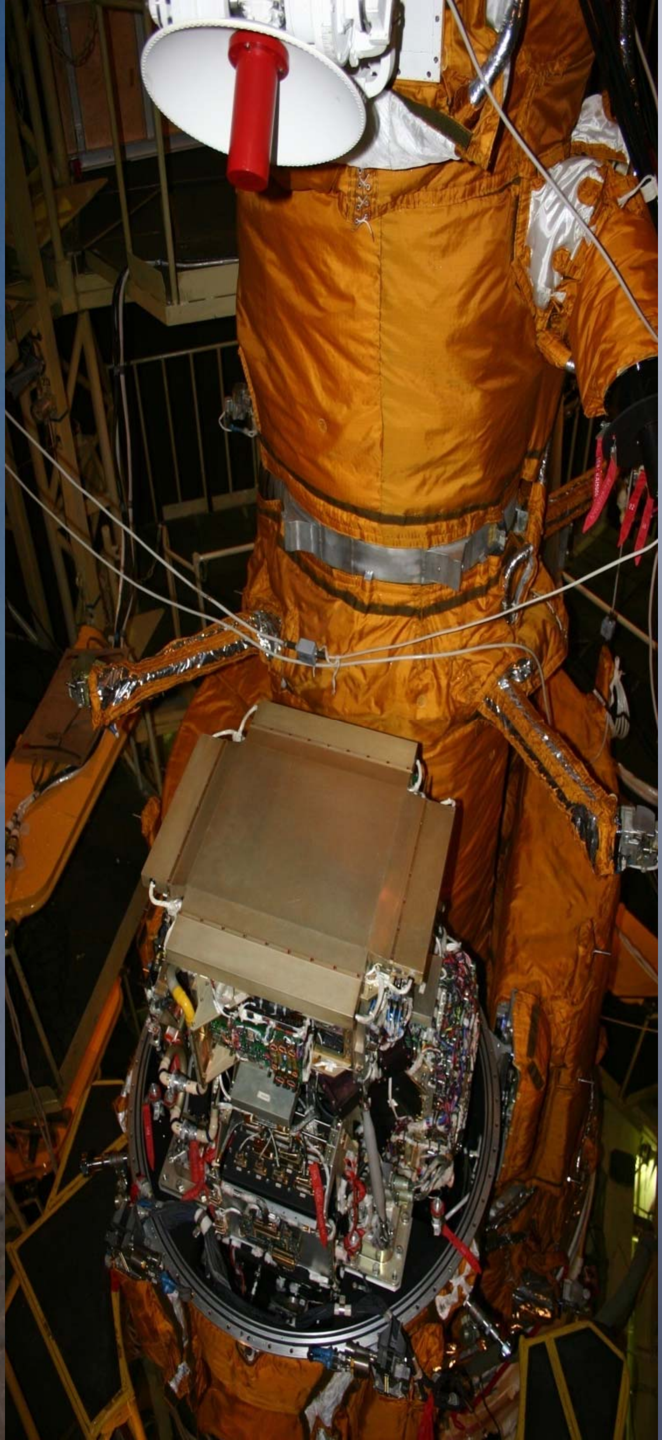


The Science of the PAMELA Space Mission

Mirko Boezio

INFN Trieste, Italy

Joint Experimental-Theoretical Seminar

May 2nd, 2008

Fermilab

PAMELA

Payload for Antimatter Matter Exploration and Light Nuclei Astrophysics

PAMELA Collaboration

Italy:

Bari Florence Frascati Naples Rome Trieste CNR, Florence

Russia:

Moscow
St. Petersburg

Germany:

Siegen

Sweden:

KTH, Stockholm

Pamela as a Space Observatory at 1AU

Search for dark matter annihilation

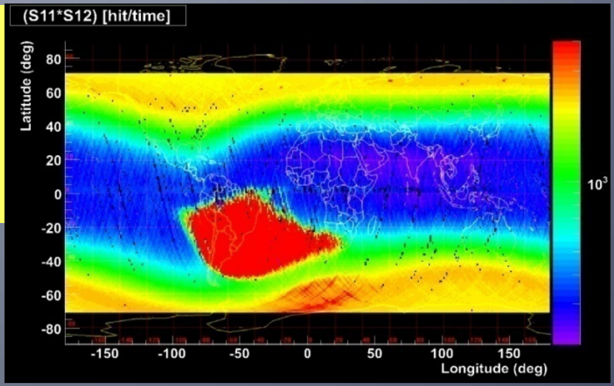
Search for antihelium (primordial antimatter)

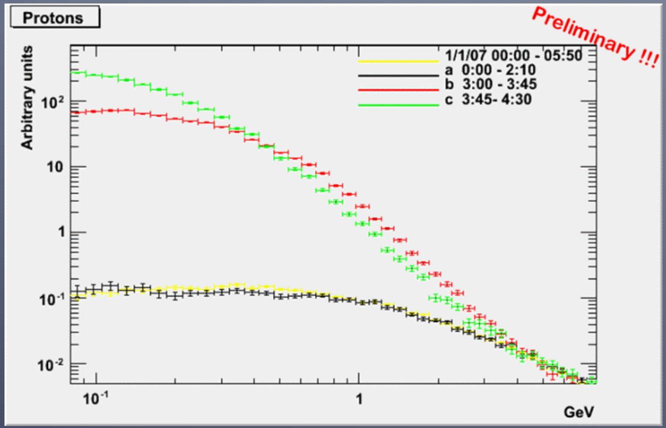
Search for new Matter in the Universe (Strangelets?)

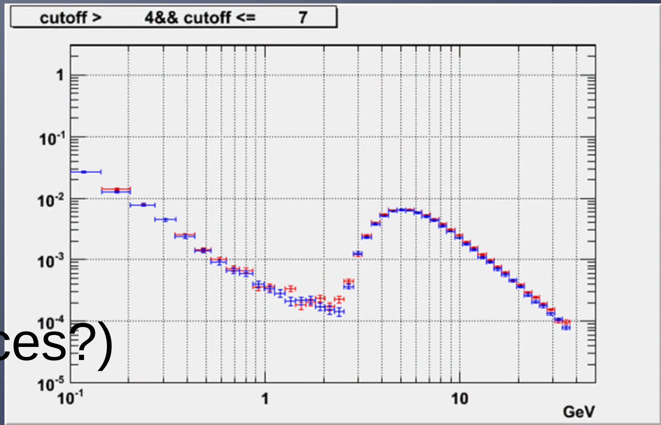
Study of cosmic-ray propagation

Study of solar physics and solar modulation

Study of terrestrial magnetosphere

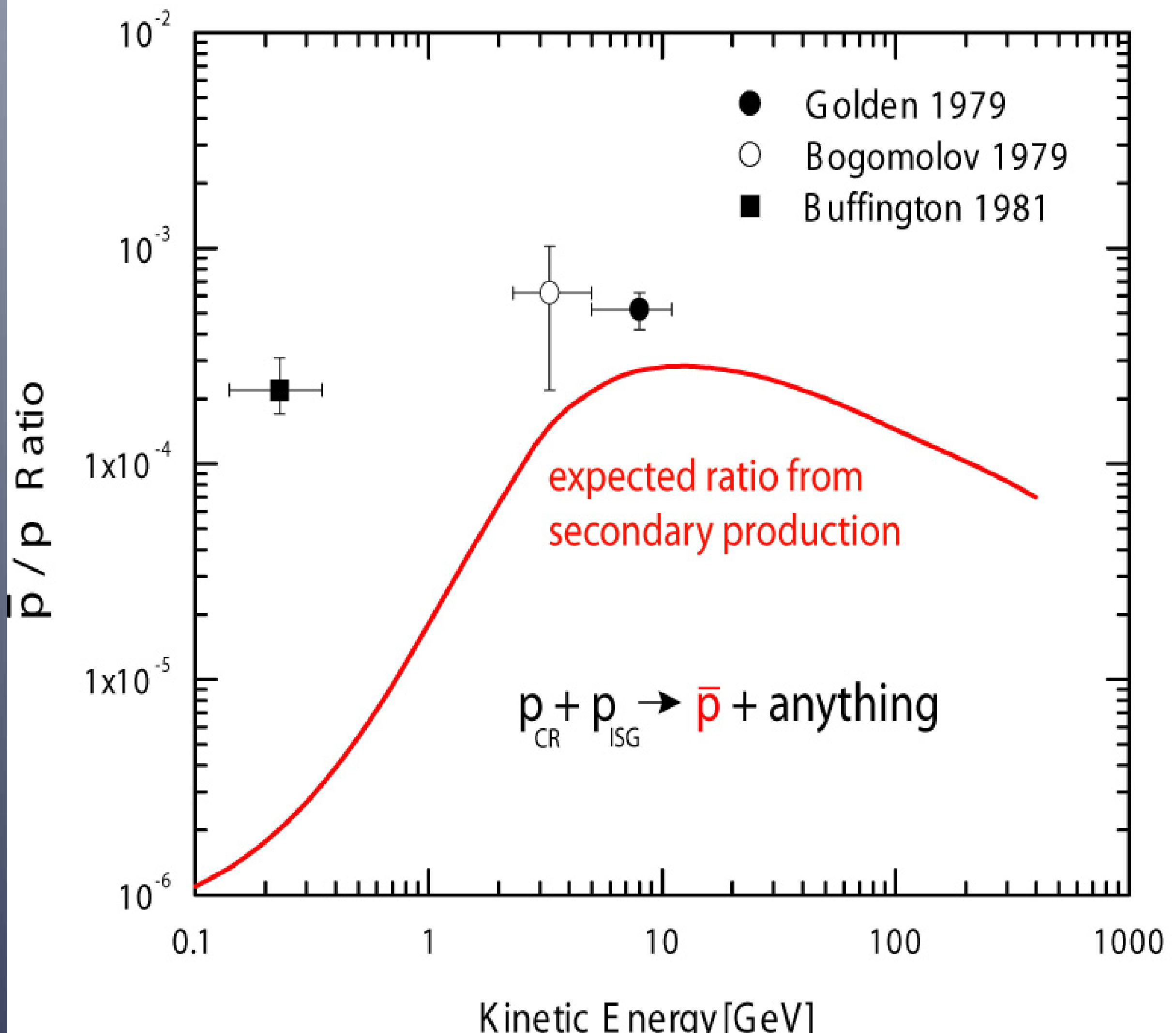




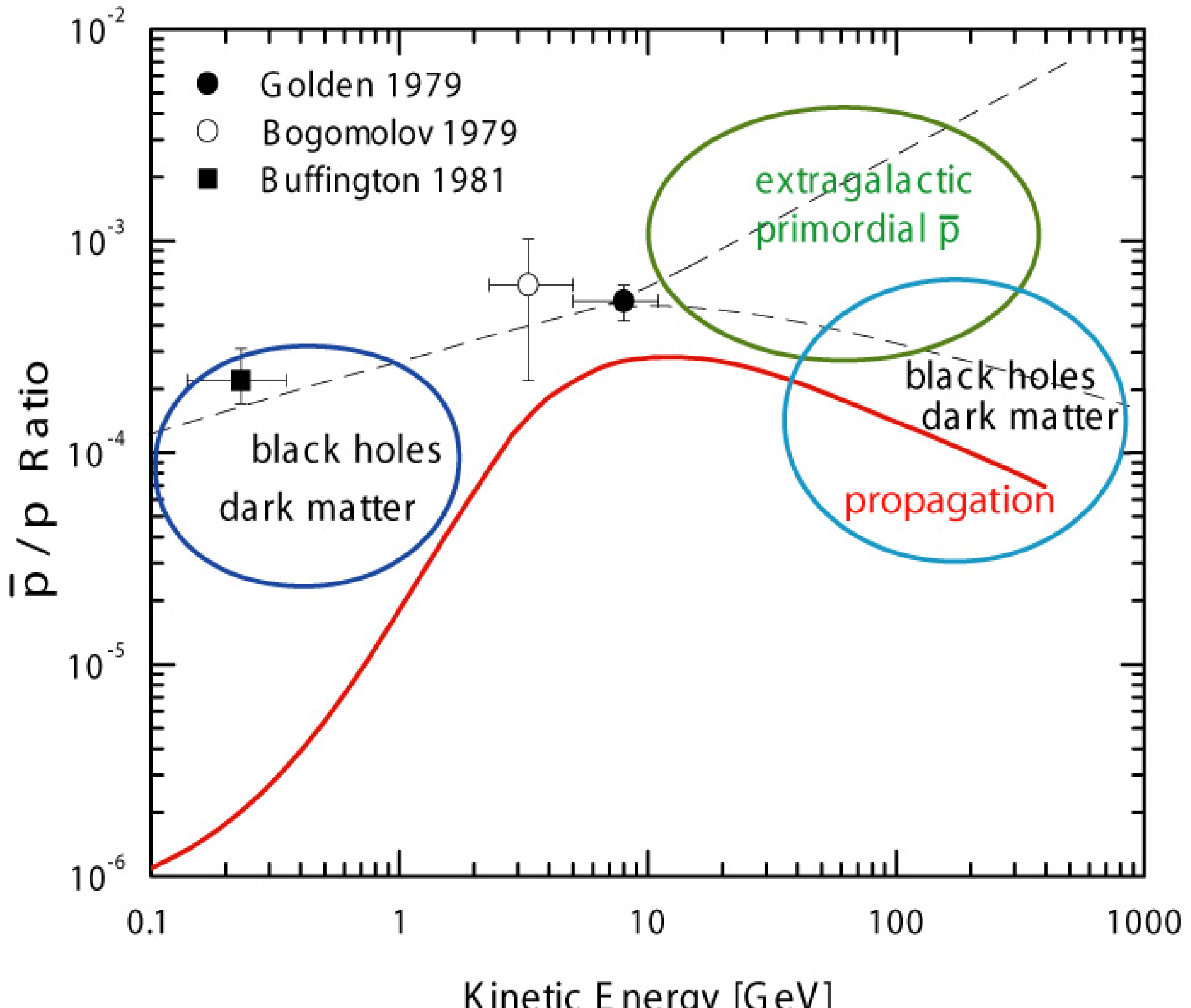


Study of high energy electron spectrum (local sources?)

The first historical measurements on galactic antiprotons



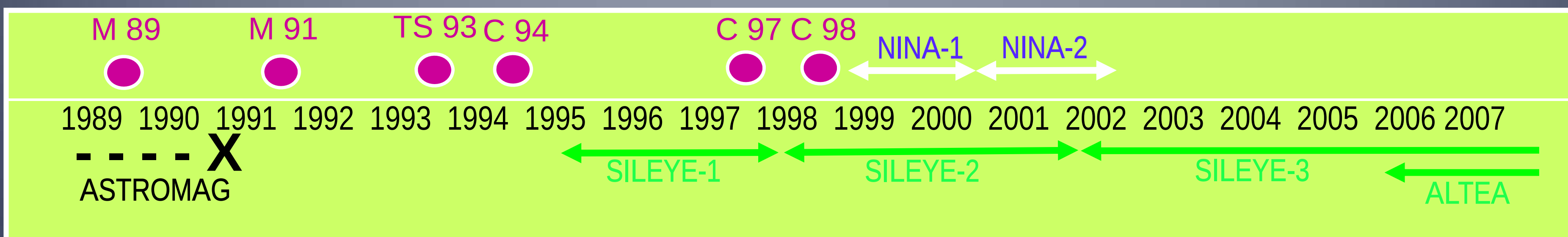
The first historical measurements of the $\bar{p}/p$ - ratio and various Ideas of theoretical Interpretations

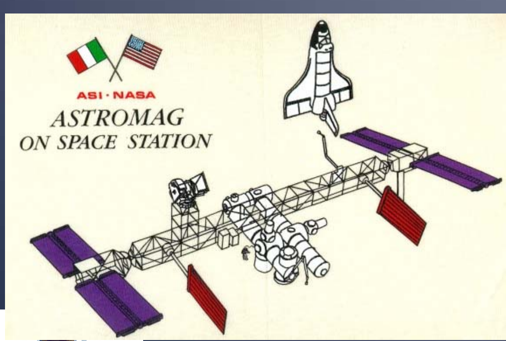


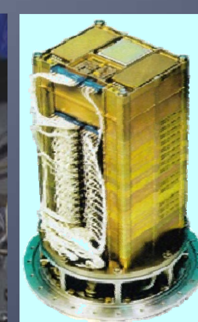
PAMELA prehistory

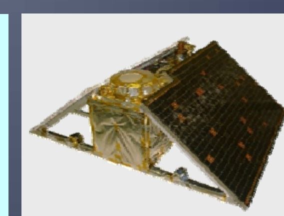
- Astromag/WiZard project (PAMELA precursor) on board of the Space Station Freedom → CANCELED
- Balloon-borne experiments: MASS-89,91 TS-93 CAPRICE-94,97,98
- Space experiments*: NINA-1,2 SILEYE-1,2,3 ALTEA

(*study of low energy nuclei and space radiation environment)









PAMELA history

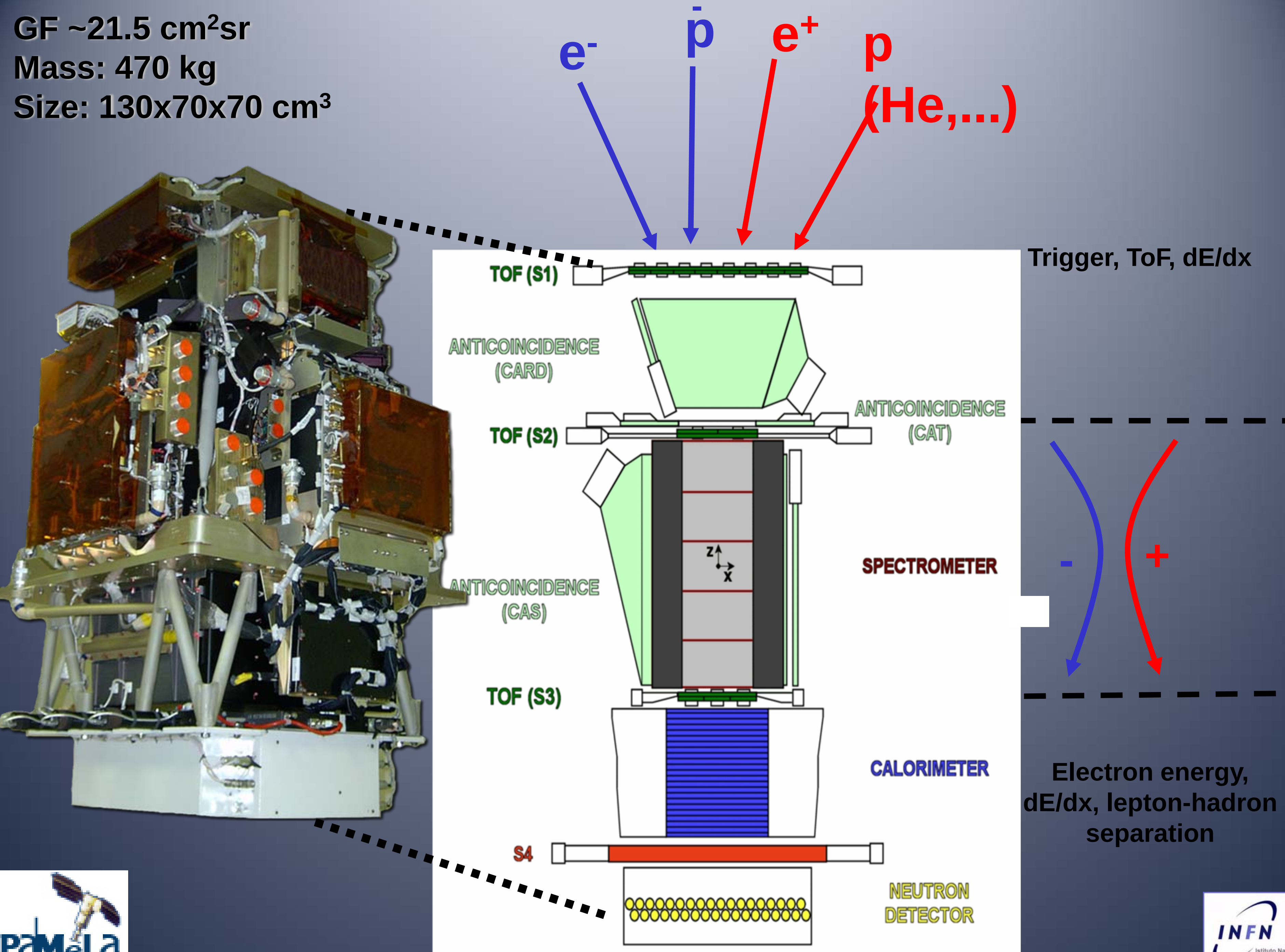
- 1996: PAMELA proposal
- 22.12.1998: agreement between RSA (Russian Space Agency) and INFN to build and launch PAMELA.

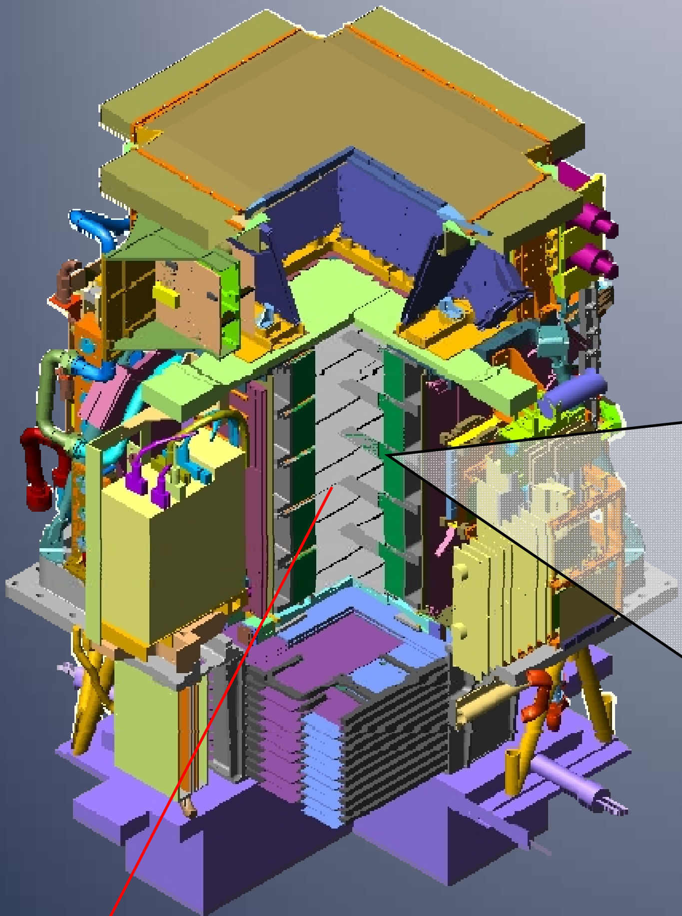
  Three models required by the RSA:
  - Mass-Dimensional and Thermal Model (MDTM)
  - Technological Model (TM)
  - Flight Model (FM)

  → ***Starts PAMELA construction***
- 2001: change of the satellite → ***complete redefinition of mechanics***
- 2006: flight!!!

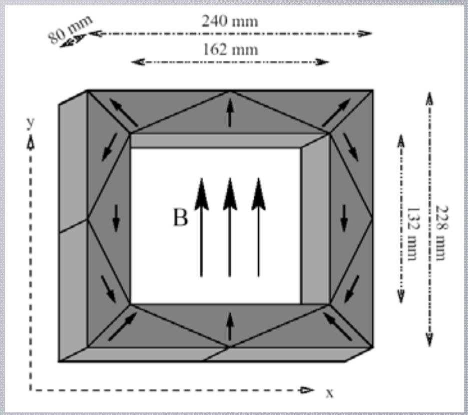
1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007

GF ~21.5 $cm^2 sr$
Mass: 470 kg
Size: 130x70x70 cm^3





The magnet



Characteristics:

- 5 modules of permanent magnet (Nd-B-Fe alloy) in aluminum mechanics
- Cavity dimensions 162x132x445 cm^3
  → GF 21.5 cm^2sr
- Magnetic shields
- 5mm-step field-map
- B=0.43 T (average along axis), B=0.48 T (@center)

The tracking system

Main tasks:

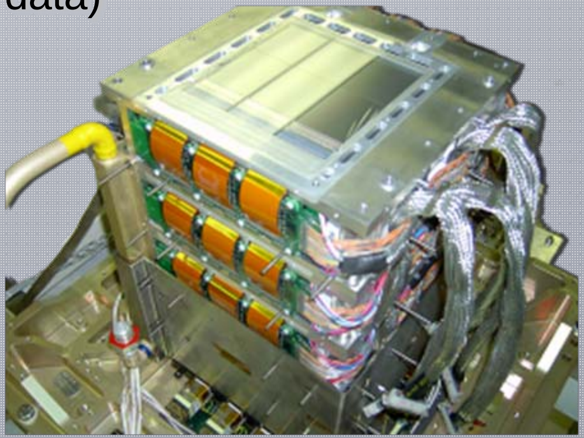
- Rigidity measurement
- Sign of electric charge
- dE/dx

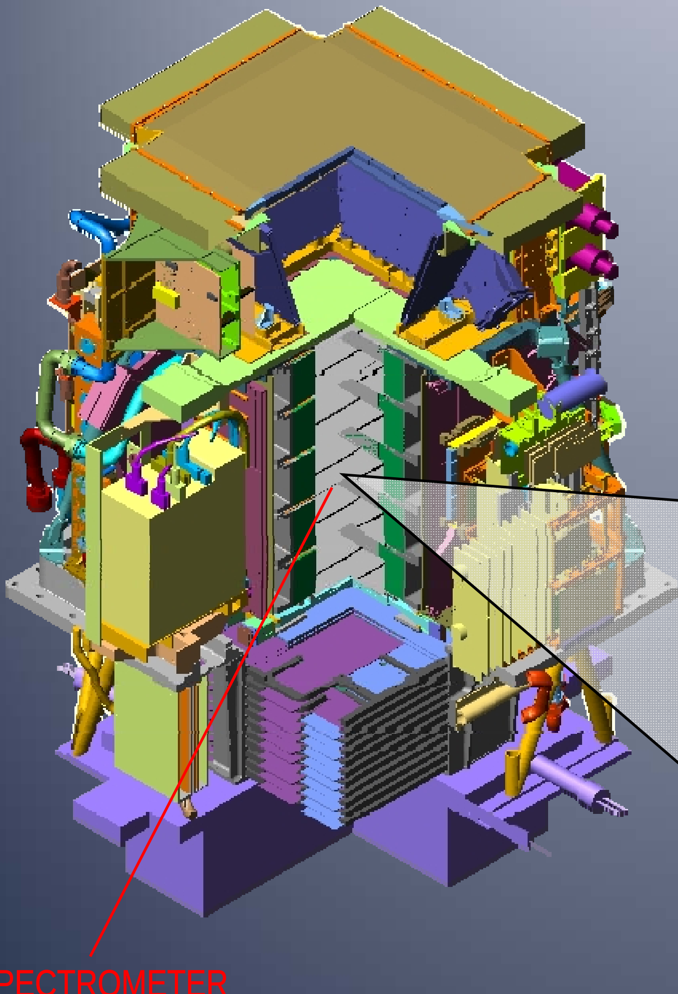
Characteristics:

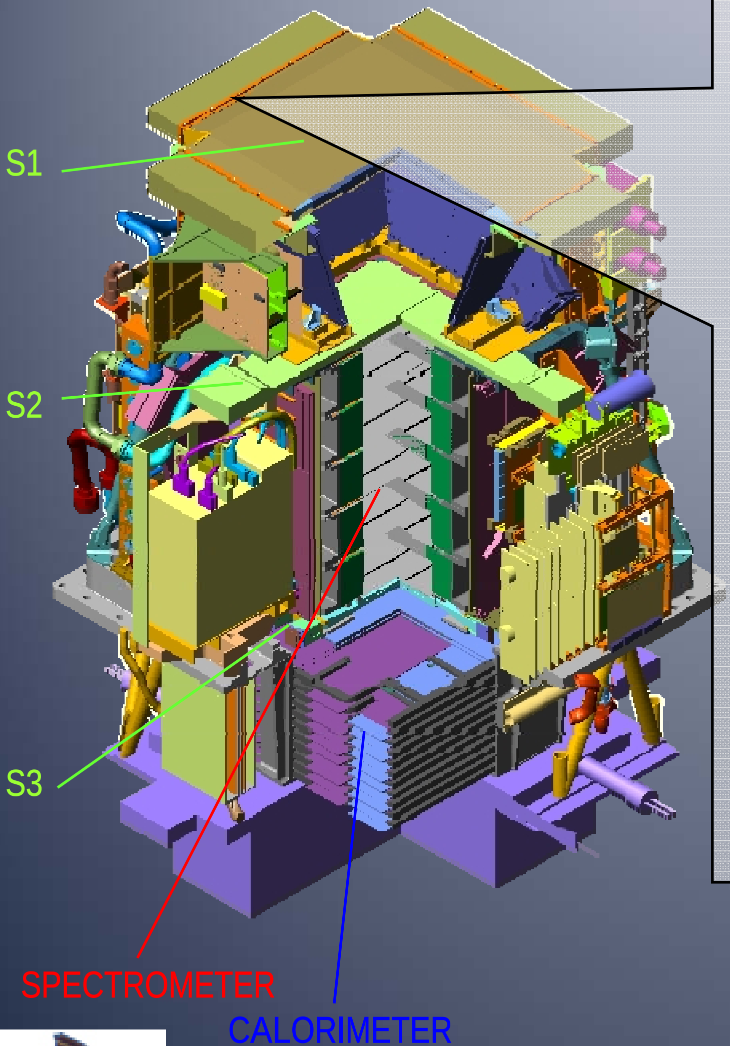
- 6 planes double-side (x&y view) microstrip Si sensors
- 36864 channels
- Dynamic range 10 MIP

Performances:

- Spatial resolution: 3-4μm
- MDR ~1TV/c (from test beam data)







The time-of-flight system

Main tasks:

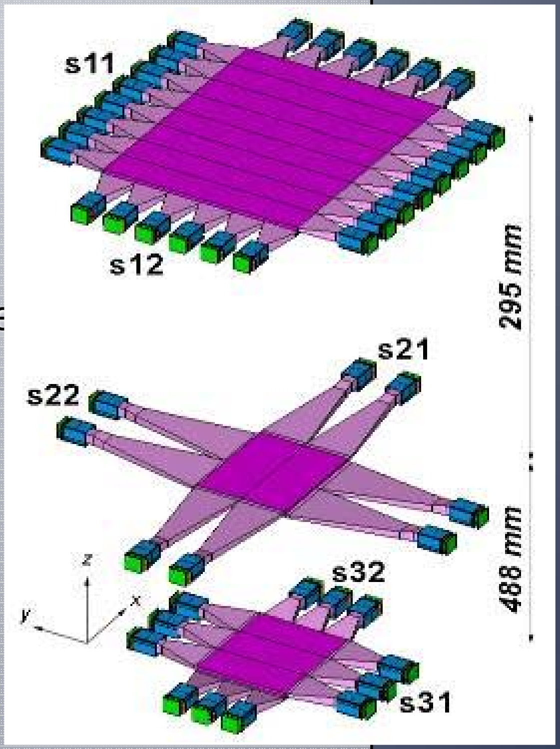
- First-level trigger
- Albedo rejection
- dE/dx
- Particle identification (<1 Ge

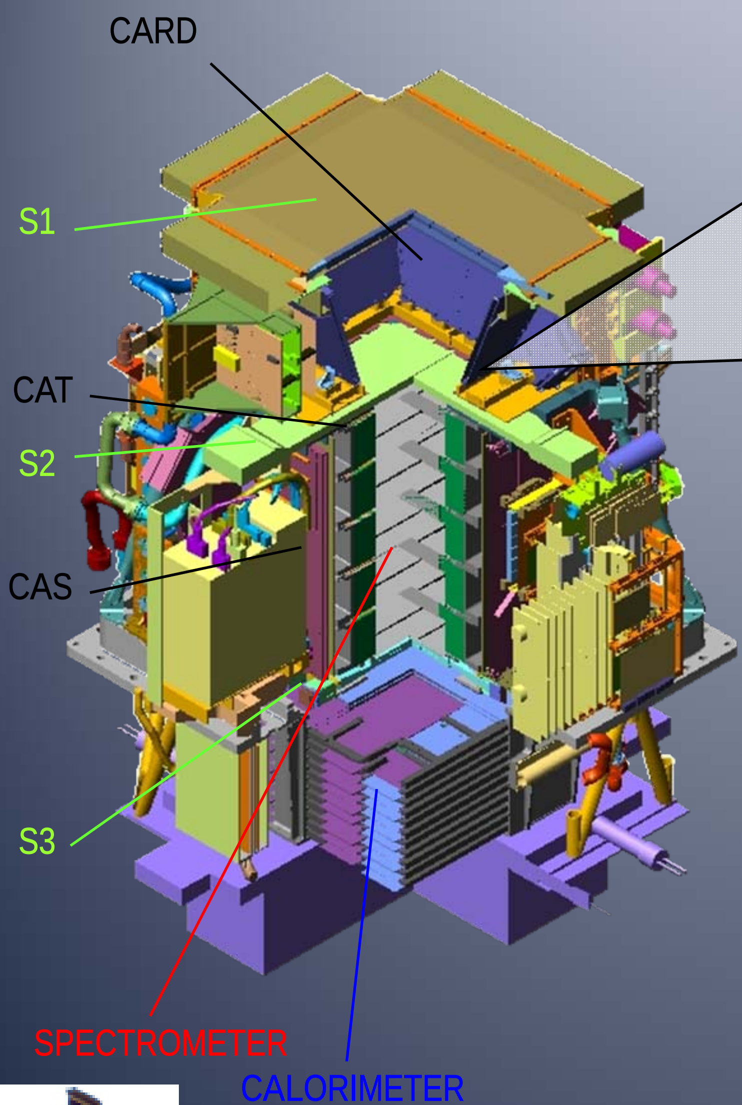
Characteristics:

- 3 double-layer scintillator paddles
- X/Y segmentation
- Total: 48 Channels

Performances:

- σ(paddle) ~ 110ps
- σ(TOF) ~ 330ps (for MIPs)





