The Science of the Pamela Space Mission

Payload for **A**ntimatter **M**atter **E**xploration and **L**ight Nuclei **A**strophysics

Piergiorgio Picozza
INFN and University of Rome
“Tor Vergata”

Whorkshop on the Russian-Italian Cooperation in the Cosmic Ray Physics and Astroparticle Physics

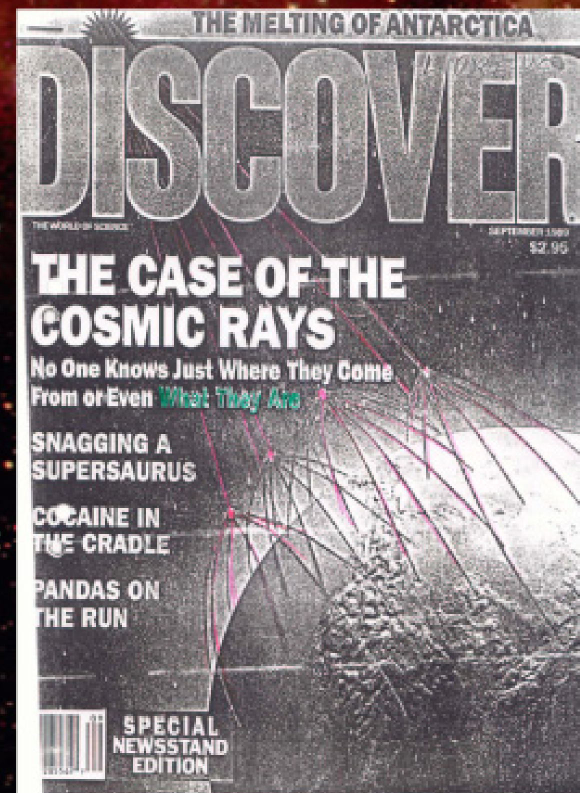
Moscow, 17-20 October 2005

~100 years of Cosmic Rays Research

1912

Discovery of radiation from space

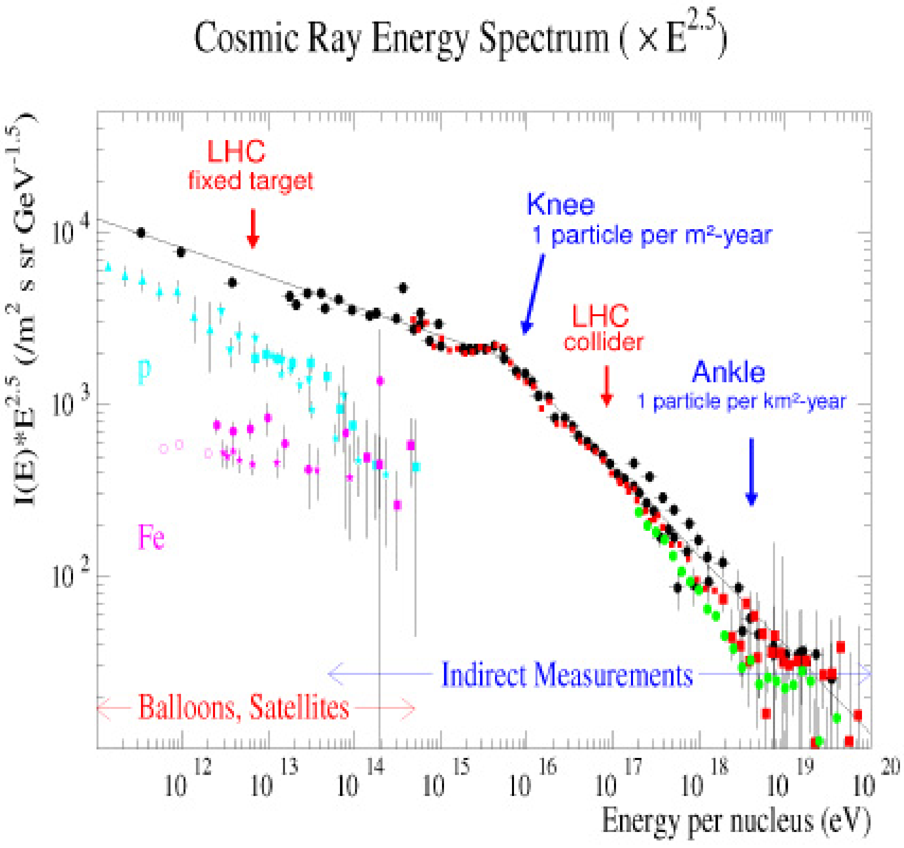
~ 2000

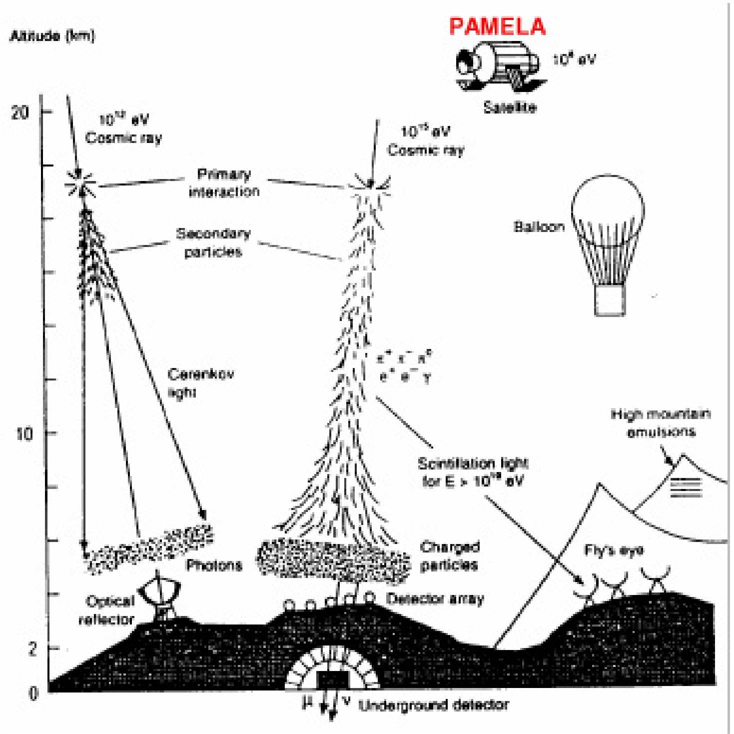


The Main Questions in Cosmic Ray Research

- Where do the particles come from?
- How and where do they get accelerated?
- How do they propagate through the interstellar medium and what kind of interactions do they encounter?
- What role do they play in the energy budget of the interstellar medium?
- Do we find hints of the existing of "exotic " particles. (Relict particles from the early Univers)? Dark Matter , Antimatter

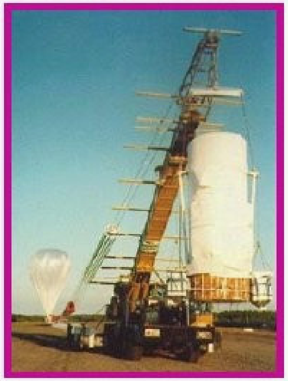
The Cosmic Ray Energy Spectrum
and various Techniques of their Measurements





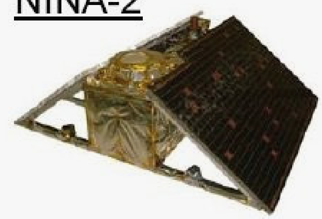
WiZard RIM Program

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

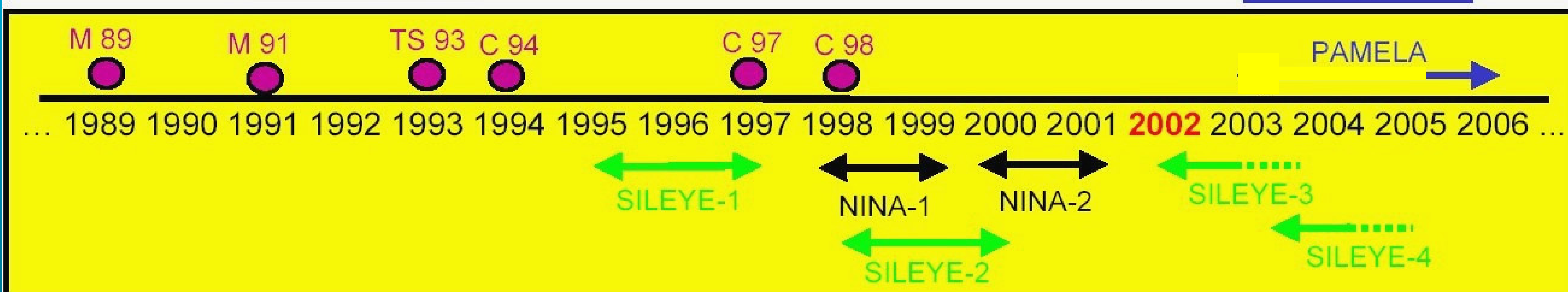


NINA-1

NINA-2



PAMELA



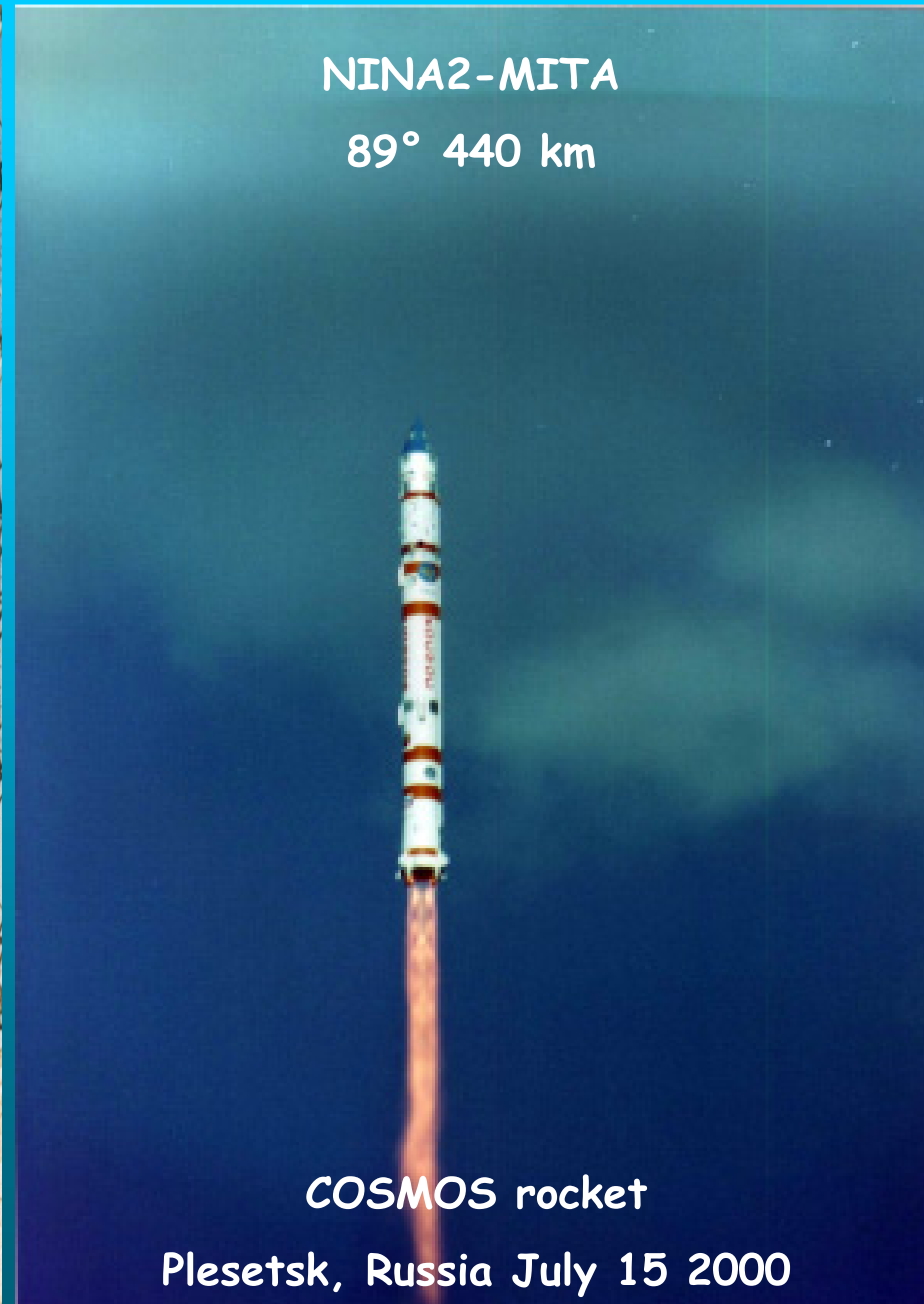
SILEYE-1

SILEYE-2

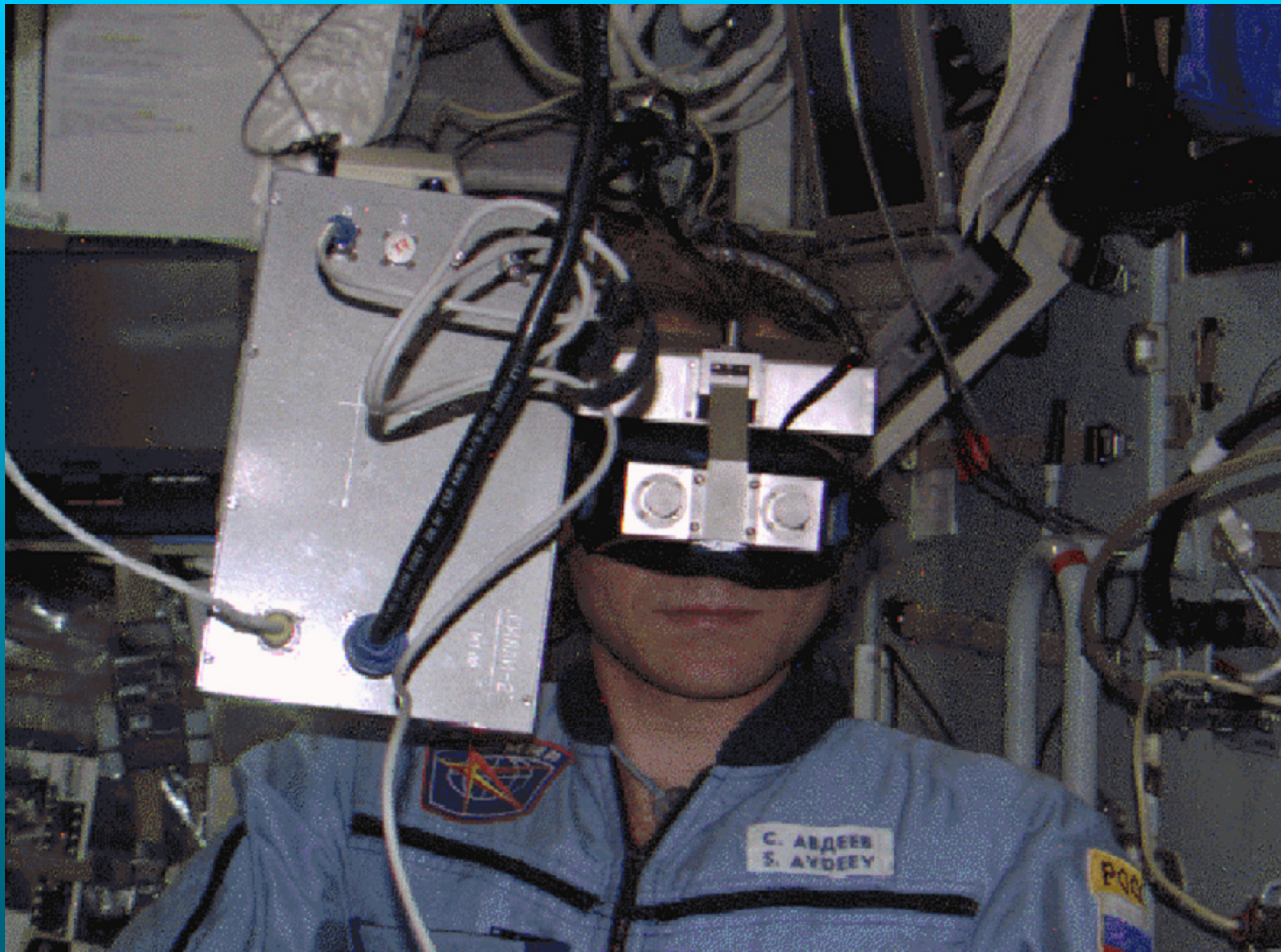
ALTEINO: SILEYE-3

ALTEA: SILEYE-4


NINA-RESURS
97° 810 km
ZENIT rocket
Baikonur, Kazakhstan July 10 1998


NINA2-MITA
89° 440 km
COSMOS rocket
Plesetsk, Russia July 15 2000

Cosmonaut S. Avdeev during measurements with SilEye-2 apparatus on "Mir" Space Station



Pamela Collaboration

Italy:

Bari

Florence

LNF

Frascati

Naples

Tor Vergata

Rome

Trieste

IFAC

CNR, Florence

Russia:

Физический Институт

Ioffe Physico-Technical Institute

Moscow

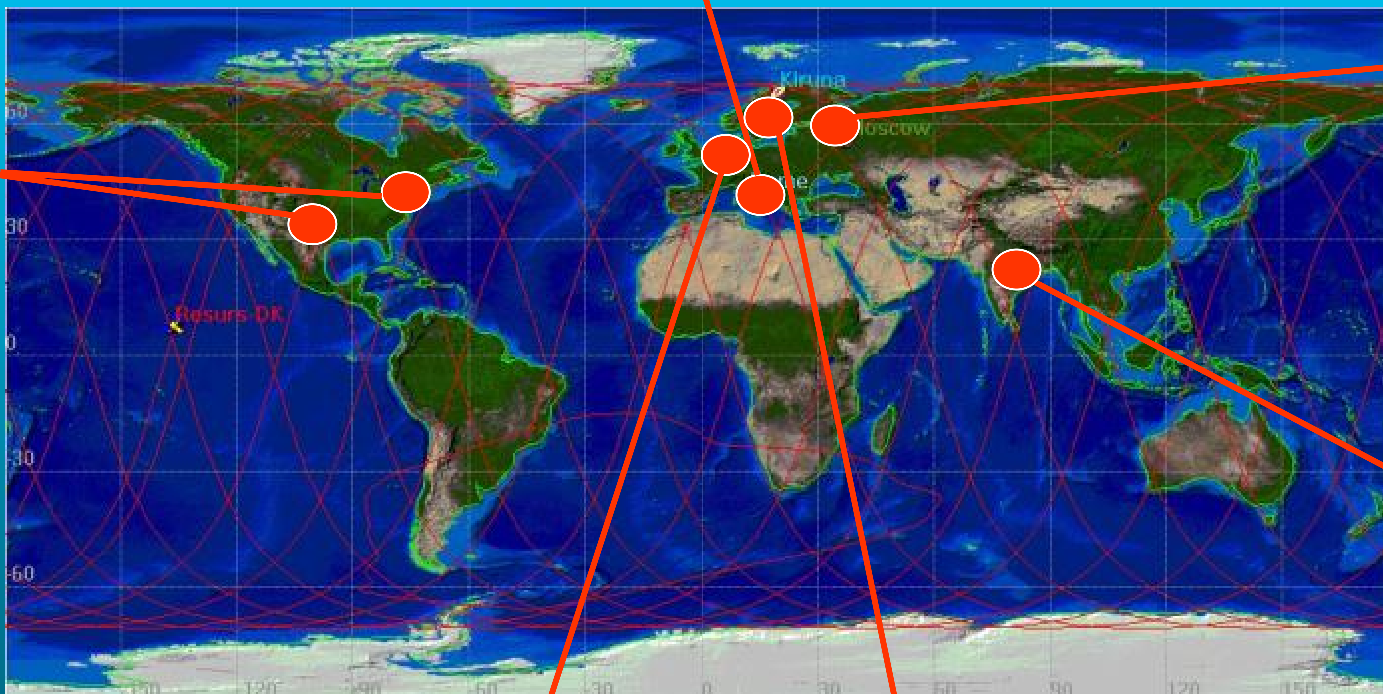
St. Petersburg

USA:

NASA

GSFC

NMSU



India:

TIFR

Tata Institute of Fundamental Research

Mumbay

Germany:

Universität Gesamthochschule Siegen

Siegen

Sweden:

Kungl Tekniska Högskolan

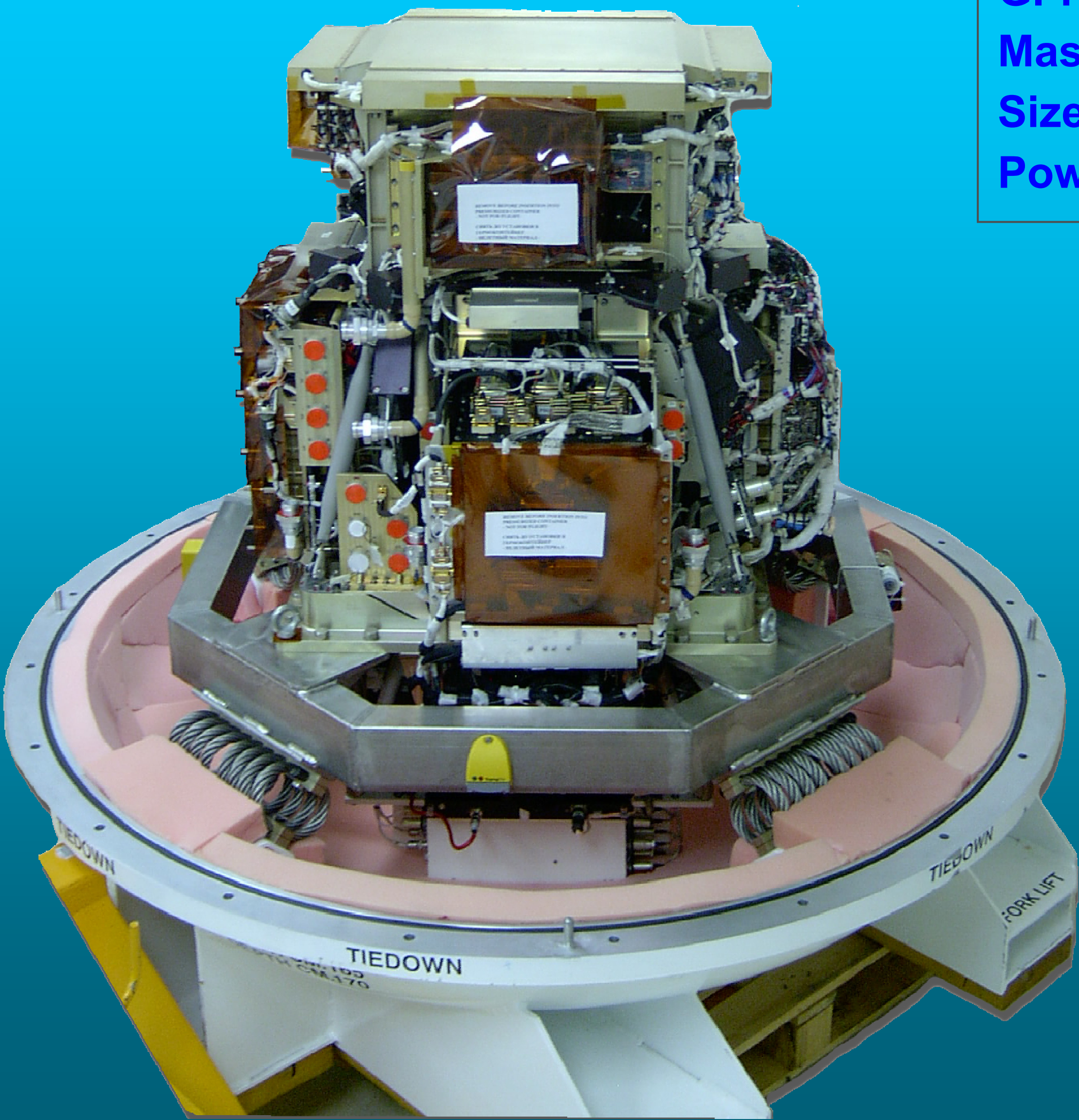
KTH, Stockholm

Main Funding Agencies

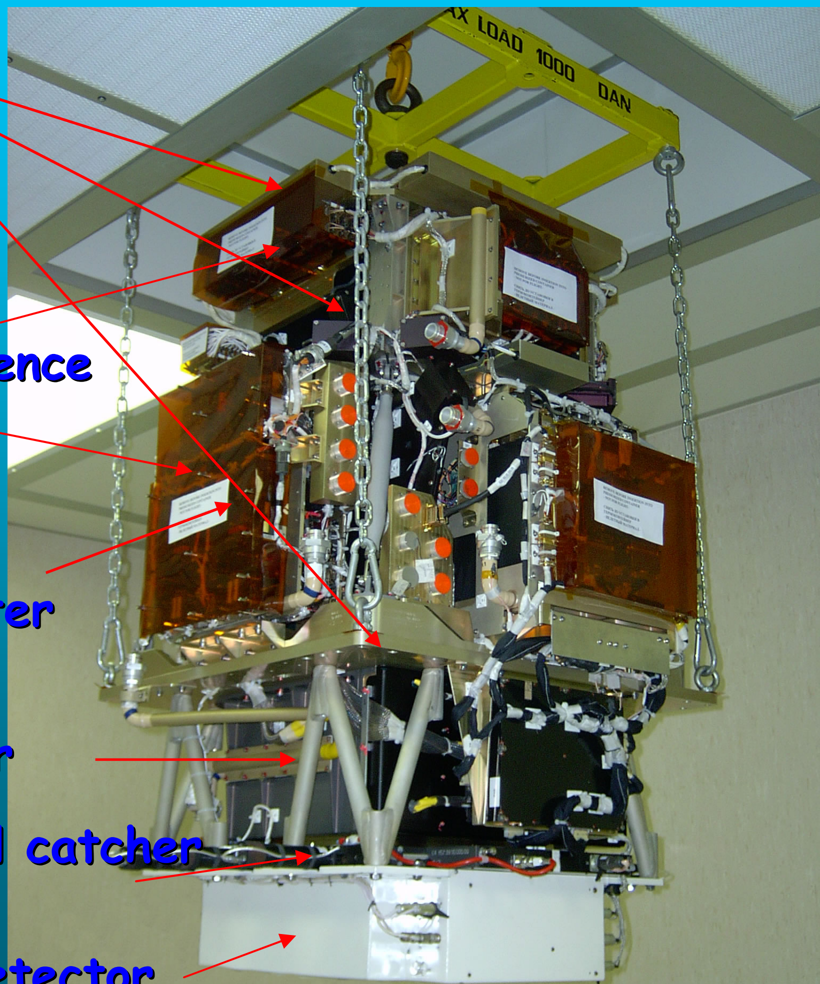
Roscosmos	Russia
RAS	Russia
INFN	Italy
ASI	Italy
MIUR	Italy
MAE	Italy
DLR	Germany
SNSB	Sweden

