The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization
IAEA International Atomic Energy Agency

2036-17

International Workshop: Quantum Chromodynamics from Colliders to Super-High Energy Cosmic Rays

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Antimatter Search The PAMELA Satellite Experiment A Positron Abundance Signal

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Antimatter search
The P A M E L A Satellite experiment
A Positron Abundance Signal

Payload for Antimatter / Matter Exploration and Light-nuclei Astrophysics

"An anomalous positron abundance in the cosmic radiation between 1.5 and 100 GeV"
Nature 2 April 2009
http://arxiv.org/abs/0810.4995
http://physics.aps.org/viewpoint-for/10.1103/PhysRevLett.102.051101

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

The PAMELA Collaboration

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Russia

Физический Институт

Ioffe Physico-Technical Institute

Moscow

S. Petersburg

Sweden

KTH VETENSKAP OCH KONST

Stockholm

Germany

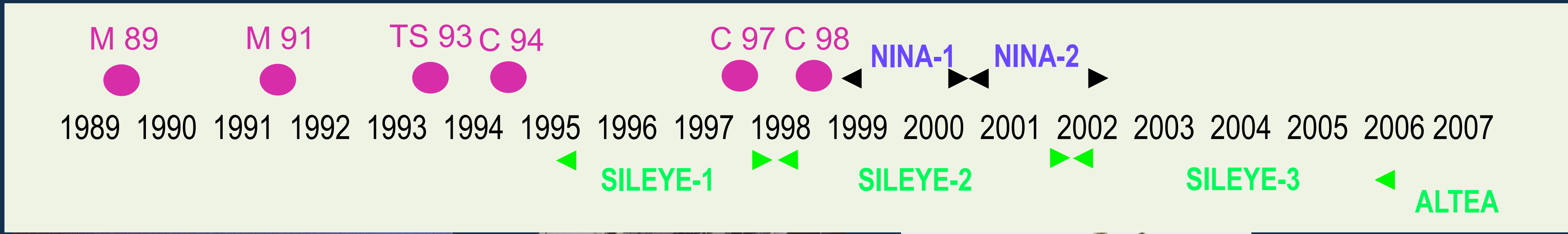
Universität Gesamthochschule Siegen

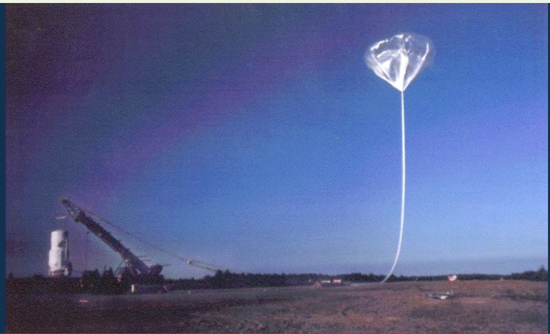
Siegen

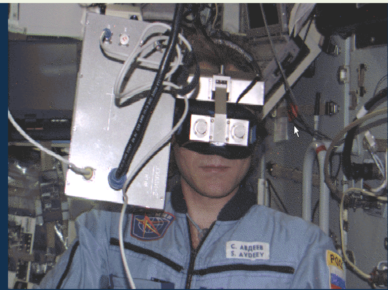
Italy

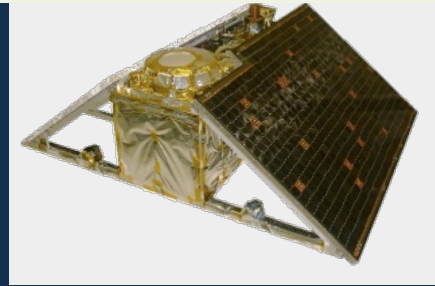
Bari | Florence | LNF Frascati | Naples | Tor Vergata Rome | Trieste | IFAC CNR Florence

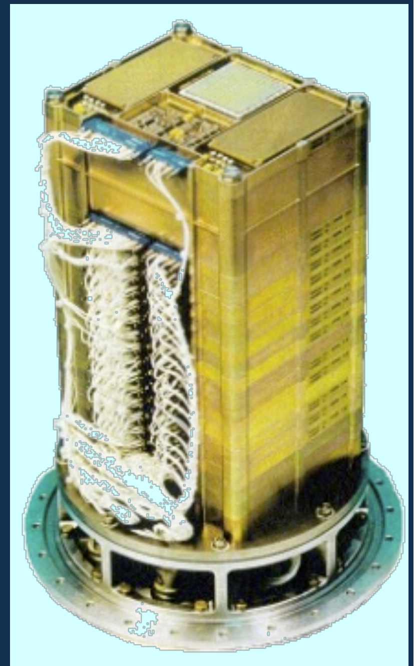
PAMELA long history











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)

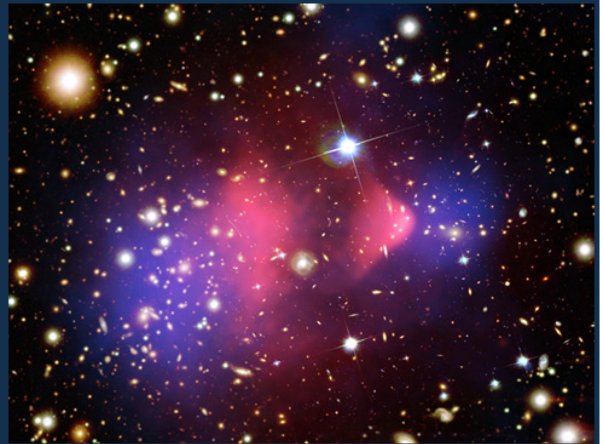
2001: change of the satellite

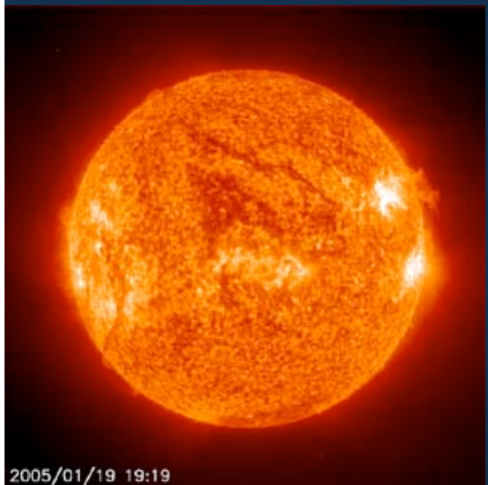
→ *complete redefinition of mechanics*

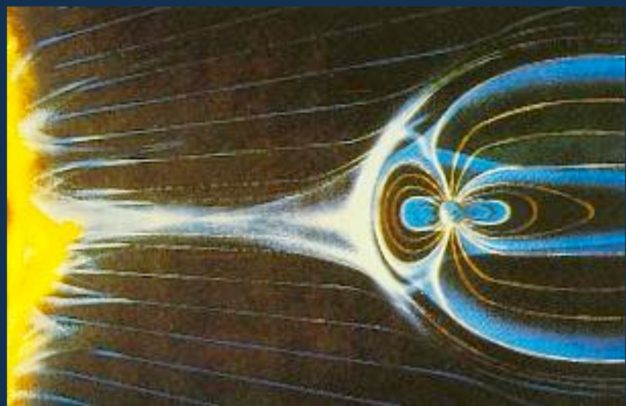
2006: flight!!!

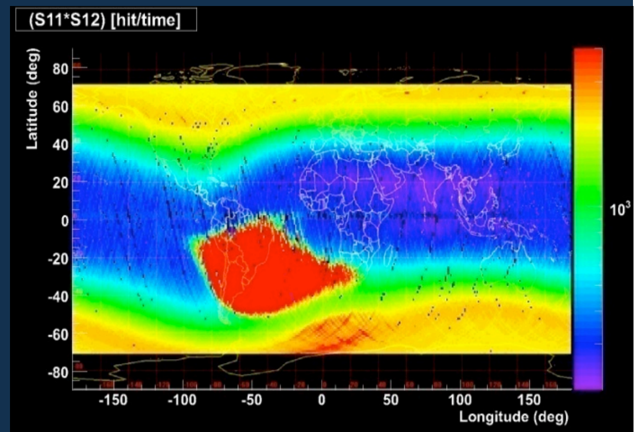
The PAMELA experiment

- 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?)







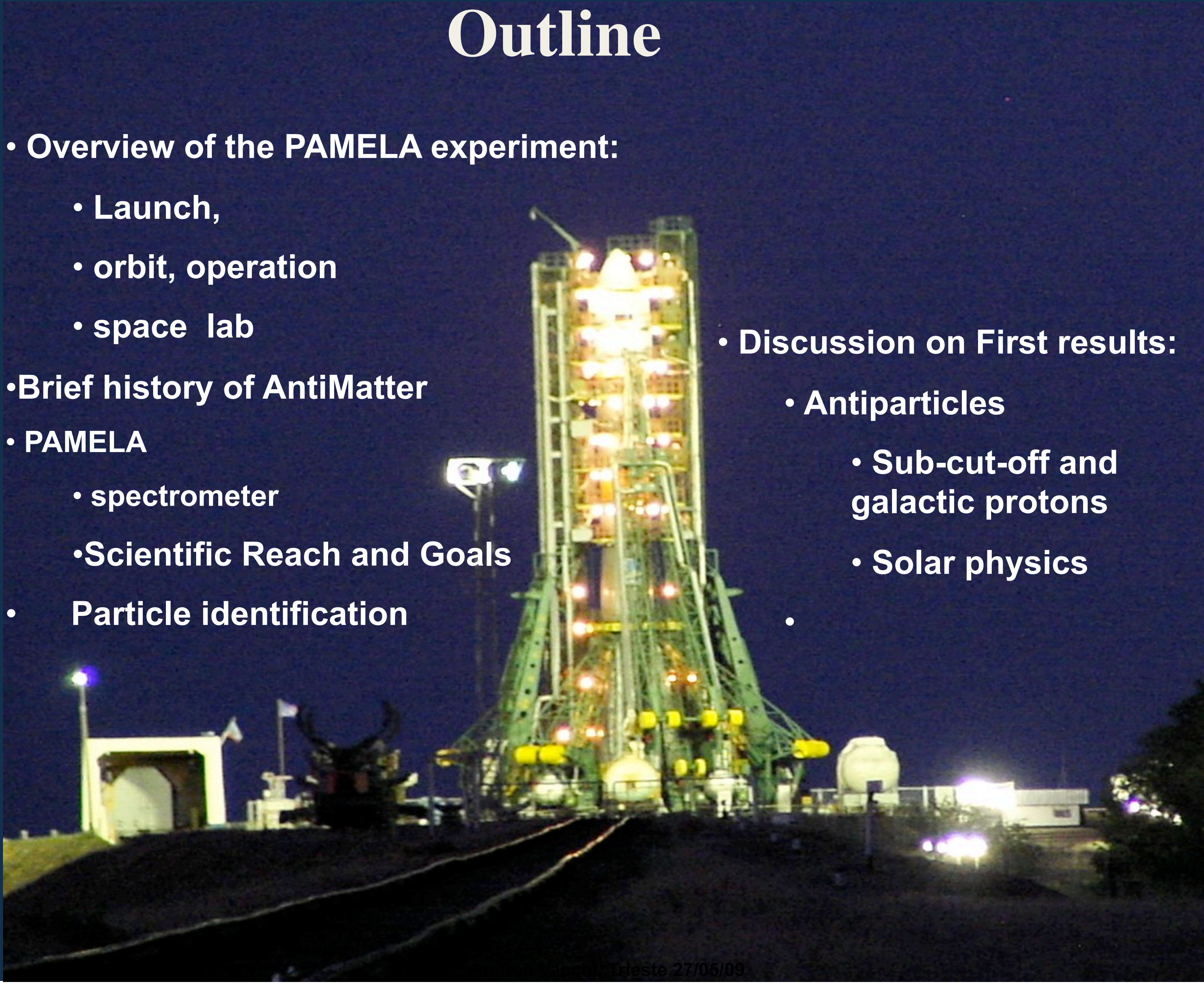


is carried out at 1 AU

approximately 150 million km from the Sun

the Space Observatory ->

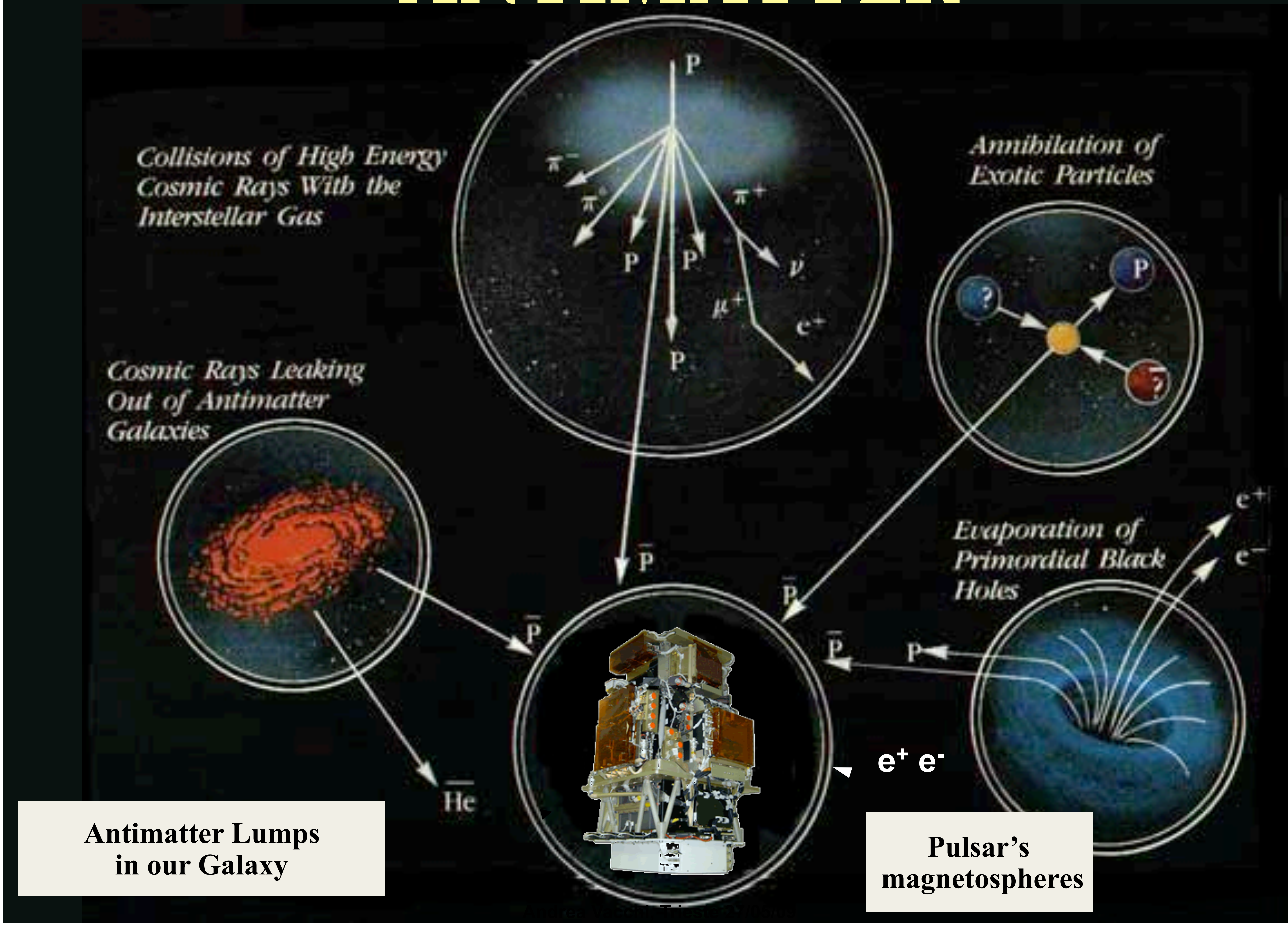
Outline



- Overview of the PAMELA experiment:
    - Launch,
    - orbit, operation
    - space 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
    -

ANTIMATTER


Collisions of High Energy Cosmic Rays With the Interstellar Gas
Annihilation of Exotic Particles
Cosmic Rays Leaking Out of Antimatter Galaxies
Evaporation of Primordial Black Holes
P
π⁻
π⁰
π⁺
ν
μ⁺
e⁺
e⁻
He
e⁺ e⁻
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 α'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 α's must satisfy the conditions

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

They may conveniently be expressed in terms of six variables ρ_1, ρ_2, ρ_3, σ_1, σ_2, σ_3 that satisfy

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

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

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

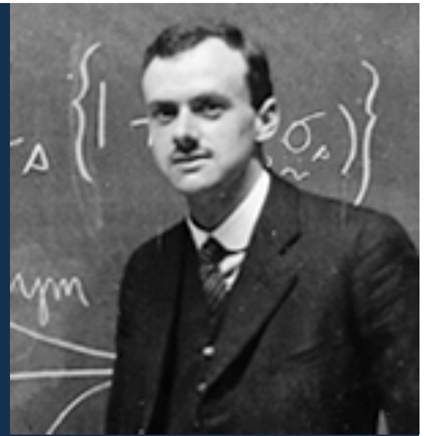
The variables σ_1, σ_2, σ_3 now form the three components of a vector, which corresponds (apart from a constant factor) to the spin angular momentum vector that appears in Pauli's theory of the spinning electron. The ρ's and σ's vary with the time, like other dynamical variables. Their equations of motion, written in the Poisson Bracket notation [ ], are

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

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

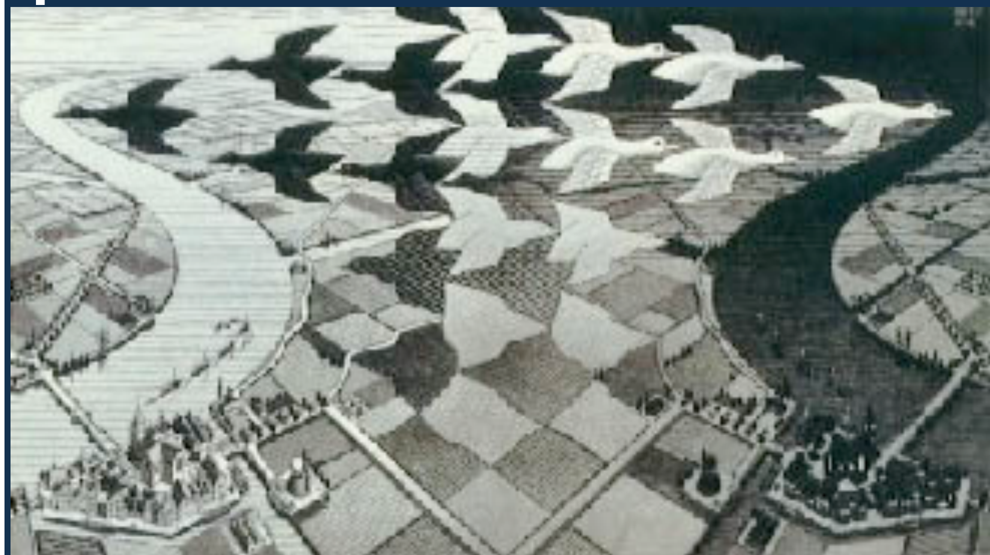
***Paul Dirac** published his works exactly **eighty years** ago February and March 1928.*

"The Quantum Theory of the Electron"



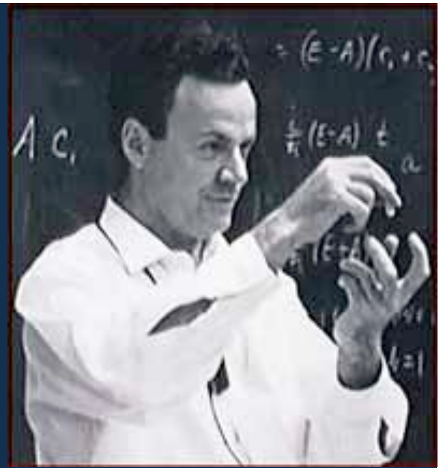
"A great deal of my work is just playing with equations and seeing what they give."

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



Paul Dirac, **pointed out 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)



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

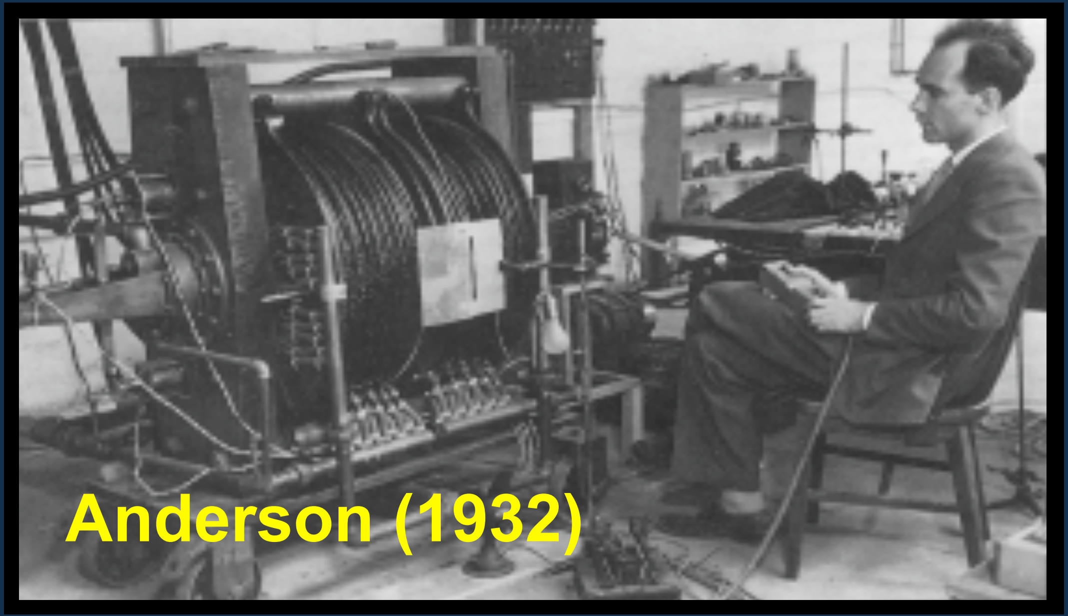
Which are the quantum waves able to describe electrons? And which the wave equations governing the dynamics of those equations while compatible with the conditions of relativity and able to give reasonable prediction.

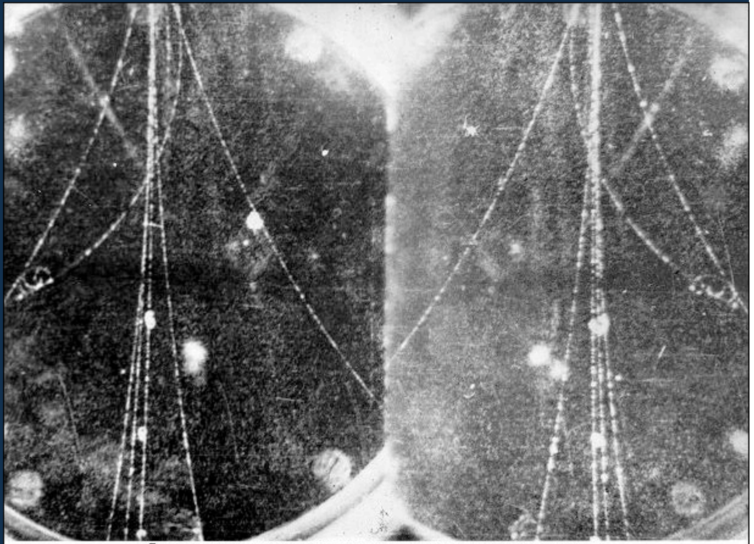
"I think that the discovery of antimatter was probably the biggest jump among the jumps of physics in our century."

Heisemberg 1972

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.





Dirac's equation implies:

Mass of the positron = mass of the electron

Positron's charge = +e

Bevatron 1955 the discovery of the antiproton

Chamberlain, Segrè, Wiegand, Ypsilantis Nobel 1959

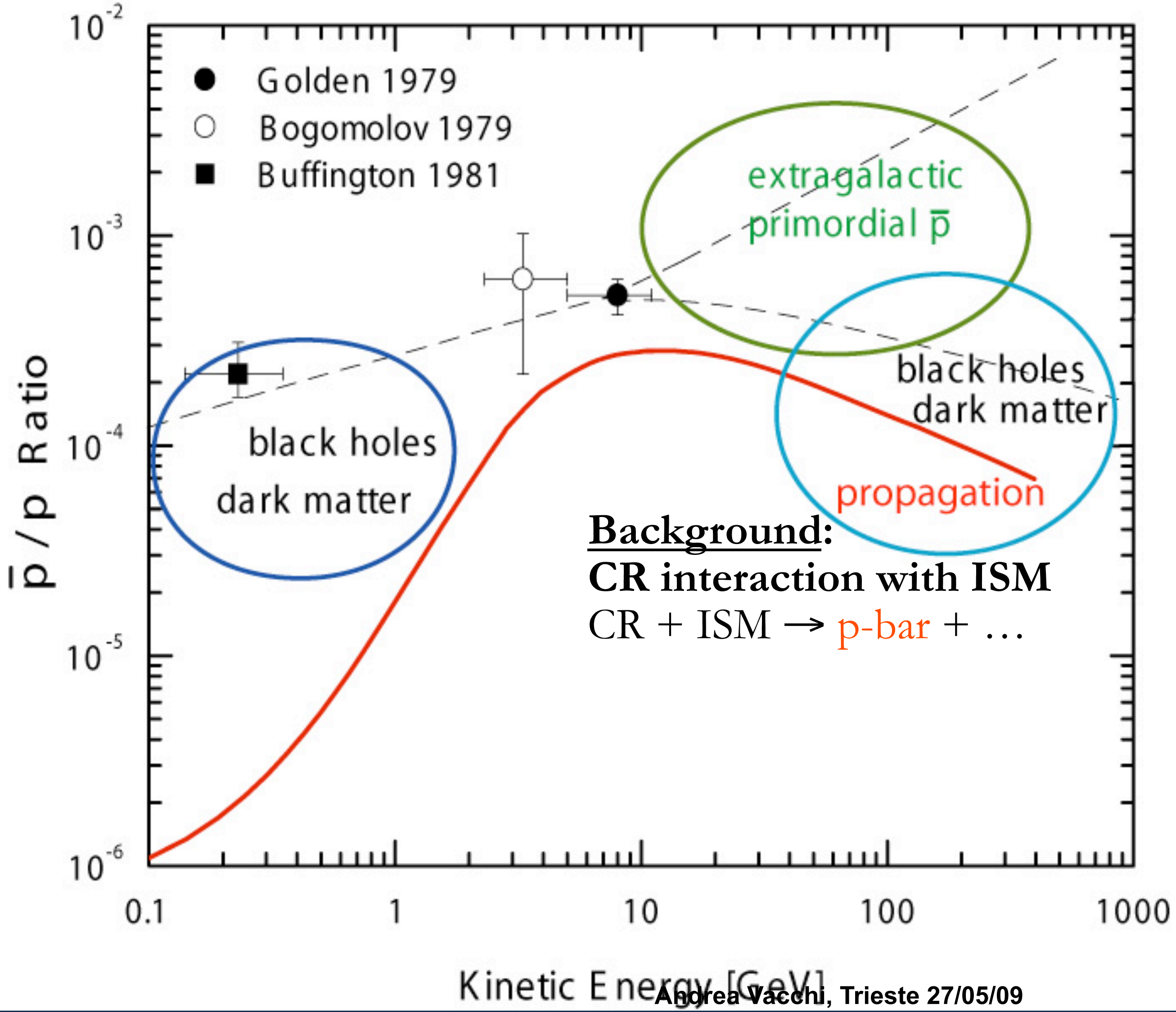
- The existence of a particle with a mass equal to the proton but with negative charge the antiproton (able to annihilate with a proton) was a guess suggested by the possibility to extend Dirac theory to heawwier particles.

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:

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

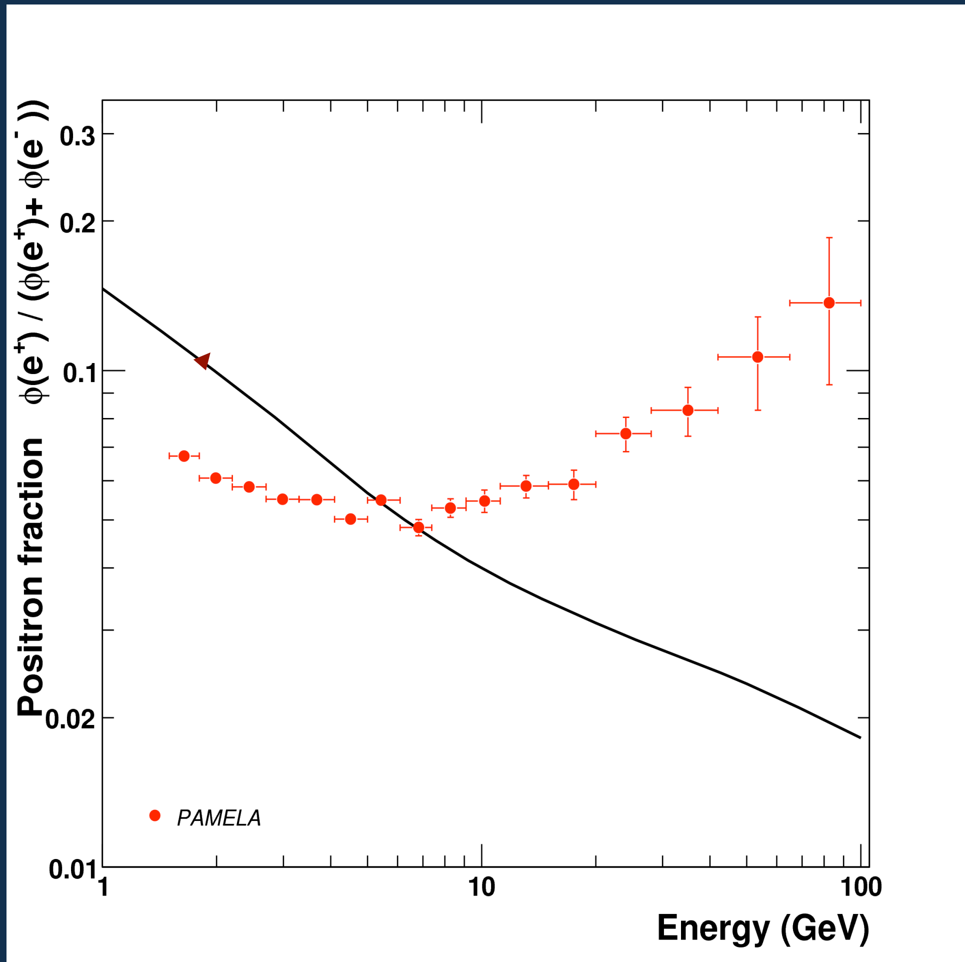
20 years ago

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



Pamela data: steep rise in the positron fraction

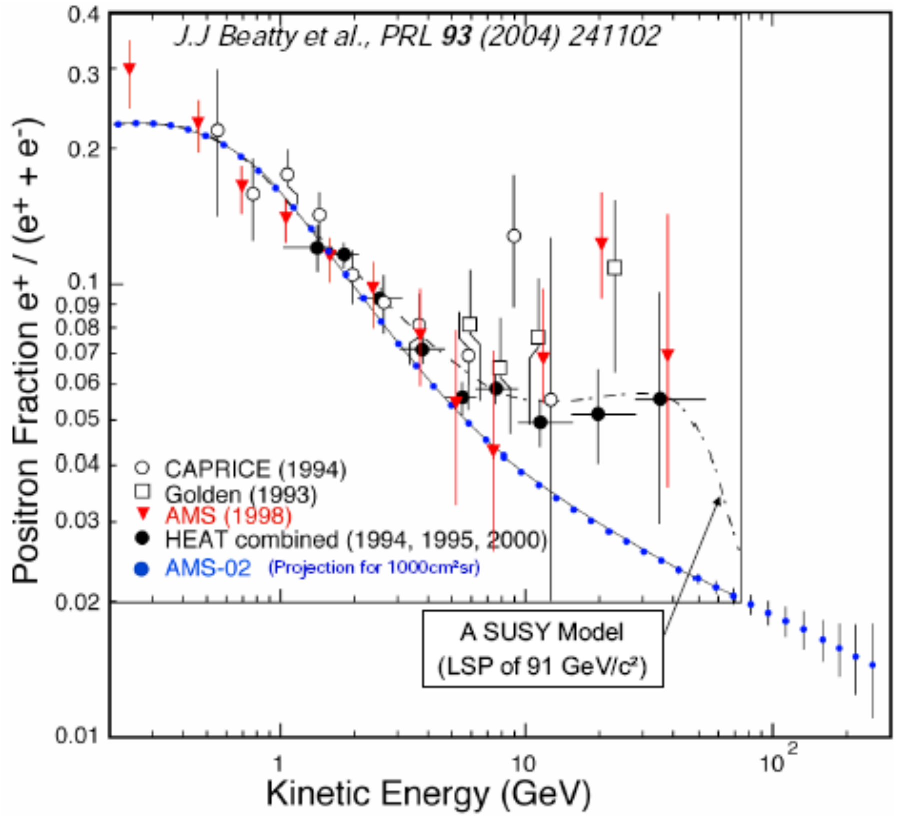
$$R(E) = \frac{\Phi_{e^+}}{\Phi_{e^+} + \Phi_{e^-}}$$



Secondary production model

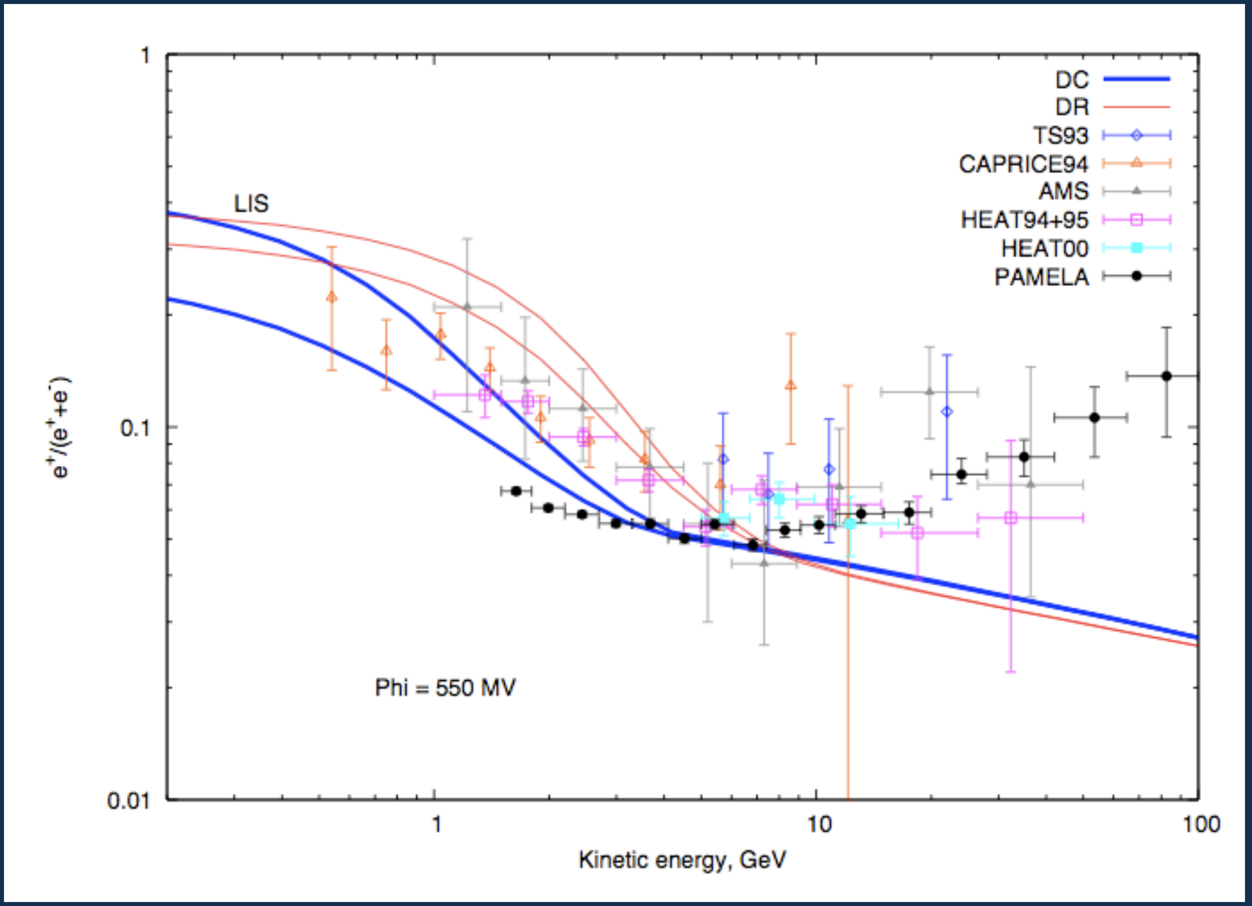
2004
Excess of positrons in primary cosmic rays?

Measurements from AMS (1998) and high-altitude balloon experiments showed more positrons in primary cosmic rays (above the atmosphere) than expected at high energies.



This is well described by models where the neutralino (a particle predicted by supersymmetric theories) constitutes a significant fraction of the Dark Matter of the universe.

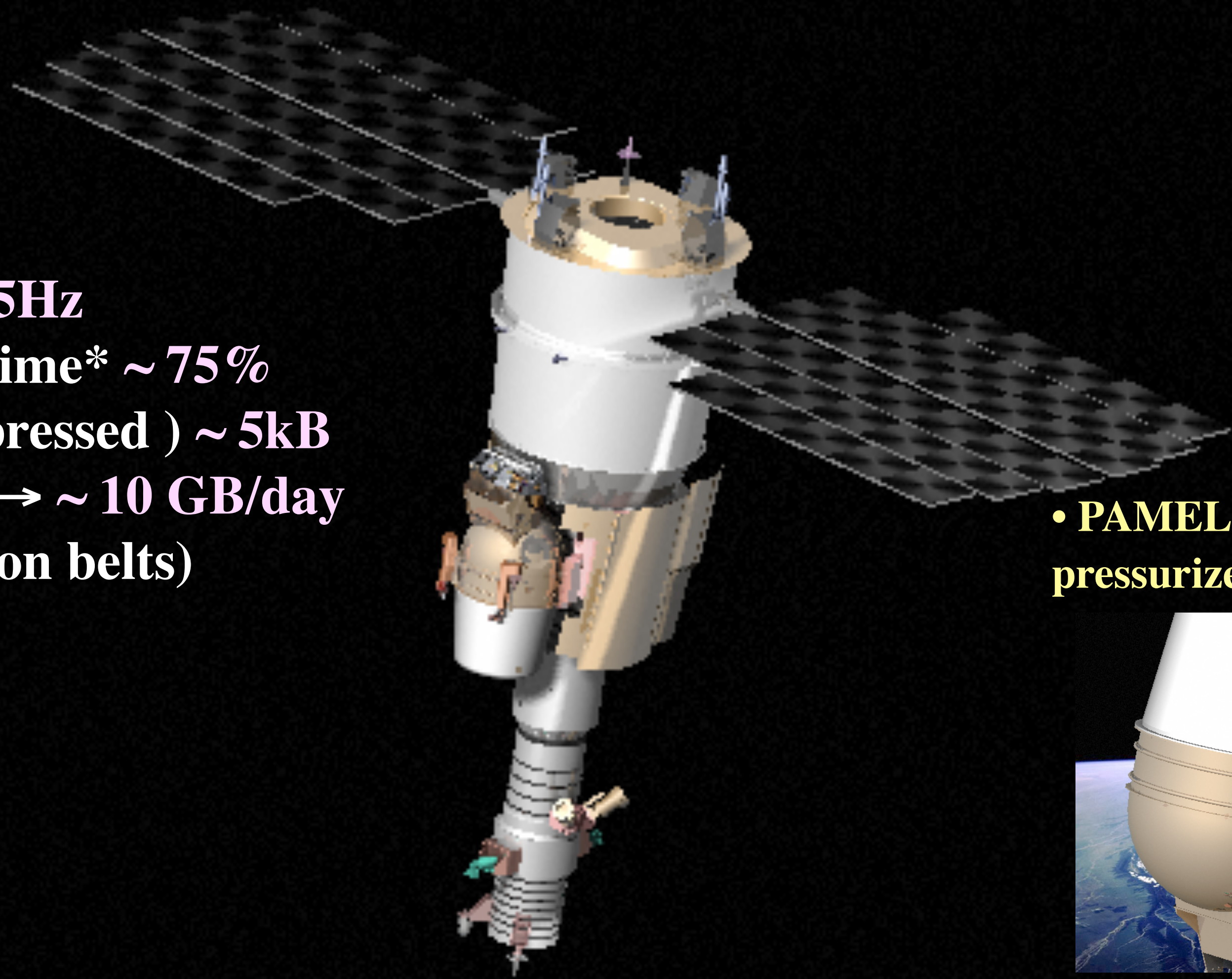
No claim as yet for the ‘discovery’ of the neutralino but an interesting hint.