The anticounter shields

Main tasks:

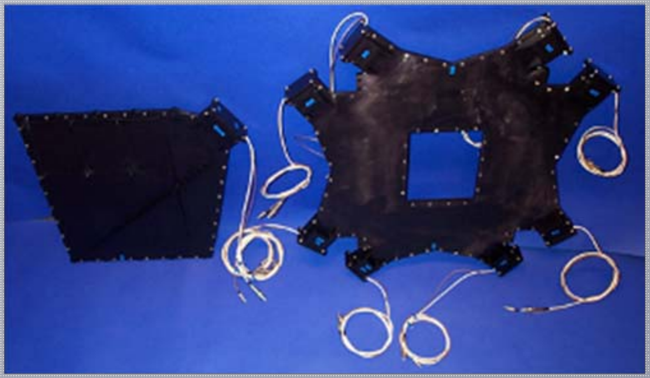
- Rejection of events with particles interacting with the apparatus (off-line and second-level trigger)

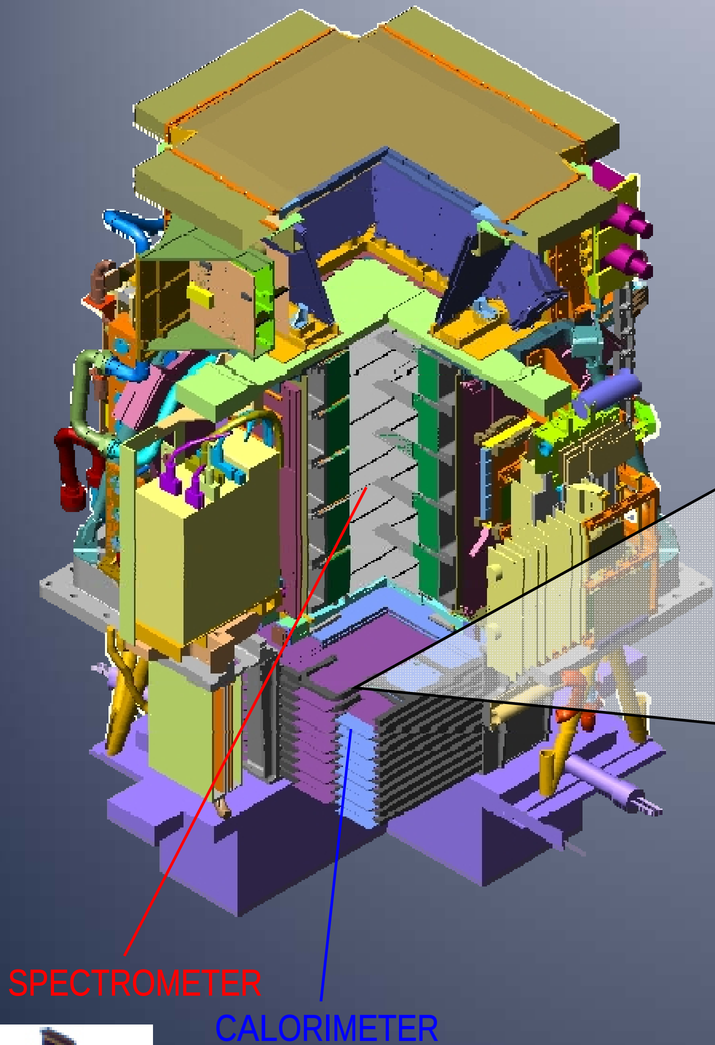
Characteristics:

- scintillator paddles 10mm thick
- 4 up (CARD), 1 top (CAT), 4 side (CAS)

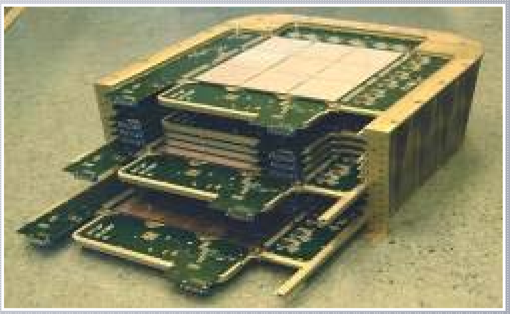
Performances:

- Efficiency > 99.9%





The electromagnetic calorimeter



Main tasks:

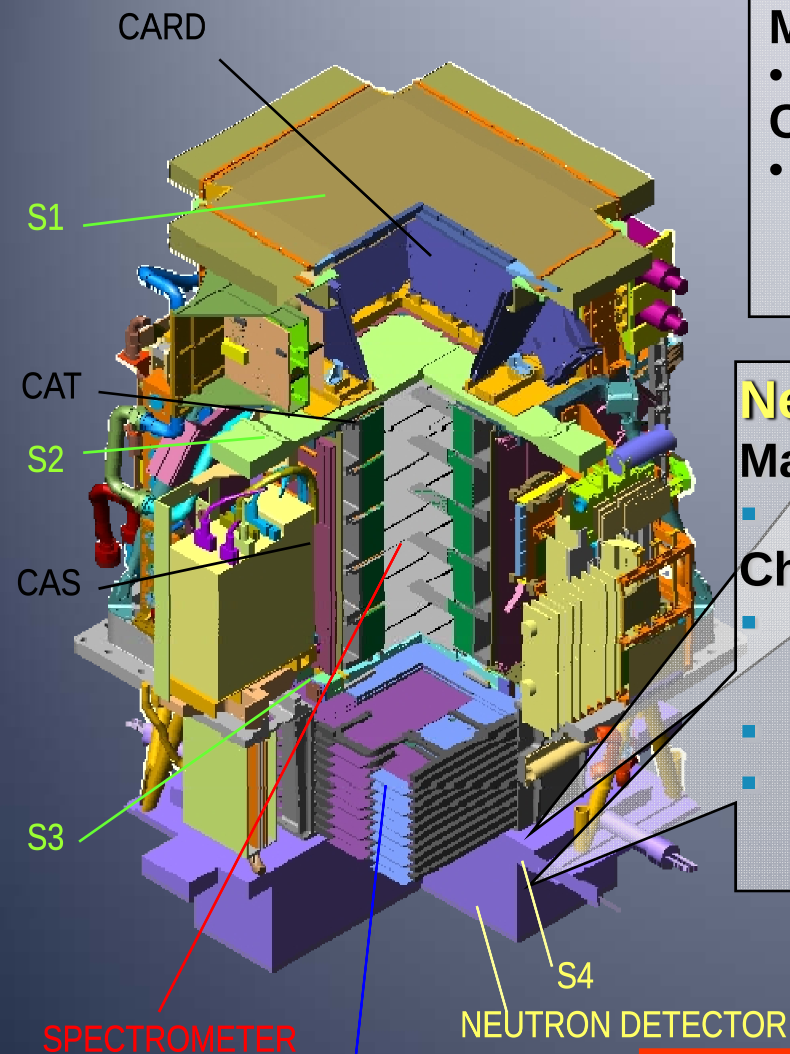
- e/h discrimination
- $e^{+/-}$ energy measurement

Characteristics:

- 44 Si layers (X/Y) +22 W planes
- 16.3 X_o / 0.6 λ_0
- 4224 channels
- Dynamic range 1400 mip
- Self-trigger mode (> 300 GeV GF~600 cm^2 sr)

Performances:

- p-bar and e^+ selection efficienecy ~ 90%
- p rejection factor ~10^5
- e^- rejection factor ~10^4
- Energy resolution ~5% @200GeV



Shower-tail catcher (S4)

Main tasks:

- ND trigger

Characteristics:

- 1 scintillator paddle 10mm thick

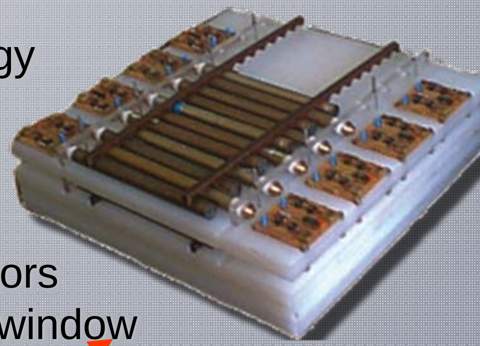
Neutron detector

Main tasks:

- e/h discrimination @high-energy

Characteristics:

- 36 ^{3}He counters: ^{3}He(n,p)T → Ep=780 keV
- 9 cm thick polyetilene moderators
- n collected within 200 μs time-window



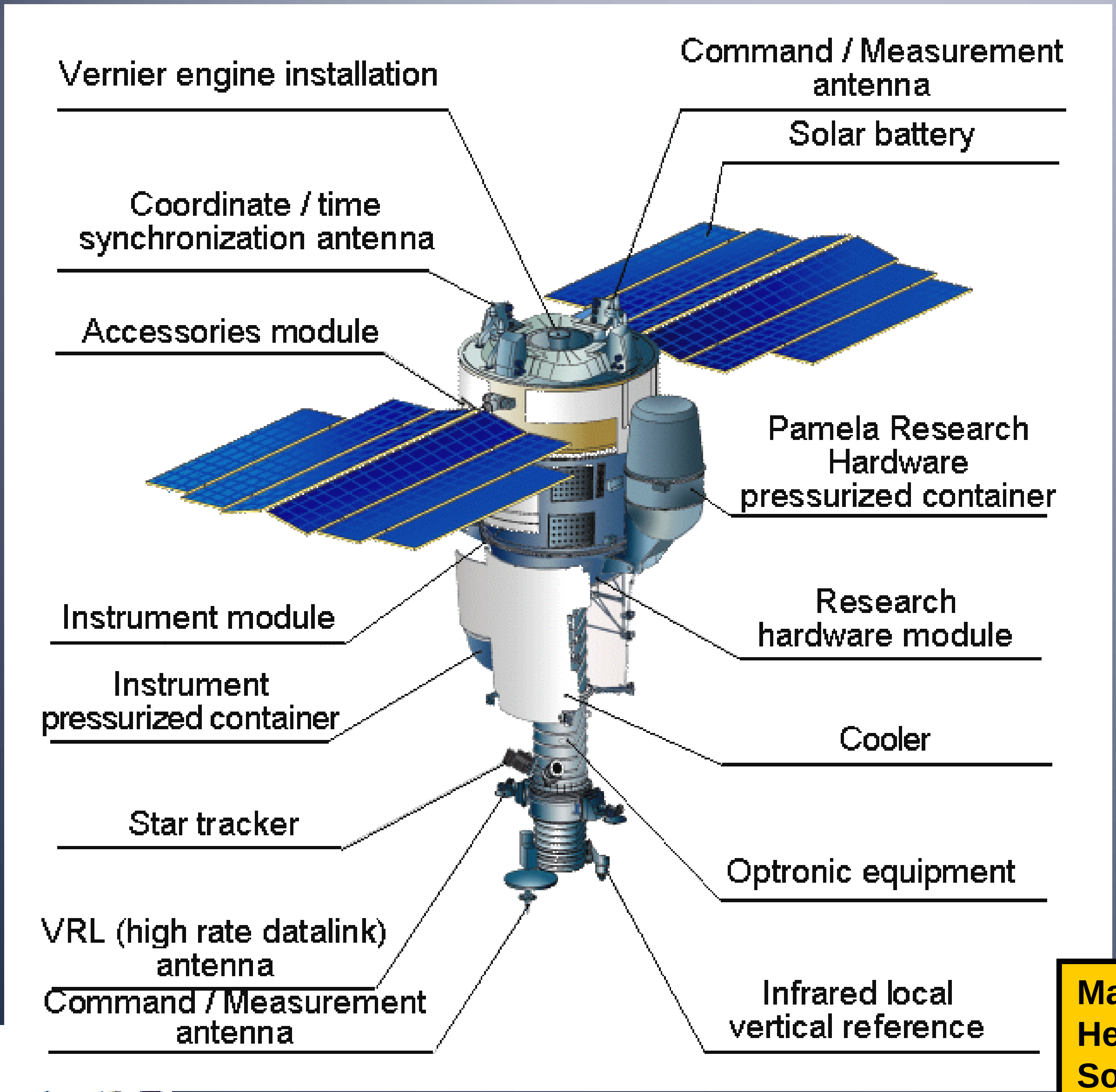
Very important to help the Calorimeter in the particle separation

Design Performance

	energy range	particles in 3 years
▪ Antiprotons	80 MeV - 190 GeV	$O(10^4)$
▪ Positrons	50 MeV – 270 GeV	$O(10^5)$
▪ Electrons	up to 400 GeV	$O(10^6)$
▪ Protons	up to 700 GeV	$O(10^8)$
▪ Electrons+positrons	up to 2 TeV (from calorimeter)	
▪ Light Nuclei	up to 200 GeV/n	He/Be/C: $O(10^{7/4/5})$
▪ AntiNuclei search	sensitivity of 3×10^{-8} in $\overline{\text{He}}$/He	

→ **Simultaneous measurement of many cosmic-ray species**
→ **New energy range**
→ **Unprecedented statistics**

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**

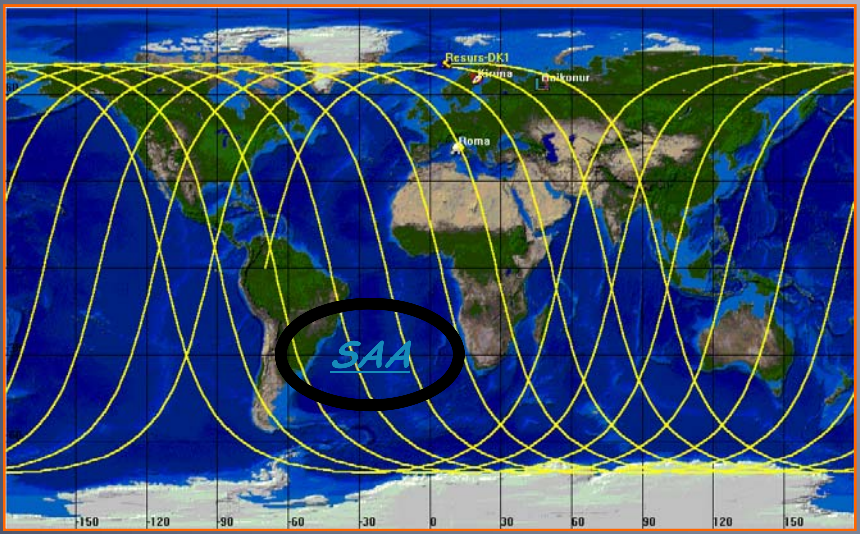
Mass: 6.7 tonnes
Height: 7.4 m
Solar array area: 36 m²

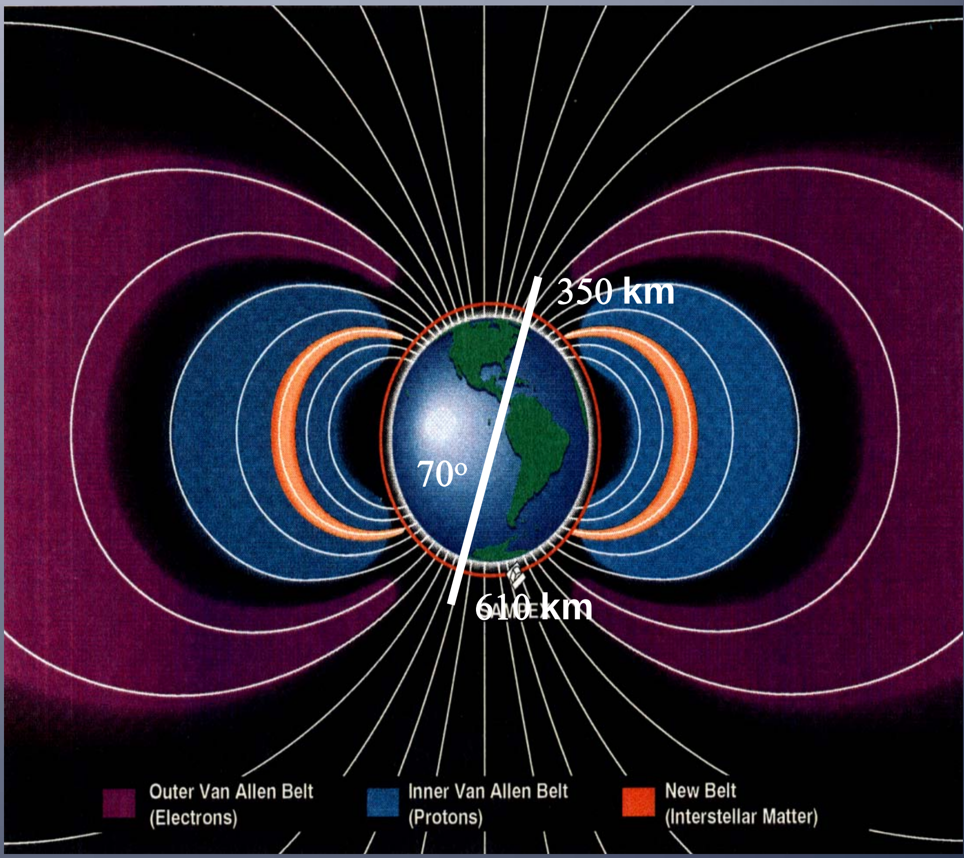
PAMELA

Launch
15/06/06

16 Gigabytes trasmitted daily to Ground NTsOMZ Moscow

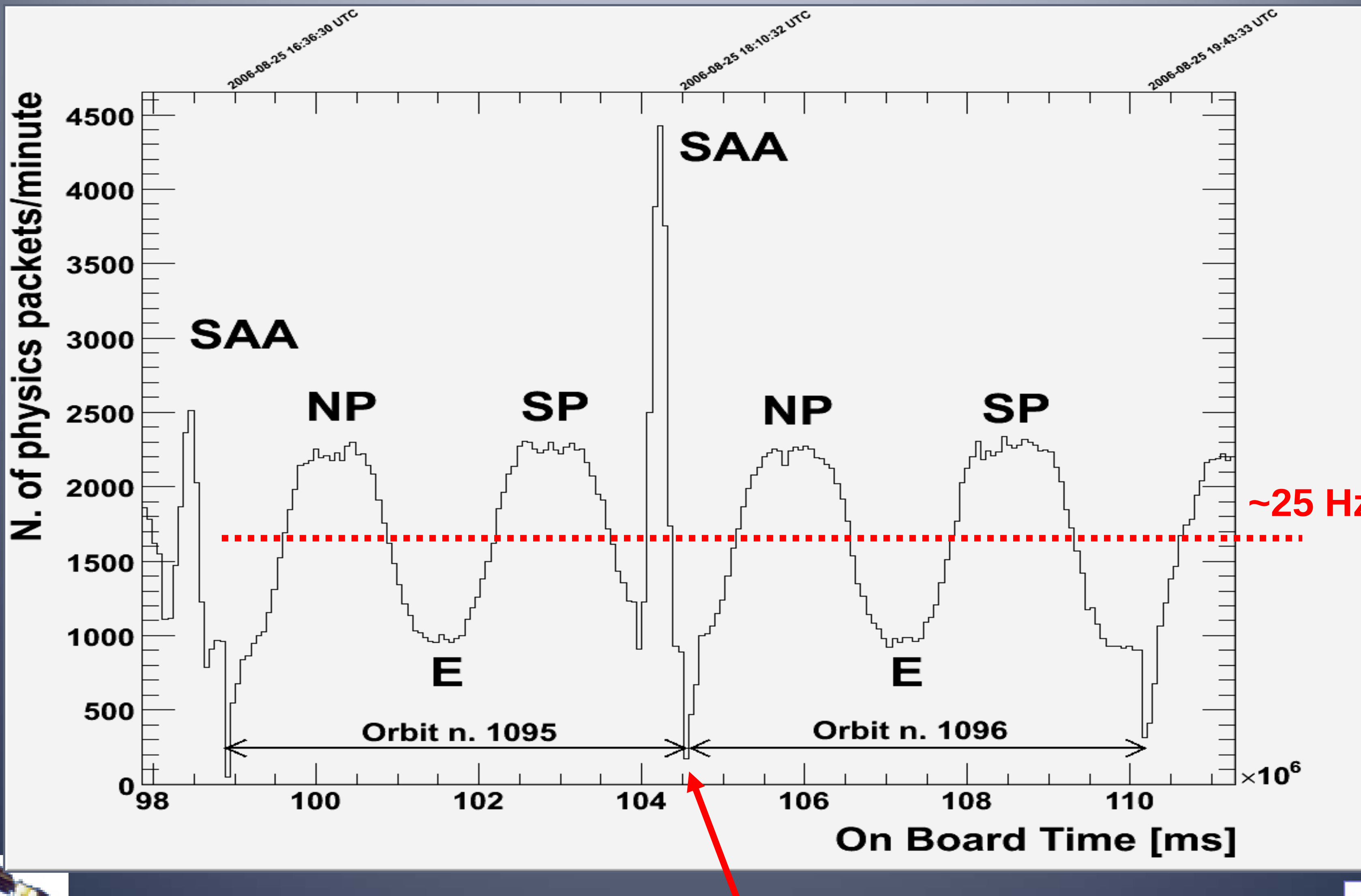
Orbit Characteristics



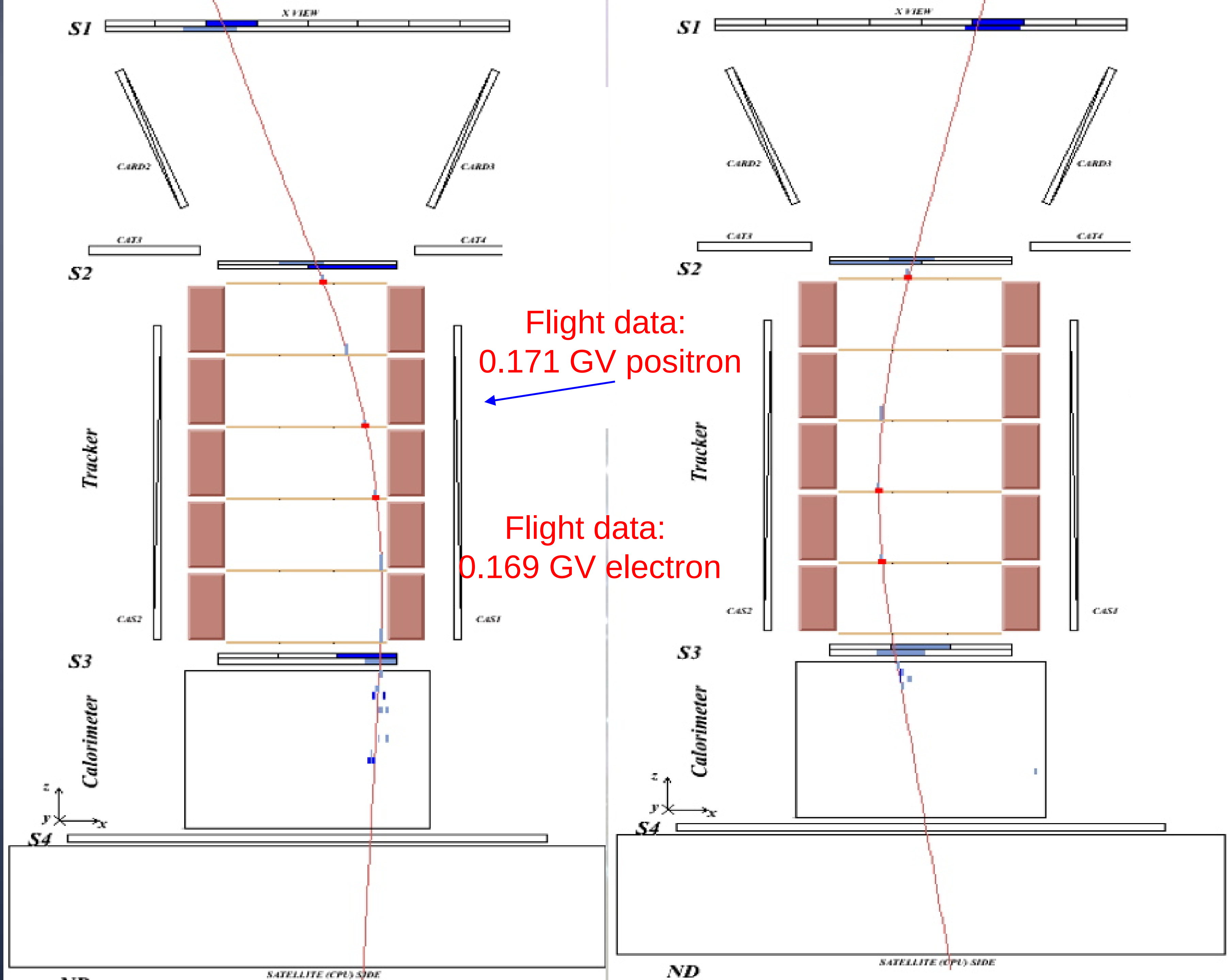


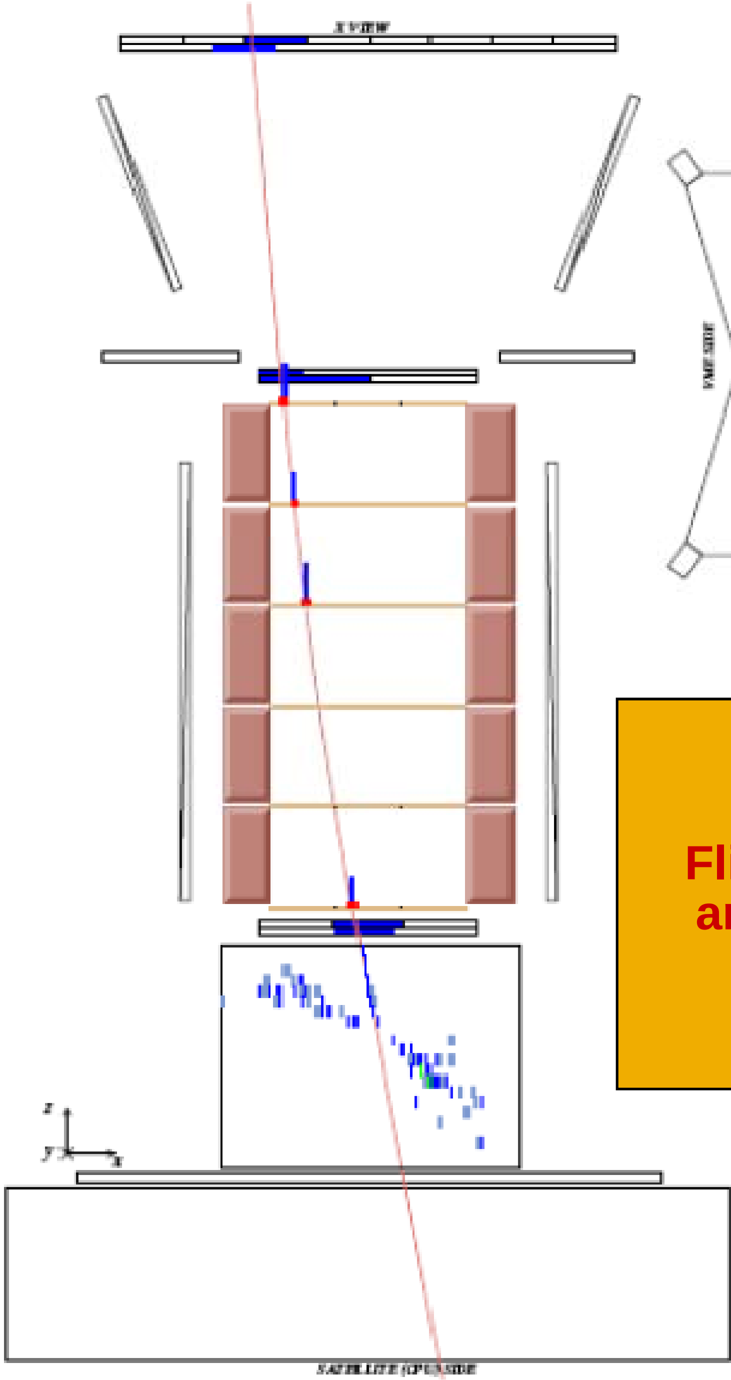
- Low-earth elliptical orbit
- 350 – 610 km
- Quasi-polar (70° inclination)
- Lifetime >3 years (assisted)

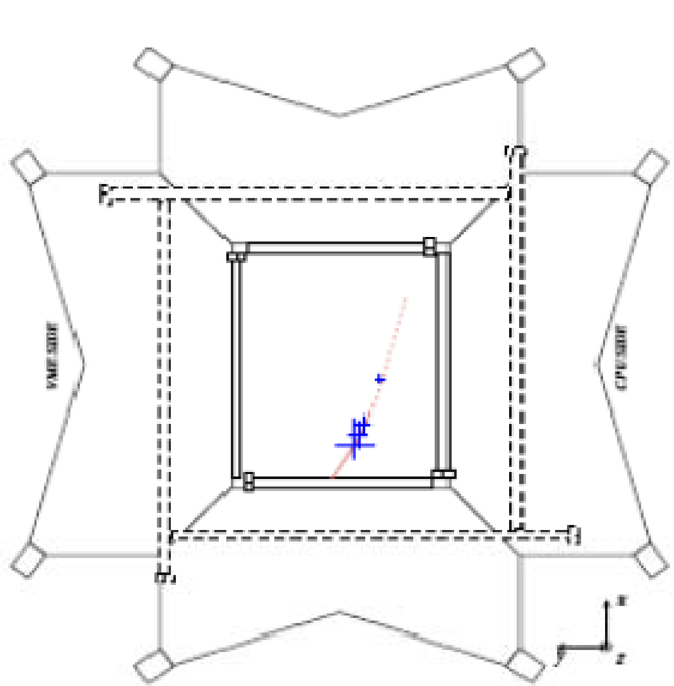
Trigger rate

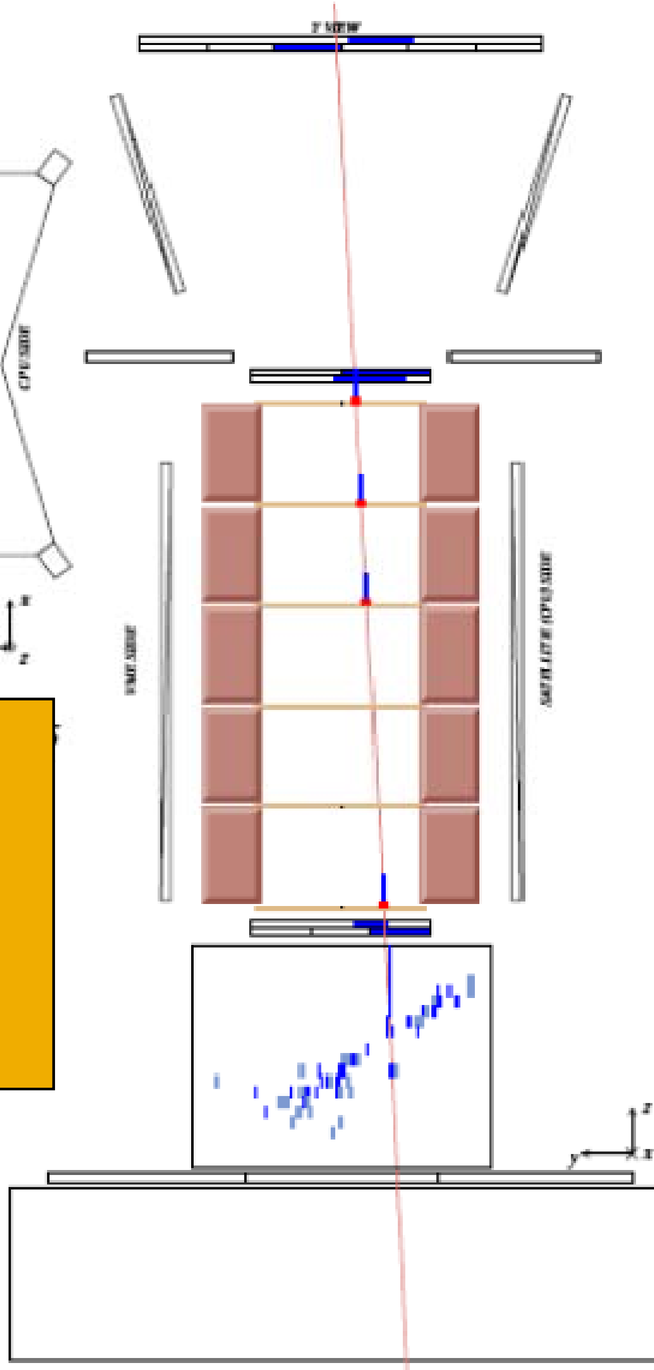


Calibration @ ascending node


X VIEW
S1
CARD2
CARD3
CAT3
CAT4
S2
Tracker
CAS2
CAS1
S3
Calorimeter
S4
SATELLITE (CPU) SIDE
ND
Flight data:
0.171 GV positron
Flight data:
0.169 GV electron







Flight data: 0.632 GeV/c antiproton annihilation

PALETTE

TOF, TRK, CALO, S4 [MIP]:

0	0 - 2	2 - 10	10 - 100	100 - 500	> 500

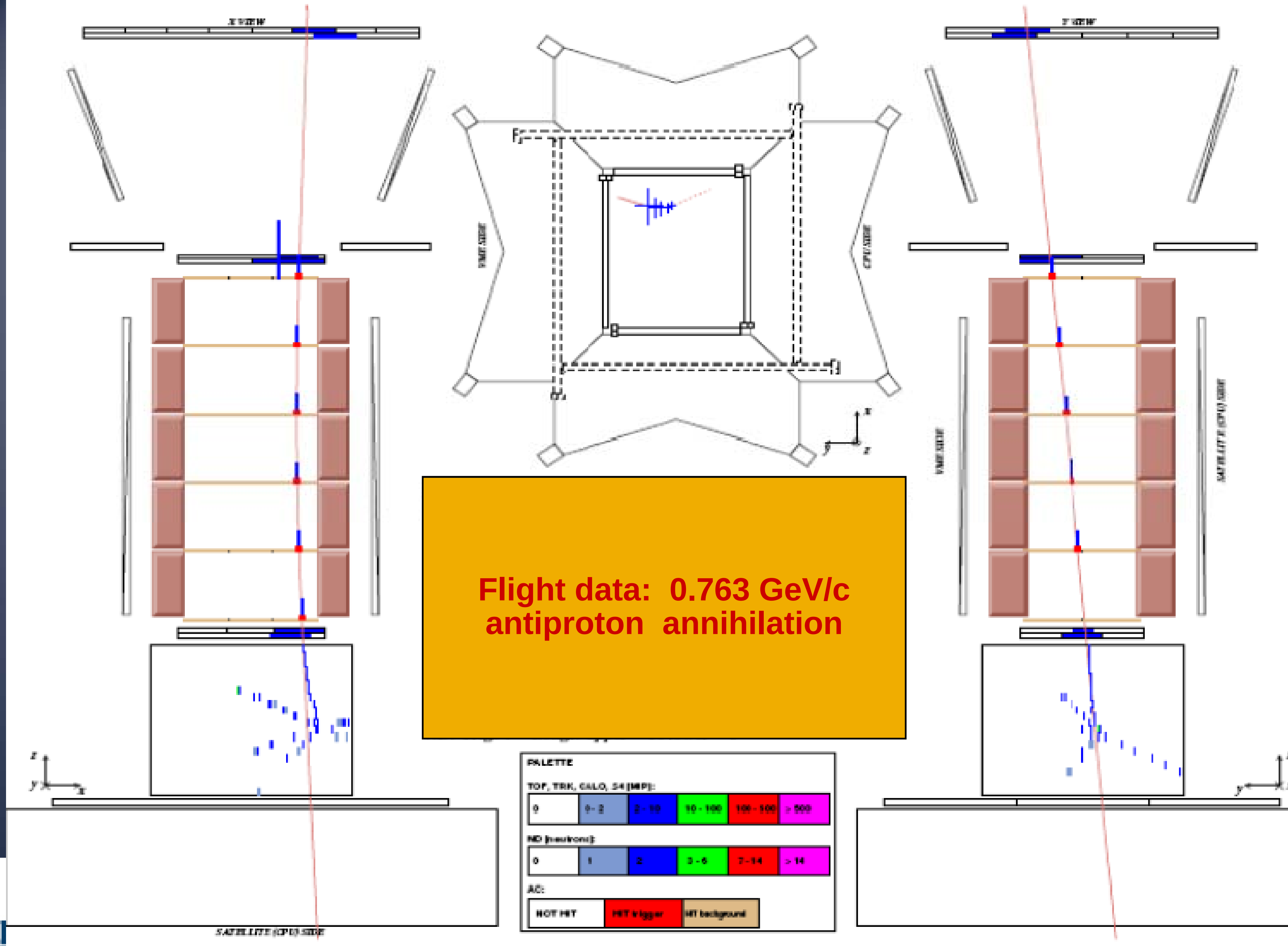
ND [neutrons]:

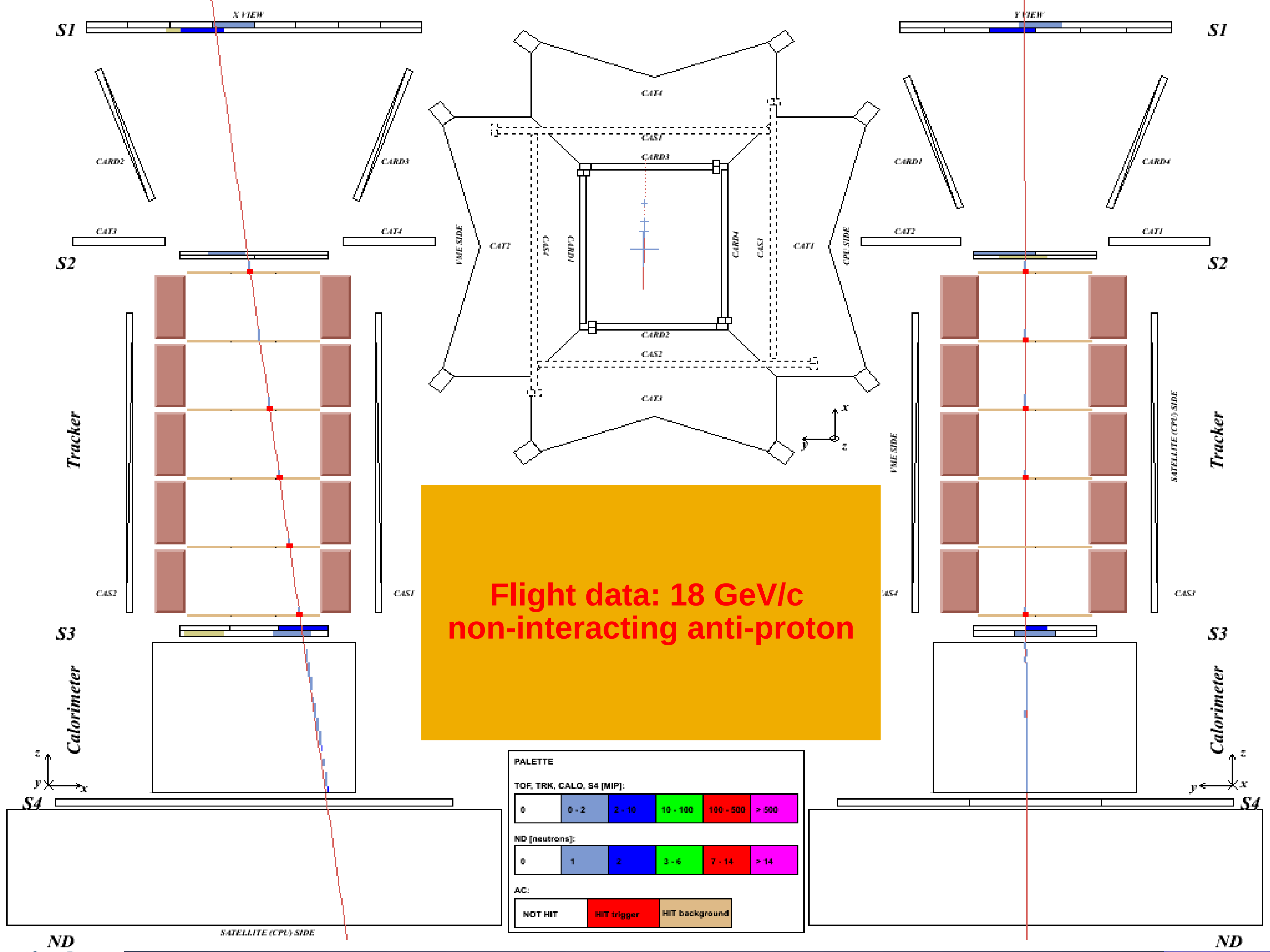
0	1	2	3 - 6	7 - 14	> 14

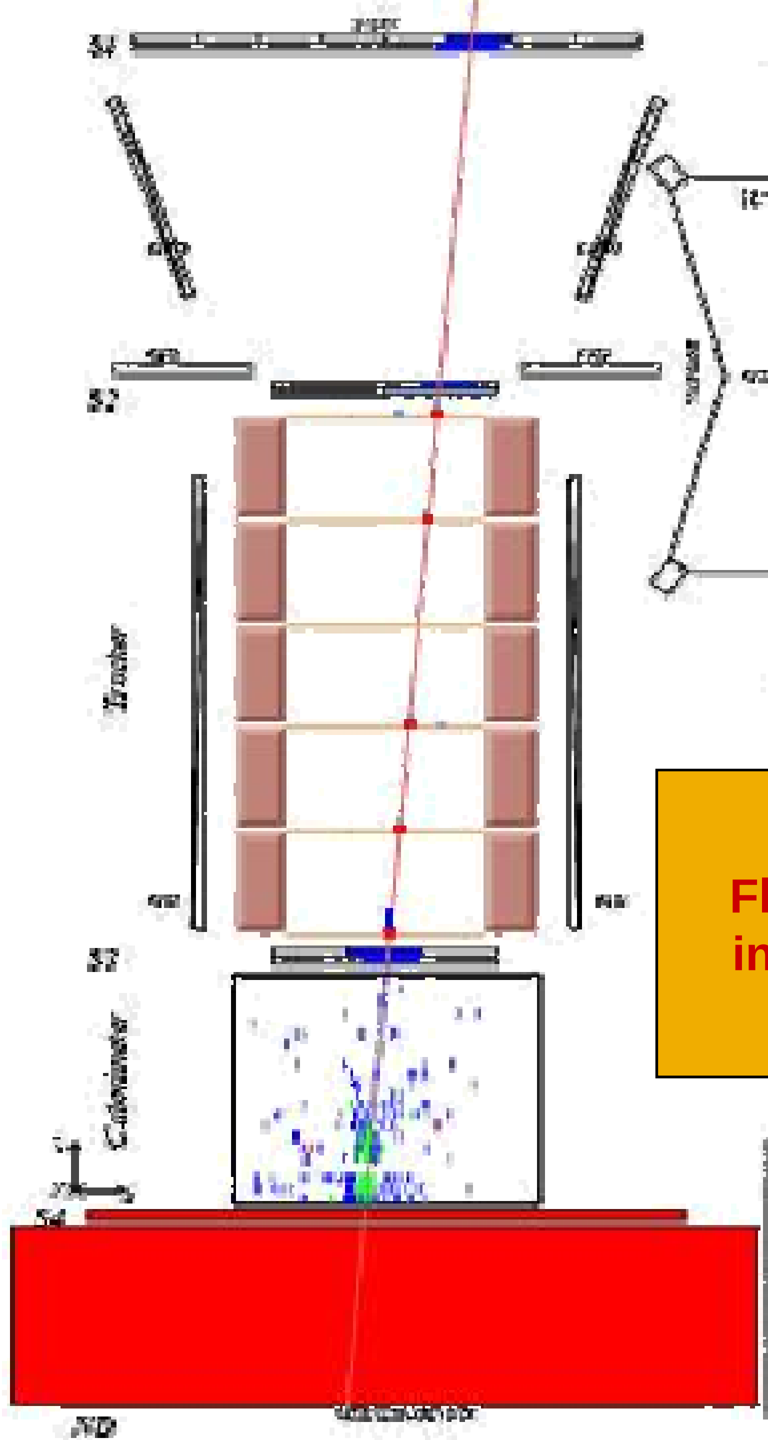
AC:

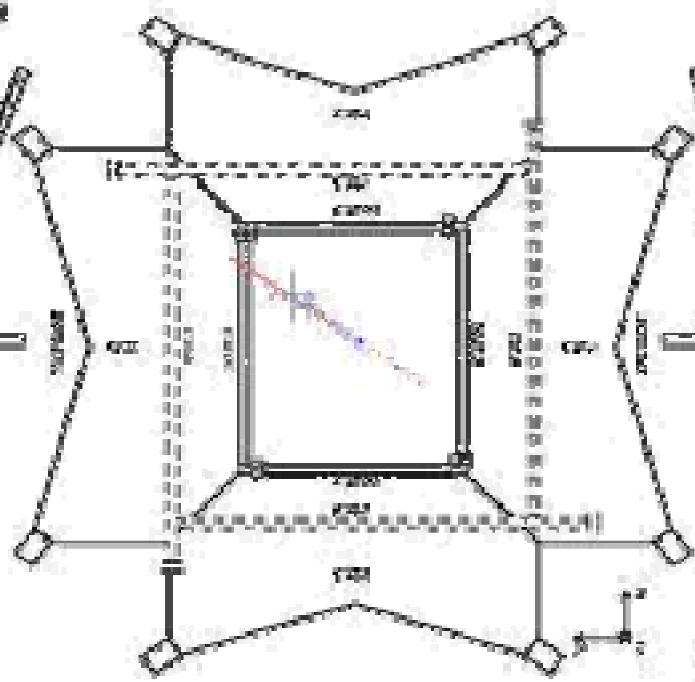
NOT HIT	HIT trigger	HIT background

Flight data: 0.763 GeV/c antiproton annihilation

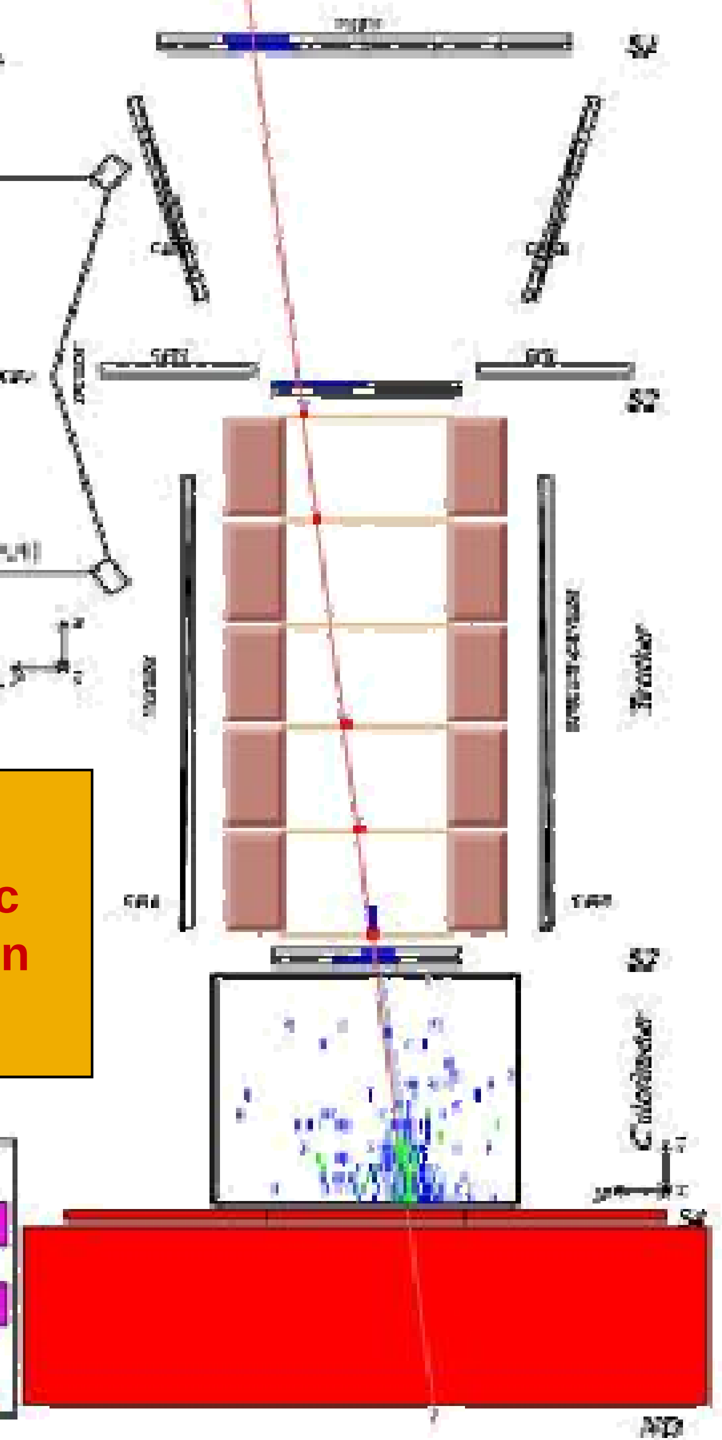


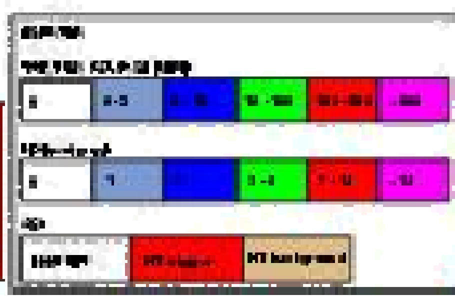

Flight data: 18 GeV/c
non-interacting anti-proton
X VIEW
Y VIEW
S1
S2
S3
S4
ND
Tracker
Calorimeter
CARD1
CARD2
CARD3
CARD4
CAT1
CAT2
CAT3
CAT4
CAS1
CAS2
CAS3
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 -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

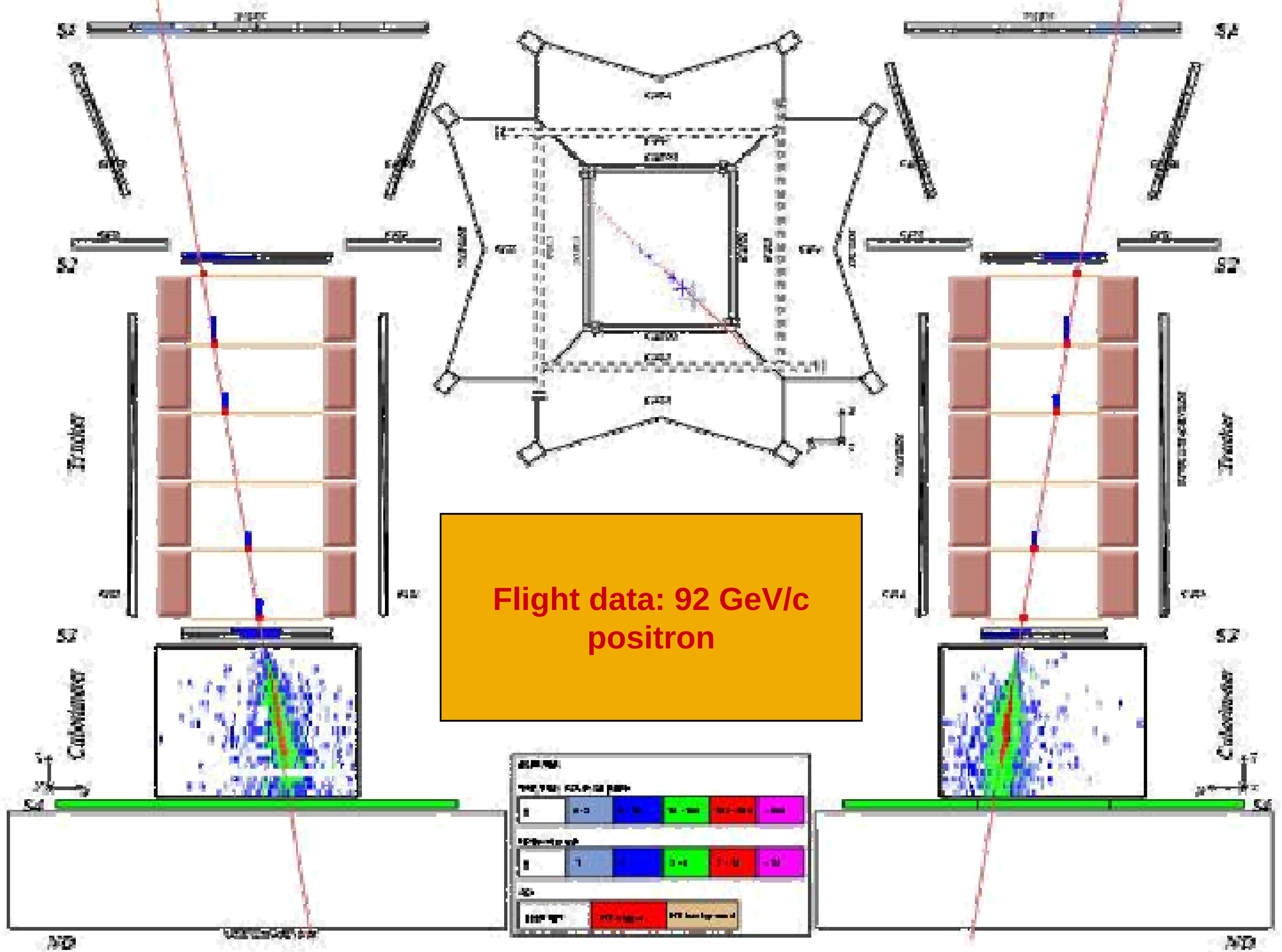


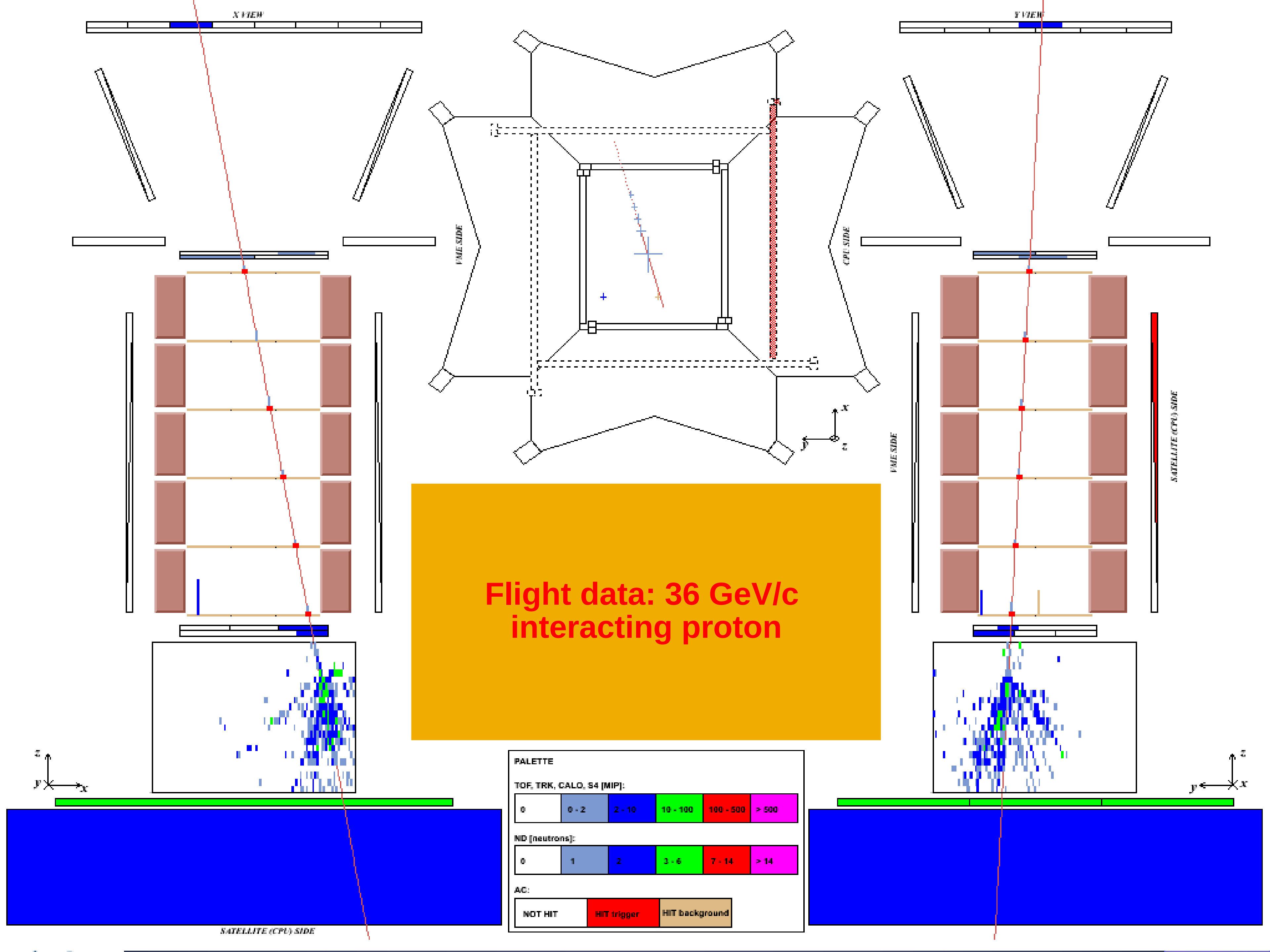


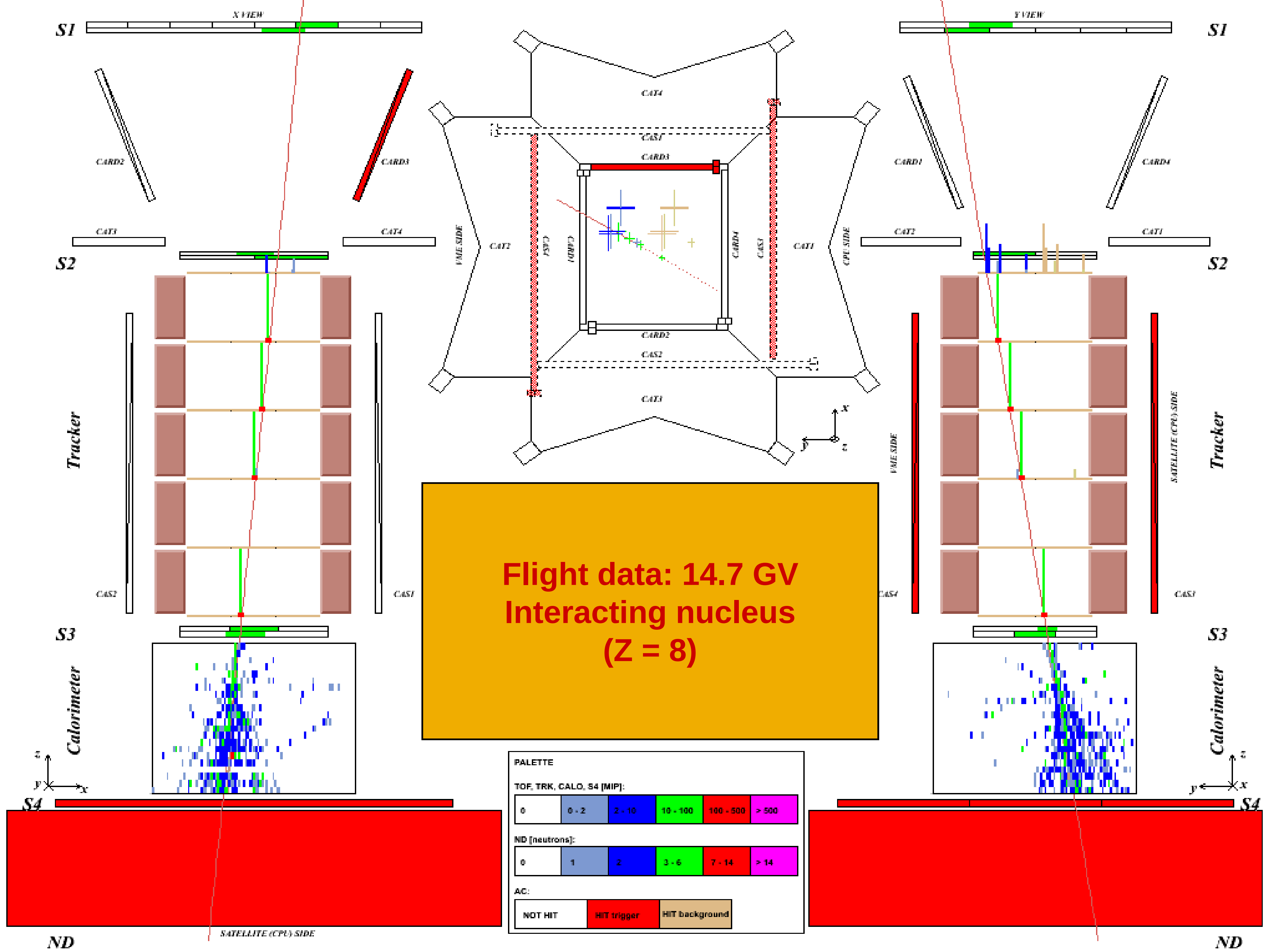
Flight data: 84 GeV/c interacting antiproton






S1
S2
S4
ND
Tracker
Calorimeter
Flight data: 92 GeV/c positron


X VIEW
Y VIEW
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
Flight data: 36 GeV/c
interacting proton
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



Flight data: 14.7 GV
Interacting nucleus
(Z = 8)
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
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

Matter in the Universe

Microwave Anisotropy
WMAP - NASA - Explorer Mission →

$$\Omega_{total} = \frac{\rho_{total}}{\rho_{crit.}} = 1$$

(Universe is flat)

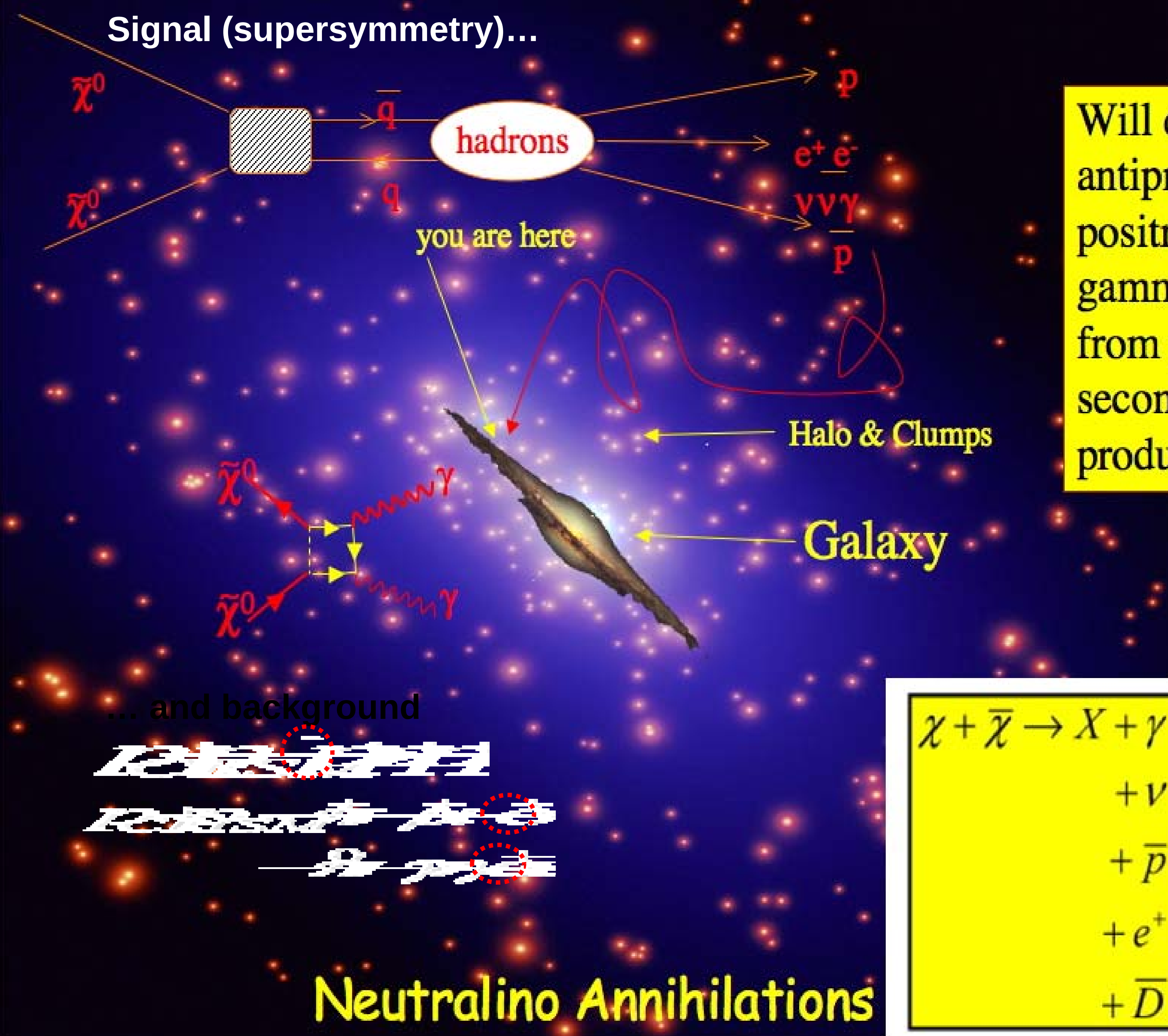
$$\rho_{crit.} = \frac{3H^2(t)}{8\pi G}$$

$$\Omega_{total} = \Omega_{total,baryon.} + \Omega_{dyn.} + \Omega_{required}$$

baryonic matter	**dark matter**	**dark energy**
4%	23%	73%
	??	???
stars, galaxies	candidates:	quintessence

Dark matter candidates:

- WIMPs
- Q-balls
- axions
- Kaluza-Klein-part.



Will distort the antiproton positron and gamma spectra from purely secondary production

$$\chi + \bar{\chi} \to X + \gamma$$ (GLAST AMS-02)

$$+\nu$$ (AMANDA / IceCube)

$$+\bar{p}$$

$$+e^+$$

$$+\bar{D}$$

PAMELA (and Bess, HEAT, AMS etc.)

UED models: Kaluza-Klein dark matter

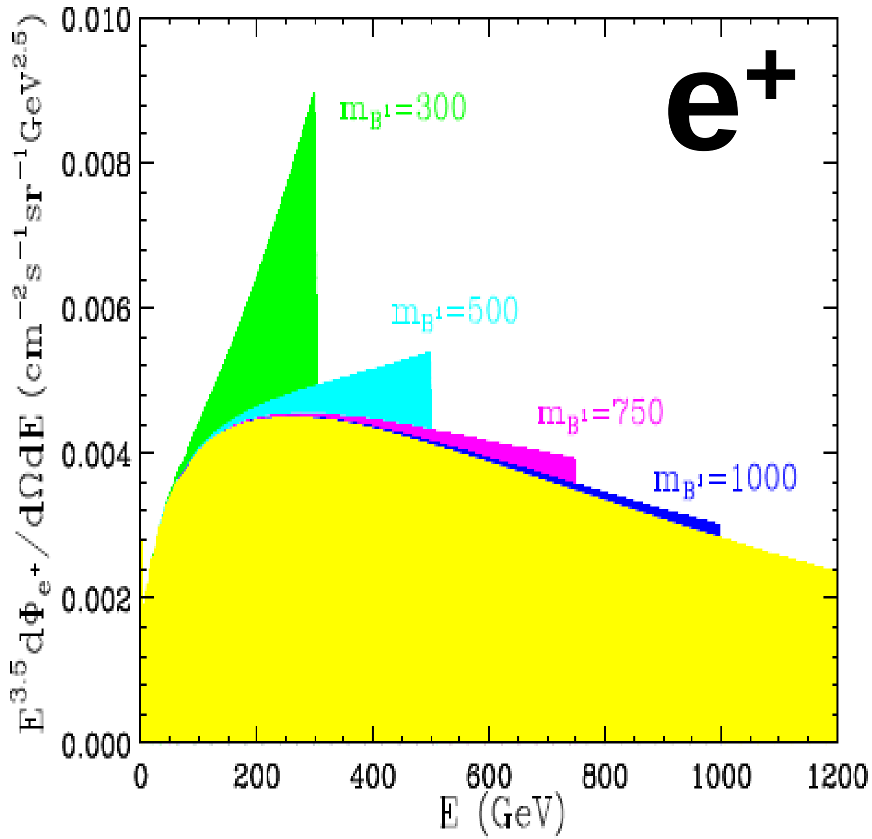


FIG. 2: Predicted positron signals (dark shaded) above background (light shaded) as a function of positron energy for $m_{B^1} = m_{e^1_L} = m_{e^1_R} = 100$, 500, 750, and 1000 GeV.

