Cosmic Ray Antimatter search
The P A M E L A Satellite experiment

Payload for Antimatter / Matter Exploration and Light-nuclei Astrophysics

A Positron Abundance Signal & its possible explanations

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

Nature 2 April 2009

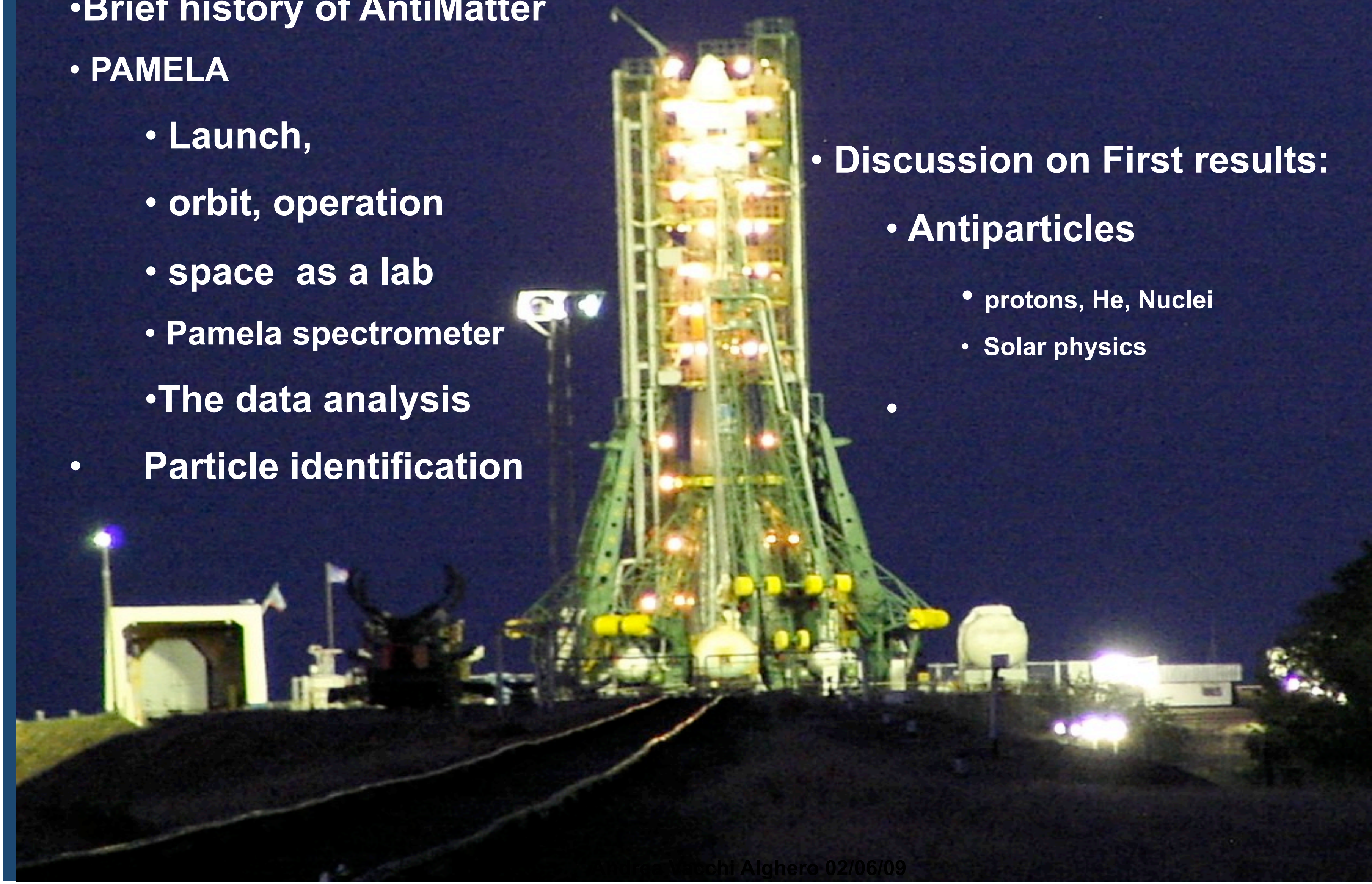
Andrea Vacchi
INFN Trieste, Italy
On behalf of the PAMELA collaboration

http://arxiv.org/abs/0810.4995

http://physics.aps.org/viewpoint-for/10.1103/PhysRevLett.102.051101

Outline

- Overview of the PAMELA experiment:
- Brief history of AntiMatter
- PAMELA
  - Launch,
  - orbit, operation
  - space as a lab
  - Pamela spectrometer
  - The data analysis
- Particle identification
- Discussion on First results:
  - Antiparticles
    - protons, He, Nuclei
    - Solar physics
  -



The PAMELA Collaboration

•O. Adriani, M. Ambriola, G. C. Barbarino, A. Basili, G. A. Bazilevskaja, R. Bellotti, M. Boezio, E. A. Bogomolov, L. Bonechi, M. Bongi, L. Bongiorno, V. Bonvicini, A. Bruno,

•F. Cafagna, D. Campana, P. Carlson, M. Casolino, G. Castellini, M. P. De Pascale, G. De Rosa, V. Di Felice, D. Fedele, A. M. Galper, P. Hofverberg, S. V. Koldashov,

•S. Y. Krutkov, A. N. Kvashnin, O. Maksumov, V. Malvezzi, L. Marcelli, W. Menn, V. V. Mikhailov, M. Minori, S. Misin, E. Mocchiutti, A. Morselli, N. N. Nikonov, S. Orsi, G. Osteria, P. Papini, M. Pearce, P. Picozza, M. Ricci, S. B. Ricciarini, M. F. Runtso, S. Russo, M. Simon, R. Sparvoli, P. Spillantini,Y. I. Stozhkov, E. Taddei, A. Vacchi, E. Vannuccini, G. Vasilyev, S. A. Voronov, Y. T. Yurkin, G. Zampa, N. Zampa and V. G. Zverev

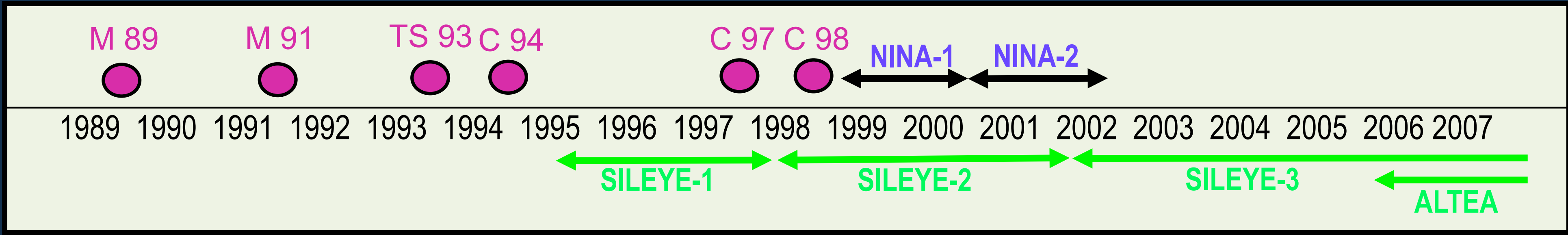
Russia
Moscow
S. Petersburg

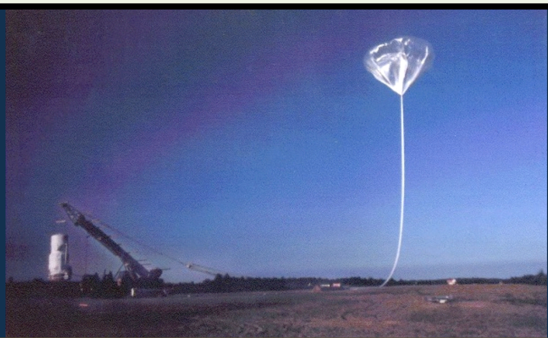
Sweden
Stockholm

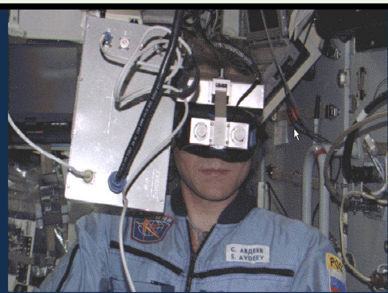
Germany
Siegen

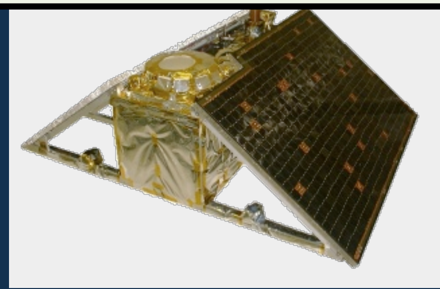
Italy
Bari Florence Frascati Naples Rome Trieste CNR Florence

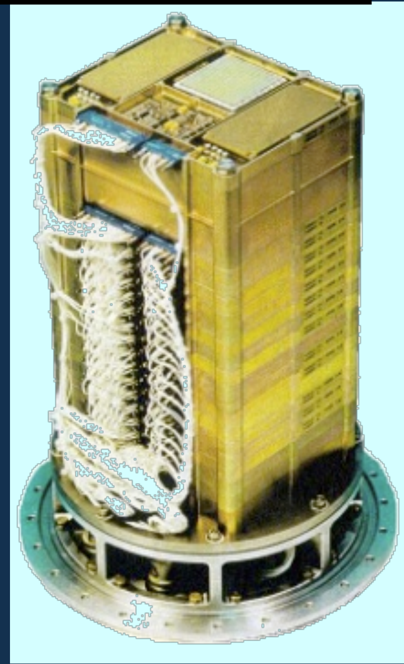
PAMELA long history











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)**

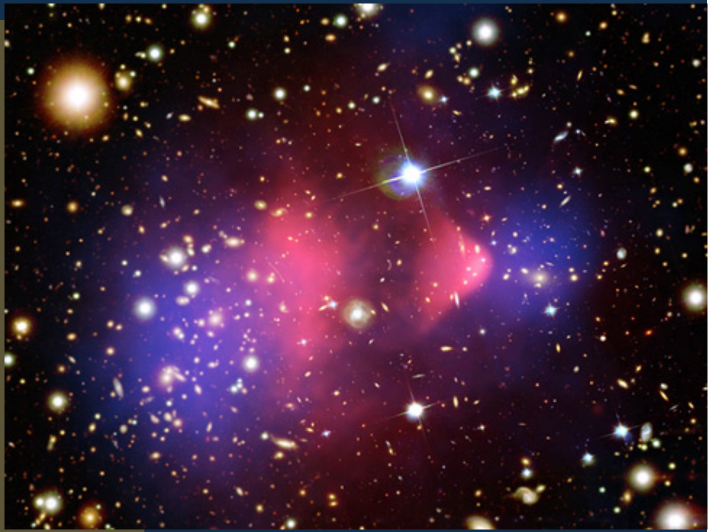
2001: **change of the satellite**

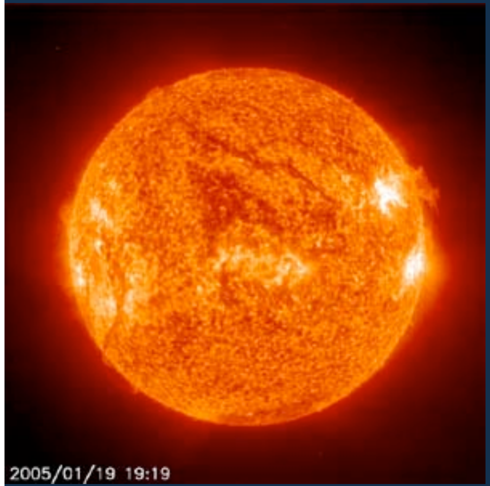
→ ***complete redefinition of mechanics***

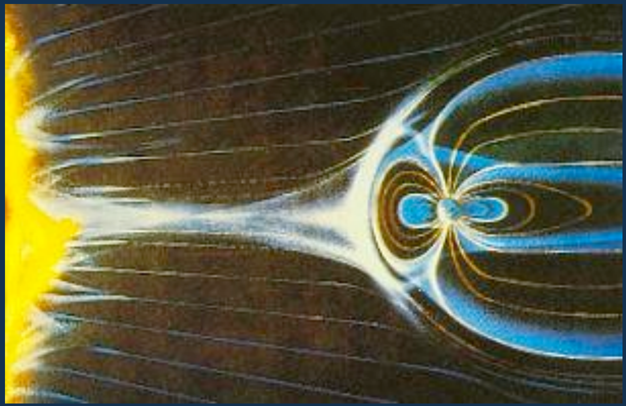
2006: **flight!!!**

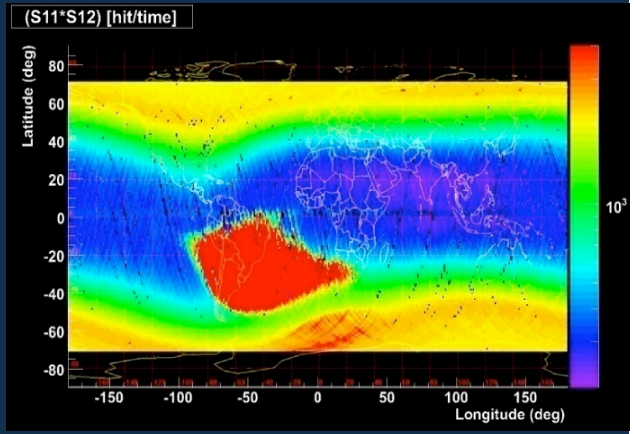
The PAMELA experiment

- Search for positrons & antiprotons
- 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 ->

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

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

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

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

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

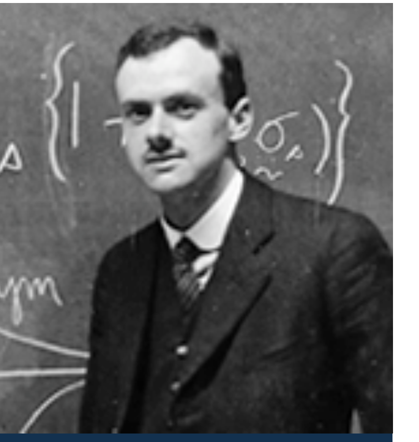
The variables σ_1, σ_2, σ_3 now form the three components of a vector, which corresponds (apart from a constant factor) to the spin angular momentum vector that appears in Pauli's theory of the spinning electron. The ρ's and σ's vary with the time, like other dynamical variables. Their equations of motion,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

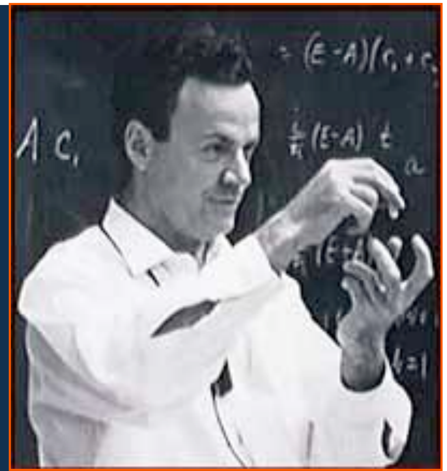


"A great deal of my work is just playing with equations and seeing what they give."

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

INFN

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.

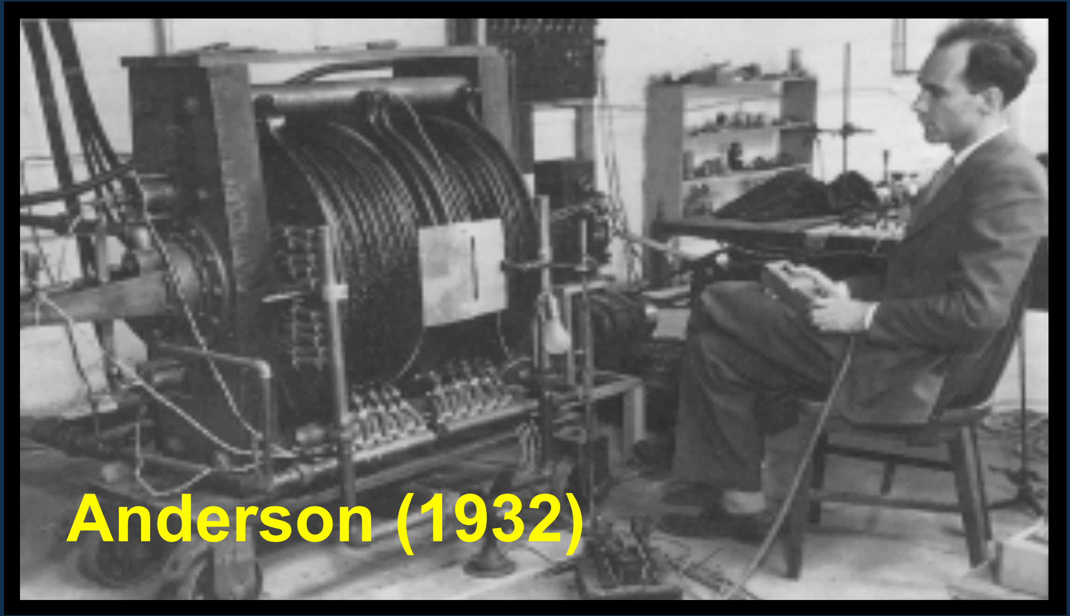
"I think that the discovery of antimatter was probably the biggest jump among the jumps of physics in our century."

Heisemberg 1972

INFN

In 1932 four years later Andreson discovered, in cosmic rays, the positive electron ANTIELECTTRON or POSITRON.

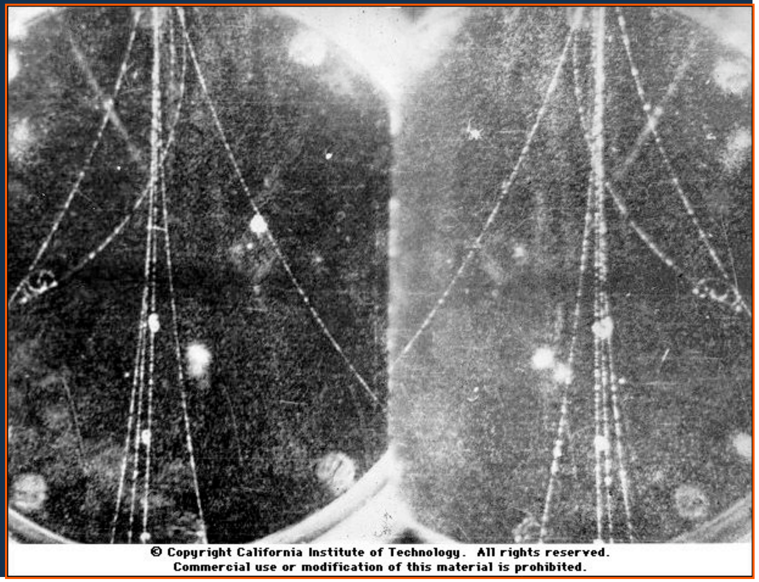
Little latter Blackett and Ochialini in Cambridge confirmed Anderson and discovered the pair production in the showers generated by cosmic rays.



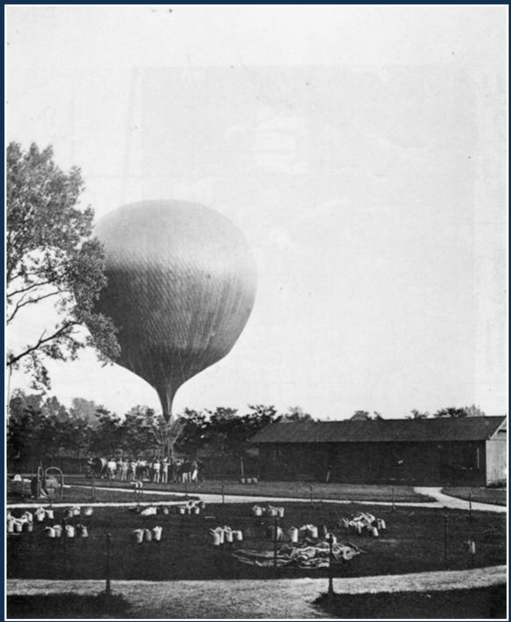
Dirac's equation implies:

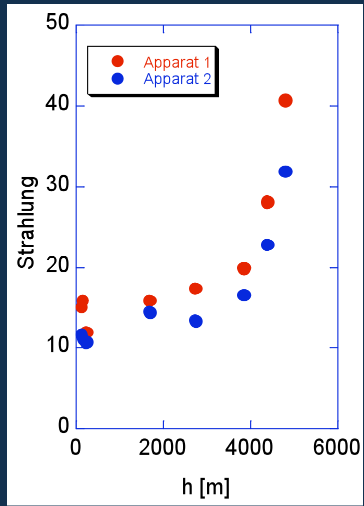
Mass of the positron = mass of the electron

Positron's charge = +e

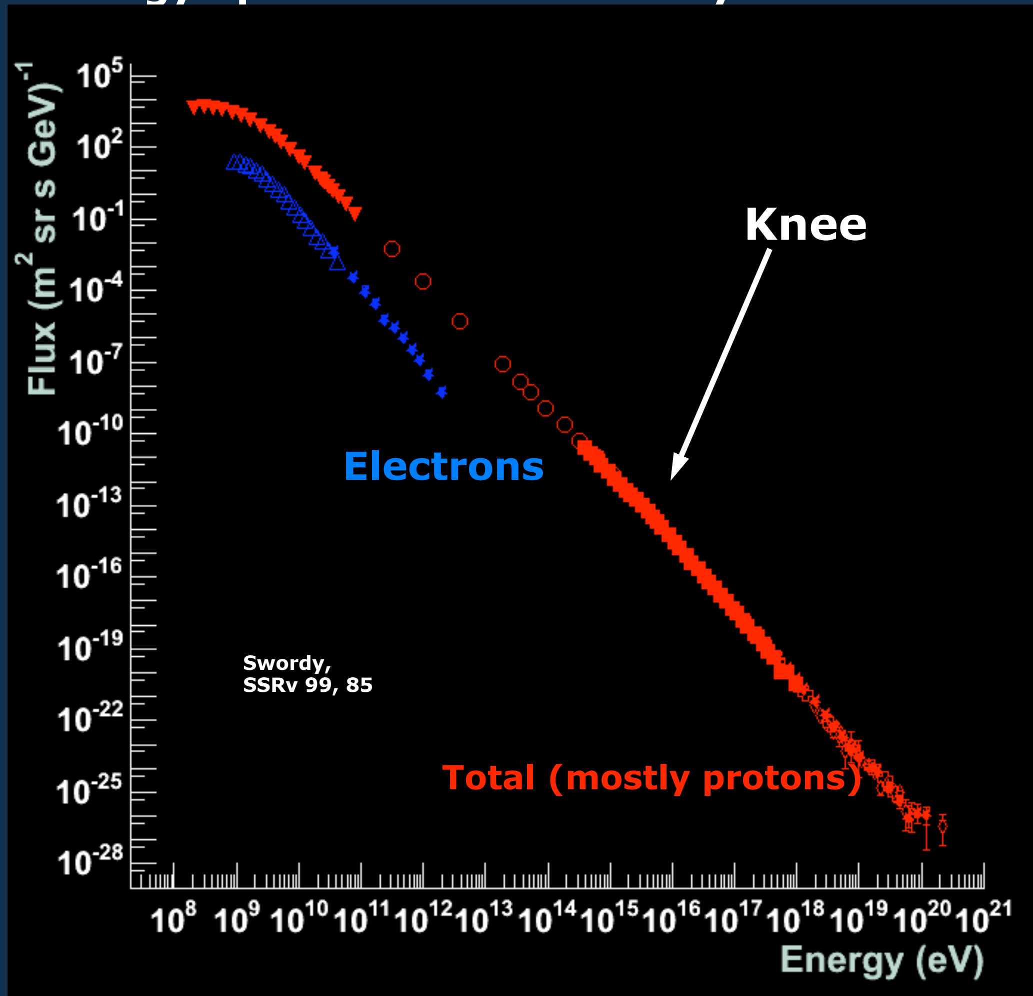


Cosmic Rays





Energy Spectrum of Cosmic Rays



"The results of my observations are best explained by the assumption that a radiation of very great penetrating power enters our atmosphere from above"

(V. Hess 1912)

How are they accelerated? Where do they come from?

Bevatron 1955 the discovery of the antiproton

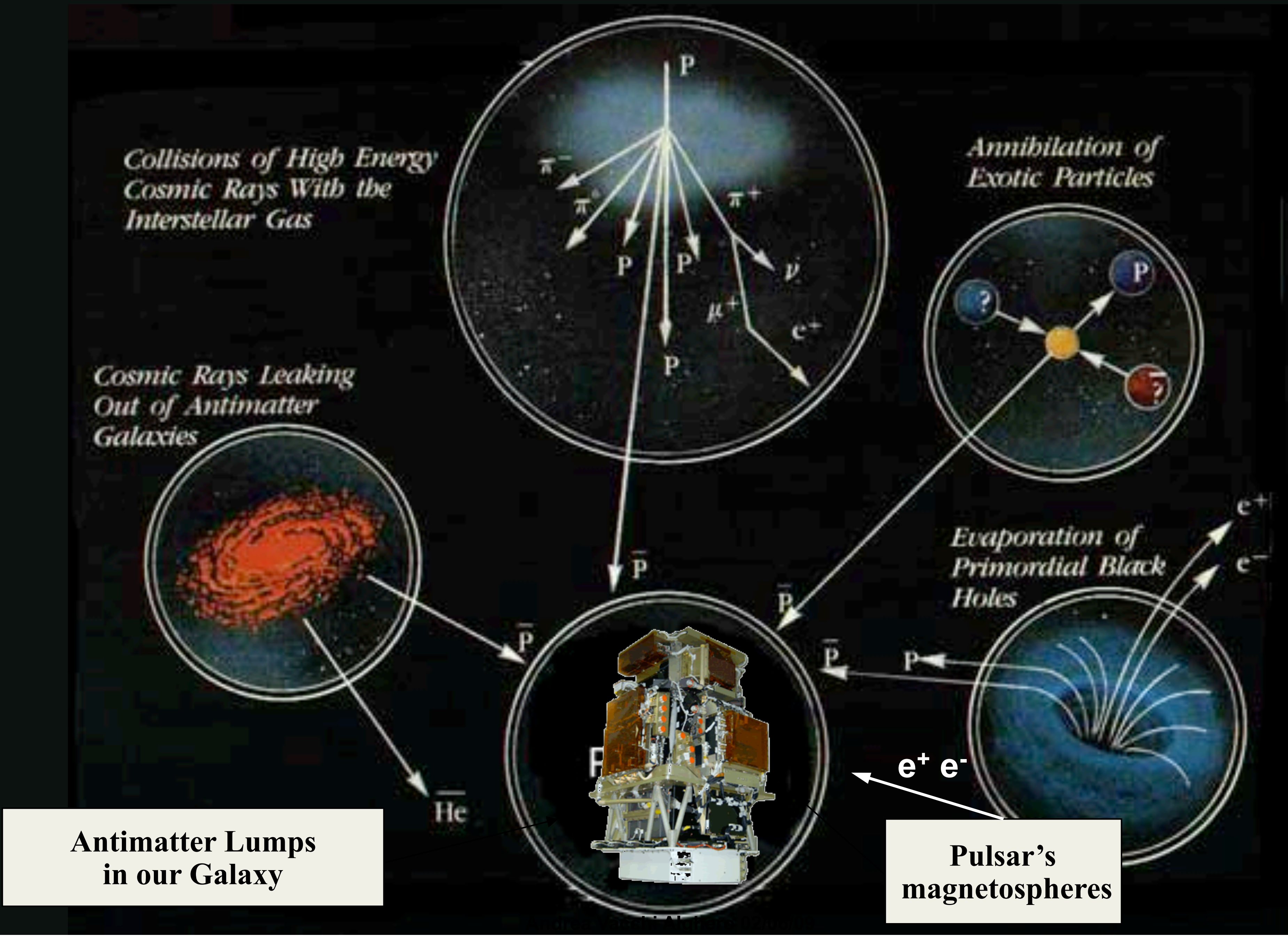
Chamberlain, Segrè, Wiegand, Ypsilantis Nobel 1959

- 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.

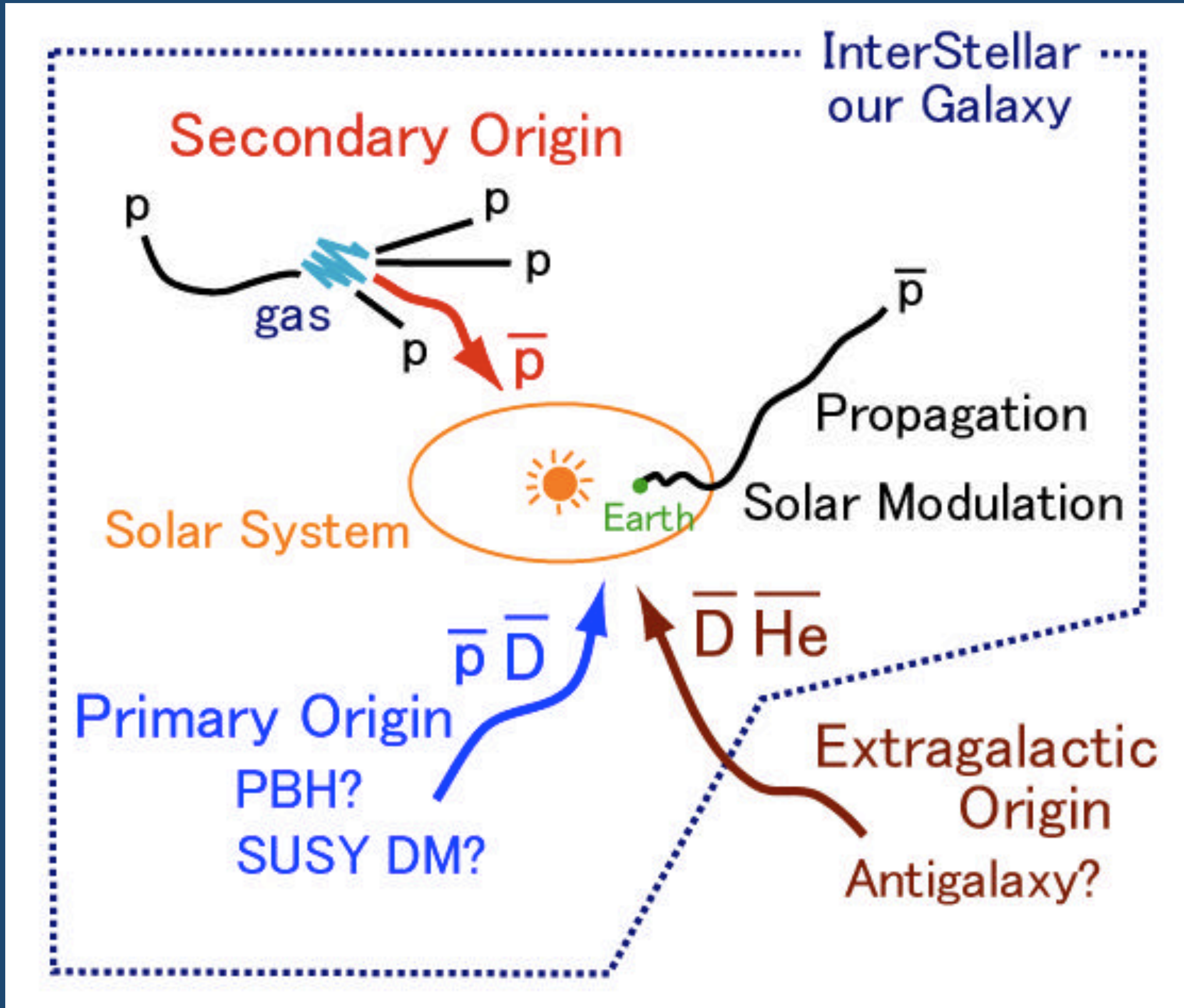
Create artificially the proton-antiproton pairs in the collisions produced by accelerated protons on a fixed target and then detect the antiprotons required the energies obtainable at an accelerator developed for this task:

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

Cosmic Ray ANTIMATTER



$\overline{p}$, $\overline{D}$, $\overline{He}$, e^+ ; Where do they come from ?



History of Antimatter Theory and Experiments

We must regard it rather as an accident that the Earth and presumably the whole solar system contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about. P. A.M. Dirac Nobel Prize lecture

1928: Dirac

1932: Discovery of positron (Anderson, 1933, PhysRev 491)

1955: Antiprotons manufactured (Chamberlain et al. 1933 PhysRev 100, 947)

1930-60s: BSU cosmologies favored (Alfven, 1965, RevModPhys 37, 652)

1964: CP violation is seen in kaon decay (Christenson, Cronin, Fitch & Turlay 1964, PRL 13, 138)

1965: Microwave background discovered and Big Bang cosmology moves to forefront.

1967: Sakharov conditions (JETP Lett. 5, 24)

~1980: Sakharov conditions “local” in domains?

(Brown and Stecker 1979, PRL 43, 315 and Sato, 1981, PhysLettB 99, 66)

1983: Fluctuations don’t separate matter and antimatter (Kolb and Turner AnnRevNuclPartSci, 33, 645)

1991: Antimatter is gravitationally normal (Hughes and Holzschieter, 1991, PRL,66, 854)

2004: New BaBar result on b and anti b, but no baryon number violating decay has been seen

Antimatter in our universe: Baryogenesis

Andrei Shakarov put the necessary conditions for baryogenesis [JETP Lett. 91B,24 (1967)] :

Baryon number B non conservation
C and CP non conservation
Out of equilibrium decay

- The inflation is a natural scenario where a baryogenesis can take place: it allows the out of equilibrium condition and it can avoid the a-prori hypothesis of initial symmetric conditions [L.F. Abbott et Al.,Physics Lett.117B(1982)]

Antimatter in our universe: Baryogenesis

Is the Universe globally or only locally asymmetric?

In a totally symmetric universe, high energy CRs could escape from an antimatter domain and get to our galaxy

On the basis of γ-rays observations our matter dominated region has at least the size of cluster of galaxies

Is there place for antimatter in a totally asymmetric Universe as seem to be ours?

INFN

[M. Y. Khlopov, S.G.Rubin and Al.S.Sakharov hep-ph/0210012]

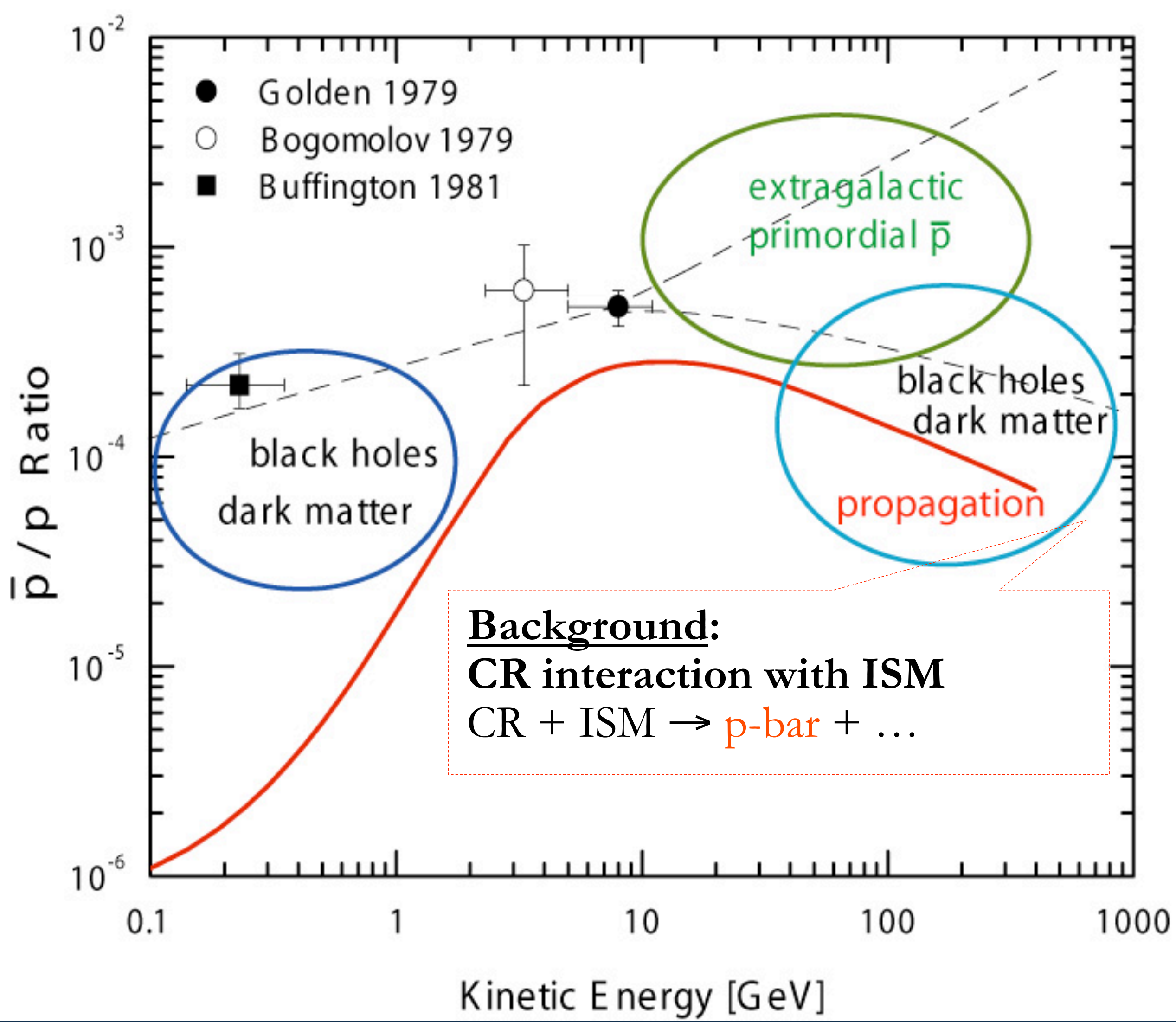
In the matter dominated universe there is also the possibility of small insertions of antimatter regions :

Quantum fluctuations of a complex, baryonic charged scalar field caused by inflation can generate antimatter regions that can survive annihilation

There can exist antistar global clusters in our galaxy
The expected signature of such scenario is a flux of anti ^{3}He and ^{4}He accessible to high precision experiments

20 years ago first measurements of antiprotons in cosmic rays with stratospheric balloons

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



History of the Search for Cosmic-ray Antiprotons

1960s: L. Alvarez et al. Balloons & HEAO

1979: First claimed observations (Bogomolov et al. and Golden et al.)

1981: Low-energy excess (Buffington et al.)

1985: ASTROMAG Study Started

1987: LEAP, PBAR (upper limits)

1991: MASS

1992: IMAX (16 mass-resolved antiprotons)

1993: BESS (6 antiprotons), TS93

1994: CAPRICE94, HEAT-e±

1996-7: BESS series to Solar minimum

1998: CAPRICE98, AMS-01

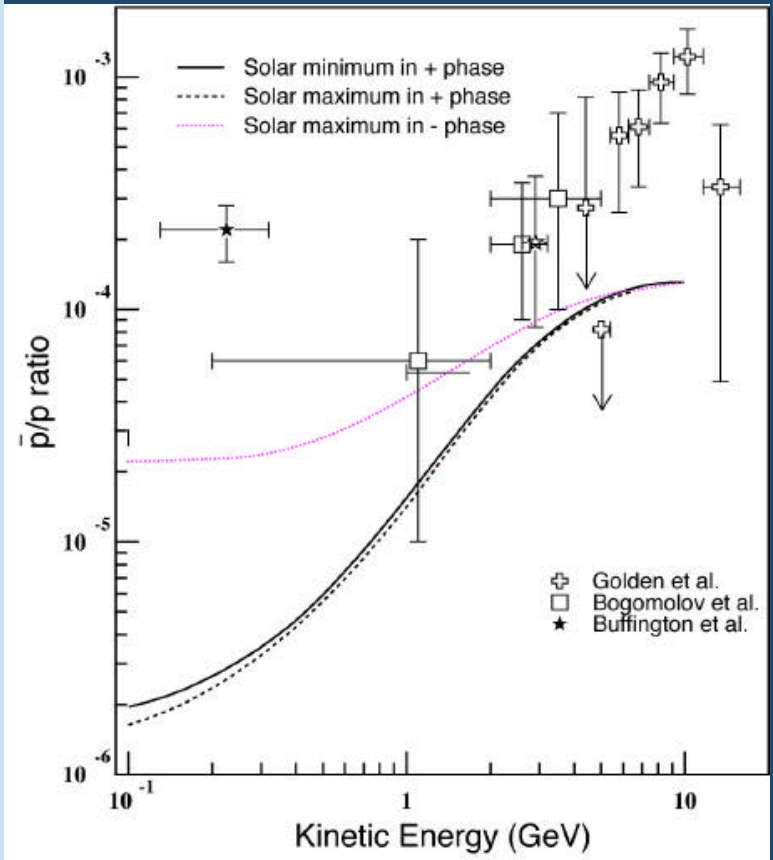
2000: BESS 99-00, HEAT-pbar

2004-5: BESS-Polar,

2006: BESS-Polar, PAMELA

2007: Solar minimum

2010: AMS



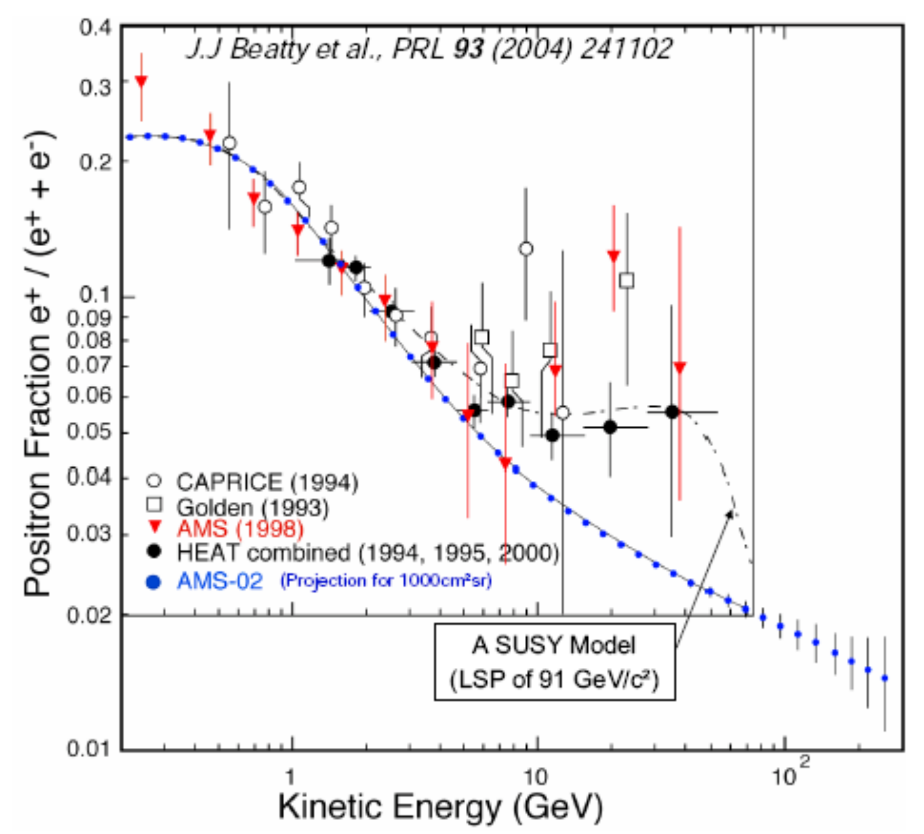
Antiproton measurements, ca 1980
Disagreement with "theory"

INFN

Prepared with R. E. Streitmatter

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.

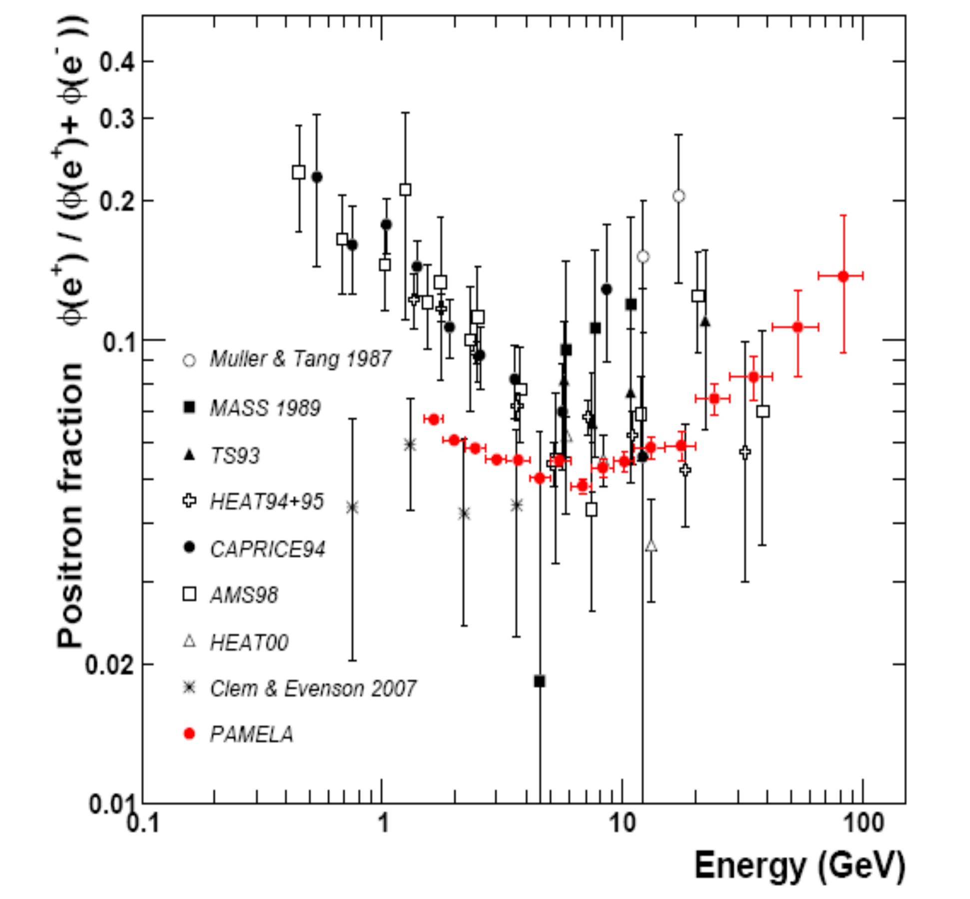


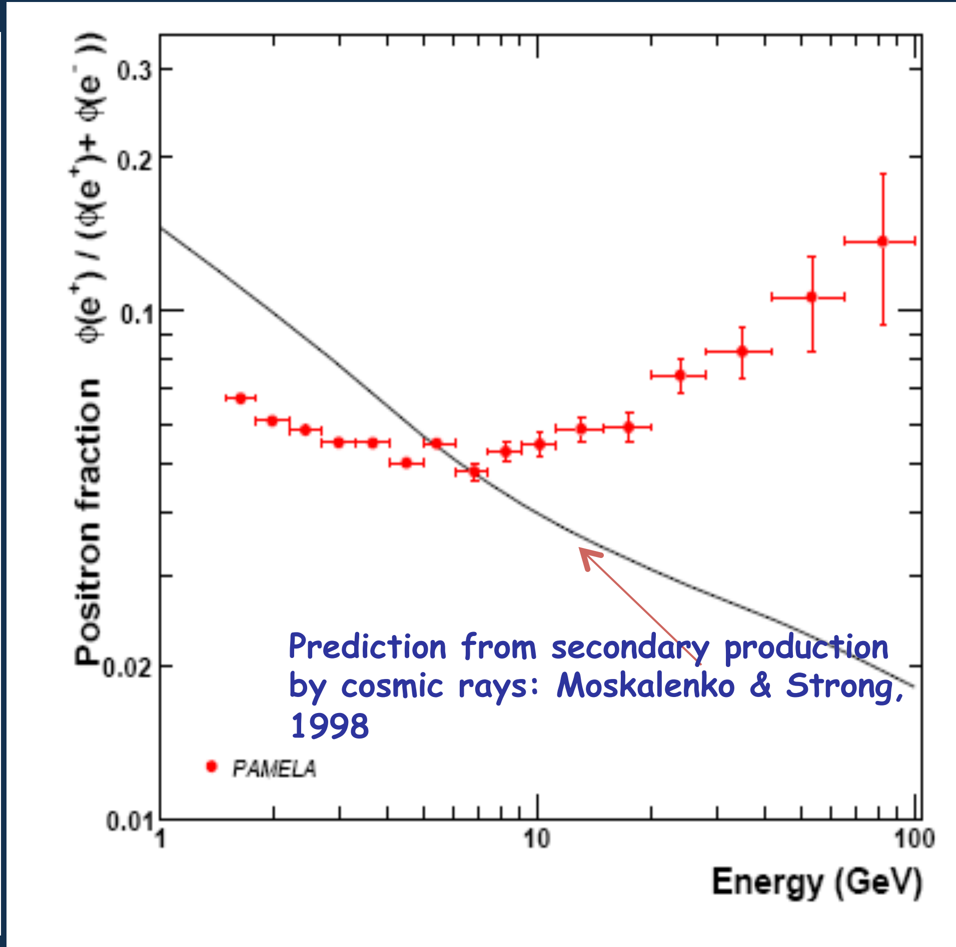
This is well described by models where the neutralino (a particle predicted by supersymmetric theories) constitutes a significant fraction of the Dark Matter of the universe.

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

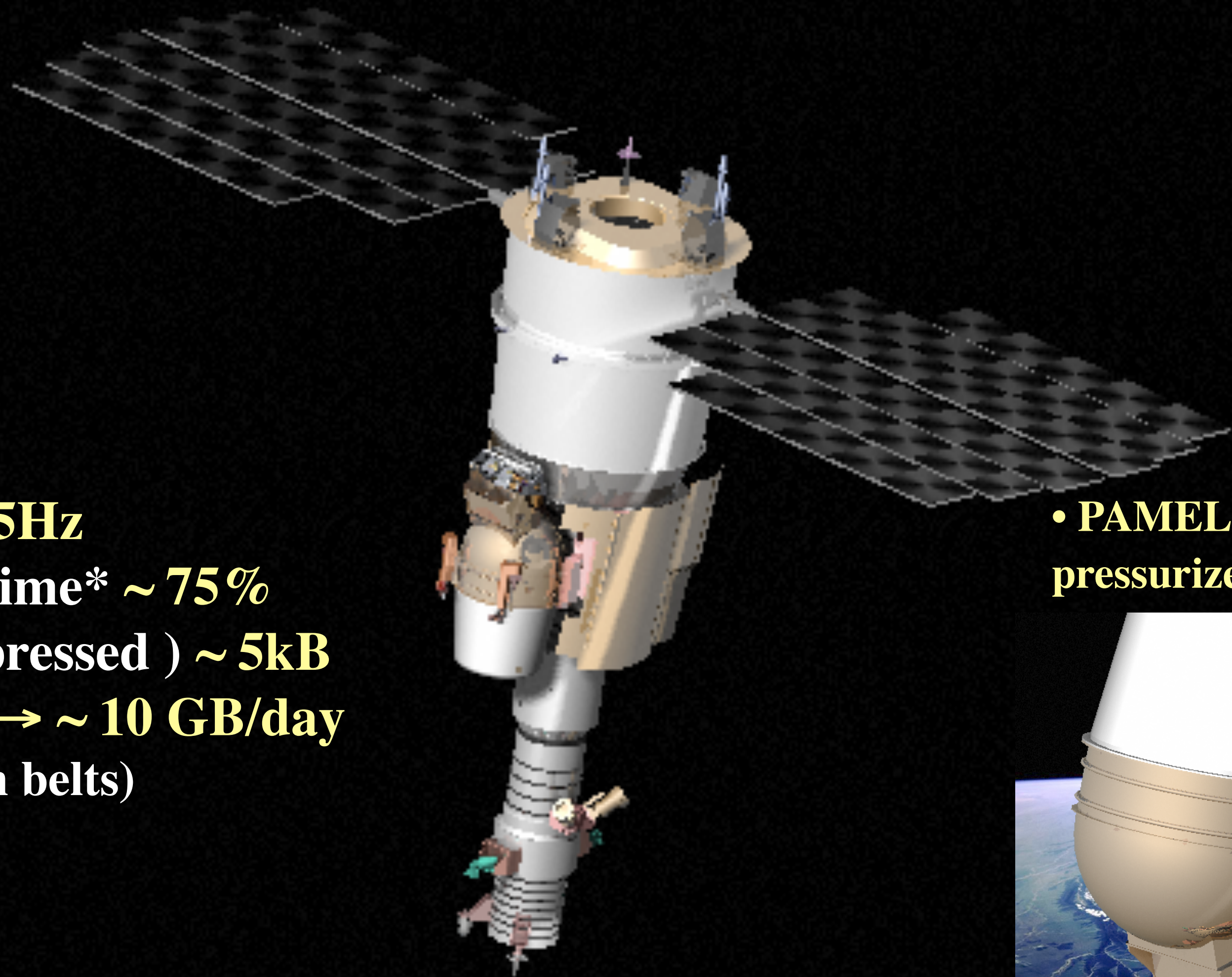
Pamela data 2009:
steep rise in the positron fraction.
An additional, primary source of positrons **that becomes dominant at ~10 GeV !!!** is needed.

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



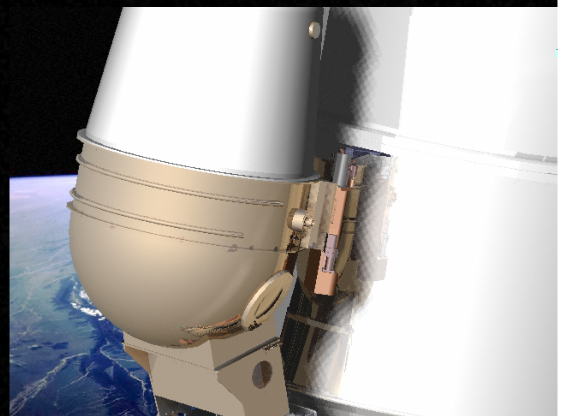


Launch from Baikonur → June 15th 2006, 0800 UTC.
'First light' → June 21st 2006, 0300 UTC, commissioning.
Continuous data-taking since July 11th 2006.



