Antimatter and Antiparticles in the Cosmic Radiation

The Existence of Antimatter

Paul A.M. Dirac

Theory of electrons and positrons

Nobel Lecture, December 12, 1933

Relativity:

$$\frac{W^2}{c^2} - p_{r^2} - m^2 c^2 = 0$$

Quantum Theory:

$$\left[\frac{W^2}{c^2} - p_{r^2} - m^2 c^2 \right] \Psi = 0$$

$$m^2 = (m)(m) = (-m)(-m)$$

Dirac asked: What is (-m) ➡ Theory of antimatter

Antiparticles and Antimatter

We must regard it rather as an accident that the Earth and presumably the whole solar system contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about.

P. A.M. Dirac Nobel Prize lecture

History of antimatter: theory and experiments

1928: Prediction existence of positrons (Dirac)

1932: Detection of positrons (Anderson)

1955: Production of antiproton at accelerator (Chamberlain et al.)

1960’s: BSU cosmologies (Klein, Alven,…)

1965: Discovery of the Microwave Background Radiation e Big Bang Cosmologies

1967: Sakharov’s conditions (Sakharov)

1970’s: gamma-ray limits

1979: Detection of cosmic-ray antiprotons (Golden et al., Bogomolov et al.)

1996: Antihydrogen produced in a laboratory (Baur et al.)

Baryogenesis, matter and antimatter

Theoretically:

- There is an almost exact symmetry between matter and antimatter.

Experimental facts:

- There is no evidence for significant amounts of antimatter in the Universe, e.g.:
  - The primary cosmic ray nuclei are found to be completed dominated by nuclei rather than antinuclei
  - No evidence for the intense γ- and X-ray emissions expected from matter in galaxies colliding with 'clouds' of antimatter

Simple Big Bang Model

The early Universe was a hot expanding plasma with equal number of baryons, antibaryons and photons. In thermal equilibrium the two-ways reaction was:

$$B + \text{anti-}B \longleftrightarrow \gamma + \gamma$$

As the Universe expands, the density of particles and antiparticles falls, annihilation process ceases, effectively freezing the ratio:

- baryon/photon = antibaryon/photon ~ 10^{-18}.

- Annihilation catastrophe.

Instead, in the present real Universe:

– Baryon/photon ~ 10^{-9} (from direct observ. & microwave background);

– Antibaryon/baryon < 10^{-4}.

Sakharov criteria

To account for the predominance of matter over antimatter, Sakharov (1967) pointed out the necessary conditions:

- *B violating interactions;*
- *non-equilibrium situation;*
- *CP and C violation*.

GUT theories ?

Leptogenesys ?

The processes really responsible are not presently understood!

What about the observations?

Indirect ->

By measuring: the spectrum of the Cosmic Diffuse Gamma emission

Direct ->

By searching for Antinuclei

By measuring anti-p and e^+ energy spec

PAMELA

AMS

a "matter trail" from the solar system to the Galaxy

solar system

micro-meteorites and solar wind particles are continuously bombarding the earth without causing annihilation radiation. Aproximating the a solar wind flux with $nv \approx 2 \cdot 10^8 (d/1\mathrm{AU})^{-2}\ cm^{-2}\ s^{-1}$, one can roughly estimat the annihilation radiation from an anti-planet :

$$F_\gamma(100\,MeV) \approx 10^8 (r/d)^2\ ph\ cm^{-2}\ s^{-1}$$

r,d : radius, distance of anti-planet

example : Jupiter ($r = 7 \cdot 10^7$ m, $d = 7 \cdot 10^{11}$ m) : $F_\gamma \approx 1$ ph cm^{-2} s^{-1}
FERMI features ~10^{-8} ph cm^{-2} s^{-1} sensitivites

stars

Bondi Hoyle accretion of galactic gas onto an anti-star would produce detectable 100 MeV fluxes (FERMI) out to at least 100 pc, corresponding to ~ 100'000 stars => antimatter fraction $f_{AM} \leq 10^{-5}$

galactic gas

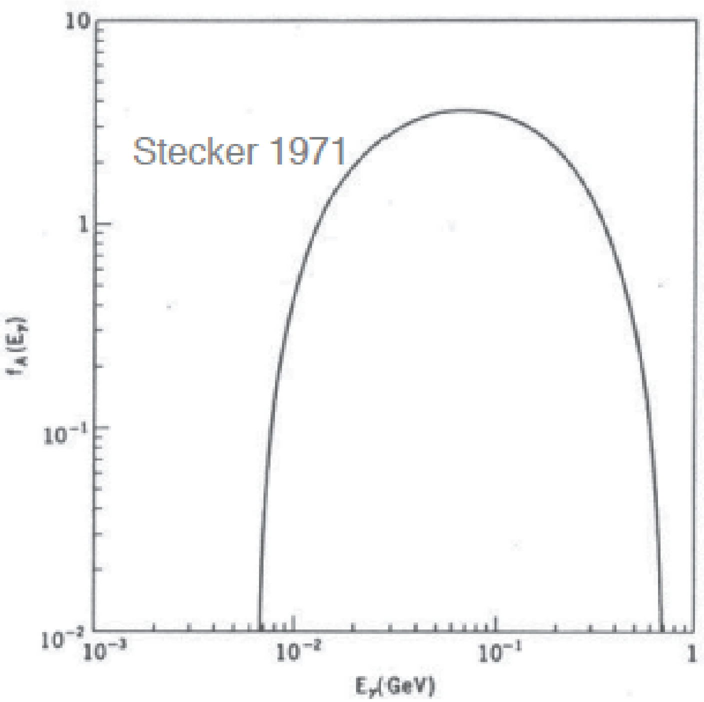
the observed diffuse galactic gamma ray flux (well exlained by CR interaction) limits the antimatter fraction $f_{AM} \leq 10^{-15}$!

the argument can obviously be extended as long as a sufficiently dense matter trail extends out to the next bigger structure ...

gamma rays from nucleon-antinucleon annihilation

$$N - \bar{N} \rightarrow \begin{cases} \pi^0 \rightarrow \boxed{\gamma + \gamma \qquad \text{1/3 of } 2m_Nc^2 \rightarrow \text{200 MeV } \gamma\text{'s}} \\ \pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu) \end{cases}$$

$$\hookrightarrow \pi^\pm \rightarrow e^\pm + \nu_e(\bar{\nu}_\mu) + \nu_\mu(\bar{\nu}_\mu)$$



1/2 of $2m_Nc^2 \rightarrow \nu$'s

1/6 of $2m_Nc^2 \rightarrow$ 100 MeV e^- / e^+

typical rest-frame spectrum produced by p-$\bar{\text{p}}$ annihilation with π° decay

maximum intensity at $m_\pi c^2/2 \sim 70$ MeV

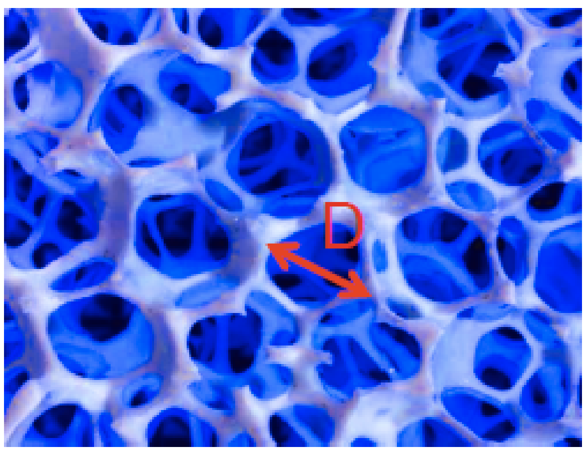
antimatter domains and the diffuse gamma-ray background

Annihilation radiation from the boundaries of matter-antimatter regions, emitted in the early Universe before - and/or - after recombination.

Stecker et al. (1971) solved the cosmological photon transport equation accounting for pair production and Compton scattering at high z.

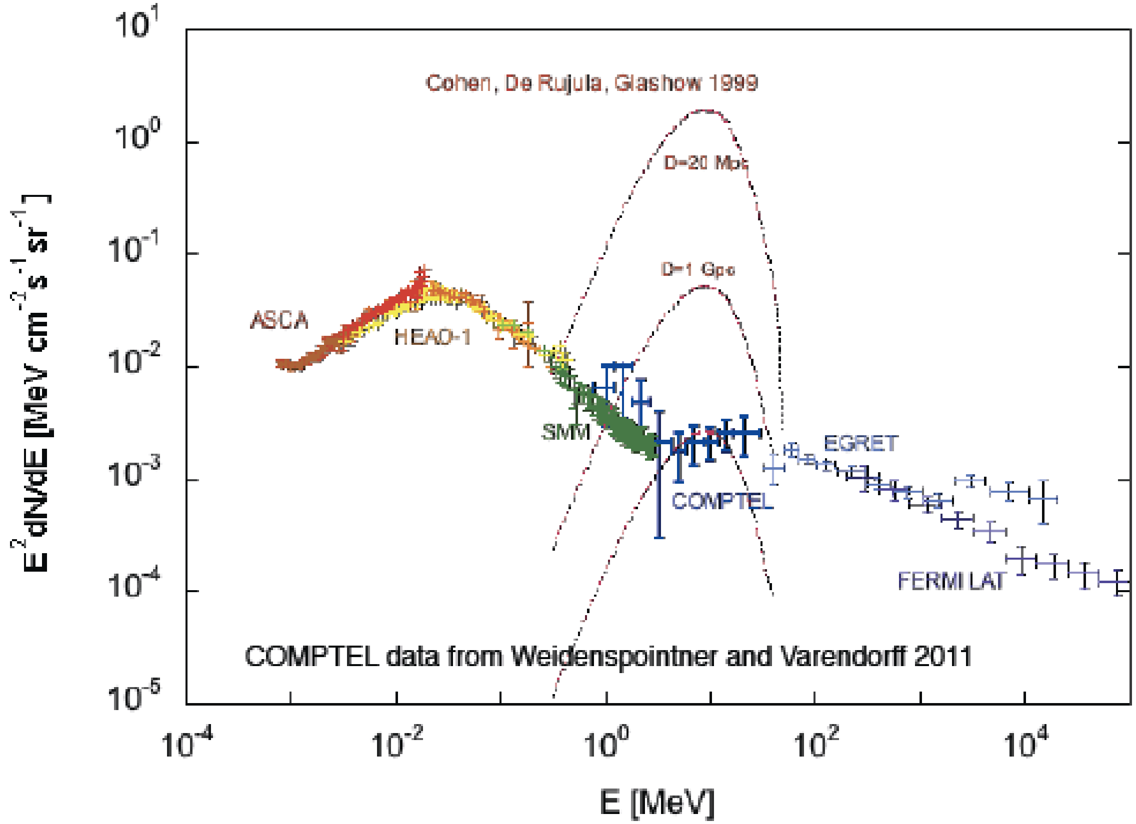
$$y\frac{\partial I}{\partial y}+\epsilon\frac{\partial I}{\partial \epsilon}=2I+\frac{y^2\Omega\nu}{[1+\Omega(y-1)]^{1/2}}\left[A(\epsilon)I-\int_\epsilon^{b(\epsilon)}d\epsilon' B(\epsilon|\epsilon')I(\epsilon',y)-\xi^2\Omega n_c y^3 v(T(y))\,\frac{\sigma_A(T(y))}{\pi r_e^2}\,G_A(\epsilon)\right]\ldots$$

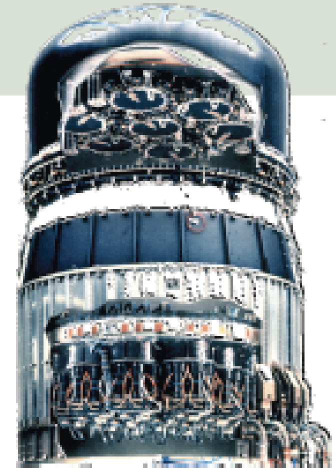
=> redshifted gamma-ray "bump" above ~ 1 MeV



what domain-size D (> 20 Mpc)
is compatible with
the observed MeV gamma-ray sky ?

Cosmic diffuse X- and Gamma-Ray Background

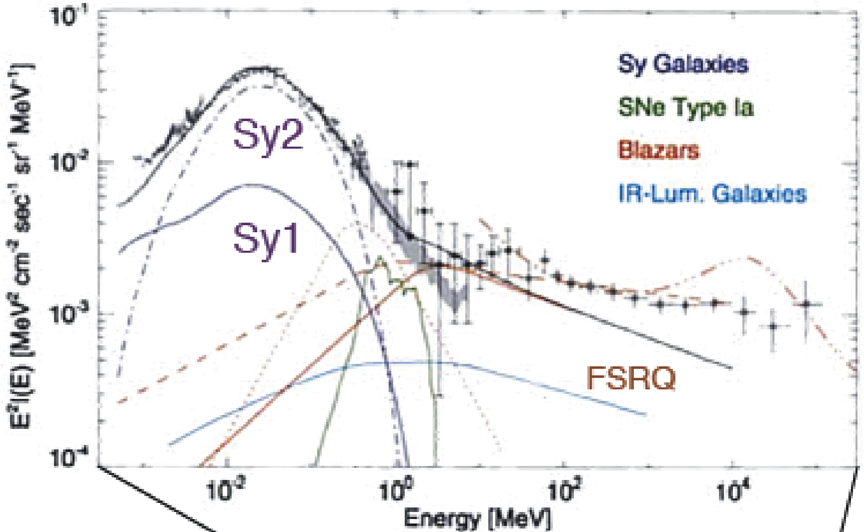


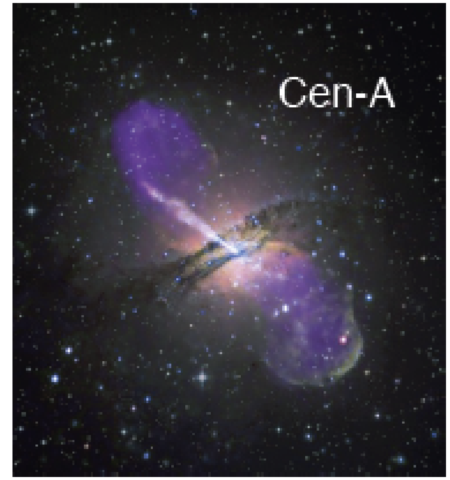


COMPTEL

- no MeV bump
- transition from a softer to a harder component at ~ 5 MeV
- no deviation from isotropy within statistics

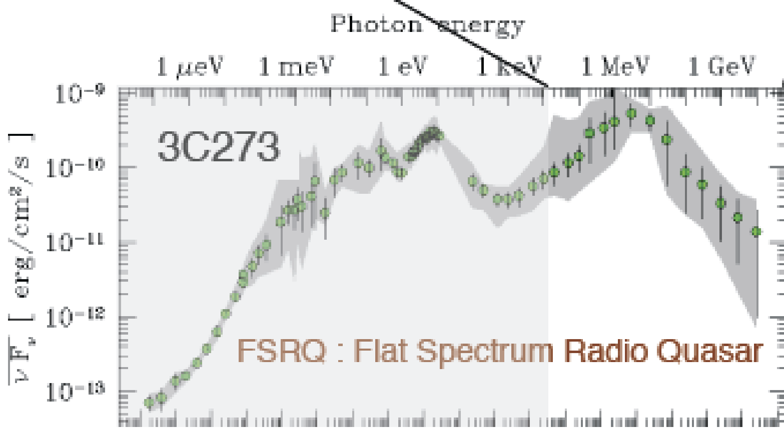
MeV background explained as unresolved AGN's

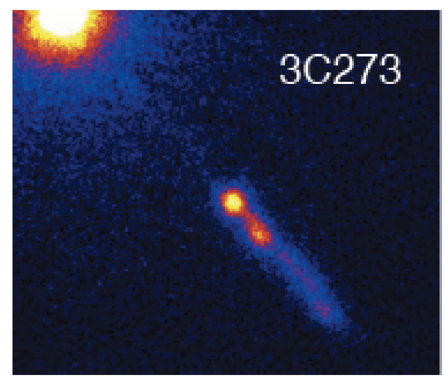




superposition of spectra from various classes of unresolved point sources

=> no need for antimatter domains with sizes D ≈ the observable Universe





Direct searches: current status

Antiprotons: DETECTED! secondary production

$P_{CR}+H_{ISM}$
$P_{CR}+He_{ISM}$
$\alpha_{CR}+H_{ISM}$
$\alpha_{CR}+He_{ISM}$

⇒ p + anti-p — secondary antiprotons

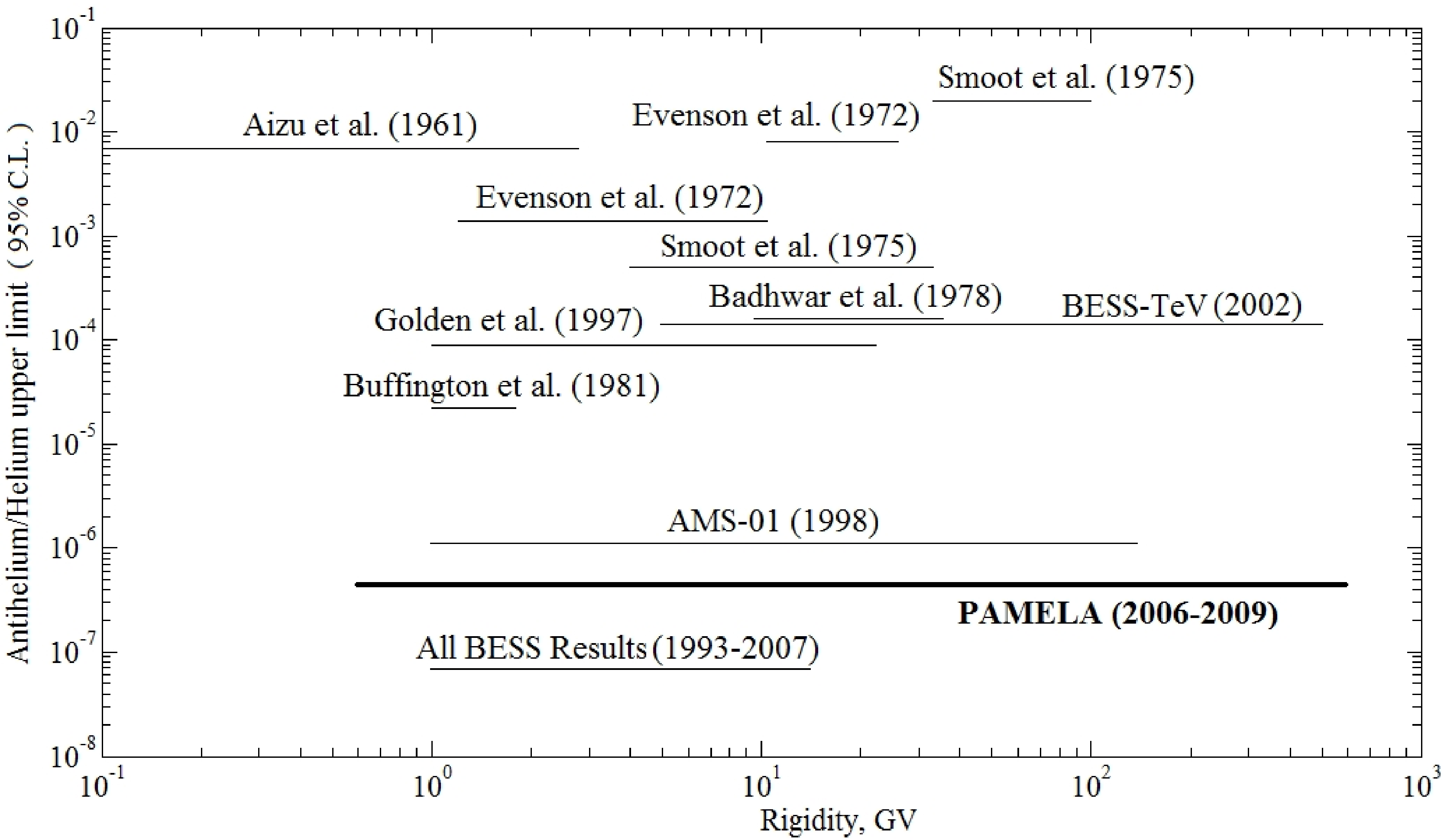
- Positrons: DETECTED! secondary production

$P_{CR}+ ISM$
$N_{CR}+ISM$

⇒ π+ -> μ+ -> e+ — secondary positrons

- Anti-nuclei: never detected !
  - They would be the real signature of antistars because their production by "spallation" is negligible

Antihelium Searches



Antiparticles

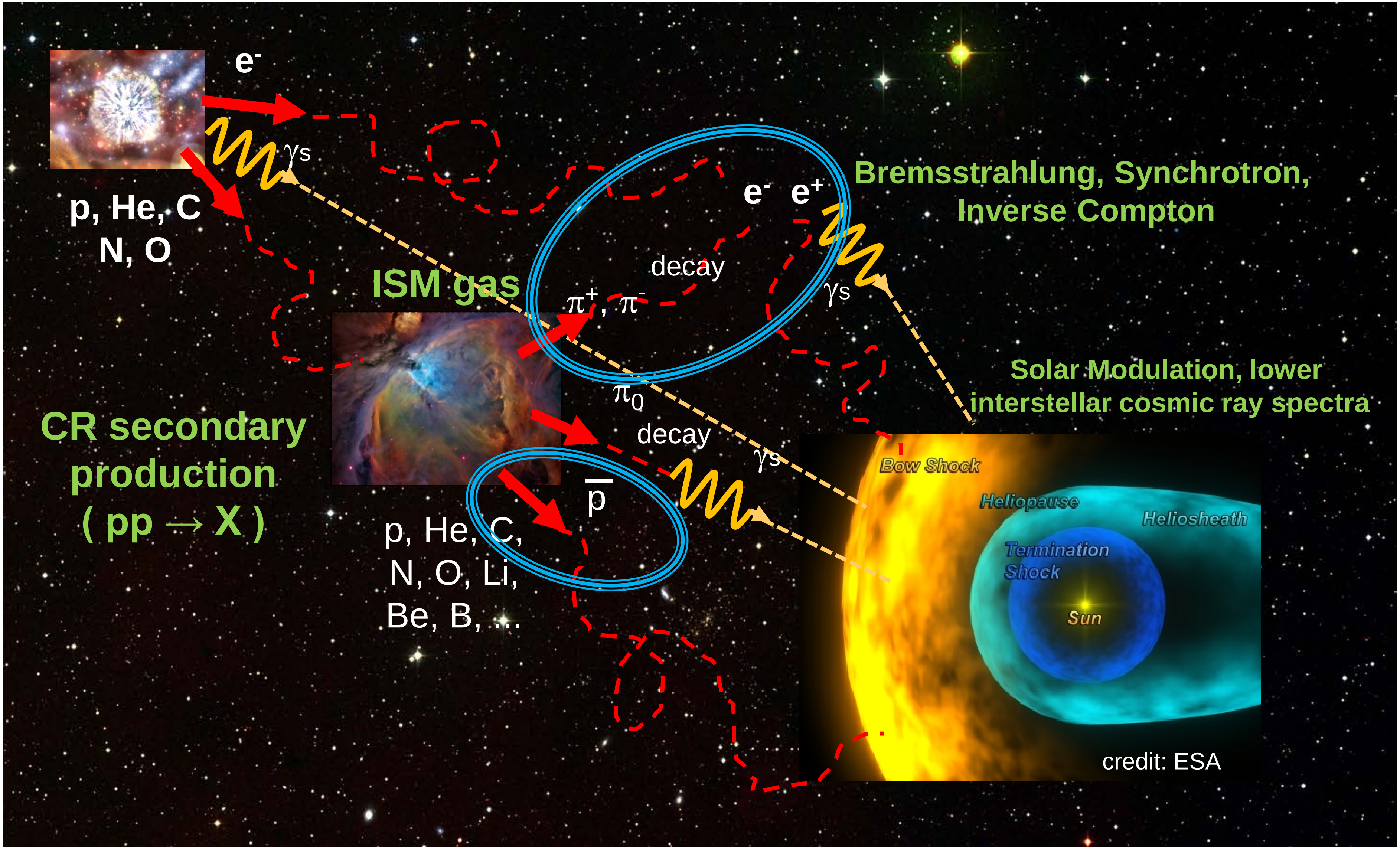
Astrophysics and Cosmology compelling Issues

Origin and propagation of the cosmic radiation

Nature of the Dark Matter that pervades the Universe

Apparent absence of cosmological Antimatter

Cosmic Rays and Anti-Particles

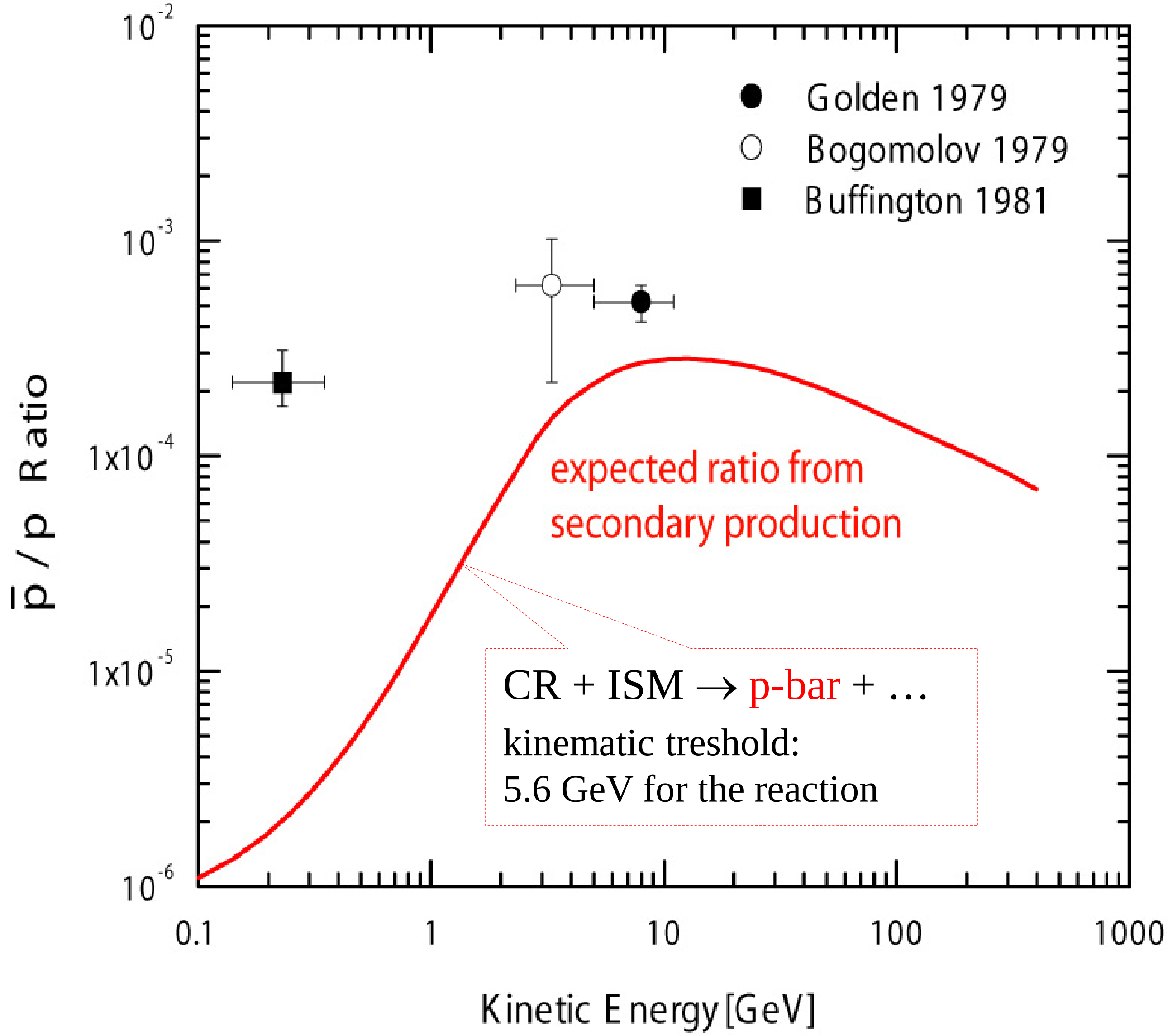


First Detection in the Cosmic Rays

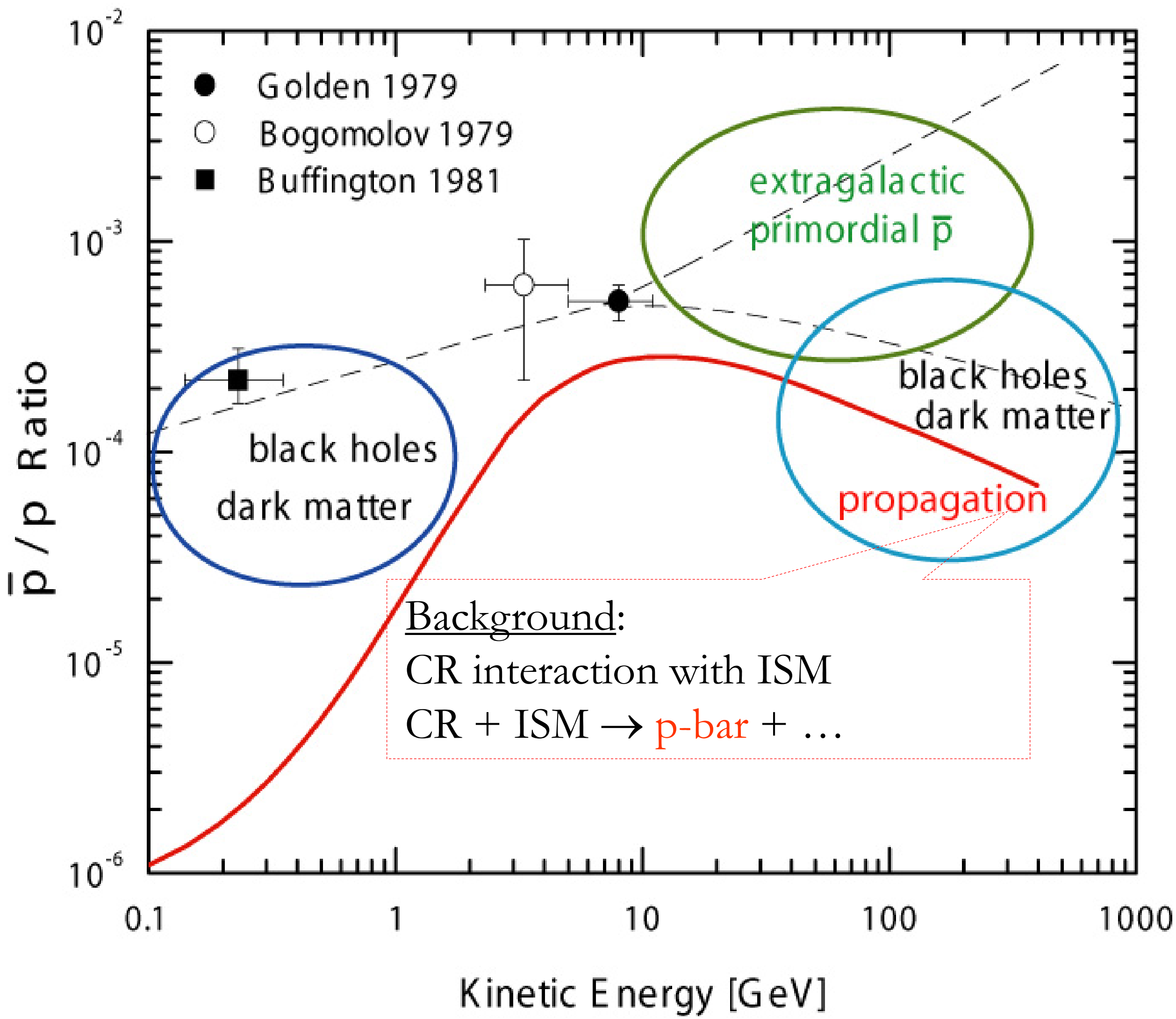
First detection of positrons in the cosmic radiation in 1964 by J.A. De shong, R.H. Hildebrand & P. Meyer (Phys. Rev. Let. **12**, 3, 1964)

First detection of antiprotons in the cosmic radiations in 1979 by R.L. Golden et al. Phys. Rev. Let. **43**, 1264, 1964) and by E. Bogomolov et al.

