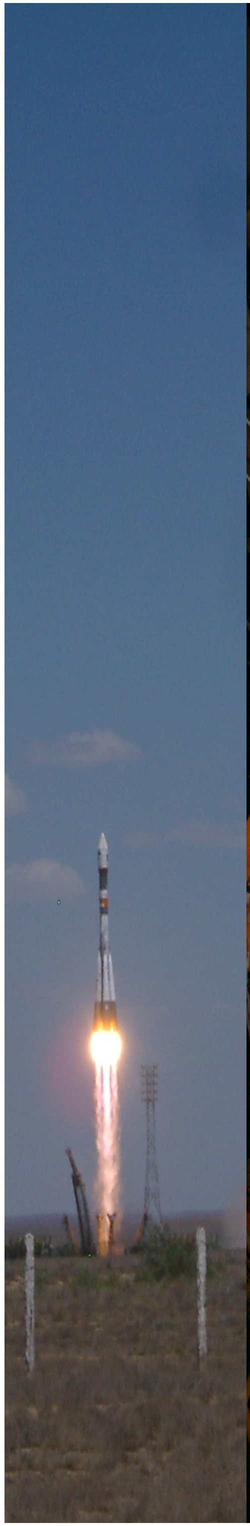
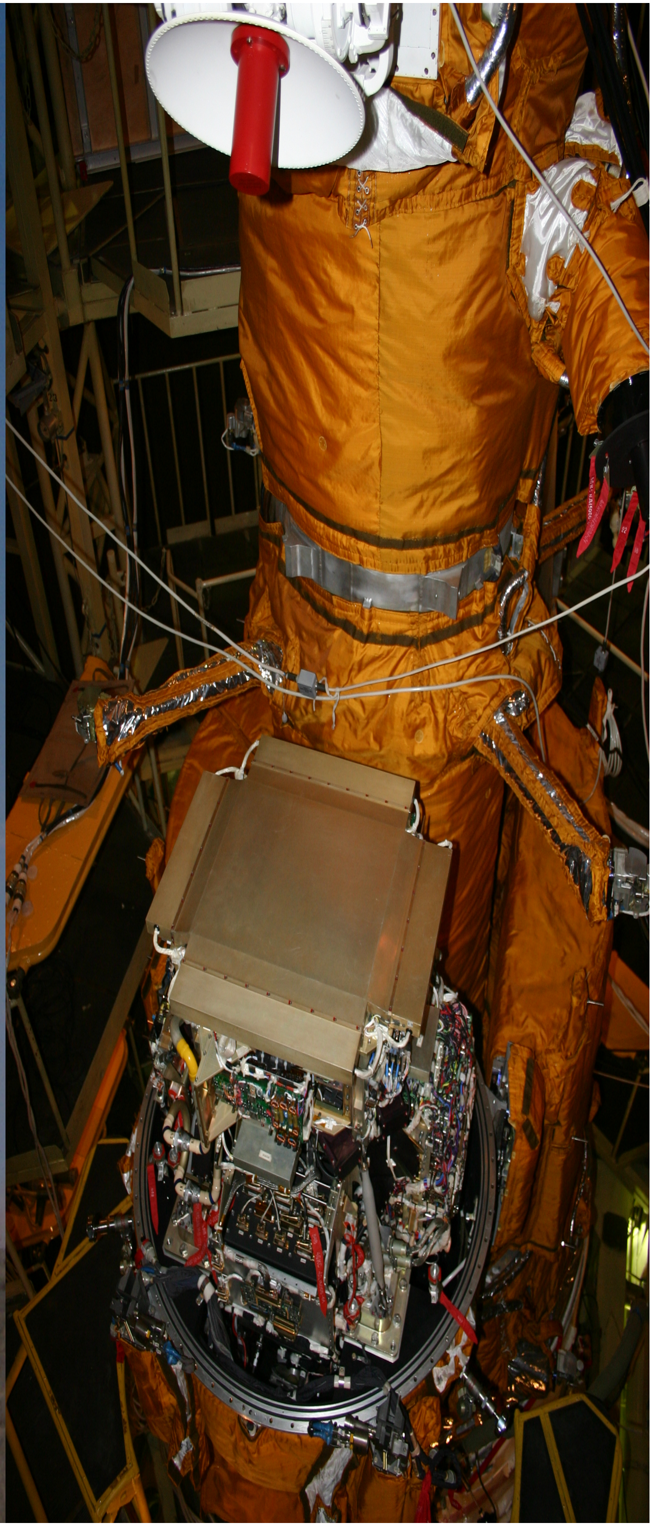




Studies of cosmic antiparticles with PAMELA

Mark Pearce

KTH, Department of Physics

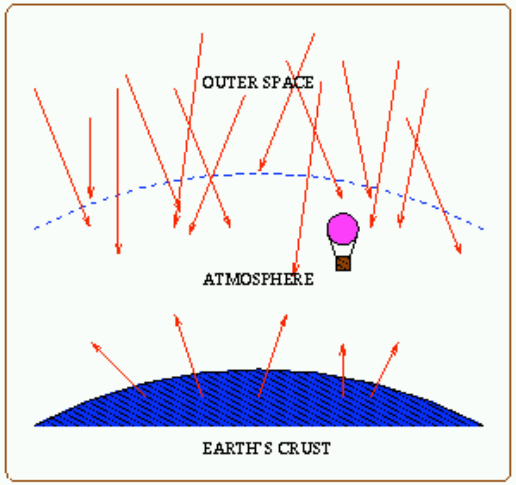
IPPP, Durham University - 5th February 2009

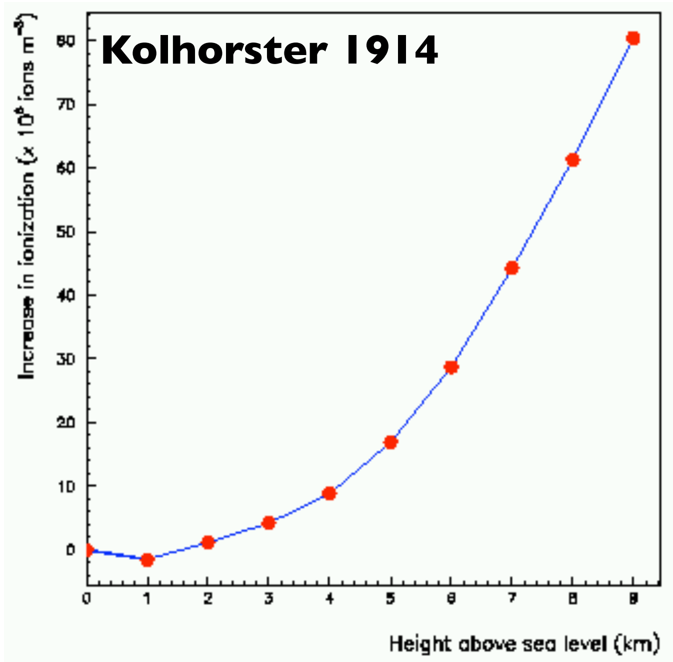
Overview

- (Very) brief introduction to cosmic rays
- The PAMELA experiment
- In-orbit status
- Searching for dark matter
- First results:
  - Antiprotons
  - Positrons

The discovery of cosmic rays

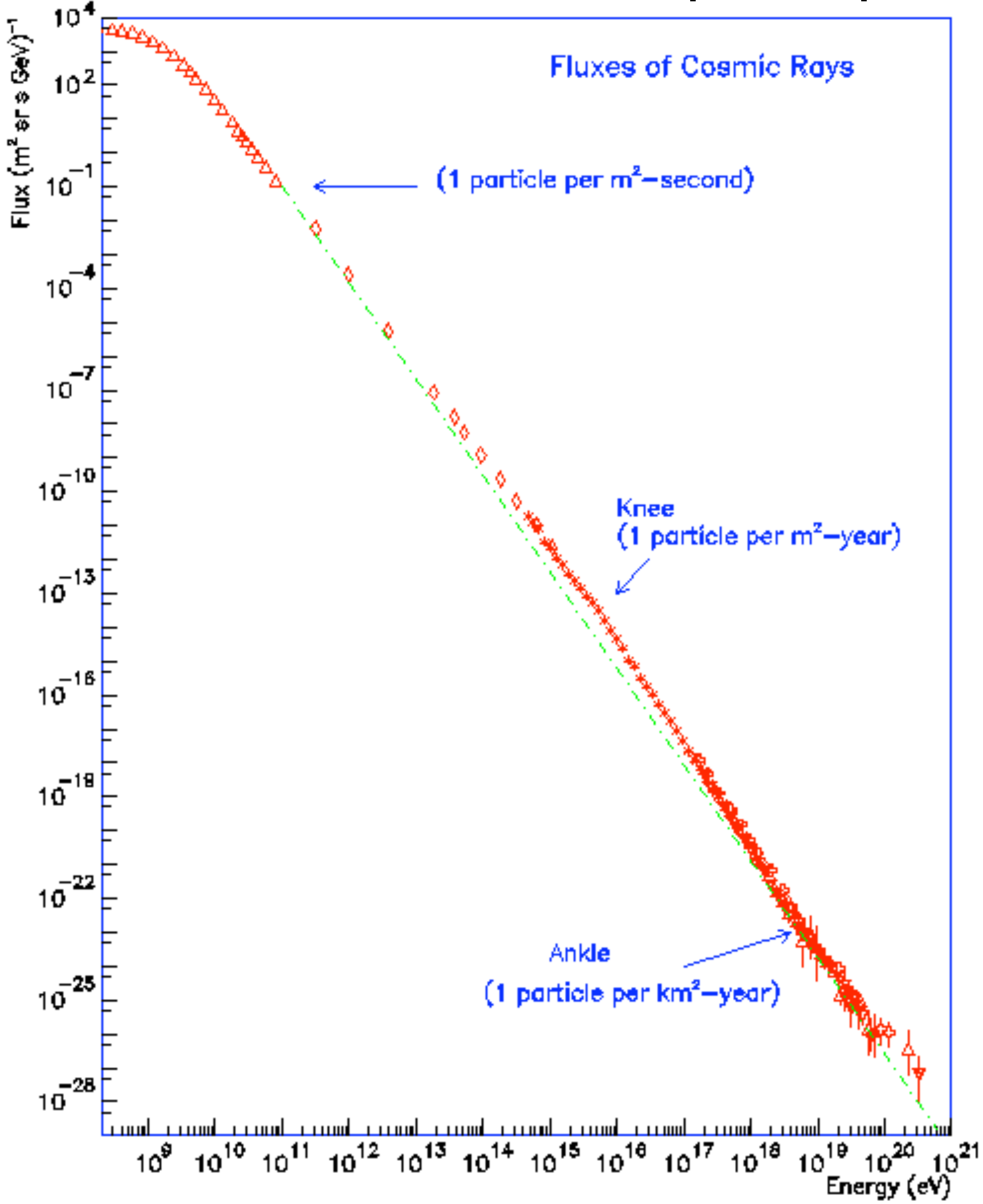
- Victor Hess ascended to 5000 m in a balloon in 1912
- ... and noticed that his electroscope discharged more rapidly as altitude increased
- Not expected, as background radiation was thought to be terrestrial
- Nobel Prize in Physics 1936 (with Carl 'e$^+$' Anderson)

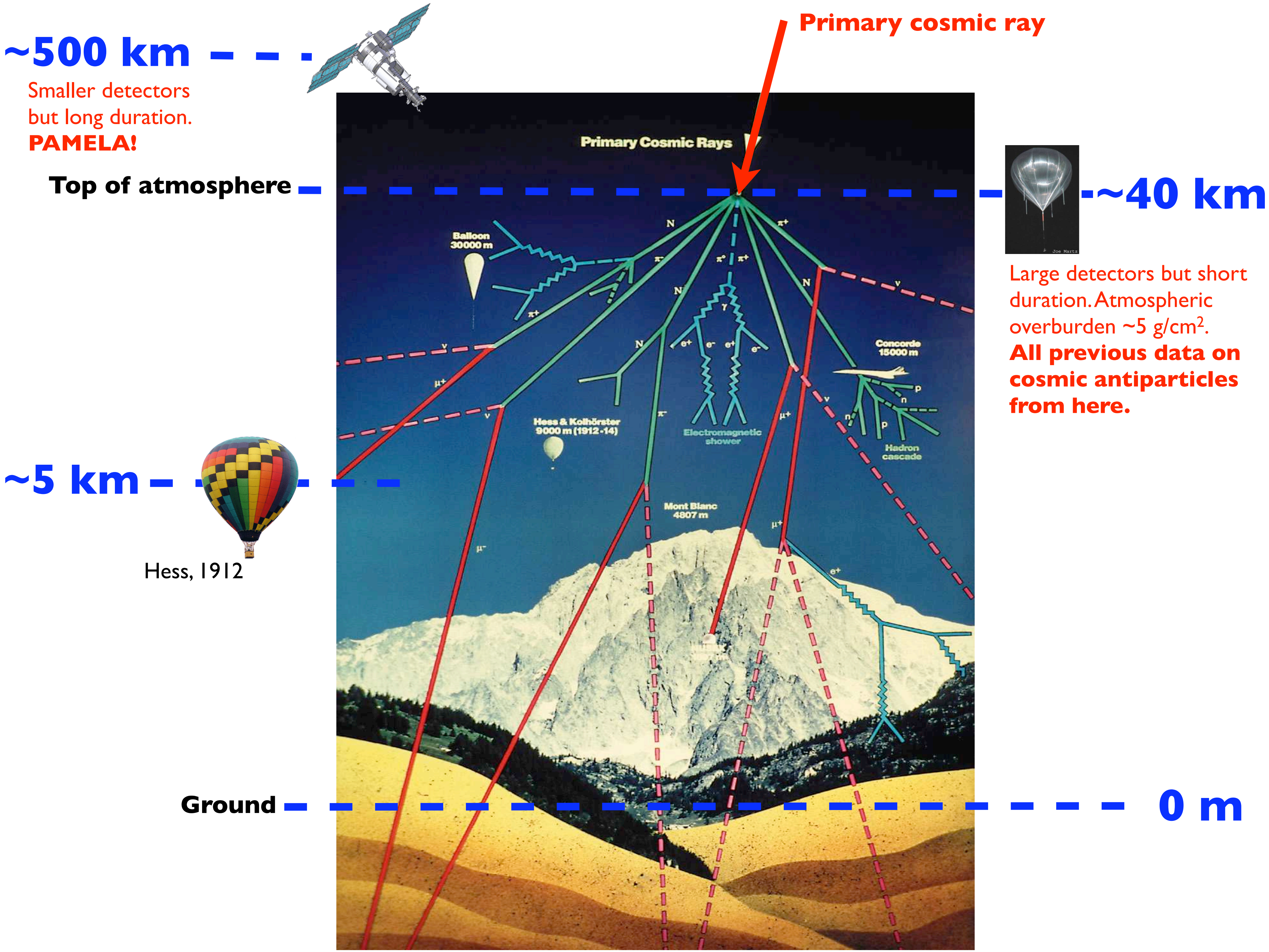




Cosmic ray energy spectrum

Top of atmosphere




~500 km
Smaller detectors
but long duration.
PAMELA!
Primary cosmic ray
Primary Cosmic Rays
Top of atmosphere
~40 km
Large detectors but short
duration. Atmospheric
overburden ~5 g/cm2.
All previous data on
cosmic antiparticles
from here.
Balloon
30000 m
Concorde
15000 m
Hess & Kolhörster
9000 m (1912-14)
Electromagnetic
shower
Hadron
cascade
~5 km
Hess, 1912
Mont Blanc
4807 m
Ground
0 m

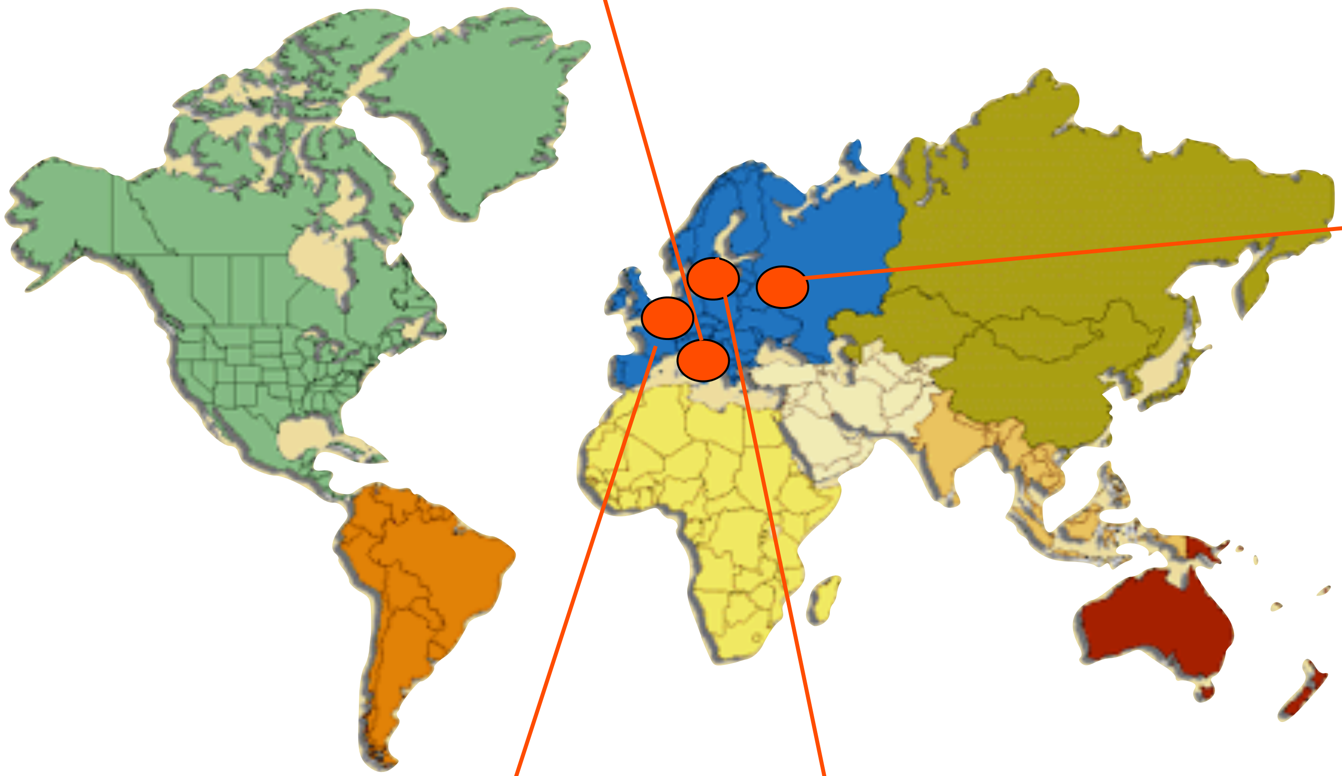
PAMELA Collaboration

Italy

Bari Florence Frascati Naples Rome Trieste CNR, Florence

Russia

Moscow
St. Petersburg

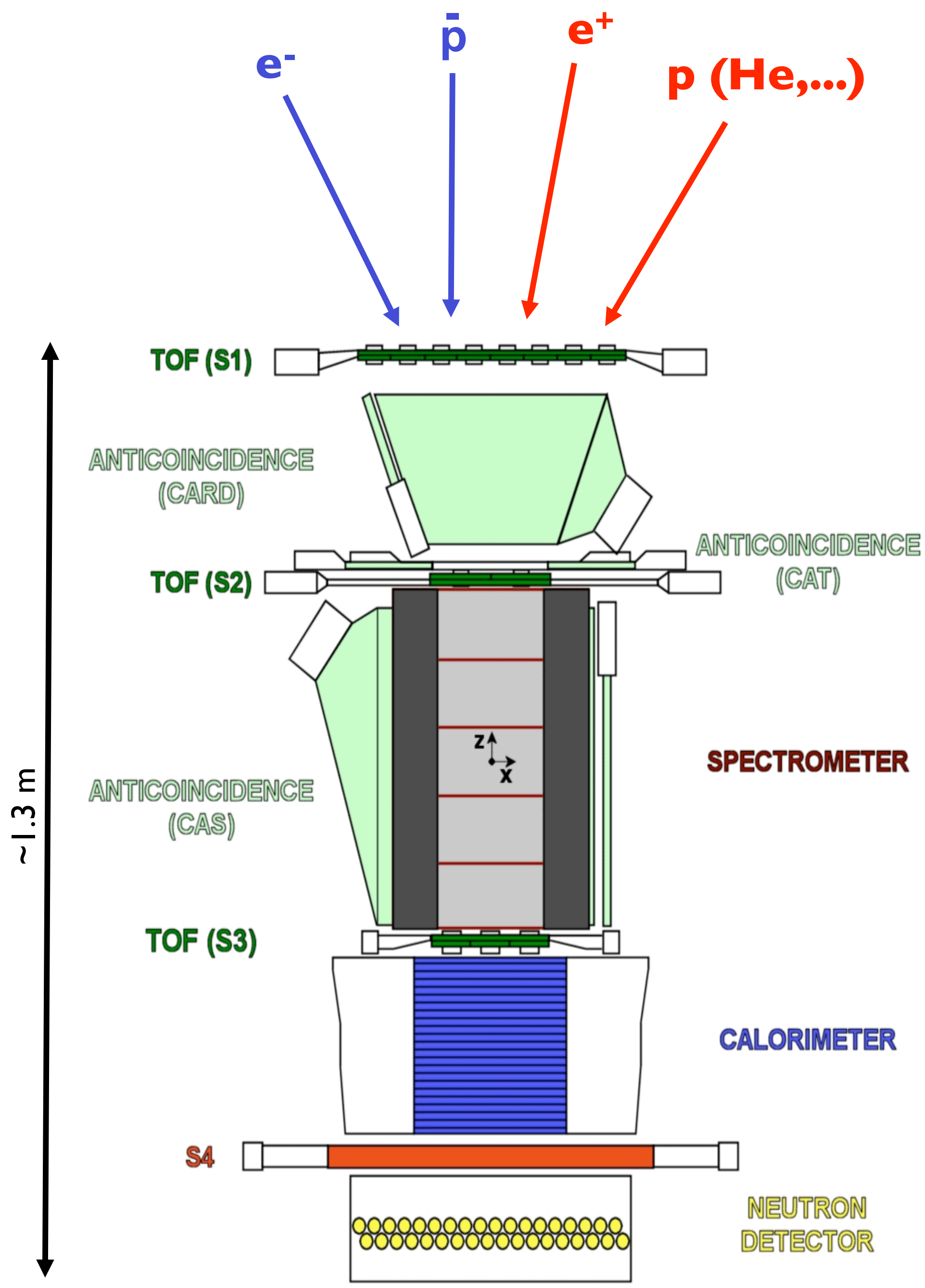


Germany

Siegen

Sweden

KTH, Stockholm



~470 kg / ~360 W

Trigger, ToF, dE/dx

- S1, S2, S3; double layers, x-y
- plastic scintillator (8 mm) + PMT
- ToF resolution ~300 ps (S1-3 ToF >3 ns)
- lepton-hadron separation < 1 GeV/c
- S1.S2.S3 (low rate) / S2.S3 (high rate)

Sign of charge, rigidity, dE/dx

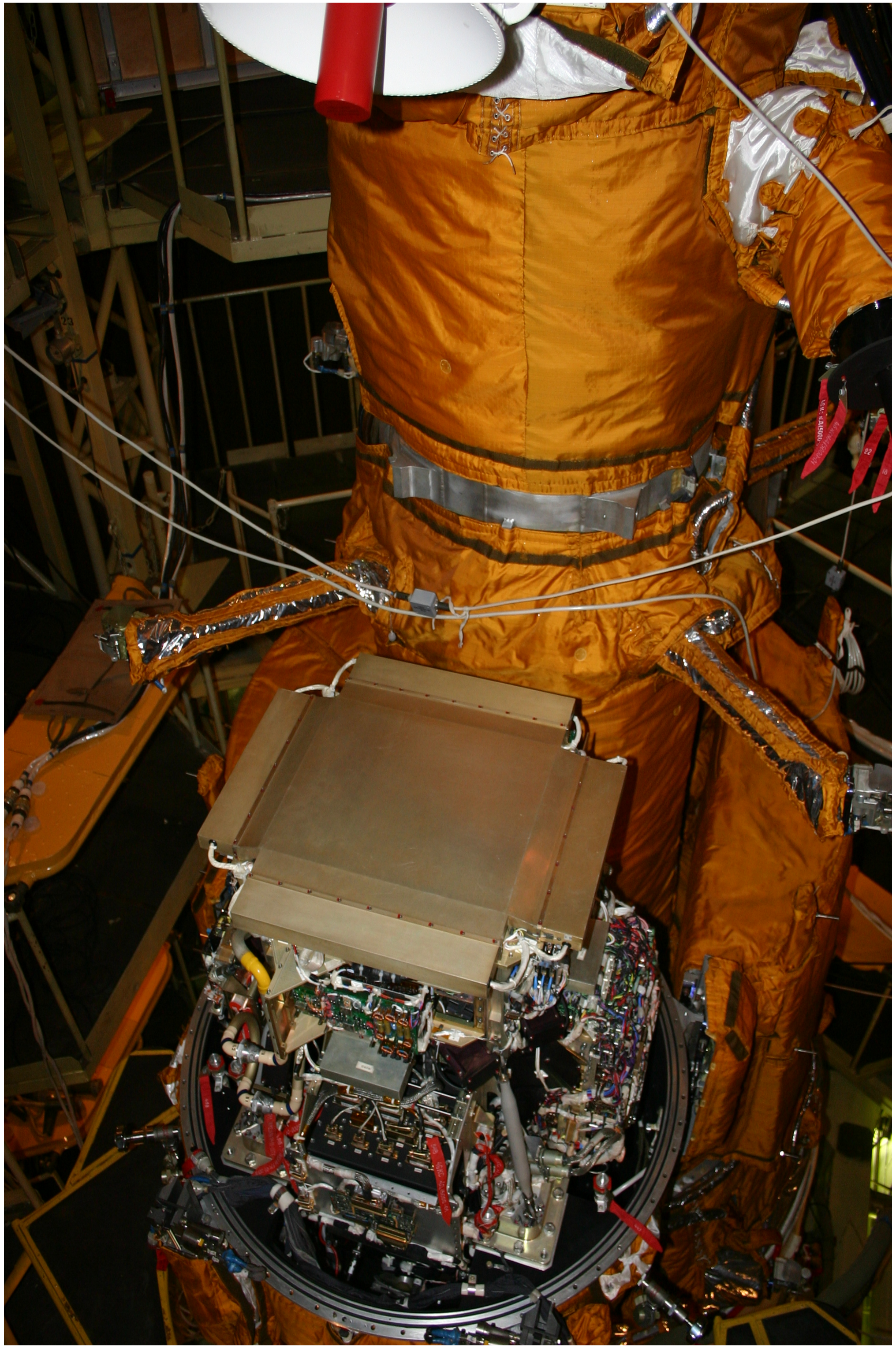
- Permanent magnet, 0.43 T
- 21.5 $cm^2 sr$
- 6 planes double-sided silicon strip detectors (300 μm)
- 3 μm resolution in bending view ⇒ MDR ~ 1000 GV (6 plane) ~600 GV (5 plane)

Electron energy, dE/dx, lepton-hadron separation

- 44 'Si-x / W / Si-y' planes (380 μm)
- 16.3 X_0 / 0.6 λ_L
- dE/E ~5.5 % (10 - 300 GeV)
- Self trigger > 300 GeV / 600 $cm^2 sr$

Lepton-hadron separation

- 36 ^3He counters
- $^3He(n,p)T$; E_p = 780 keV
- 1 cm thick poly + Cd moderator
- 200 μs collection time

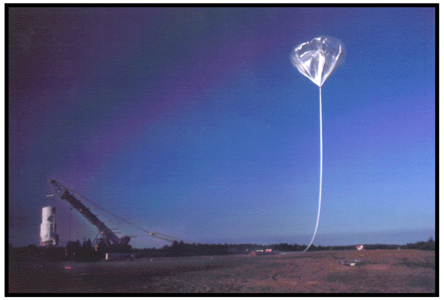


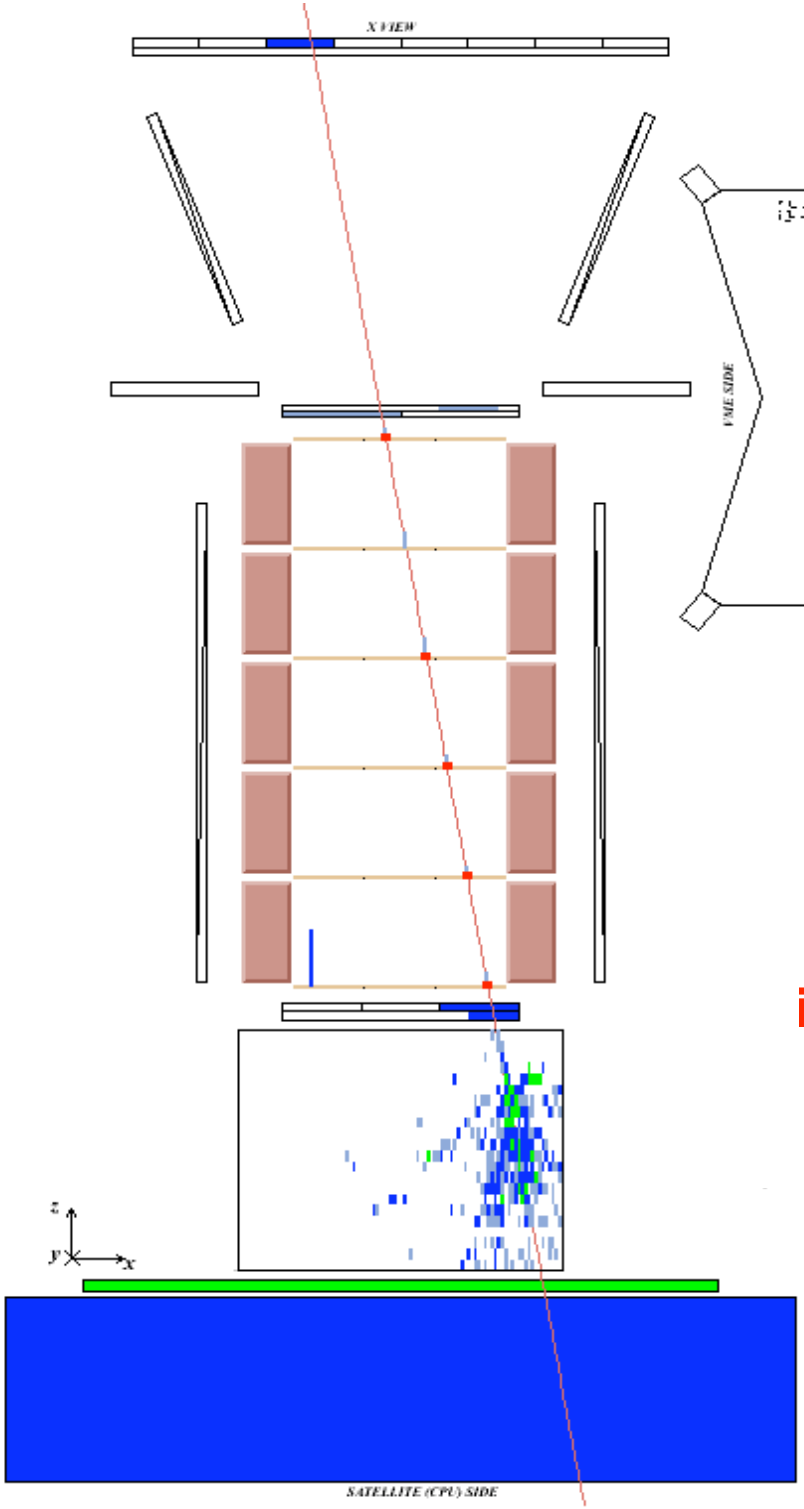
Design goals

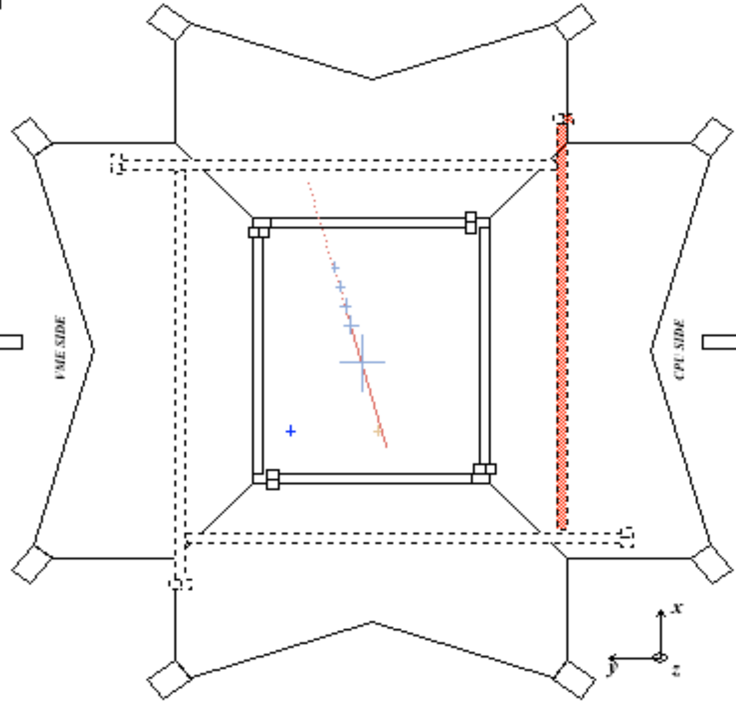
	Energy range	Particles/3 years
Antiproton flux	80 MeV - 190 GeV	$O(10^4)$
Positron flux	50 MeV – 270 GeV	$O(10^5)$
Electron/positron flux	up to 2 TeV (from calo)	
Electron flux	up to 400 GeV	$O(10^6)$
Proton flux	up to 700 GeV	$O(10^8)$
Light nuclei (up to Z=6)	up to 200 GeV/n	He/Be/C: $O(10^{7/4/5})$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

