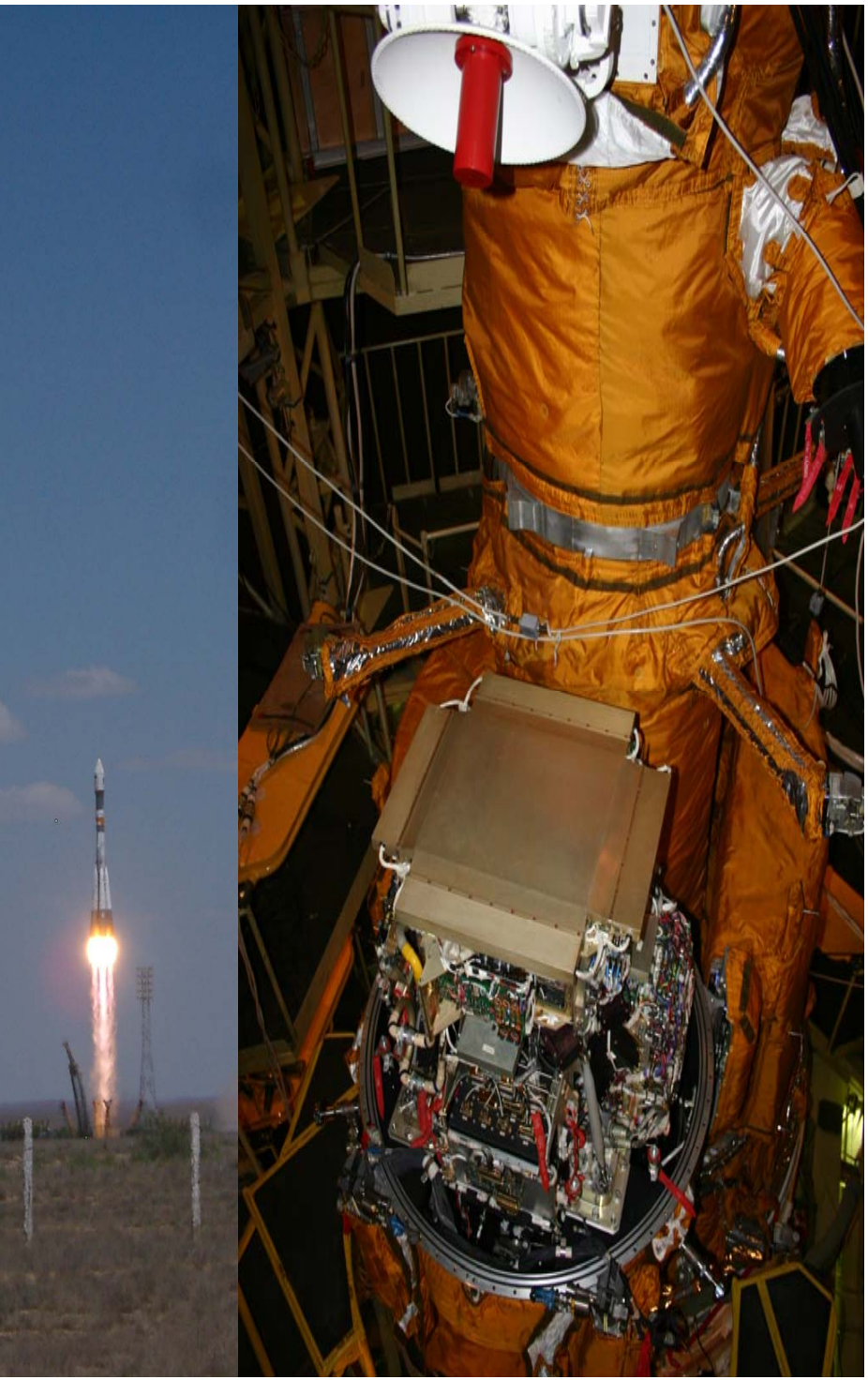


PAMELA – a satellite experiment studying antiparticles in the cosmic radiation

Mark Pearce

KTH, Department of Physics

AlbaNova Instrumentation Seminar, 2007-05-03

Overview

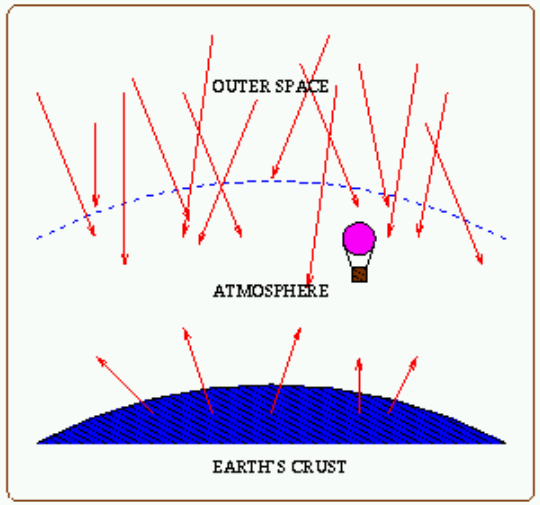
- Cosmic rays (briefly…)
- PAMELA science programme
  - Indirect searches for dark matter with antiparticles
- Description of PAMELA instrument and performance
- Status since launch (15th June 2006)
- A first look at flight data
  - Orbital environment
  - Charge separation
  - Matter / antimatter separation
- Summary

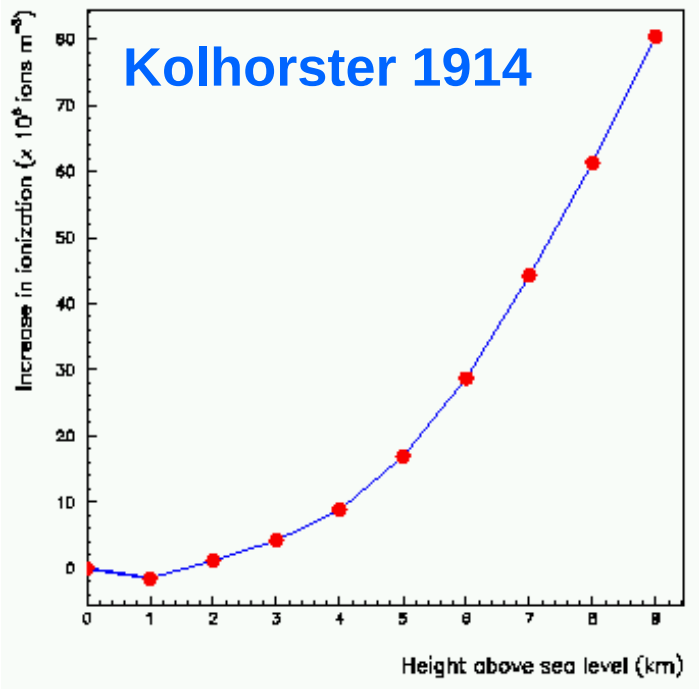
RYMDSTYRELSEN Swedish National Space Board
KTH VETENSKAP OCH KONST
Vetenskapsrådet
Göran Gustafsson Stiftelse

The discovery of cosmic rays

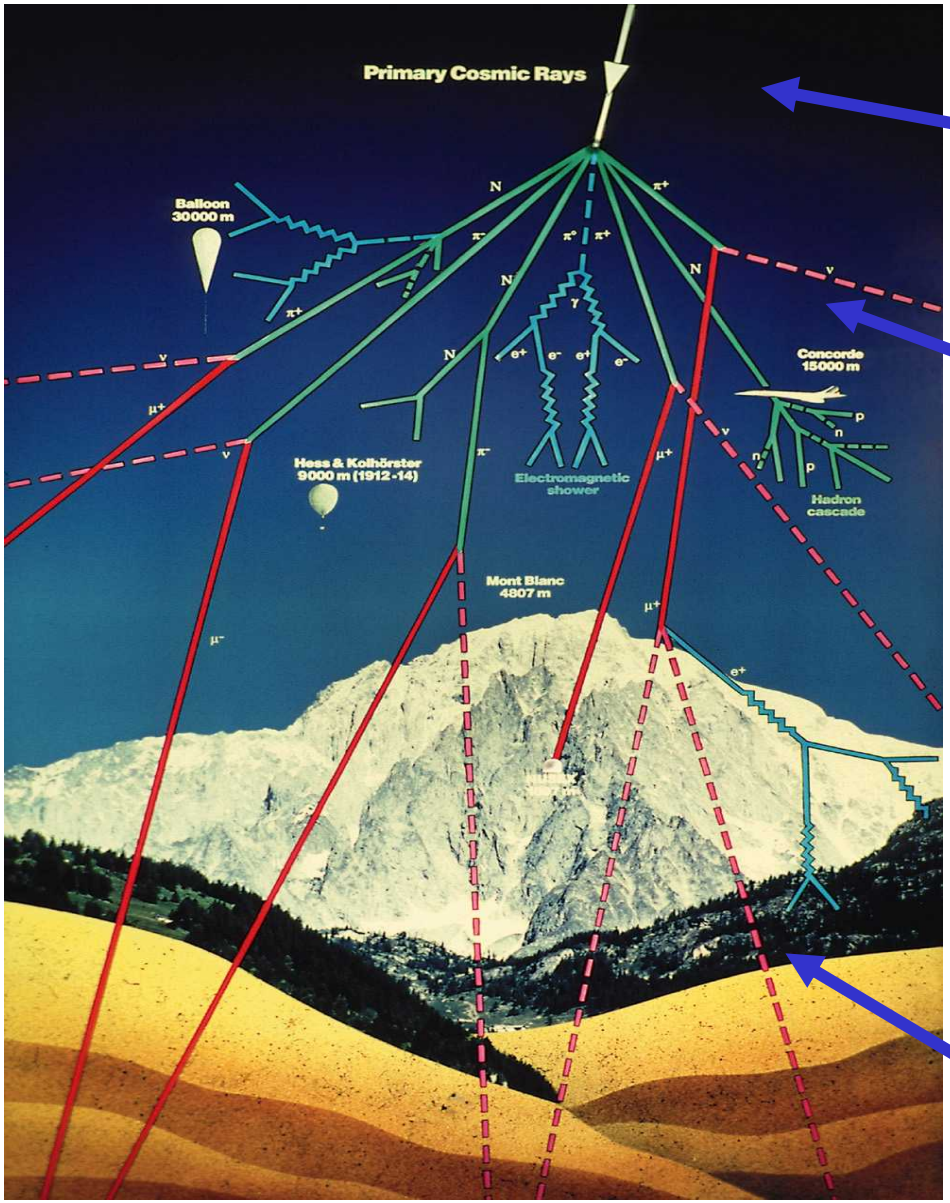
- Victor Hess ascended to 5000 m in a balloon in 1912
- Noticed that his electroscope discharged more rapidly as altitude increased
- Not expected, as background radiation was thought to be terrestrial

- NPP 1936 (with Carl ‘e^{+}’ Anderson)





Investigating cosmic rays



In space (>40km) ⇒ nuclei, protons, electrons and neutrinos (and antiparticles)

Smaller detectors but long duration.
PAMELA!

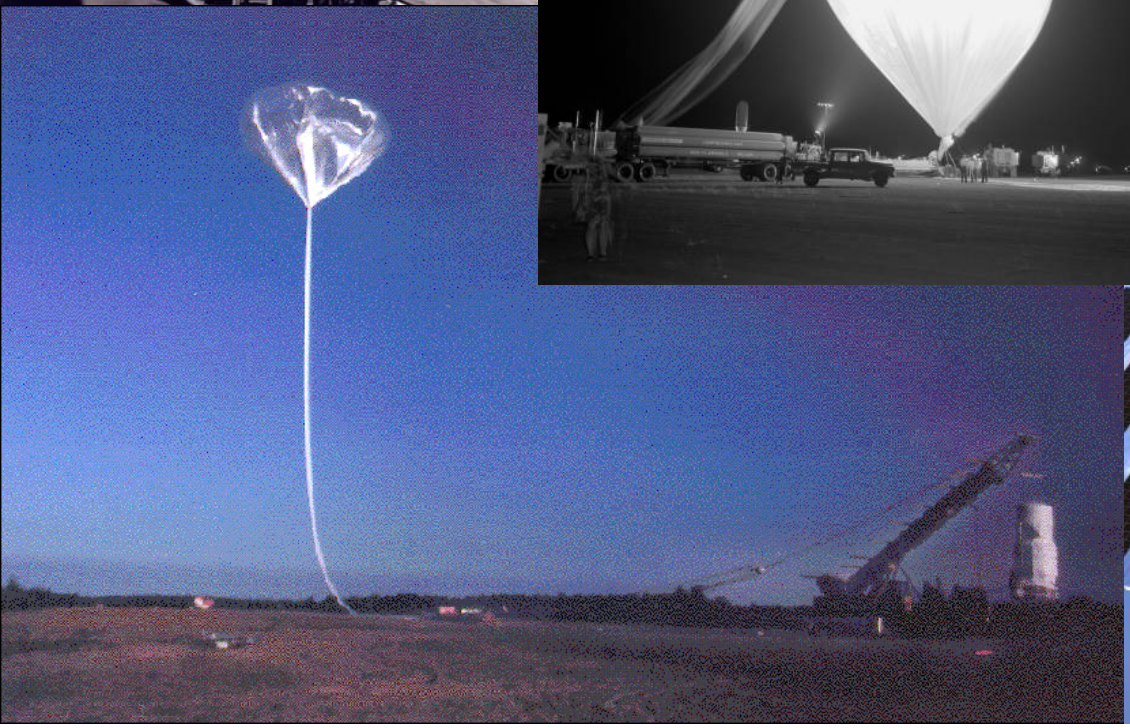
In balloons (~40km) ⇒ nuclei, protons, pions, electrons, muons and neutrinos (and antiparticles)

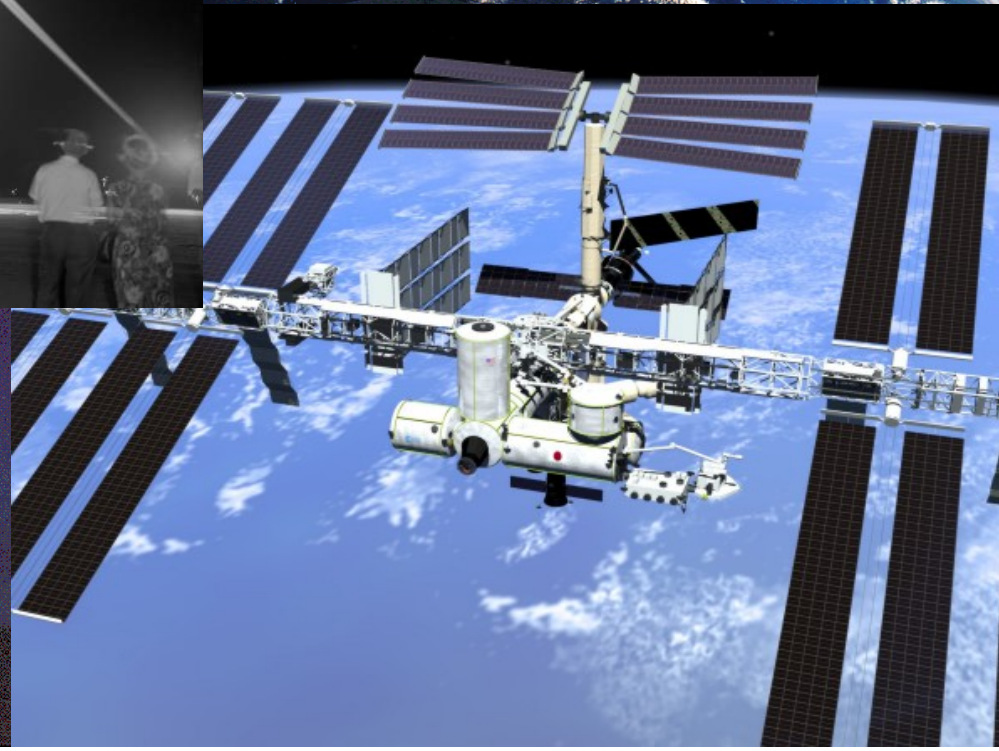
Larger detectors but short duration.
Atmospheric overburden ~5 g/cm^2.
Almost all data on cosmic antiparticles from here.

On ground ⇒ mostly muons and neutrinos. (UHECR experiments).

'Infinite' size and duration but atmospheric overburden ~1000 g/cm^2 !


University of Bristol



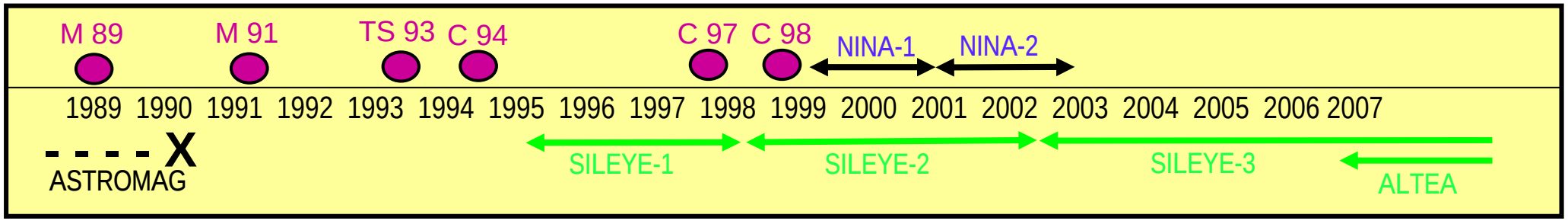


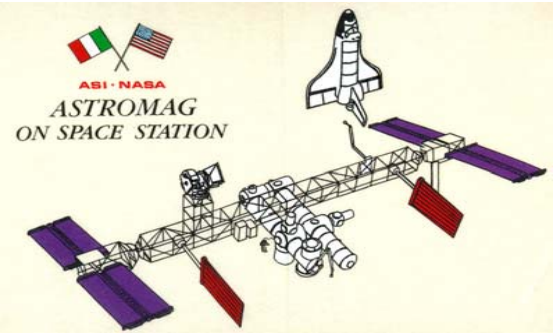
PAMELA pre-history

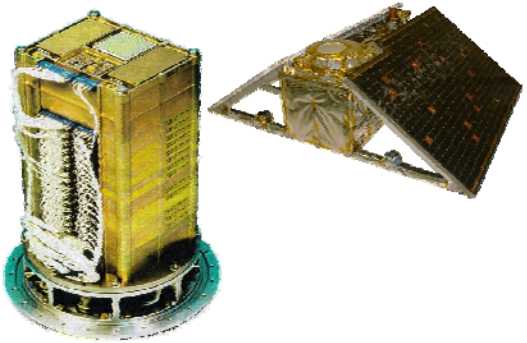
• Astromag/WiZard project (PAMELA precursor) on board of the Space Station Freedom – cancelled (Challenger disaster and 1st Gulf War)

• Meanwhile, balloon-borne experiments: MASS-89,91 TS-93 CAPRICE-94,97,98 (in collaboration with NASA) and then, space experiments*: NINA-1,2 SILEYE-1,2,3 ALTEA (building links to Russian Space Agency).

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



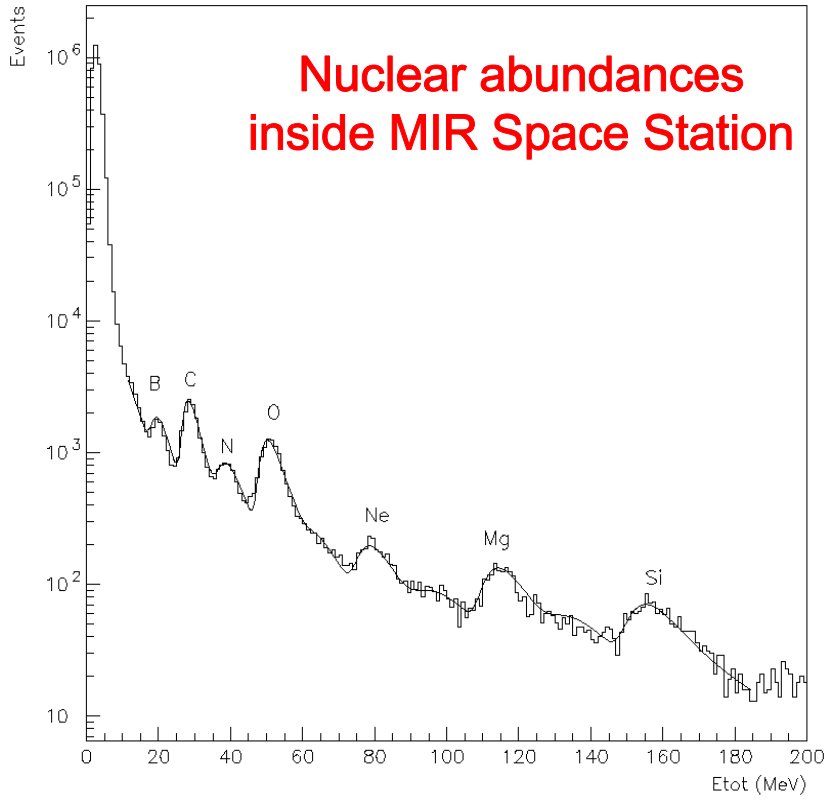





SilEye-1


SilEye-2

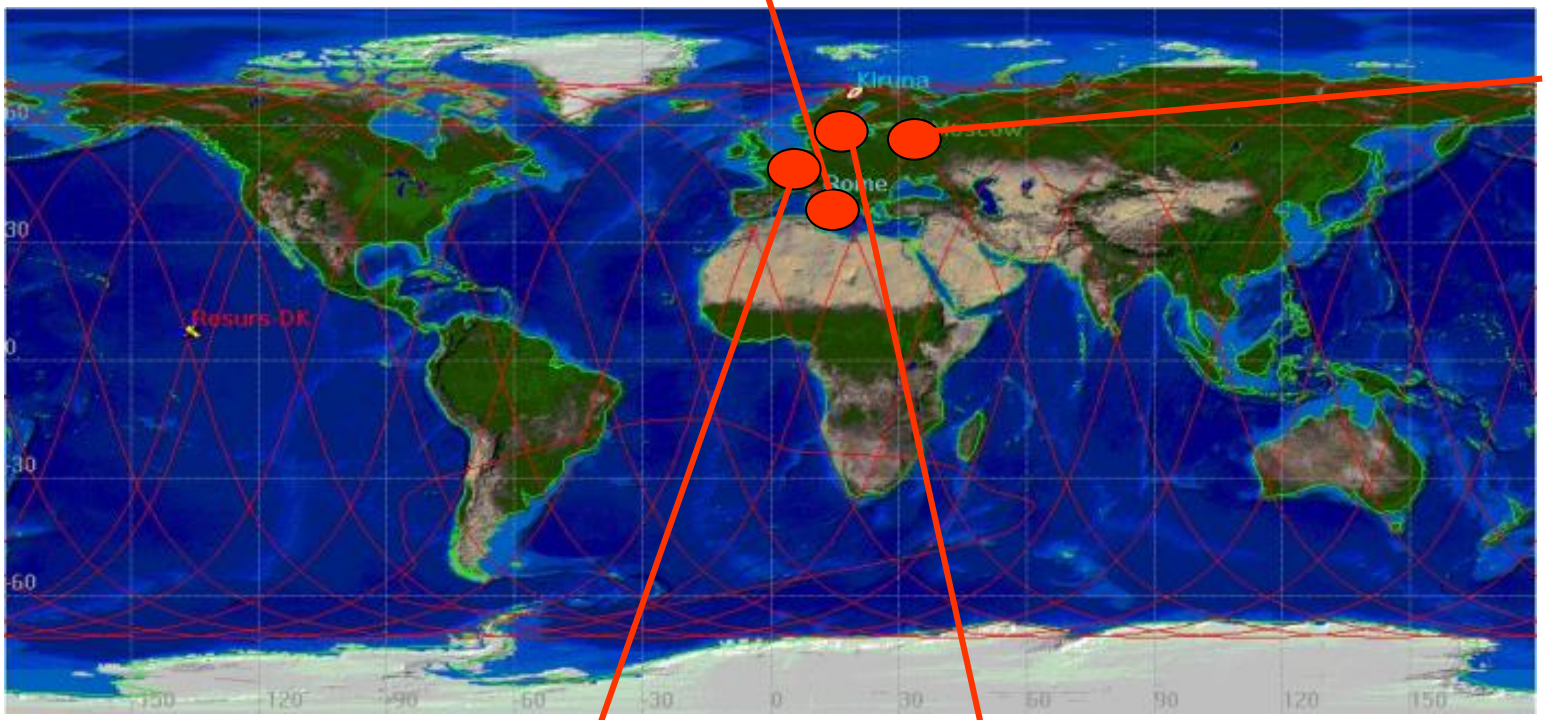

SilEye-3


Nuclear abundances
inside MIR Space Station
Events
10^6
10^5
10^4
10^3
10^2
10
B
C
N
O
Ne
Mg
Si
0
20
40
60
80
100
120
140
160
180
200
Etot (MeV)

PAMELA Collaboration

Italy:

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



Russia:

Moscow
St. Petersburg

Germany:

Siegen

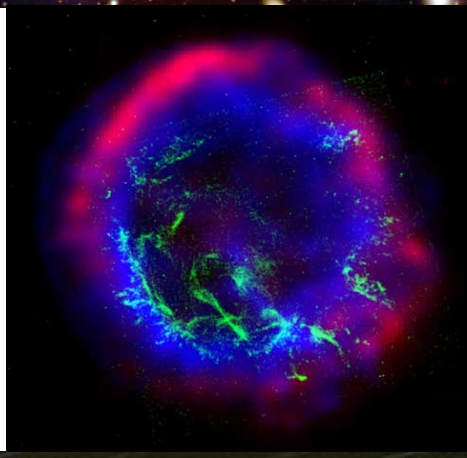
Sweden:

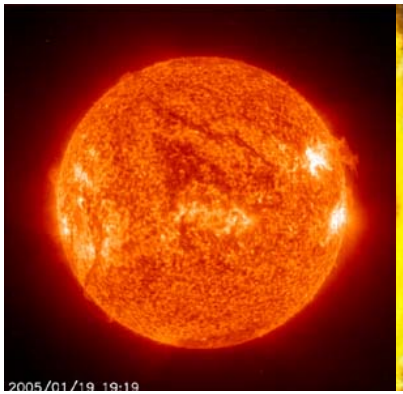
KTH, Stockholm

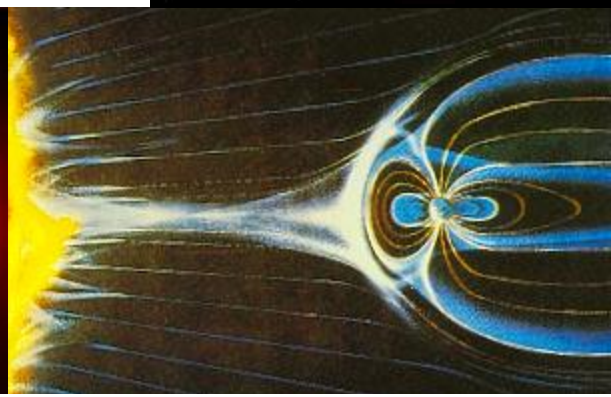
PAMELA science programme

- **Search for dark matter**
- **Search for antimatter**

- Study of cosmic-ray propagation
- Study solar physics and solar modulation
- Study of electron spectrum (local sources?)
- Study terrestrial magnetosphere