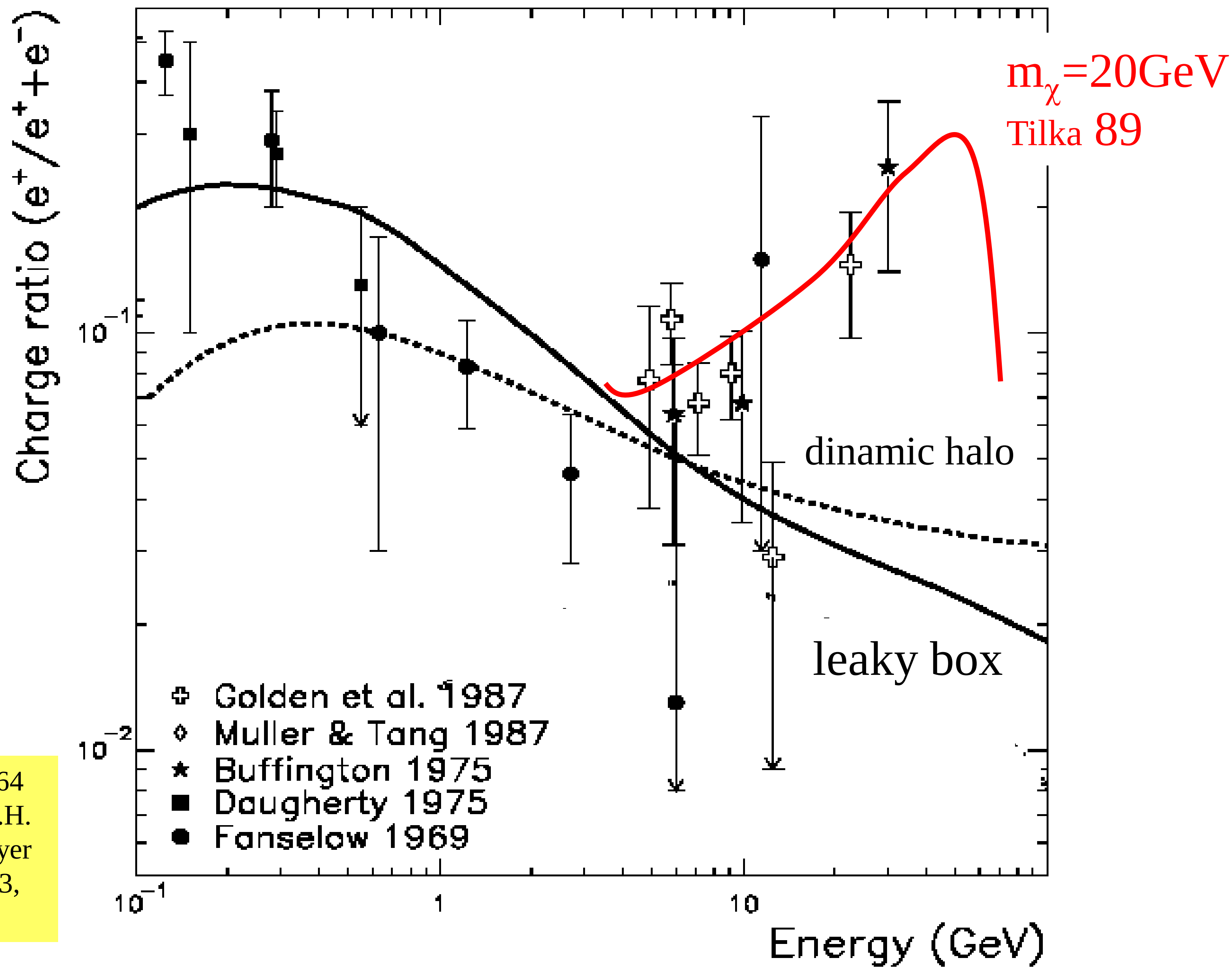
The first historical measurements on galactic antiprotons



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



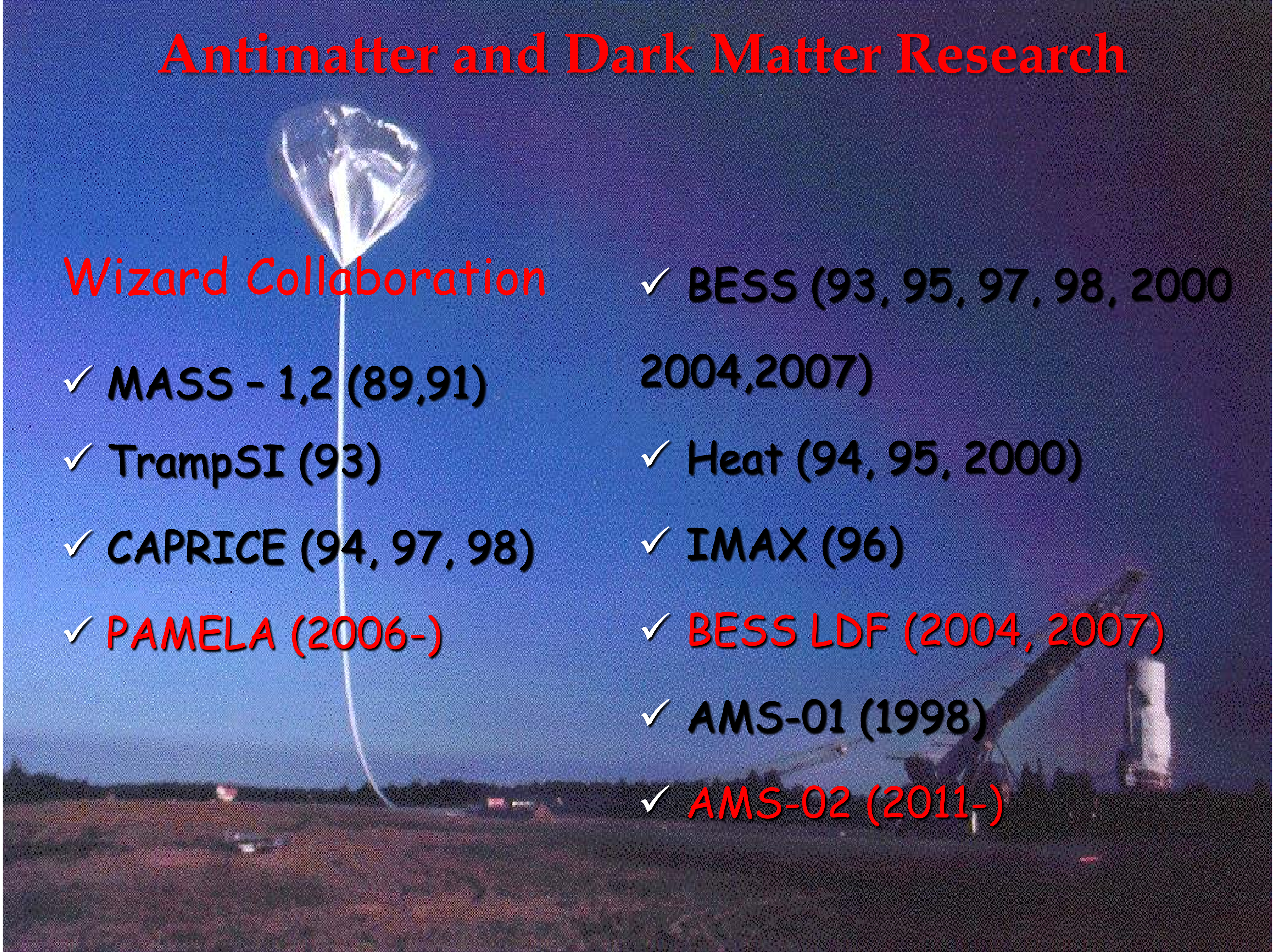
Balloon data : Positron fraction before 1990



First detection in 1964 by J.A. De shong, R.H. Hildebrand & P. Meyer (Phys. Rev. Let. 12, 3, 1964)

Antiparticle Experiments
(old and new)

Antimatter and Dark Matter Research



Wizard Collaboration

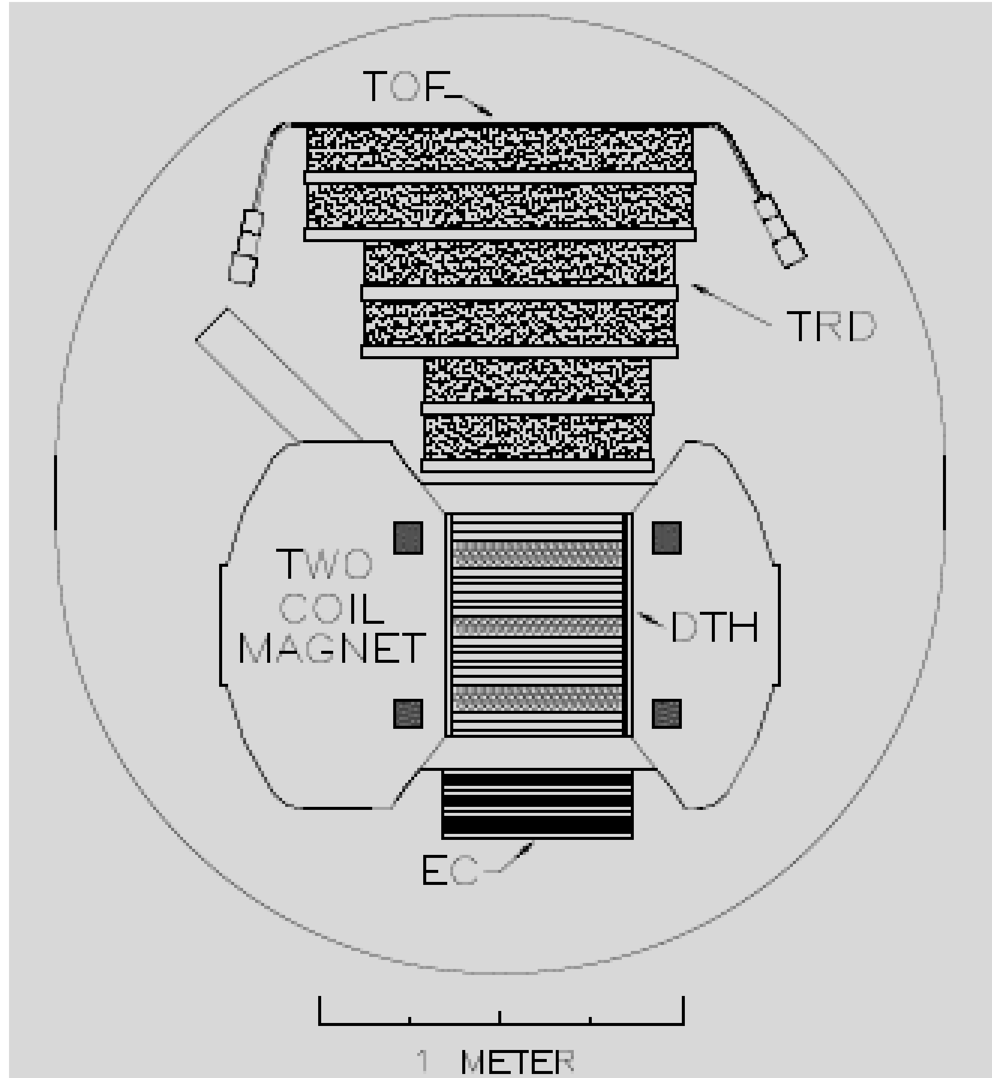
- ✓ MASS - 1,2 (89,91)
- ✓ TrampSI (93)
- ✓ CAPRICE (94, 97, 98)
- ✓ PAMELA (2006-)

- ✓ BESS (93, 95, 97, 98, 2000 2004,2007)
- ✓ Heat (94, 95, 2000)
- ✓ IMAX (96)
- ✓ BESS LDF (2004, 2007)
- ✓ AMS-01 (1998)
- ✓ AMS-02 (2011-)

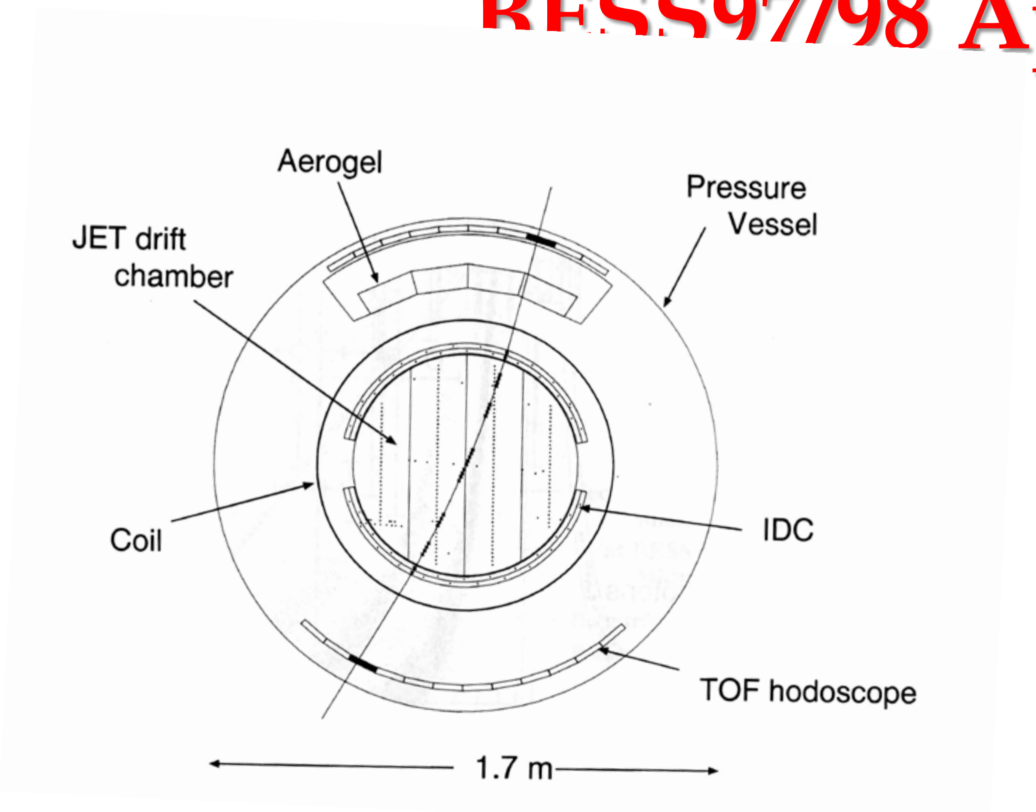
HEAT 94-95

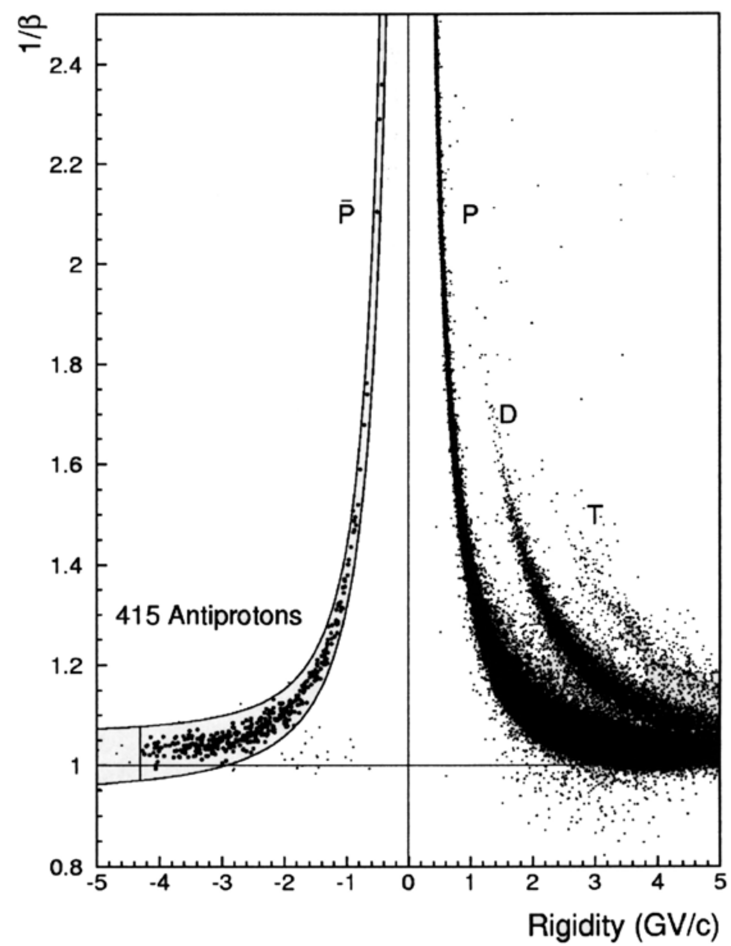
Subnuclear Physics Techniques in Space Experiments

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



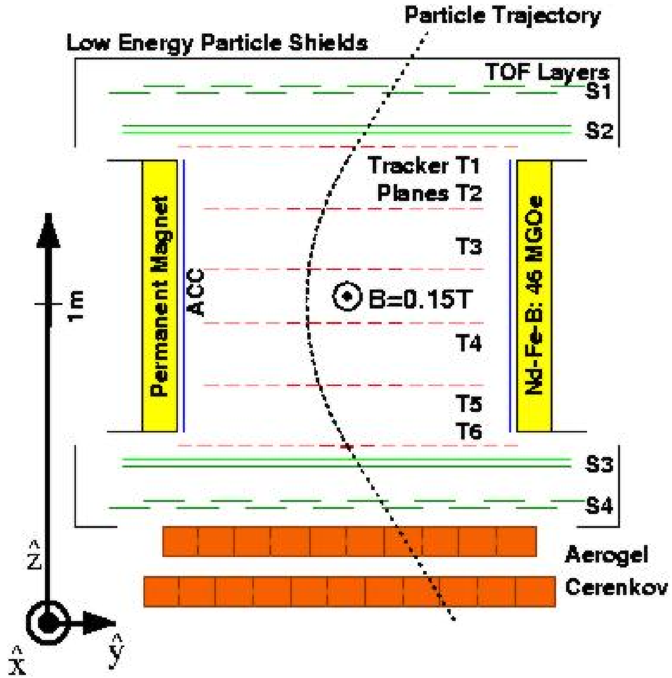
BESS97/98 Apparatus

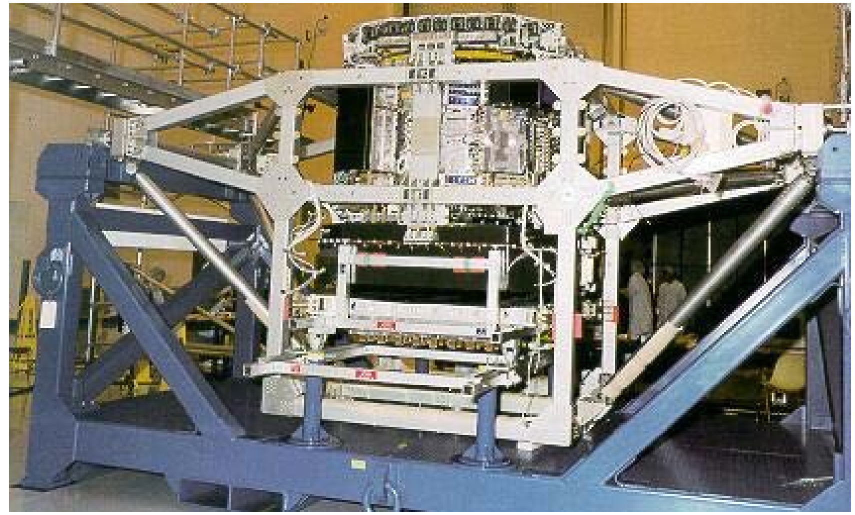




T. Maeno et al., Astropart. Phys. 16 (2011) 121

AMS-01 : the Detector

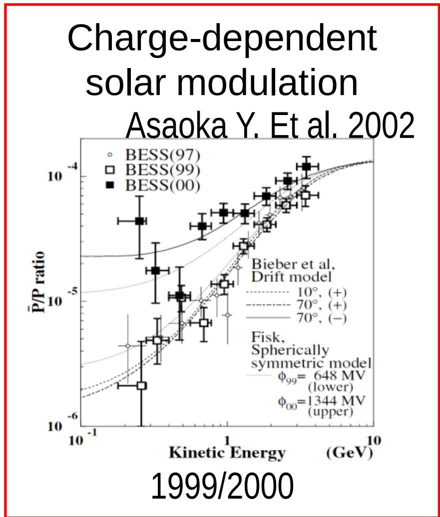




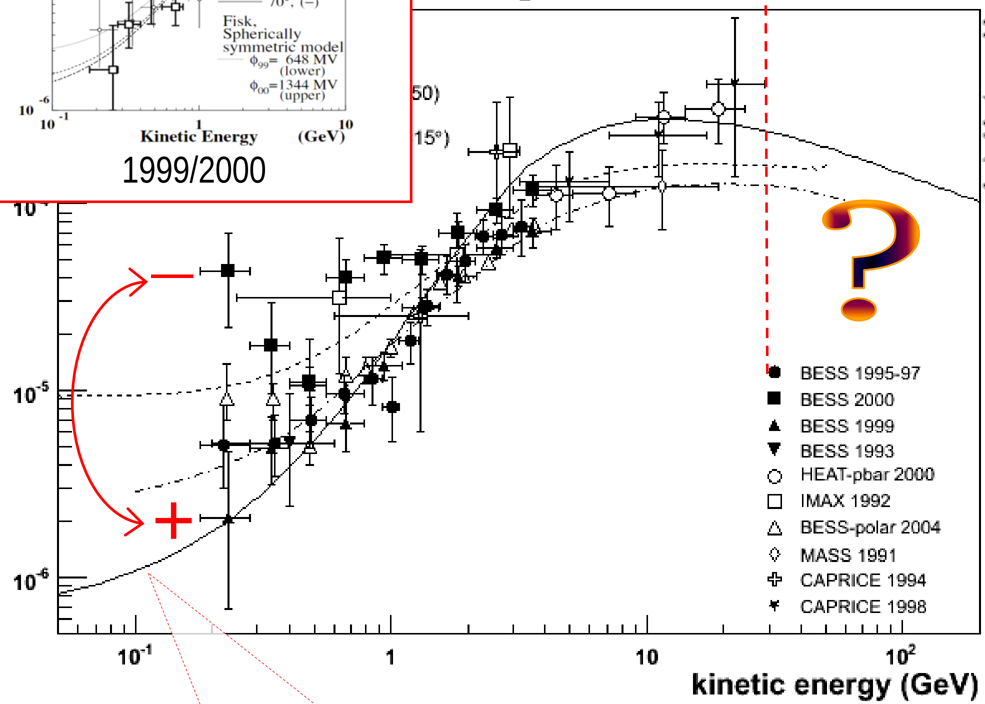
- Acceptance: Ω » 0.15 m^2sr
- Bending power » 0.14 Tm^2
- TOF : trigger + β and dE/dx meas.
- Tracker: sign Z + Rigidity + dE/dx meas.
- Cherenkov: e/p separation up to ~ 3 GeV.

CR antimatter

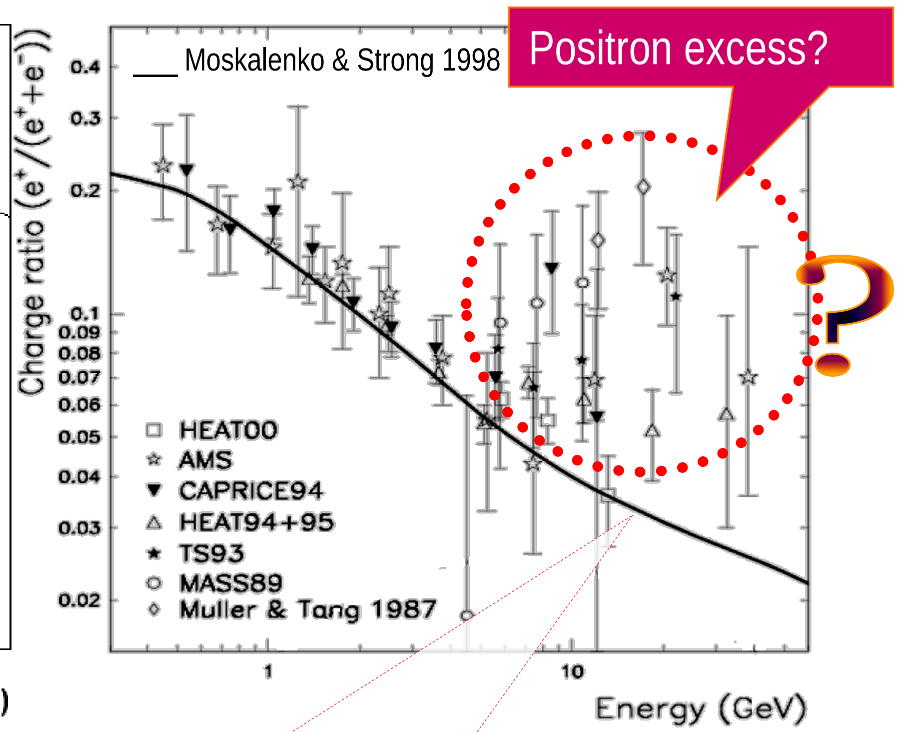
Status in 2006



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

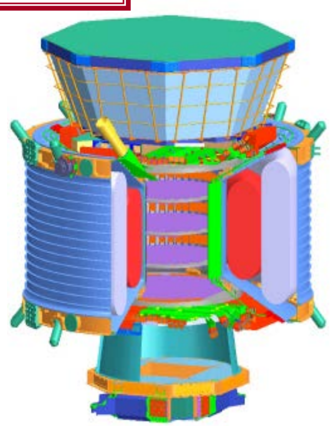
CR + ISM → π^{0} + x → $\gamma\gamma$ → $e^{\pm}$

Antimatter Missions in "Space"

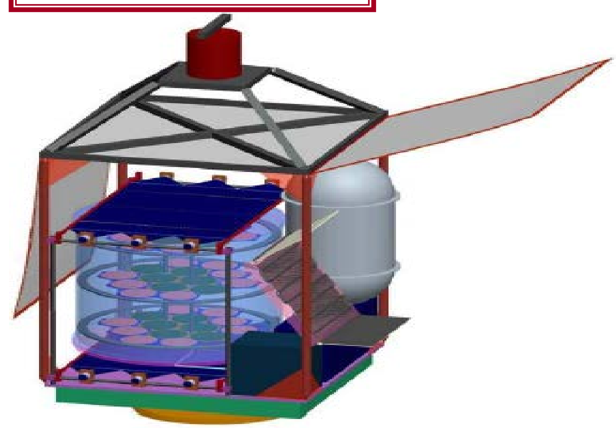
BESS LDBF
2004, 2007

PAMELA
2006-

AMS-02
2011-



GAPS
2020?



BESS-Polar Program

Status of the BESS-Polar I Flight

Observation Time: 8.5 days

Float Time: 8.5 days (12/13/2004-12/21/2004)

Events recorded: > 0.9×10^9

Data volume: ~ 2.1 terabytes
Data recovery: **completed** 2004
Payload recovery: **completed** 2004

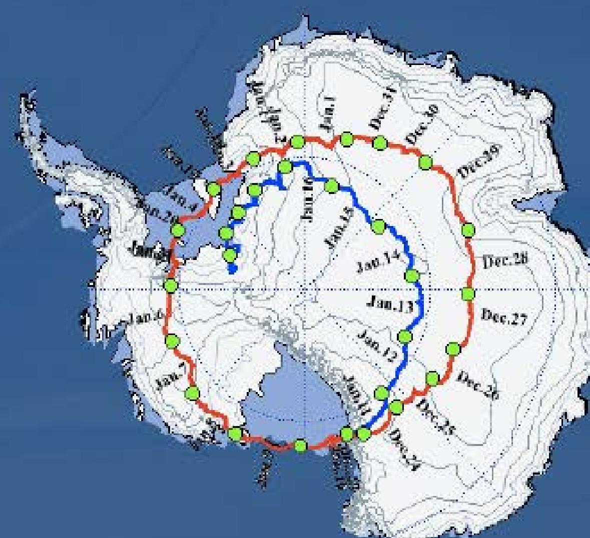
Status of the BESS-Polar II Flight

Observation Time: 24.5 days

Float Time: 29.5 days (12/23/2007-01/21/2008)

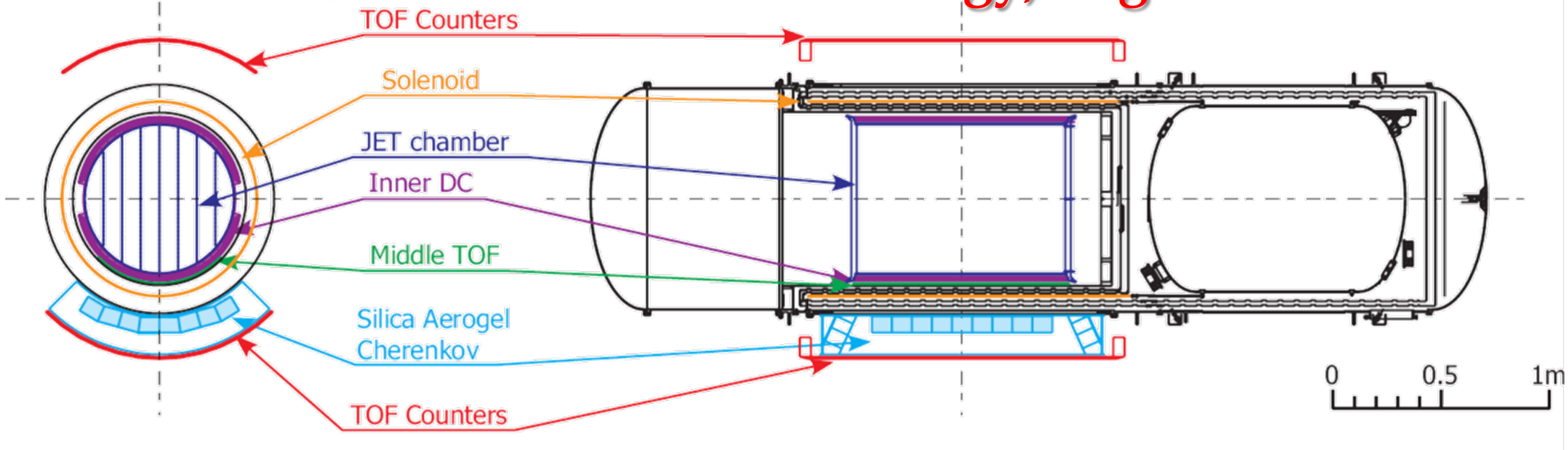
Events recorded: > 4.7×10^9

Data volume: ~ 13.5 terabytes
Data recovery: **completed** Feb 3, 2008
Payload recovery: **completed** Jan 16, 2010



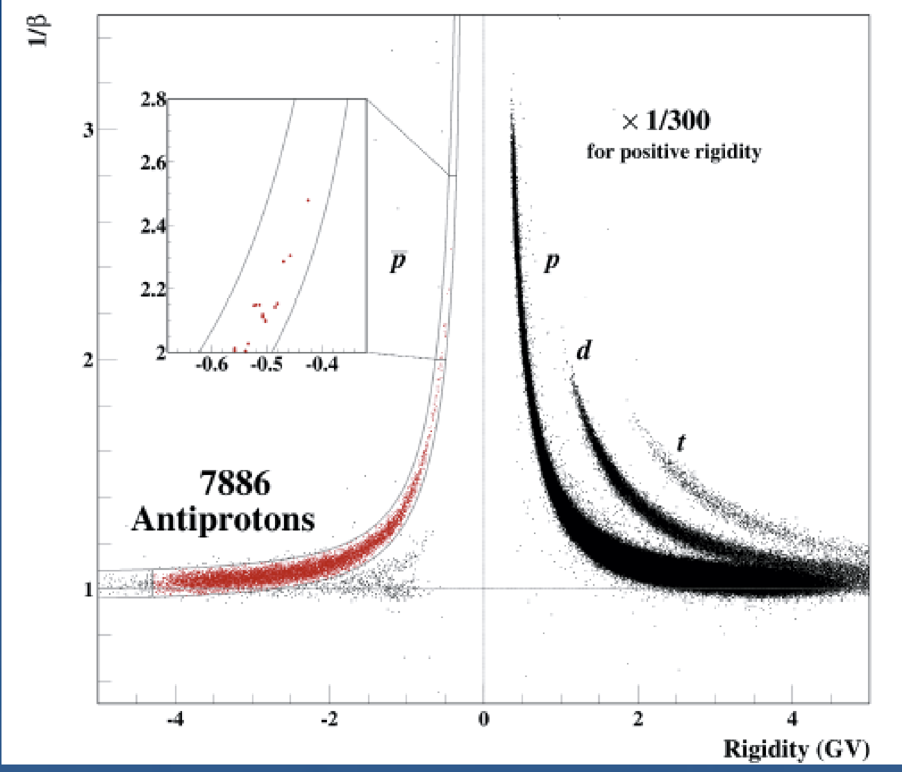
Makoto Sasaki, Antideuteron 2014, UCLA

BESS-Polar II: Lower Energy, High Statistics

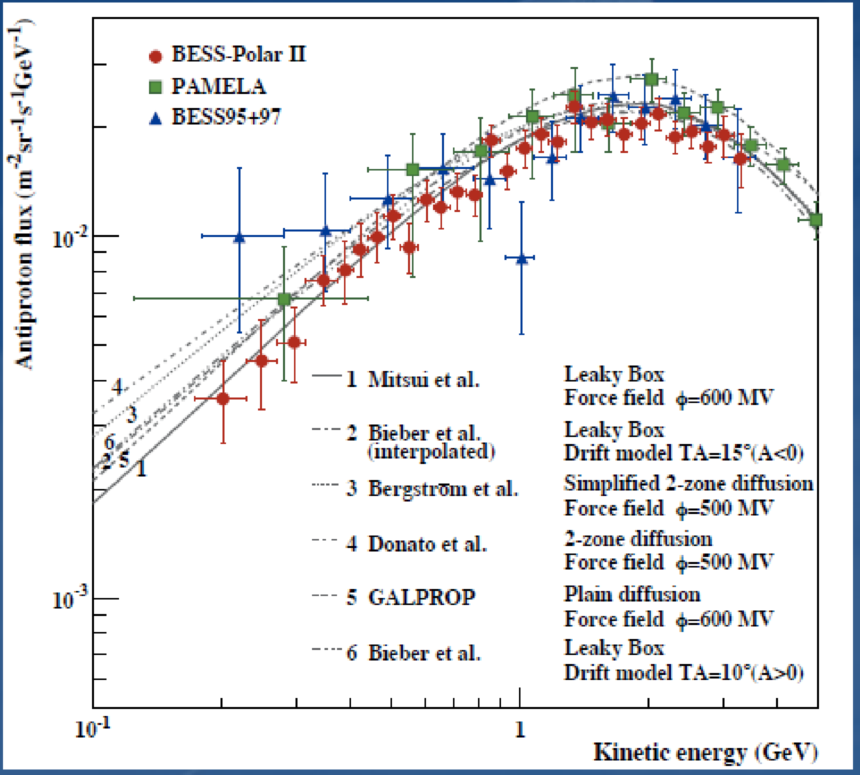


Antiproton Measurement

BESS-Polar II Z=1 Particle Id



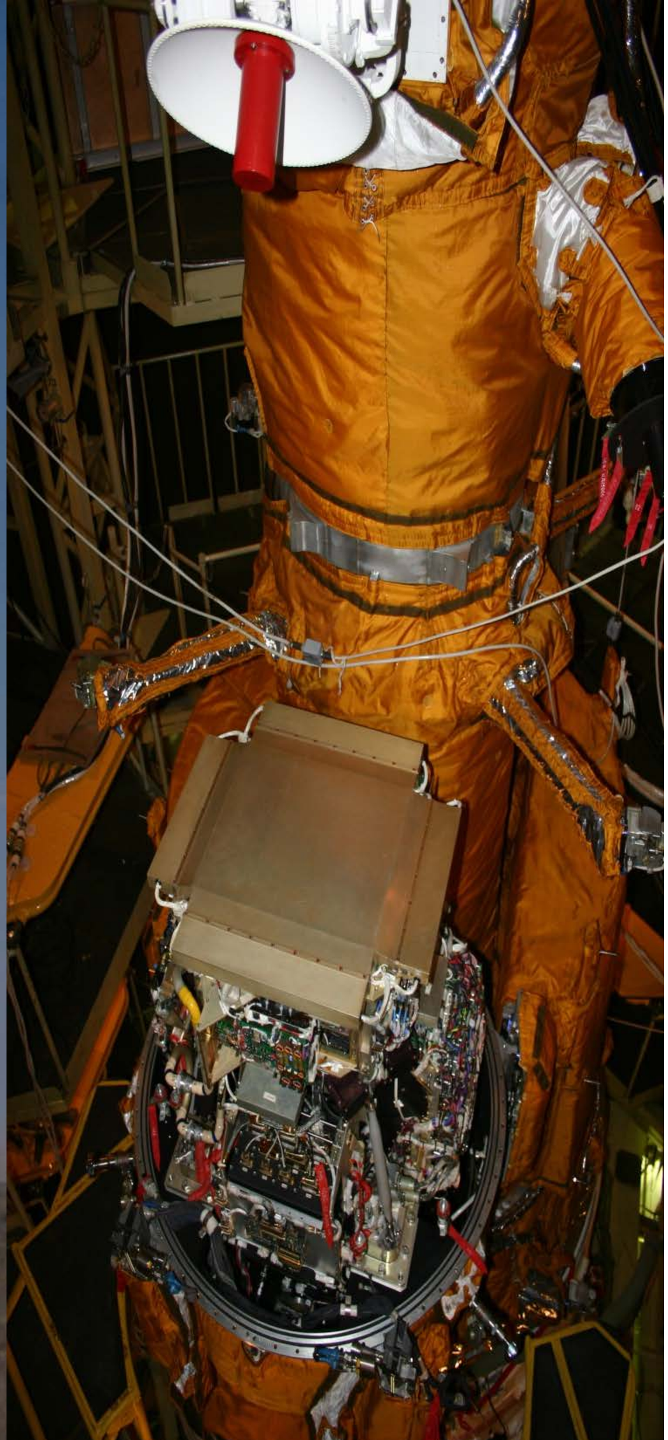
Antiproton Spectrum



- MDR 240 GV, TOF 120 ps, ACC rejection 6100
- 7886 Antiprotons ~10-20 times previous Solar minimum dataset

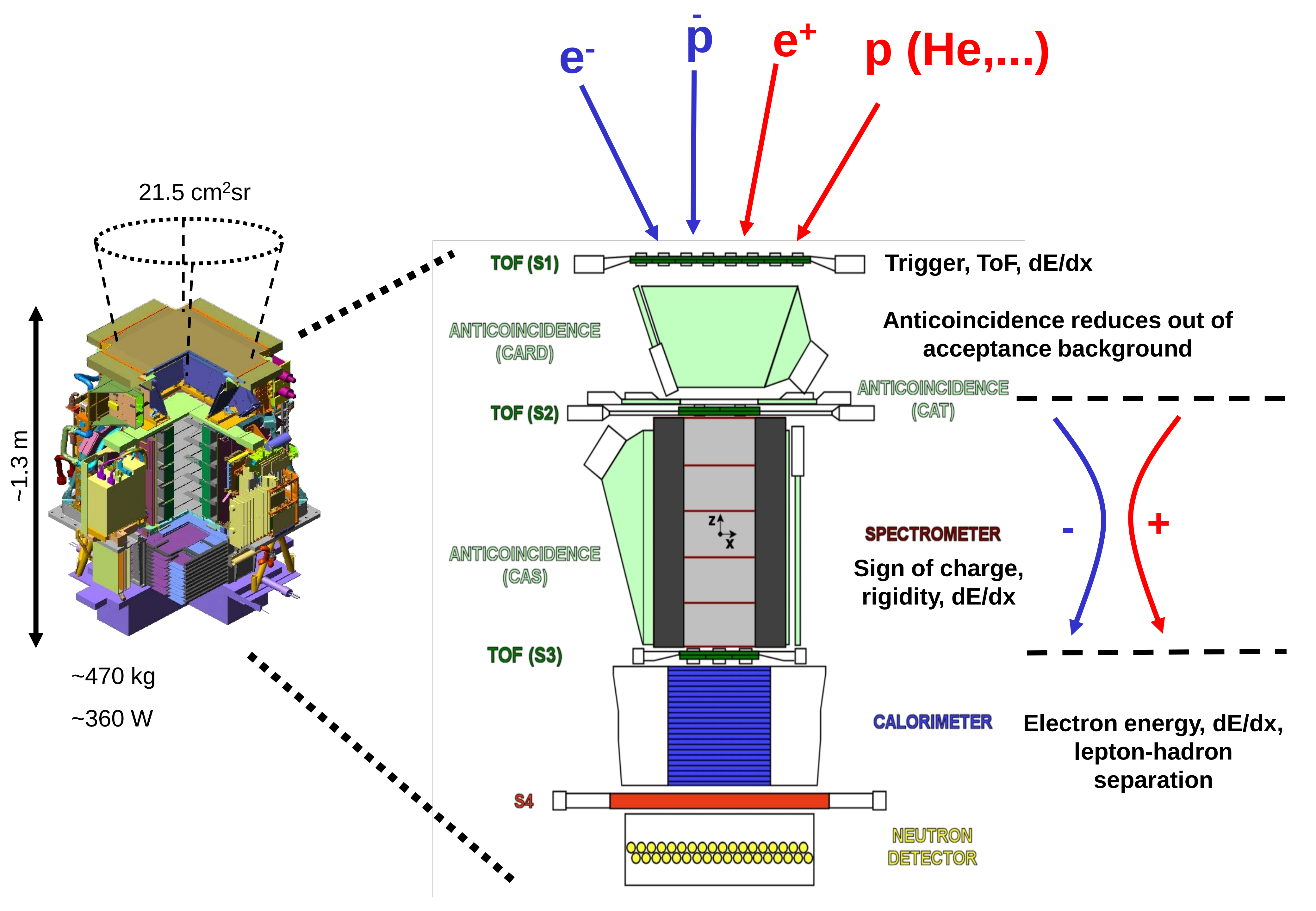
- BESS-Polar II and PAMELA spectra agree in shape but differ ~14% in absolute flux
- Both agree in shape with secondary

