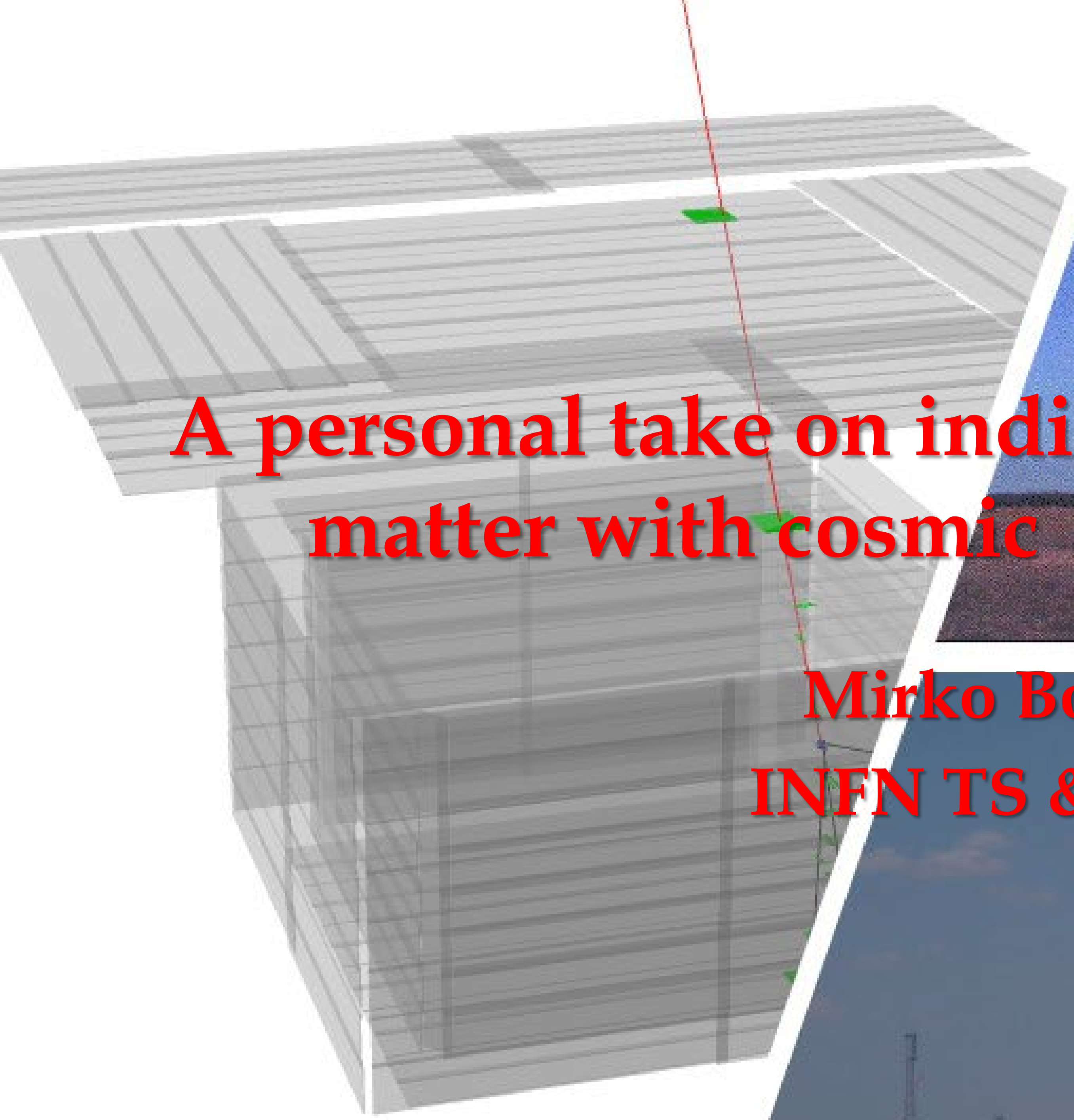
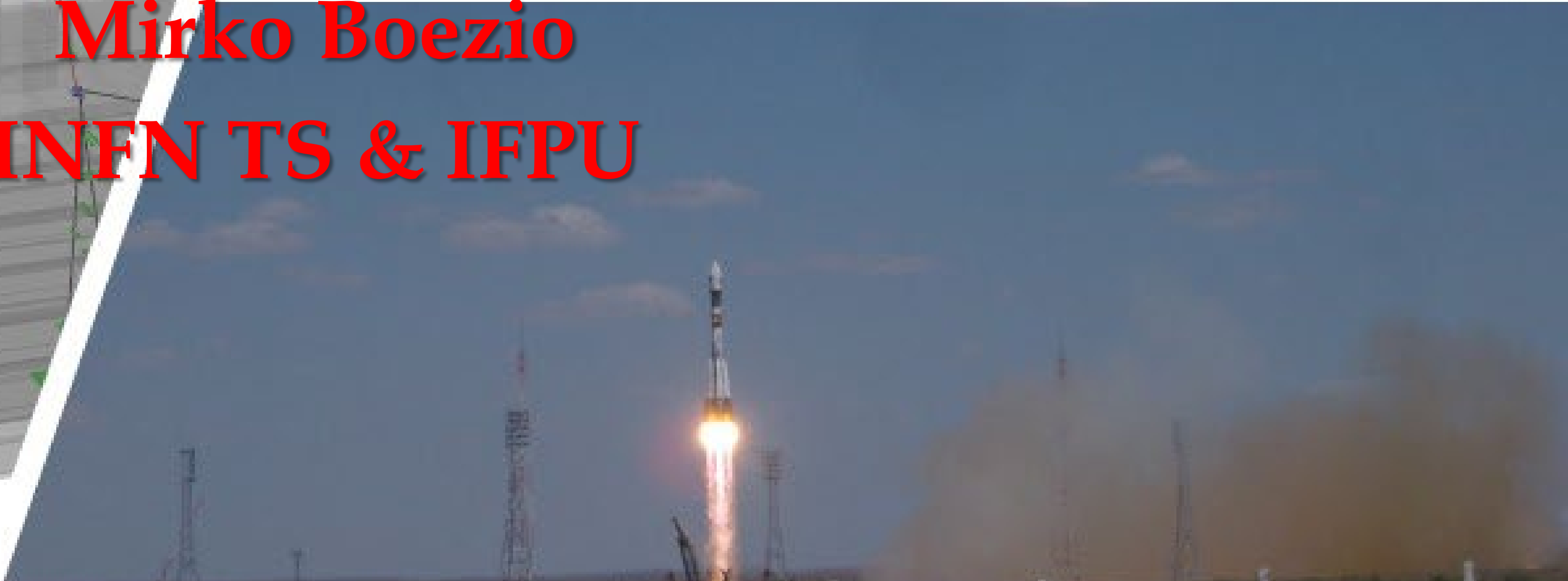
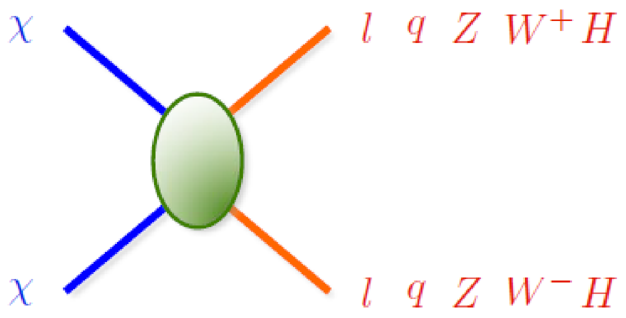




A personal take on indirect searches of dark matter with cosmic rays (antimatter)

Mirko Boezio
INFN TS & IFPU

Features of the astrophysical signals

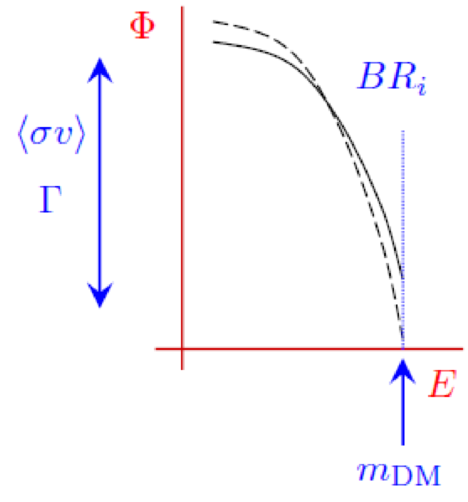


Non-relativistic annihilation (or decay)

$$S \sim \left(\frac{\rho_{\rm DM}}{m_{\rm DM}}\right)^{2,1} \times \{\langle\sigma v\rangle\ ,\ \Gamma\} \times [\text{energy spectrum}]$$

Relevant particle physics properties:

1. Annihilation cross section (or decay rate)
2. Mass of the DM particle
3. BR in the different final states



1 + 2 : Size of the signal

2 + 3 : Spectral features

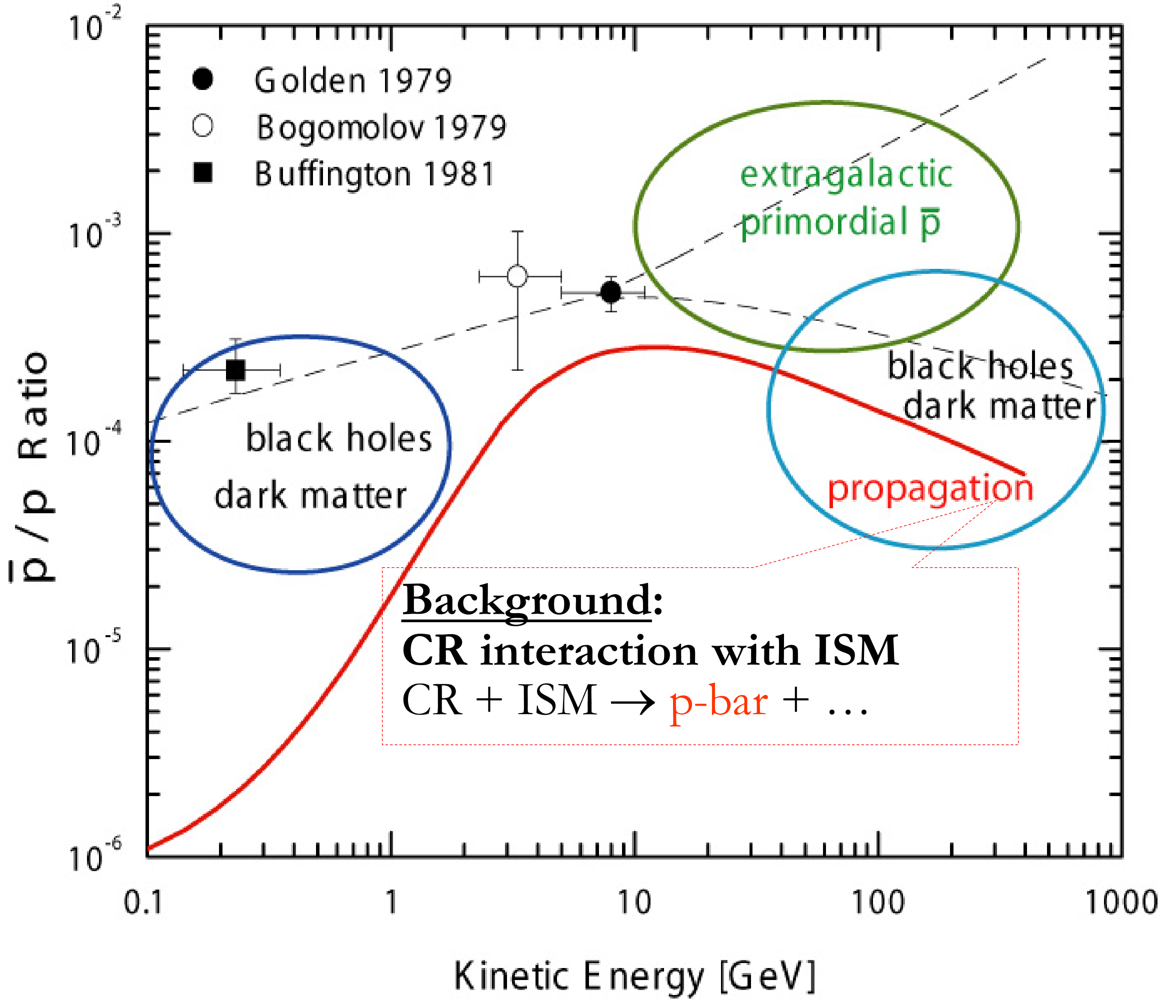
Courtesy by N. Fornengo

First Detection of Antiparticles in the Cosmic Rays

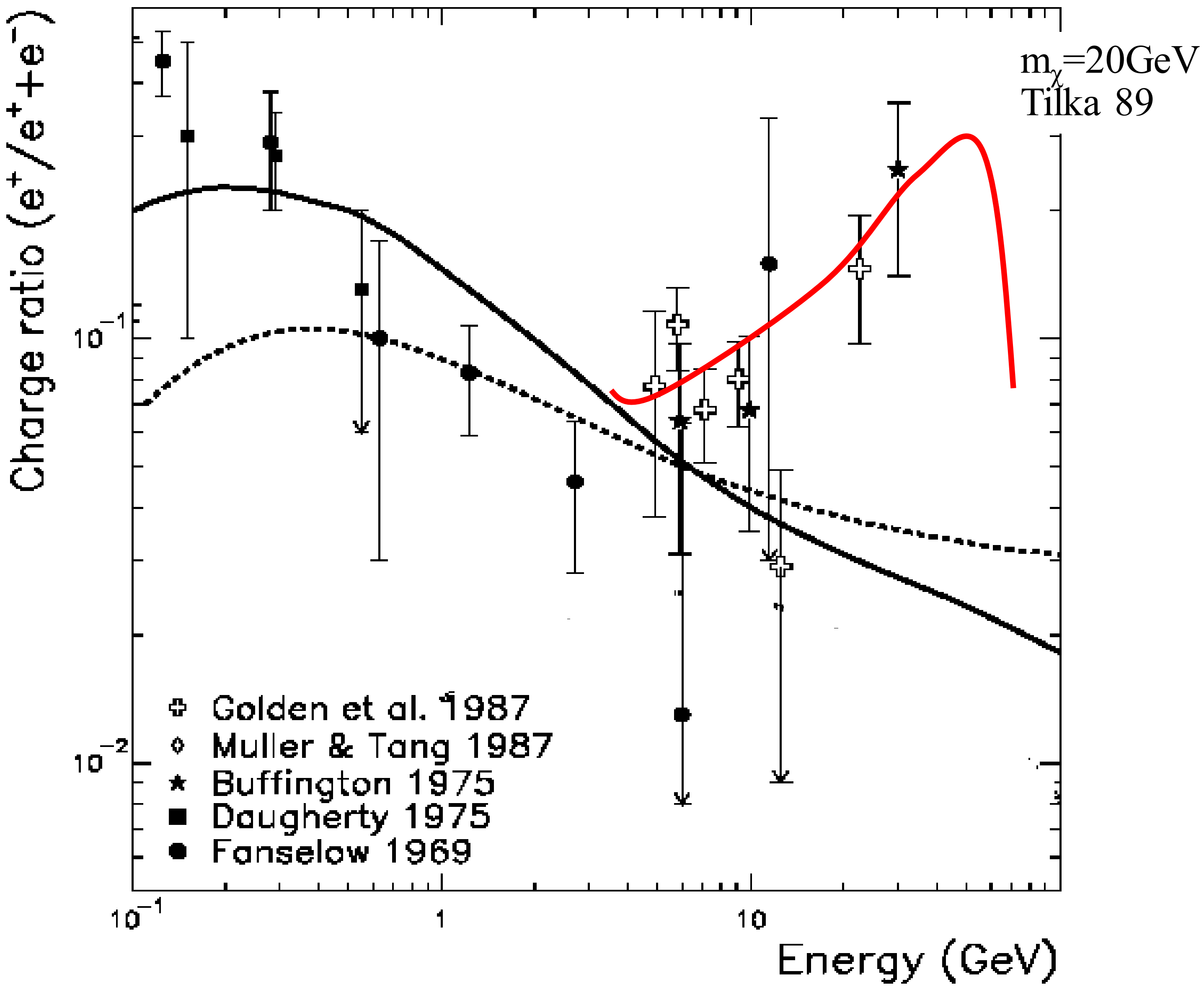
- First detection of positrons in the cosmic radiation in 1964 by J.A. De shong, R.H. Hildebrand & P. Meyer Phys. Rev. Let. **12** (1964) 3

- First detection of antiprotons in the cosmic radiations in 1979 by R.L. Golden et al. Phys. Rev. Let. **43** (1979) 1196, and by E. Bogomolov et al., 16th ICRC (1979), Tokyo, Japan

The first historical measurements of the $\bar{p}/p$ - ratio and various Ideas of theoretical Interpretations



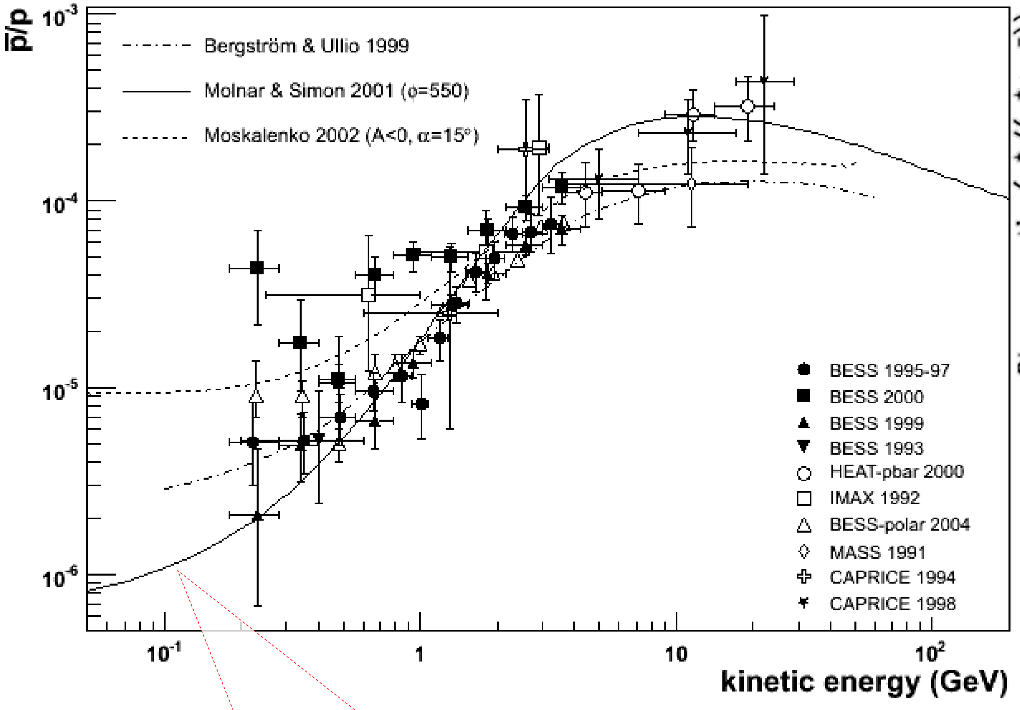
Balloon data : Positron fraction before 1990



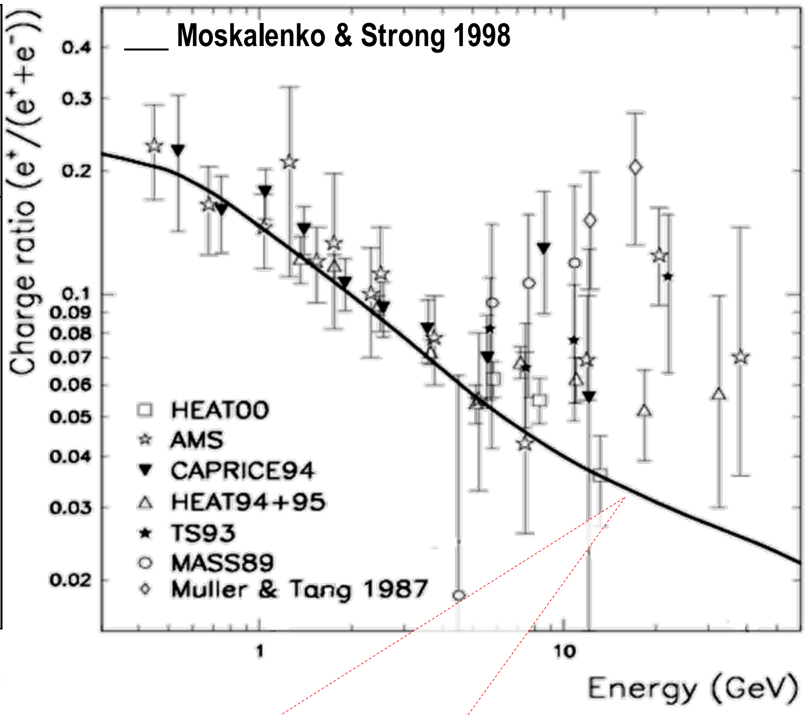
CR antimatter

Status in 2006

Antiprotons



Positrons



CR + ISM → **p-bar** + …

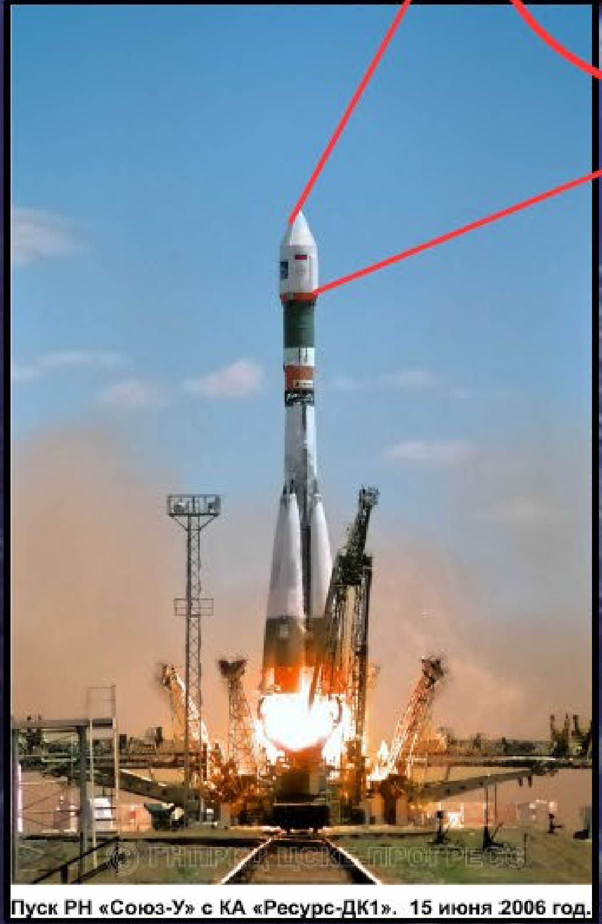
kinematic treshold:
5.6 GeV for the reaction