PAMELA sensitivity

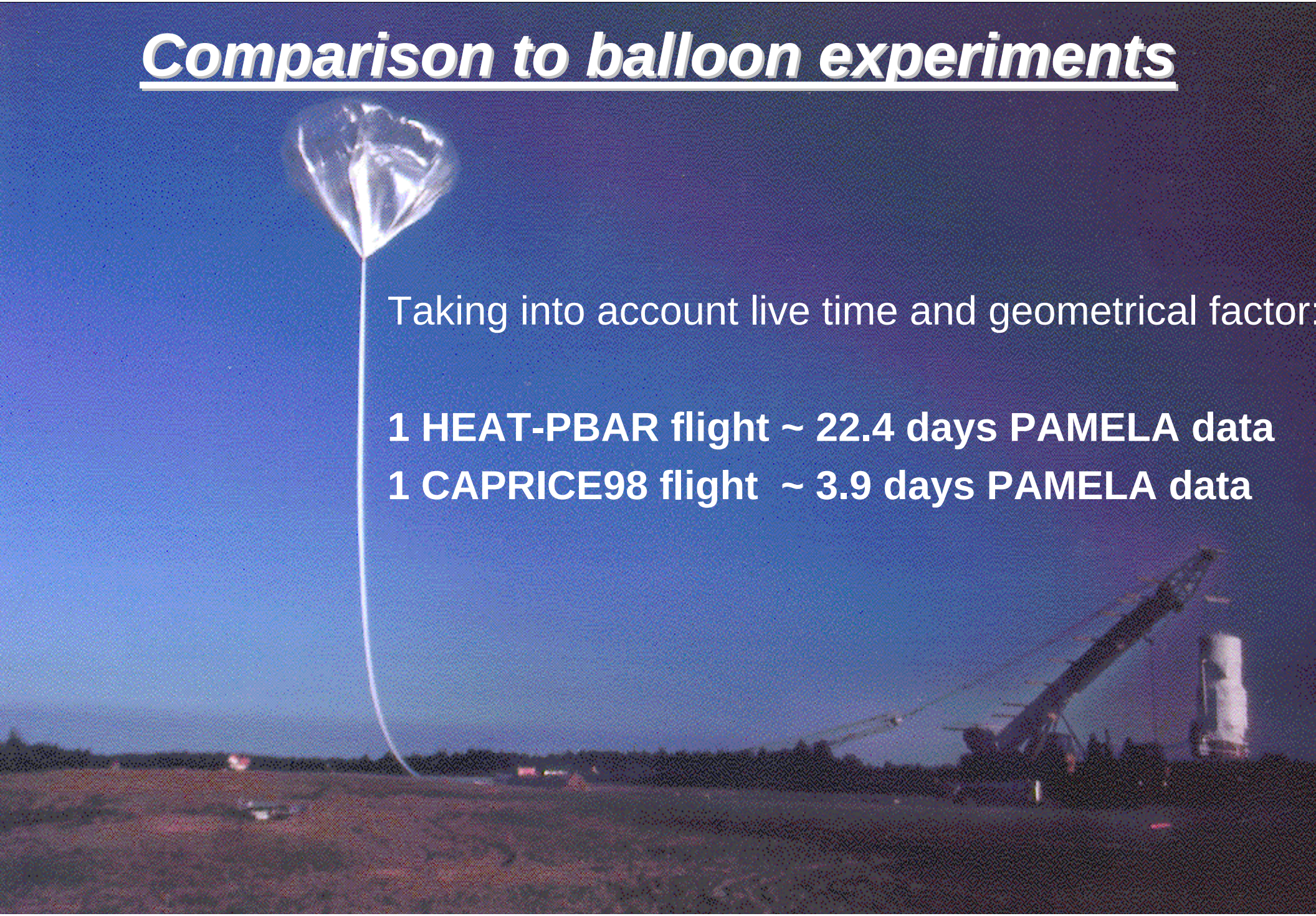
	Energy range	Particles/3 years
Antiproton flux	80 MeV - 190 GeV	$>3\times10^{4}$
Positron flux	50 MeV – 270 GeV	$>3\times10^{5}$
Electron flux	up to 400 GeV	6×10^{6}
Proton flux	up to 700 GeV	3×10^{8}
Electron/positron flux	up to 2 TeV (from calorimeter)	
Light nuclei (up to Z=6)	up to 200 GeV/n He/Be/C: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

Comparison to balloon experiments



Taking into account live time and geometrical factor:

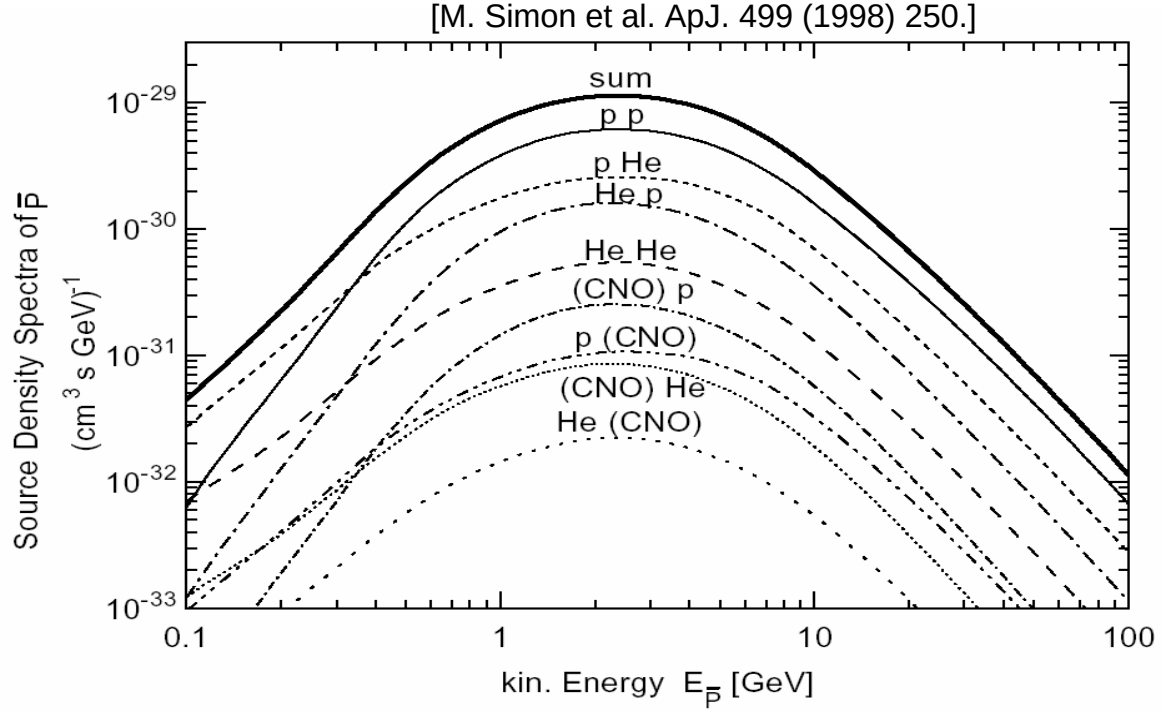
1 HEAT-PBAR flight ~ 22.4 days PAMELA data

1 CAPRICE98 flight ~ 3.9 days PAMELA data

Antiparticles in cosmic rays

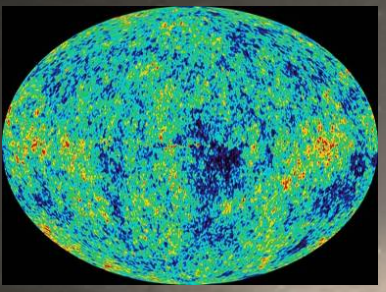
$$p_{CR} + p_{ISM} \rightarrow \bar{p} + p + p + p$$

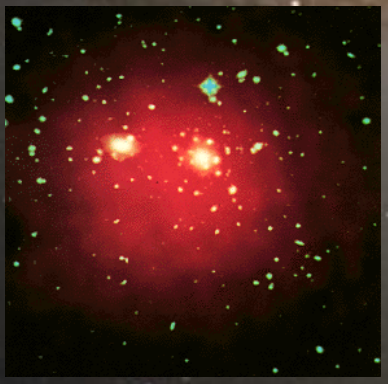
[M. Simon et al. ApJ. 499 (1998) 250.]

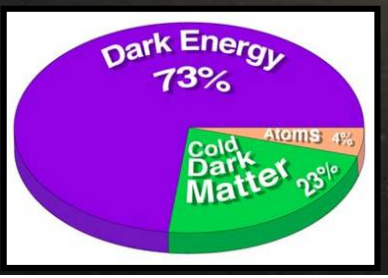


$$p_{CR} + p_{ISM} \rightarrow \pi^{+} + X; \pi^{+} \rightarrow \mu^{+} + \nu_{\mu}; \mu^{+} \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu}$$

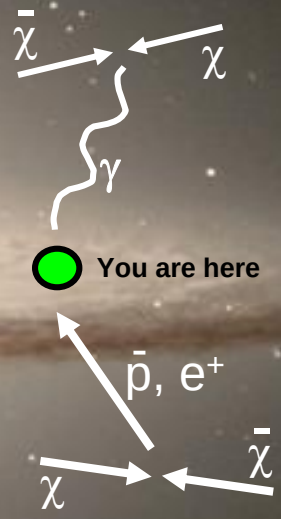
$$p_{CR} + p_{ISM} \rightarrow \pi^{0} + X; \pi^{0} \rightarrow \gamma + \gamma; \gamma \rightarrow e^{+} + e^{-}$$

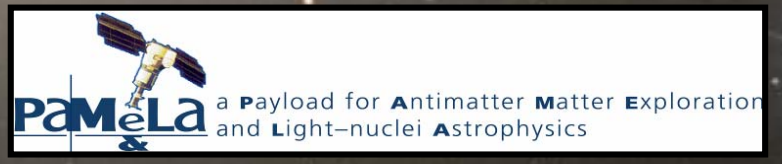




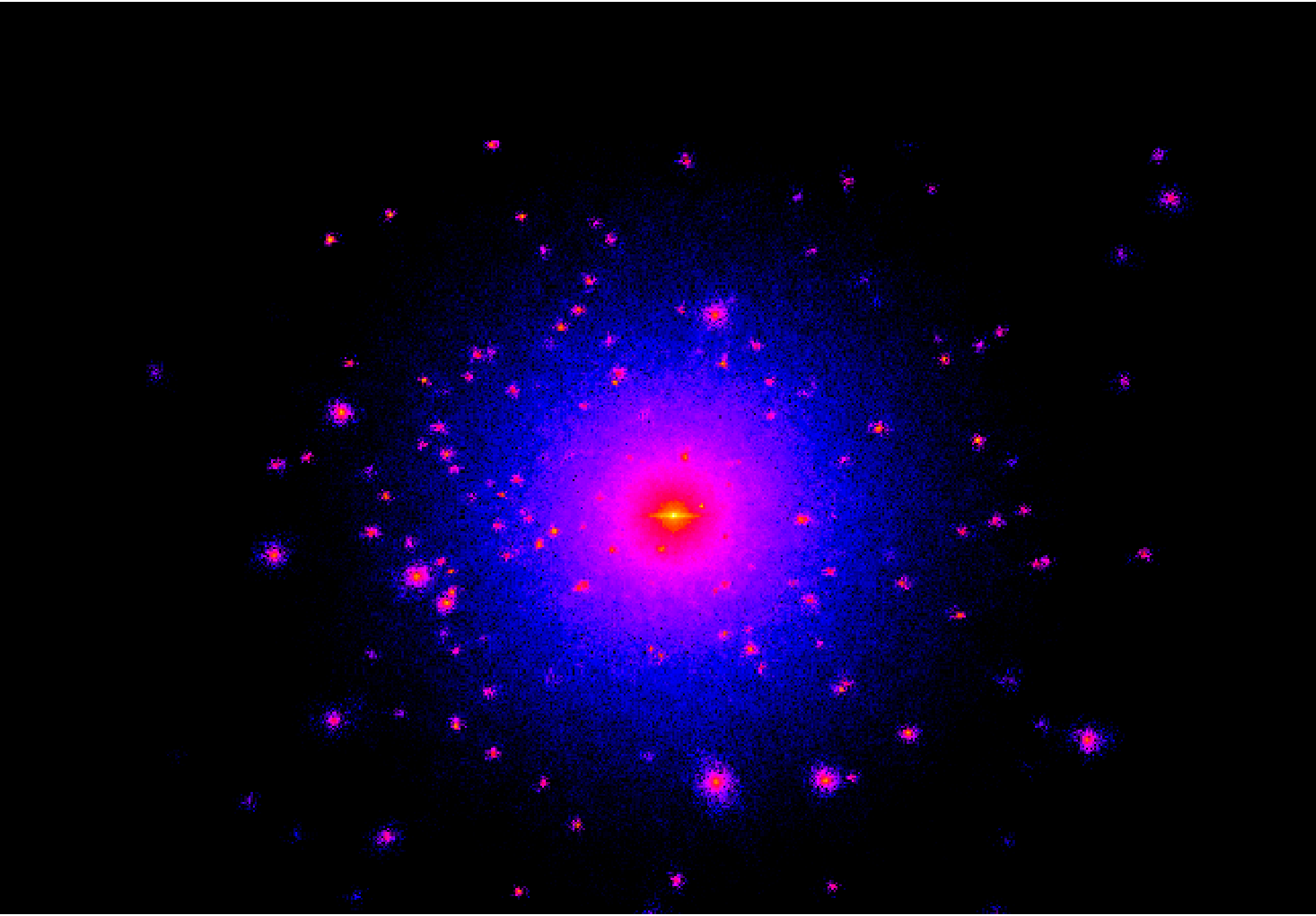


[Late 2007+ε]

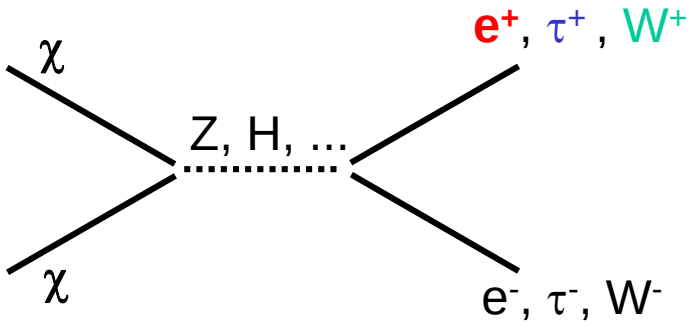


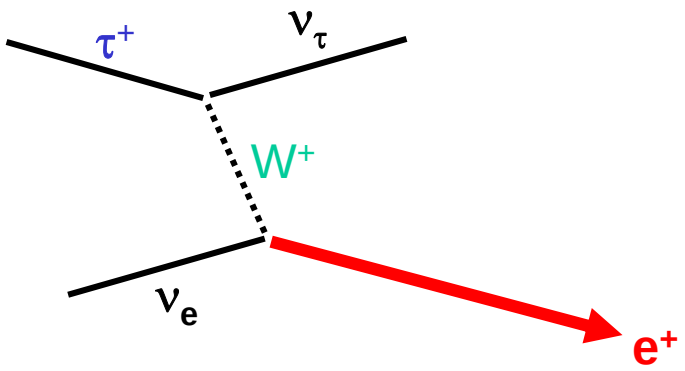


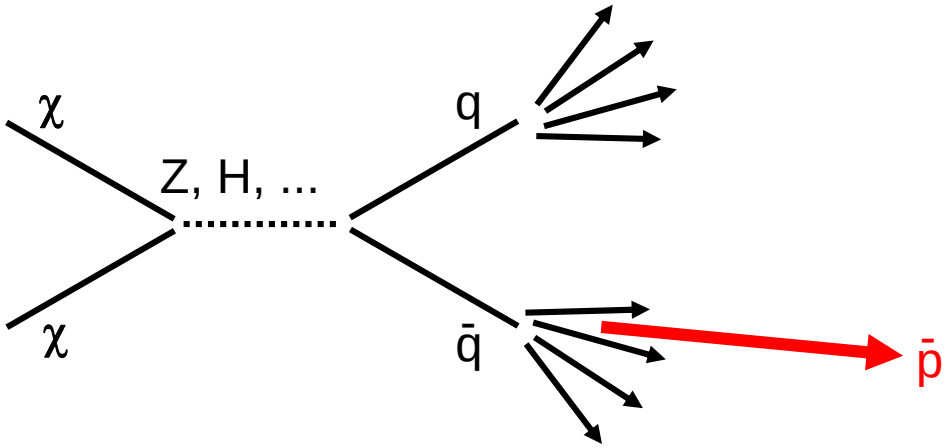
[June 2006]



Antiparticles as probes of dark matter



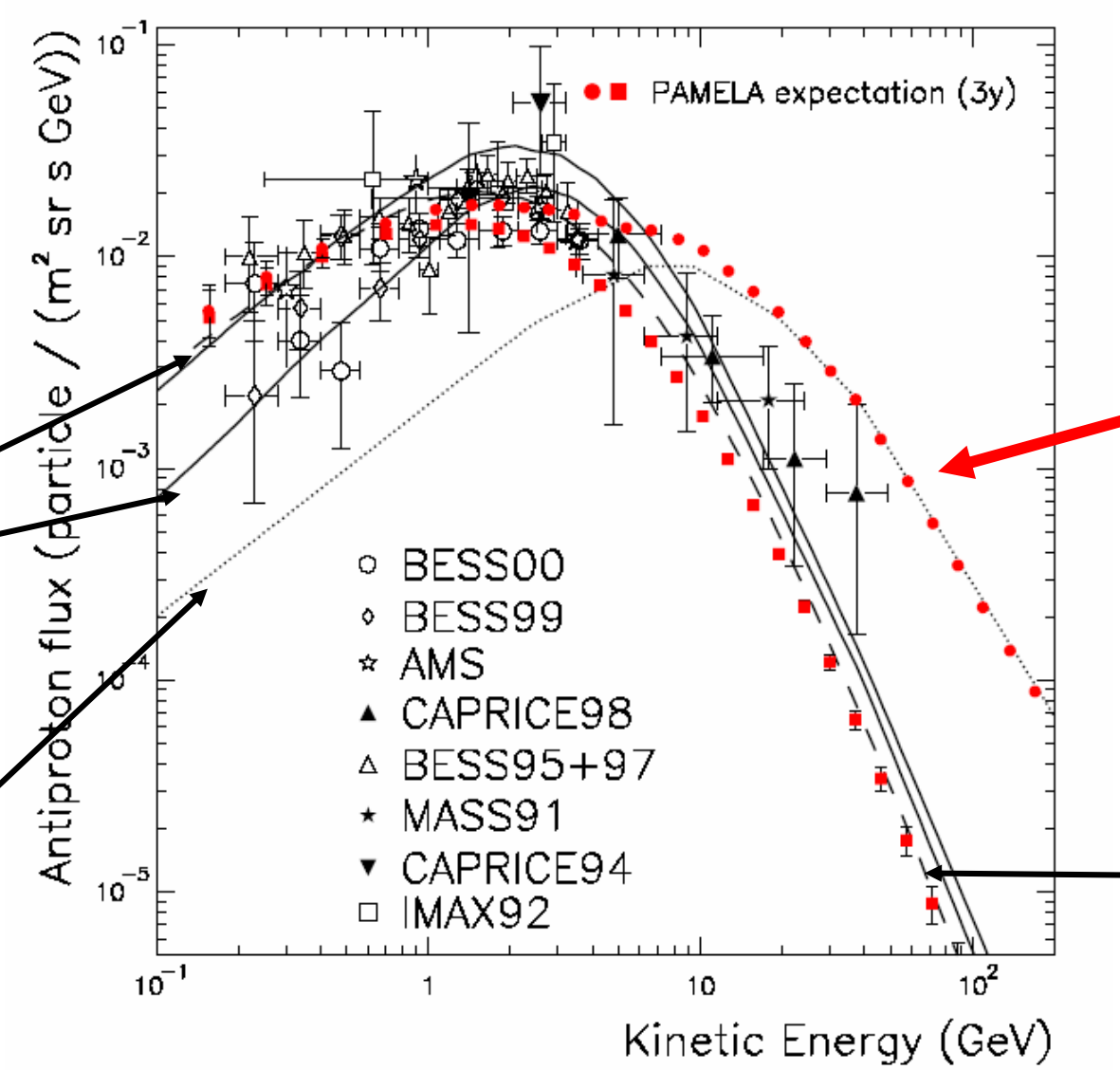




Aim: search for distortions in the antiproton and positron energy spectrum expected from purely secondary production

Antiprotons

AMS-01: space shuttle, 1998



PAMELA

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

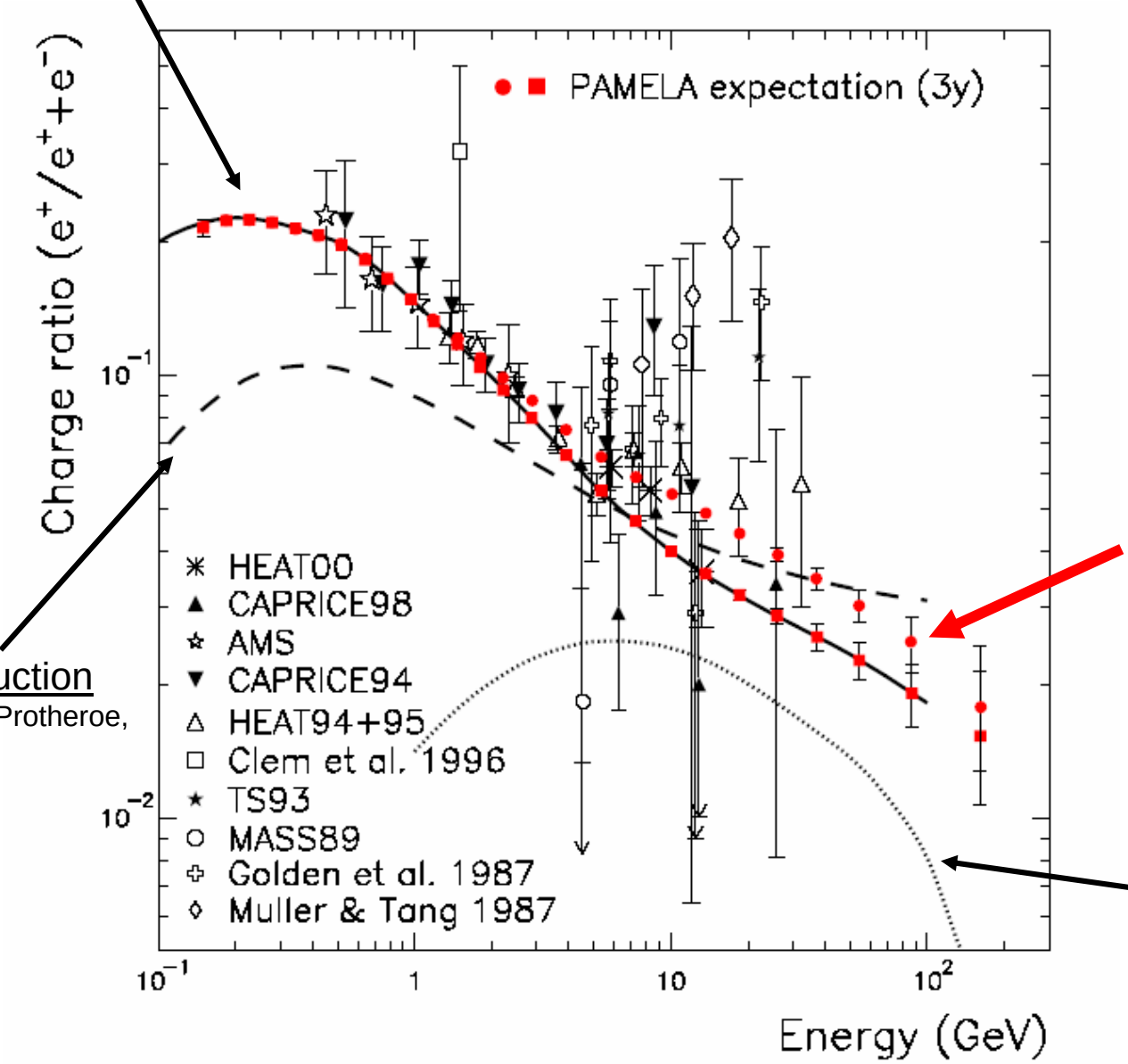
Secondary production
(upper and lower limits)
Simon et al. ApJ 499 (1998) 250.

Primary production from $\chi\chi$ annhilation ($m(\chi)$ = 964 GeV)
Ullio : astro-ph/9904086

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

Positrons

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

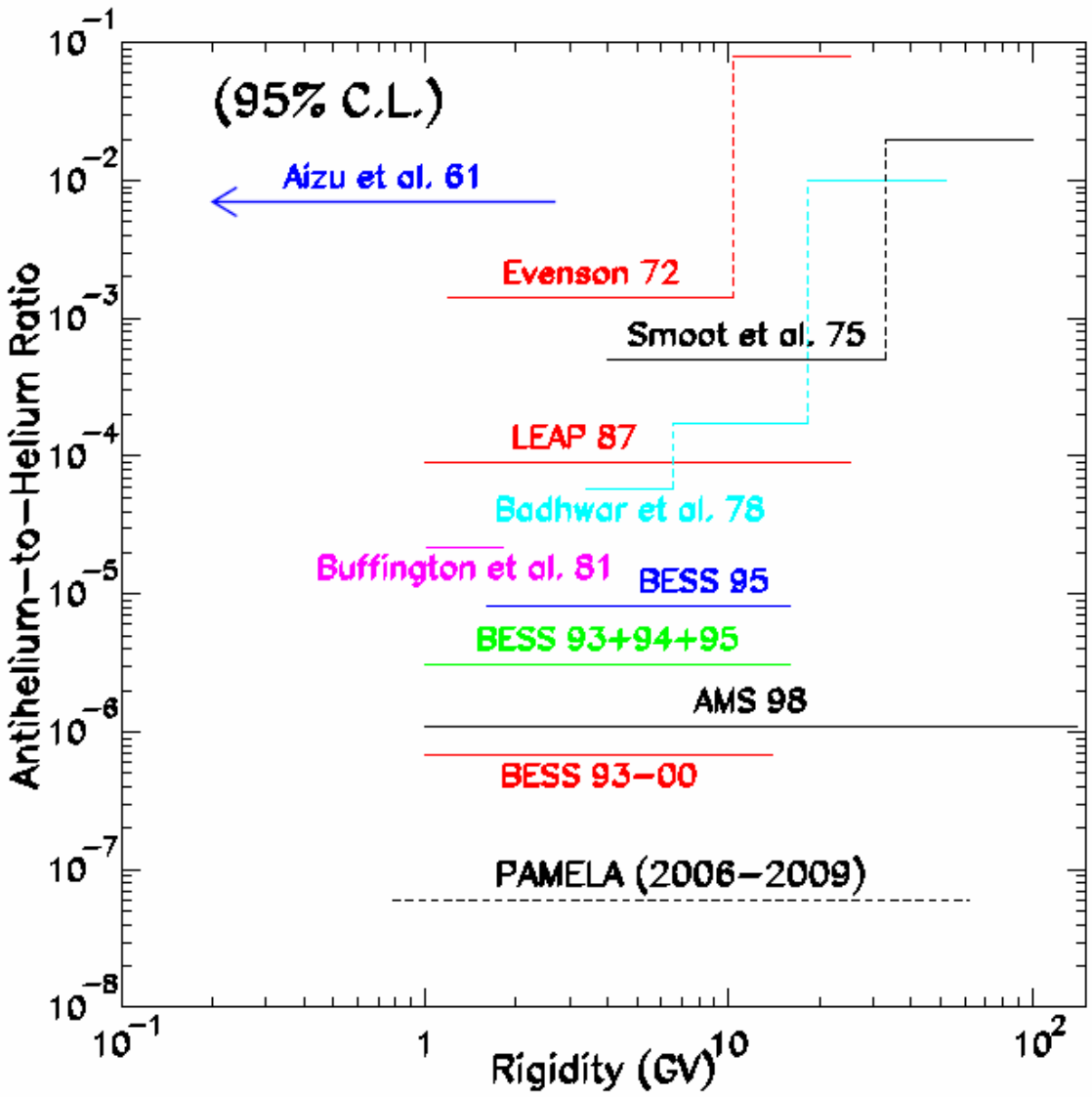


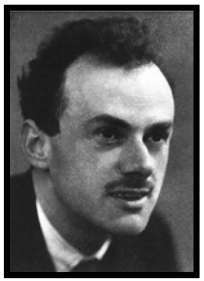
Secondary production
'Leaky box model' R. Protheroe, ApJ 254 (1982) 391.

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.