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

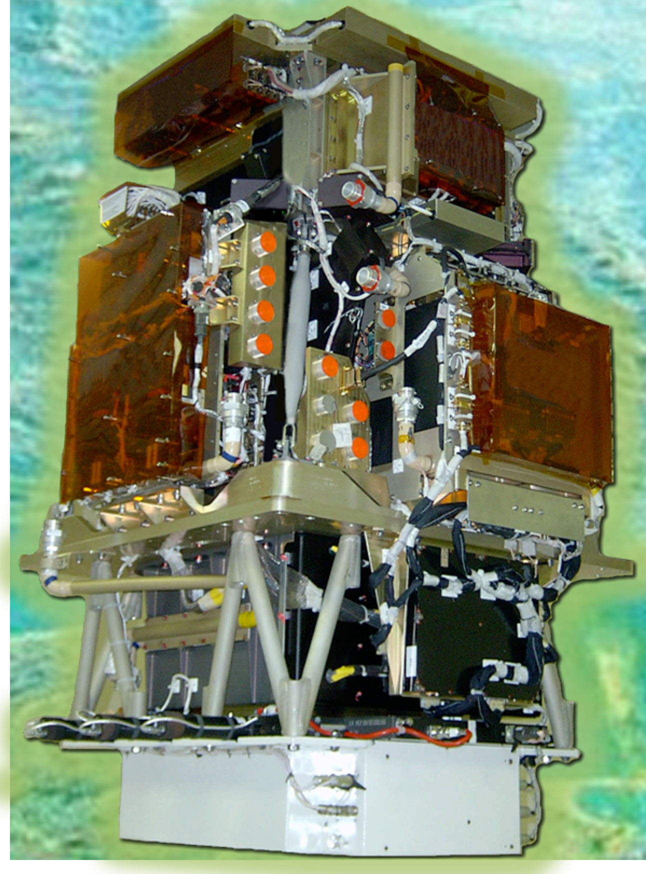
• PAMELA installed in a pressurized container

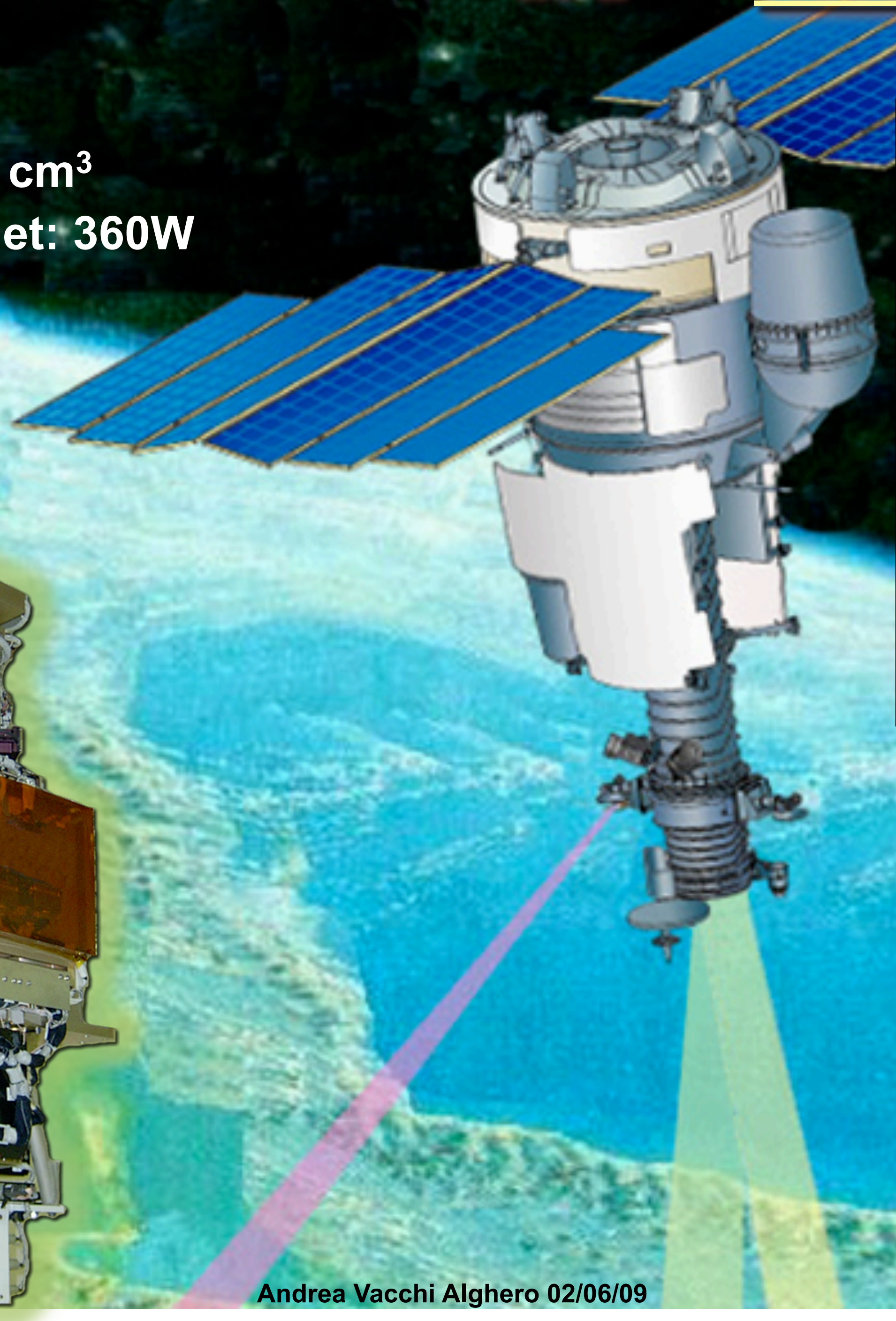


• Detectors have operated as expected after launch
• Different trigger and hardware configurations used

Pamela and *Resurs-DK1 satellite*

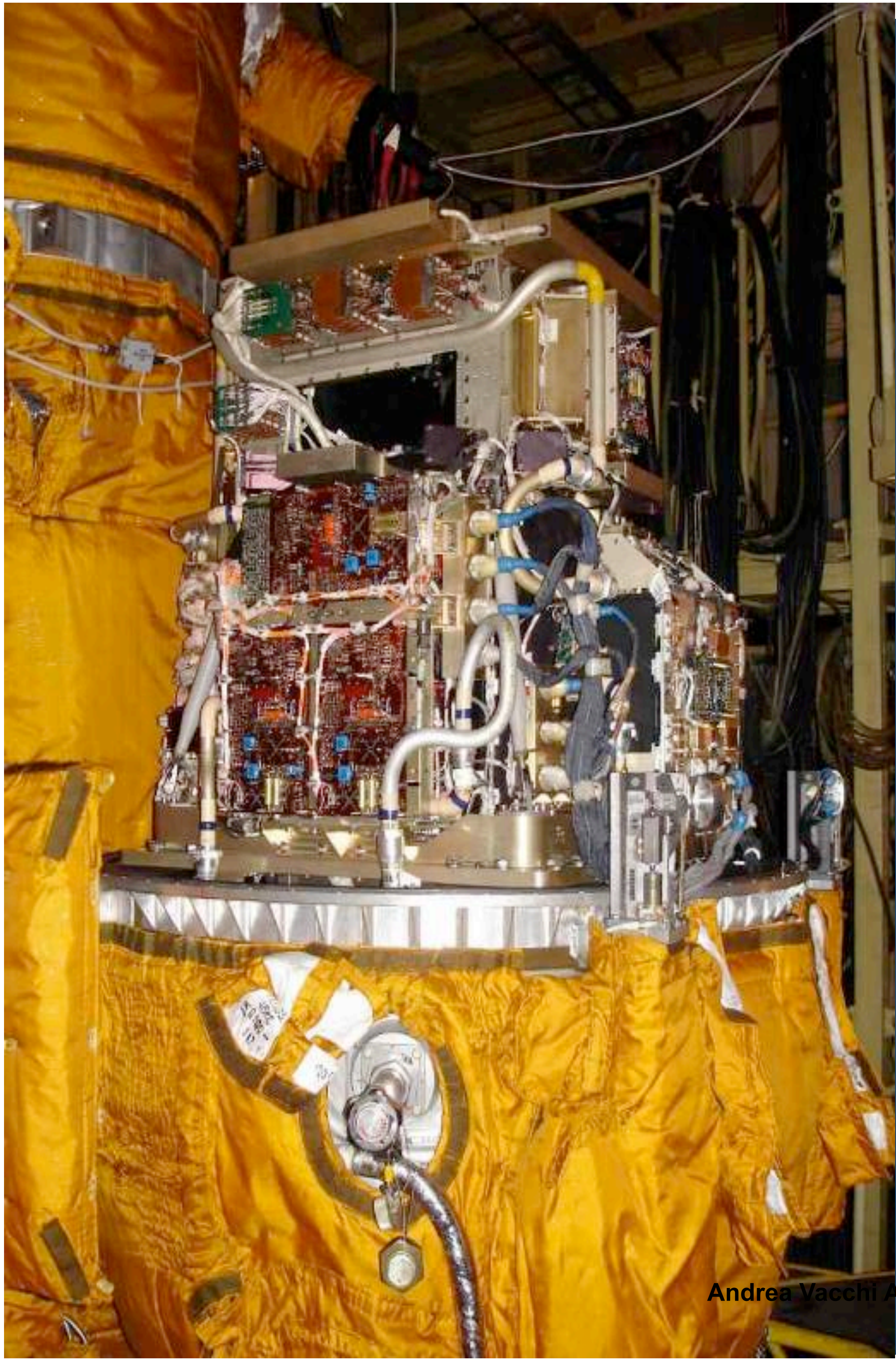
GF: 21.5 cm^2 sr
Mass: 470 kg
Size: 130x70x70 cm^3
Power Budget: 360W

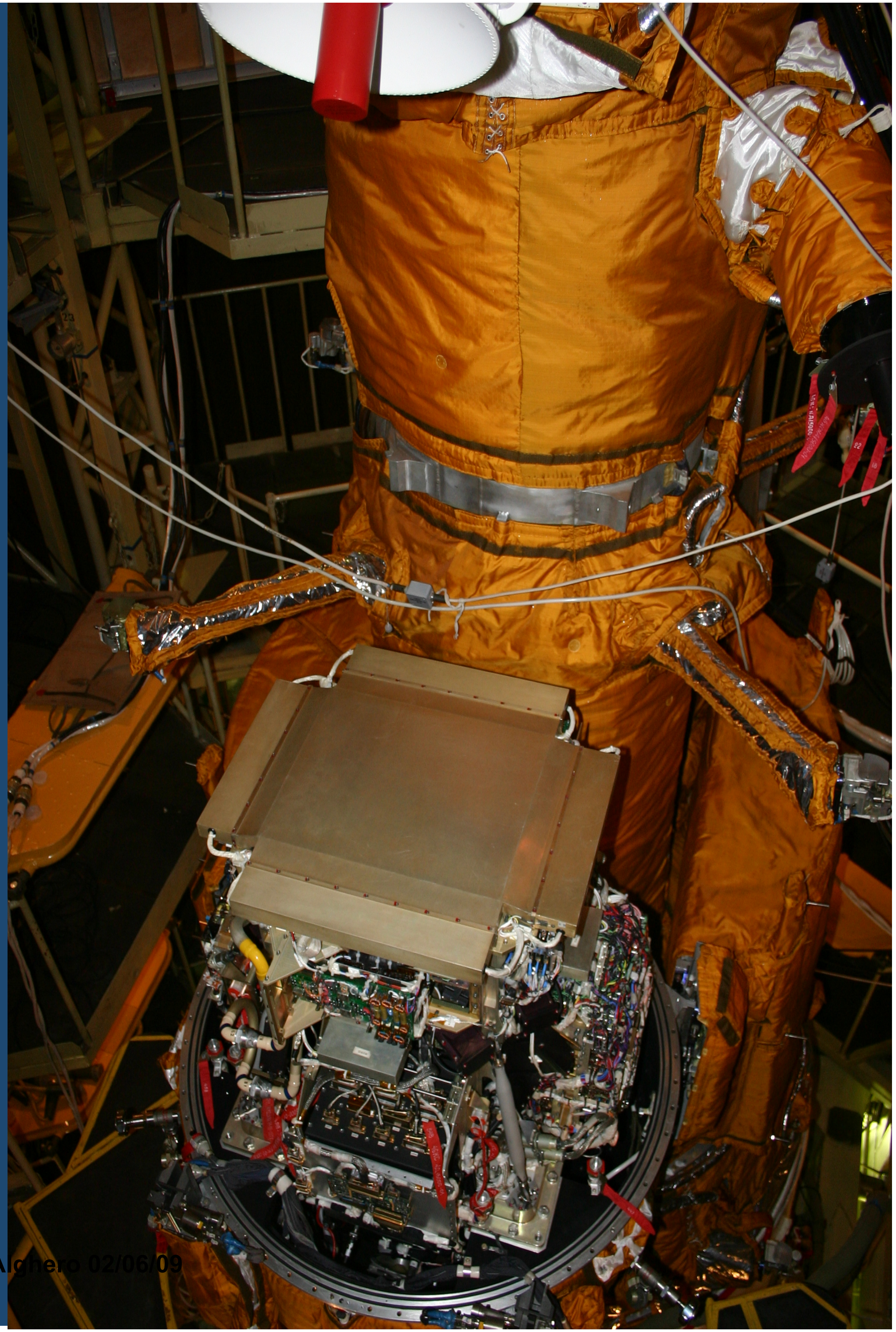




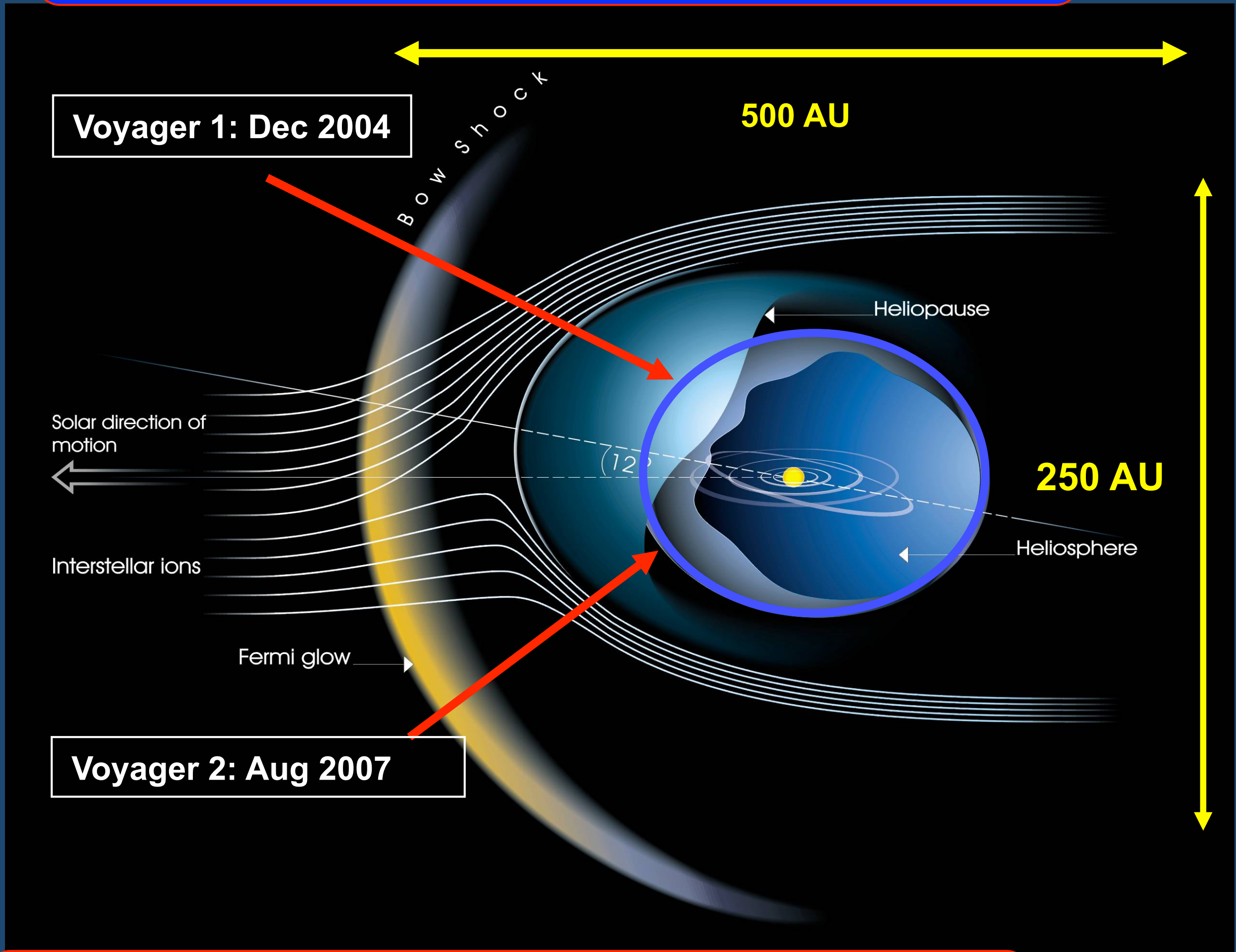
Mass: 6.7 tonnes
Height: 7.4 m
Solar array area: 36 m^2

- **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

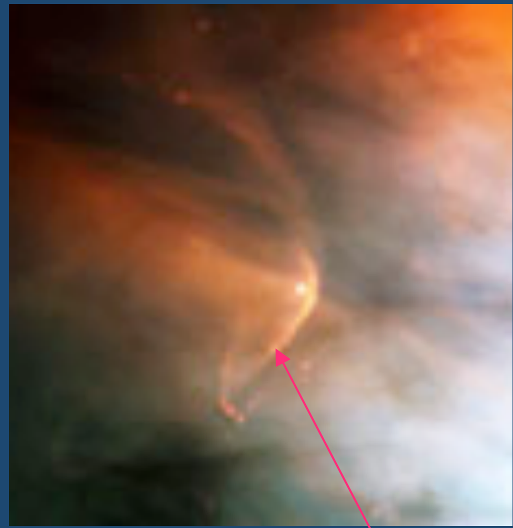




Heliospace



The heliosphere

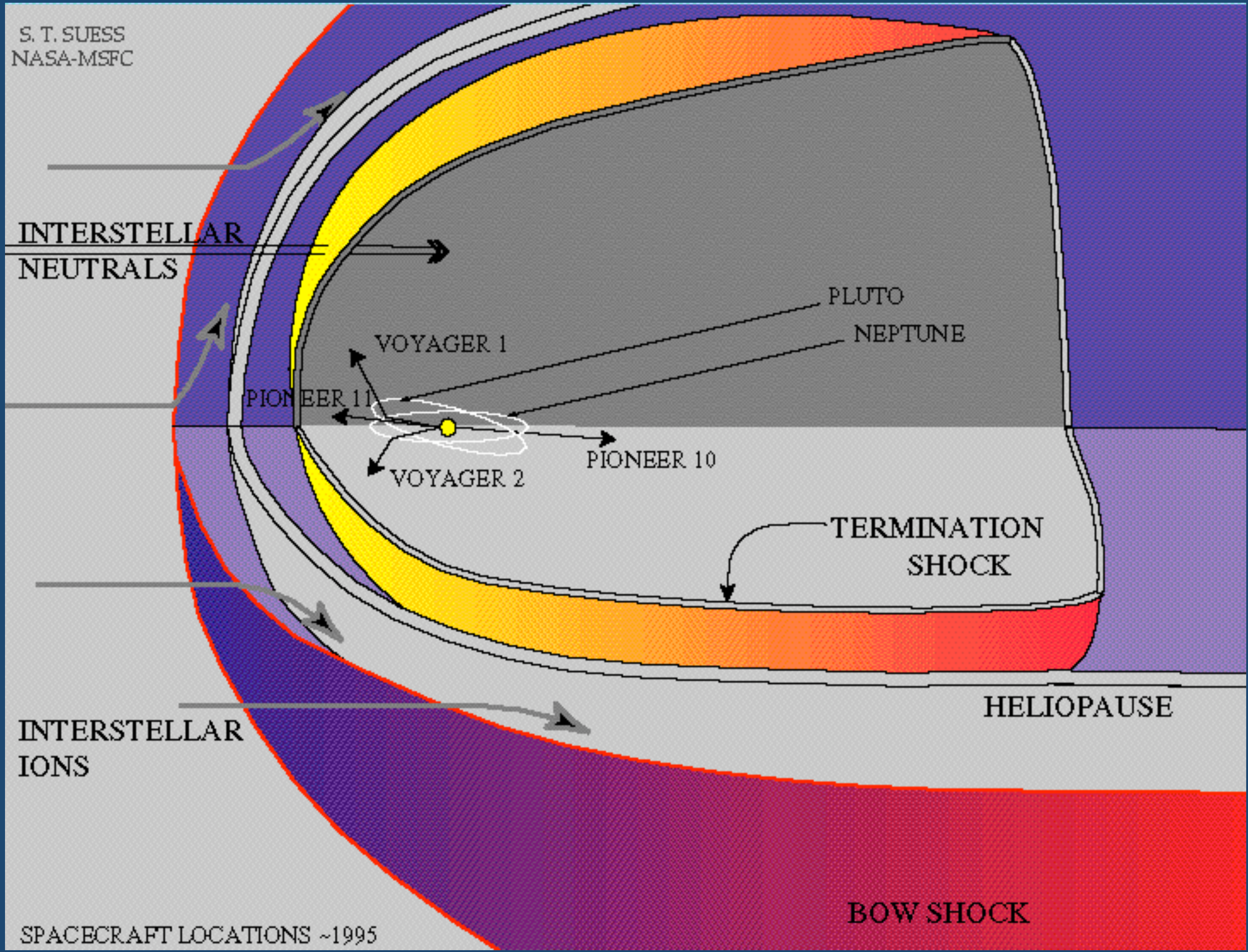


Bow Shocks

What would the heliosphere look like if we could see it from the outside? Something like this image of the Helix Planetary Nebula, photo courtesy of D. Malin. The central region in this image of the Helix Nebula consists of a high velocity wind (1000 km/sec) like the solar wind

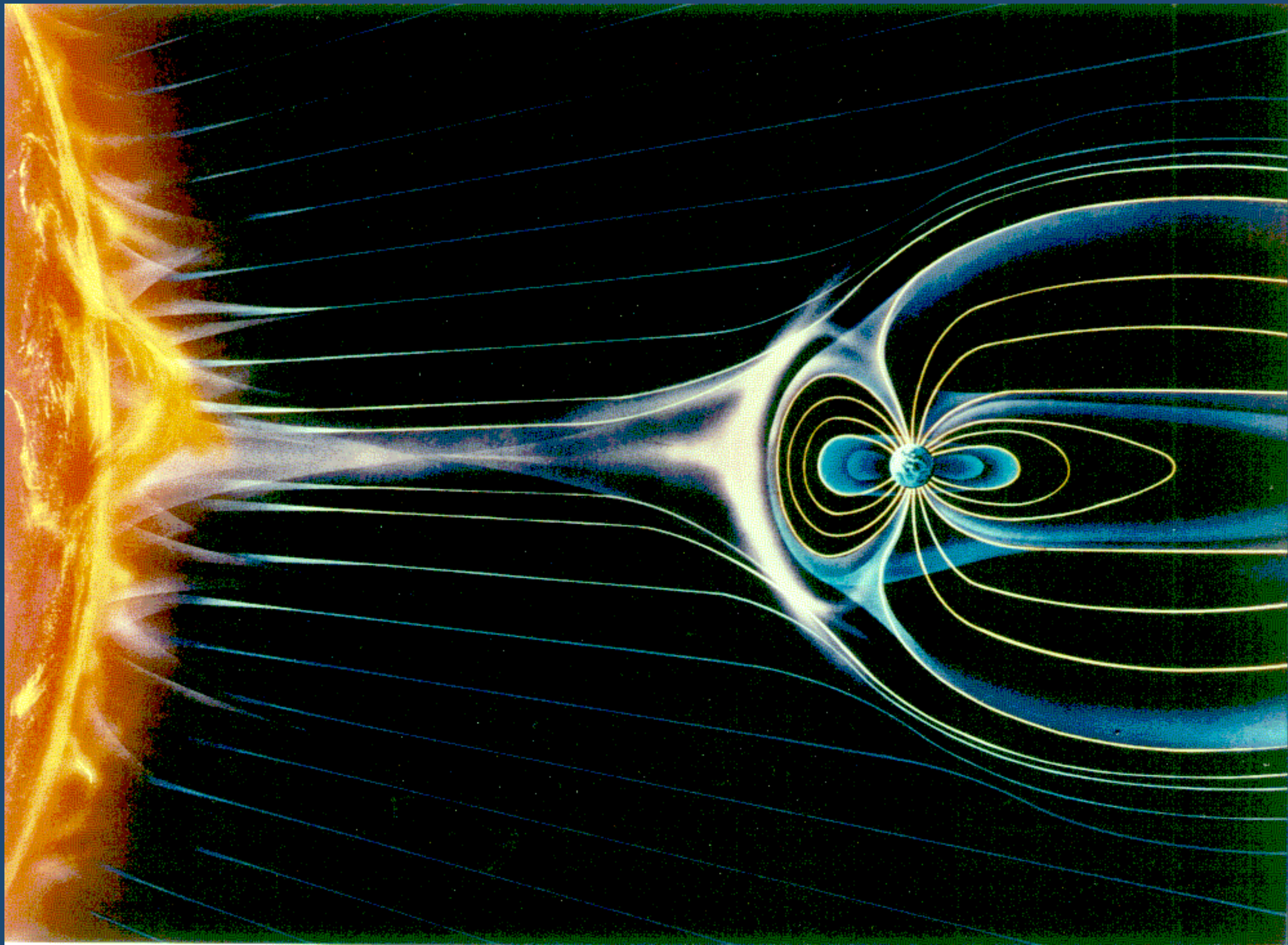
the central objects blow bubbles in the local interstellar medium by ejection of mass

The heliosphere is a large region of space where the solar wind interacts with the surrounding interstellar gas. The plasma (ionized) component of the interstellar medium interacts directly with the solar wind. The physics of the heliosphere is made considerably more complex, however, by the presence of neutral hydrogen in the interstellar medium. It behaves very differently from the plasma; both species, however, are weakly coupled to each other.



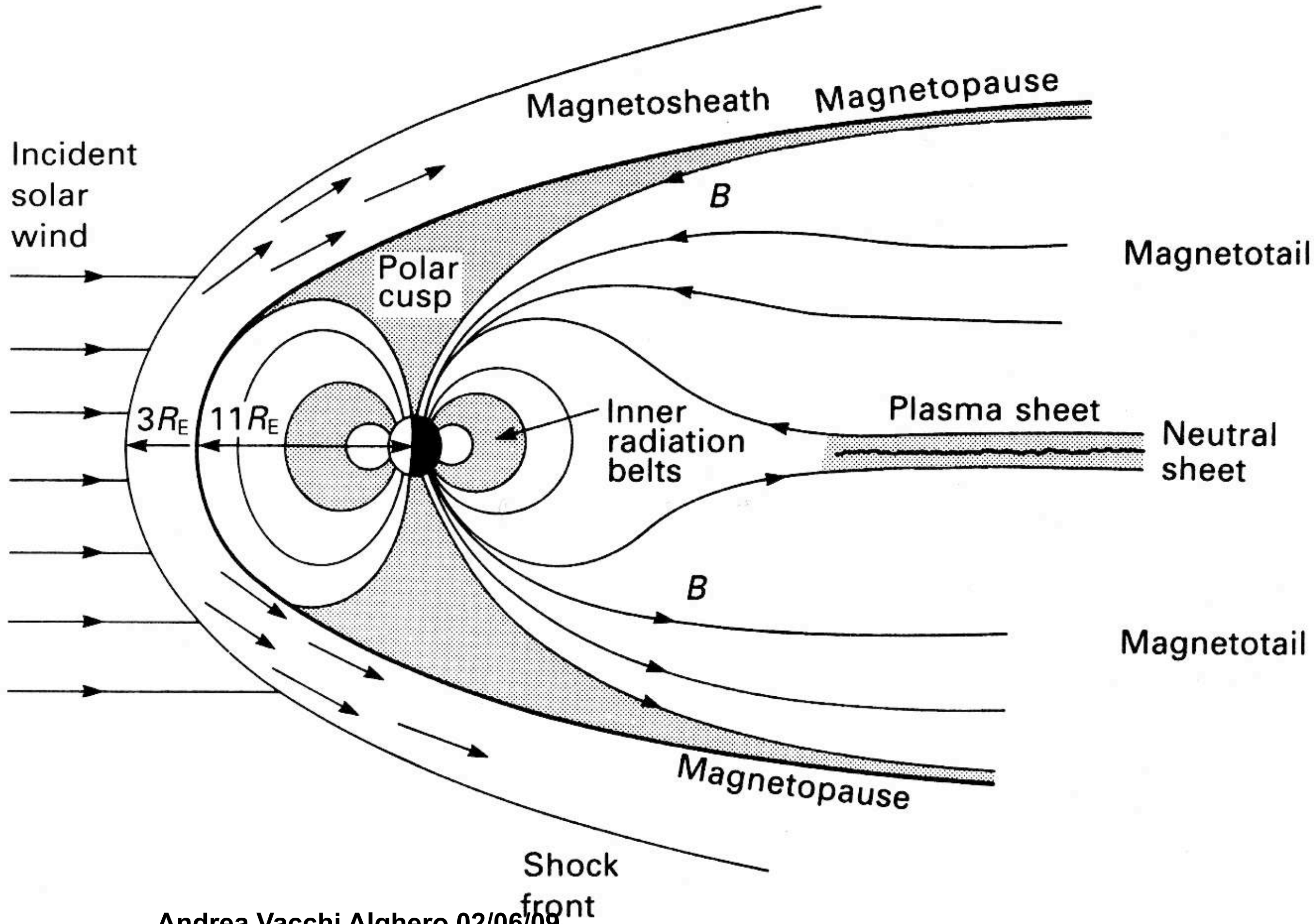
The heliosphere is a bubble in space produced by the solar wind. Although electrically neutral atoms from interstellar space can penetrate this bubble, virtually all of the material in the heliosphere emanates from the Sun itself.

The magnetosphere



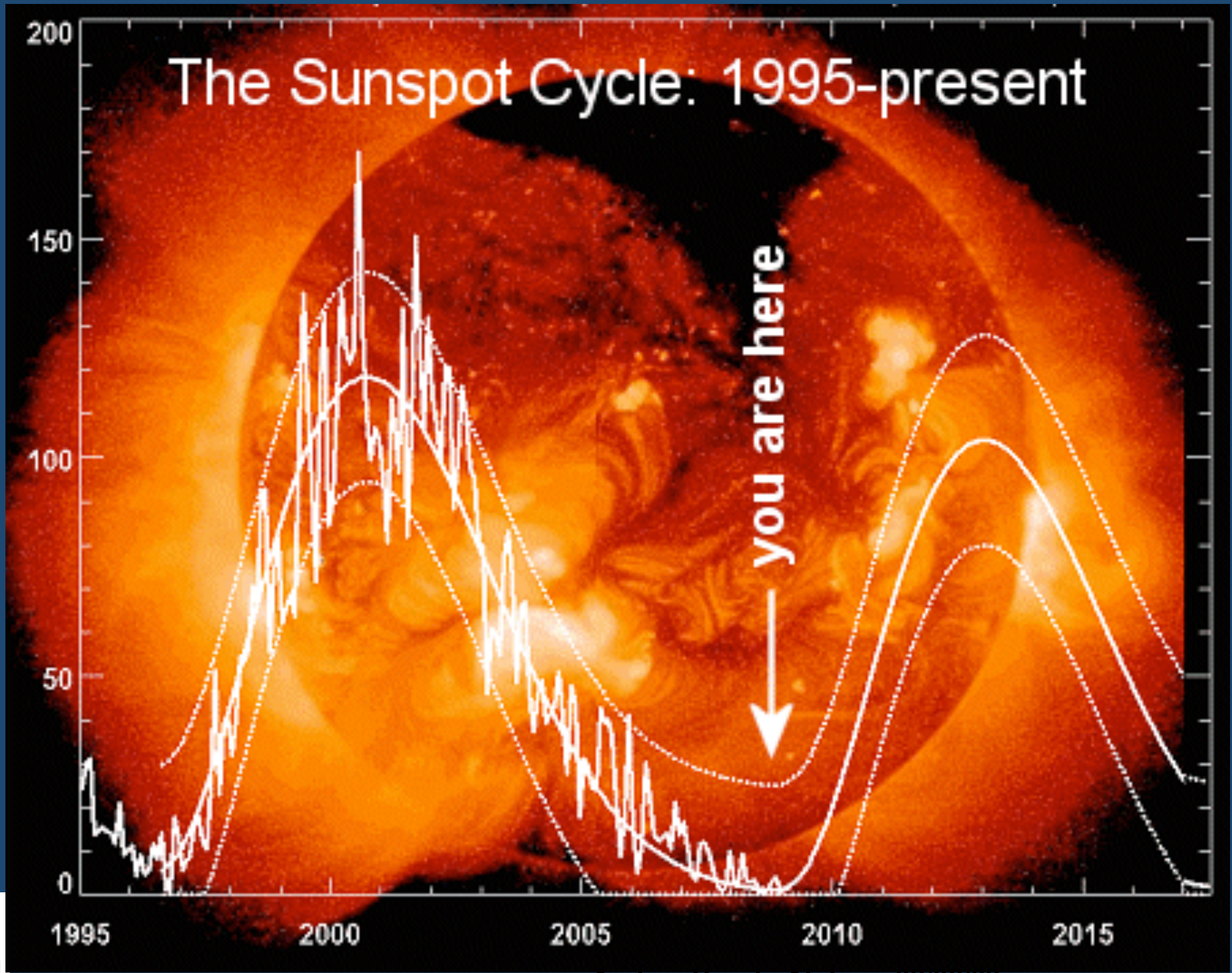
Structure of the earth's magnetosphere, taken from [Longair1992]. Analogously to the relative motion of the eliosphere in the interstellar medium, a bow shock emerges as the solar wind encounters the magnetosphere.

Low energetic cosmic rays up to energies of about several GeV (geomagnetic cutoff) are shielded additionally from the earth by its magnetosphere

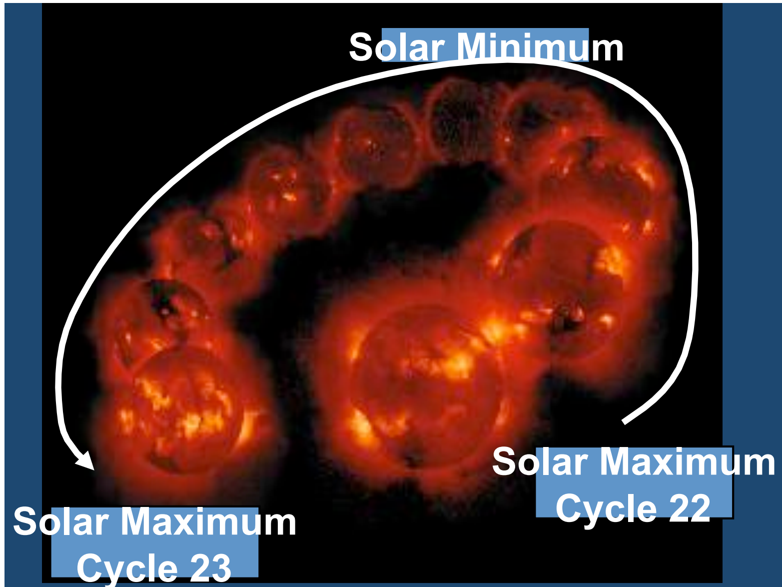


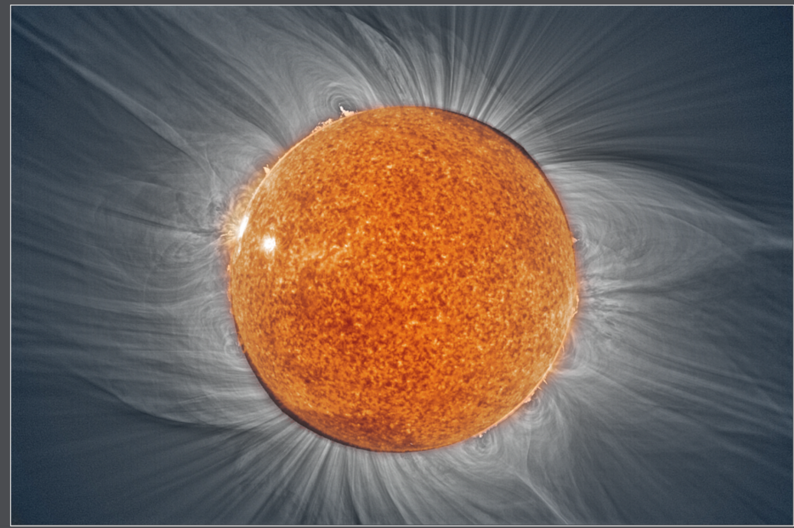
11 years cycle

discovered by German astronomer Heinrich Schwabe in the mid-1800s. Sunspots are planet-sized islands of magnetism on the surface of the sun; they are sources of solar flares, coronal mass ejections and intense UV radiation. Plotting sunspot counts, Schwabe saw that peaks of solar activity were always followed by valleys of relative calm—a clockwork pattern that has held true for more than 200 years:

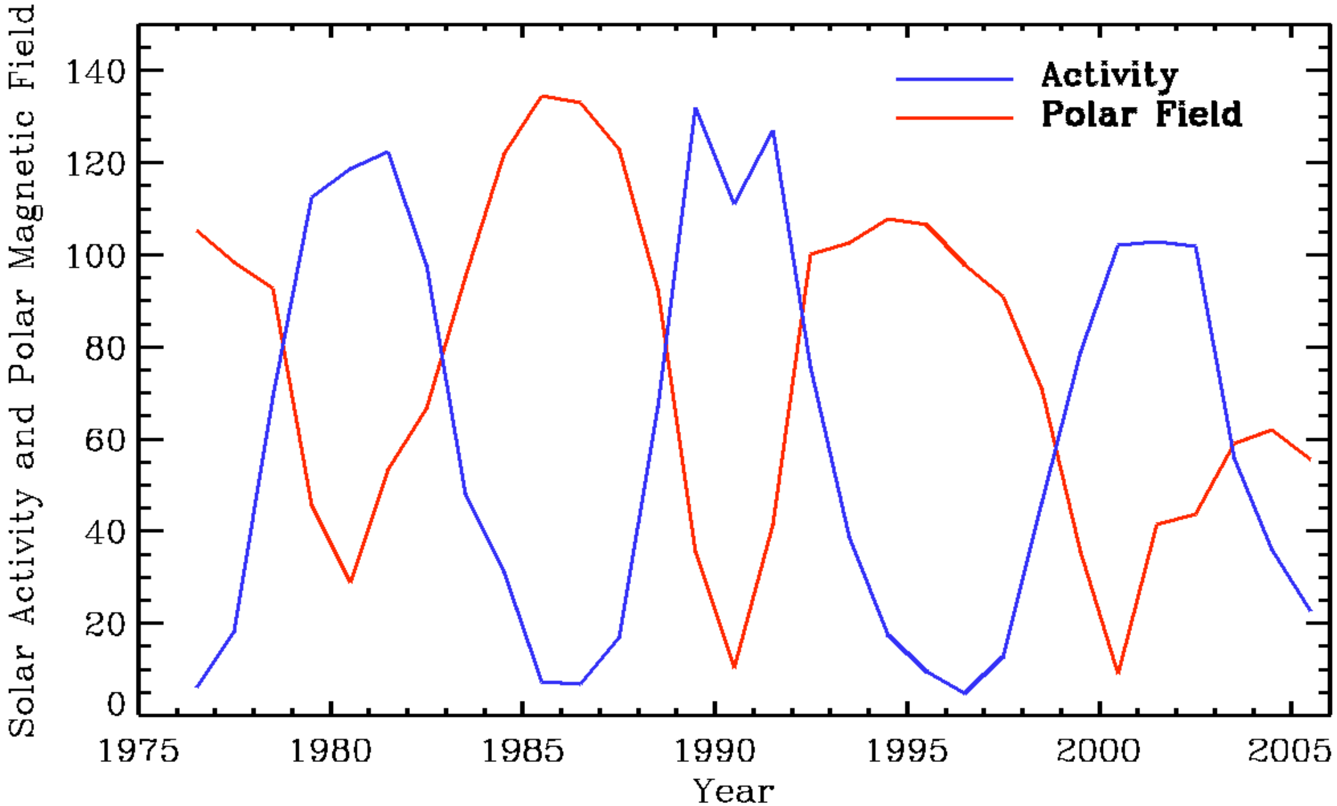


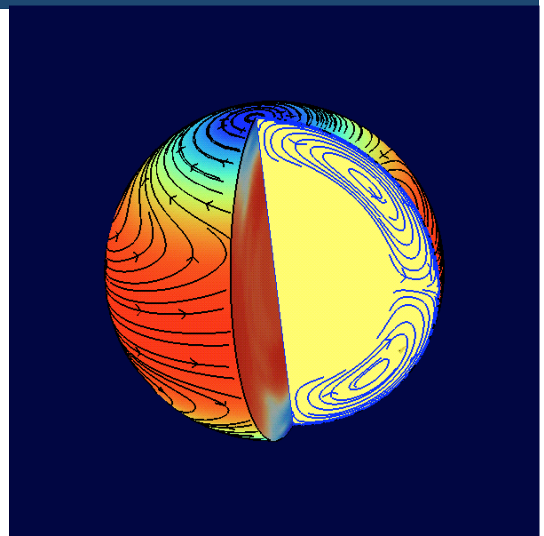
The solar wind helps keep galactic cosmic rays out of the inner solar system. With less wind, more cosmic rays are permitted to enter,





Total Solar Eclipse 2006 © 2006 Miloslav Druckmüller, Peter Aniol, ESA/NASA



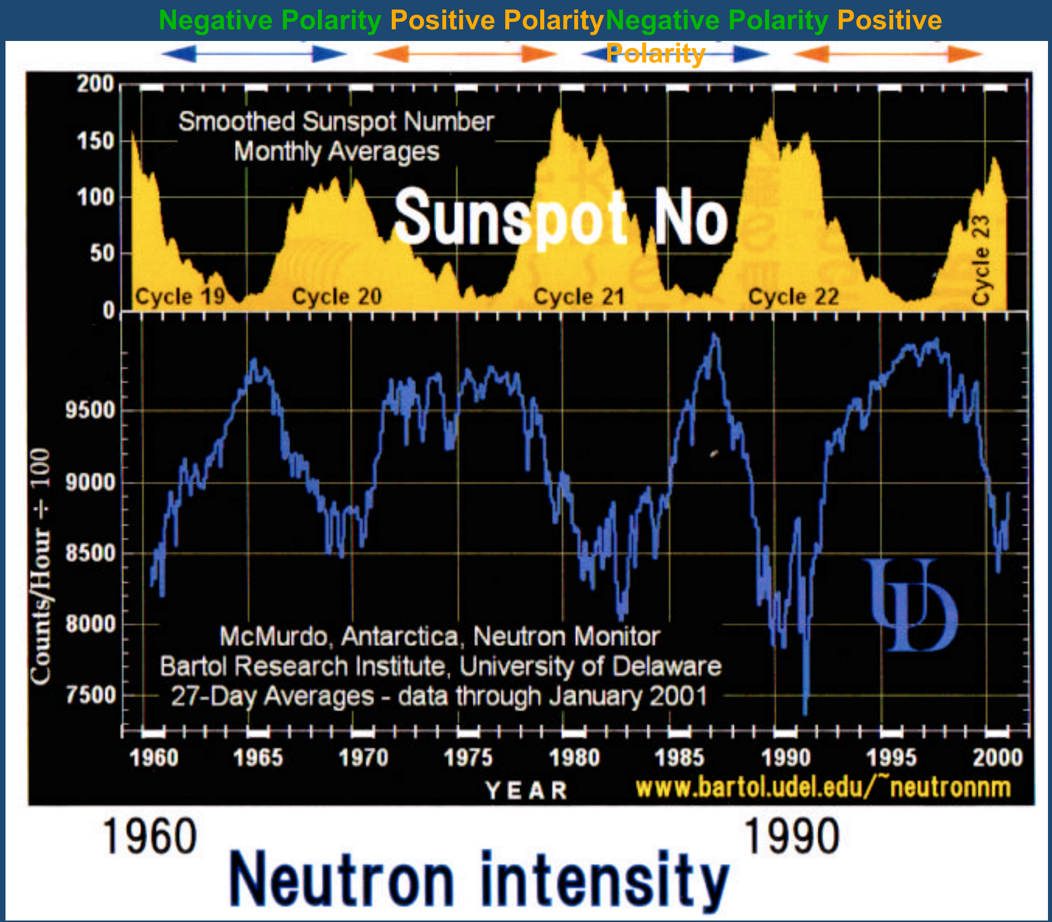


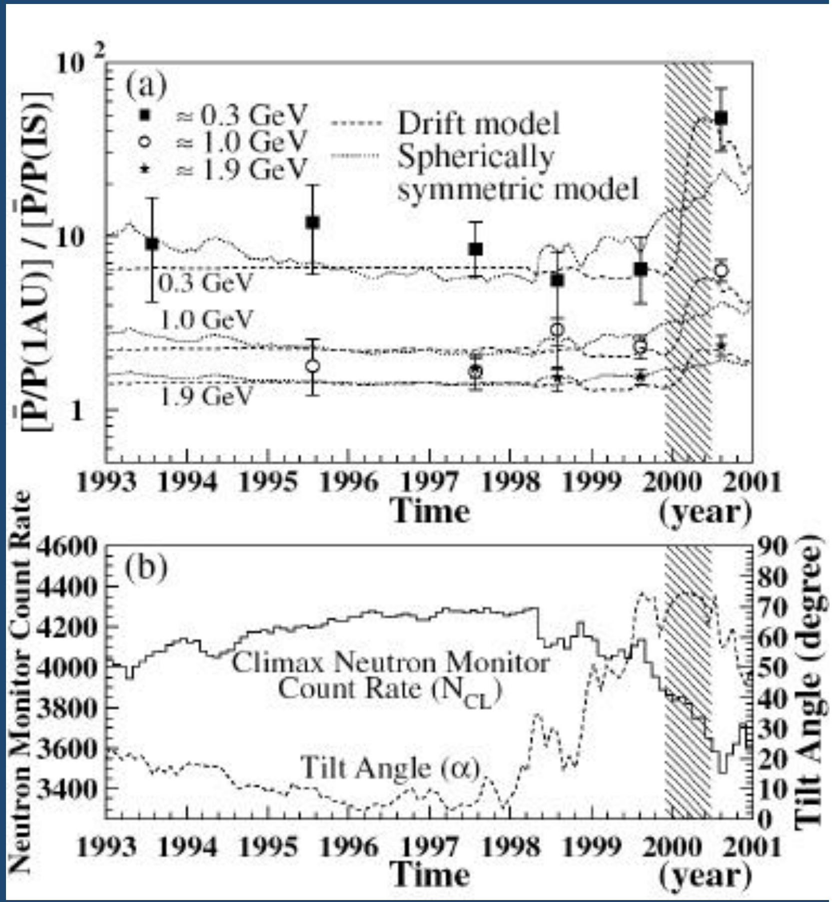
Understanding Solar Modulation

Solar magnetic field 22 year cycle

Sunspots & Neutron Monitors 11 year cycle

The solar activity influences the low energetic galactic cosmic rays up to energies above 5 GeV. For a high activity state the galactic cosmic rays are shielded stronger by the small-scale plasma wave turbulence superimposed on the solar wind.

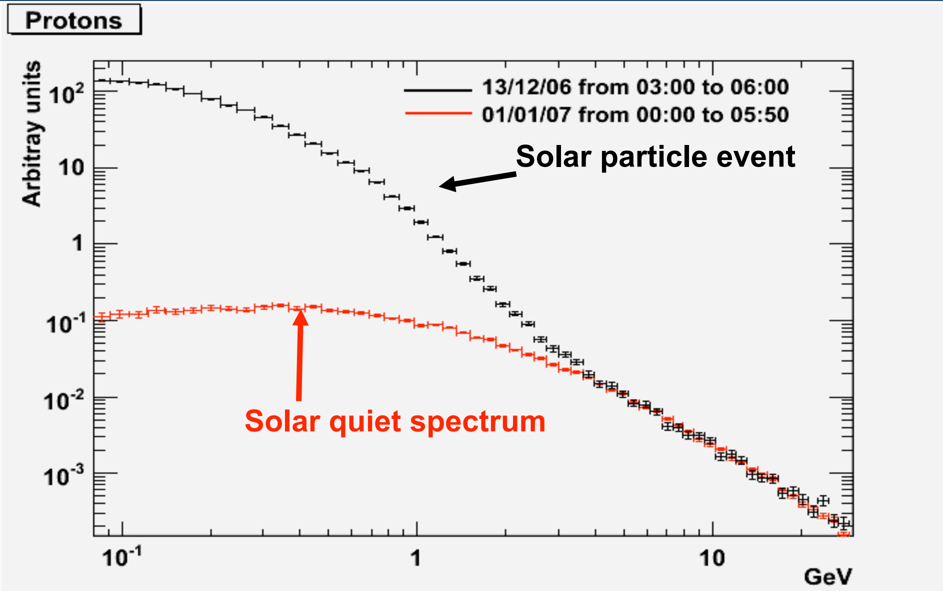




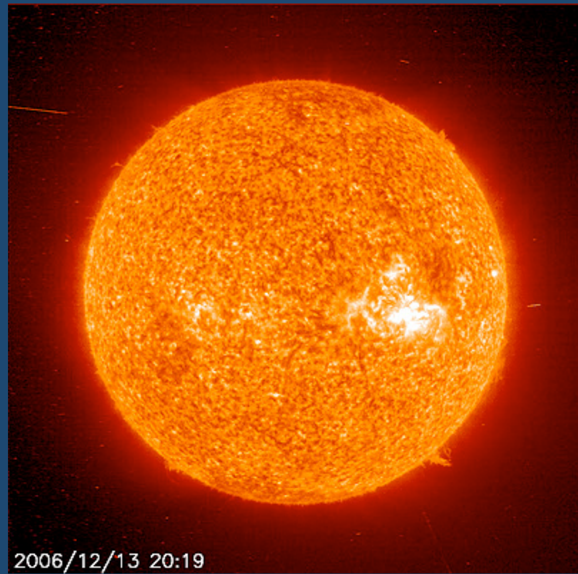
13th Dec. 2006 – solar particle event

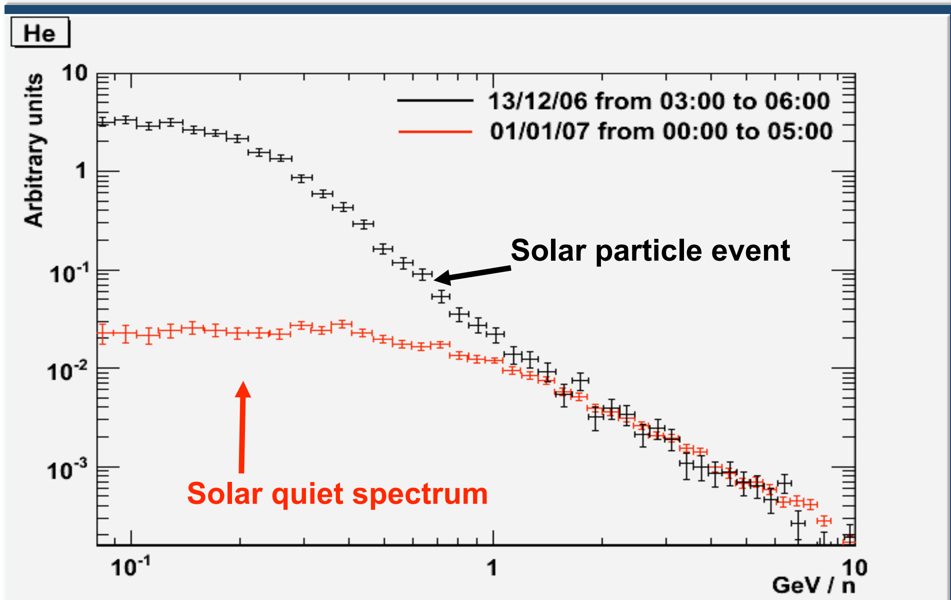
Largest CME since 2003, anomalous at solar minimum

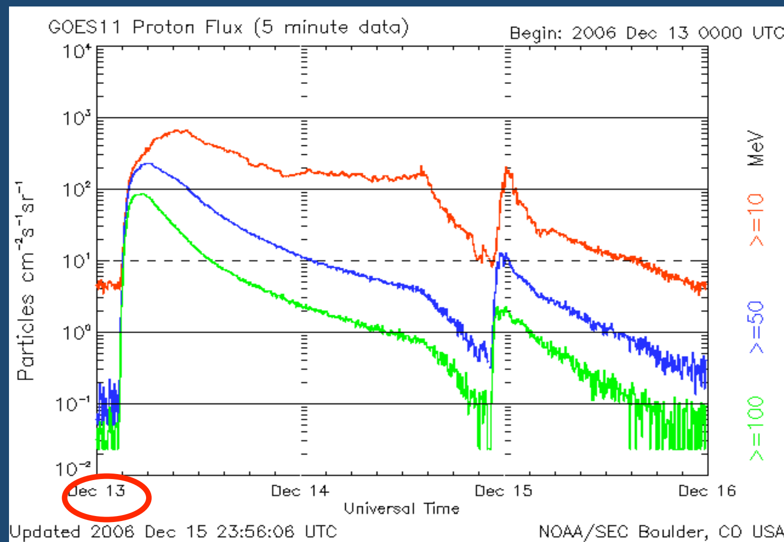
Preliminary



SOHO







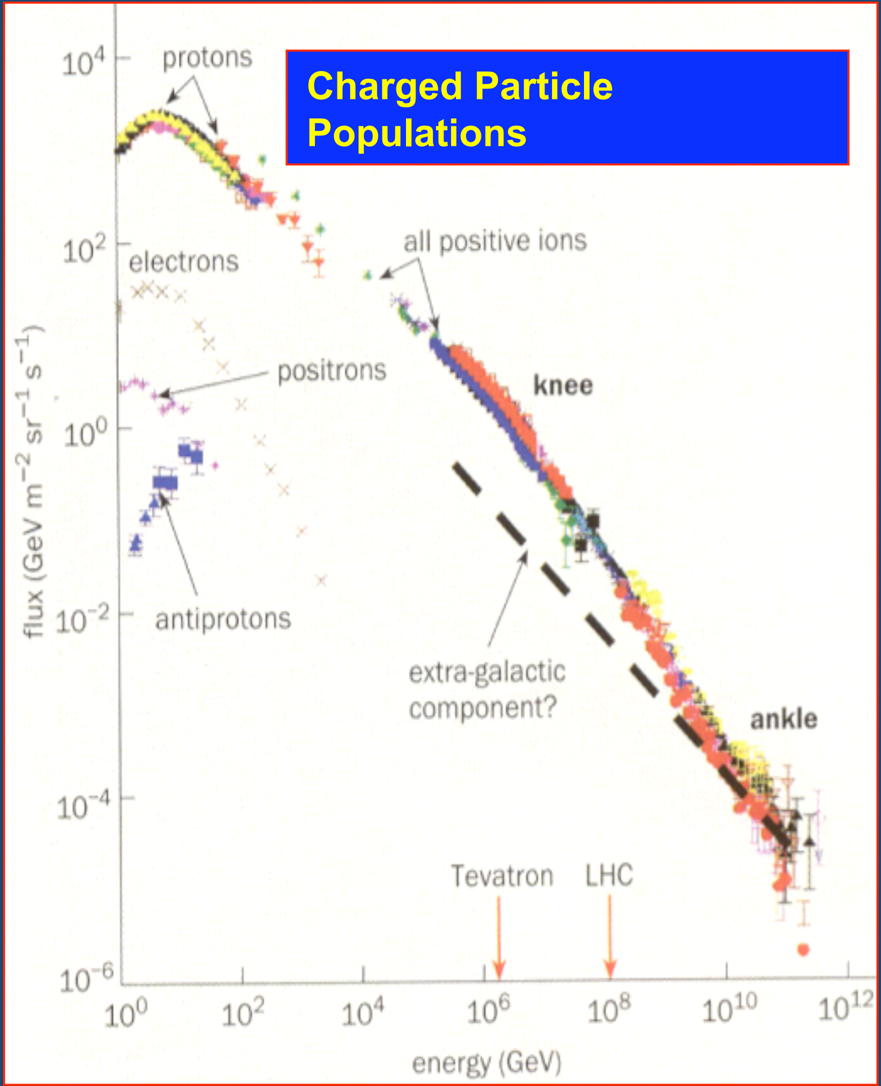
Several production processes for energetic particles can be found in the solar system:

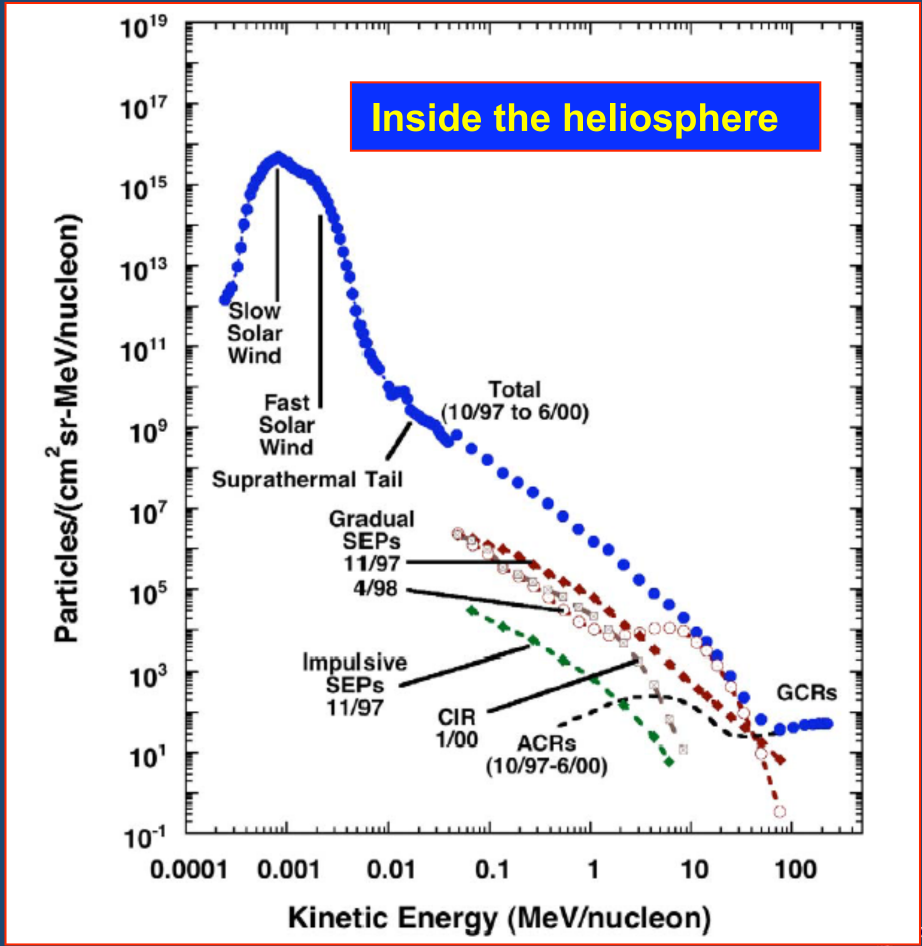
solar flares in the corona can accelerate ions up to energies of several GeV and electrons up to energies of 100 MeV;

shock waves occur at coronal mass ejections (CMEs), which are fed by the energy stored in the coronal magnetic field and released in violent reconnection processes;

corotating interaction regions (CIRs) in the solar wind plasma, forming when slow solar wind streams are overtaken by fast ones and, as a consequence, the resulting shocks can accelerate particles to higher energies;

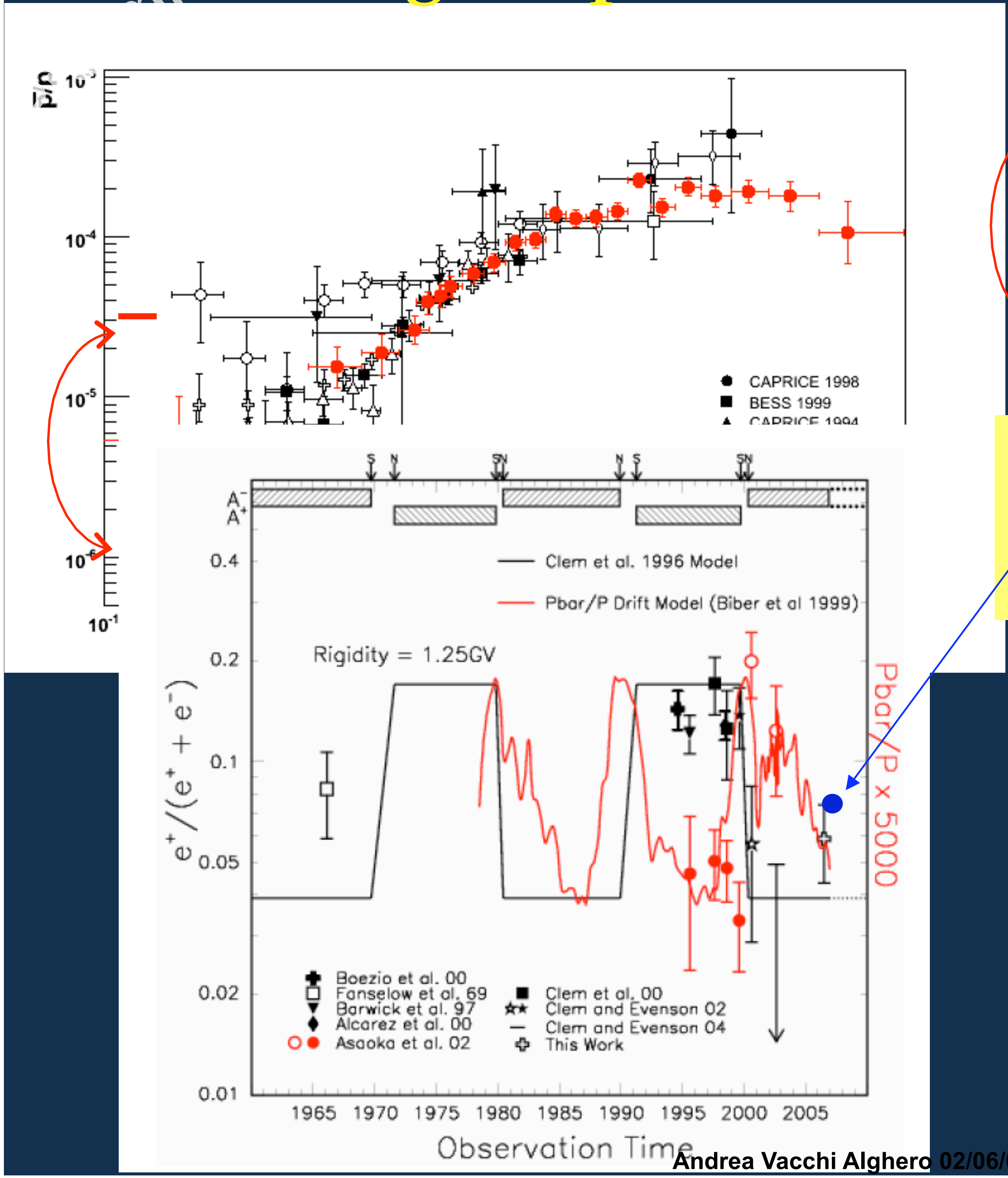
Cosmic Rays from the Galaxy

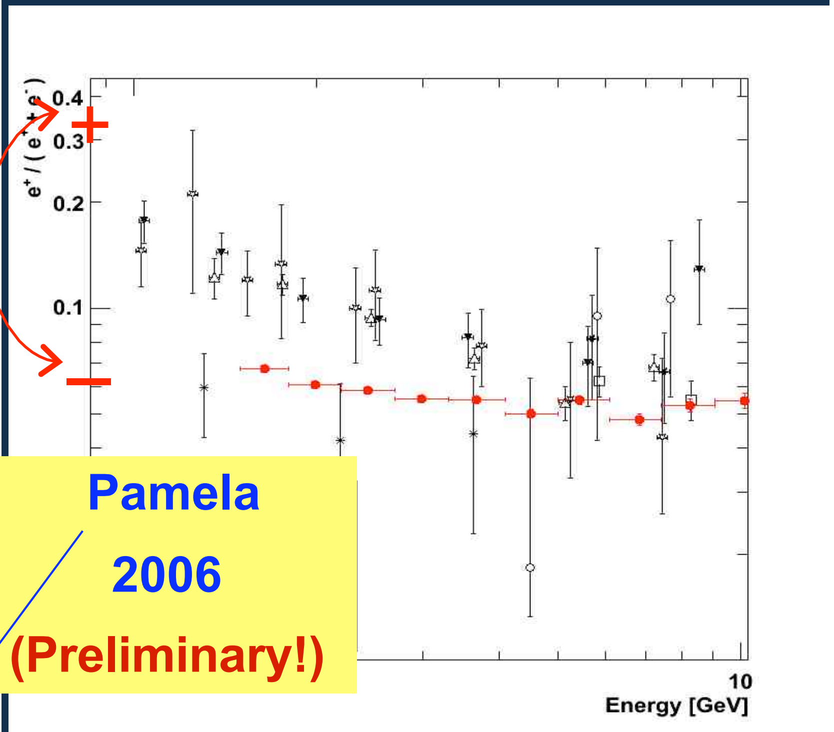




minary!!

Charge dependent solar modulation

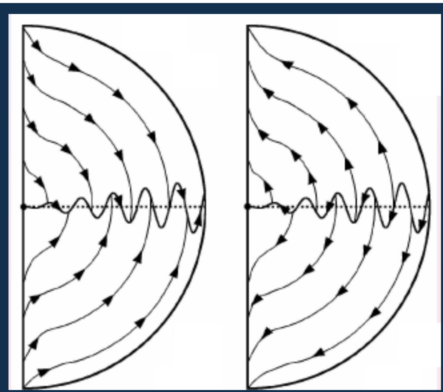




Pamela

2006

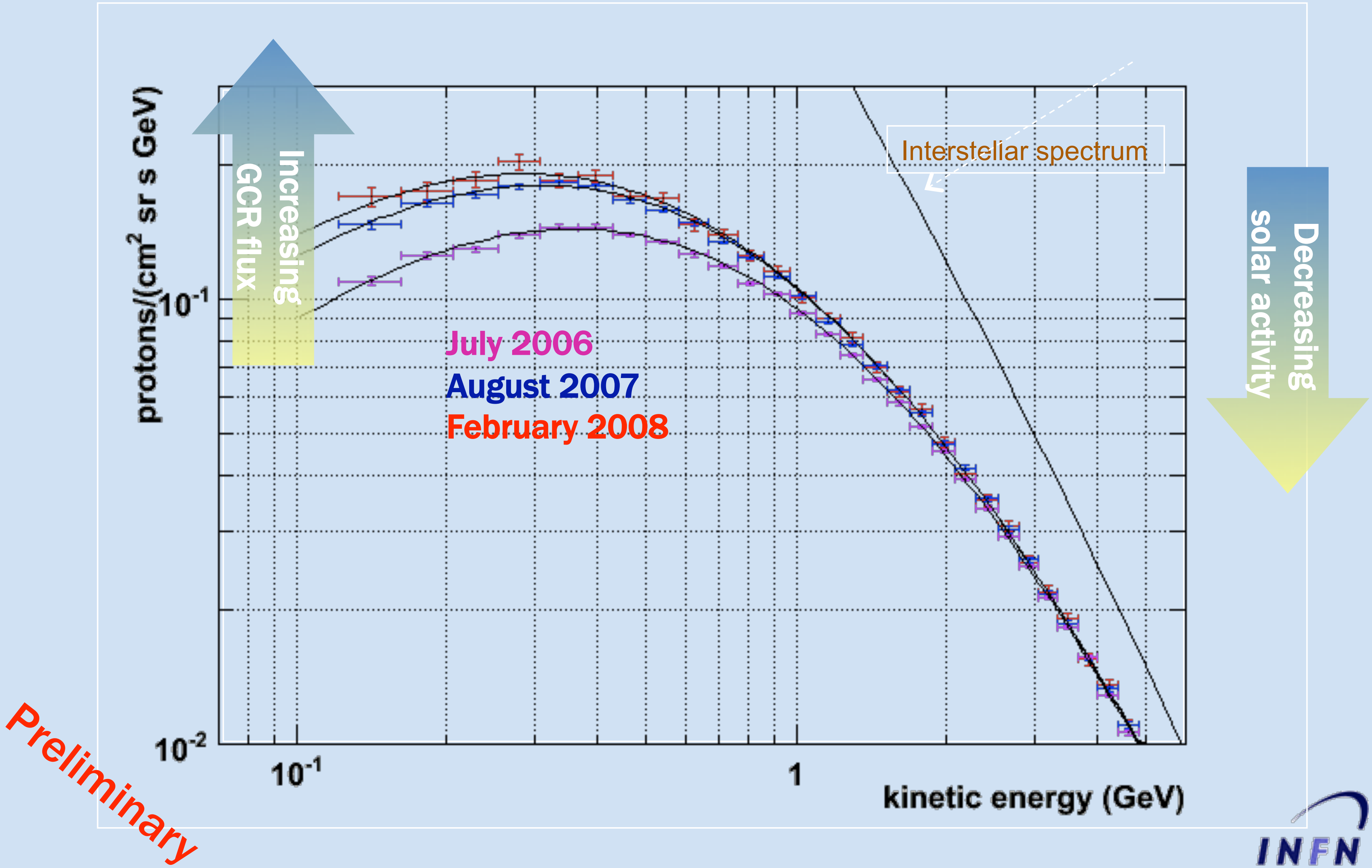
(Preliminary!)