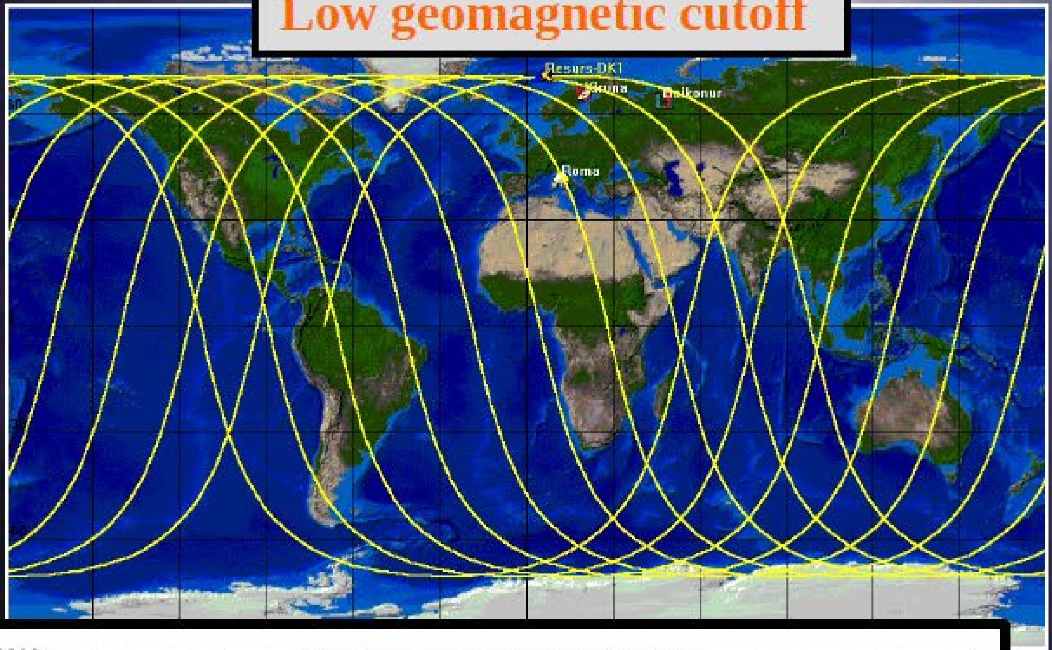
$$pp \to \bar{p}ppp$$

$$CR + ISM \to \pi^{\pm} + x \to \mu^{\pm} + x \to \mathbf{e^{\pm}} + x$$

$$CR + ISM \to \pi^{0} + x \to \gamma\gamma \to \mathbf{e^{\pm}}$$

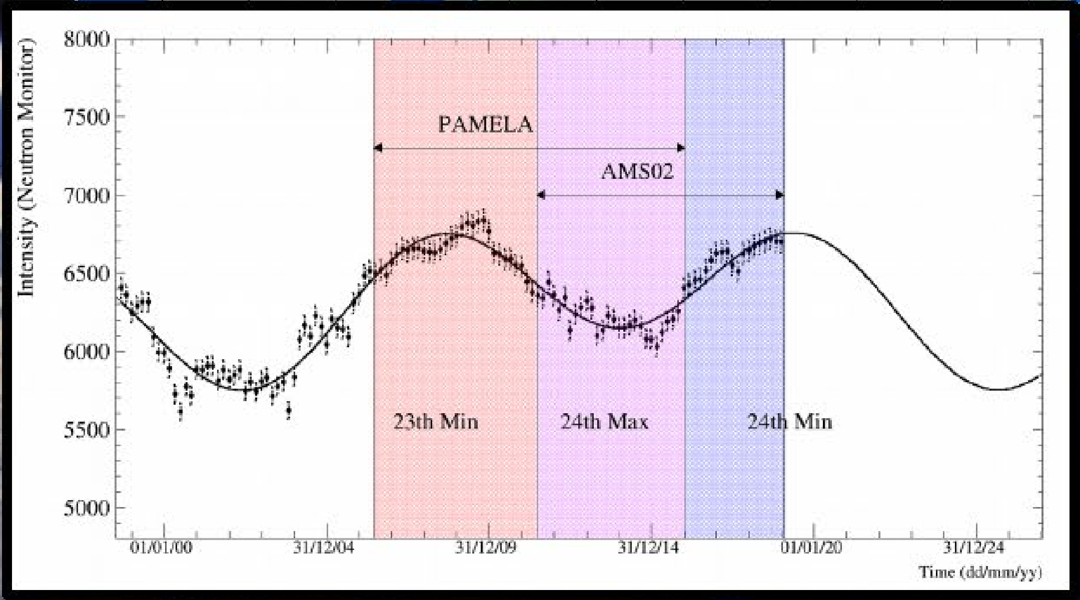
Launch: 15 June 2006 – Stopped in January 2016





Quasi-polar elliptical orbit
70 degree inclination
350/610 km.
Allows to measure low energy particles (70 MeV electrons)

Long flight duration: 10 years of data
Allows to test model over different period of solar activity

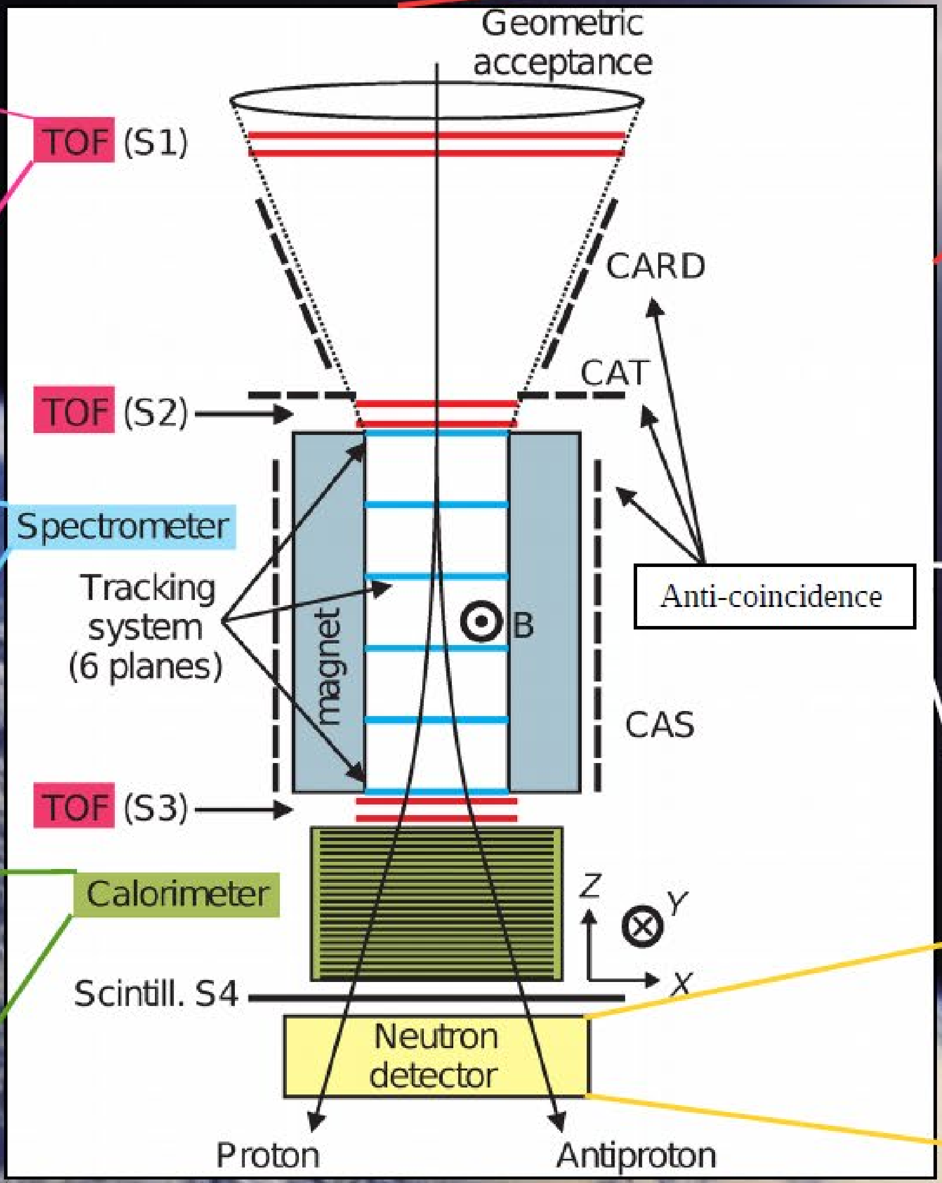


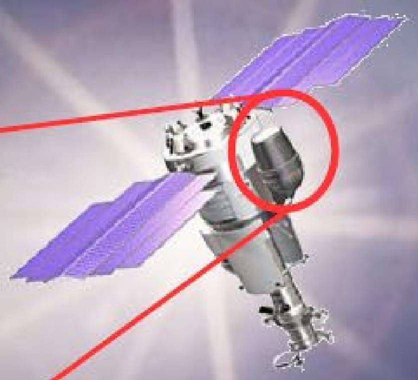
The PAMELA instrument

24 bars of plastic scintillator arranged in six plane, S11, S12, S21, S22, S31, S32: velocity, absolute charge Z<8.

Six planes of double side microstrip silicon detectors inside a magnetic cavity: rigidity, absolute charge Z<6, charge sign.

44 planes of Si detector interleaved with 22 tungsten planes, 16.3 radiation length: hadron lepton separation.



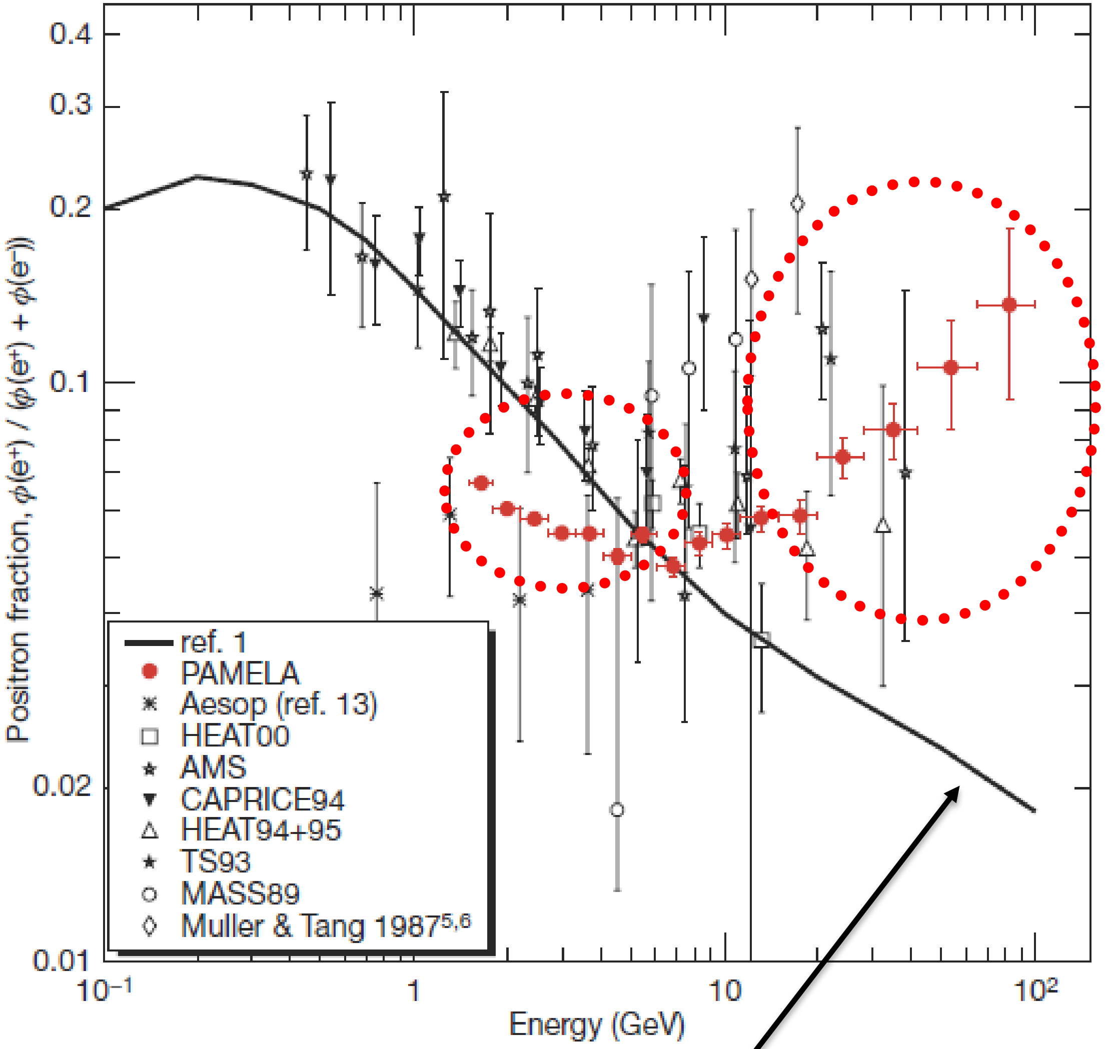


GF: 21.5 cm2 sr
Mass: 470 kg
Size: 130x70x70 cm
Power budget: 360 W

(CAS, CARD e CAT) nine planes of plastic scintillator around the apparatus: reject false triggers or multi-particle events.

36 proportional counters filled with 3He: improve hadron rejection.

PAMELA Results: Positrons



Secondary production: Moskalenko & Strong 98

nature International weekly journal of science

Vol 458 | 2 April 2009 | doi:10.1038/nature07942 nature

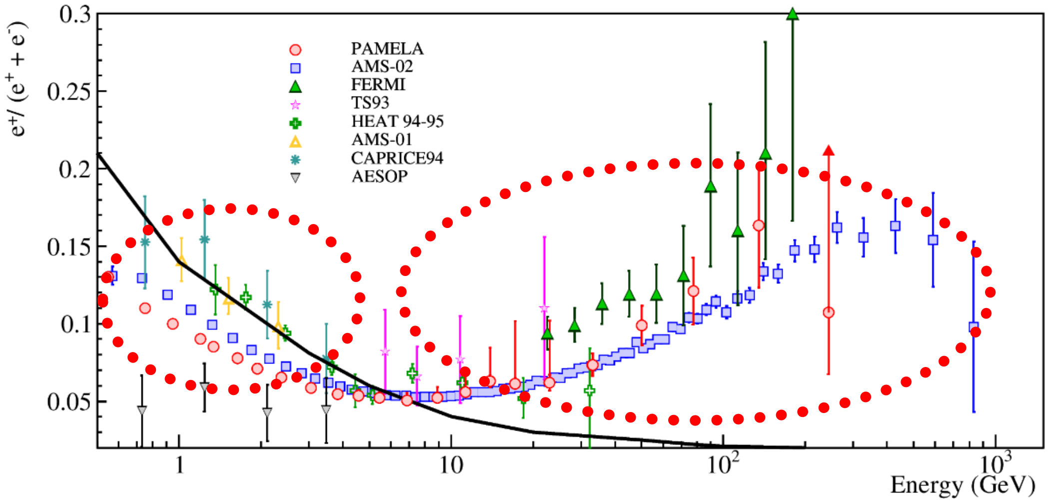
LETTERS

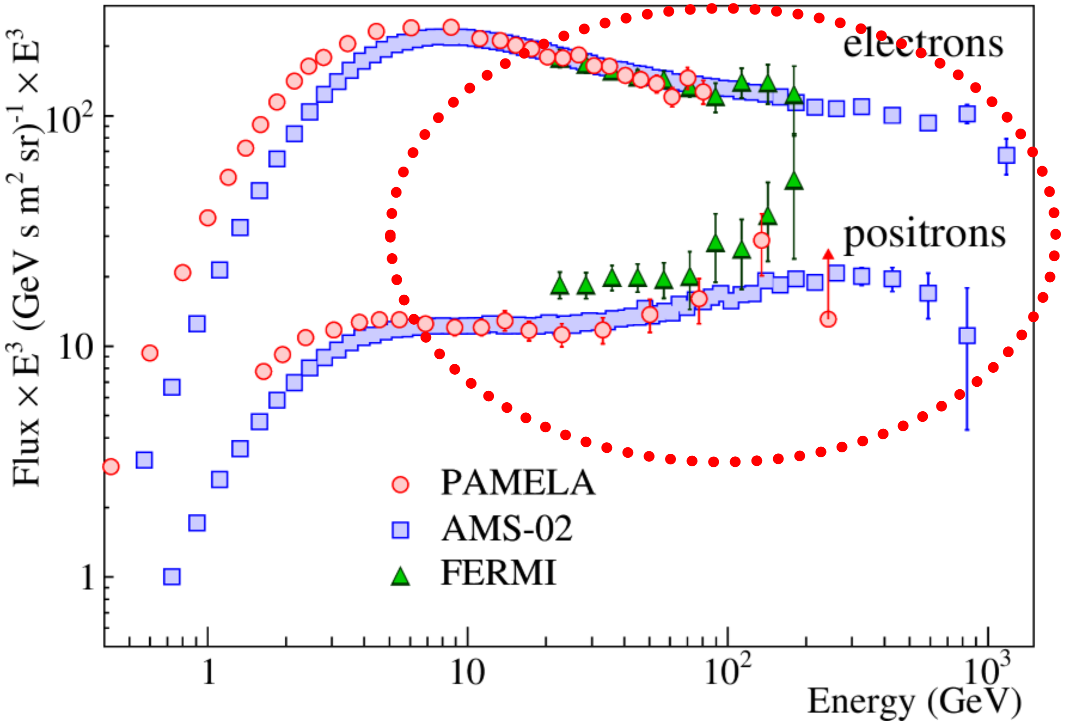
An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

O. Adriani[1,2], G. C. Barbarino[3,4], G. A. Bazilevskaya[5], R. Bellotti[6,7], M. Boezio[8], E. A. Bogomolov[9], L. Bonechi[1,2], M. Bongi[2], V. Bonvicini[8], S. Bottai[2], A. Bruno[6,7], F. Cafagna[7], D. Campana[4], P. Carlson[10], M. Casolino[11], G. Castellini[12], M. P. De Pascale[11,13], G. De Rosa[4], N. De Simone[11,13], V. Di Felice[11,13], A. M. Galper[14], L. Grishantseva[14], P. Hofverberg[10], S. V. Koldashov[14], S. Y. Krutkov[9], A. N. Kvashnin[5], A. Leonov[14], V. Malvezzi[11], L. Marcelli[11], W. Menn[15], V. V. Mikhailov[14], E. Mocchiutti[8], S. Orsi[10,11], G. Osteria[4], P. Papini[2], M. Pearce[16], P. Picozza[11,13], M. Ricci[17], S. B. Ricciarini[2], M. Simon[15], R. Sparvoli[11,13], P. Spillantini[1,2], Y. I. Stozhkov[5], A. Vacchi[8], E. Vannuccini[2], G. Vasilyev[9], S. A. Voronov[14], Y. T. Yurkin[14], G. Zampa[8], N. Zampa[8] & V. G. Zverev[14]

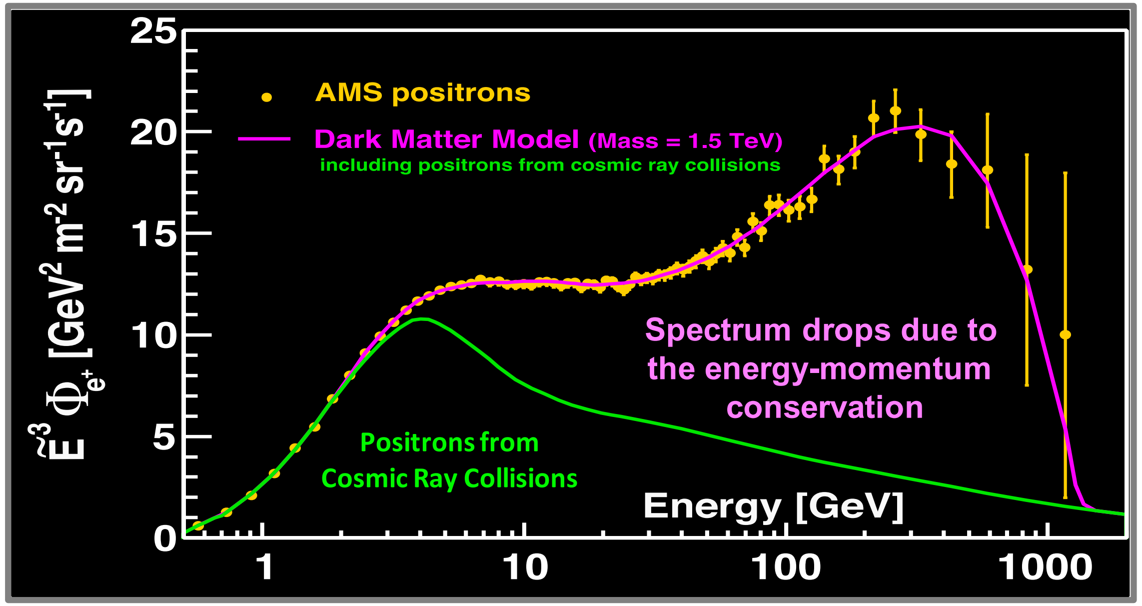
- **High energy**: first clear evidence of increasing positron fraction above 10 GeV with respect to pure secondary production;
- **Low energy**: charge-dependent solar modulation

