Istituto Nazionale di Fisica Nucleare

Search of Dark Matter in Cosmic-Ray Antimatter

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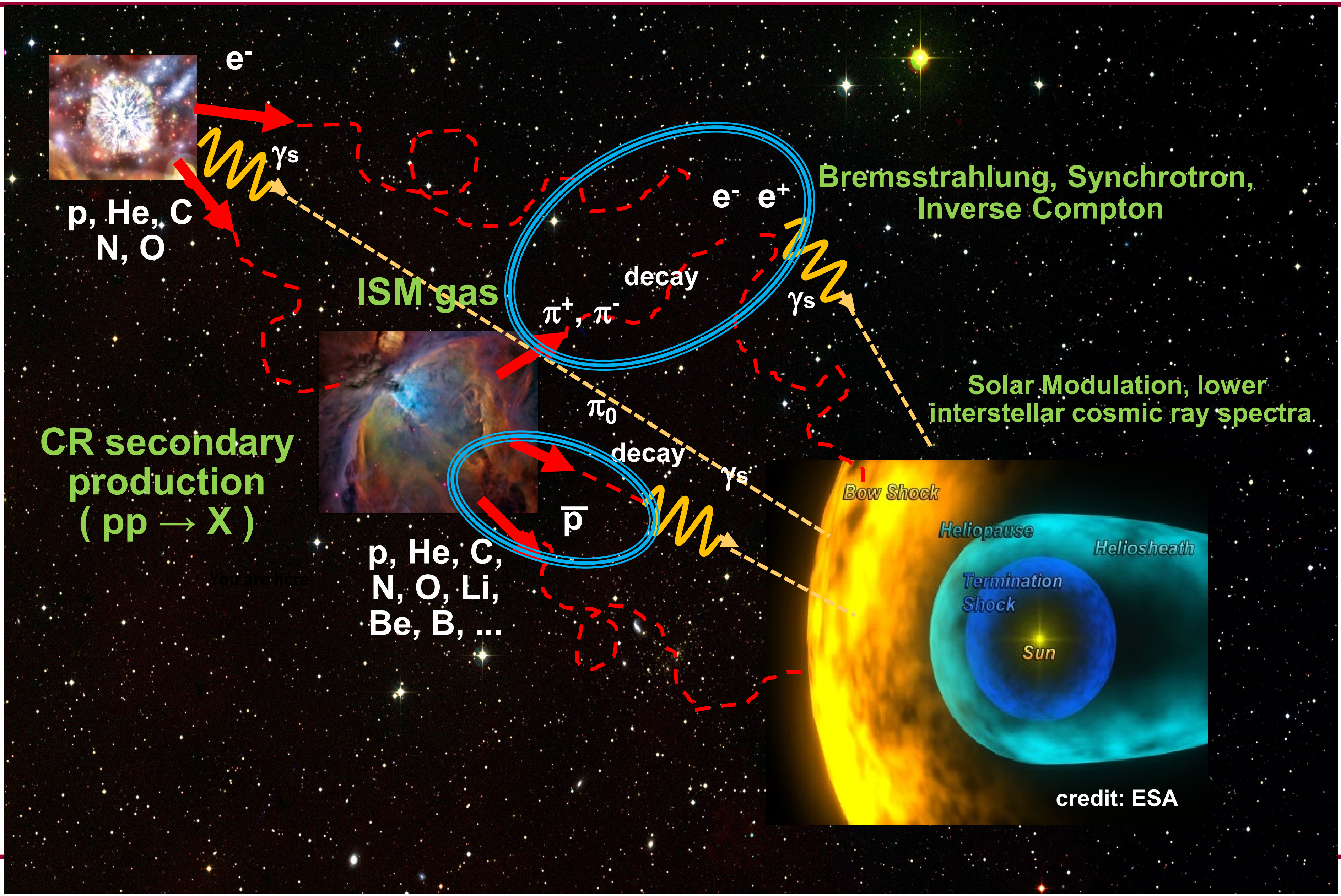
IDM 2024, L'Aquila, Italy
July 11th 2024

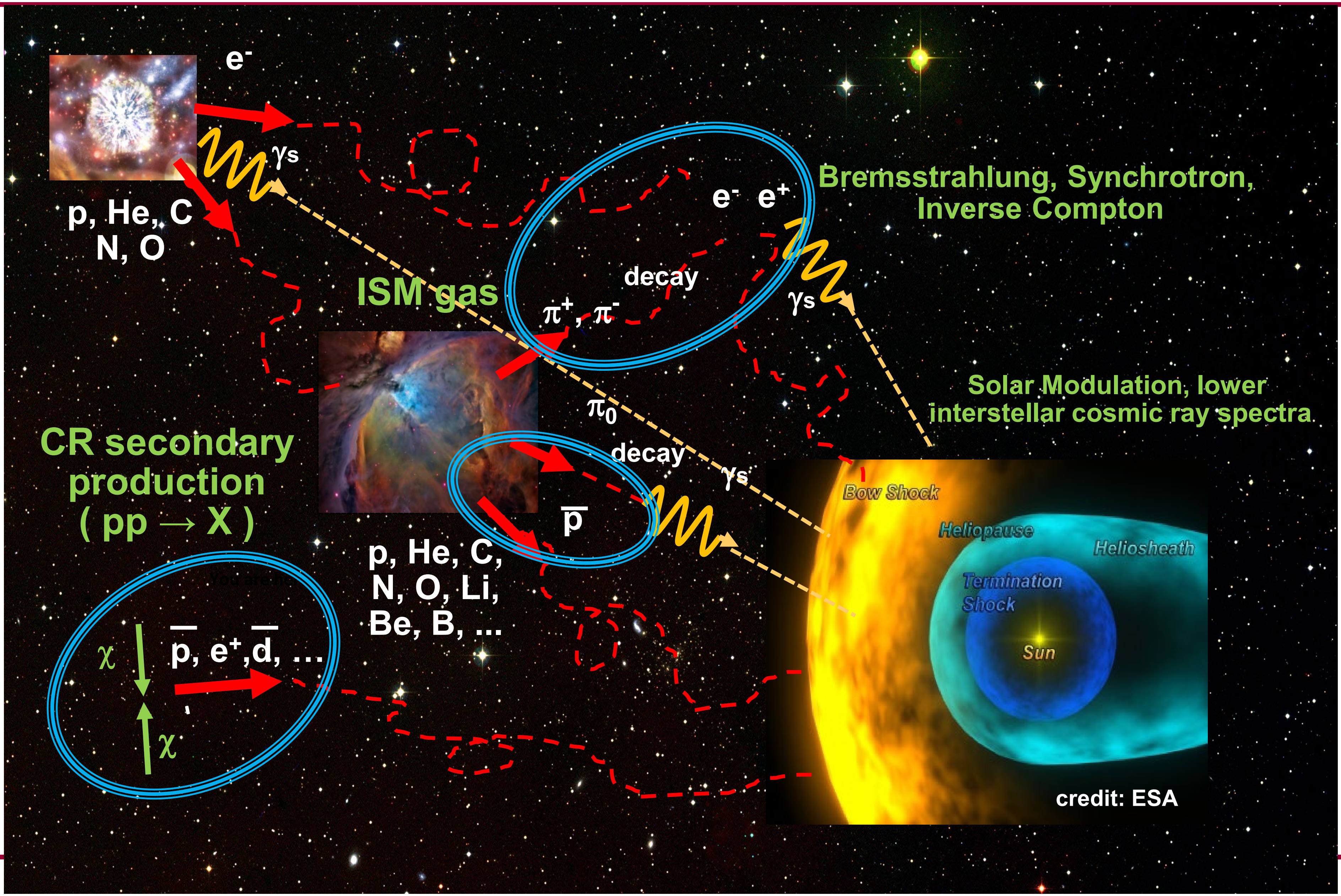
Astrophysics and Cosmology compelling Issues

- Origin and propagation of the cosmic radiation
- Apparent absence of cosmological Antimatter
- **Nature of the Dark Matter that pervades the Universe**

Cosmic Rays and Anti-Particles

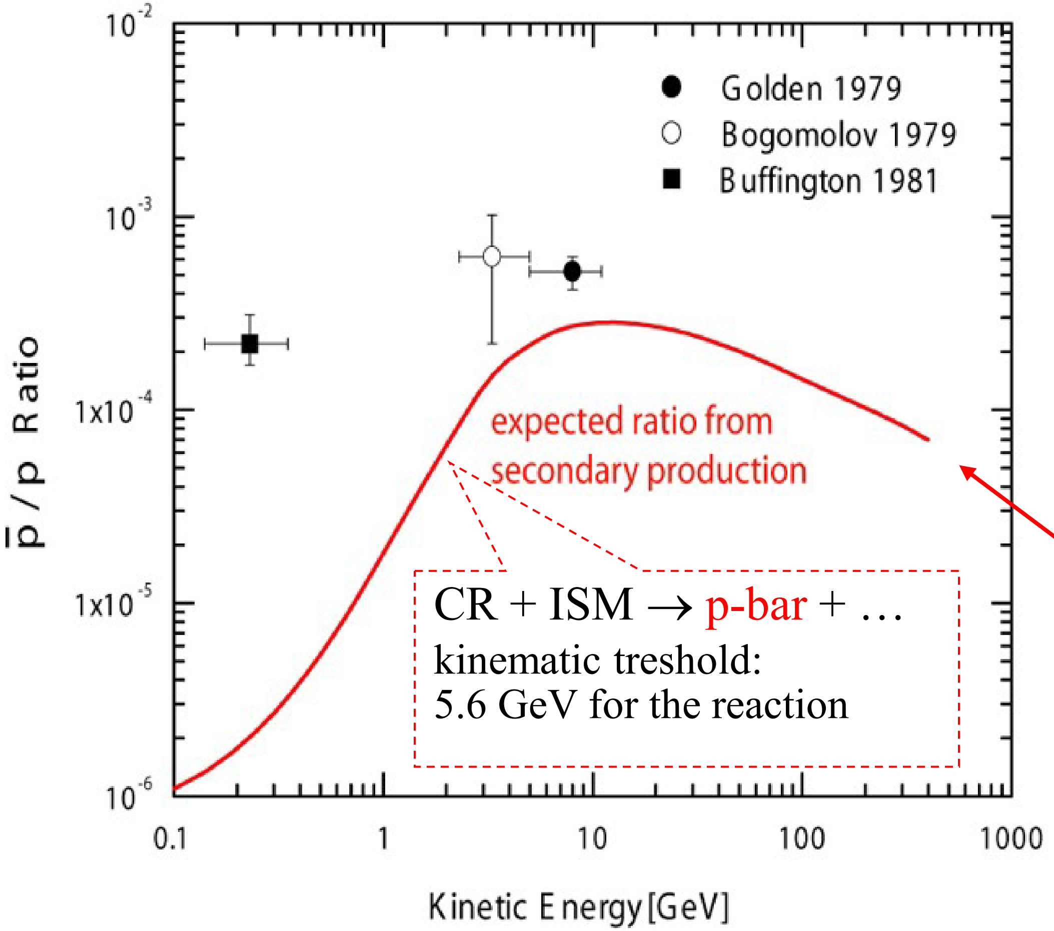


Cosmic Rays and Anti-Particles



Cosmic-ray antiprotons

The first historical measurements on galactic antiprotons

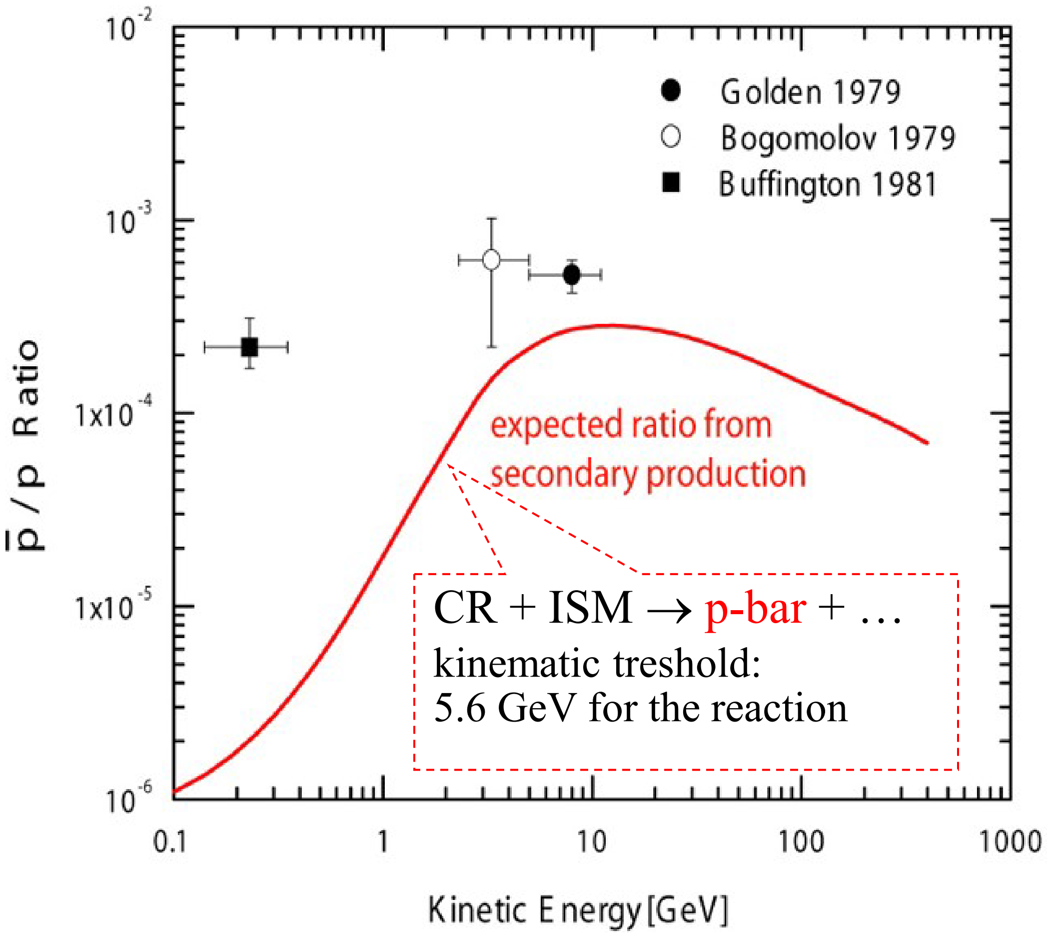


- L. Golden et al., PRL **43** (1979) 1196
- E. Bogomolov et al., 16^{th} ICRC (1979), Tokyo, Japan
- A. Buffington et al., ApJ **248** (1981) 1179

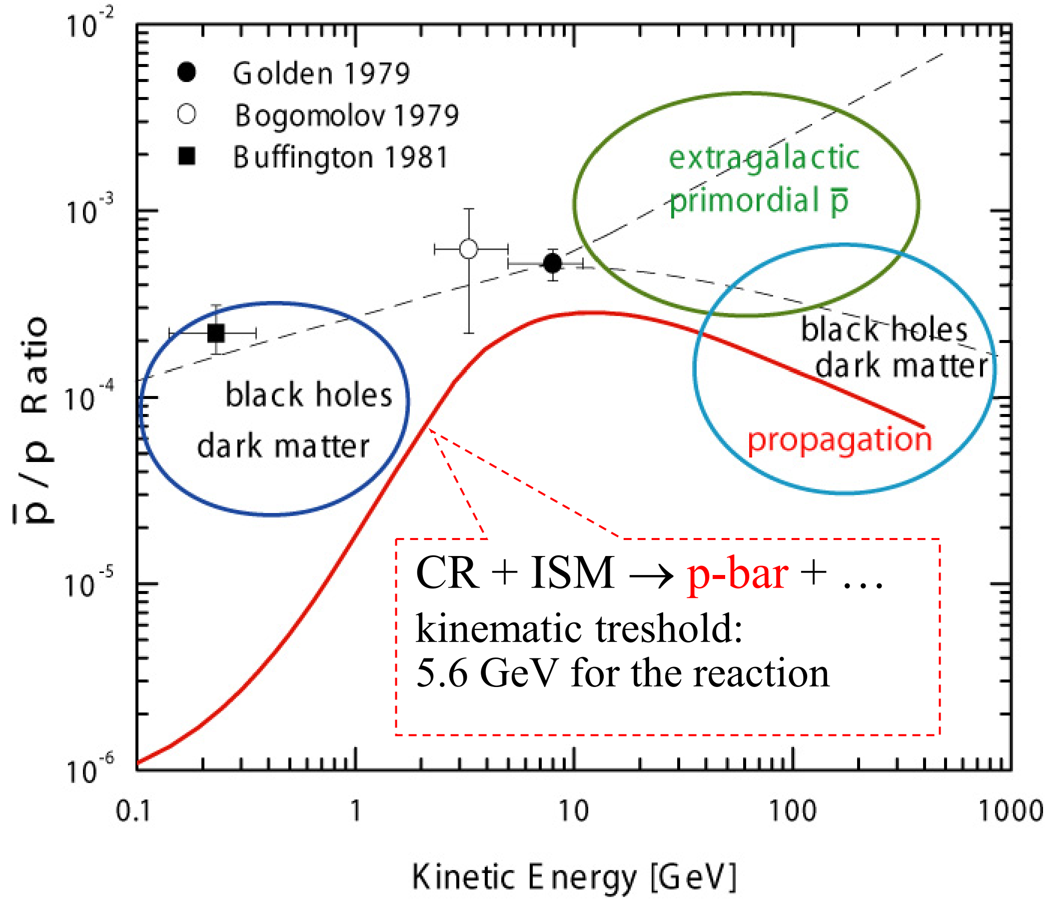
T. K. Gaisser, E. H. Levy, Phys. Rev. D 10 (1974) 1731

Cosmic-ray antiprotons

The first historical measurements on galactic antiprotons



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



e.g. see:

P. Kiraly et al., Nature 293, 120 (1981)

G. Jungman, M. Kamionkowski, and K. Griest, Phys. Rep. 267, 195 (1996)

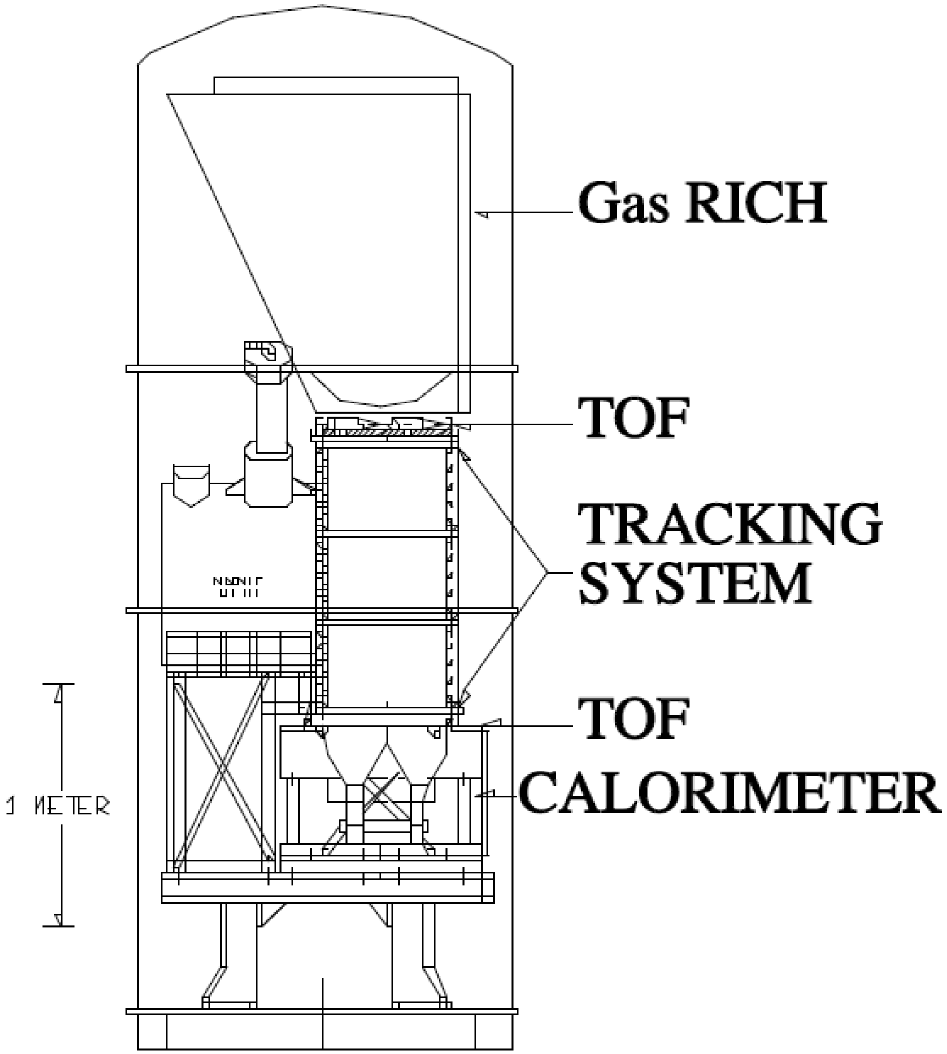
Antimatter and Dark Matter Research

- ✓ MASS – 1,2 (89,91)
- ✓ TrampSI (93)
- ✓ CAPRICE (94, 97, 98)
- ✓ PAMELA (2006-2016)
- ✓ BESS (93, 95, 97, 98, 2000)
- ✓ Heat (94, 95, 2000)
- ✓ IMAX (96)
- ✓ BESS LDF (2004, 2007)
- ✓ AMS-01 (1998)
- ✓ AMS-02 (2011-)
- ✓ GAPS (2024-)

Image credit: NASA (cropped)

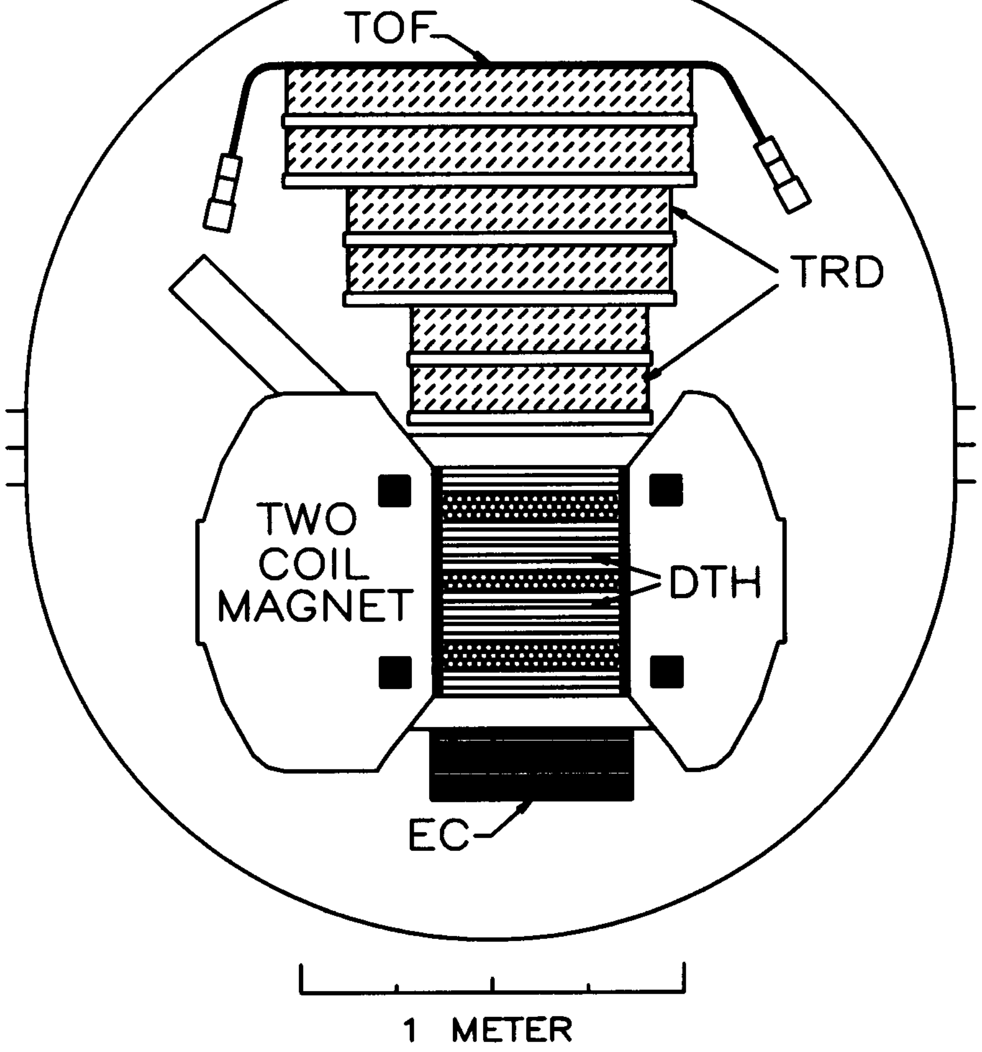
Subnuclear Physics Techniques in Space Experiments

CAPRICE 97-98 M. Boezio et al., ApJ **561** (2001) 787, …



- Charge sign and momentum
- Beta selection
- Z selection
- hadron – electron discrimination

HEAT 94-95



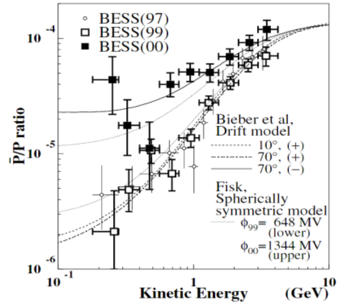
S.W. Barwick et al., ApJL **482** (1997) L191, …

CR antiparticles

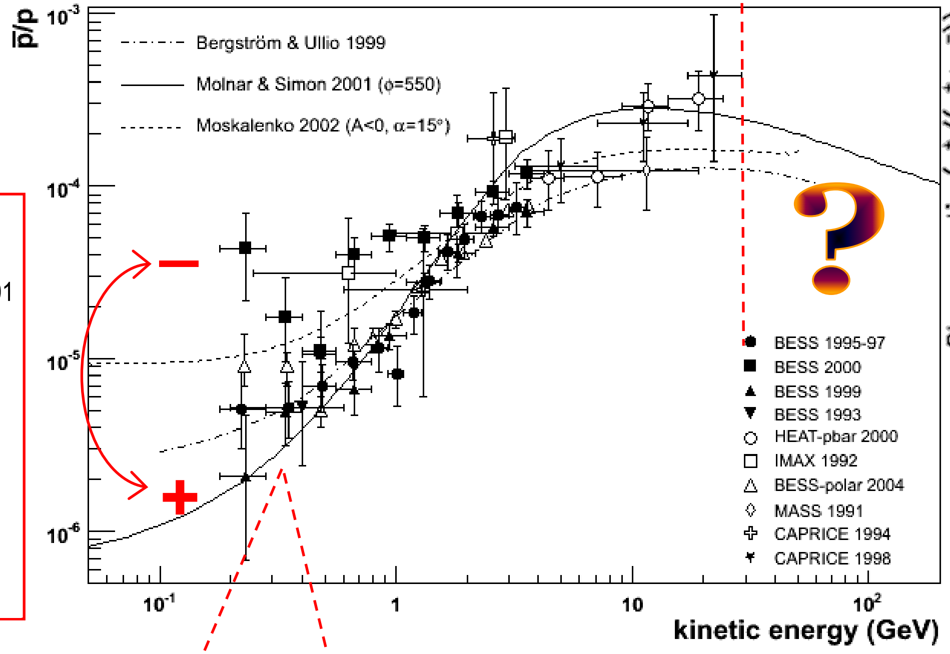
Status in 2006

Charge-dependent solar modulation?

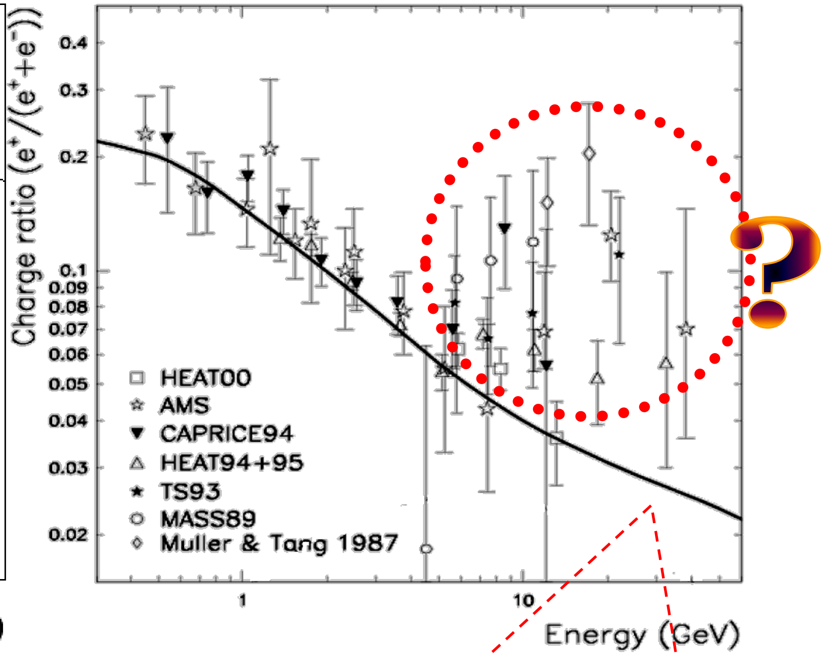
Y. Asaoka et al., PRL **88** (2002) 051101



Antiprotons



Positrons



CR + ISM → **p-bar** + …

kinematic treshold:
5.6 GeV for the reaction

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

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

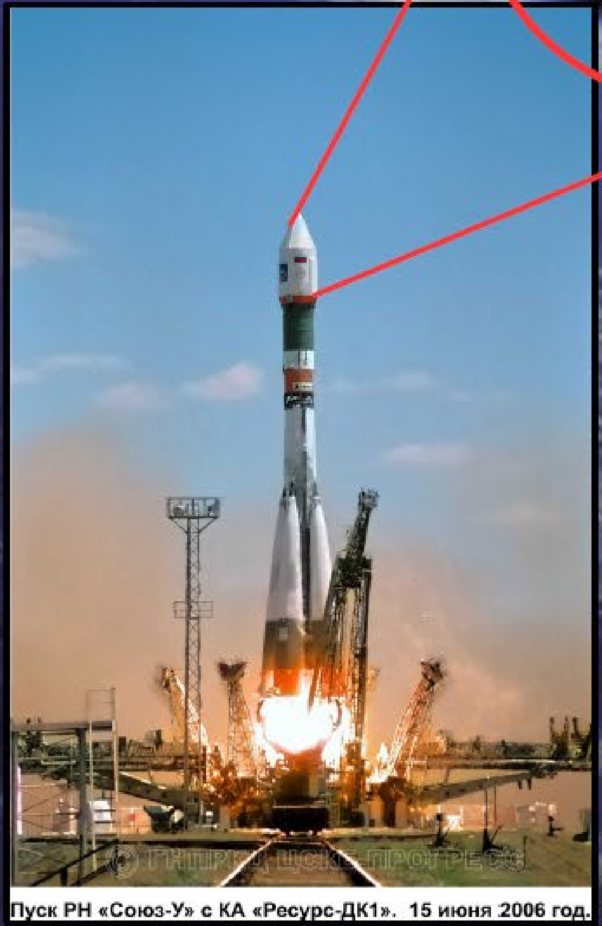
CR + ISM → π^0 + x → $\gamma\gamma$ → $e^{\pm}$

What do we need?

- Measurements at higher energies
- High statistic
- Better knowledge of background
- Continuous monitoring of solar modulation

Long Duration Flights

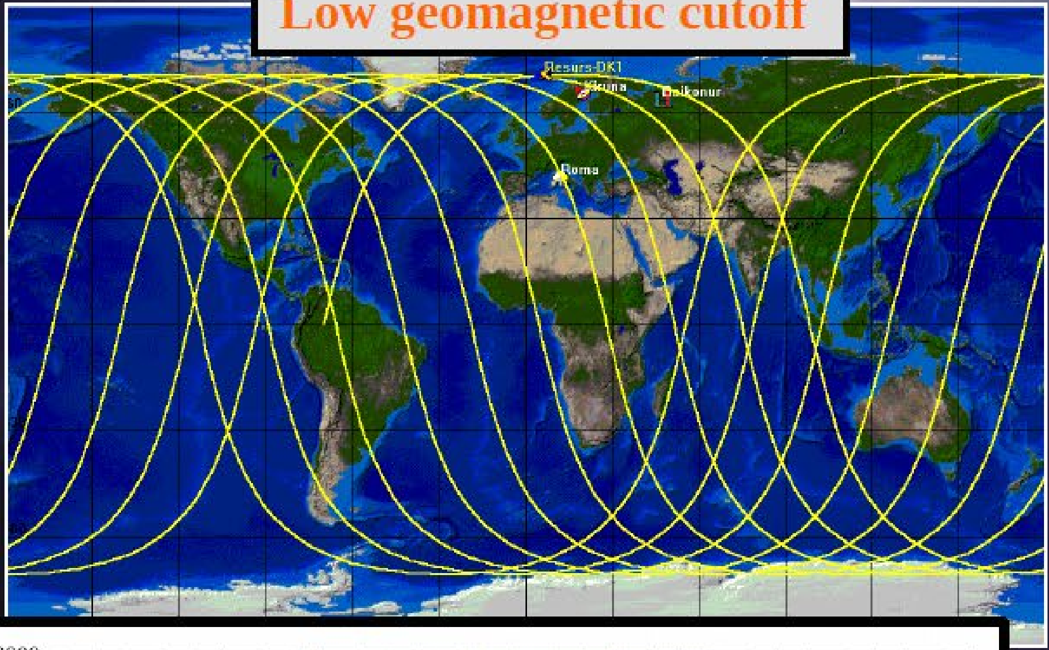
Launch: 15 June 2006 – Stopped in January 2016

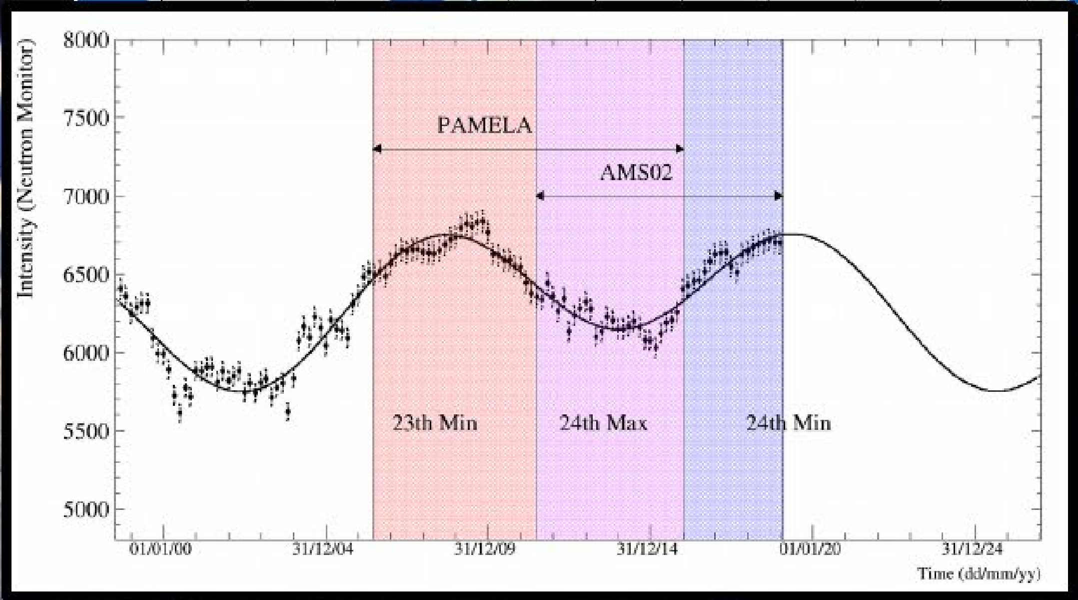


Quasi-polar elliptical orbit
70 degree inclination
350/610 km.
Allows to measure low energy particles (70 MeV electrons)