- **Unprecedented statistics and new energy range for cosmic ray physics**
  - e.g. contemporary antiproton & positron energy, $E_{max} \approx 50$ GeV
- Simultaneous measurements of many species
  - constrain secondary production models

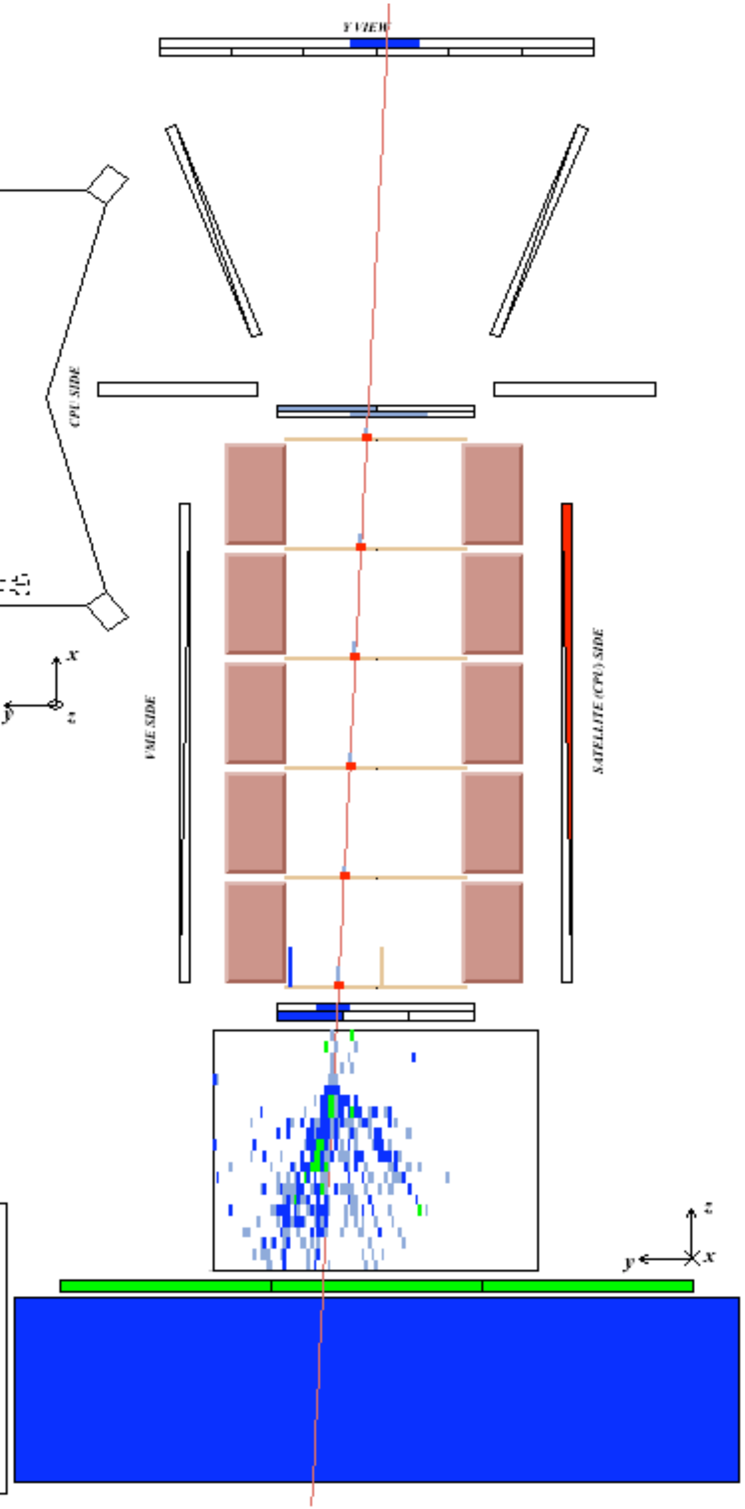
1 HEAT-PBAR flight ~ 25 days PAMELA data
1 CAPRICE98 flight ~ 5 days PAMELA data

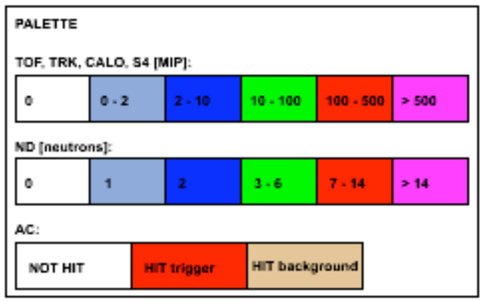


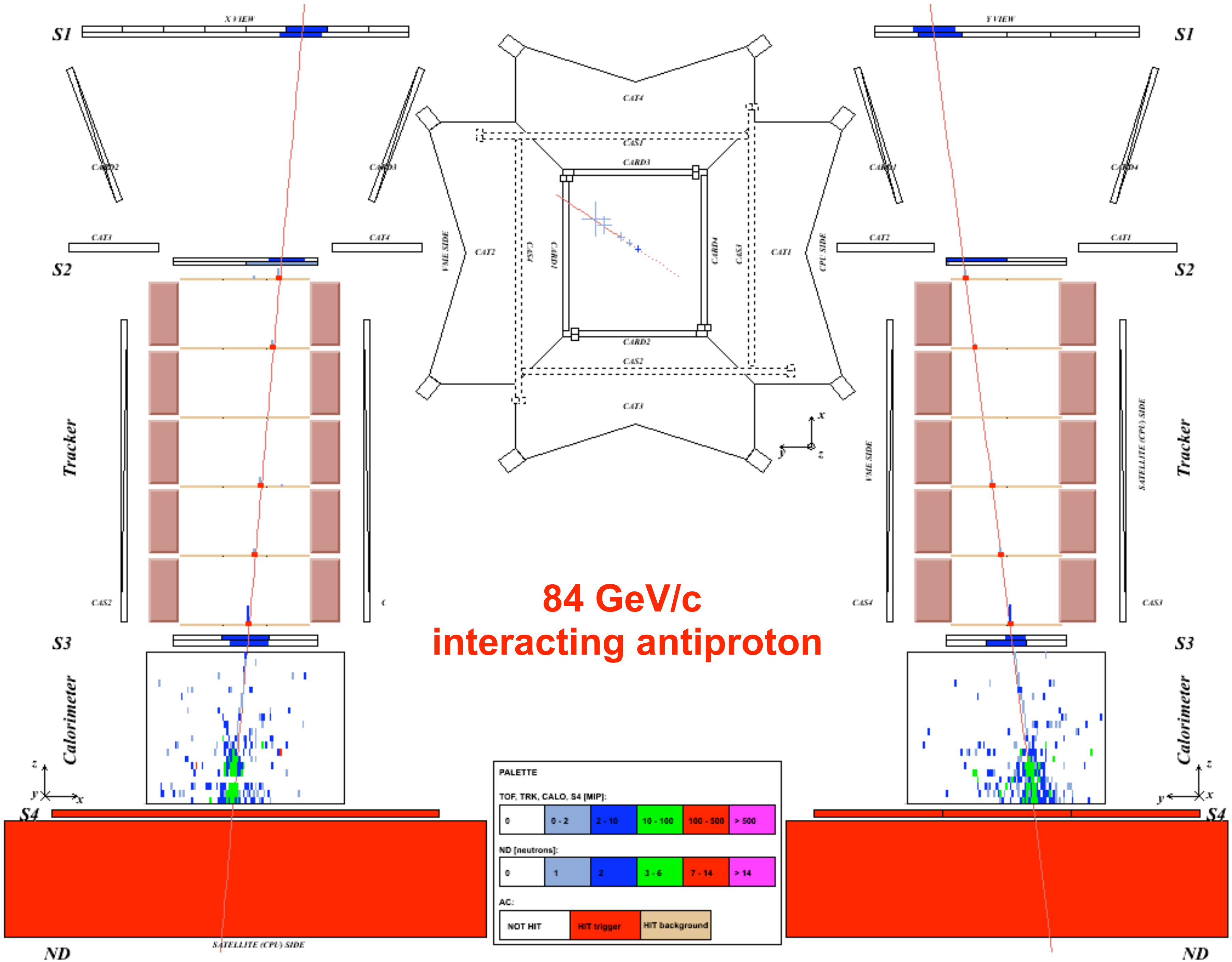


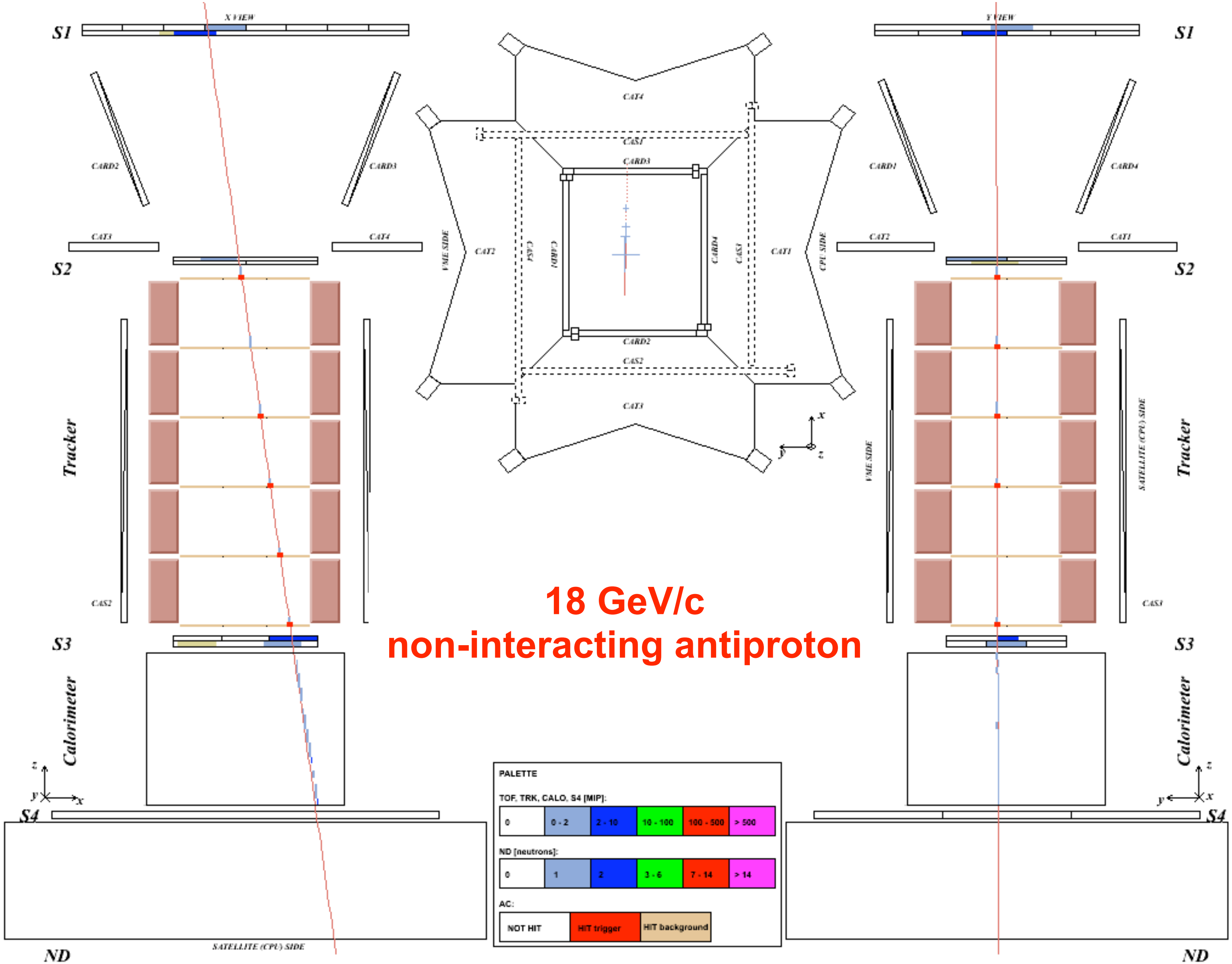


36 GeV/c interacting proton

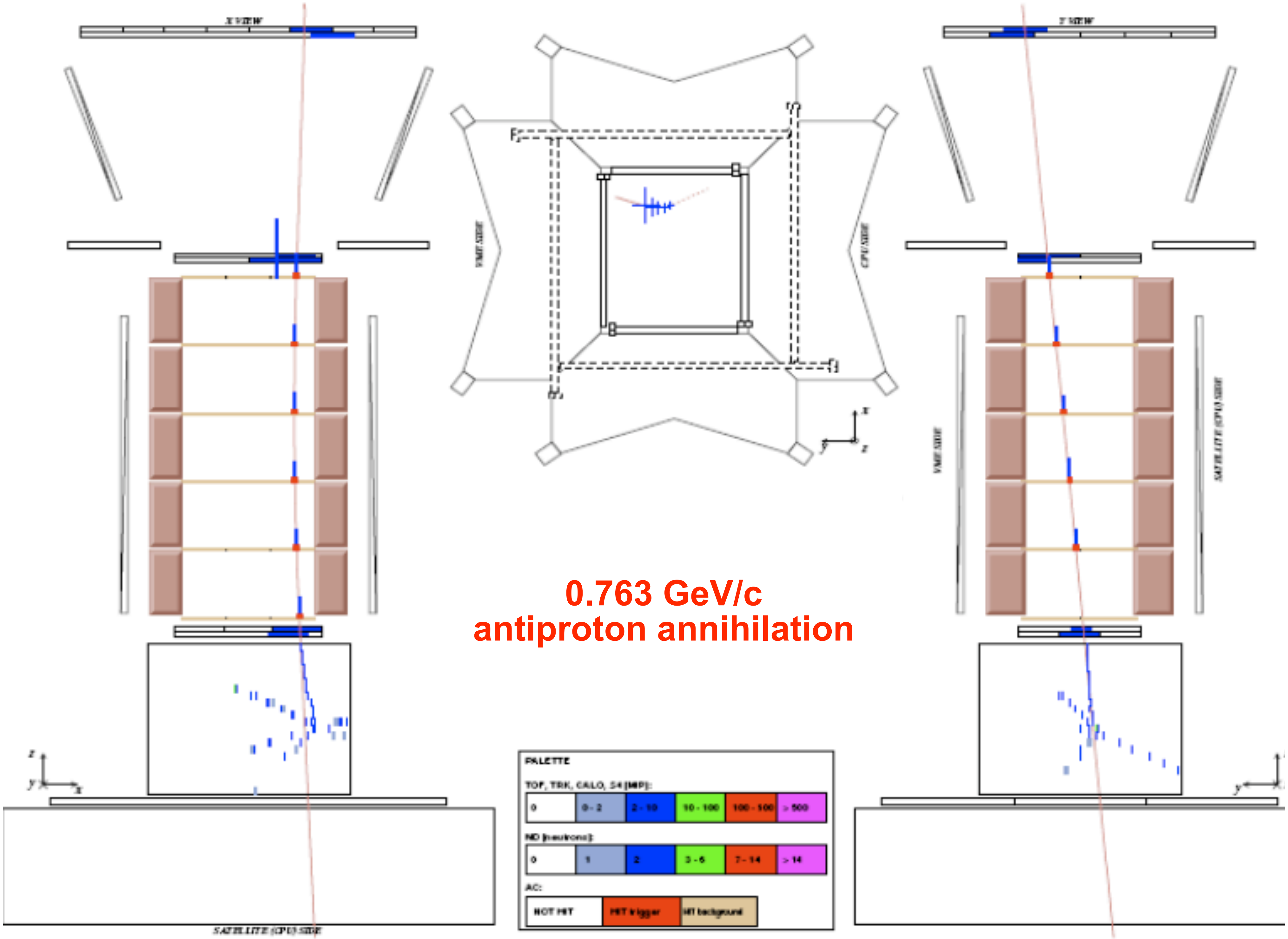




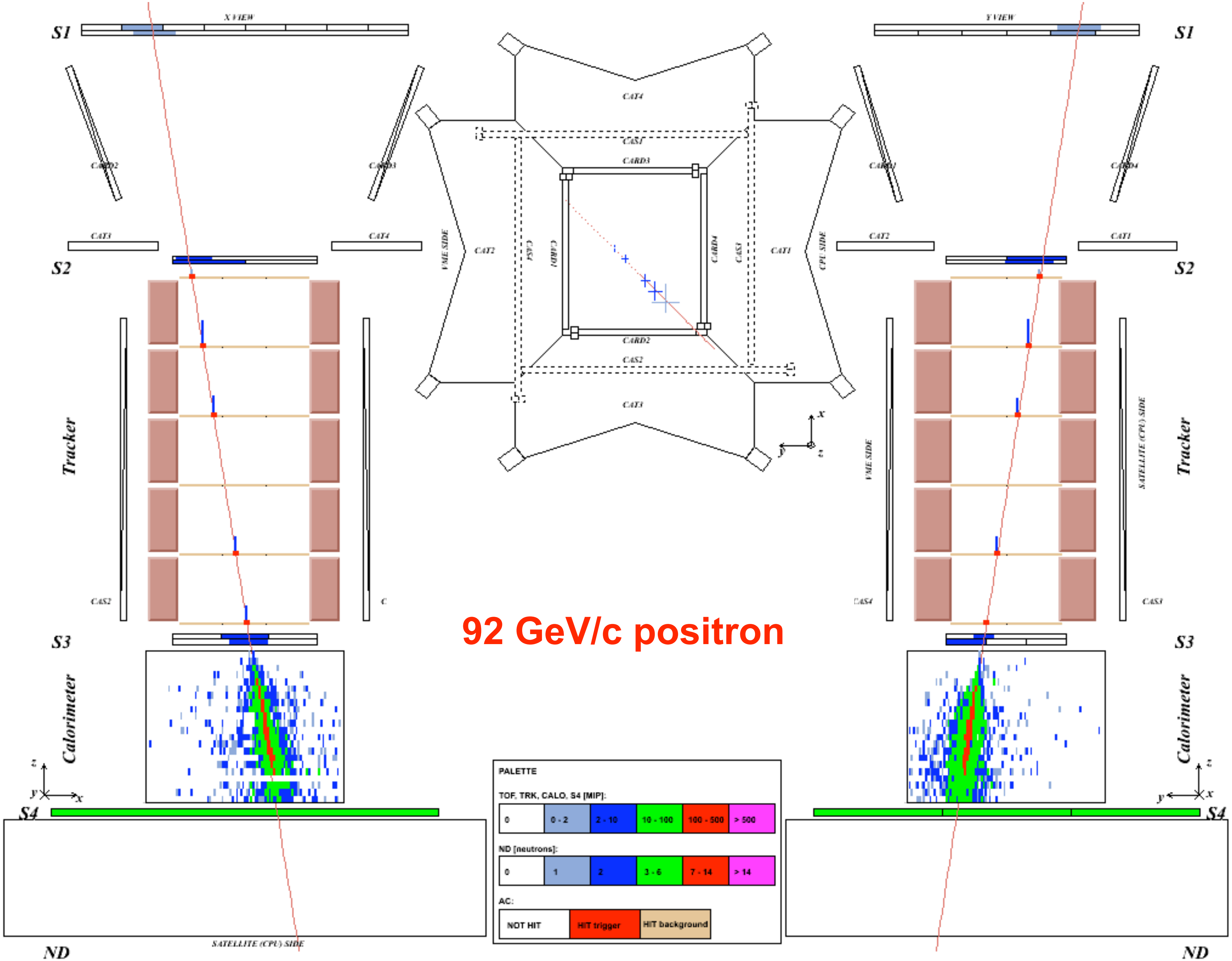

84 GeV/c
interacting antiproton
X VIEW
Y VIEW
S1
S2
S3
S4
ND
Tracker
Calorimeter
CARD1
CARD2
CARD3
CARD4
CAT1
CAT2
CAT3
CAT4
CAS1
CAS2
CAS3
CAS4
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC: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

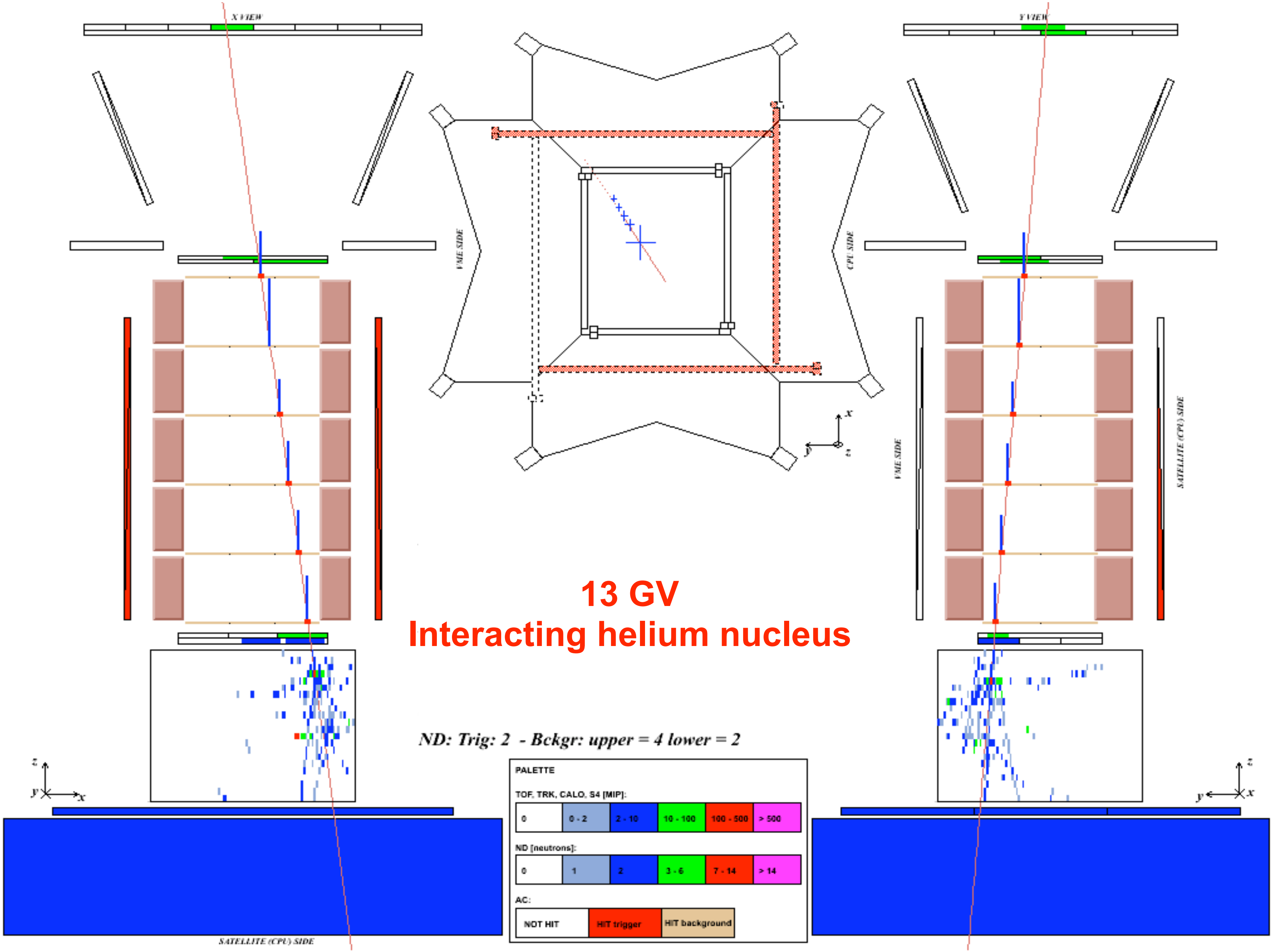


18 GeV/c
non-interacting antiproton



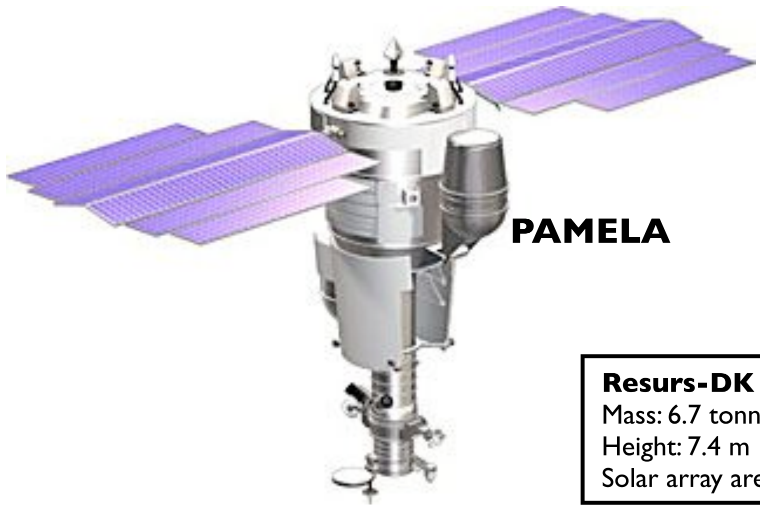
0.763 GeV/c
antiproton annihilation


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

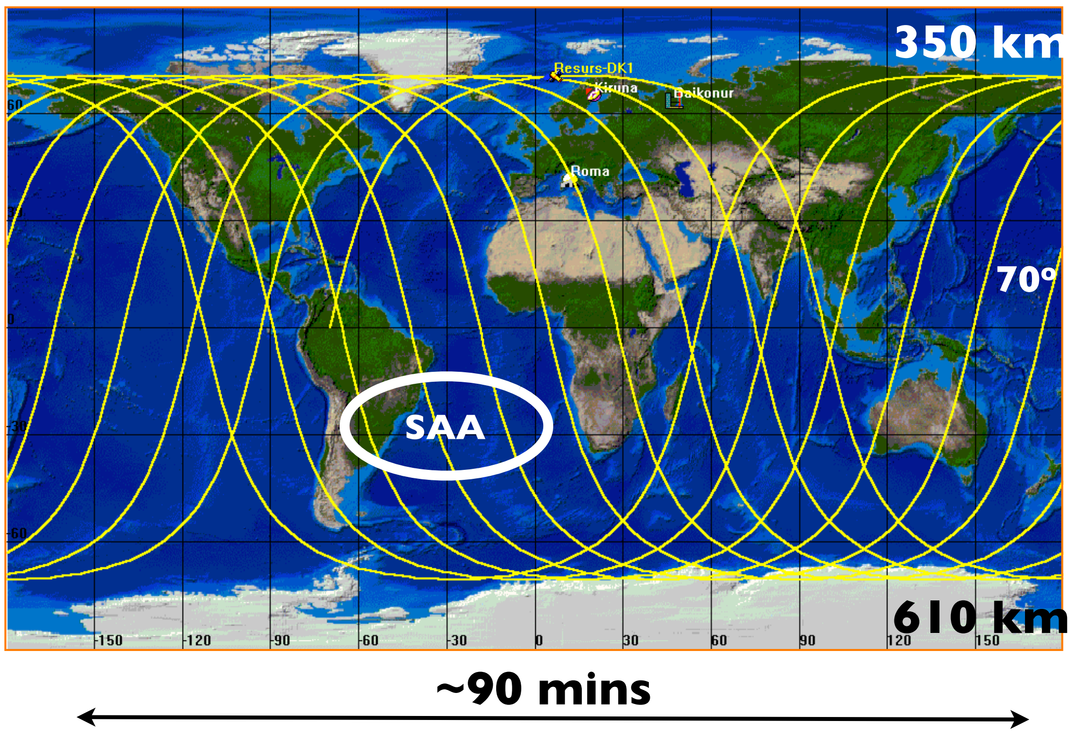

X VIEW
Y VIEW
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
13 GV
Interacting helium nucleus
ND: Trig: 2 - Bckgr: upper = 4 lower = 2
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background
SATELLITE (CPU) SIDE

Launch: 15th June 2006, 0800 UTC

Resurs-DK1 satellite + orbit

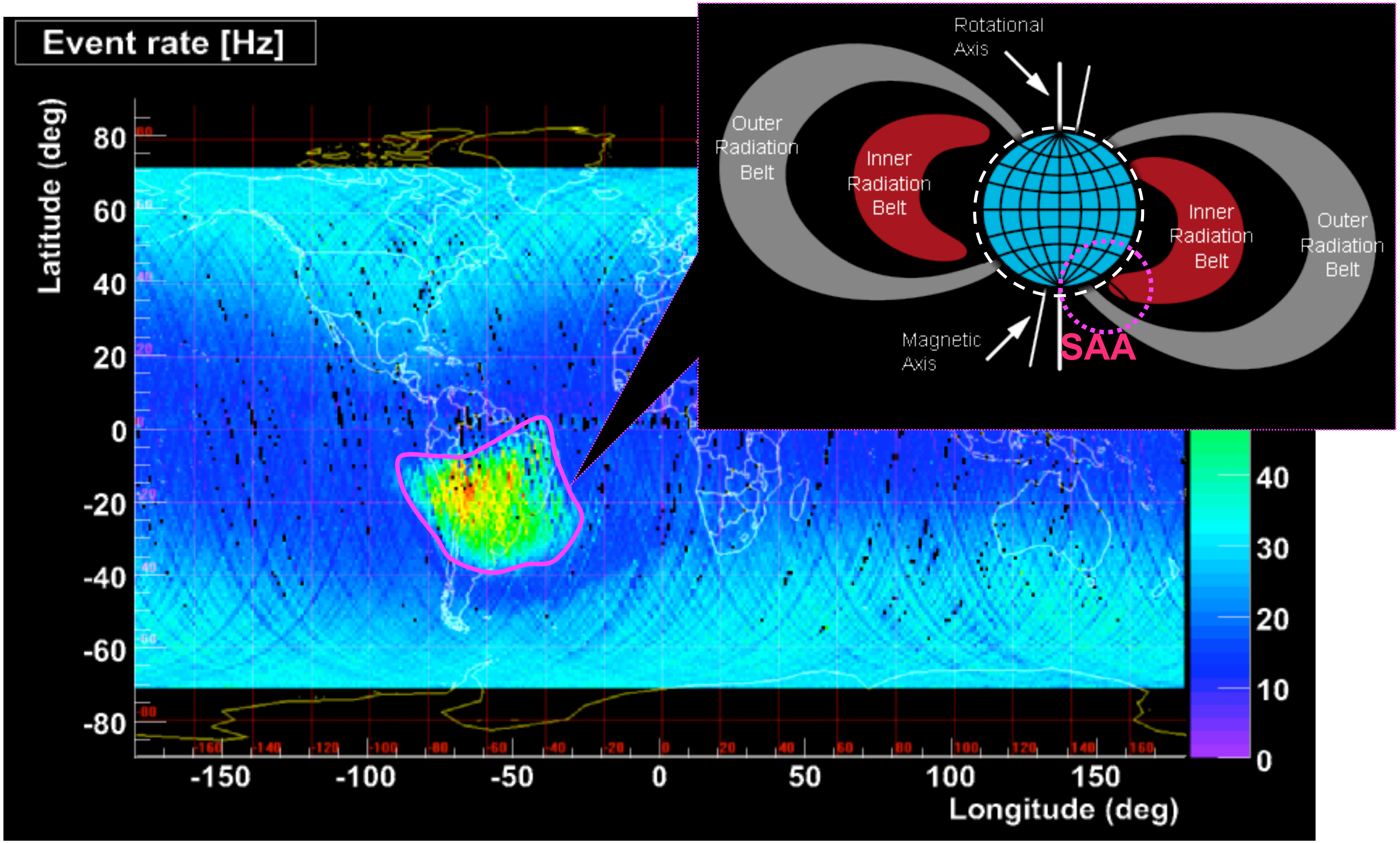


Resurs-DK1
Mass: 6.7 tonnes
Height: 7.4 m
Solar array area: 36 m^2



- **Resurs-DK1:** multi-spectral imaging of earth's surface
- **PAMELA mounted inside a pressurized container**
- **Lifetime >3 years (assisted)**
- Data transmitted to NTsOMZ, Moscow via high-speed radio downlink. ~15 GB per day
- Quasi-polar and elliptical orbit (70.0°, 350 km - 600 km)
- Traverses the South Atlantic Anomaly
- Crosses the outer (electron) Van Allen belt at south pole

Trigger rate



PAMELA milestones

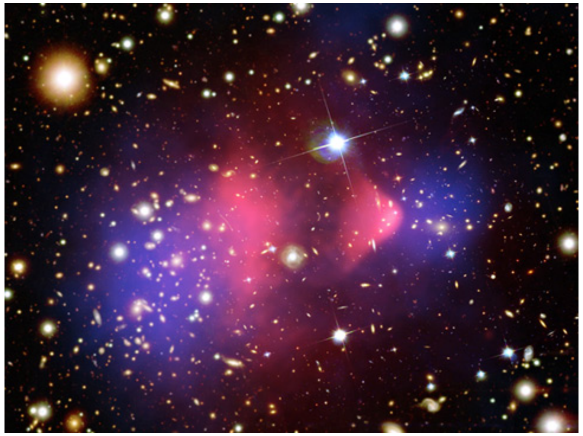
- **Launch from Baikonur:** June 15th 2006, 0800 UTC.
- **'First light':** June 21st 2006, 0300 UTC.