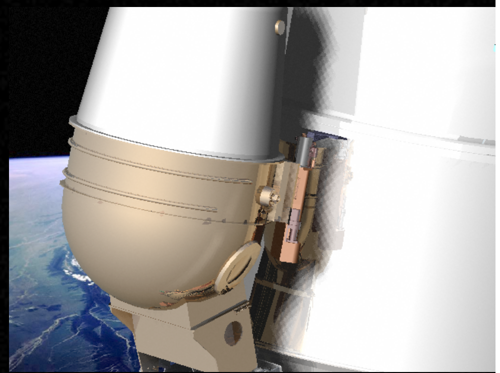
A new source of electrons & positrions that becomes dominant at ~10 GeV

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**

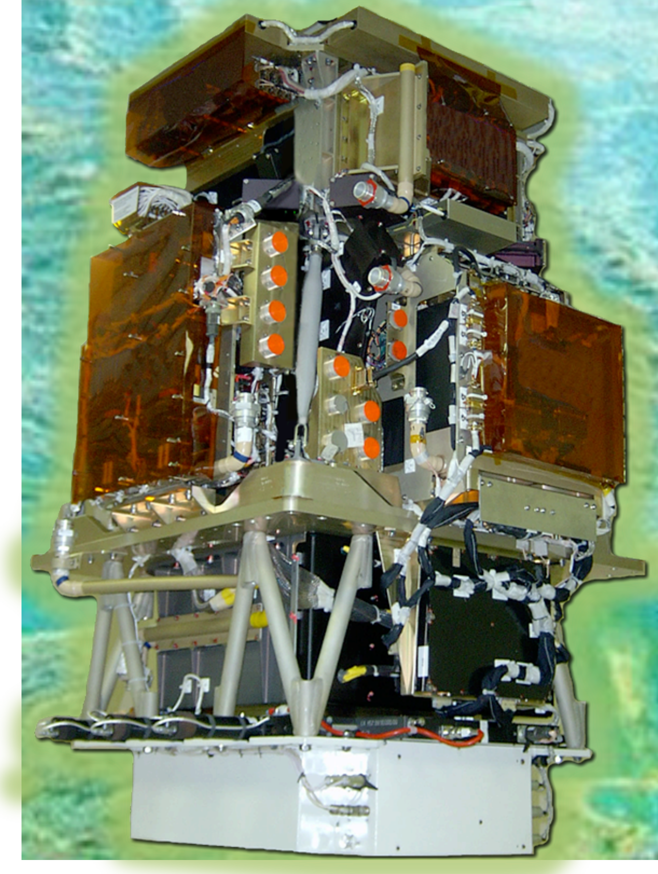
Pamela and *Resurs-DK1 satellite*

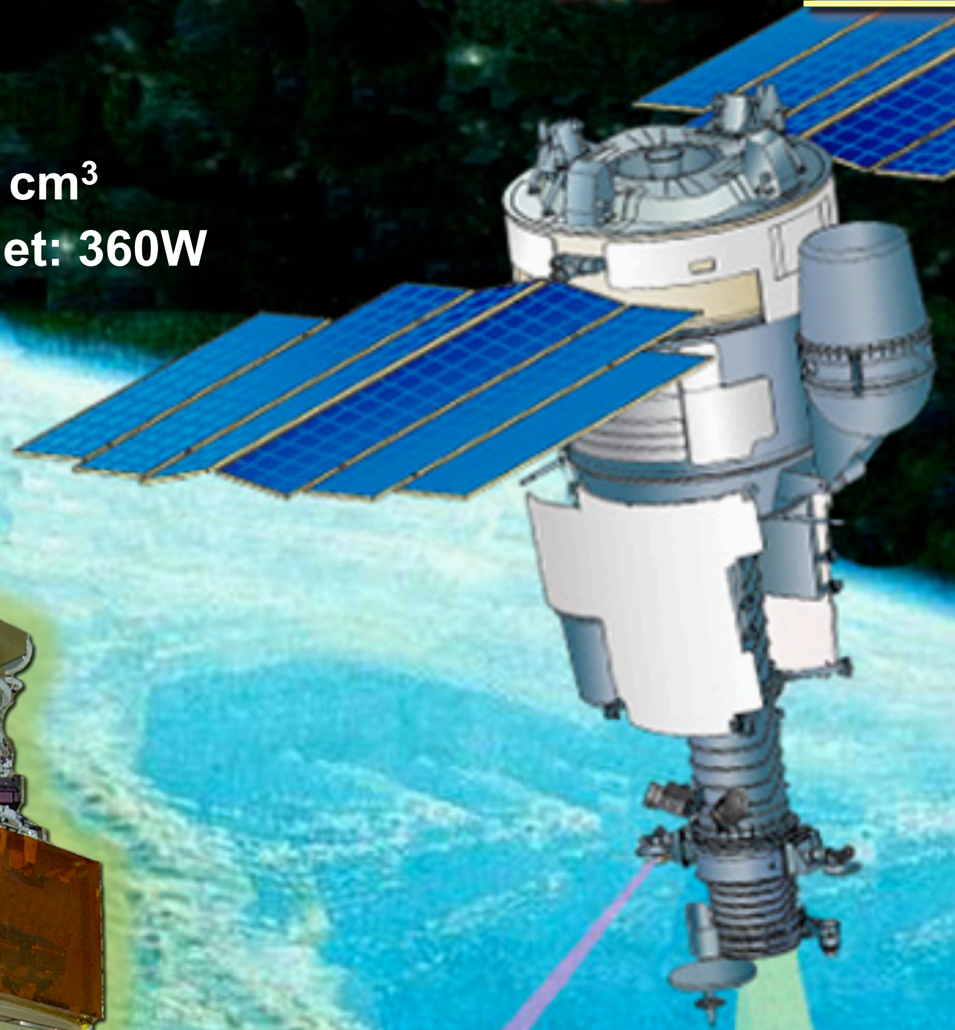
GF: 21.5 cm^2 sr

Mass: 470 kg

Size: 130x70x70 cm^3

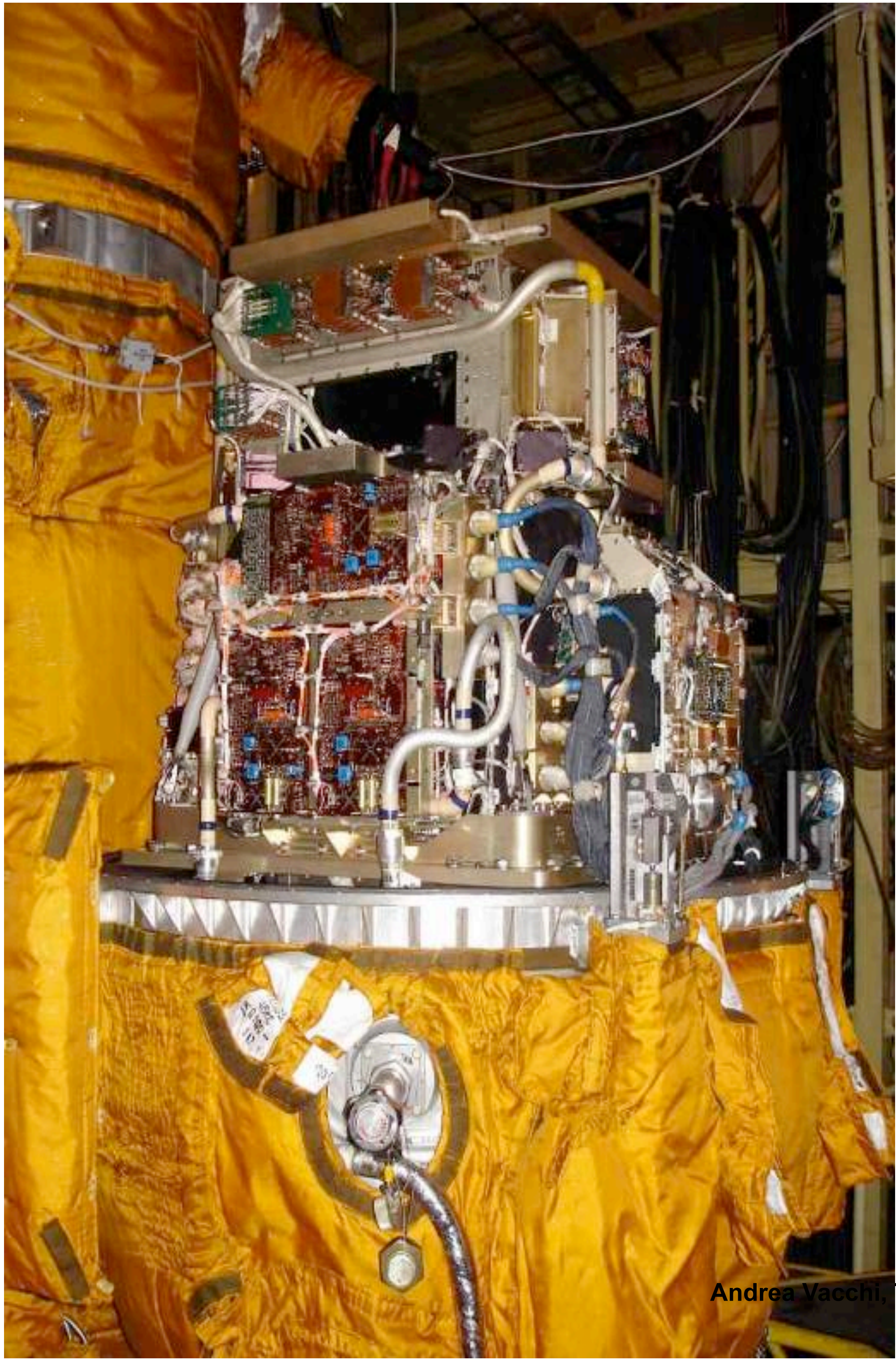
Power Budget: 360W

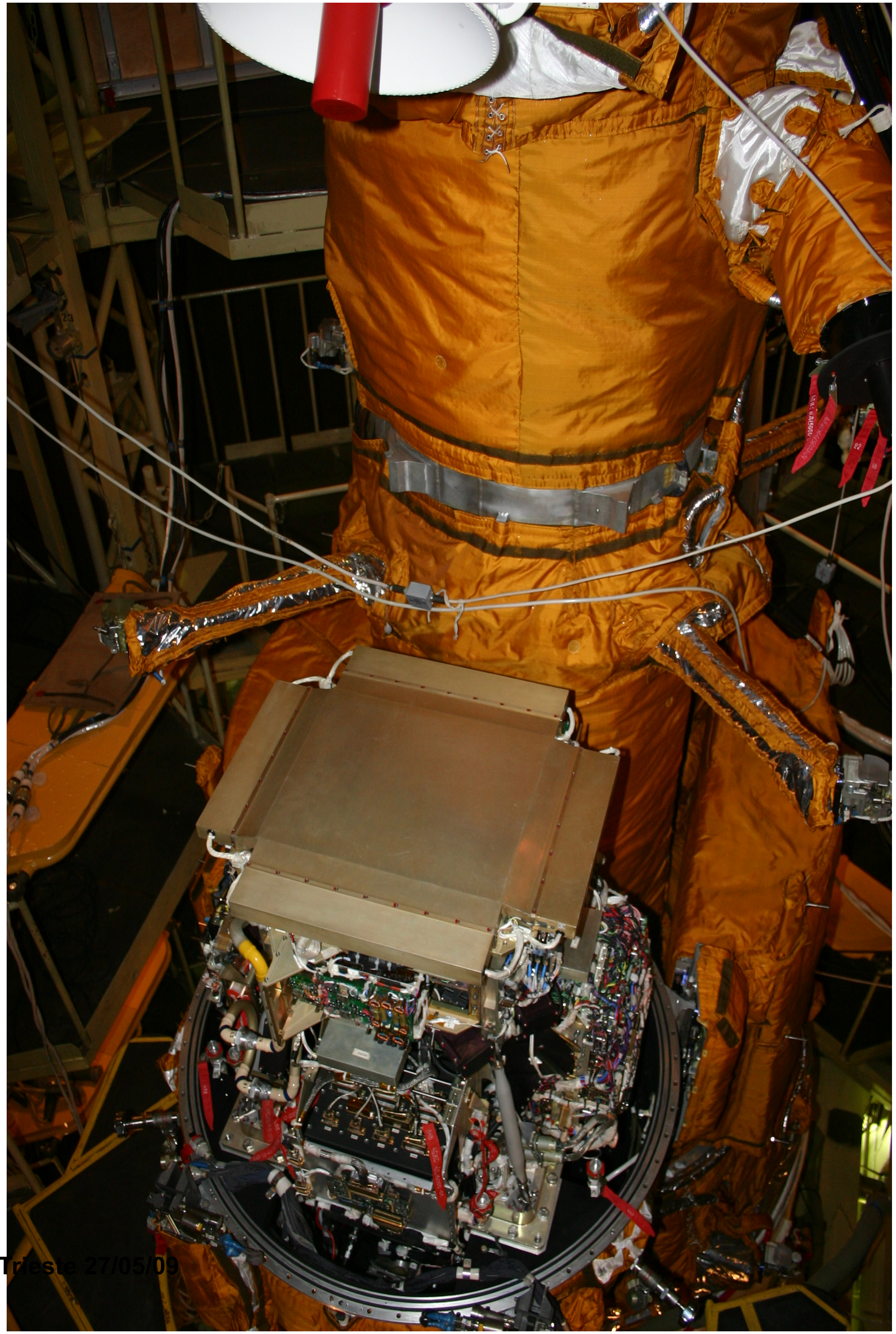




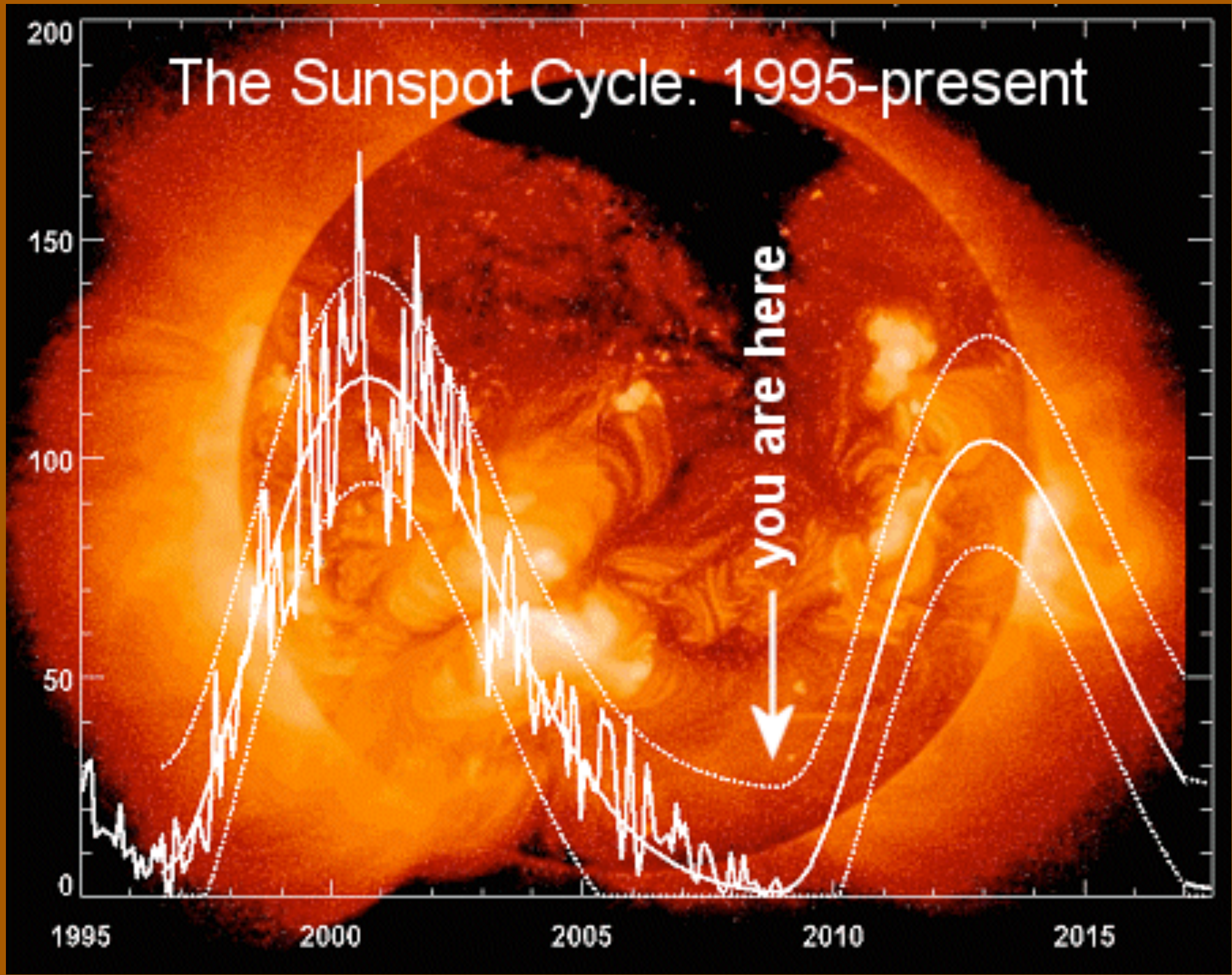
Mass: 6.7 tonnes
Height: 7.4 m
Solar array area: 36 m^2

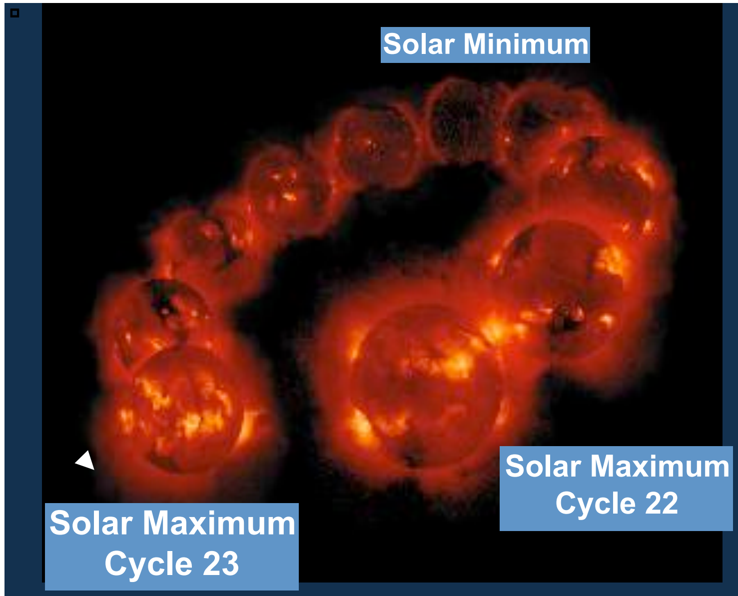
- **Main task: multi-spectral remote sensing of earth's surface**
- **Built by TsSKB Progress in Samara, Russia**
- **Lifetime >3 years (assisted)**
- **Data transmitted to ground via high-speed radio downlink** ~16 GB per day

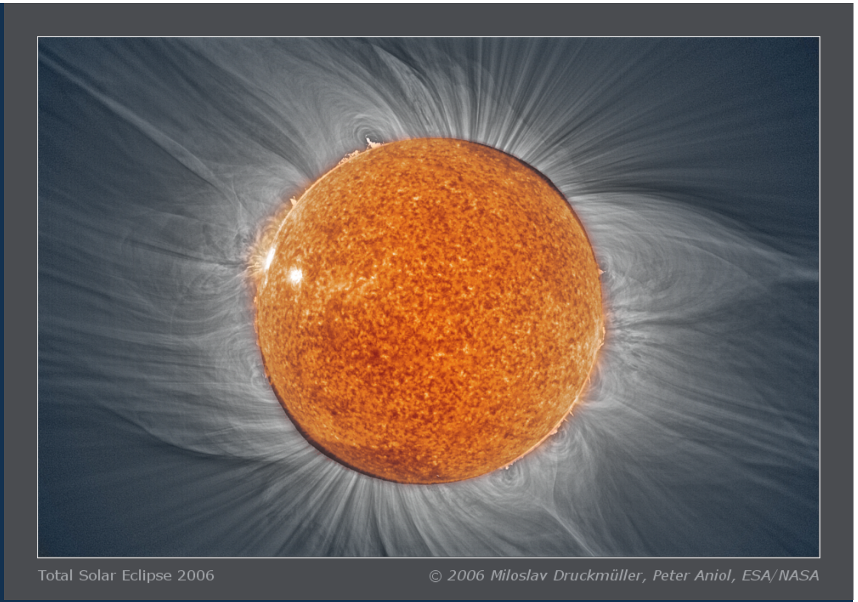


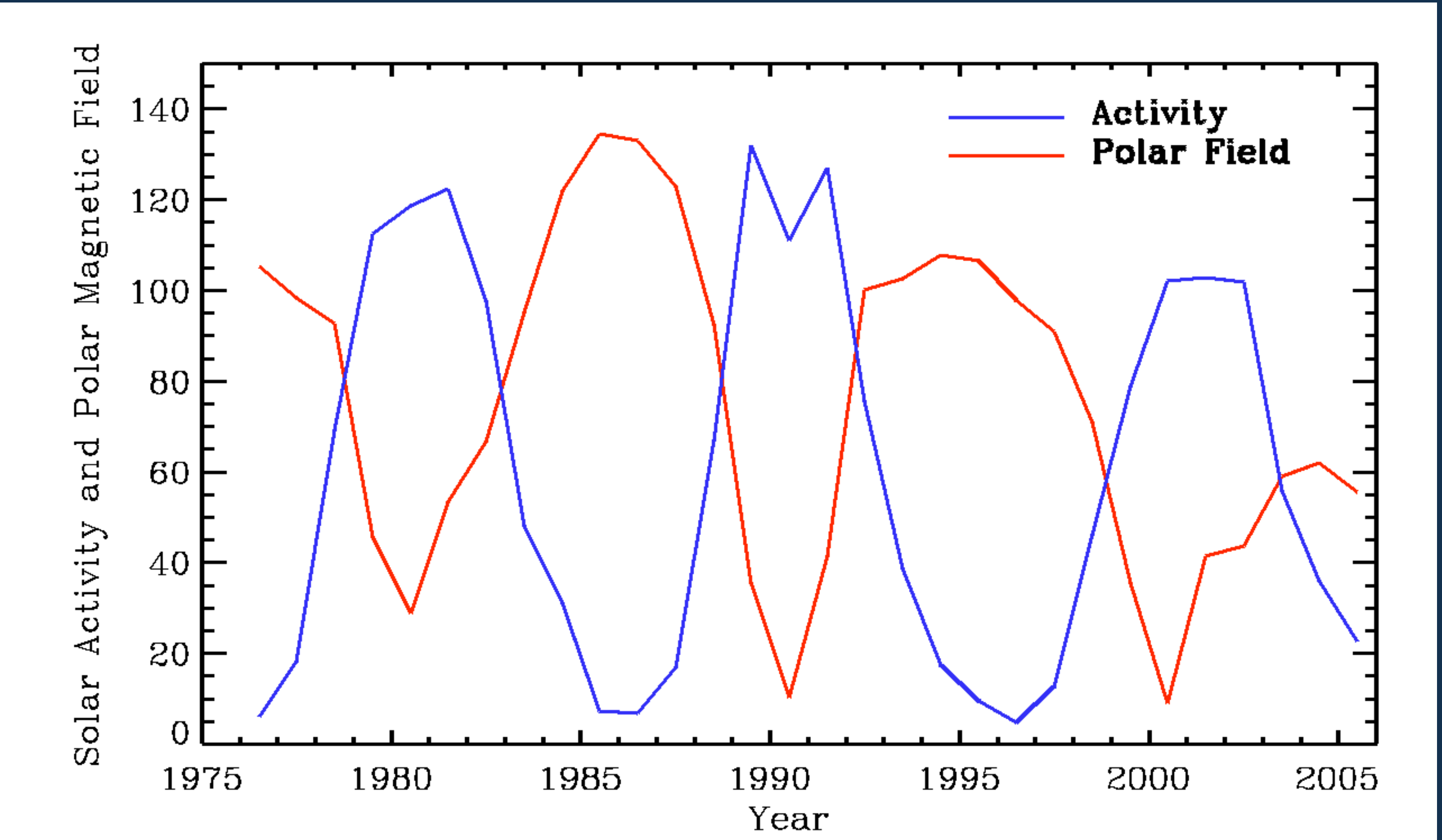


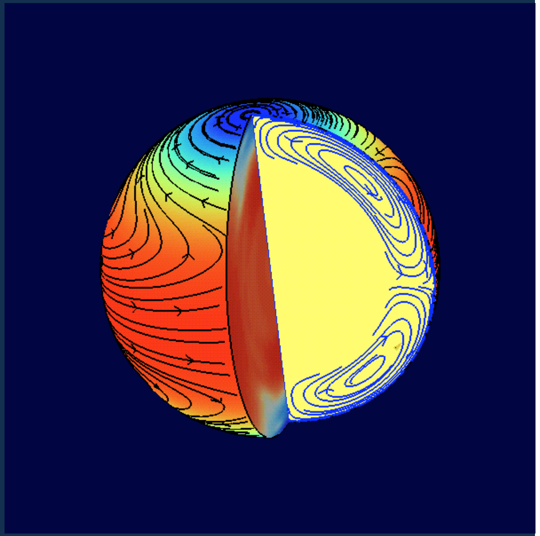
11 years cycle









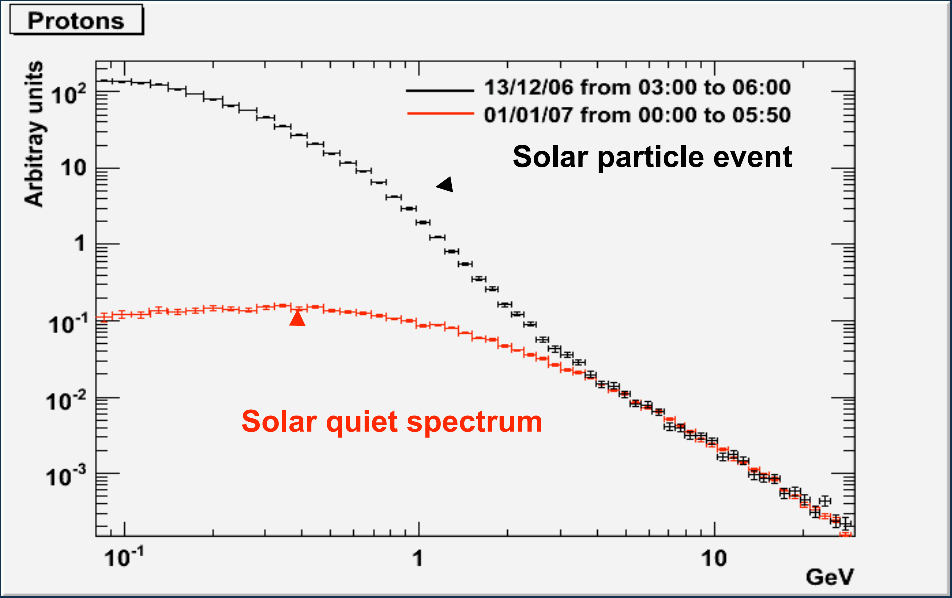


Andrea Vacchi, Trieste 27/05/09

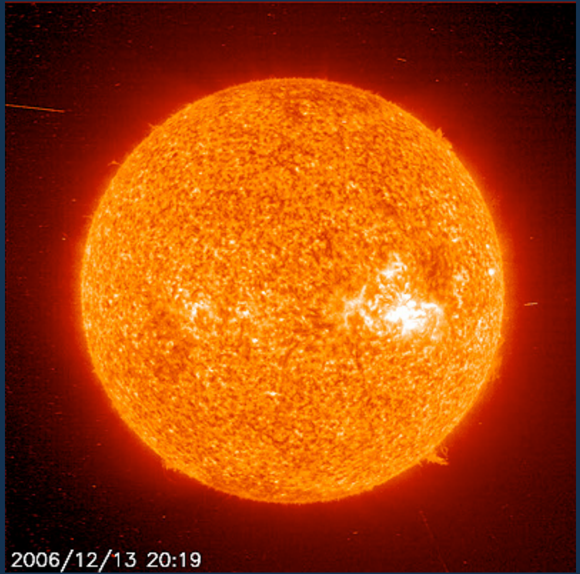
13th Dec. 2006 – solar particle event

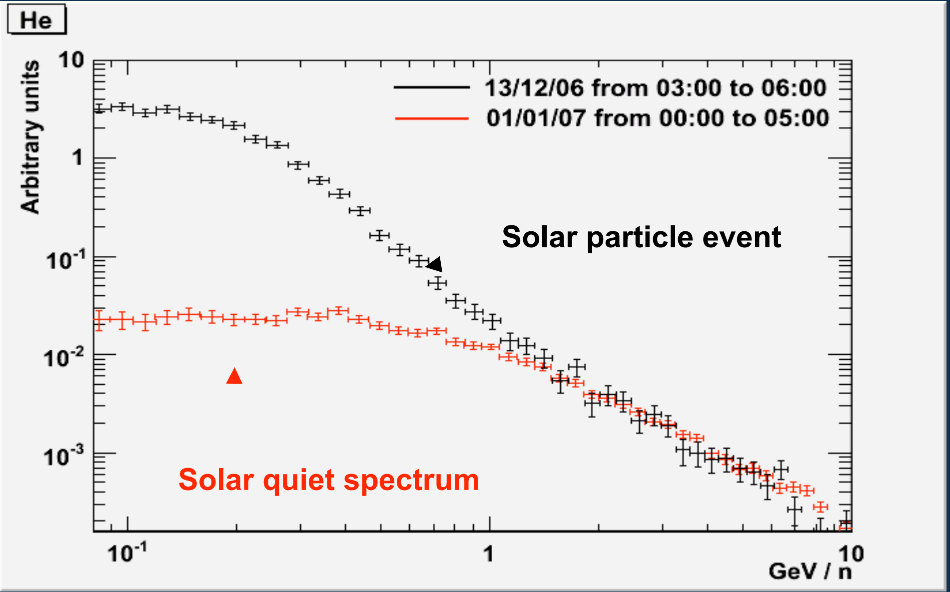
Largest CME since 2003, anomalous at solar minimum

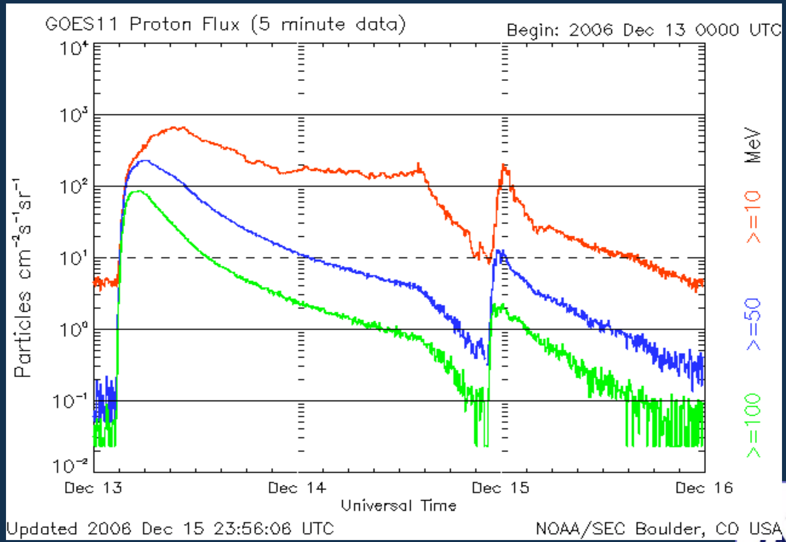
Preliminary



SOHO



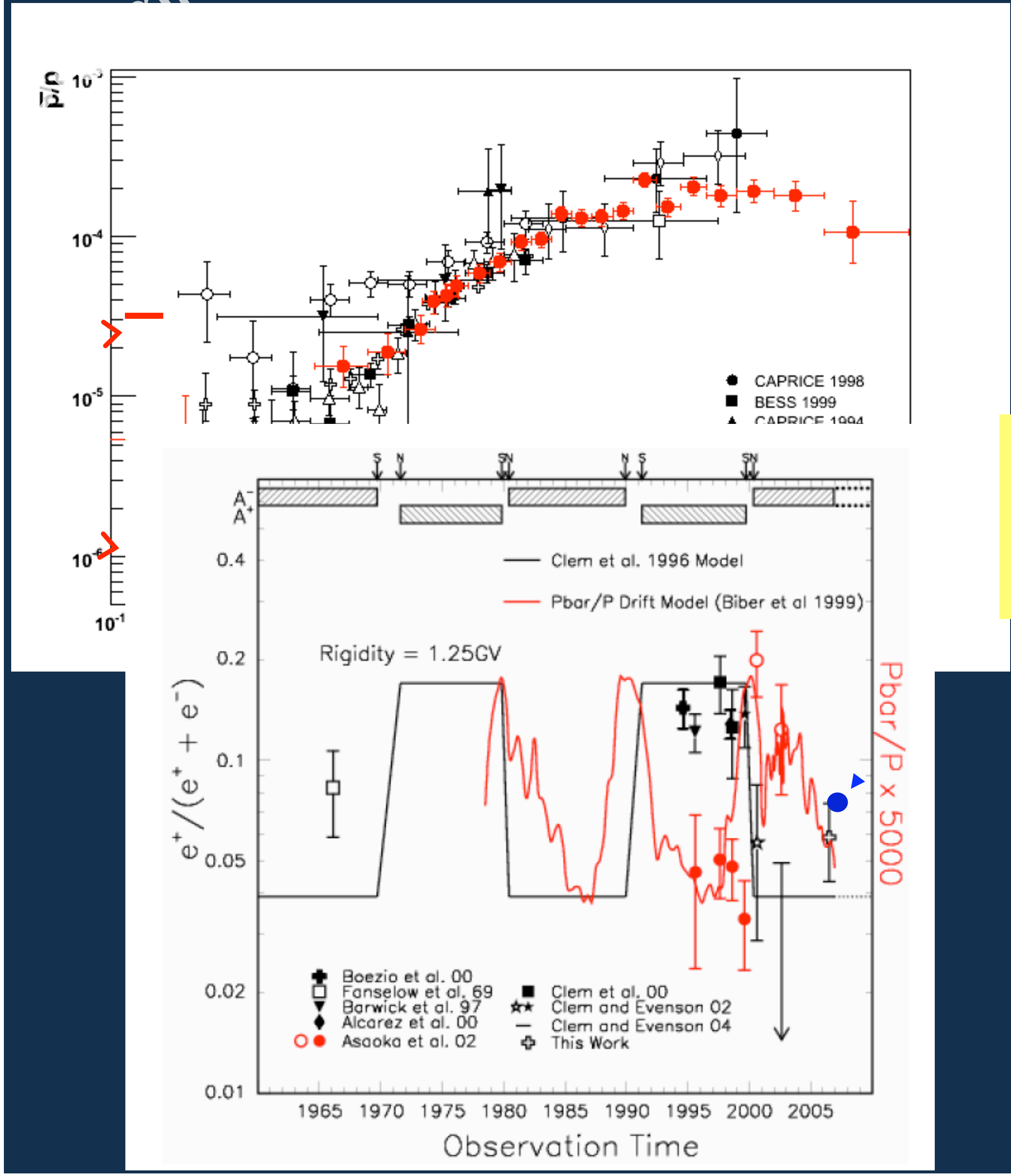


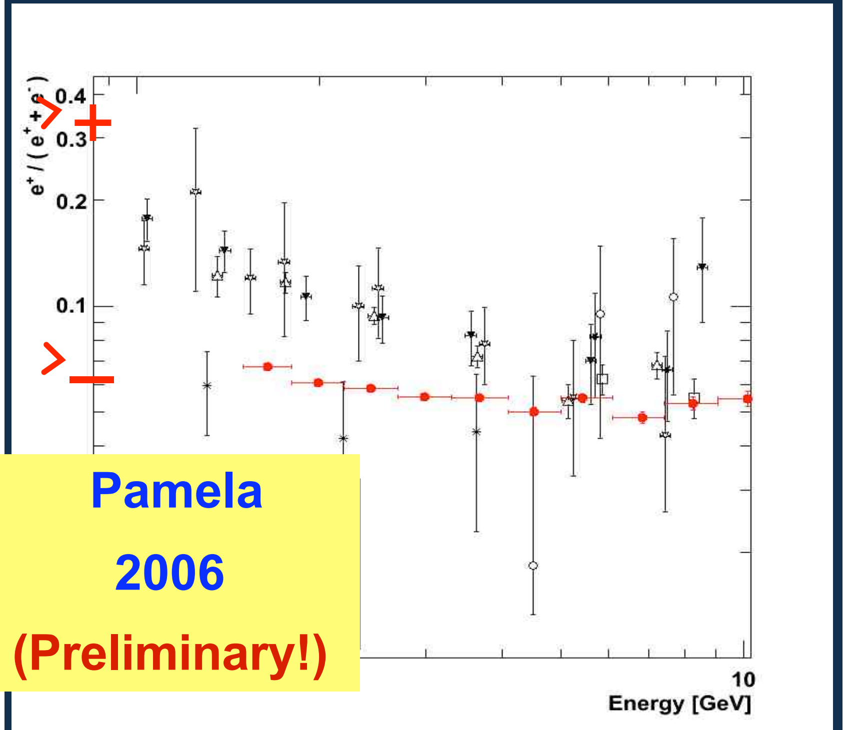


INFN Istituto Nazionale di Fisica Nucleare

Charge dependent solar modulation

minary!!

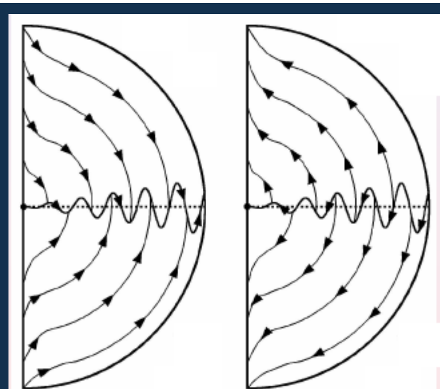




Pamela

2006

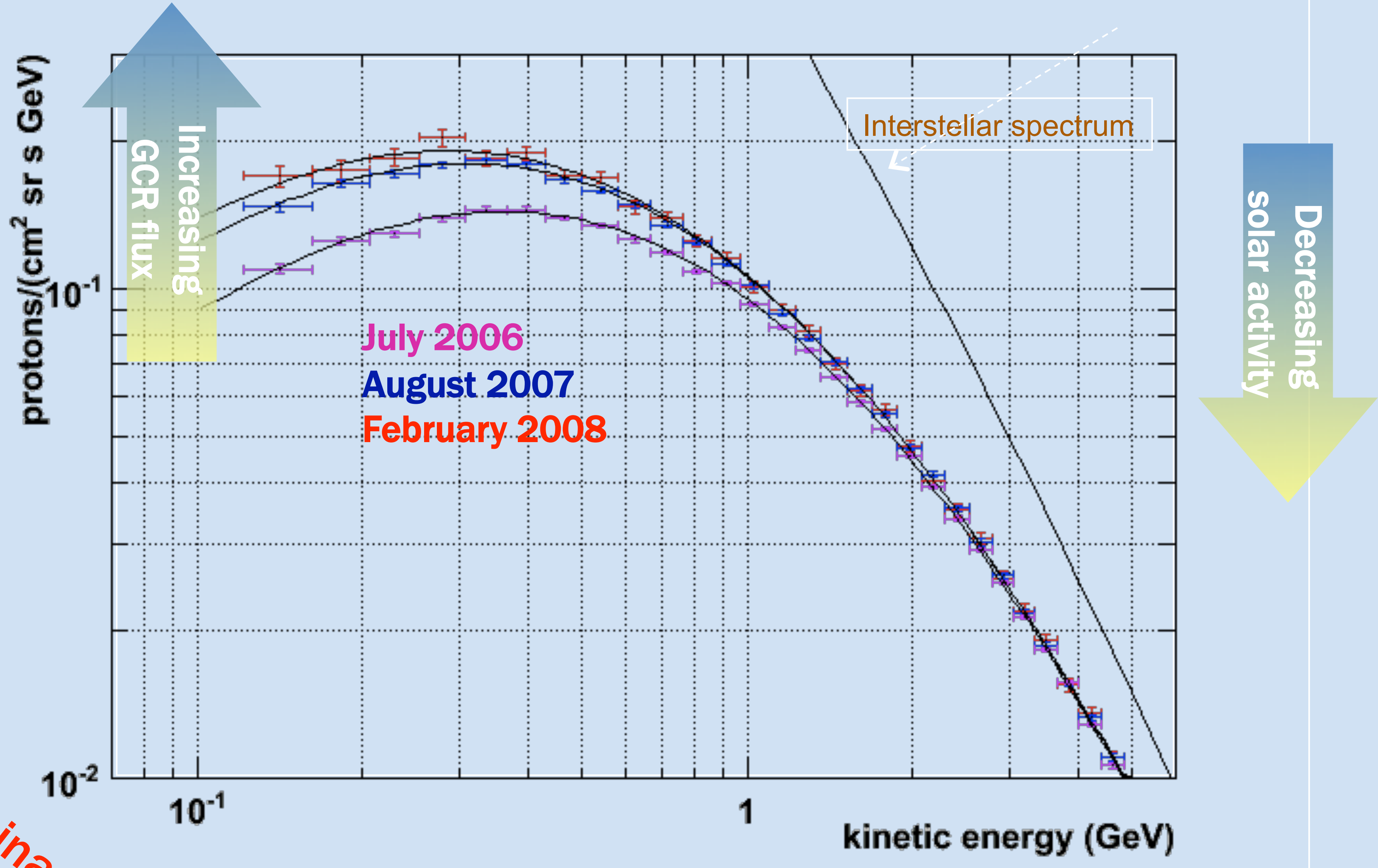
(Preliminary!)