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

Low geomagnetic cutoff



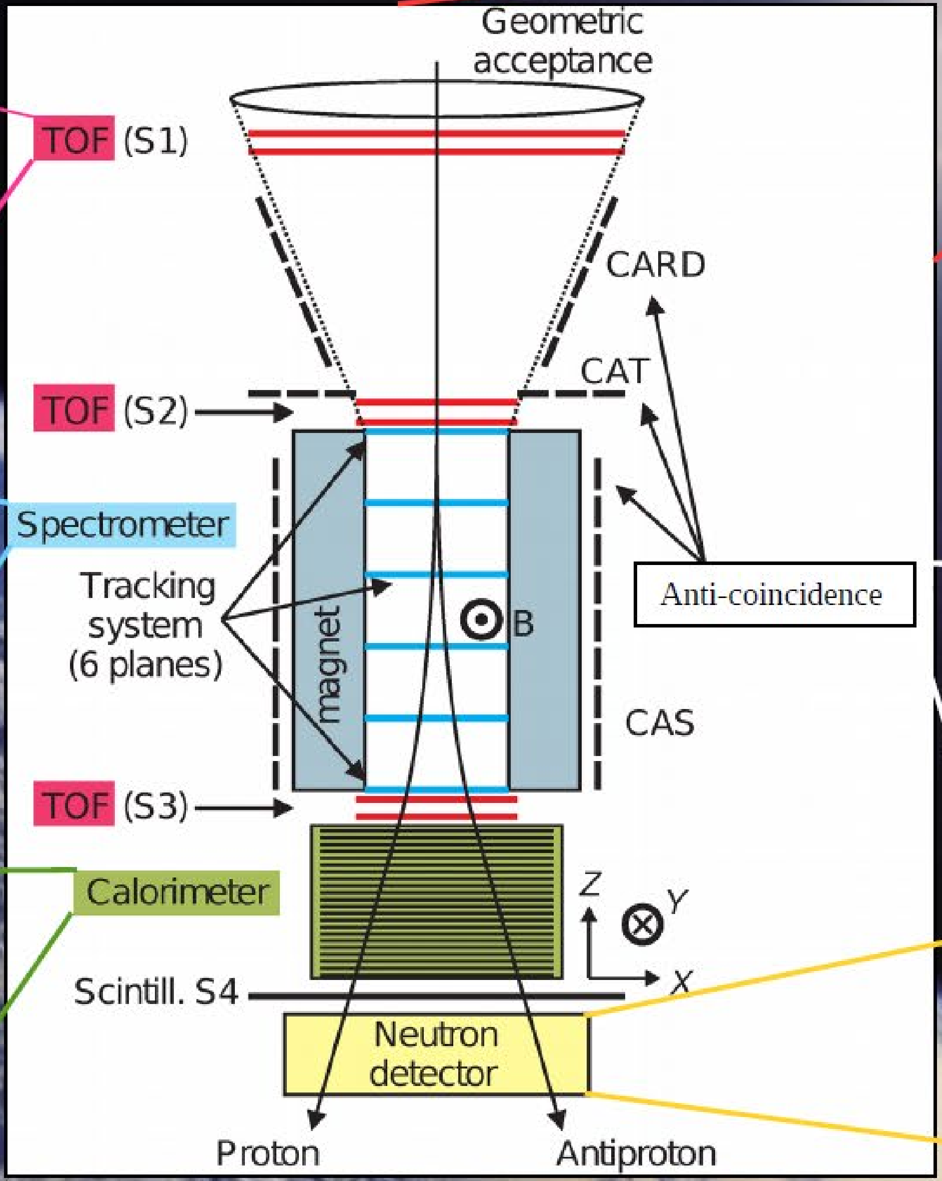


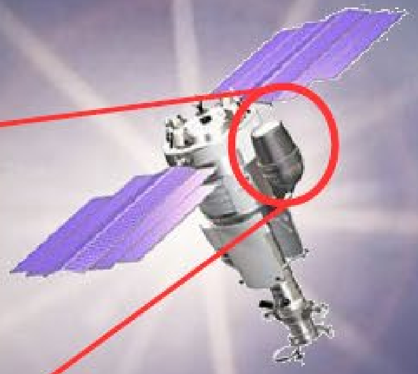
The PAMELA instrument

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.



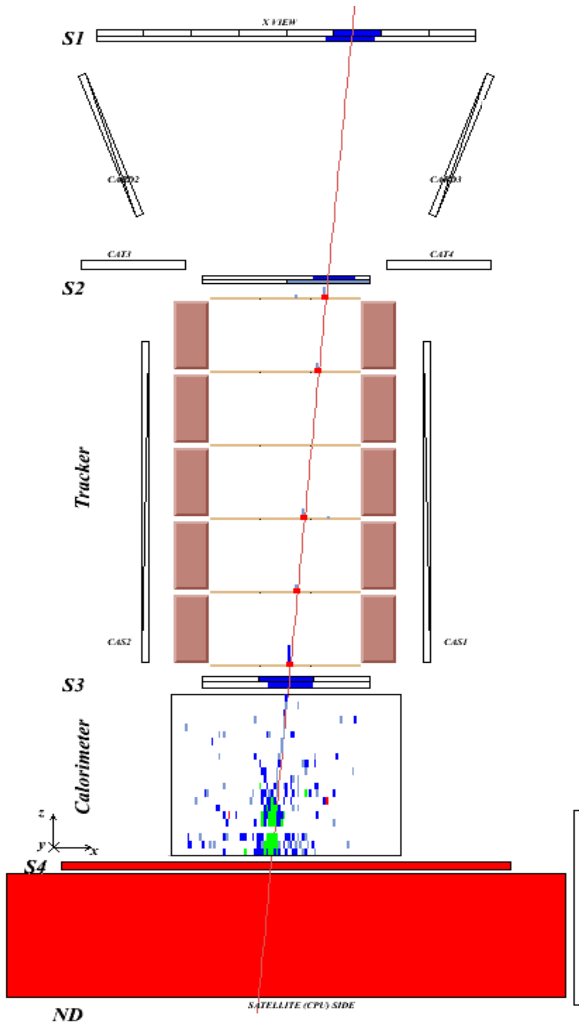


GF: 21.5 cm2 sr
Mass: 470 kg
Size: 130x70x70 cm
Power budget: 360 W

(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: Antiproton / positron identification



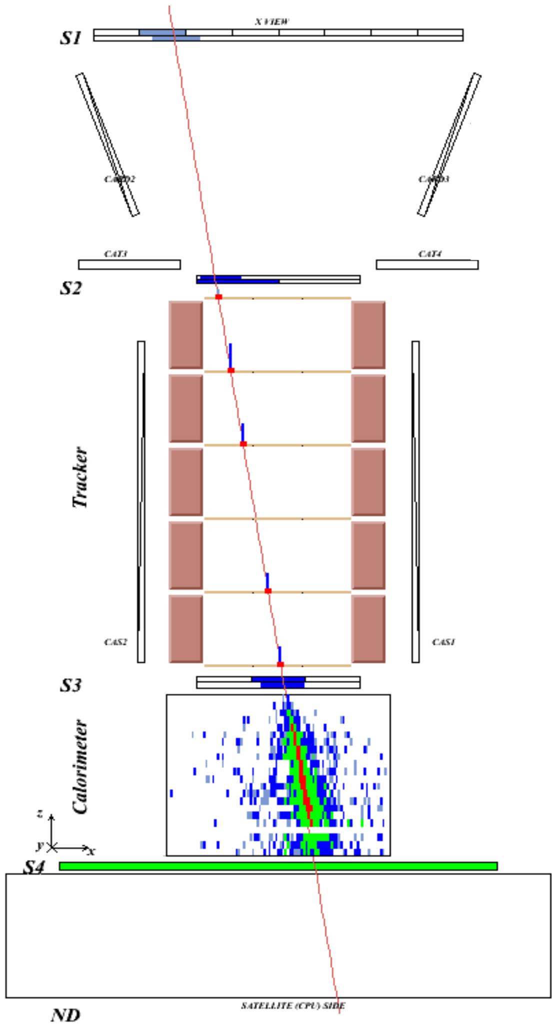
Antiproton
(NB: $e^-/\bar{p} \sim 10^2$)

Time-of-flight:
trigger, albedo rejection, mass determination (up to 1 GeV)

Bending in spectrometer:
sign of charge

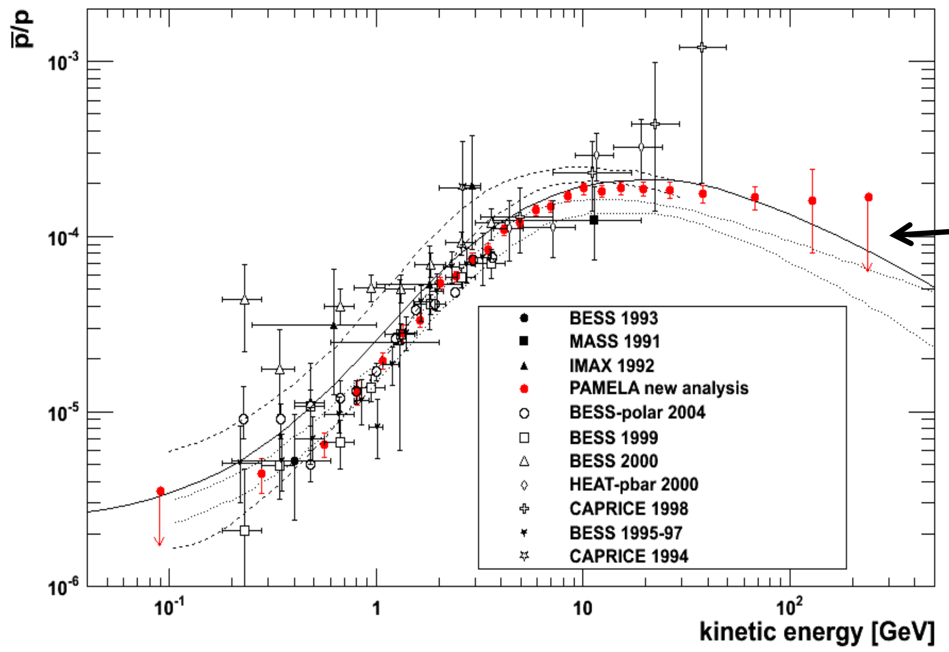
Ionisation energy loss (dE/dx):
magnitude of charge

Interaction pattern in calorimeter:
electron-like or proton-like, electron energy



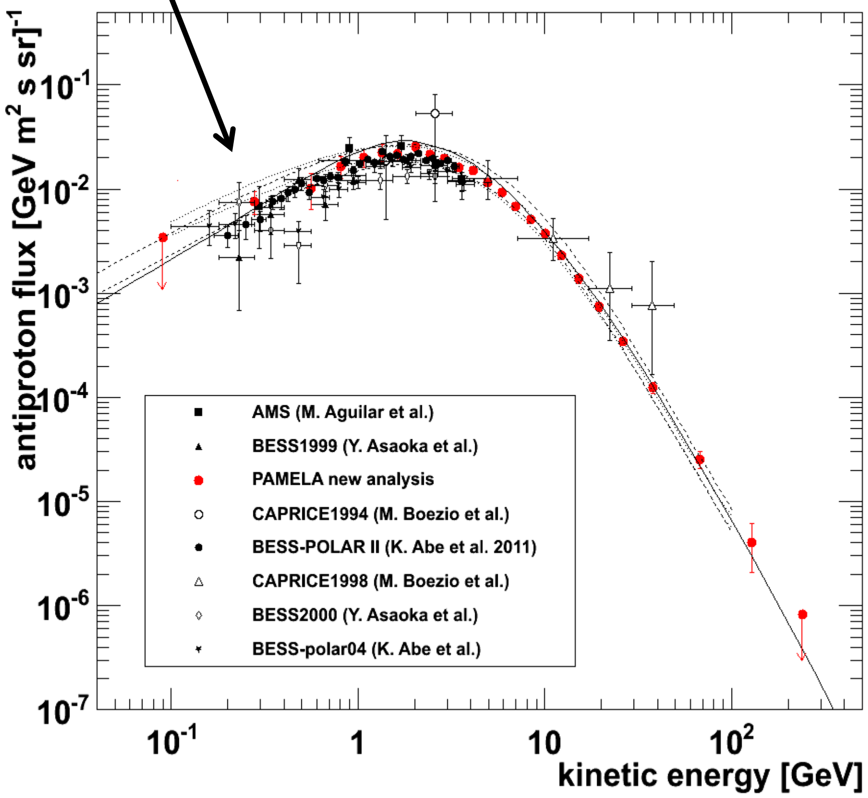
Positron
(NB: $p/e^+ \sim 10^{3\text{-}4}$)