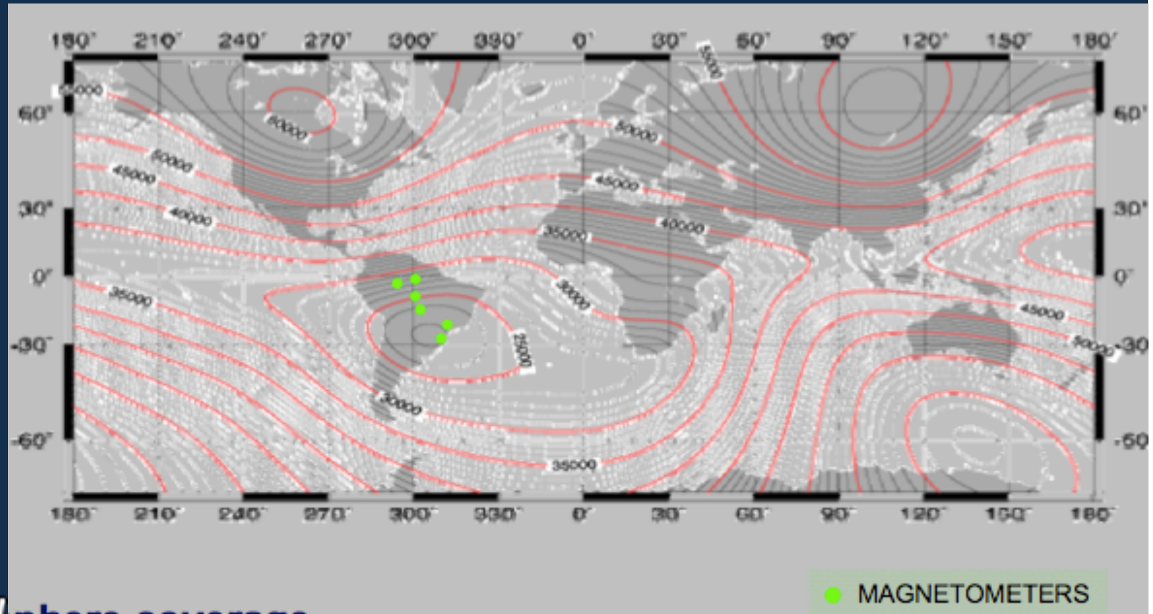
A > 0 **A < 0**

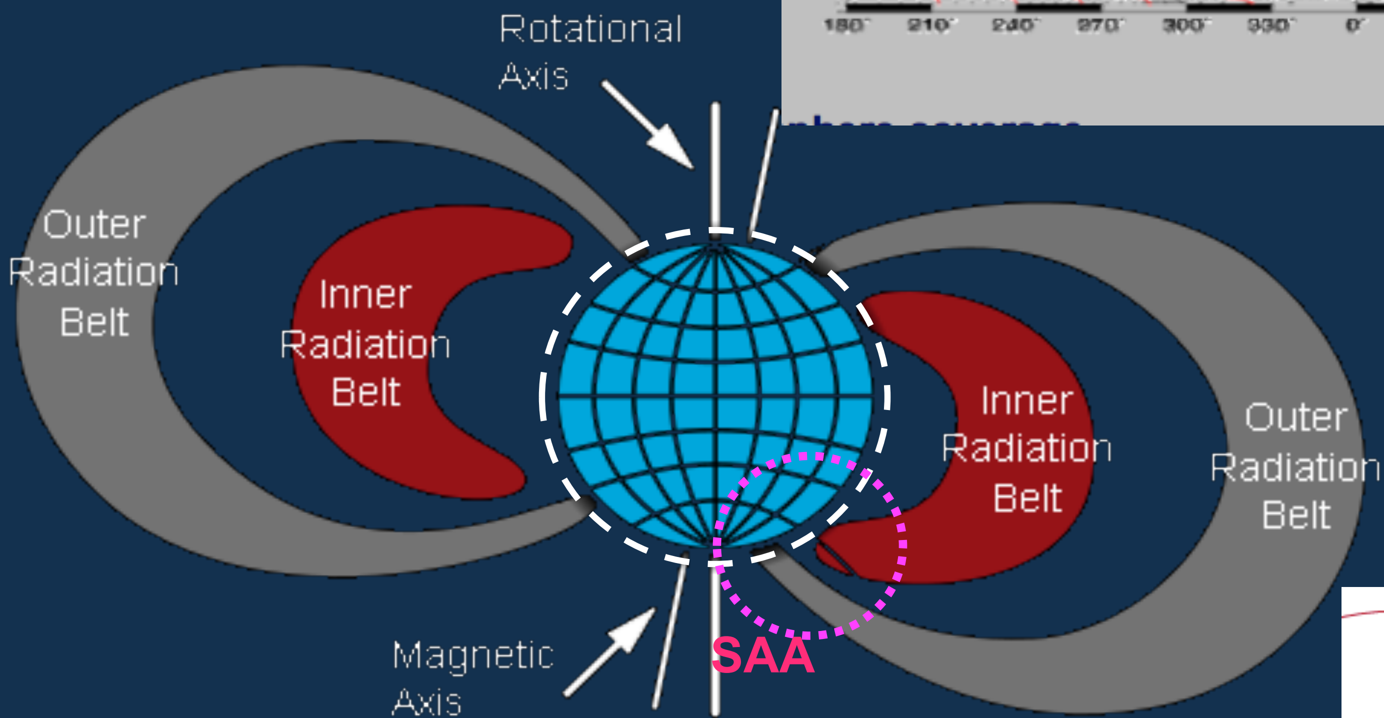
Positive particles

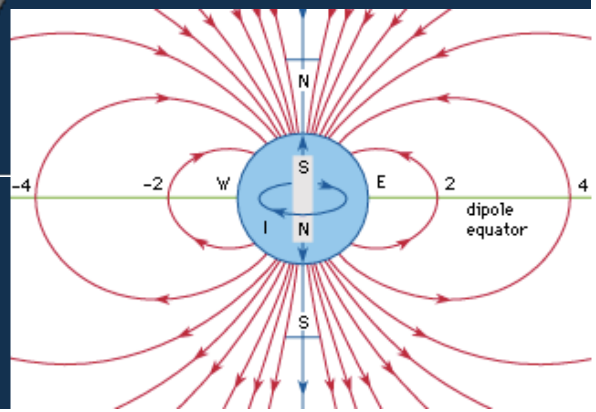
Proton spectra and solar modulation



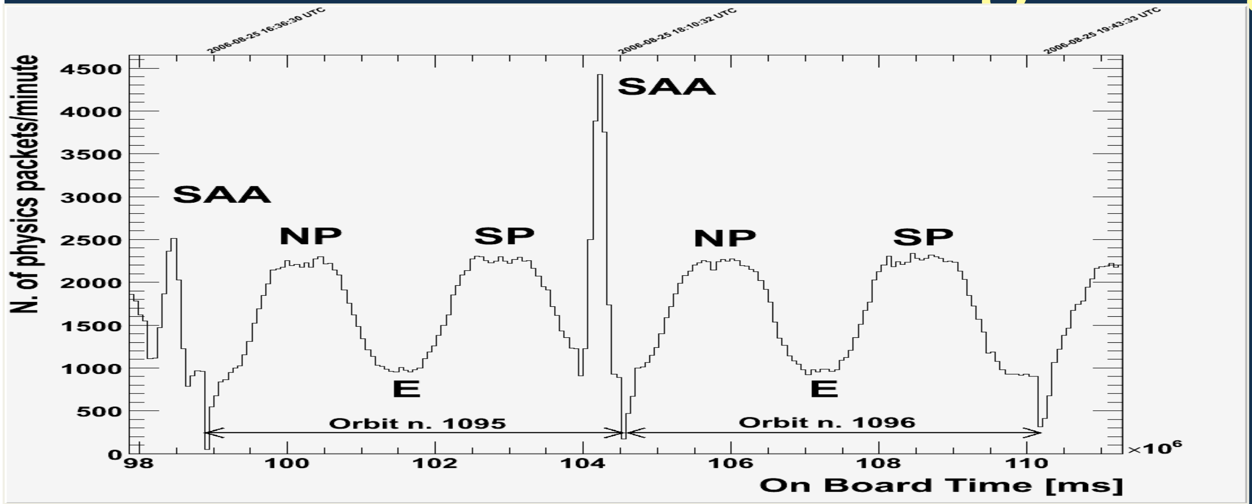
Geomagnetic cut-off

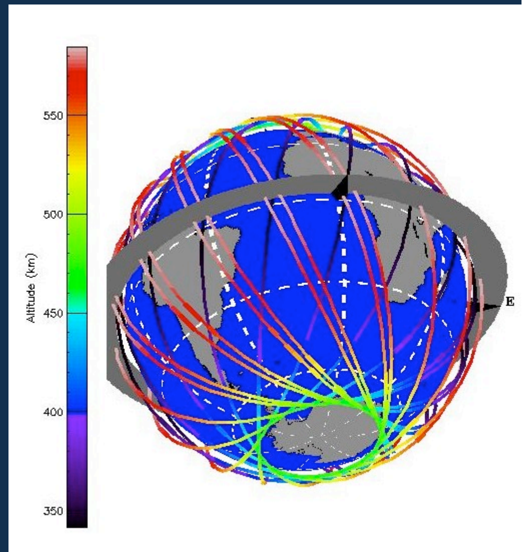


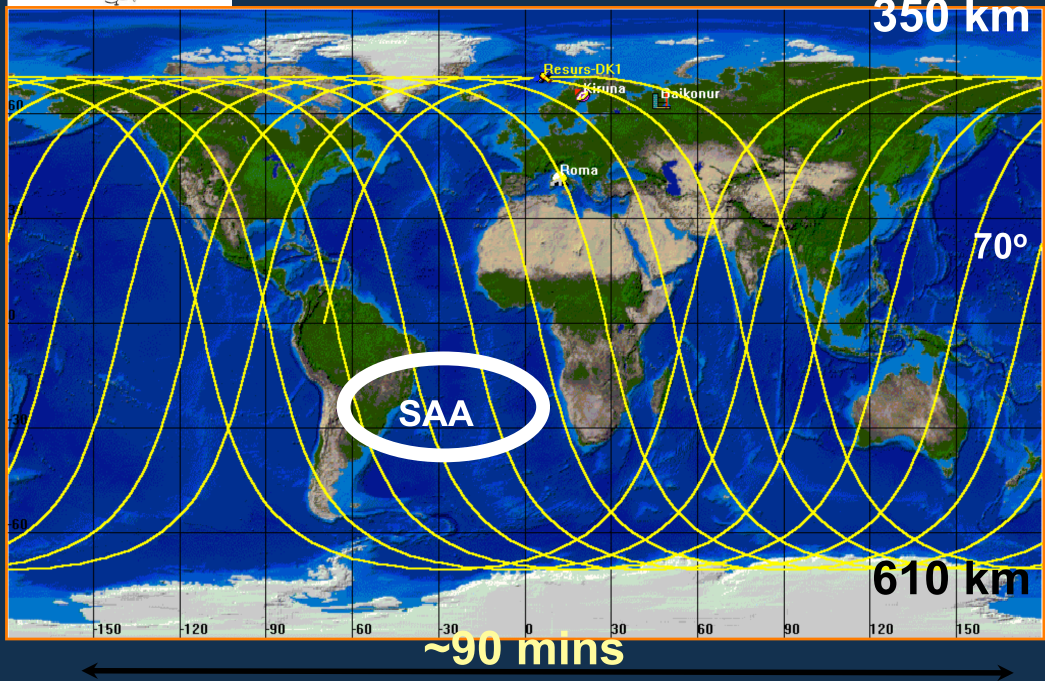




Pamela Orbit and geomagnetic cutoff



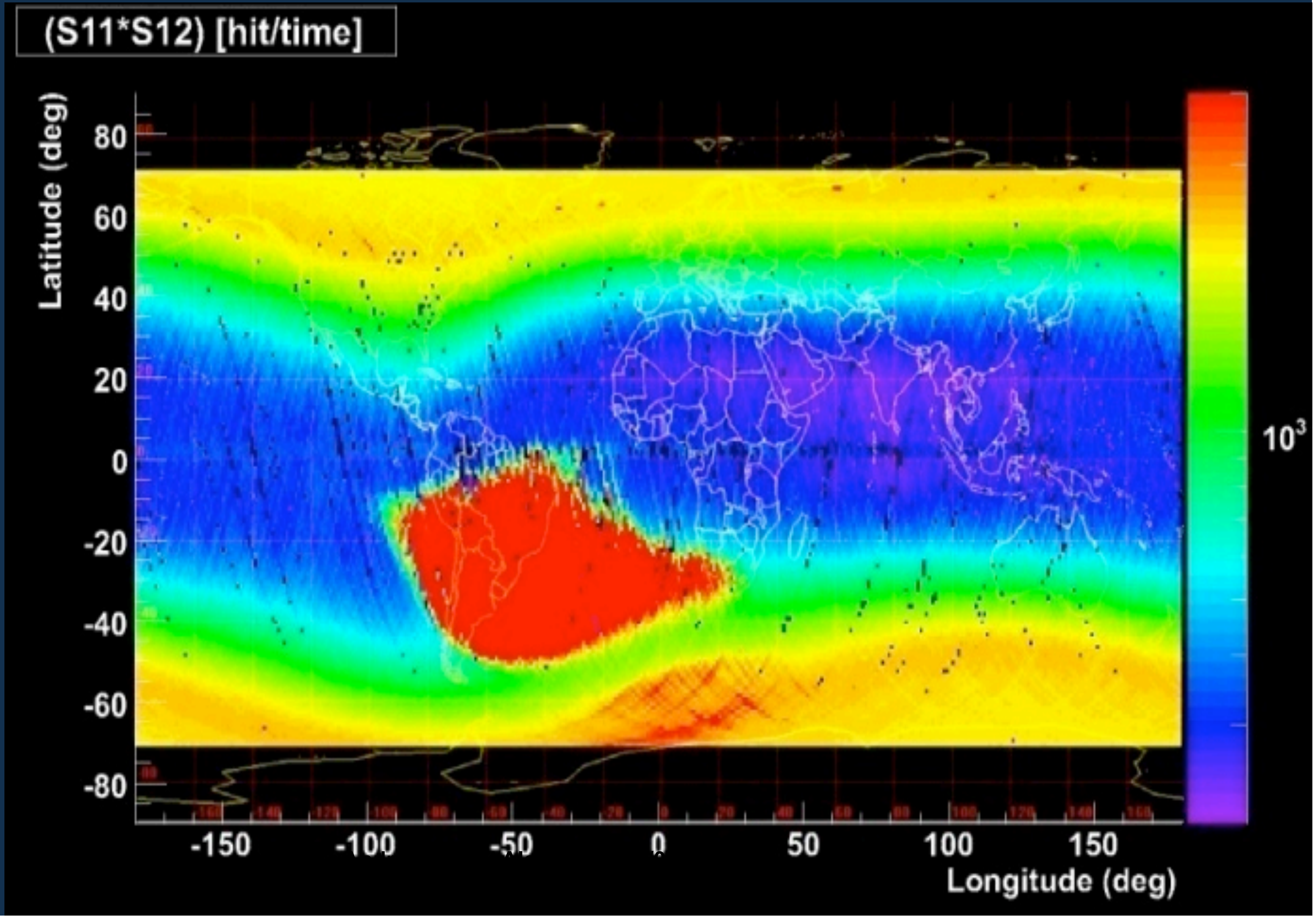




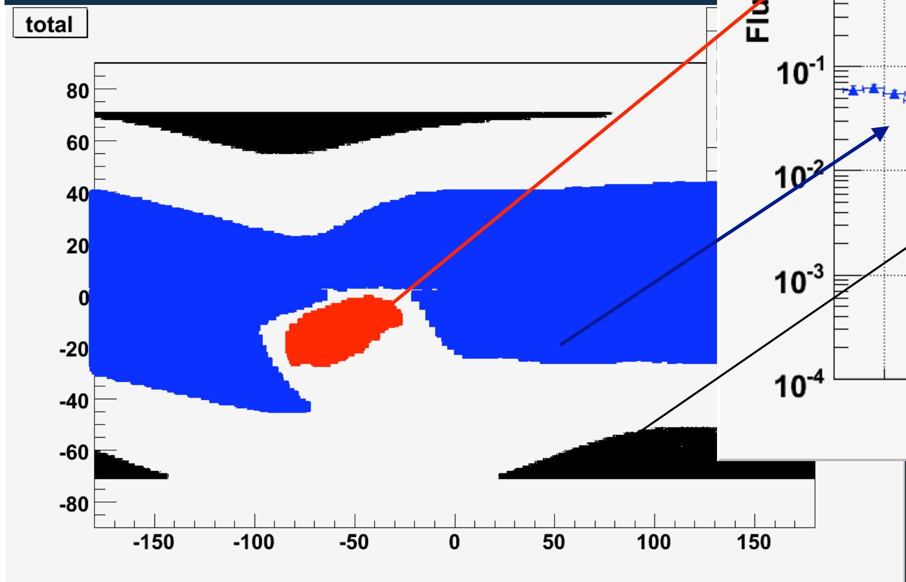
- Quasi-polar and elliptical orbit
  (inclination 70.0°, 350 km - 600 km)
- Traverses the South Atlantic Anomaly
- Crosses the outer (electron) Van Allen belt at south pole
- 3 axis stabilization. Information about the satellite attitude is know with accuracy ~1 degree

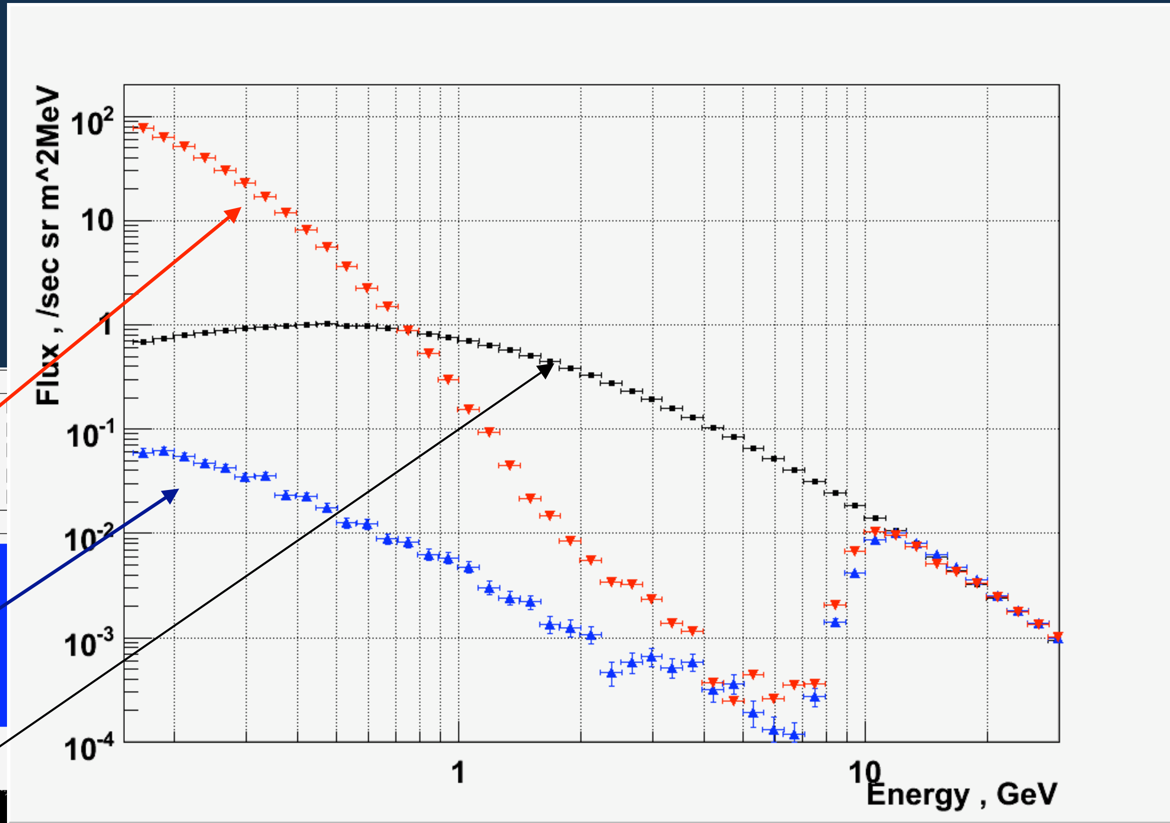
PAMELA in the magnetosphere

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



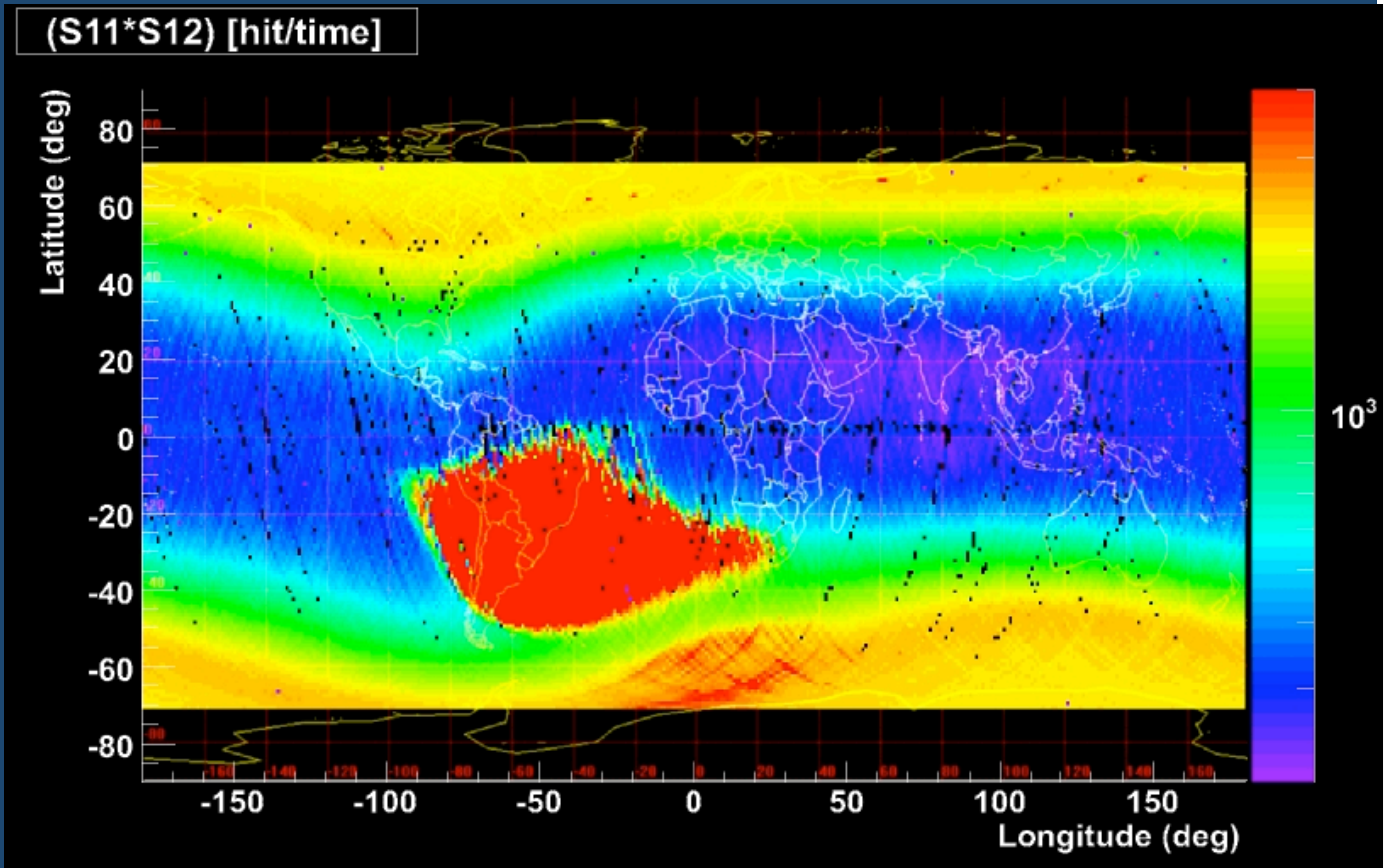
Proton spectrum in the SAA, polar and equatorial regions





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

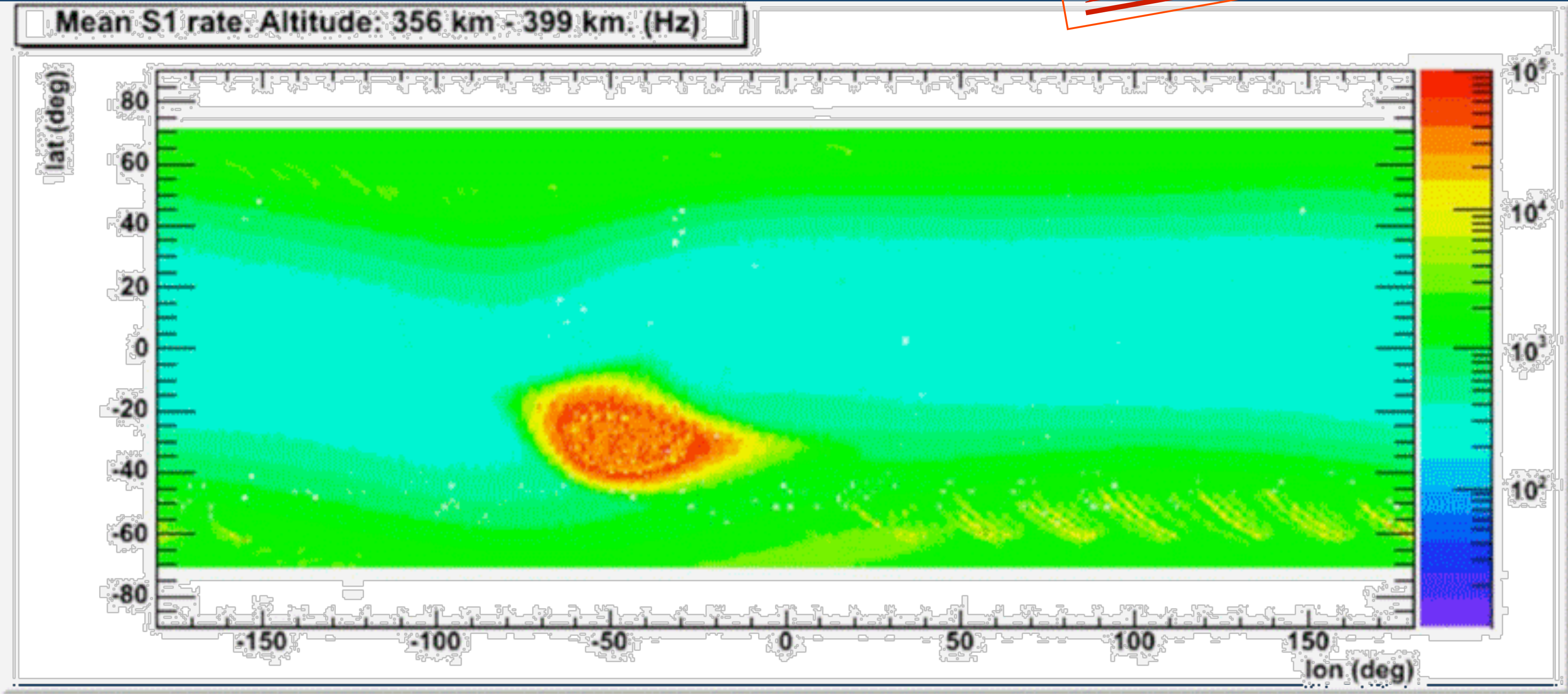
Pamela World Maps: 350 – 650 km alt



36 MeV p, 3.5 MeV e$^-$

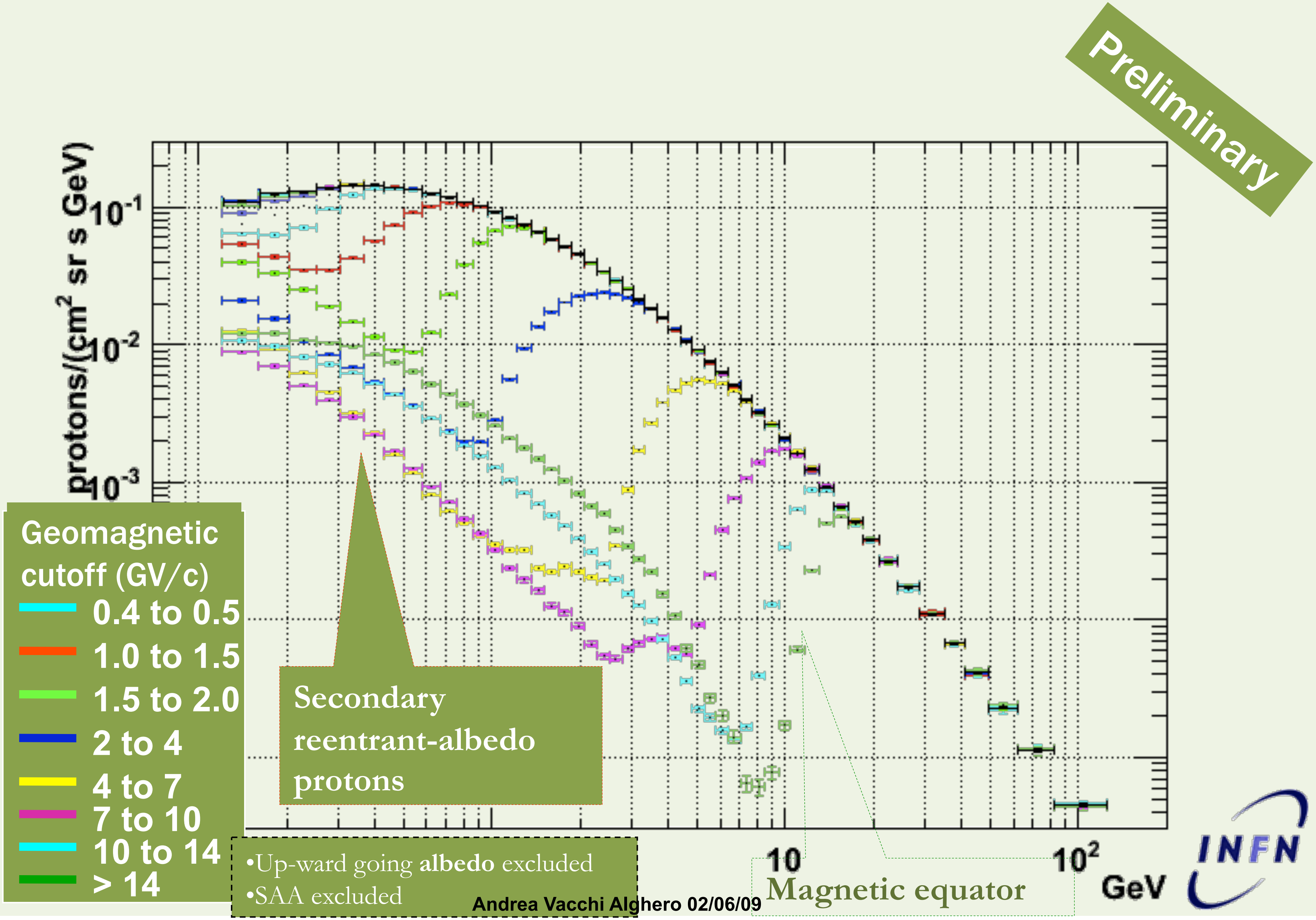
Pamela maps at various altitudes

PRELIMINARY !!!!



Altitude scanning

Primary and Albedo (sub-cutoff) measurements



•Up-ward going **albedo** excluded
•SAA excluded

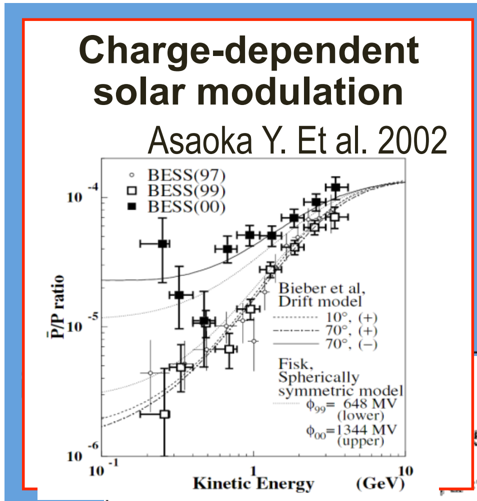
PAMELA Design Performance

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

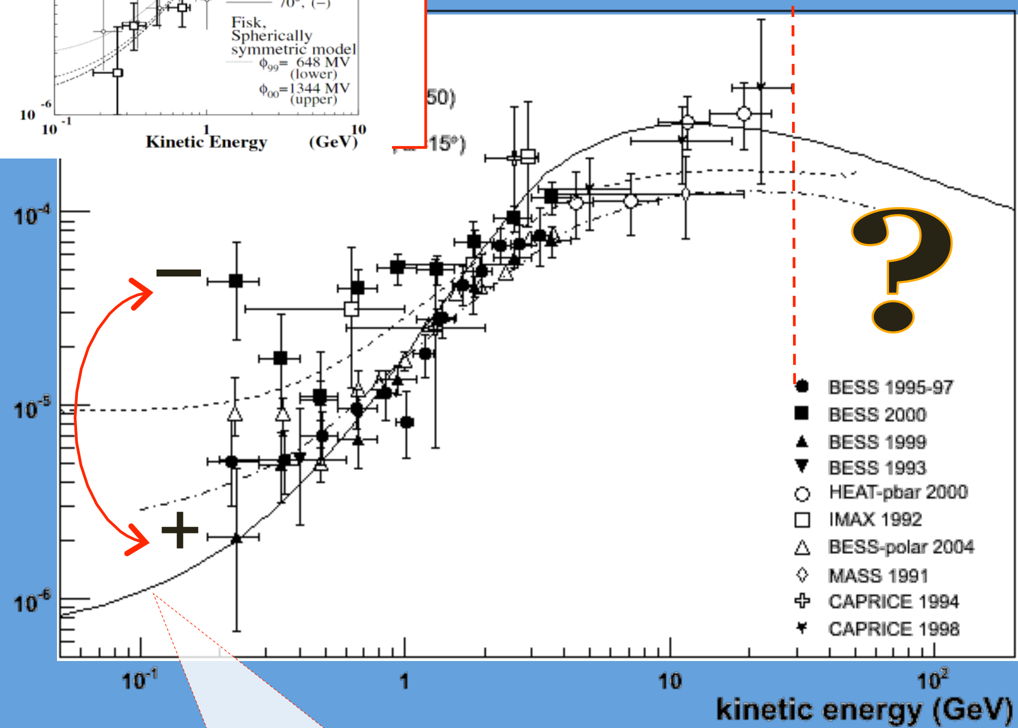
	Energy range		Particles / 3 years
• Antiproton flux	80 MeV - 190 GeV		$O(10^4)$
• Positron flux	50 MeV – 270 GeV		$O(10^5)$
• Electron/positron flux	up to 2 TeV (from calorimeter)		
• Electron flux	up to 400 GeV		$O(10^6)$
• Proton flux	up to 700 GeV		$O(10^8)$
• Light nuclei (up to Z=6)	up to 200 GeV/n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

CR antimatter search status

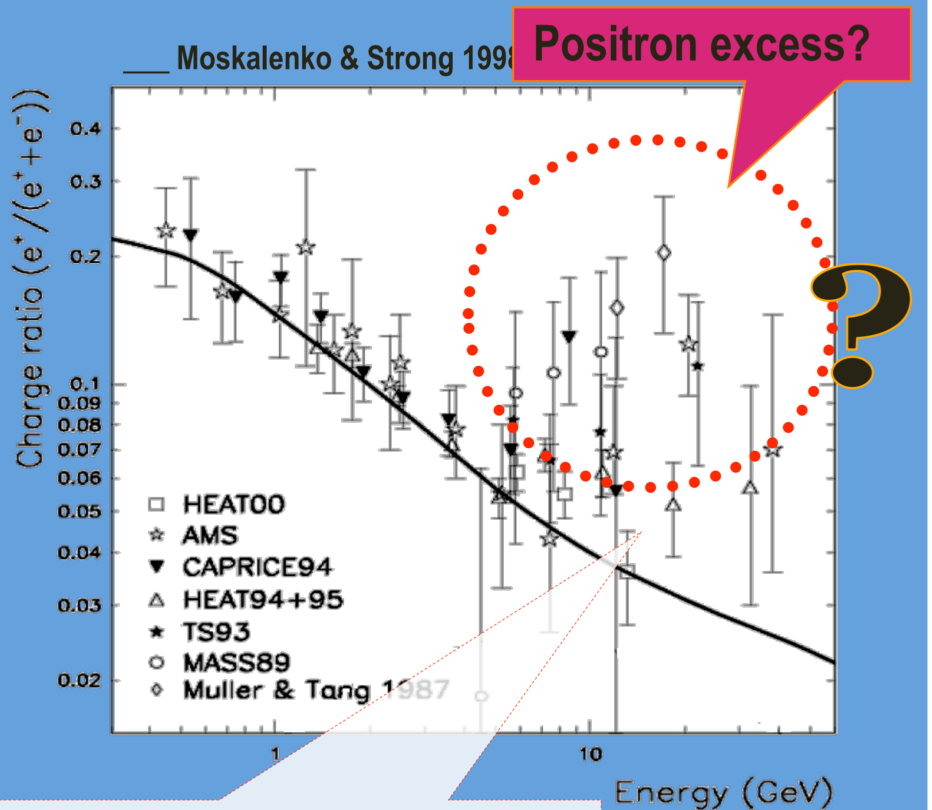
BP



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 → $\gamma\gamma$ → **$e^{\pm}$**

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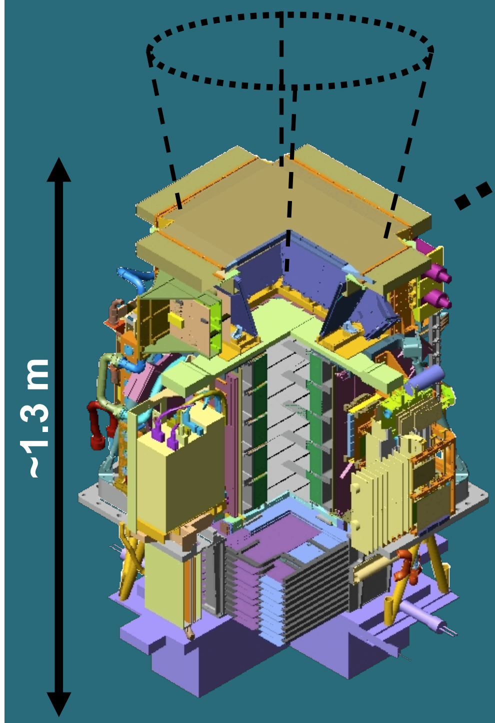
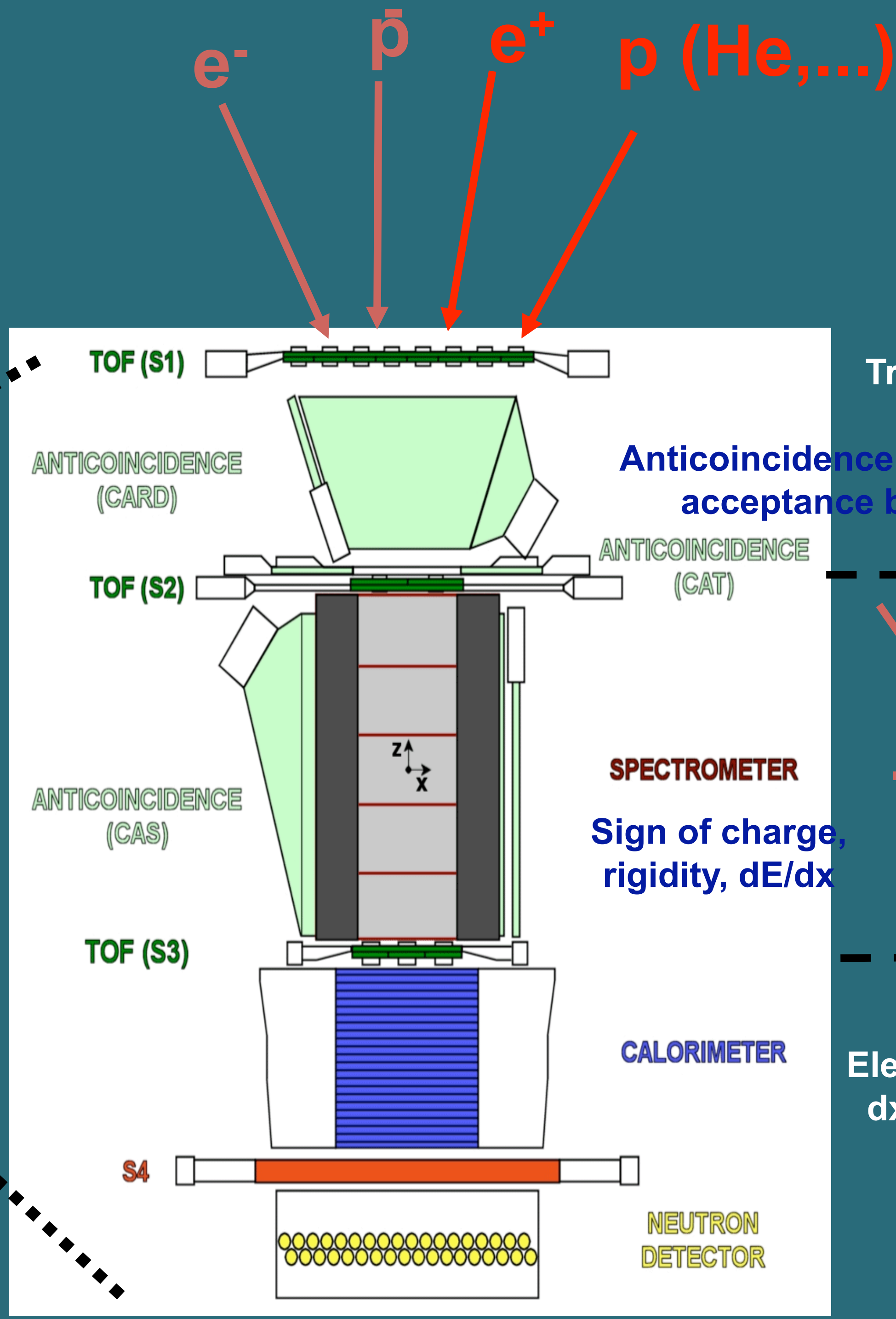
21.5 cm²sr



~470 kg

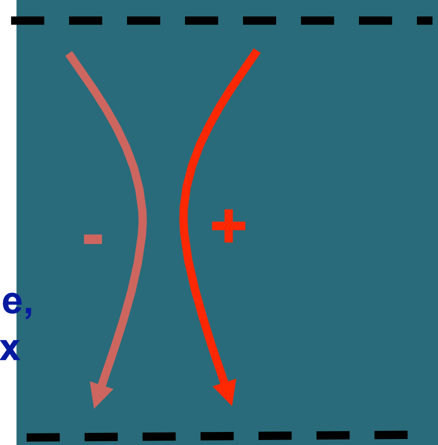
~360 W



Trigger, ToF, dE/dx

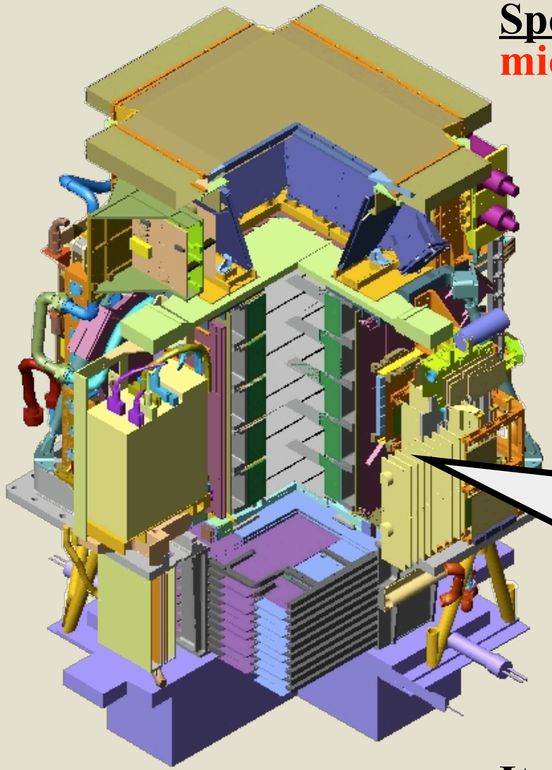
Anticoincidence reduces out of acceptance background

Sign of charge, rigidity, dE/dx



Electron energy, dE/dx, lepton-hadron separation

INFN



Spectrometer

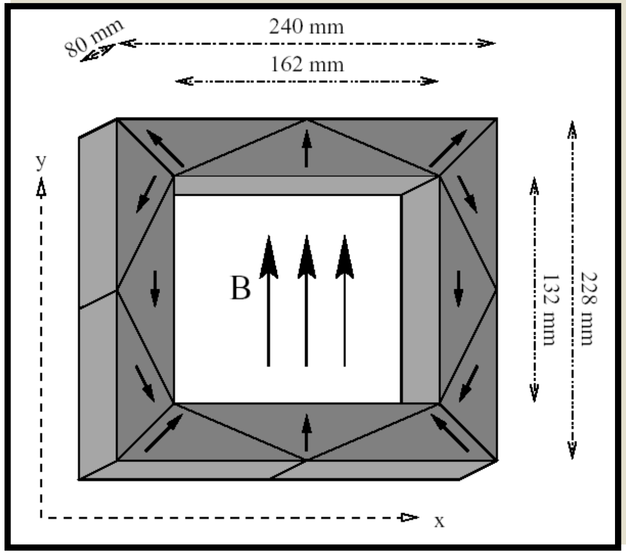
microstrip silicon tracking system + permanent magnet

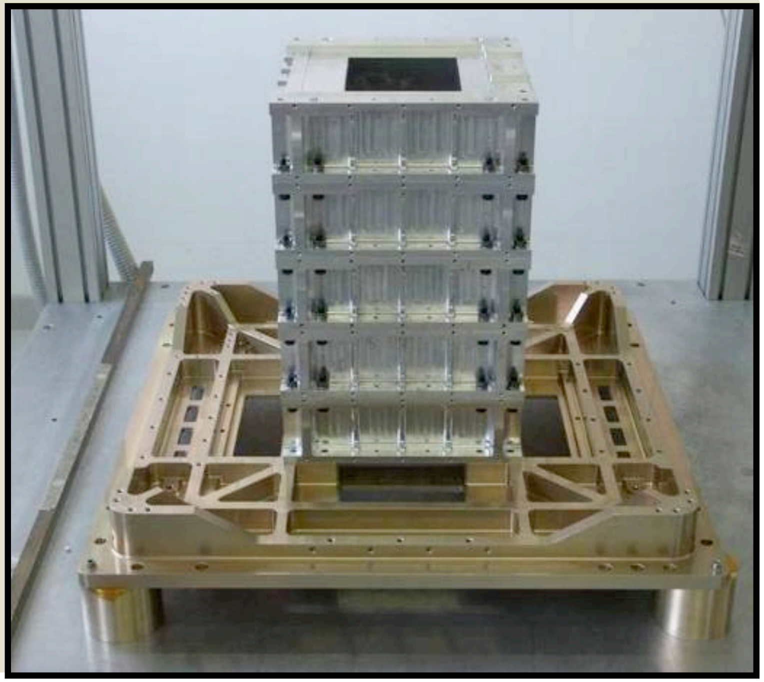
•Characteristics:

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

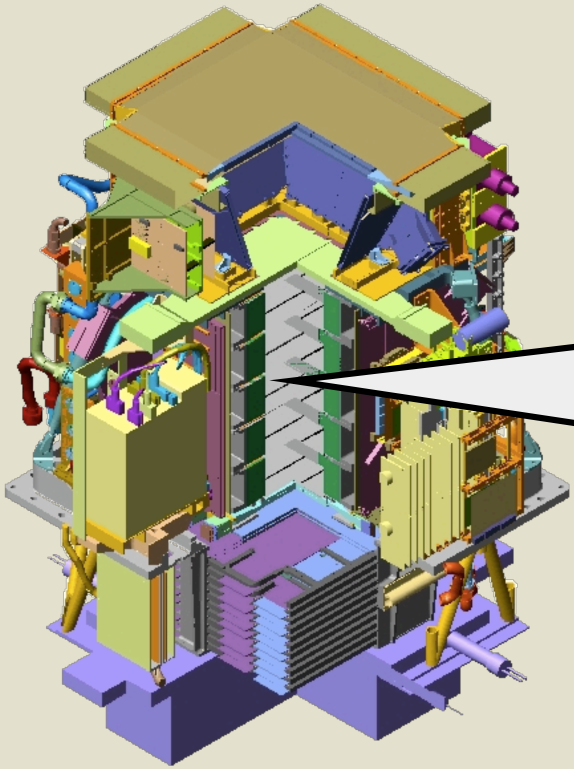
It provides:

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





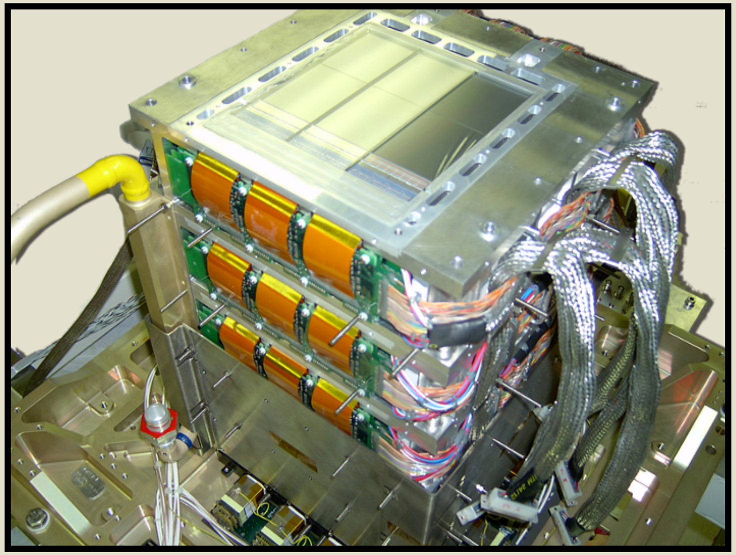
The tracking system

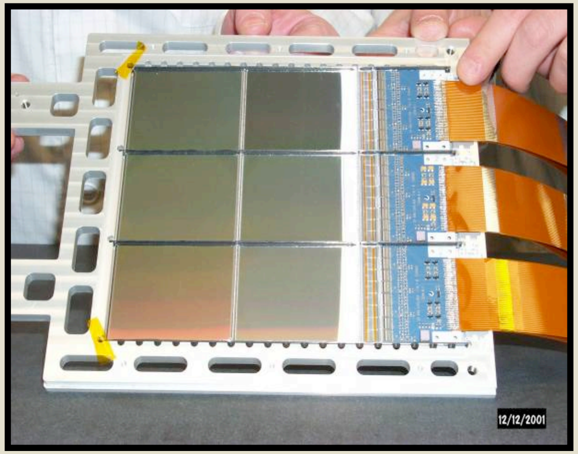


- **Main tasks:**
- **Rigidity measurement**
- **Sign of electric charge**
- **dE/dx (ionisation loss)**

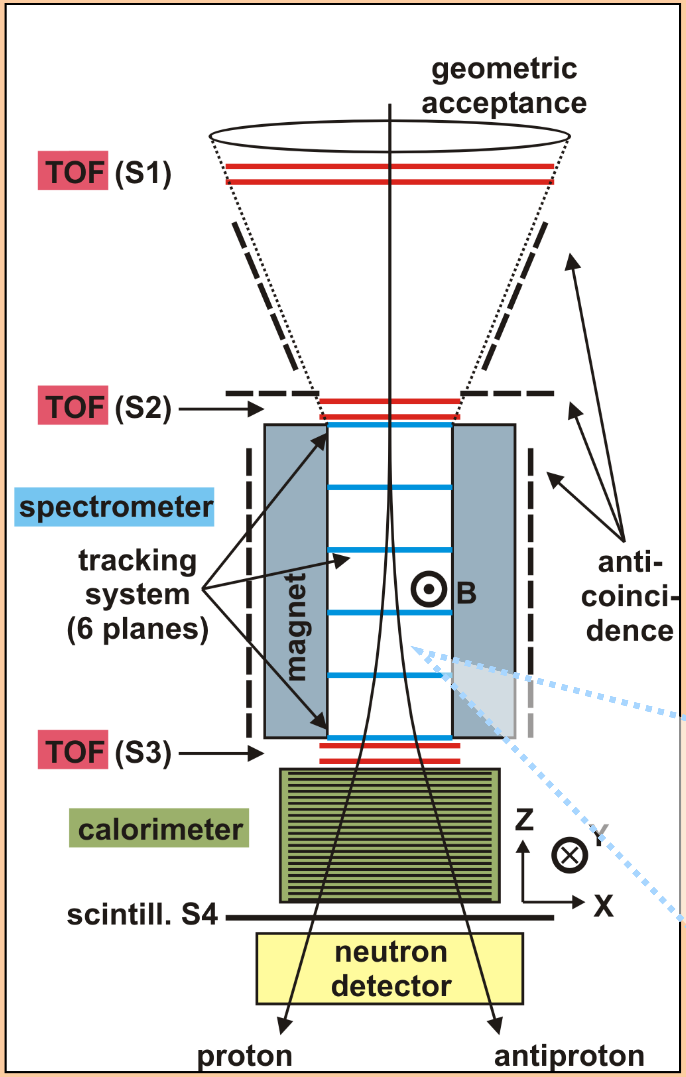
- **Characteristics:**
- **6 planes double-sided (x&y view) microstrip Si sensors**
- 36864 channels
- Dynamic range: 10 MIP

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

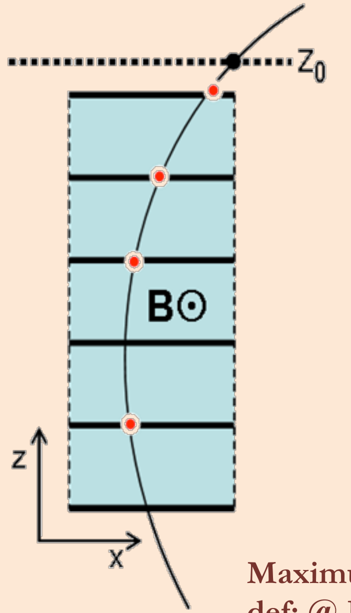




Principle of operation



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 ⇒ $\sigma_R/R=1$

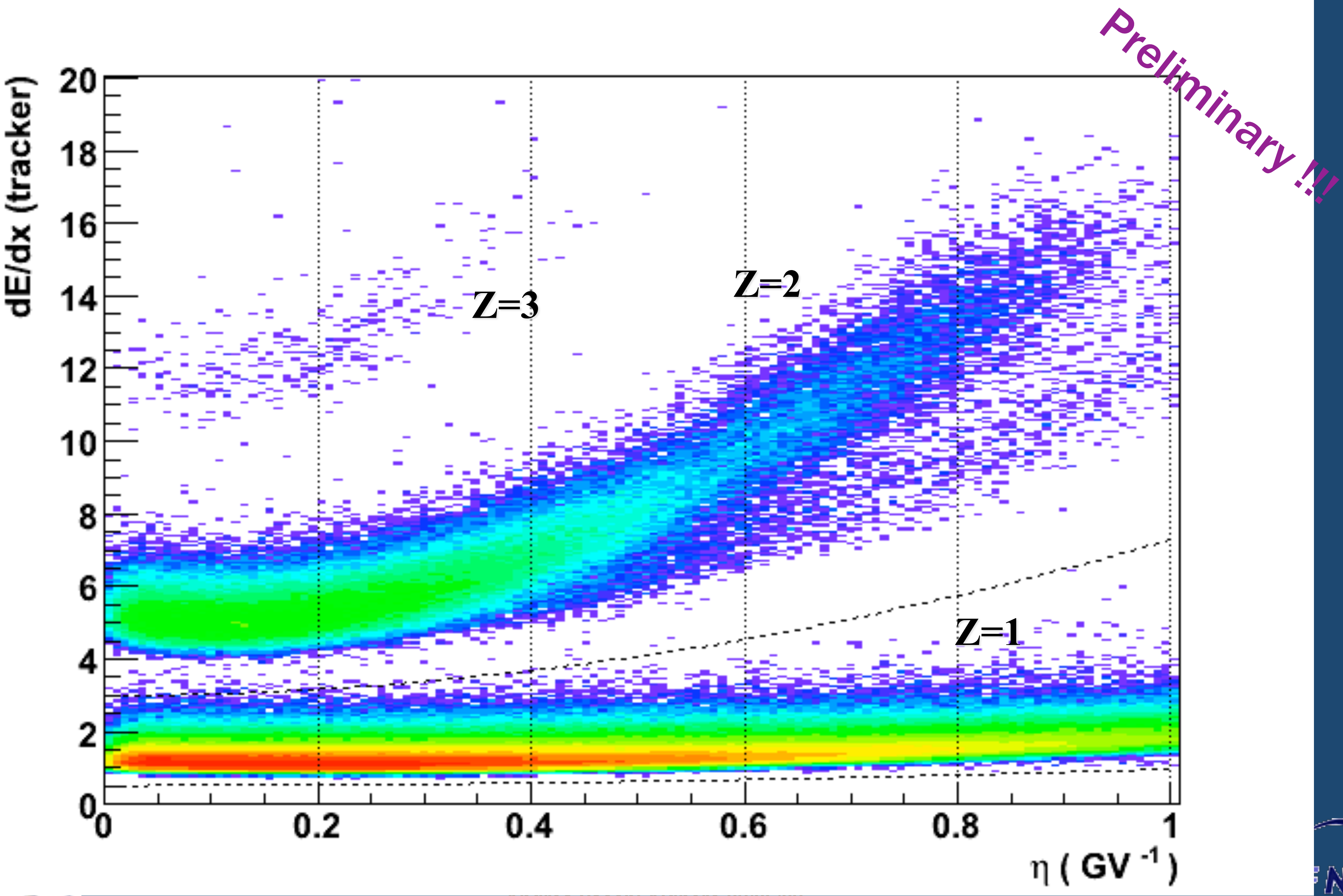
$MDR = 1/\sigma_\eta$

- Measured @ground with protons of known momentum

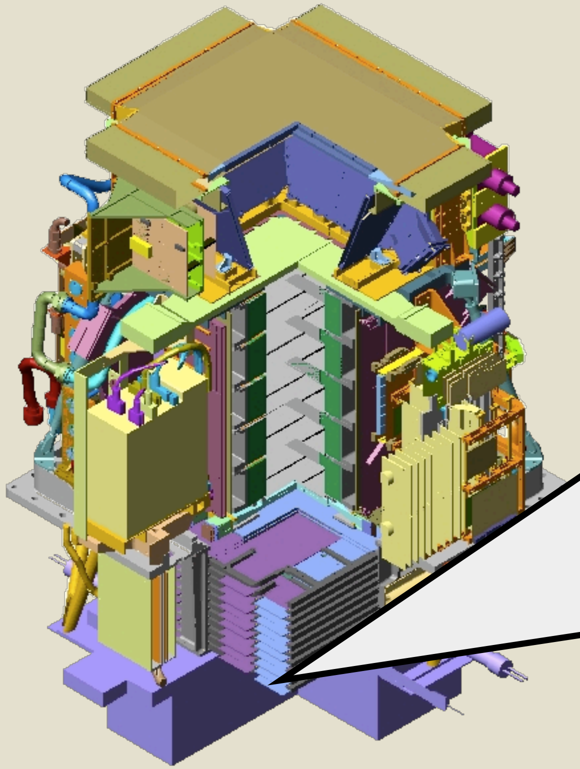
  → MDR~1TV

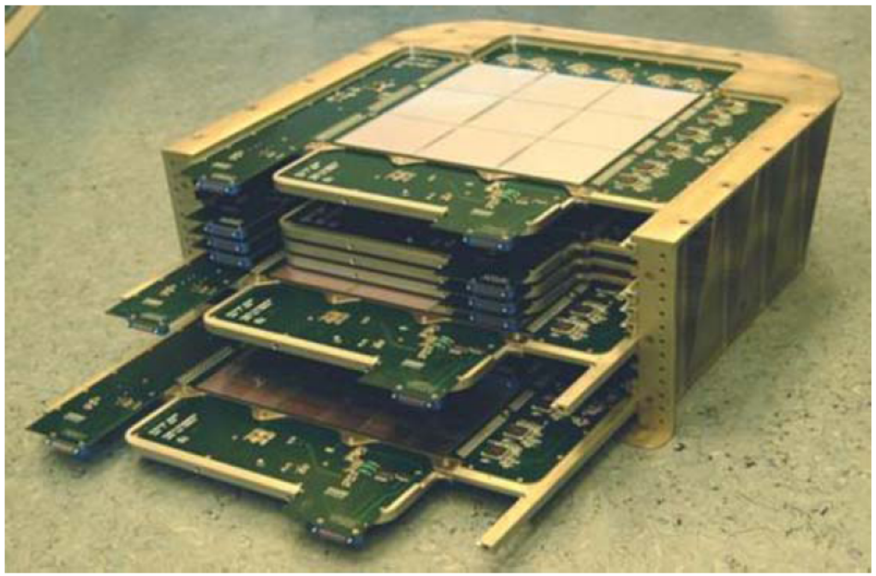
- Cross-check in flight with protons (alignment) and electrons (energy from calorimeter)

dE/dx from Tracker Sensors



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_0
  - 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

PaMeLa

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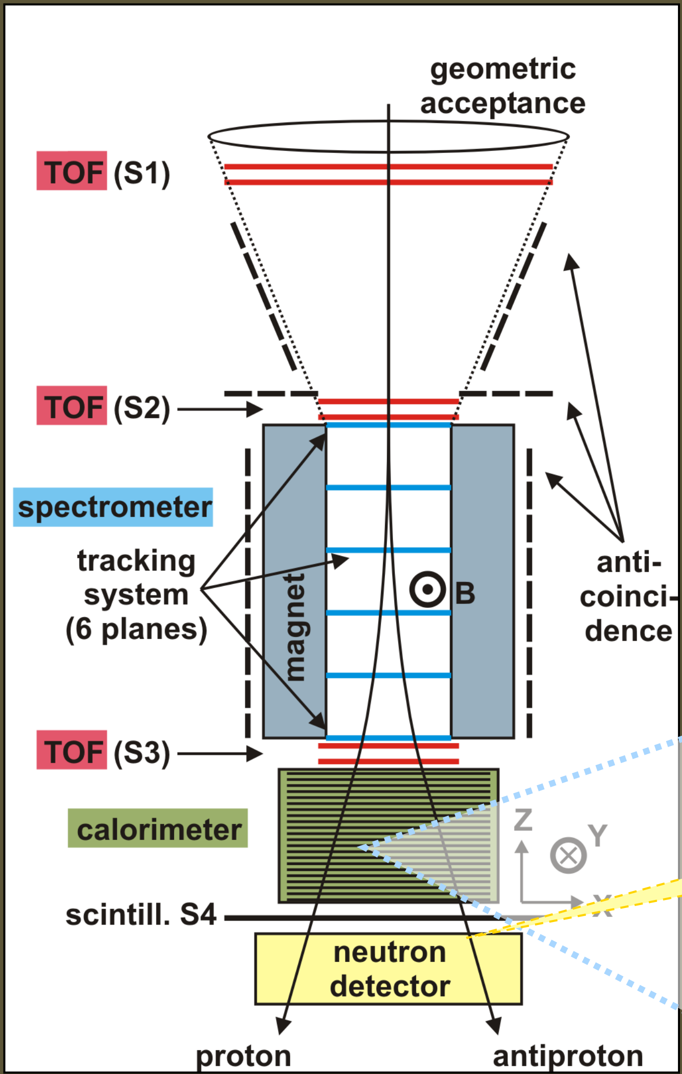
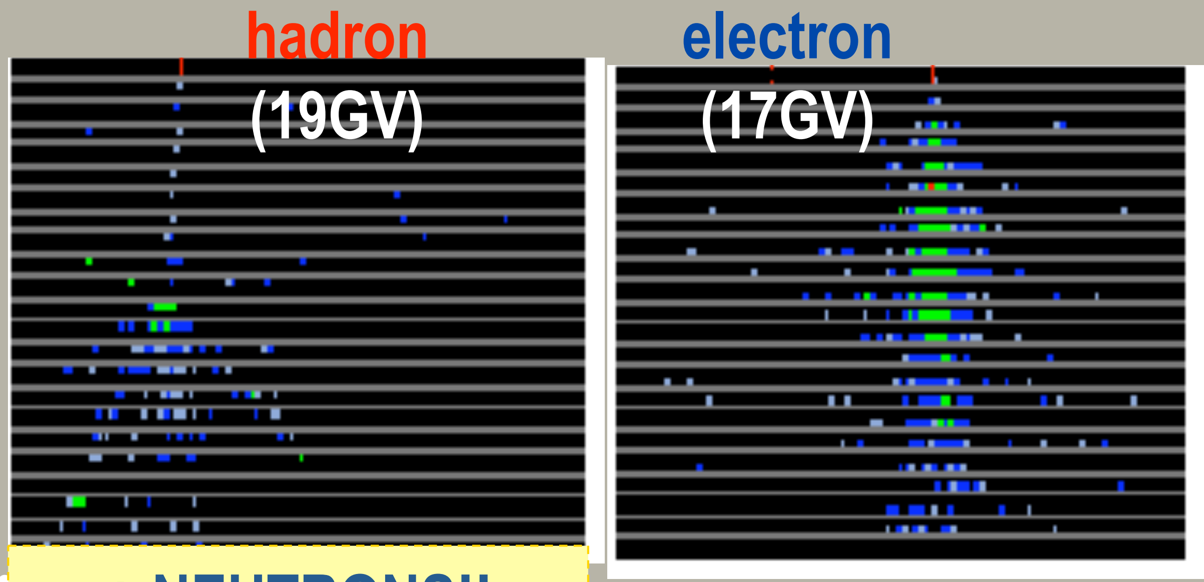
Principle of operation



Electron/hadron separation

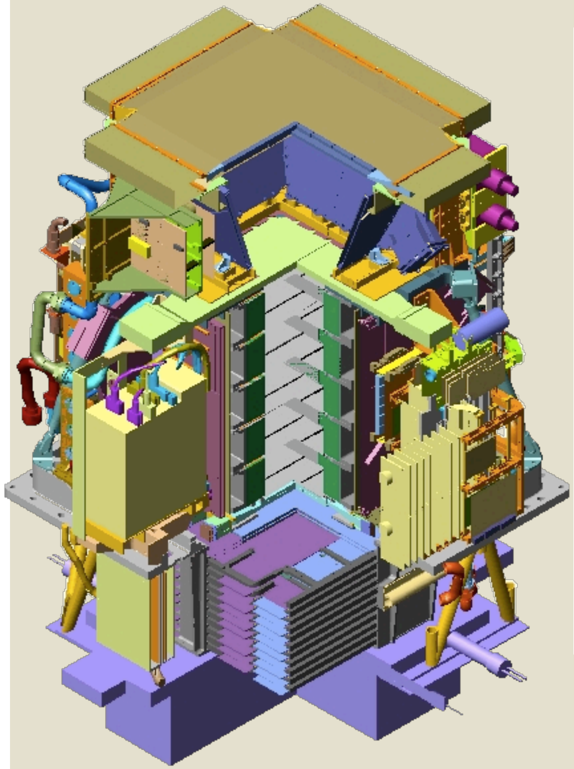
- Interaction topology e/h separation

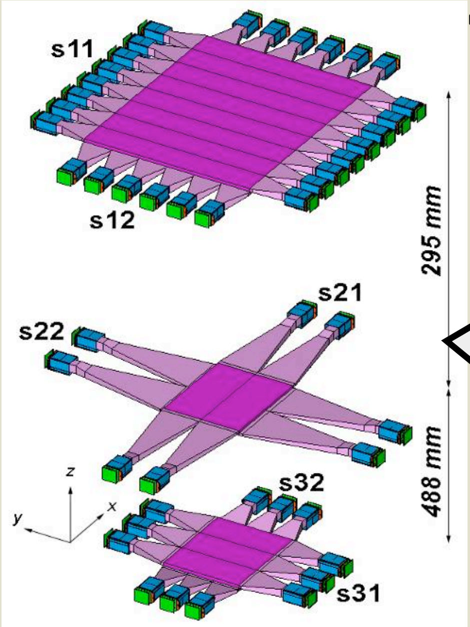


+ NEUTRONS!!

