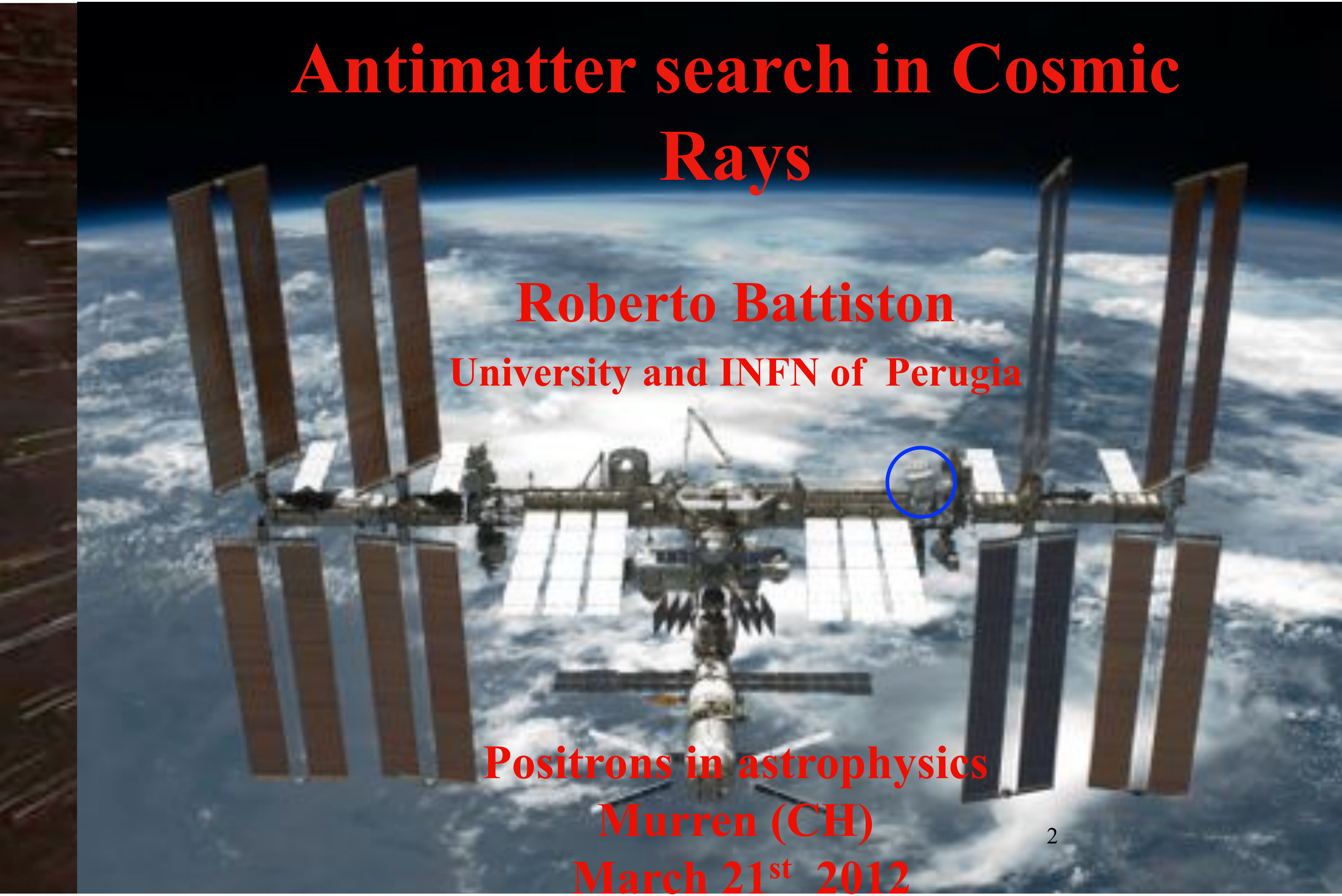
Purpose of the meeting

"cross fertilization among different communities working on antimatter"

Antimatter search in Cosmic Rays



Roberto Battiston

University and INFN of Perugia

Positrons in astrophysics

Murren (CH)

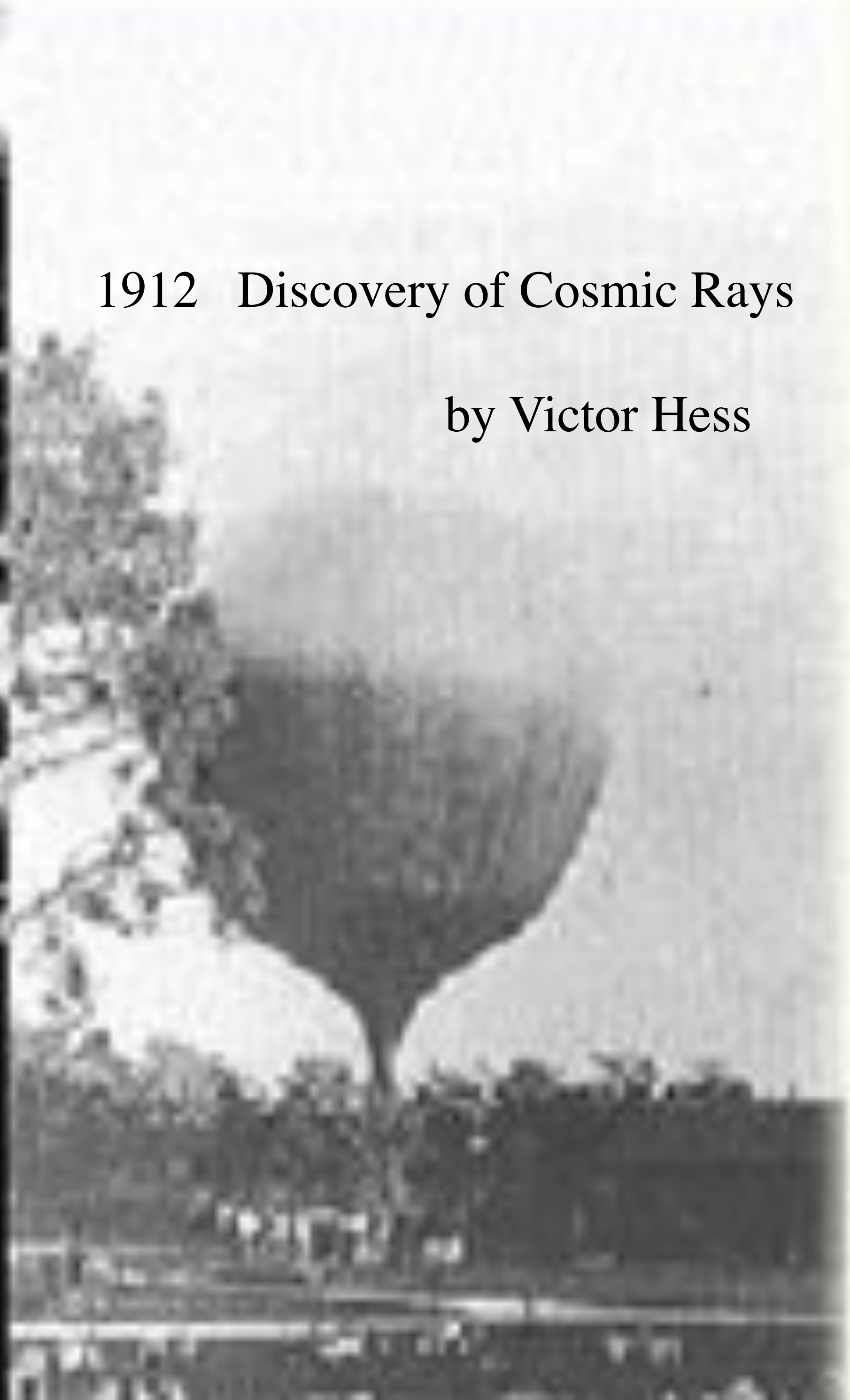
March 21st 2012

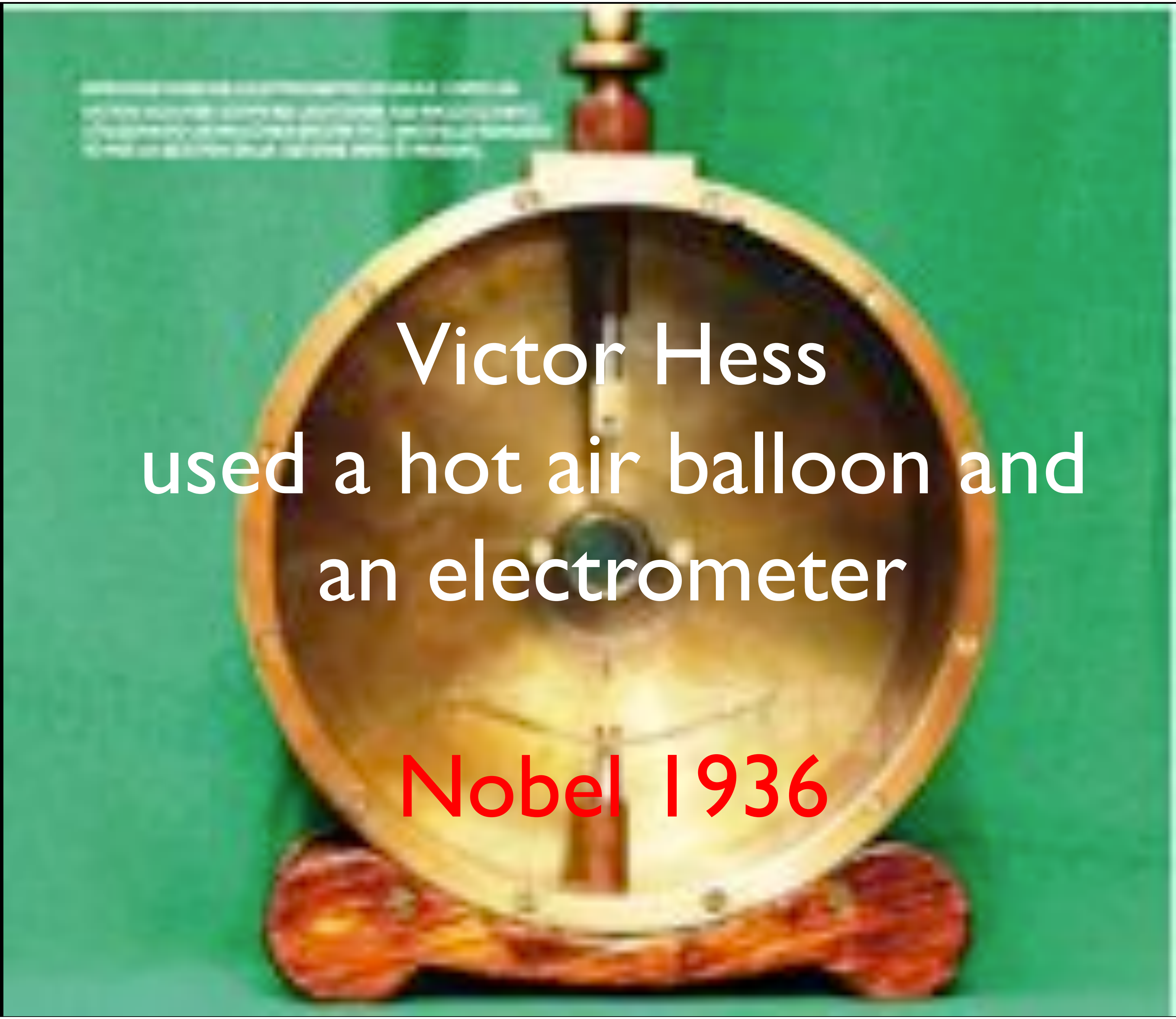
Outline

- Cosmic Rays
- Dirac equation
- The discovery of the positron
- Search for primordial antimatter
- The Alpha Magnetic Spectrometer
- High energy antiprotons in Cosmic Rays
- High energy positrons in Cosmic Rays

1912 Discovery of Cosmic Rays

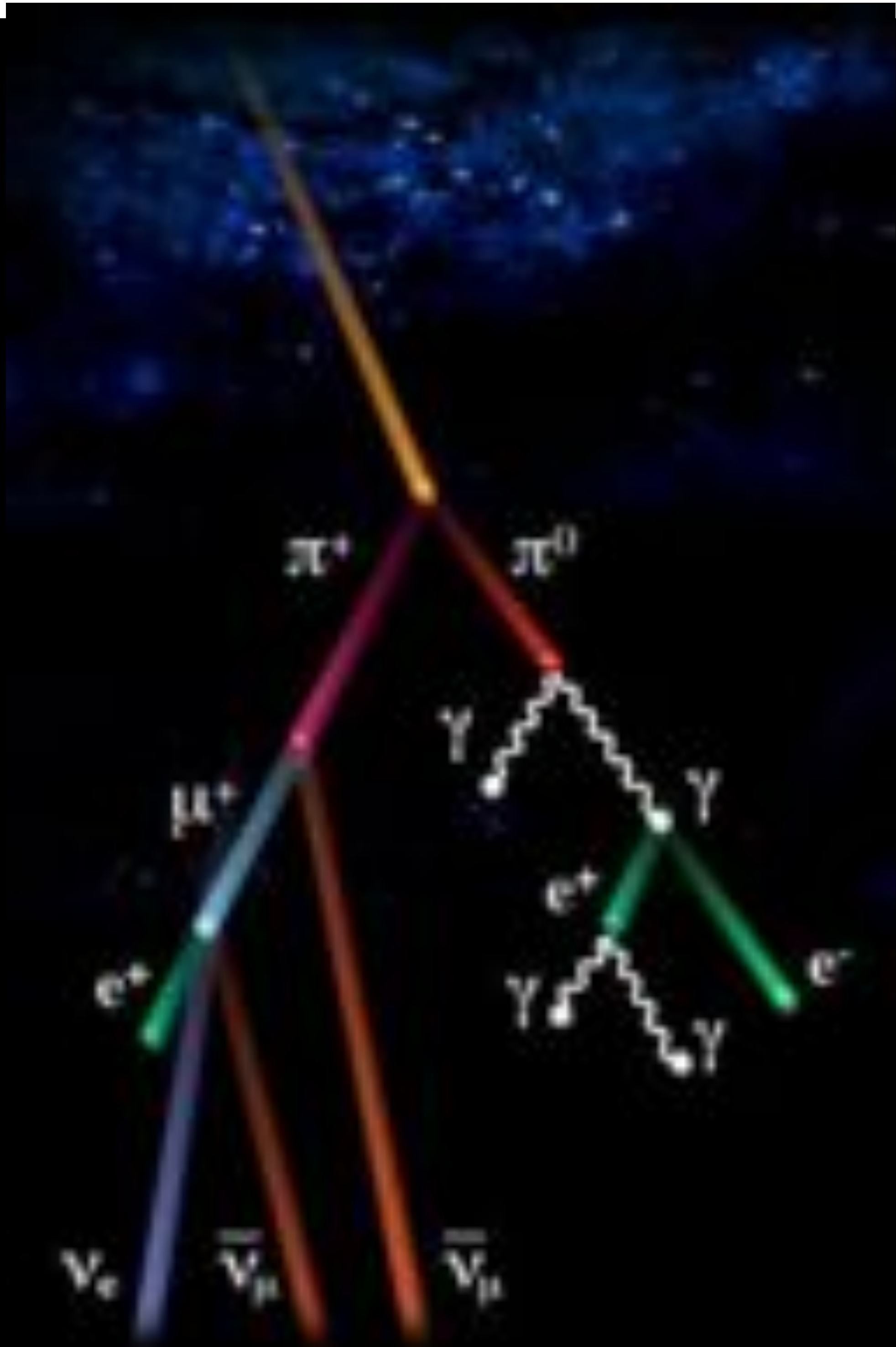
by Victor Hess





Victor Hess used a hot air balloon and an electrometer

Nobel 1936


π+
π0
γ
γ
μ+
e+
e+
e-
γ
γ
νe
ν̄μ
ν̄μ

e+ 1932
∝+ ∝− 1937
π+ π- 1947
K+K- 1949
π° 1950
K° 1950
Λ° Δ 1952
Σ+ Σ- 1953
Ξ- 1953
Symposium on Cosmic Ray, 1939 (The University of Chicago, U.S.A.)

Existence of antimatter

Paul A.M. Dirac

Theory of electrons and positrons, 1928

Nobel Lecture, December 12th, 1933

Relativity:

$$\frac{W^2}{c^2} - p_r^2 - m^2c^2 = 0$$

Quantum mechanics :

$$\left[\frac{W^2}{c^2} - p_r^2 - m^2c^2\right]\Psi = 0$$

$$m^2 = (m)(m) = (-m)(-m)$$

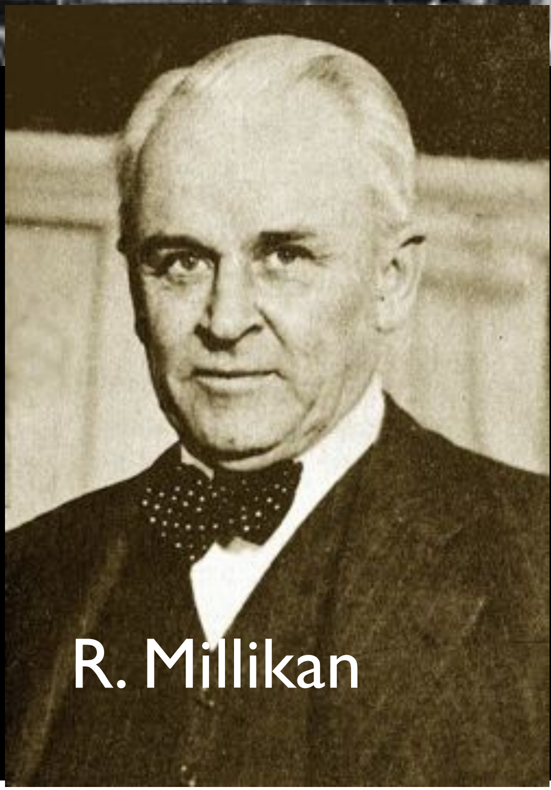
Dirac asked himself: what is (-m) → antimatter theory

The positron story


Dmitri Skobeltzyn

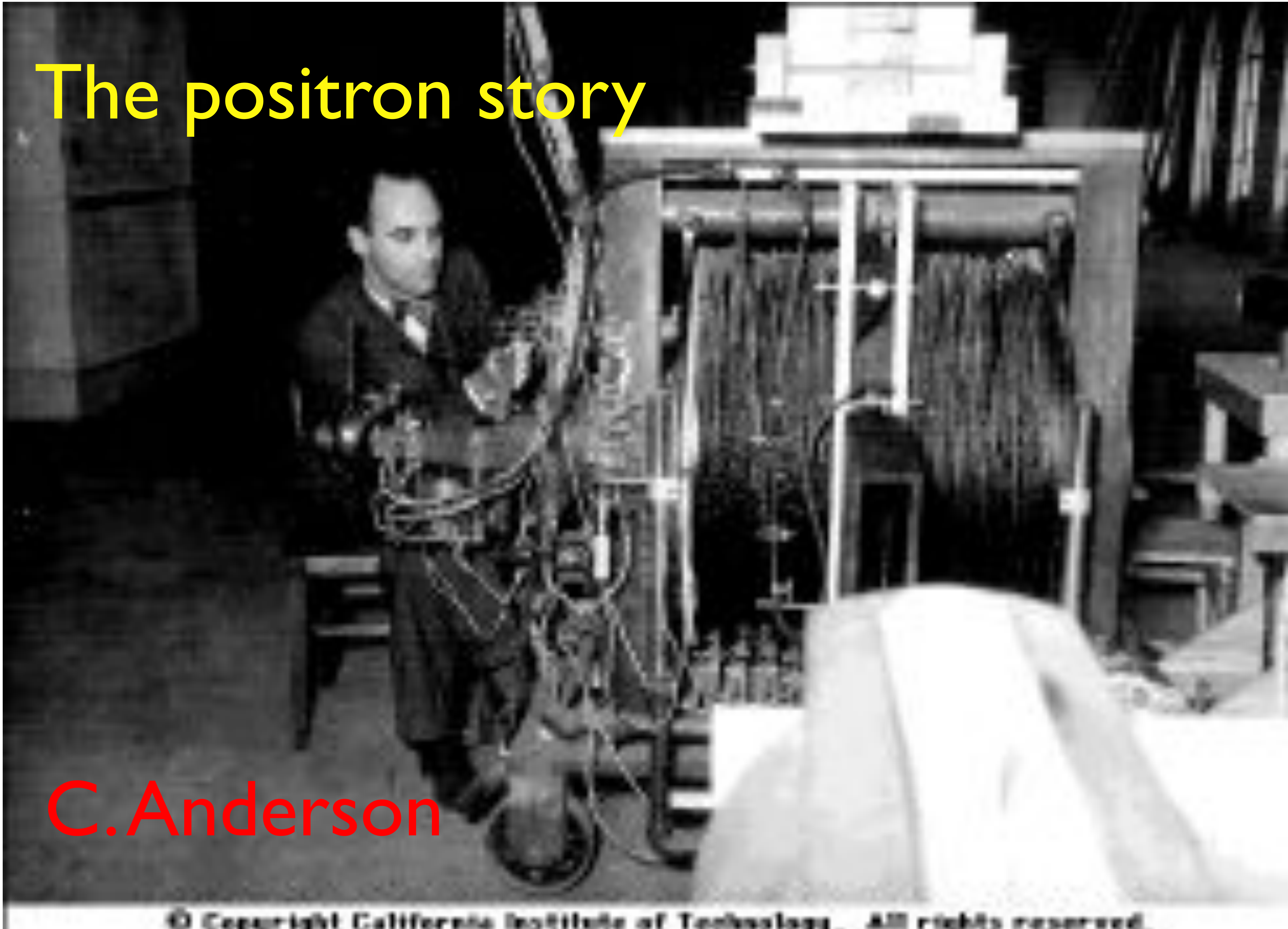

P.A.M. Dirac


Patrick M.S. Blackett


R. Millikan

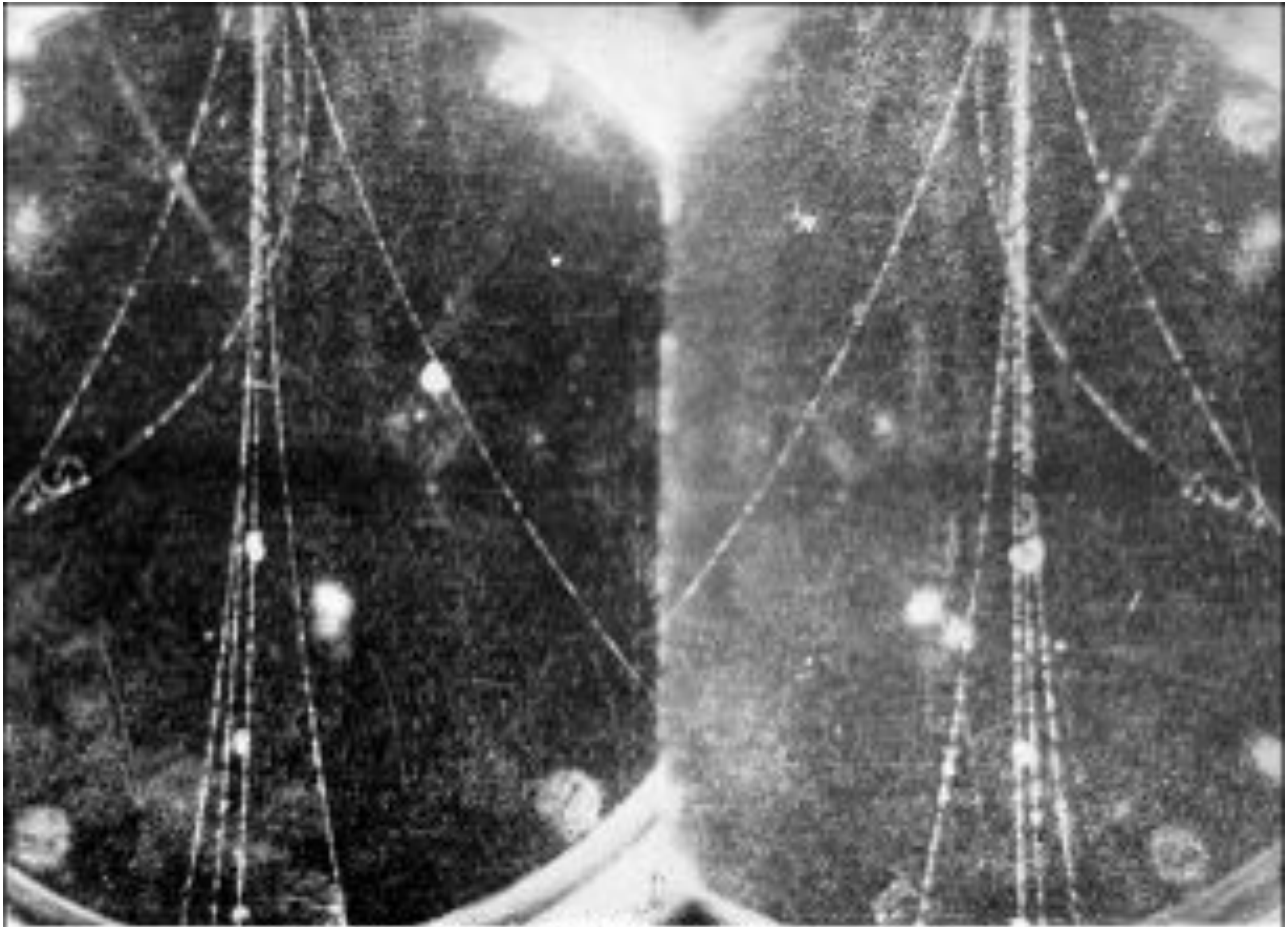

Giuseppe "Beppo" Occhialini

The positron story

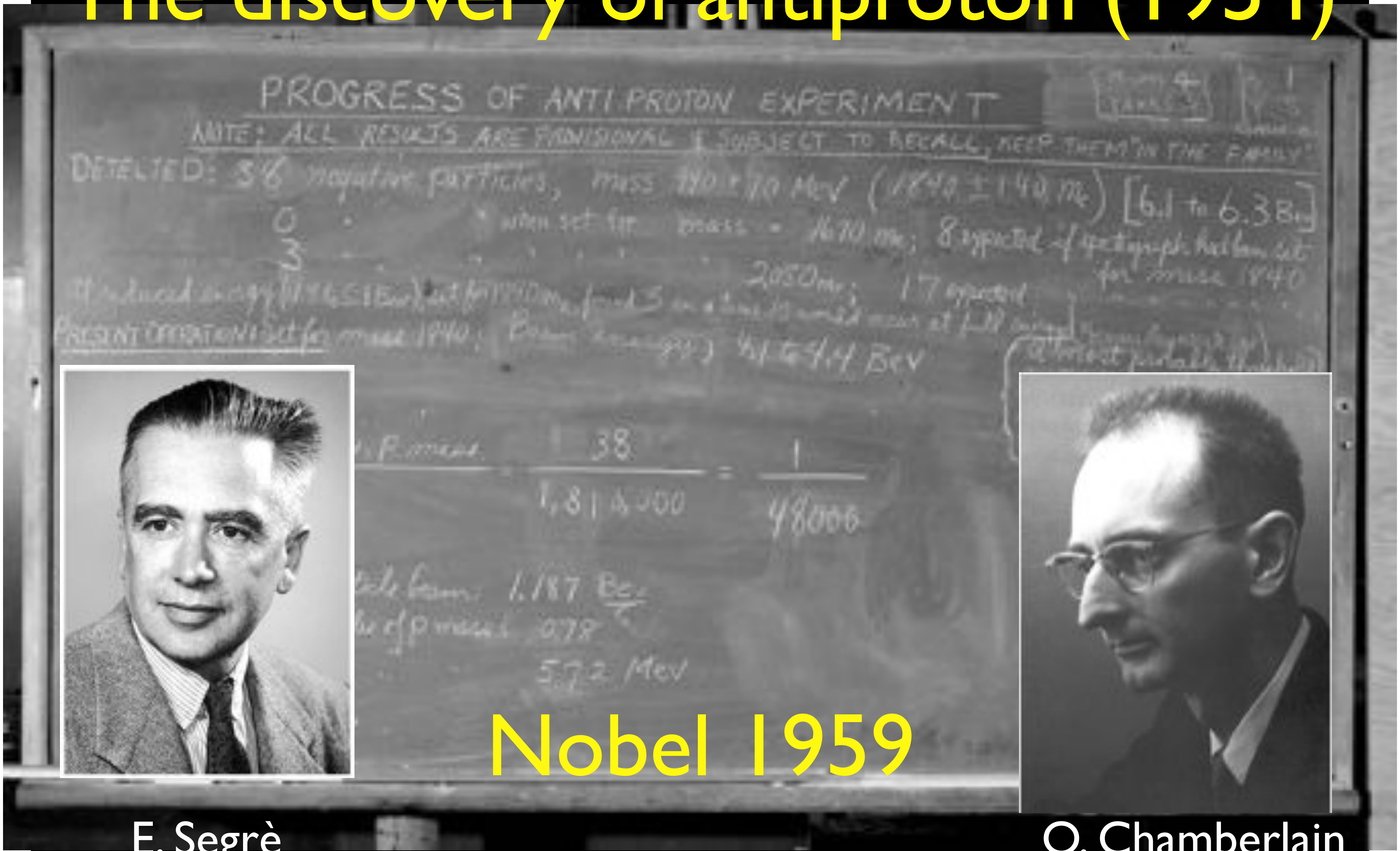


C. Anderson 1932 discovery of the positron in the Cosmic Rays

Nobel 1936



The discovery of antiproton (1954)



E. Segrè

Nobel 1959

O. Chamberlain

A few examples of our past work using accelerators:

Example 1: The discovery of nuclear antimatter

New York Times, June 14, 1965, Page 1.

