# A Possible Signal of Dark Matter from a Satellite experiment

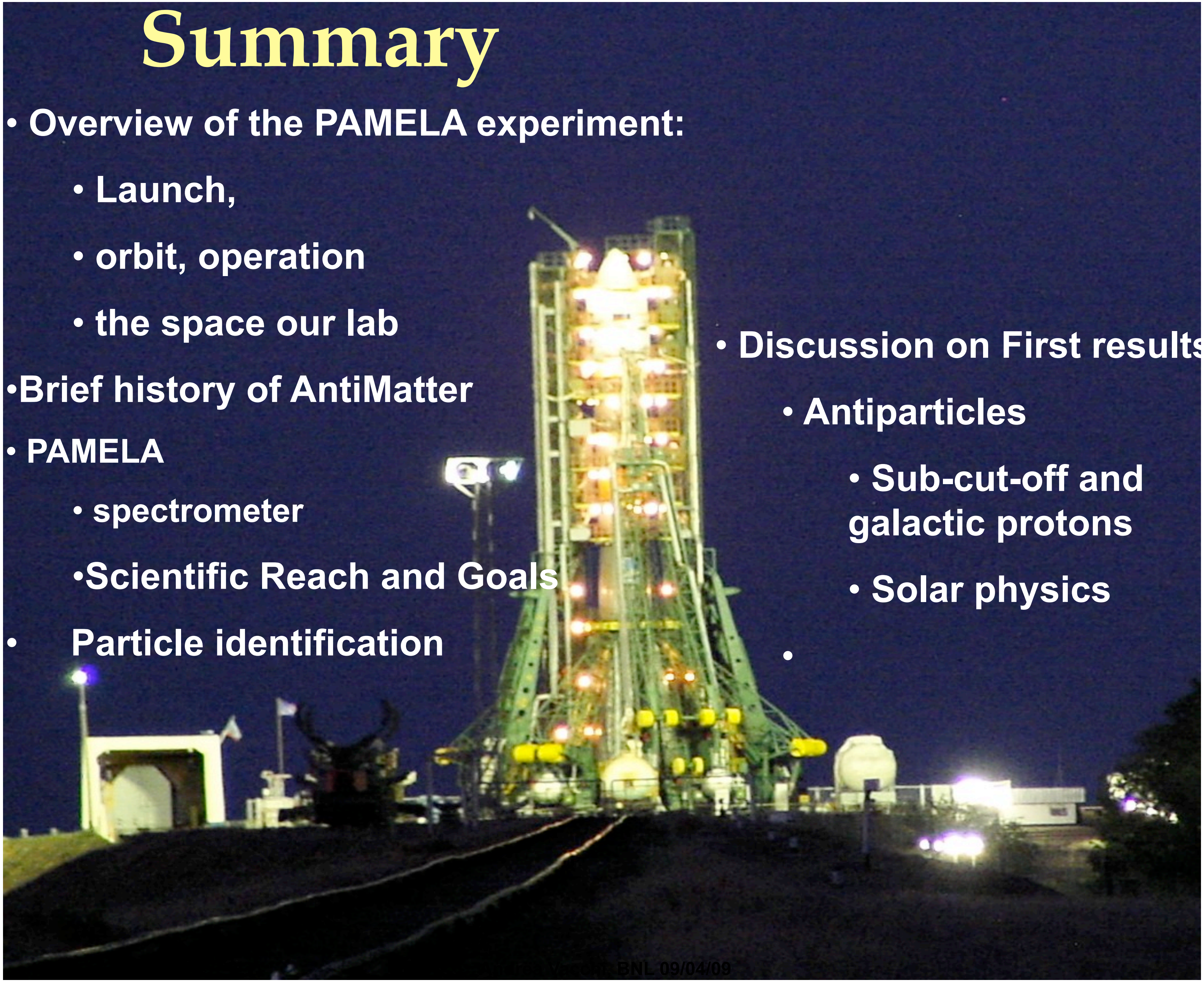
# P A M E L A

**P**ayload for **A**ntimatter / **M**atter **E**xploration and **L**ight-nuclei **A**strophysics

**"An anomalous positron abundance in the cosmic radiation between 1.5 and 100 GeV”**

**published on Nature the 2 April 2009** http://arxiv.org/abs/0810.4995

*Andrea Vacchi*
*INFN Trieste, Italy*
On behalf of the PAMELA collaboration



# Summary

- Overview of the PAMELA experiment:
  - Launch,
  - orbit, operation
  - the space our lab
- Brief history of AntiMatter
- PAMELA
  - spectrometer
  - Scientific Reach and Goals
- Particle identification

- Discussion on First results
  - Antiparticles
    - Sub-cut-off and galactic protons
    - Solar physics
  - 

# The PAMELA Collaboration

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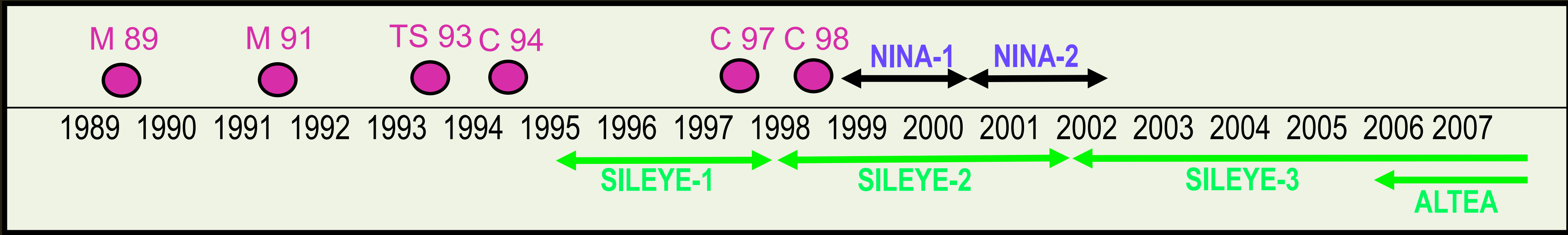
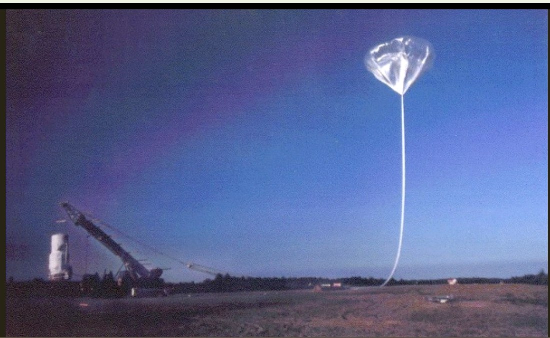
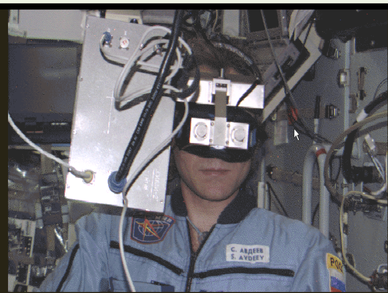
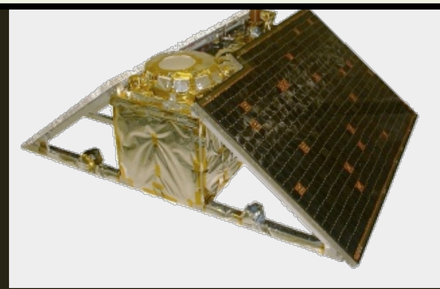
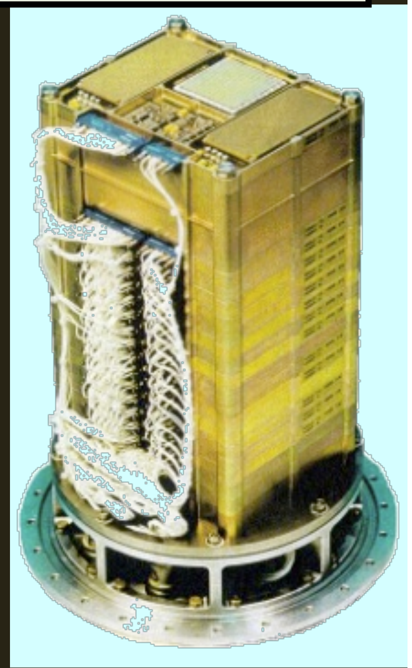
# PAMELA decadal history









**1996**: first PAMELA proposal

**Dec 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)**

**2001**: **change of the satellite**

→ ***complete redefinition of mechanics***

**2006**: **flight!!!**

Page last updated at 17:47 GMT, Wednesday, 1 April 2009 18:47 UK

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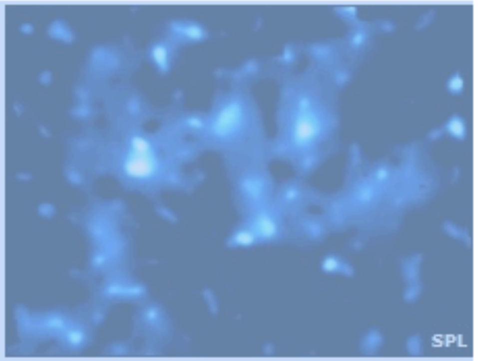
# Signals could be from dark matter

By Victoria Gill
Science reporter, BBC News

**Scientists have detected particles that may come from invisible "dark matter".**



Dark matter remains elusive despite strong evidence for its role

This is thought to make up 23% of the Universe, but can only be detected through its effects on "normal" matter.

Writing in the journal Nature, scientists relate how a satellite-borne instrument found an unexplained source of positrons in space.

But the researchers say their mysterious signal must be further investigated before they will know if they have "discovered dark matter".

The space-based experiment, known as Pamela, was launched in June 2006, and carries instruments designed to investigate dark matter particles.

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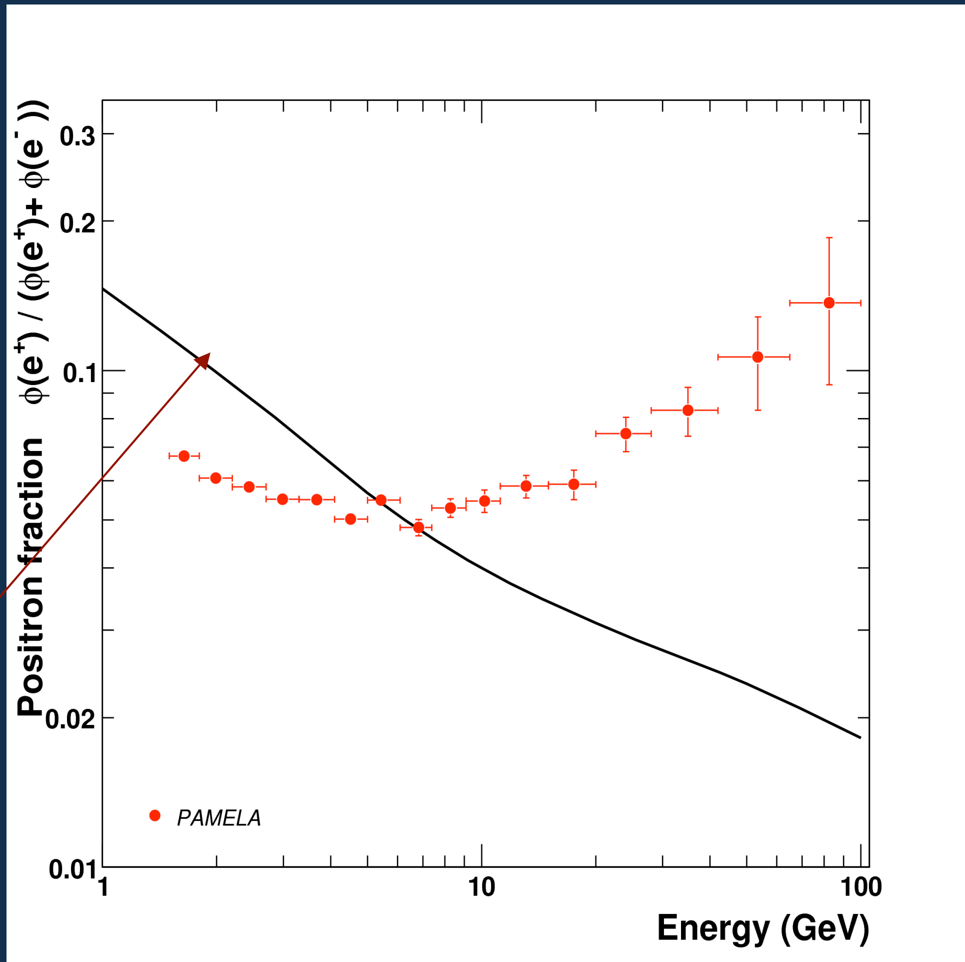
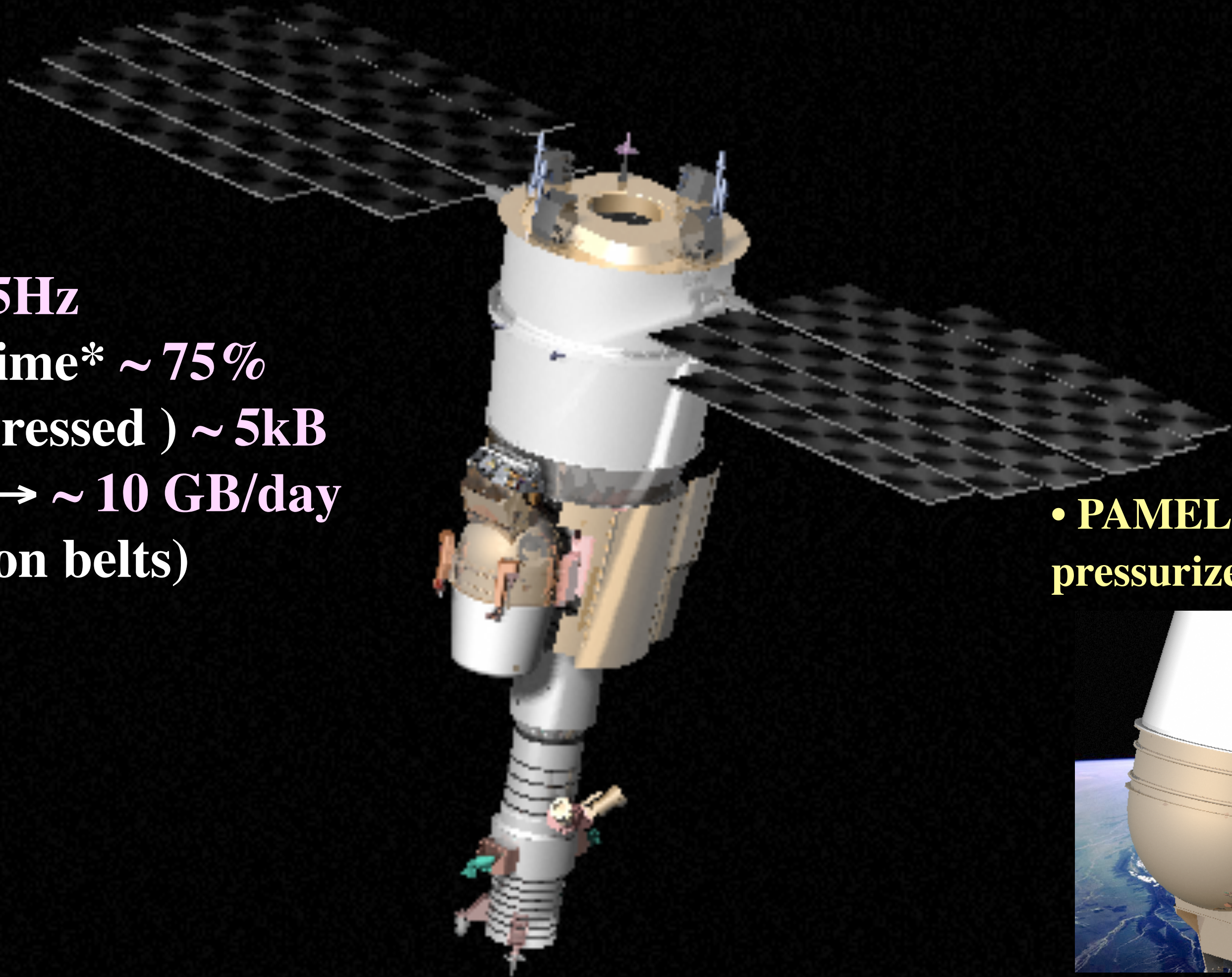
# Pamela data: steep rise in the positron fraction

$$R(E) = \frac{\Phi_{e^+}}{\Phi_{e^+} + \Phi_{e^-}}$$



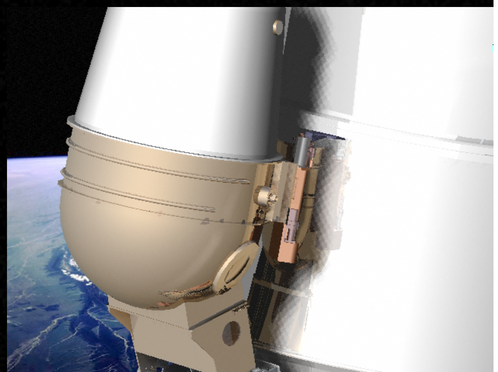

**Secondary production model**

Launch from Baikonur → June 15th 2006, 0800 UTC.
'First light' → June 21st 2006, 0300 UTC, commissioning.
Continuous data-taking since July 11th 2006.



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

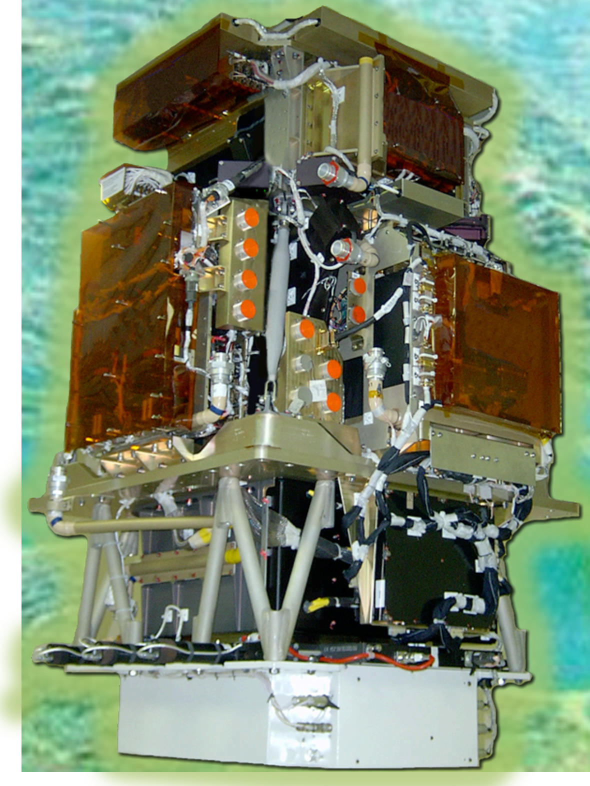
• PAMELA installed in a pressurized container

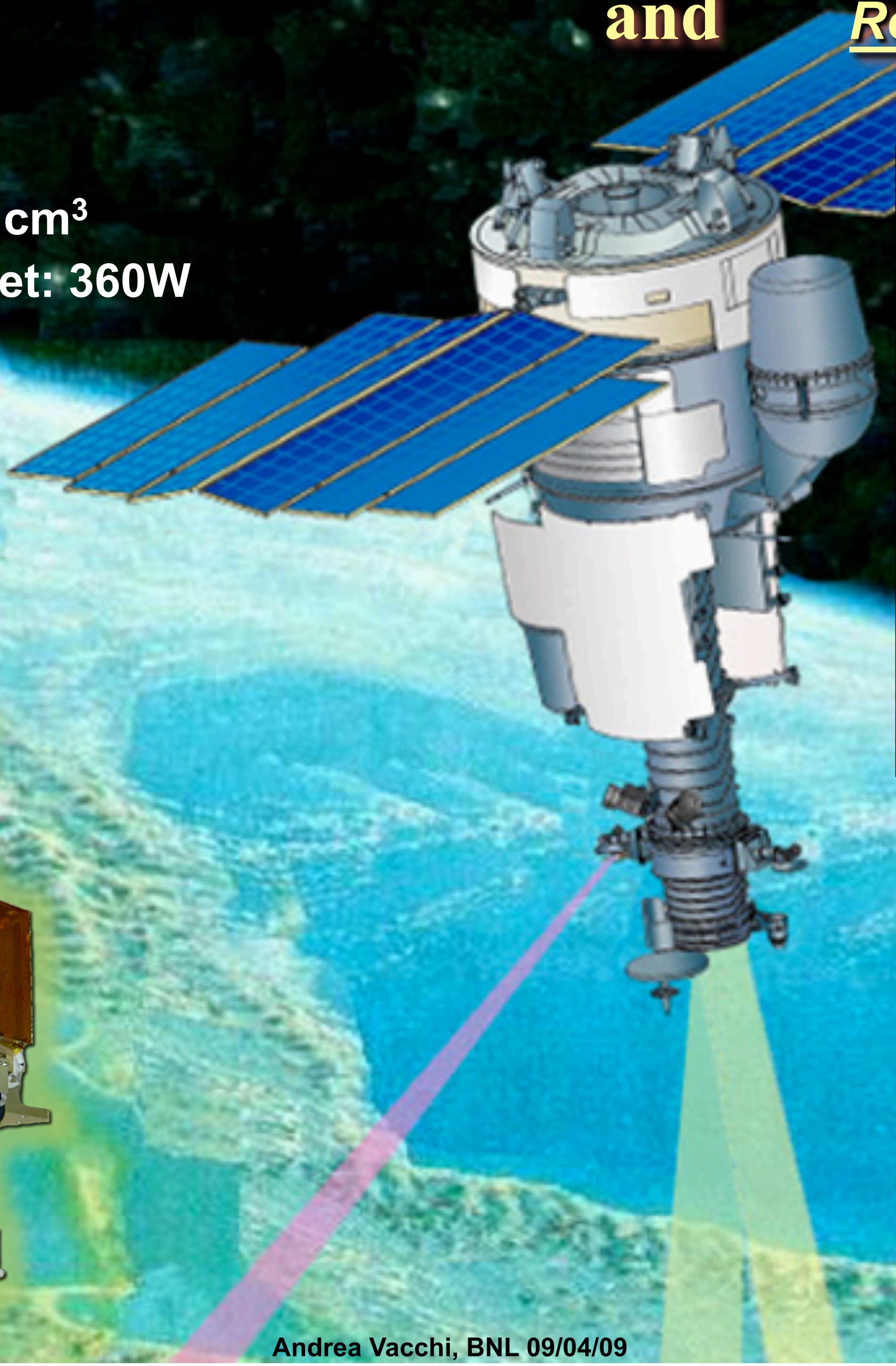


• Detectors operated as expected after launch
• Different trigger and hardware configurations evaluated

# Pamela and *Resurs-DK1 satellite*

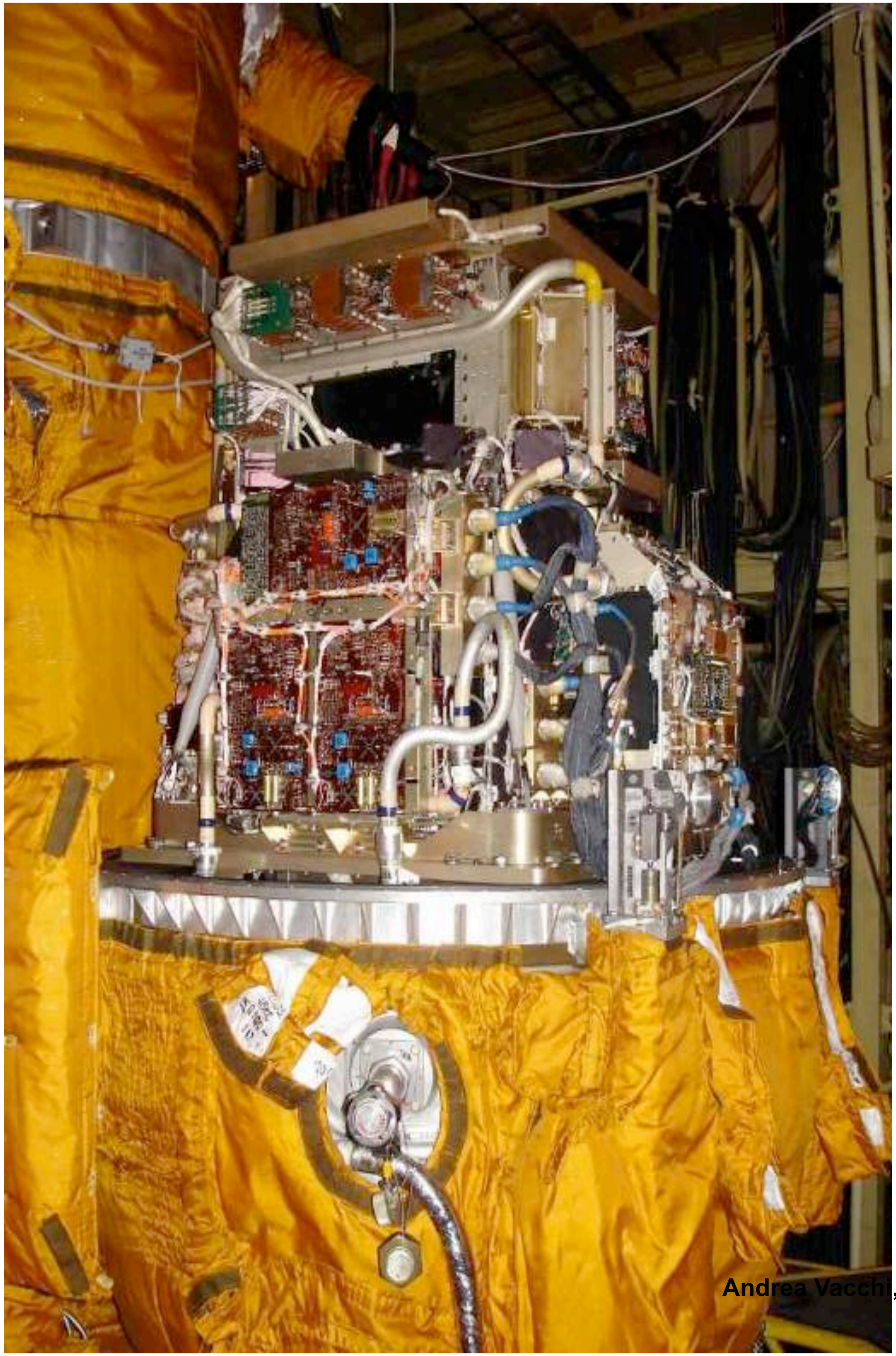
GF: 21.5 cm$^2$ sr
Mass: 470 kg
Size: 130x70x70 cm$^3$
Power Budget: 360W

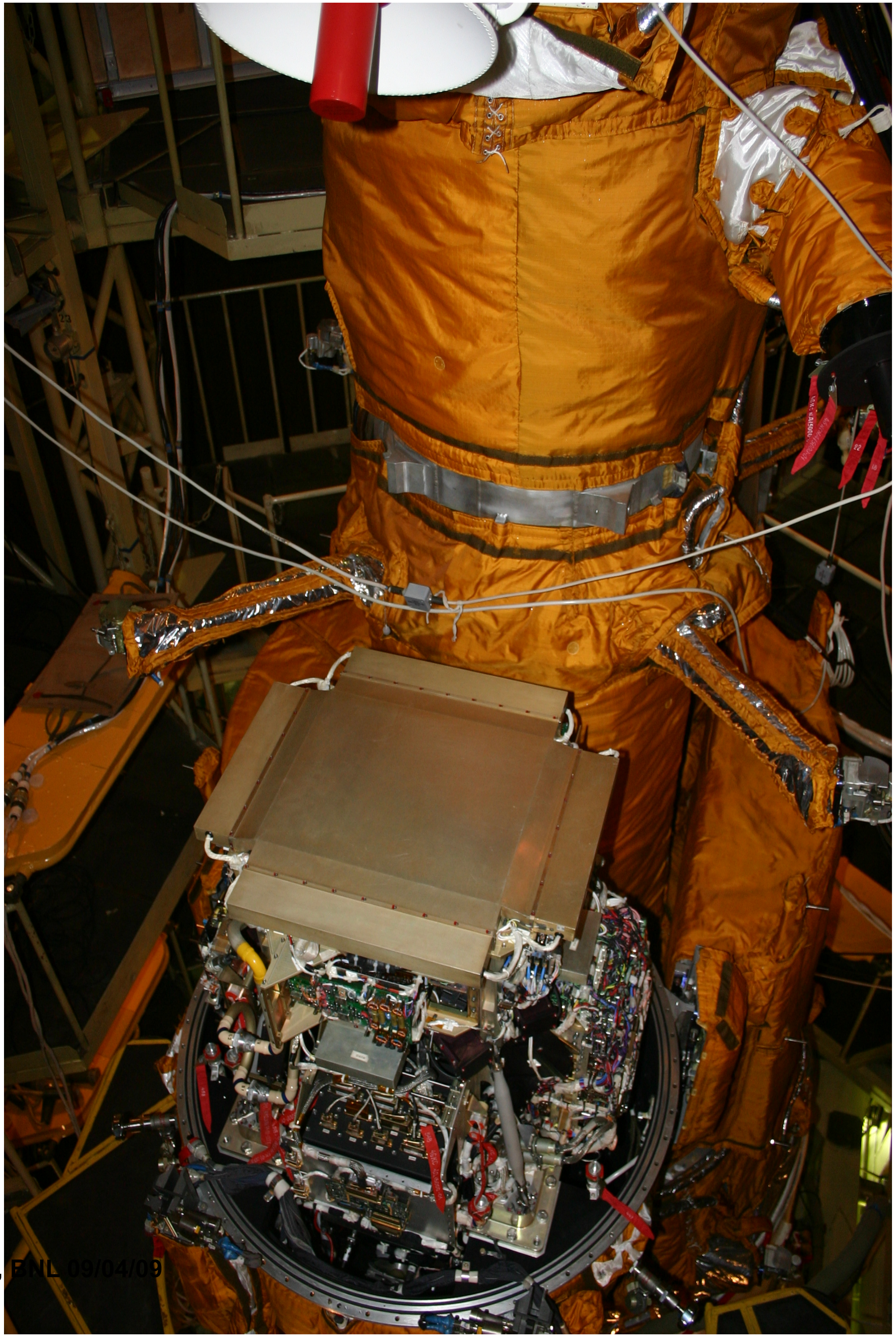




Mass: 6.7 tonnes
Height: 7.4 m
Solar array area: 36 m$^2$

- **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** ~16 GB per day

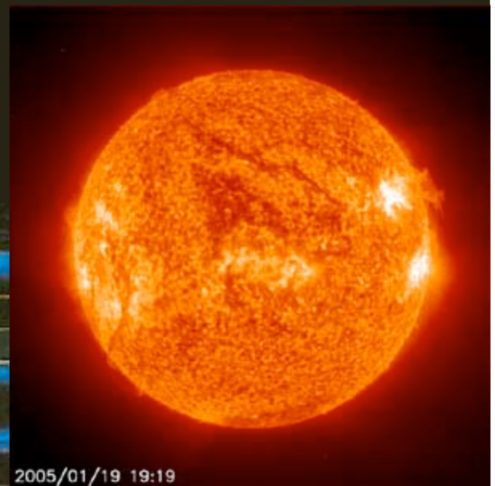


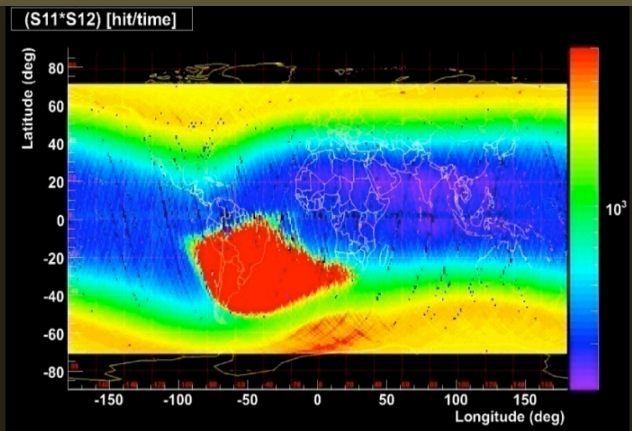


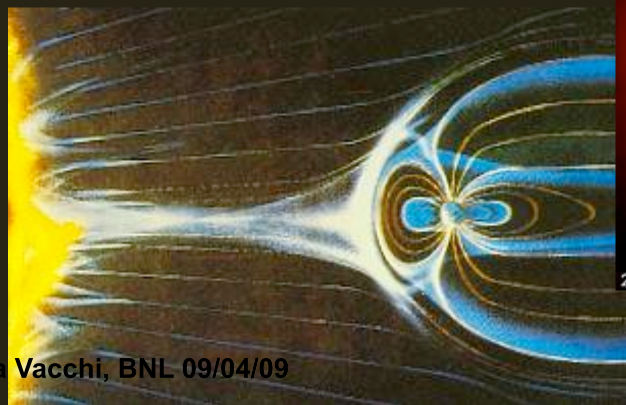
# The PAMELA experiment is carried out in the Space Observatory at 1 AU

## approximately 150 million km from the Sun

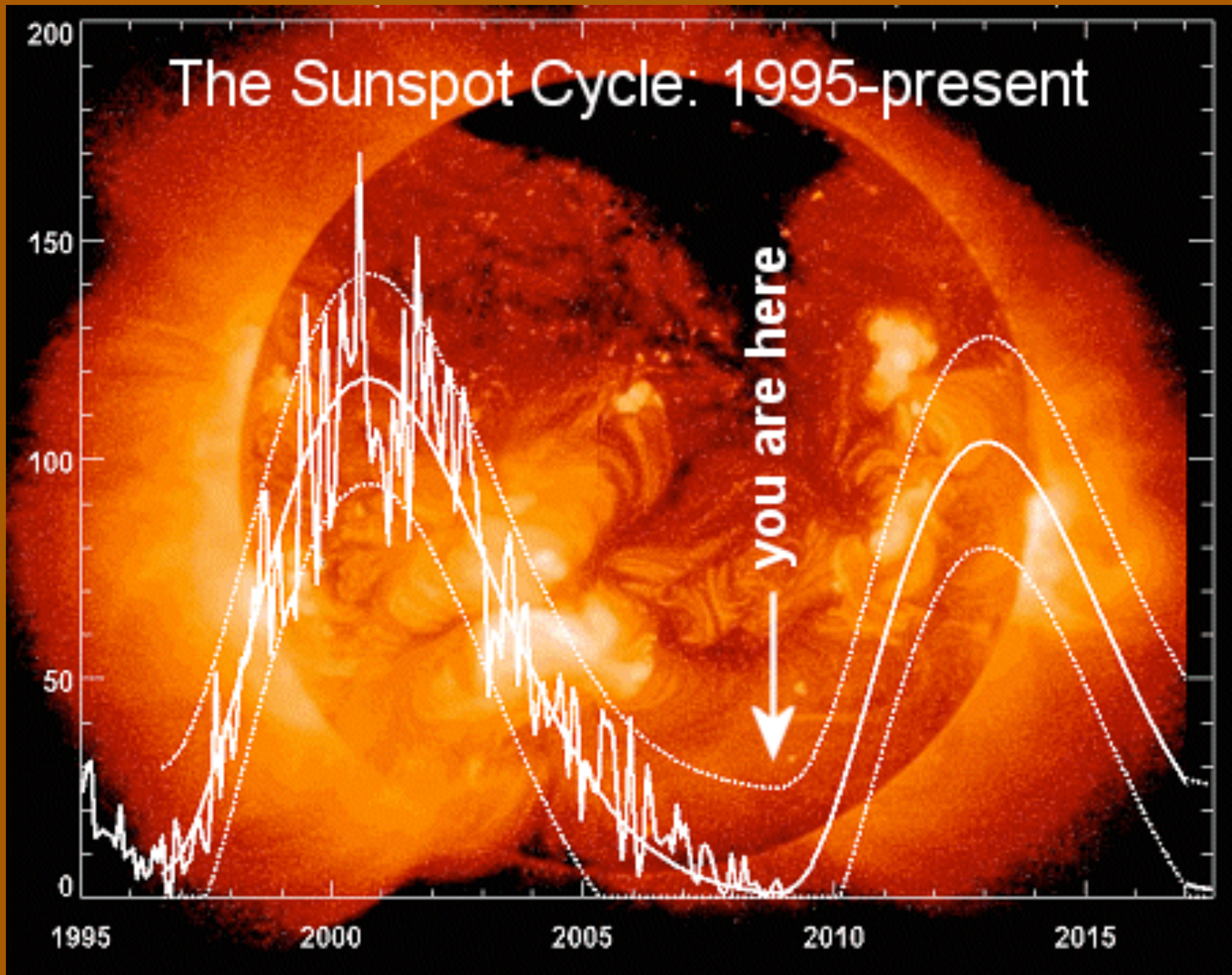
- **Search for dark matter annihilation**
- **Search for antihelium (primordial antimatter)**
- **Study of cosmic-ray propagation**
- **Study of solar physics and solar modulation**
- **Study of terrestrial magnetosphere**
- **Study  high energy electron spectrum (local sources?)**