- 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:

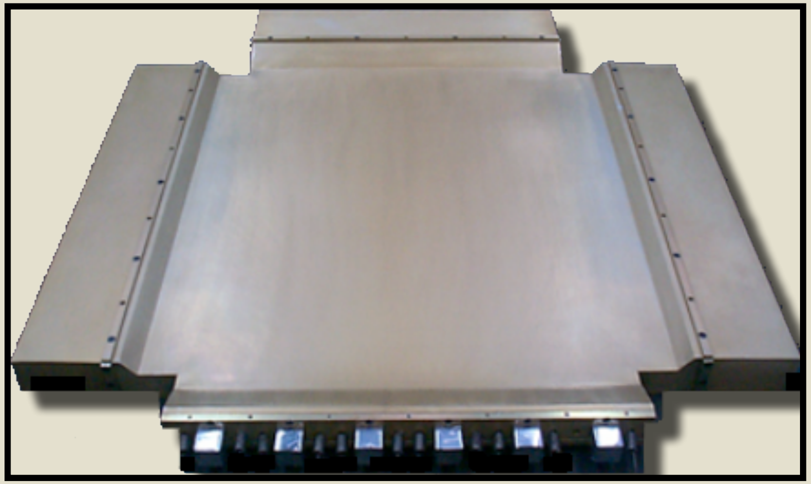
- First-level trigger
- Albedo rejection
- dE/dx (ionisation losses)
- Time of flight particle identification (<1GeV/c)

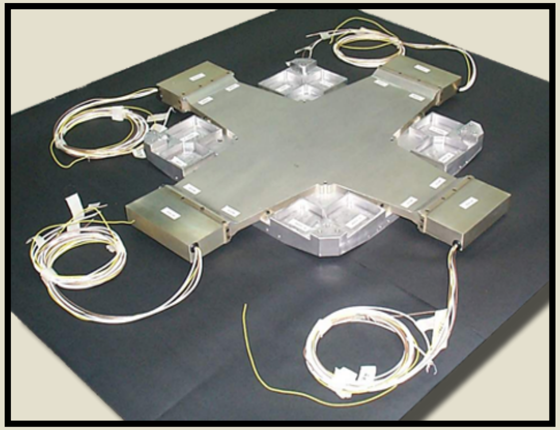
•Characteristics:

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

•Performance:

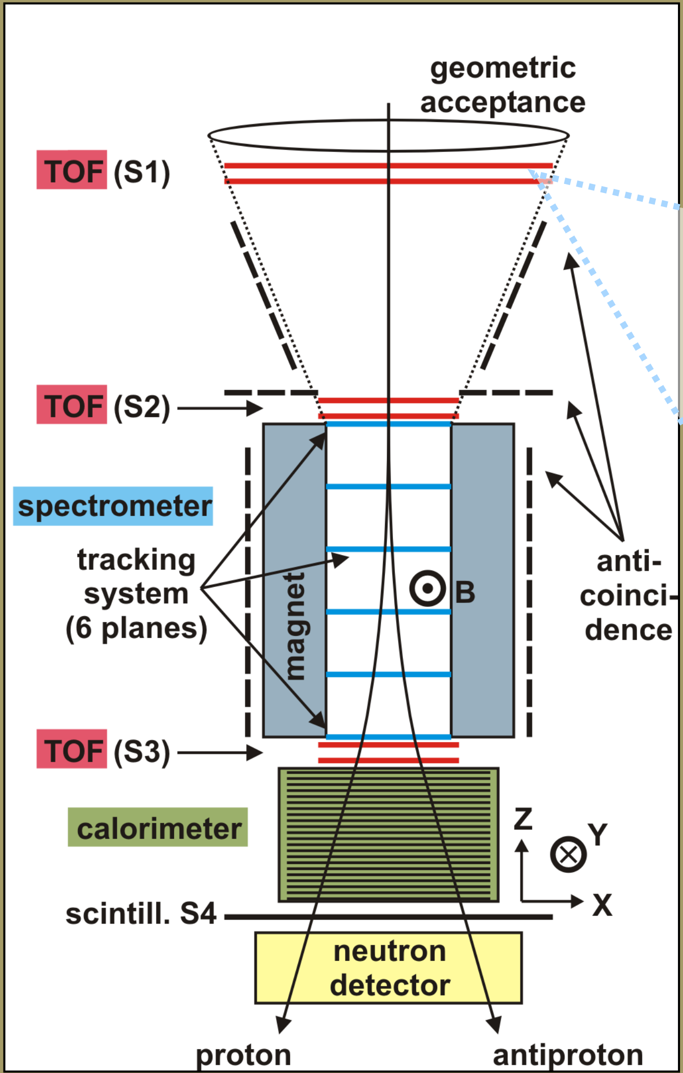
- σ(paddle) ~ 110ps
- σ(ToF) ~ 330ps (for MIPs)



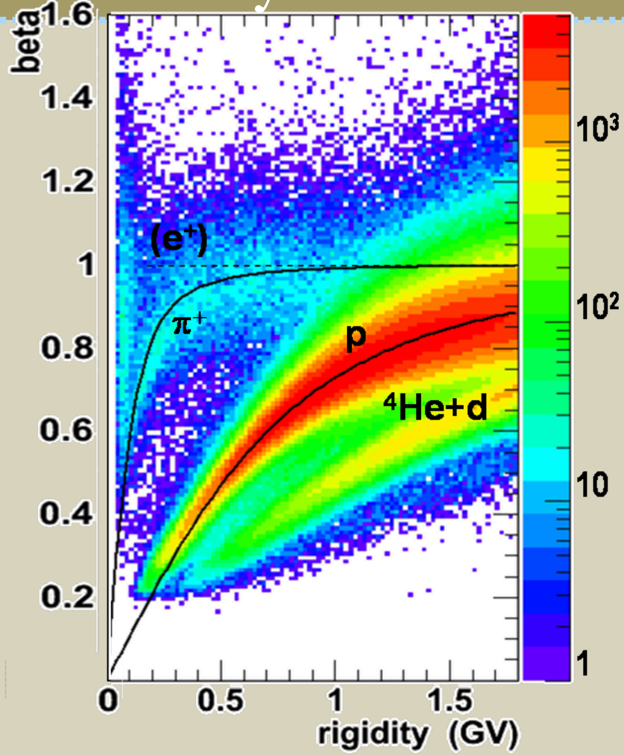


INFN

Principle of operation



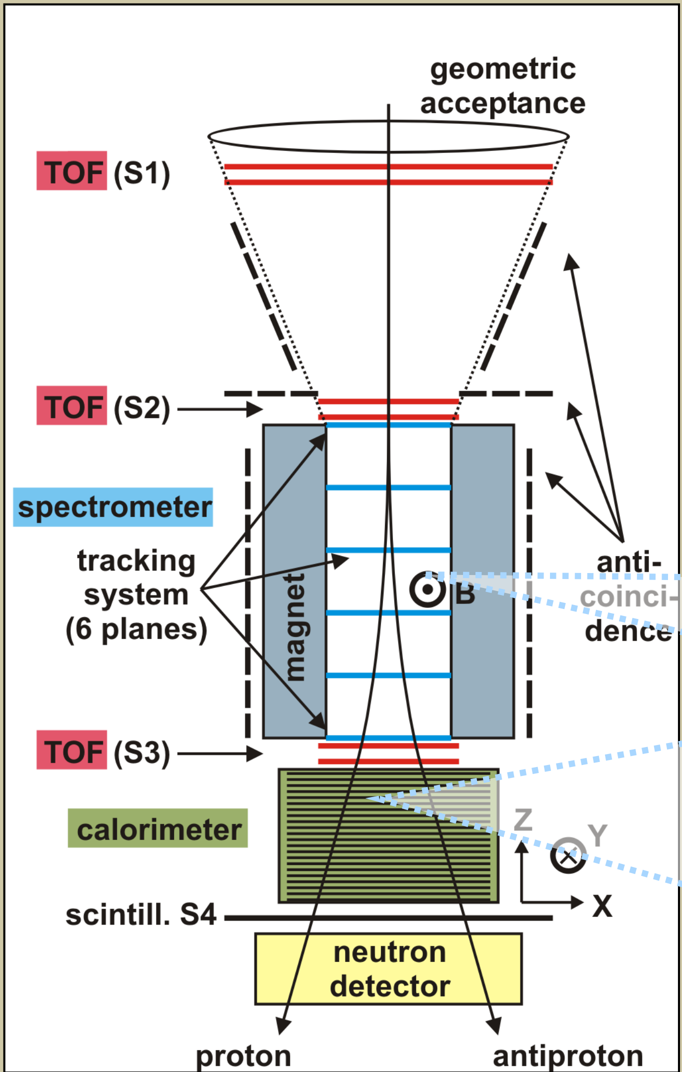
Velocity measurement



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

→ NB! They mimic antimatter!

dE/dx

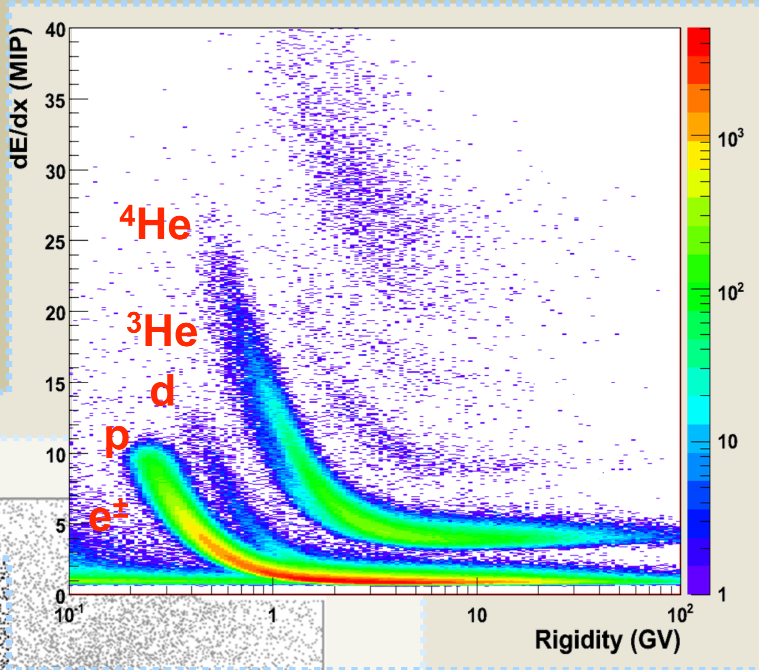


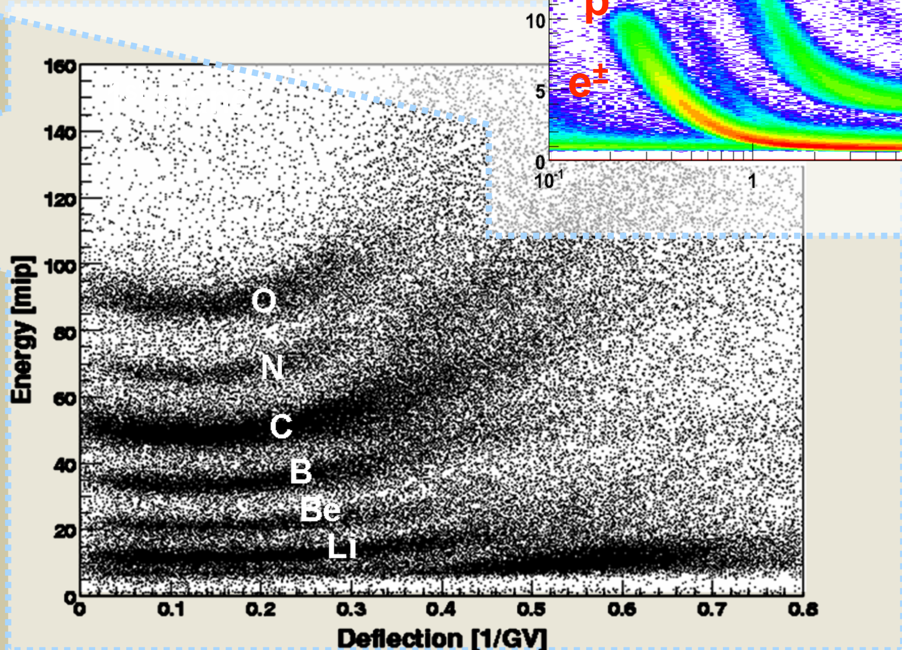
Z measurement

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

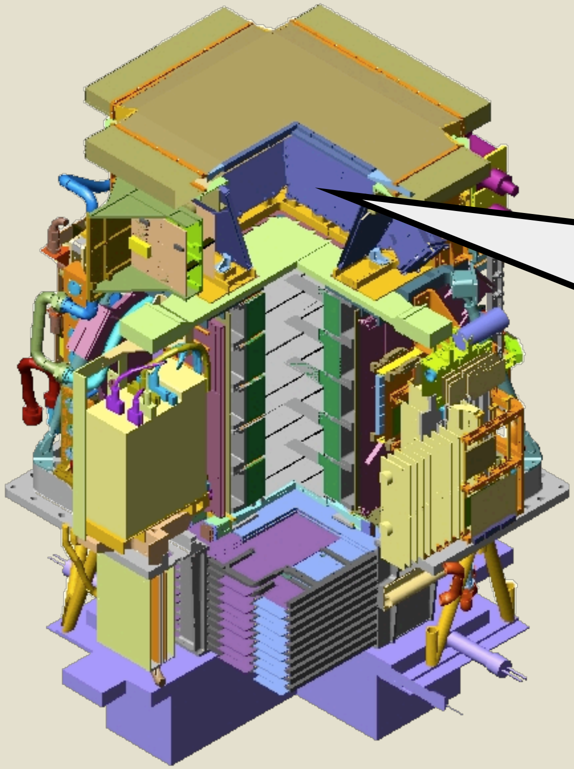
Bethe Bloch

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





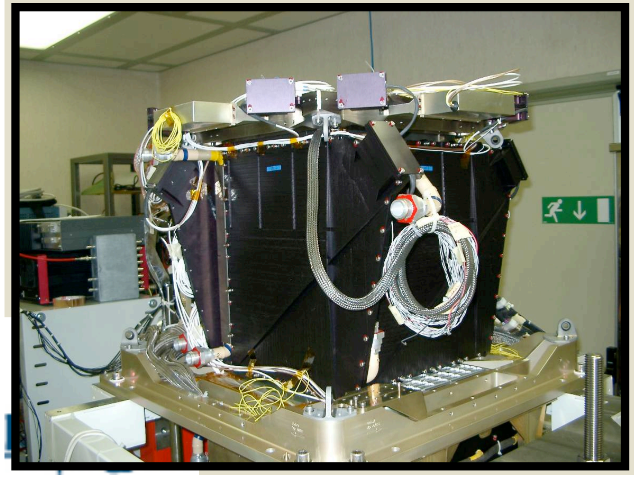
The anticounter shields

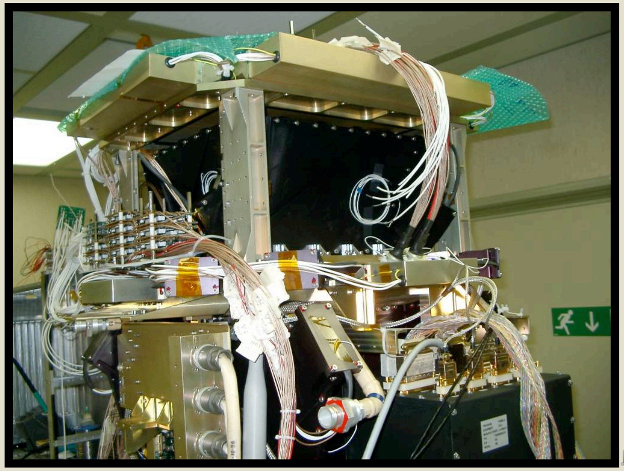


- **Main tasks:**
- **Rejection of events with particles interacting with the apparatus (off-line and second-level trigger)**

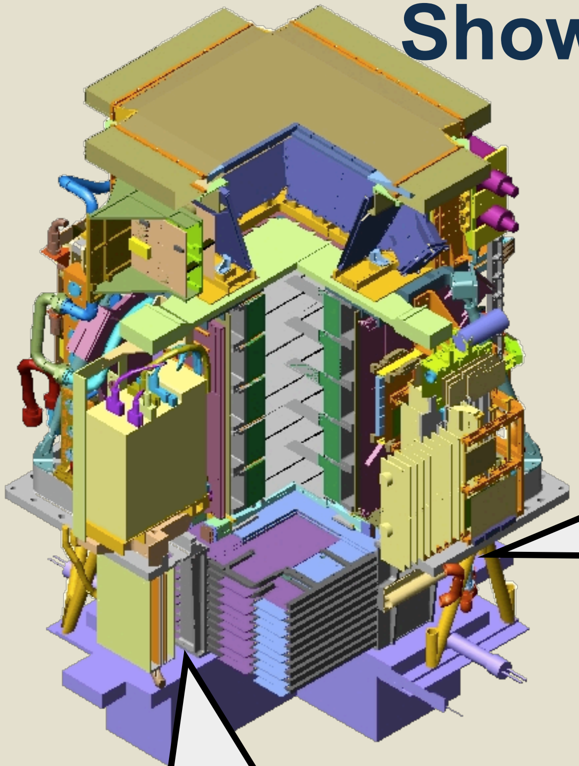
- **Characteristics:**
- **Plastic scintillator paddles, 8mm thick**
- **4 upper (CARD), 1 top (CAT), 4 side (CAS)**

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





Shower-tail catcher & Neutron detector



- Main tasks:
- e/h discrimination at high energy

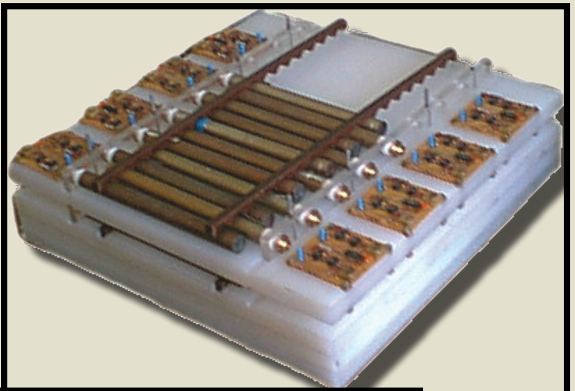
- Characteristics:
- 36 ^{3}He counters:
- $^{3}He(n,p)T$ - Ep=780 keV
- 1cm thick polyethylene + Cd moderators
- n collected within 200 μs time-window

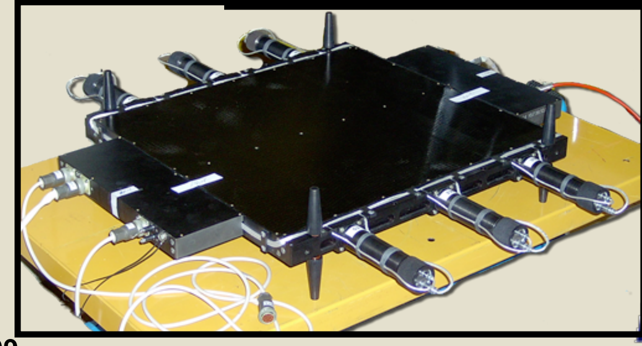
S4 Main tasks:

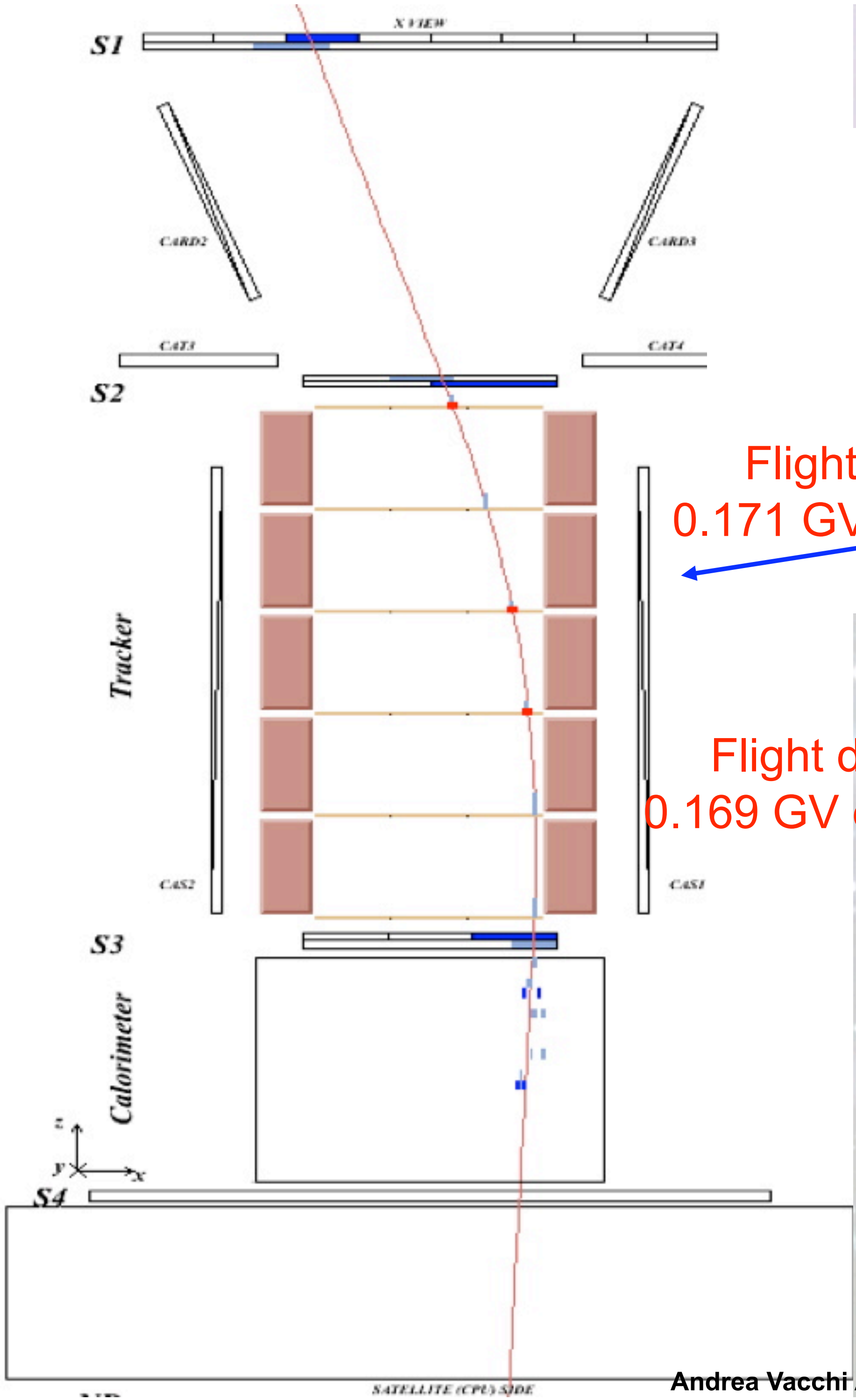
- Neutron detector trigger

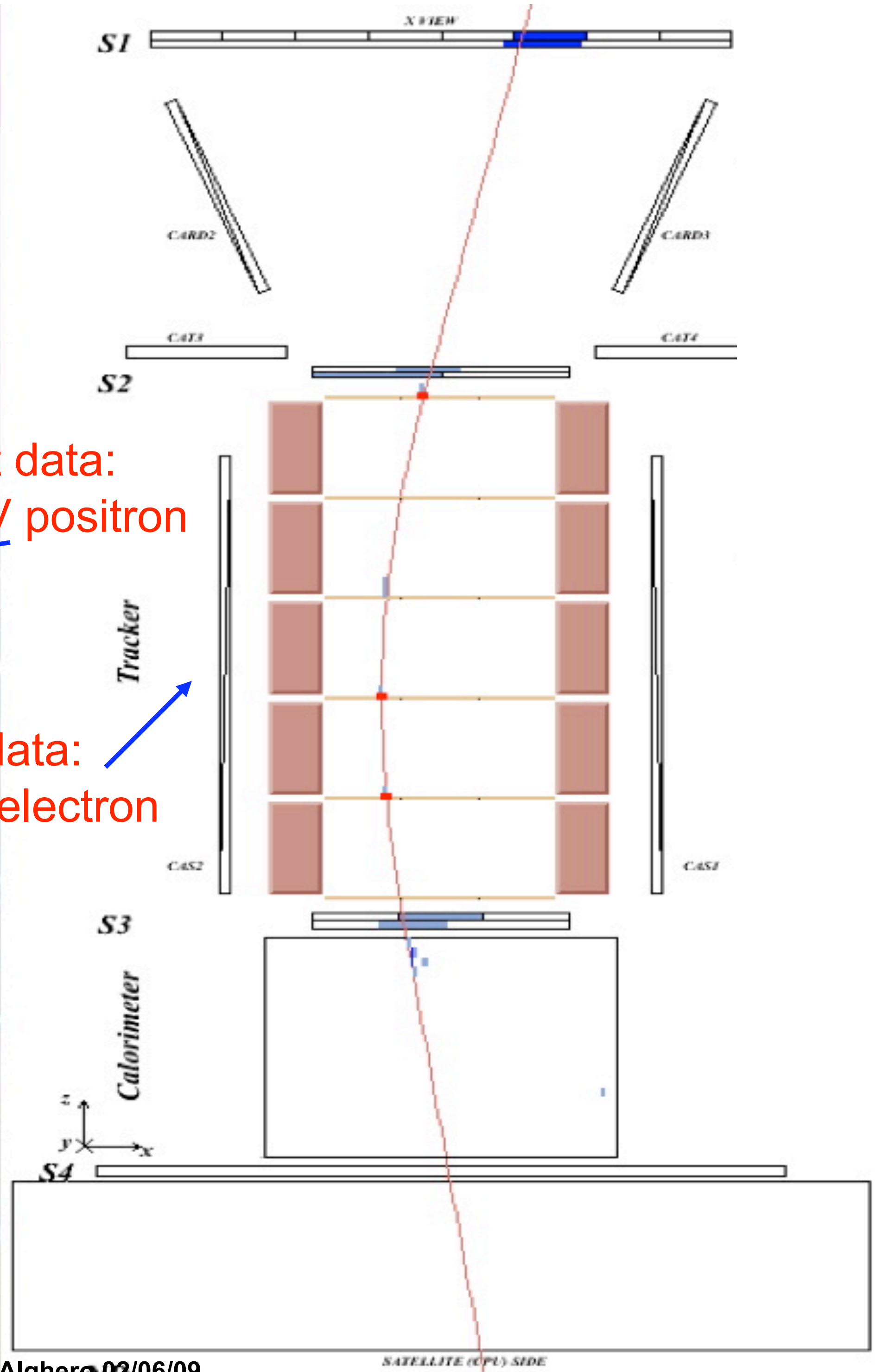
Characteristics:

- Plastic scintillator paddle, 1 cm thick



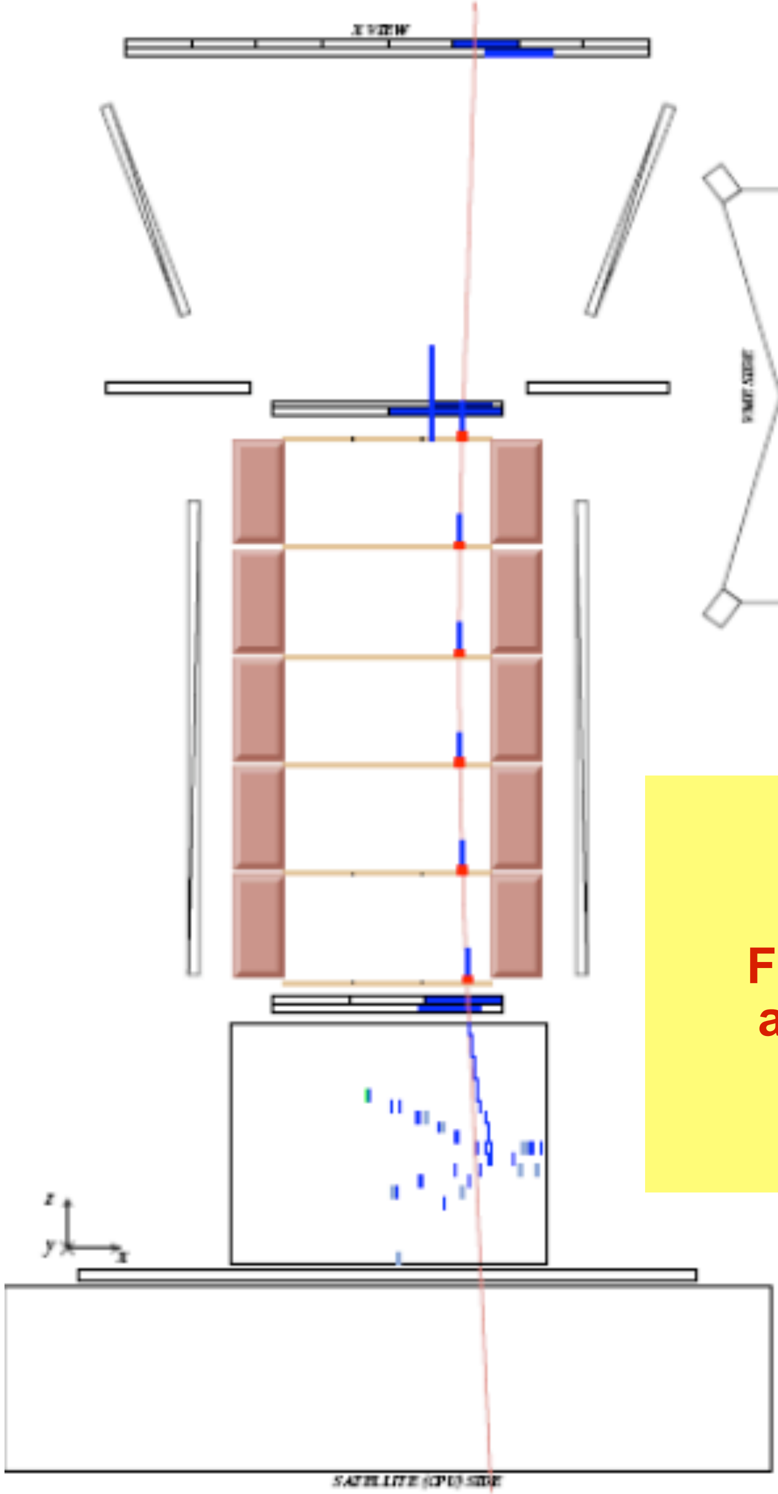


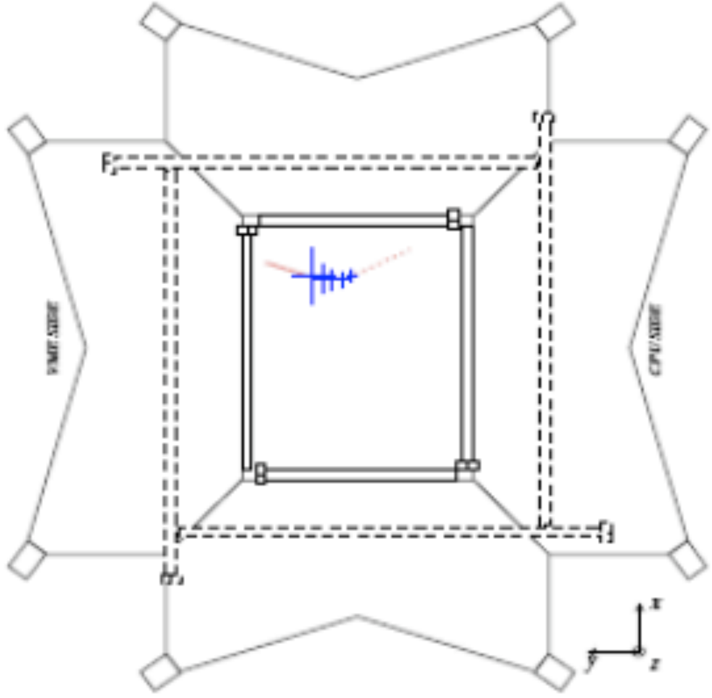


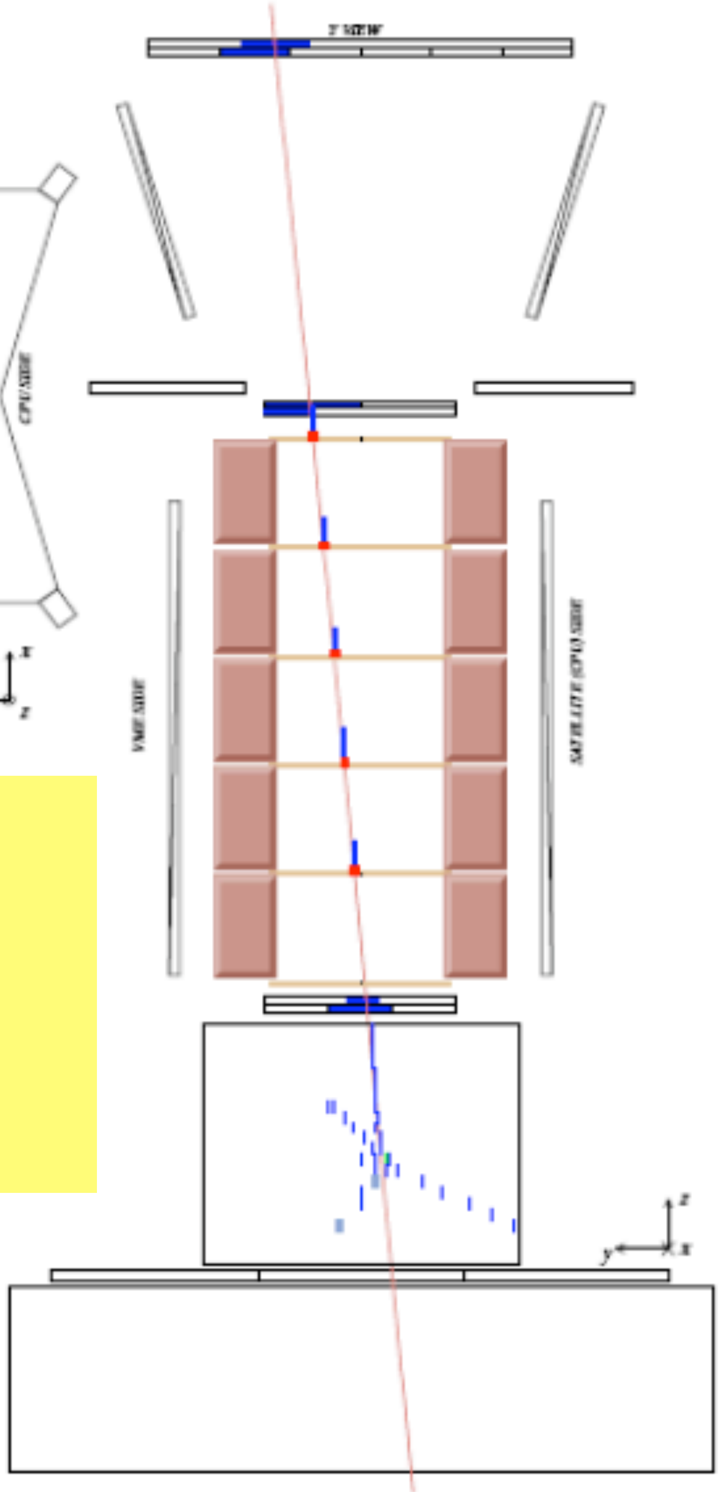


Flight data:
0.171 GV positron

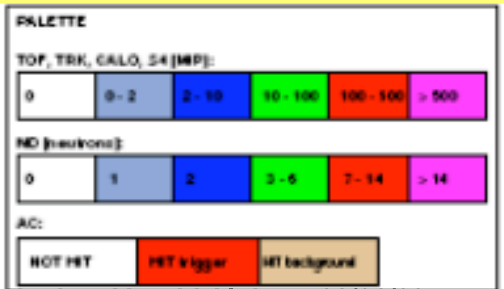
Flight data:
0.169 GV electron



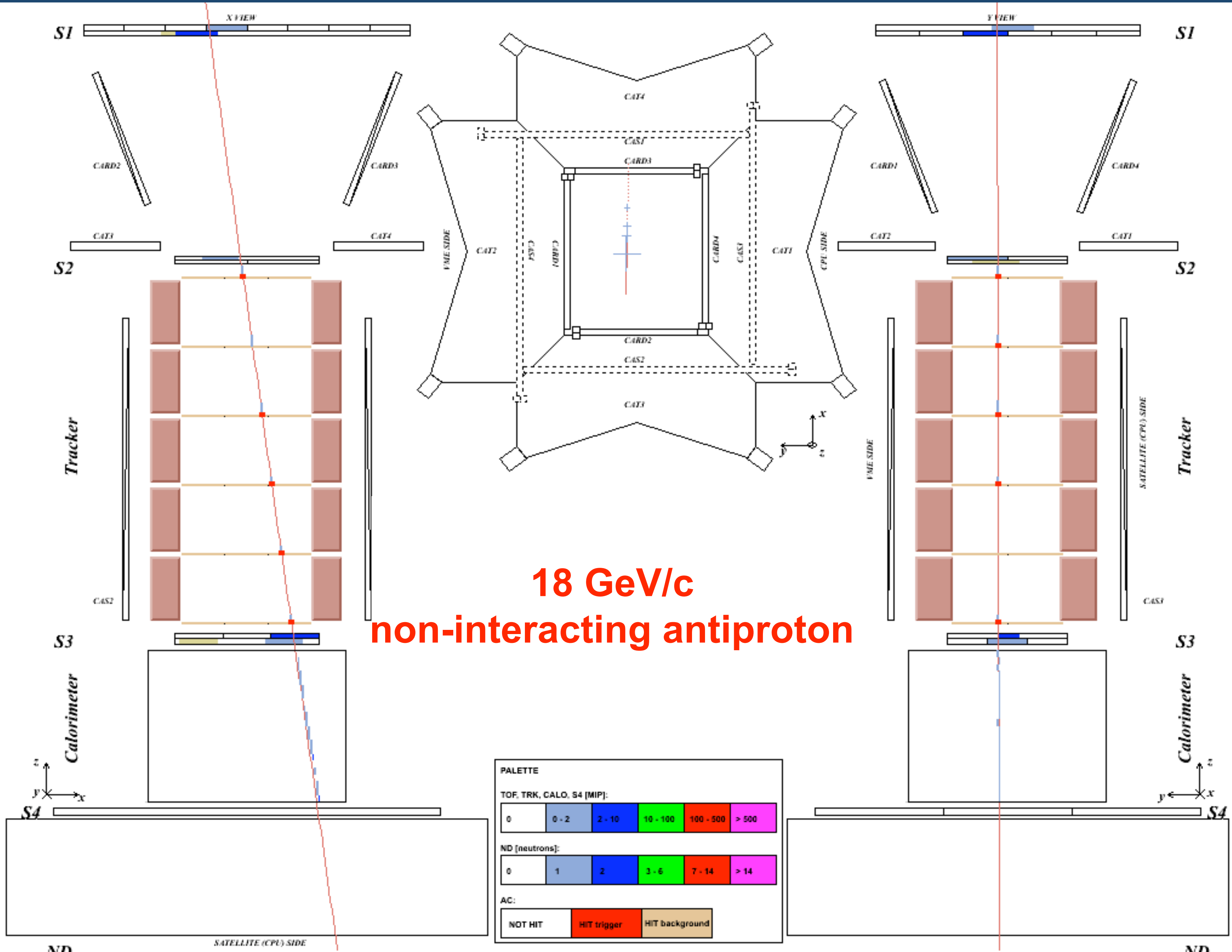




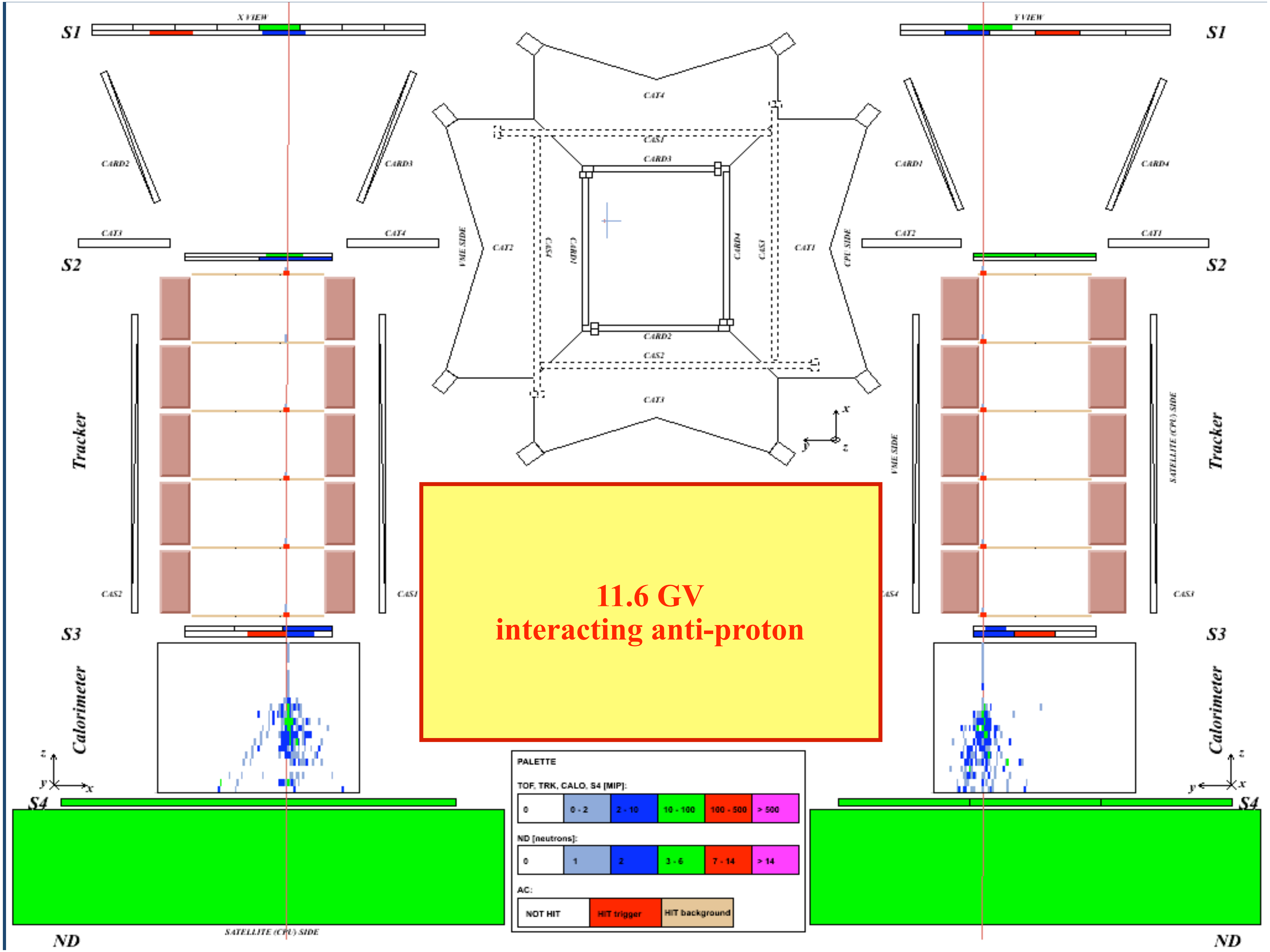
Flight data: 0.763 GeV/c antiproton annihilation

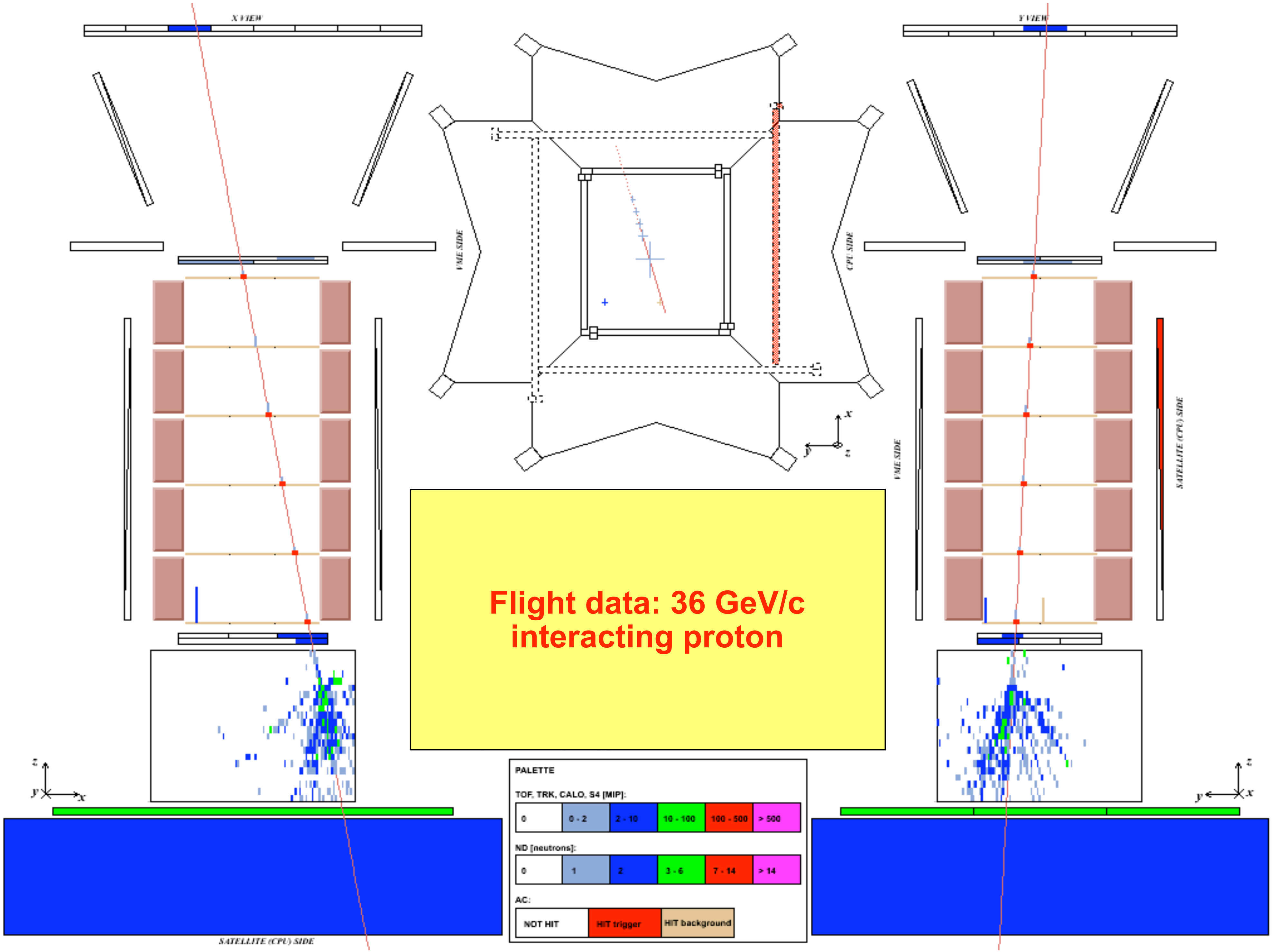


Andrea Vacchi Alghero 02/06/09

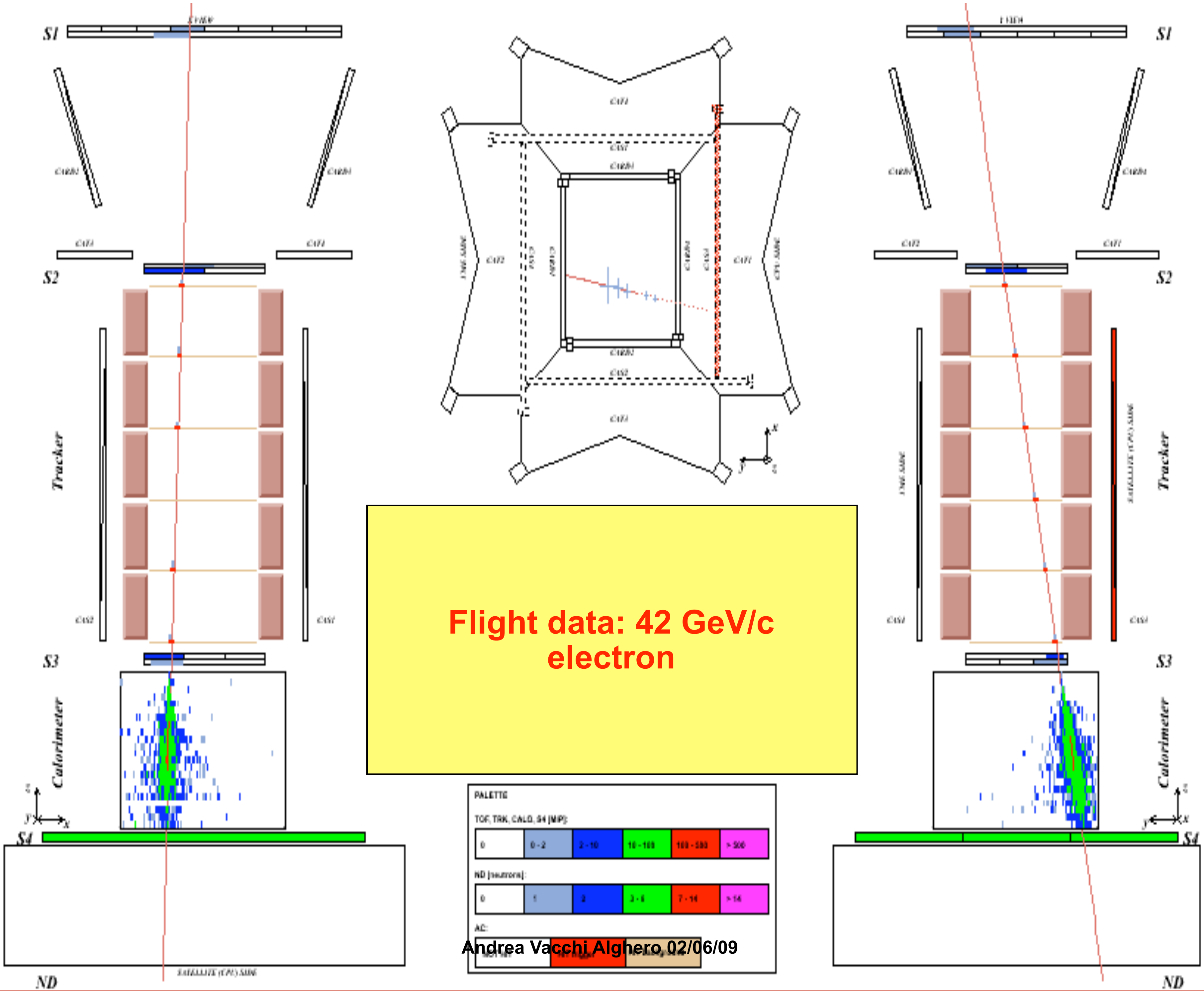


18 GeV/c non-interacting antiproton

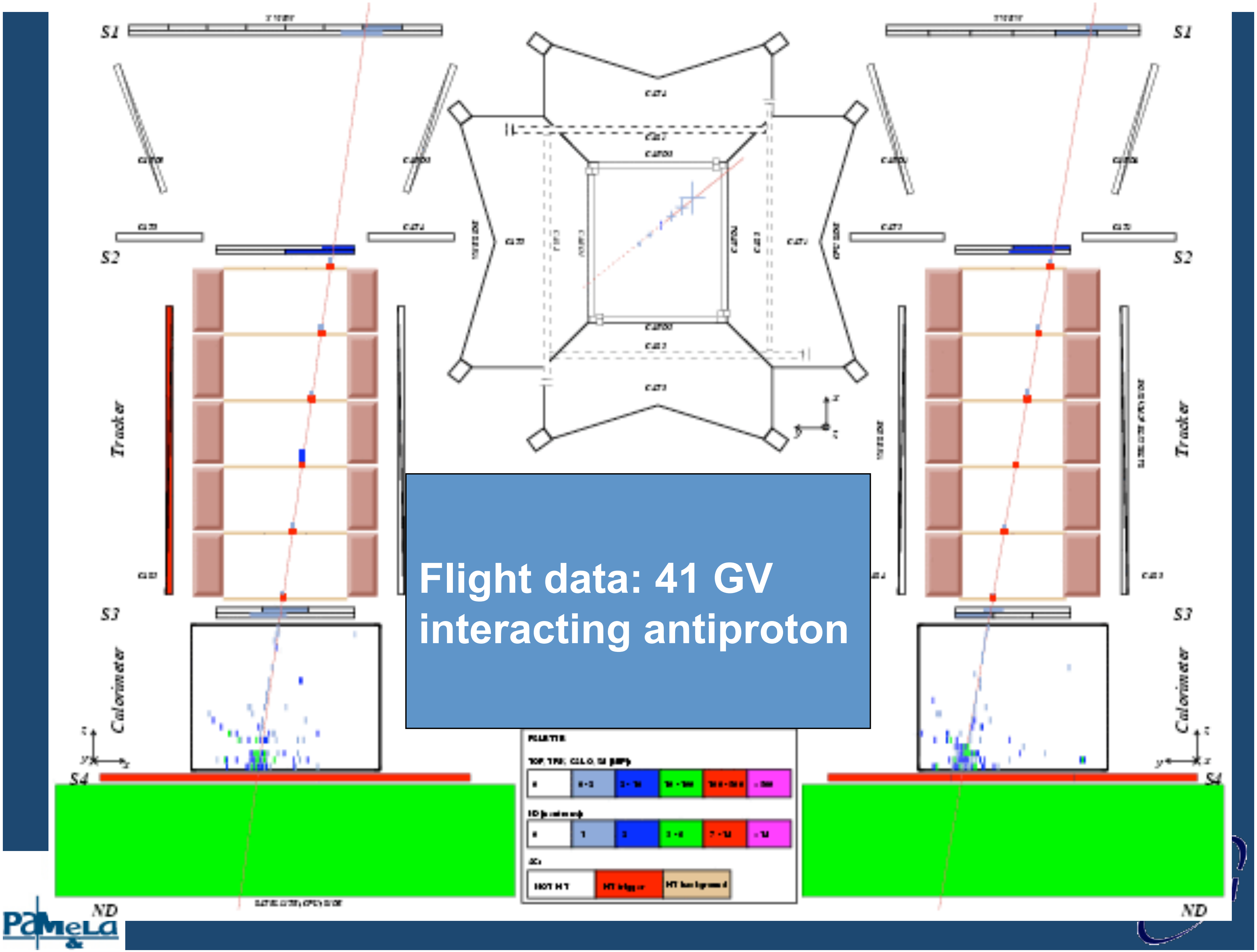

11.6 GV
interacting anti-proton
X VIEW
Y VIEW
S1
S2
S3
S4
ND
Tracker
Calorimeter
CARD1
CARD2
CARD3
CARD4
CAT1
CAT2
CAT3
CAT4
CAS1
CAS2
CAS3
CAS4
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
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

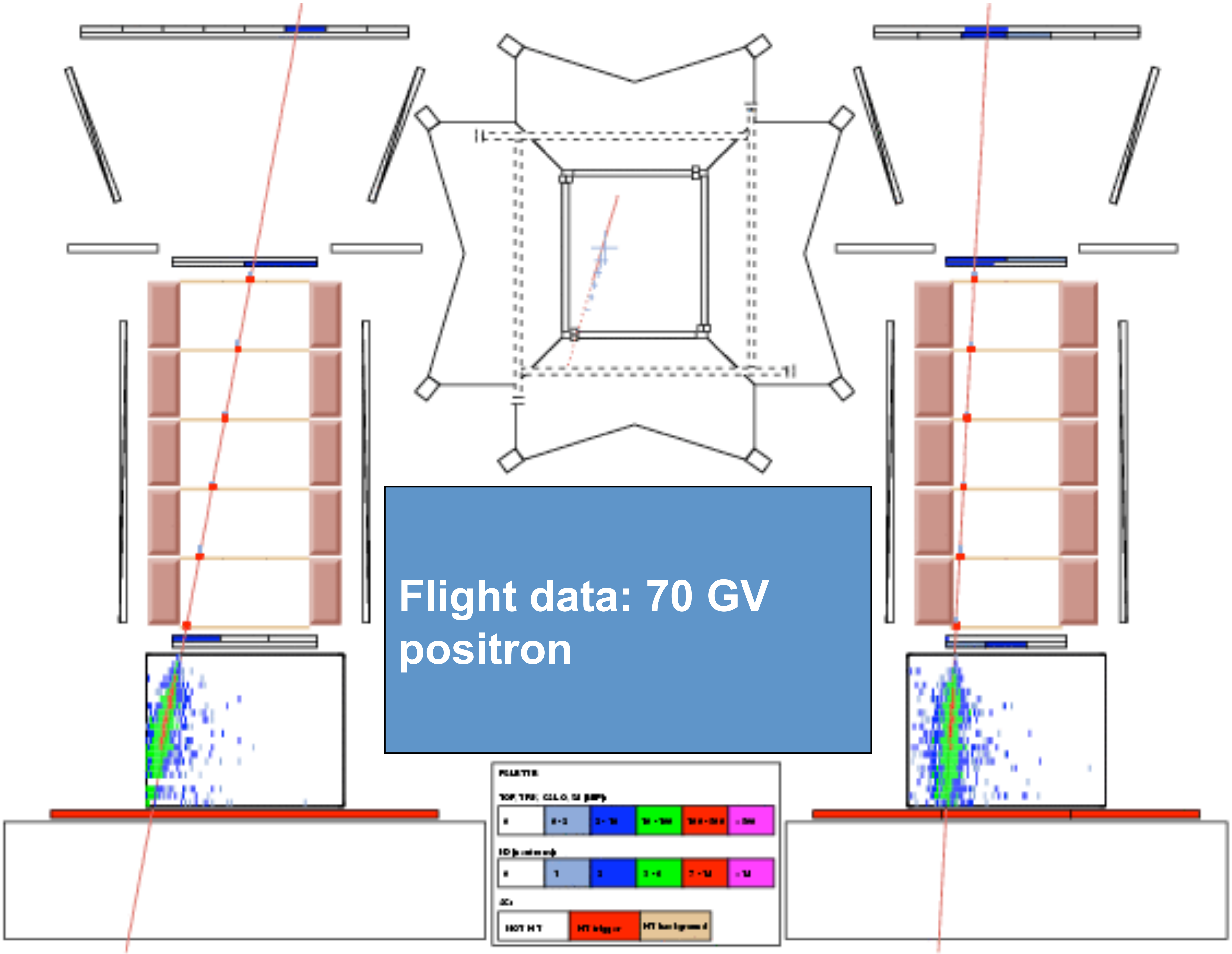


Flight data: 42 GeV/c electron



Flight data: 41 GV
interacting antiproton
S1
S2
S3
S4
ND
Tracker
Calorimeter

Flight data: 70 GV positron



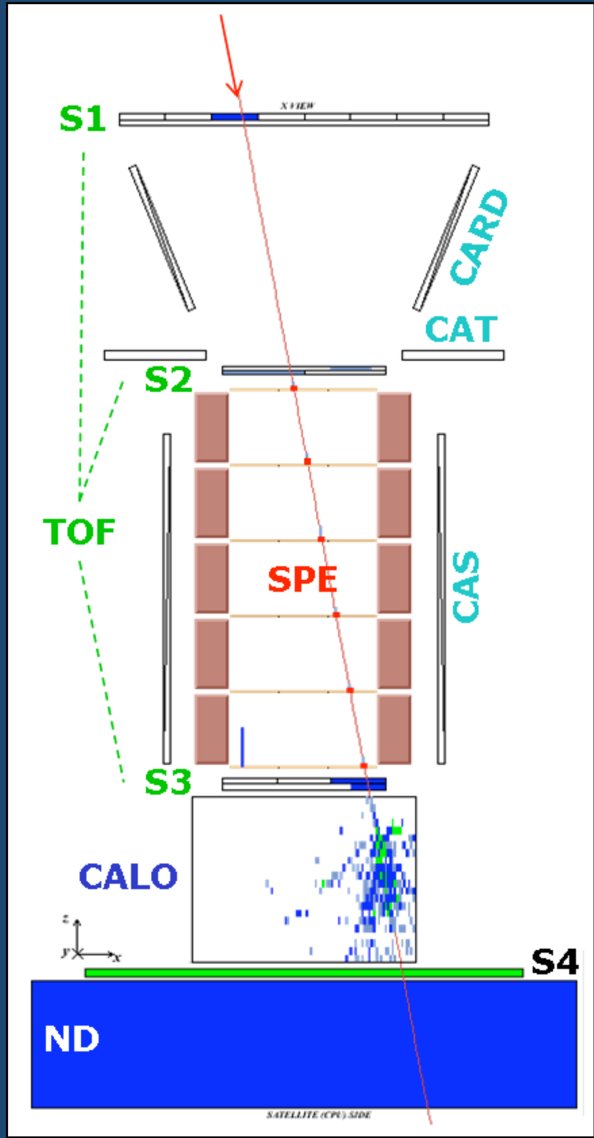
High-energy antiproton analysis

- Analyzed data July 2006 – February 2008 (~500 days)
- Collected triggers ~10^8
- Identified ~ 10 10^6 protons and ~ 1 10^3 antiprotons between 1.5 and 100 GeV (100 p-bar above 20GeV)

