Understanding Cosmic rays and Searching for Exotic Sources with the PAMELA Space Experiment

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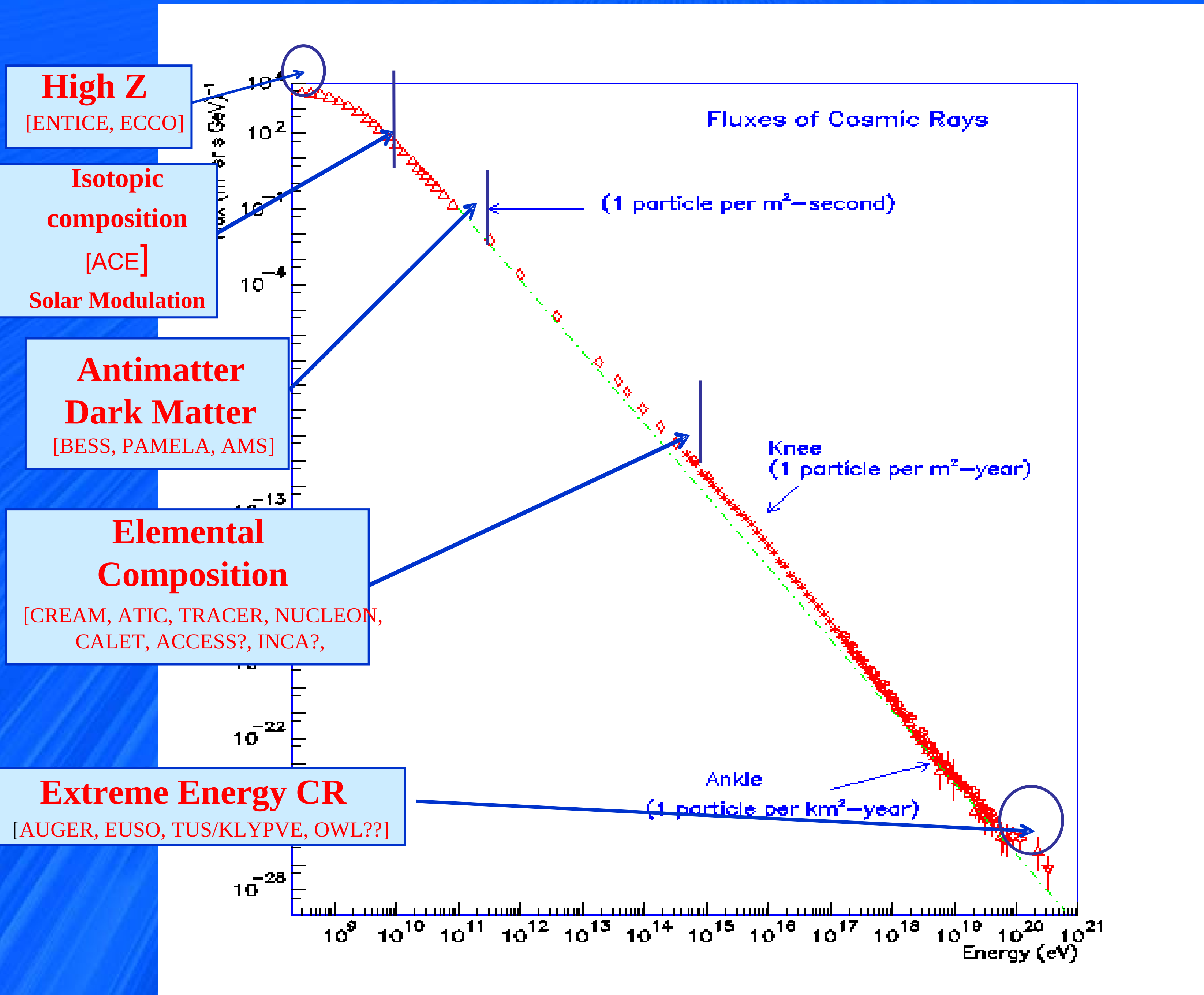
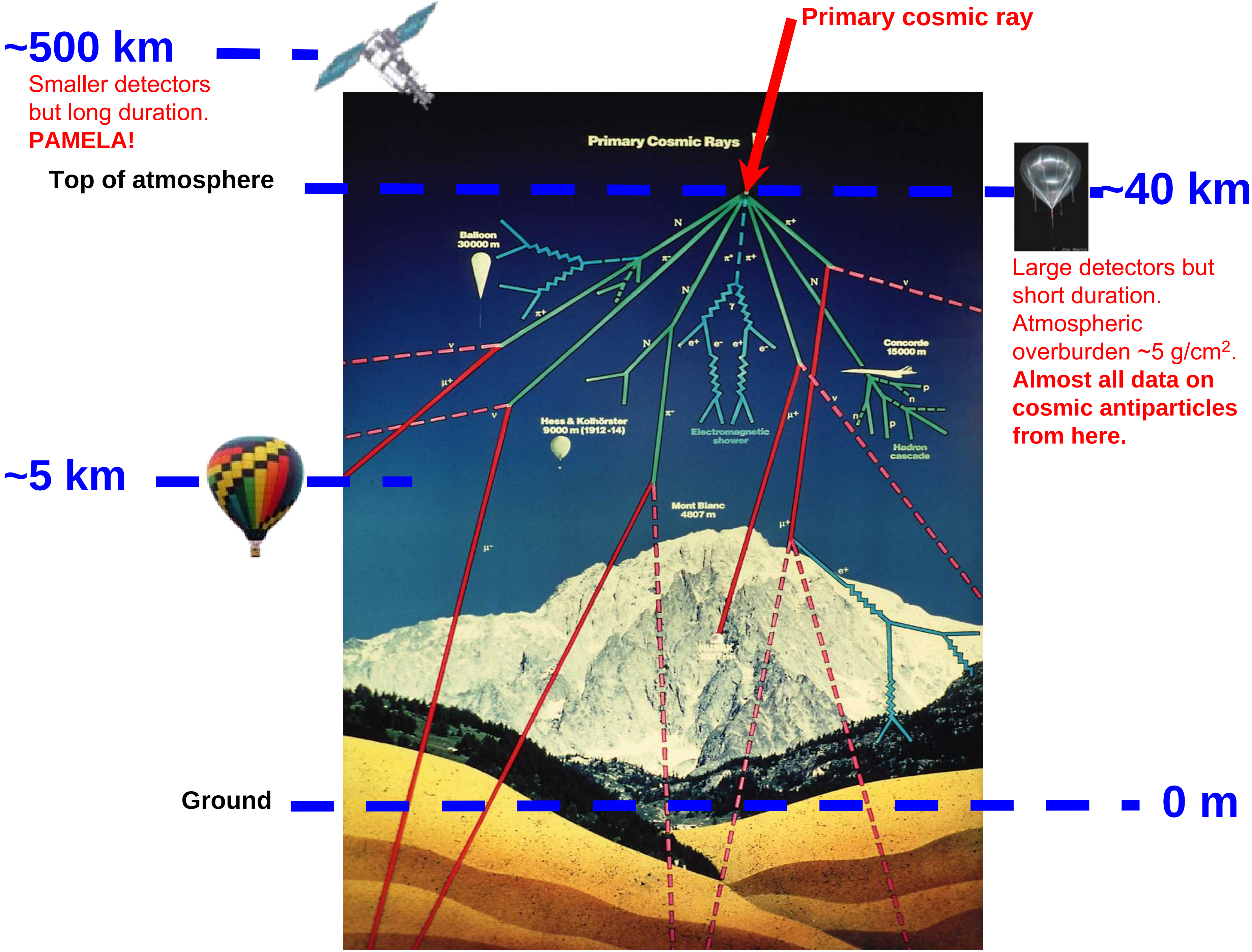
Faculty of Physics

MSU

Moscow, April 26th, 2010

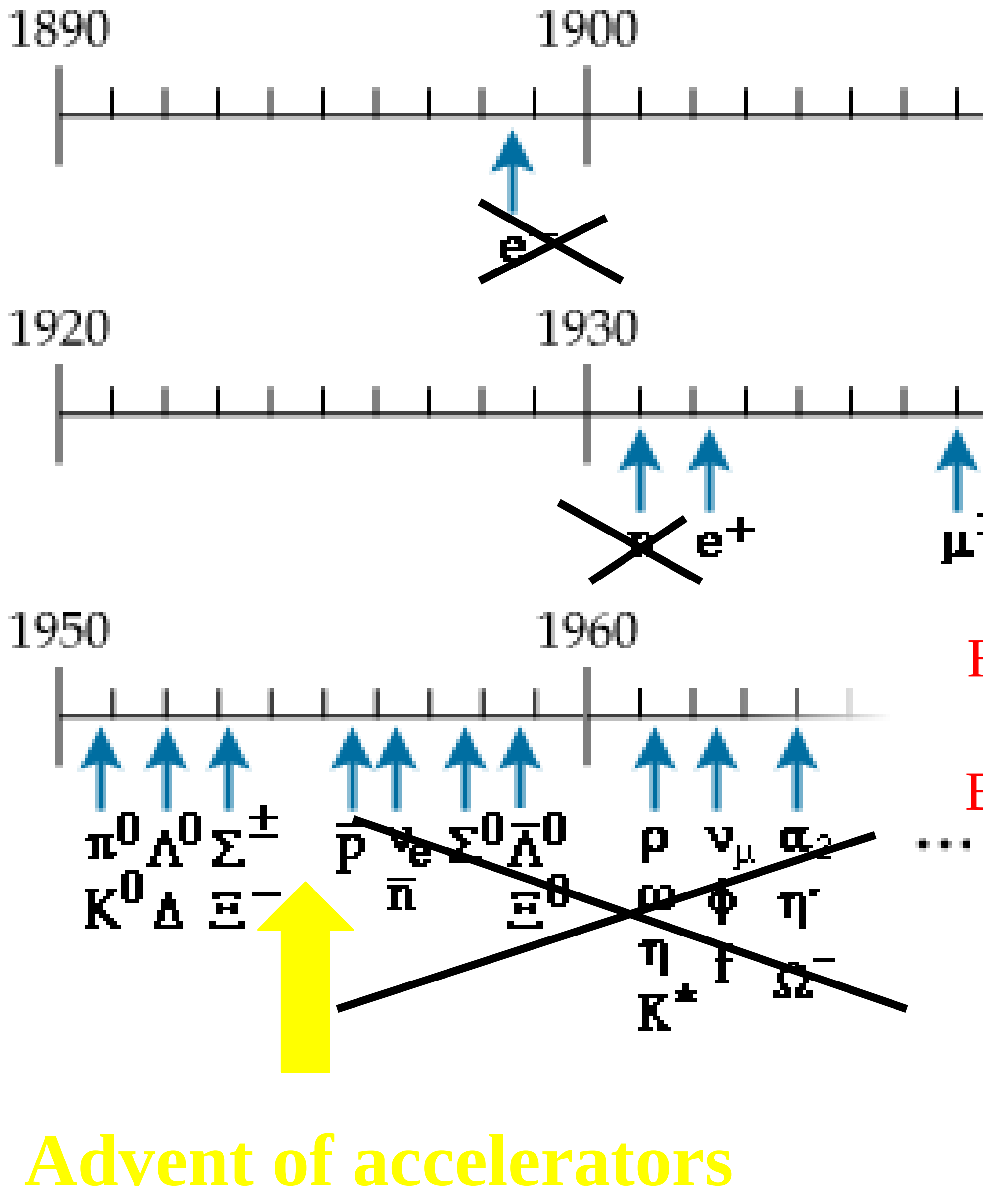


High Z
[ENTICE, ECCO]
Isotopic composition
[ACE]
Solar Modulation
Antimatter
Dark Matter
[BESS, PAMELA, AMS]
Elemental Composition
[CREAM, ATIC, TRACER, NUCLEON, CALET, ACCESS?, INCA?,
Extreme Energy CR
[AUGER, EUSO, TUS/KLYPVE, OWL??]
Fluxes of Cosmic Rays
(1 particle per m²–second)
Knee
(1 particle per m²–year)
Ankle
(1 particle per km²–year)
10⁴
10²
10⁻¹
10⁻⁴
10⁻¹³
10⁻²²
10⁻²⁸
10⁹ 10¹⁰ 10¹¹ 10¹² 10¹³ 10¹⁴ 10¹⁵ 10¹⁶ 10¹⁷ 10¹⁸ 10¹⁹ 10²⁰ 10²¹
Energy (eV)



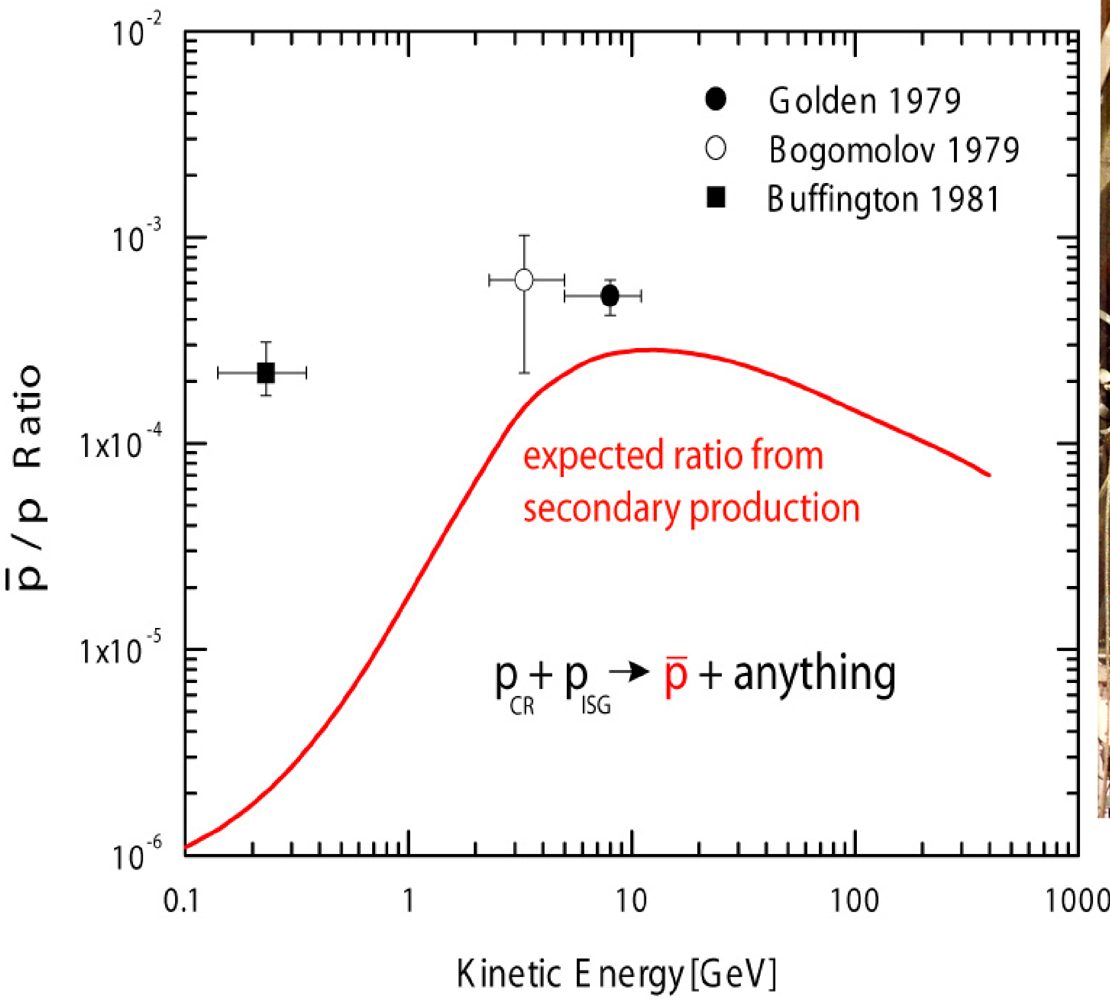
Primary cosmic ray
~500 km
Smaller detectors
but long duration.
PAMELA!
Top of atmosphere
~40 km
Large detectors but
short duration.
Atmospheric
overburden ~5 g/cm².
Almost all data on
cosmic antiparticles
from here.
~5 km
Ground
0 m
Primary Cosmic Rays
Balloon
30000 m
Concorde
15000 m
Hess & Kolhörster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

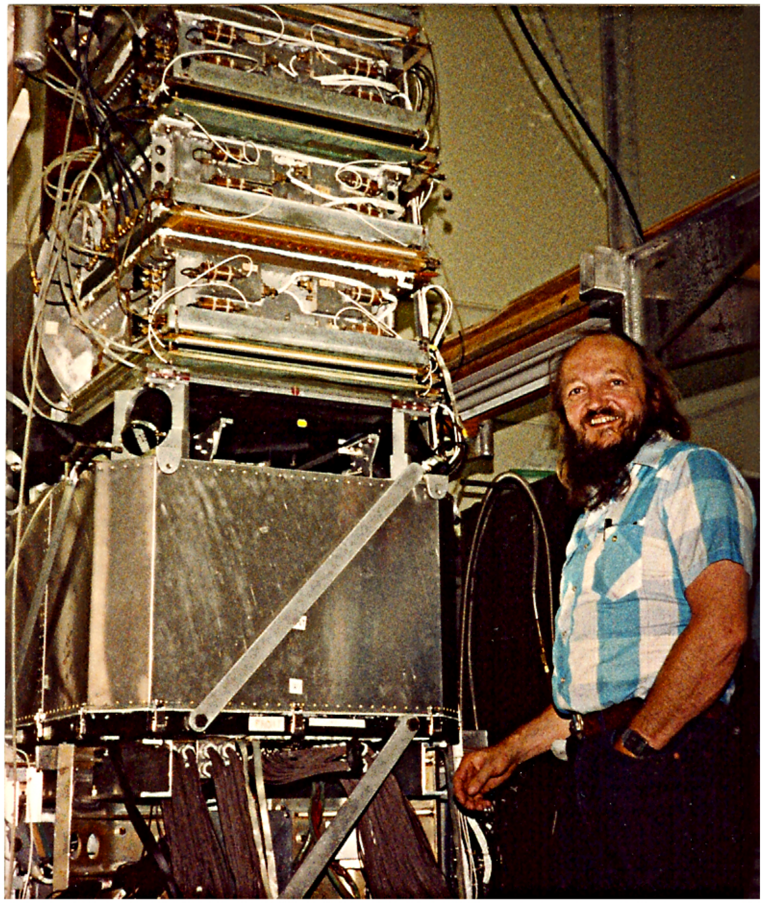
PARTICLE PHYSICS BIRTH WAS DUE TO COSMIC RAYS



Hesse, Wulf, Wilson, Anderson, Bothe, Kohlorster, Millikan, Blackett, Skobeltsyn, Rochester, Butler, Rossi, Pancini , Conversi, Powell, Occhialini ……

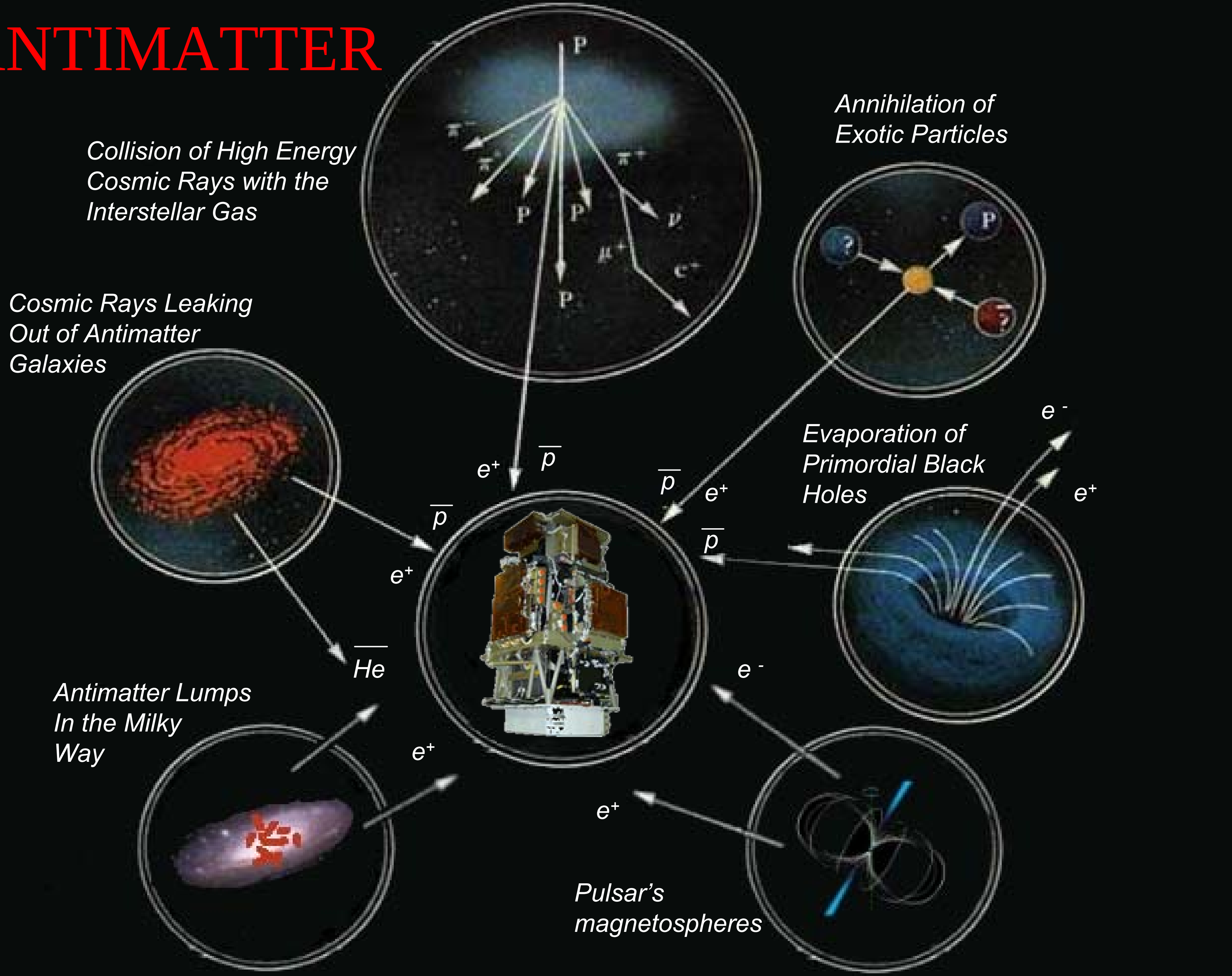
The first historical measurements on galactic antiprotons





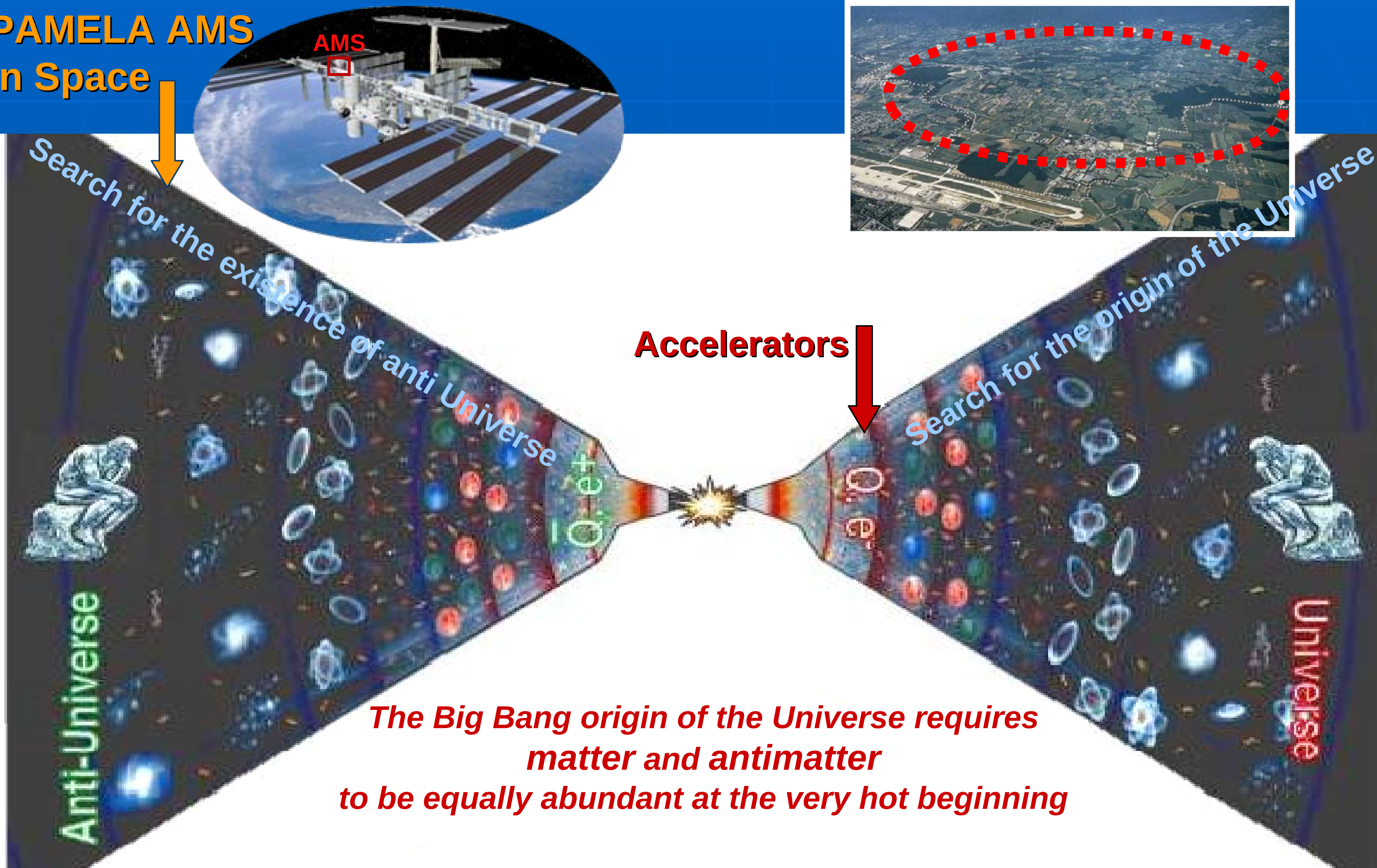
Robert L. Golden

ANTIMATTER



Collision of High Energy Cosmic Rays with the Interstellar Gas
Annihilation of Exotic Particles
Cosmic Rays Leaking Out of Antimatter Galaxies
Evaporation of Primordial Black Holes
Antimatter Lumps In the Milky Way
Pulsar's magnetospheres
P
P
P
P
π^-
π^+
ν
μ^+
e^+
?
P
e^+
$\overline{p}$
$\overline{p}$
e^+
$\overline{p}$
e^+
$\overline{p}$
e^-
e^+
$\overline{He}$
e^-
e^+
e^+

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 Direct research

Observation of cosmic radiation hold out the possibility of directly observing a particle of antimatter which has escaped as a cosmic ray from a distant antigalaxy, traversed intergalactic space filled by turbulent magnetic field, entered the Milky Way against the galactic wind and found its way to the Earth.

Sreitmatter, R. E., Nuovo Cimento, 19, 835 (1996)

High energy particle or antinuclei

Antimatter Direct research

Antimatter from globular clusters of antistars in our Galaxy as antistellar wind or anti-supernovae explosion

K. M. Belotsky et al., Phys. Atom. Nucl. 63, 233 (2000), astro-ph/9807027

Antimatter and Dark Matter Search

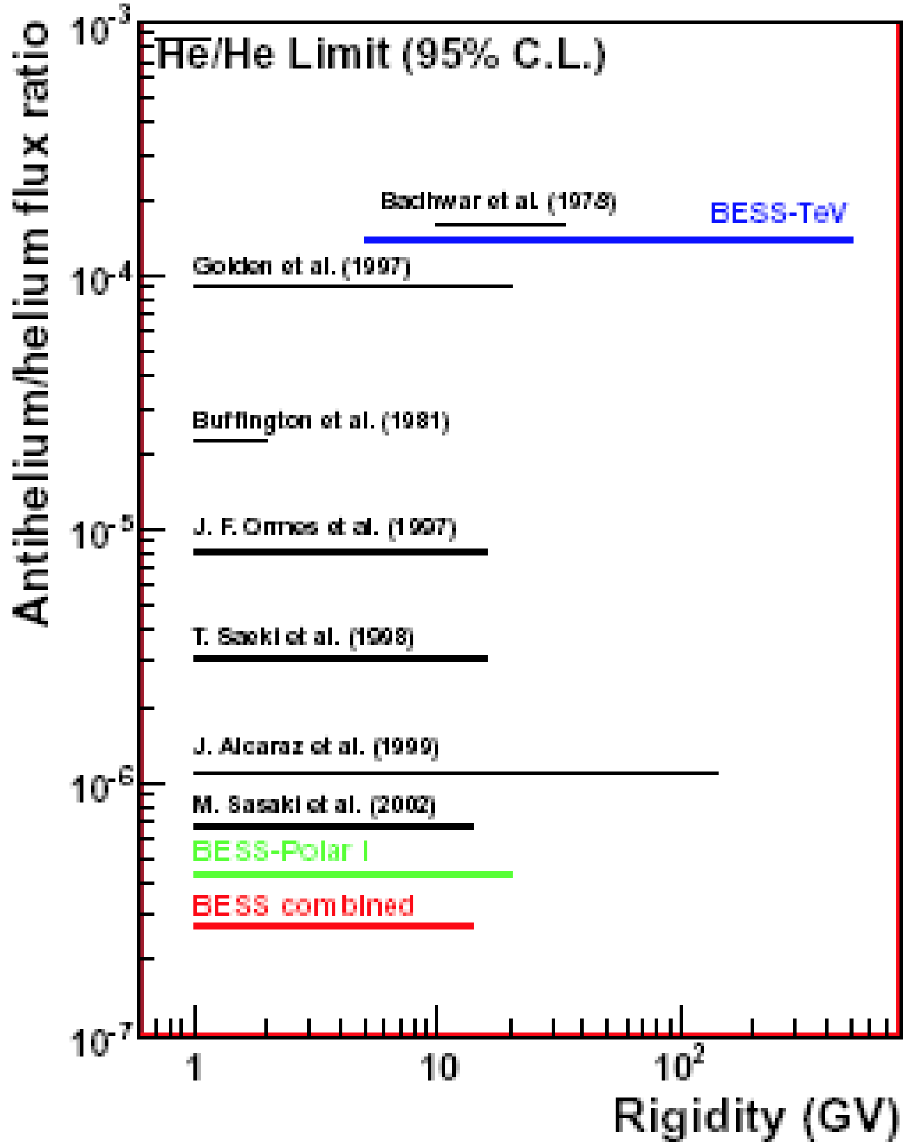
WiZard Collaboration

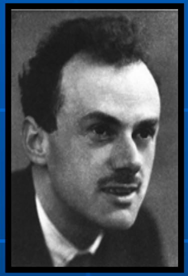
- ✓ MASS - 1,2 (89,91)
- ✓ TrampSI (93)
- ✓ CAPRICE (94, 97, 98)

- ✓ BESS (93, 95, 97, 98, 2000)
- ✓ Heat (94, 95, 99, 2000)
- ✓ IMAX (96)
- ✓ BESS LDF (2004, 2007)

- ✓ AMS-01 (1998)

Antimatter



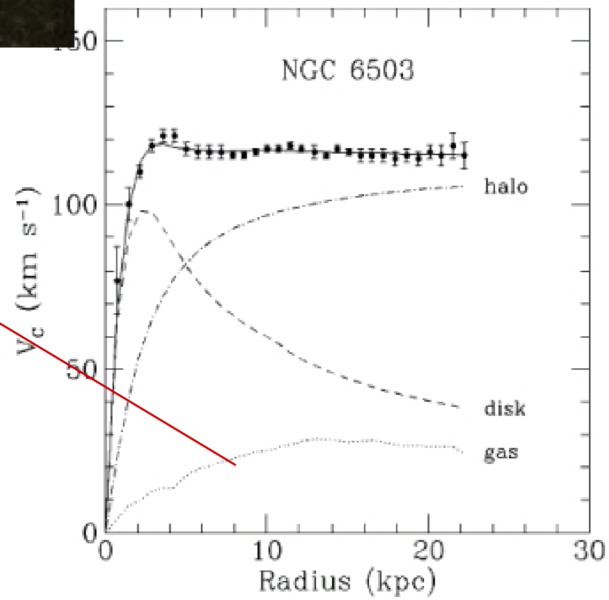


"We must regard it rather an accident that the Earth and presumably the whole Solar System contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about"

P. Dirac, Nobel lecture (1933)

What is the Universe made of ?

Rotational Curves



Från Jungman et al, Phys. Rep. 267(1996)195.

$$F_{centripetal} = \frac{mv(r)^2}{r}$$

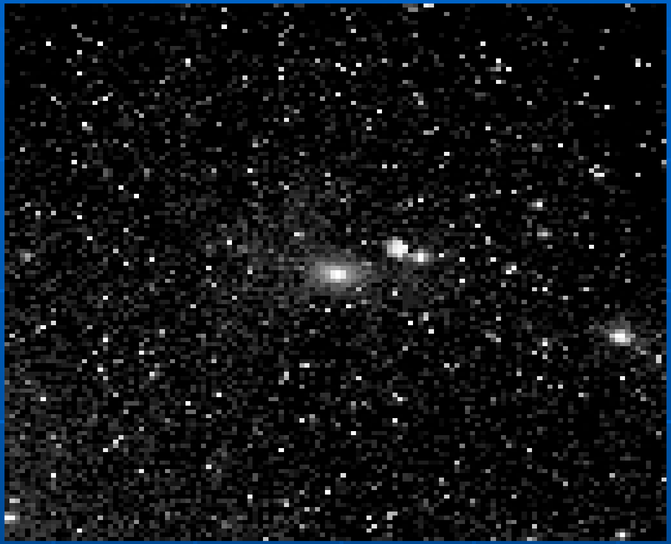
$$F_{gravitational} = G\frac{M(r)m}{r^2}$$

$$F_{centripetal} = F_{gravitational}$$

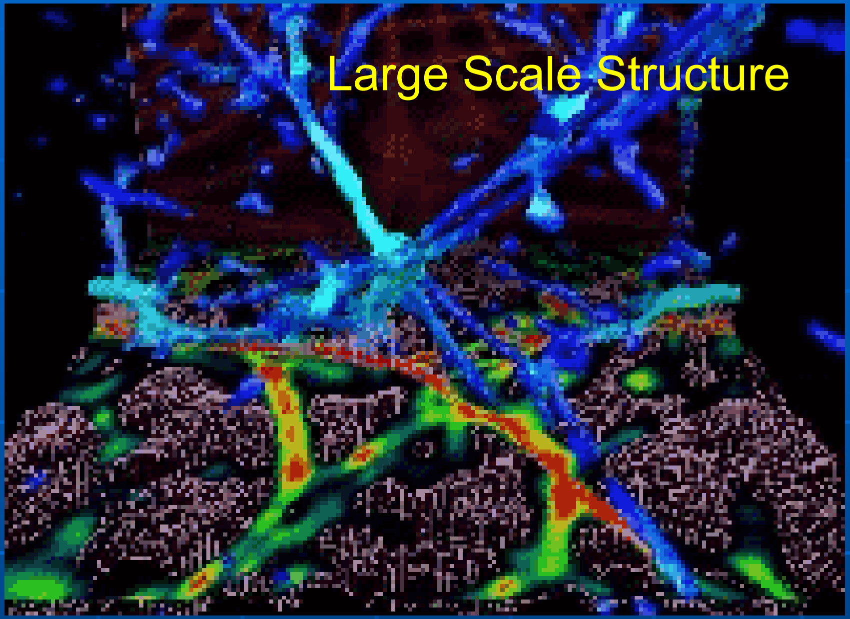
$$M(r) = M_{visible}$$

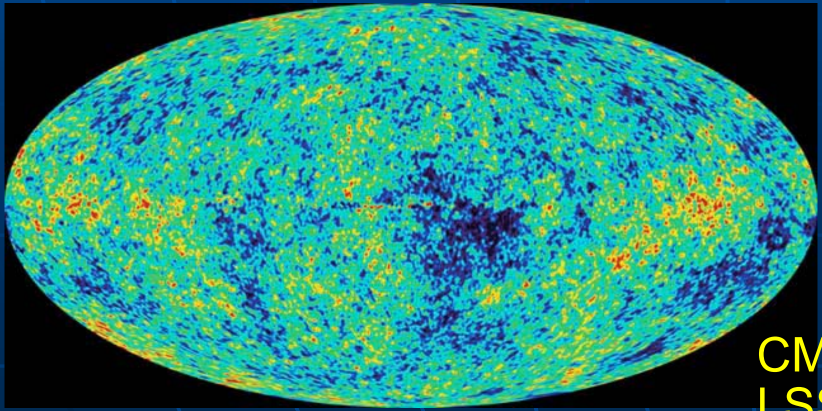
$$\Rightarrow v(r) \approx \sqrt{\frac{GM_{visible}}{r}}$$

Evidence for Dark Matter

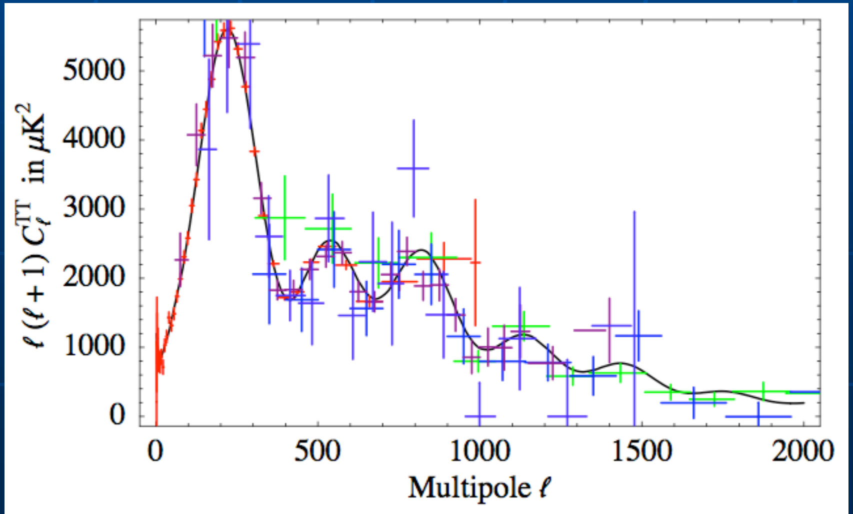


Cluster of Galaxies

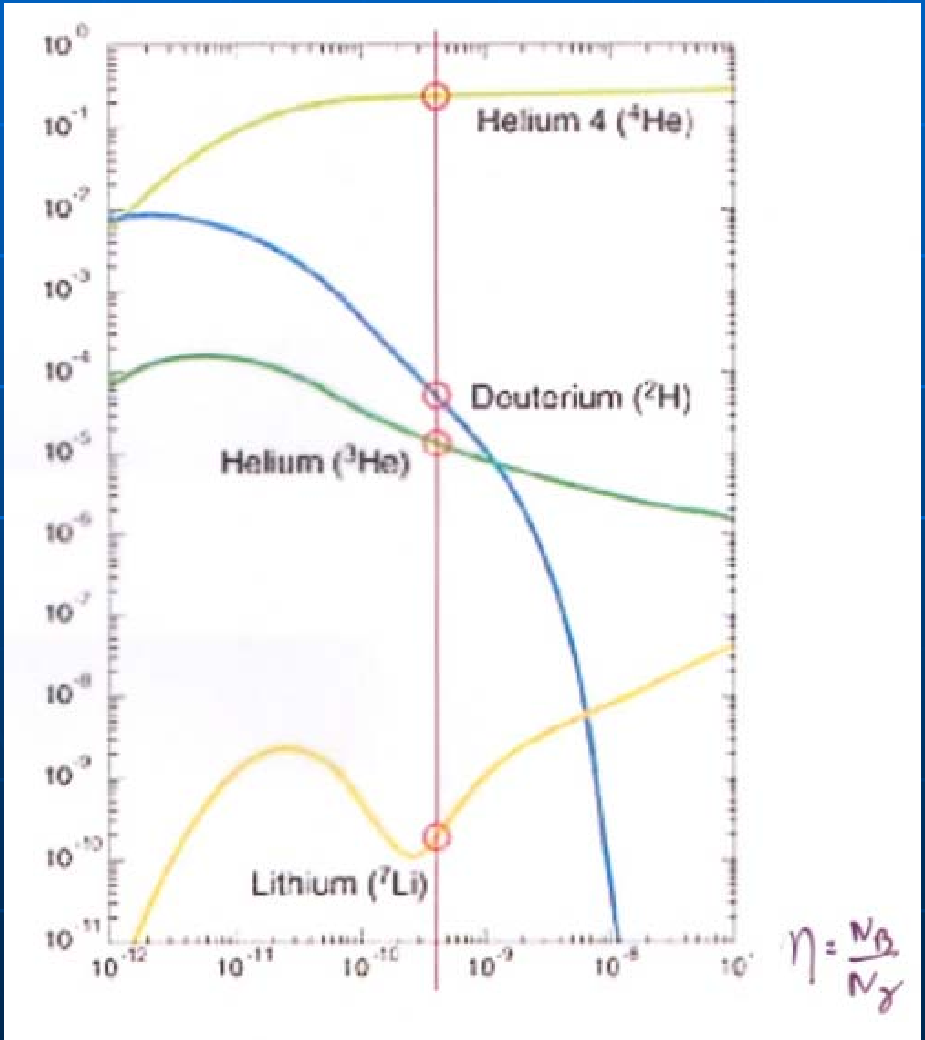


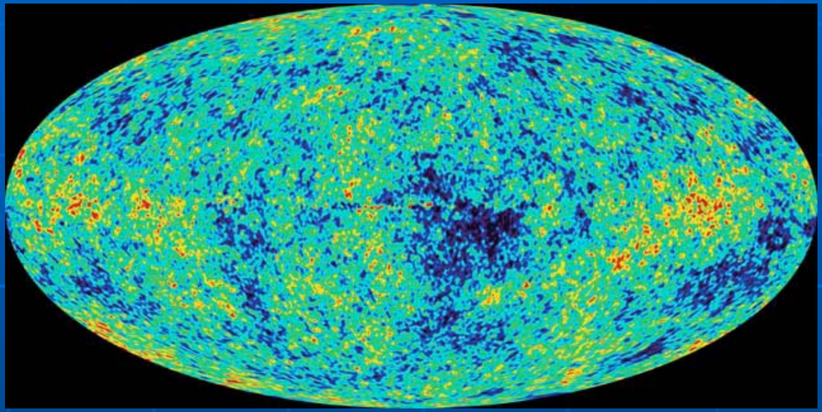


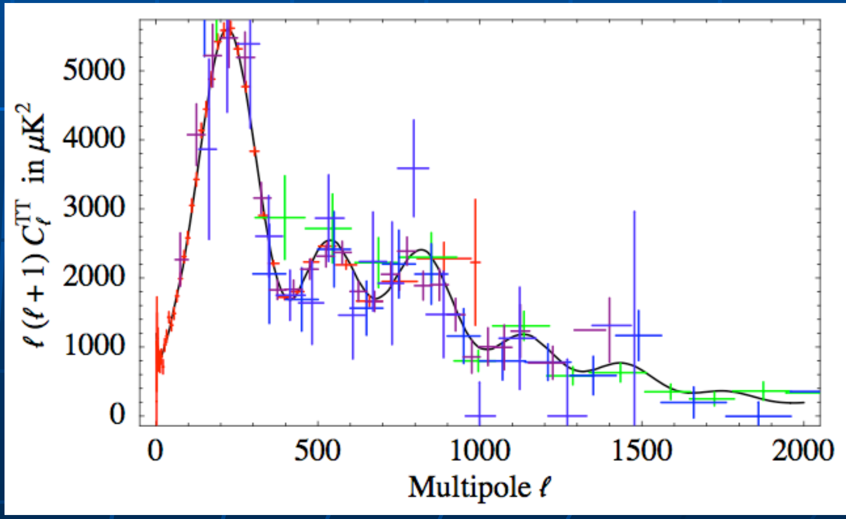
CMB
LSS



Baryonic Matter ?



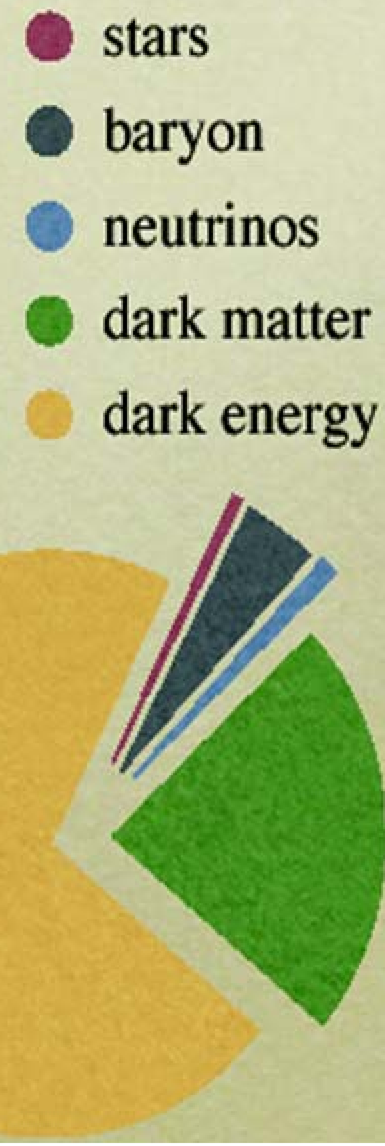




CMB
LSS

THE UNIVERSE ENERGY BUDGET

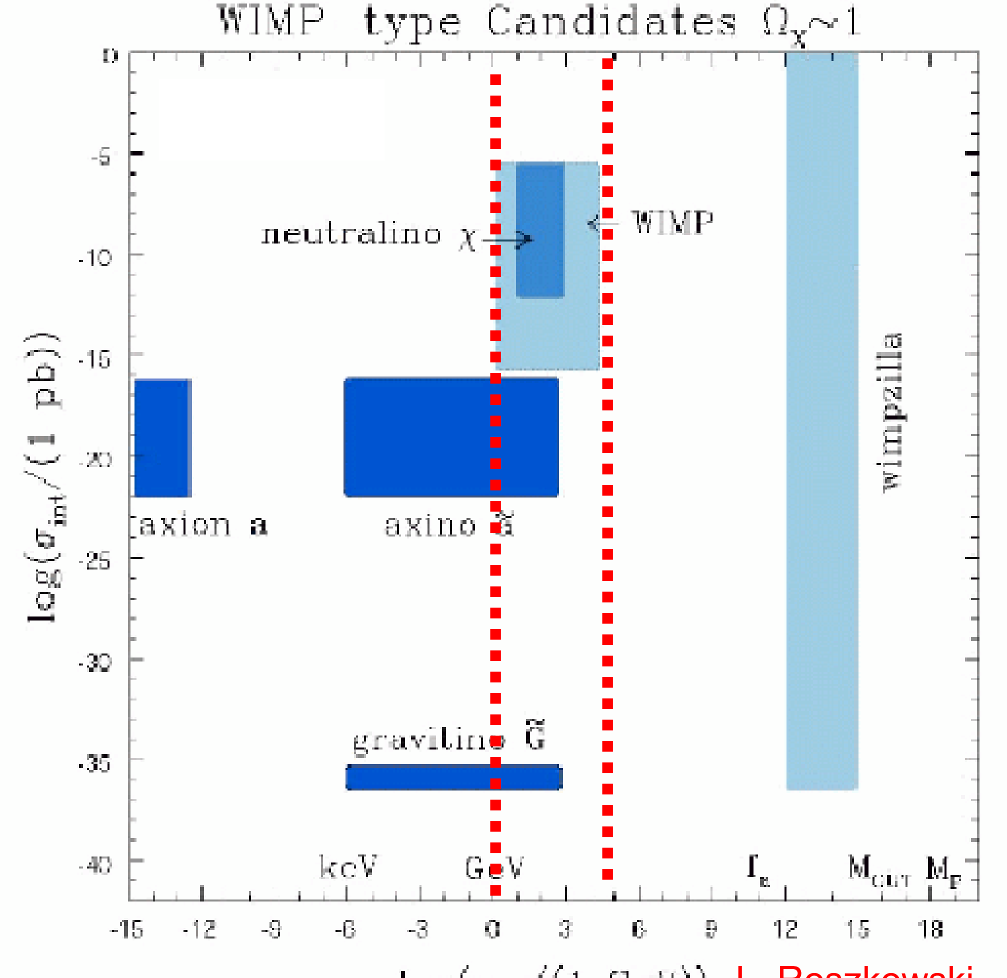
- *Stars and galaxies are only ~0.5%*
- *Neutrinos are ~0.1–1.5%*
- *Rest of ordinary matter*
  (electrons, protons & neutrons) are 4.4%
- *Dark Matter 23%*
- *Dark Energy 73%*
- *Anti-Matter 0%*
- *Higgs Bose-Einstein condensate*
  ~10^{62}%??