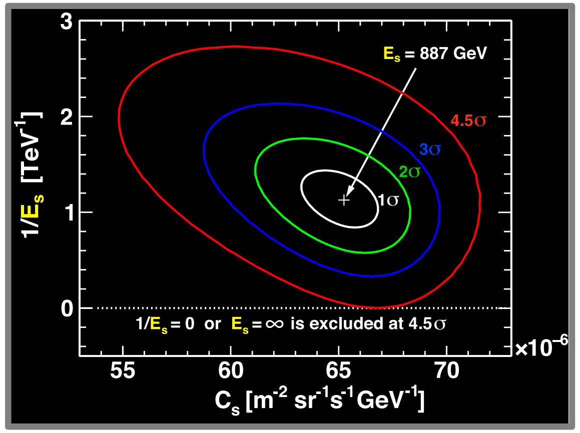
Electrons and Positrons





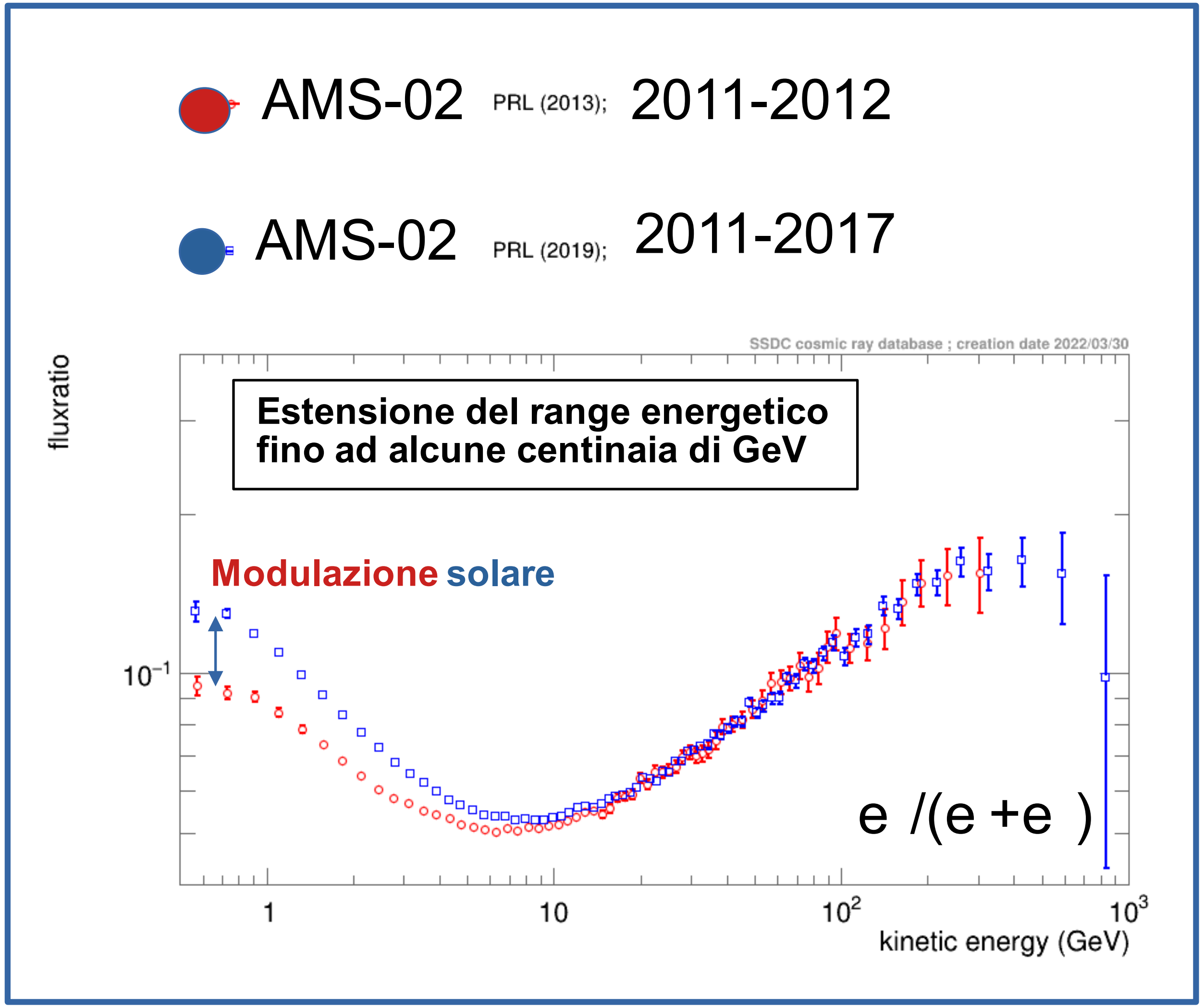
Positron Anomaly: AMS-02





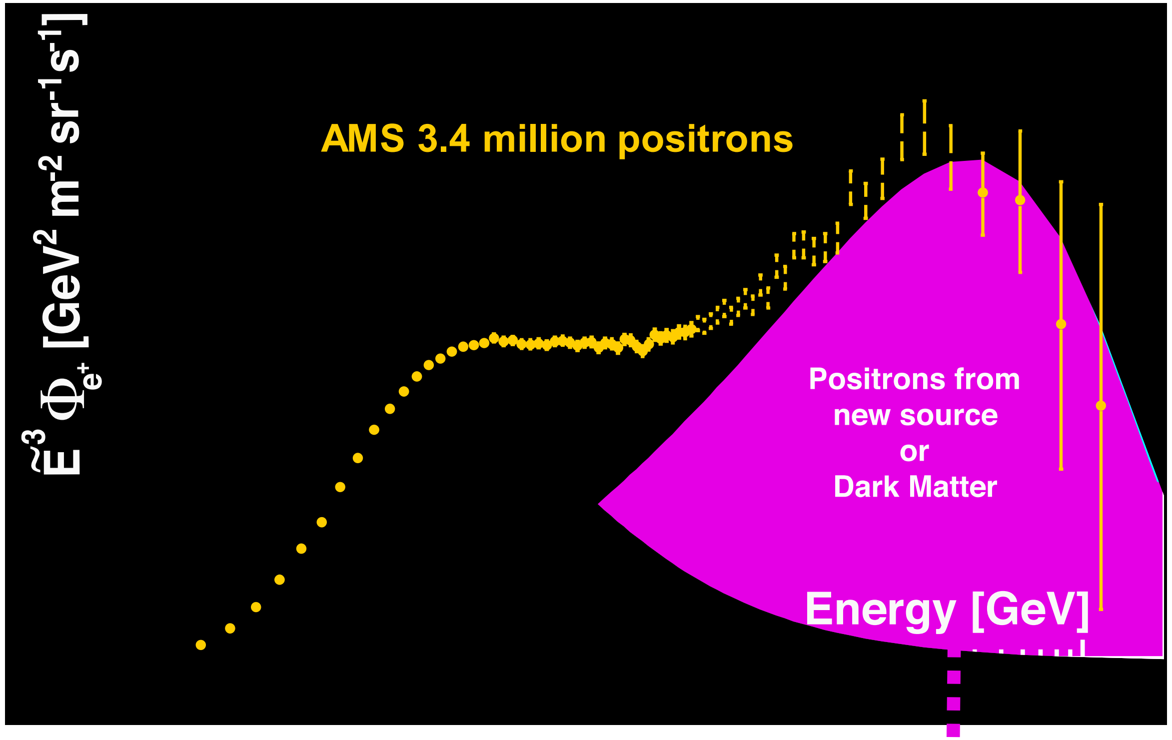
The finite cutoff energy E_S is established at 4.5 σ

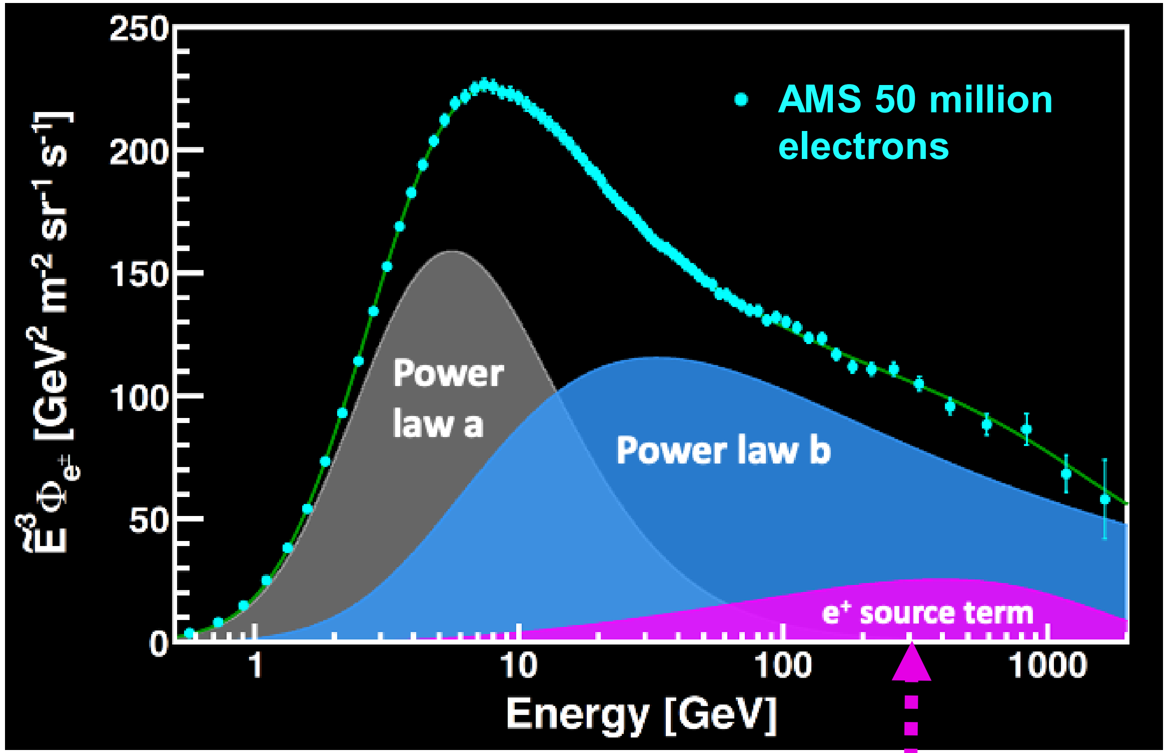
P. Zuccon, MIAPP 2022



Positrons vs Electrons

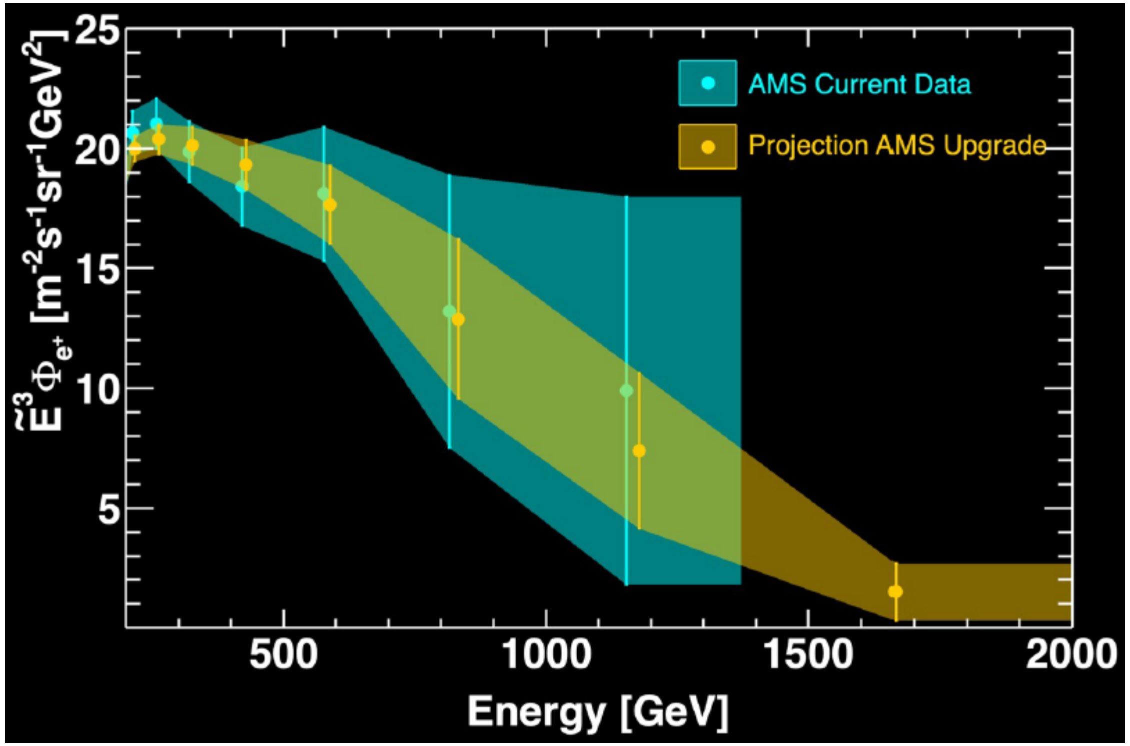
Electron spectrum favors the contribution of the positron-like source term at 95% confidence level → However, this does not allow to discriminate between pulsar and DM contributions

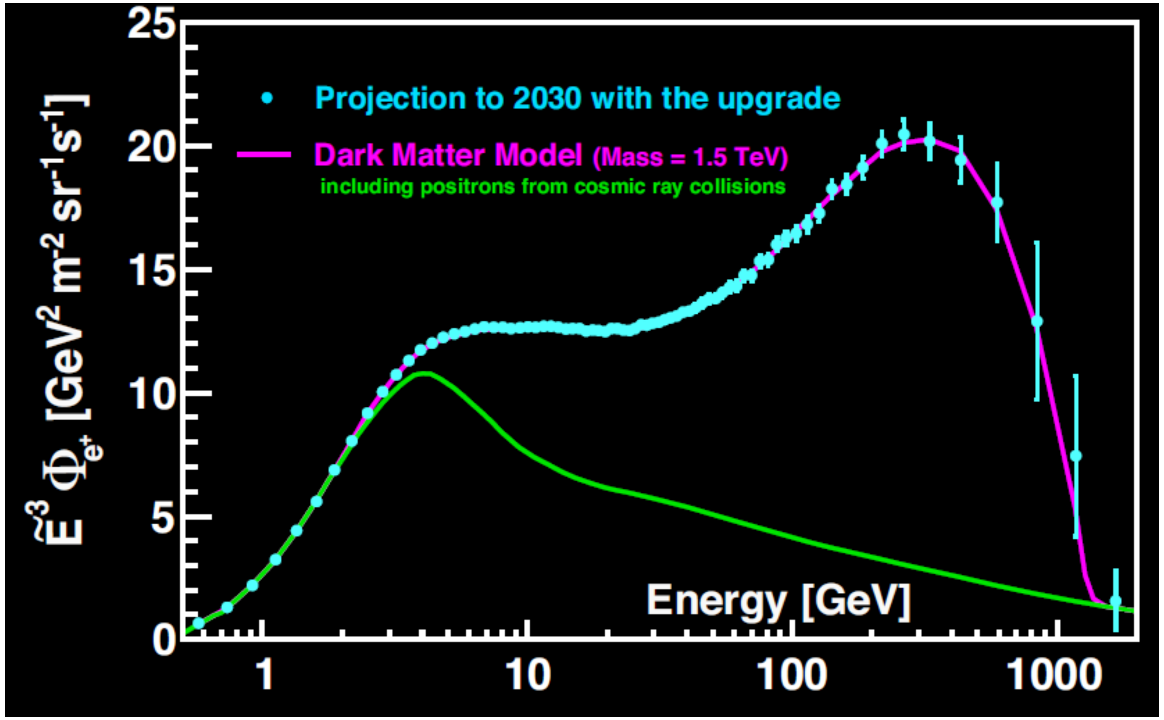




P. Zuccon, MIAPP 2022

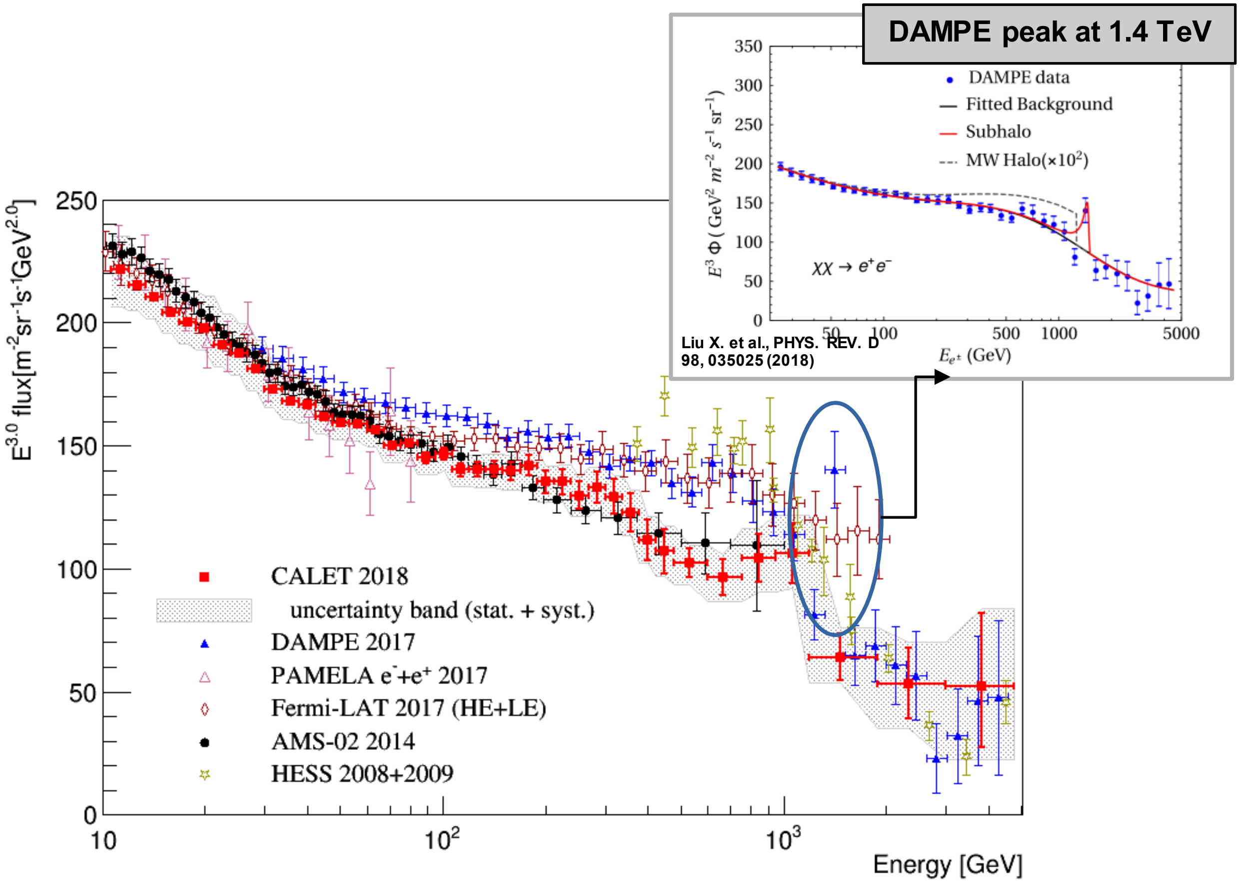
Positrons with AMS-02 upgrade



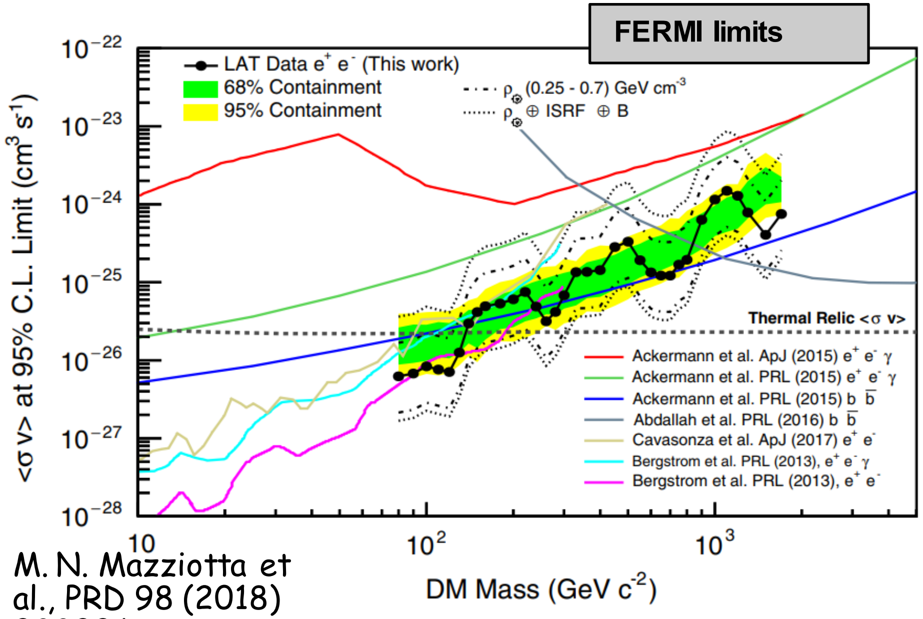


P. Zuccon, MIAPP 2022

All Electron Spectrum ($e^- + e^+$)