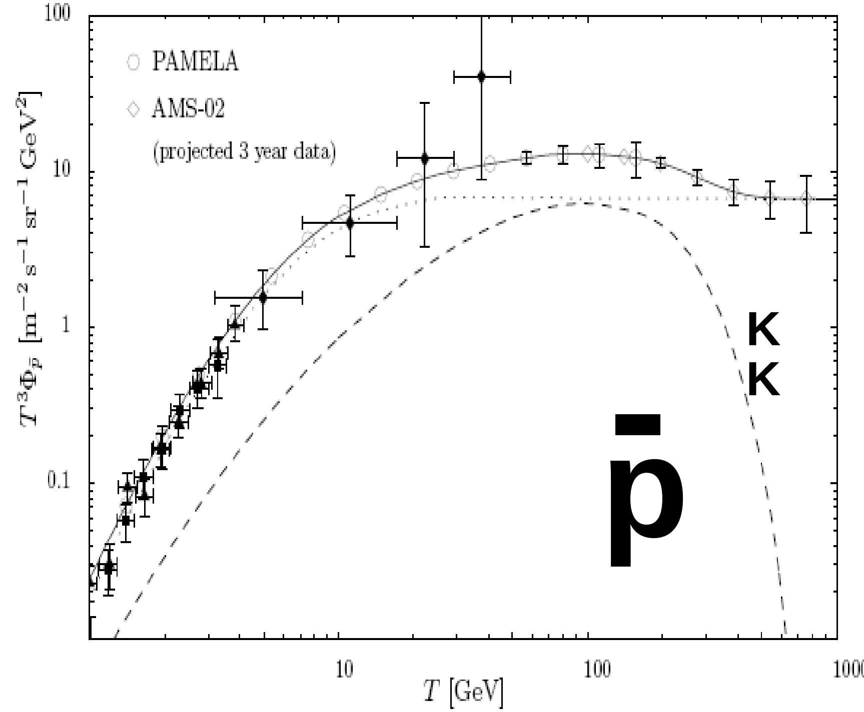
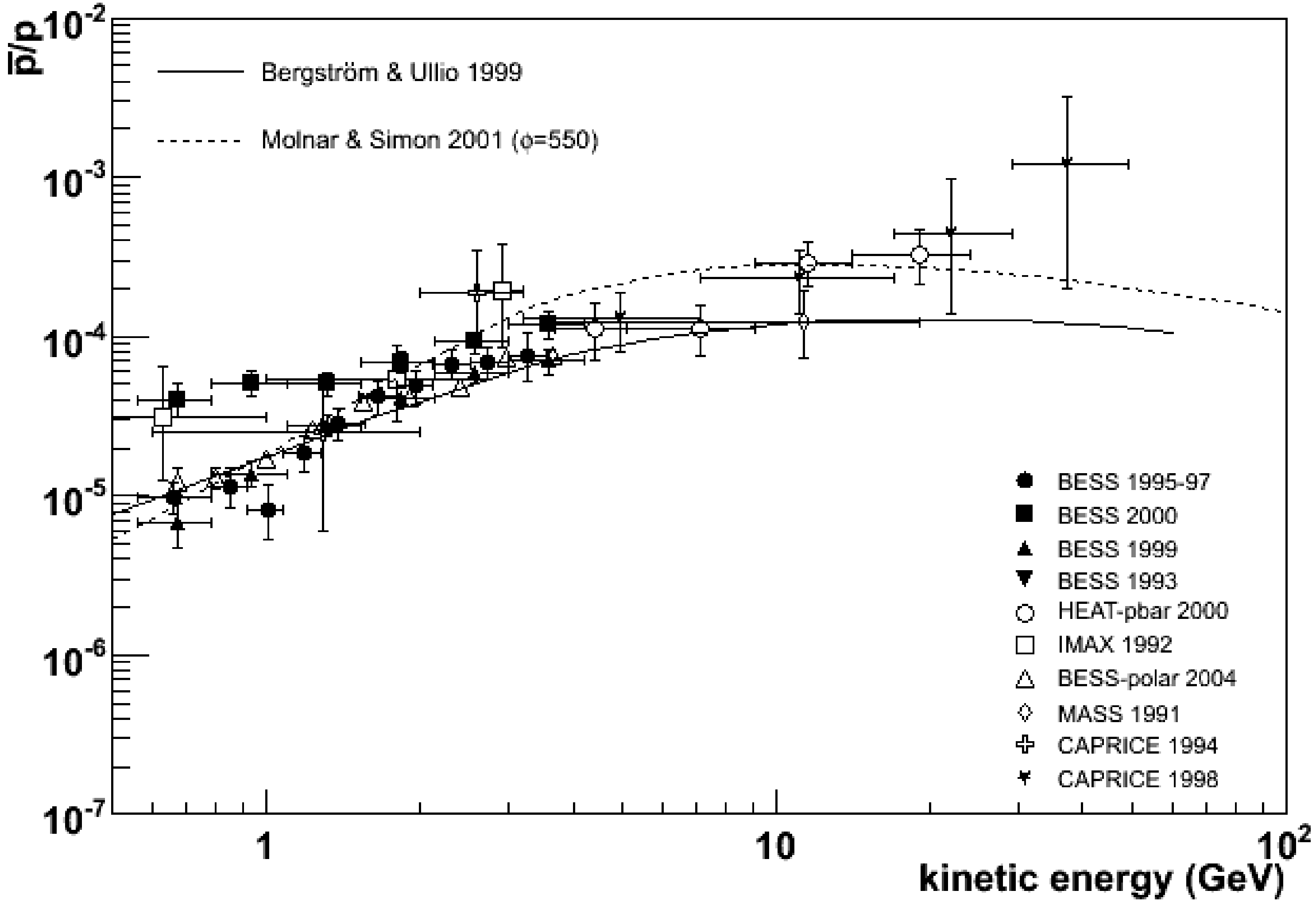


Figure 4. The solid line shows the expected antiproton spectrum for the case of a clumpy NFW profile with $f\delta = 200$ and $m_{B^{(1)}} = 800$ GeV; the dotted and dashed lines give, respectively, the background flux and the contribution from LKP annihilations alone. The data points are the same as those of Fig. 2; in addition, the detectional prospects of PAMELA [48] and AMS-02 [49] are indicated by displaying their projected data after three years of operation (only statistical errors are included; error bars smaller than the symbol size are not shown). For AMS-02, only energies above 100 GeV are considered.

Cheng, Feng, Matchev, hep-ph/0207125v2

Bringmann, astro-ph/0506219v2

Antiproton-Proton Ratio

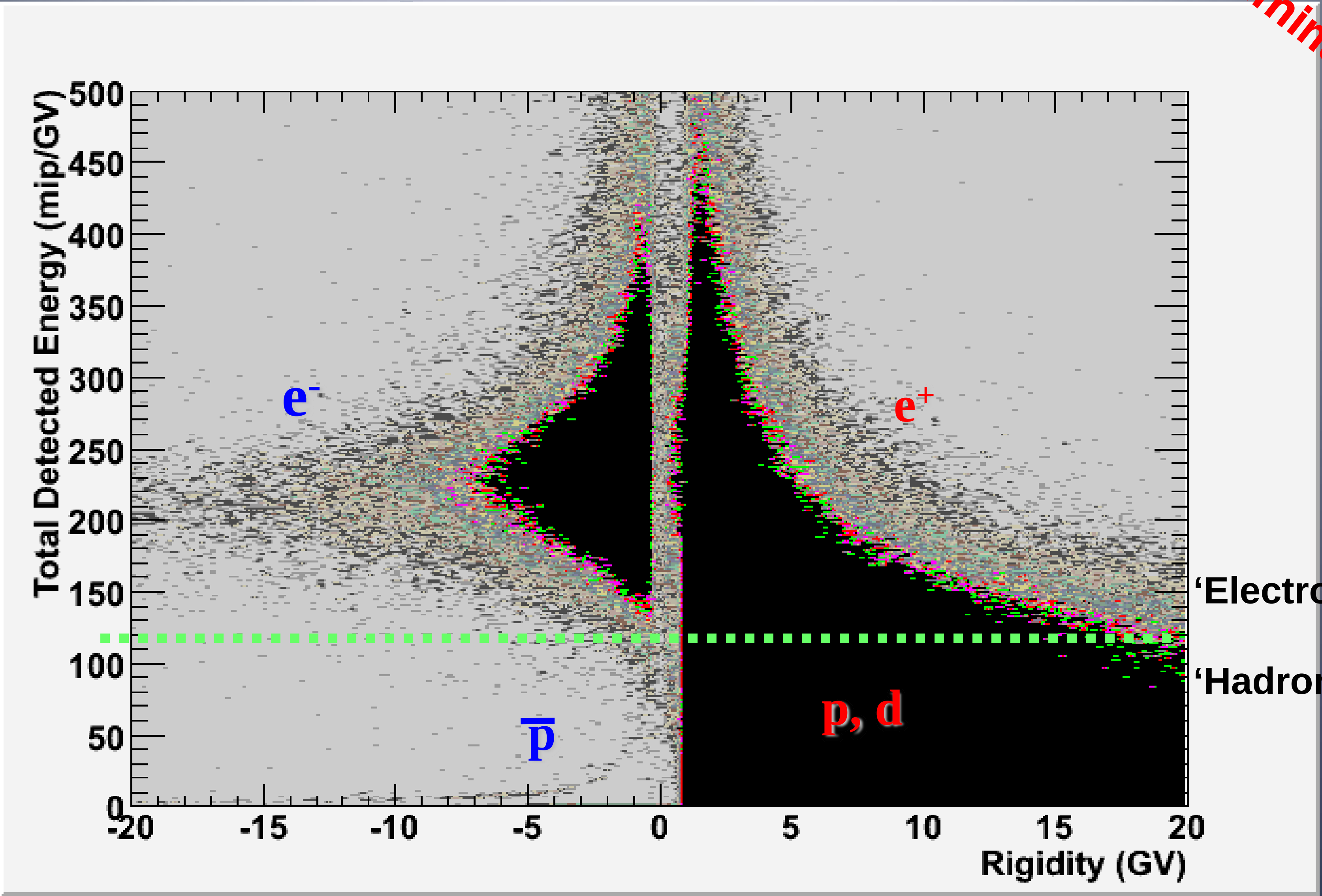


PAMELA Status and Antiprotons

- Till 2nd of March 2008 PAMELA has collected ~ 8.8TB of data, corresponding to ~ 1×10^9 triggers
  - More than 10^7 p and 800 $\bar{p}$ have been identified between 1 and 100 GeV.

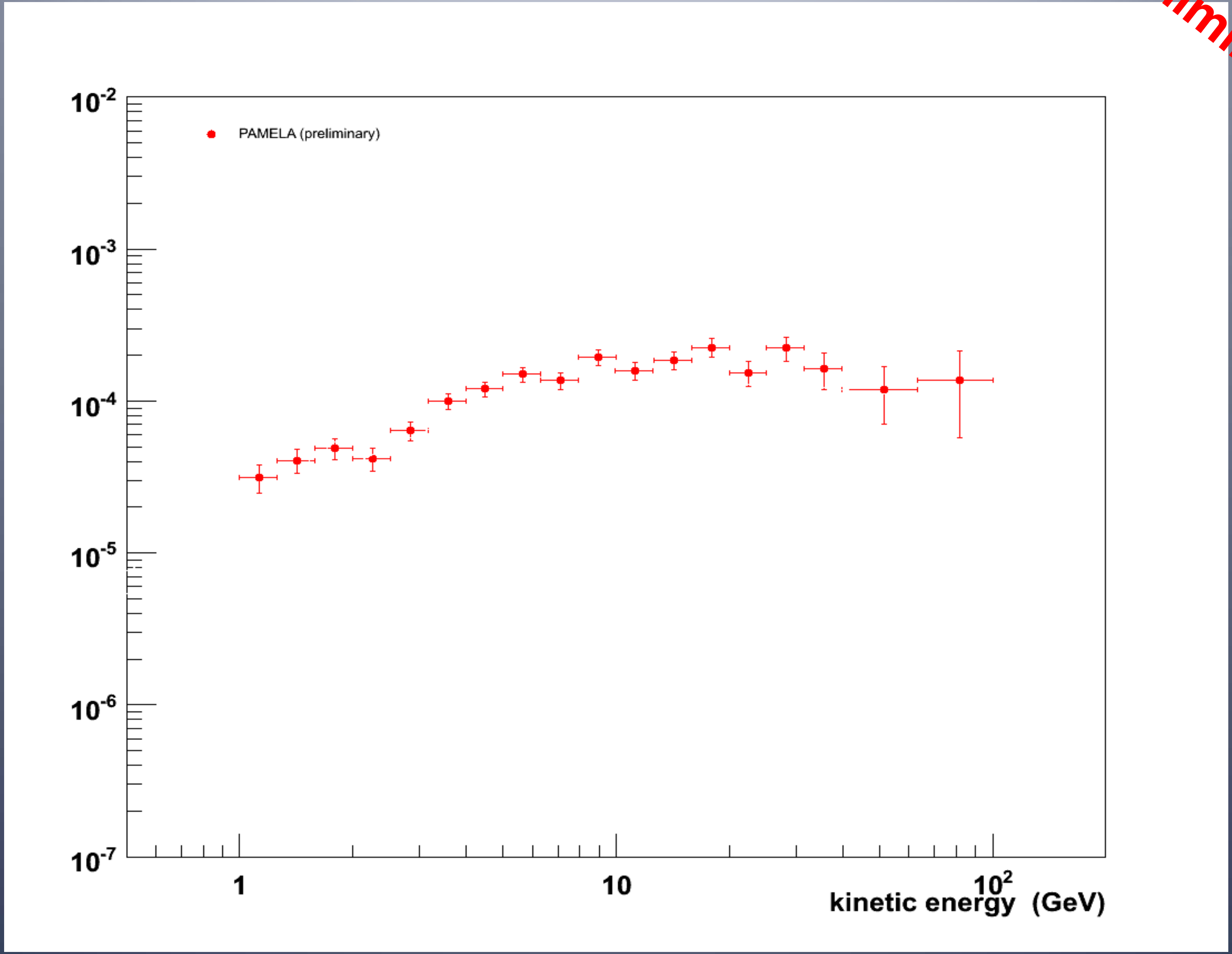
Antiparticle selection

Preliminary



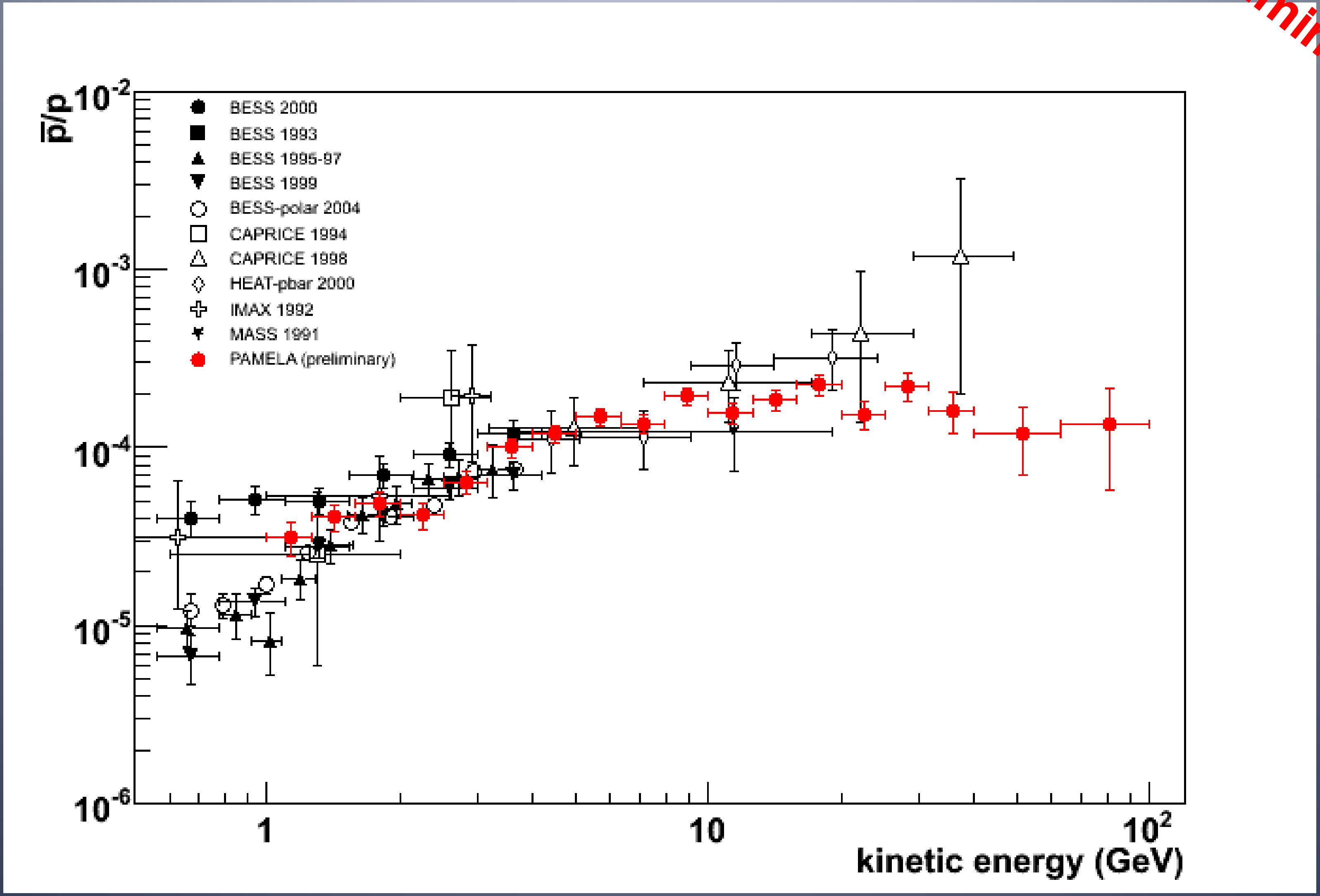
Antiproton-Proton Ratio

Preliminary



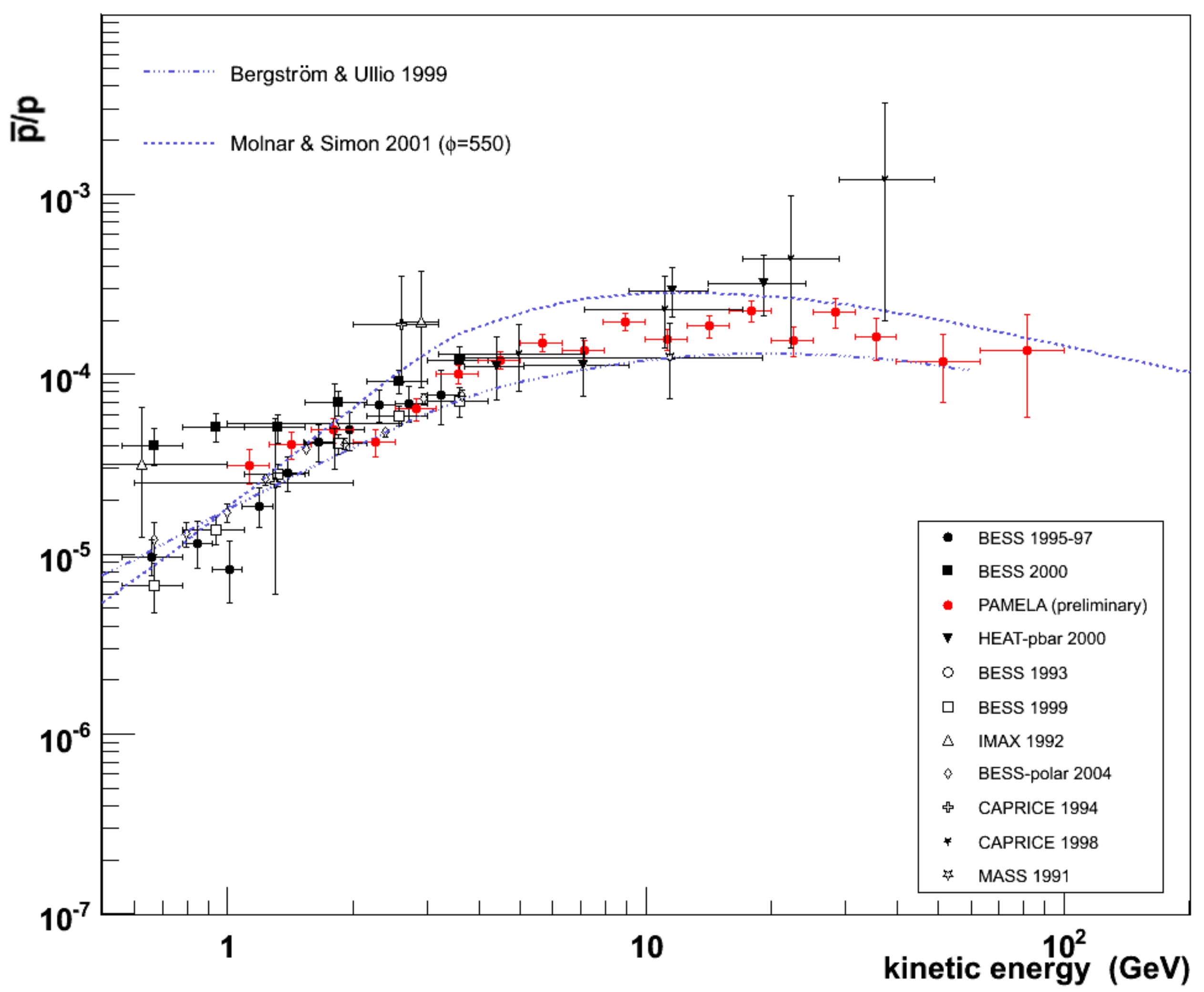
Antiproton to Proton Ratio

Preliminary

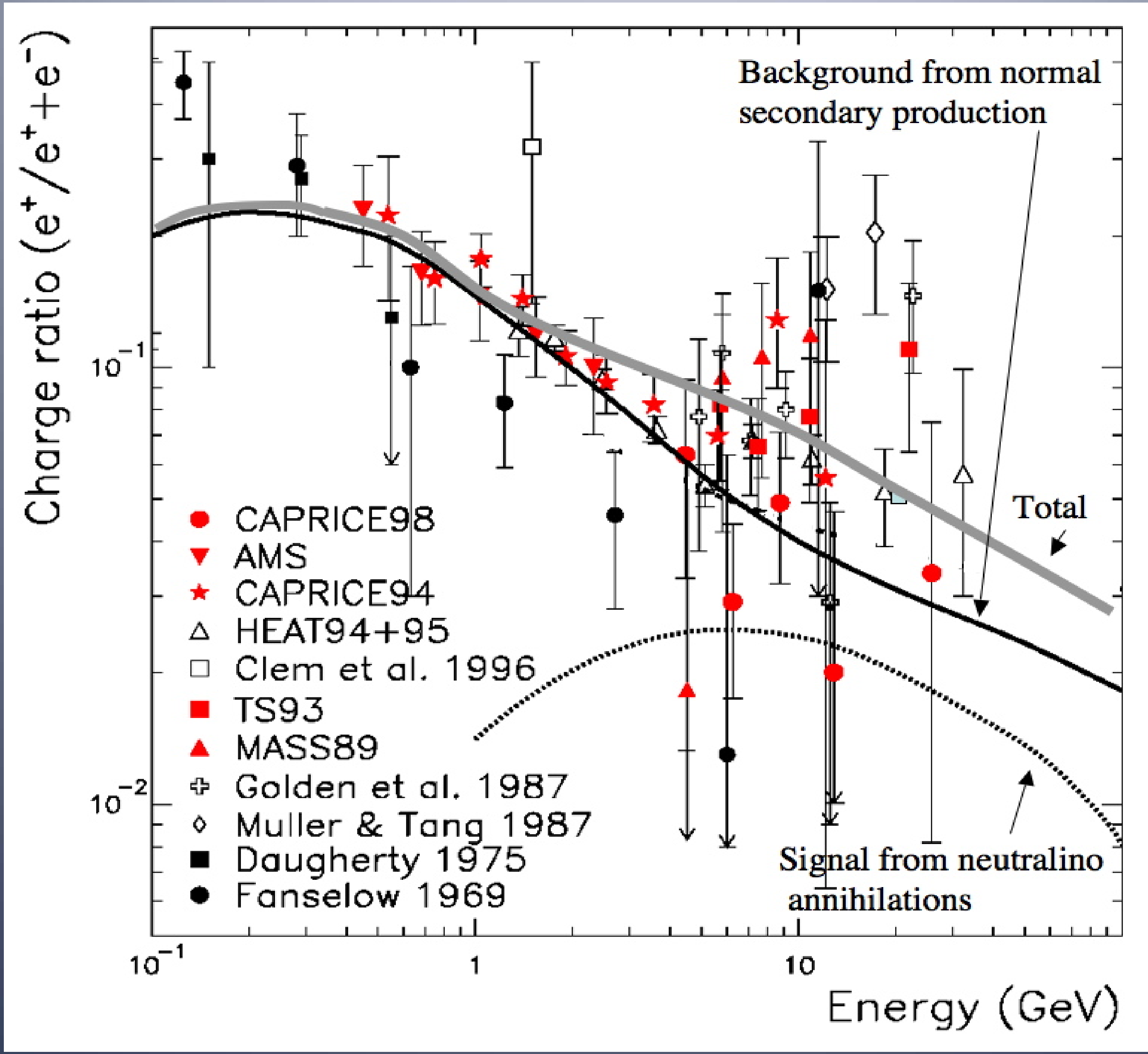


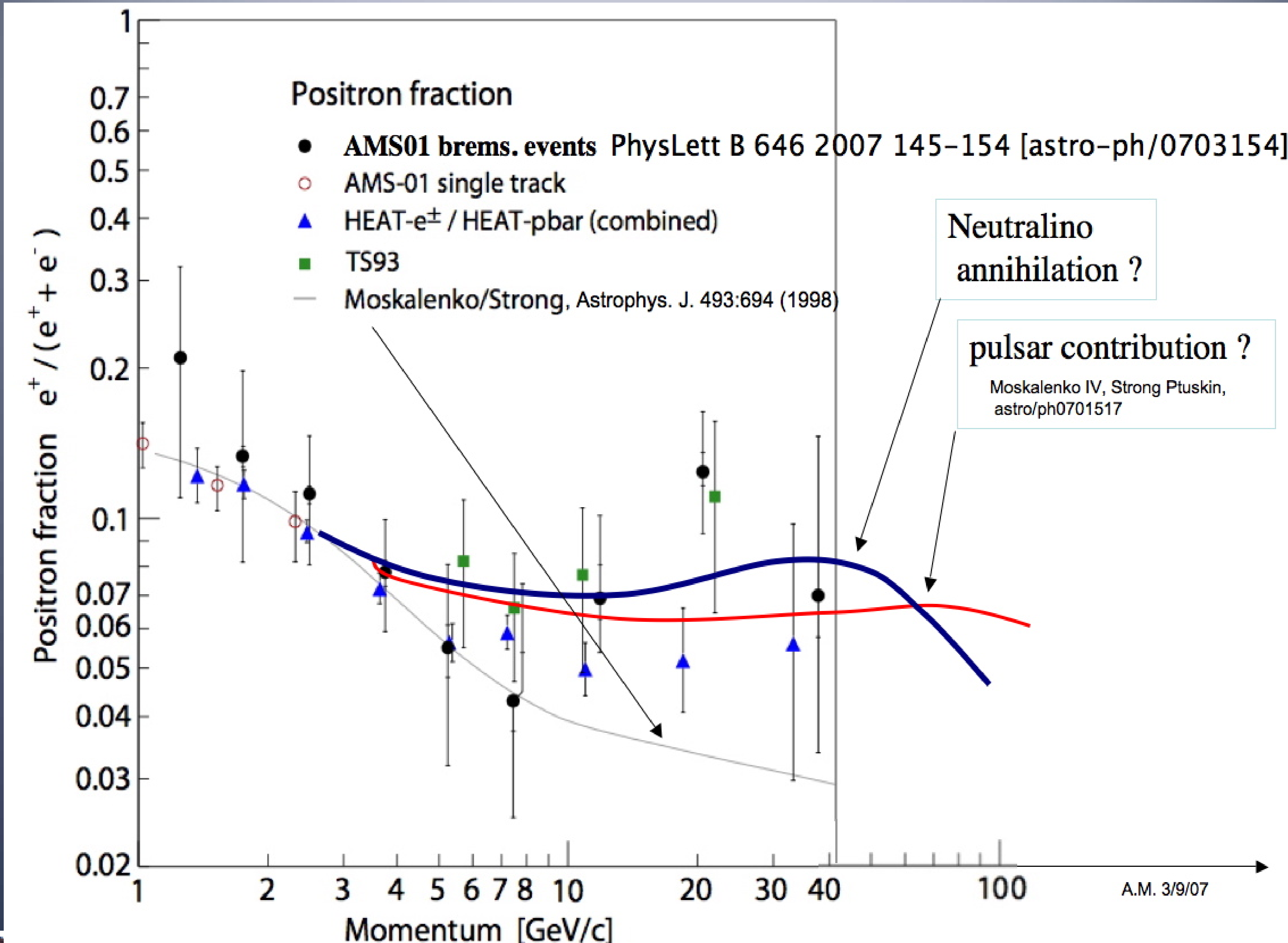
Antiproton to Proton Ratio

Preliminary

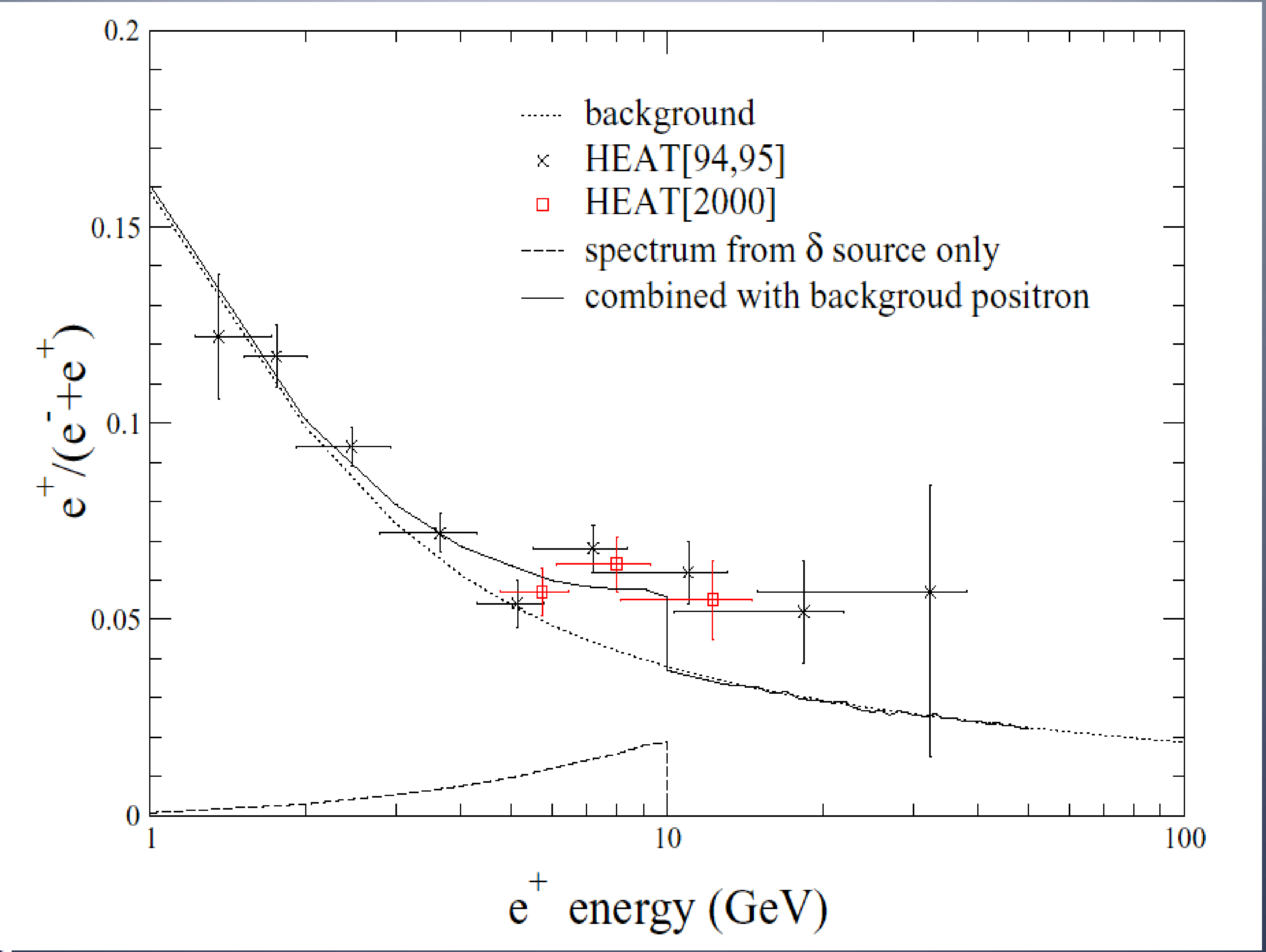


Positron Fraction




Positron fraction
AMS01 brems. events PhysLett B 646 2007 145-154 [astro-ph/0703154]
AMS-01 single track
HEAT-e± / HEAT-pbar (combined)
TS93
Moskalenko/Strong, Astrophys. J. 493:694 (1998)
Neutralino annihilation ?
pulsar contribution ?
Moskalenko IV, Strong Ptuskin, astro/ph0701517
Positron fraction e+/(e+ + e-)
Momentum [GeV/c]
A.M. 3/9/07
1
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.07
0.06
0.05
0.04
0.03
0.02
1 2 3 4 5 6 7 8 10 20 30 40 100