Dark Matter Candidates

- Kaluza-Klein DM in UED
- Kaluza-Klein DM in RS
- Axion
- Axino
- Gravitino
- Photino
- SM Neutrino
- Sterile Neutrino
- Sneutrino
- Light DM
- Little Higgs DM
- Wimpzillas
- Q-balls
- Mirror Matter
- Champs (charged DM)
- D-matter
- Cryptons
- Self-interacting
- Superweakly interacting
- Braneworld DM
- Heavy neutrino
- NEUTRALINO
- Messenger States in GMSB
- Branons
- Chaplygin Gas
- Split SUSY
- Primordial Black Holes

$$v(r) = \sqrt{\frac{GM(r)}{r}}$$



L. Roszkowski

The SUSY Particle Spectrum

Standard Model

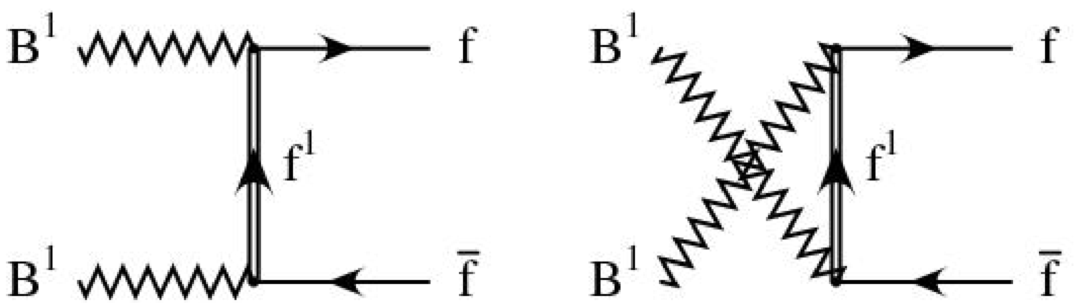
Particles			Sparticles		
Name	**Symbol**	**Spin**	**Name**	**Symbol**	**Spin**
leptons	l, ν	1/2	sleptons	$\tilde{l}_R, \tilde{l}_L, \tilde{\nu}_L$	0
quarks	q_L, q_R	1/2	squarks	$\tilde{q}_L, \tilde{q}_R (\tilde{b}_{1,2}, \tilde{t}_{1,2})$	0
photon Z boson light Higgs heavy Higgs pseudoscalar Higgs	γ Z h H A	1 1 0 0 0	neutralinos	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$	1/2
W boson charged Higgs	$W^{\pm}$ $H^{\pm}$	1 1	charginos	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{\pm}$	1/2
gluon	g	1	gluino	$\tilde{g}$	1/2
graviton	G	2	gravitino	$\tilde{G}$	3/2

'LSP'
(usually)

$$\chi = N_1\tilde{\gamma} + N_2\tilde{Z}^0 + N_3\tilde{H}_1^0 + N_4\tilde{H}_2^0; \sum_{i=1}^{4} |N_i|^2 = 1$$

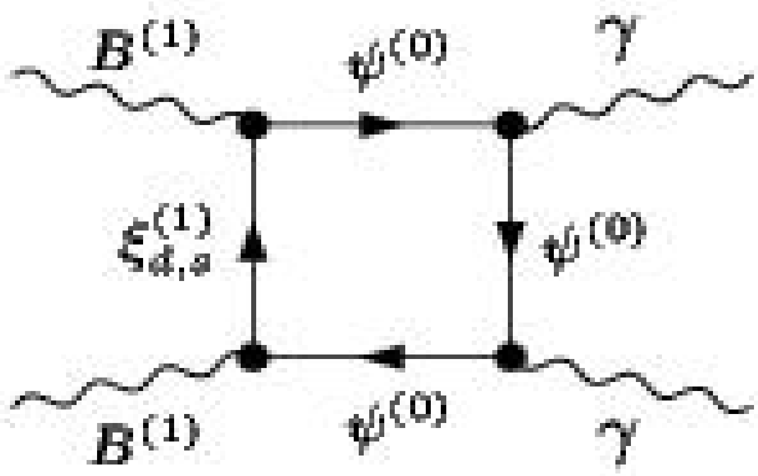
Another possible scenario:
KK Dark Matter

Lightest Kaluza-Klein Particle (LKP): $B^{(1)}$



Bosonic Dark Matter:
fermionic final states
no longer helicity
suppressed.
e^+e^- final states
directly produced.

As in the neutralino case
there are 1-loop
processes that produces
monoenergetic
$\gamma\ \gamma$ in the final state.



WIMP
Evolution in time of number density n_x
Boltzman Equation

$$\frac{dn_x}{dt} = -3Hn_x - n_x^2 < \sigma_{x\bar{x}\to f\bar{f}}\, v > + n_f^2 < \sigma_{f\bar{f}\to x\bar{x}} v >$$

$$\frac{dn_x}{dt} = -3Hn_x - (n_x^2 - n_x^{eq,2}) < \sigma_{ann} v >$$

$$n_{eq} \propto (mT)^{\frac{3}{2}} e^{\frac{-m_x c^2}{kT}}$$

$$\Omega_x = \frac{n_x(t_0)m_x}{\rho_c(t_0)} = \frac{3\text{x}10^{-27}\text{cm}^2\text{sec}^{-1}}{< \sigma_{ann} v > h^2}$$

Thermal Relics from the Early Universe

Boltzmann equation
in the Early Universe:

$$\Omega_\chi \simeq \frac{6 \cdot 10^{-27}\, \mathrm{cm}^3\, \mathrm{s}^{-1}}{\langle \sigma\, v \rangle}$$

In order to have:

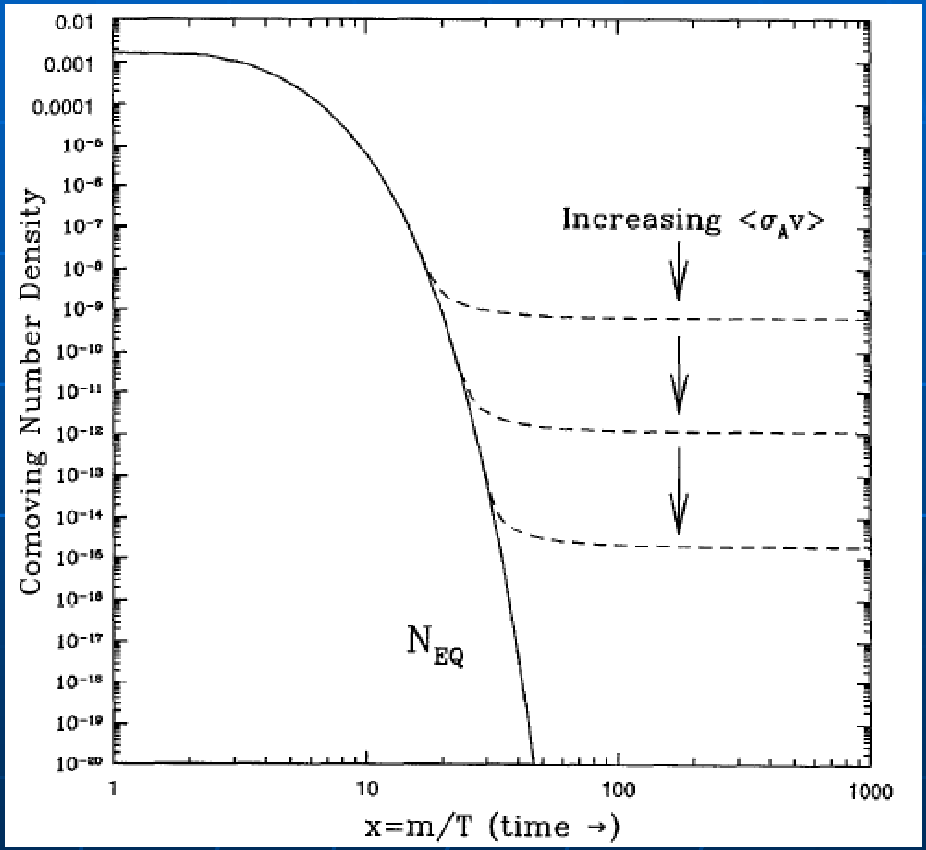
$$\Omega_\chi = \Omega_{\mathrm{DM}} \simeq 0.23$$

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

Weak scale cross section

$$\langle \sigma\, v \rangle \simeq \frac{\alpha_{EW}^2}{M^2}$$ for M≤1 TeV

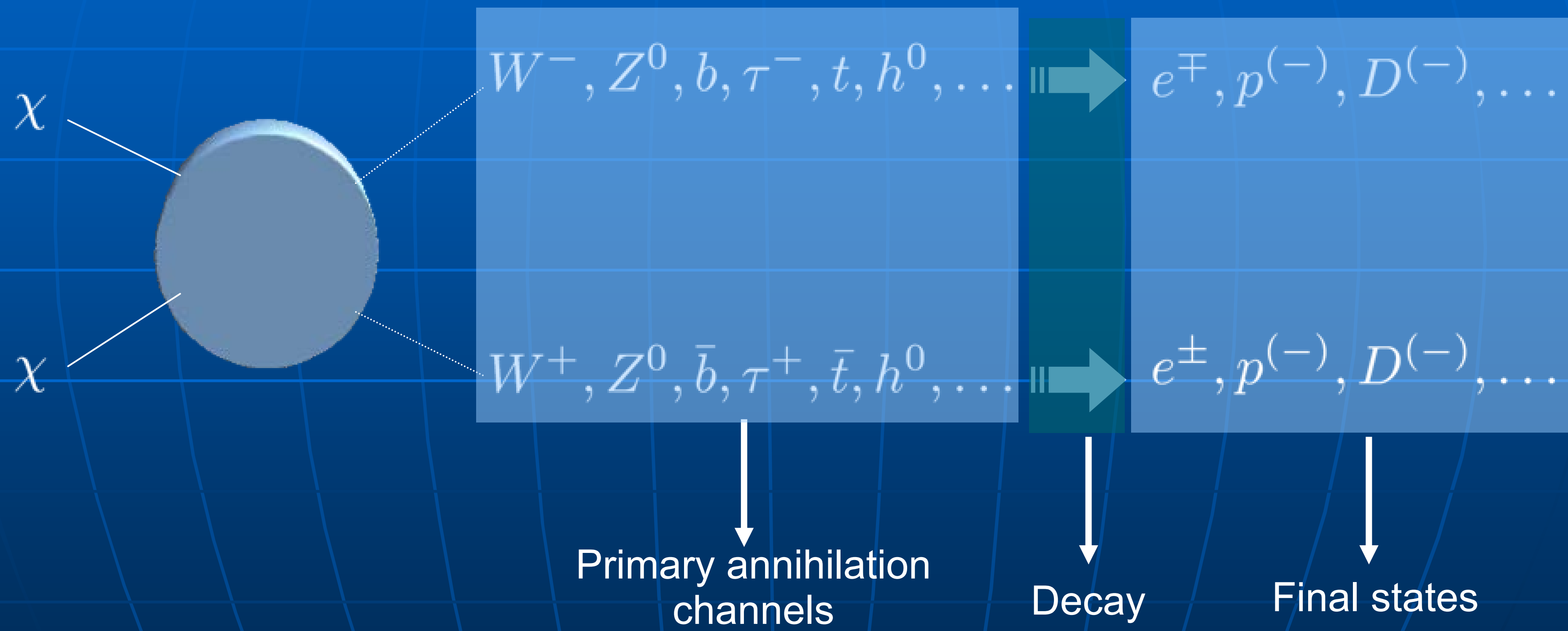
Kolb&Turner, "The Early Universe" (1995)



WIMP

DM annihilations

DM particles are stable. They can annihilate in pairs.



flux $\propto n^2 \, \sigma_{\text{annihilation}}$

astro& cosmo — particle

reference cross section:

$\sigma = 3 \cdot 10^{-26} \text{cm}^3/\text{sec}$

$\sigma_a = \langle \sigma v \rangle$

Decay Channels

Positron fraction from decaying dark matter: model independent analysis

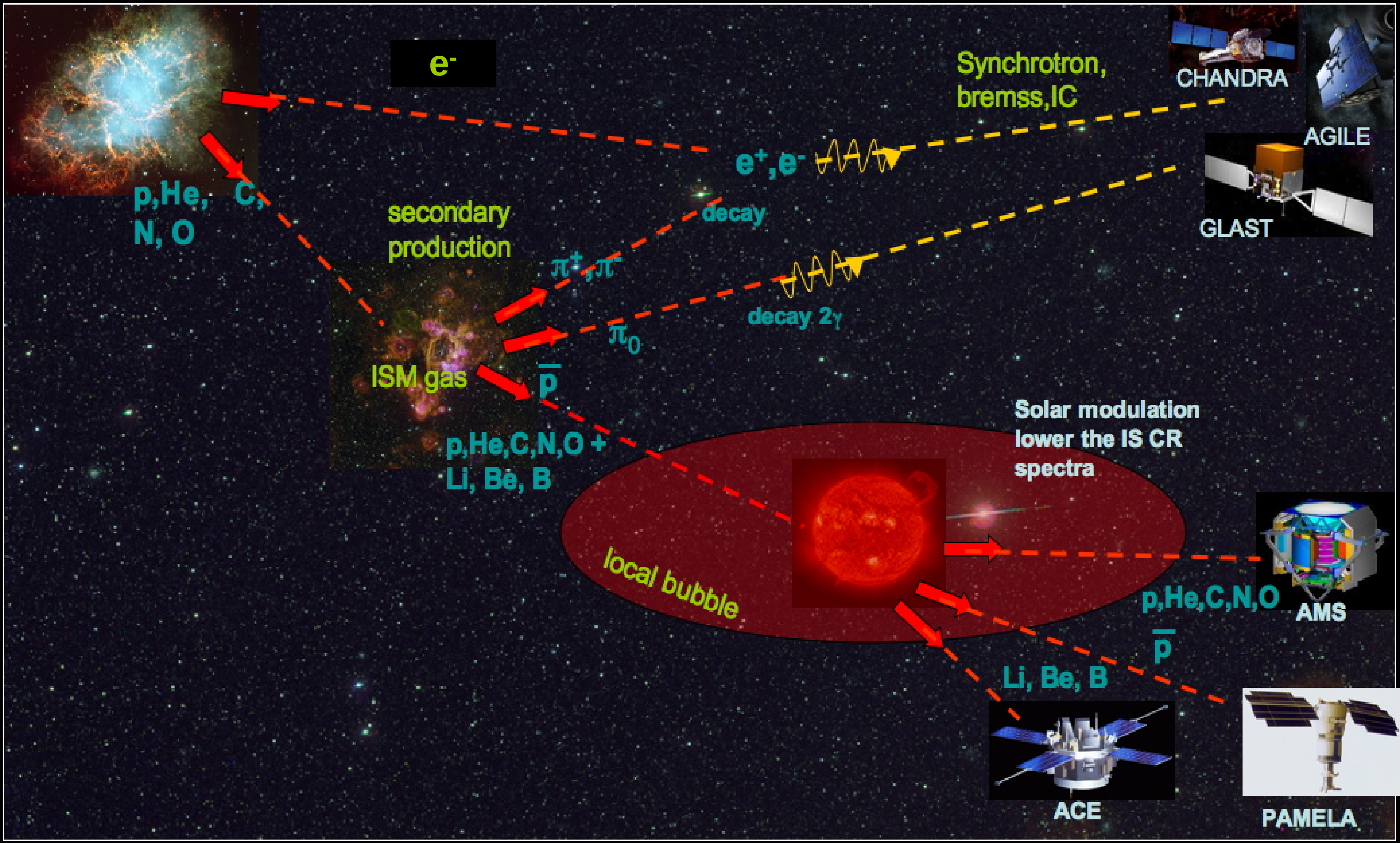
AI, Tran

Possible decay channels

$$\text{fermionic DM} \left\{ \begin{array}{l} \psi \to Z^0 \nu \\ \psi \to W^{\pm} \ell^{\mp} \\ \psi \to \ell^+ \ell^- \nu \end{array} \right.$$

$$\text{scalar DM} \left\{ \begin{array}{l} \phi \to Z^0 Z^0 \\ \phi \to W^+ W^- \\ \phi \to \ell^+ \ell^- \end{array} \right.$$

COSMIC RAYS PRODUCTION MECHANISMS

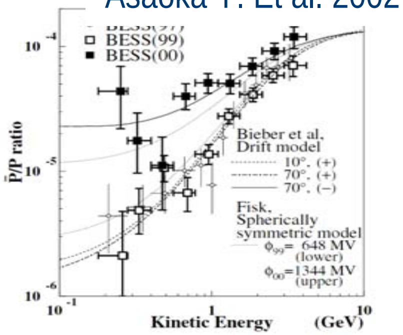


Cosmic Ray Antimatter

Pre-PAMELA status

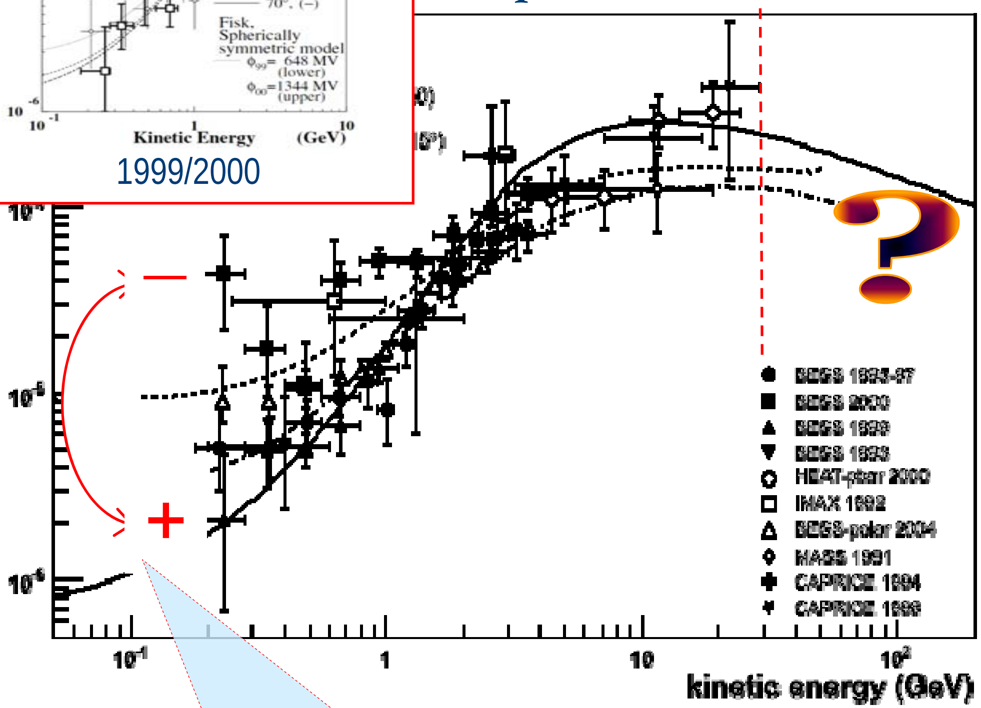
Charge-dependent solar modulation

Asaoka Y. Et al. 2002

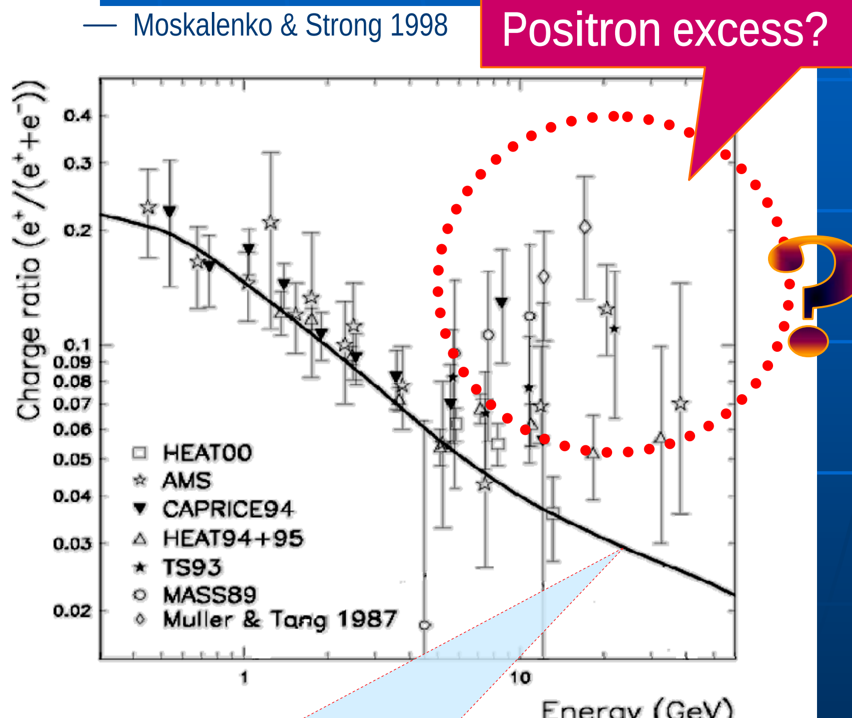


1999/2000

Antiprotons



Positrons



CR + ISM → **p-bar** + …

kinematic threshold:

5.6 GeV for the reaction

$pp \rightarrow \bar{p}ppp$

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

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

What do we need?

- Measurements at higher energies
- Better knowledge of background
- High statistics
- Continuous monitoring of solar modulation

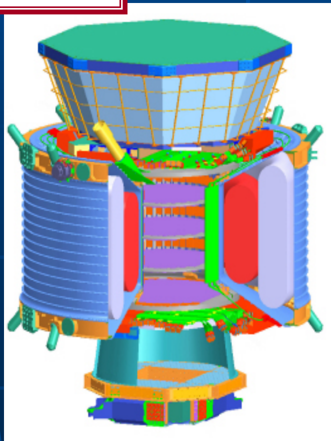
Long Duration Flights

Antimatter Dark Matter Space Missions

PAMELA
15-06-2006

Fermi
11-6-2008

AMS-02
2010



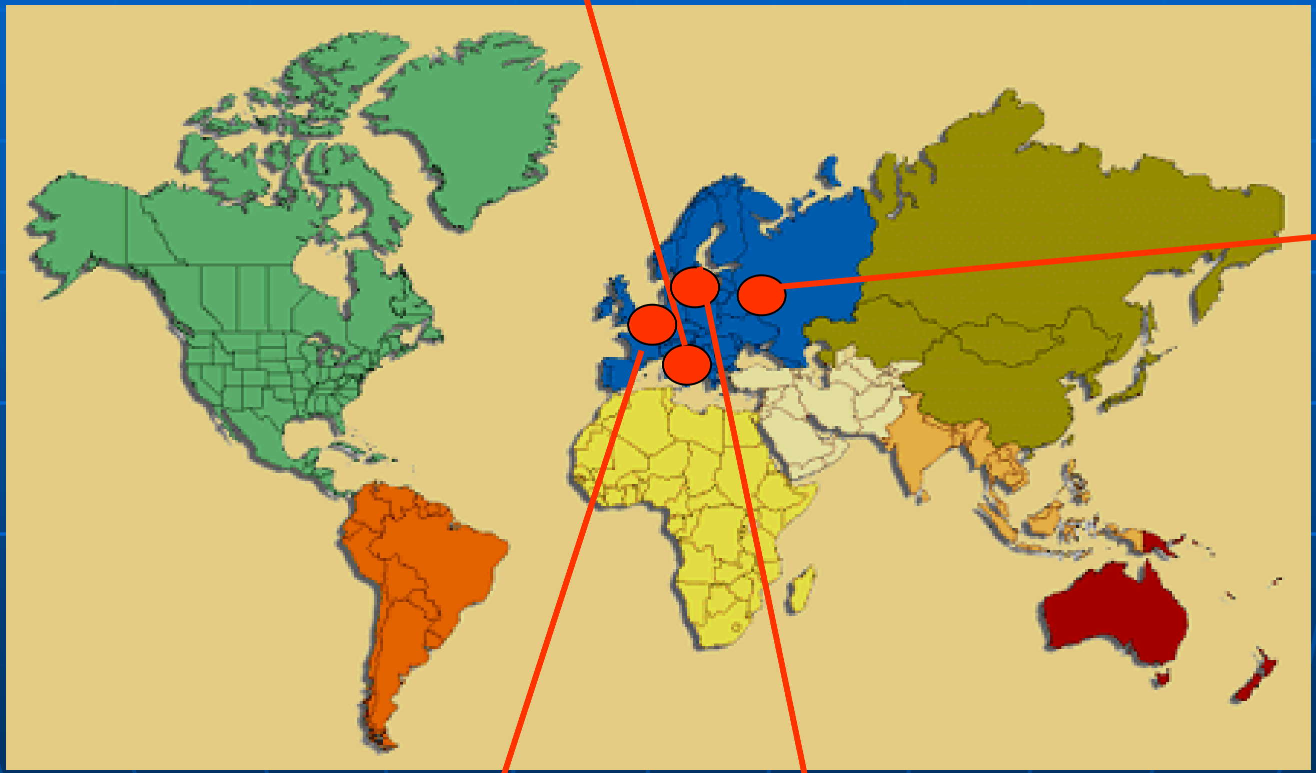
PAMELA

Payload for Antimatter Matter Exploration and Light Nuclei Astrophysics

PAMELA Collaboration

Italy:

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



Russia:

Ioffe Physico-Technical Institute

Moscow
St. Petersburg

Germany:

Universität Gesamthochschule Siegen

Siegen

Sweden:

Kungl Tekniska Högskolan

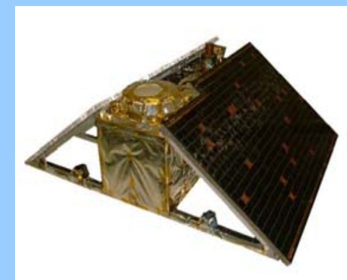
KTH, Stockholm

WiZard Russian Italian Missions

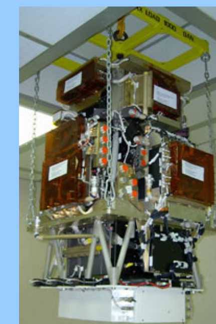
MASS-89, 91, TS-93, CAPRICE 94-97-98

NINA-1

NINA-2



PAMELA

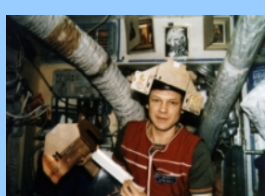


M 89 · M 91 · TS 93 · C 94 · C 97 · C 98 · PAMELA

…1989 · 1990 · 1991 · 1992 · 1993 · 1994 · 1995 · 1996 · 1997 · 1998 · 1999 · 2000 · 2001 · 2002 · 2003 · 2004 · 2005 · 2006 · 2007..

SILEYE-1 · NINA-1 · NINA-2 · Alteino-SILEYE-3

SILEYE-2 · ALTEA-SILEYE-4



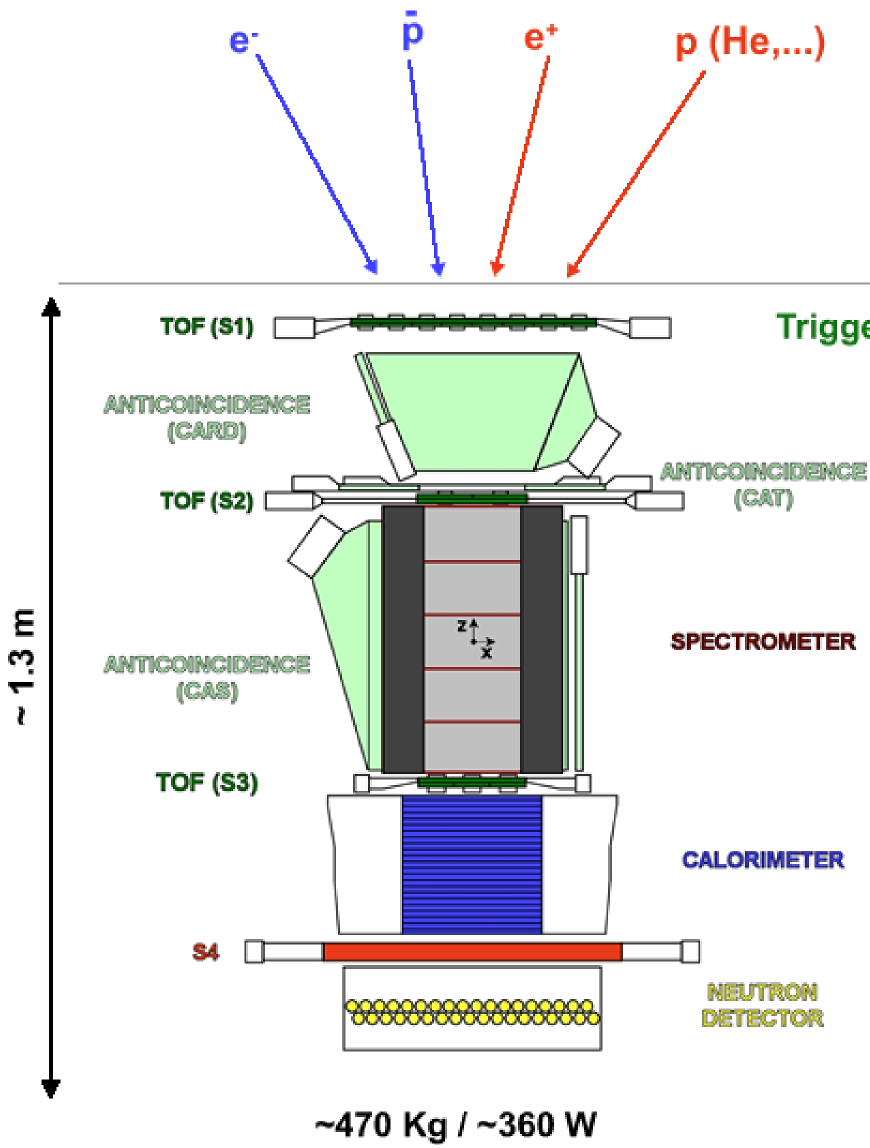
SILEYE-1

SILEYE-2

ALTEINO:
SILEYE-3

LAZIO
SIRAD

ALTEA:
SILEYE-4



Trigger, ToF, dE/dx

- S1, S2, S3; double layers, x-y
- plastic scintillator (8mm)
- 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

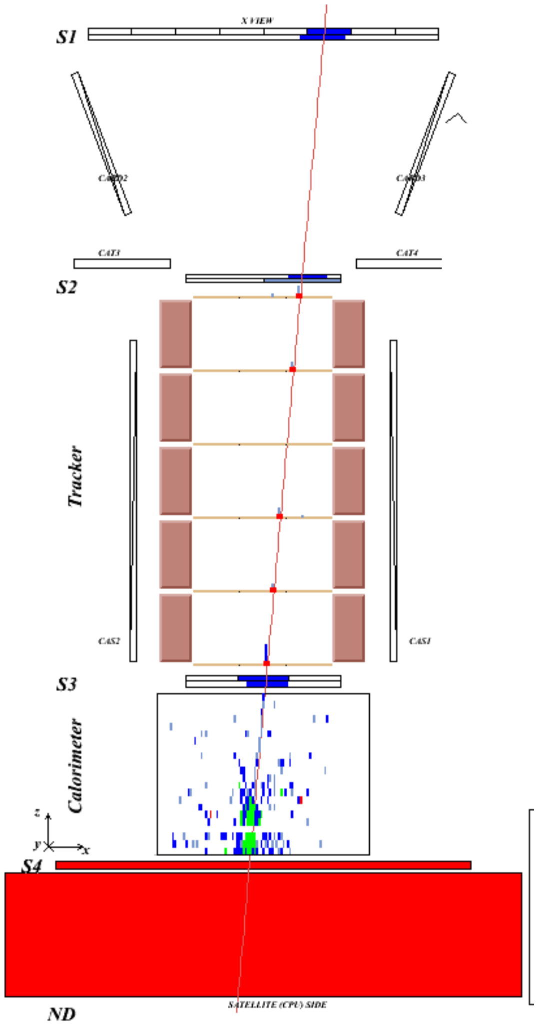
- Permanent magnet, 0.43 T
- 21.5 cm^2 sr
- 6 planes double-sided silicon strip detectors (300 μm)
- 3 μm resolution in bending view → MDR ~800 GV (6 plane) ~500 GV (5 plane)

Electron energy, dE/dx, lepton-hadron separation

- 44 Si-x / W / Si-y planes (380)
- 16.3 X0 / 0.6 L
- dE/E ~5.5 % (10 - 300 GeV)
- Self trigger > 300 GeV / 600 cm^2 sr

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

Antiproton / positron identification



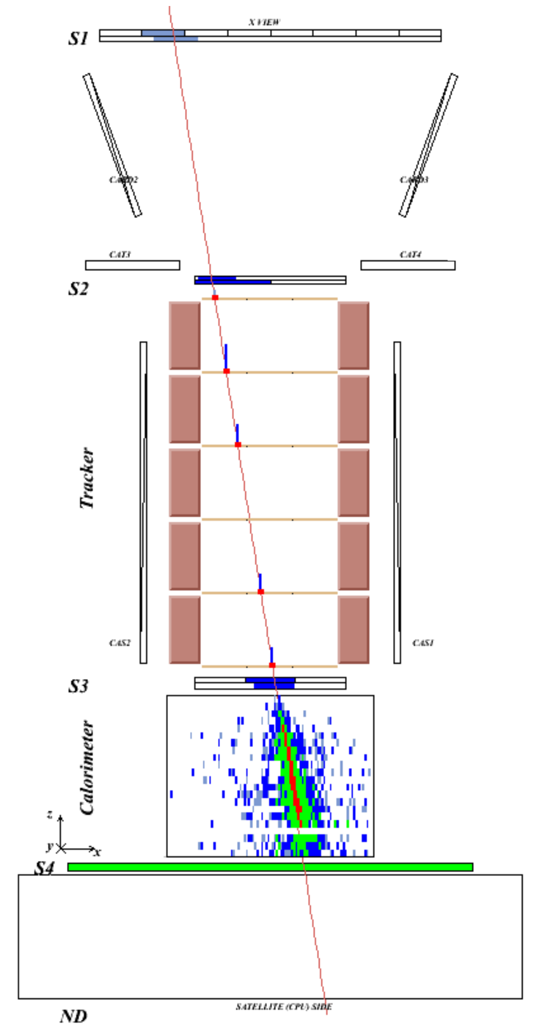
Antiproton
(NB: $e^-/\bar{p} \sim 10^2$)

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

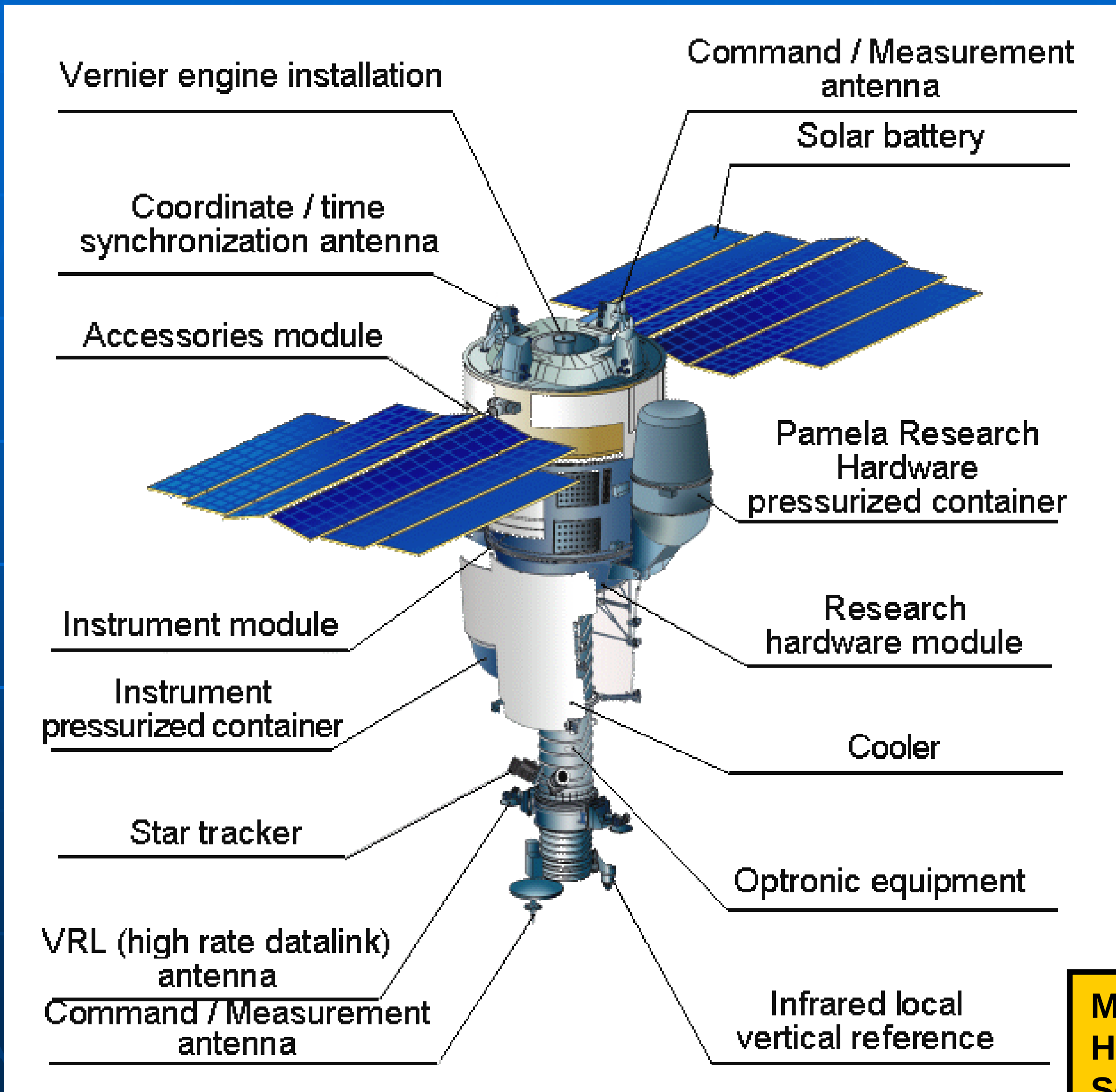


Positron
(NB: $p/e^+ \sim 10^{3\text{-}4}$)

Design Performance

	Energy range
Antiprotons	80 MeV - 190 GeV
Positrons	50 MeV – 300 GeV
Electrons	up to 600 GeV
Protons	up to 1 TeV
Helium	up to 400 GeV/n
Electrons+positrons	up to 2 TeV (from calorimeter)
Light Nuclei (Li/Be/B/C)	up to 200 GeV/n
AntiNuclei search	sensitivity of 3×10^{-8} in $\overline{\mathrm{He}}/\mathrm{He}$

Resurs-DK1 satellite



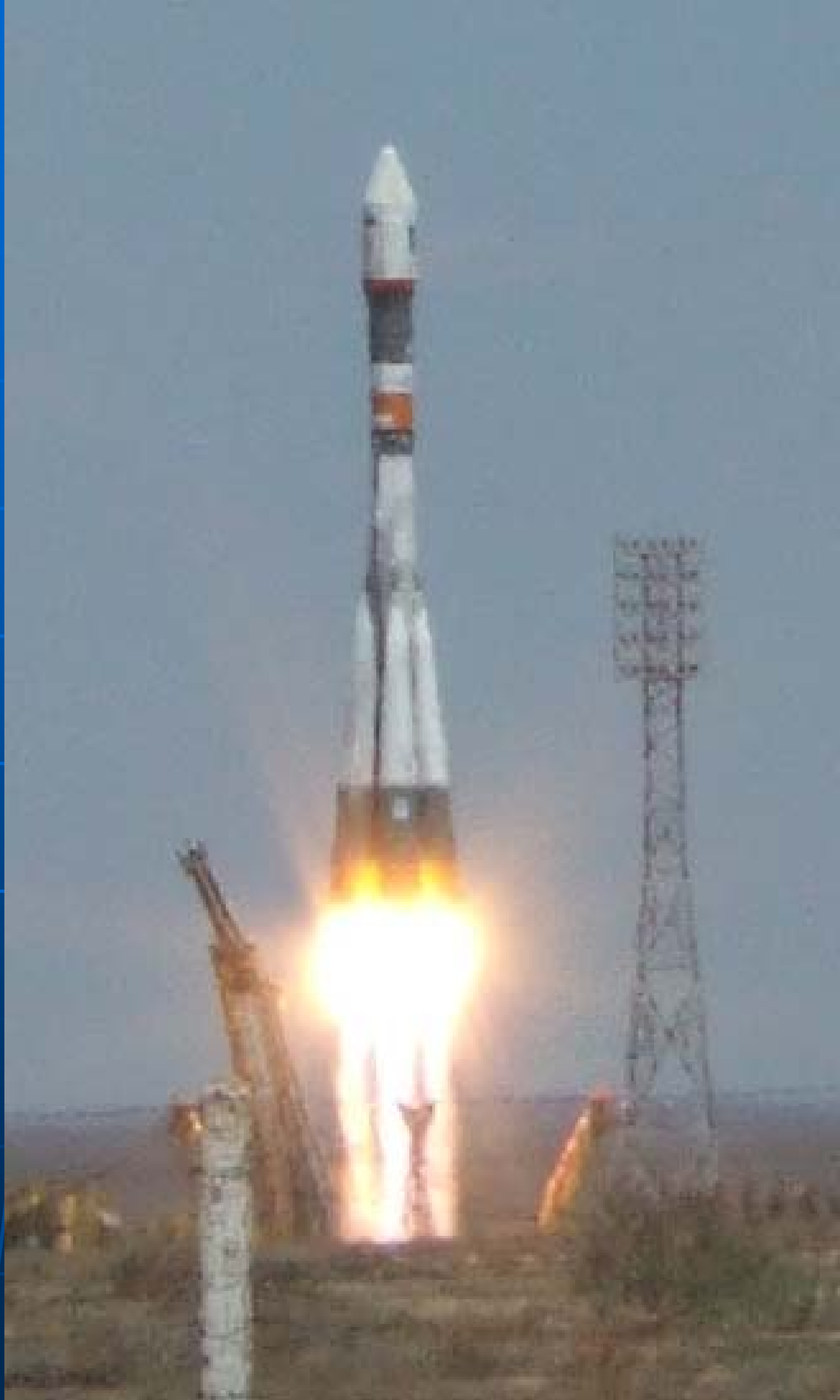
- **Main task:** multi-spectral remote sensing of earth's surface
- Built by TsSKB Progress in Samara, Russia
- **Lifetime >3 years (assisted)**
- Data transmitted to ground via high-speed radio downlink
- **PAMELA mounted inside a pressurized container**