A > 0 **A < 0**

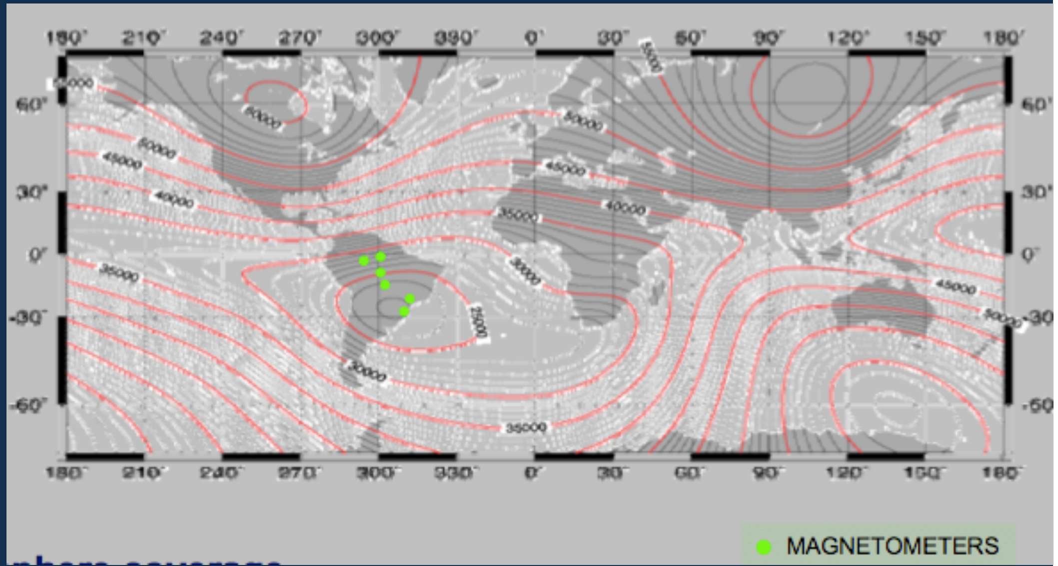
Positive particles

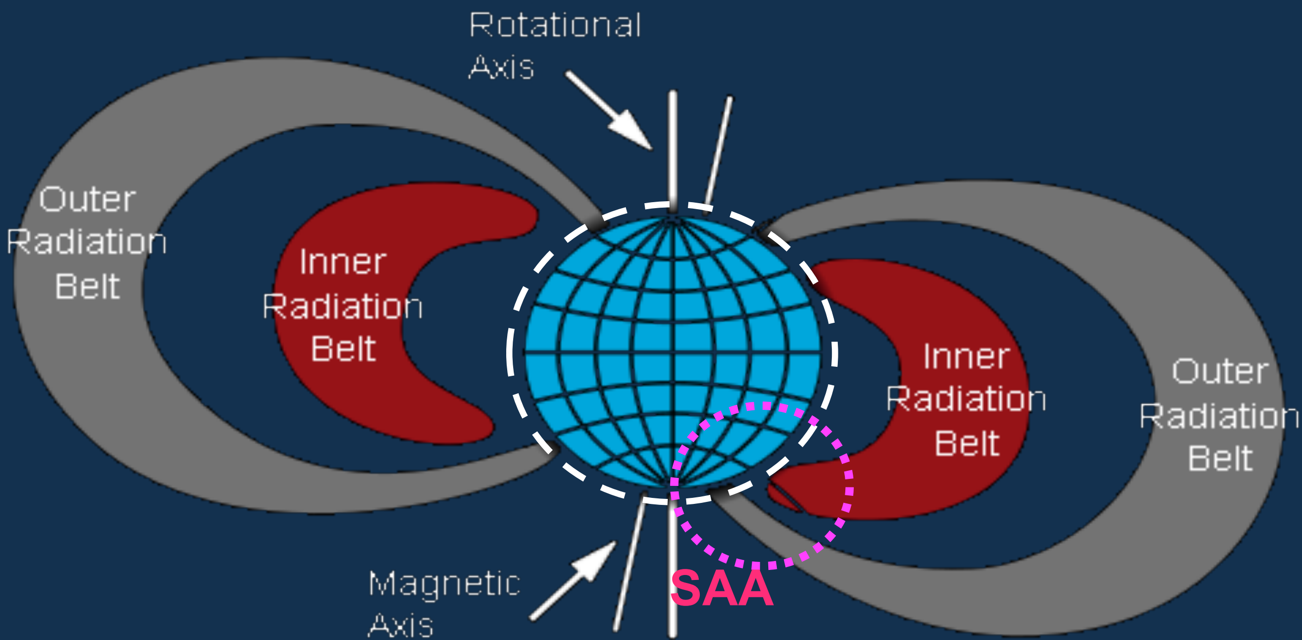
Proton spectra and solar modulation

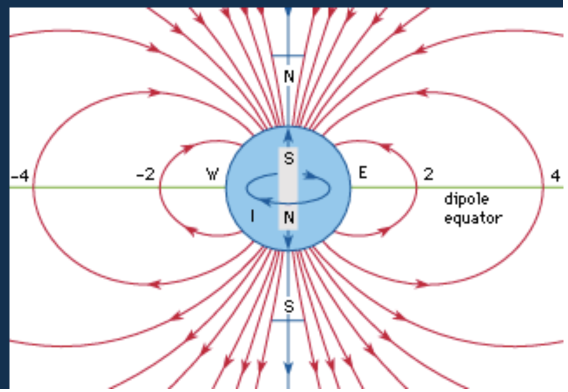


Preliminary

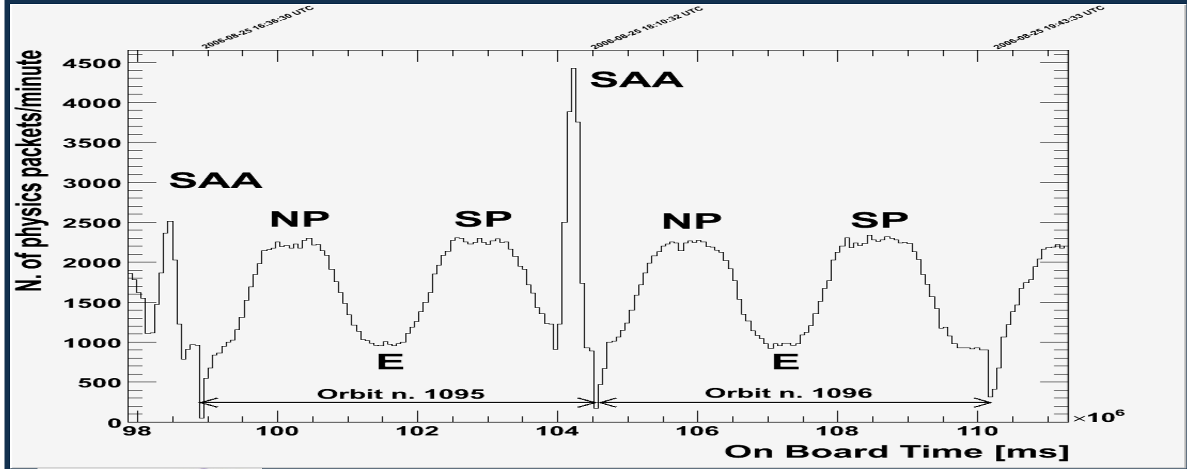
Geomagnetic cut-off

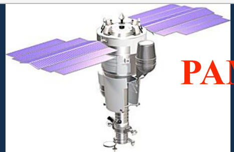


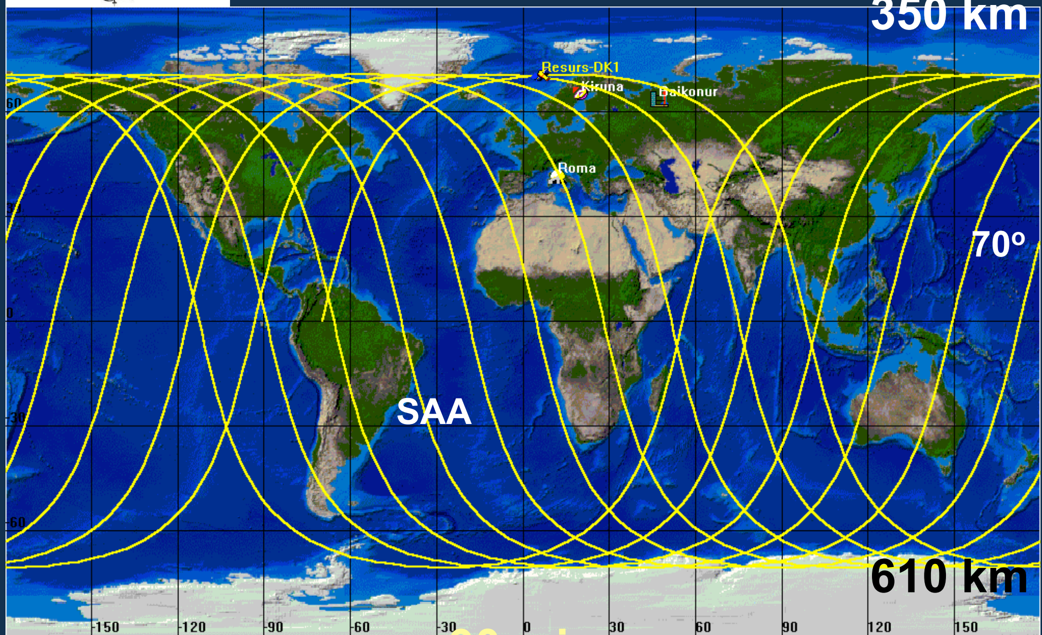




Orbit and geomagnetic cutoff

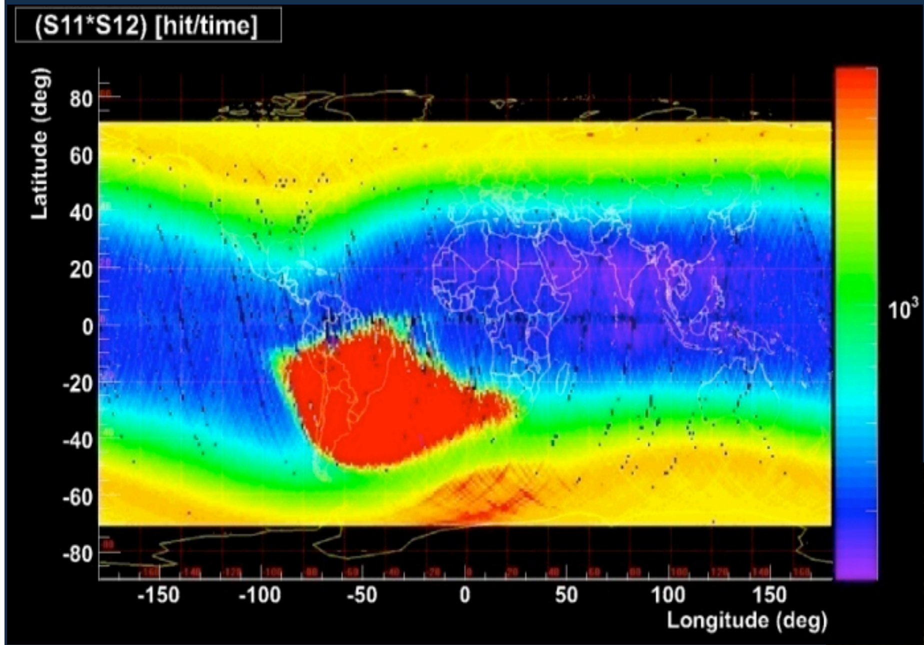




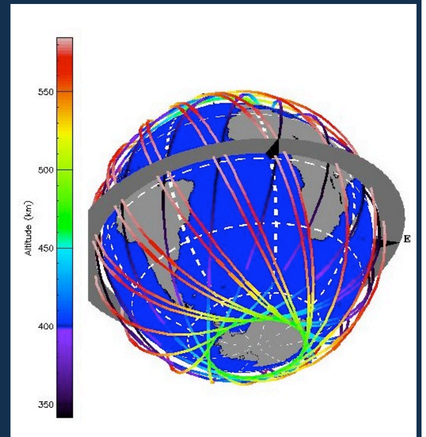


- Quasi-polar and elliptical orbit (70.0°, 350 km - 600 km)
- Traverses the South Atlantic Anomaly
- Crosses the outer (electron) Van Allen belt at south pole
- 3 axis stabilization. Information about the satellite attitude is know with accuracy ~1 degree

PAMELA in the magnetosphere



Satellite ResursDK №1 has elliptical orbit : 350- 610km with inclination ~70^0



Count rate of top PAMELA counter:
low energy ~MeV protons rate.
Polar region , Equatorial region and South Atlantic Anomaly (SAA) are clearly seen

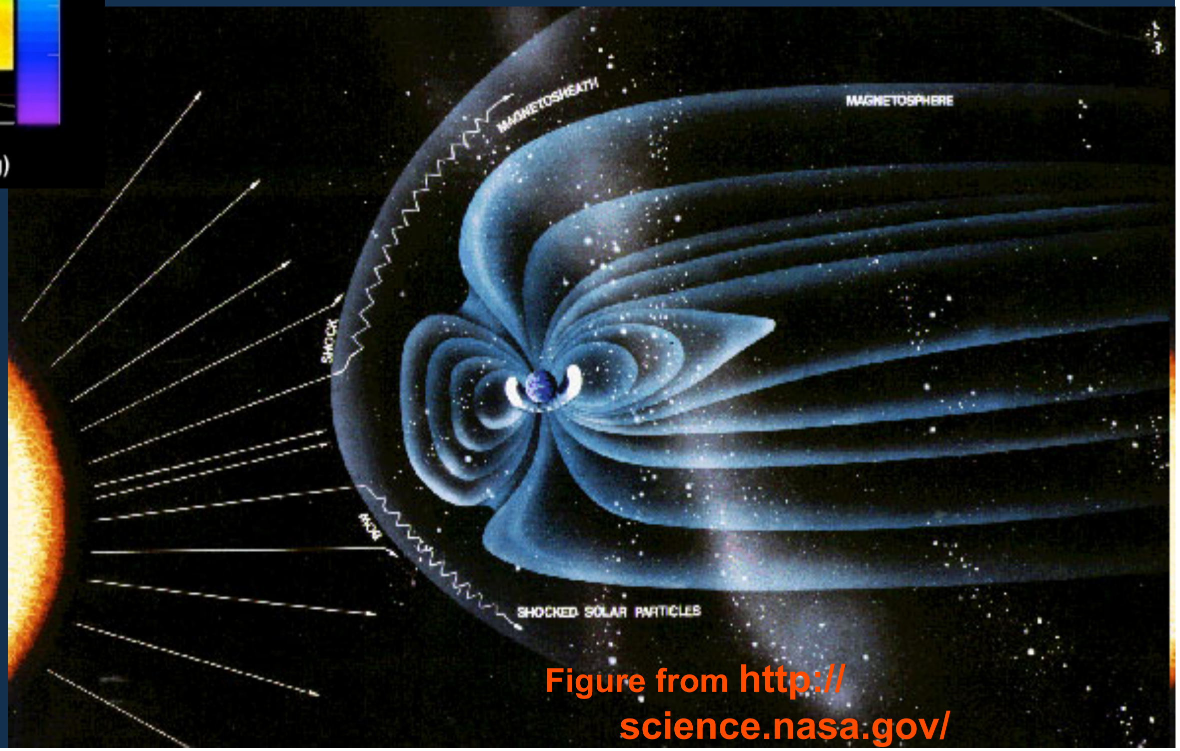
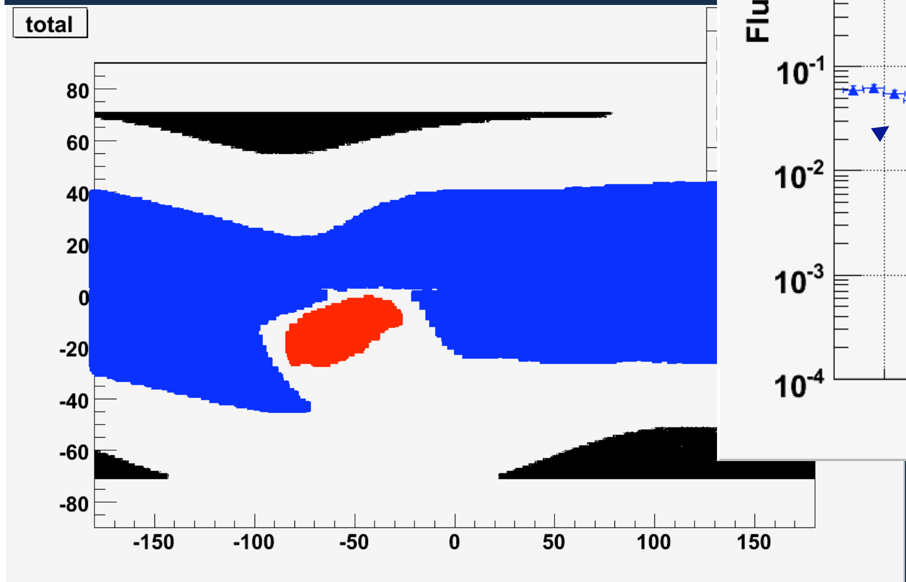
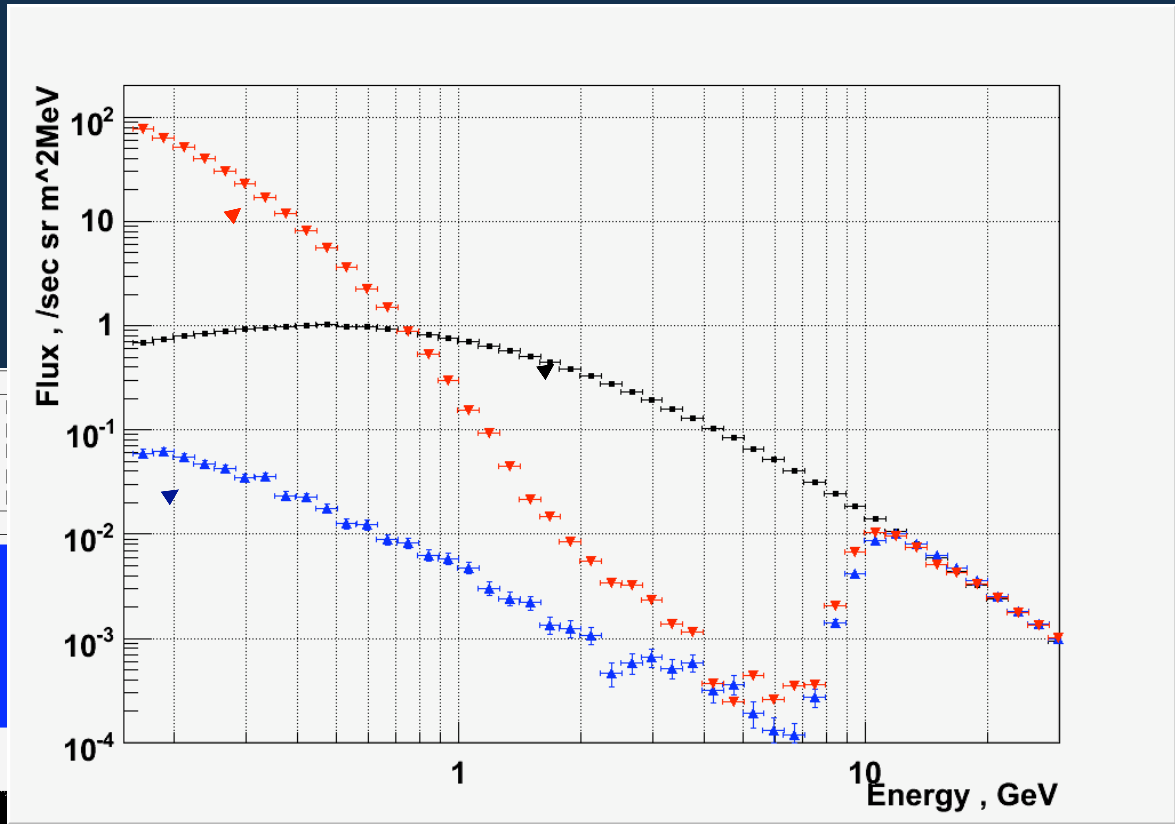


Figure from http:// science.nasa.gov/

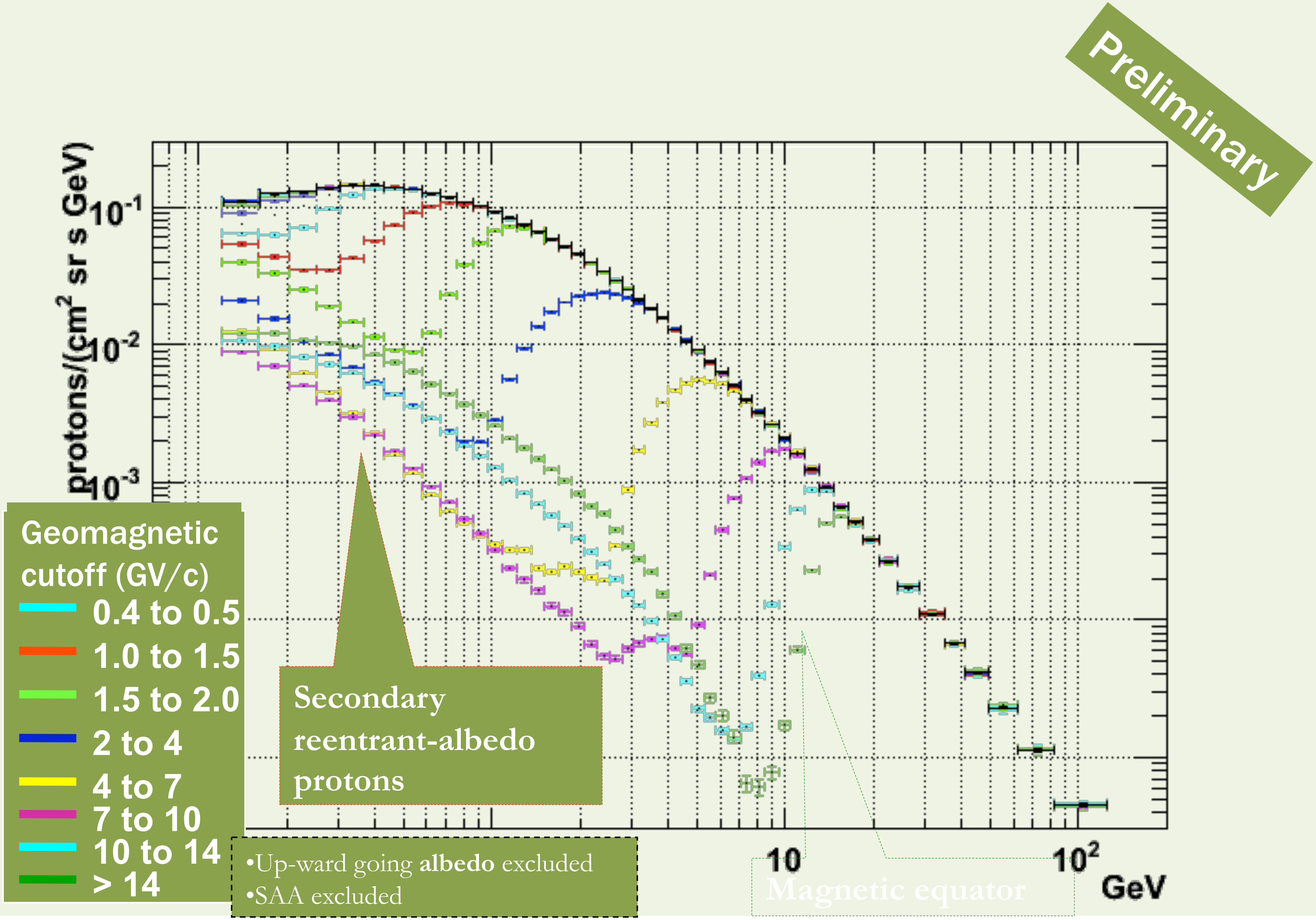
Proton spectrum in the SAA, polar and equatorial regions



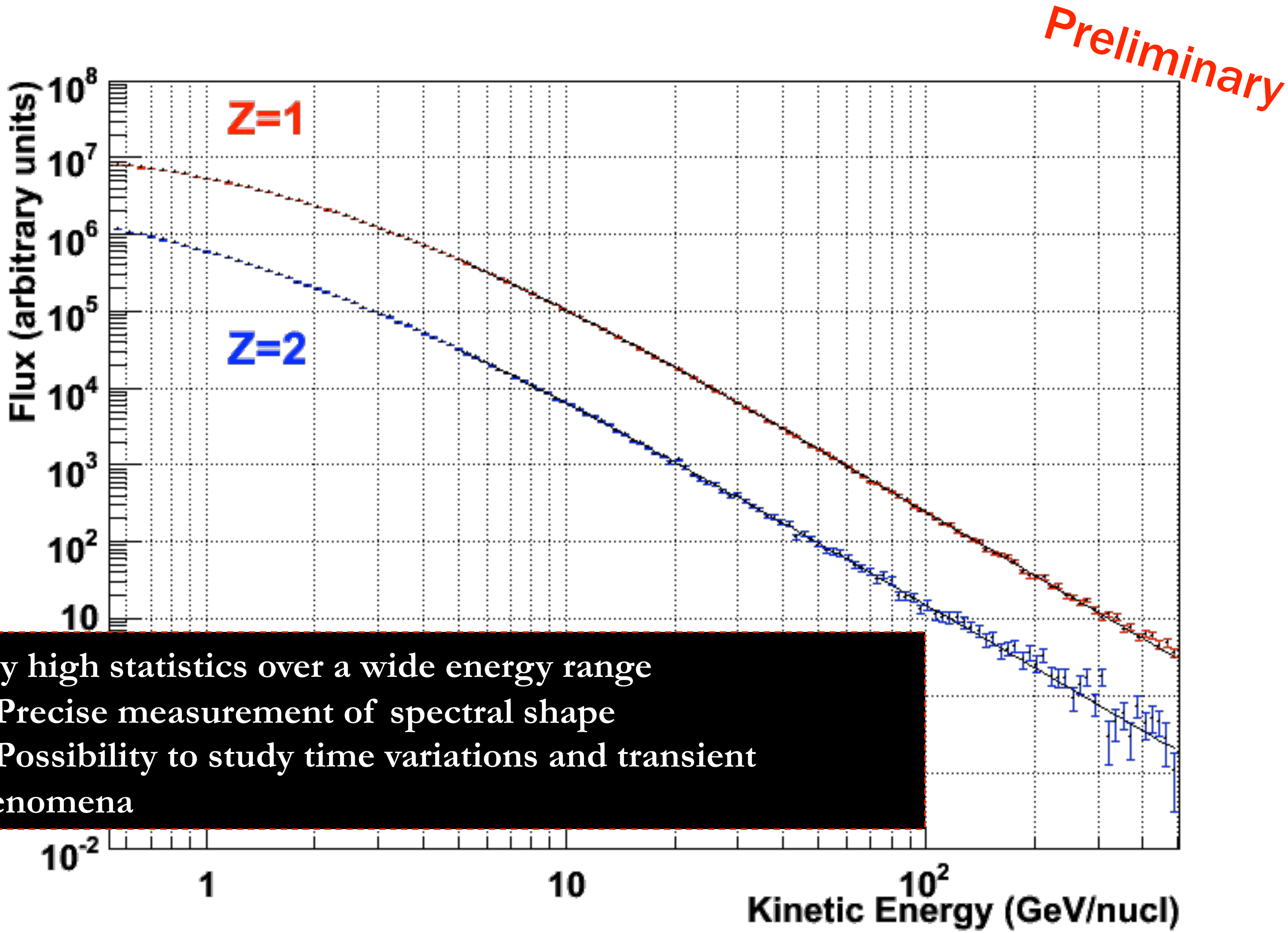


At low energy
Proton Spectra are affected by geomagnetic field at middle latitudes.

Primary and Albedo (sub-cutoff) measurements



Proton and Helium spectra



Very high statistics over a wide energy range

→ Precise measurement of spectral shape

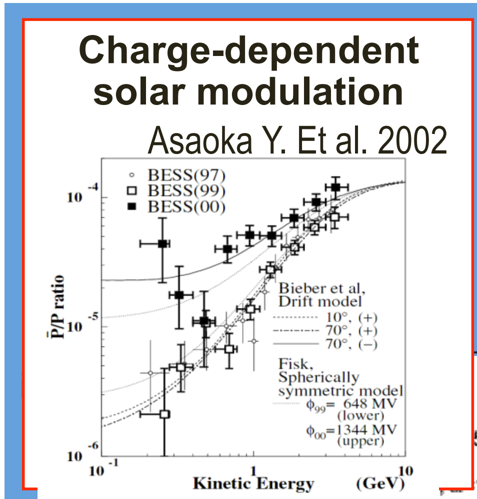
→ Possibility to study time variations and transient phenomena

PAMELA Design Performance

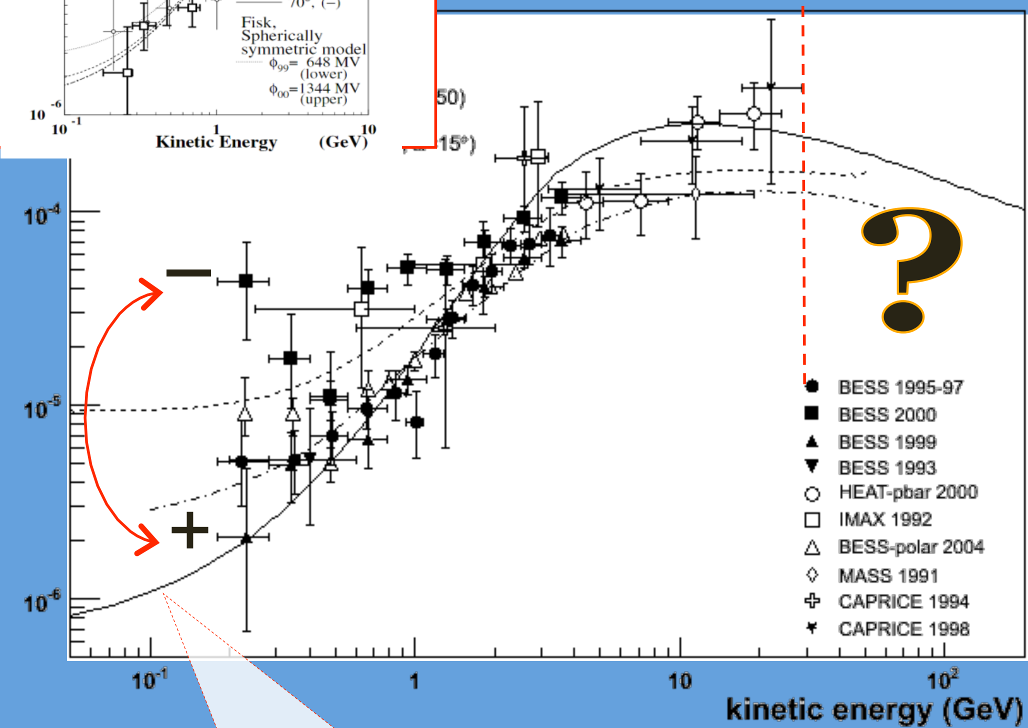
→ Simultaneous measurement of many cosmic-ray species
→ New energy range
→ Unprecedented statistics
→ Constrain secondary production models

	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 He / He		

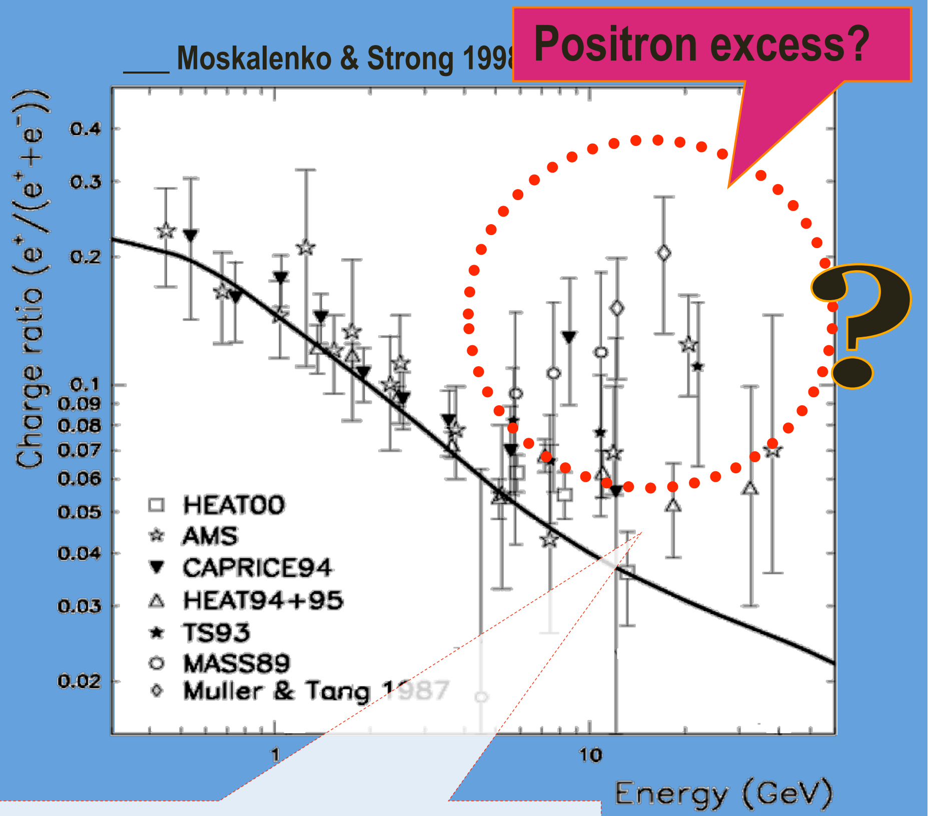
CR antimatter status BP



Antiprotons



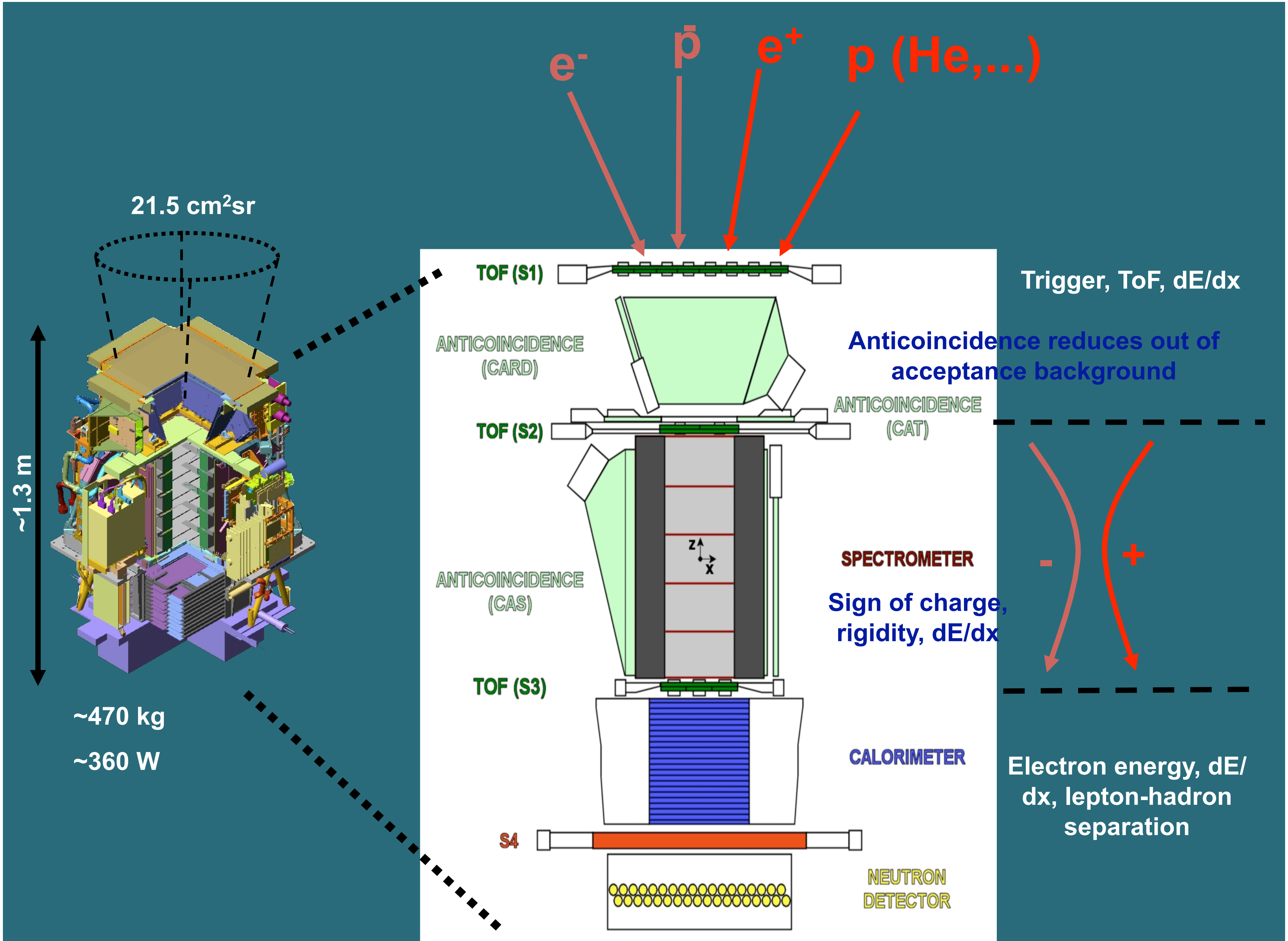
Positrons

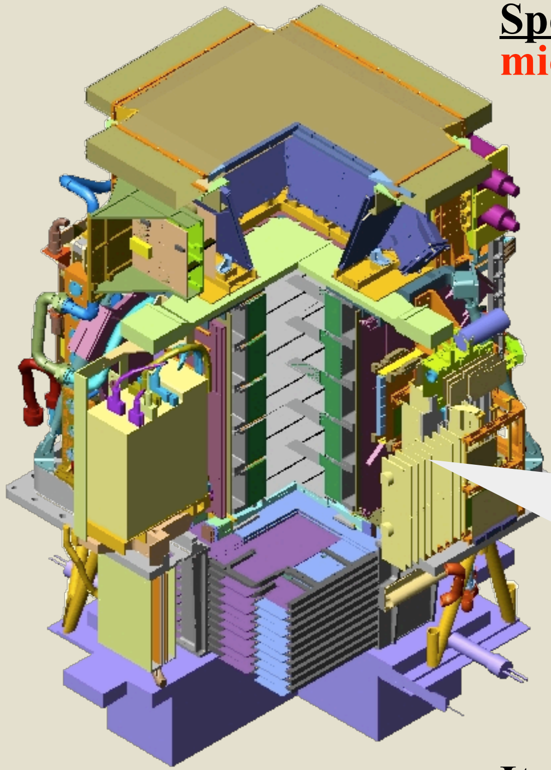


CR + ISM → **p-bar** + …
kinematic treshold:
5.6 GeV for the reaction

$$pp \rightarrow \bar{p}ppp$$

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


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



Spectrometer

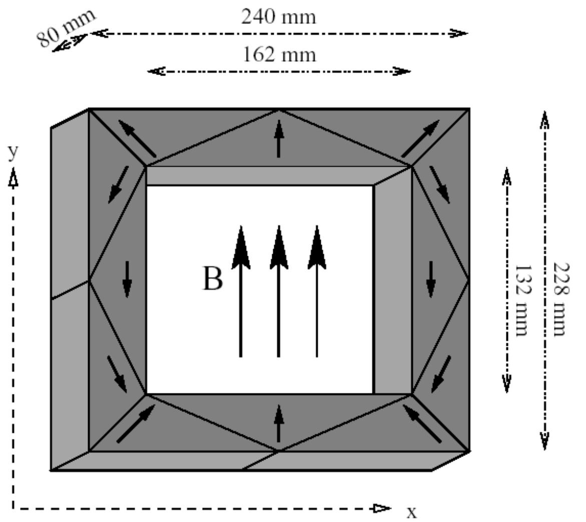
microstrip silicon tracking system + permanent magnet

•Characteristics:

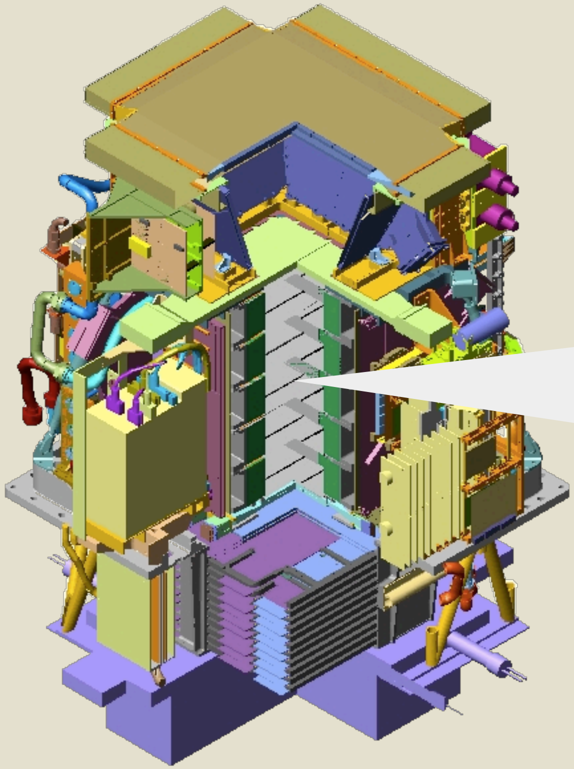
- **5 modules of permanent magnet (Nd-B-Fe alloy) in aluminum mechanics**
- Cavity dimensions (162 x 132 x 445) cm^3
- → **GF ~ 21.5 cm^2sr**
- Magnetic shields
- 5mm-step field-map on ground:
  - **B=0.43 T (average along axis),**
  - **B=0.48 T (@center)**

It provides:

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



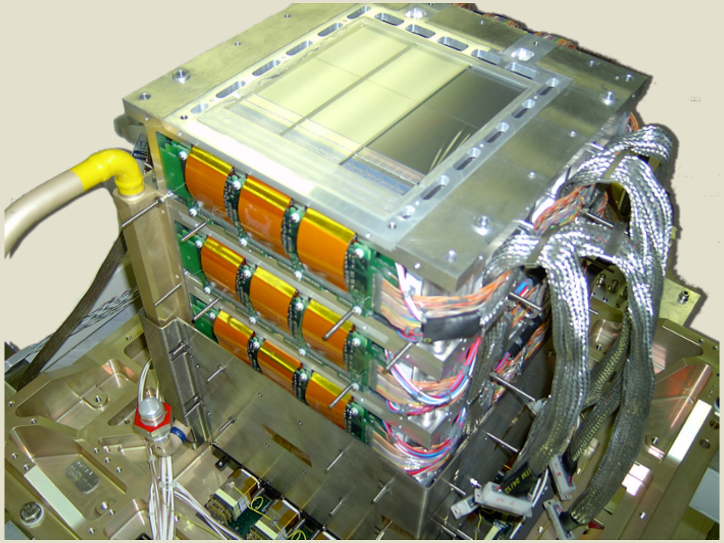
The tracking system

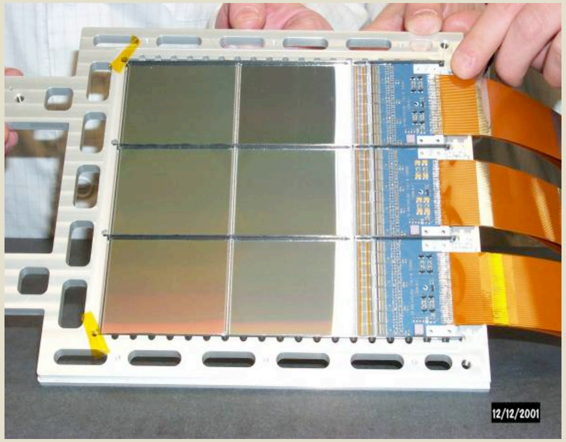


- **Main tasks:**
- **Rigidity measurement**
- **Sign of electric charge**
- **dE/dx (ionisation loss)**

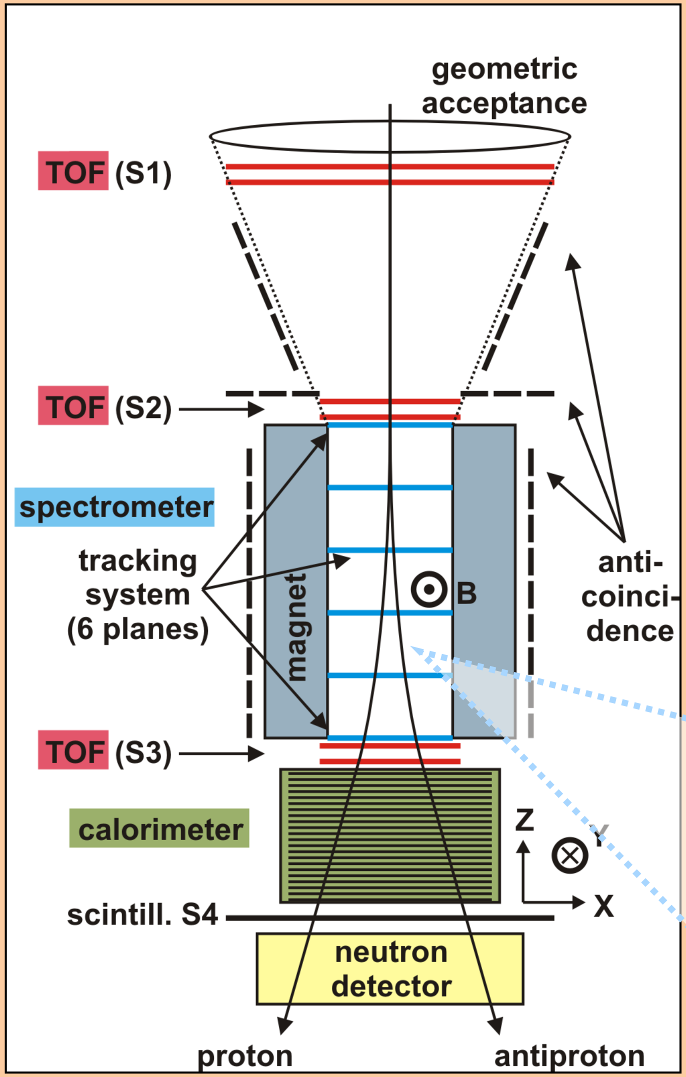
- **Characteristics:**
- **6 planes double-sided (x&y view) microstrip Si sensors**
- 36864 channels
- Dynamic range: 10 MIP

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



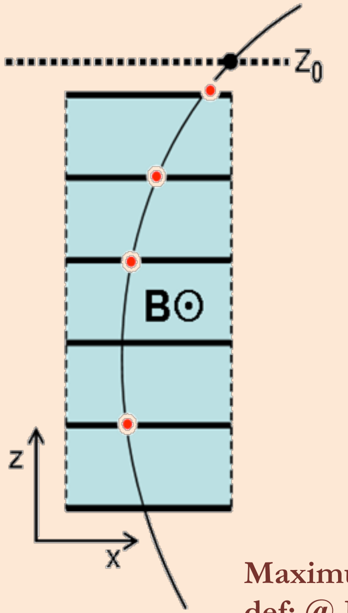


Principle of operation



Track reconstruction

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



Iterative χ^2 minimization as a function of track state-vector components α

Magnetic deflection

$|\eta| = 1/R$

$R = pc/Ze$ → magnetic rigidity

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

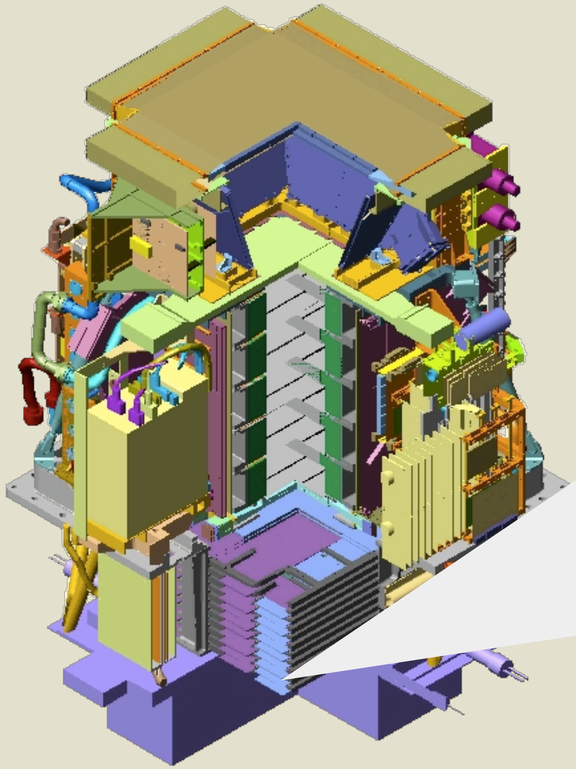
Maximum Detectable Rigidity (MDR)

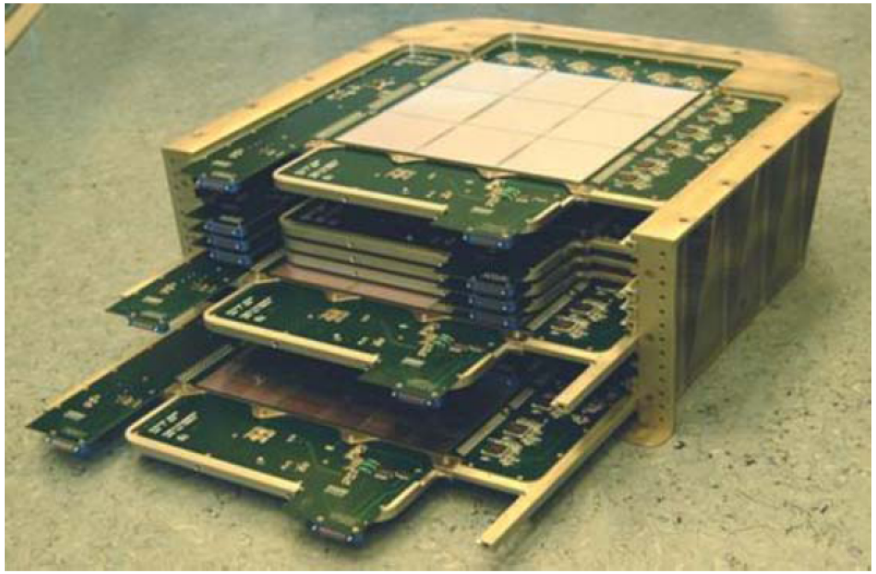
def: @ R=MDR ⇒ $\sigma_R/R=1$

$MDR = 1/\sigma_\eta$

- Measured @ground with protons of known momentum → MDR~1TV
- Cross-check in flight with protons (alignment) and electrons (energy from calorimeter)

The electromagnetic calorimeter





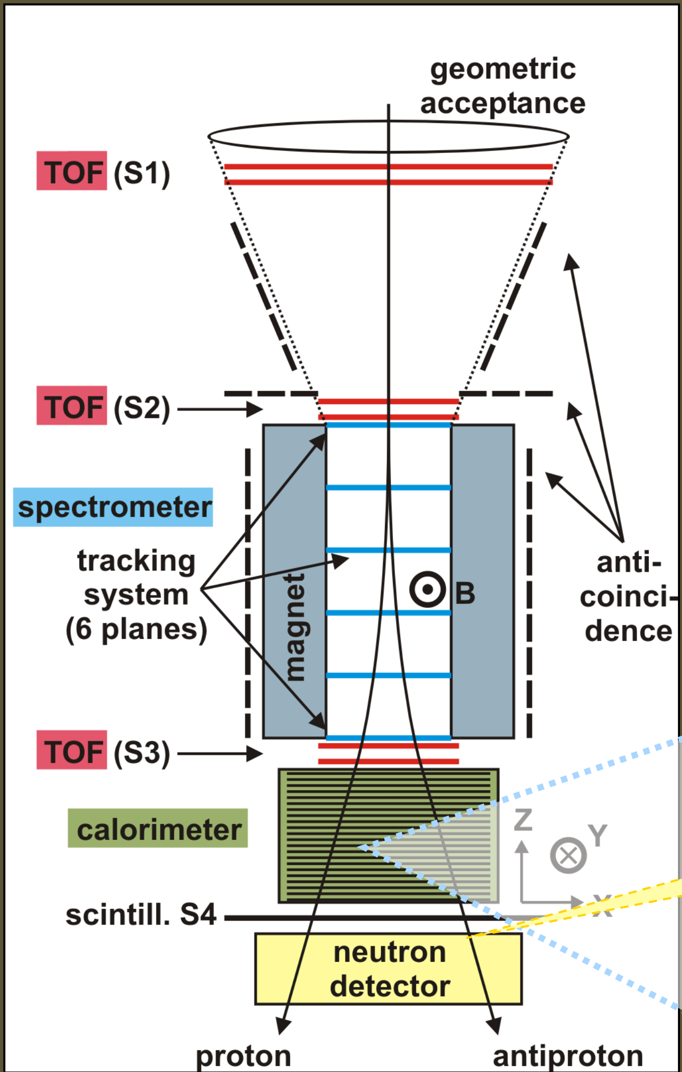
- **Main tasks:**
- lepton/hadron discrimination
- $e^{+/-}$ energy measurement

- **Characteristics:**
- 44 Si layers (x/y) + 22 W planes
- 16.3 X_o / 0.6 λ_L
  - 22 W absorbers 0.26 cm/0.74 X_o
  - 44 Si planes (380μm thick)
  - 8x8 cm^2 detectors in 3x3 matrix
  - 96 strips of 0.24 cm per plane
- **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

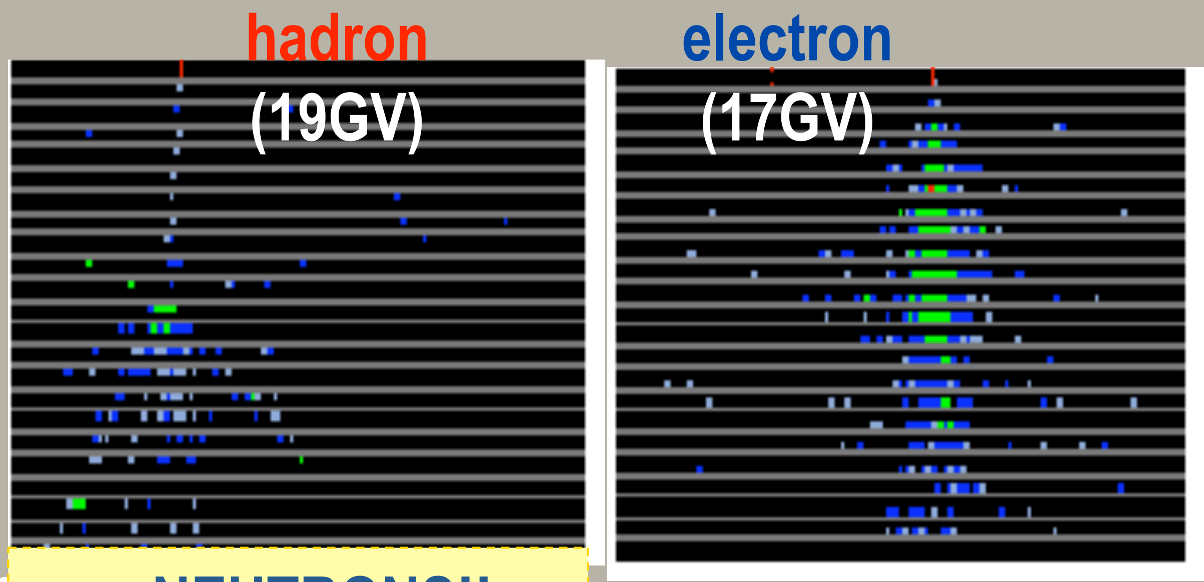
- Mass 110 kg
- Power consumption 48 W

Principle of operation



Electron/hadron separation

- Interaction topology e/h separation



+ NEUTRONS!!

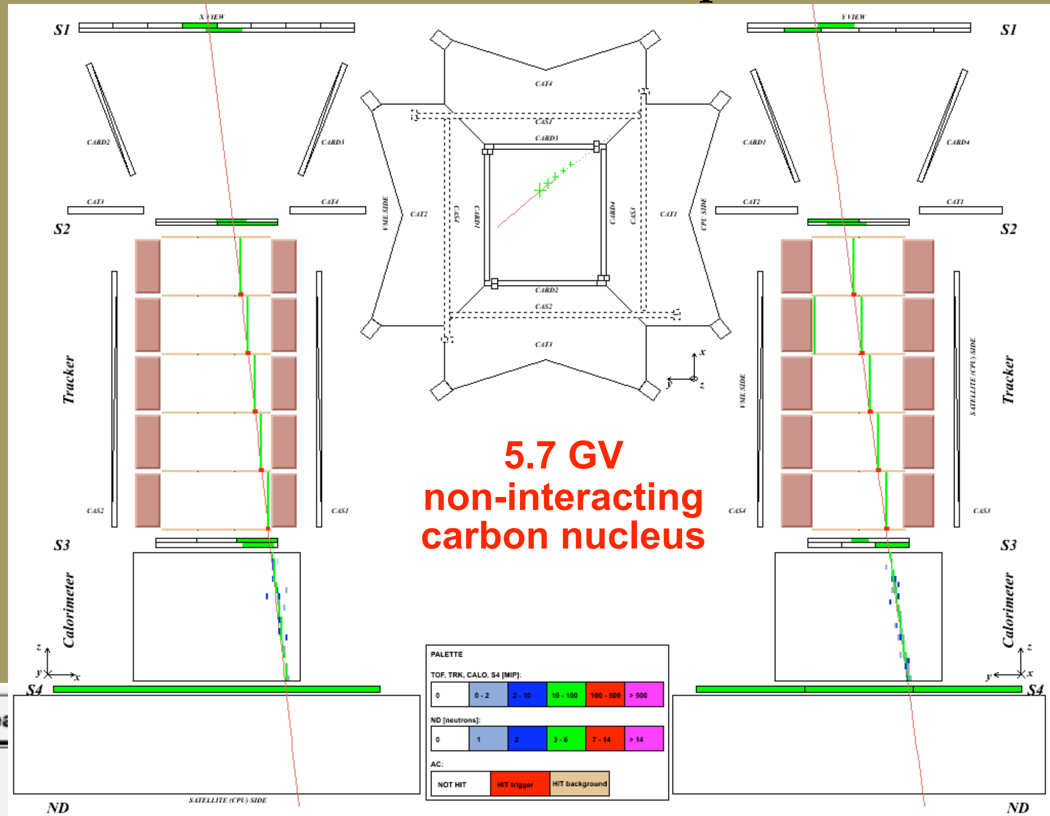
- Energy measurement of electrons and positrons (~full shower containment)

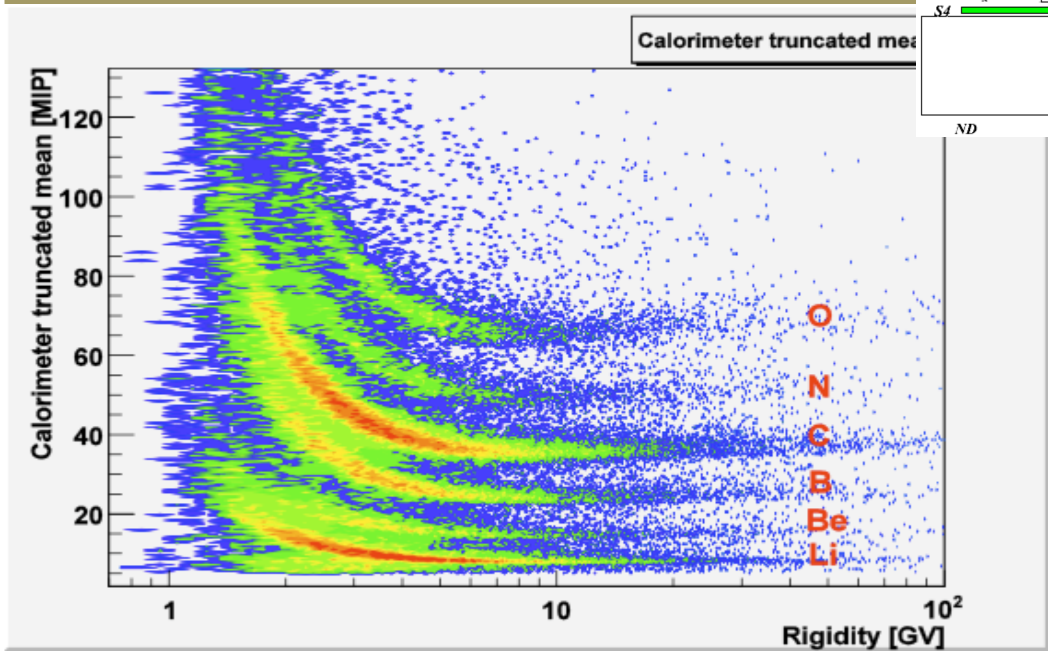
$$\frac{\sigma_E}{E} = a \oplus \frac{b}{\sqrt{E}} \qquad \rightarrow a < 5\%$$

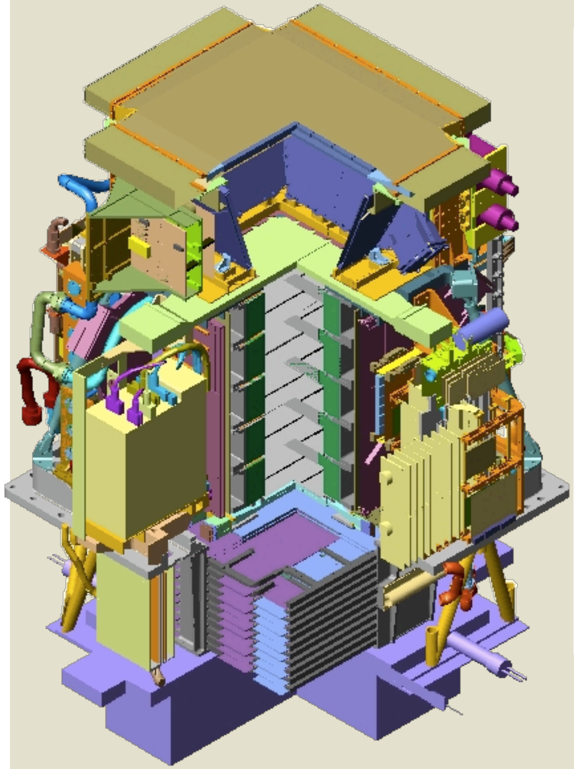
Calorimeter Nuclei identification

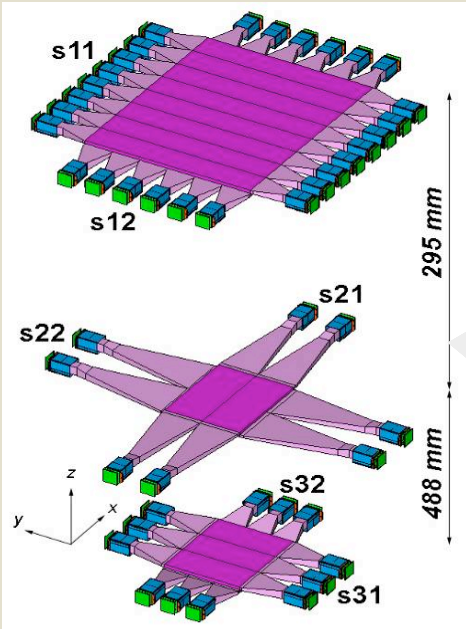
Truncated mean of multiple dE/dx measurements in different silicon planes

- 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









The time-of-flight system

•Main tasks:

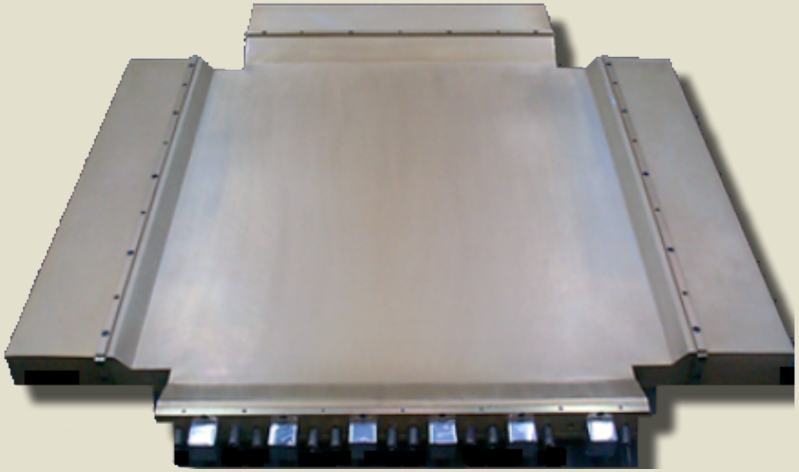
- First-level trigger
- Albedo rejection
- dE/dx (ionisation losses)
- Time of flight particle identification (<1GeV/c)

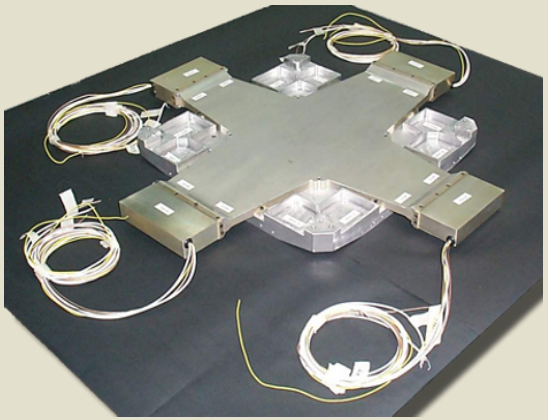
•Characteristics:

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

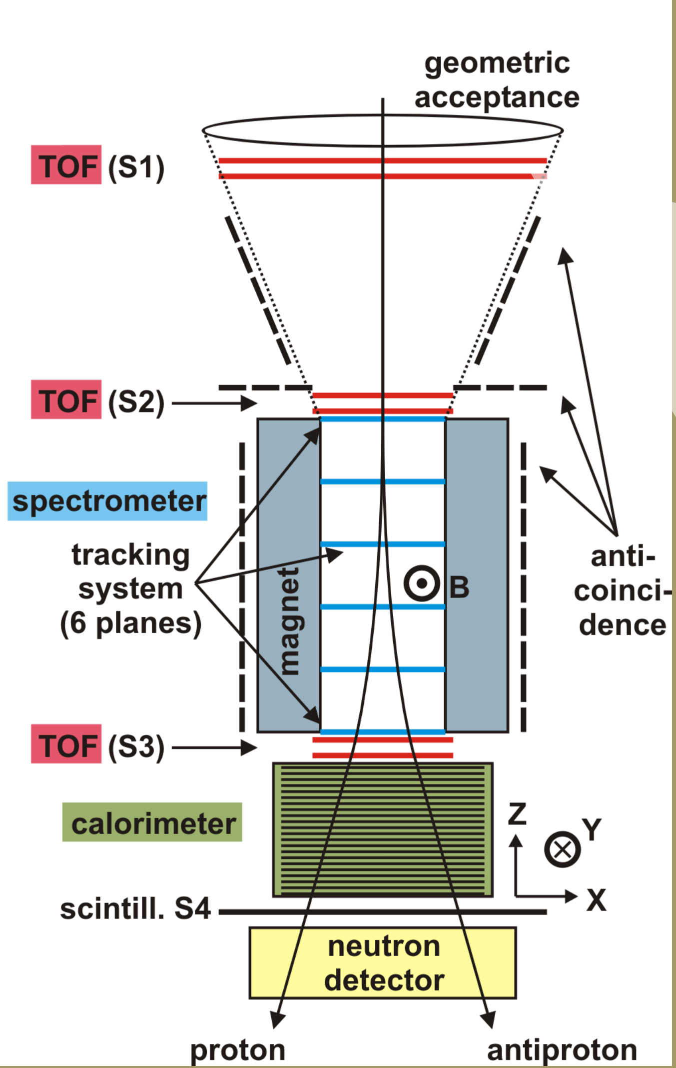
•Performance:

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

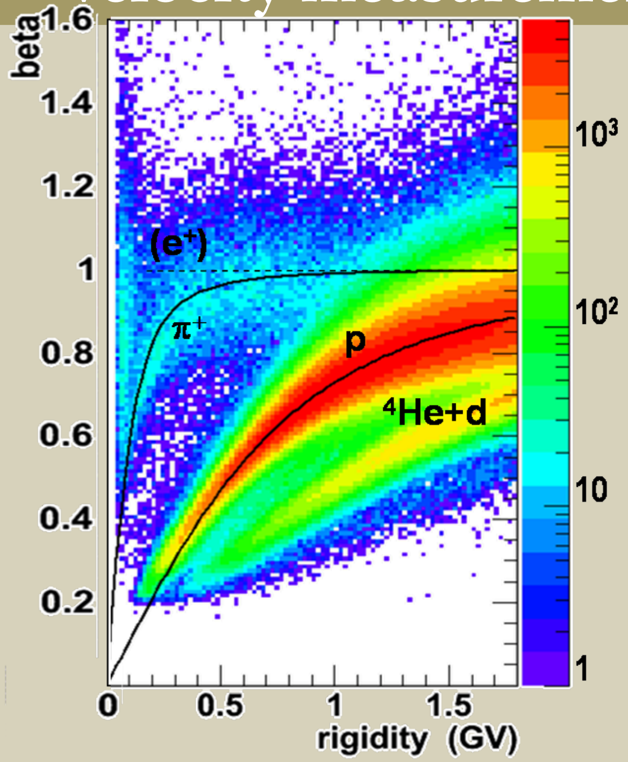




Principle of operation



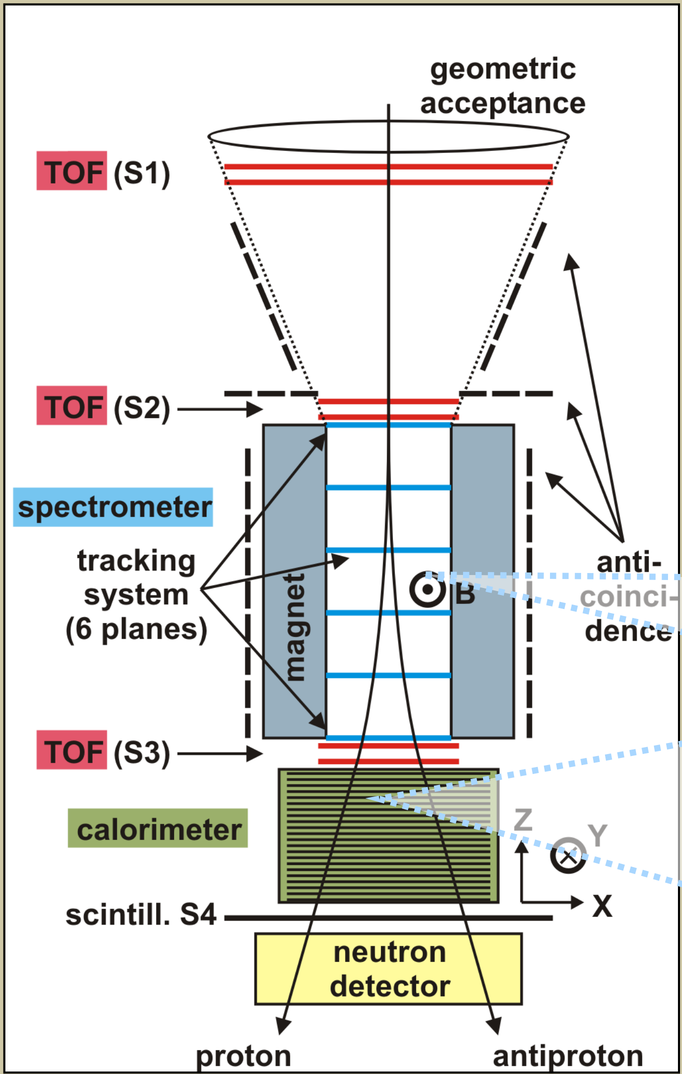
Velocity measurement



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

→ NB! They mimic antimatter!

dE/dx

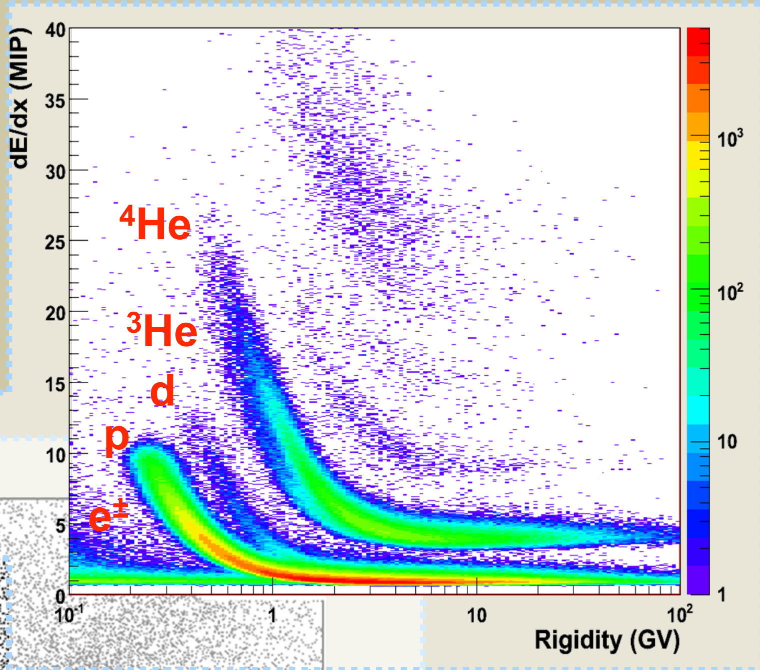


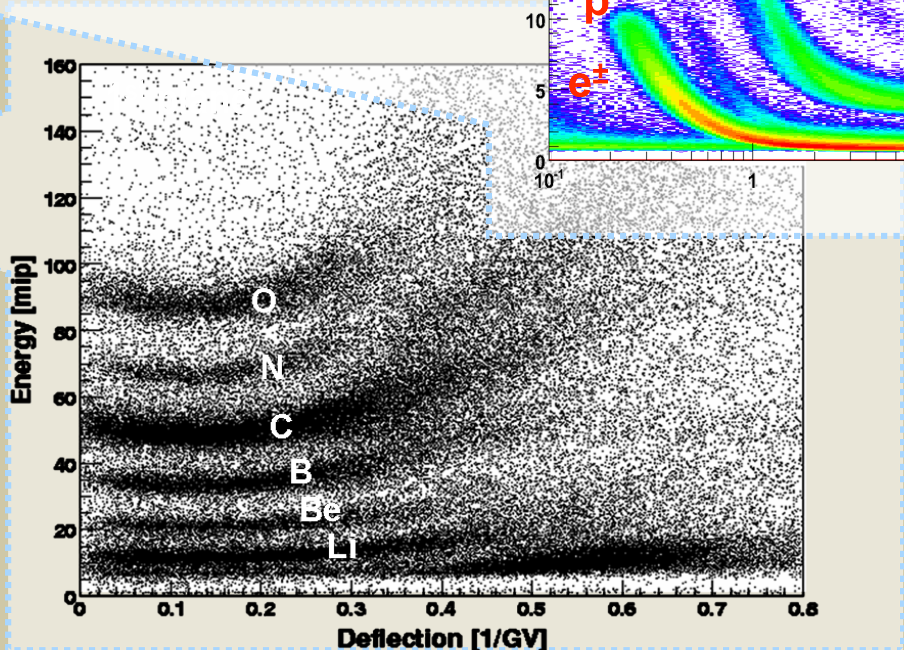
Z measurement

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

Bethe Bloch

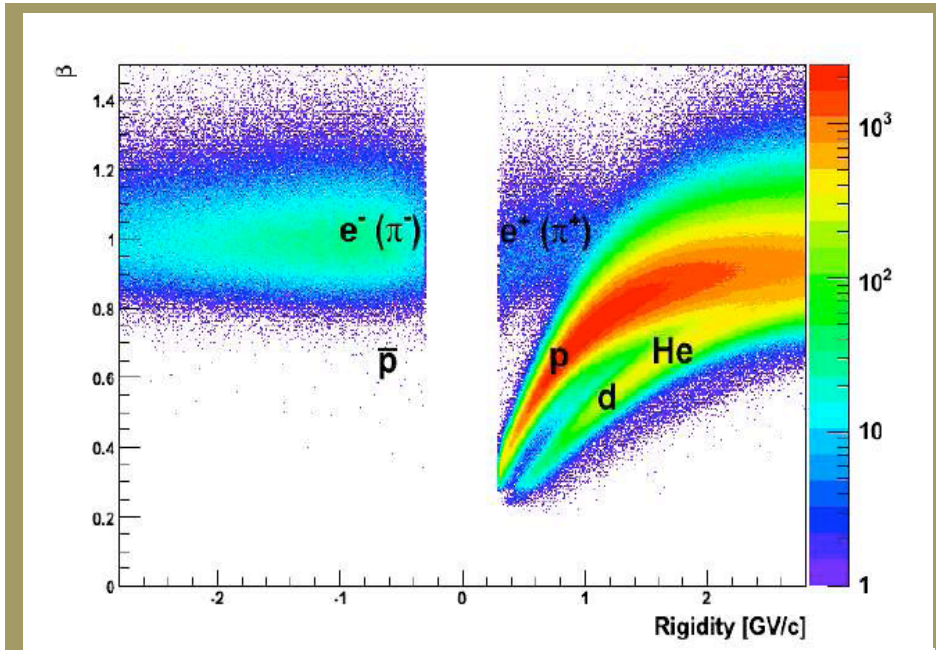
ionization energy-loss of heavy (M>>me) charged particles

