Search for Primary Antiparticles and Cosmological Antimatter with BESS

Akira Yamamoto (KEK) and John W. Mitchell (NASA-GSFC)

for the BESS Collaboration

To be presented at SpacePart12, held at CERN, November 5-7, 2012

BESS Collaboration

High Energy Accelerator Research Organization(KEK)

National Aeronautical and Space Administration Goddard Space Flight Center

The University of Tokyo

University of Maryland

Kobe University

University of Denver

Institute of Space and Astronautical Science/JAXA

Balloon-borne Experiment with a Superconducting Spectrometer

BESS Collaboration

A. Yamamoto[a*], J.W. Mitchell[b], K. Yoshimura[a], K. Abe[c,1], H. Fuke[d], S. Haino[a,2], T. Hams[b,3], M. Hasegawa[a], A. Horikoshi[a], A. Itazaki[c], K.C. Kim[e], T. Kumazawa[a], A. Kusumoto[c], M.H. Lee[e], Y. Makida[a], S. Matsuda[a], Y. Matsukawa[c], K. Matsumoto[a], A.A. Moiseev[b], Z. Myers[b,4], J. Nishimura[f], M. Nozaki[a], R. Orito[c,5], J.F. Ormes[g], K. Sakai[f], M. Sasaki[b,6], E.S. Seo[e], Y. Shikaze[c,7], R. Shinoda[f], R.E. Streitmatter[b], J. Suzuki[a], Y. Takasugi[c], K. Takeuchi[c], K. Tanaka[a], T. Taniguchi[a,8], N. Thakur[g], T. Yamagami[d], and T. Yoshida[d]

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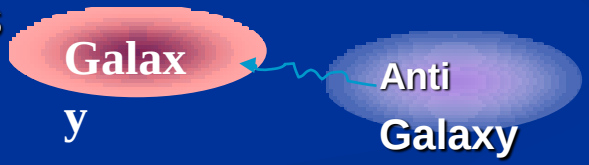
Balloon-borne Experiment with a Superconducting Spectrometer

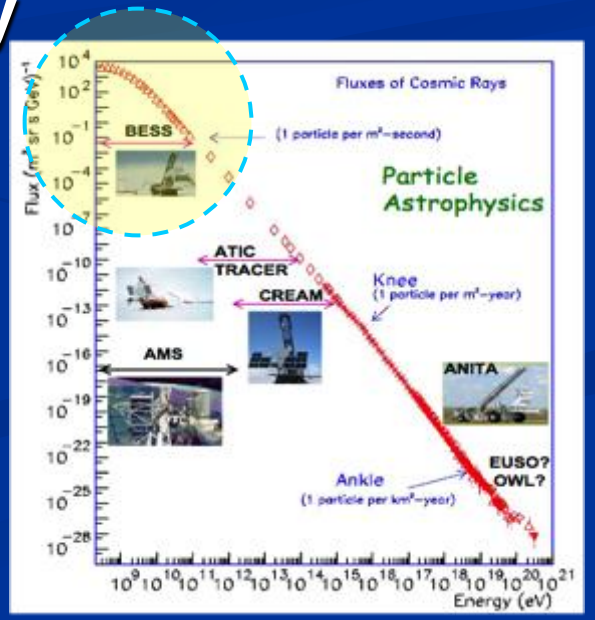
BESS Objectives

Balloon-borne **E**xperiment with a **S**uperconducting **S**pectrometer

- **Search for Antiparticle/Antimatter**
  - $\bar{p}$, $\bar{D}$ Novel、primary cosmic origins
    - Evaporation of Primordial Black Holes (PBHs)
    - Annihilation of super-symmetric particles
  - $\bar{He}$ Baryon asymmetry in Universe



- **Provide Fundamental Cosmic-ray Data**
  - **Precise p, He, μ spectra**
    - Propagation, solar modulation,
    - Atmospheric secondaries,
    - Atmospheric neutrinos
  - **Light isotopes**

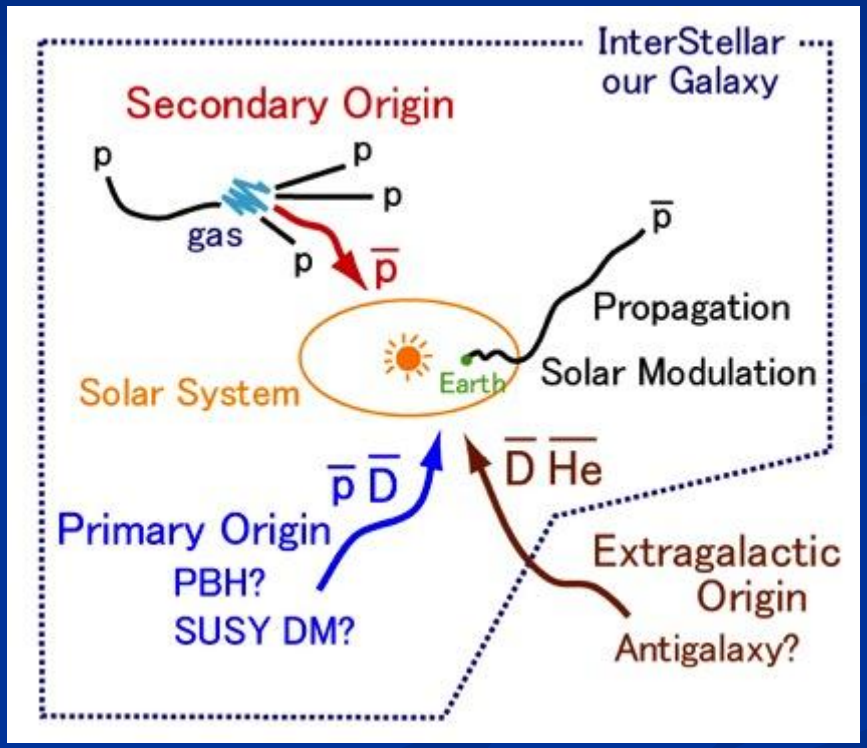


Outline

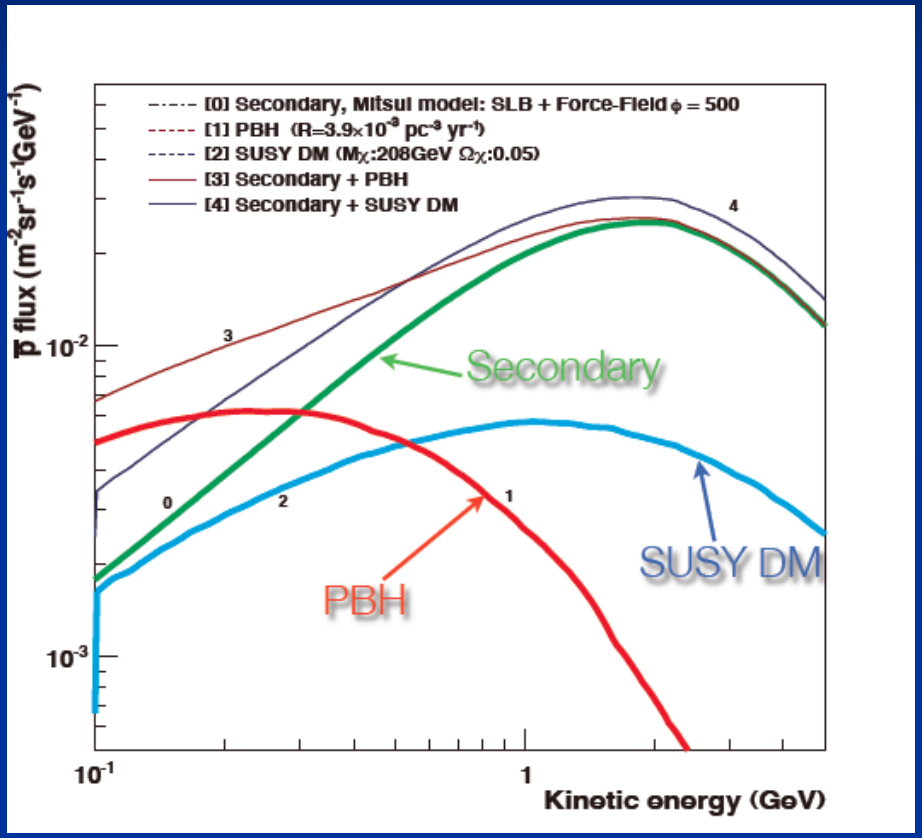
- **Introduction**
  - Cosmic-ray antiparticles
  - BESS history and progress
- **New results from BESS-Polar**
  - **Low-energy Antiproton Measurement**
  - **Antihelium Search**
  - Antidueteron Search in progress
  - Proton flux and annual/daily variation during flight (not covered, in this talk)
- **Summary**

Cosmic-ray Antiparticles

- **Provide Unique Information**
  - Elementary particle phenomena in the early universe
  - Matter/Antimatter asymmetry,
  - SUSY dark matter,
  - Primordial black hole (PBH), etc.
- **Fundamental Cosmic-ray data**
  - Production, propagation
  - Solar modulation
  - Interaction in the atmosphere