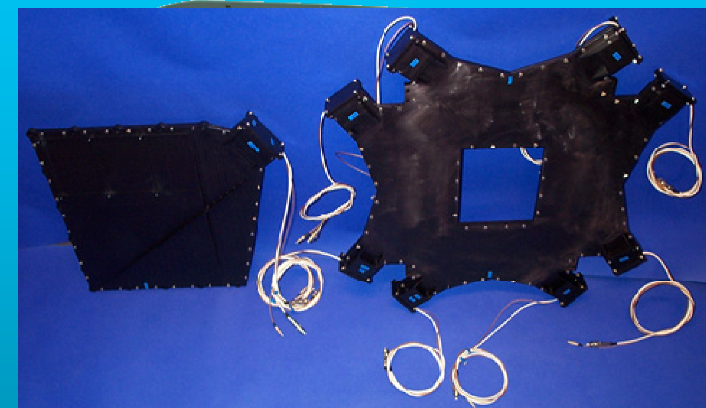
Pamela Flight Model

GF: 20.5 cm^2 sr
Mass: 470 kg
Size: 120x40x45 cm^3
Power Budget: 360W



PAMELA detectors





Particle identification

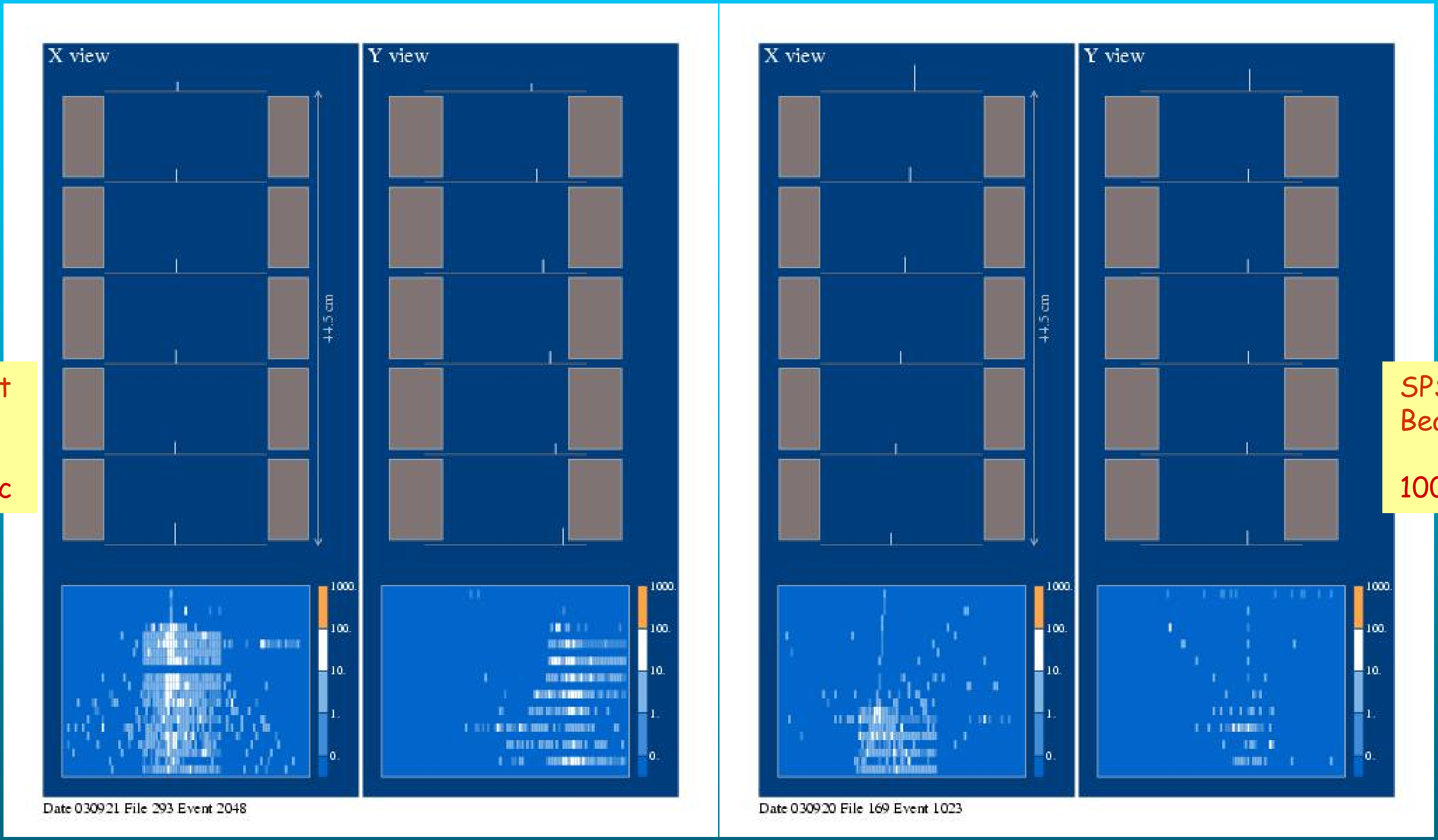
ANTICOINCIDENCE SHIELD

- Scintillator paddles 10 mm thick
- Dynamic range of 1÷1000 mip

between very high energy electron and proton components

Pamela Calibration

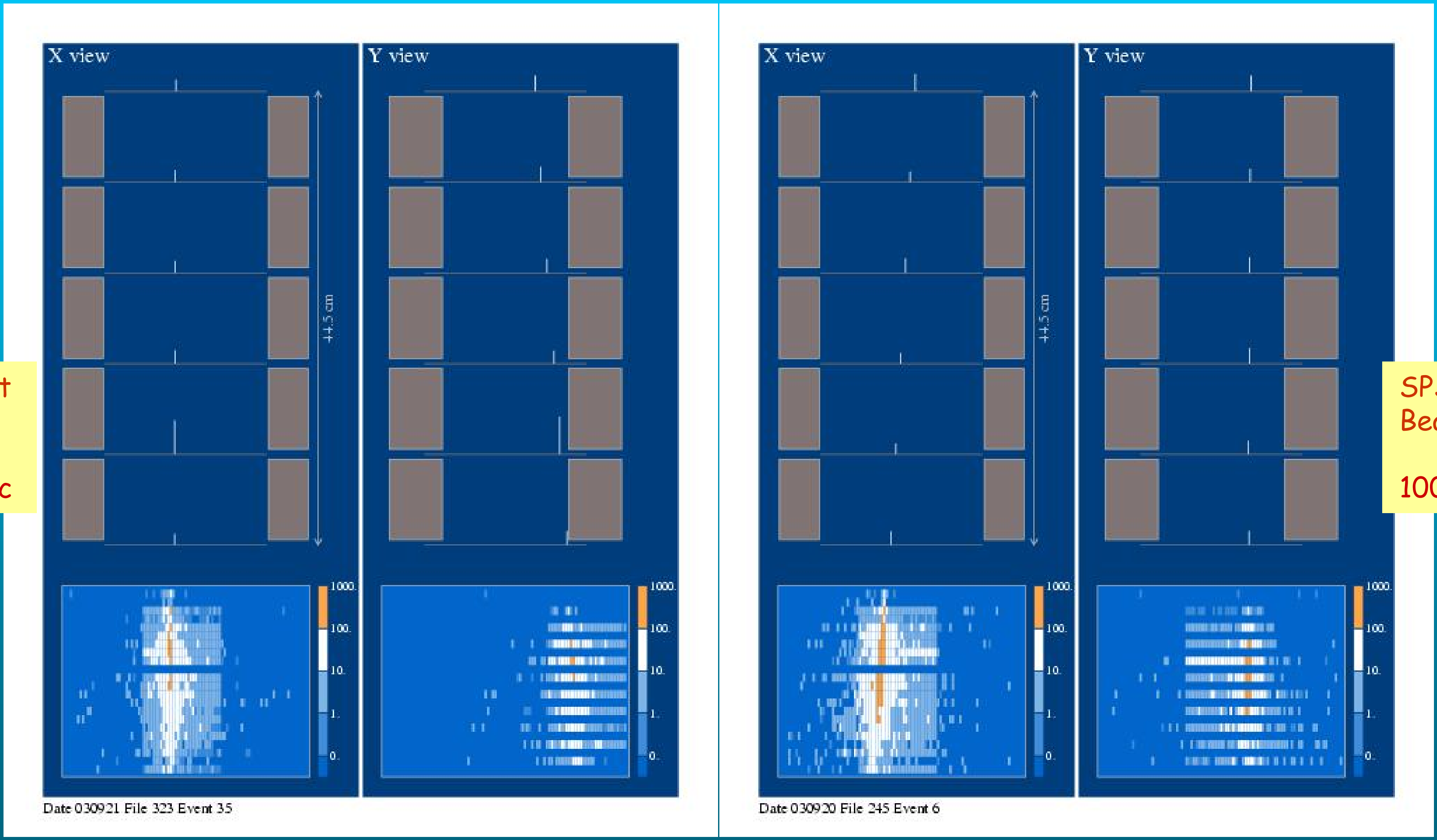
SPS Test Beam Data: p 50 GeV/c



SPS Test Beam Data: p 100 GeV/c

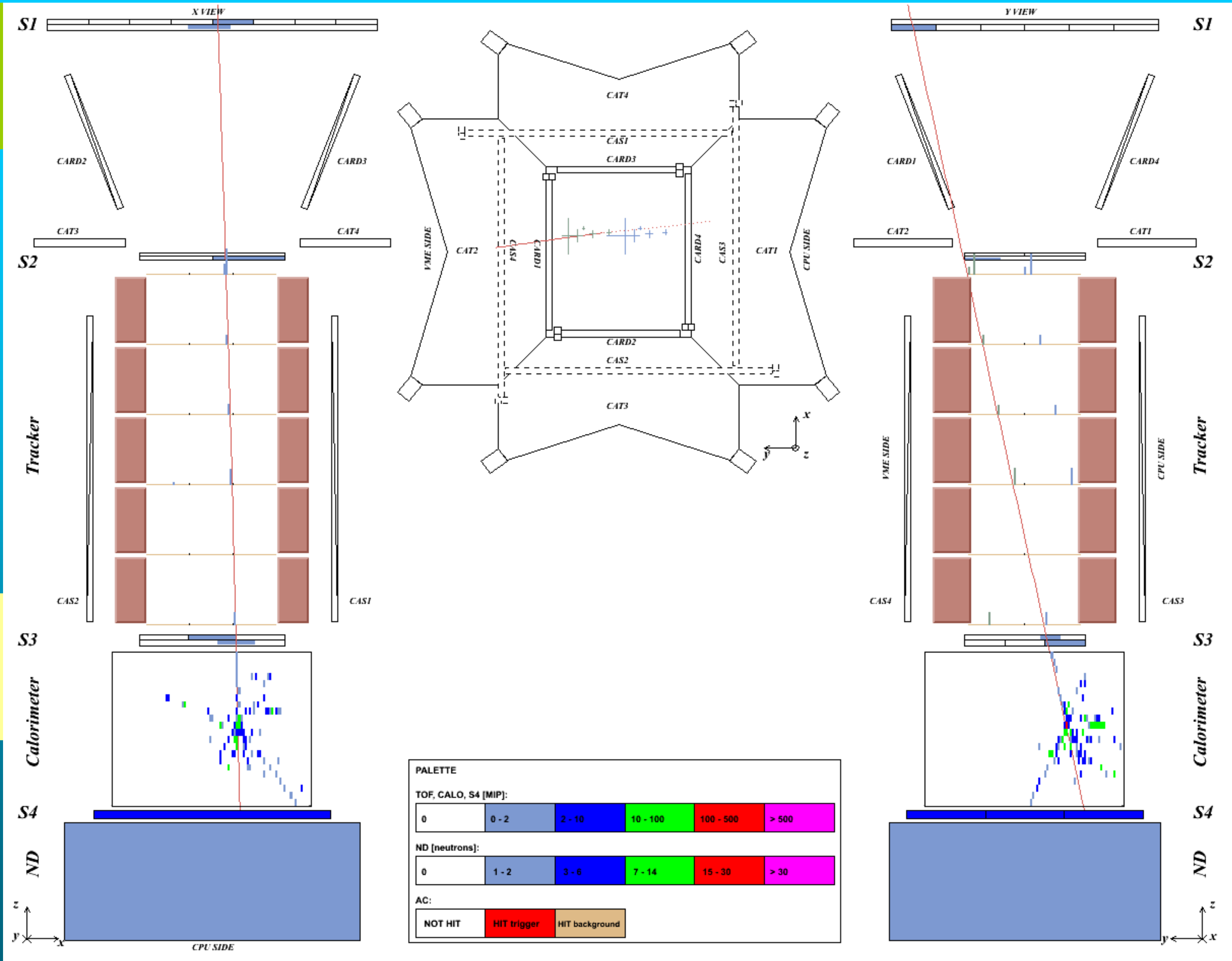
Pamela Calibration

SPS Test Beam Data: e^- 50 GeV/c



SPS Test Beam Data: e^- 100 GeV/c

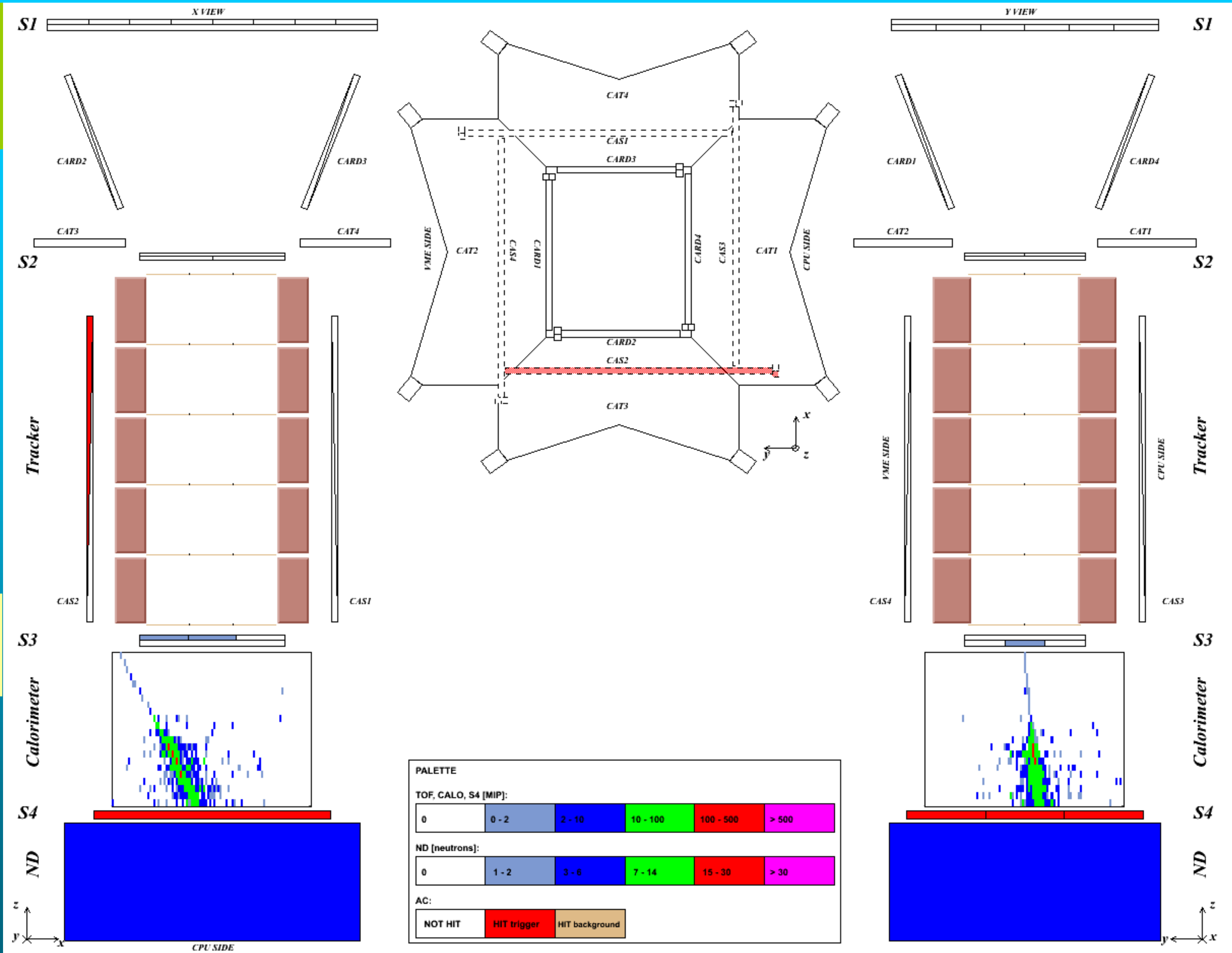
PAMELA Event



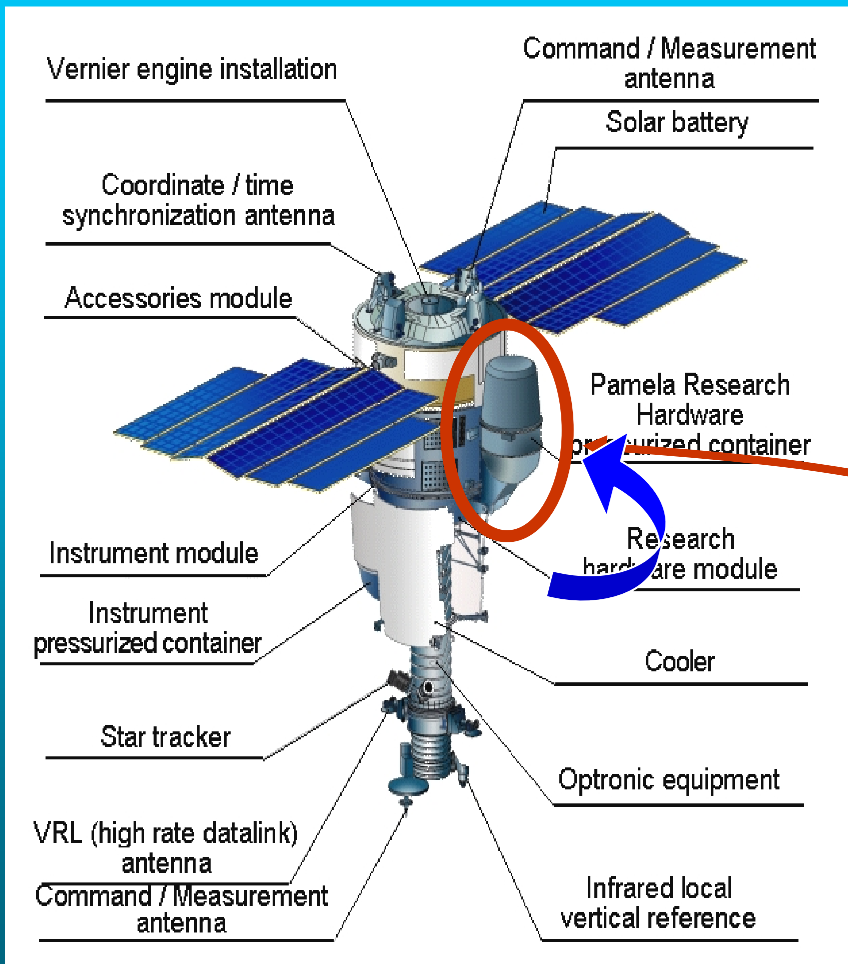
Ground Data Hadron: 6.6 GV

PAMELA Event

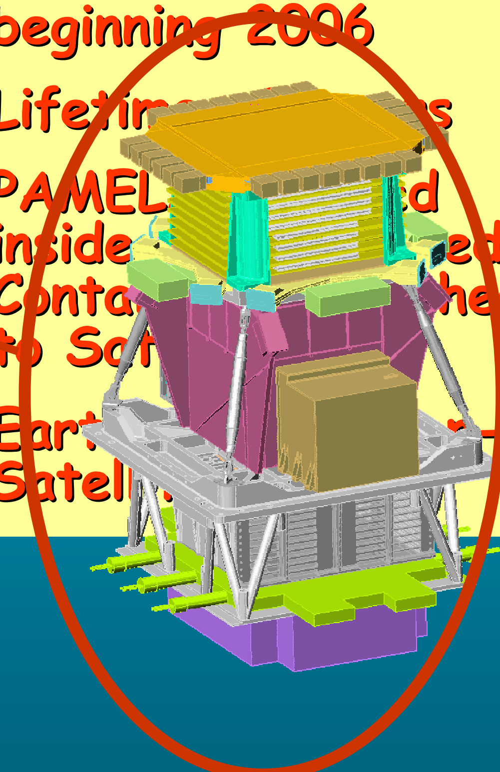
Calorimeter Self Trigger



The Satellite: Resurs DK1



- Soyuz-TM Launcher from Baikonur
- Launch end 2005- beginning 2006
- Lifeti s
- PAMEL d inside ed Conta hed to So
- Eart Satell

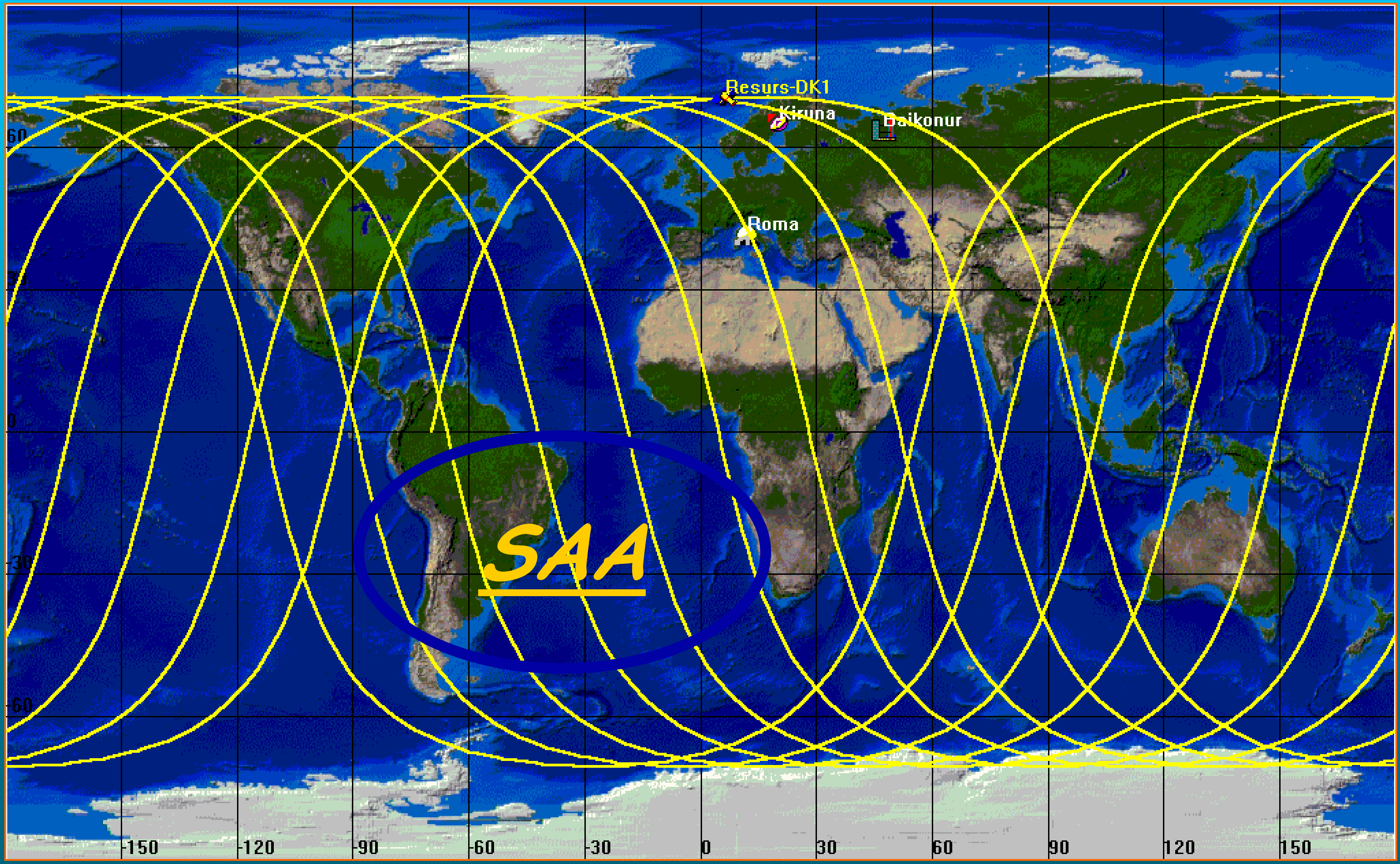


TsSKB-Progress-Samara-Russia

RESURS DK1 Satellite

quasi-polar (70.4°)
elliptical (300÷600 km)
3-years-long mission

Orbit characteristics



PAMELA Capabilities

- Positrons 50 MeV - 270 GeV
- Antiprotons 80 MeV – 190 GeV
- Limit on antinuclei ~10^{-8} ($\overline{He}$ /He)

- Electrons 50 MeV – 2TeV
- Protons 80 MeV – 700 GeV
- Nuclei < 200 GeV/n (Z < 6)
- Electron and proton components up to 10 TeV
- Long term monitoring of the solar modulation of Cosmic Rays

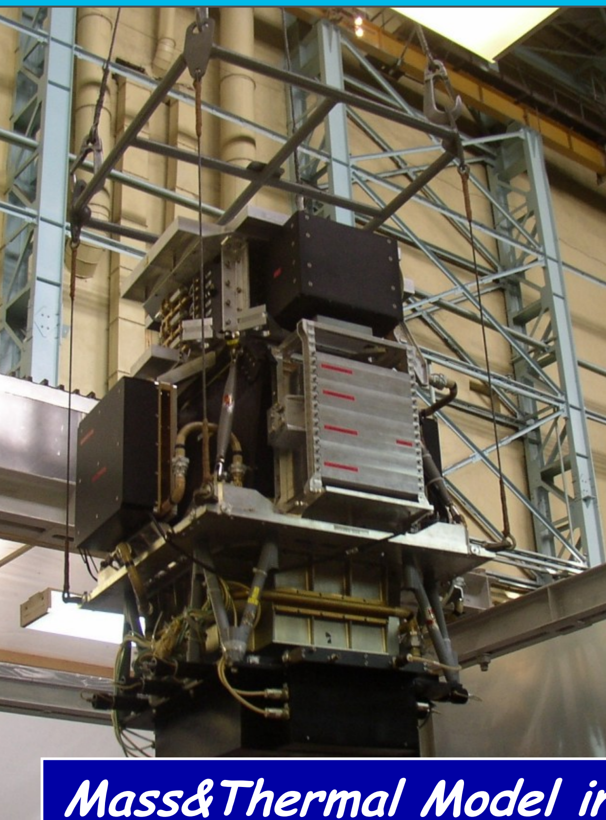
PAMELA: The " 3 Models "