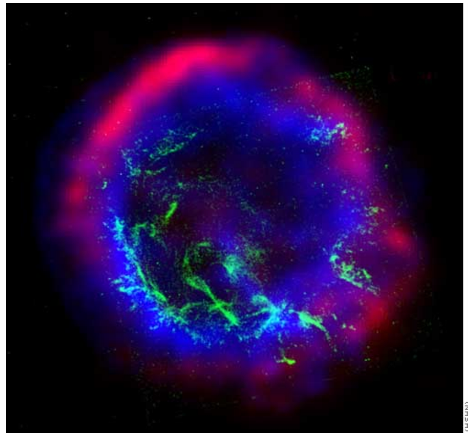
- **PAMELA in continuous data-taking mode since commissioning phase ended on July 11th 2006**

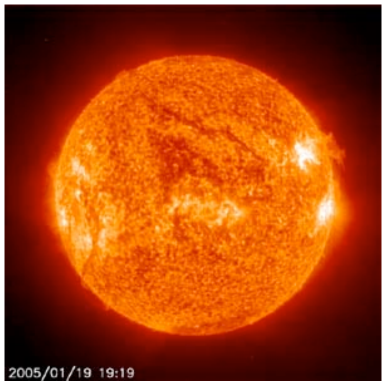
- **As of ~now:**
  - ~700 days of data taking (~73% live-time)
  - ~12 TByte of raw data downlinked
  - $>10^9$ triggers recorded and under analysis

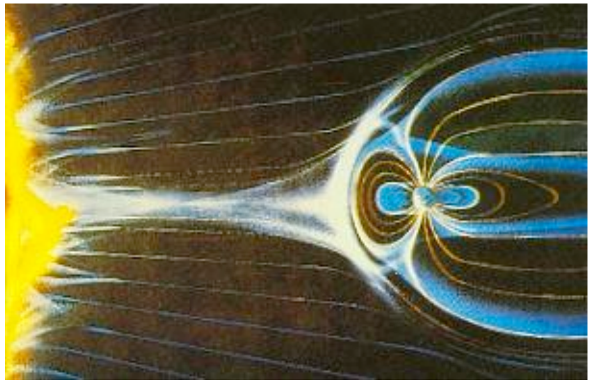
Scientific goals

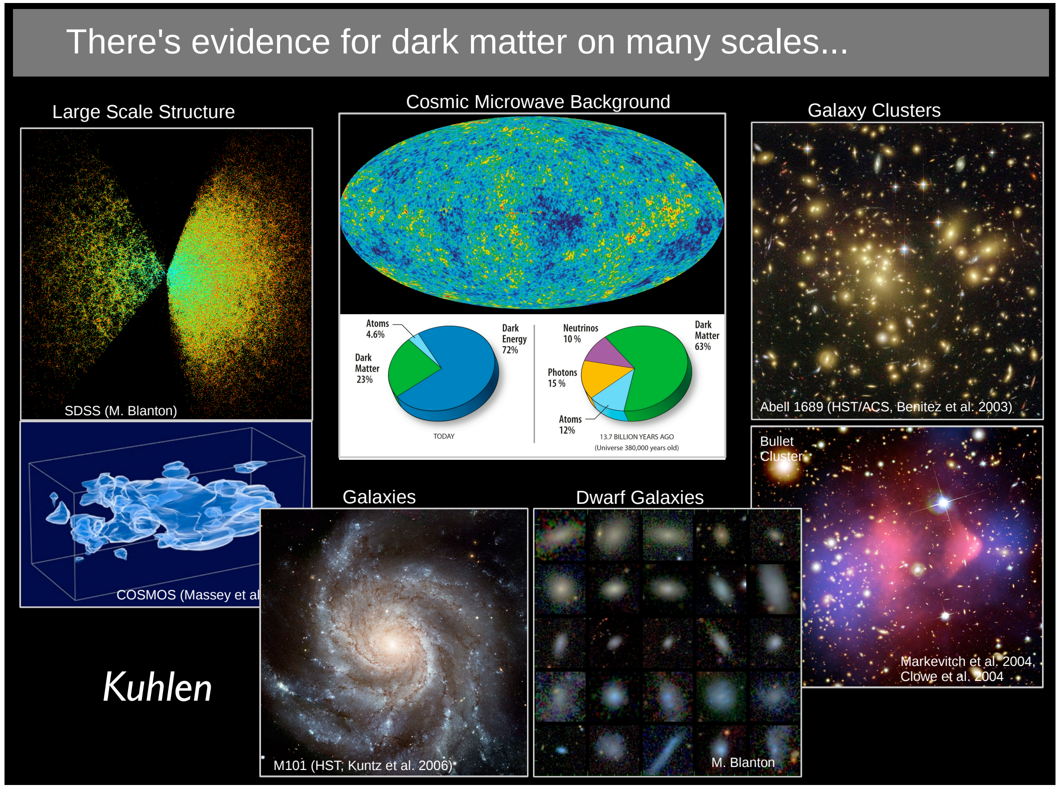
- **Search for dark matter annihilation**
- Search for antihelium (primordial antimatter)
- Study of cosmic-ray propagation (light nuclei and isotopes)
- Study of electron spectrum (local sources?)
- Study solar physics and solar modulation
- Study terrestrial magnetosphere

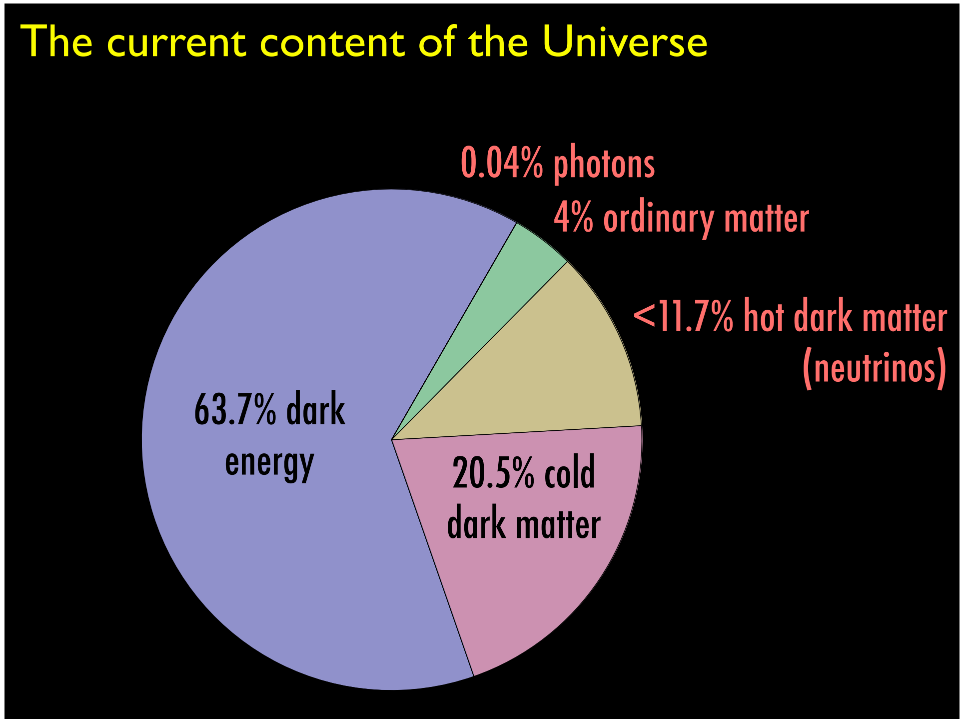




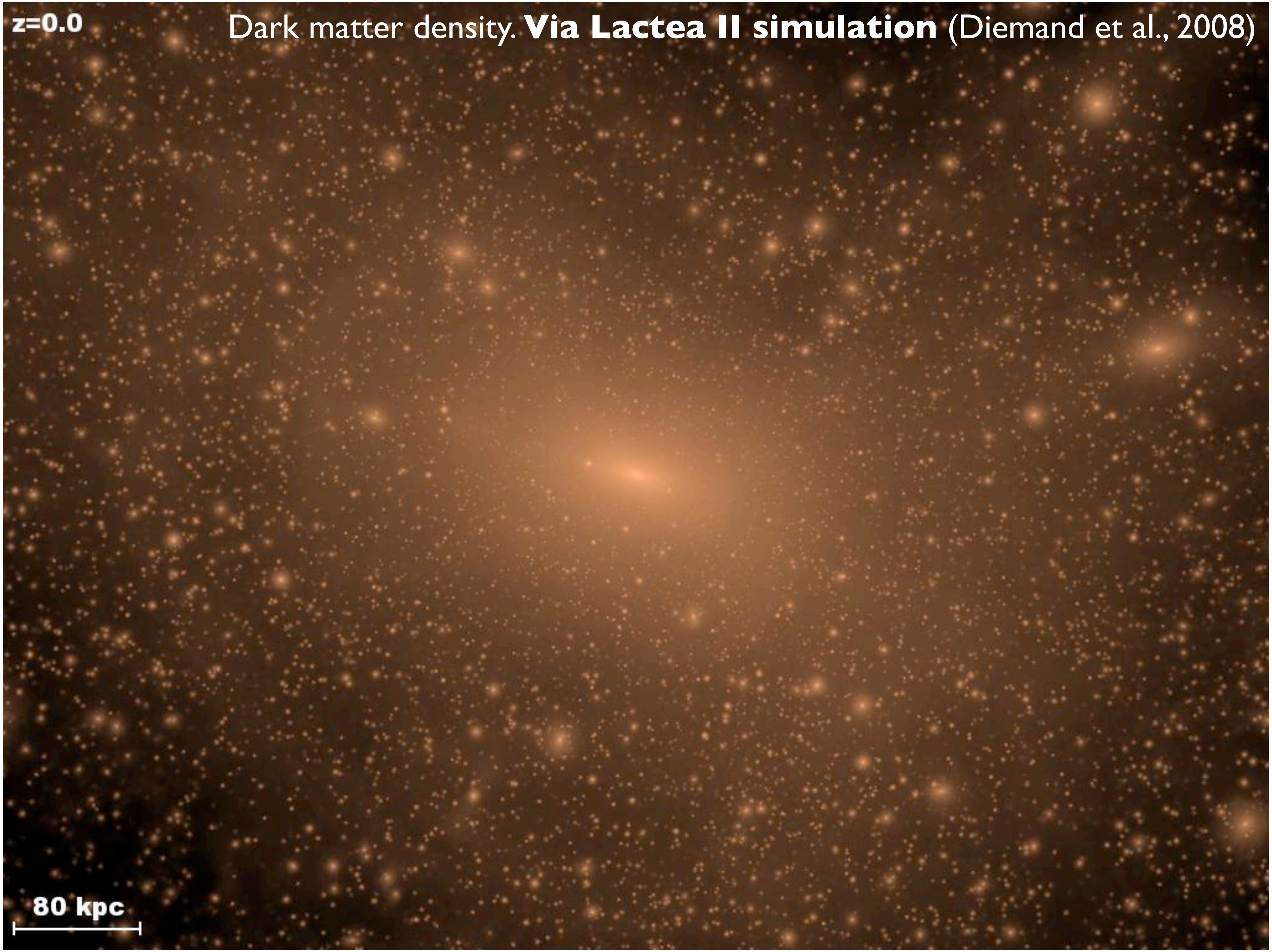


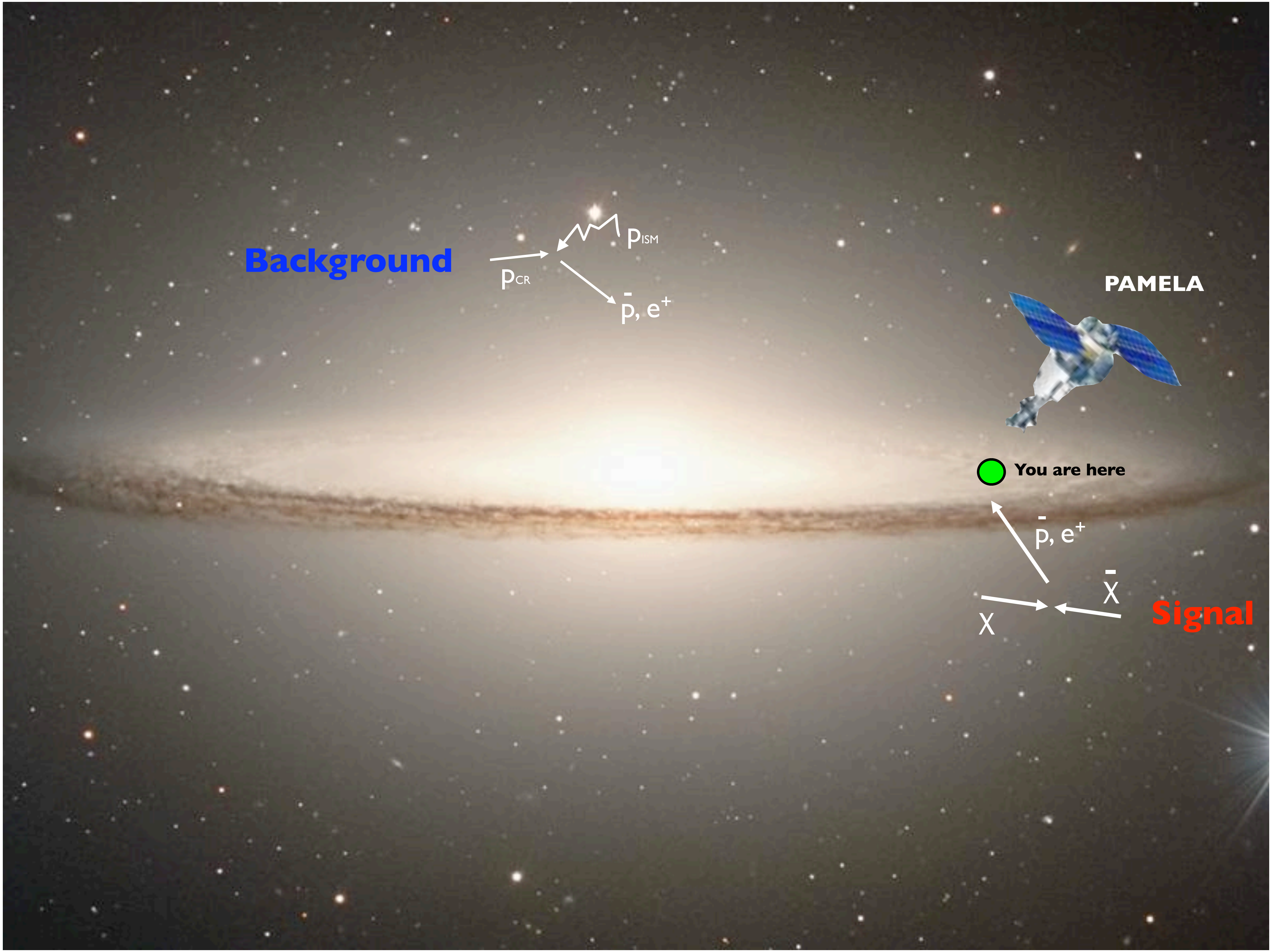




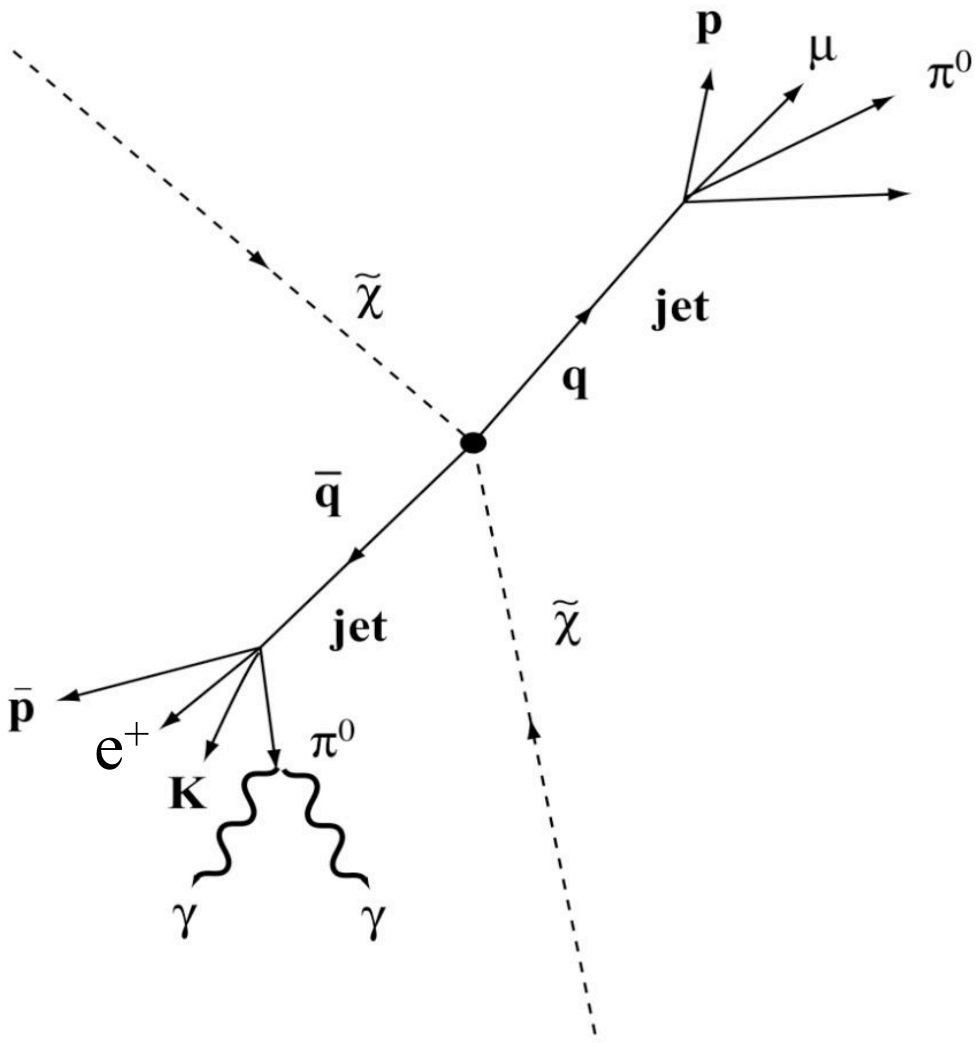


P. Gondolo, **IDM 2008**

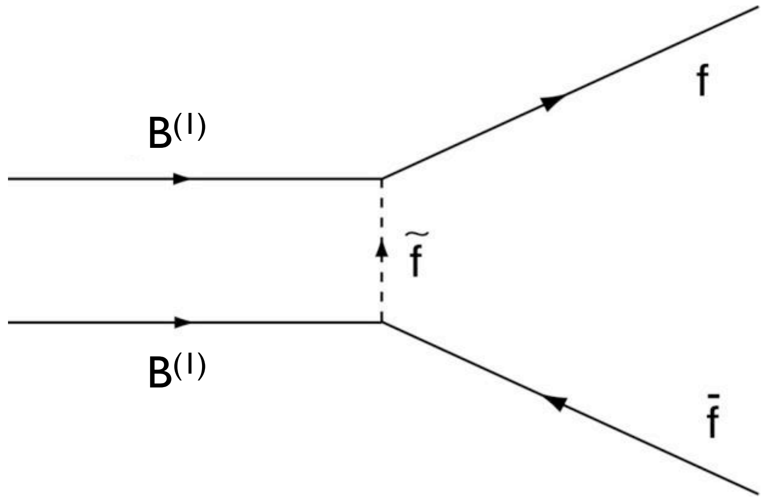

z=0.0
Dark matter density. **Via Lactea II simulation** (Diemand et al., 2008)
80 kpc


Background
p_{ISM}
p_{CR}
$\bar{p}$, e^+
PAMELA
You are here
$\bar{p}$, e^+
$\bar{X}$
X
Signal

WIMP annihilation

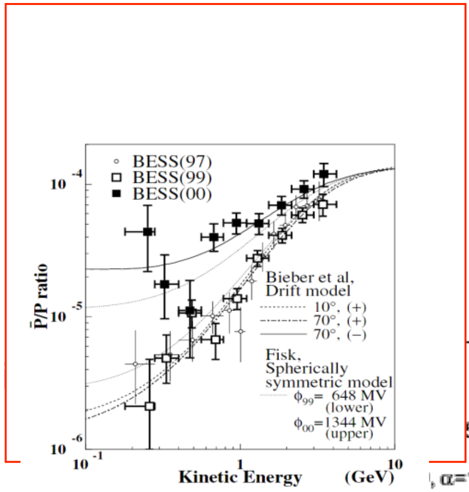


Majorana
e.g. supersymmetric neutralino, $\tilde{\chi}$

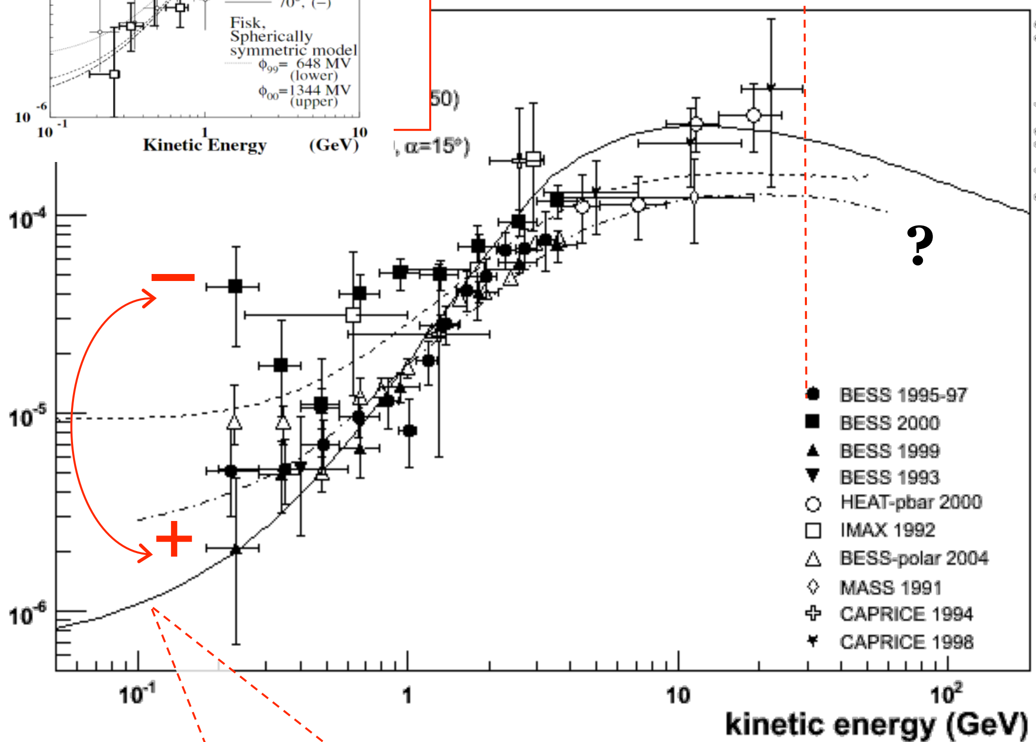


Dirac
e.g. Kaluza Klein particle from Universal Extra Dimension models

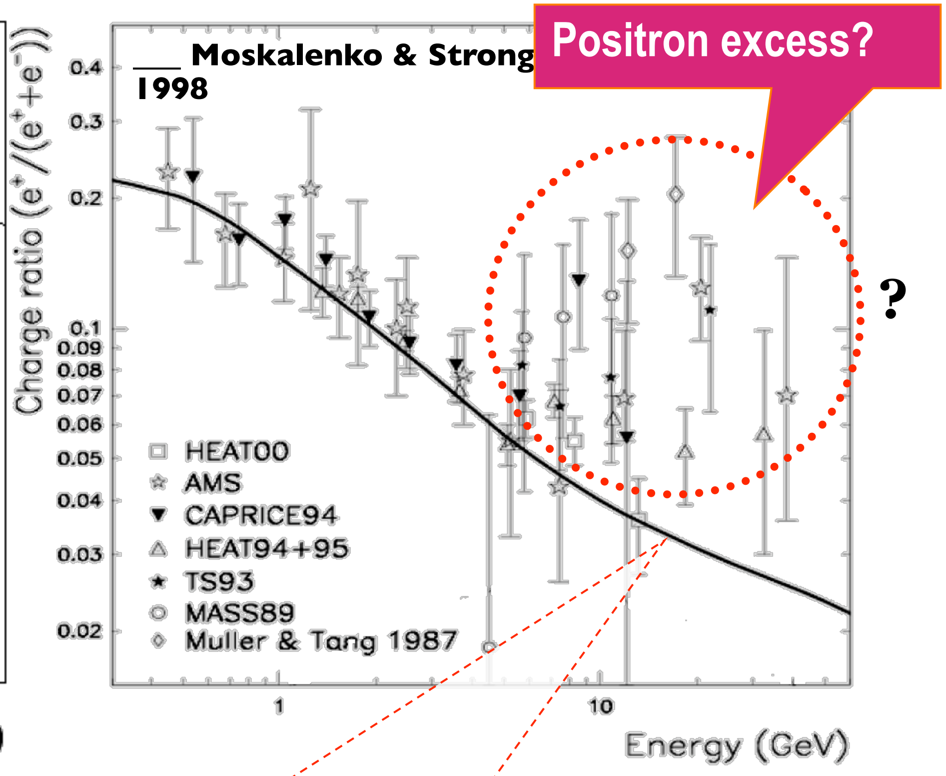
Present status



Antiprotons



Positrons



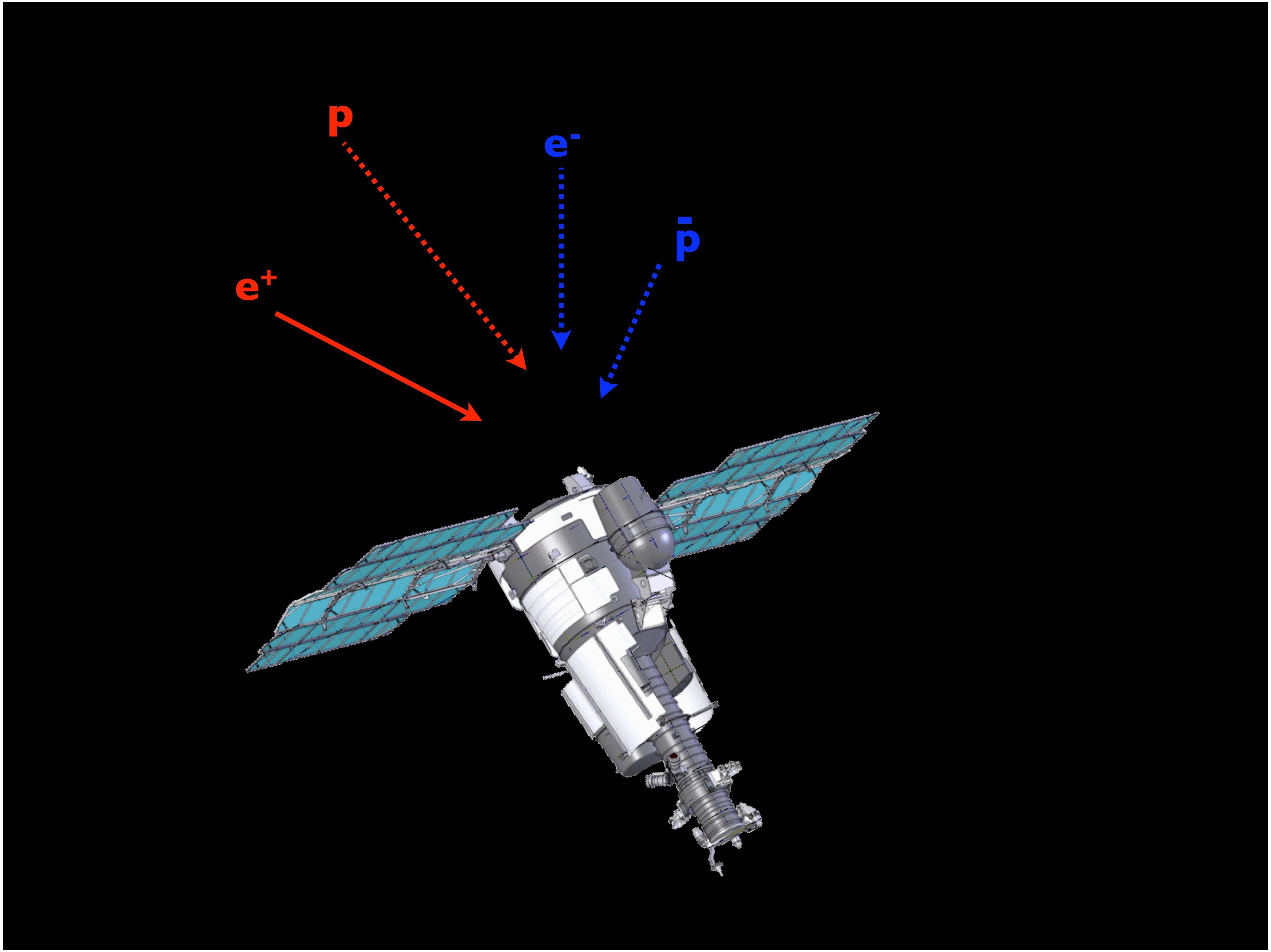
CR + ISM → **p-bar** + …

kinematic threshold:
5.6 GeV for the reaction

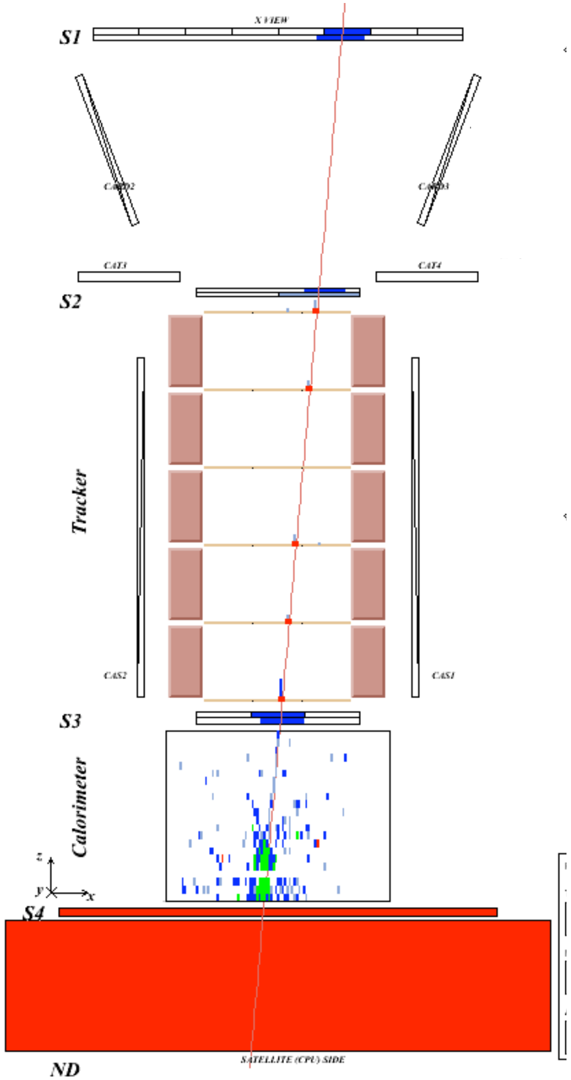
$$pp \longrightarrow \bar{p}ppp$$

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

CR + ISM → π^0 + x → γγ → $e^{\pm}$


p
e-
p̄
e+

Antiproton / positron identification



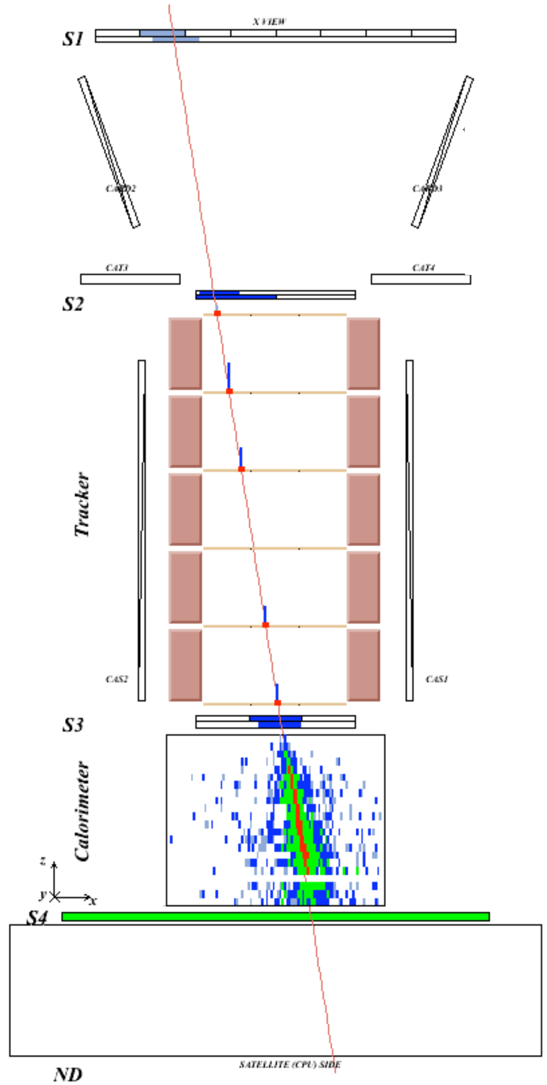
Antiproton
(NB: $e^-/\bar{p} \sim 10^2$)