Possible Origin of Antiprotons



- **Collision Origin (Secondary)**

$$p + p, N \rightarrow \bar{p} + X$$

  - Kinematically suppressed in low energy

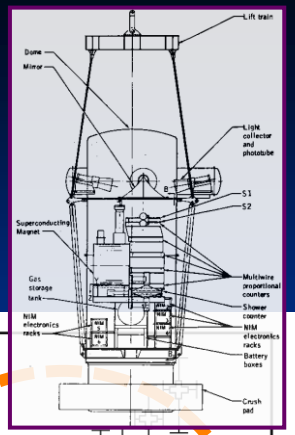
- **Primary Origin**
  - Evaporation of primordial black holes (PBH)
  - Annihilation of SUSY DM
  - Could be probed by spectral shape

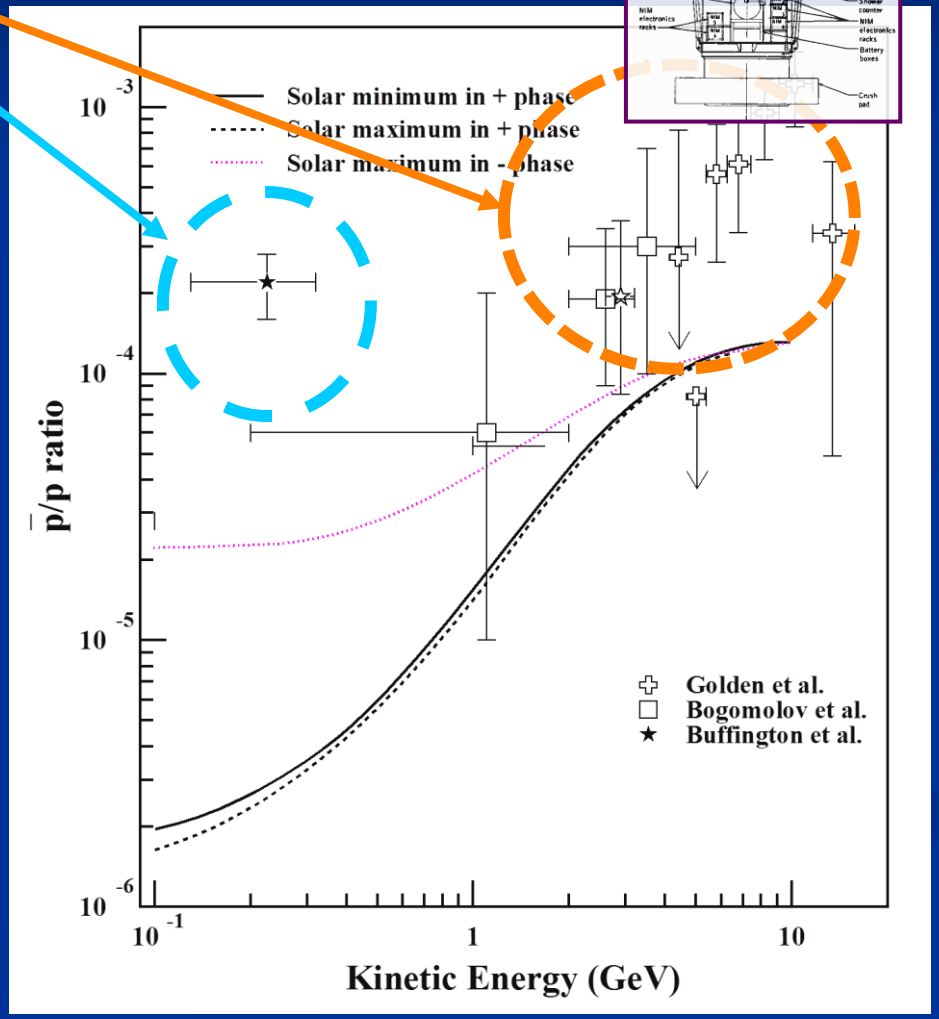
Search for Antiparticle/Antimatter Novel Cosmic Origin

1979: p-bar first observation

(Golden et al, , Bogomolov et al.)

1981: Anomalous excess (Buffington et al)
1985: ASTROMAG proposed
1987: LEAP, PBAR
1988: *Astromag frozen*
1991: MASS
1992: IMAX
1993: BESS, TS93
1994: CAPRICE, HEAT
1996: *Solar minimum*
1998: CAPRICE, AMS-01
2000/2: Heat-pbar
2004: BESS-Polar I
2006-present PAMELA (Polar-orbit)
2007: BESS-Polar II - *Solar minimum*
2011-present: AMS-02 (ISS)





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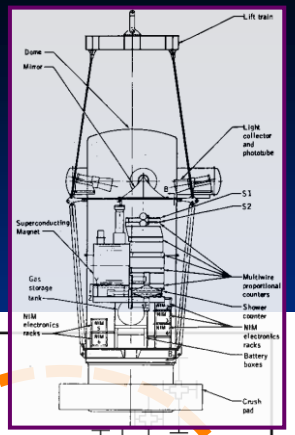

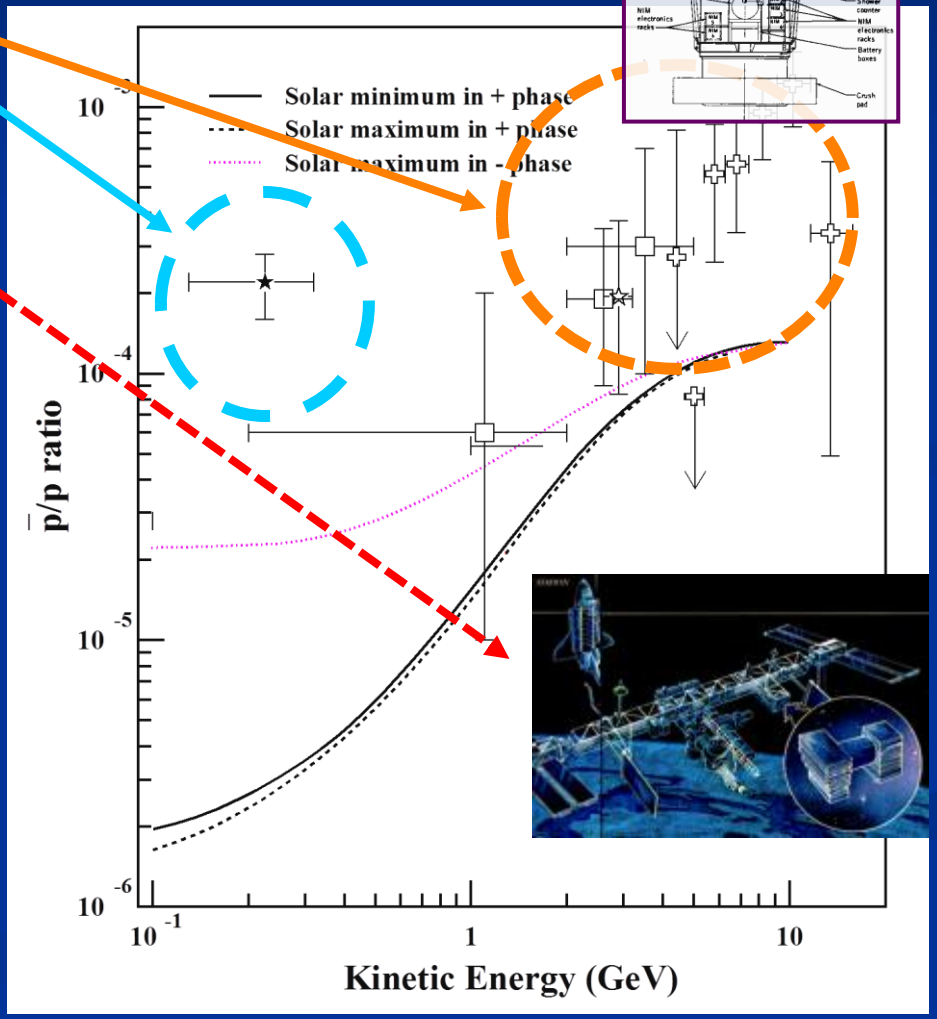

Search for Antiparticle/Antimatter Novel Cosmic Origin

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1993: TS93, BESS first flight
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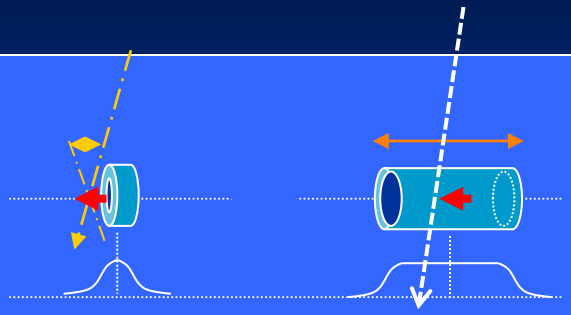
Consistent

BESS:

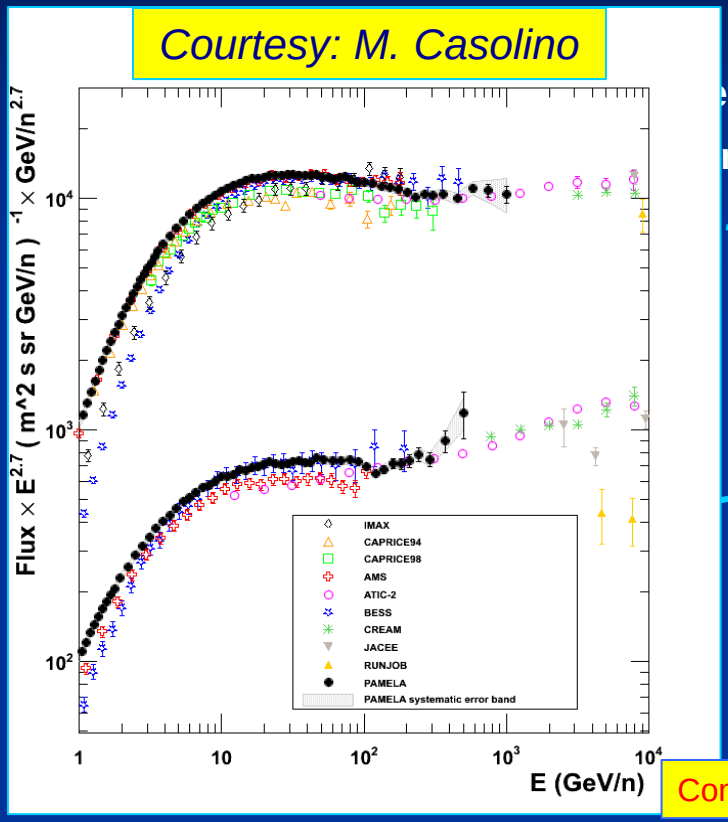


1985	**Thin Solenoid conf. proposed**
	U.Tokyo started preparation
1987:	Collaboration formed
1993:	**First flight,** p-bar mass identified
1995:	Distinctive peak observed at 2 GeV
1998:	Spectrum up to 4.2 GeV
	Precise p spectrum: ~ 120 GeV
2000:	Charge dependence, p-bar/p
2001:	Atmospheric p and p-bar, mu
2002:	BESS-TeV: p spectrum: ~ 500 GeV
2004:	BESS-Polar I
2007/8	**BESS-Polar II**

11 flights successful

Search for Antiparticle/Antimatter Novel Cosmic Origin

Courtesy: M. Casolino



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Consistent

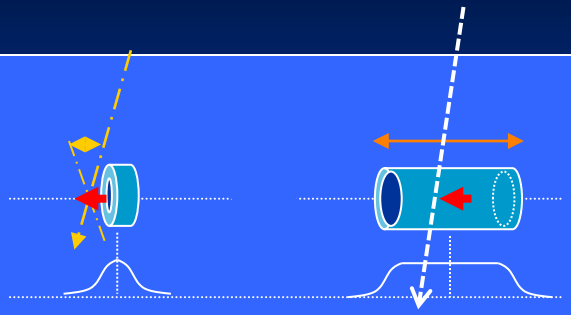
2004: BESS-Polar I

2006-present: PAMELA (Polar)

2007: BESS-Polar II *Solar minimum*

2011-present: AMS-02 (ISS)

BESS:



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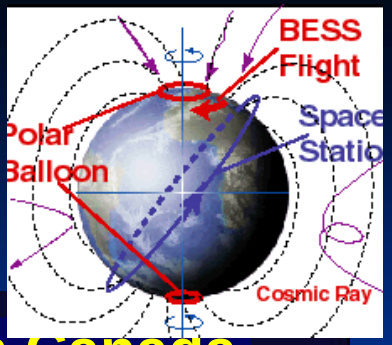
11 flights successful

BESS Ballooning



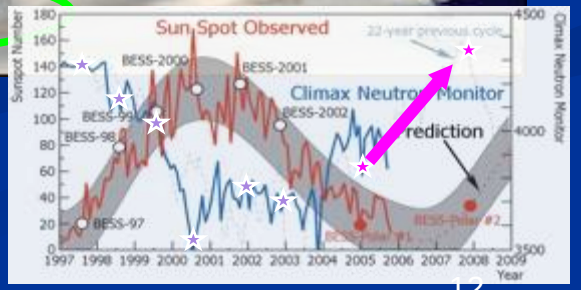
1993~ 2000, BESS, North Canada
2002, BESS-TeV

1999, 2001, BESS-Ground, Japan

2001, BESS-TeV, Fort Sumner

2004, 2007 /08: BESS-Polar, Antarctica

11 scientific balloon flights



BESS Spectrometer: Concept

Rigidity measurement

SC Solenoid (L=~1m, B=~1T)

Transparent

Min. material (5 g/cm^2)