Makoto Sasaki, Antideuteron 2014, UCLA

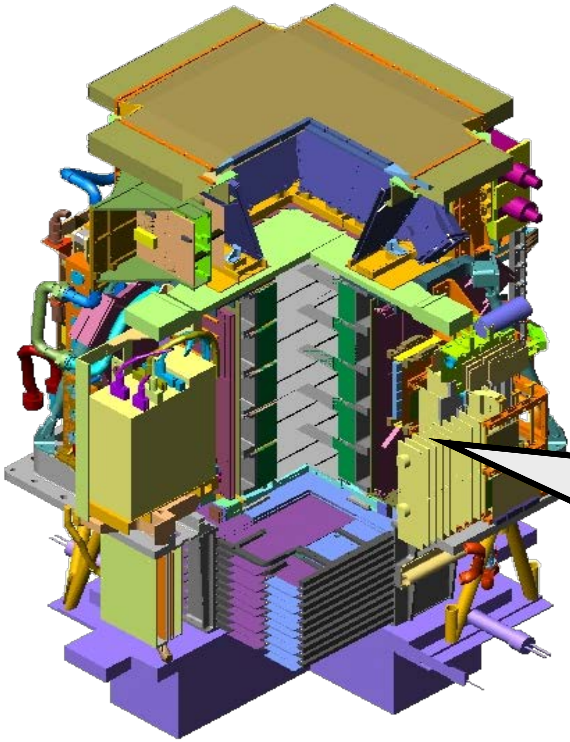


P A M E L A

Payload for Antimatter / Matter Exploration and Light-nuclei Astrophysics



e-
p̄
e+
p (He,...)
21.5 cm²sr
~1.3 m
~470 kg
~360 W
TOF (S1)
Trigger, ToF, dE/dx
ANTICOINCIDENCE (CARD)
Anticoincidence reduces out of acceptance background
ANTICOINCIDENCE (CAT)
TOF (S2)
ANTICOINCIDENCE (CAS)
SPECTROMETER
Sign of charge, rigidity, dE/dx
-
+
TOF (S3)
CALORIMETER
Electron energy, dE/dx, lepton-hadron separation
S4
NEUTRON DETECTOR

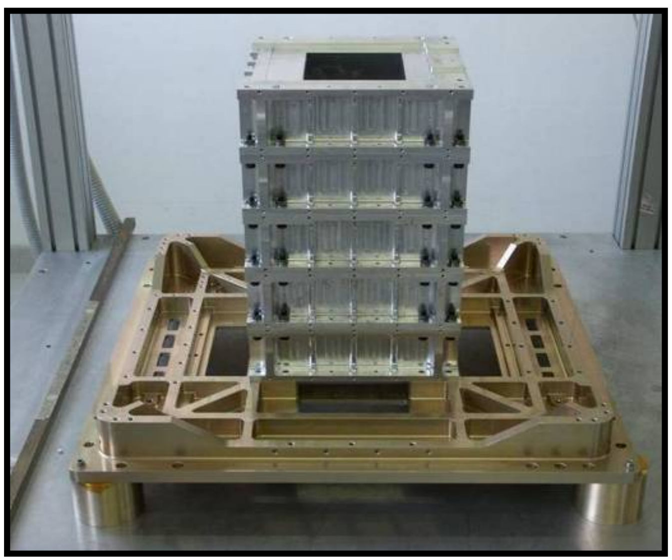


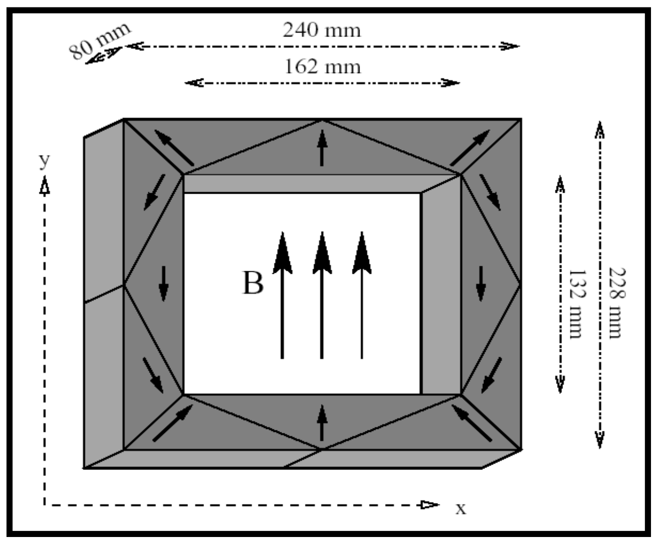
The magnet

Characteristics:

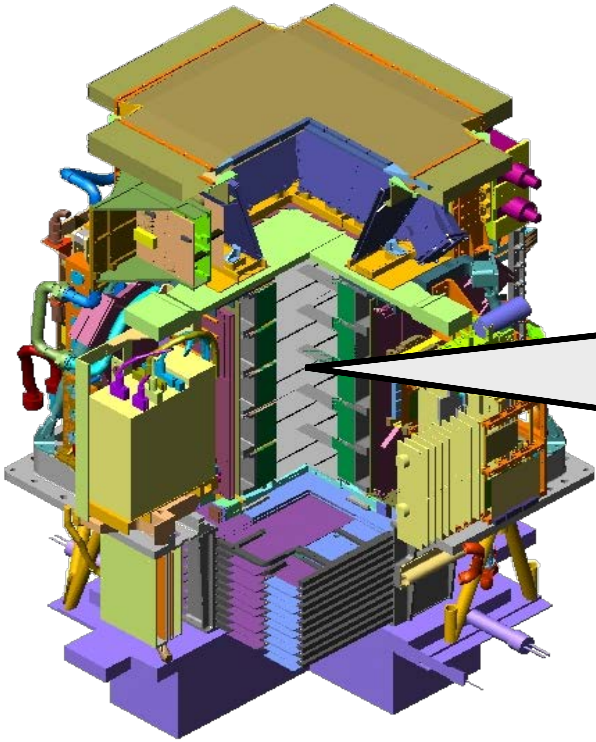
- **5 modules of permanent magnet (Nd-B-Fe alloy) in aluminum mechanics**
- Cavity dimensions (162 x 132 x 445) cm^3

  → GF ~ 21.5 cm^2sr
- Magnetic shields
- 5mm-step field-map on ground:
  - **B=0.43 T (average along axis),**
  - **B=0.48 T (@center)**





The tracking system



Main tasks:

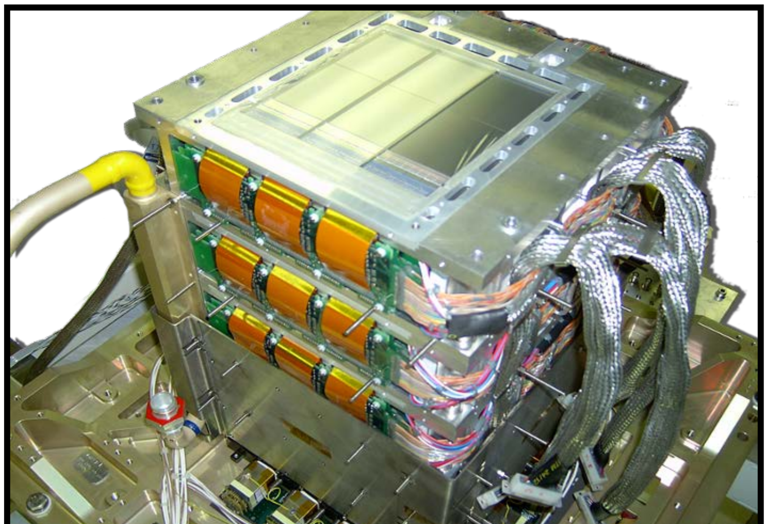
- Rigidity measurement
- Sign of electric charge
- dE/dx (ionisation loss)

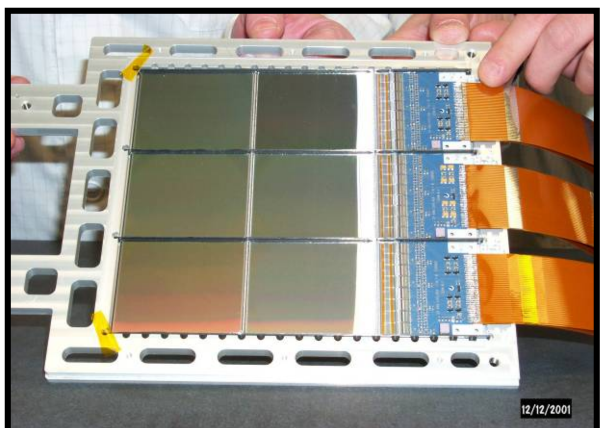
Characteristics:

- 6 planes double-sided (x&y view) microstrip Si sensors
- 36864 channels
- Dynamic range: 10 MIP

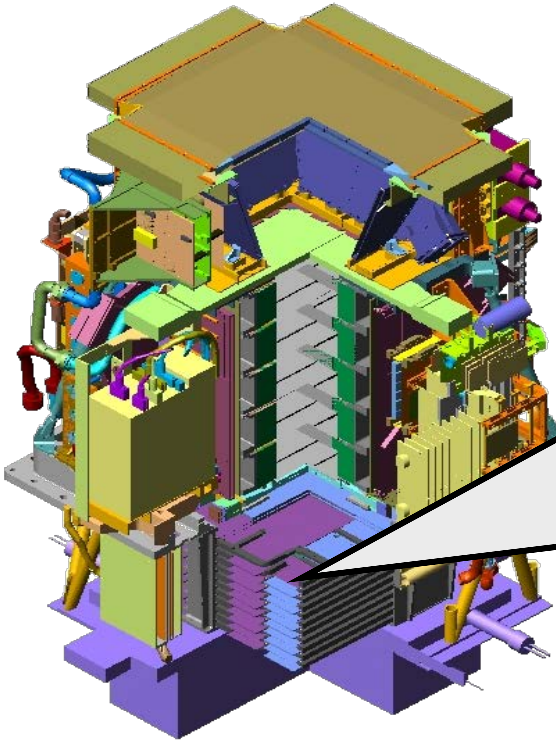
Performance:

- Spatial resolution: ~3 µm (bending view)
- MDR ~1 TV/c (from test beam data)





The electromagnetic calorimeter



Main tasks:

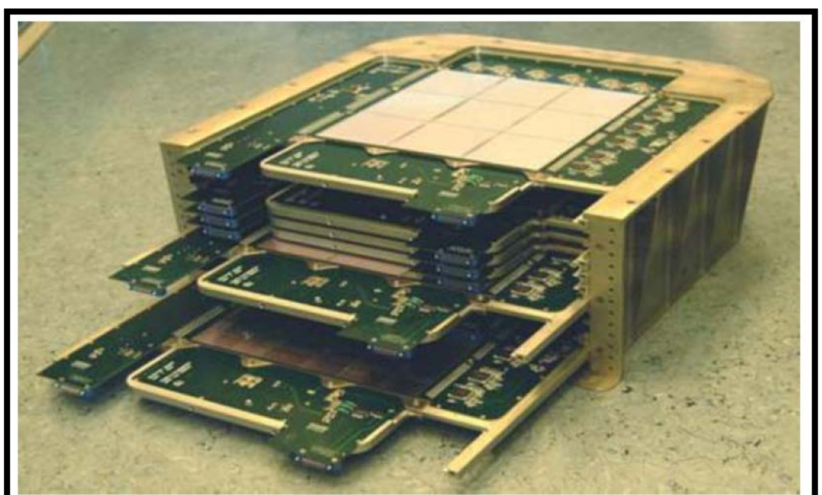
- **lepton/hadron discrimination**
- **$e^{+/-}$ energy measurement**

Characteristics:

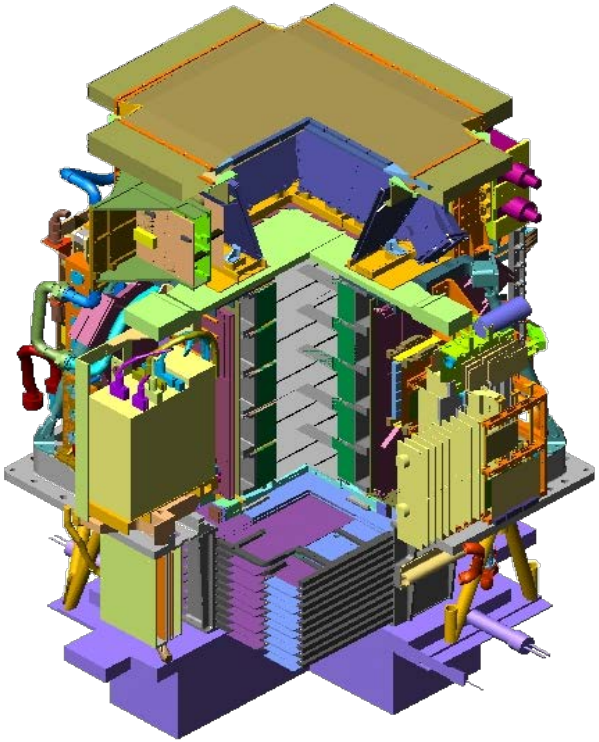
- **44 Si layers (x/y) + 22 W planes**
- **16.3 X_o / 0.6 λ_L**
- 4224 channels
- Dynamic range: 1400 mip
- **Self-trigger mode (> 300 GeV; GF~600 cm^2 sr)**

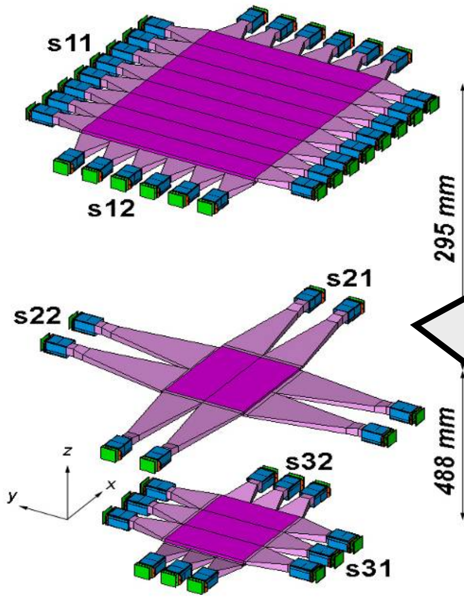
Performance:

- p/e^+ selection efficiency ~ 90%
- p rejection factor ~10^5
- e rejection factor > 10^4
- **Energy resolution ~5% @ 200 GeV**



The time-of-flight system





Main tasks:

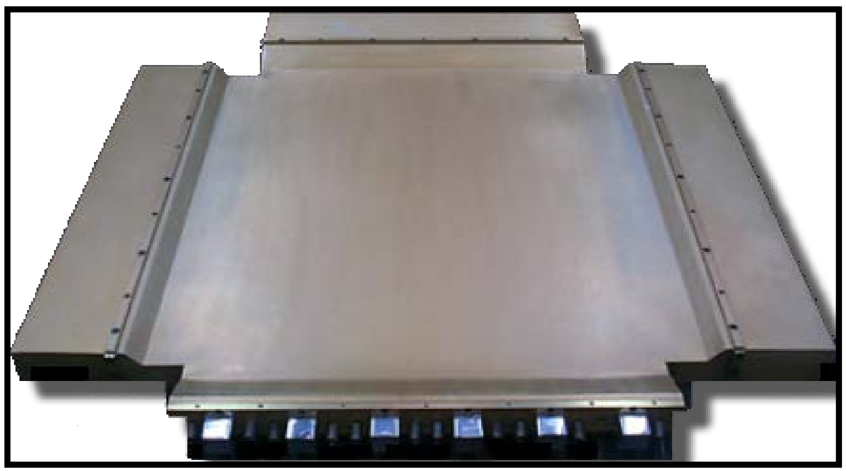
- **First-level trigger**
- **Albedo rejection**
- **dE/dx (ionisation losses)**
- **Time of flight particle identification (<1GeV/c)**

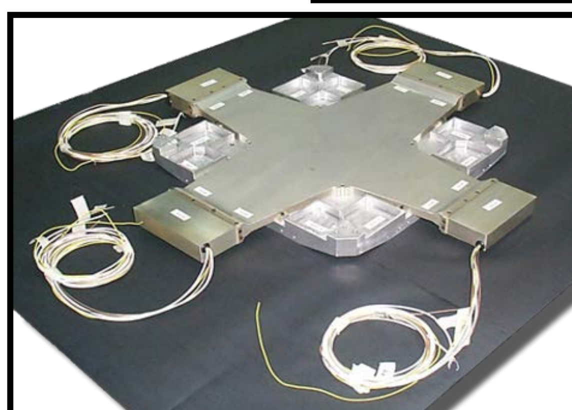
Characteristics:

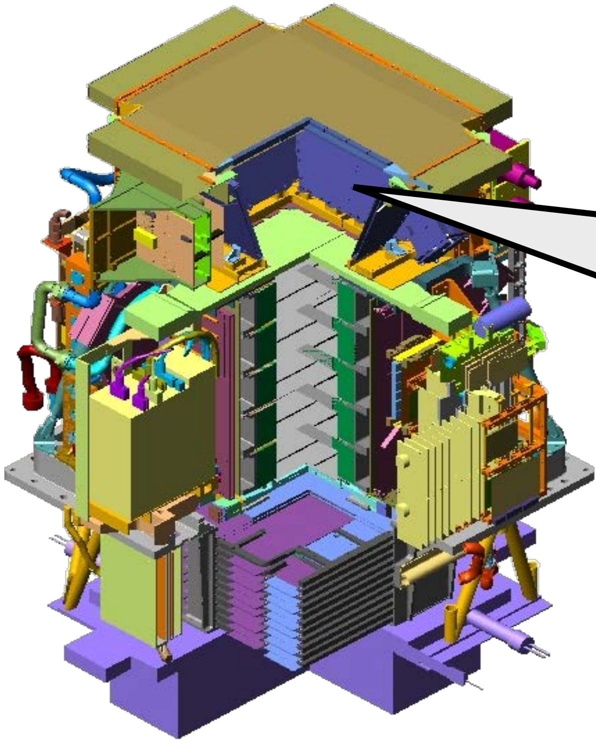
- **3 double-layer scintillator paddles**
- **x/y segmentation**
- Total: 48 channels

Performance:

- σ(paddle) ~ 110ps
- **σ(ToF) ~ 330ps (for MIPs)**







The anticounter shields

Main tasks:

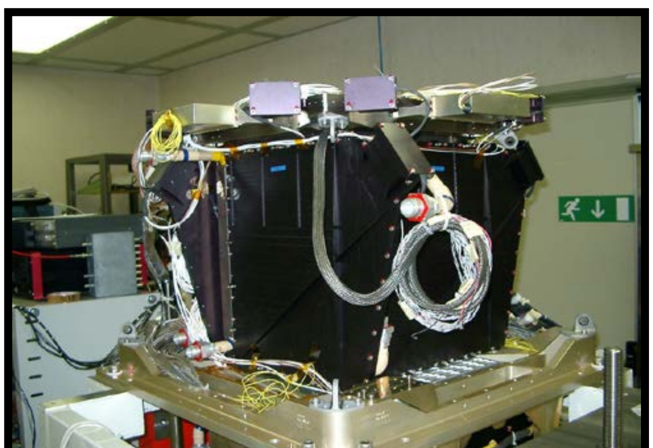
- **Rejection of events with particles interacting with the apparatus** (off-line and second-level trigger)

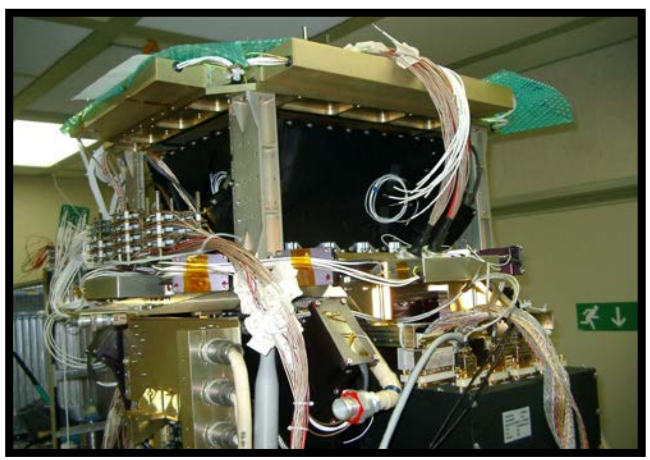
Characteristics:

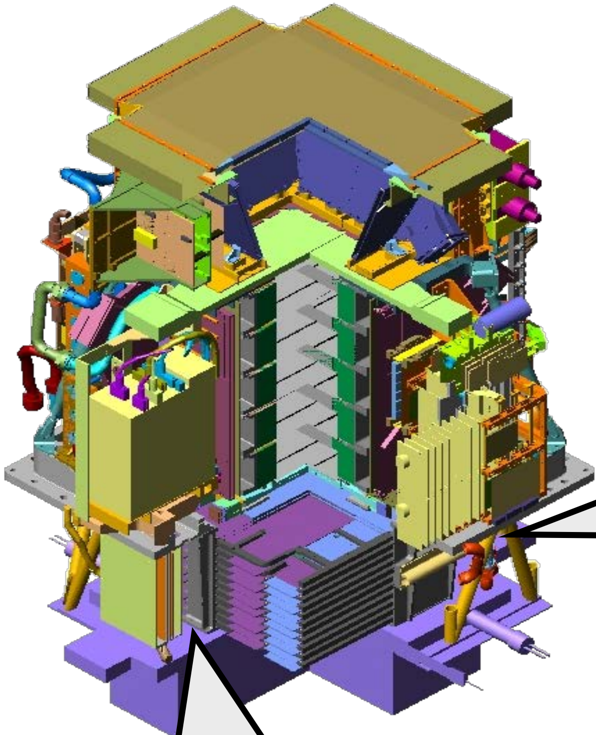
- **Plastic scintillator paddles, 8mm thick**
- 4 upper (CARD), 1 top (CAT), 4 side (CAS)

Performance:

- MIP efficiency > 99.9%







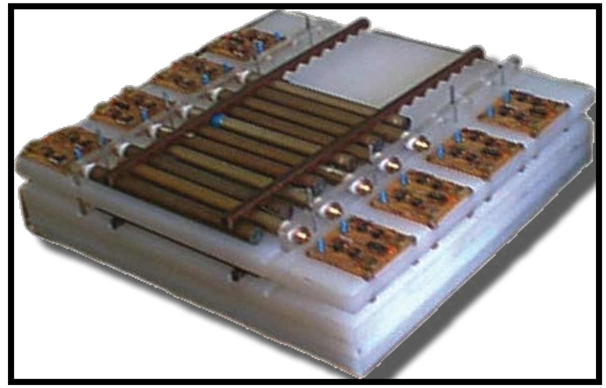
Neutron detector

Main tasks:

- **e/h discrimination at high energy**

Characteristics:

- **36 ^{3}He counters**:
  ^{3}He(n,p)T - Ep=780 keV
- 1cm thick polyethylene + Cd moderators
- n collected within 200 µs time-window



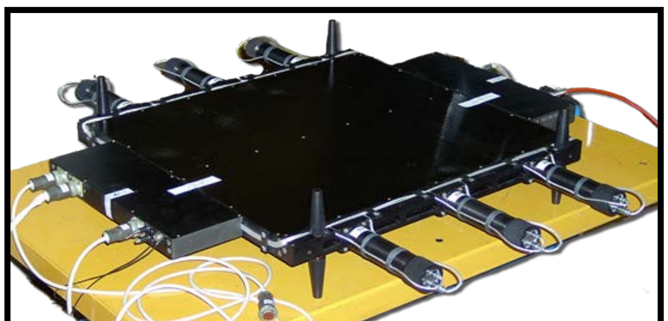
Main tasks:

- **Neutron detector trigger**

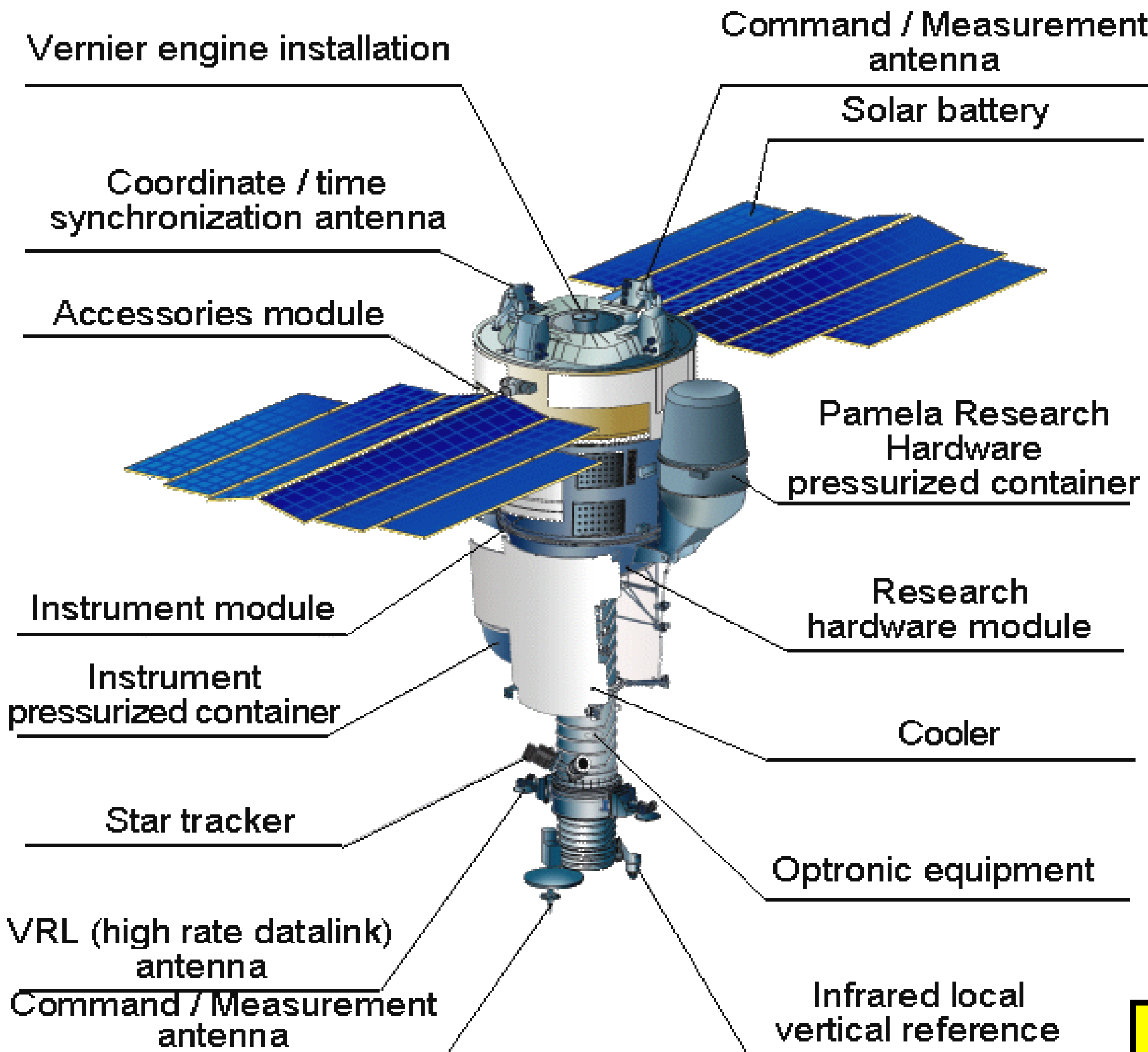
Characteristics:

- **Plastic scintillator paddle, 1 cm thick**

Shower-tail catcher



Resurs-DK1 satellite

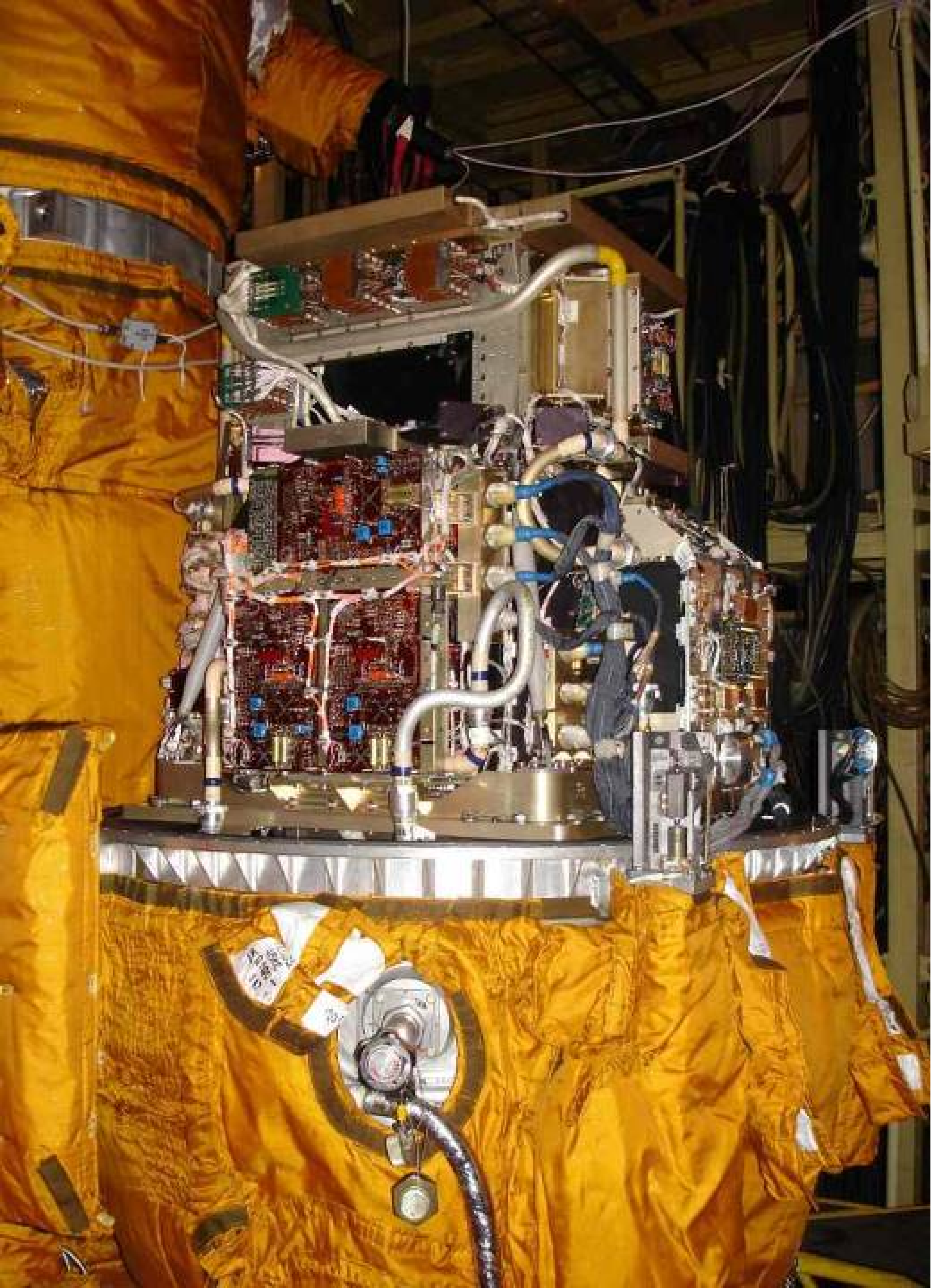


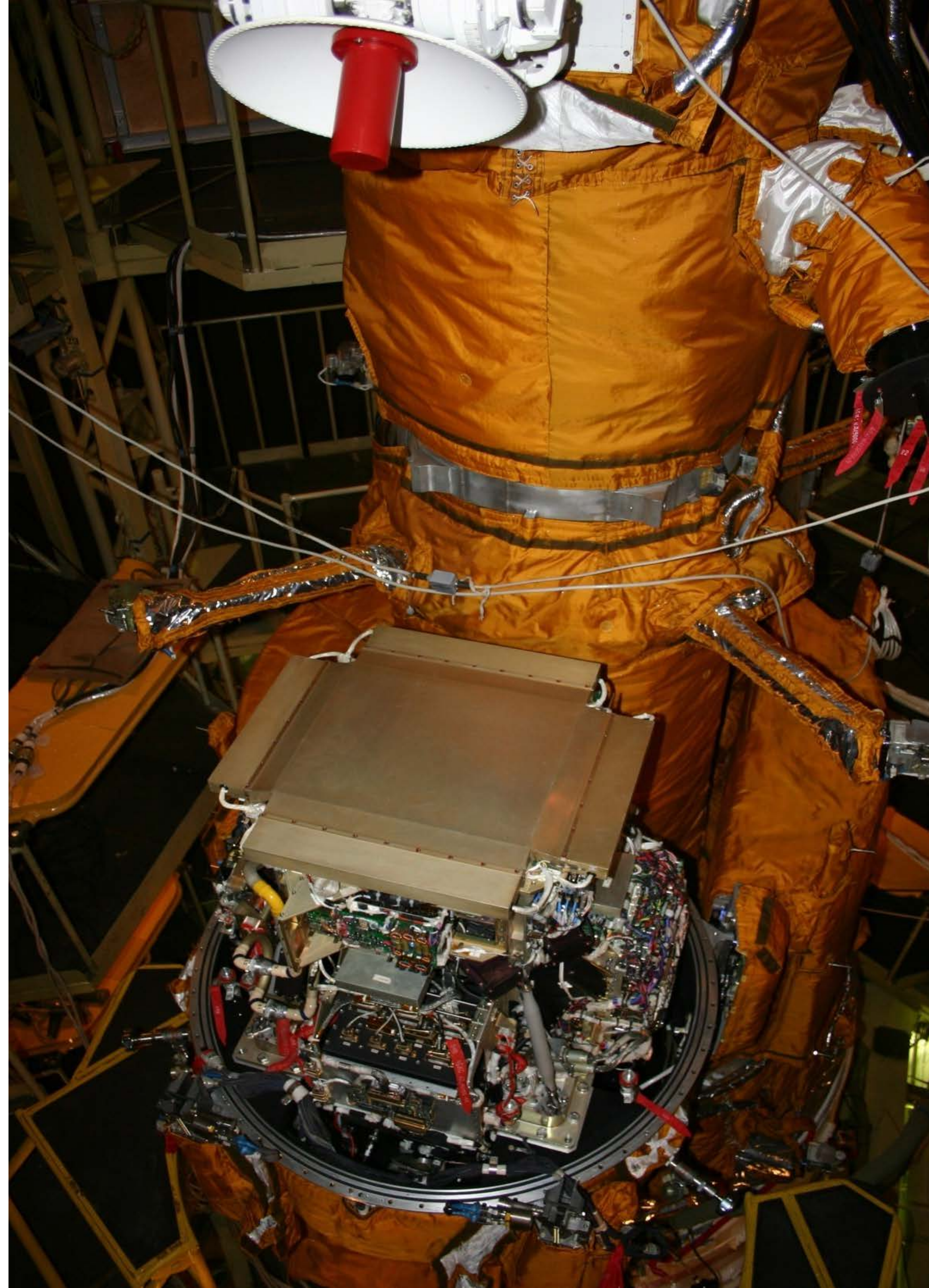
- **Main task:** multi-spectral remote sensing of earth's surface
- Built by TsSKB Progress in Samara, Russia