PAMELA Antiparticle Results: Antiprotons

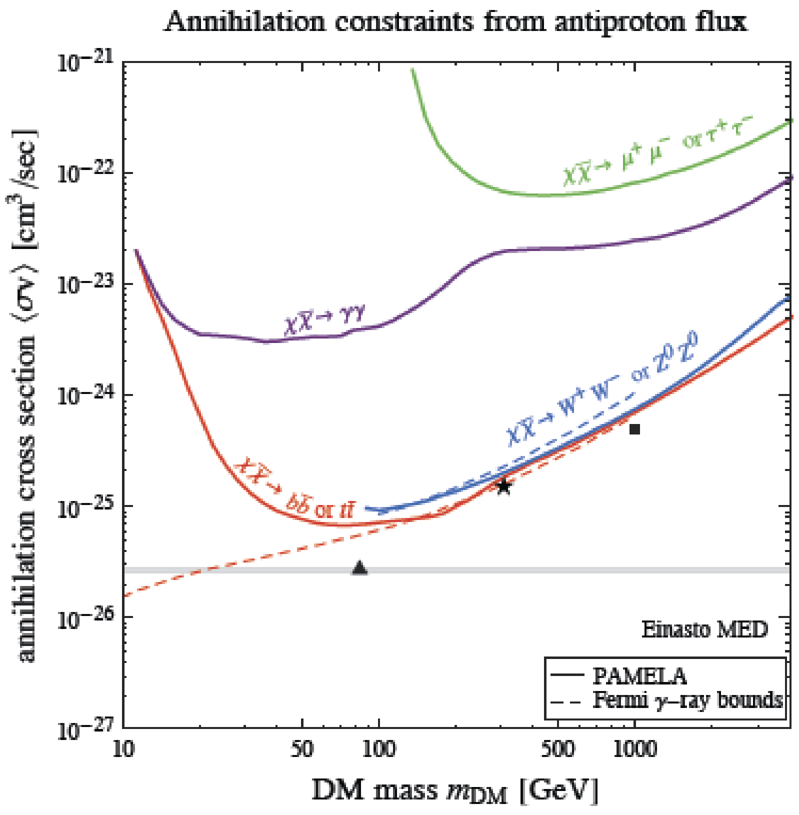


O. Adriani et al,
PRL **102** (2009) 051101;
PRL **105** (2010) 121101;
Phys. Rep. **544** (2014) 323.

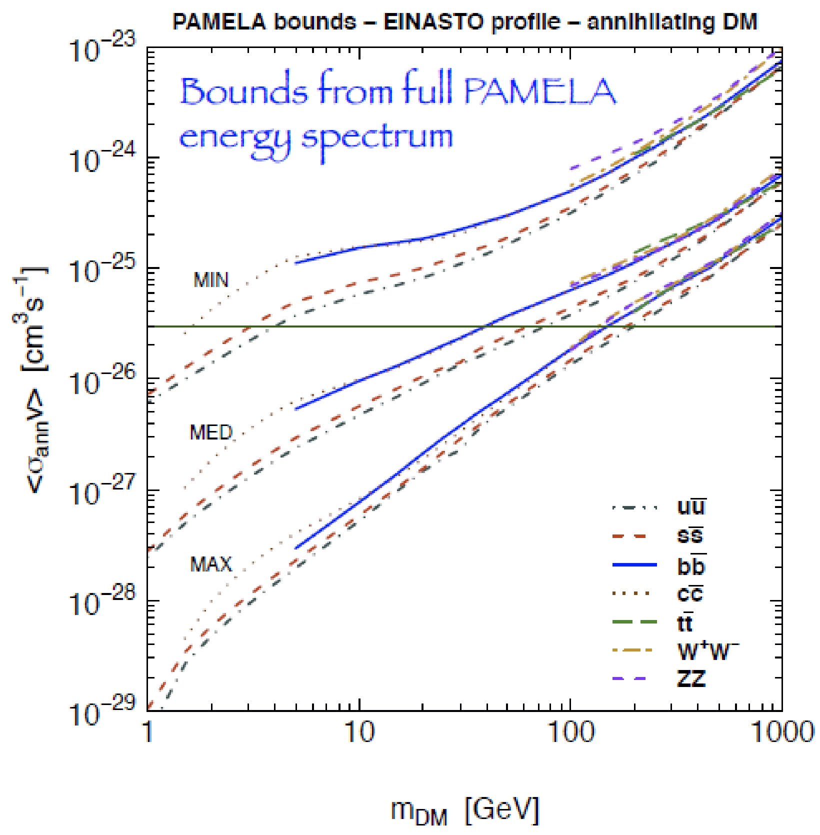
Secondary production calculations



PAMELA Antiprotons and DM limits

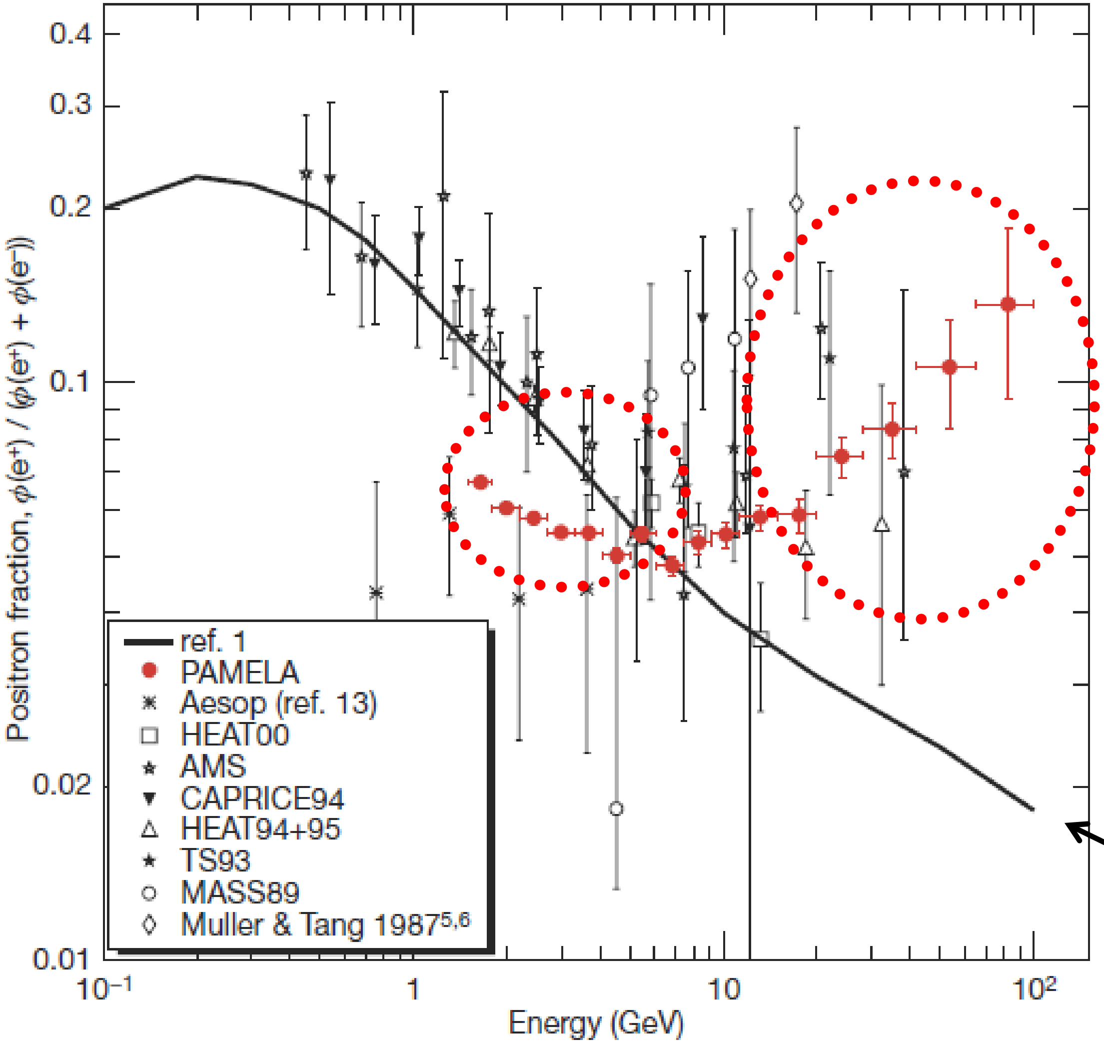


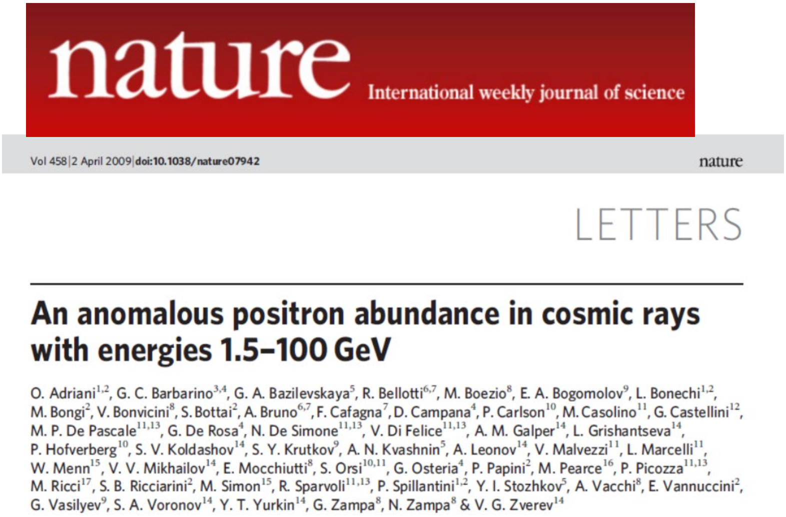
M. Cirelli & G. Giesen, JCAP **1304** (2013) 015



Fornengo, Maccione, Vittino,
JCAP **1404** (2014) 04, 003

PAMELA Results: Positrons




nature International weekly journal of science

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

LETTERS

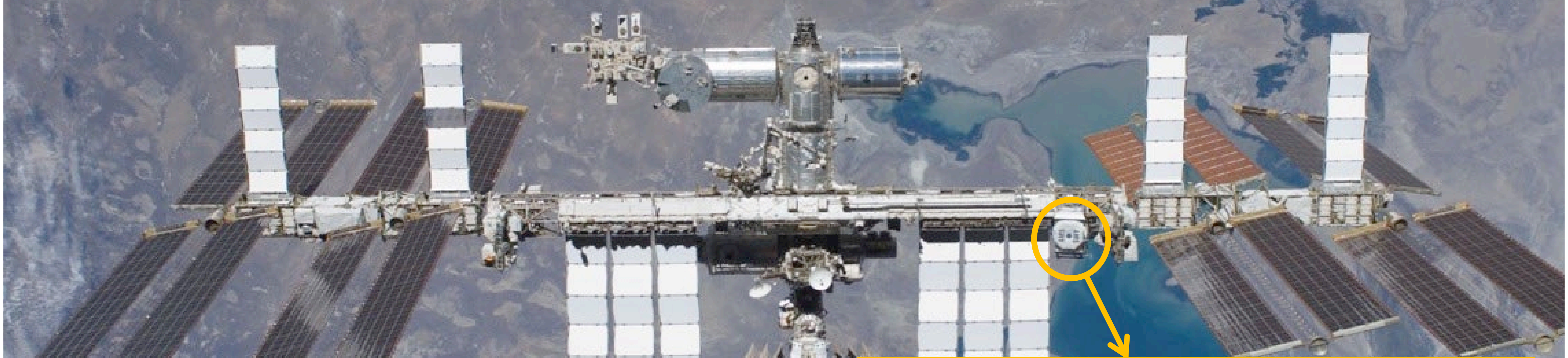
An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

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]

Secondary production
Moskalenko & Strong 98

AMS-02: The Alpha Magnetic Spectrometer

**The prototype, AMS-01, flown in 1998. AMS-02 has been designed and built in 2000-2011.
Installed in 2011 on the ISS. Takes data continuously since then.
AMS-02 has collected more than 230 billion cosmic rays up to now.**

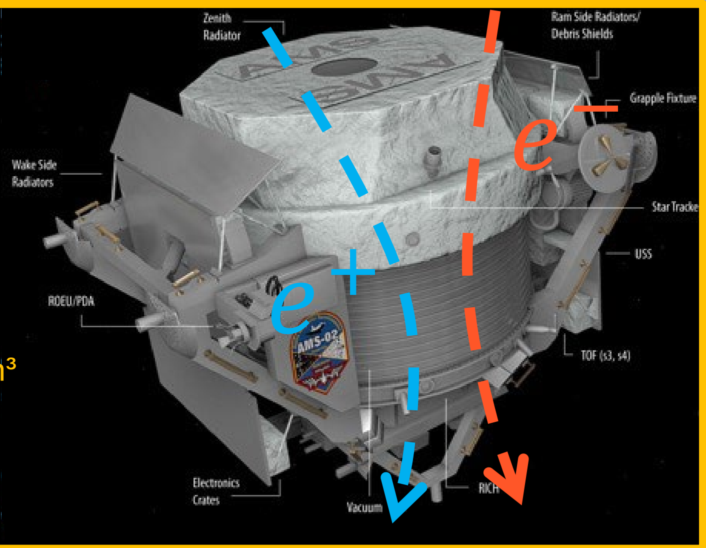


International Space Station (ISS)

Altitude	~ 400 km
Inclination	51°
Period	93 min
Construction	1998 - …
Dimensions	73×109 m^2
Weight	420 t

AMS-02

Launch	16/5/2011
	STS-134
	Endeavour
Dim.	$3 \times 4 \times 5$ m^3
Weight	7.5 t
Power	2500 W

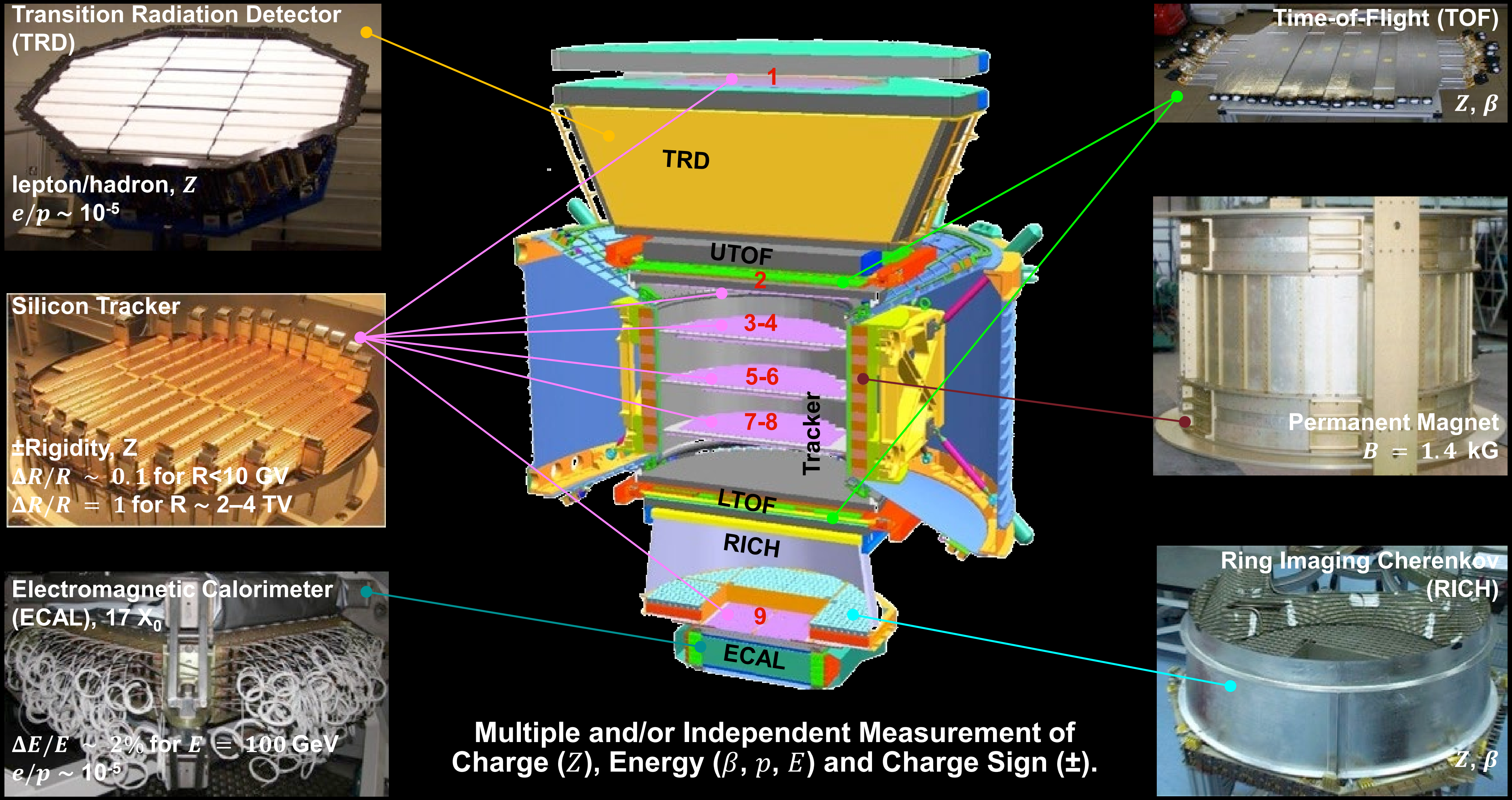


Courtesy of A. Oliva

AMS-02: A TeV Multi-Purpose Spectrometer

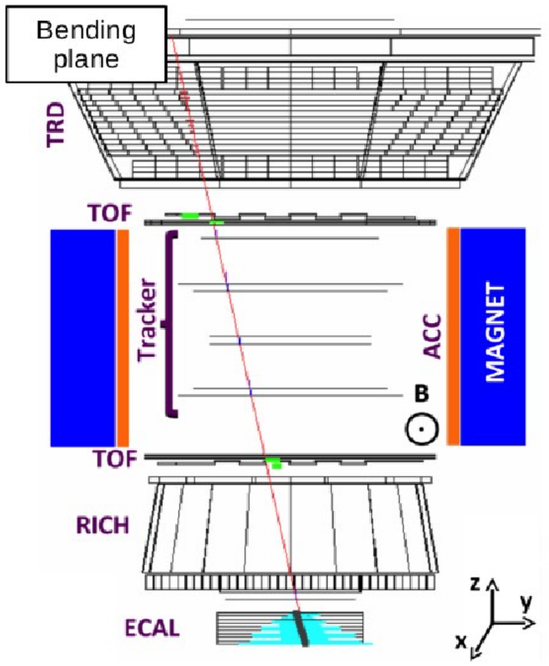
Courtesy of A. Oliva

AMS-02 separates hadrons from leptons, matter from anti-matter, chemical and isotopic composition from fraction of GeV to multi-TeV.



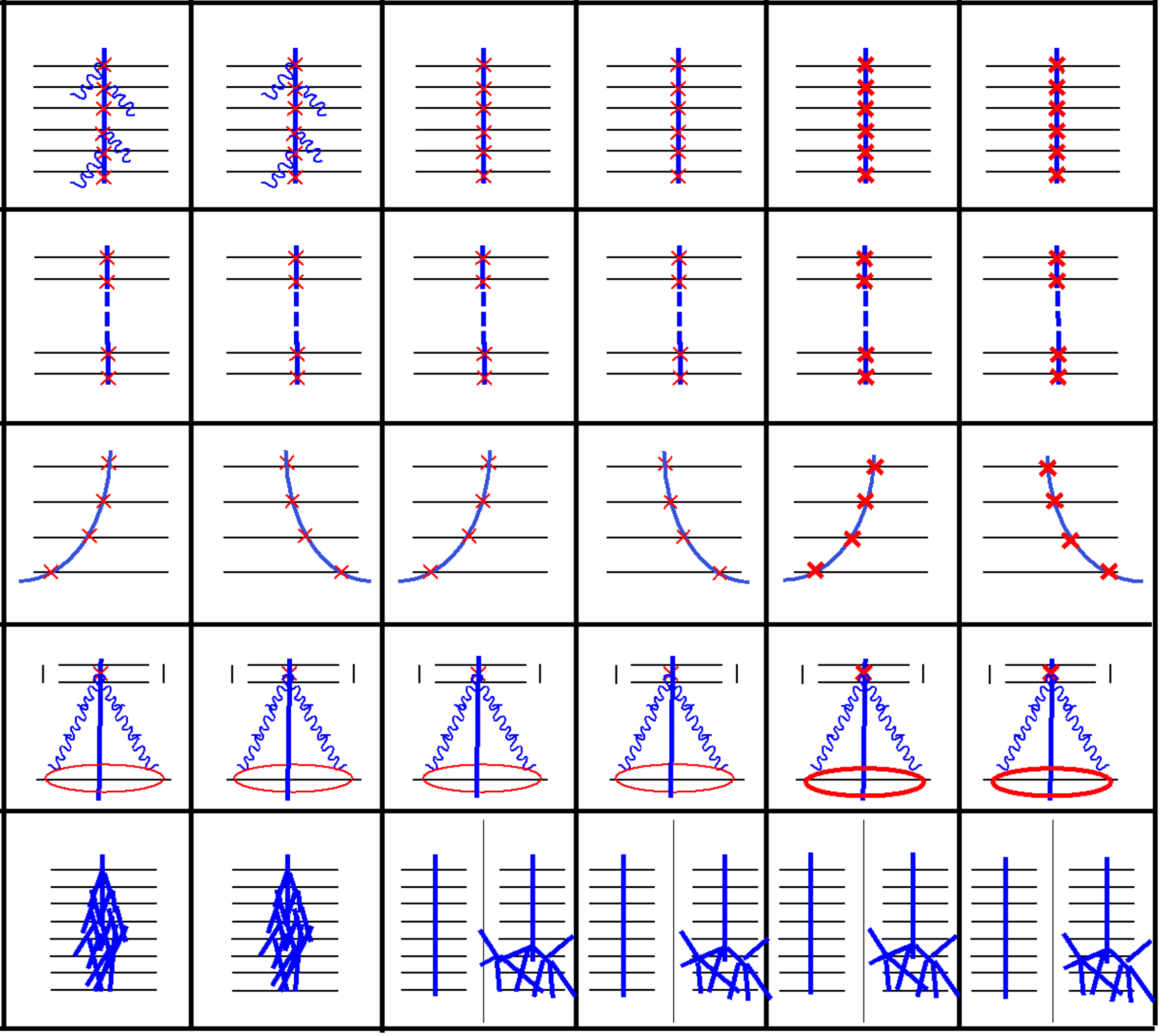
Multiple and/or Independent Measurement of Charge (Z), Energy (β, p, E) and Charge Sign (±).

