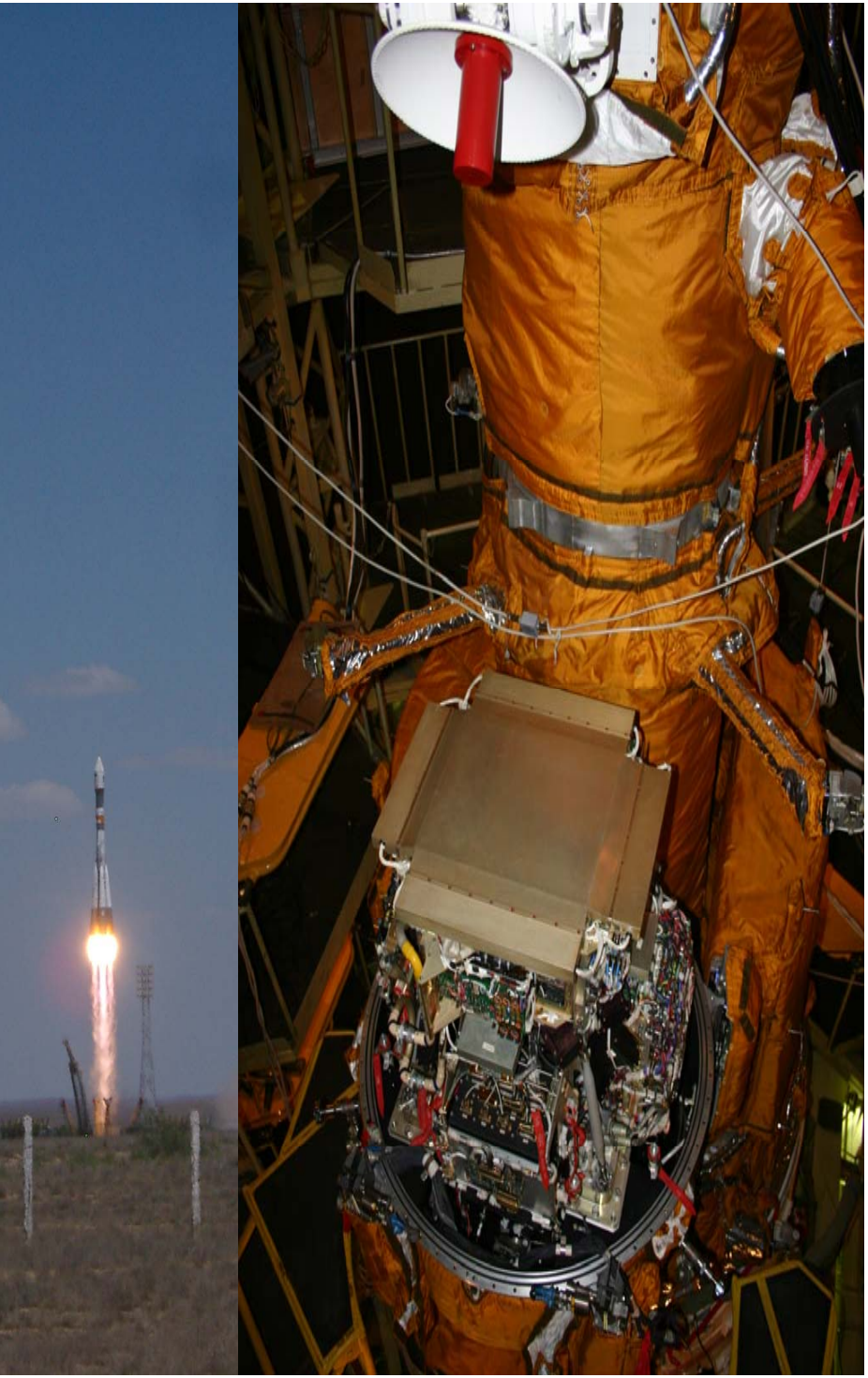


P A M E L A

Payload for Antimatter / Matter Exploration and Light-nuclei Astrophysics

Mark Pearce

KTH, Department of Physics, Stockholm, Sweden

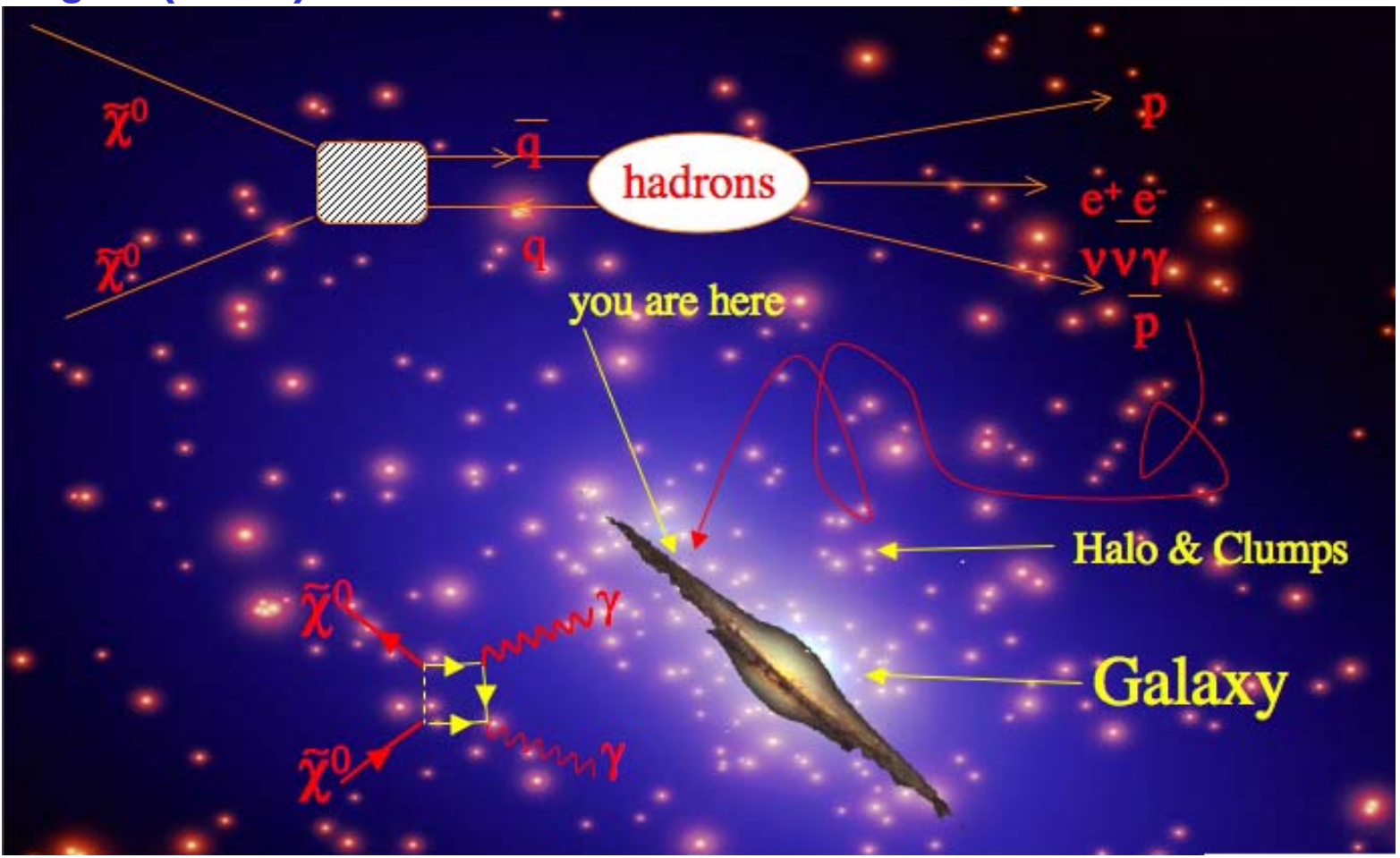
Dark Matter
FROM THE COSMOS TO THE LABORATORY

SLAC Summer Institute / 2007-08-07

Overview

- **Indirect searches for dark matter** with **antiparticles** (briefly - already covered by Lars Bergström)
- Description of **PAMELA instrument** and performance
- **Launch** into orbit (15th June 2006)
- **Flight data** (i.e. does it work?)

Signal (SUSY)…



… background

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

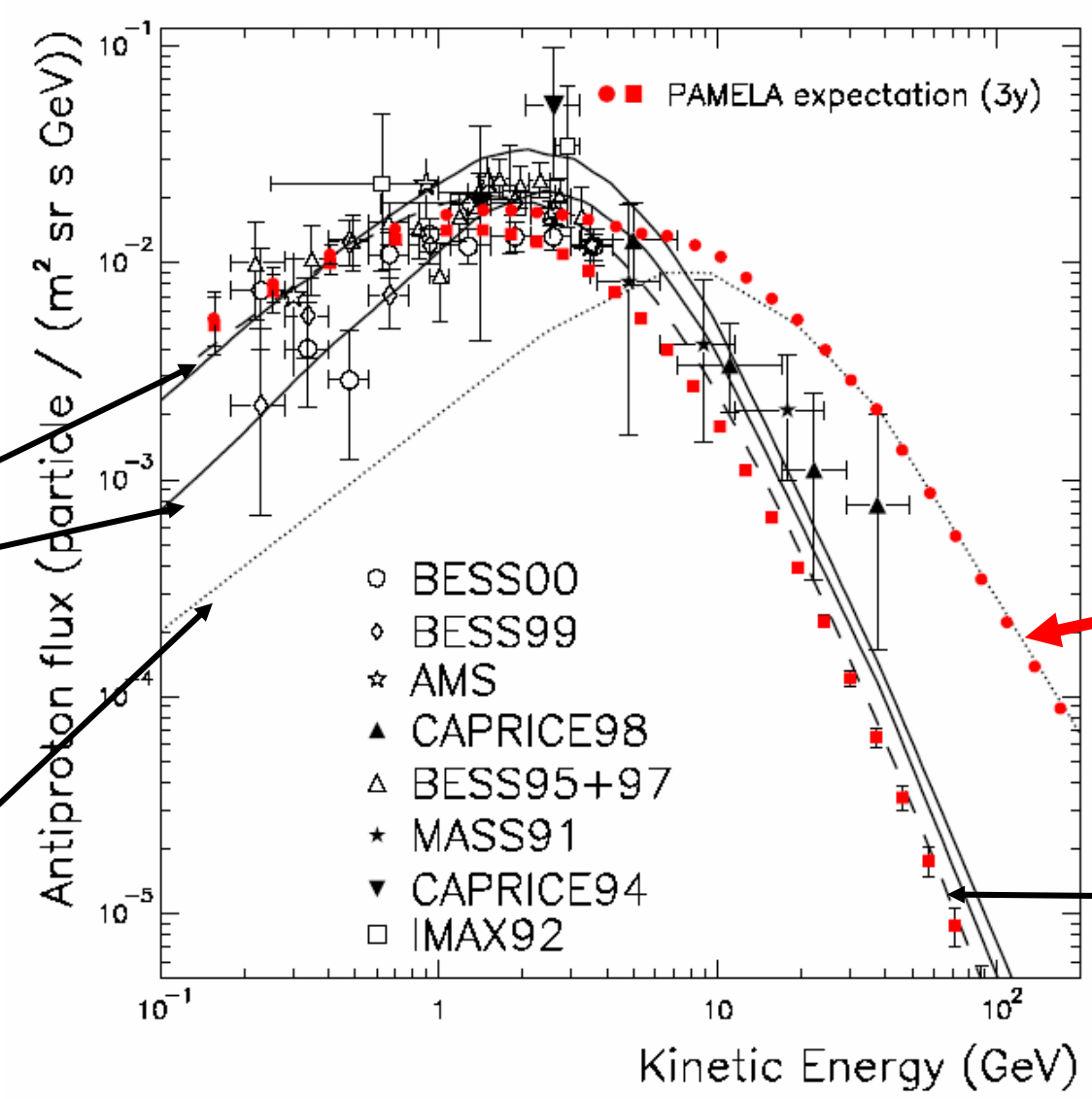
$$p_{CR} + p_{ISM} \rightarrow \pi^+ + X; \pi^+ \rightarrow \mu^+ + \nu_\mu; \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$p_{CR} + p_{ISM} \rightarrow \pi^0 + X; \pi^0 \rightarrow \gamma + \gamma; \gamma \rightarrow e^+ + e^-$$

Antiprotons

AMS-01: space shuttle, 1998

CAPRICE balloon experiment, 1998



Secondary production (upper and lower limits)

Simon et al. ApJ 499 (1998) 250.

Primary production from $\chi\chi$ annhilation ($m(\chi)$ = 964 GeV)

Ullio : astro-ph/9904086

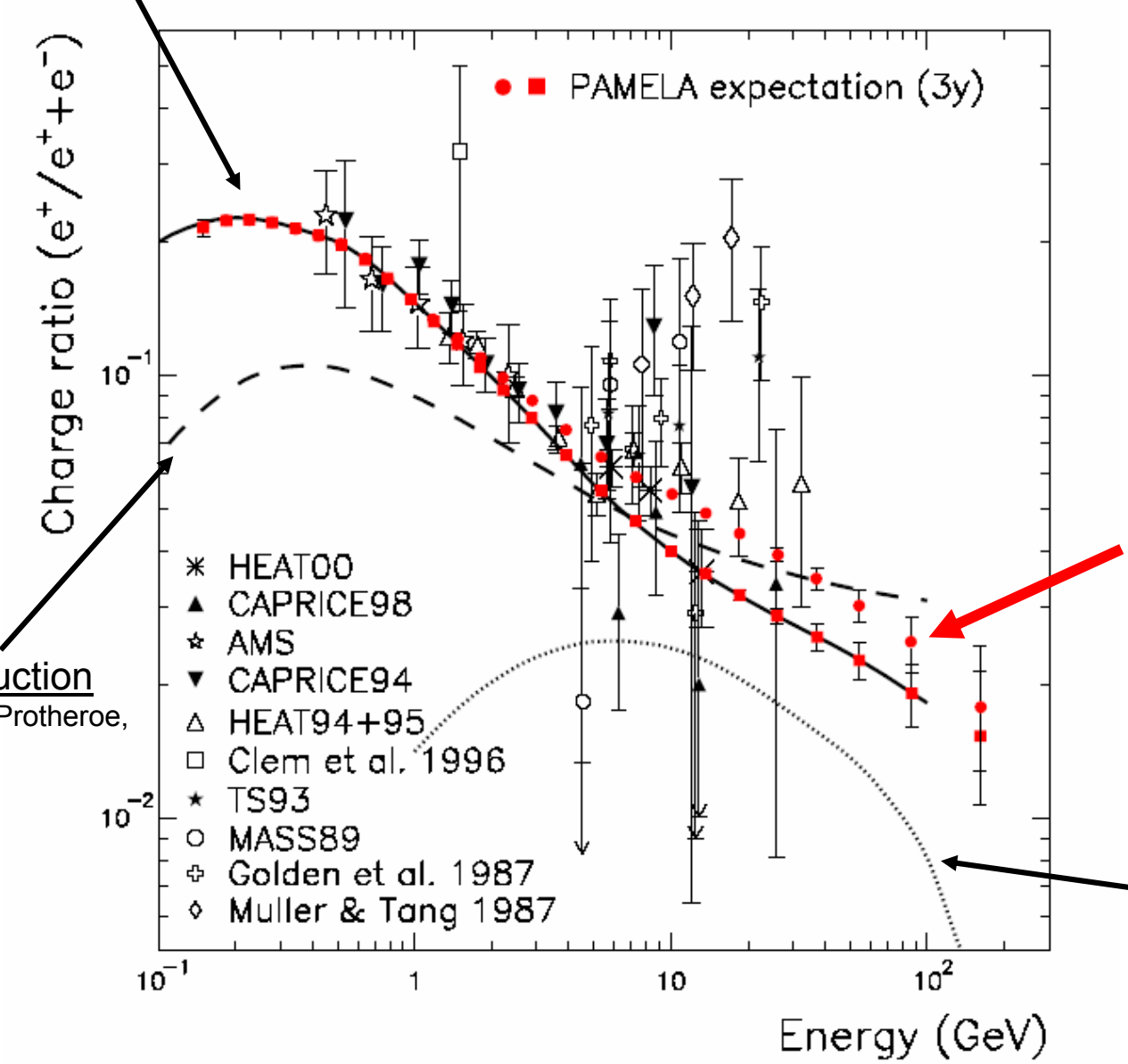
PAMELA

Secondary production 'C94 model' + primary $\chi\chi$ distortion

Secondary production (CAPRICE94-based) Bergström et al. ApJ 526 (1999) 215

Positrons

Secondary production
'Moskalenko + Strong model' without reacceleration. ApJ 493 (1998) 694.



Secondary production
'Leaky box model' R. Protheroe, ApJ 254 (1982) 391.

PAMELA

Secondary production
'M+S model' + primary $\chi\chi$ distortion

Primary production from $\chi\chi$ annhilation ($m(\chi)$ = 336 GeV)
Baltz + Edsjö, Phys Rev D59 (1999) 023511.