Cosmic-ray Antimatter Search

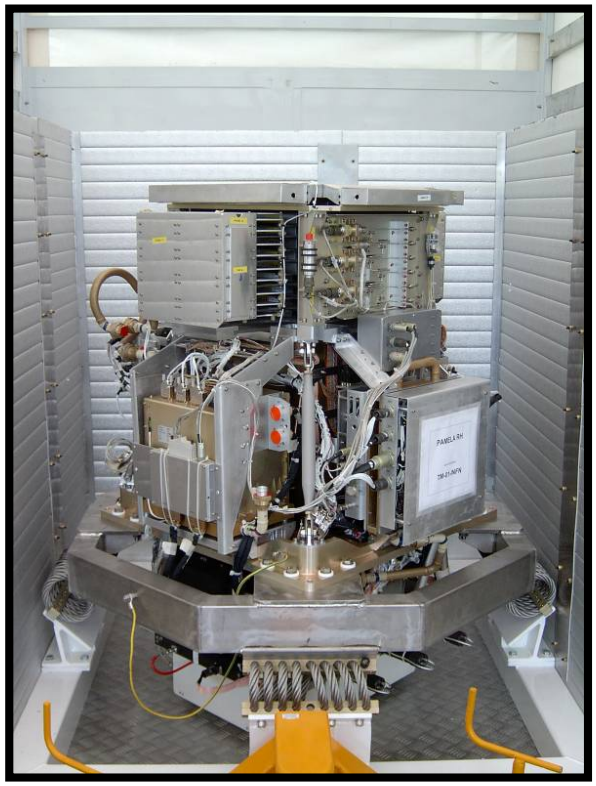




"We must regard it rather an accident that the Earth and presumably the whole Solar System contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about"

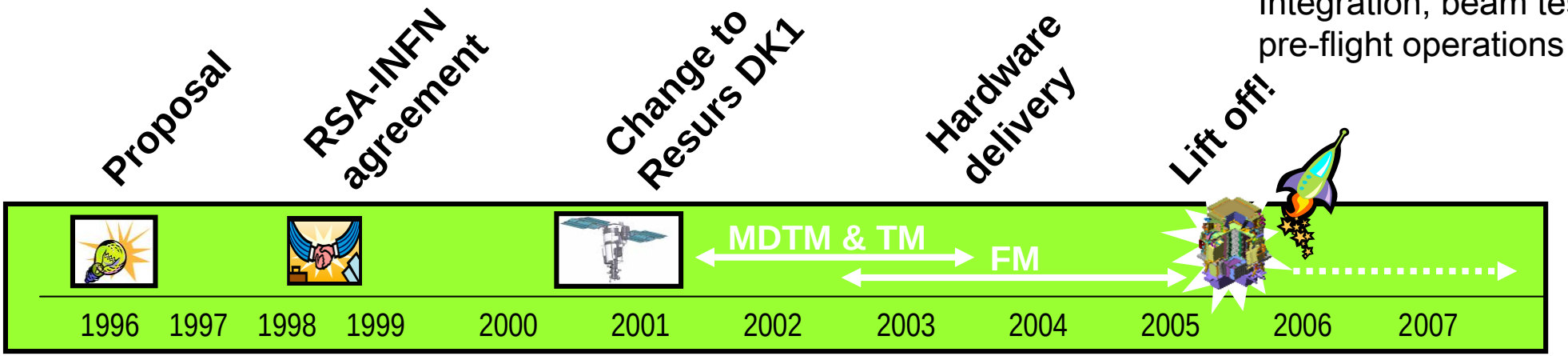
P. Dirac, Nobel lecture (1933)

Mass & Thermal Model
Vibration / shock / transport tests

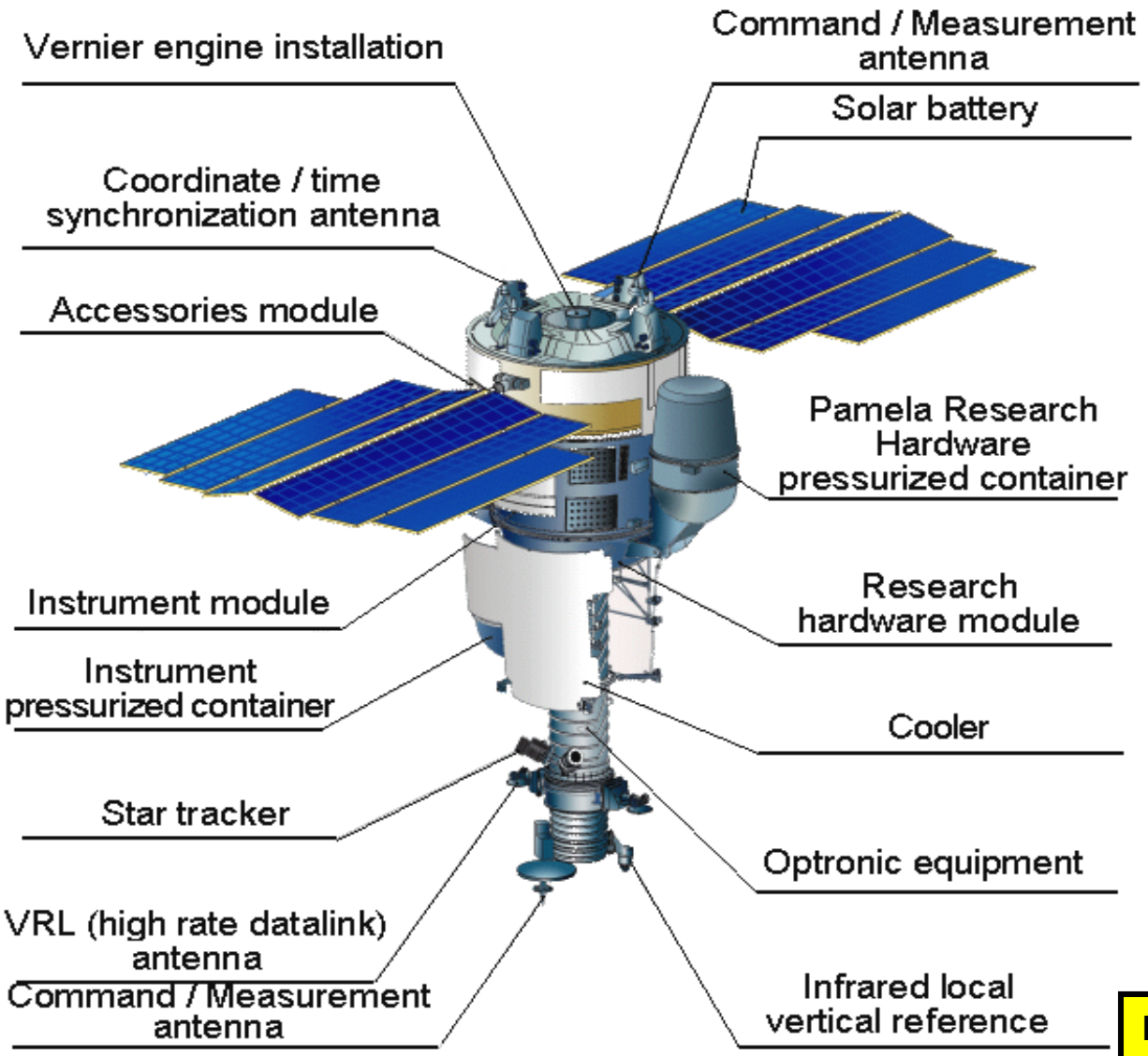


Technological Model
Preliminary acceptance tests with EGSE: power on/off, telecommands, data transmission through adapter; magnetic tests

Flight Model
Integration, beam tests; pre-flight operations

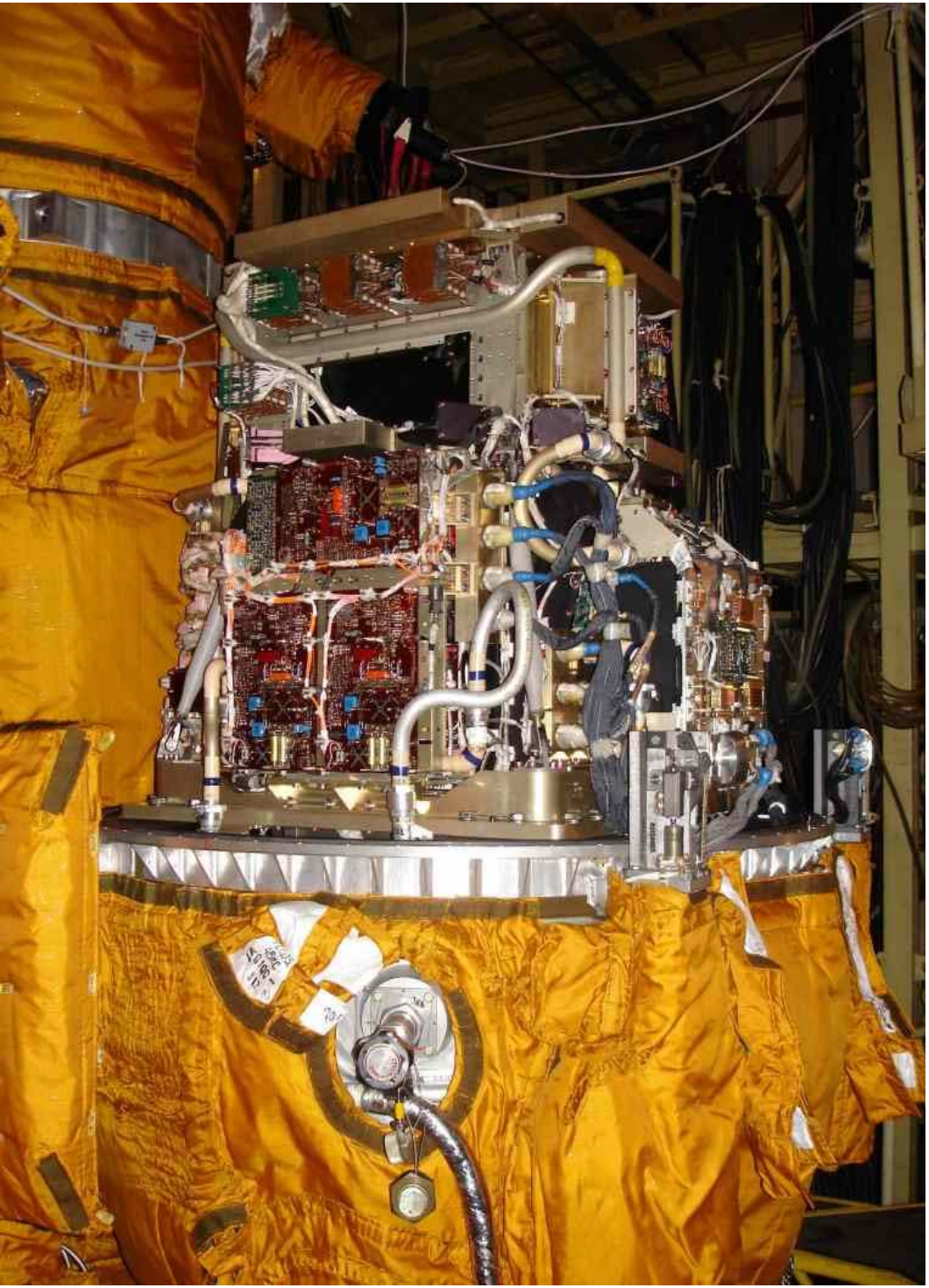


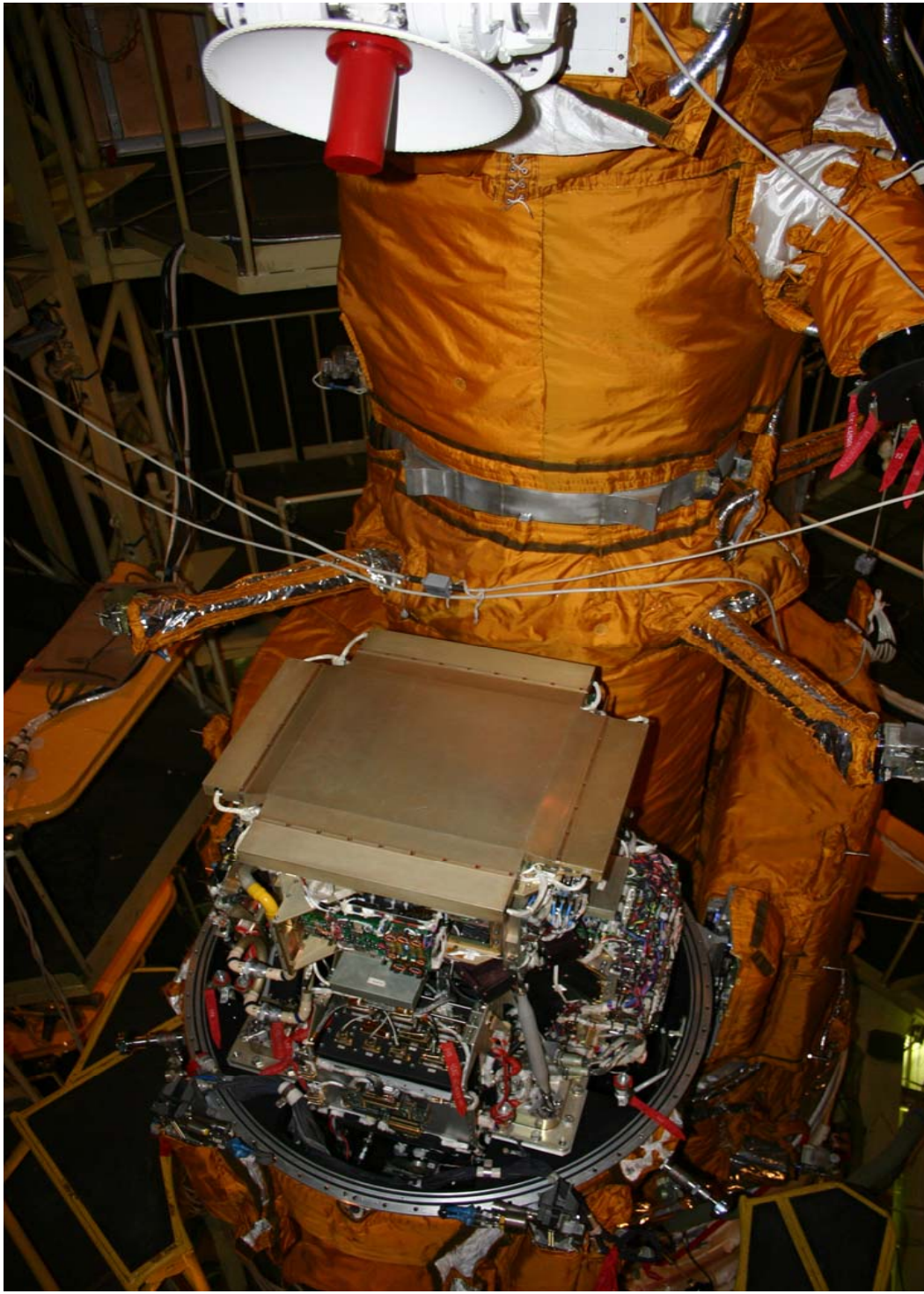
Resurs-DK1 Satellite

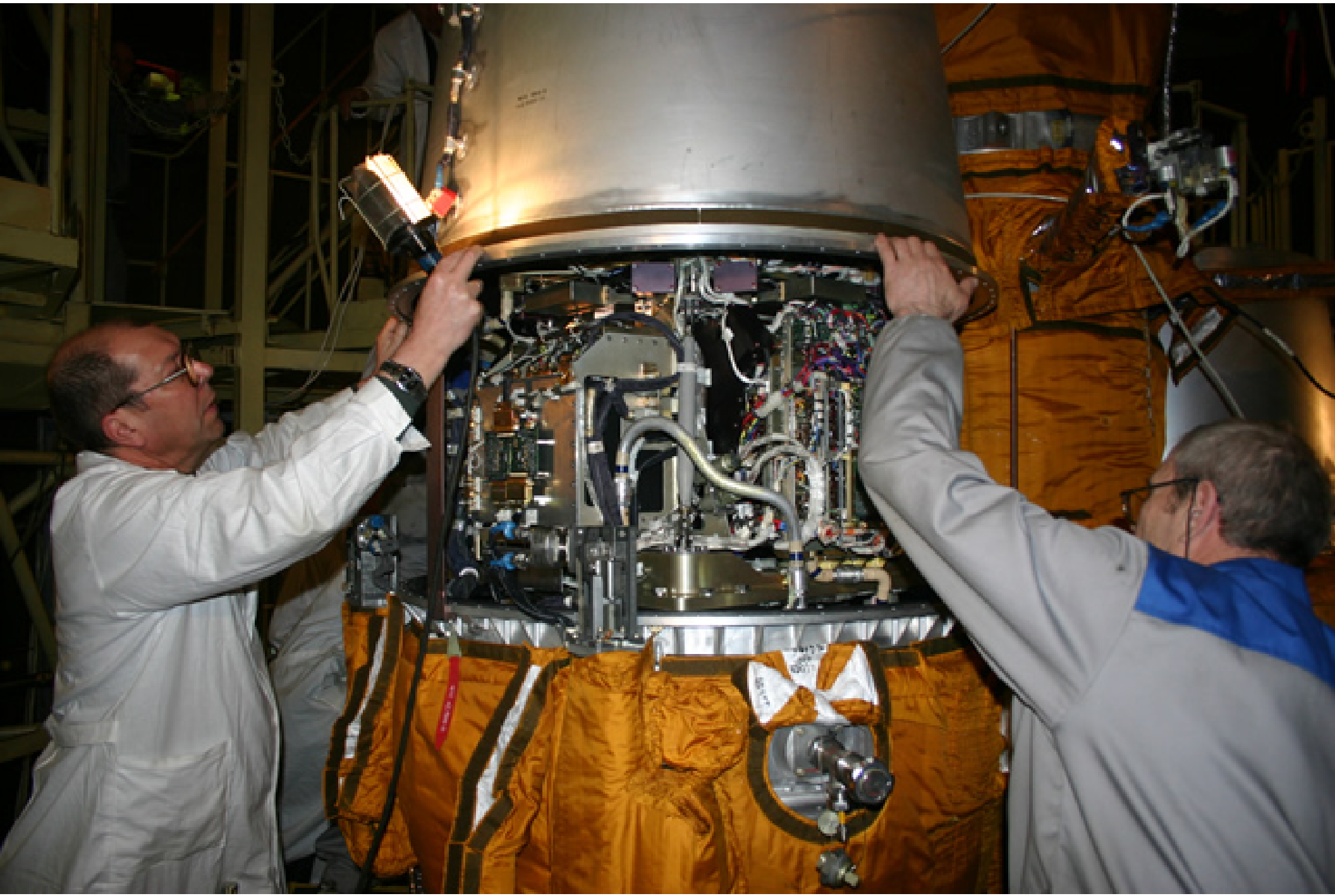


- Main task: multi-spectral remote sensing of earth's surface
- Built by TsSKB Progress in Samara (Russia)
- Active life >3 years
- Data transmitted to ground via radio downlink
- PAMELA mounted inside a pressurized container

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



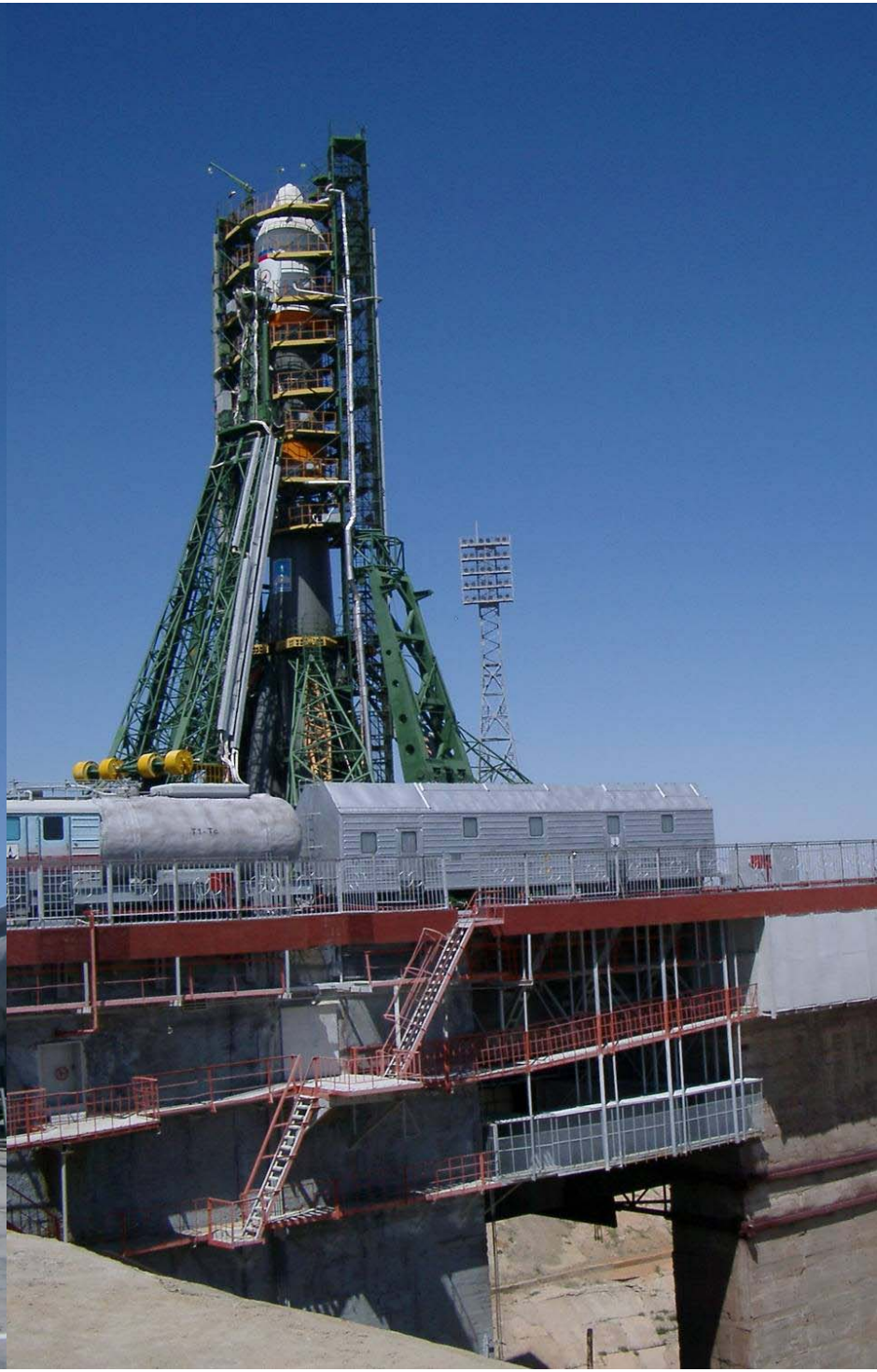




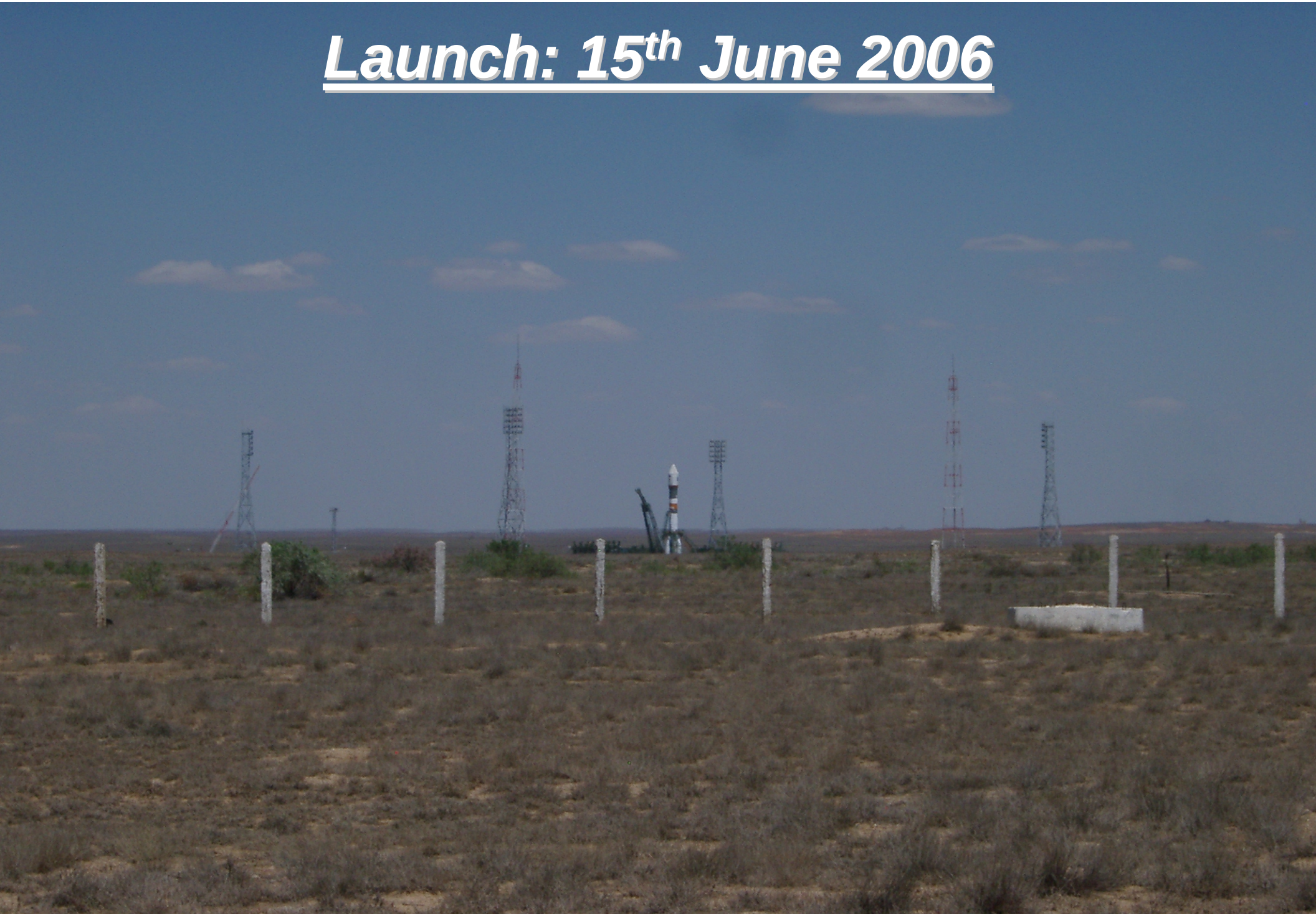

RUSSIA
KAZAKSTAN
Baikonur
Cosmodrome
UZBEKISTAN
KYRGYZSTAN
CHINA
© 1992 MAGELLAN Geographix, Santa Barbara, CA