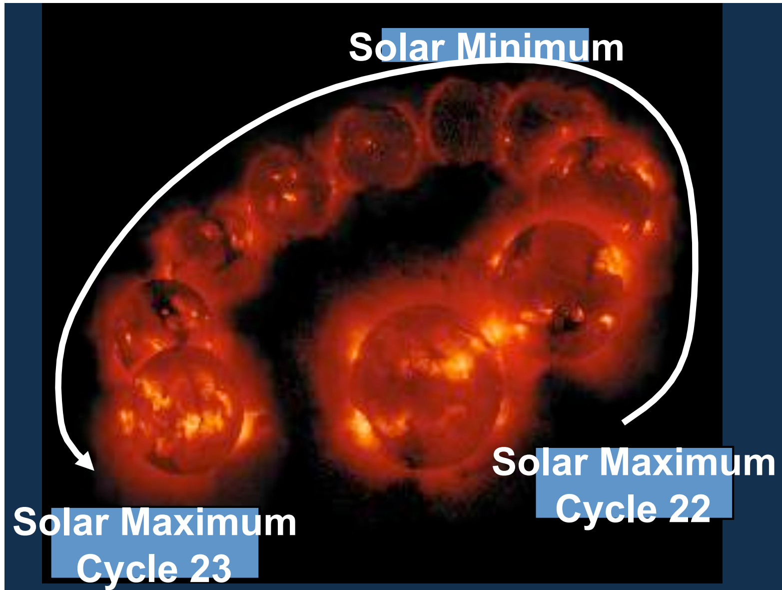


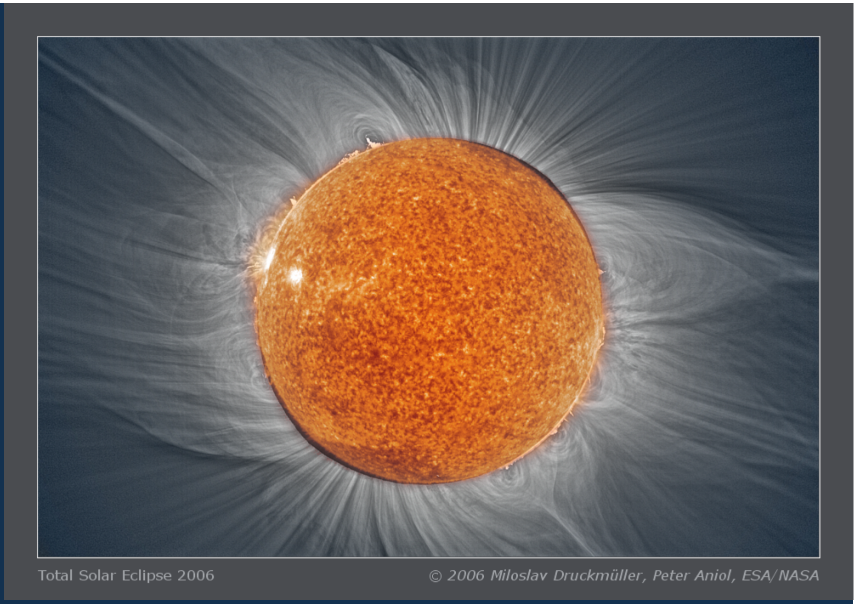



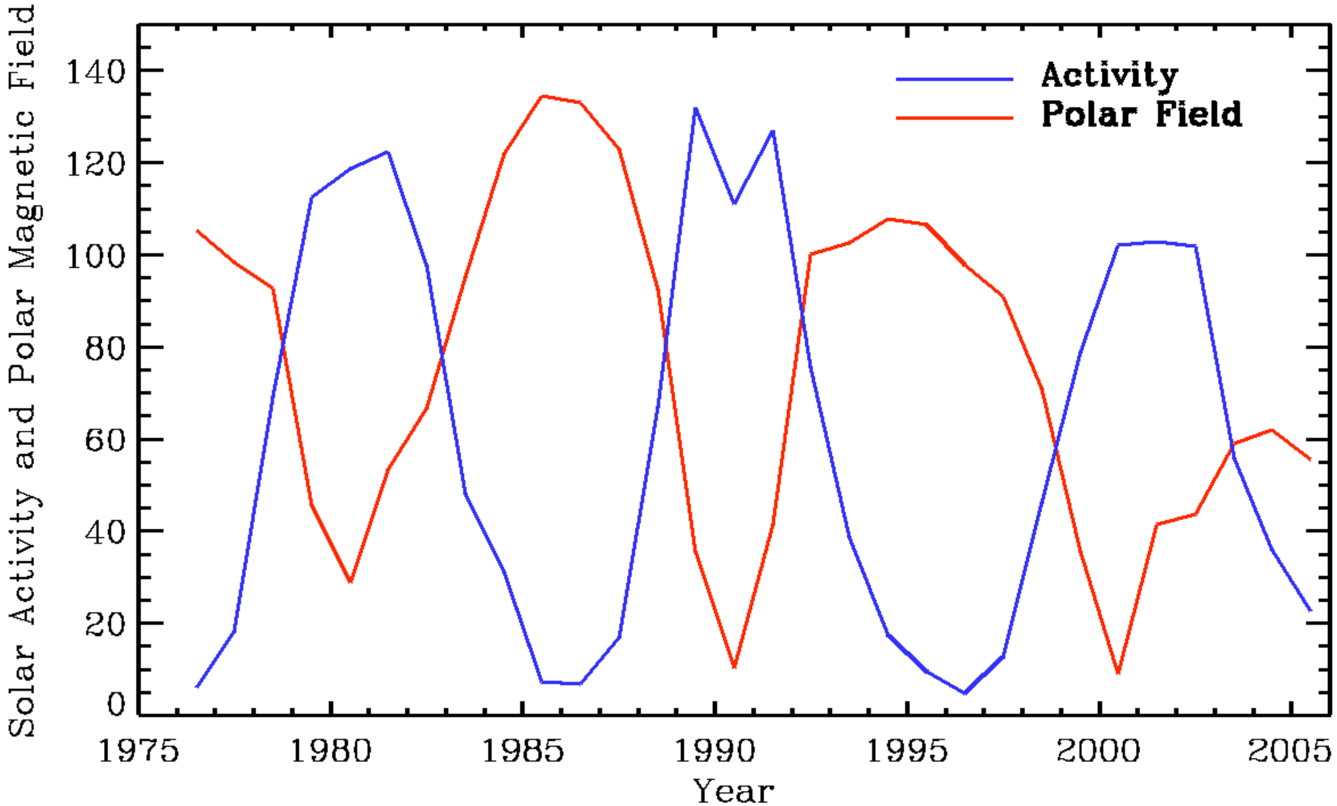



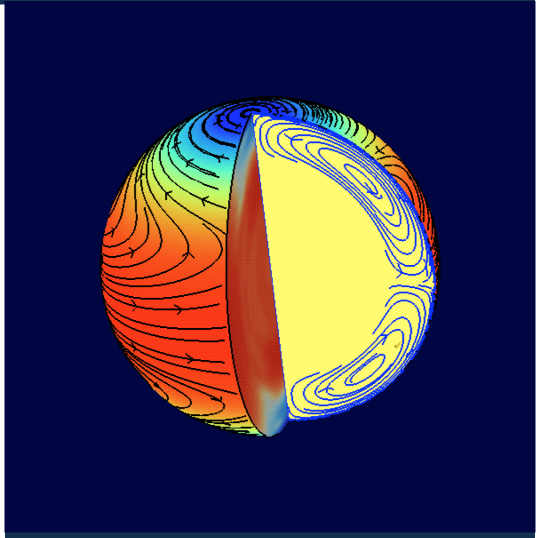
# 11 years cycle





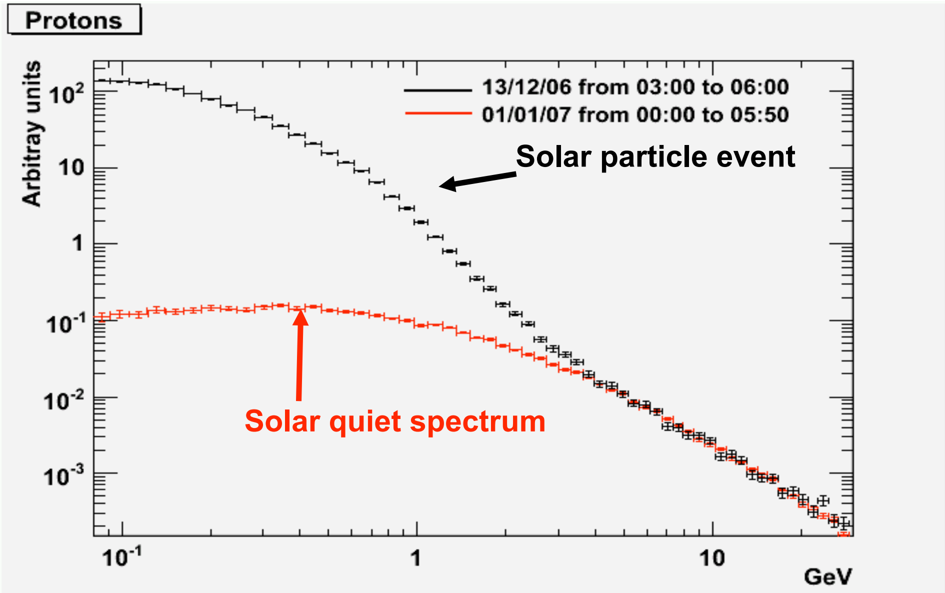



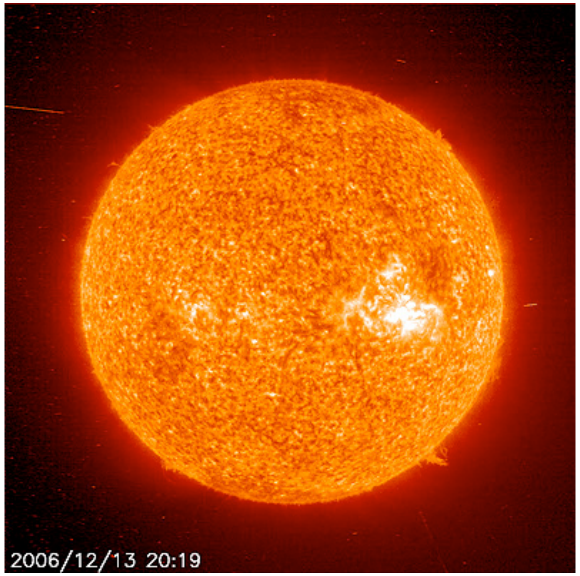
Andrea Vacchi, BNL 09/04/09

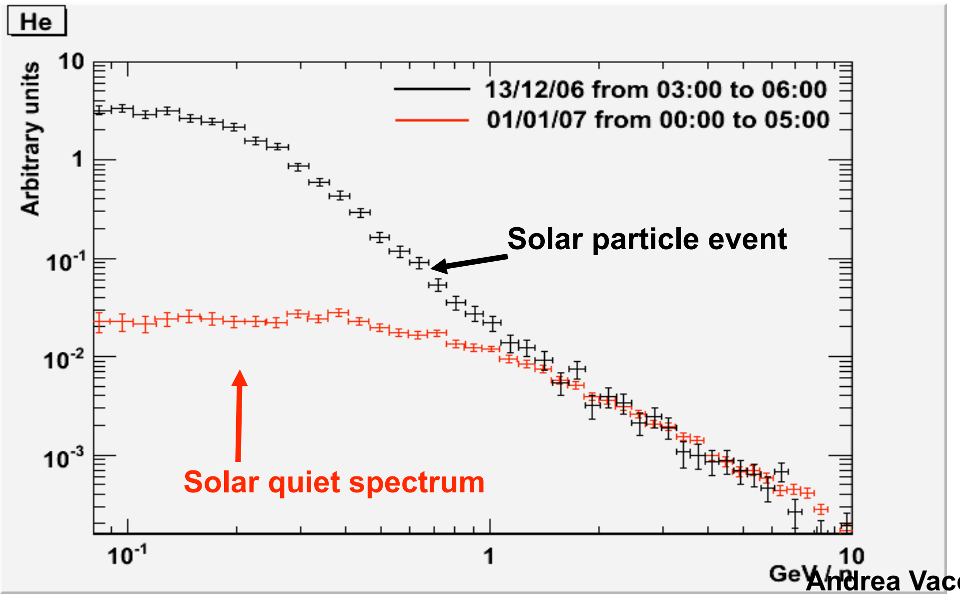
# 13th Dec. 2006 – solar particle event

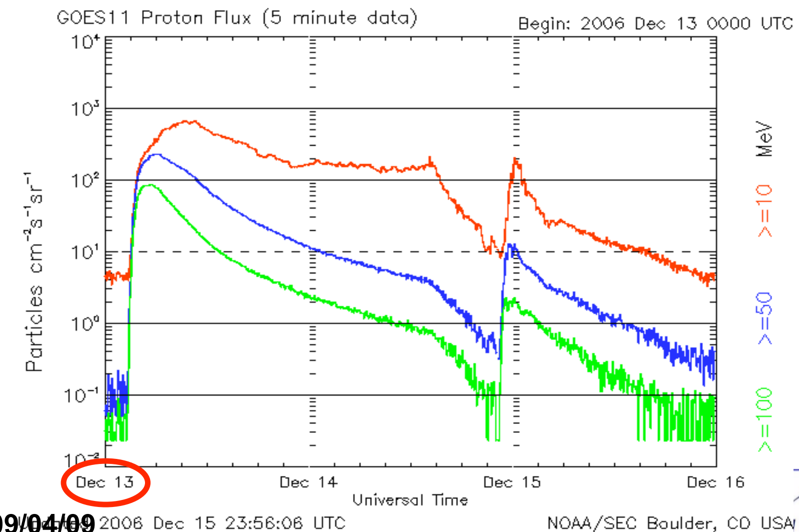
**Largest CME since 2003, anomalous at solar minimum**

Preliminary

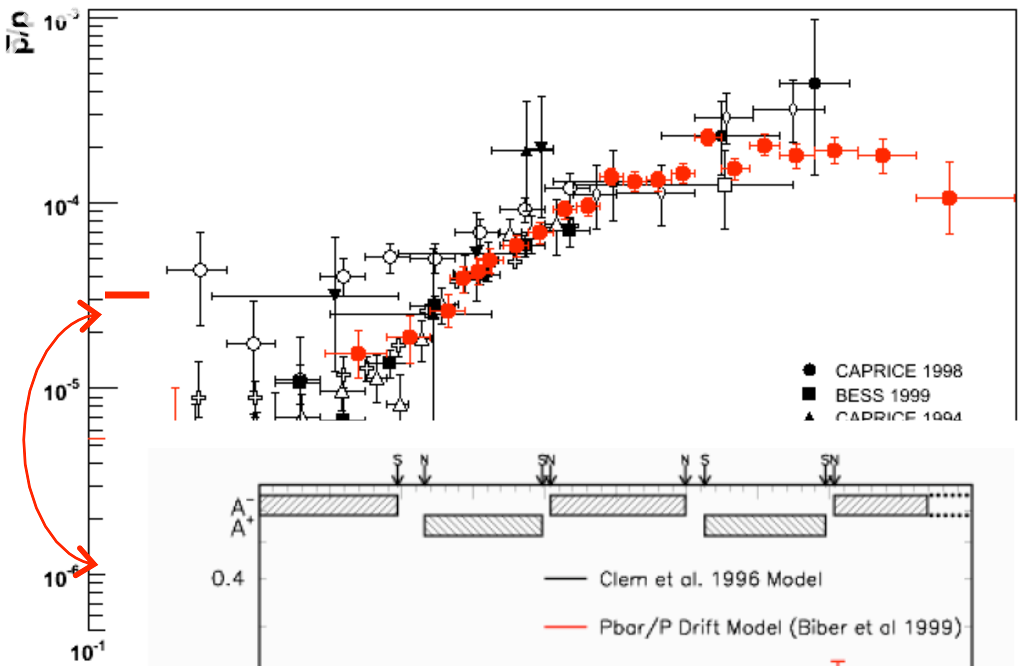


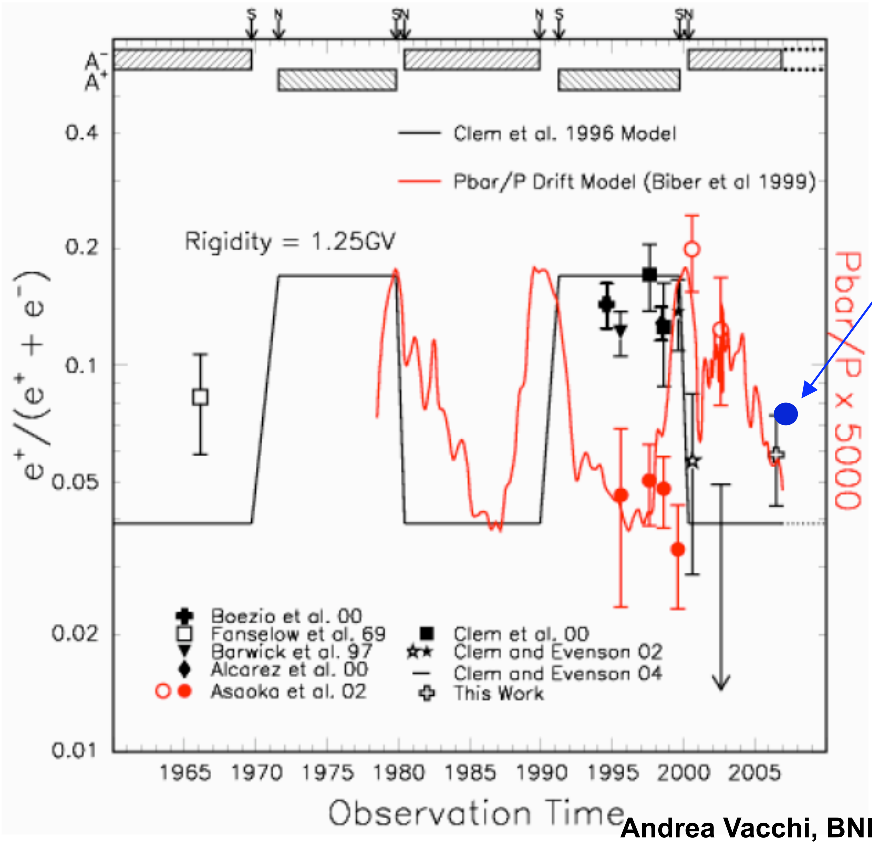



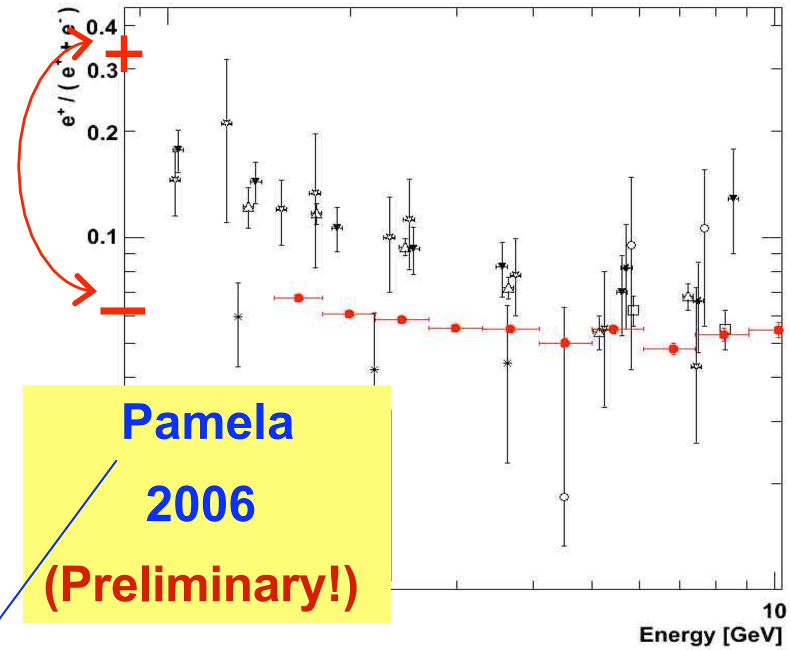



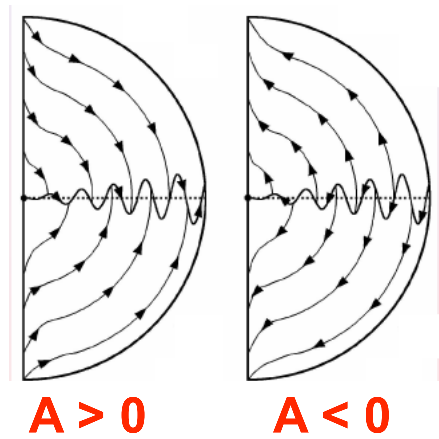



# Charge dependent solar modulation

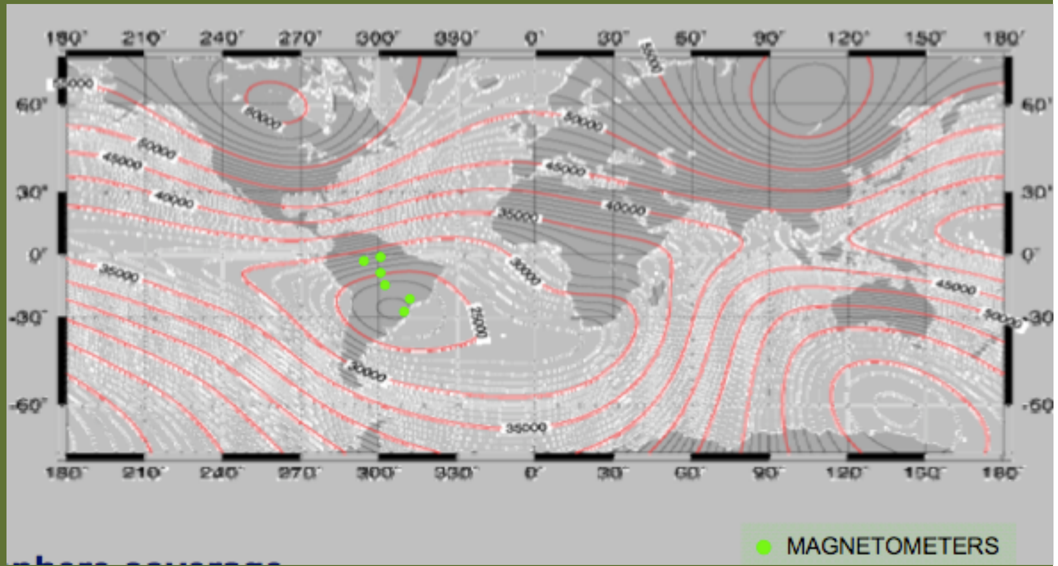


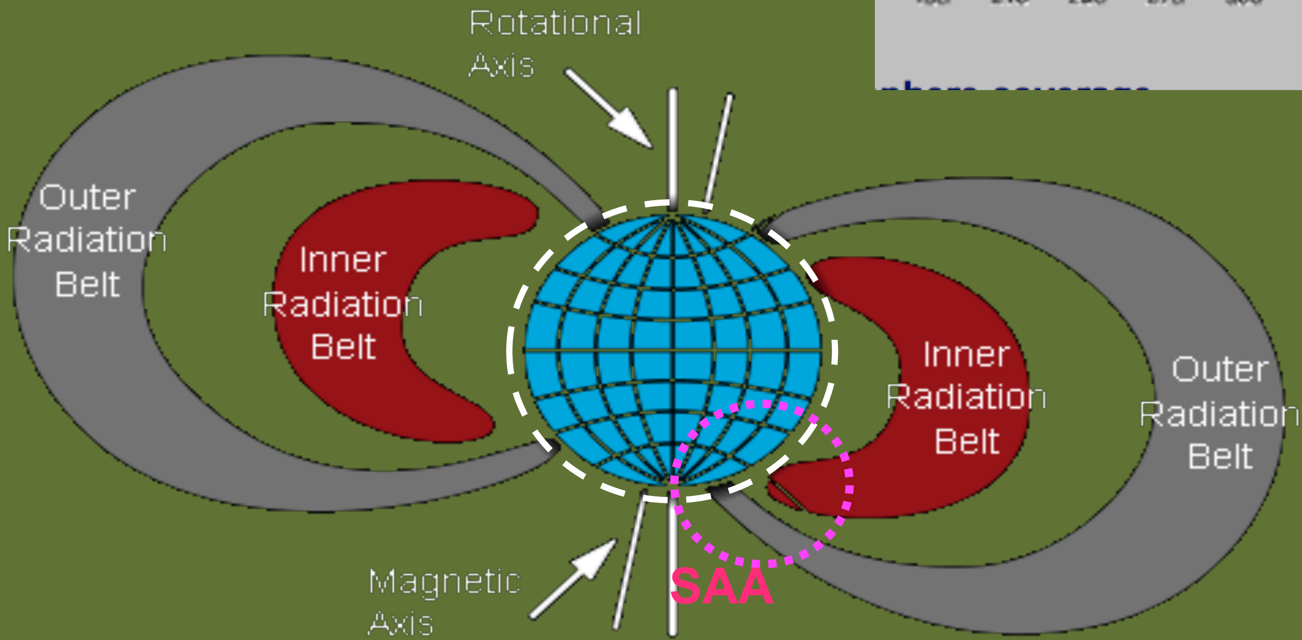



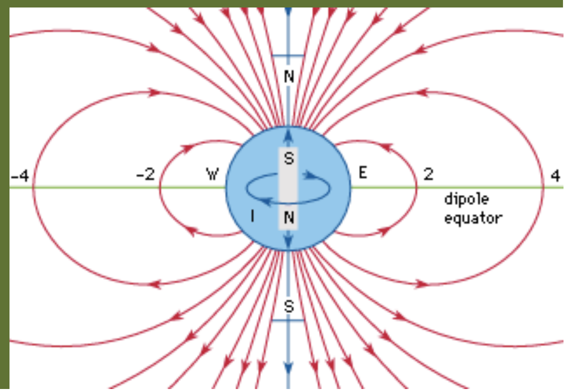



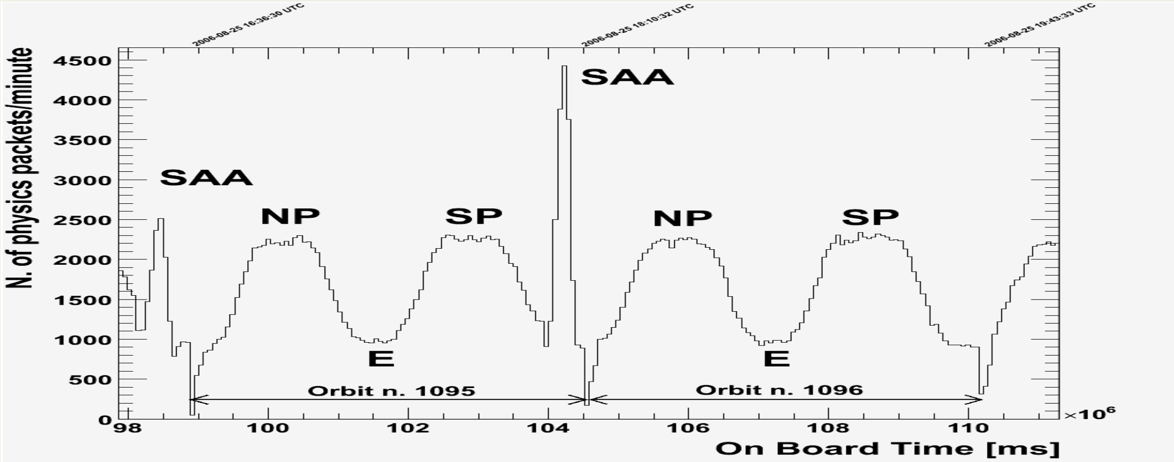
# Geomagnetic cut-off



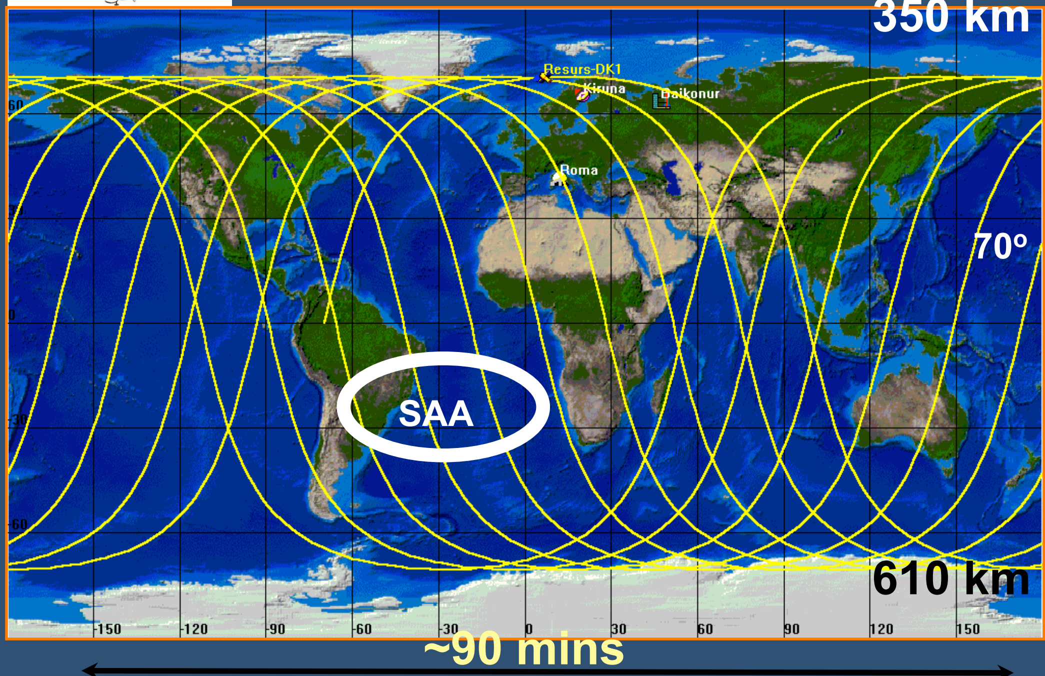



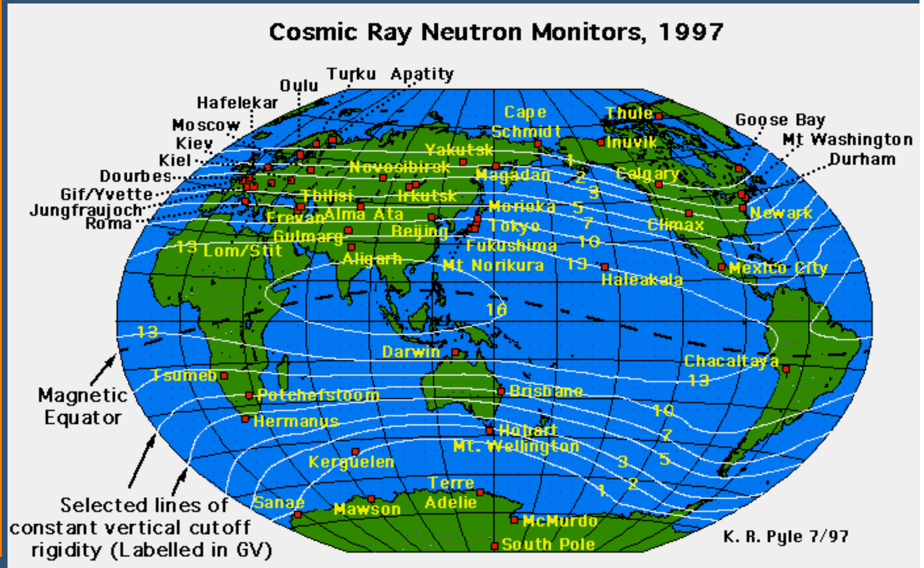
# Orbit and geomagnetic cutoff

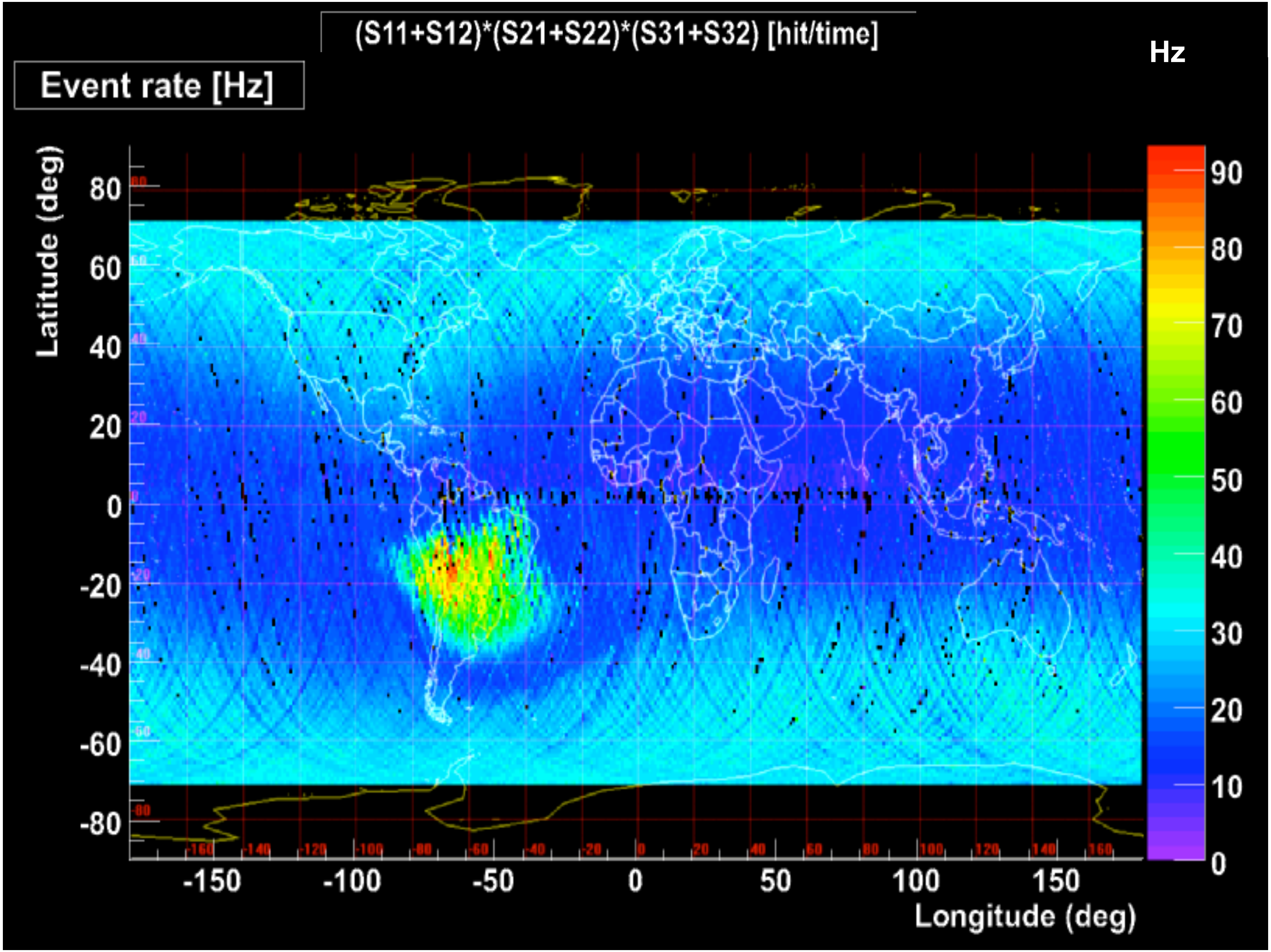



- Quasi-polar and elliptical orbit (70.0°, 350 km - 600 km)
- Traverses the South Atlantic Anomaly
- Crosses the outer (electron) Van Allen belt at south pole

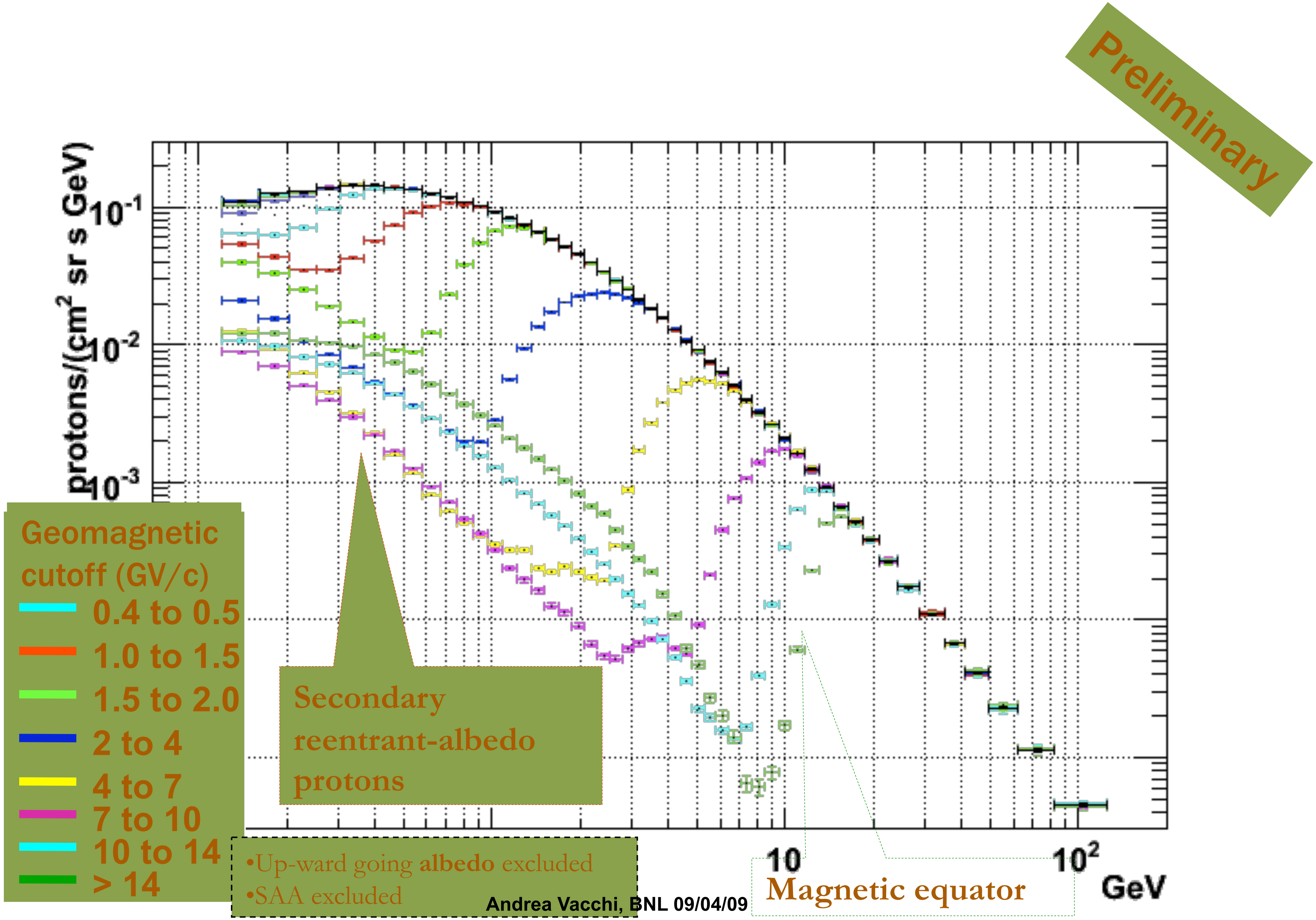




Worldwide Neutron Monitor Network acts as a single huge solar particle recorder




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

# Primary and Albedo (sub-cutoff) measurements

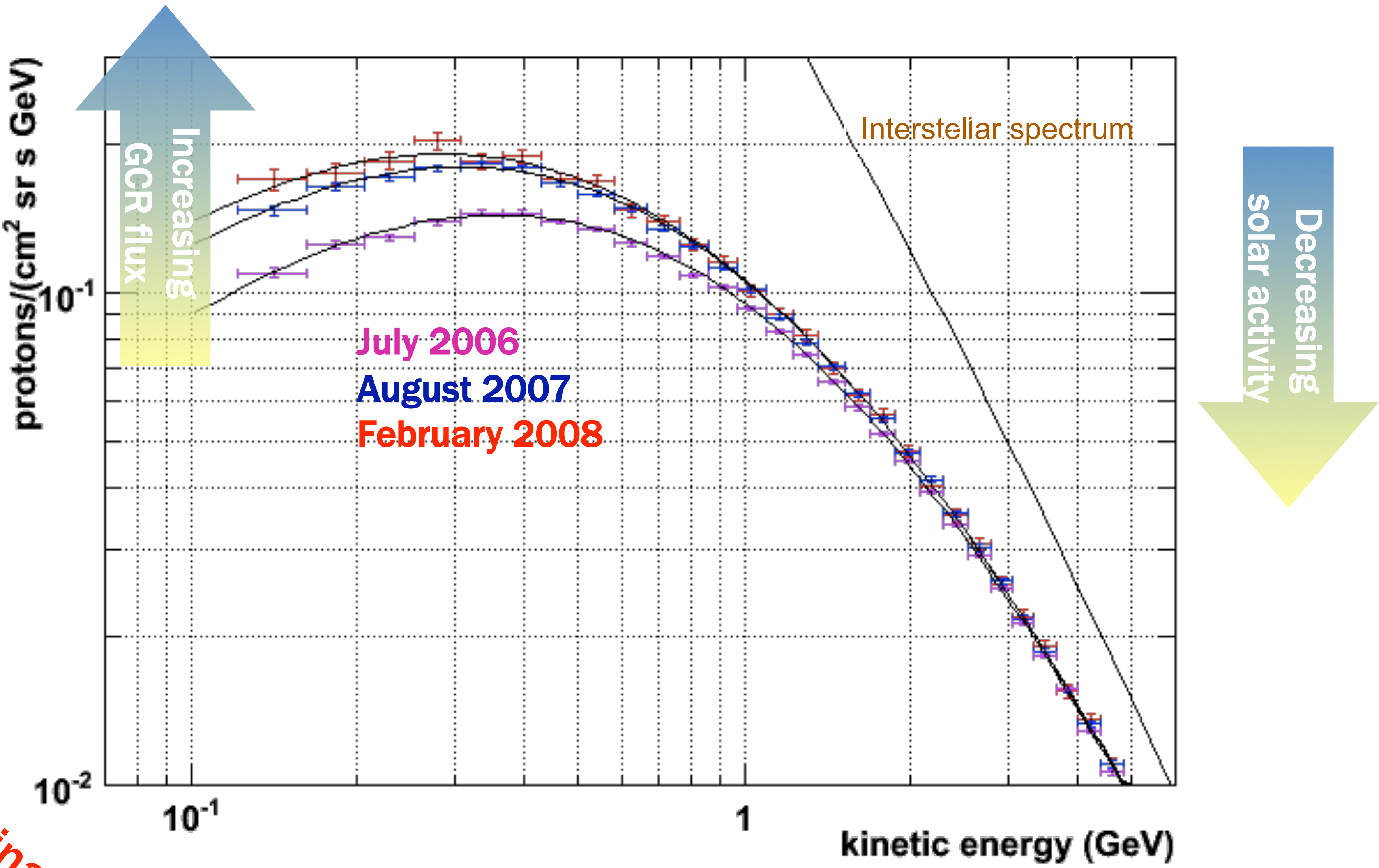


# Design Performance

- → Simultaneous measurement of many cosmic-ray species
- → New energy range
- → Unprecedented statistics
- → Constrain secondary production models