UED models: Kaluza-Klein dark matter

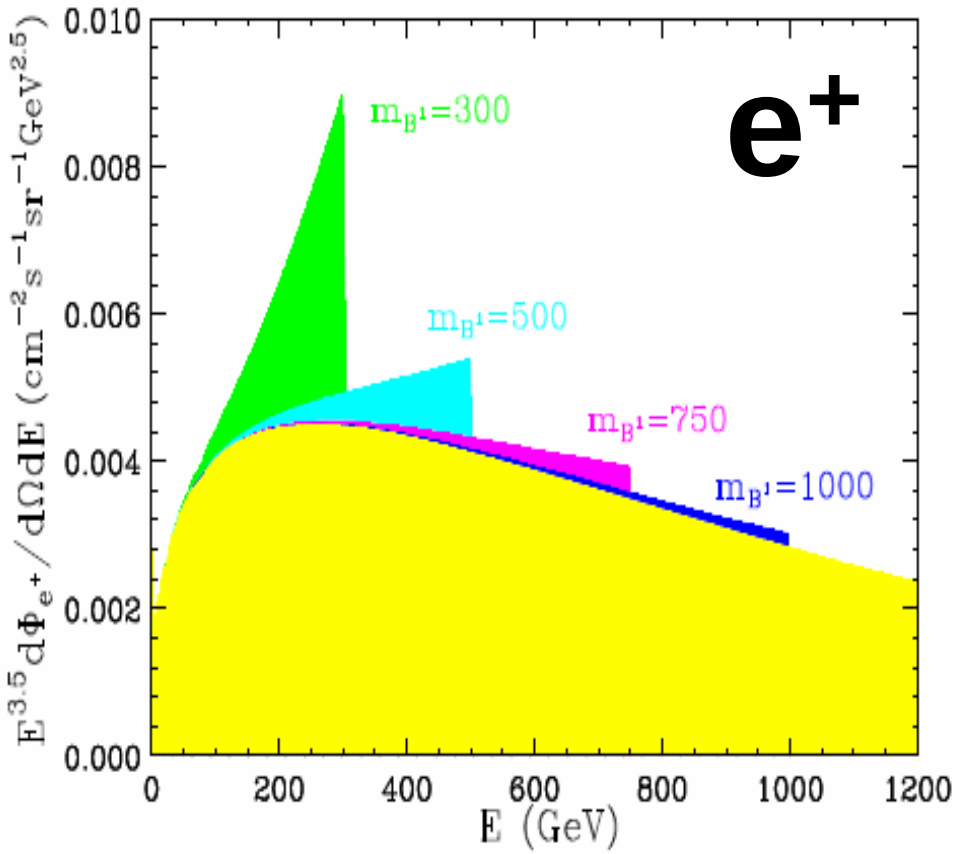


FIG. 2: Predicted positron signals (dark shaded) above background (light shaded) as a function of positron energy for $m_{B^1} = m_{e_L^1} = m_{e_R^1} = 100$, 500, 750, and 1000 GeV.

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

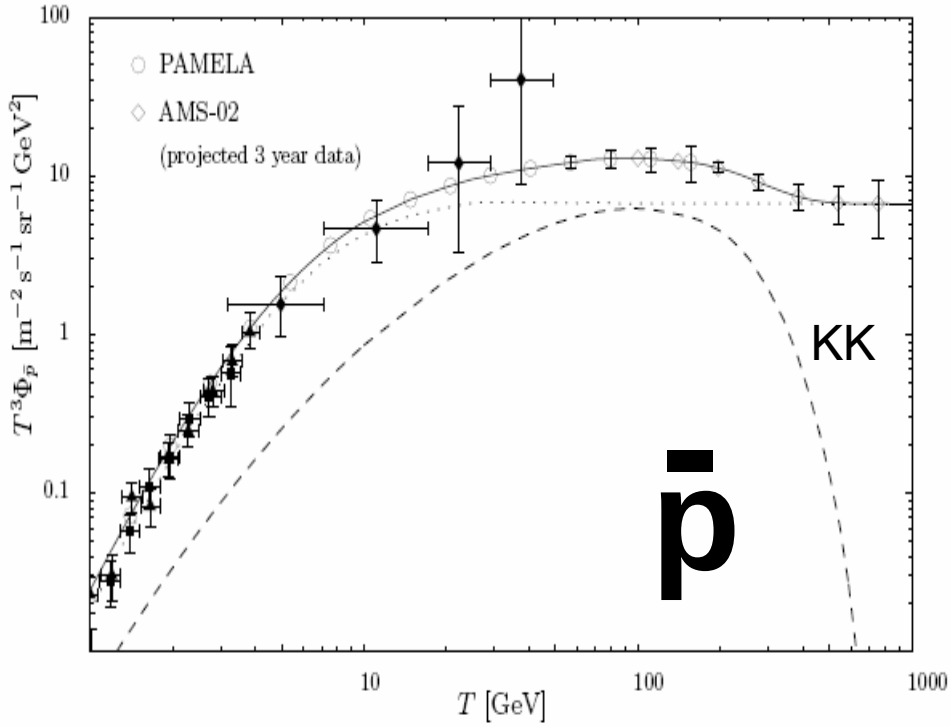
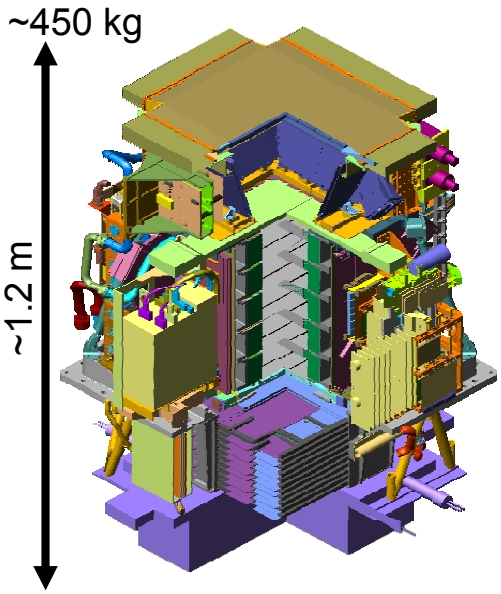


Figure 4. The solid line shows the expected antiproton spectrum for the case of a clumpy NFW profile with $f\delta = 200$ and $m_{B^{(1)}} = 800$ GeV; the dotted and dashed lines give, respectively, the background flux and the contribution from LKP annihilations alone. The data points are the same as 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.

Bringmann, astro-ph/0506219v2



e^- $\bar{p}$ e^+ p (He...)

Trigger, ToF, dE/dx

TOF (S1)

ANTICOINCIDENCE (CARD)

ANTICOINCIDENCE (CAT)

TOF (S2)

ANTICOINCIDENCE (CAS)

SPECTROMETER

+ -

Sign of charge, rigidity, dE/dx

Anticoincidence system reduces background.

TOF (S3)

CALORIMETER

Electron energy, dE/dx, lepton-hadron separation

S4

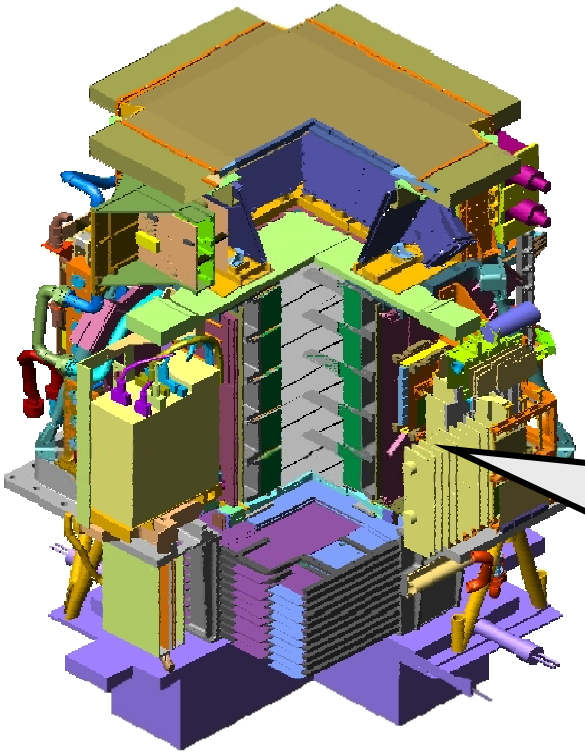
NEUTRON DETECTOR

NB:

e^+/p: 10^3 (1 GeV) → 5.10^3 (10 GeV)

p'/e^-: 5.10^3 (1 GeV) → $<10^2$ (10 GeV)

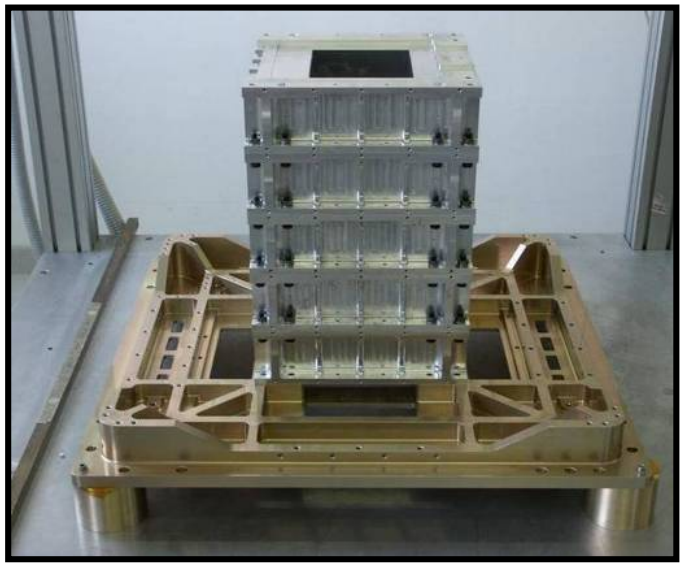
The magnet

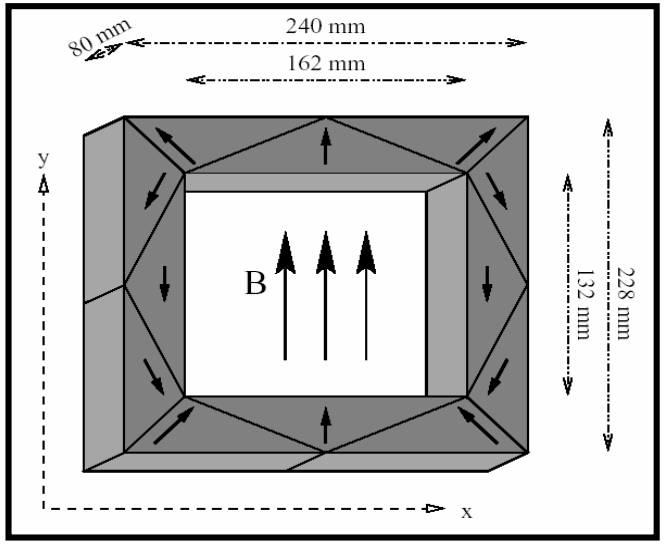


Characteristics:

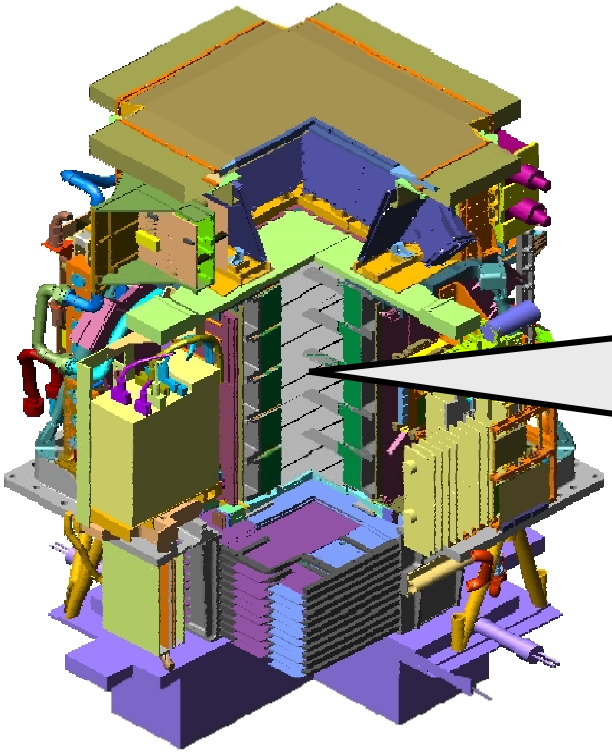
- **5 modules of permanent magnet (Nd-B-Fe alloy) in aluminum mechanics**
- Cavity dimensions (162 x 132 x 445) cm^3

  → GF ~ 21.5 $cm^2 sr$
- 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:

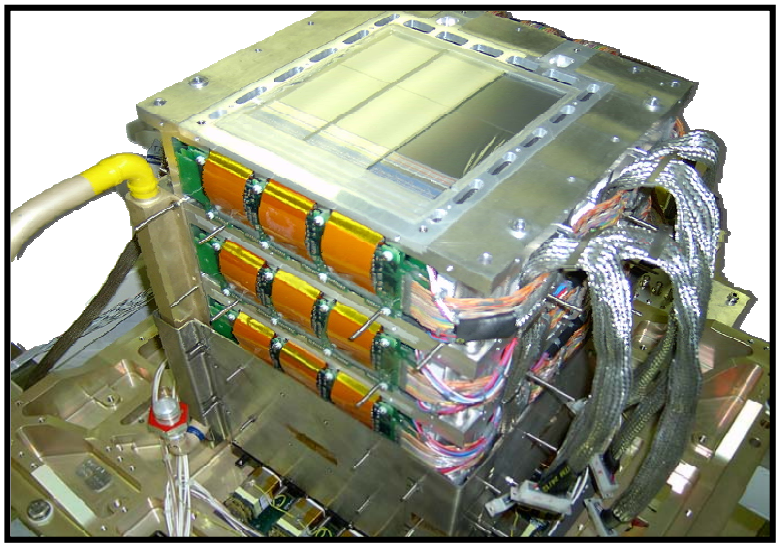
- **Rigidity measurement**
- **Sign of electric charge**
- **dE/dx (ionisation loss)**

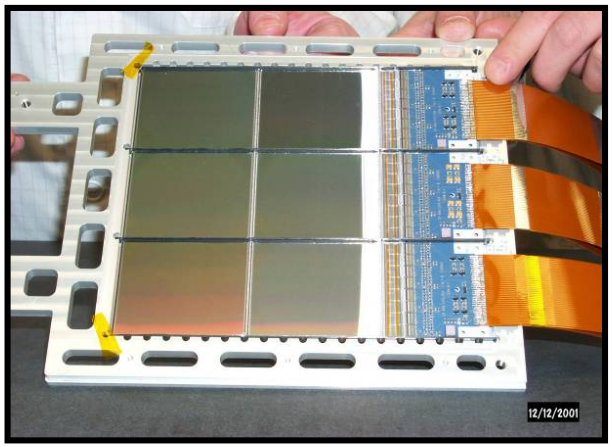
Characteristics:

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

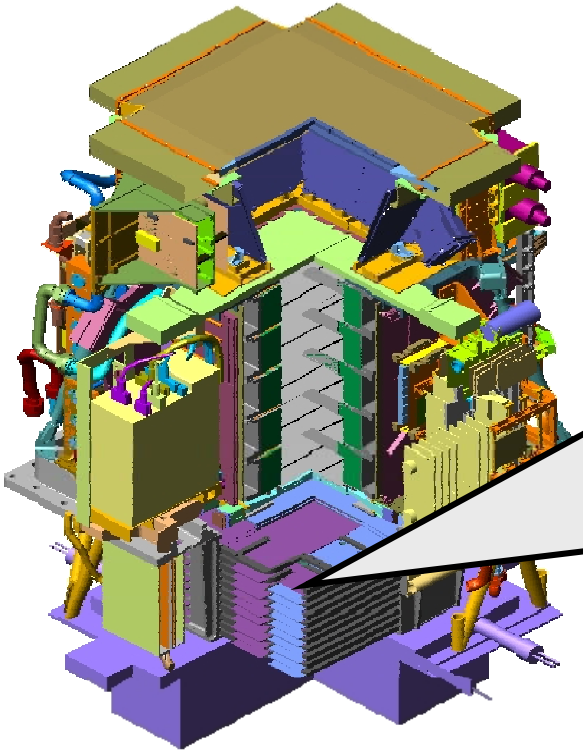
Performance:

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





The electromagnetic calorimeter



Main tasks:

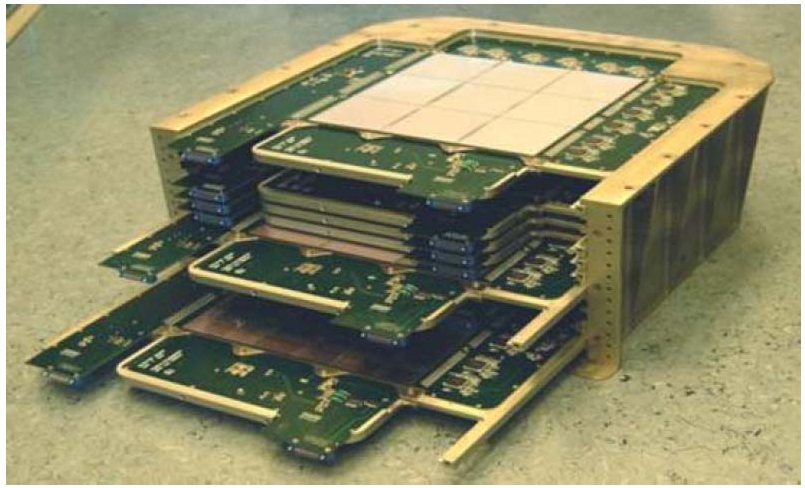
- **lepton/hadron discrimination**
- **$e^{+/-}$ energy measurement**