AMS-02: A TeV Multi-Purpose Spectrometer

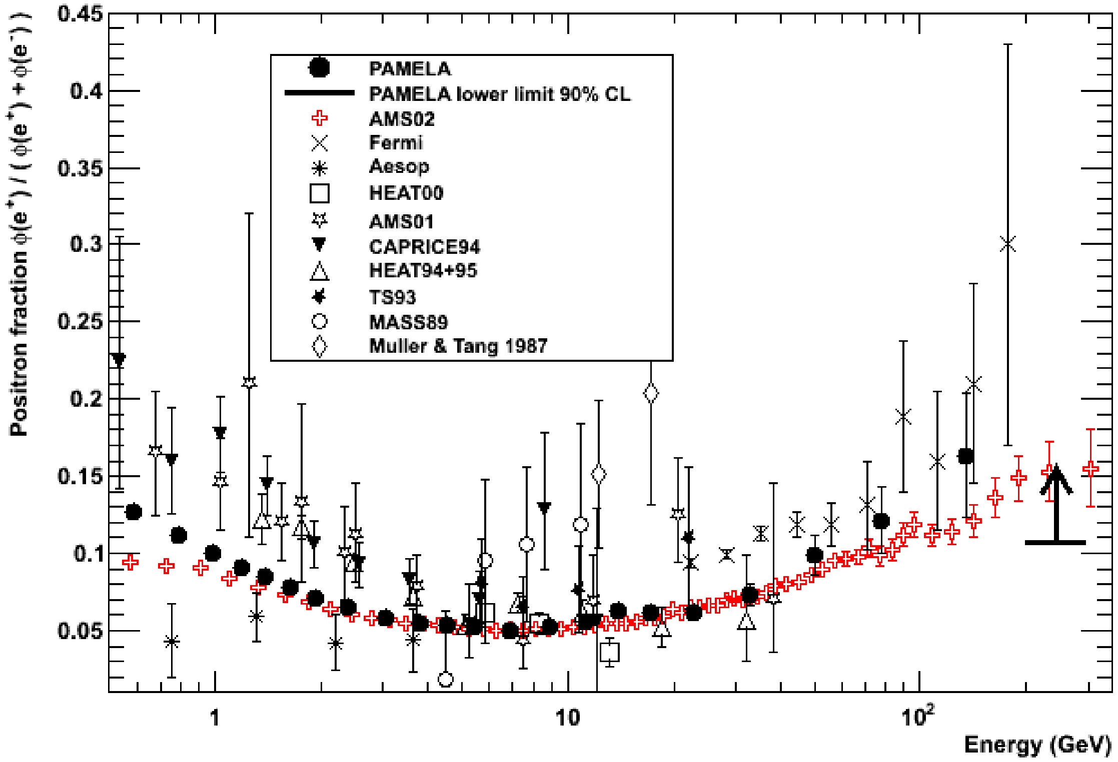


Courtesy of A. Oliva

	e^+	e^-	p	$\bar{p}$	He	$\overline{He}$	
TRD 20 layers							e/p separation charge, z
TOF 4 layers							trigger velocity, β charge, z
TRK 9 layers							rigidity, p/Z sign, $\pm$ charge, z
RICH							velocity (β) charge, z
ECAL 18 layers							$e^{\pm}$,γ energy e/p separation EM-trigger

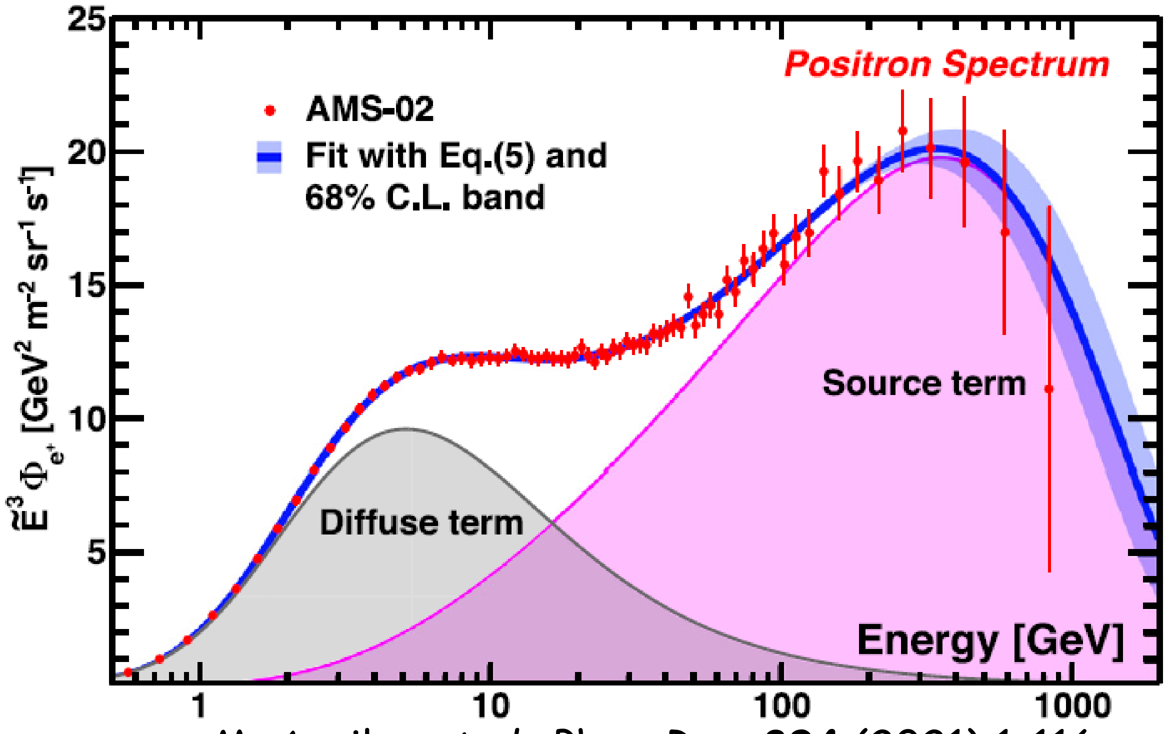


AMS-02: Positrons



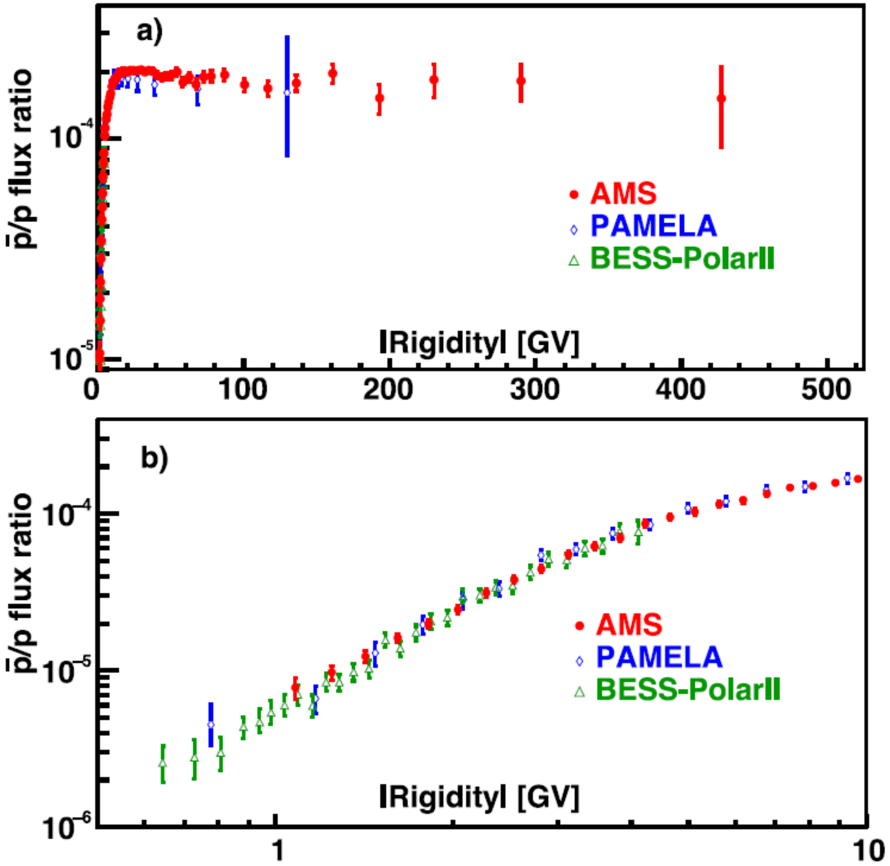
M. Aguilar *et al.*, PRL **110** (2013) 141102

$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}[C_d\,(\hat{E}/E_1)^{\gamma_d} + C_s\,(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)]$$

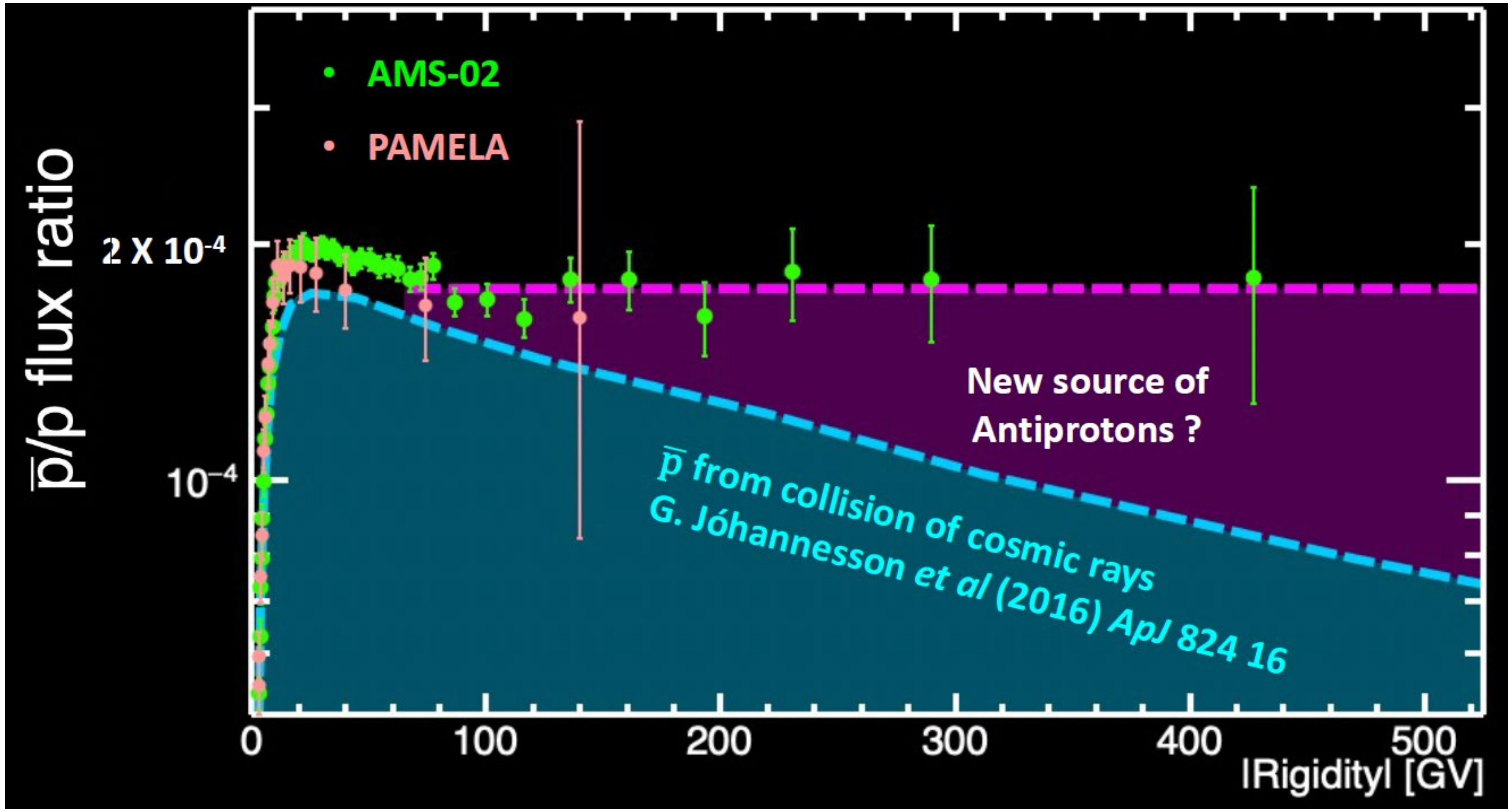


M. Aguilar *et al.*, Phys. Rep. **894** (2021) 1-116

AMS-02: antiprotons



M. Aguilar *et al.*, Phys. Rep. **894** (2021) 1-116

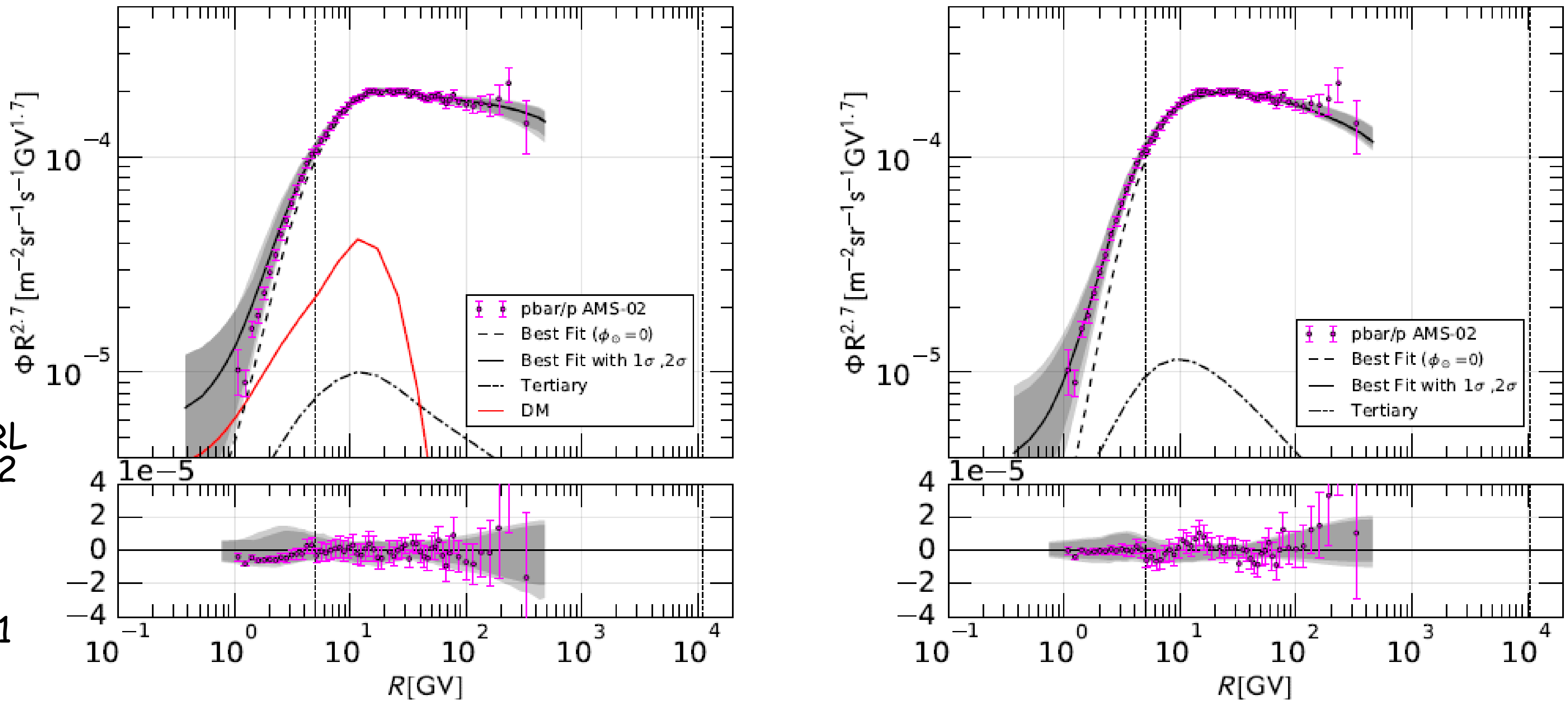


A. Kounine, **PAW'24**, 2023

Anomaly in the AMS-02 antiproton flux?