- Antiproton/proton identification:
  - rigidity (R) → SPE
  - |Z|=1 (dE/dx vs R) → SPE&ToF
  - β vs R consistent with M_p → ToF
  - p-bar/p separation (charge sign) → SPE
  - p-bar/e^- (and p/e^+) separation → CALO

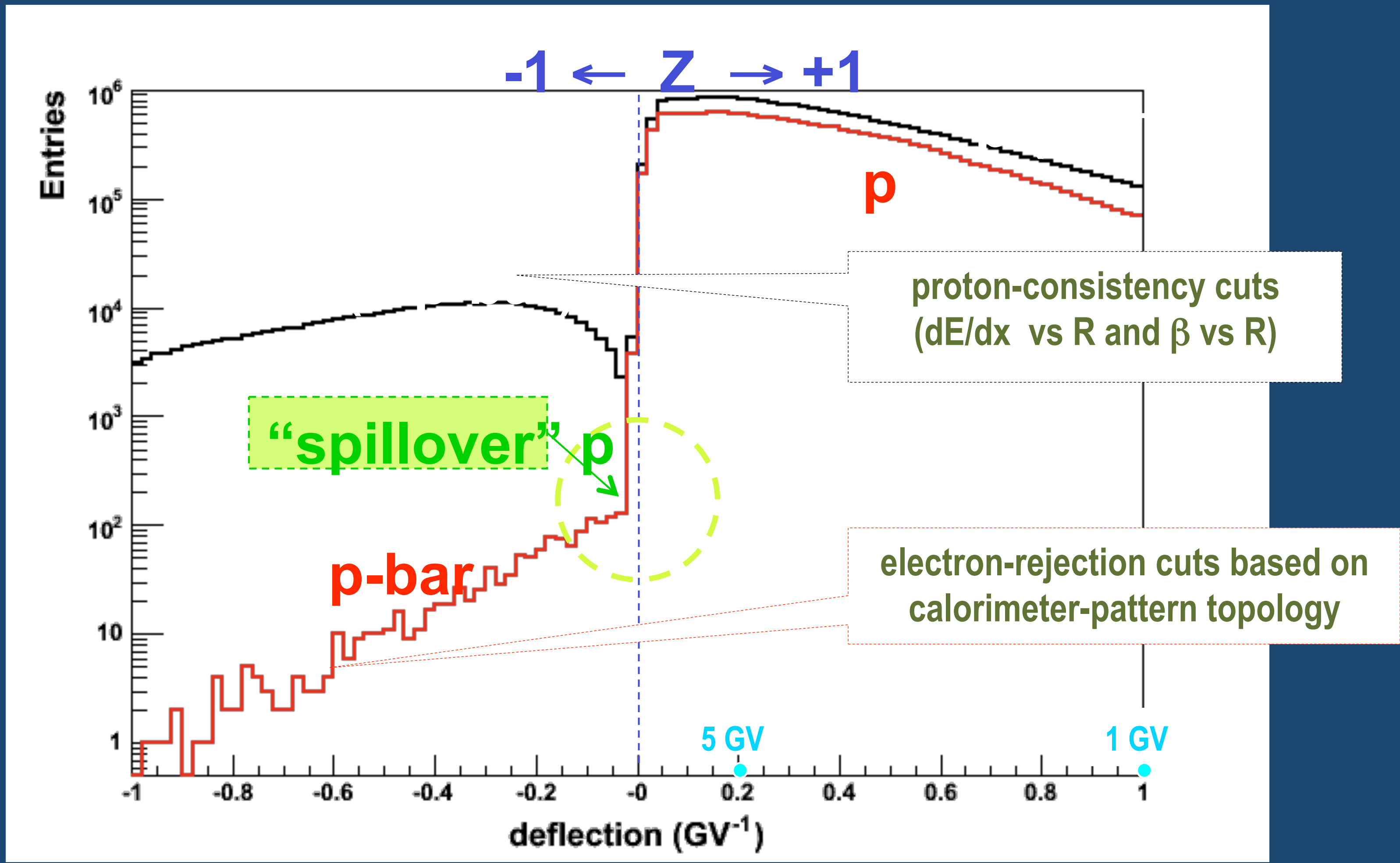
- Dominant background → spillover protons:
  - finite deflection resolution of the SPE ⇒ wrong assignment of charge-sign @ high energy
  - proton spectrum harder than positron ⇒ p/p-bar increase for increasing energy (10^3 @1GV 10^4 @100GV)

→ Required strong SPE selection



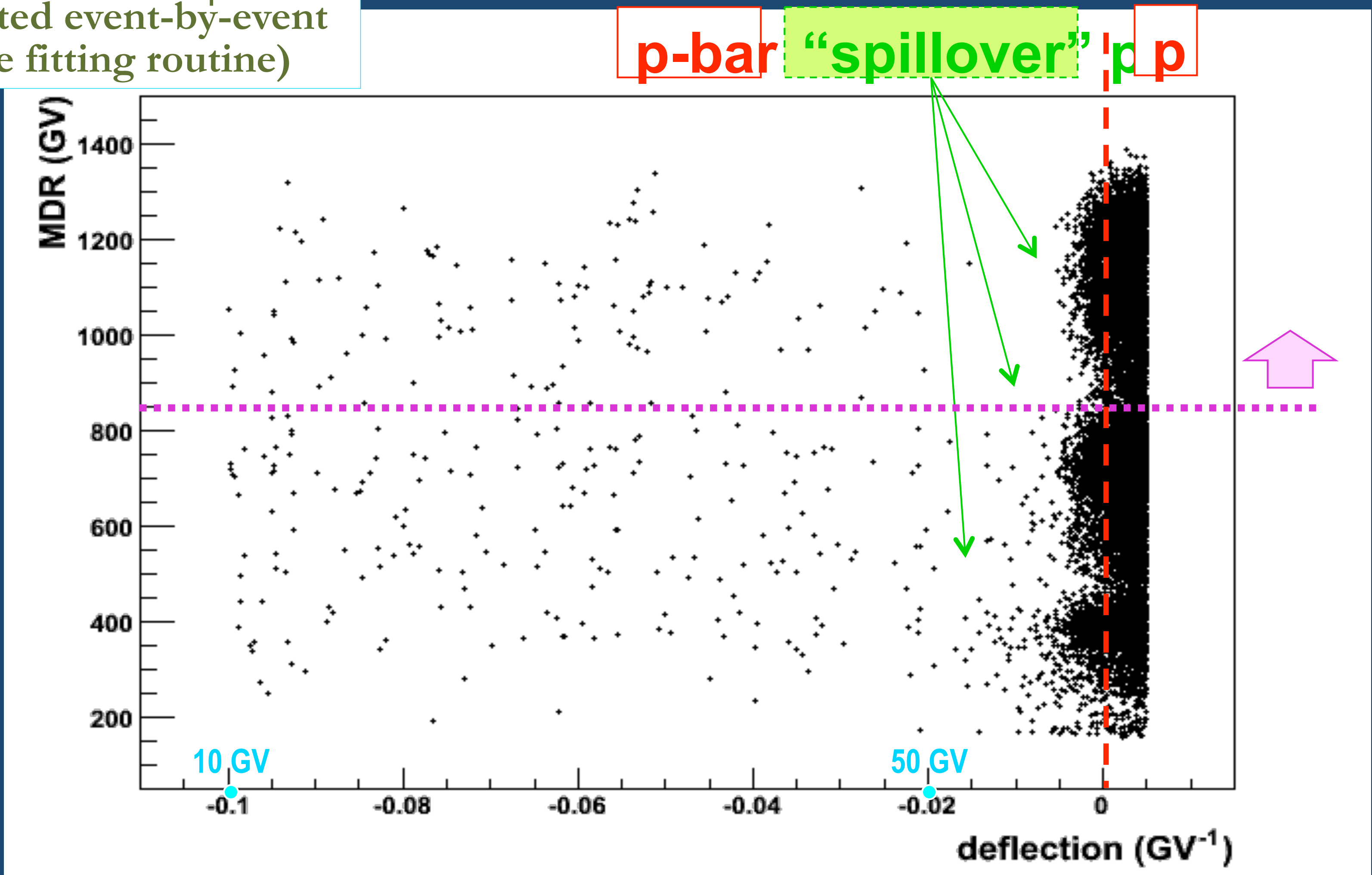
INFN

Antiproton identification



Proton-spillover background

MDR = $1/\sigma_\eta$
(evaluated event-by-event
by the fitting routine)

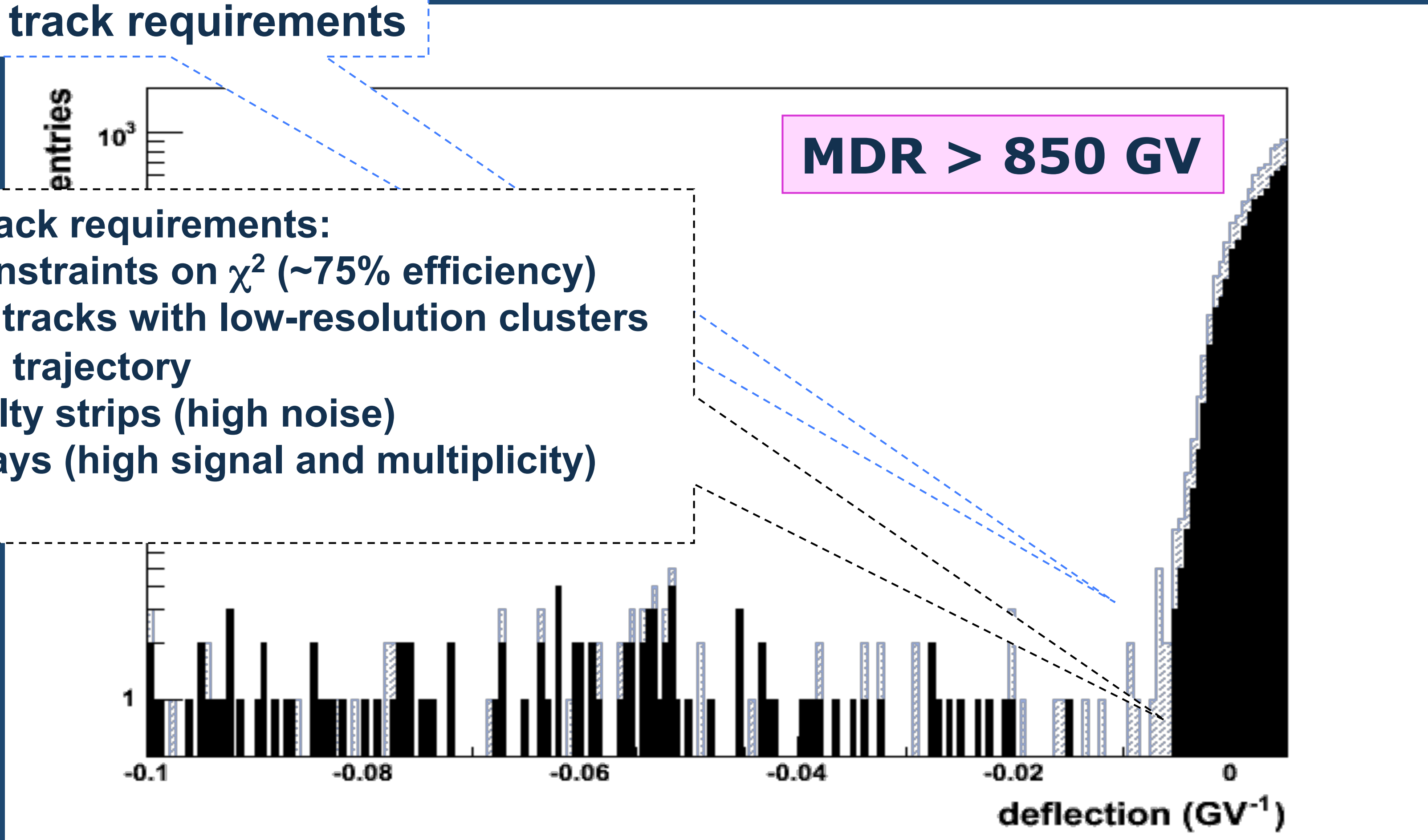


MDR depends on:
- number and distribution of fitted points along the trajectory
- spatial resolution of the single position measurements
- magnetic field intensity along the trajectory

INFN

Proton-spillover background

Minimal track requirements

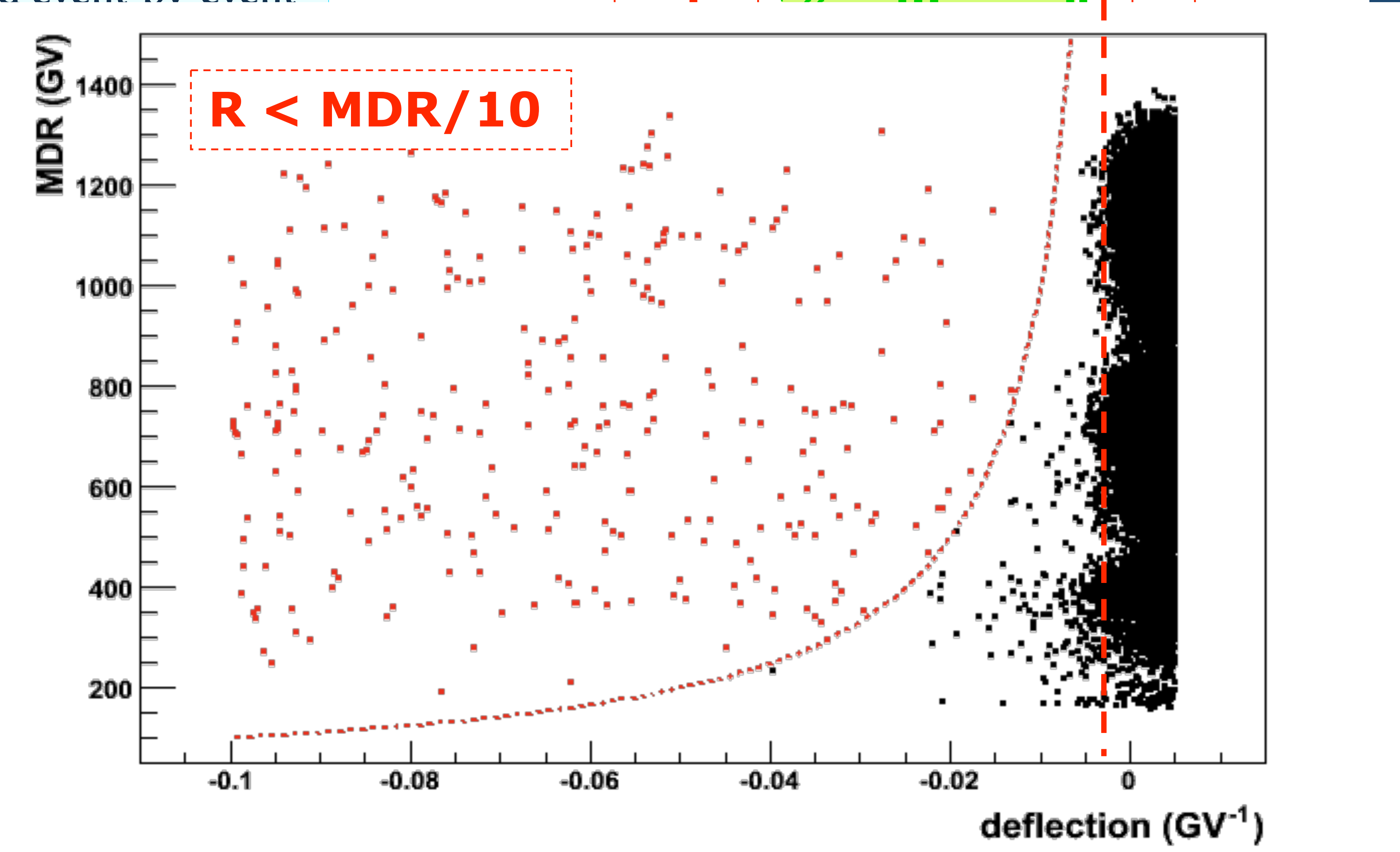


MDR > 850 GV

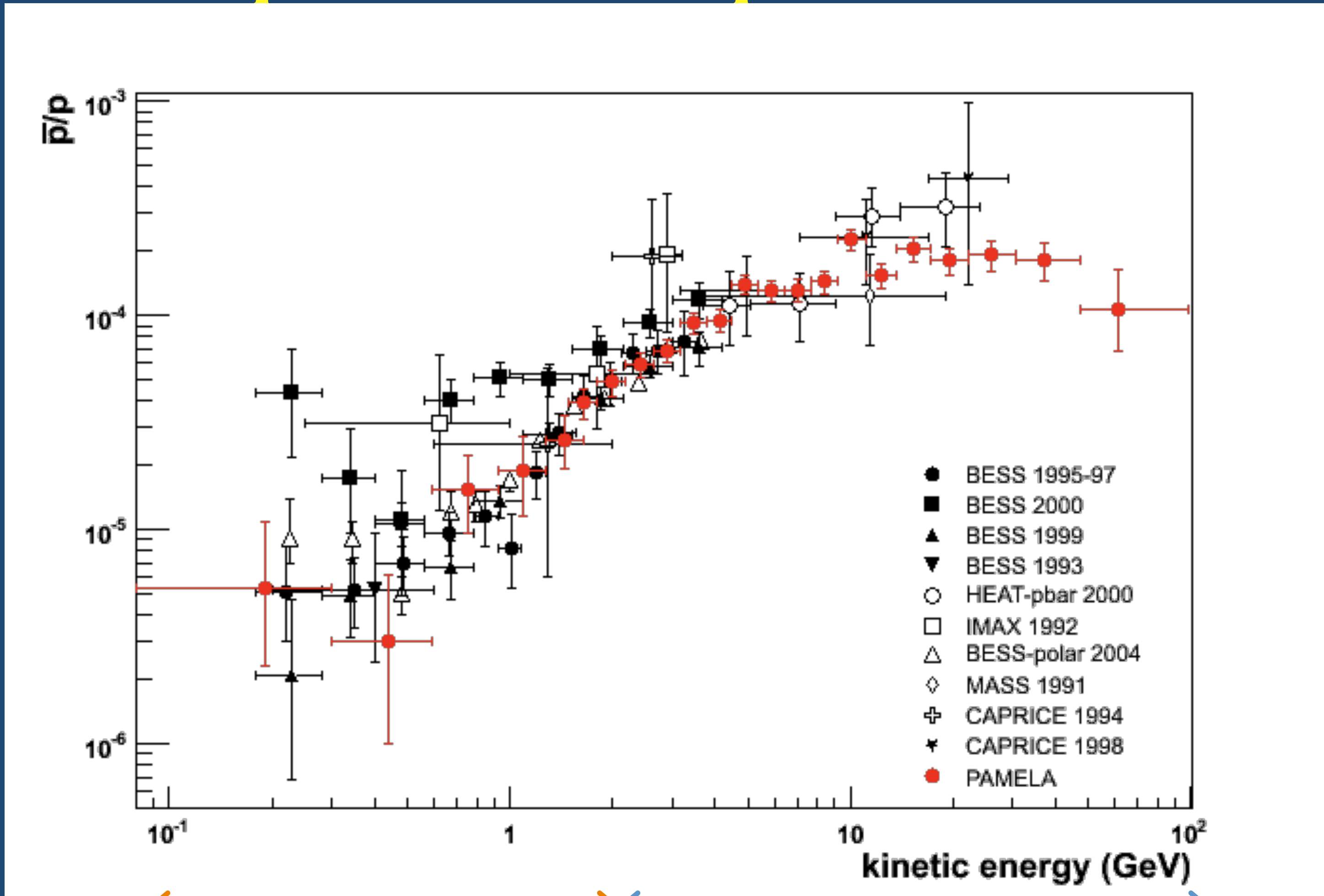
Strong track requirements:
- strict constraints on χ^2 (~75% efficiency)
- rejected tracks with low-resolution clusters along the trajectory
  - faulty strips (high noise)
  - δ-rays (high signal and multiplicity)

Proton-spillover background

MDR = $1/\sigma_\eta$
(evaluated event-by-event
by the f



Antiproton-to-proton ratio



preliminary
(Petter Hofverberg's PhD Thesis)

astro-ph 0810.4994

Positrons

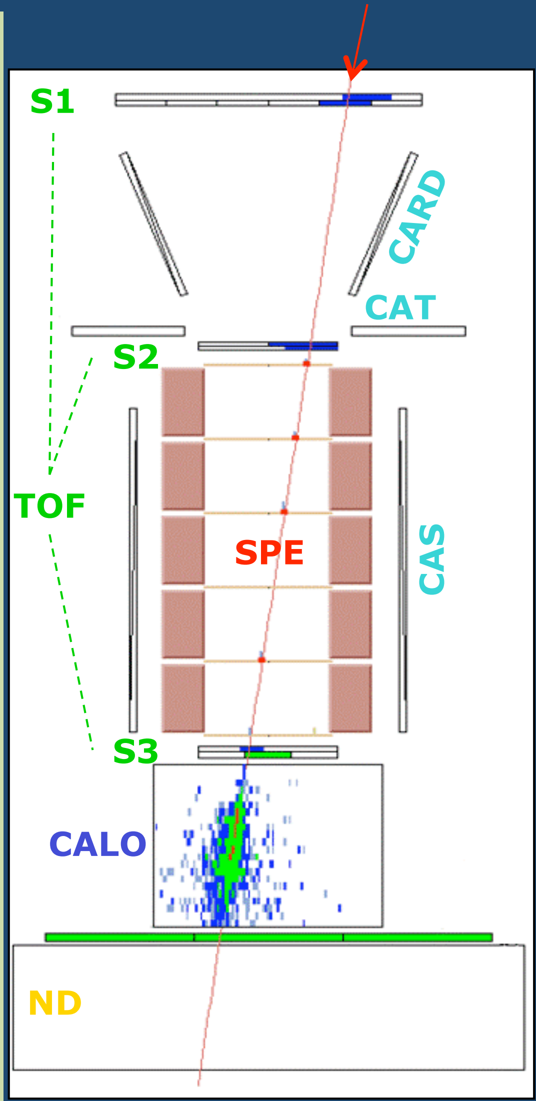
High-energy positron analysis

- Analyzed data July 2006 – February 2008 (~500 days)
- Collected triggers ~10^8
- Identified ~ 150 10^3 electrons and ~ 9 10^3 positrons between 1.5 and 100 GeV (180 positrons above 20GeV)

- Electron/positron identification:
  - rigidity (R) → SPE
  - |Z|=1 (dE/dx=MIP) → SPE&ToF
  - β=1 → ToF
  - e^-/e^+ separation (charge sign) → SPE
  - e^+/p (and e^-/p-bar) separation → CALO

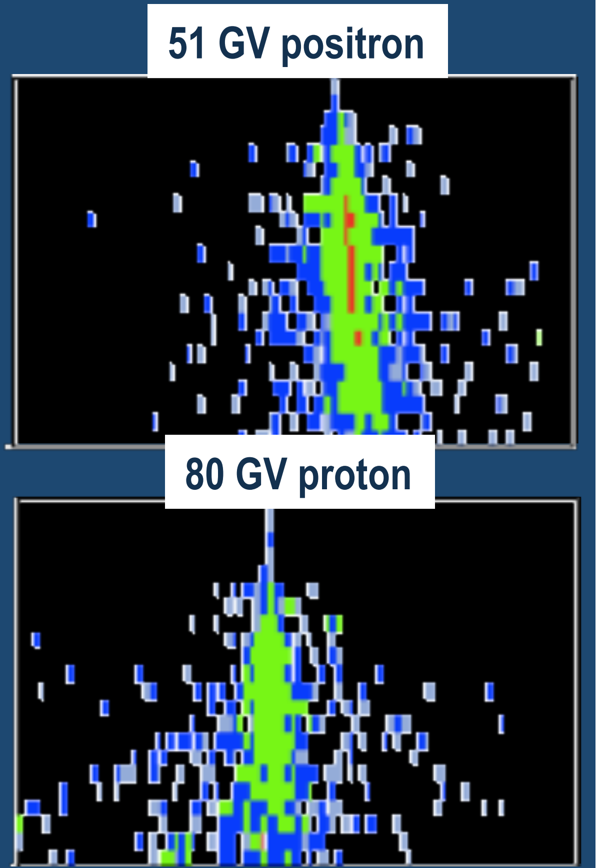
- Dominant background → interacting protons:
  - fluctuations in hadronic shower development ⇒ $\pi_0 \rightarrow \gamma\gamma$ might mimic pure em showers
  - proton spectrum harder than positron ⇒ p/e^+ increase for increasing energy (10^3 @1GV 10^4 @100GV)

→ Required strong CALO selection



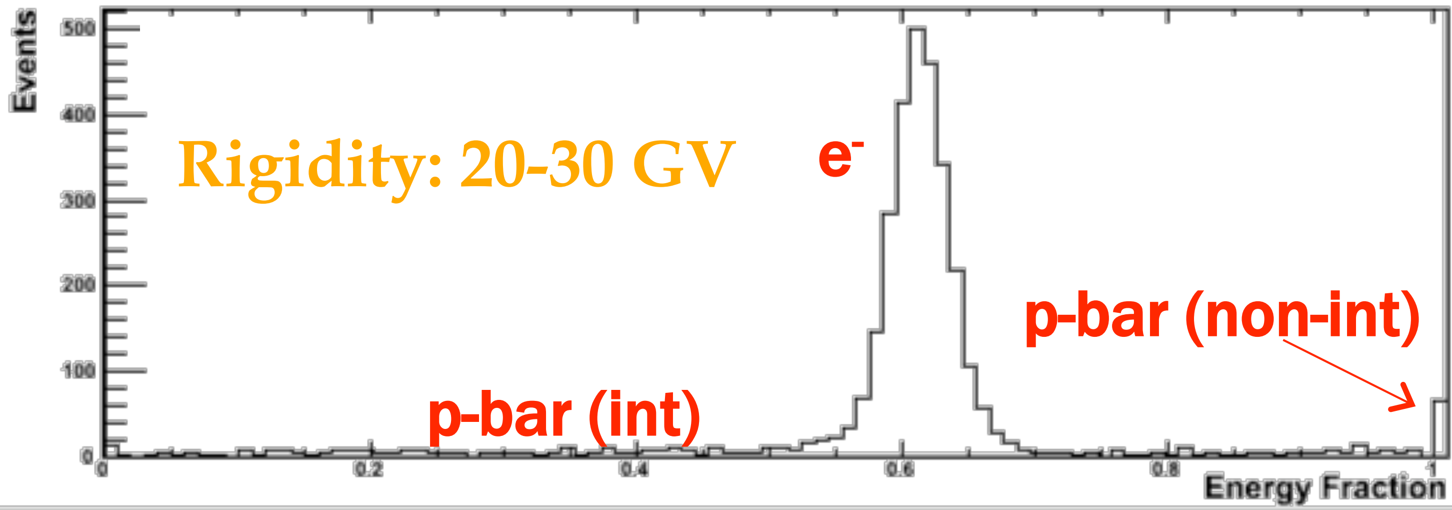
Positron identification with CALO

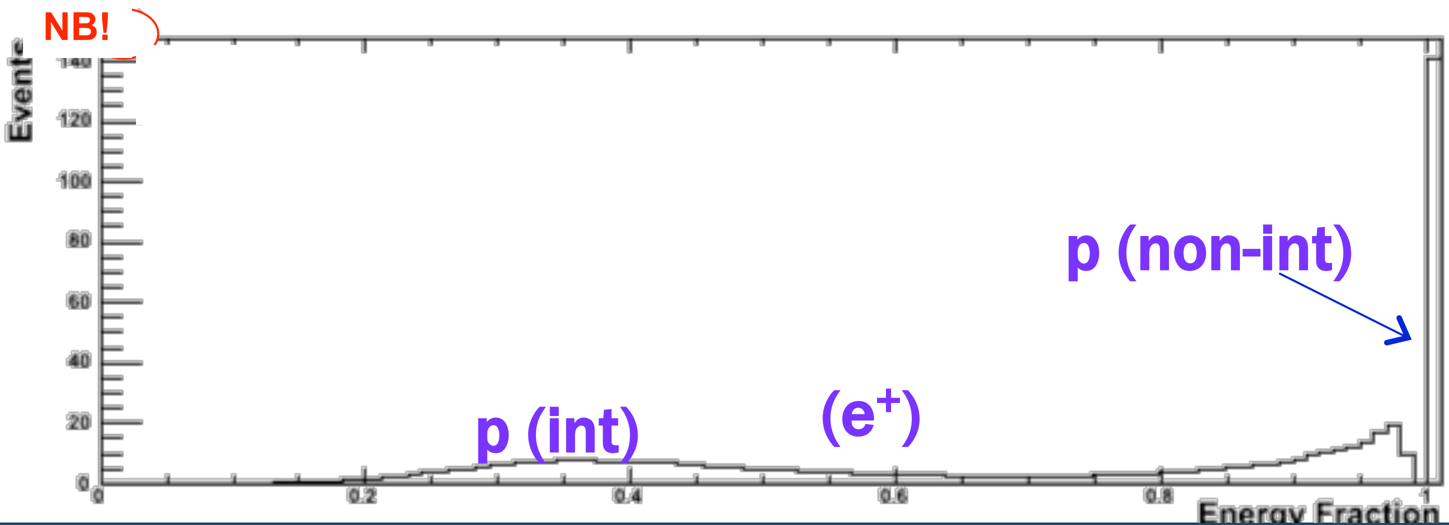
- Identification based on:
  - Shower topology (lateral and longitudinal profile, shower starting point)
  - Total detected energy (energy-rigidity match)
- Analysis key points:
  - Tuning/check of selection criteria with:
    - test-beam data
    - simulation
    - flight data → dE/dx from SPE & neutron yield from ND
  - Selection of pure proton sample from flight data ("pre-sampler" method):
    - *Background-suppression method*
    - *Background-estimation method*



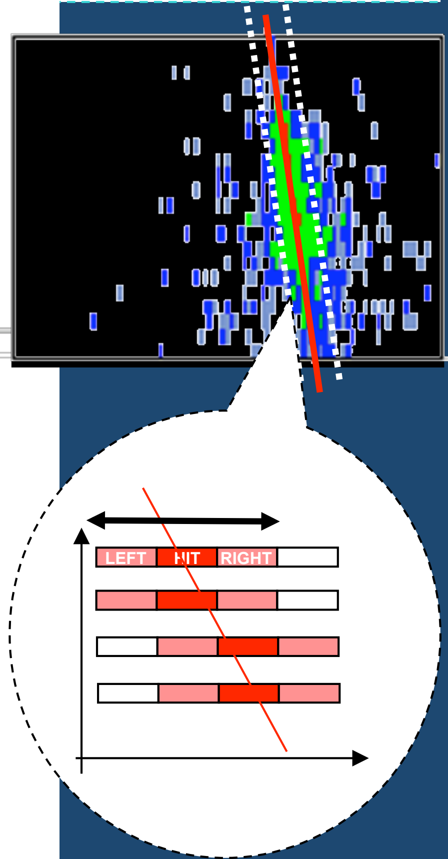
Final results make <u>NON USE</u> of test-beam and/or simulation calibrations.
The measurement is based only on flight data
with the <u>background-estimation</u> method

Positron identification

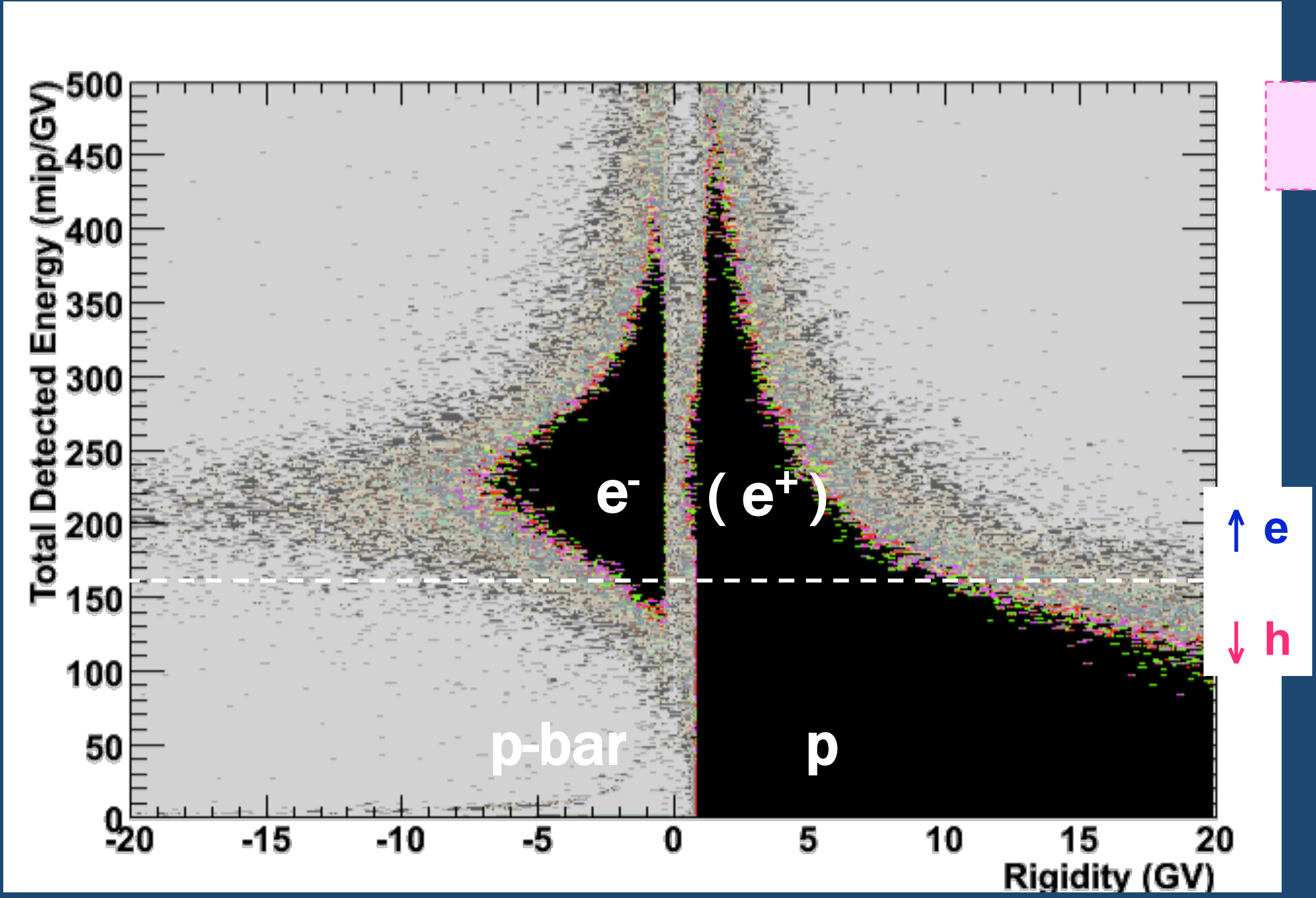




Fraction of charge released along the calorimeter track

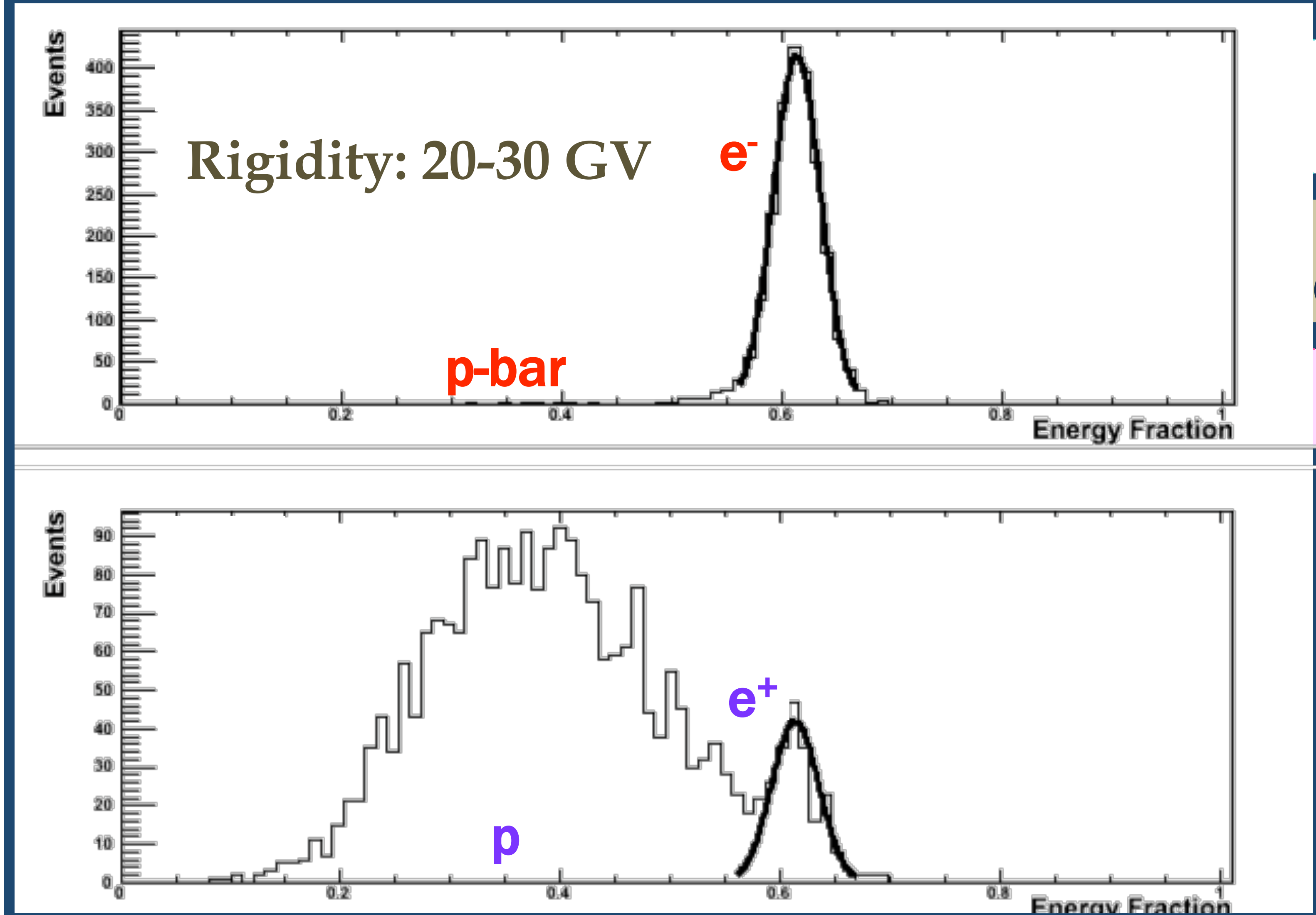


Positron identification



Energy-momentum match

Positron identification



Fraction of charge released along the calorimeter track

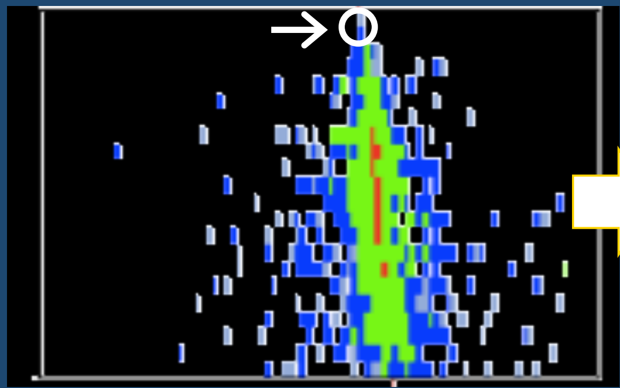
\+
Constraints on:

Energy-momentum match

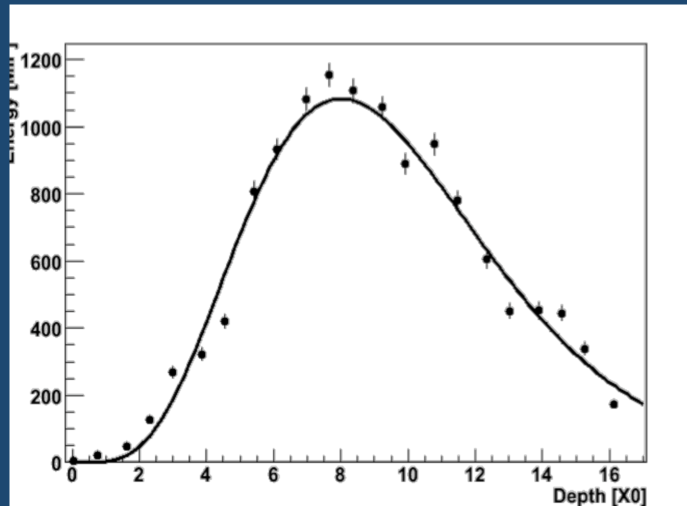
Positron identification

Shower starting-point

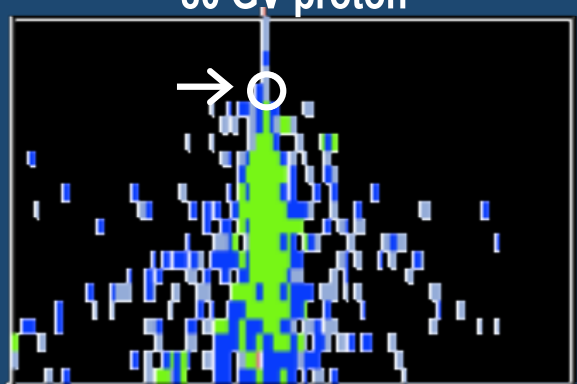
51 GV positron



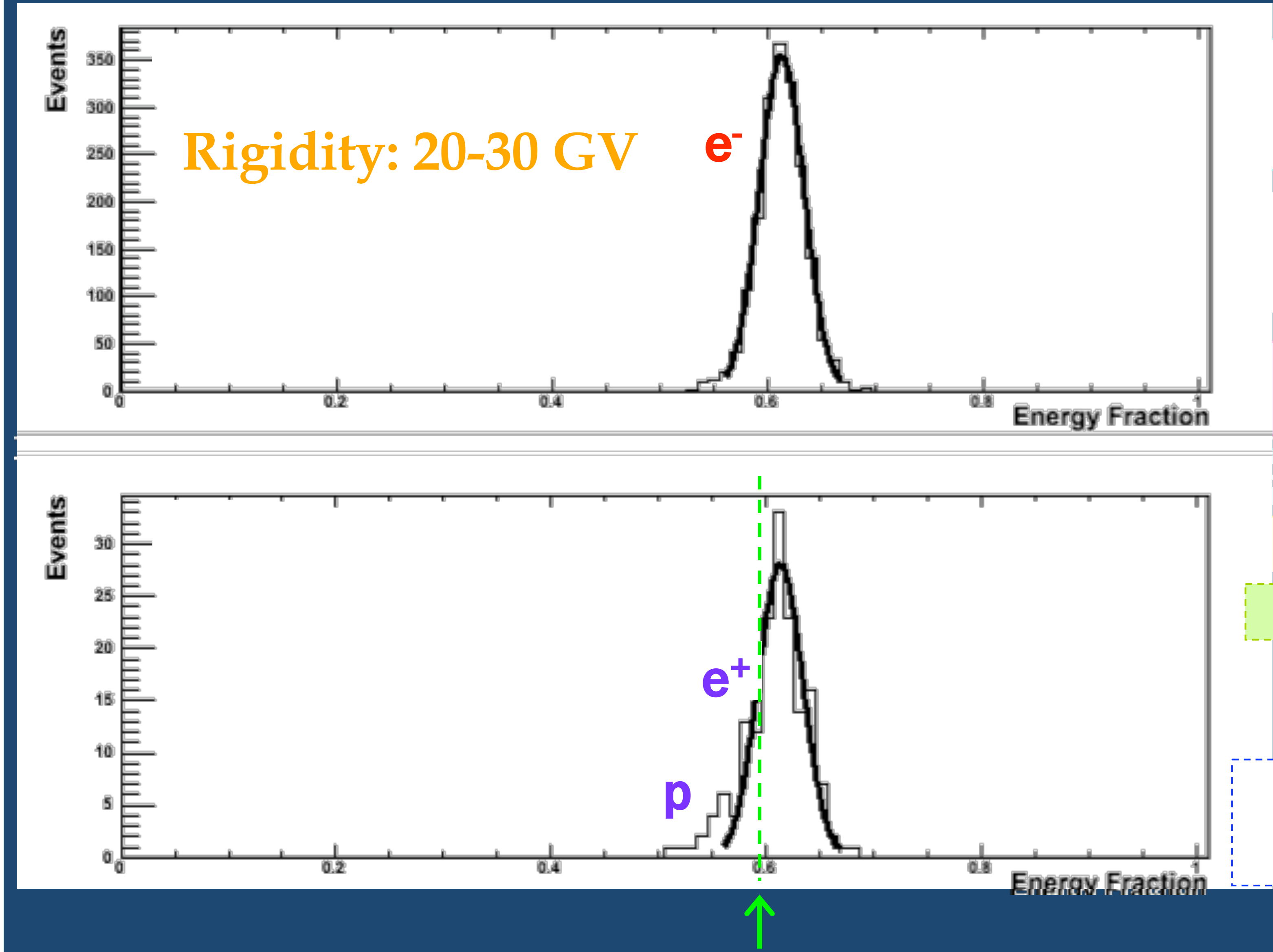
Longitudinal profile



80 GV proton



Positron identification



Fraction of charge released along the calorimeter track

+
Constraints on:

Energy-momentum match

Shower starting-point

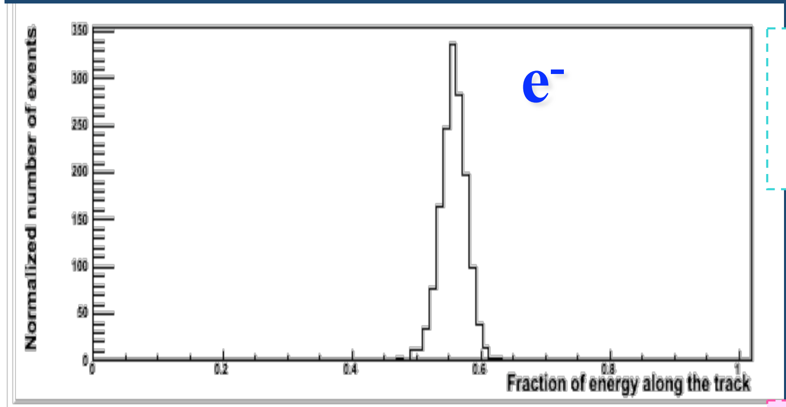
Longitudinal profile

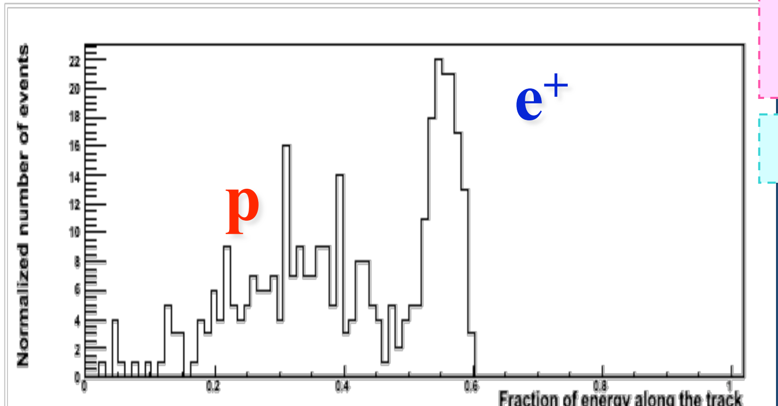
Lateral profile

BK-suppression method

Check of calorimeter selection

Flight data
Rigidity: 20-30 GV





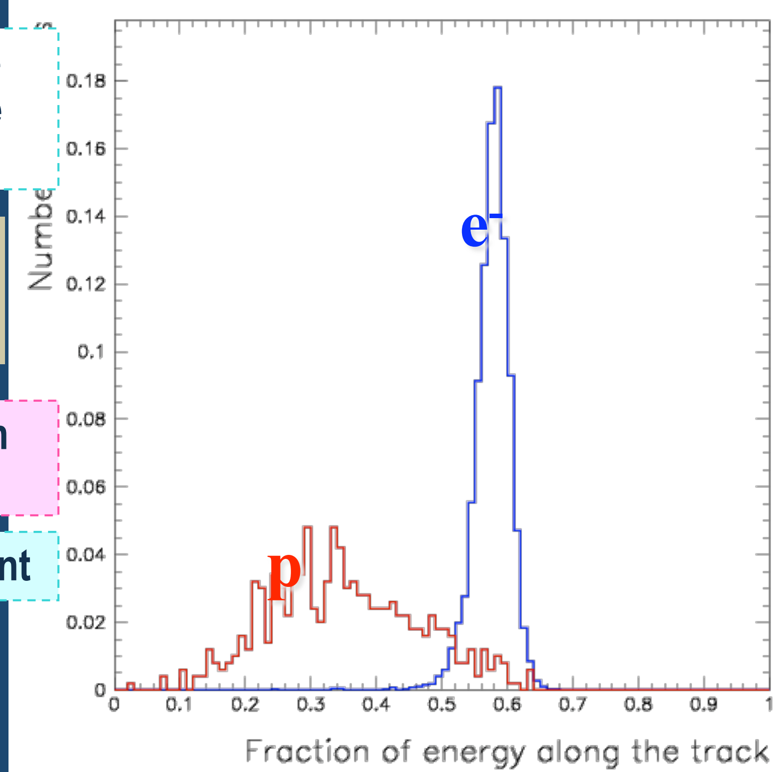
Fraction of charge released along the calorimeter track

+
Constraints on:

Energy-momentum match

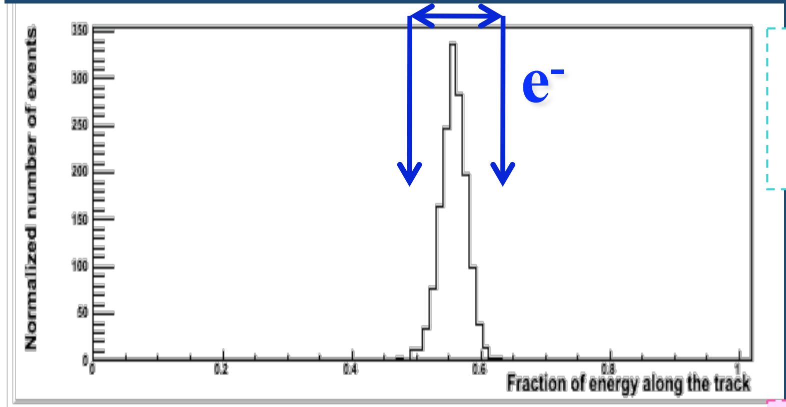
Shower starting-point

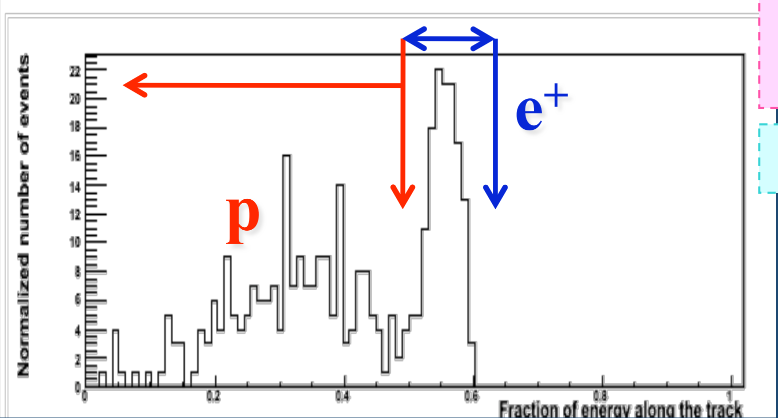
Test beam data
Momentum: 50GeV/c



Check of calorimeter selection

Flight data
Rigidity: 20-30 GV





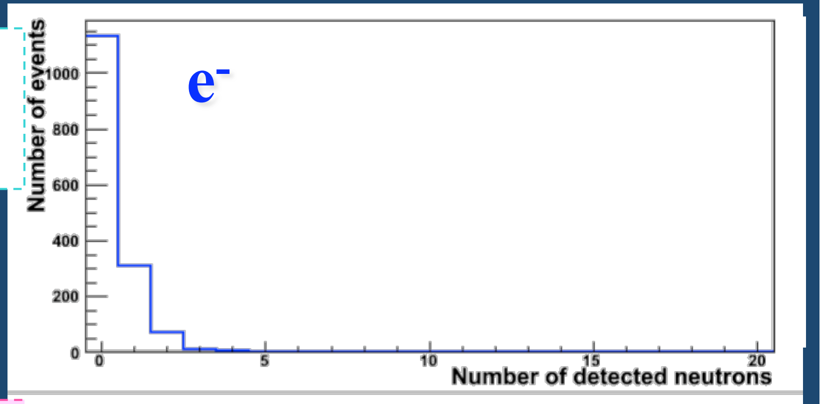
Fraction of charge released along the calorimeter track

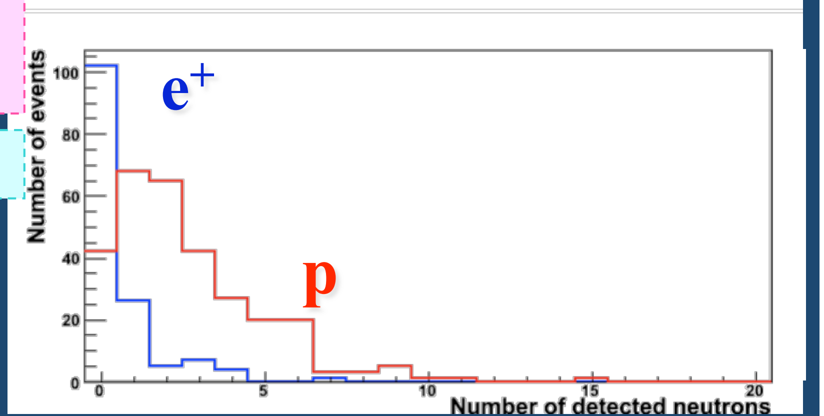
+
Constraints on:

Energy-momentum match

Shower starting-point

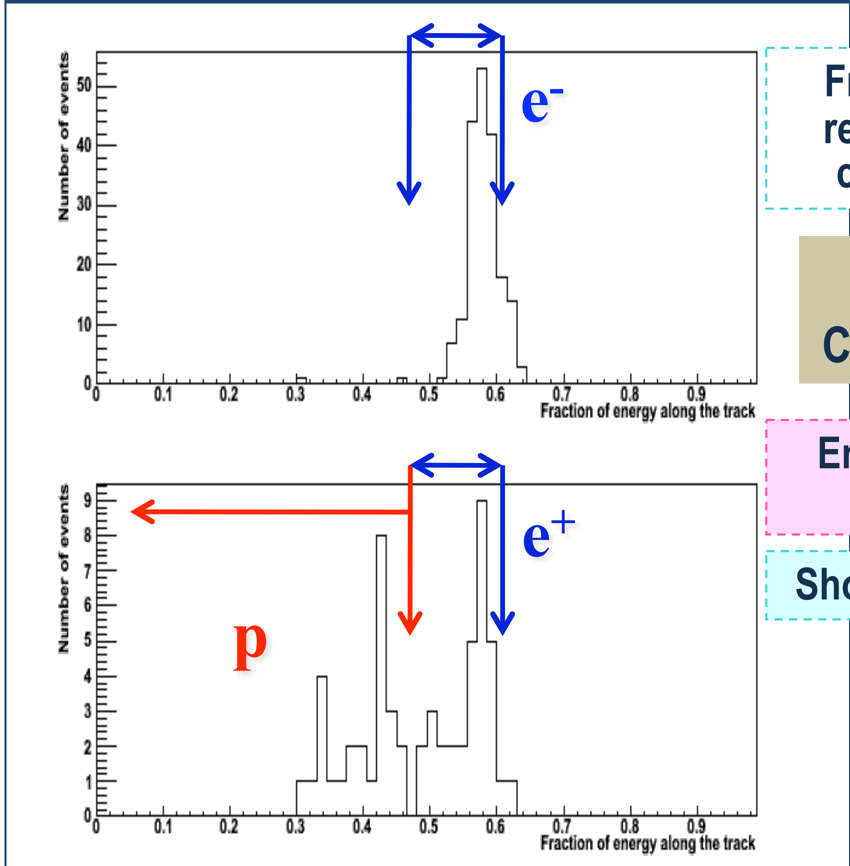
Flight data
Neutron yield in ND





Check of calorimeter selection

Flight data
Rigidity: 42-65 GV



Fraction of charge released along the calorimeter track

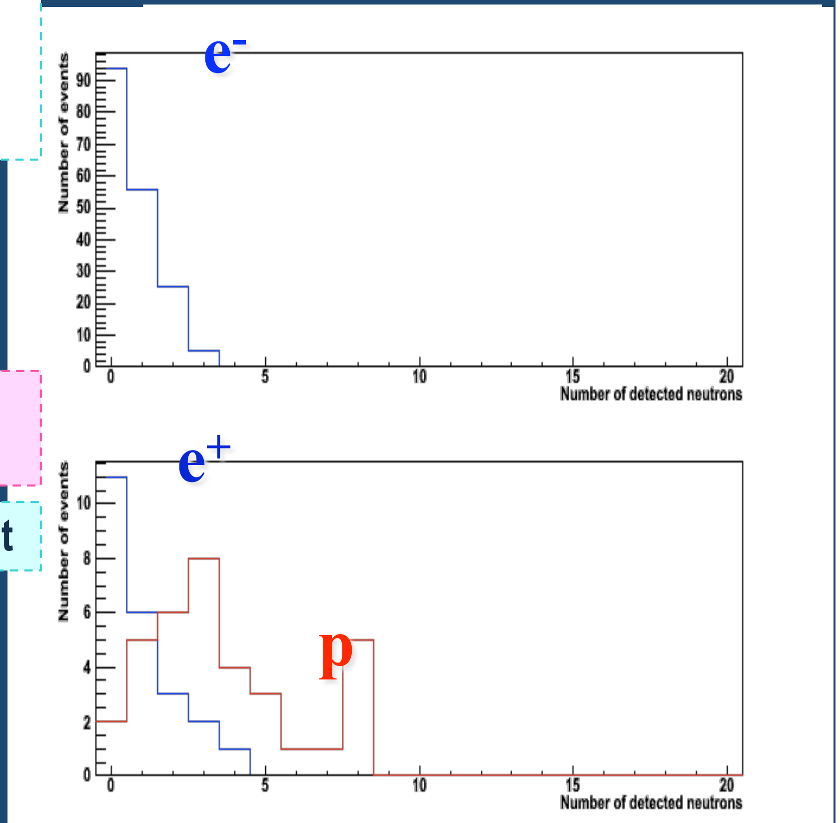
\+

Constraints on:

Energy-momentum match

Shower starting-point

Flight data
Neutron yield in ND



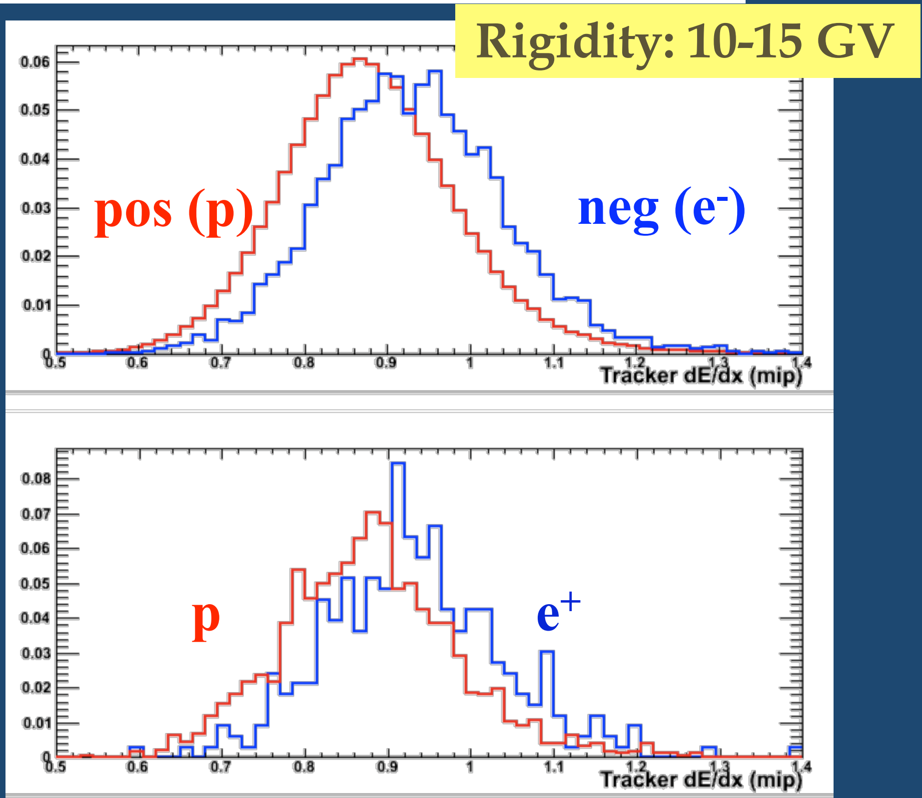
Check of calorimeter selection

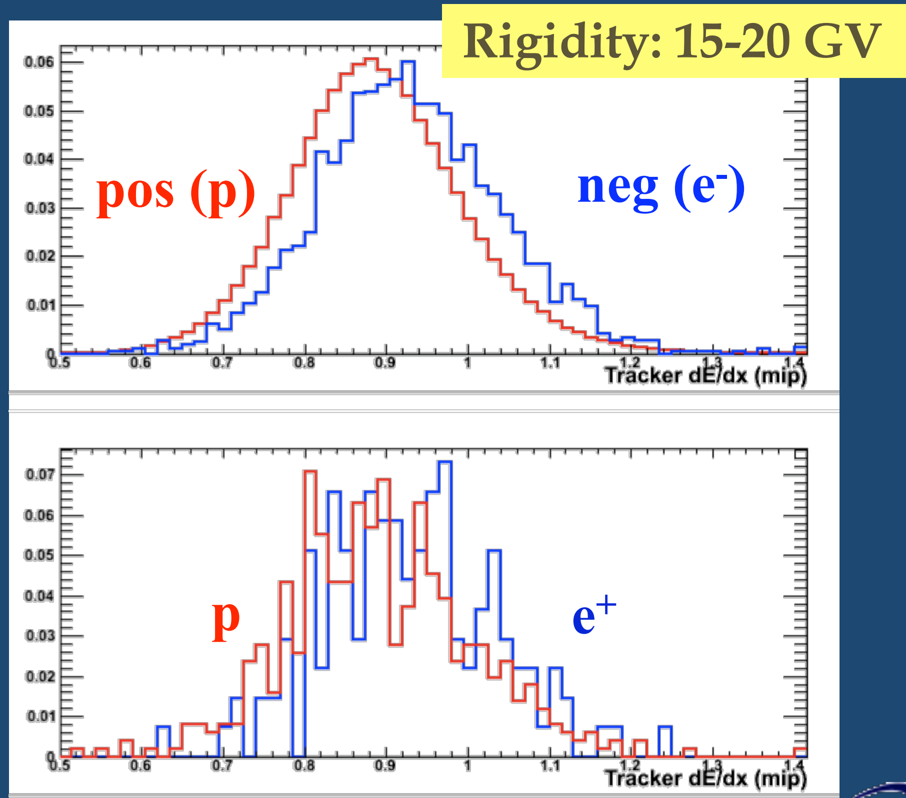
Energy loss in silicon tracker detectors:

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

Relativistic rise

- Top: positive (mostly p) and negative events (mostly e$^-$)
- Bottom: positive events identified as p and e$^+$ by trasversal profile method

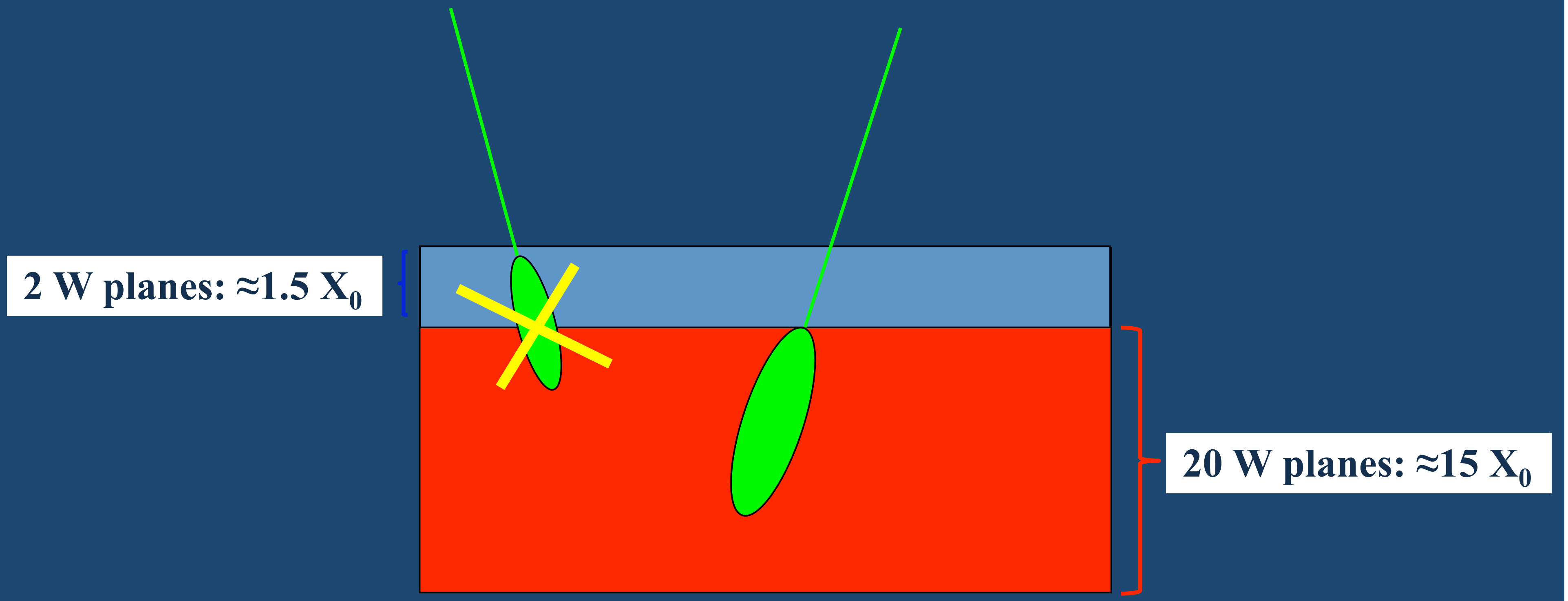




The "pre-sempler" method

Selection of a pure sample of protons from flight data

CALORIMETER: 22 W planes: 16.3 X_0



Proton background evaluation

Rigidity: 20-28 GV

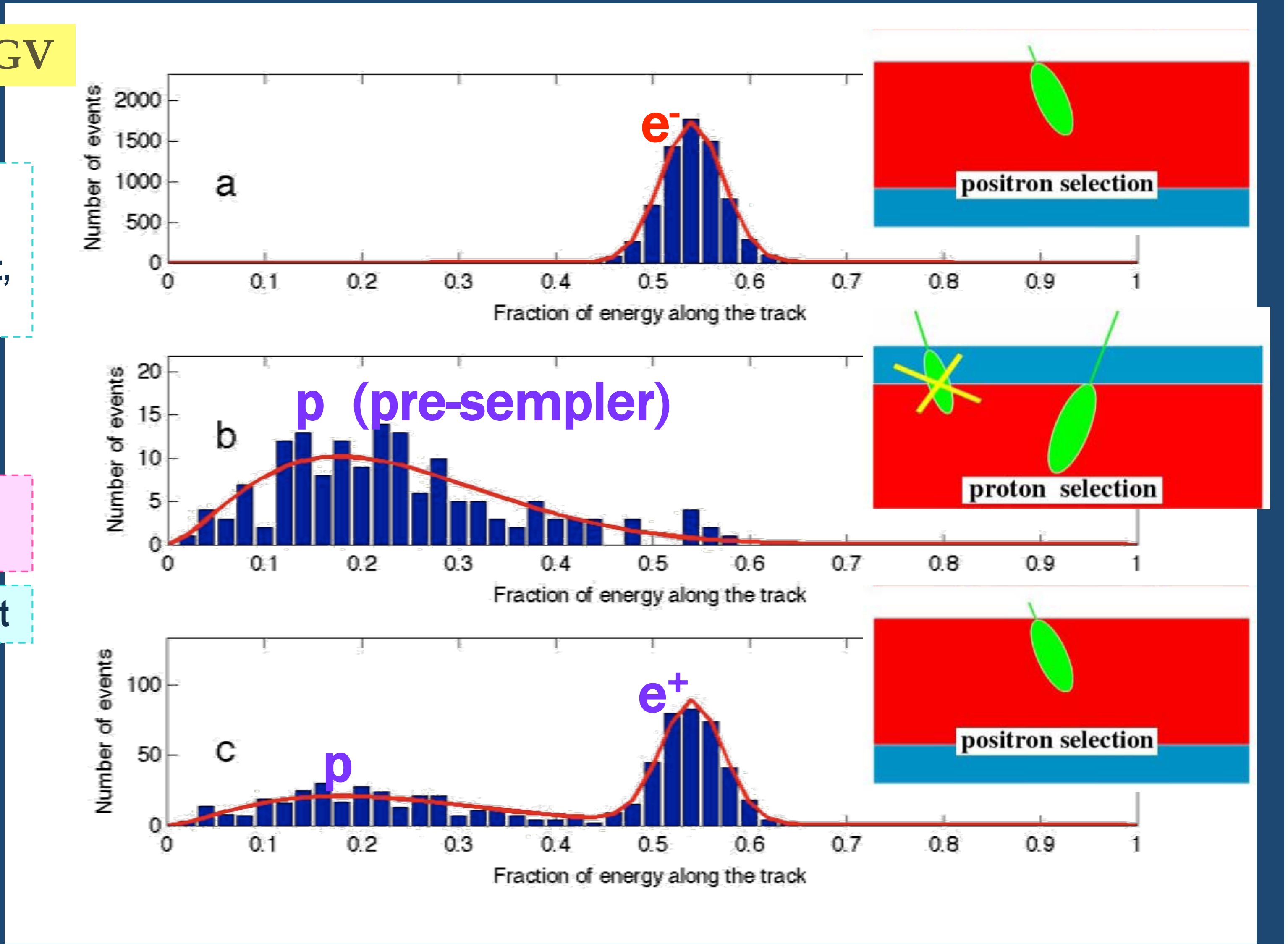
Fraction of charge released along the calorimeter track (left, hit, right)

+

Constraints on:

Energy-momentum match

Shower starting-point



Proton background evaluation

Rigidity: 28-42 GV

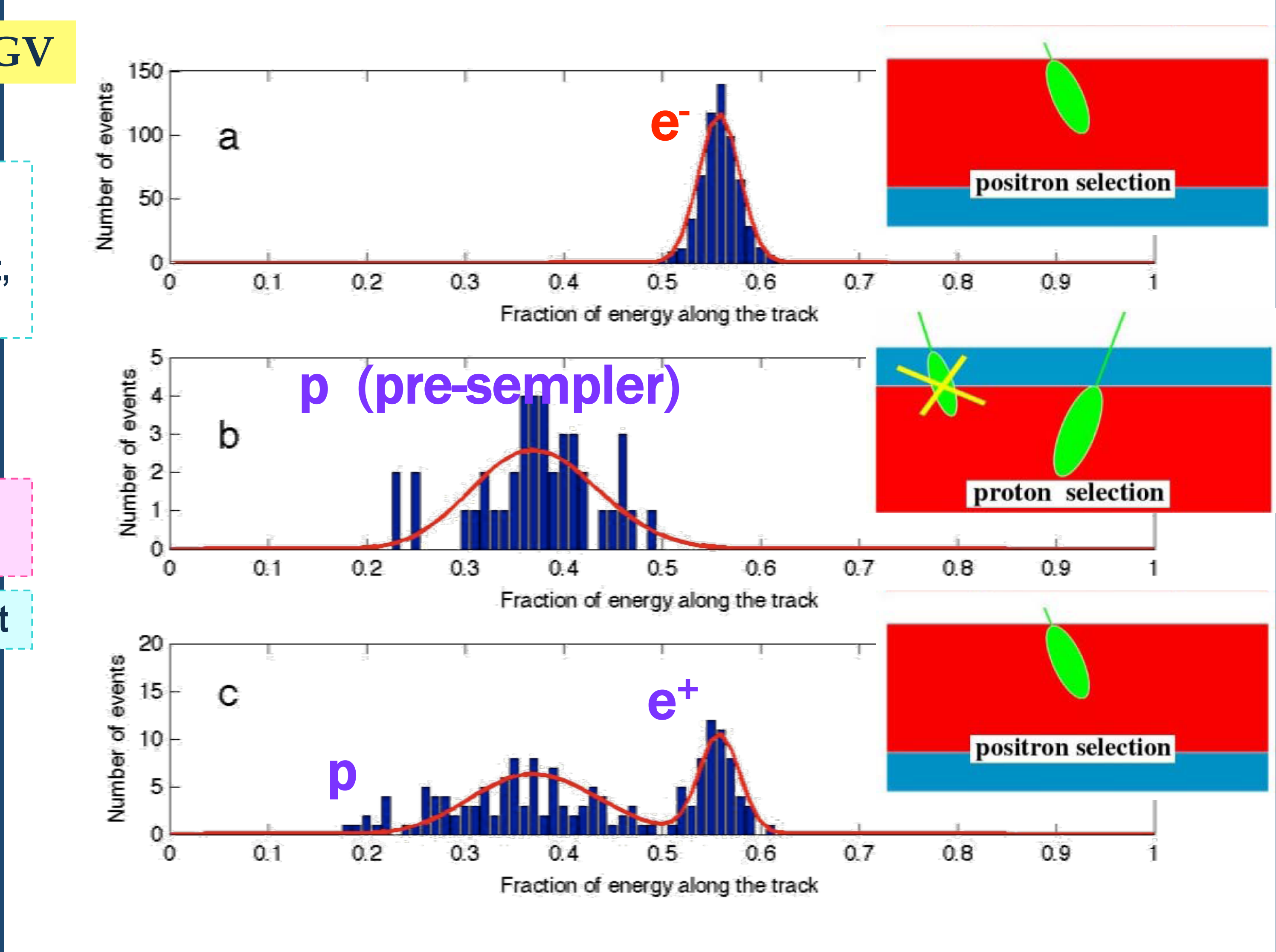
Fraction of charge released along the calorimeter track (left, hit, right)

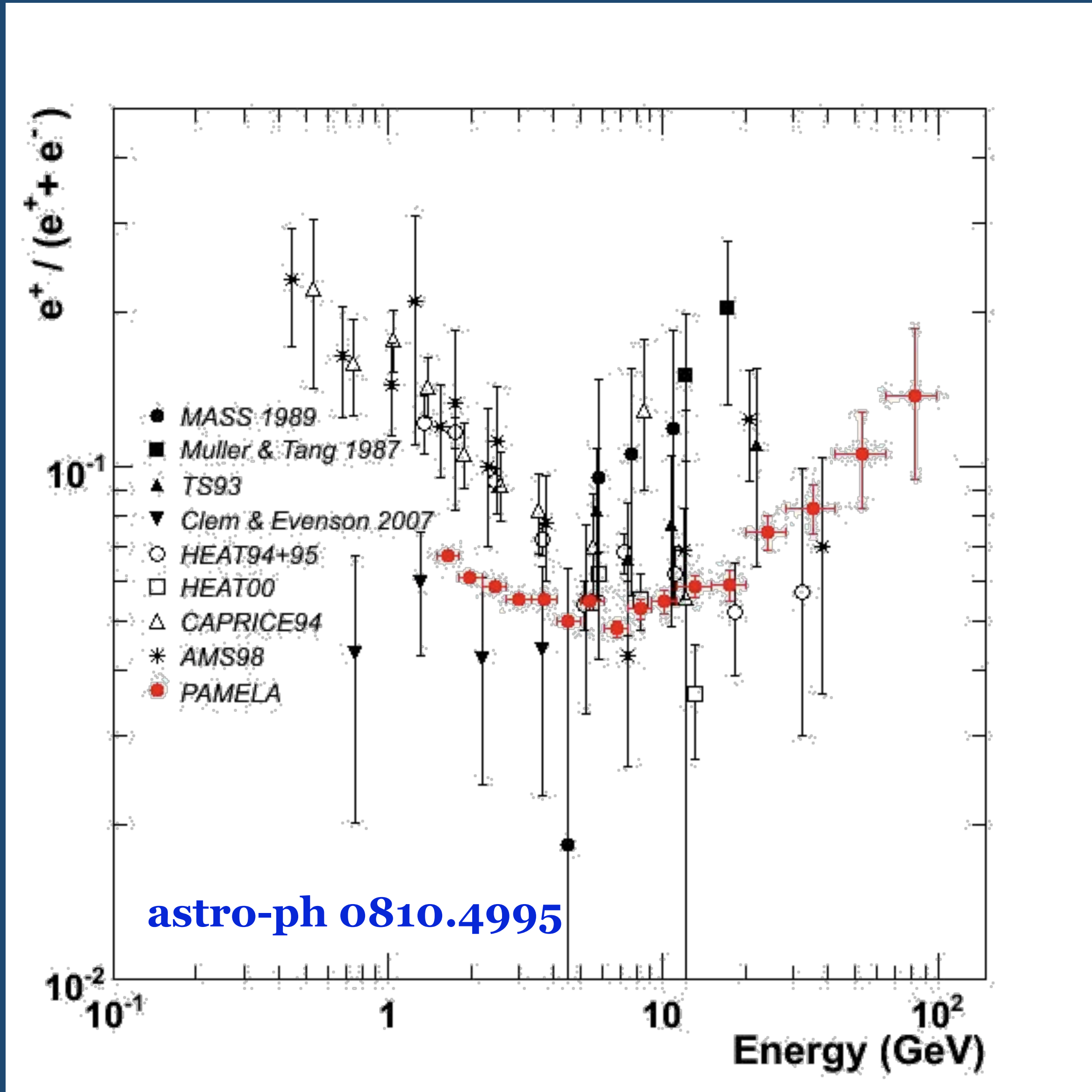
\+

Constraints on:

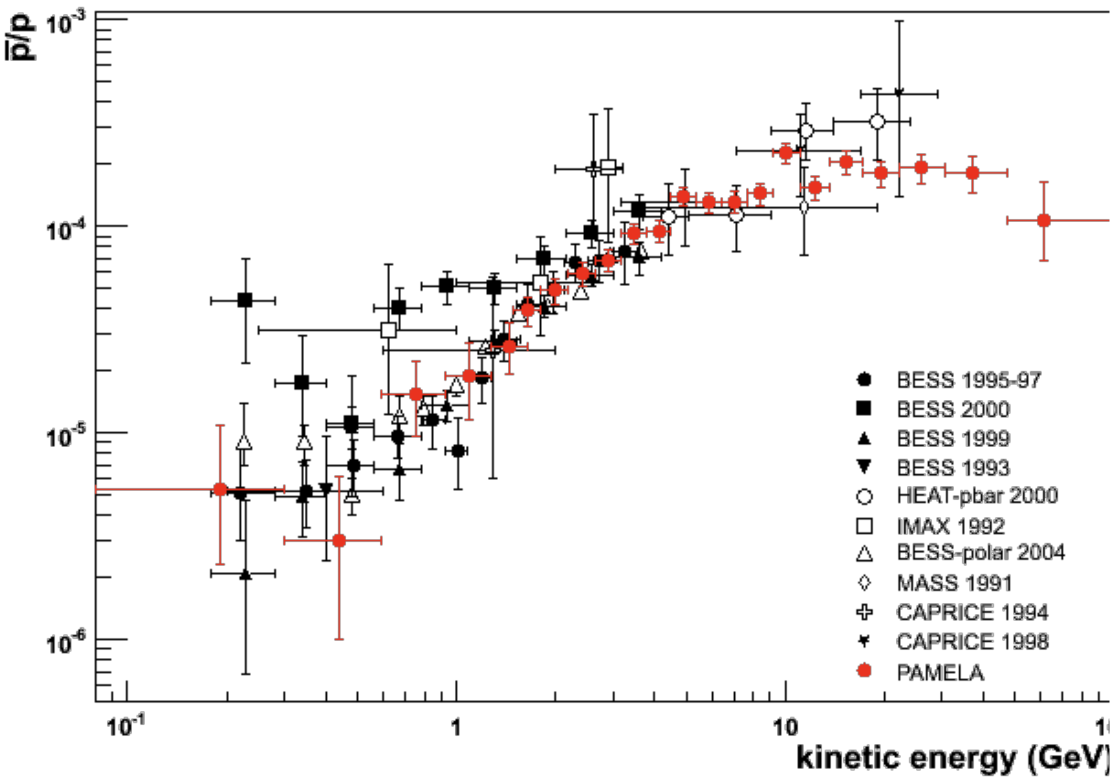
Energy-momentum match

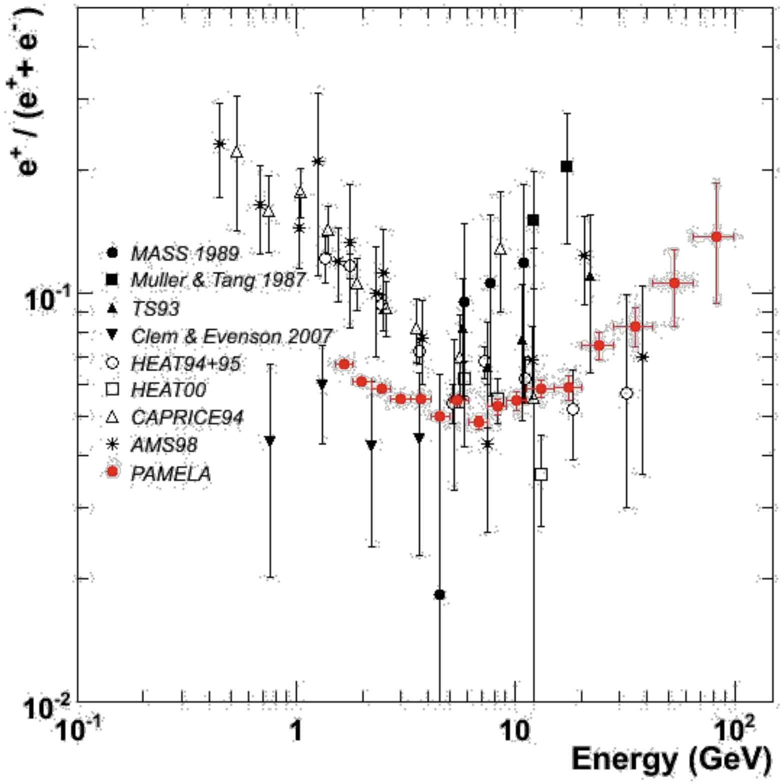
Shower starting-point





e+ / (e+ + e-)
10-1
10-2
10-1
1
10
10^2
Energy (GeV)
MASS 1989
Muller & Tang 1987
TS93
Clem & Evenson 2007
HEAT94+95
HEAT00
CAPRICE94
AMS98
PAMELA
astro-ph 0810.4995

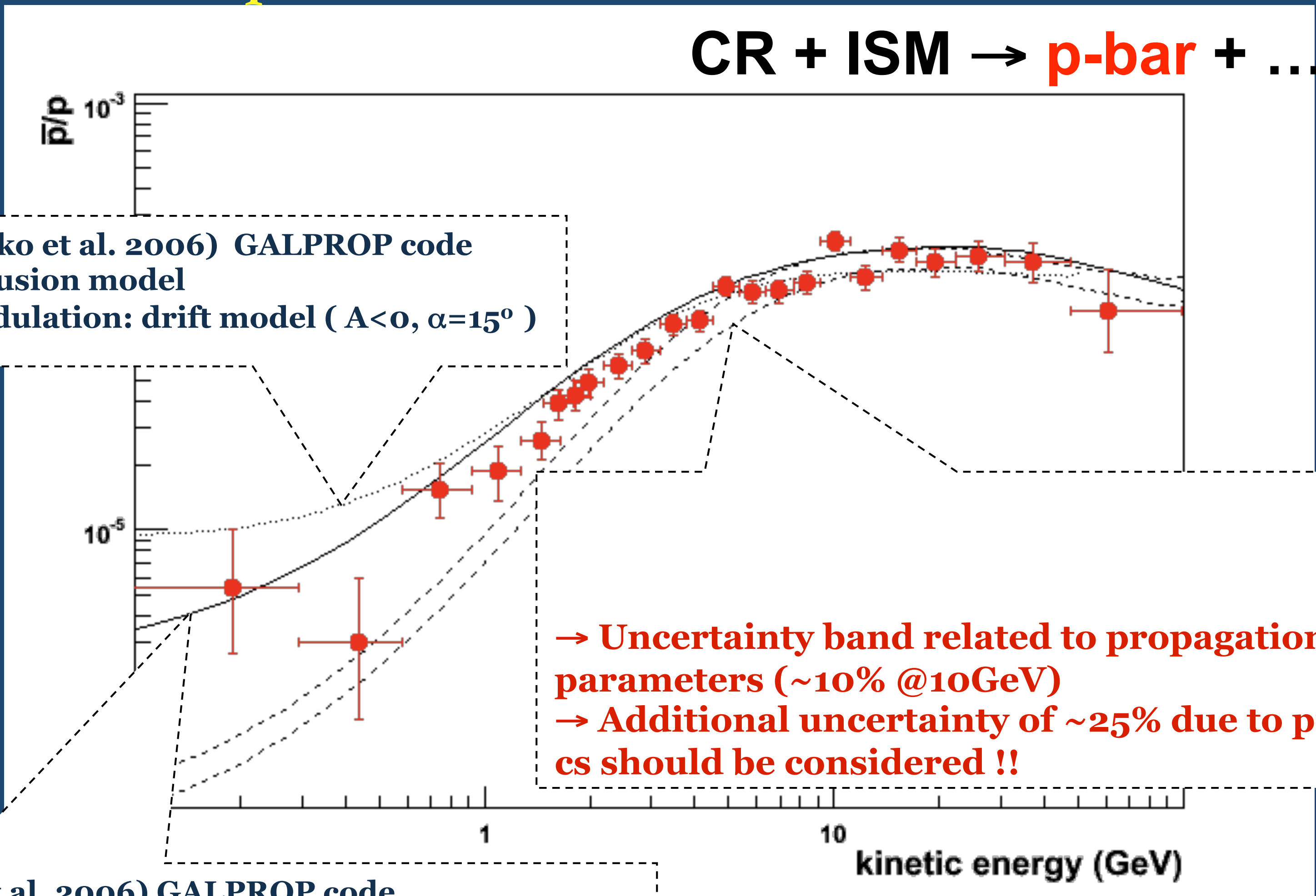




((Do we have any antimatter excess in CRs?))

Antiproton-to-proton ratio

Secondary Production Models



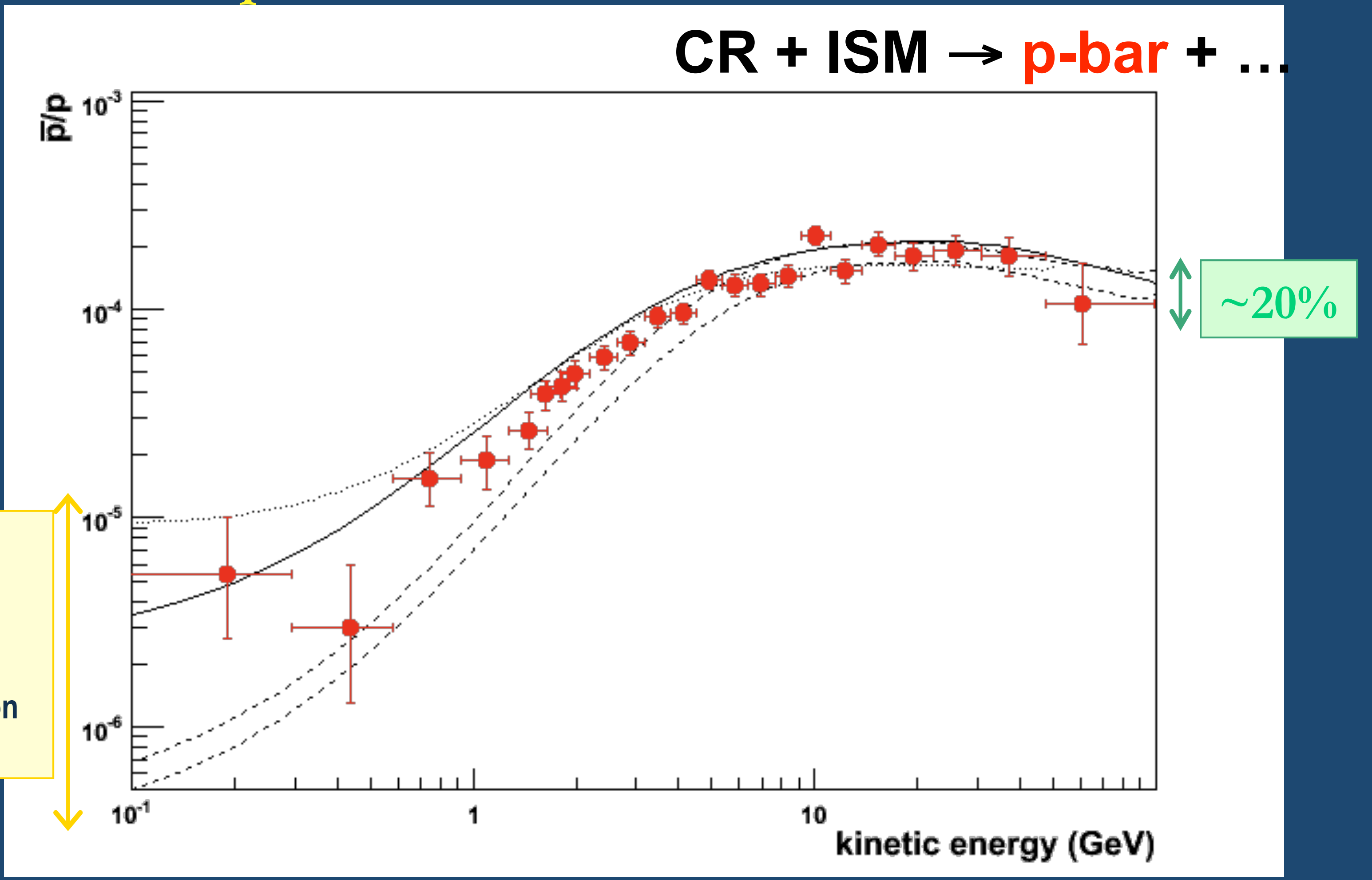
(Moskalenko et al. 2006) GALPROP code
- Plain diffusion model
- Solar modulation: drift model (A<0, α=15°)

(Ptuskin et al. 2006) GALPROP code
- Plain diffusion model
- Solar modulation: spherical model (f=550MV)

→ Uncertainty band related to propagation parameters (~10% @10GeV)
→ Additional uncertainty of ~25% due to production cs should be considered !!

Antiproton-to-proton ratio

Secondary Production Models



NB!
- Solar modulation
- Nuclear cross-section
- …

No evidence for any antiproton excess

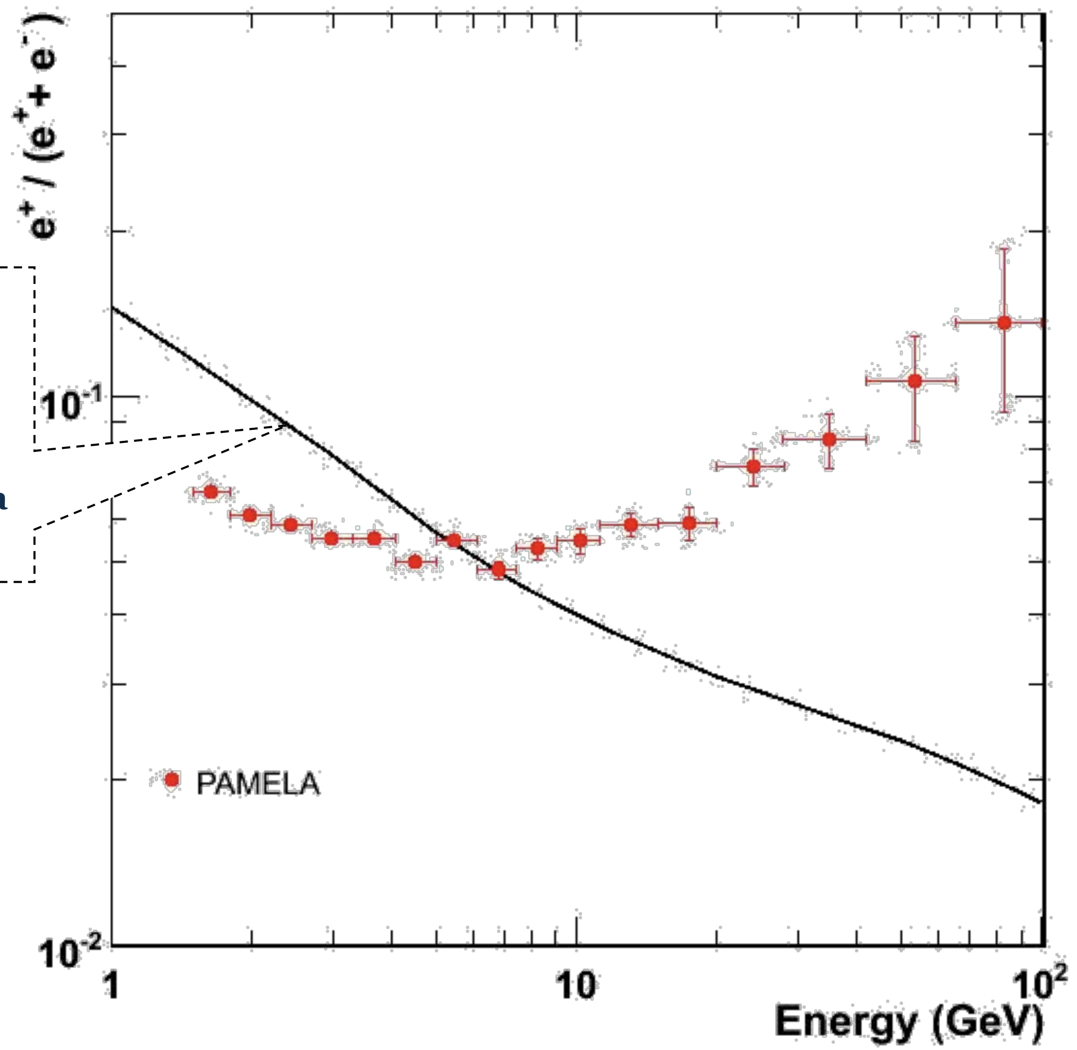
Positron fraction

Secondary Production Models

$$CR + ISM \rightarrow \pi^{\pm} + \ldots \rightarrow \mu^{\pm} + \ldots \rightarrow e^{\pm} + \ldots$$

$$CR + ISM \rightarrow \pi^{0} + \ldots \rightarrow \gamma\gamma \rightarrow e^{\pm}$$

(Moskalenko & Strong 1998)
GALPROP code
• Plain diffusion model
• Interstellar spectra

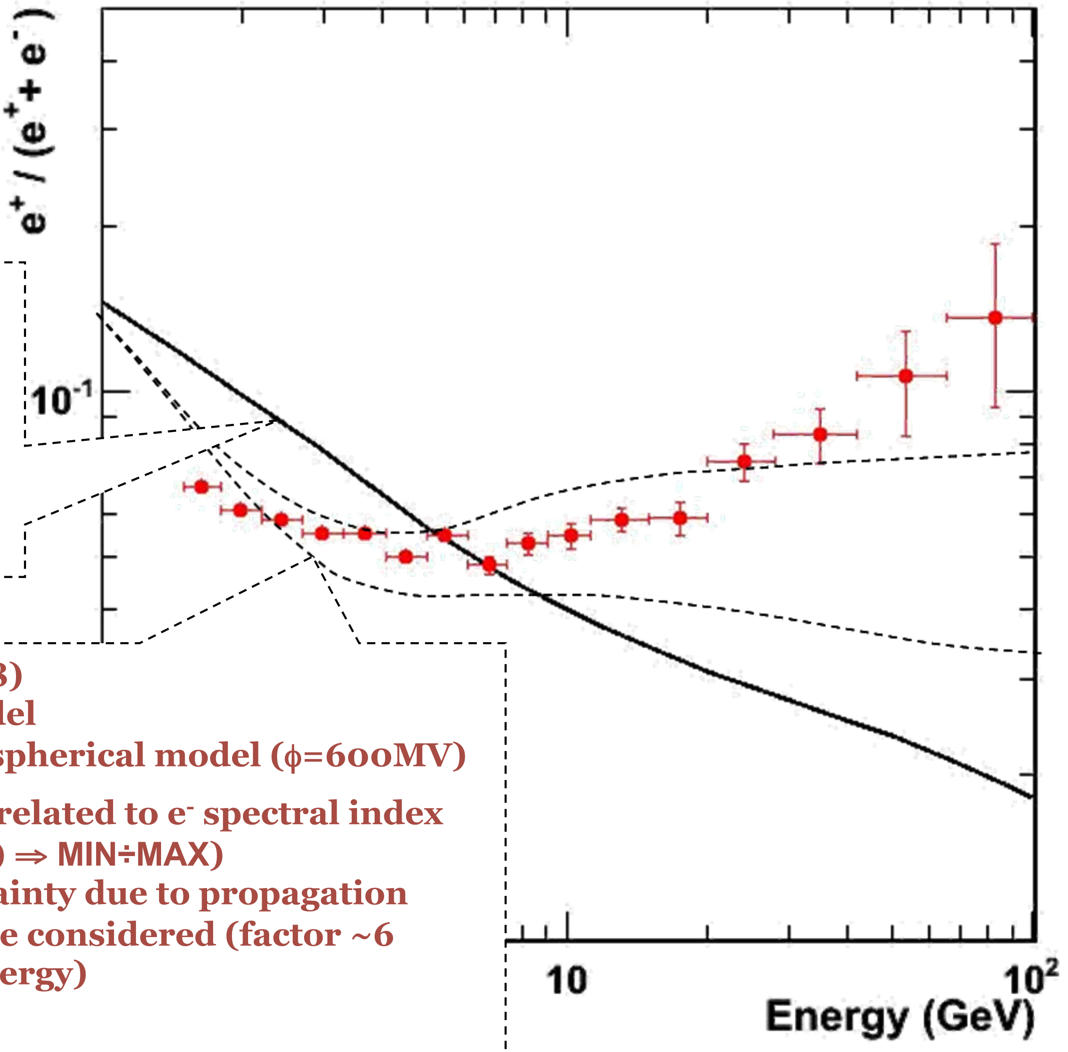


Positron fraction

Secondary Production Models

$CR + ISM \rightarrow \pi^{\pm} + \ldots \rightarrow \mu^{\pm} + \ldots \rightarrow e^{\pm} + \ldots$

$CR + ISM \rightarrow \pi^{0} + \ldots \rightarrow \gamma\gamma \rightarrow e^{\pm}$



(Moskalenko & Strong 1998)
GALPROP code
- Plain diffusion model
- Interstellar spectra

(Delahaye et al. 2008)
- Plain diffusion model
- Solar modulation: spherical model (ϕ=600MV)

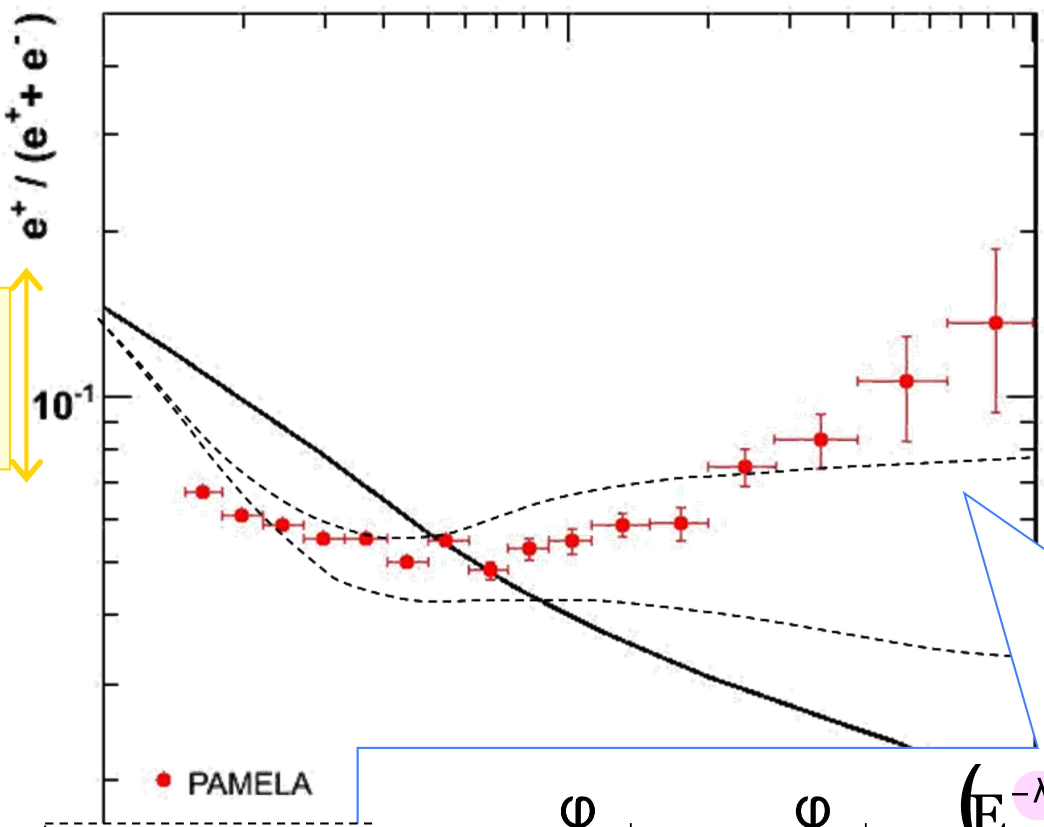
→ Uncertainty band related to e^- spectral index ($\gamma_e = 3.44 \pm 0.1$ (3σ) ⇒ MIN÷MAX)
→ Additional uncertainty due to propagation parameters should be considered (factor ~6 @1GeV ~4 @high-energy)

Positron fraction

Secondary Production Models

$CR + ISM \rightarrow \pi^{\pm} + \ldots \rightarrow \mu^{\pm} + \ldots \rightarrow e^{\pm} + \ldots$

$CR + ISM \rightarrow \pi^{0} + \ldots \rightarrow \gamma\gamma \rightarrow e^{\pm}$



NB!
• Solar modulation

Increasing positron fraction only if $\lambda_e - \lambda_p > 0.6$

→ unlikely

(Serpico 2008)

$$N_P \propto Q_P \lambda_{esc}^{l}$$

$$\frac{N_S}{N_P} \propto \lambda_{esc}^{l} \cdot \sigma_{P\rightarrow S}$$

$$\frac{\varphi_{e^+}}{\varphi_{e^+} + \varphi_{e^-}} \sim \frac{\varphi_{e^+}}{\varphi_{e^-}} \sim \frac{\left(E^{-\lambda_p - \delta}\right) E^{-l}}{E^{-\lambda_e - l}} \sim E^{\lambda_e - \lambda_p - \delta}$$

p spectral index @source

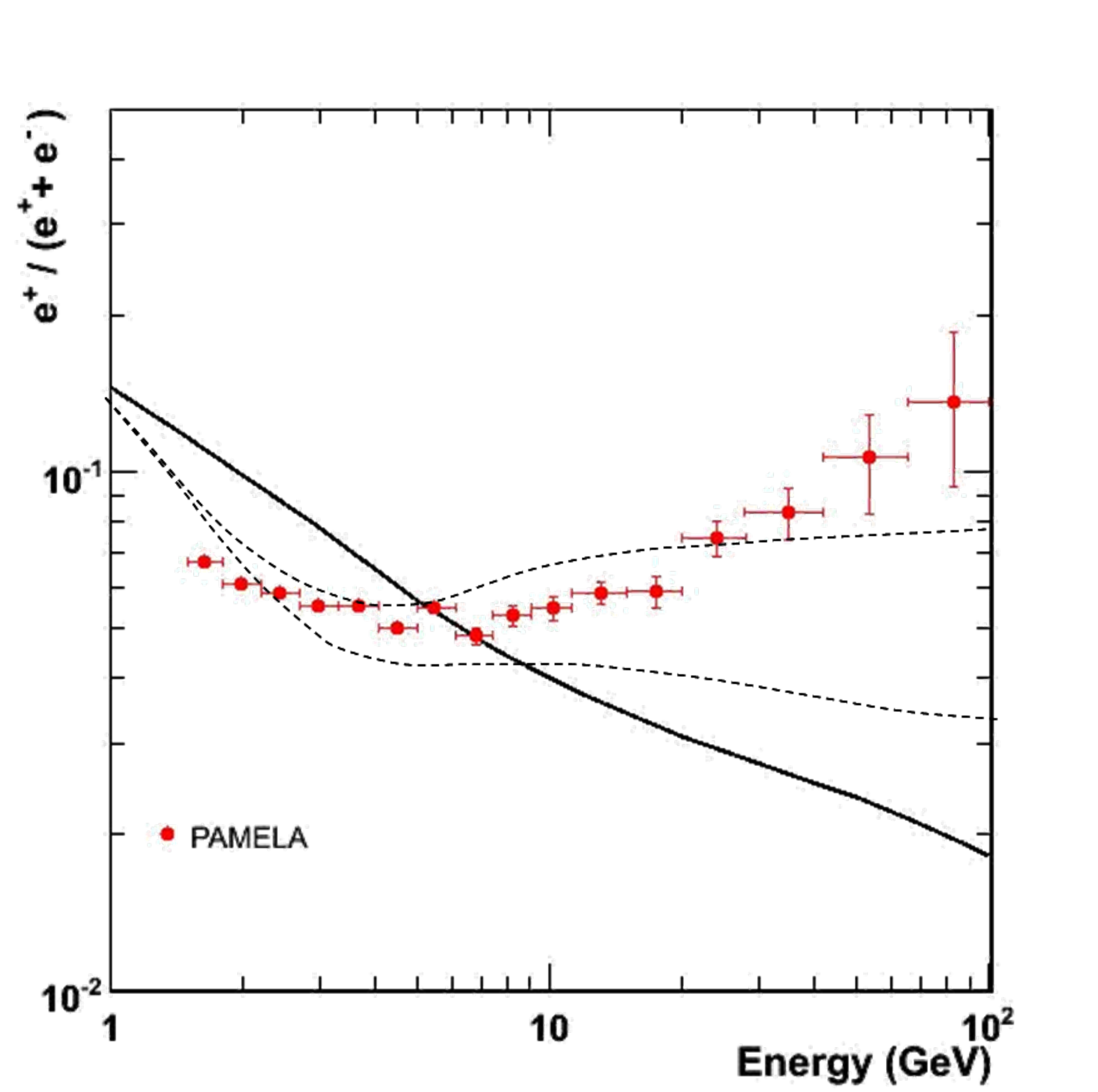
e- spectral index @source

nuclear diffusion (δ ~ 0.6 from B/C)

lepton diffusion & en.loss (l=1 if en.loss dominate)

Positron fraction

Secondary Production Models



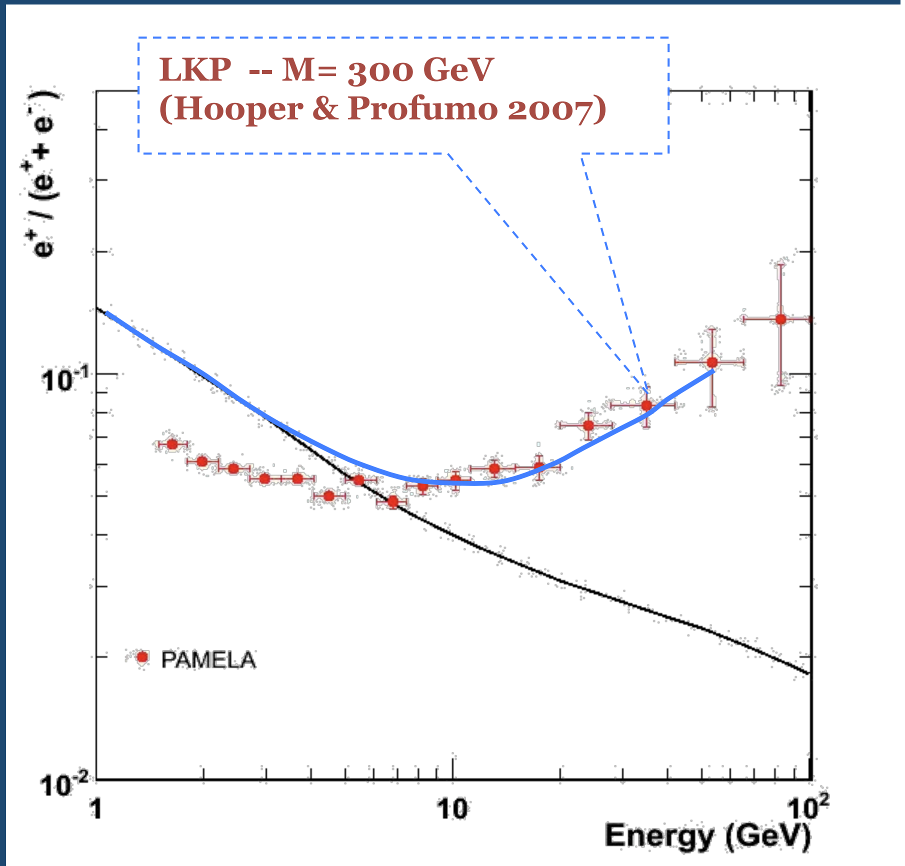
Quite robust evidence for a positron excess

Primary positron sources

Dark Matter

- e^+ yield depend on the dominant decay channel
  - → **LSPs** seem <u>disfavored</u> due to suppression of e^+e^- final states
    - → low yield (relative to p-bar)
    - → soft spectrum from cascade decays
  - → **LKPs** seem <u>favored</u> because can annihilate directly in e^+e^-
    - → high yield (relative to p-bar)
    - → hard spectrum with pronounced cutoff @ M_{LKP} (>300 GeV)

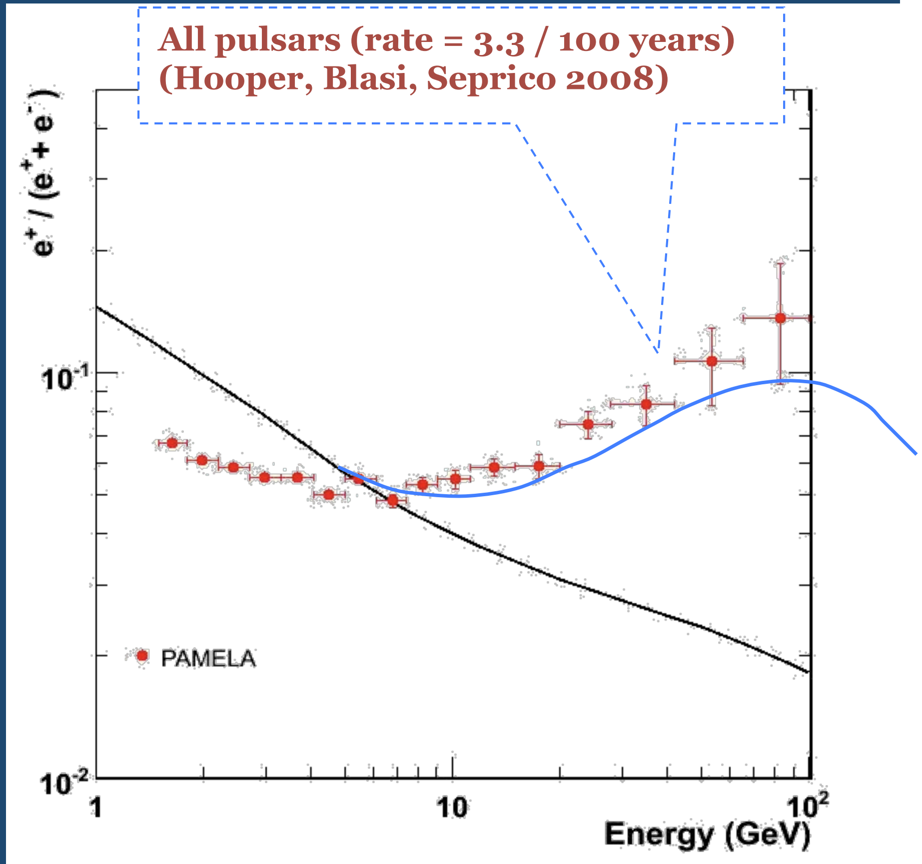
- Boost factor required to have a sizable e^+ signal
  - → NB: constraints from p-bar data!!

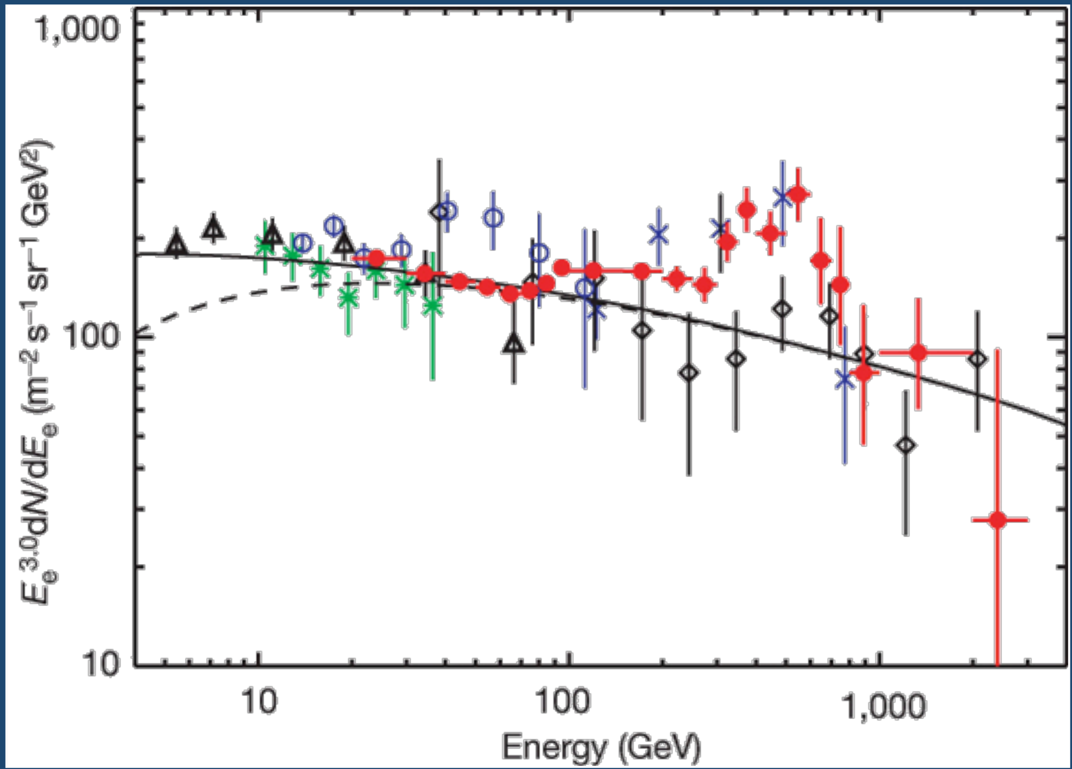


Primary positron sources

Astrophysical processes

- Local **pulsars** are well-known sites of e^+e^- pair production:
  - → they can individually and/or coherently contribute to the e^+e^- galactic flux and explain the PAMELA e^+ excess (both spectral feature and intensity)
    - → No fine tuning required
  - → if one or few nearby pulsars dominate, anisotropy could be detected in the angular distribution
    - → possibility to discriminate between pulsar and DM origin of e^+ excess





PAMELA positron excess might be connected with ATIC electron+positron structures

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.

Propagation of cosmic rays

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

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

- $\frac{\partial \Phi}{\partial t}$: differential flux
- $D(E)\nabla^2\Phi$: diffusion
- $\frac{\partial}{\partial E}\left(b(E)\Phi\right)$: energy loss
- $\frac{\partial}{\partial z}\left(V_c\Phi\right)$: convection
- $Q(E)$: source term
- $2h\delta(z)\Gamma_{\mathrm{spall}}\Phi$: spallation

Solution is of the form:

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

- n^2: astro&cosmo
- $\langle \sigma v \rangle$: particle physics

Thermal relic requires:

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

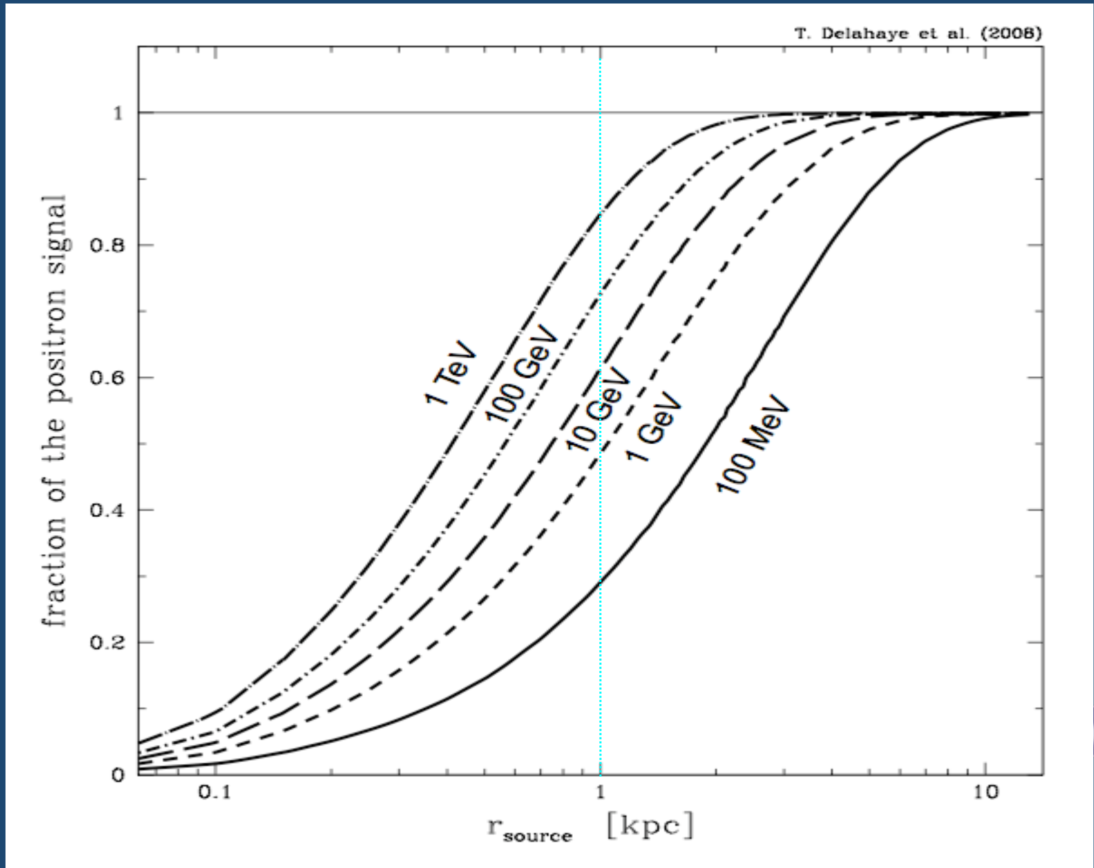
Indirect DM detection

Where do positrons come from?

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

Typical lifetime

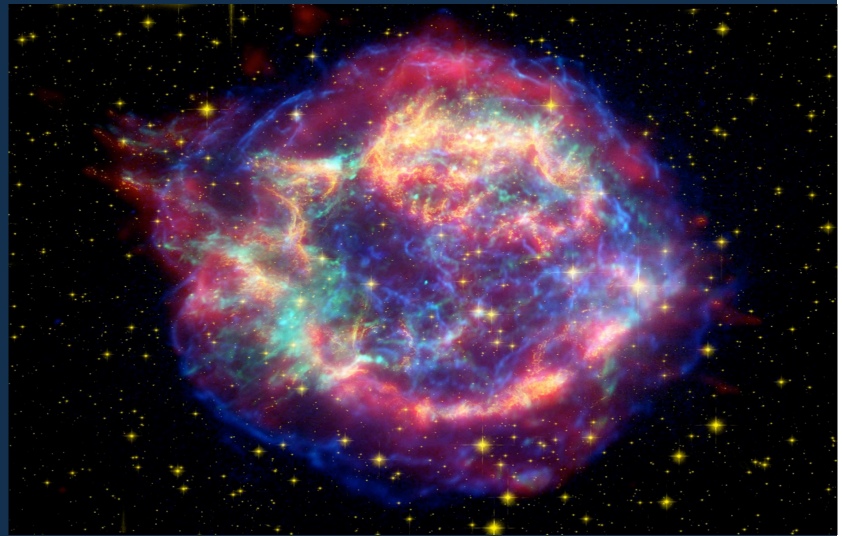
$$\tau \simeq 5 \cdot 10^5 \mathrm{yr} \left(\frac{1\,\mathrm{TeV}}{E} \right)$$

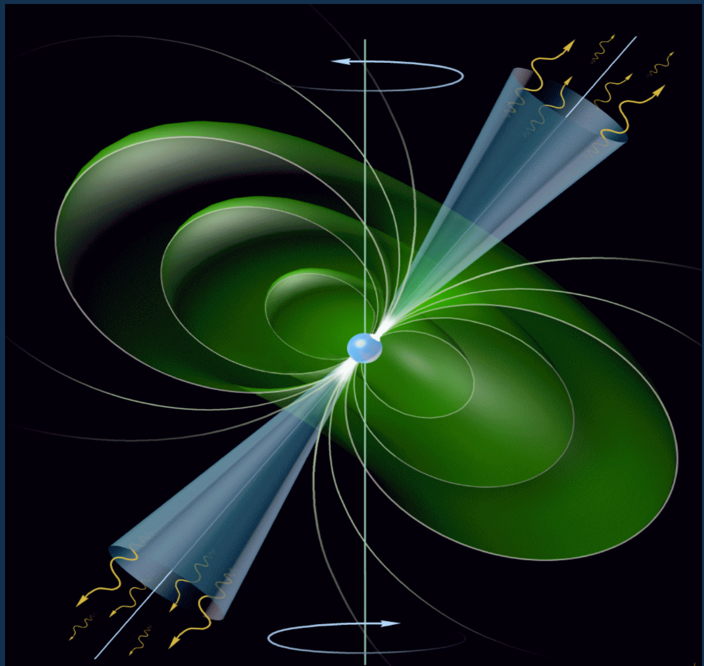


• Positron Excess possible explanations New? or Near?