THE NEW YORK TIMES, MONDAY, JUNE 14, 1965.

AY PRESSES TO LIBERALS

alks With Dubinsky
se and Is Reported
raged by Results

ndsay-for-Mayor forces

Physicists Produce Antimatter Particles In a Complex Form

By HAROLD M. SCHMECK Jr.

Are there somewhere anti-worlds, populated, perhaps, by antipeople?

The question seems like fantasy, but the answer could conceivably be yes in the light of research just reported from

HOUSE WILL VOTE ON CABINET POST

Johnson Faces Major Test This Week on New Urban and Housing Agency

By MARJORIE HUNTER

Moscow Uncertain Whether to Speed Economic Reform

By THEODORE SHABAD
Special to The New York Times

MOSCOW, June 13—A year ago the Soviet Union embarked on an experiment in economic reform. The implications were immense, for the whole notion of rigid central control, the

as "tantamount to capitalism."

The letter emphas Chinese Communist more militaristic ideo asserted that there was torical precedent for a transition" of any co Socialism.

Collusion Charge

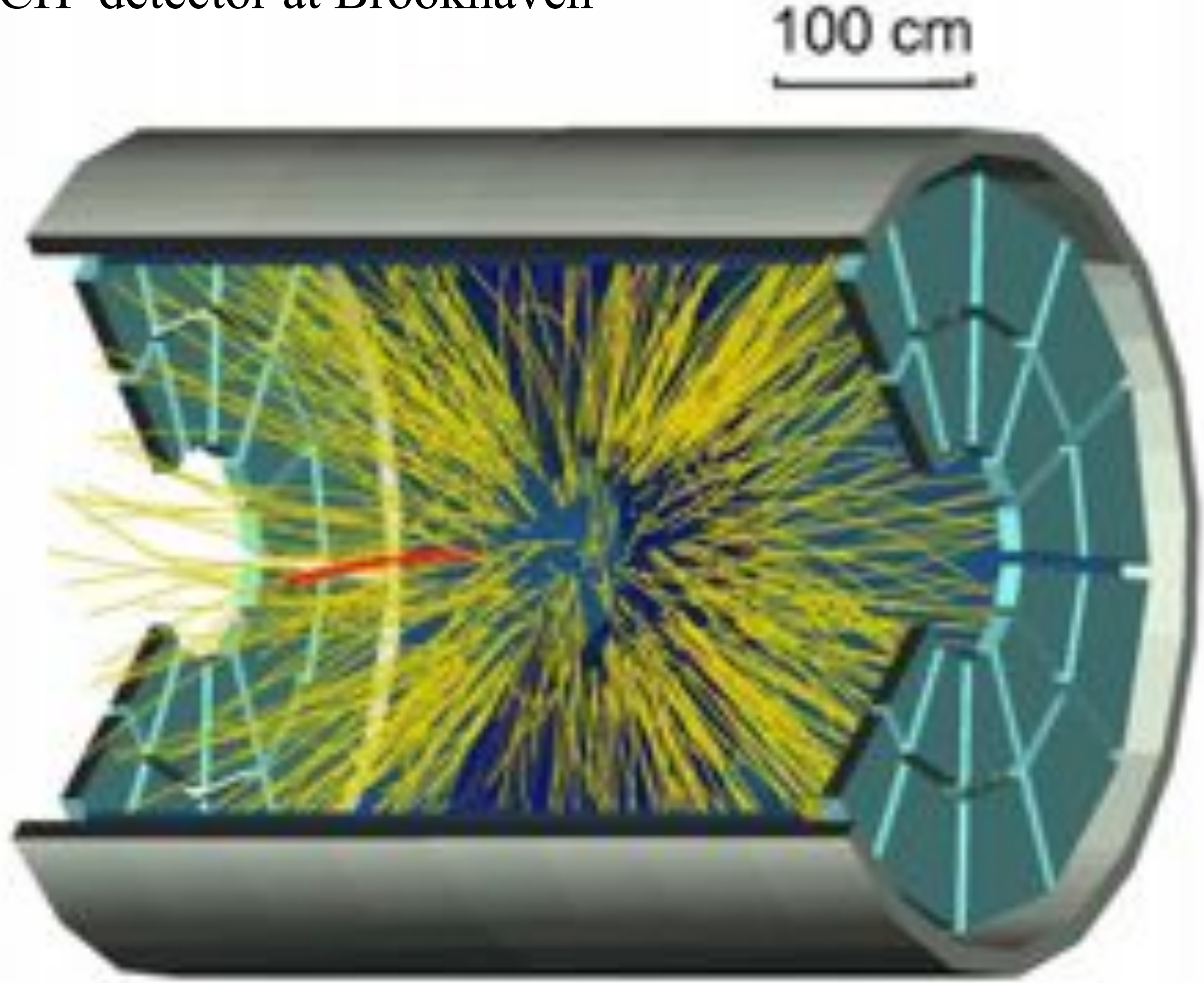
The current article Soviet policy on Viet charged that while Mos made "some gestures in Vietnam, it had dis

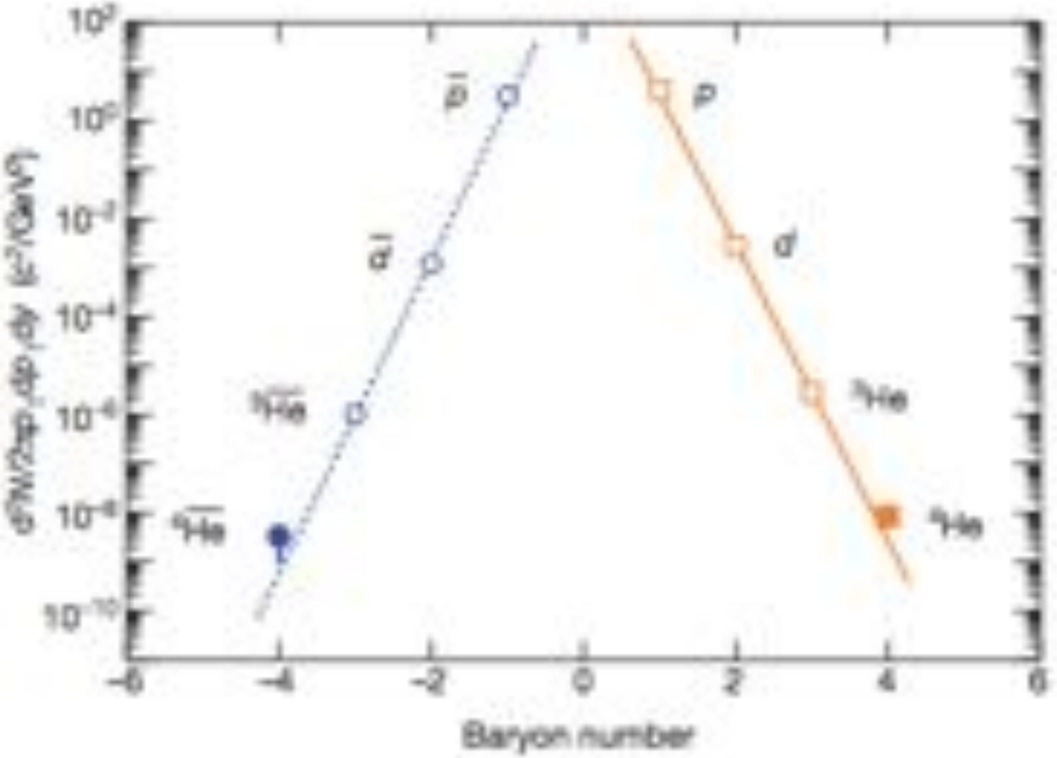
<u>Nuclear Matter</u> (Deuteron) = proton + neutron

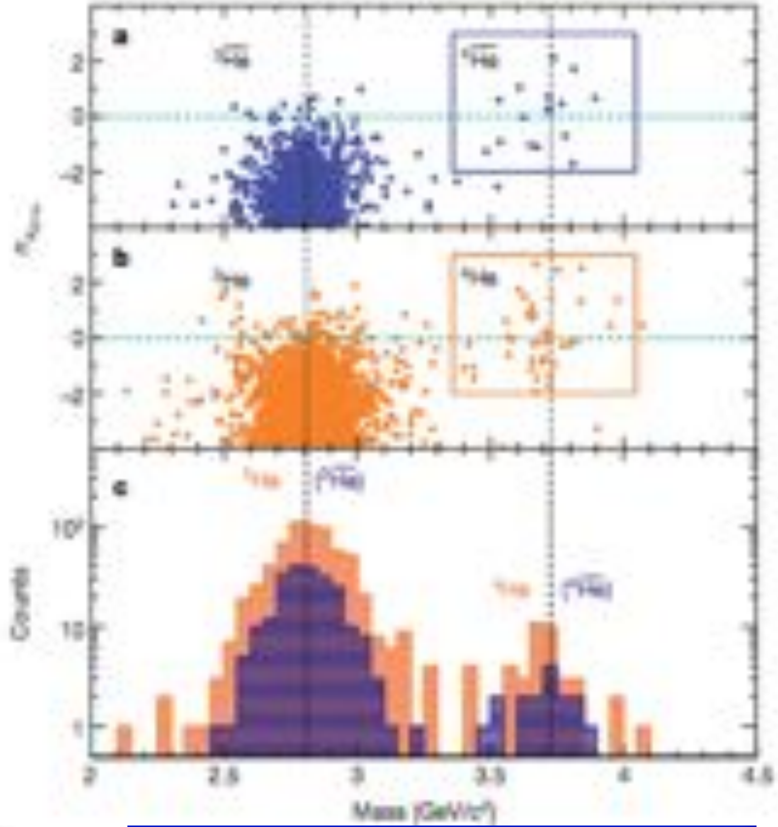
<u>Nuclear Anti-Matter</u> (anti-Deuteron)
= anti-proton + anti-neutron

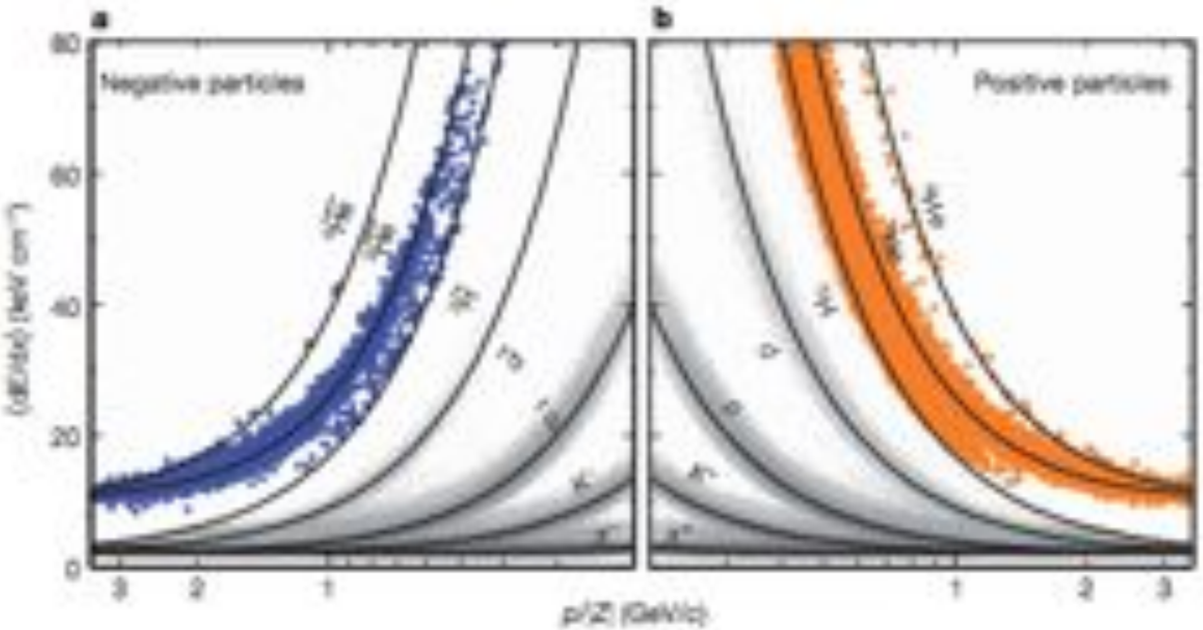
Particles		Anti-particles
e^- *(electron)*	*(positron)*	e^+
P^+ *(proton)*	*(anti proton)*	P^-
π^-		π^+
K^-		K^+
d^+		d^-
$^{3,4}He^+$		$^{3,4}He^-$
$H + e^-$ *(atom)*	*(anti atom)*	$H^- + e^+$

RICH detector at Brookhaven




Baryon number
$d^2N/2\pi p_T dp_T dy$ (c^2/GeV^2)
$\bar{p}$
$\bar{d}$
$^3\overline{He}$
$^4\overline{He}$
p
d
^{3}He
^{4}He


a
b
c
Counts
Mass (GeV/c²)

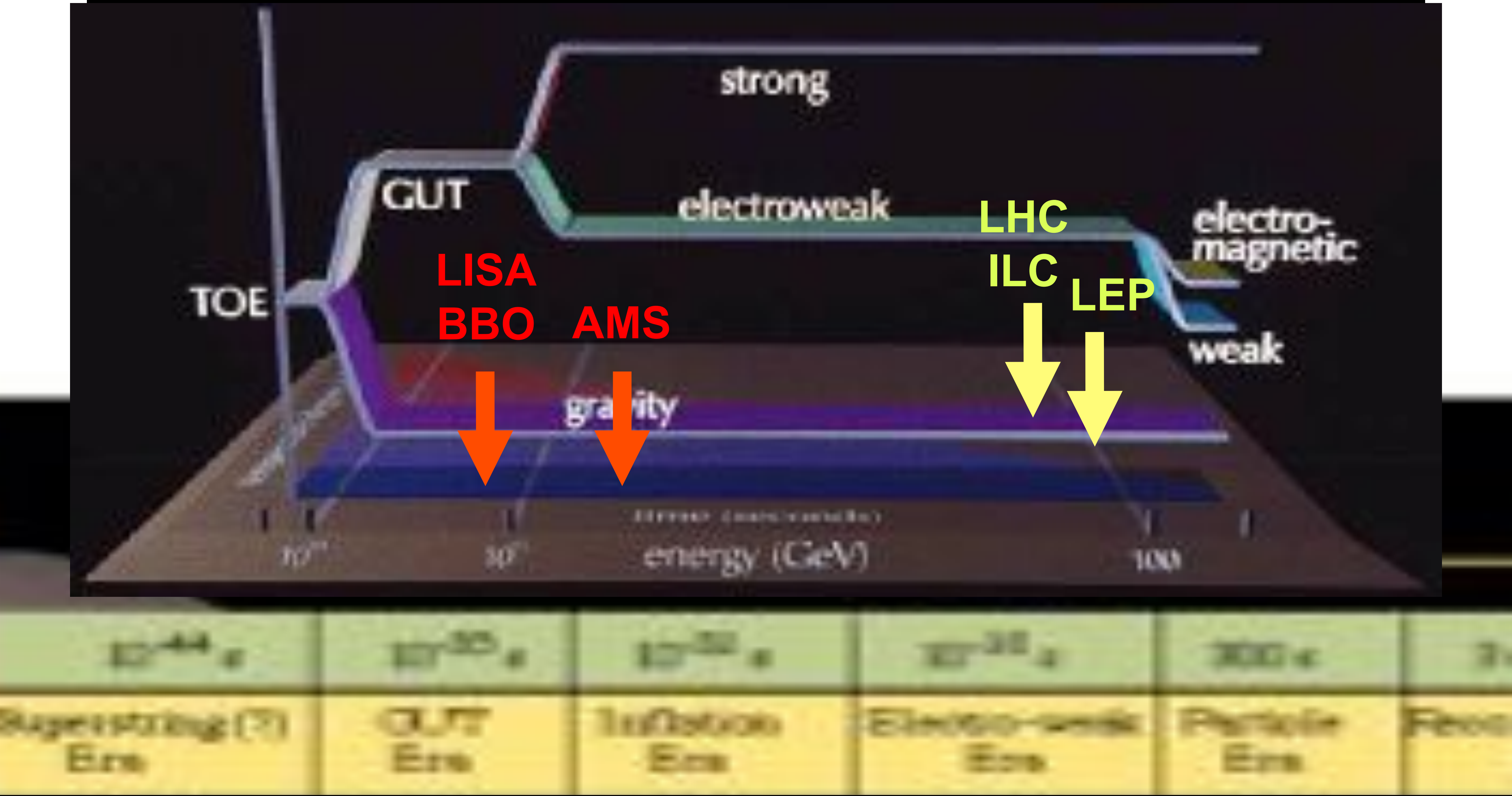

a
b
Negative particles
Positive particles
⟨dE/dx⟩ (keV cm⁻¹)
p/|Z| (GeV/c)

Primordial antimatter in the Universe

The Universe began with the Big Bang.

Before the Big Bang there was "nothing".

After the Big Bang
there must have been
equal amounts of matter and antimatter.


strong
GUT
electroweak
TOE
LHC
ILC
LEP
LISA
BBO
AMS
electro-
magnetic
weak
gravity
energy (GeV)
100

VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the Universe is asymmetrical with respect to the number of particles and antiparticles (C asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a non-zero baryon charge (baryonic asymmetry). We wish to point out a possible explanation of C asymmetry in the hot model of the expanding Universe (see [1]) by making use of effects of CP invariance violation (see [2]). To explain baryon asymmetry, we propose in addition an approximate character for the baryon conservation law.

Sakharov's Conditions for Baryogenesis (1967)

1) Baryon number (B) is not conserved.
   Otherwise an initially baryon symmetric case could never change.

2) CP is not an exact symmetry.
   Otherwise an initially CP-invariant symmetric universe could not evolve into a CP-noninvariant universe.

3) Baryogenesis could have occurred only when the universe was not in thermal equilibrium, e.g. during the GUT era or at the Electroweak phase transition.

Baryon Number Violation
No data has yet provided evidence for baryon number violation.
Proton Lifetime > $1.6\ 10^{33}$ yr ($e^+\pi^0$ mode)

CP Violation
Has been observed in K_L and B only.
Both results are in agreement with the Standard Model.
Need a new type of CP Violation for Baryogenesis.

Questions not answered by the Big Bang Theory:

Why is the universe so:

Big, Old, Flat, Homogenous and Isotropic ?

These questions were solved by inflation

(Starobinsky 1979, Guth 1981, Linde 1982, Albrecht and Steinhardt 1982).

One question remains: ***What is the origin of the small baryon density and, apparently, the matter-antimatter asymmetry ?***

"COBE: New Sky Maps of the Early Universe"
G. Smoot IUAP Conference Proceedings
in Primordial Nucleosynthesis and Evolution of Early Universe (1990)

"Cosmic Microwave Background Probes Models of Inflation"
R. Davis, H. Hodges, G.F. Smoot, P.S. Steinhardt and M.S. Turner
Physical Review Letters 69, 13 (1992)

Evolution with EW Baryogenesis

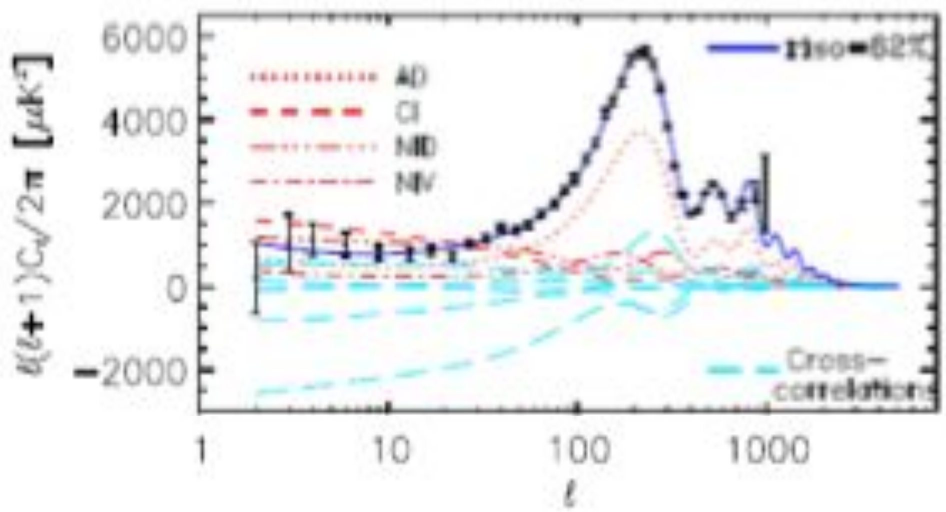
Planck era	10^{-43} sec	10^{19} GeV
	inflation begins	
GUT era	10^{-35} sec	10^{15} GeV
	inflation decay, particle creation starts	
	hot Big Bang	
Electroweak	10^{-9} sec	10^{2} GeV
	baryogenesis-> baryon asymmetry	
	(requires baryon number violation, CP violation beyond the Standard Model and a Higgs very close to the LEP limit)	
… … … … …		
~ 3K today	13.7 Gyr	3×10^{-4} eV

Could our universe be matter-antimatter symmetric ?

If so, regions of matter and antimatter are either close to each other and annihilate or far away from each other, which contradicts the isotropy of the CMB (Cohen, DeRujula, Glashow ApJ 495 (1998) 539). This assumes adiabatic fluctuations (i.e. matter and radiation fluctuate together).

But there could be isocurvature fluctuations (i.e. radiation fluctuates independently (differently) from matter and antimatter). Matter and antimatter could be separated by regions of low baryon density and uniform photon background.

In this case annihilation would be weak. The universe could consist of large matter and antimatter domains with small voids - the isotropy of the CMB radiation would not be affected.



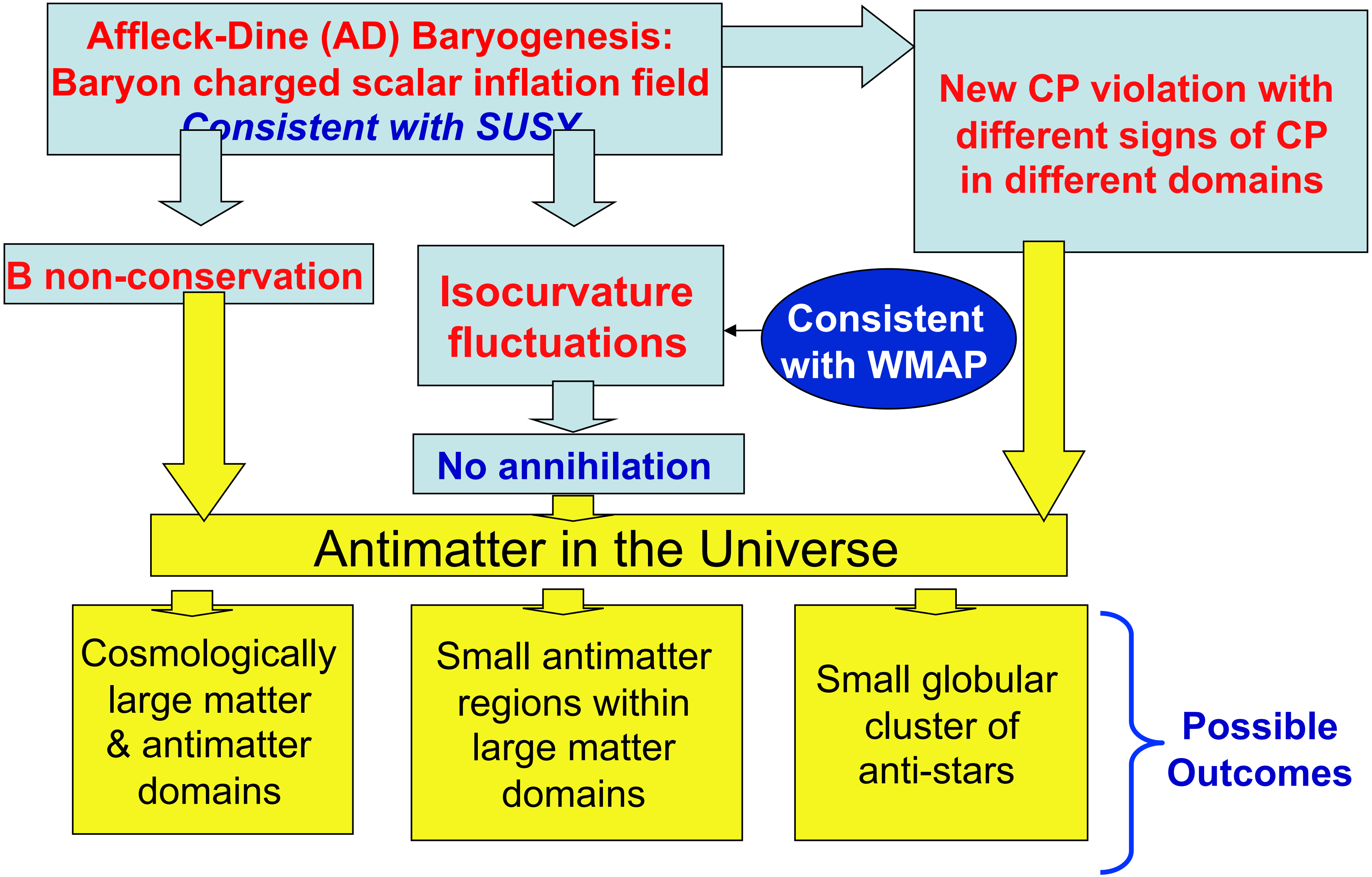
Constraining Isocurvature Initial conditions with WMAP 7-year data

S. Larsen et al. March 2010

AD: Adiabatic Fluctuations
CI: Cold Dark Matter Isocurvature
NID: Neutrino Isocurvature Density
NIV: Neutrino Isocurvature Velocity
riso: Isocurvature fraction <13%

($\Omega_b h^2$= 0.037, $\Omega_c h^2$= 0.13, $\Omega_\Lambda h^2$= 0.75, …)

Our Universe can have some fraction of antimatter:



These predictions are consistent with current limits (γ spectra, AMS-01)

AMS-02 will provide 10^3 to 10^6 more sensitivity

Matter – Antimatter domain separation?

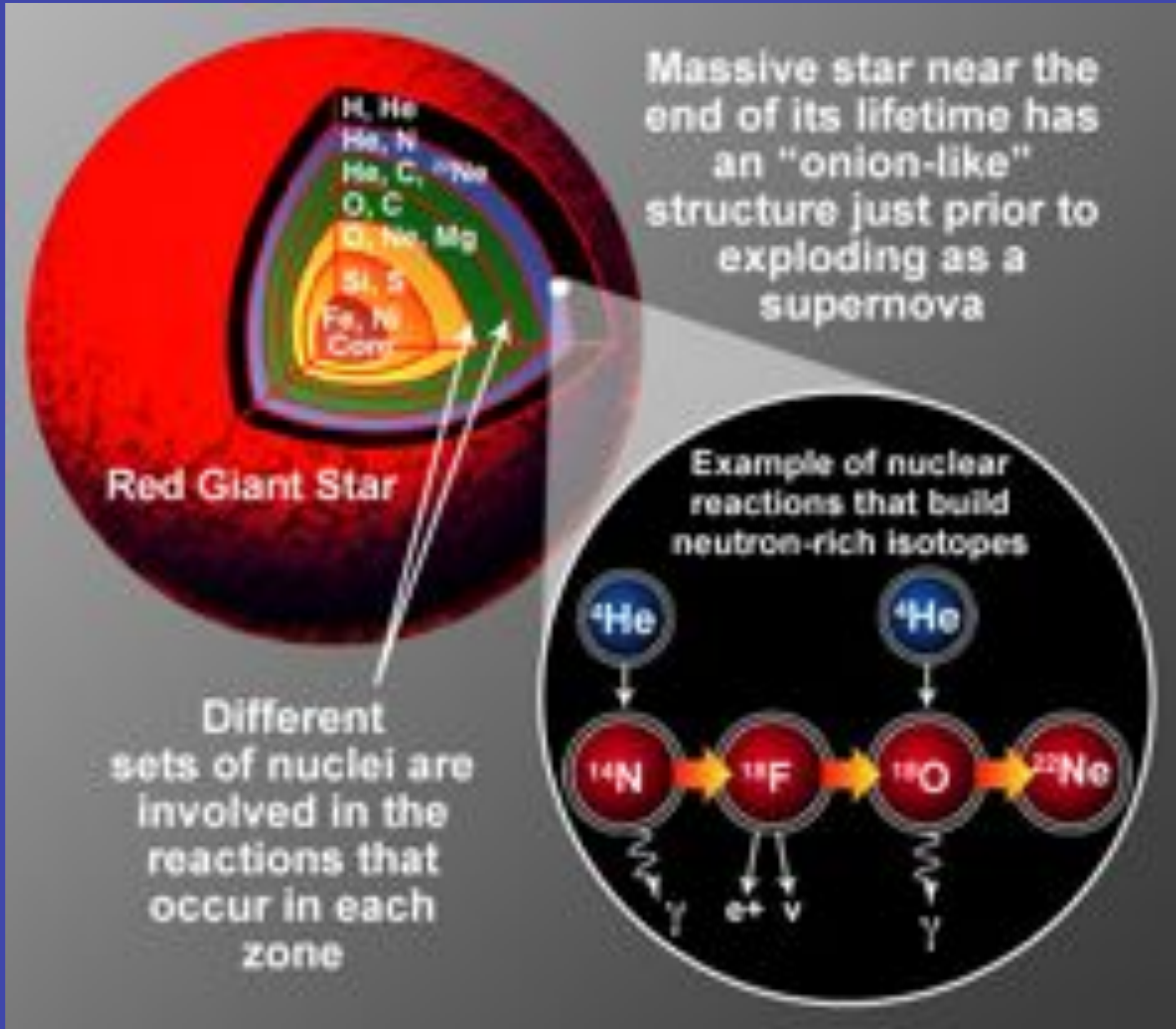
γ-ray ≈ 0.1 GeV from annihilation in boundary regions

- ***Current limit: separation above cluster of galaxy (≥ 10 Mpc)***

Steigman, G. 1976, Ann. Rev. Astron. Astrophys. 14, 339,
"Observational tests of antimatter cosmologies"

Observable?
Magnetic fields ?
Survival probability?