(1) MASS &
THERMAL MODEL, for mechanical and thermal tests

(2) TECHNOLOGICAL MODEL, for electric, magnetic and data trasmission tests

(3) FLIGHT MODEL, now installed on the satellite and under final test

Mass & Thermal Model

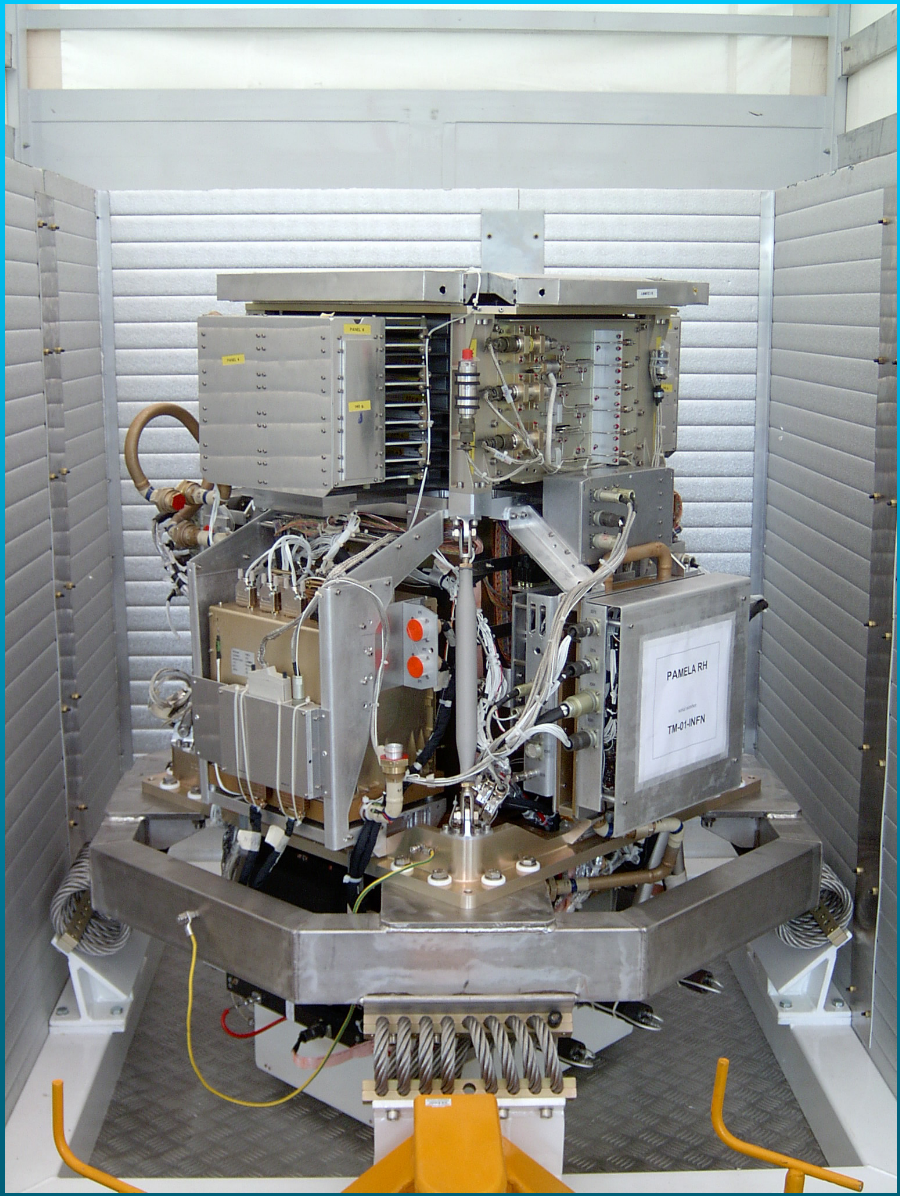


Mass&Thermal Model in TsSKB

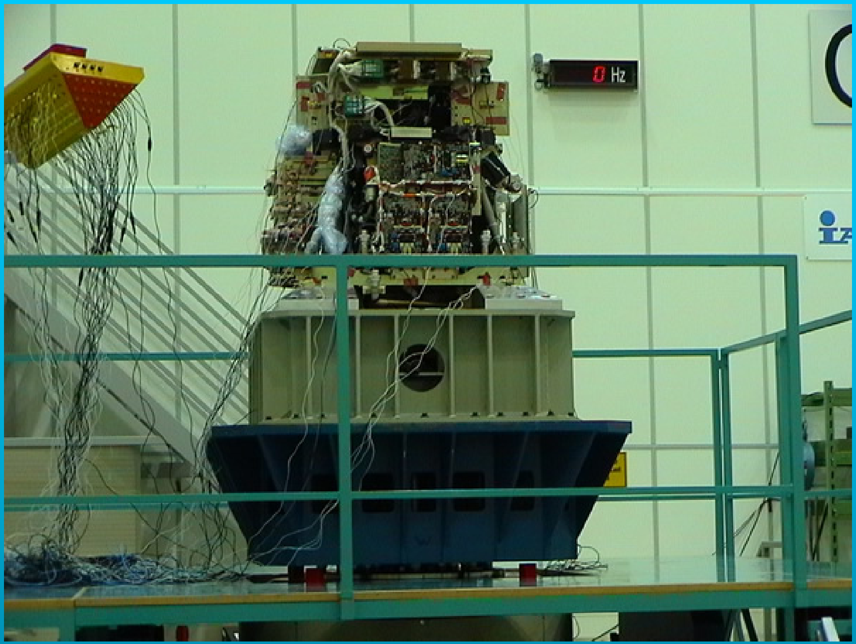
Pressurized C

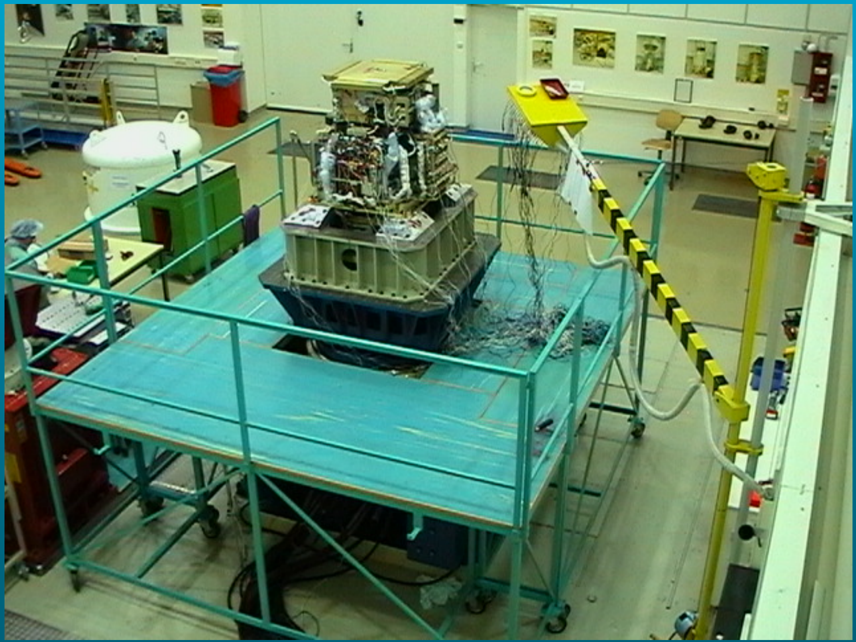
Integration in the Container

Technological Model

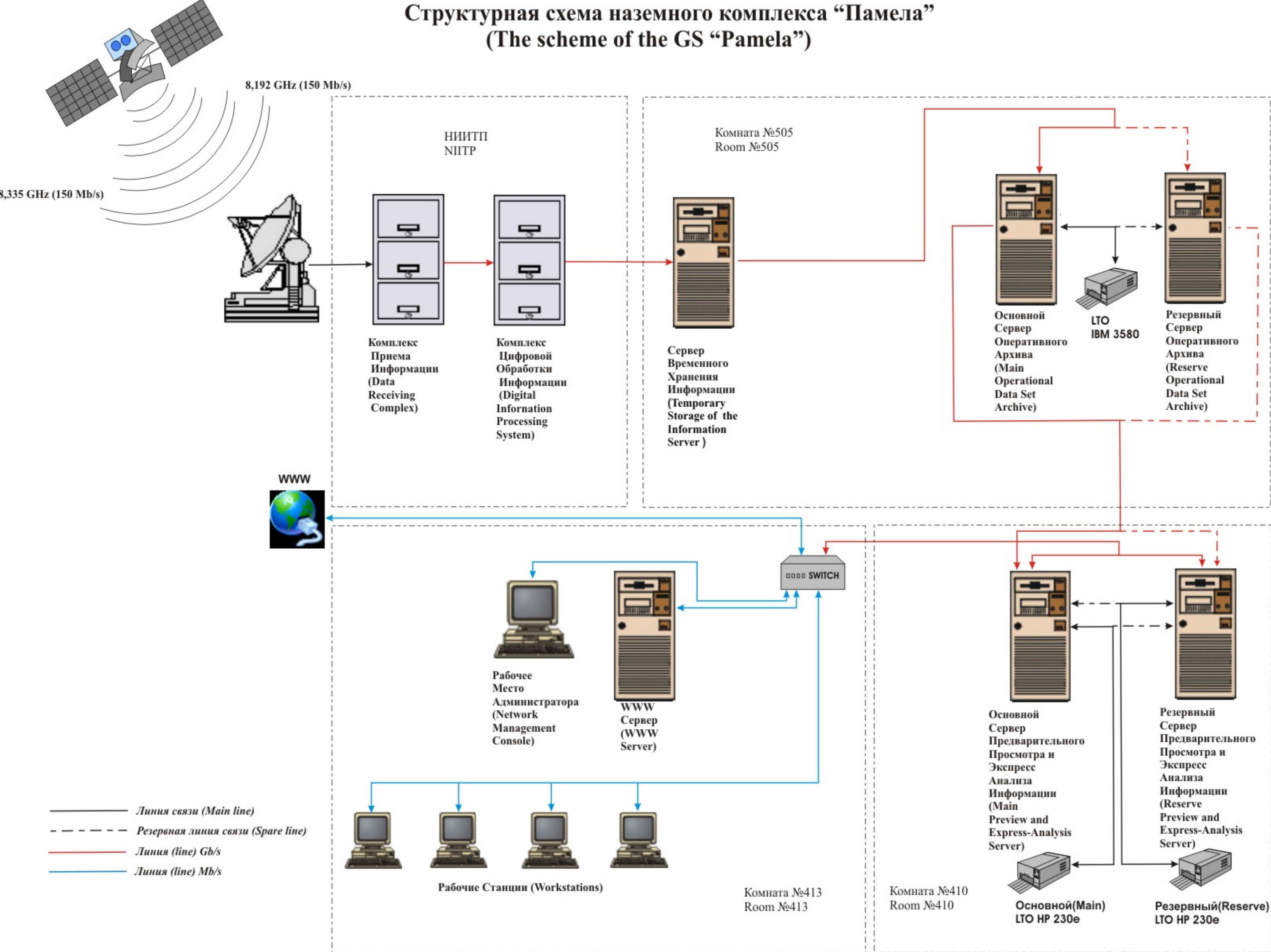


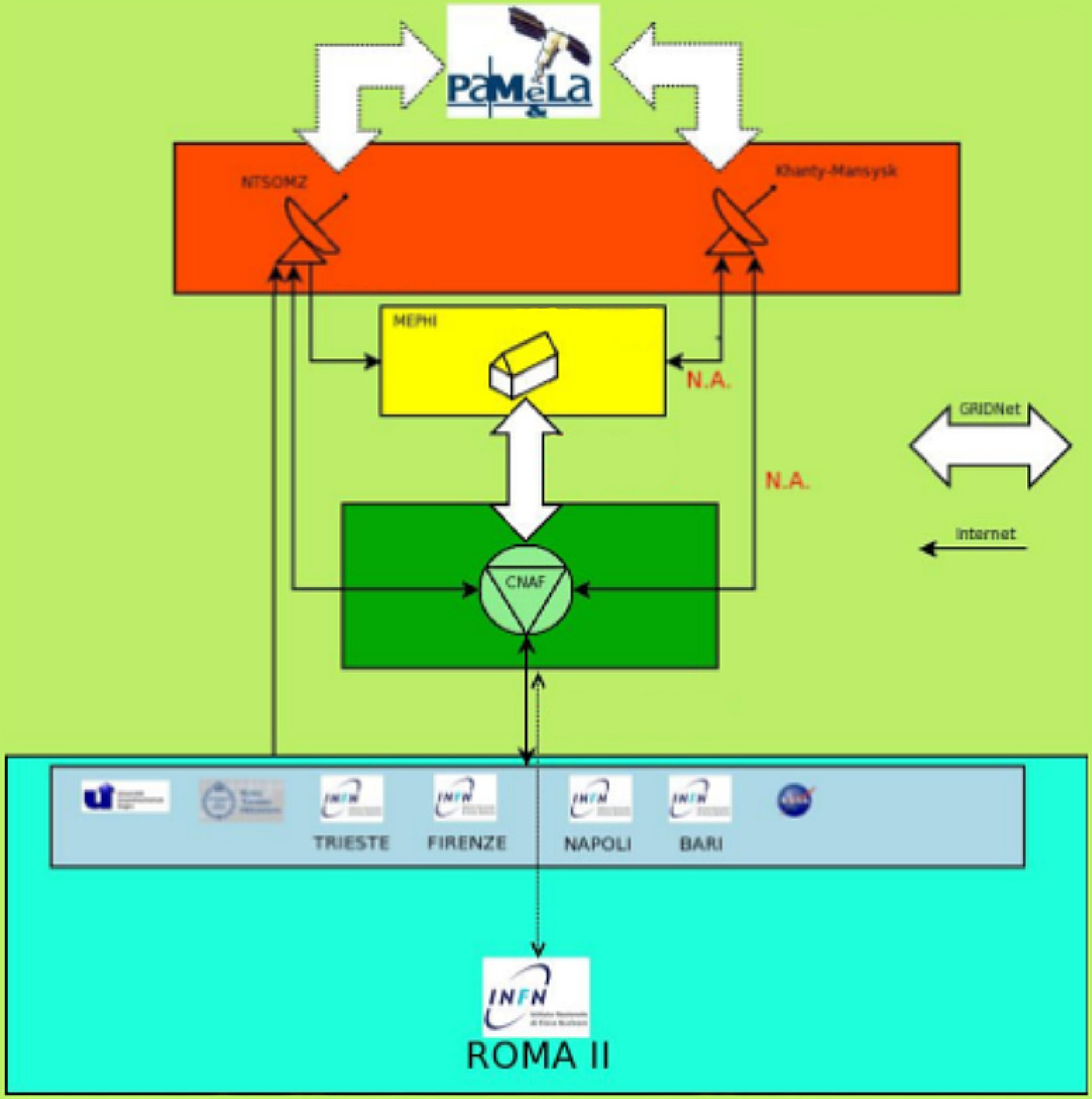
FLIGHT MODEL TEST - IABG/ Munich, January 2005





Структурная схема наземного комплекса “Памела”
(The scheme of the GS “Pamela”)



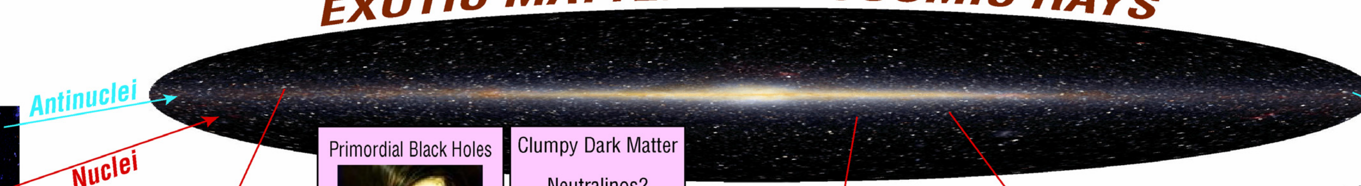


PaMeLa
NTSOMZ
Khanty-Mansysk
MEPHI
N.A.
GRIDNet
N.A.
Internet
CNAF
TRIESTE
FIRENZE
NAPOLI
BARI
INFN
ROMA II

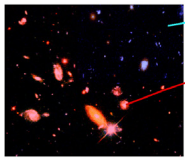
The Science of PAMELA

TEMPO

EXOTIC MATTER AND COSMIC RAYS

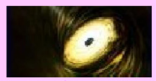


Extragalactic matter and antimatter domains?



~100 Mpc

Primordial Black Holes



Clumpy Dark Matter

Neutralinos? Other WIMPs?

SOLAR ACTIVITY

Measurements of primary proton and helium spectra and spectra of heavier nuclei

Search for dark matter

Search for an excess of positron and antiproton flux over the predicted secondary spectra

Precise measurements of antiproton and positron spectra; modeling secondary antiproton and positron spectra

Fluxes of protons, antiprotons, electrons and positrons measured simultaneously

Study of cosmic ray transport models

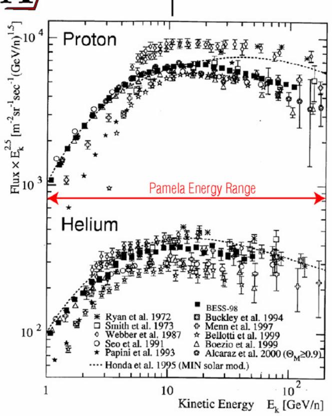
Study of charge-sign dependence of solar modulation

Search for primary antimatter

Study of solar flares

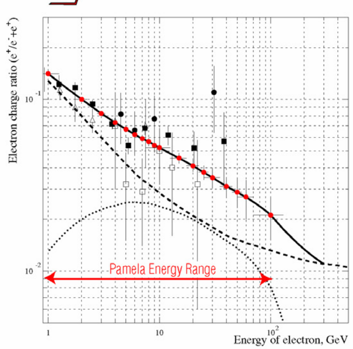
Study of acceleration processes; abundances of the elements; measurement of the positron fraction

A



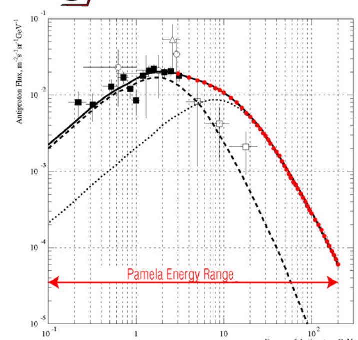
Cosmic Ray Proton and Helium Spectra. Pamela will measure these fluxes with a precision of 1% for protons and 5% for helium at the highest energy of 200 GeV/n.

B



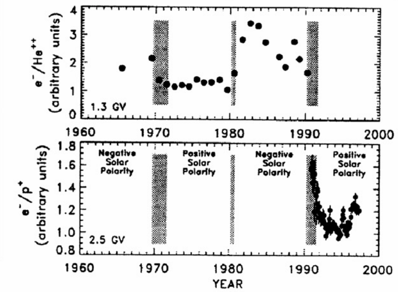
Distortion of the secondary positron fraction (dashed line) due to one possible contribution from neutralino annihilation (dotted line, from Baltz and Edsjo, 1998). Filled circles - TS-93 (Golden et al. 1996), open triangles - CAPRICE-94 (Barbiellini et al. 1996), filled squares - combined HEAT data (Barwick et al. 1997), and open squares - CAPRICE -98 (Boezio et al. 1999). Expected data from Pamela for one year of operation are shown by red circles.

C



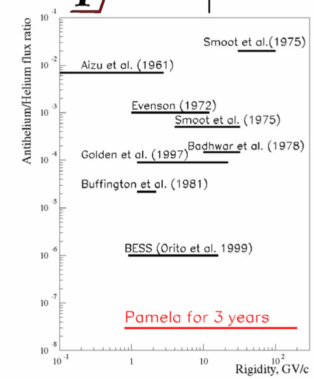
Distortion on the antiproton flux (dashed line) due to one possible contribution from neutralino annihilation (dotted line, from Ullio 1999). Total expected flux is shown by solid line. Filled squares - BESS data (Orito et al. 1999), open squares - MASS-91 (Stochaj et al. 2000), open circles - IMAX (Mitchell et al. 1996), and open triangles - CAPRICE (Boezio et al. 1999). Expected data from Pamela experiment for 1 year of operation are shown by red circles.

D



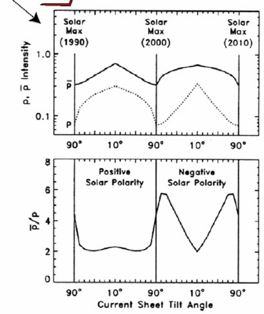
Electron, positron, proton and helium isotope abundance ratios affected by solar modulation in different phases (collected in different experiments, Bieber et al. 1999 and references therein). Pamela will make all these measurements simultaneously.

F



Current upper limits on the flux of antihelium compared to the sensitivity of Pamela in 3 years.

E



Predicted effect of charge-sign dependent solar modulation on the antiproton to proton ratio (Bieber et al. 1999). Pamela will measure this ratio over the period of expected high variability, testing the model.

Scientific Primary Goals and Objectives

Search for evidence of exotic matter:

- Heavy Antinuclei
- Nonbaryonic particles outside the Standard Model

Understanding formation and evolution of our Galaxy and the Universe

Exploring the cycles of matter and energy in the Universe.

Search for Heavy 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.

- Gamma ray observations place strong limitations on antimatter domains within 50 Mpc and further.

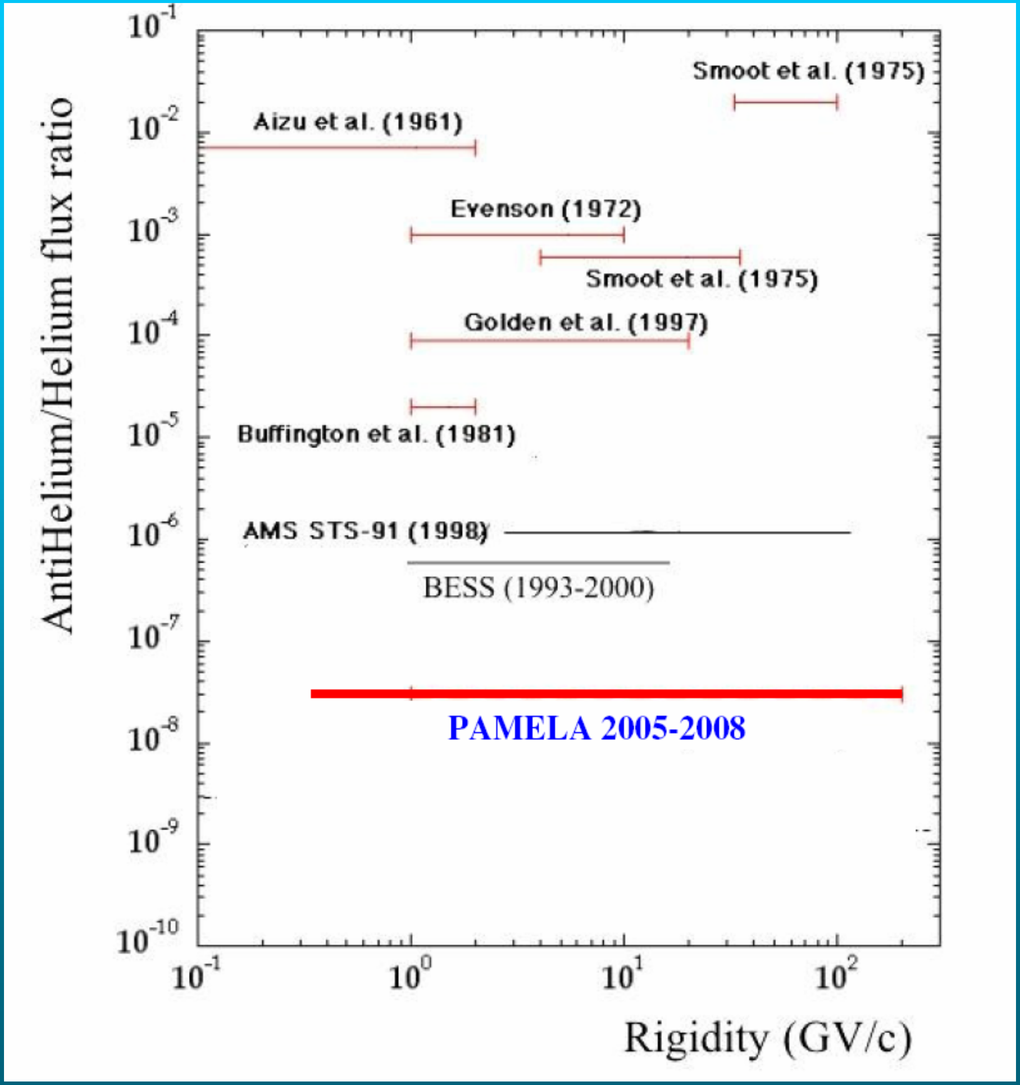
- Search for high-energy nuclei from antimatter domains beyond the gamma limits.