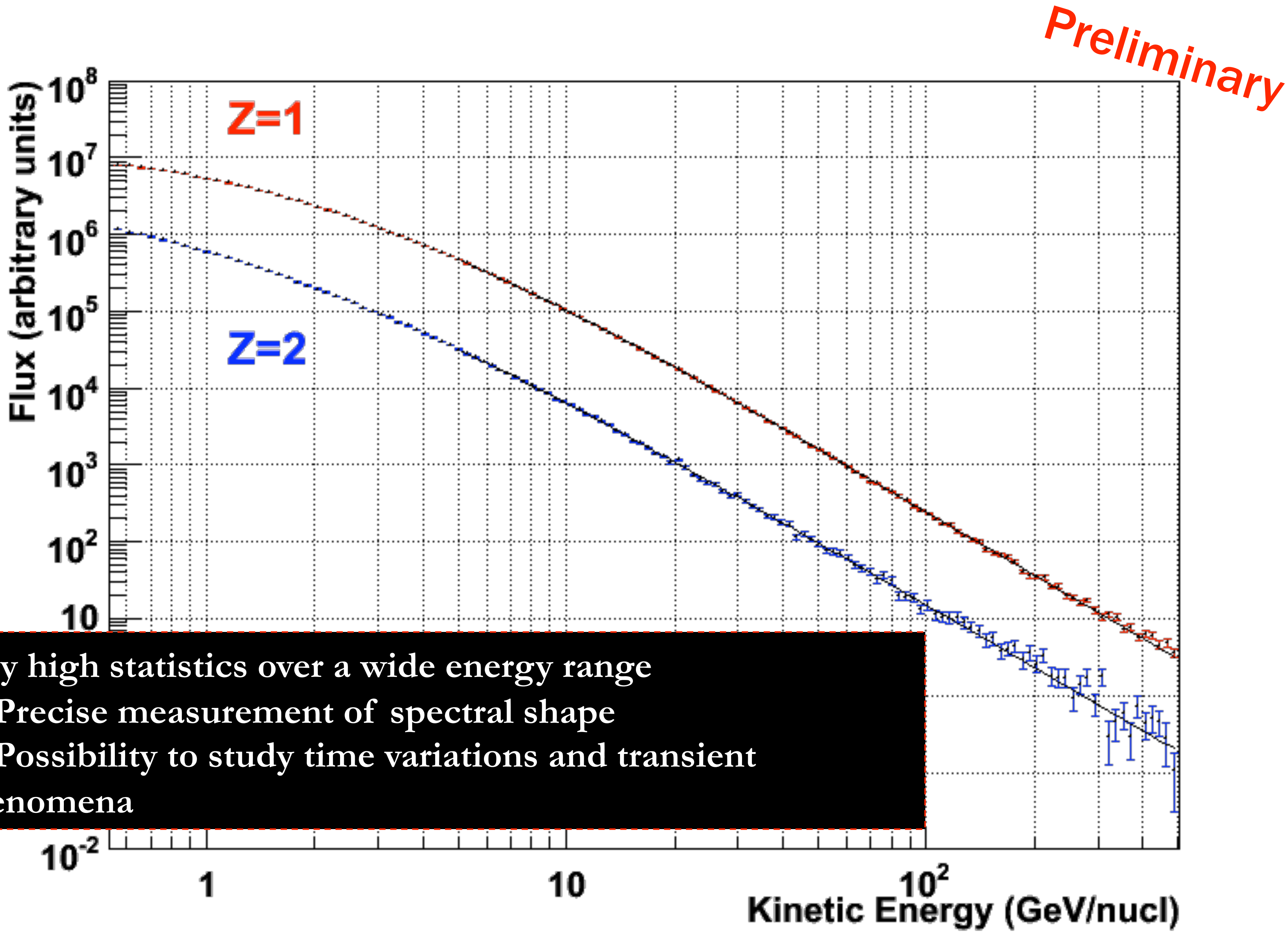
| | Energy range | | Particles / 3 years |
|---|---|---|---|
| • Antiproton flux | 80 MeV - 190 GeV | | $O(10^4)$ |
| • Positron flux | 50 MeV – 270 GeV | | $O(10^5)$ |
| • Electron/positron flux | up to 2 TeV (from calorimeter) | | |
| • Electron flux | up to 400 GeV | | $O(10^6)$ |
| • Proton flux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

# Proton spectra and solar modulation



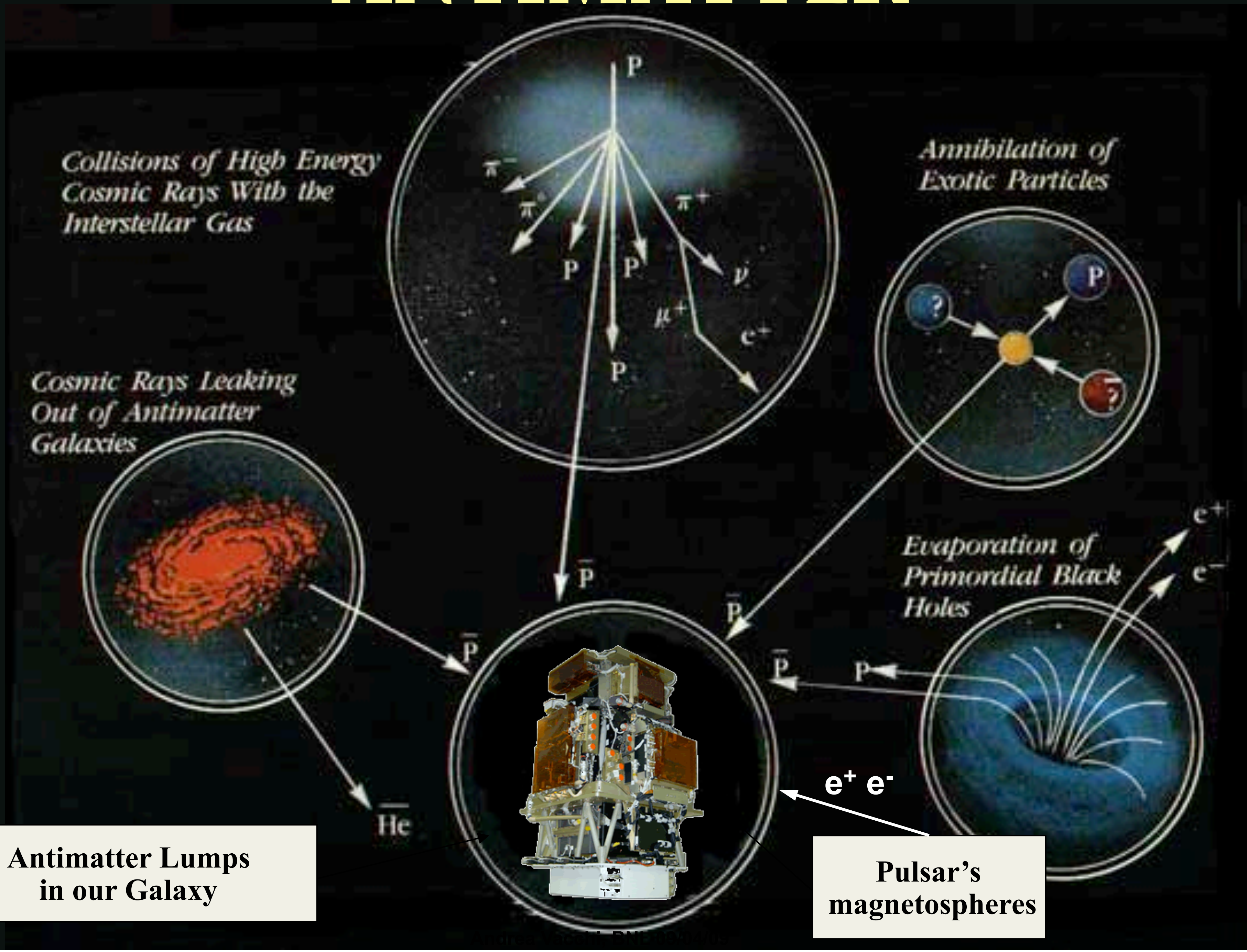

Preliminary

# Proton and Helium spectra




Very high statistics over a wide energy range
→ Precise measurement of spectral shape
→ Possibility to study time variations and transient phenomena

# ANTIMATTER




Antimatter Lumps
in our Galaxy

Pulsar's
magnetospheres

*The Quantum Theory of the Electron.*

By P. A. M. DIRAC, St. John's College, Cambridge.

(Communicated by R. H. Fowler, F.R.S.—Received January 2, 1928.)

The new quantum mechanics, when applied to the problem of the structure of the atom with point-charge electrons, does not give results in agreement with experiment. The discrepancies consist of "duplexity" phenomena, the observed number of stationary states for an electron in an atom being twice the number given by the theory. To meet the difficulty, Goudsmit and Uhlenbeck have introduced the idea of an electron with a spin angular momentum of half a quantum and a magnetic moment of one Bohr magneton. This model for the electron has been fitted into the new mechanics by Pauli,* and Darwin,† working with an equivalent theory, has shown that it gives results in agreement with experiment for hydrogen-like spectra to the first order of accuracy.

The question remains as to why Nature should have chosen this particular model for the electron instead of being satisfied with the point-charge. One would like to find some incompleteness in the previous methods of applying quantum mechanics to the point-charge electron such that, when removed, the whole of the duplexity phenomena follow without arbitrary assumptions. In the present paper it is shown that this is the case, the incompleteness of the previous theories lying in their disagreement with relativity, or, alternatetively, with the general transformation theory of quantum mechanics. It appears that the simplest Hamiltonian for a point-charge electron satisfying the requirements of both relativity and the general transformation theory leads to an explanation of all duplexity phenomena without further assumption. All the same there is a great deal of truth in the spinning electron model, at least as a first approximation. The most important failure of the model seems to be that the magnitude of the resultant orbital angular momentum of an electron moving in an orbit in a central field of force is not a constant, as the model leads one to expect.

* Pauli, 'Z. f. Physik,' vol. 43, p. 601 (1927).
† Darwin, 'Roy. Soc. Proc.,' A, vol. 116, p. 227 (1927).

*The Quantum Theory of the Electron. Part II.*

By P. A. M. DIRAC, St. John's College, Cambridge.

(Communicated by R. H. Fowler, F.R.S.—Received February 2, 1928.)

In a previous paper by the author* it is shown that the general theory of quantum mechanics together with relativity require the wave equation for an electron moving in an arbitrary electromagnetic field of potentials, $A_0$, $A_1$, $A_2$, $A_3$ to be of the form

$$F\psi \equiv \left[p_0 + \frac{e}{c}A_0 + \alpha_1\left(p_1 + \frac{e}{c}A_1\right) + \alpha_2\left(p_2 + \frac{e}{c}A_2\right) + \alpha_3\left(p_3 + \frac{e}{c}A_3\right) + \alpha_4 mc\right]\psi = 0. \quad (1)$$

The $\alpha$'s are new dynamical variables which it is necessary to introduce in order to satisfy the conditions of the problem. They may be regarded as describing some internal motion of the electron, which for most purposes may be taken to be the spin of the electron postulated in previous theories. We shall call them the spin variables.

The $\alpha$'s must satisfy the conditions

$$\alpha_\mu^2 = 1, \quad \alpha_\mu\alpha_\nu + \alpha_\nu\alpha_\mu = 0. \quad (\mu \neq \nu.)$$

They may conveniently be expressed in terms of six variables $\rho_1$, $\rho_2$, $\rho_3$, $\sigma_1$, $\sigma_2$, $\sigma_3$ that satisfy

and

$$\left.\begin{array}{ll} \rho_r^2 = 1, \quad \sigma_r^2 = 1, \quad \rho_r\sigma_s = \sigma_s\rho_r & (r, s = 1, 2, 3) \\ \rho_1\rho_2 = i\rho_3 = -\rho_2\rho_1, \quad \sigma_1\sigma_2 = i\sigma_3 = -\sigma_2\sigma_1 & \end{array}\right\}, \quad (2)$$

together with the relations obtained from these by cyclic permutation of the suffixes, by means of the equations

$$\alpha_1 = \rho_1\sigma_1, \quad \alpha_2 = \rho_1\sigma_2, \quad \alpha_3 = \rho_1\sigma_3, \quad \alpha_4 = \rho_3.$$

The variables $\sigma_1$, $\sigma_2$, $\sigma_3$ now form the three components of a vector, which corresponds (apart from a constant factor) to the spin angular momentum vector that appears in Pauli's theory of the spinning electron. The $\rho$'s and $\sigma$'s vary with the time, like other dynamical variables. Their equations of motion, written in the Poisson Bracket notation [ ], are

$$\dot{\rho}_r = c\,[\rho_r, F], \quad \dot{\sigma}_r = c\,[\sigma_r, F].$$

* 'Roy. Soc. Proc.,' A, vol. 117, p. 610 (1928). This is referred to later by *loc. cit.*

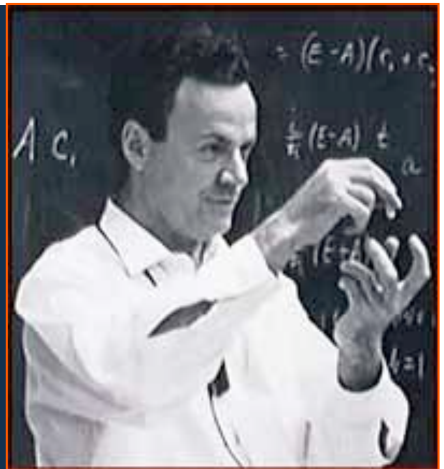
# Two articles February and March 1928

**Which are the quantum waves able to describe electrons?**

**And which the wave equations governing the dynamics of those equations while compatible with the conditions of relativity and able to give reasonable prediction.**

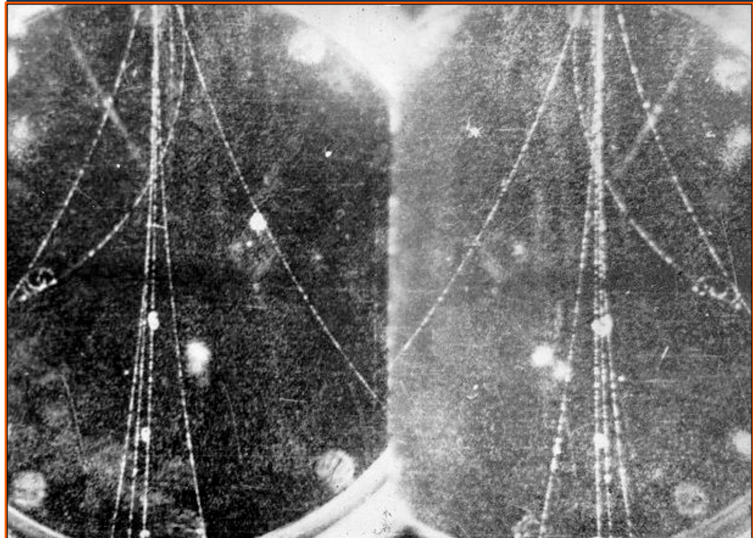
**Paul Dirac, pointed out in 1928 that the physics of quantum mechanics and relativity together leads to states of negative energy appearing like particles with quantum numbers inversed to the "normal" matter.**

(Proc. R. Soc. London, A, 117, (1928), 610)



$$(i\gamma\cdot\partial - m)\psi = 0$$

- **In 1932 four years later Andreson discovered, in cosmic rays, the positive electron ANTIELECTTRON or POSITRON.**
- **Little latter Blackett and Ochialini in Cambridge confirmed Anderson and discovered the pair production in the showers generated by cosmic rays.**





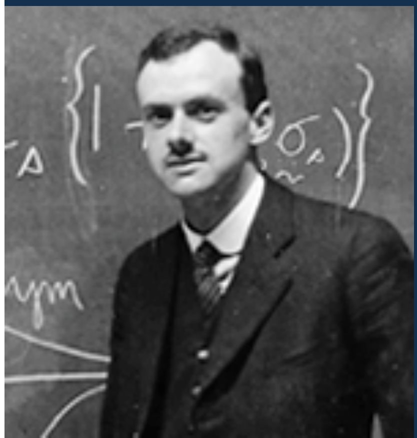
**"I think that the discovery of antimatter was probably the biggest jump among the jumps of physics in our century."**

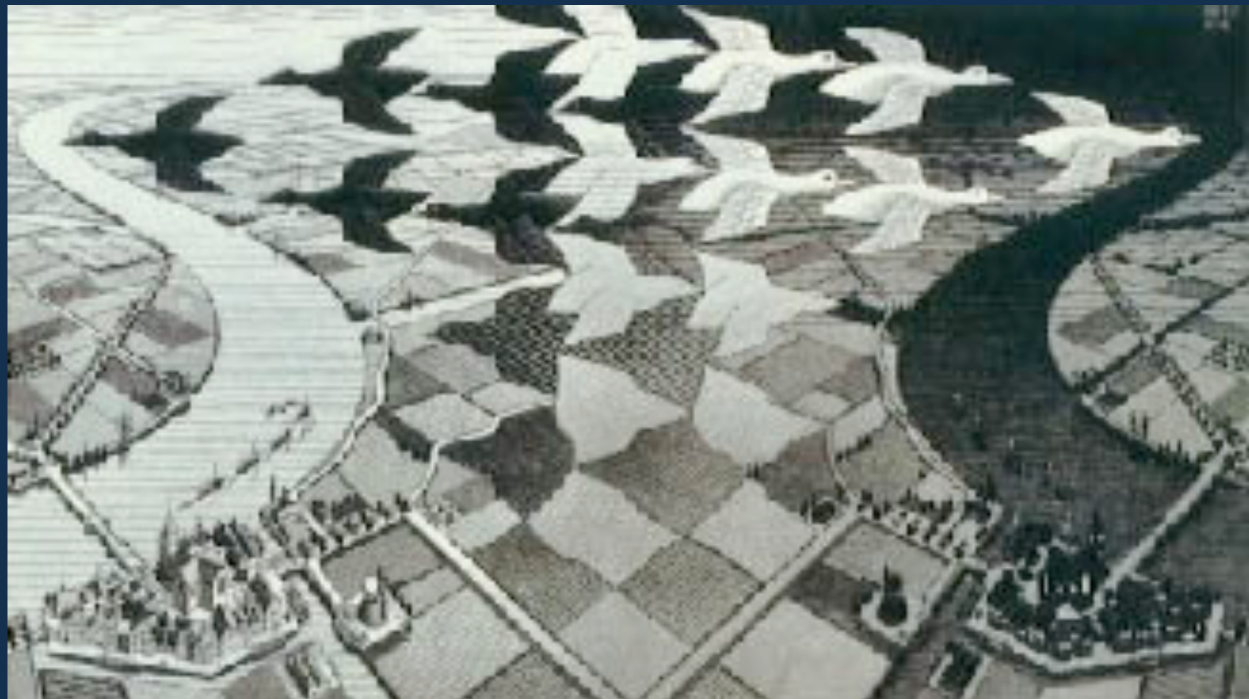
**Heisemberg 1972**

"A great deal of my work is just playing with equations and seeing what they give."

Paul Dirac published his work exactly eighty years ago February 1928.

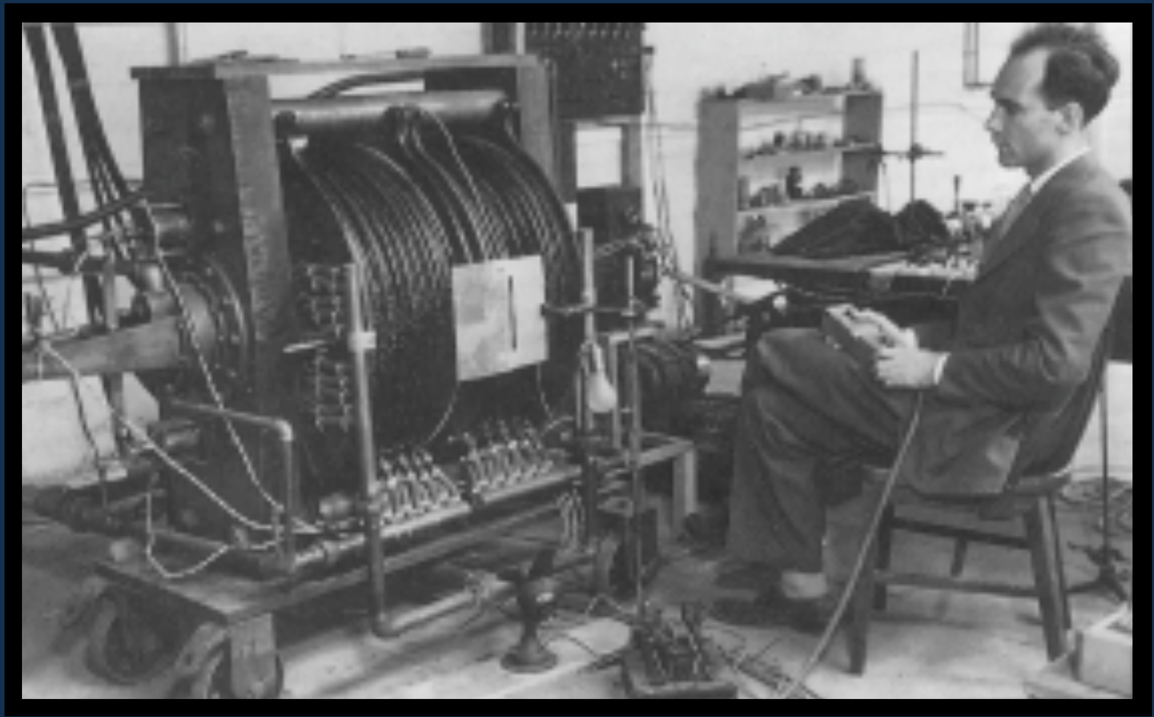
"The Quantum Theory of the Electron"





**State of negative energy appear as particles with quantum numbers inverted to normal**

# Discovery of  antimatter in cosmic rays



**Anderson (1932)**

## Bevatron 1955 the discovery of the antiproton

## Chamberlain, Segrè, Wiegand, Ypsilantis Nobel 1959

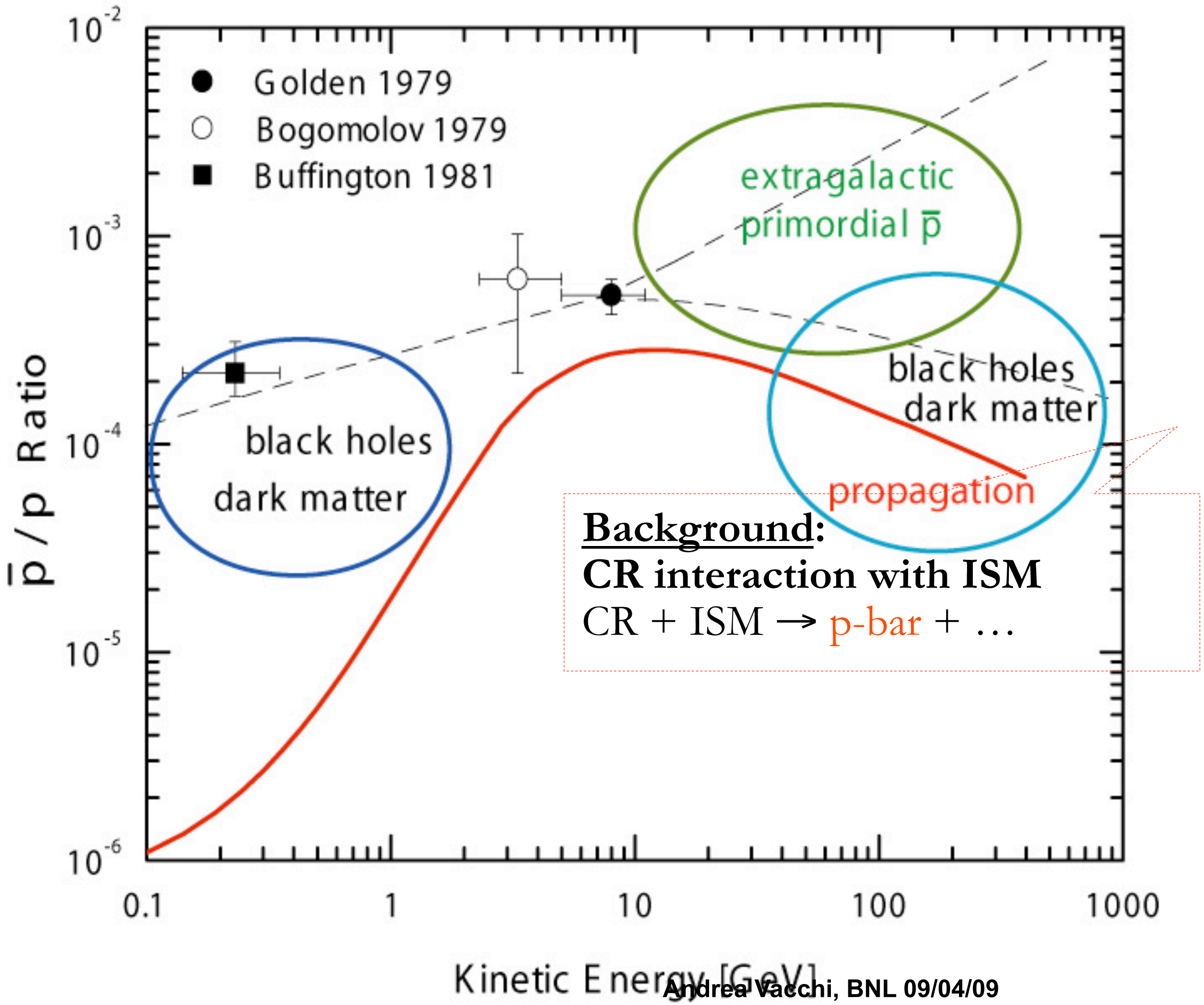
- The existence of a particle with a mass equal to the proton but with negative charge the antiprotone (able to annihilate with a proton) it was a guess suggested by the possibility to extend Dirac theory to heawwier particles.

**Create artificially the proton-antiproton pairs in the collisions produced by accelerated protons on a fixed target and then detect the antiprotons required the energies obtainable at an accelerator developed for this task:**

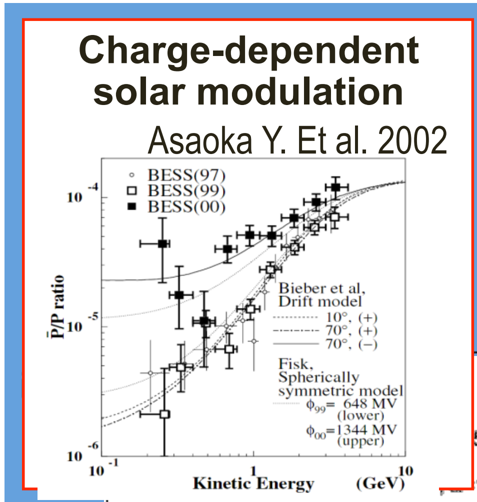
**the Bevatron (p 6 GeV) designed by the Lawrence group with a sufficient energy to allow cinematically the production of protons and antiprotons**

# 20 years ago

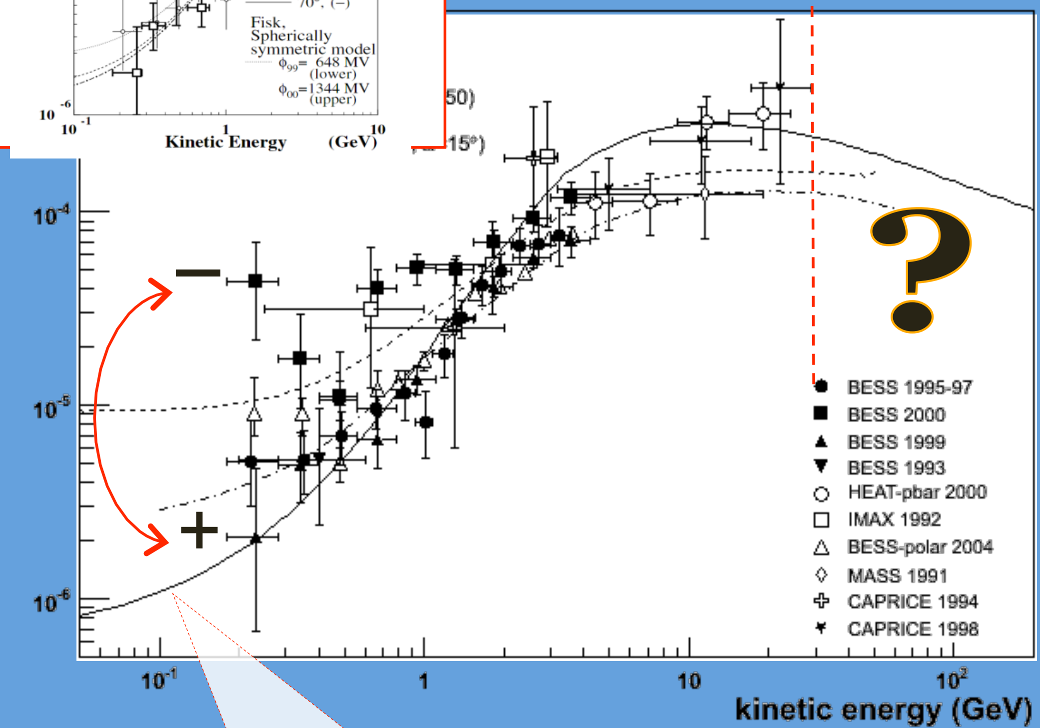
The first historical measurements of the p̄/p - ratio and various Ideas of theoretical Interpretations



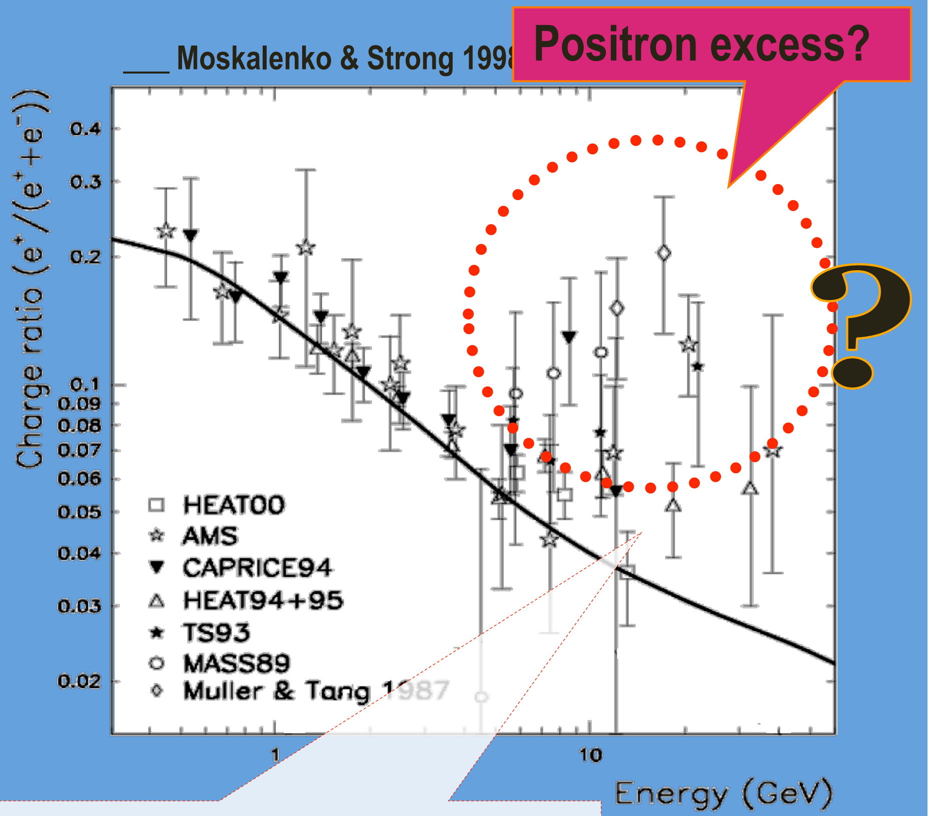
# CR antimatter status BP




## Antiprotons



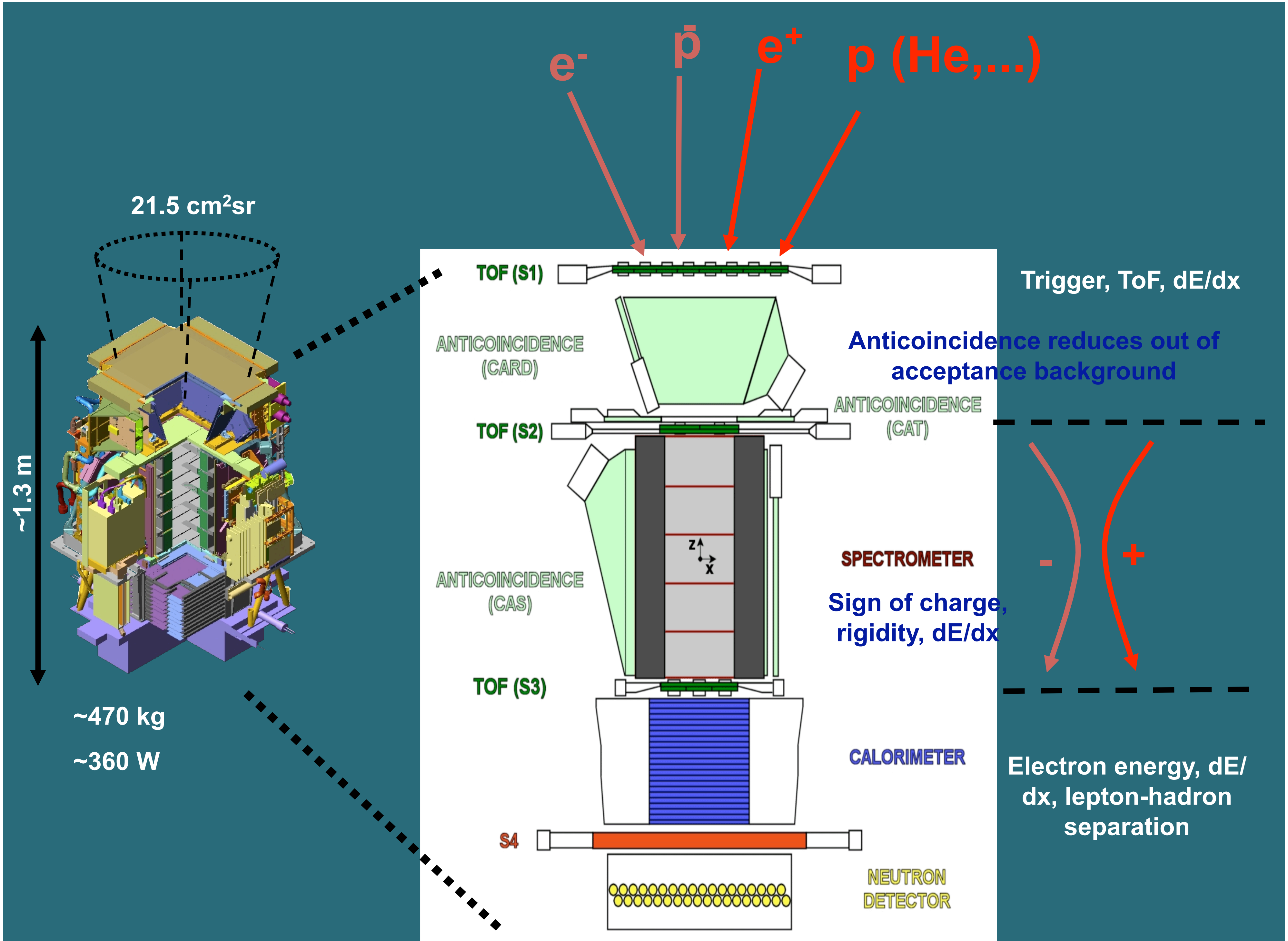

## Positrons

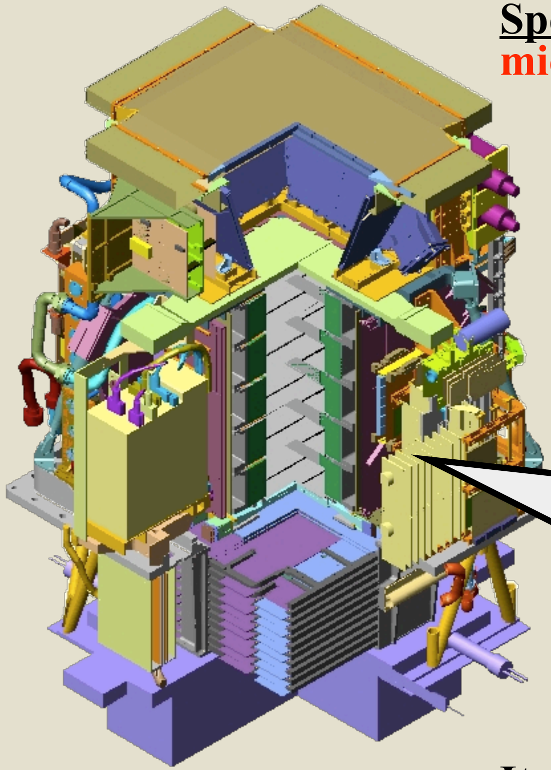



CR + ISM → **p-bar** + …
kinematic treshold:
5.6 GeV for the reaction

$pp \rightarrow \bar{p}ppp$

CR + ISM → $\pi^{\pm}$ + x → $\mu^{\pm}$ + x → **e±** + x
CR + ISM → $\pi^0$ + x → γγ → **e±**


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



**Spectrometer**

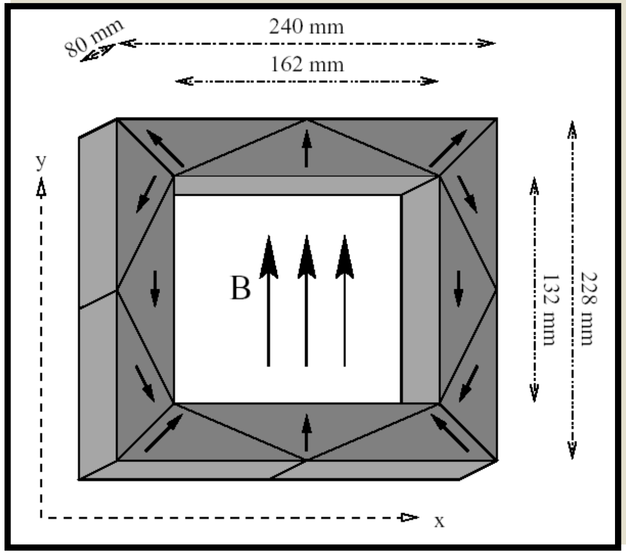
microstrip silicon tracking system + permanent magnet

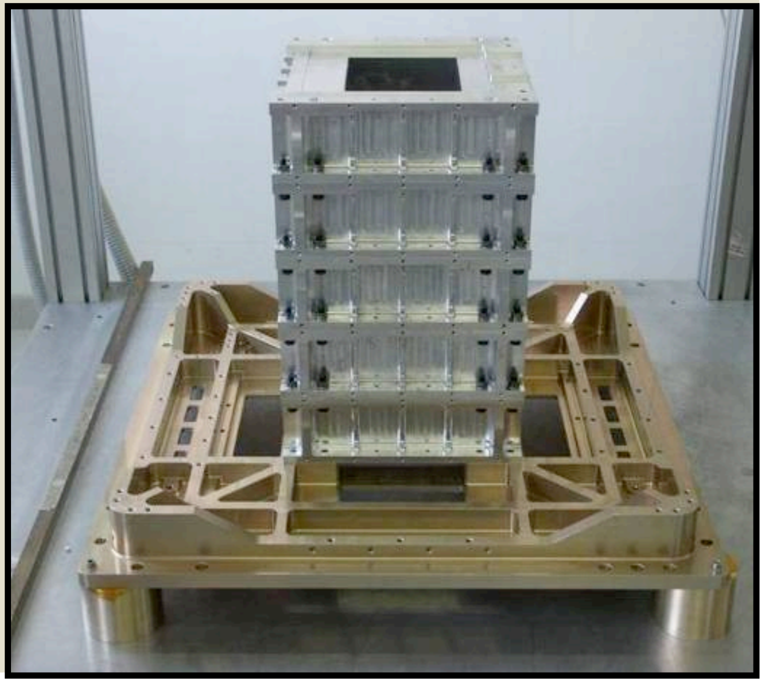
**•Characteristics:**

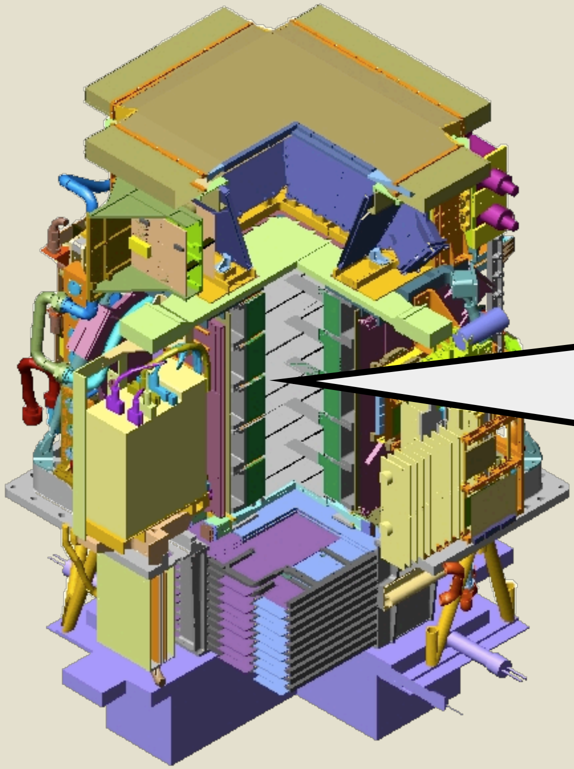
- 5 modules of permanent magnet (Nd-B-Fe alloy) in aluminum mechanics
- Cavity dimensions (162 x 132 x 445) $cm^3$
- → GF ~ 21.5 $cm^2sr$
- Magnetic shields
- 5mm-step field-map on ground:
    - B=0.43 T (average along axis),
    - B=0.48 T (@center)