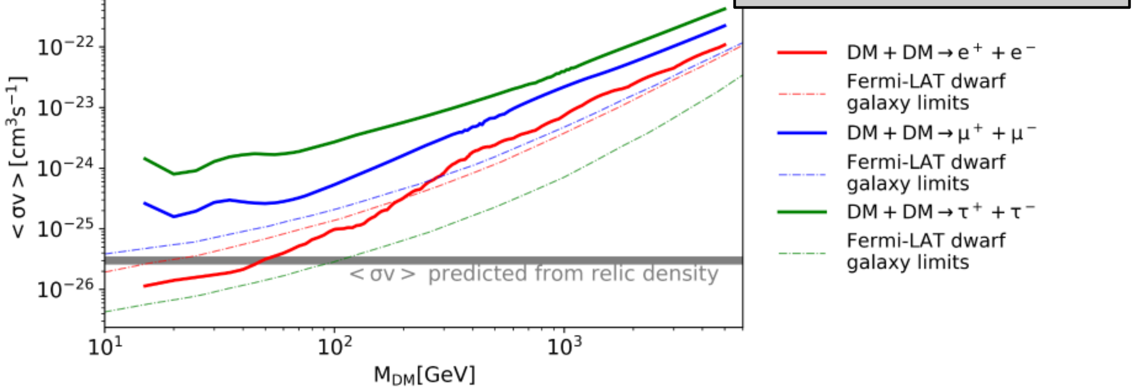


CALET → no structure at 1.4 TeV



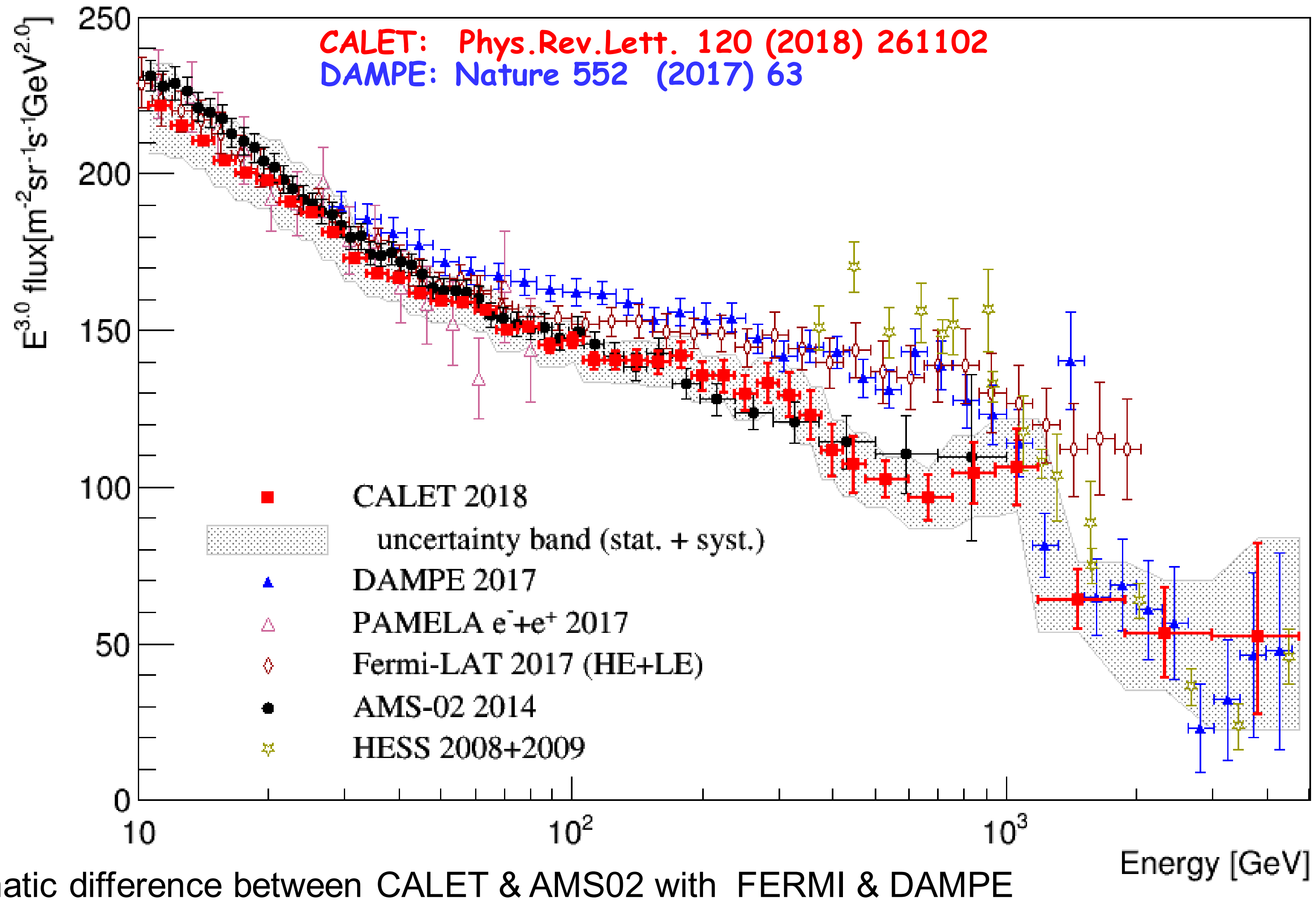
M. N. Mazziotta et al., PRD 98 (2018) 022006

Motz H et al., PoS(ICRC2019)533



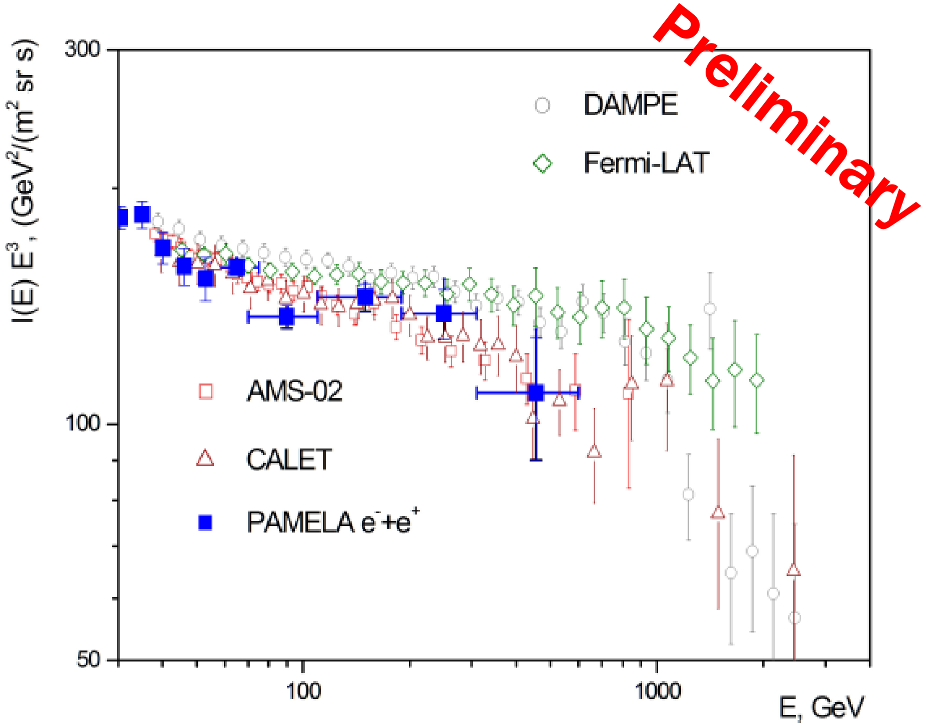
R. Munini, CSN2 April 2022

All Electron Spectrum ($e^- + e^+$)

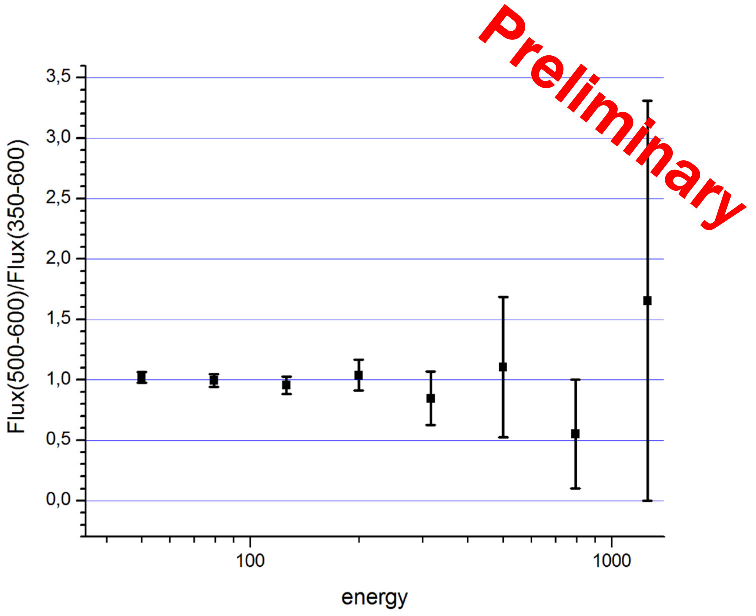


Systematic difference between CALET & AMS02 with FERMI & DAMPE

Elettroni e Positroni Galattici

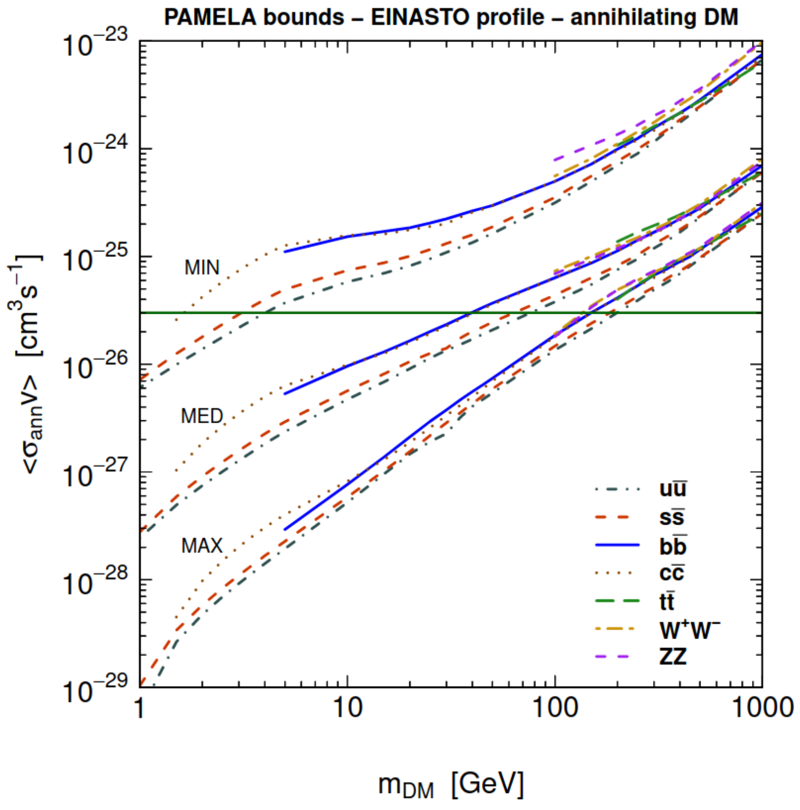


V. V. Mikhailov et al., J. Phys. Conf. Ser. 1390 (2019) 012061

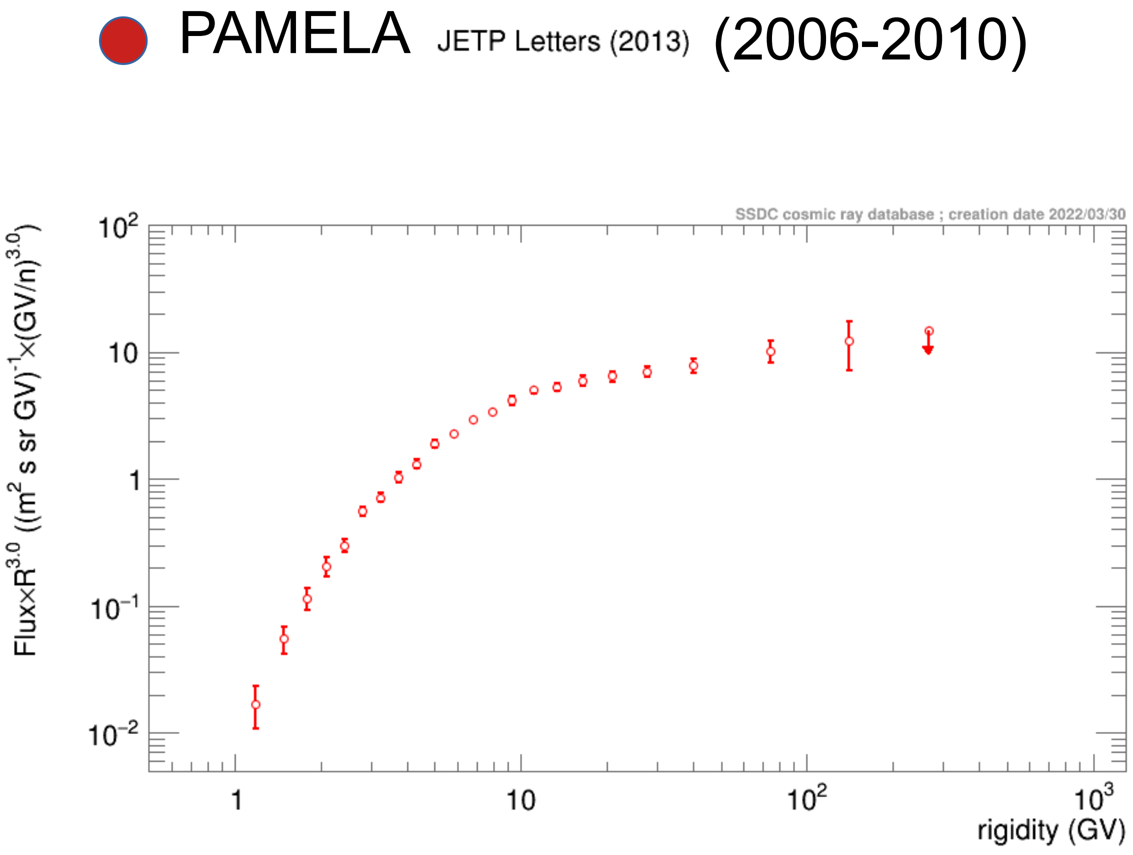


PAMELA: Antiprotons

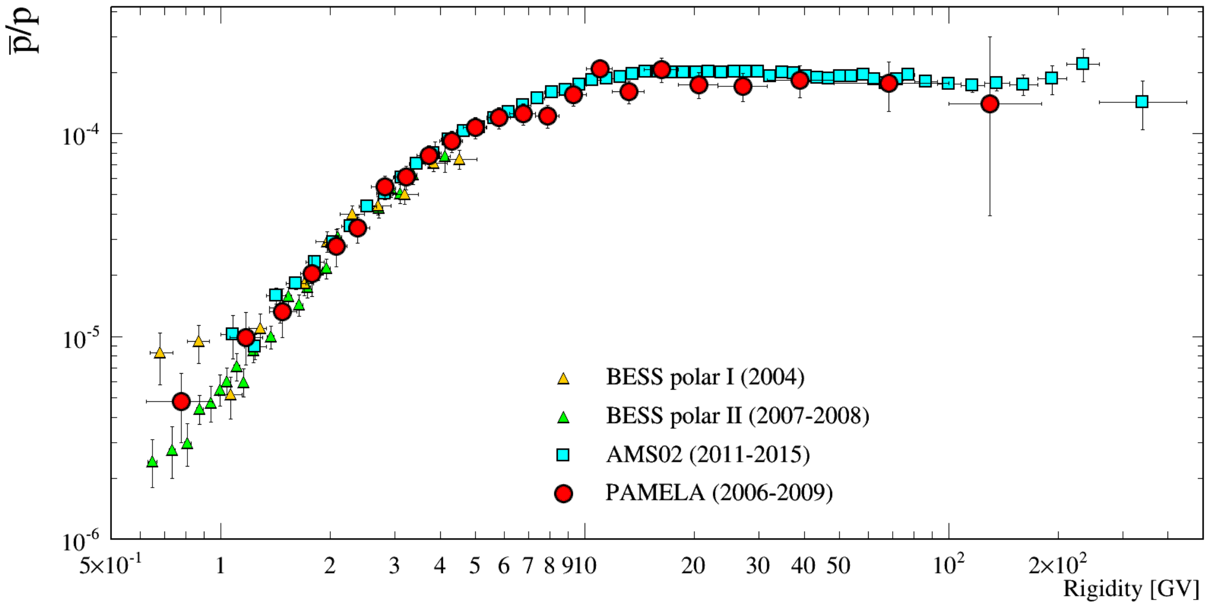
PAMELA greatly increases the existing statistics significantly extending the observed energy range

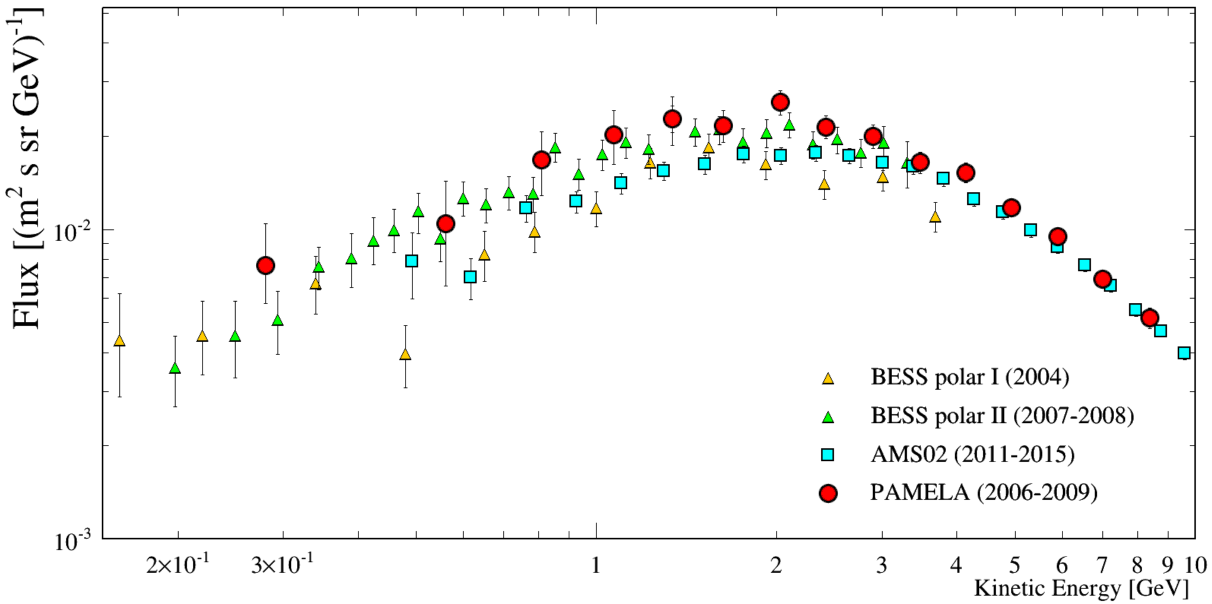


Fornengo N. et al,, JCAP 1404 (2014) 003

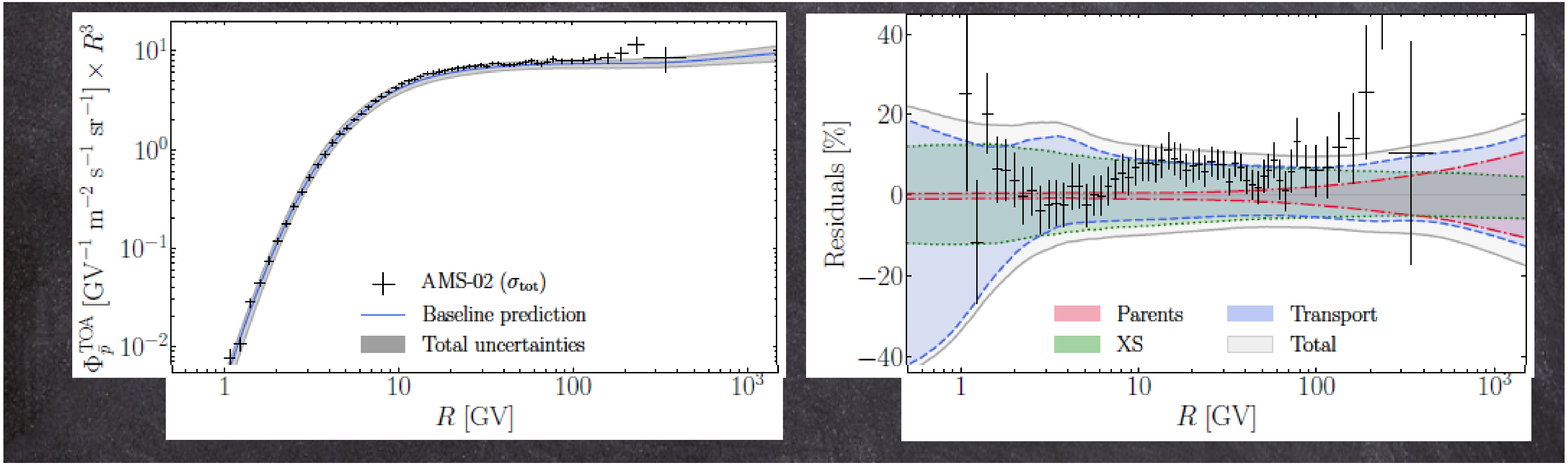


PAMELA antiproton results vs BESS Polar & AMS-02: Agreement!