ГАГАРИНСКИЙ
СТАРТ
12th April 1961

T – 1 day



Launch: 15th June 2006



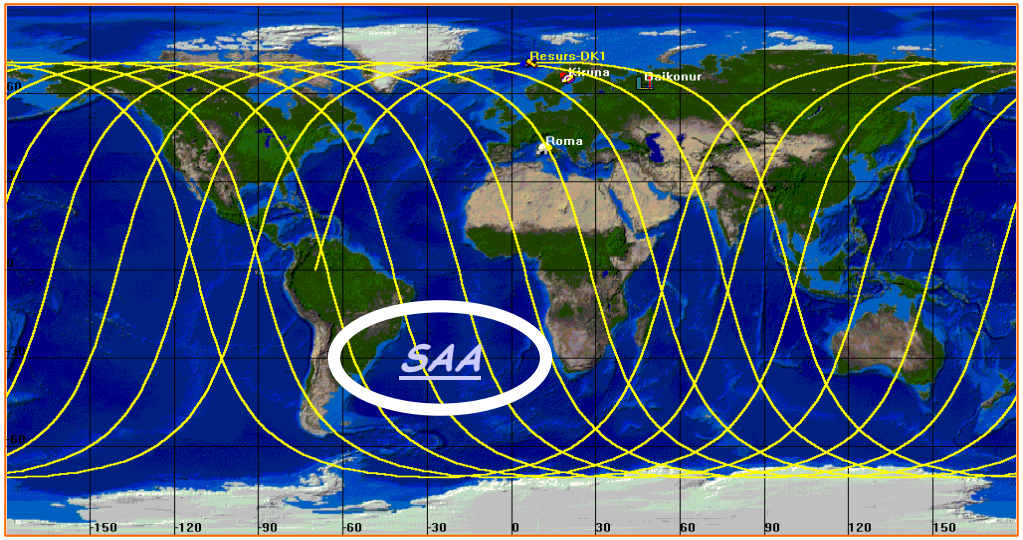
Launch: 15th June 2006

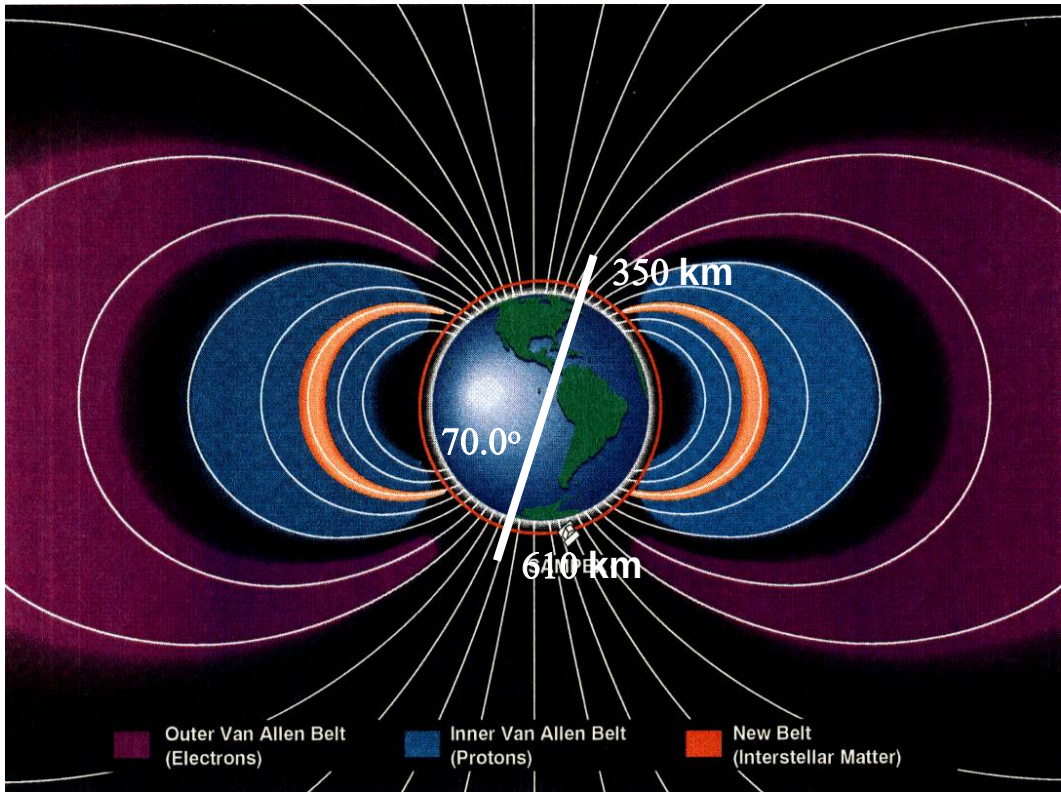
Launch: 15th June 2006

Launch: 15th June 2006

Launch: 15th June 2006

Orbital characteristics



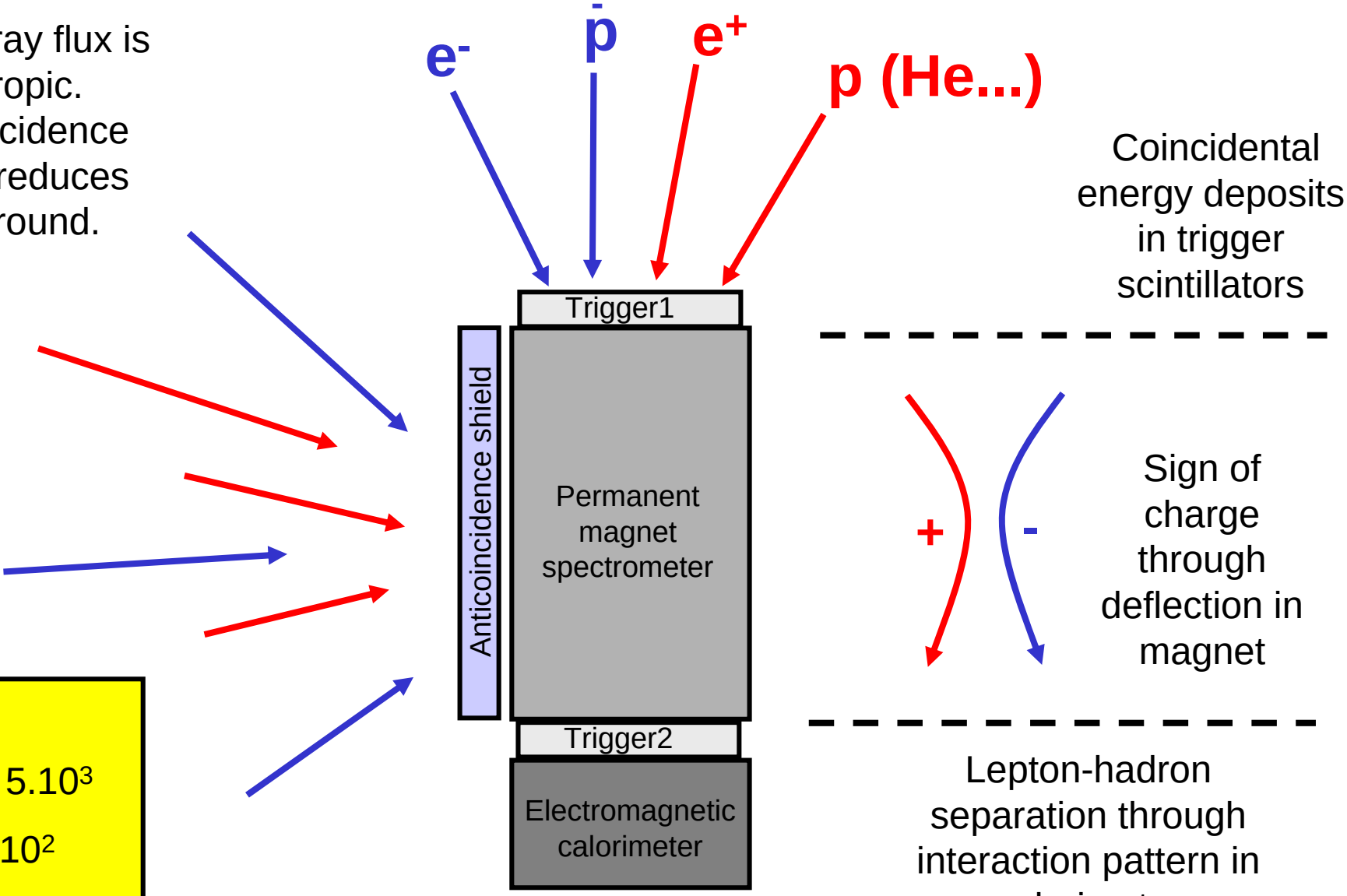


- Quasi-polar (70.0°)
- Elliptical (350 km - 600 km)
- PAMELA traverses the South Atlantic Anomaly
- At the South Pole PAMELA crosses the outer (electron) Van Allen belt

- Orbital tracking via on-board GLONASS or **NORAD** (used!)

Principle of operation

Cosmic ray flux is ~isotropic. Anticoincidence system reduces background.



Coincidental energy deposits in trigger scintillators

Sign of charge through deflection in magnet

Lepton-hadron separation through interaction pattern in calorimeter

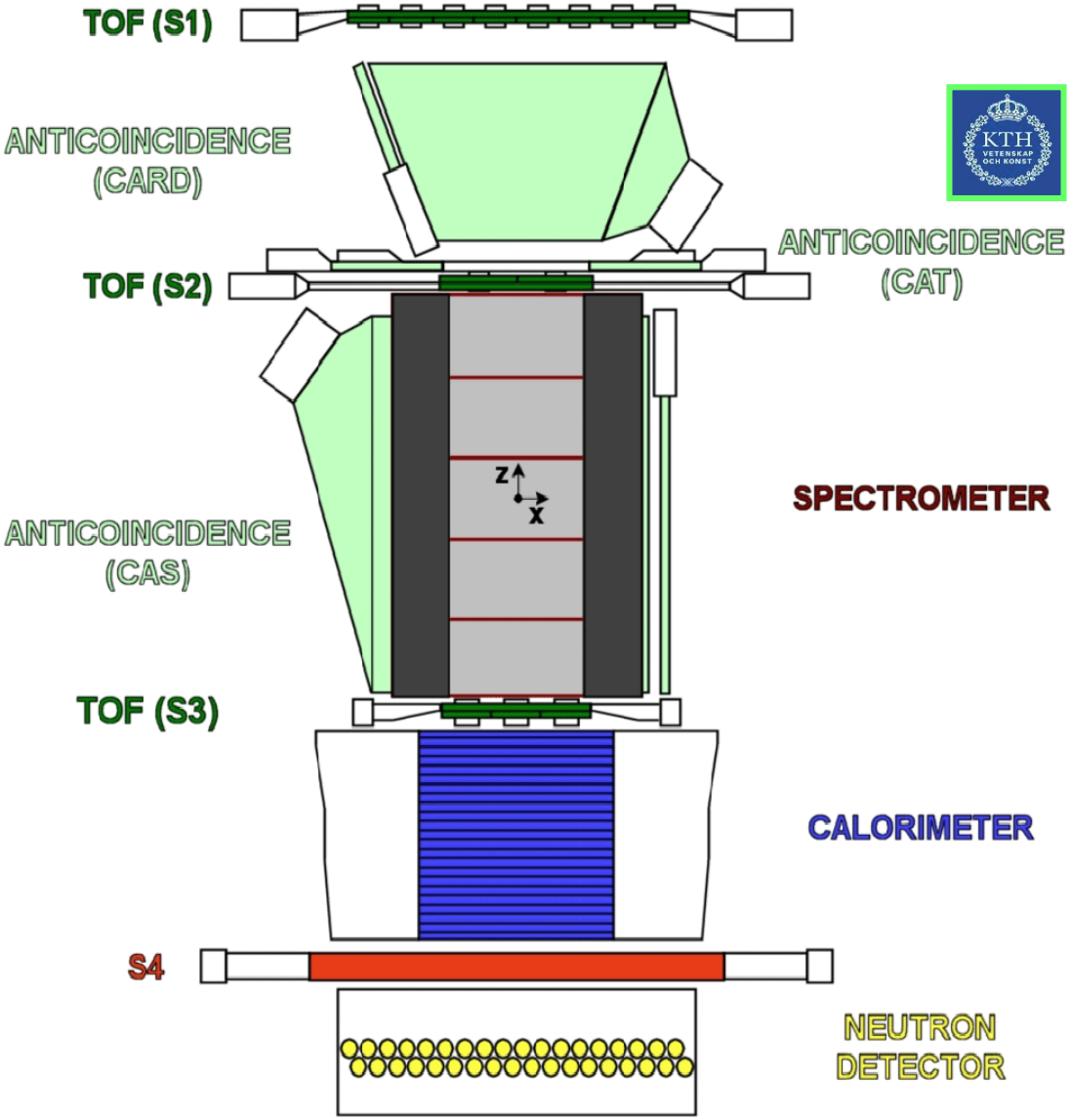
At ~10 GeV:

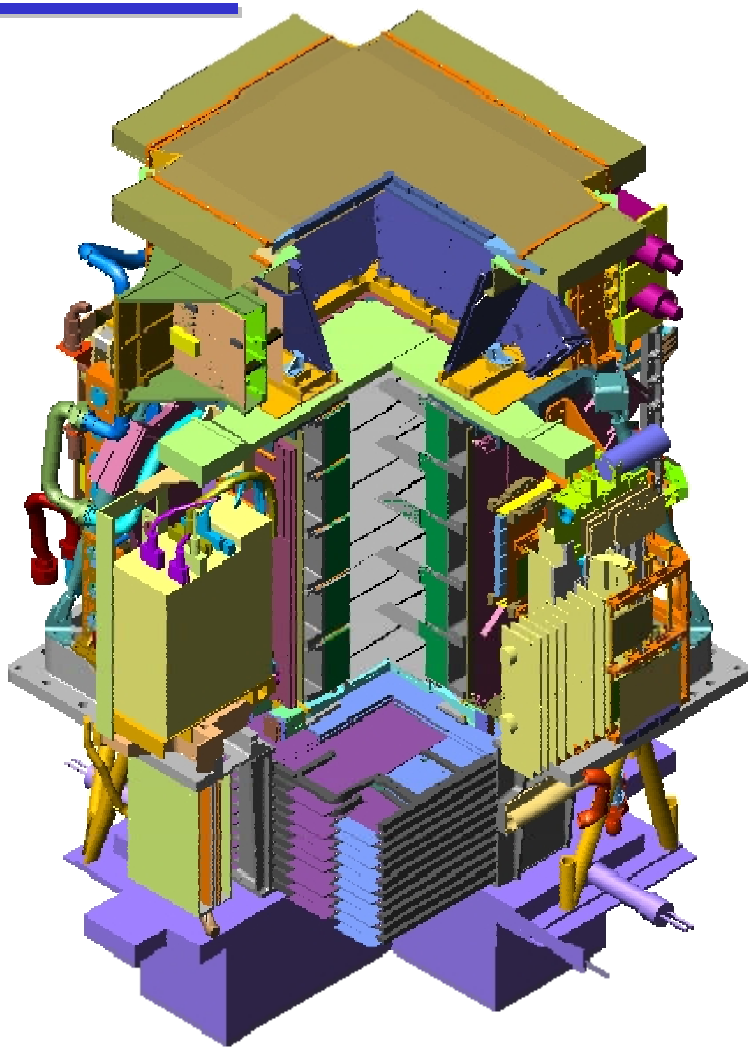
$N(p) / N(e^+) \sim 5.10^3$

$N(e^-) / N(\bar{p}) \sim 10^2$

$(N(p) / N(e^-) \sim 10^2)$

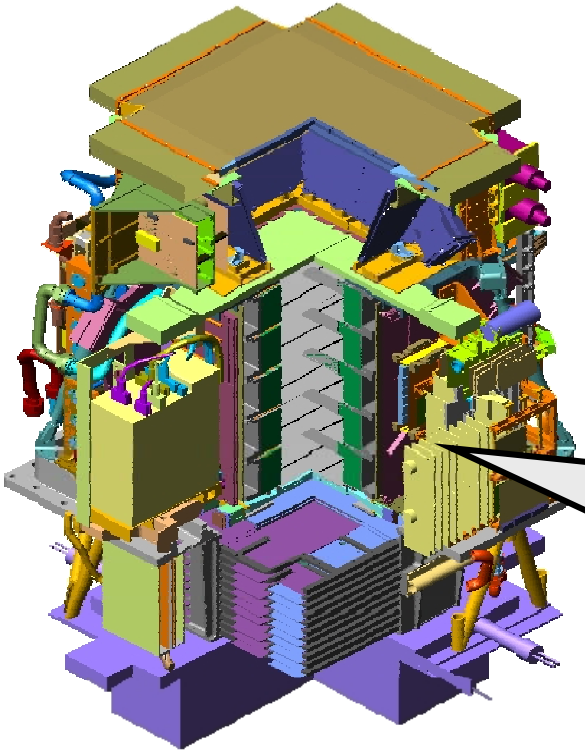
PAMELA apparatus





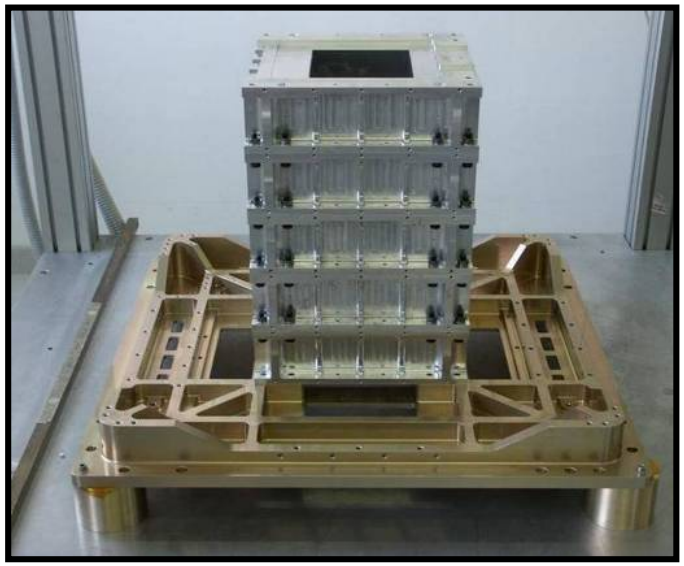
GF: 21.5 cm^2 sr
Mass: 470 kg
Size: 130 x 70 x 70 cm^3
Power budget: 360 W

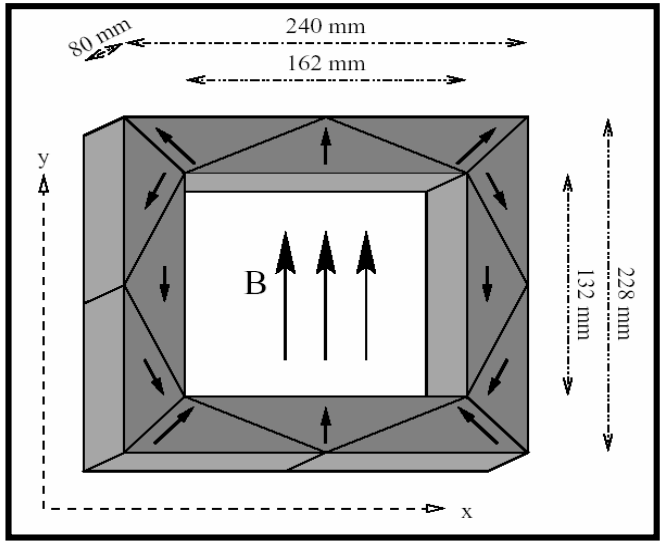
The magnet



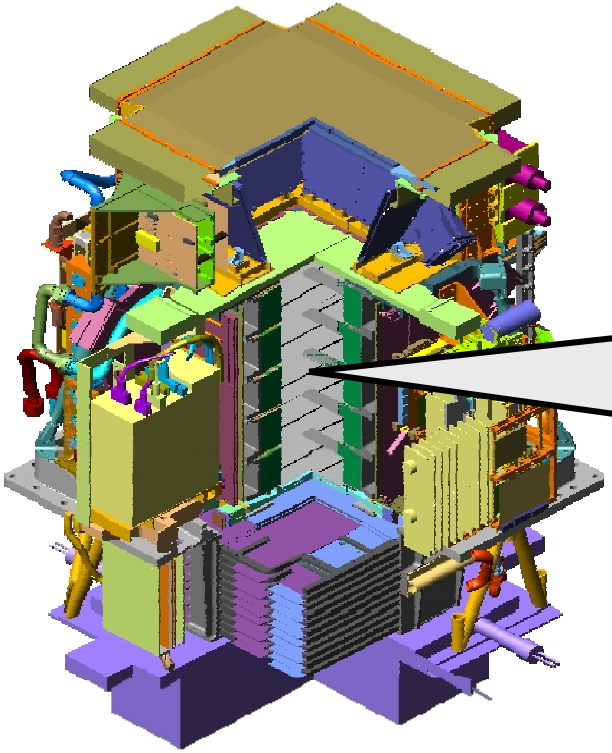
Characteristics:

- 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:

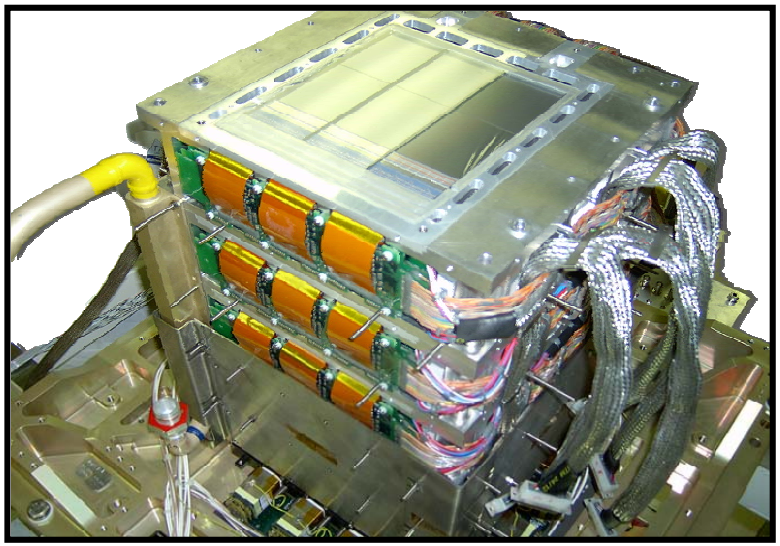
- Rigidity measurement
- Sign of electric charge
- dE/dx (ionisation loss)

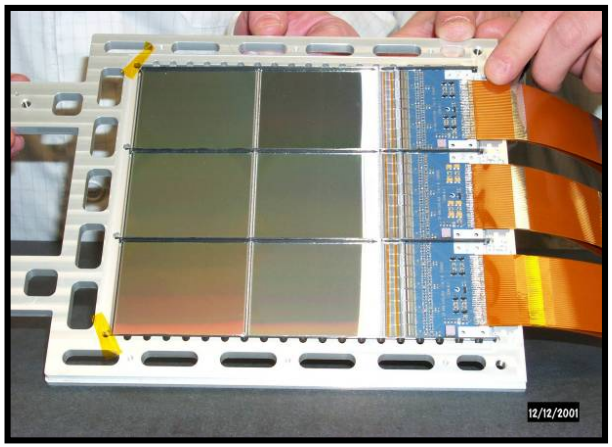
Characteristics:

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

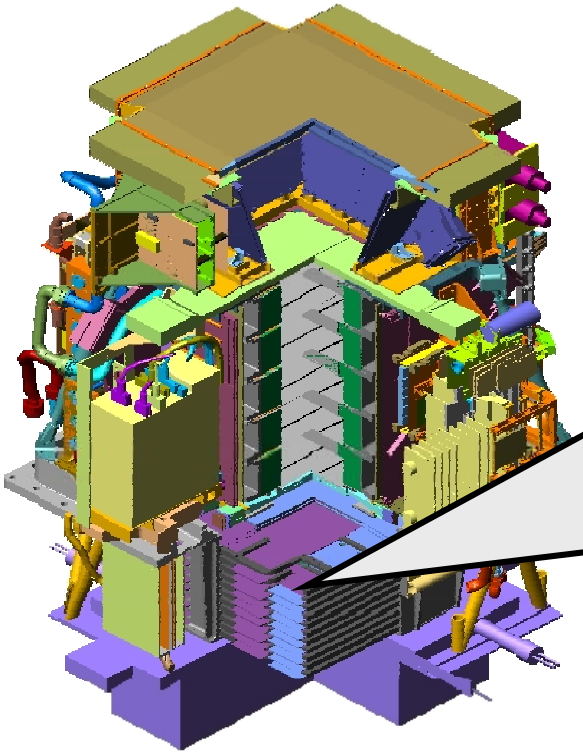
Performance:

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





The electromagnetic calorimeter



Main tasks:

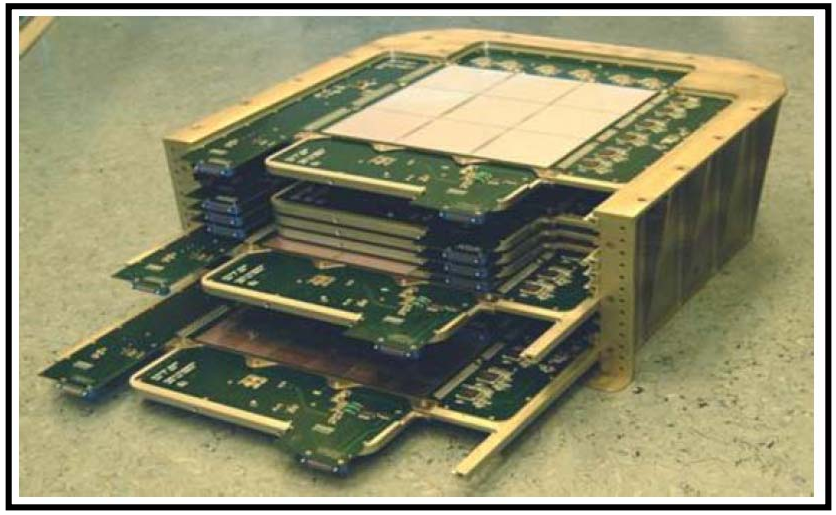
- lepton/hadron discrimination
- $e^{+/-}$ energy measurement

Characteristics:

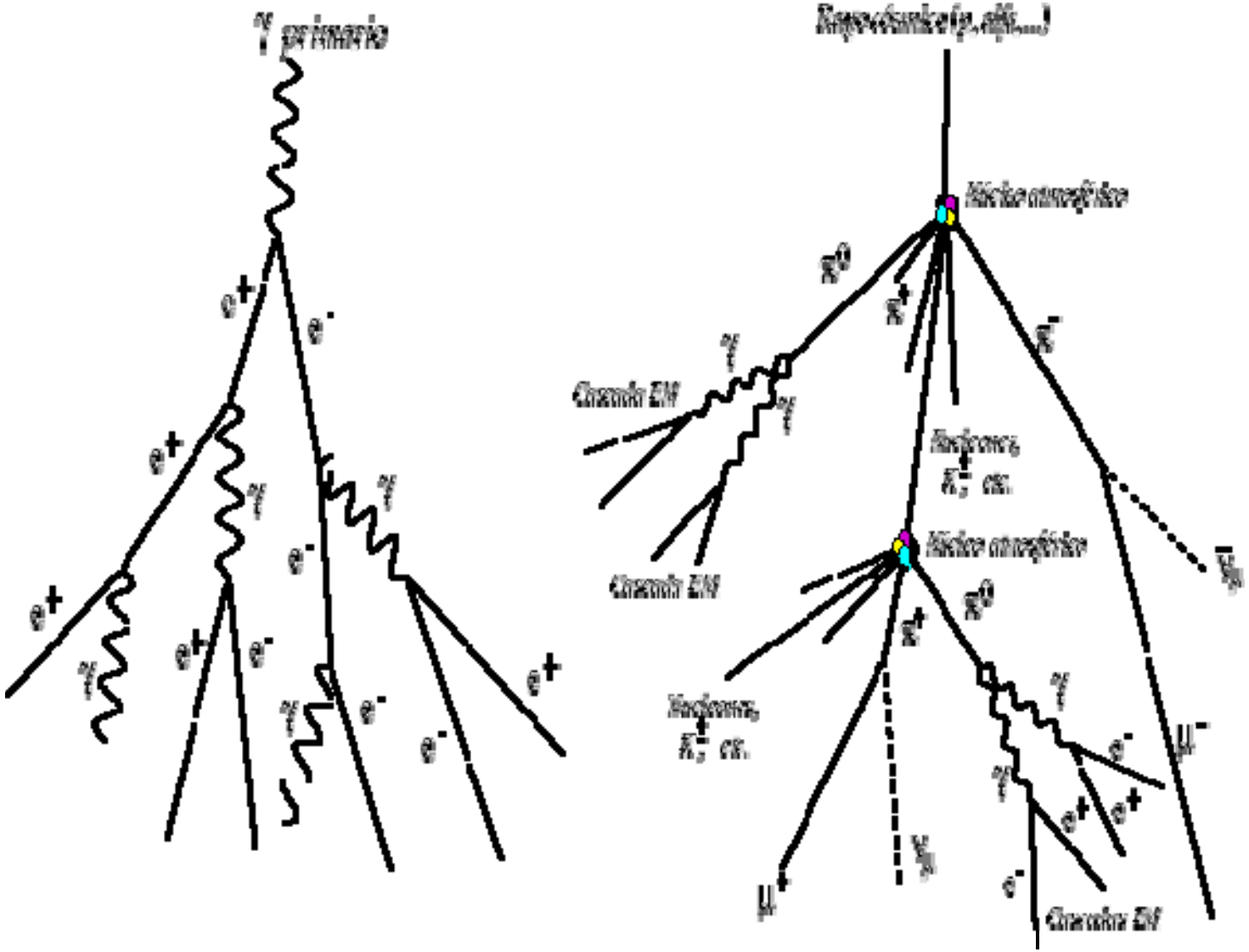
- 44 Si layers (X/Y) + 22 W planes
- 16.3 X_o / 0.6 λ_L
- 4224 channels
- Dynamic range: 1400 mip
- Self-trigger mode (> 300 GeV; GF~600 cm^2 sr)

Performance:

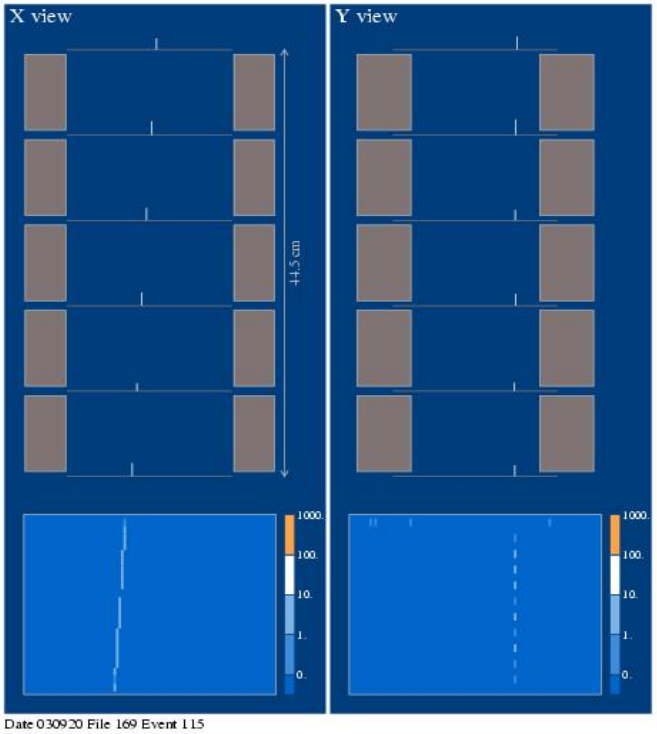
- p/e^+ selection efficiency ~ 90%
- p rejection factor ~10^6
- e rejection factor > 10^4
- Energy resolution ~5% @ 200 GeV