Time-of-flight:
trigger, albedo rejection, mass determination (up to 1 GeV)

Bending in spectrometer:
sign of charge

Ionisation energy loss (dE/dx):
magnitude of charge

Interaction pattern in calorimeter:
electron-like or proton-like, electron energy

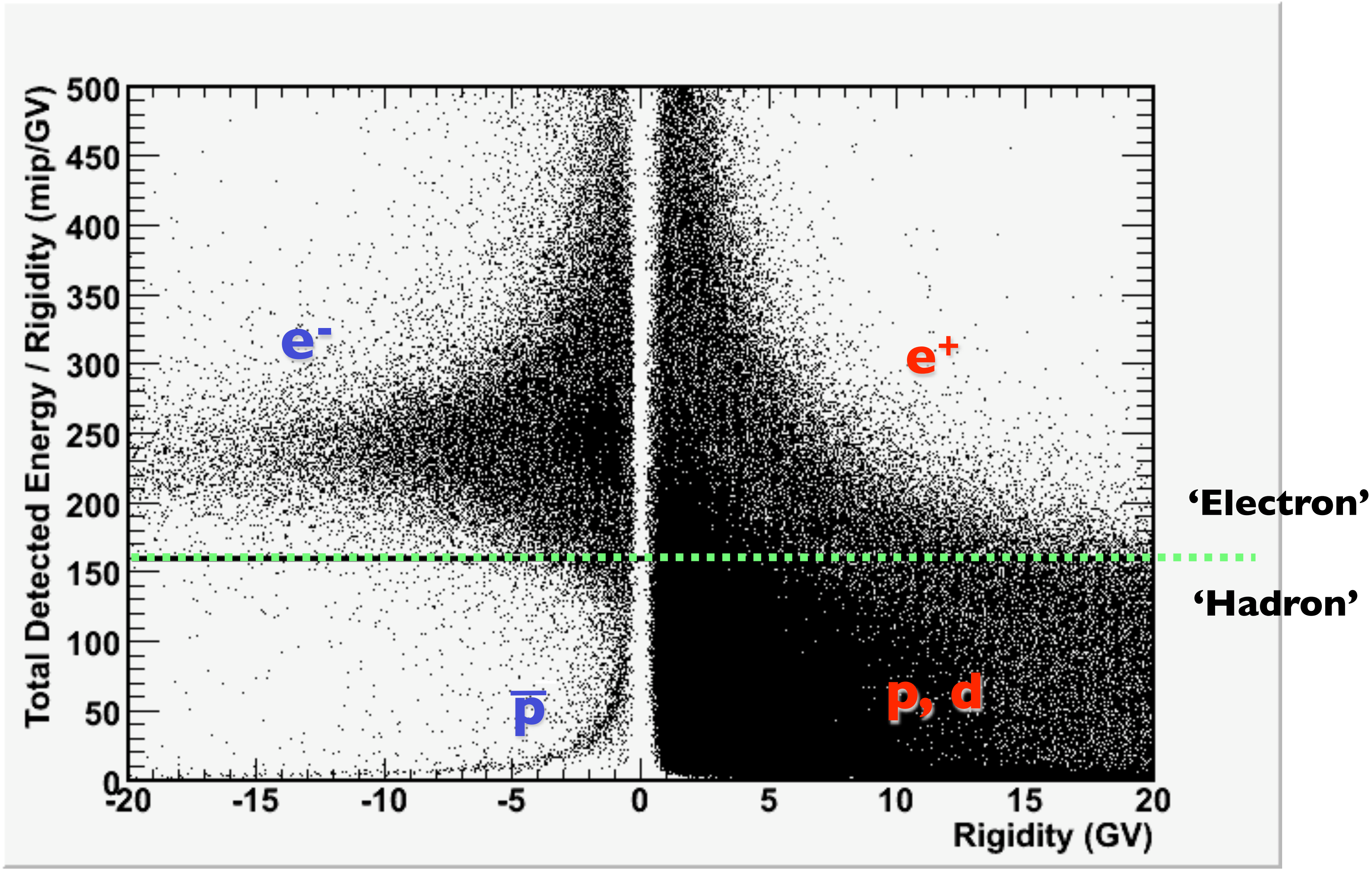


Positron
(NB: $p/e^+ \sim 10^{3-4}$)

Analysis ‘recipe’

- Select downward-going particles with ToF ($\Delta t \sim 0.3$ ns)
- Select MIPs with dE/dx (ToF + tracker)
- Multiplicity cuts on S1/S2, AC to reject interactions
- Quality cuts on tracker fit, derive rigidity
- Check rigidity is compatible with geomagnetic location
- Use shower topology to reject electrons
- Use ToF β for particle ID, < 1 GeV/c

Antiparticle selection



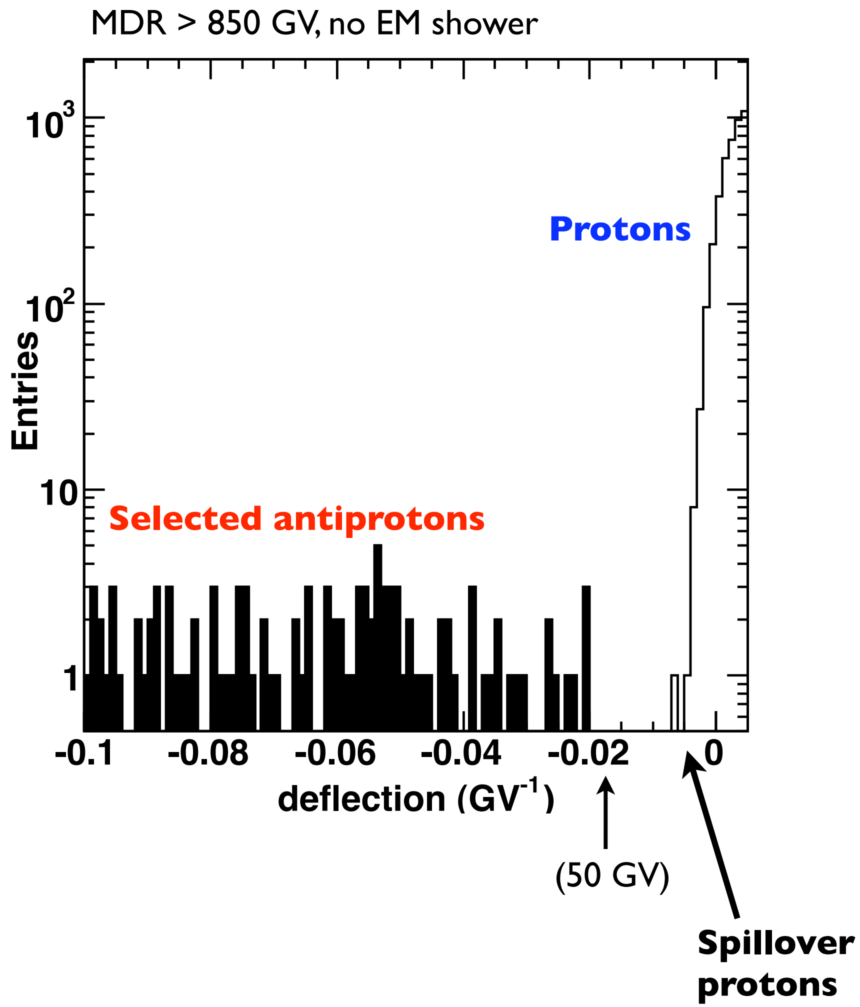
Proton 'spillover' background

- **Spectrometer tracking information is crucial for high-energy antiproton selection**

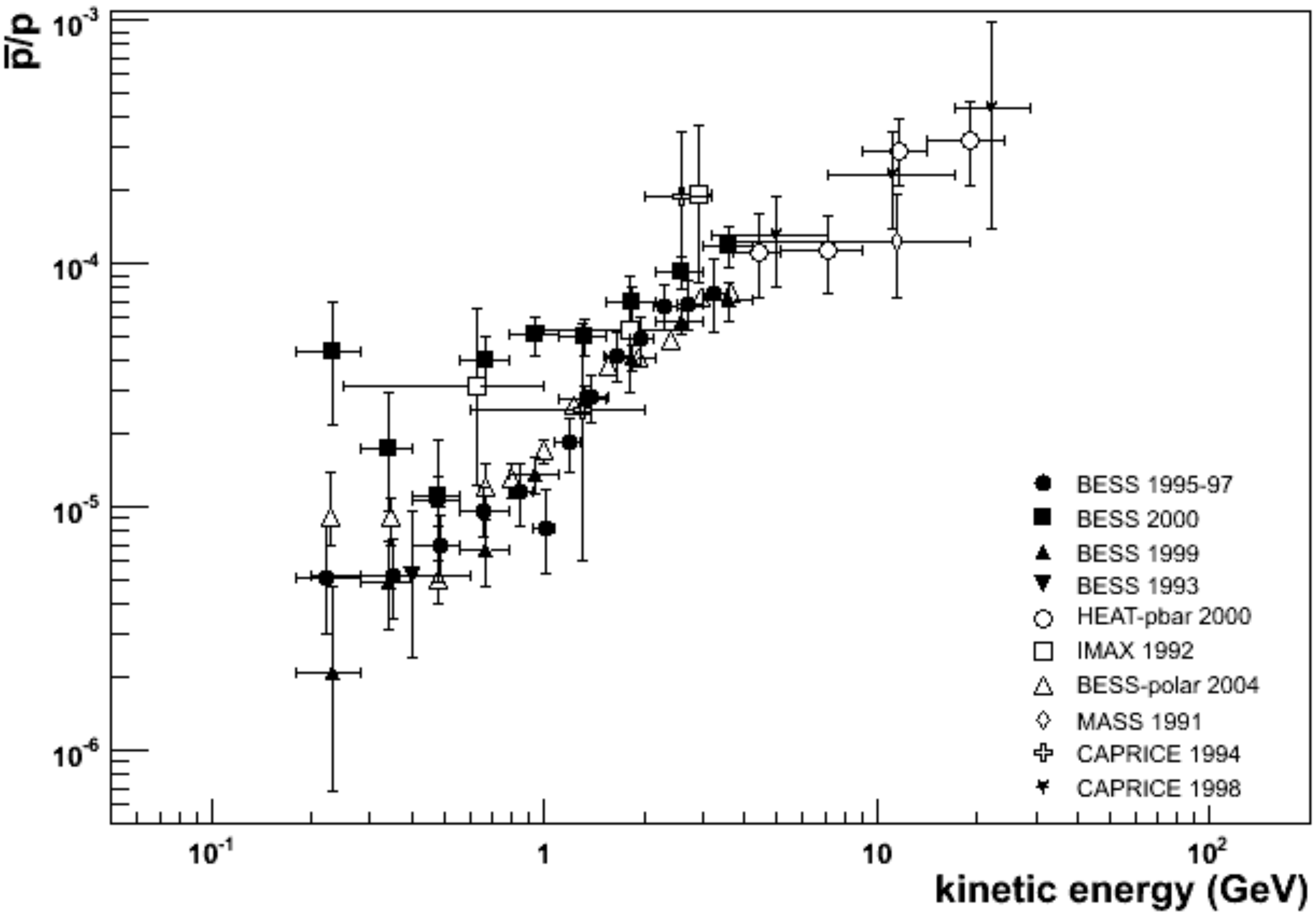
- **Finite spectrometer resolution - high rigidity protons may be assigned wrong sign-of-charge**
- Also background from scattered protons

- **Eliminate 'spillover' using strict track cuts** (χ^2, lever arm, no δ-rays, etc)
- MDR > 10 × reconstructed rigidity

- **Spillover limit for antiprotons expected to be ~200 GeV.**



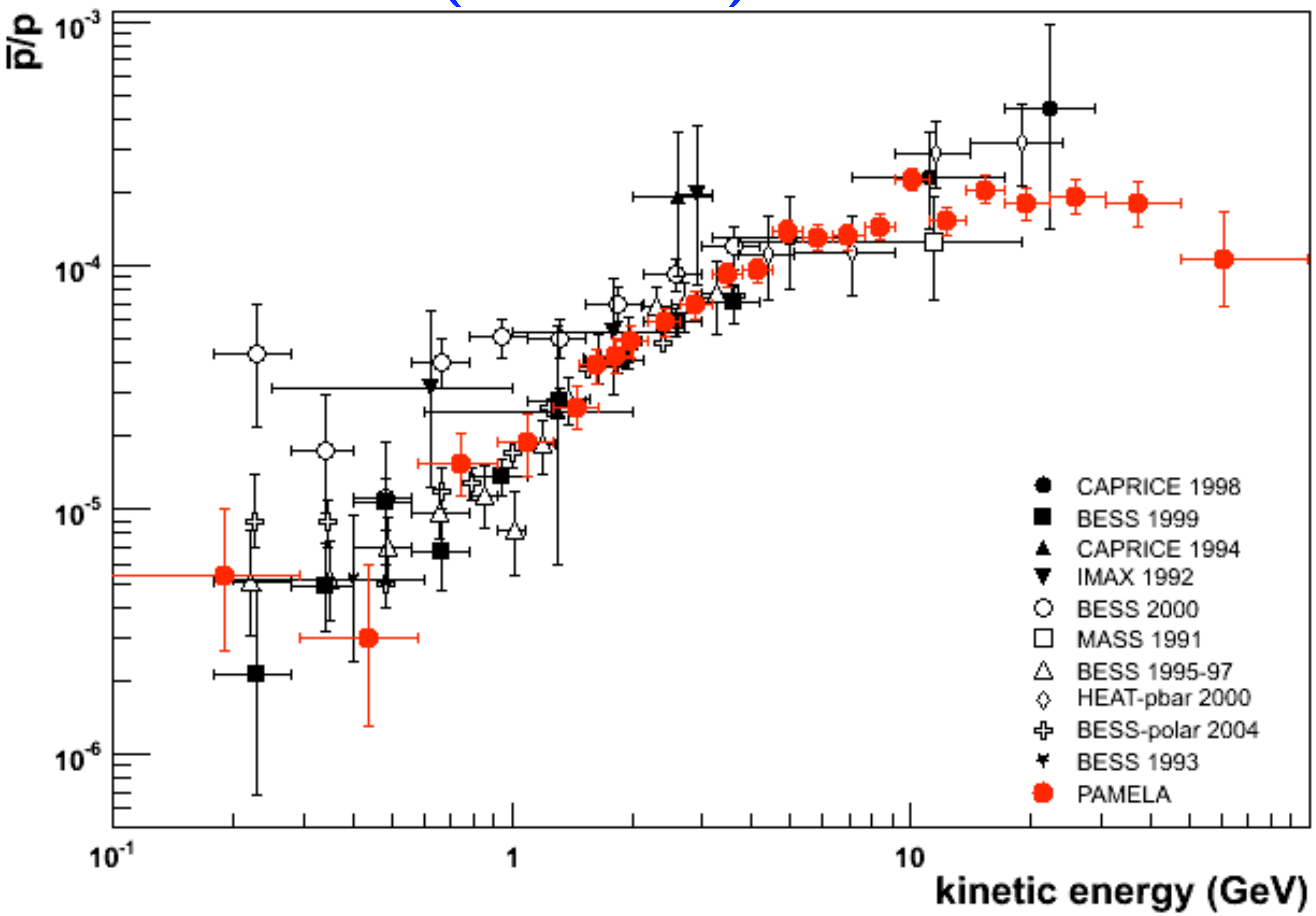
Pre-PAMELA antiproton-to-proton flux ratio



Antiproton-to-proton flux ratio

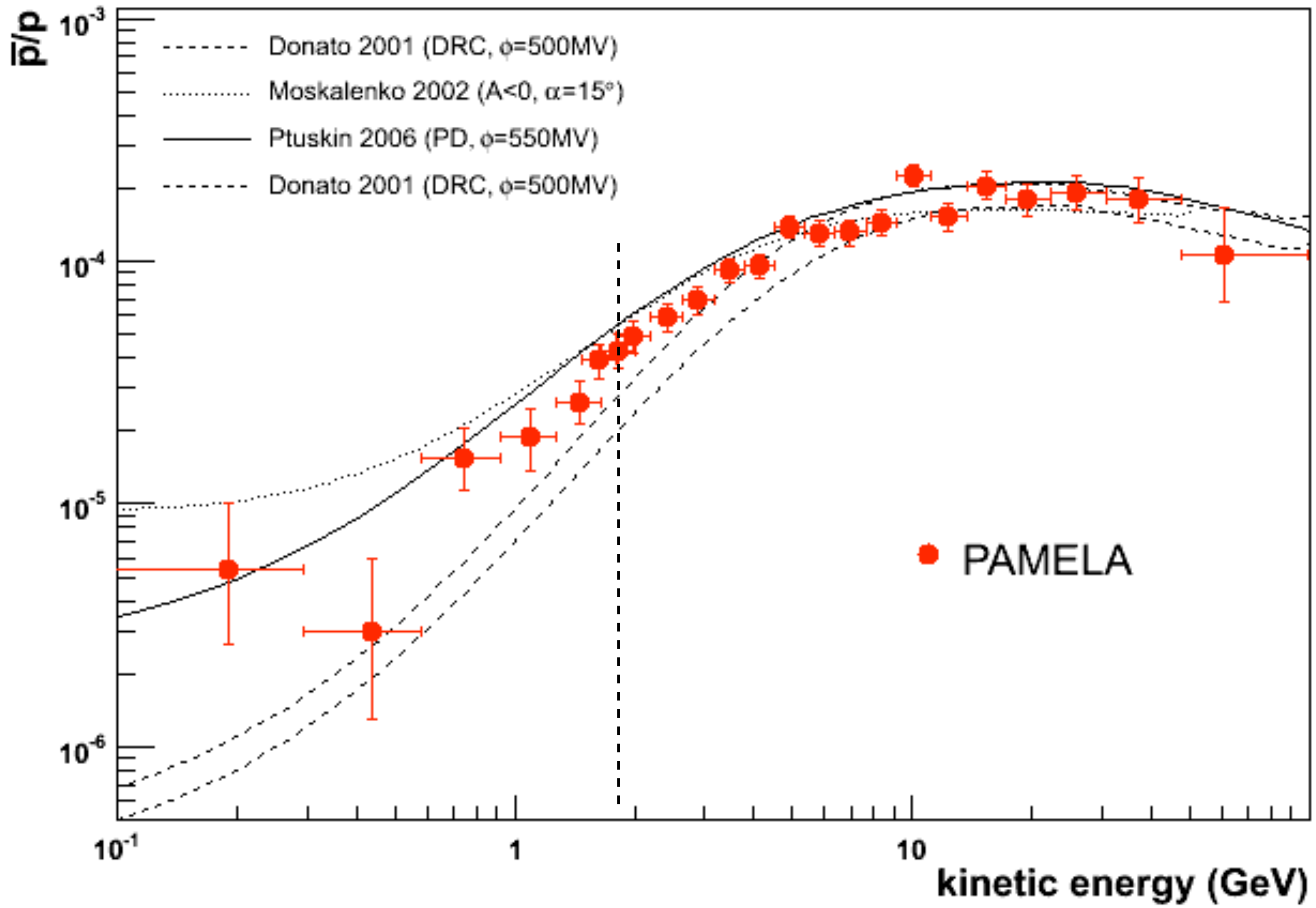
2nd Feb. 2009!

Adriani et al., Phys. Rev. Lett. 102, 051101 (2009)
arXiv 0810.4994 (28th Oct. 2008)

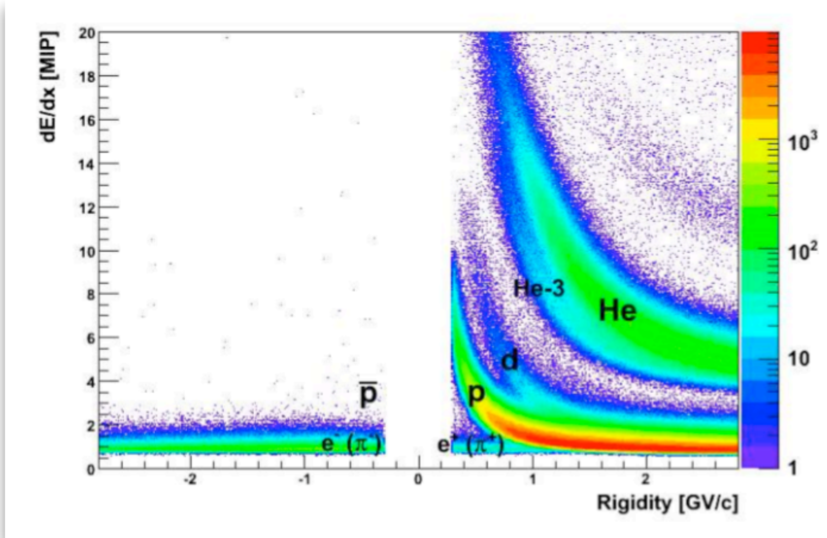


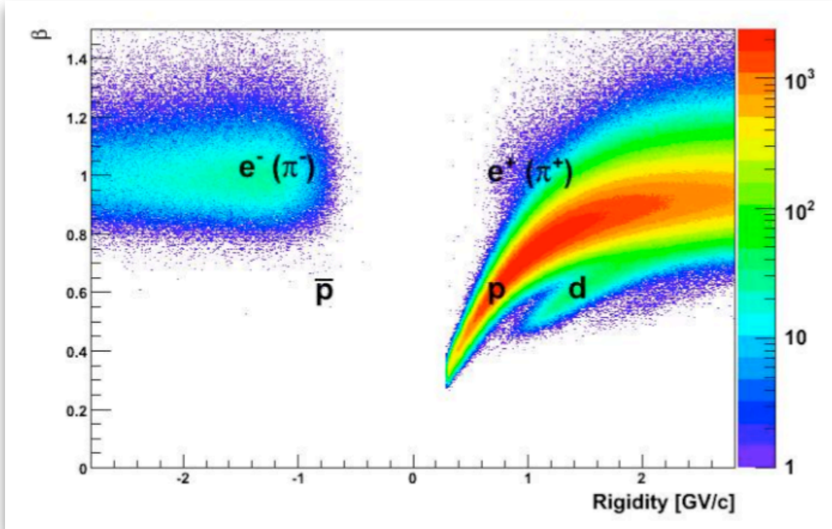
Secondary production models

Adriani et al., Phys. Rev. Lett. 102, 051101 (2009)
arXiv 0810.4994 (28th Oct. 2008)

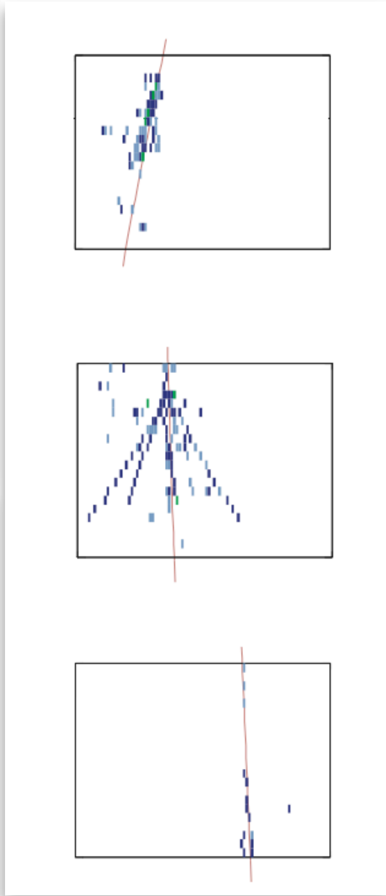


Low energy antiproton selection





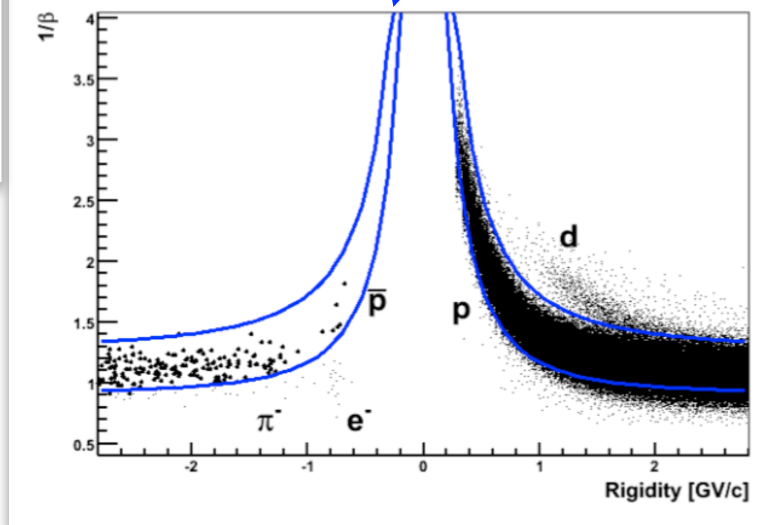
Selected with tracker dE/dx



Calorimeter interaction topology

Selected antiprotons

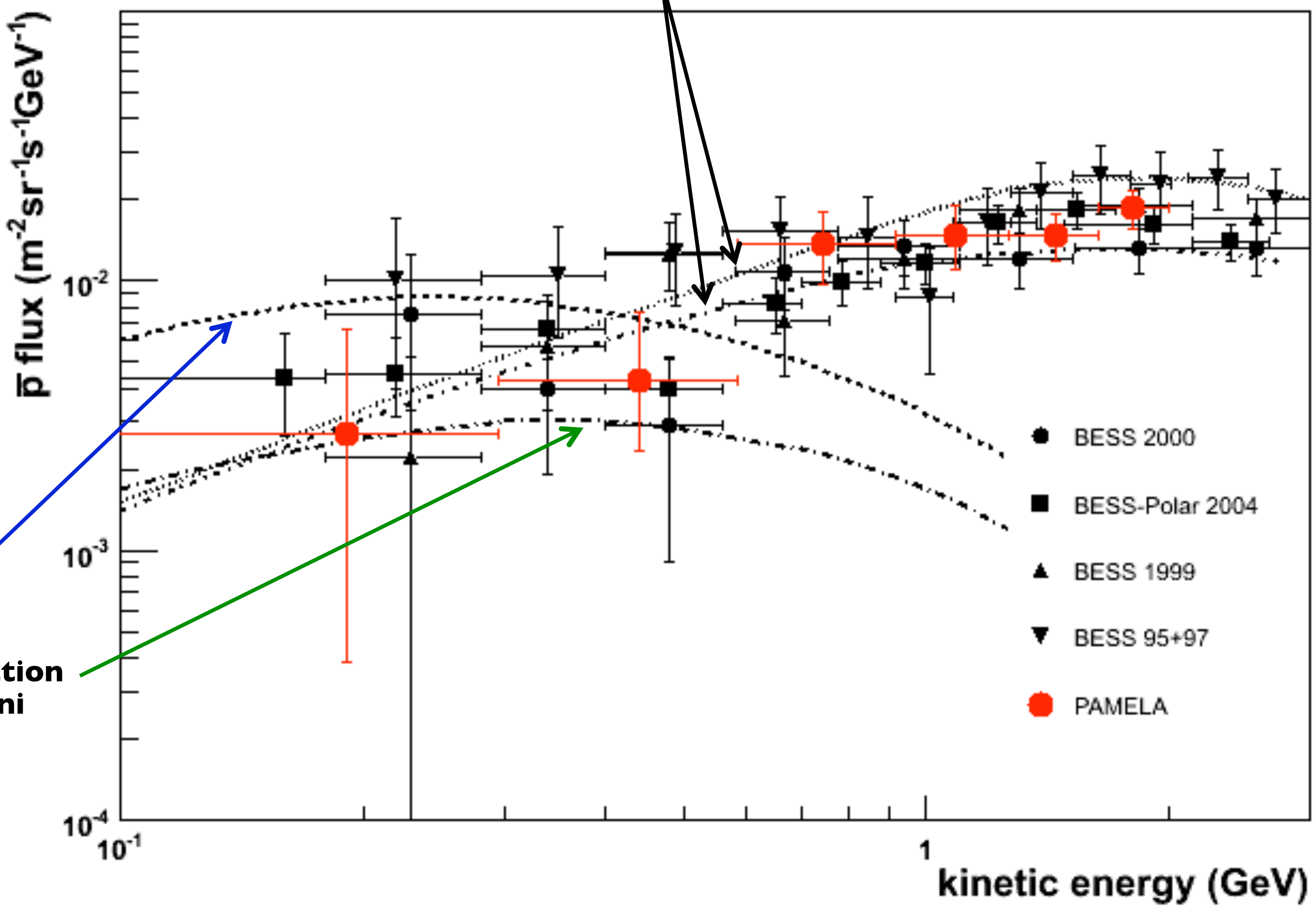
β selection



Antiproton flux

Secondary production

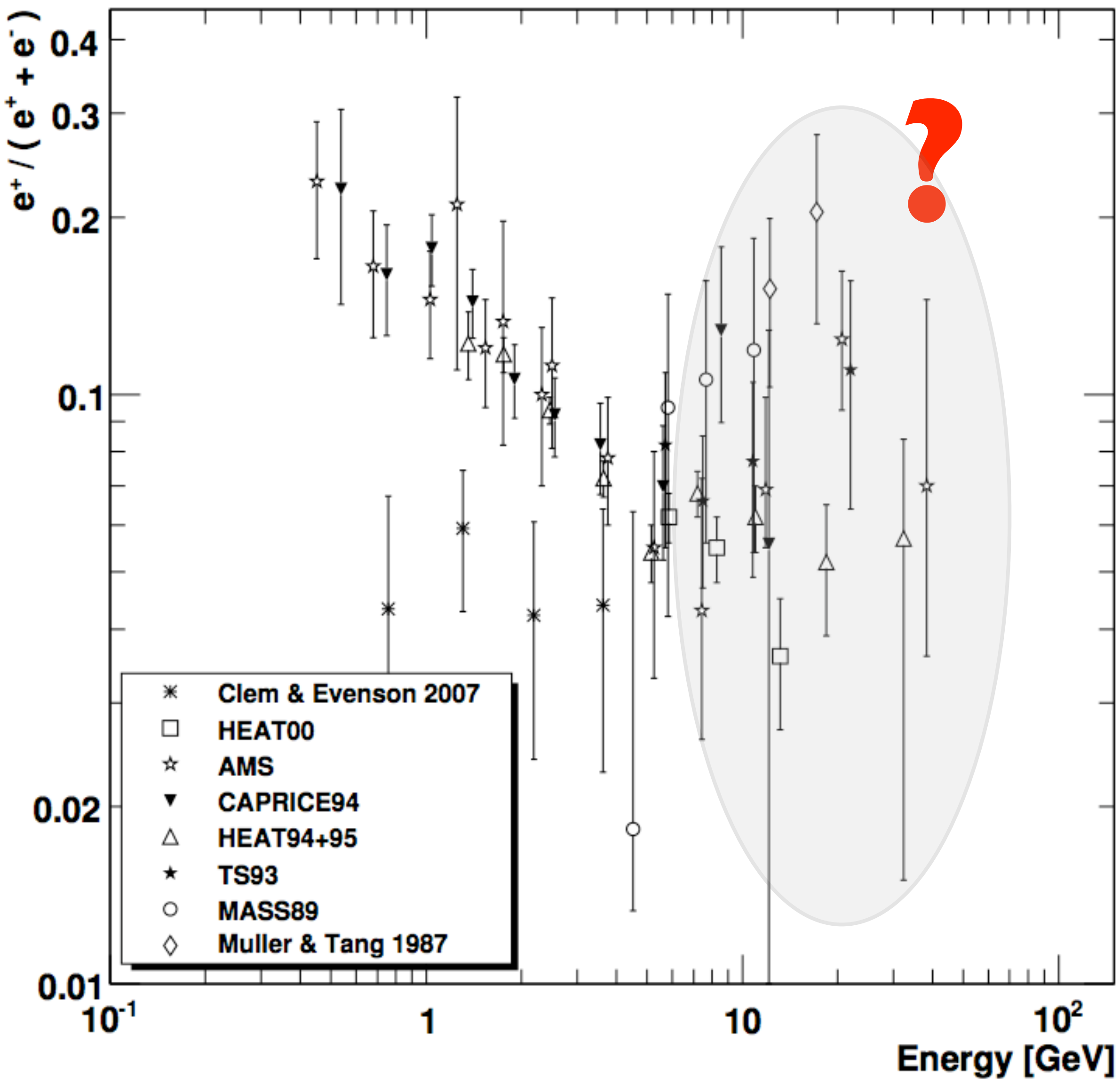
Preliminary



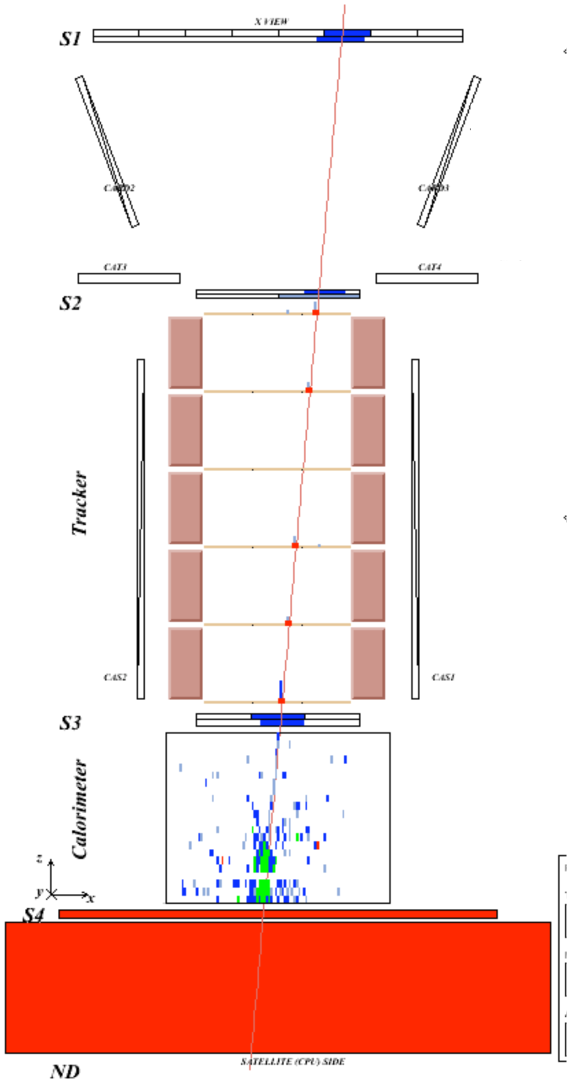
Primary production
Evaporation Mini
Black Holes:
Yoshimura et al.
Maki et al.