Ahlen, S.P. et al. 1982, ApJ, 260, 20,
"Can we detect antimatter from other galaxies?"



The detection of an antinucleus of He or and higher Z antinucleus would have profound implications on our understanding of the fundamental laws of particle interactions

Search for Antimatter

NATURE VOL. 236 APRIL 14 1972 335

Search for Antimatter in Primary Cosmic Rays

A. BUFFINGTON, L. H. SMITH, G. F. SMOOT &
L. W. ALVAREZ
Space Sciences Laboratory, University of California, Berkeley

M. A. WAHLIG
Lawrence Berkeley Laboratory, University of California

VOLUME 35, NUMBER 4 PHYSICAL REVIEW LETTERS 28 JULY 1975

Search for Cosmic-Ray Antimatter

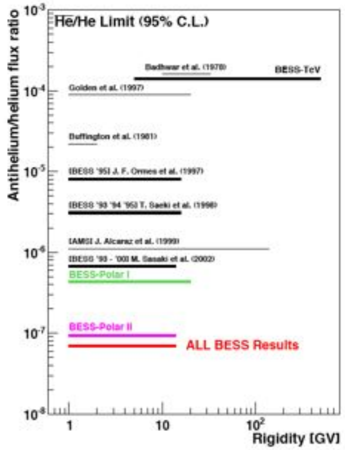
G. F. Smoot, A. Buffington, and C. D. Orth
Space Sciences Laboratory and Lawrence Berkeley Laboratory, University of California,
Berkeley, California 94720
(Received 21 April 1975)

In a sample of 1.5×10^6 helium and 4.0×10^4 higher-charged nuclei, obtained with balloon-borne superconducting magnetic spectrometers, we find the ratio of antinuclei to nuclei in the cosmic rays to be less than 8×10^{-5} for rigidities (momentum/charge) between 4 and 33 GV/c and less than 10^{-2} between 33 and 100 GV/c, at the 95% confidence level.

Search for Antimatter Universe

Experimental work on Antimatter in the Universe

Direct search



AMS-01
BESS

AMS

Increase in sensitivity: x 10^3 – 10^6
Increase in energy to ~TeV

Search for Baryogenesis

New CP

BELLE

BaBar

(sin 2β= 0.672±0.023 consistent with SM)

FNAL KTeV

(Re(ε'/ ε) = $(19.2\pm2.1)*10^{-4}$)

CERN NA-48

CDF, D0

LHC-b, ATLAS,CMS

Proton decay

Super K

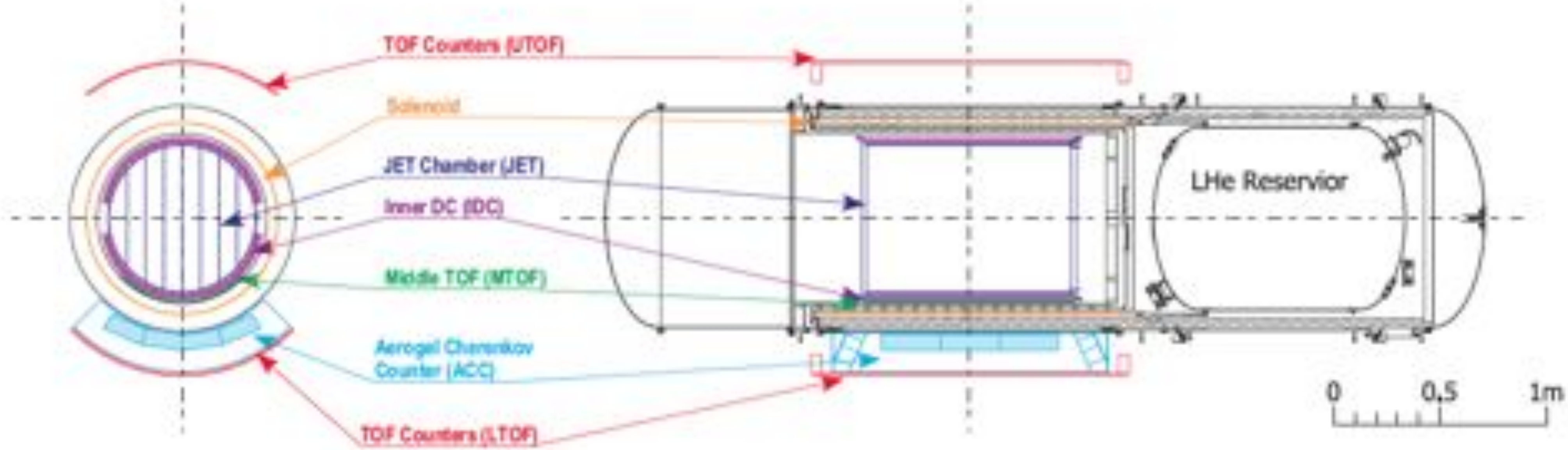
(τ_p > 6.6 * 10^{33} years)

No explanation found for the absence of antimatter (no reason why antimatter should not exist)

BESS

repeated measurement of velocity and momentum

superconducting magnet on several ballon flights



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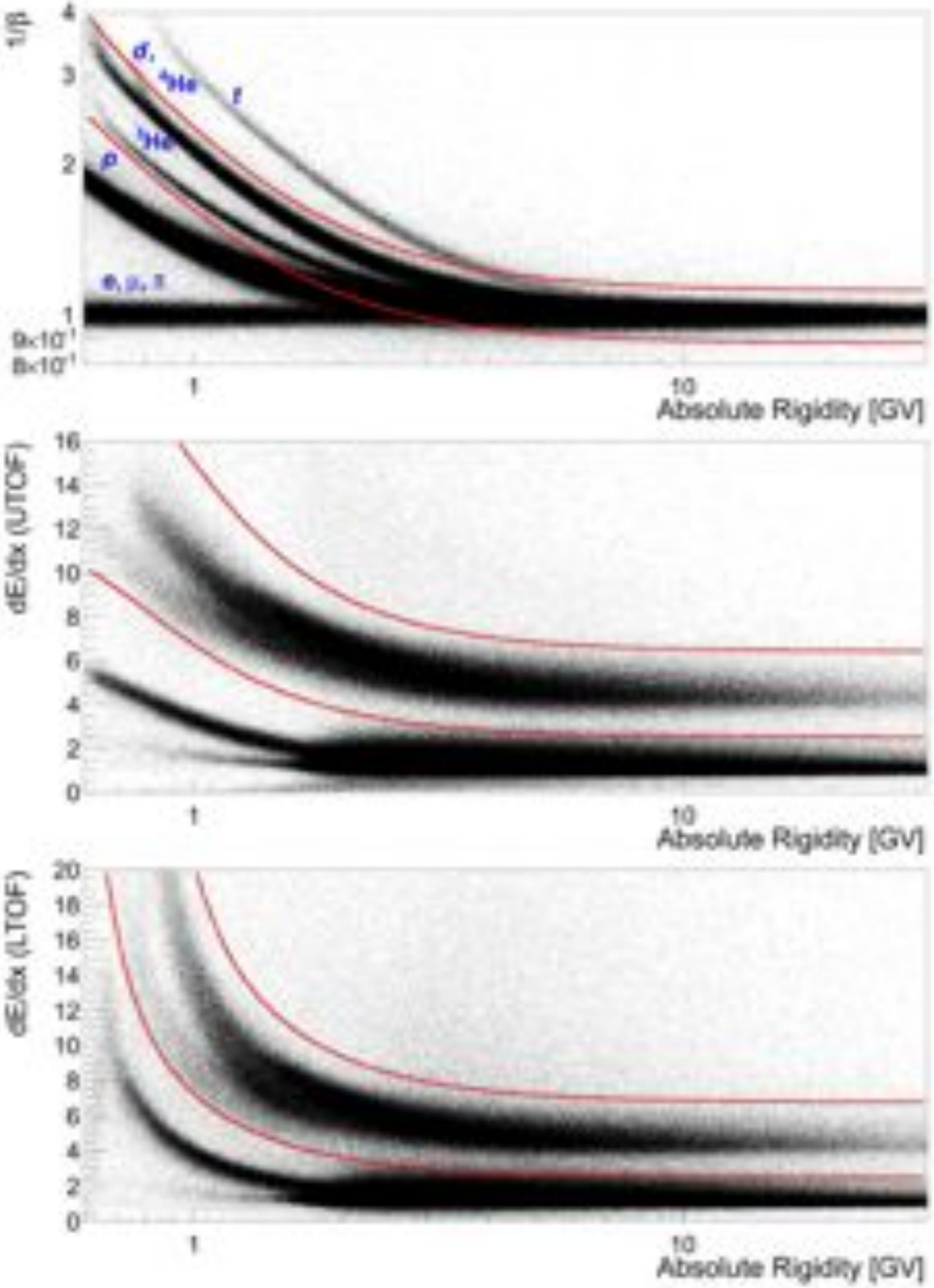
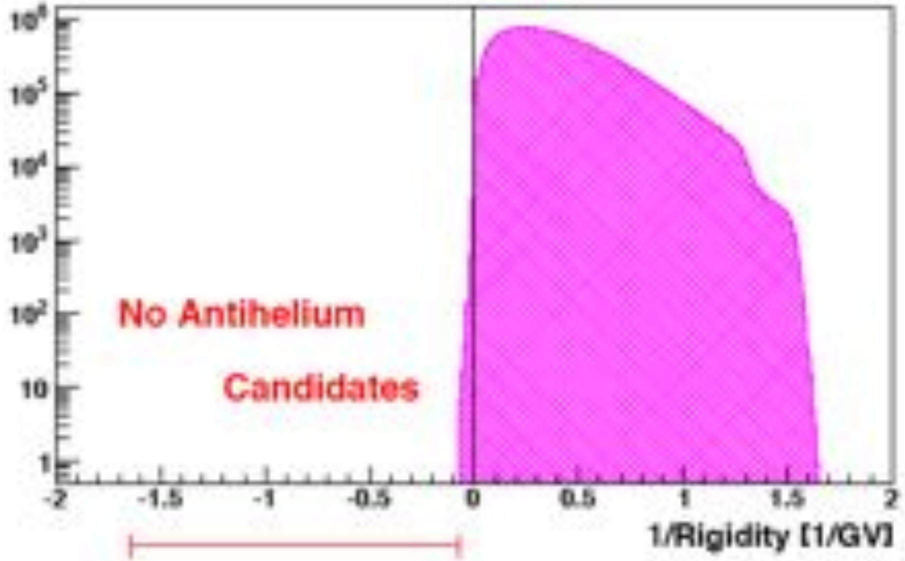

1/β
p
e, μ, π
Absolute Rigidity [GV]
dE/dx (UTOF)
Absolute Rigidity [GV]
dE/dx (LTOF)
Absolute Rigidity [GV]

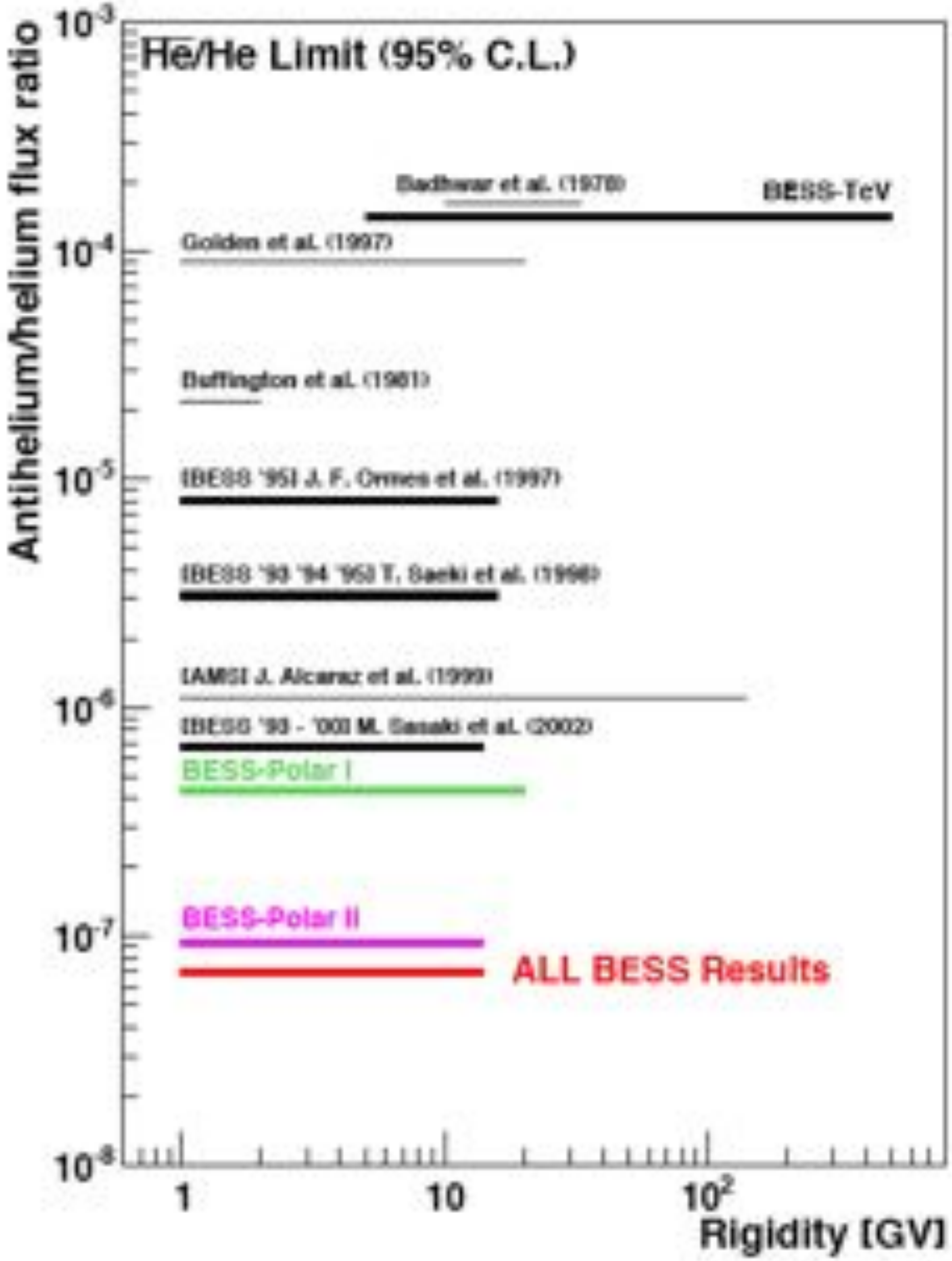

No Antihelium
Candidates
1/Rigidity [1/GV]

Limit (98% CL) if same spectrum for He and anti He is assumed

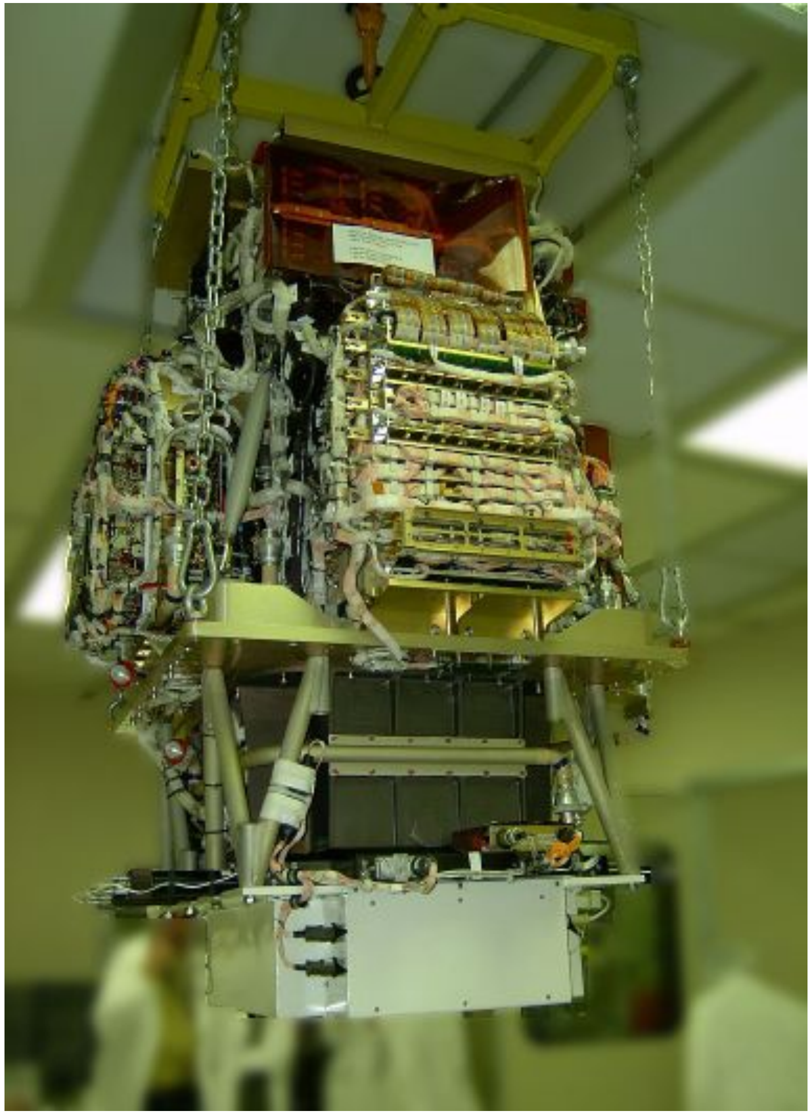
$$R_{\overline{\mathrm{He}}/\mathrm{He}} < \frac{3.1}{\int N_{Obs,\mathrm{He}} \times \overline{\eta} \times \overline{\epsilon}_{sngl}/(\eta \times \epsilon_{sngl})\; dE}.$$

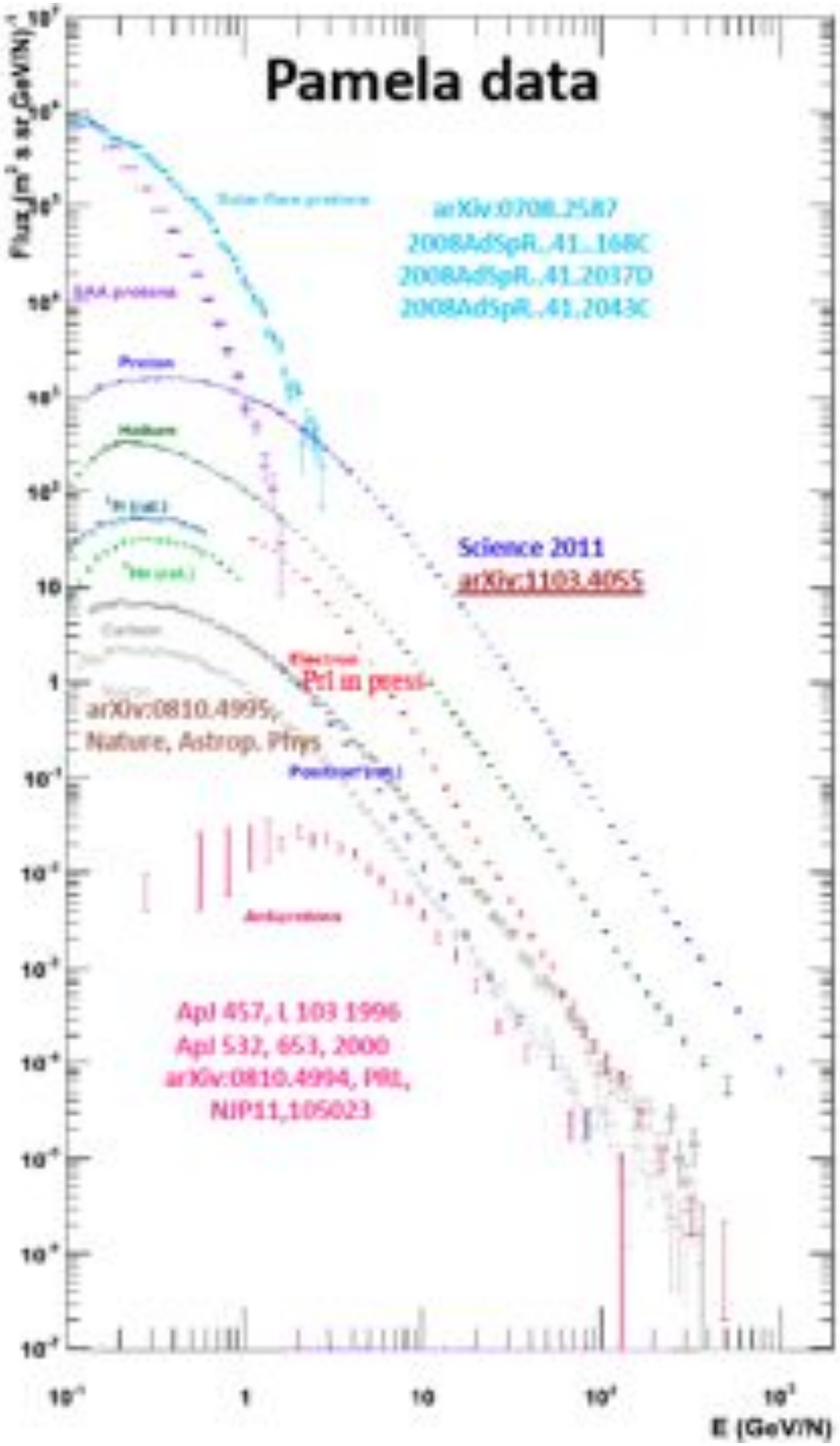
Limit (98% CL) if different spectrum for He and anti He is assumed

$$R_{\overline{\mathrm{He}}/\mathrm{He}} < \frac{3.1 \;/\; [\overline{\eta} \times \overline{\epsilon}_{sngl} \times \overline{\epsilon}_{dE/dx} \times \overline{\epsilon}_{\beta} \times \overline{\epsilon}_{DQ}]_{MIN}}{\int N_{Obs,\mathrm{He}}/(\eta \times \epsilon_{sngl} \times \epsilon_{dE/dx} \times \epsilon_{\beta} \times \epsilon_{DQ})\; dE}.$$

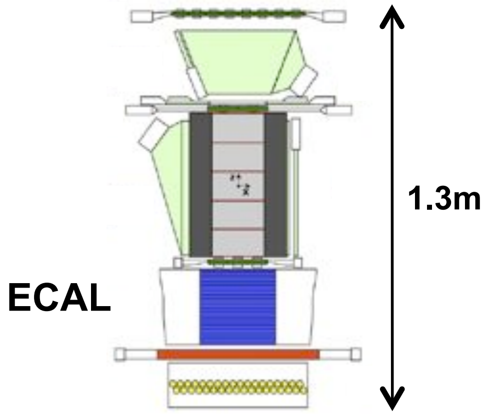

He/He Limit (95% C.L.)
Antihelium/helium flux ratio
Badhwar et al. (1978)
BESS-TeV
Golden et al. (1997)
Buffington et al. (1981)
[BESS '95] J. F. Ormes et al. (1997)
[BESS '93 '94 '95] T. Saeki et al. (1998)
[AMS] J. Alcaraz et al. (1999)
[BESS '93 - '00] M. Sasaki et al. (2002)
BESS-Polar I
BESS-Polar II
ALL BESS Results
Rigidity [GV]

PAMELA 2006-2012





PAMELA



<u>Acceptance</u>

21.5 $cm^2 sr$

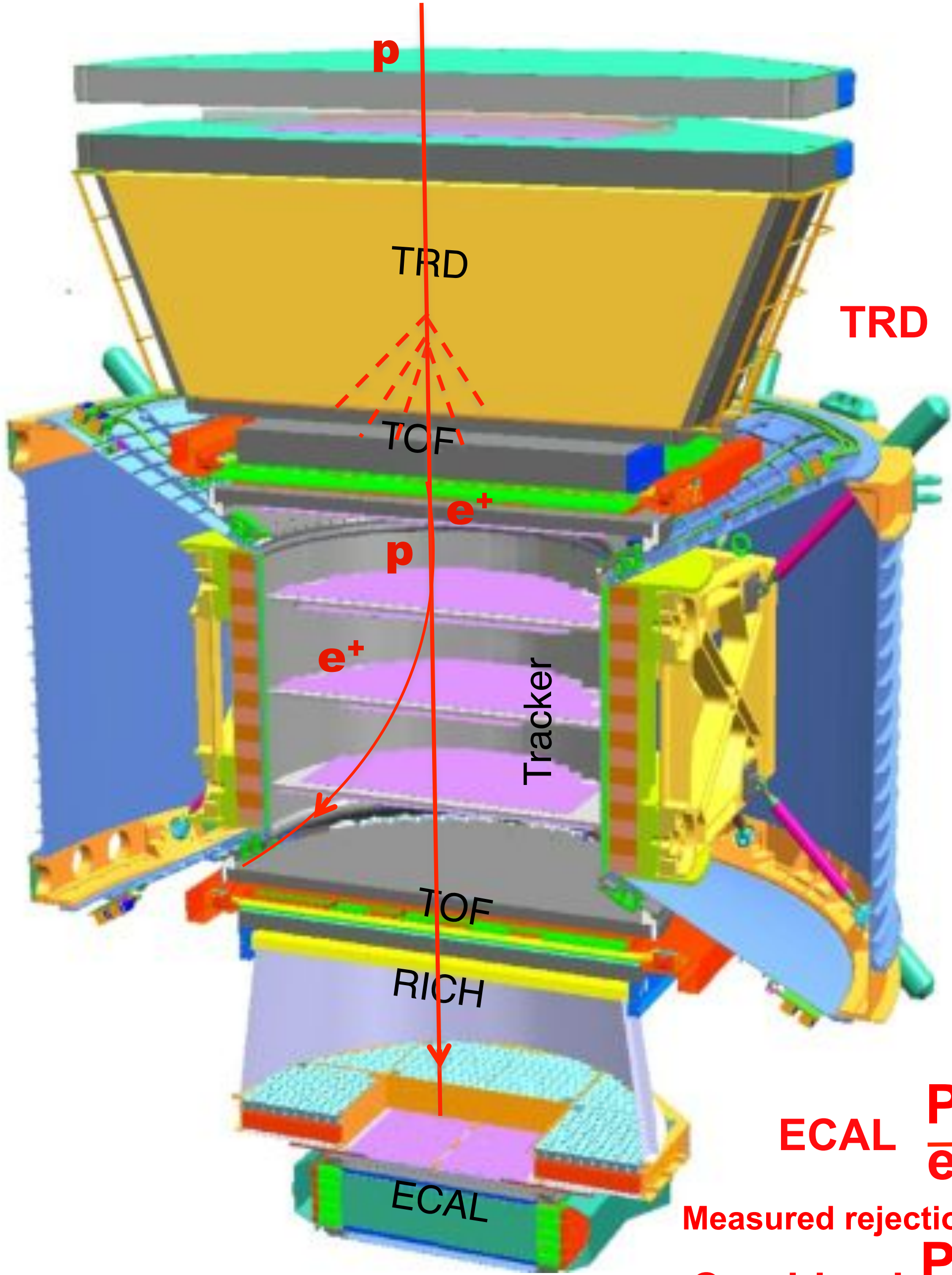
Astroparticle Physics
27 *(2007) 296–315*

<u>Exposure (5yrs)</u>

2006-2011

Published e^+ data up to ~ 100 GeV

AMS-02



TRD $\frac{P}{e^+} > 10^2$

Magnet

ECAL $\frac{P}{e^+} > 10^4$

Measured rejection at 0.4 TeV

Combined $\frac{P}{e^+} > 10^6$

<u>Acceptance</u>

e^+ 950 $cm^2 sr$

$\overline{p}$, He, $\overline{He}$, … **4,500 $cm^2 sr$**

<u>Exposure</u> (20 yrs)