Characteristics:

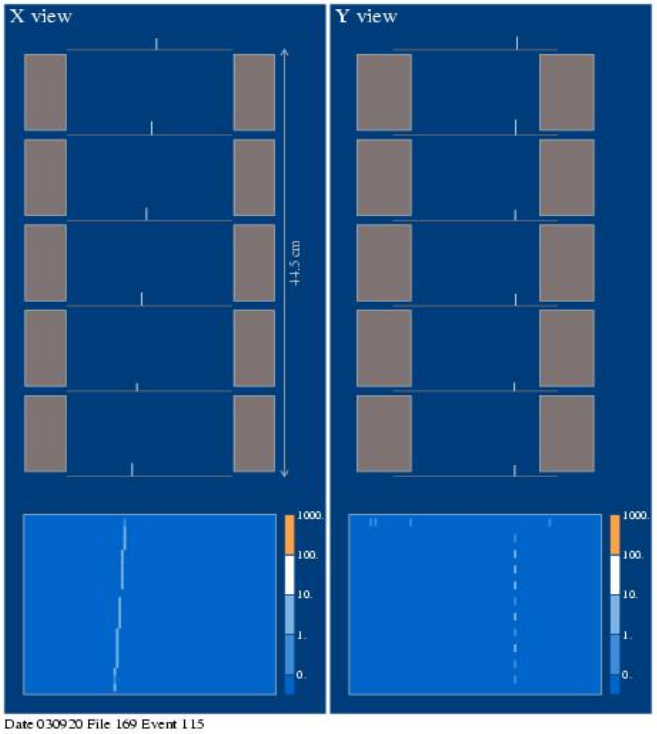
- **44 Si layers (X/Y) + 22 W planes**
- **16.3 X_o / 0.6 λ_L**
- 4224 channels
- Dynamic range: 1400 mip
- Self-trigger mode (> 300 GeV; GF~600 cm^2 sr)

Performance:

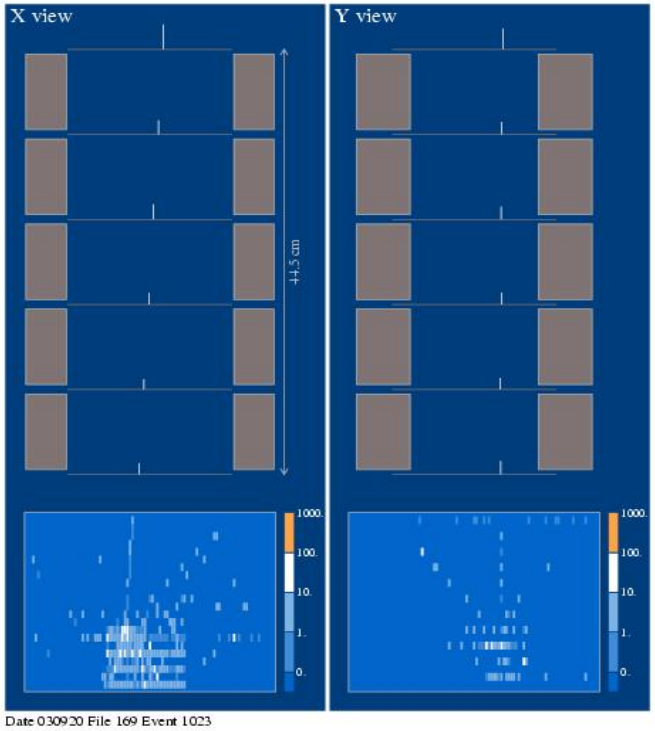
- p/e^+ selection efficiency ~ 90%
- p rejection factor ~10^6
- e rejection factor > 10^4
- **Energy resolution ~5% @ 200 GeV**



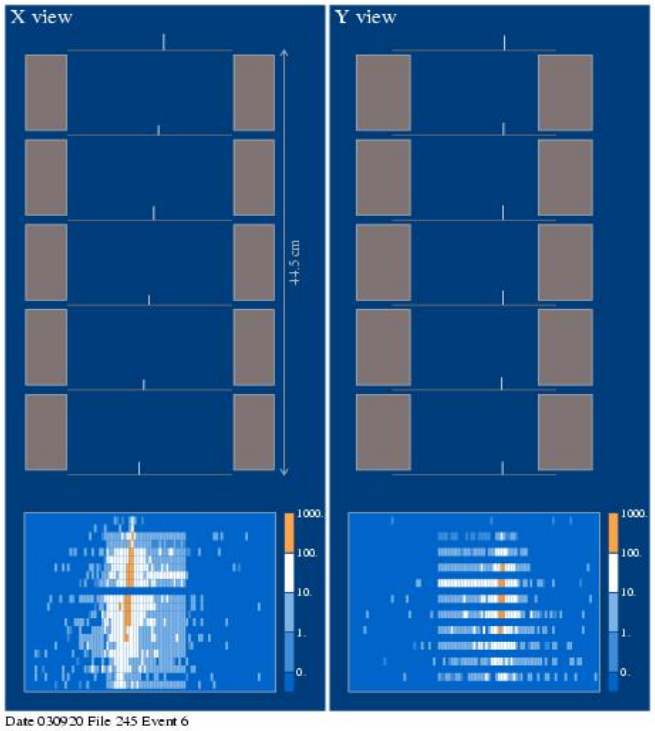
Combined tracker + calorimeter performance



Non-interacting p 100 GeV/c



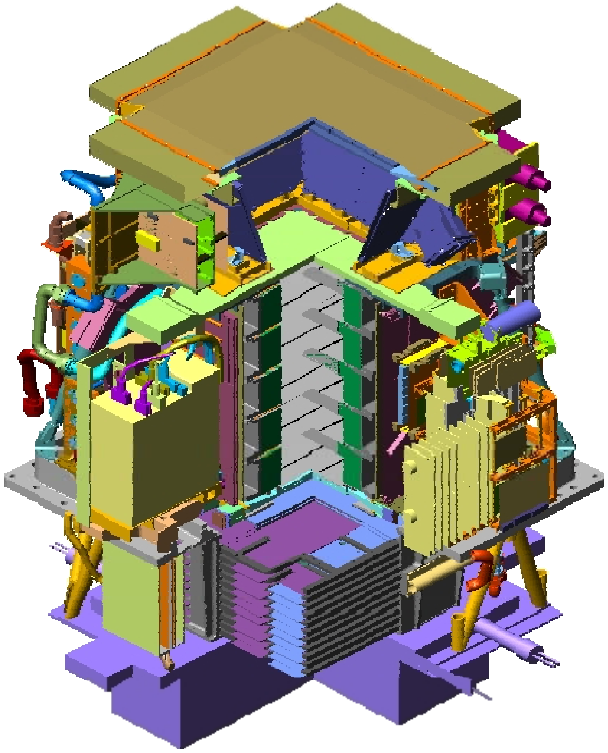
Interacting p 100 GeV/c

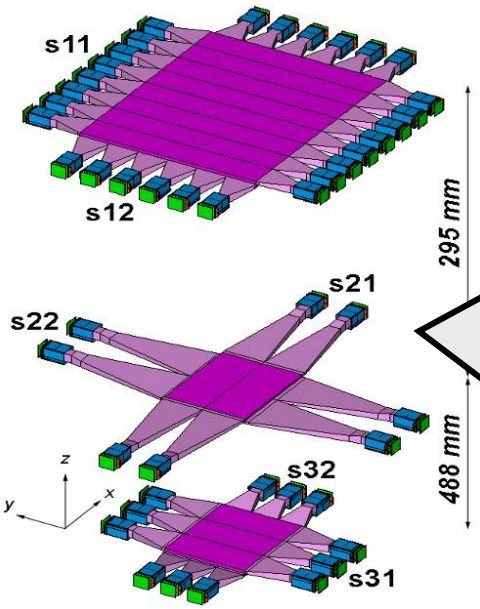


Interacting e^- 100 GeV/c

(CERN SpS testbeam 2003)

The time-of-flight system





Main tasks:

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

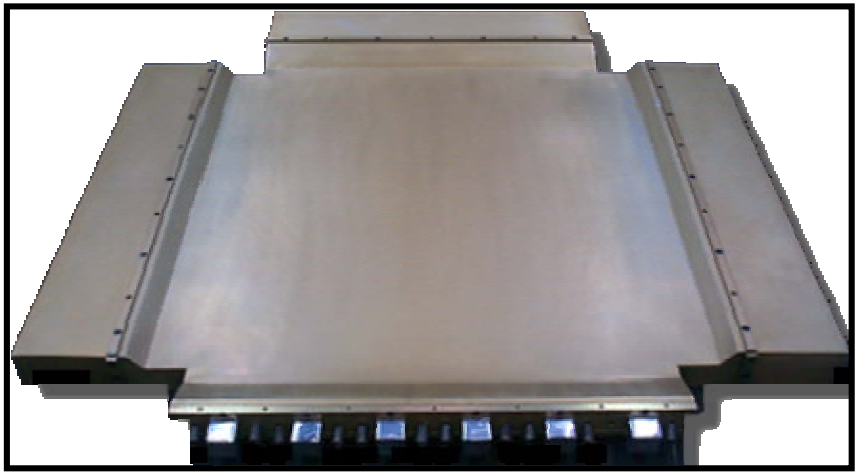
Characteristics:

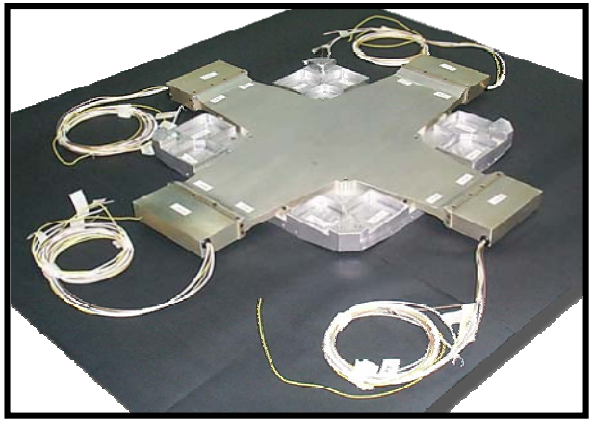
- **3 double-layer scintillator paddles**
- **X/Y segmentation**
- Total: 48 channels

Performance:

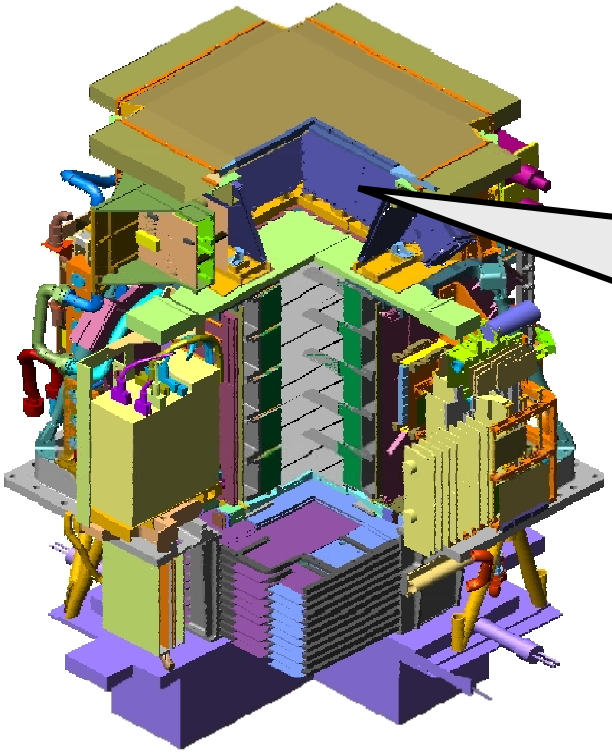
σ(paddle) ~ 110ps

σ(ToF) ~ 330ps (for MIPs)





The anticounter shields



Main tasks:

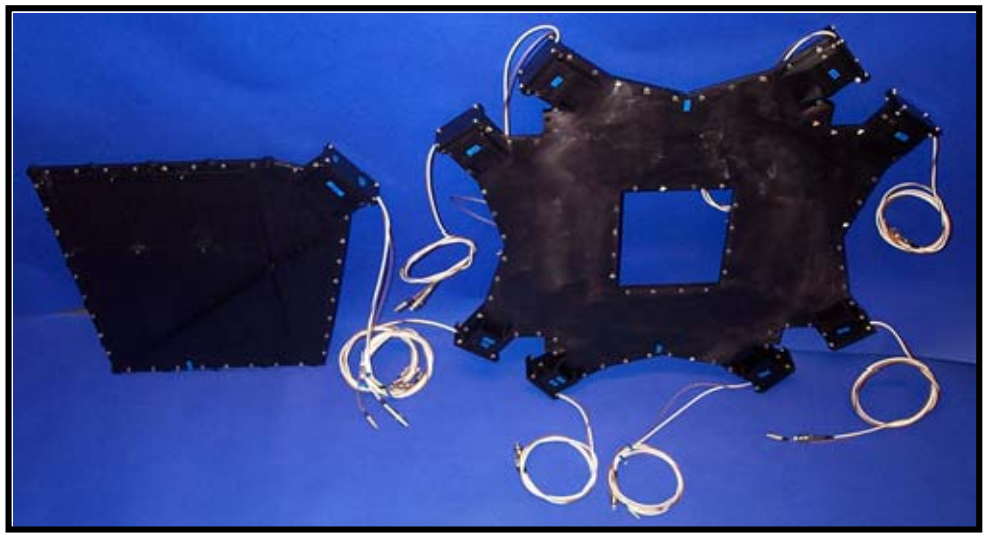
- **Rejection of events with particles interacting with the apparatus** (off-line and second-level trigger)

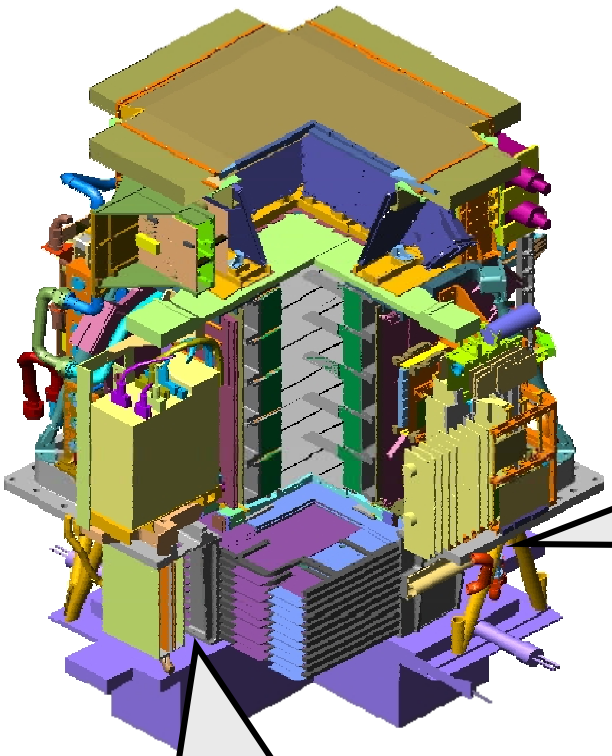
Characteristics:

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

Performance:

- MIP efficiency > 99.9%





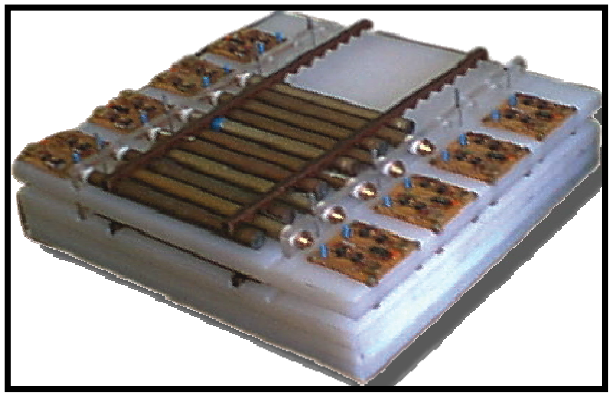
Neutron detector

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

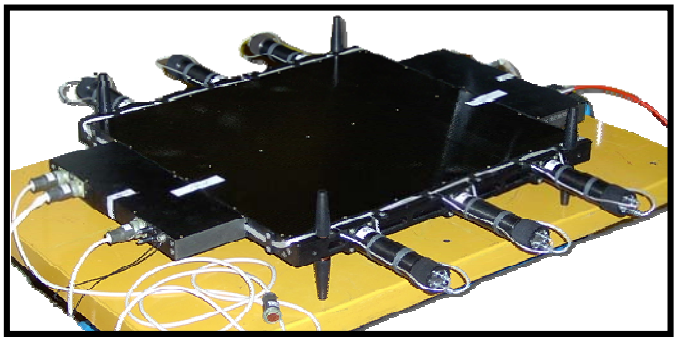


Main tasks:

- **Neutron Detector trigger**

Characteristics:

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



Shower-tail catcher

Design performance

Magnetic curvature (trigger)

'Spillover'

EM shower containment

Maximum Detectable Rigidity (MDR)