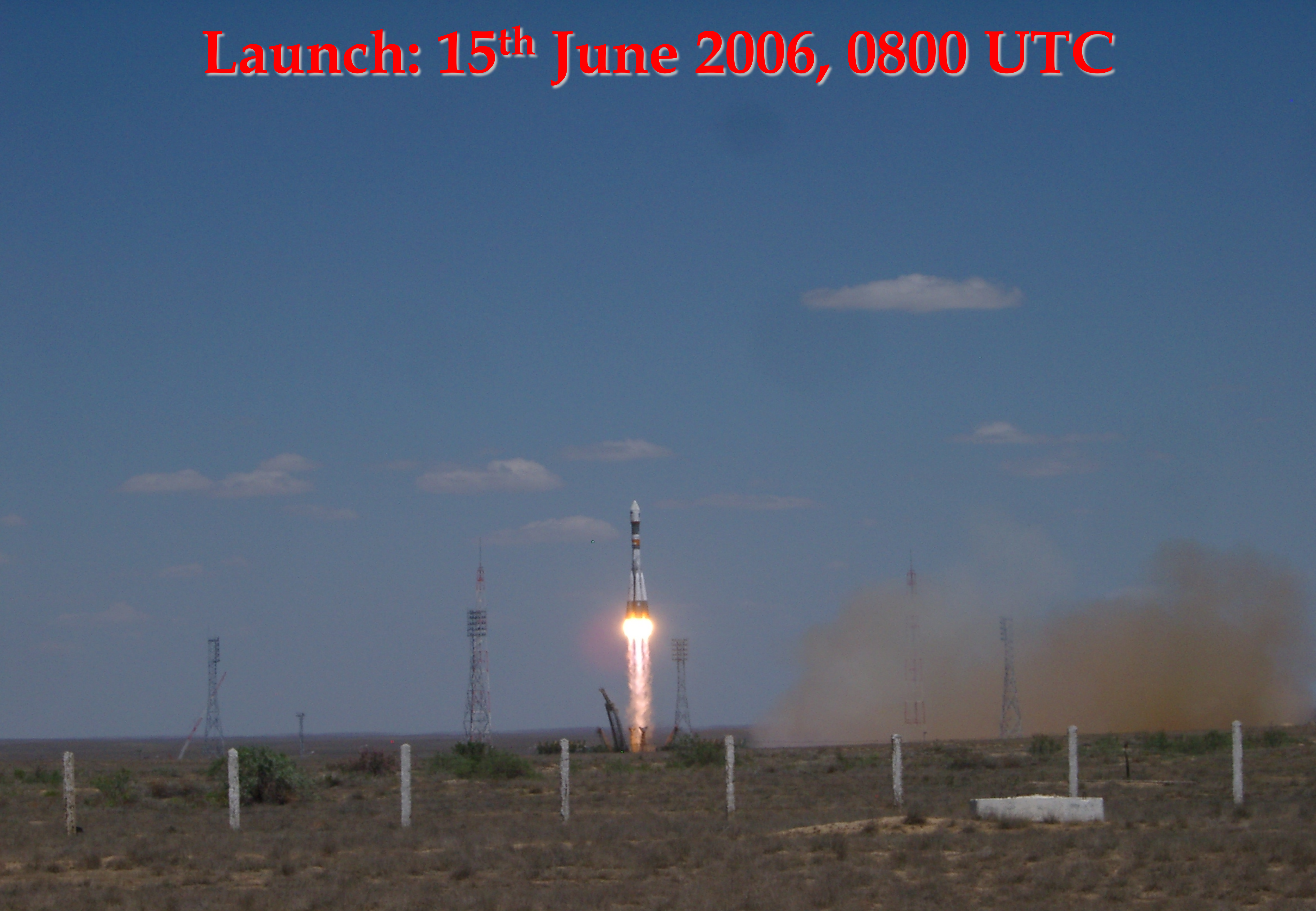
- **Lifetime >3 years (assisted)**
- Data transmitted to ground via high-speed radio downlink

- **PAMELA mounted inside a pressurized container**

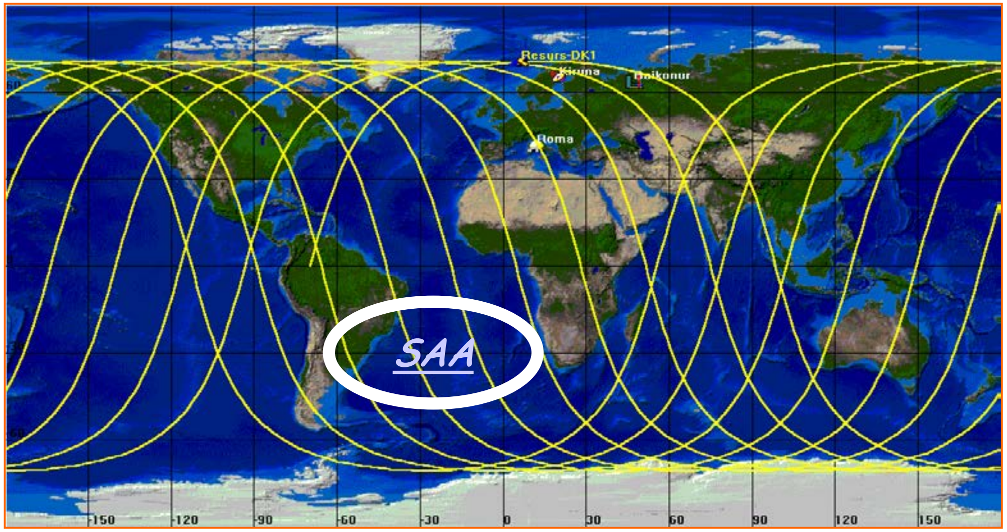
Mass: 6.7 tonnes
Height: 7.4 m
Solar array area: 36 m^2

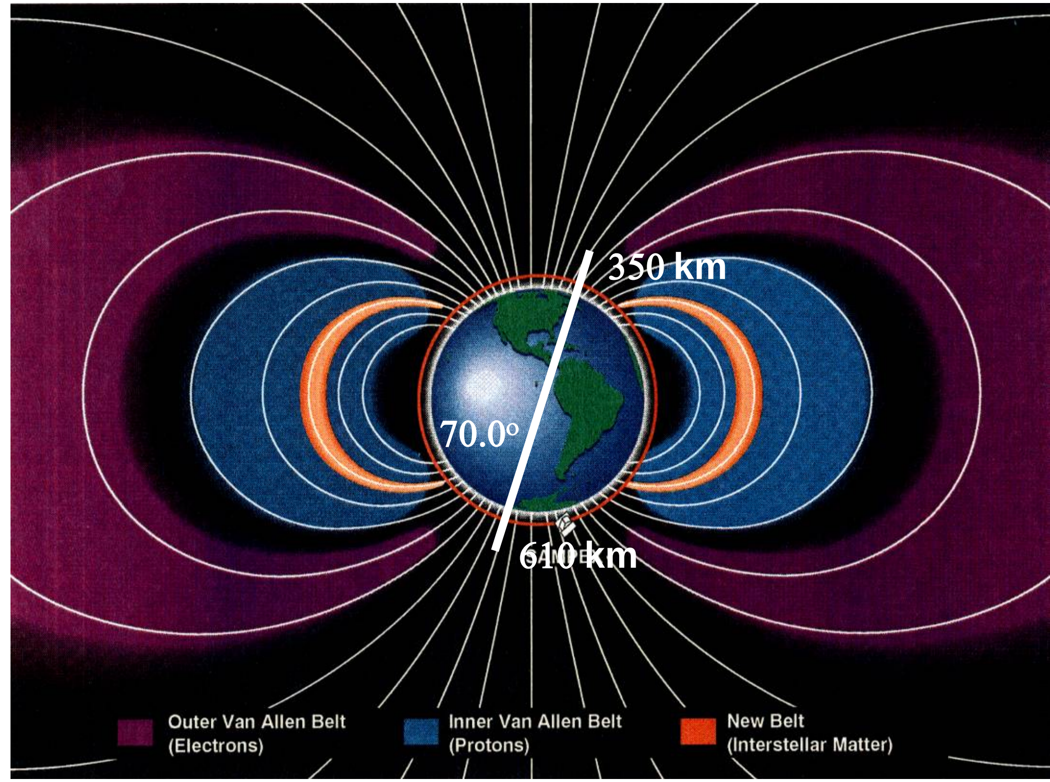





Launch: 15th June 2006, 0800 UTC

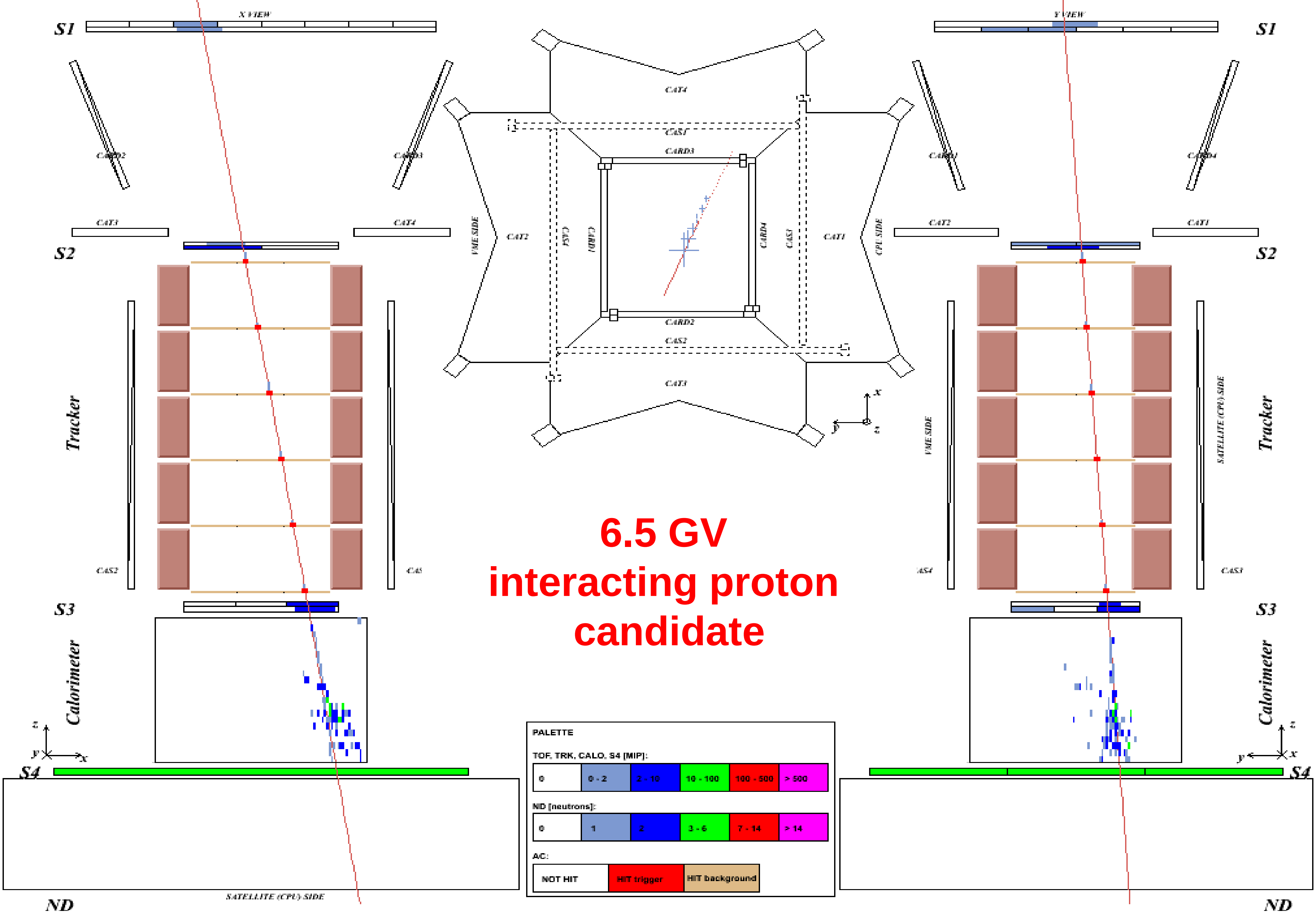
Orbit characteristics



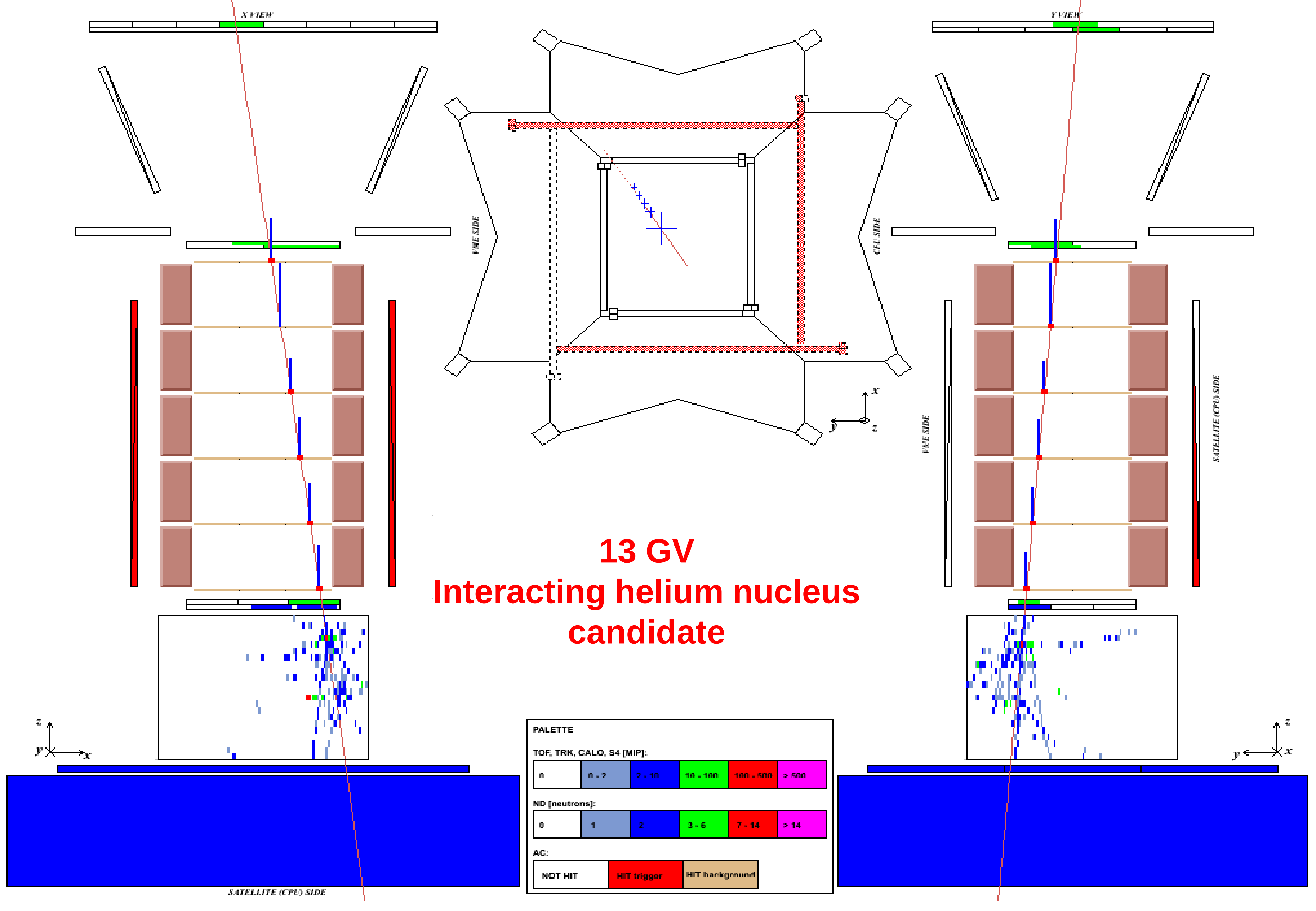


- Quasi-polar (70.0°)
- Elliptical (350 km - 600 km)

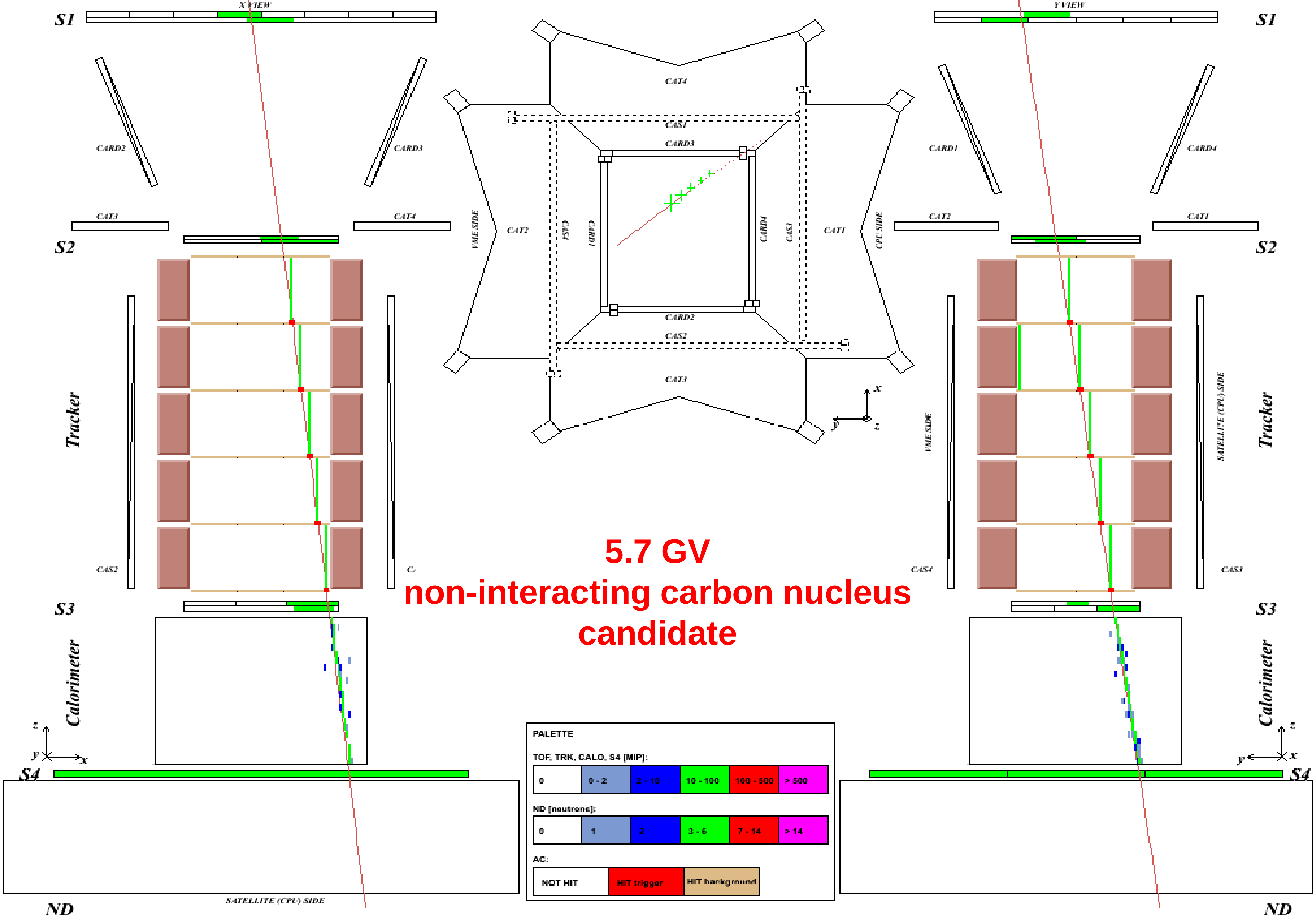
- PAMELA traverses the South Atlantic Anomaly
- At the South Pole PAMELA crosses the outer (electron) Van Allen belt

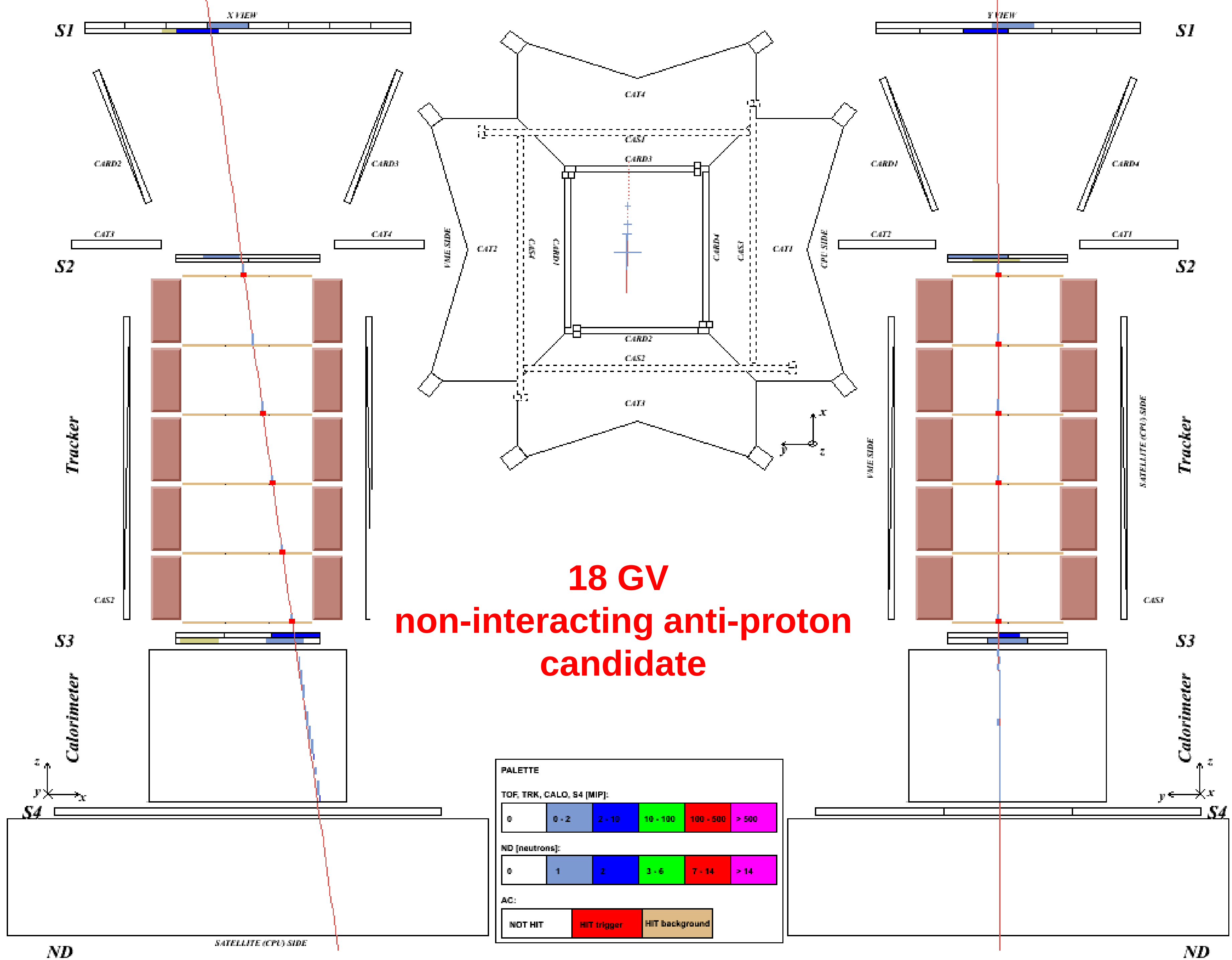


X VIEW
Y VIEW
S1
S2
S3
S4
ND
Tracker
Calorimeter
CAT1
CAT2
CAT3
CAT4
CARD1
CARD2
CARD3
CARD4
CAS1
CAS2
CAS3
CAS4
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
6.5 GV
interacting proton
candidate
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background

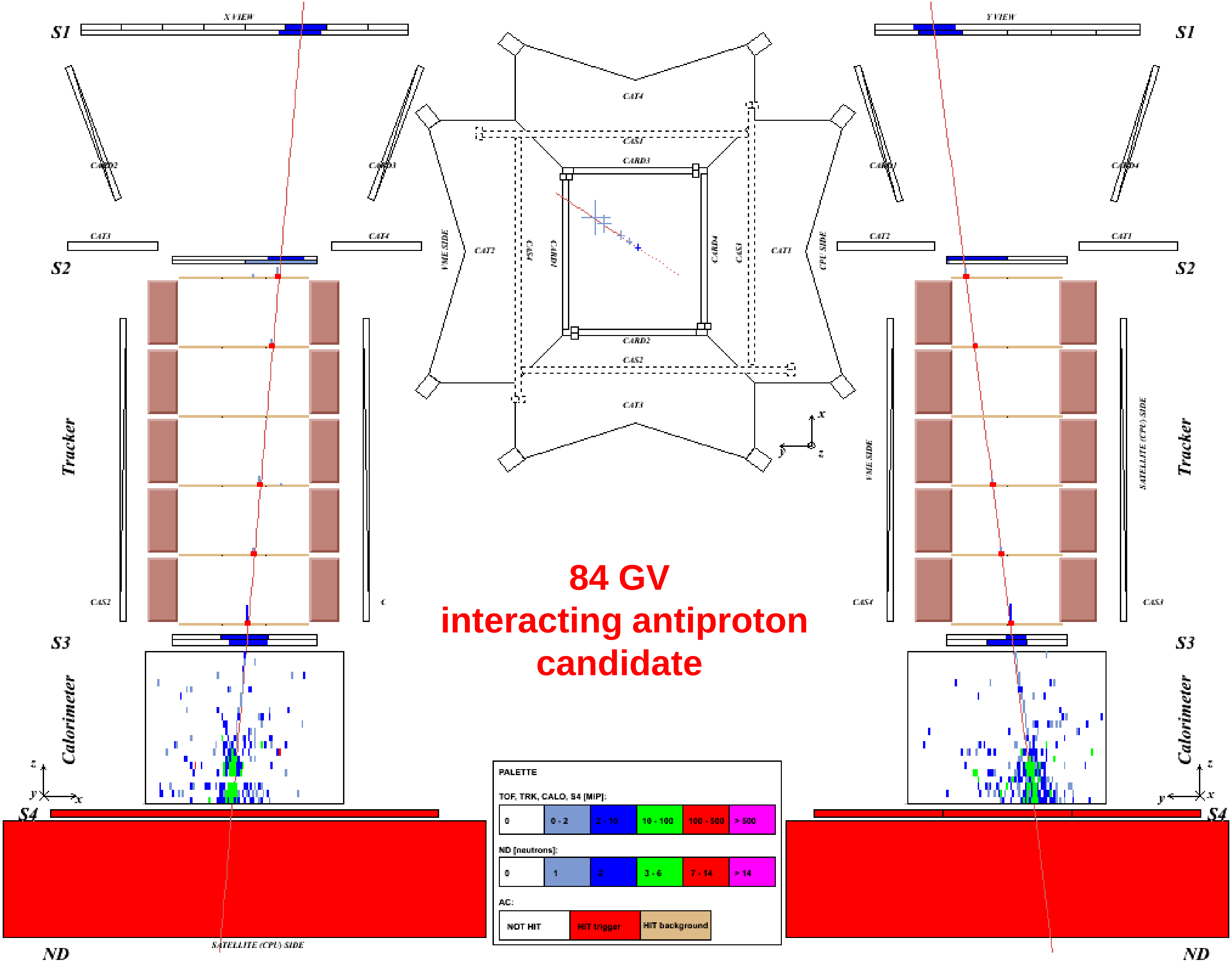

X VIEW
Y VIEW
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
13 GV
Interacting helium nucleus
candidate
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background

5.7 GV non-interacting carbon nucleus candidate

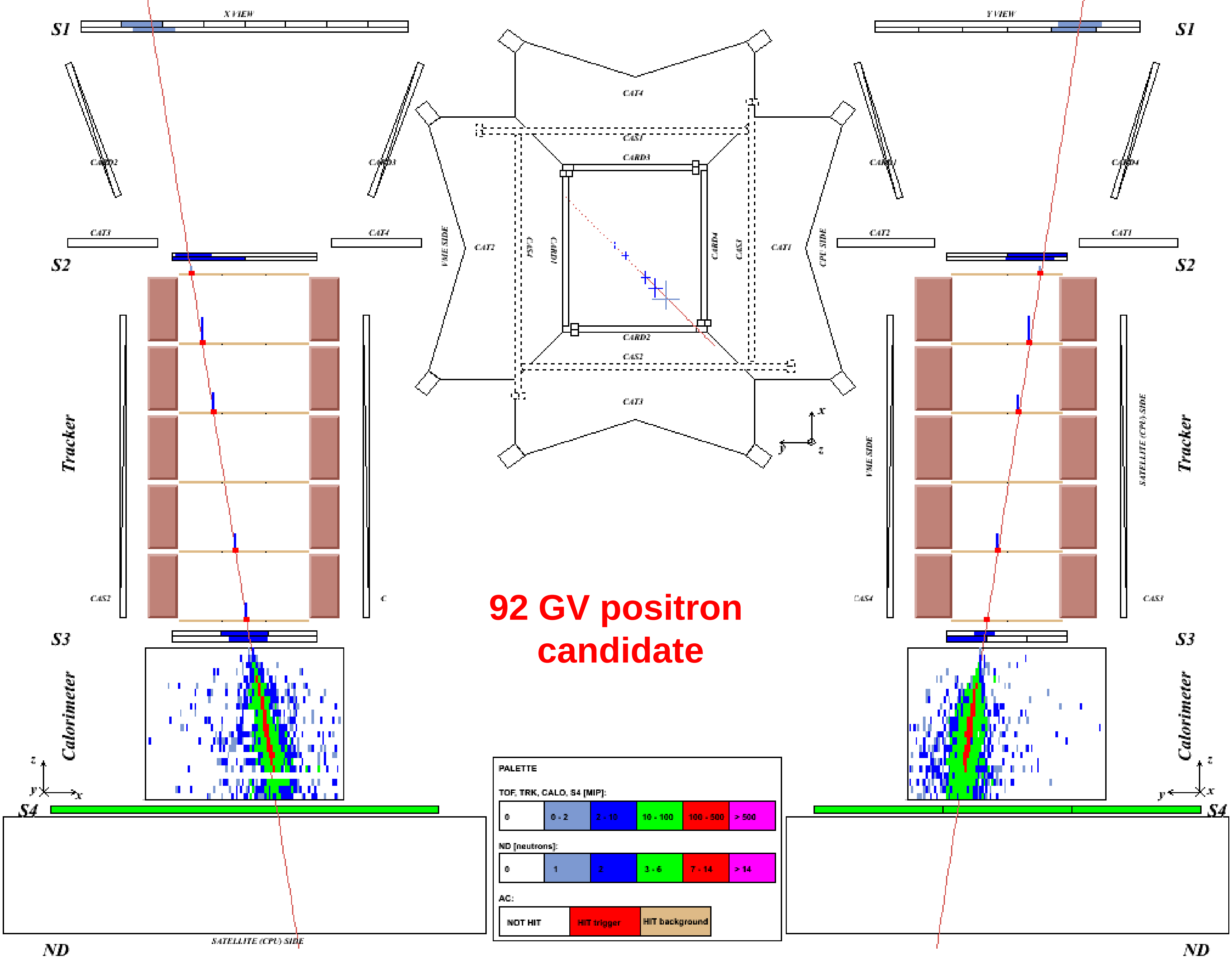




18 GV
non-interacting anti-proton candidate
X VIEW
Y VIEW
S1
S2
S3
S4
ND
Tracker
Calorimeter
CARD1
CARD2
CARD3
CARD4
CAT1
CAT2
CAT3
CAT4
CAS1
CAS2
CAS3
CAS4
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
SATELLITE (CPU) SIDE
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background

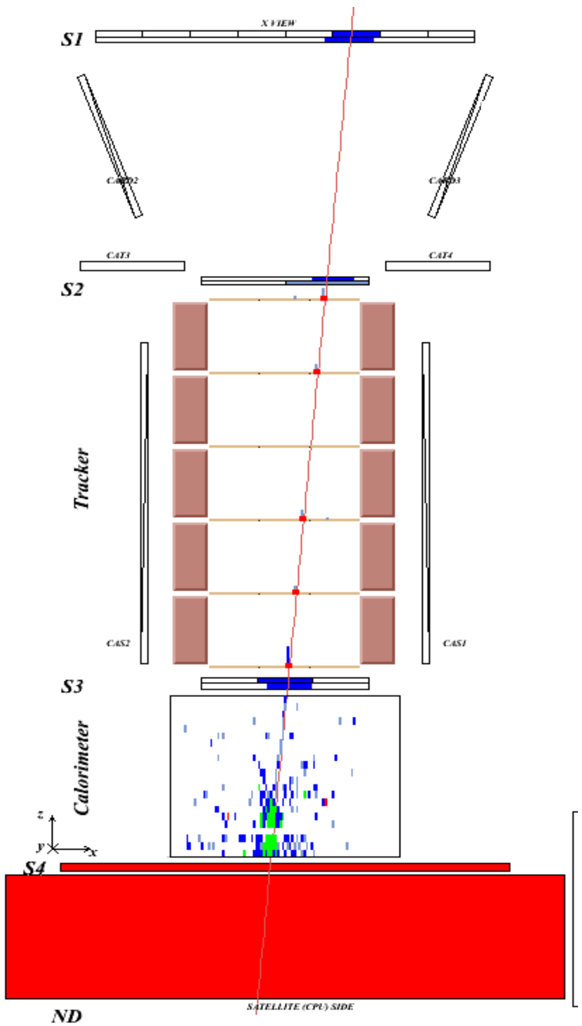


X VIEW
Y VIEW
S1
S2
S3
S4
ND
Tracker
Calorimeter
CARD1
CARD2
CARD3
CARD4
CAT1
CAT2
CAT3
CAT4
CAS1
CAS2
CAS3
CAS4
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
84 GV
interacting antiproton
candidate
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background


92 GV positron candidate
X VIEW
Y VIEW
S1
S2
S3
S4
ND
Tracker
Calorimeter
CAT1
CAT2
CAT3
CAT4
CAS1
CAS2
CAS3
CAS4
CARD1
CARD2
CARD3
CARD4
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background

Antiprotons

Antiproton / positron identification



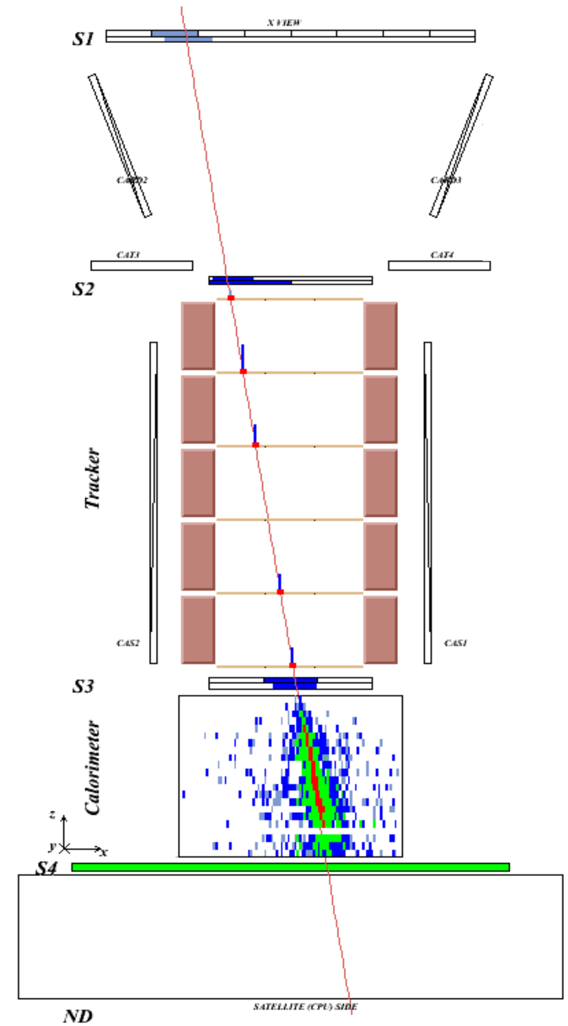
Antiproton
(NB: $e^-/p \sim 10^2$)