New Mechanisms standard Sources

SNR

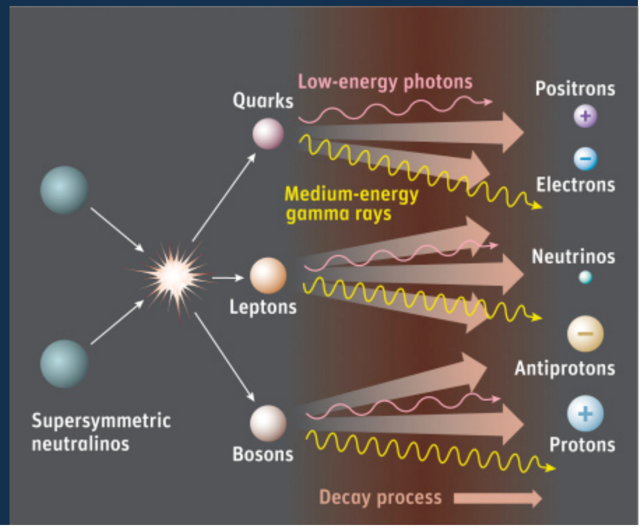




Near Astrophysical Sources Pulsars

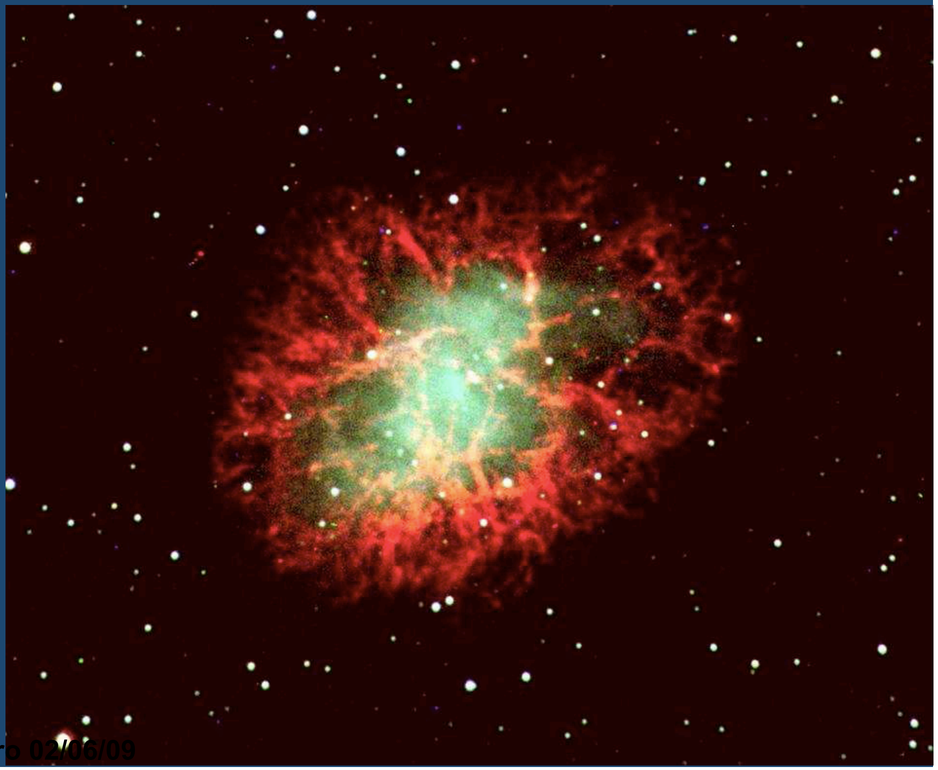
NEW Sources

indirect Dark Mater detection



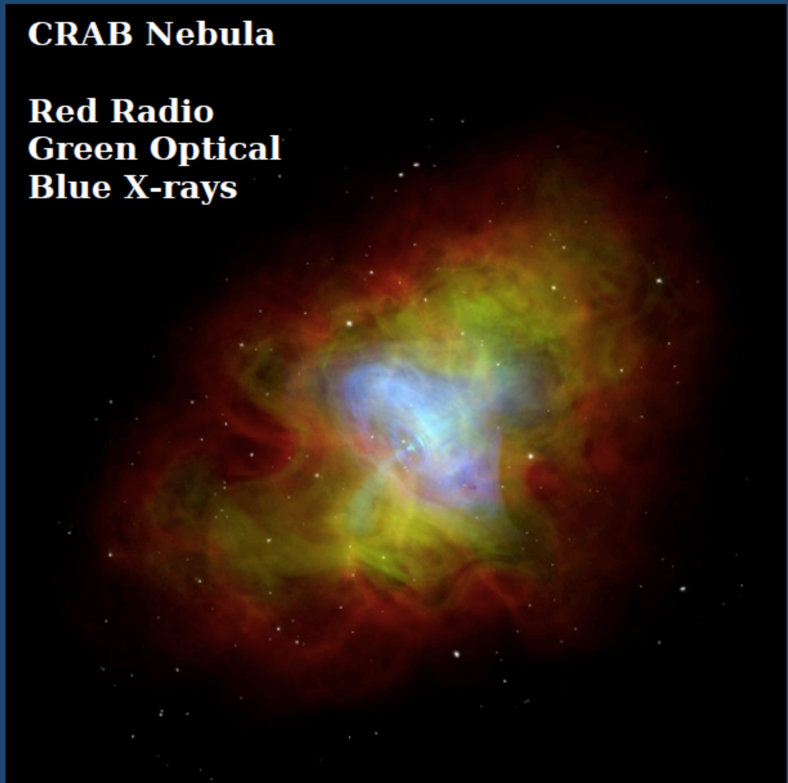
Possible Sources

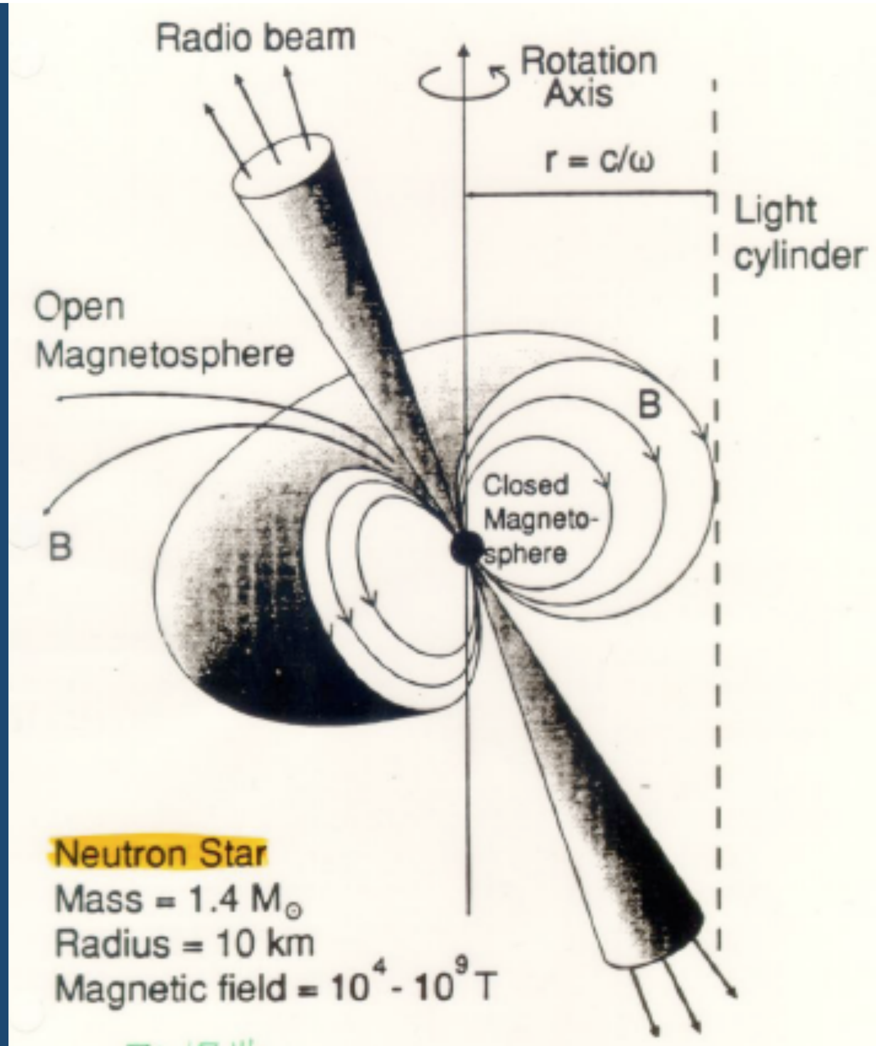
The Crab Nebula, a remnant of a supernova that exploded in 1054. In the center lies a pulsar with a frequency of 30 Hz. The red color indicates the recombination of electrons with protons to form neutral hydrogen. The green color traces the ultrarelativistic electrons gyrating around the strong magnetic field of the inner nebula. Such a supernova remnant with a pulsar supplying energetic electrons emitting sychrotron radiation is called a plerion.



Pulsars

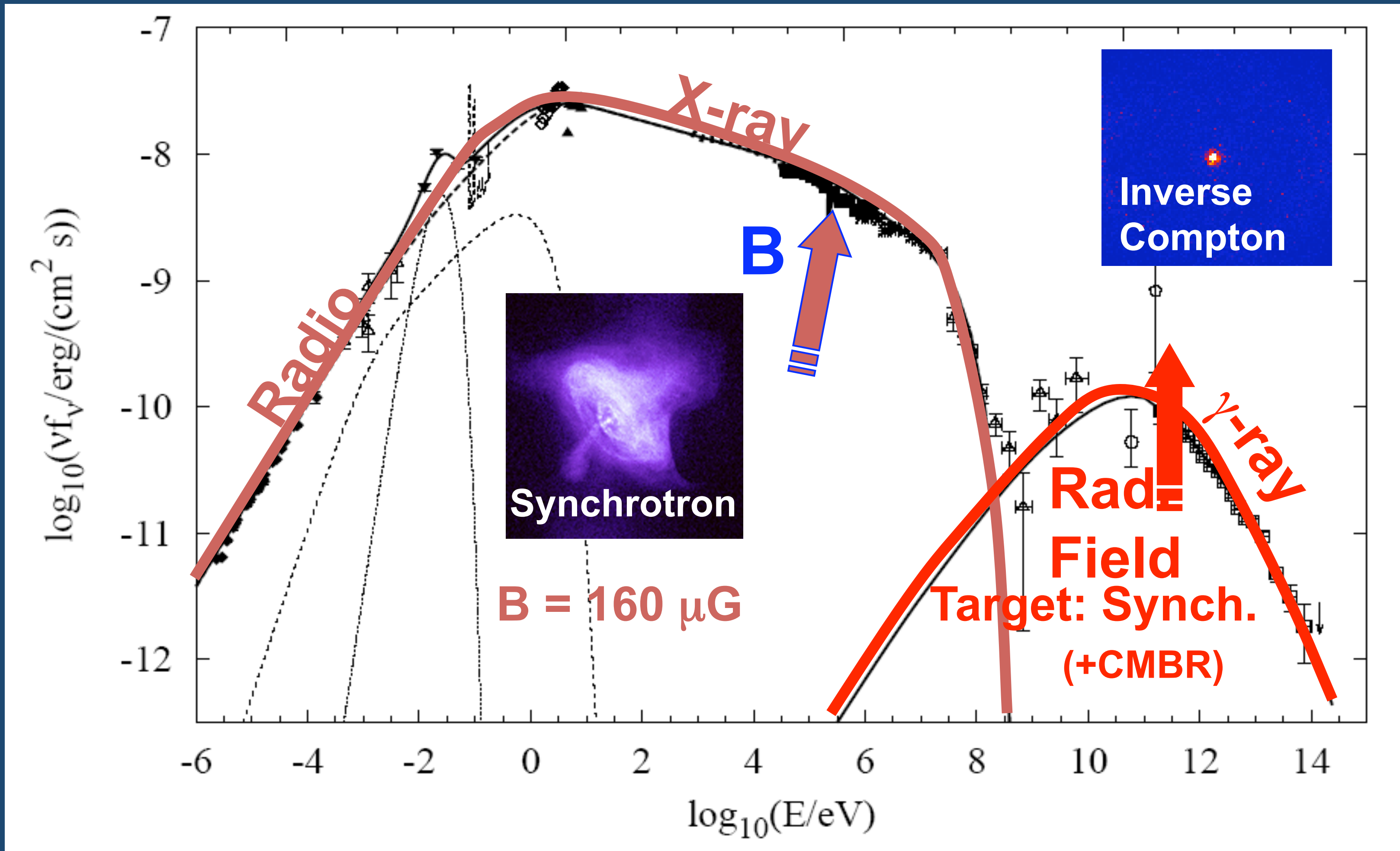
Crab Pulsar





- 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.

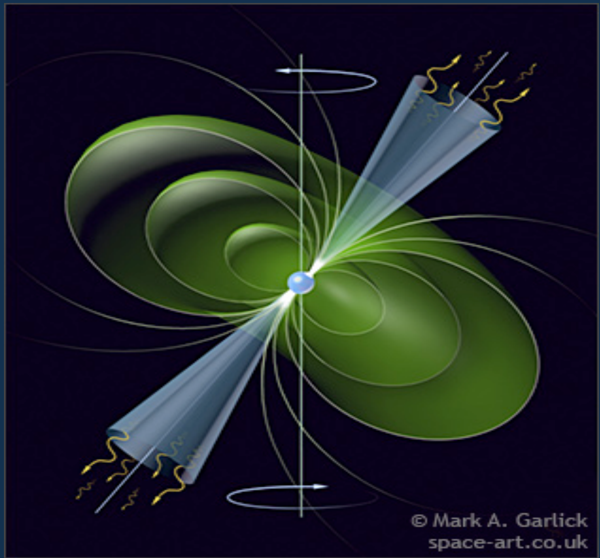
The best example: Crab Nebula



Astrophysical explanations

Young, nearby pulsars ?

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



"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

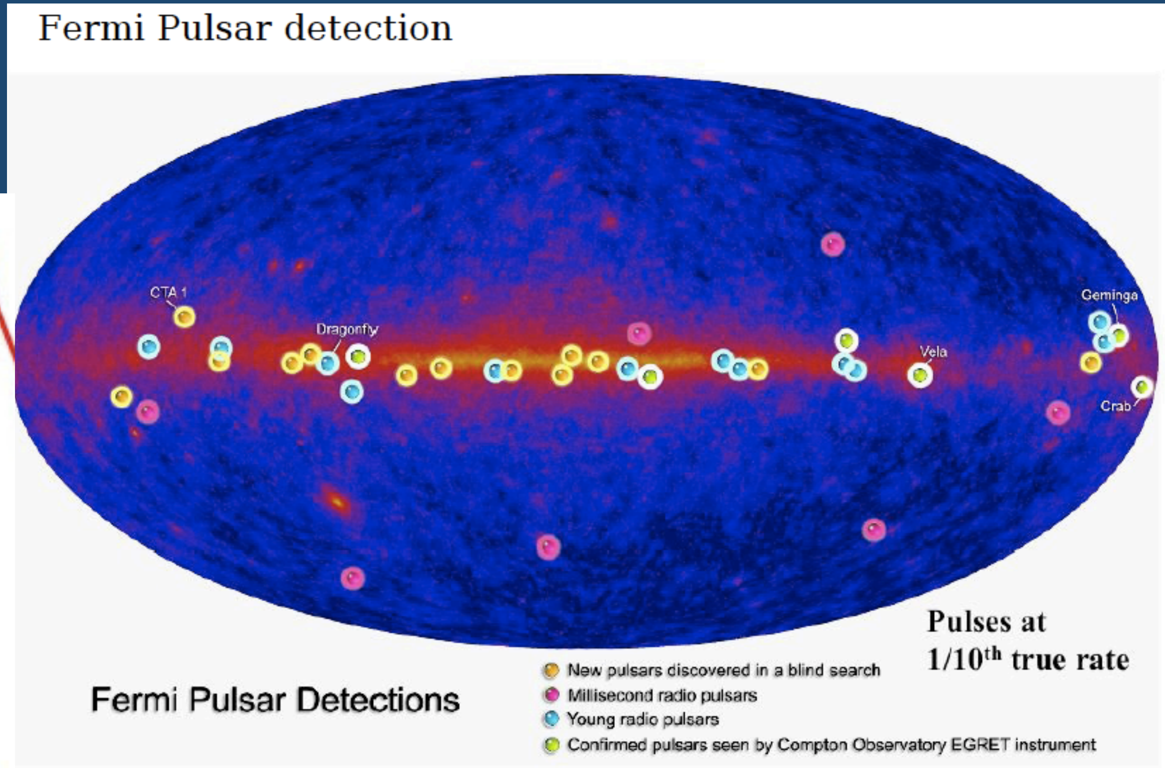
$$\tau \simeq 0 \rightarrow 10^5\,\mathrm{yr} \qquad E_{tot} \simeq 10^{46}\,\mathrm{erg}$$

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 as sources of high energy cosmic positrons?

- Very different characteristics from the normal γ-ray pulsars:
  - Spinning 100 times faster
  - Magnetic fields ~10,000 times lower
  - ~10,000 times older
- "Recycled" pulsars spun-up by binary companion stars (movie)
  - Old recycled pulsars can accelerate particles to very high (TeV) energies
  - *Fermi* is seeing so far the nearby ms pulsar population
  - This may be the tip-of-the-iceberg with many more to be discovered



Pulsars as the Sources of High Energy Cosmic Ray Positrons

Dan Hooper, Pasquale Blasi, Pasquale Dario SerpicoarXiv: 0810.1527v1

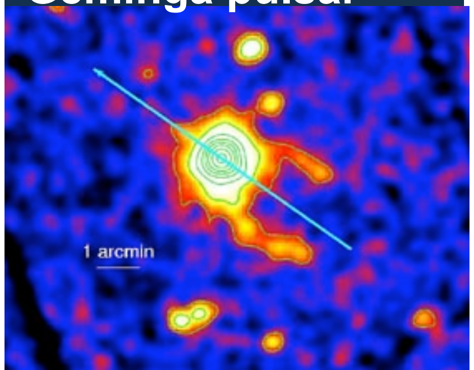
we find that the spectrum observed by PAMELA could plausibly originate frompulsars (rapidly spinning, magnetized neutron stars) a significant contribution is expected from the sum of all mature pulsars throughout the Milky Way, as well as from the most nearby mature pulsars (such as Geminga and B0656+14).

At 10 GeV, we estimate that on average only ~20% of the cosmic ray positrons originate from pulsars within 500 parsecs from the Solar System.

Above ~50 GeV, however, the positron spectrum is likely to be dominated by a single or small number of nearby pulsars.

If the high energy electron-positron spectrum is dominated by a single nearby source, it opens the possibility of detecting a dipole anisotropy in their angular distribution.

Geminga pulsar



Single pulsar

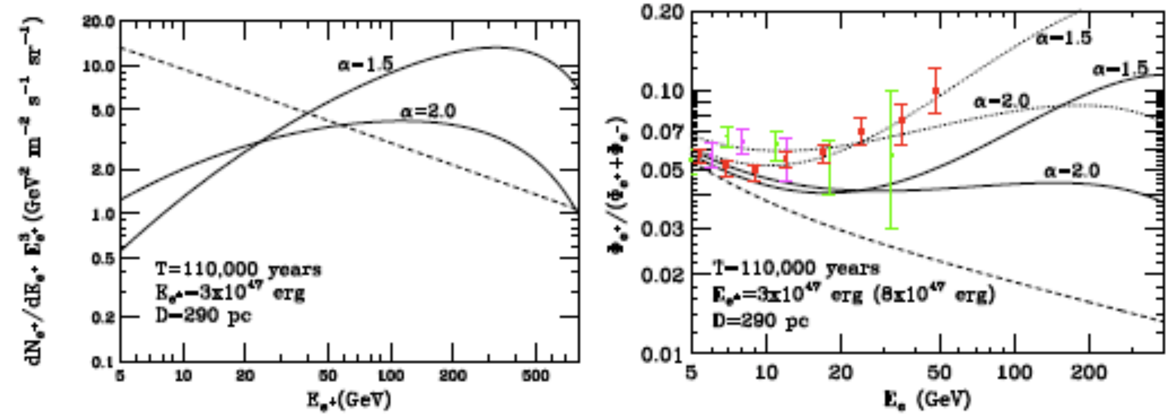


FIG. 3: As in Fig. 2 but from the nearby pulsar B0656+14. The solid lines correspond to an energy in pairs given by 3×10^{47} erg, while the dotted lines require an output of 8×10^{47} erg.

Sum of pulsars

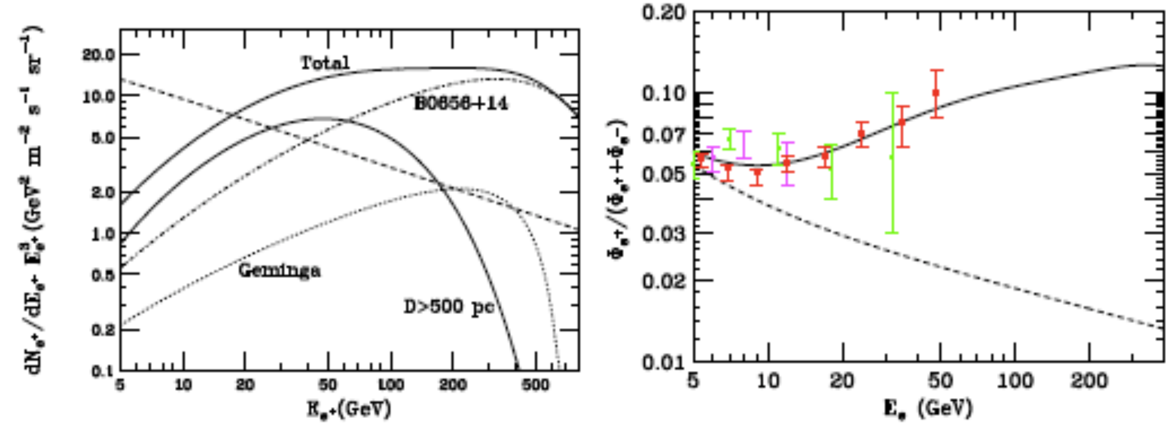
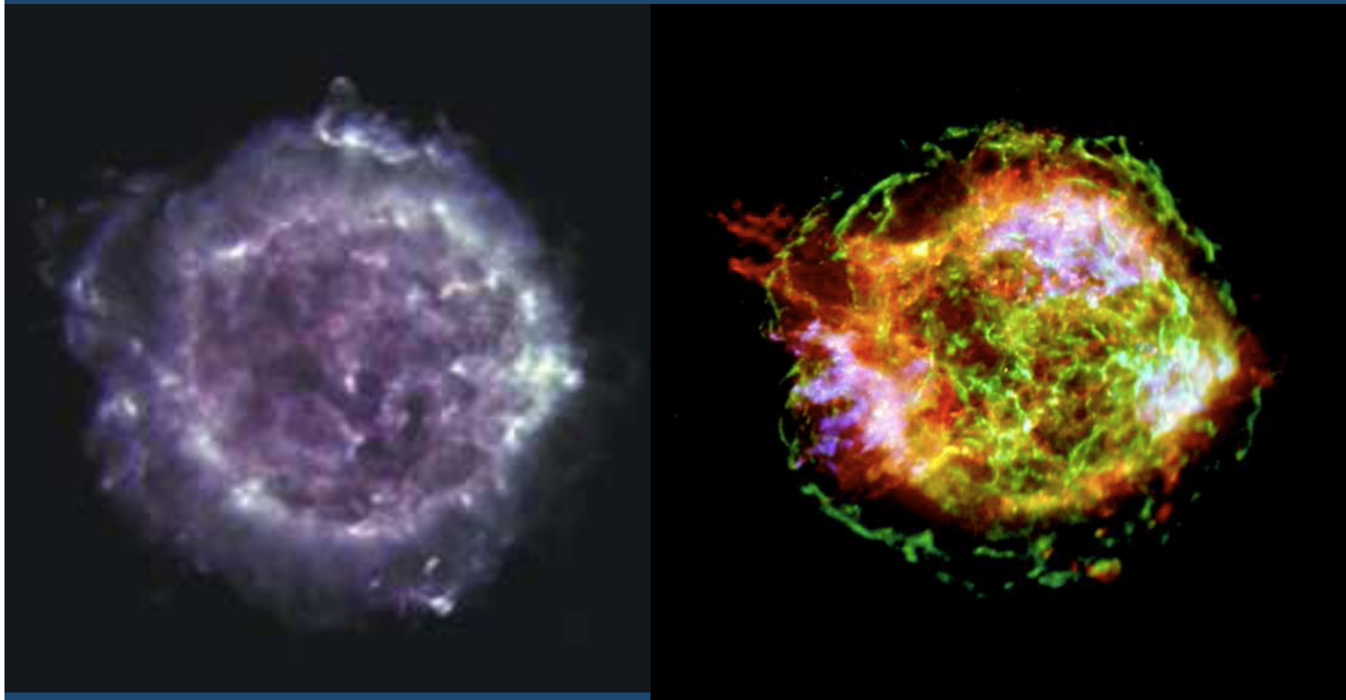


FIG. 4: The positron spectrum and positron fraction from the sum of contributions from B0656+14, Geminga, and all pulsars farther than 500 parsecs from the Solar System.

Supernova remnant Cas A in radio (left) and in X-ray (right) frequency range.



Cassiopeia A is the remnant of a supernova explosion that occured over 300 years ago in our galaxy. The radio emission is synchrotron radiation of shock-accelerated electrons detected with the VLA (Very Large Array) telescope in New Mexico. The X-ray picture from the CHANDRA observatory is a composite of three X-ray bands: low energy (red), medium energy (green) and high energy (blue). The bright outer ring marks the location of a shock wave generated by the supernova explosion. Cas A is also a TeV gamma-ray emitter, due to high energy electrons.

SNR are the canonical sources of CRs

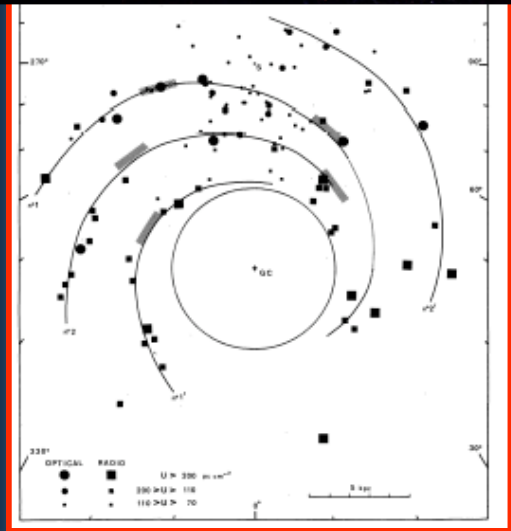
Tsvi Piran, Nir J. SHaviv (Hebrew U) Ehud Narkar (Tel Aviv U) Astro-ph/09020376 astro-ph/0905.0904

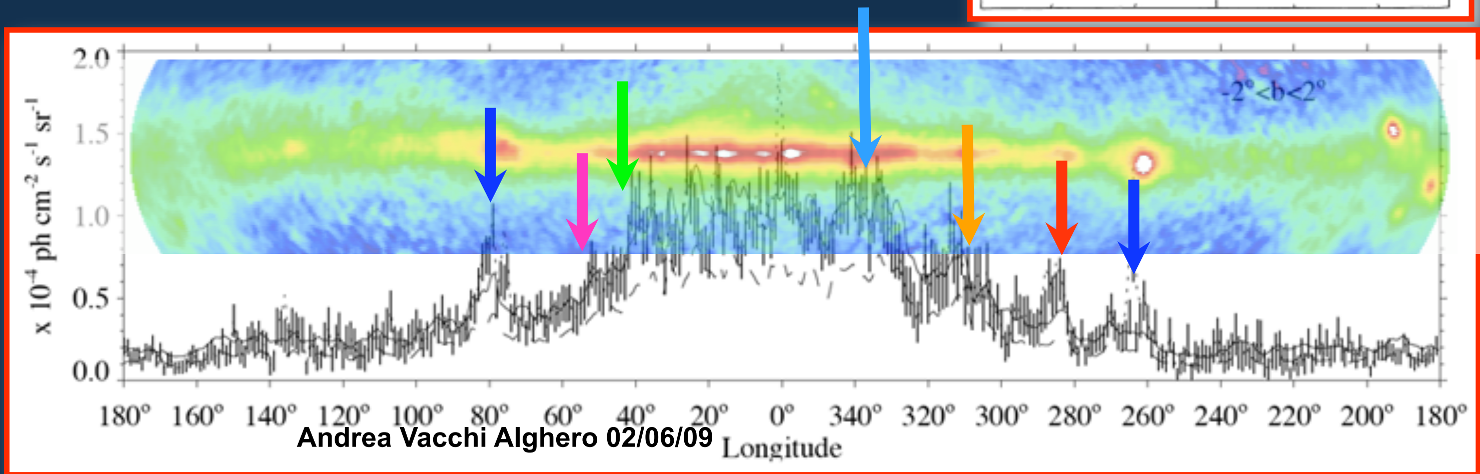
- Mechanism exists (1st order diffusive / shock acceleration)
- Ginzburg & Syrovatskii (1963) - Energy requirements agree with CR density/lifetime (assuming ~ 3% - 10% efficiency)
- Observations of Synchrotron from SNe reveals efficient electron acceleration

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

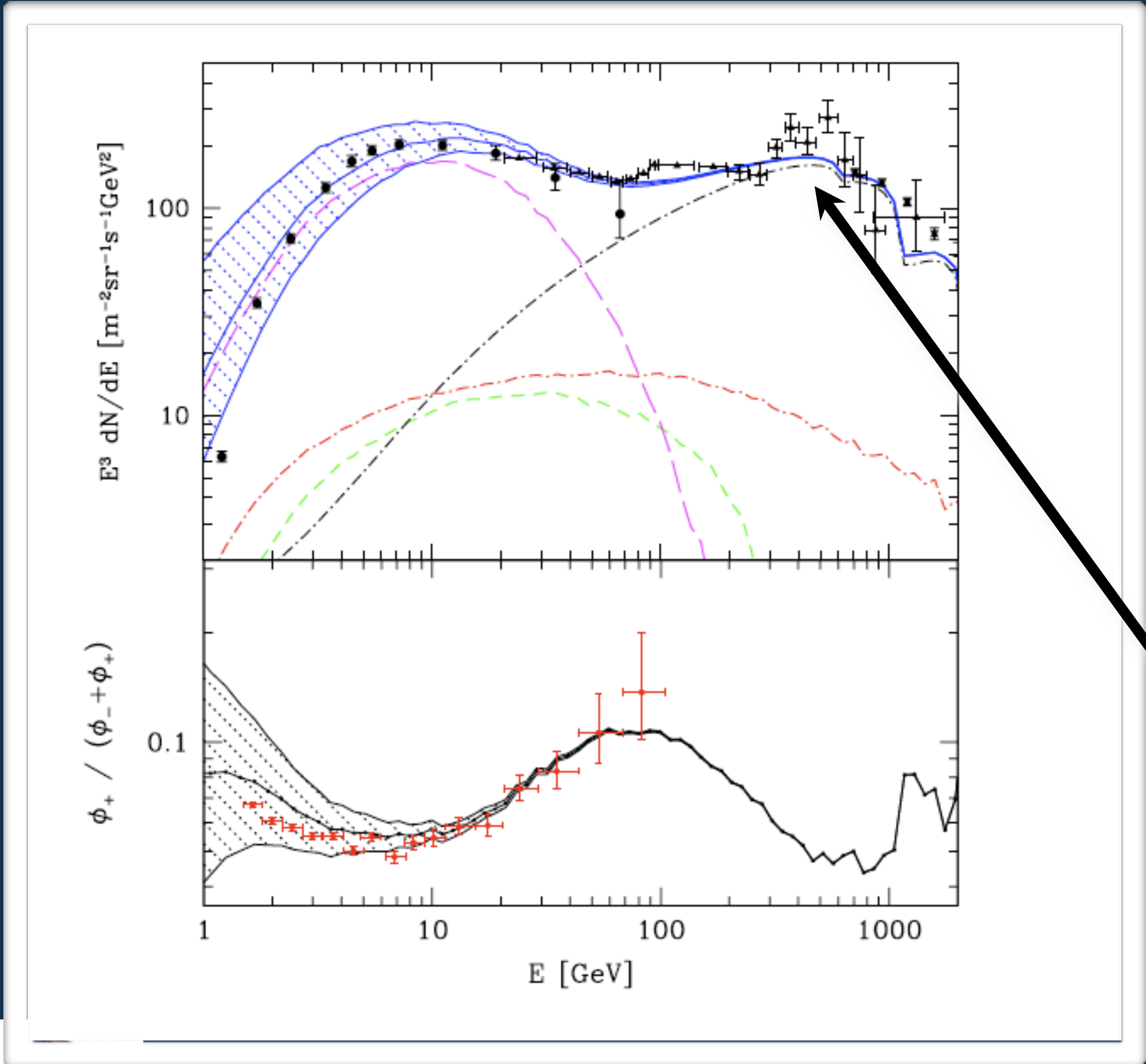
- In the Milky Way: Almost all Sne occur where most of star formation takes place: In the Spiral Arms
- Meteorites: Show that density changes by a factor of > 2.5
- Deconvolved Synchrotron: Shows arm to inter-arm ratio of ~ 3





$e^+/(e^++e^-)$ 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

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

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.

Missing Matter

- Zwicky (1933) measured the radial velocities for eight galaxies in the Coma cluster and found an **unexpectedly large velocity dispersion** of ~1000 km/s.
- He used the **Virial Theorem** to deduce that the mass density of Coma would have to be ~400 times that of the luminous matter -- although he assumed a Hubble parameter of ~500 km/s/Mpc. For present day value of Hubble parameter mass discrepancy of ~50.
- What caused this **mass discrepancy**? What could resolve it?

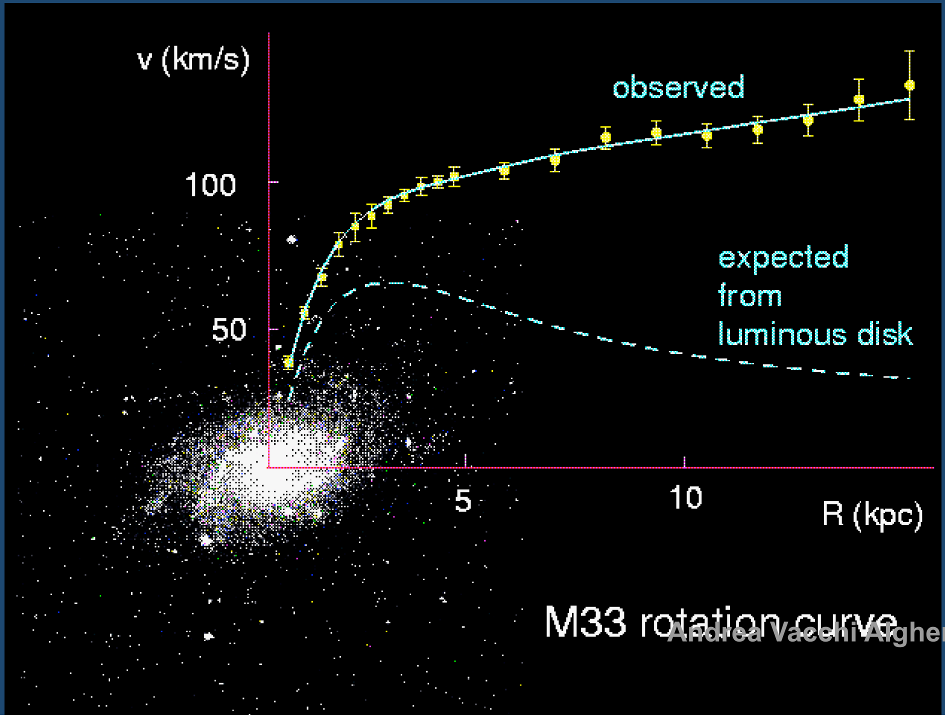
THE PROBLEM OF ROTATION CURVES

- One can compute the rotational velocity of isolated stars or hydrogen clouds in the outer parts of Galaxies simply using Newton's law

$$\frac{v_{\text{rot}}^2}{r} = \frac{G\ M(r)}{r^2} \quad \Longrightarrow \quad v_{\text{rot}} = \sqrt{\frac{G\ M(r)}{r}}$$

Thus for $r > r_{\text{luminous disk}}$, $M(r) = M_{\text{luminous disk}} = constant$ $\Longrightarrow$ $v_{\text{rot}} \propto \frac{1}{\sqrt{r}}$

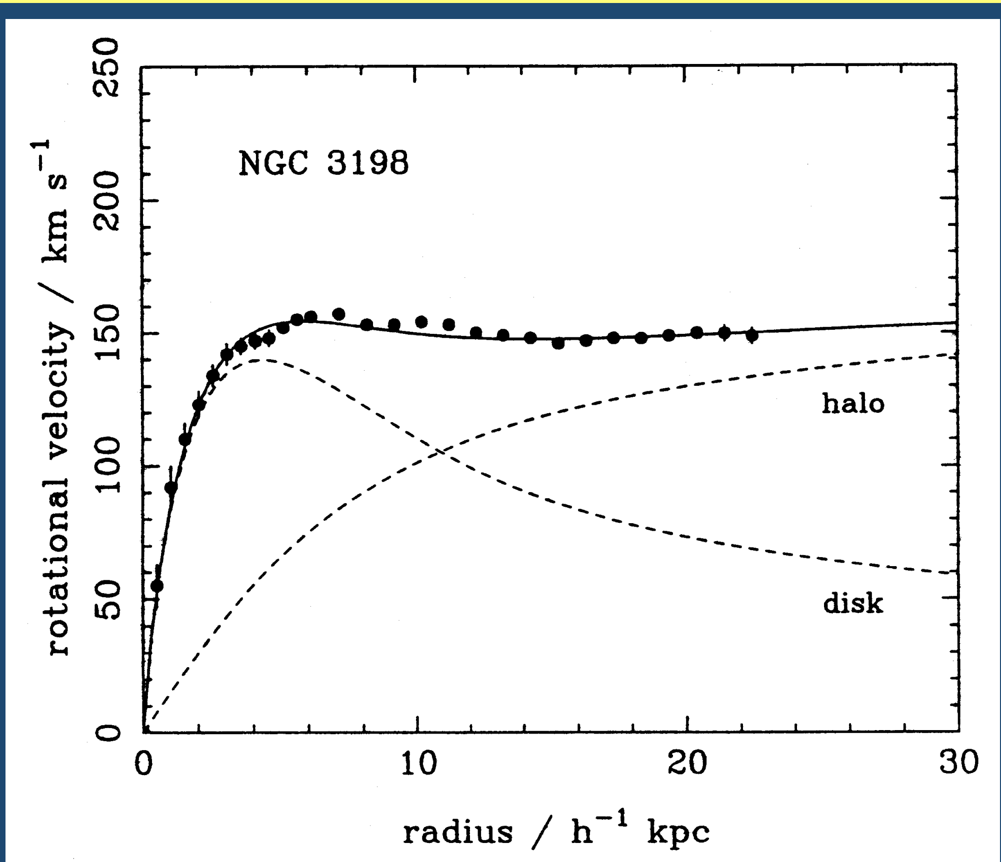
- **However, astronomers observe e.g.**

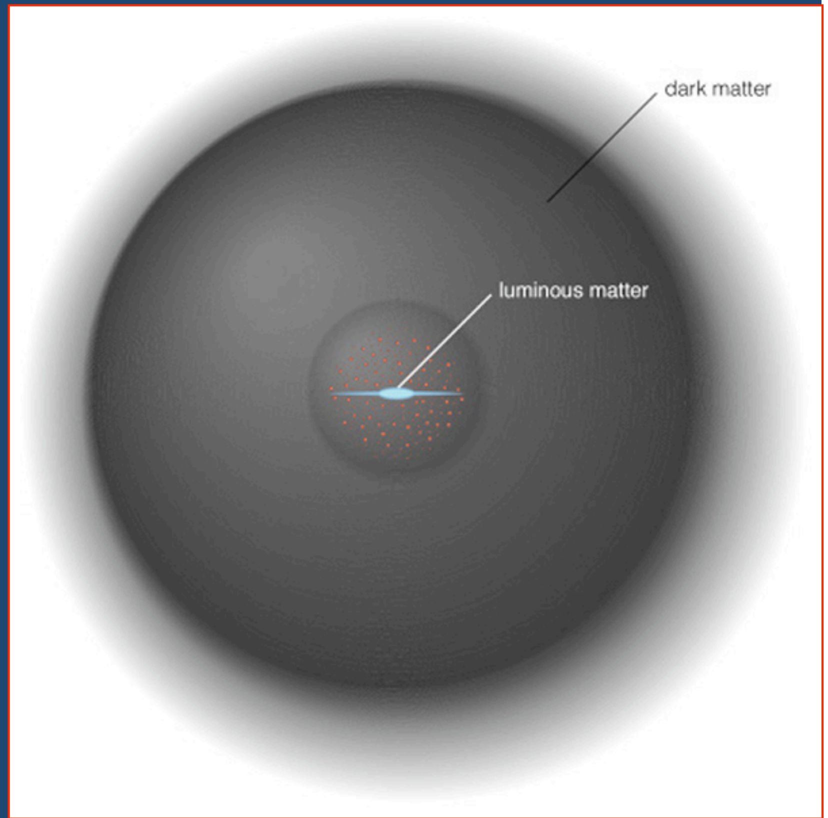


$\Omega_{\text{LM}}\, h^2 \approx 0.01$

$\Omega_{\text{DM}}\, h^2 \approx 0.1$

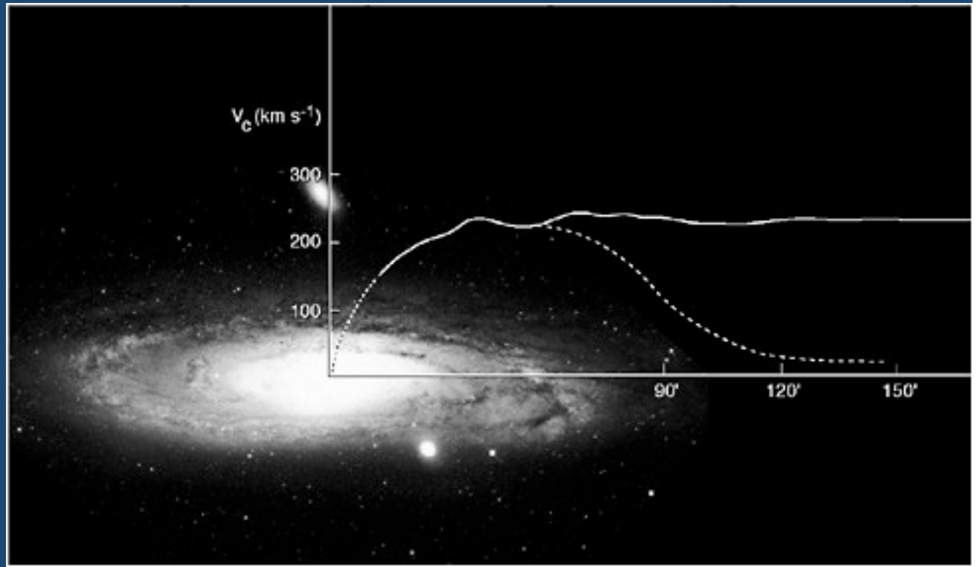
~1970: Vera Rubin, Ken Freeman and others explore rotation curves and (re-)find the need for dark matter (formerly called *missing matter*).





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

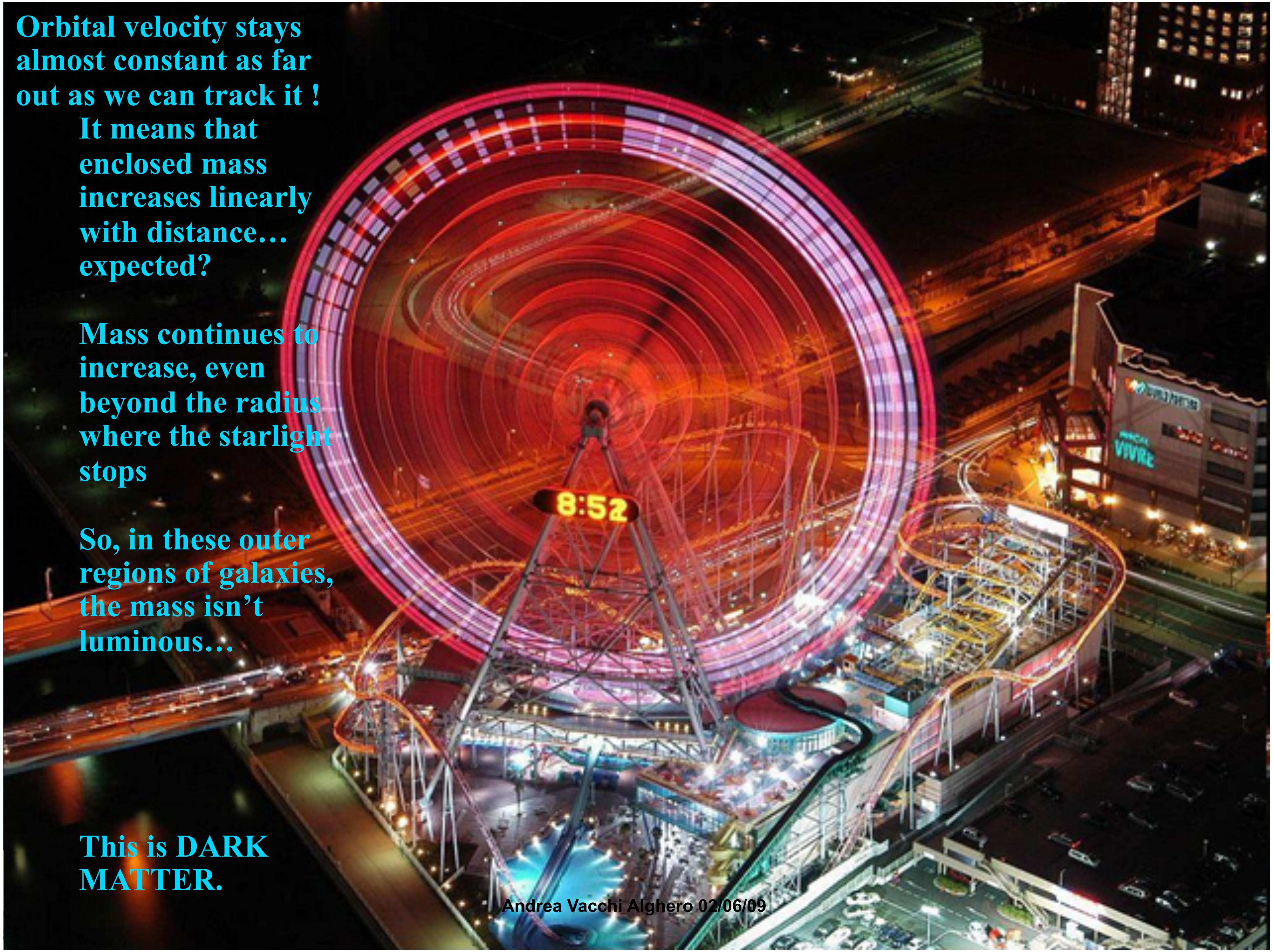
At around this time there were a number theoretical studies of the implications of "dark matter" in galaxies...

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?

INFN



Orbital velocity stays almost constant as far out as we can track it !

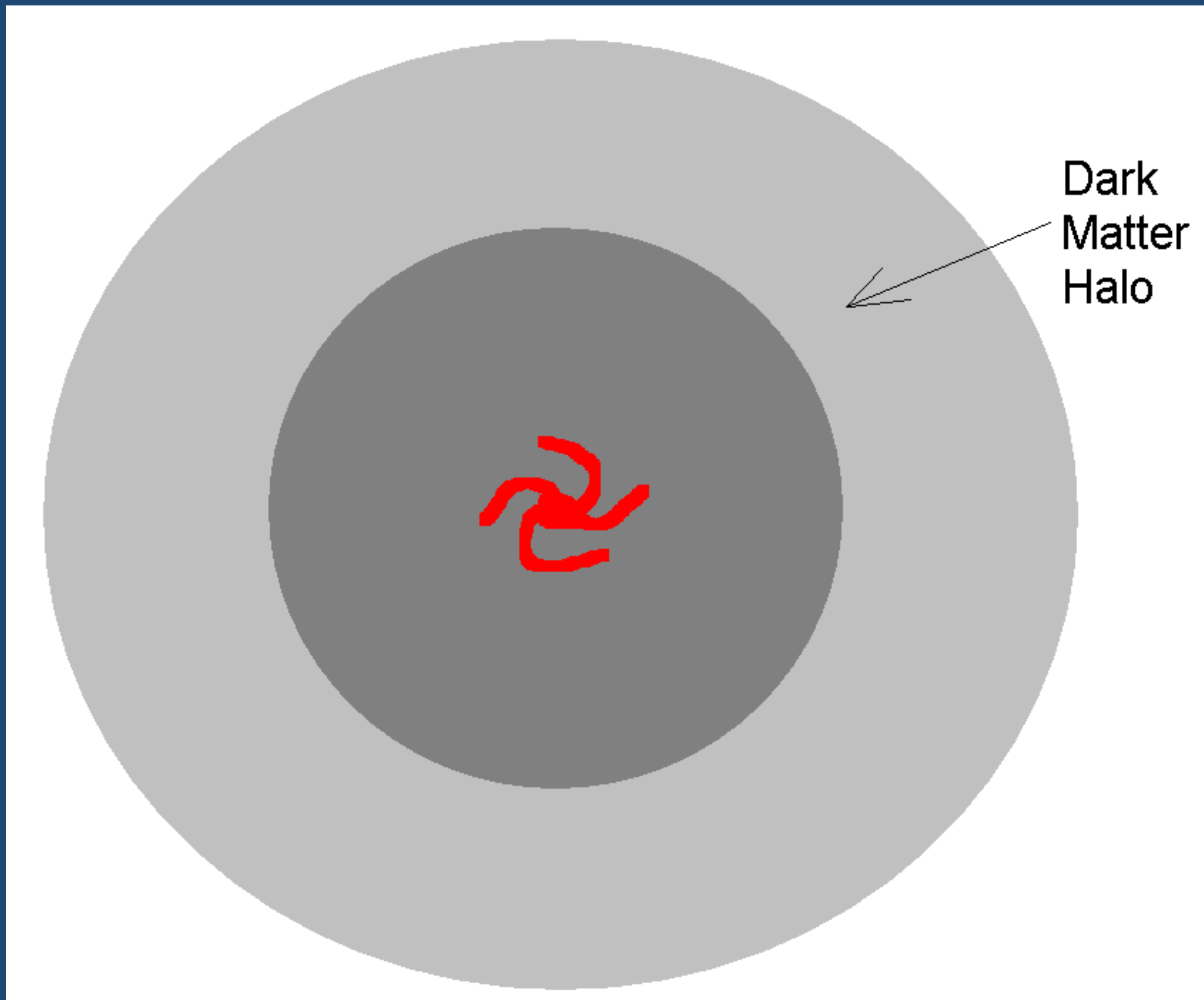
It means that enclosed mass increases linearly with distance… expected?

Mass continues to increase, even beyond the radius where the starlight stops

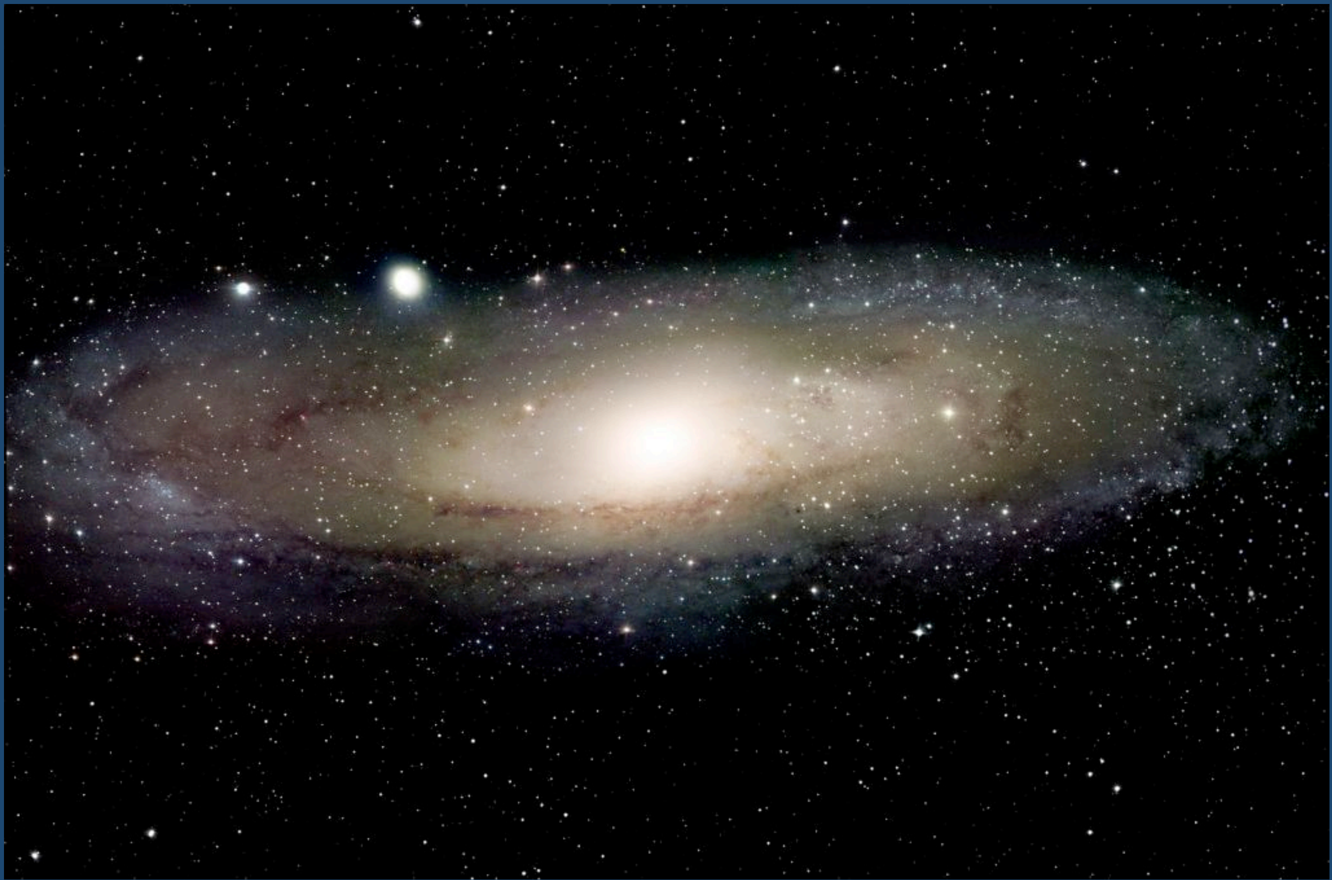
So, in these outer regions of galaxies, the mass isn’t luminous…

This is DARK MATTER.

Called a dark matter "halo"



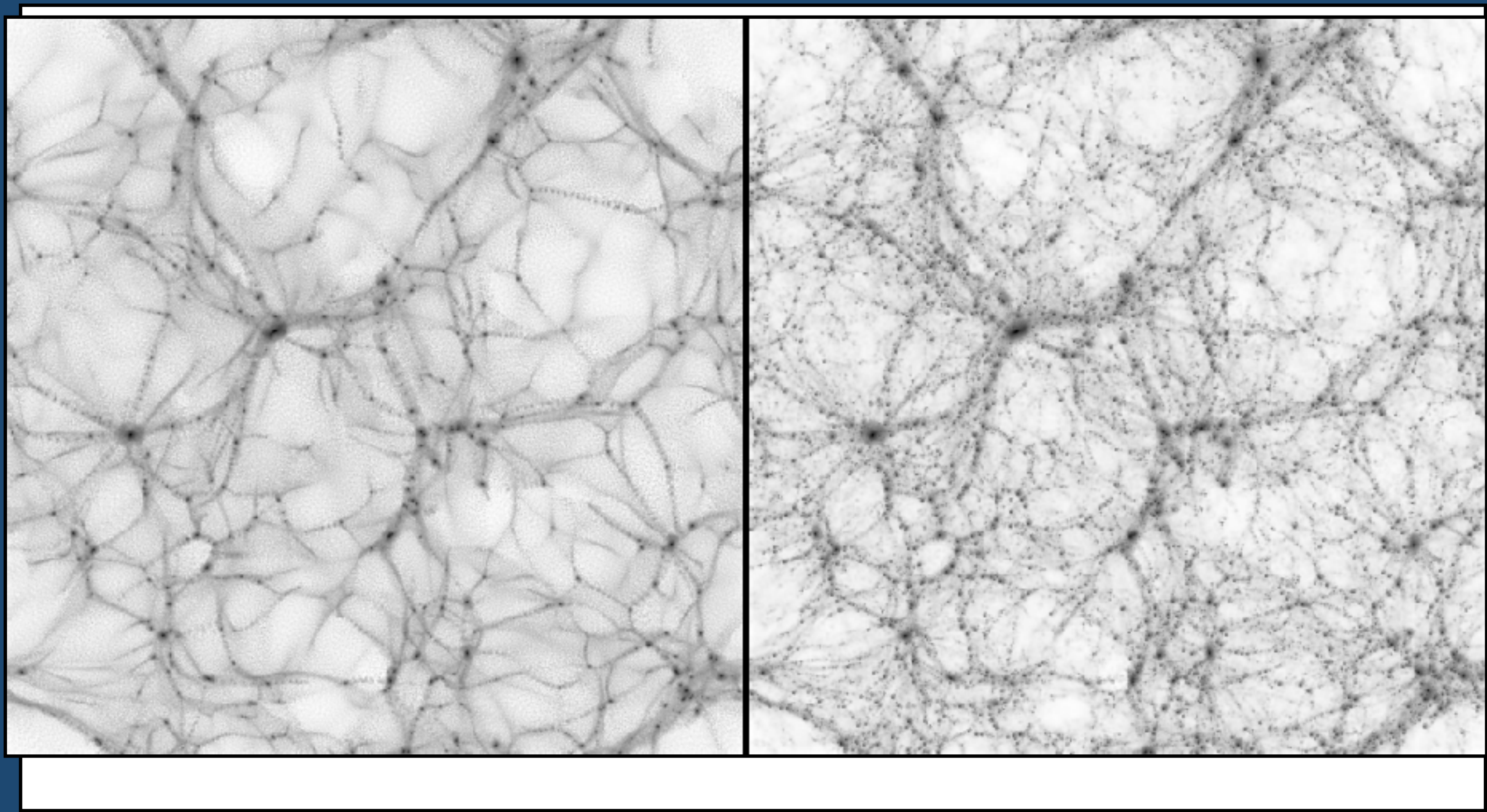
- **Apply same arguments to a galaxy…**



The Cold Dark Matter Model

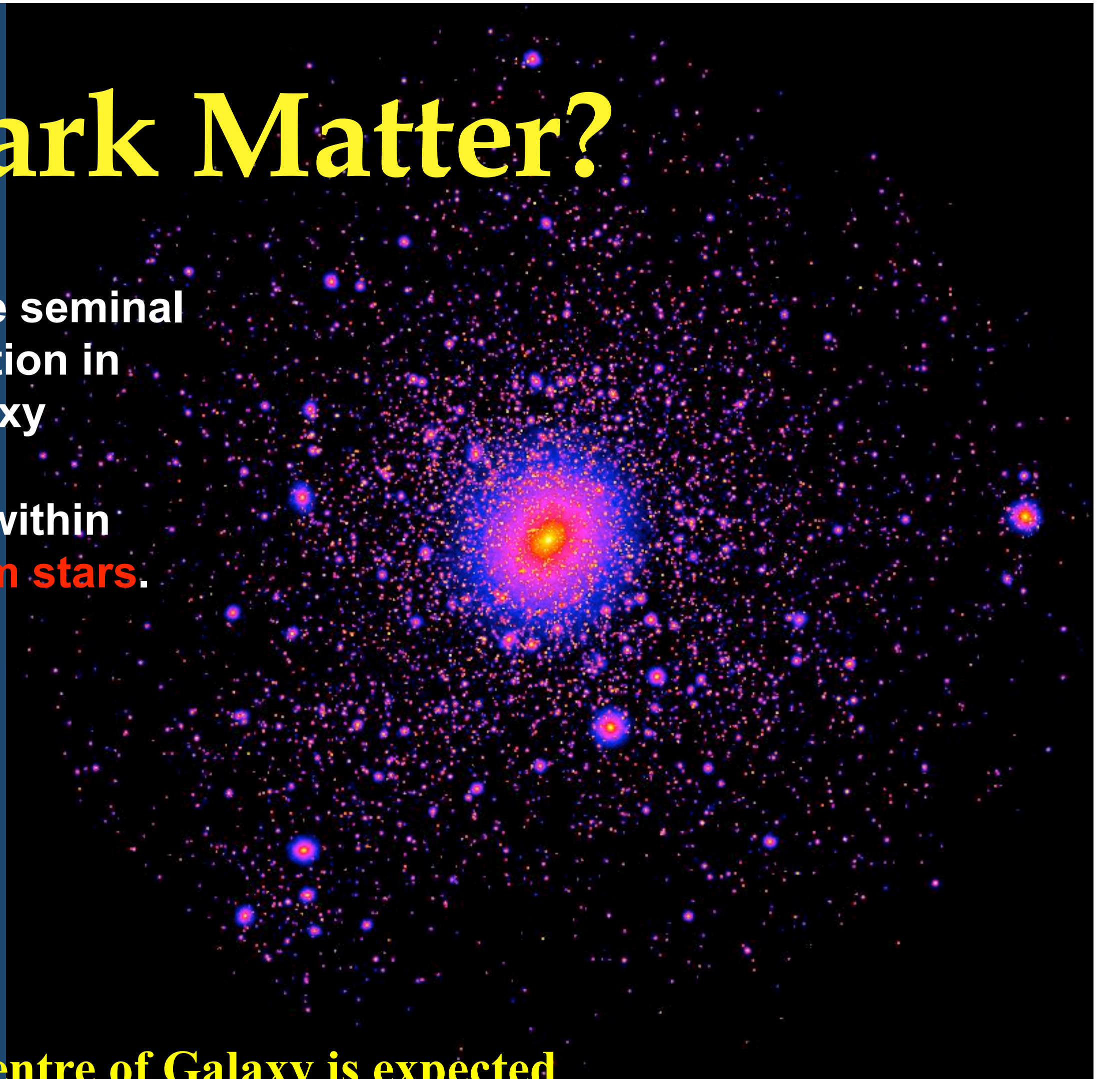
- Standard theoretical framework for cosmological structure formation :-
  - The Universe is spatially flat..
  - It underwent a period of rapid exponential inflation shortly after the Big Bang
  - The matter content is dominated by non-baryonic Cold Dark Matter.
  - The expansion rate of the Universe at the present epoch is accelerating, driven by dark energy.

Evidence for Dark Matter



What about Dark Matter?

White & Rees (1978) published one of the seminal studies in cosmology -- "Core condensation in heavy halos - A two stage theory for galaxy formation and clustering" -- dark matter aggregates provided the potential wells within which gas could cool, condense and form stars.