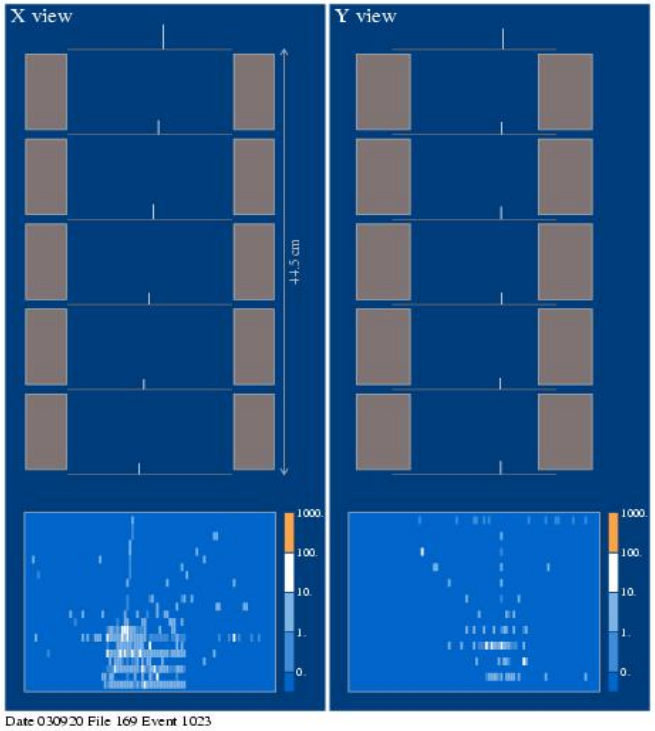
Electromagnetic and hadronic showers



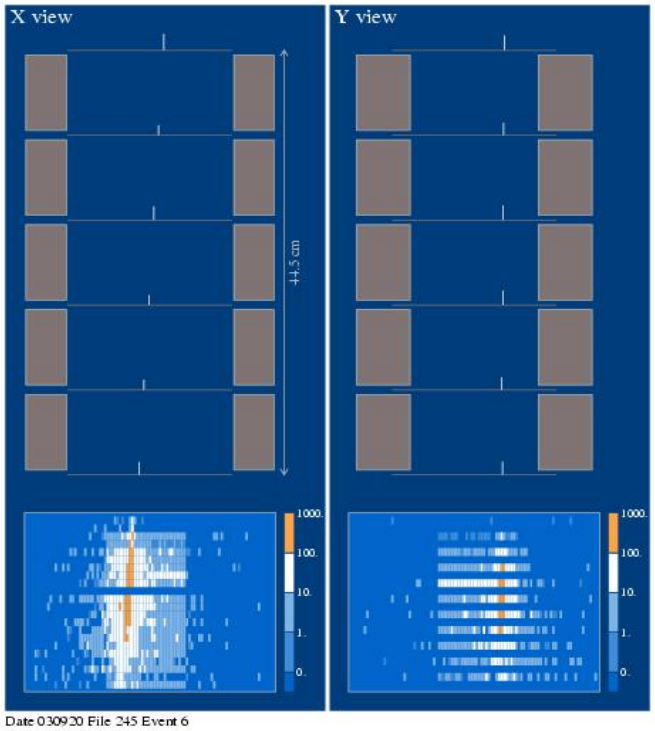
Combined tracker + calorimeter performance



Non-interacting p 100 GeV/c



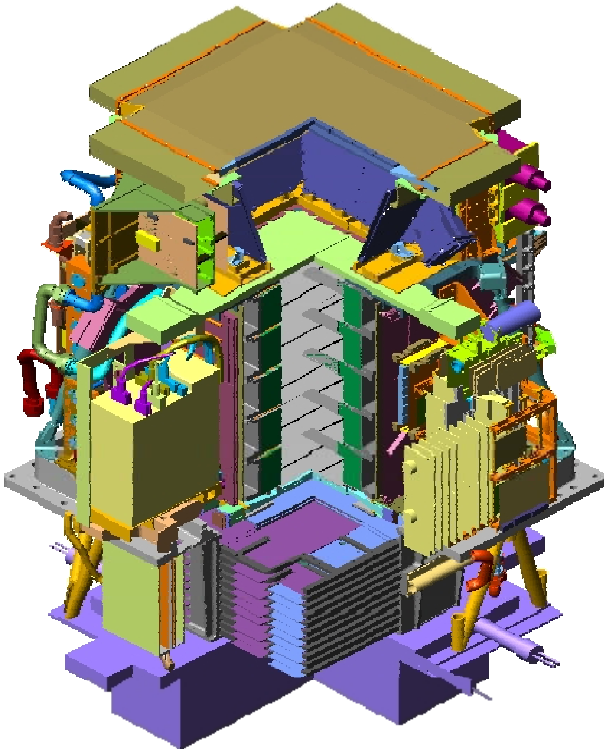
Interacting p 100 GeV/c

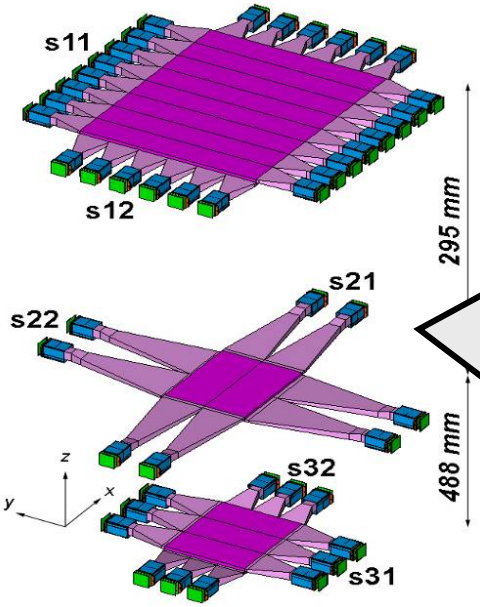


Interacting e^- 100 GeV/c

(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)

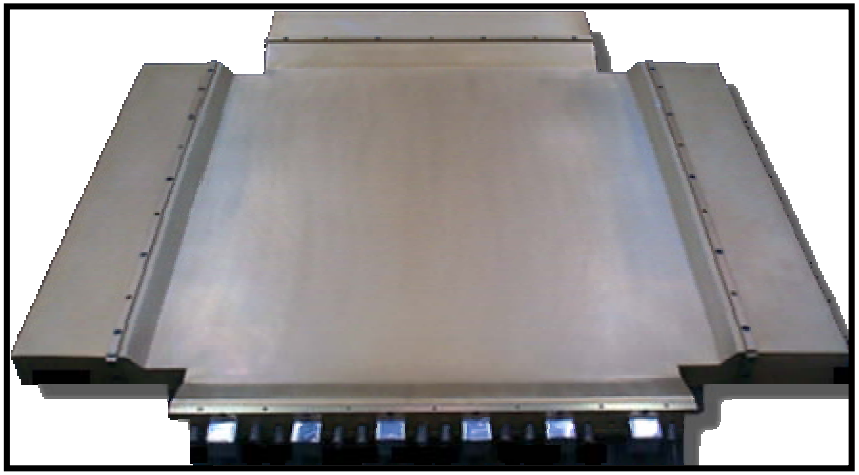
Characteristics:

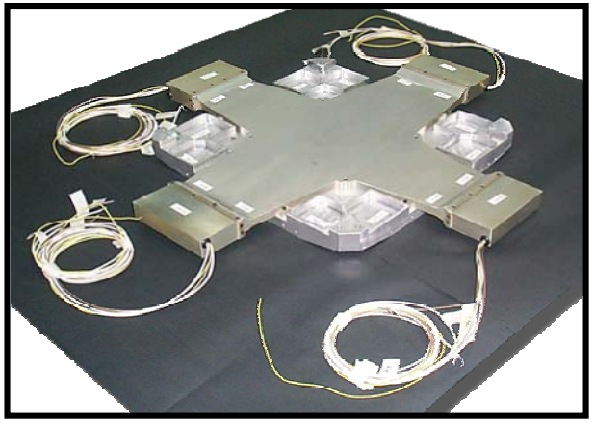
- 3 double-layer scintillator paddles
- X/Y segmentation
- Total: 48 Channels

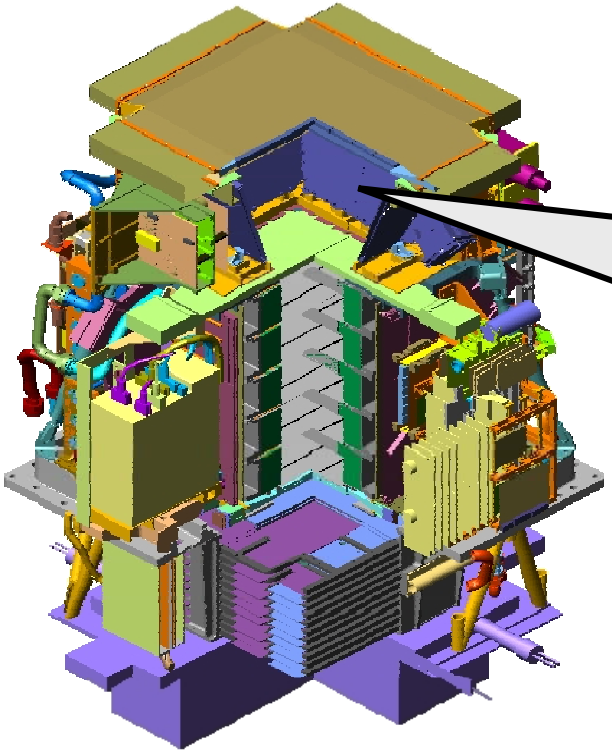
Performance:

σ(paddle) ~ 110ps

σ(ToF) ~ 330ps (for MIPs)







The anticounter shields

Main tasks:

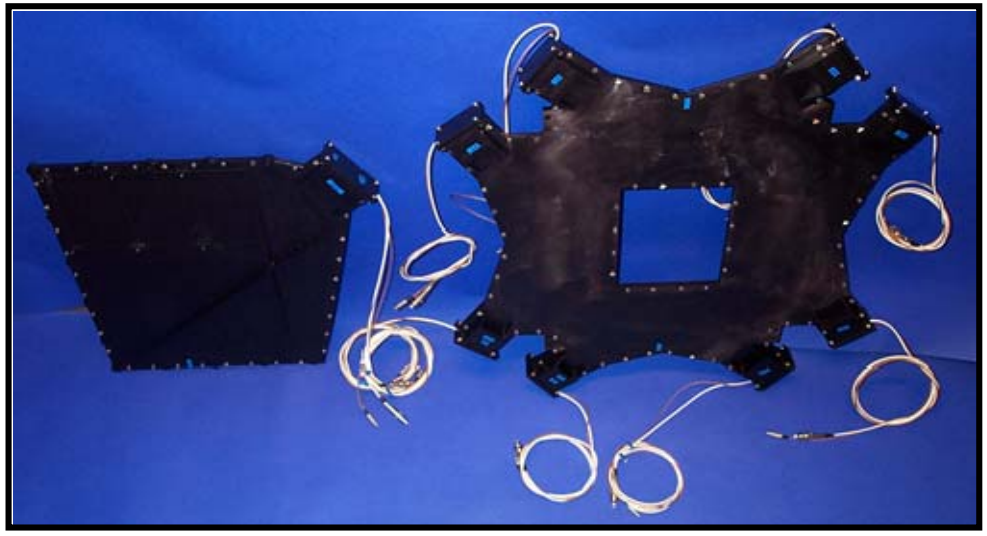
- Rejection of events with particles interacting with the apparatus (off-line and second-level trigger)

Characteristics:

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

Performance:

- MIP efficiency > 99.9%



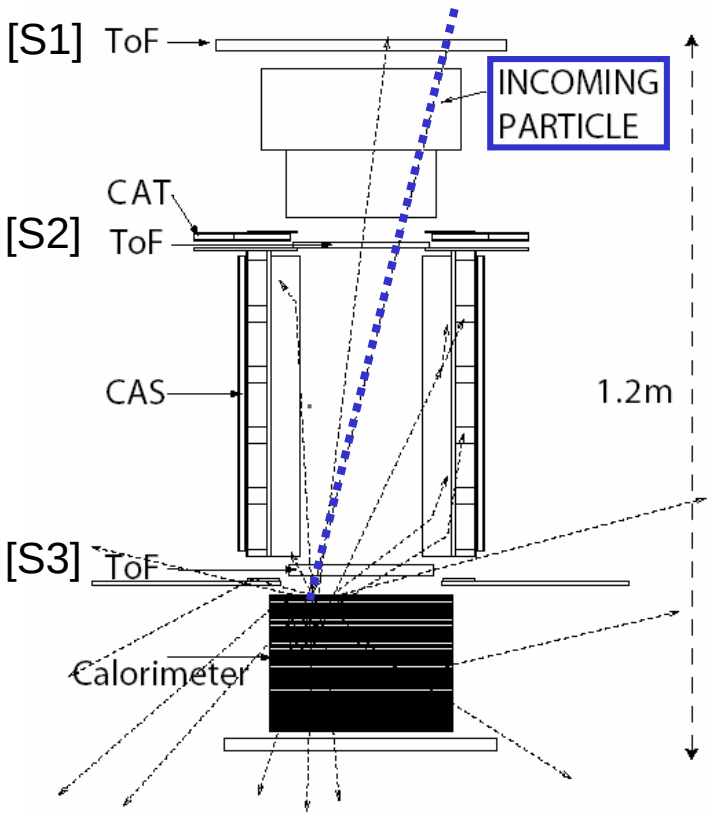
RYMDSTYRELSEN
Swedish National Space Board

Swedish Space Corporation

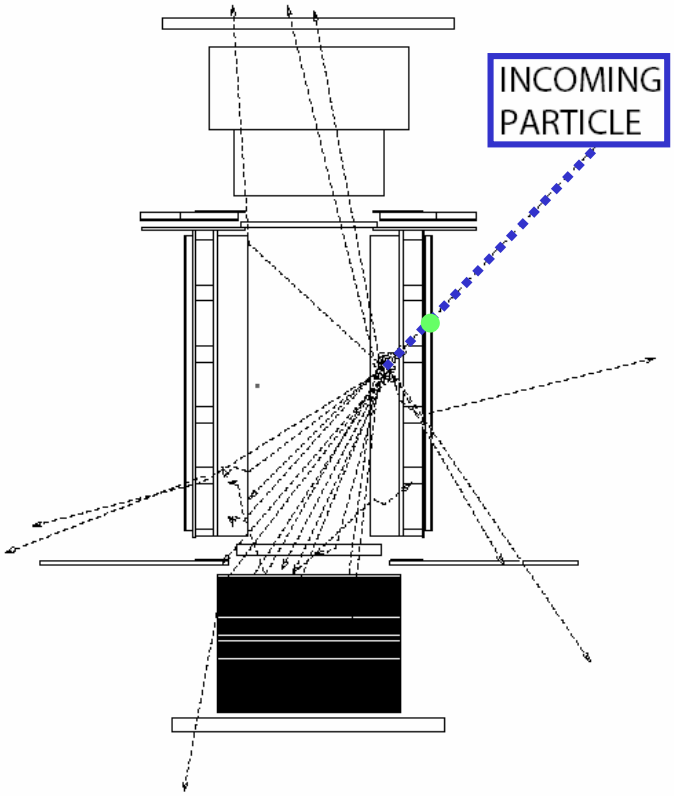
KTH
VETENSKAP OCH KONST

Anticounter purpose

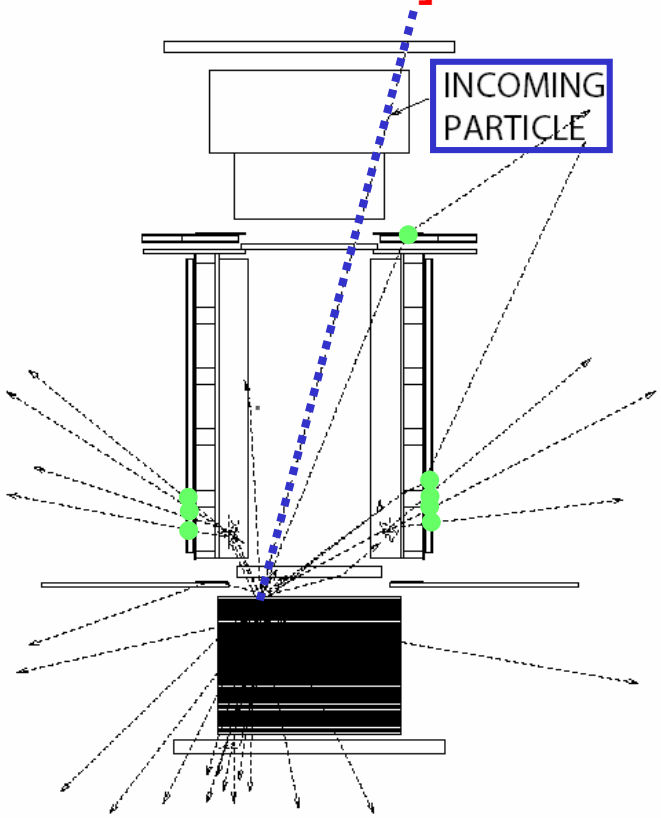
[Good trigger]



[False trigger]



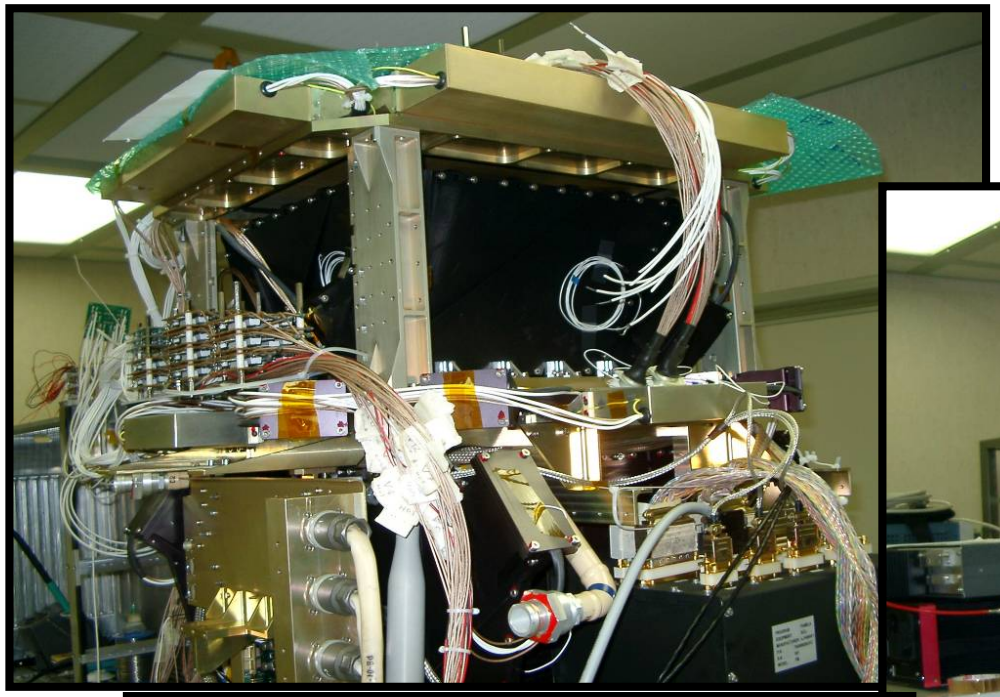
[Good trigger with AC self-veto]

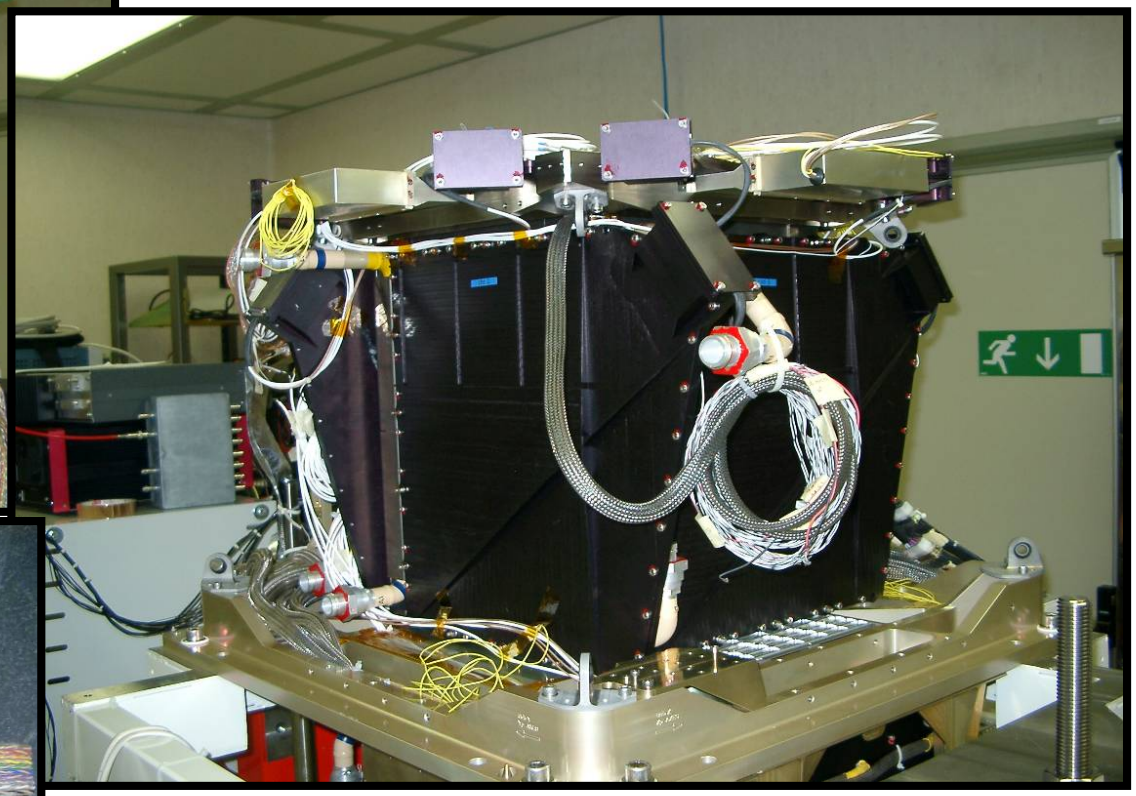


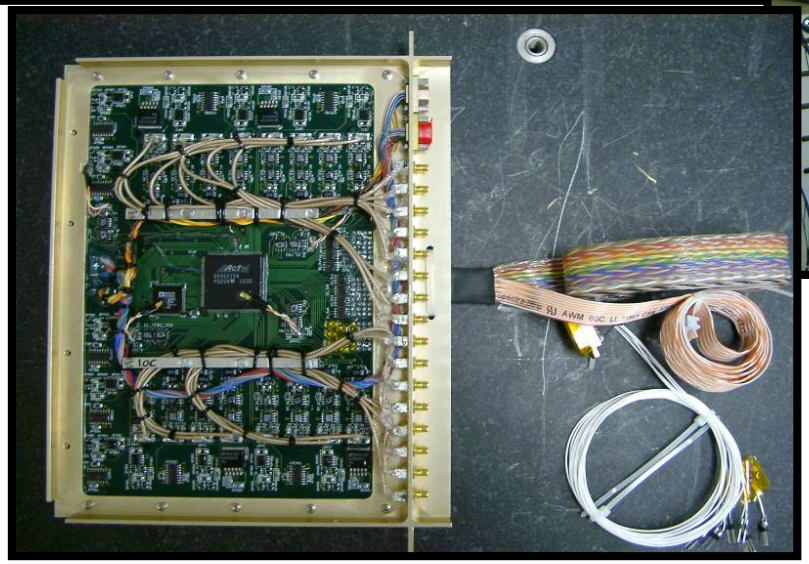
- Main trigger = S1 .and. S2 .and. S3

- Use AC offline or in L2 trigger to reduce false triggers
- **NB:** background from self-veto

Anticoincidence systems

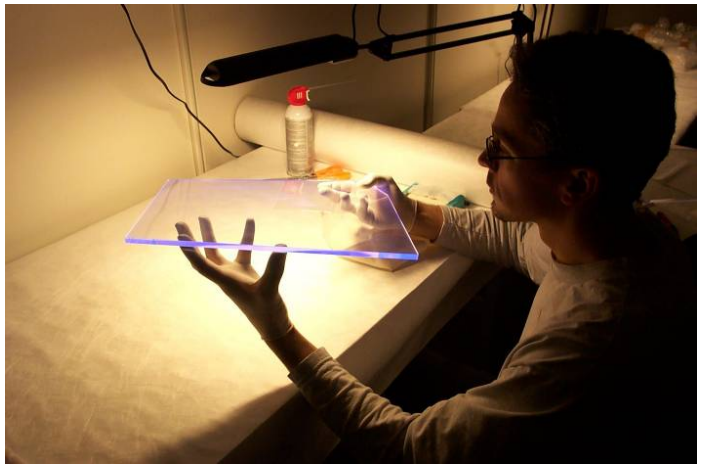






Examples of qualification tests

[QA]



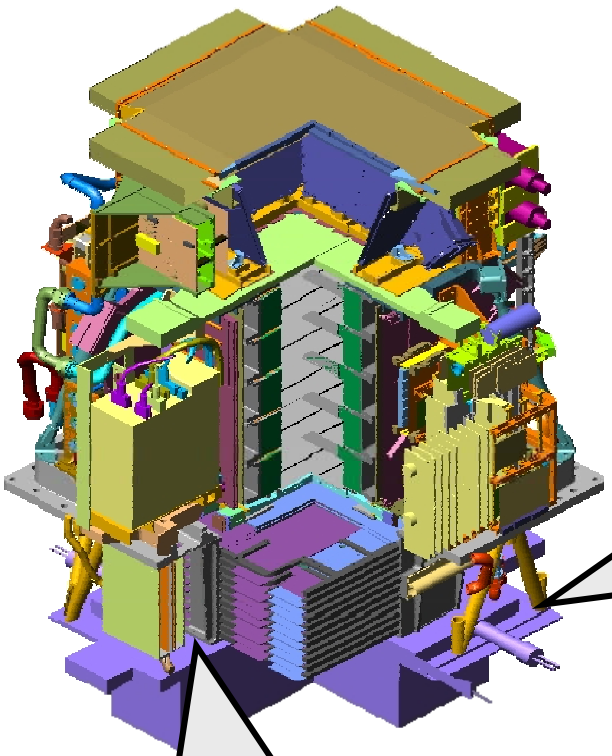
[Beam tests]

[Irradiation]

[Thermal, burn in]

[Vibrations]

[On-ground]



Neutron detector

Main tasks:

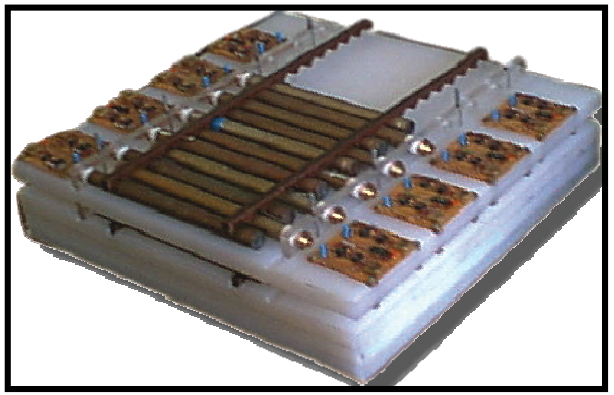
- e/h discrimination at high-energy

Characteristics:

- 36 ^{3}He counters:

^{3}He(n,p)T → Ep=780 keV

- 1cm thick polyethylene moderators
- n collected within 200 μs time-window



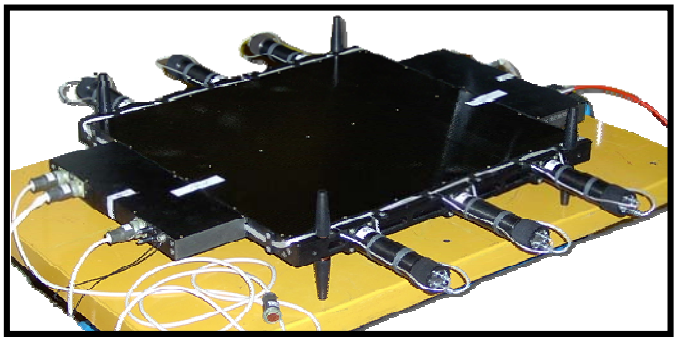
Shower-tail catcher

Main tasks:

- Neutron Detector trigger

Characteristics:

- 1 plastic scintillator paddle, 1 cm thick



PAMELA milestones

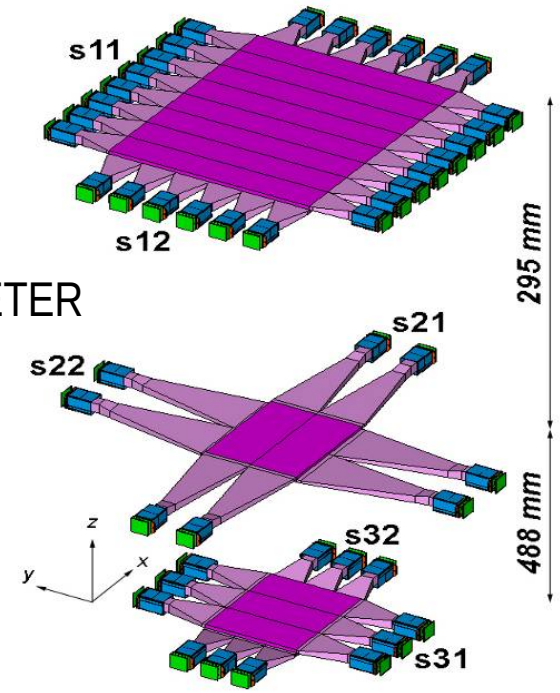
- **Launch from Baikonur:** June 15th 2006.
- **'First light':** June 21st 2006, 0300 UTC.