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

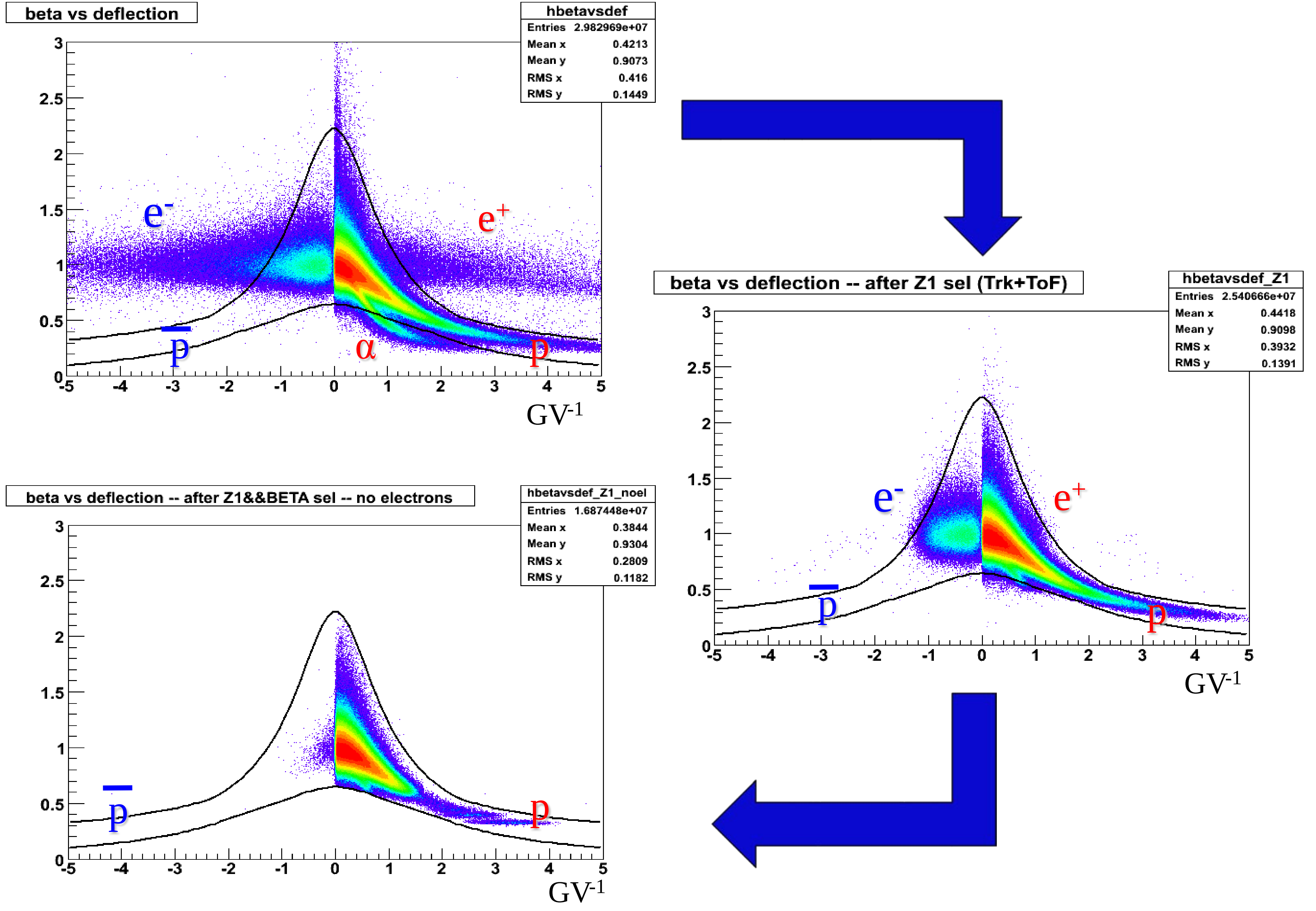
Bending in spectrometer:
sign of charge

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

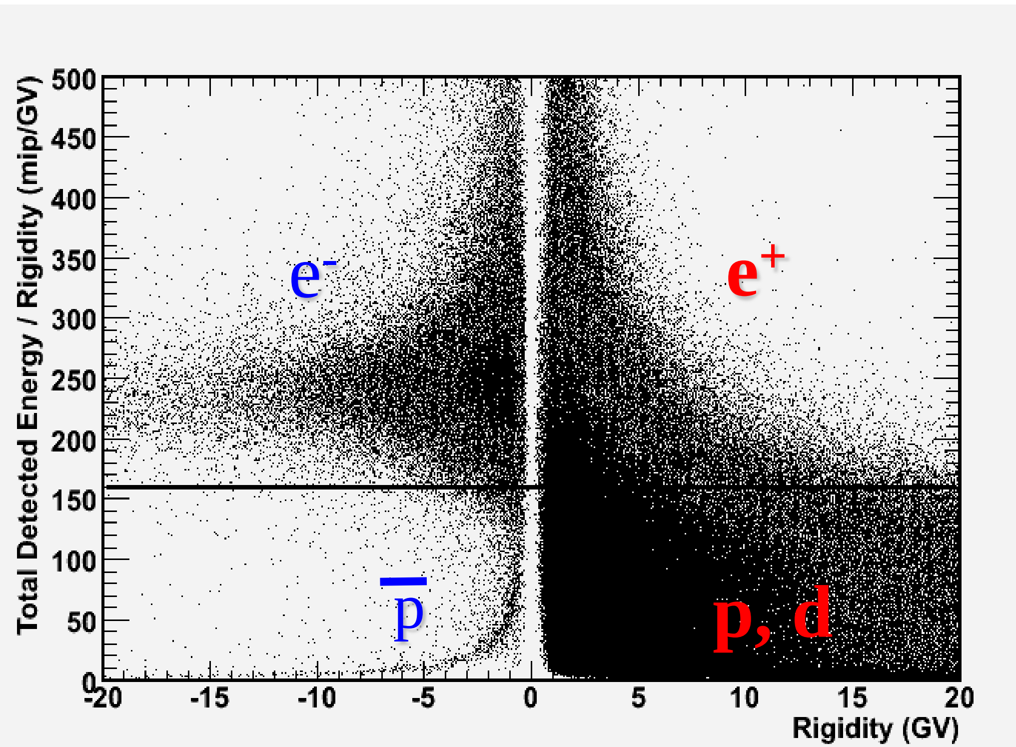
Interaction pattern in calorimeter:
electron-like or proton-like, electron energy

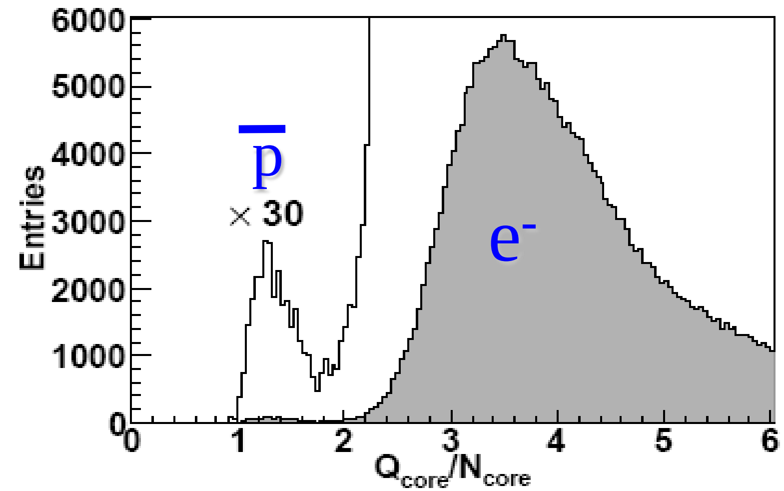


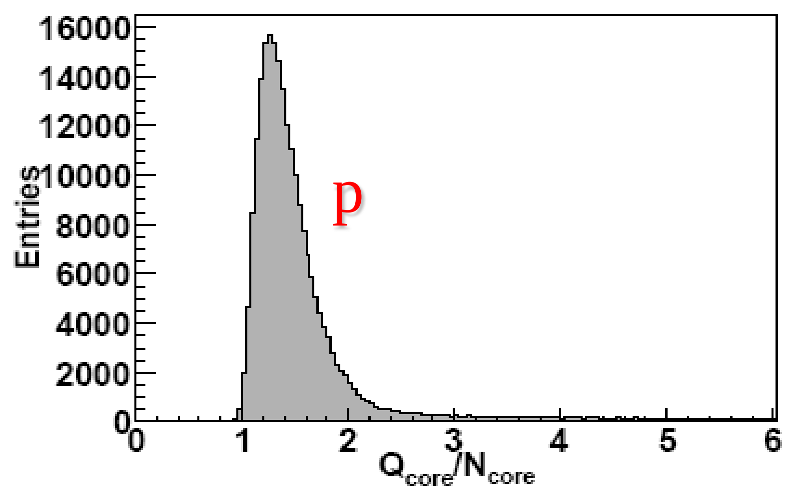
Positron
(NB: $p/e^+ \sim 10^{3\text{-}4}$)


beta vs deflection
hbetavsdef
Entries 2.982969e+07
Mean x 0.4213
Mean y 0.9073
RMS x 0.416
RMS y 0.1449
e-
e+
p̄
α
p
GV-1
beta vs deflection -- after Z1 sel (Trk+ToF)
hbetavsdef_Z1
Entries 2.540666e+07
Mean x 0.4418
Mean y 0.9098
RMS x 0.3932
RMS y 0.1391
e-
e+
p̄
p
GV-1
beta vs deflection -- after Z1&&BETA sel -- no electrons
hbetavsdef_Z1_noel
Entries 1.687448e+07
Mean x 0.3844
Mean y 0.9304
RMS x 0.2809
RMS y 0.1182
p̄
p
GV-1

Calorimeter Selection







Proton Background

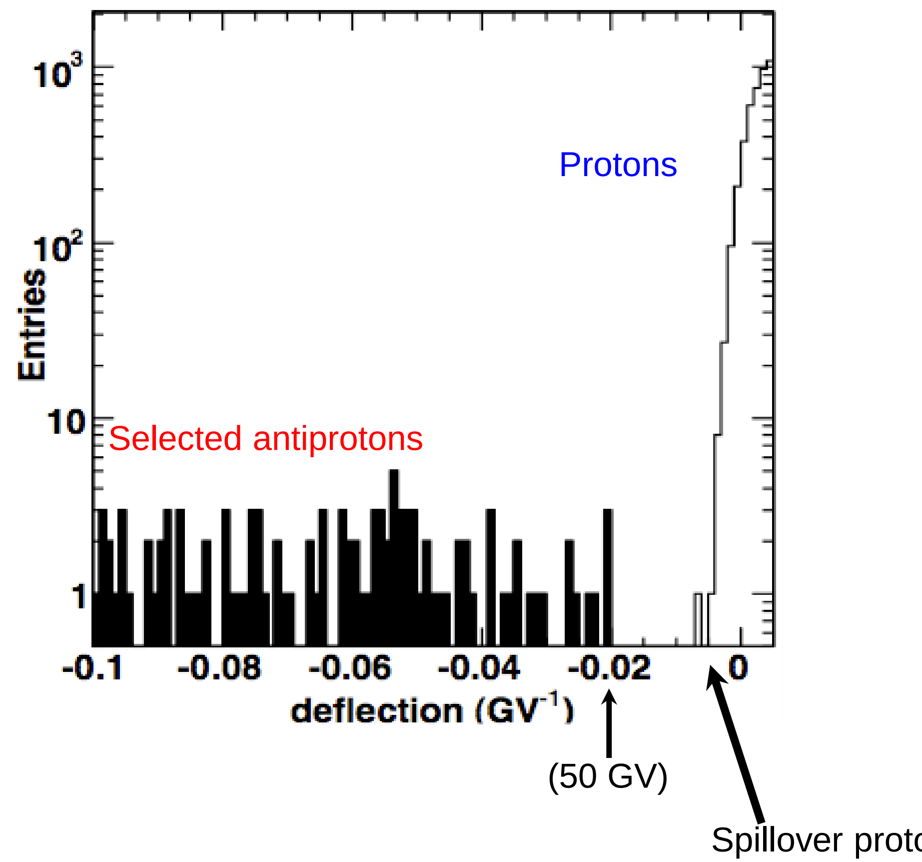
- Spectrometer tracking information is crucial for high-energy antiproton selection

- Finite spectrometer resolution - high rigidity protons may be assigned wrong sign-of-charge
- Also background from scattered protons

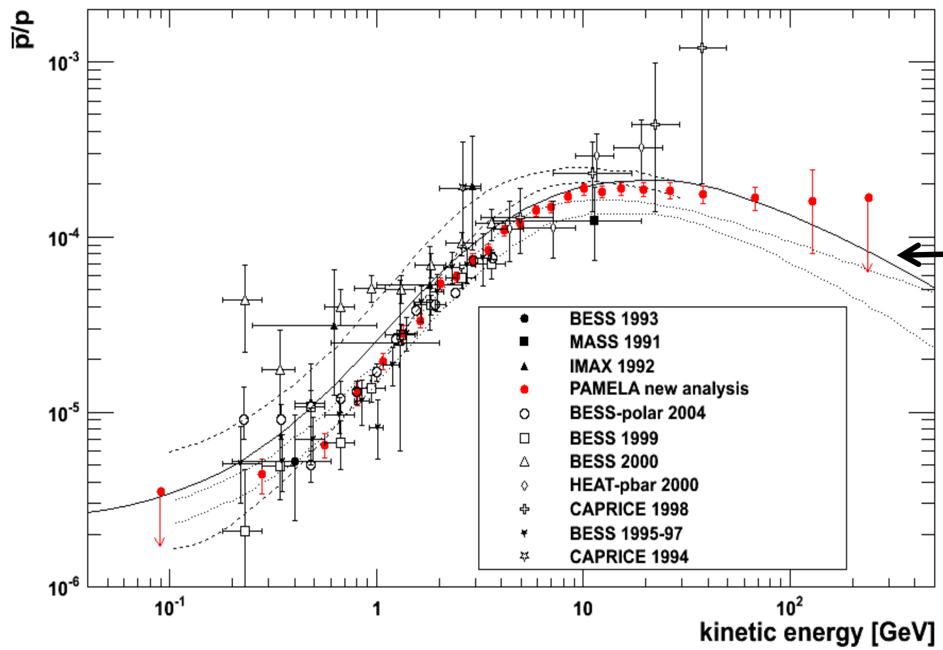
- Eliminate 'spillover' using strict track cuts (χ^2, lever arm, no δ-rays, etc)
- MDR > 10 × reconstructed rigidity

- Spillover limit for antiprotons expected to be ~200 GeV.

MDR > 850 GV, no EM shower

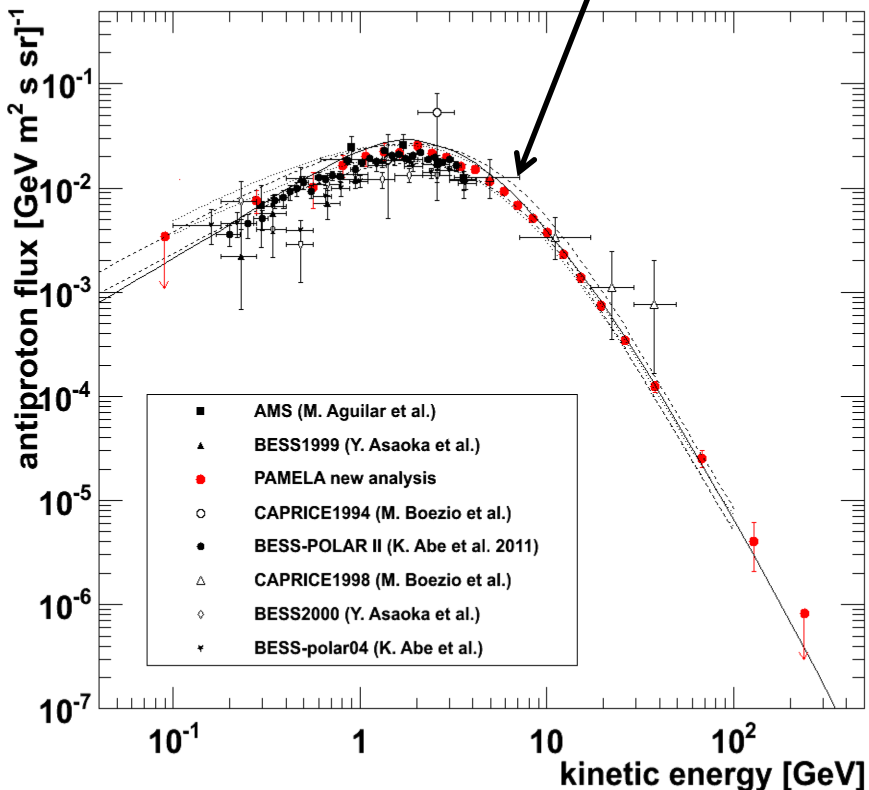


PAMELA Antiparticle Results: Antiprotons



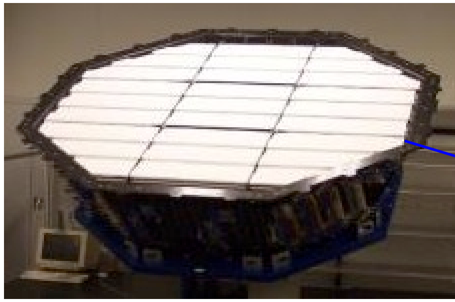
O. Adriani et al,
PRL 102 (2009) 051101;
PRL 105 (2010) 121101;
Phys. Rep. 544 (2014) 323.

Secondary production calculations

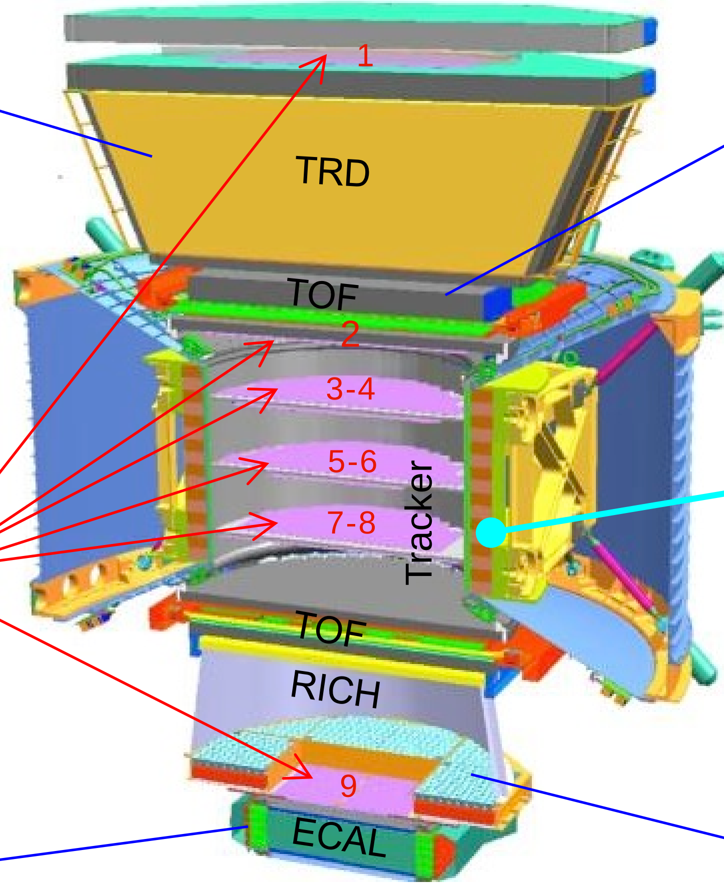


AMS : A TeV precision, multipurpose spectrometer

Transition Radiation Detector
Identify electrons

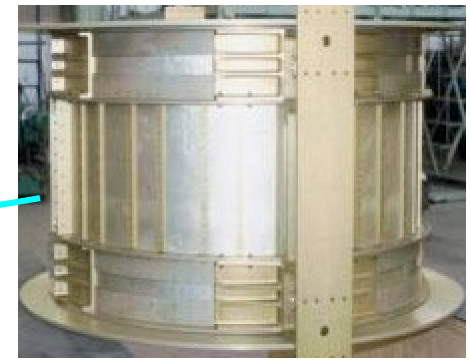


Particles are defined by their
charge (**Z**) and energy (**E**) or momentum (**P**)

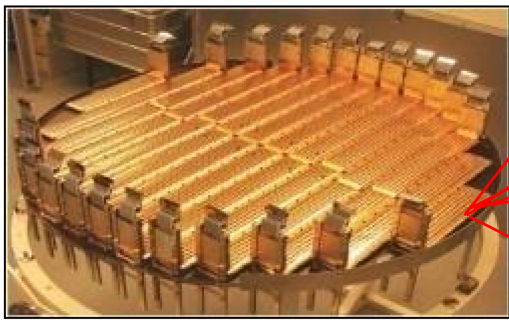


Time of Flight
Z, E

Magnet
±Z

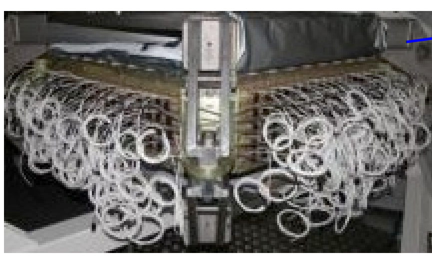


Silicon Tracker
Z, P



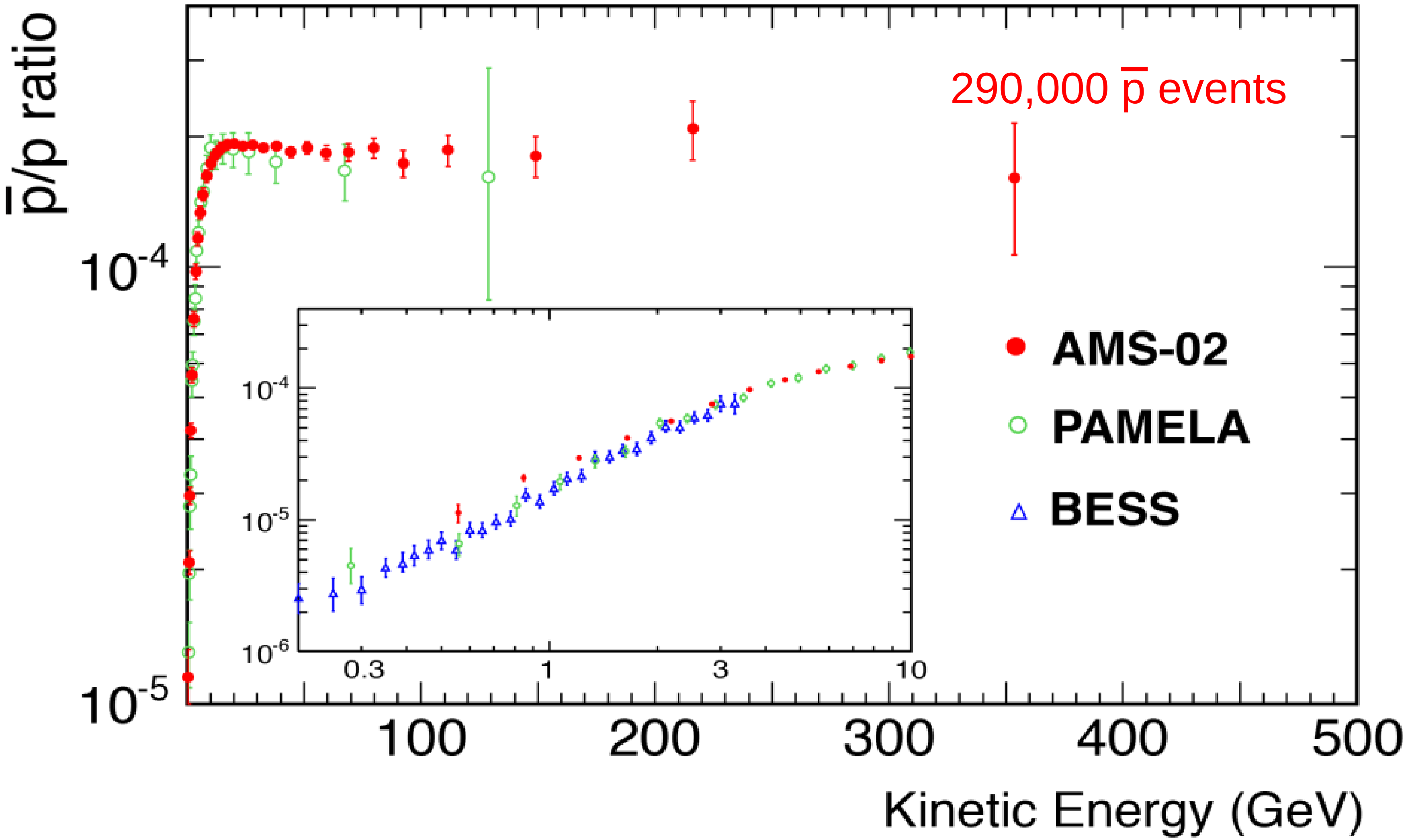
Ring Imaging Cherenkov
Z, E

Electromagnetic Calorimeter
E of electrons



The Charge and Energy (momentum) are measured independently by many detectors

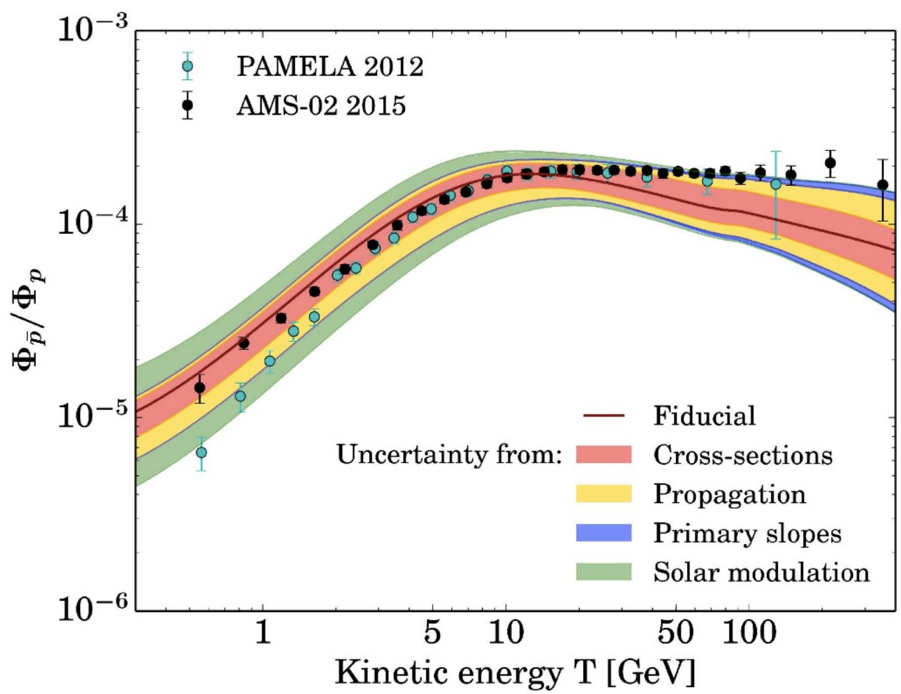
AMS-02 vs PAMELA & BESS



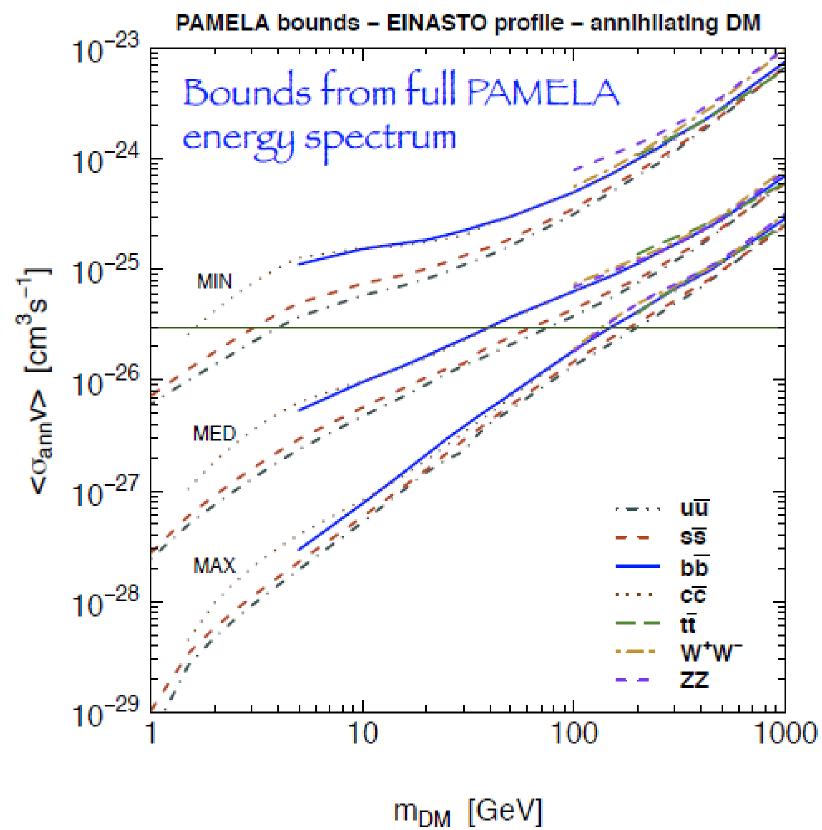
B. Bertucci, CRIS 2015, Gallipoli, Italy

Cosmic-Ray Antiprotons and DM limits

PAMELA and preliminary AMS-02 antiproton data constrains on various dark matter models and astrophysical uncertainties.



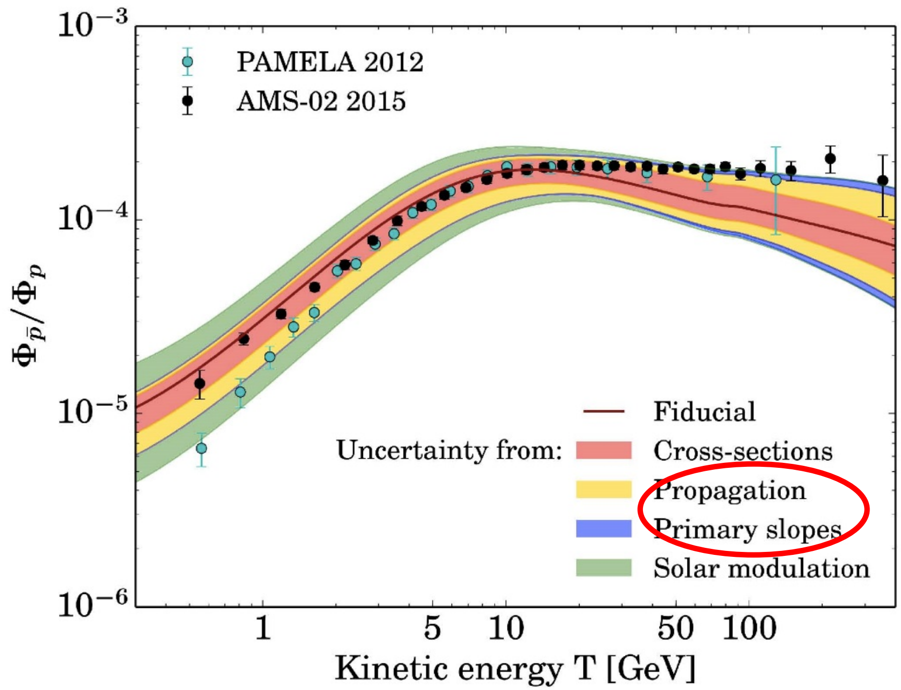
G. Giesen et al., JCAP 1509 (2015) 023, arXiv: 1504:04276



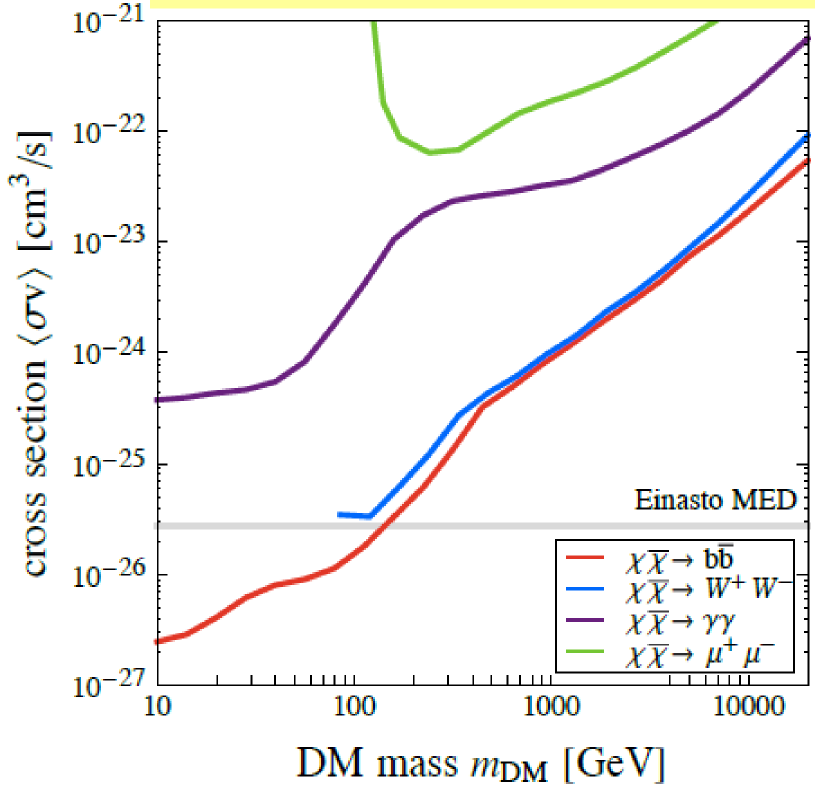
Fornengo, Maccione, Vittino, JCAP 1404 (2014) 04, 003

Cosmic-Ray Antiprotons and DM limits

PAMELA and preliminary AMS-02 antiproton data constrains on various dark matter models and astrophysical uncertainties.

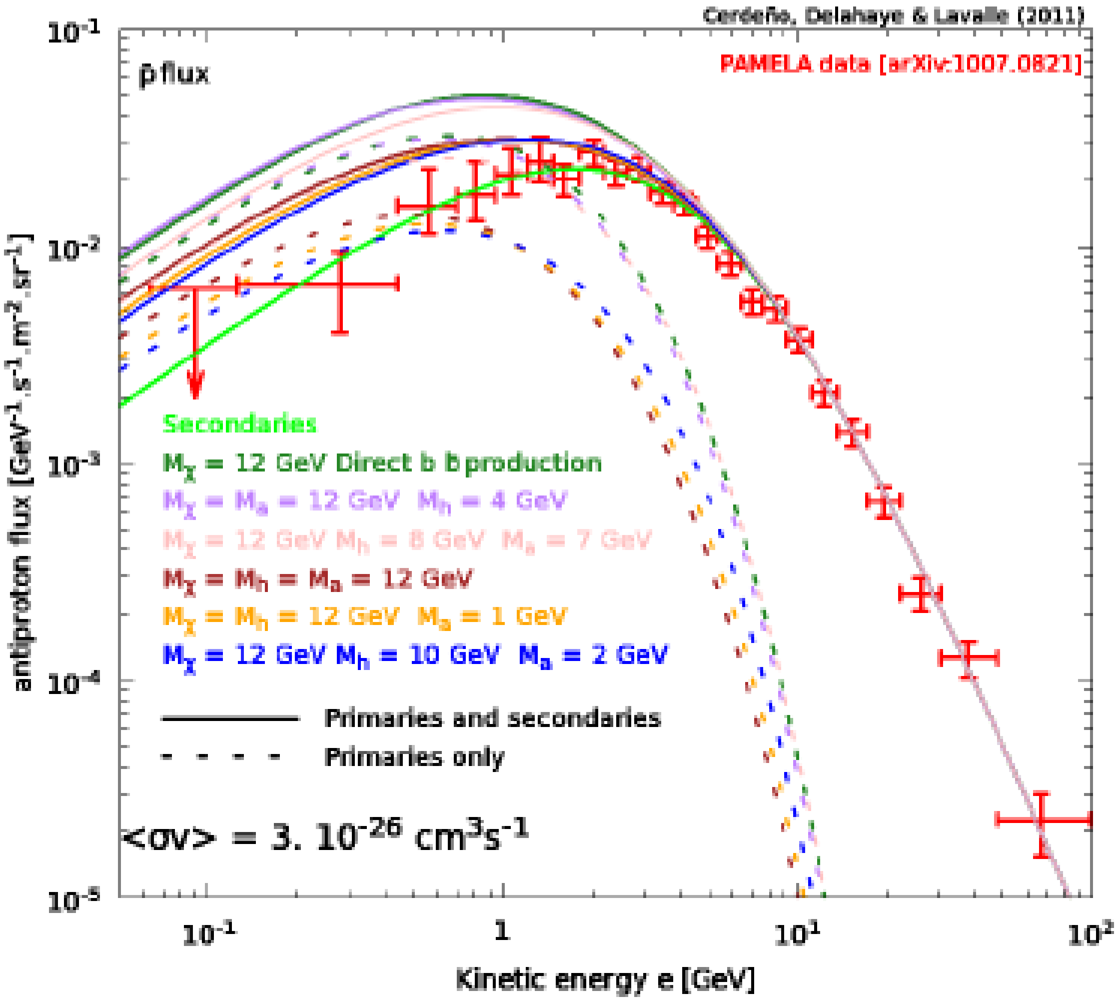


Annihilation constraints from AMS-02 $\bar{p}/p$



G. Giesen et al., JCAP 1509 (2015) 023, arXiv: 1504:04276

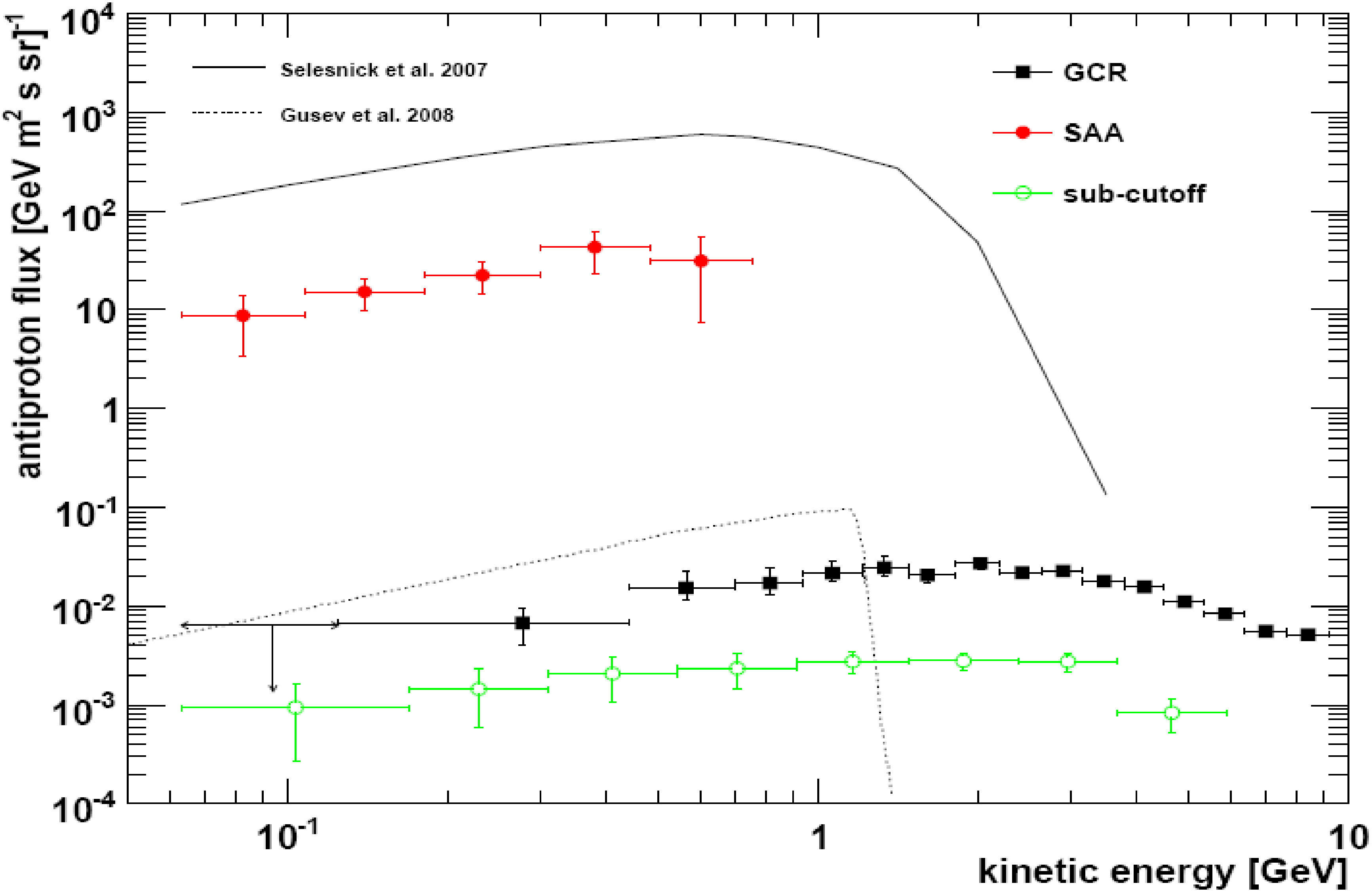
Cosmic-Ray Antiprotons and DM limits



D. G. Cerdeno, T. Delahaye & J. Lavalle, Nucl. Phys. B 854 (2012) 738
Antiproton flux predictions for a 12 GeV WIMP annihilating into different mass combinations of an intermediate two-boson state which further decays into quarks.