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

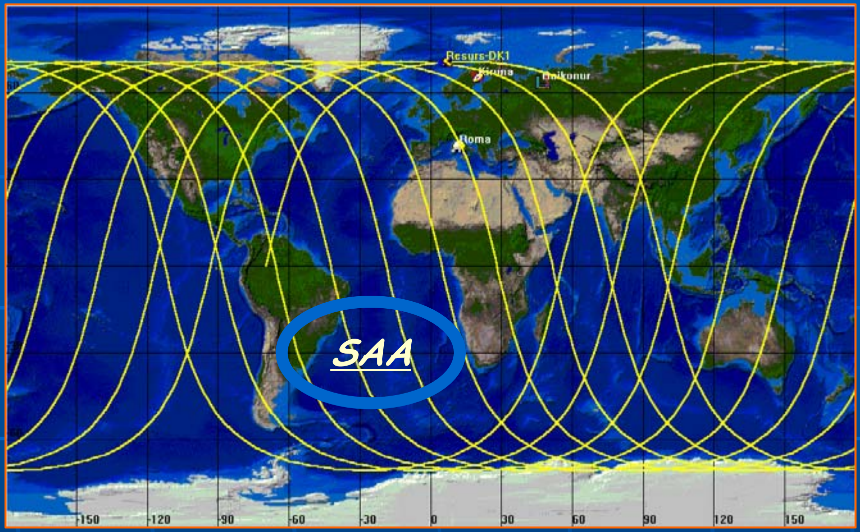
PAMELA

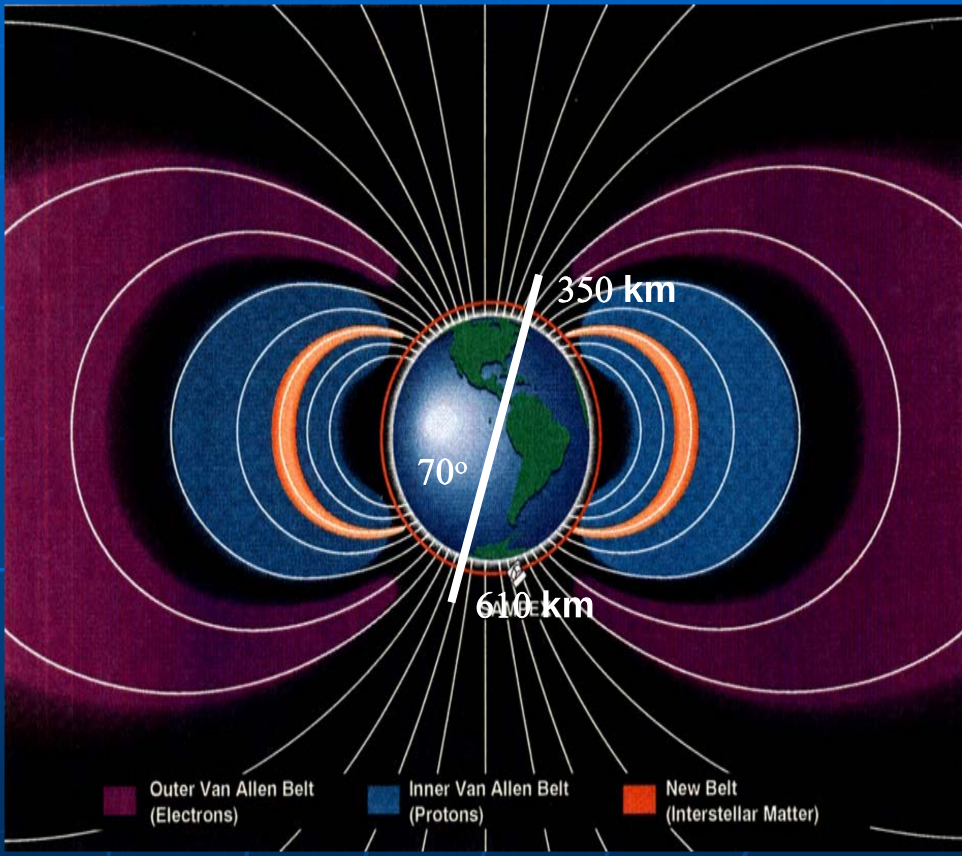
Launch 15/06/06

16 Gigabytes trasmitted daily to Ground NTsOMZ Moscow



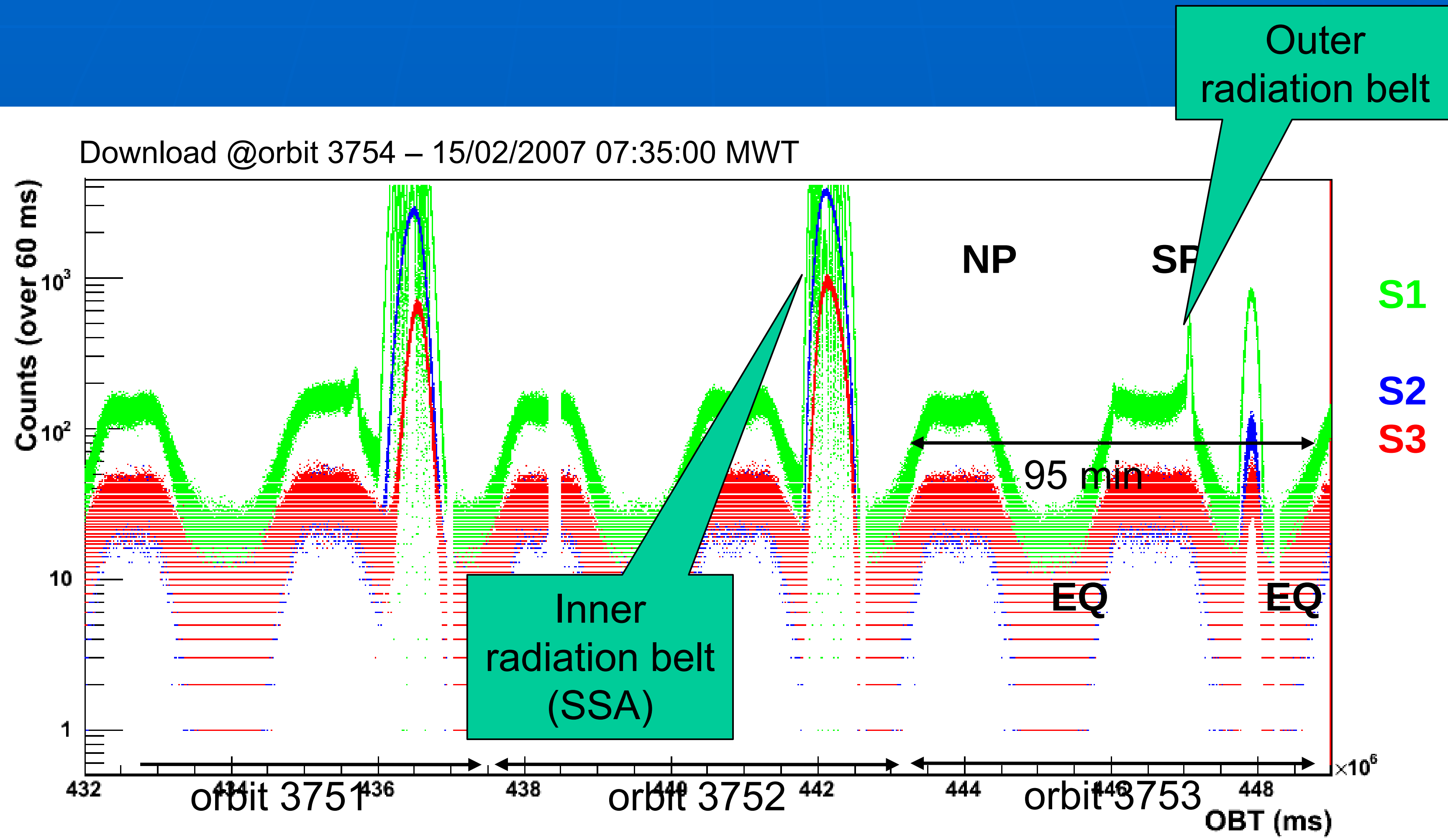
Orbit Characteristics

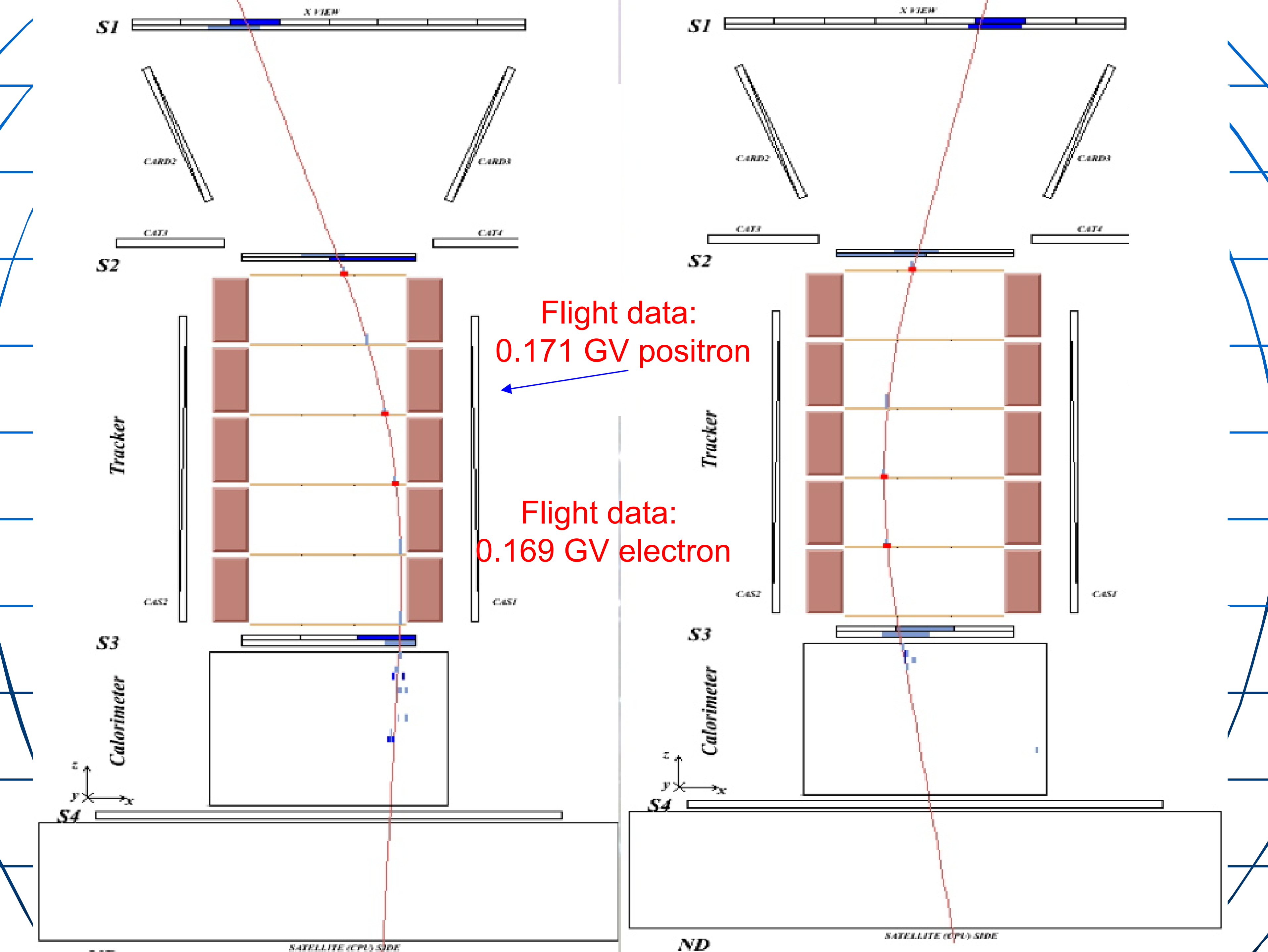


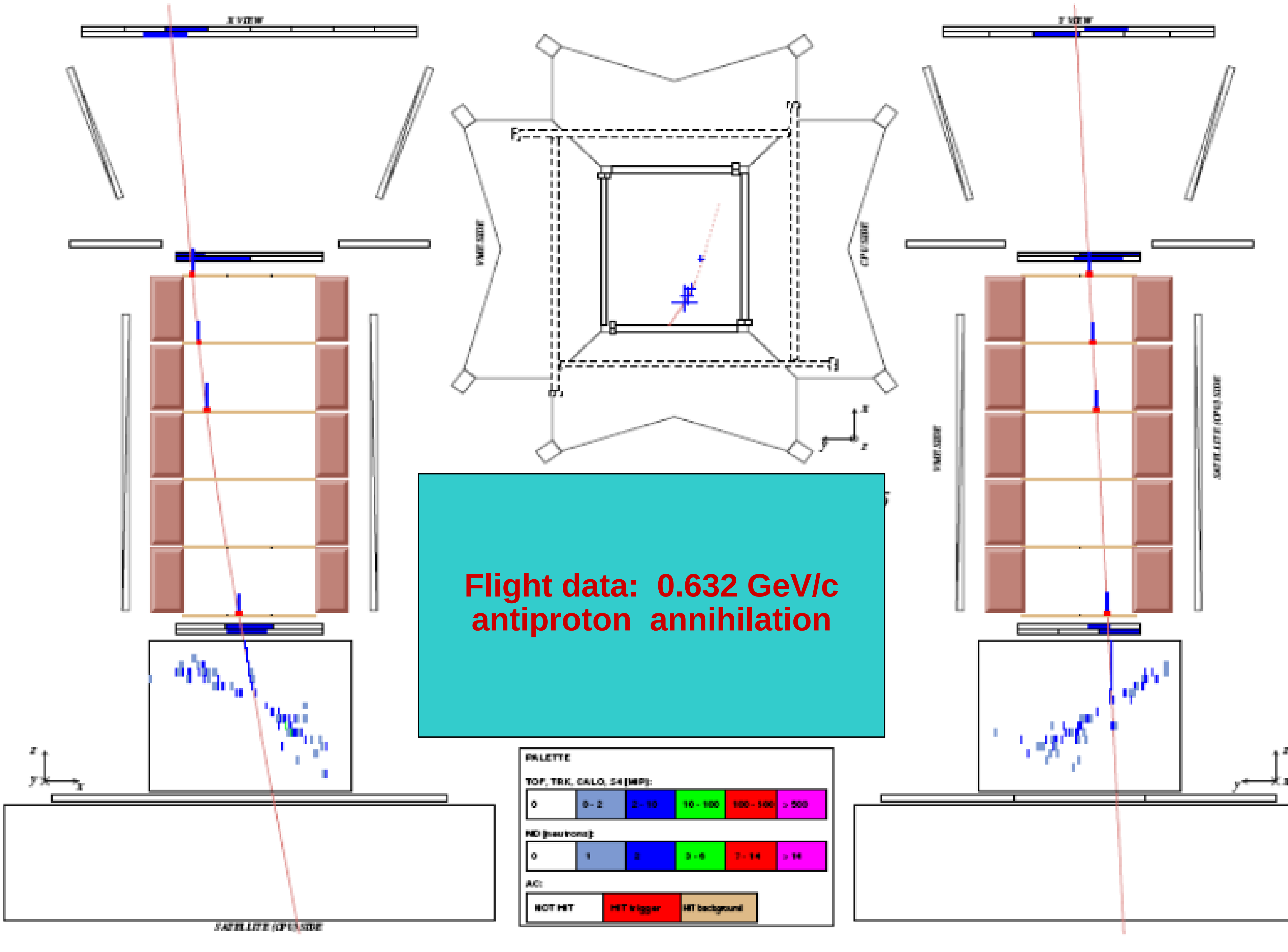


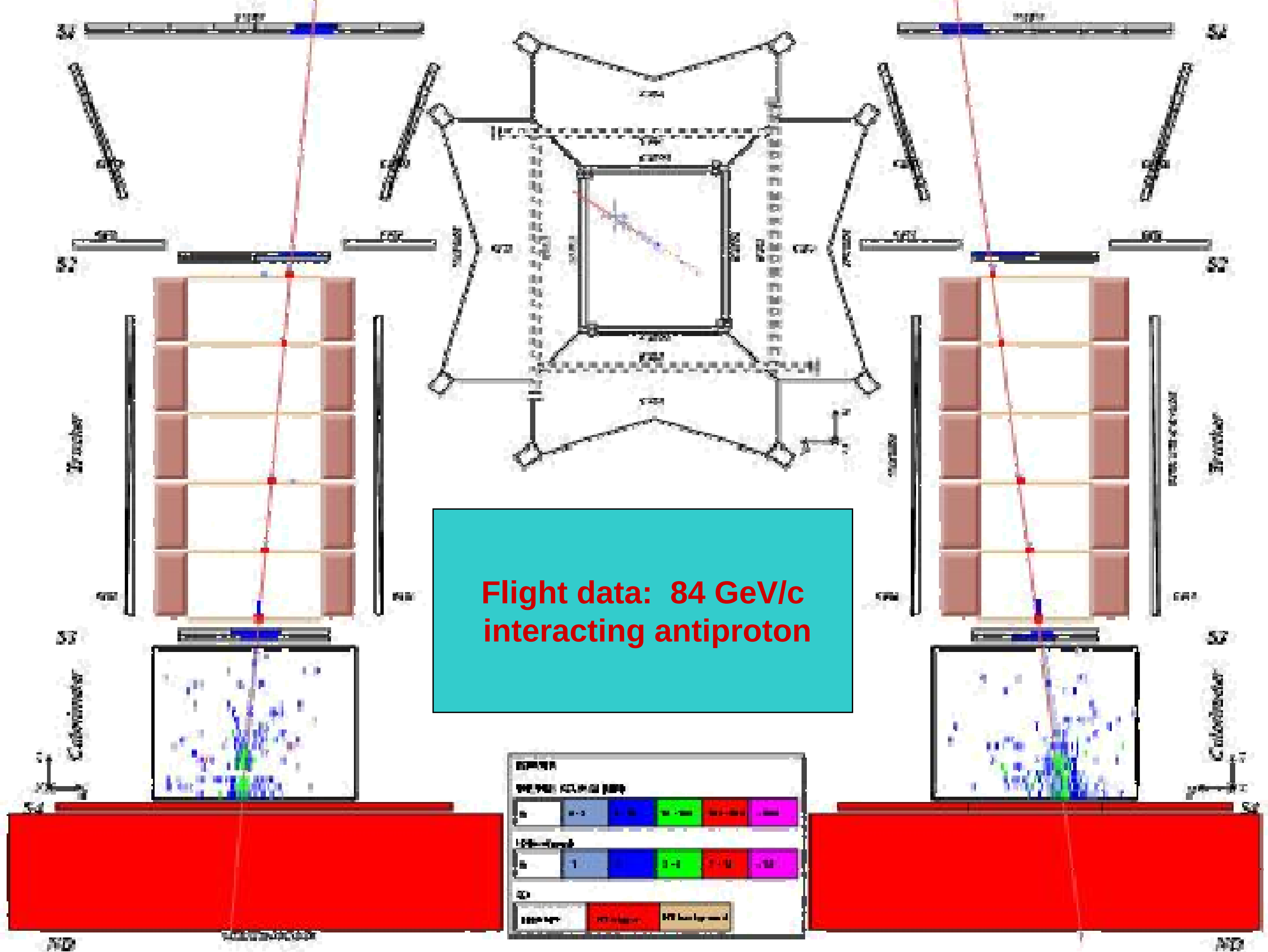
- Low-earth elliptical orbit
- 350 – 610 km
- Quasi-polar (70º inclination)
- SAA crossed

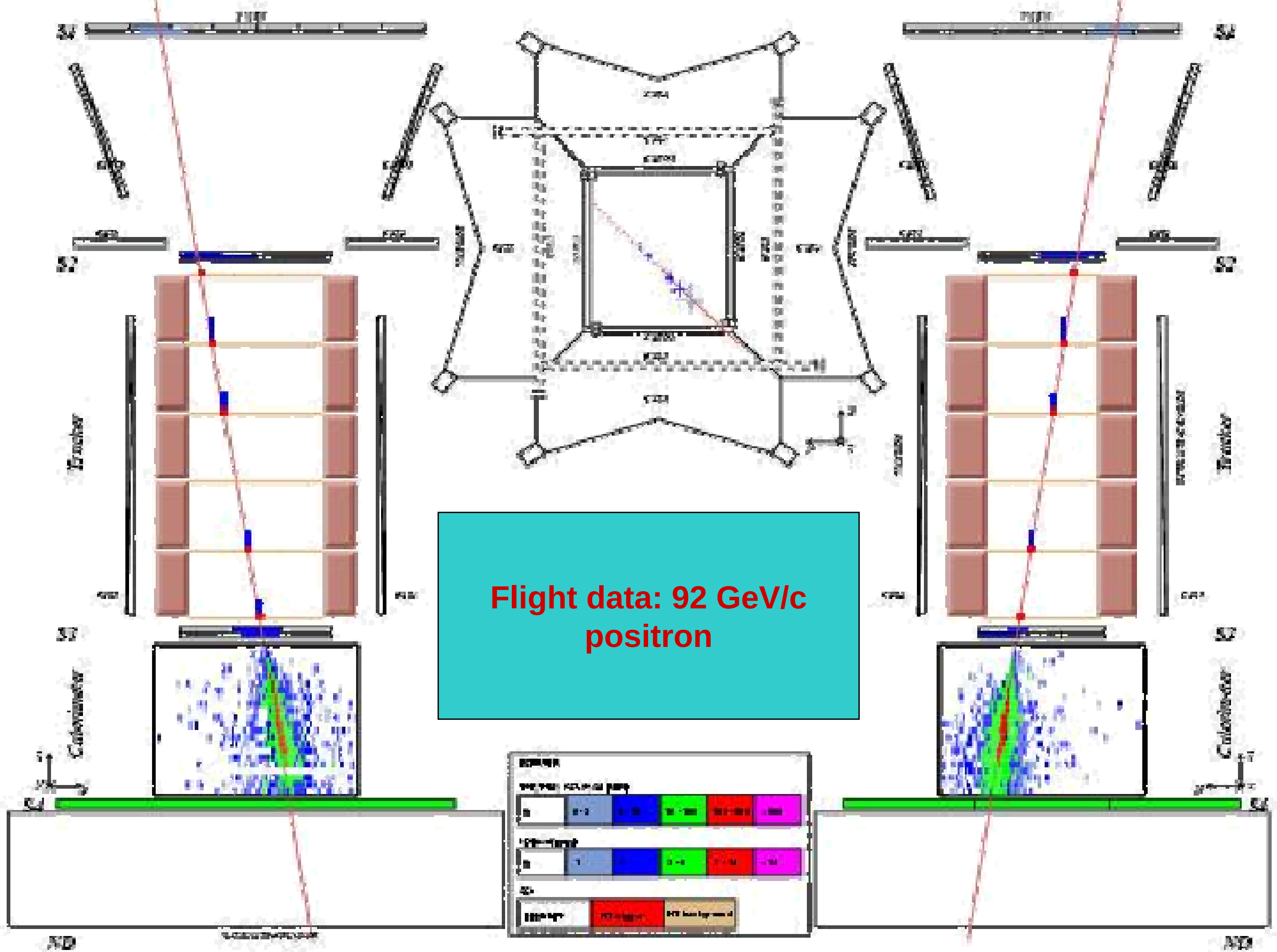
PAMELA Orbit

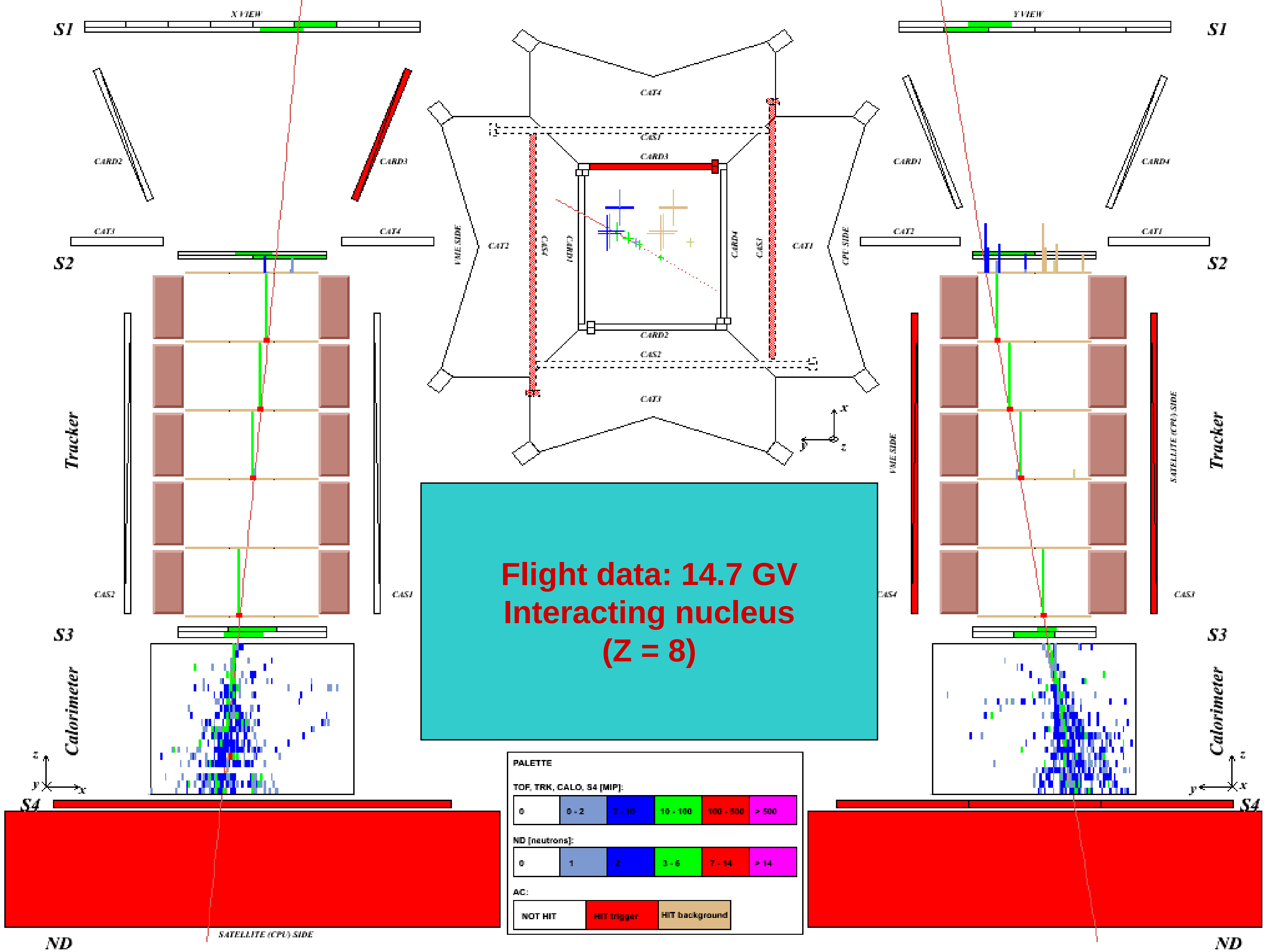



Flight data:
0.171 GV positron
Flight data:
0.169 GV electron
X VIEW
S1
CARD2
CARD3
CAT3
CAT4
S2
Tracker
CAS2
CAS1
S3
Calorimeter
S4
ND
SATELLITE (CPU) SIDE
z
y
x

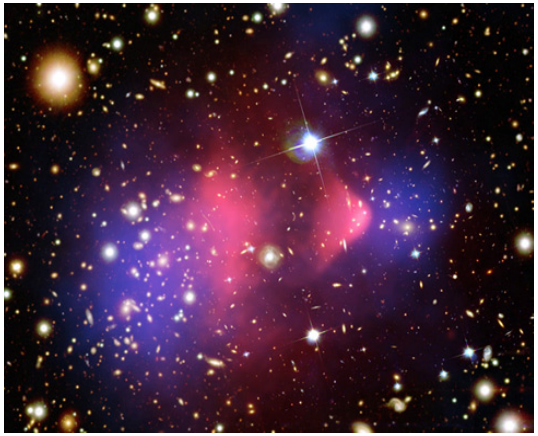

X VIEW
Y VIEW
VMT SIDE
CPU SIDE
SATELLITE (CPU) SIDE
Flight data: 0.632 GeV/c
antiproton annihilation
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background


Flight data: 84 GeV/c
interacting antiproton
S1
S2
S3
S4
ND
Tracker
Calorimeter


S1
S2
S3
S4
ND
Tracker
Calorimeter
Flight data: 92 GeV/c
positron


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

The Physics of PAMELA

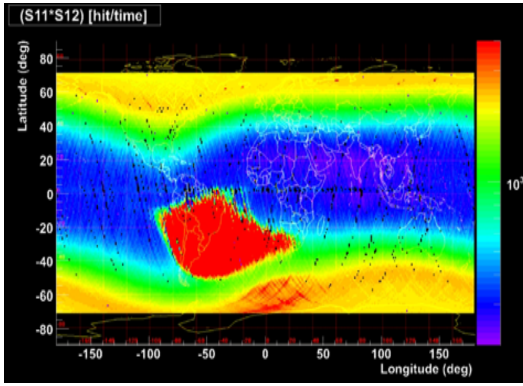


Search for dark matter annihilation

Search for antihelium (primordial antimatter)

Search for new Matter in the Universe (Strangelets?)

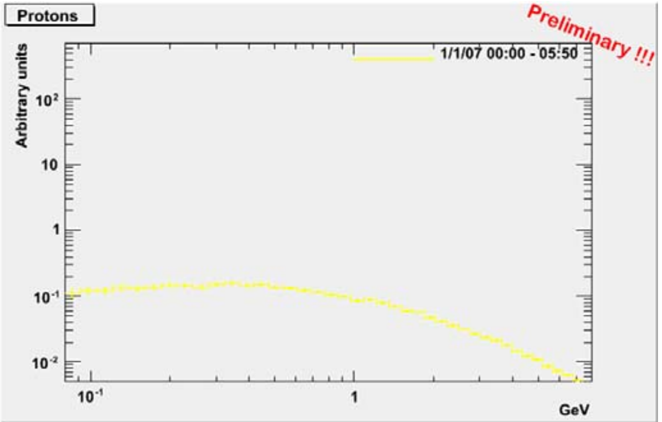
Study of cosmic-ray propagation

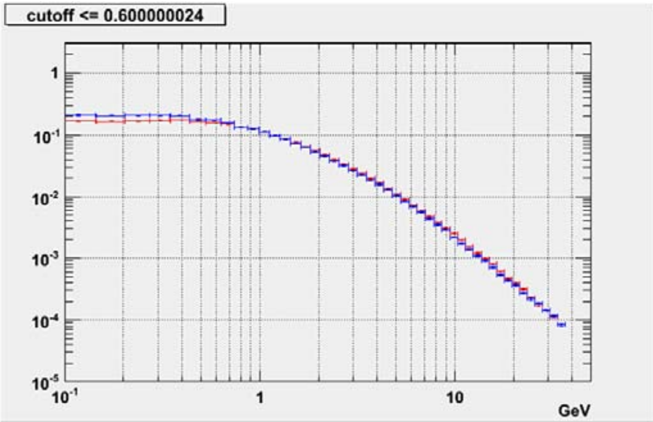


Study of solar physics and solar modulation

Study of terrestrial magnetosphere

Study of high energy electron spectrum (local sources?)





PAMELA Status

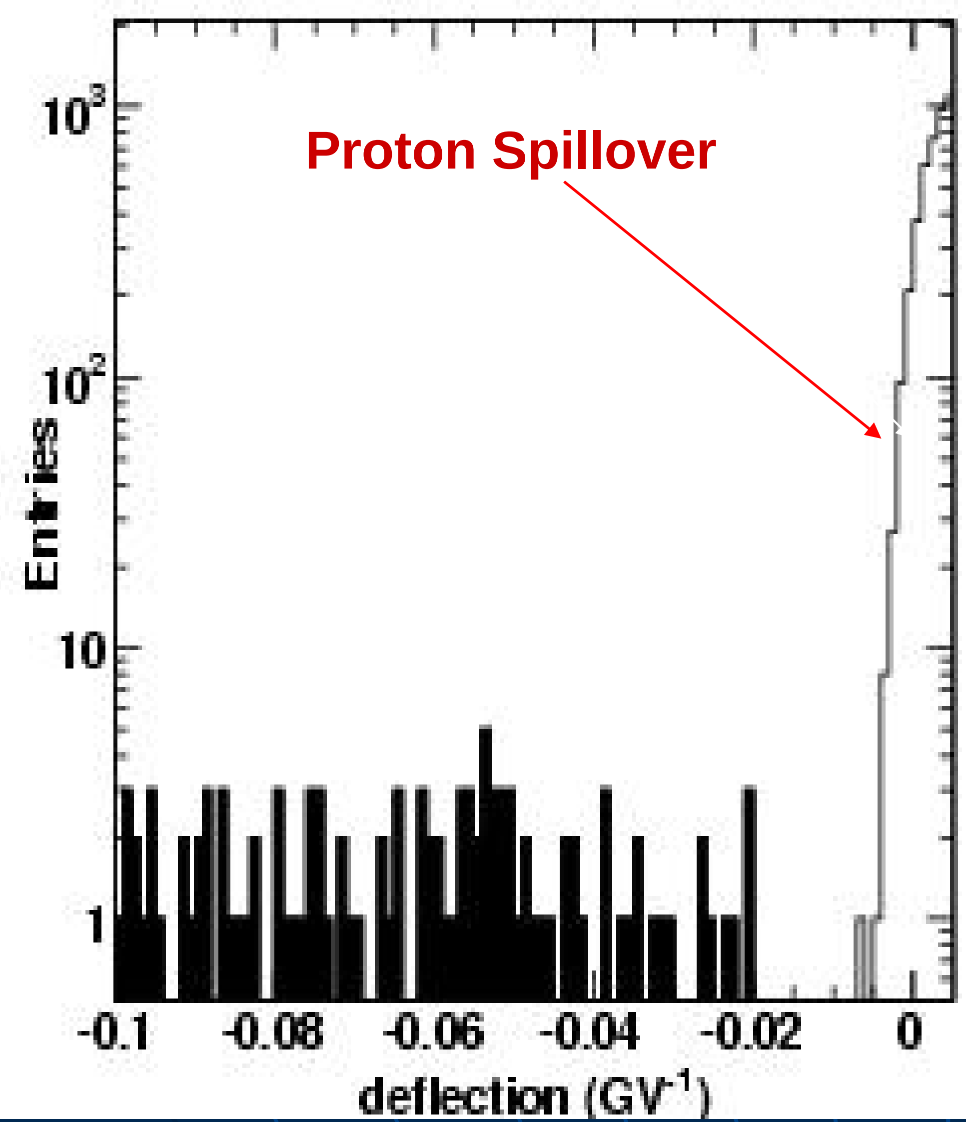
- Today 1413 days in flight
- data taking ~73% live-time

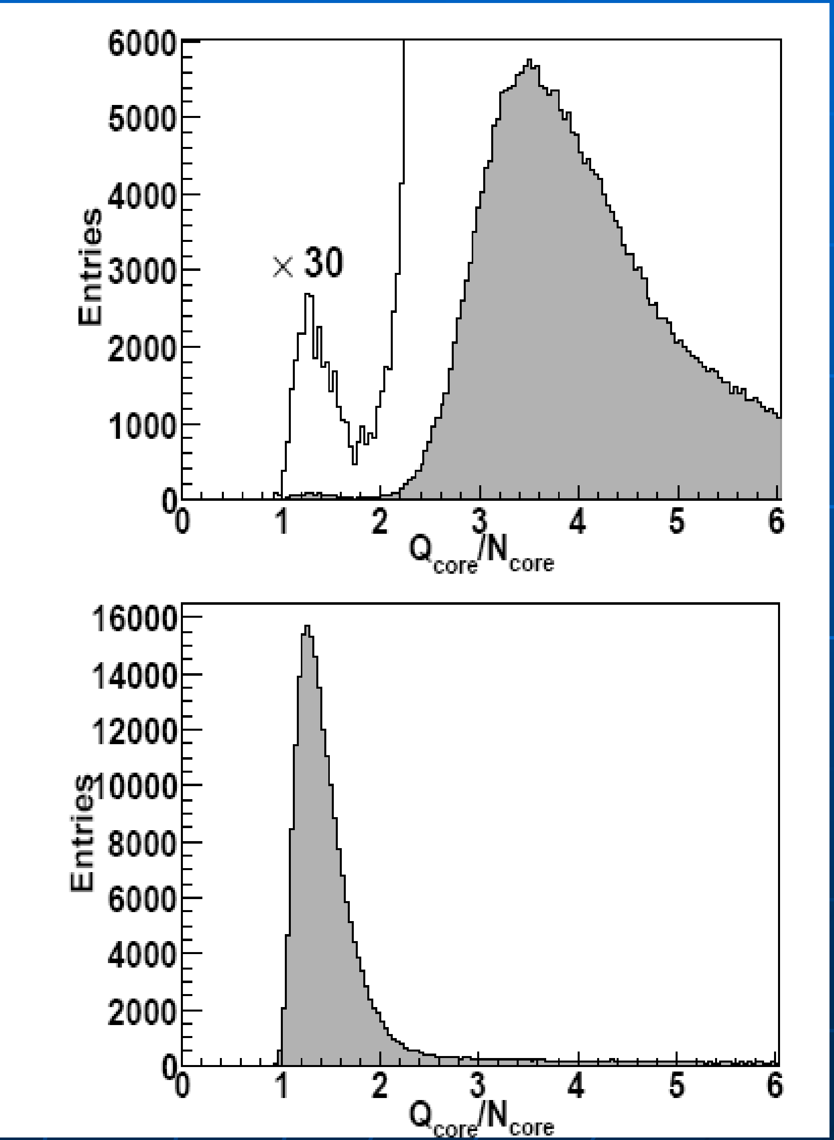
- ~20 TBytes of raw data downlinked

- $>2.10^9$ triggers recorded and under analysis

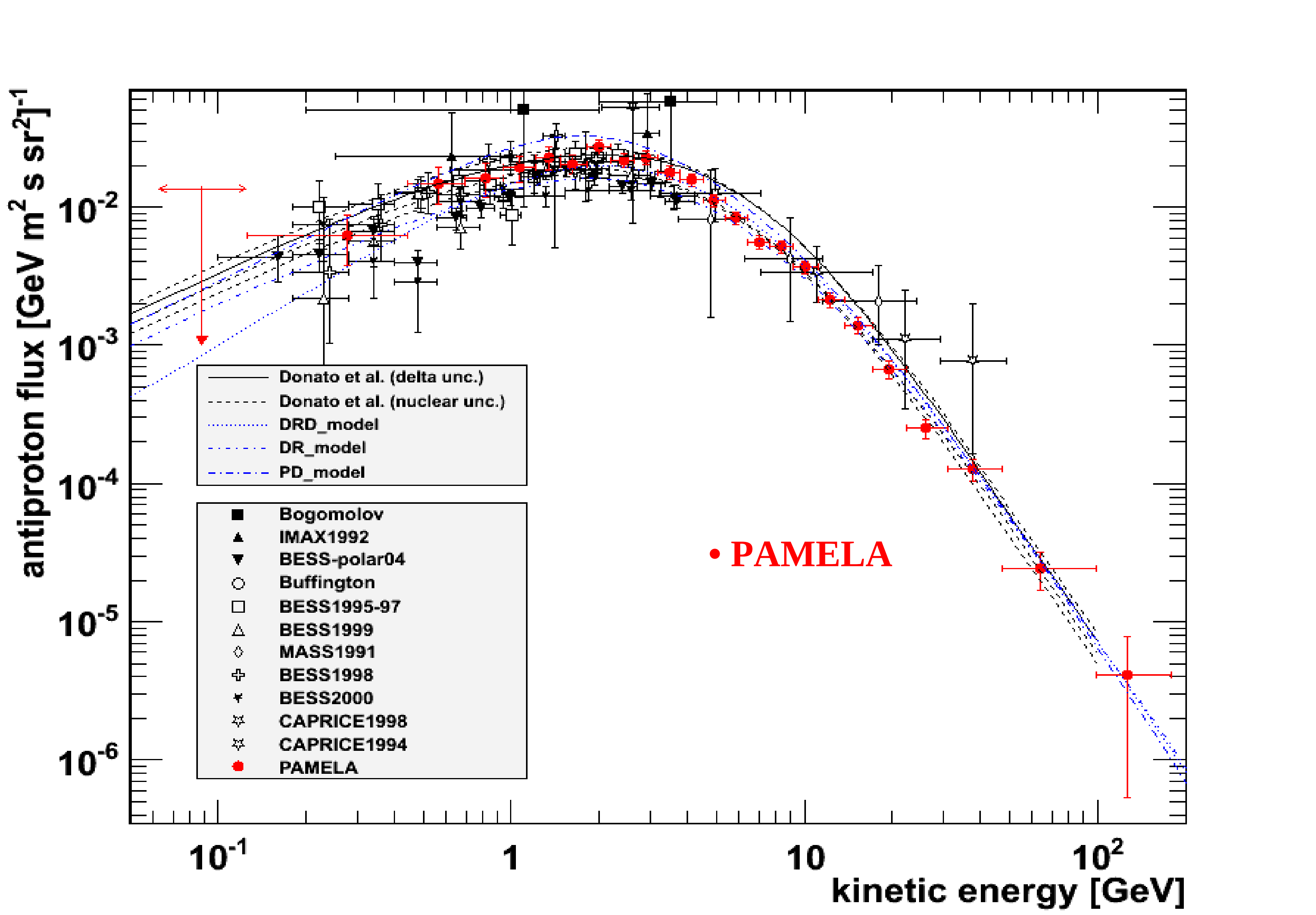
Antiprotons

PAMELA antiproton selection

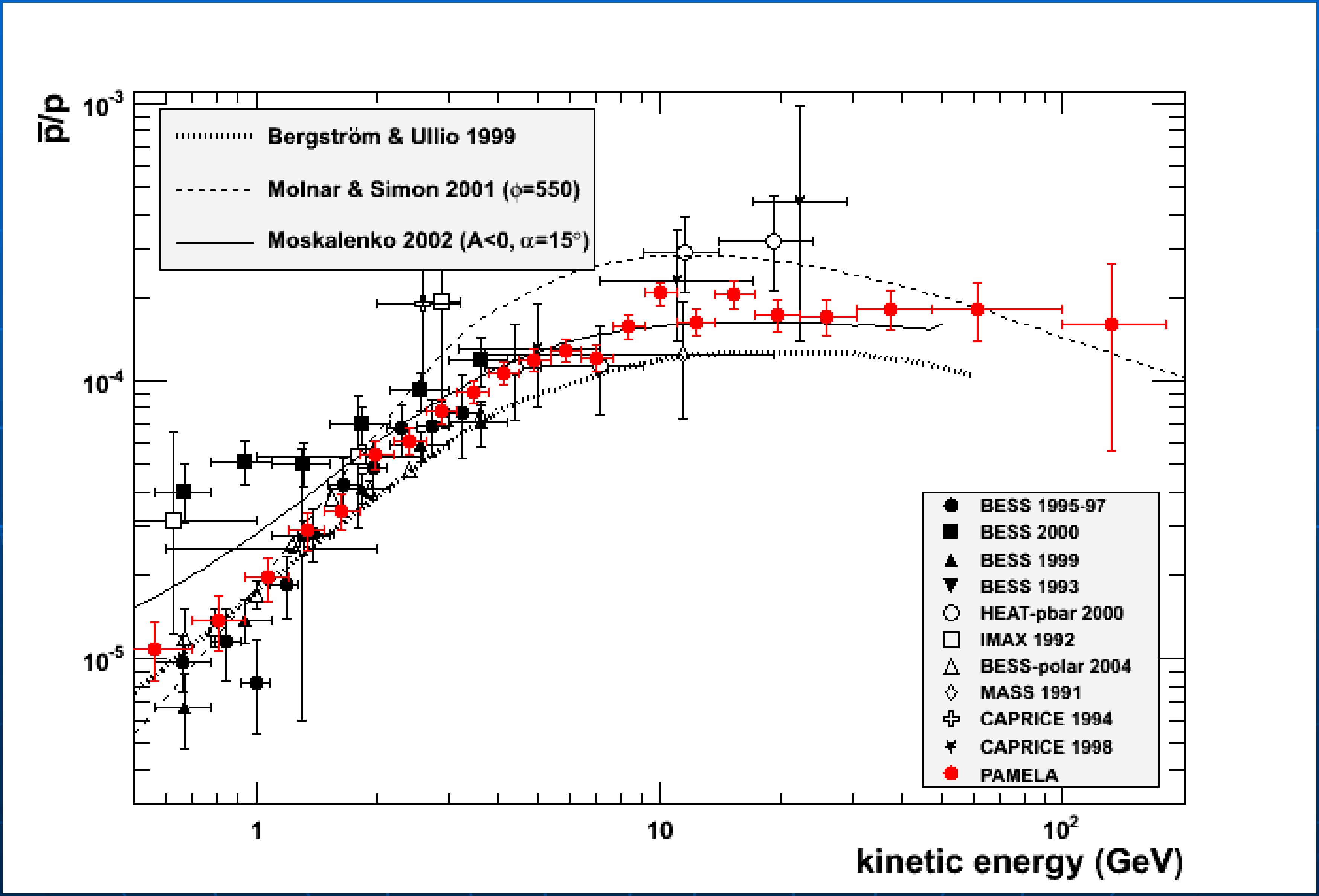




Antiproton flux



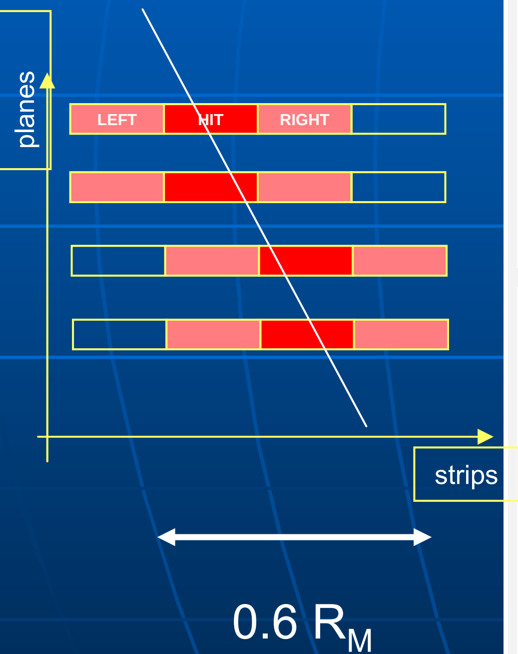
Antiproton to proton ratio

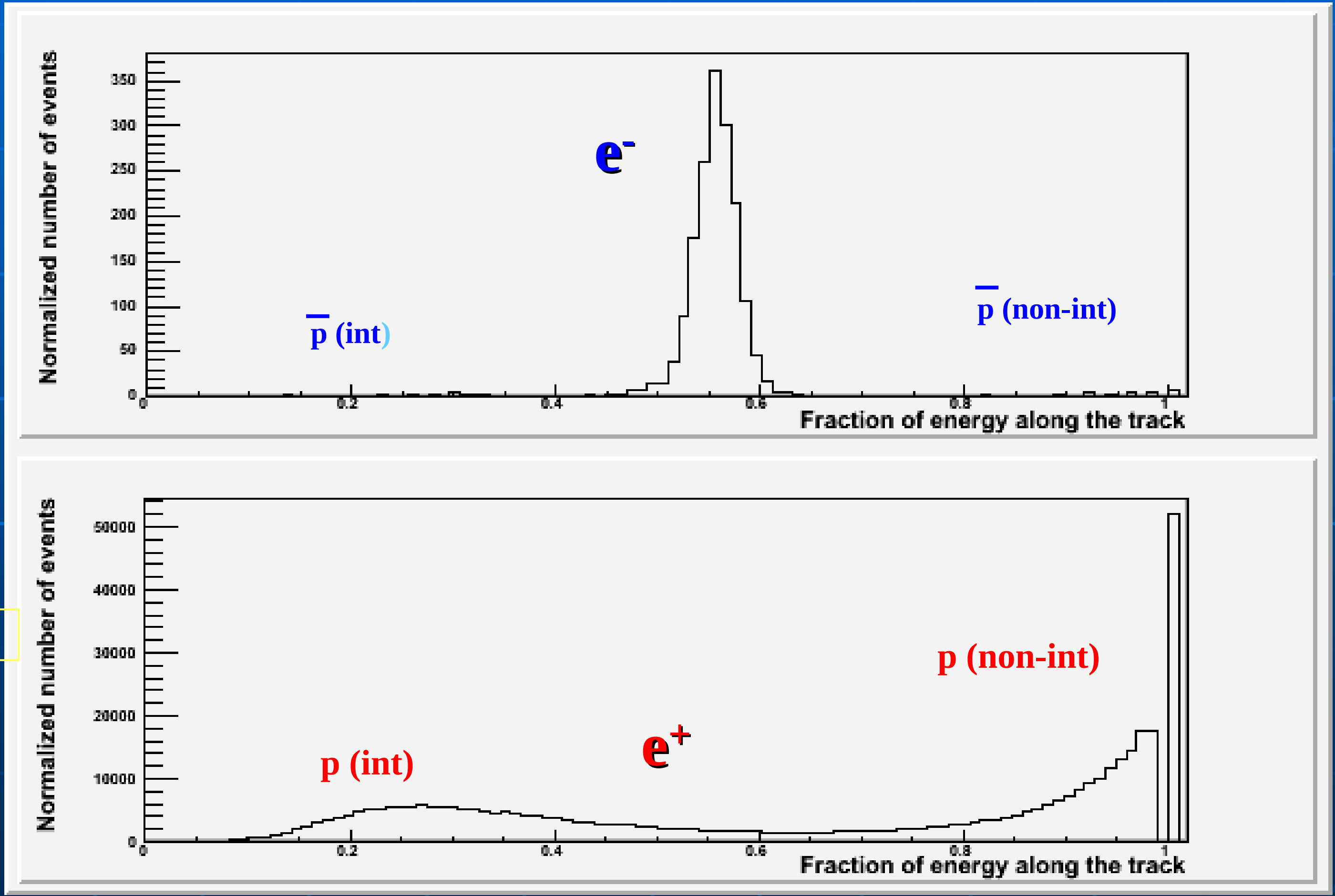


Positrons

Positron selection with calorimeter

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

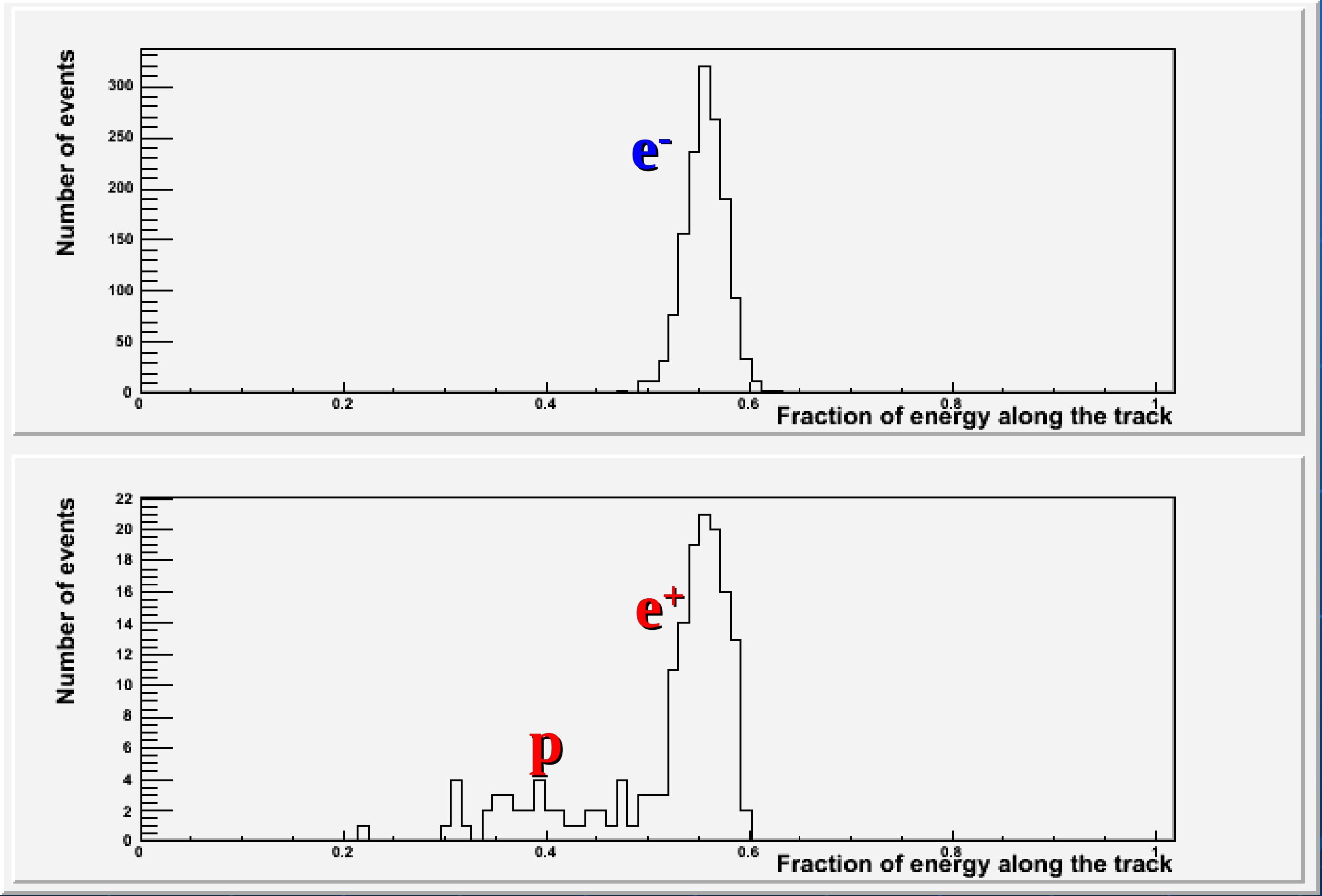




Rigidity: 20-30 GV

Positron selection with calorimeter

Rigidity: 20-30 GV



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

+

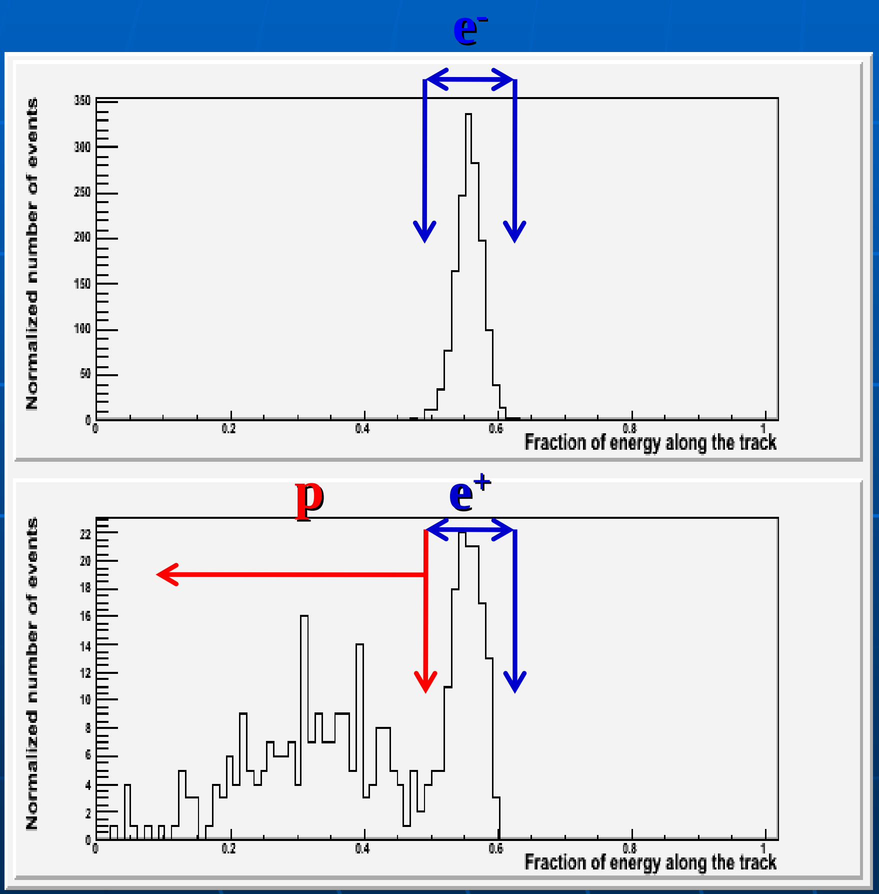
- Energy-momentum match
- Starting point of shower
- Longitudinal profile