- Detectors operated as expected (i.e.: no problems due to the launch).
- Tested different trigger and hardware configurations
- **Commissioning phase ended successfully on July 11th 2006**
- **PAMELA in continuous data-taking mode since then**

- As of ~now:
  - PAMELA has acquired data for ~220 days
  - 4 TB of raw data downlinked
  - ~480 million triggers recorded

Data acquisition details

- Trigger configurations:
  - High-radiation environment
    → (S21 AND S22) AND (S31 AND S32) + CALORIMETER
  - Low-radiation environment
    → (S11 OR S12) AND (S21 OR S22) AND (S31 OR S32) + CALORIMETER



- Trigger rate* ~25Hz
- Fraction of live time* ~ 75% (*outside radiation belts)
- Event size (compressed mode) ~ 5kB
  → 25 Hz x 5 kB/ev ~ 10 GB/day

Ground station

- **Main Station:** Research Centre for Earth Operative Monitoring **"NtsOMZ"** (Moscow, Russia);

  • Collected data stored in PAMELA mass-memory (2GB)
  • Download (PAMELA → satellite): 7-8 per day → 14-16 GB
  • Downlink (satellite→ ground) 2-3 sessions per day
  • Bit Error Rate $<10^{-9}$

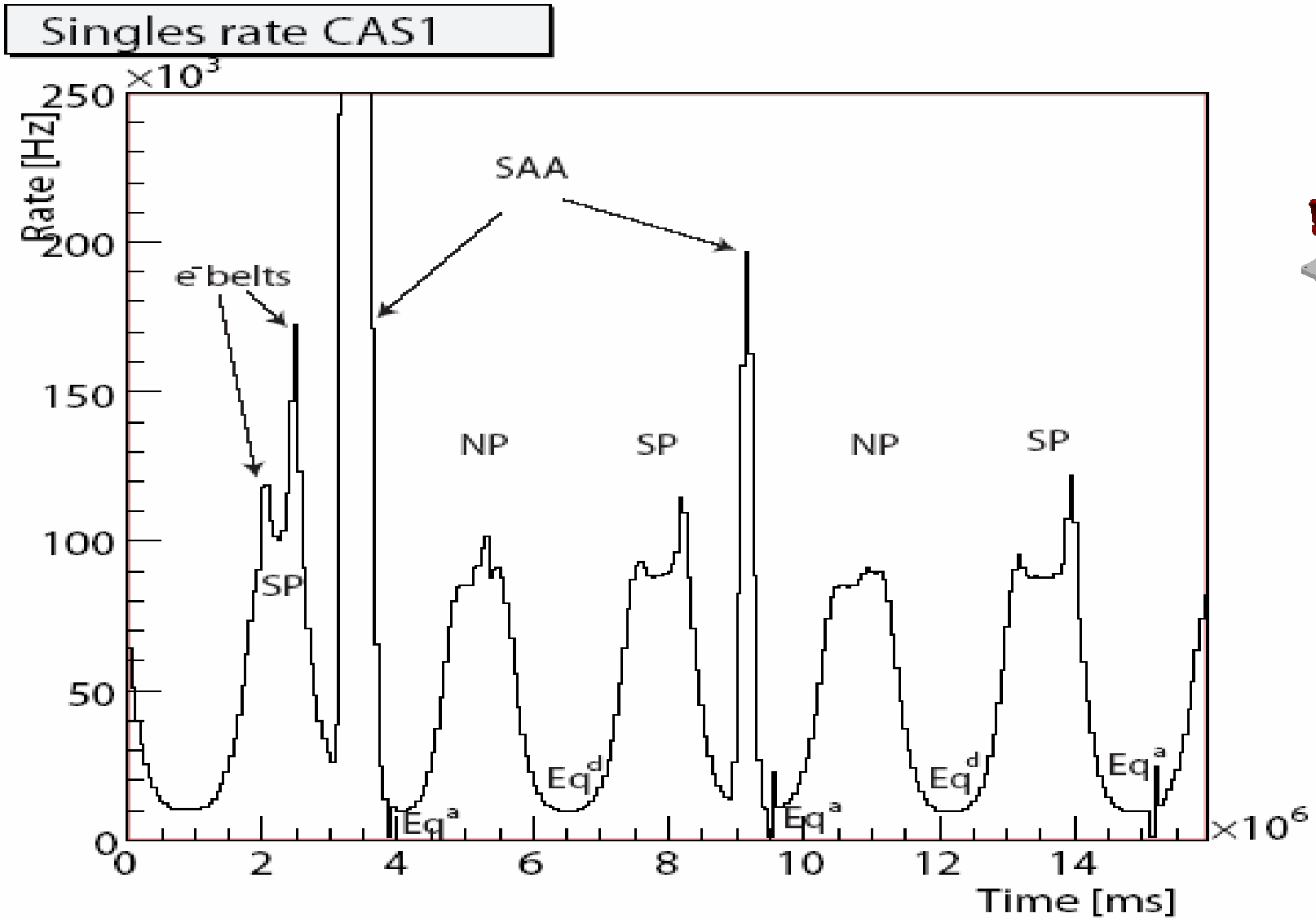
  • Real time 'Quicklook' at NtsOMZ
  • Corrective uplinks are possible

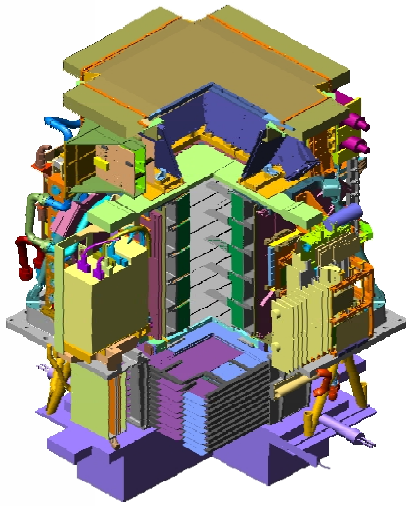
Main antenna in NTsOMZ

- Data distributed to MePHI (Moscow Engineering and Physics Institute) and then onto Europe via GridFTP.

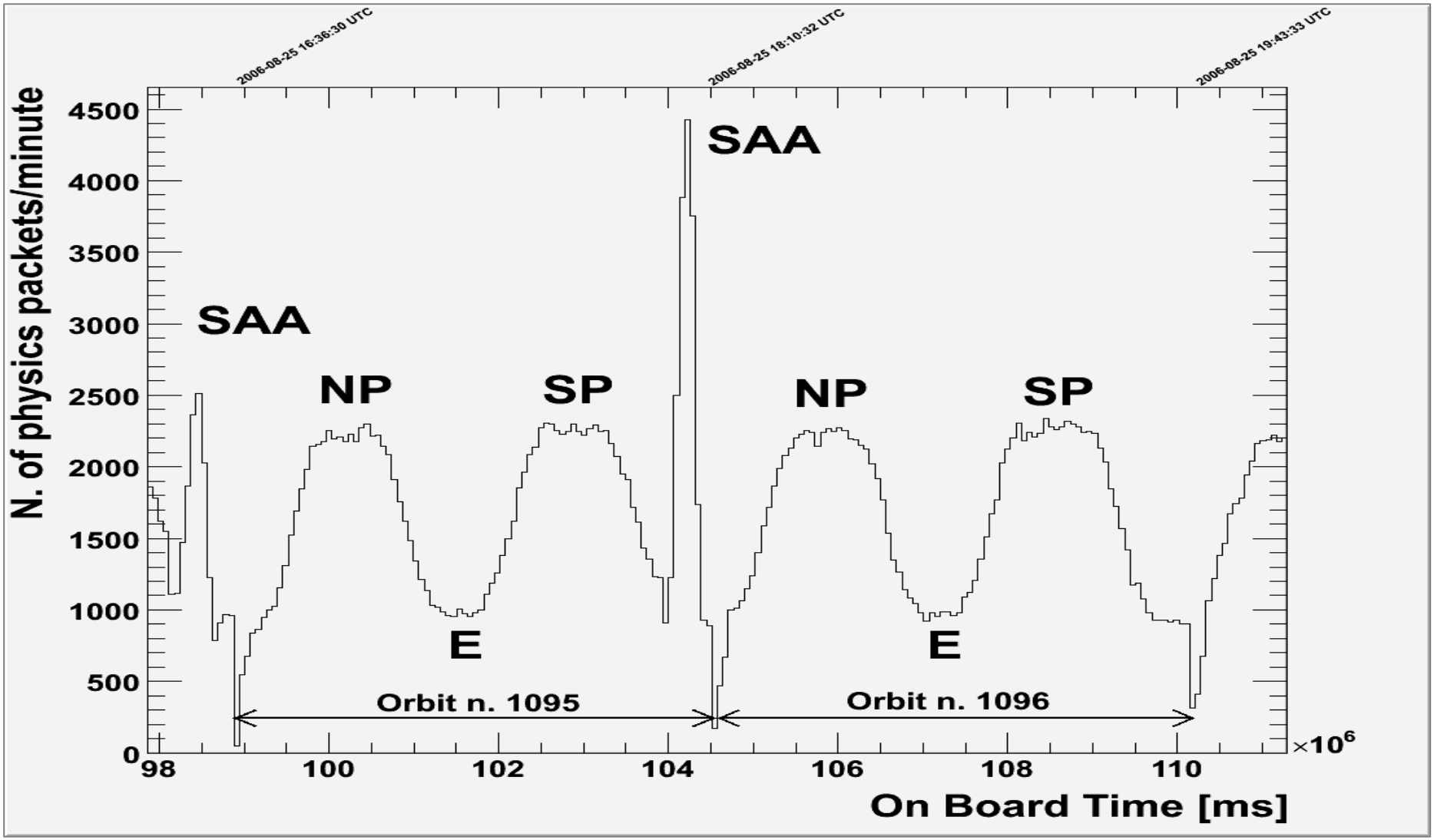
Orbital environment

Anticoincidence counting rate

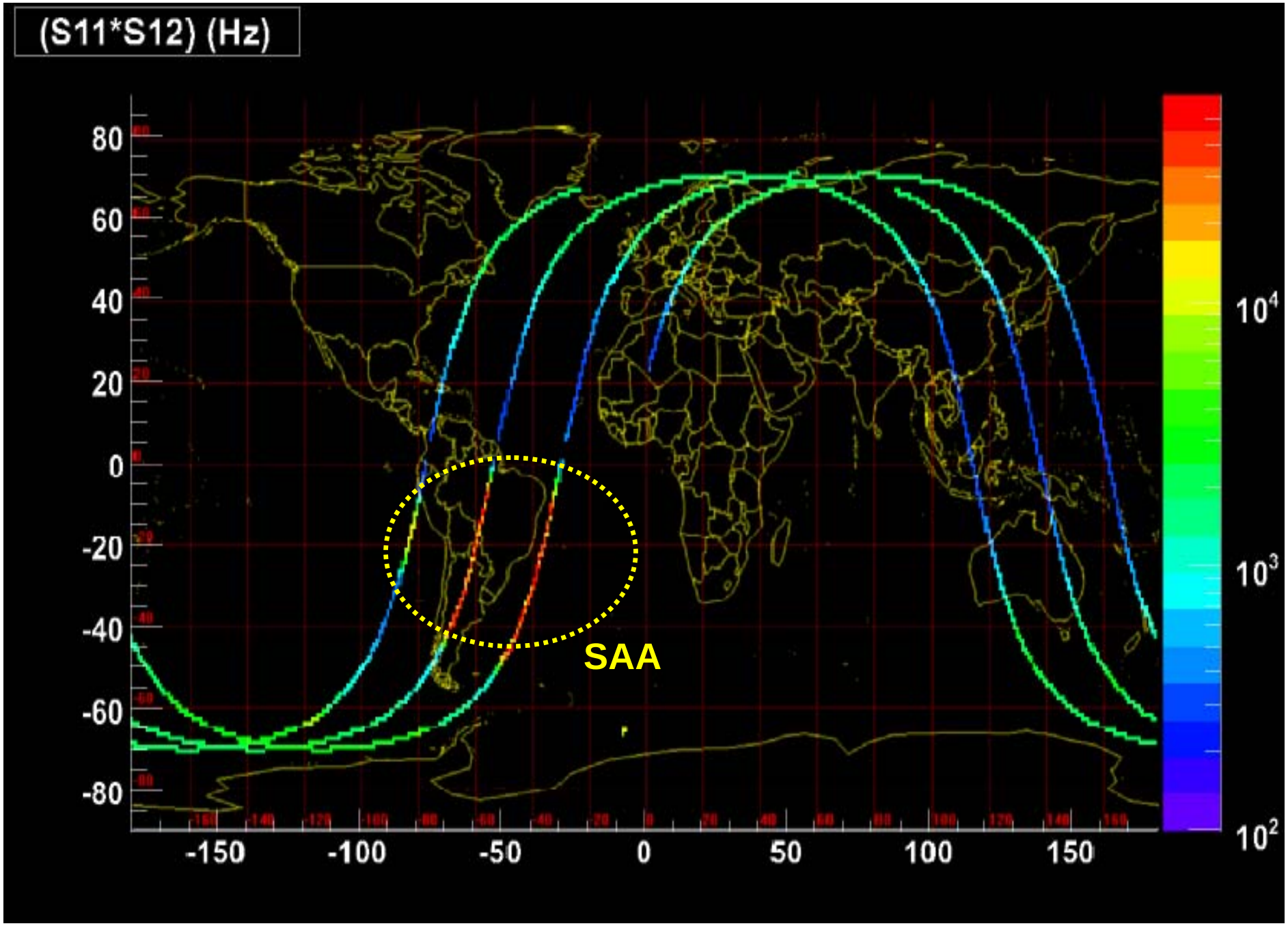


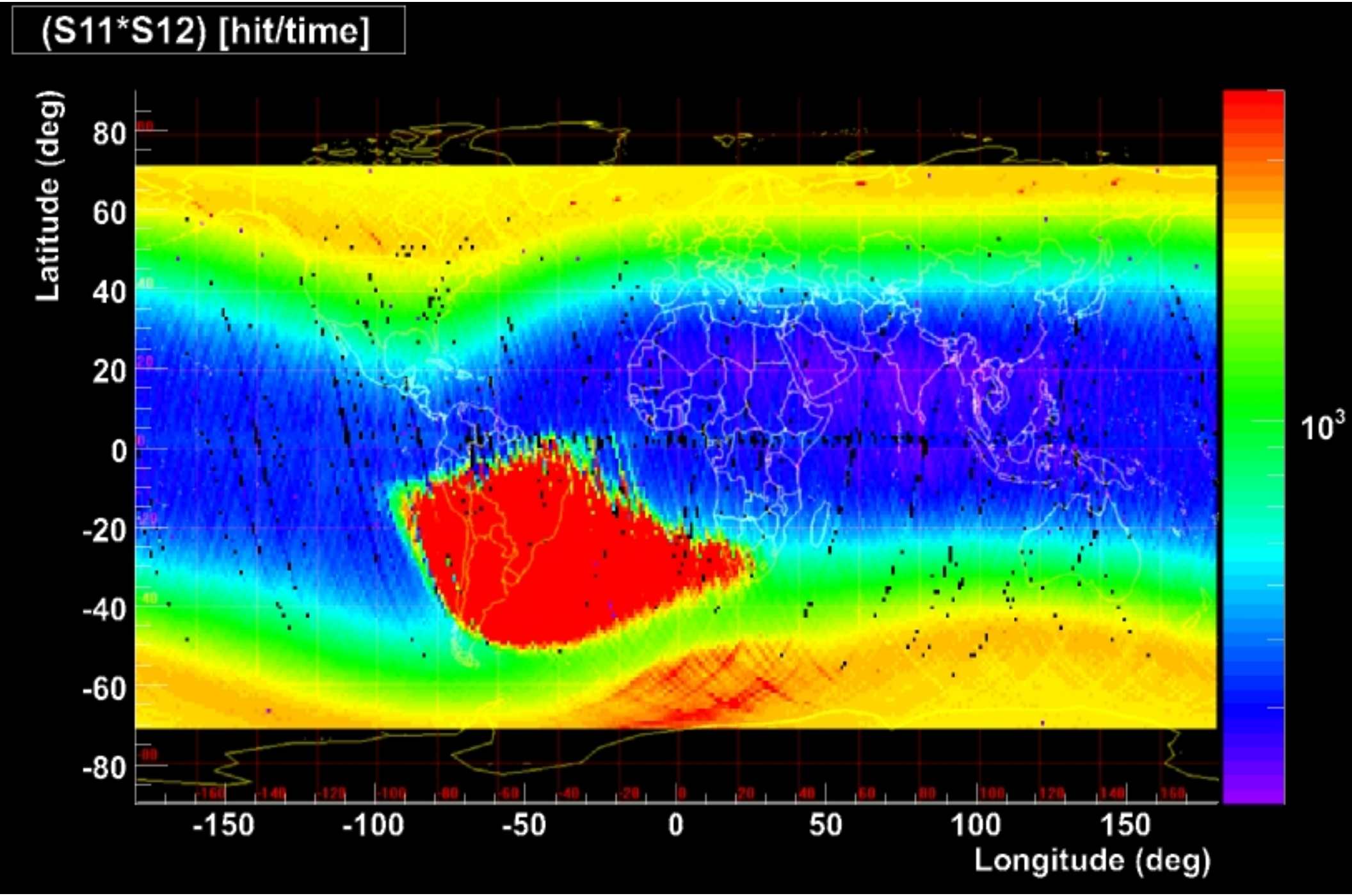


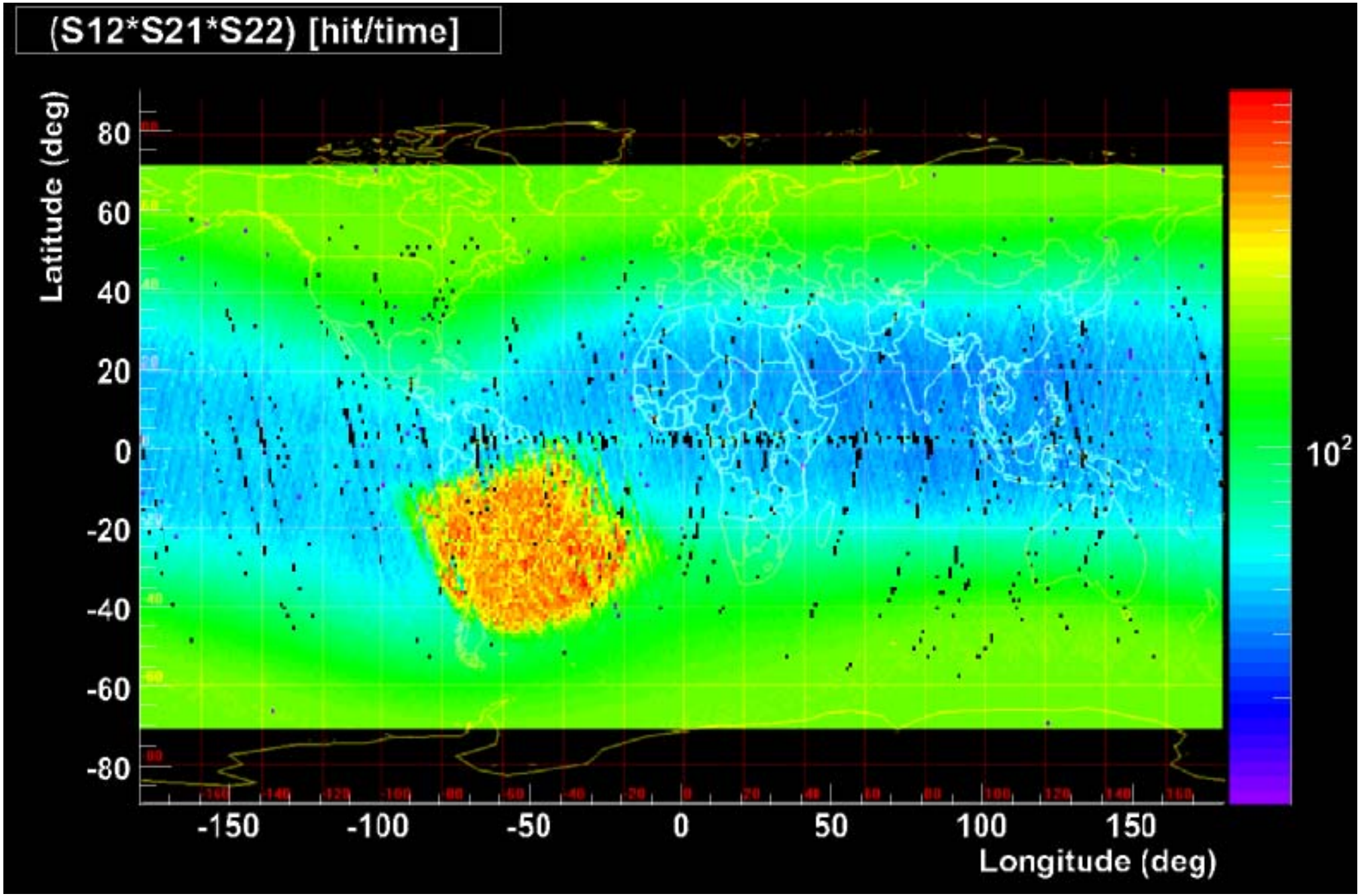
Trigger rate

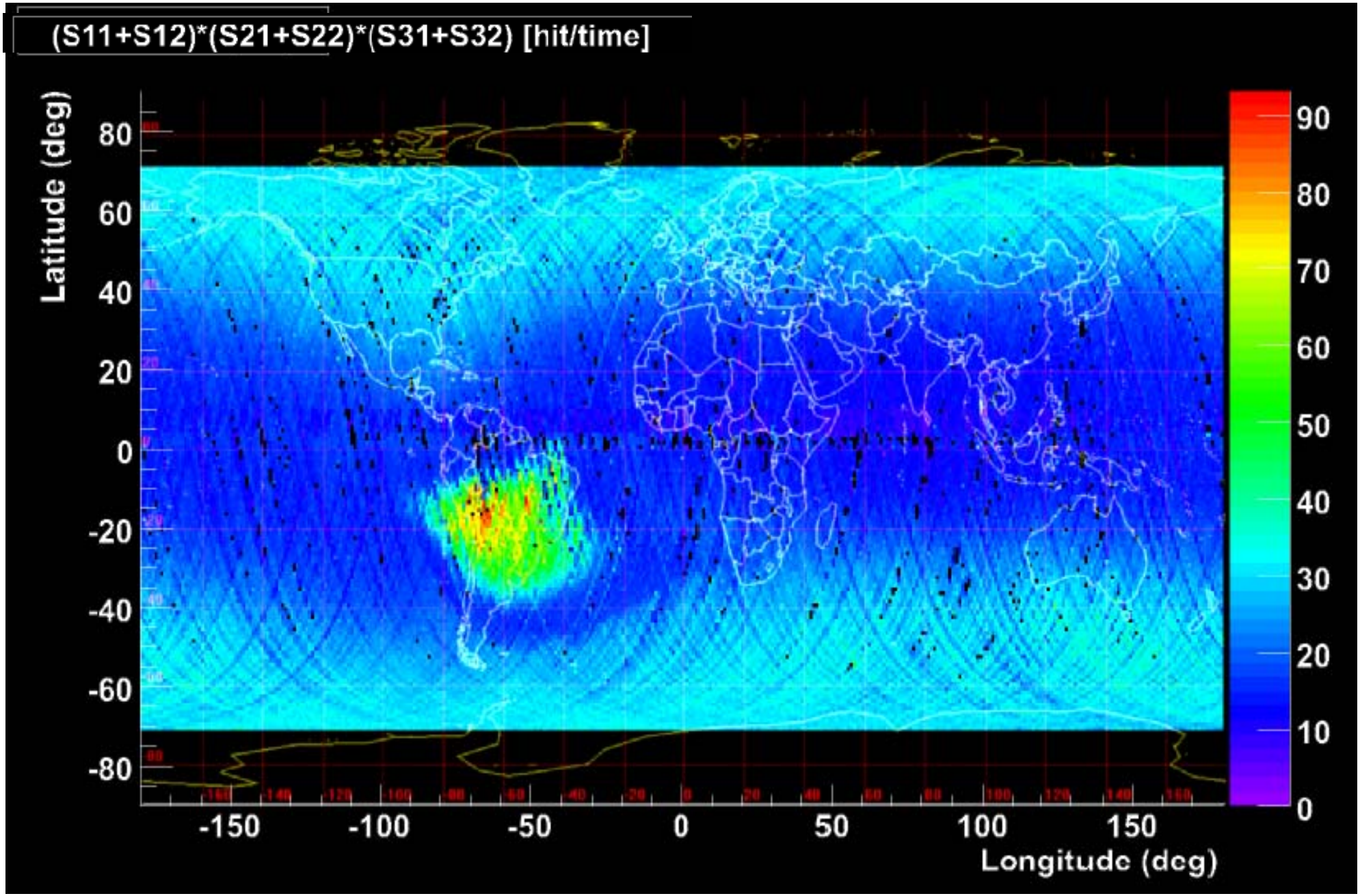


Download @orbit 3754 – 15/02/2007 07:35:00 MWT




(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

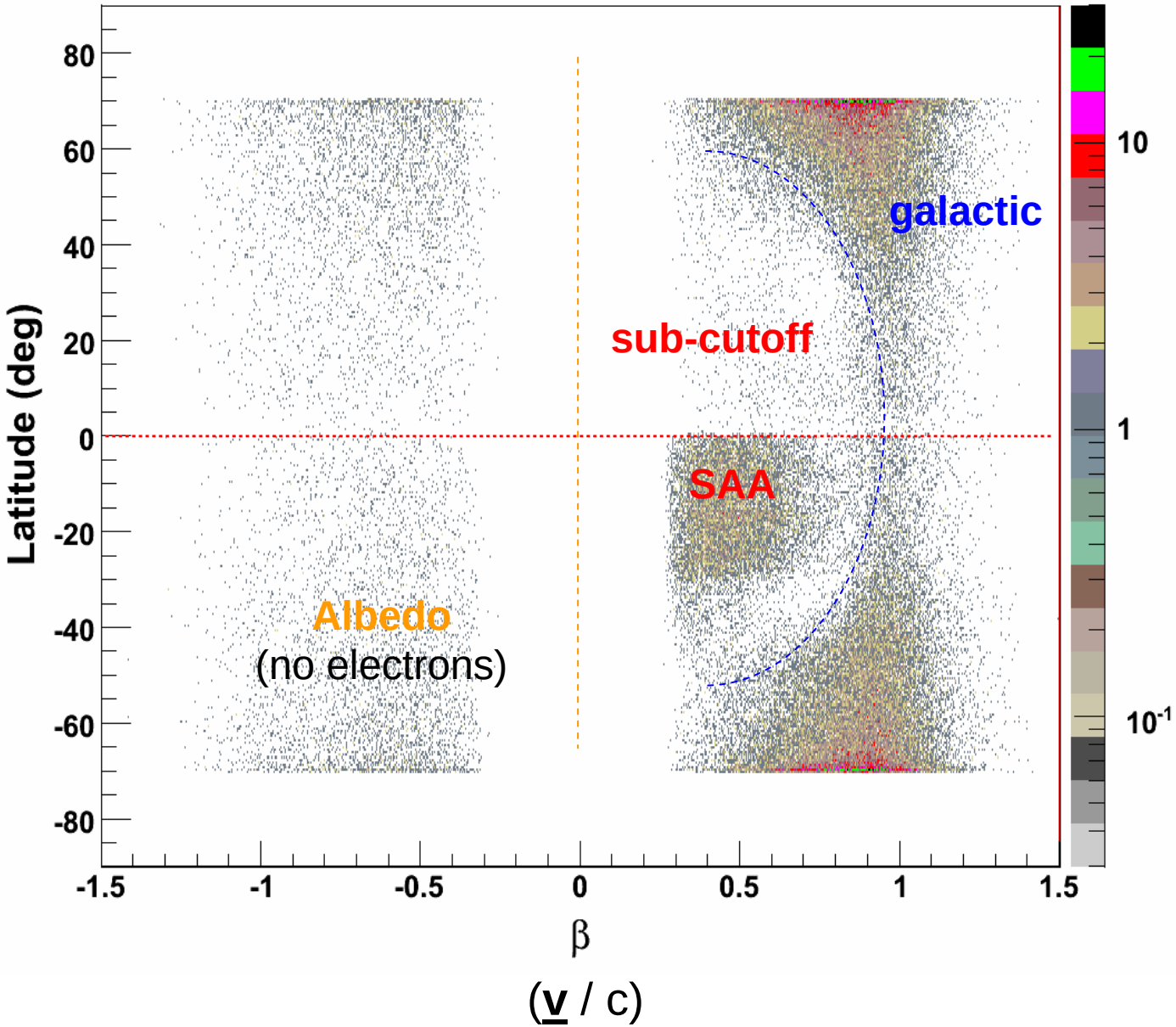

(S12*S21*S22) [hit/time]
Latitude (deg)
80
60
40
20
0
-20
-40
-60
-80
-150
-100
-50
0
50
100
150
Longitude (deg)
10^2


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

Time-of-flight

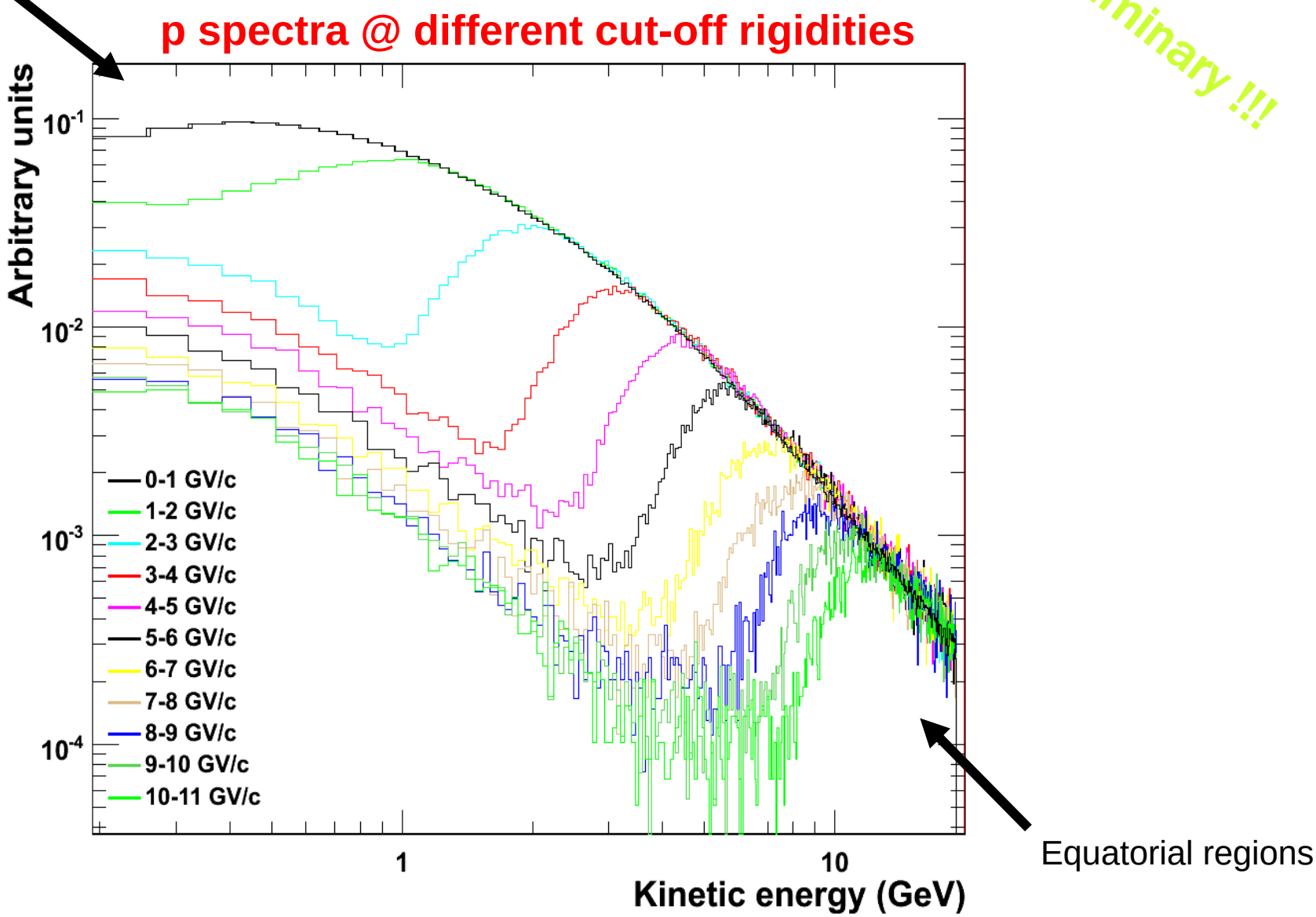
Latitude -vs- beta (Z=1)

Preliminary !!!