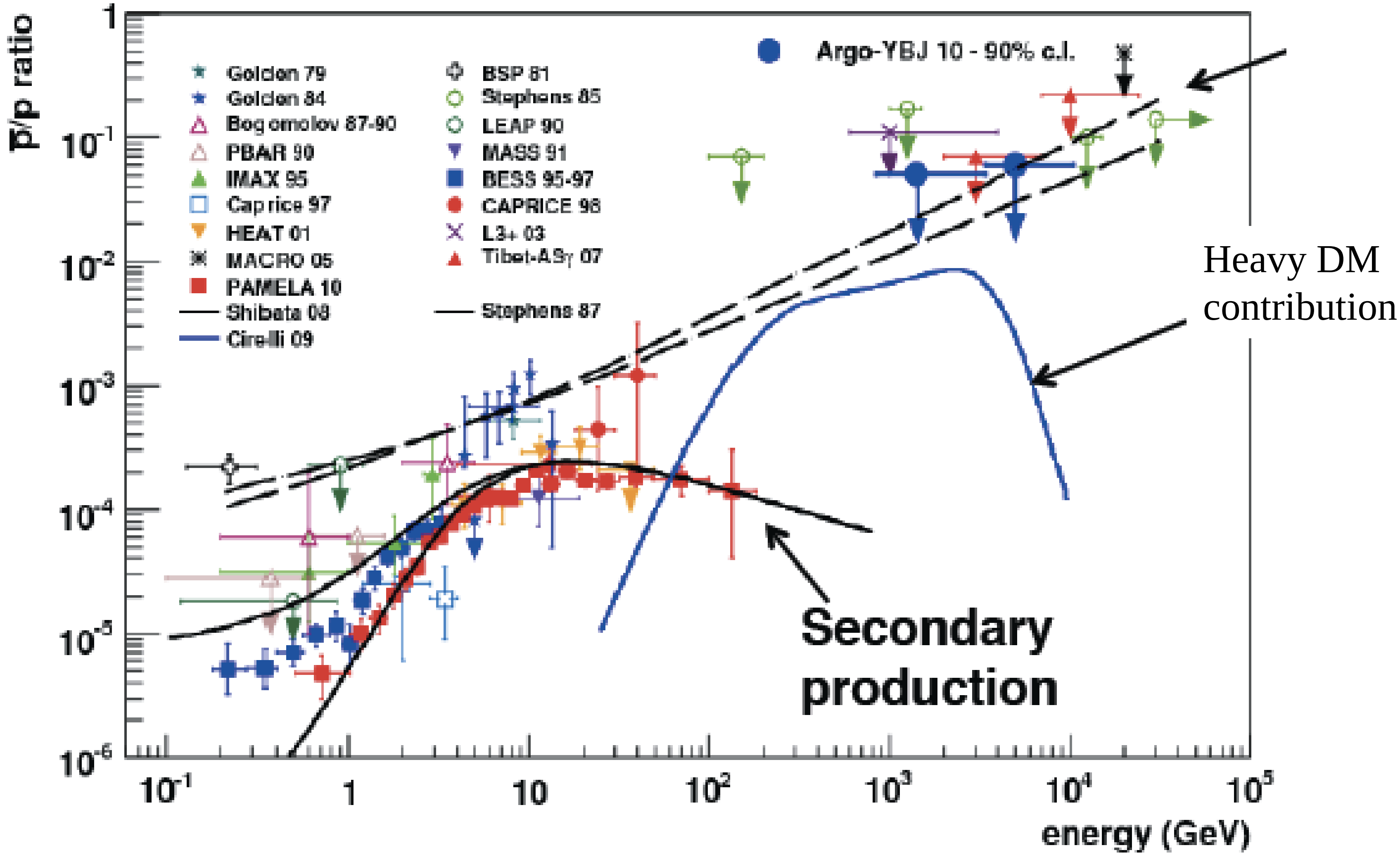
See also:
- M. Asano, T. Bringmann & C. Weniger, Phys. Lett. B 709 (2012) 128.
- M. Garny, A. Ibarra & S. Vogl, JCAP 1204 (2012) 033
- R. Kappl & M. W. Winkler, PRD 85 (2012) 123522

PAMELA trapped antiprotons



Adriani et al., APJL 737 L29 (2011); arXiv:1107.4882

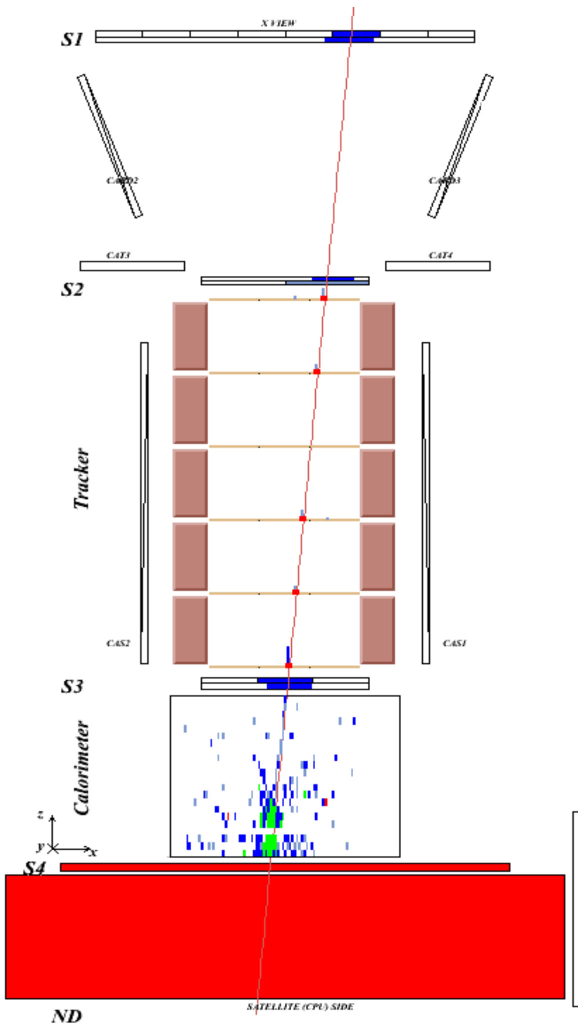
Antiproton to Ptoron Flux Ratio



G. Di Sciascio, TeVPA 2011, Stockholm (2011)

Positrons

Proton / positron discrimination



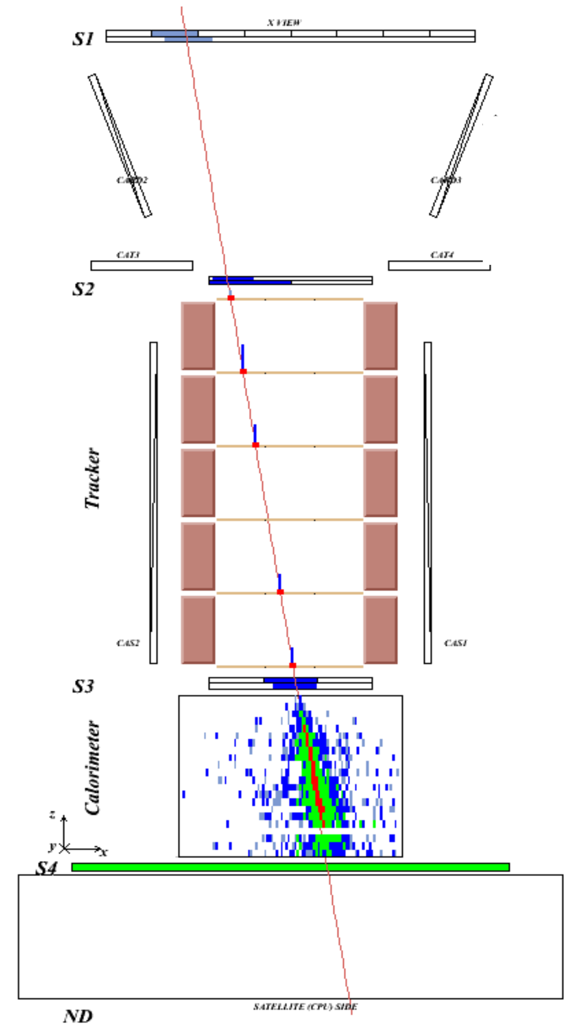
Proton

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

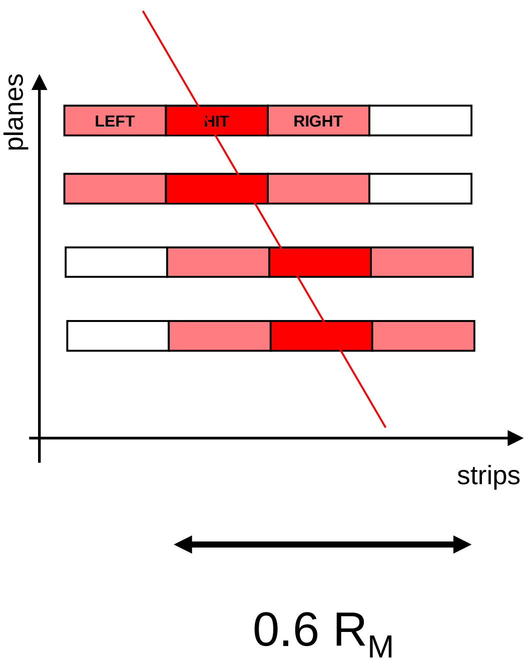
Interaction pattern in calorimeter: electron-like or proton-like, electron energy

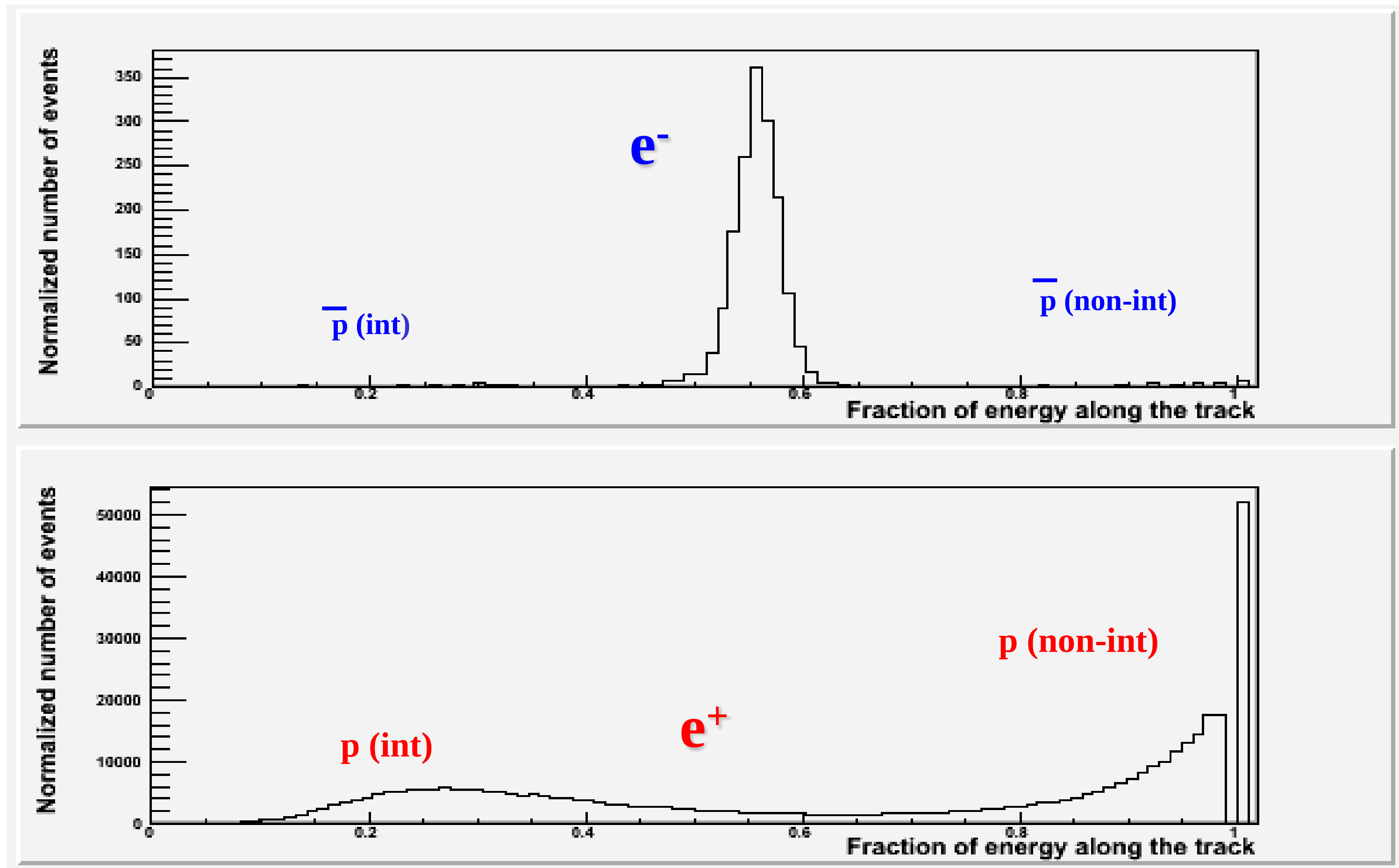


Positron

Positron selection with calorimeter

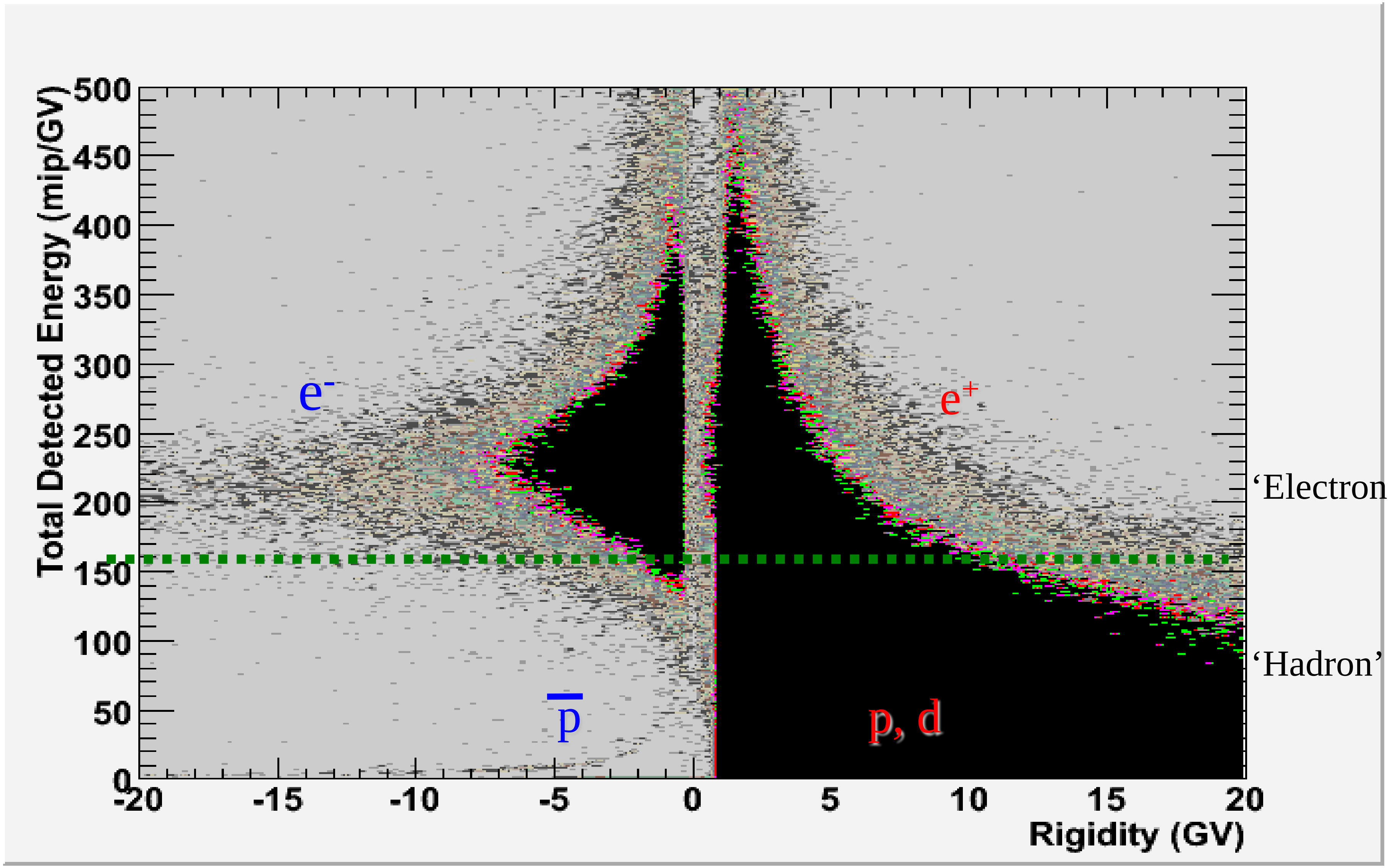
Fraction of energy released along the calorimeter track (left, hit, right)





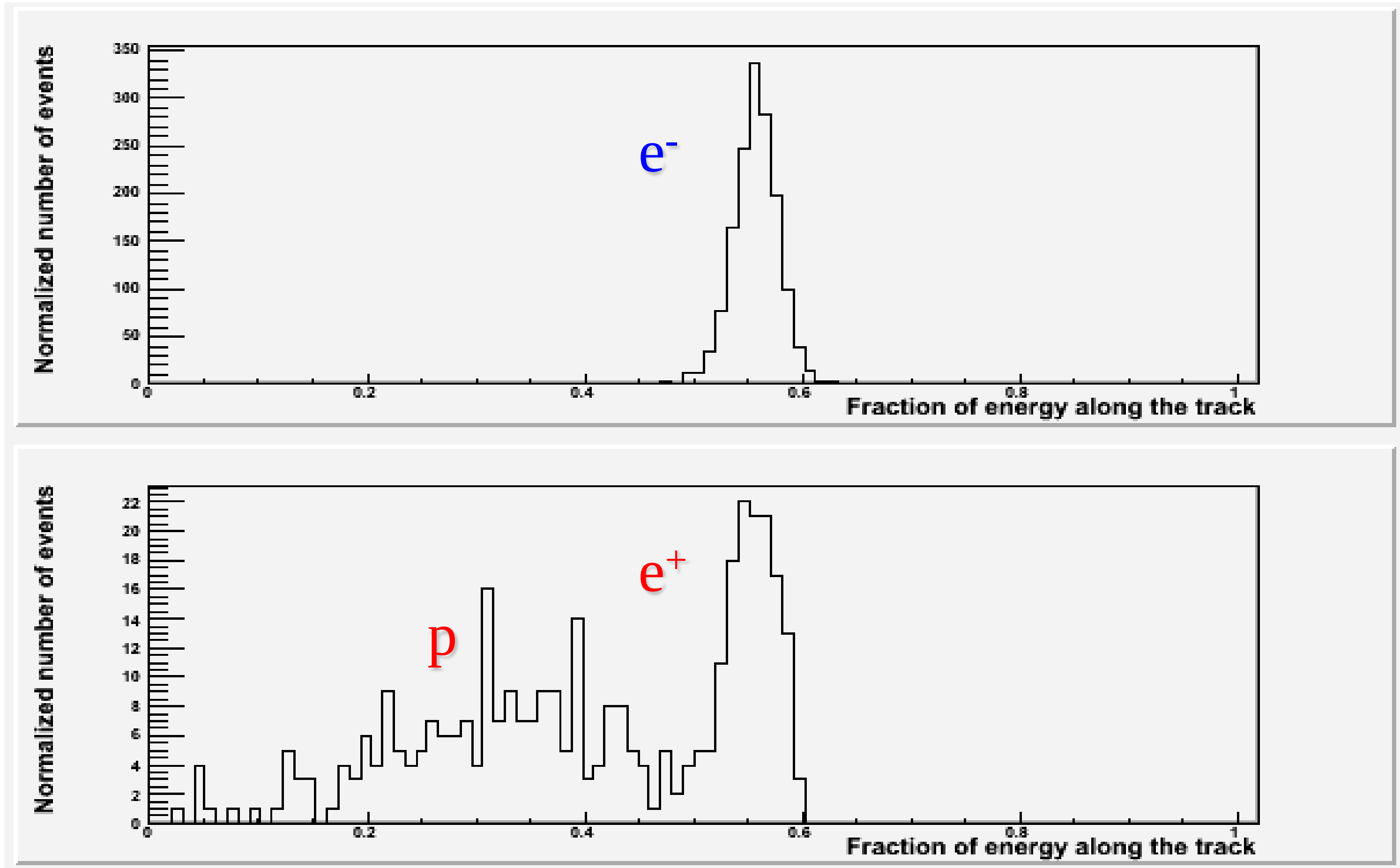
Rigidity: 20-30 GV

Antiparticle selection



Positron selection with calorimeter

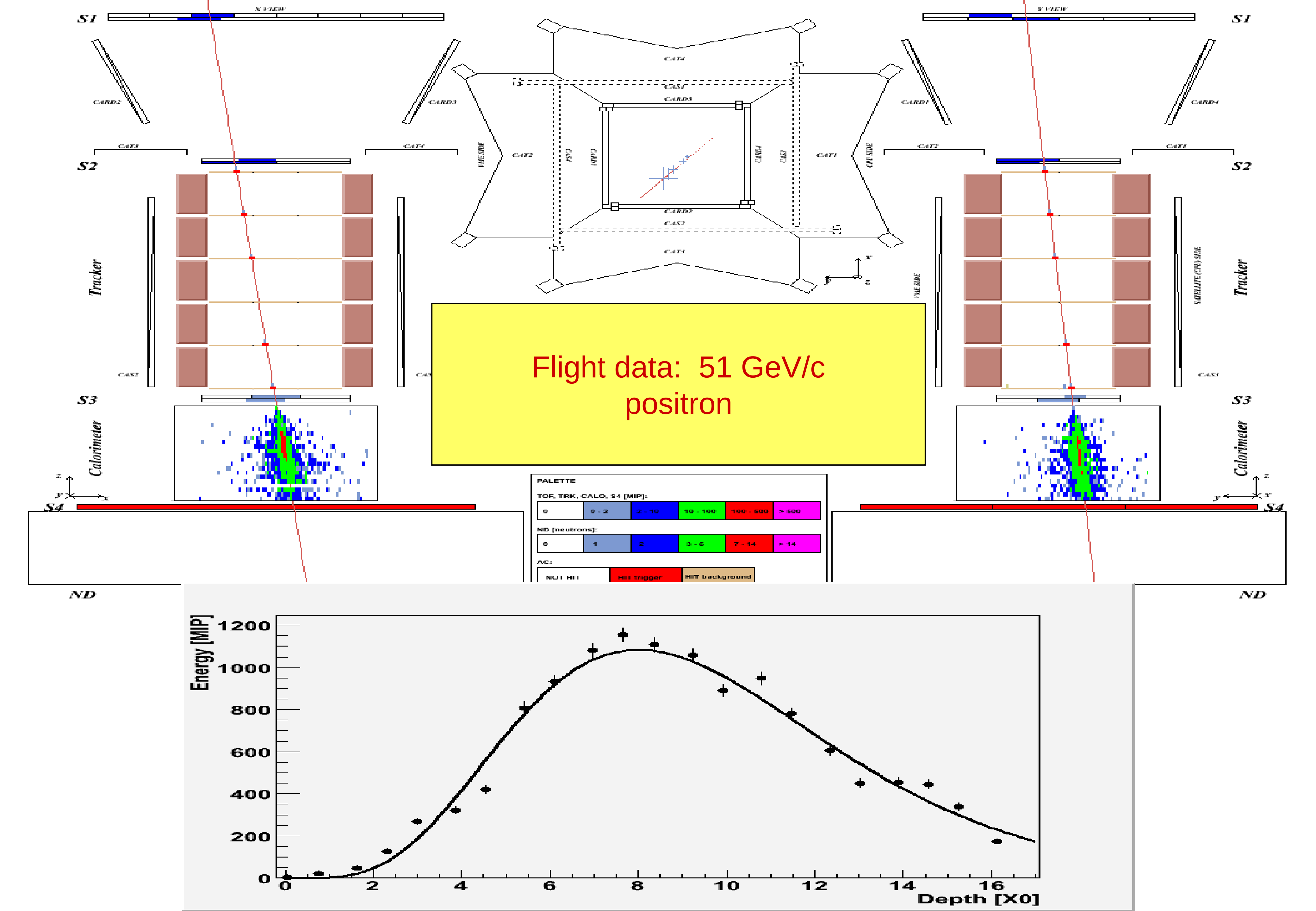
Rigidity: 20-30 GV



Fraction of charge released along the calorimeter track (left, hit, right)

+

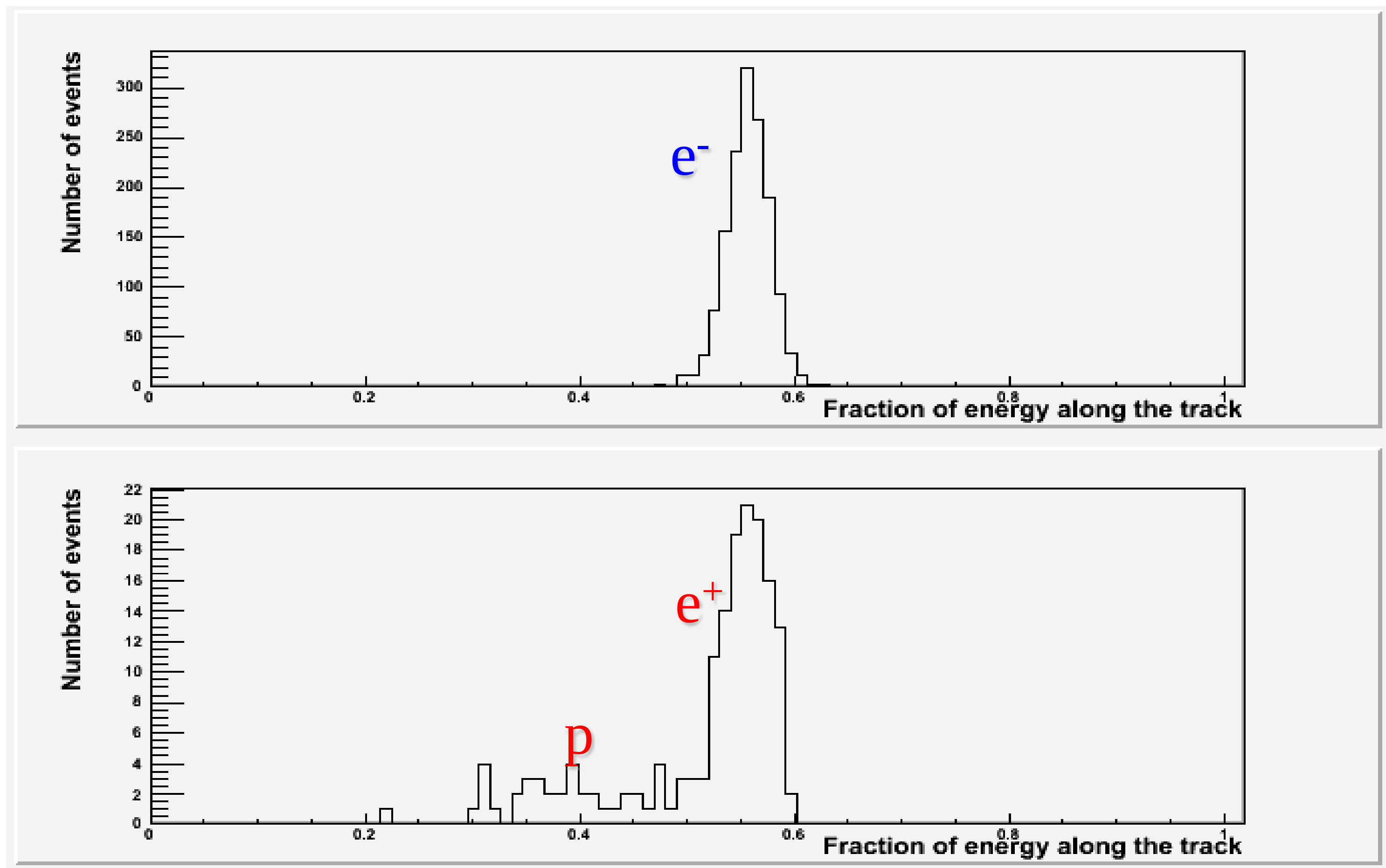
- Energy-momentum match
- Starting point of shower



Flight data: 51 GeV/c positron
S1
S2
S3
S4
ND
Tracker
Calorimeter
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background
Energy [MIP]
Depth [X0]

Positron selection with calorimeter

Rigidity: 20-30 GV

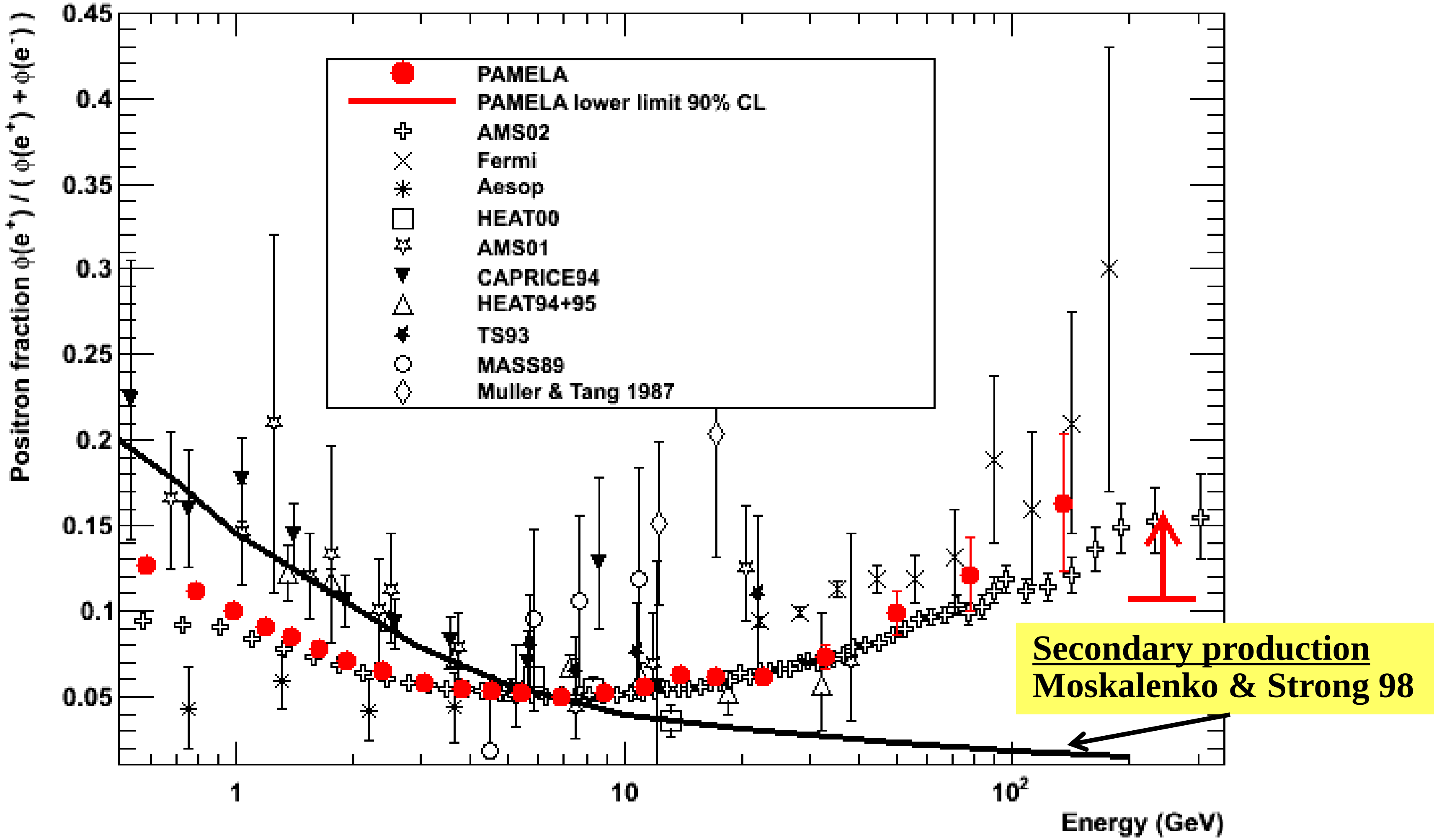


Fraction of charge released along the calorimeter track (left, hit, right)

