ~$10^{-6}$ |
| G.F. (e) | >3 $m^2$sr@200 GeV |
| G.F. (p) | >2 $m^2$sr@100 TeV |
| Pointing | Zenith |
| Field of View | +/-70 deg (targeting +/-90 deg) |
| Measur. accuracy of attitude | <0.1 deg |
| Measur. accuracy of angular speed | <0.005 deg/s |
| Lifetime | >10 years |

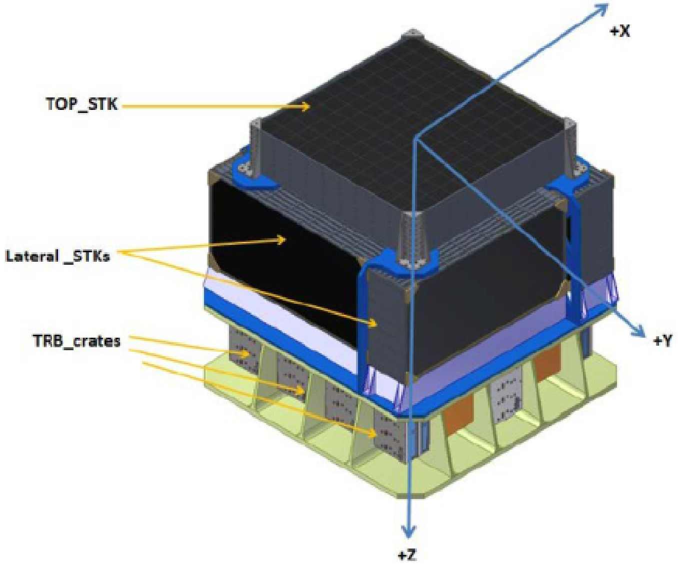
4

De Mitri CRATER 2018

# The HERD Si-Tracker

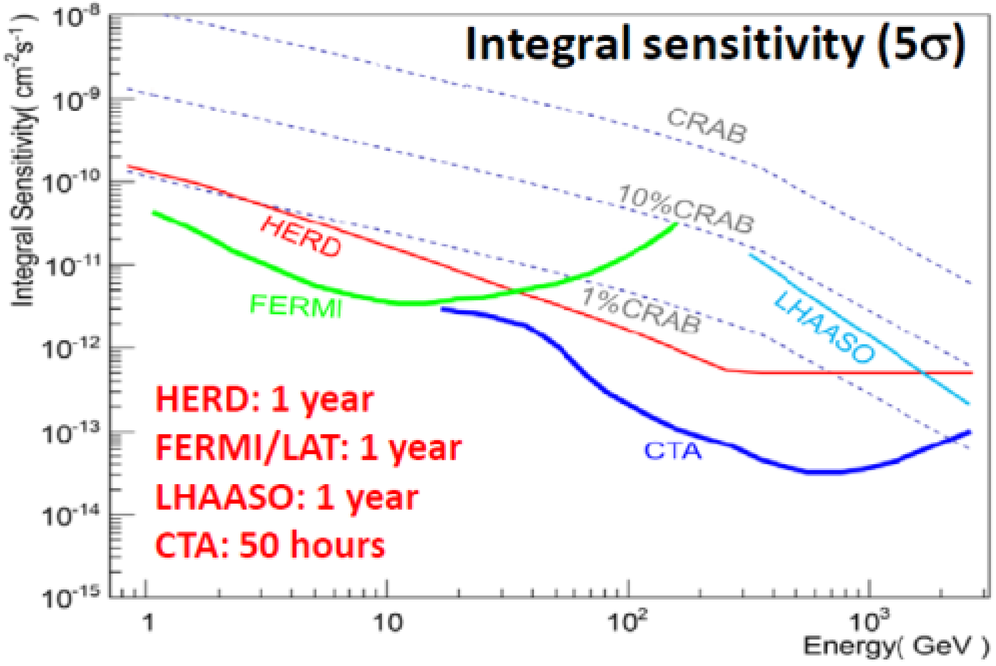
- CR/e trajectory
- Gamma ray conversion & tracking
- Complementary charge measurement