	Energy range	Particles/3 years
Antiproton flux	80 MeV - 190 GeV	$>3\times10^4$
Positron flux	50 MeV – 270 GeV	$>3\times10^5$
Electron flux	up to 400 GeV	6×10^6
Proton flux	up to 700 GeV	3×10^8
Electron/positron flux	up to 2 TeV (from calorimeter)	
Light nuclei (up to Z=6)	up to 200 GeV/n He/Be/C:	$4\ 10^{7/4/5}$
Antinuclei search	Sensitivity of 3×10^{-8} in He-bar/He	

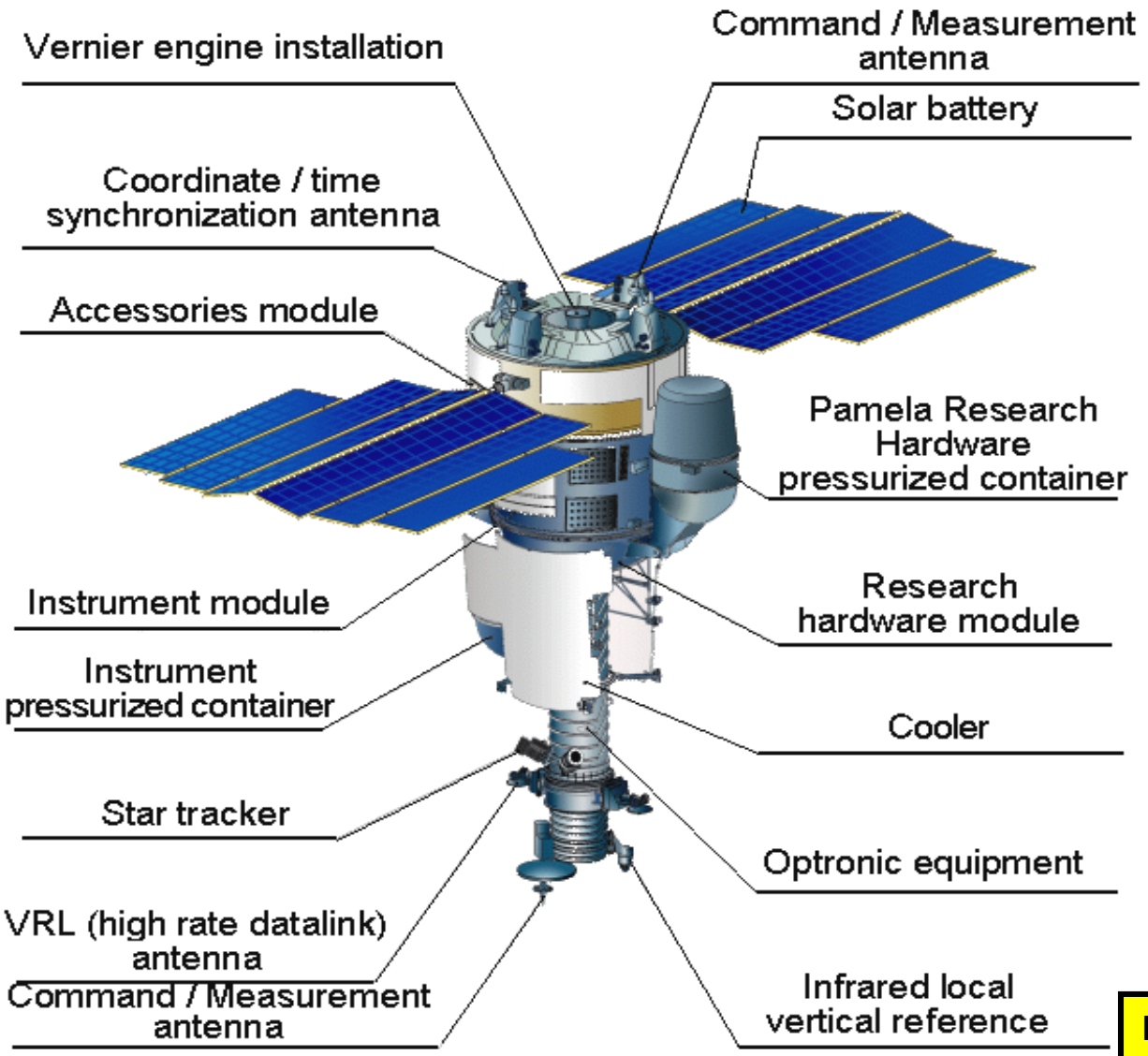
→ Unprecedented statistics and new energy range for cosmic ray physics

→ e.g. contemporary antiproton & positron energy, $E_{max} \approx 40$ GeV

→ Simultaneous measurements of many species – constrains secondary production models

1 HEAT-PBAR flight ~ 22.4 days PAMELA data
1 CAPRICE98 flight ~ 3.9 days PAMELA data

Resurs-DK1 Satellite

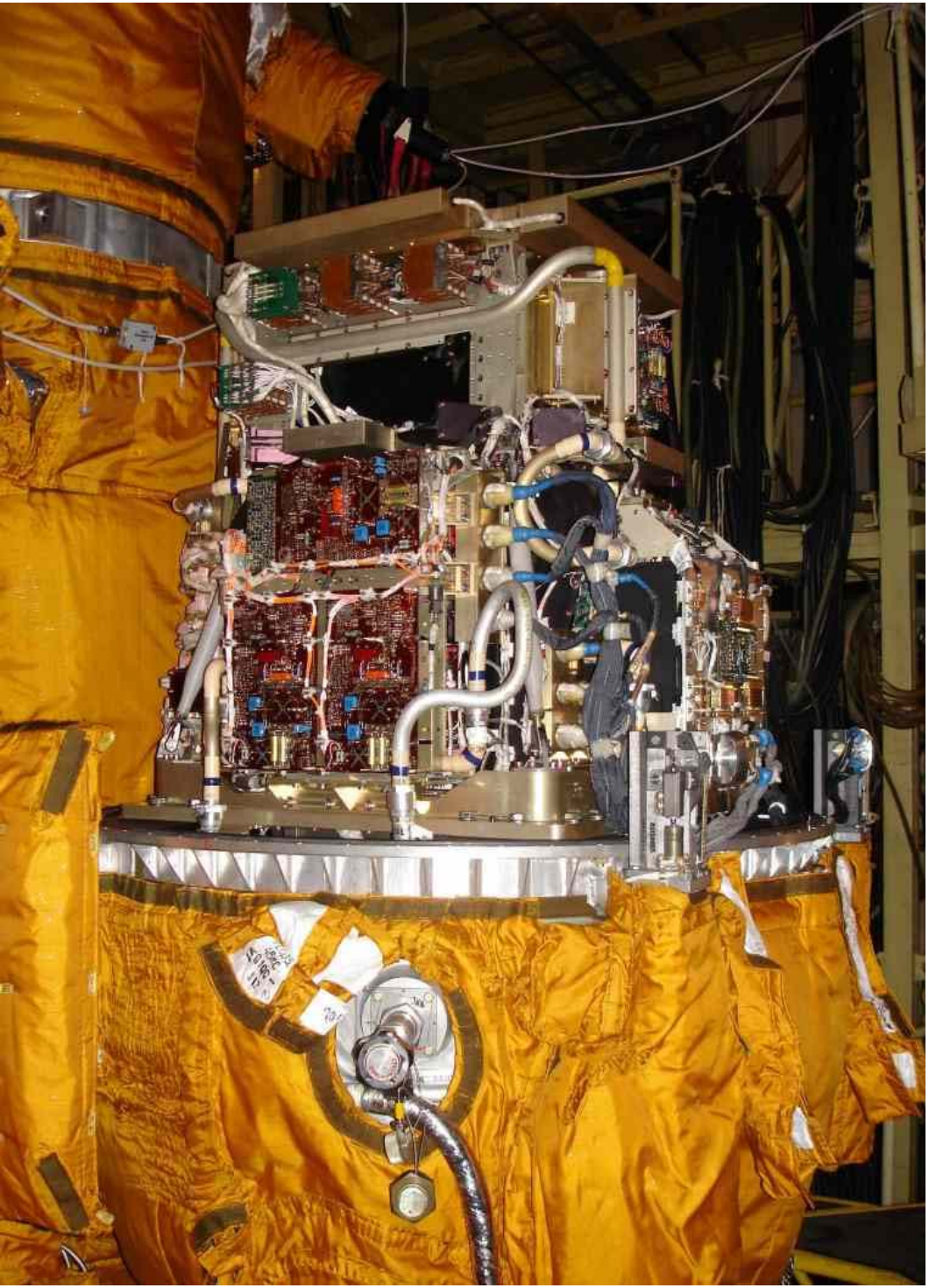


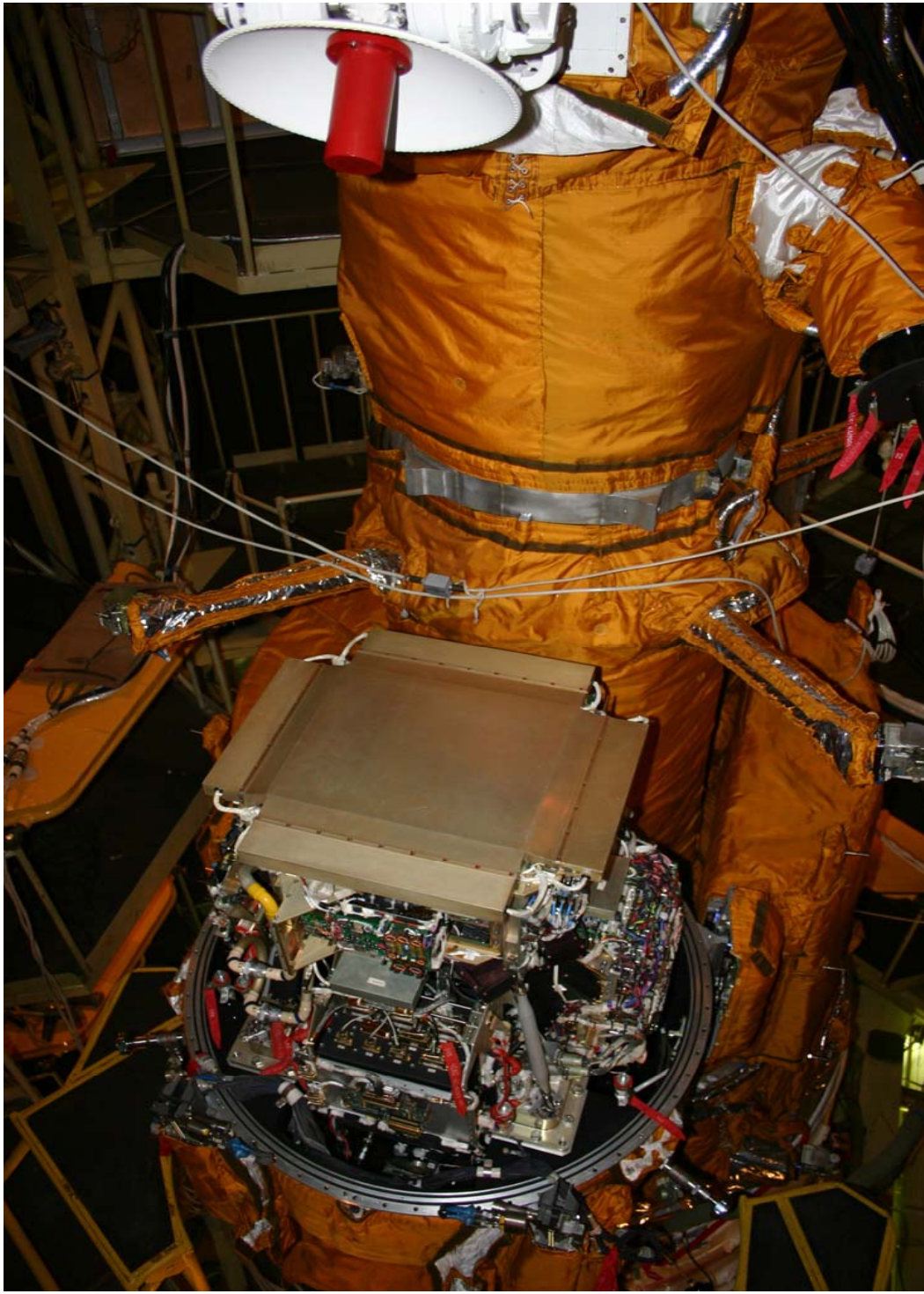
- Main task: multi-spectral remote sensing of earth's surface
- Built by TsSKB Progress in Samara (Russia)

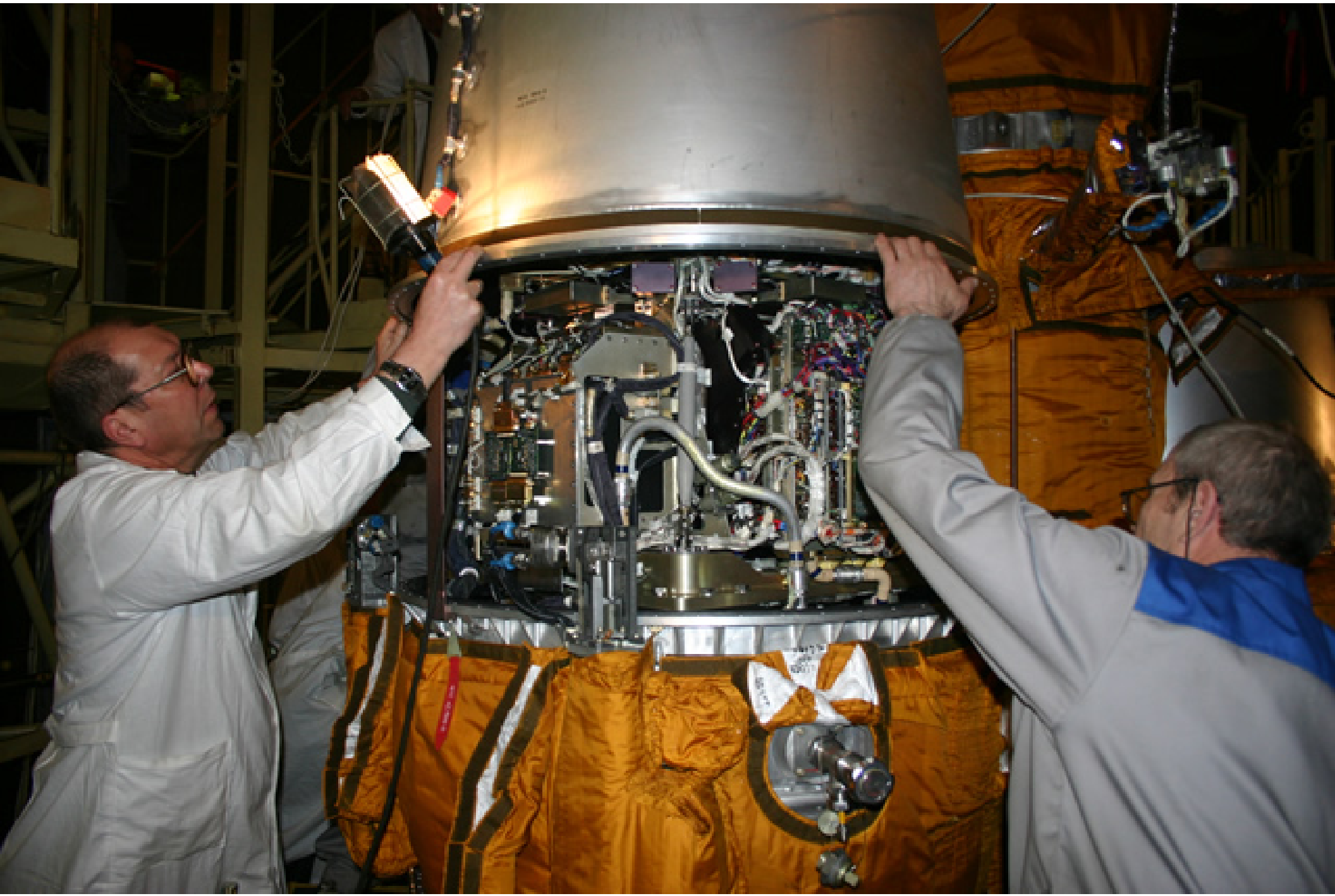
- Lifetime >3 years (assisted)
- Data transmitted to ground via radio downlink