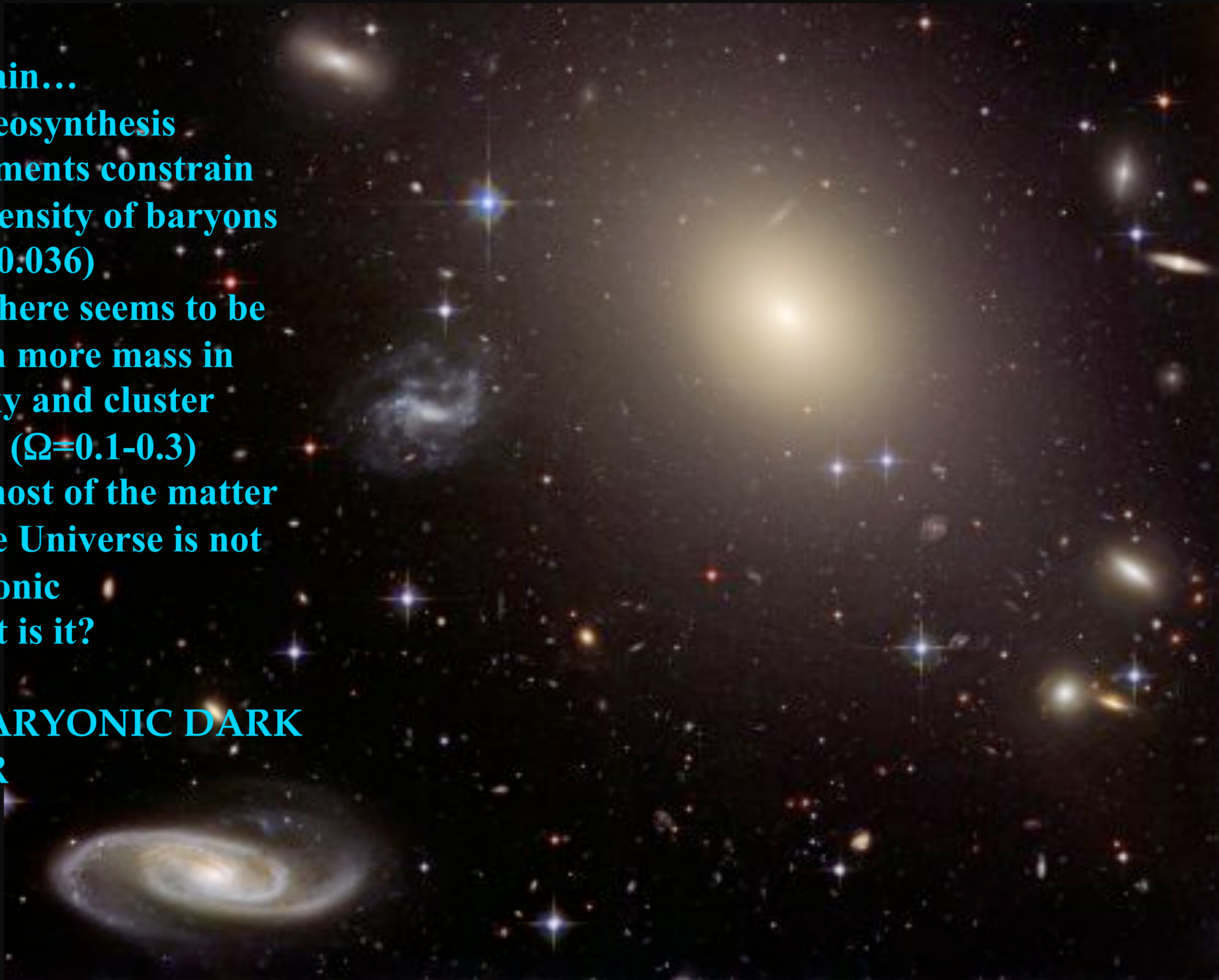
- Cusp of dark matter at centre of Galaxy is expected
- Annihilation of DM particles in Galactic Halo could produce energetic particles:
  - Antiprotons
  - Positrons
  - Gamma-rays (lines or through hadronisation)
- Annihilation signal ~ density^2

Recap again…

- Nucleosynthesis arguments constrain the density of baryons ($\Omega_B \approx 0.036$)
- But there seems to be much more mass in galaxy and cluster halos (Ω=0.1-0.3)
- So, most of the matter in the Universe is not baryonic

So… what is it?

NON-BARYONIC DARK MATTER



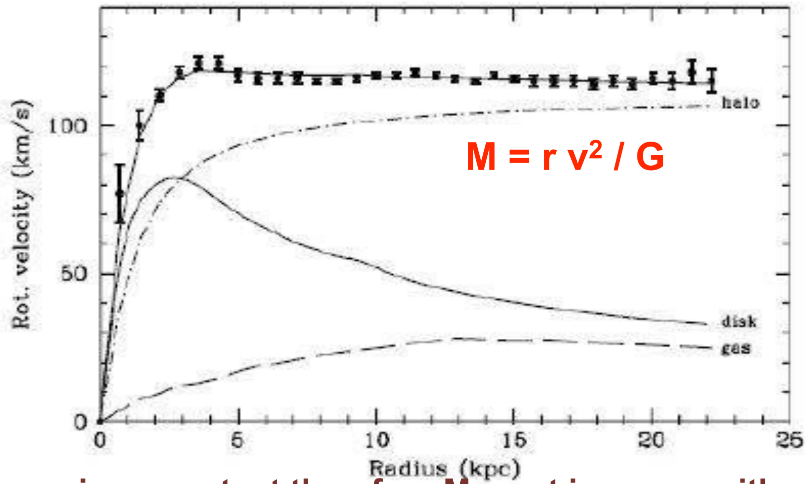
Observing Dark matter

1. Galaxy rotation speeds
   → There is dark matter in our galaxy
2. Gravitational lensing
   → There is dark matter in the Universe
   → → Cosmic lensing has great prospects
3. Big bang nucleosynthesis
   → There is non-baryonic dark matter

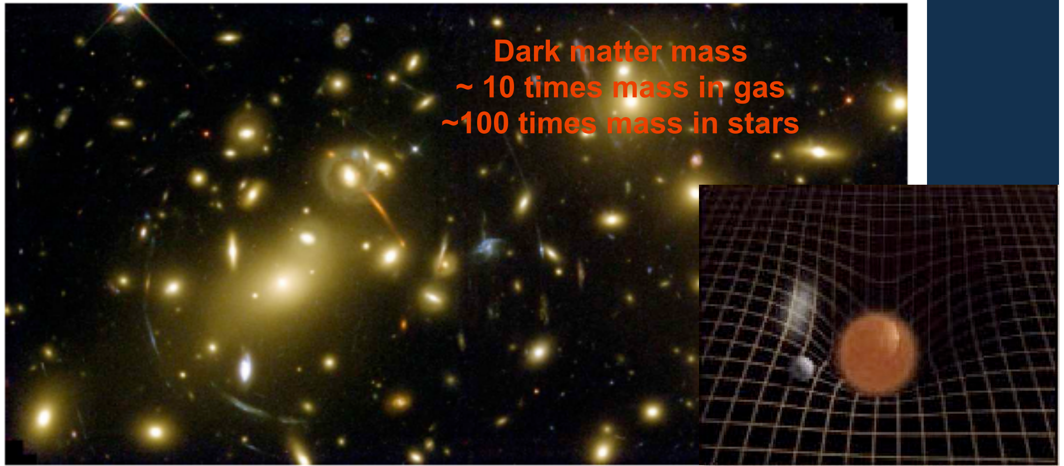
INFN

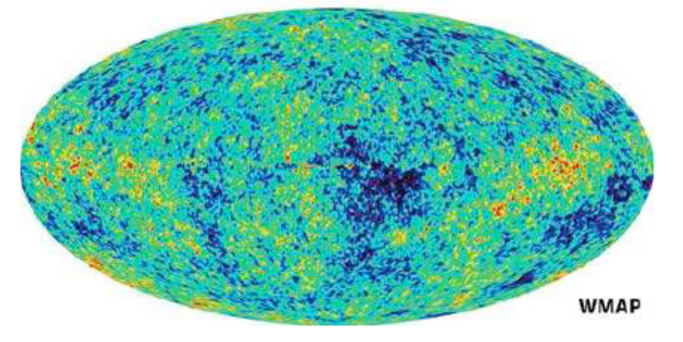
DM evidences

- 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)



v is a constant therefore M must increase with r





Dark matter problem: observations

SCALE

OMEGA

Galactic

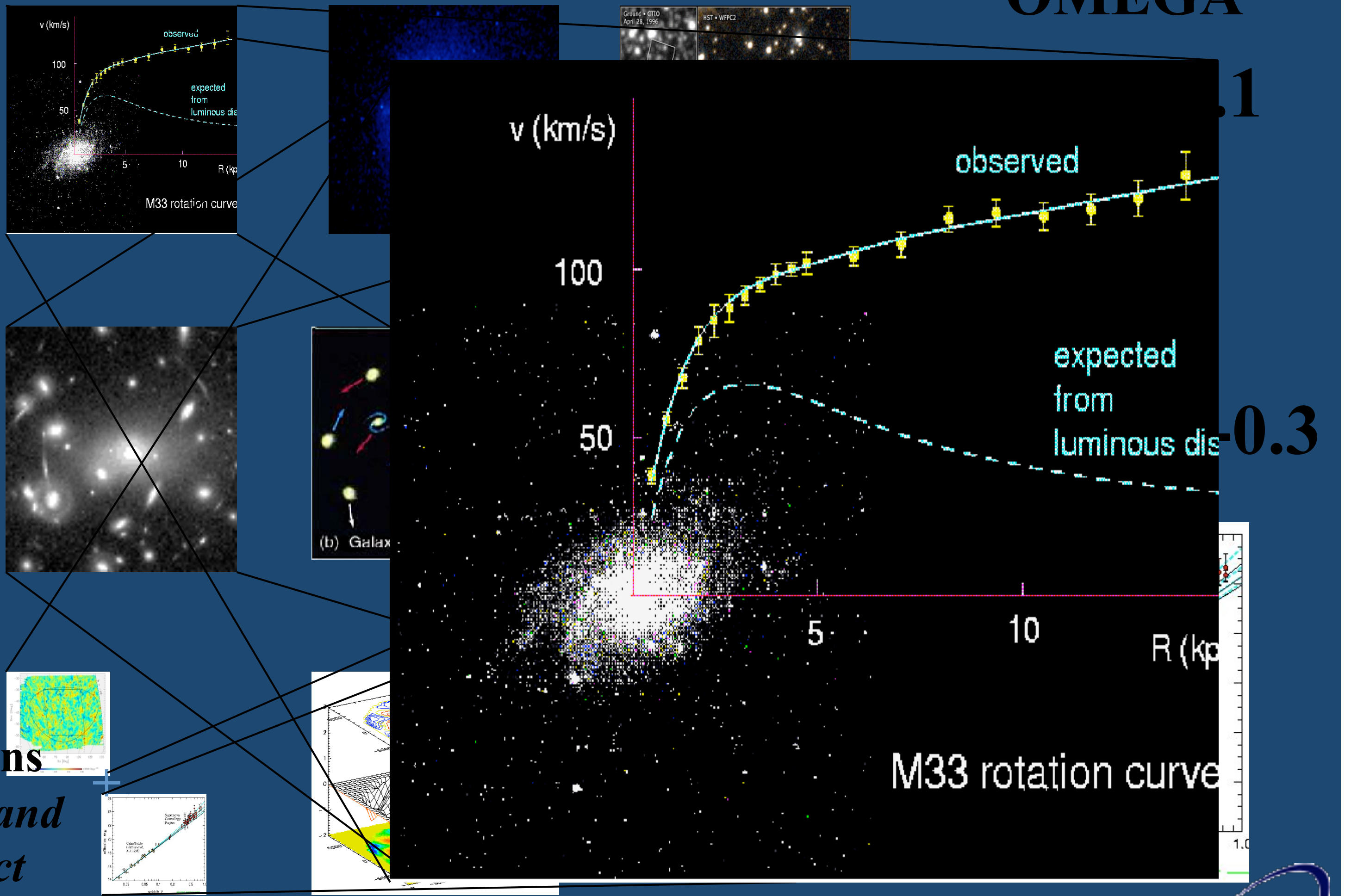
Galaxy rotation curves
Credit:
Corbell, Salucci (1999)

Cluster

Gravitational lensing
Credit: HST

Cosmological

CMB + SNIa observations
Credit: BOOMERANG and the SN Cosmology Project



.1

-0.3

Matter in the Universe

Microwave Anisotropy

WMAP - NASA - Explorer Mission →

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

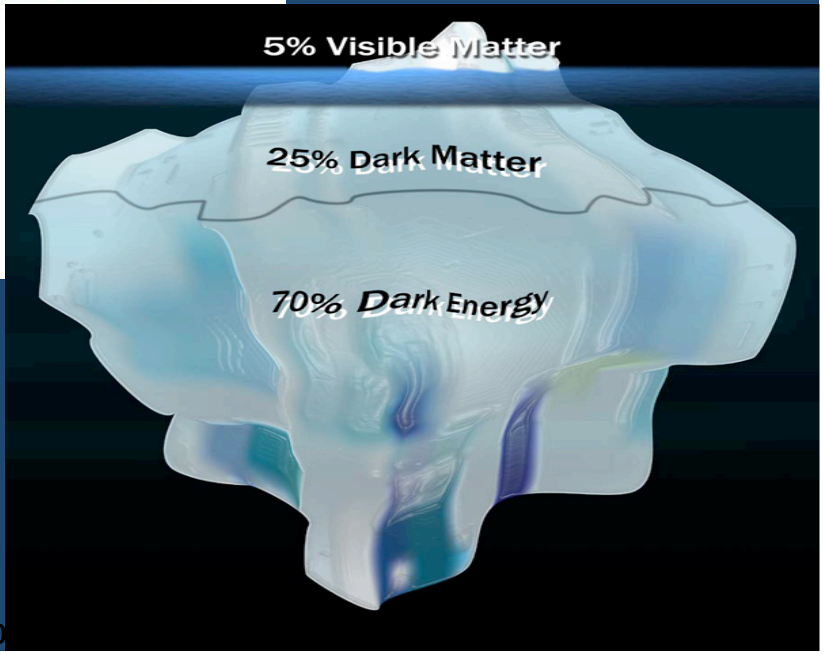
(Universe is flat)

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

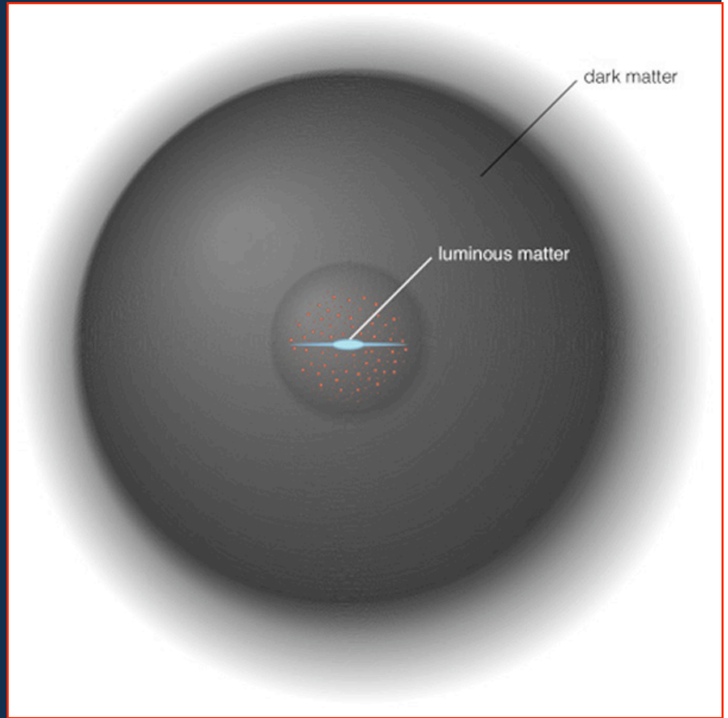
$$\Omega_{total} = \Omega_{total,baryon.} + \Omega_{dyn.} + \Omega_{required}$$

baryonic matter	dark matter	dark energy
5%	23%	72%
	??	???
stars, galaxies	candidates:	quintessence

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



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.

Cosmic-ray Antimatter from Dark Matter annihilation?

→ Distortion of antiproton and positron spectra from purely secondary production

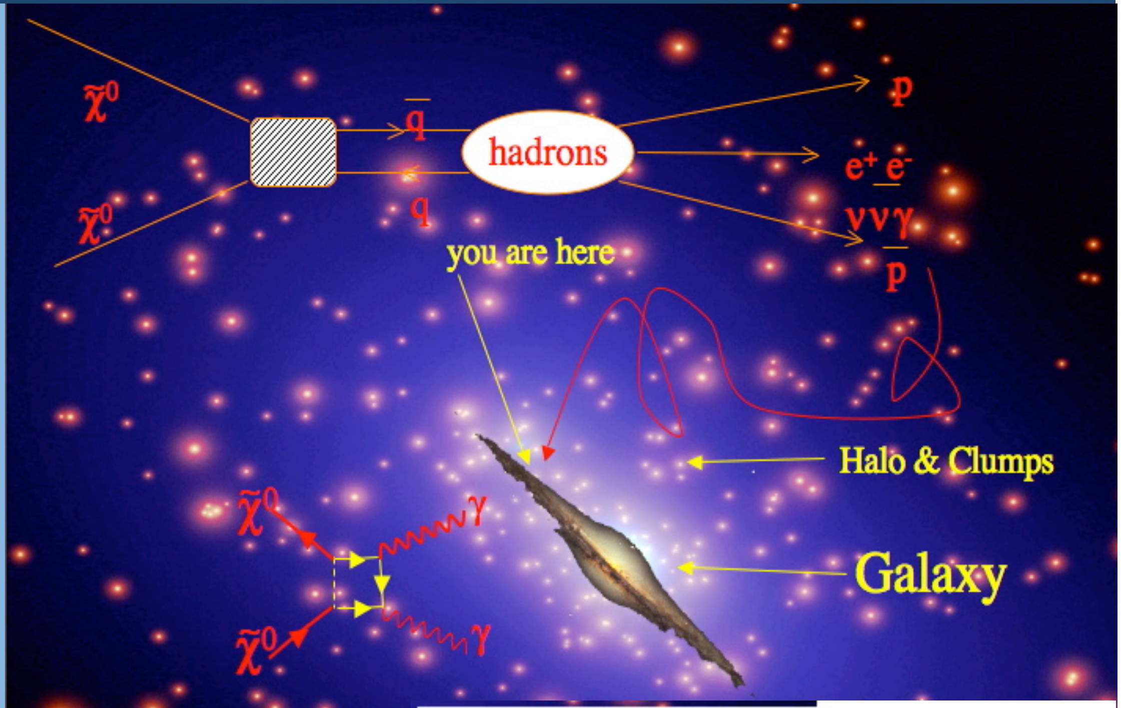
A plausible dark matter candidate is neutralino (χ), the lightest SUSY particle.

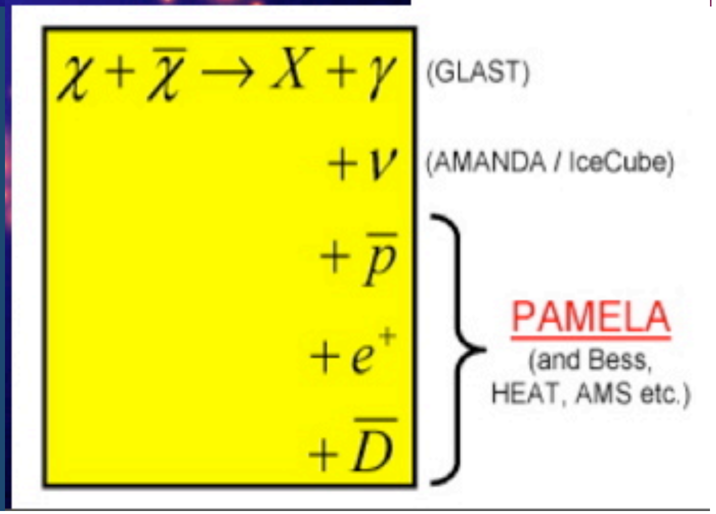
Annihilation of relic χ gravitationally confined in the galactic halo

Most likely processes:

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

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



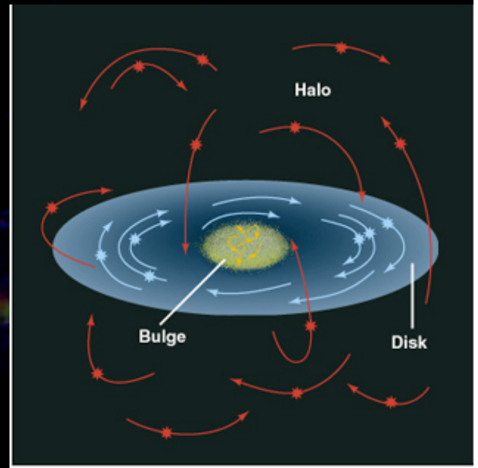


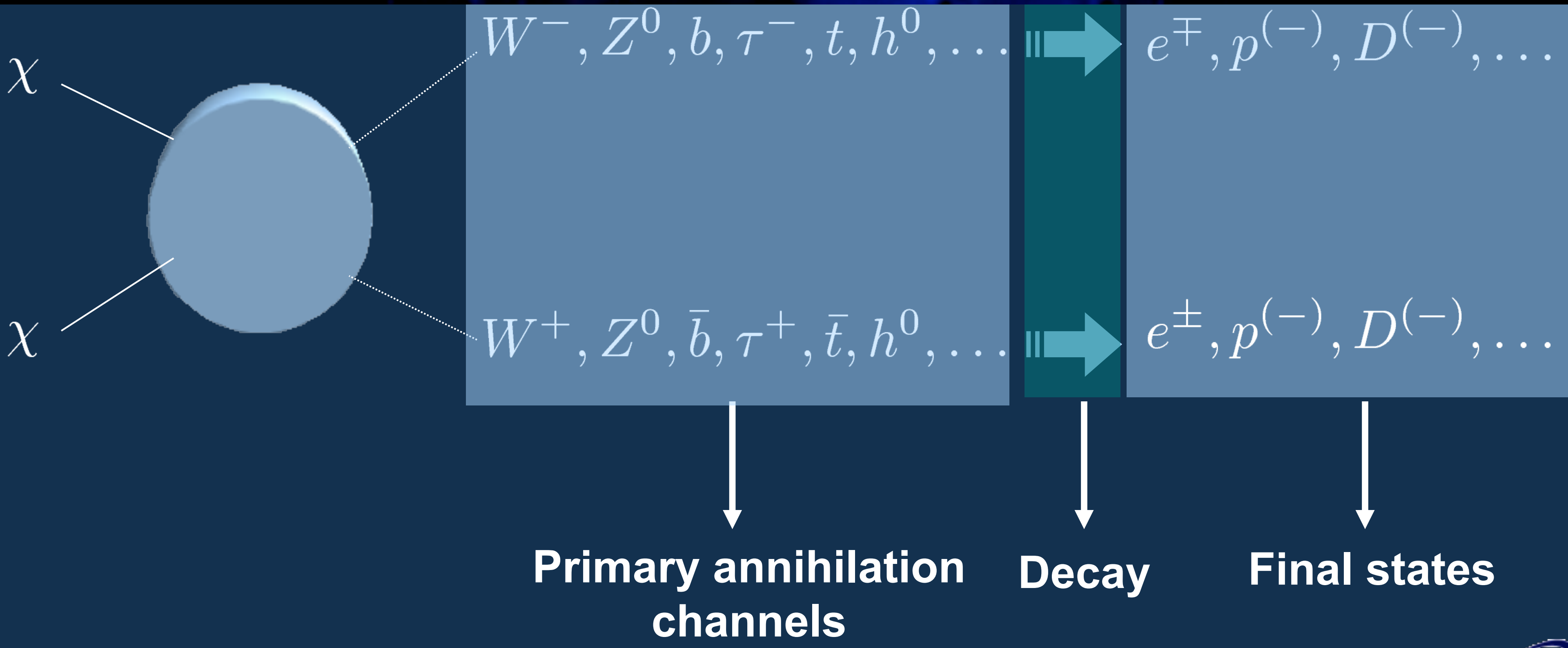
Dark matter annihilation

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





INFN

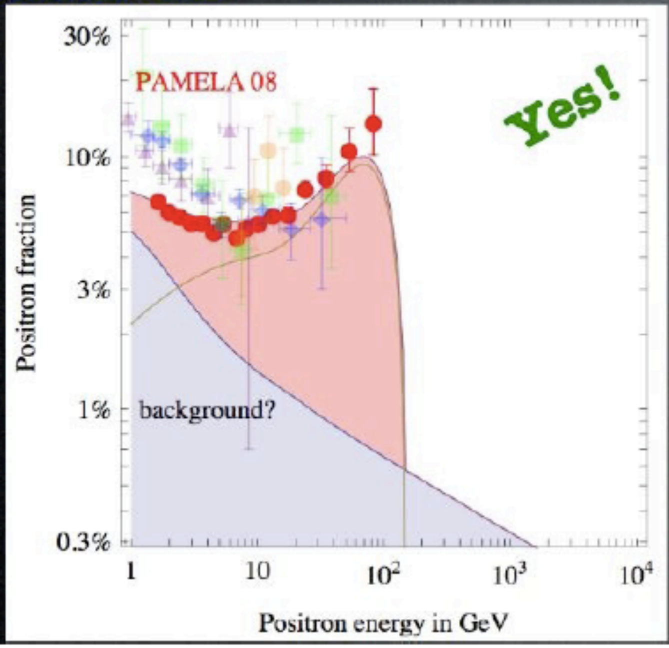
Which DM spectra can fit the data?

E.g. a DM with: -mass $M_{\rm DM} = 150\,\mathrm{GeV}$

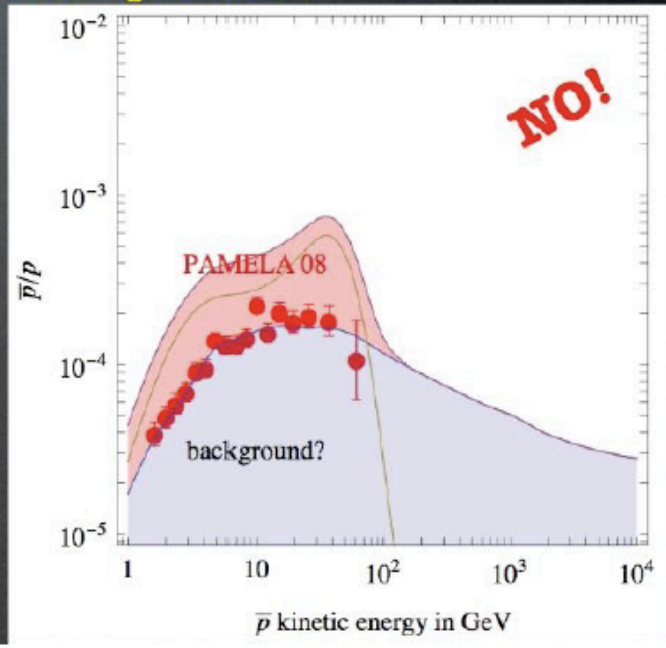
-annihilation $\mathrm{DM\ DM} \to W^+W^-$

(a possible SuperSymmetric candidate: wino)

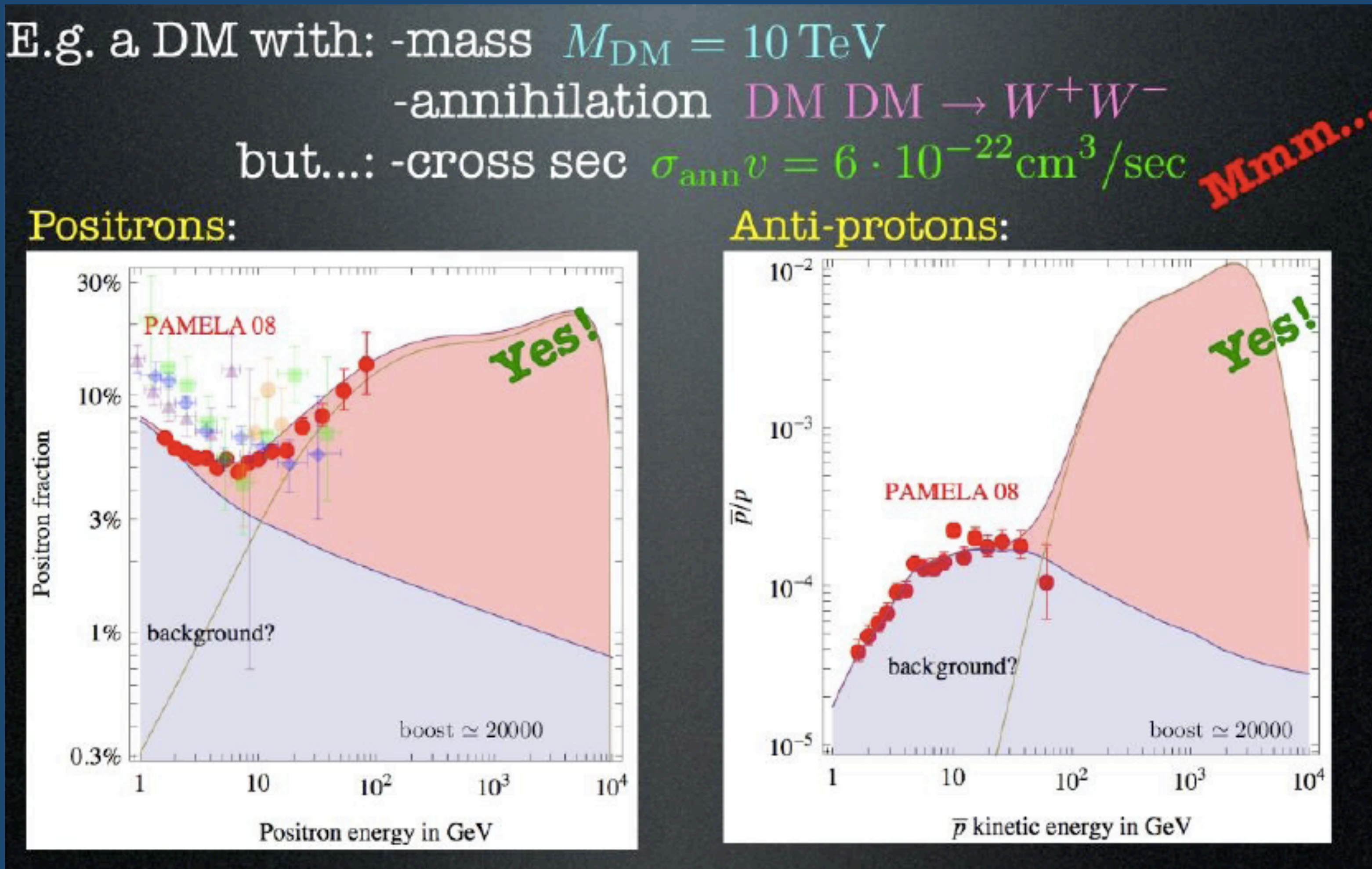
Positrons:



Anti-protons:



Leptonically decaiyng DM ?
Boost factor from clumpy DM?



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

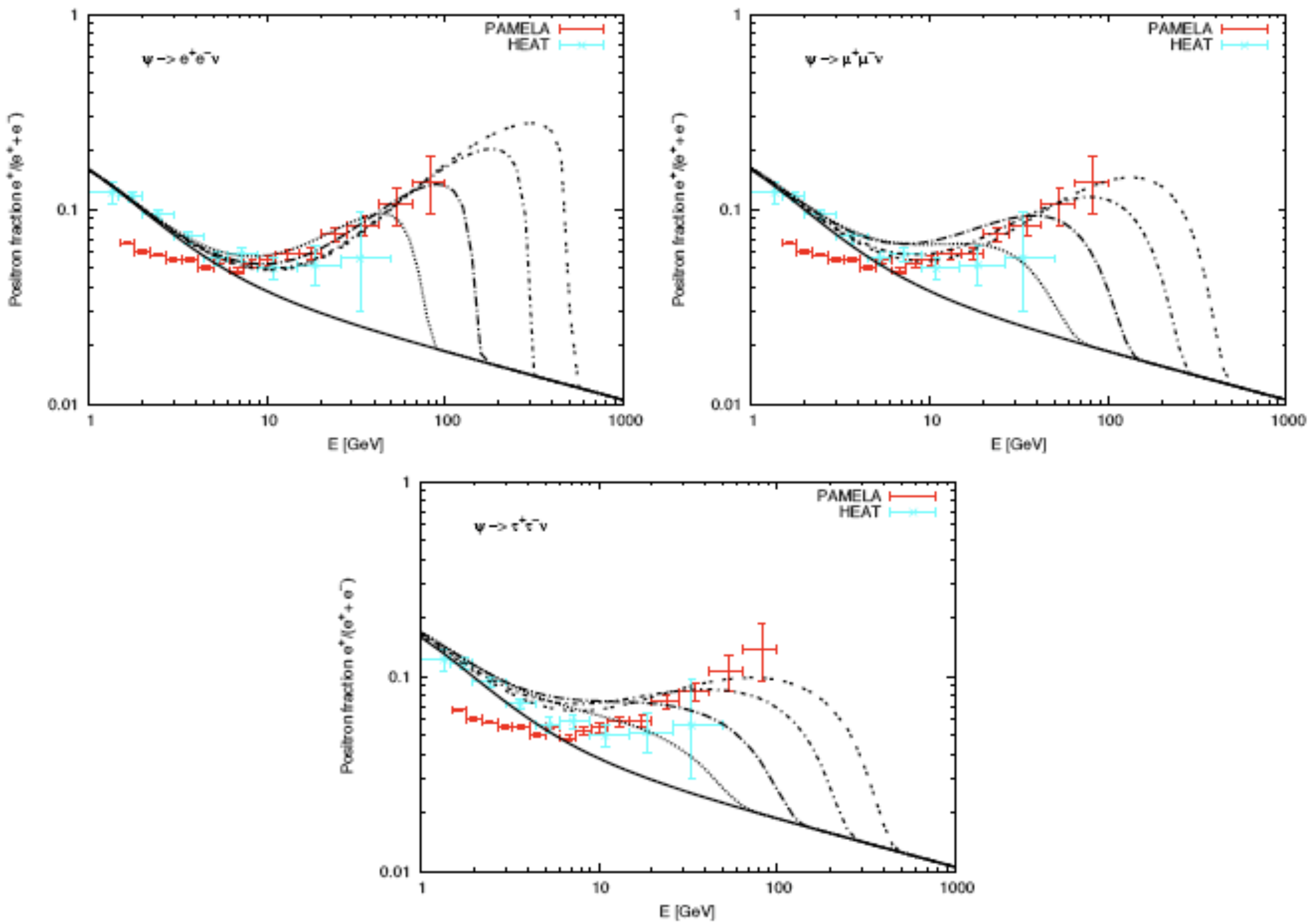
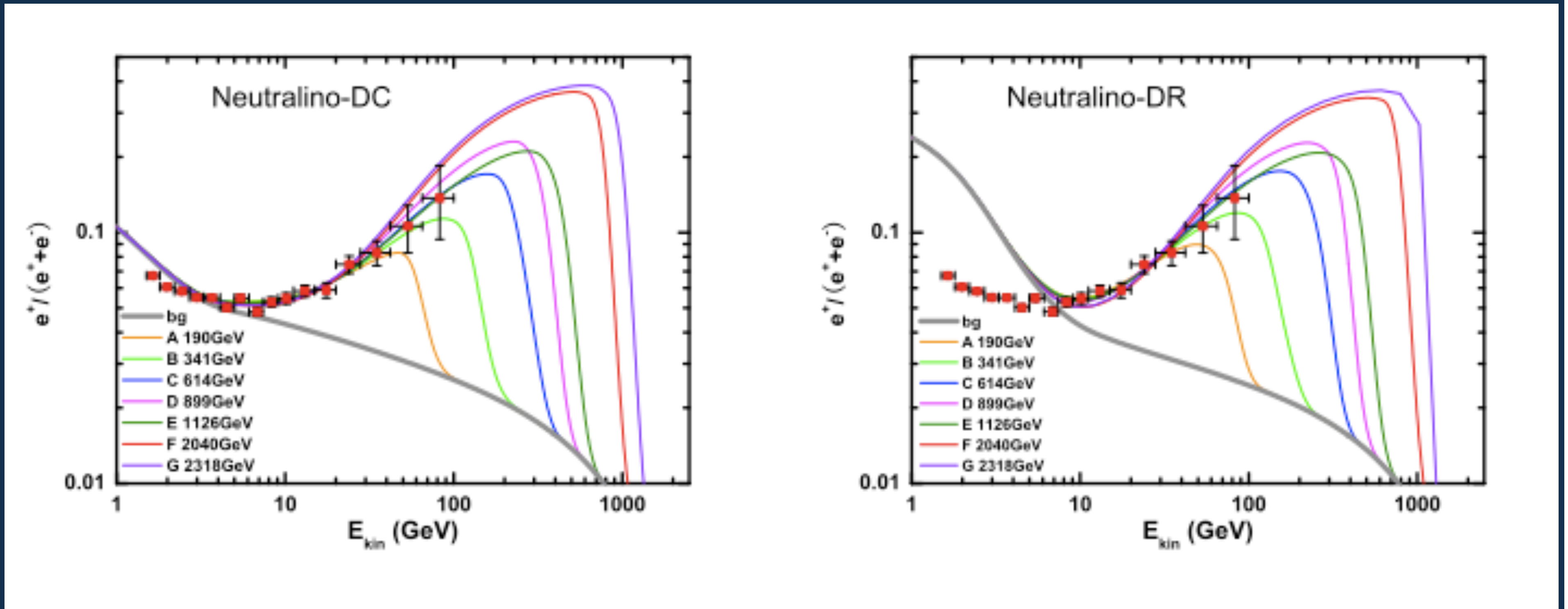


Figure 3: Positron fraction from the decay of the fermionic dark matter particle in the channels $\psi \to e^+e^-\nu$ (top-left panel), $\psi \to \mu^+\mu^-\nu$ (top-right panel) and $\psi \to \tau^+\tau^-\nu$ (bottom panel), when the dark matter mass is, from left to right, $m_{DM} = 150,\ 300,\ 600,\ 1000$ GeV. The lifet[illegible] 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.



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.

Primary positron sources

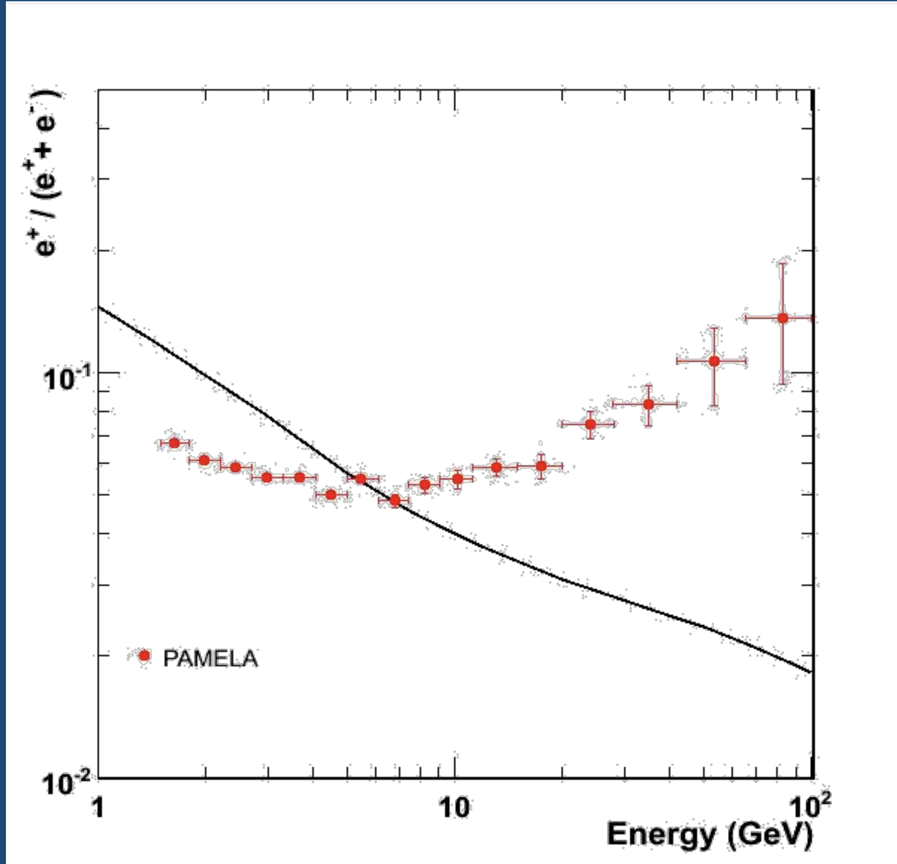
PAMELA positron fraction alone insufficient to understand the origin of positron excess

Additional experimental data will be provided by PAMELA:

- e^+ fraction @ higher energy (up to 300 GeV)
- individual $e^- e^+$ spectra
- anisotropy (…maybe)
- high energy $e^+ + e^-$ spectrum (up to 2 TV)

Complementary information from:

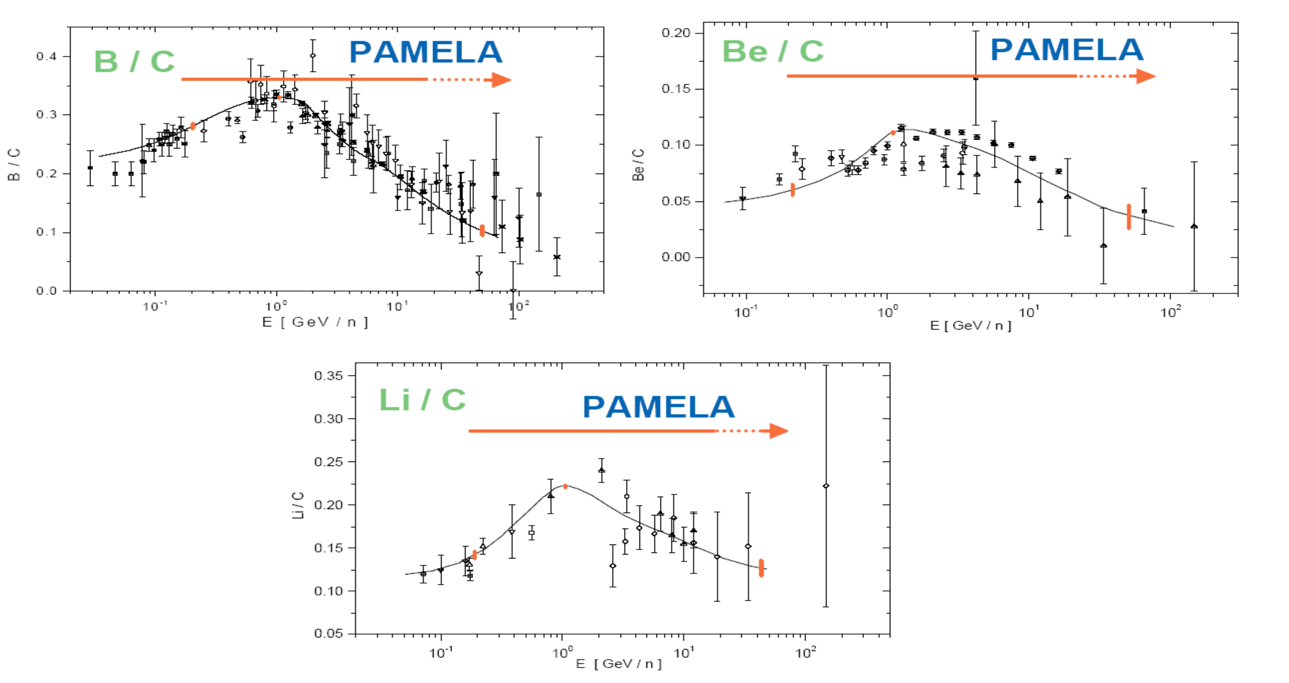
- gamma rays
- neutrinos



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**

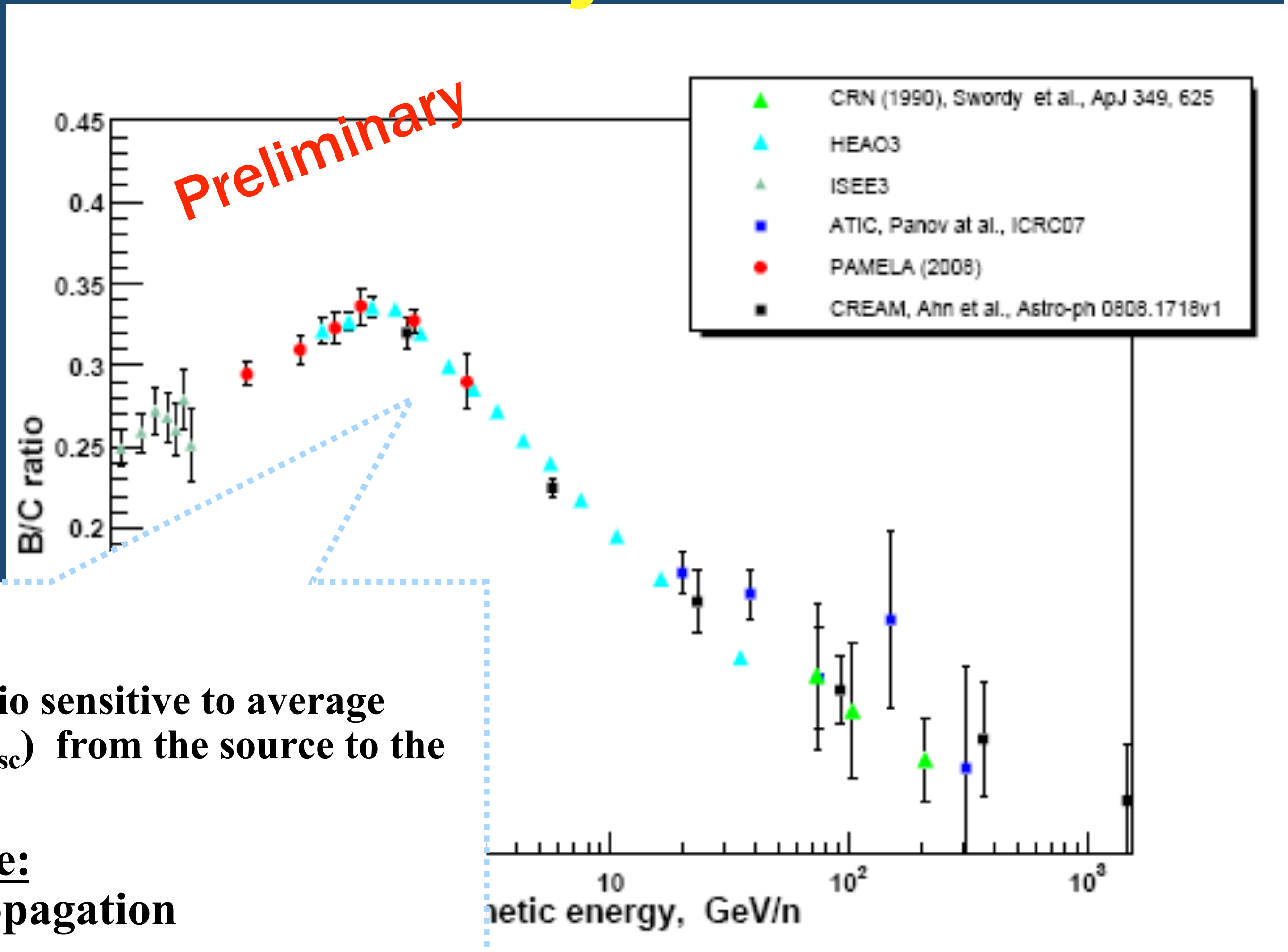
C and B to measure the ratio of Carbon to its spallation secondary Boron up to 200GeV/n allows to study:

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

LBM

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

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?

"If you find one, you'll know it reached you."

The discovery of one unqualified antinucleus $Z \geq 2$ in the galactic cosmic rays would have profound implications for both particle physics and astrophysics.

- Assumes antimatter domains exist

- 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)

-How far can cosmic rays travel in a Hubble time? Not more than 100 Mpc even with conservative estimates of intergalactic fields

-(Ormes et al. 1997 ApJLett. 482, L187; Adams et al. ApJ 491, 6 (1997); Tarlé et al. 1998 ApJ 498#2, 779)

- Did a domain of matter inflate to the size of the Universe? Is there baryon decay? Is CP violation strong enough to explain the large baryon to photon ratio? Can leptogenesis help?

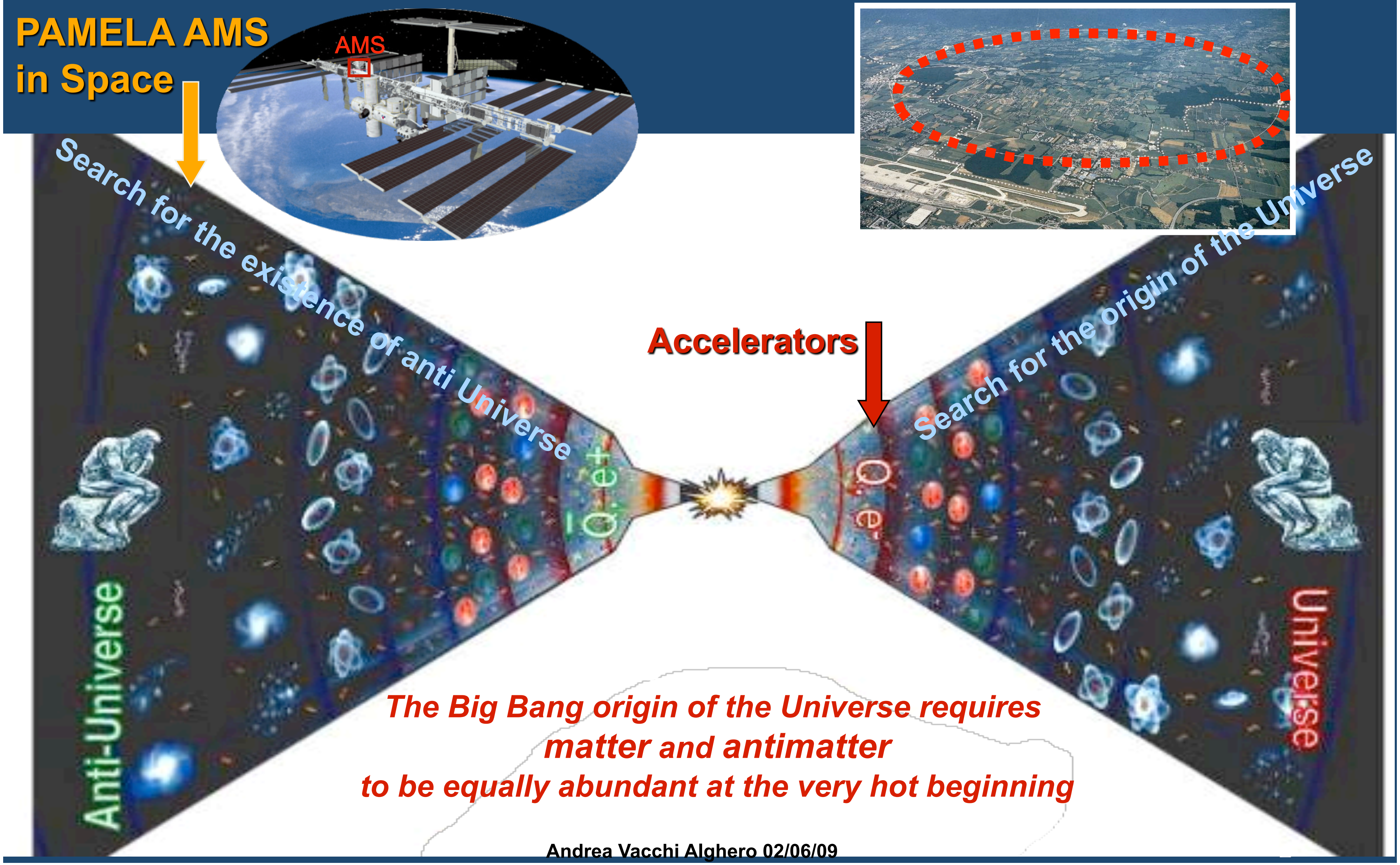
What about antinuclei?

- 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 in the universe: Antinuclei, antiparticles

- *The antiparticles are "secondaries" produced by CR interactions with ISM through inelastic collisions – "spallation"*

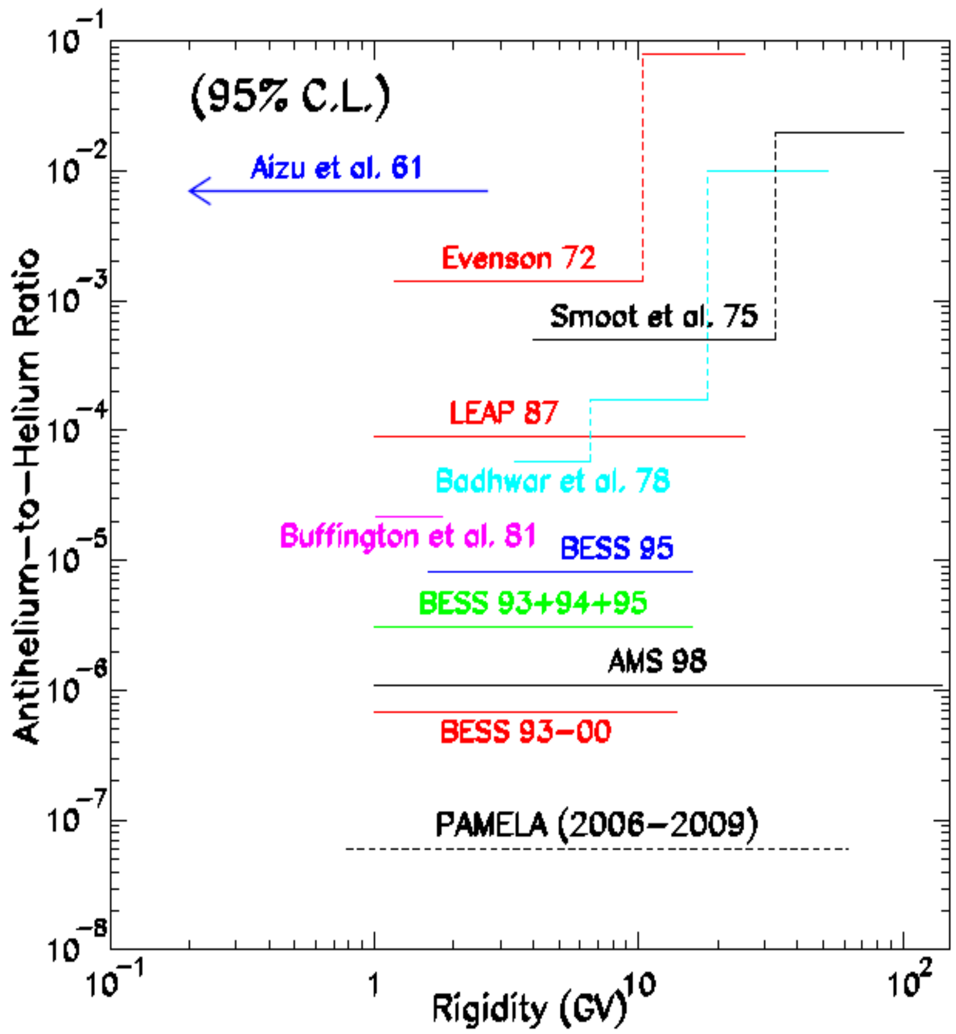
  Flux $^{4}\underline{\mathrm{H}}\mathrm{e}$ $O(10^{-12})$, $\underline{\mathrm{D}}$ $O(10^{-8})$, $\underline{\mathrm{p}}$ $O(10^{-4})$, e+ $O(10^{-3})$

- *But some antiparticles can be "primaries" from exotic sources of antimatter or DM annihilation*

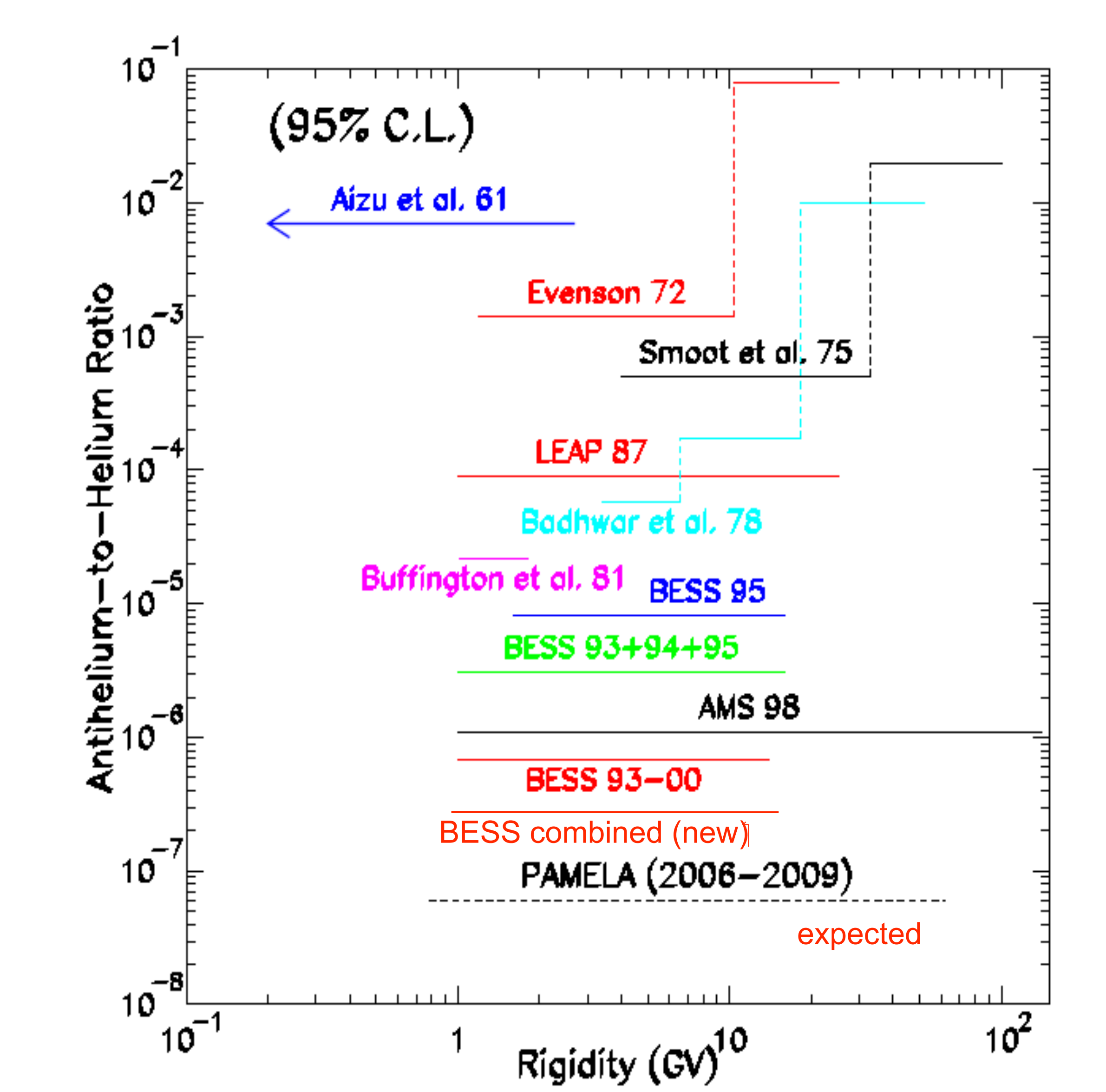
  (an $\underline{\mathrm{He}}$ would be evidence of antistars)

Antimatter in our universe: Experimental searches

An anti-nucleus can be found in Cosmic Rays, with a spectrometer on a satellite (Pamela, AMS)



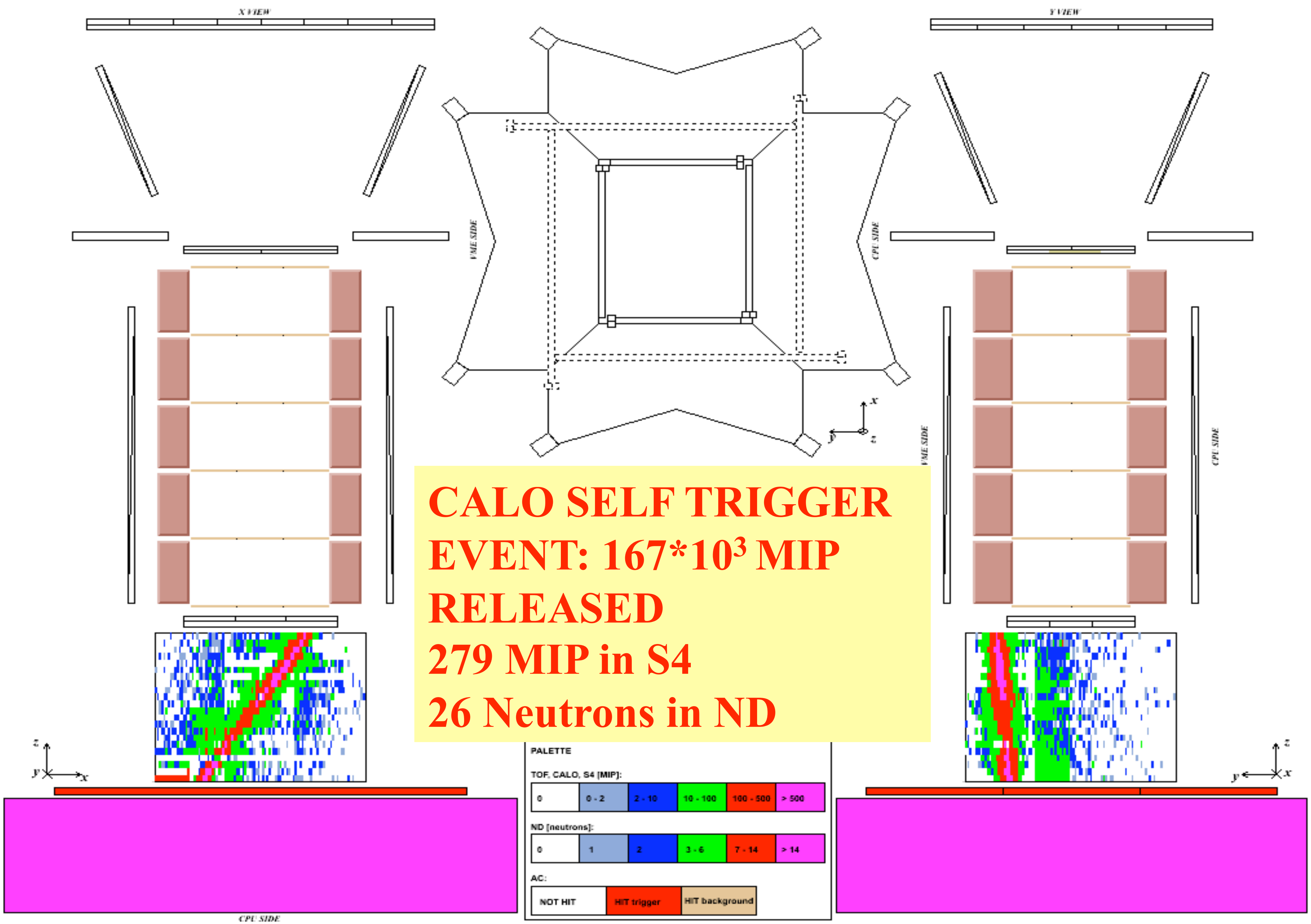
Antimatter search



Andrea Vacchi Alghero 02/06/09

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≤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

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.