Uniform field

Large acceptance

Central tracker

Drift chamber

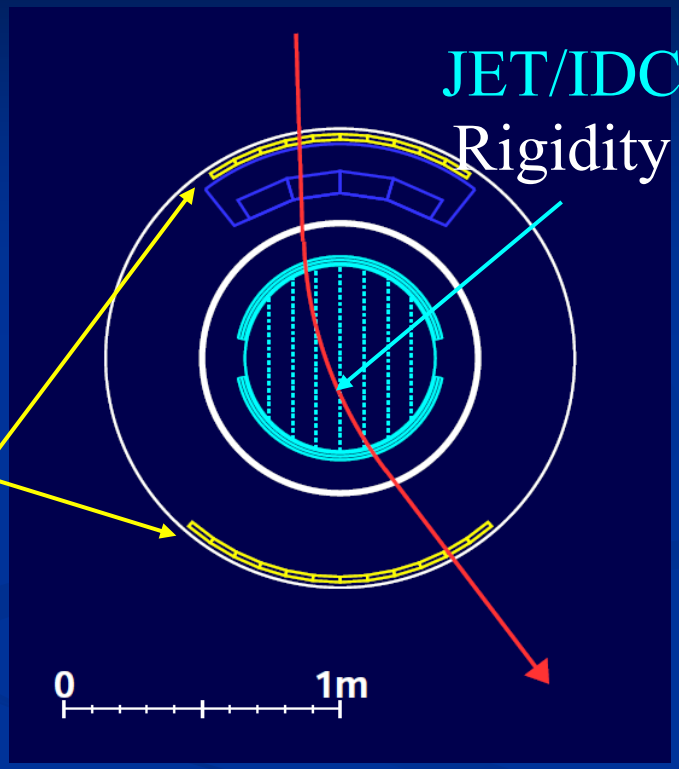
Minimize scattering

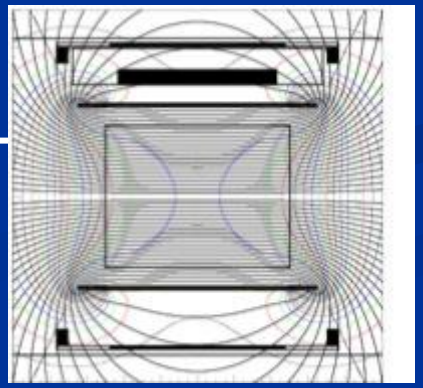
$\delta \sim 150 \mu m$

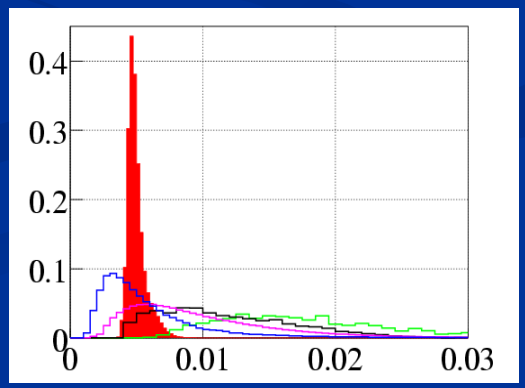
***Z, m* measurement**

$R, \beta \rightarrow m = ZeR\sqrt{1/\beta^2 - 1}$

$dE/dx \rightarrow Z$

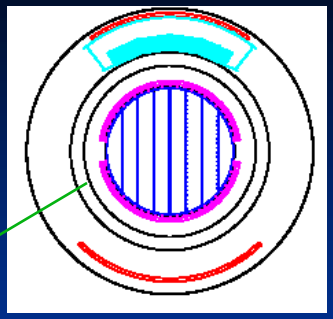




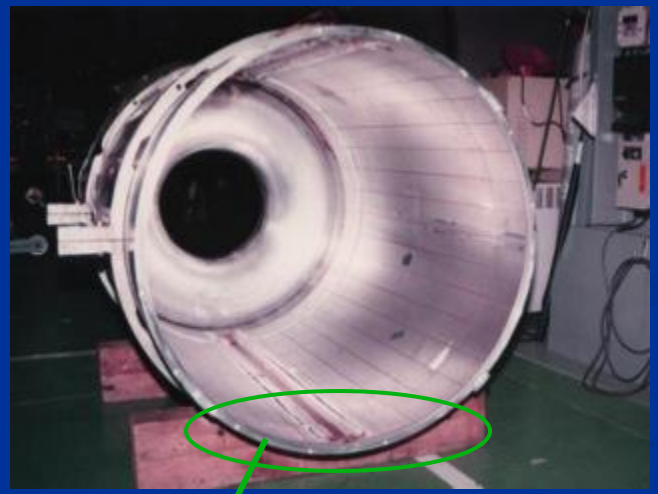


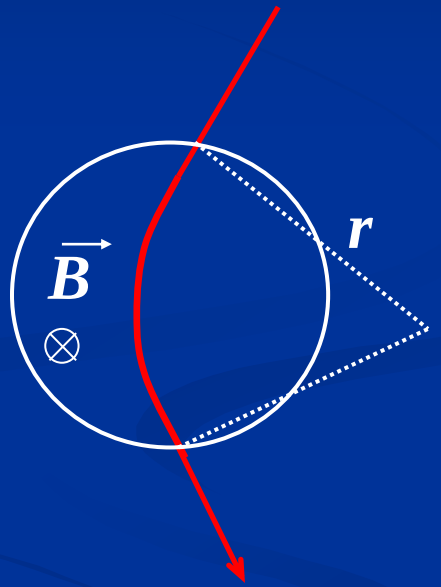
Transparent Superconducting Magnet

- Strong magnetic field with thin coil
- Persistent current

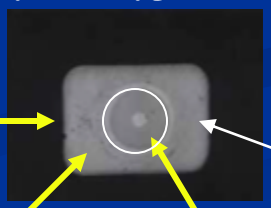


BESS:
Diameter: 1 m
Coil thickness: 8 mm
B: 1.0 T

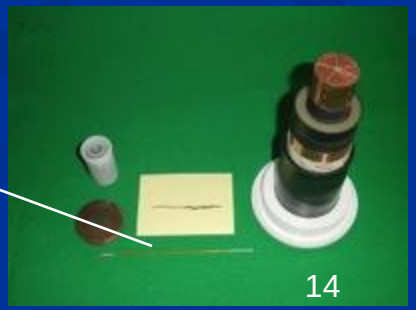




1.2 x 1.8 mm^2

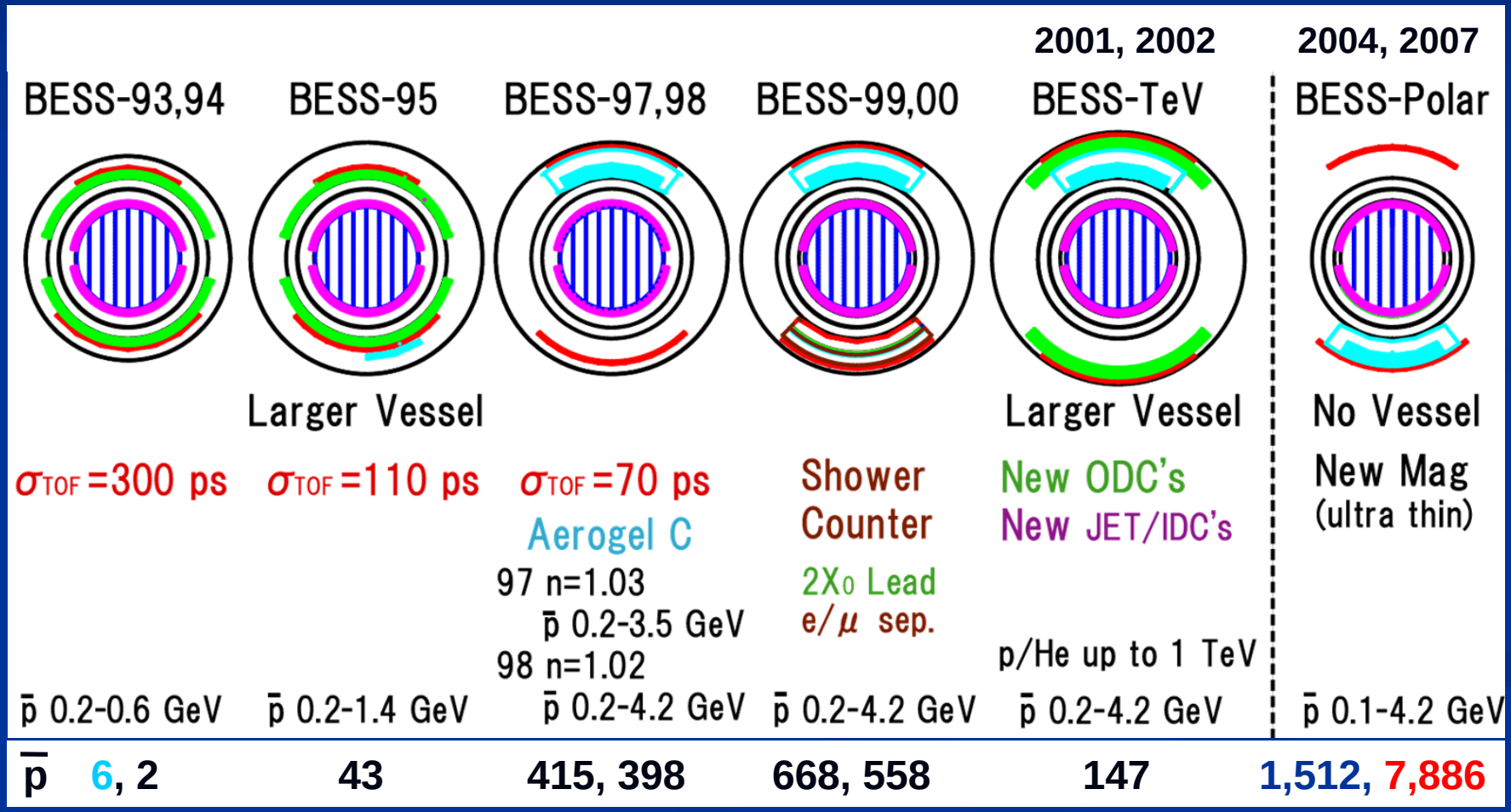


Al, NbTi/Cu



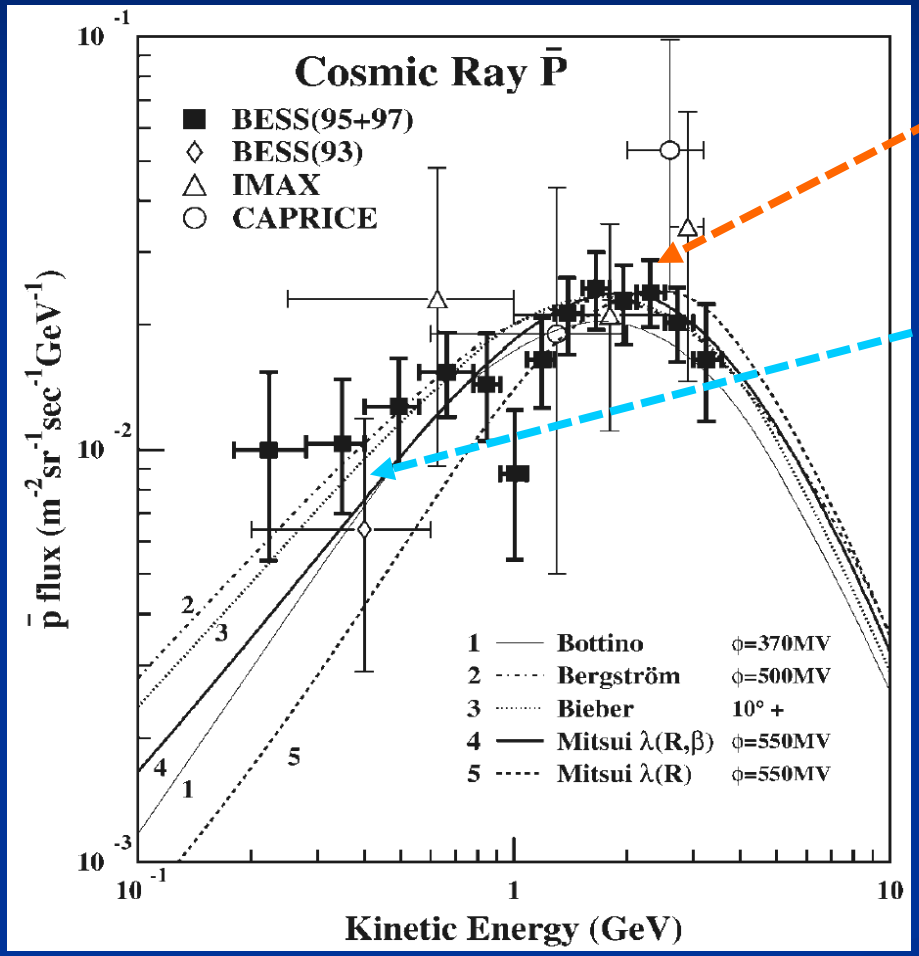
Evolution of BESS

- Nine northern latitude flights (1+ days) 1993-2002 and two Antarctic flights in 2004 (8.5 days) and 2007 (24.5 days)
- Including BESS-Polar I and II: **11,643 antiprotons** reported 0.2 - 4.2 GeV



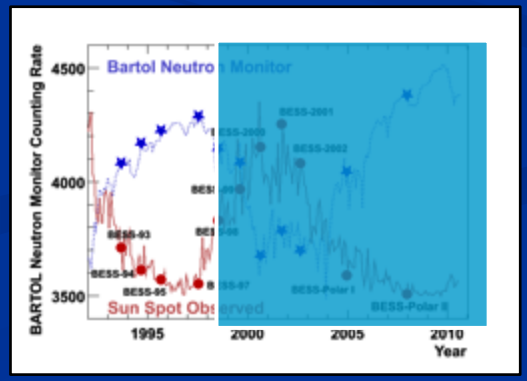
Maximizing advantages with balloon experiments