P. Hofverberg, KTH, PhD Thesis, 2008-11-28

Pre-PAMELA positron fraction



Proton / positron discrimination

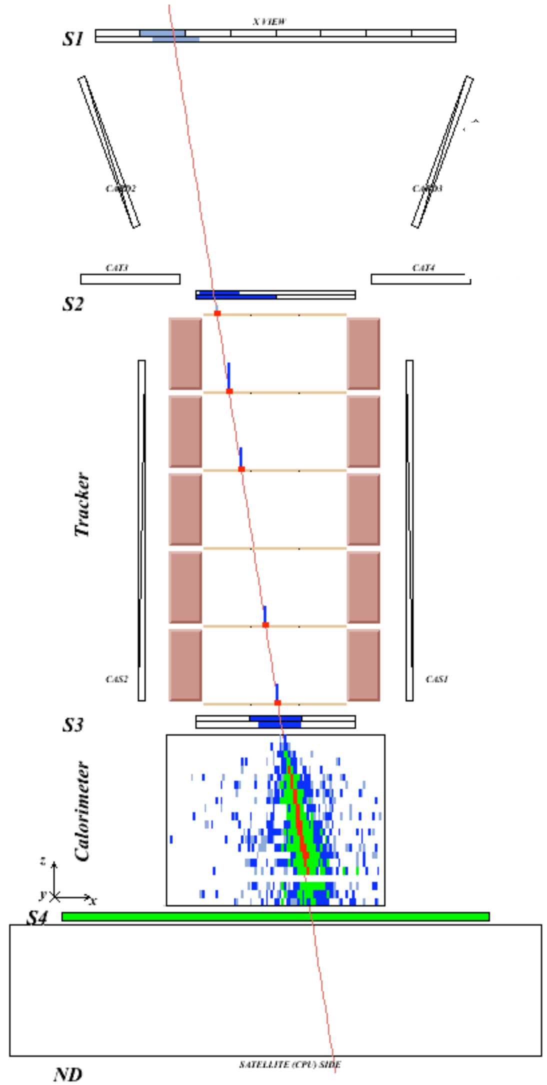


Time-of-flight:
trigger, albedo rejection, mass determination (up to 1 GeV)

Bending in spectrometer:
sign of charge

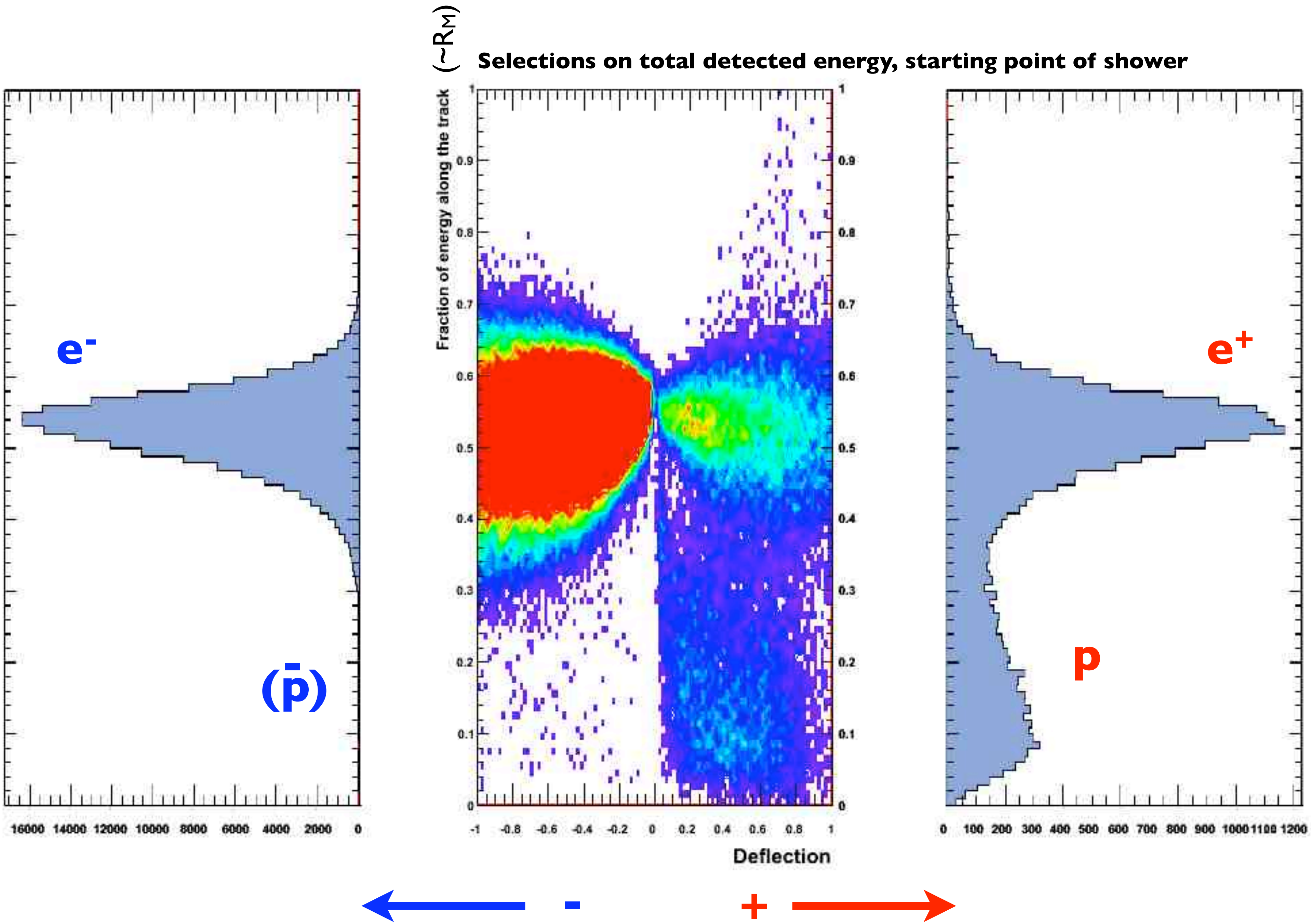
Ionisation energy loss (dE/dx):
magnitude of charge

Interaction pattern in calorimeter:
electron-like or proton-like, electron energy



Proton

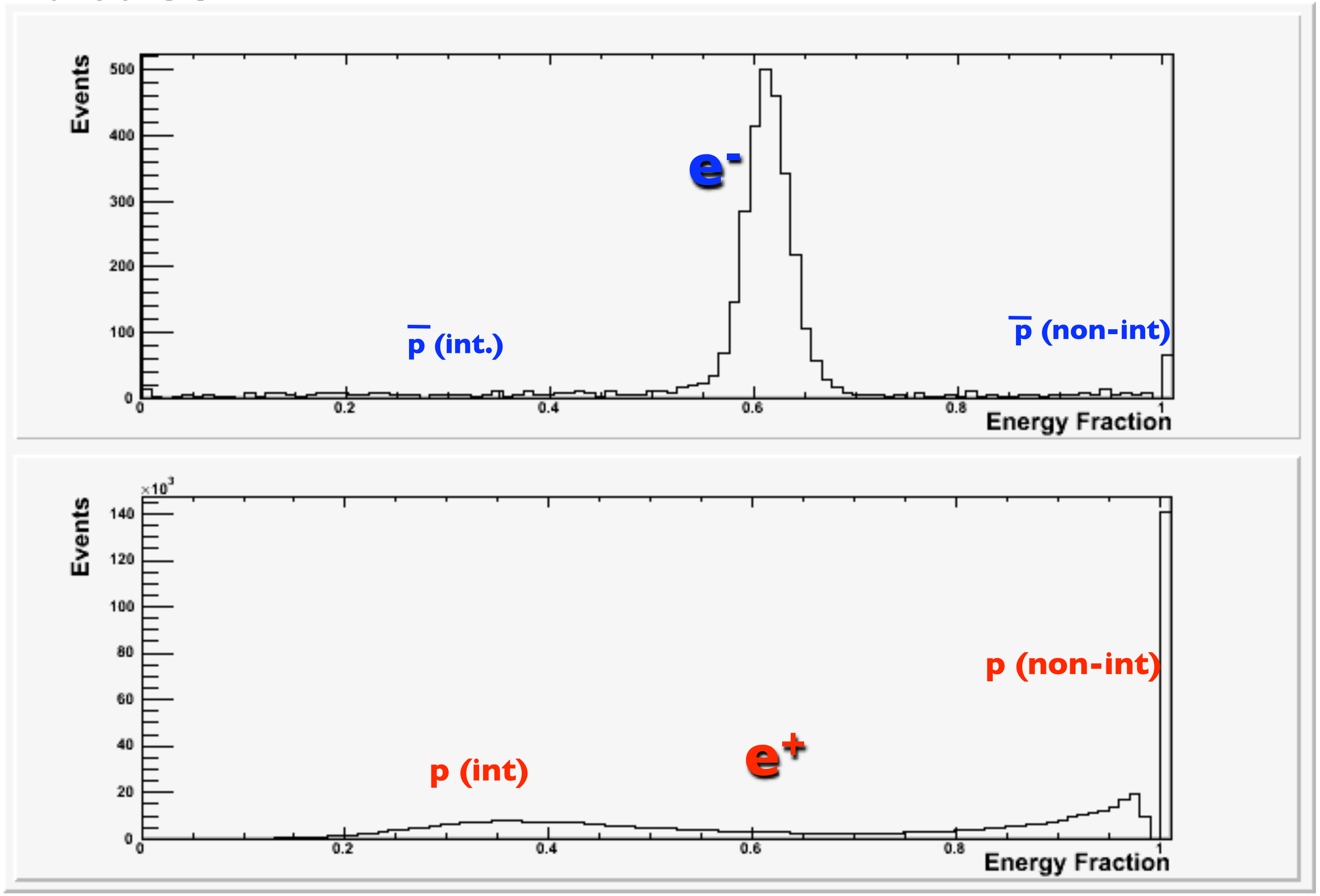
Positron



Selections on total detected energy, starting point of shower
Fraction of energy along the track (~R_M)
Deflection
e-
(p̄)
e+
p
-
+

Positron selection with calorimeter

Rigidity: 20-30 GV

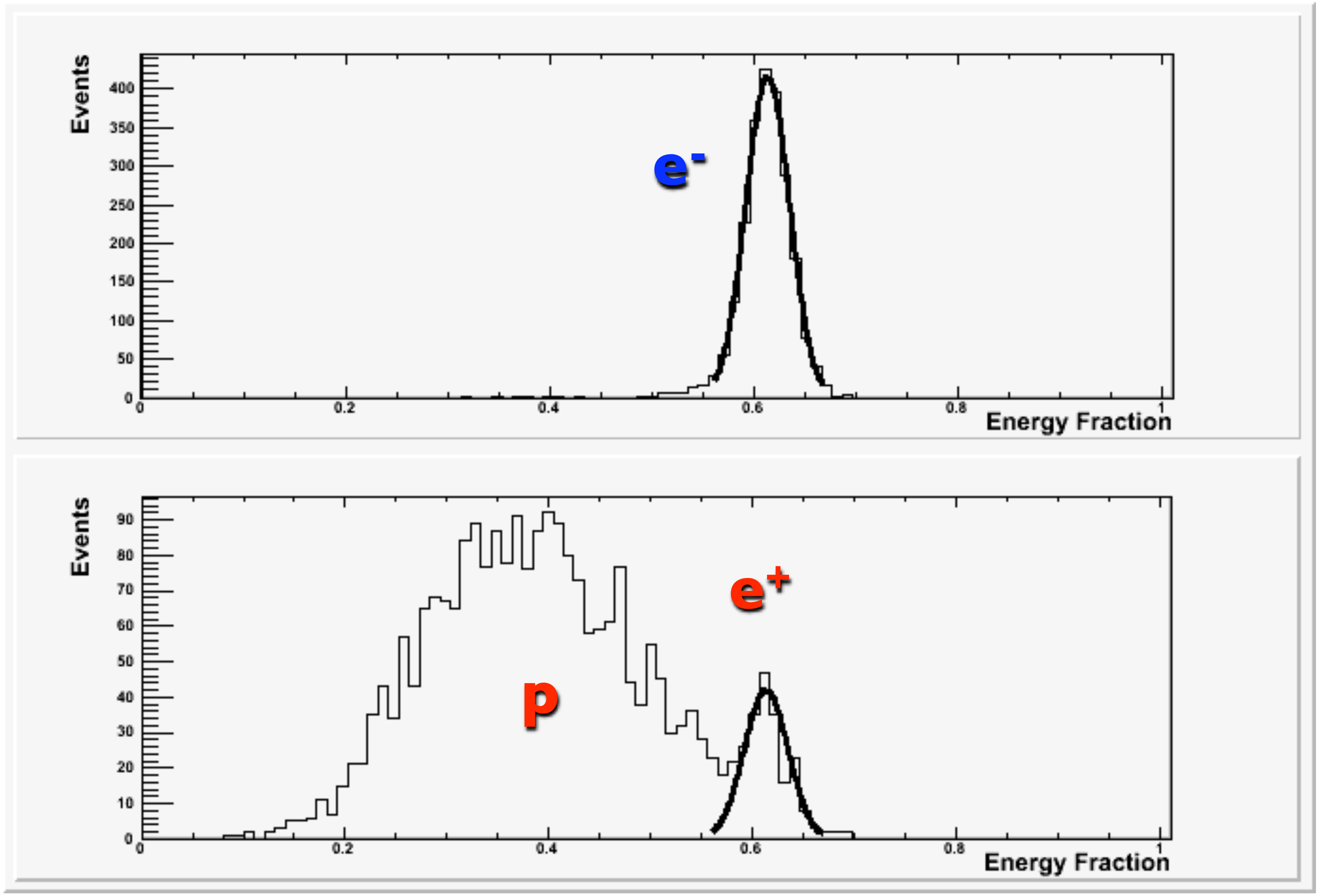


Fraction of charge released along the calorimeter track (left, hit, right)

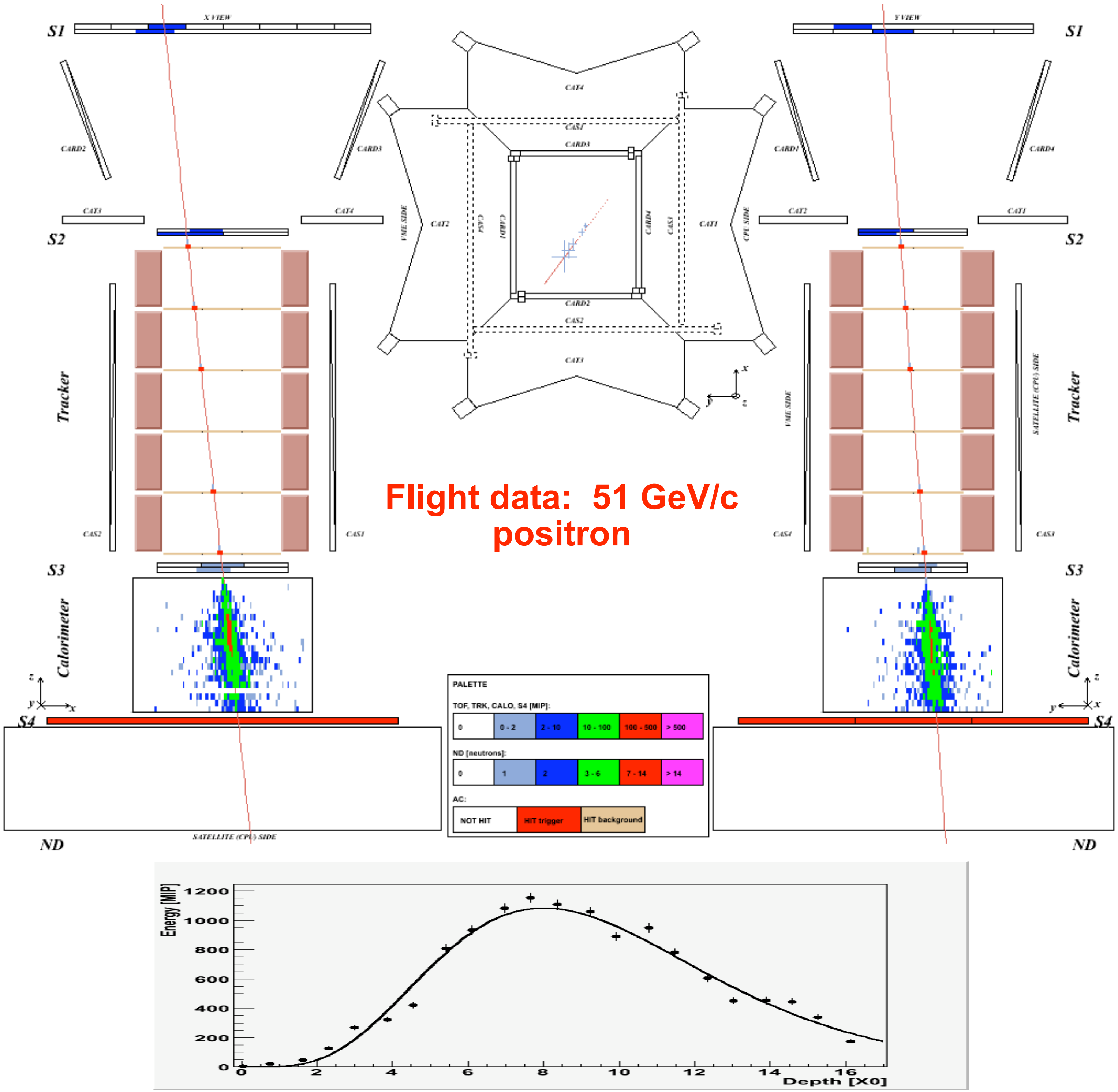
(~ R_m)

Positron selection with calorimeter

Rigidity: 20-30 GV



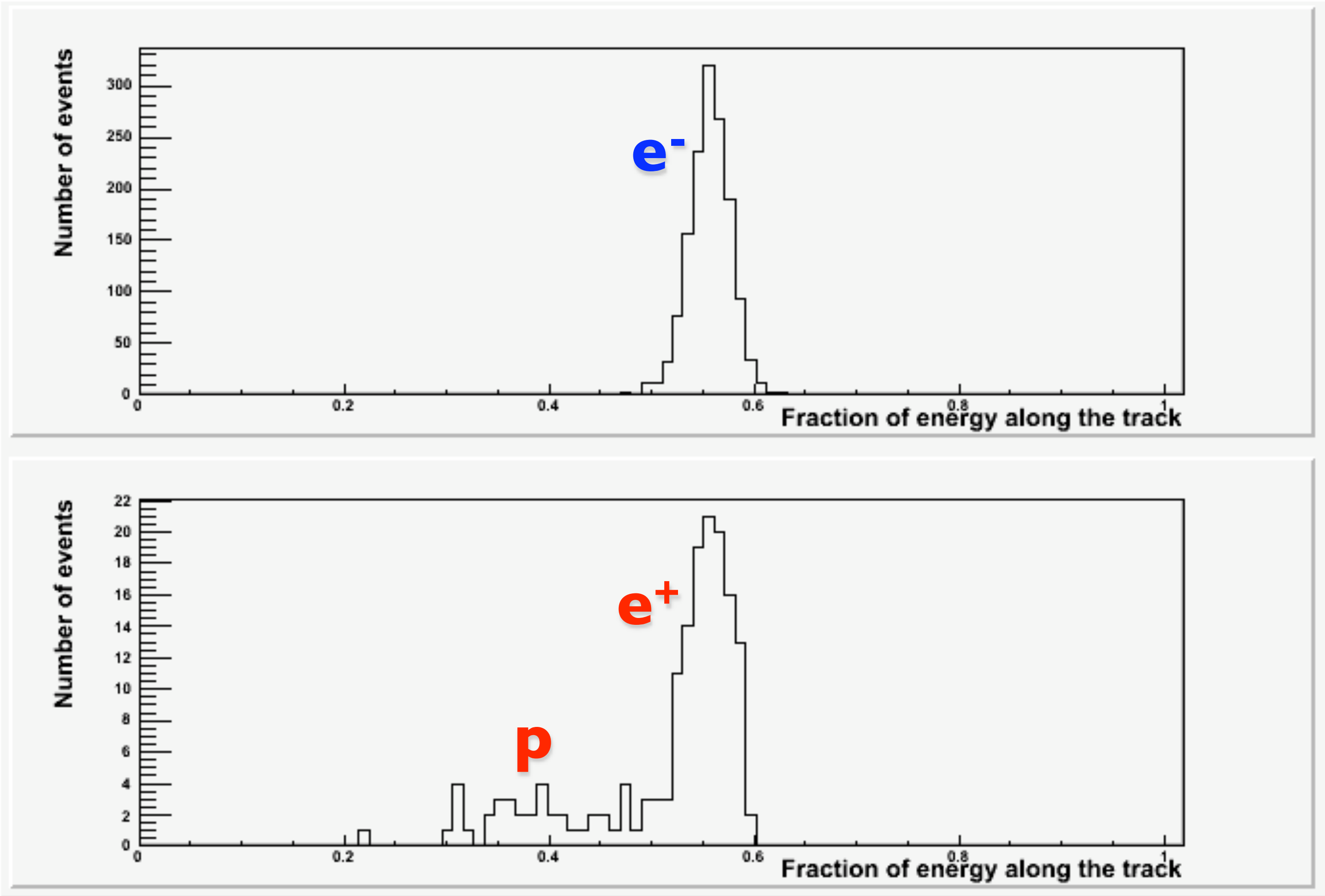
Fraction of charge released along the calorimeter track (left, hit, right) **+** **Energy-momentum match**



Flight data: 51 GeV/c positron
S1
S2
S3
S4
ND
Tracker
Calorimeter
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
Energy [MIP]
Depth [X0]

Positron selection with calorimeter

Rigidity: 20-30 GV



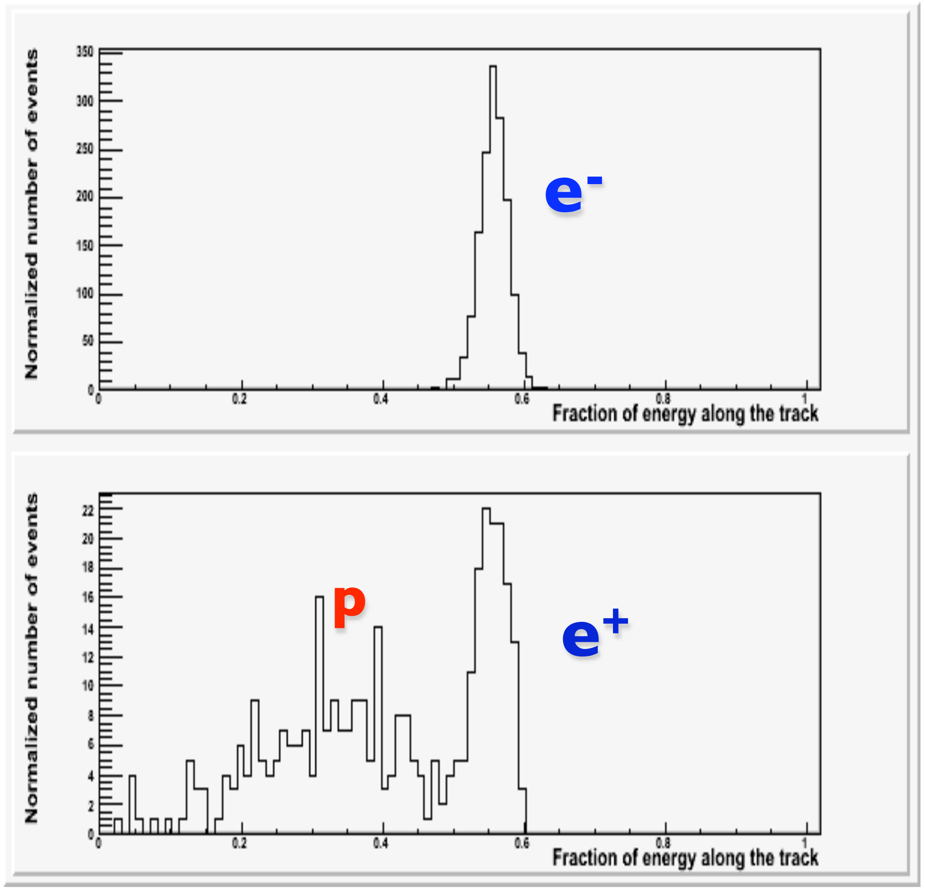
Fraction of charge released along the calorimeter track (left, hit, right)

+

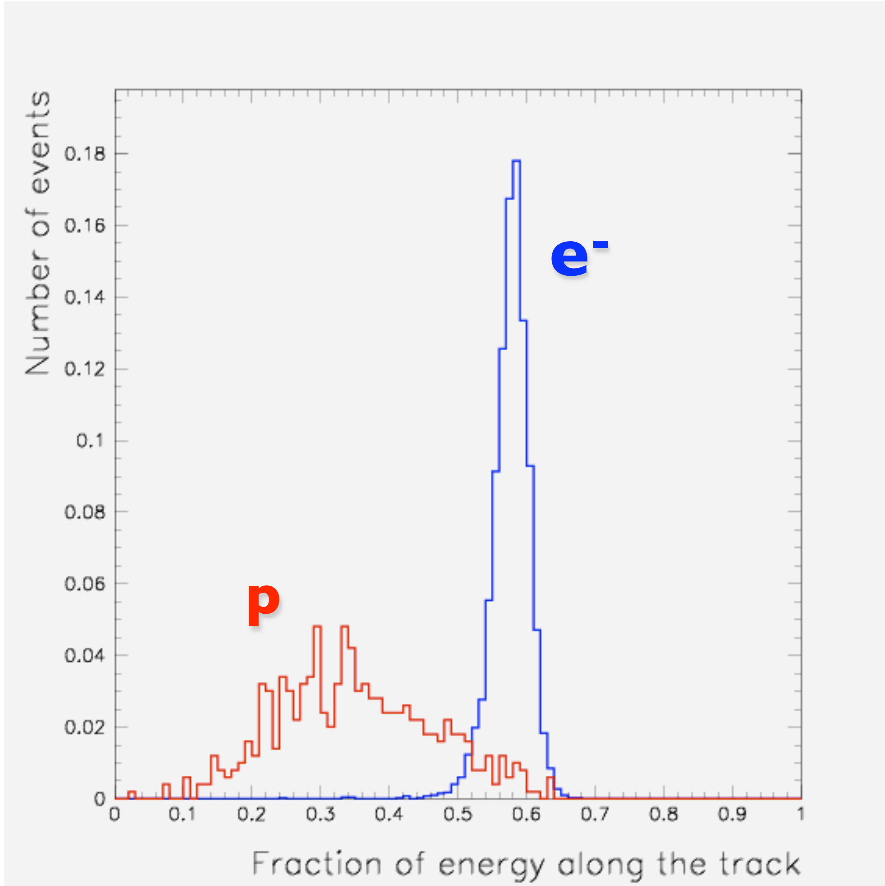
- **Energy-momentum match**
- **Starting point of shower**
- **Longitudinal profile**