- Antihelium/Helium from cosmic ray collision $=10^{-14}$

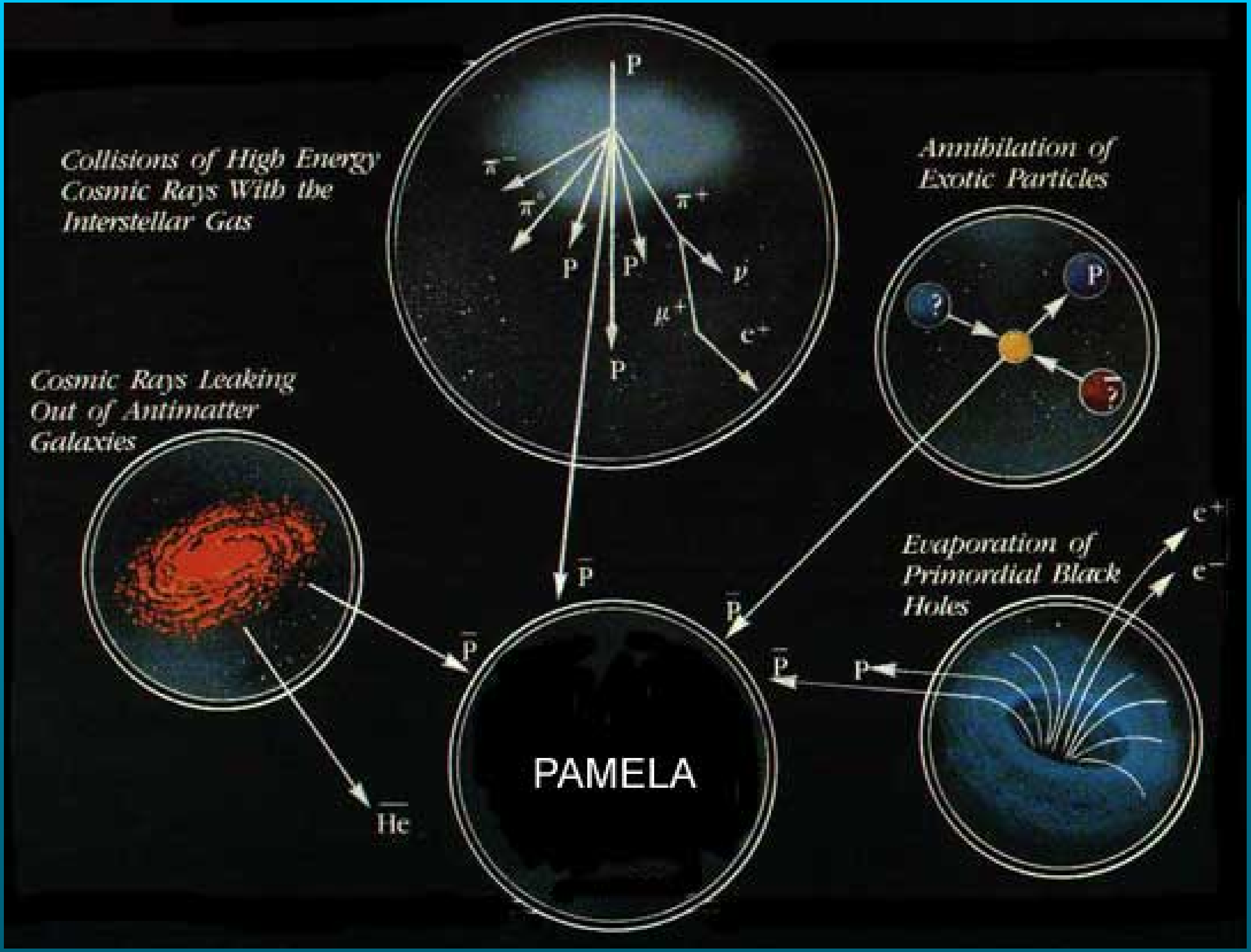
- AntiIron/Iron $=10^{-56}$

Necessity of an excellent identification capability

Cosmic-ray Antimatter Search



Antiproton Measurements



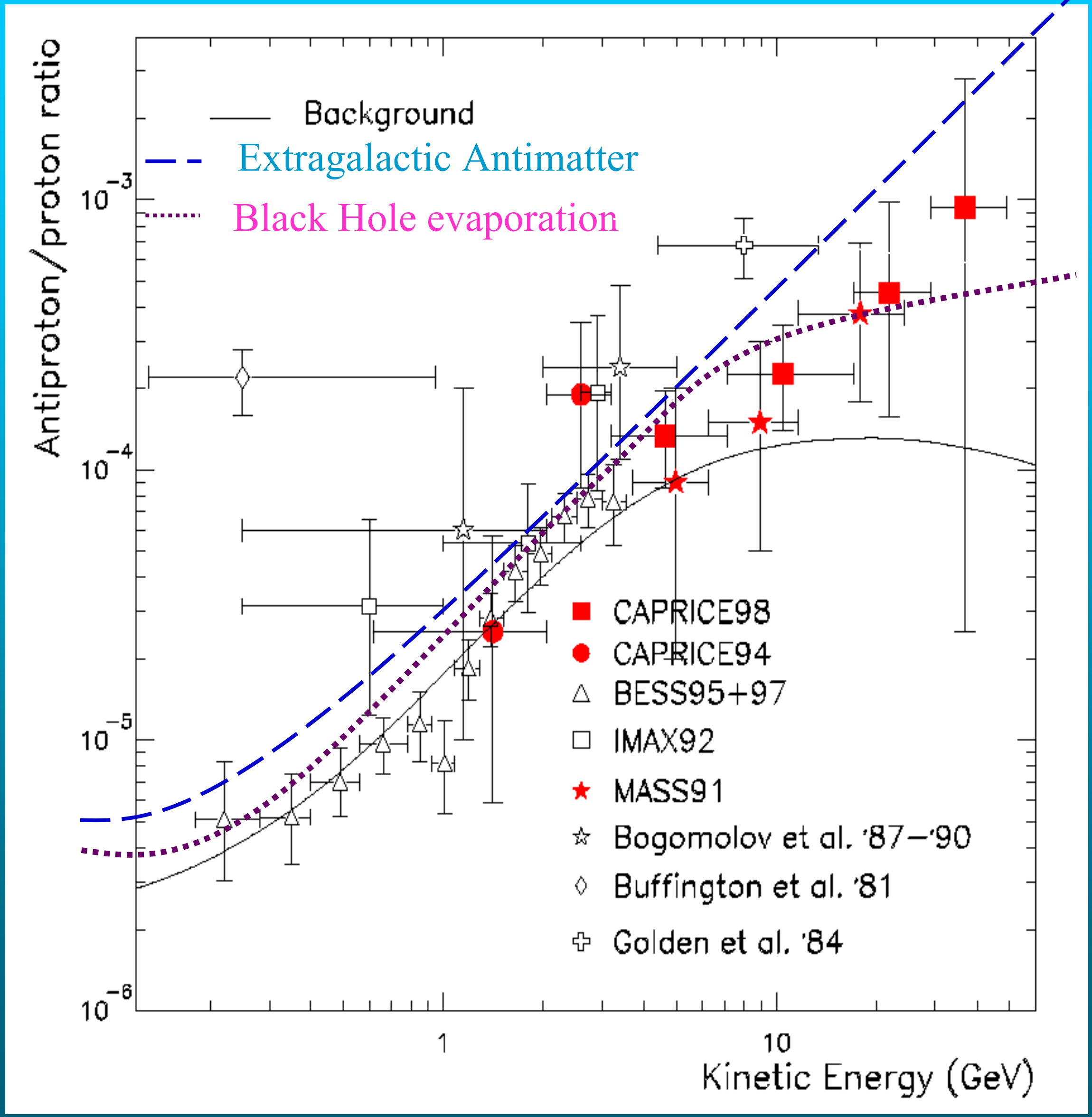
Distortion on the secondary antiproton flux induced by an Extragalactic Antimatter and Black Hole evaporation components

- Background from normal secondary production

- Mass91 data from XXVI ICRC, OG.1.1.21 , 1999

- Caprice94 data from ApJ , 487, 415, 1997

- Caprice98 data from ApJ Letters 534, L177, 2000



Matter in the Universe

Microwave Anisotropy

WMAP - NASA - Explorer Mission → $\Omega_{total} = \frac{\rho_{total}}{\rho_{crit.}} = 1$

(Universe is flat)

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

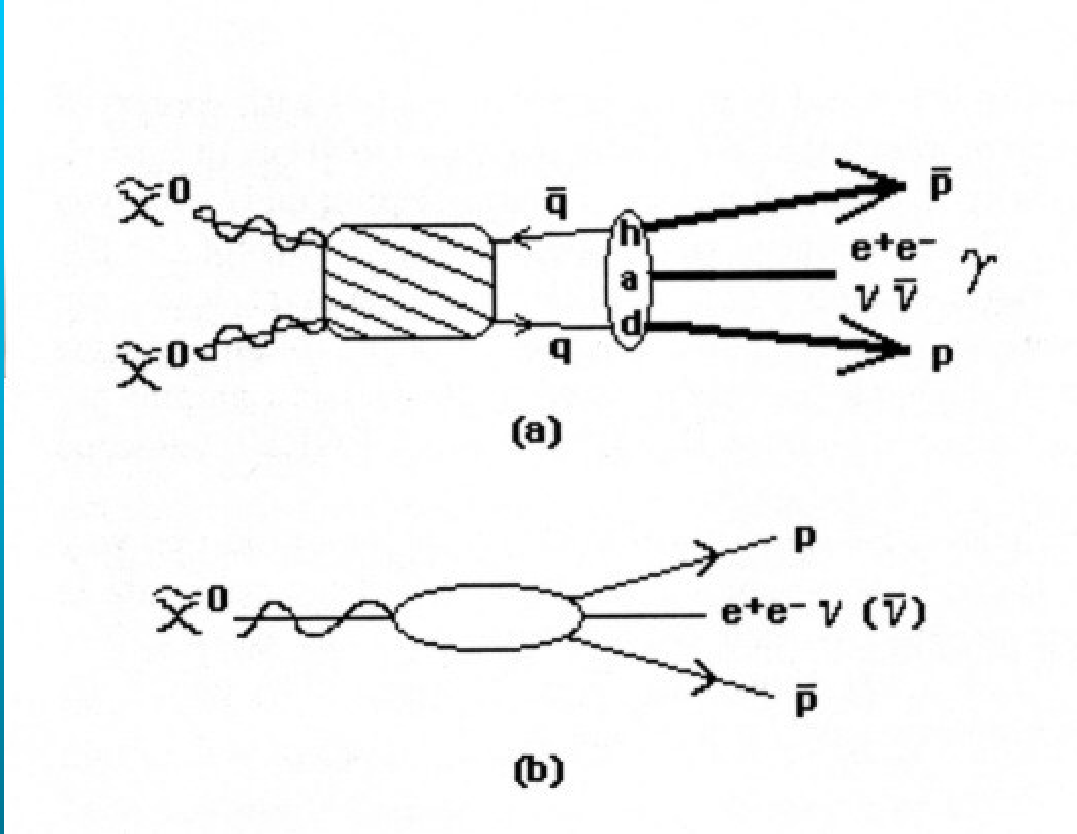
$$\Omega_{total} = \underbrace{\Omega_{total,baryon.}}_{} + \underbrace{\Omega_{dyn.}}_{} + \underbrace{\Omega_{required}}_{}$$

baryonic matter	dark matter	dark energy
5%	25%	70%
	??	???
stars, galaxies	candidates:	quintessence

candidates:

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

NEUTRALINO ANNIHILATION



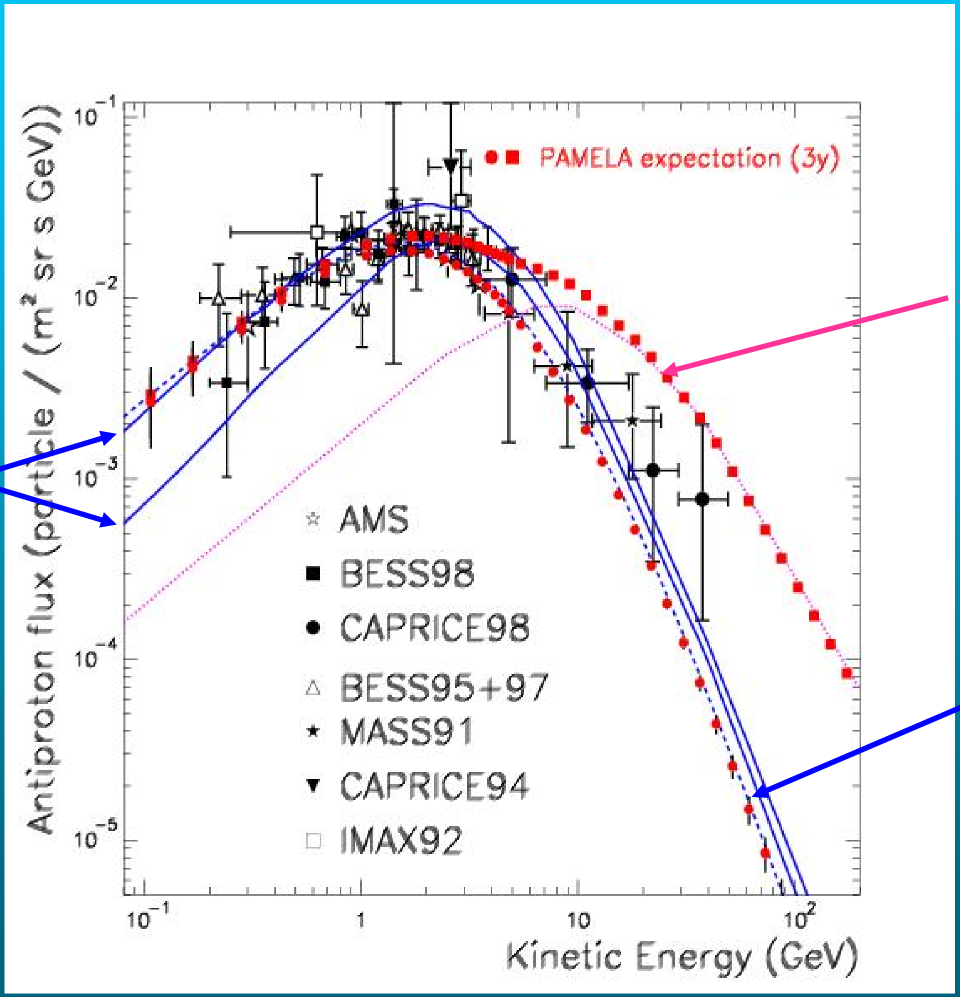
a) CDM neutralinos annihilation in the Galactic halo in minimal SUSY

b) In R-parity- violating SUSY

What do we espect from PAMELA?

Search of structures in antiproton spectrum

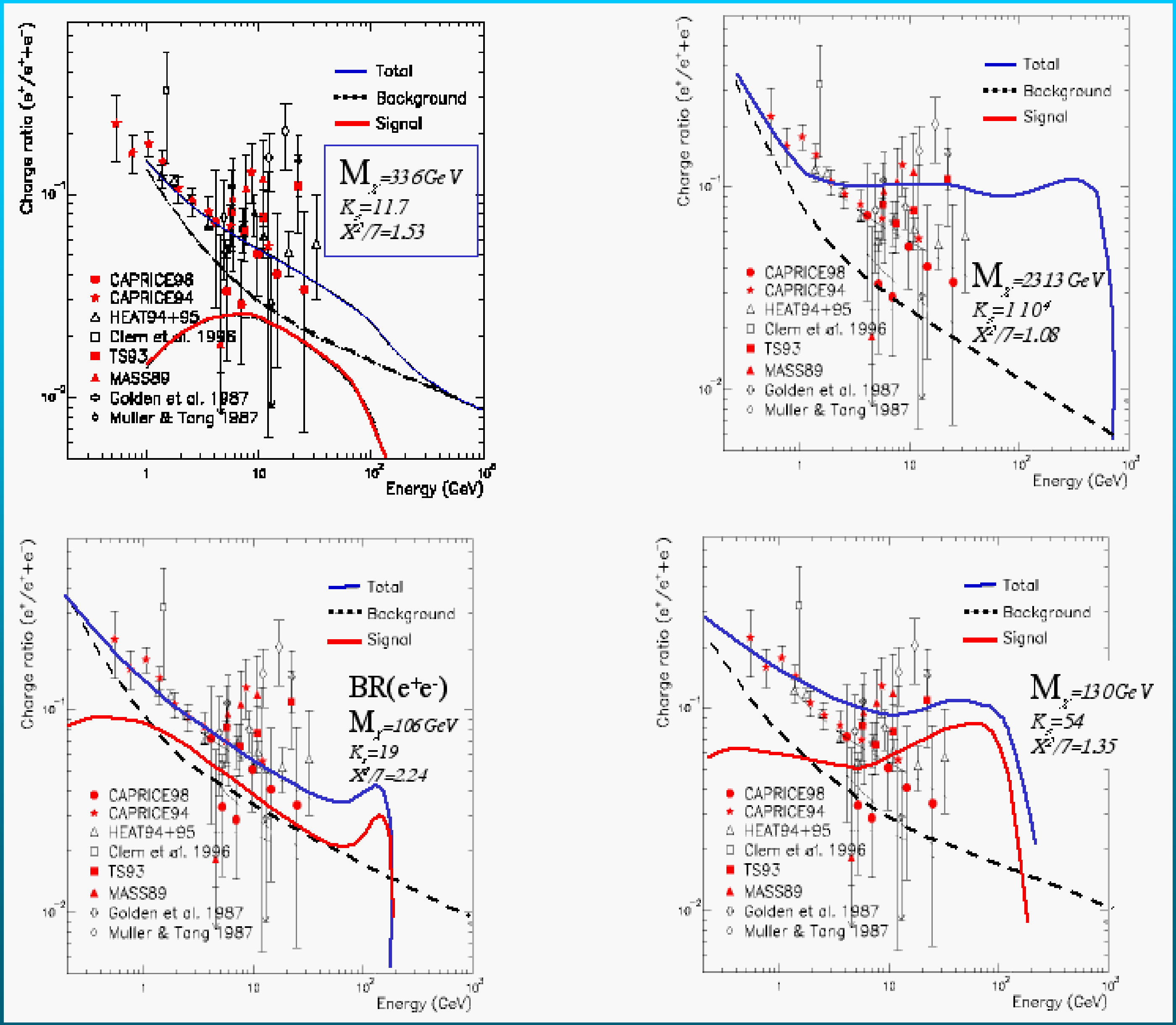
Secondary production (upper and lower limits) Simon et al.



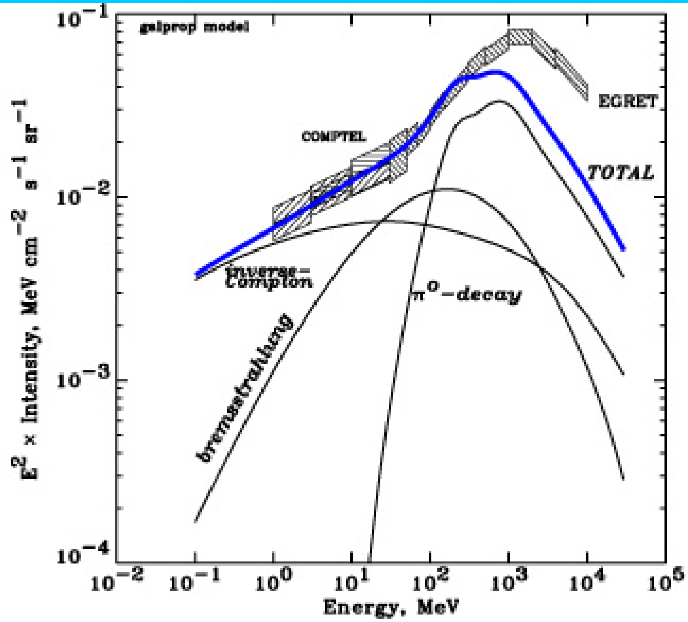
Primary production from $\chi\chi$ annihilation ($m(\chi)$ = 964 GeV)
(astro-ph 9904086)

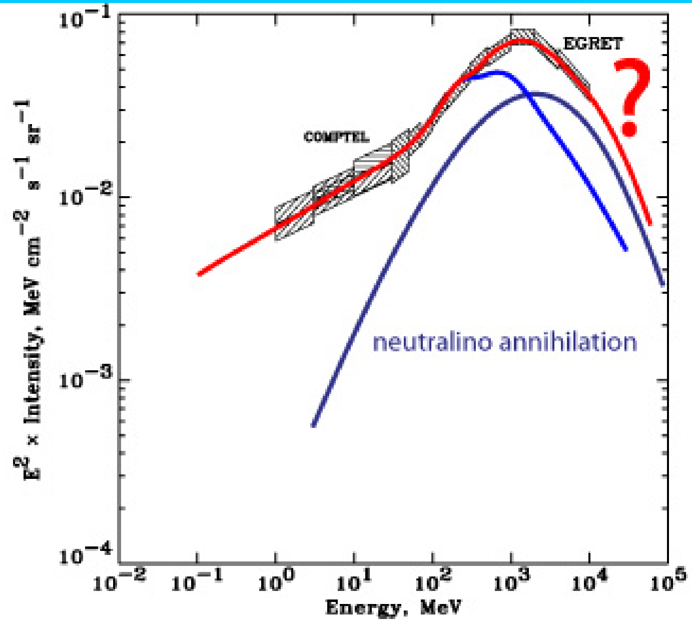
Secondary production (CAPRICE94-based) Bergström et al.