Polar regions

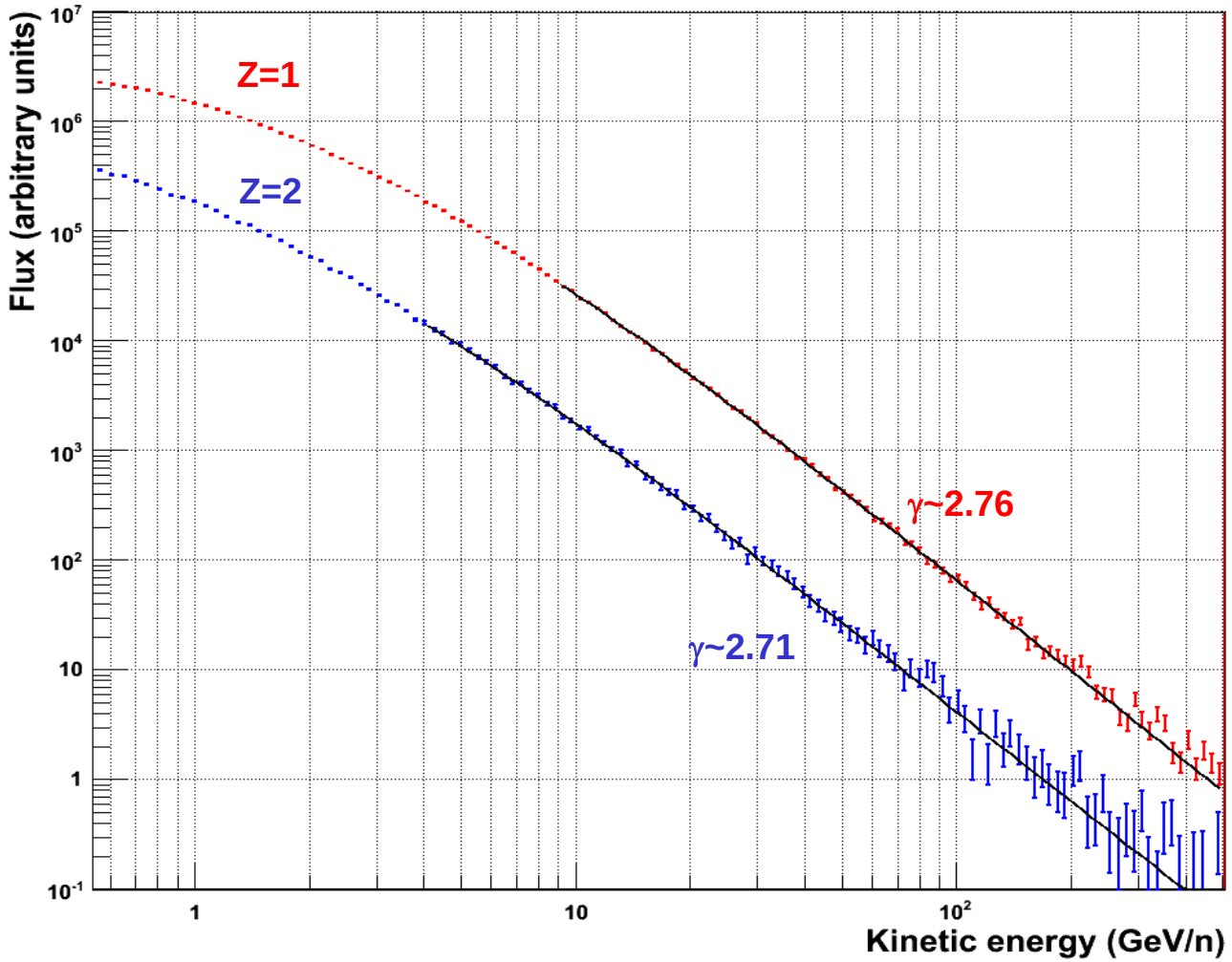
Preliminary !!!



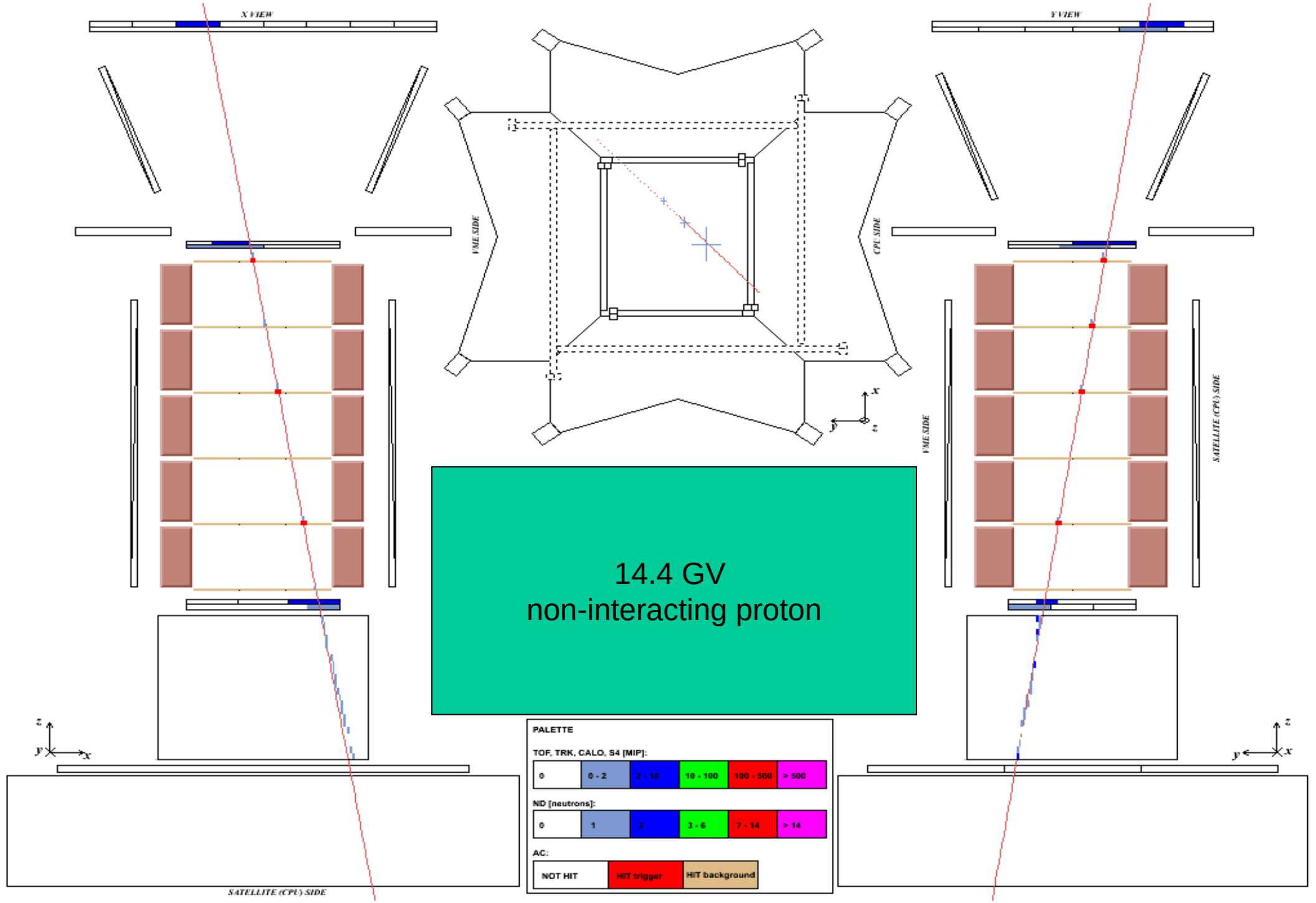
Equatorial regions

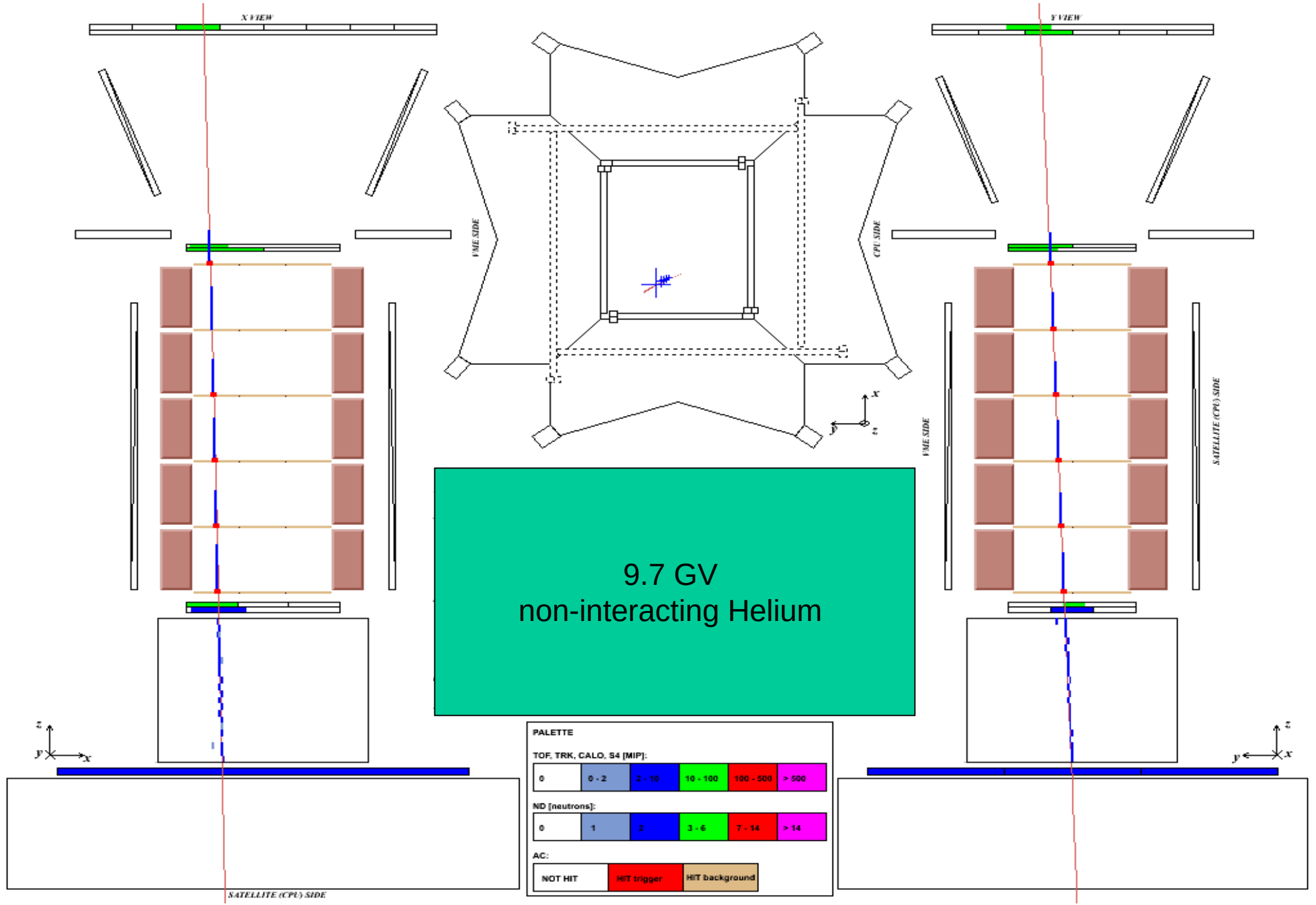
Galactic p and He spectra

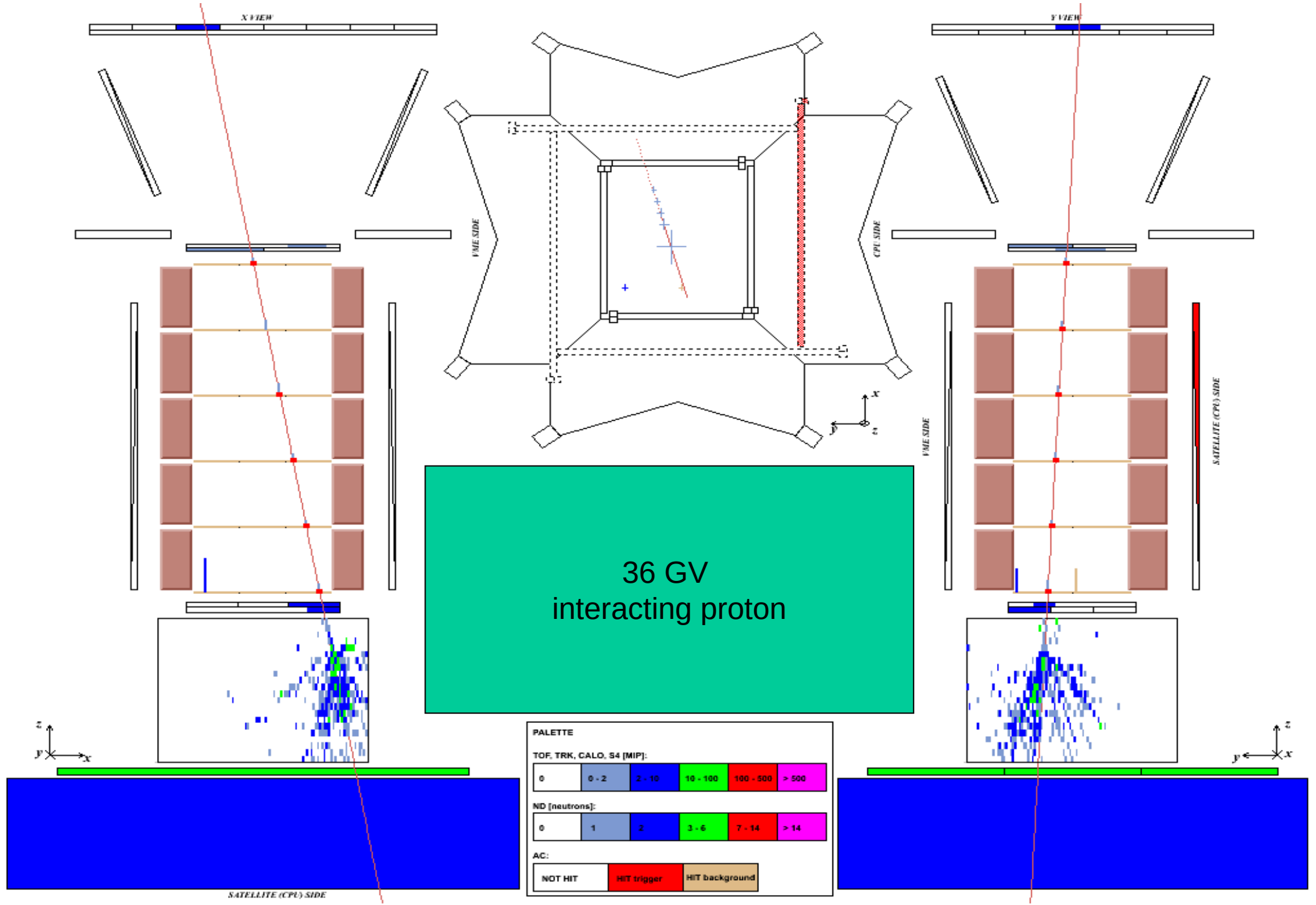
Preliminary !!!

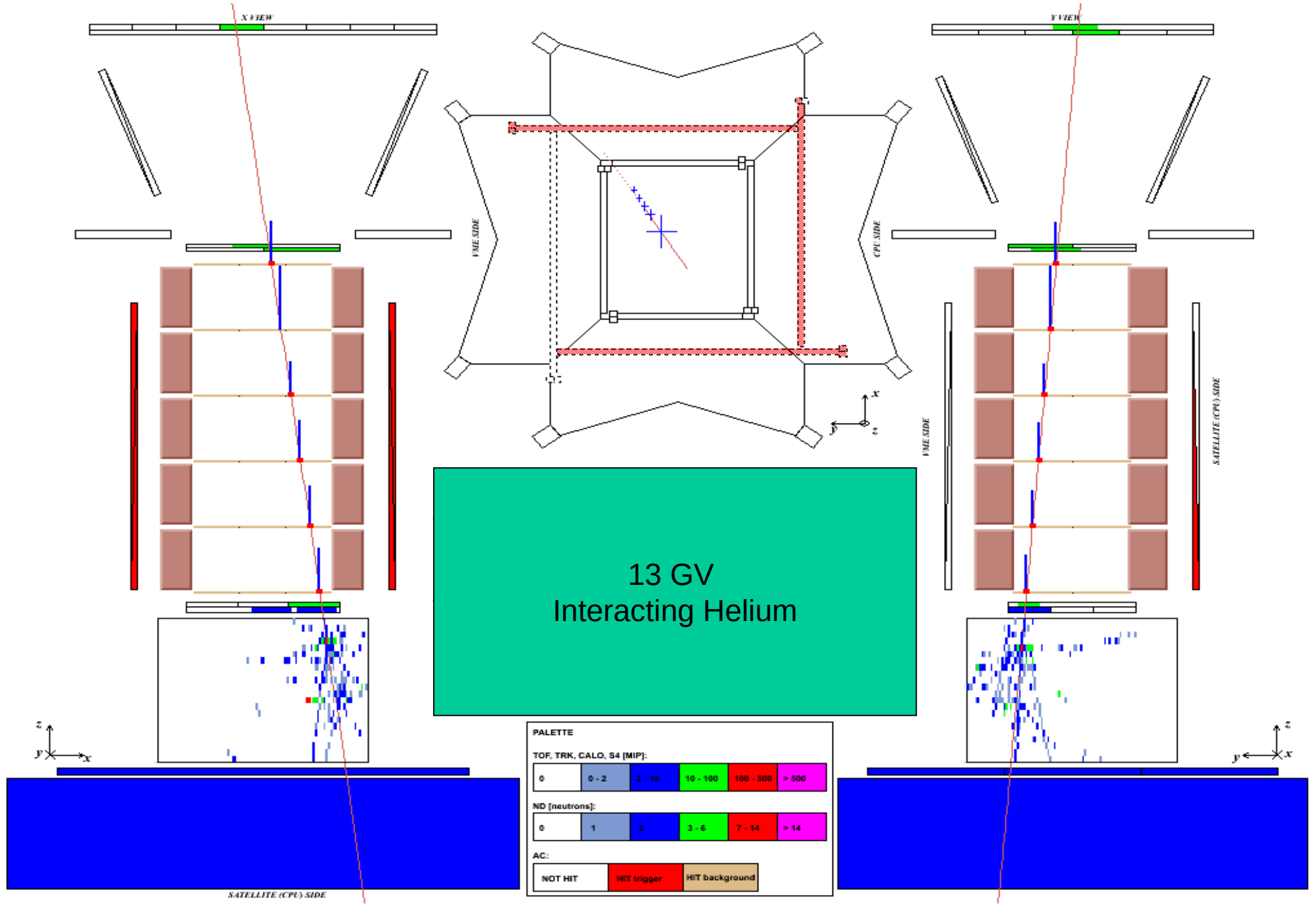


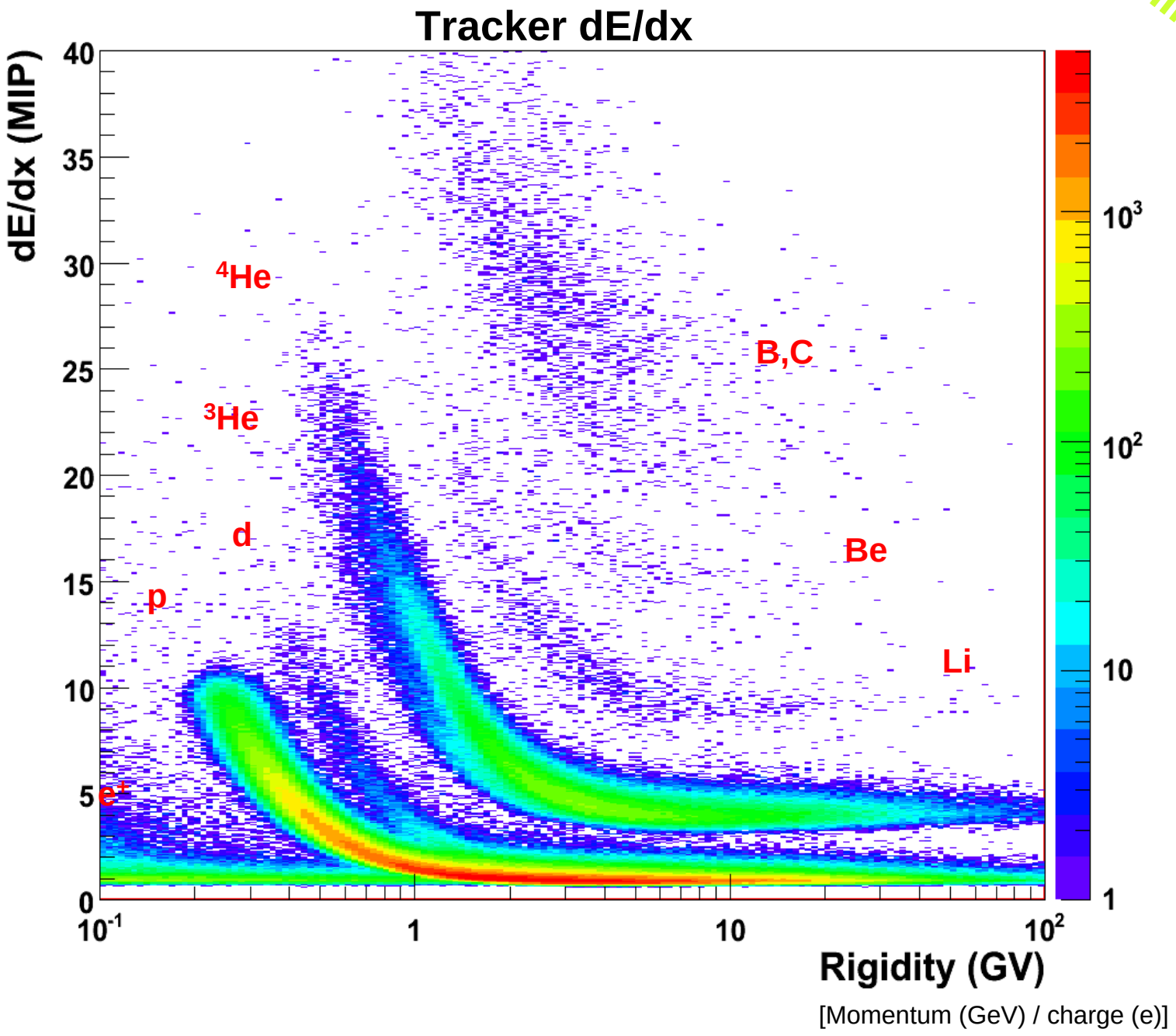
Charge separation


X VIEW
Y VIEW
VME SIDE
CPL SIDE
VME SIDE
SATELLITE (CPL) SIDE
14.4 GV
non-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
SATELLITE (CPL) SIDE


X VIEW
Y VIEW
VME SIDE
CPU SIDE
VME SIDE
SATELLITE (CPU) SIDE
SATELLITE (CPU) SIDE
9.7 GV
non-interacting Helium
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

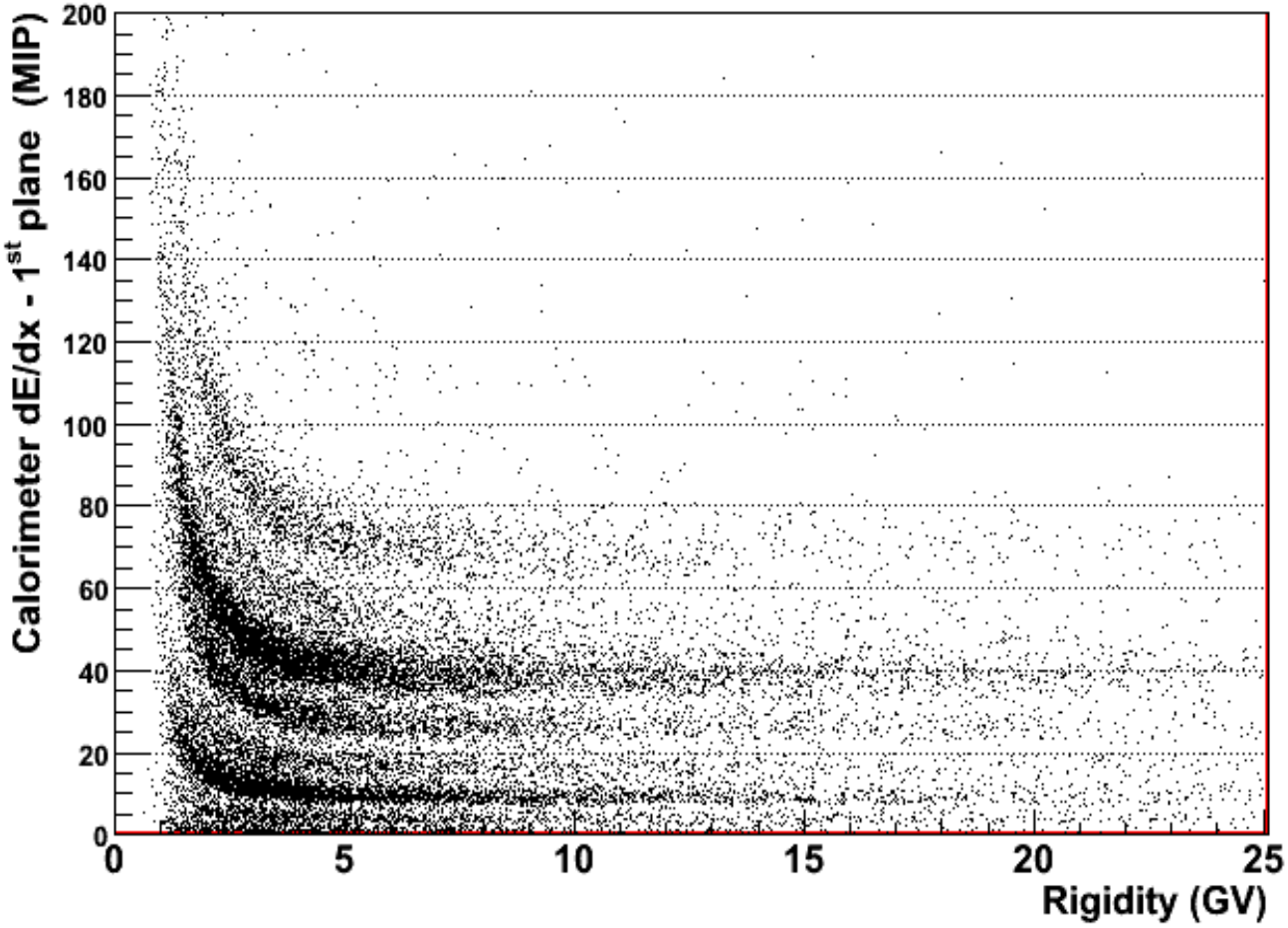

X VIEW
Y VIEW
VME SIDE
CPU SIDE
VME SIDE
SATELLITE (CPU) SIDE
SATELLITE (CPU) SIDE
36 GV
interacting proton
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background