- PAMELA mounted inside a pressurized container

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

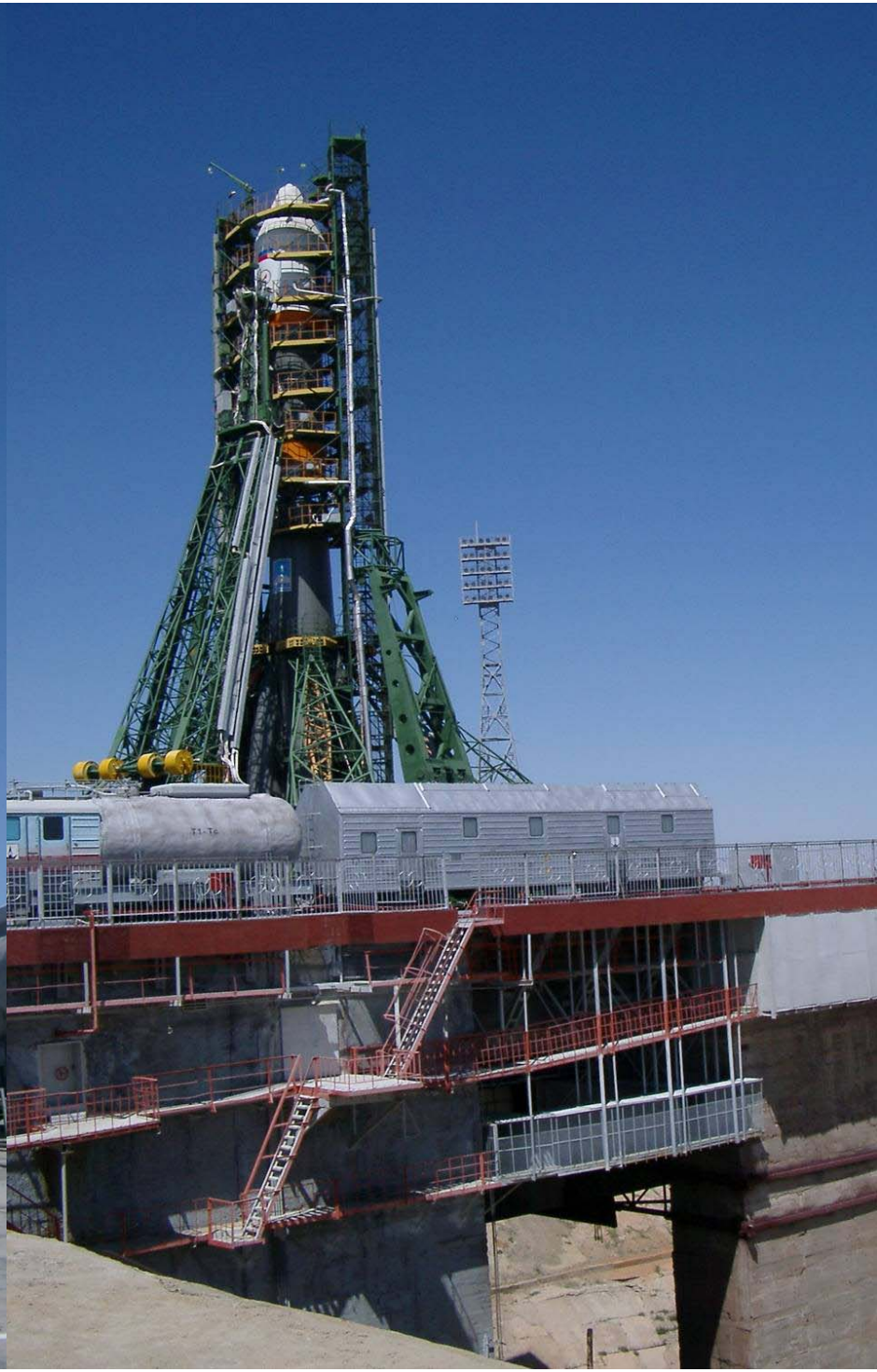






Gagarin - 12th April 1961

T – 1 day



Launch: 15th June 2006, 0800 UTC

PAMELA milestones

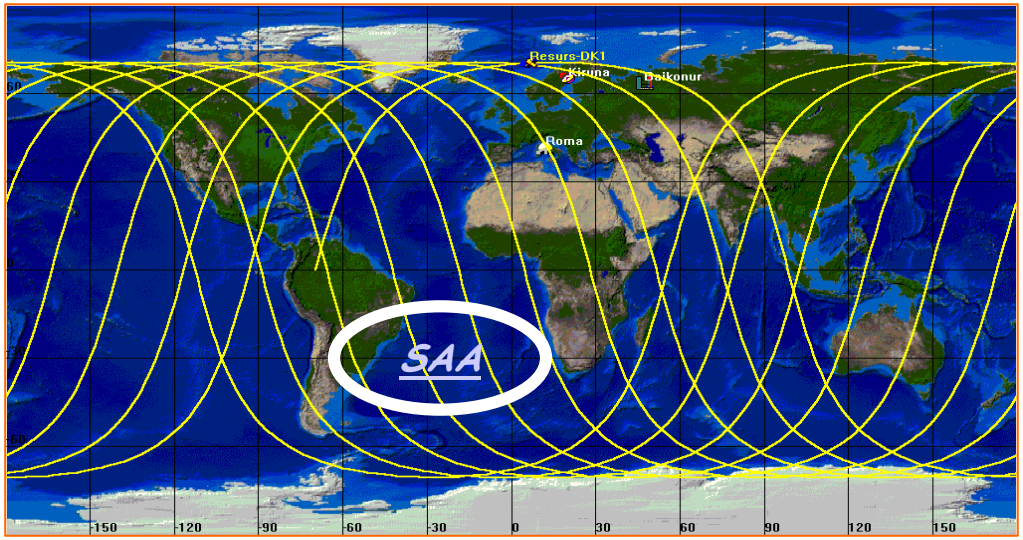
- **Launch from Baikonur:** June 15th 2006, 0800 UTC.
- **'First light':** June 21st 2006, 0300 UTC.

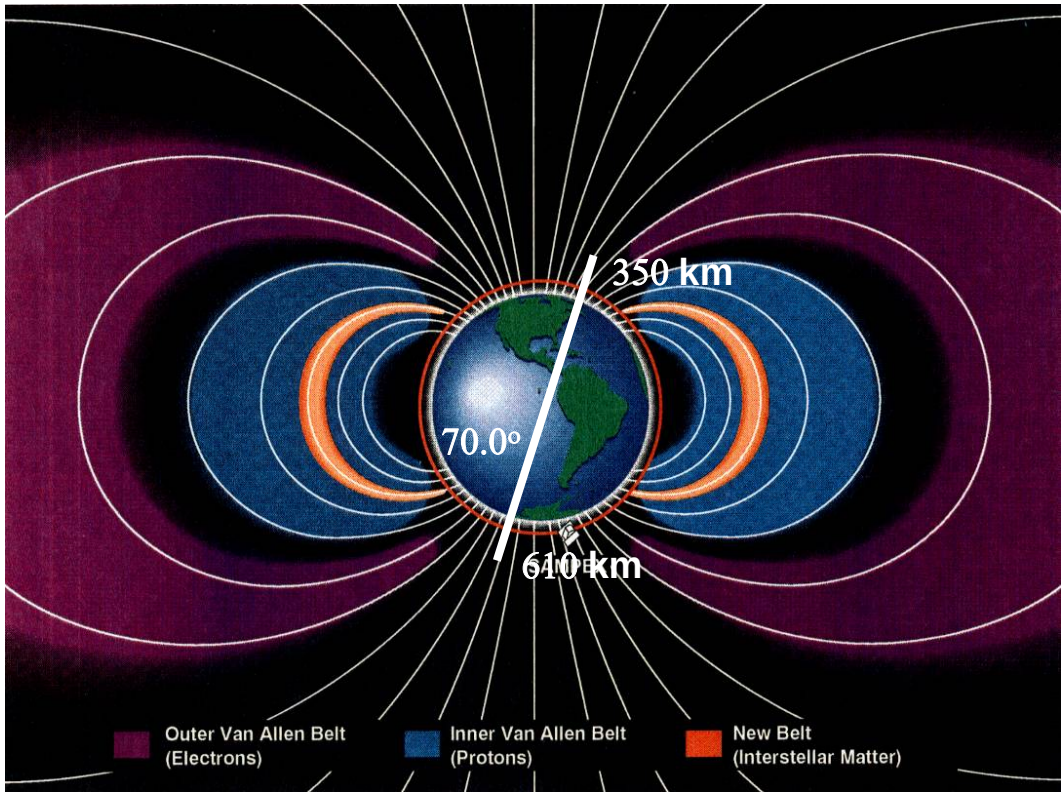
- Detectors operated as expected after launch
- Different trigger and hardware configurations evaluated

- **PAMELA in continuous data-taking mode since commissioning phase ended on July 11th 2006**

- **As of ~now:**
  - > 300 days of data taking (70% live-time)
  - ~5.5 TByte of raw data downlinked
  - ~610 million triggers recorded and under analysis

Orbit characteristics



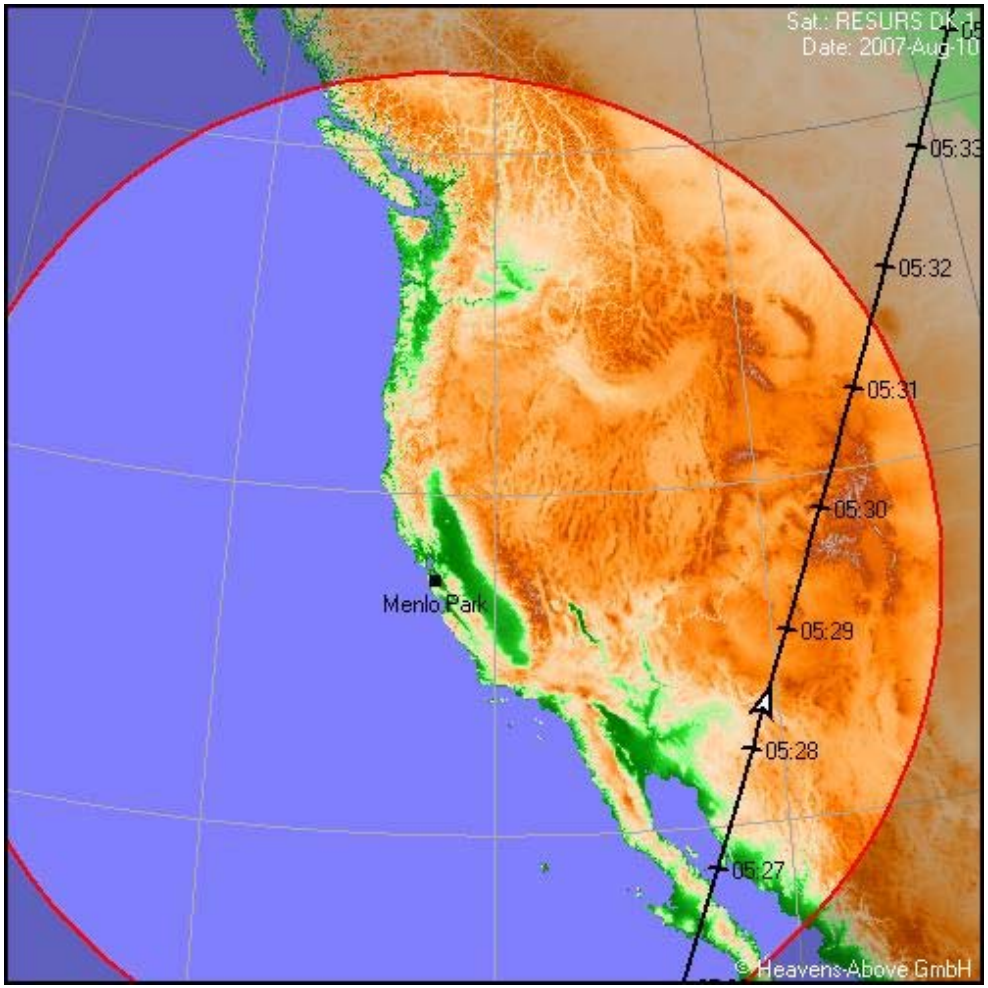


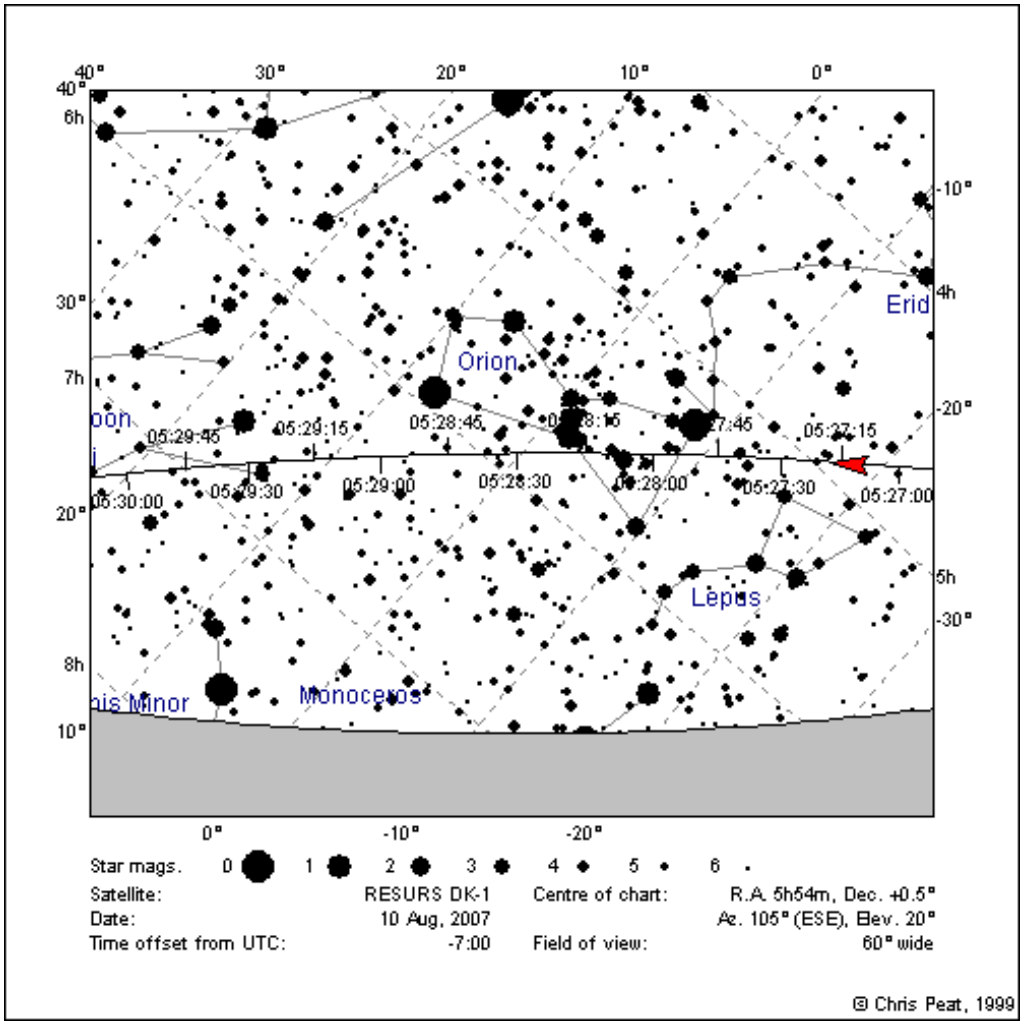
- Quasi-polar (70.0°)
- Elliptical (350 km - 600 km)
- PAMELA traverses the South Atlantic Anomaly
- At the South Pole PAMELA crosses the outer (electron) Van Allen belt

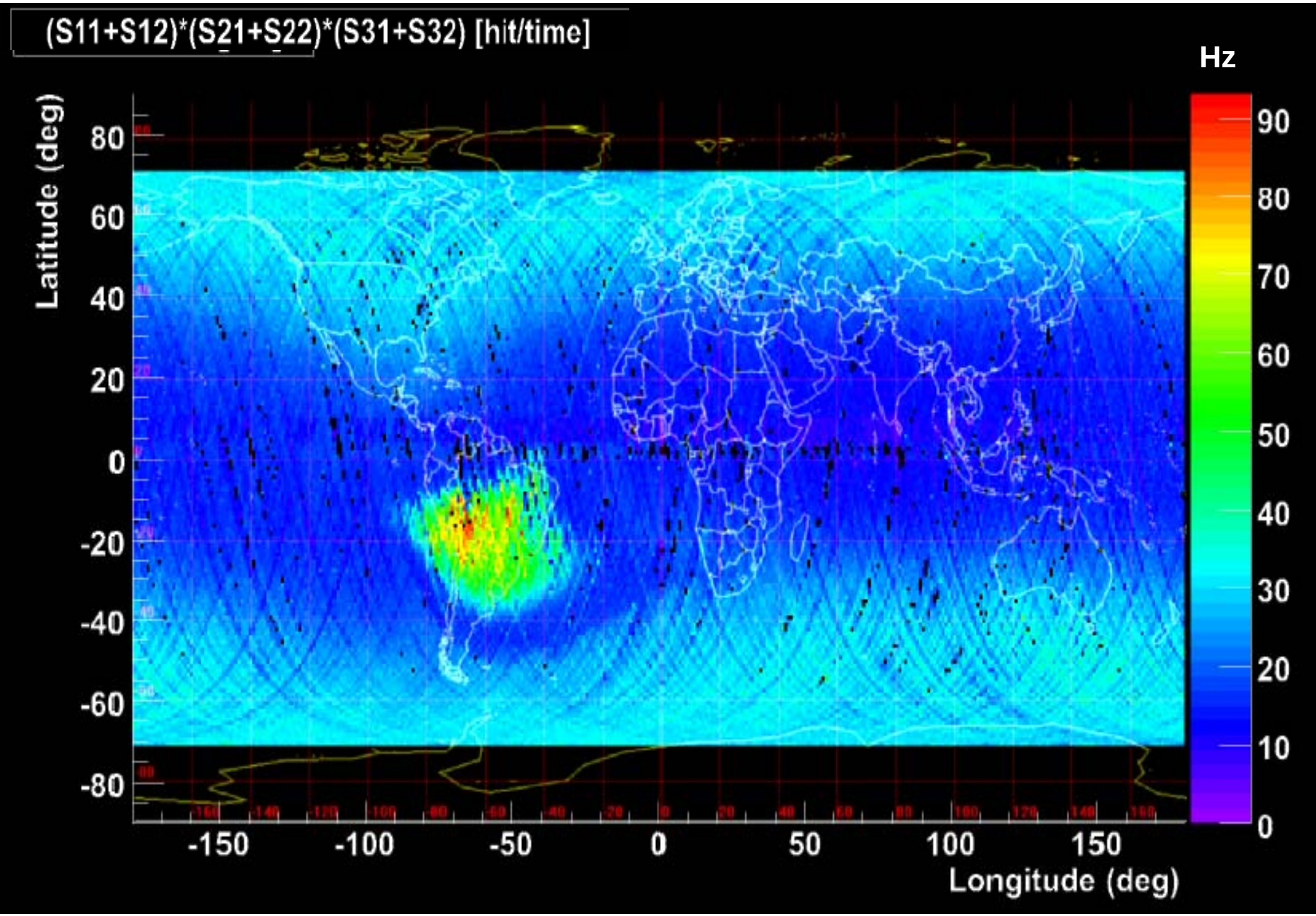
- Data downlinked to Moscow. ~15 GByte per day (2-3 sessions)