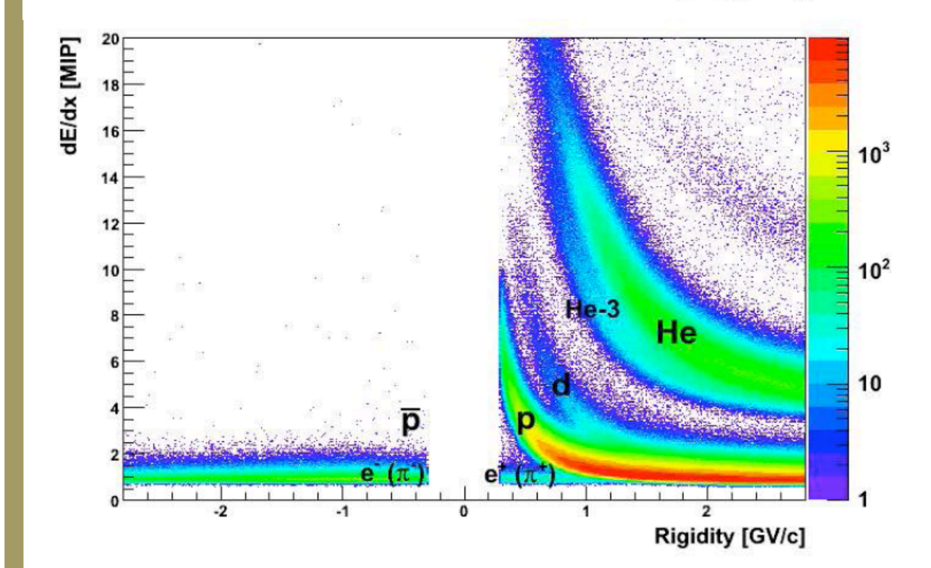


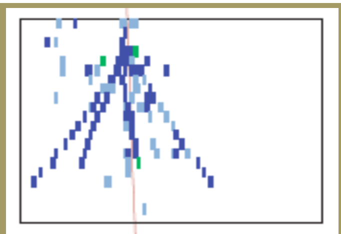


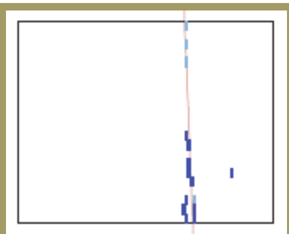
The p-bar / p Low energy selection

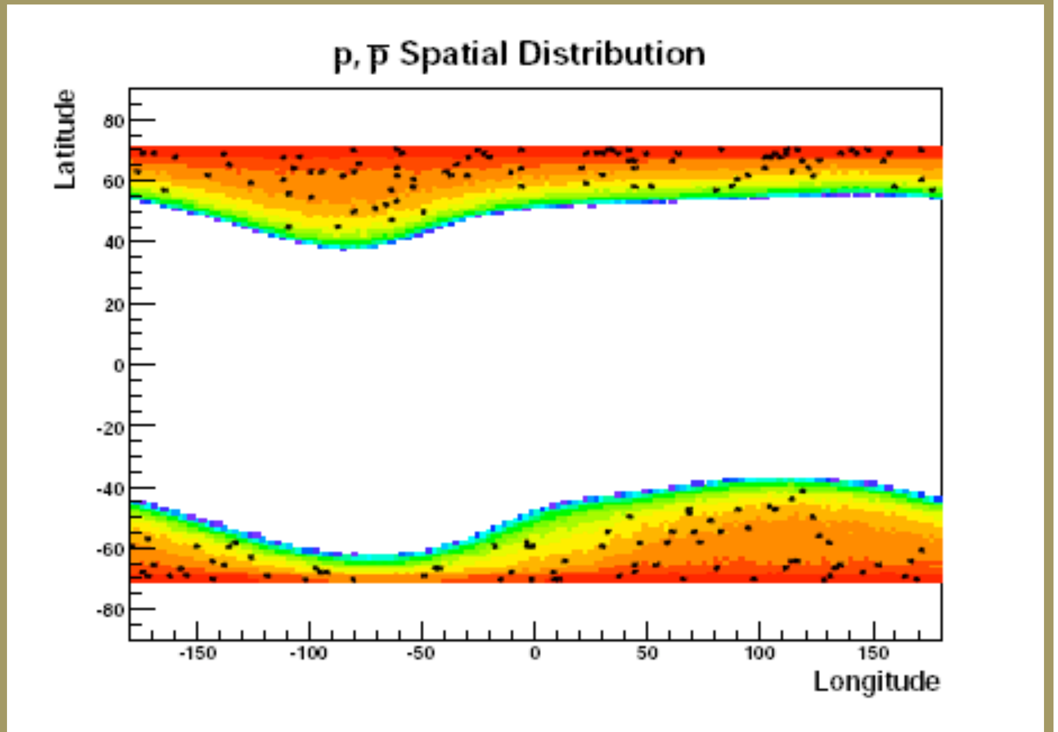
p-bar flux Between 80 MeV and 2 GeV

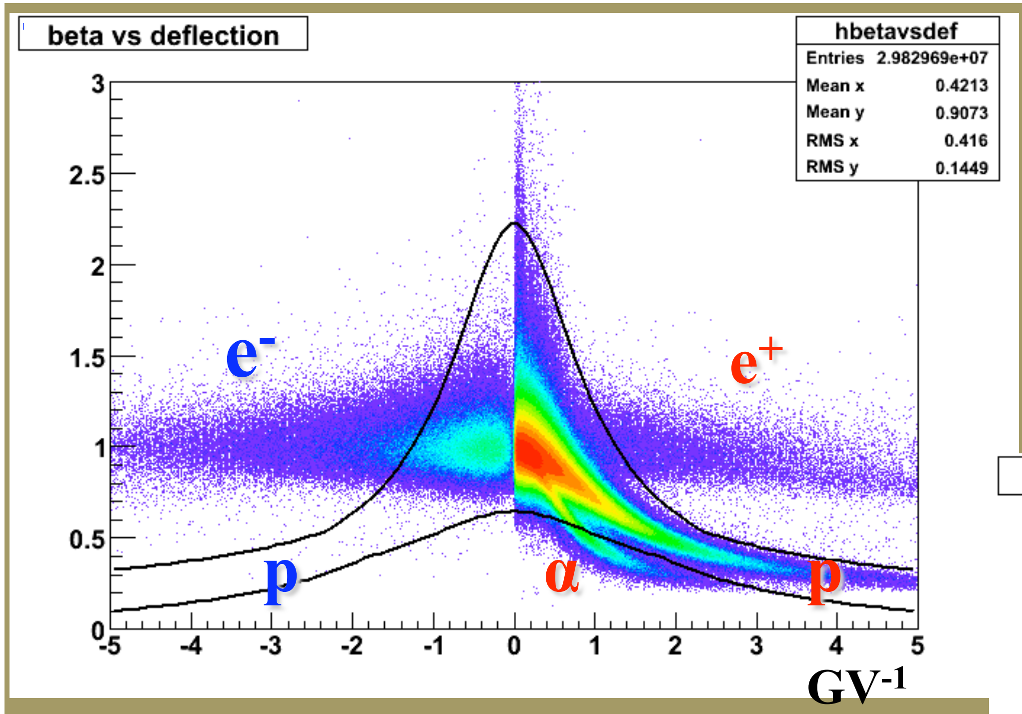


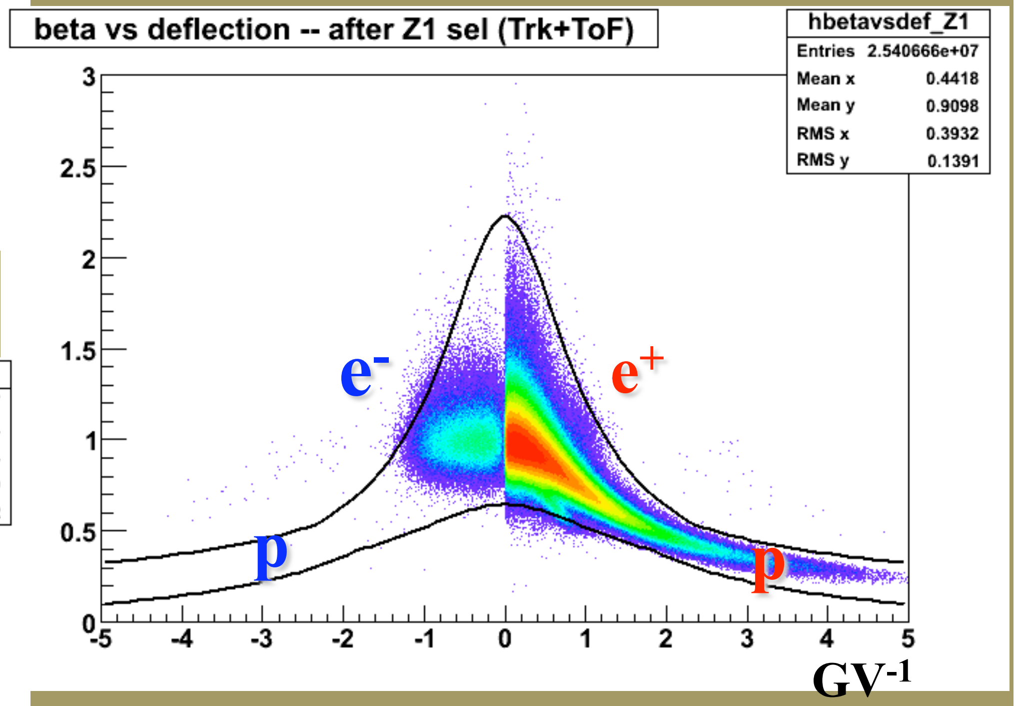


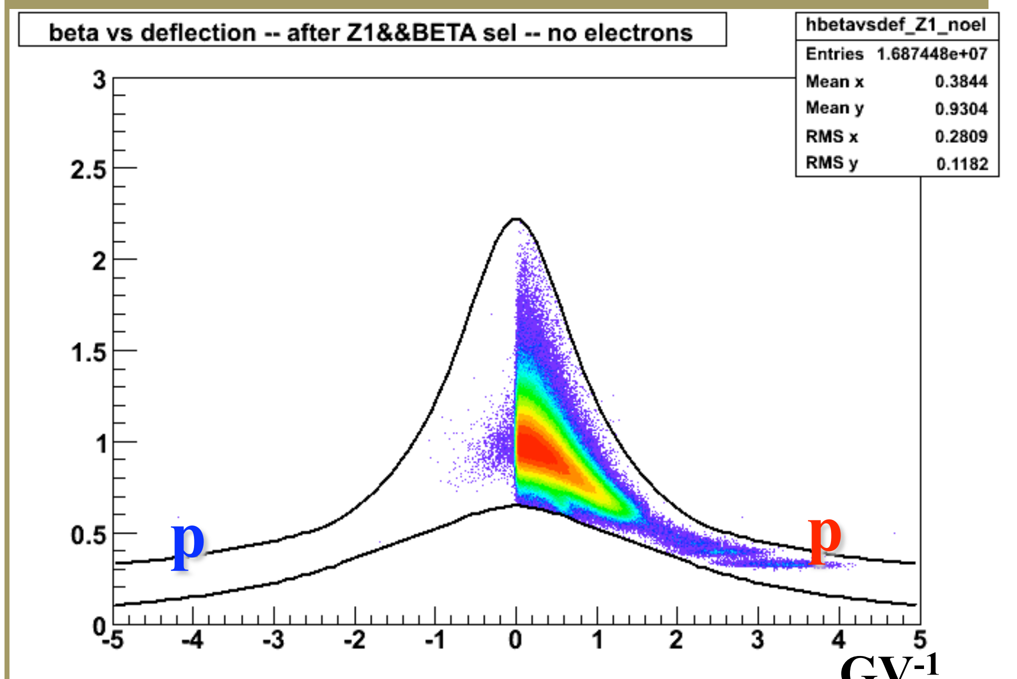


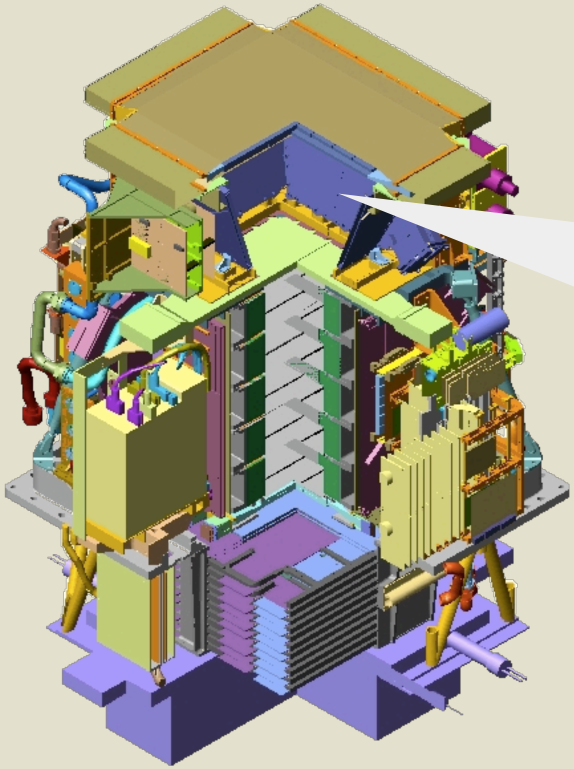





beta vs deflection
hbetavsdef
Entries 2.982969e+07
Mean x 0.4213
Mean y 0.9073
RMS x 0.416
RMS y 0.1449
e-
e+
p
α
p
GV-1

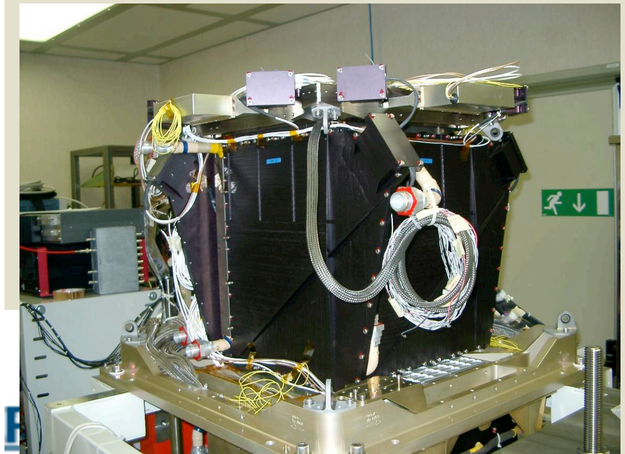

beta vs deflection -- after Z1 sel (Trk+ToF)
hbetavsdef_Z1
Entries 2.540666e+07
Mean x 0.4418
Mean y 0.9098
RMS x 0.3932
RMS y 0.1391
e-
e+
p
p
GV-1

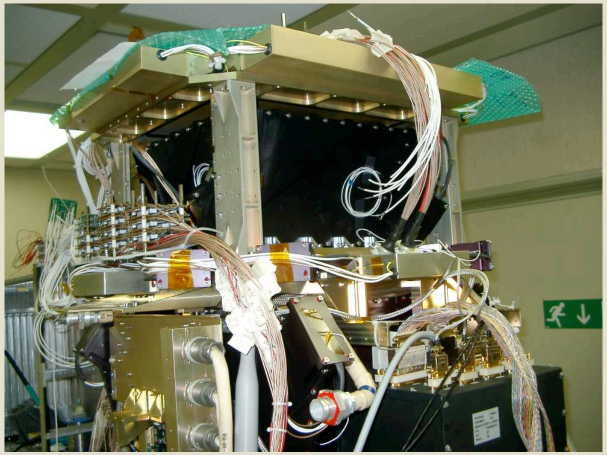

beta vs deflection -- after Z1&&BETA sel -- no electrons
hbetavsdef_Z1_noel
Entries 1.687448e+07
Mean x 0.3844
Mean y 0.9304
RMS x 0.2809
RMS y 0.1182
p
p
GV-1



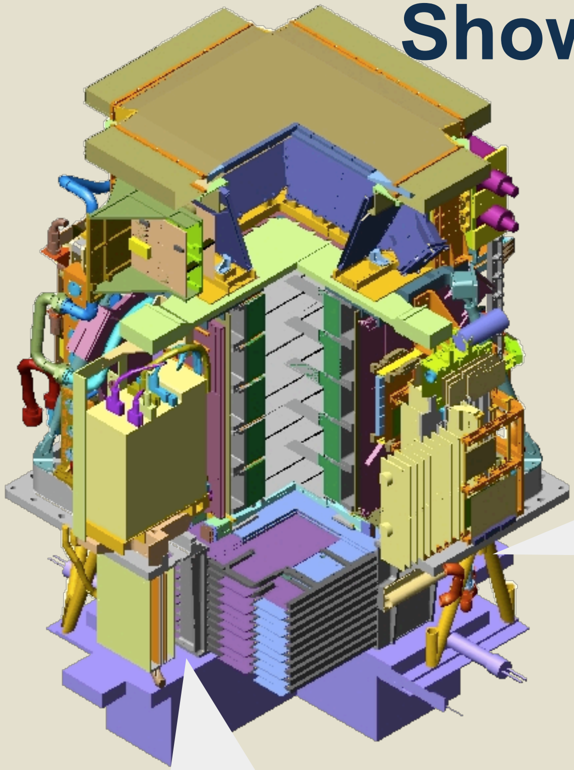
The anticounter shields

- **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%**



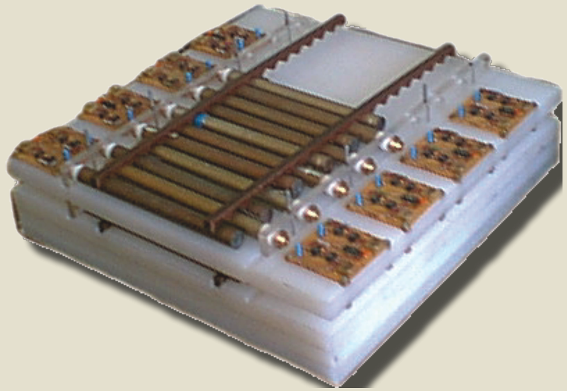


Shower-tail catcher & Neutron detector



- **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**

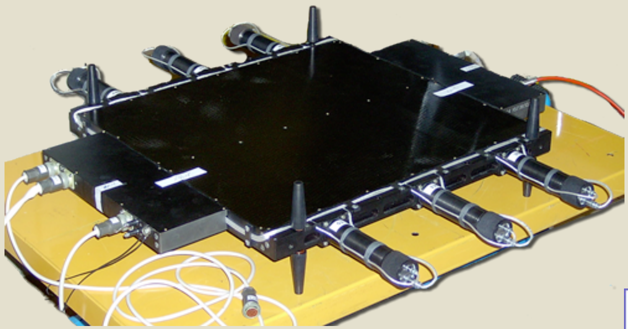


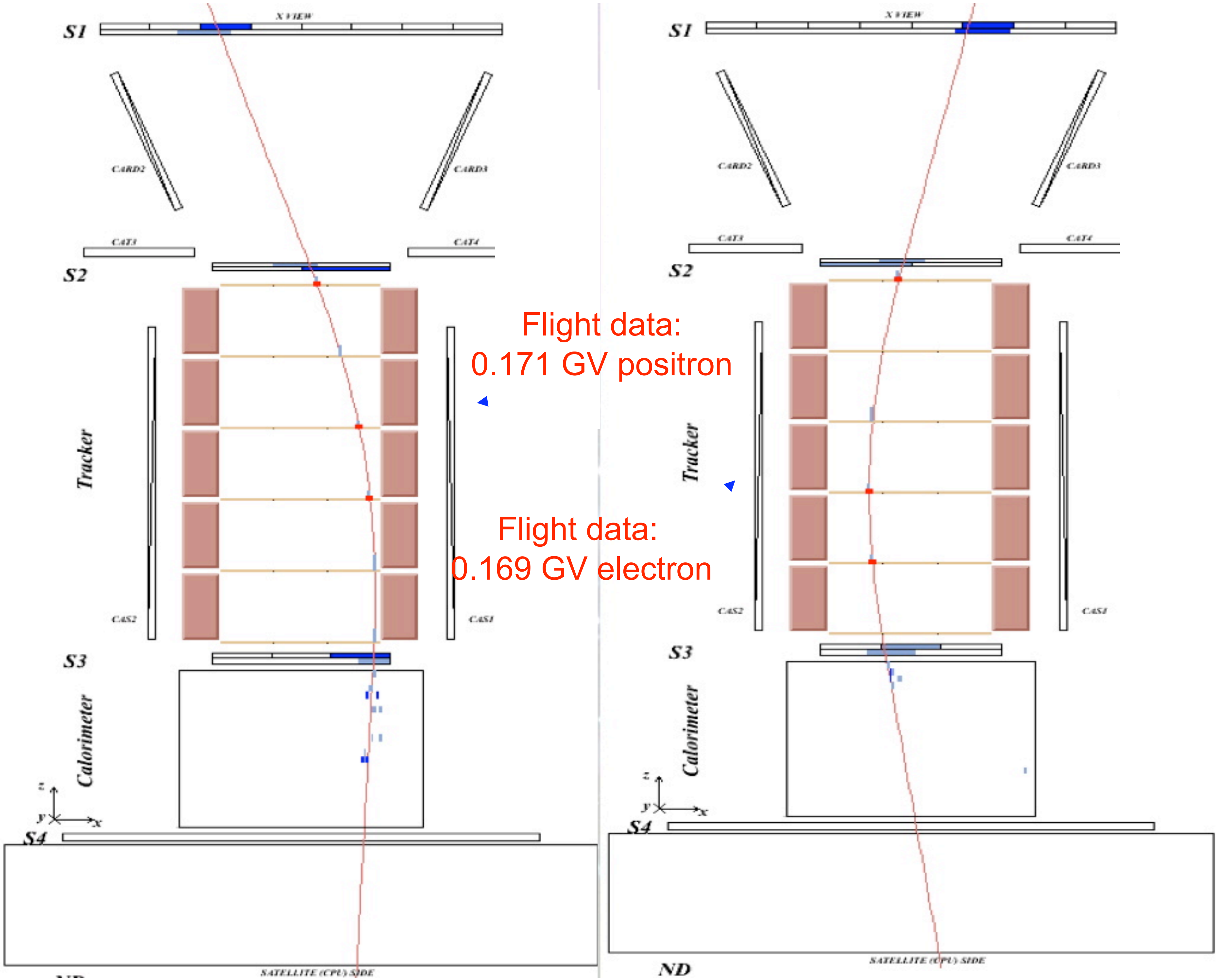
S4 Main tasks:

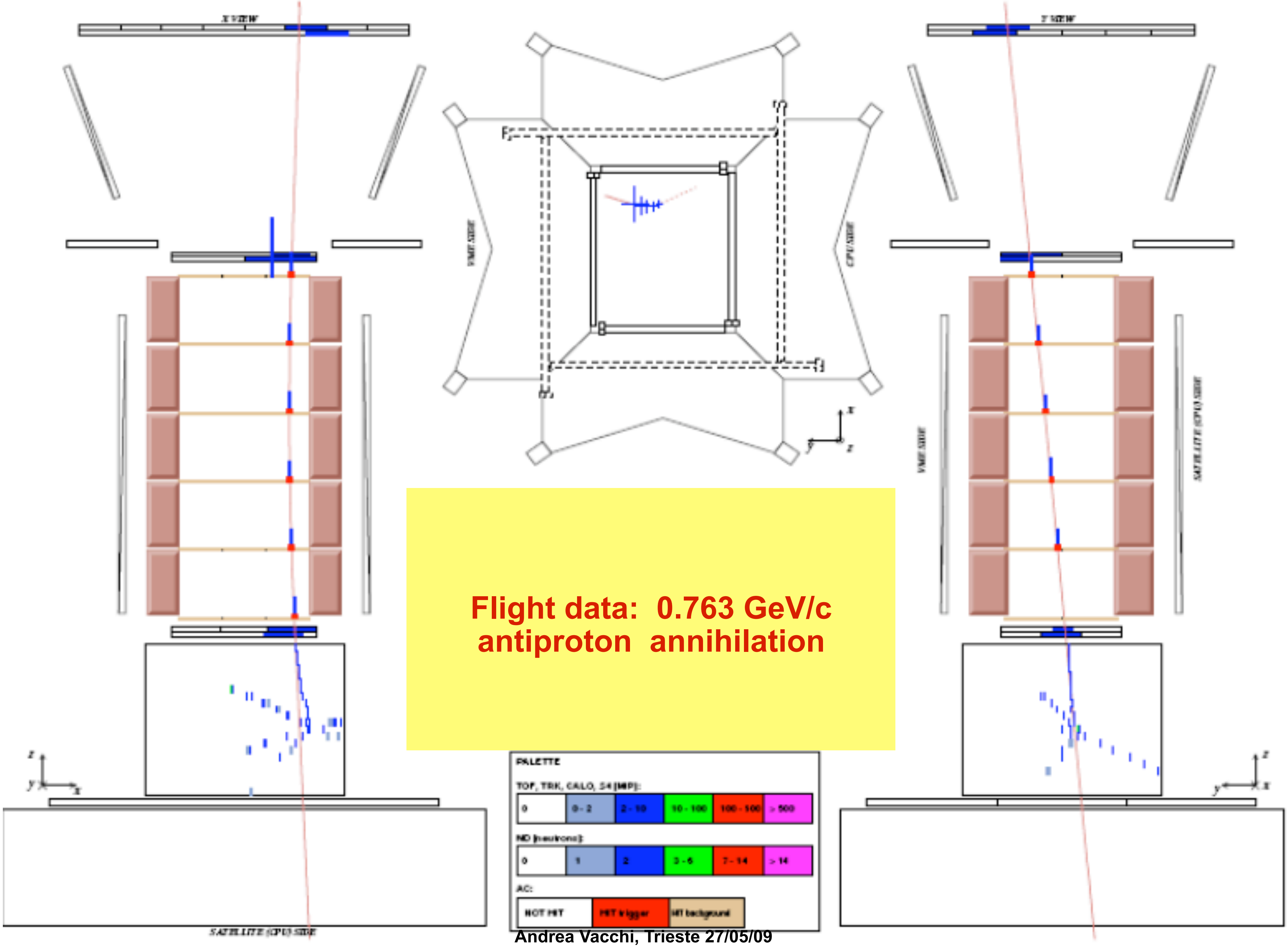
- Neutron detector trigger

Characteristics:

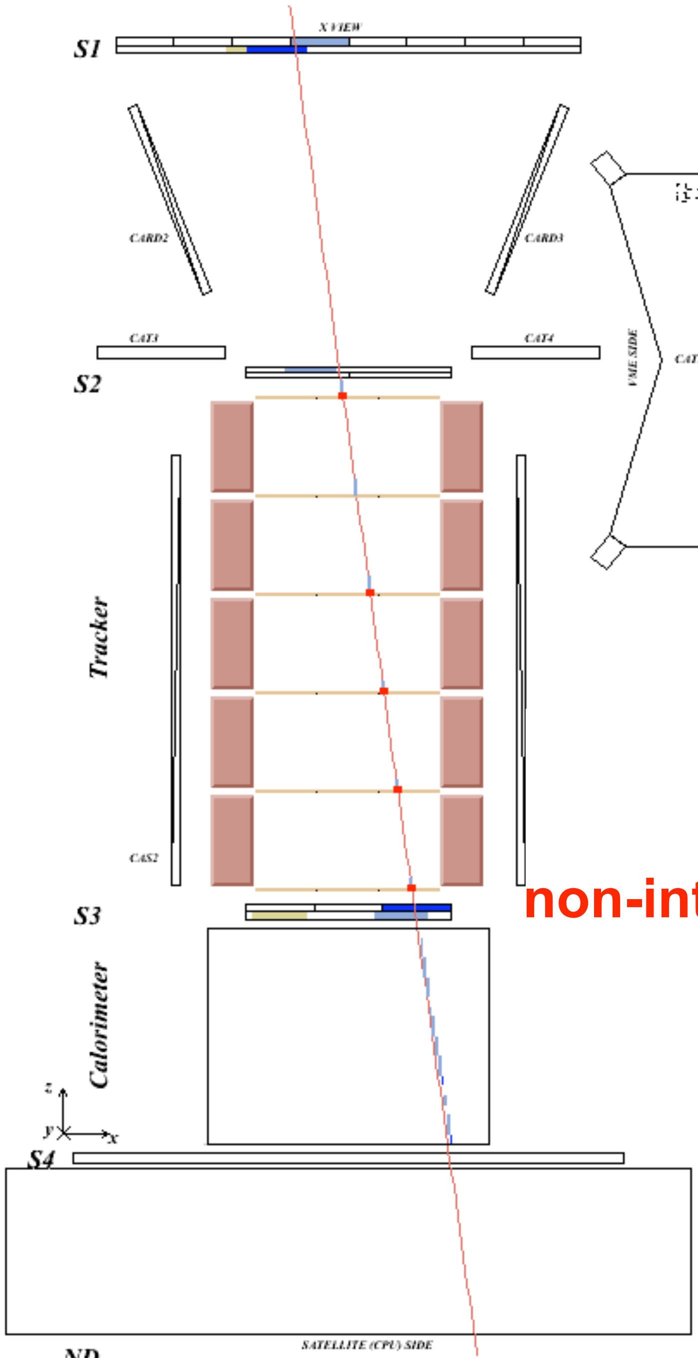
- Plastic scintillator paddle, 1 cm thick

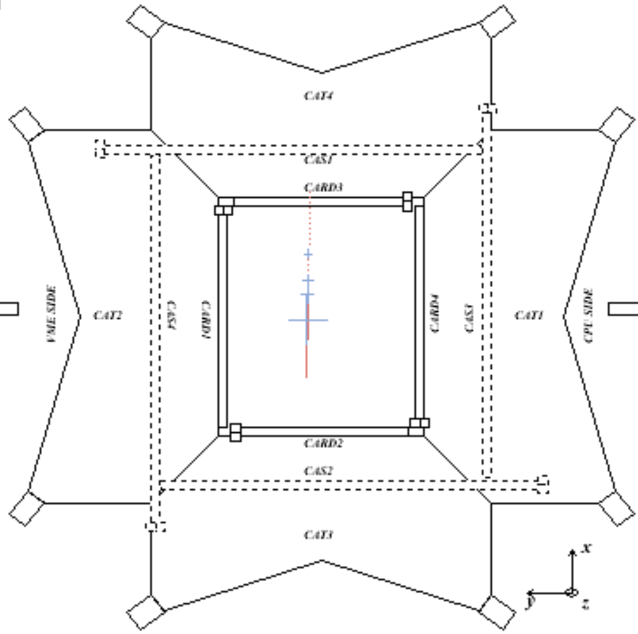



S1
X VIEW
CARD2
CARD3
CAT3
CAT4
S2
Tracker
CAS2
CAS1
S3
Calorimeter
S4
SATELLITE (CPU) SIDE
ND
Flight data:
0.171 GV positron
Flight data:
0.169 GV electron

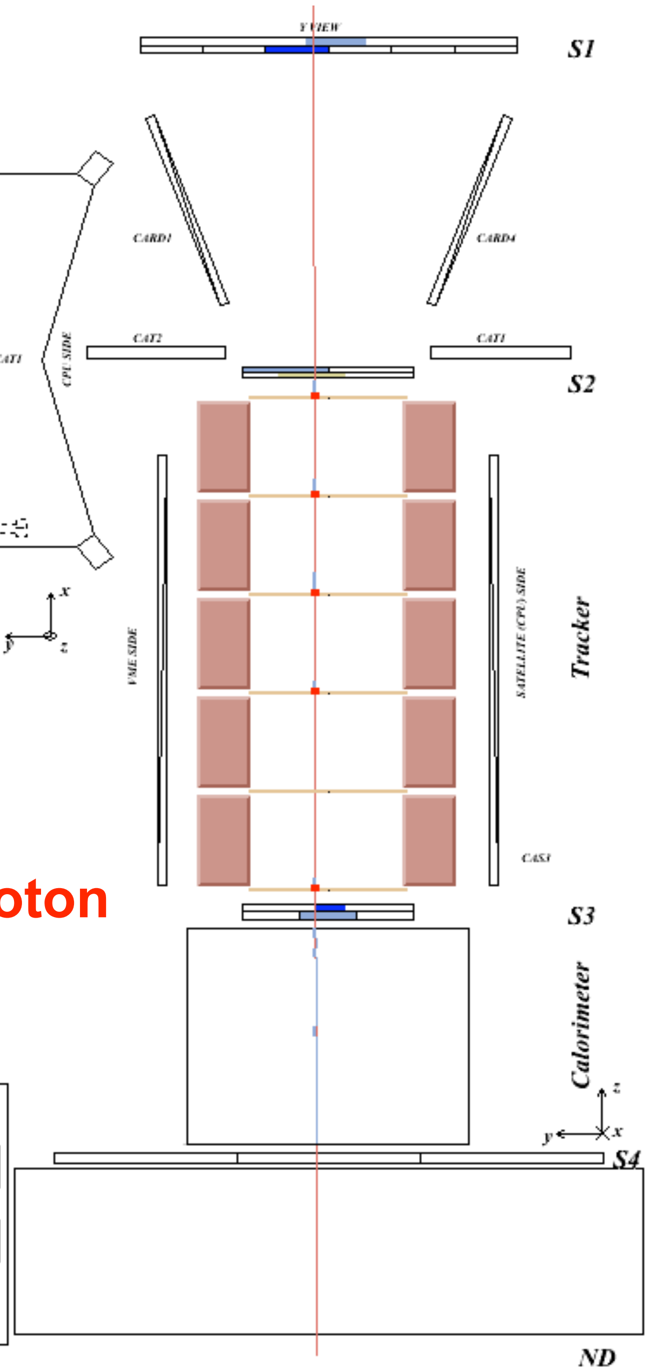


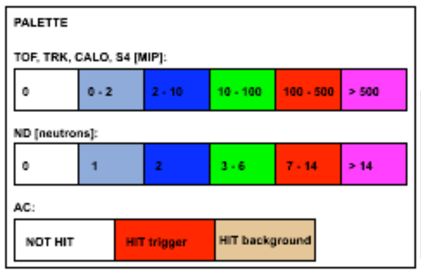
Flight data: 0.763 GeV/c antiproton annihilation

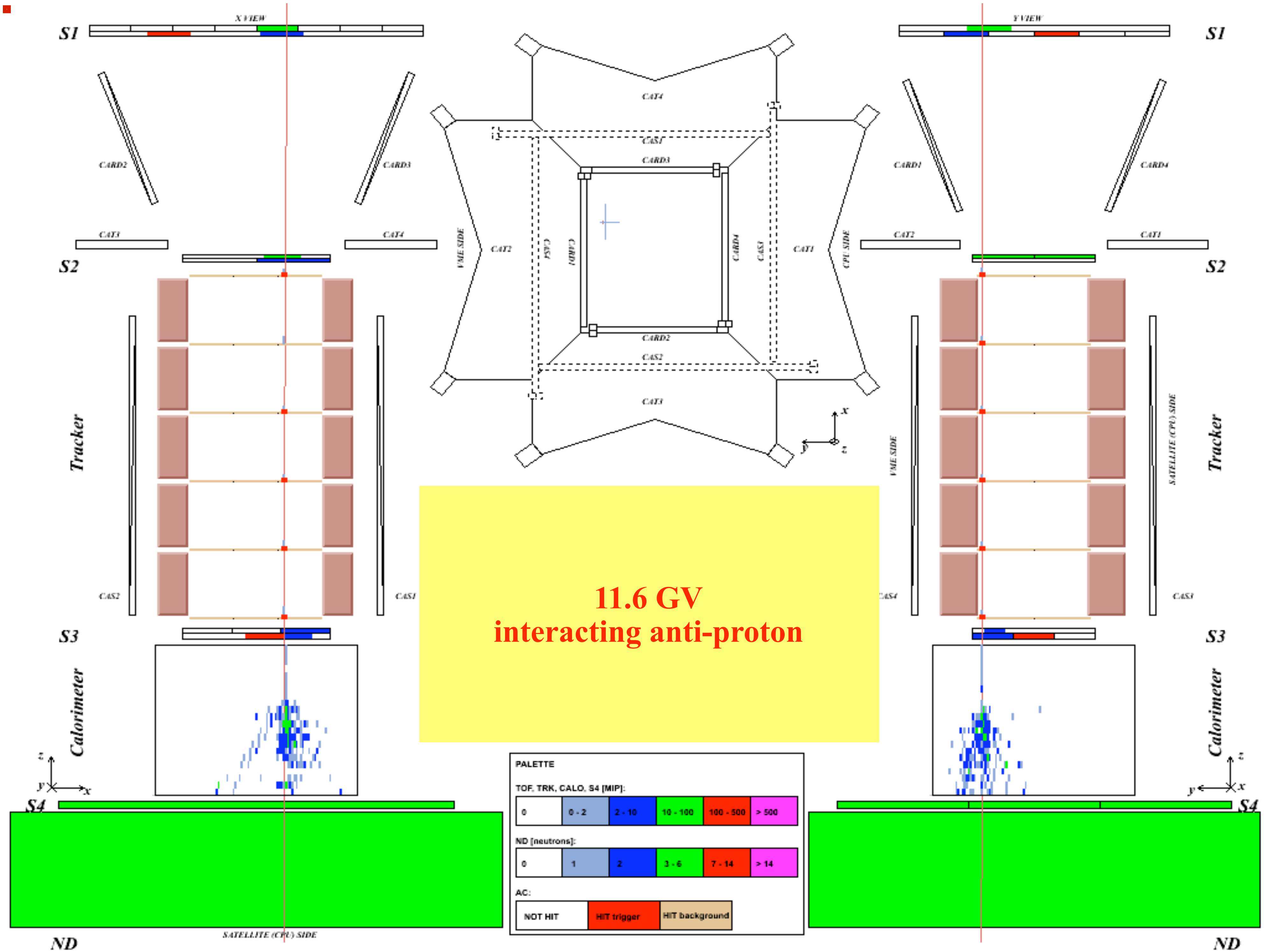


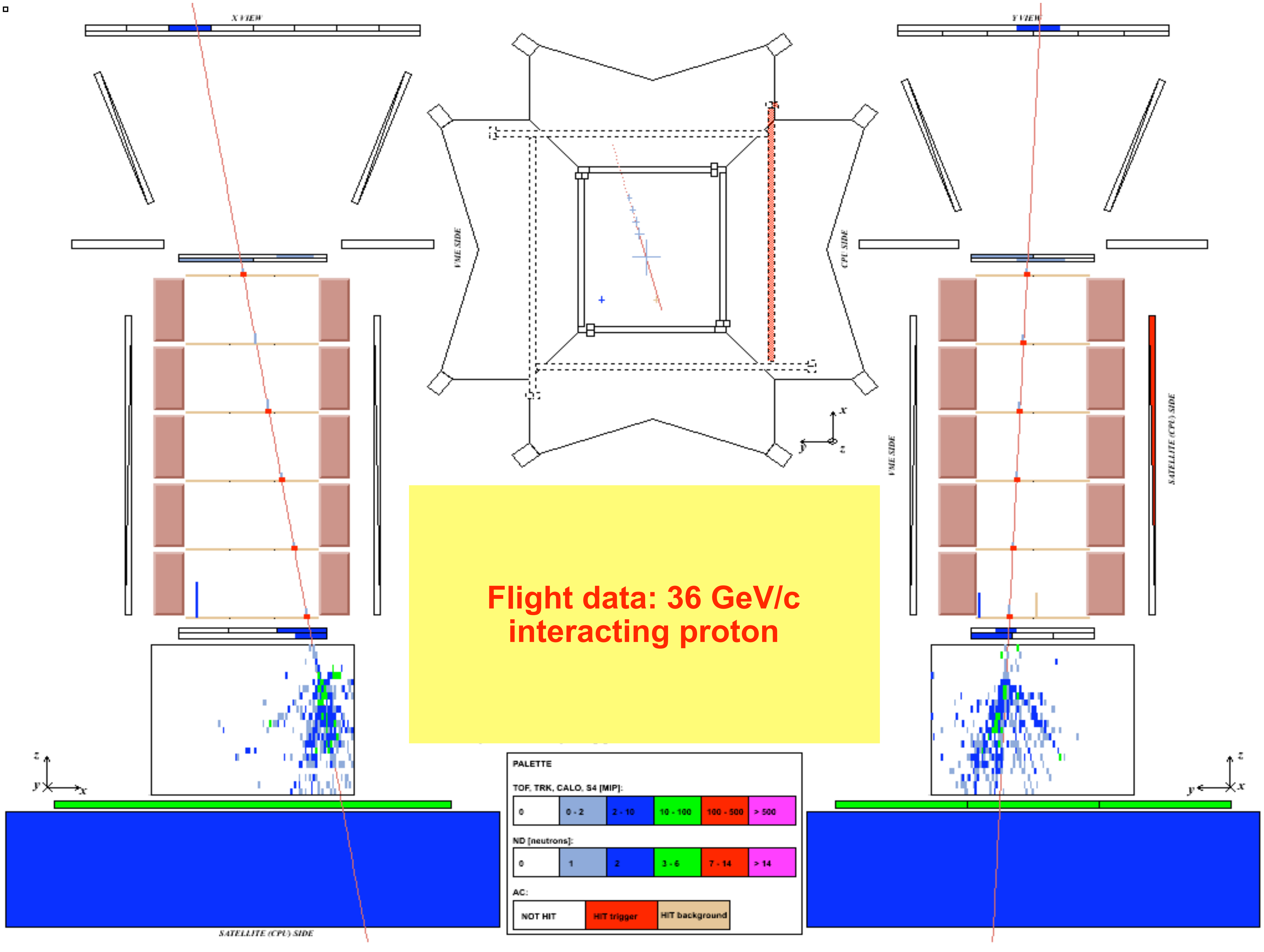


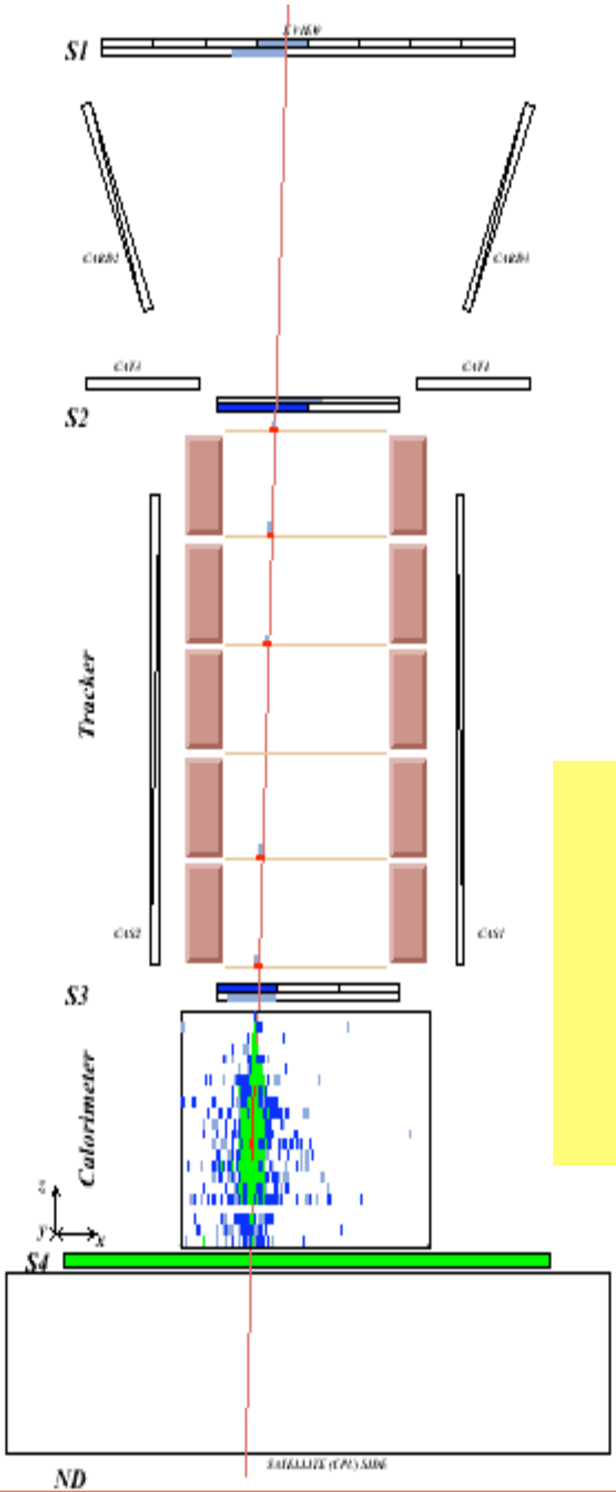
18 GeV/c non-interacting antiproton

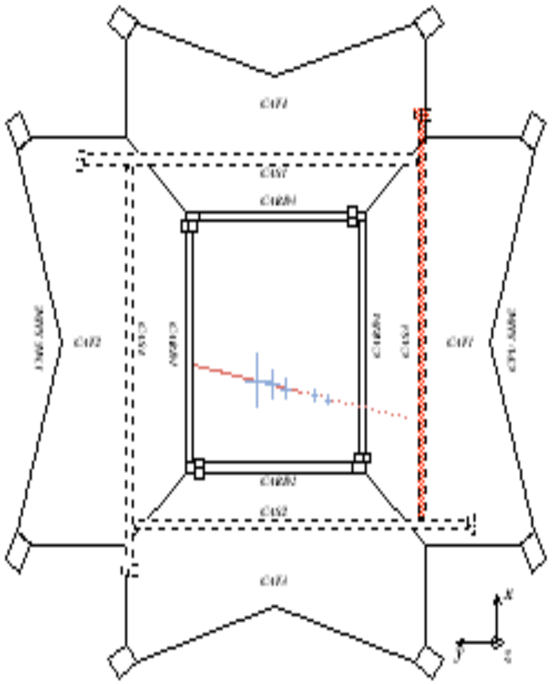


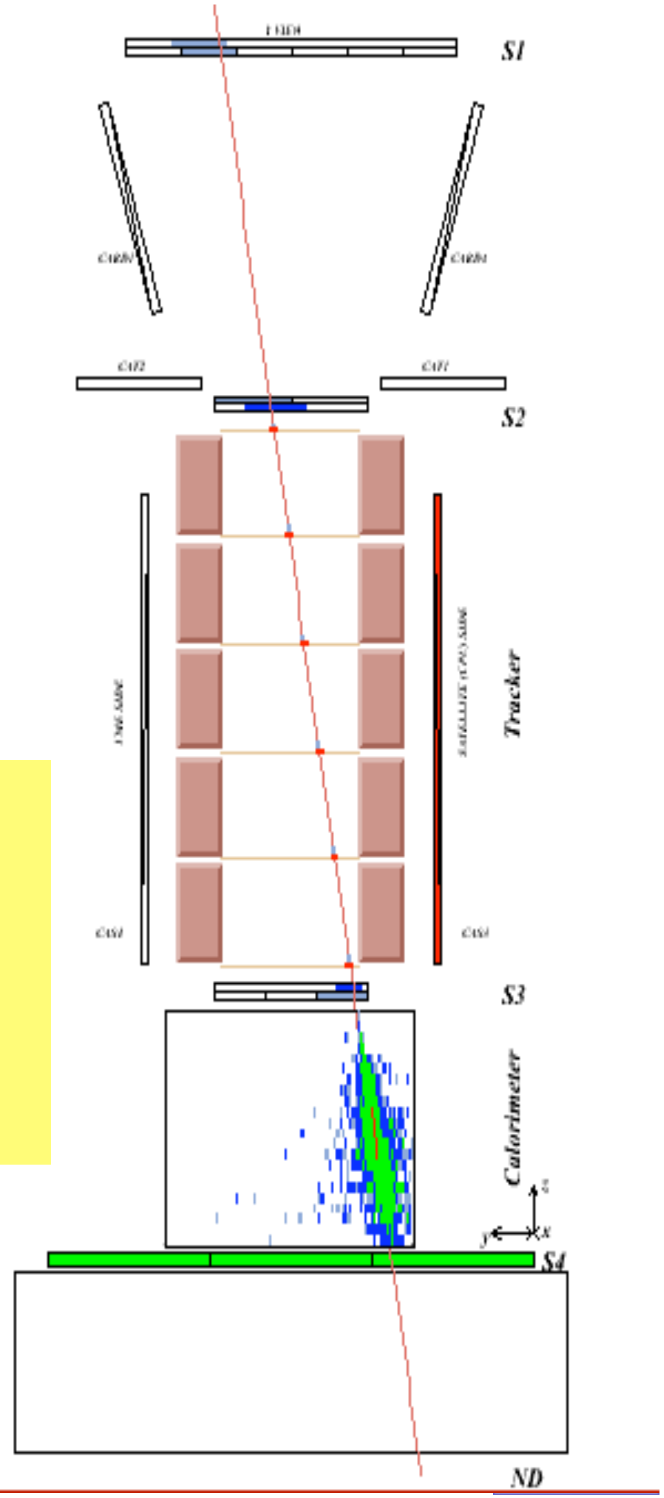



11.6 GV
interacting anti-proton
X VIEW
Y VIEW
S1
S2
S3
S4
ND
Tracker
Calorimeter
CARD1
CARD2
CARD3
CARD4
CAT1
CAT2
CAT3
CAT4
CAS1
CAS2
CAS3
CAS4
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC: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