**It provides:**

- *Magnetic rigidity* → R = pc/Ze
- *Charge sign*
- *Charge value from dE/dx*



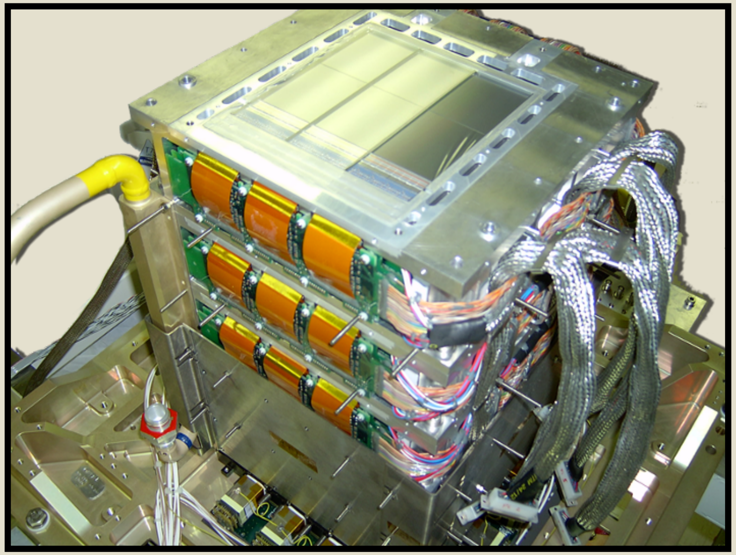


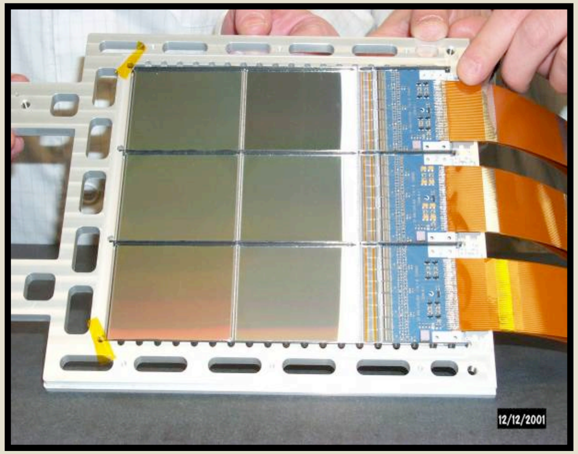
# The tracking system

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

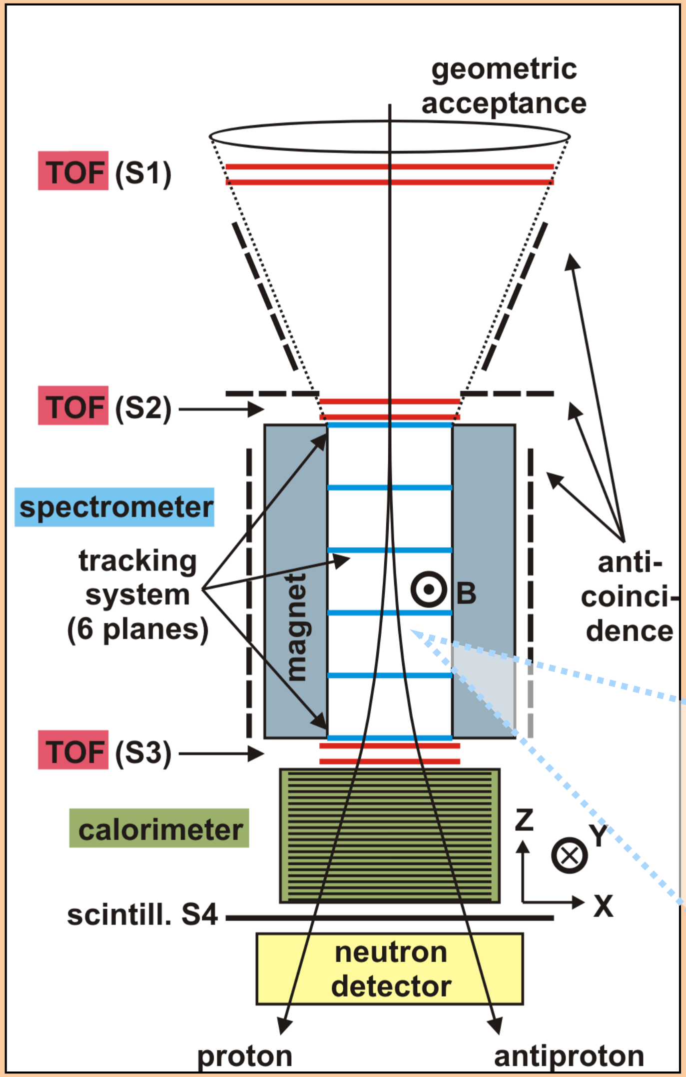
- **Characteristics:**
- **6 planes double-sided (x&y view) microstrip Si sensors**
- 36864 channels
- Dynamic range: 10 MIP

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



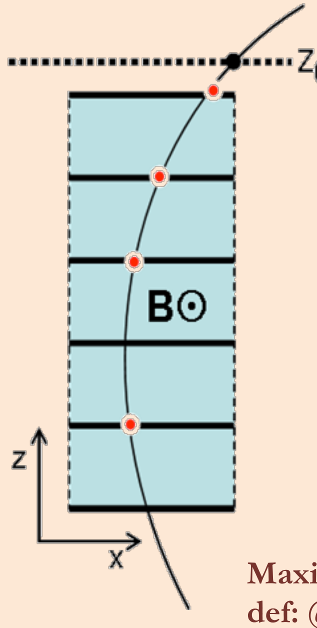


# Principle of operation




## Track reconstruction

$\alpha = (x_0, y_0, \sin\theta, \phi, \eta)$




Iterative $\chi^2$ minimization as a function of track state-vector components $\alpha$

<u>Magnetic deflection</u>

$|\eta| = 1/R$

$R = pc/Ze$ → <u>magnetic rigidity</u>

$\sigma_R/R = \sigma_\eta/\eta$

Maximum Detectable Rigidity (MDR)

def: @ R=MDR $\Rightarrow \sigma_R/R=1$

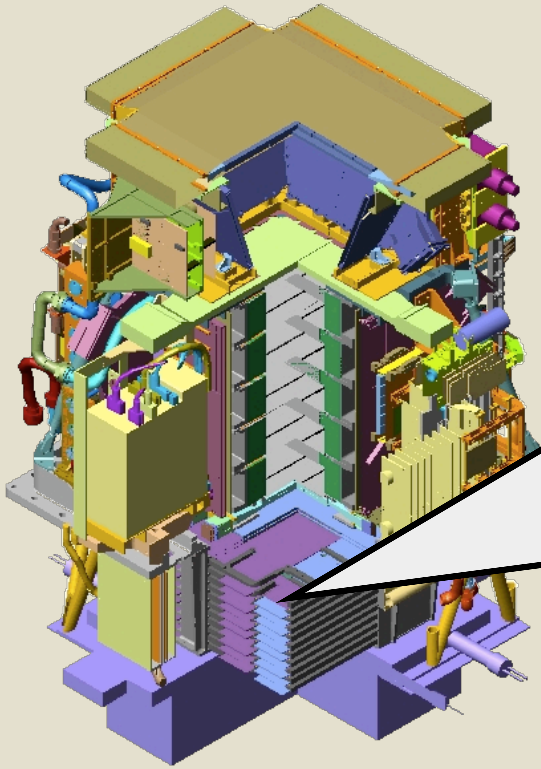
$MDR = 1/\sigma_\eta$

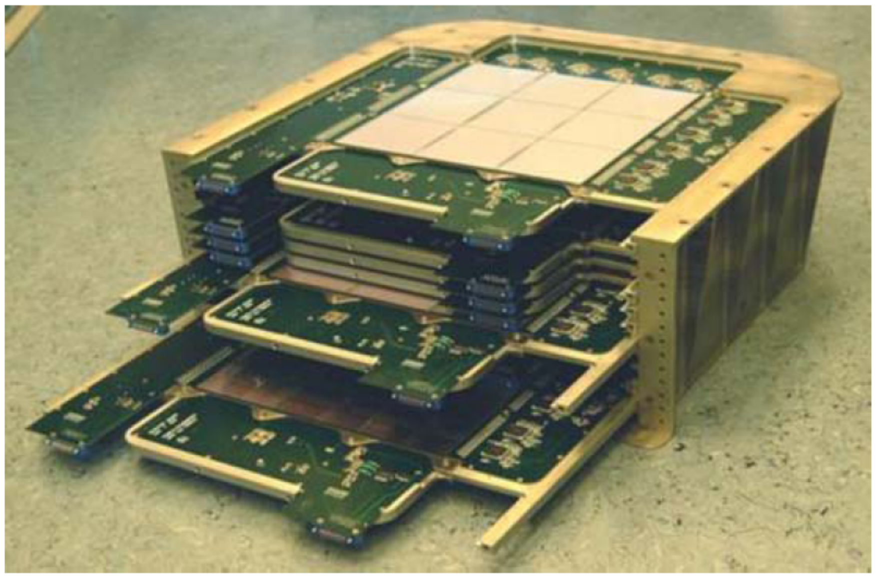
- Measured @ground with protons of known momentum

  → MDR~1TV

- Cross-check in flight with protons (alignment) and electrons (energy from calorimeter)

# The electromagnetic calorimeter



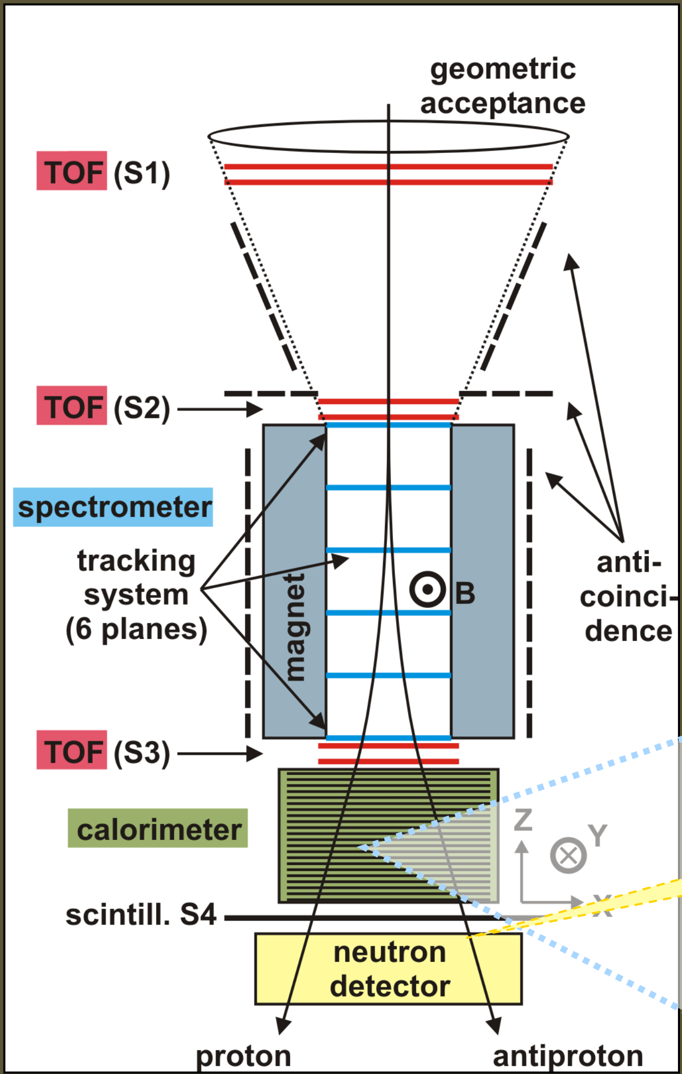


- **Main tasks:**
- lepton/hadron discrimination
- $e^{+/-}$ energy measurement

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

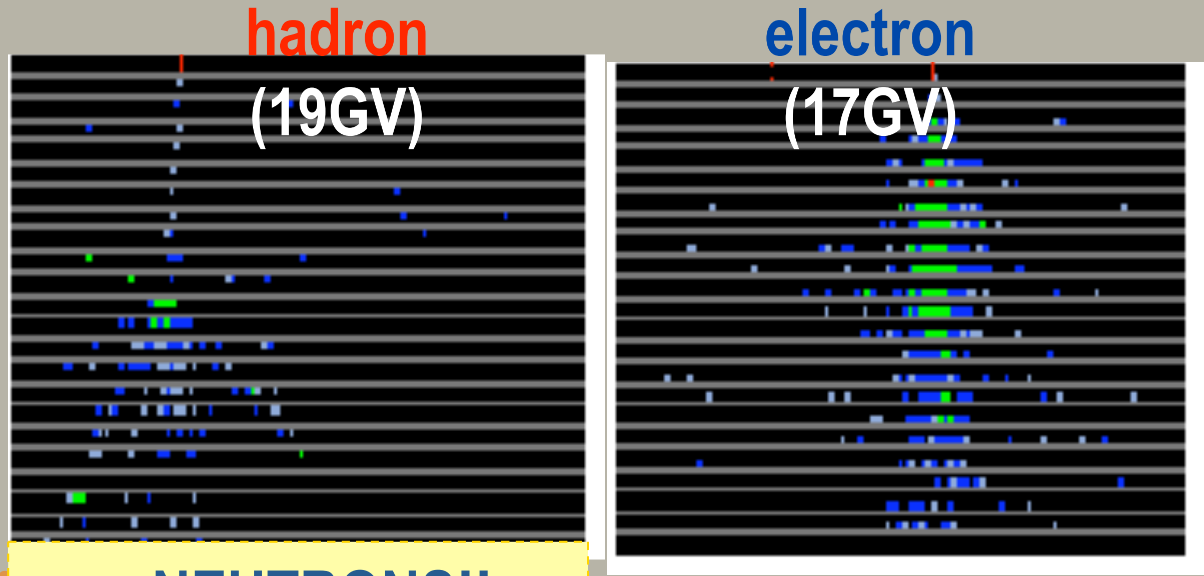
- **Performance:**
- $p/e^+$ selection efficiency ~ 90%
- p rejection factor ~$10^5$
- e rejection factor > $10^4$
- Energy resolution ~5% @ 200 GeV

# Principle of operation




## Electron/hadron separation

• Interaction topology    e/h separation

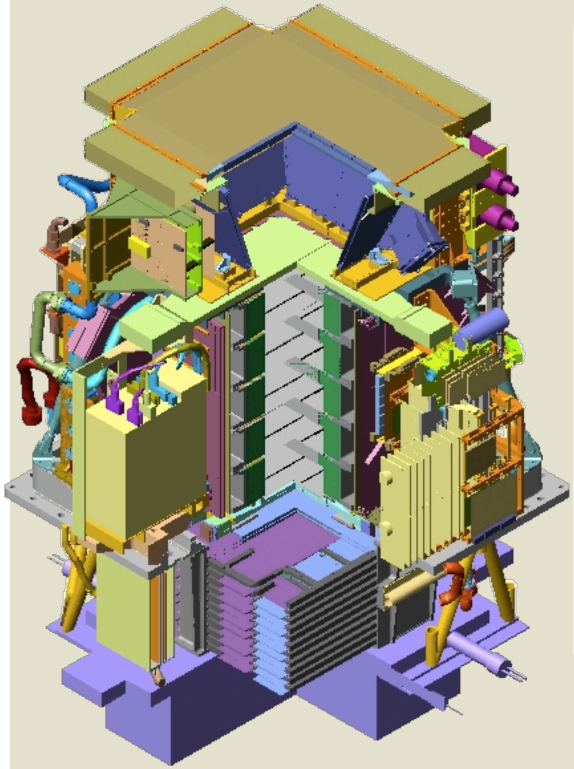


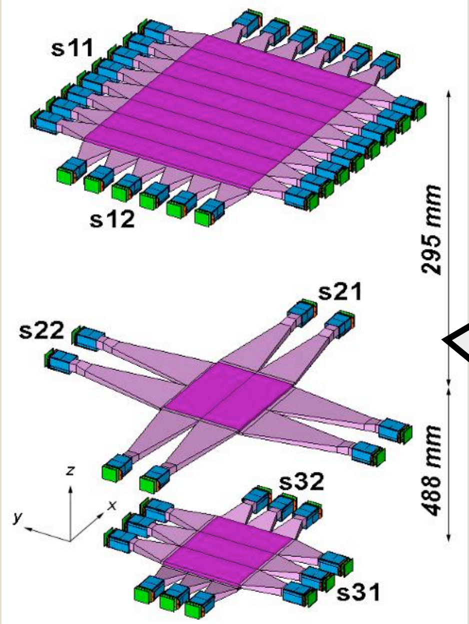

+ NEUTRONS!!

•Energy measurement of electrons and positrons (~full shower containment)

$$\frac{\sigma_E}{E} = a \oplus \frac{b}{\sqrt{E}} \quad \rightarrow a < 5\%$$

# The time-of-flight system






**•Main tasks:**

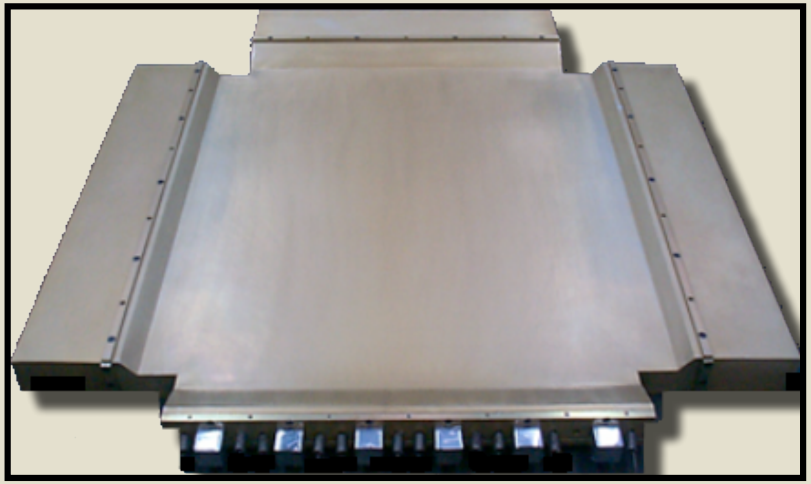
- First-level trigger
- Albedo rejection
- dE/dx (ionisation losses)
- Time of flight particle identification (<1GeV/c)

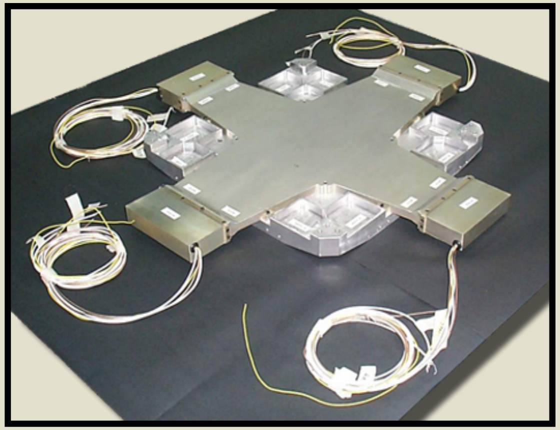
**•Characteristics:**

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

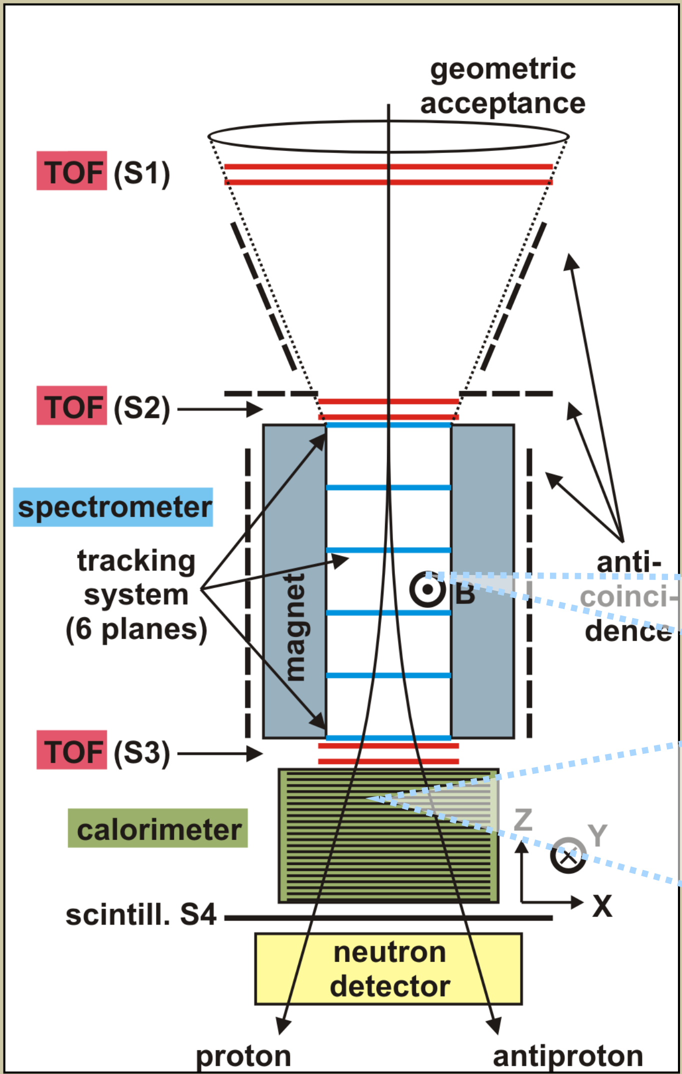
**•Performance:**

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





# Principle of operation

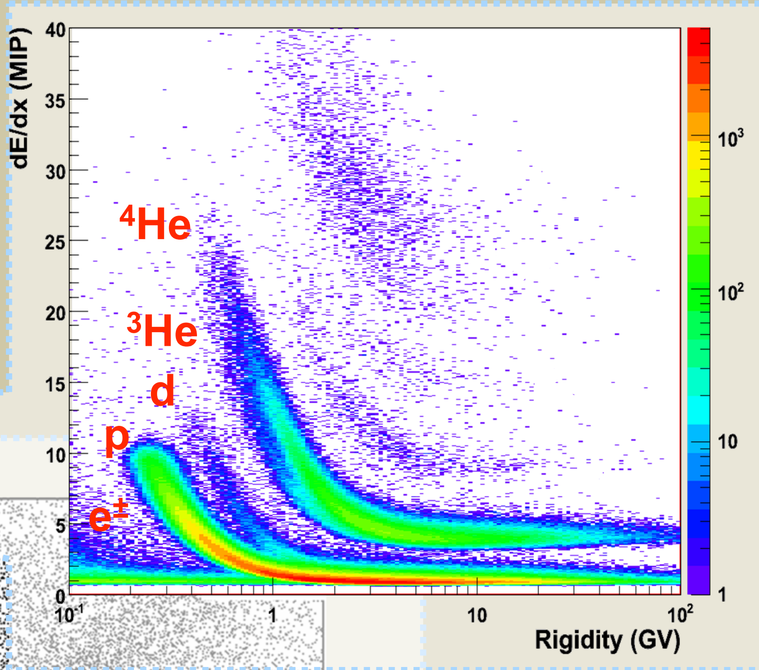


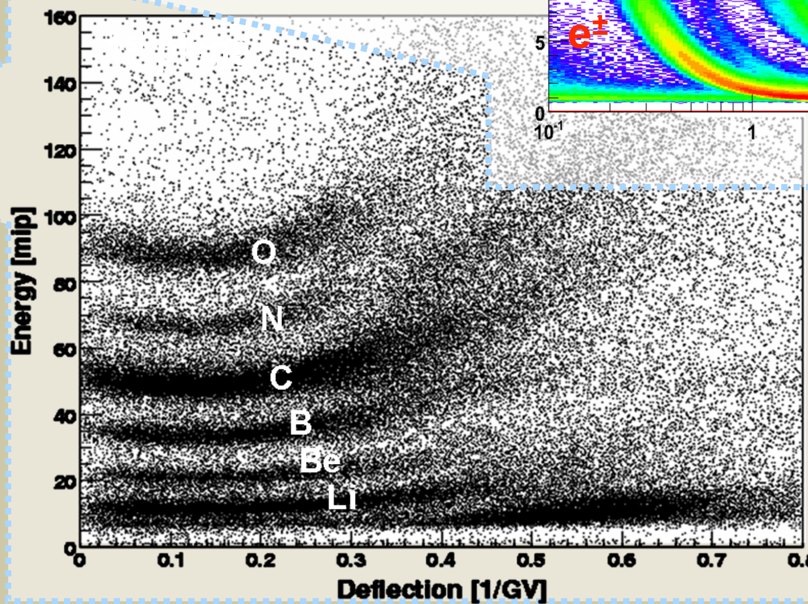

## Z measurement

$$-\frac{dE}{dx} = K z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

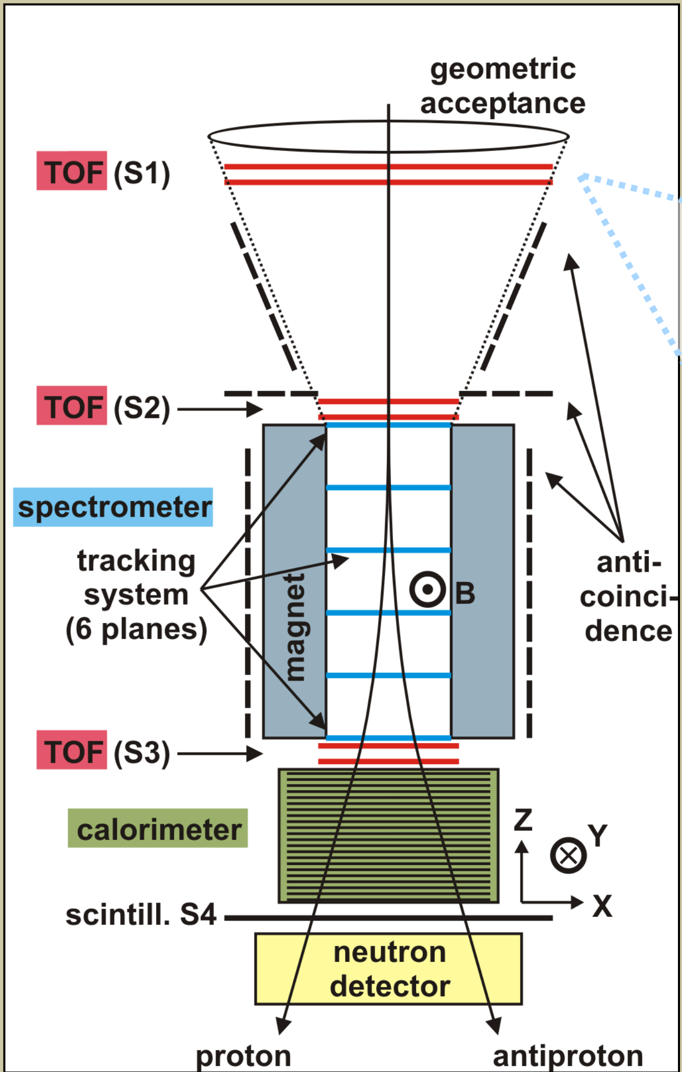
**Bethe Bloch**

ionization energy-loss of heavy (M>>me) charged particles

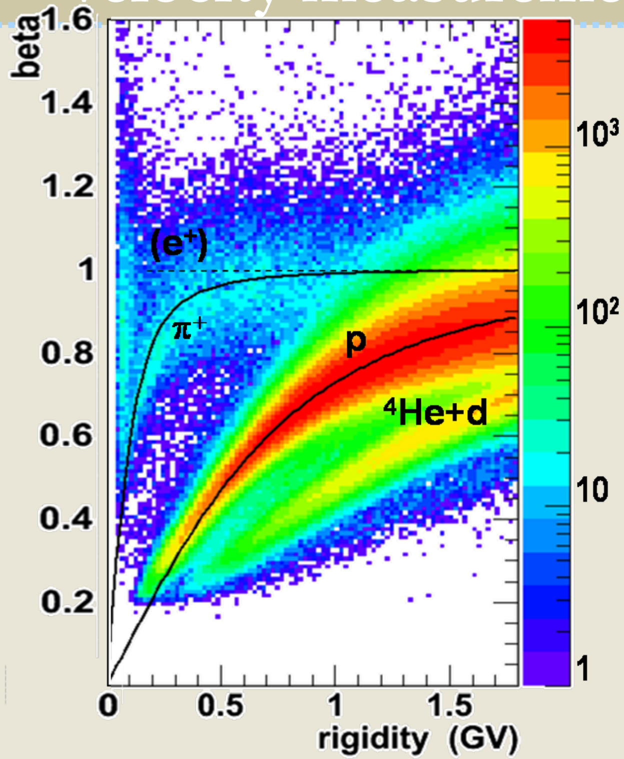


# Principle of operation

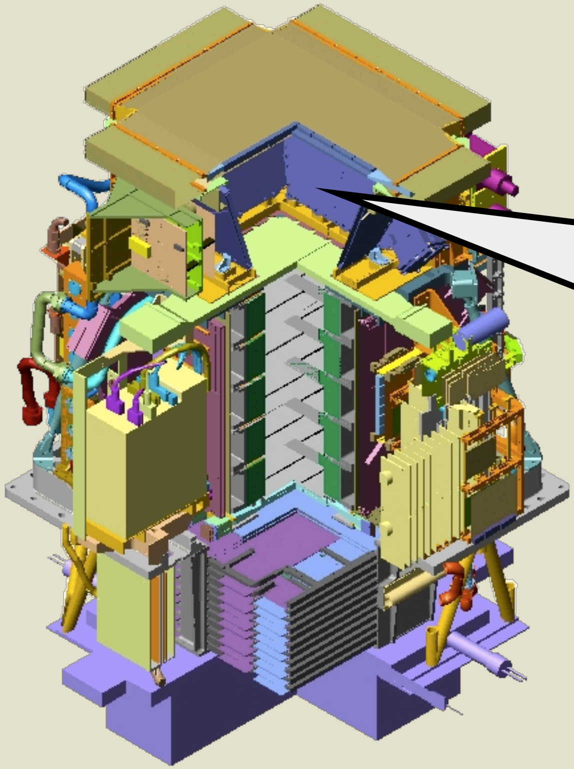



## Velocity measurement




- Particle identification @ low energy
- Identify albedo (up-ward going particles →$\beta < 0$ )

→ NB! They mimic antimatter!

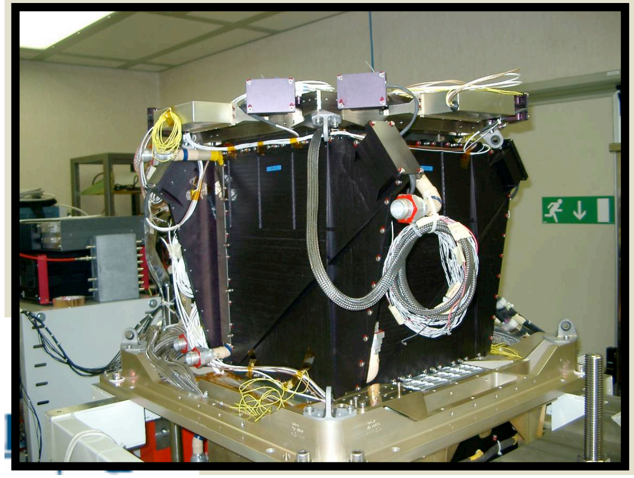


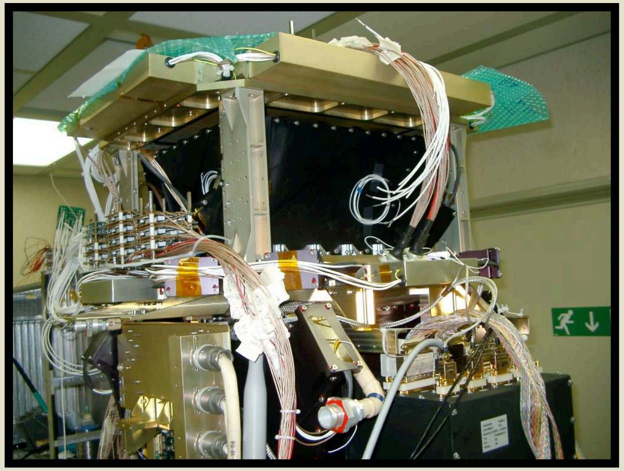
# The anticounter shields

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

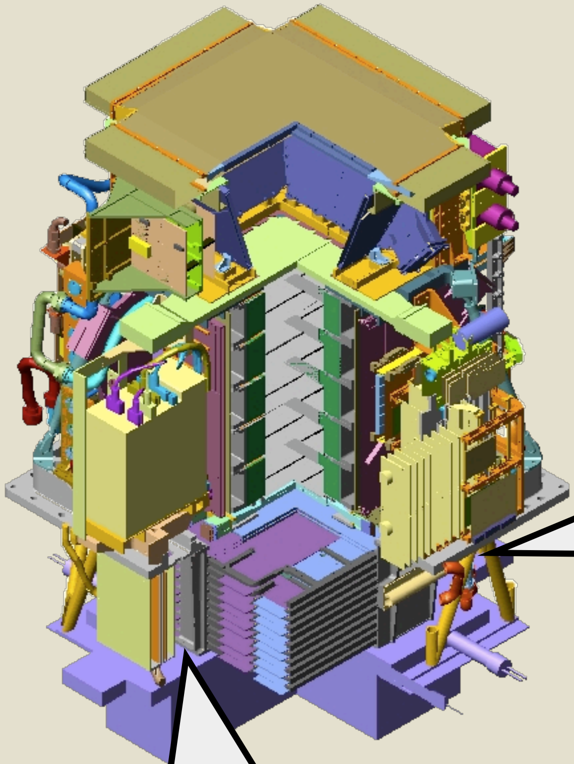
- **Characteristics:**
- **Plastic scintillator paddles, 8mm thick**
- **4 upper (CARD), 1 top (CAT), 4 side (CAS)**