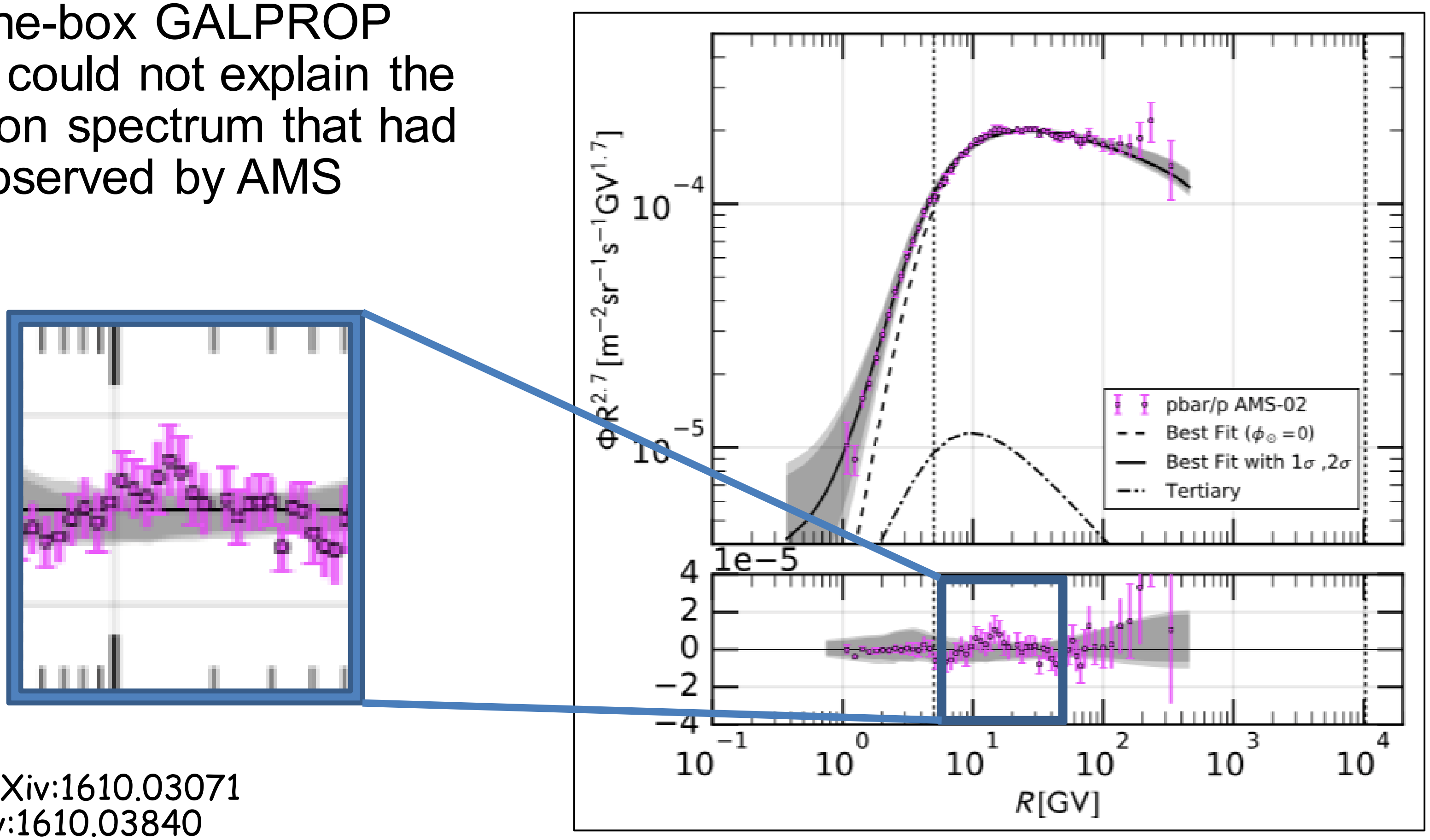
AMS-02 Antiprotons and Secondary Production



M. Boudaud et al., Phys. Rev. Res. 2 (2020) 023022

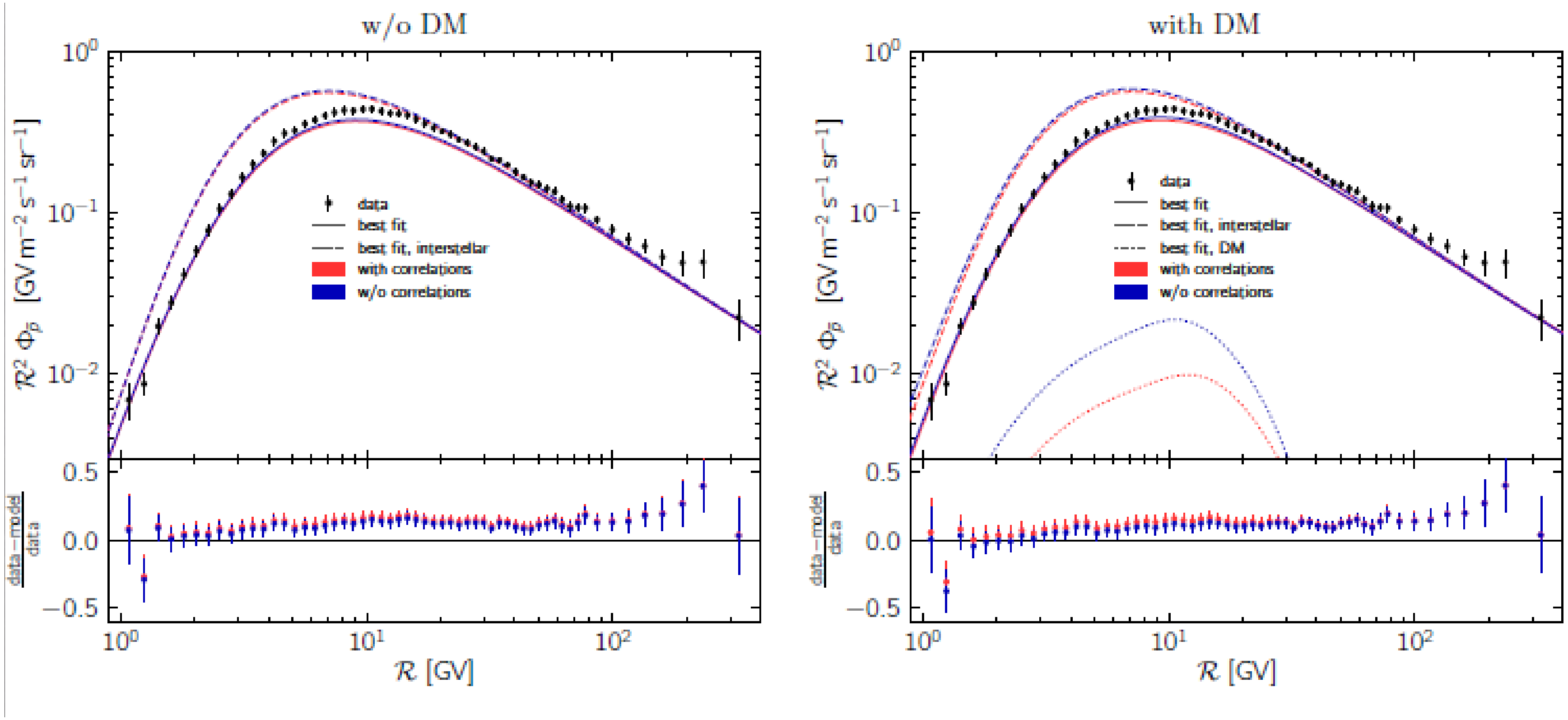
The Antiproton Excess

- The AMS antiproton excess was pointed out in 2016 by two independent groups (Cuoco, Krämer, Korsmeier and Cui, Yuan, Tsai, Fan)
- Both papers identified a small, but statistically significant excess (~4.5σ)
- These papers made it clear that out-of-the-box GALPROP models could not explain the antiproton spectrum that had been observed by AMS



Cuoco et al., arXiv:1610.03071
Cui et al., arXiv:1610.03840

The Antiproton Excess



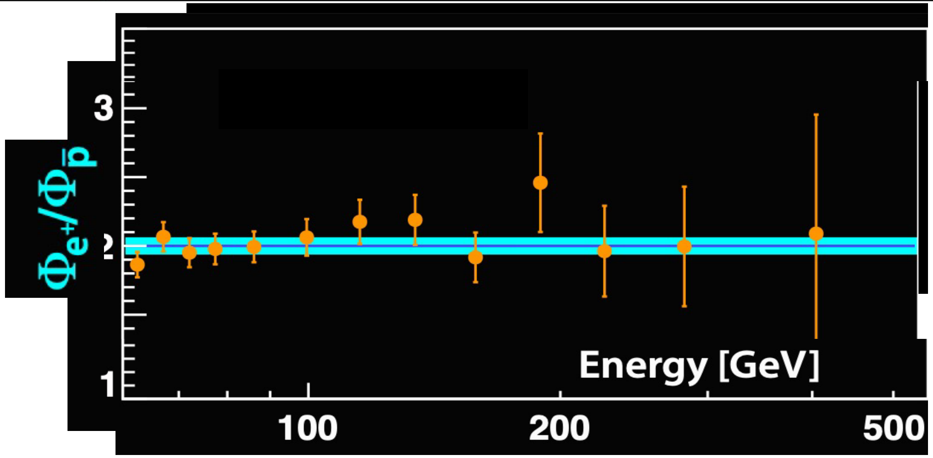
J. Heisig, M. Korsmeier, and M. W. Winkler, Phys. Rev. Res. **2** (2020), 043017:
"We find that the global significance of the antiproton excess is reduced to below 1 σ once all systematics, including the derived AMS-02 error correlations, are taken into account. No significant preference for a dark-matter signal in the AMS-02 antiproton data is found in the mass range 10-10000 GeV.."

Do we understand propagation correctly?

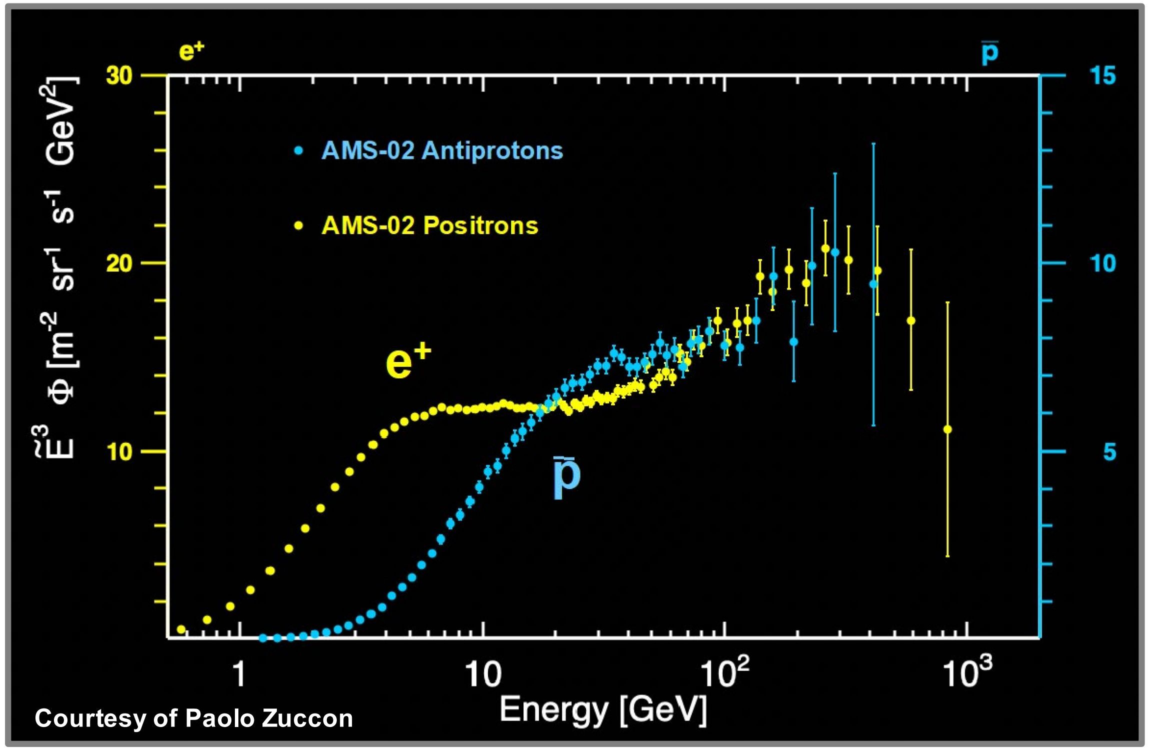
Paolo Lipari arXiv:1902.06173, 16 Feb 2019

“Alternative” interpretation: the e^+ flux is entirely of secondary origin, but its residence time in the Galaxy must be small than that usually inferred from CR nuclei

$$\Phi_{e^+}/\Phi_{\bar{p}} = 2.00 \pm 0.035(\text{stat.}) \pm 0.06(\text{syst.})$$

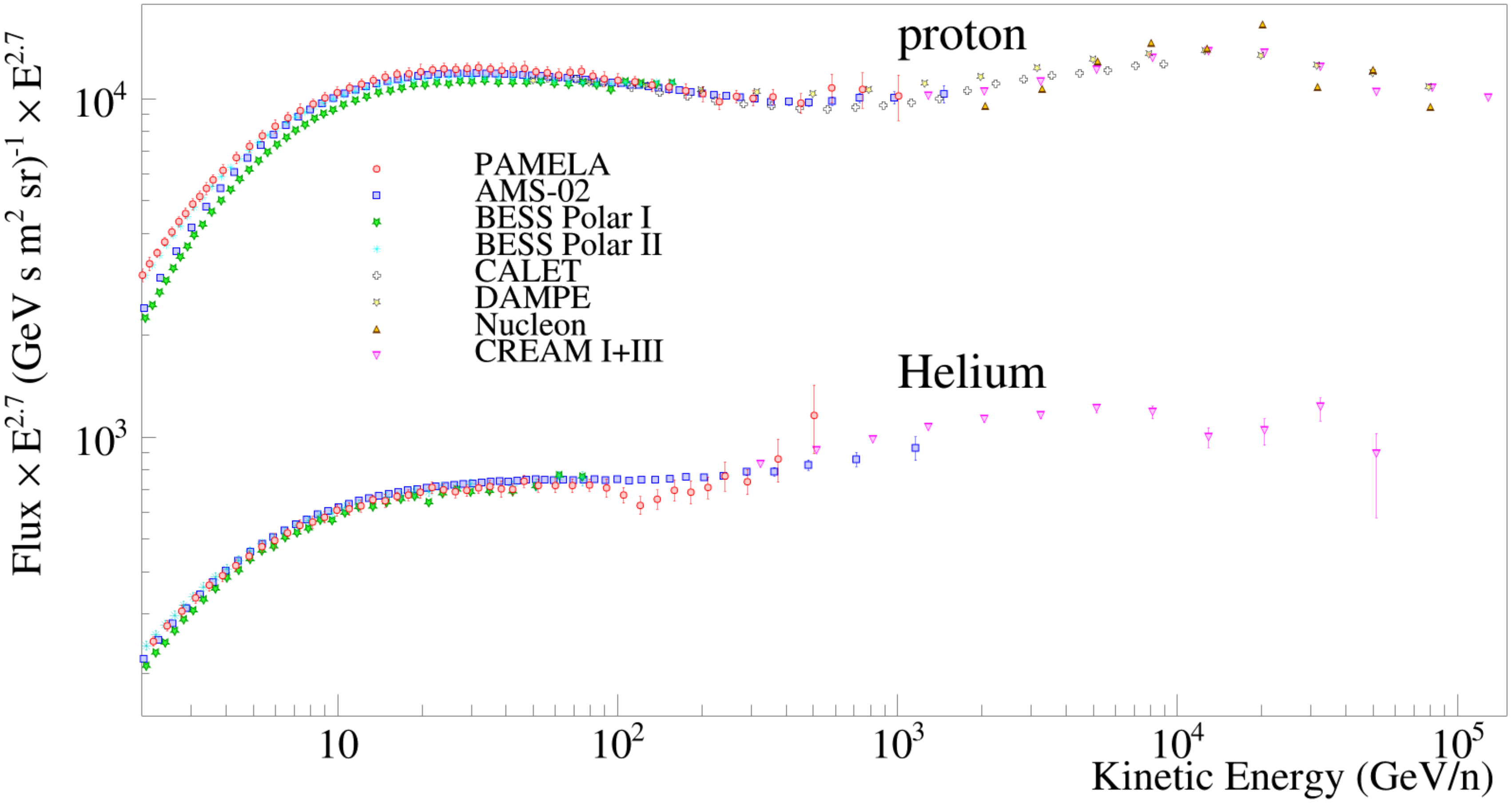


Antiprotons show a similar trend to positrons.