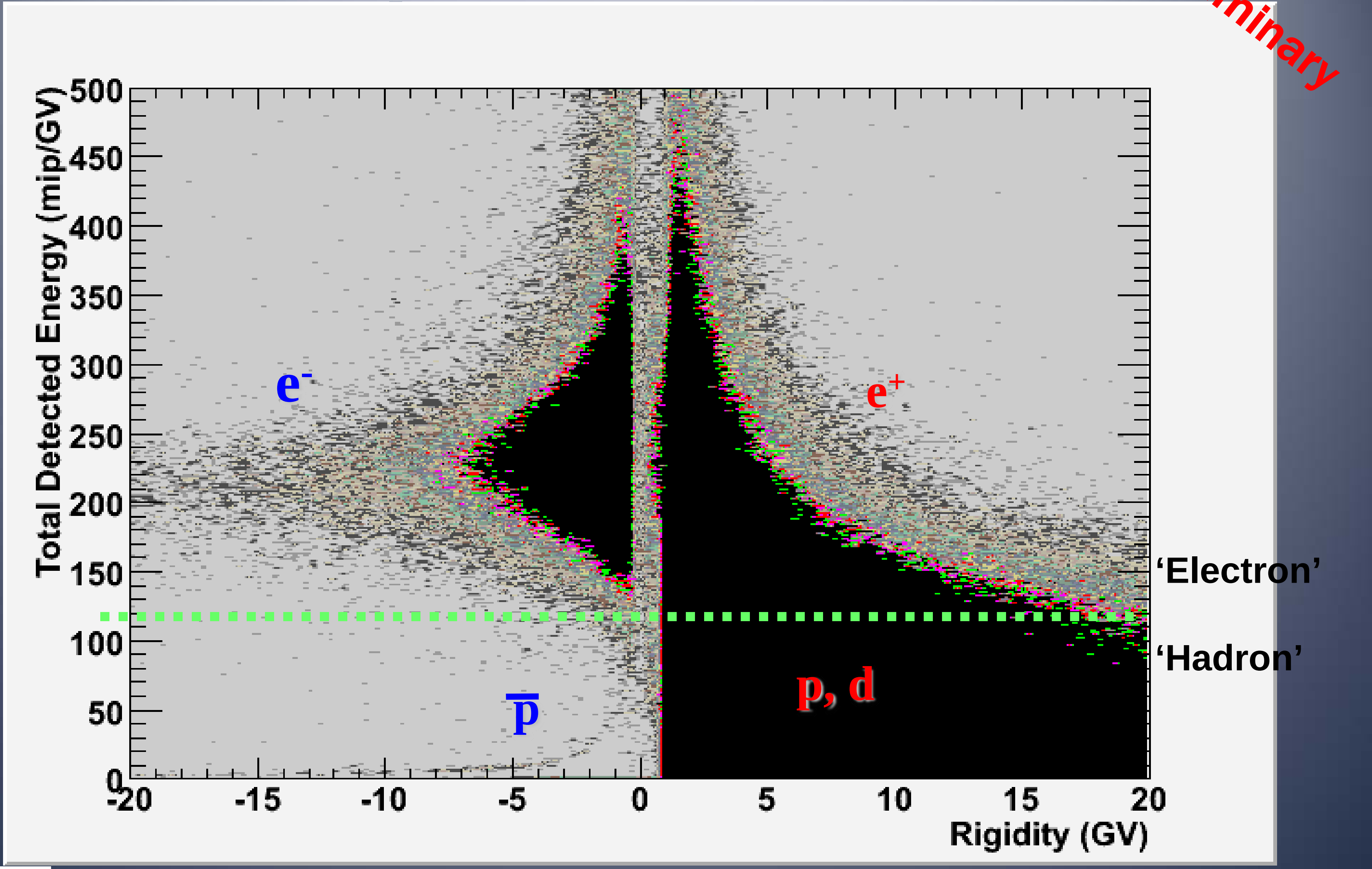
Positrons with HEAT



Pamela Positrons

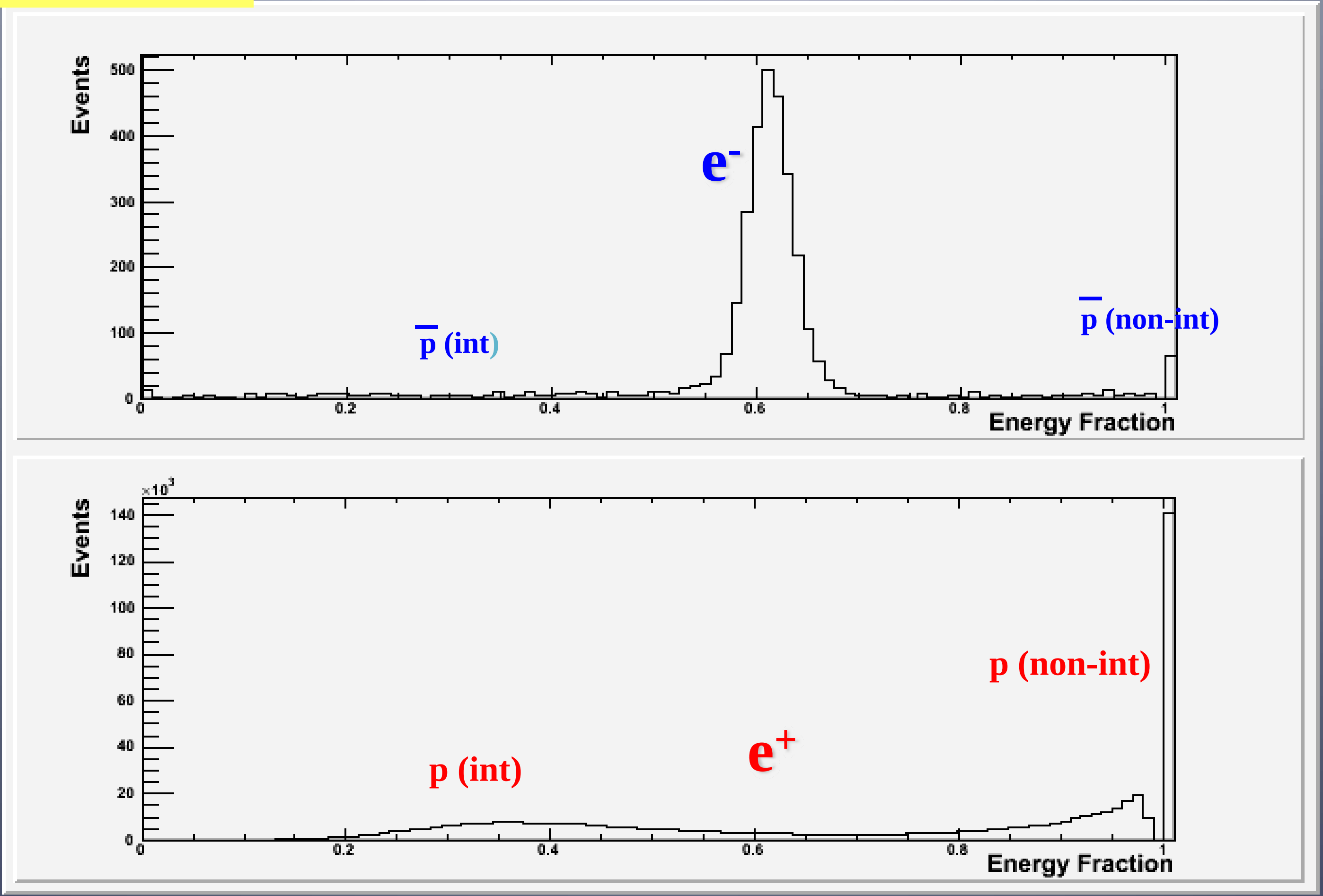
- Till August 30th ~$2x10^5$ e^- and ~ $2x10^4$ e^+ from 200 MeV up to 10 GeV have been identified
- About 15000 positrons over 1 GeV
- Other eight months data yet to be analyzed

Antiparticle selection



Positron selection with calorimeter

Rigidity: 20-30 GV

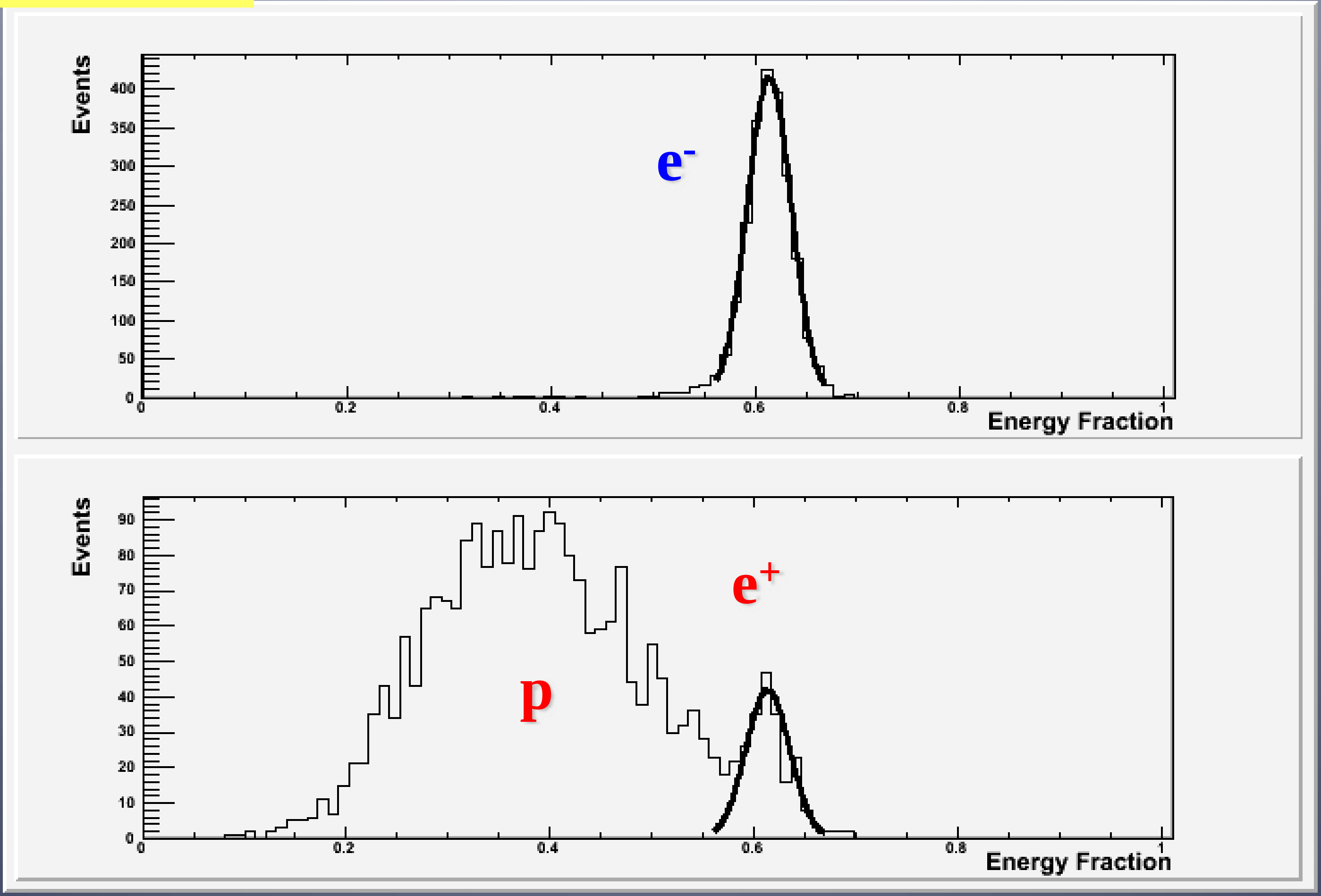


Preliminary

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

Positron selection with calorimeter

Rigidity: 20-30 GV

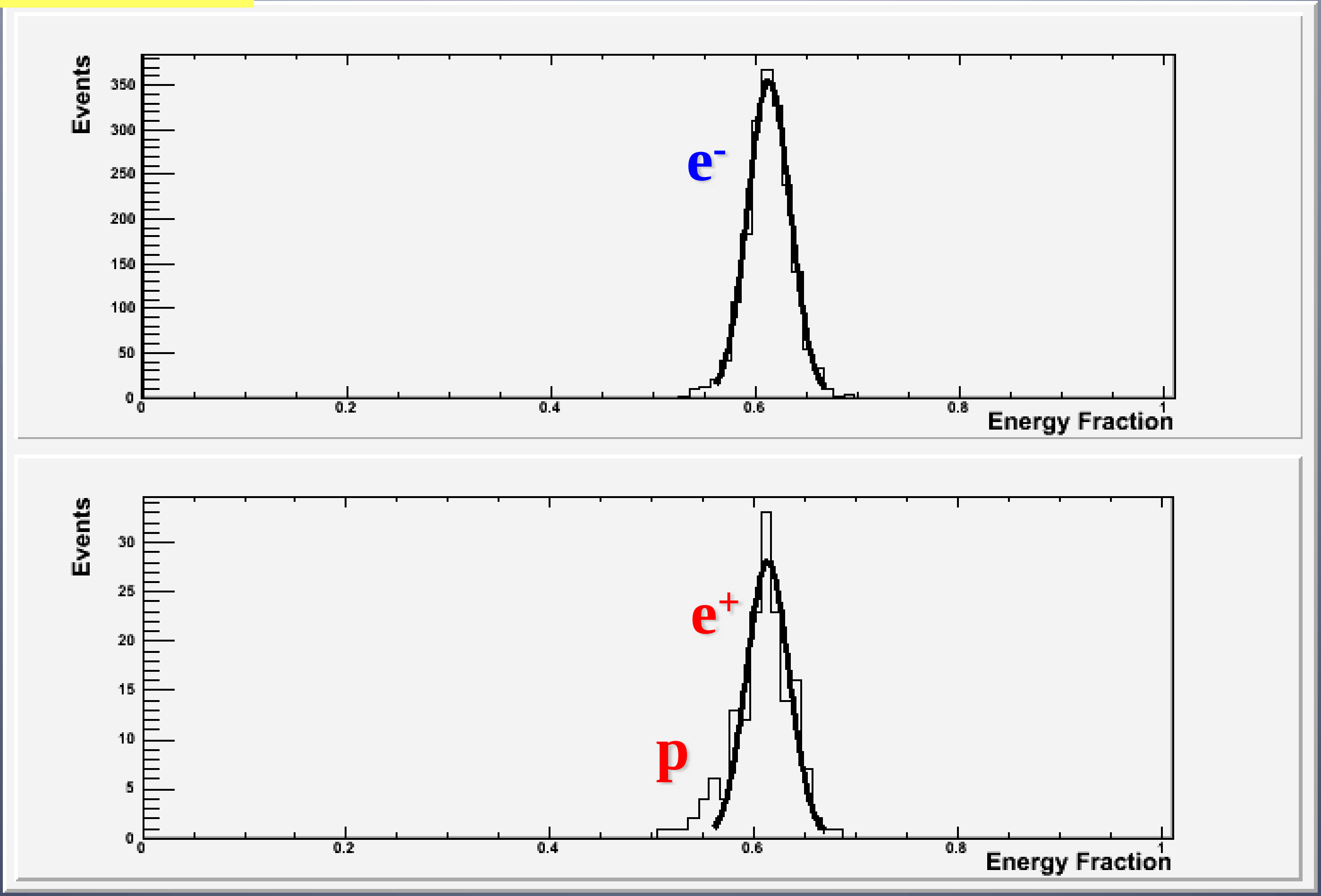


Preliminary

Fraction of charge released along the calorimeter track (left, hit, right) **+** Energy-momentum match

Positron selection with calorimeter

Rigidity: 20-30 GV



Preliminary

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

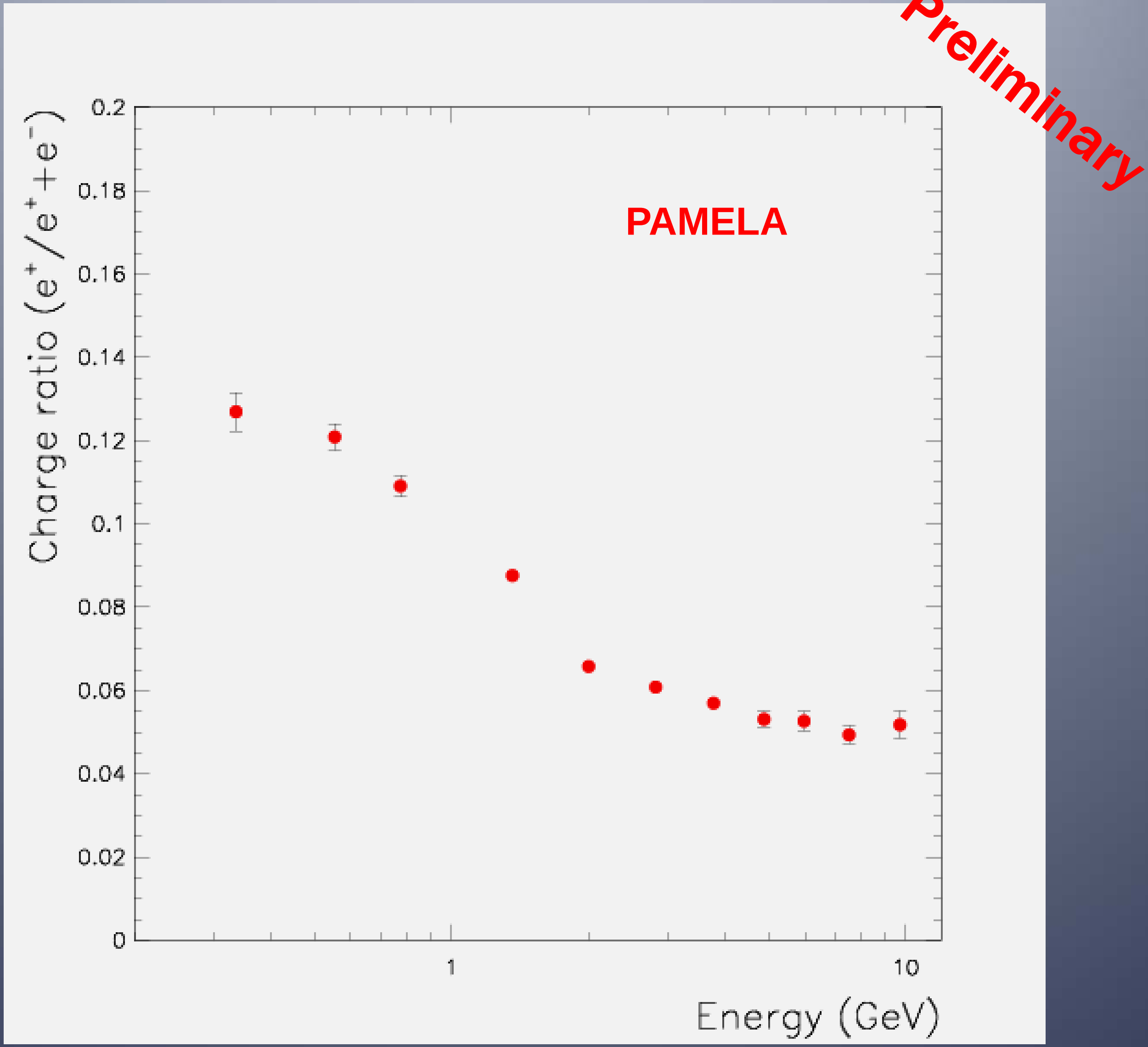
+

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

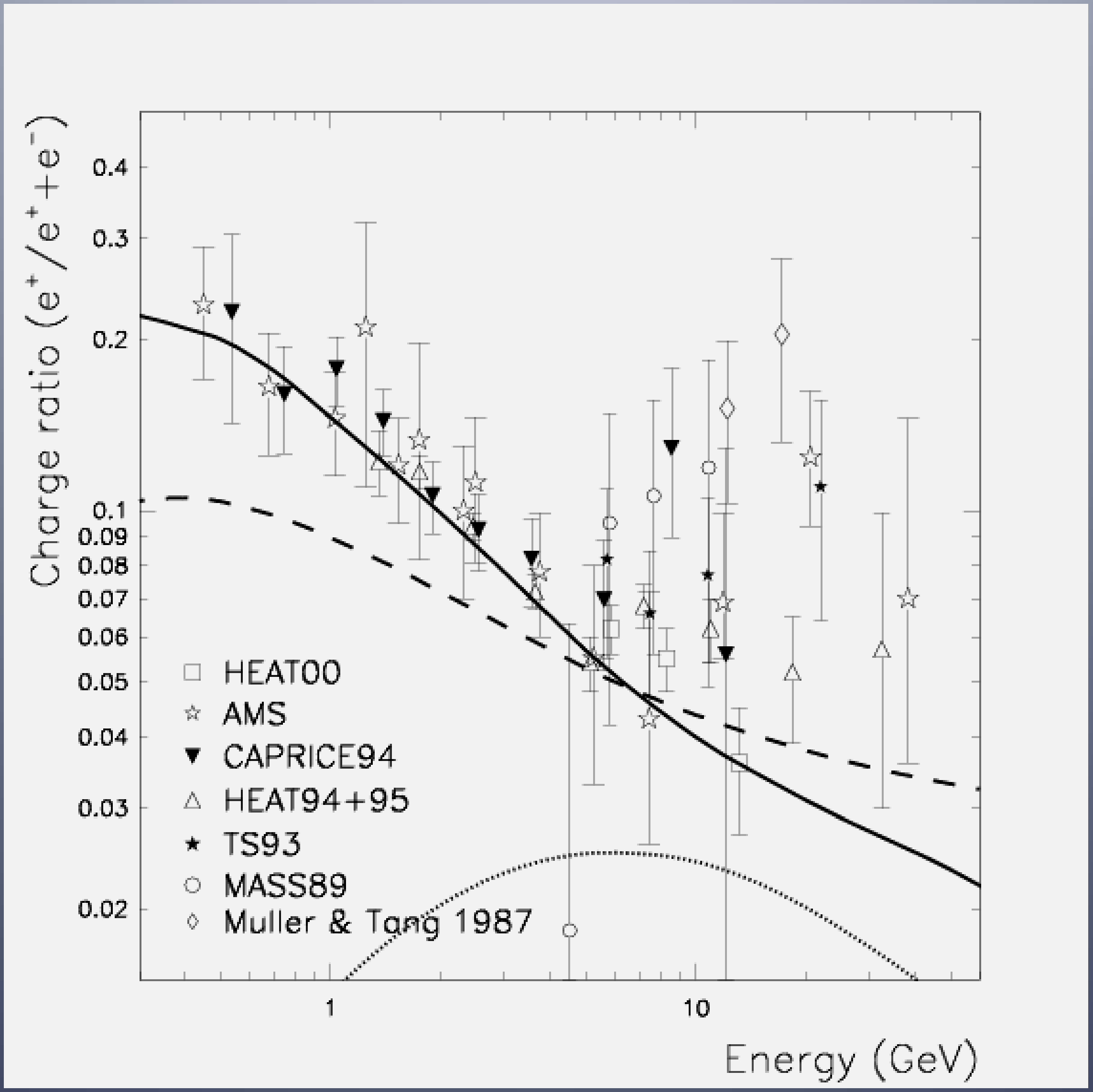
PaMeLa

INFN Istituto Nazionale di Fisica Nucleare

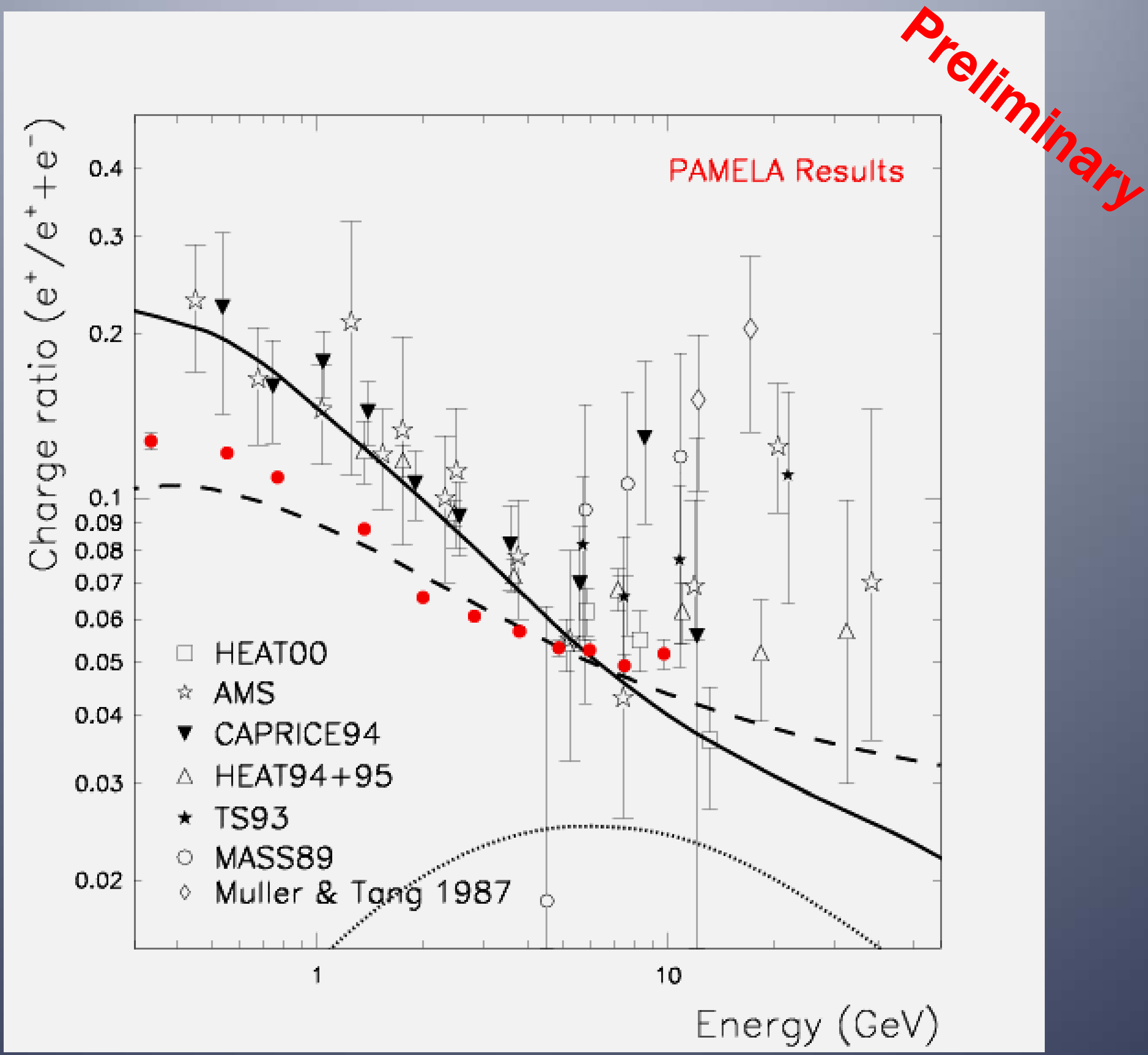
Positron - Electron ratio



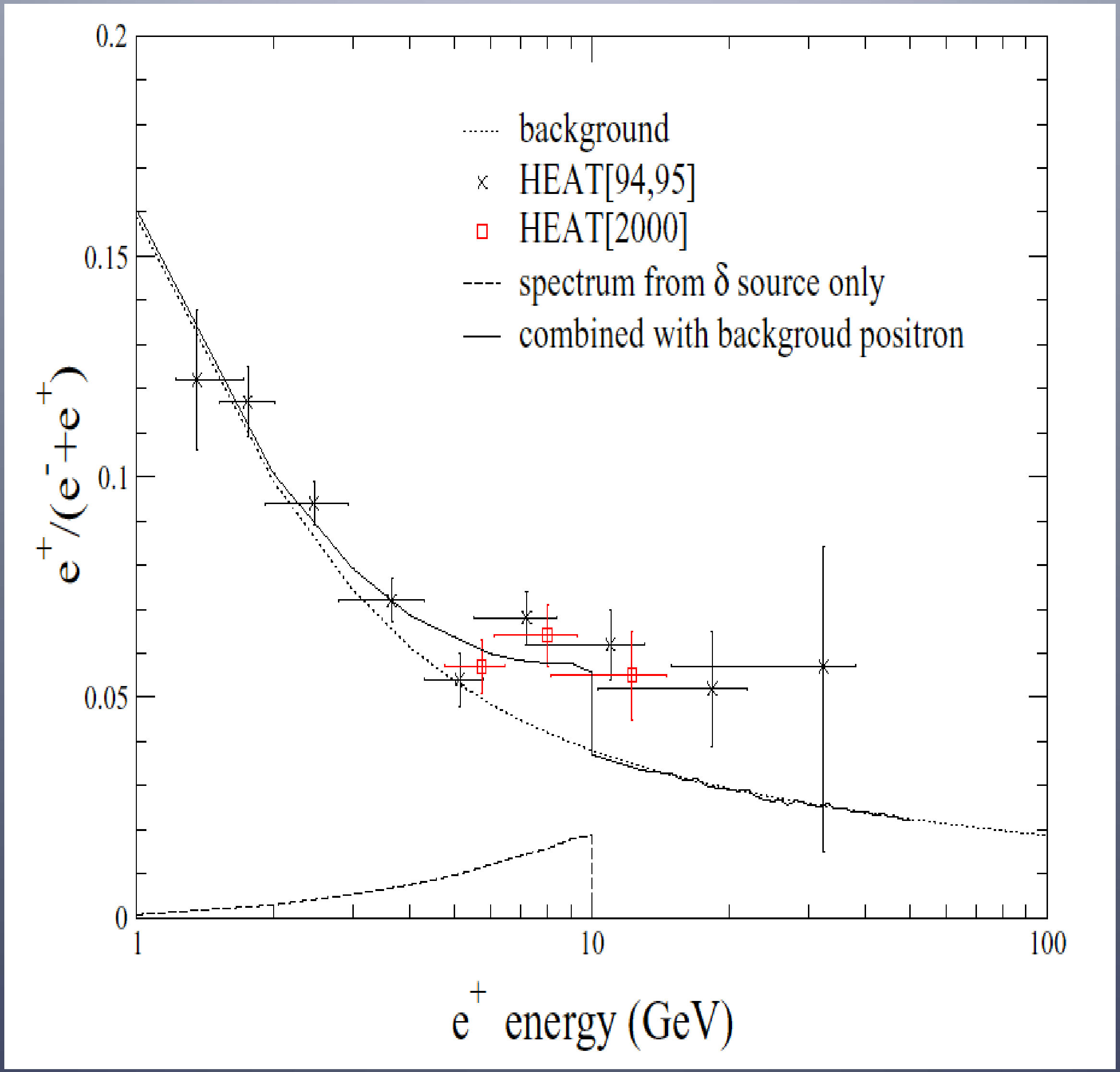
Positron - Electron ratio



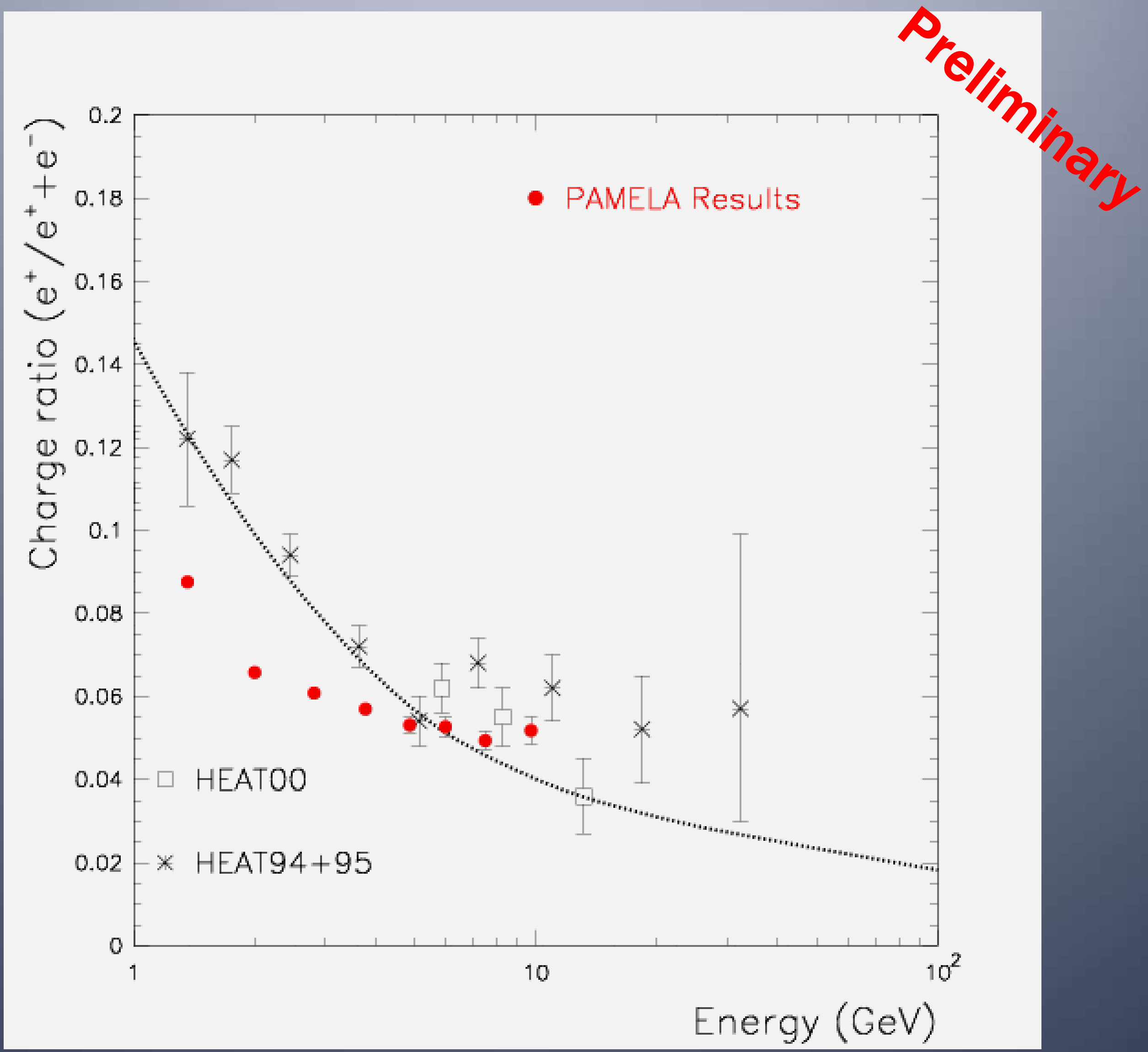
Positron - Electron ratio



Positrons with HEAT



Positrons with HEAT & PAMELA

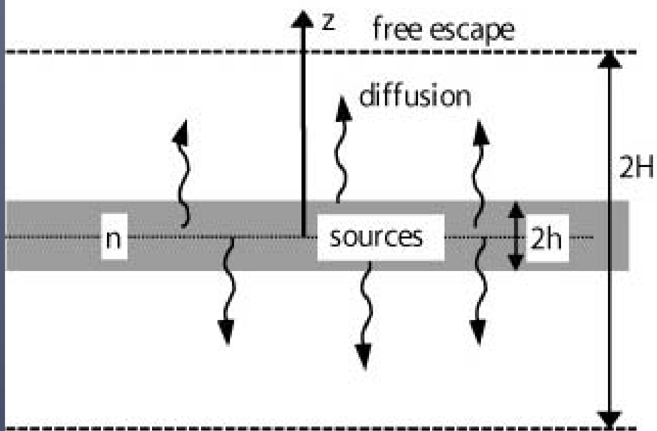


Problems

- ✓ **Background calculation**
- ✓ **Solar Modulation at low energies**
- ✓ **Charge-sign dependence of solar modulation**