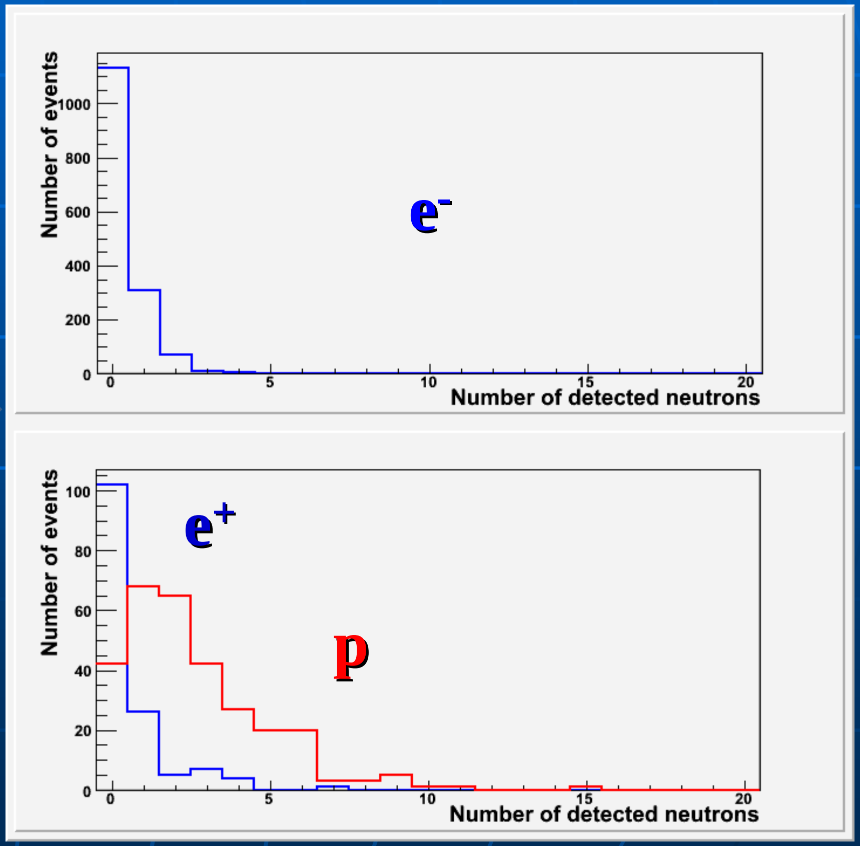
Positron selection

Rigidity: 20-30 GV

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

Neutrons detected by ND



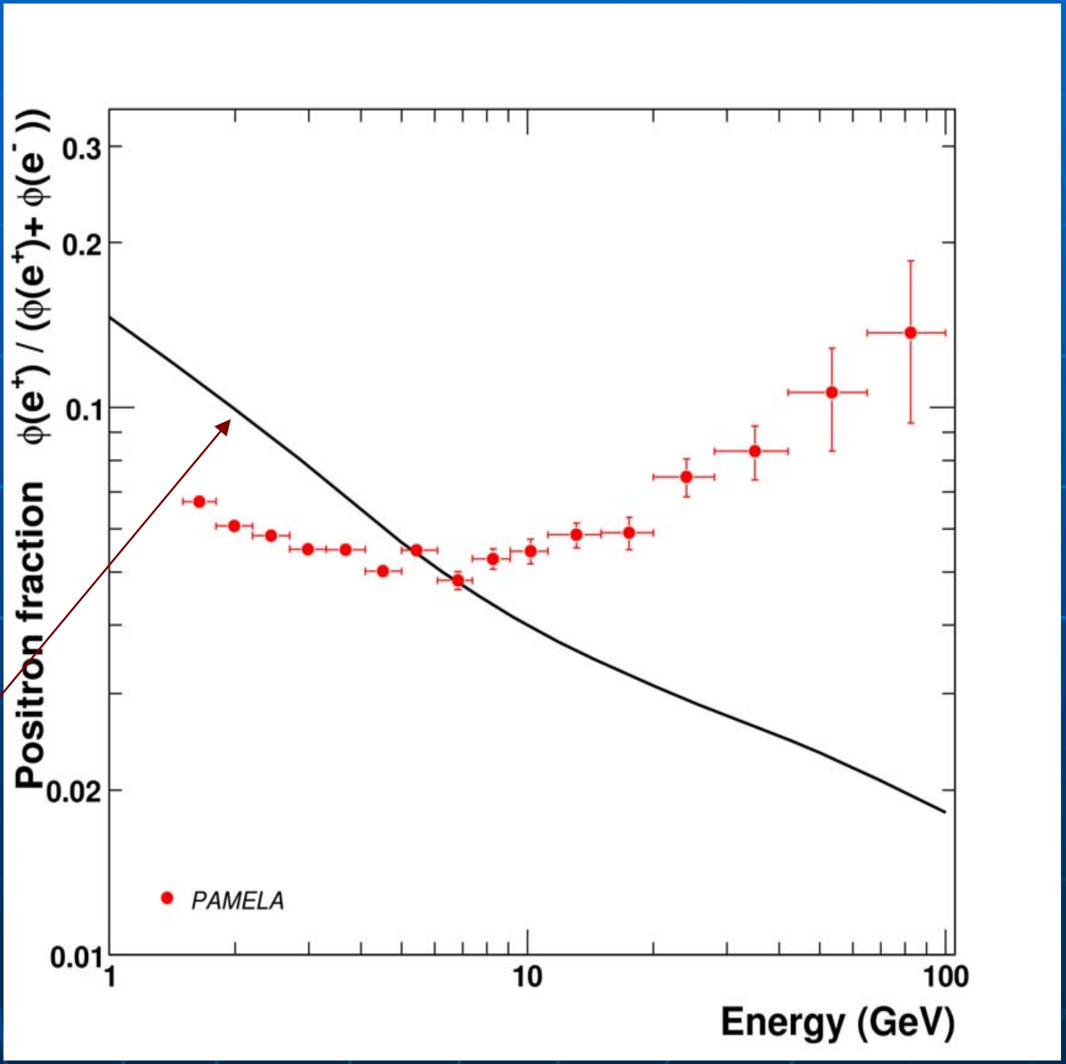


- Energy-momentum match
- Starting point of shower

Positron to all electron ratio

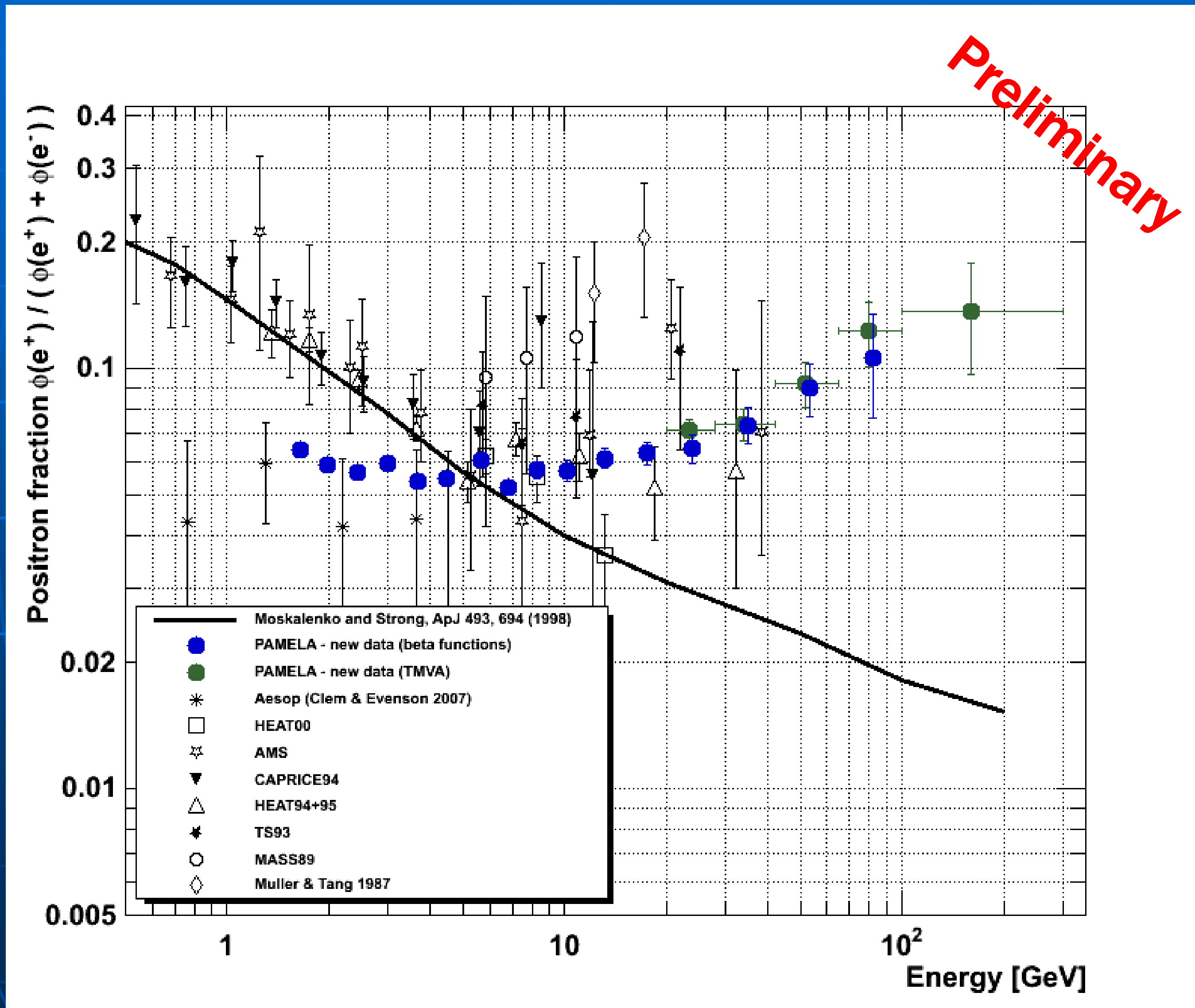
Nature 458, 697, 2009

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



<u>Secondary production</u>
Moskalenko & Strong 98

Positron Fraction



PRIMARY PROTONS:

$$n_{CR}(E) = \mathrm{N}_{\mathrm{CR}}(\mathrm{E})\ \mathrm{R}\ \tau_{\mathrm{esc}}(\mathrm{E}) \propto \mathrm{E}^{-\gamma}\mathrm{E}^{-\delta}$$

PRIMARY ELECTRONS:

$$n_e(E) = \mathrm{N}_{\mathrm{e}}(\mathrm{E})\ \mathrm{R}\ \mathrm{Min}\left[\tau_{\mathrm{esc}}(E), \tau_{loss}(E)\right] \propto E^{-\gamma_e} E^{-\beta}$$

b= d for diffusion
b=1 for losses

SECONDARY POSITRONS INJECTION:

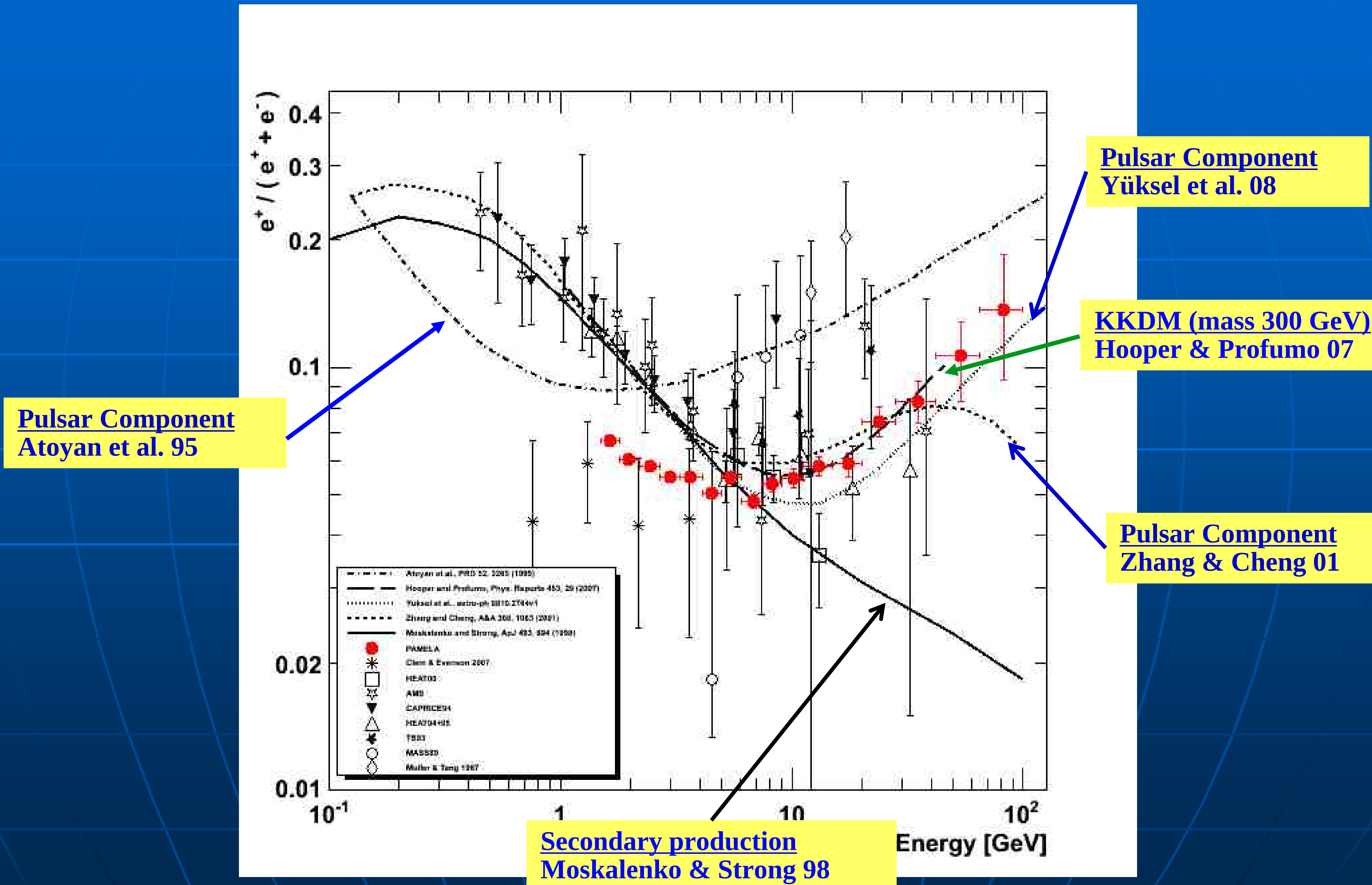
$$\mathrm{q}_{+}(\mathrm{E}')\mathrm{dE}' = \mathrm{n}_{\mathrm{CR}}(\mathrm{E})\mathrm{dE}\ \mathrm{n}_{\mathrm{H}}\ \sigma_{\mathrm{pp}}\ \mathrm{c} \propto \mathrm{E}^{-\gamma-\delta}$$

SECONDARY POSITRONS EQUILIBRIUM:

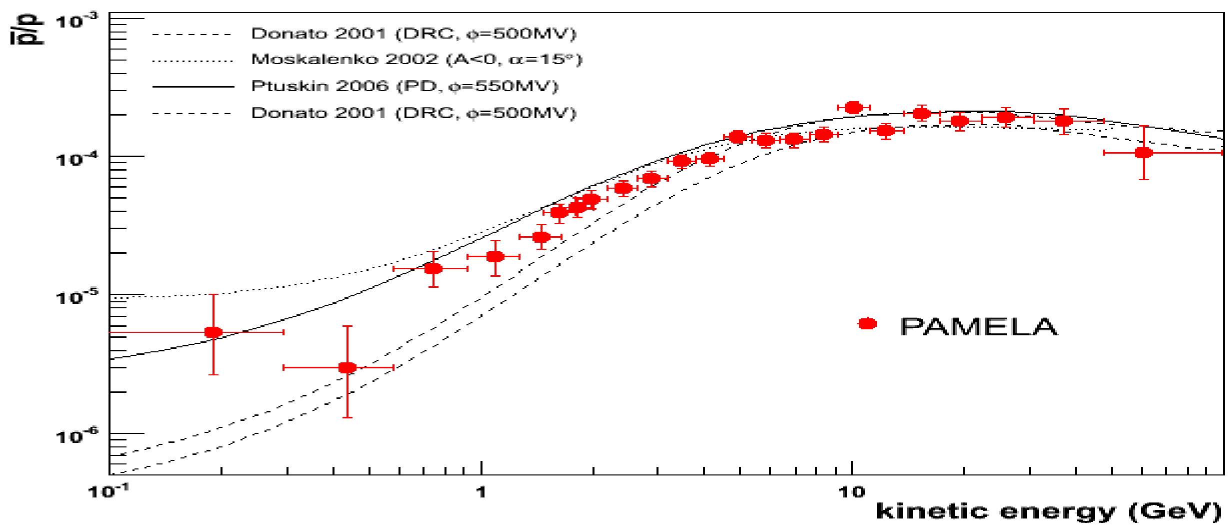
$$n_{+}(E) = q_{+}(E)\ \mathrm{Min}\left[\tau_{\mathrm{esc}}(E), \tau_{loss}(E)\right] \propto E^{-\gamma-\delta-\beta}$$

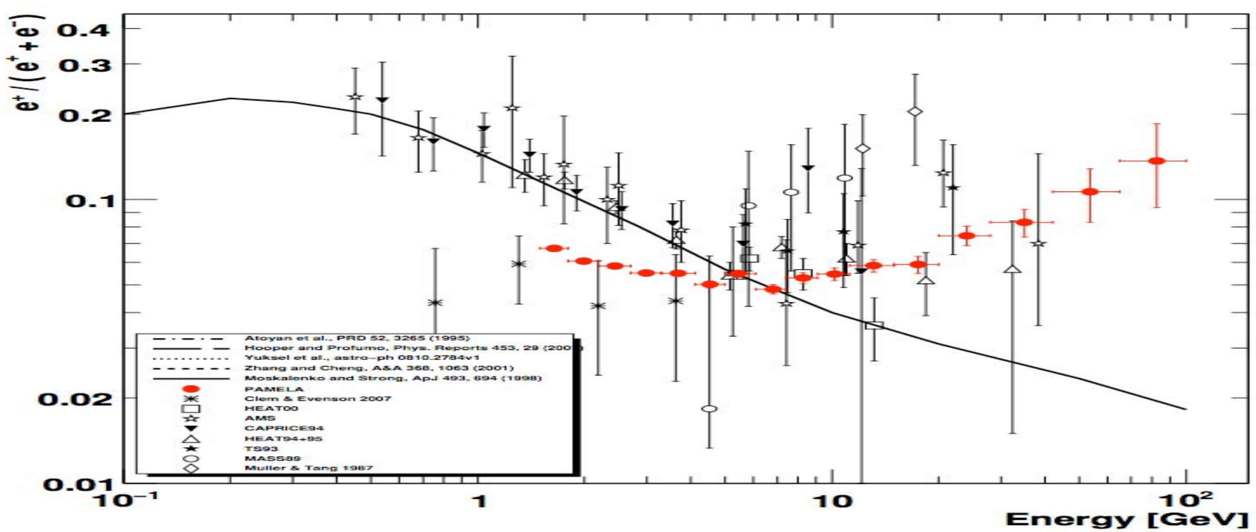
$$\frac{n_{+}}{n_e} \propto E^{-(\gamma-\gamma_e)-\delta}$$

Positron Fraction



A Challenging Puzzle for Dark Matter Interpretation

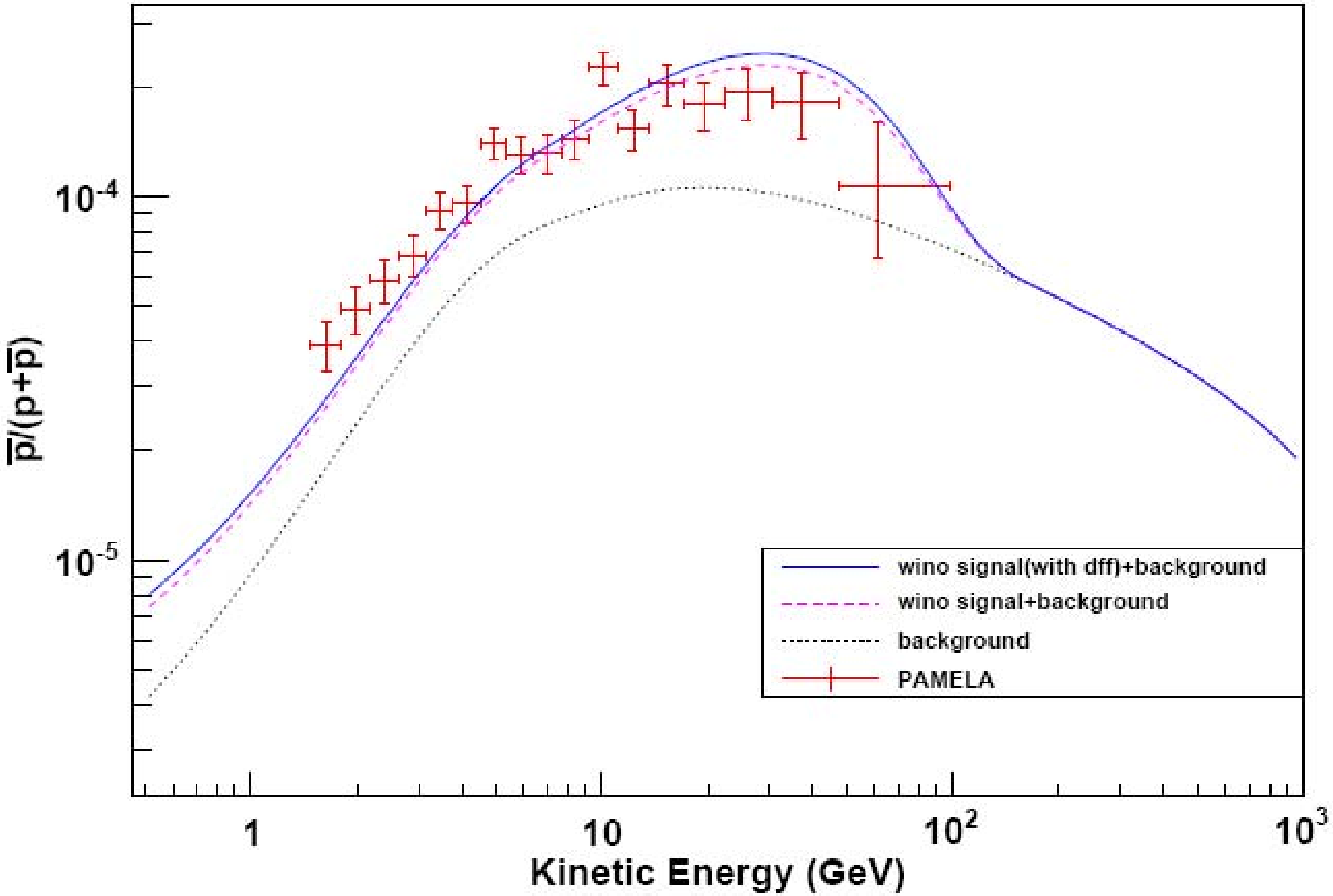




Wino Dark Matter in a non-thermal Universe

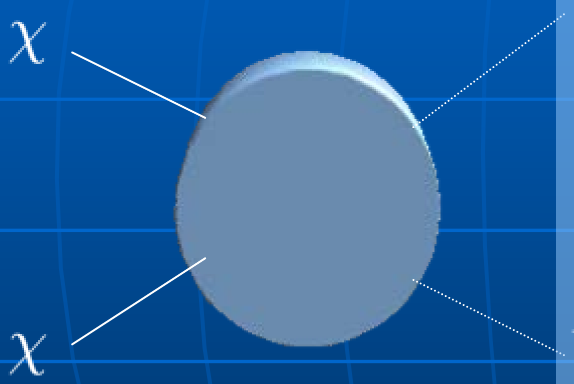
G. Kane, R. Lu, and S. Watson

arXiv:0906.4765v3 [astro-ph.HE)



DM annihilations

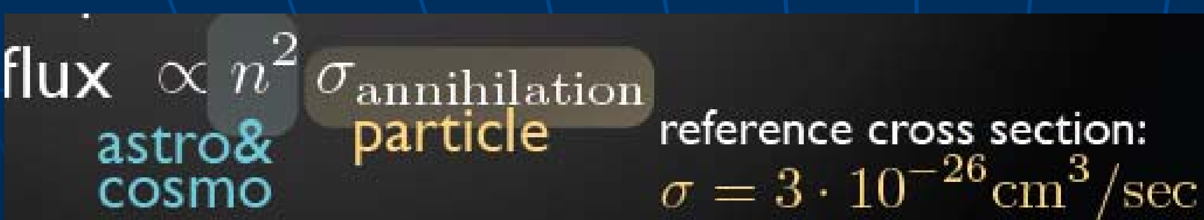
DM particles are stable. They can annihilate in pairs.



$W^-, Z^0, b, \tau^-, t, h^0, \ldots \Rightarrow e^{\mp}, p^{(-)}, D^{(-)}, \ldots$

$W^+, Z^0, \bar{b}, \tau^+, \bar{t}, h^0, \ldots \Rightarrow e^{\pm}, p^{(-)}, D^{(-)}, \ldots$

Primary annihilation channels | Decay | Final states



$\sigma_a = \langle \sigma v \rangle$

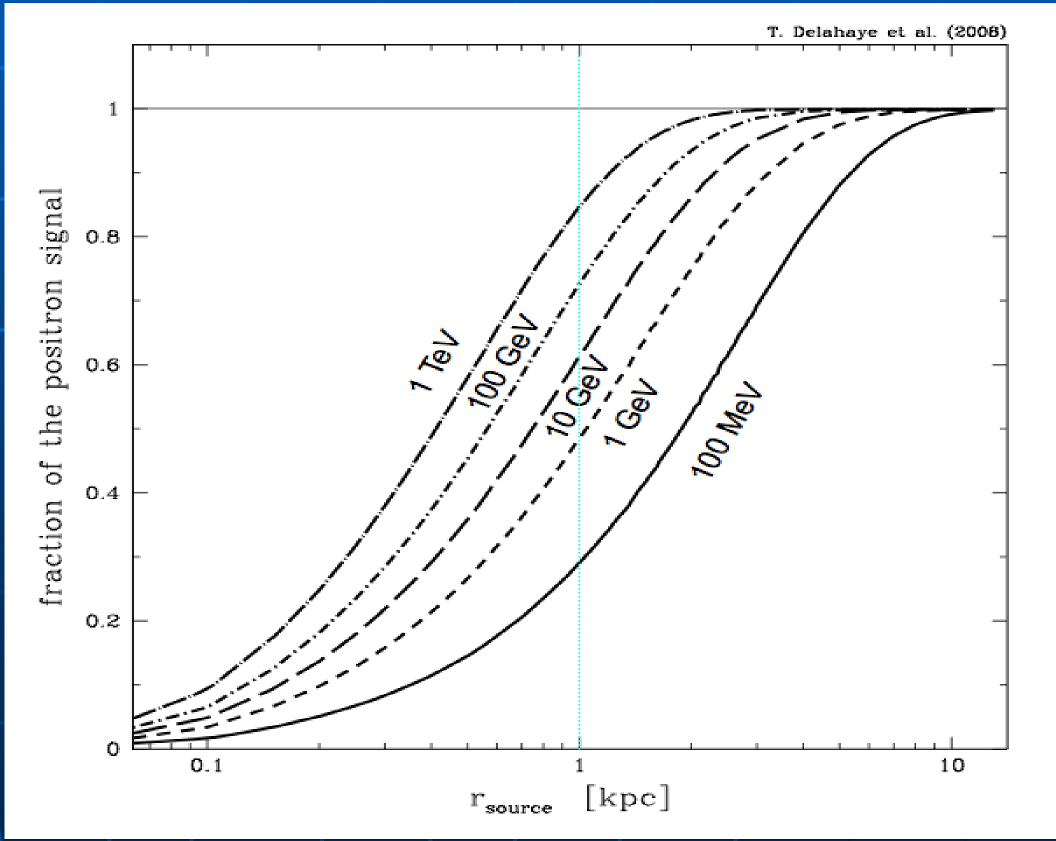
Positrons detection

Where do positrons come from?

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

Typical lifetime

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



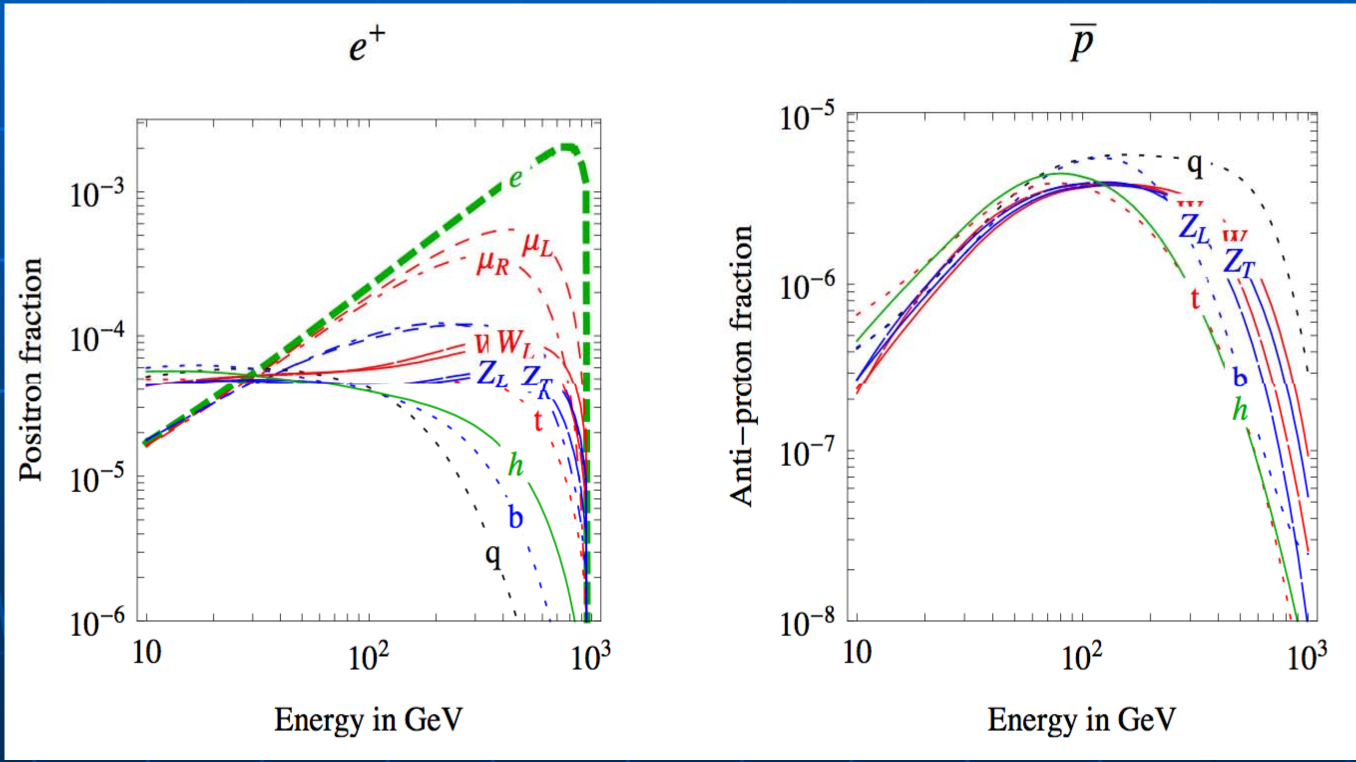
Antiprotons within 10 Kpc

DM annihilations

Resulting spectrum for positrons and antiprotons
M= 1 TeV

The flux shape is completely determined by:

1) WIMP mass
2) Annihilations channels

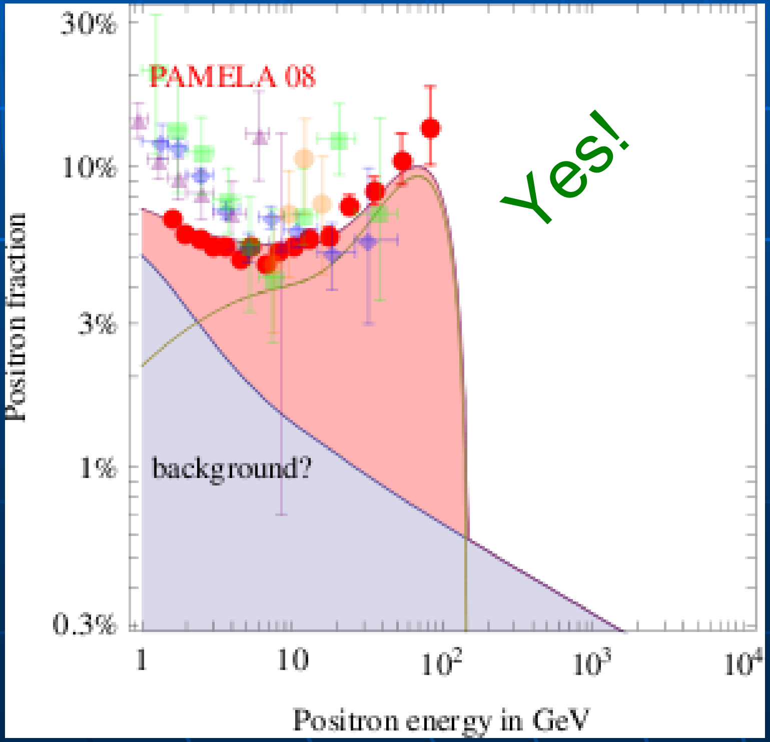


Data fitting

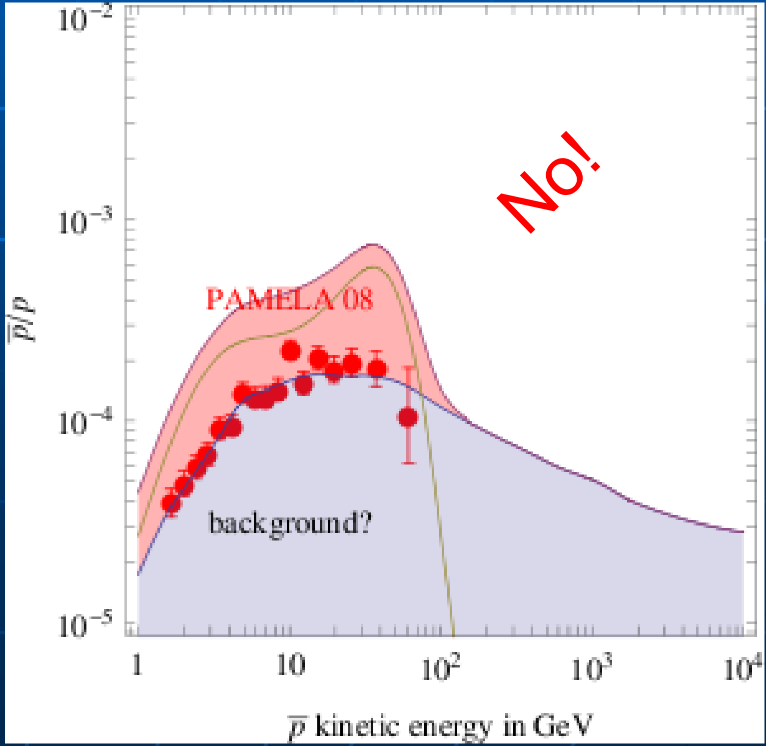
Which DM spectra can fit the data?

DM with $m_\chi \simeq 150\,\mathrm{GeV}$ and W^+W^- dominant annihilation channel (possible candidate: Wino)

positrons



antiprotons



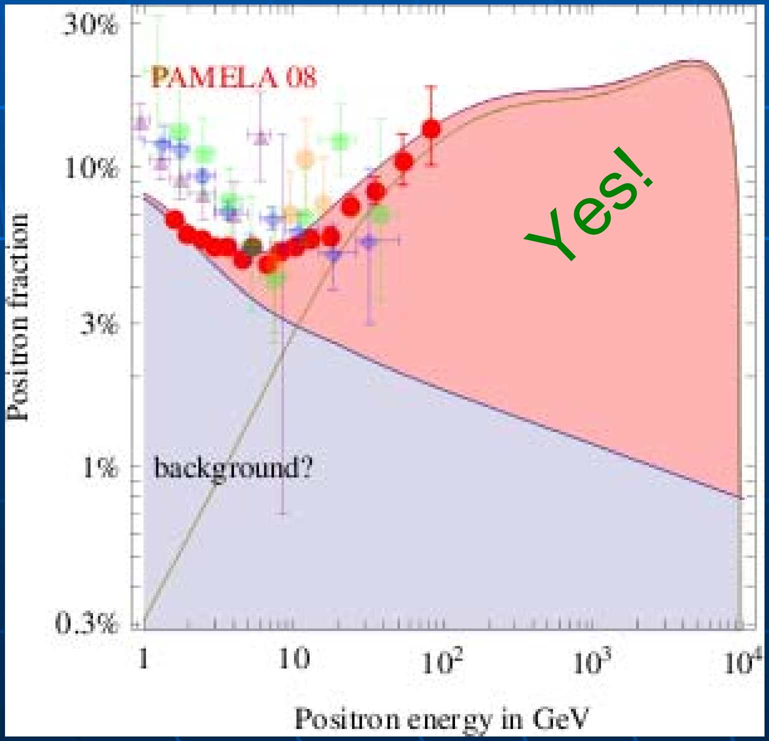
Data fitting

Which DM spectra can fit the data?