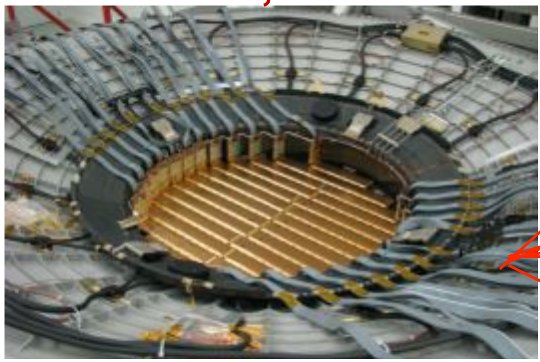
e^+ energy > 1 TeV

AMS: A TeV precision, multipurpose spectrometer

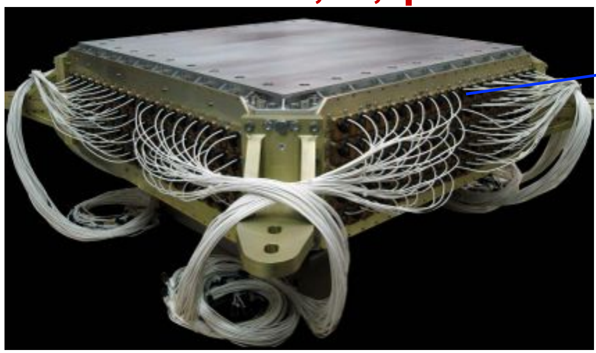
Particles and nuclei are defined by their charge (Z) and energy **(E ~ P)**

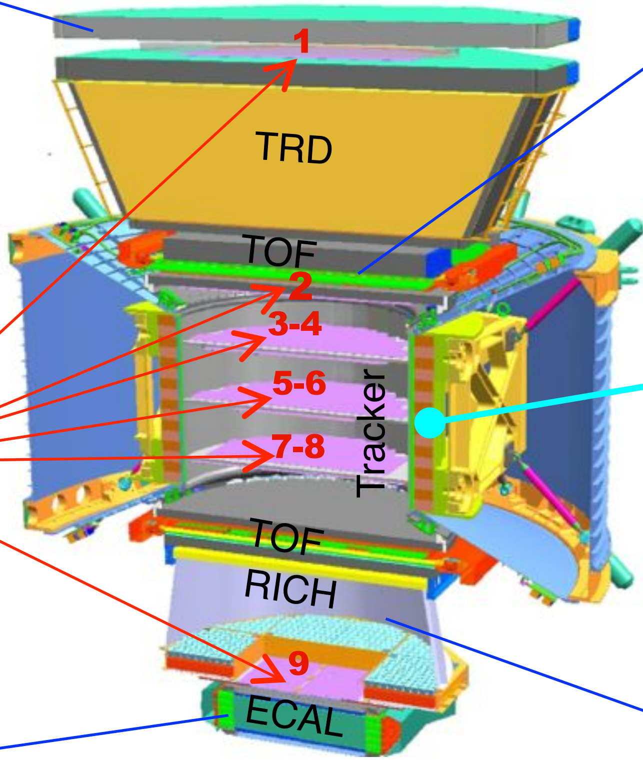
TRD
Identify e^+, e^-

Silicon Tracker
Z, P



ECAL
E of e^+, e^-, γ

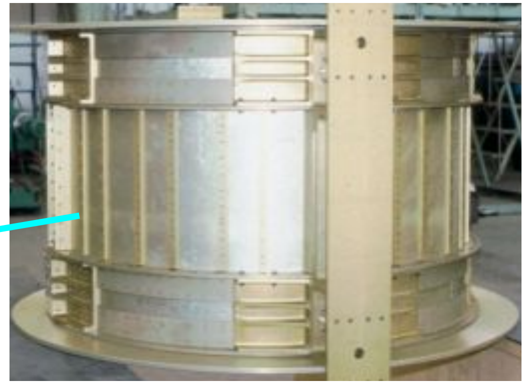




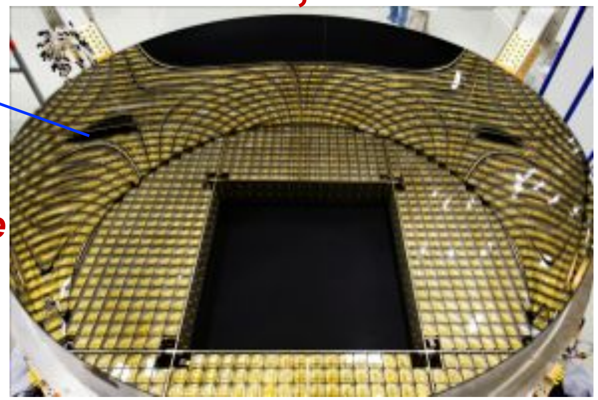
***Z, P* are measured independently by the Tracker, RICH, TOF and ECAL**

TOF
Z, E

Magnet
±Z



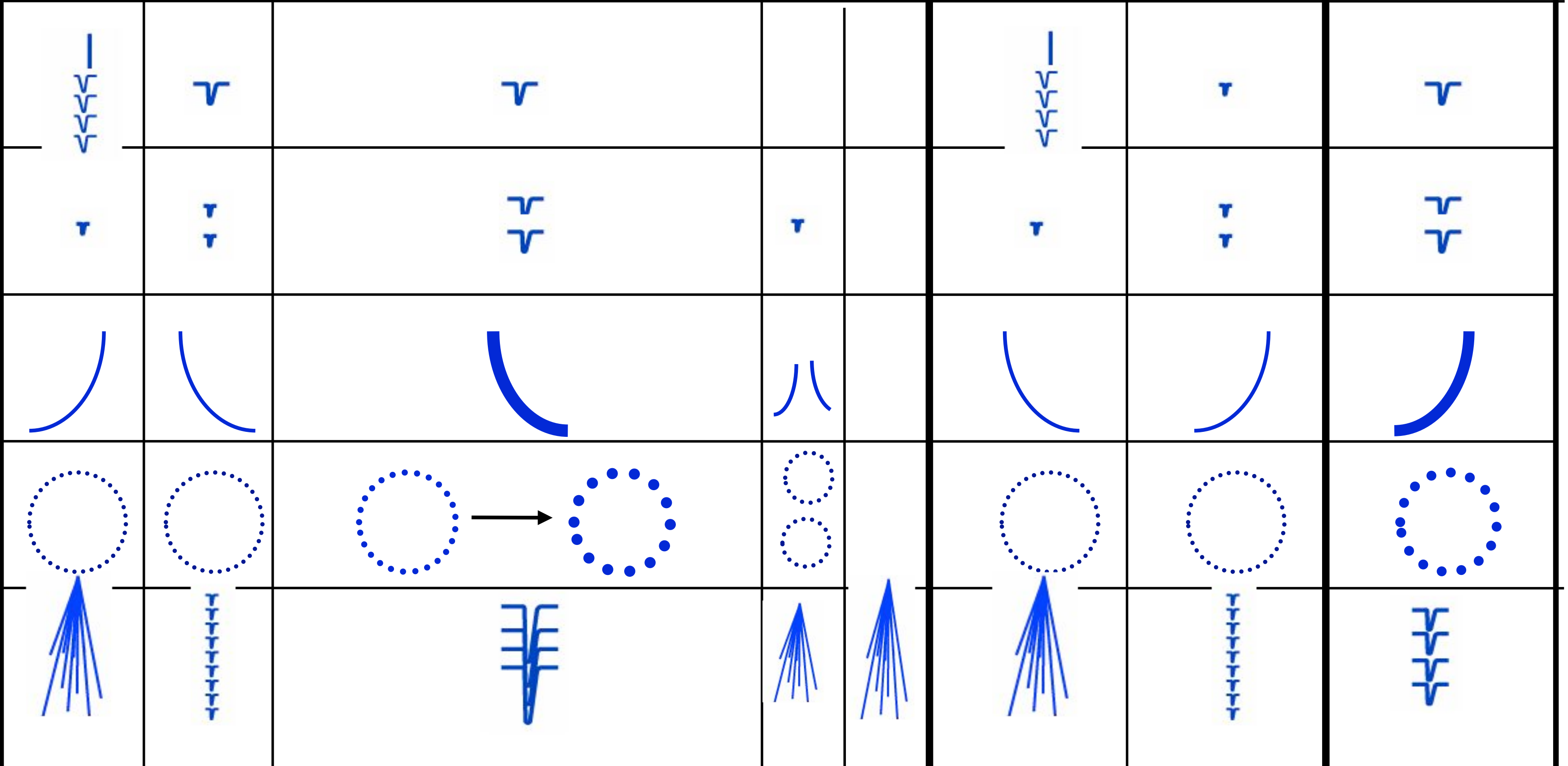
RICH
Z, E



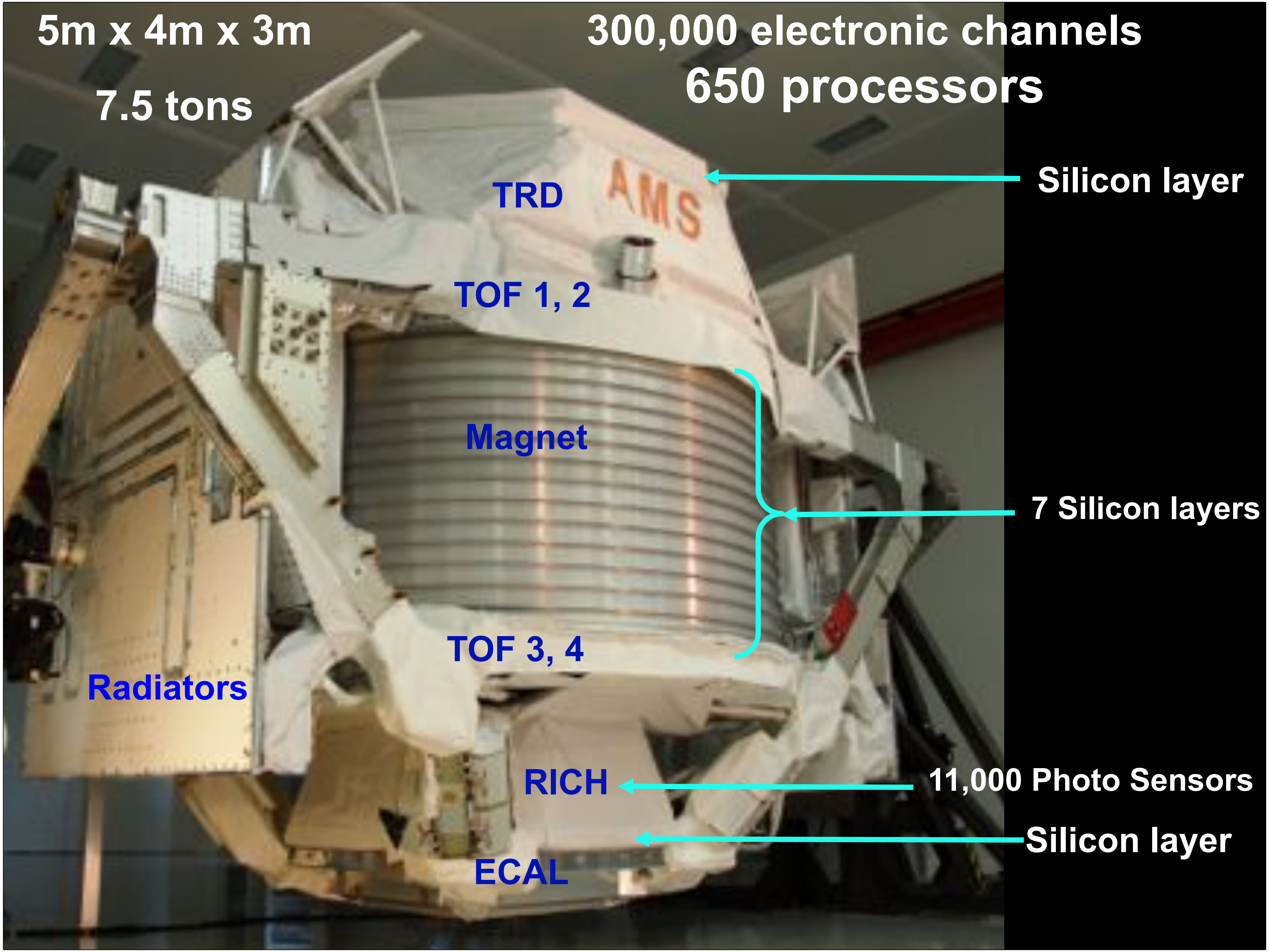
Characteristics of AMS-02

$\Delta t = 100$ ps, $\Delta x = 10$ µm, $\Delta v/v = 0.001$

	e^-	P	He,Li,Be,..Fe	γ		e^+	$\bar{P}, \bar{D}$	$\overline{He}, \bar{C}$
TRD								
TOF								
Tracker								
RICH								
ECAL								
Physics example	Cosmic Ray Physics Strangelets					Dark matter		Antimatter



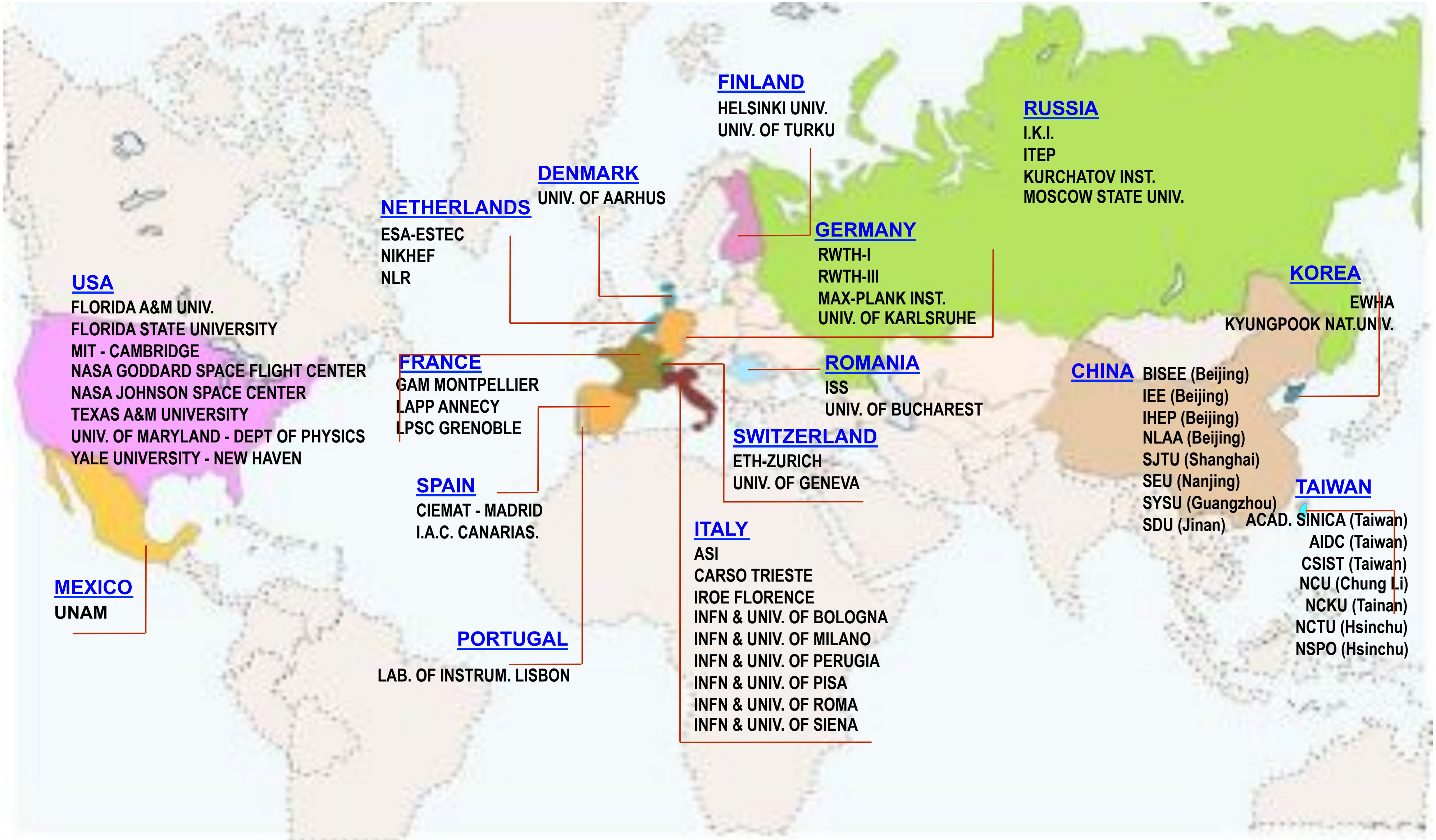
y06K307

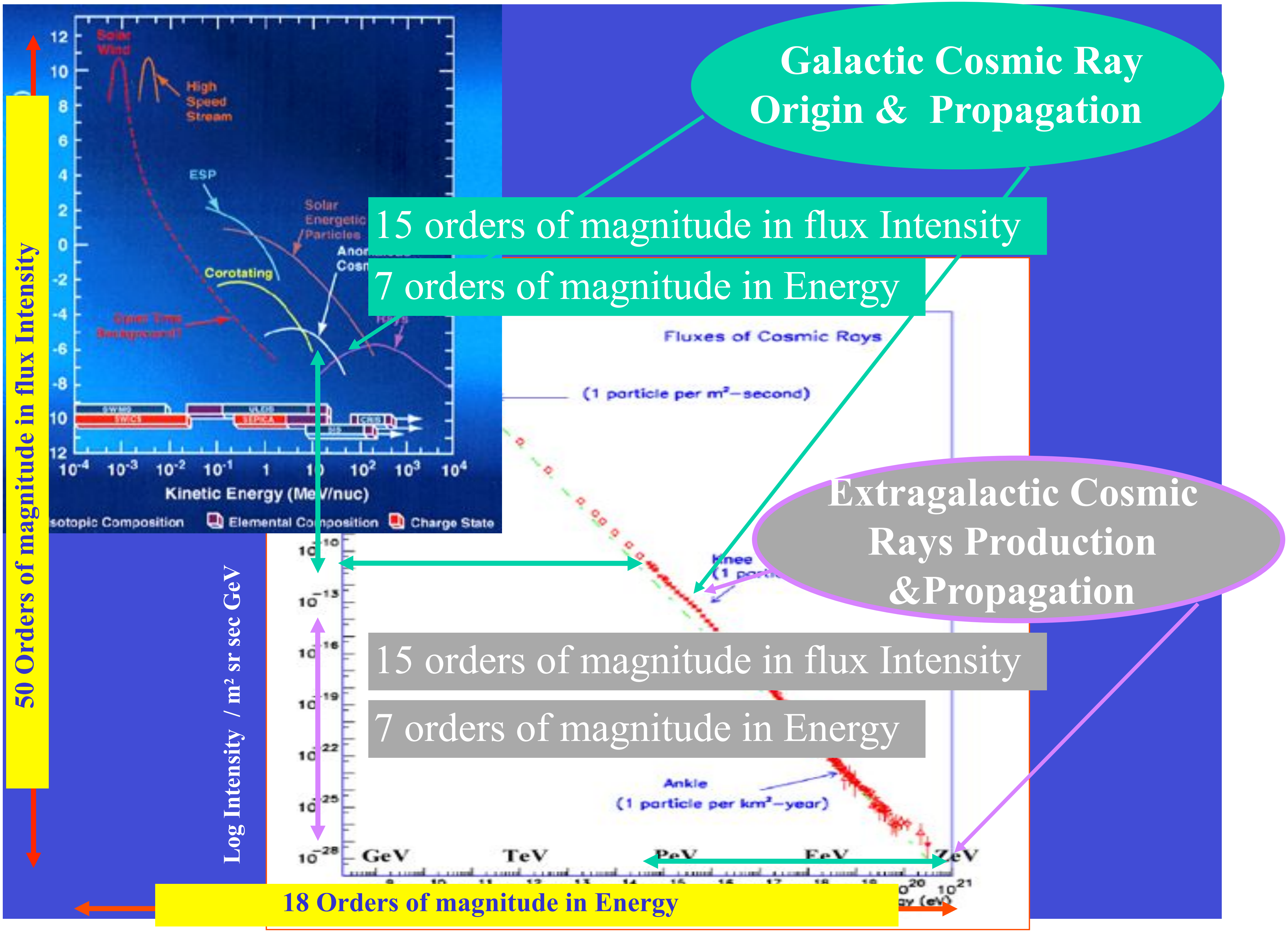


5m x 4m x 3m
7.5 tons
300,000 electronic channels
650 processors
AMS
TRD
Silicon layer
TOF 1, 2
Magnet
7 Silicon layers
TOF 3, 4
Radiators
RICH
11,000 Photo Sensors
Silicon layer
ECAL

AMS is an International Collaboration

16 Countries, 60 Institutes and 600 Physicists





Galactic Cosmic Ray Origin & Propagation
15 orders of magnitude in flux Intensity
7 orders of magnitude in Energy
Extragalactic Cosmic Rays Production &Propagation
15 orders of magnitude in flux Intensity
7 orders of magnitude in Energy
50 Orders of magnitude in flux Intensity
18 Orders of magnitude in Energy
Log Intensity / m² sr sec GeV
Solar Wind
High Speed Stream
ESP
Solar Energetic Particles
Corotating
Kinetic Energy (MeV/nuc)
Elemental Composition
Charge State
Fluxes of Cosmic Rays
(1 particle per m²–second)
Knee
Ankle
(1 particle per km²–year)
GeV
TeV
PeV
EeV
ZeV

TRIBUNE DE GENÈVE

JEUDI 26 AOUT 2010
TRIBUNE DE GENÈVE

Aéroport de Cointrin.

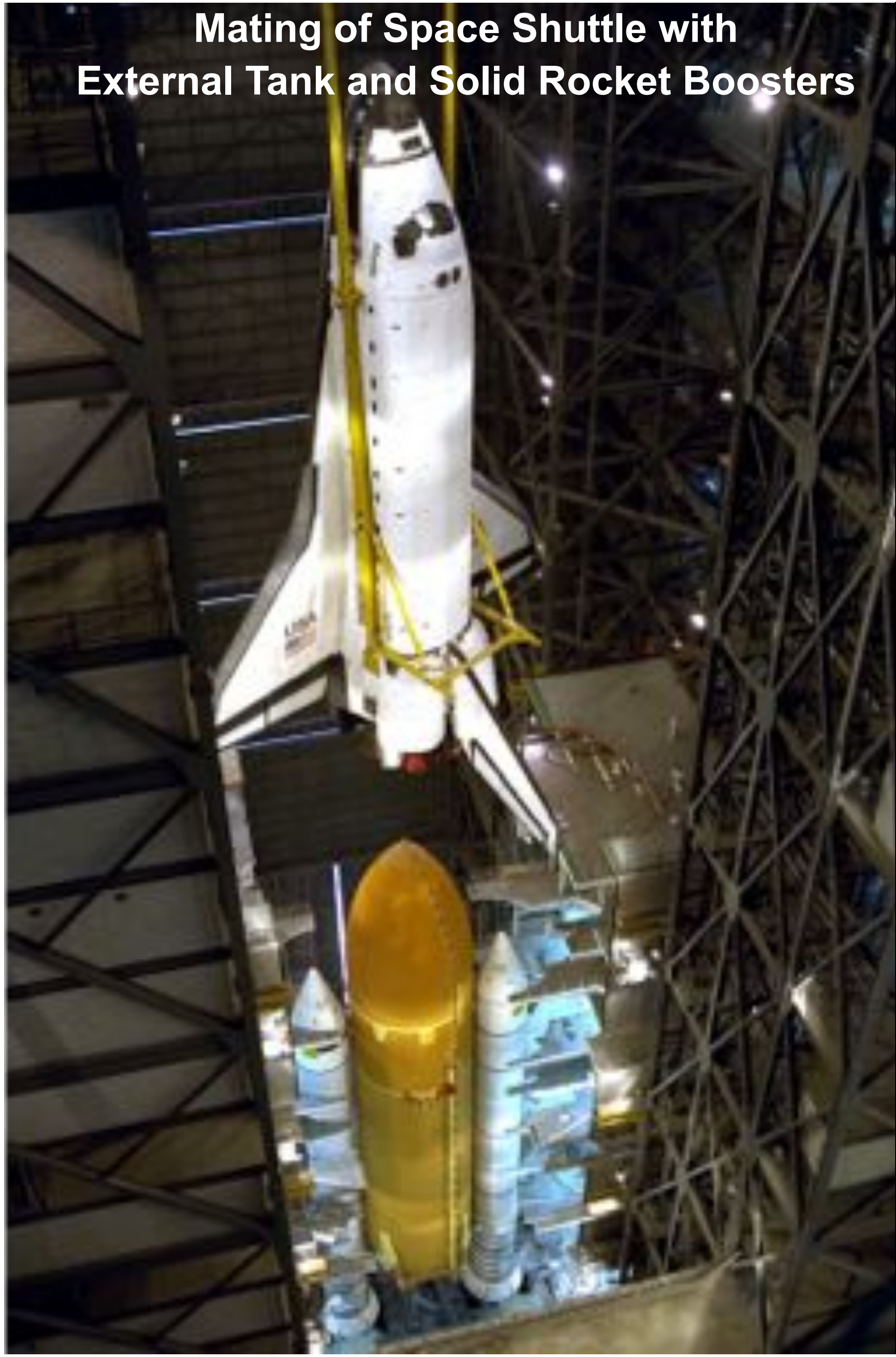
Vol spécial pour l'aimant chasseur d'antimatière

PHYSIQUE Assemblé au CERN, l'AMS quitte Cointrin pour la Floride d'où il doit être lancé dans l'espace en février.

Le Spectromètre magnétique Alpha (AMS).