Positron selection with calorimeter

Flight data: rigidity: 20-30 GV



Test beam data: momentum: 50 GeV/c

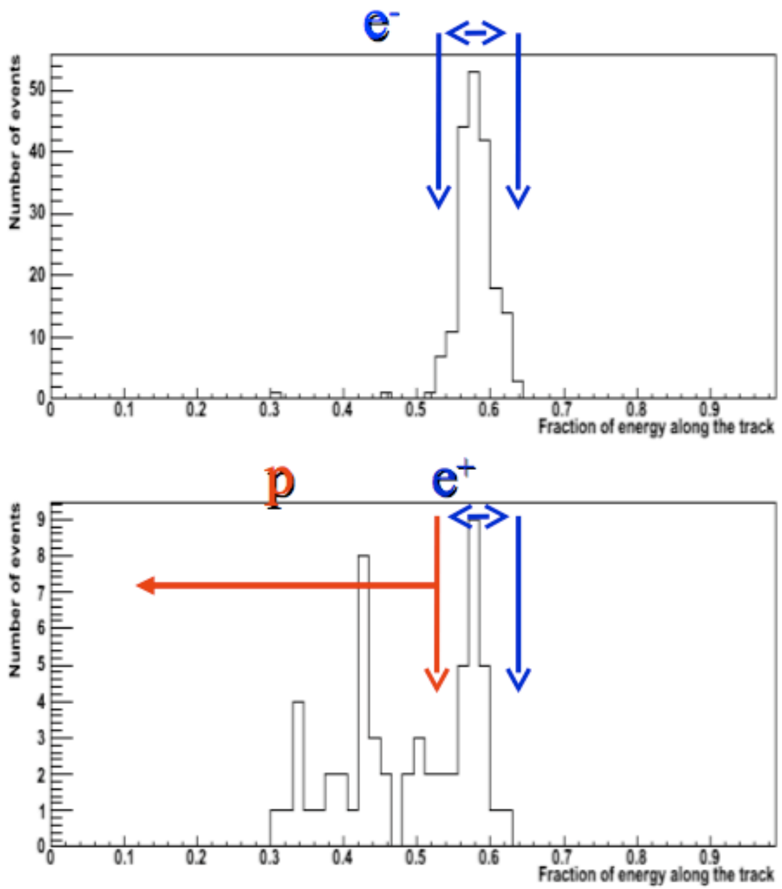


- **Energy-momentum match**
- **Starting point of shower**

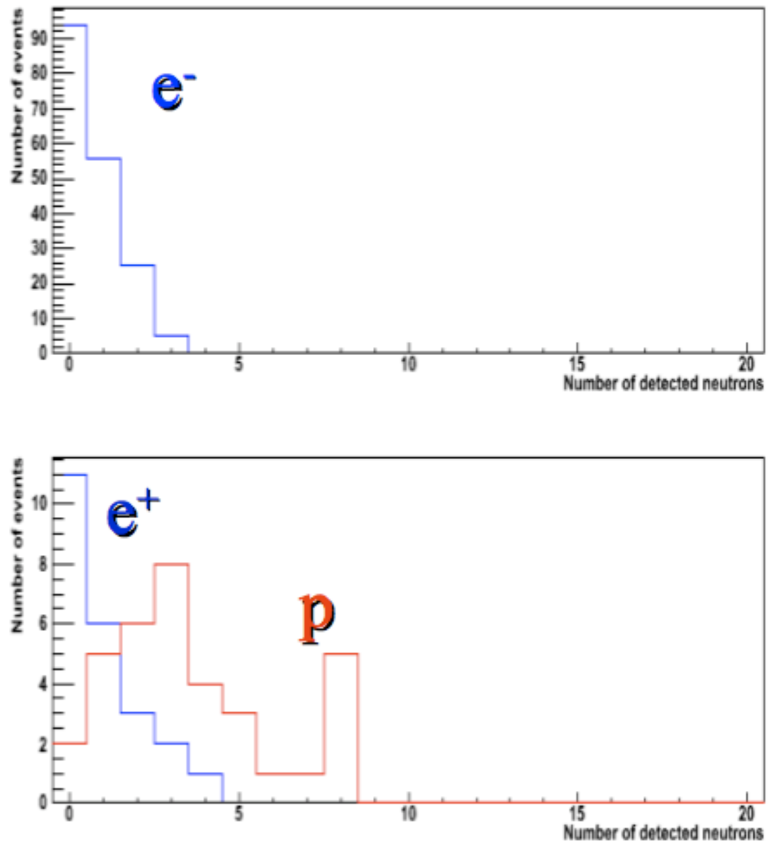
Neutron yield

Rigidity: 42-65 GV

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



Neutrons detected by ND

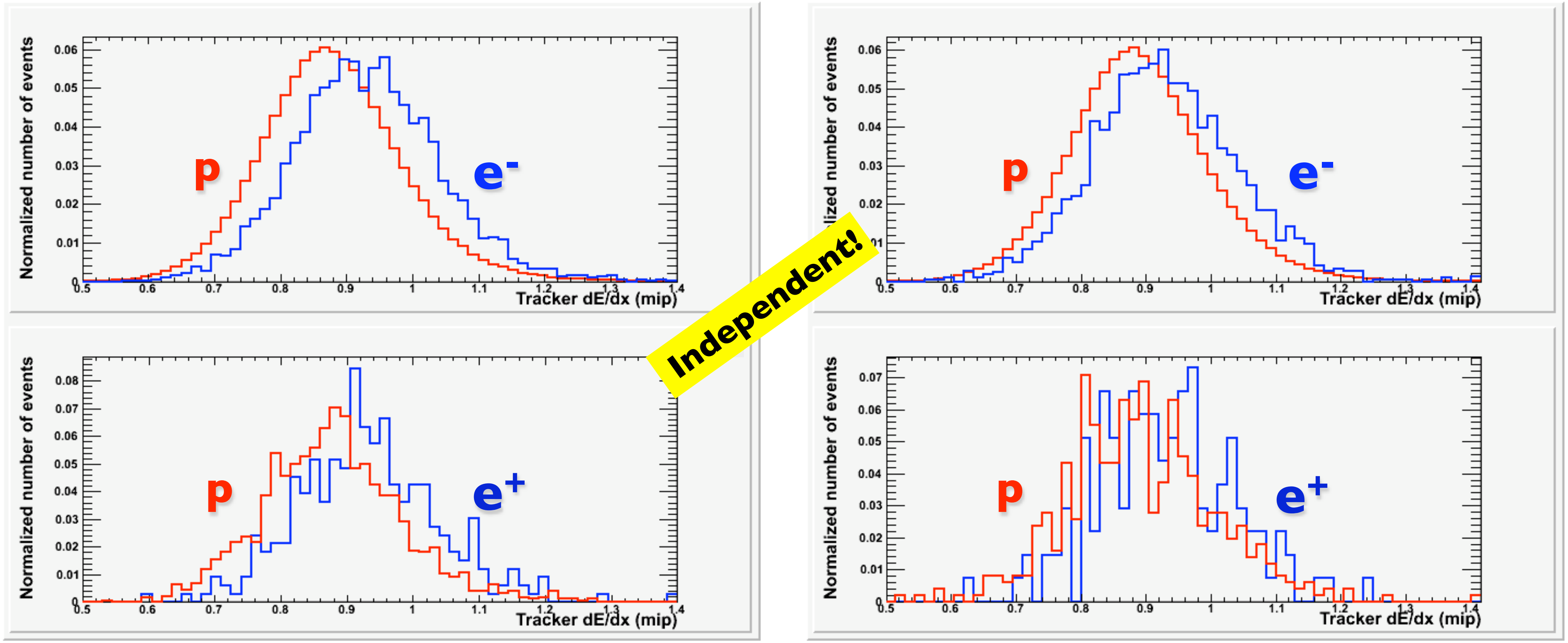


- Energy-momentum match
- Starting point of shower

Positron selection with dE/dX

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

TOP: positive (mostly p) and negative events (mostly e^-)

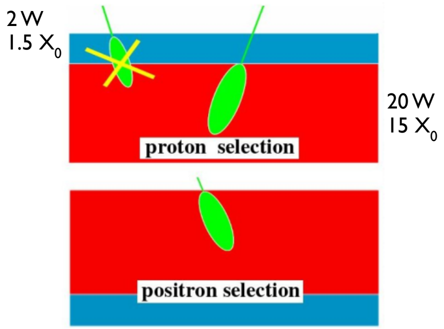


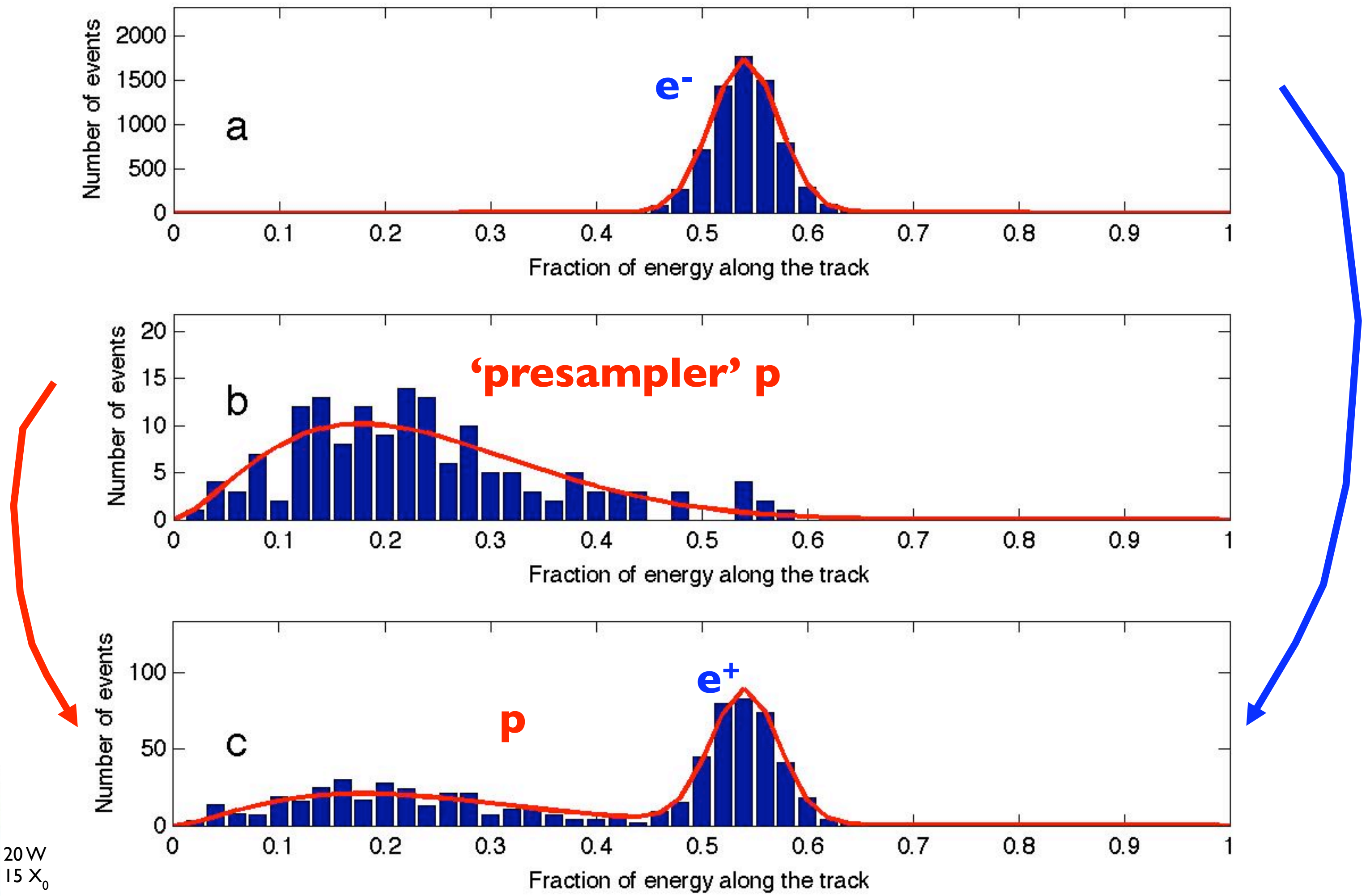
BOTTOM: positive events identified as p and e^+ by transverse profile method

Rigidity: 10-15 GV | **Rigidity: 15-20 GV**

Background estimation from data

Rigidity: 20-28 GV

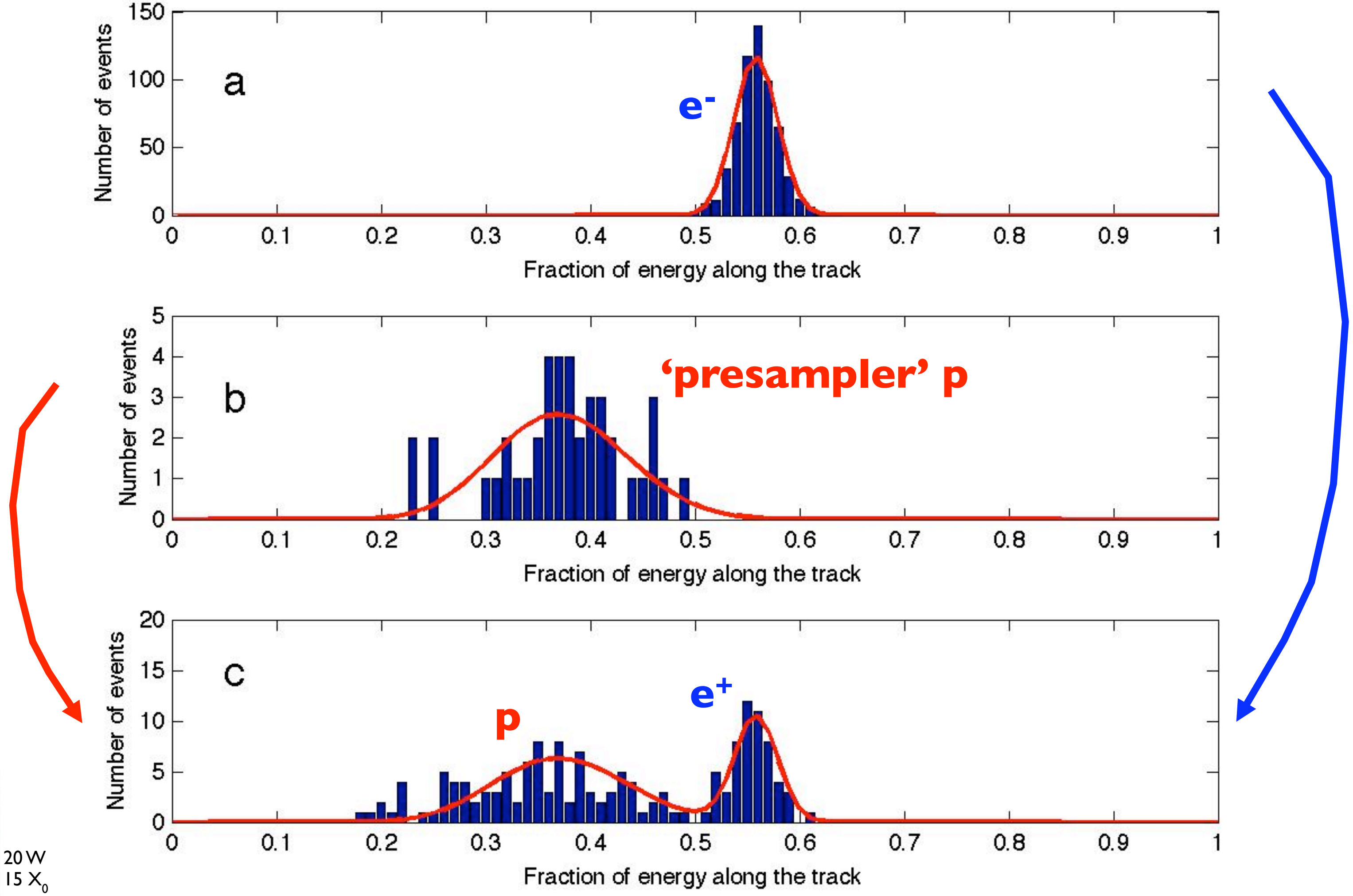


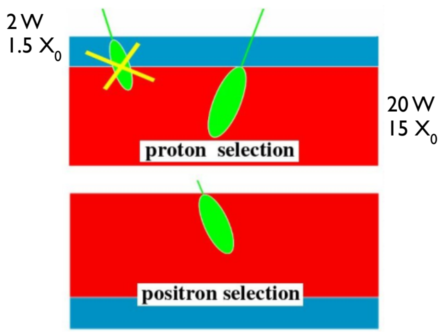


+
- **Energy-momentum match**
- **Starting point of shower**

Background estimation from data

Rigidity: 28-42 GV



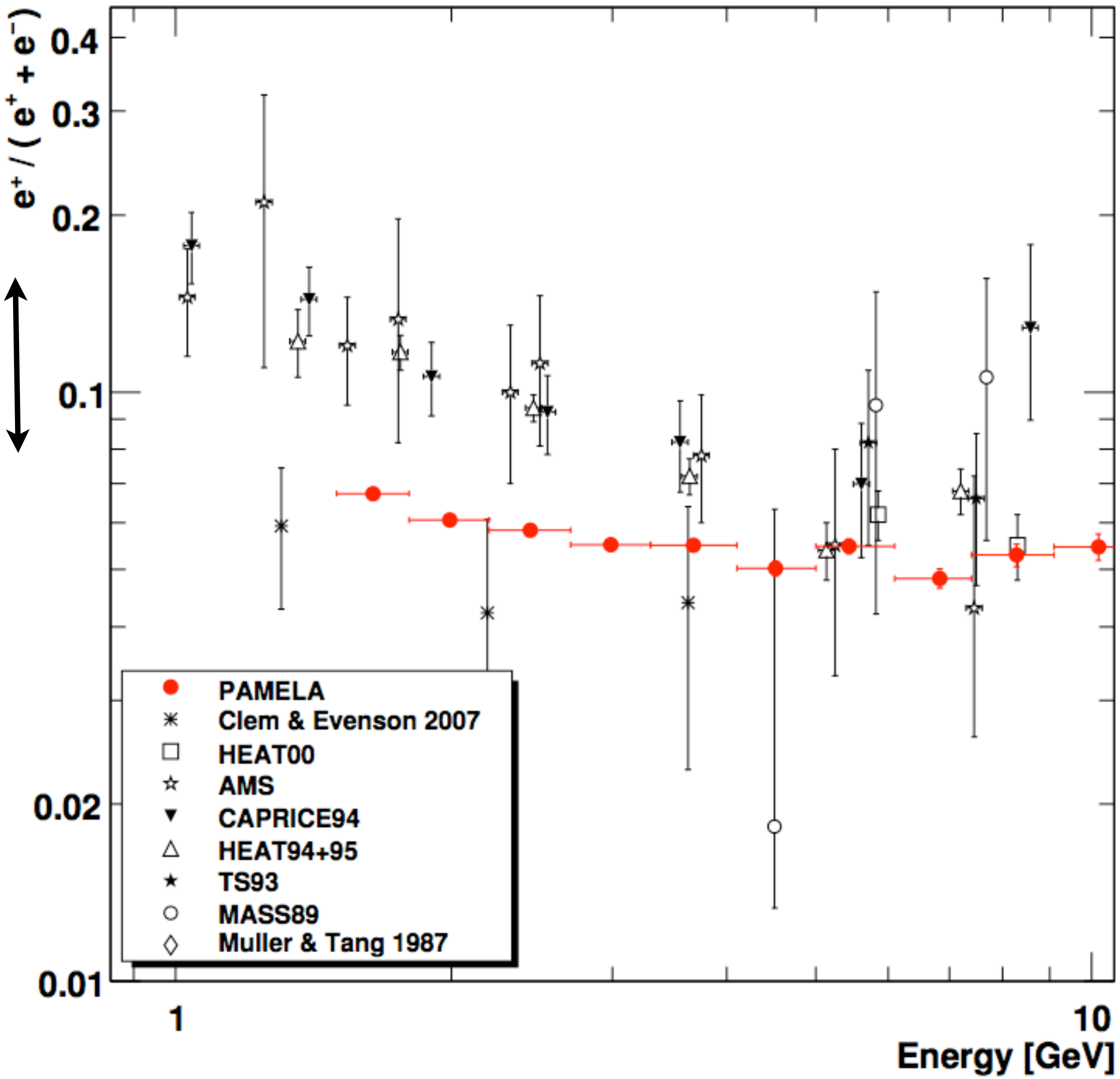


+
- **Energy-momentum match**
- **Starting point of shower**

Low energy positron fraction

Nature, in press (arXiv 0810.4995)

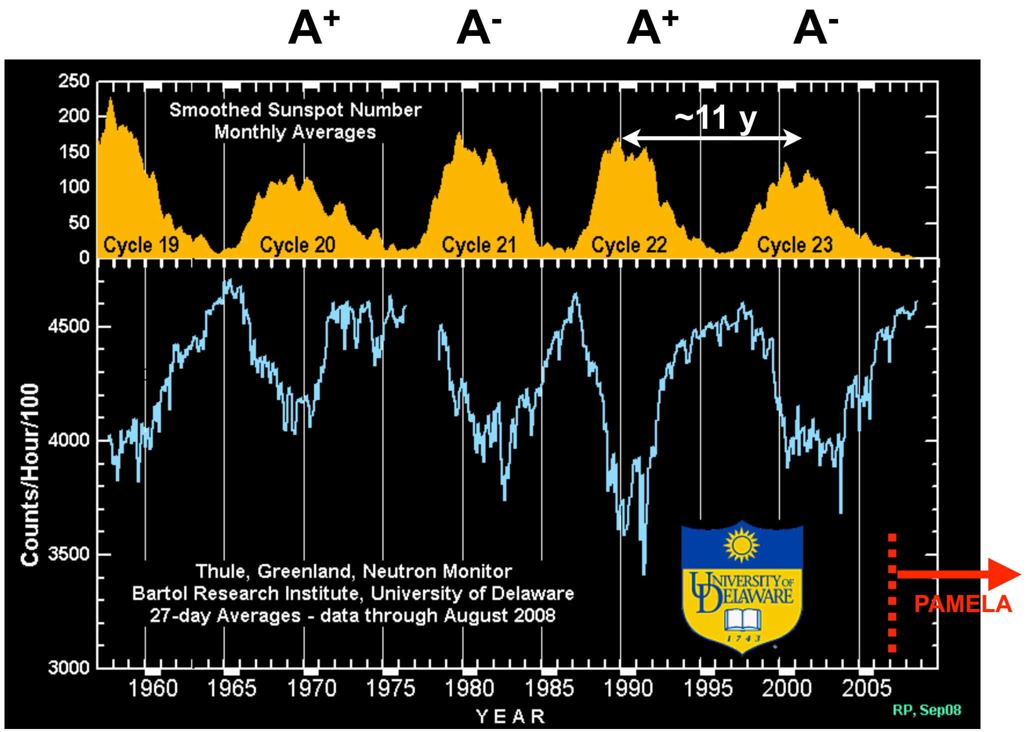
Solar modulation

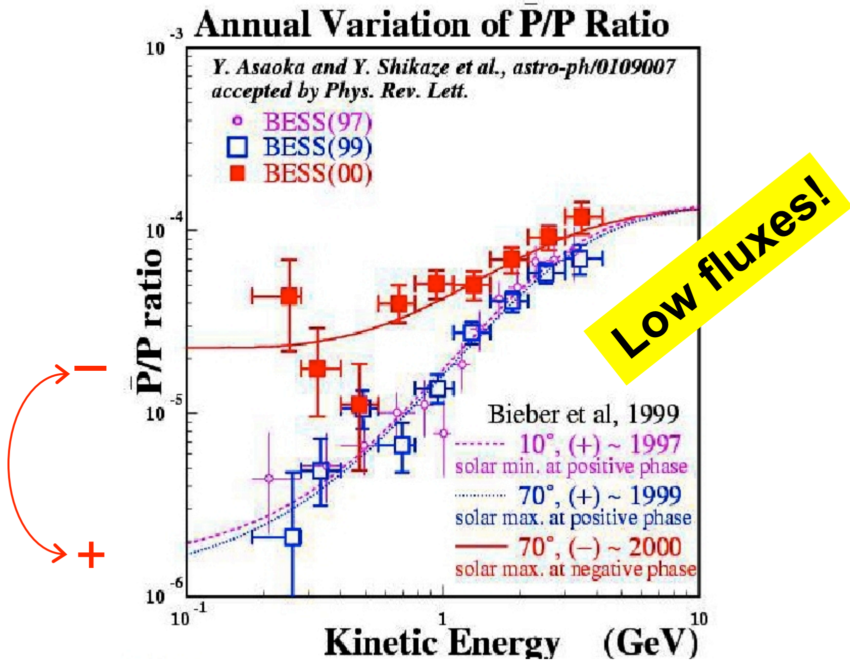


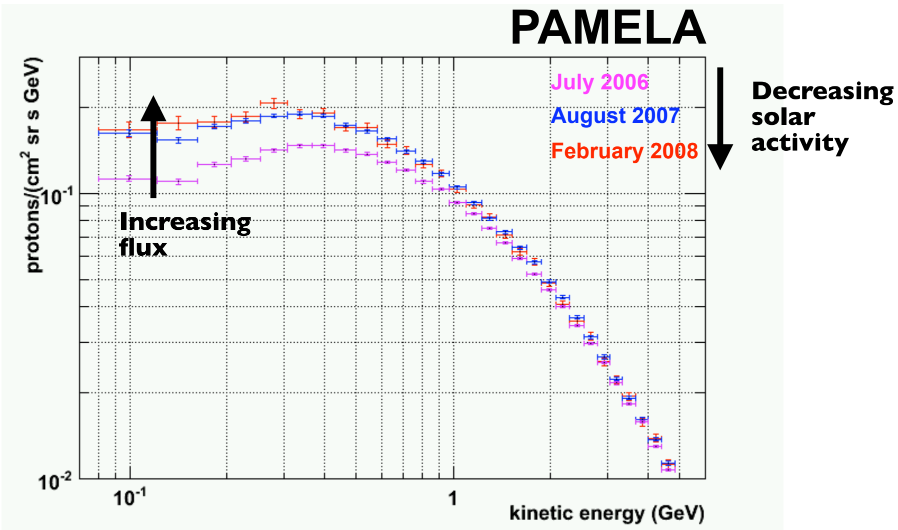
To end 2007:

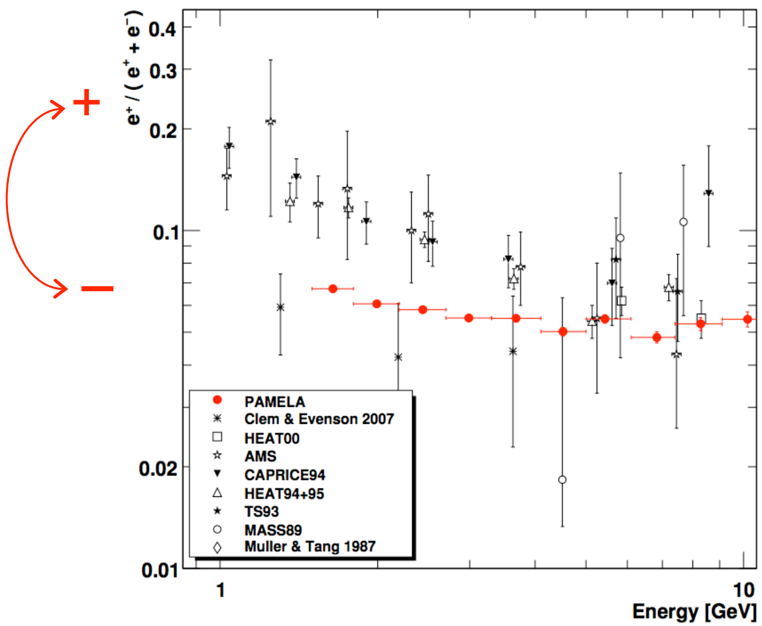
~10^4 e^+ > 1.5 GeV

Solar modulation

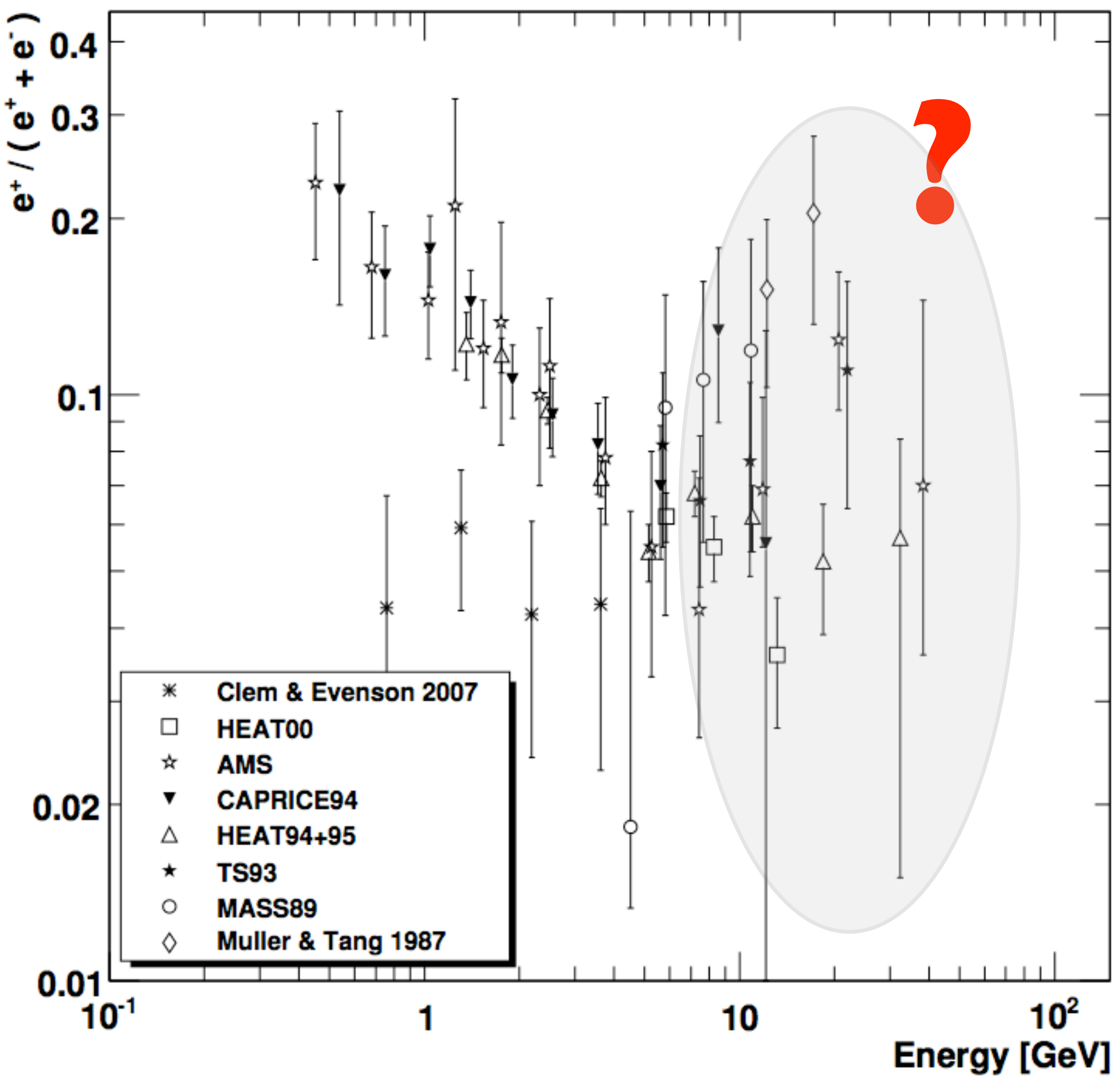






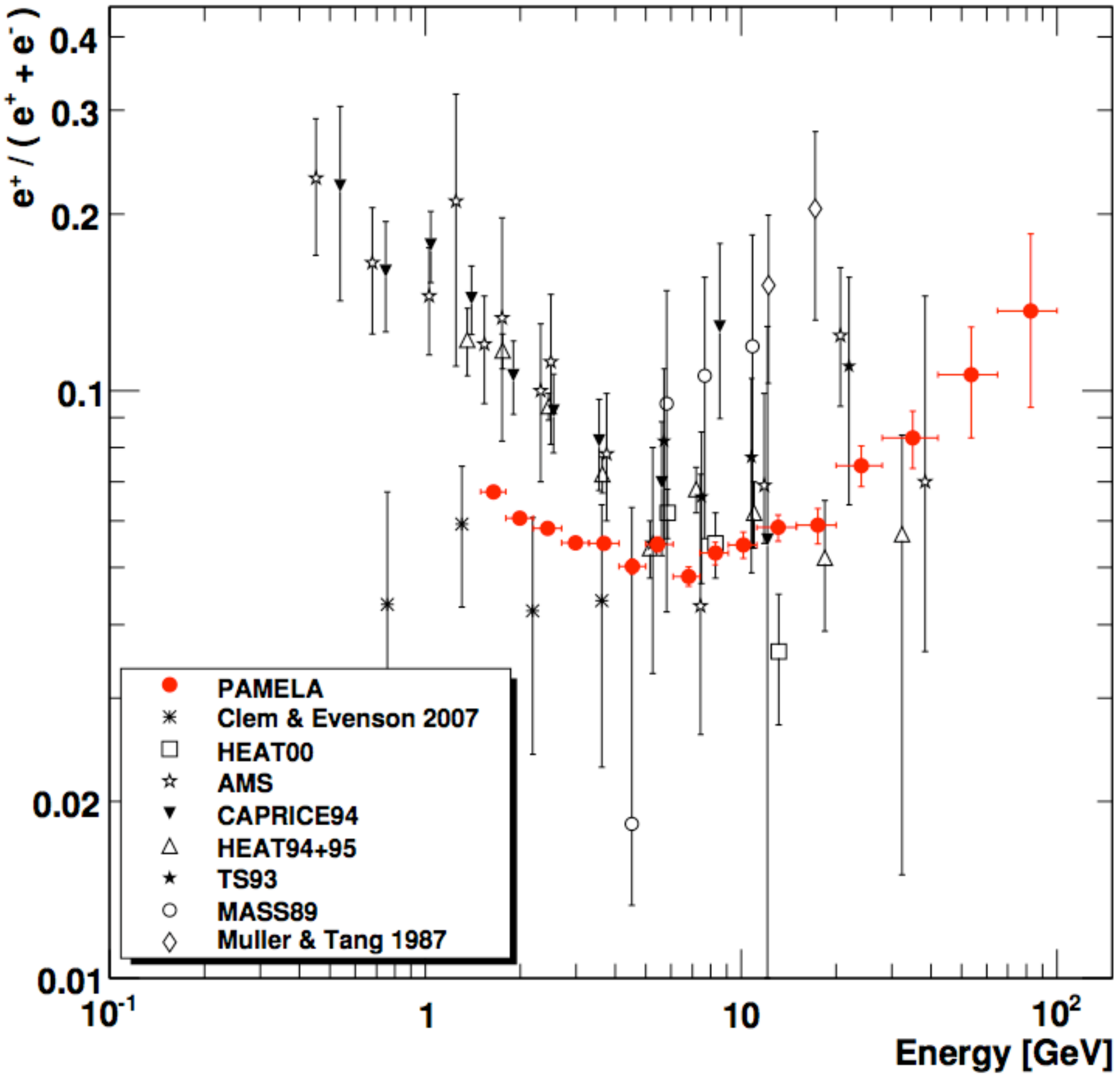


Pre-PAMELA positron fraction



PAMELA positron fraction

Nature, in press (arXiv 0810.4995)