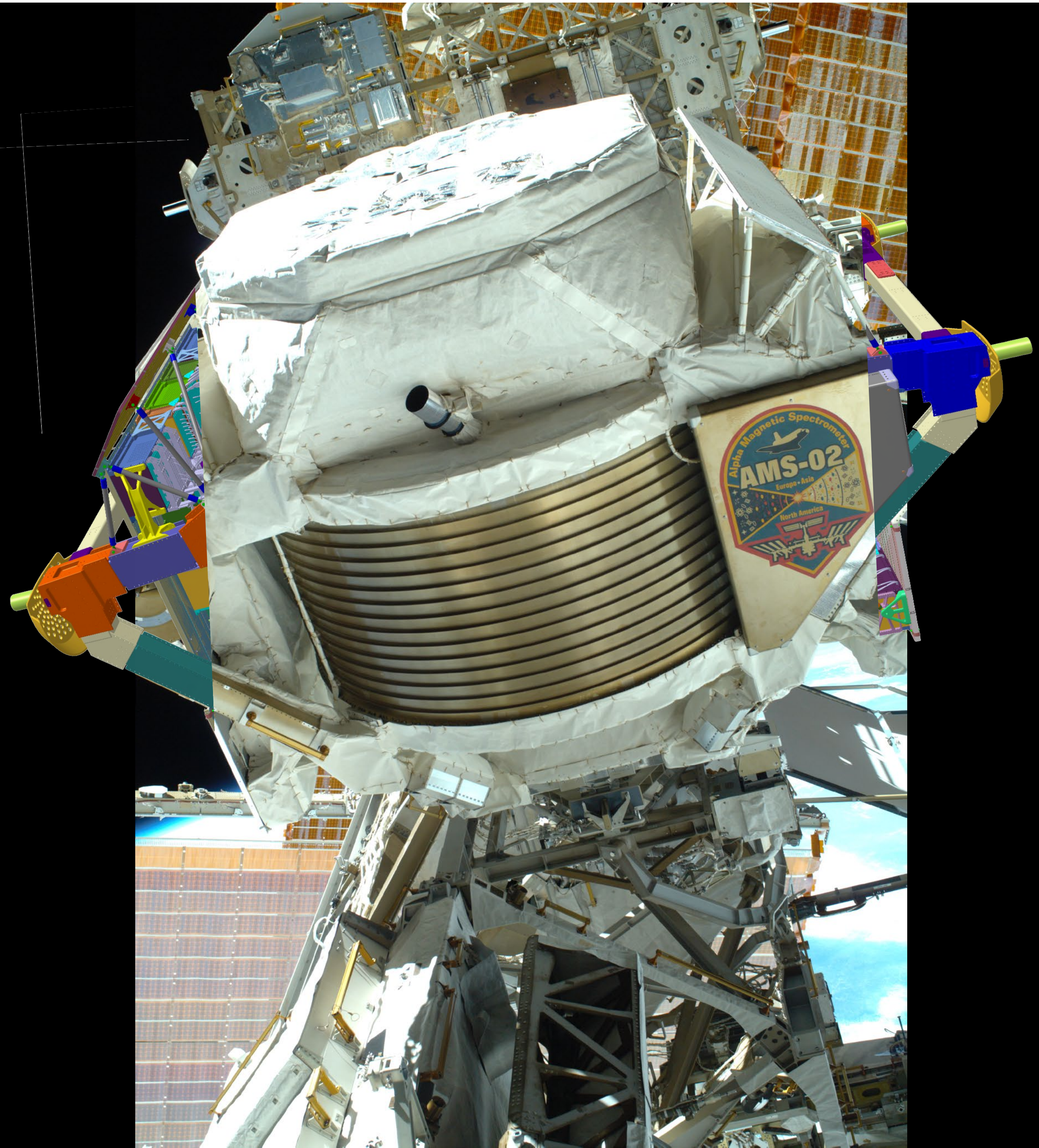
A. Cuoco et al., PRL **118** (2017) 191102

See also
M. Cui et al., PRL **118** (2017) 191101



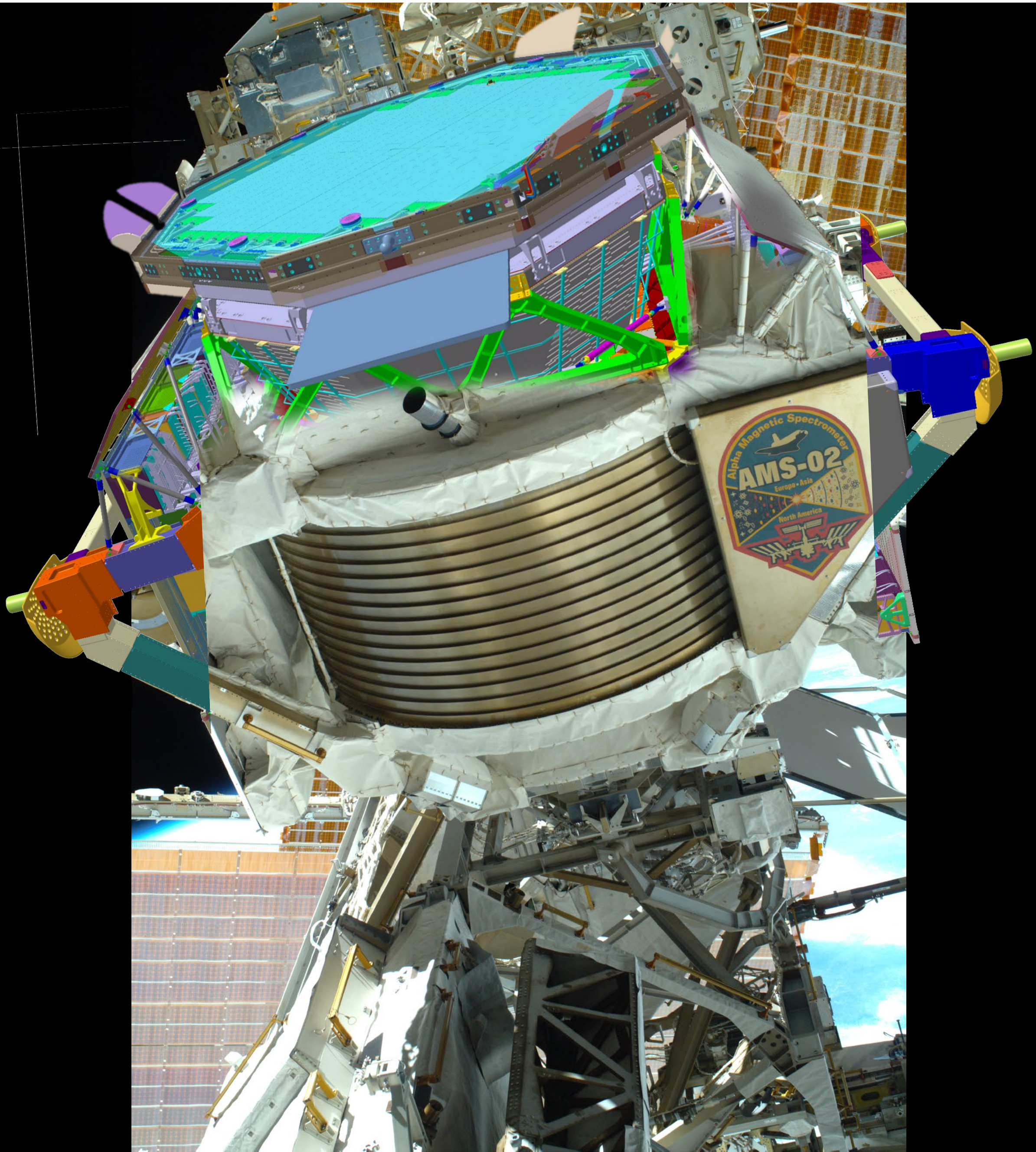
A. Cuoco et al: "A deeper examination of such a potential signal would require a more accurate determination of the antiproton production cross-section, to constrain the flux of secondary antiprotons, as well as an accurate modeling of solar modulation at low rigidities of less than about 5 GV."

The AMS-02 Upgrade (AMS-02.2)



Courtesy of A. Oliva

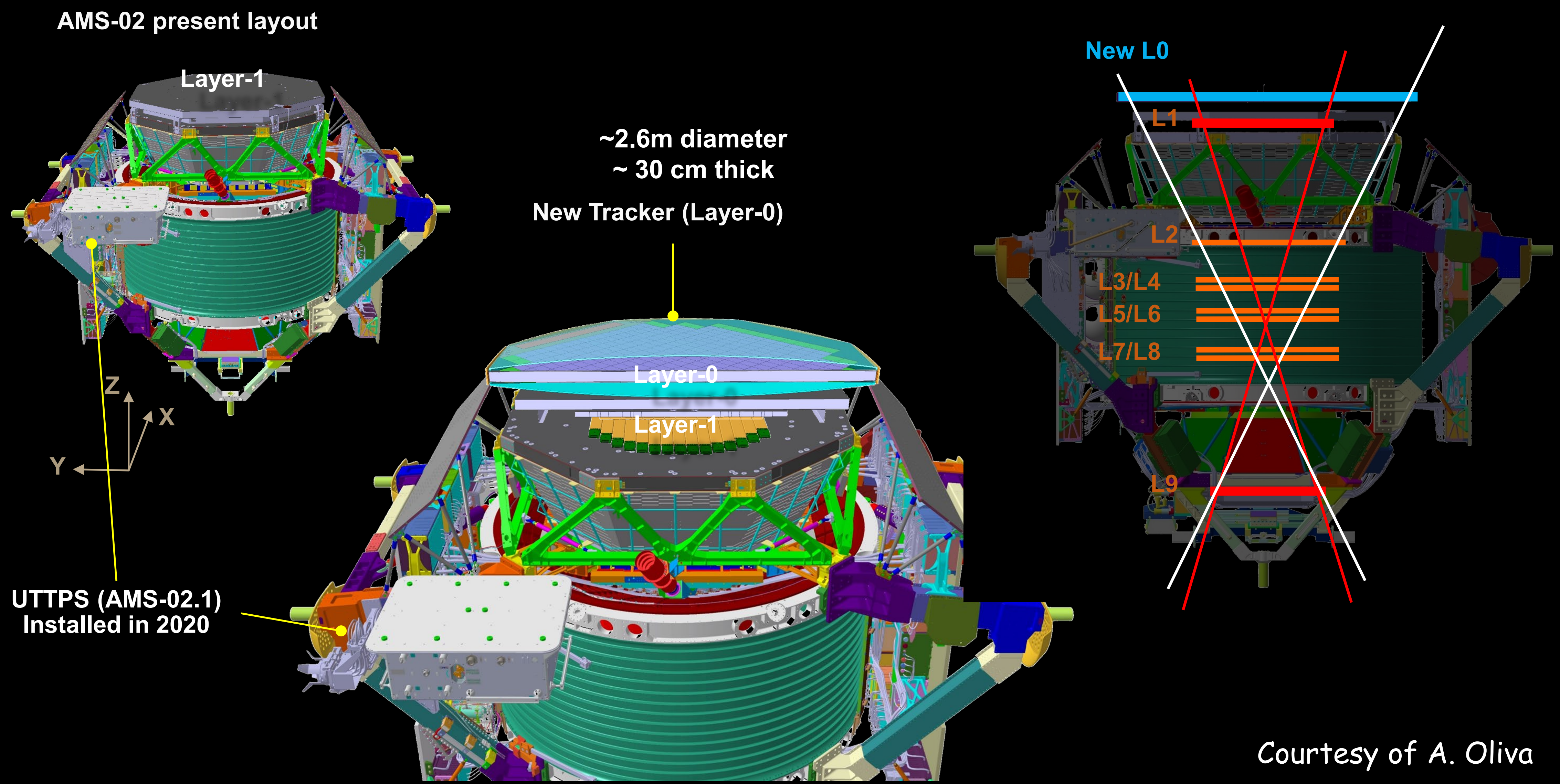
The AMS-02 Upgrade (AMS-02.2)



Courtesy of A. Oliva

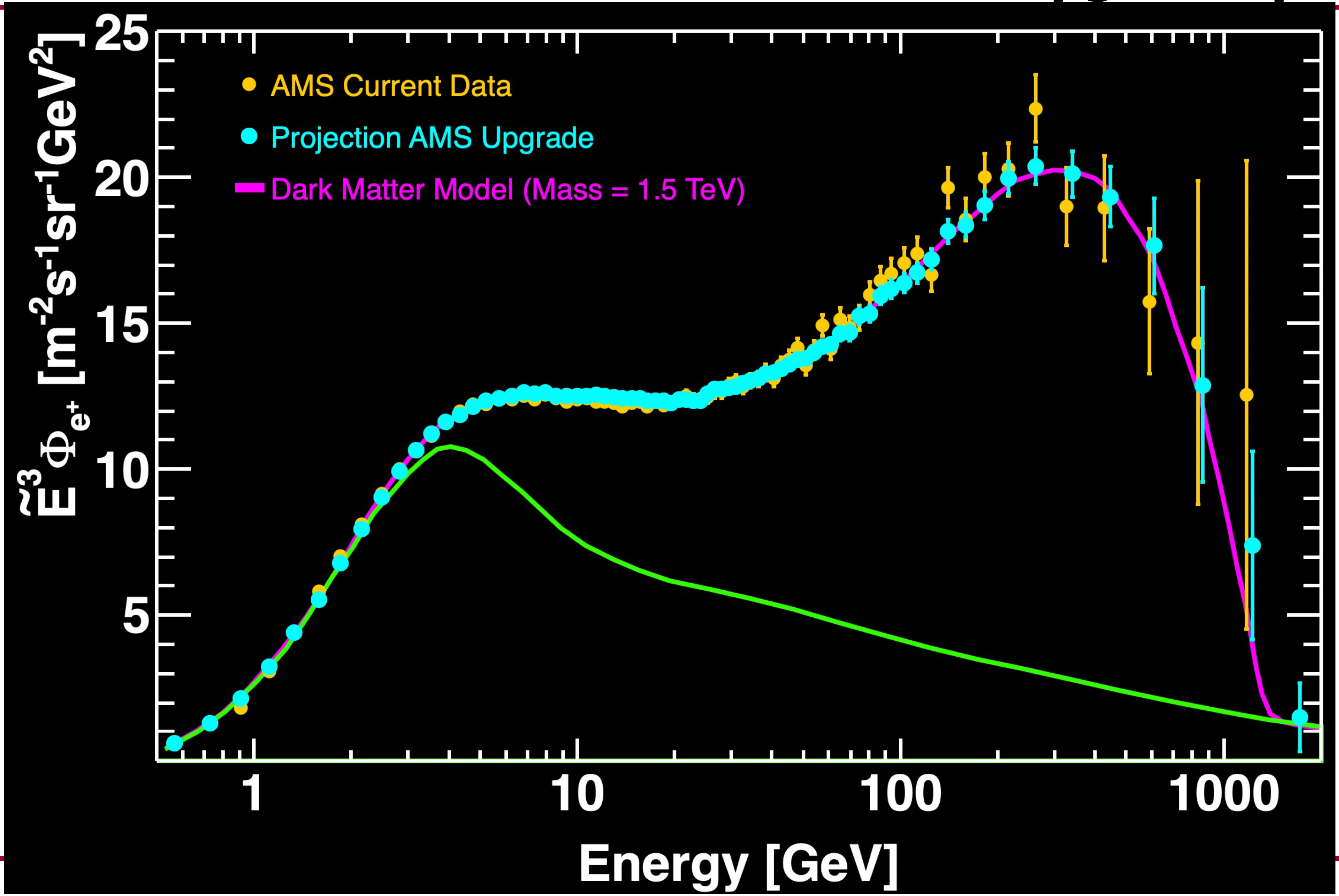
A New Tracking Layer (Layer-0)

The increase of 300% in the acceptance will allow for the best use of the time left on the ISS, allowing higher rate in data collection for many analysis channels (positrons, nuclei, …).



Courtesy of A. Oliva

Future measurements with AMS-02 upgrade: positrons



A. Kounine, PAW'24, 2023

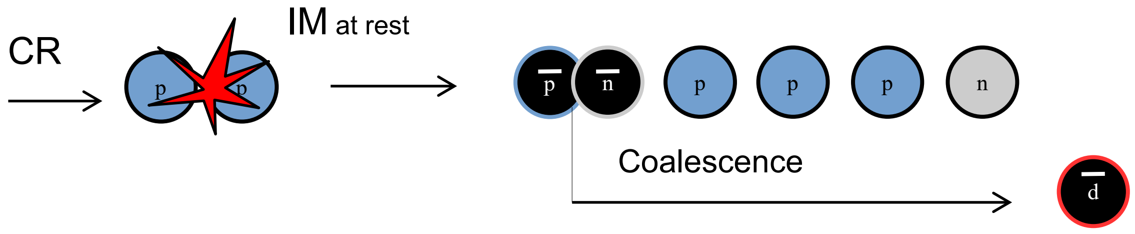
Background “free” Signals?

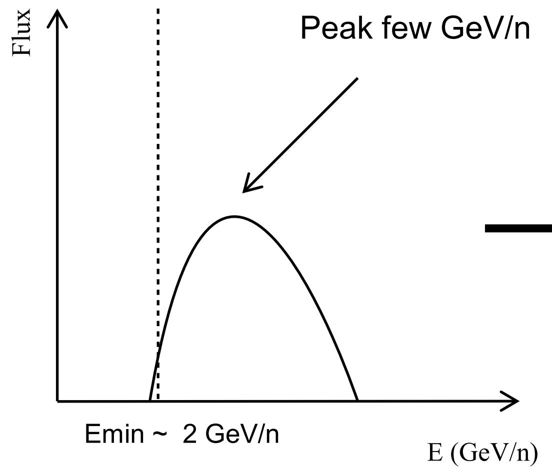
Antinuclei

See also today 14:00-16:00 session in GSSI, Sala Rossa

Antideuteron: a background free signal?