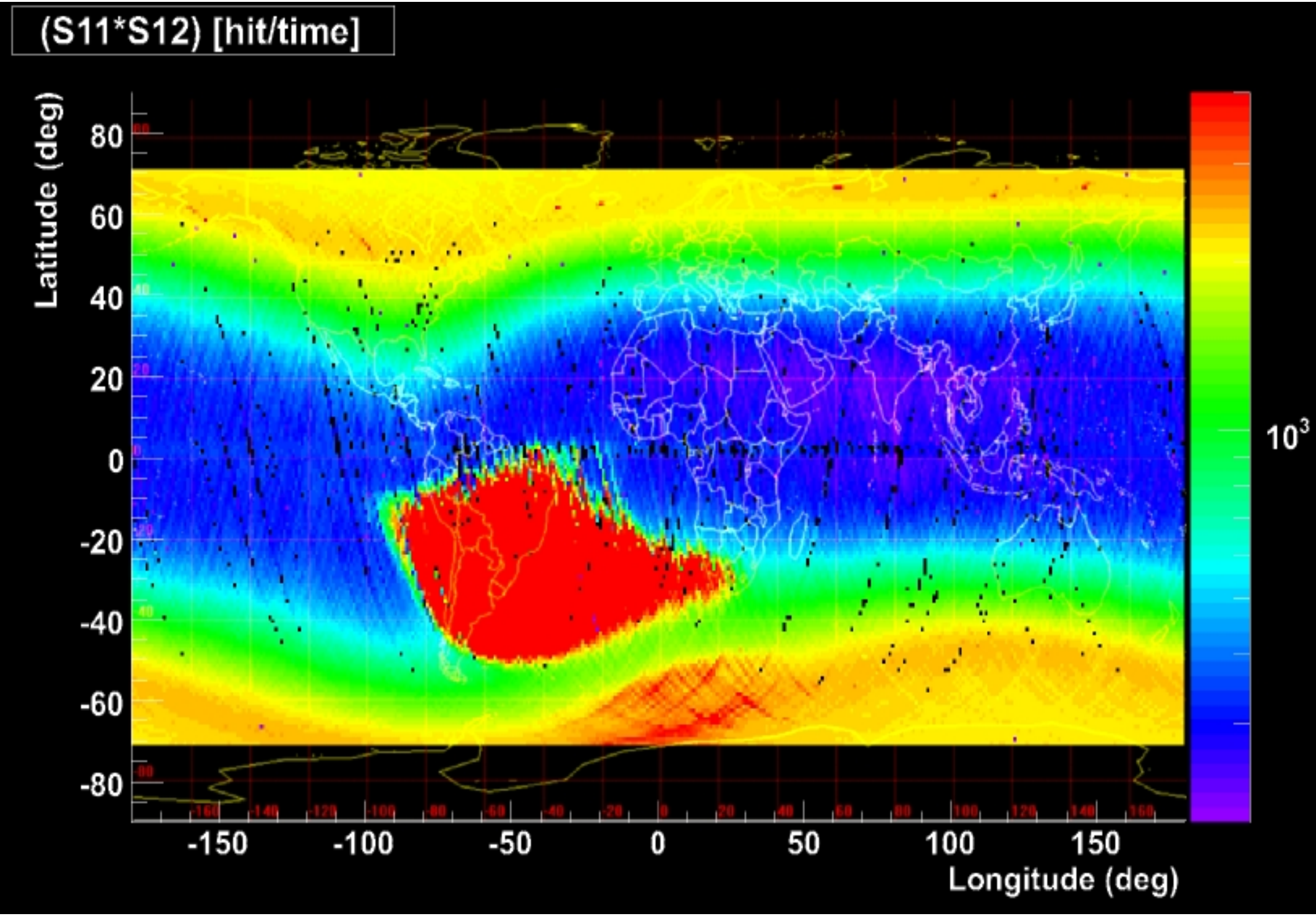
www.heavens-above.com

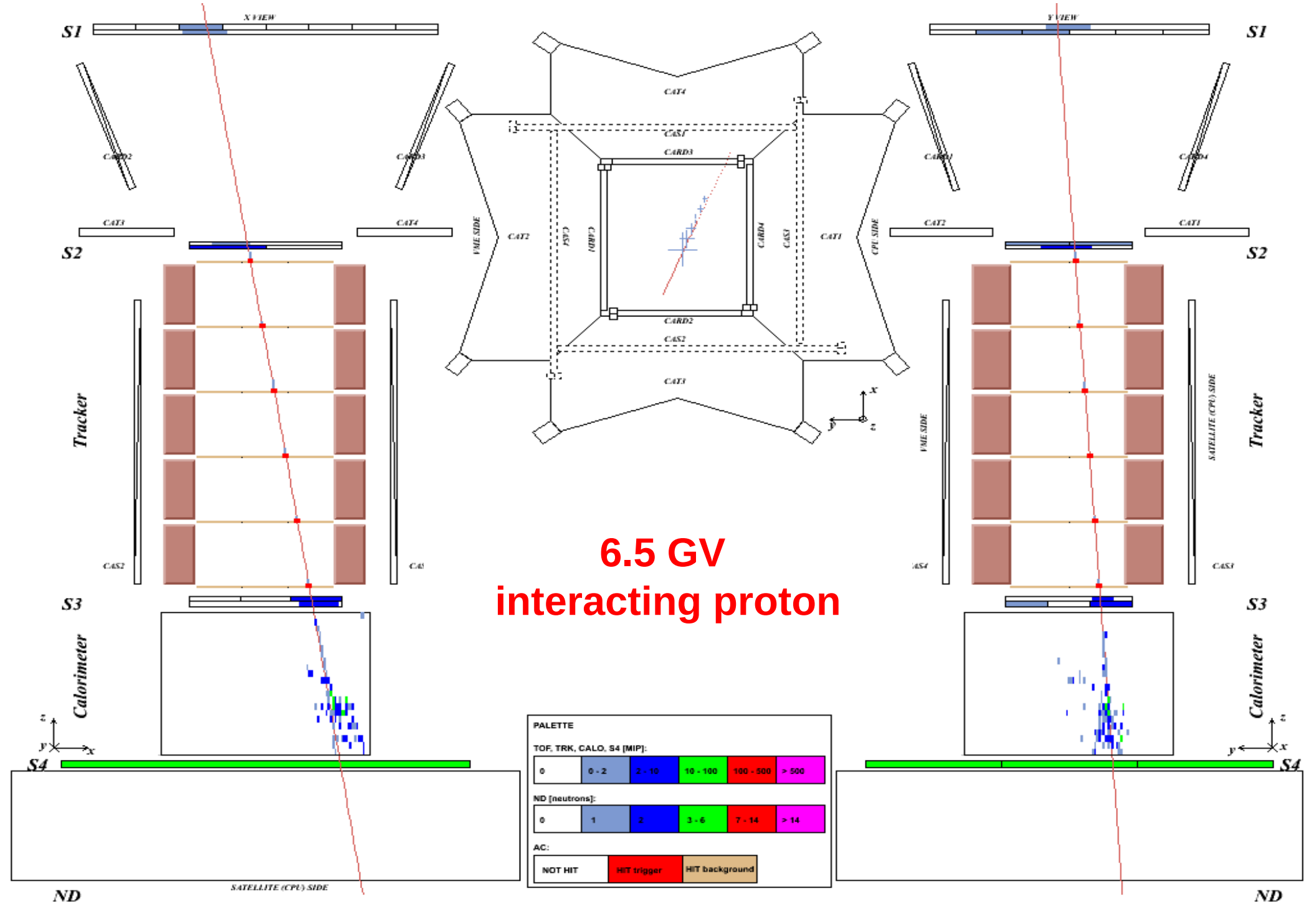
Next visible pass: Friday August 10th / ~0530






(S11+S12)*(S21+S22)*(S31+S32) [hit/time]
Hz
90
80
70
60
50
40
30
20
10
0
Latitude (deg)
80
60
40
20
0
-20
-40
-60
-80
-150
-100
-50
0
50
100
150
Longitude (deg)


(S11*S12) [hit/time]
Latitude (deg)
80
60
40
20
0
-20
-40
-60
-80
-150
-100
-50
0
50
100
150
Longitude (deg)
10^3

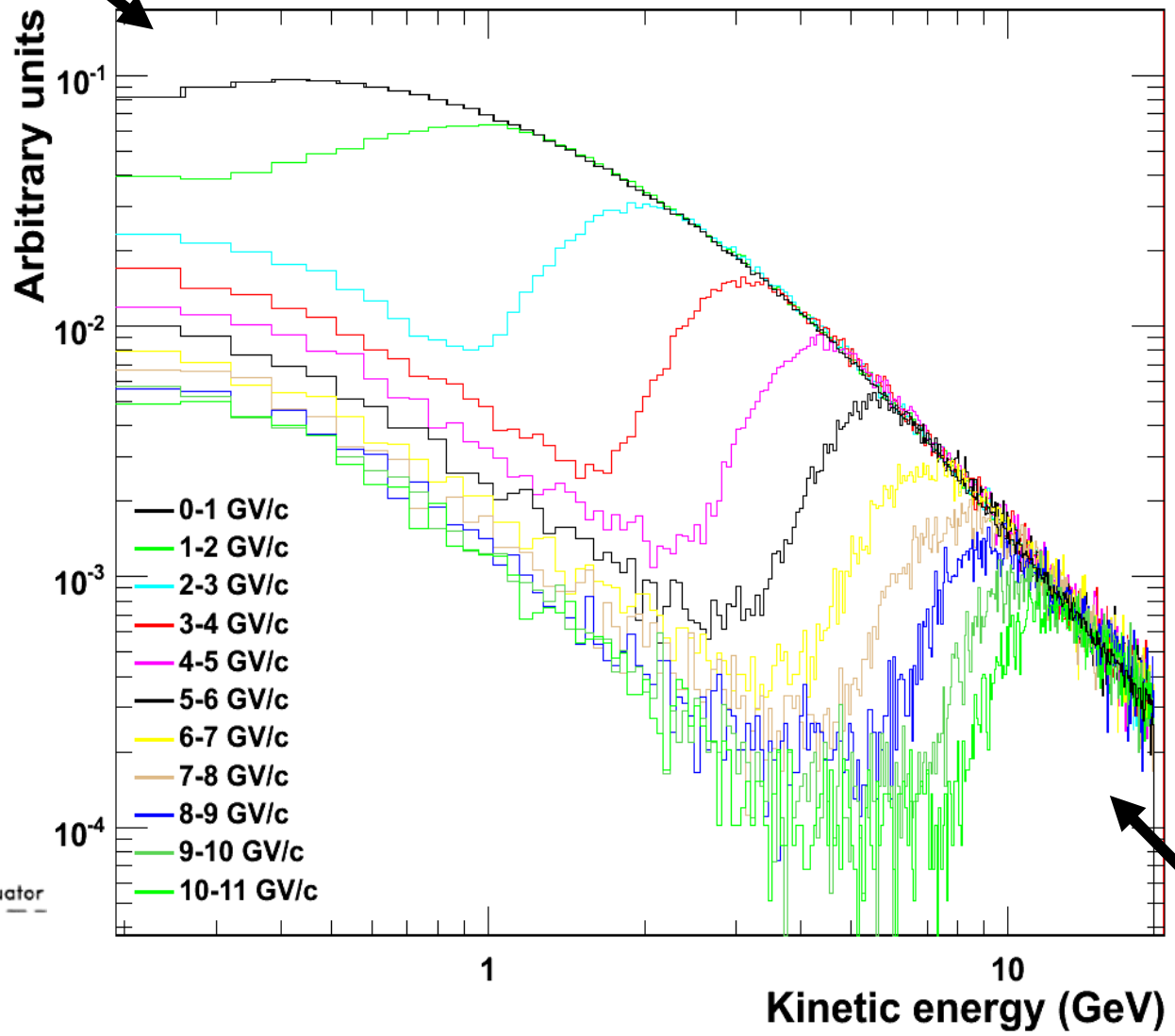


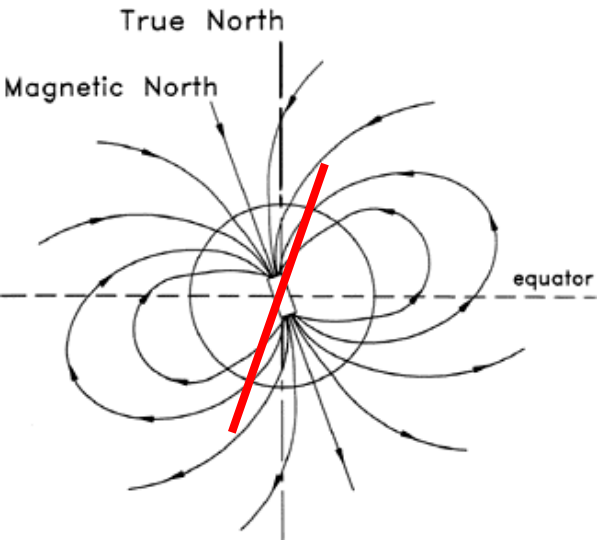
6.5 GV
interacting proton

Preliminary !!!