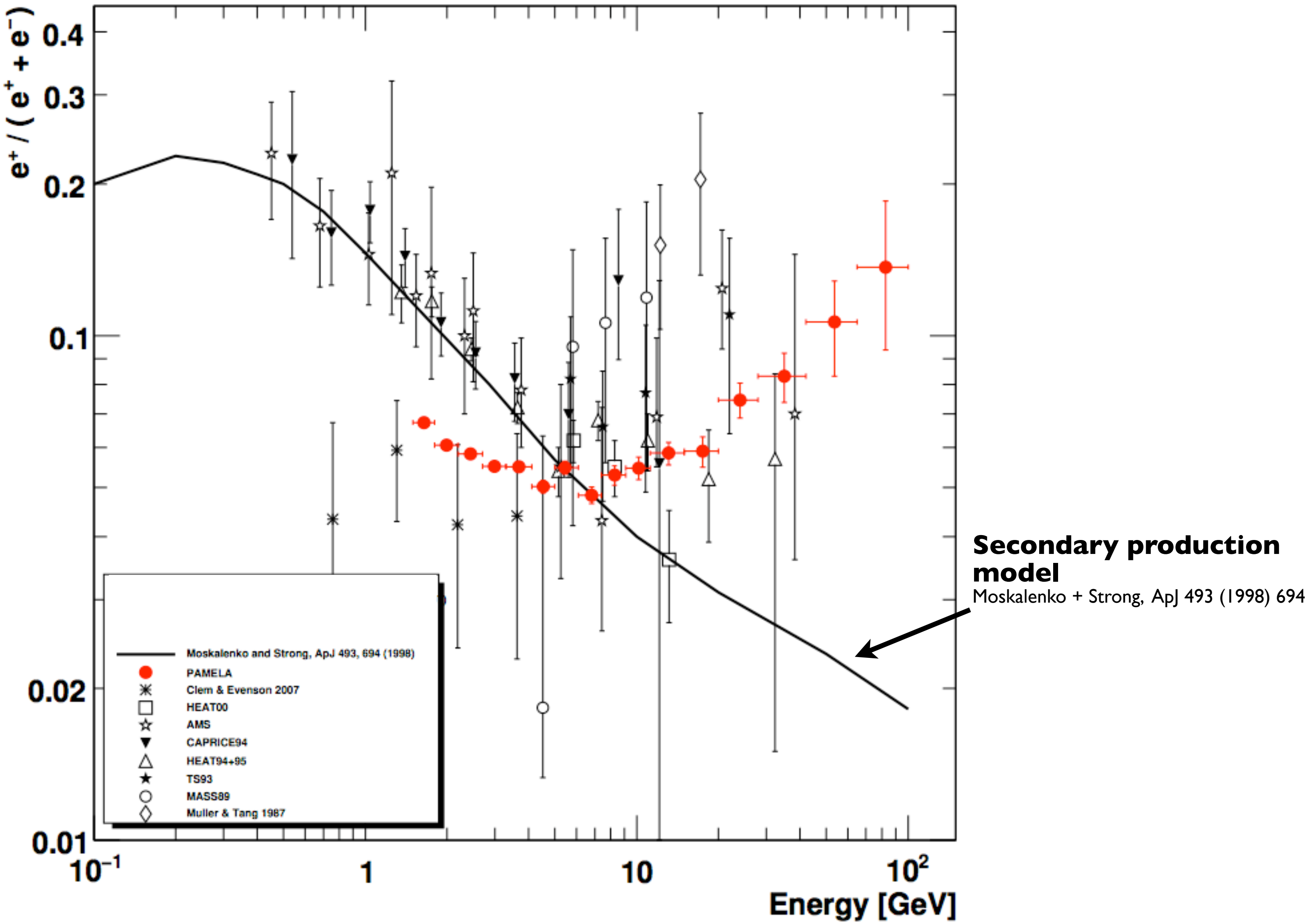


To end 2007:

~10 000 e^+ > 1.5 GeV
~2000 > 5 GeV

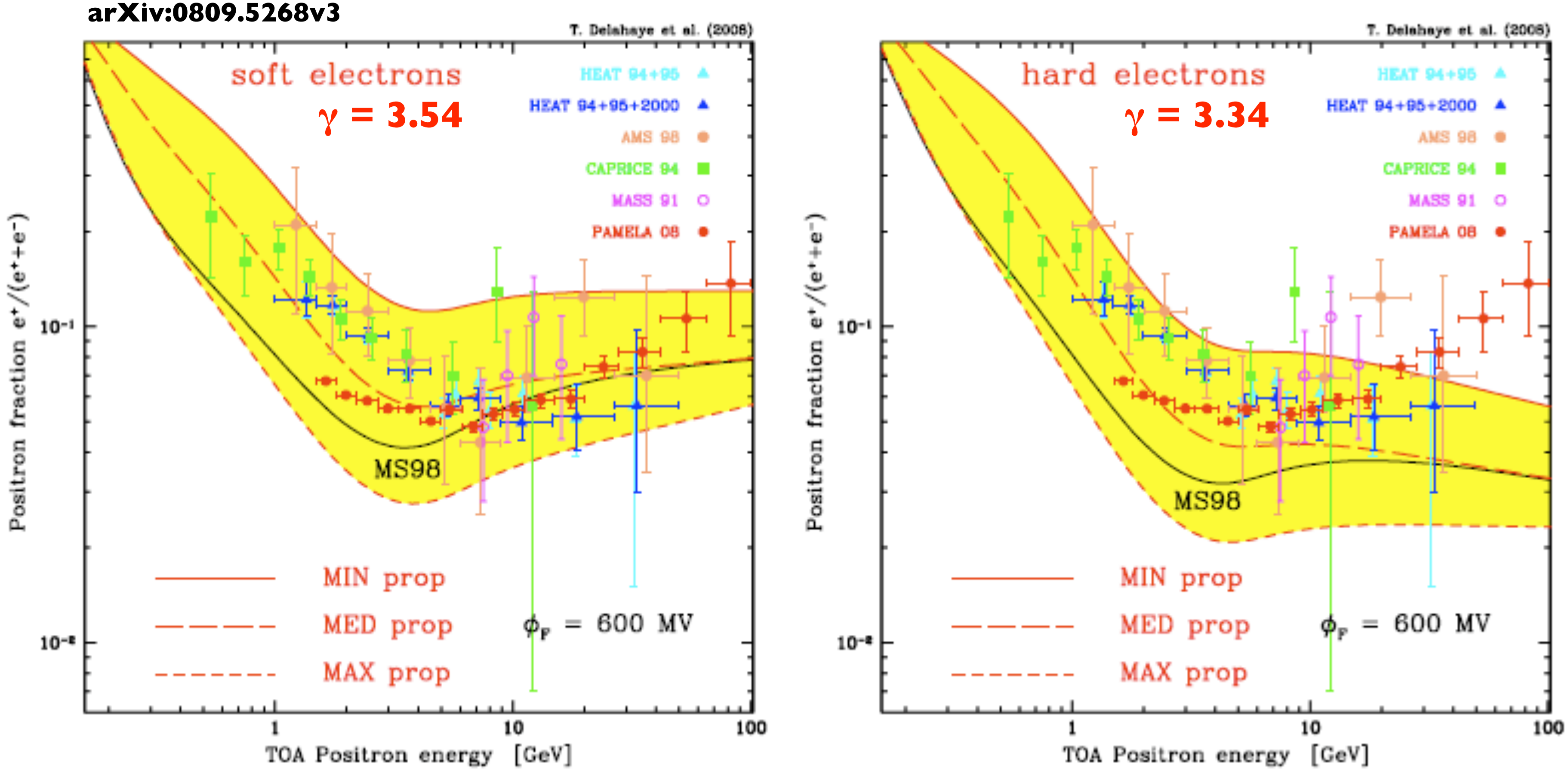
Secondary production expectation

Nature, in press (arXiv 0810.4995)



Theoretical uncertainties

Delahaye et al.
arXiv:0809.5268v3

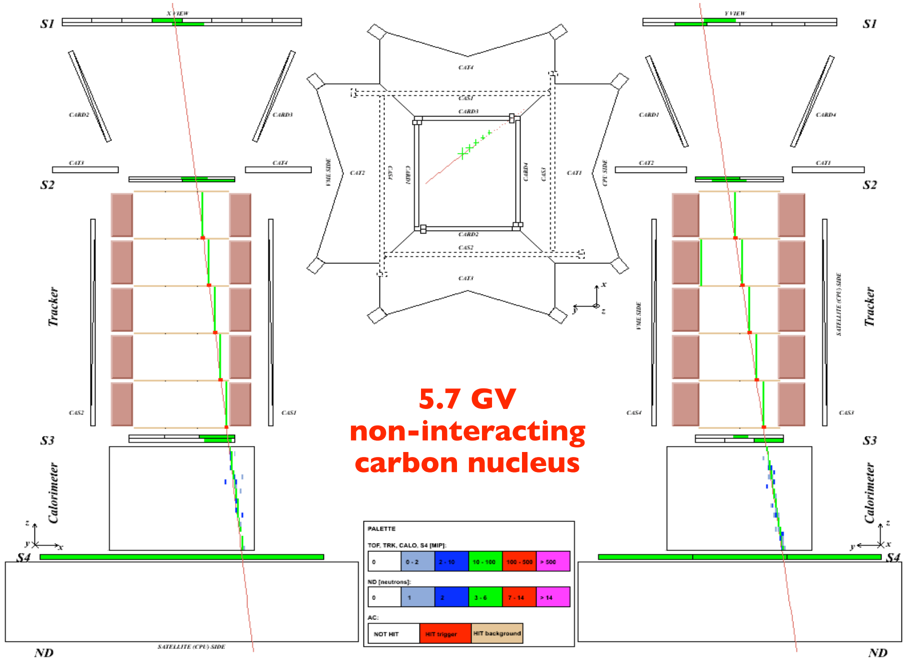


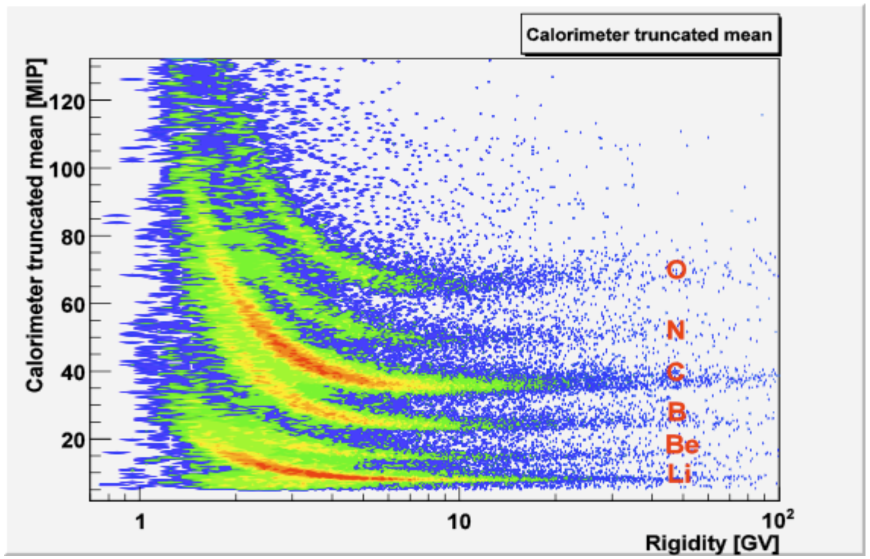
Electron (e^-) spectral index poorly defined above ~10 GeV...

...until now.

Nuclei identification

- **Important input to secondary production + propagation models**
  - Secondary to primary ratios:
    - B / C
    - Be / C
    - Li / C
  - Helium and hydrogen isotopes:
    - ^{3}He / ^{4}He
    - d / He

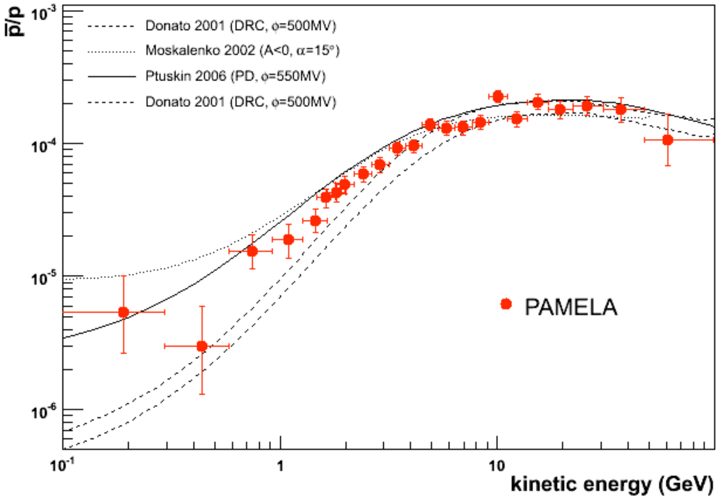




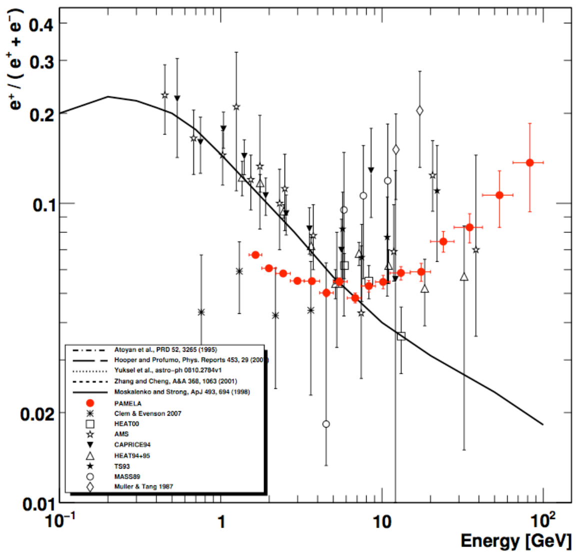
Truncated mean of multiple dE/dx measurements in different silicon planes

During first week after PAMELA results posted on arXiv

Adriani et al., Phys. Rev. Lett. 102 (2009) 051101
arXiv 0810.4994



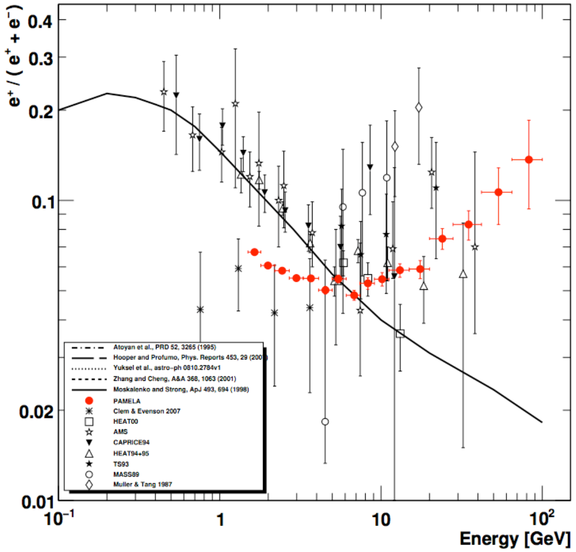
Nature, in press
arXiv 0810.4995



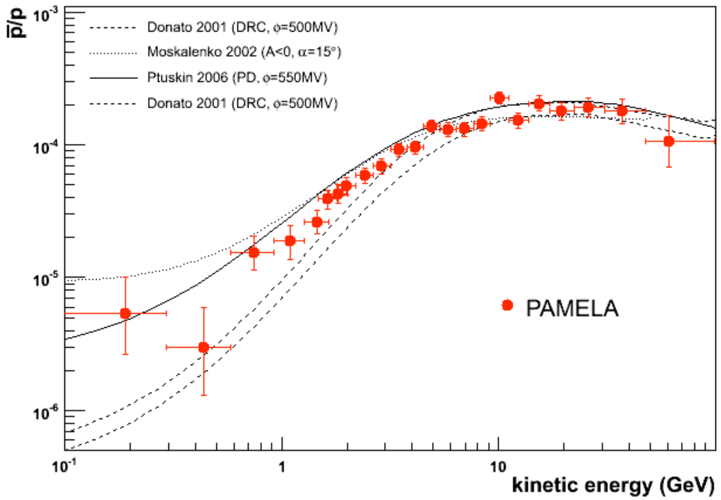
- 0808.3725 DM
- 0808.3867 DM
- 0809.2409 DM
- 0810.2784 Pulsar
- 0810.4846 DM / pulsar
- 0810.5292 DM
- 0810.5344 DM
- 0810.5167 DM
- 0810.5304 DM
- 0810.5397 DM
- 0810.5557 DM
- 0810.4147 DM
- 0811.0250 DM
- 0811.0477 DM

DM interpretation of positron excess

Nature, in press
arXiv 0810.4995



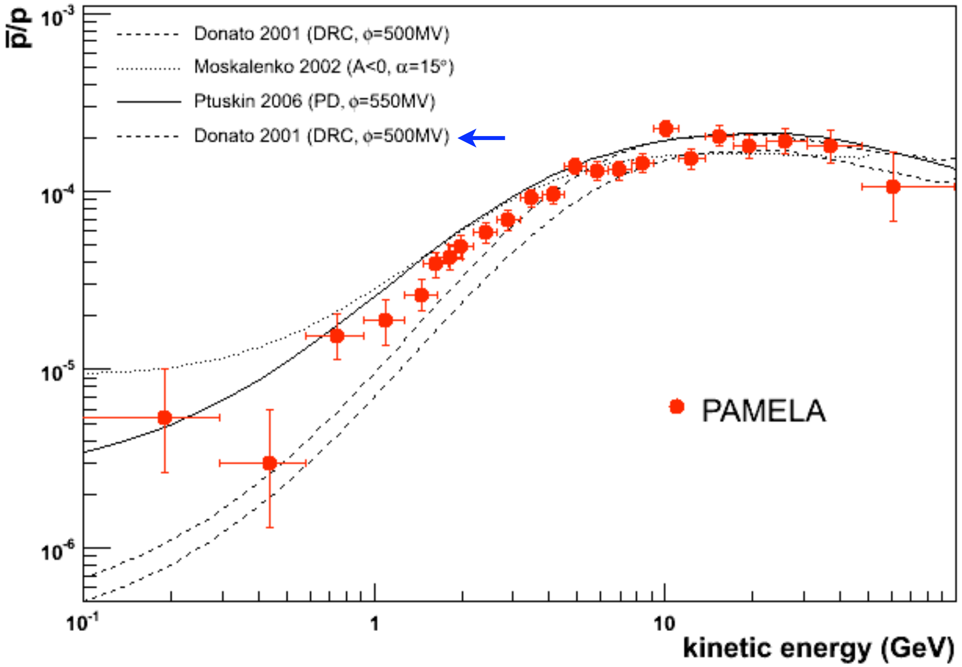
Adriani et al., Phys. Rev. Lett. 102 (2009) 051101
arXiv 0810.4994



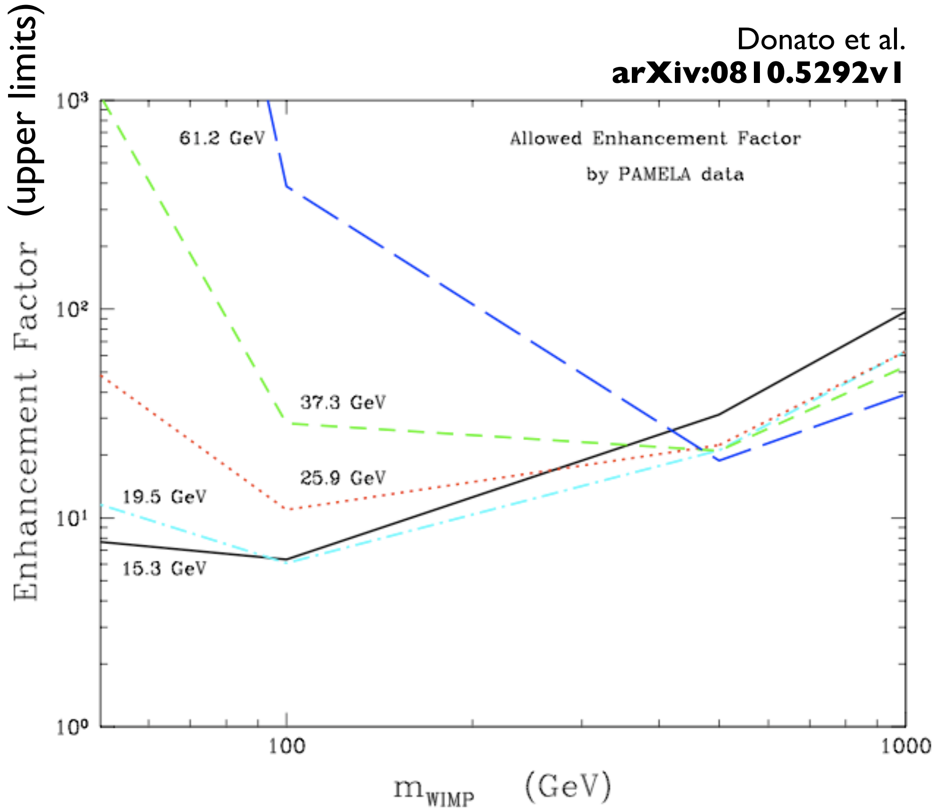
- Sharp rise! DM annihilation spectrum from SUSY is too soft (qq or WW dominant final states). 'Leptophilic' decays appear favoured.
- The required DM annihilation rate is much higher ($\times 10^{2\text{-}3}$) than predicted for a thermal relic from Big Bang.
  - Inhomogeneous DM distribution?
  - Enhanced σ_{ann}?
- **NB:** a large DM annihilation rate will generally result in an overproduction of **antiprotons** (and gammas)

DM constraints from pbar/p

Adriani et al., Phys. Rev. Lett. 102 (2009) 051101
arXiv 0810.4994



Donato et al.
arXiv:0810.5292v1



Results place strict limits on Dark Matter models where quark jets are a dominant final state...

- 'Enhancement factor' cannot exceed 6 / 20 / 40 for WIMP mass 100 / 500 / 1000 GeV
- **NB:** Factor from clumpy halo ≤10 in standard models of structure formation. e.g. Lavalle et al., A&A 479 (2008) 427.

Donato et al.
arXiv:0810.5292v1

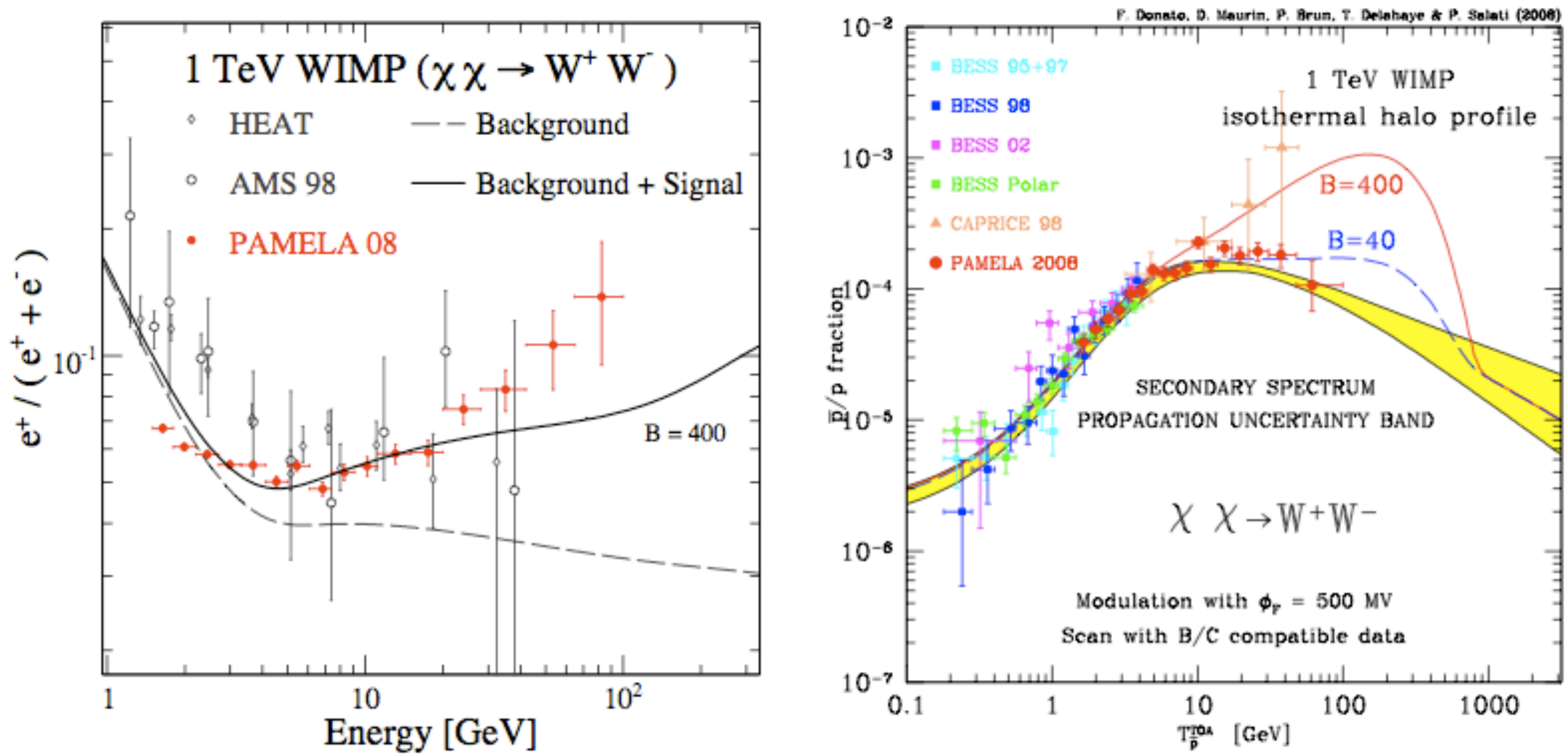


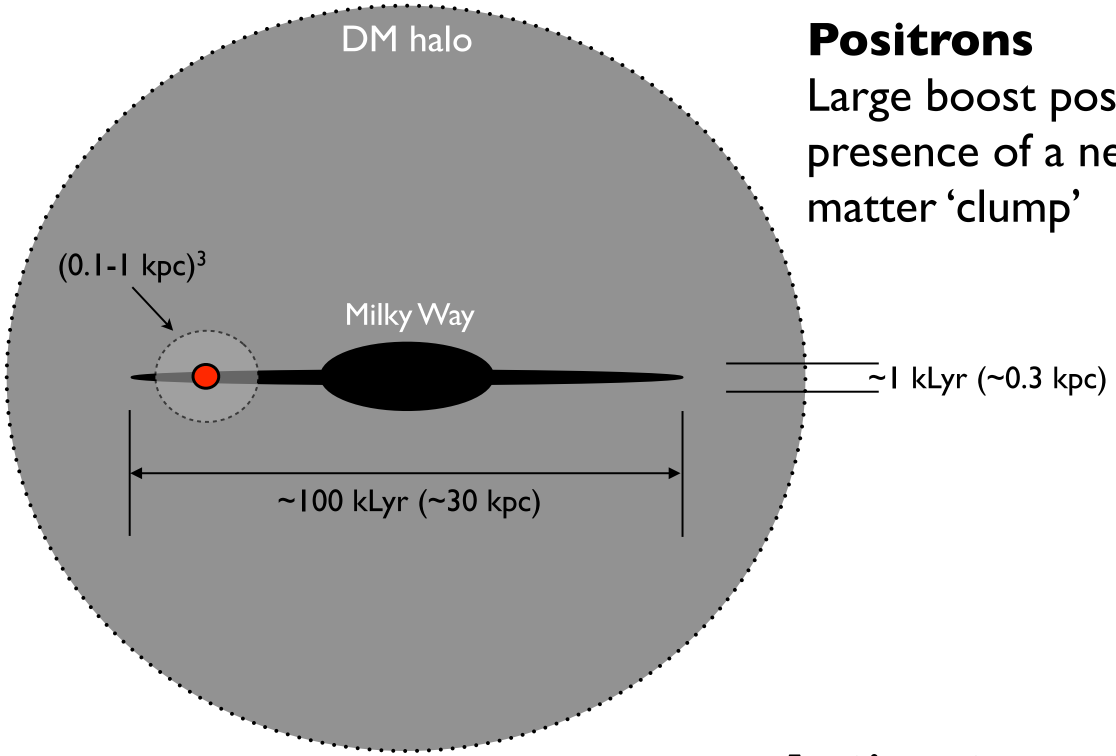
FIG. 3: The fiducial case of a 1 TeV LSP annihilating into a W^+W^- pair is featured. In the left panel, the positron signal which this DM species yields has been increased by a factor of 400, hence the solid curve and a marginal agreement with the PAMELA data. Positron fraction data are from HEAT [36], AMS-01 [37, 38] and PAMELA [39]. If the so–called Sommerfeld effect [35] is invoked to explain such a large enhancement of the annihilation cross section, the same boost applies to antiprotons and leads to an unacceptable distortion of their spectrum as indicated by the red solid line of the right panel.

Dark Matter scenarios often require 'Boost Factors' of 10^2 - 10^4

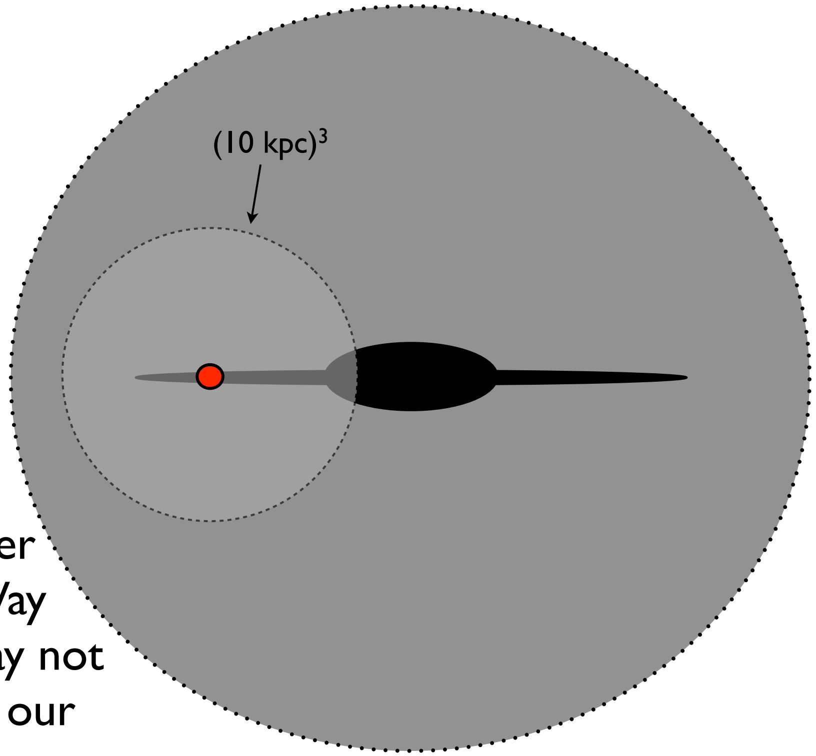
Boost factor:

$$B_{\Delta V} = B_n^{\Delta V} \times B_{\sigma v} = \frac{\langle n^2(\vec{r}) \rangle_{\Delta V}}{\langle n^2_{NFW}(\vec{r}) \rangle_{\Delta V}} \times \frac{\langle \sigma v \rangle_{v/c \approx 10^{-3}}}{\langle \sigma v \rangle_{v/c \approx 0.3}}$$

Cosmology — Particle physics



Positrons
Large boost possible in presence of a nearby dark matter 'clump'

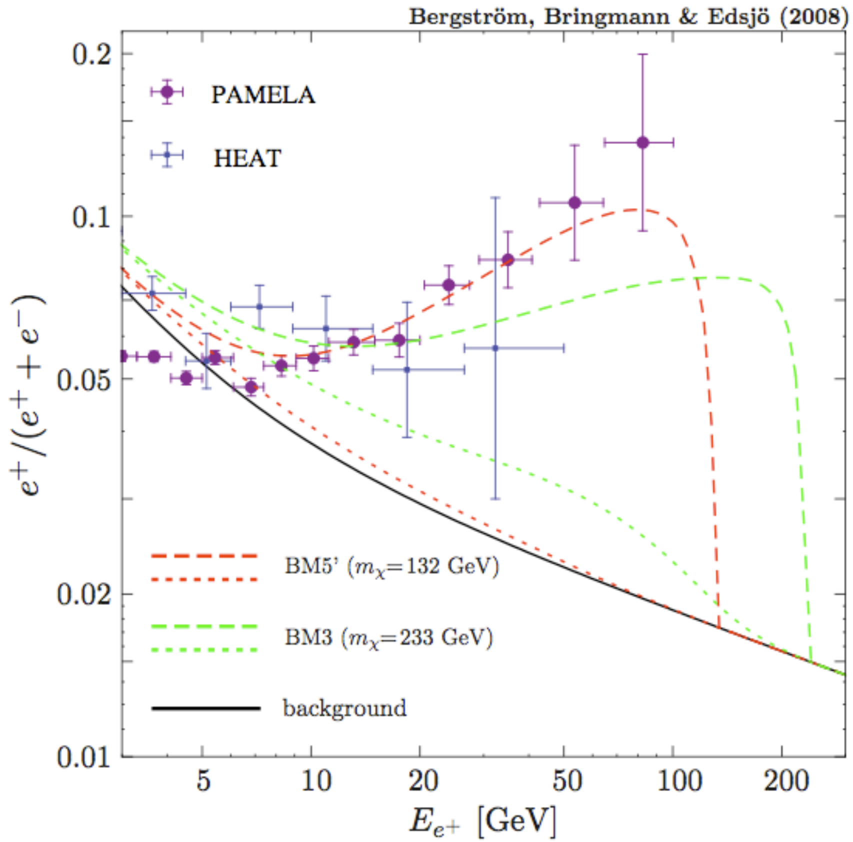


Antiprotons
Originate from a larger region of the Milky Way halo. Substructure may not be as important as in our vicinity...