Diffusion Halo Model

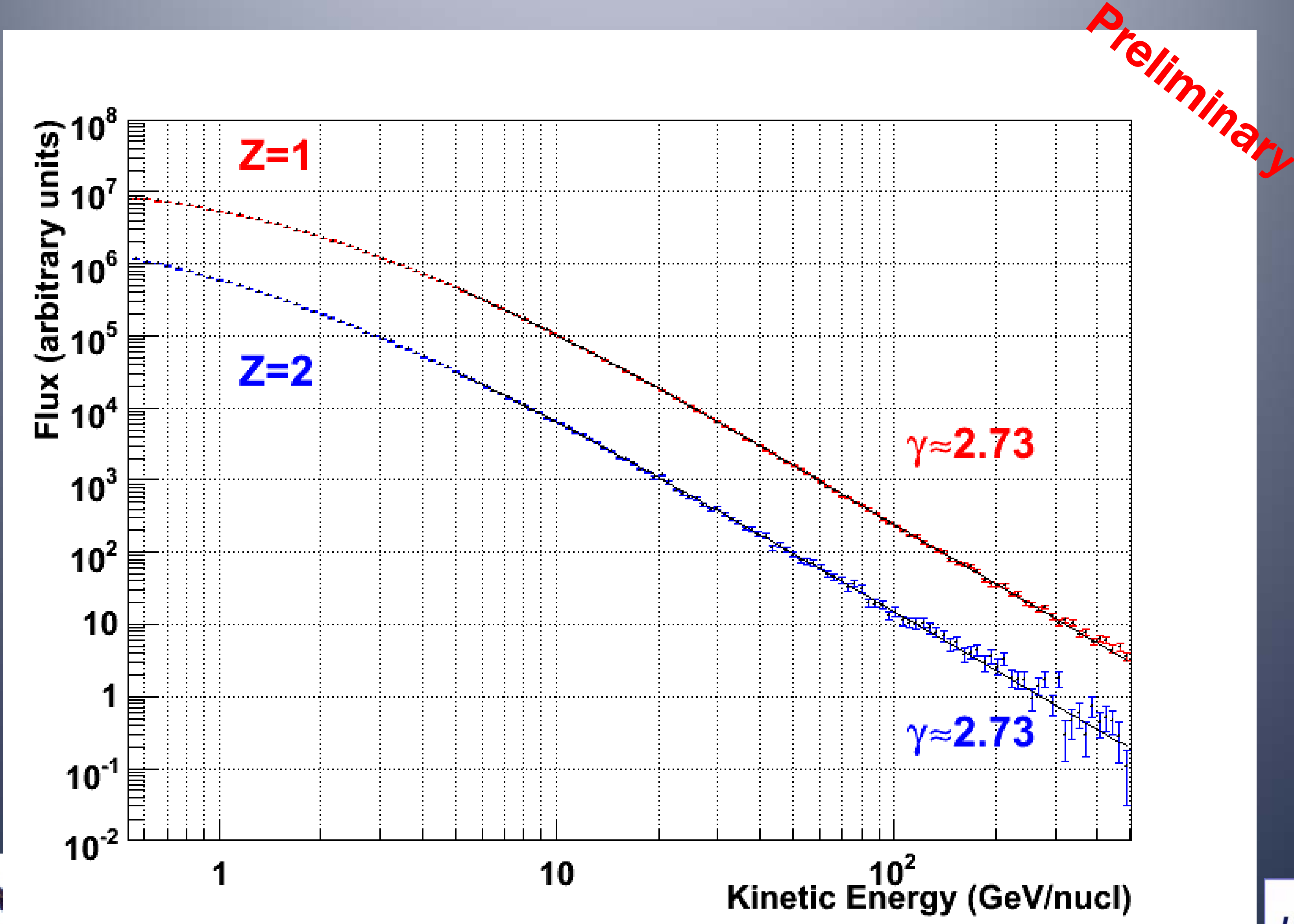
$$\frac{\partial N_i(E,z,t)}{\partial t} = \underbrace{D(E)\cdot\frac{\partial^2}{\partial z^2}N_i(E,z,t)}_{\text{diffusion}} - \underbrace{N_i(E,z,t)\left\{\frac{1}{\tau_i^{\text{int}}(E,z)}+\frac{1}{\gamma(E)\tau_i^{dec}}\right\}}_{\text{interaction and decay}}$$



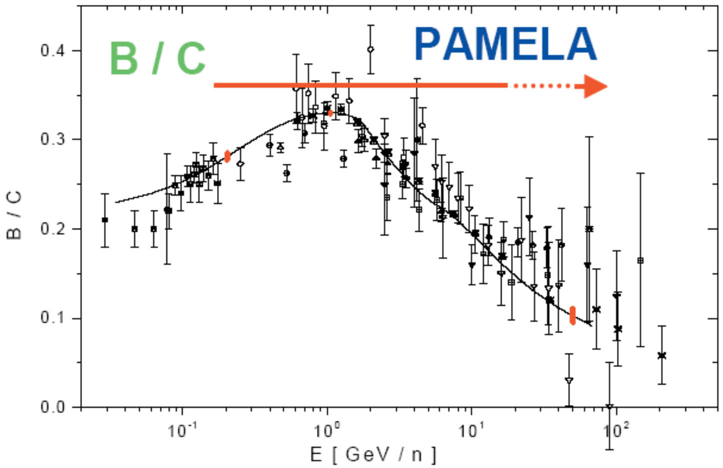
$$+ \underbrace{\sum_{k>i}\frac{N_k(E,z,t)}{\tau_{\text{int}}^{k\to i}(E,z)}}_{\text{secondary production}} + \underbrace{Q_i(E,z)}_{\text{primary sources}}$$

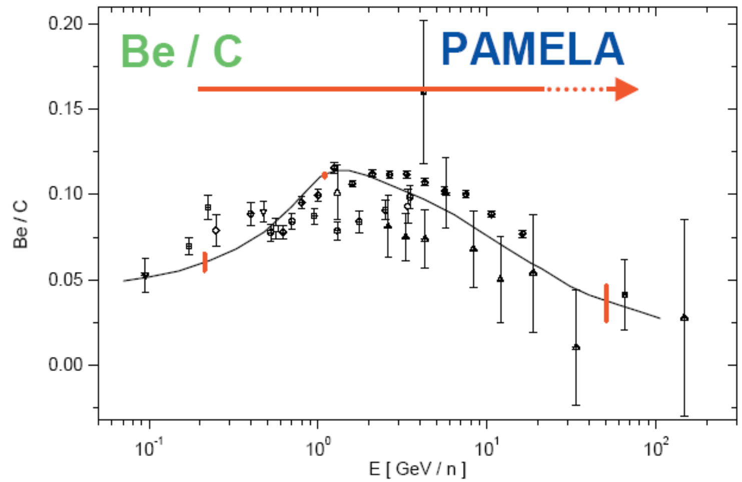
$$\underbrace{-\frac{\partial}{\partial E}\left\{\left\langle\frac{\partial E}{\partial t}\right\rangle\cdot N_i(E,z,t)\right\} + \frac{1}{2}\frac{\partial^2}{\partial E^2}\left\{\left\langle\frac{\Delta E^2}{\Delta t}\right\rangle\cdot N_i(E,z,t)\right\}}_{\text{energy changing processes (ionisation, reacceleration)}}$$

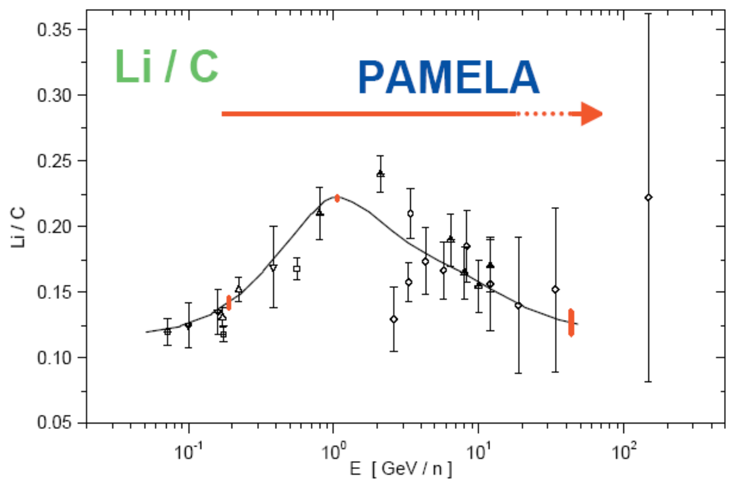
Galactic H and He spectra



Secondary to Primary ratios

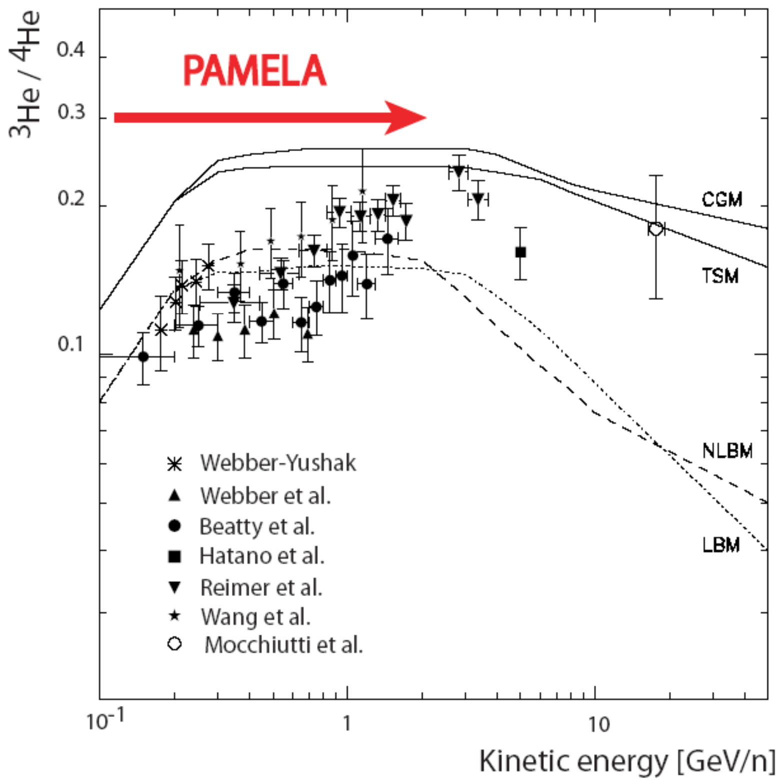




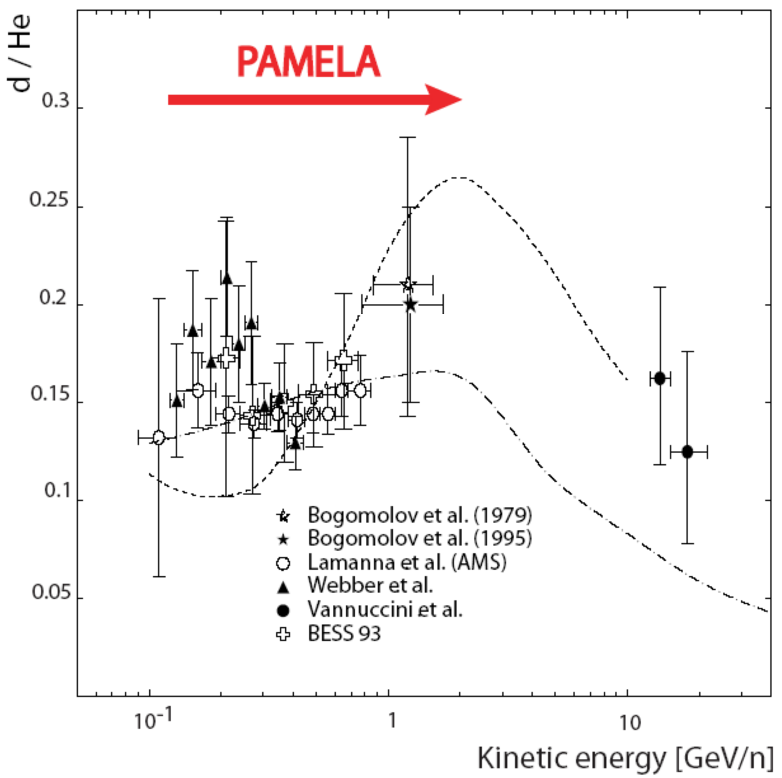


Helium and Hydrogen Isotopes

The current situation of the 3He / 4He ratio

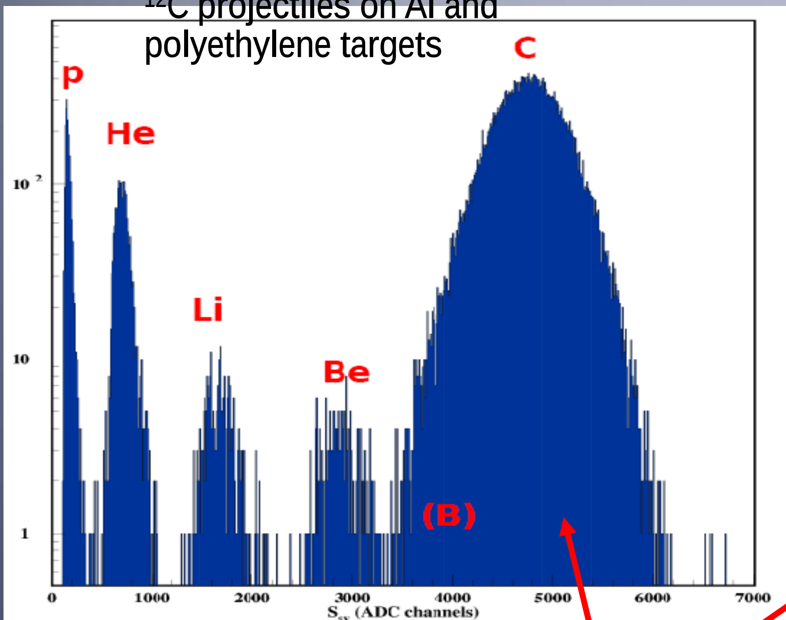


The current situation of the d / He ratio

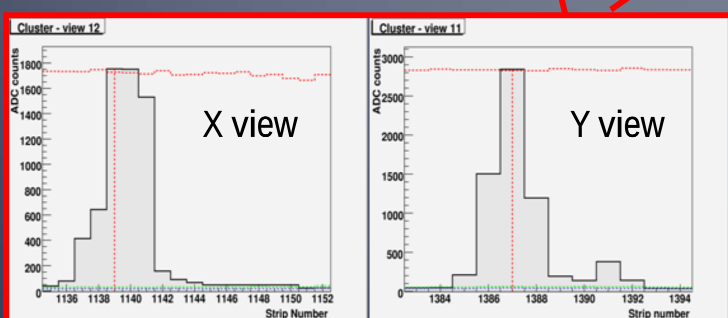


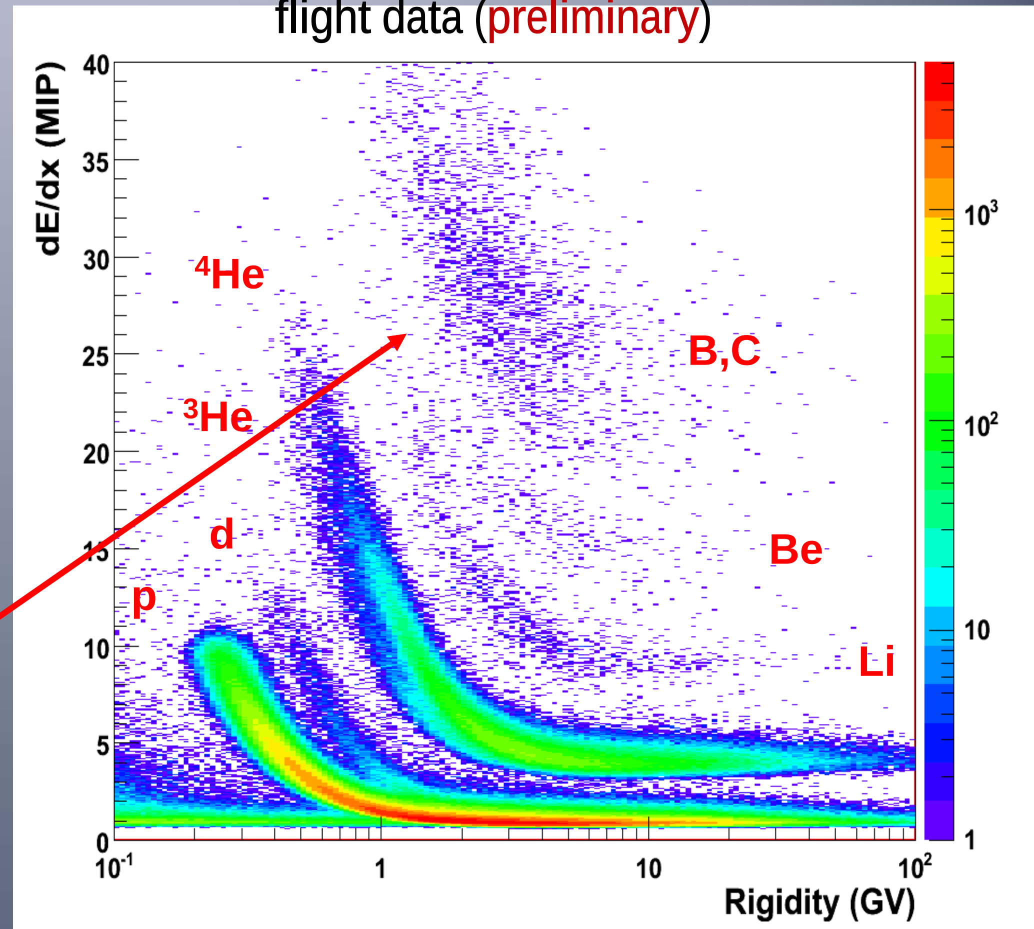
Charge identification capabilities (tracker)

Beam-test data (@GSI 2006)



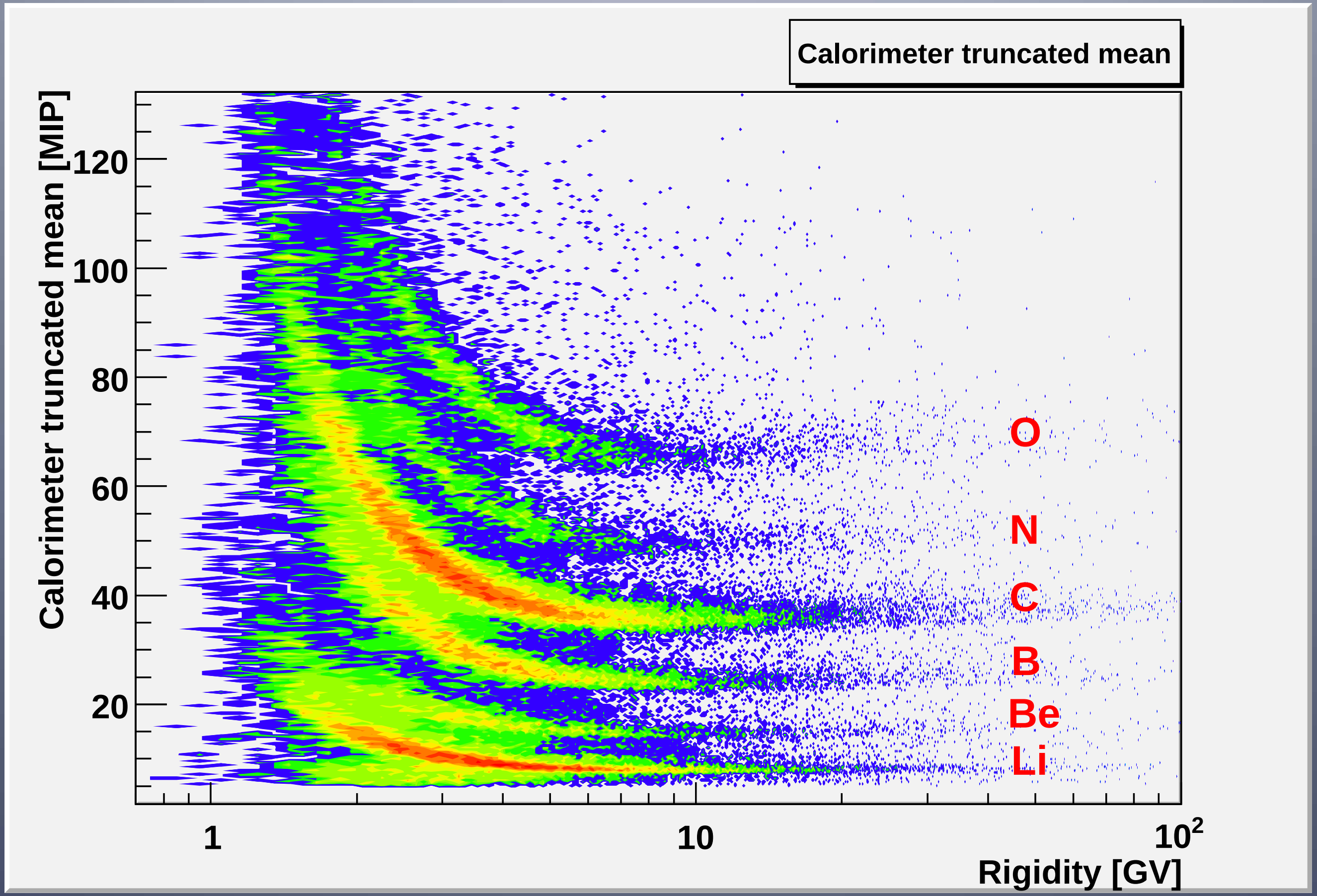
Saturated clusters





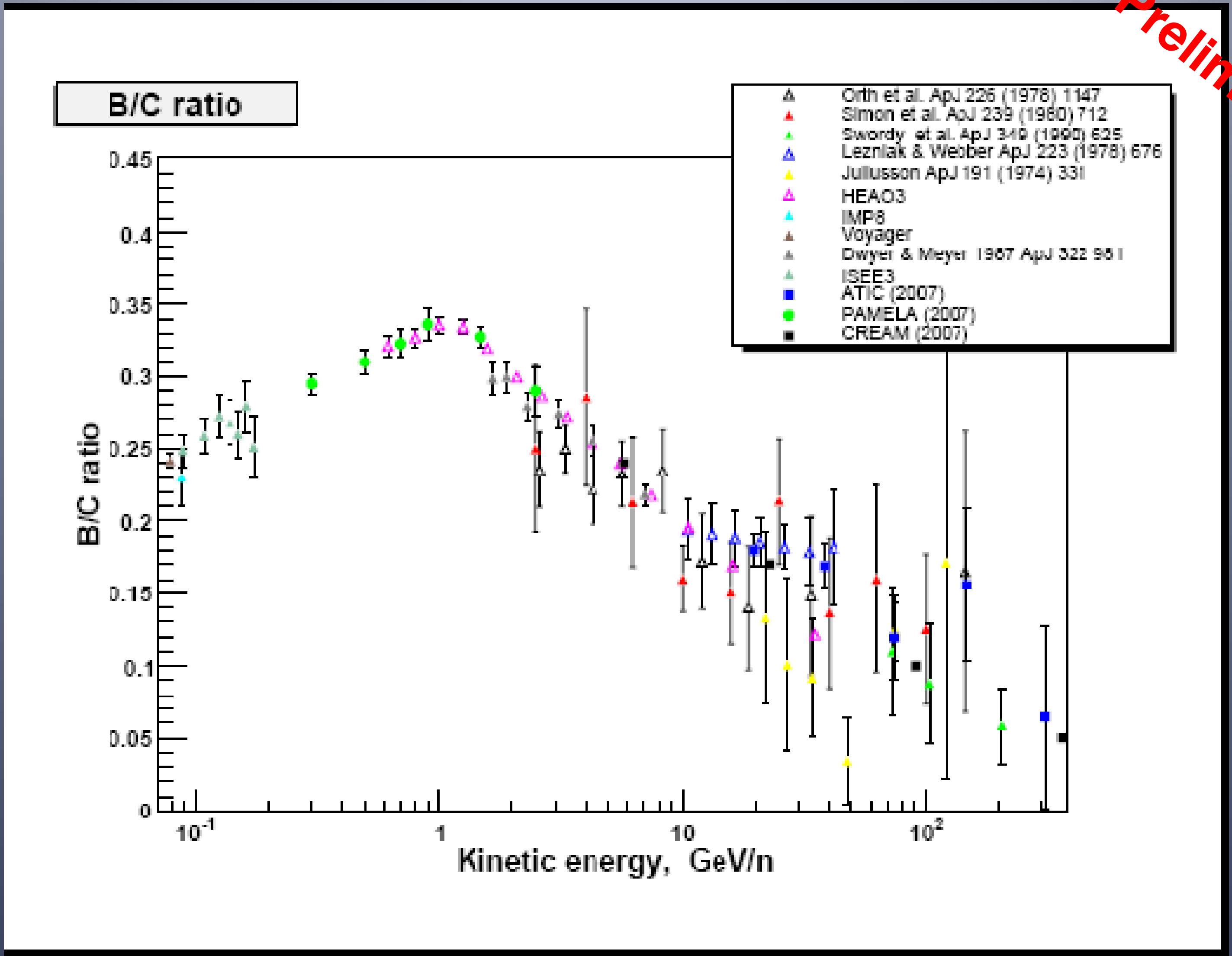
- **Good charge discrimination of H and He**
- **Single-channel saturation at ~10MIP affects B/C discrimination**

Charge identification capabilities (calorimeter)



Truncated mean of multiple dE/dx measurements in different silicon planes

Preliminary Results B/C



Mirko Boezio, INFN Trieste - Fermilab, 2008/05/02

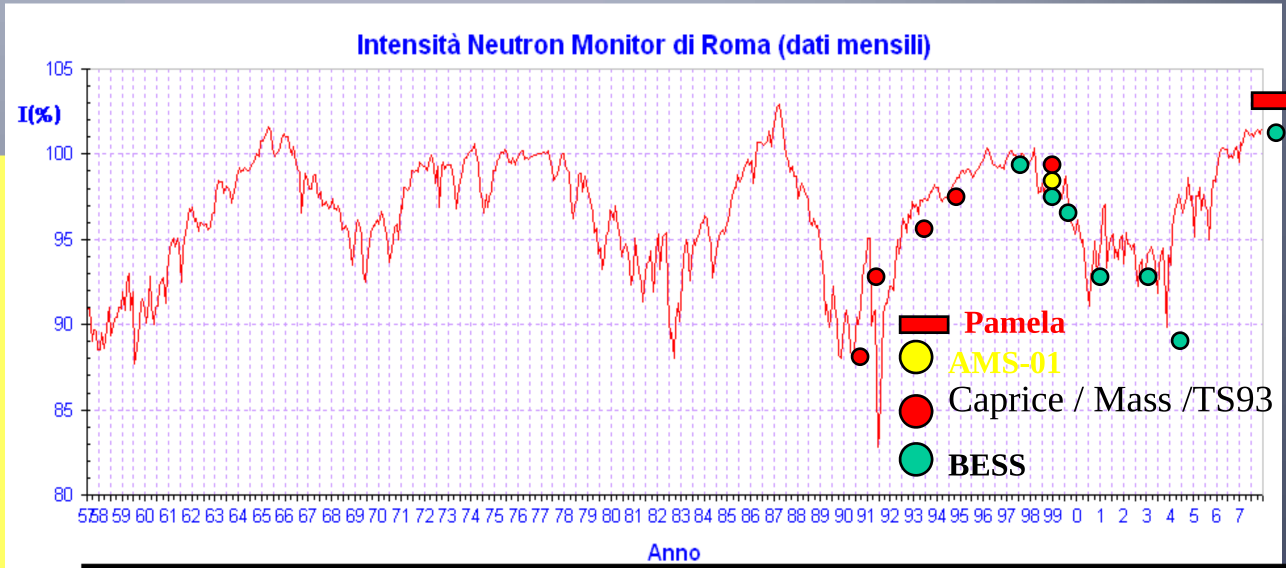
Solar Modulation of galactic cosmic rays

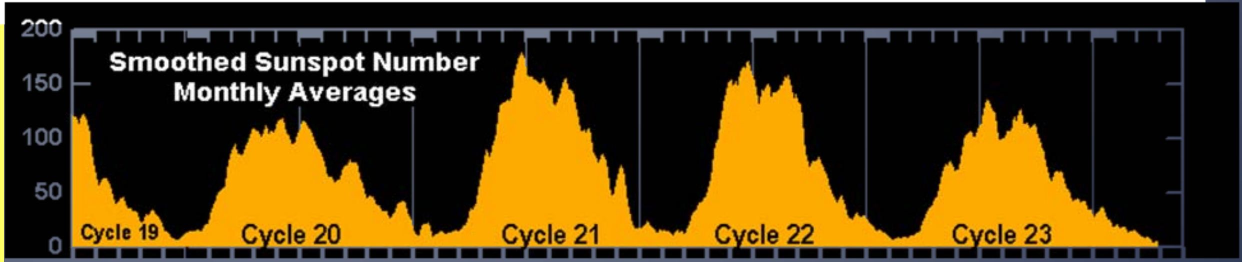
- **Continuous monitoring of solar activity**
- **Study of charge sign dependent effects**

Asaoka Y. et al. 2002, Phys. Rev. Lett. 88, 051101),

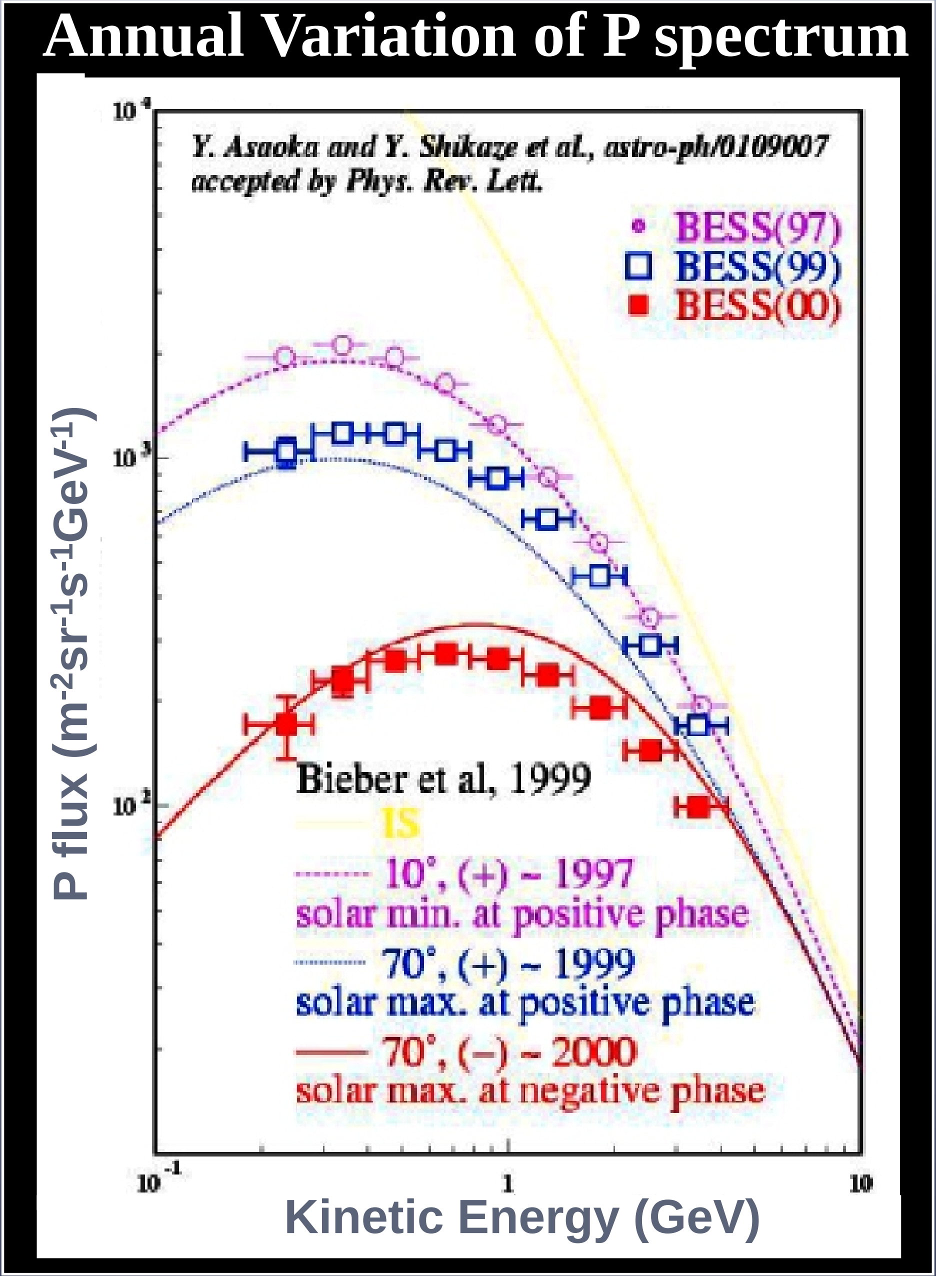
Bieber, J.W., et al. Physi-cal Review Letters, 84, 674, 1999.