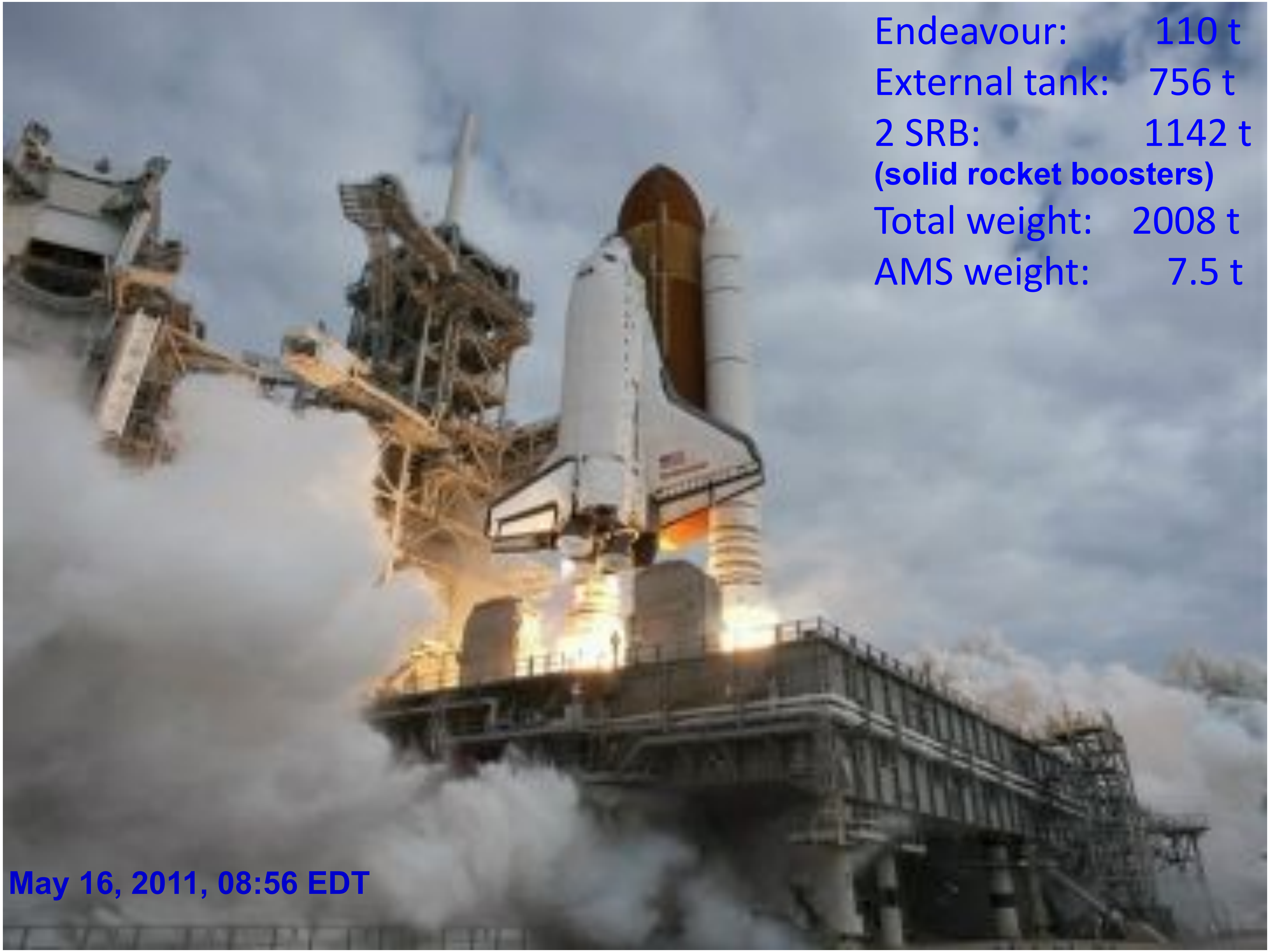
Bouquet de surprises

AMS mated with the Payload Attach System simulator (A) during Space Station interface verification test



Mating of Space Shuttle with
External Tank and Solid Rocket Boosters

Transfer of STS-134
to the launch pad,
March 10, 2011

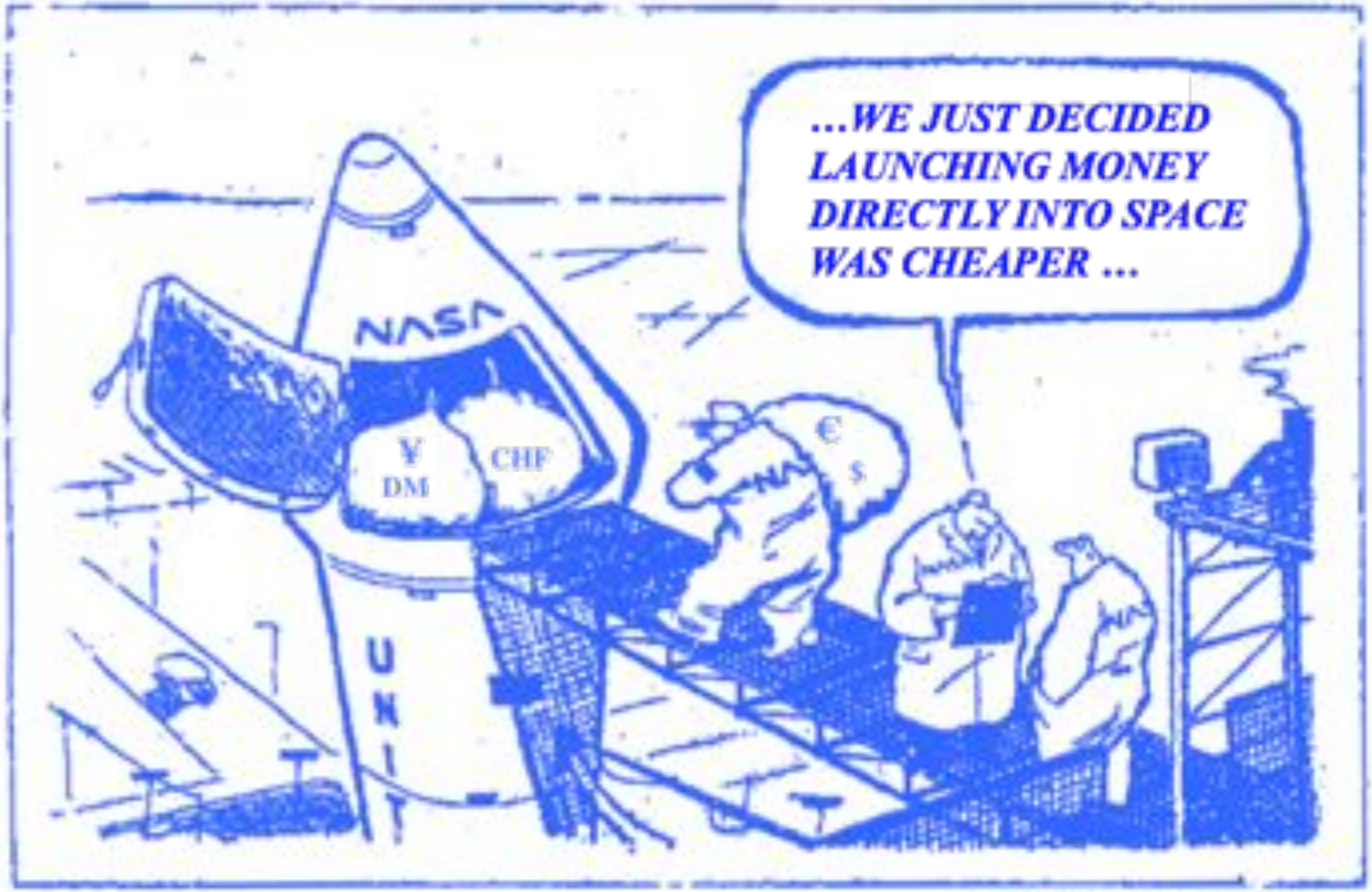

Endeavour: 110 t
External tank: 756 t
2 SRB: 1142 t
(solid rocket boosters)
Total weight: 2008 t
AMS weight: 7.5 t
May 16, 2011, 08:56 EDT

After 123 seconds,
1,000 tons of fuel is spent.

Endeavour approaching the Space Station, May 18, 2011

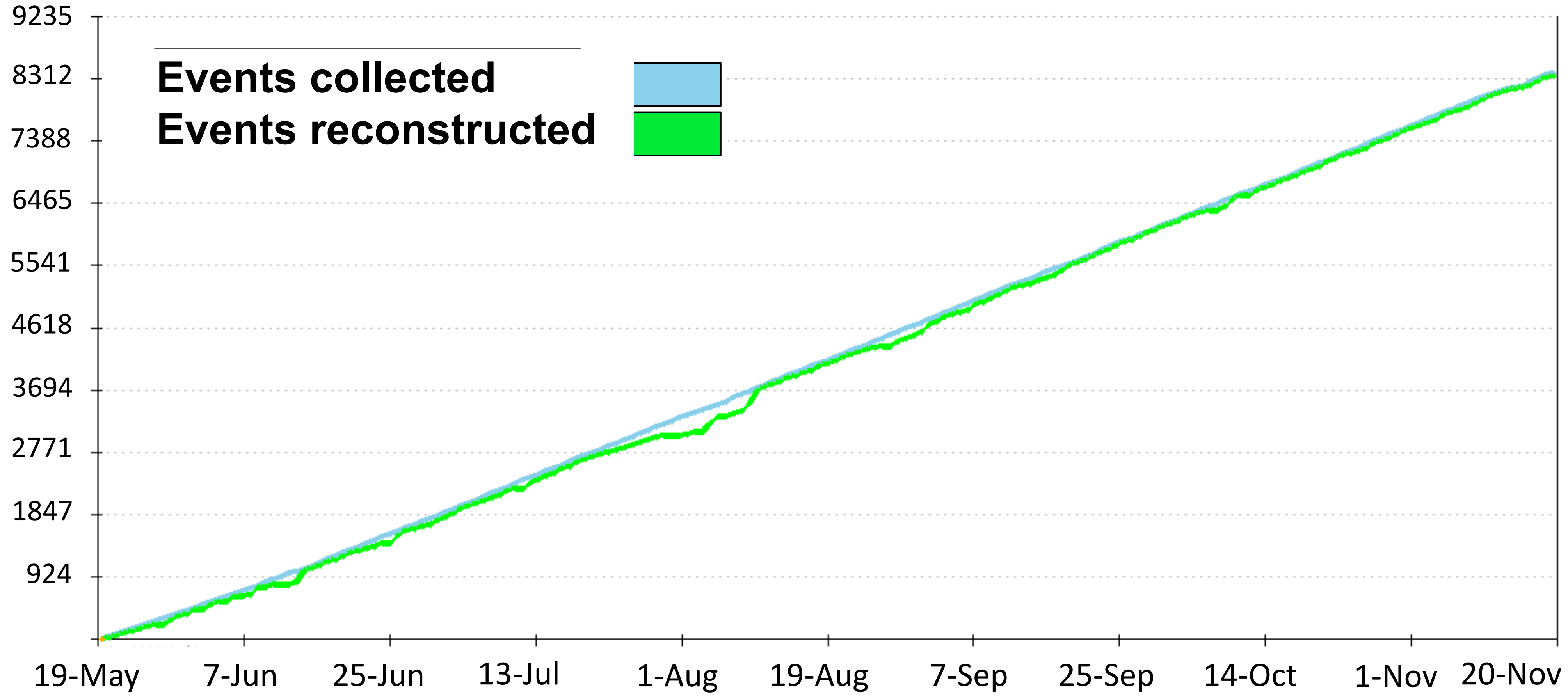
AMS is grappled by the
Shuttle Arm
May 19, 2011

May 19: AMS installation completed at 5:15 CDT, and data taking started at 9:35 CDT

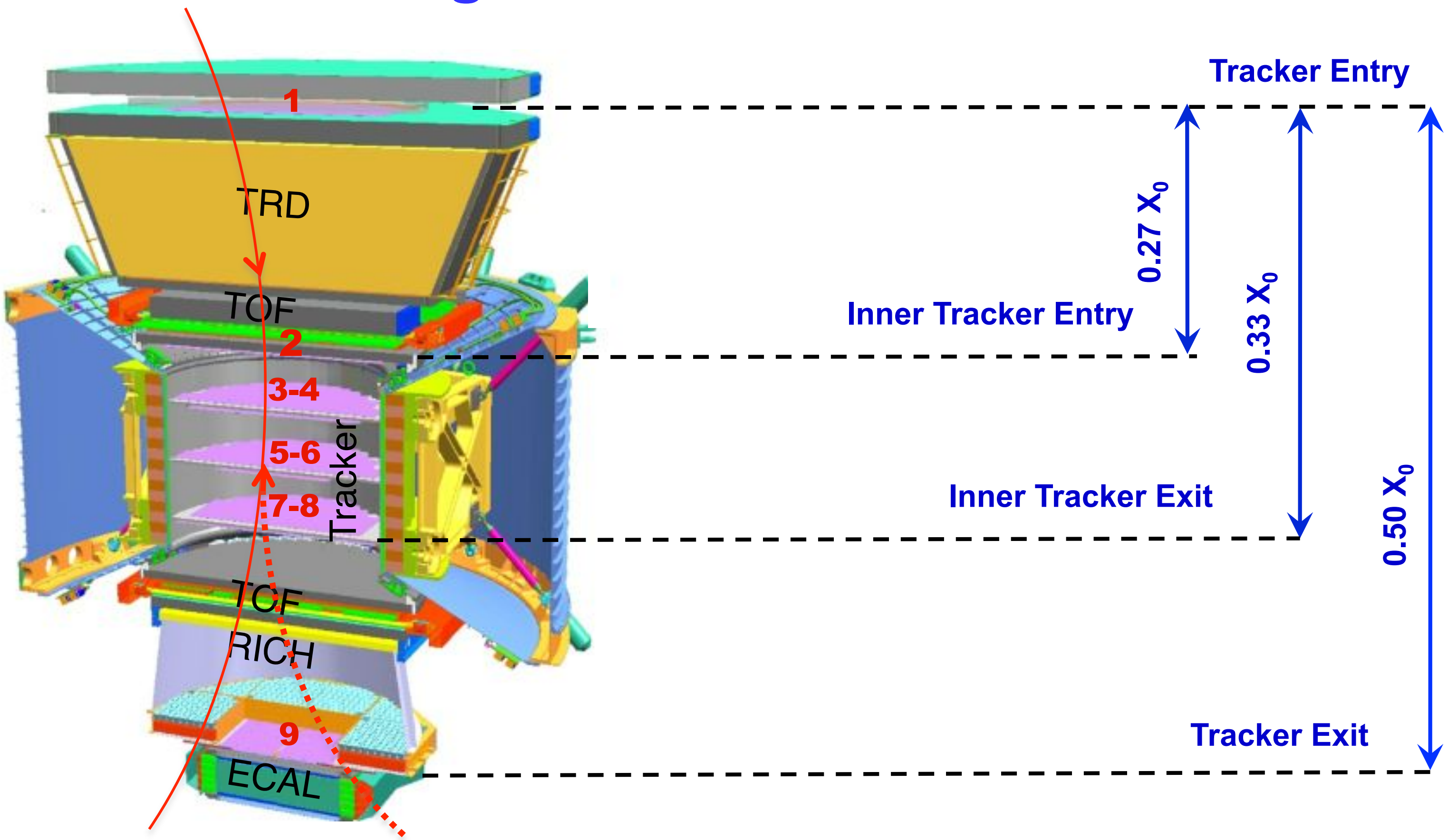

…WE JUST DECIDED LAUNCHING MONEY DIRECTLY INTO SPACE WAS CHEAPER …
NASA
¥
DM
CHF
€
$
UNIT

Payload Operations Control Center (POCC)
at CERN in control of AMS since 19 June 2011

AMS collected over 8 billion events over the first 6 months



AMS goals: $He/\overline{He} > 10^{10}$



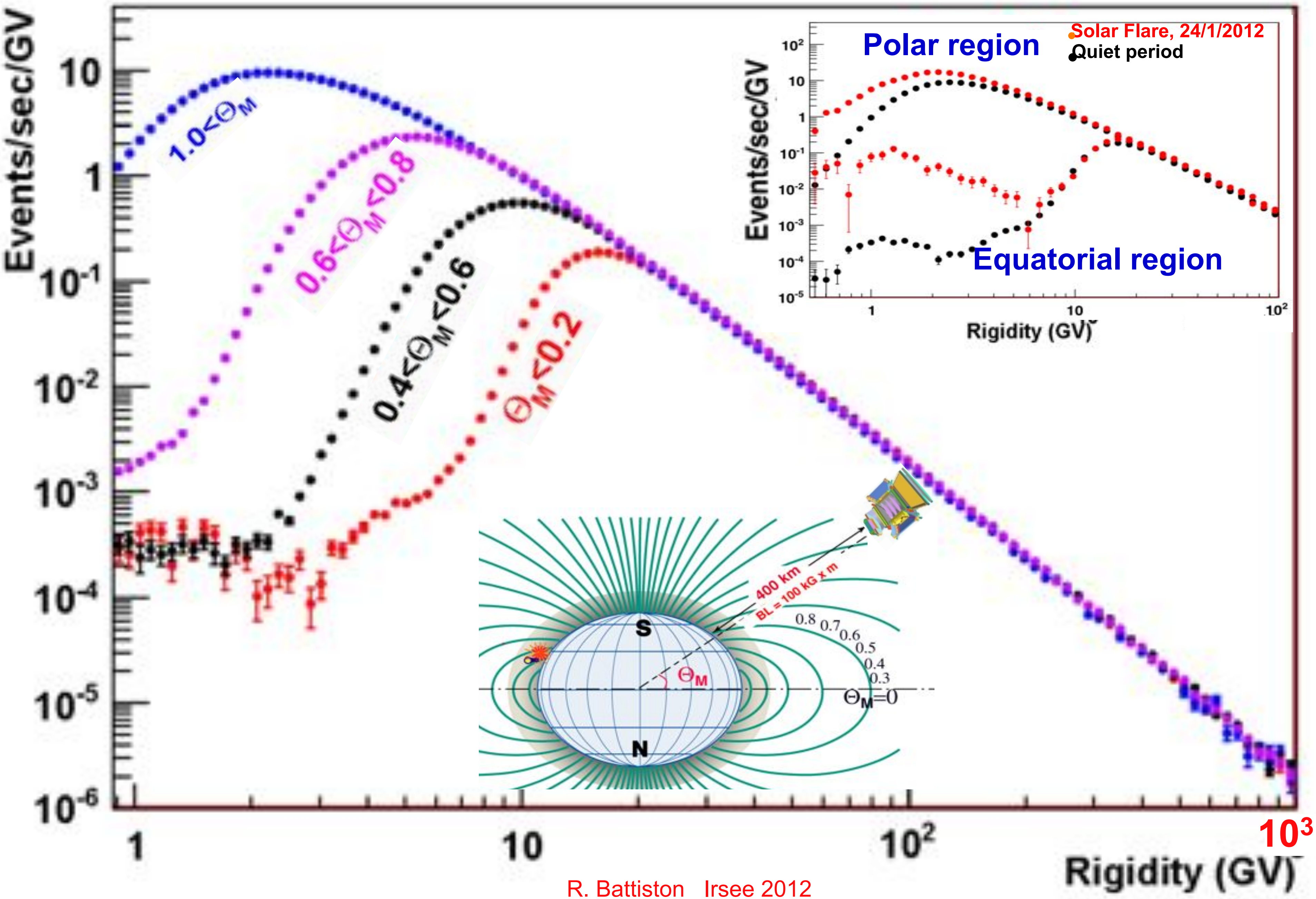
a) Minimal material in the detector
So that the detector does not become a source of background nor of large angle scattering

b) Repetitive measurements of momentum
To ensure that particles which had large angle scattering are not confused with the signal.

Momentum from tracker planes:

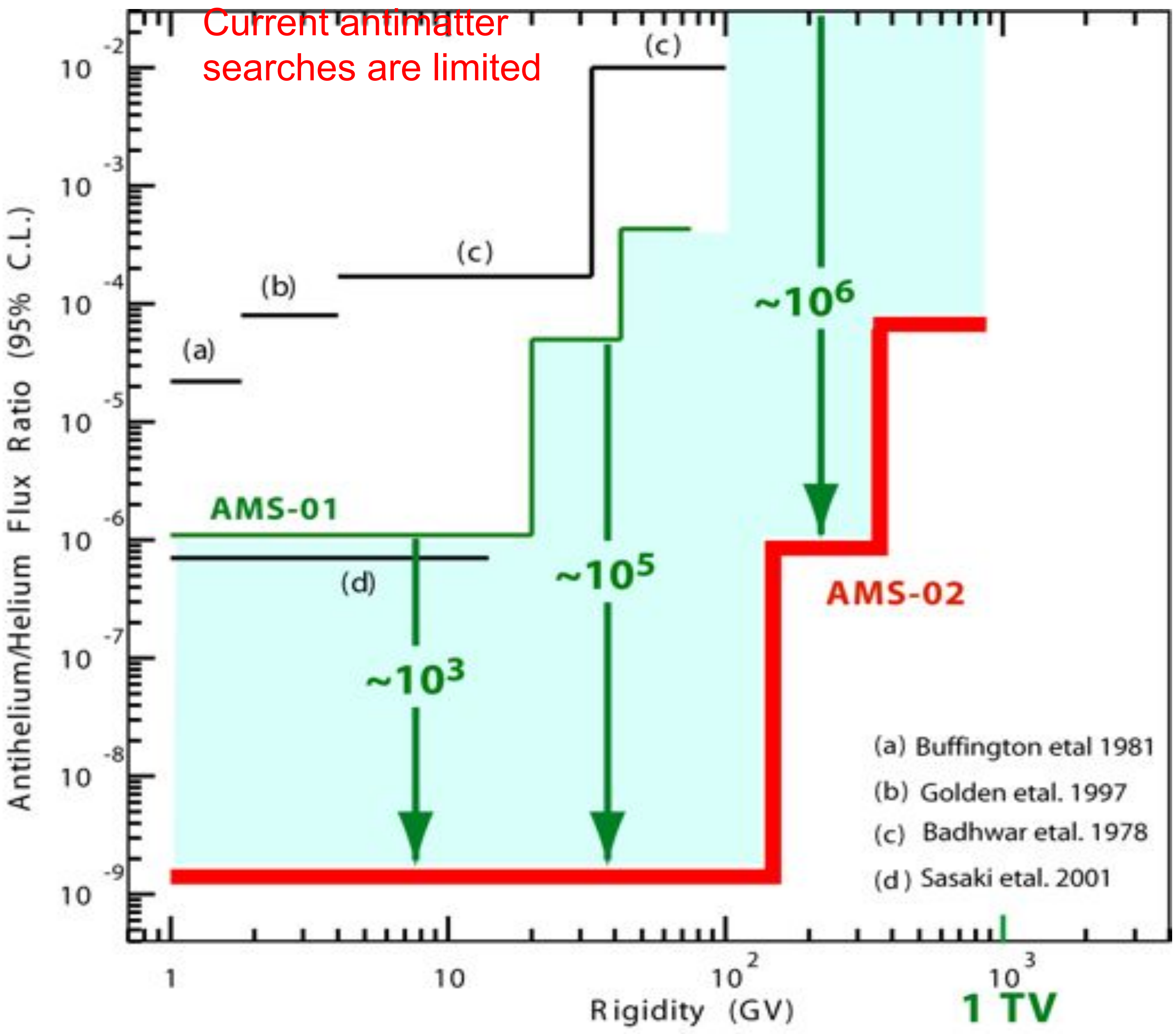
1 2 3 4 5 6 7 8 = 2+3+4+5+6+7+8+9

AMS data: He rate



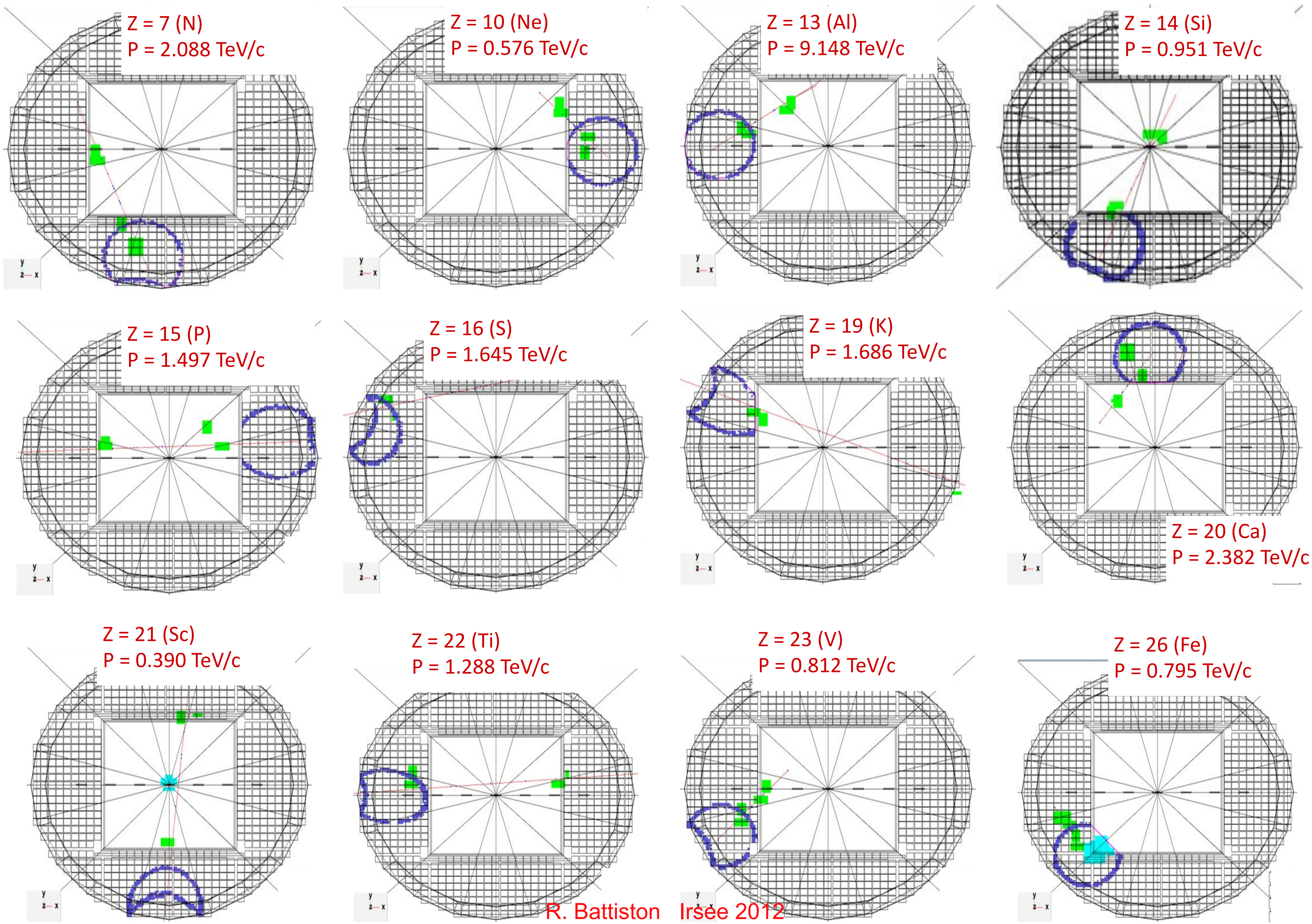
R. Battiston Irsee 2012

AMS-02 Antihelium Limits with AMS-02



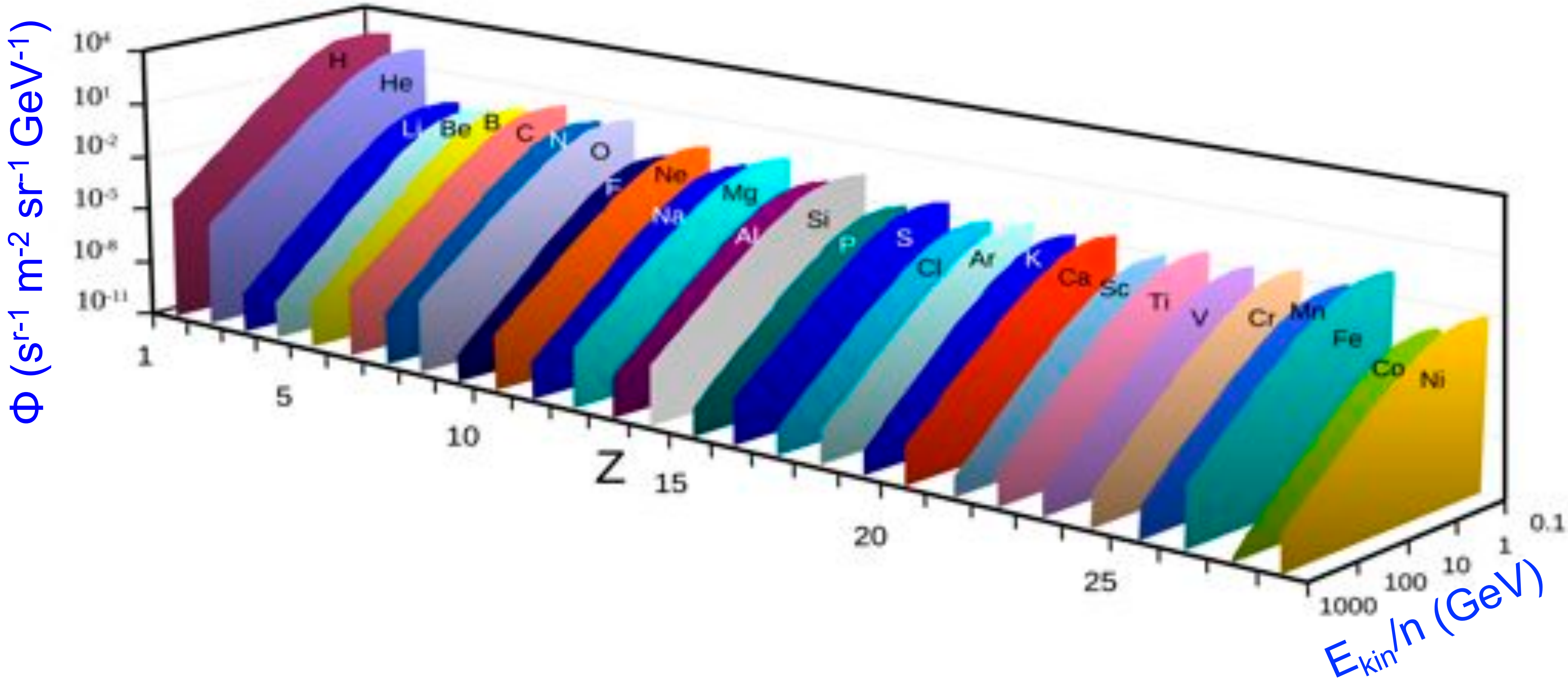
y06K301

AMS data: Nuclei in the TeV range



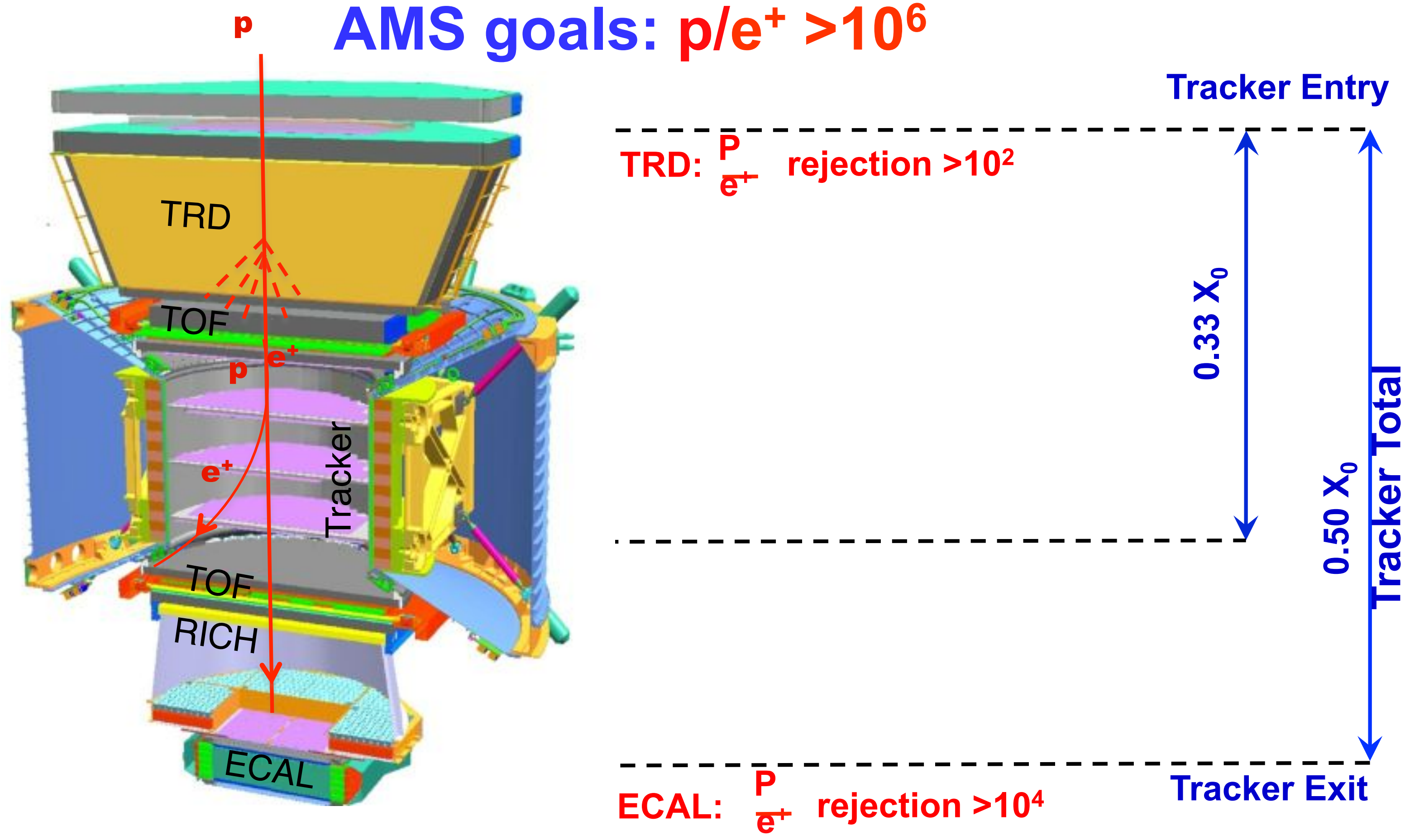
Physics of AMS: Nuclear Abundances Measurements

For energies from 100 MeV/n to 2 TeV/n
with 1% accuracy over the 11-year solar cycle.