Polar regions

p spectra @ different cut-off rigidities

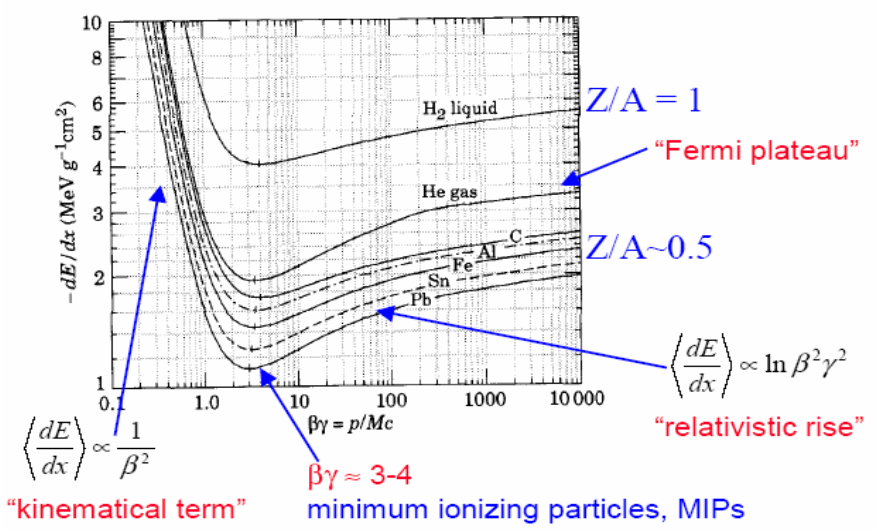


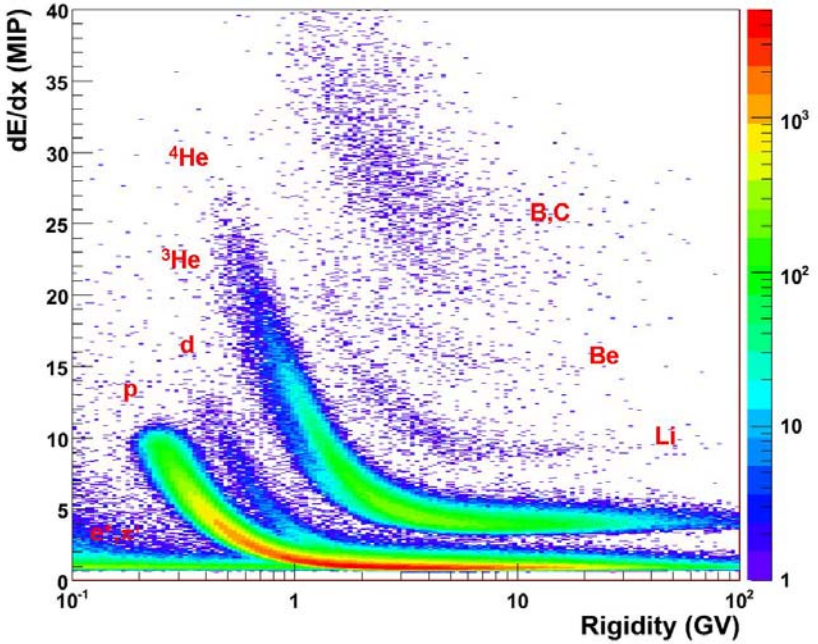


Equatorial regions

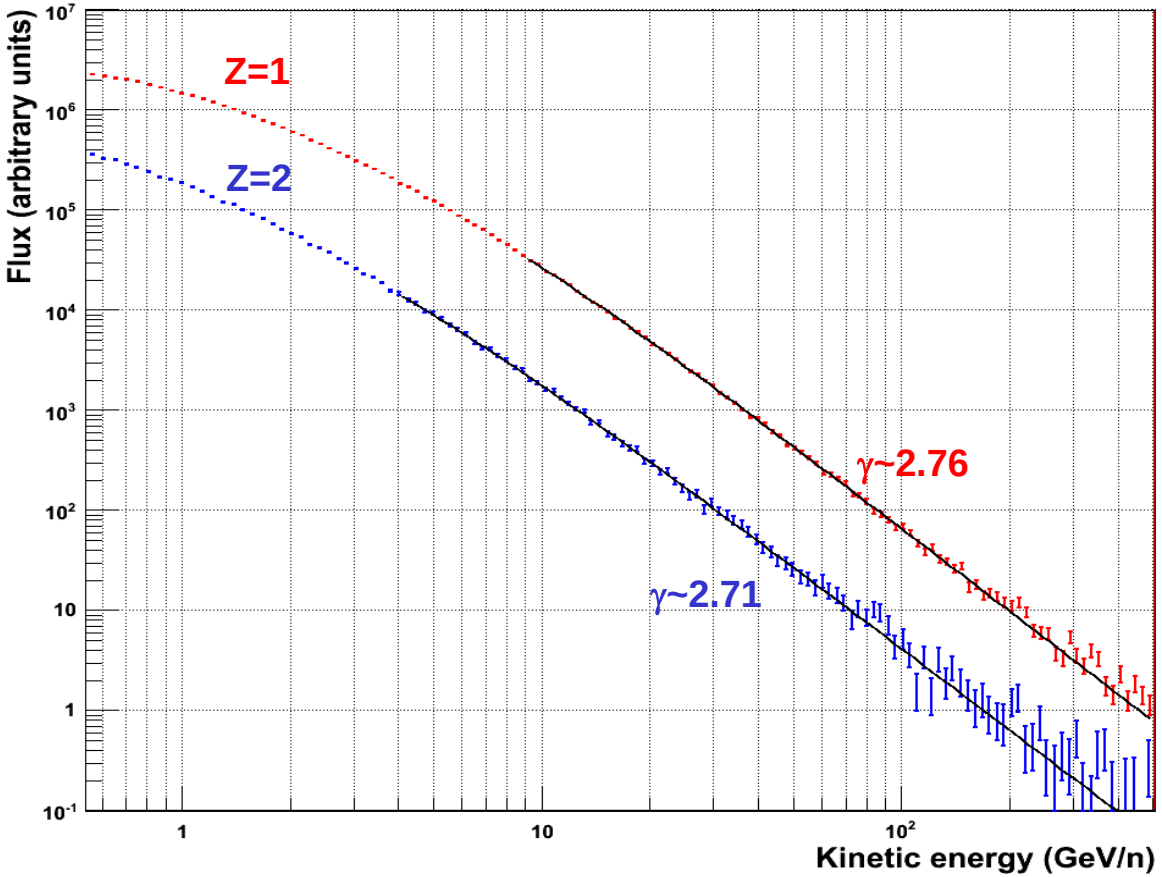
Preliminary !!!

dE/dx ~ Z^2



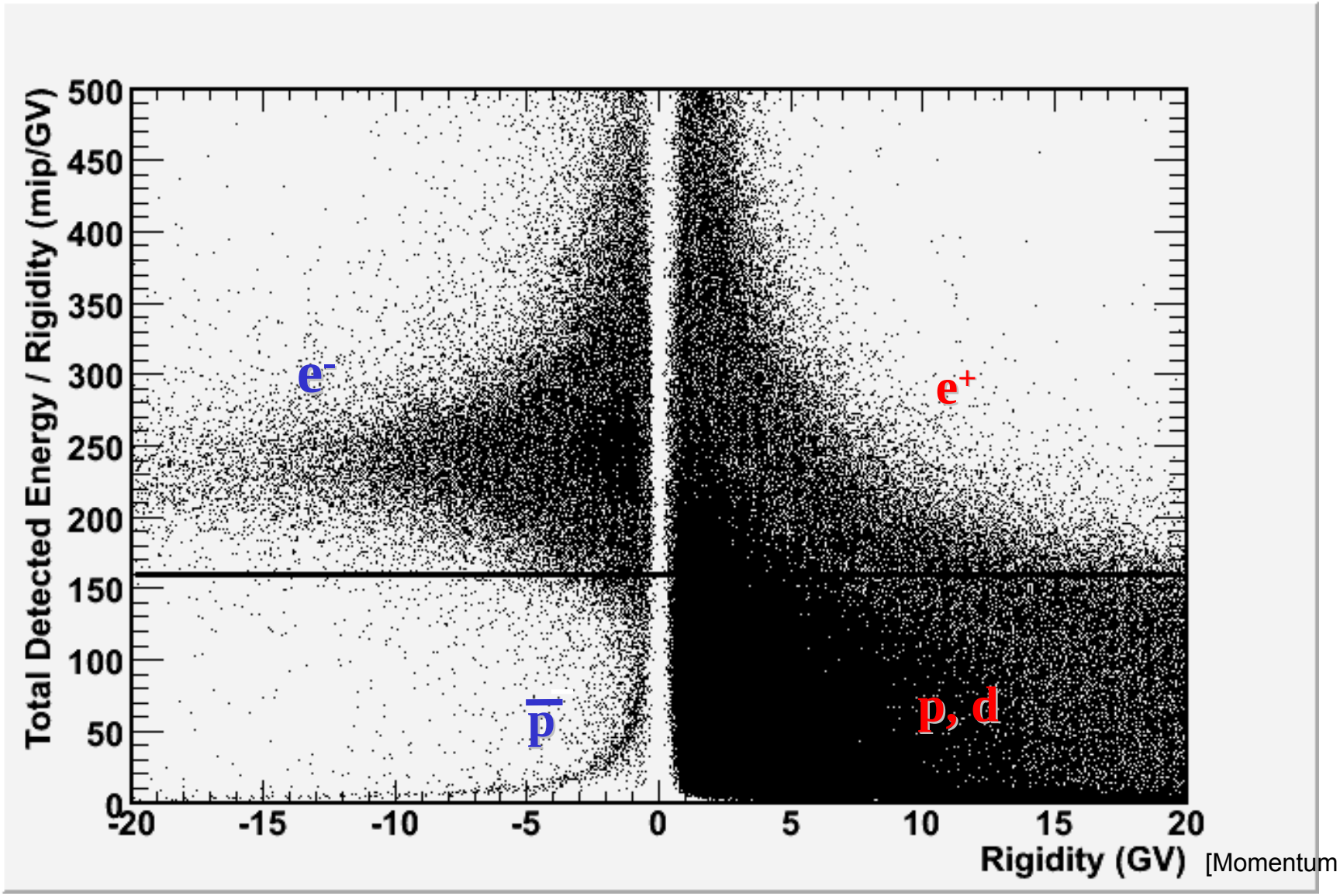


Galactic p and He spectra



Antiparticle selection

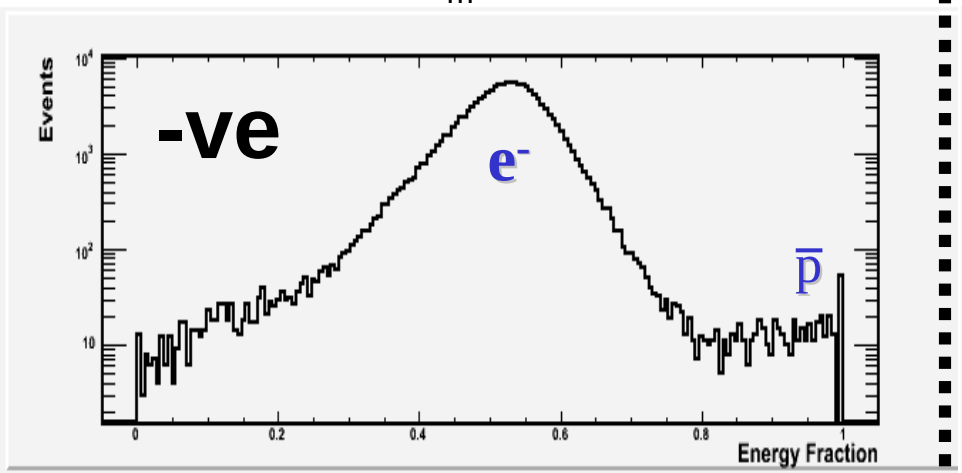
Preliminary !!!

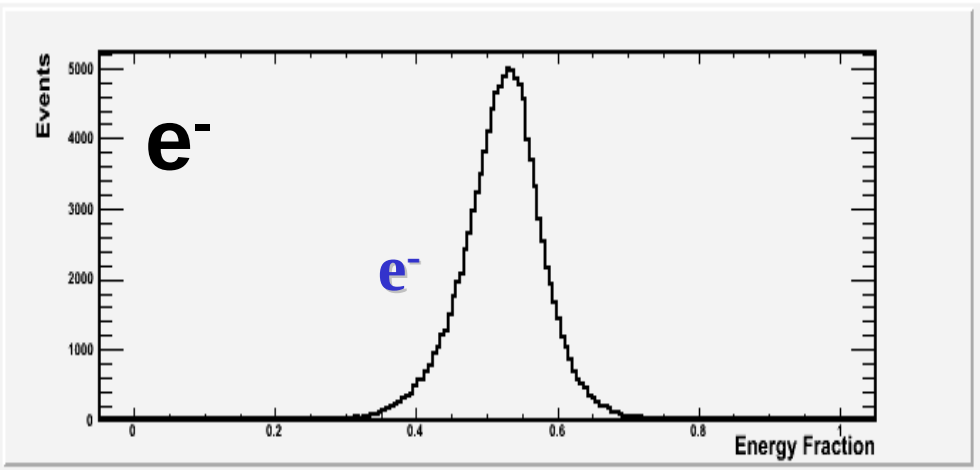


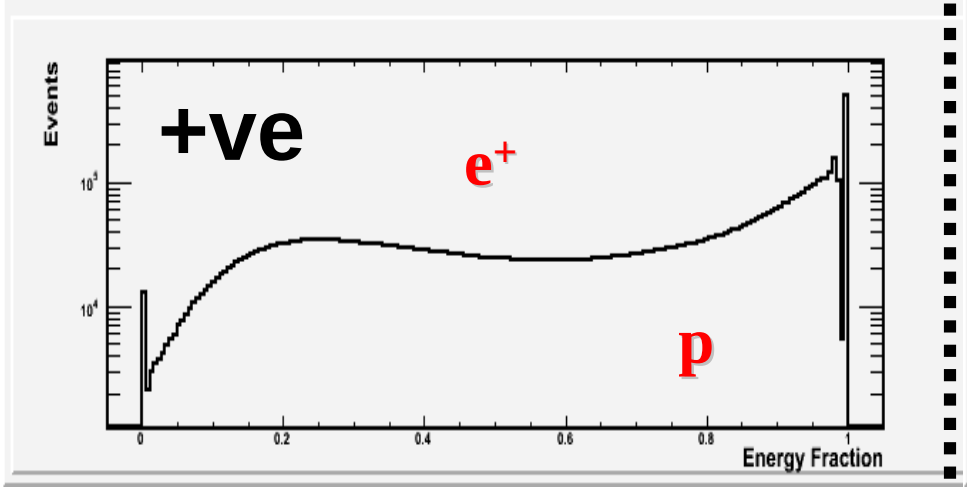
[Momentum (GeV) / charge (e)]

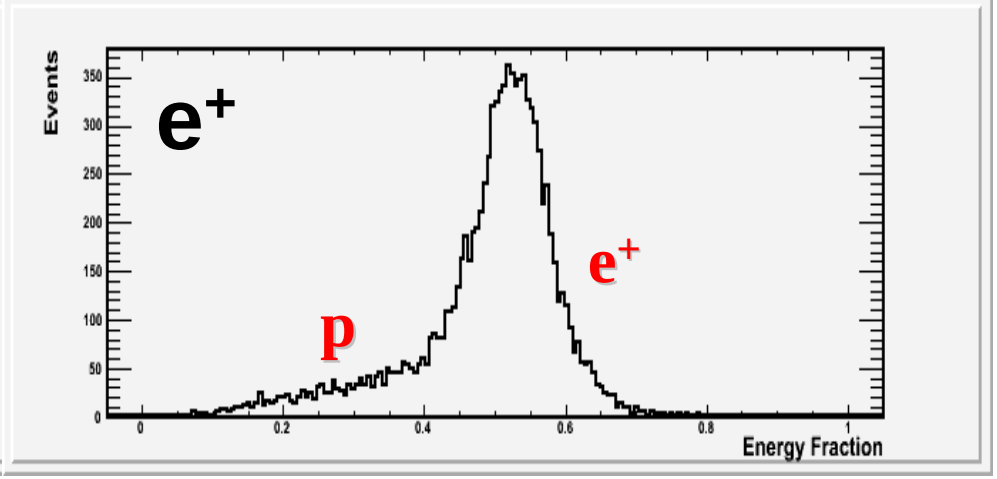
Positron selection with calorimeter

~R_m => 50%









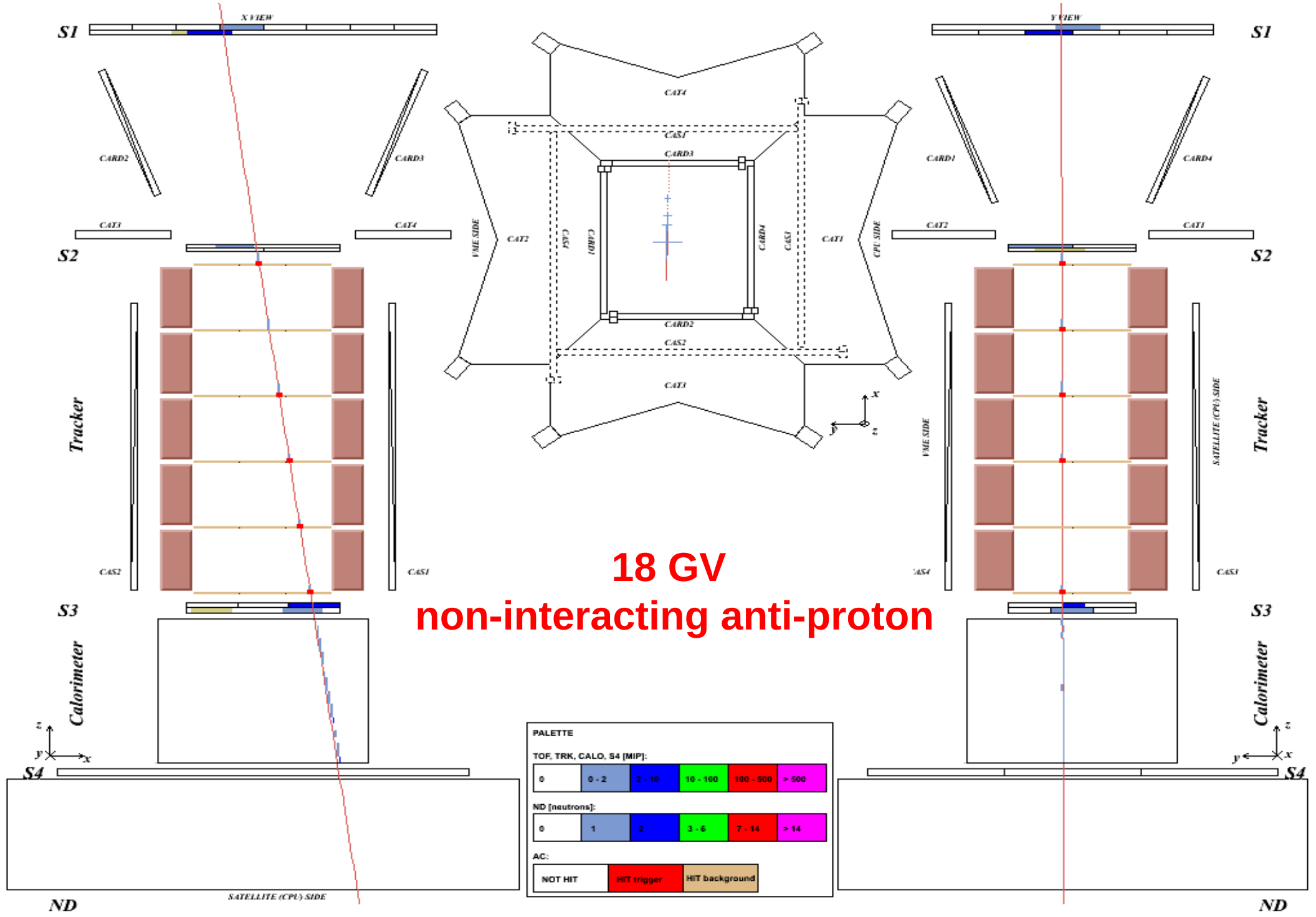
Fraction of charge released along the calorimeter track (left, hit, right)