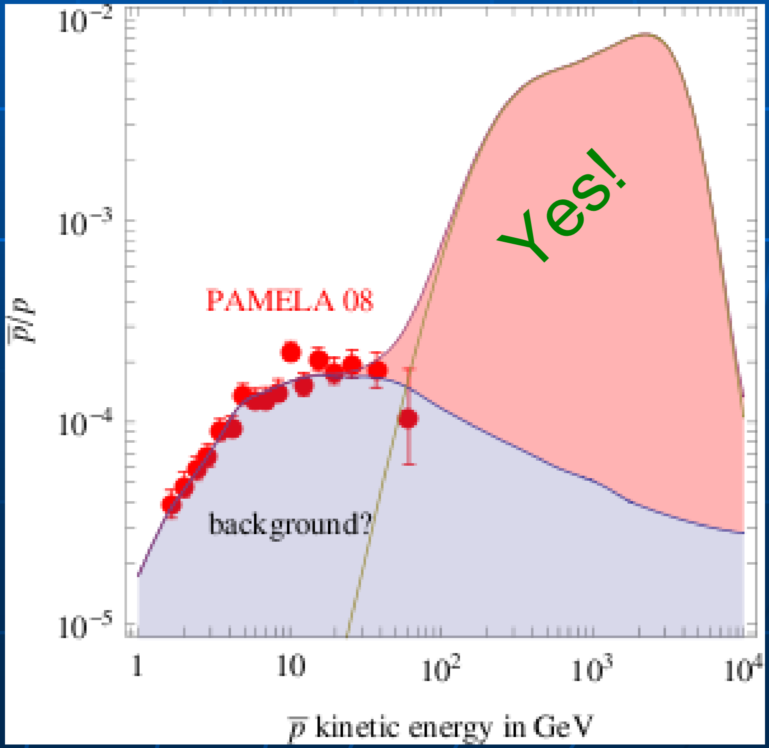
DM with $m_\chi \simeq 10\,\mathrm{TeV}$ and W^+W^- dominant annihilation channel (no "natural" SUSY candidate)

But $B \approx 10^4$ No!

positrons



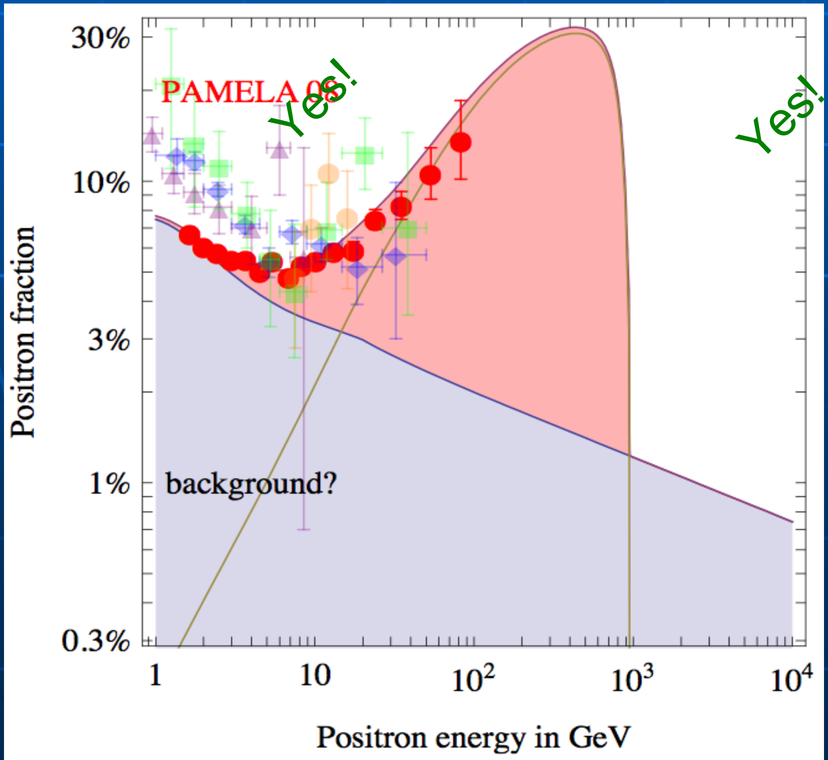
antiprotons



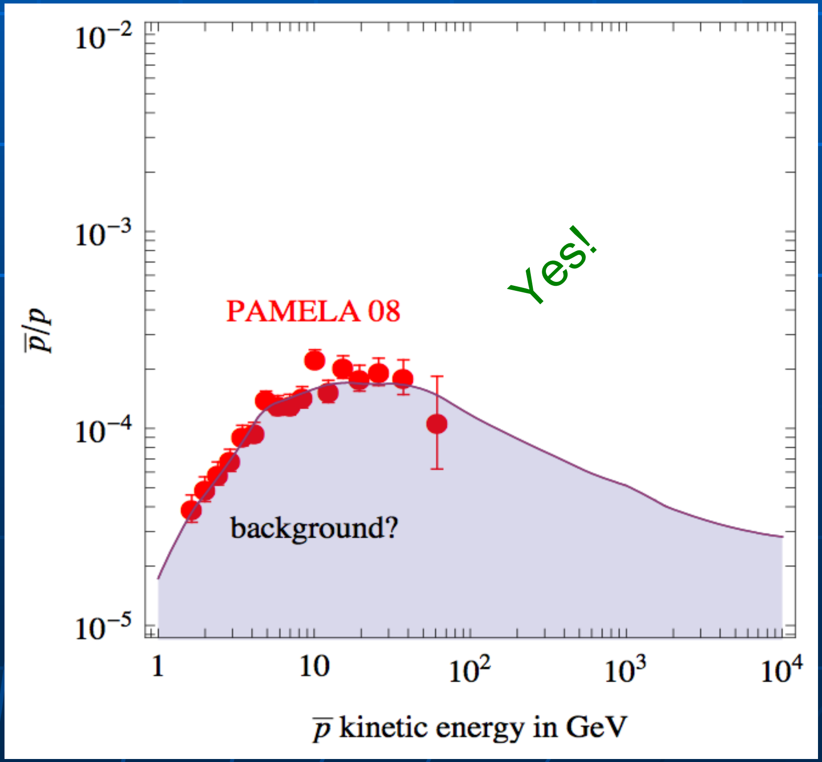
Data fitting

DM with $m_\chi \simeq 1\,\mathrm{TeV}$ and $\mu^+\mu^-$ dominant annihilation channel

positrons



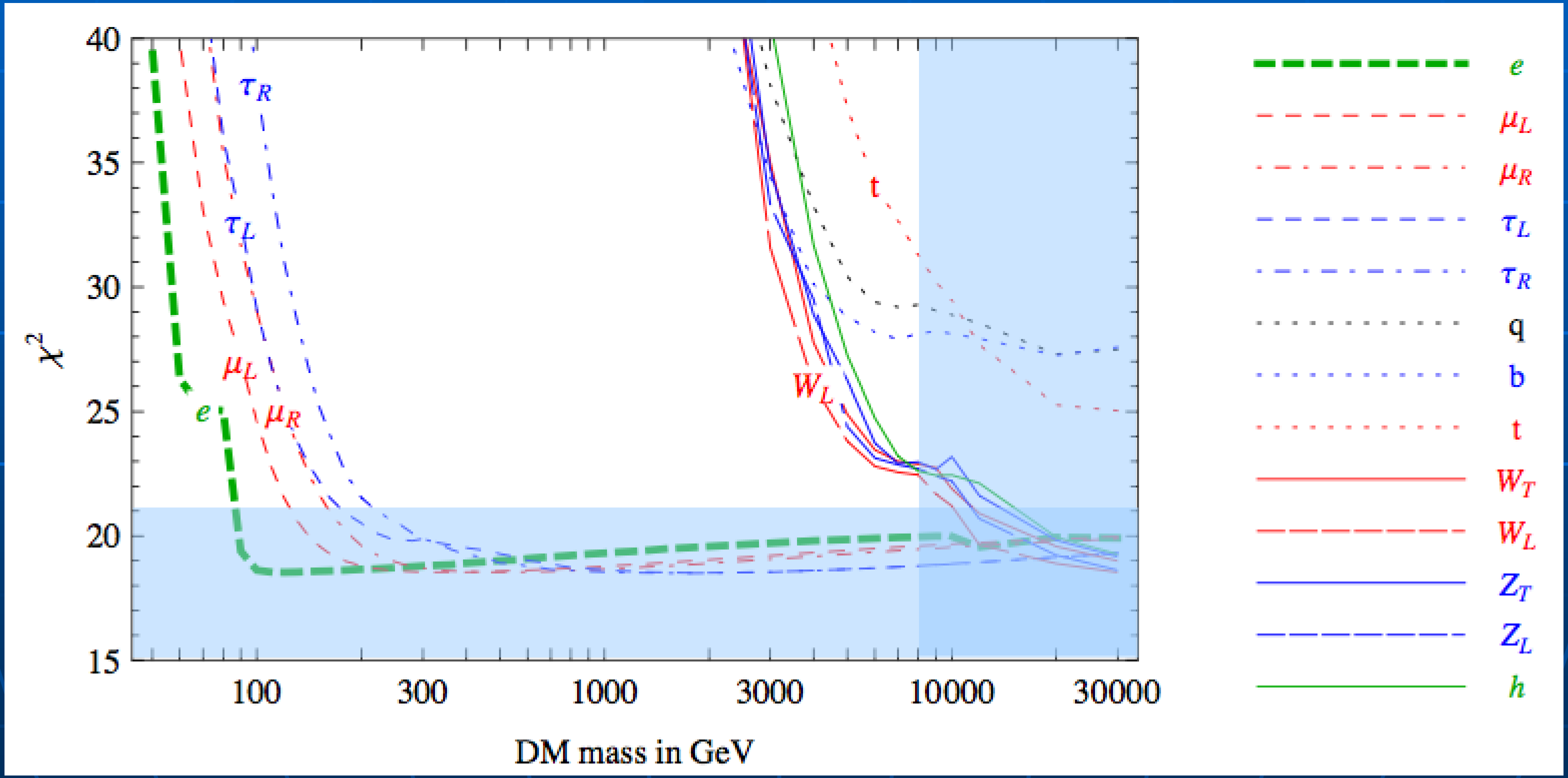
antiprotons



Model independent results

Which DM spectra can fit the data?

Fit of PAMELA positrons+antiprotons

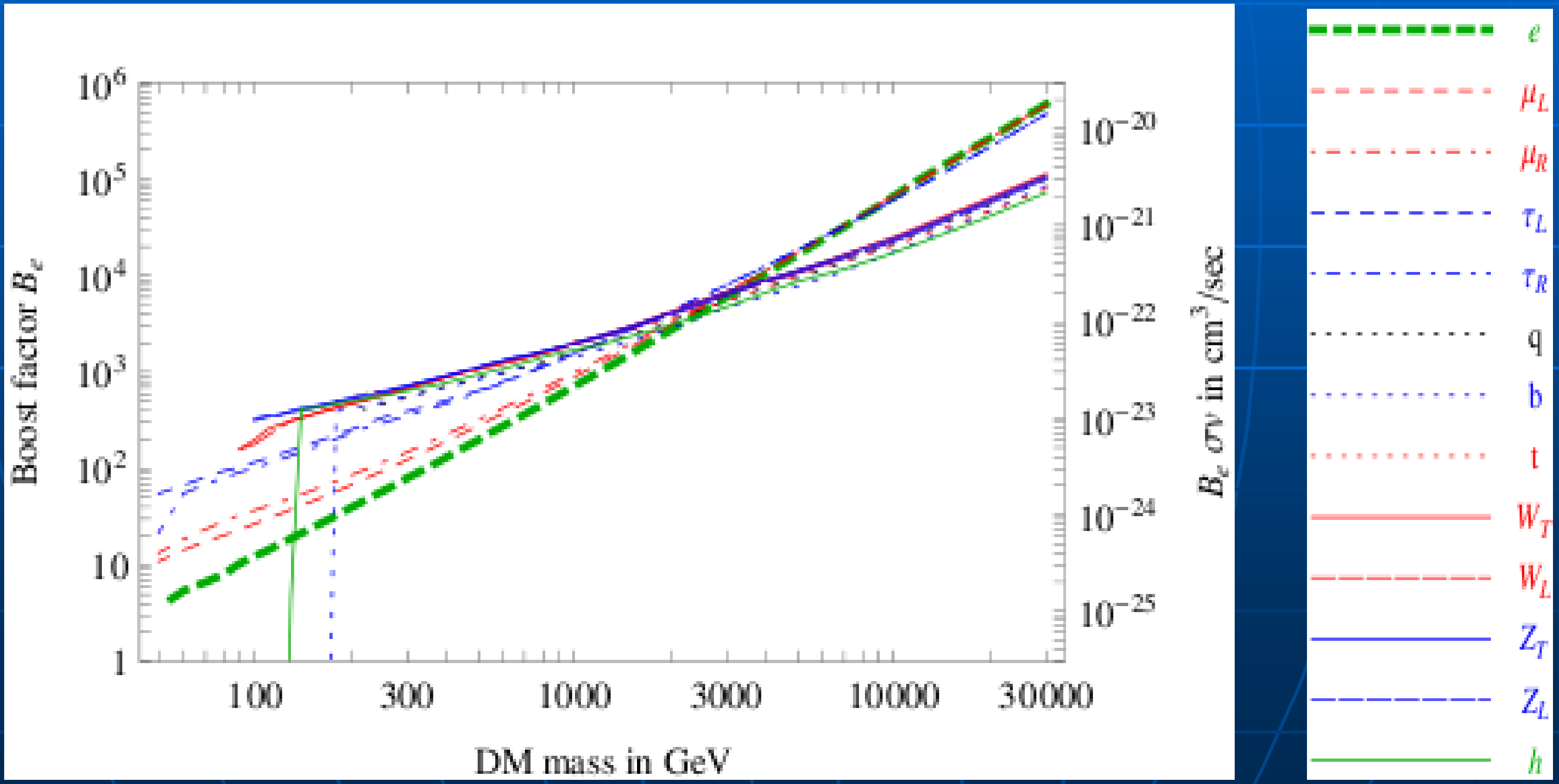


Annihilations into quarks, gauge and Higgs bosons hardly constrained and $m_\chi \gtrsim 10\,\mathrm{TeV}$

Model independent results

Which DM spectra can fit the data?

Boost required by PAMELA



Enhancement

How to reconcile $\sigma = 3 \cdot 10^{-26} \text{cm}^3/\text{sec}$ with $\sigma \simeq 10^{-23} \text{cm}^3/\text{sec}$?

- DM is produced non-thermally: the annihilation cross section today is unrelated to the production process

	at freeze-out	*today*
- astrophysical boost	no clumps	clumps
- resonance effect	off-resonance	on-resonance
- Sommerfeld effect	$v/c \simeq 0.1$	$v/c \simeq 10^{-3}$

+ (Wimponium)

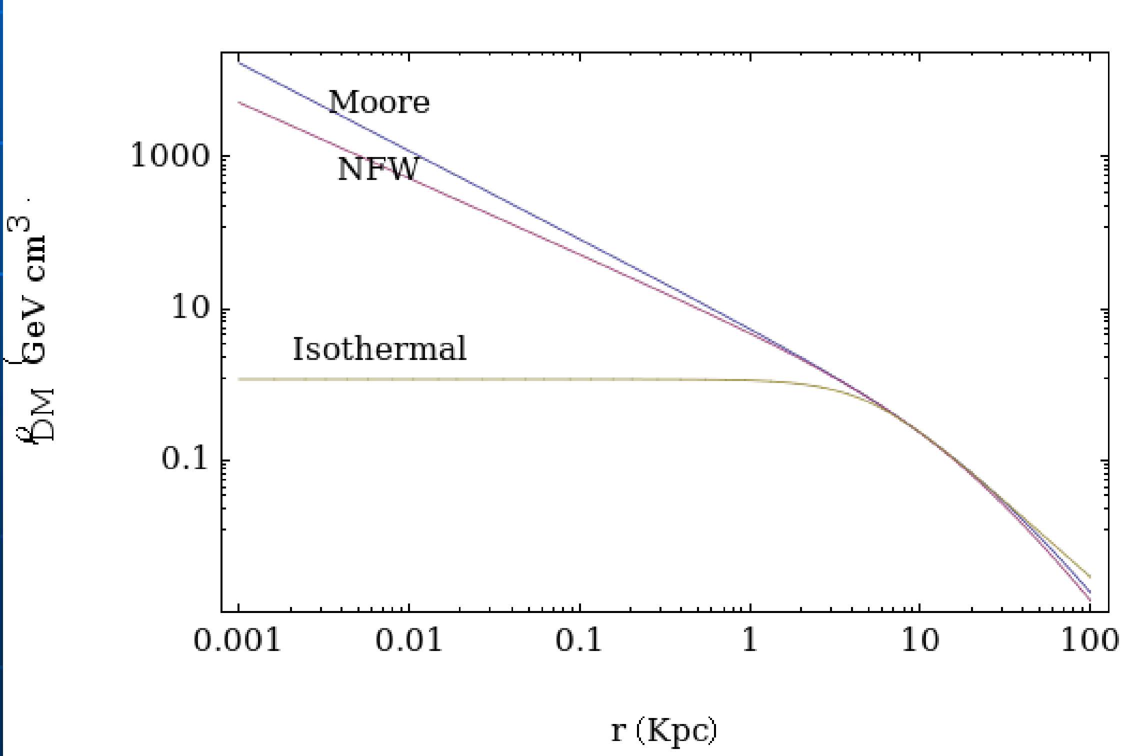
DM Halo profile

Results from N-body simulations

$$\rho(r) = \rho_\odot \left(\frac{r_\odot}{r}\right) \left[\frac{1+(r_\odot/r_s)^\alpha}{1+(r/r_s)^\alpha}\right]^{(\beta-\gamma)/\alpha}$$

For r→0:

$$\rho(r) \propto r^{-\gamma}$$

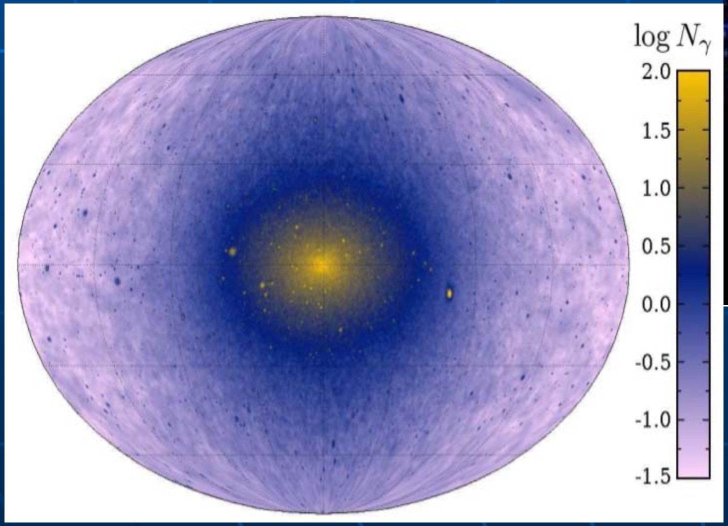


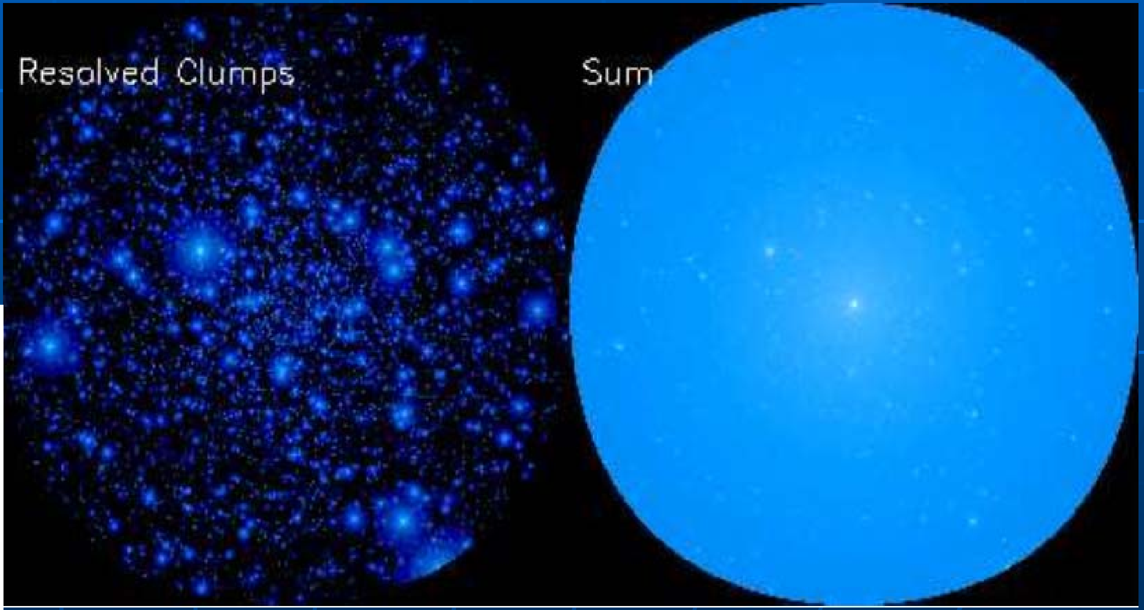
Cuspy: NFW, Moore
Mild: Einasto
Smooth: Isothermal

Boost Factor

Boost Factor: local clumps in the DM halo enhance the density, boost the flux from annihilations

$$B \in (1, 20)\ (10^4)$$

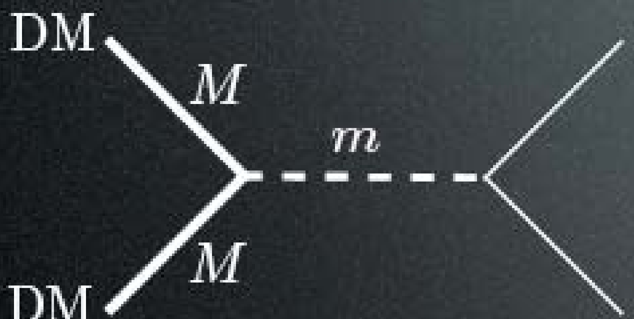




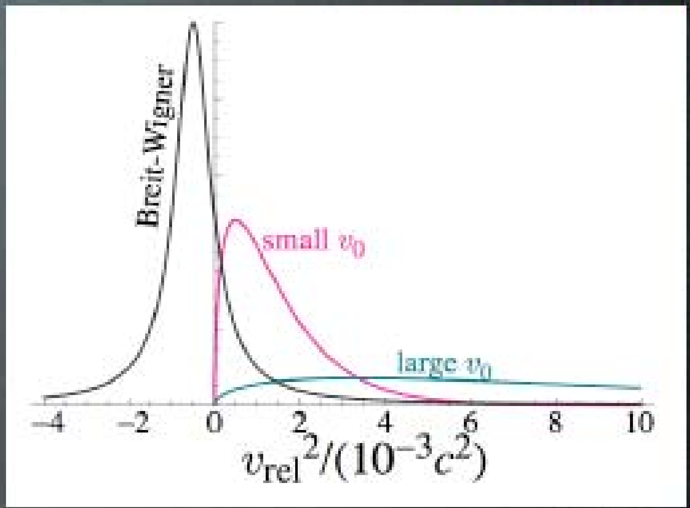
Resonance Enhancement

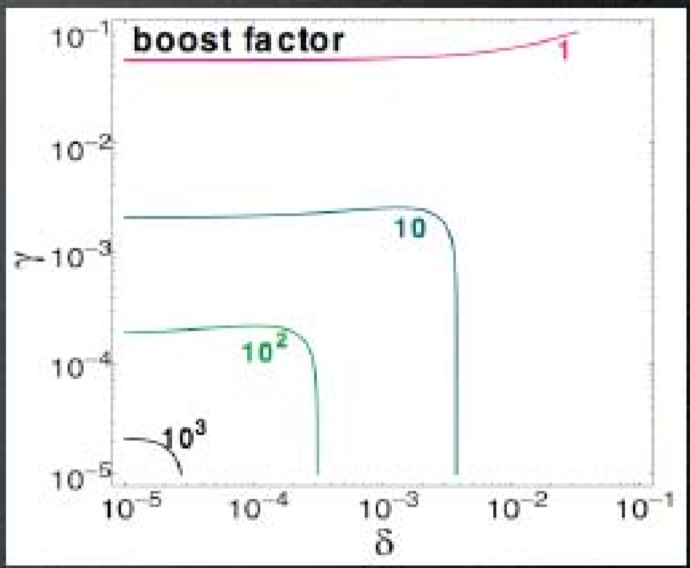
Cirelli, Kadastik, Raidal, Strumia, 2008, Sec.2
Ibe, Murayama, Yanagida 0812.0072
P.Nath et al. 0810.5762

DM annihilation via a narrow resonance just below the threshold:



$m \lesssim 2M$





$$\sigma = \frac{16\pi}{E^2\bar{\beta}_i\beta_i}\frac{m^2\Gamma^2}{(E_{\rm cm}^2 - m^2)^2 + m^2\Gamma^2}B_iB_f$$

$$\langle\sigma v_{\rm rel}\rangle \simeq \frac{32\pi}{m^2\bar{\beta}_i}\frac{\gamma^2}{(\delta+\xi v_0^2)^2+\gamma^2}B_iB_f$$

$$m^2 = 4M^2(1-\delta) \qquad \gamma = \Gamma/m$$

Enhancement can reach 10^3 with very fine tuned models.

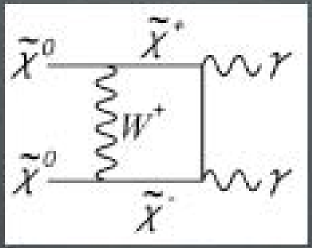
Sommerfeld Enhancement

NP QM effect that can enhance the annihilation cross section by orders of magnitude in the regime of small velocity and relatively long range force.

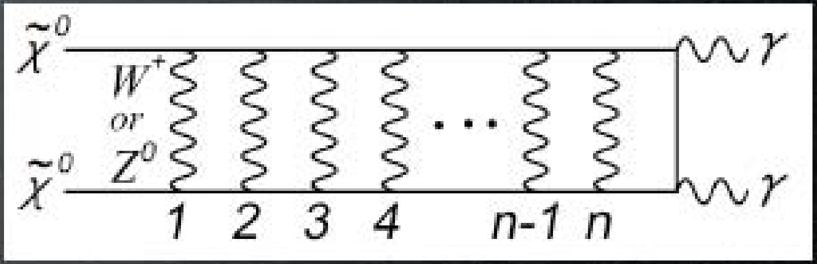
In terms of Feynman diagrams:

Hisano et al. hep-ph/0412403

First order cross section:



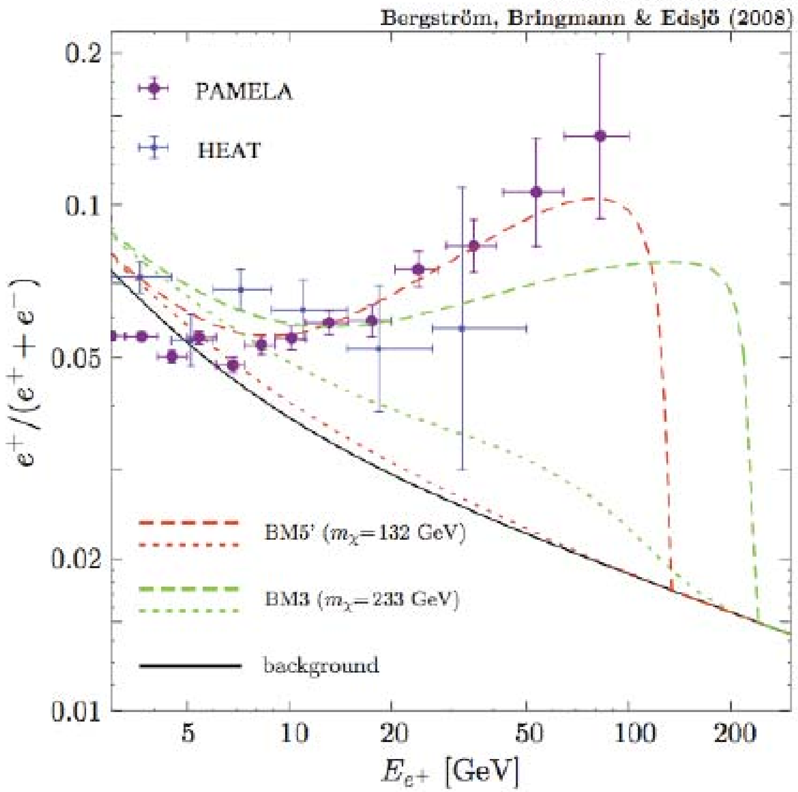
Adding a rung to the ladder: $\times \left(\frac{\alpha M}{m_W}\right)$



For $\alpha M/m_V \gtrsim 1$ the perturbative expansion breaks down,
need to resum all orders
i.e.: keep the full interaction potential.

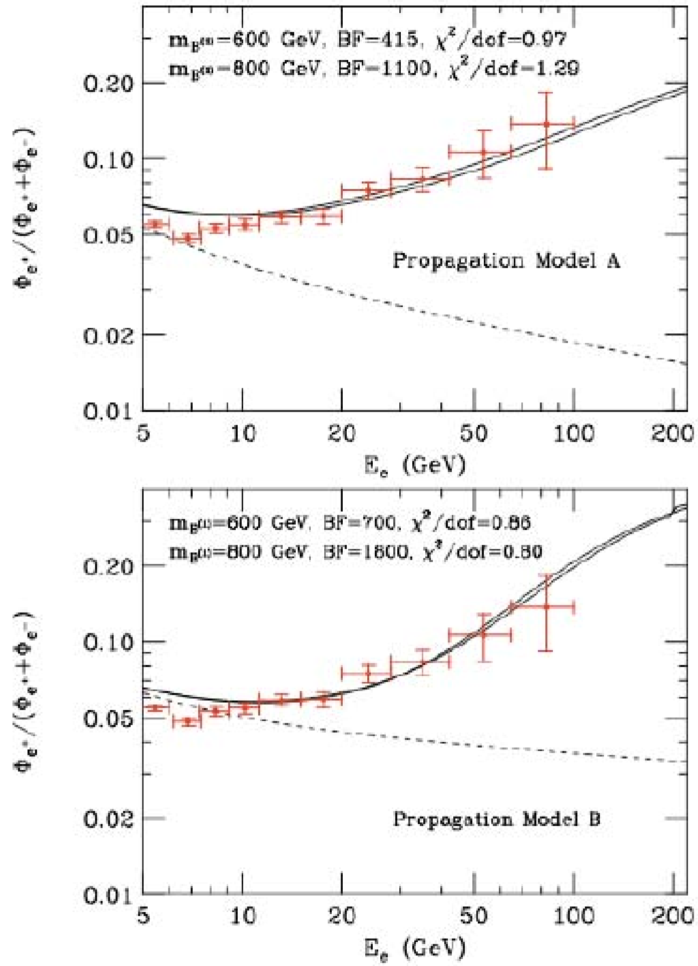
Example: Dark Matter

arXiv:0808.3725



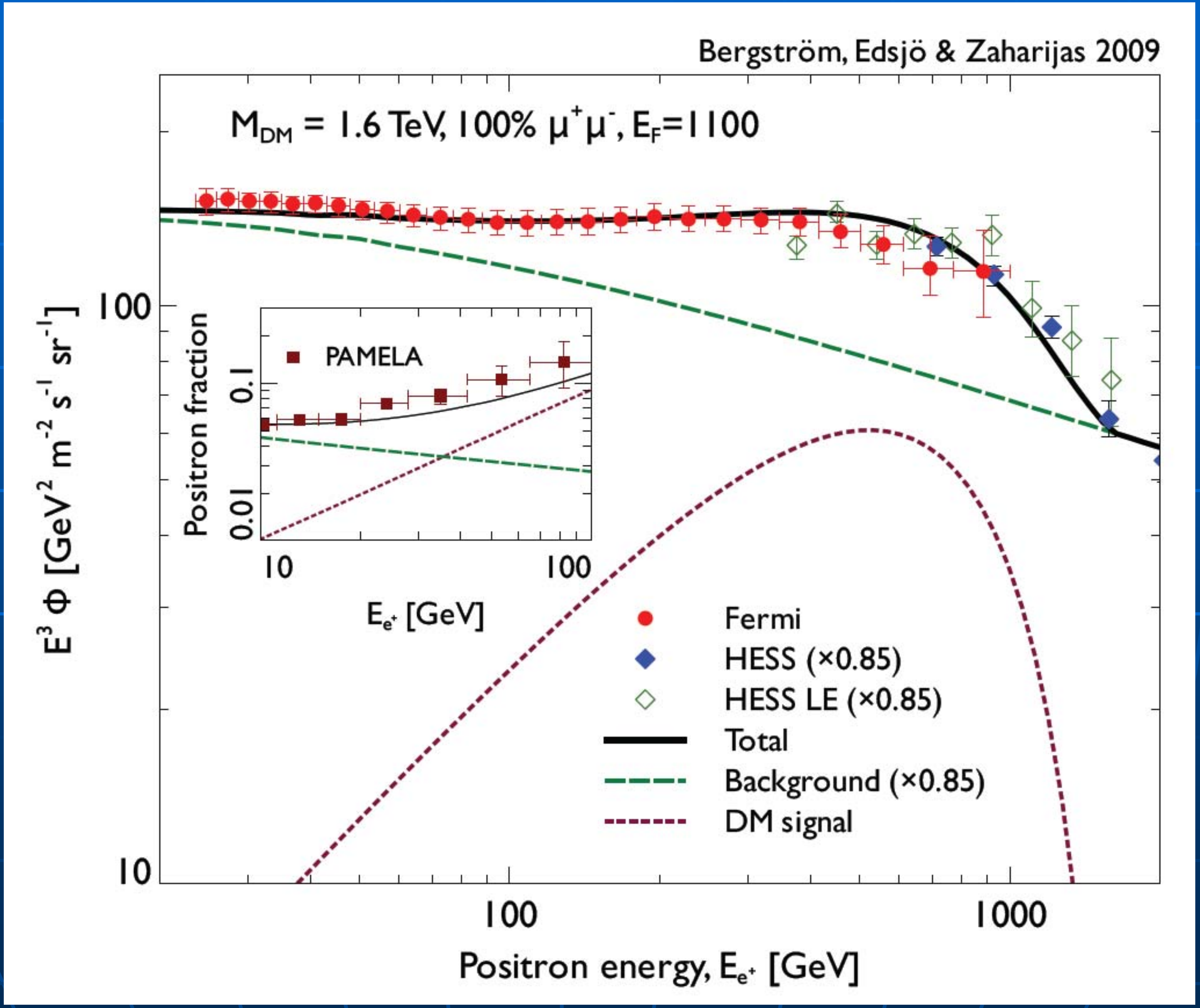
Majorana DM with **new** internal bremsstrahlung correction. NB: requires annihilation cross-section to be 'boosted' by >1000.

Hooper and Zurek
arXiv:0902.0593v1

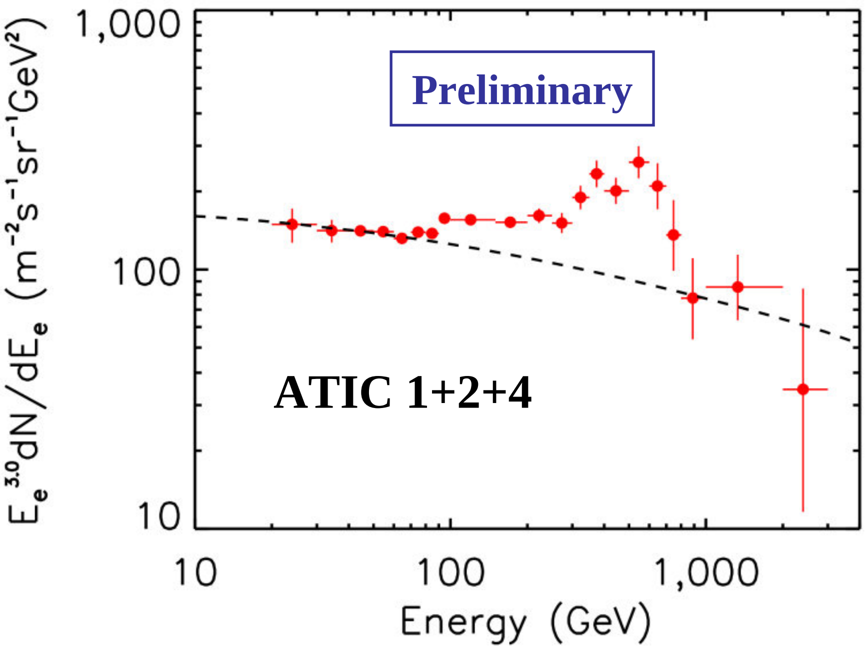


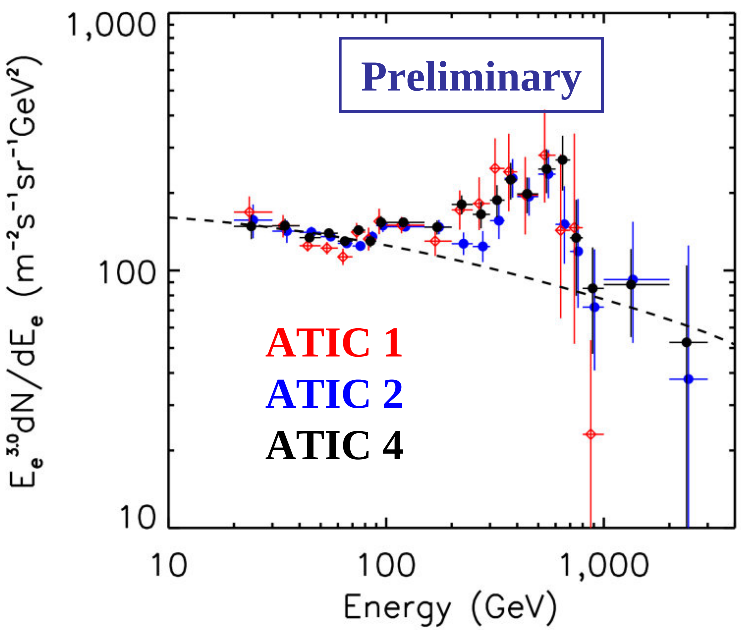
Kaluza-Klein dark matter

Fermi (e^{+}+ e^{-}) *and* PAMELA ratio
Bergstrom et al. astro-ph 0905.0333v1



All three ATIC flights are consistent





"Source on/source off" significance of bump for ATIC1+2 is about 3.8 sigma

J Chang *et al. Nature* **456**, 362 (2008)

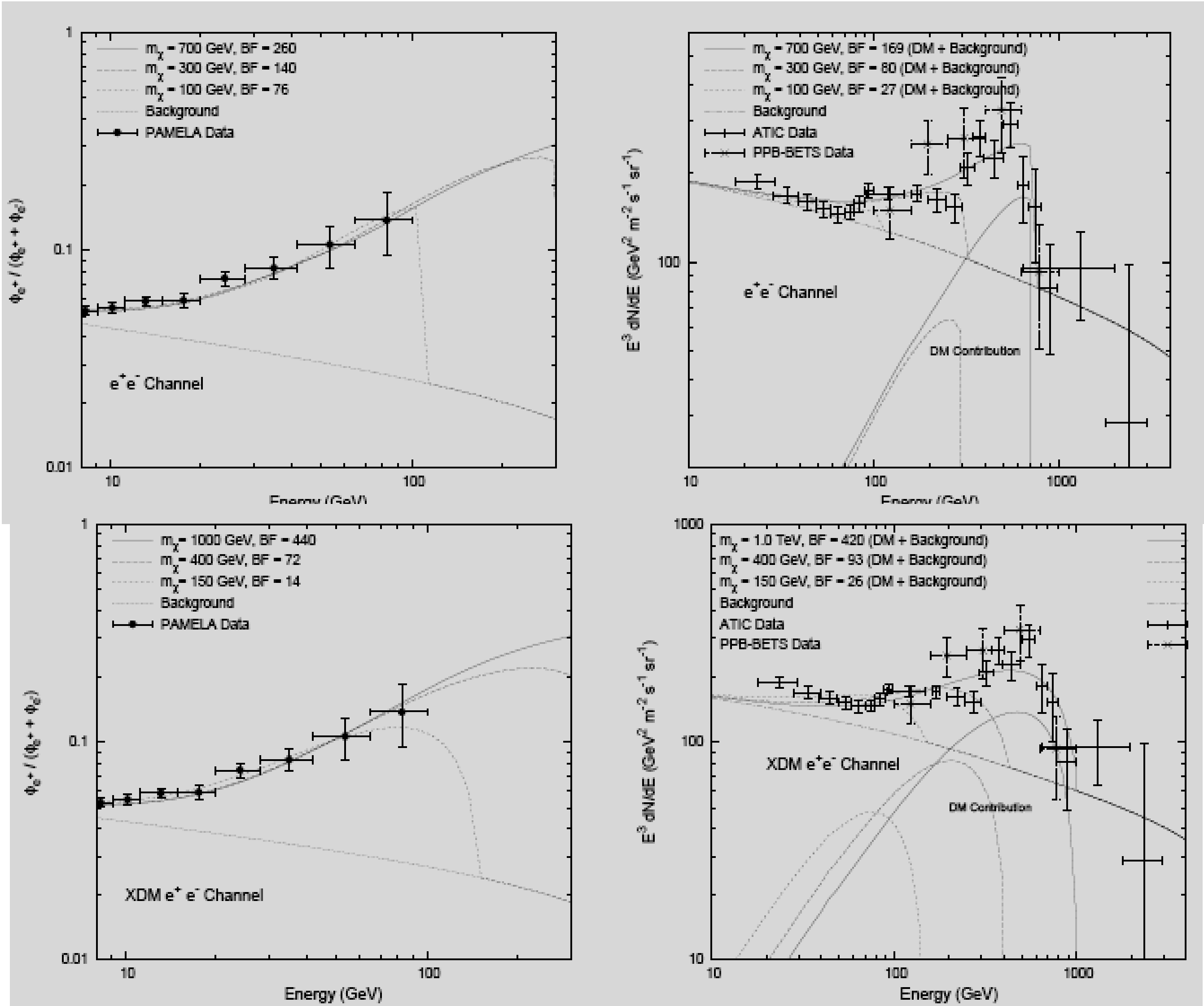
ATIC-4 with 10 BGO layers has improved e , p separation. **(~4x lower background)**

"Bump" is seen in all three flights.

Significance for ATIC1+2+4 is 5.1 sigma

Example: DM

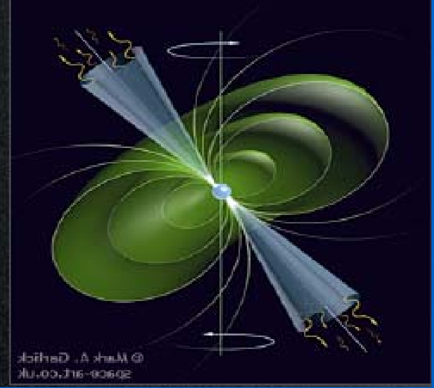
I. Cholis et al. arXiv:0811.3641v1



- 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

Gamma Constraints

- *γ from DM annihilation*
- *radio-waves from synchrotron radiation of $e^{\pm}$*
- *γ from Inverse Compton on $e^{\pm}$ in halo*
  -upscatter of CMB, infrared and starlight photons on energetic $e^{\pm}$



Astrophysical Explanation
Pulsars

S. Profumo Astro-ph 0812-4457

- Mechanism: the spinning $\vec{\mathbf{B}}$ of the pulsar strips e^- that accelerated at the polar cap or at the outer gap emit γ that make production of $e^\pm$ that are trapped in the cloud, further accelerated and later released at $\tau \sim 10^5$ years.

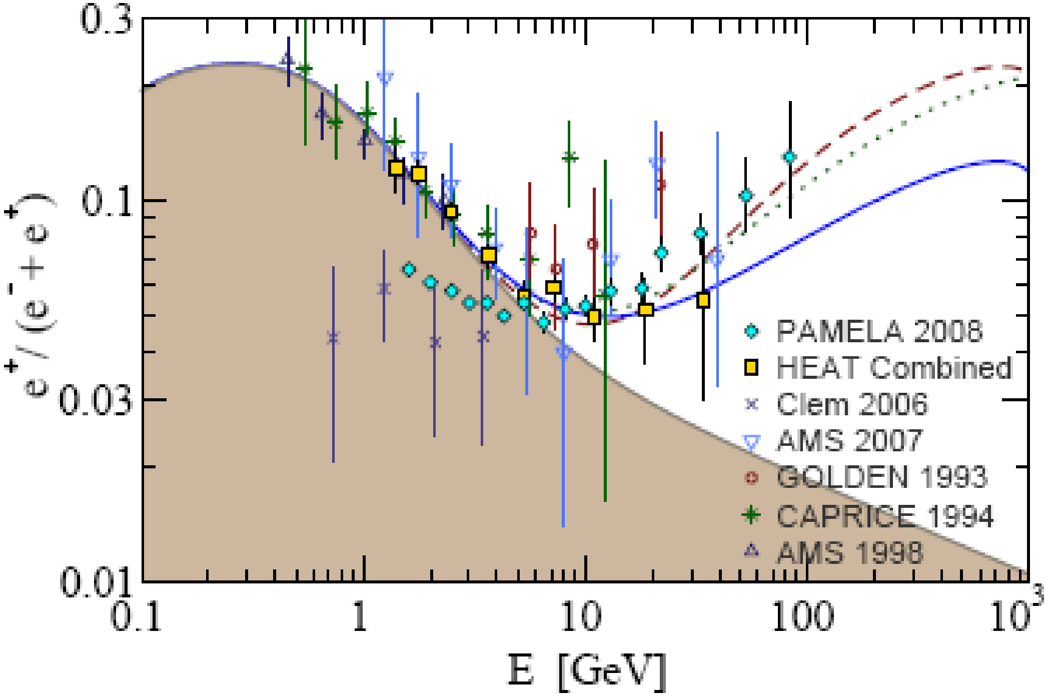
$$E_{tot} \simeq 10^{46}\ \mathrm{erg}$$

- Young ($T \sim 10^5$ years) and nearby (< 1kpc)
- If not: too much diffusion, low energy, too low flux.

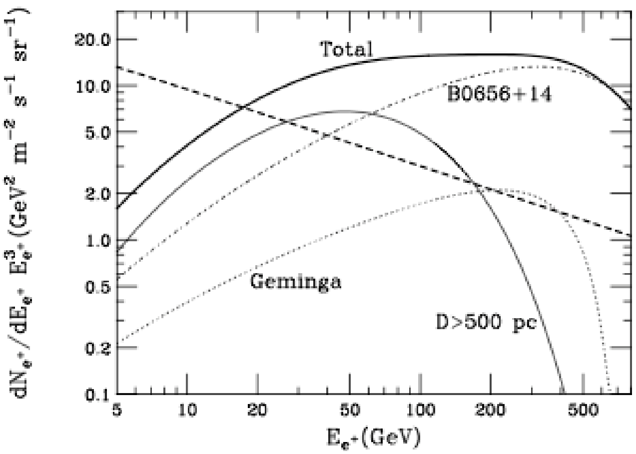
- Geminga: 157 parsecs from Earth and 370,000 years old
- B0656+14: 290 parsecs from Earth and 110,000 years old
- Many others after Fermi/GLAST

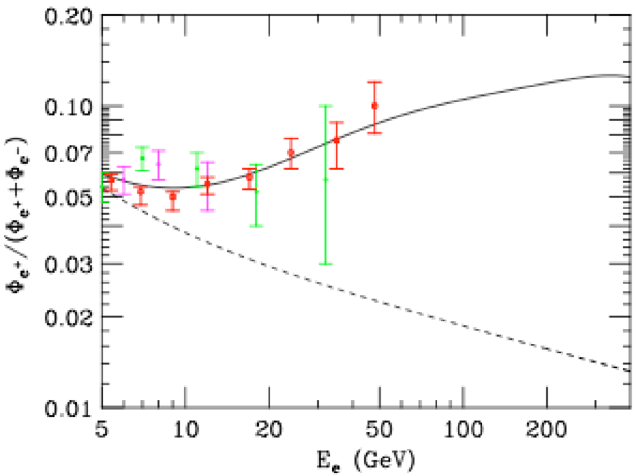
- Diffuse mature pulsars

Example: pulsars



H. Yüksak et al., arXiv:0810.2784v2
Contributions of e- & e+ from Geminga assuming different distance, age and energetic of the pulsar

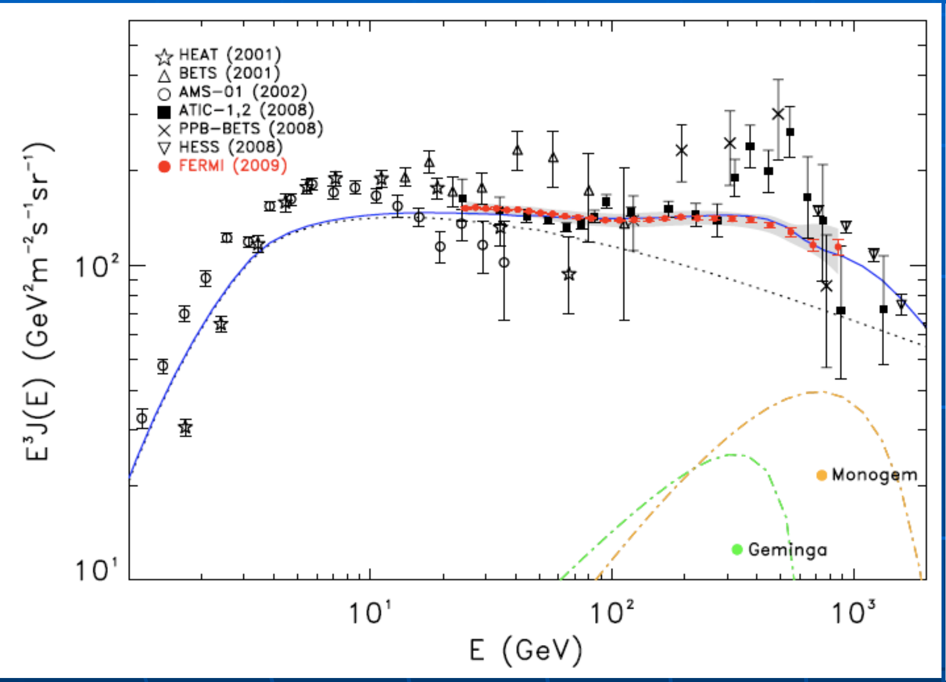


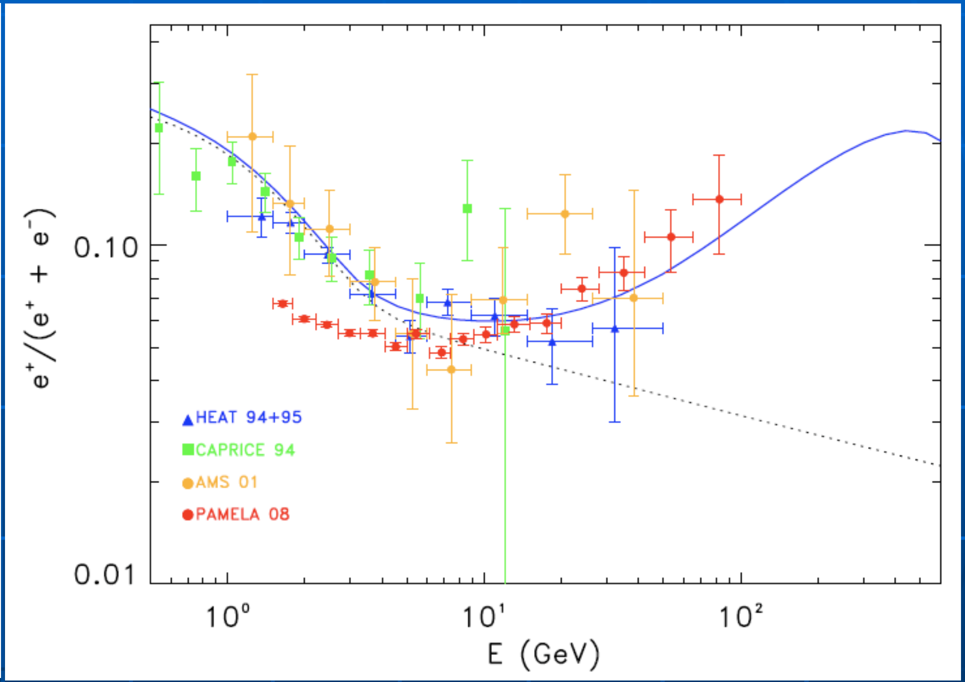


diffuse mature &nearby young pulsars
Hooper, Blasi, and Serpico
arXiv:0810.1527

Pulsars: Most significant contribution to high-energy CRE: **Nearby** (d < 1 kpc) and **Mature** (104 < T/yr < 106) Pulsars

D. Grasso et al.





- Example of fit to both **Fermi** and **Pamela** data with known (ATNF catalogue) nearby, mature pulsars and with a single, nominal choice for the **e+ / e- injection** parameters

Pulsar or Dark Matter?