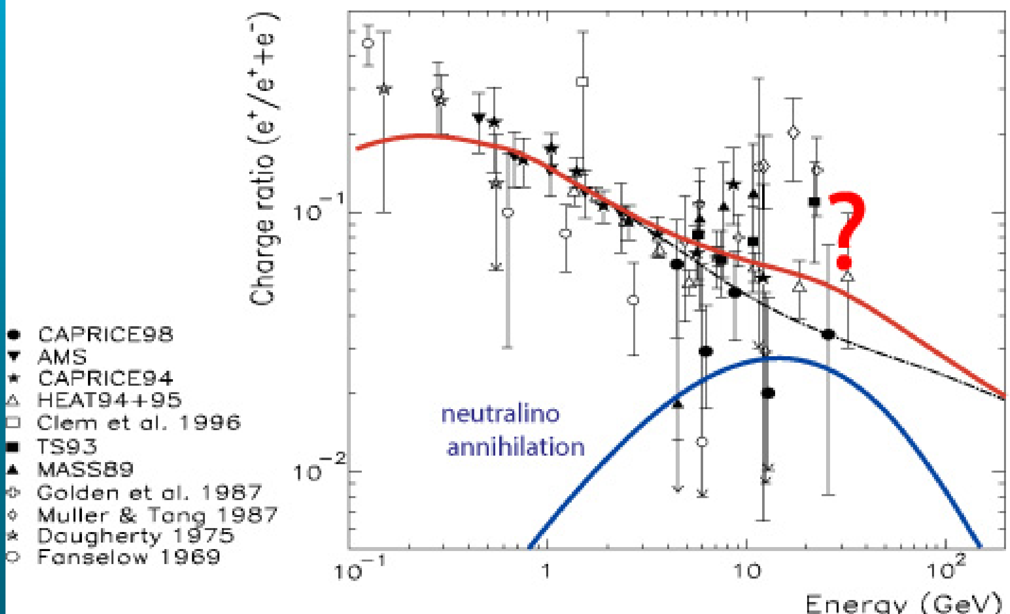
Distortion of the secondary positron fraction induced by a signal from a heavy neutralino.



Baltz & Edsjö
Phys.Rev. D59 (1999)
astro-ph 9808243

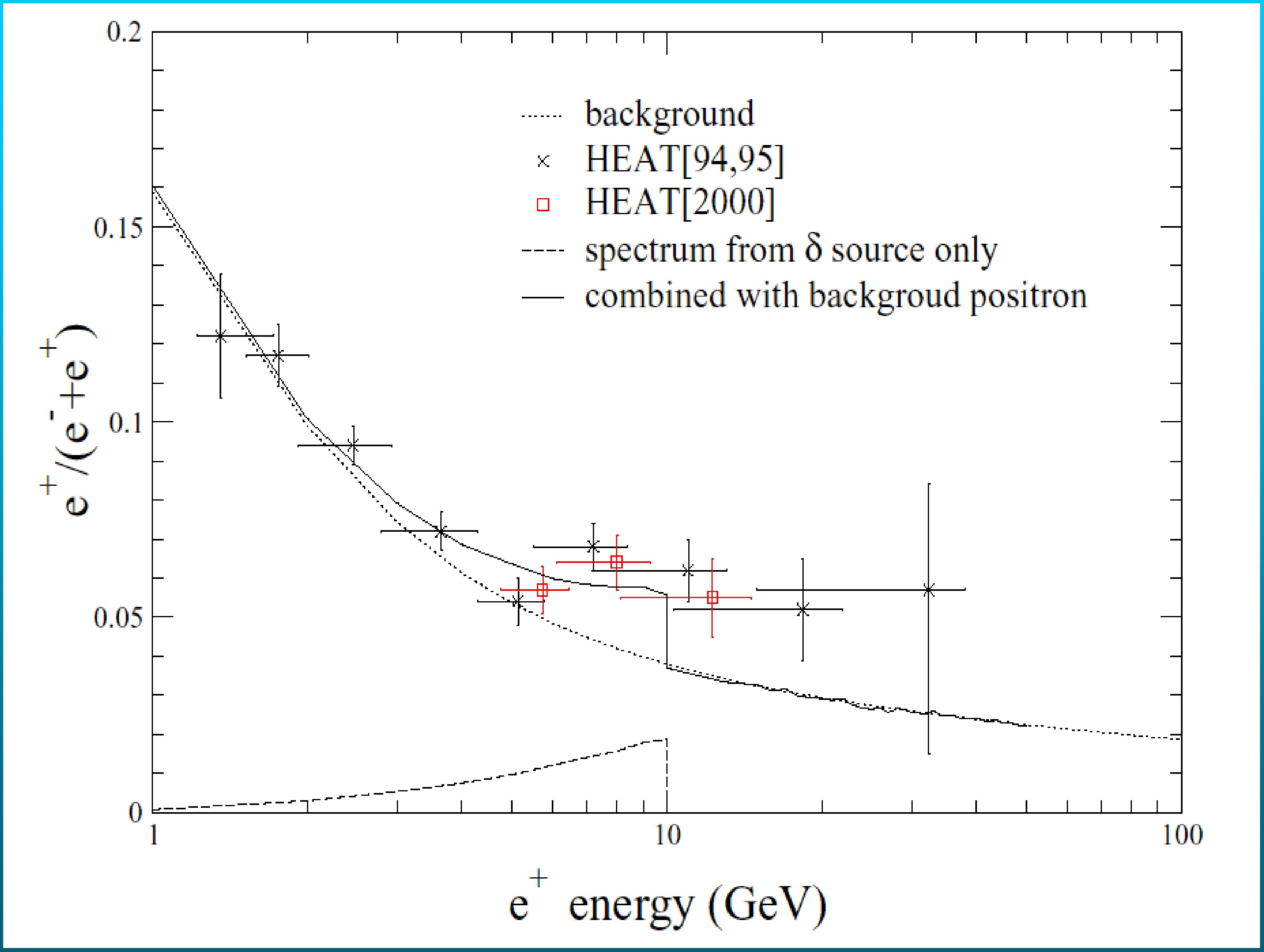






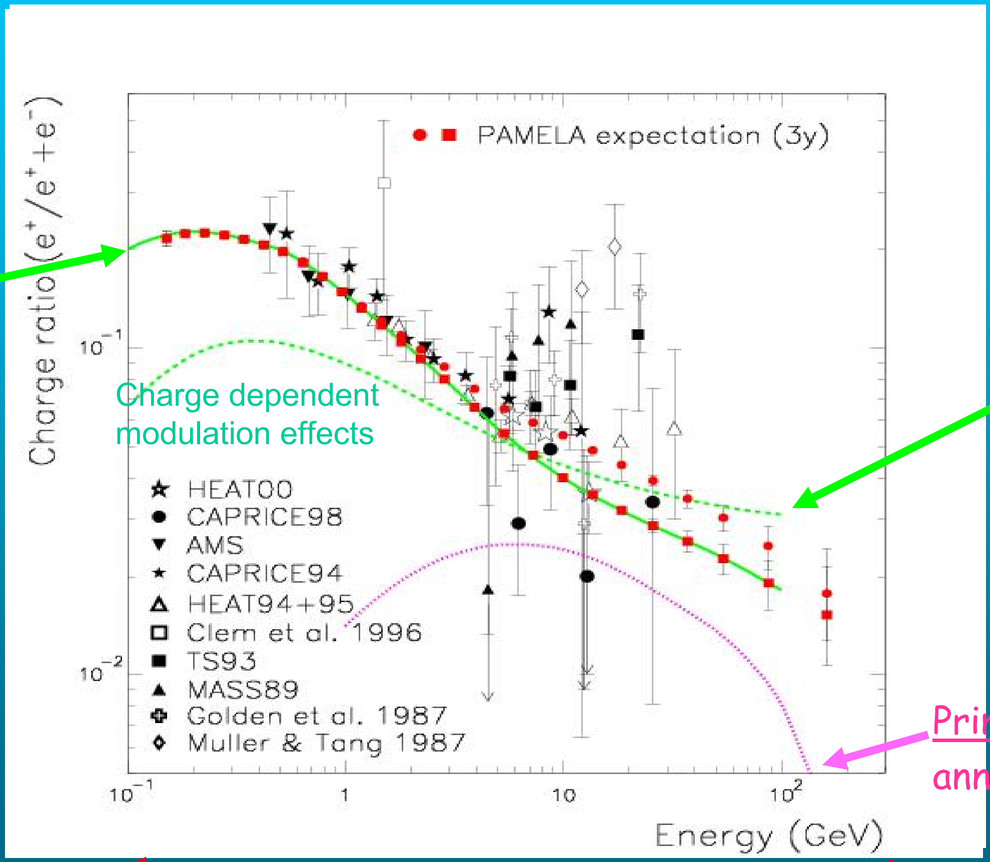
Do we see hints of
neutralino annihilation?

Positron with HEAT



Cosmic-ray antiparticle measurements: positrons

Secondary production 'Moskalenko + Strong model' (1998) without reacceleration



Secondary production 'Leaky box model' (Protheroe 1982)

Primary production from $\chi\chi$ annihilation ($m(\chi)$ = 336 GeV)

PAMELA energy range

Primary and Secondary Spectra

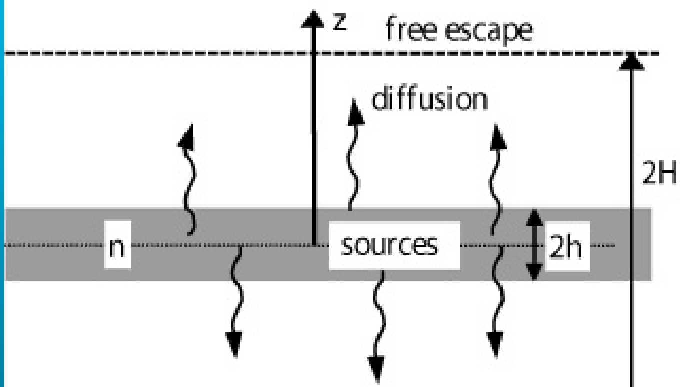
- Unambiguous interpretation of exotic matter signature requires a clear understanding of the secondary spectra and their sources.
- Primary cosmic ray spectra as a powerful tool to quantify the source of atmospheric neutrino anomaly.

Diffusion Halo Model

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

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

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

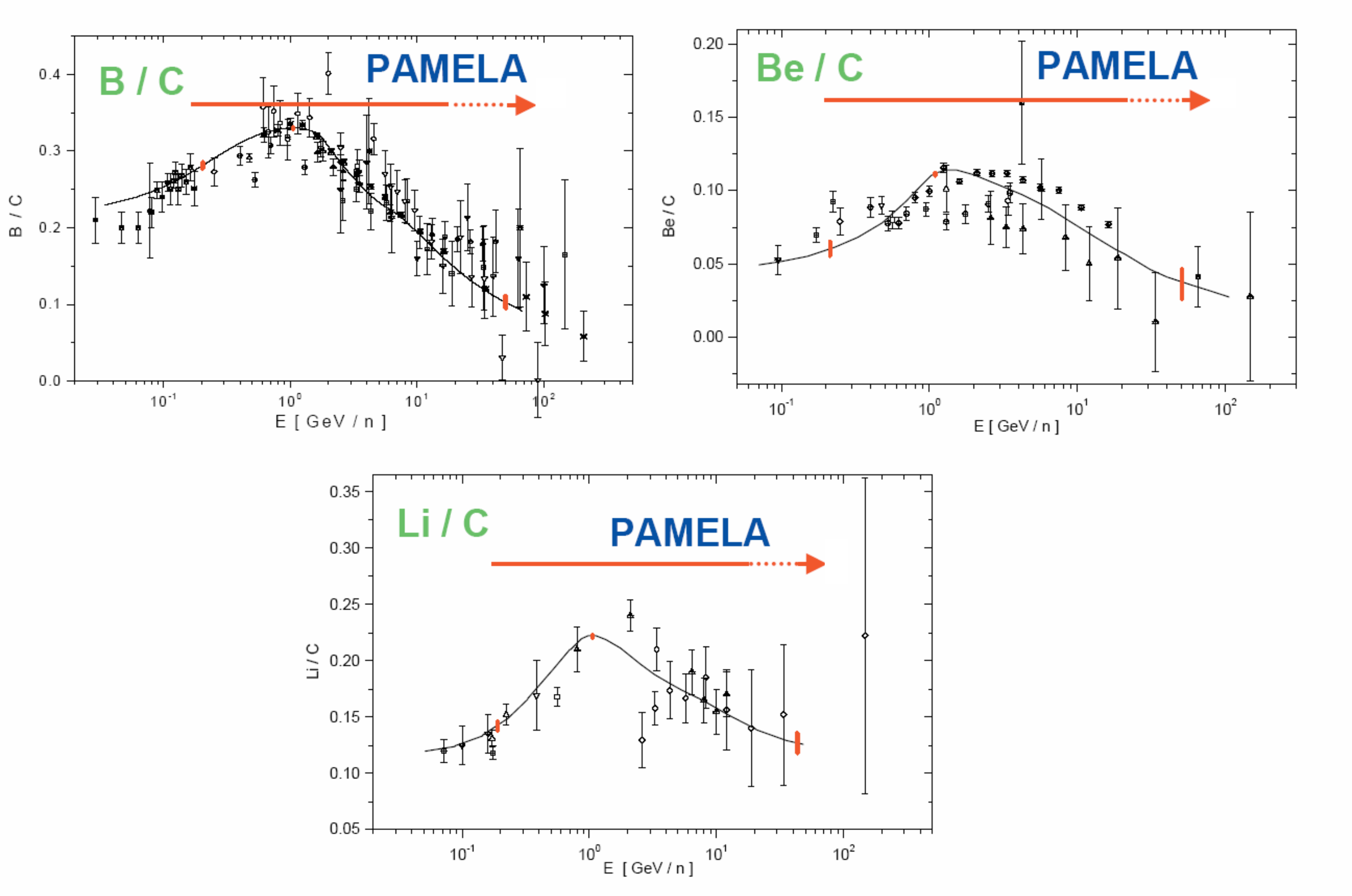


Elemental Energy Spectra

Secondary to primary CR ratios are the most sensitives quantities to fix the propagation parameters in the trasport model. [e.g. Carbon (directly produced by nucleosynthesis), Boron (from fragmentation)]

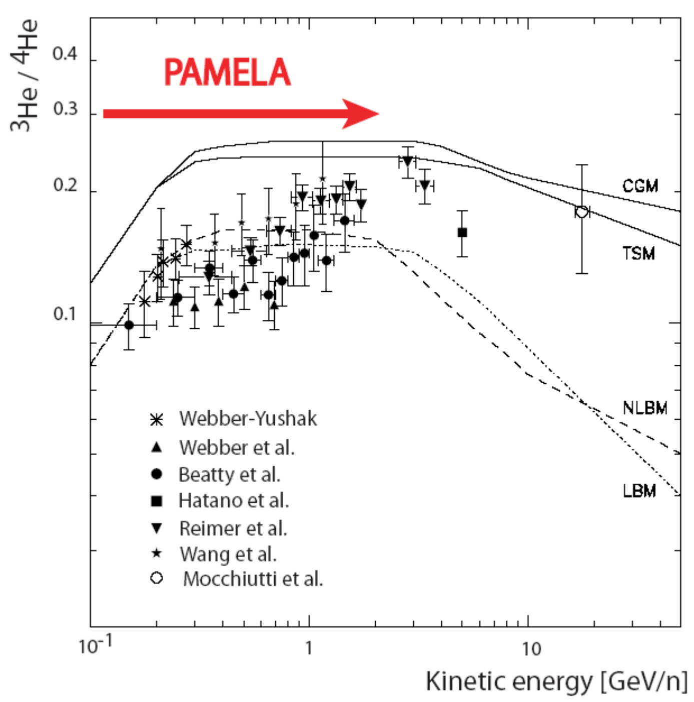
Energy profiles validate the transport model and the matter density hypothesis.