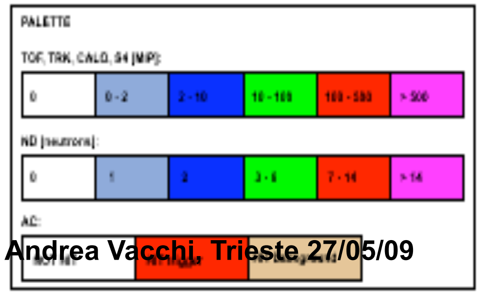

X VIEW
Y VIEW
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
Flight data: 36 GeV/c
interacting proton
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background



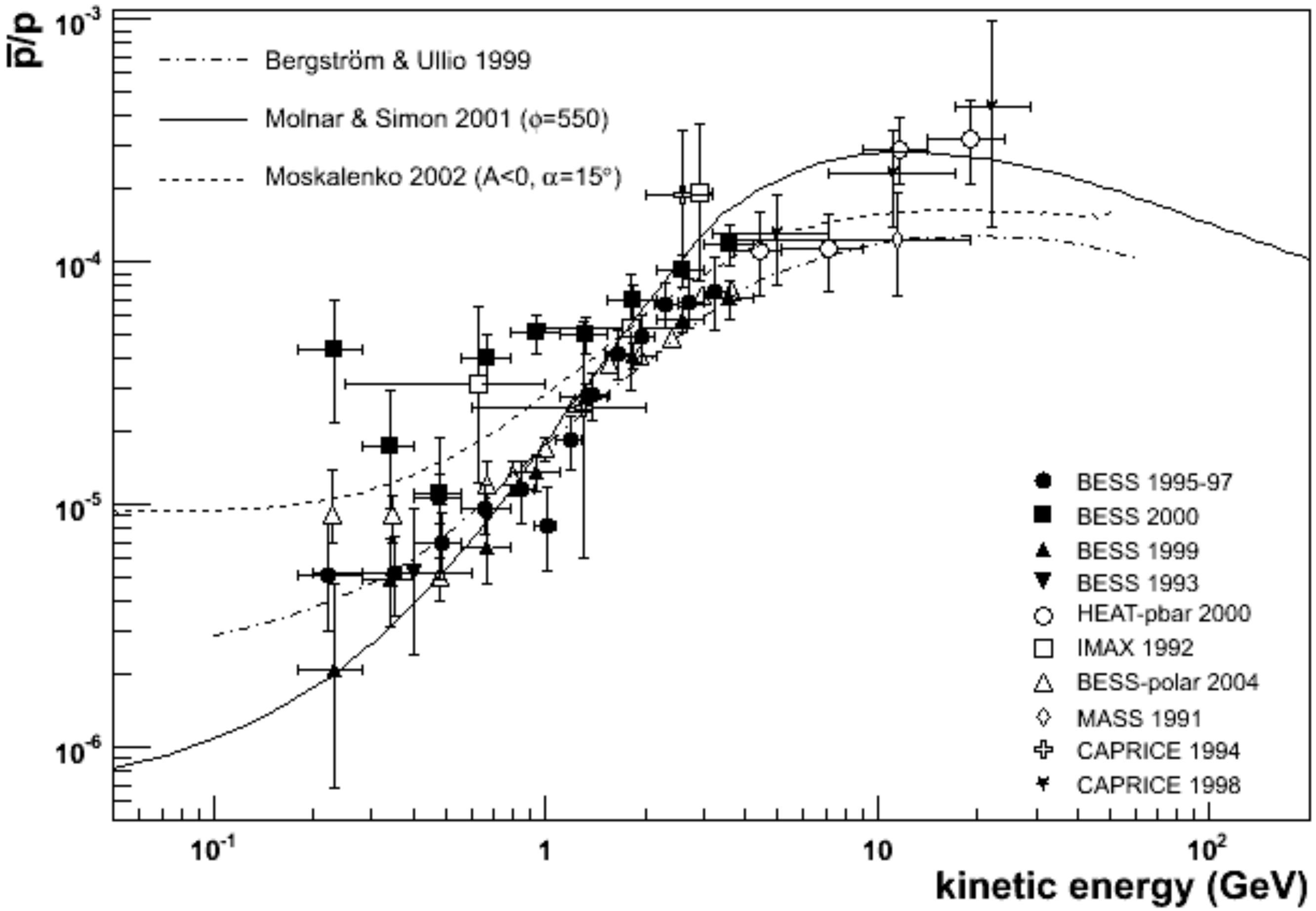




Flight data: 42 GeV/c electron

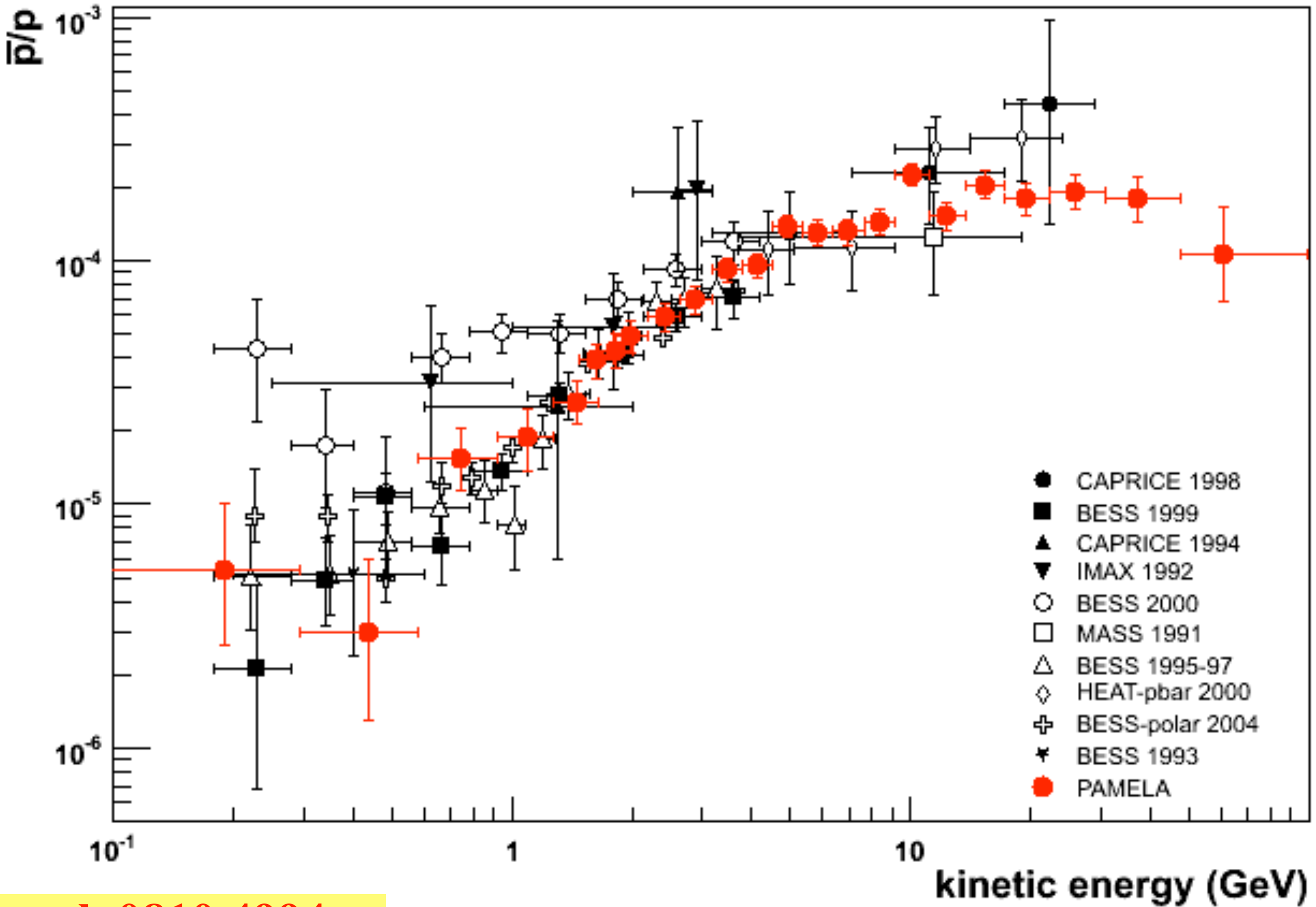


Antiproton to proton ratio BP



Antiproton to proton ratio

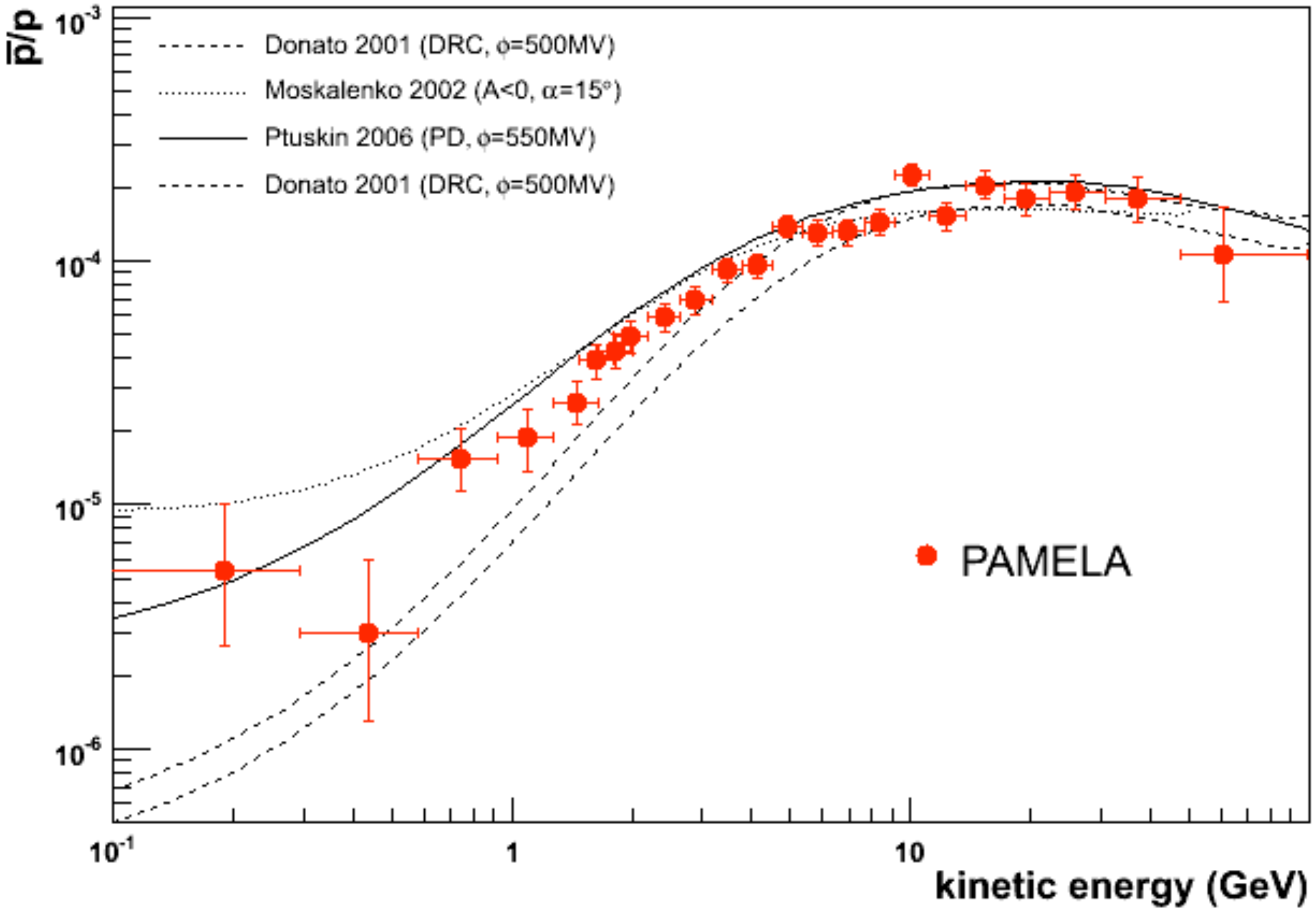
More than 10^7 p and ~1000 pbar have been identified between 1 and 100 GeV
~300 pbar over 10 GeV



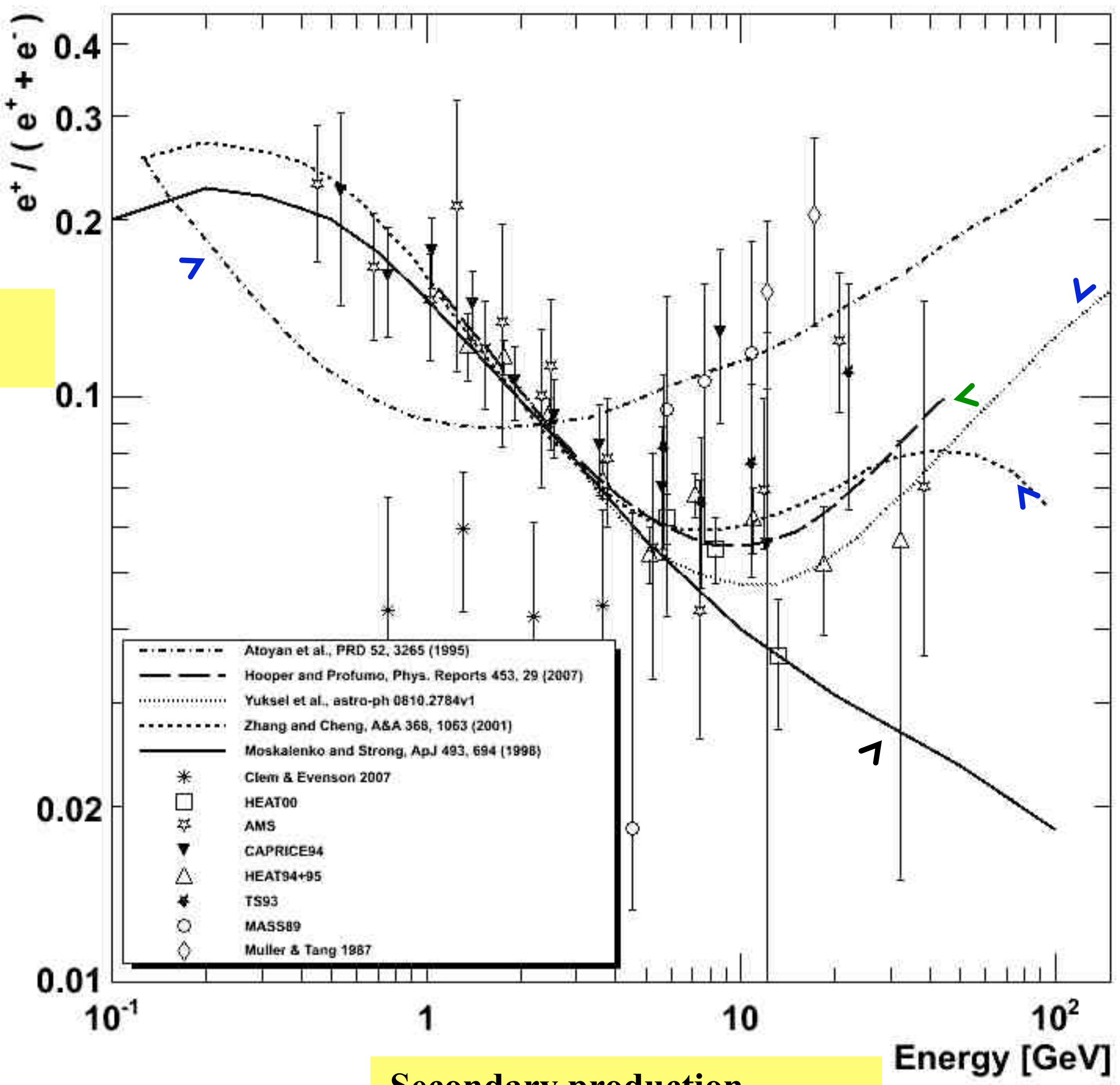
Astro-ph 0810.4994

Antiproton to proton ratio

Seconday Production Models



Positrons BP



Pulsar Component
Atoyan et al. 95

Pulsar Component
Yüksel et al. 08

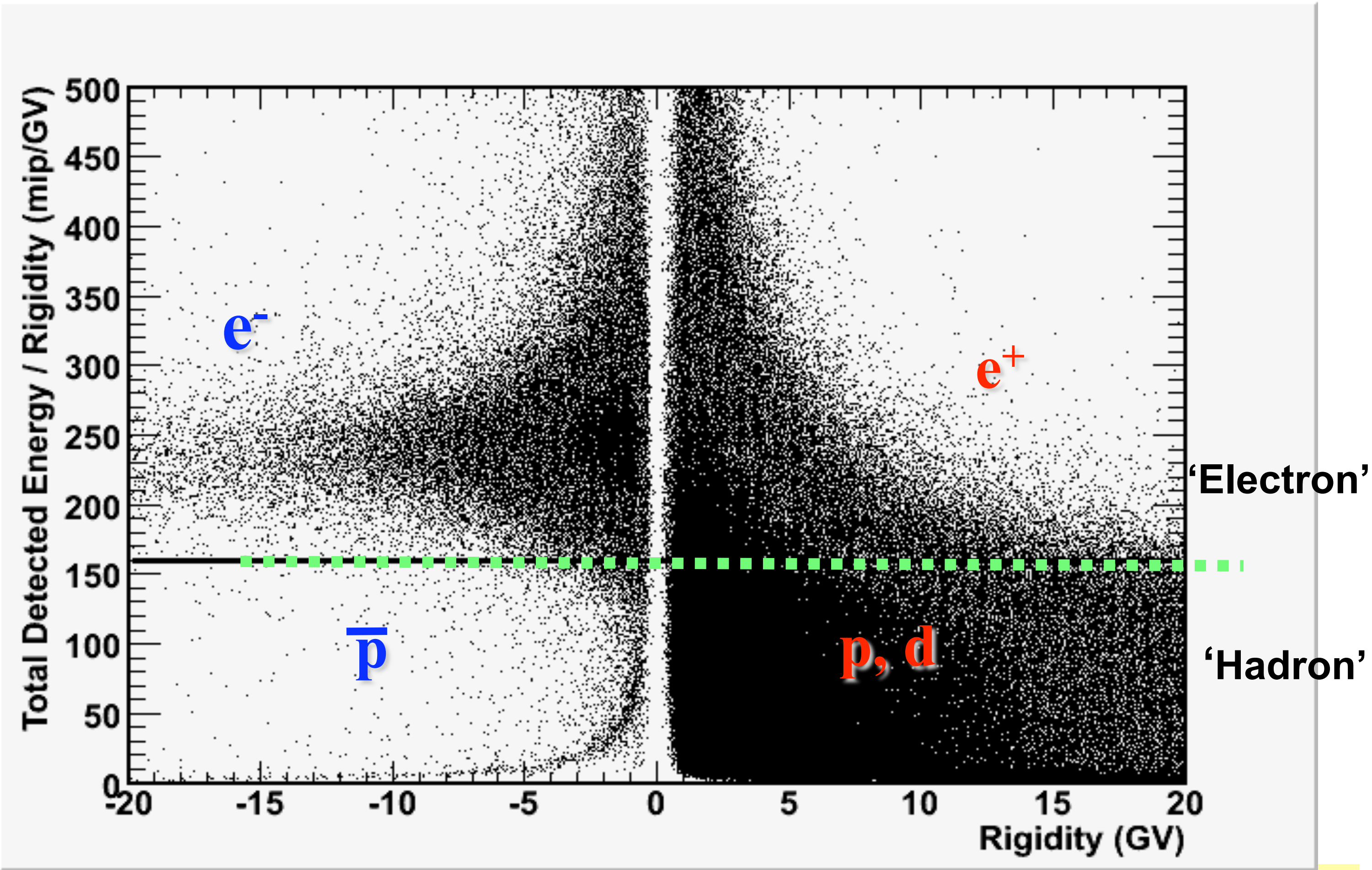
KKDM (mass 300 GeV)
Hooper & Profumo 07

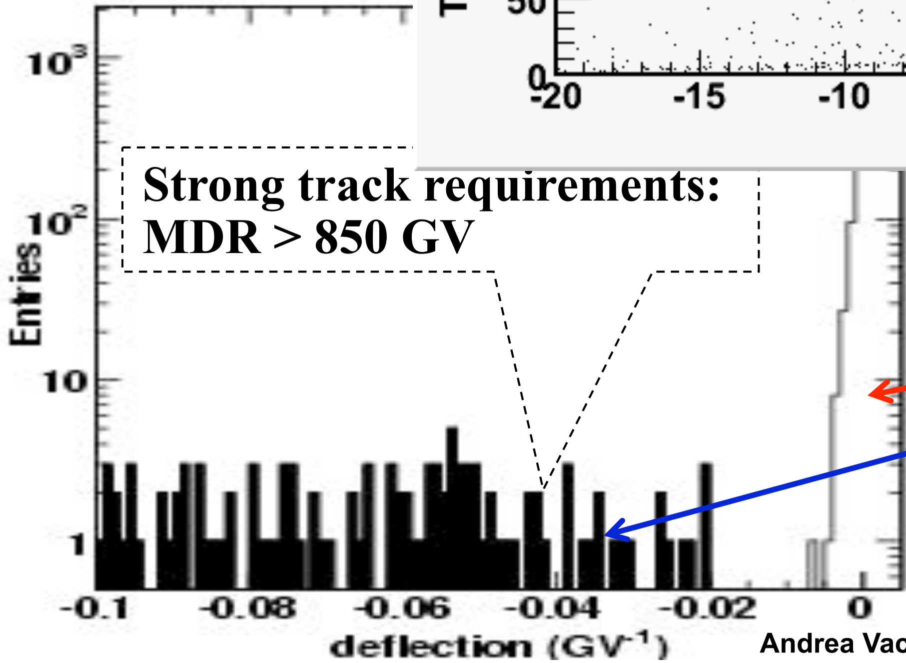
Pulsar Component
Zhang & Cheng 01

Secondary production
Moskalenko & Strong 98

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





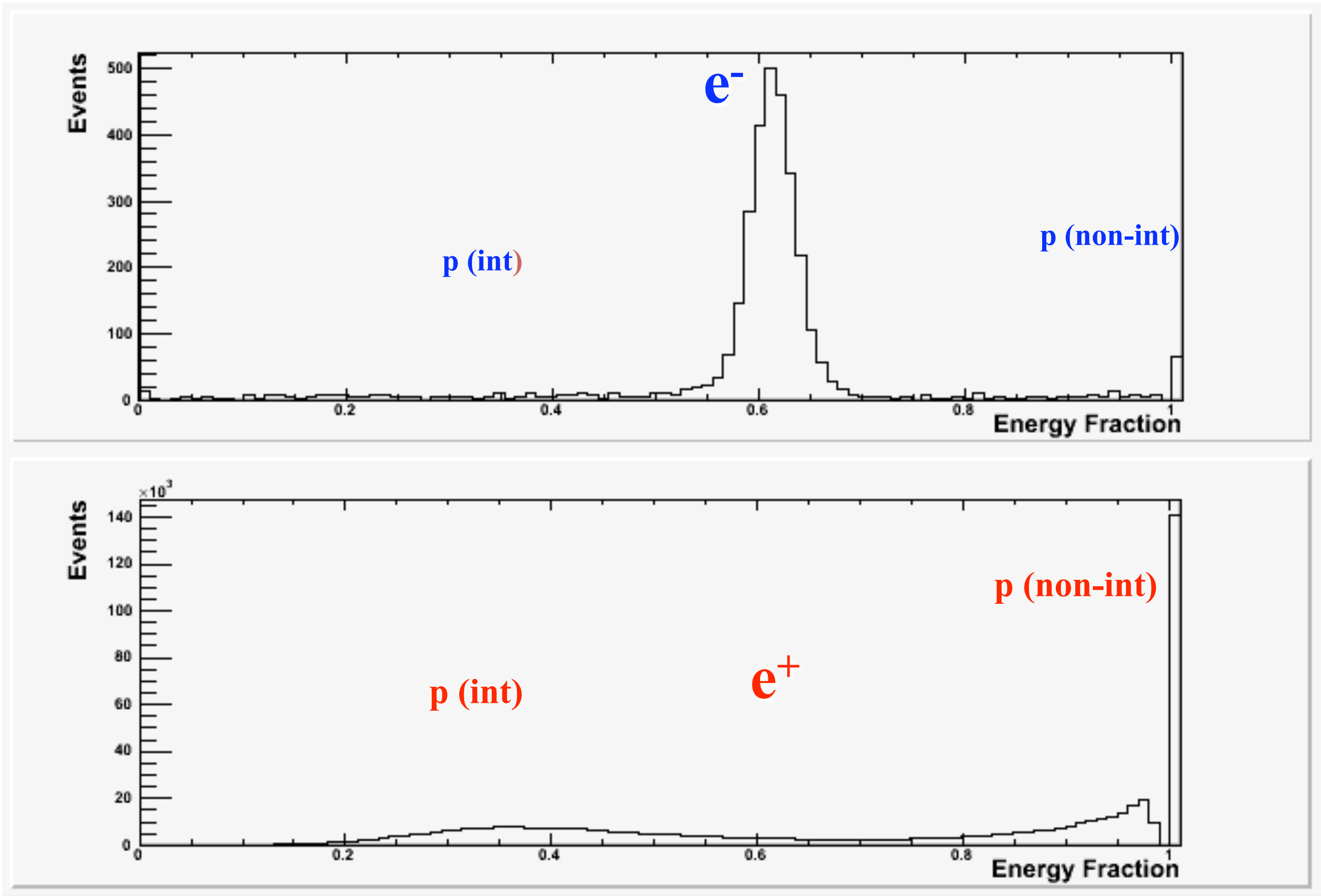
Tracker Identification

Protons (& spillover)

Antiprotons

Positron selection 0

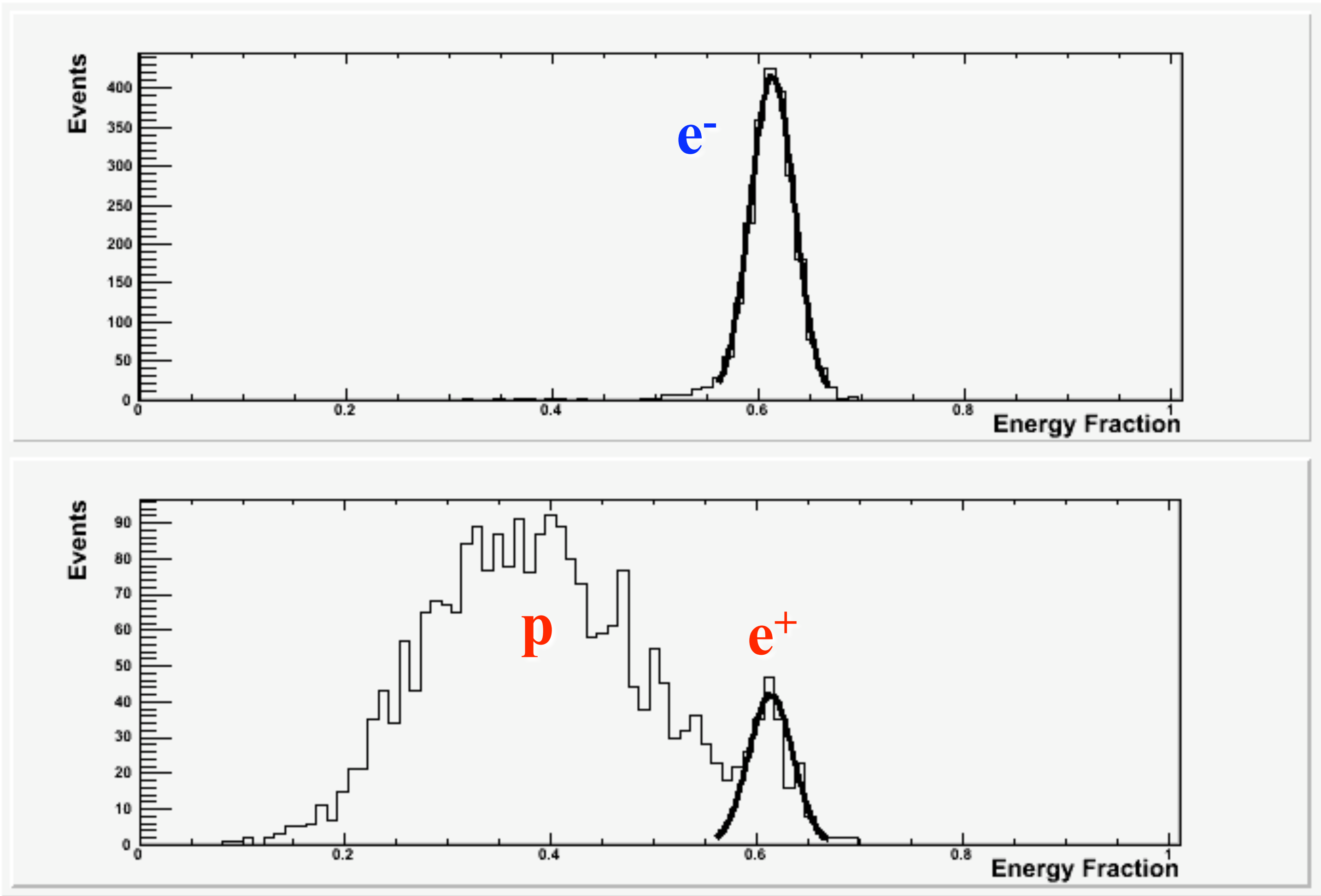
p background suppression



: 1

Fraction of charge released along the calorimeter track shower shape

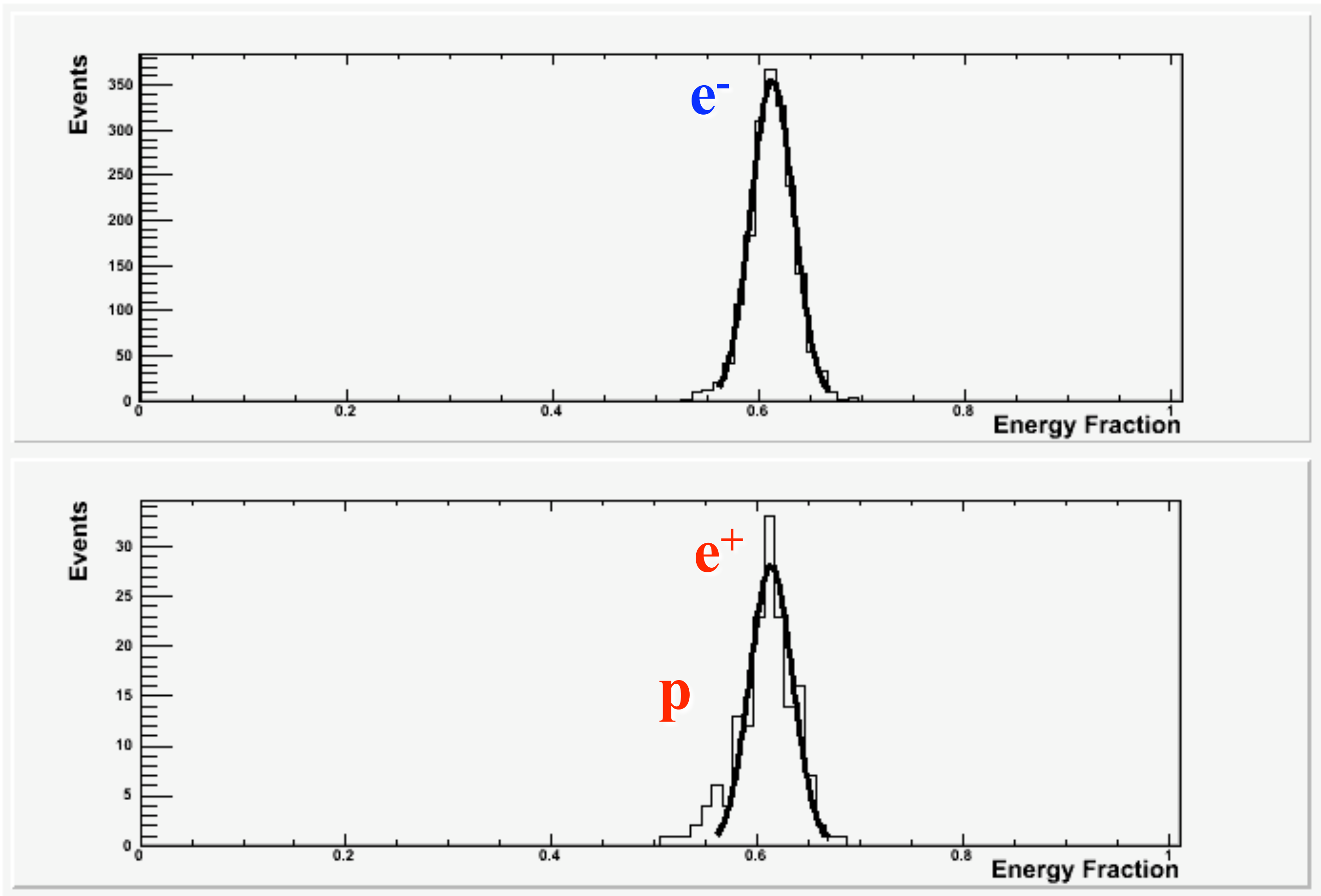
Positron 1
p background suppression



Fraction of charge released along the calorimeter track **+** **Energy-momentum match**

Positron 2

p background suppression



Fraction of charge released along the calorimeter track

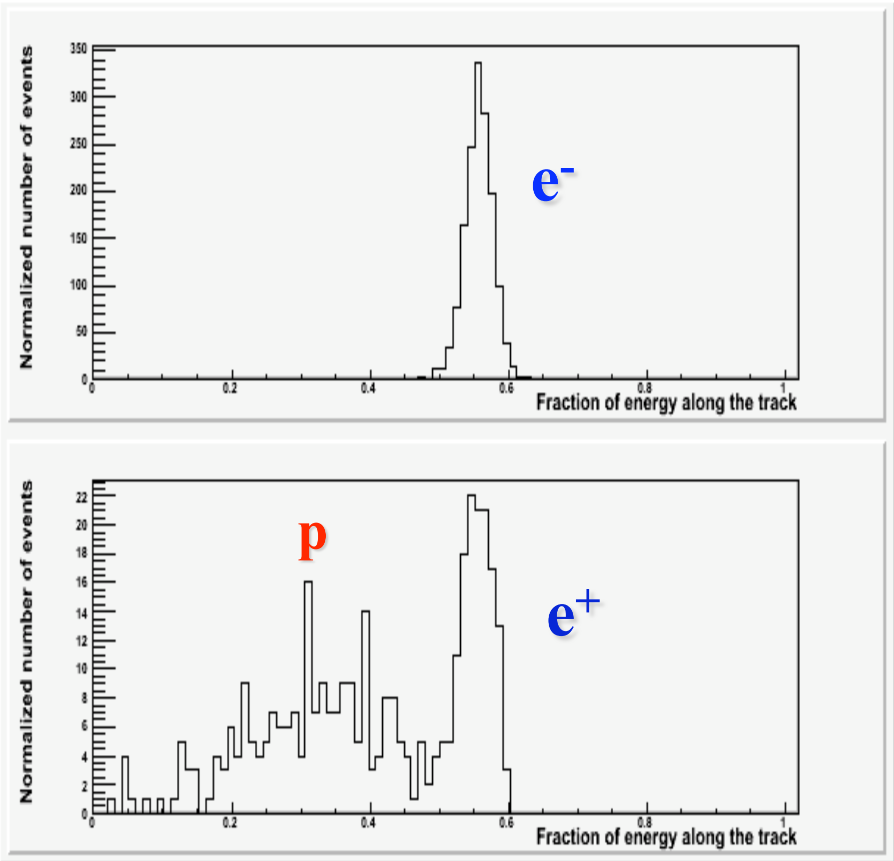
+

Energy-momentum match
Starting point of shower
Longitudinal profile

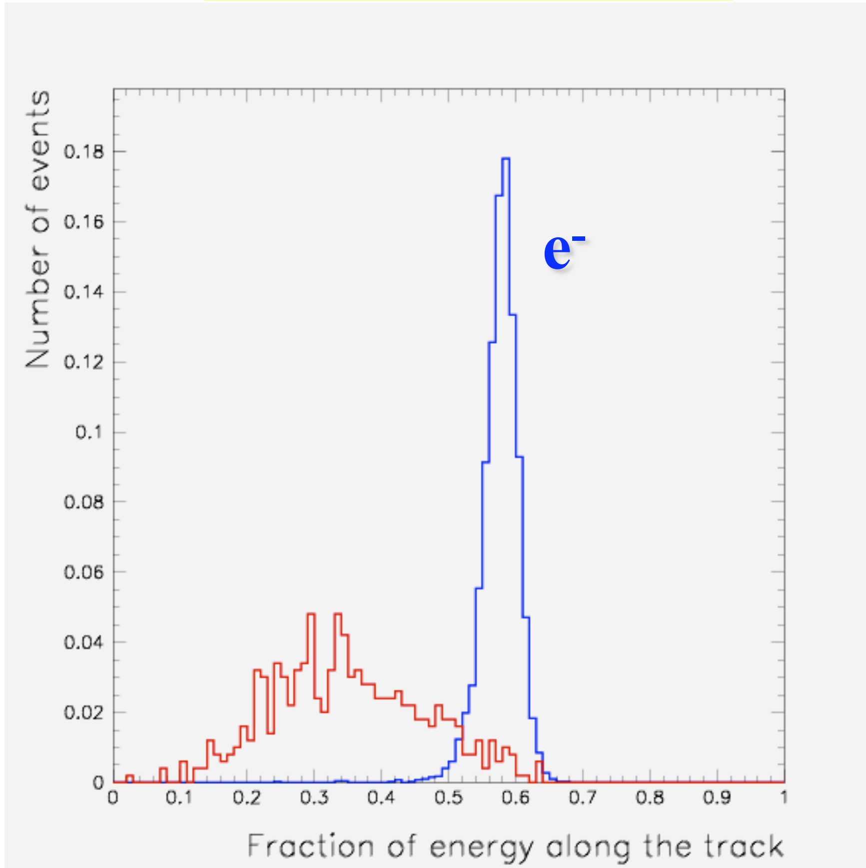
Positron selection with calorimeter

Fraction of charge released along the calorimeter track

Flight data:
rigidity: 20-30 GV



Test beam data
Momentum: 50GeV/c

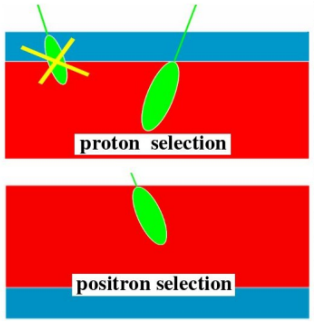


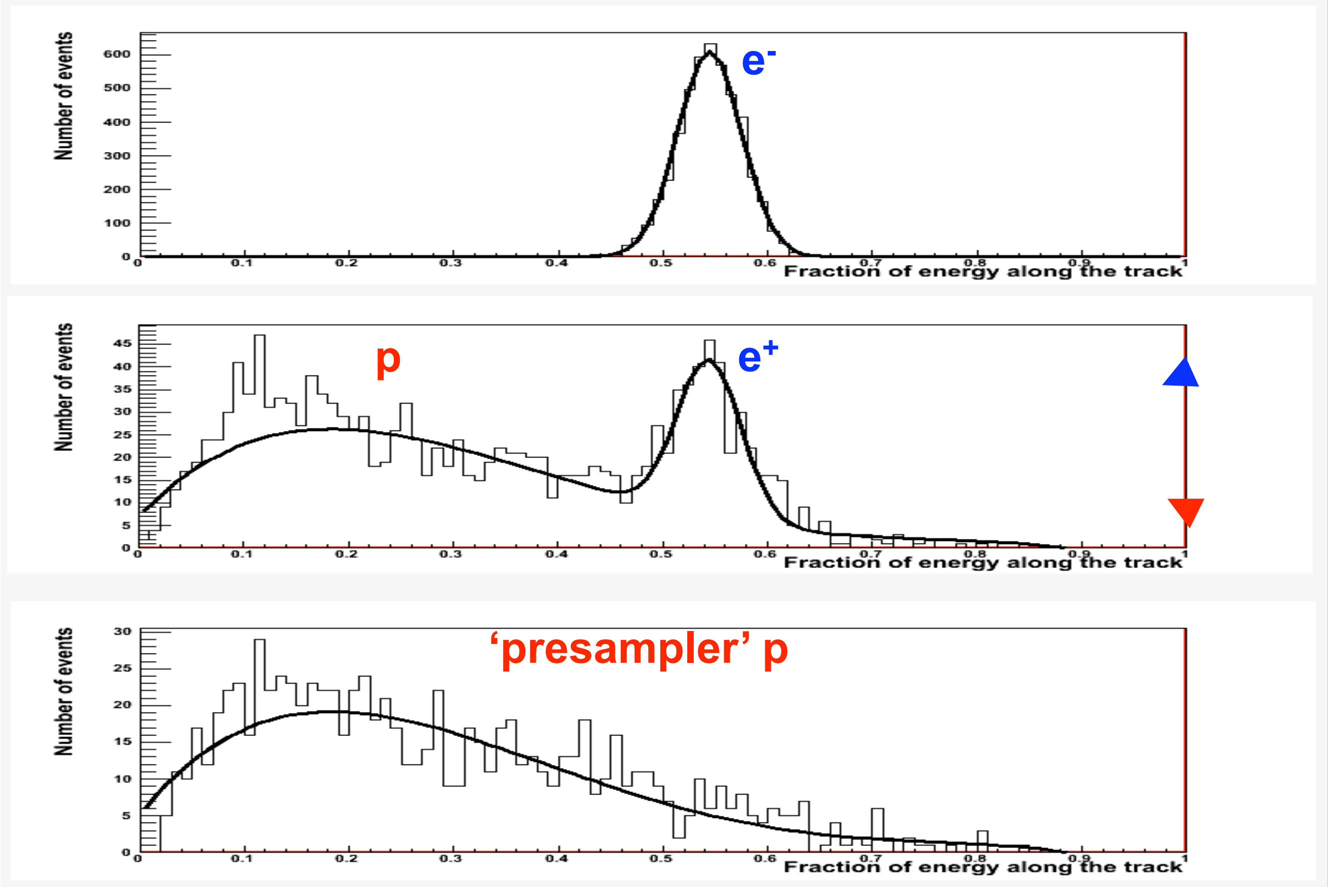
- **Energy-momentum match**
- **Starting point of shower**

e^+ background estimation from data

Rigidity: 6-8 GV

Preliminary





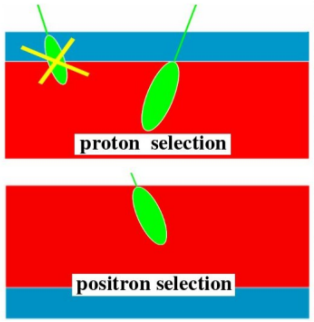
Fraction of charge released along the calorimeter track