Antiproton Spectrum Measured at
Solar Minimum in 1995 - 1997



S. Orito et al. PRL, Vol. 84, No, 6, 2000

- Peak for Secondary
- Flatter in low energy?
  - Primary Origin?
- More statistics necessary at solar minimum



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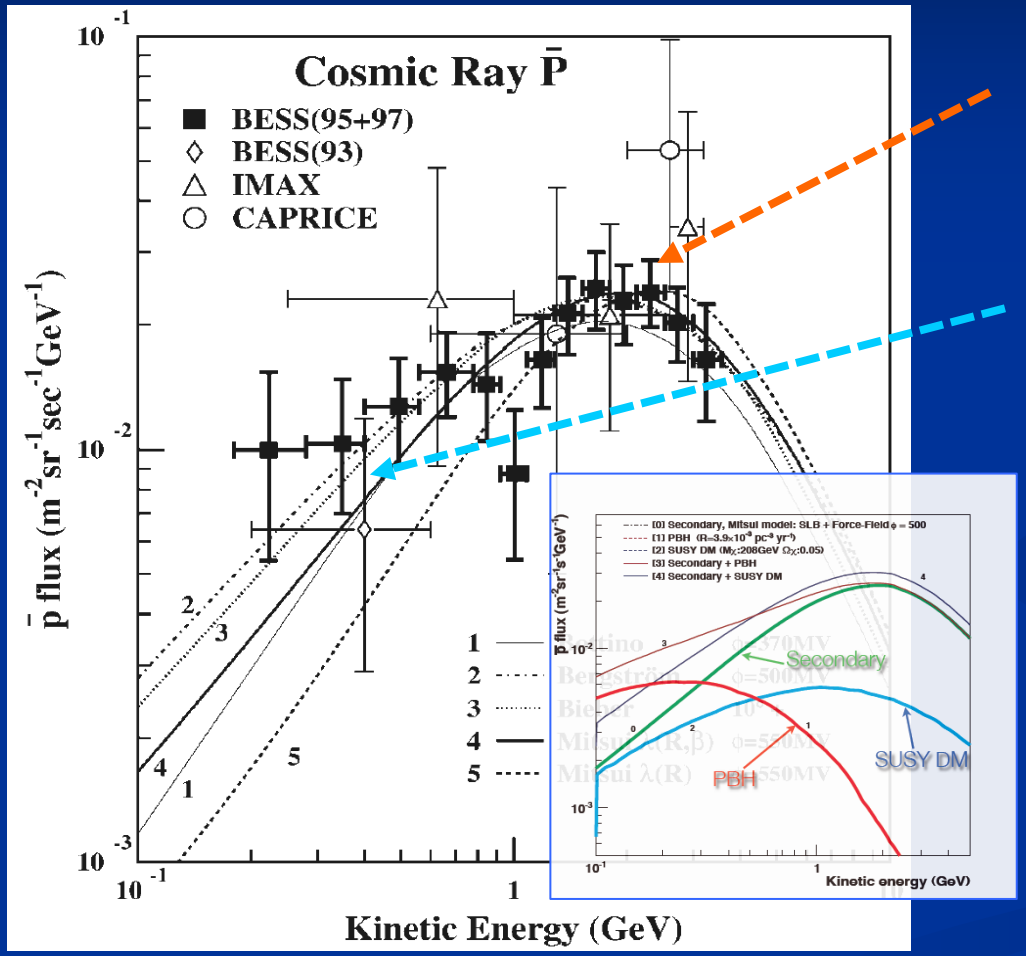

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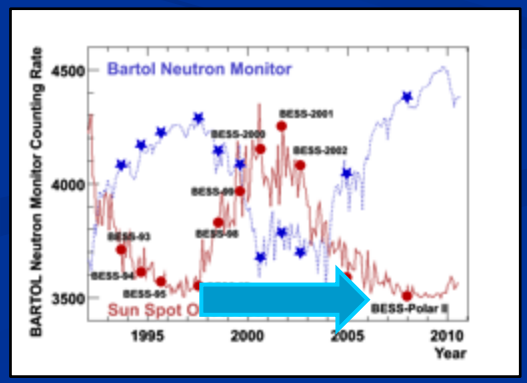
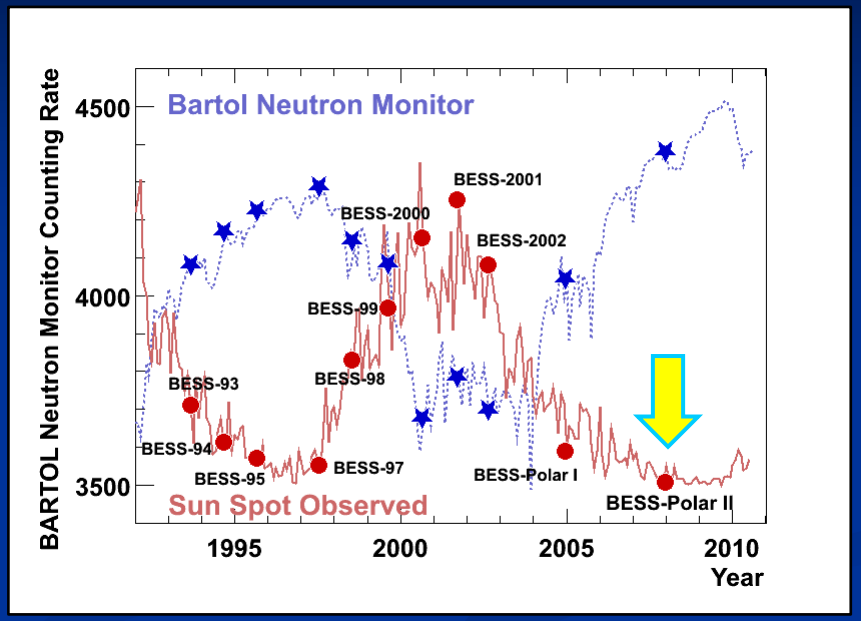


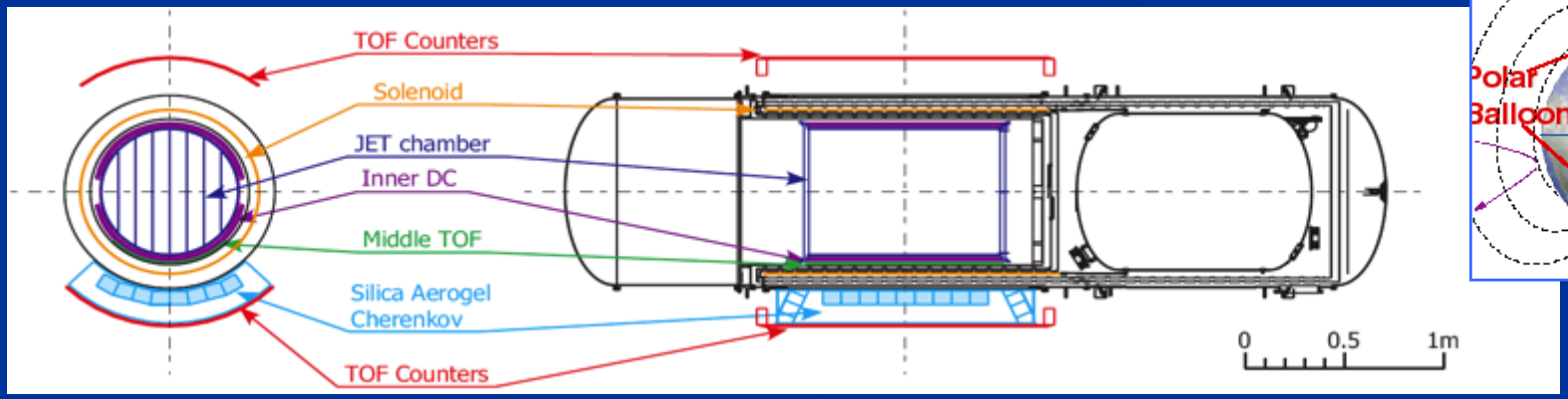
BESS-Polar Experiment

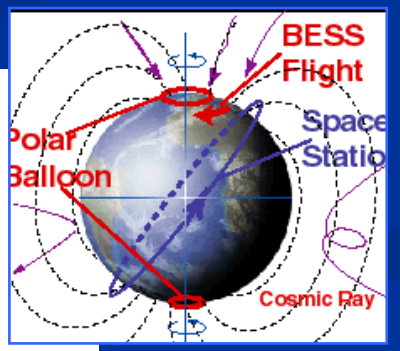
- **Very precise measurement**
  at solar minimum

- **Antarctica Long duration flight**
  at high latitude,
  low rigidity cut-off,