(After Bergström, 2009)

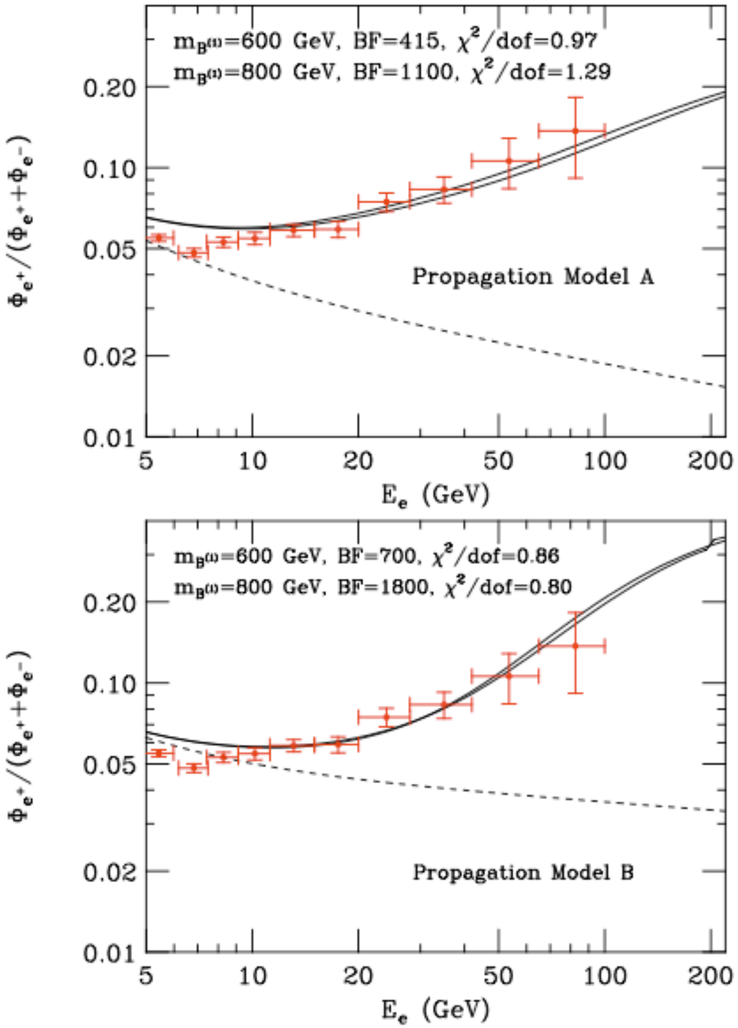
Example: Dark Matter

arXiv:0808.3725



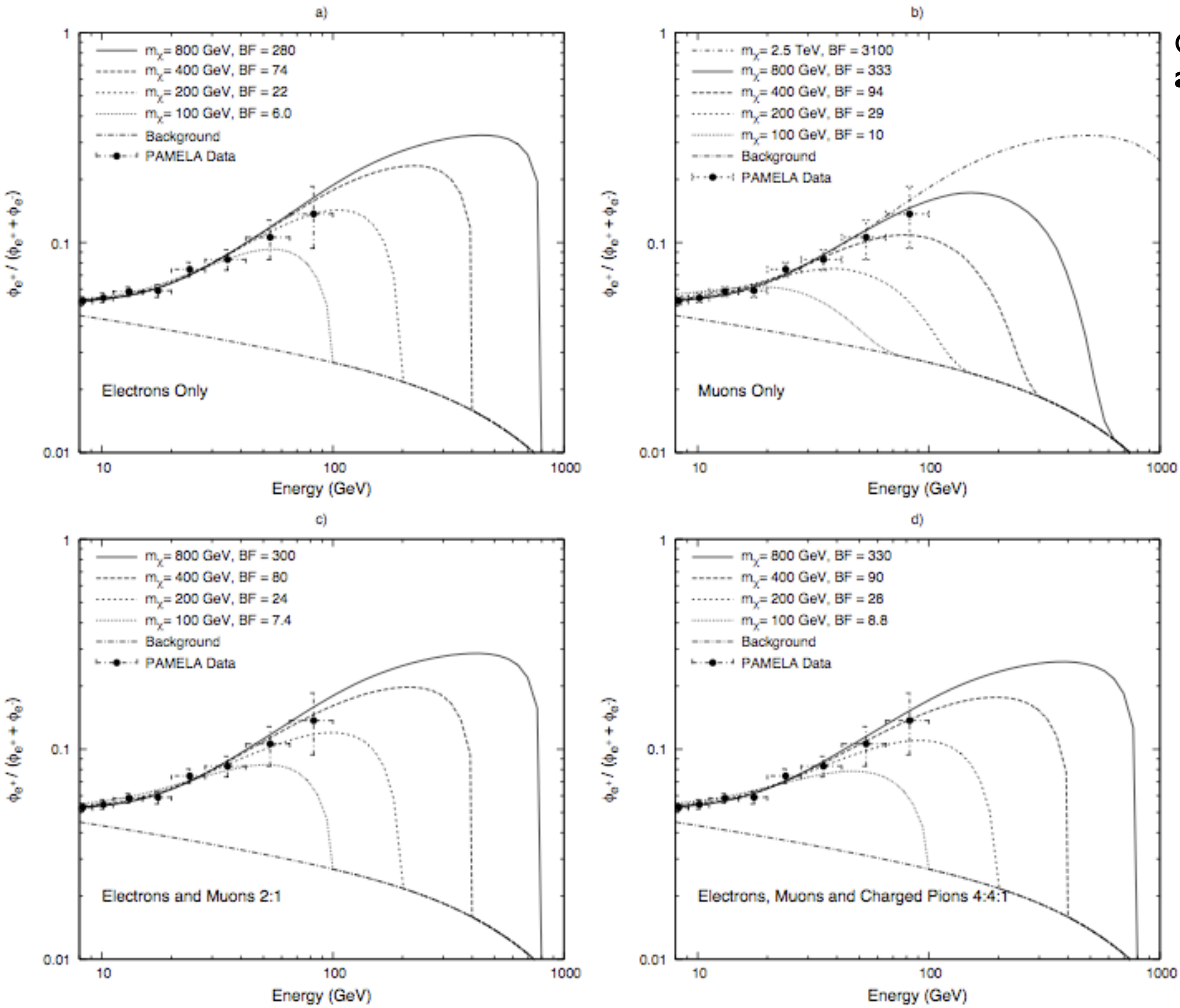
Majorana DM with **new** internal bremsstrahlung correction. NB: requires annihilation cross-section to be 'boosted' by >1000.

Hooper and Zurek
arXiv:0902.0593v1



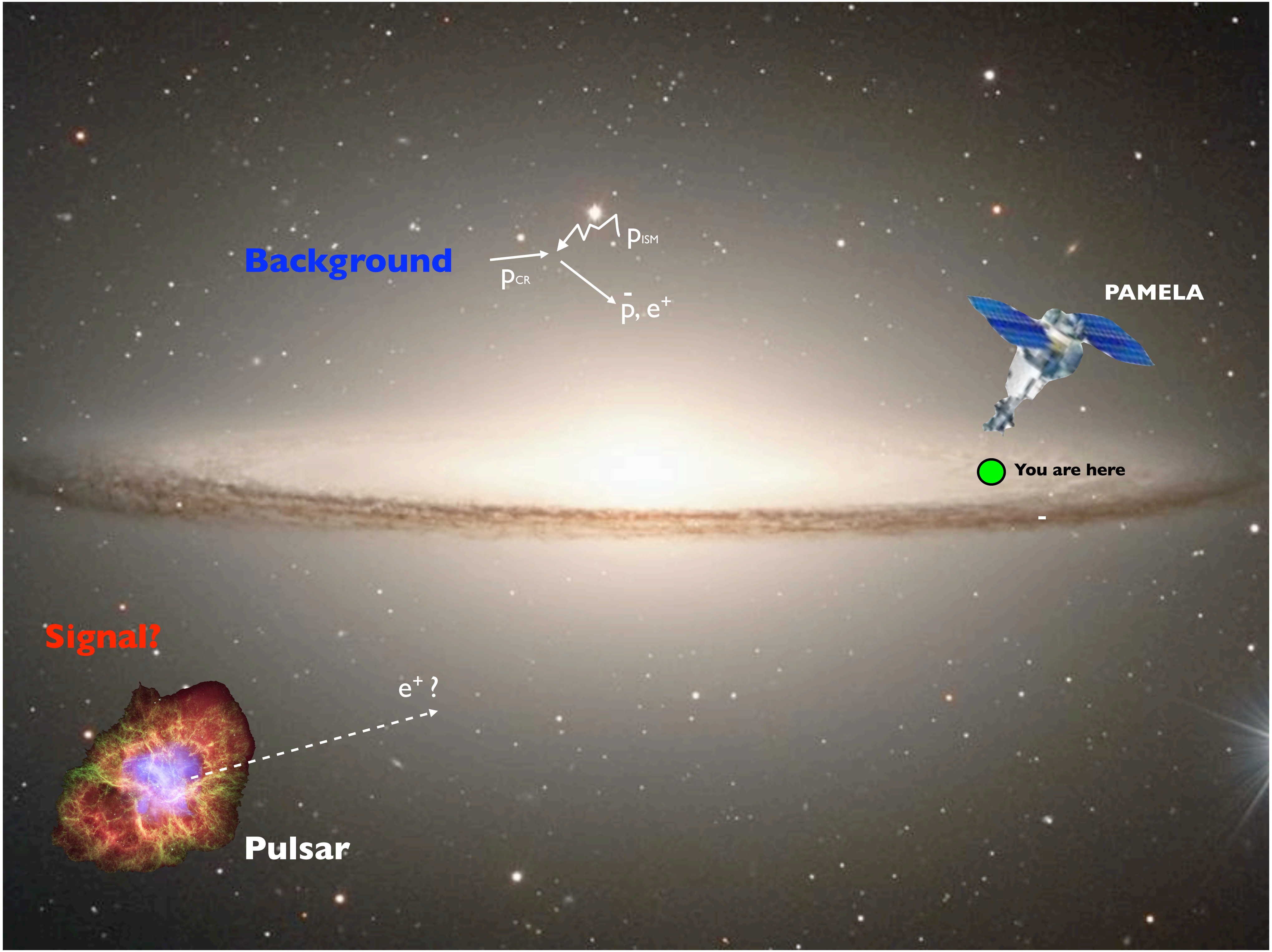
Kaluza-Klein dark matter

Leptophilic Dark Matter



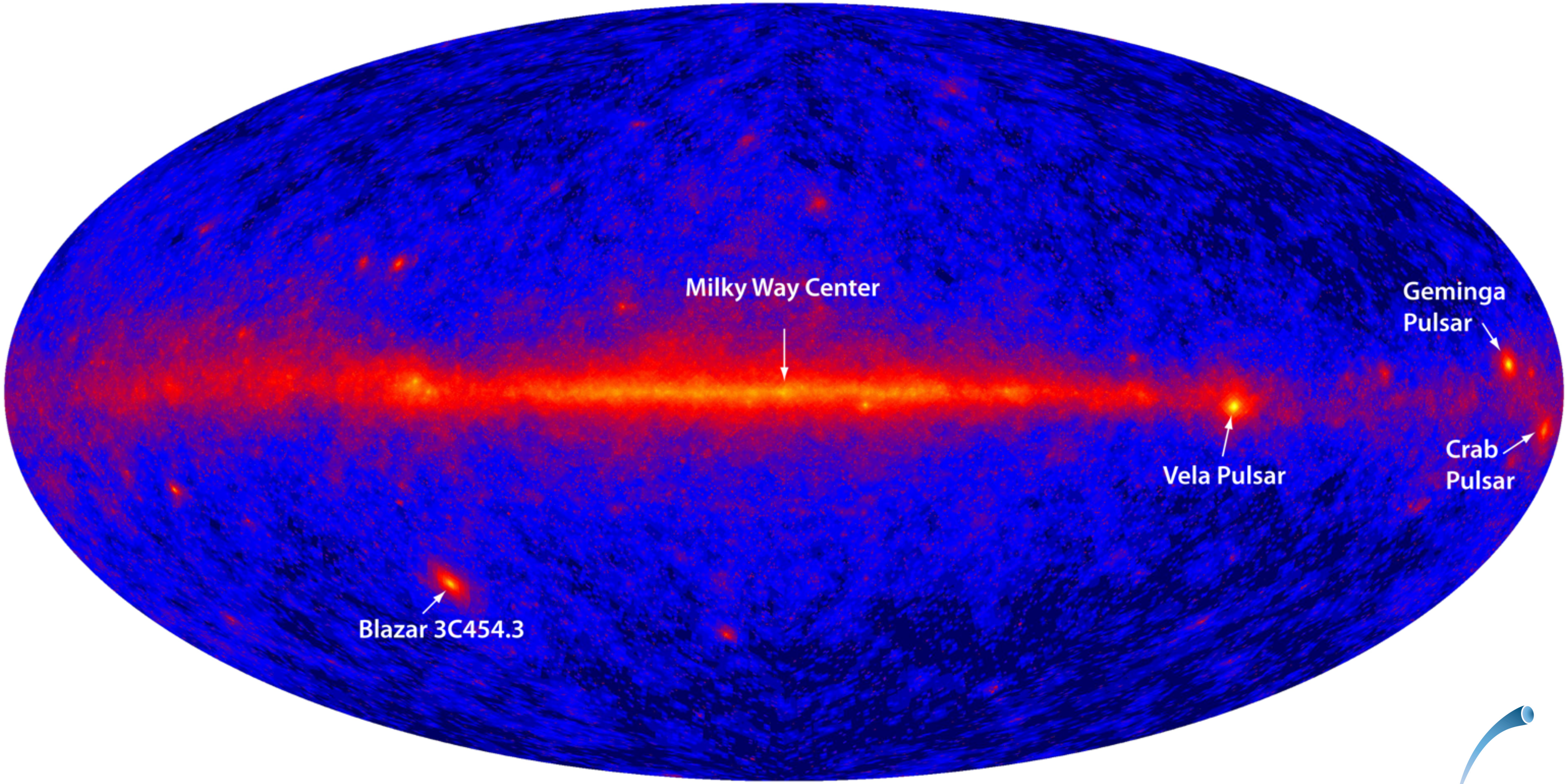
Cholis et al.,
arXiv:0810.5344v2

- Propose a new light boson ($m_\Phi \leq$ GeV), such that $\chi\chi \rightarrow \Phi\Phi$; $\Phi \rightarrow e^+e^-$, $\mu^+\mu^-$, ...
- Light boson, so decays to antiprotons are kinematically suppressed



Background
p_{CR}
p_{ISM}
$\bar{p}$, e^+
PAMELA
You are here
Signal?
e^+ ?
Pulsar

The Fermi-GST gamma-ray sky

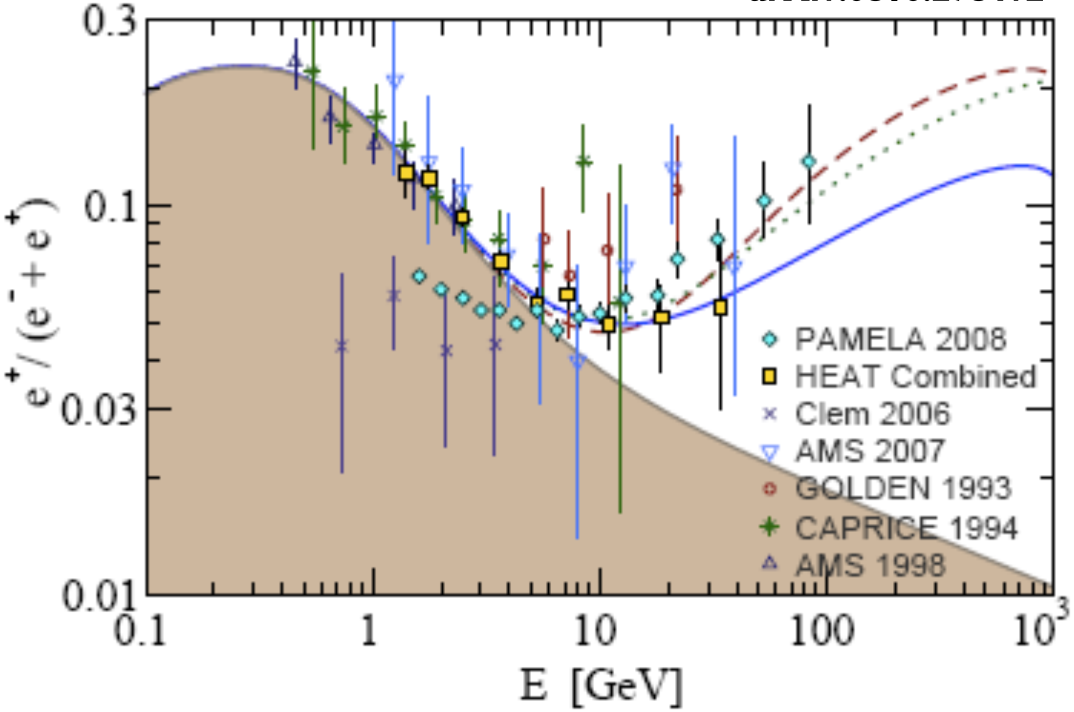


Fermi Gamma-ray Space Telescope

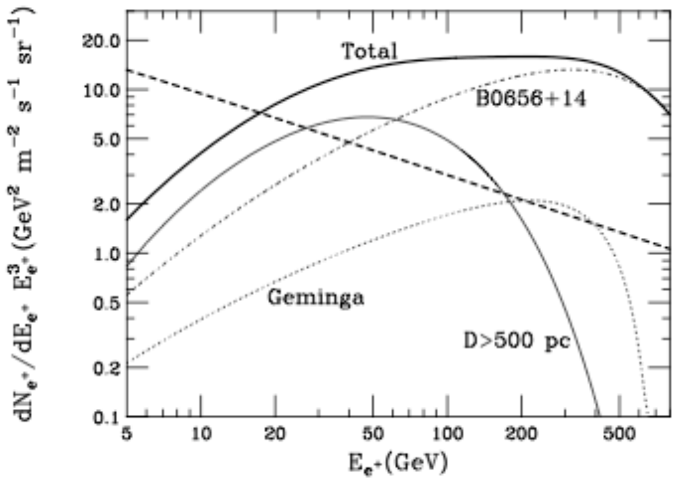
Fermi Gamma-ray Space Telescope (formerly GLAST) launched 11th June 2008

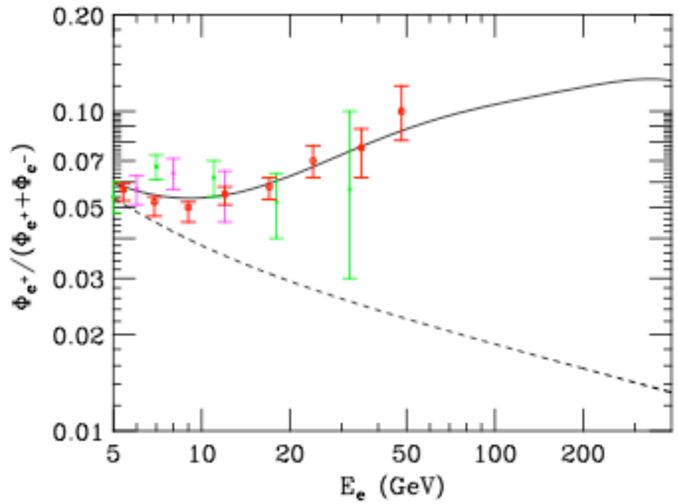
Example: pulsars

Yüksak et al.
arXiv:0810.2784v2



Hooper, Blasi, and Serpico
arXiv:0810.1527





Geminga (d ~ 250 $\pm^{250}_{62}$ pc)

• TeV emission recently discovered by Milagro (Abdo et al., Ap.J. 664 L91 (2007))
• Different distance, age and pulsar energy assumed

• Contributions from nearby Geminga and B0656+14, and pulsars >500 pc from Earth

Vol 456|20 November 2008 nature

NEWS & VIEWS

ASTROPHYSICS

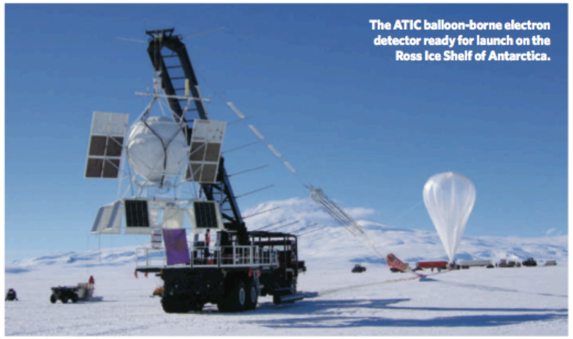
A message from the dark side

Yousaf M. Butt

Both astrophysicists and particle physicists are in on the hunt for the elusive dark matter that is thought to pervade the Universe. A high-altitude balloon-borne experiment offers the latest hints as to what it could be.

Humiliating as it may sound, you, me and everything we see — the Earth, Moon, Sun and stars — may be little more than cosmic contamination. Most of the 'stuff' in the Universe is thought to be in the form of invisible and elusive particles of dark matter. To date, the existence of this cosmic exotica has been inferred through its gravitational effects. But on page 362 of this issue, Chang and collaborators report[1] on a surprising bump detected in the spectrum of celestial electrons that could be a more direct signal of this mysterious substance — or there may be other intriguing explanations.

For 75 years, astronomers have collected data that point to the existence of a type of non-luminous matter that outweighs normal ('baryonic') matter by a factor of about six. Several independent lines of evidence seem to make its reality compelling. For one, the meas-



The ATIC balloon-borne electron detector ready for launch on the Ross Ice Shelf of Antarctica.

T. G. GUZIK

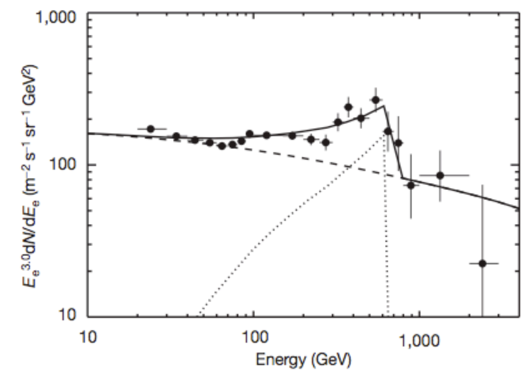


Figure 4 | Assuming an annihilation signature of Kaluza–Klein dark matter, all the data can be reproduced. The GALPROP general electron spectrum resulting from sources across the galaxy is shown as the dashed line. The dotted curve represents the propagated electrons from the annihilation of a Kaluza–Klein particle. The dotted curve assumes an isothermal dark matter halo of 4-kpc scale height, a local dark matter density of 0.43 GeV cm^{-3}, a Kaluza–Klein mass of 620 GeV, and an annihilation cross section rate of 1×10^{-23} cm^3 s^{-1}, which implies a boost factor of ~200. The sum of these signals is the solid curve. Here the spectrum is multiplied by $E^{3.0}$ for clarity. The solid curve provides a good fit to both the magnetic spectrometer data[30,31] and calorimeter data[16,32] and reproduces all of the measurements from 20 GeV to 2 TeV, including the cut-off in the observed excess. All error bars are one standard deviation.

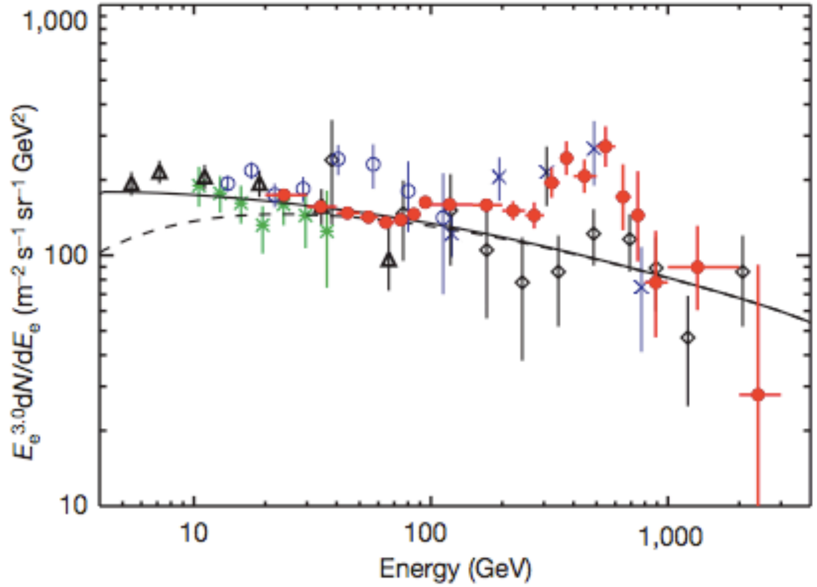
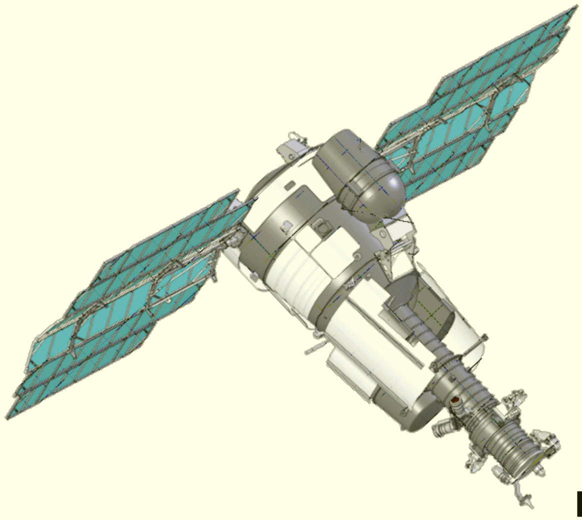


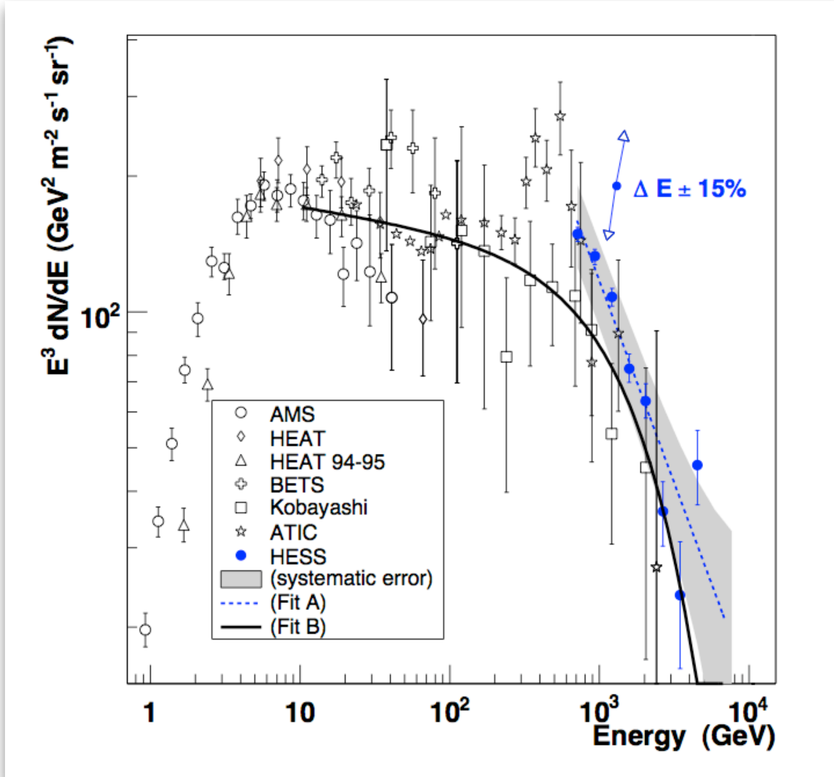
Figure 3 | ATIC results showing agreement with previous data at lower energy and with the imaging calorimeter PPB-BETS at higher energy. The electron differential energy spectrum measured by ATIC (scaled by E^3) at the top of the atmosphere (red filled circles) is compared with previous observations from the Alpha Magnetic Spectrometer AMS (green stars)[31], HEAT (open black triangles)[30], BETS (open blue circles)[32], PPB-BETS (blue crosses)[16] and emulsion chambers (black open diamonds)[4,8,9], with uncertainties of one standard deviation. The GALPROP code calculates a power-law spectral index of −3.2 in the low-energy region (solid curve)[14]. (The dashed curve is the solar modulated electron spectrum and shows that modulation is unimportant above ~20 GeV.) From several hundred to ~800 GeV, ATIC observes an 'enhancement' in the electron intensity over the GALPROP curve. Above 800 GeV, the ATIC data returns to the solid line. The PPB-BETS data also seem to indicate an enhancement and, as discussed in Supplementary Information section 3, within the uncertainties the emulsion chamber results are not in conflict with the ATIC data.

Chang et al.
Nature 456, 362-365 (2008)

Future observations of electrons

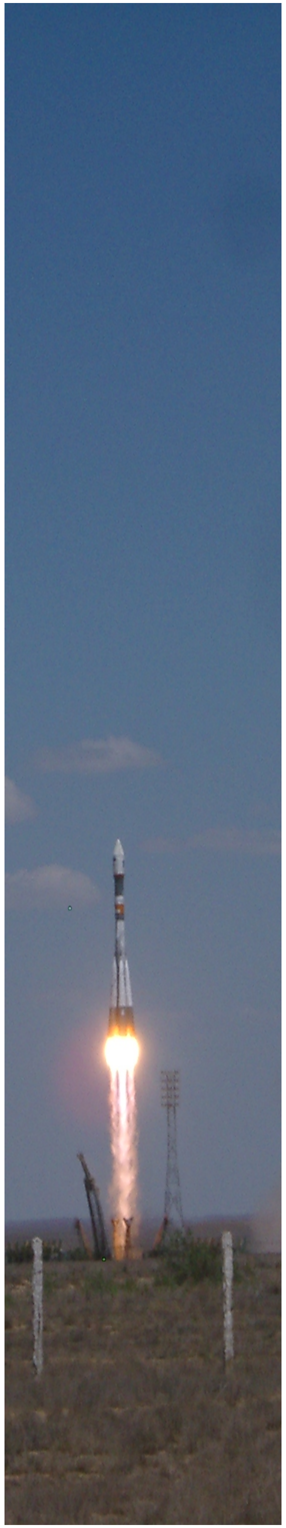


PAMELA:
$\Phi_{e^\pm}$ up to ~1TeV
Φ_{e^+} up to ~300 GeV
Φ_{e^-} up to ~500 GeV



HESS Collaboration
arXiv:0811.3894

Fermi GST: $\Phi_{e^\pm}$ up to ~700 GeV



Summary

- **PAMELA** has been in orbit and studying cosmic rays for ~30 months. >10^9 triggers registered, and >10 TB of data has been down-linked.

- **Antiproton-to-proton flux ratio** (~100 MeV - ~100 GeV) shows no significant deviations from secondary production expectations. Additional high energy data in preparation (up to ~150 GeV).

- **Low energy positron fraction** (~1.5 - ~5 GeV) shows solar modulation effects. Excellent statistics!

- **High energy positron fraction** (>10 GeV) increases significantly (and unexpectedly!) with energy. **Primary source?**
- Data at higher energies will help to resolve origin of rise (spillover limit ~300 GeV).

http://pamela.roma2.infn.it