Anisotropy

Fermi

Interaction of high energy gamma-rays with star-light

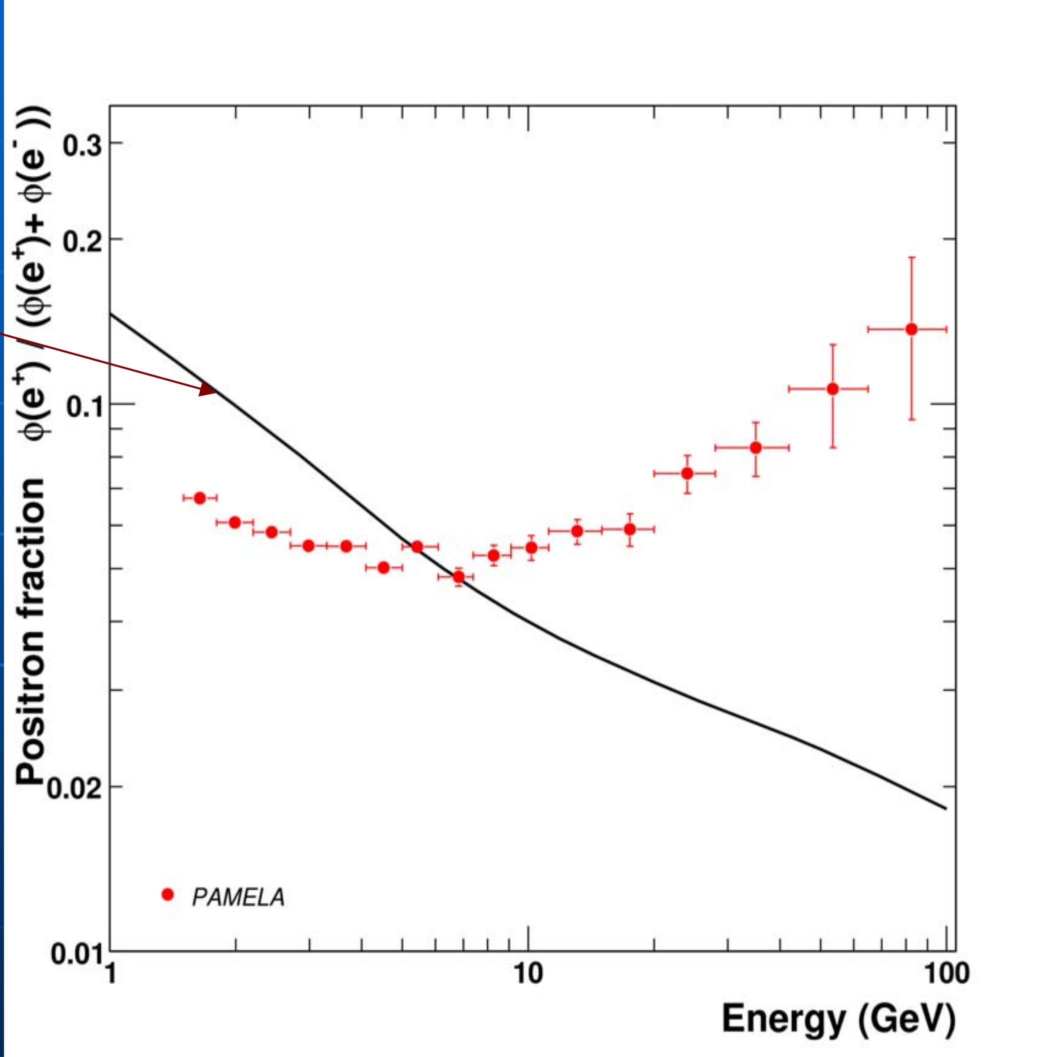
F. A. Aharonian and A M Atoyan
J. Phys. G: **Nucl.** Pan. Phys. **17 (1991) 1769-1778.**

A. Eungwanichayapant and F. A. Aharonian
0907.2971v1 [astro-ph.HE]

After discovery of TeV binaries like LS5039 and LSI 61 by HESS/Magic/VERITAS in which the powerful production of high and very high energy gamma-rays is accompanied by their absorption (which leads to the modulation of the gamma-ray signal), it is clear that these objects are also sources of electron-positron pairs.

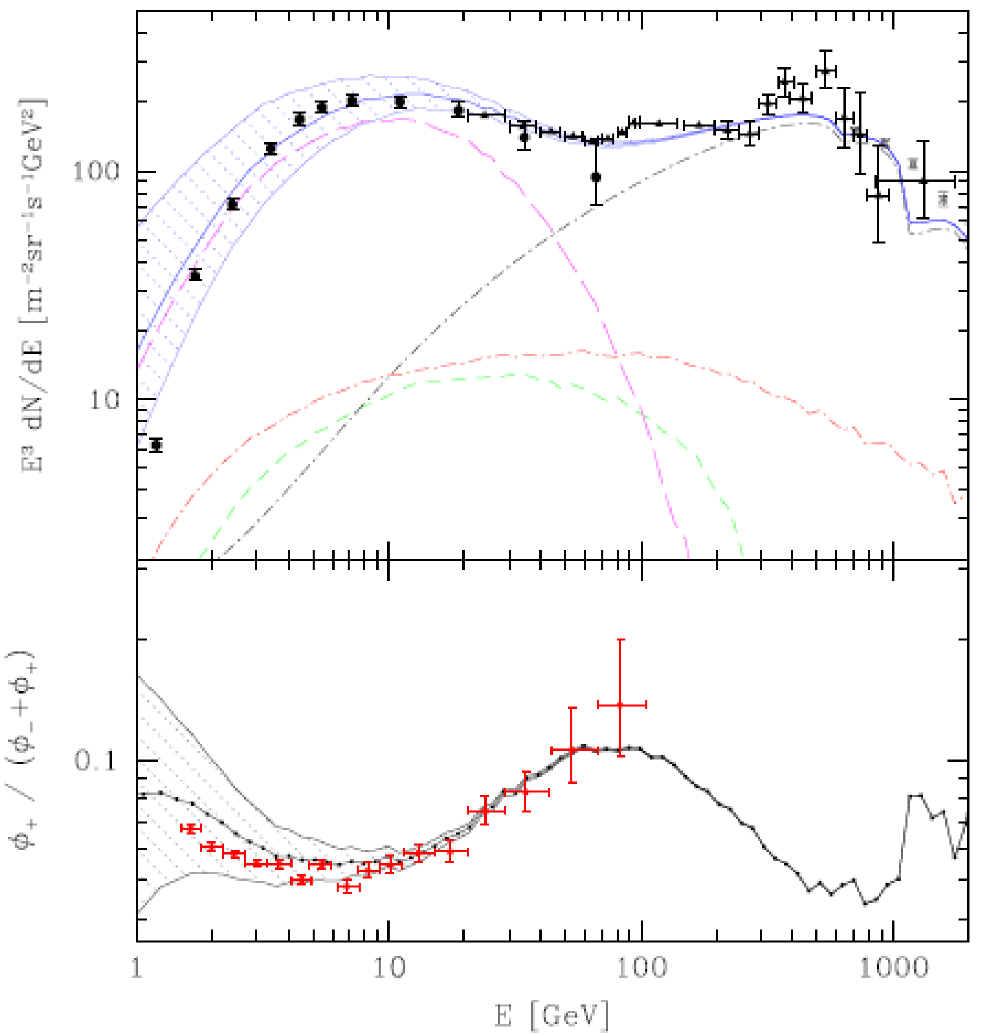
How reliable is the background calculation?

Secondary production
Moskalenko & Strong 98



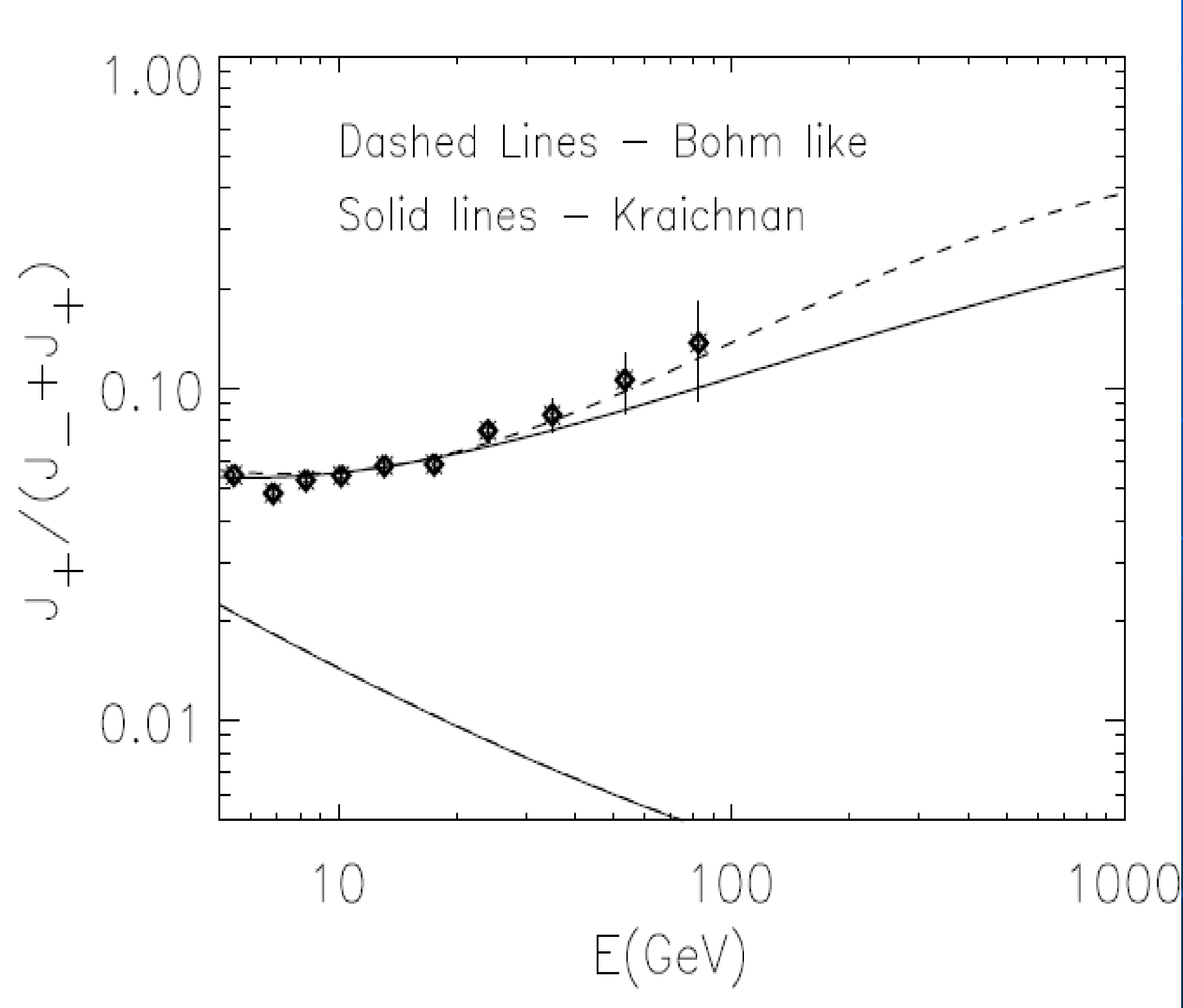
Explanation with supernovae remnants

Shaviz and al. astro-ph.HE 0902.0376



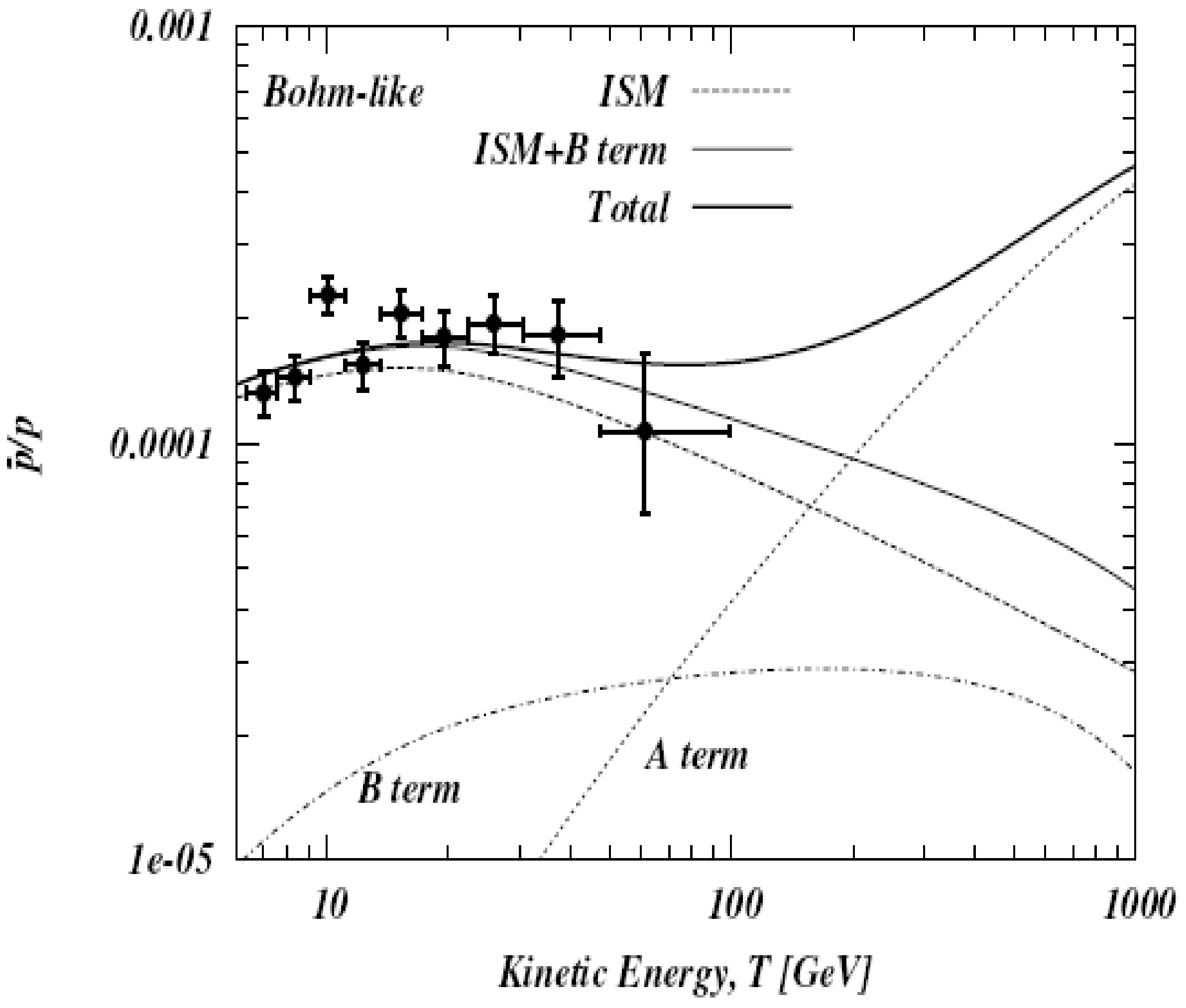
Positrons from old SNR's

P. Blasi astyro-ph 0903.2794

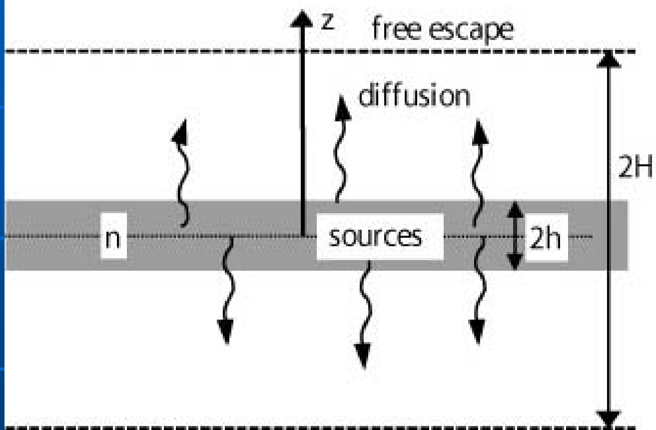


Antiprotons from old SNR's

P.Blasi Astro-ph.HE 0904.0871



Cosmic Rays Propagation in the Galaxy

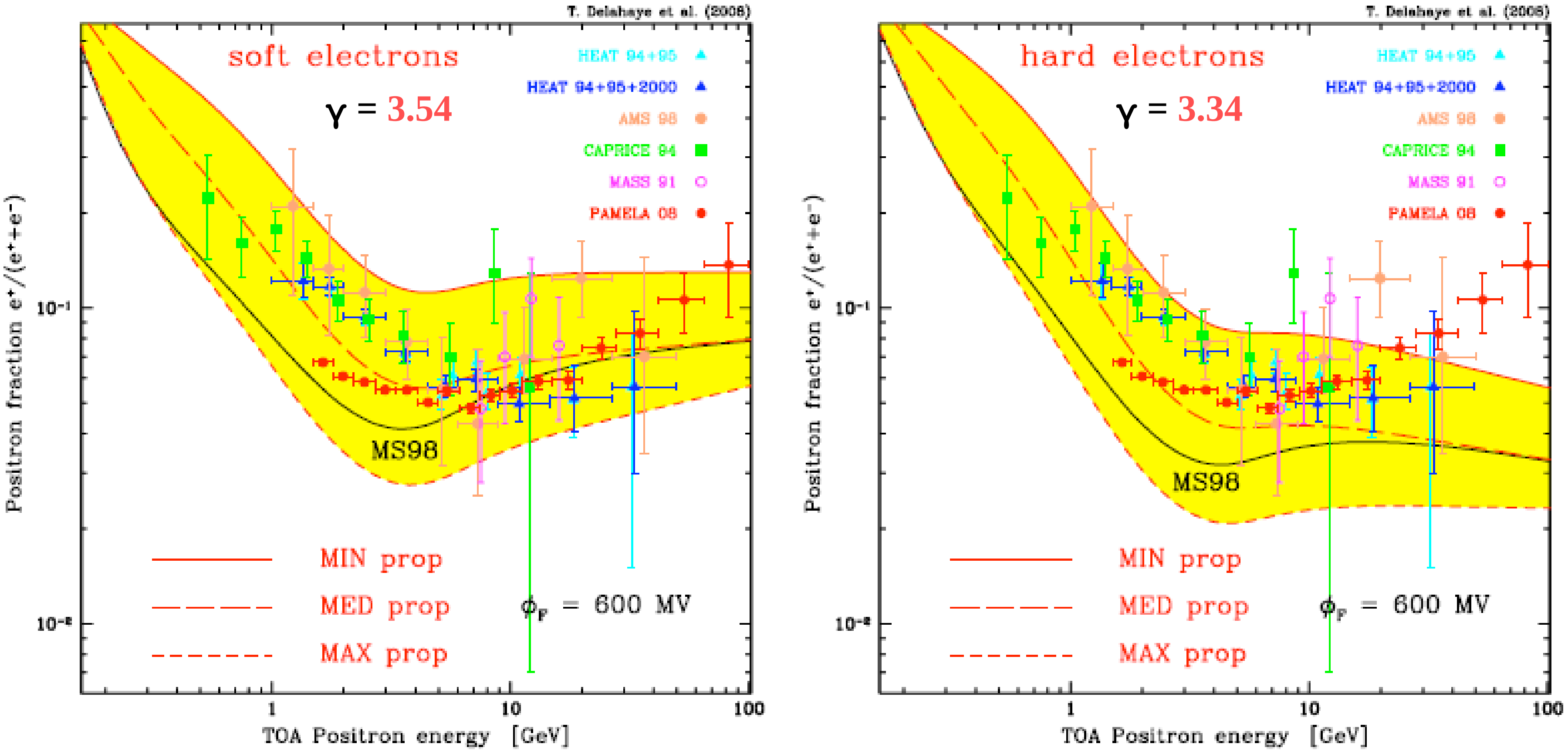


$$\frac{\partial N_i(E,z,t)}{\partial t} = \underbrace{D(E)\cdot\frac{\partial^2}{\partial z^2}N_i(E,z,t)}_{\text{diffusion}} - \underbrace{N_i(E,z,t)\left\{\frac{1}{\tau_i^{\mathrm{int}}(E,z)} + \frac{1}{\gamma(E)\tau_i^{dec}}\right\}}_{\text{interaction and decay}}$$

$$+ \underbrace{\sum_{k>i}\frac{N_k(E,z,t)}{\tau_{\mathrm{int}}^{k\to i}(E,z)}}_{\text{secondary production}} + \underbrace{Q_i(E,z)}_{\text{primary sources}}$$

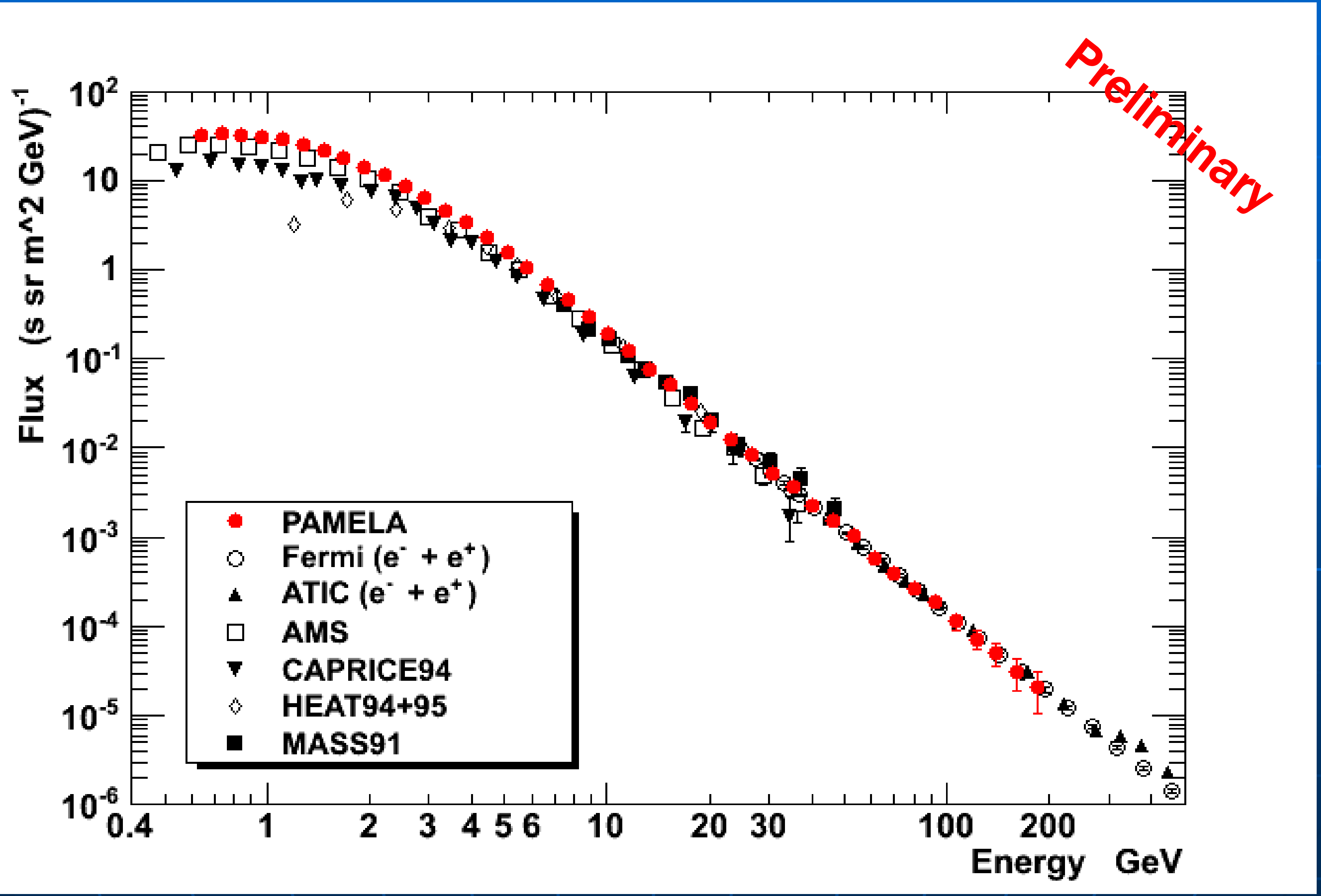
$$\underbrace{-\frac{\partial}{\partial E}\left\{\left\langle\frac{\partial E}{\partial t}\right\rangle\cdot N_i(E,z,t)\right\} + \frac{1}{2}\frac{\partial^2}{\partial E^2}\left\{\left\langle\frac{\Delta E^2}{\Delta t}\right\rangle\cdot N_i(E,z,t)\right\}}_{\text{energy changing processes (ionisation, reacceleration)}}$$