- **Performance:**
- **MIP efficiency > 99.9%**



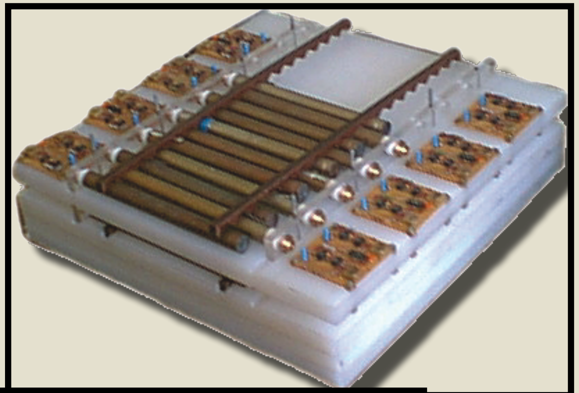


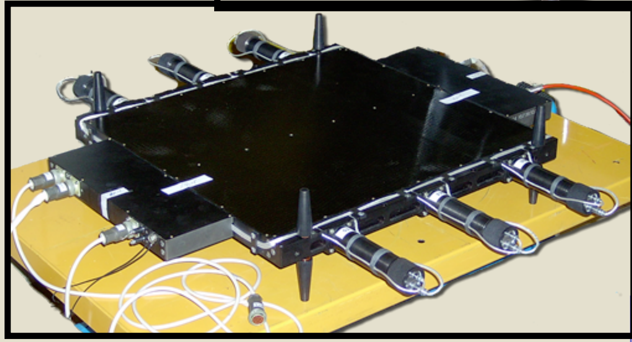
# Neutron detector



- **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**





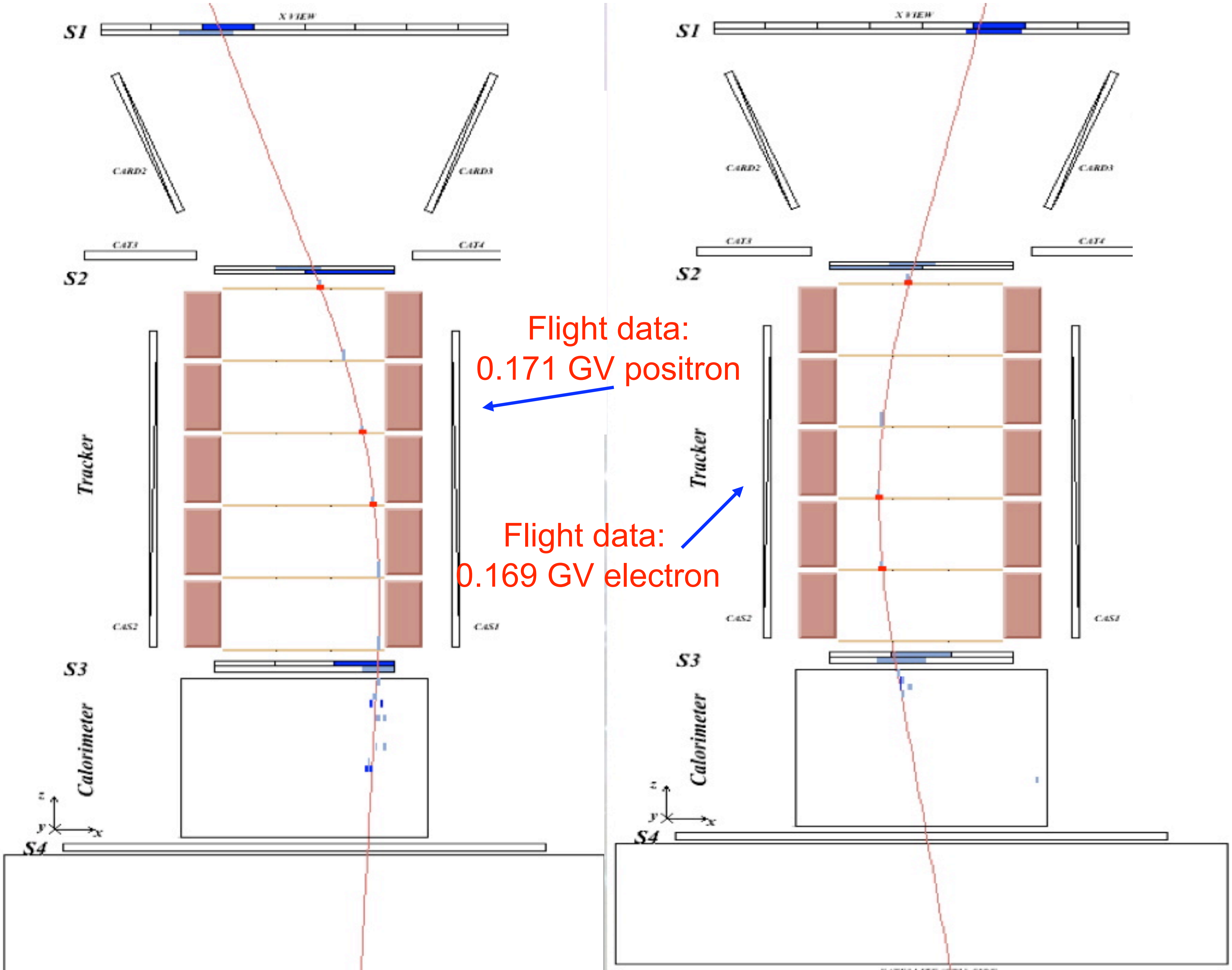
**Main tasks:**

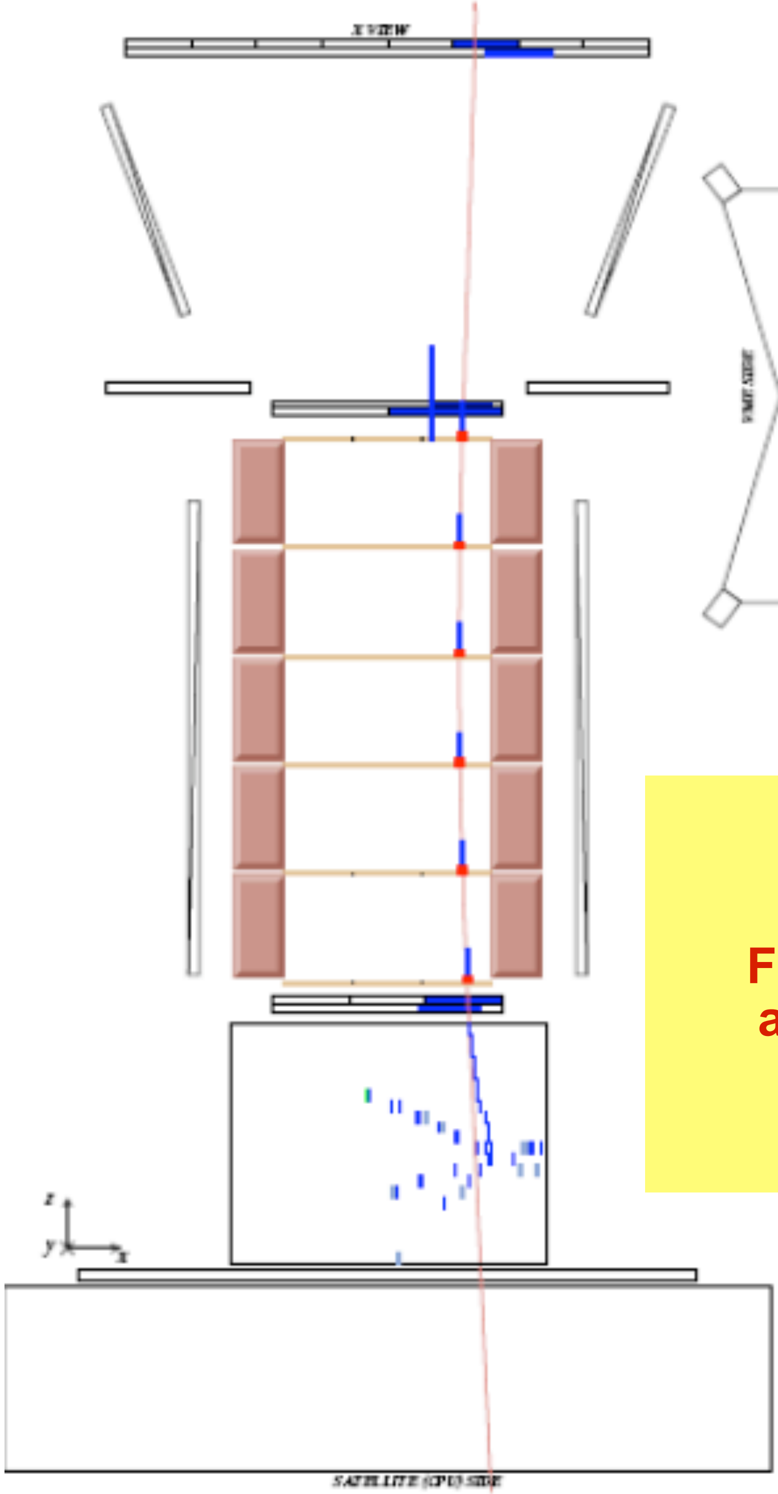
- **Neutron detector trigger**

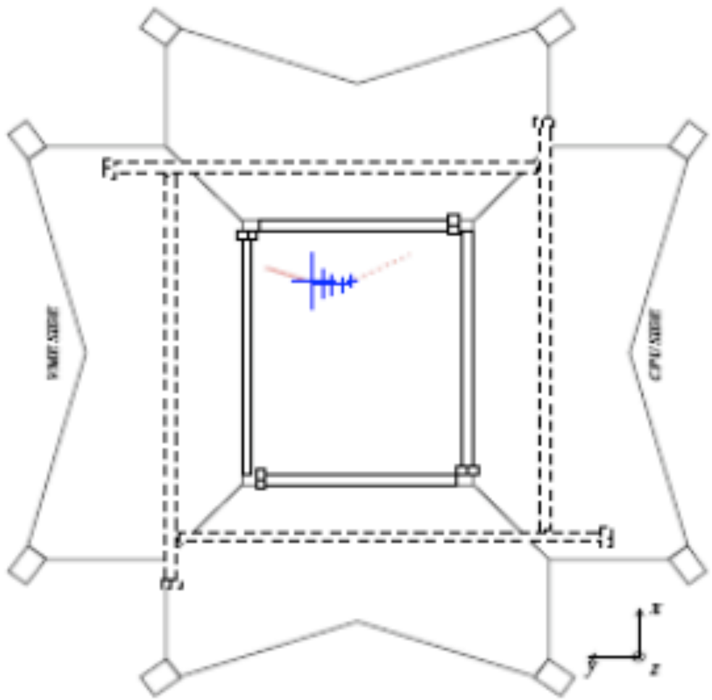
**Characteristics:**

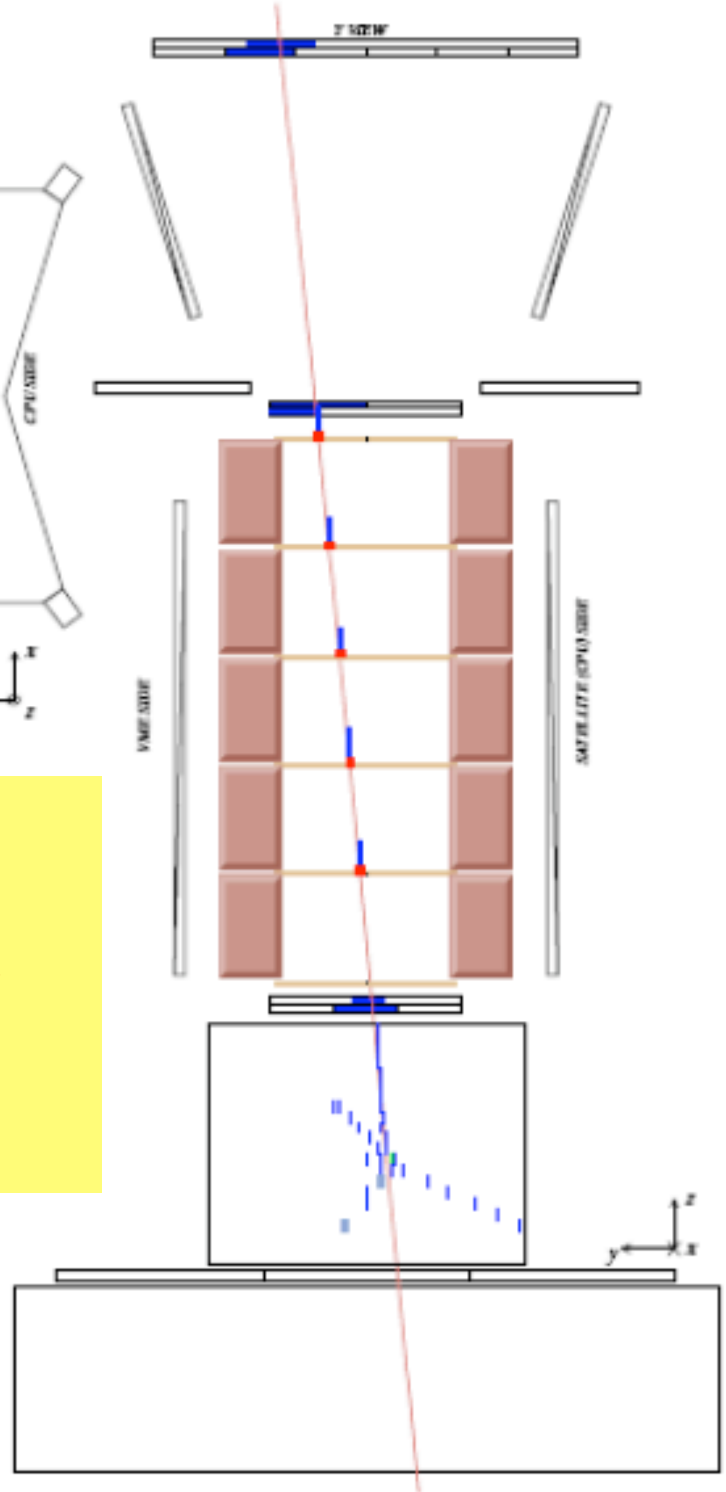
- **Plastic scintillator paddle, 1 cm thick**

# Shower-tail catcher

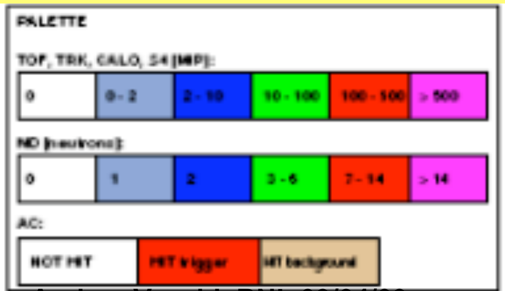

S1
X VIEW
CARD2
CARD3
CAT3
CAT4
S2
Tracker
CAS2
CAS1
S3
Calorimeter
S4
SATELLITE (CPU) SIDE
Flight data:
0.171 GV positron
Flight data:
0.169 GV electron



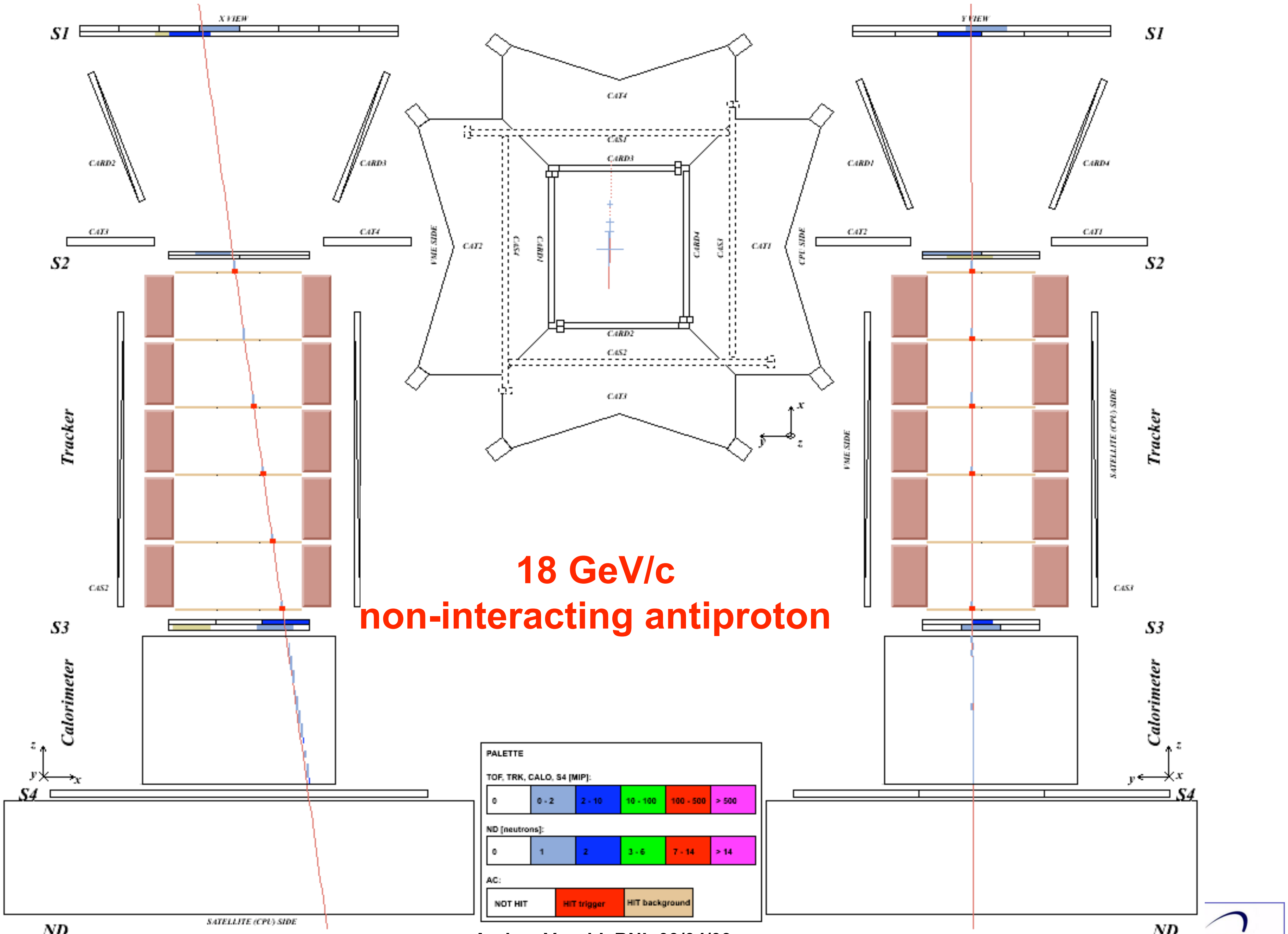



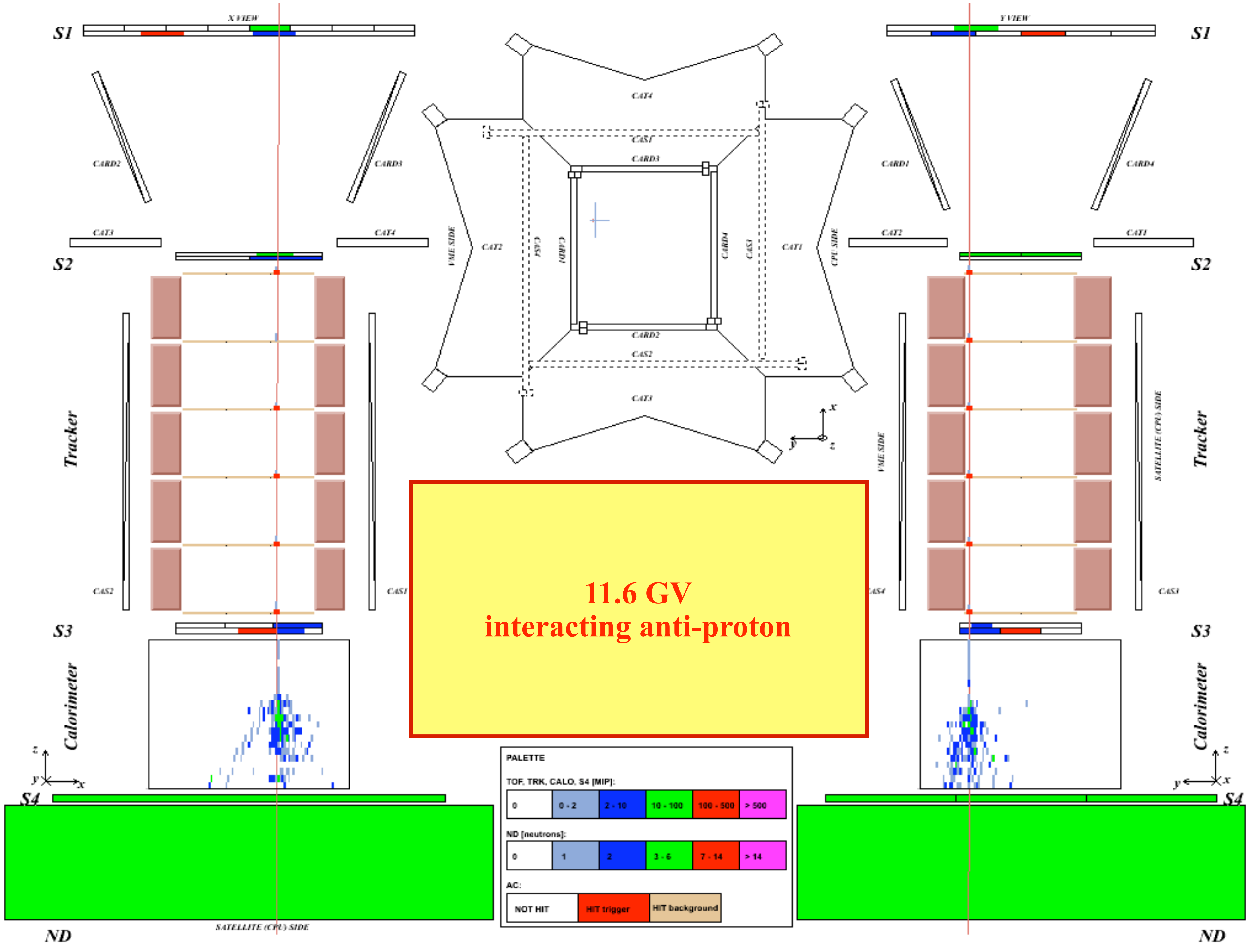




**Flight data: 0.763 GeV/c antiproton annihilation**

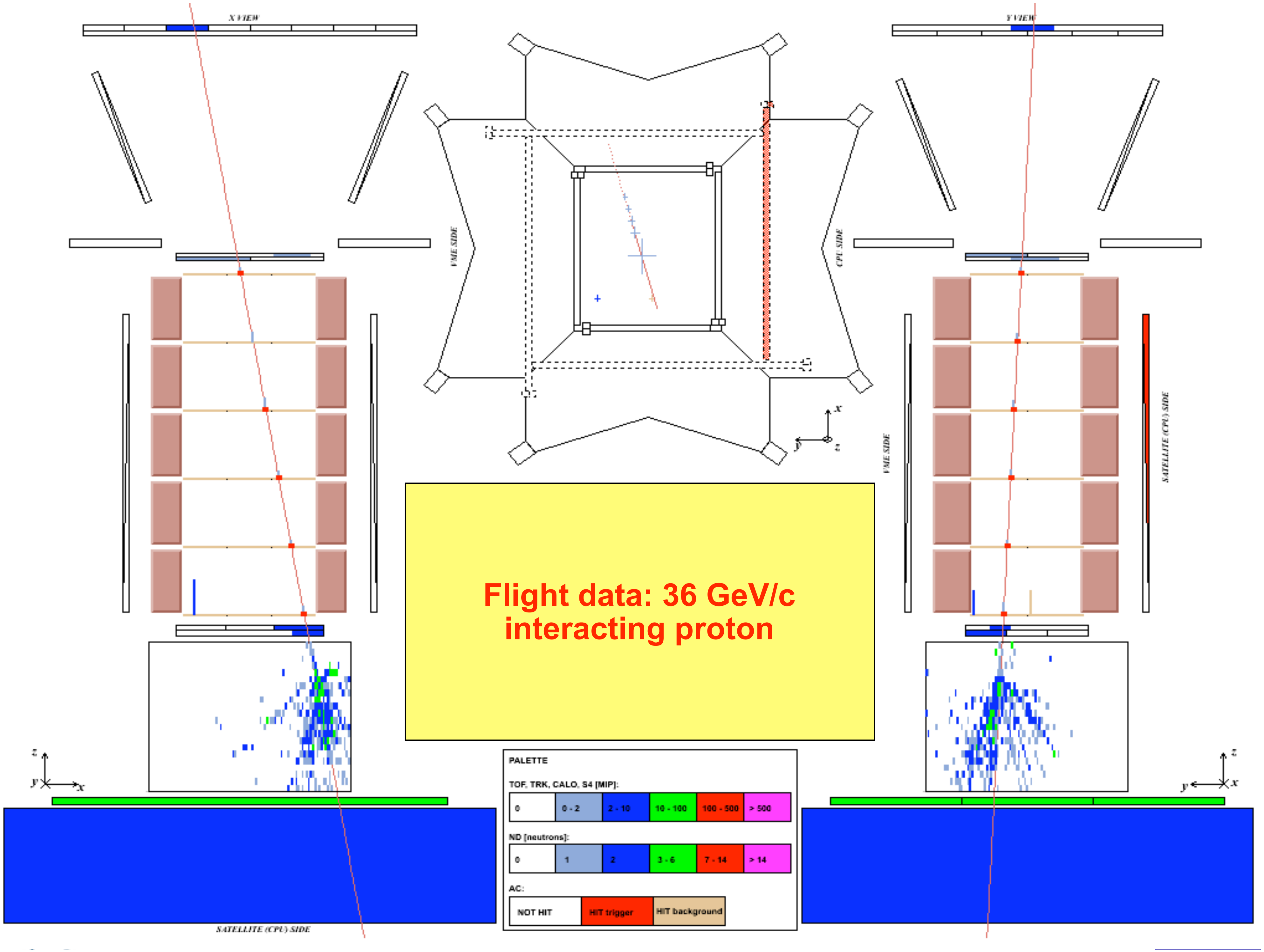


# 18 GeV/c non-interacting antiproton

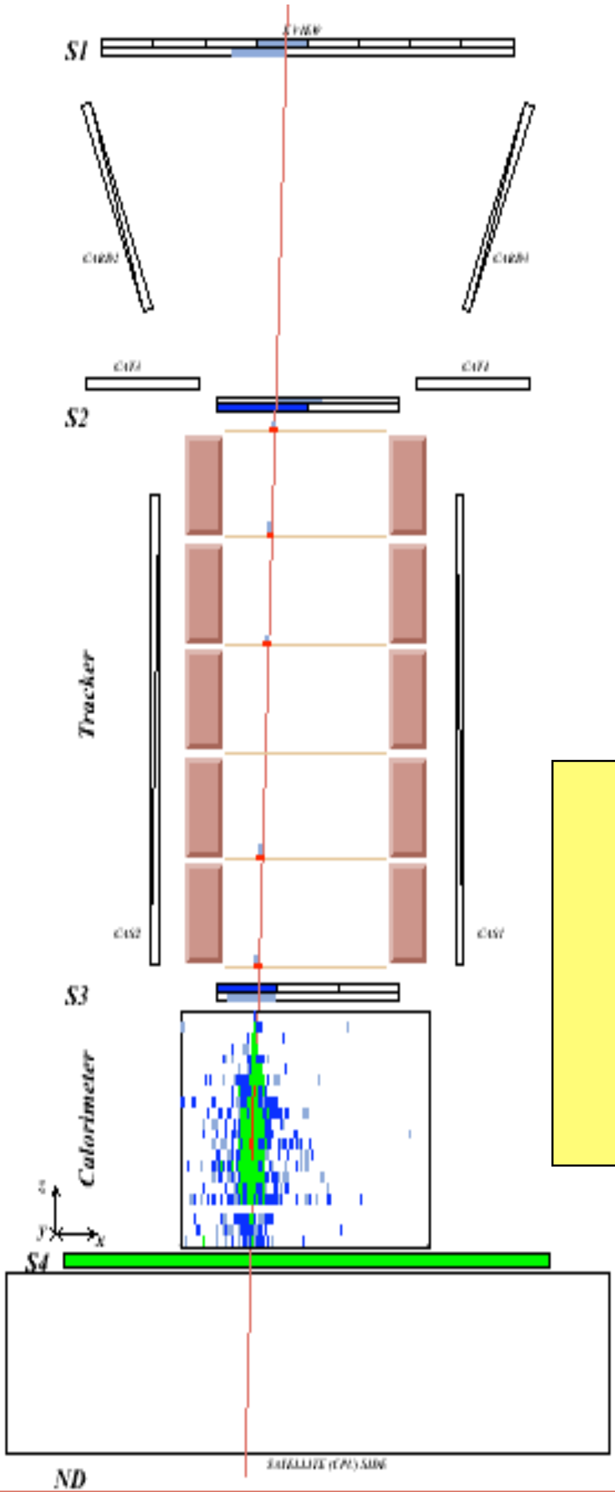


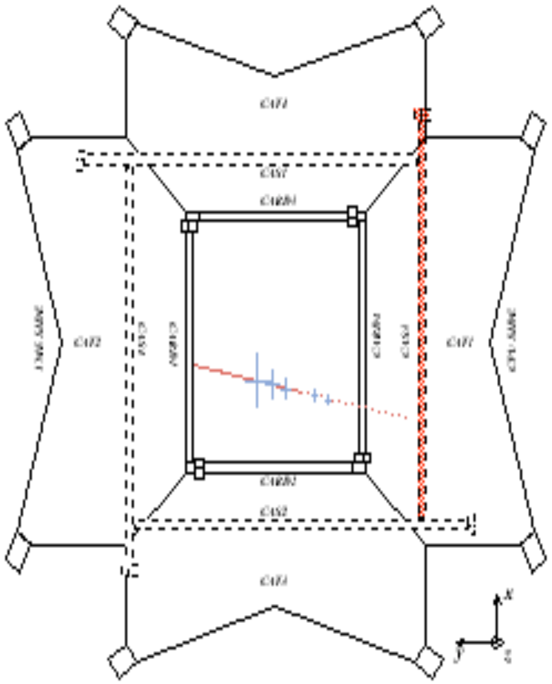


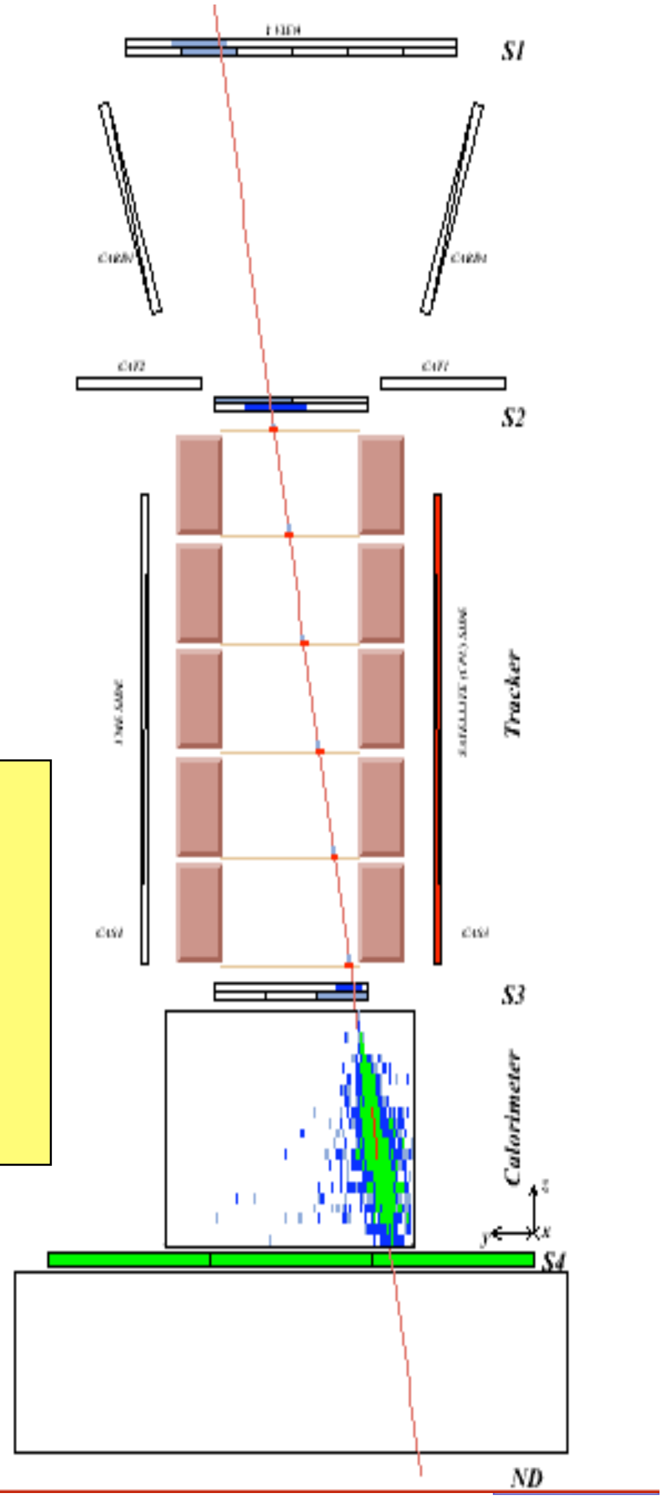
X VIEW
Y VIEW
S1
S2
S3
S4
ND
Tracker
Calorimeter
CARD1
CARD2
CARD3
CARD4
CAT1
CAT2
CAT3
CAT4
CAS1
CAS2
CAS3
CAS4
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
11.6 GV
interacting anti-proton
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC: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



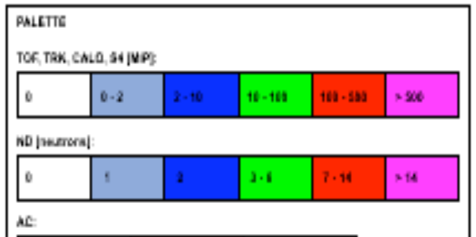
X VIEW
Y VIEW
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
Flight data: 36 GeV/c
interacting proton
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background






**Flight data: 42 GeV/c electron**

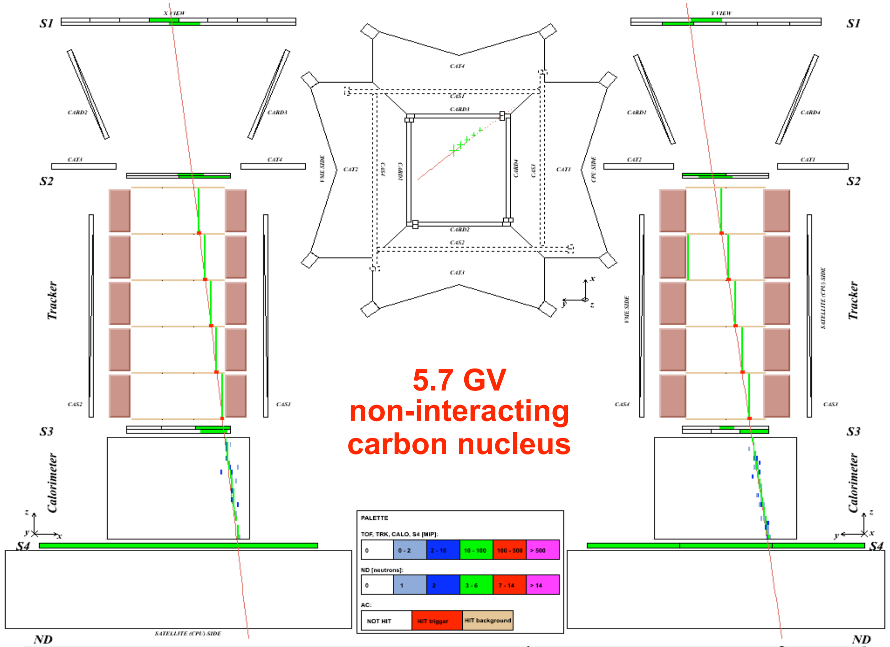


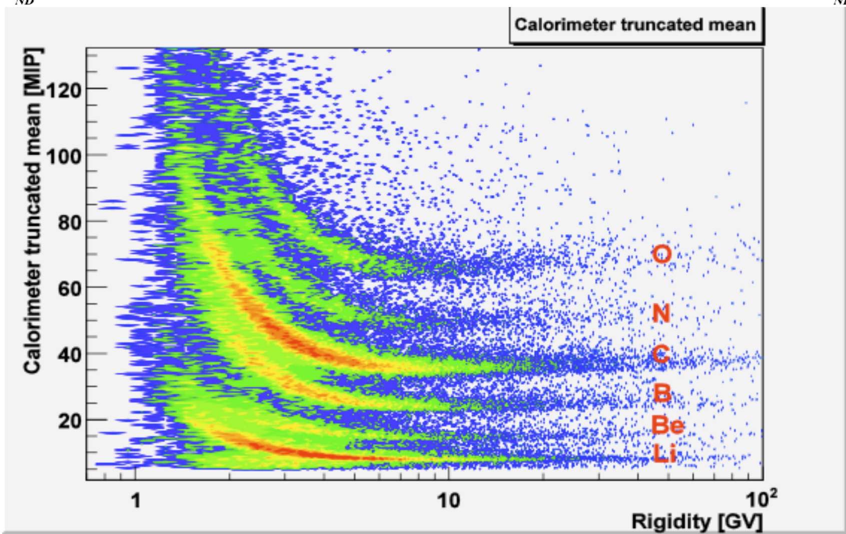
# Nuclei identification

- Important input to secondary production / propagation models

- Secondary to primary ratios
  - B / C
  - Be / C
  - Li / C

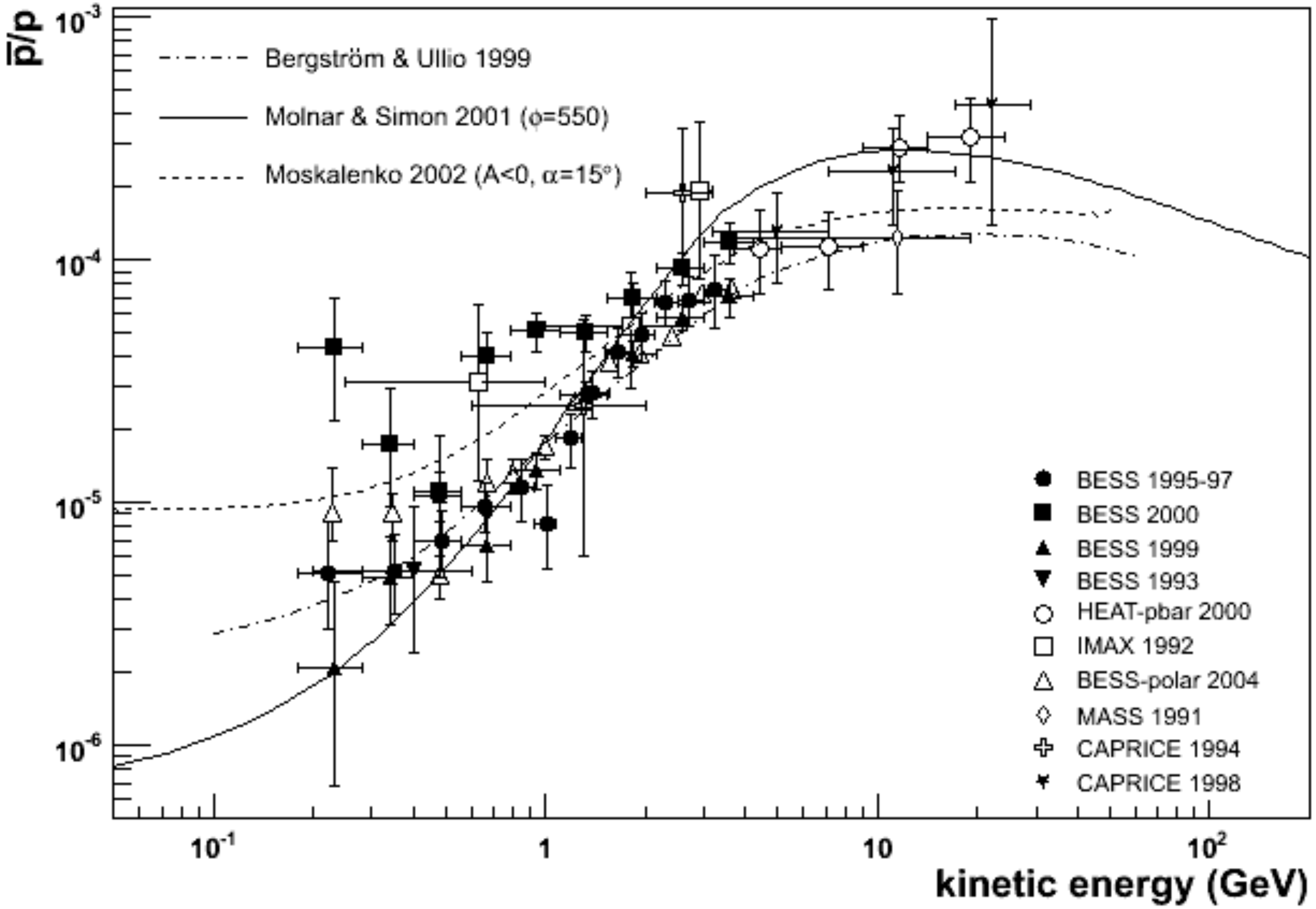
- Helium and hydrogen isotopes
  - $^{3}$He / $^{4}$He
  - d / He