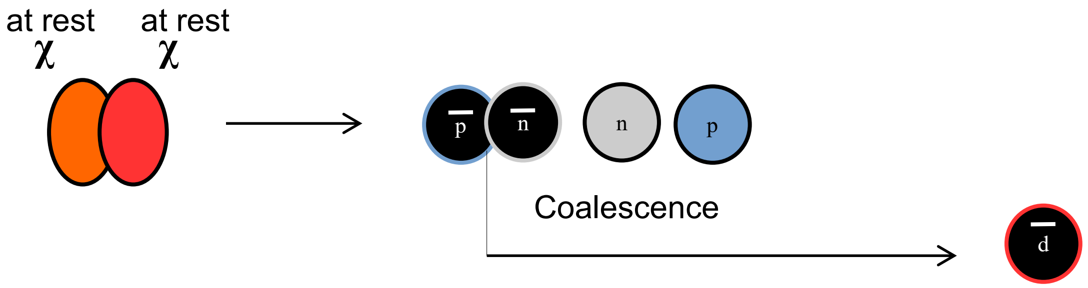
Secondary antideuteron

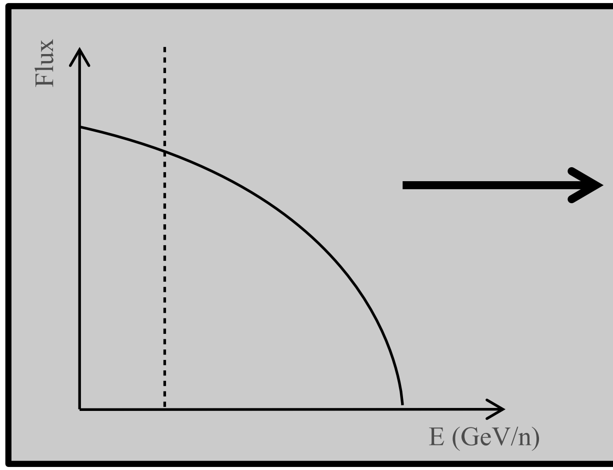




Strongly suppressed below few GeV

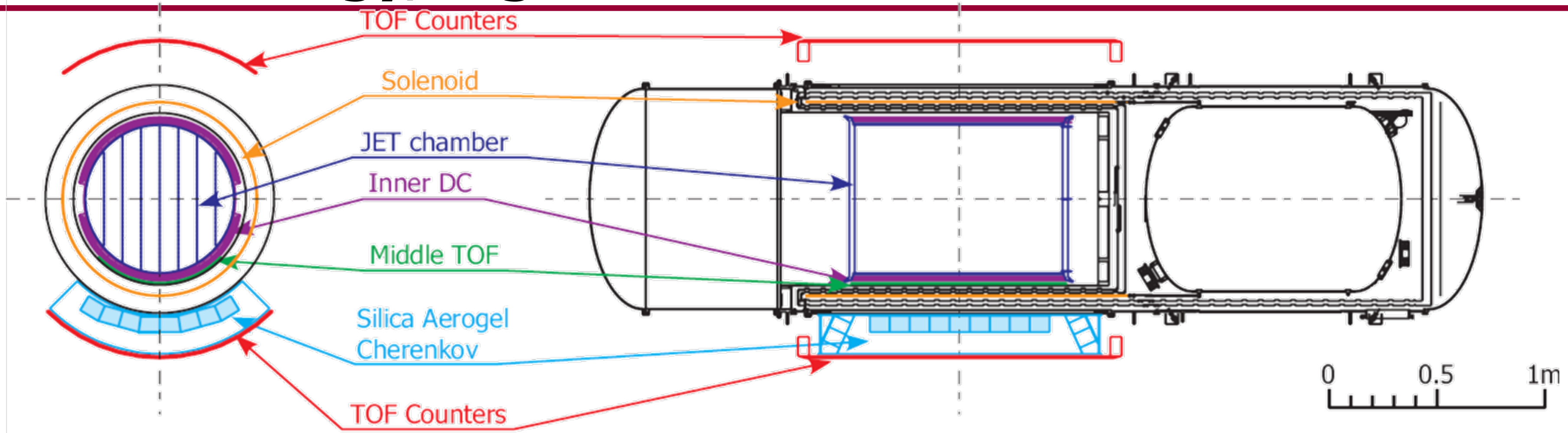
Primary antideuteron





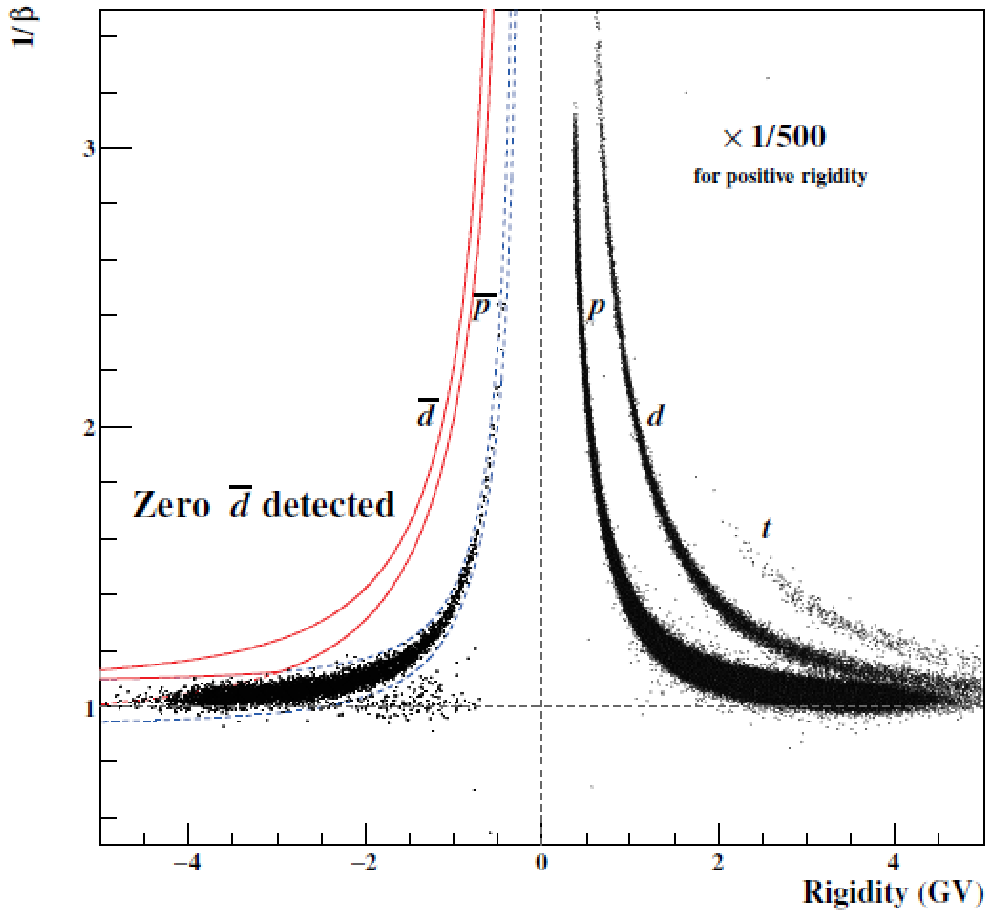
Soft or flat spectrum below few GeV in many DM models

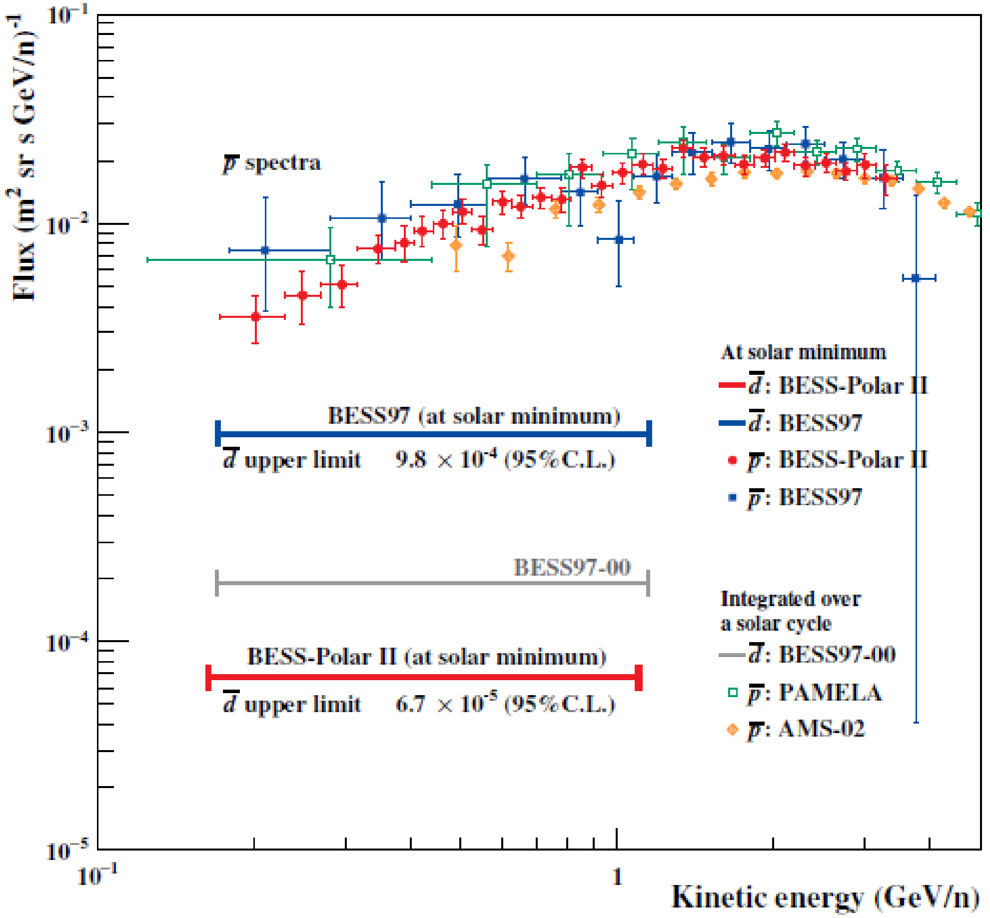
BESS-Polar II: Lower Energy, High Statistics



- Longer Observing Time
  - ~30 days of data taking
  - 16 TB data storage
  - Total events ~4.7 x 10^9
- Improved Reliability
  - Pressurized TOF PMT units
  - Improved electronics efficiency
- Improved Performance
  - ACC rejection power
  - Middle TOF resolution
  - Outer TOF resolution
- ~22 times present solar-minimum $\bar{p}$ statistics

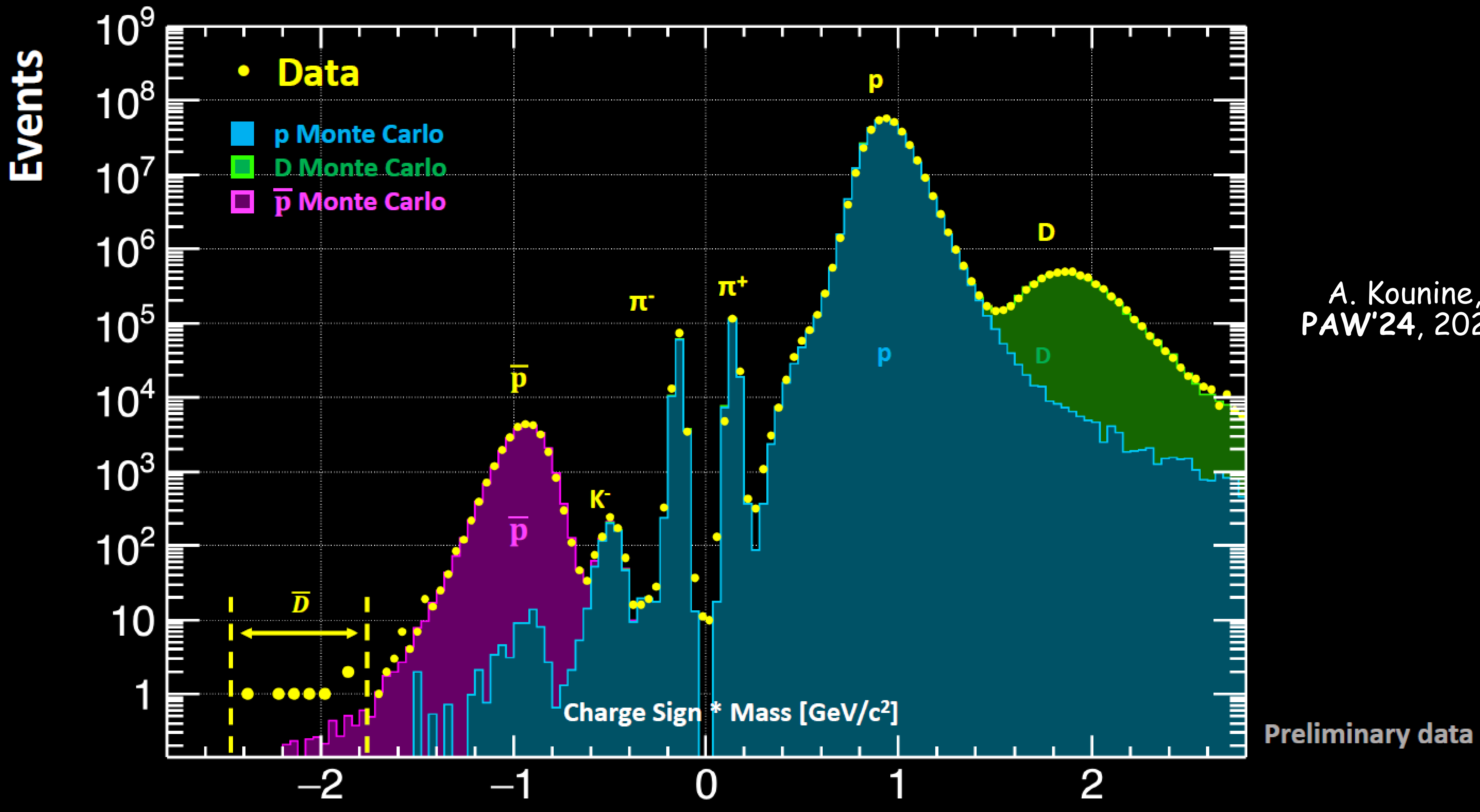
BESS-Polar II: Anti-deuteron limit (and antiproton data)





K. Sakai et al., PRL **132** (2024) 131001

Current Status with 11 Years of AMS Data: Antideuterons in 5.7<|R|<9.3 GV



A. Kounine, PAW'24, 2023

- Future AMS upgrade will provide additional measurement point to antideuterons.
- Improve analysis techniques, further MC study to better understand the background.

The GAPS Experiment

GAPS compatibility test at CSBF facility, Palestine, Texas, July 1, 2024

- The **G**eneral **A**nti**P**article **S**pectrometer is the first experiment dedicated and optimized for low-energy cosmic-ray antinuclei search

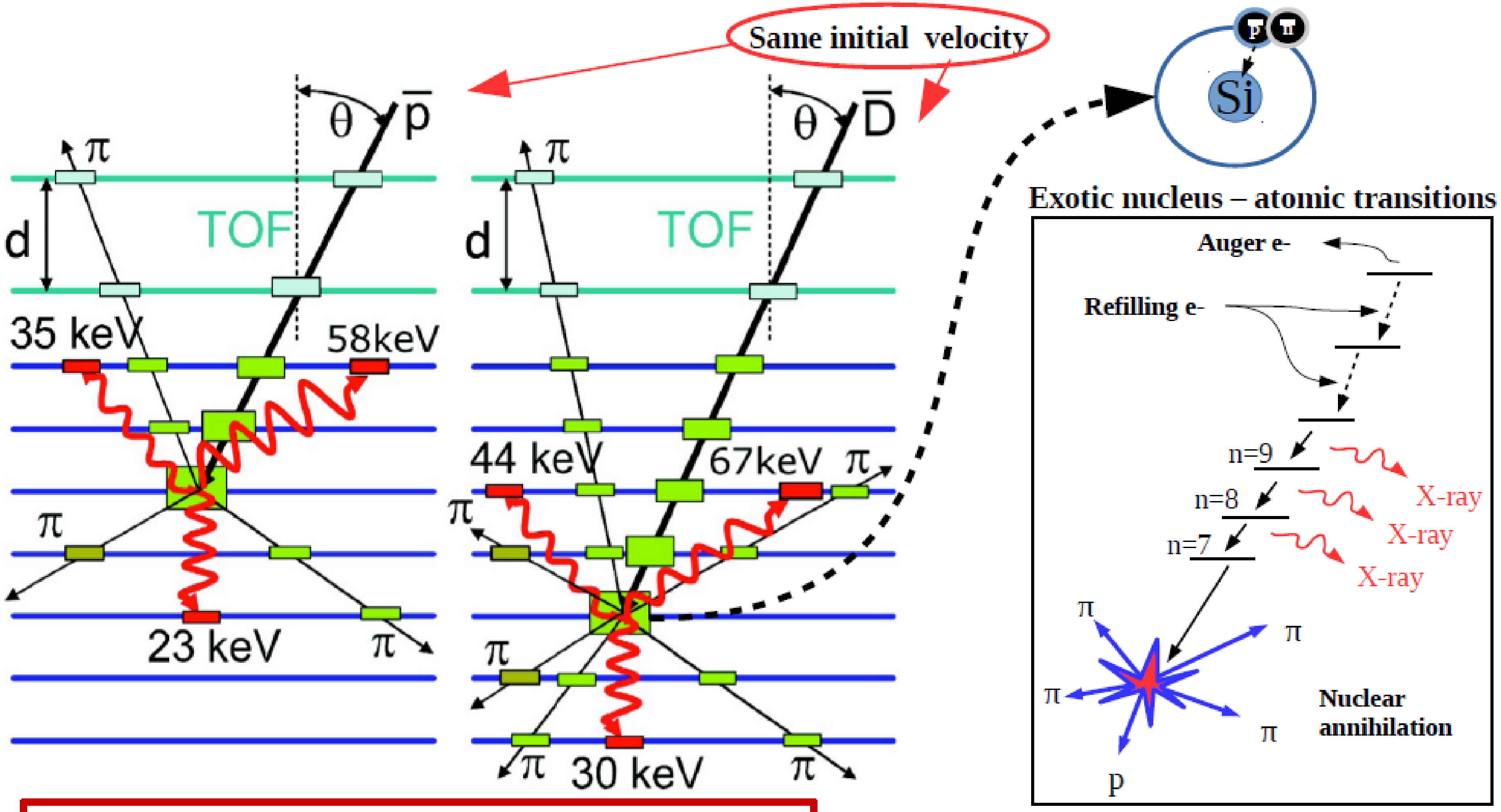
- Requirements: long flight time, large acceptance, large identification power, flight at low-geomagnetic cutoff location