Secondary to Primary ratios

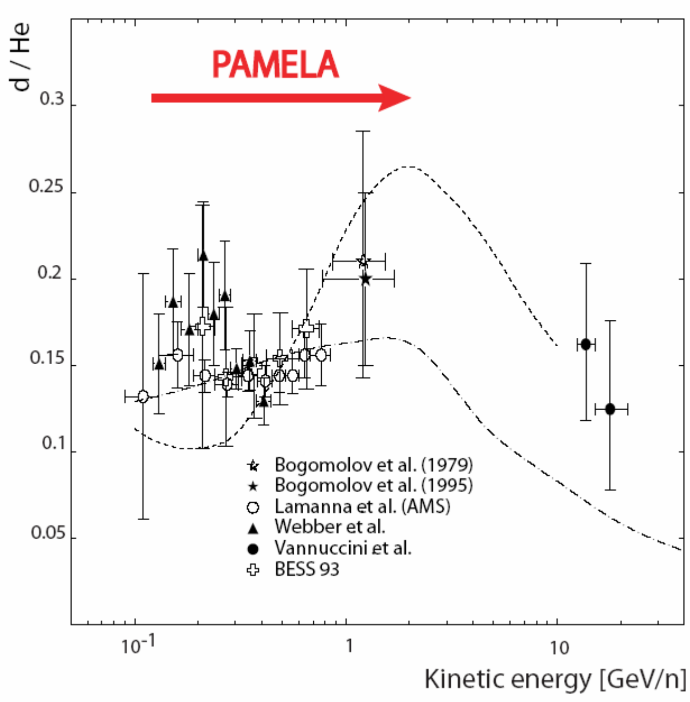


Helium and Hydrogen Isotopes

The current situation of the 3He / 4He ratio

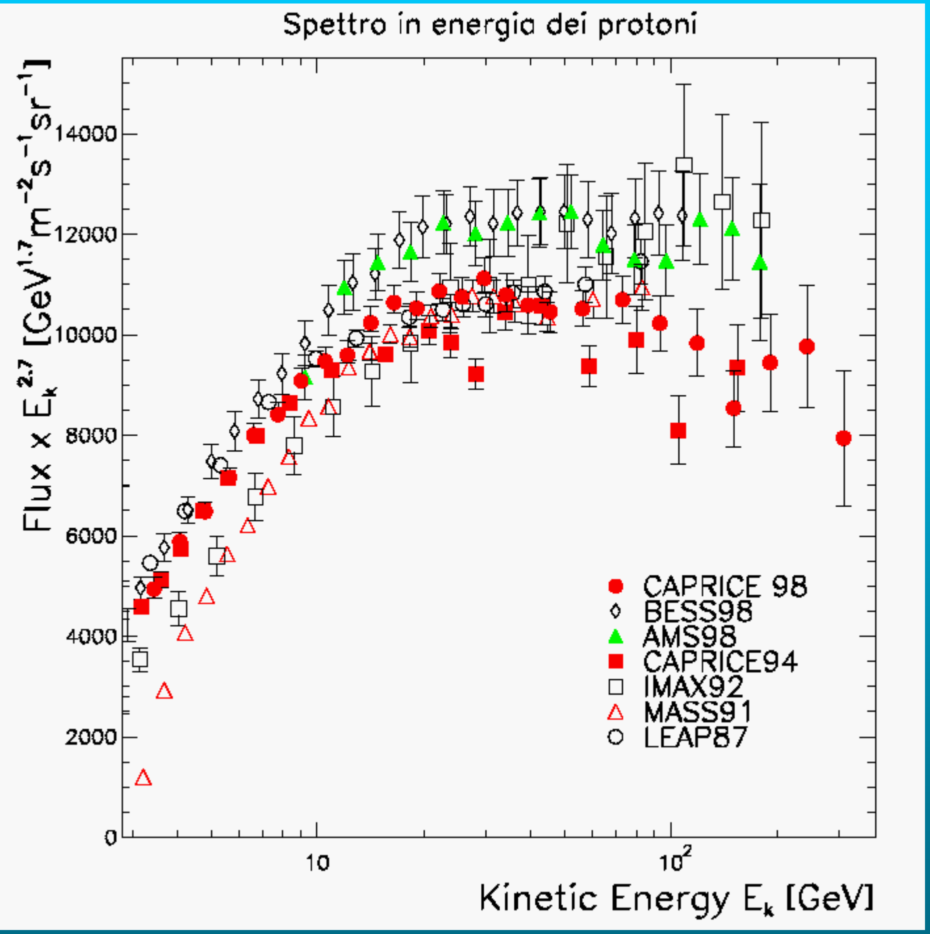


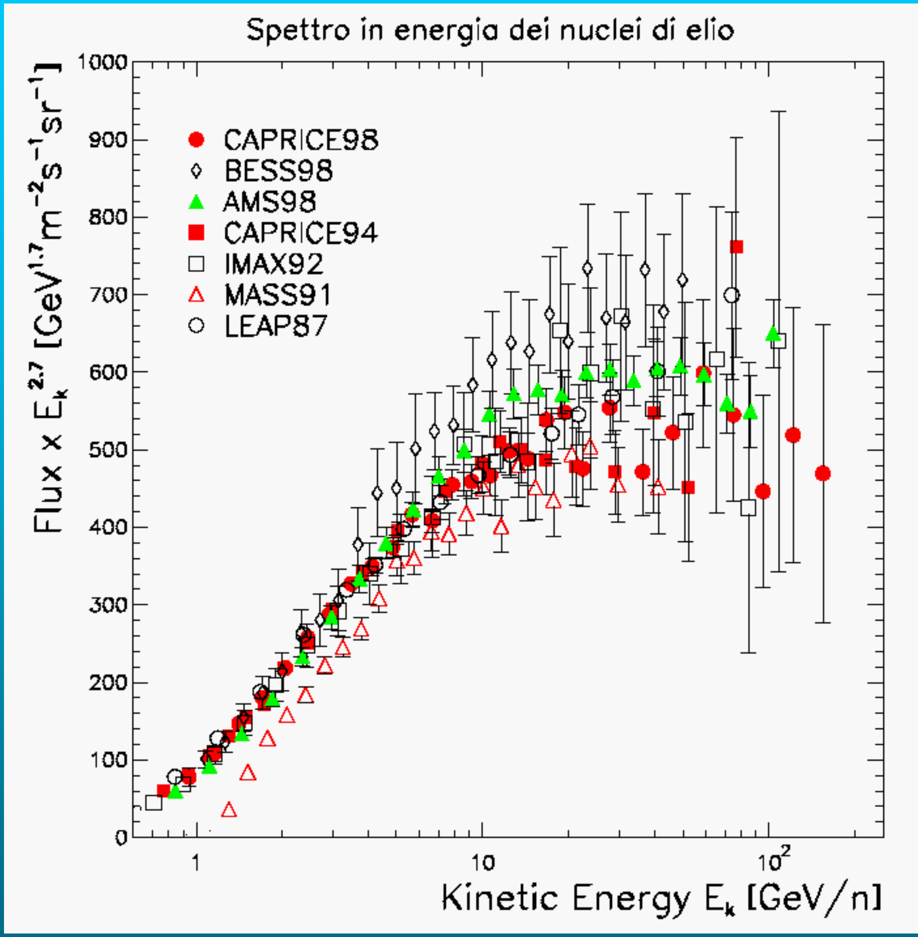
The current situation of the d / He ratio



Protons

Helium





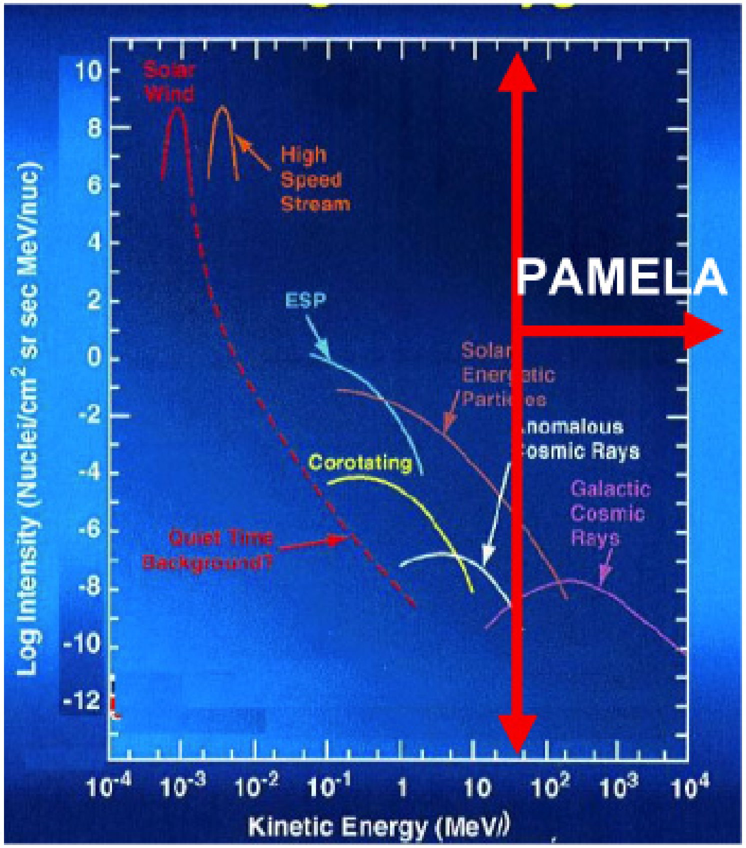
Concomitant Goals

- Near electrons sources
- Solar Flare Particle Spectra
- Charge-Sign Dependent Solar Modulation
- New Radiation Belts

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)

Solar Physics with PAMELA



- Solar Modulation effects
- High energy component of Solar Proton Events (from 80 MeV to 10 GeV)
- High energy component of electrons and positrons in Solar Proton Events (from 50 MeV)
- Nuclear composition of Gradual and Impulsive events
- ^{3}He and ^{4}He isotopic composition

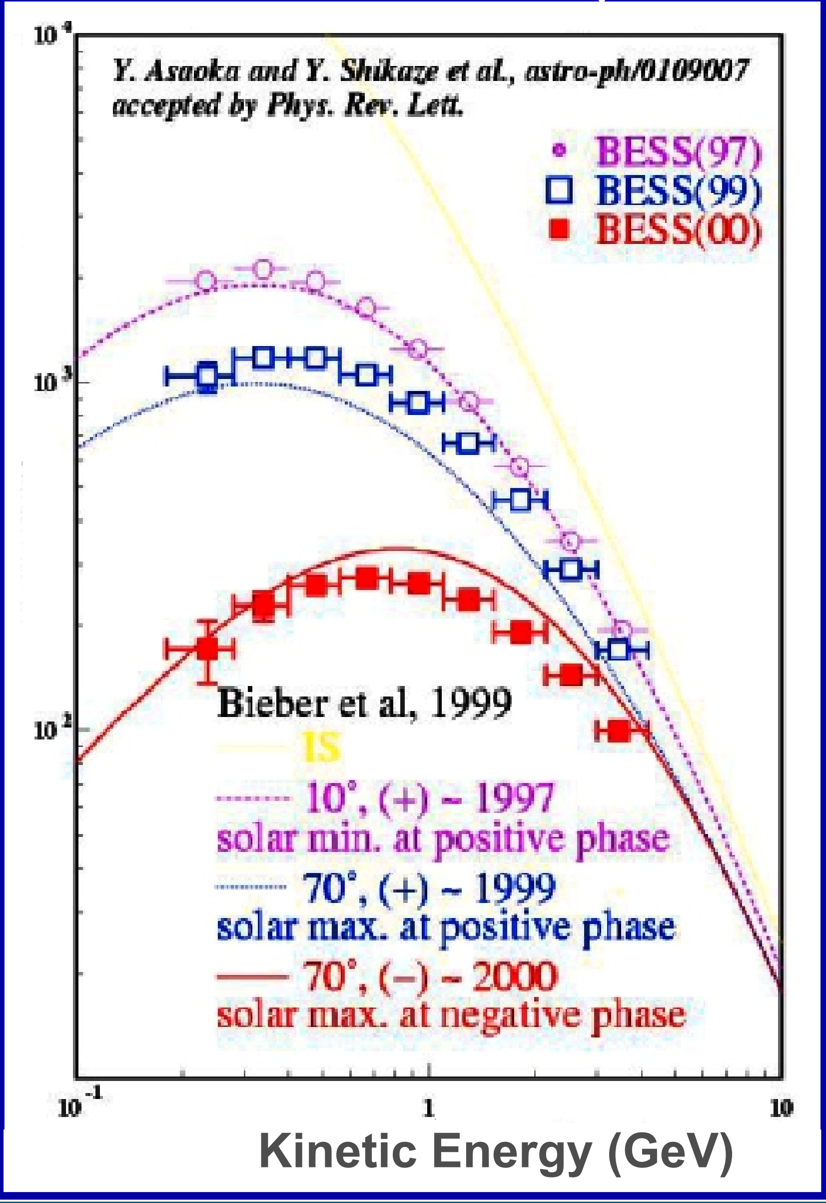
Charge-Sign Dependent Solar Modulation

- Osservational evidence that the negative charge component of galactic cosmic rays is modulated in the heliosphere differently than the positive one.
- Modification and modulation of Galactic Cosmic Ray spectra in the heliosphere complicate the interpretation of the exotic matter results at low energy.

Measurements of the abundances of species with the same mass but different charge sign in A^+ and A^- of the solar cycle.

Proton fluxes at TOA

Annual Variation of P spectrum



Comparison of $\bar{p}/p$ ratio with model

Time variation of $\bar{p}/p$ ratio at solar maximum

Observed data by BESS

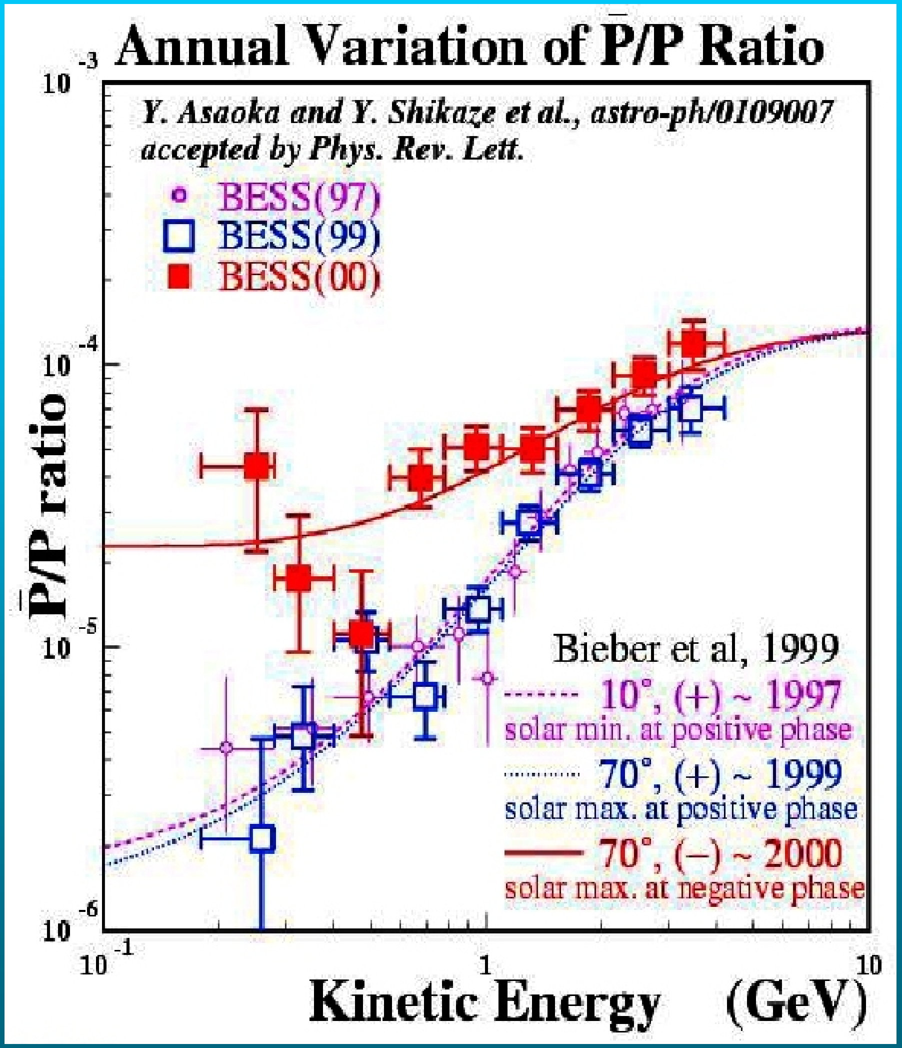
Charge dependent model

prediction(Bieber et al.)

Charge dependent solar modulation model well follows

the suddenly increase of $\bar{p}/p$ ratio observed by BESS

at the solar polarity reversal between 1999 and 2000



High Energy Radiation Belts

- High energy from ~ 1 GeV to ~ 10 GeV
- Contains e+, e-, p, 3He
- e+ over e- dominance
- Low L- shell ⇔ low altitude
- Life time O(seconds)

⇒ Secondary production from CR interaction with atmosphere

Conclusion

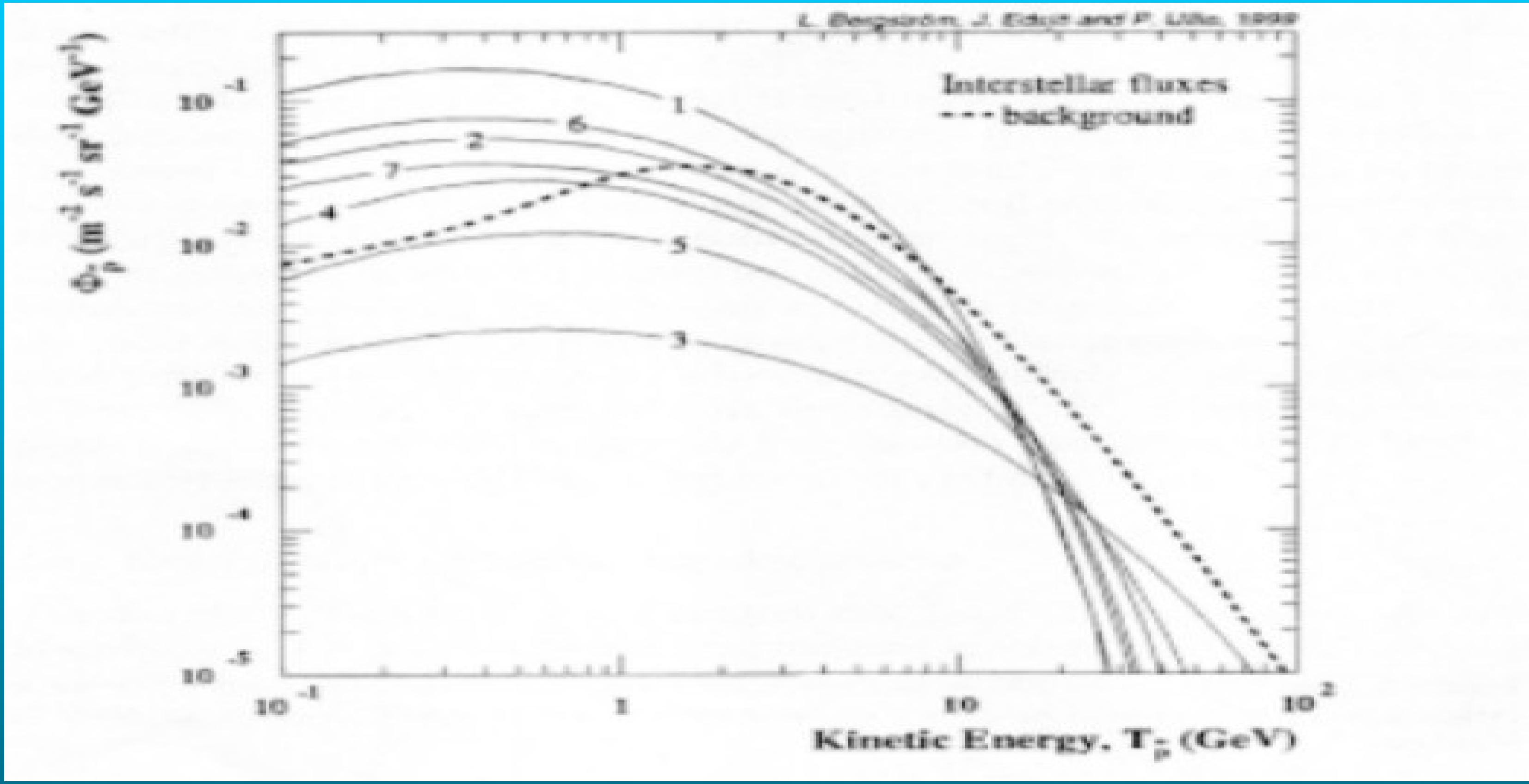
- PAMELA is the first space experiment which will measure the Antiprotons and Positrons to high energies $\approx$ 200GeV with an unprecedented statistical precision
- PAMELA will set a new lower limit of finding Antihelium
- PAMELA will look for Dark Matter candidates
- PAMELA will provide measurements on elemental spectra and low mass Isotopes with an unprecedented statistical precision and will help to improve the understanding of particle propagation in the interstellar medium.
- PAMELA will be able to measure the high energy tail of solar spectra and for the first time solar positrons
- PAMELA will be able to measure electrons at very high energy to discover sources near the solar system

Dirac Nobel Speech (1933)

"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"

- Earliest example of the interplay between particles physics and cosmology

Antiproton fluxes



A range of minimal (R-parity-conserving) SUSY predictions of Galactic antiprotons spectrum, with neutralino masses = 45-700 GeV

Distortion of the secondary antiproton flux induced by a signal from a heavy Higgsino-like neutralino.