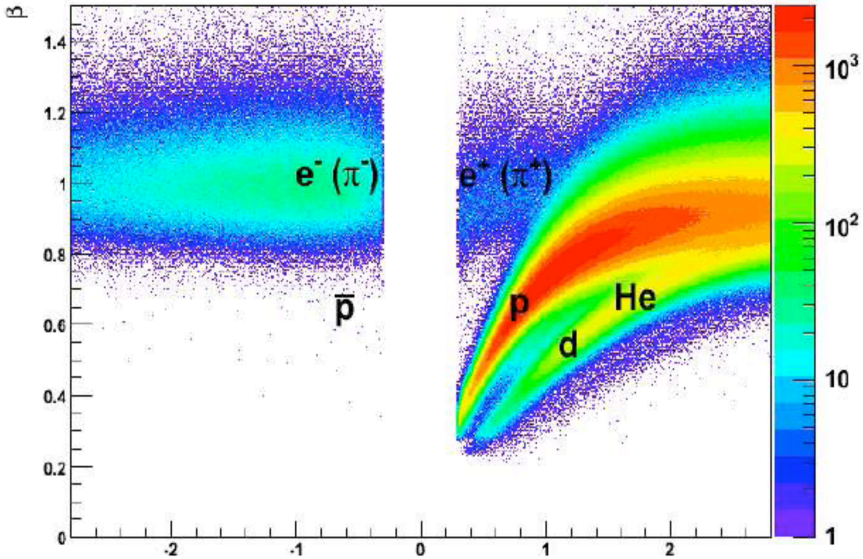

Truncated mean of multiple dE/dx measurements in different silicon planes

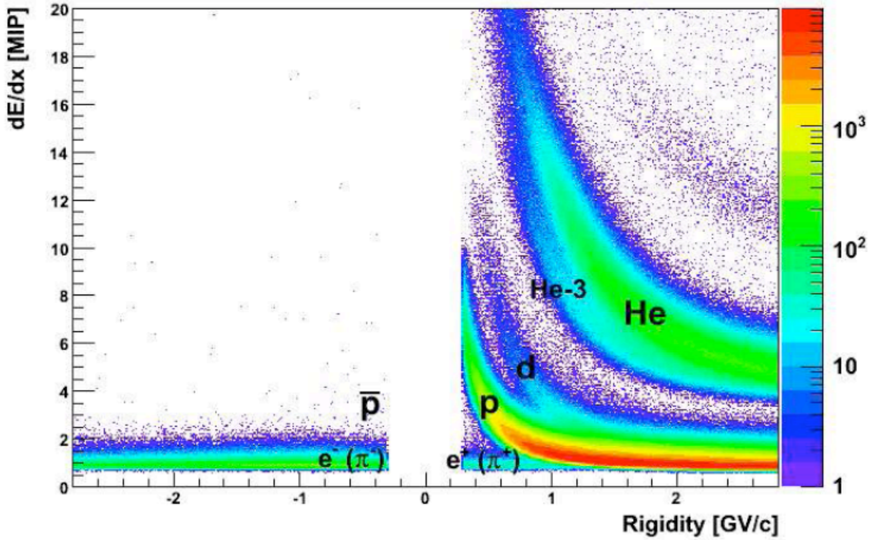
# Antiproton to proton ratio

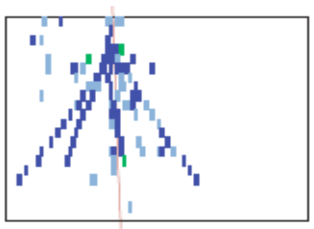


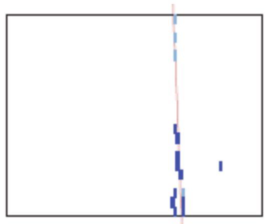

Andrea Vacchi, BNL 09/04/09

# The p-bar / p flux ratio

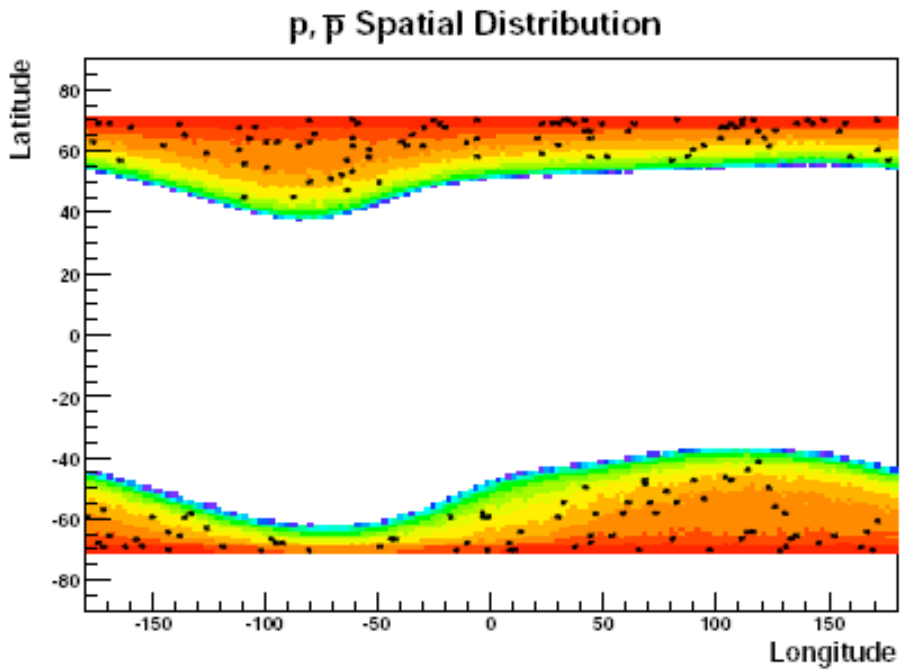


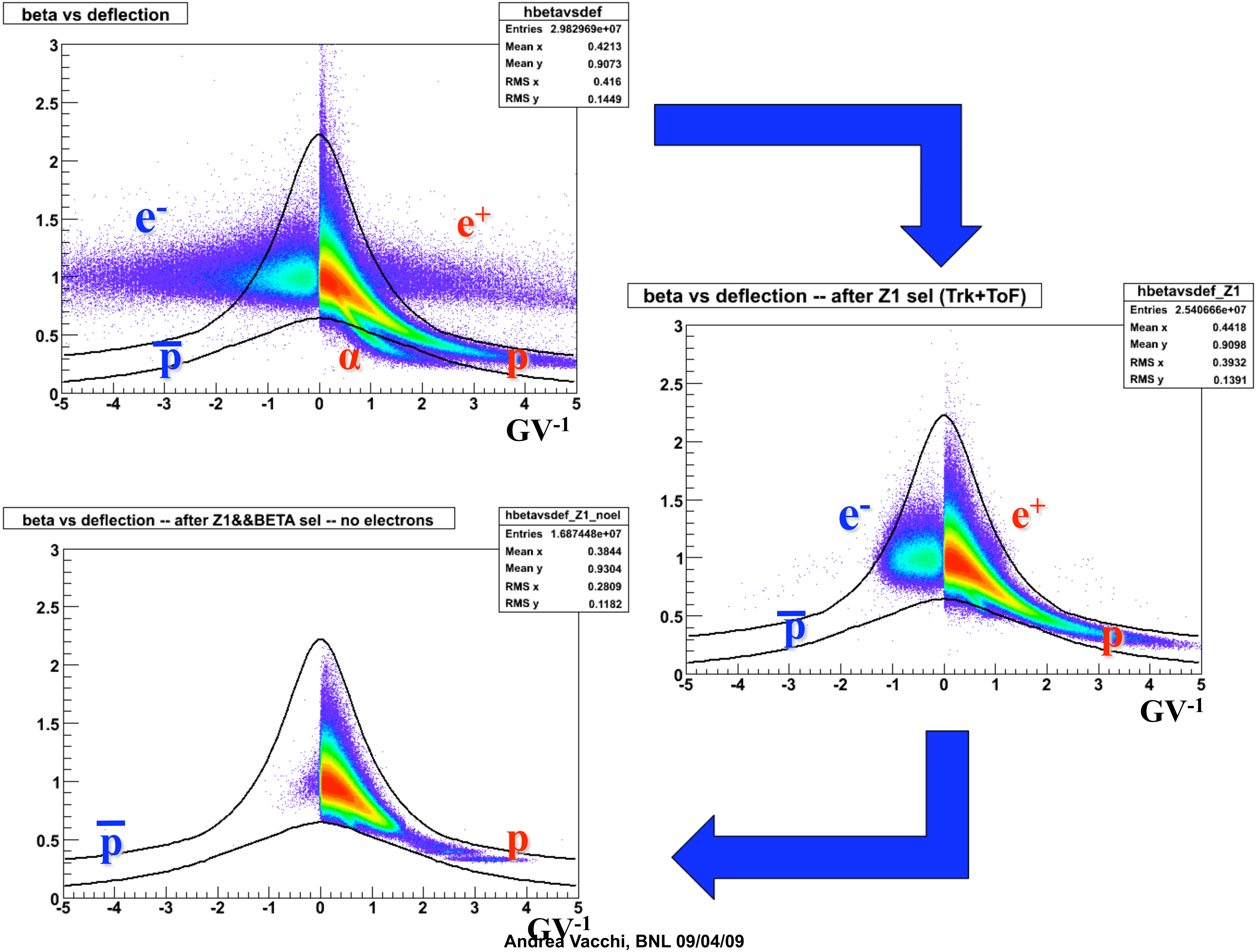





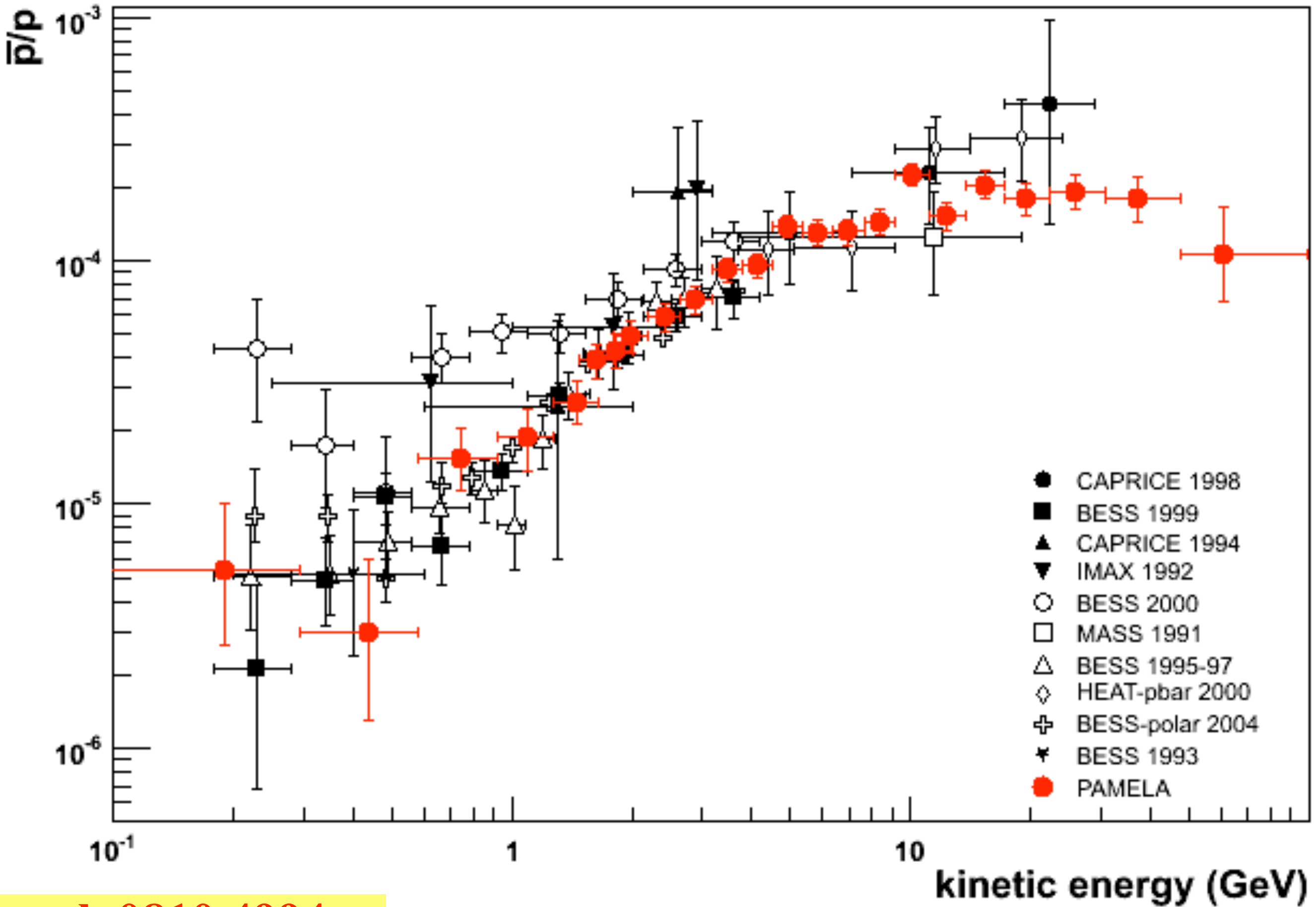
## p-bar flux Between 80 MeV and 2 GeV




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

# Antiproton to proton ratio

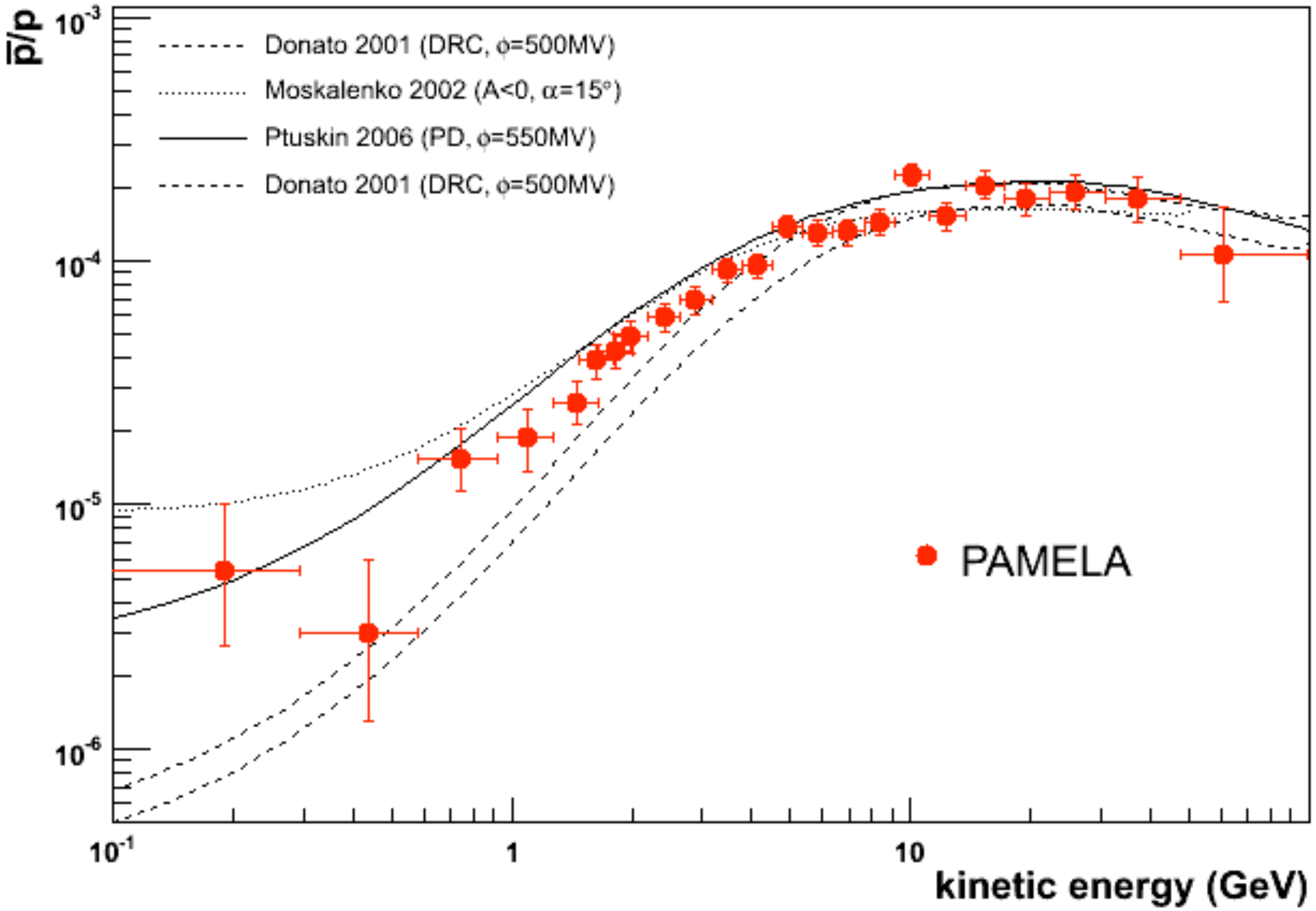
**More than $10^7$ p and ~1000 pbar have been identified between 1 and 100 GeV**
**~300 pbar over 10 GeV**




Astro-ph 0810.4994

# Antiproton to proton ratio

Seconday Production Models

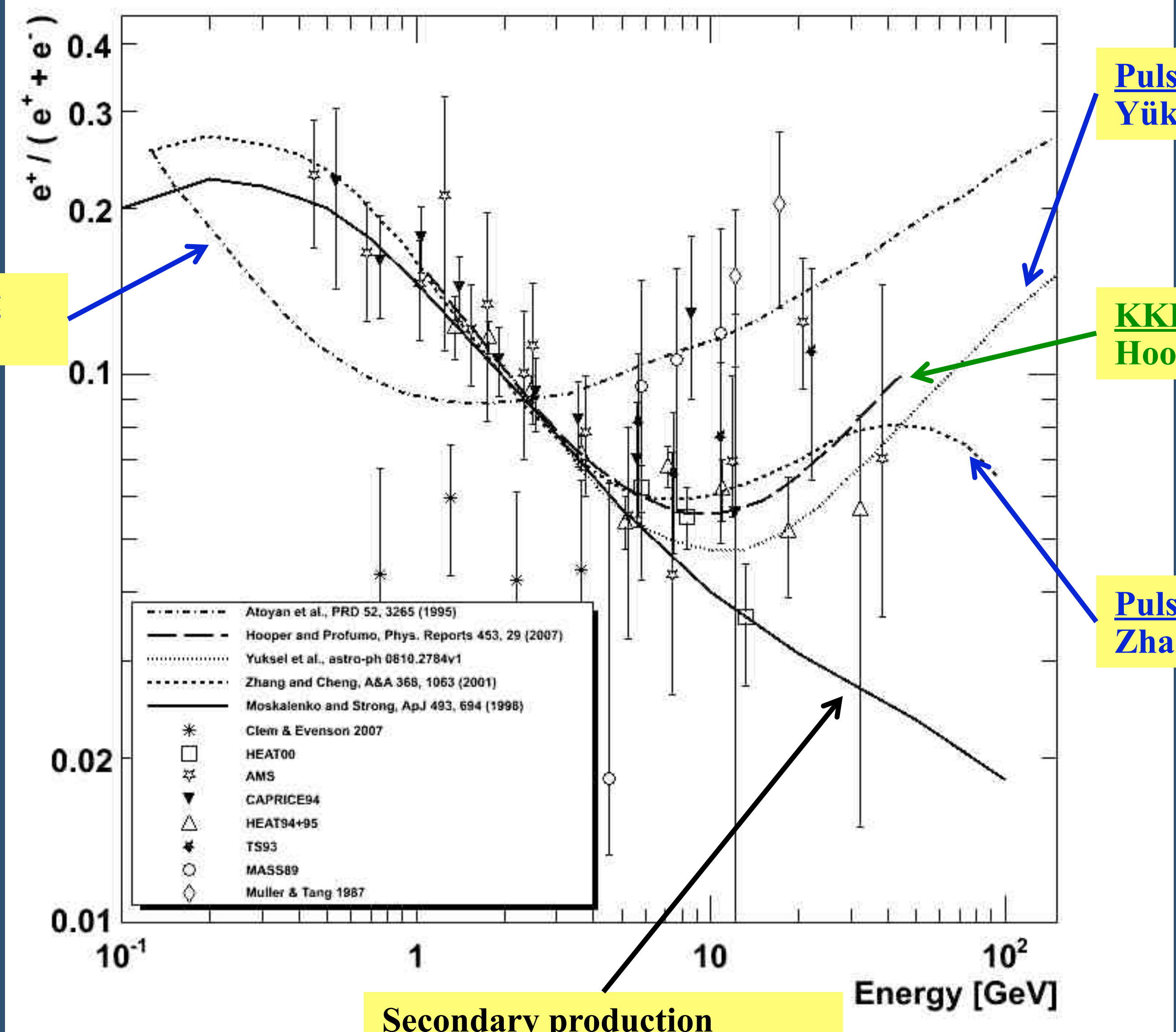


# antiproton flux and the antiproton-to-proton flux ratio

## at the top of the atmosphere between 80 MeV and 2.0 GeV

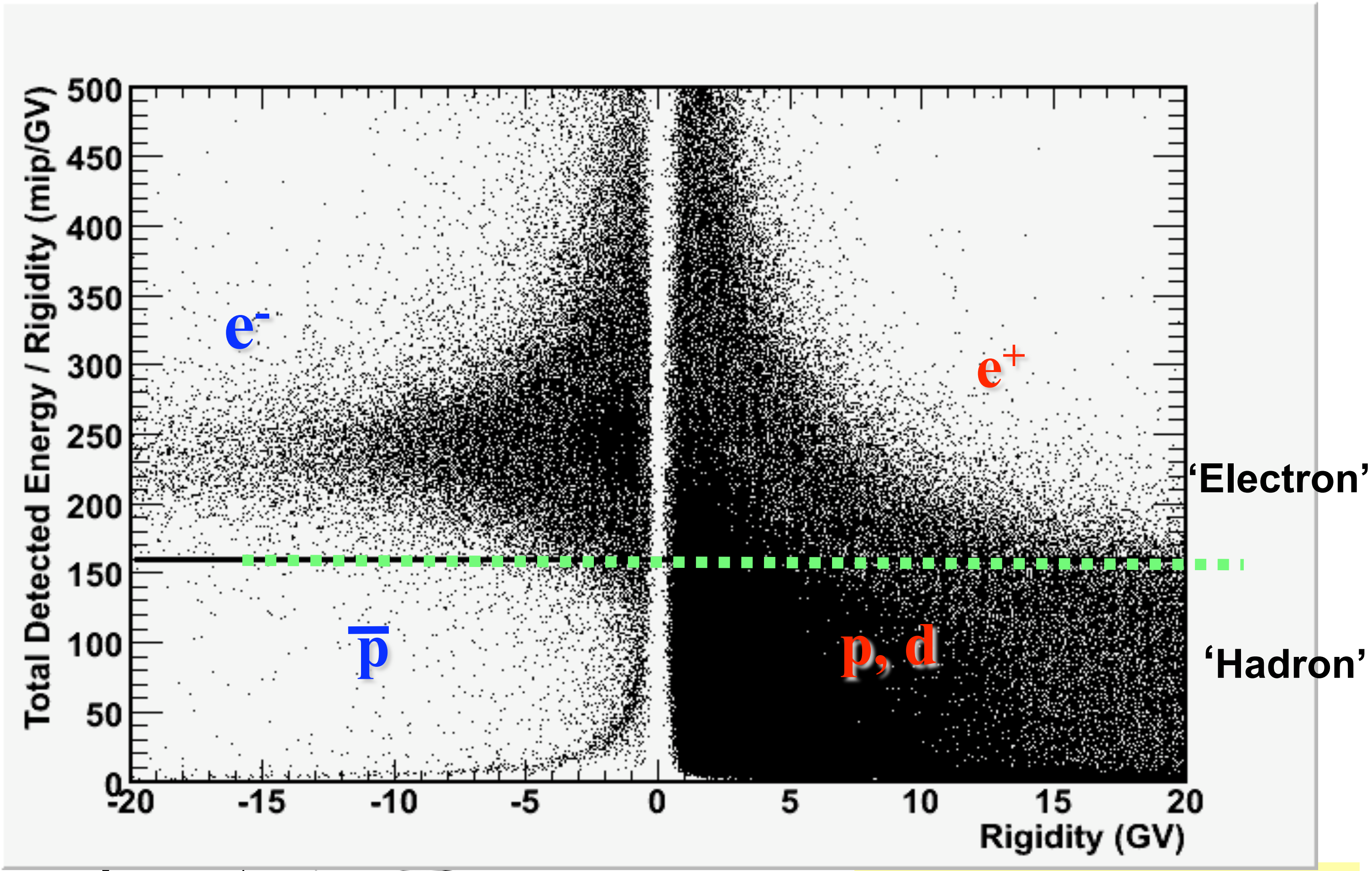
- **The derived antiproton spectrum shows a steep increase up to 2 GeV as expected for pure secondary production of galactic antiprotons.**
- **The antiproton flux is over-estimated by most current models of secondary production compared to PAMELA results.**
- **There are no indications of the excess of antiprotons at low energy predicted by theories of primordial black hole evaporation.**

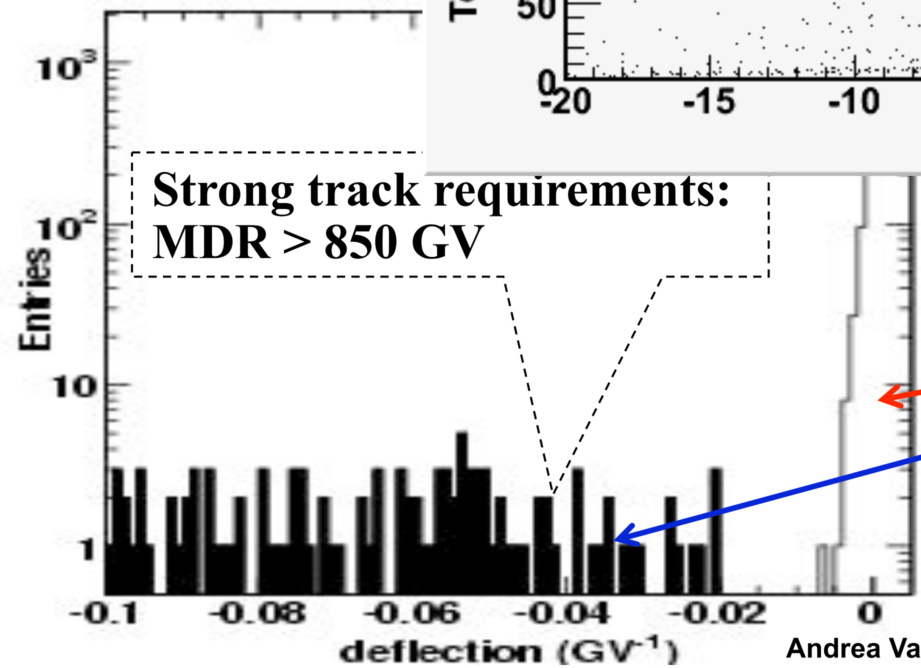
# Positrons BP




Positrons
The relative fluxes of electrons and positrons are very uncertain at energies above 10 GeV.
Discovery potential
sensible to local DM distribution. High sensitivity to local clumpiness.

**Calorimeter selection**



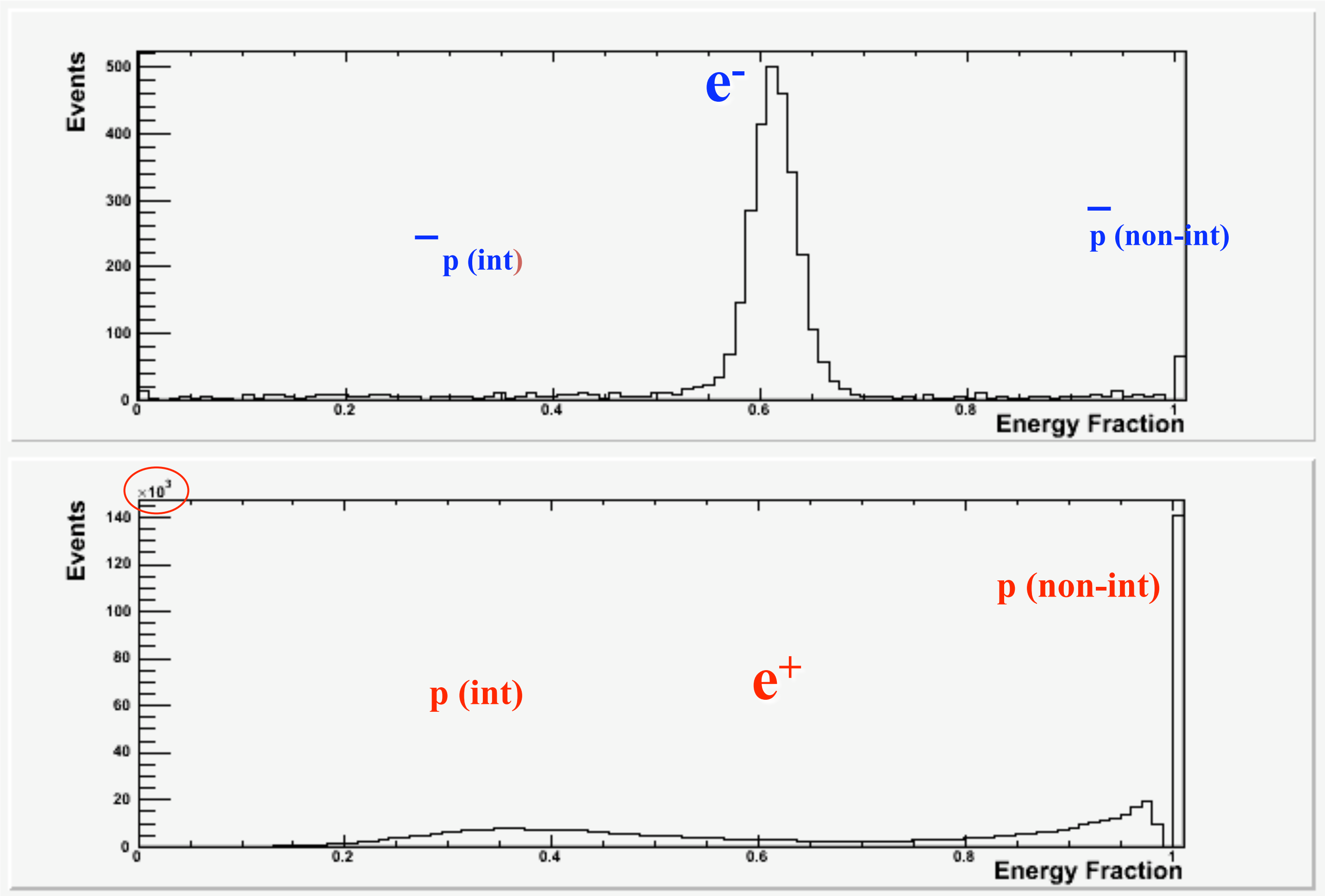




**Tracker Identification**

**Protons (& spillover)**

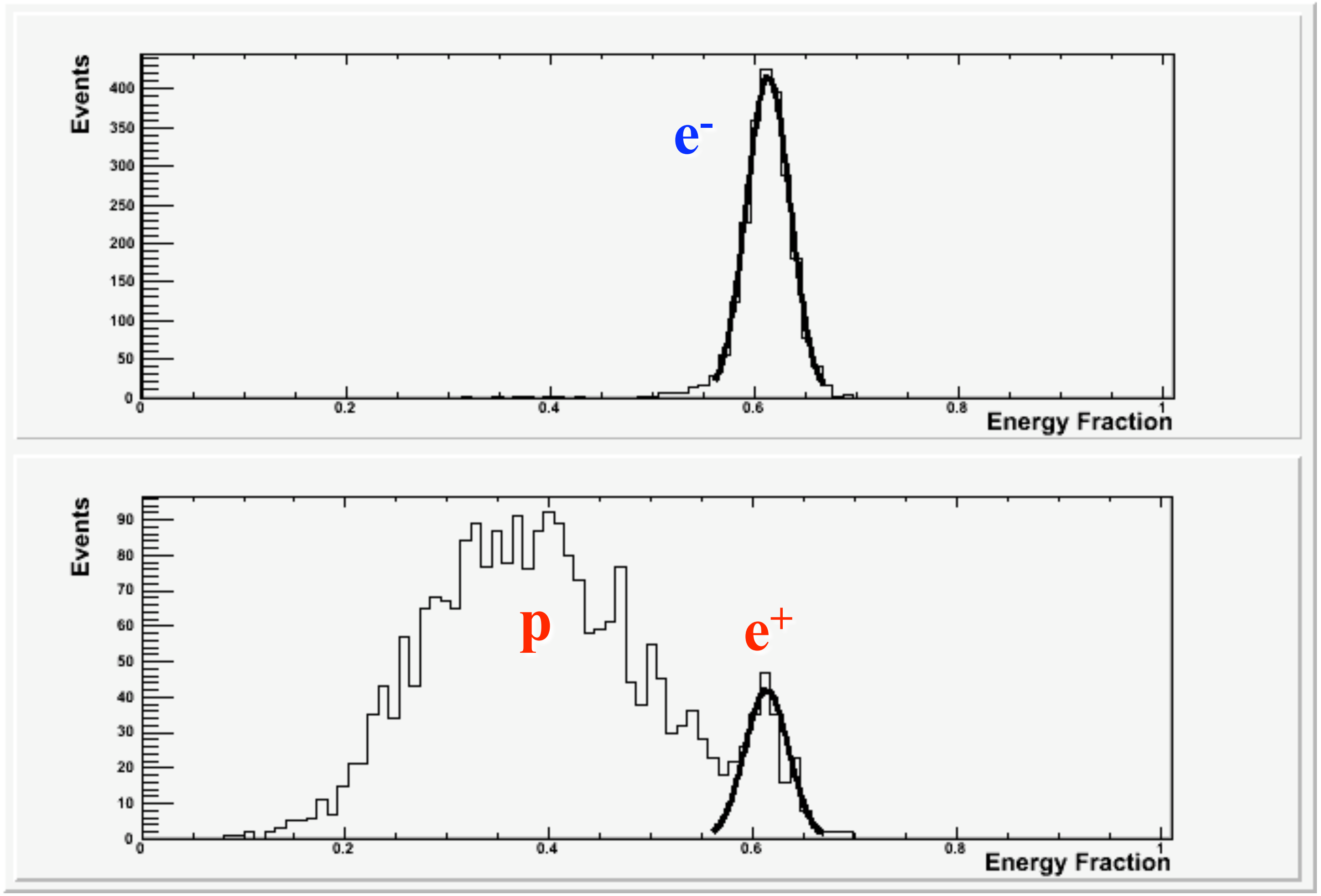
**Antiprotons**

# Positron: p background suppression




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

# Positron: p background suppression

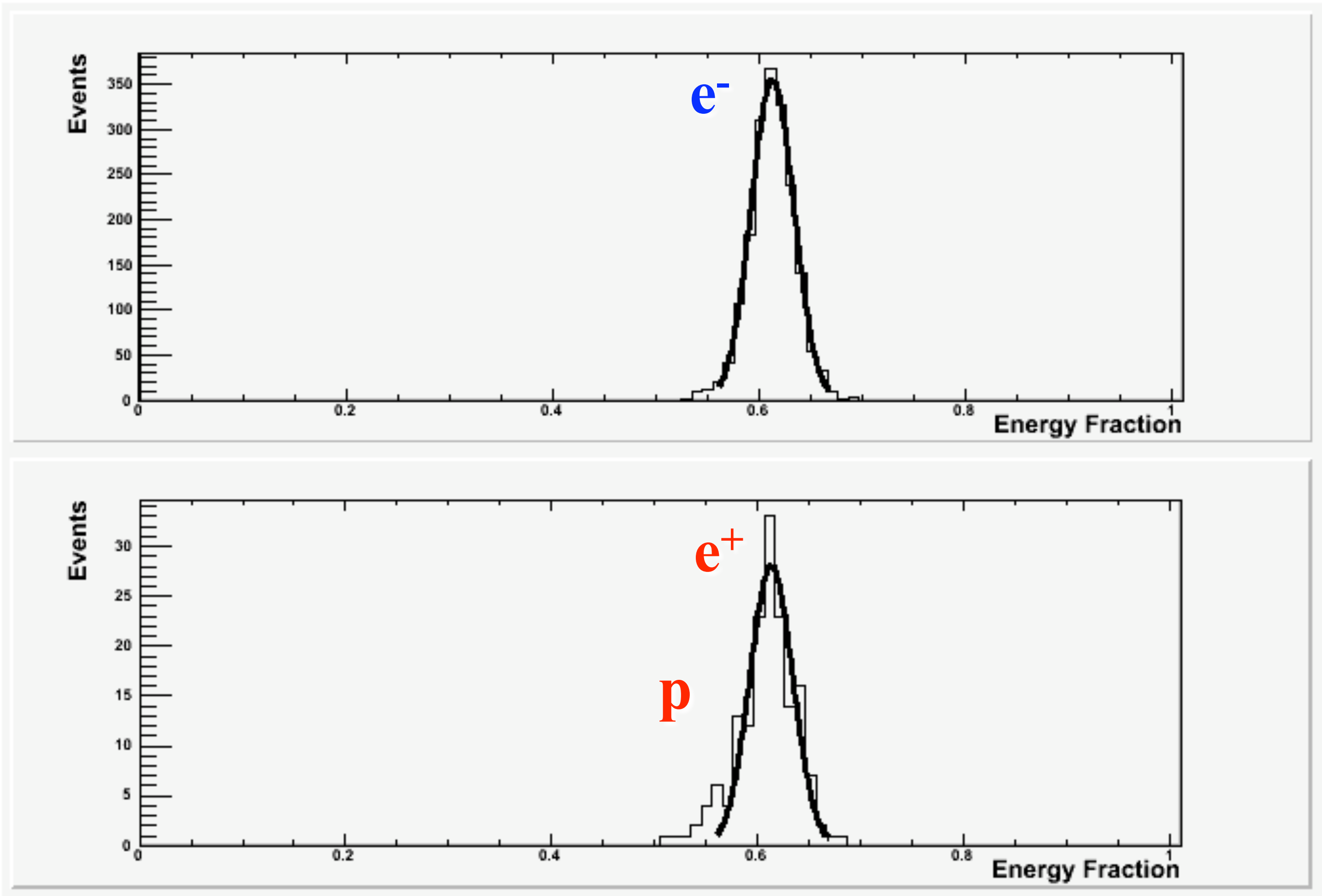



Fraction of charge released along the calorimeter track (left, hit, right)

+

Energy-momentum match

# Positron: p background suppression




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

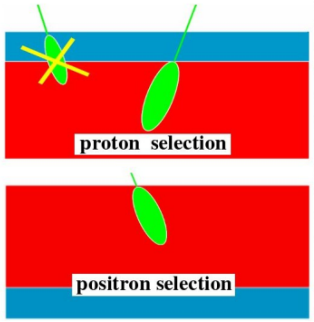
**+**

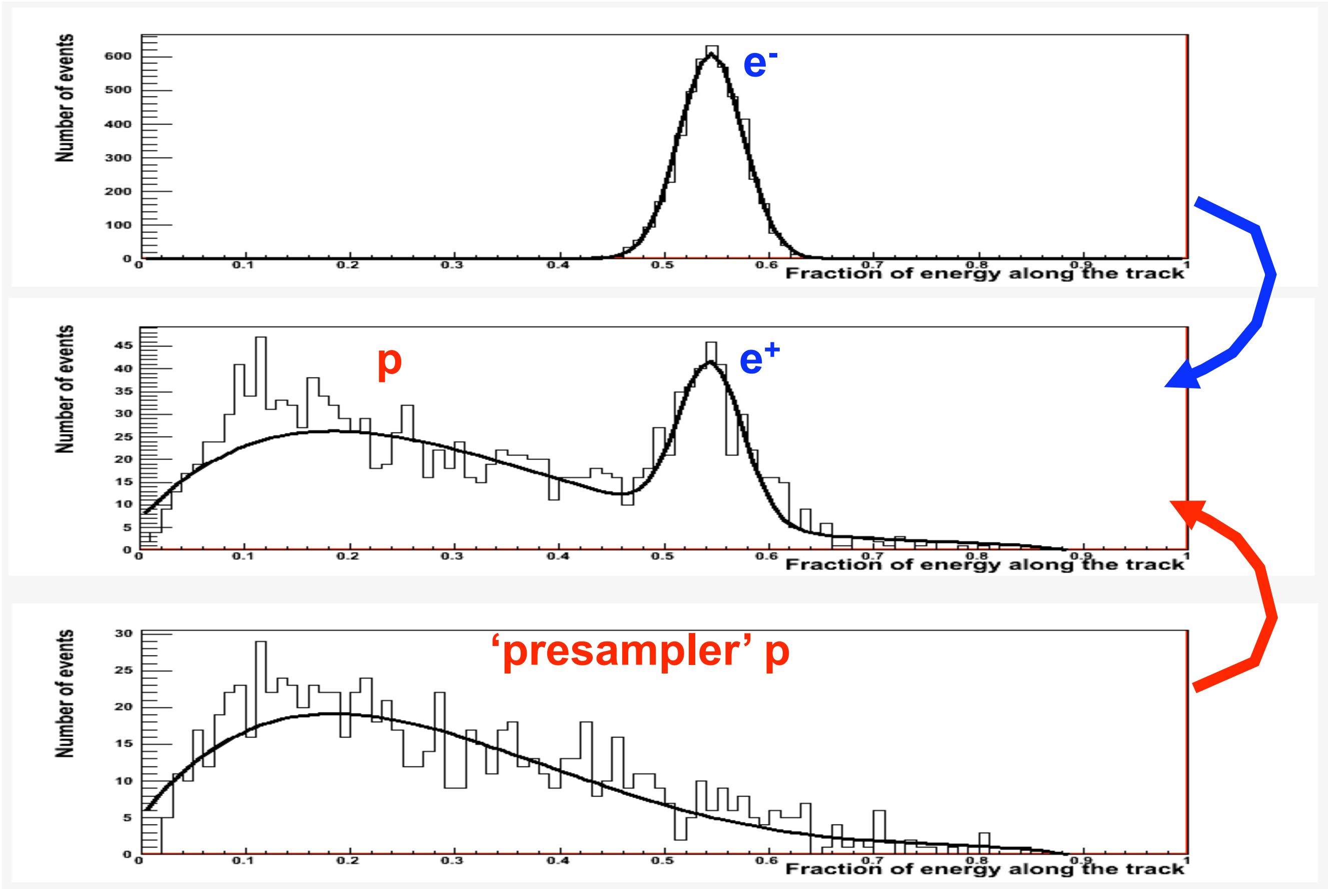
Energy-momentum match
Starting point of shower
Longitudinal profile

# $e^+$ background estimation from data

Rigidity: 6-8 GV

Preliminary



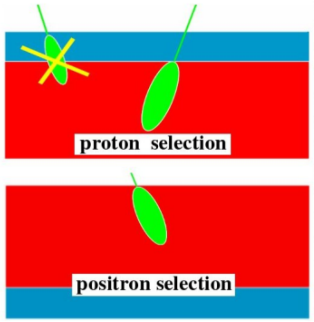

Fraction of charge released along the calorimeter track (left, hit, right)

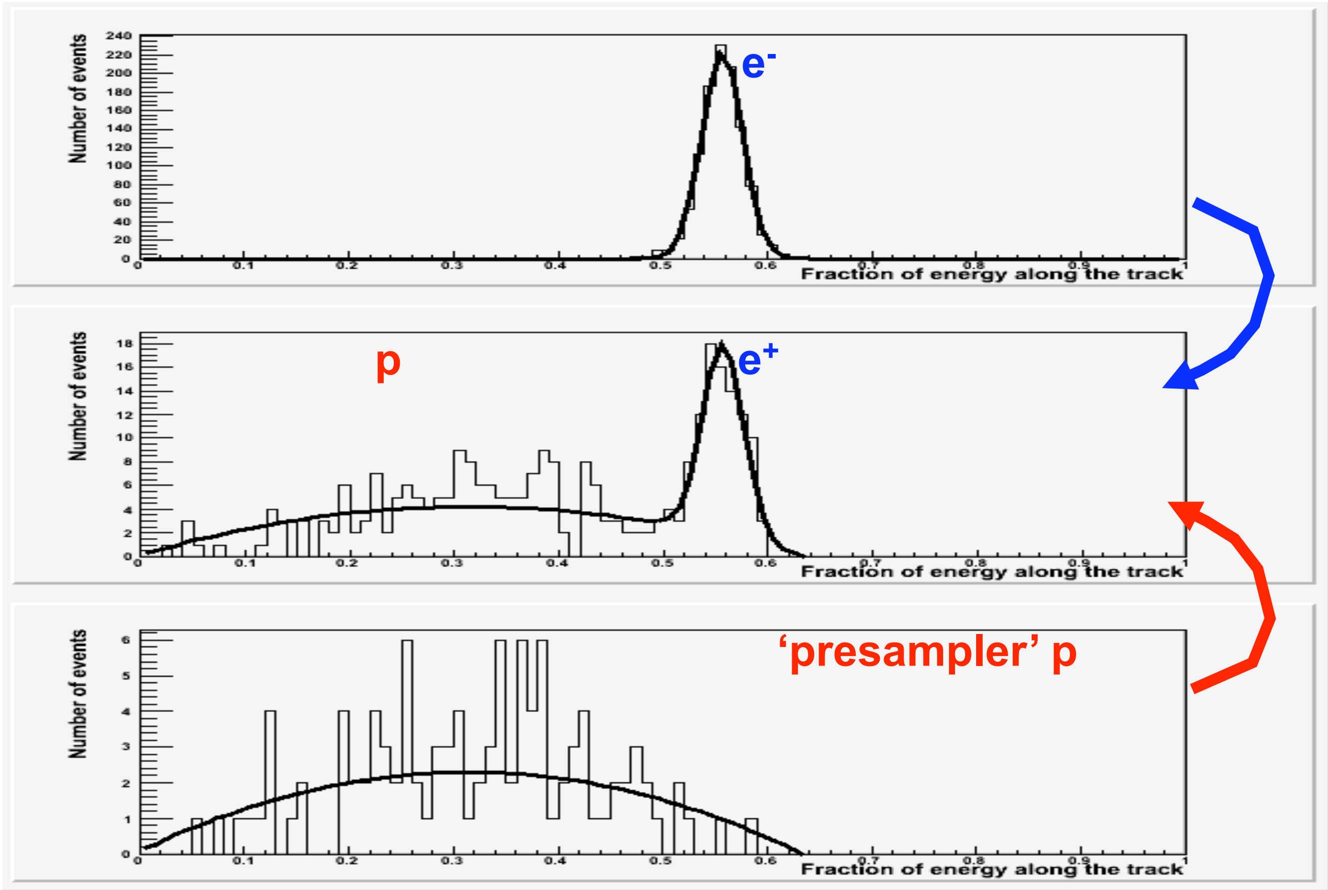
+
- Energy-momentum match
- Starting point of shower