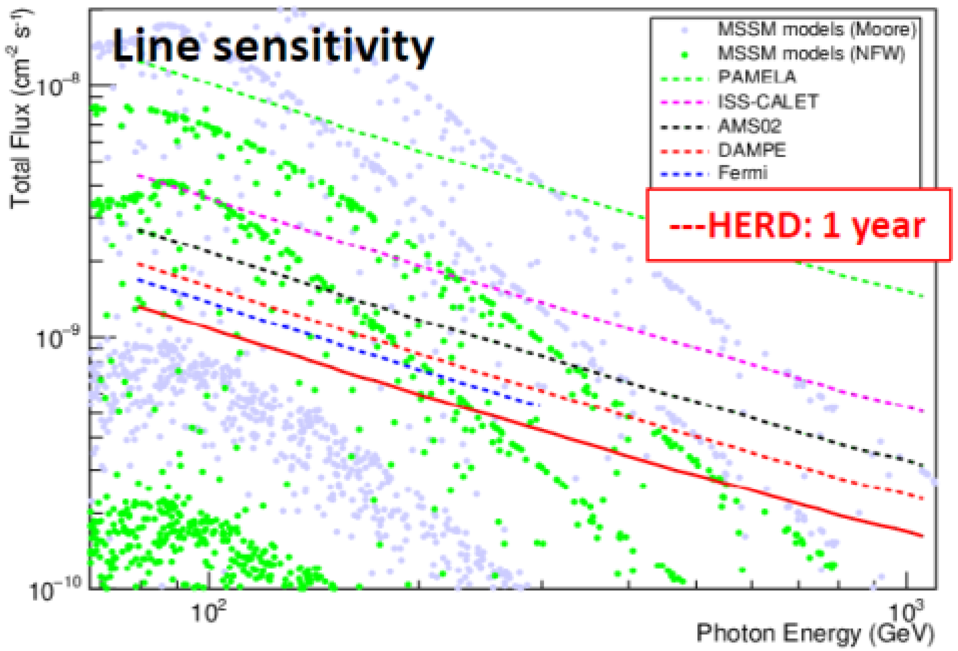
| Item | Value |
|---|---|
| Coverage ratio | >80% |
| Z measurement | Z = 1 - 20 (26); 0.1-0.15 c.u |
| Angle resolution | 0.1 deg.@10 GeV |
| Layers of SSD | 6 X/Y (top);3/6 X/Y (Lateral) |
| Active converter | 1 R.L. |
| Dead time | <2 ms |
| Working mode | External trigger |
| Eff. Area (top) | ~133 cm*133 cm |
| Eff. Area (lateral) | ~114 cm*66.5 cm |
| Channels | ~240,000/368,000 |