These spectra will provide experimental measurements of the assumptions that go into calculating the background in searching for Dark Matter,
i.e., $p + C \rightarrow e^+, \bar{p}$, …

AMS goals: $p/e^+ > 10^6$



a) Minimal material in the TRD and TOF

So that the detector does not become a source of e^+ from P+A -> P + e^+ ....

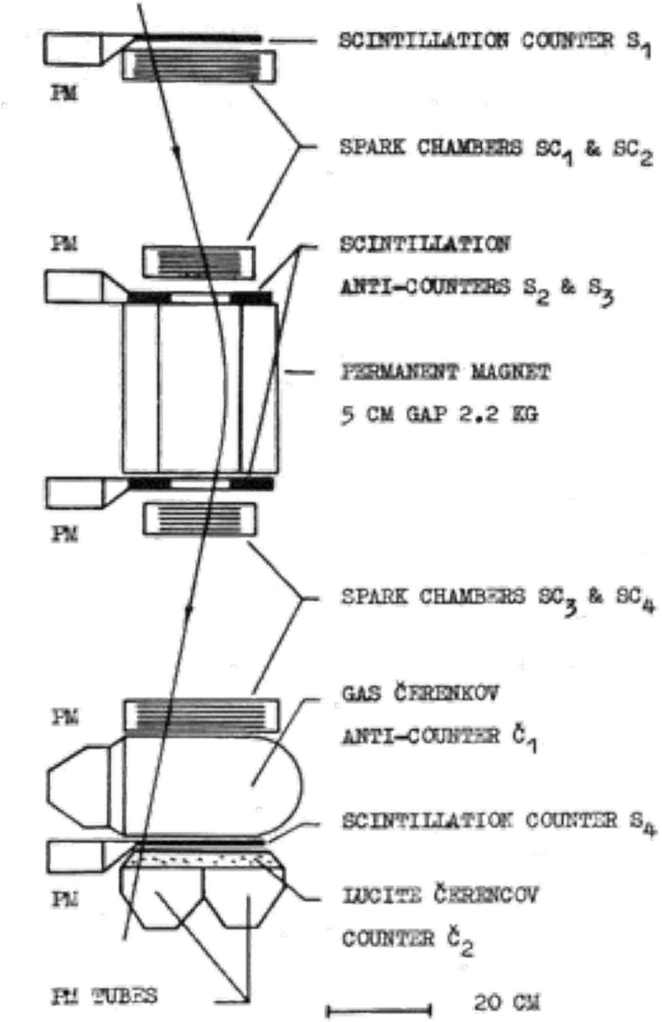
b) A magnet separates TRD and ECAL so that a low energy e^+ produced in TRD will be swept away and not enter ECAL

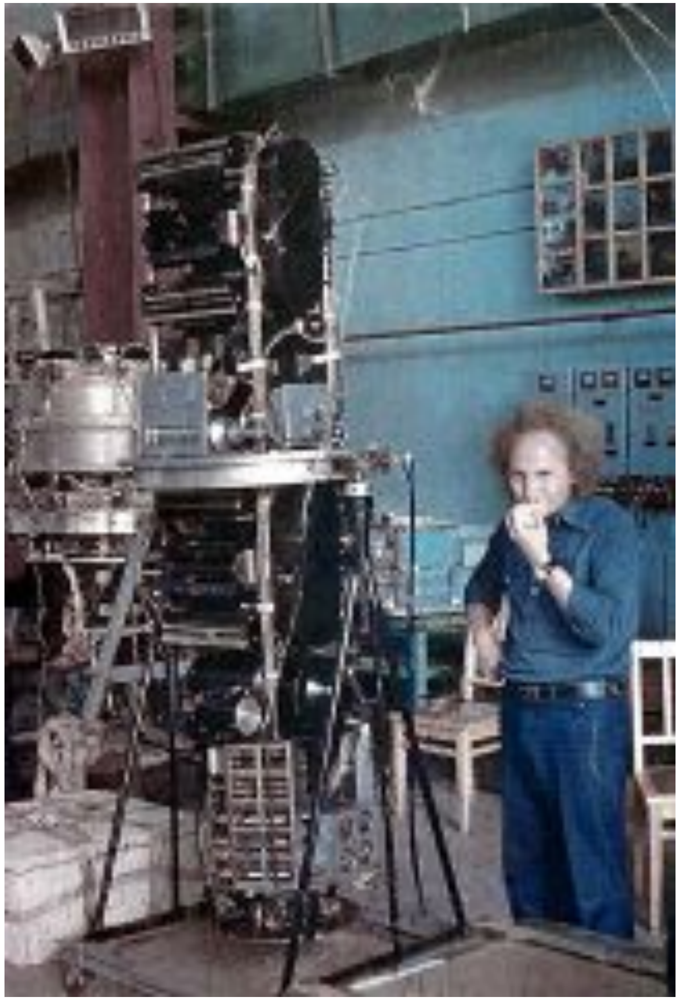
In this way the rejection power of TRD and ECAL are independent

c) Matching momentum of 9 tracker planes with ECAL momentum measurements

Antiprotons in cosmic rays

Discovery of antiprotons in CR, 1979





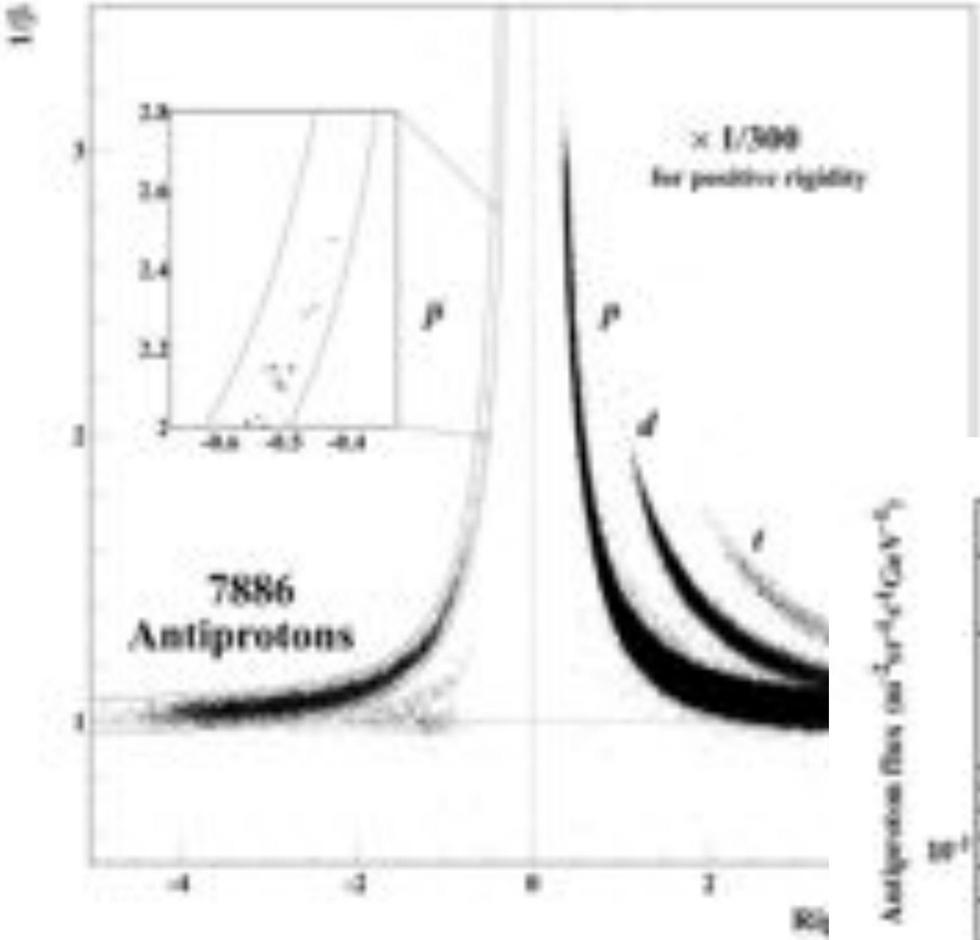
$\bar{p}/p$ ratio

6×10^{-4}

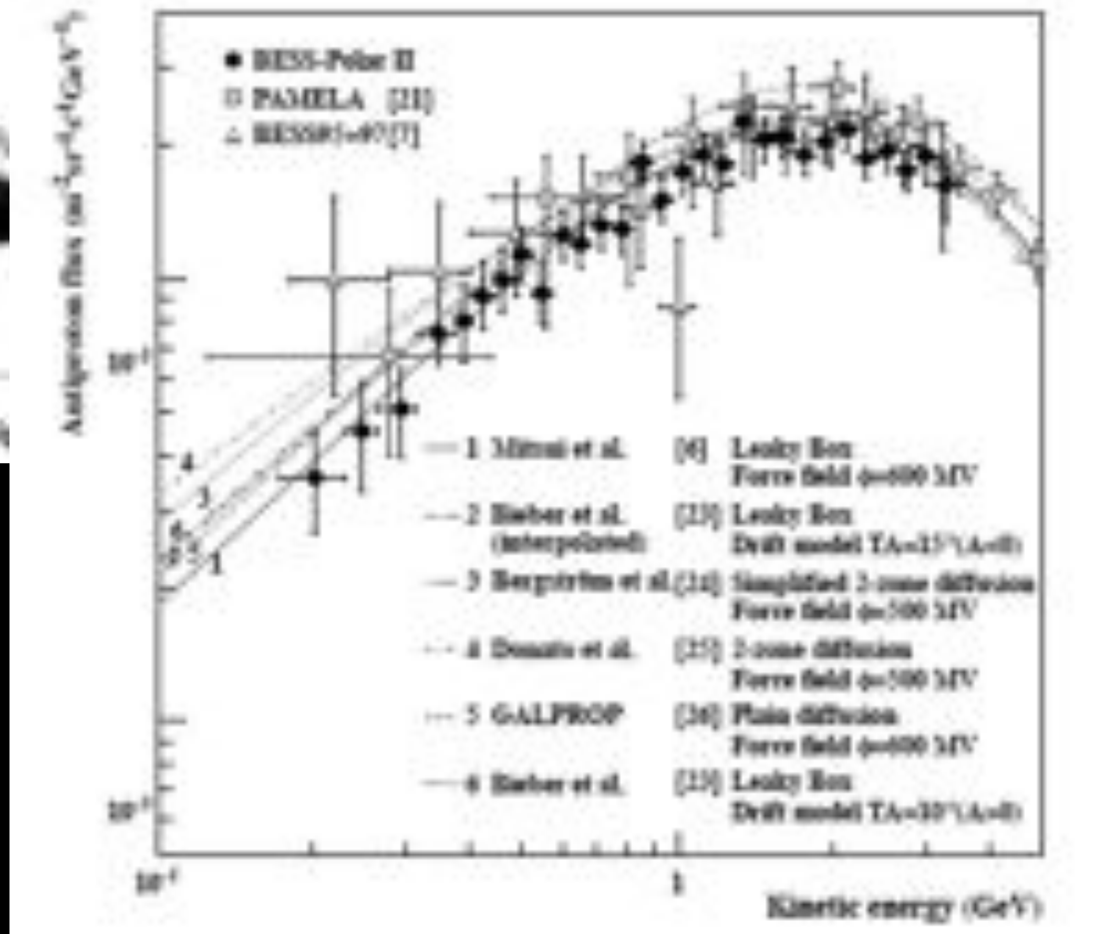
2-5 GeV

From
Robert E. Streitmatter

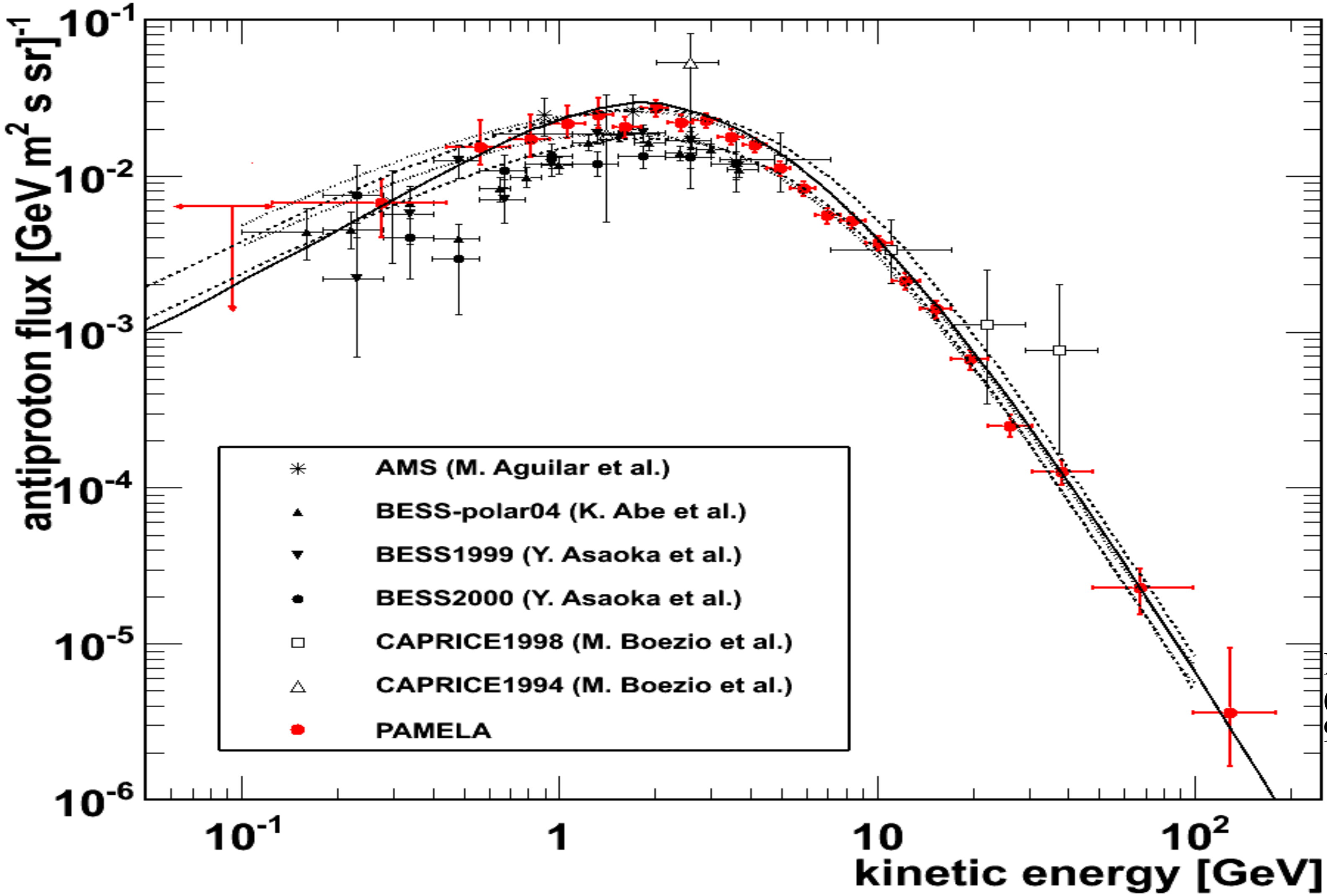
Bogomolov, E.A. et al. 1979, Proc. 16th ICRC, Kyoto, 1, 330,
"A Stratospheric Magnetic Spectrometer Investigation of the Singly Charged Component Spectra and Composition of the Primary and Secondary Cosmic Radiation"



BESS Abe et al . arXiv:1107.6000v2



Antiproton Flux
(0.06 GeV - 180 GeV)



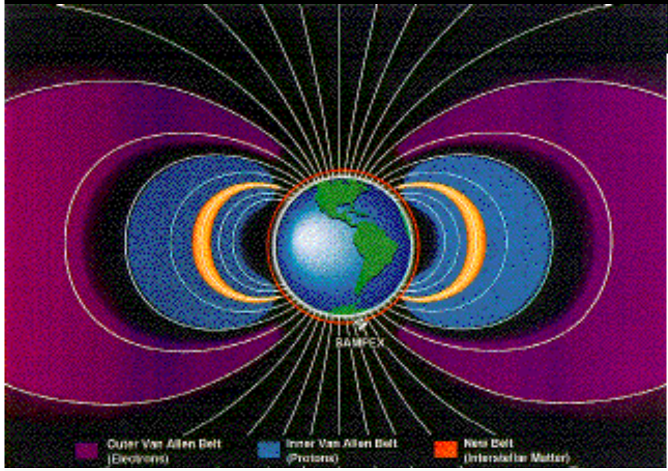
Donato et al.
(ApJ 563 (2001) 172)

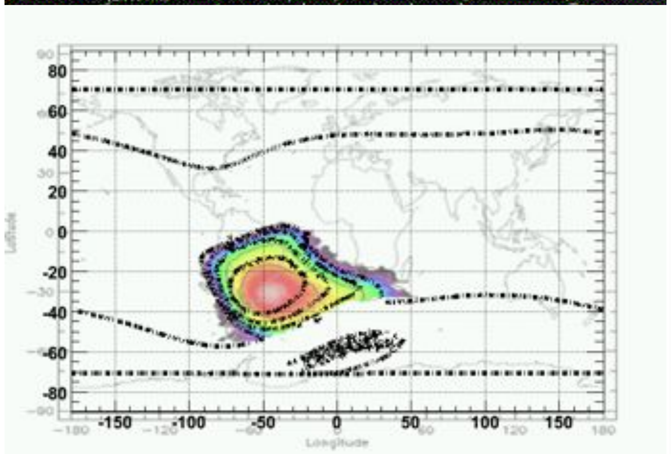
Ptuskin et al.
(ApJ 642 (2006) 902)

PRL. 105, 121101 (2010)

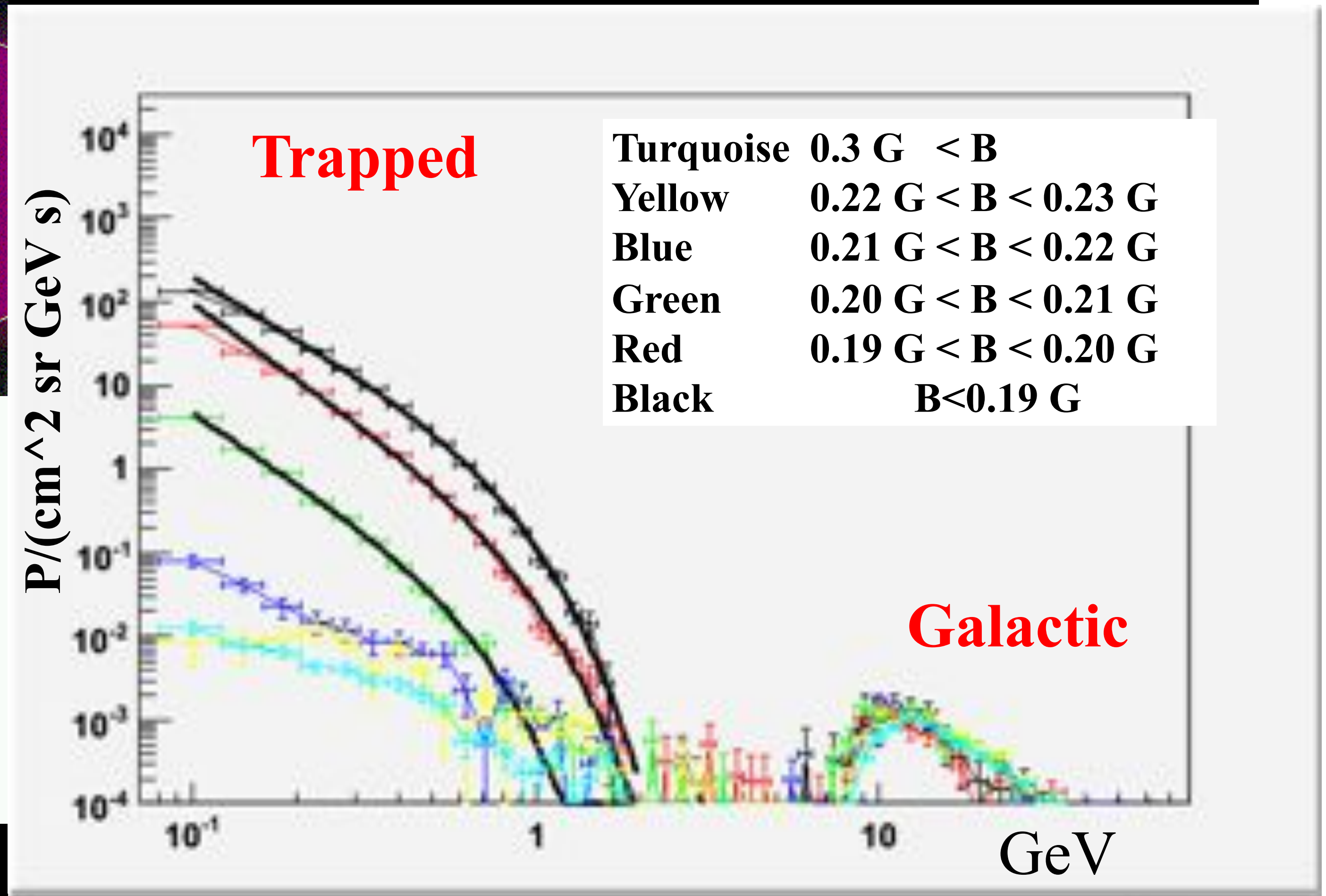
Trapped proton flux in the Van Allen belt (South Atlantic Anomaly)

Arxiv 0810.4980v1



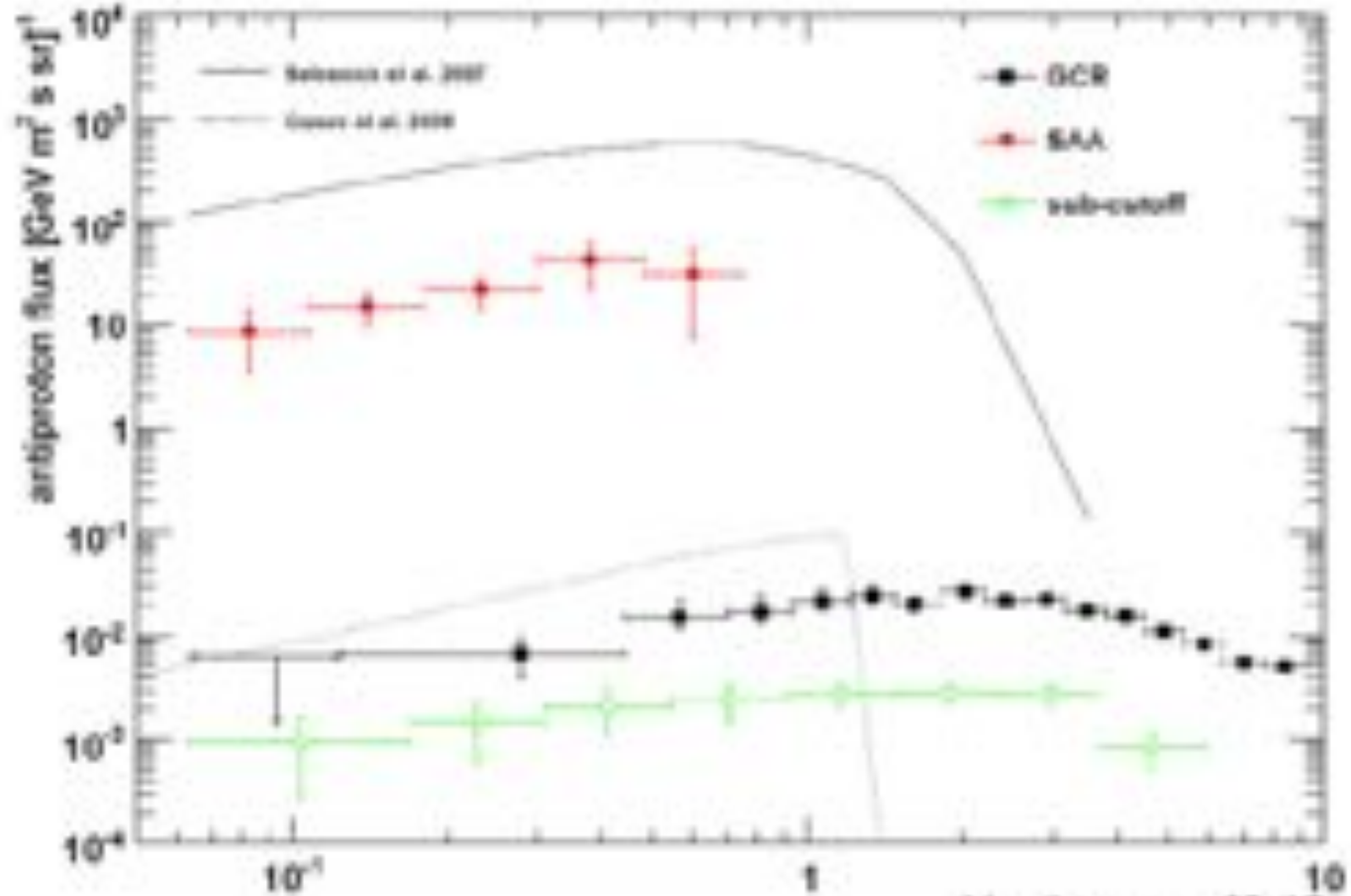


Integral Pamela flux
(E>35 MeV)
(PSB97 plot by SPENVIS project, model by BIRA-IASB)



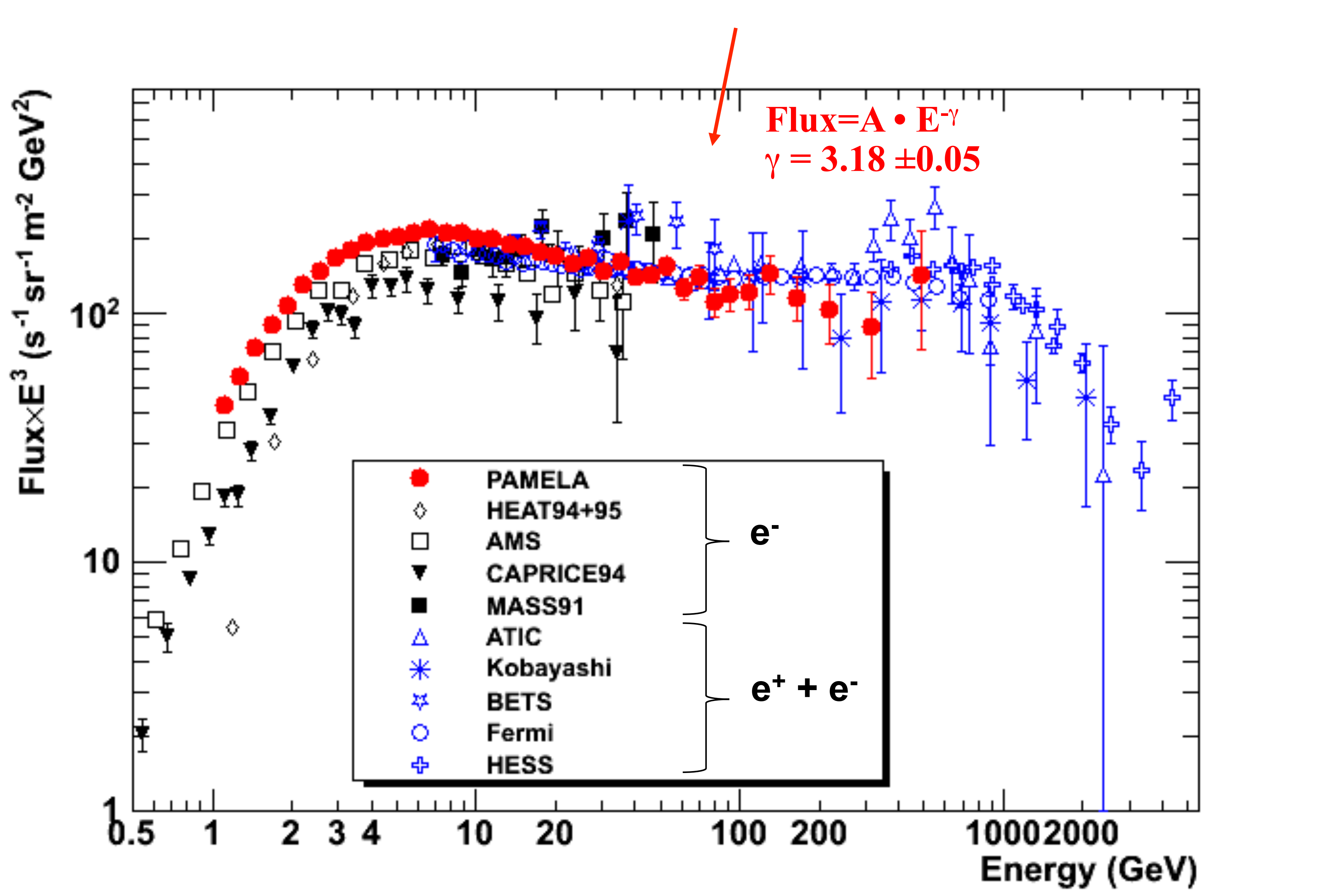
	A	γ_0	γ_1	χ^2/ndf
nero	0.11±0.01	6.0±0.4	3.1±0.5	7.1
rosso	$(2.3\pm0.3)\ 10^{-2}$	5.9±0.5	2.6±0.6	6.8
verde	$(5\pm3)\ 10^{-4}$	8.1±1.8	4.7±1.8	10.