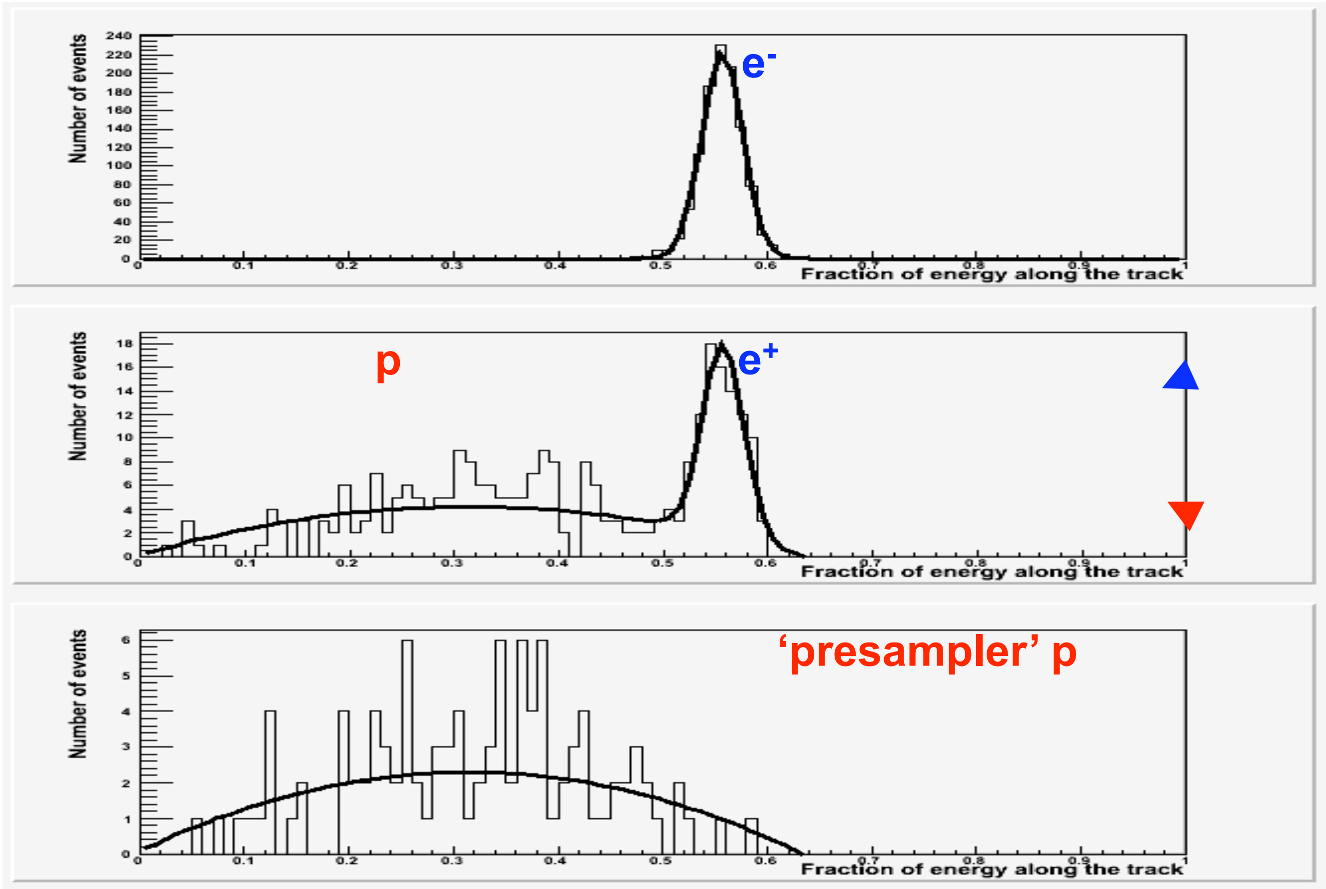
+
- Energy-momentum match
- Starting point of shower

e^+ background estimation from data

Preliminary

Rigidity: 20-30 GV





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

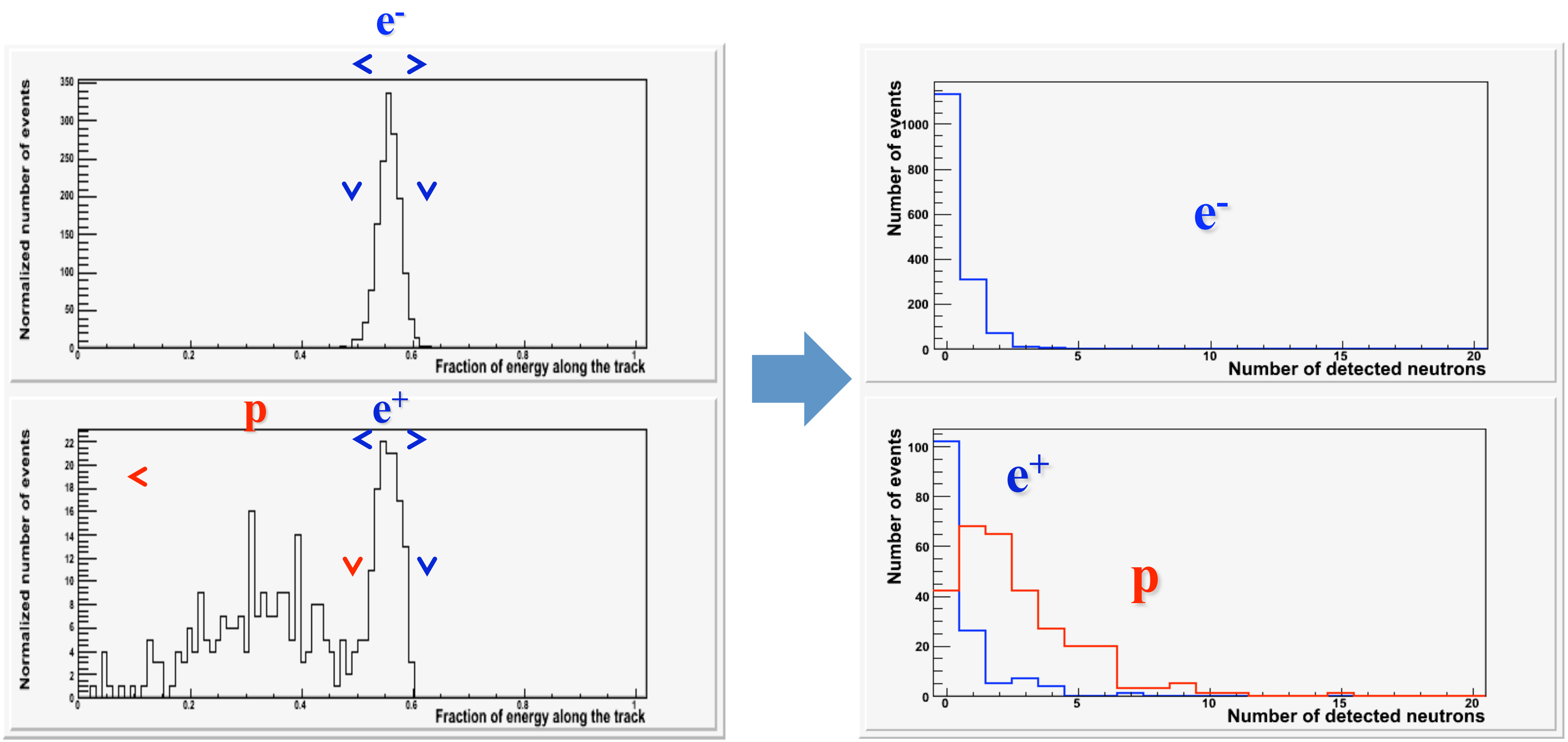
+
- Energy-momentum match
- Starting point of shower

Positron selection

Rigidity: 20-30 GV

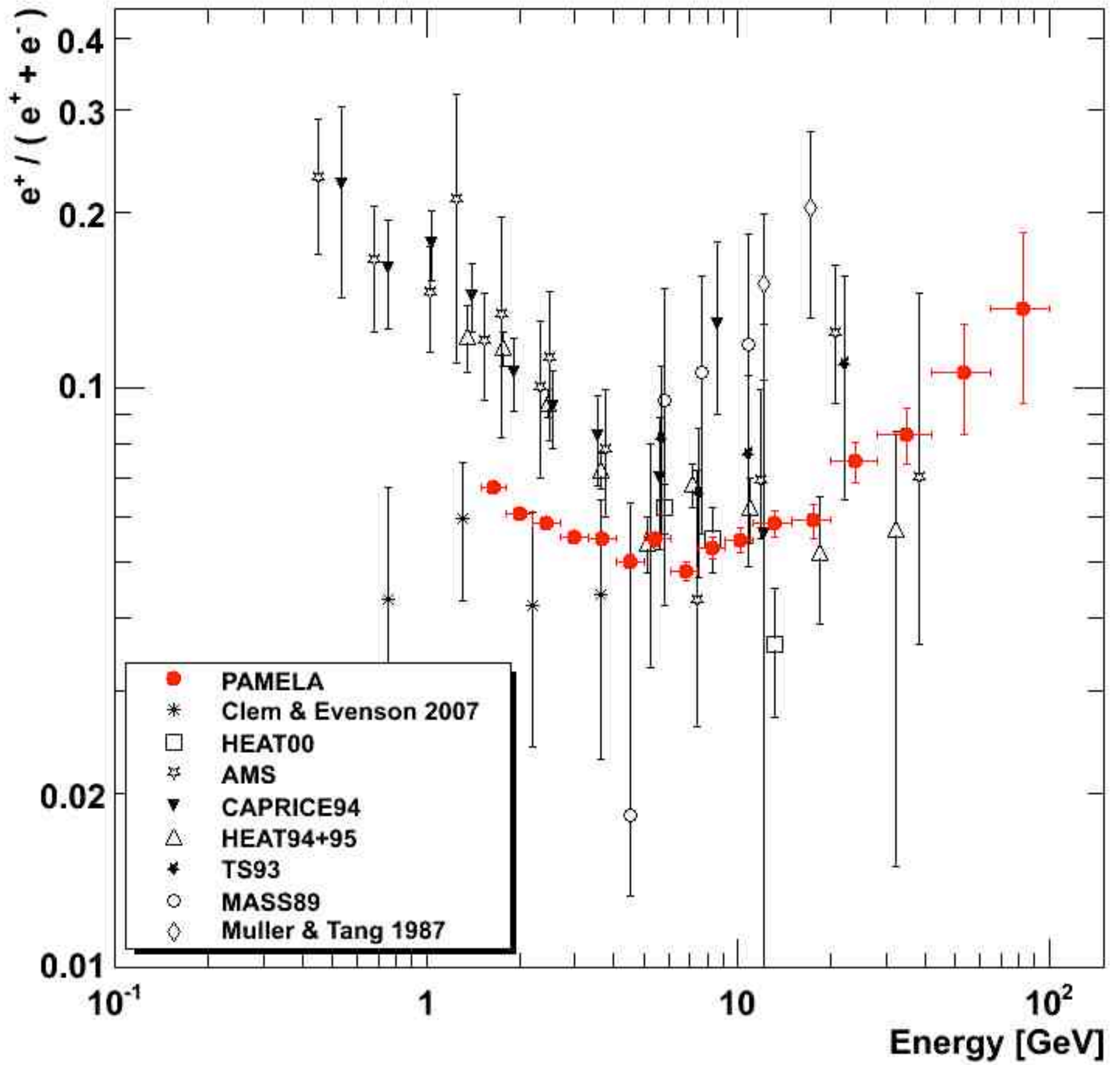
Fraction of charge released along the calorimeter track

Neutrons detected by ND



- Energy-momentum match
- Starting point of shower

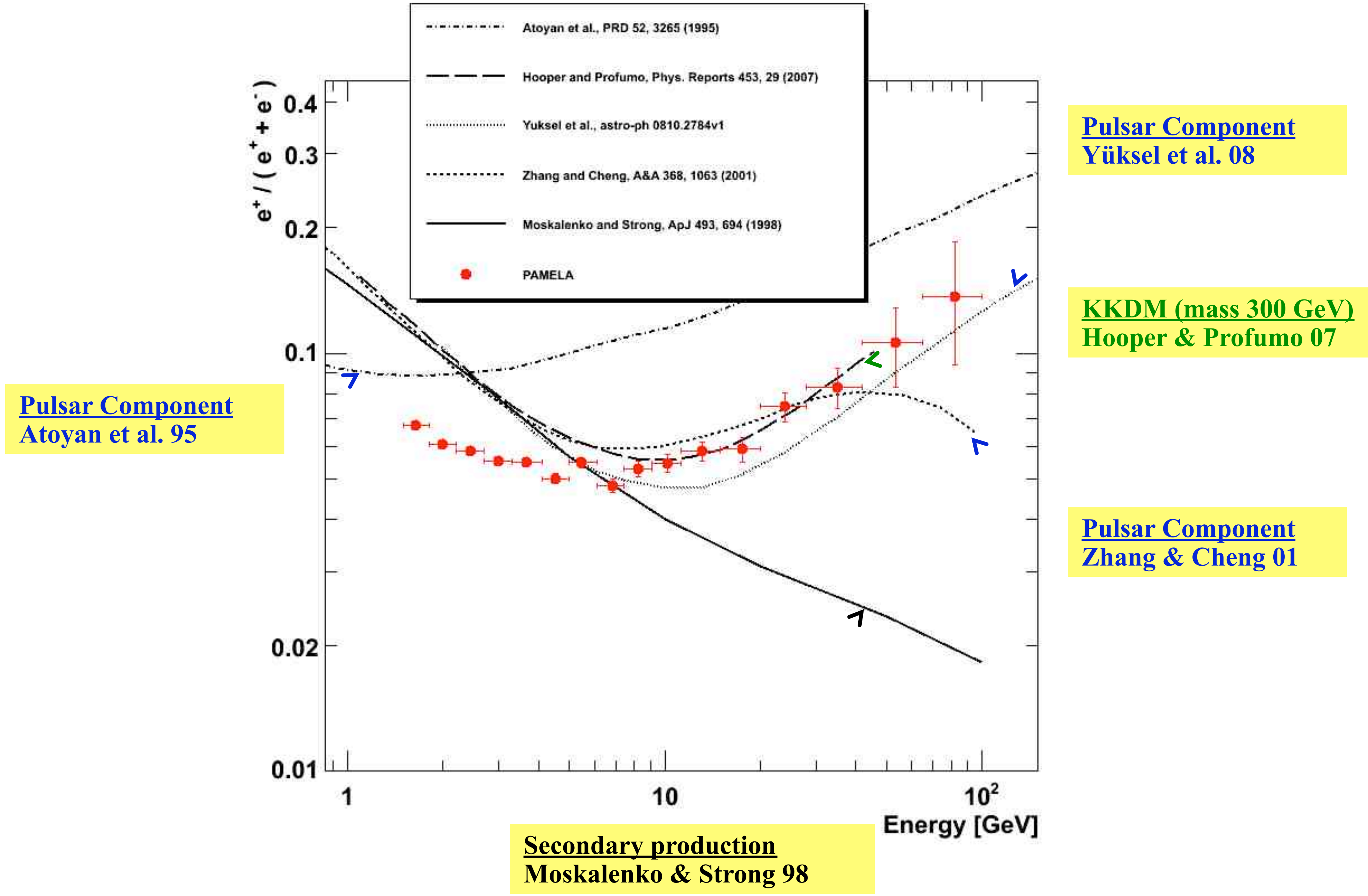
Positron to Electron Fraction



End 2007:
~10 000 e⁺ > 1.5 GeV

~2000 > 5 GeV

Astro-ph 0810.4995



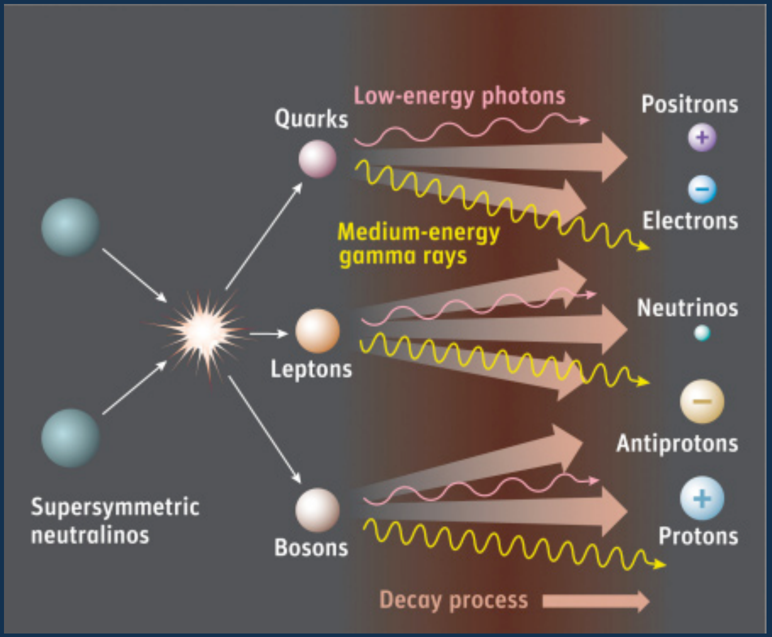
Atoyan et al., PRD 52, 3265 (1995)
Hooper and Profumo, Phys. Reports 453, 29 (2007)
Yuksel et al., astro-ph 0810.2784v1
Zhang and Cheng, A&A 368, 1063 (2001)
Moskalenko and Strong, ApJ 493, 694 (1998)
PAMELA
e+ / (e+ + e-)
Energy [GeV]
Pulsar Component
Yüksel et al. 08
KKDM (mass 300 GeV)
Hooper & Profumo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

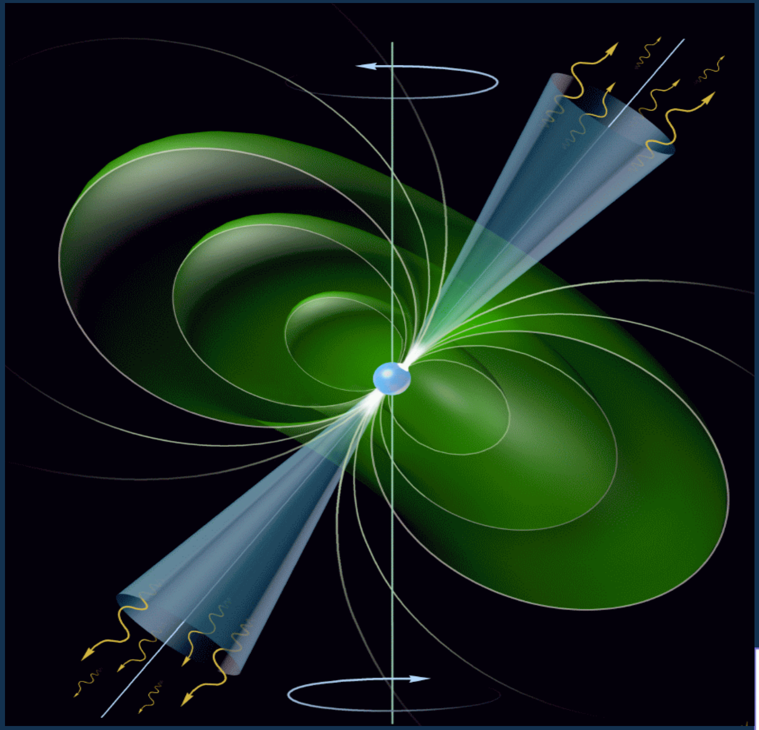
Positron Abundance

- **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.**

- Standard solutions require
- Dark Mater - NEW PHYSICS
- or
- Pulsars - NEW ASTROPHYSICS

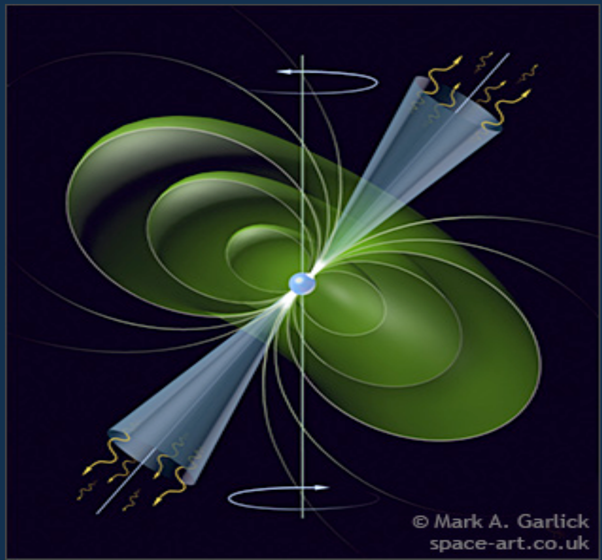
- Is there a simpler solution?





Astrophysical explanations?

Young, nearby pulsars



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

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

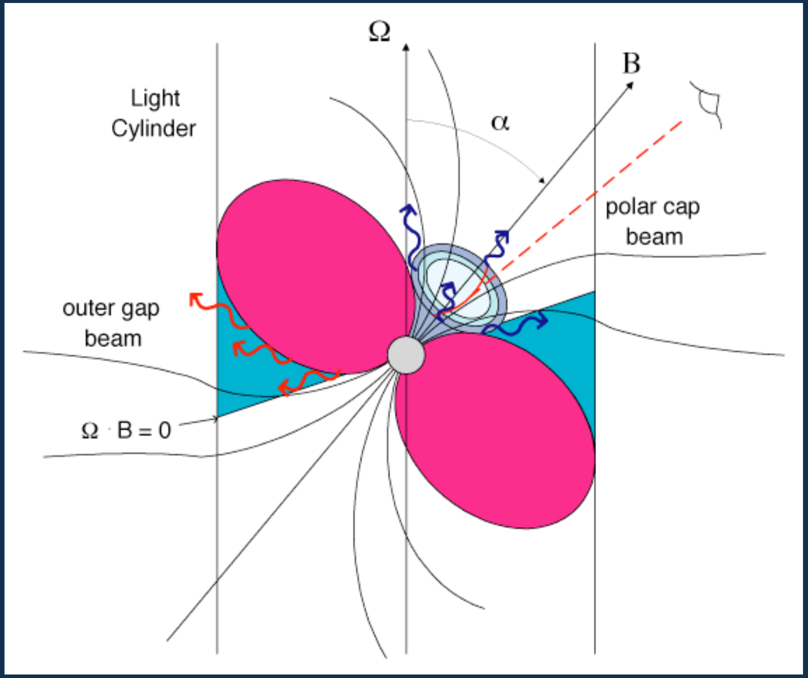
Must be young (T<10^5 yr) and nearby (<1 kpc). If not: too much diffusion, low energy, too low flux.

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

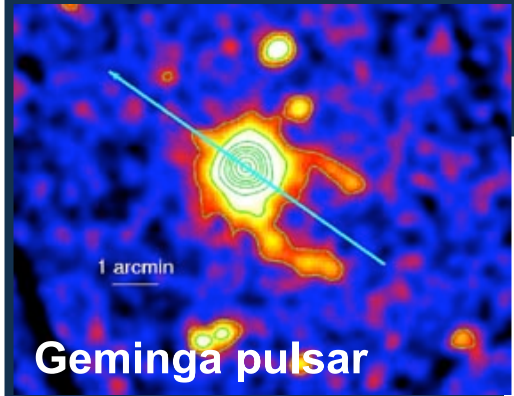


- Highly magnetized rotating neutron star accelerates charged particles.
- These charges escape along open magnetic field lines in jets.
- In the process, they radiate and scatter photons to high energies.
- Details depend on specific models.

Pulsars as the Sources of High Energy Cosmic Ray Positrons

Dan Hooper, Pasquale Blasi, Pasquale Dario Serpico

arXiv: 0810.1527v1



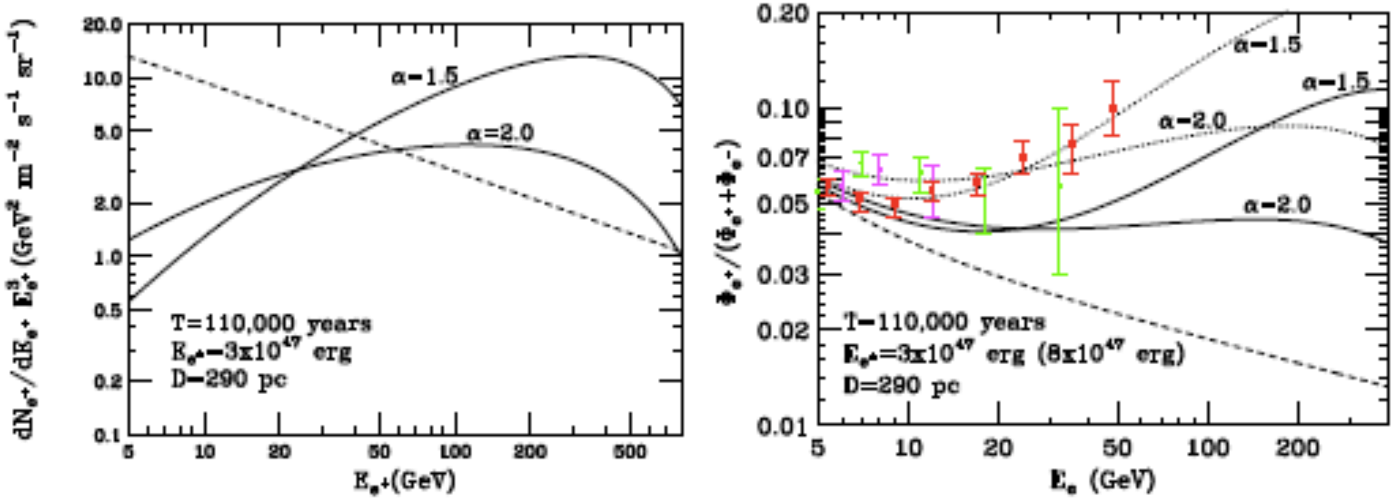


FIG. 3: As in Fig. 2, but from the nearby pulsar B0656+14. The solid lines correspond to an energy in pairs given by 3×10^{47} erg, while the dotted lines require an output of 8×10^{47} erg.

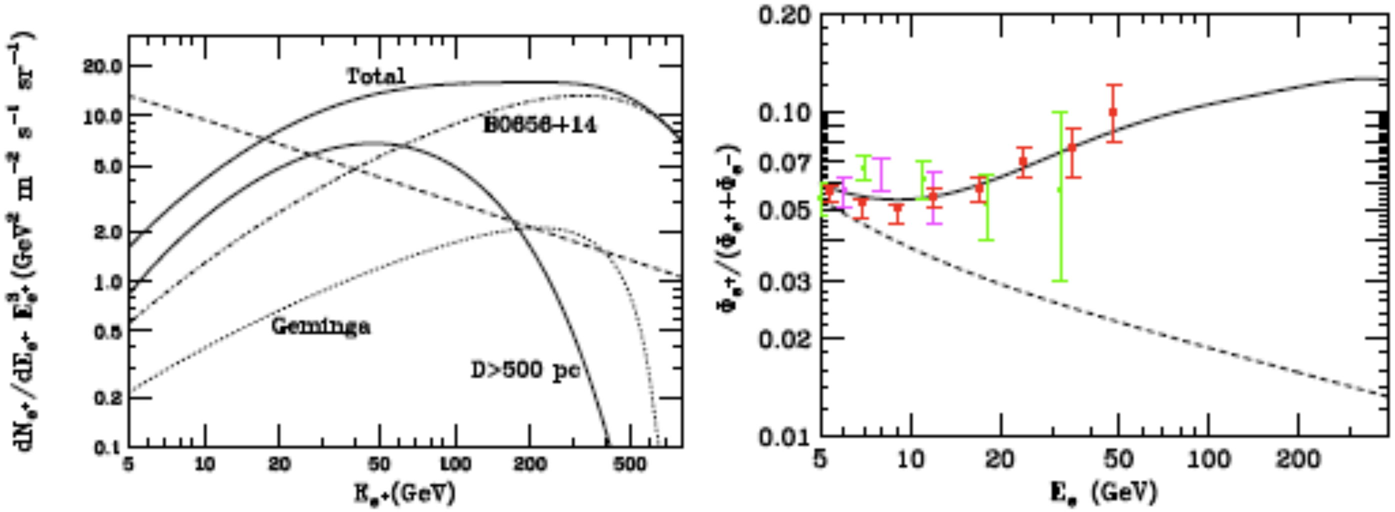


FIG. 4: The positron spectrum and positron fraction from the sum of contributions from B0656+14, Geminga, and all pulsars farther than 500 parsecs from the Solar System.

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

arXiv:0904.0921v1 [hep-ph] 6 Apr 2009

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

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

[2] *International School for Advanced Studies (SISSA)*
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`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.

SNR are the canonical sources of CRs

Tsvi Piran, Nir J. SHaviv (Hebrew U) Ehud Narkar
(Tel Aviv U) Astro-ph/09020376 astro-ph/0905.0904

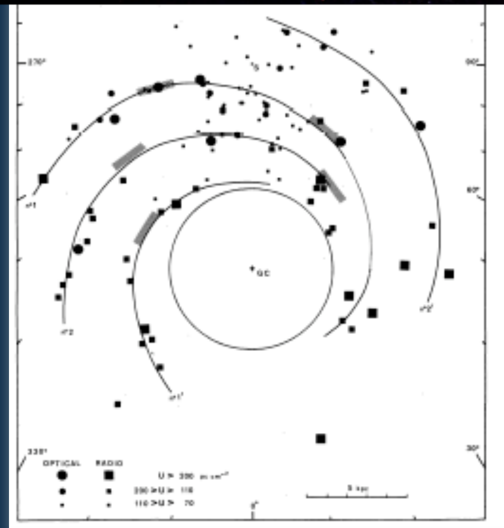
- Mechanism exists (1^{st} order diffusive / shock acceleration)
- Ginzburg & Syrovatskii (1963) - Energy requirements agree with CR density/lifetime (assuming ~ 3% - 10% efficiency)
- Observations of Synchrotron from SNe reveals efficient electron acceleration

PaMeLa

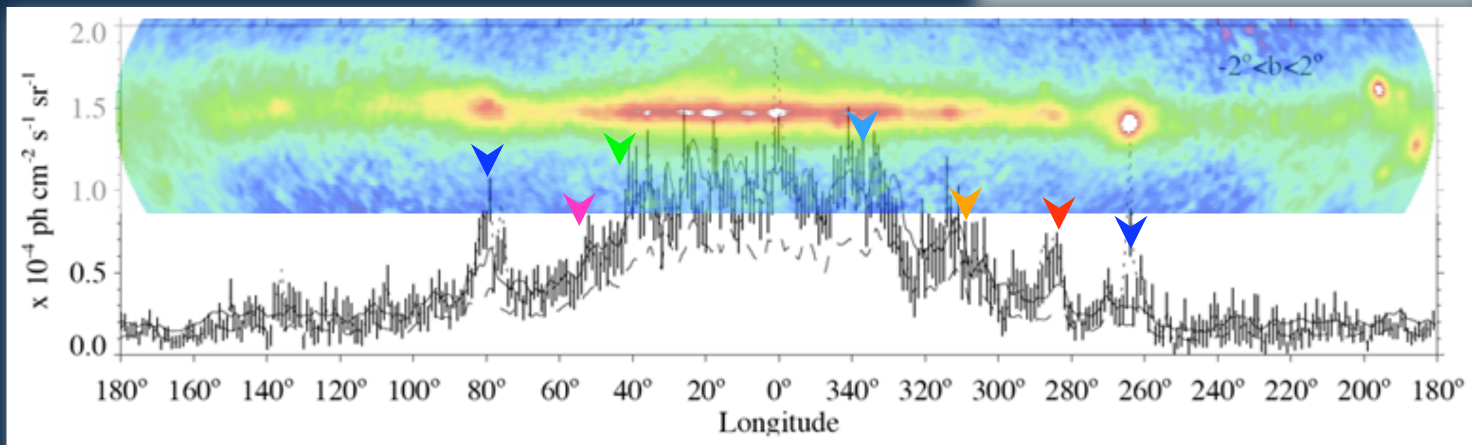
INFN Istituto Nazionale di Fisica Nucleare

Most SNe occur in the spiral arms

Tsvi Piran, Nir J. SHaviv (Hebrew U) Ehud Narkar (Tel Aviv U) Astro-ph/09020376 astro-ph/0905.0904

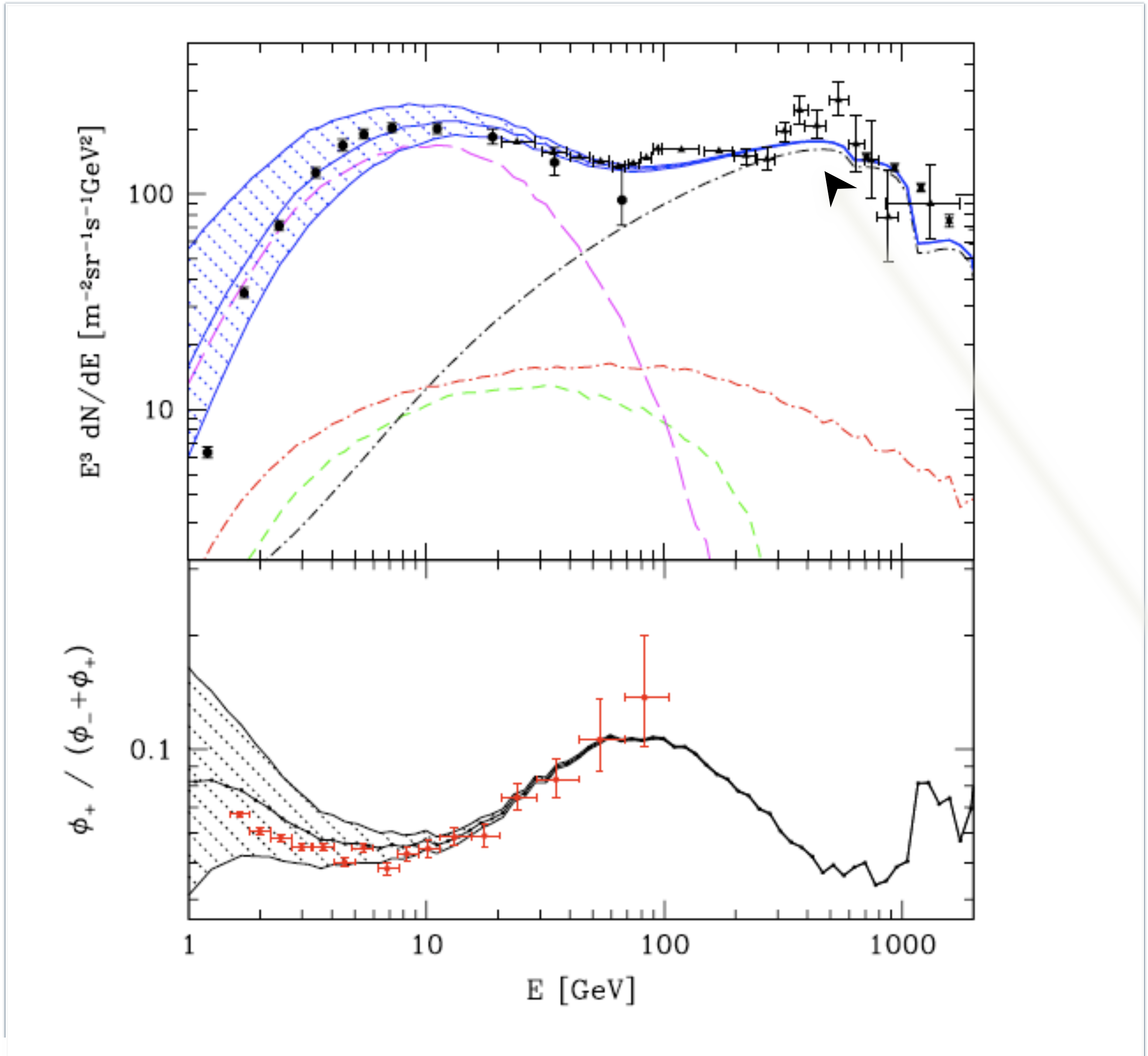


- In the Milky Way: Almost all SNe are non-Type Ia, and occur where almost all star formation takes place: In the Spiral Arms
- Meteorites: Show that density changes by a factor of > 2.5
- Deconvolved Synchrotron: Shows arm to inter-arm ratio of ~ 3



$e^+/(e^++e^-)$ ratio and e^- spectrum

Tsvi Piran, Nir J. SHaviv (Hebrew U) Ehud Narkar (Tel Aviv U) Astro-ph/09020376 astro-ph/0905.0904



Contribution from nearby KNOWN young SNRs: Geminga, Monogem, Gela LoopI and Cygnus Loop

Dark Matter and Pamela Results

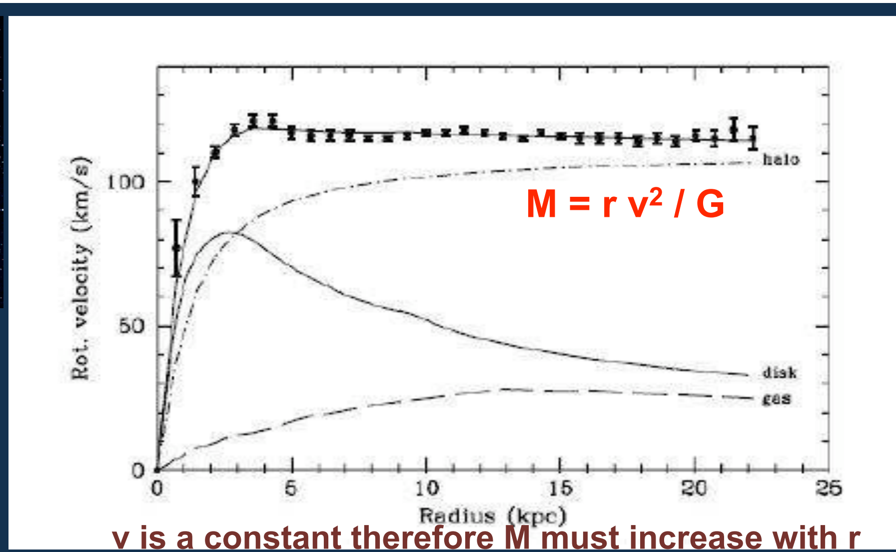
The identity of dark matter is one of the greatest puzzles of our Universe. Its solution may be associated with supersymmetry the fundamental space-time symmetry that was so far not experimentally verified.

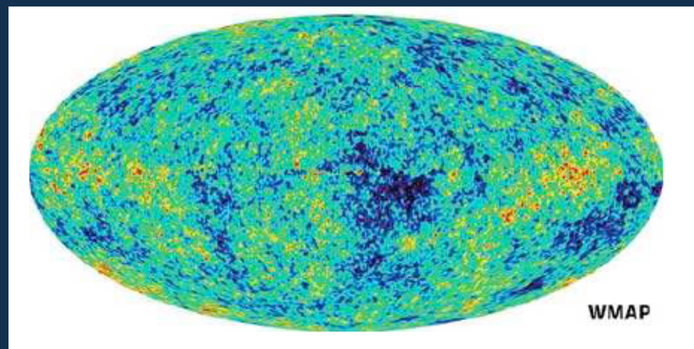
In many supersymmetric extensions of the Standard Model of particle physics, the lightest supersymmetric particle cannot decay and is hence a promising dark matter candidate.

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.