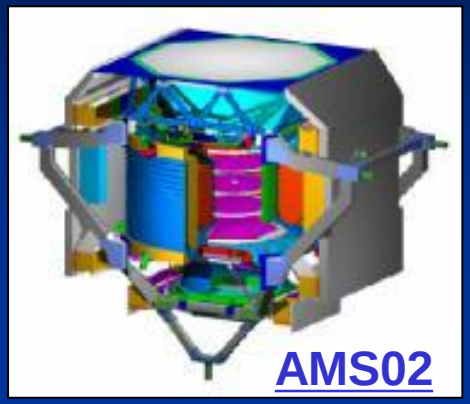
- **Large AΩ and transparent**
  with a new high-resolution
  spectrometer

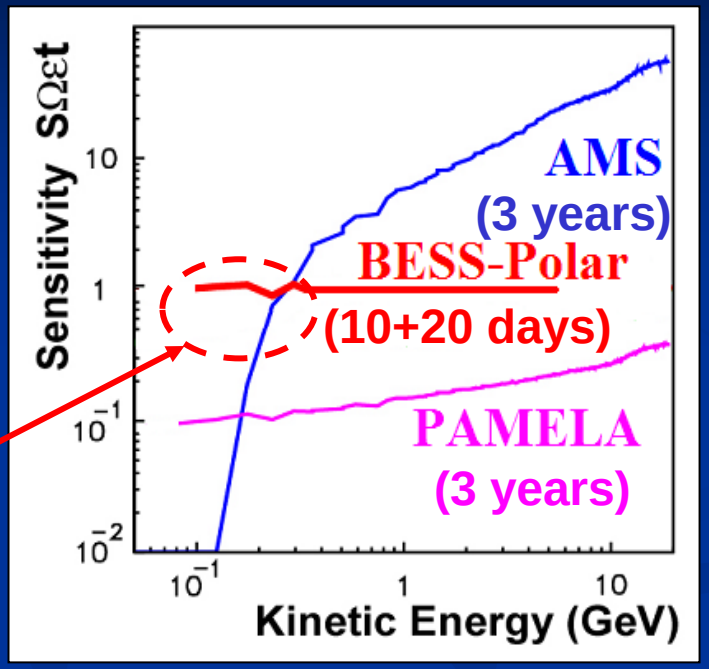






BESS-Polar Feature

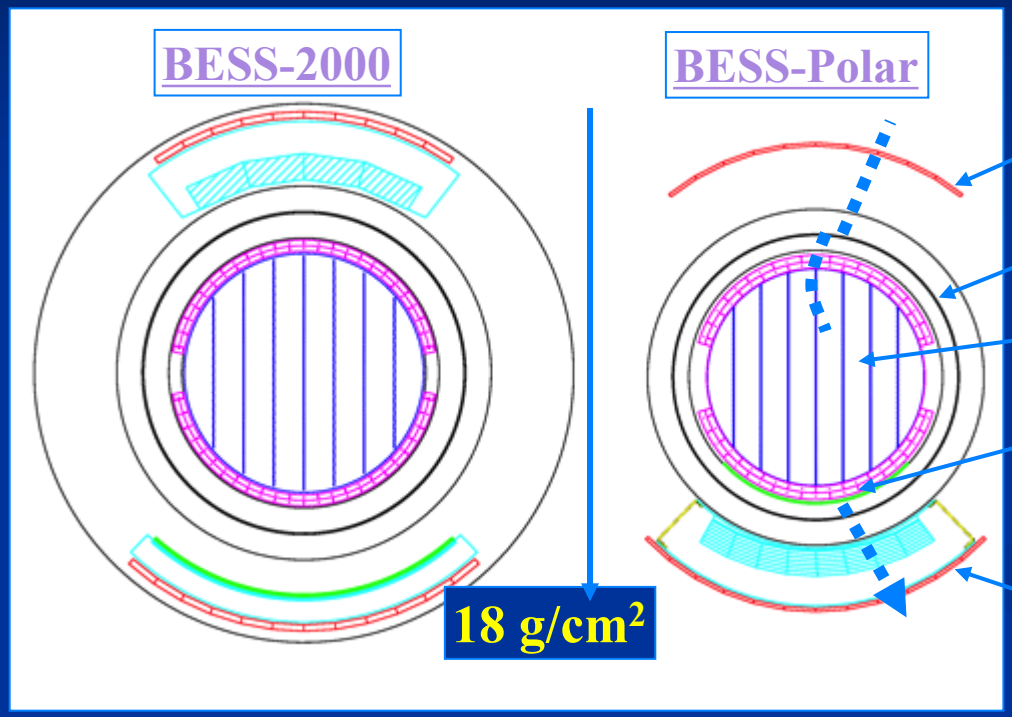




BESS-Polar provides the best sensitivity in low energy

	Acceptance (m^2sr)	Flight Time	Latitude	Altitude (km)	Launch
AMS	0.5	TBD	< 51.7	690	2011
PAMELA	0.0021	>6 years	<70.4	320-390	2006
BESS-Polar II	0.3	25 days	> 75	36	2007

BESS-Polar Spectrometer
Minimizing Material in particle path



Minimize material in spectrometer
New detector (Middle TOF)

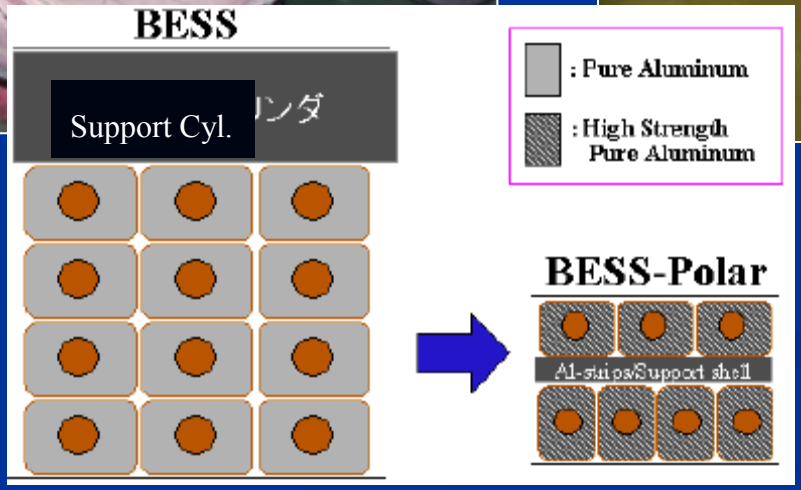
→ **Energy range extended down to 0.1 GeV**

Low power electronics
Solar Power System, Longer life of LHe cryogen

→ **Long duration flight**

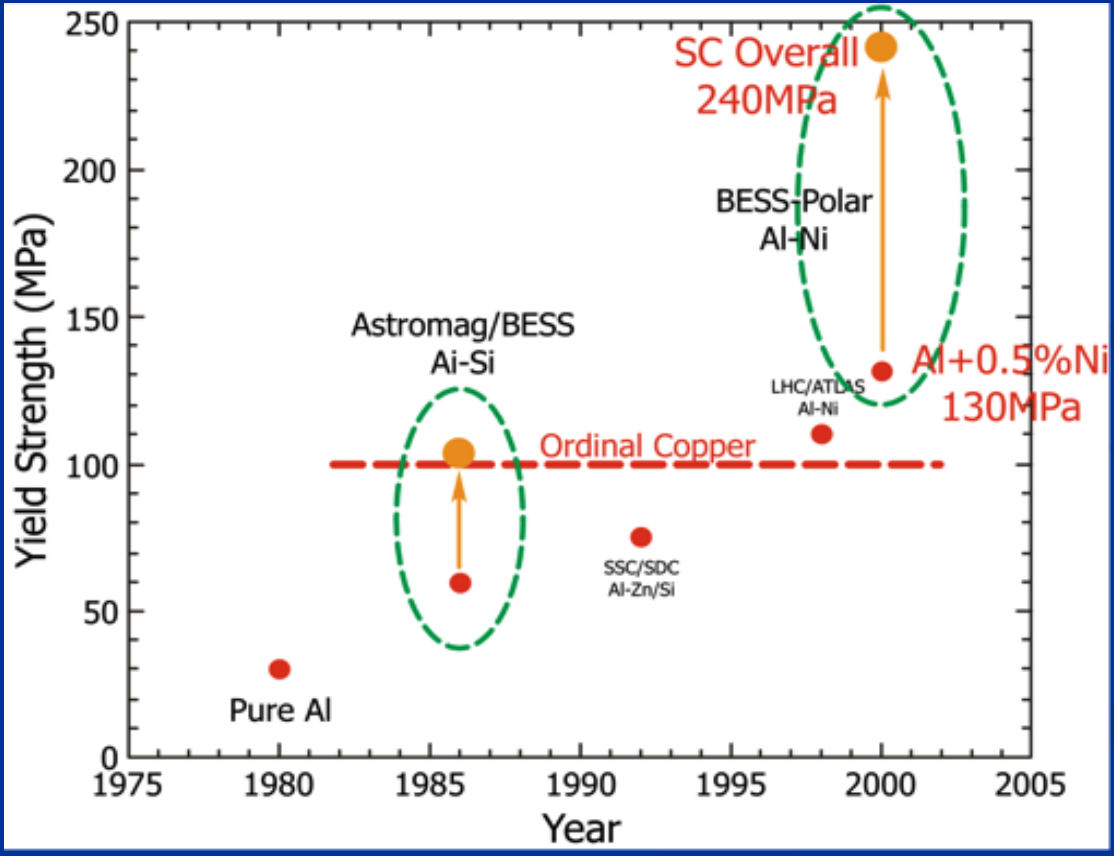
BESS-Polar : Superconducting Magnet:

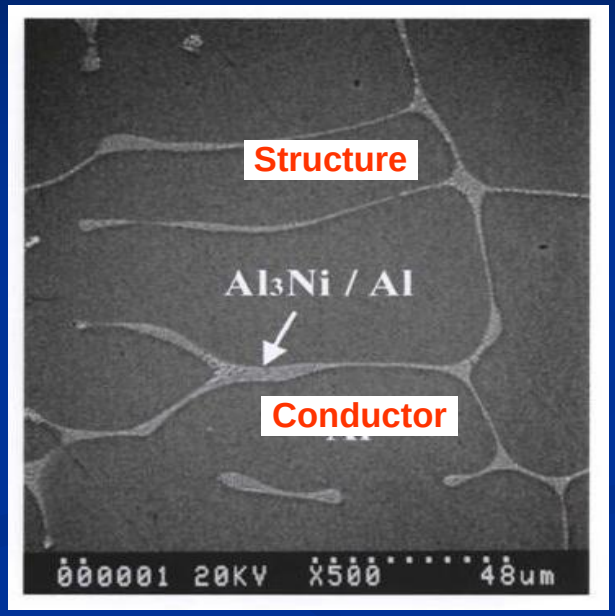
much thinner and more transparent

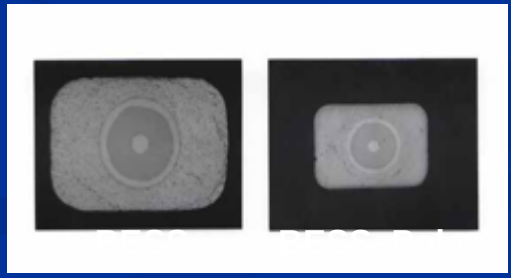


A Key: High-Strength Al stabilized Superconductor

- Micro alloying **Al+Ni 0.5%**
- Cold-work hardening **15~20%**



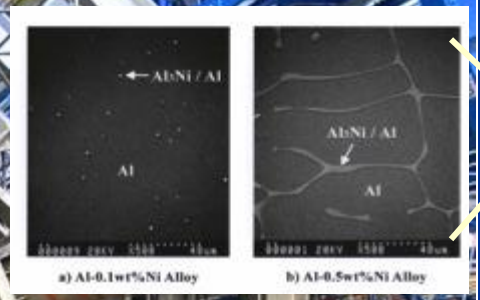


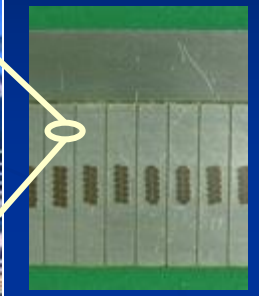


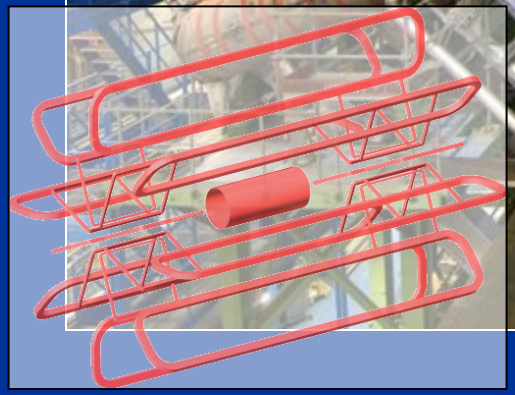
1.2 1.8 0.8· 1.1

LHC: ATLAS Central Solenoid

using the same technology



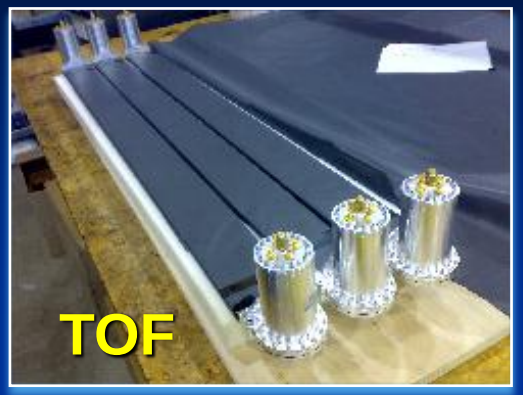


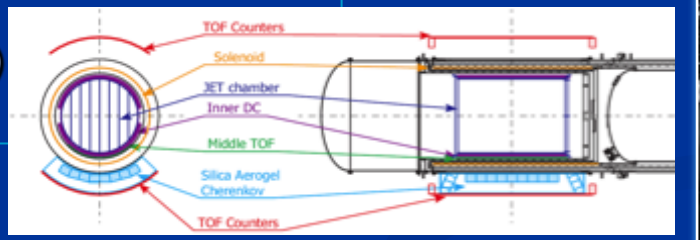


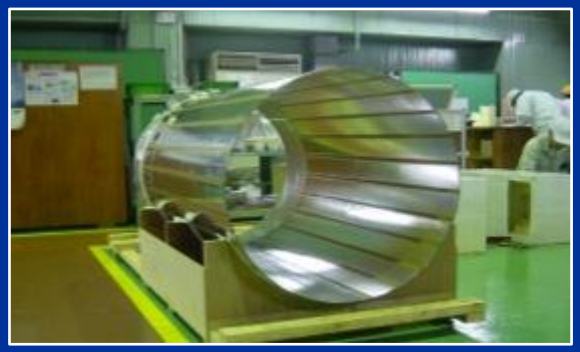
Solenoid

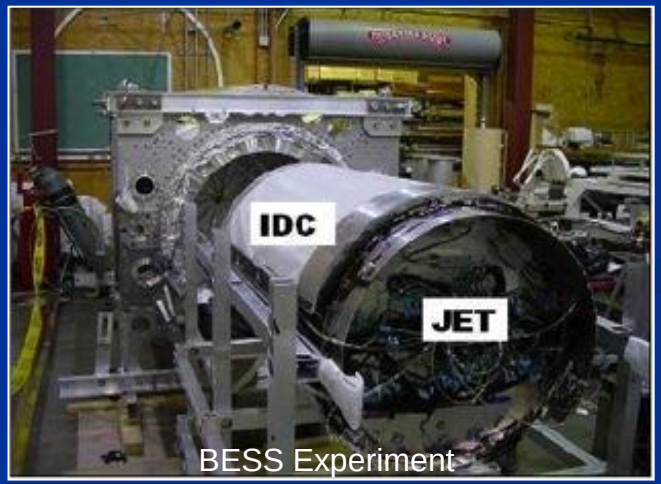
BESS Polar II Spectrometer

- **Large acceptance**
  - Uniform B field ~0.8Tesla
  - Cylindrical coaxial layout
  - **0.3 m^2sr**
- **Transparency for low E particles**
  - Thin solenoid 0.1 X_0/wall
- **Precise momentum measurement**
  - Central Tracker σ=100 ~150um 52 points
  - MDR ~ 270 GV
- **Redundant Particle ID**
  - dE/dX (JET, TOF, MTOF)
  - TOF, ACC