Trapped antiprotons



ApJL 2011

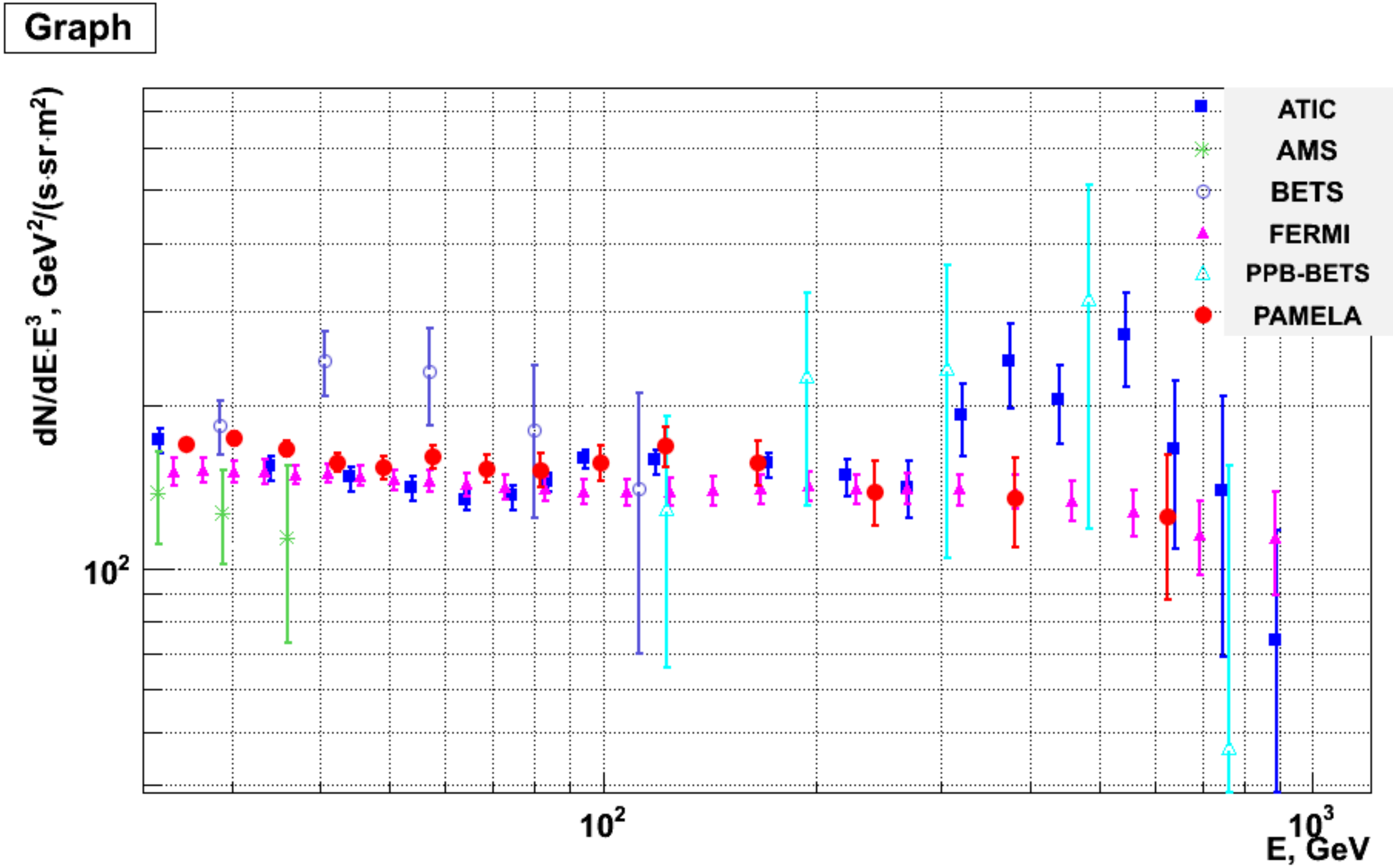
PAMELA electron (e^-) spectrum



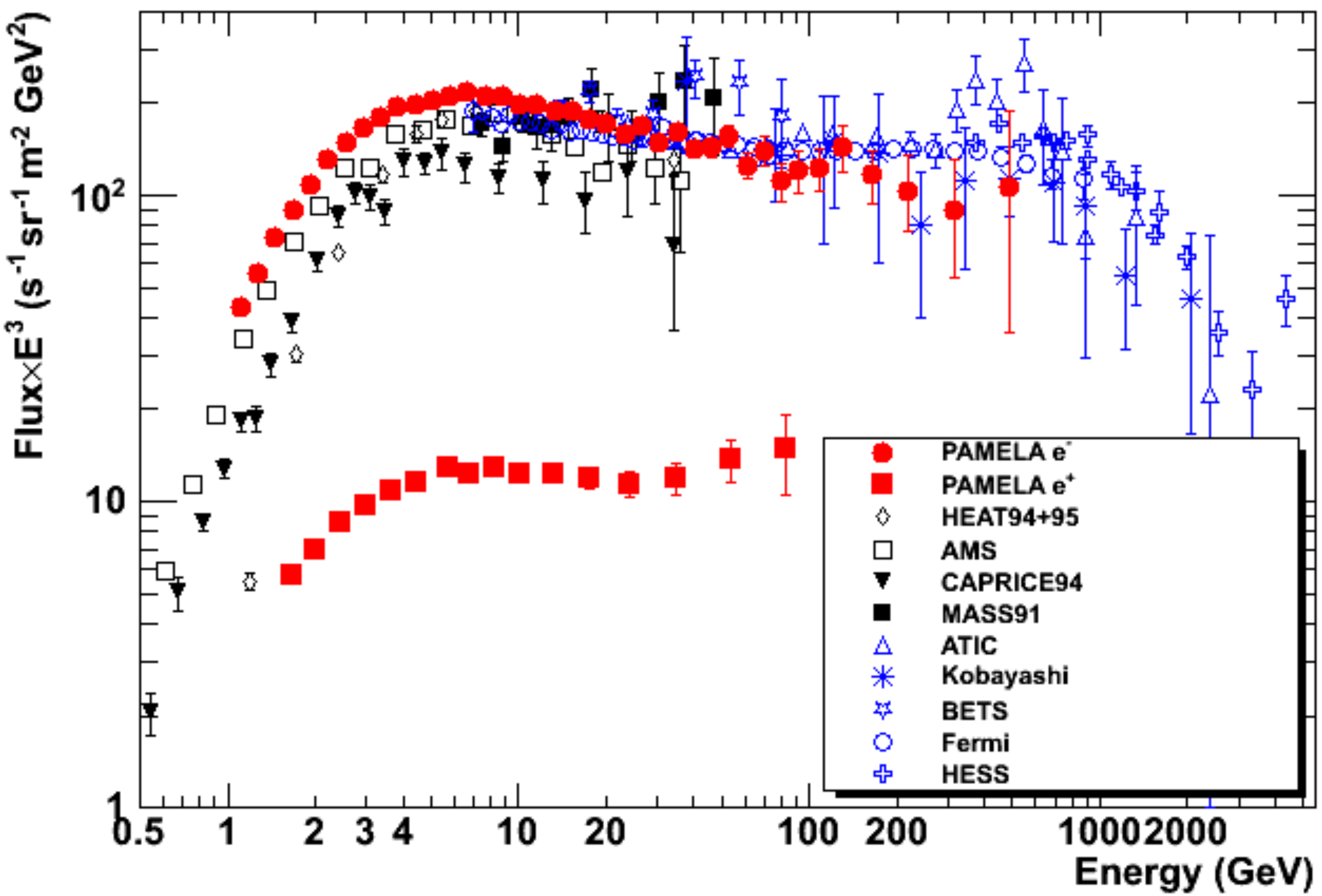
O. Adriani et al., PRL 106 (2011) 201101.

Positrons in cosmic rays

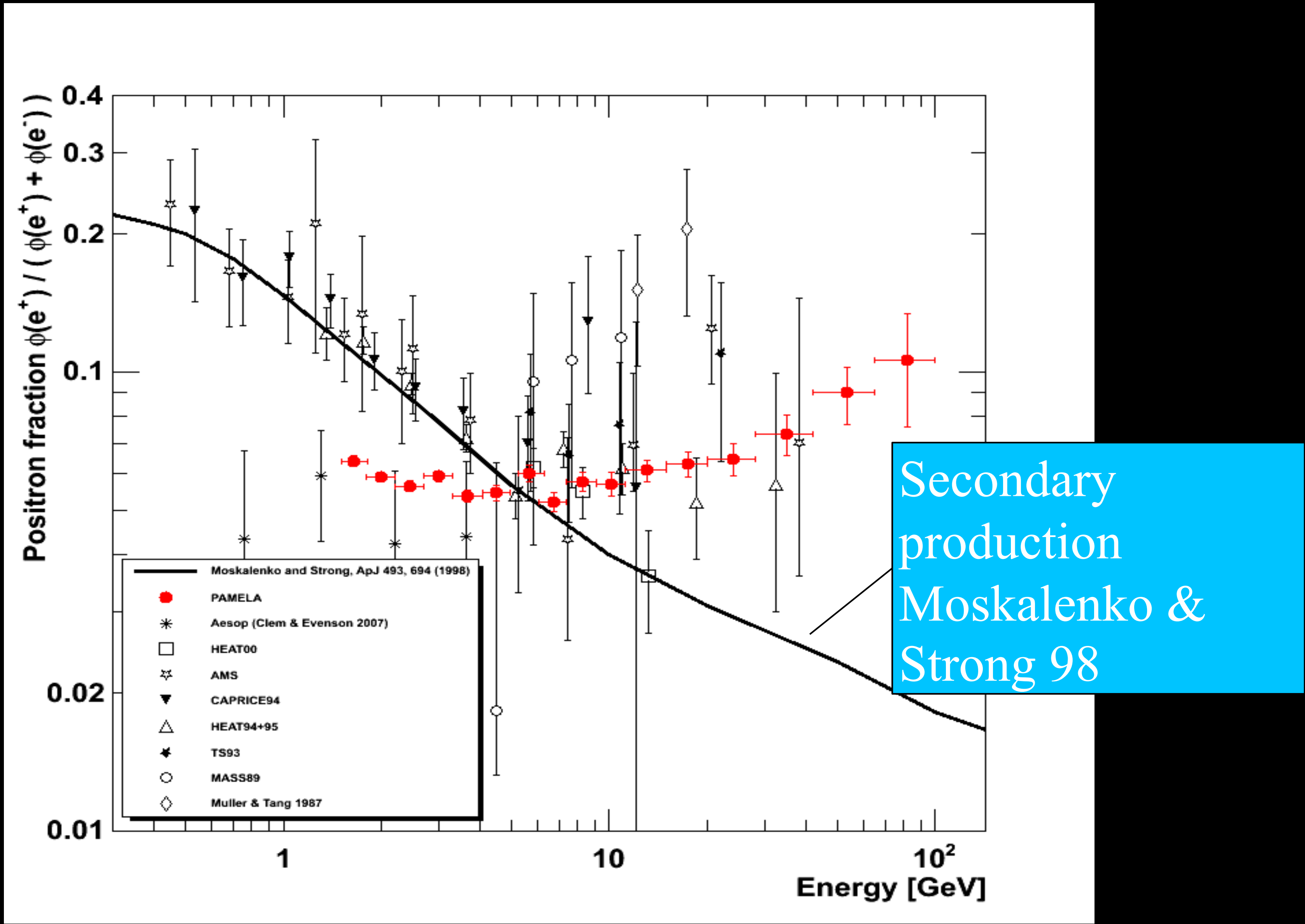
All electrons



Positron flux

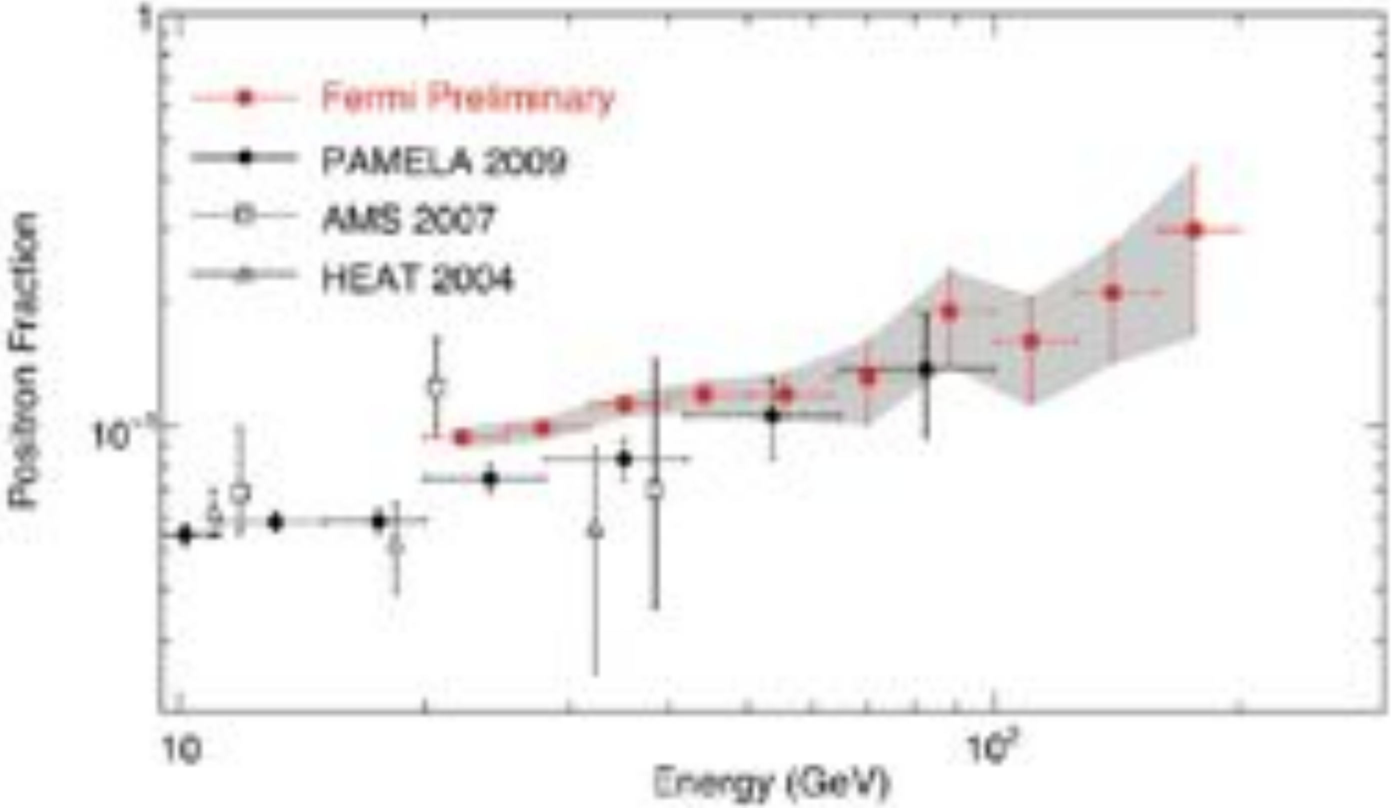


Positron to Electron fraction : the PAMELA result



Adriani et al, Nature 458, 697, 2009 and Astropart. Phys. 34 (2010) 1

Final results: positron fraction

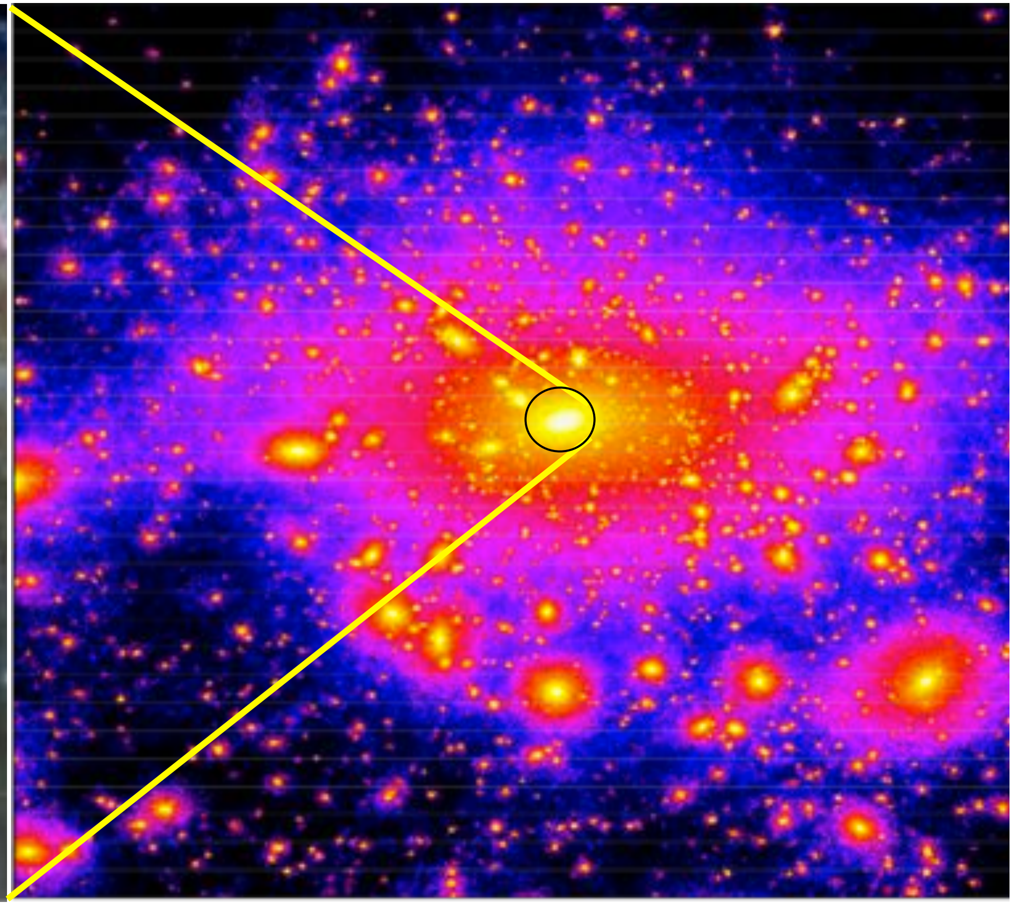


- Fraction = $\varphi(e^+) / [\varphi(e^+) + \varphi(e^-)]$
- We don't use the both-allowed region except as a cross check
- **Positron fraction increases with energy from 20 to 200 GeV**

The Origin of Dark Matter

~ 24% of Matter in the Universe is not visible and is called Dark Matter

A Galaxy as seen by telescope

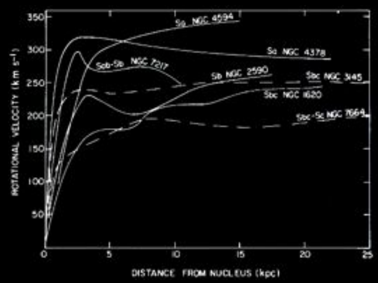


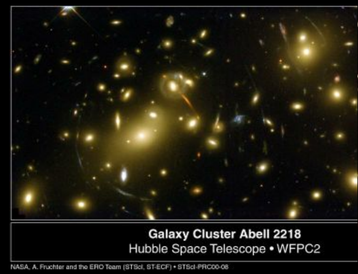
If we could see Dark Matter in the Galaxy

Dark Matter Searches

•Cosmology

Detection, not identification





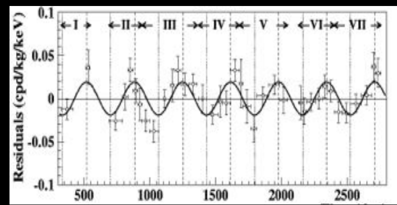
1E 0657-56 - Bullet Cluster

•LHC Search

Supersymmetry, not necessarily DM

•Direct Detection

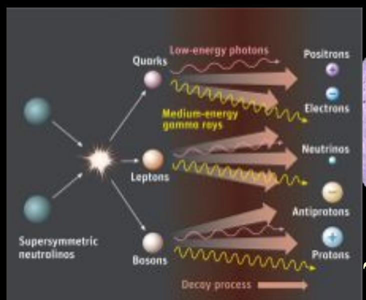
Local structure and nature

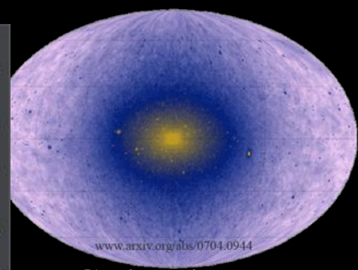


DAMA

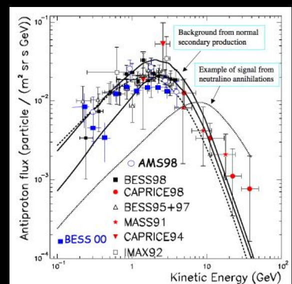
•Indirect Detection

Various galactic scales

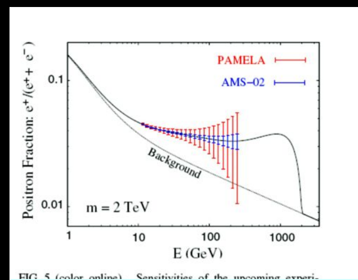




γ: ***Galactic centre***

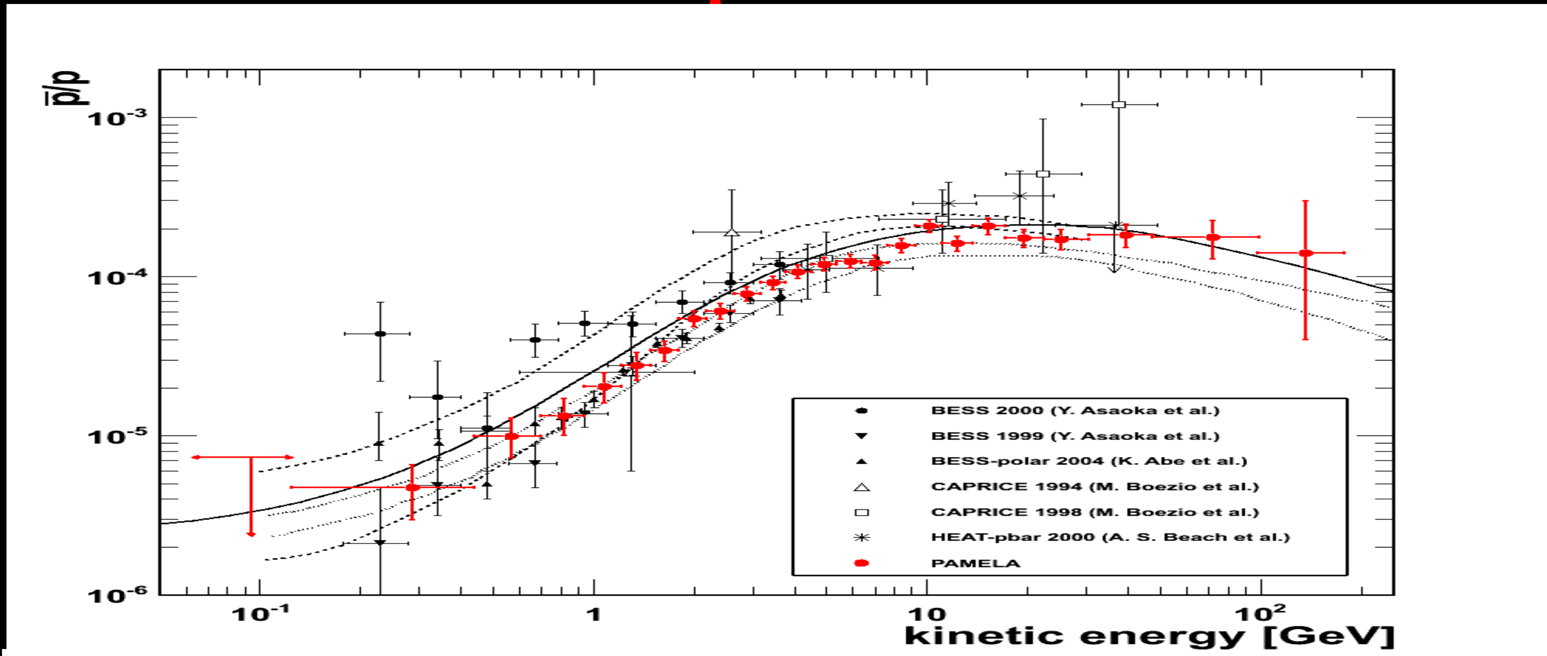


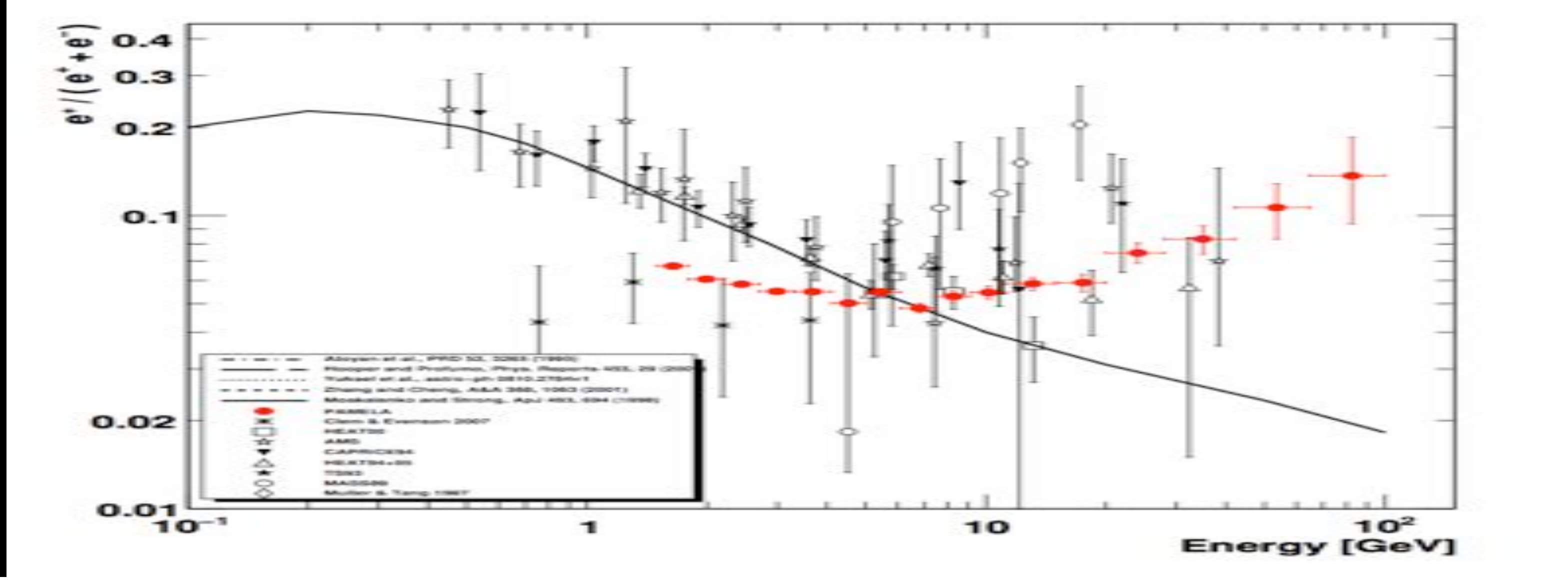
Antiprotons: Galactic average



positrons: Local galactic 1kpc

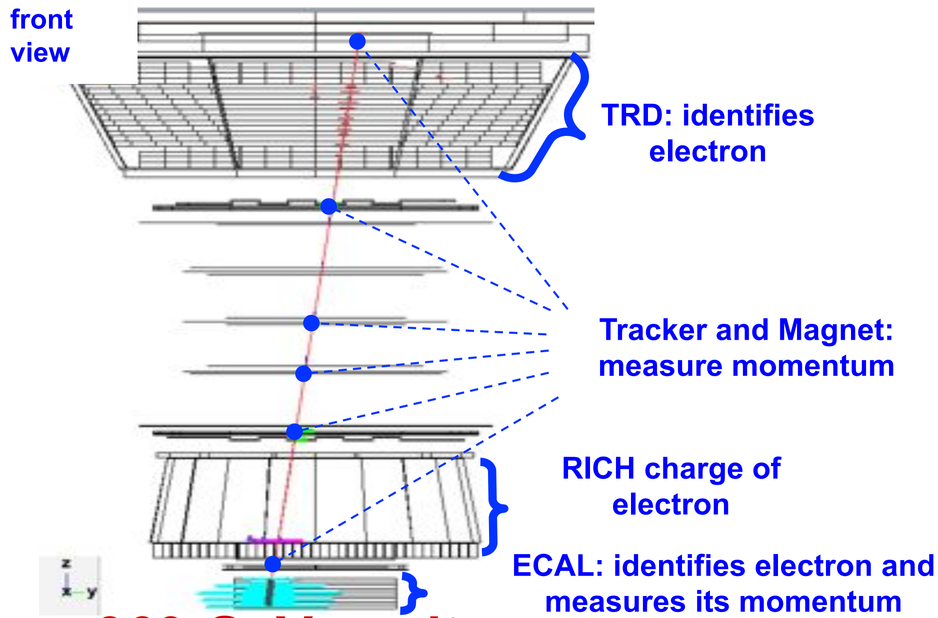
A Challenging Puzzle for Dark Matter Interpretation