# $e^+$ background estimation from data

Preliminary

Rigidity: 20-30 GV



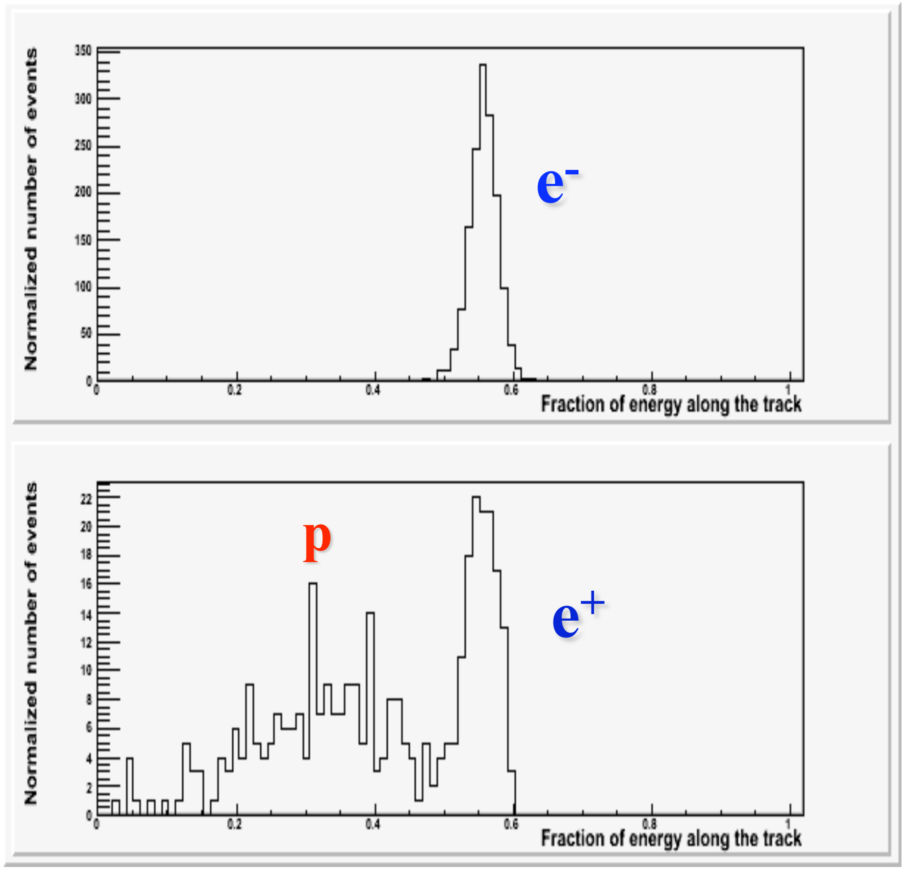

Fraction of charge released along the calorimeter track (left, hit, right)

+ • Energy-momentum match
• Starting point of shower

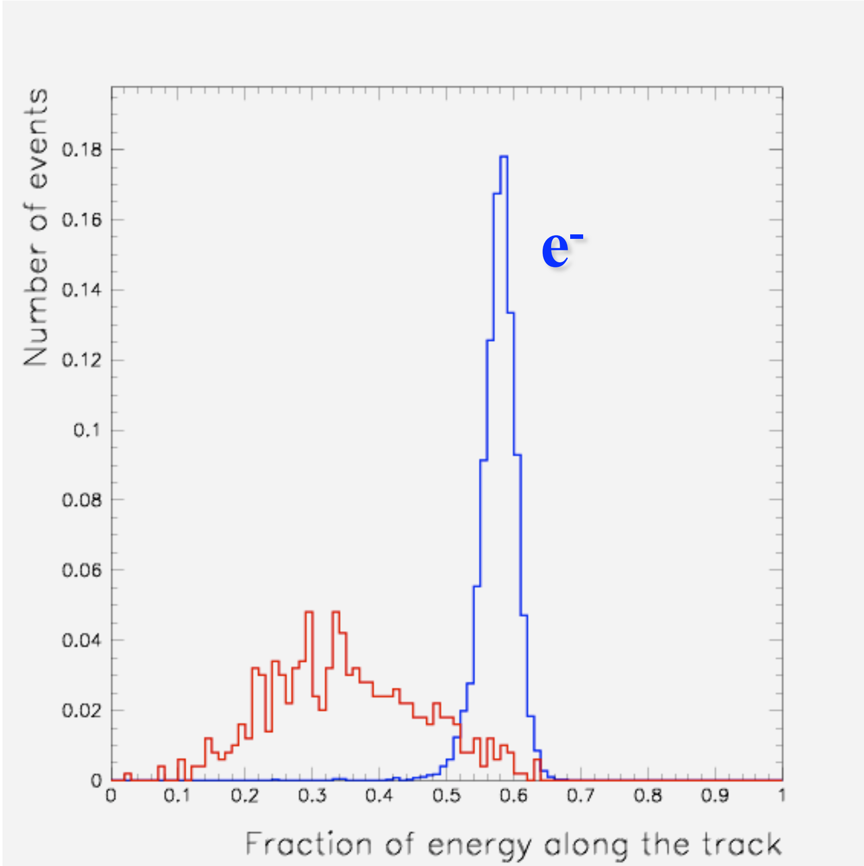
# Positron selection with calorimeter

**Fraction of charge released along the calorimeter track**

**Flight data:**
**rigidity: 20-30 GV**




**Test beam data**
**Momentum: 50GeV/c**



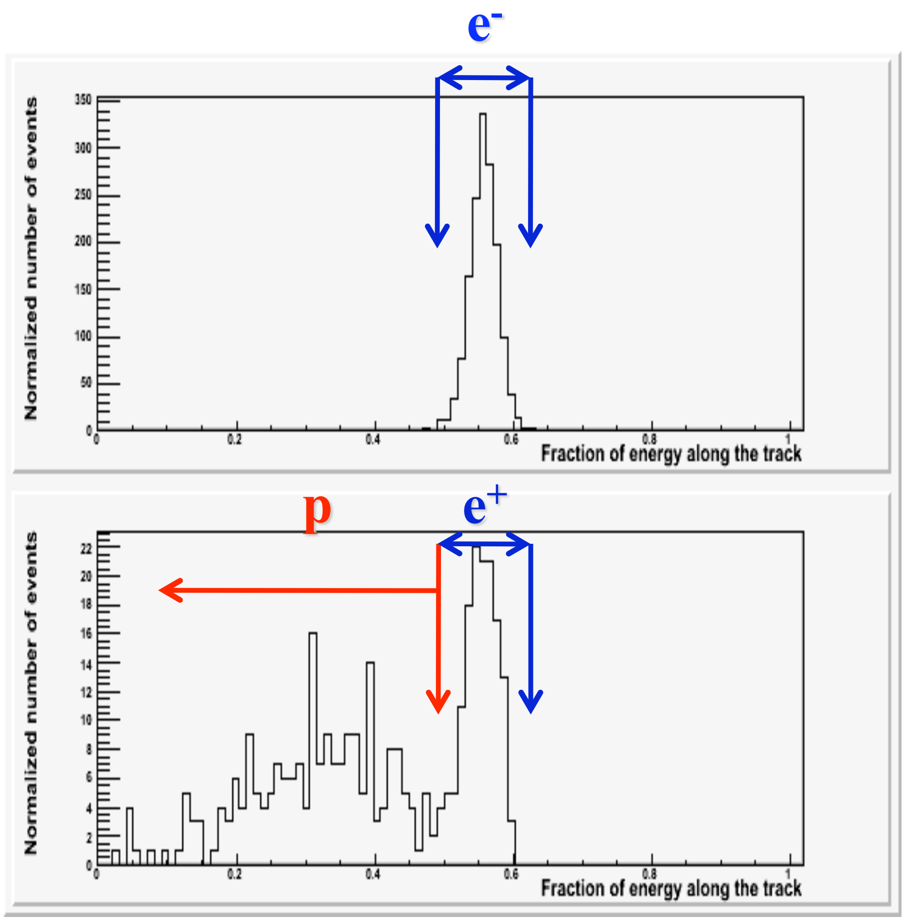

- **Energy-momentum match**
- **Starting point of shower**

Andrea Vacchi, BNL 09/04/09

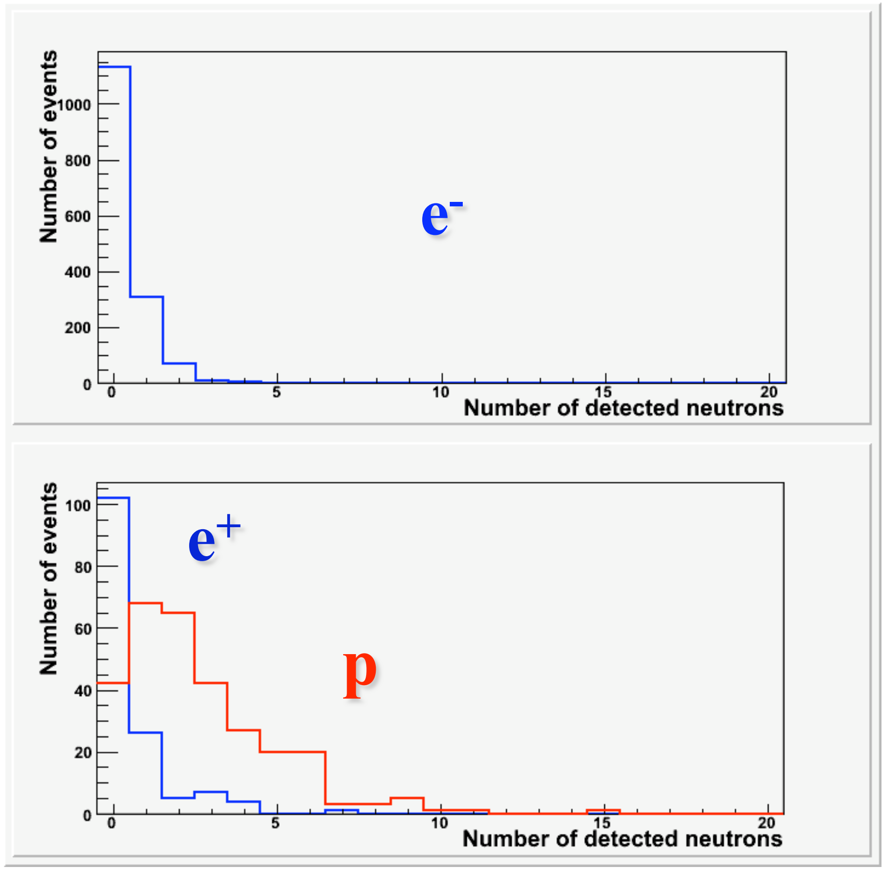
# Positron selection

**Rigidity: 20-30 GV**

**Fraction of charge released along the calorimeter track**

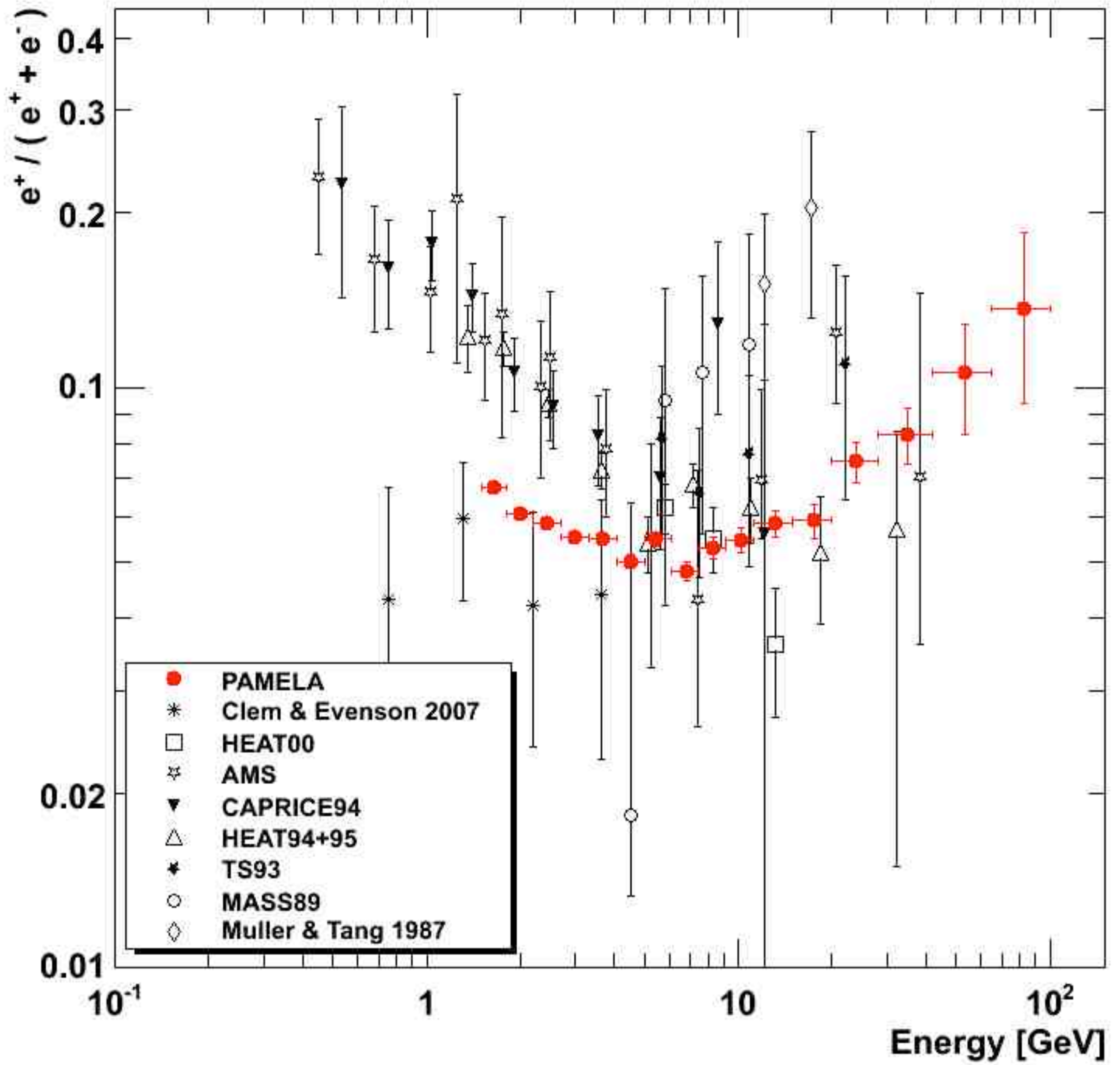



**Neutrons detected by ND**




- Energy-momentum match
- Starting point of shower

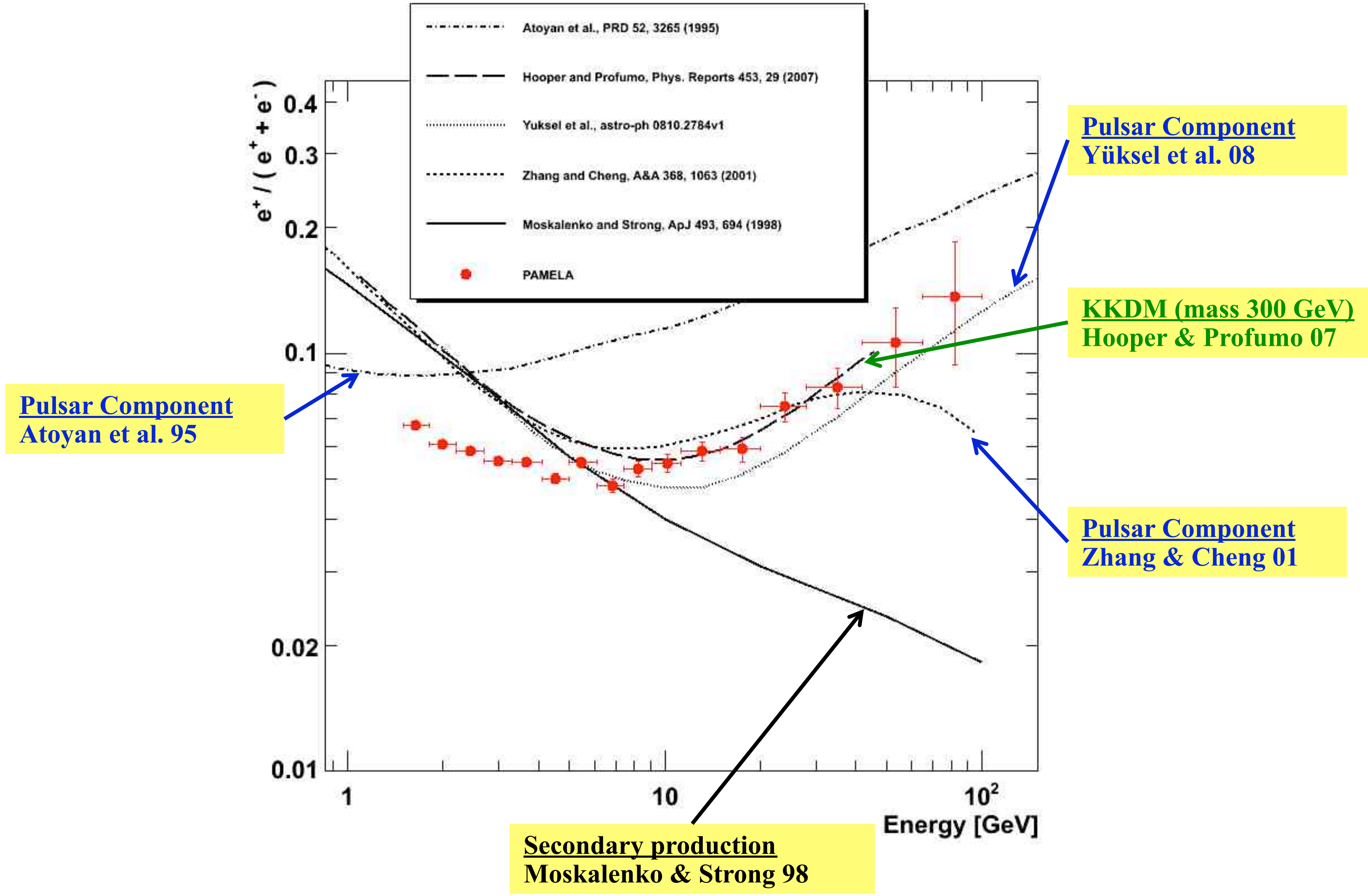
# Positron to Electron Fraction




**End 2007:**
**~10 000 $e^+$ > 1.5 GeV**

**~2000 > 5 GeV**

**Astro-ph 0810.4995**

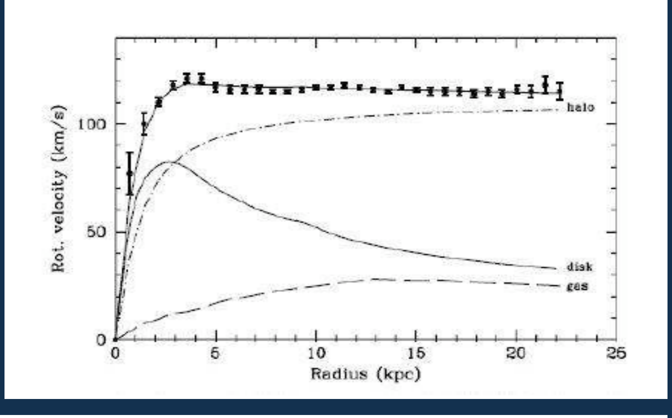

Atoyan et al., PRD 52, 3265 (1995)
Hooper and Profumo, Phys. Reports 453, 29 (2007)
Yuksel et al., astro-ph 0810.2784v1
Zhang and Cheng, A&A 368, 1063 (2001)
Moskalenko and Strong, ApJ 493, 694 (1998)
PAMELA
e+ / (e+ + e-)
0.4
0.3
0.2
0.1
0.02
0.01
1
10
10²
Energy [GeV]
Pulsar Component
Yüksel et al. 08
KKDM (mass 300 GeV)
Hooper & Profumo 07
Pulsar Component
Atoyan et al. 95
Pulsar Component
Zhang & Cheng 01
Secondary production
Moskalenko & Strong 98

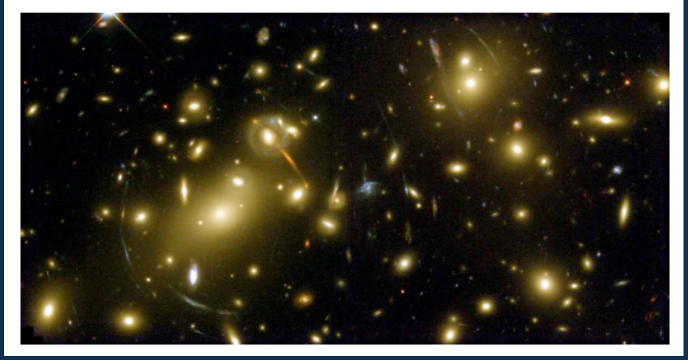
# Positron Abundance

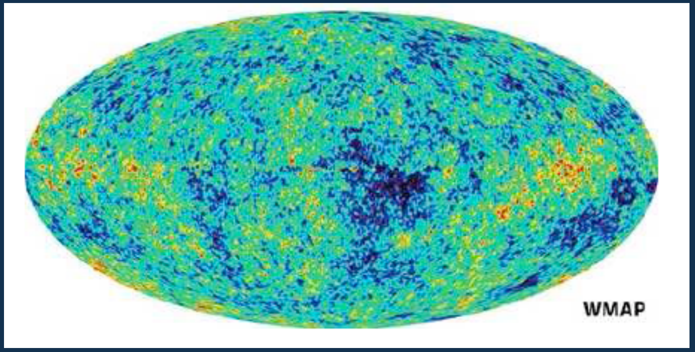
- Cosmic-ray positrons are a sensitive probe of the local astrophysical environment,
- may be produced by the annihilation of dark matter particles which are gravitationally bound to our galaxy.
- Our high energy data deviate from predictions of standard astrophysical models where positrons are produced through the interaction of cosmic-ray nuclei with the interstellar gas.

# DM evidences

- Evidences:
  - DM hints on all cosmological scales:
    - rotational curves of galaxies
    - motion of galaxies in clusters
    - gravitational lensing
  - DM seems cold (CDM)
  - The DM must be:
    - Massive (acts gravitationally)
    - Stable (justify abundances)
    - Neutral in charge and colour (no X ray emission)
    - Maybe  weakly interacting
    - Non baryonic (no candidate)

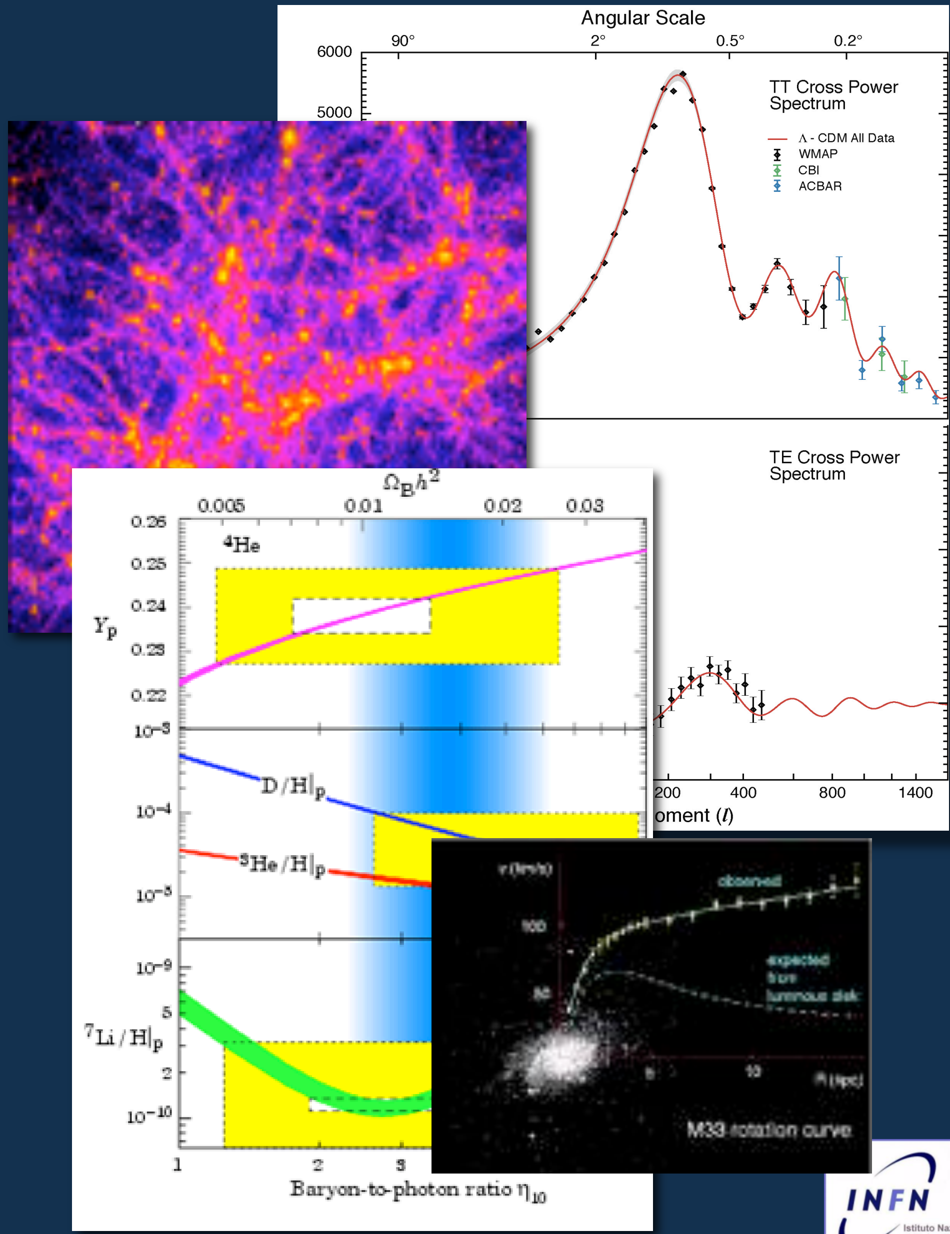




# Dark Matter

- Evidence from a wide range of astrophysical observations including rotation curves, CMB, lensing, clusters, BBN, SN1a, large scale structure
- Each observes dark matter through its gravitational influence
- Still no (reliable) observations of dark matter's electroweak interactions (or other non-gravitational interactions)
- Still no (reliable) indications of dark matter's particle nature



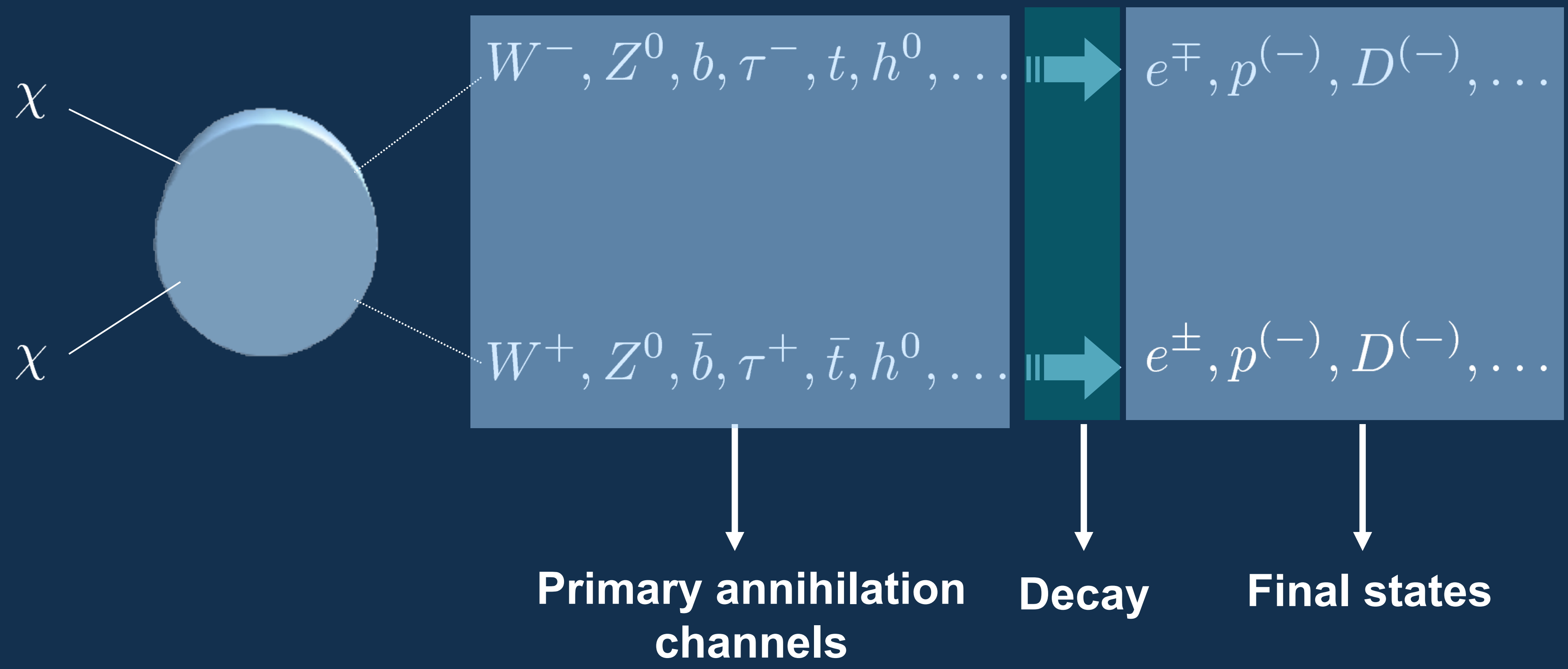
# Neutralino Annihilation

Galactic Center

- The lightest SUSY particle (neutralino?) is a leading candidate for the WIMP.
- Density should be biggest in centers of galaxies
- Annihilation to different final states might be detectable.

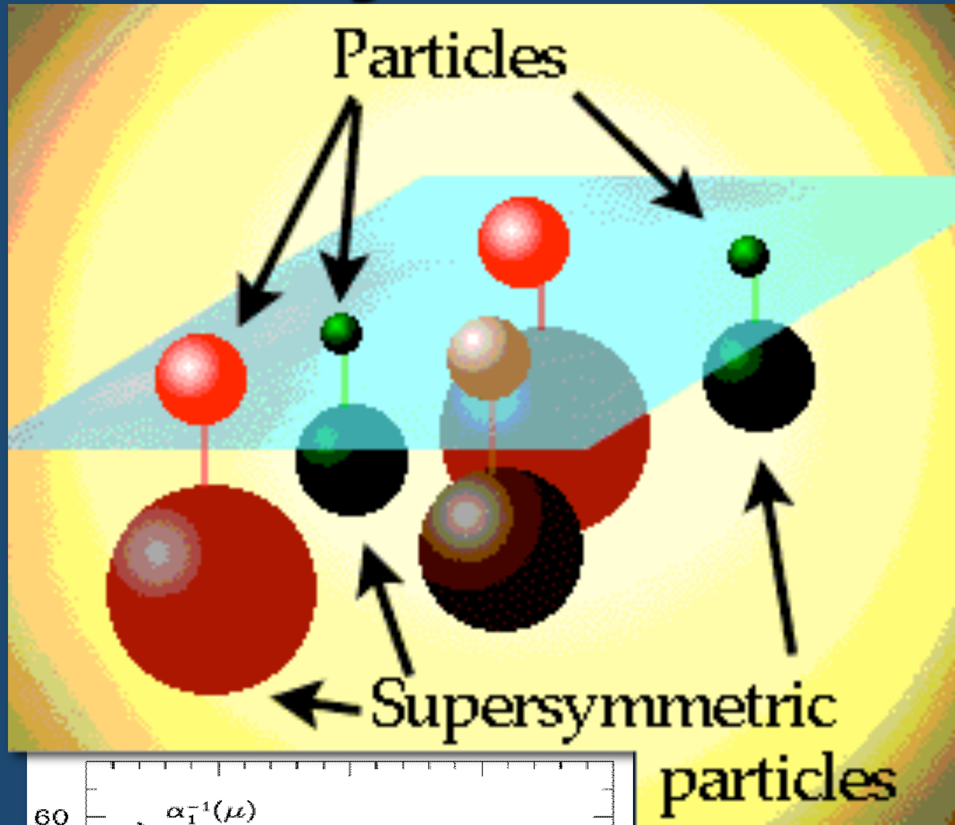
# DM annihilations

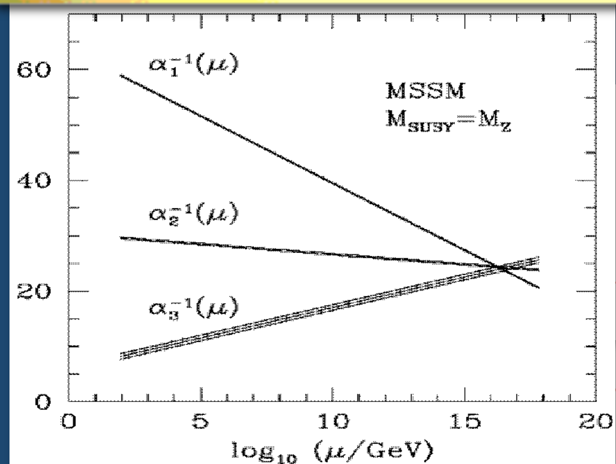
**DM particles are stable. They can annihilate in pairs.**

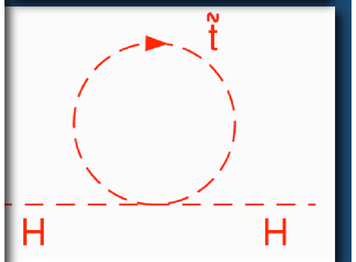


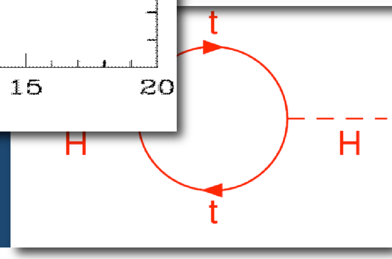
# Supersymmetry

- Perhaps the most theoretically appealing (certainly the most well studied) extension of the Standard Model
- Natural solution to hierarchy problem (stabilizes quadradic divergences to Higgs mass)
- Restores unification of couplings
- Vital ingredient of string theory
- Naturally provides a compelling candidate for dark matter



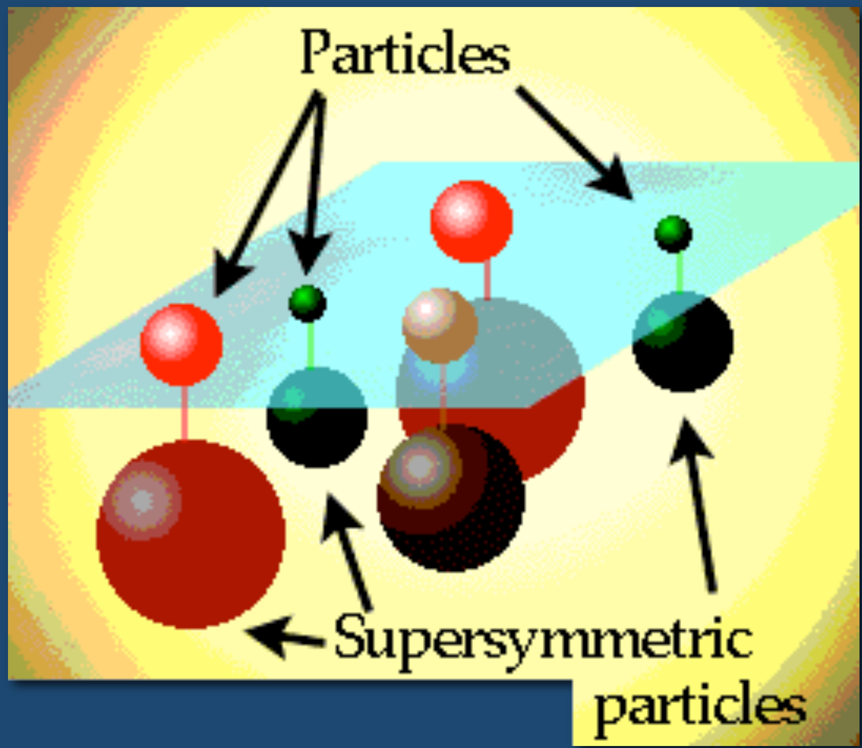



# Supersymmetric Dark Matter

•R-parity must be introduced in supersymmetry to prevent rapid proton decay

•Another consequence of R-parity is that superpartners can only be created and destroyed in pairs, making the lightest supersymmetric particle (LSP) stable

•Possible WIMP candidates from supersymmetry include:




$\tilde{\gamma}, \tilde{Z}, \tilde{h}, \tilde{H}$ ← 4 Neutralinos

$\tilde{\nu}$ ← 3 Sneutrinos

From Dan Hooper

# DM detection

- Direct detection Xenon, CDMS, Dama/Libra
- Production at colliders LHC
- Indirect
  - $\gamma$ from annihil in the galactic halo or GC Fermi/GLAST
  - $e^+, \bar{p}$ from annihil in the galactic halo or GC Pamela, AMS02, balloons
  - $\bar{D}$ from annihil in the galactic halo or GC GAPS
  - $\nu, \bar{\nu}$ from annihil in massive bodies Icecube, Km3Net

# Cosmic-ray Antimatter from Dark Matter annihilation?

→ Distortion of antiproton and positron spectra from purely secondary production

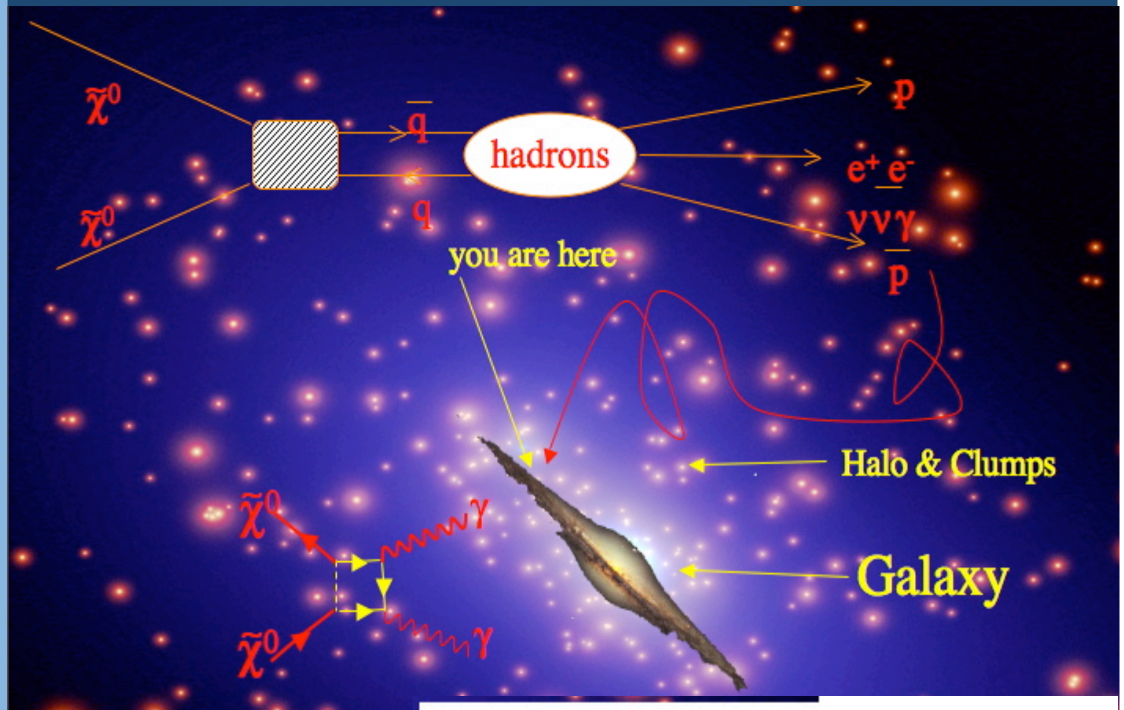
**A plausible dark matter candidate is neutralino ($\chi$), the lightest SUSY particle.**

**Annihilation of relic $\chi$ gravitationally confined in the galactic halo**

**Most likely processes:**

- **$\chi\chi$ → qq → hadrons→ anti-p, $e^+$,…**
- **$\chi\chi$ → $W^+W^-$,$Z^0Z^0$,… → $e^+$,…**

**direct decay ⇒ positron peak Ee+~Mc/2**
**other processes ⇒ positron continuum Ee+~M$\chi$/20**




$\chi + \bar{\chi} \rightarrow X + \gamma$ (GLAST)

$+ \nu$ (AMANDA / IceCube)

$+ \bar{p}$

$+ e^+$

$+ \bar{D}$

PAMELA (and Bess, HEAT, AMS etc.)