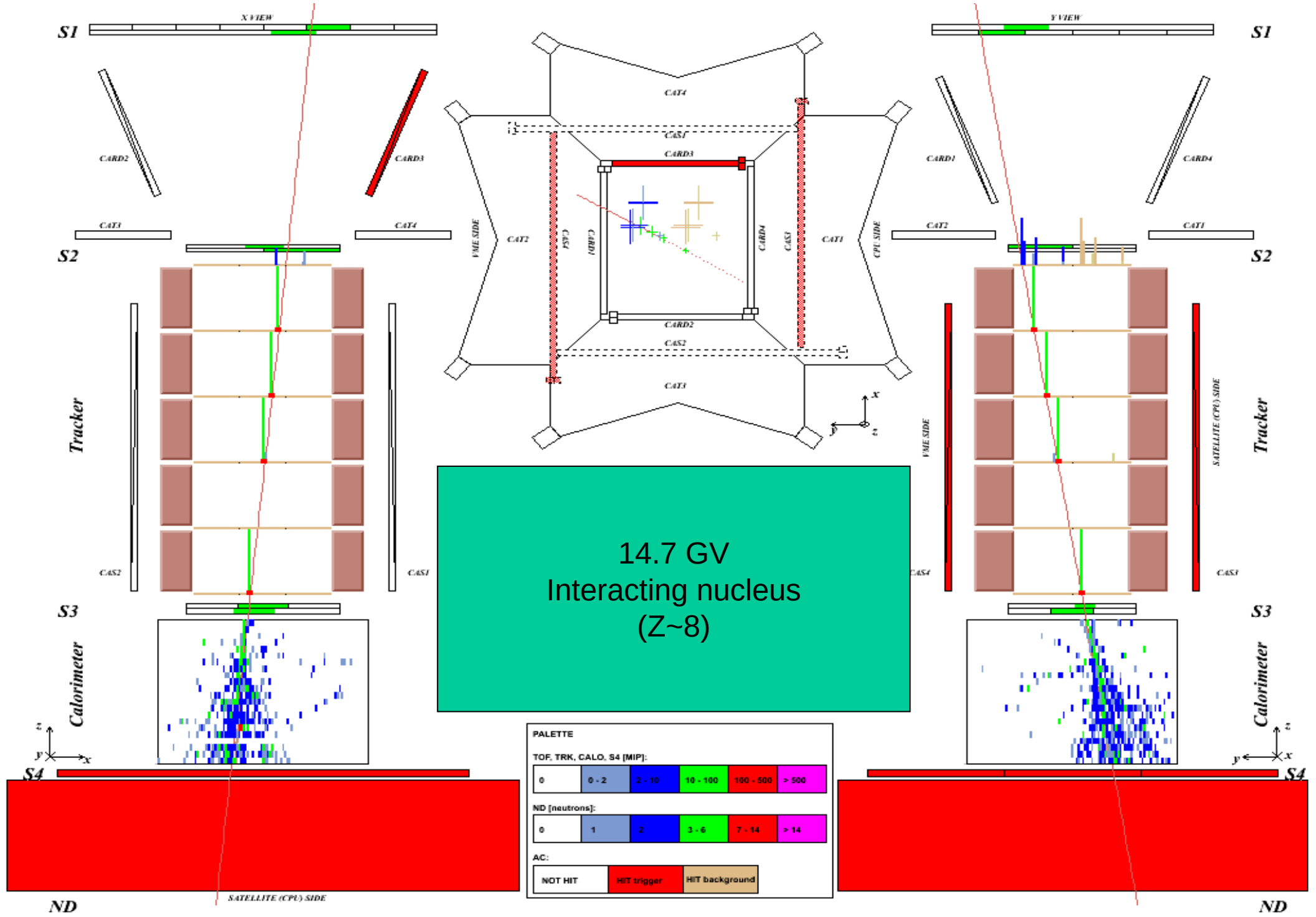

X VIEW
Y VIEW
VME SIDE
CPU SIDE
VME SIDE
SATELLITE (CPU) SIDE
SATELLITE (CPU) SIDE
13 GV
Interacting Helium
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background

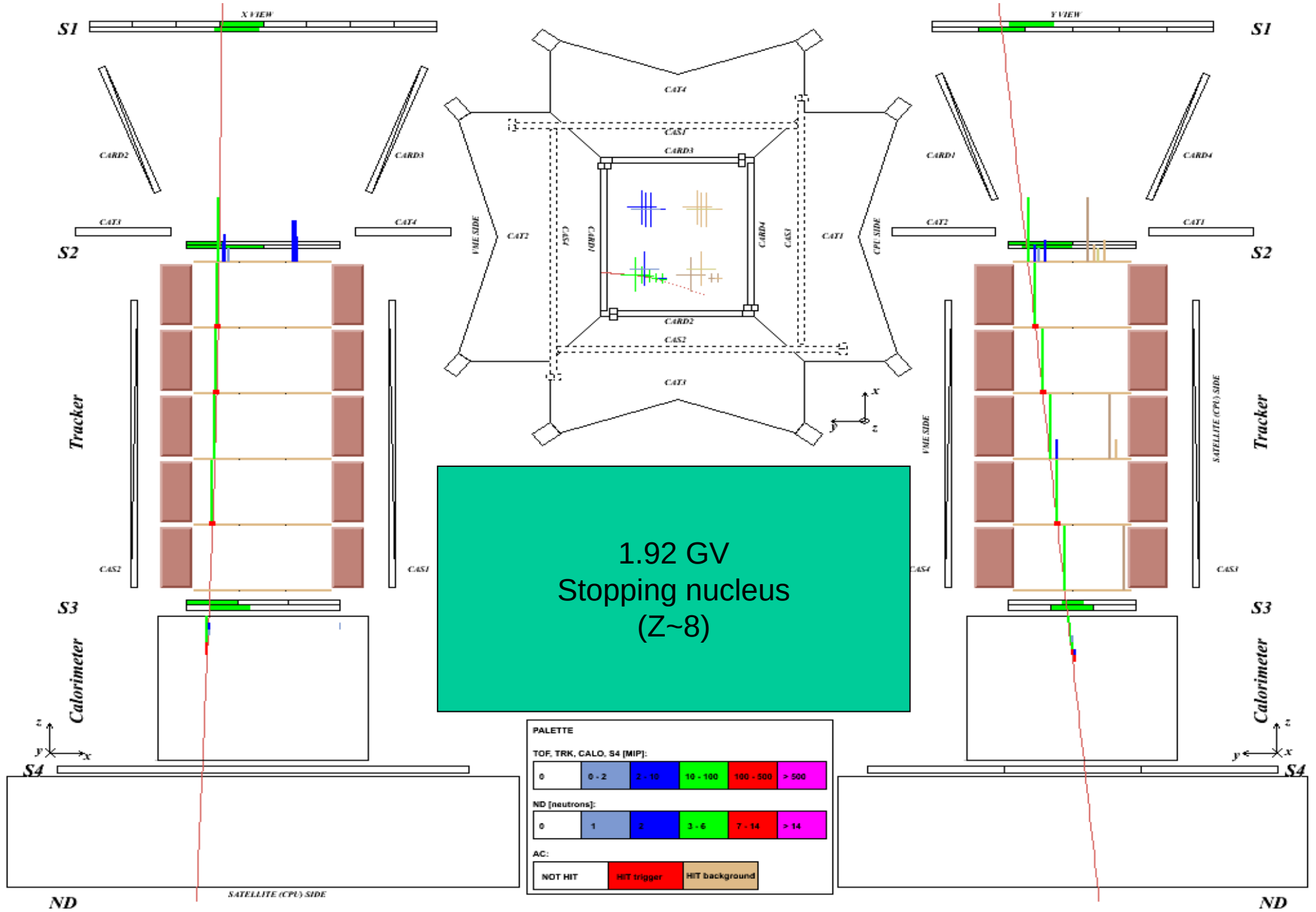

Tracker dE/dx
Preliminary !!!
dE/dx (MIP)
Rigidity (GV)
[Momentum (GeV) / charge (e)]
^{4}He
^{3}He
d
p
e$^+$
B,C
Be
Li
0
5
10
15
20
25
30
35
40
10^{-1}
1
10
10^2
1
10
10^2
10^3

Preliminary !!!

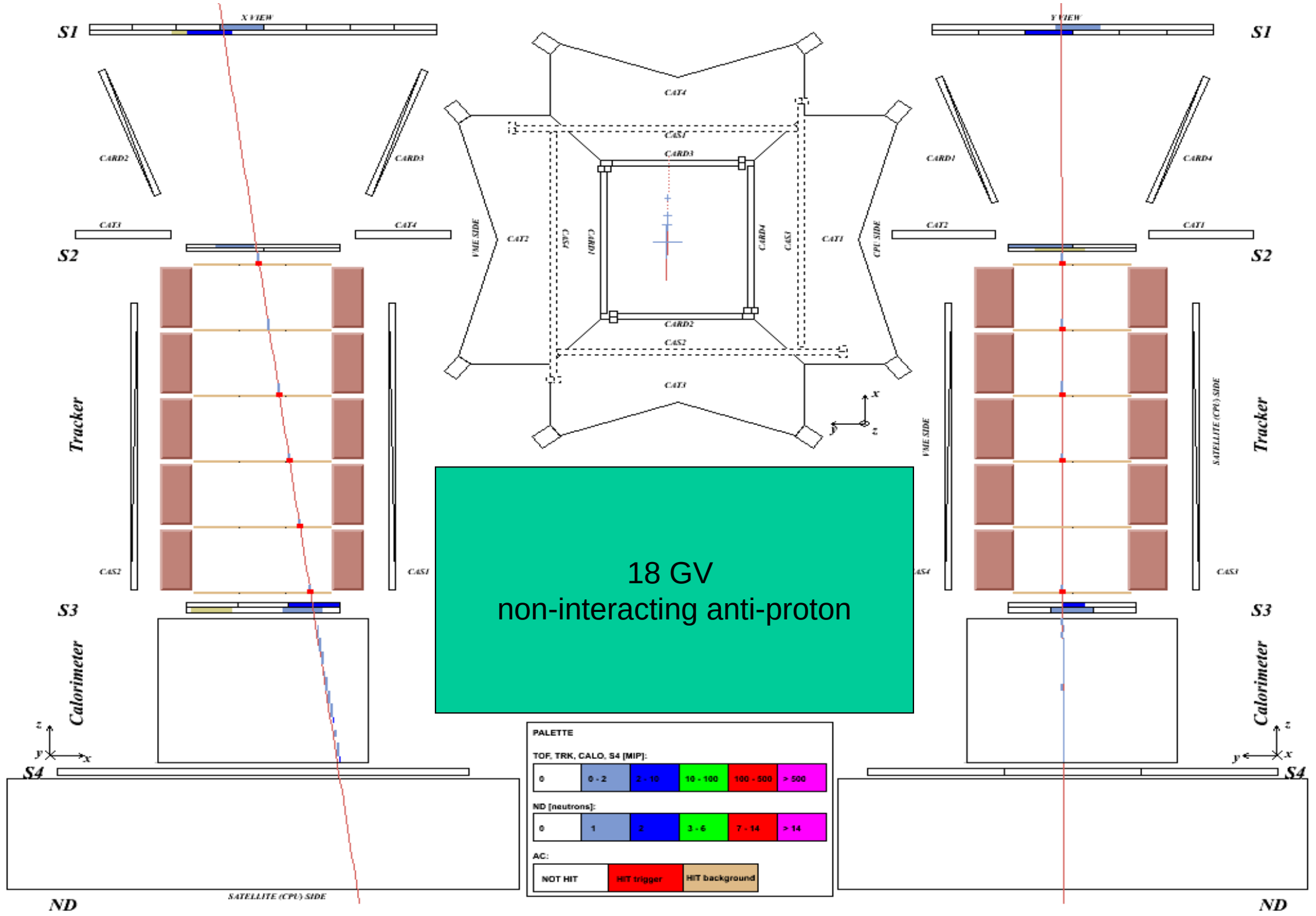
Calorimeter dE/dx (first Si-layer)

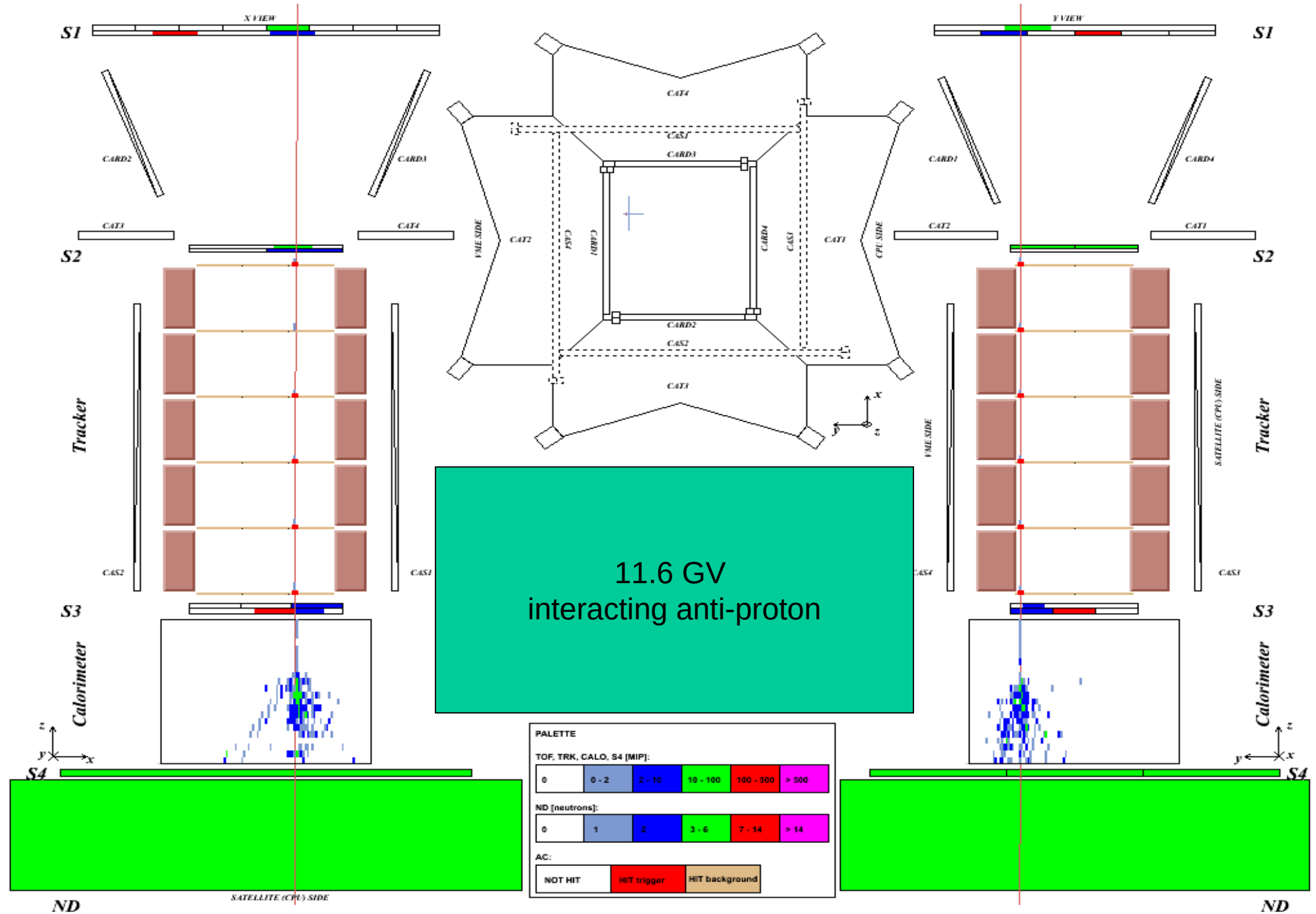


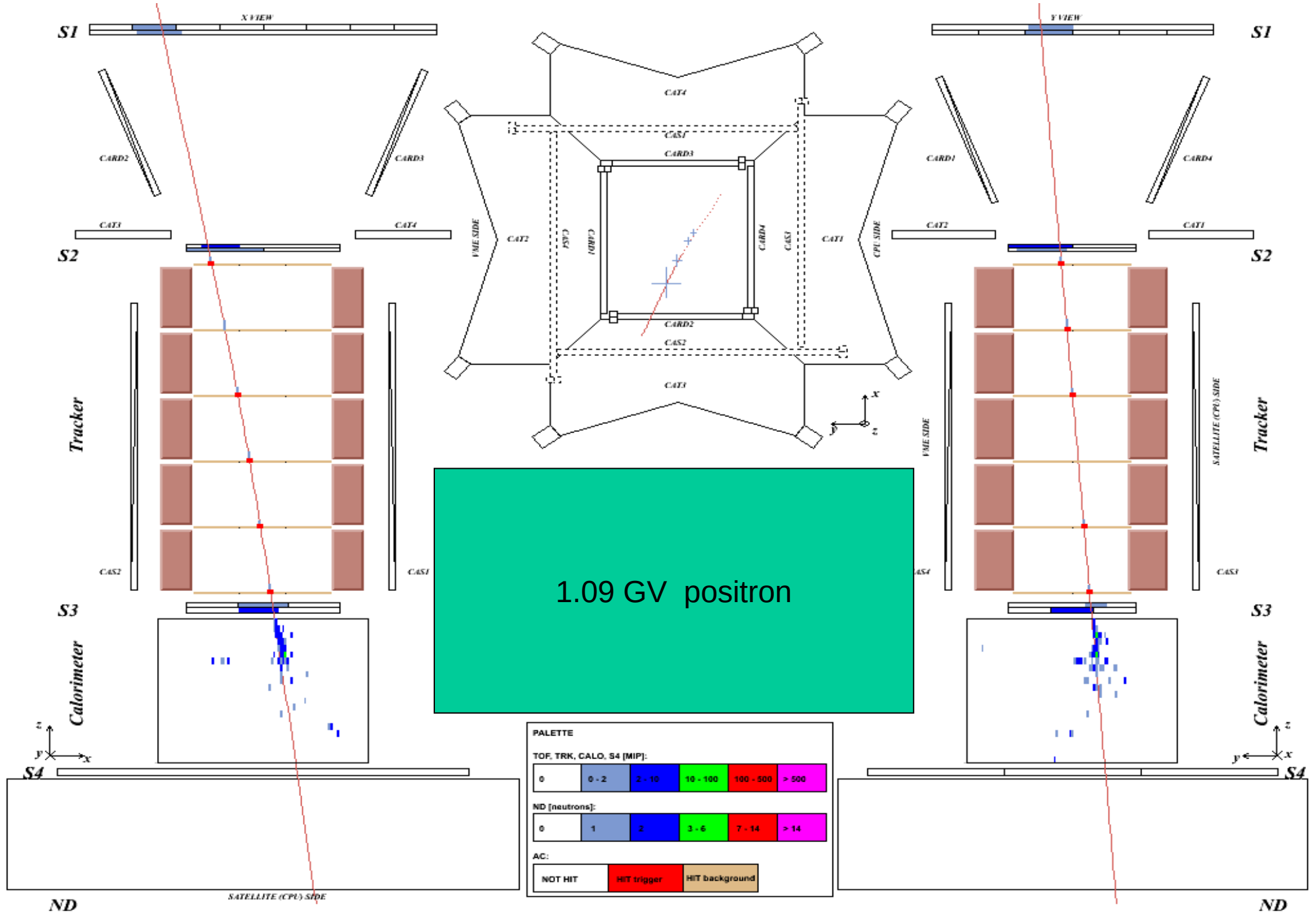

X VIEW
Y VIEW
S1
S2
S3
S4
Tracker
Calorimeter
ND
CARD1
CARD2
CARD3
CARD4
CAT1
CAT2
CAT3
CAT4
CAS1
CAS2
CAS3
CAS4
VME SIDE
CPE SIDE
SATELLITE (CPE) SIDE
14.7 GV
Interacting nucleus
(Z~8)
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background

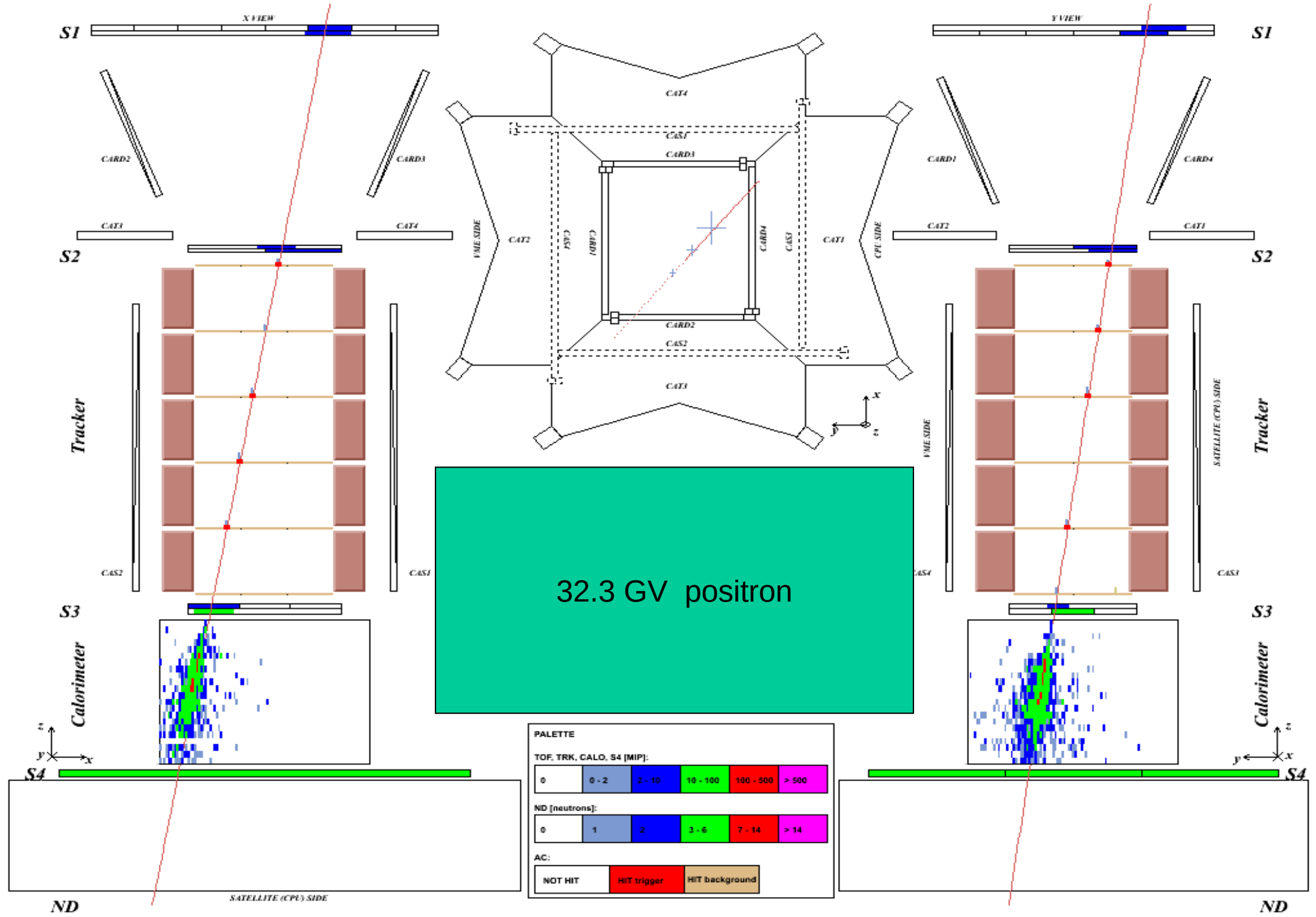

X VIEW
Y VIEW
S1
S2
S3
S4
ND
Tracker
Calorimeter
CAT1
CAT2
CAT3
CAT4
CARD1
CARD2
CARD3
CARD4
CAS1
CAS2
CAS3
CAS4
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
1.92 GV
Stopping nucleus
(Z~8)
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background

Matter / antimatter identification


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

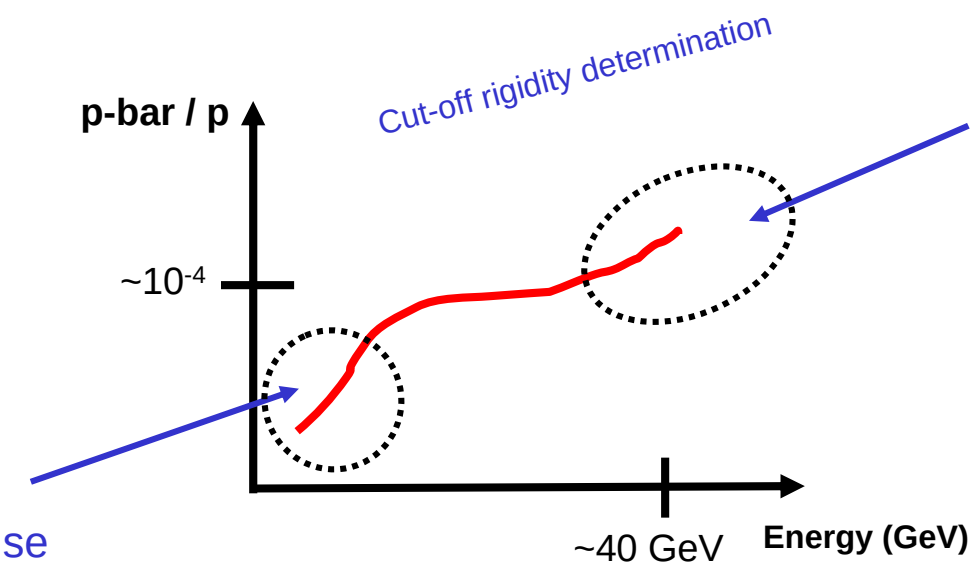

X VIEW
Y VIEW
S1
S2
S3
S4
CARD1
CARD2
CARD3
CARD4
CAT1
CAT2
CAT3
CAT4
CAS1
CAS2
CAS3
CAS4
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
Tracker
Calorimeter
ND
11.6 GV
interacting anti-proton
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC: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


S1
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
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
Y VIEW
CARD1
CARD4
CAT2
CAT1
S1
S2
VME SIDE
SATELLITE (CPU) SIDE
Tracker
CAS4
CAS3
S3
Calorimeter
S4
ND


S1
X VIEW
CARD2
CARD3
CAT3
CAT4
S2
Tracker
CAS2
CAS1
S3
Calorimeter
S4
ND
SATELLITE (CPU) SIDE
CAT4
CAS1
CARD3
VME SIDE
CAT2
CARD1
CARD4
CAS3
CAT1
CPU SIDE
CARD2
CAS2
CAT3
32.3 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
Y VIEW
CARD1
CARD4
CAT2
CAT1
VME SIDE
SATELLITE (CPU) SIDE
CAS4
CAS3

Antiparticle data analysis

- Data analysis is currently in full swing. **Top priority:** to reconstruct the energy spectra of antiprotons and positrons
- An experimental challenge!
  - e.g. – reconstructing the antiproton flux ratio:



- Alignment of silicon planes in spectrometer
- Determination of MDR
- Spillover limit for p-bar
- Purity of lepton-hadron separation (neutron detector)

- Contamination from locally produced π^- (use ToF system!)

Summary

- **PAMELA** is currently conducting an indirect search for dark matter using antiparticles in the cosmic radiation.
- Other scientific goals being actively pursued include a search for antihelium, tests of cosmic ray propagation, and solar-terrestrial physics
- **PAMELA** is a complex instrument built by a European consortium which has gone through a progression of prototyping, tests with particle beams and space qualification tests, prior to production of the flight hardware
- Launched on June 15th 2006. In-orbit commissioning tests concluded successfully. **PAMELA** has been in continuous data taking mode since 11th July 2006. ~4 TB of data downlinked.
- Data analysis is on-going. We expect to air first public results (probably antiparticle flux ratios) after the summer.

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