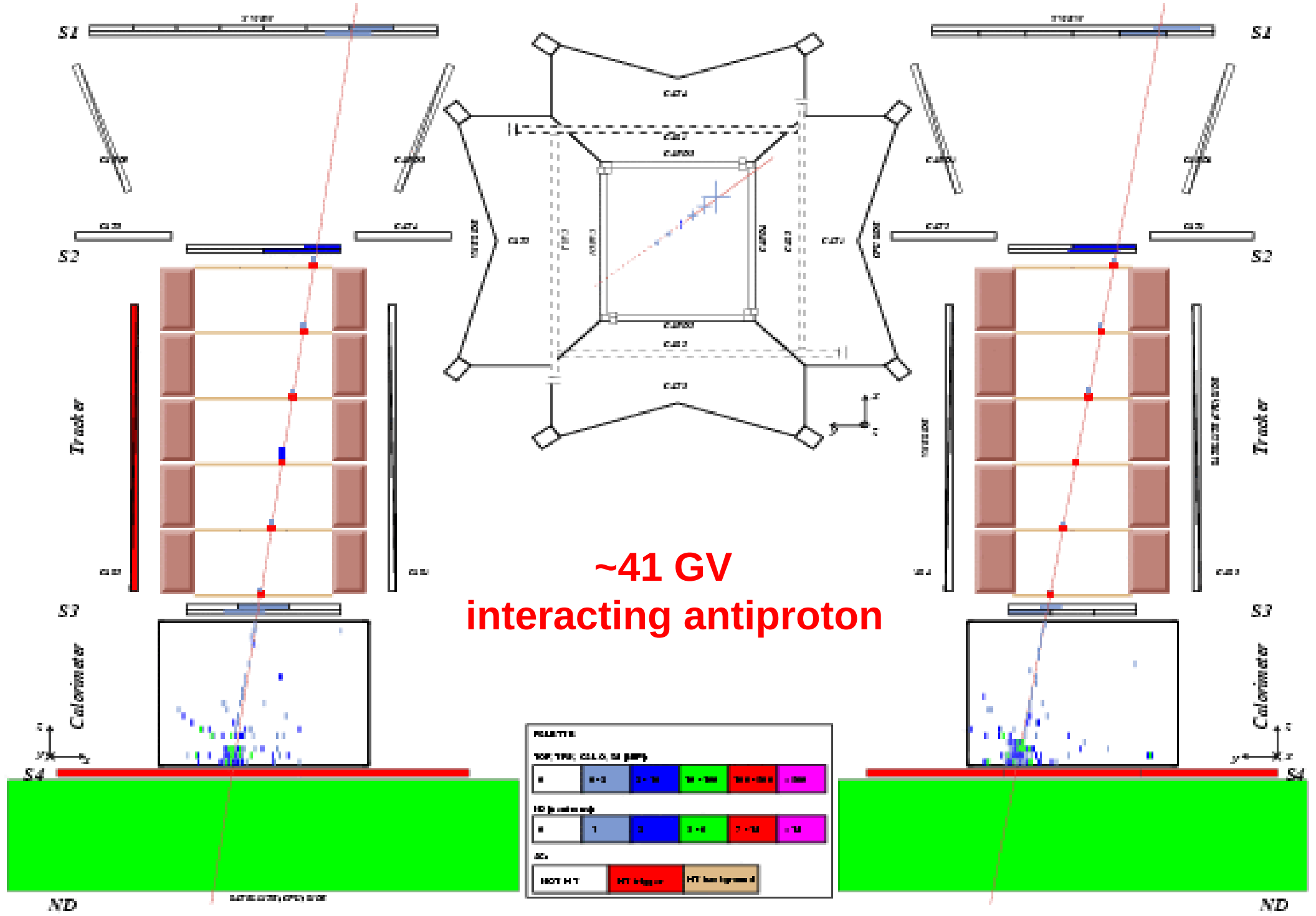
+

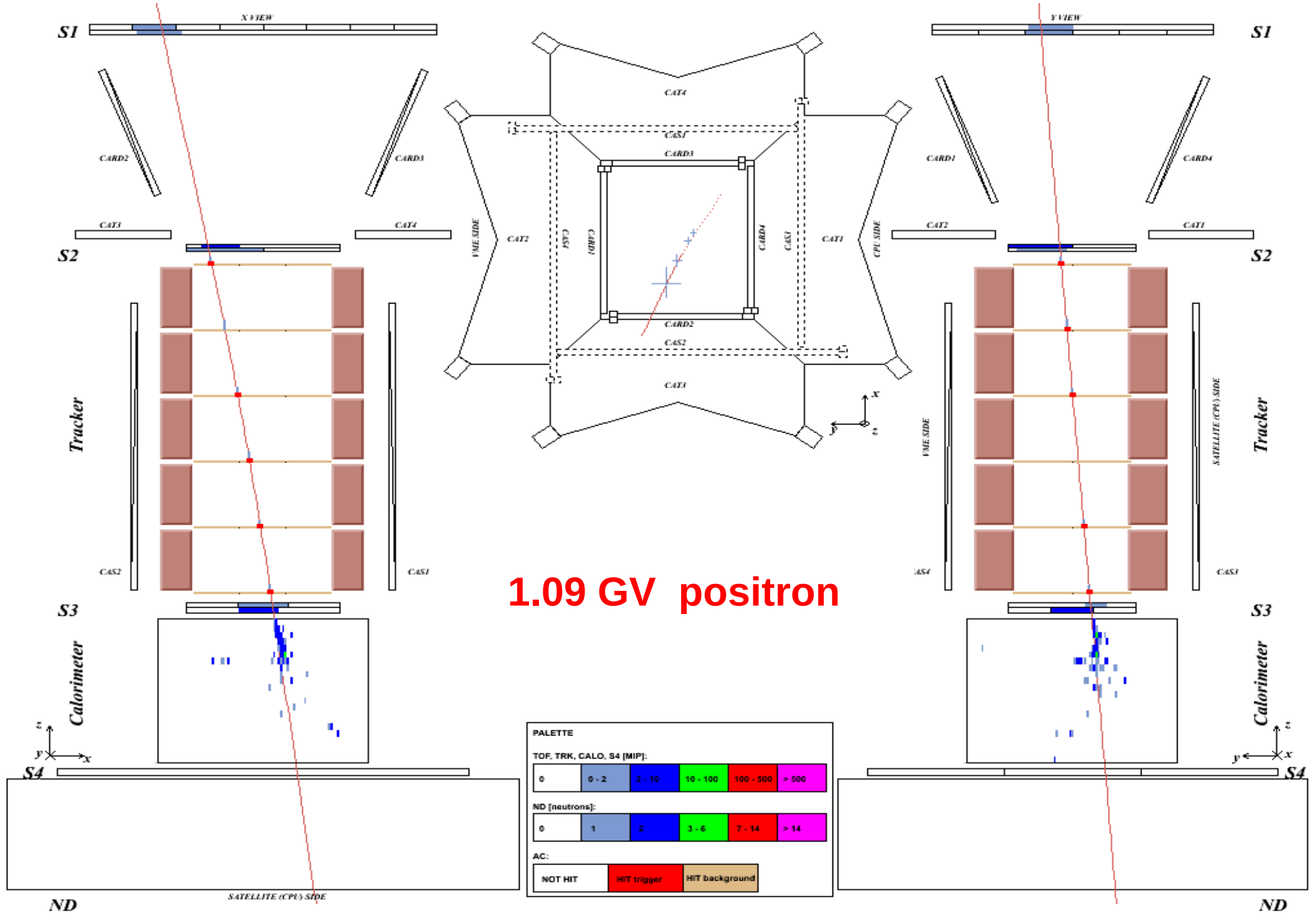
Example calorimeter selection criteria:

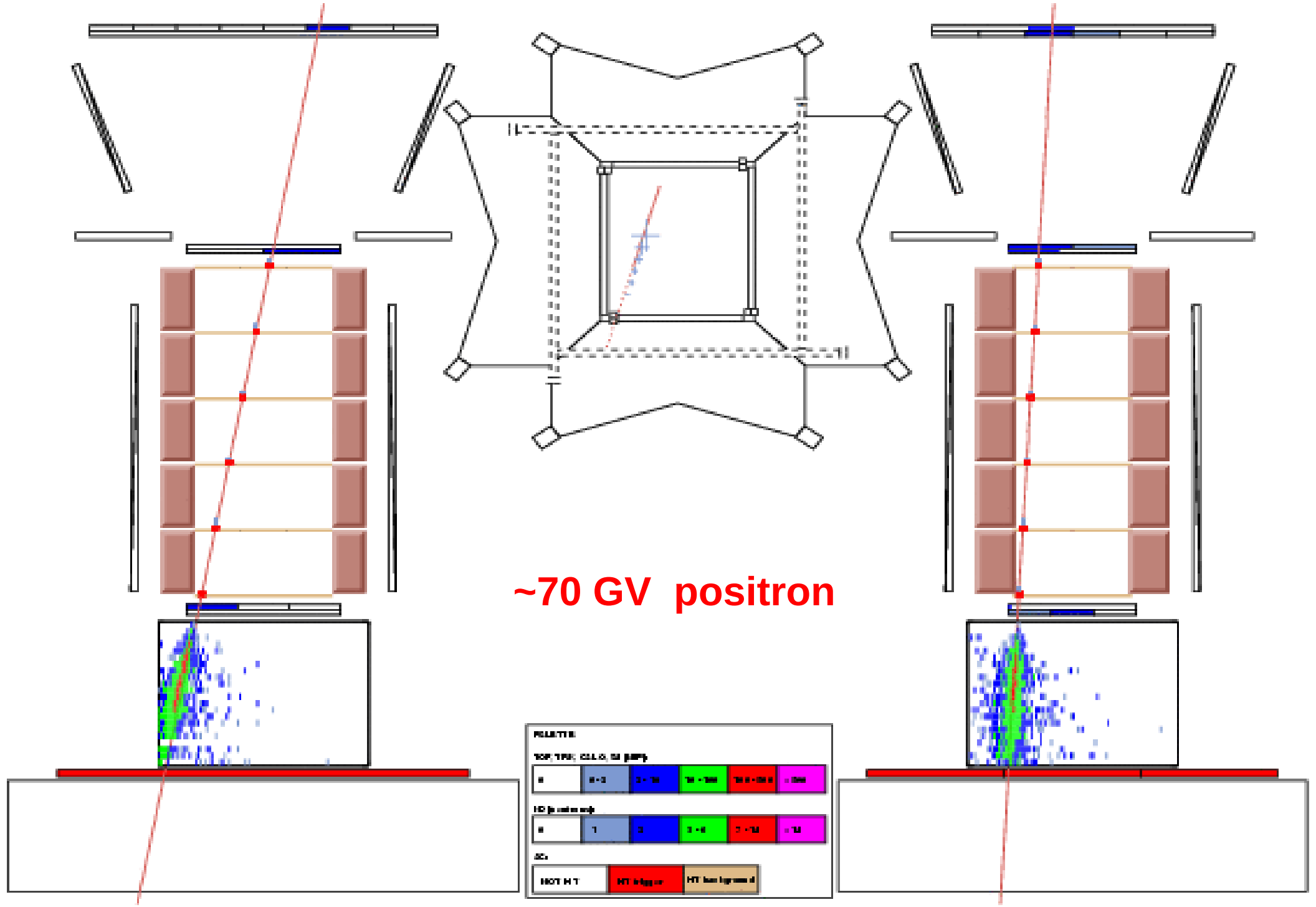
- Total energy release
- Longitudinal and lateral shower development
- Shower topology
- …

Preliminary !!!


S1
X VIEW
CARD2
CARD3
CAT3
CAT4
S2
Tracker
CAS2
CAS1
S3
Calorimeter
S4
ND
SATELLITE (CPU) SIDE
CAT4
CAS1
CARD3
VME SIDE
CAT2
CSA1
CAMB1
CARD4
CAS3
CAT1
CPU SIDE
CARD2
CAS2
CAT3
Y VIEW
CARD1
CARD4
CAT2
CAT1
VME SIDE
SATELLITE (CPU) SIDE
CAS4
CAS3
18 GV
non-interacting anti-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


S1
S2
S3
S4
Tracker
Calorimeter
ND
~41 GV
interacting antiproton


S1
X VIEW
CARD2
CARD3
CAT3
CAT4
S2
Tracker
CAS2
CAS1
S3
Calorimeter
S4
ND
SATELLITE (CPU) SIDE
CAT4
CAS1
CARD3
VME SIDE
CAT2
PSCI
CARD1
CARD4
CAS3
CAT1
CPU SIDE
CARD2
CAS2
CAT3
Y VIEW
CARD1
CARD4
CAT2
CAT1
VME SIDE
SATELLITE (CPU) SIDE
CAS4
CAS3
1.09 GV positron
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


~70 GV positron

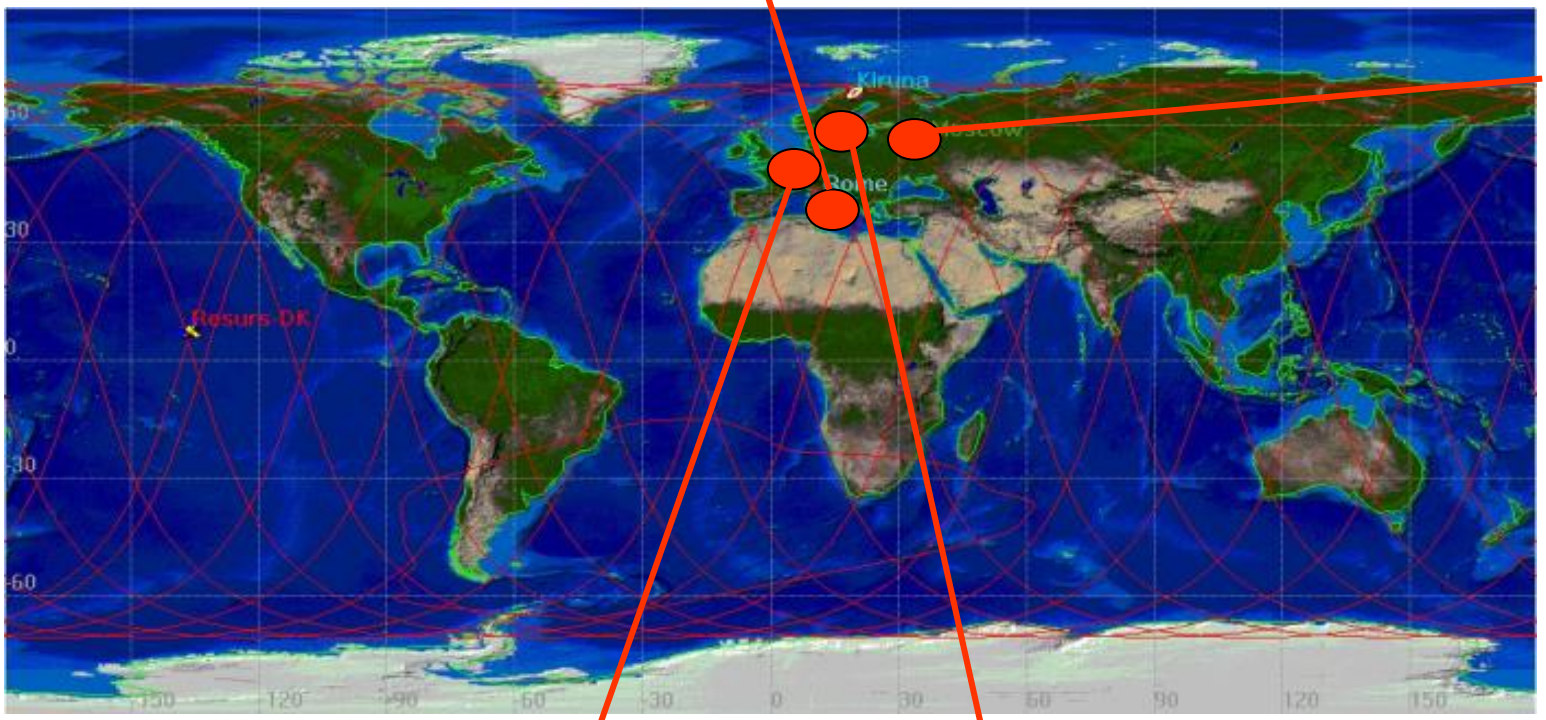
Summary

- **PAMELA** is conducting an indirect search for dark matter using antiparticles (e^+, p-bar) in the cosmic radiation.
- Launched on June 15th 2006. **PAMELA** has been in continuous data taking mode since 11th July 2006. ~5.5 TB of data downlinked, to date.
- **Data analysis is on-going**. First science results (probably antiparticle flux ratios) should appear before the end of this year.

[http://wizard.roma2.infn.it/pamela]

The PAMELA Collaboration

Italy: Bari, Florence, Frascati, Naples, Rome, Trieste, CNR, Florence



Russia: Moscow, St. Petersburg

Germany: Siegen

Sweden: KTH, Stockholm

[http://wizard.roma2.infn.it/pamela]