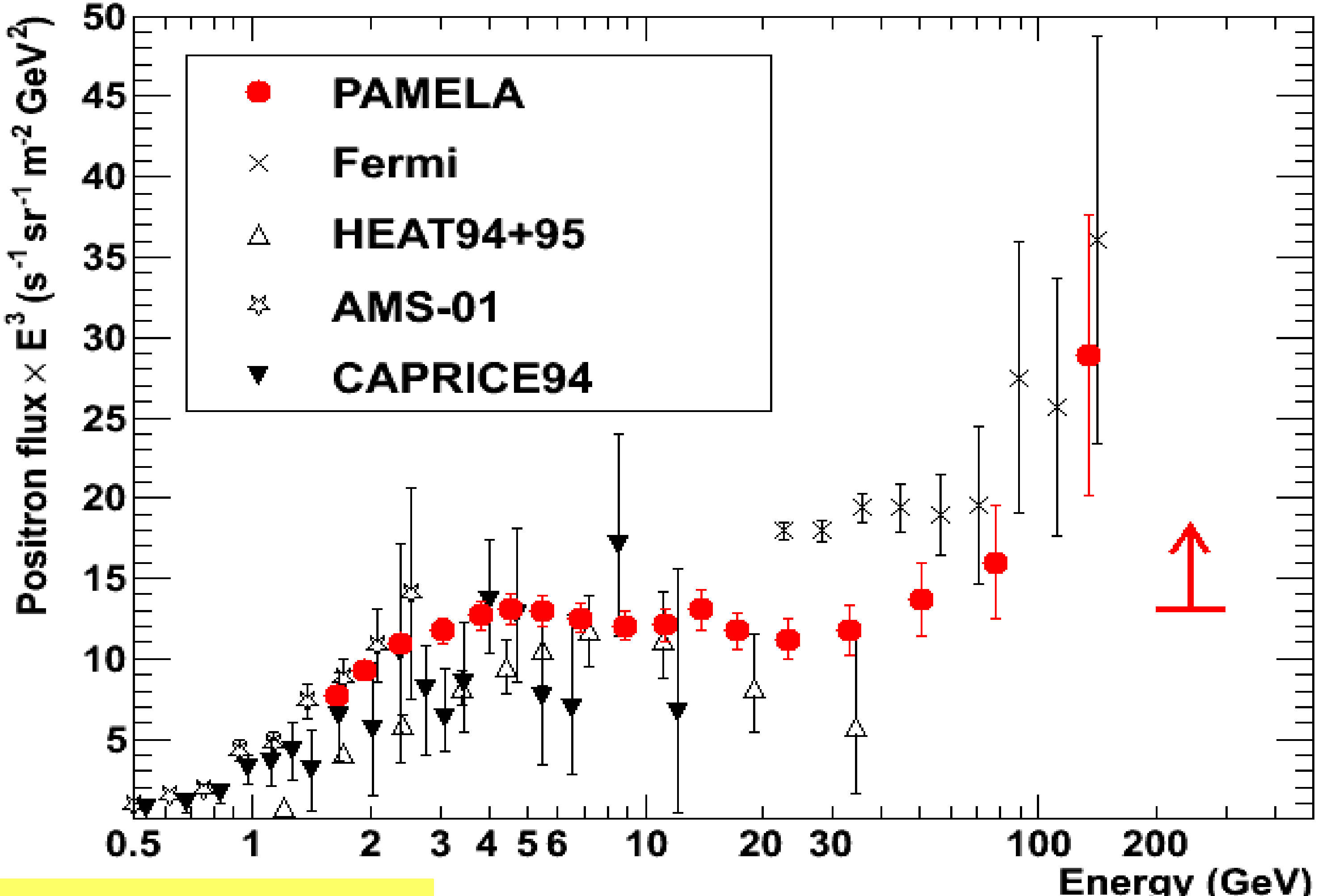
+

- Energy-momentum match
- Starting point of shower
- Longitudinal profile

Positron to Electron Fraction



Positron Energy Spectrum

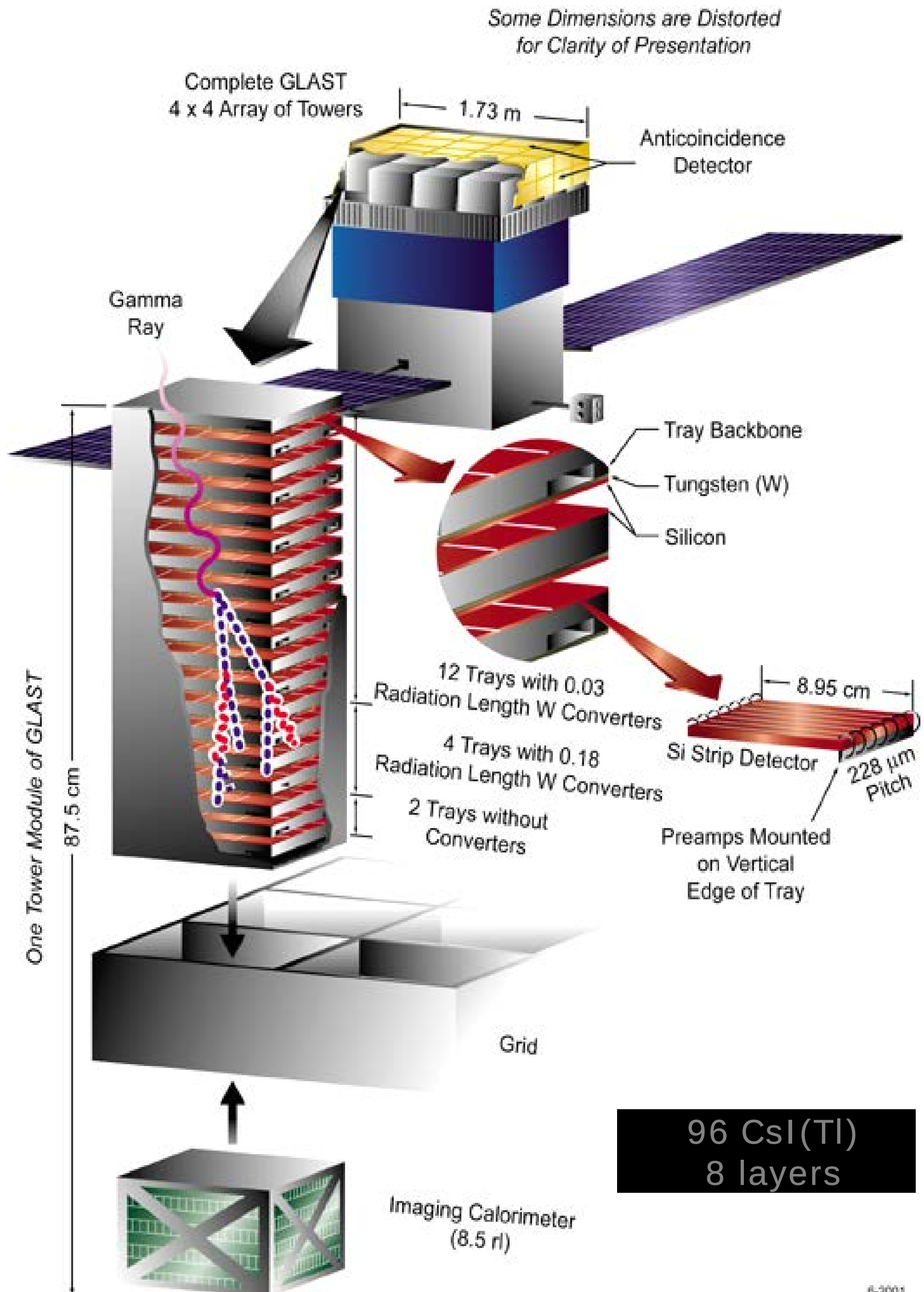


O. Adriani et al., PRL 111 (2013) 081102; arXiv:1308.0133

GLAST/ FERMI

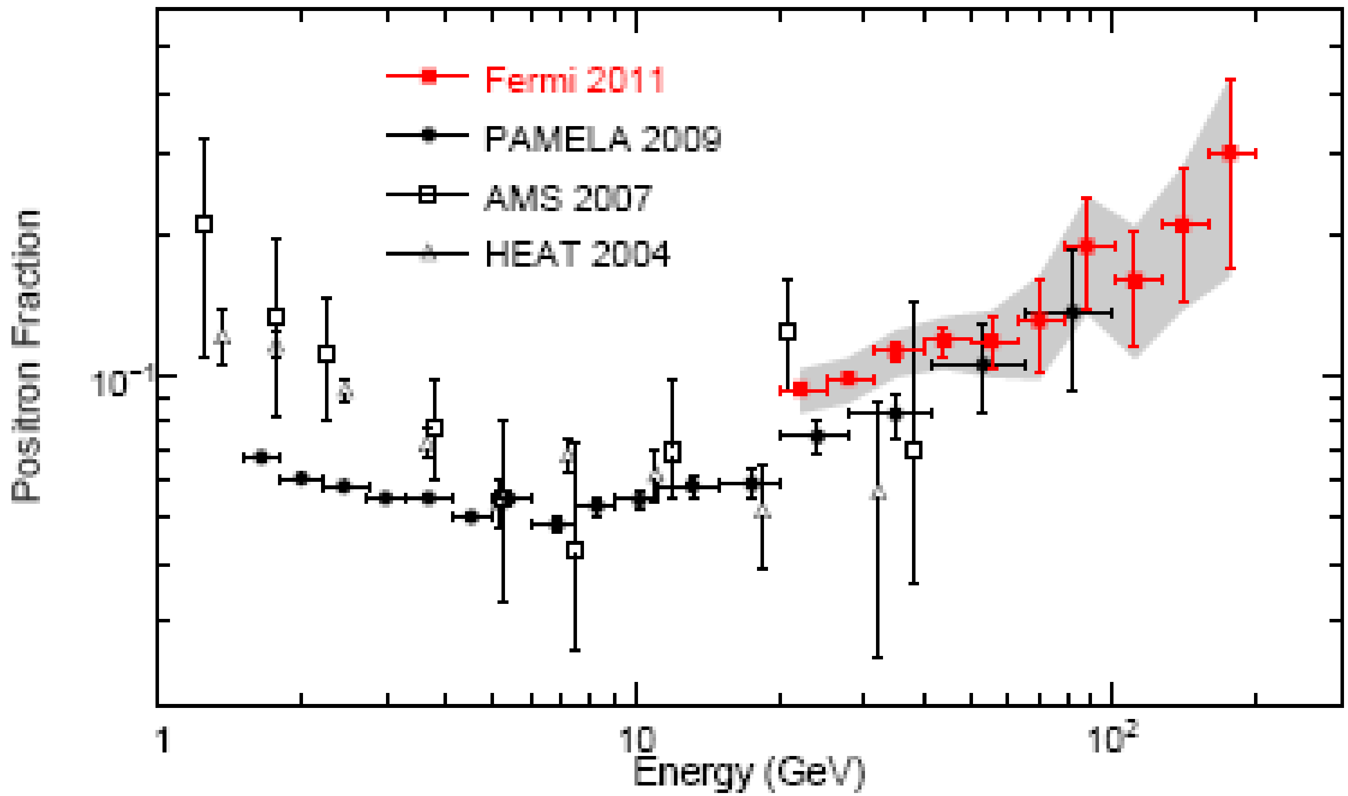
Gamma-Ray Large Area Space Telescope

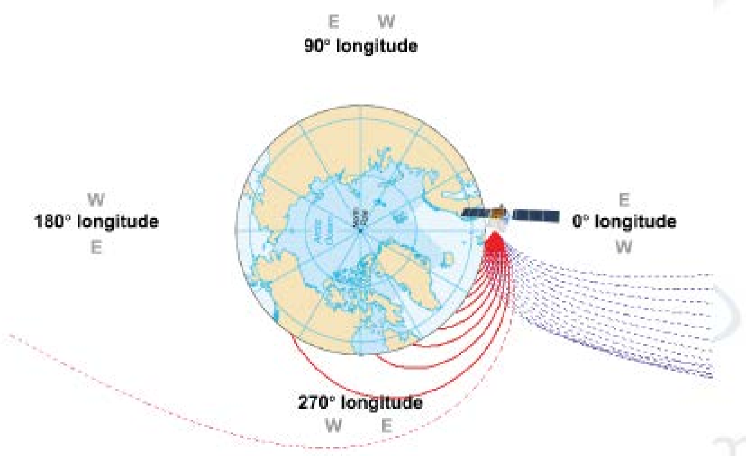
3000 kg, 650 W
1.8 m x 1.8 m x 1 m
20 MeV – 300 GeV



96 CsI(Tl)
8 layers

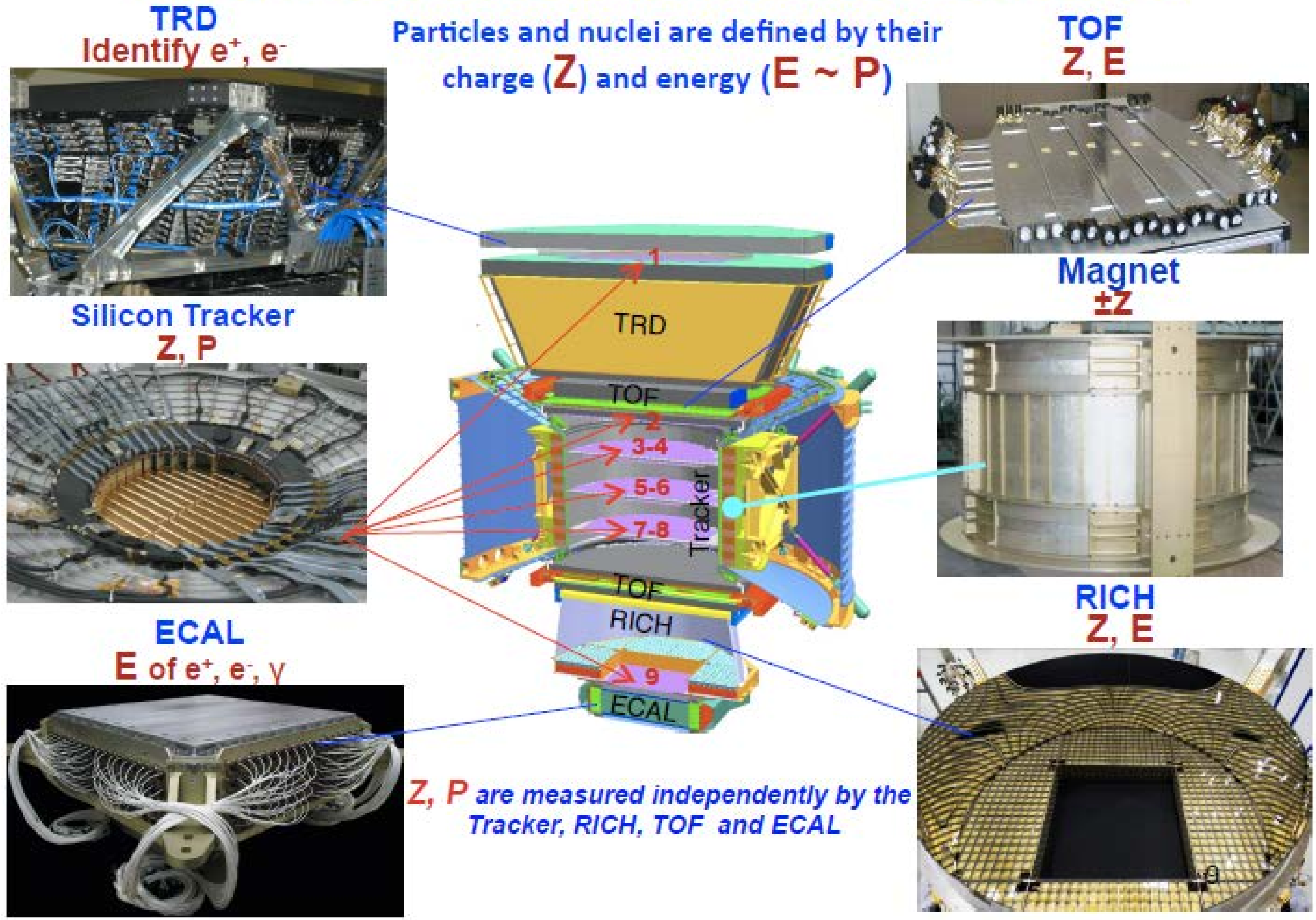
Fermi Positron Fraction



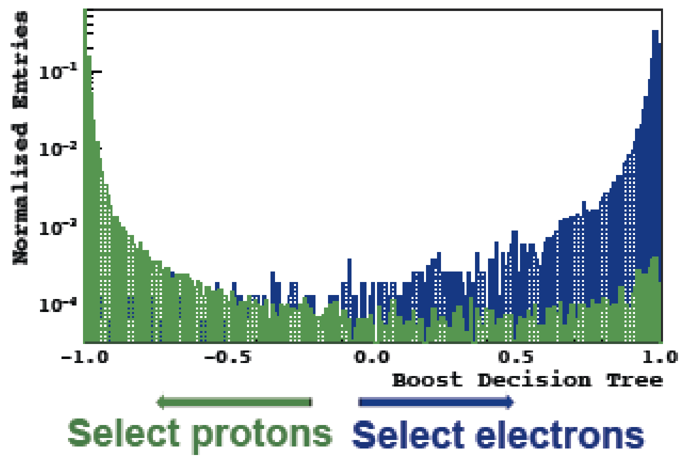


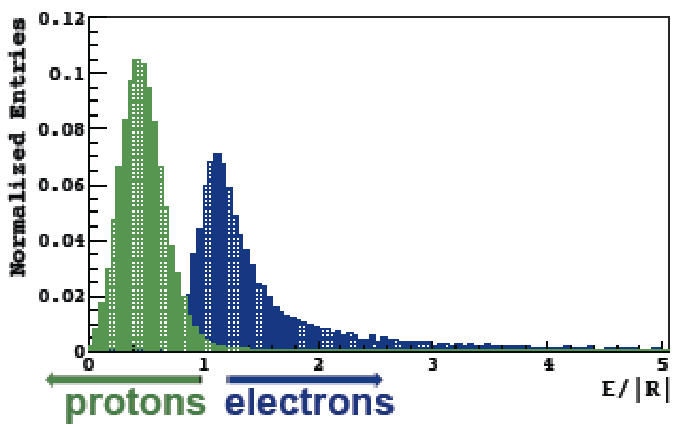
M. Ackermann, Phys.Rev.Lett. 108 (2012) 011103; **astro**-ph: 1109.0521

AMS: A TeV precision, multipurpose spectrometer



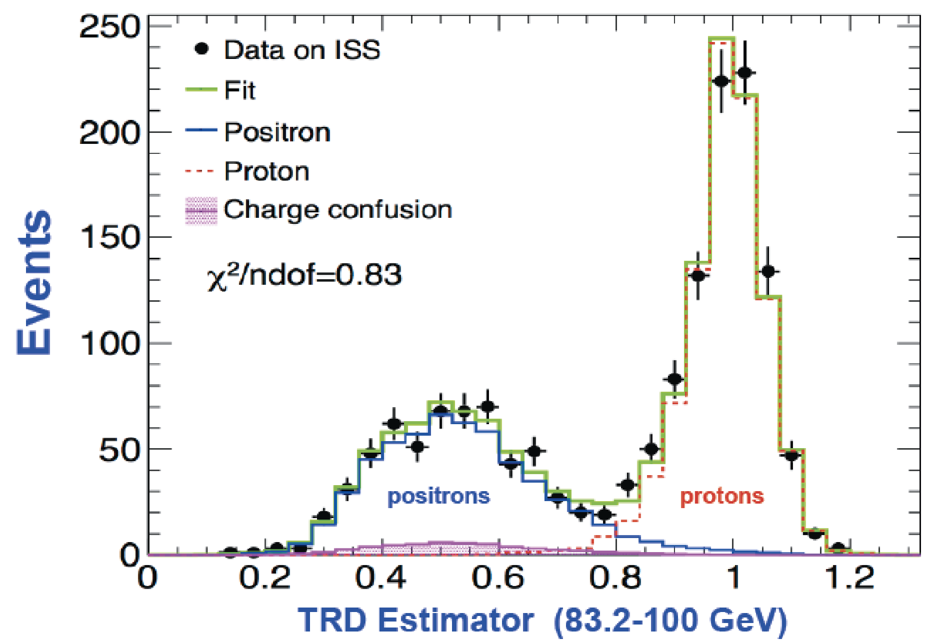
AMS Positron Selection



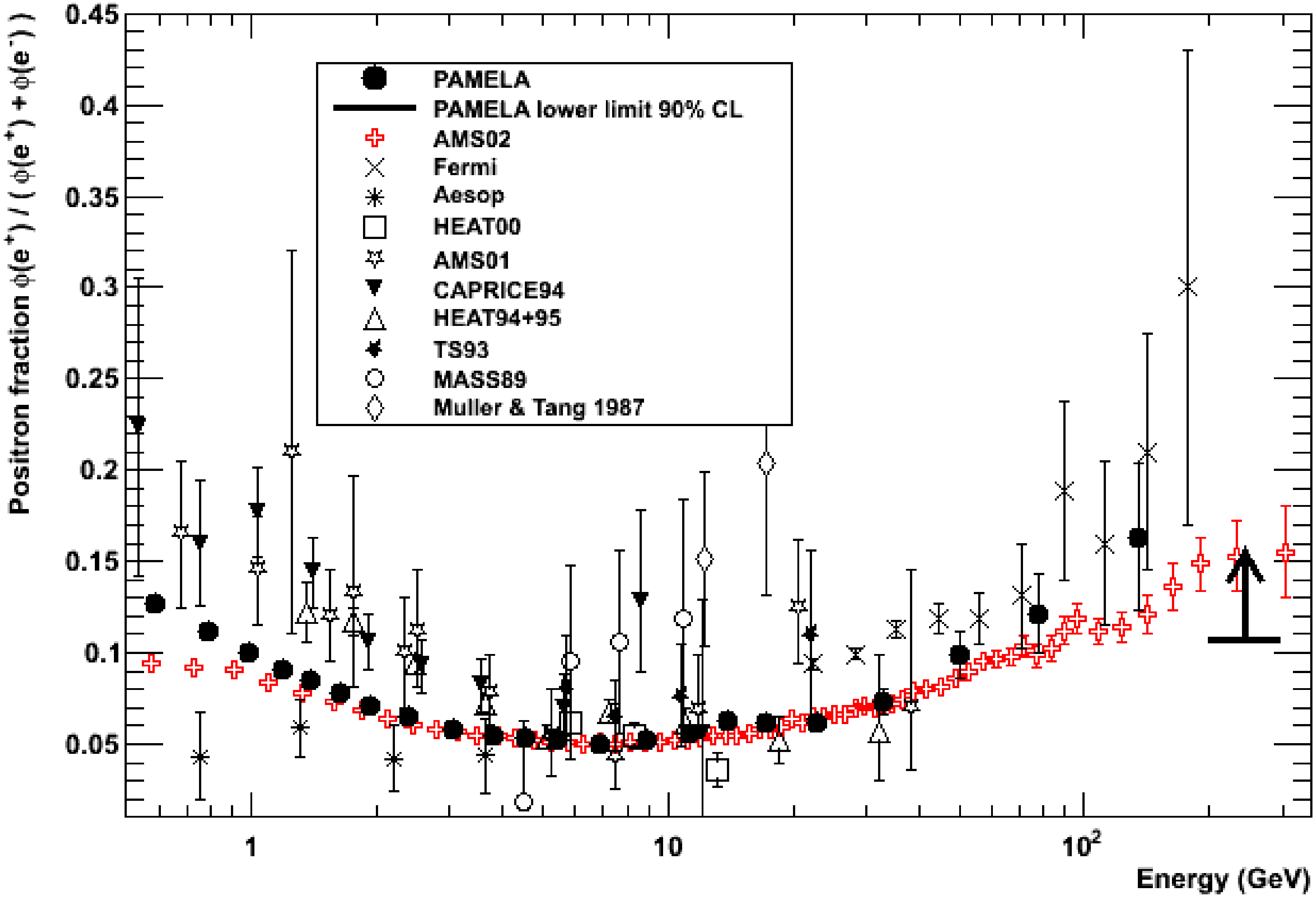


e/p separation with calorimeter+tracker

Example of Positron Selection:
The TRD Estimator shows clear separation between protons and positrons with a small charge confusion background

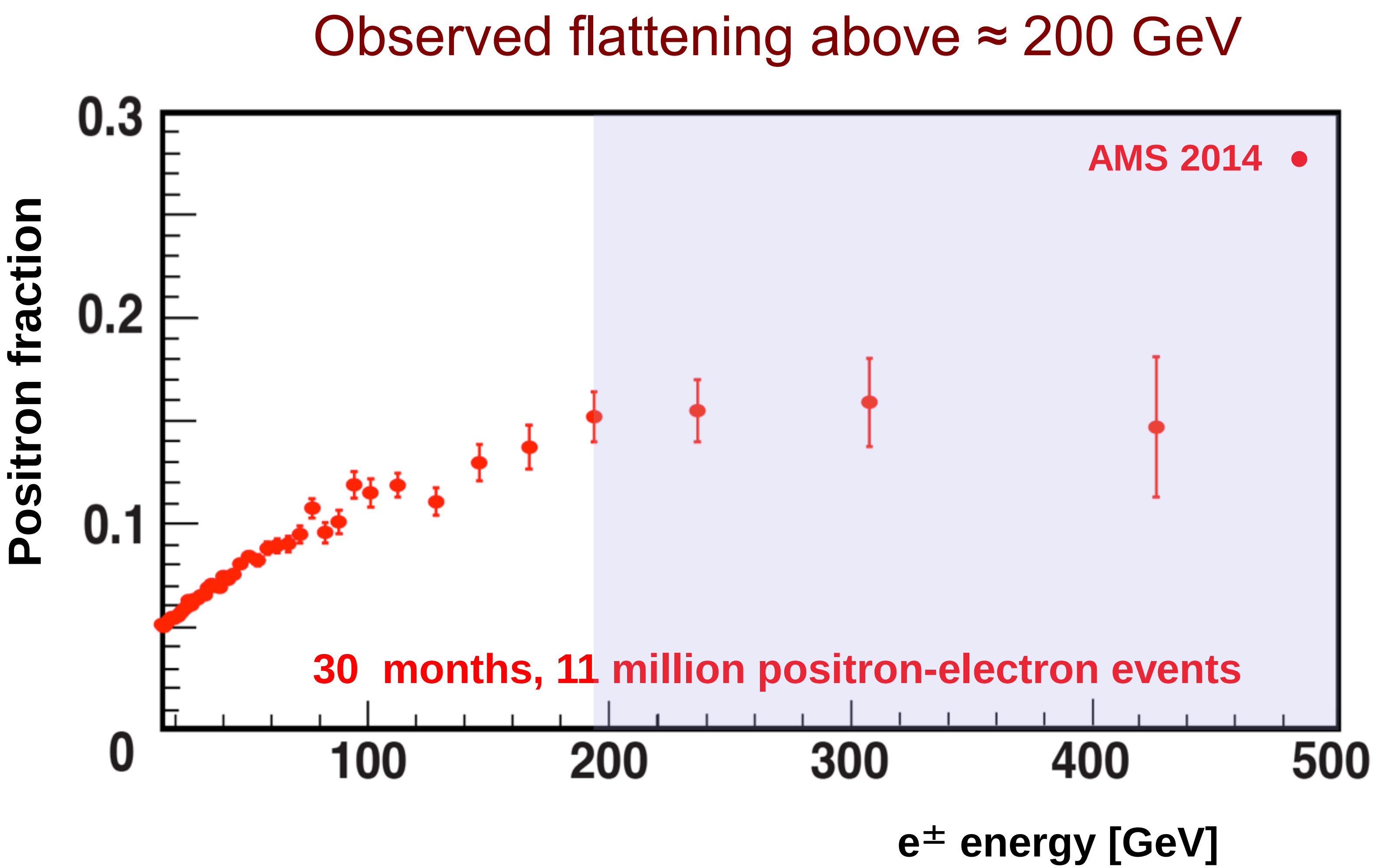


AMS Positron Fraction



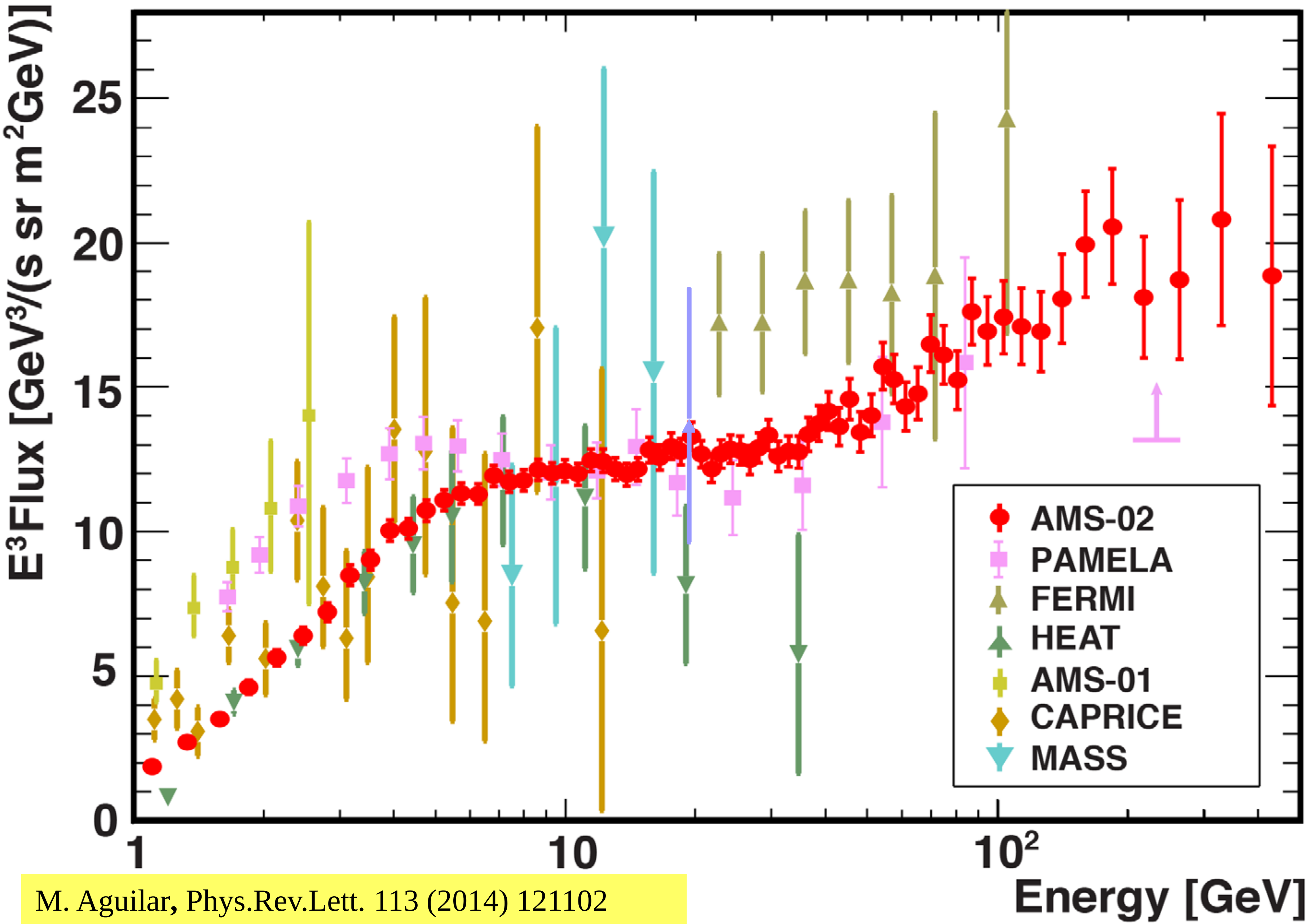
M. Aguilar, Phys.Rev.Lett. 110 (2013) 141102

2014: New Results on Positron Fraction



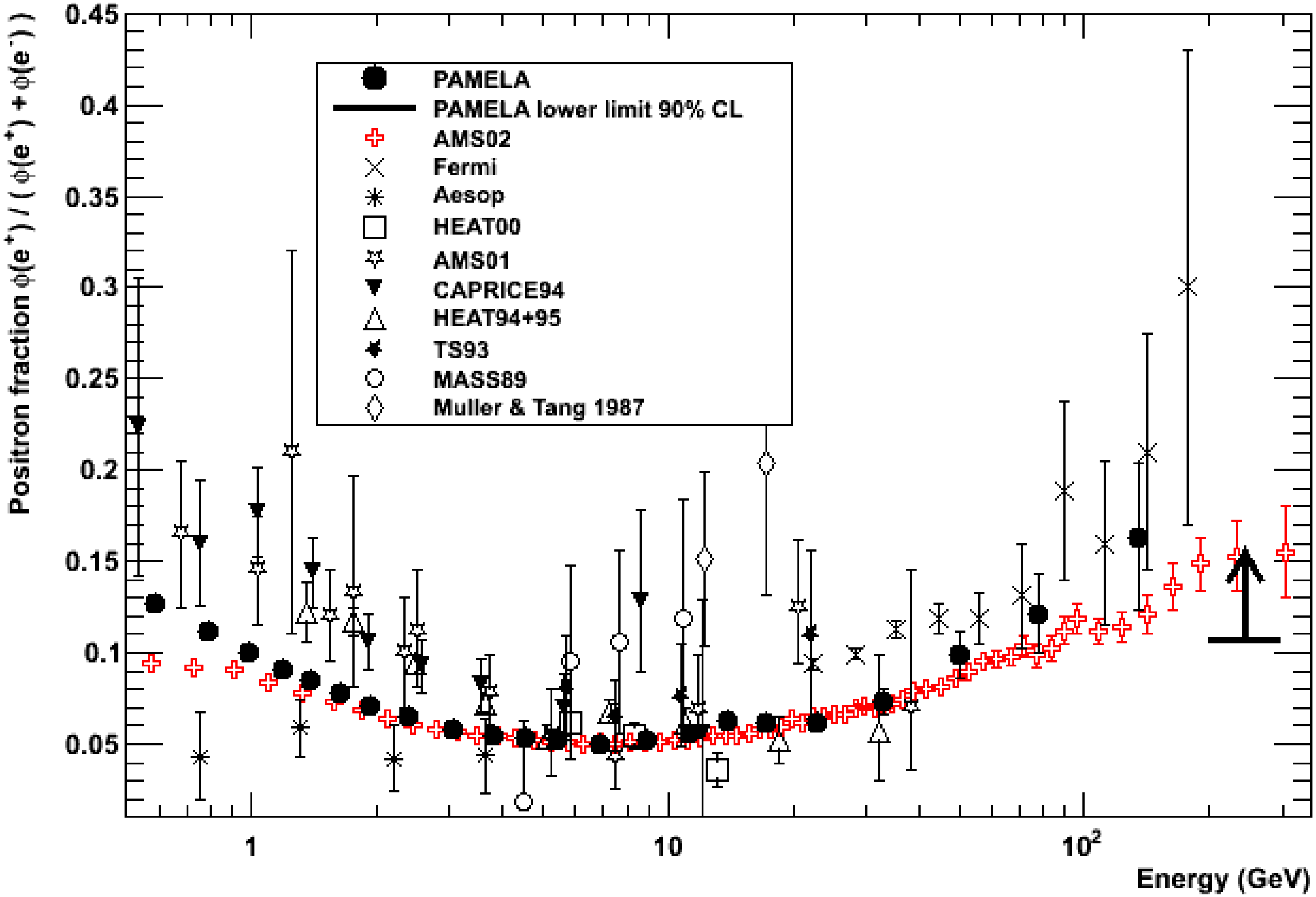
M. Aguilar, Phys.Rev.Lett. 113 (2014) 121101

Positron Flux Data with AMS



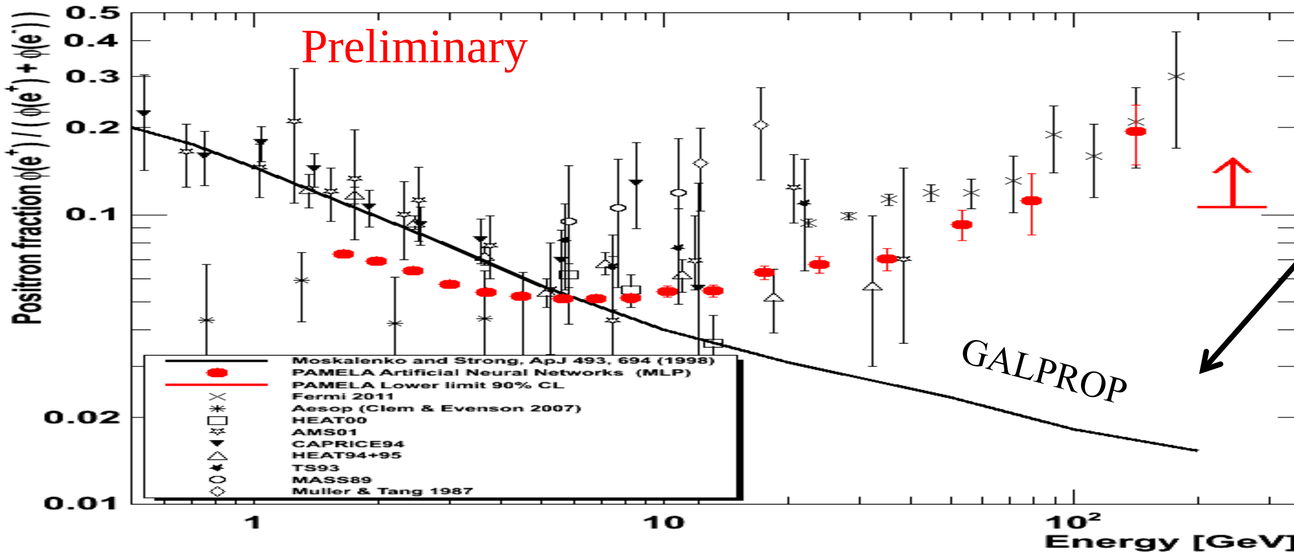
M. Aguilar, Phys.Rev.Lett. 113 (2014) 121102

AMS Positron Fraction

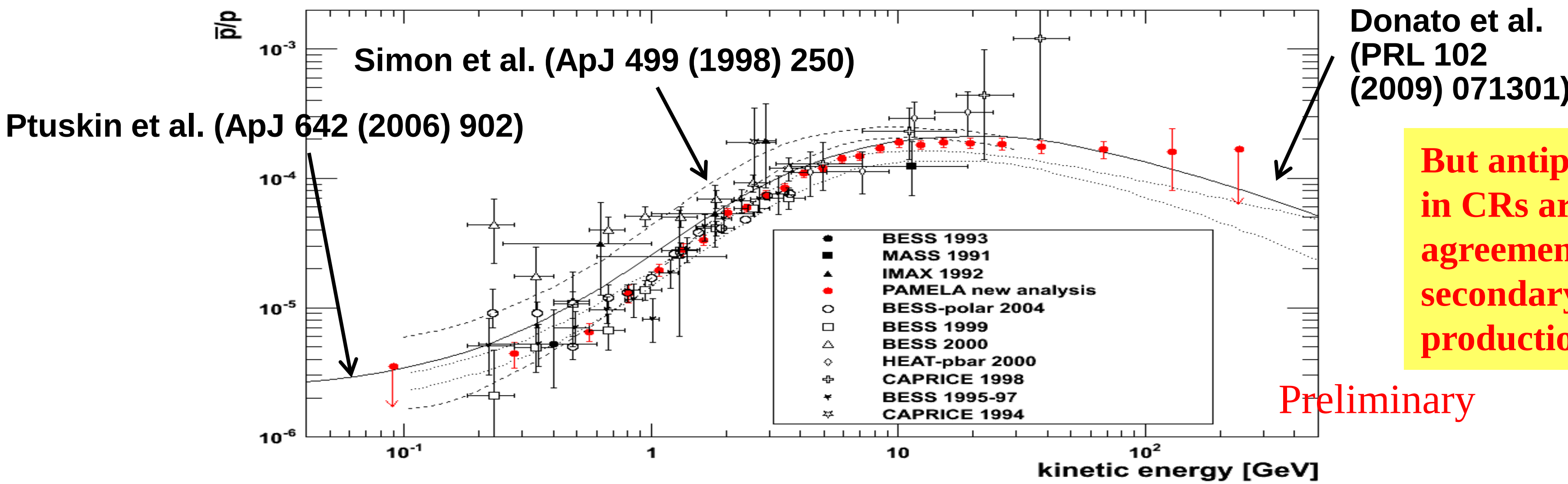


M. Aguilar, Phys.Rev.Lett. 110 (2013) 141102

A Challenging Puzzle for CR Physics

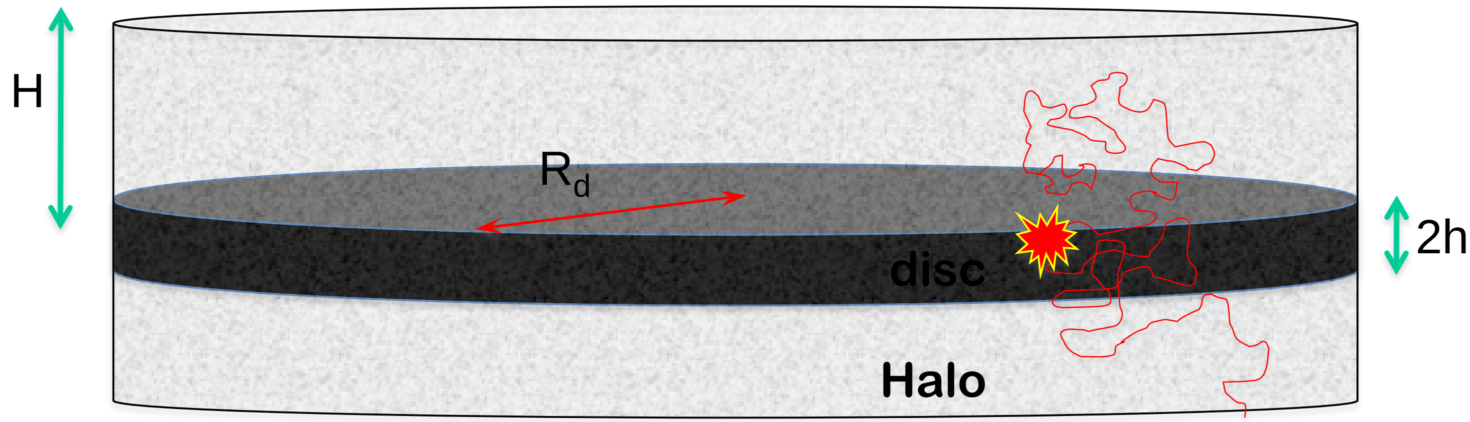


CR Positron spectrum significantly harder than expectations from secondary production