J. Clem et al. 30th ICRC 2007





Proton Fluxes at TOA

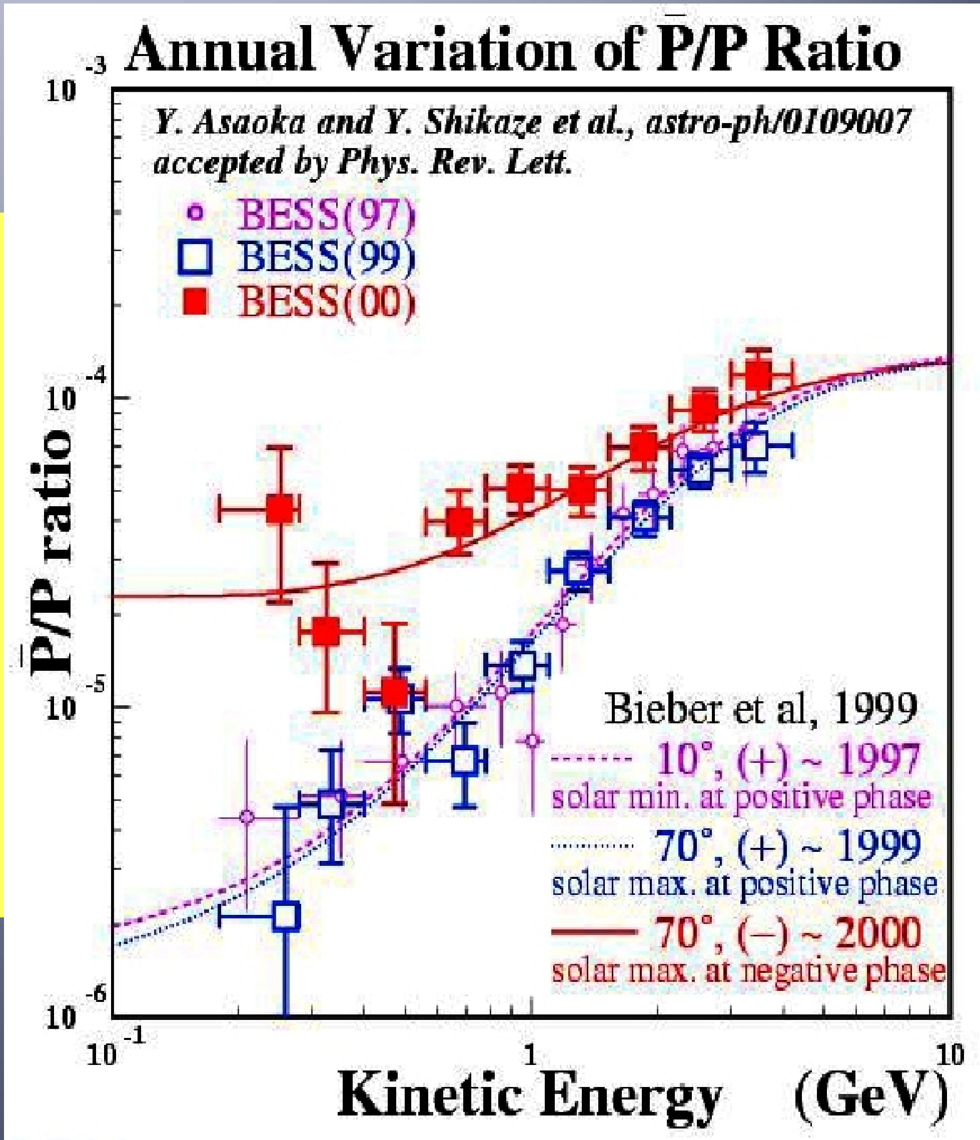


$\bar{p}$/p Ratio

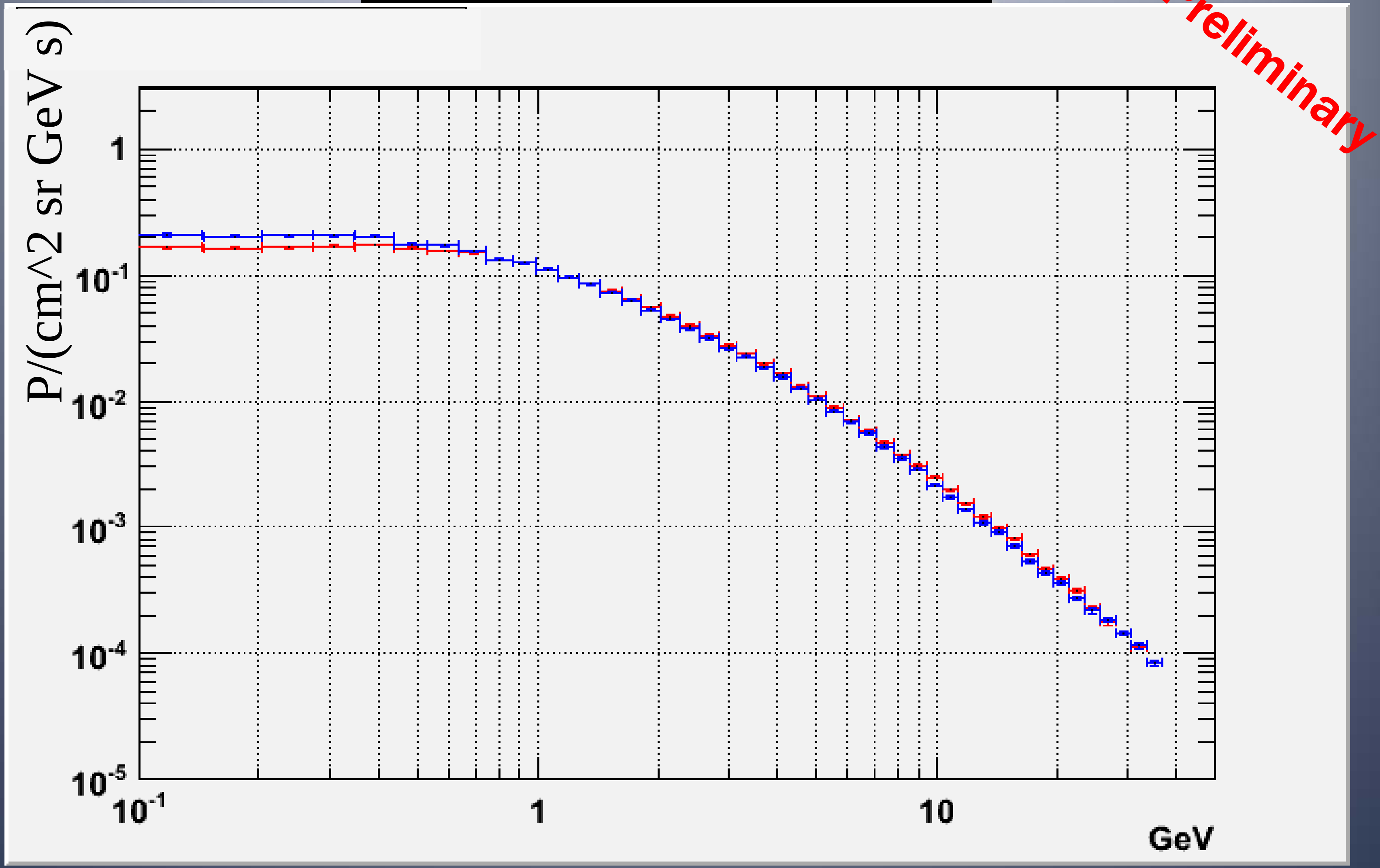
Time variation of $\bar{p}$/p ratio at solar maximum

Observed data by BESS

Charge dependent modelprediction(Bieber et al.)
Bieber, J.W., et al. Phys. Rev. Letters, 84, 674, 1999.

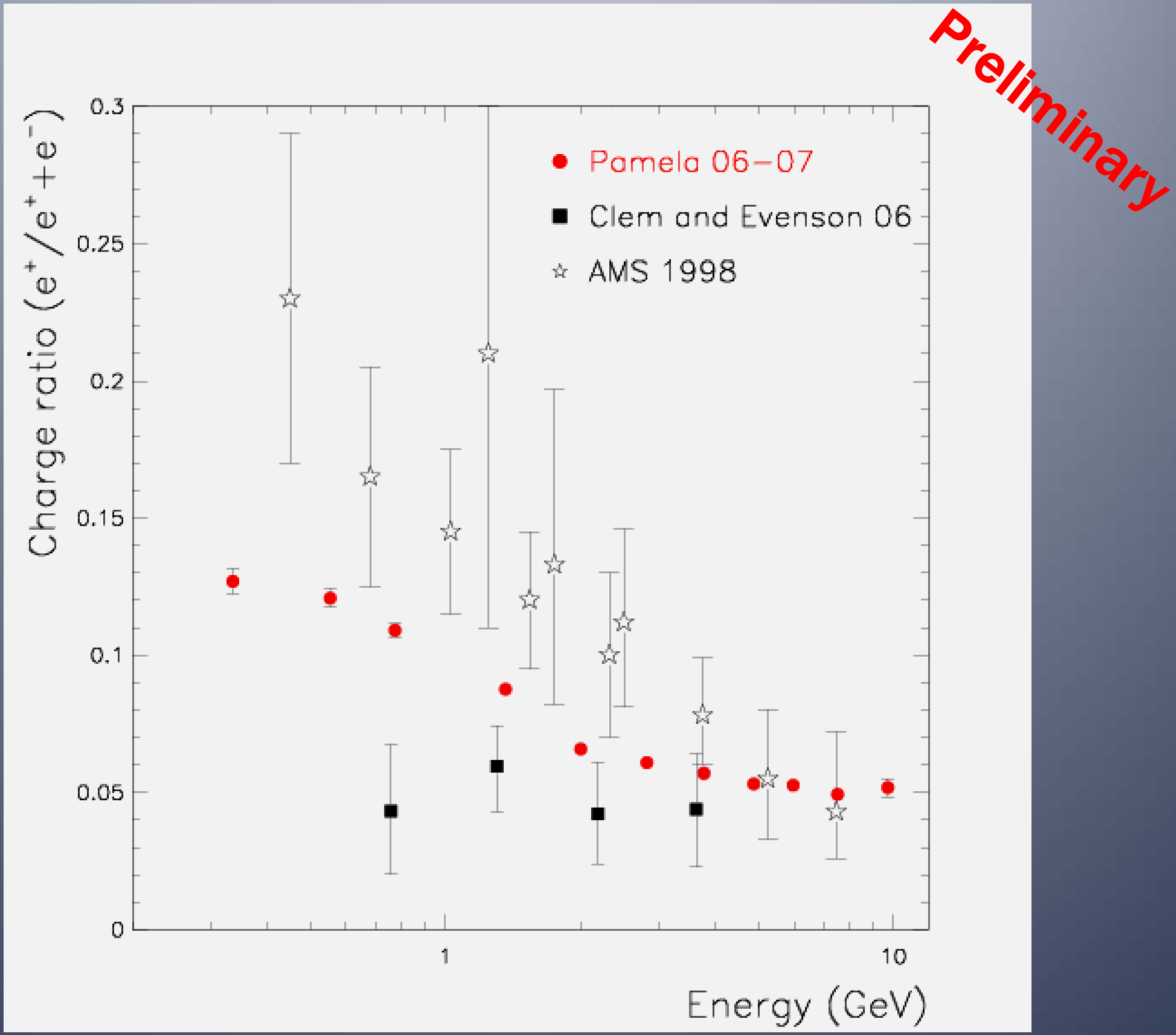


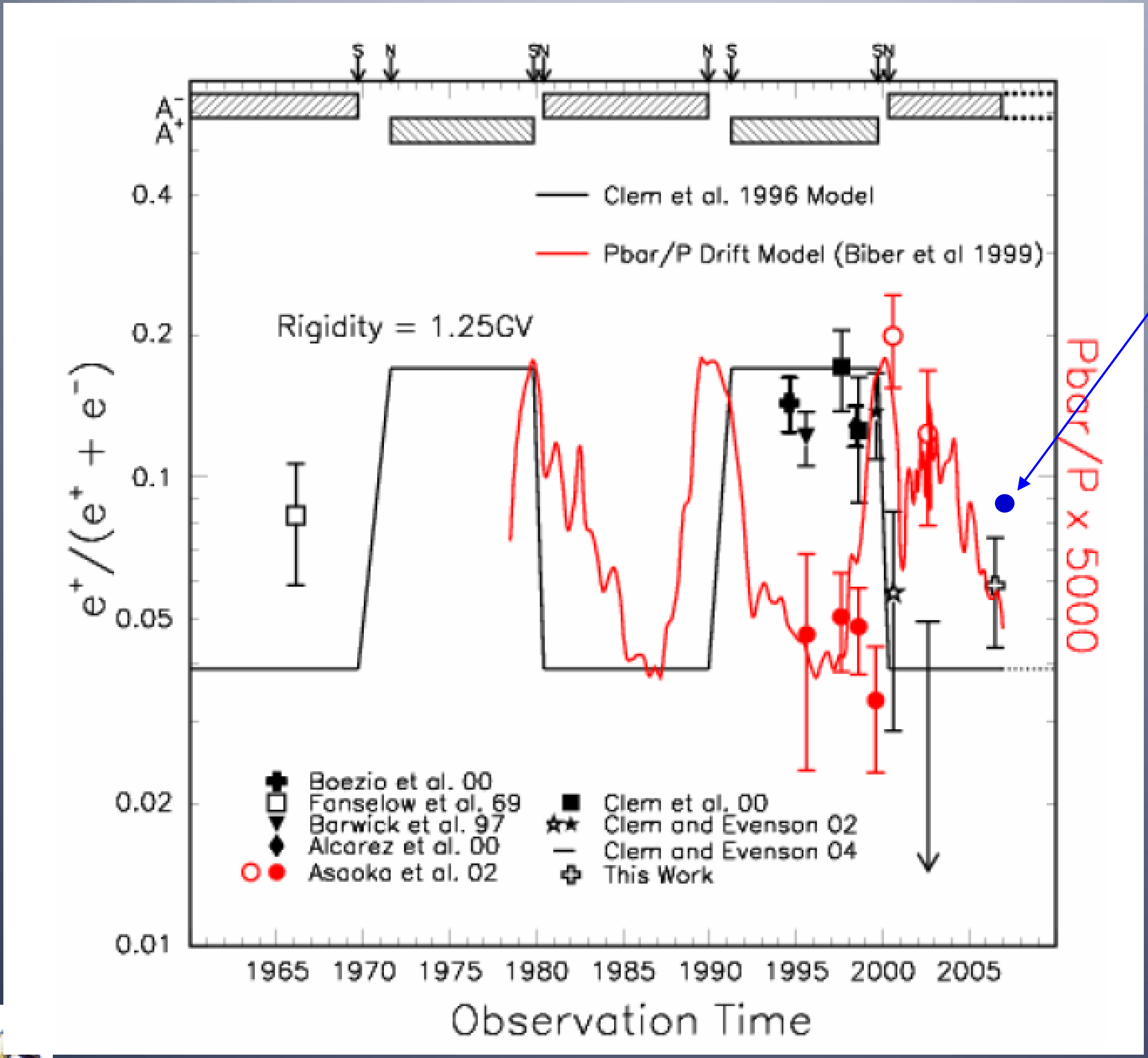
Proton Spectra



RED: JULY 2006
BLUE: AUGUST 2007

Positron Fraction

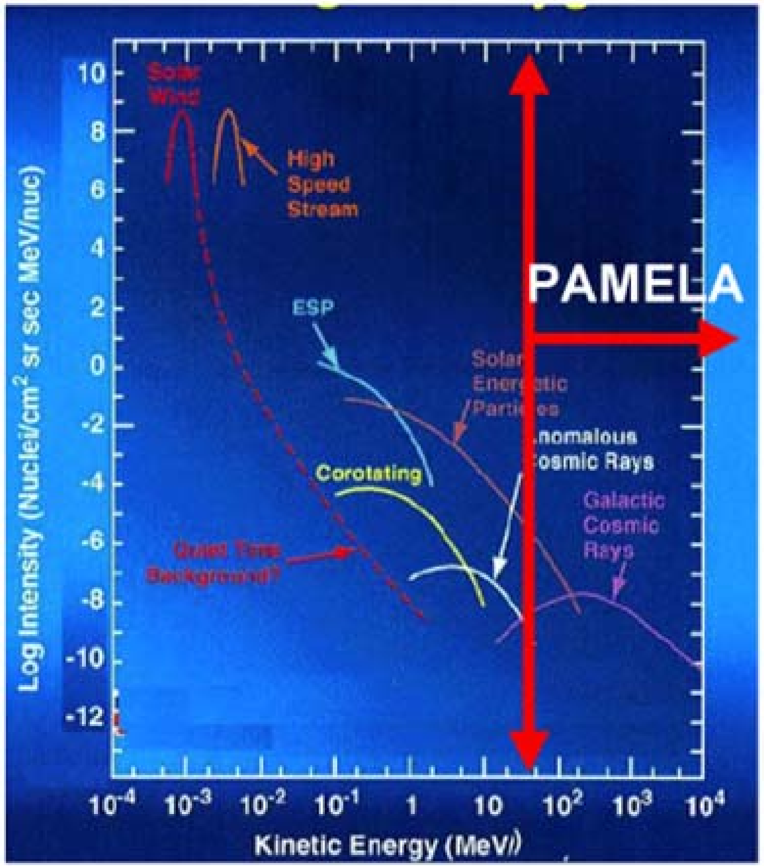




Pamela 2006 (Preliminary!)

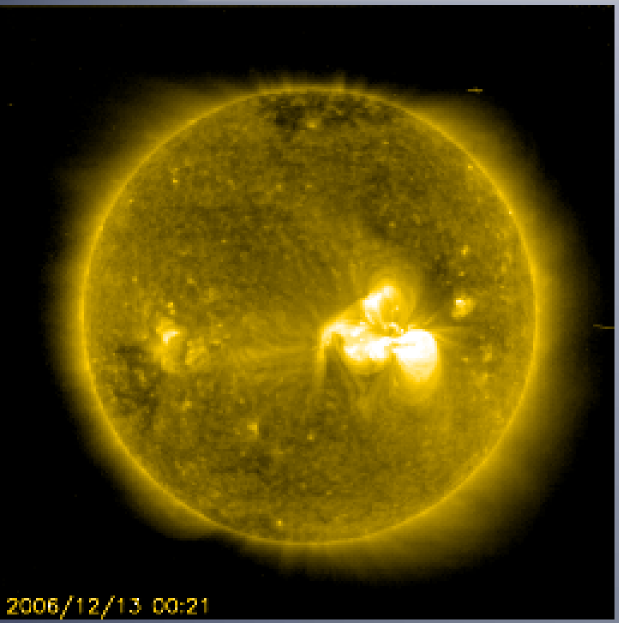
Clem at al.
30th ICRC 2007

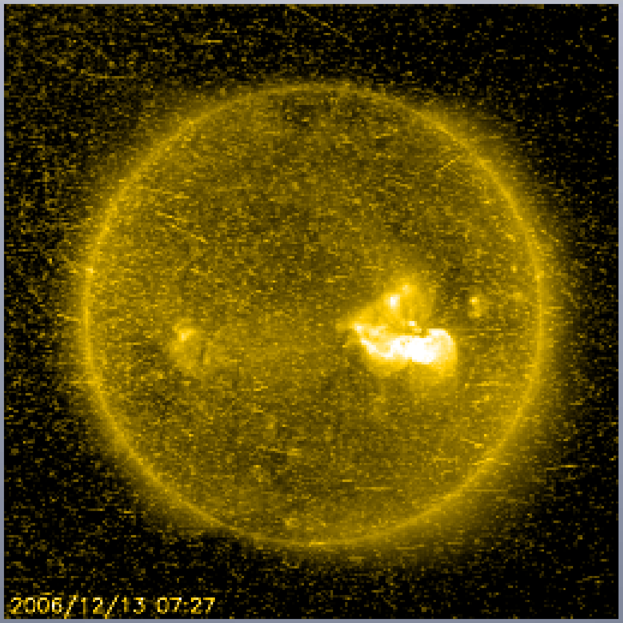
Solar Physics with PAMELA

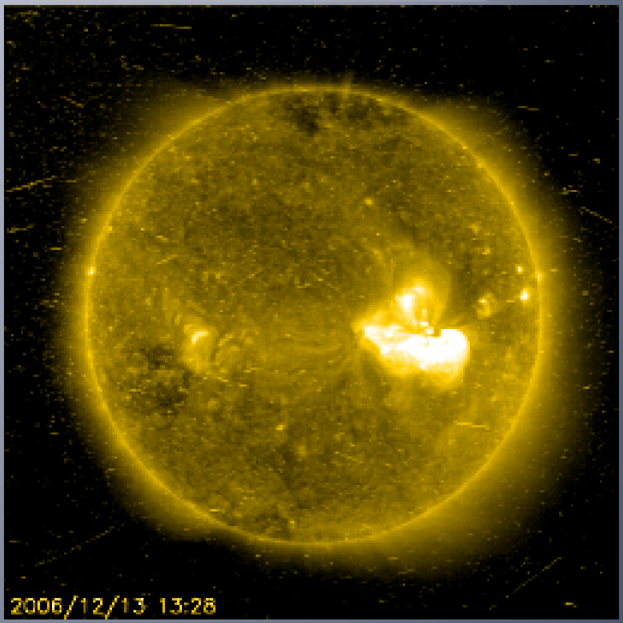


- Solar Modulation effects
- High energy component of Solar Proton Events (from 80 MeV to 10 GeV)
- High energy component of electrons and positrons in Solar Proton Events (from 50 MeV)
- Nuclear composition of Gradual and Impulsive events
- ^3He and ^4He isotopic composition

December 2006 Solar particle events

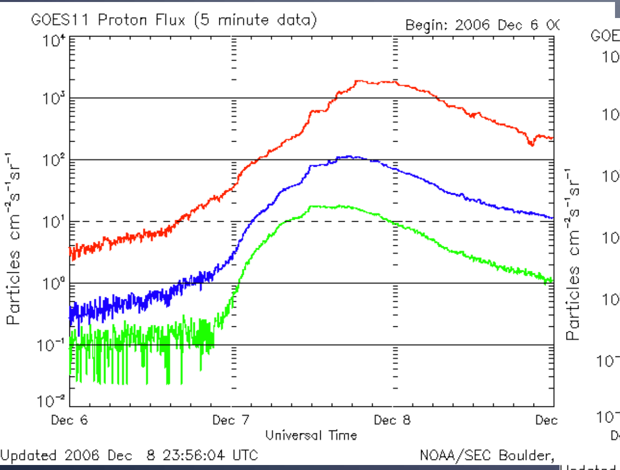


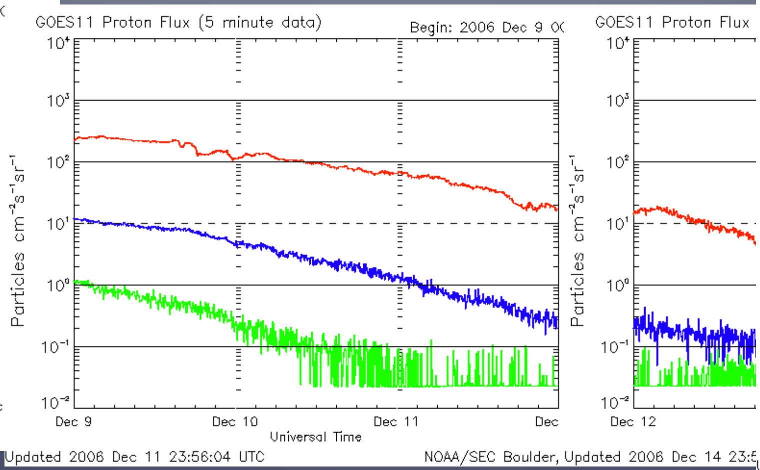


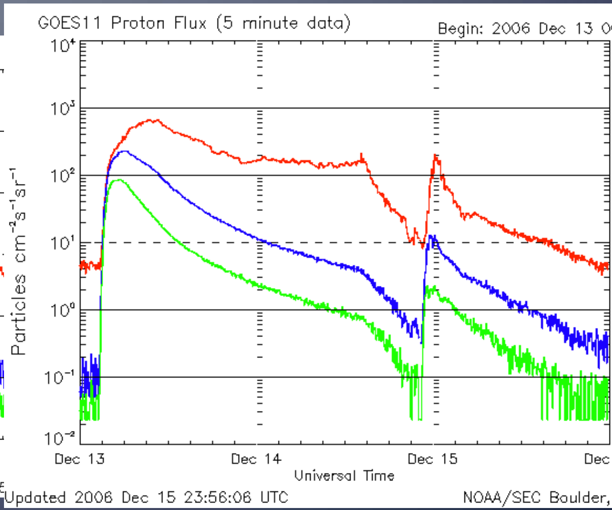


Dec 13th largest CME since 2003, anomalous at sol min

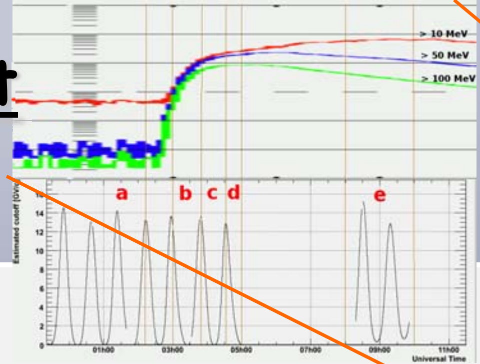
X3.4 solar flare.

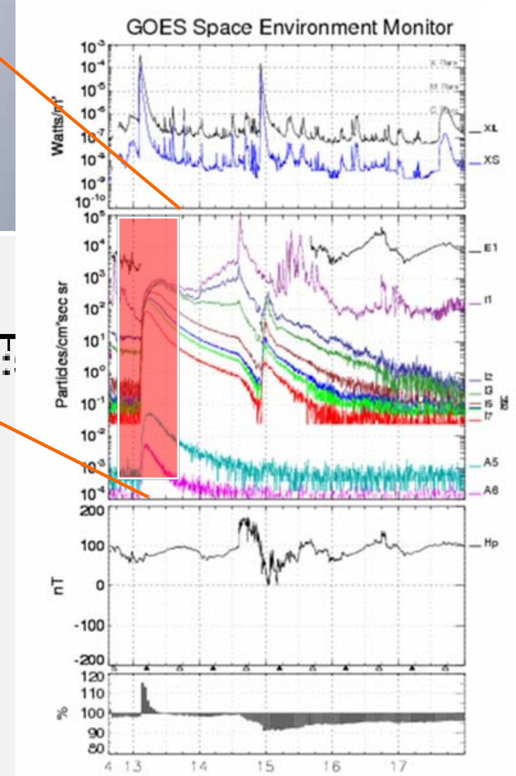


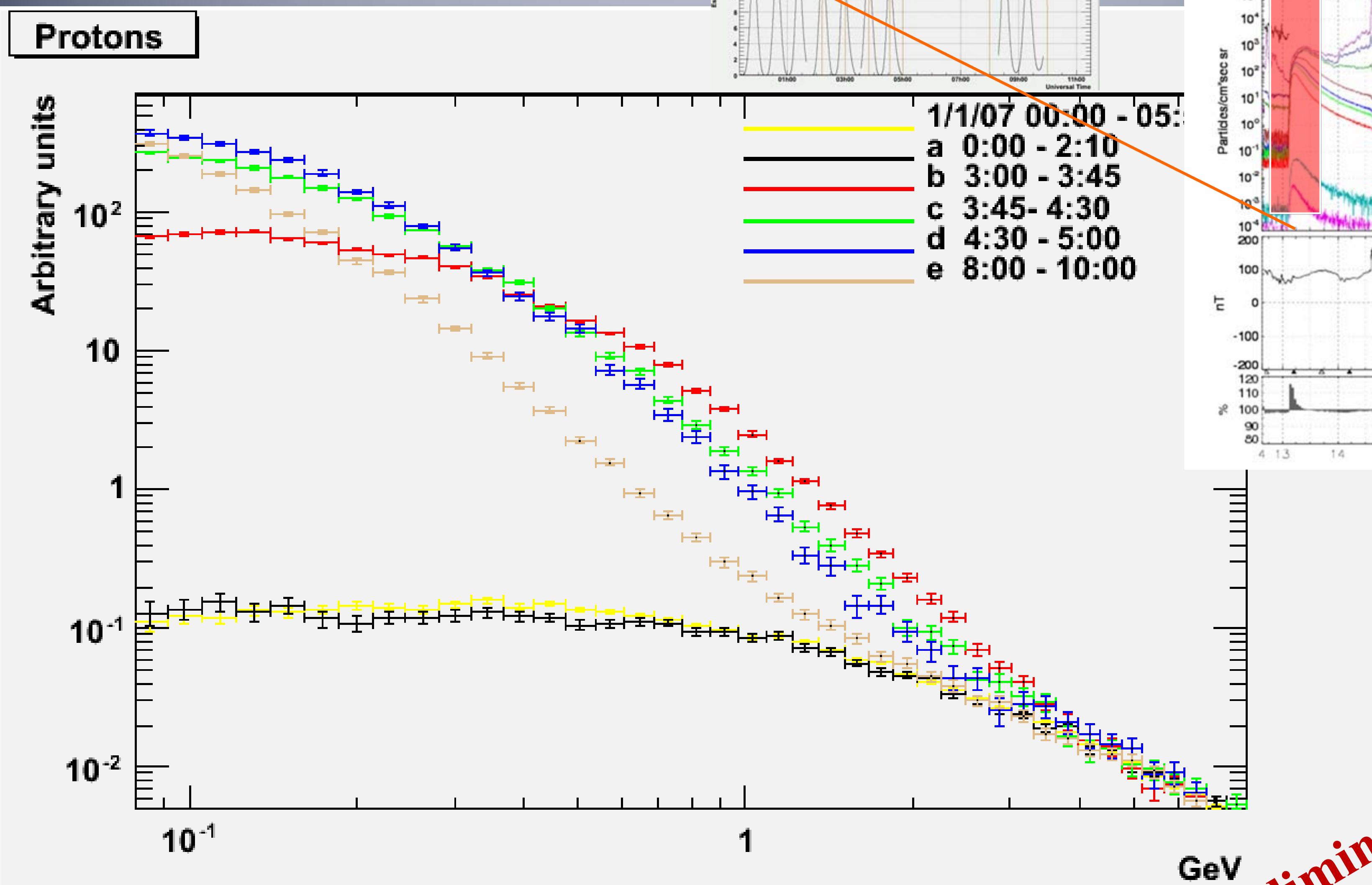




December 13th 2006 event



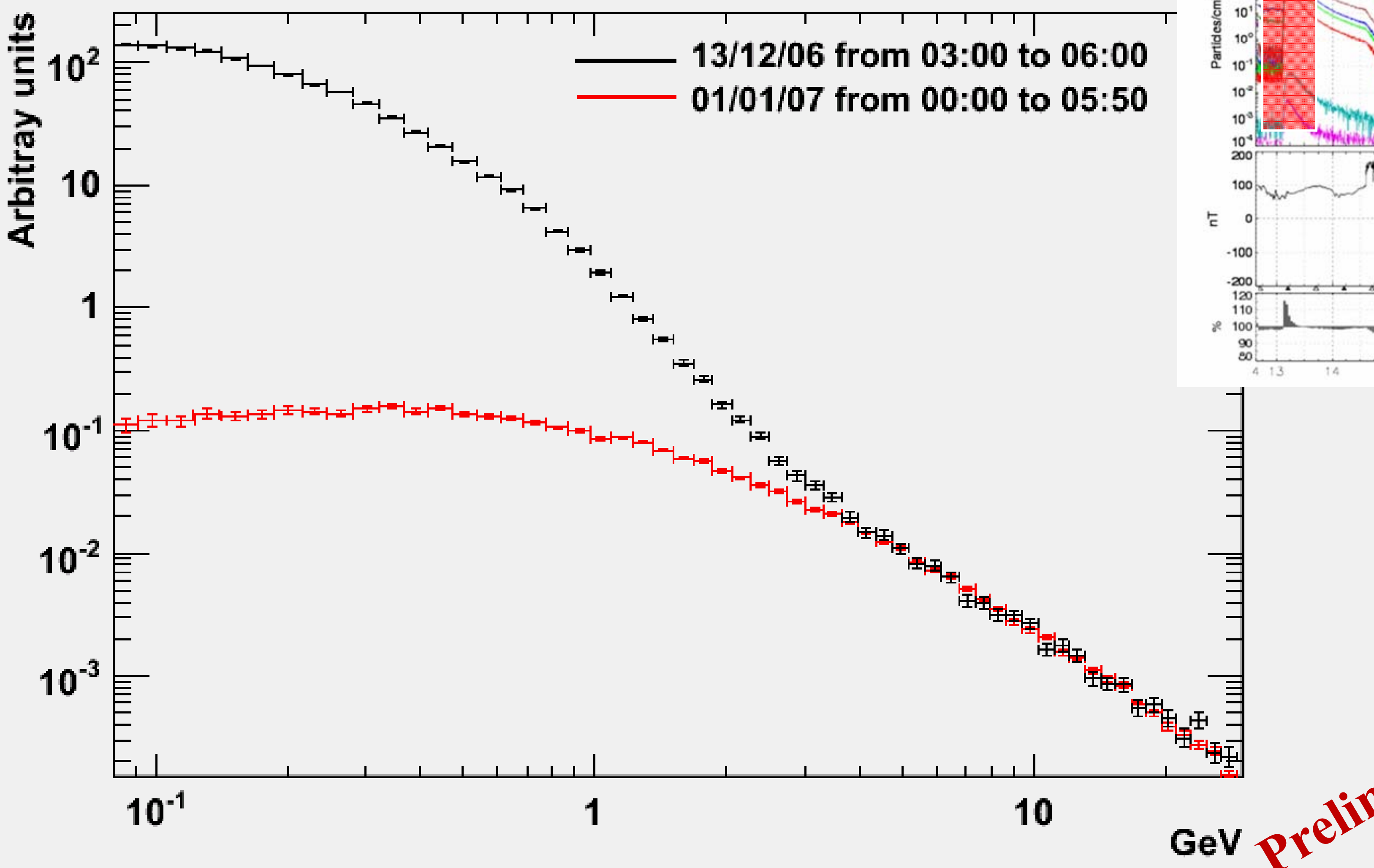


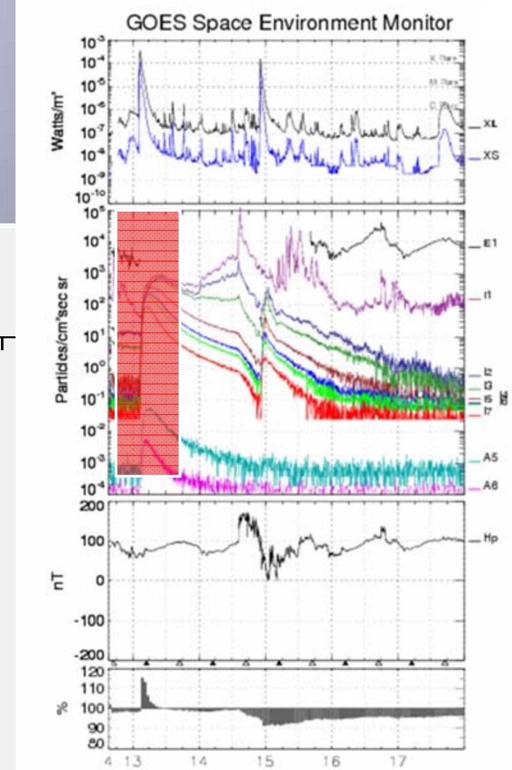


Preliminary!