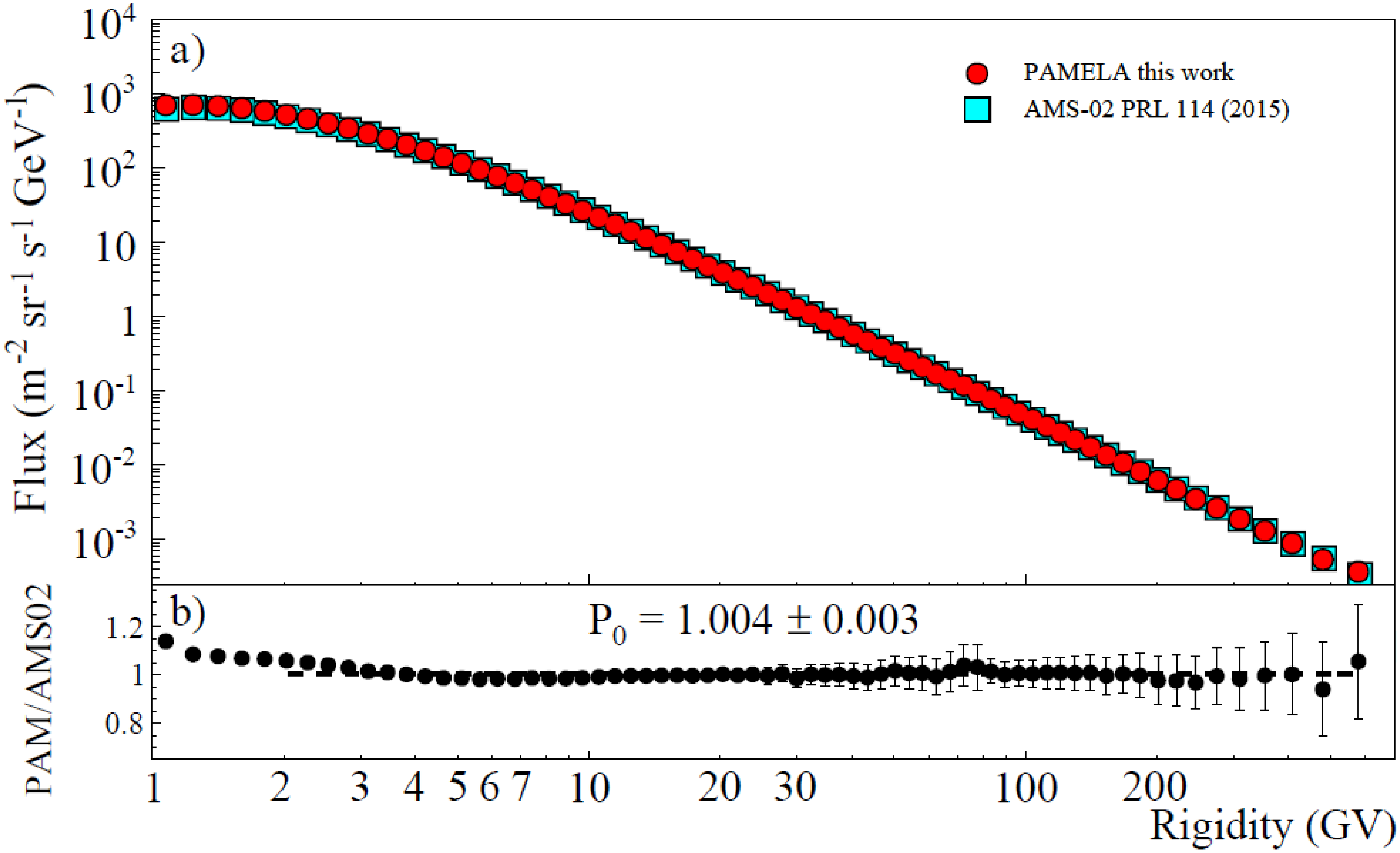


R. Munini, CSN2 April 2022

Recent proton spectrum measurements



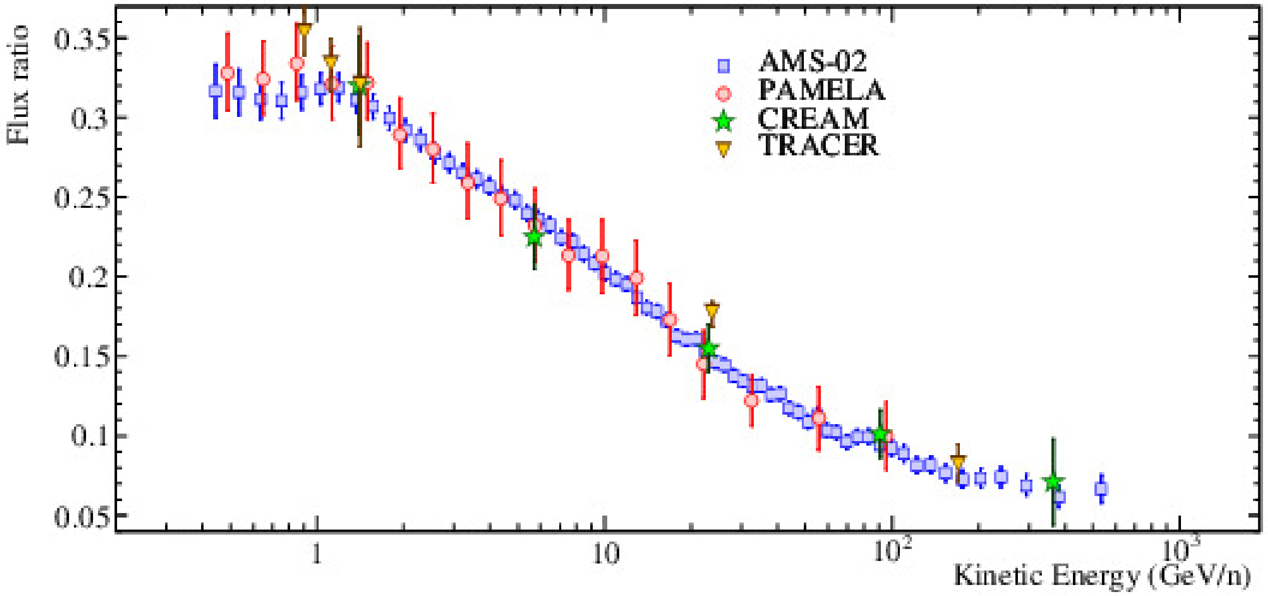
PAMELA & AMS-02 Proton Spectrum

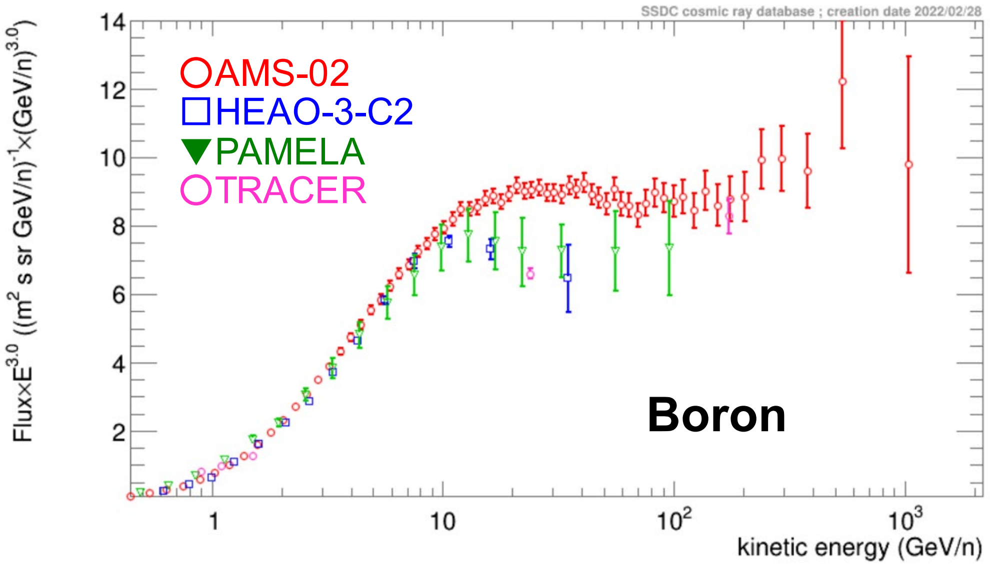


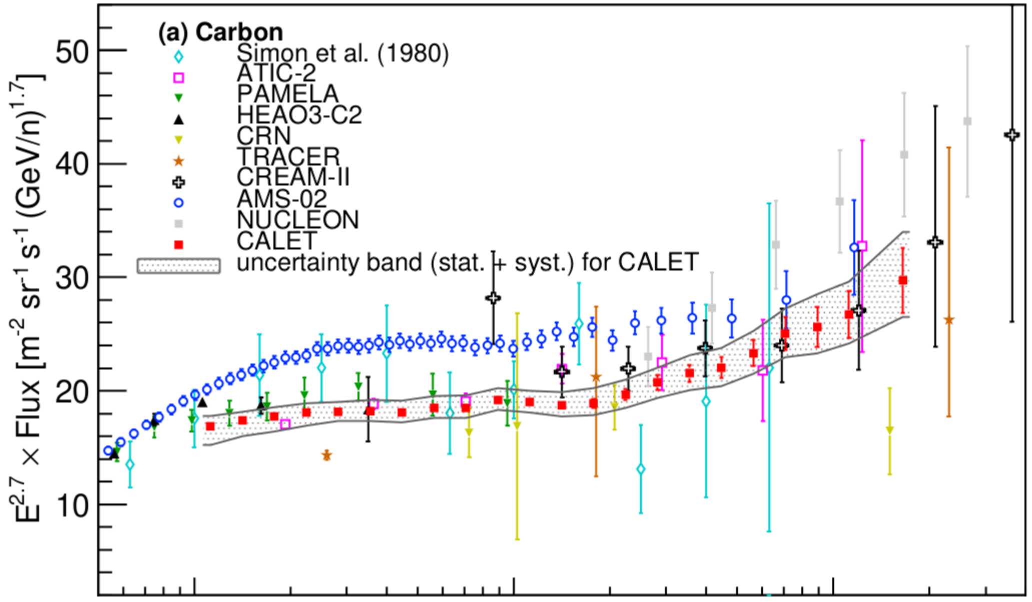
M. Martucci et al., ApJL 854 (2018)L2

Boron & Carbon

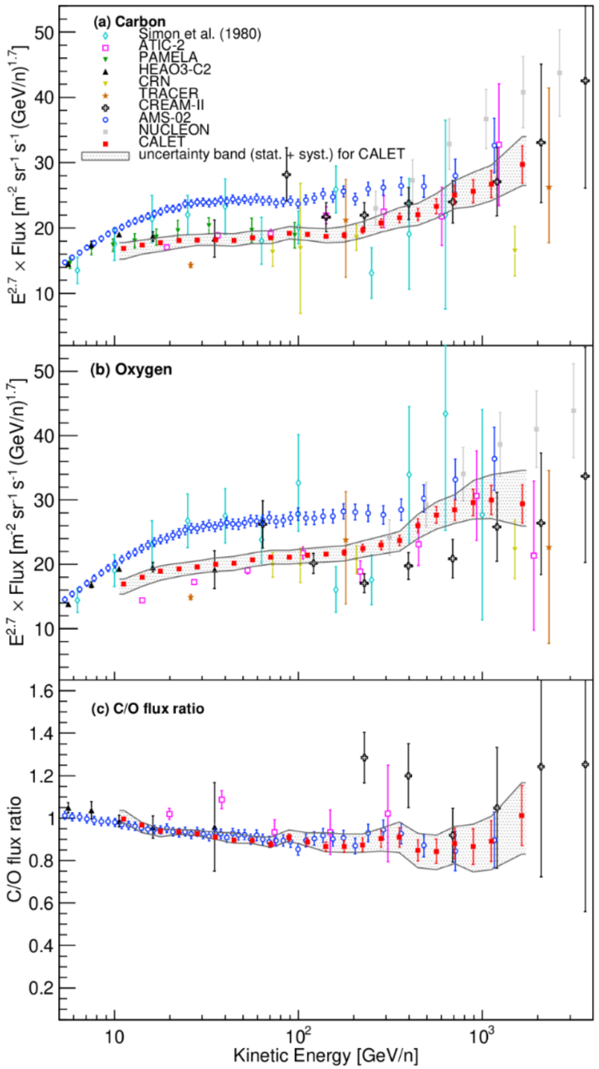
Boron-to-Carbon flux ratio

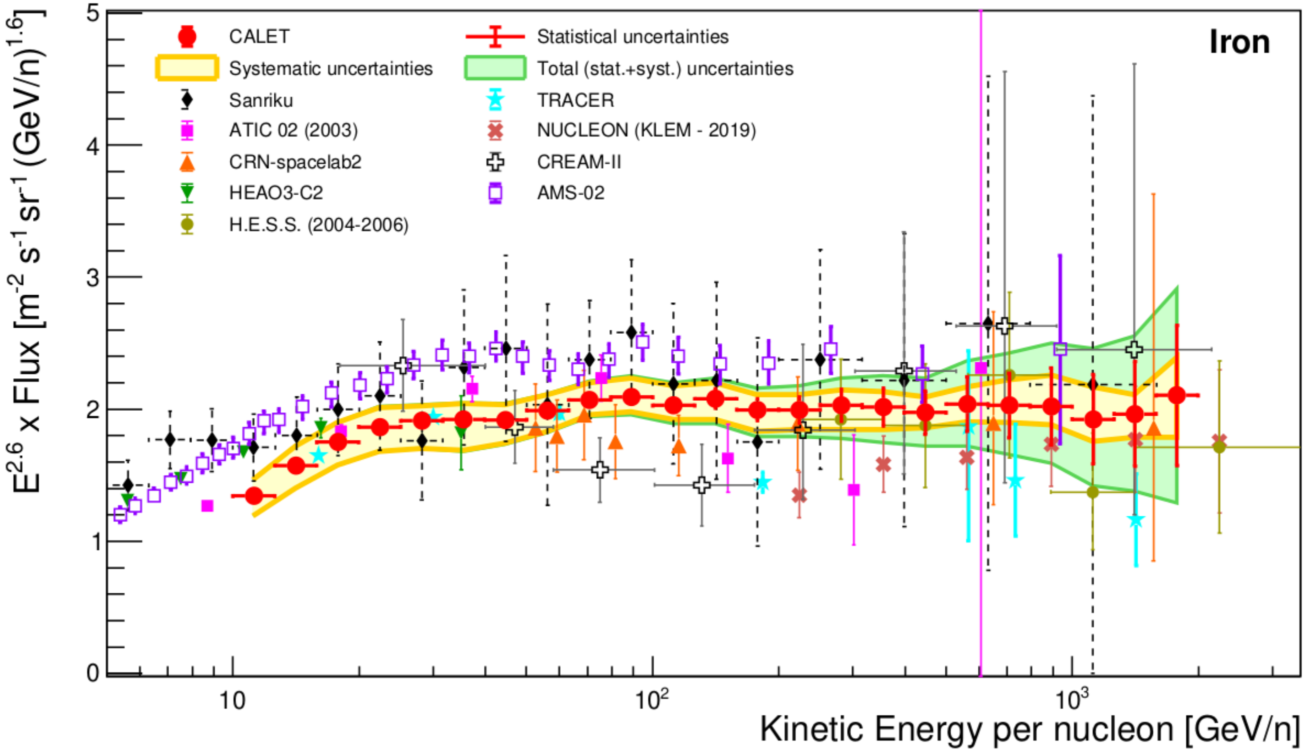






Recent measurements of nuclei spectra: C, O & Fe



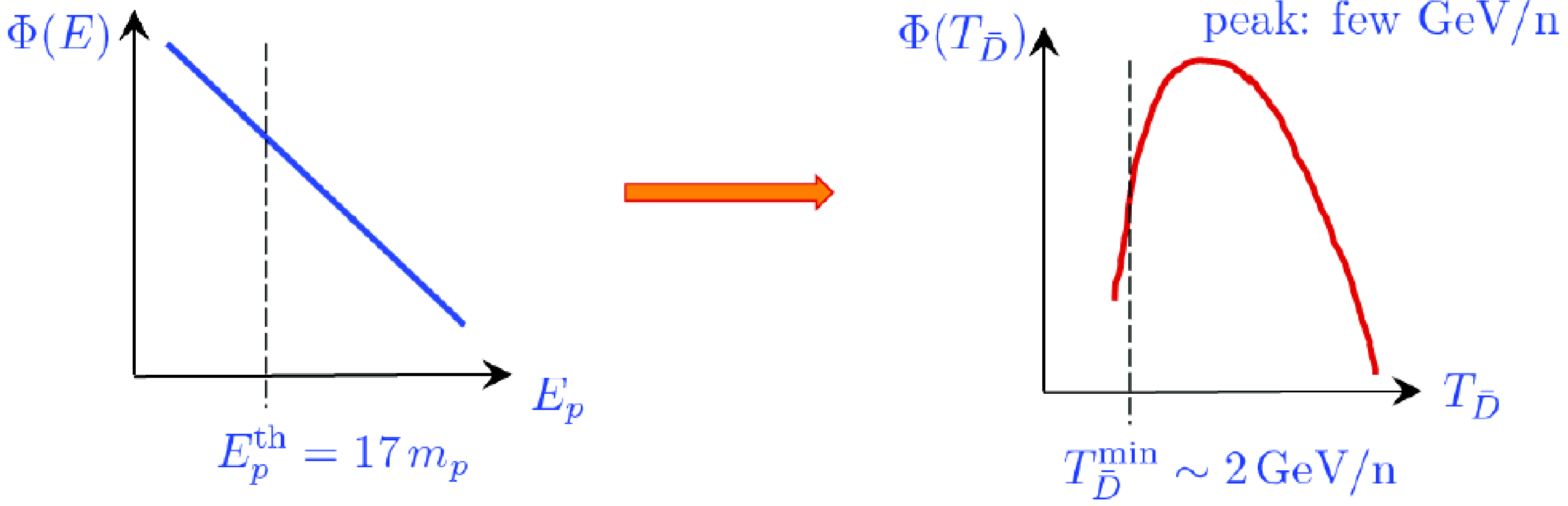


Background "free" Signals?

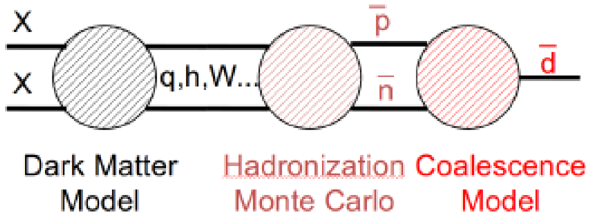
Antinuclei

Why Anti-Deuterium? Background

$$\underbrace{p_{CR}}_{} + \overbrace{p_{ISM}}^{\text{at rest}} \longrightarrow \bar{p}\bar{n} + pn + pp$$



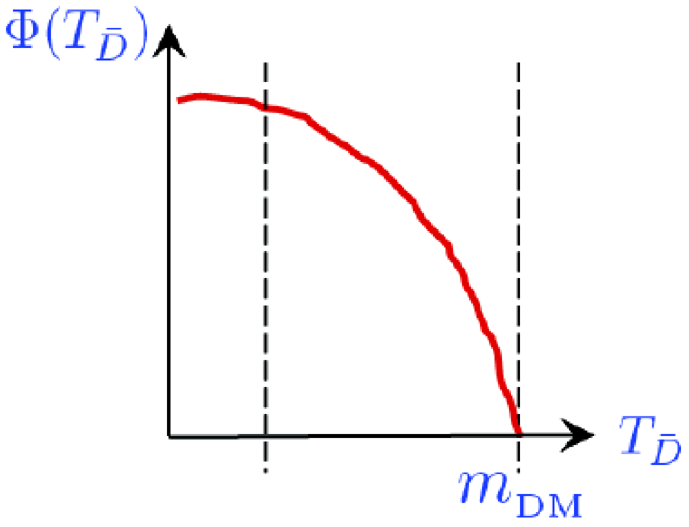
Why Anti-Deuterium? Signal



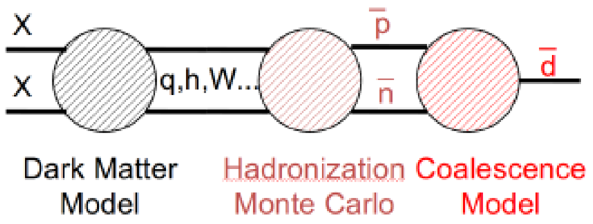
AntiDeuteron Flux

$$\phi(\bar{D}) \propto <\sigma v>_{\text{annihilitaion}} \left(\frac{\rho_{DM}}{M_{DM}}\right)^2 \otimes (\text{cohalescence } p_0)^3 \otimes \text{propagation}$$

$$\underbrace{\chi}_{\text{at rest}} + \overbrace{\chi}^{\text{at rest}} \longrightarrow \bar{p}\bar{n} + pn$$



Why Anti-Deuterium? Signal



AntiDeuteron Flux

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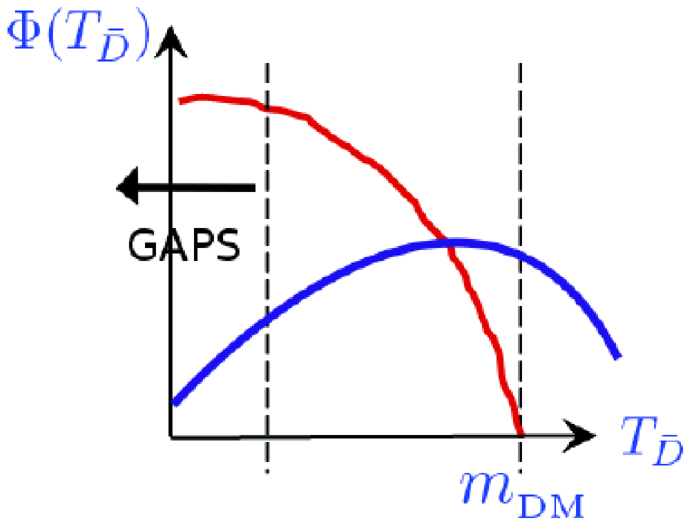
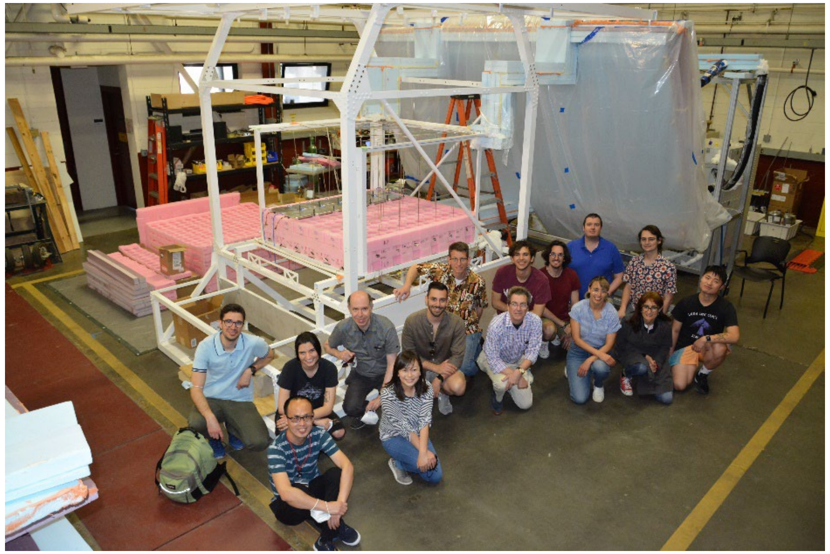
$$\underbrace{\chi}_{\text{at rest}} + \overbrace{\chi}^{\text{at rest}} \longrightarrow \bar{p}\bar{n} + pn$$



The GAPS experiment

- International collaboration between US, Japanese, and Italian institutes



The GAPS experiment

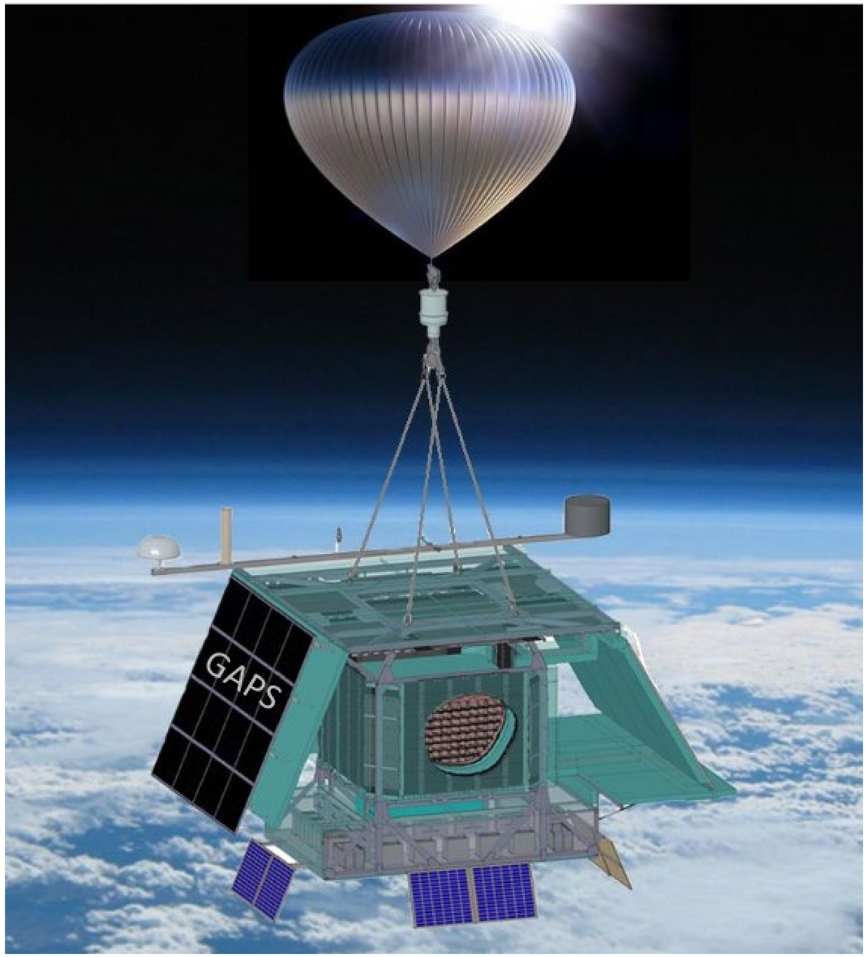
- GAPS is a balloon flight experiment for low energy (<0.25 GeV/n) **antideuteron in cosmic rays** (CRs) that would result from certain dark matter (DM) interactions

- GAPS will also conduct a high statistics measurement of low energy **antiproton** and will search for **antihelium**