- **First flight in December 2024 from McMurdo base, Antarctica**

The General AntiParticle Spectrometer

Mass: ~2,500kg
Power: 1.3kW

GAPS detection tecnique



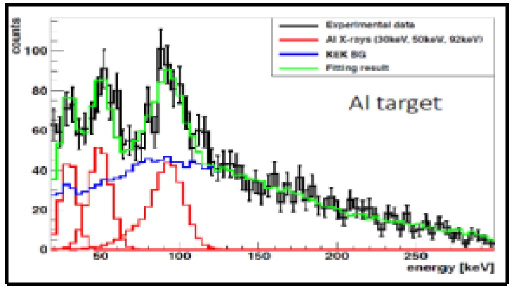
Stopping particles inside tracker volume

$$E_{X-ray} = (zZ)^2 \frac{M}{m_e} R_H \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$

AntiD - antiP identification

- Time of flight
- Depth - multiple dEdx
- X-rays emission
- Pion multiplicity

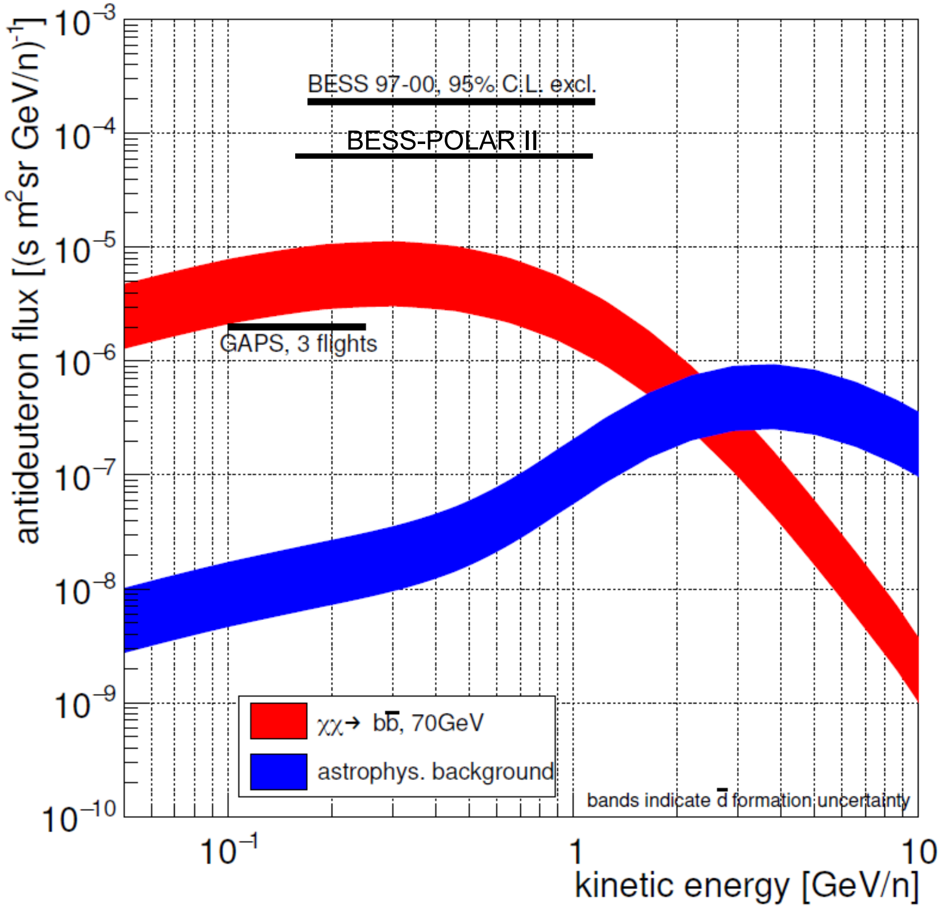
Aramaki et al. Astro.Ph. 49 (2013) 52



X-raymeasured at KEK in 2004/2005

GAPS: Antideuteron sensitivity

- GAPS will search for antideuteron over the kinetic energy region 100-250 MeV/n
- Expected astrophysical d background heavily suppressed at these energies
- Over three Long Duration Balloon flights for a total of ~100 days of data taking.
- **Antideuteron sensitivity more than one order of magnitude below the current best limits, probing a variety of DM models across a wide mass range**
- GAPS will also measure p, p, d, and He fluxes

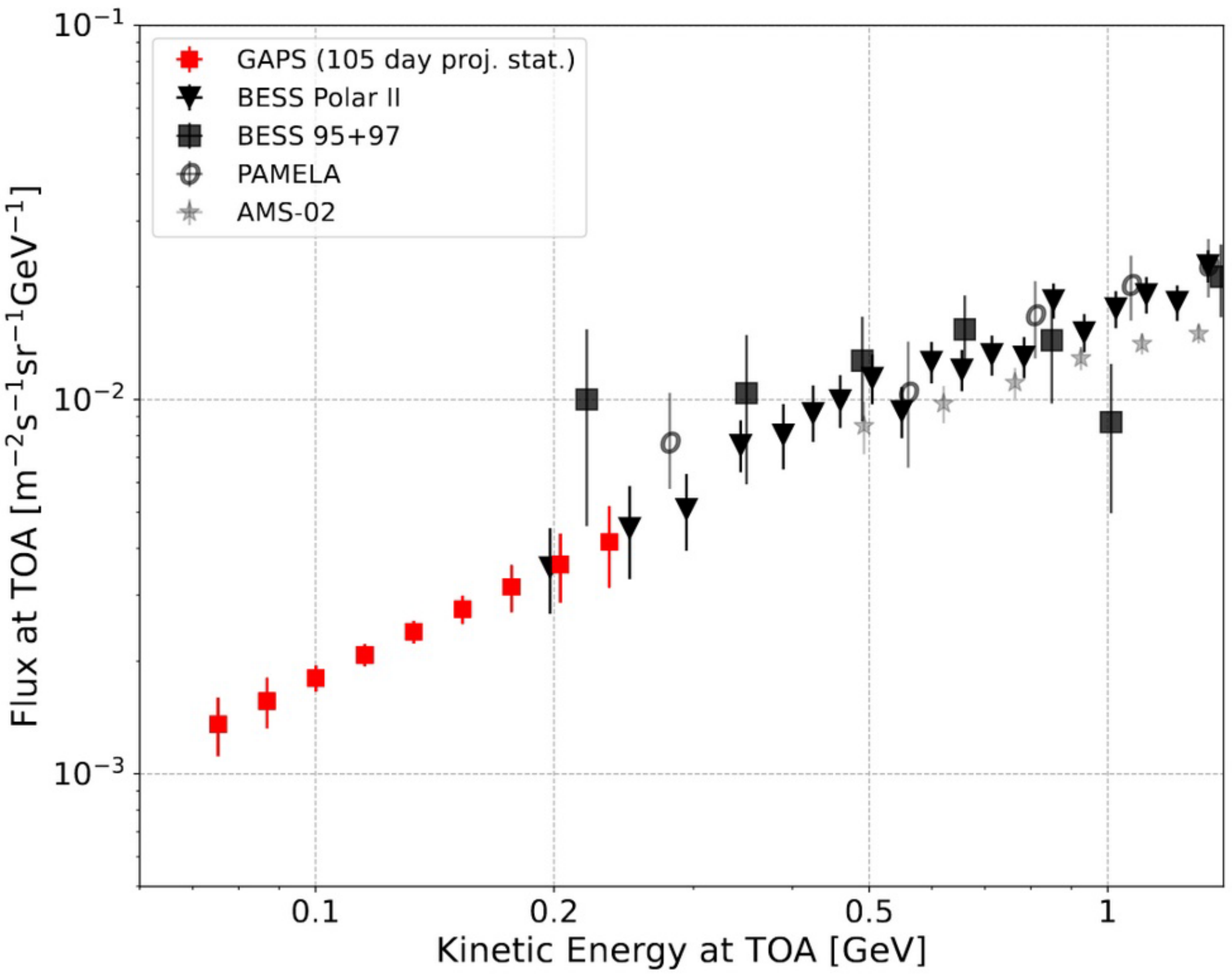


M. Korsmeier et al., Phys. Rev. D 97, 103011 (2018)

T. Aramaki et al, AstroPart. Phys. **74** (2016) 6

GAPS: Antiproton Sensitivity
Precision Spectrum at Unexplored Energies

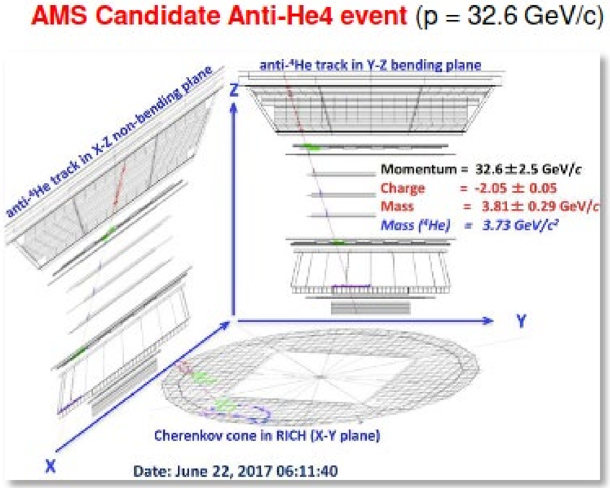
- ❑ GAPS will provide a precision $\bar{p}$ spectrum in the previously unexplored energy range <250 MeV/n
- ❑ Expected ~500 $\bar{p}$ per LDB flight
- ❑ Validate the GAPS technique using flight data
  - ✓ First cosmic-rays detected using exotic atoms for particle identification
  - ✓ Reconstruction of exotic atoms
  - ✓ X-rays from de-excitation
- ❑ Test models of atmospheric attenuation and production
- ❑ Probe light DM models and local primordial black hole evaporation



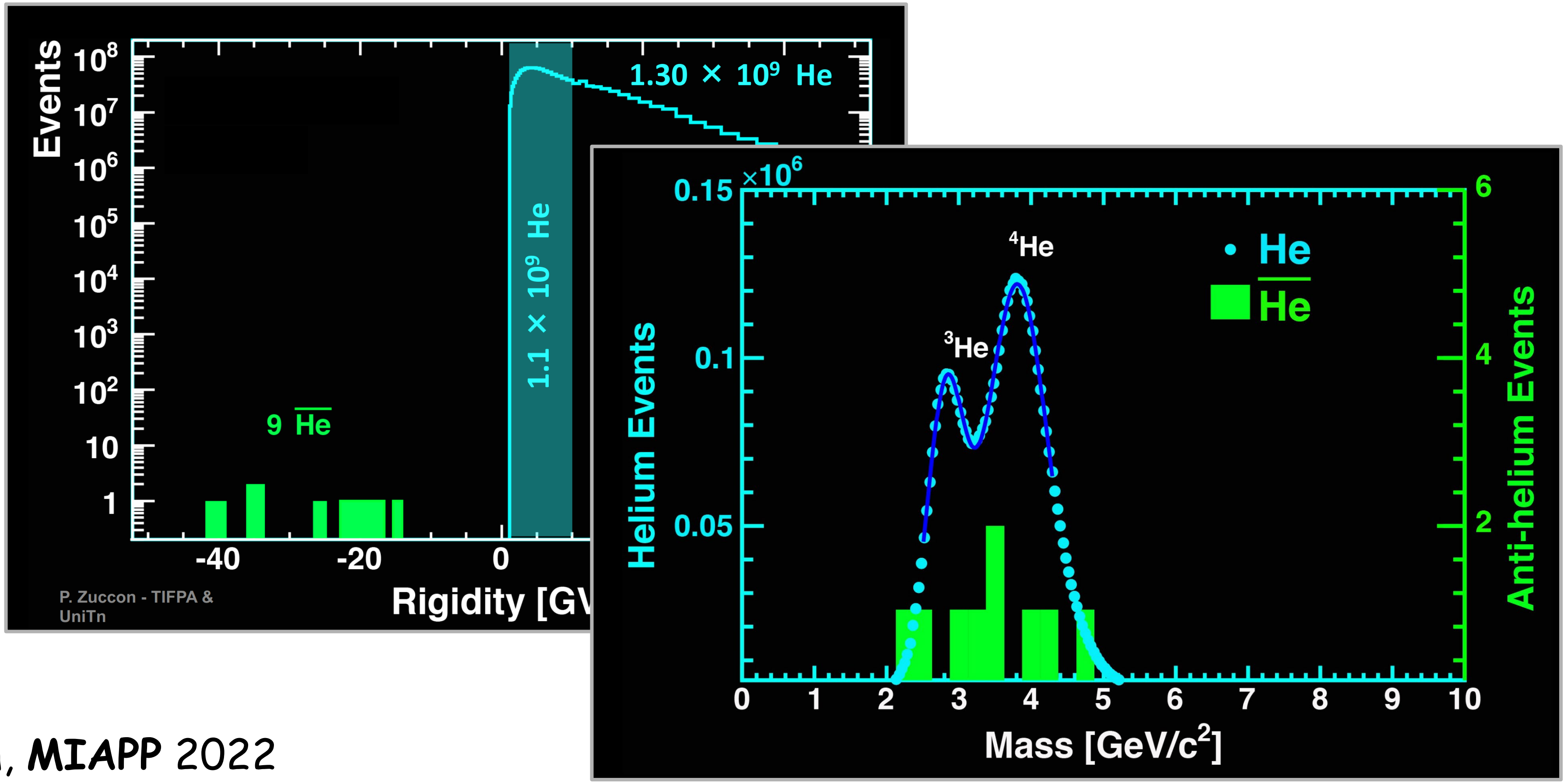
F. Rogers et al, AstroPart. Phys. **145** (2023) 102791

AMS-02: Anti-helium

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)



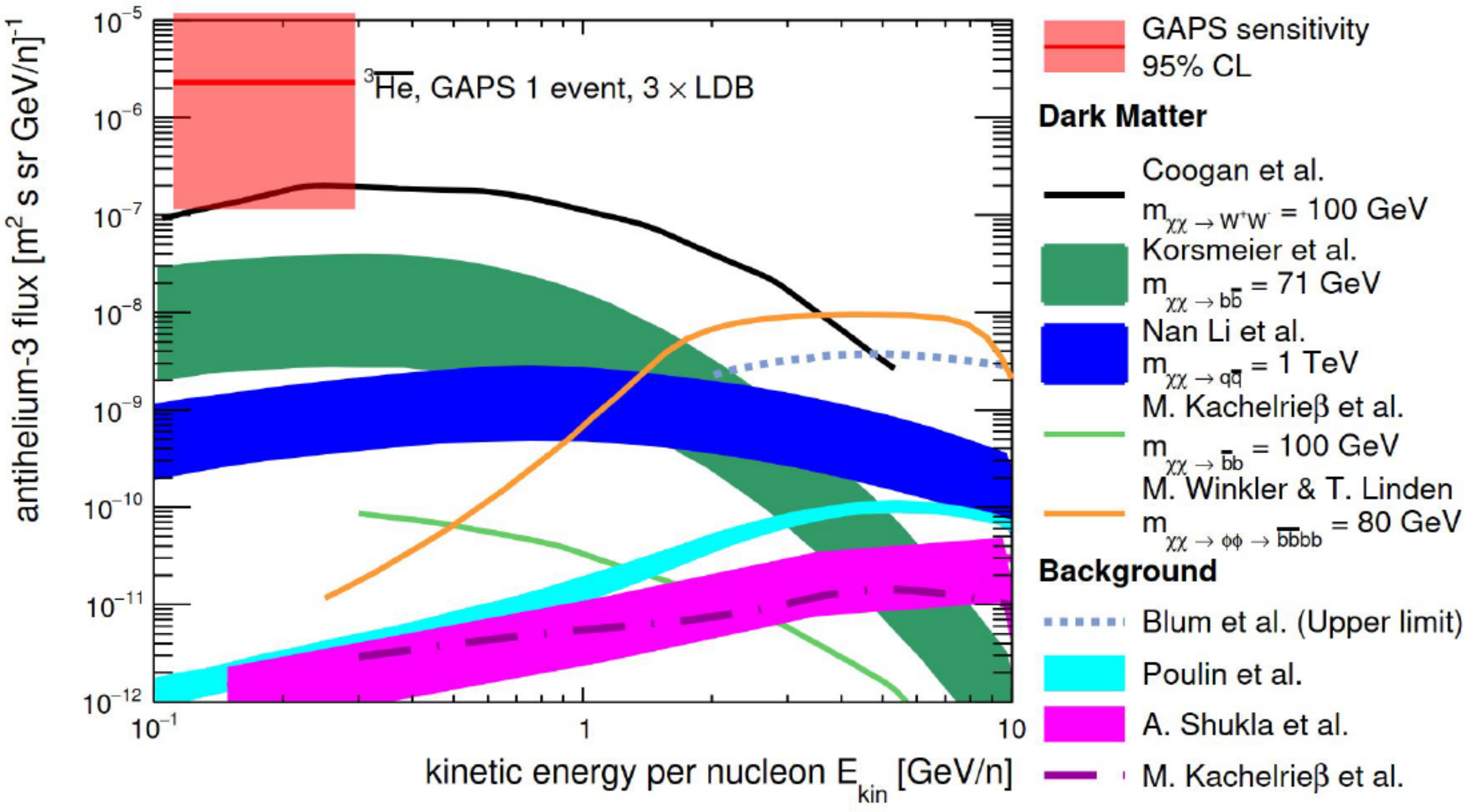
Rate ~ 1 event/year



P. Zuccon, **MIAPP** 2022

GAPS: Anti-He3 sensitivity

- GAPS will provide sensitivity to He3 with orthogonal instrumental systematics compared to AMS-02
- GAPS will extend the energy coverage to low energy (0.1-0.3 GeV/n)



N. Saffold. et al., AstroPart. Phys. **130** (2021) 102580

Conclusions

- Cosmic-ray physics is a fascinating field, fertile and rich in scientific potential.
- State-of-art experiments are directly measuring cosmic rays and their antimatter component.
- Intriguing results have already been published, and more are coming that may shed light on the origin of this component.

Thanks!