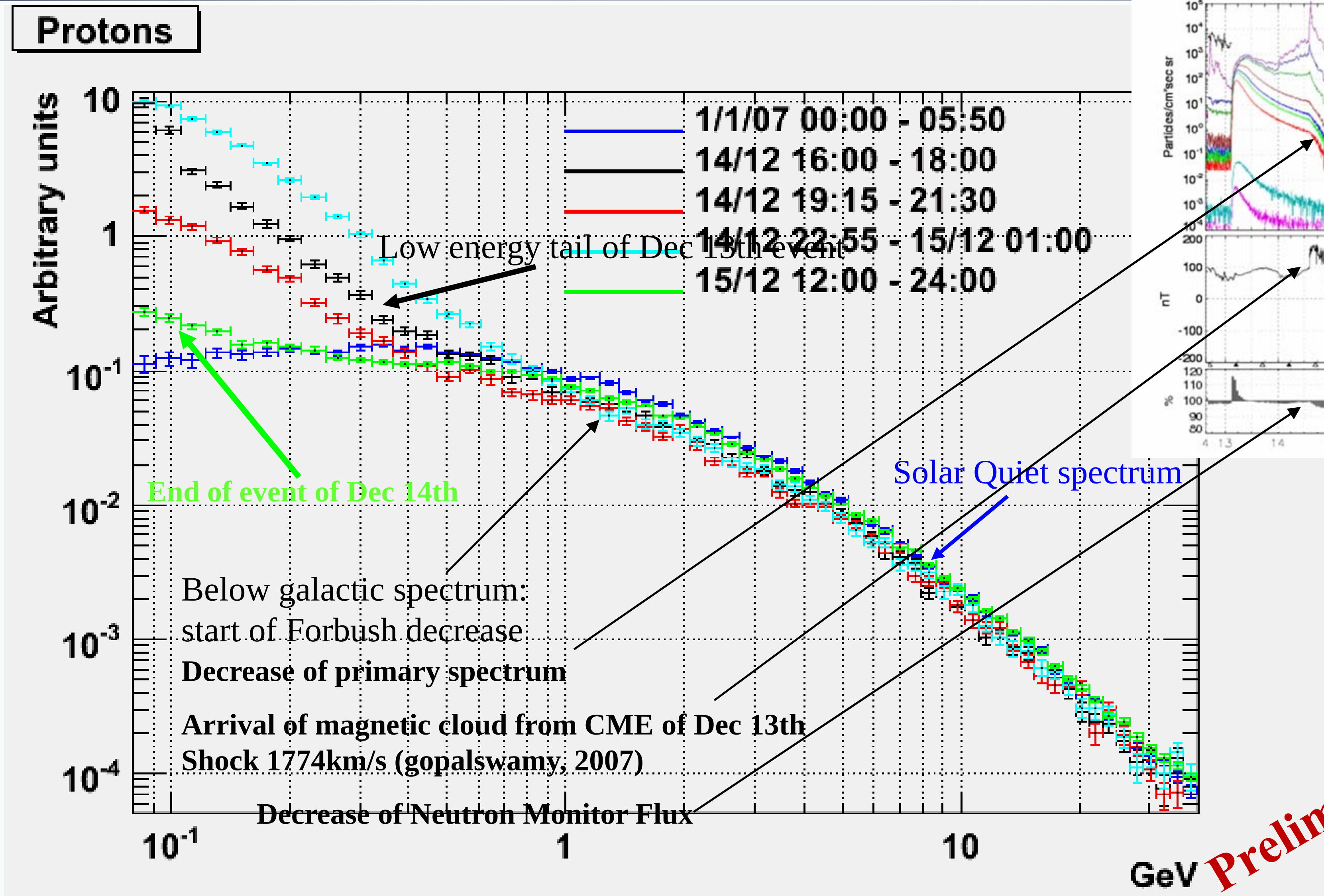
December 13th 2006 He differential spectrum

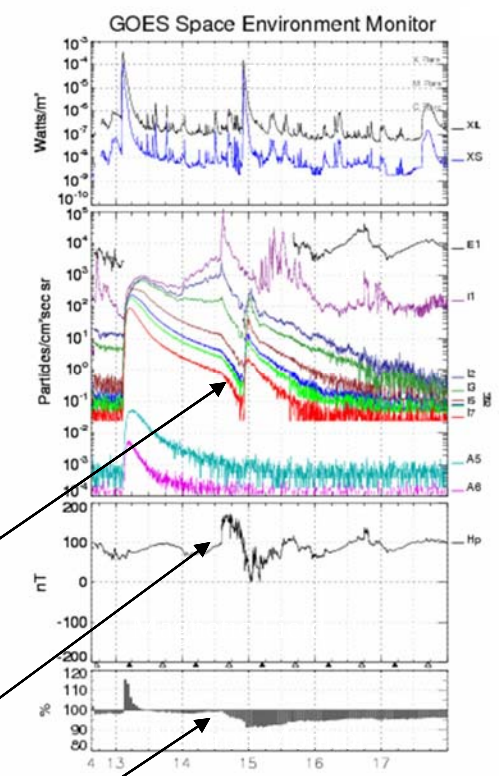
[redacted]





December 14th 2006 event



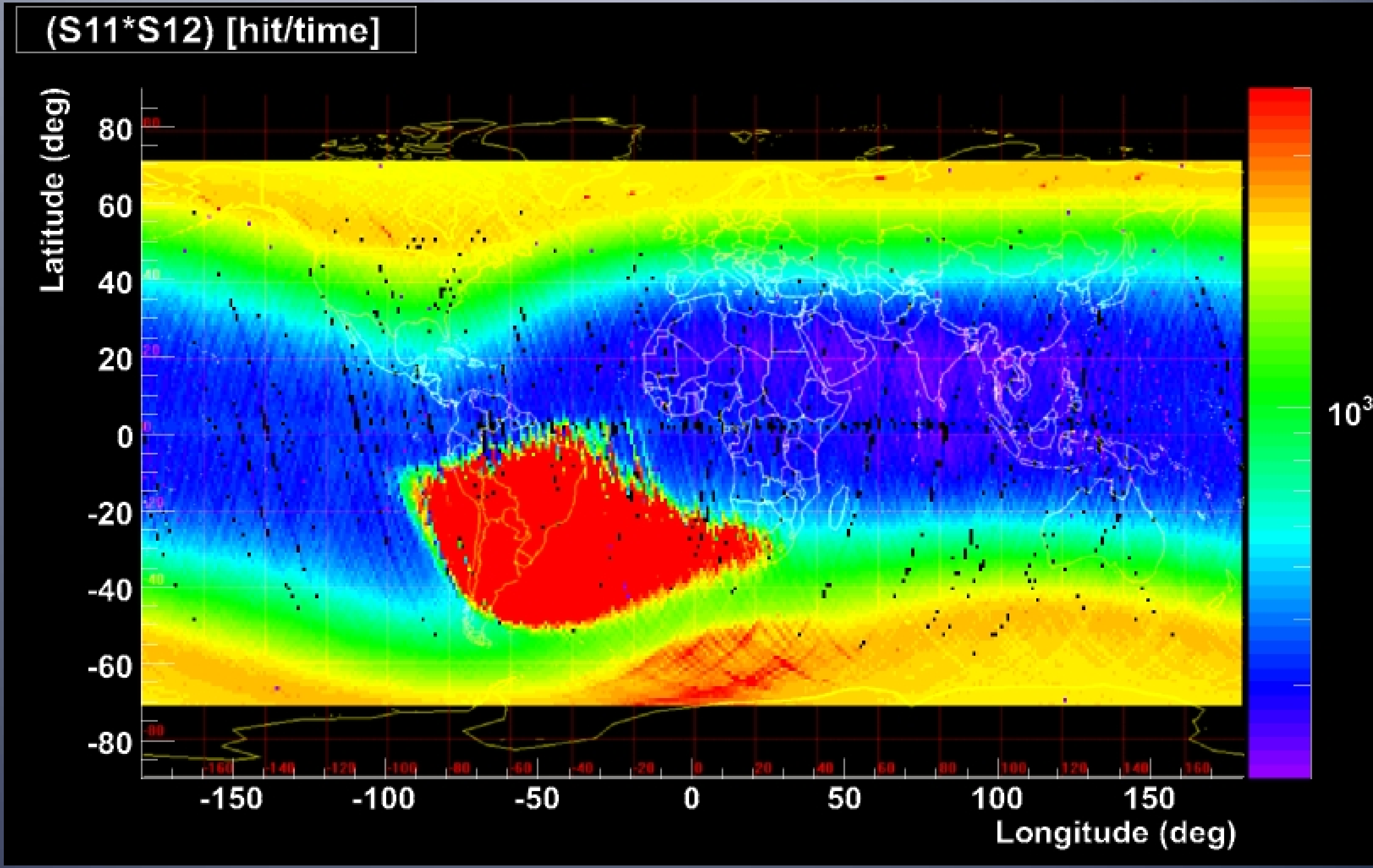


Radiation Belts

South Atlantic Anomaly

Secondary production from CR interaction with atmosphere

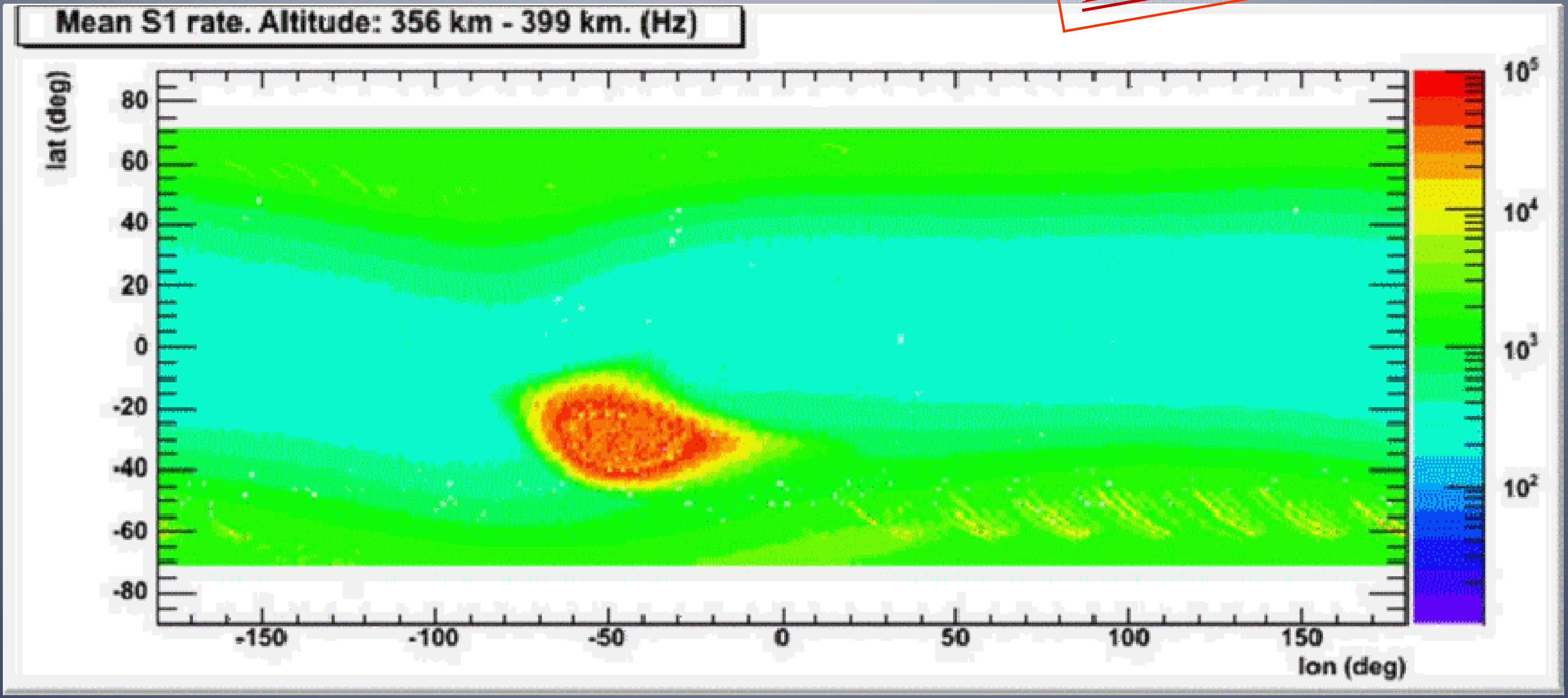
Pamela World Maps: 350 – 650 km alt



36 MeV p, 3.5 MeV e^-

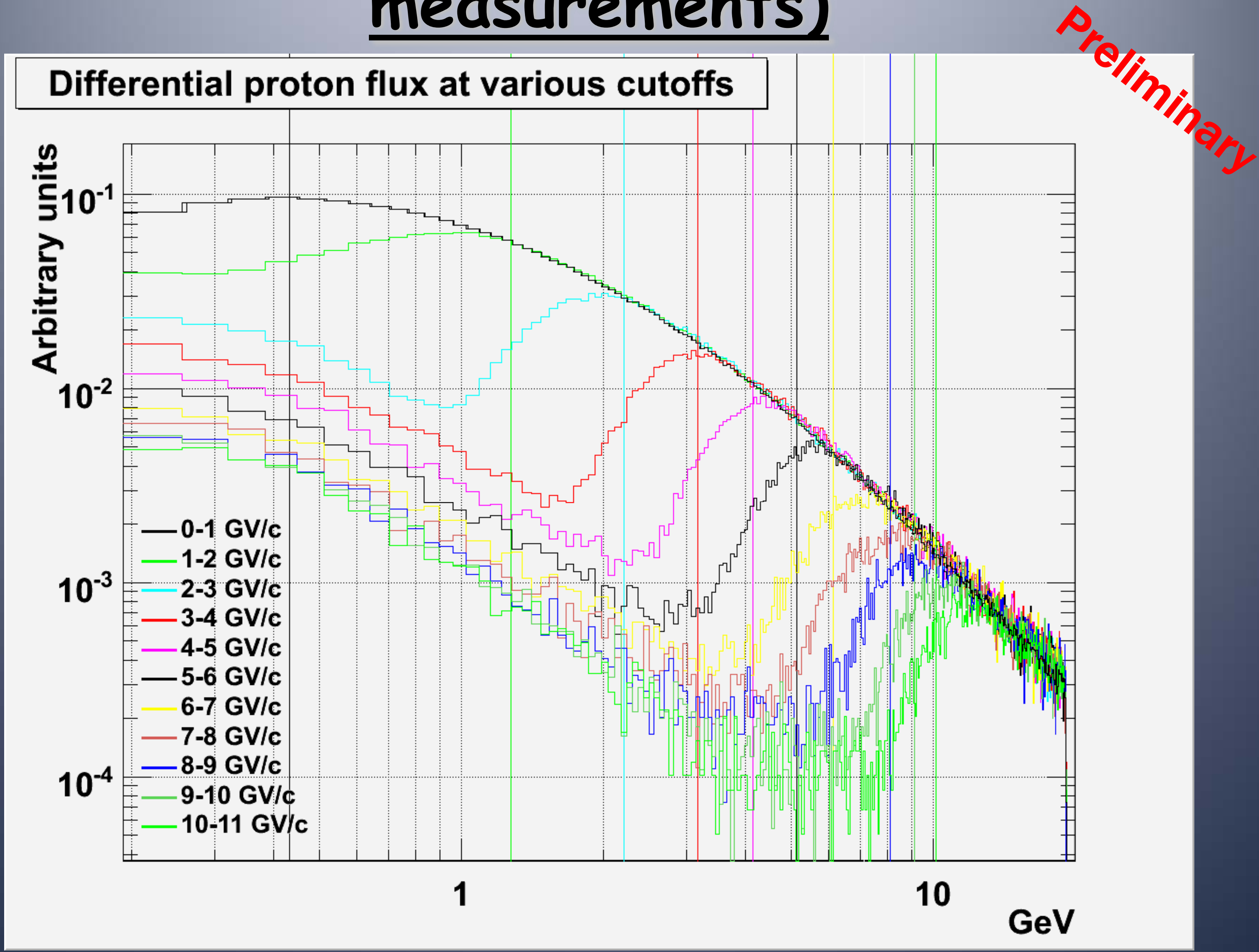
Pamela maps at various altitudes

PRELIMINARY !!!!



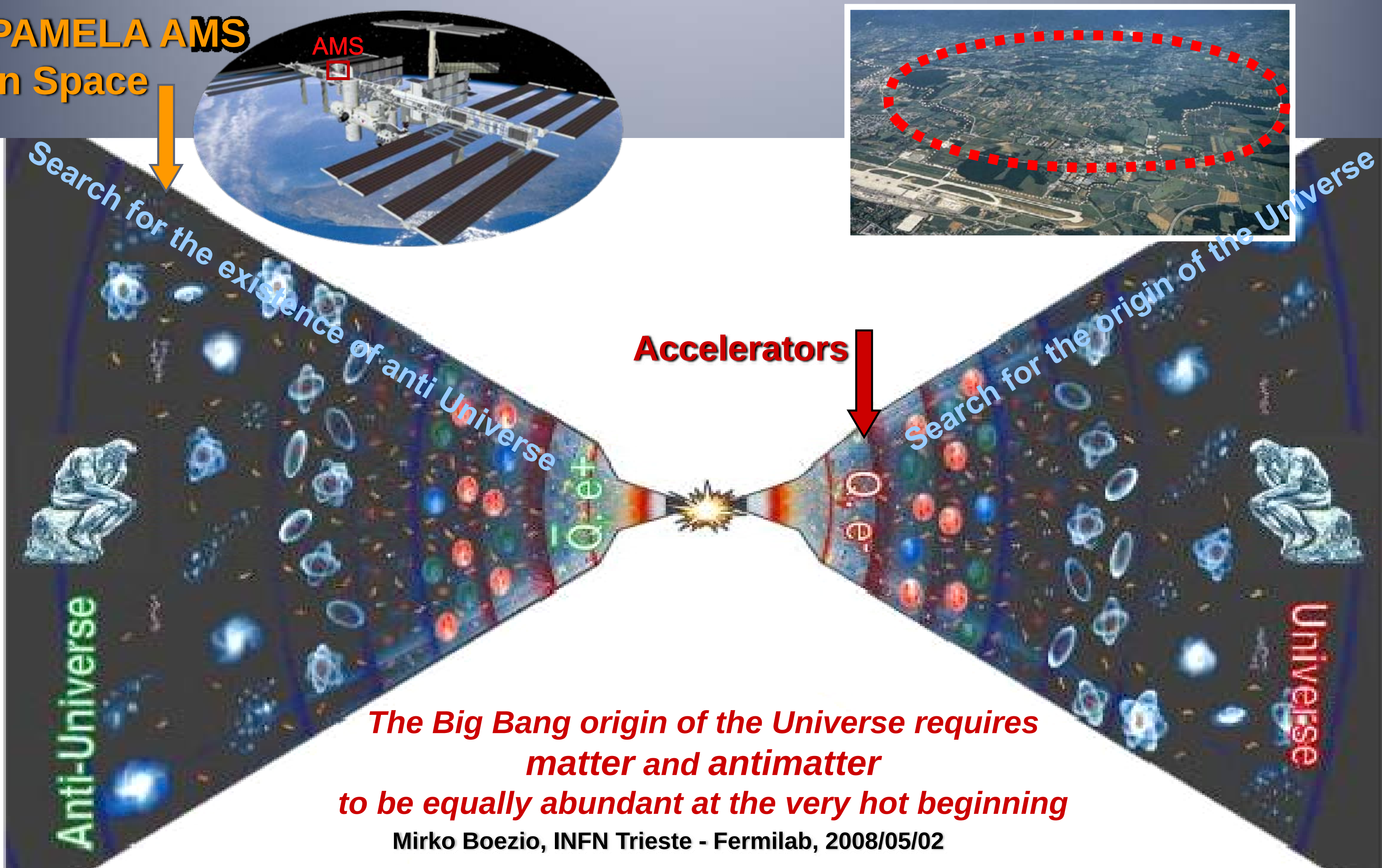
Altitude scanning

Primary and Albedo (sub-cutoff measurements)



Other Objectives

Search for the existence of Antimatter in the Universe



The Big Bang origin of the Universe requires
matter** and **antimatter
to be equally abundant at the very hot beginning

What about heavy antinuclei?

- **The discovery of one nucleus of antimatter ($Z \geq 2$) in the cosmic rays would have profound implications for both particle physics and astrophysics.**

  - **For a Baryon Symmetric Universe Gamma rays limits put any domain of antimatter more than 100 Mpc away**

    (Steigman (1976) Ann Rev. Astr. Astrophys., ***14****, 339; Dudarerwicz and Wolfendale (1994) M.N.R.A.* ***268****, 609, A.G. Cohen, A. De Rujula and S.L. Glashow, Astrophys. J. 495, 539, 1998)*

Antimatter Direct research

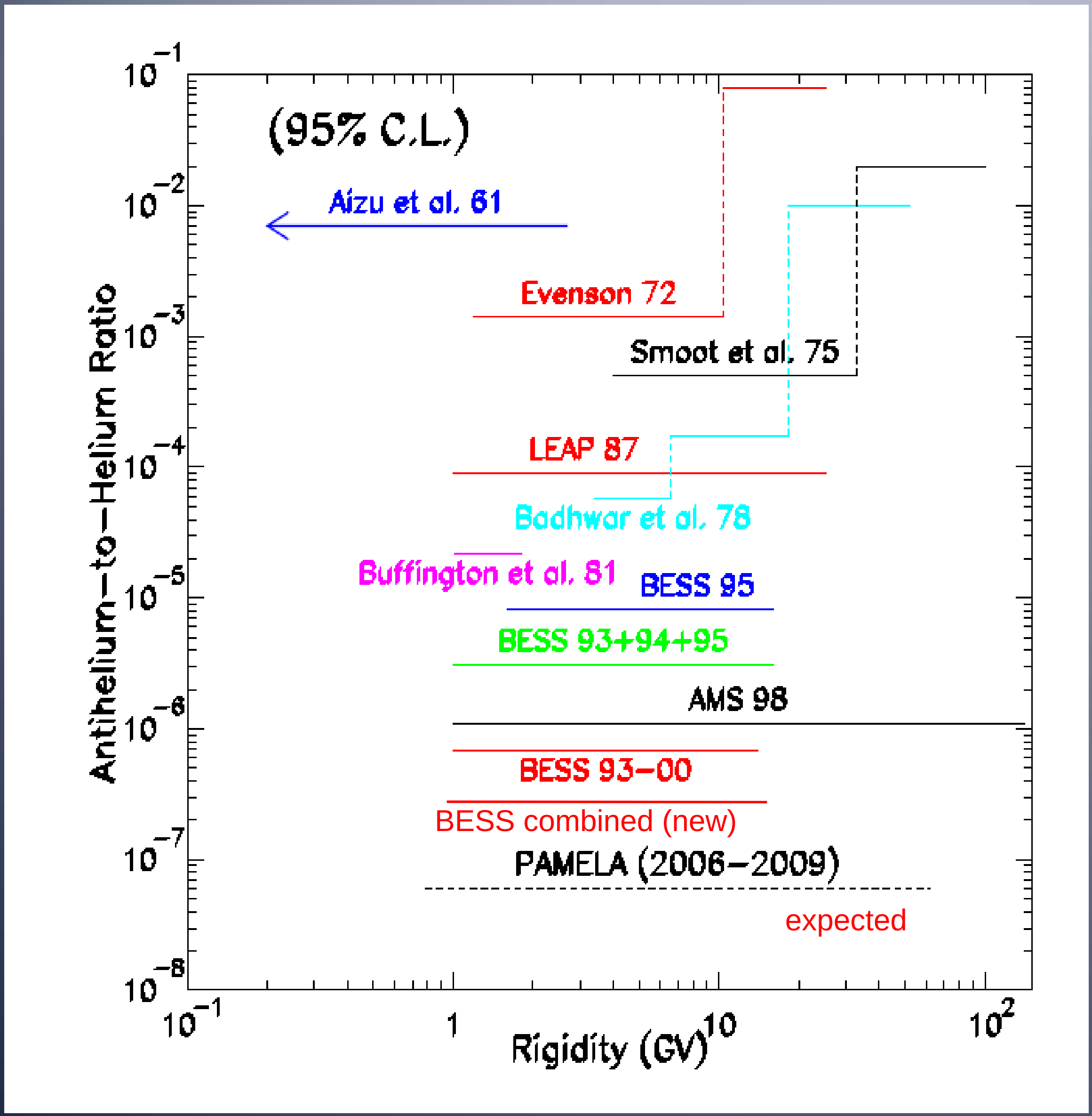
- **Antimatter** which has escaped as a cosmic ray from a distant antigalaxy

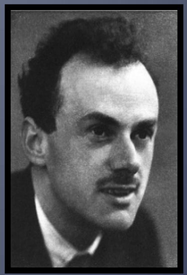
  Streitmatter, R. E., Nuovo Cimento, 19, 835 (1996)

- **Antimatter** from globular clusters of antistars in our Galaxy as antistellar wind or anti-supernovae explosion

  K. M. Belotsky et al., Phys. Atom. Nucl. 63, 233 (2000), astro-ph/9807027

Cosmic-ray antimatter search



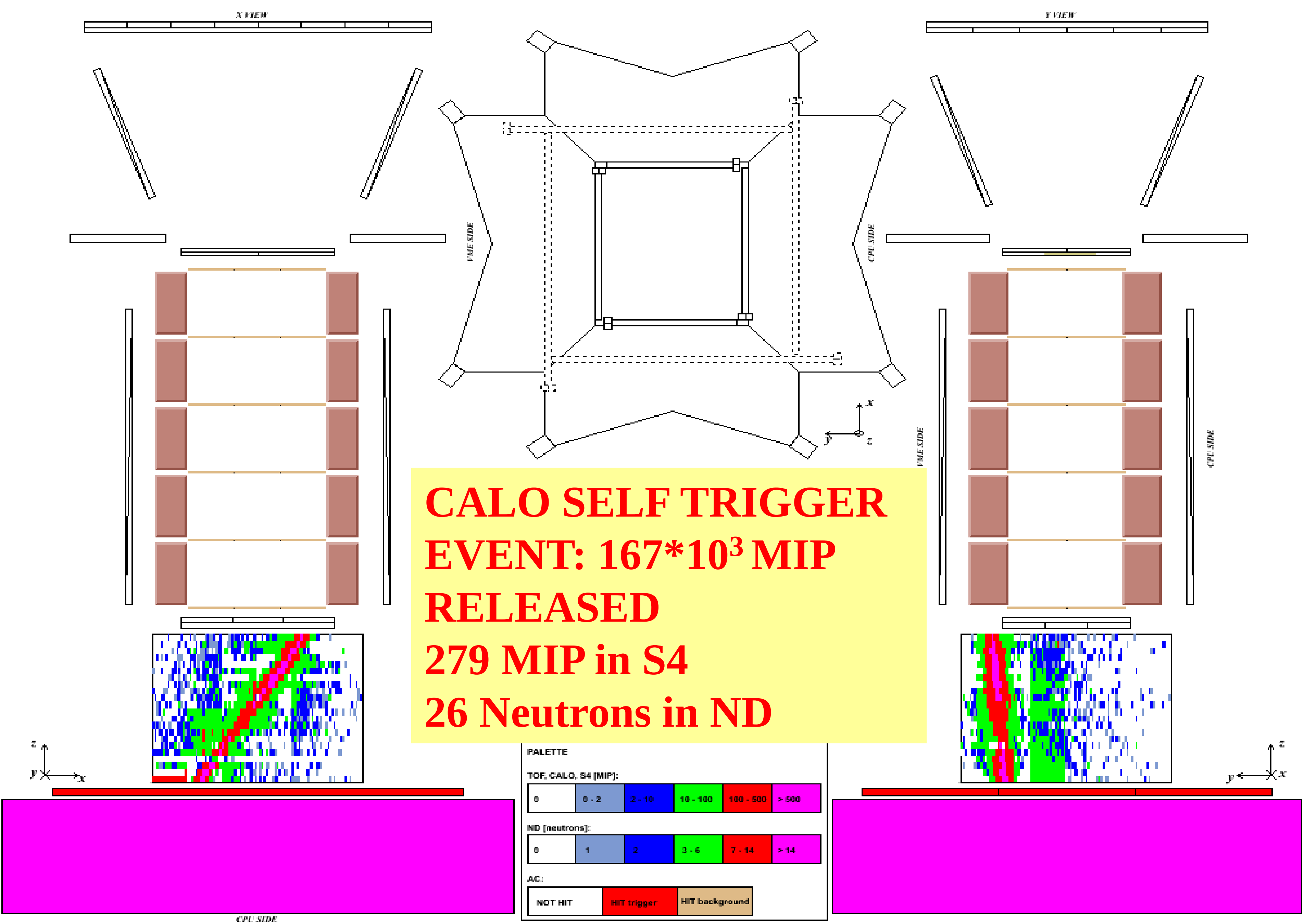


"We must regard it rather an accident that the Earth and presumably the whole Solar System contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about"

P. Dirac, Nobel lecture (1933)

High Energy electrons

- The study of primary electrons is especially important because they give information on the nearest sources of cosmic rays
- Electrons with energy above 100 MeV rapidly loss their energy due to synchrotron radiation and inverse Compton processes
- The discovery of primary electrons with energy above 10^{12} eV will evidence the existence of cosmic ray sources in the nearby interstellar space ($r \leq 300$ pc)



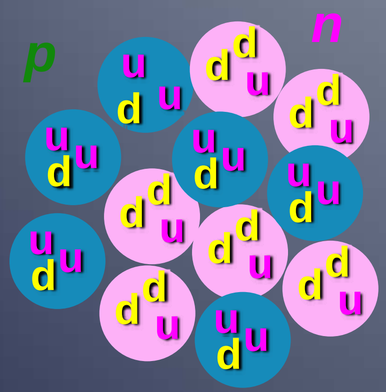
CALO SELF TRIGGER
EVENT: 167*10^3 MIP
RELEASED
279 MIP in S4
26 Neutrons in ND

Search for New Matter in the Universe:

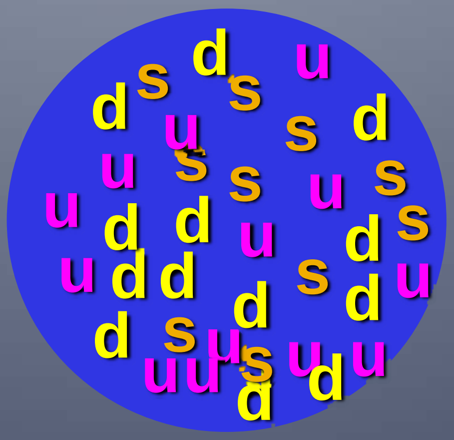
An example is the search for "strangelets".

There are six types of Quarks found in accelerators.
All matter on Earth is made out of only two types of quarks. "Strangelets" are new types of matter composed of three types of quarks which should exist in the cosmos.

Carbon Nucleus



Strangelet



i. A stable, single "super nucleon" with three types of quarks

ii. "Neutron" stars may be one big strangelet

AMS courtesy

Conclusion

- PAMELA is the first space experiment which is measuring the antiproton and positron energy spectra to the high energies (> 150GeV) with an unprecedented statistical precision
- PAMELA is setting a new lower limit for finding Antihelium
- PAMELA is looking for Dark Matter candidates
- PAMELA is providing measurements on elemental spectra and low mass isotopes with an unprecedented statistical precision and is helping to improve the understanding of particle propagation in the interstellar medium
- PAMELA is able to measure the high energy tail of solar particles.

THANKS

http:// pamela.roma2.infn.it