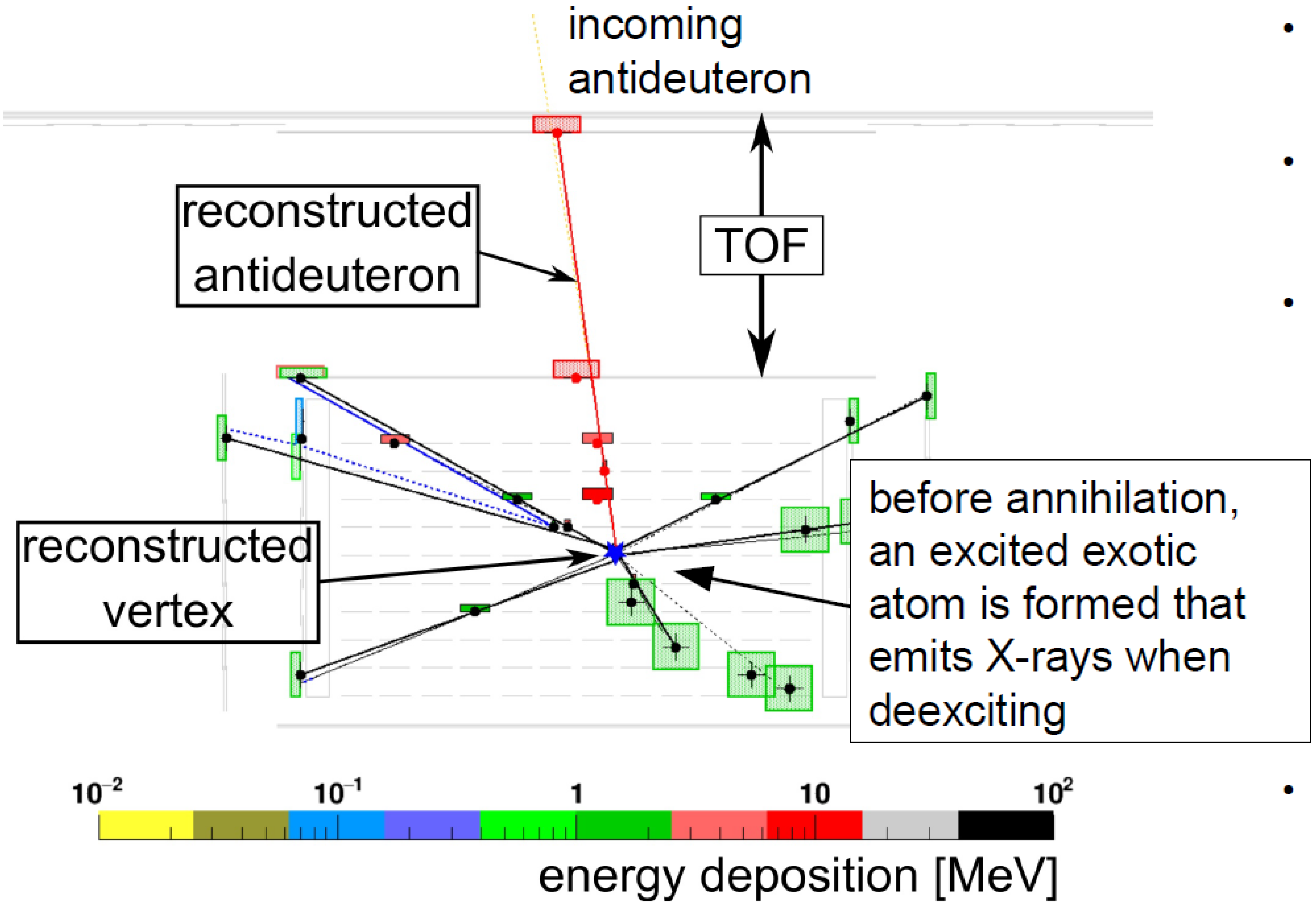
- Three flights from Antarctica are planned

- The detector is composed by a ToF system and a Tracker made of 10 plane of SiLi detector

- GAPS uses a detection technique based on exotic atom formation and subsequent decay and annihilation with X rays and pion emission



GAPS Detection Technique

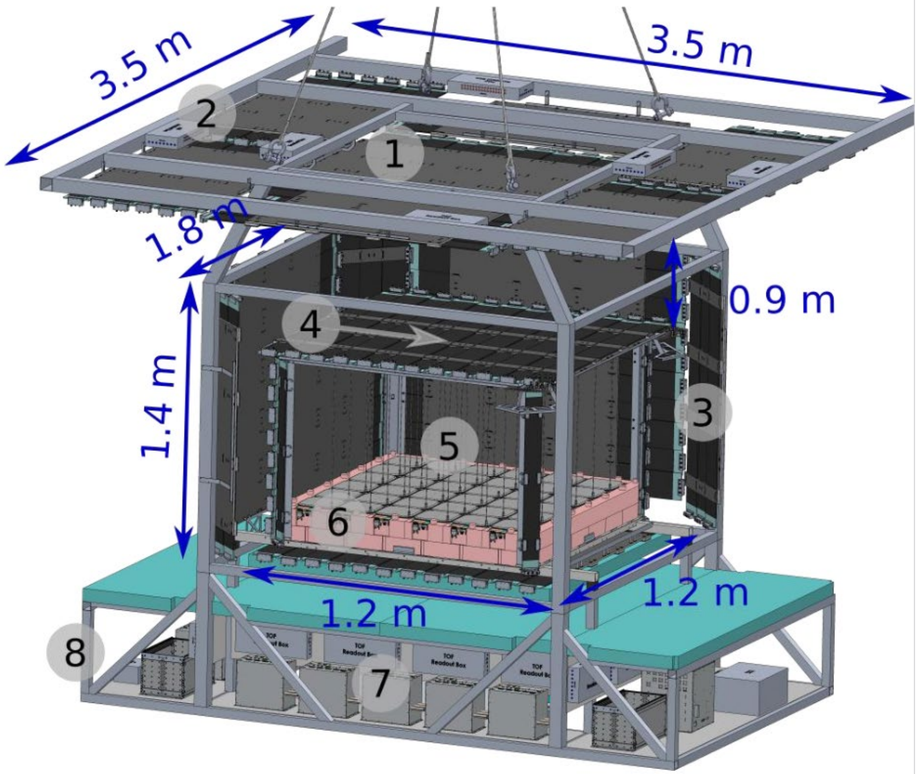


- antiparticle slows down and stops in material
- large chance for creation of an excited exotic atom (E_{kin}~E_I)
- deexcitation:
  fast ionization of bound electrons (Auger)
  → complete depletion of bound electrons
  Hydrogen-like exotic atom (nucleus+antideuteron) deexcites via characteristic X-ray transitions depending on antiparticle mass
- Nuclear annihilation with characteristic number of annihilation products

GAPS Instrument Overview

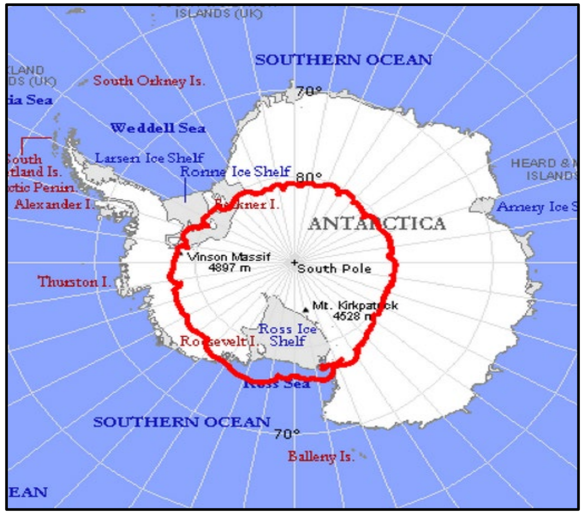
General requirements

- Large acceptance
- Restrictive trigger
- Velocity measurements
- Background rejection
  - X-rays detection
  - Track primary
  - Track secondaries



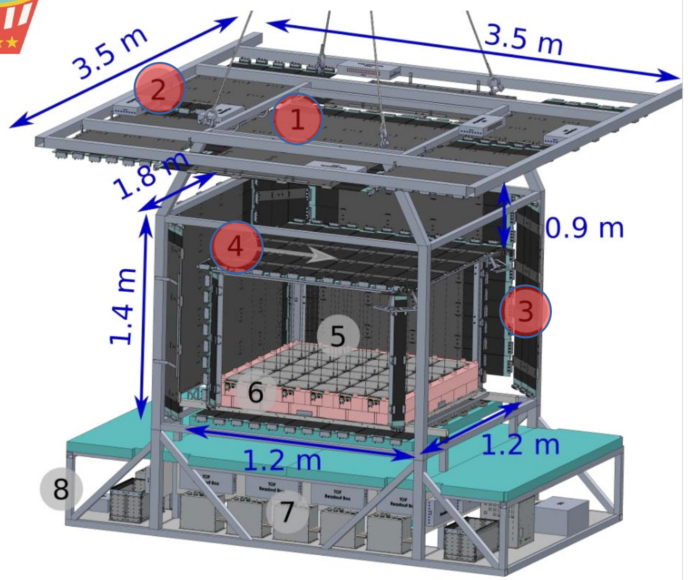
Total mass: 3500 kg
Power: 1.4 kW

1 – TOF Umbrella
2 – TOF electronics box
3 – TOF Cortina
4 – TOF Cube
5 – Heat pipe (cooling system)
6 – Si(Li) Tracker
7 – Electronics bay
8 – Gondola frame



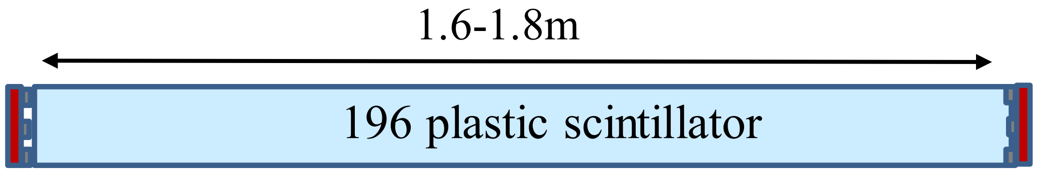
1 LDB flight (35 days) → **high-statistic antiP:** >600 (BESS < 100, 7 PAMELA)
3 LDB flights (105 days) → **antiD sensitivity**: $2 \cdot 10^{-6} m^{-2} s^{-1} sr^{-1}\, GeV/n^{-1}$

GAPS TOF System

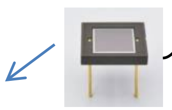


- Velocity measurements
- High speed trigger and veto
- dE/dx measurements

S. Quinn, POS (ICRC2019) 128



Si-PMs (x6)
Better performance
Save mass, power, cost



Trigger based on:

- **Beta**: rejects high beta particles
- **Charge**: rejects high Z particles
- **Hit**: count the number of paddles hit

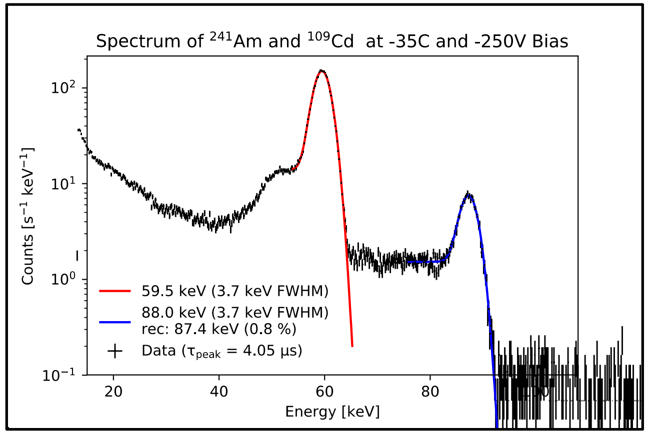
Expected Trigger Rates (H, He, C)
Raw : 82,000 Hz → After cuts ~ 500 Hz

Antiprotons Trigger		60%
Antideuterons Trigger		76%
Proton Rejection Factor		>2500

1.8m SiPM paddles

GAPS Tracker system

- 4 keV FWHM (at ~60 keV)
- Large area, relatively high temperature
- Leakage current < 5 nA/strip
- Large dynamical range (~keV→100 MeV)
- >1000 mass production with high-yield
- Novel heat-pipe system with low-power and lightweight is used for the thermal control



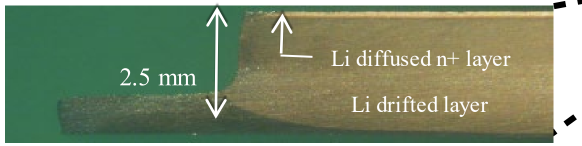
Perez et al., NIM A 905, 12 (2018)
Kozai et al., NIM A 947, 162695 (2019)
Rogers et al., JINST 14, P10009 (2019)
Saffold et al., NIM A 997, 165015 (2021)
Manghisoni et al., IEEE Trans. Nucl. Sci. 68 (11) 2661 (2021)
S. Okazaki et al., J. Astr.. Instr. 3 (2014)

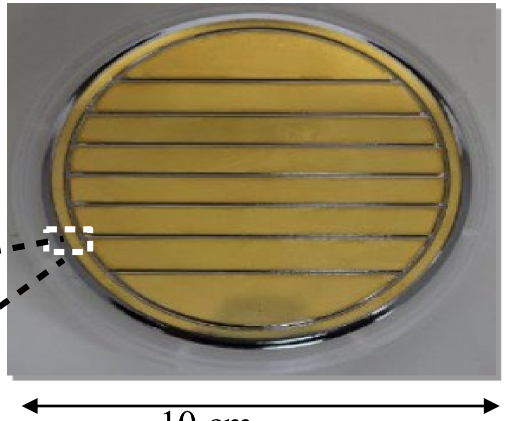
Li ions compensate impurities in boron-doped Si, creating extended thick depleted layer

Lithium-drifted Silicon

- Cylindrical detector
- -43C operational T
- 1100 SiLi detectors
- 10 planes

6x6 module each plane



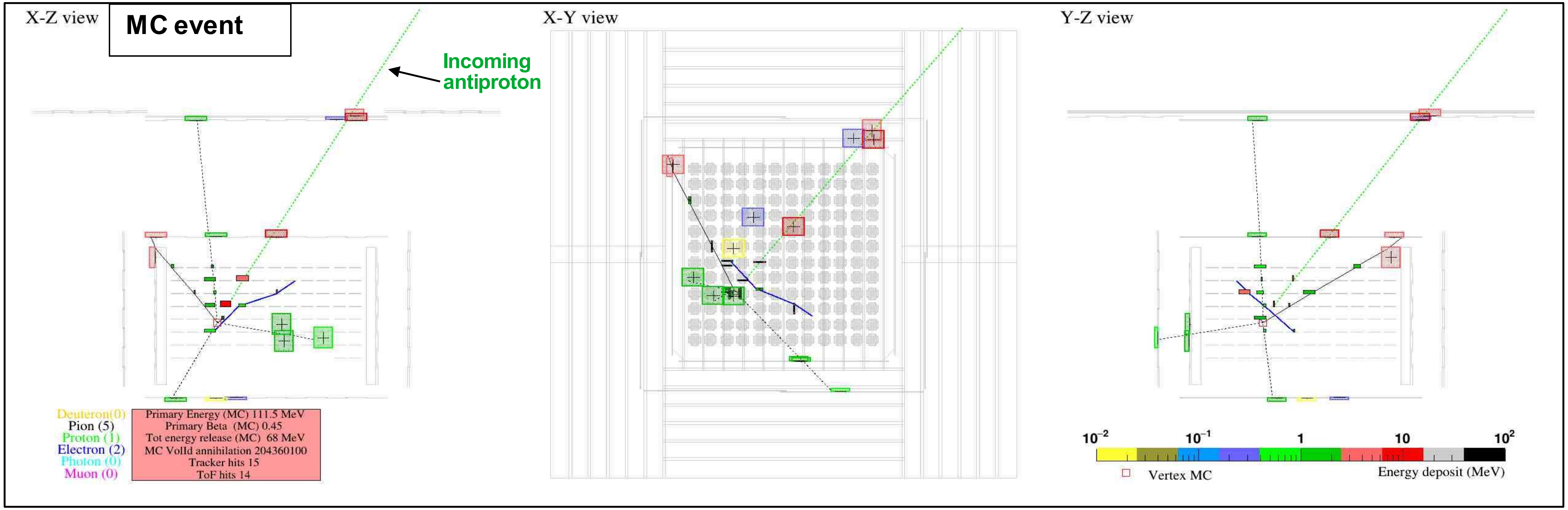


Simulated event

Fully detector simulation with (GEANT4)

Vertex reconstruction based on:

- Kalman-like filter for primary reconstruction
- Custom algorithm for secondaries
- Vertex reconstruction with minimization



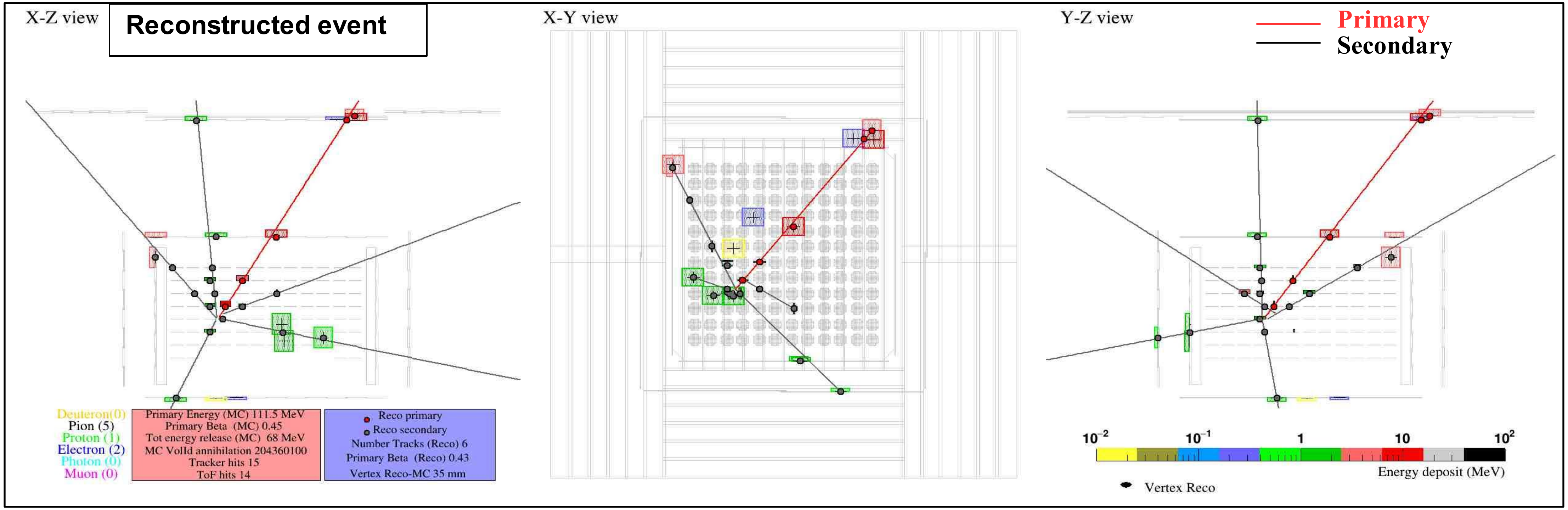
R. Munini et al. Astropart. Phys. 133 (2021) 102640

Reconstructed event

Fully detector simulation with (GEANT4)

Vertex reconstruction based on:

- Kalman-like filter for primary reconstruction
- Custom algorithm for secondaries
- Vertex reconstruction with minimization

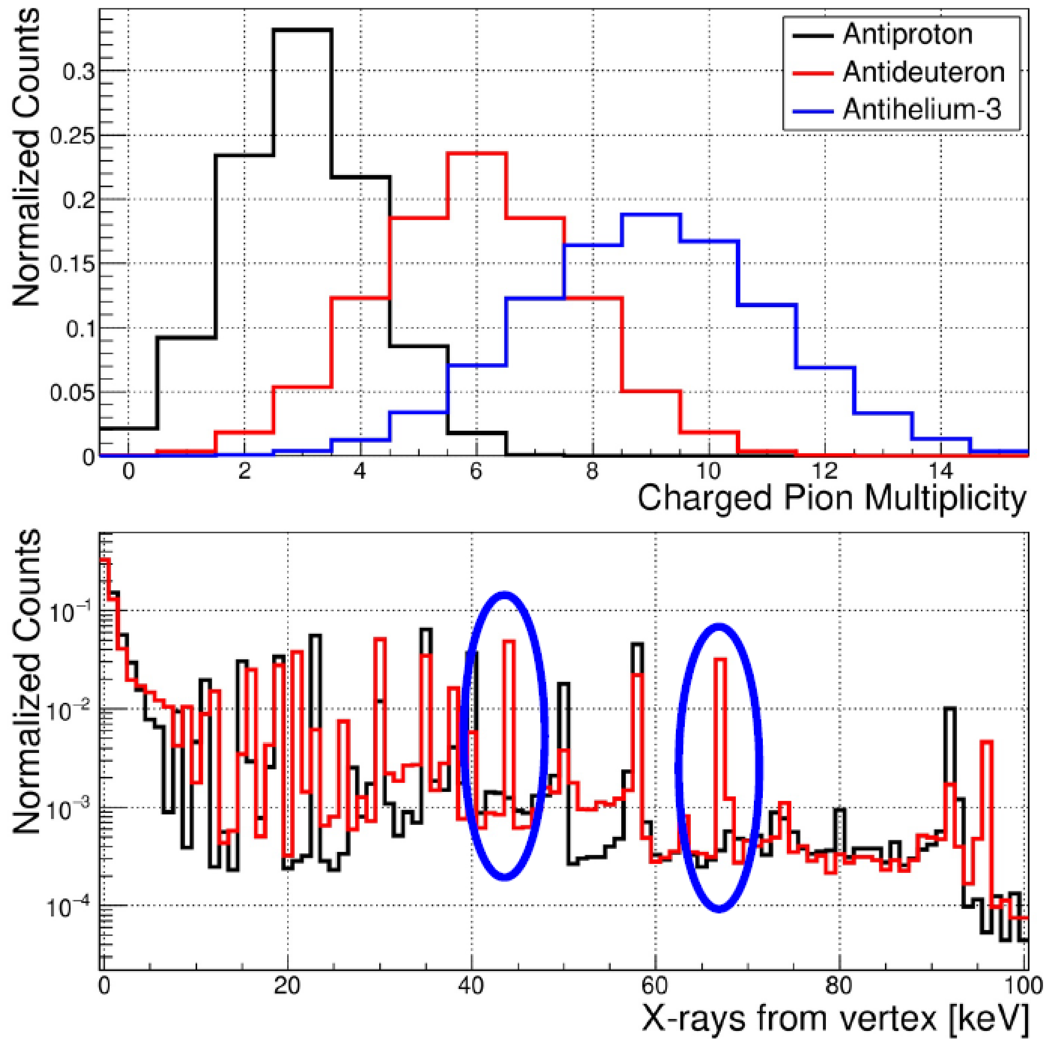


R. Munini et al. Astropart. Phys. 133 (2021) 102640

Reconstructed event

GAPS identification technique uses:

- Energy loss in the detector of the antinucleus (depends on Z and β)
- Deexcitation X-rays from exotic atom
- Multiplicity of charged annihilation products

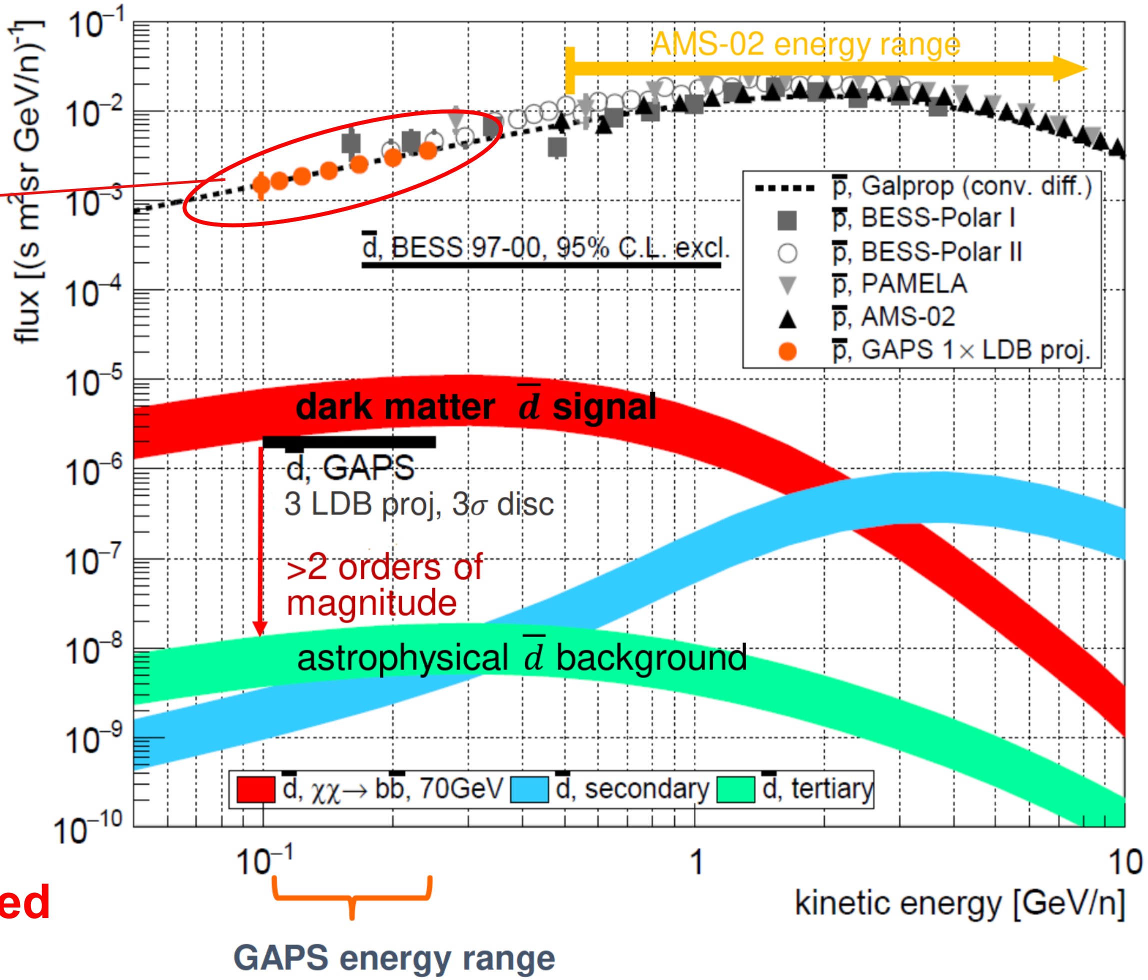


Antiproton measurement

Precision antiproton spectrum in unexplored low-energy range (<0.25 GeV/n).

- **>600 antiprotons for each long-duration balloon flight.**

- BESS : 29 at ~0.2 GeV
- PAMELA: 7 at ~0.25 GeV
- AMS-02: E>0.25 GeV

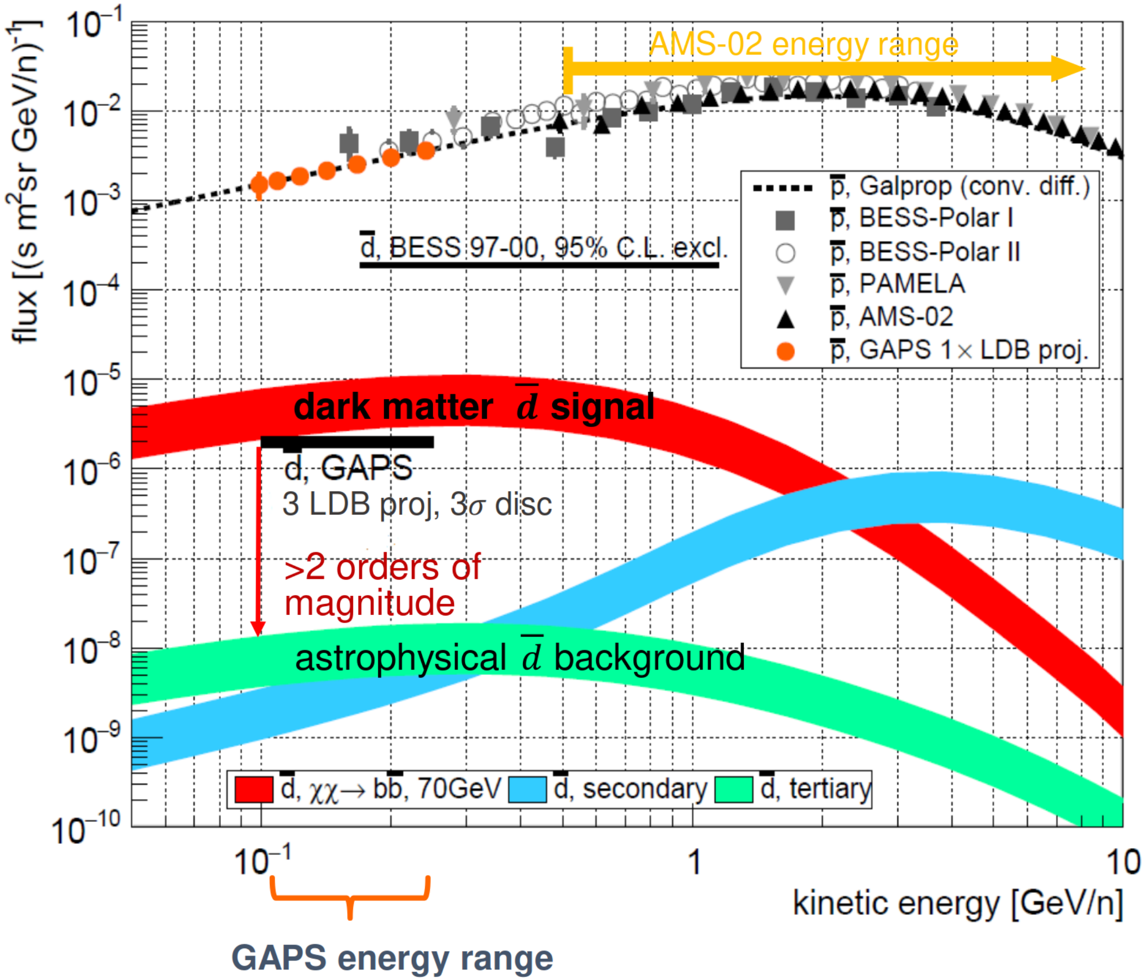


Updated antiproton sensitivity will be published soon

Antideuteron sensitivity

GAPS antideuterons: A generic new physics signature with essentially zero conventional astrophysical background!

Sensitivity will be 1-2 orders of magnitude below the current best limits.

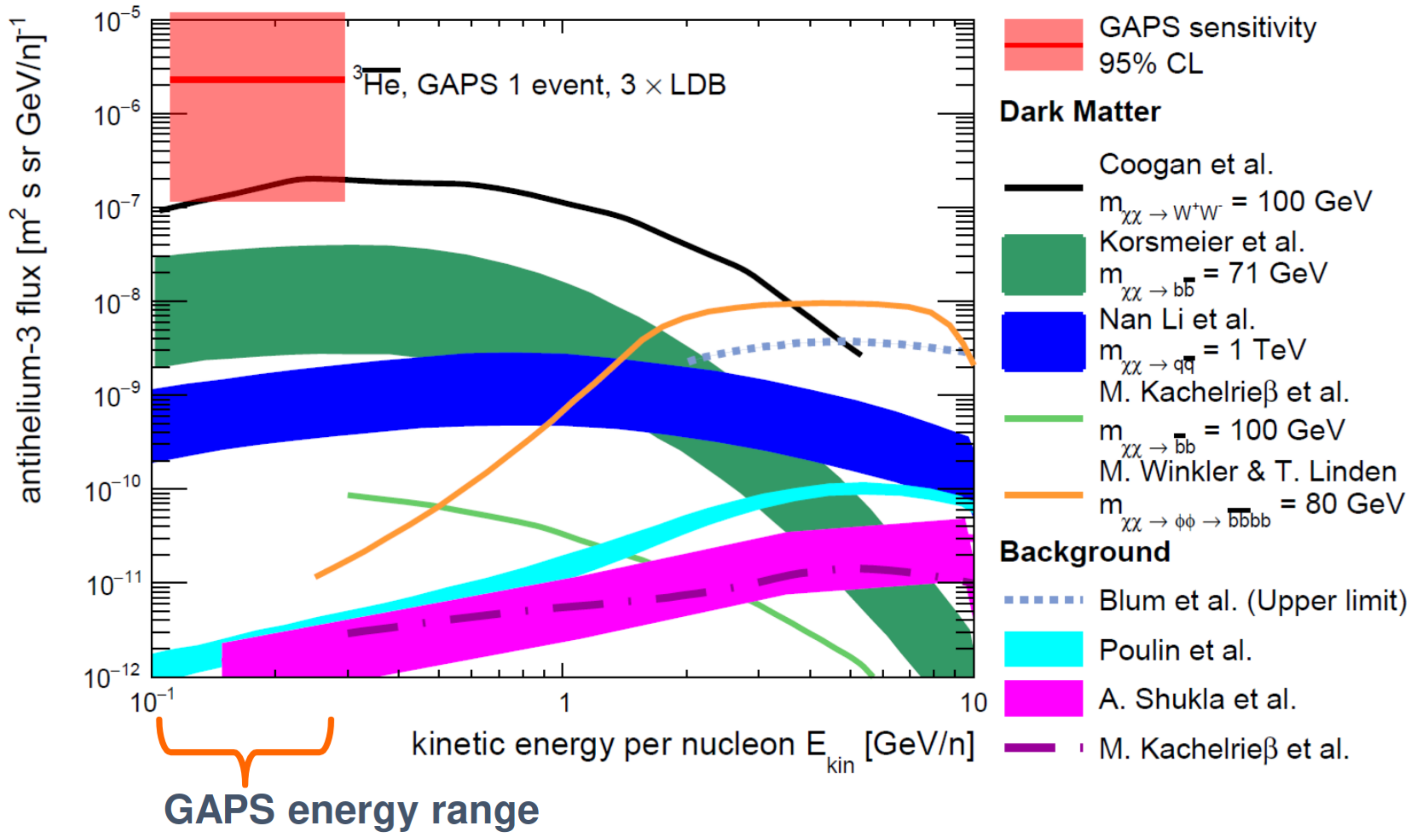


AntiHelium sensitivity

GAPS flux sensitivity to antihelium-3 (three 35-day long duration flights).

GAPS extends to lower energies (0.11-0.3 GeV/n), complementary to AMS-02.

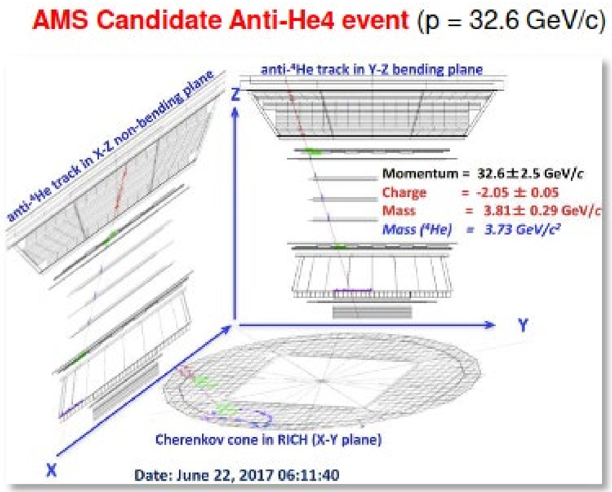
Capable of confirming signal, orthogonal detection technique, uniquely low bkg.



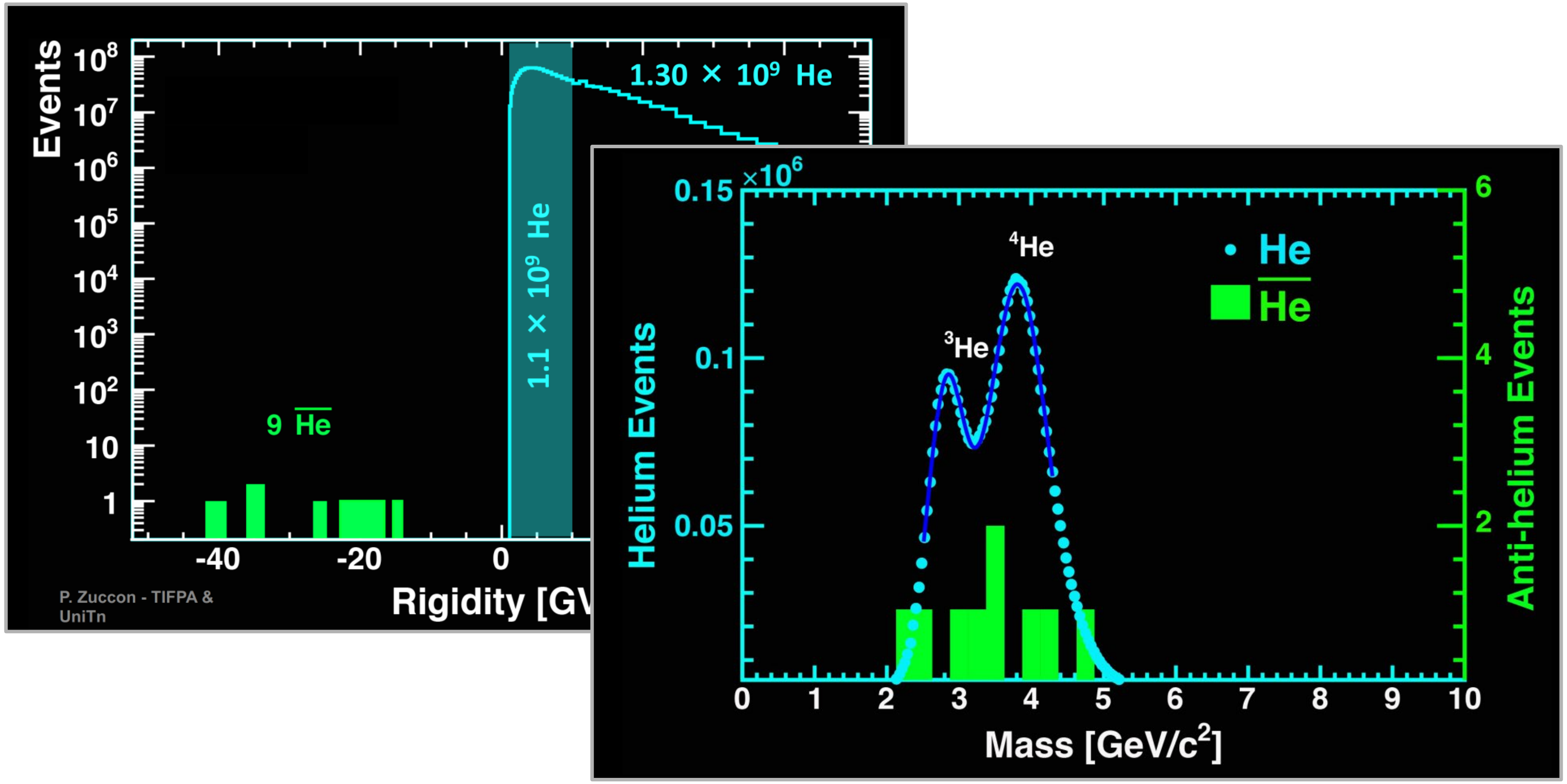
N. Saffold et al. Astropart. Phys. 130 (2021) 102580

AntiHelium: AMS02

2018: “To date, we have observed eight events...with Z = -2. All eight events are in the helium mass region.” – S. Ting (La Palma, AMS overview)

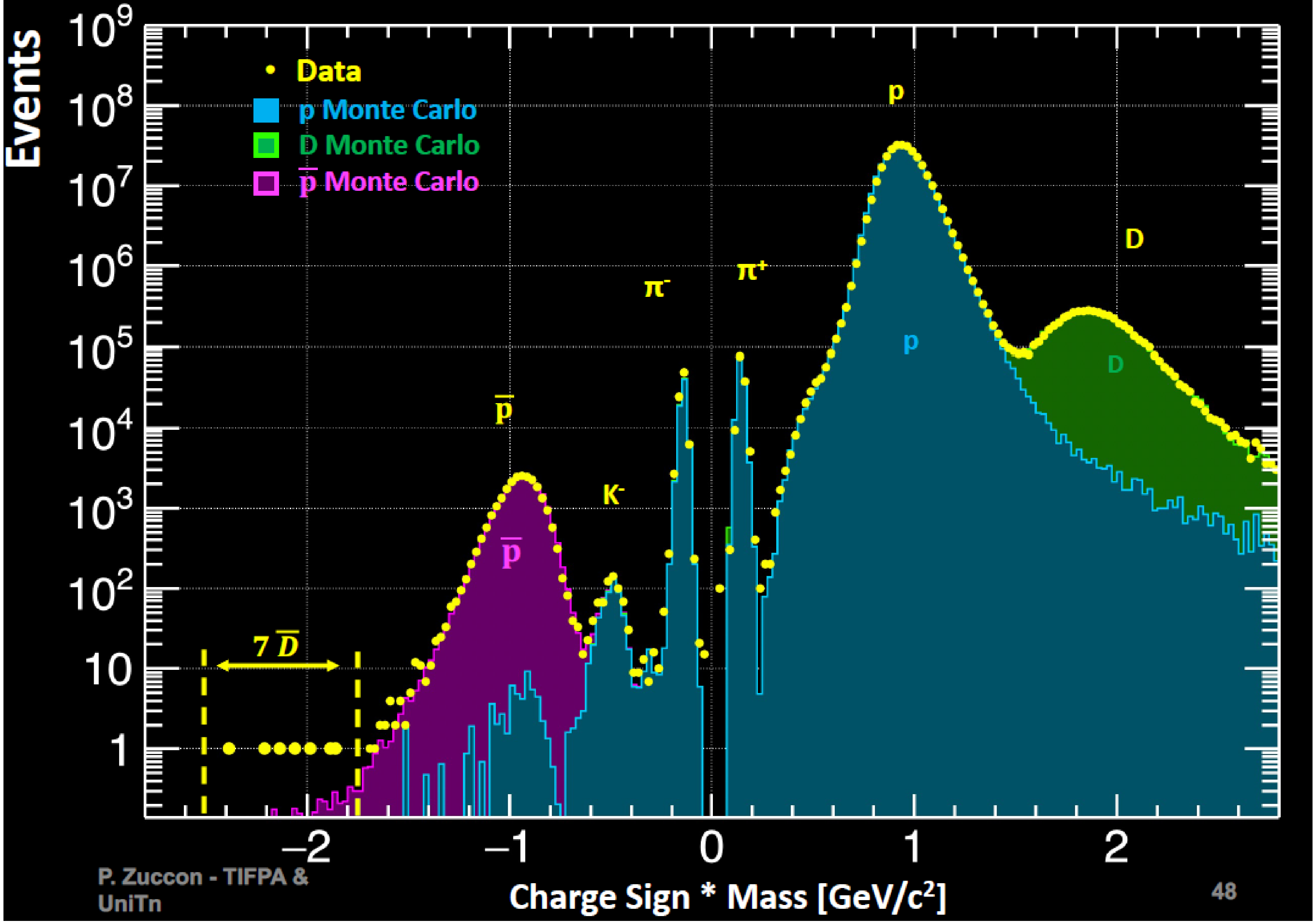


Rate ~ 1 event/year



Current AMS Anti-Deuteron Status

P. Zuccon,
MIAPP 2022



Thanks!