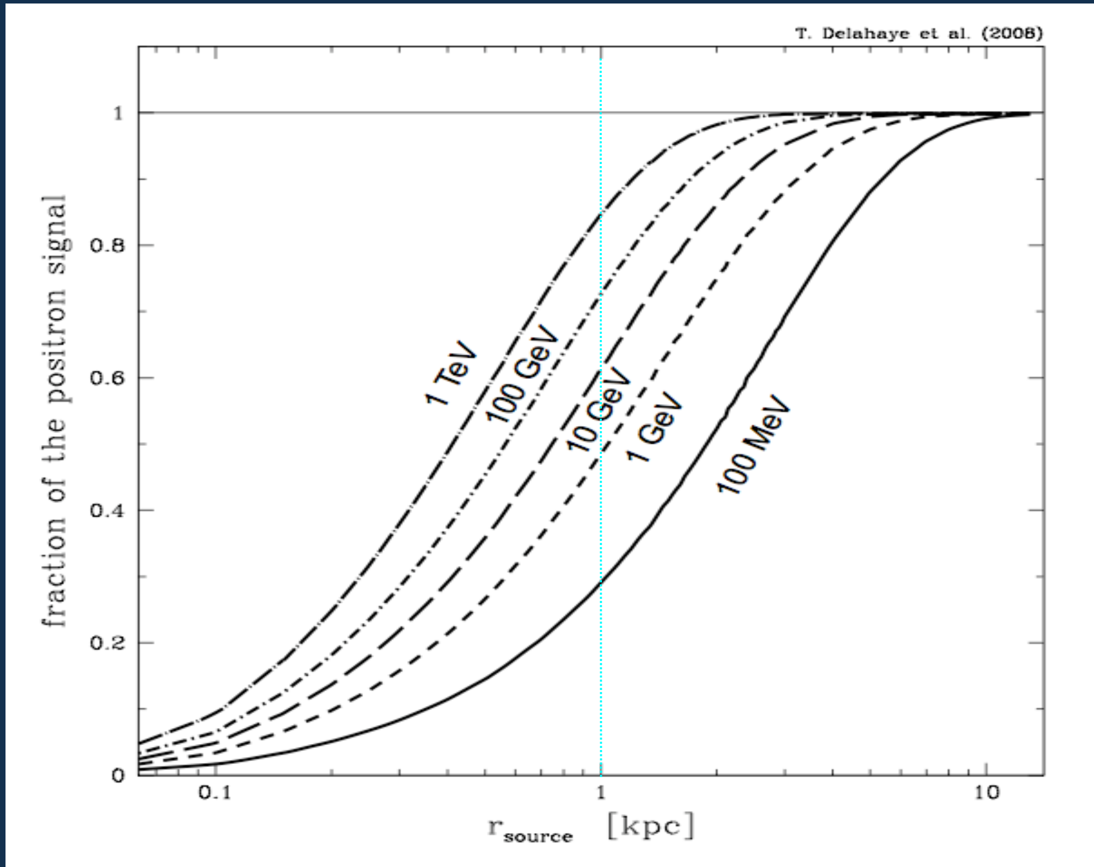
# Indirect DM detection

Where do positrons come from?

Mostly locally within 1 Kpc, due to the energy losses by Synchrotron Radiation and Inverse Compton

Typical lifetime

$$\tau \simeq 5 \cdot 10^5 \mathrm{yr} \left( \frac{1\,\mathrm{TeV}}{E} \right)$$



# Positron Abundance Pamela Data

- The low energy positron ratio can be consistent with data in the convection propagation model.
- Above ~ 10 GeV PAMELA data shows a clear excess on the positron ratio.
- However, the secondary antiproton is roughly consistent with data.
- The positron excess may be a direct evidence of dark matter annihilation or decay.
- The PAMELA data actually excludes quark pairs being the main final states, disfavors gauge boson final states.
- Only in the case of leptonic final states the positron and anti-proton spectra can be explained simultaneously.

# Propagation of cosmic rays

**In general a more involved equation (with respect to Leaky-box) models the cosmic rays propagation:**

differential flux

$$\frac{\partial \Phi}{\partial t} - D(E)\nabla^2\Phi + \frac{\partial}{\partial E}\left(b(E)\Phi\right) + \frac{\partial}{\partial z}\left(V_c \Phi\right) = Q(E) - 2h\delta(z)\Gamma_{\mathrm{spall}}\Phi$$

diffusion — energy loss — convection — source term — spallation

**Solution is of the form:**

$$\Phi \propto n^2 \langle \sigma v \rangle$$

particle physics

astro&cosmo

**Thermal relic requires:**

$$\langle \sigma \, v \rangle \simeq 3 \cdot 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$$

arXiv:0811.1555

# Decaying Dark Matter and PAMELA Anomaly

**Alejandro Ibarra David Tran*** Physik-Department T30d, TUM ,

We find that the steep rise in the positron fraction measured by PAMELA at energies larger than 10 GeV can **naturally be accommodated in several realizations of the decaying dark matter scenario**. For instance, gravitino dark matter which is unstable due to a small breaking of R-parity

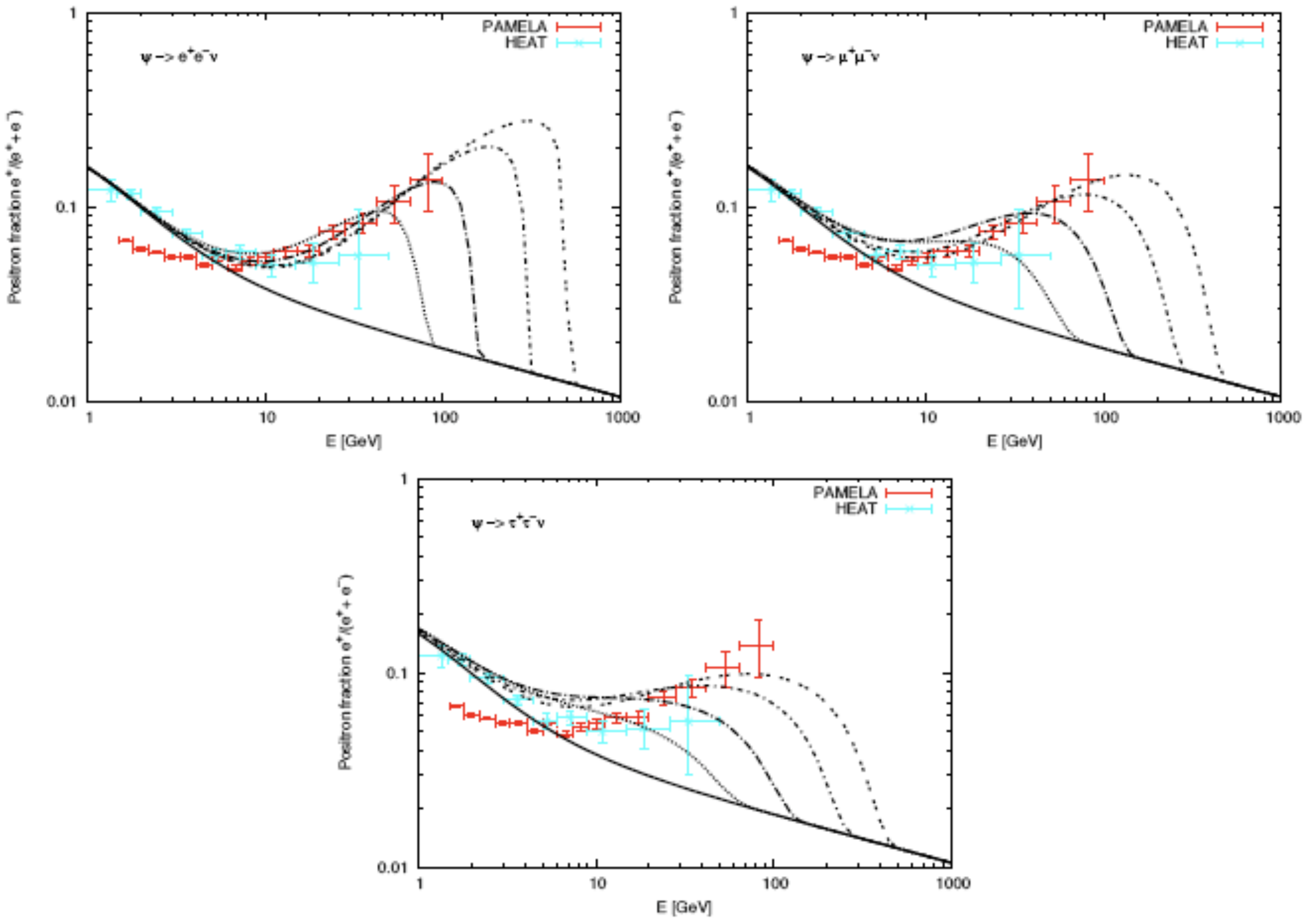
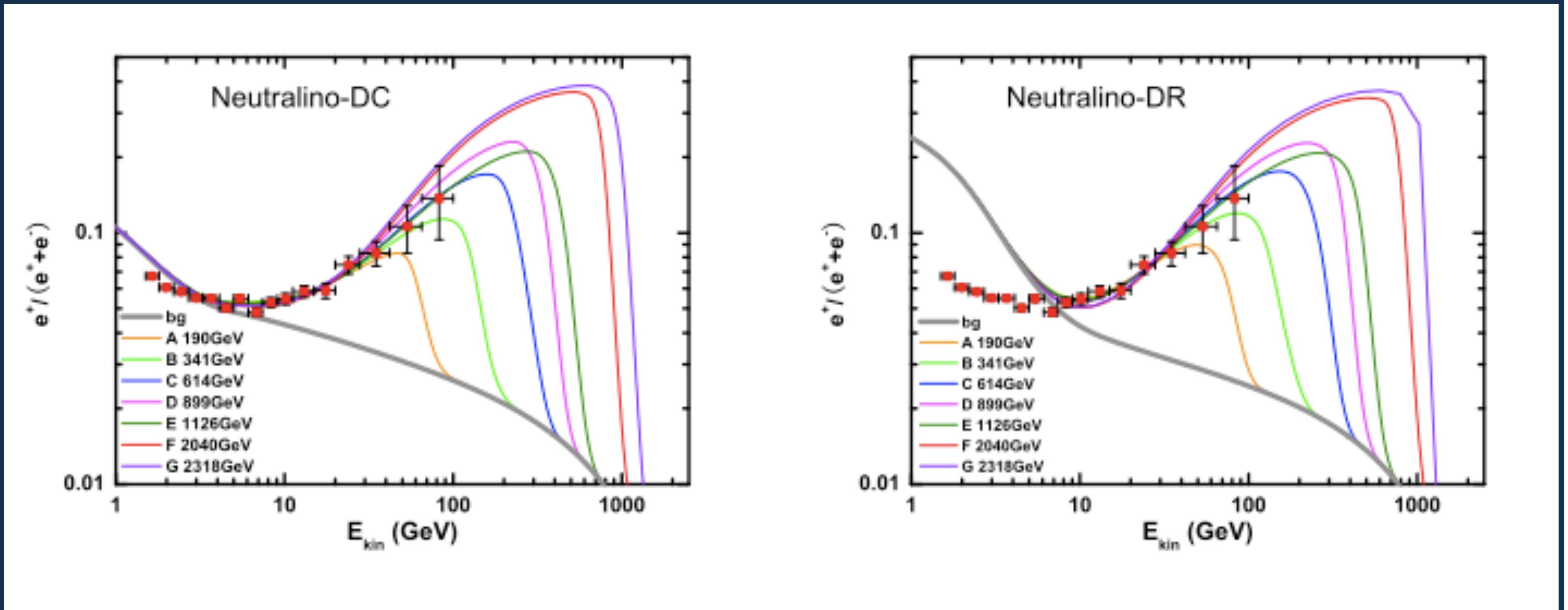



Figure 3: Positron fraction from the decay of the fermionic dark matter particle in the channels $\psi \to e^+e^-\nu$ (top-left panel), $\psi \to \mu^+\mu^-\nu$ (top-right panel) and $\psi \to \tau^+\tau^-\nu$ (bottom panel), when the dark matter mass is, from left to right, $m_{DM} = 150,\ 300,\ 600,\ 1000$ GeV. The lifetime, which ranges between $5 \times 10^{25}$ s and $8 \times 10^{26}$ s, is different in each case and has been chosen to provide a qualitatively good fit to the data.

**PAMELA data and leptonically decaying dark matter** arXiv:0811.0176v2

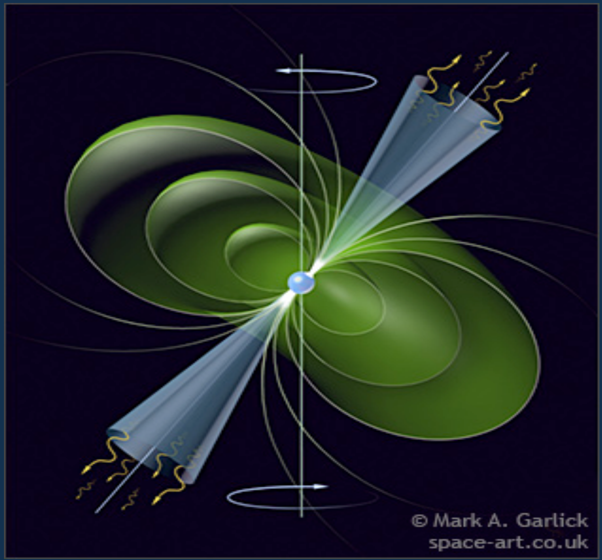
Peng-fei Yin, Qiang Yuan, Jia Liu, Juan Zhang, Xiao-jun Bi, Shou-hua Zhu and Xinmin Zhang

**We find thePAMELA data actually excludes the annihilation or decay products being quark pairs, strongly disfavors the gauge bosons and favors dominant leptonic final states.**



# Astrophysical explanations?

**Young, nearby pulsars**




**"Mechanism": the spinning $\vec{B}$ of the pulsar strips $e^-$ that emit $\gamma$ that make production of $e^\pm$ pairs trapped in the cloud, further accelerated and later released at**

$$\tau \simeq 0 \to 10^5\,\mathrm{yr} \qquad E_{tot} \simeq 10^{46}\,\mathrm{erg}$$

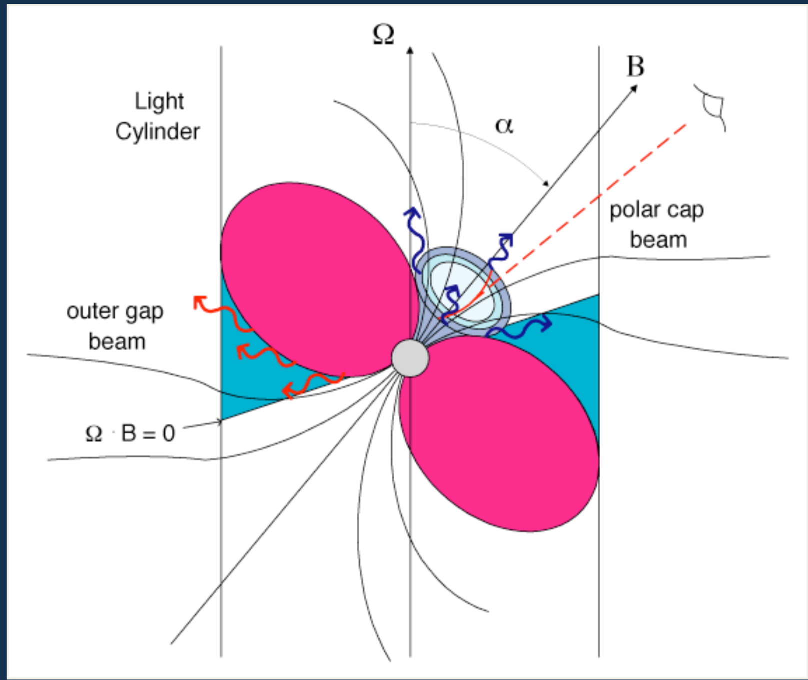
**Must be young (T<$10^5$ yr) and nearby (<1 kpc). If not: too much diffusion, low energy, too low flux.**

**Injection flux:** $\Phi_{e^\pm} \simeq E^{-p} \exp(E/E_c) \qquad p \simeq 2$

$$E_c \simeq 10 - 10^2\,\mathrm{TeV}$$

# Pulsars

### Crab Pulsar

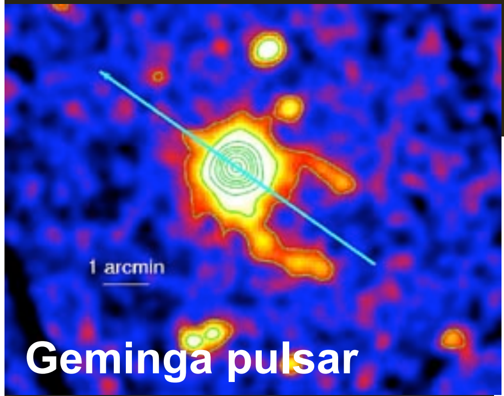



- Highly magnetized rotating neutron star accelerates charged particles.
- These charges escape along open magnetic field lines in jets.
- In the process, they radiate and scatter photons to high energies.
- Details depend on specific models.

# Pulsars as the Sources of High Energy Cosmic Ray Positrons

Dan Hooper, Pasquale Blasi, Pasquale Dario Serpico

arXiv: 0810.1527v1



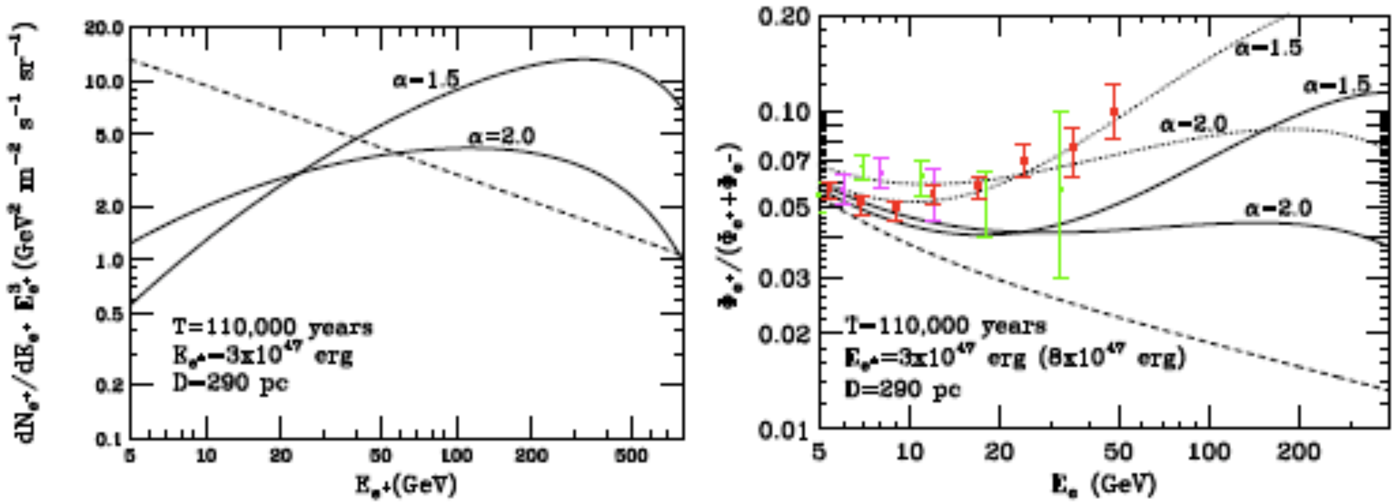




FIG. 3: As in Fig. 2, but from the nearby pulsar B0656+14. The solid lines correspond to an energy in pairs given by $3 \times 10^{47}$ erg, while the dotted lines require an output of $8 \times 10^{47}$ erg.

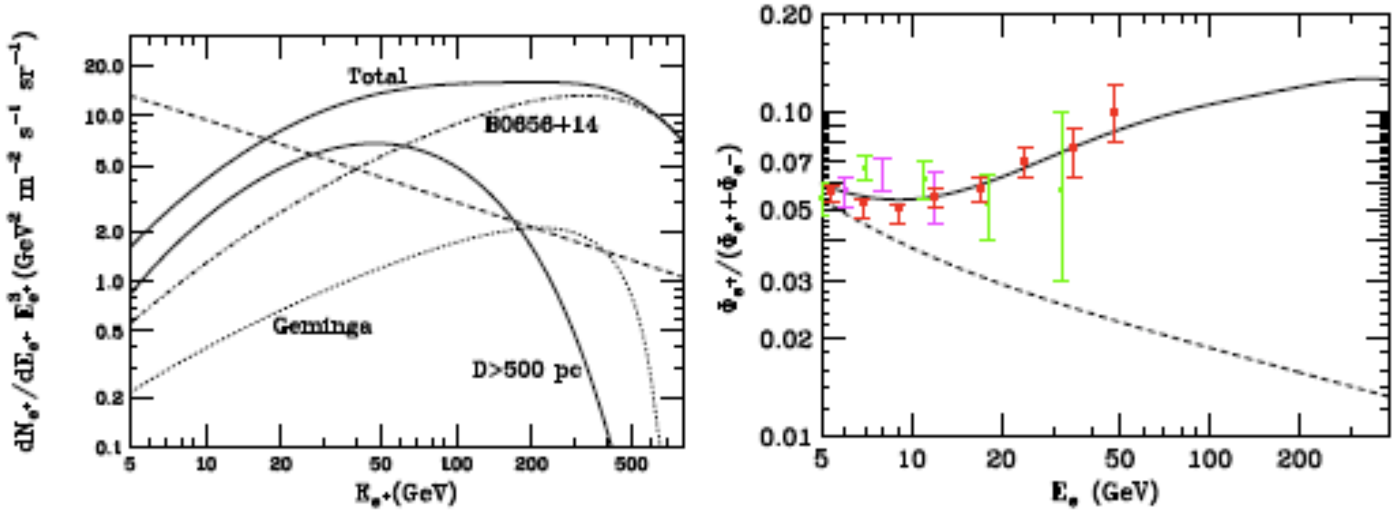



FIG. 4: The positron spectrum and positron fraction from the sum of contributions from B0656+14, Geminga, and all pulsars farther than 500 parsecs from the Solar System.

# Is the PAMELA anomaly caused by the supernova explosions near the Earth?

Yutaka Fujita,[1,*] Kazunori Kohri,[2] Ryo Yamazaki,[3] and Kunihito Ioka[4]
[1]*Department of Earth and Space Science, Graduate School of Science, Osaka University, Toyonaka, Osaka 560-0043, Japan*
[2]*Physics Department, Lancaster University, Lancaster LA1 4YB, UK*
[3] *Department of Physical Science, Hiroshima University, Higashi- Hiroshima, Hiroshima 739-8526, Japan*
[4] *Theory Division, KEK (High Energy Accelerator Research Organization) and the Graduate University for Advanced Studies (Sokendai), 1-1 Oho, Tsukuba 305-0801, Japan*
(Dated: March 31, 2009)



We show that recent supernova explosion(s) in a molecular cloud (MC) near the Earth can be attributed to the electron/positron excesses observed with PAMELA and ATIC. Protons are accelerated around the supernova remnant (SNR). If the SNR is in a radiative phase, the proton spectrum is harder than that of the background. Electrons and positrons are created through hadronic interactions insides the MC. Our model predicts that the anti-proton flux dominates that of the background for $\gtrsim$ 100 GeV, while the gamma-ray and neutrino signals could currently be absent because the SNR has destroyed the MC.

PACS numbers: Valid PACS appear here

# Cosmic-ray knee and flux of secondaries from interactions of cosmic rays with dark matter

Manuel Masip[1], Iacopo Mastromatteo[1,2]

[1] *CAFPE and Departamento de Física Teórica y del Cosmos*
*Universidad de Granada, E-18071 Granada, Spain*

[2] *International School for Advanced Studies (SISSA)*
*Via Beirut 2-4, I-34014 Trieste, Italy*

masip@ugr.es, iacopomas@infis.univ.trieste.it

**Abstract**

We discuss possible implications of a large interaction cross section between cosmic rays and dark matter particles due to new physics at the TeV scale. In particular, in models with extra dimensions and a low fundamental scale of gravity the cross section grows very fast at *transplanckian* energies. We argue that the knee observed in the cosmic ray flux could be caused by such interactions. We show that this hypothesis implies a well defined flux of secondary gamma rays that seems consistent with MILAGRO observations.

# Dark Matter and Pamela Results

The identity of dark matter is one of the greatest puzzles of our Universe. Its solution may be associated with supersymmetry the fundamental space-time symmetry that was so far not experimentally verified.

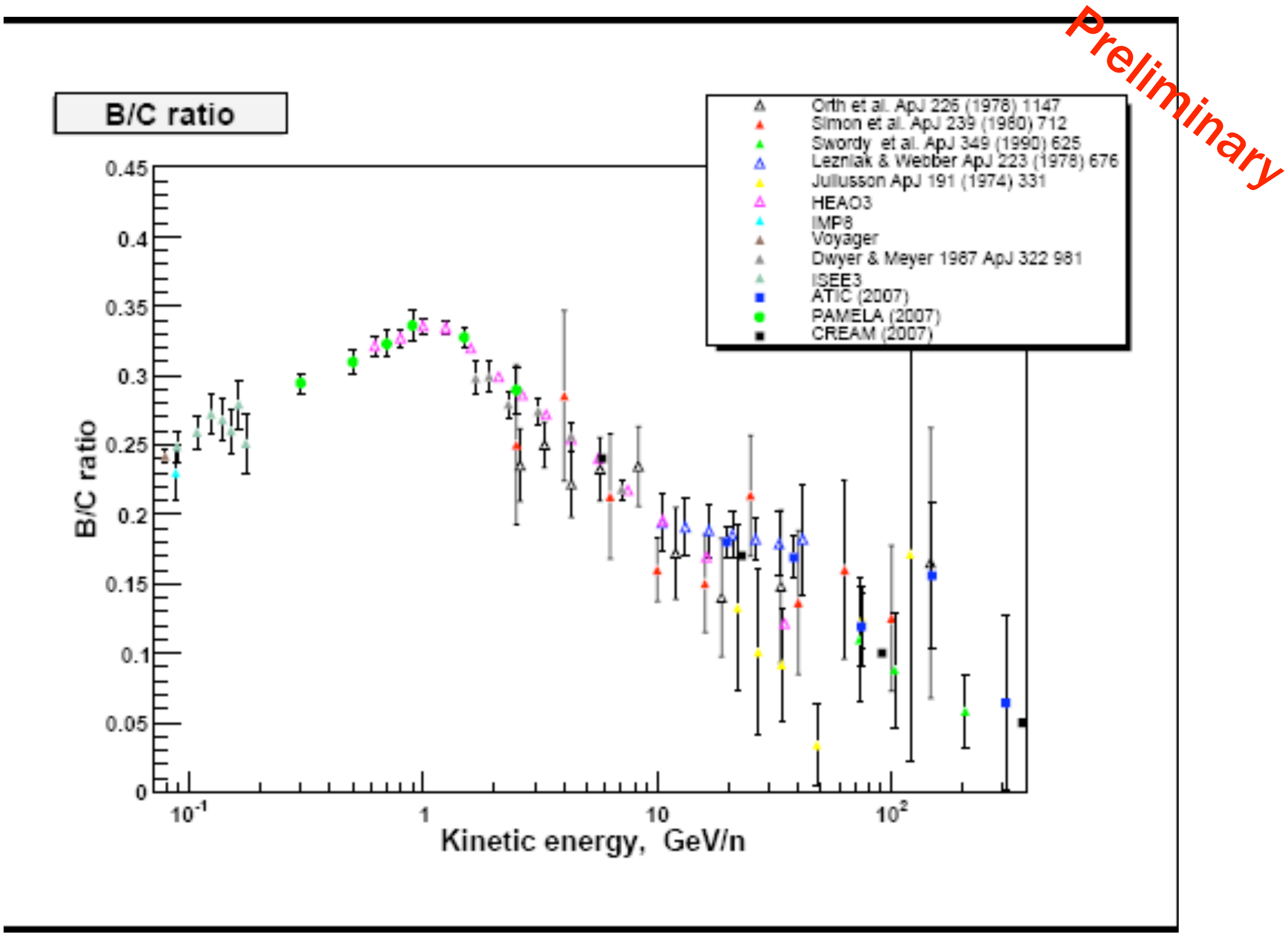
In many supersymmetric extensions of the Standard Model of particle physics, the lightest supersymmetric particle cannot decay and is hence a promising dark matter candidate.

The lightest neutralino, which appears already in the minimal supersymmetric model, can be identified as such a candidate in indirect and direct dark matter searches.

# Cosmic-Ray Propagation

B/C and Be ratios will impose severe constraints to galaxy models and diffusion parameters for background estimation.

# Preliminary Results B/C

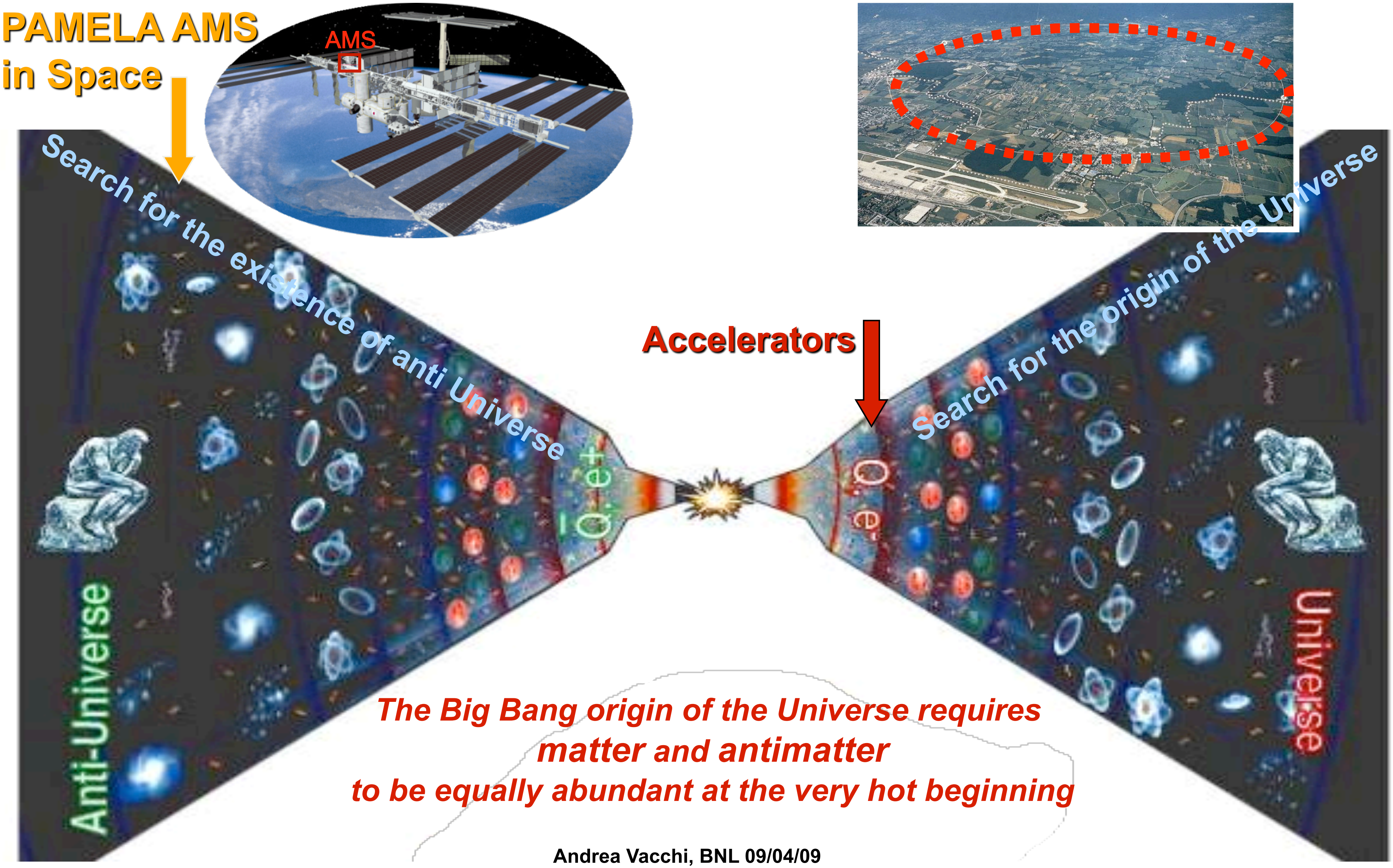


# What about antinuclei?

- **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**

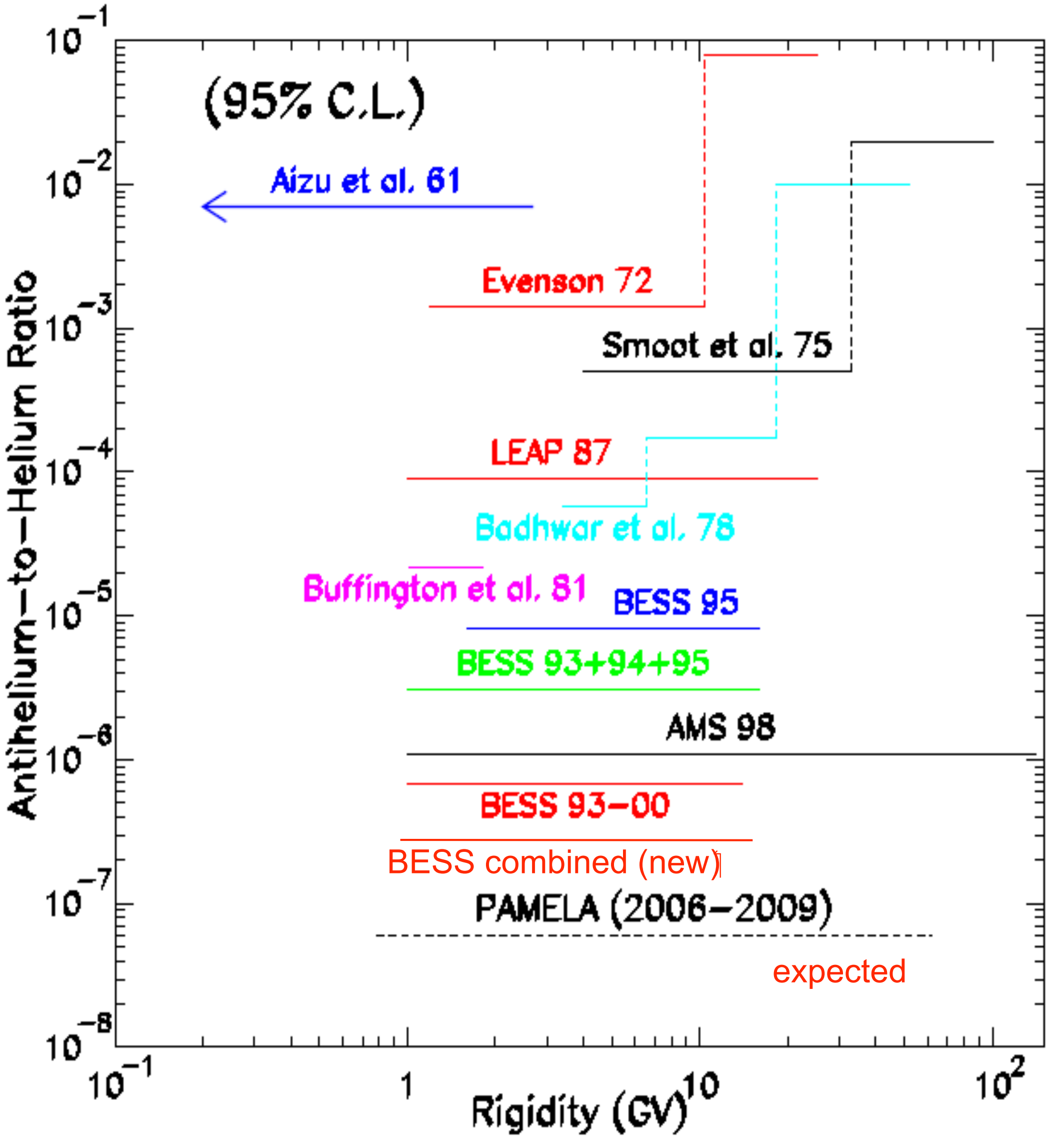
    ***(Steigman (1976) Ann Rev. Astr. Astrophys., 14, 339; Dudarerwicz and Wolfendale (1994) M.N.R.A. 268, 609, A.G. Cohen, A. De Rujula and S.L. Glashow, Astrophys. J. 495, 539, 1998)***

# Search for the existence of Antimatter in the Universe



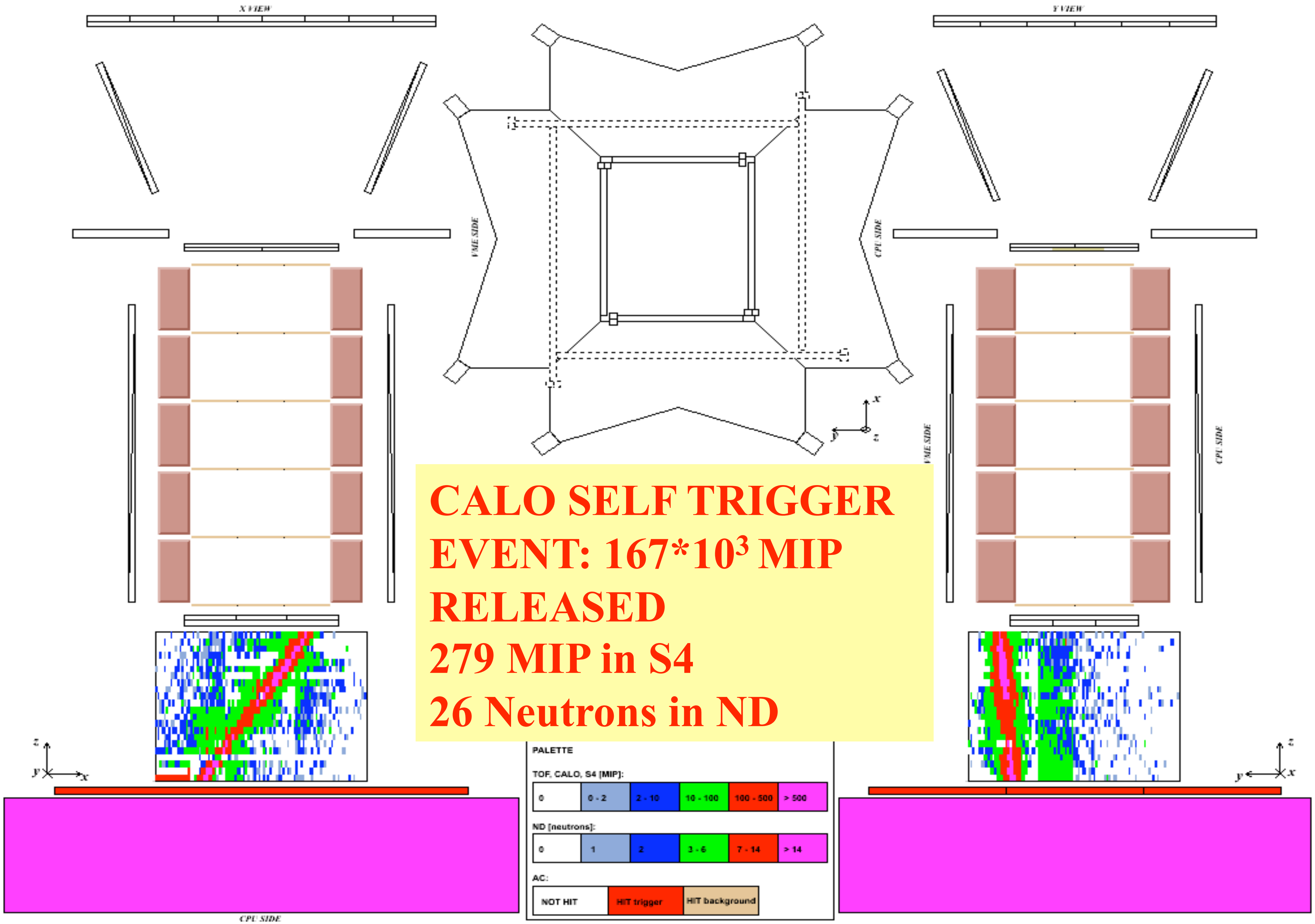

*The Big Bang origin of the Universe requires*
***matter and antimatter***
*to be equally abundant at the very hot beginning*

# Antimatter search



# 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**

A
sh
hi
co
hi
de

# Concluding

- PAMELA is the first space experiment which is measuring the antiproton and positron energy spectra to the high energies (>100GeV) with an unprecedented statistical precision
- PAMELA is looking for Dark Matter candidates
- and “ direct ” measurement of particle acceleration in astrophysical sources
- Furthermore:
  - 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.
  - PAMELA is setting a new lower limit for finding Antihelium