DM evidences

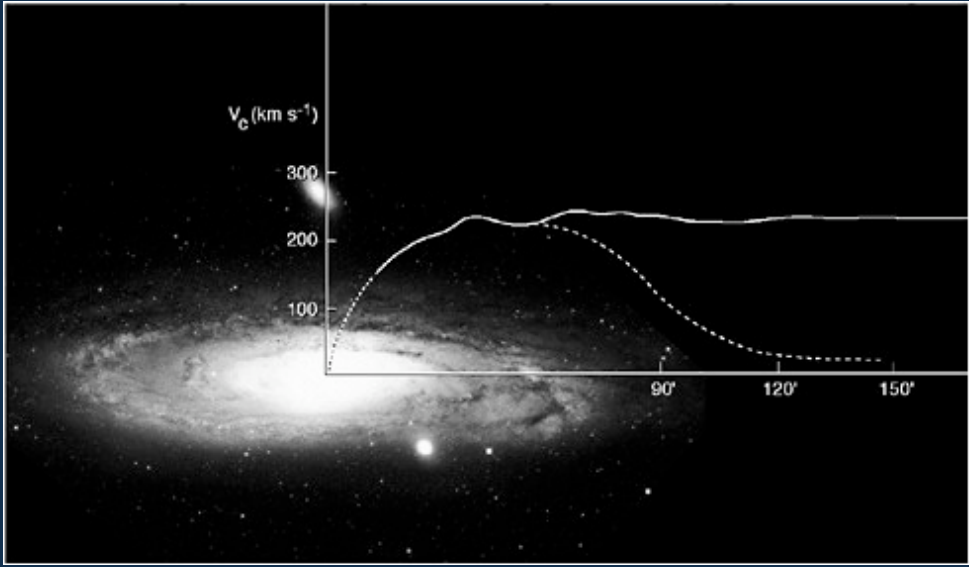
- Evidences:
  - DM hints on all cosmological scales:
    - rotational curves of galaxies
    - motion of galaxies in clusters
    - gravitational lensing
  - DM seems cold (CDM)
  - The DM must be:
    - Massive (acts gravitationally)
    - Stable (justify abundances)
    - Neutral in charge and colour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





Missing Matter

- The study of the rotation curve of M31 from Roberts & Whitehurst (1975) provided the first widely recognized observational evidence in favor of dark matter in galaxies.
- This study provided a map of rotation curve, which extended to roughly 10 times optical radius.



Credit: M. S. Roberts

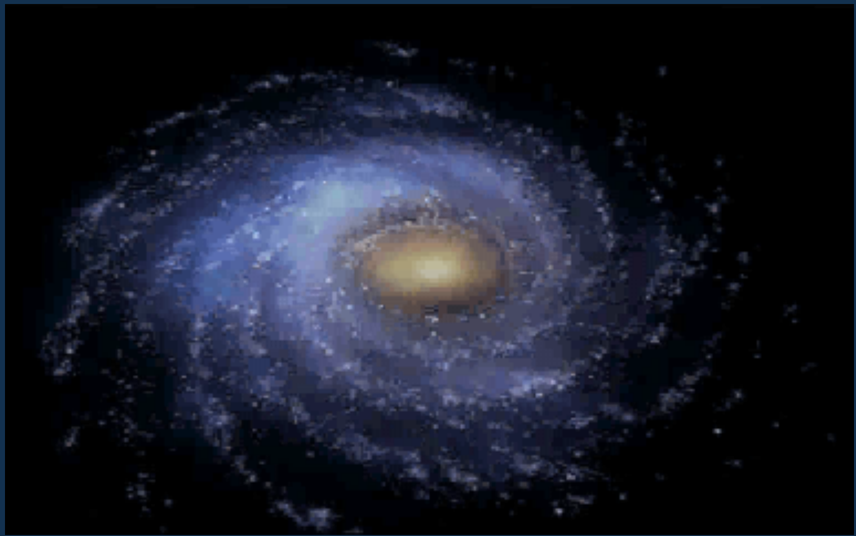
At around this time there were a number theoretical studies of the implications of "dark matter" in galaxies...

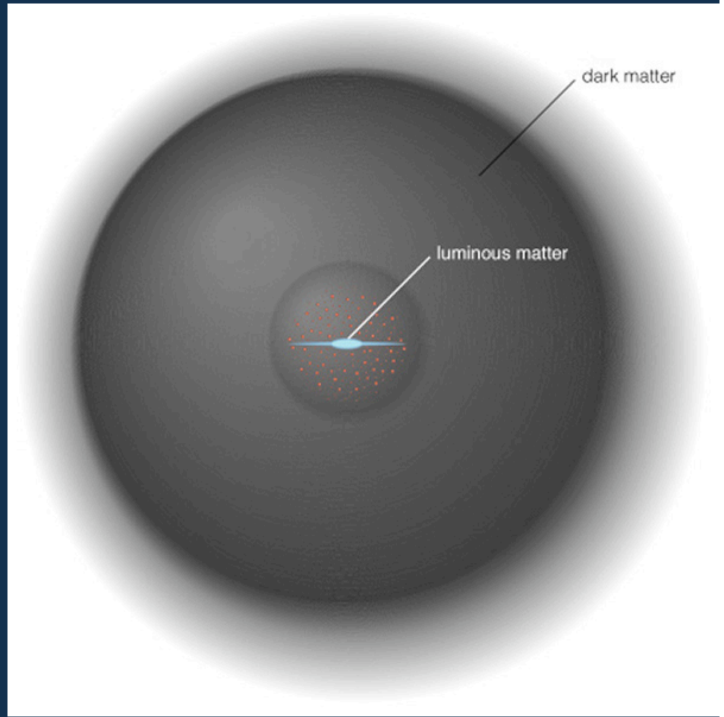
Ostriker & Peebles (1974) suggested that the stability of galactic disks required the presence of a massive halo around galaxies

Ostriker, Peebles & Yahil (1975) noted that if the mass-to-light ratios of galaxies increase with increasing radius, then this dark mass could be cosmologically significant.

But what could this dark matter be?

Neutralino Annihilation





Galactic Center

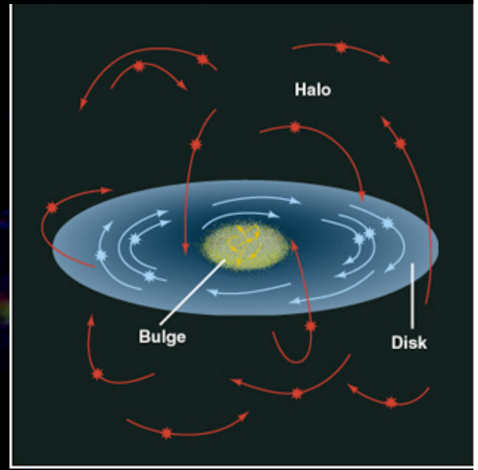
- The lightest SUSY particle (neutralino?) is a leading candidate for the WIMP.
- Density should be biggest in centers of galaxies
- Annihilation to different final states might be detectable.

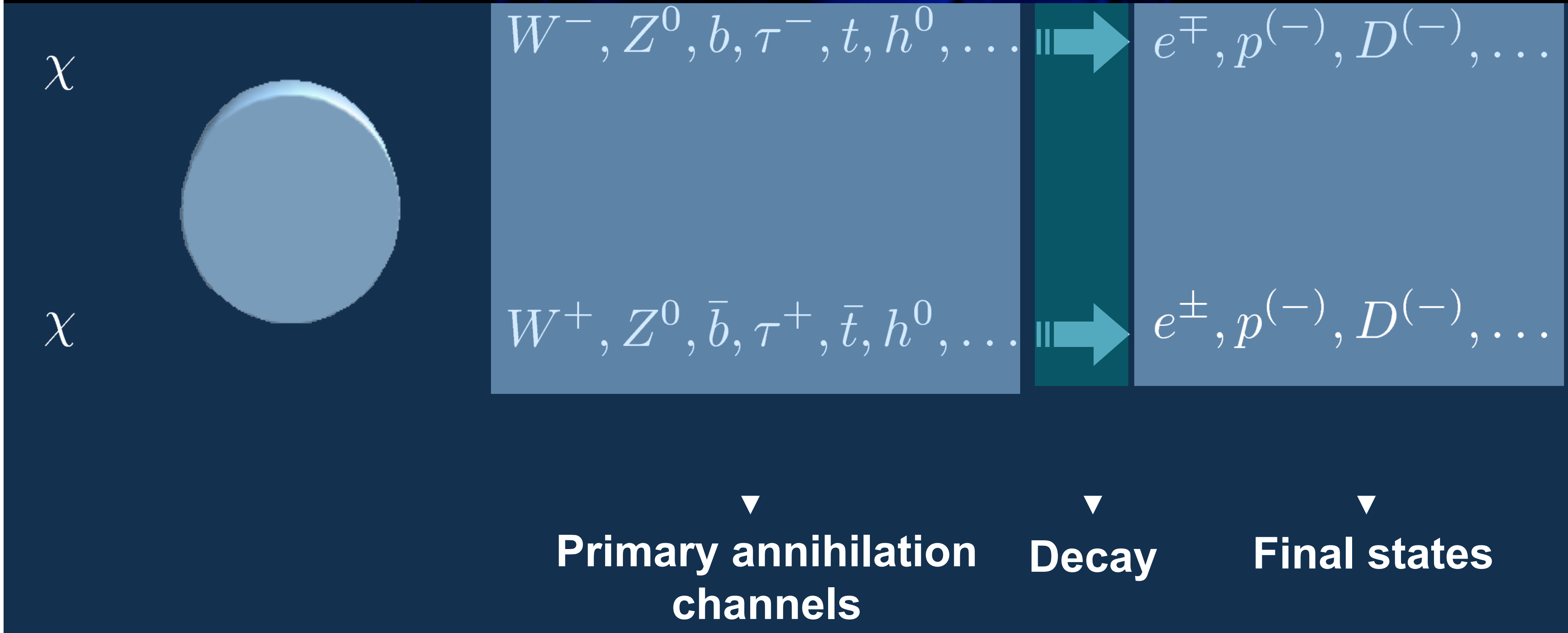
Dark matter annihilation

Cusp of dark matter at centre of Galaxy is expected
Annihilation of DM particles in Galactic Halo
could produce energetic particles:

- Antiprotons
- Positrons
- Gamma-rays (lines or through hadronisation)

Annihilation signal ~ density^2





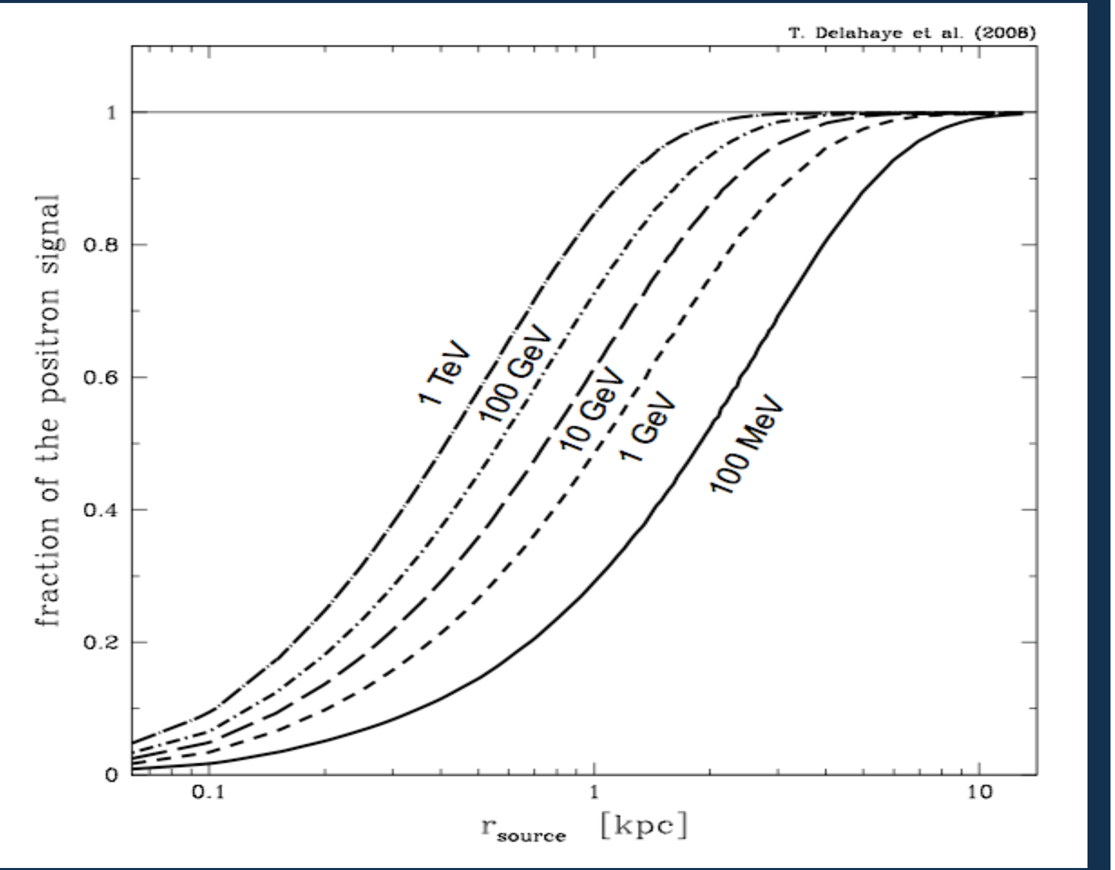
Indirect DM detection

Where do positrons come from?

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

Typical lifetime

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



Cosmic-ray Antimatter from Dark Matter annihilation?

→ Distortion of antiproton and positron spectra from purely secondary production

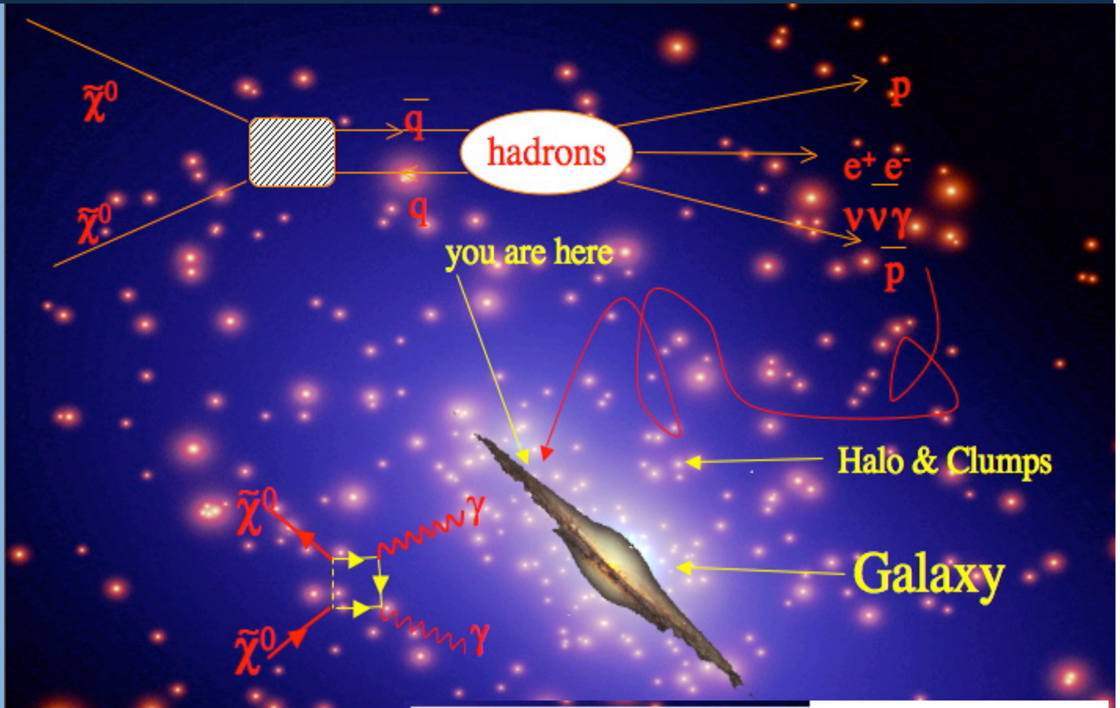
A plausible dark matter candidate is neutralino (χ), the lightest SUSY particle.

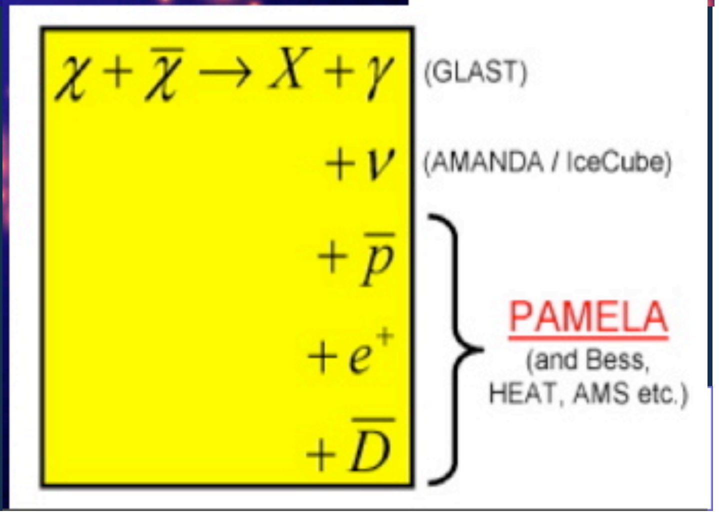
Annihilation of relic χ gravitationally confined in the galactic halo

Most likely processes:

- **χχ → qq → hadrons→ anti-p, e+,…**
- **χχ → W^+W^-,Z^0Z^0,… → e^+,…**

direct decay ⇒ positron peak Ee+~Mc/2
other processes ⇒ positron continuum Ee+~Mχ/20





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.**

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

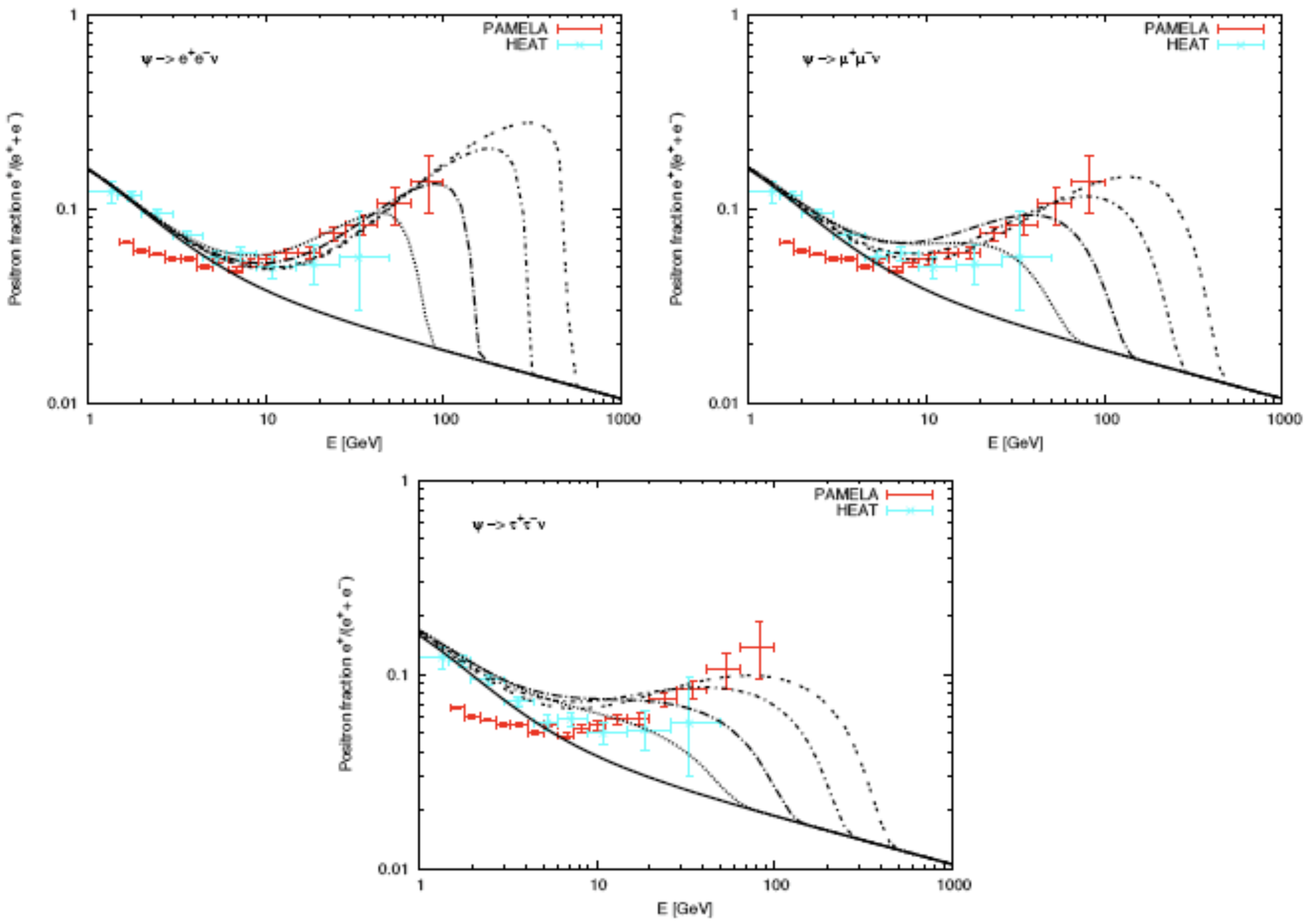
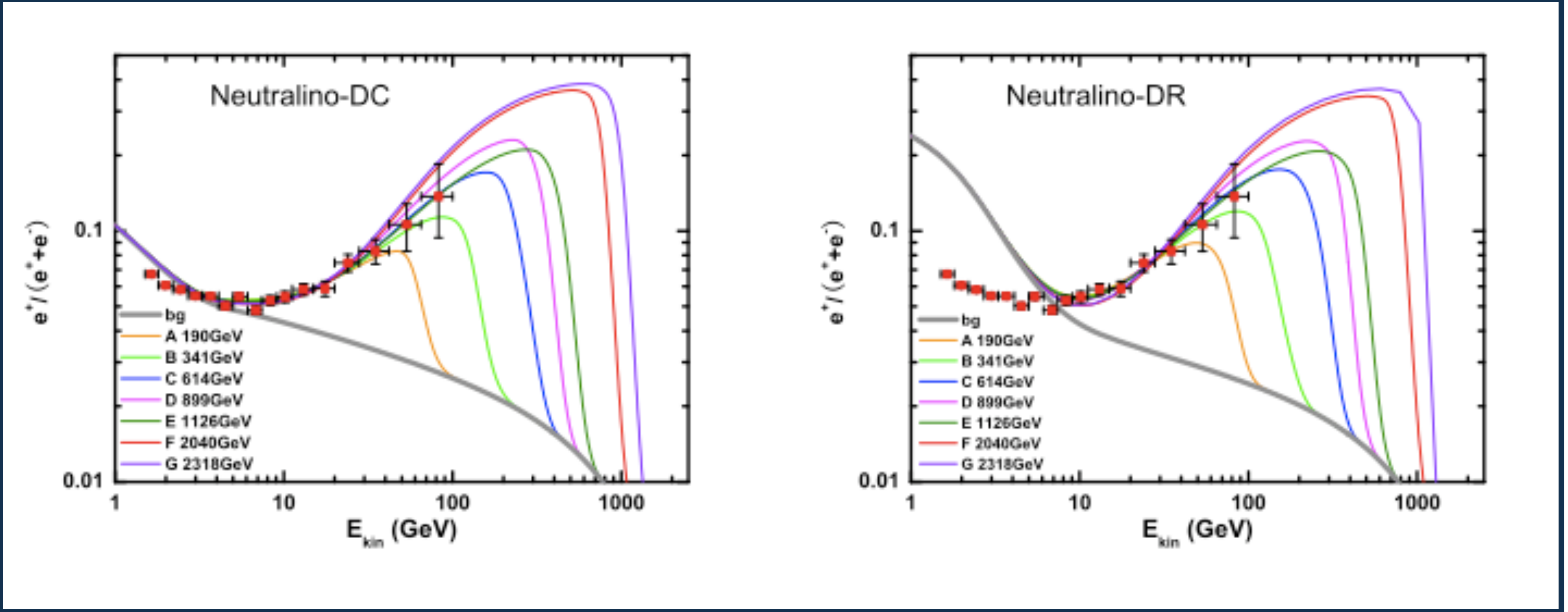


Figure 3: Positron fraction from the decay of the fermionic dark matter particle in the channels $\psi \to e^+e^-\nu$ (top-left panel), $\psi \to \mu^+\mu^-\nu$ (top-right panel) and $\psi \to \tau^+\tau^-\nu$ (bottom panel), when the dark matter mass is, from left to right, $m_{DM} = 150,\ 300,\ 600,\ 1000$ GeV. The lifetime, which ranges between 5×10^{25} s and 8×10^{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

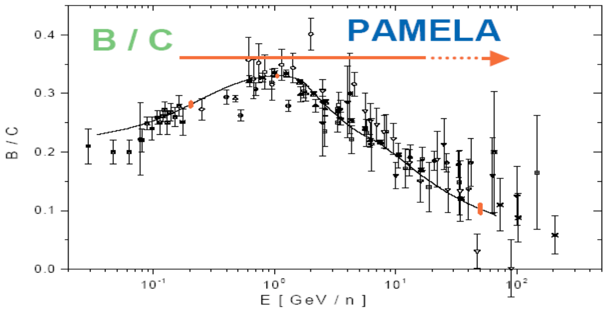
We find thePAMELA data actually excludes the annihilation or decay products being quark pairs, strongly disfavors the gauge bosons and favors dominant leptonic final states.

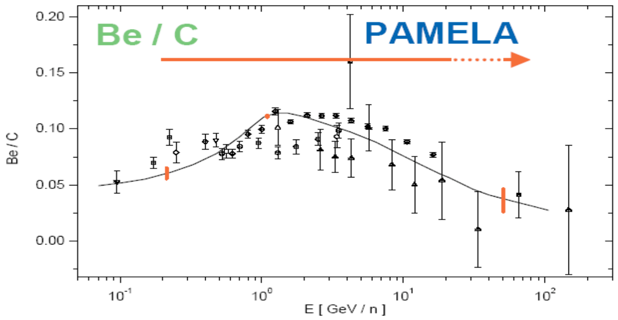


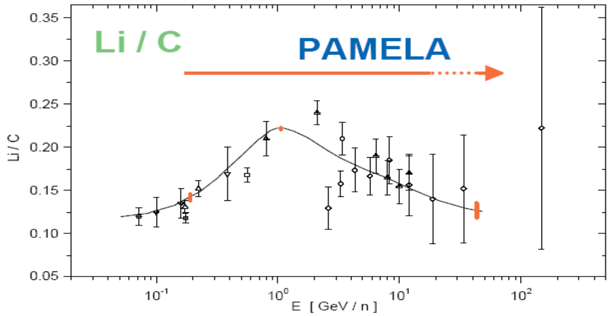
Cosmic-Ray Propagation

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

Secondary to Primary ratios







Pamela will measure ^{10}Be isotopes - Half-life of ^{10}Be in the order of confinement time brings informations on

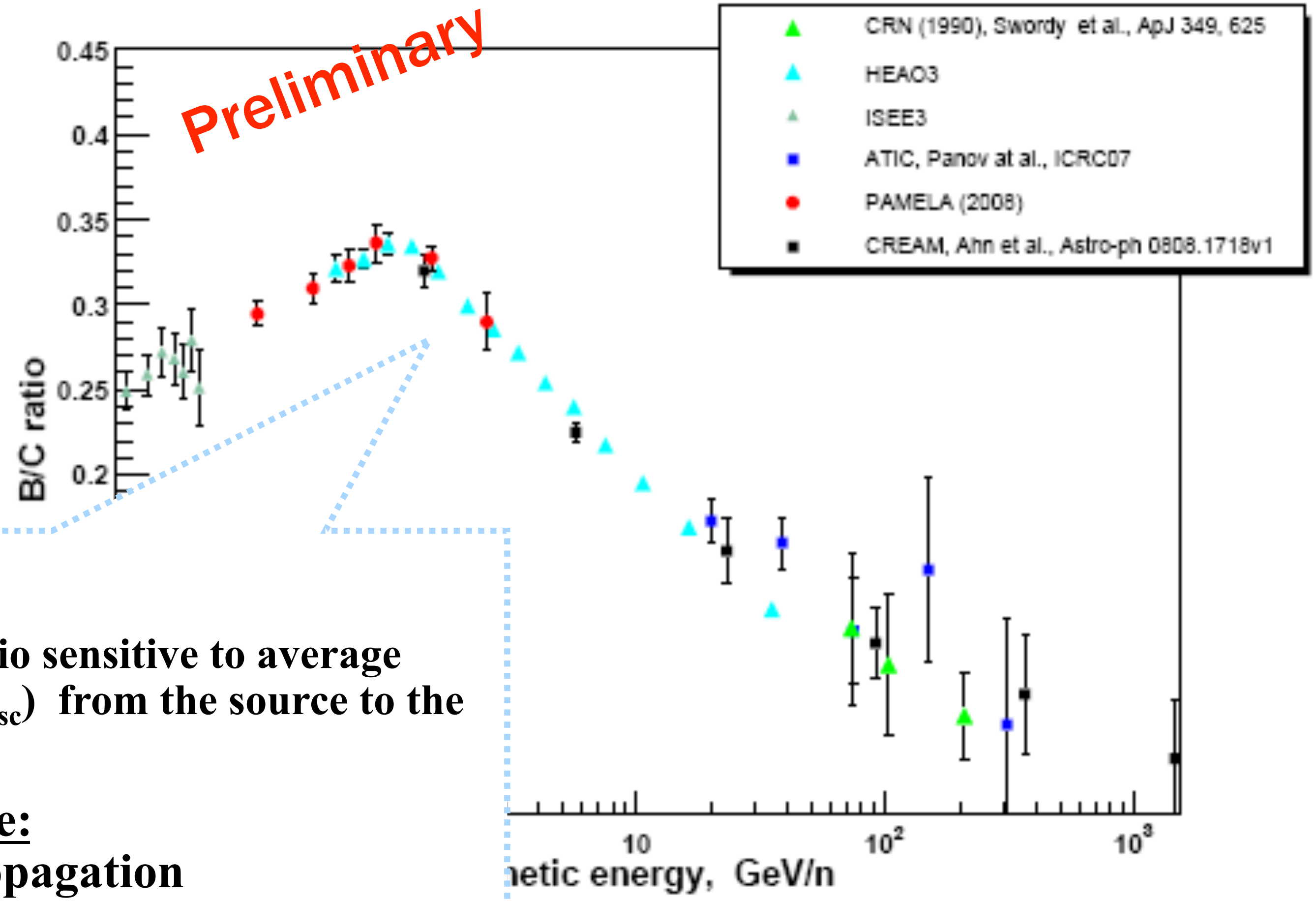
- **Confinement time**
- **Galactic halo size**

C and B to measure the ratio of Carbon to its spallation secondary Boron up to 200GeV/n allows to study:

- **Amount of matter traversed**
- **Diffusion (to understand propagation and to fix free parameters of models)**

$$\frac{N_S}{N_P} \propto \lambda_{esc} \cdot \sigma_{P \to S}$$

Secondary nuclei



- B nuclei of secondary origin:

  CNO + ISM → B + …
- Local secondary/primary ratio sensitive to average amount of traversed matter (l_{esc}) from the source to the solar system

<u>**Local secondary abundance:**</u>

⇒ study of galactic CR propagation

(B/C used for tuning of propagation models)

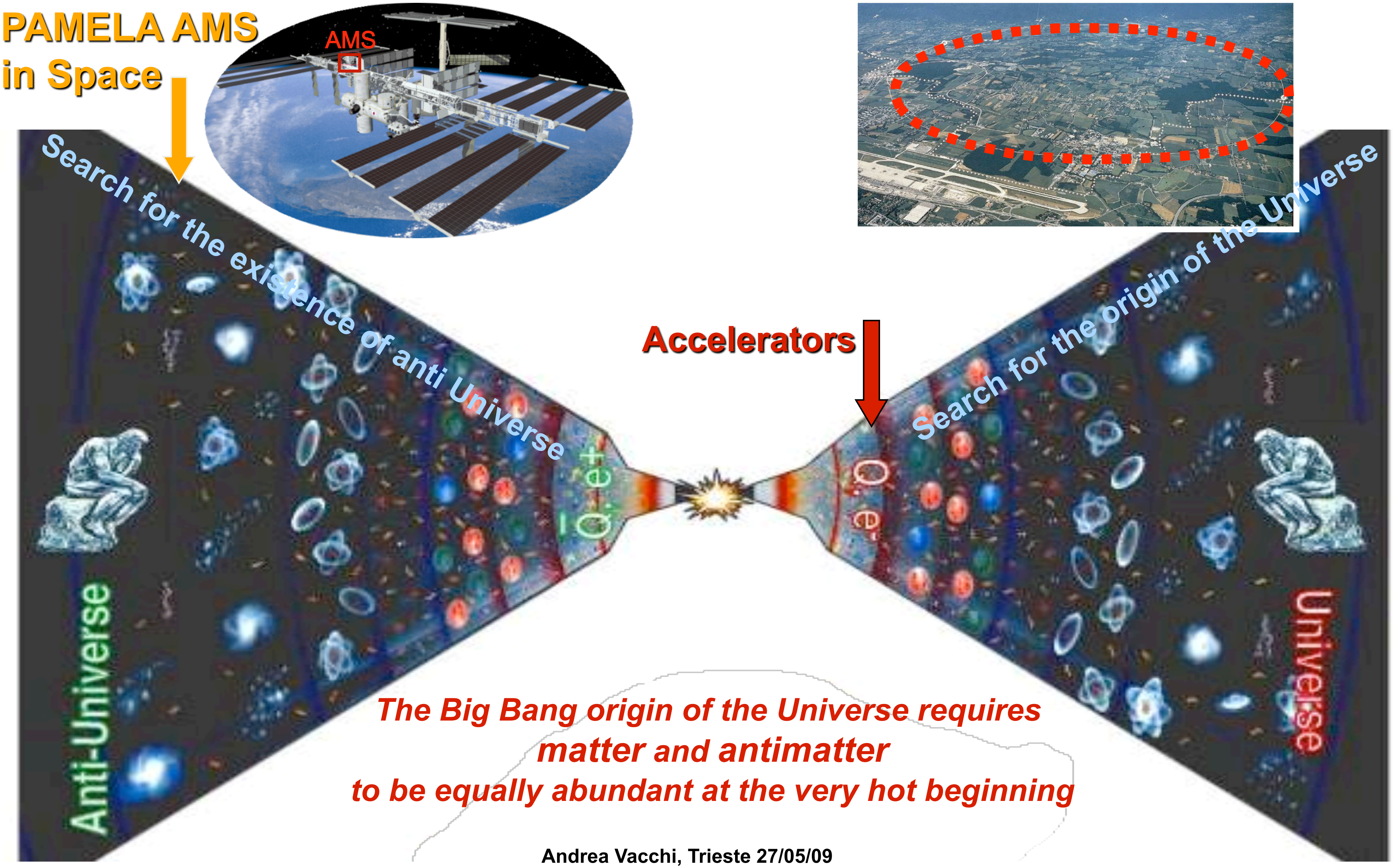
What about antinuclei?

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

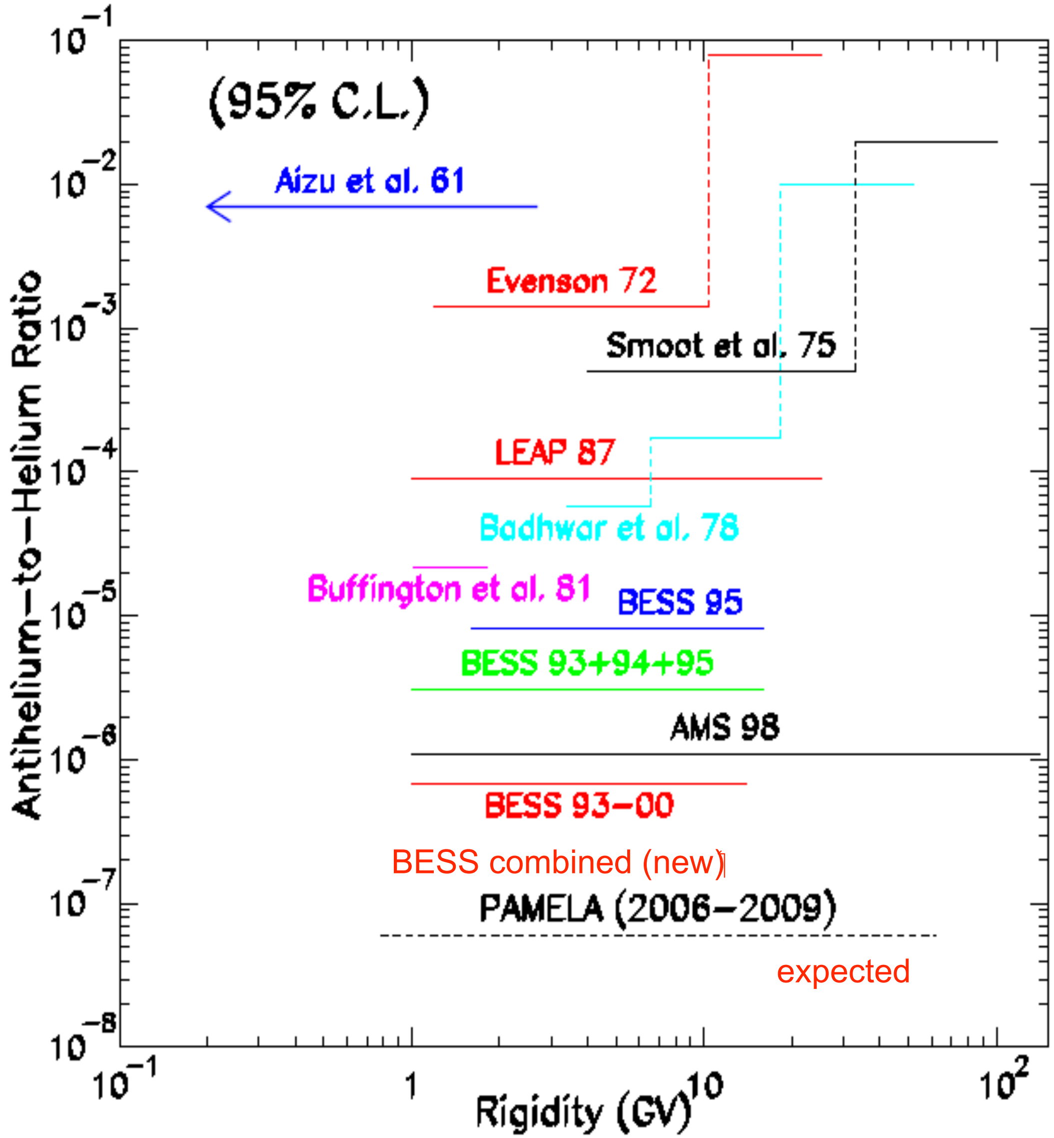
    - **For a Baryon Symmetric Universe Gamma rays limits put any domain of antimatter more than 100 Mpc away**

      (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



Antimatter search



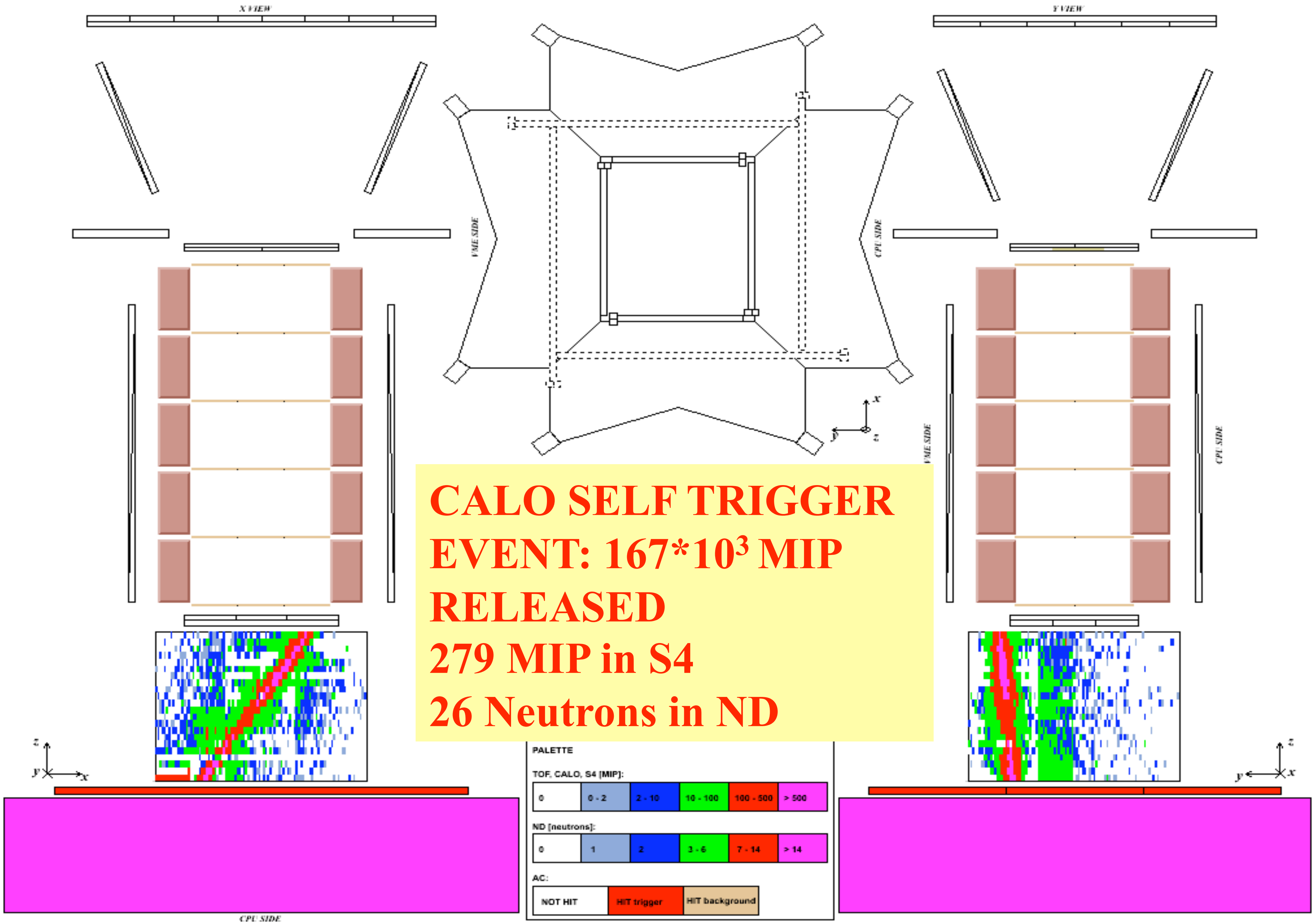
Andrea Vacchi, Trieste 27/05/09

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