Standard Positron Fraction
Theoretical Uncertainties

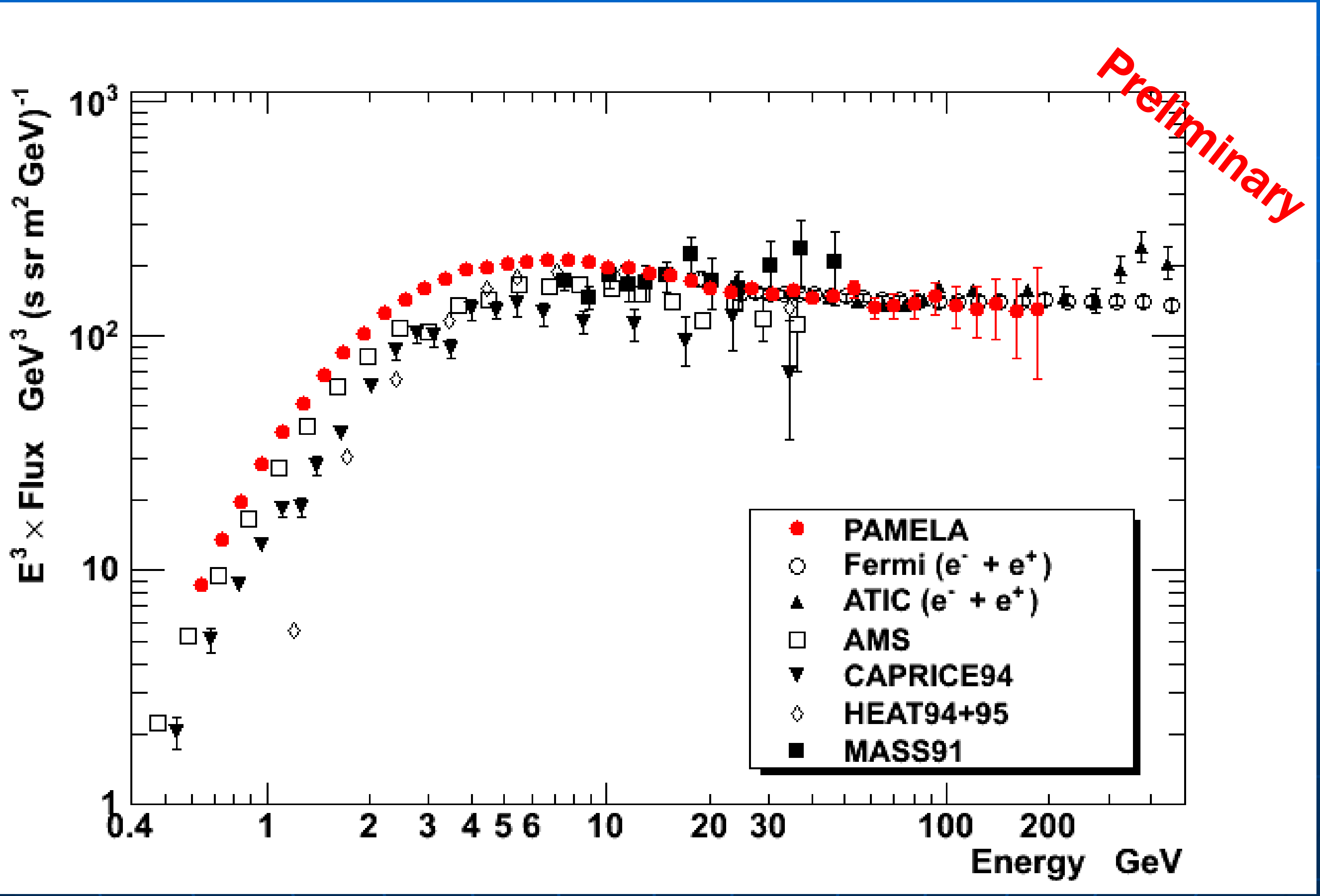


T. Delahaye et al., arXiv: 0809.5268v3

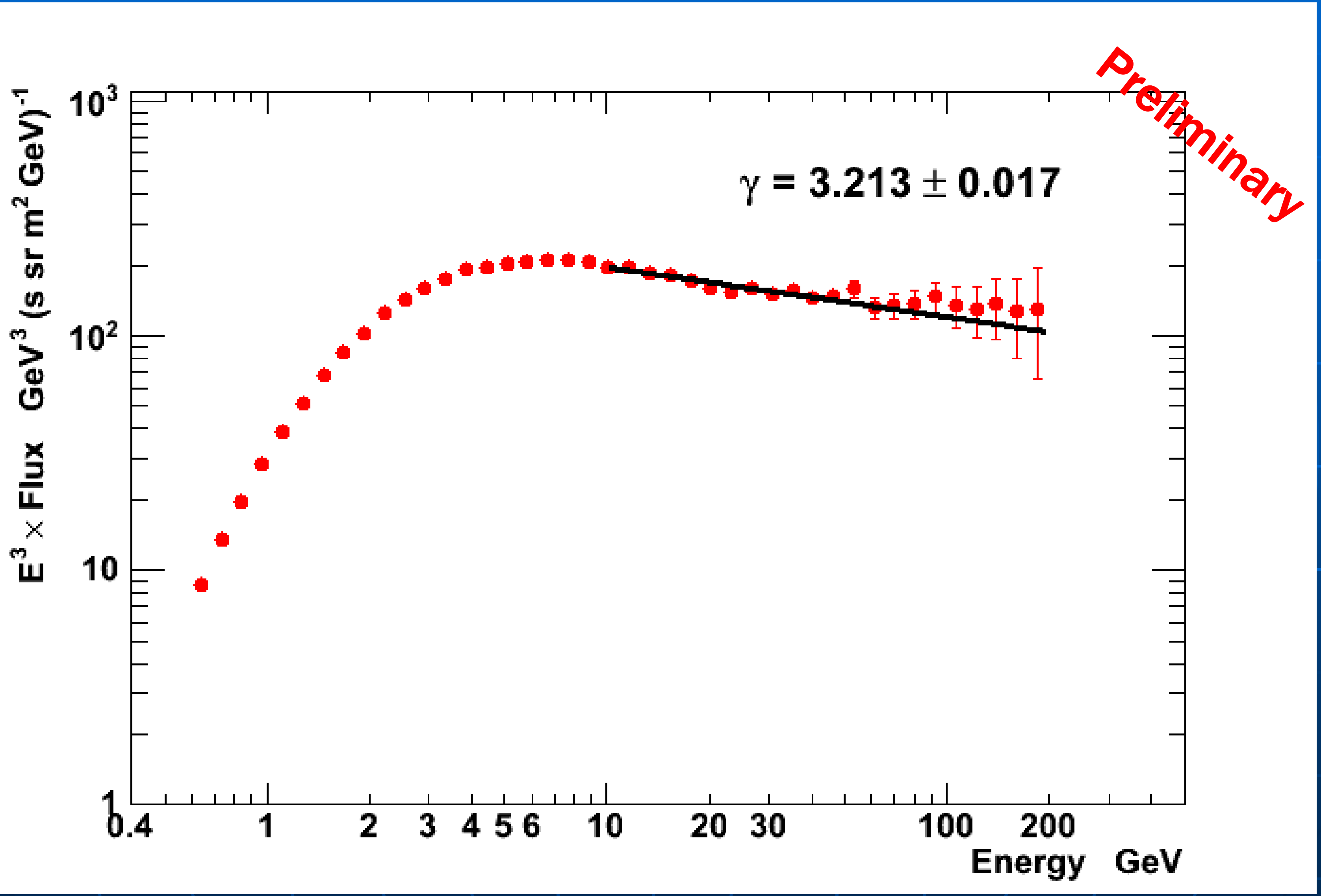
PAMELA Electron (e^-) Spectrum



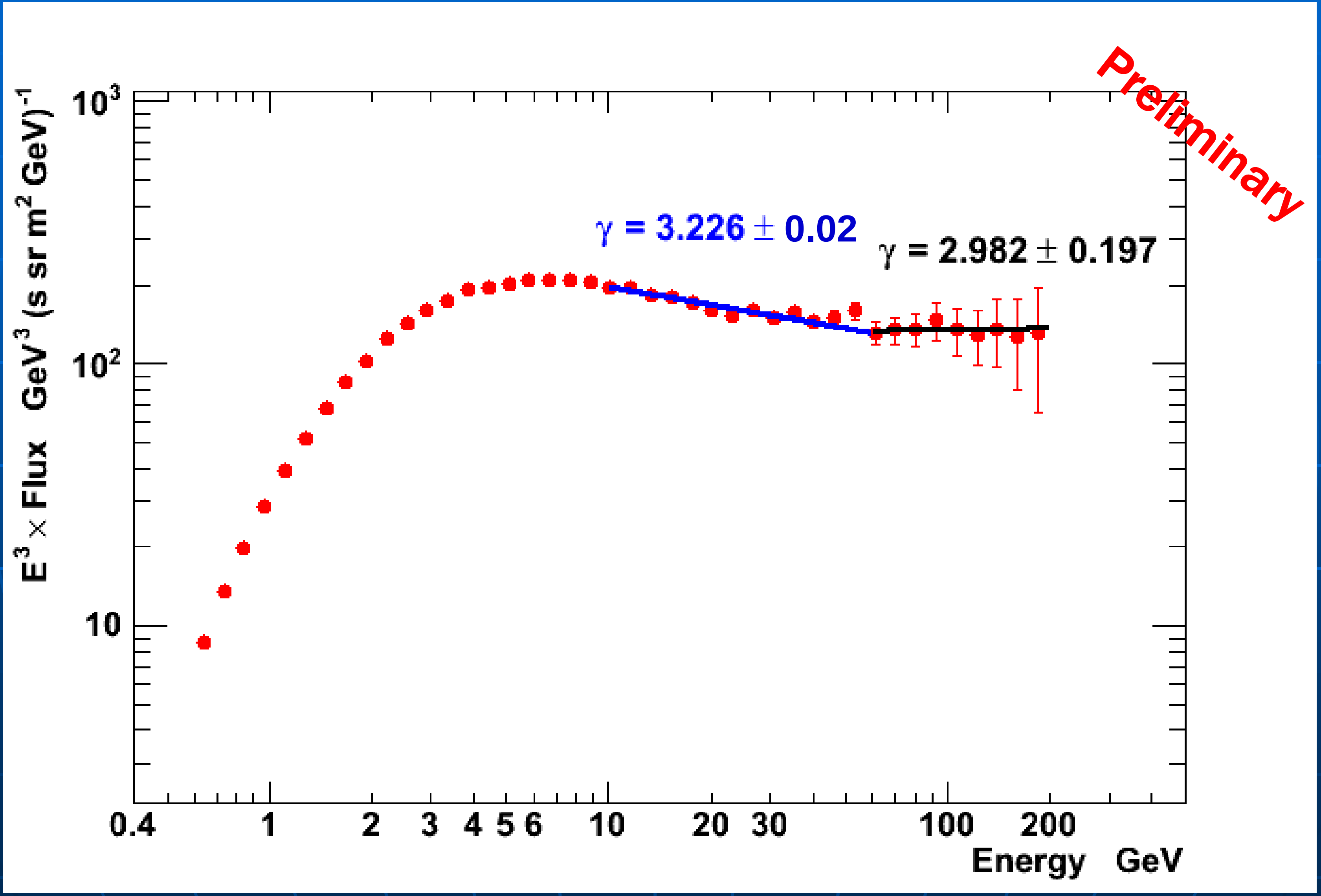
PAMELA Electron (e^-) Spectrum



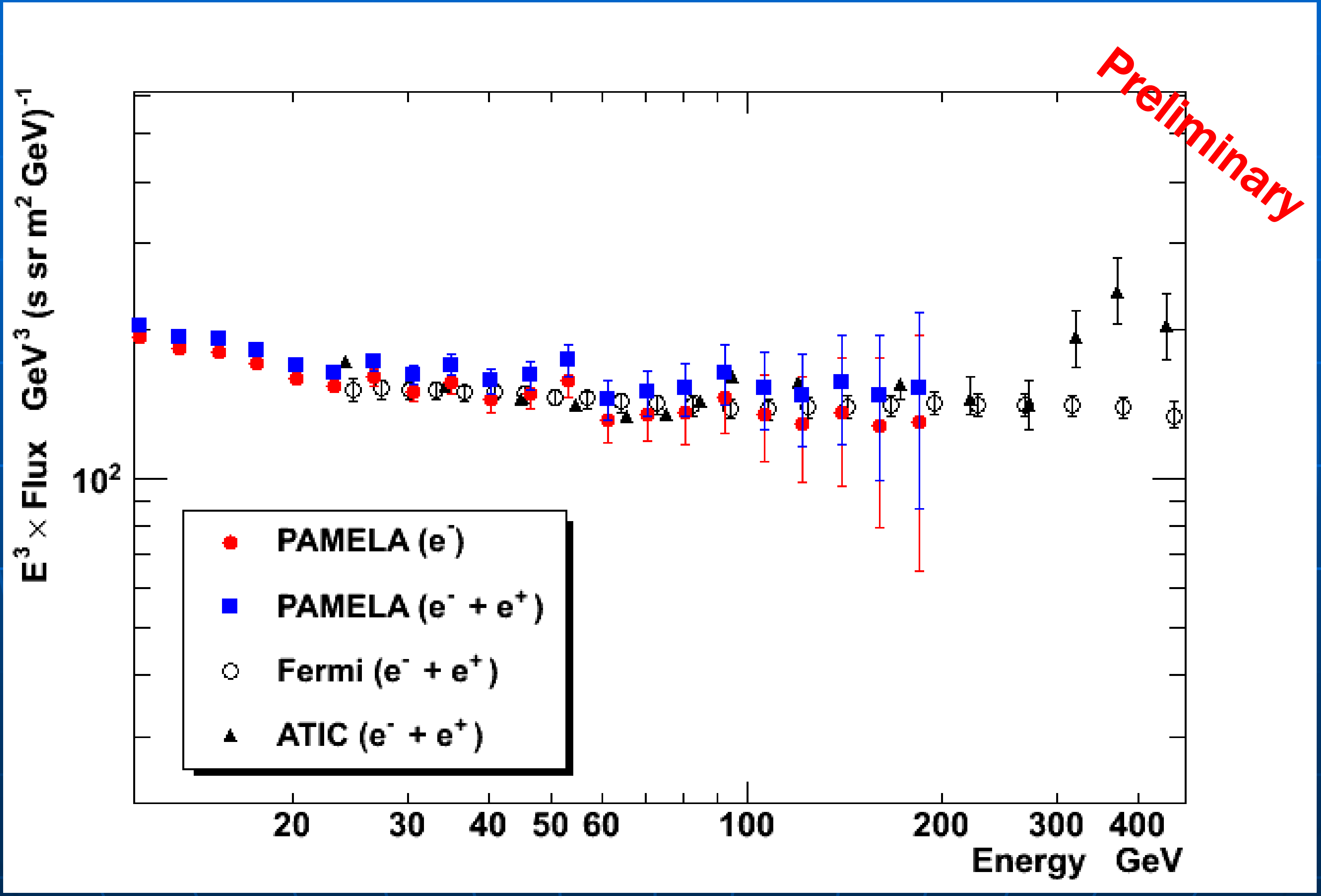
PAMELA Electron (e^-) Spectrum



PAMELA Electron (e^-) Spectrum

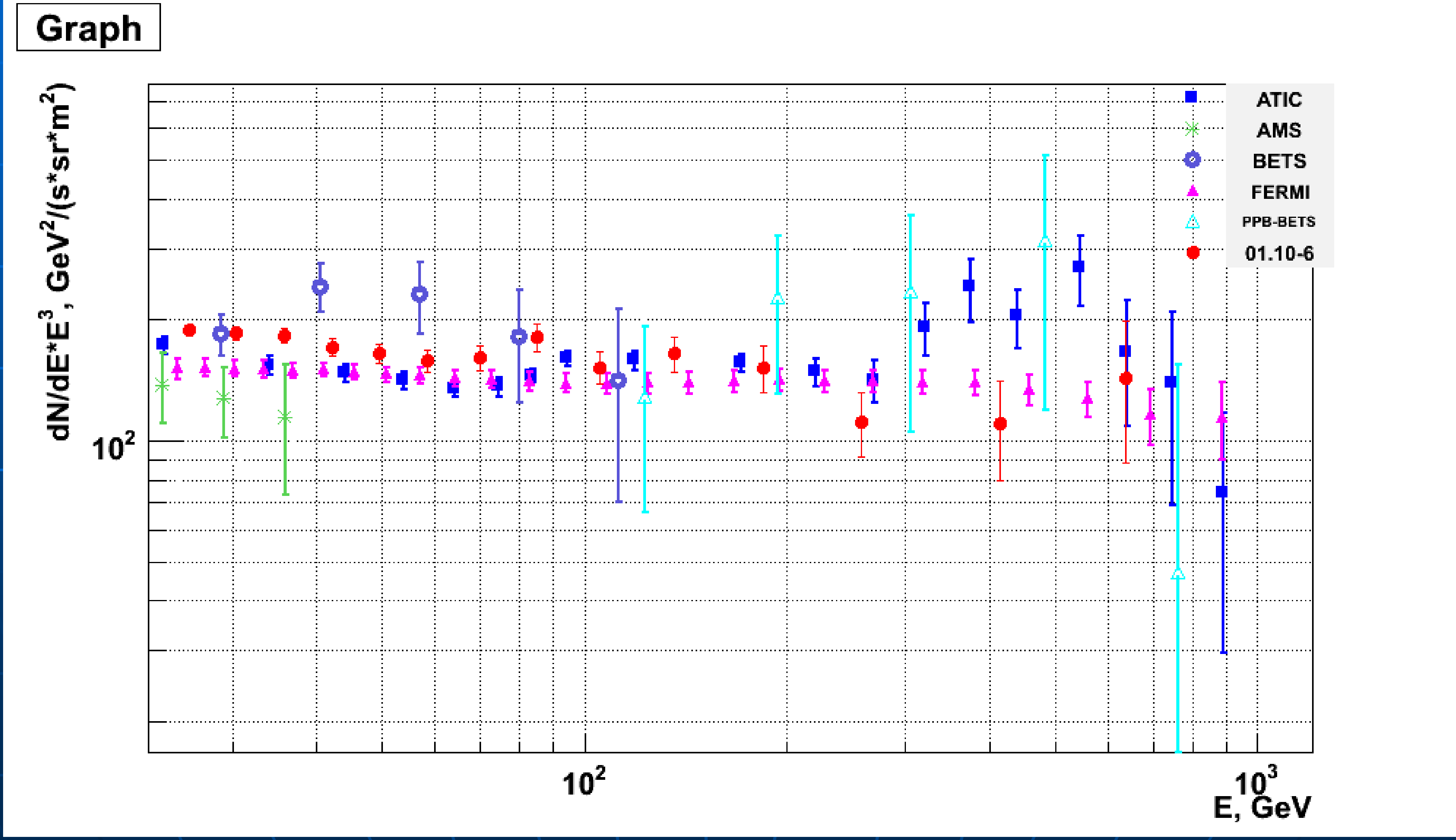


PAMELA Electron Spectrum

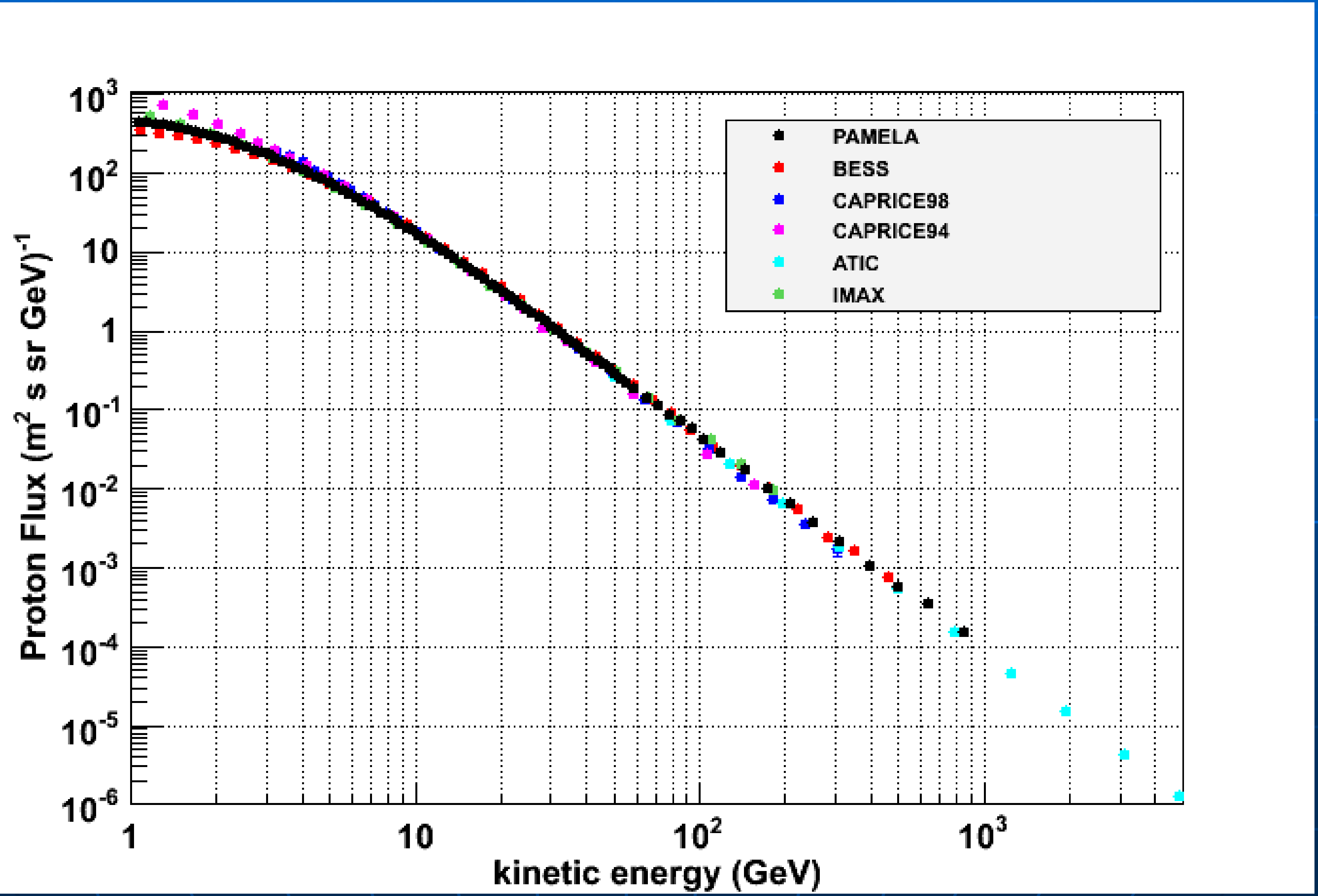


PAMELA all electrons

Preliminary

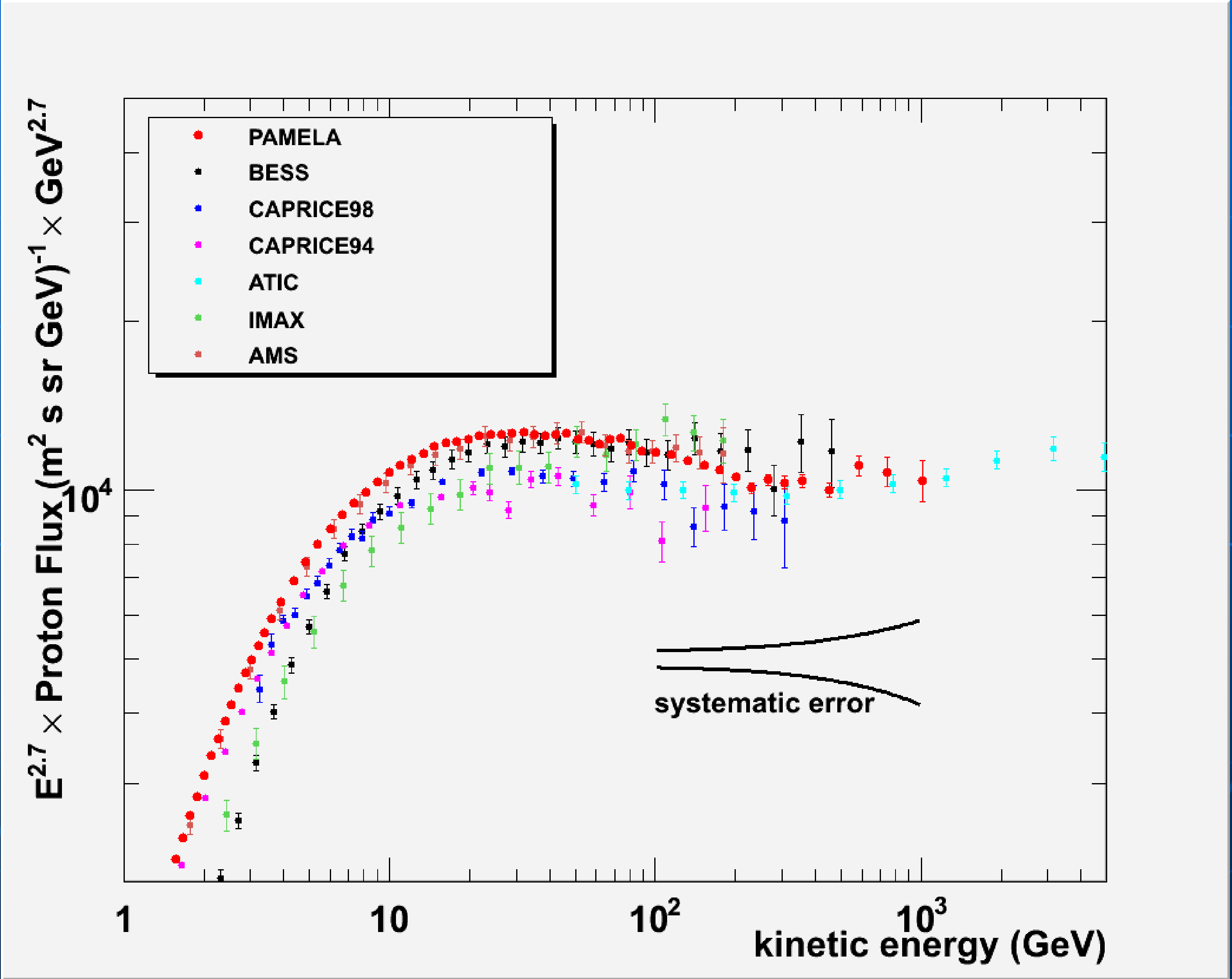


Proton flux



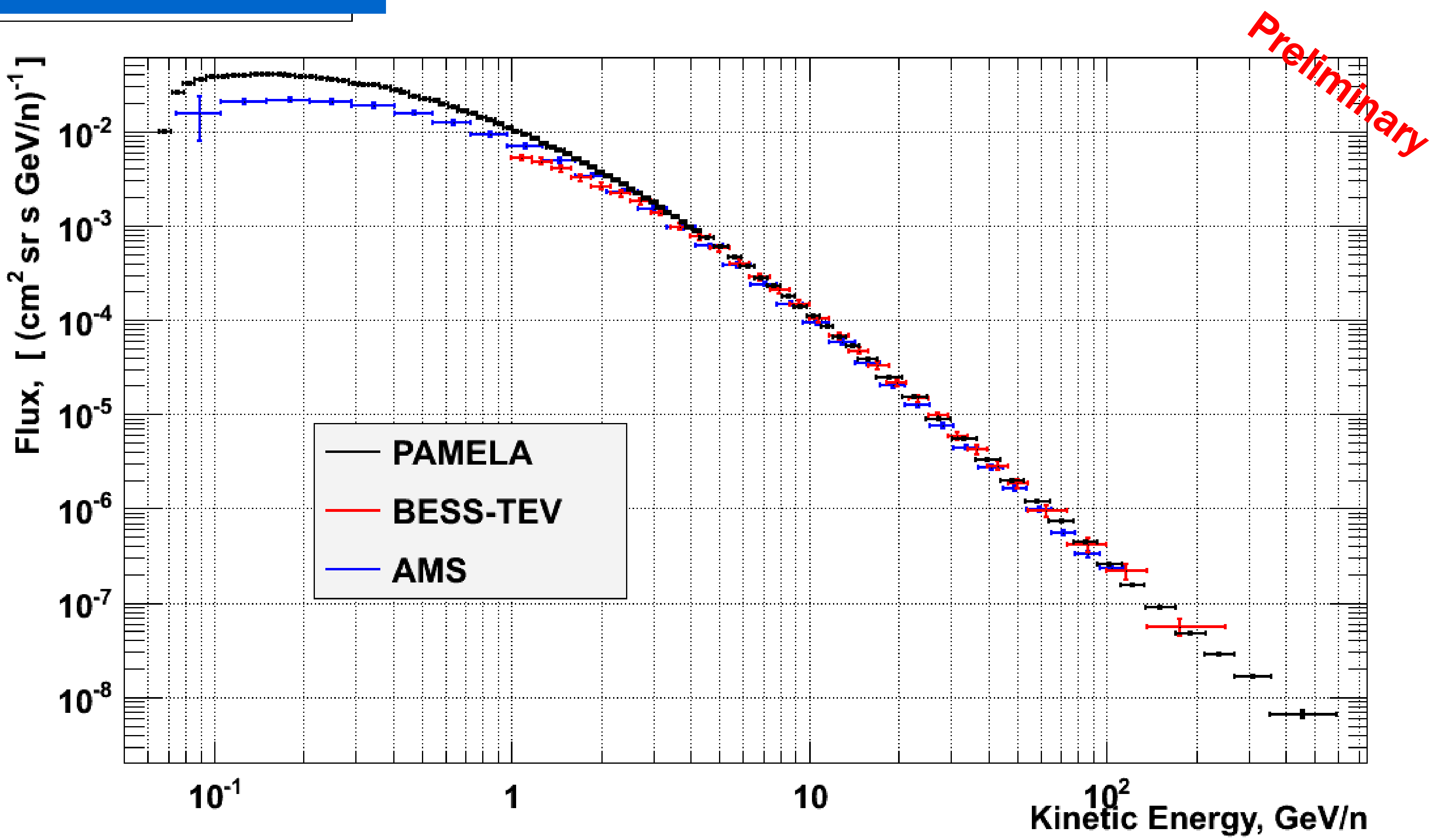
Proton Flux (m^2 s sr GeV)$^{-1}$
kinetic energy (GeV)
PAMELA
BESS
CAPRICE98
CAPRICE94
ATIC
IMAX
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1
10
10^2
10^3

Proton flux

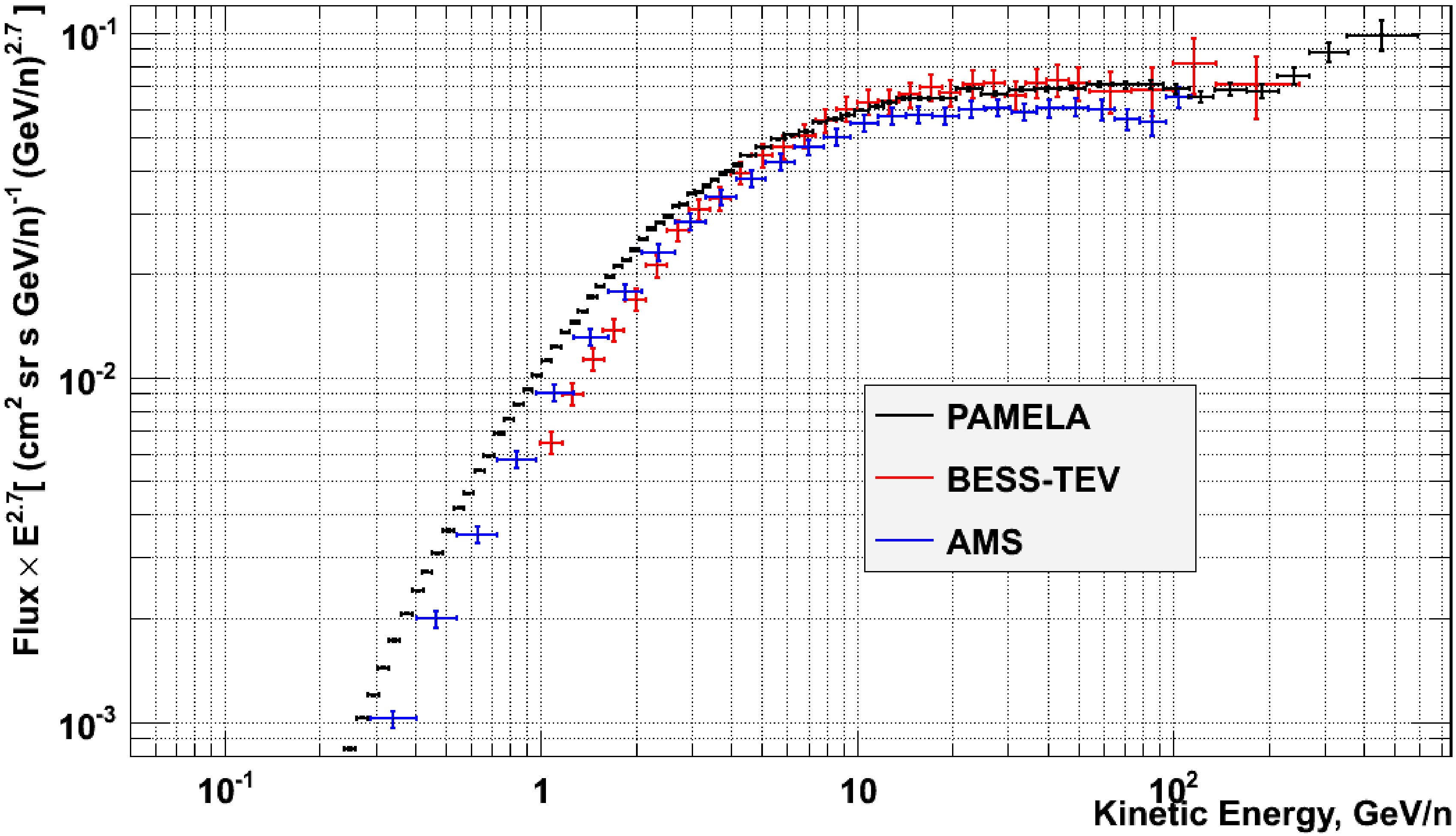


PAMELA
BESS
CAPRICE98
CAPRICE94
ATIC
IMAX
AMS
$E^{2.7} \times$ Proton Flux $(m^2\ s\ sr\ GeV)^{-1} \times GeV^{2.7}$
10^4
systematic error
1
10
10^2
10^3
kinetic energy (GeV)

Helium Spectrum



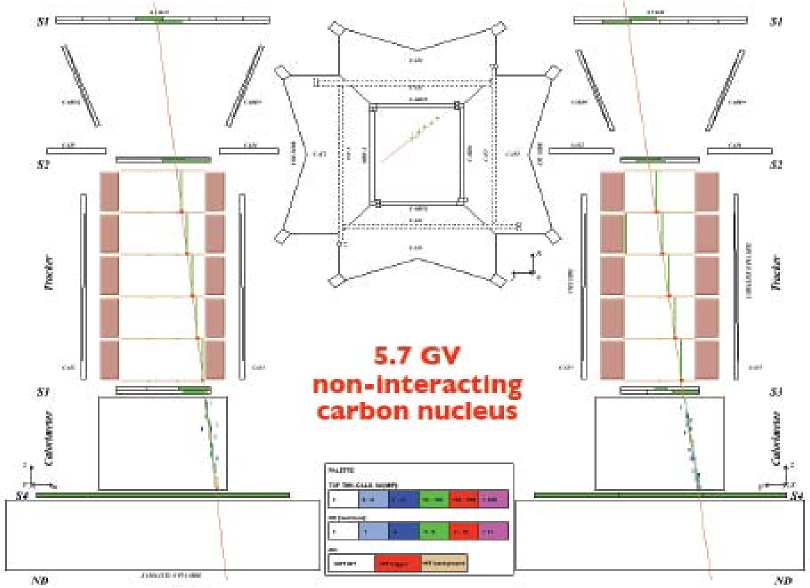
Helium flux

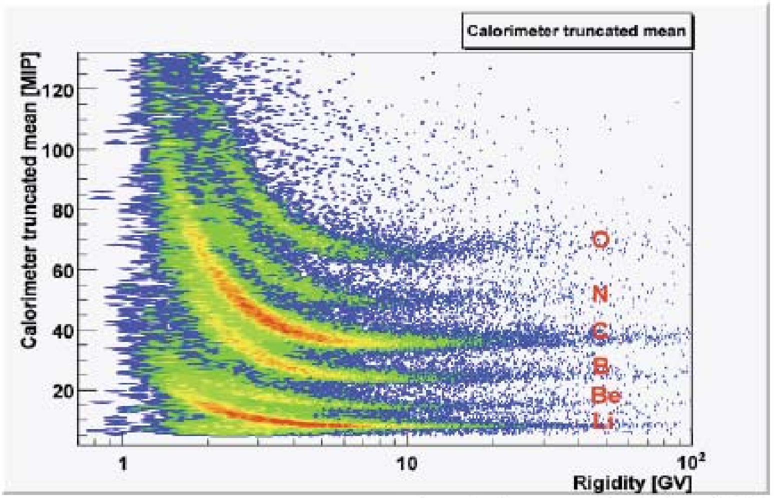


Flux × E^2.7 [(cm^2 sr s GeV/n)^-1 (GeV/n)^2.7]
10^-1
10^-2
10^-3
10^-1
1
10
10^2
Kinetic Energy, GeV/n
PAMELA
BESS-TEV
AMS

Nuclei identification

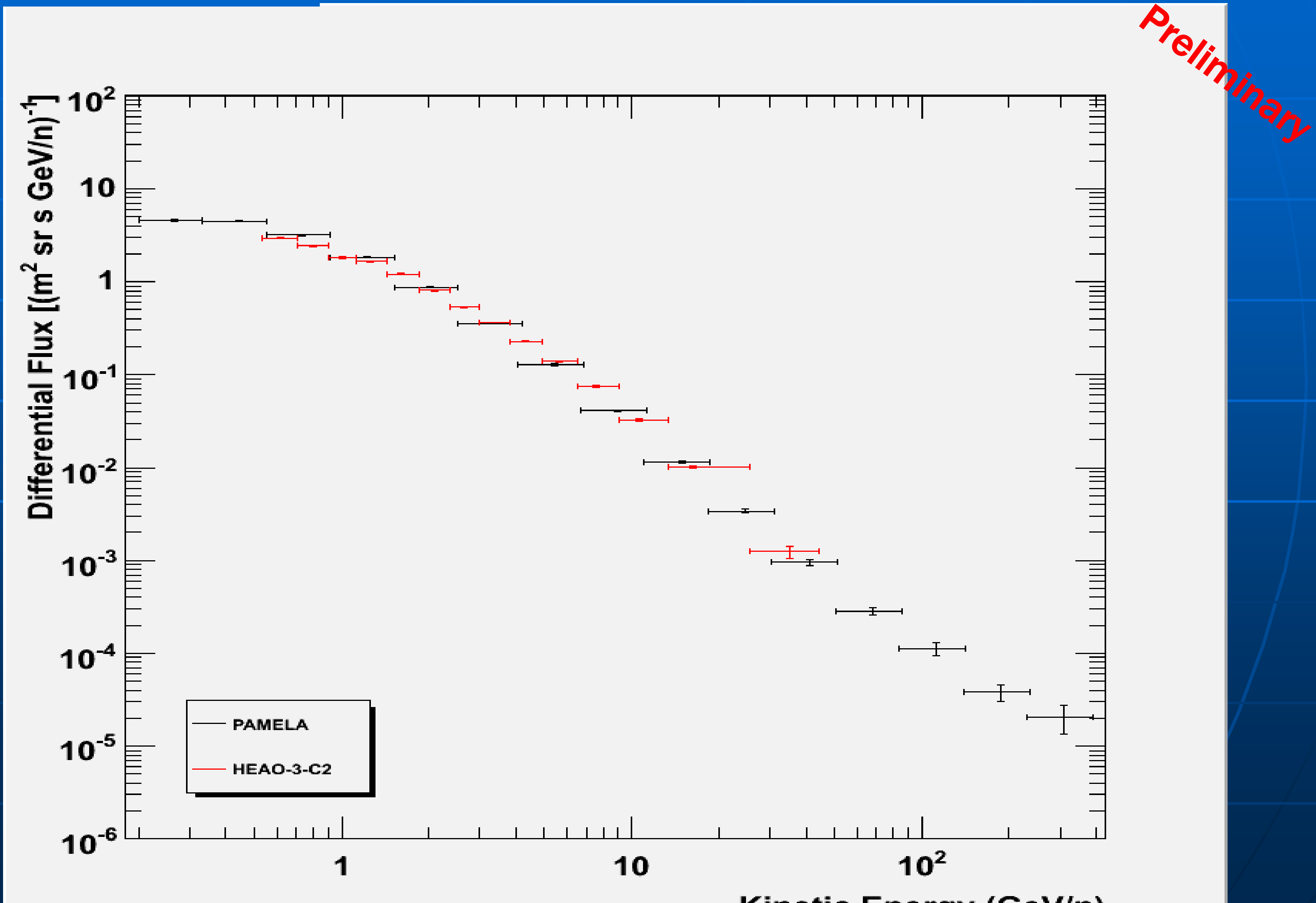
- **Important input to secondary production + propagation models**
  - Secondary to primary ratios:
    - B / C
    - Be / C
    - Li / C
  - Helium and hydrogen isotopes:
    - ^{3}He / ^{4}He
    - d / He



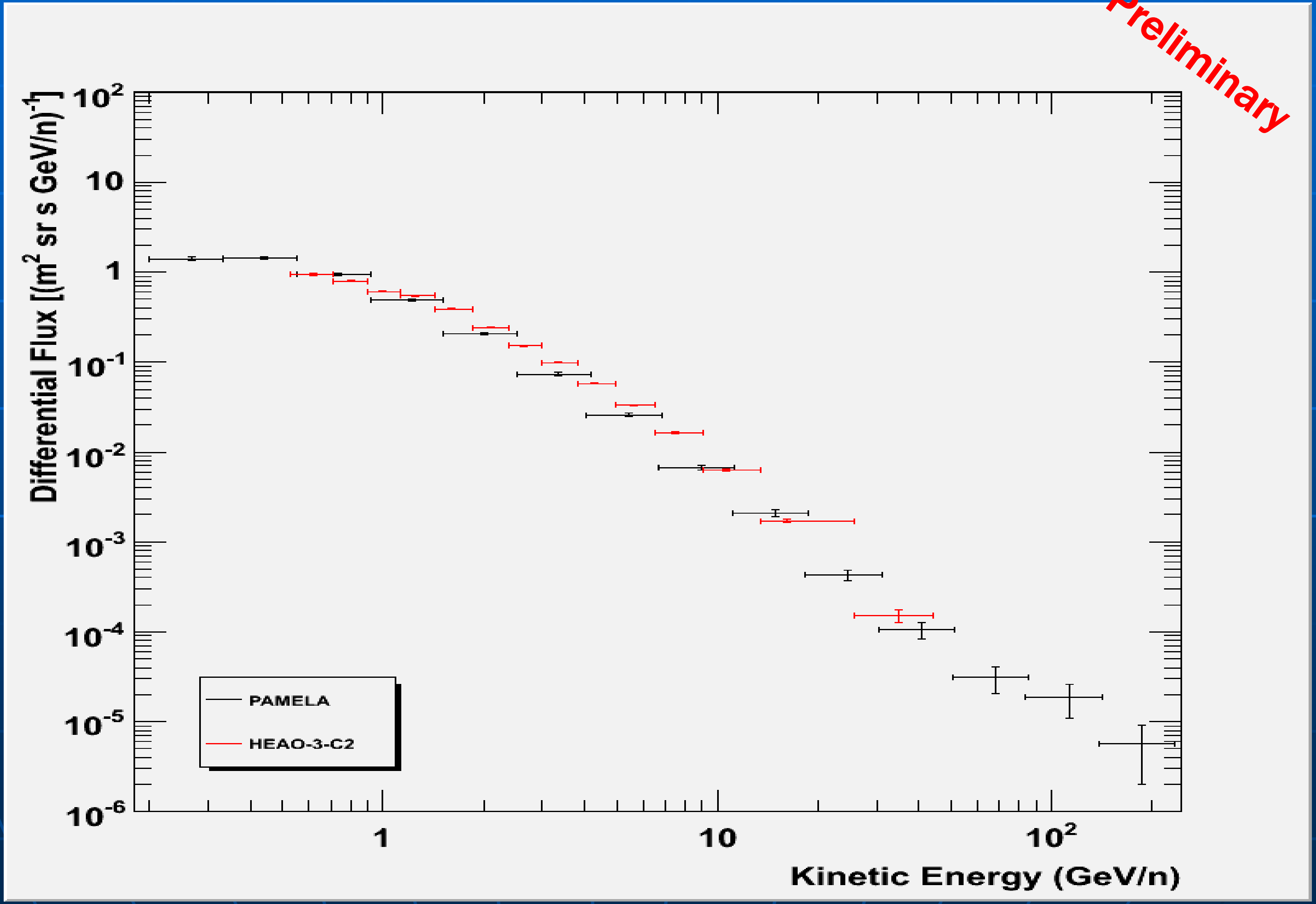


Truncated mean of multiple dE/dx measurements in different silicon planes

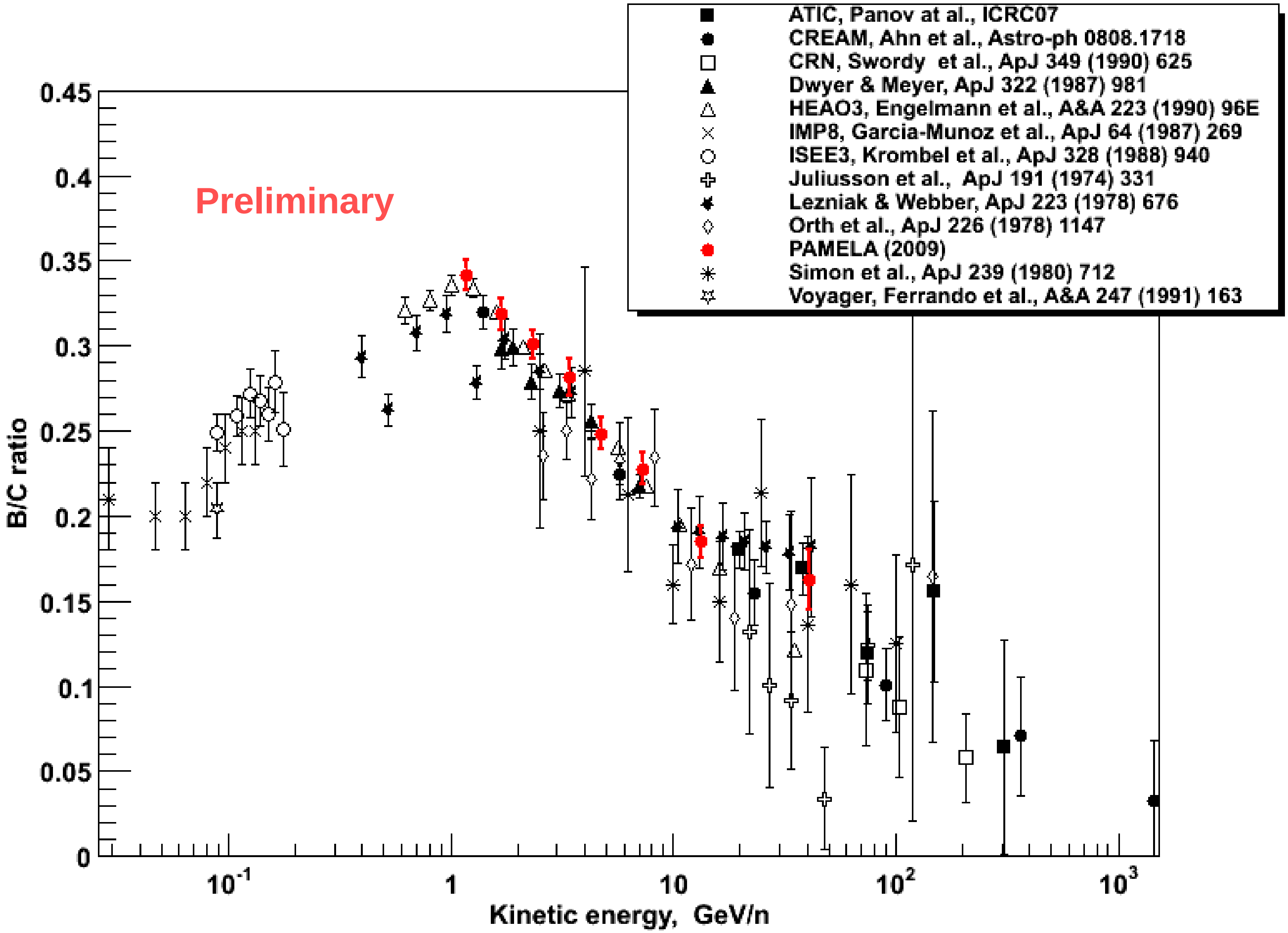
Carbon Spectrum



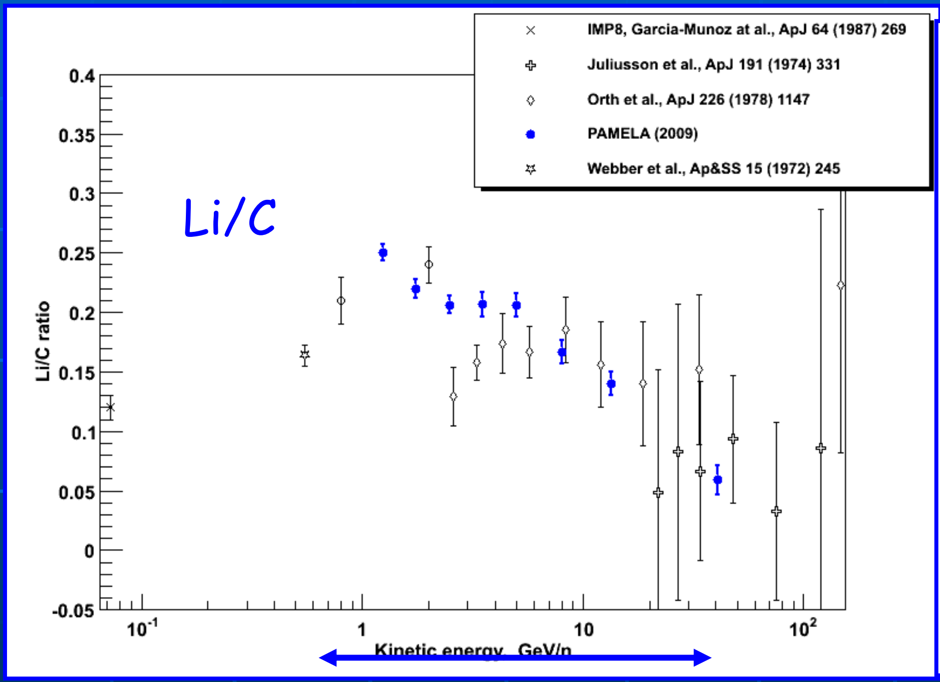
Boron Spectrum

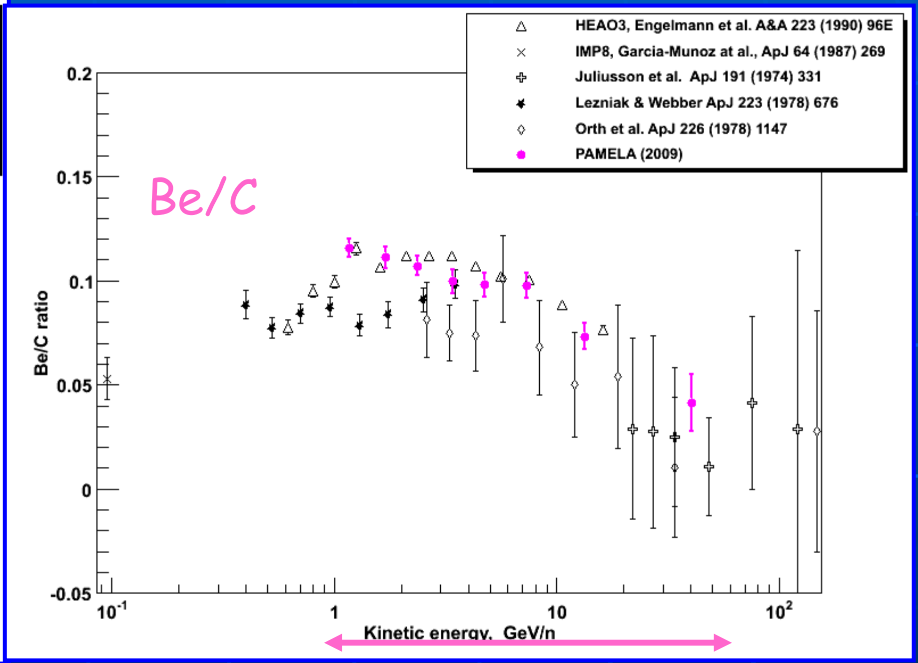


B/C

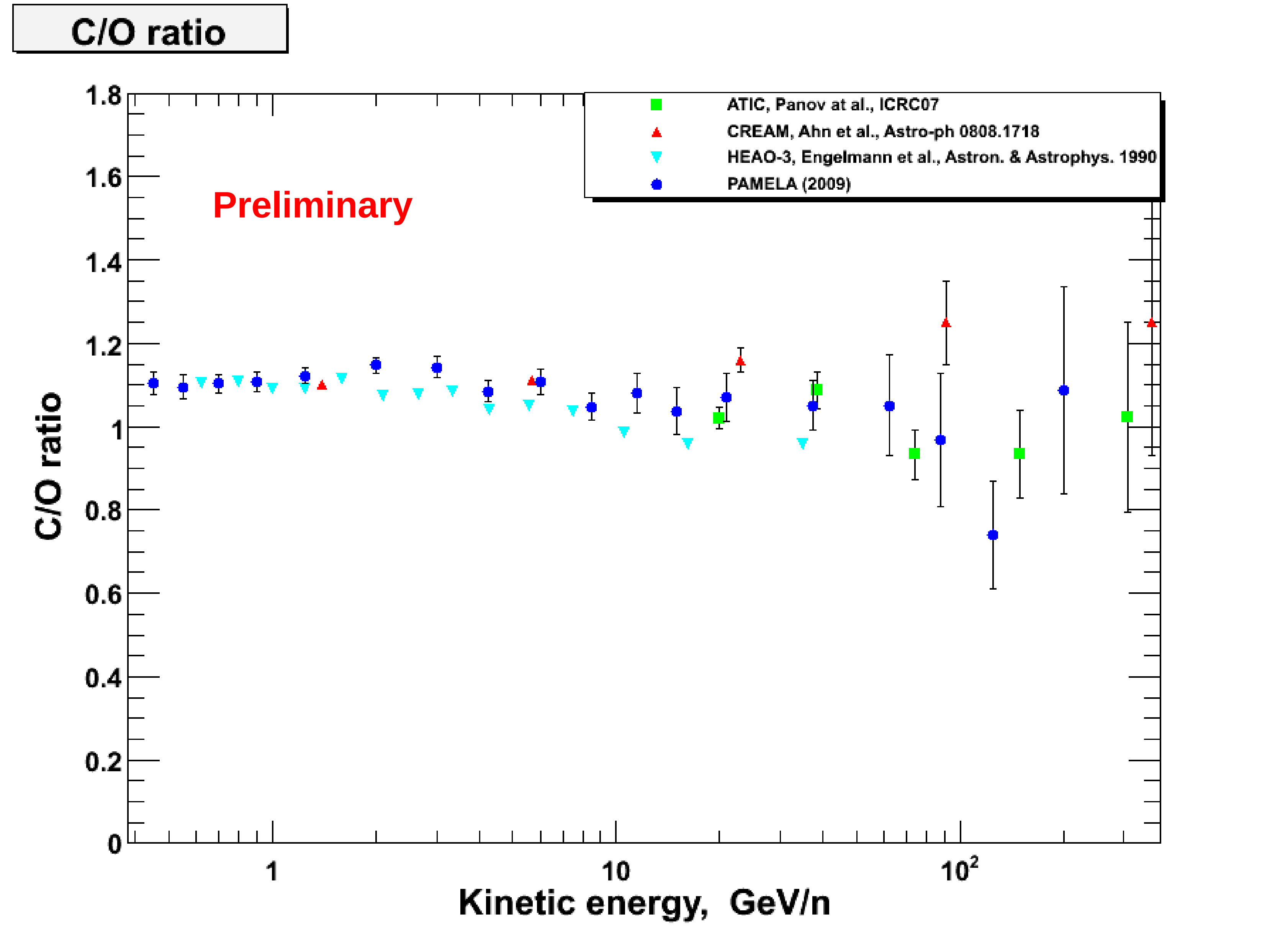

ATIC, Panov at al., ICRC07
CREAM, Ahn et al., Astro-ph 0808.1718
CRN, Swordy et al., ApJ 349 (1990) 625
Dwyer & Meyer, ApJ 322 (1987) 981
HEAO3, Engelmann et al., A&A 223 (1990) 96E
IMP8, Garcia-Munoz et al., ApJ 64 (1987) 269
ISEE3, Krombel et al., ApJ 328 (1988) 940
Juliusson et al., ApJ 191 (1974) 331
Lezniak & Webber, ApJ 223 (1978) 676
Orth et al., ApJ 226 (1978) 1147
PAMELA (2009)
Simon et al., ApJ 239 (1980) 712
Voyager, Ferrando et al., A&A 247 (1991) 163
Preliminary
B/C ratio
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
10^{-1}
1
10
10^{2}
10^{3}
Kinetic energy, GeV/n

PAMELA preliminary results



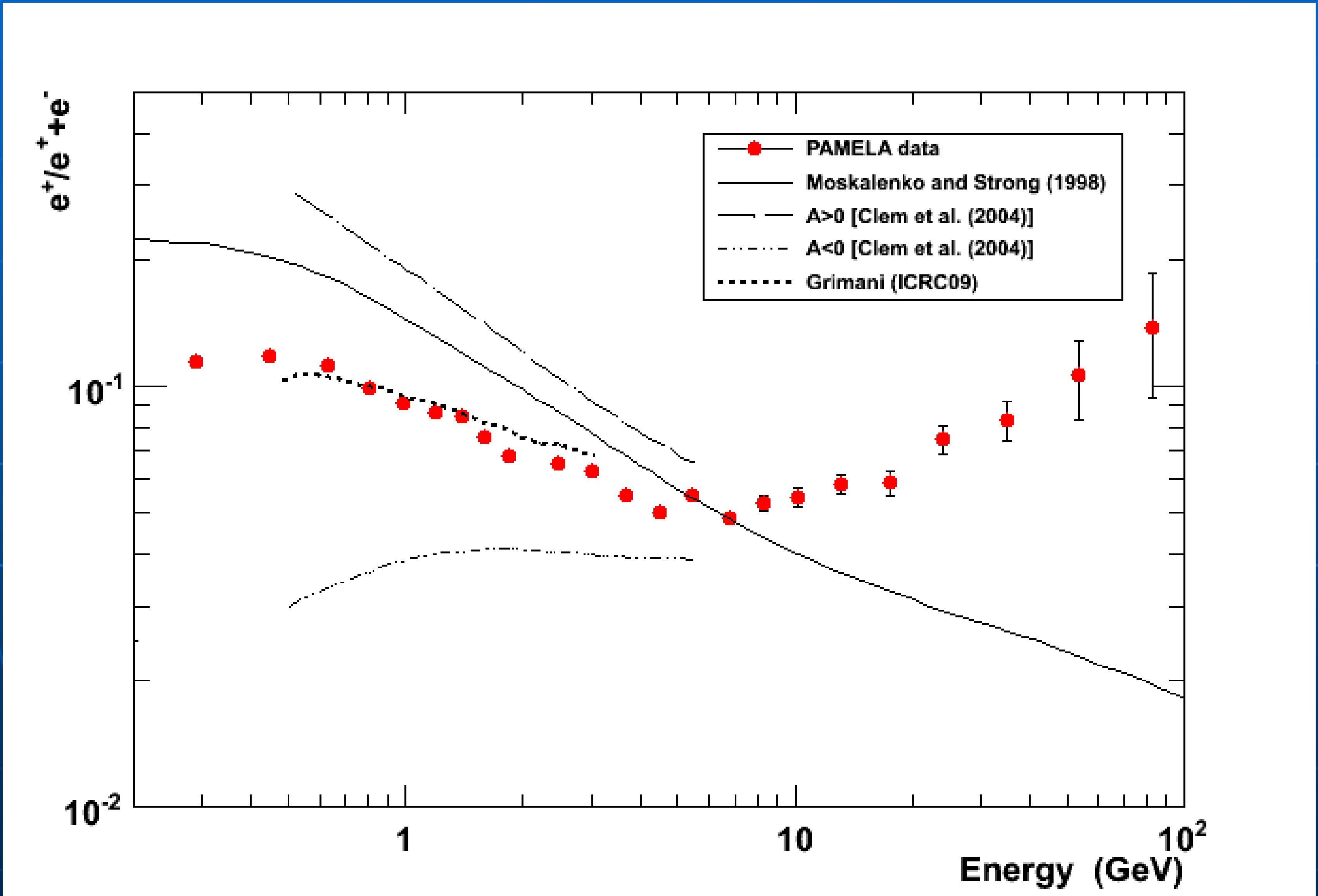


C/O ratio



C/O ratio
Preliminary
ATIC, Panov at al., ICRC07
CREAM, Ahn et al., Astro-ph 0808.1718
HEAO-3, Engelmann et al., Astron. & Astrophys. 1990
PAMELA (2009)
C/O ratio
Kinetic energy, GeV/n
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
1
10
10^2

Positron Fraction



Solar Modulation of galactic cosmic rays

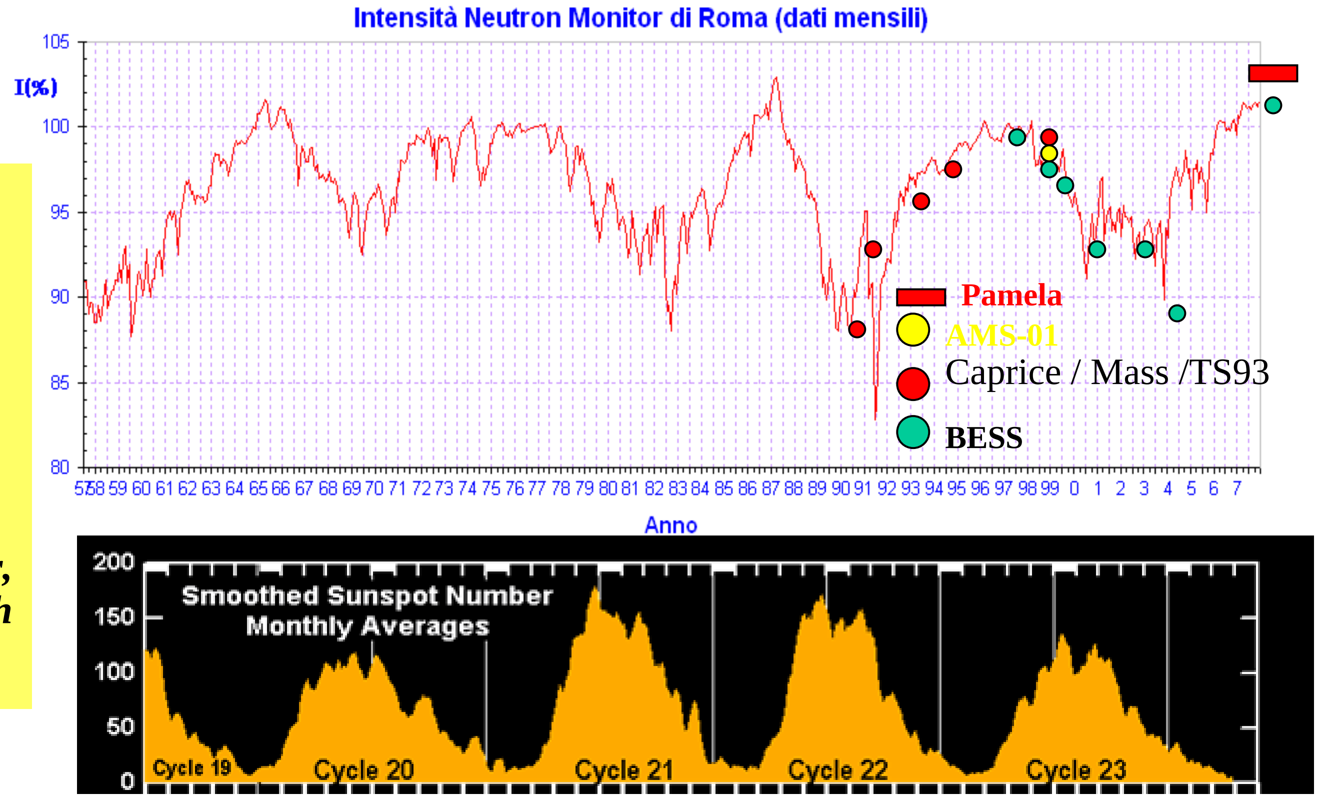
- **Study of charge sign dependent effects**

Asaoka Y. et al. 2002, Phys. Rev. Lett. 88, 051101),

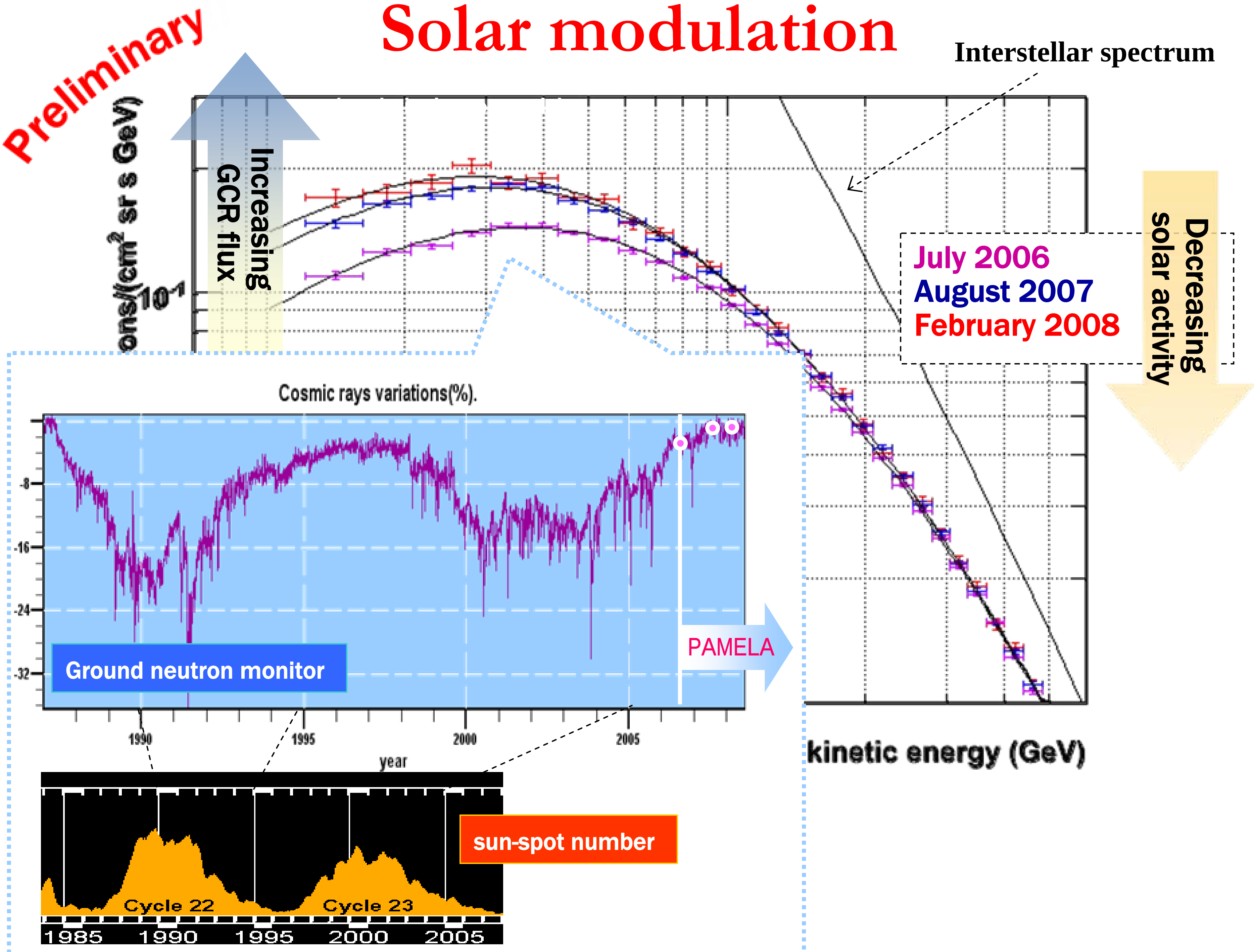
Bieber, J.W., et al. Physi-cal Review Letters, 84, 674, 1999.