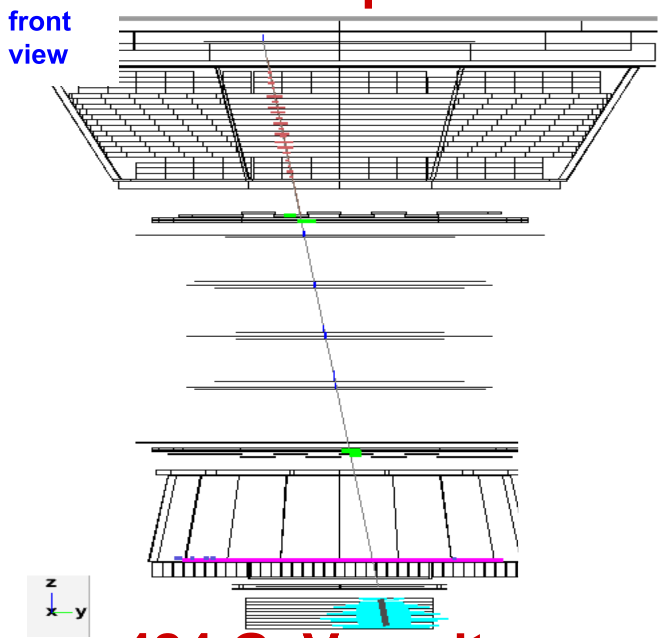


AMS data: High energy $e^{\pm}$

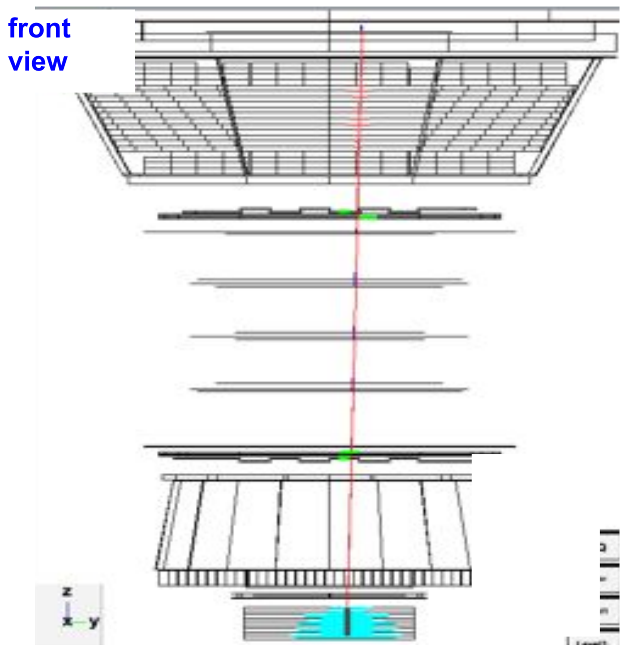
1.03 TeV electron



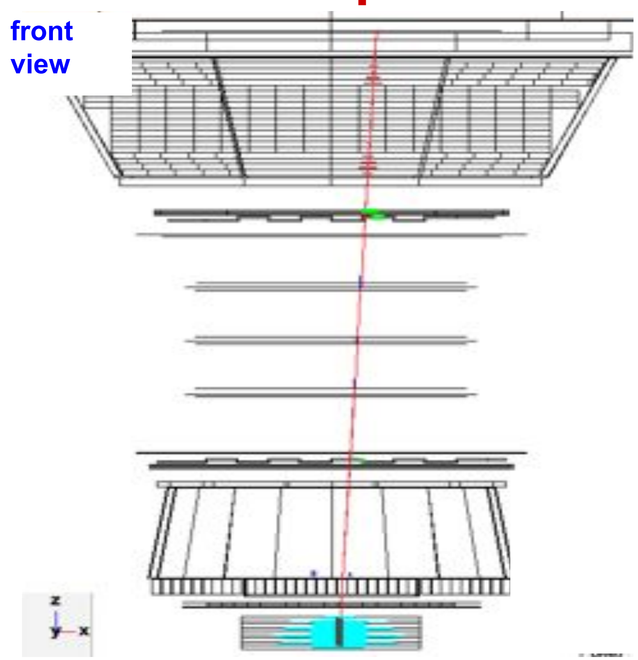
205 GeV positron



369 GeV positron

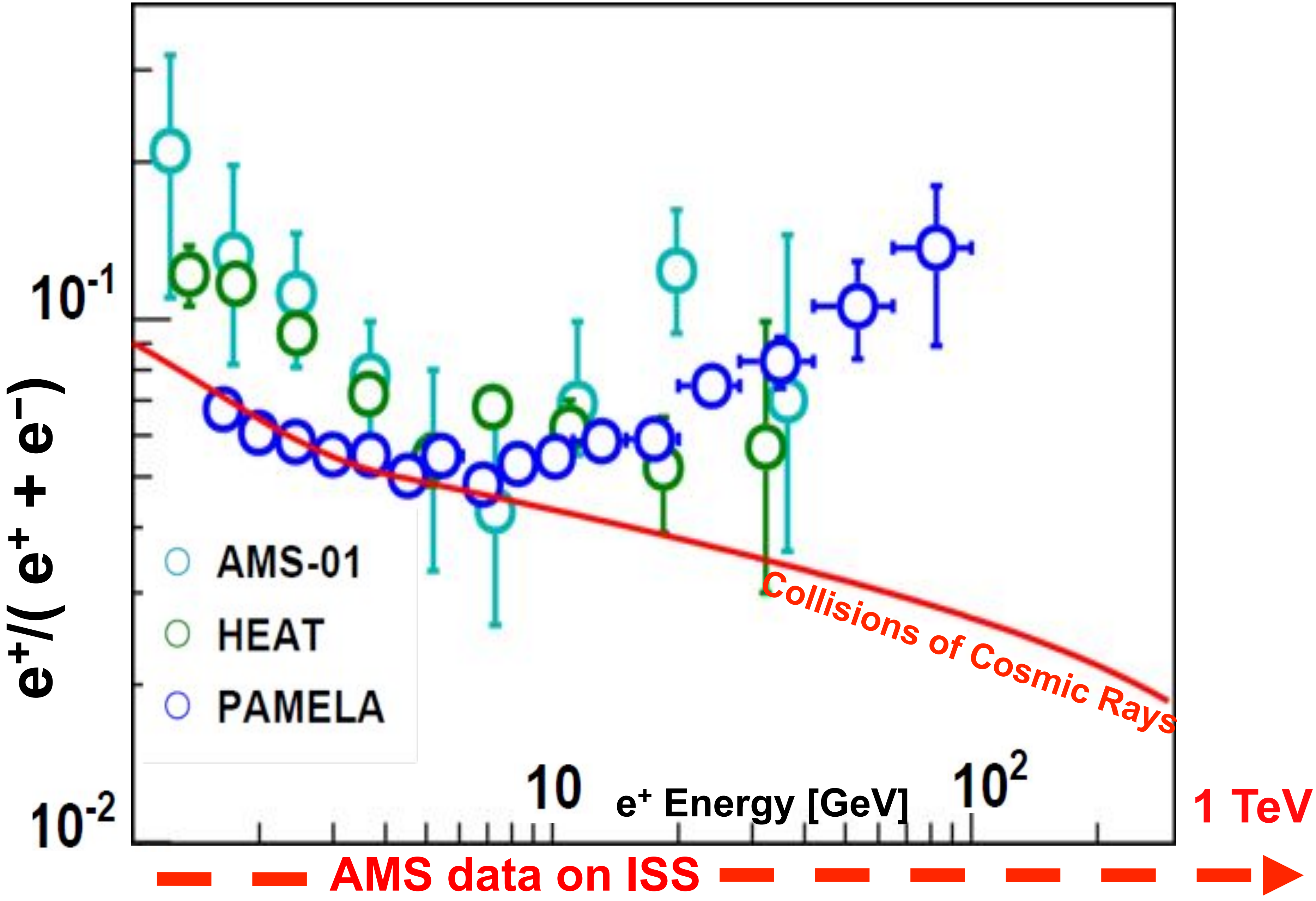


424 GeV positron

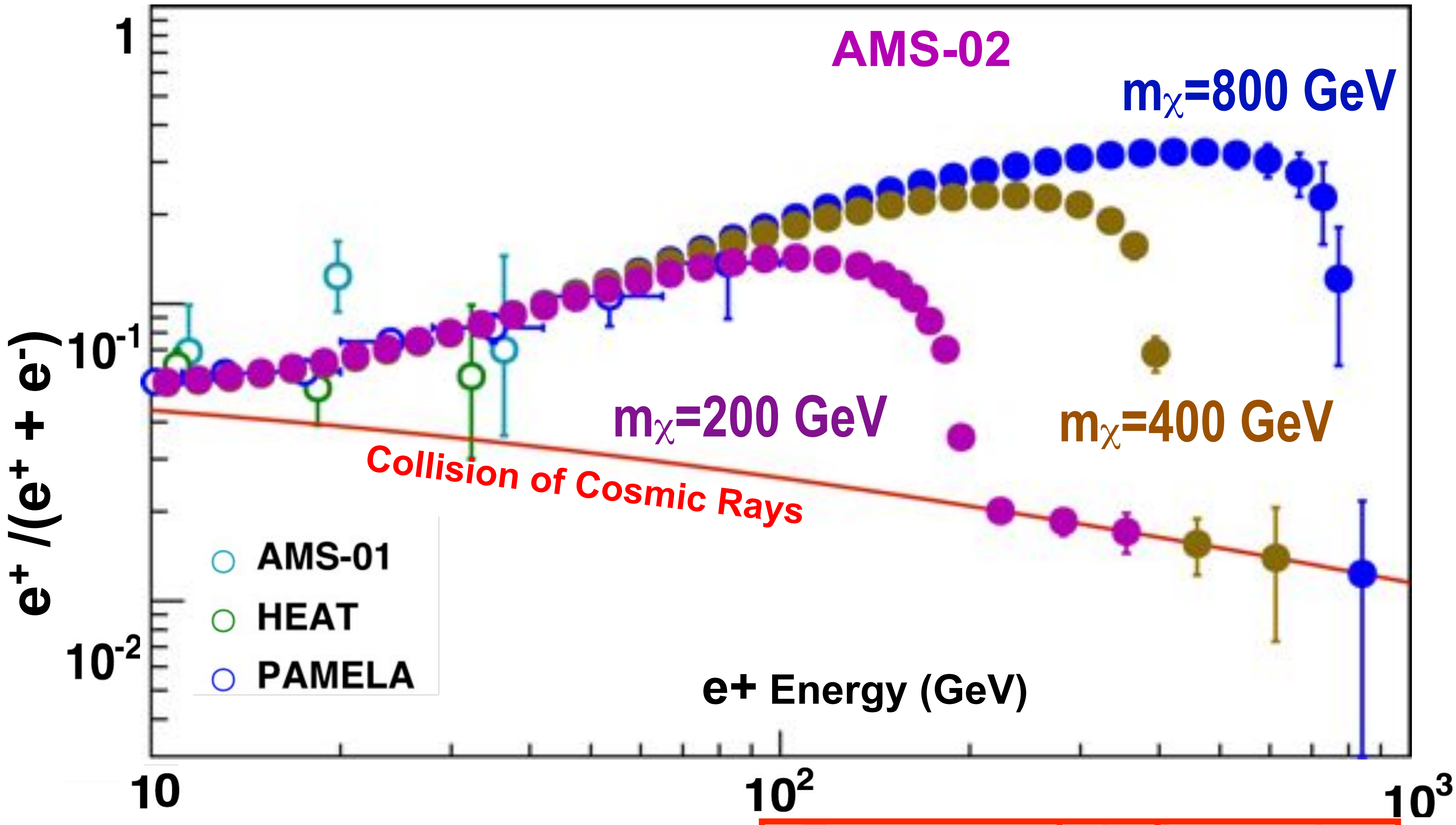


The physics of AMS include:

The Origin of Dark Matter



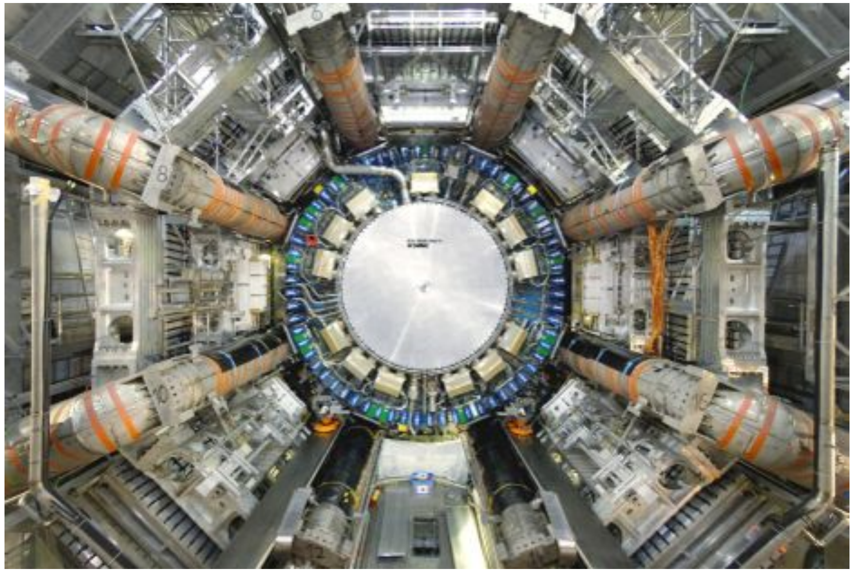
Detection of High Mass Dark Matter from ISS
MC simulations

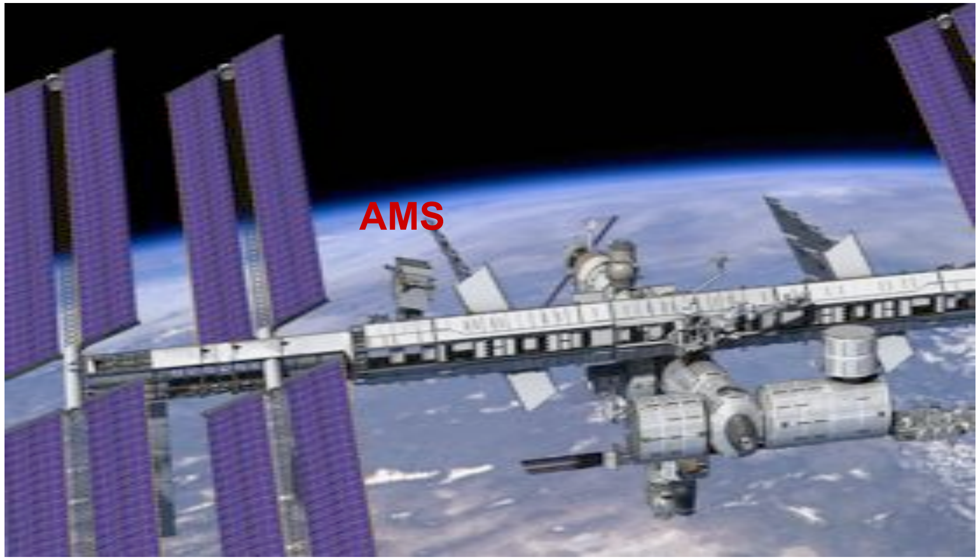


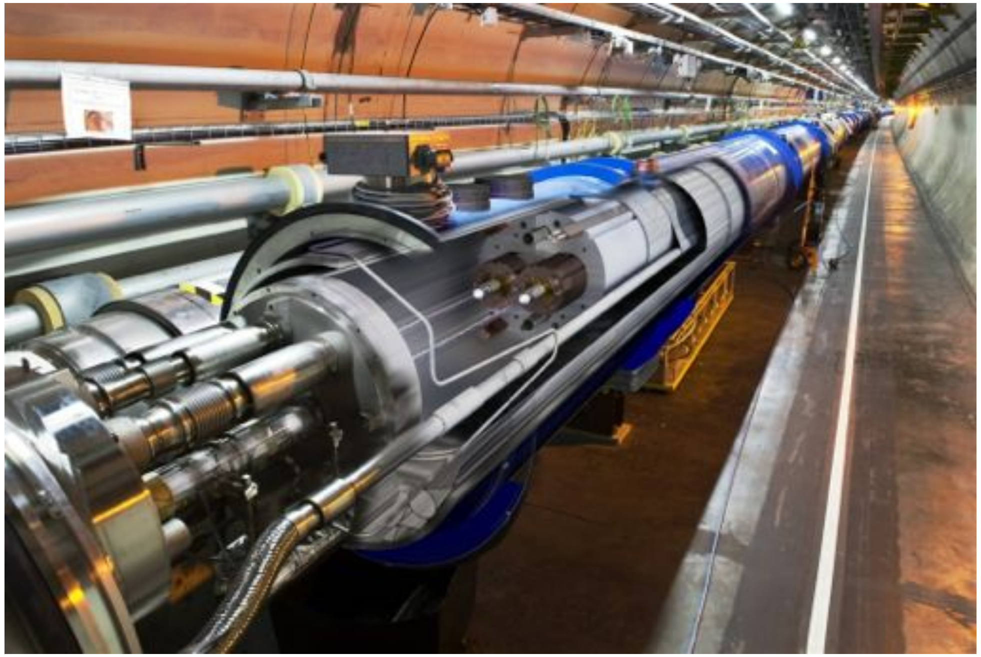
Events sample in first weeks

AMS

ATLAS, CMS, ALICE & LHCb

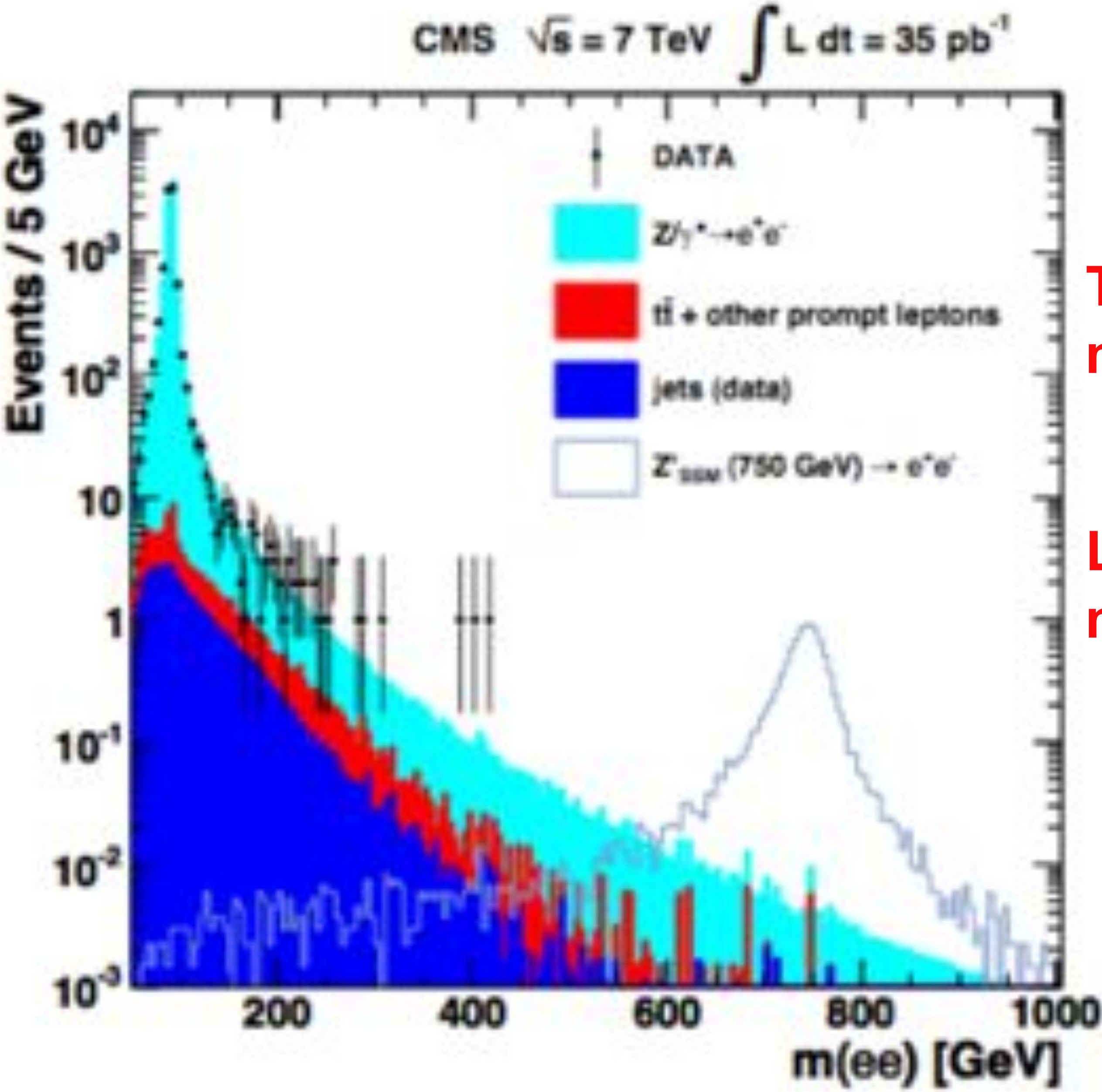






ISS cost = ~10 LHC.
LHC has 4 big experiments.
ISS only has AMS.

Particle energies observed in space by AMS-02 are already higher than at LHC detectors



Today :
max Pt = 150 GeV

Later :
max Pt = 400 GeV

The Cosmos is the Ultimate Laboratory.

Cosmic rays can be observed at energies higher than any accelerator.

The most exciting objective of AMS is to probe the unknown; to search for phenomena which exist in nature that we have not yet imagined nor had the tools to discover.

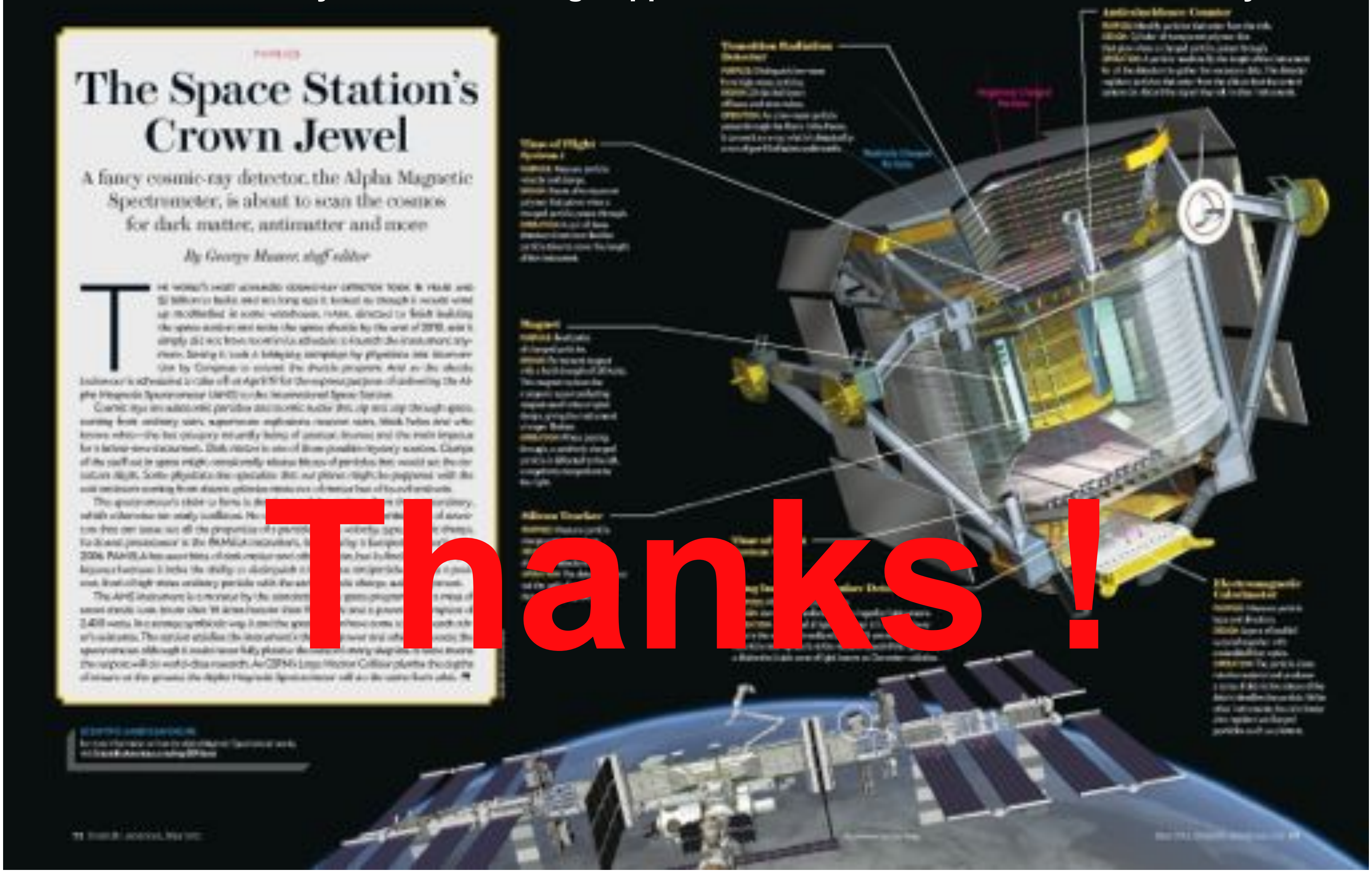
Recent Discoveries in Physics

Facility	Original purpose, Expert Opinion	Discovery with Precision Instrument
AGS Brookhaven (1960)	π N interactions	2 kinds of neutrinos, Time reversal non-symmetry, 4^{th} Quark
FNAL Batavia (1970)	neutrino physics	5^{th} Quark, 6^{th} Quark
SLAC Spear (1970)	ep, QED	Partons, 4^{th} Quark, 3^{rd} electron
PETRA Hamburg (1980)	6^{th} Quark	Gluon
Super Kamiokande (2000)	Proton Decay	Neutrino has mass
Hubble Space Telescope	Galactic Survey	Curvature of the universe
AMS on ISS	Dark Matter, Antimatter	?

Exploring a new territory with a precision instrument is the key to discovery.

y96402nac.ppt

AMS has always received strong support from the world's scientific community



Thanks !

From Scientific American, May 2011