But antiprotons in CRs are in agreement with secondary production

Secondary positrons (1)



PRIMARY COSMIC RAY SPECTRUM AT EARTH

$$n_{CR}(E) = \frac{N(E)\mathcal{R}}{2\pi R_d^2}\frac{H}{D(E)} \equiv \frac{N(E)\mathcal{R}}{2H\pi R_d^2}\frac{H^2}{D(E)} \propto E^{-\gamma-\delta}$$

SPECTRUM OF PRIMARY ELECTRONS AT EARTH

$$n_e(E) \approx \frac{N(E)\Re\,\tau_{loss}(E)}{\sqrt{D(E)\tau_{loss}(E)}} \propto E^{-\gamma-1/2-\delta/2}$$

IF ENERGY LOSSES ARE DOMINANT UPON DIFFUSION (TYPICALLY E>10 GeV

Courtesy by P. Blasi

Secondary positrons (2)

INJECTION RATE OF SECONDARY POSITRONS

$$q_{e^+}(E')dE' = n_{CR}(E)dE\, n_H\, \sigma_{pp}\, c \propto E^{-\gamma-\delta}$$

EQUILIBRIUM SPECTRUM OF SECONDARY POSITRONS (AND ELECTRONS) AT EARTH

$$n_{e^+}(E) \approx \frac{q_{e^+}(E)\tau_{loss}(E)}{\sqrt{D(E)\tau_{loss}(E)}} \propto E^{-\gamma-1/2-3\delta/2}$$

POSITRON FRACTION

$$\frac{\Phi_{e^+}}{\Phi_{e^+}+\Phi_{e^-}} \approx \frac{\Phi_{e^+}}{\Phi_{e^-}} \propto E^{-\delta}$$

MONOTONICALLY DECREASING FUNCTION OF ENERGY

Courtesy by P. Blasi

Implications

A rising positron fraction requires:

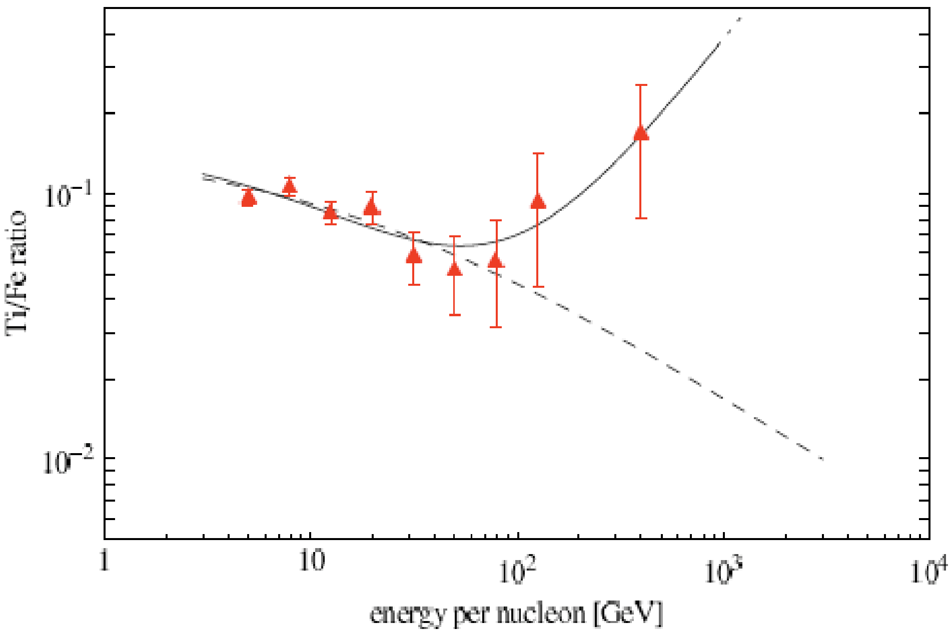
1. **An additional component of positrons with spectrum flatter than CR primary electrons**

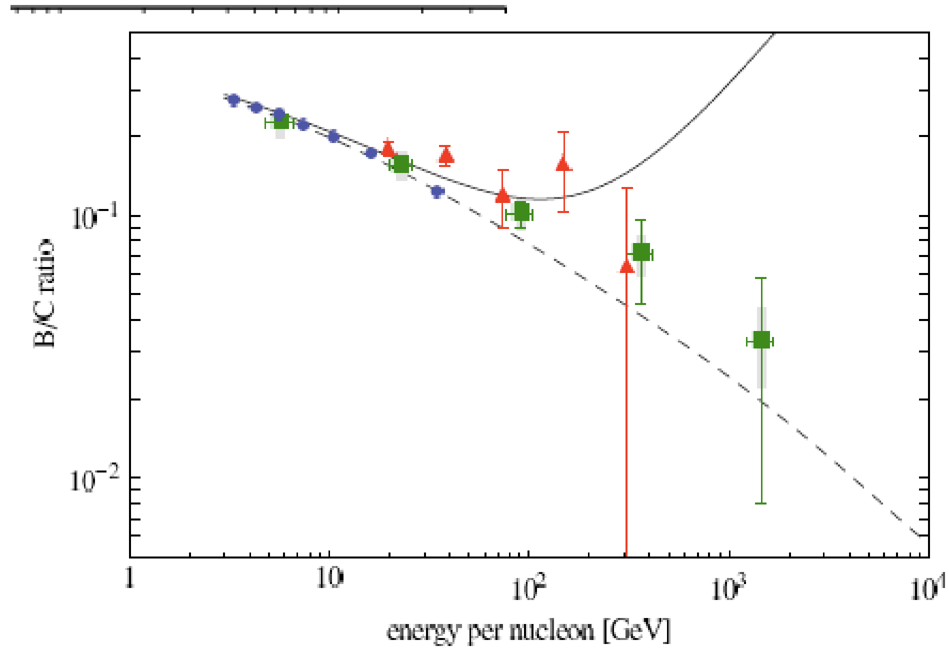
2. **A diffusion coefficient with a weird energy dependence (BUT this should reflect in the CR spectrum as well)**

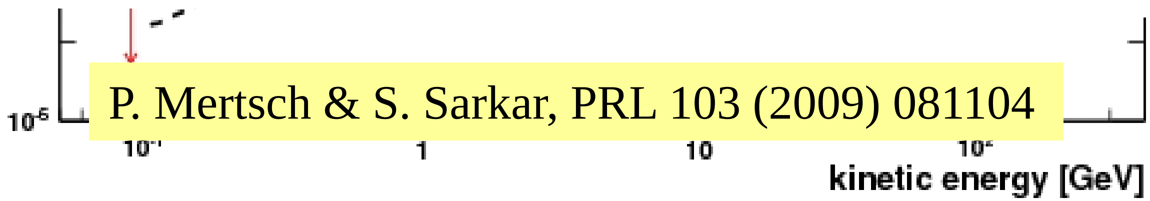
3. **Subtleties of Propagation**

Courtesy by P. Blasi

A Challenging Puzzle for CR Physics





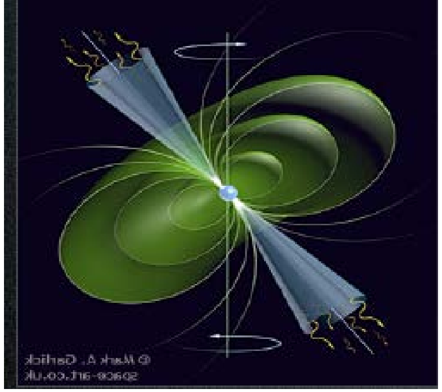


P. Mertsch & S. Sarkar, PRL 103 (2009) 081104

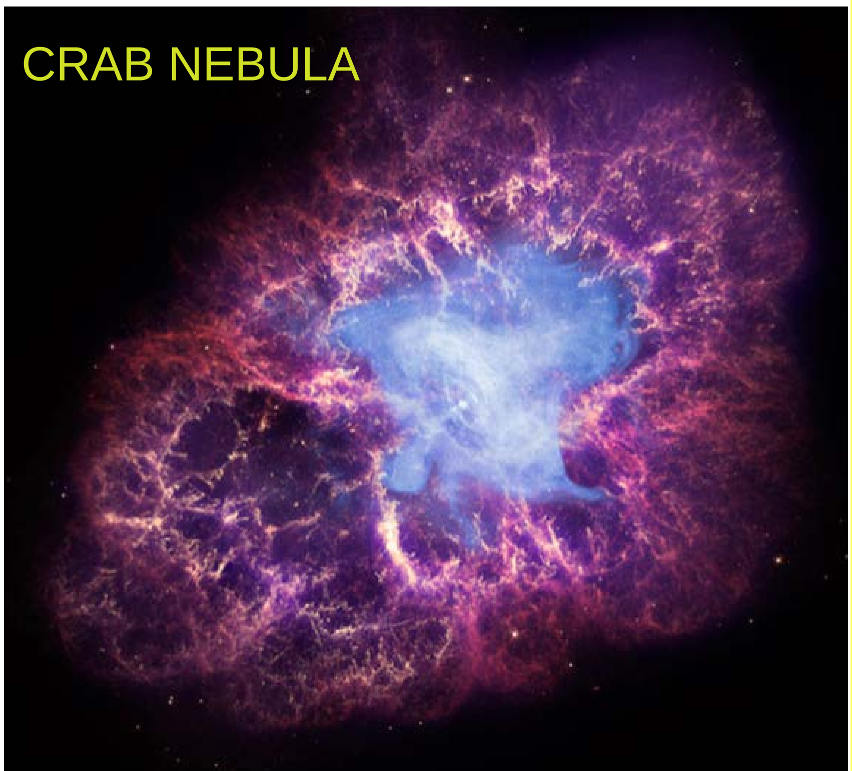
P.Blasi, PRL 103 (2009) 051104 (see also Y. Fujita et al., PRD 80 (2009) 063003, M. Ahlers et al. PRD 80 (2009) 123017) Positrons (and electrons) produced as secondaries in the sources (e.g. SNR) where CRs are accelerated.

But also other secondaries are produced: significant increase expected in the p/p and secondary nuclei ratios.

Astrophysical Explanation: Pulsars



Mechanism: the spinning B of the pulsar strips e^- that accelerated in the outer magnetosphere emit g that produce $e^\pm$. But pairs are trapped in the cloud. After (4-5)x10^4 years pulsars leave remanent and pairs are liberated (e.g. P. Blasi & E. Amato, arXiv:1007.4745).



Young ($T < 10^5$ years) and nearby (< 1kpc)

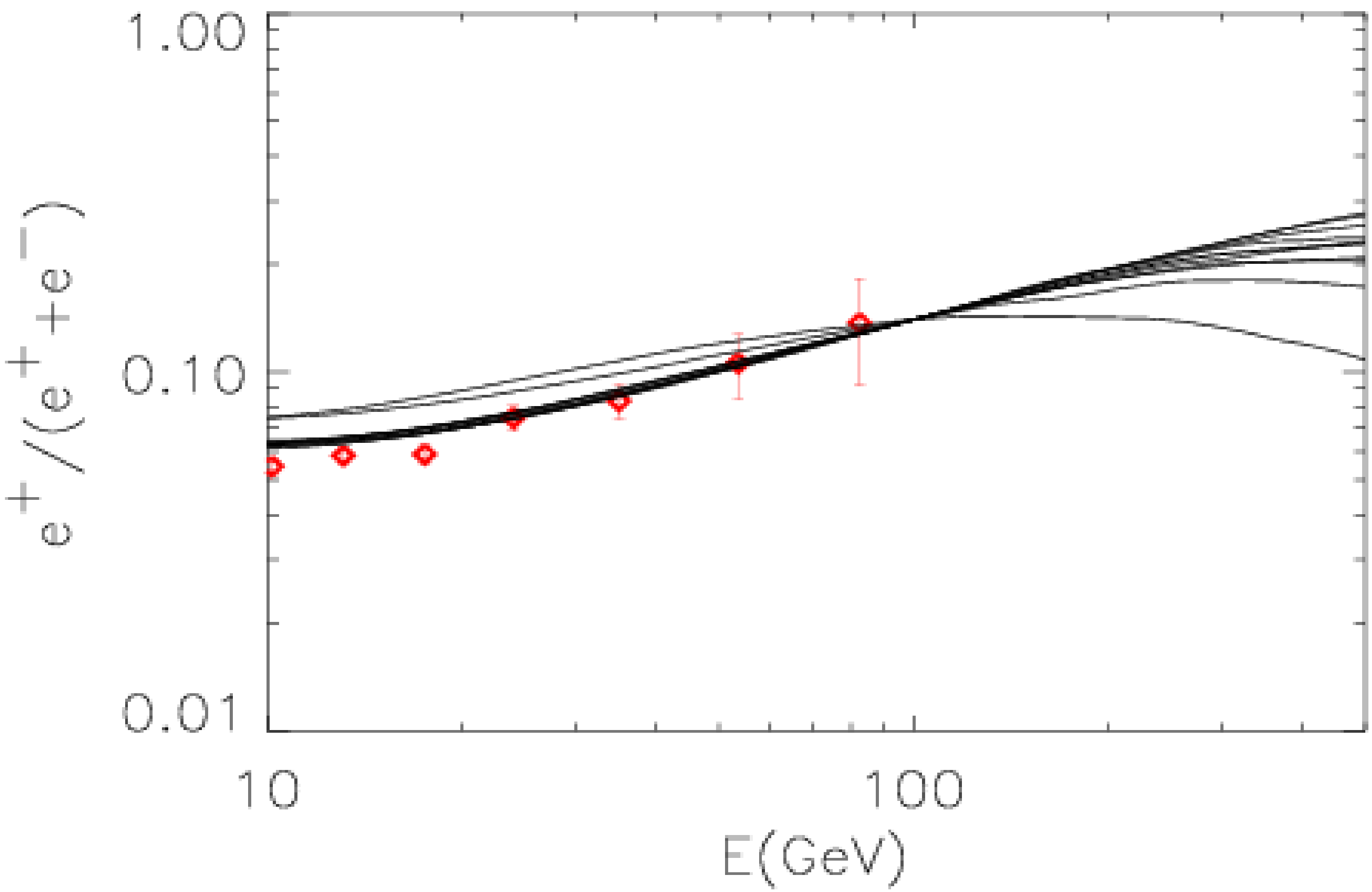
If not: too much diffusion, low energy, too low flux.

Geminga: 157 parsecs from Earth and 370,000 years old

B0656+14: 290 parsecs from Earth and 110,000 years old.

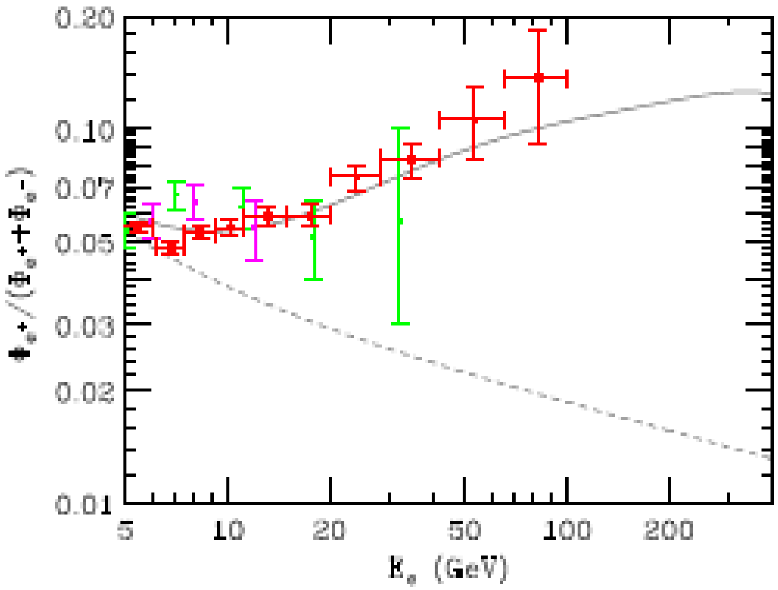
Not a new idea, e.g.: Harding & Ramaty, ICRC 2 (1987), Boulares, ApJ 342 (1989), Atoyan et al. PRD 52 (1995)

A Challenging Puzzle for CR Physics

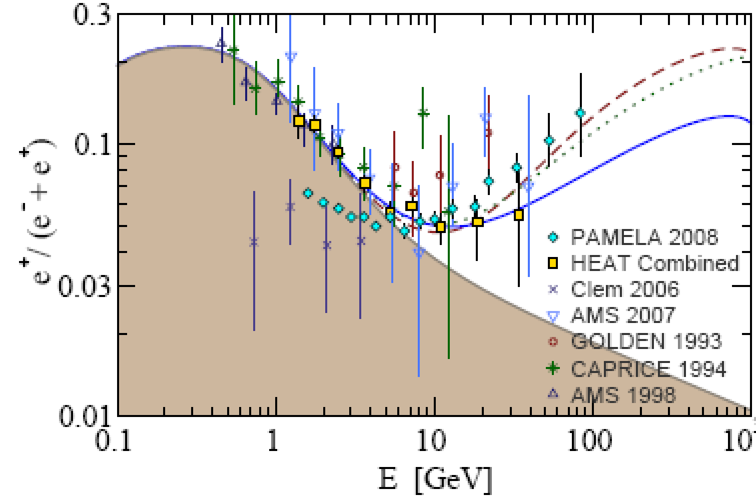


P. Blasi & E. Amato, arXiv:1007.4745
Contribution from pulsars varying the injection index and location of the sources.

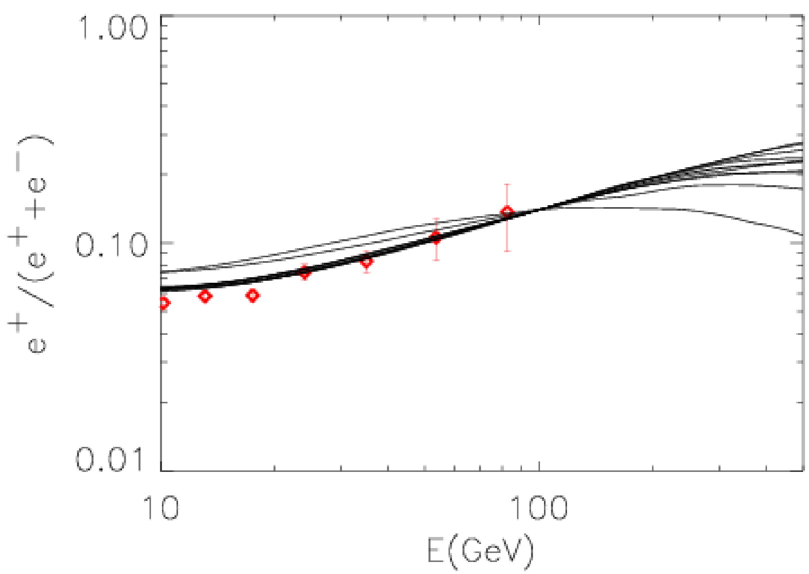
Pulsar Explanation



D. Hooper, P. Blasi, and P. Serpico, JCAP 0901:025,2009; arXiv:0810.1527
Contribution from diffuse mature &nearby young pulsars.

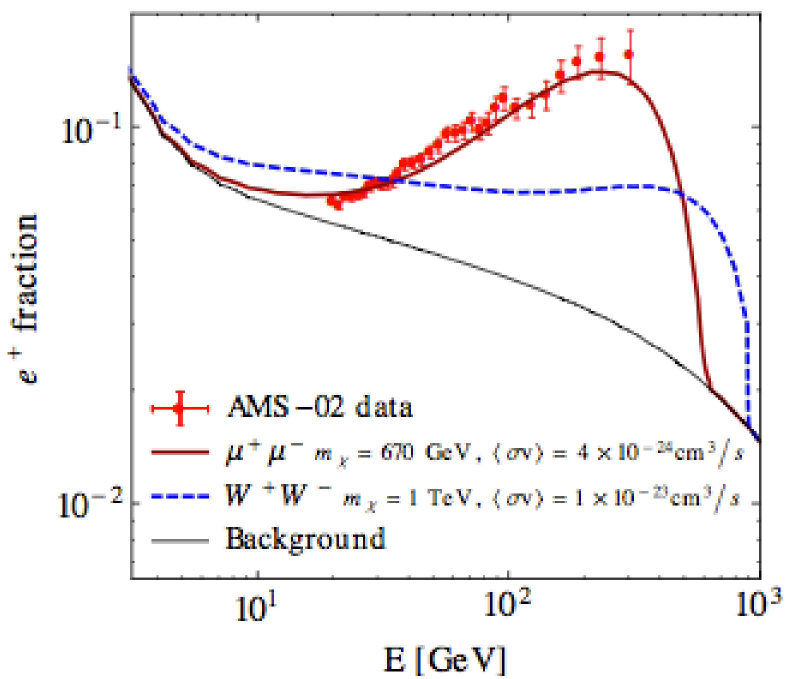


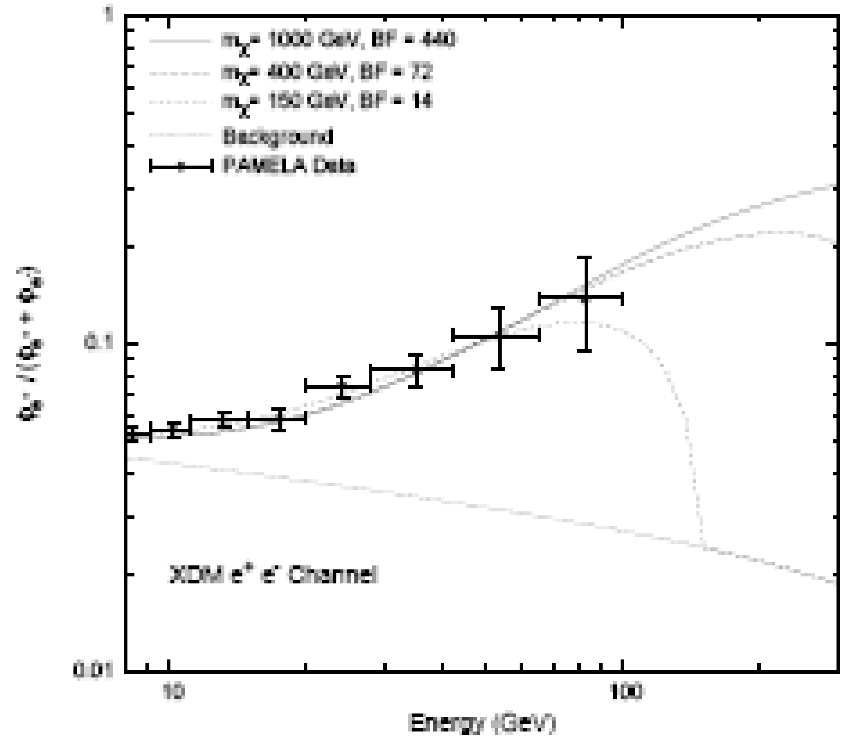
H. Yuksel et al., PRL 103 (2009) 051101; arXiv:0810.2784v2
Contributions of e^- & e^+ from Geminga assuming different distance, age and energetic of the pulsar



P. Blasi & E. Amato, arXiv:1007.4745
Contribution from pulsars varying the injection index and location of the sources.

Dark Matter Explanation



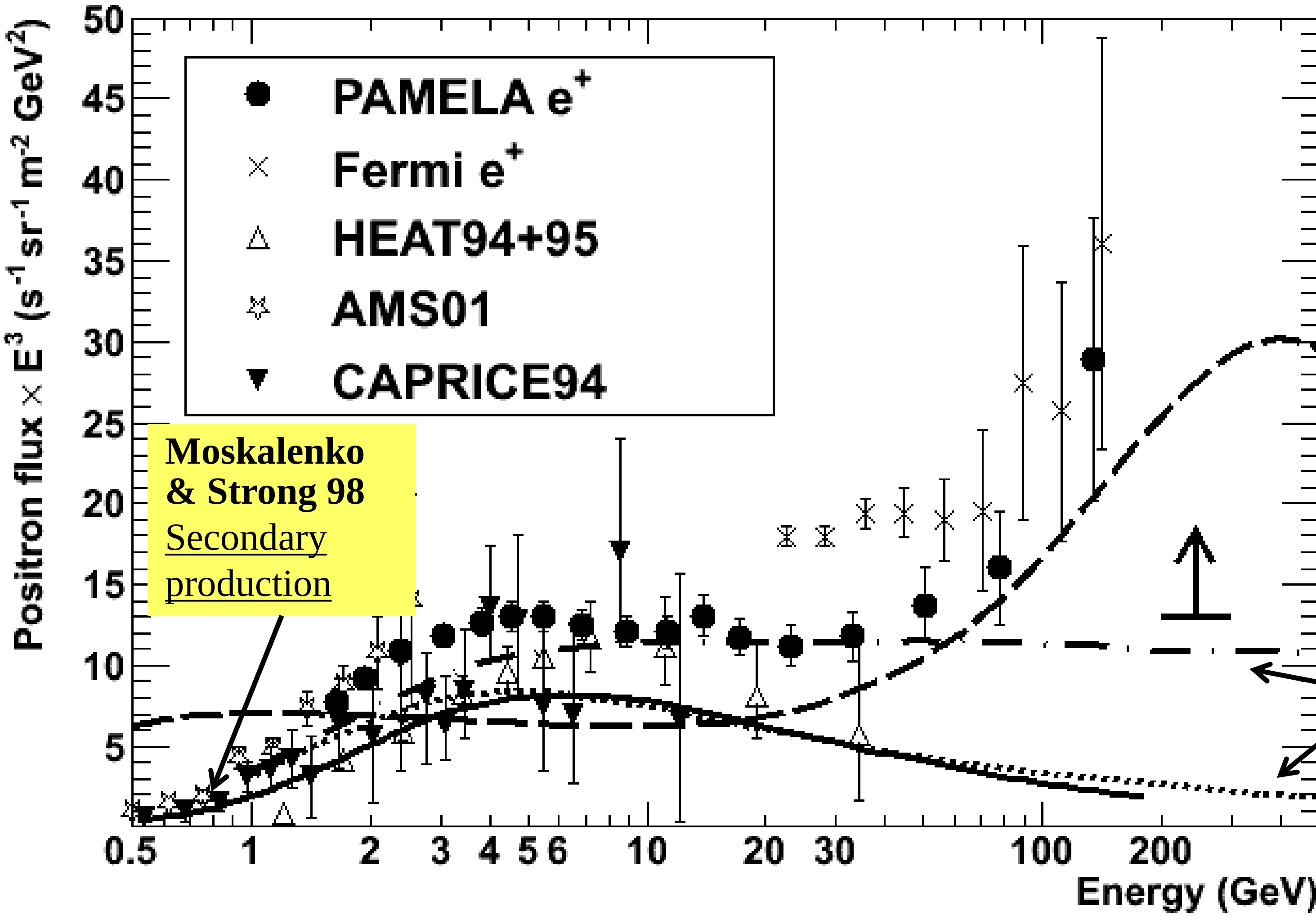


J. Kopp, Phys. Rev. D 88 (2013) 076013; arXiv:1304.1184

I. Cholis et al., Phys. Rev. D 80 (2009) 123518; arXiv:0811.3641v1

Positron Energy Spectrum

D. P. Finkbeiner et al., JCAP 1105, 002 (2011). **Secondary+ primary production (from dark matter annihilation**

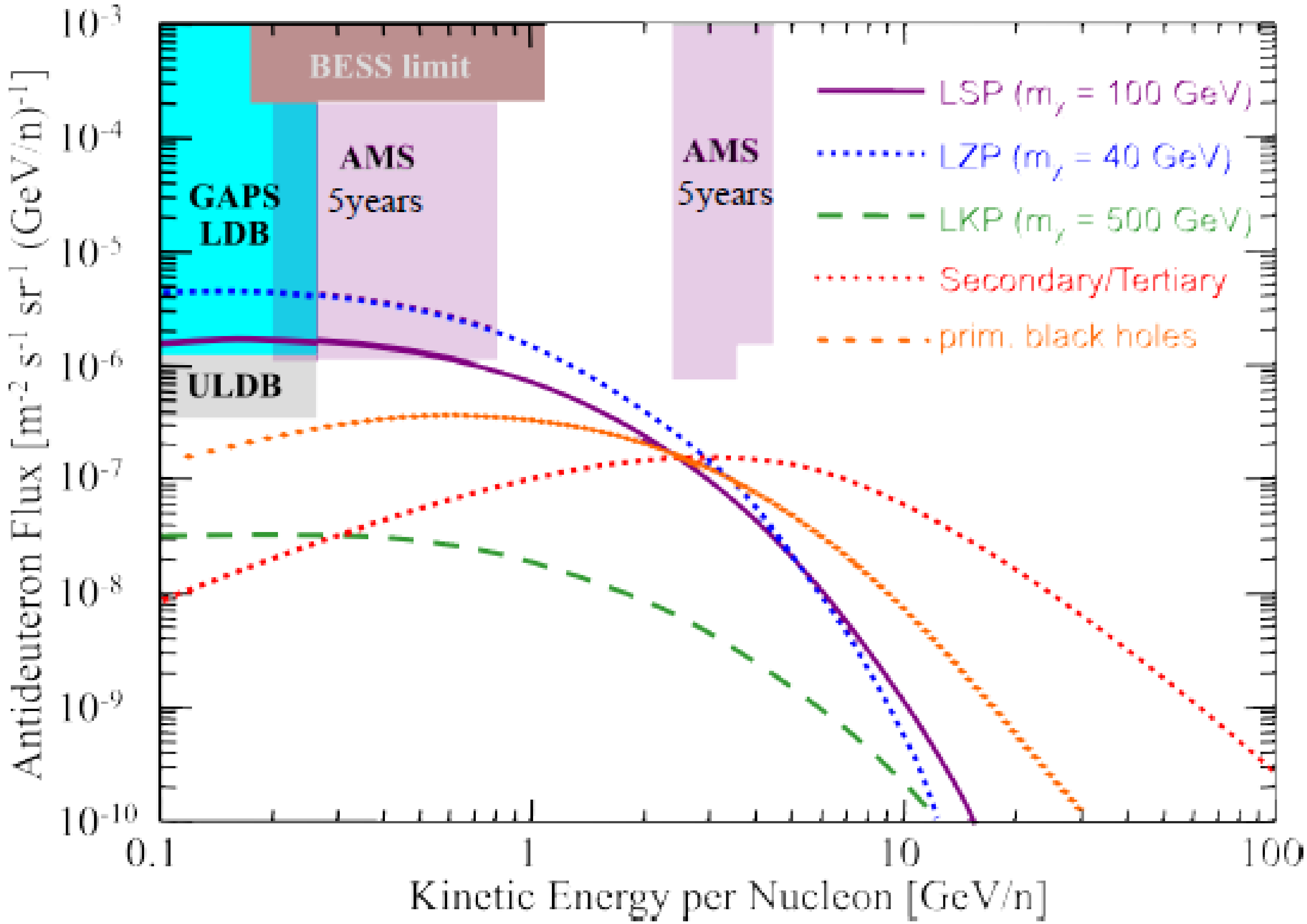


Moskalenko & Strong 98
Secondary production

T. Delahaye et al., A&A 524 (2010) A51
Secondary & Seconday+Pri **mary productions** (from Astrophysical Sources)

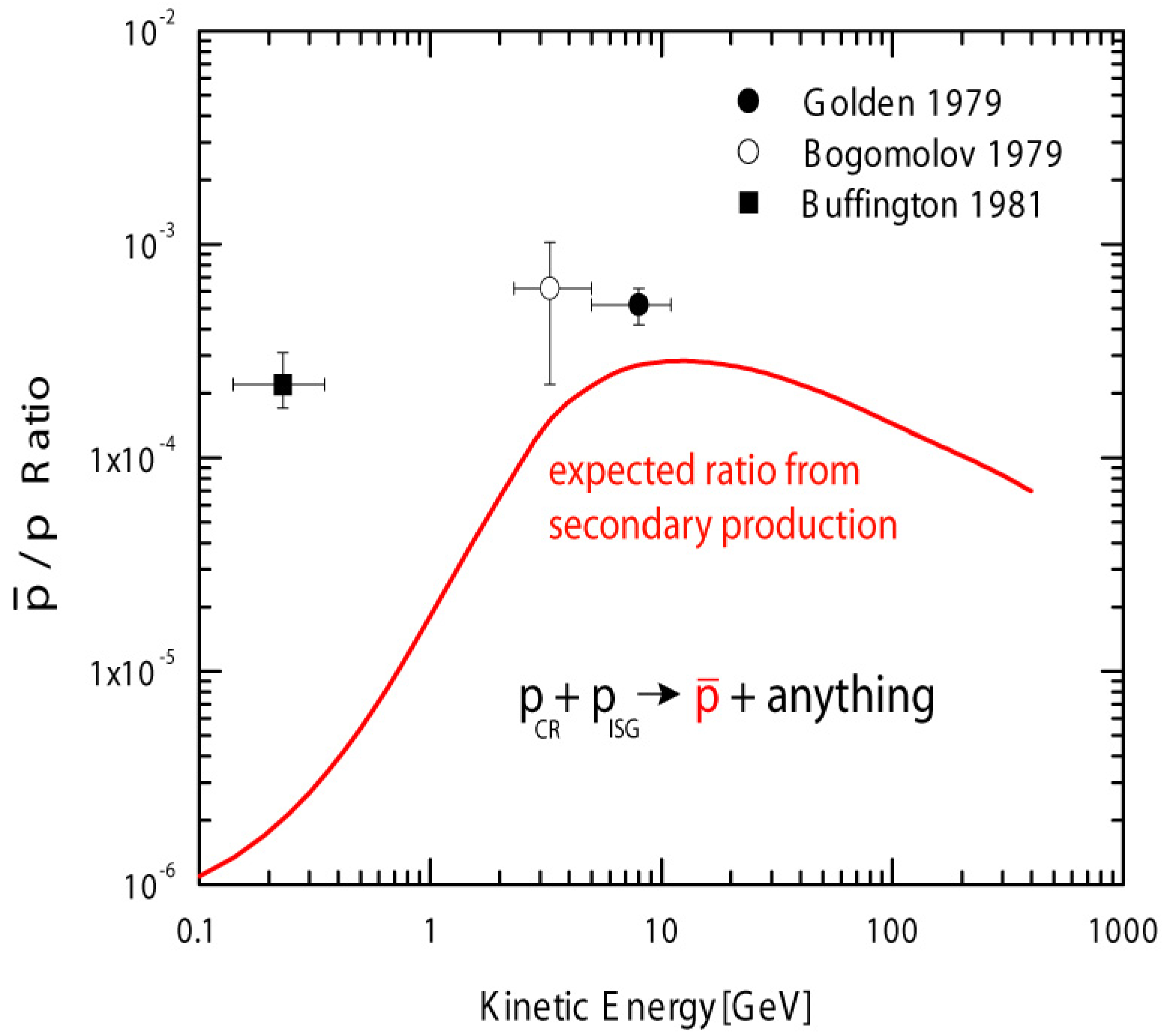
Antideuterons

P. Von Doetinchem, UCLA Dark Matter 2012



Conclusions

The first historical measurements on galactic antiprotons



Conclusions