J. Clem et al. 30th ICRC 2007

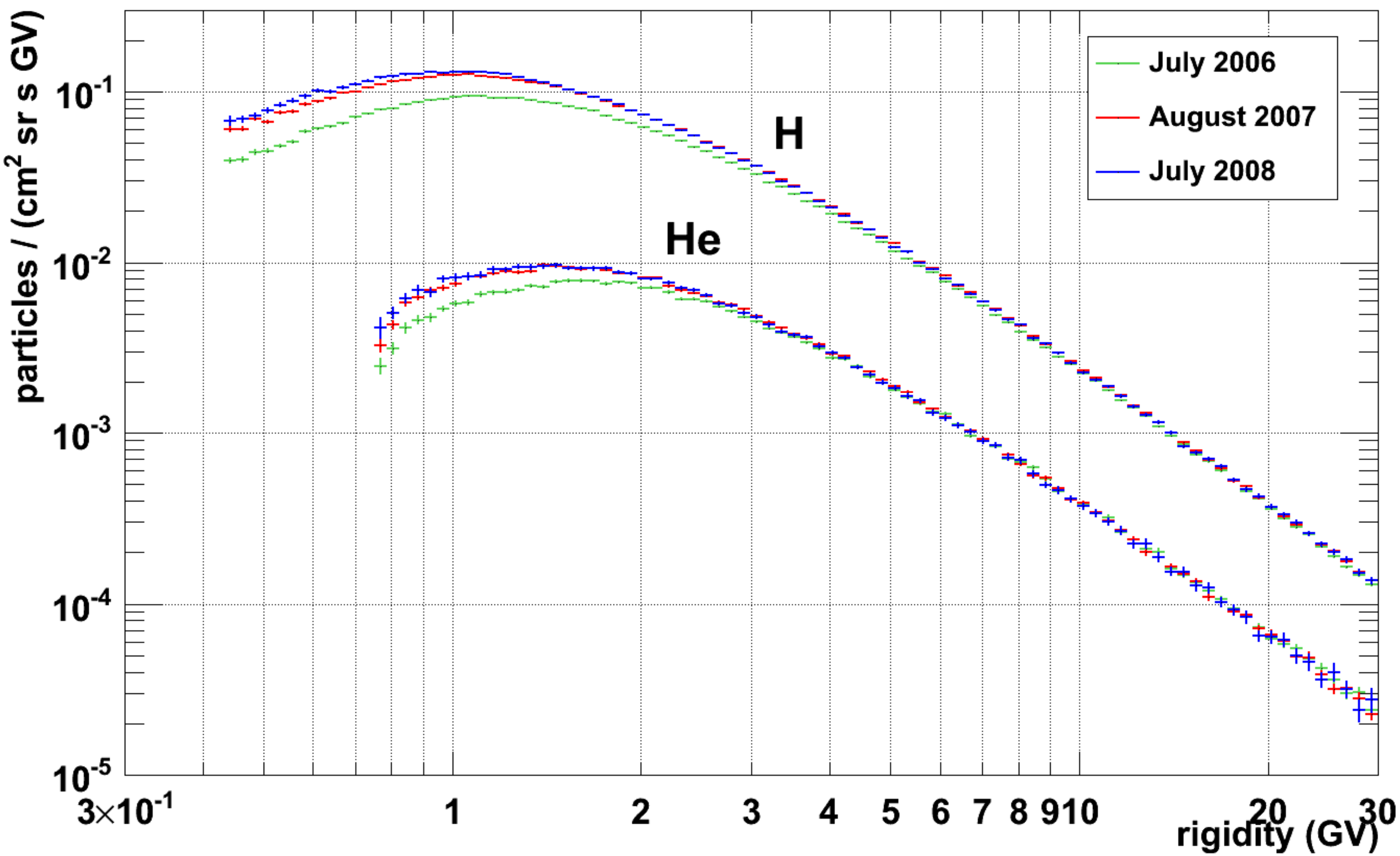
U.W. Langner, M.S. Potgieter, Advances in Space Research 34 (2004)



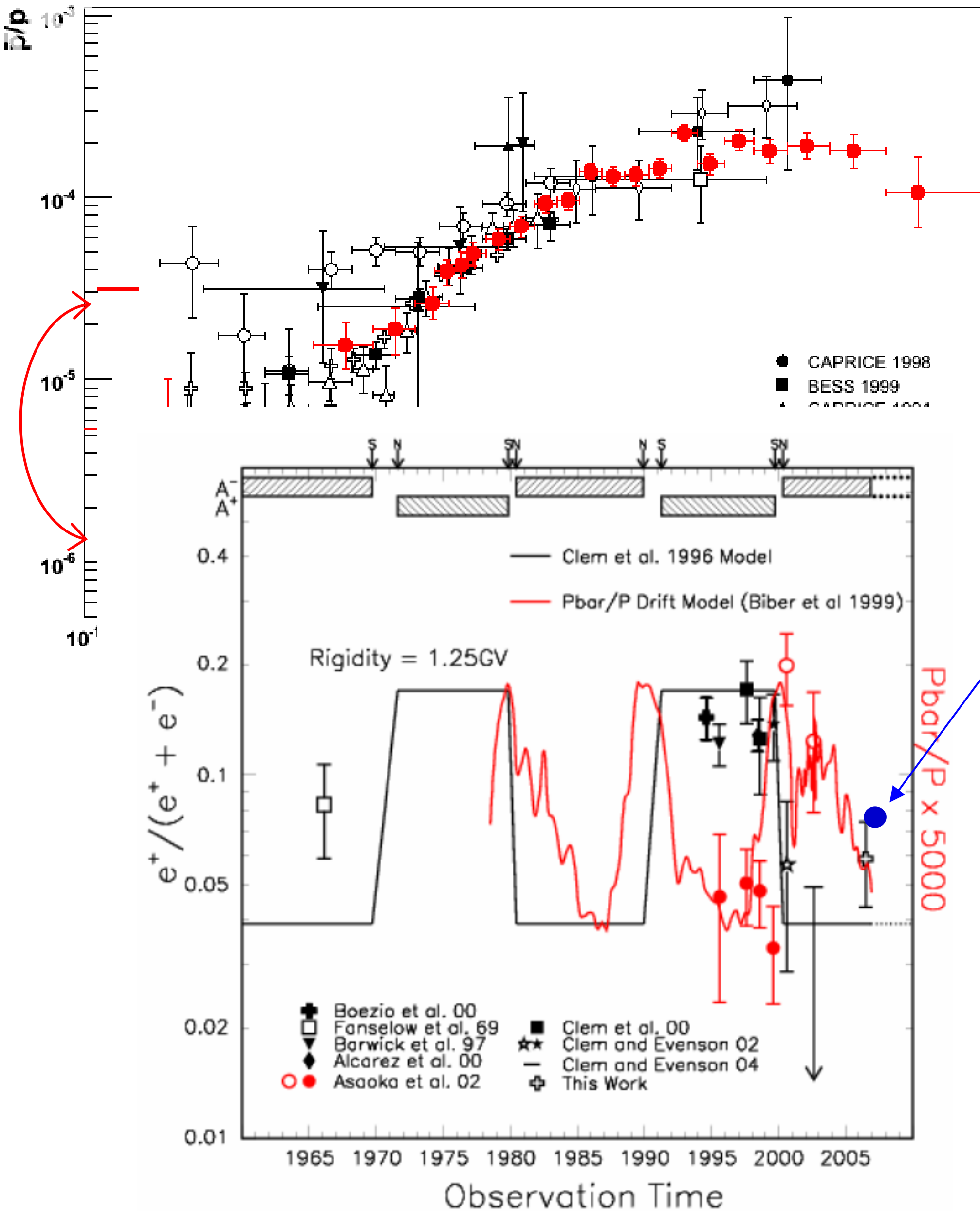
Solar modulation

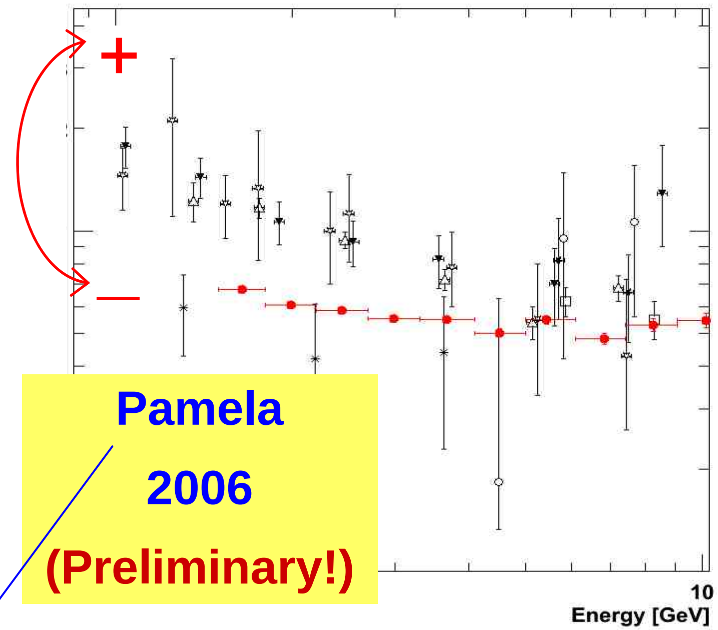


Solar modulation



Charge dependent solar modulation

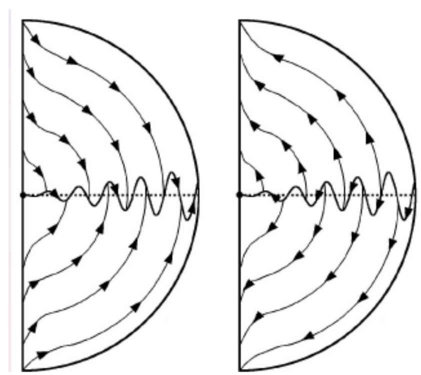




Pamela

2006

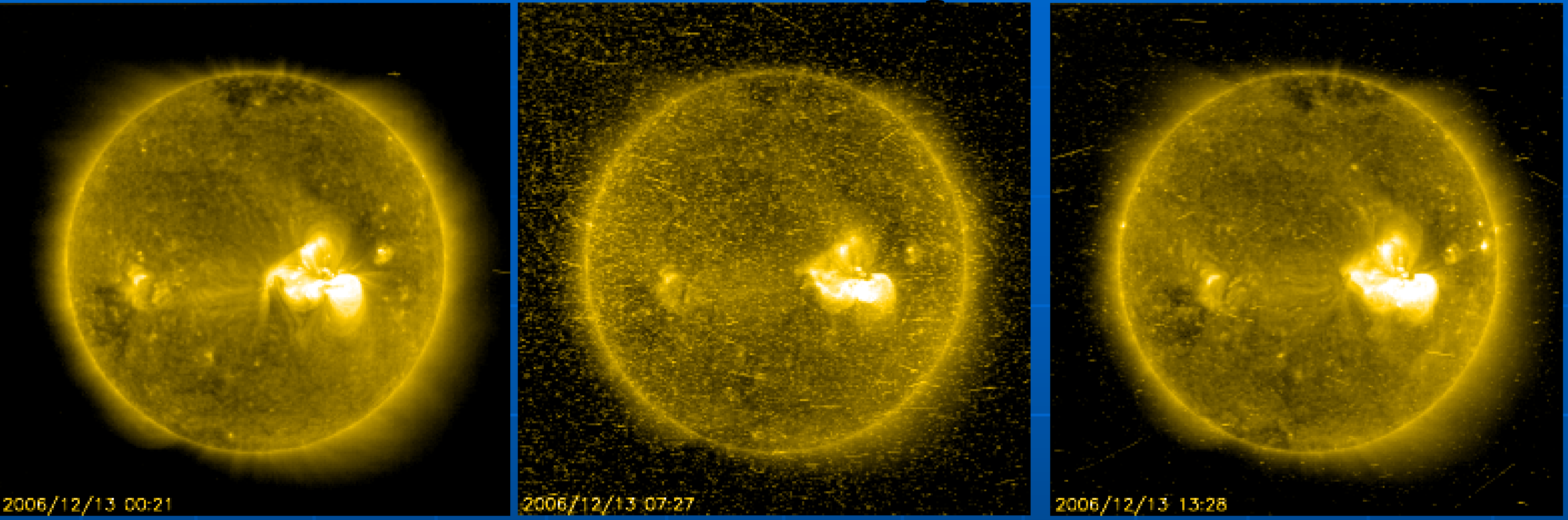
(Preliminary!)



A > 0 A < 0

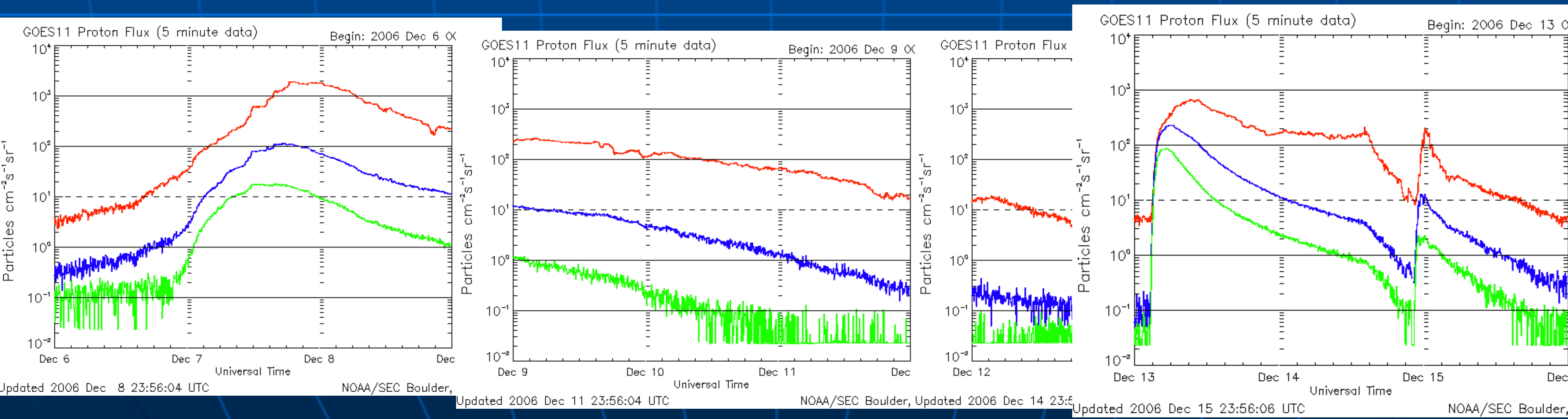
Positive particles

December 2006 Solar particle events

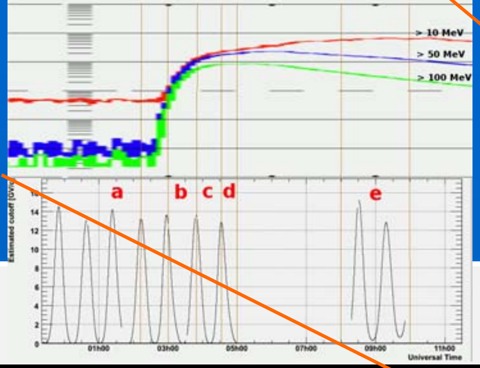


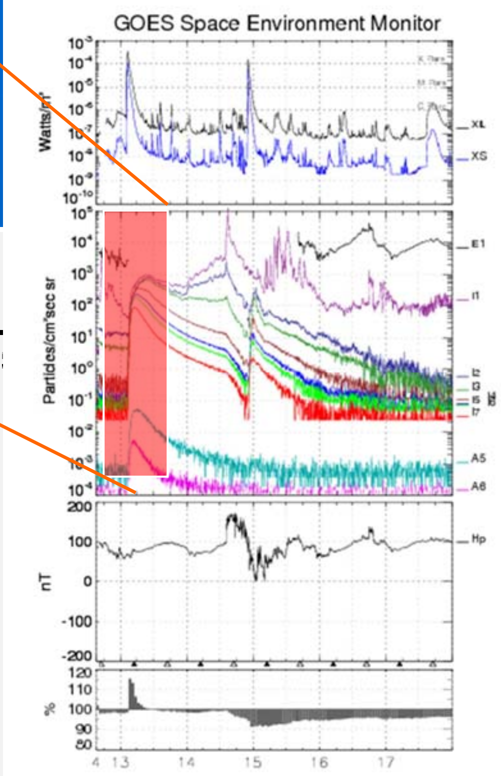
Dec 13th largest CME since 2003, anomalous at sol min

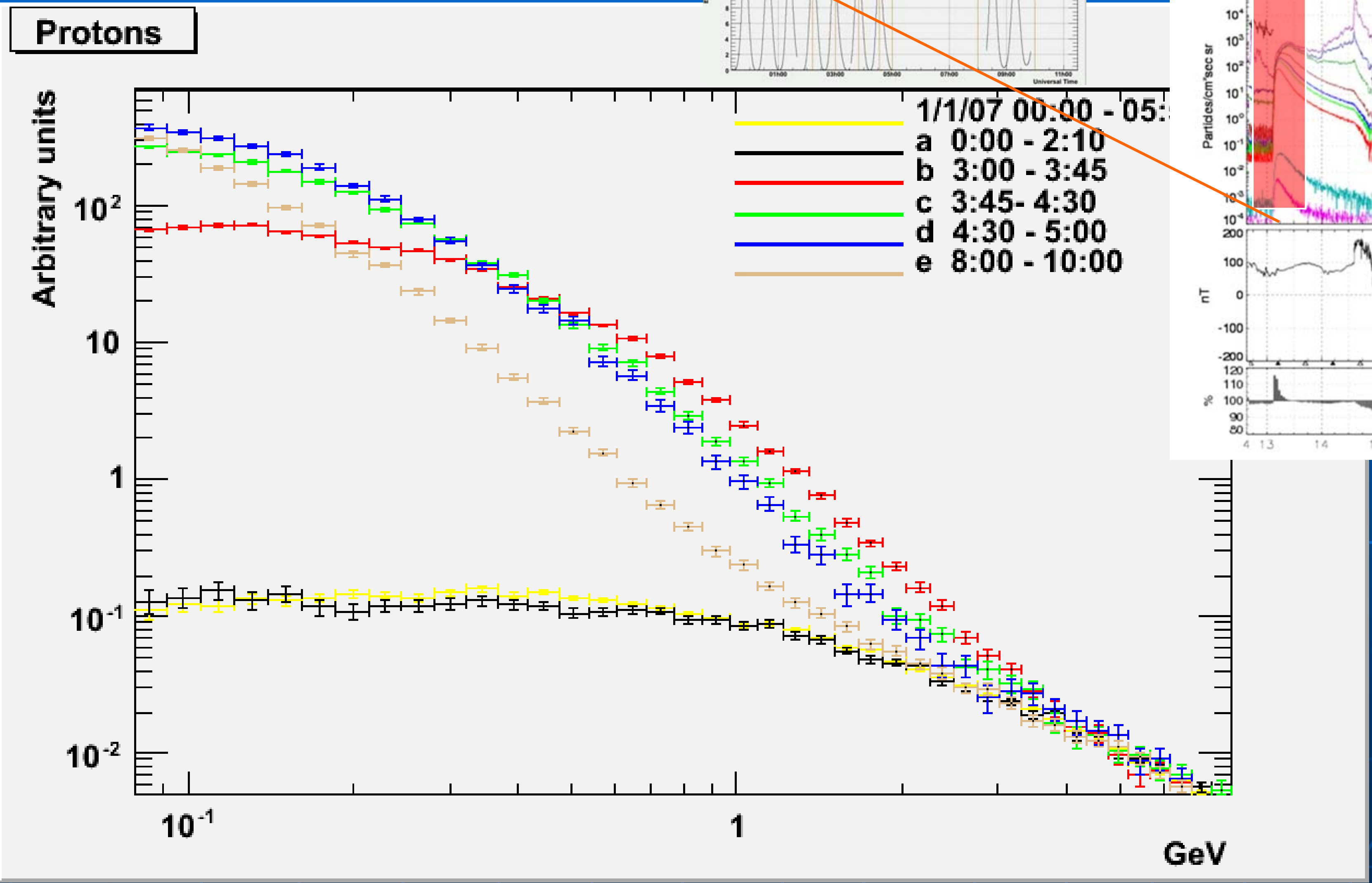
X3.4 solar flare



December 13th 2006 event

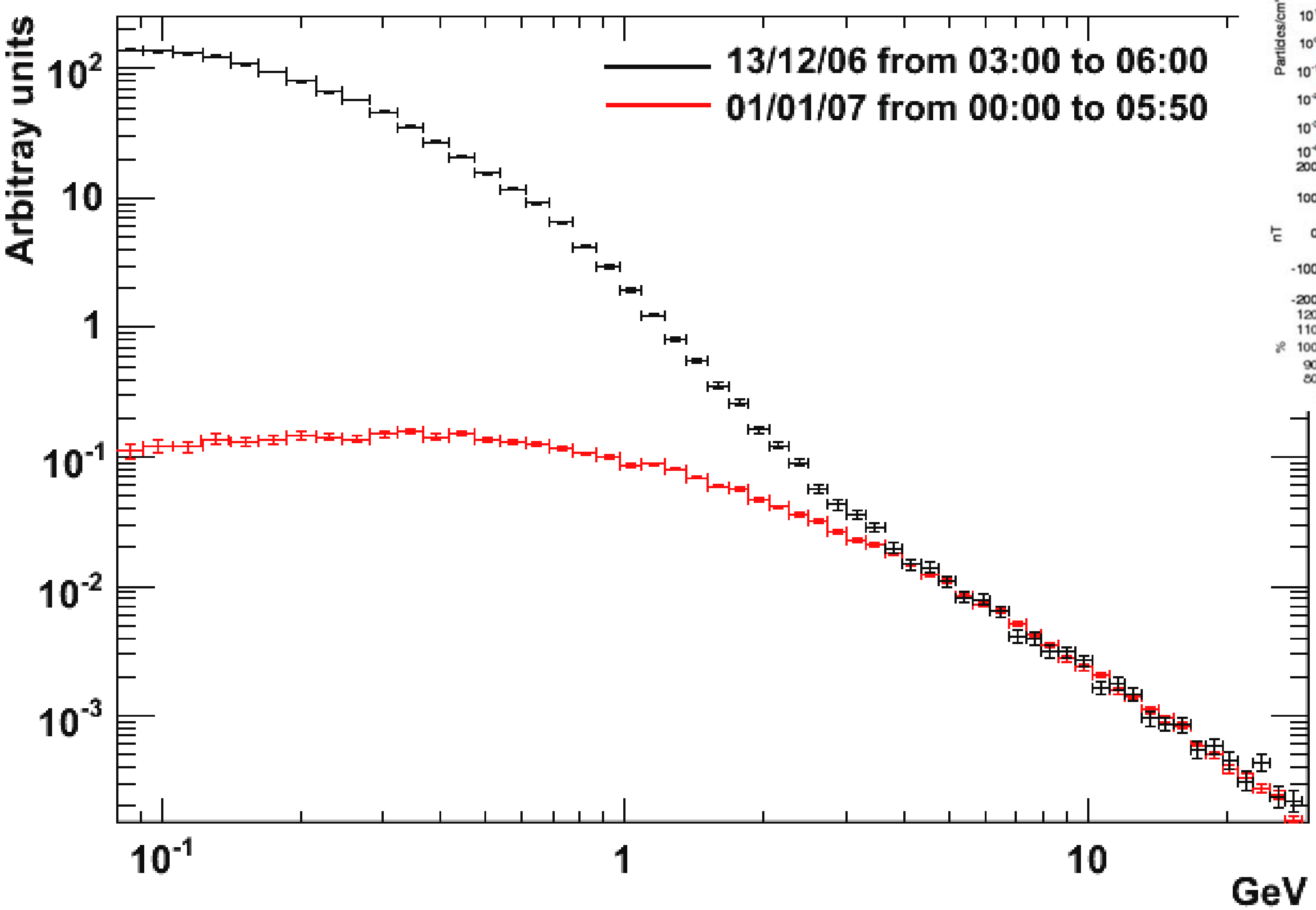


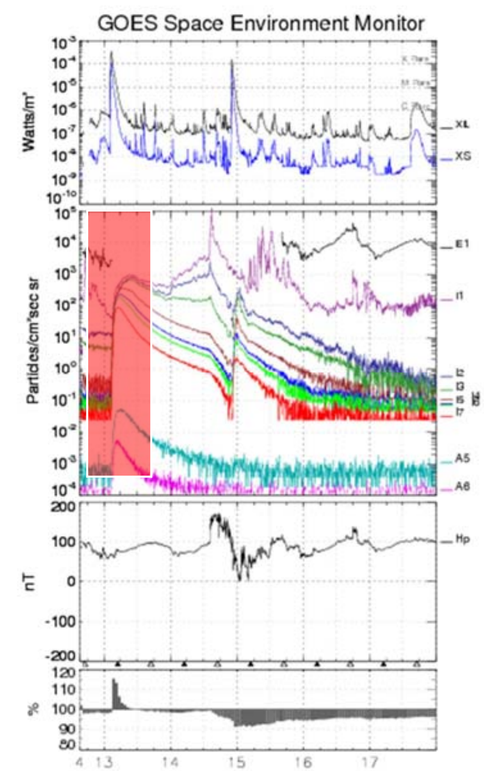




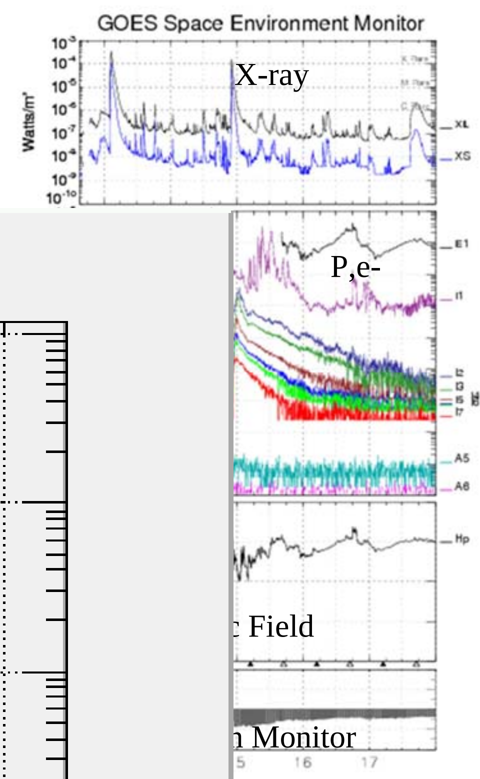
Preliminary!

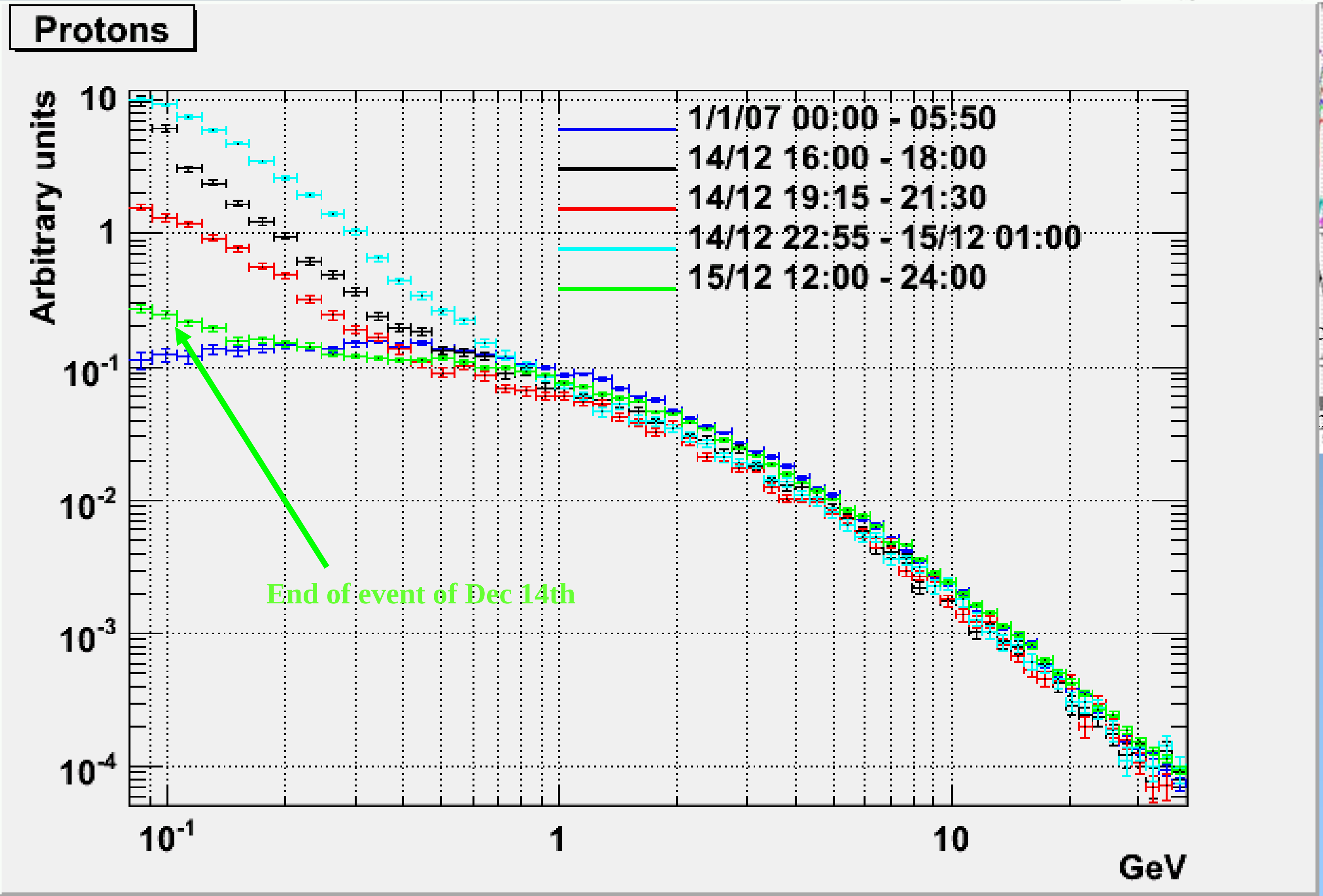
December 13th 2006 He differential spectrum





December 14th 2006 event





Preliminary!

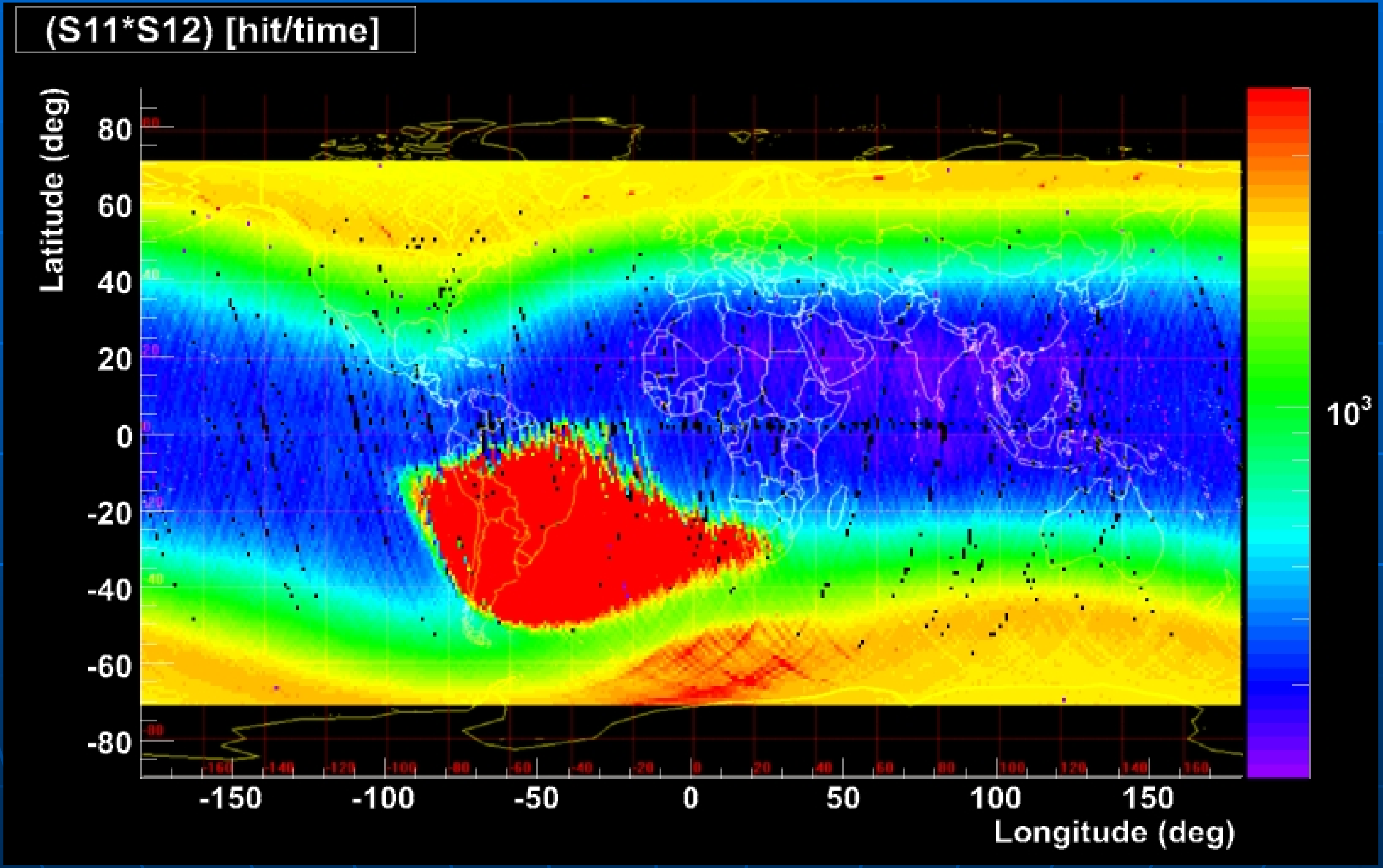
Radiation Belts

South Atlantic Anomaly

Secondary production from CR interaction with atmosphere

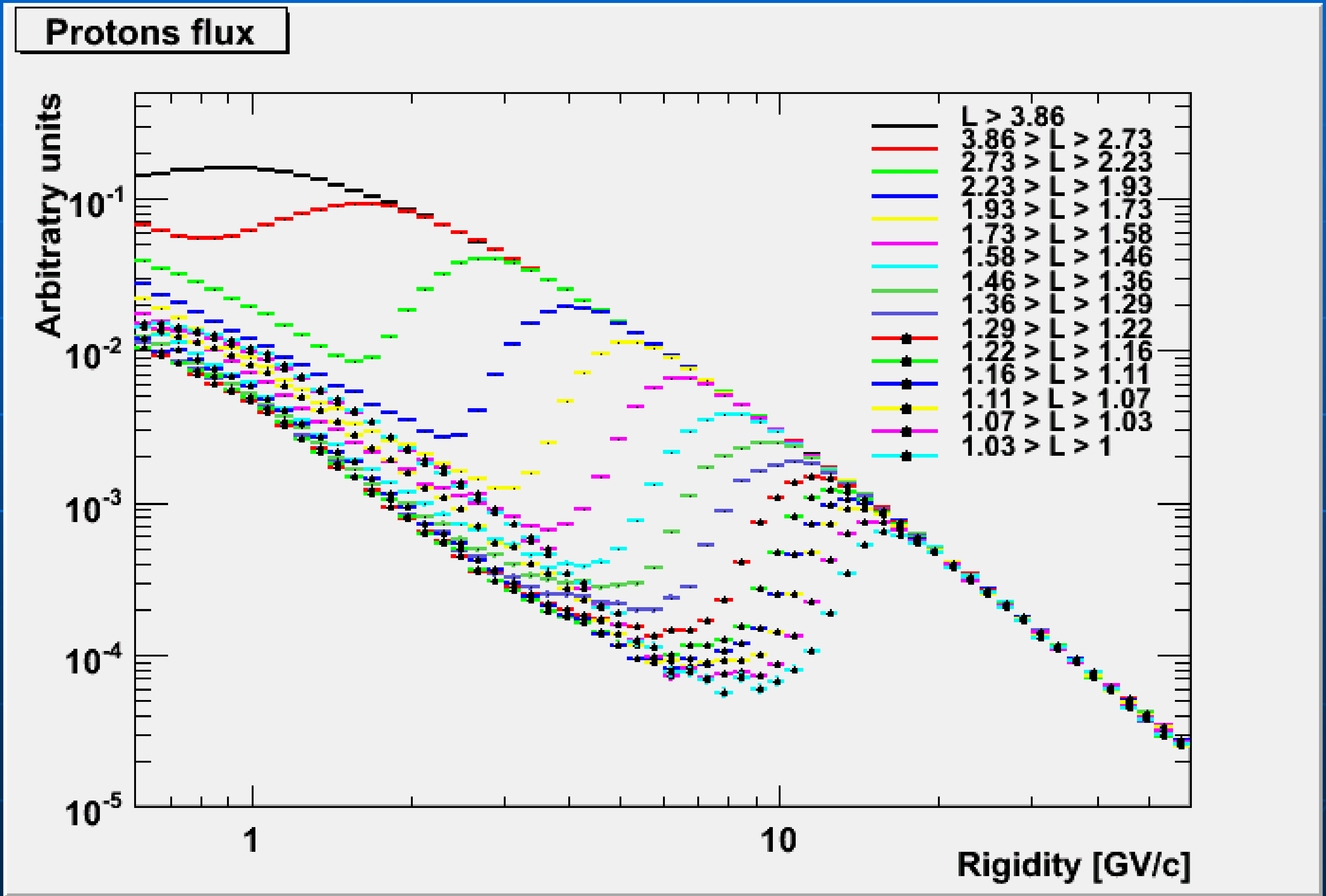
Study terrestrial magnetosphere

Pamela World Maps: 350 – 650 km alt

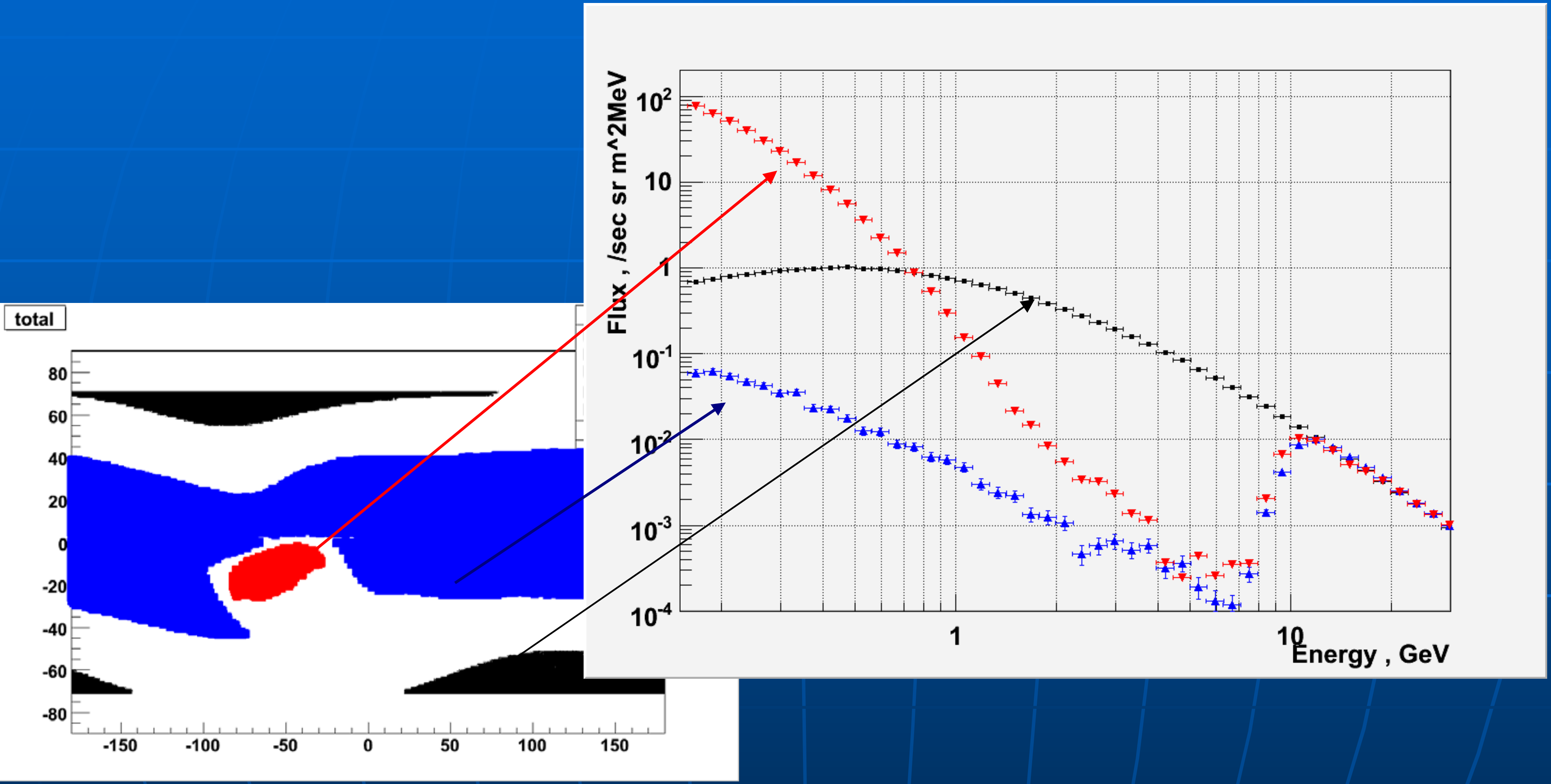


36 MeV p, 3.5 MeV e-

Subcutoff particles



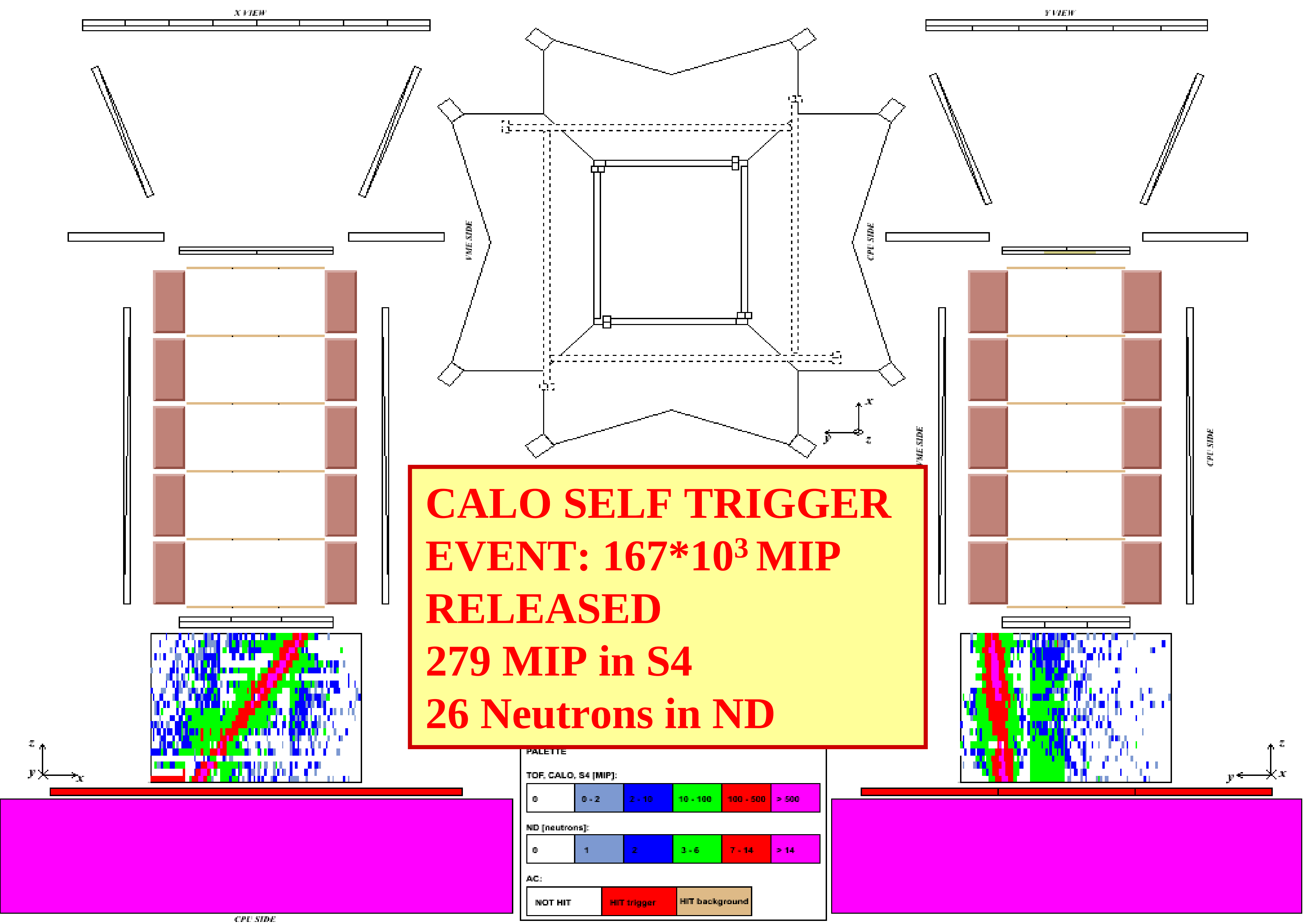
Proton spectrum in SAA, polar and equatorial regions



Other Objectives

High Energy electrons

- The study of primary electrons is especially important because they give information on the nearest sources of cosmic rays
- Electrons with energy above 100 MeV rapidly loss their energy due to synchrotron radiation and inverse Compton processes
- The discovery of primary electrons with energy above 10^{12} eV will evidence the existence of cosmic ray sources in the nearby interstellar space ($r \leq 300$ pc)



CALO SELF TRIGGER EVENT: 167*10^3 MIP RELEASED

279 MIP in S4

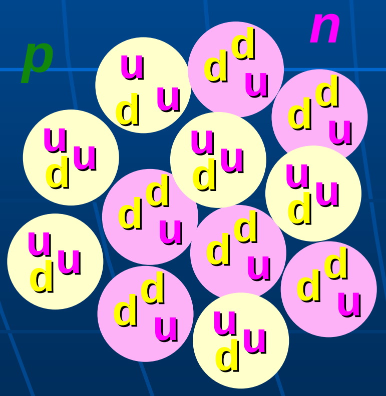
26 Neutrons in ND

Search for New Matter in the Universe:

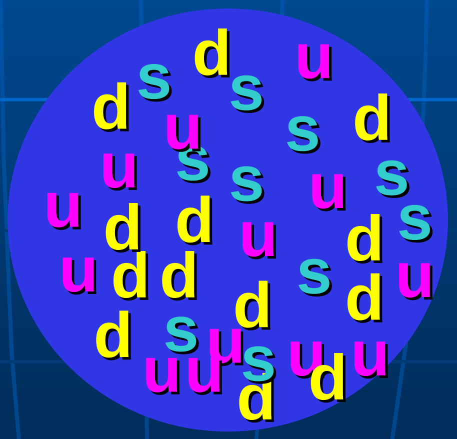
An example is the search for “strangelets”.

There are six types of Quarks found in accelerators. All matter on Earth is made out of only two types of quarks. “Strangelets” are new types of matter composed of three types of quarks which should exist in the cosmos.

Carbon Nucleus



Strangelet



i. **A stable, single “super nucleon” with three types of quarks**

ii. **“Neutron” stars may be one big strangelet**

AMS courtesy

Thanks!

http:// pamela.roma2.infn.it