Particles and photons are sensitive to different neutralinos. Gaugino-like particles are more likely to produce an observable flux of antiprotons whereas Higgsino-like annihilations are more likely to produce an observable gamma-ray signature

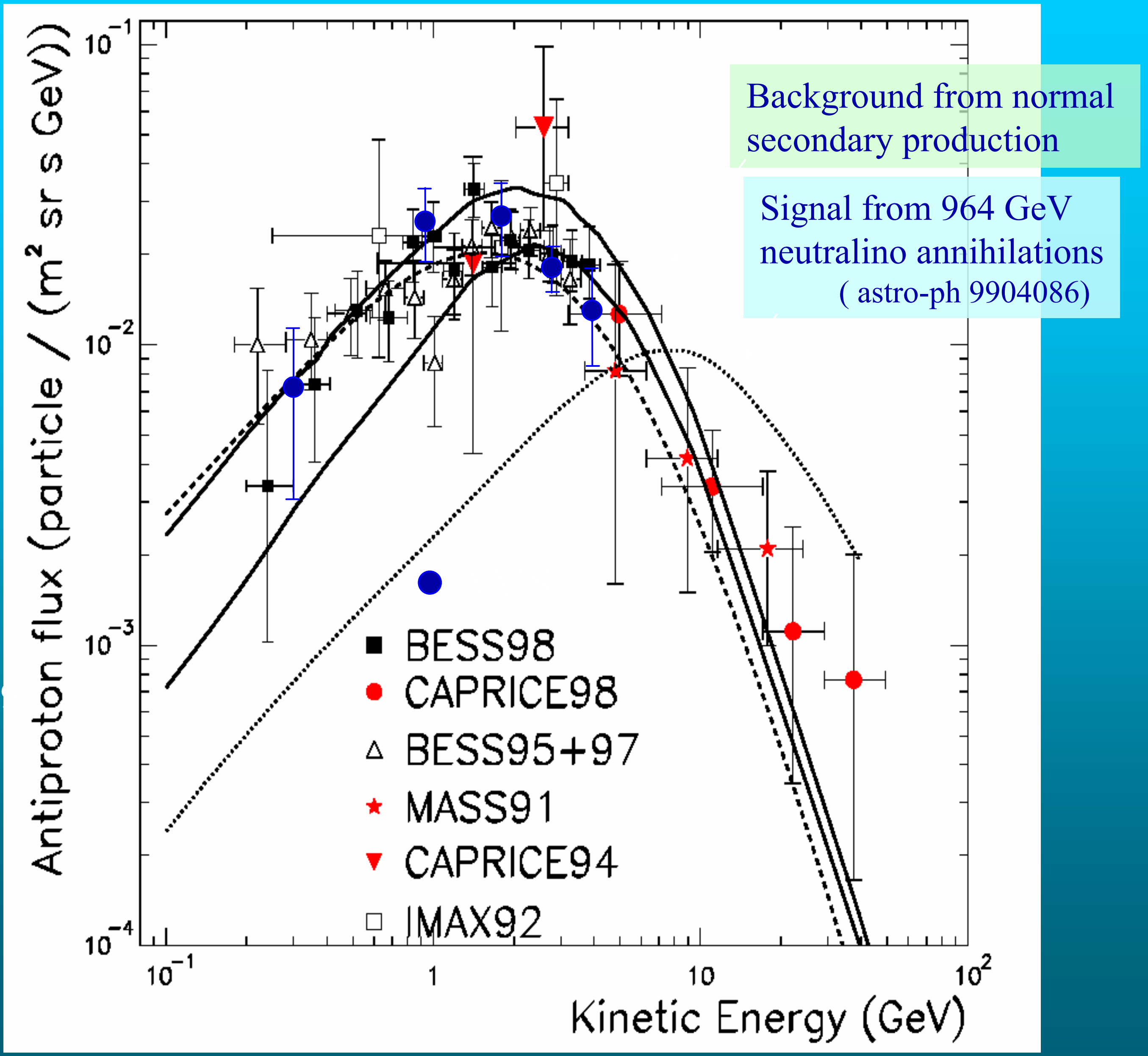
▼ Caprice94 data from ApJ, 487, 415, 1997

★ Mass91 data from XXVI ICRC, OG.1.1.21 , 199

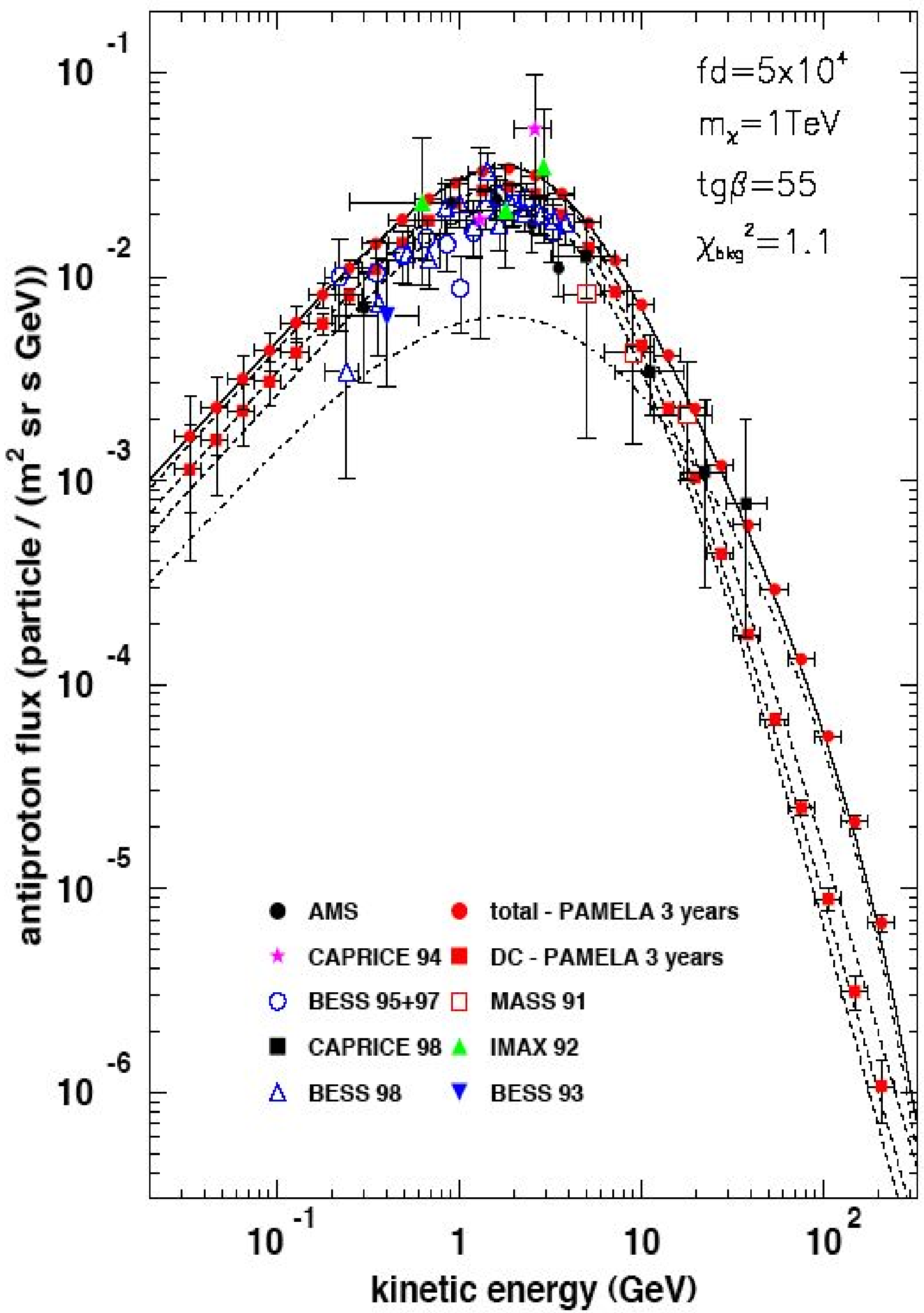
● Caprice98 data from ApJ, 561, (2001), 787. astro-ph/0103513

△ BESS data from Phys.Rev.Lett, 2000, 84, 1078

● AMS data : preliminary



PAMELA: Cosmic-Ray Antiparticle Measurements: Antiprotons



MSSM

fd: Clumpiness factors needed to disentangle a neutralino induced component in the antiproton flux

A.Lionetto, A.Morselli, V.Zdravkovic
astro-ph/0502406, 21 Feb. 05

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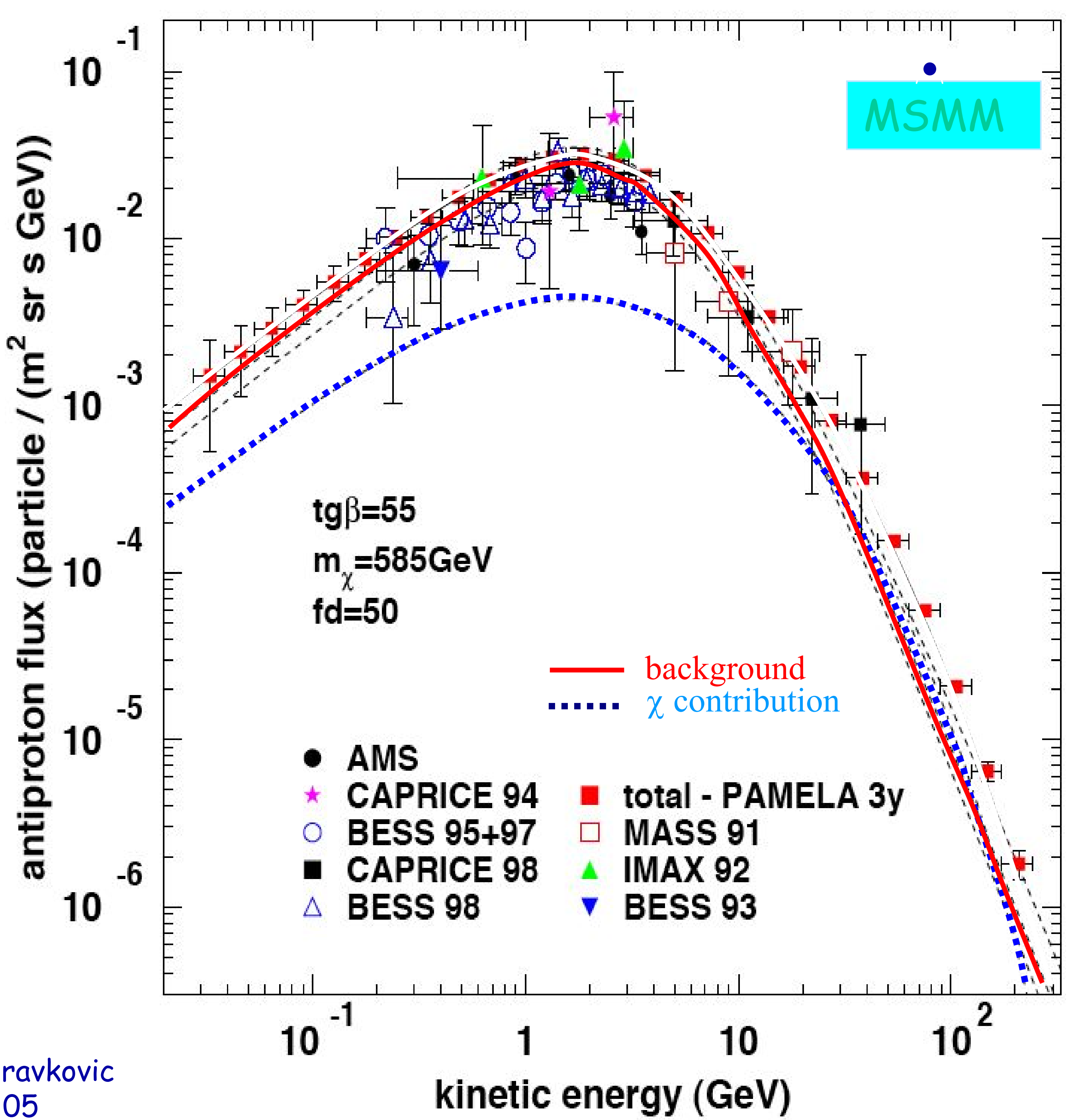

fd: Clumpiness factors needed to disentangle a neutralino induced component in the antiproton flux

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Estimated reaches with Pamela

MSSM

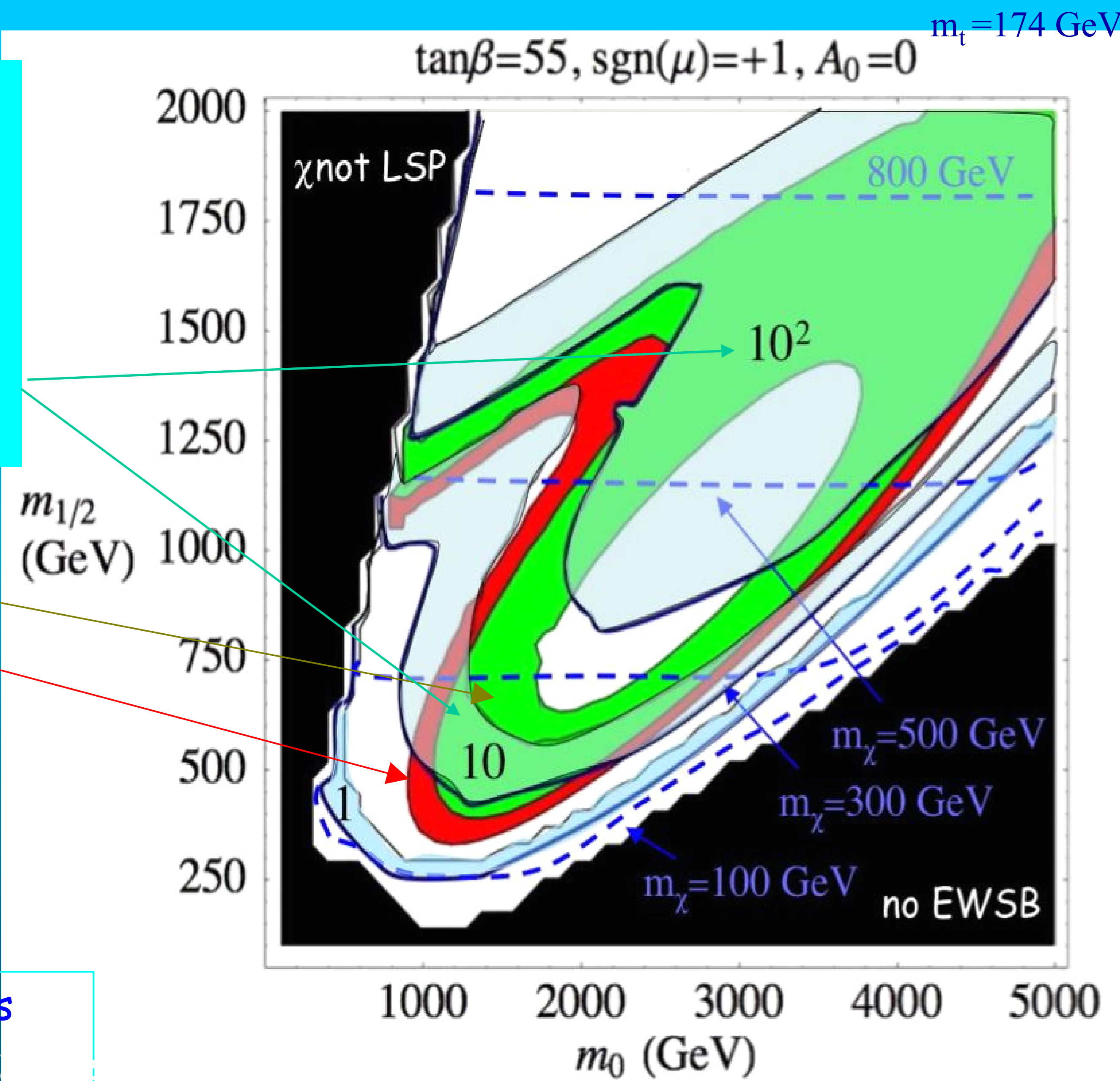
Clumpiness factors fd needed to disentangle a neutralino induced component in the antiproton flux with PAMELA (χ^2>1.8) that still give a good fit of the present data

region where $0.13 < \Omega_{CDM\tilde{M}} h^2 < 0.3$

region where $0.09 < \Omega_{CDM\tilde{M}} h^2 < 0.13$

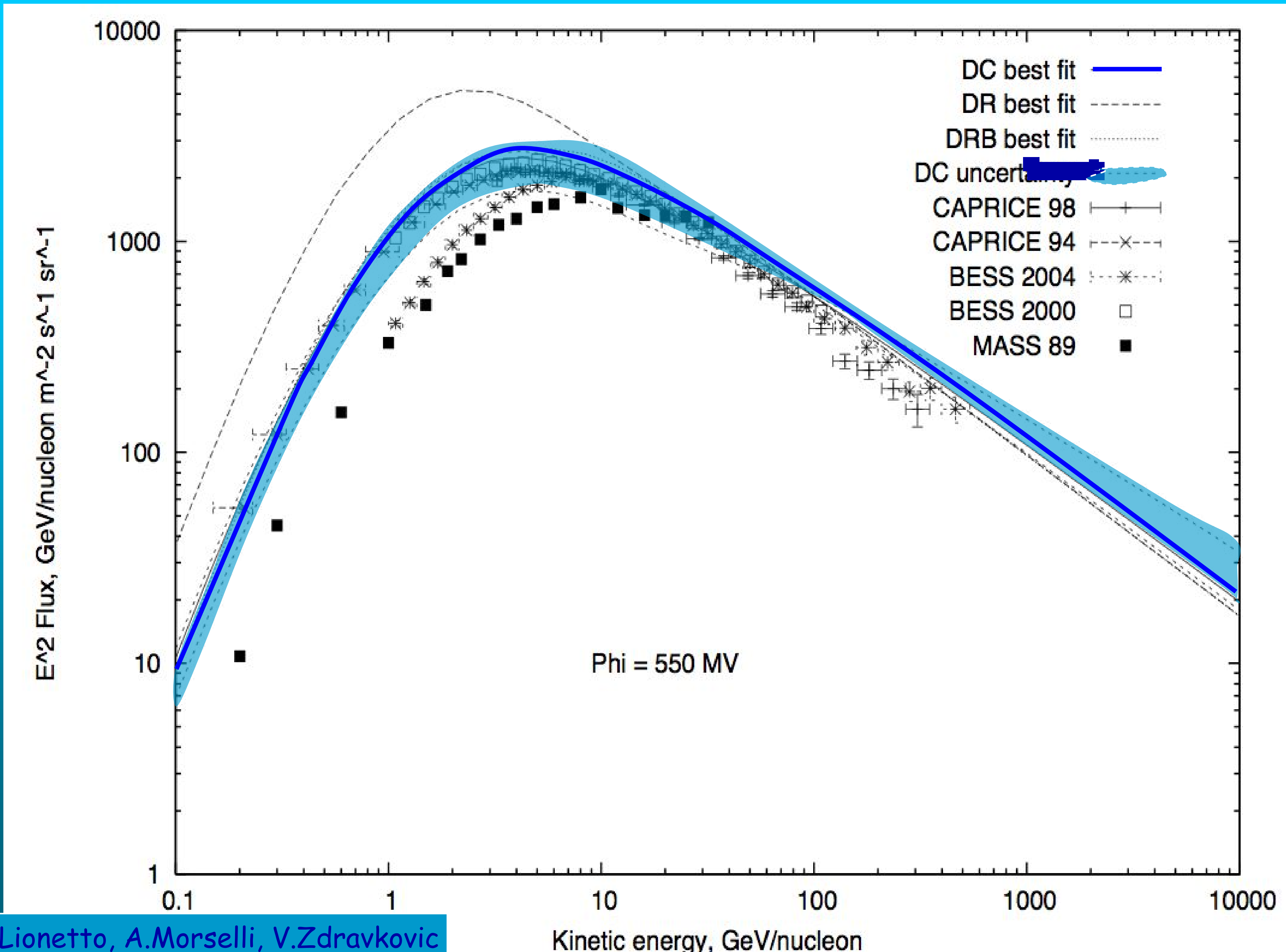
Equi-clumpiness factor density in respect to a NFW

– – Equi-neutralino mass lines



astro-ph/0502406,

Proton spectra: Upper and lower bounds are due to the uncertainties of propagation parameters



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