Based on the experience with AGILE, AMS-02,FERMI, DAMPE missions

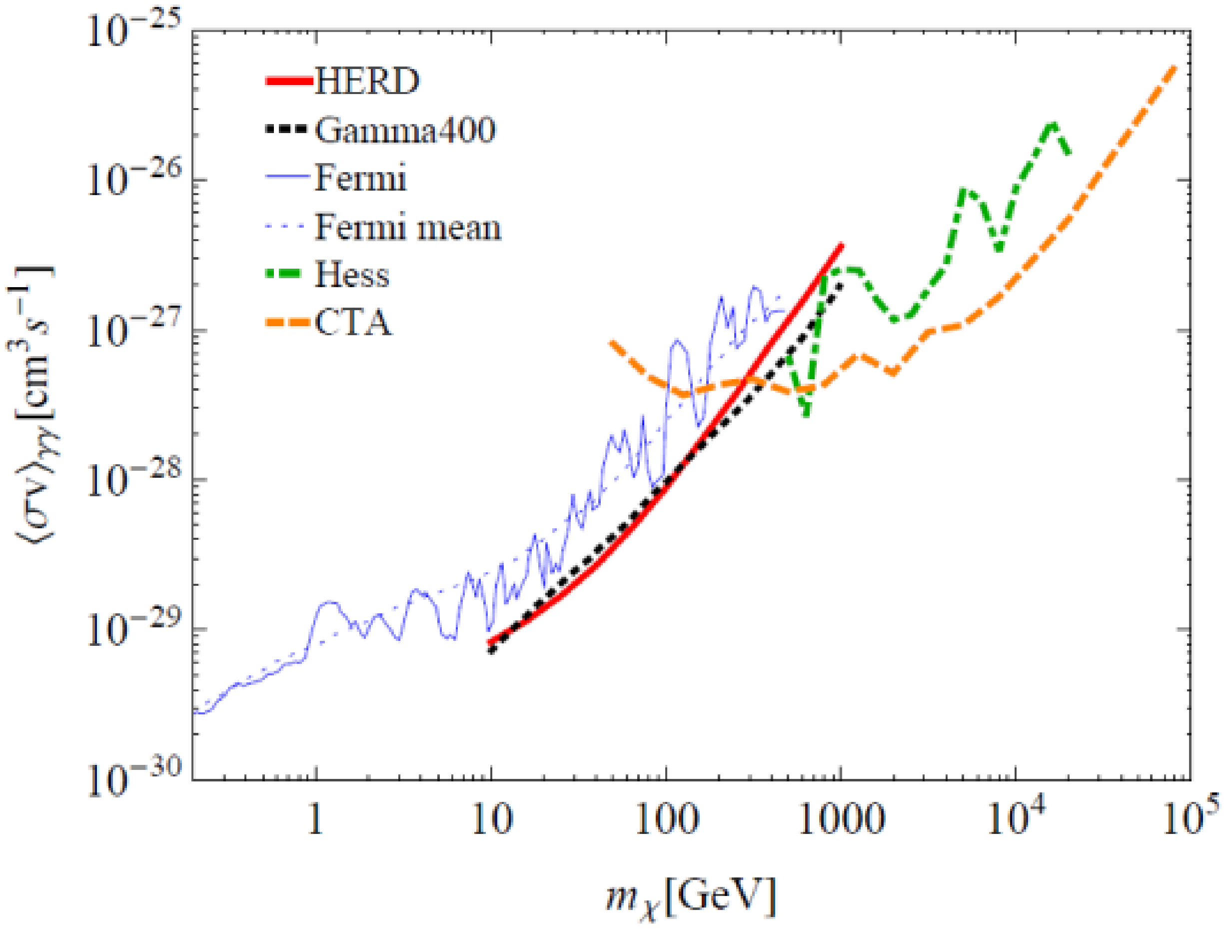
# HERD




Credits: De Mitri CRATER 2019

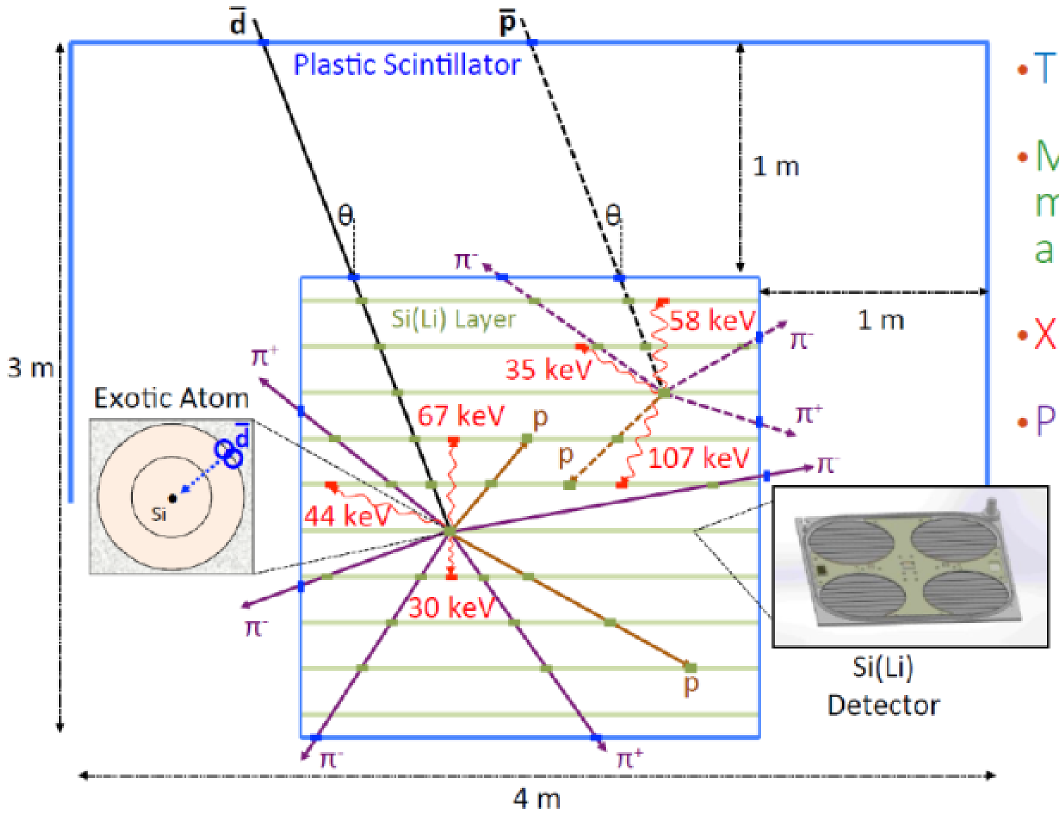
# HERD




Huang+ (2016)

# Antinuclei identification with GAPS

- Novel antiparticle identification techniques, based on antinuclei annihilation and exotic atom formation




- Time-of-light
- Multiple dE/dx measurements along antiparticle trajectory
- X-ray energies
- Pion/proton multiplicity