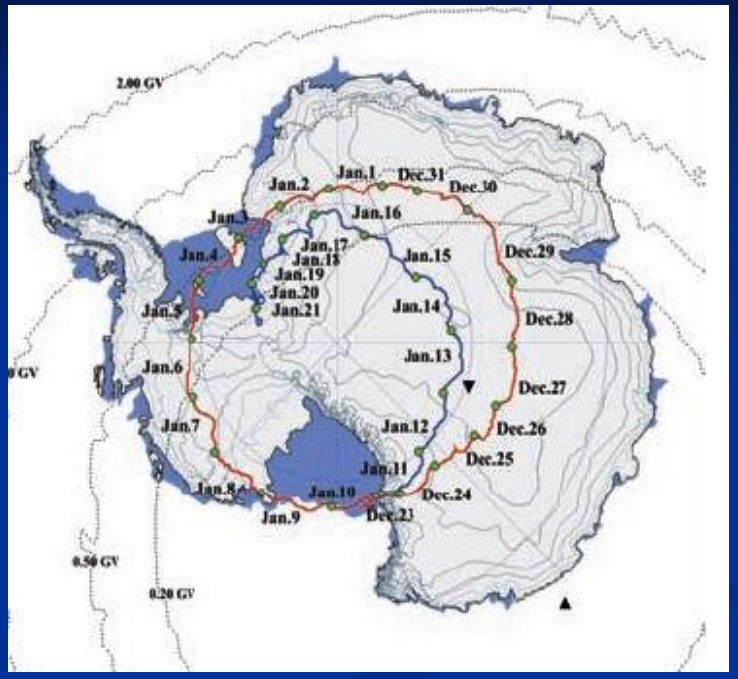


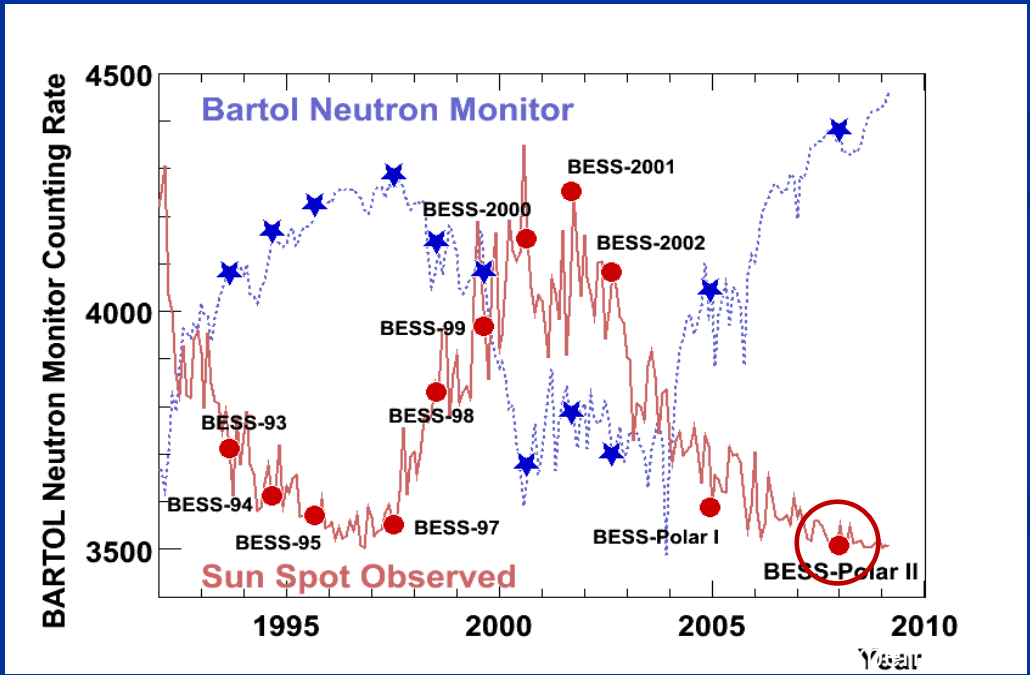
BESS-Polar II

- Launch -

BESS-Polar II Flight summary

Launch date	Dec. 23, 2007
Observation time	**24.5** days
Cosmic-ray observed	**4.7 G** events
Data size	13.5 Tb
Flight altitude	~36 km (6~5g/cm^2)
Data recovery Detector recovery	Feb. 3, 2008 Jan. 16, 2010



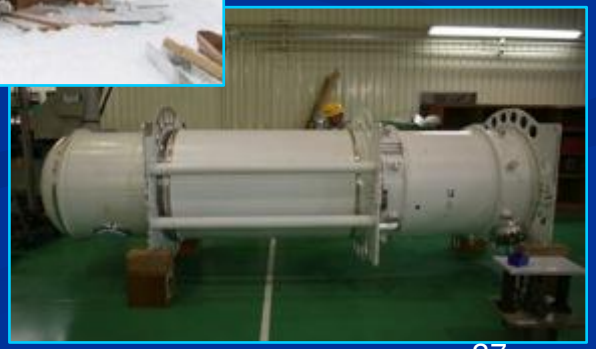


BESS-Polar II flight realized at solar minimum

BESS Recovered from Antarctica in 2010

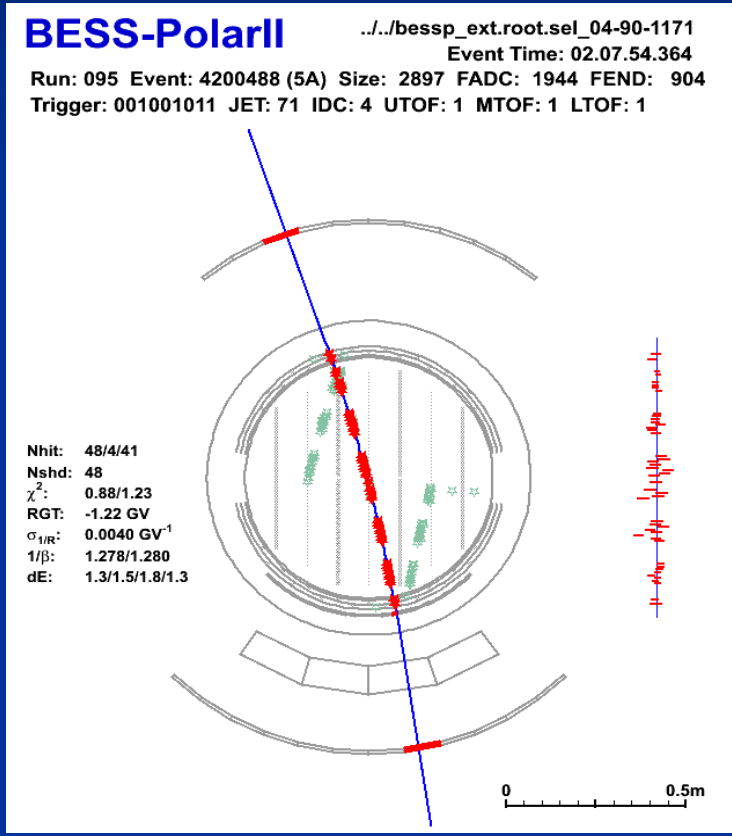
Ski-way building team

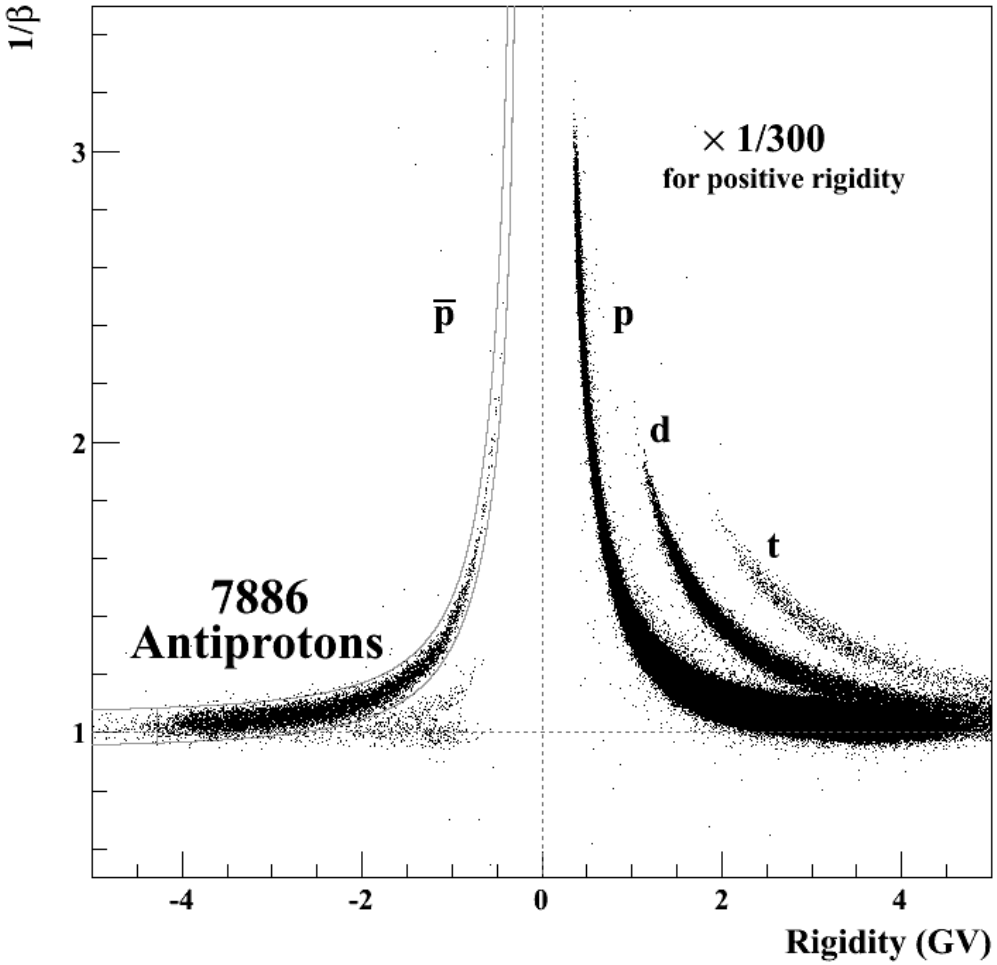
Payload recovery team



- *Magnet performance fully resumed.*
- *It may fly again, and ready for a new science proposal, with next generation , …*

Particle Identification
in BESS-Polar II

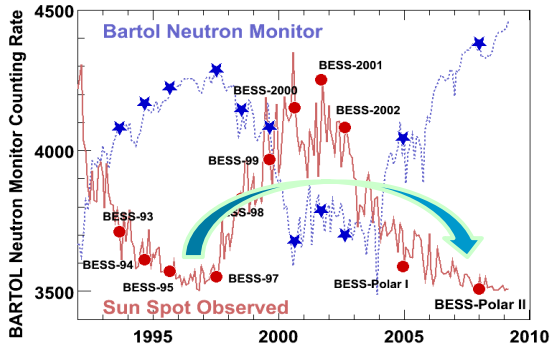


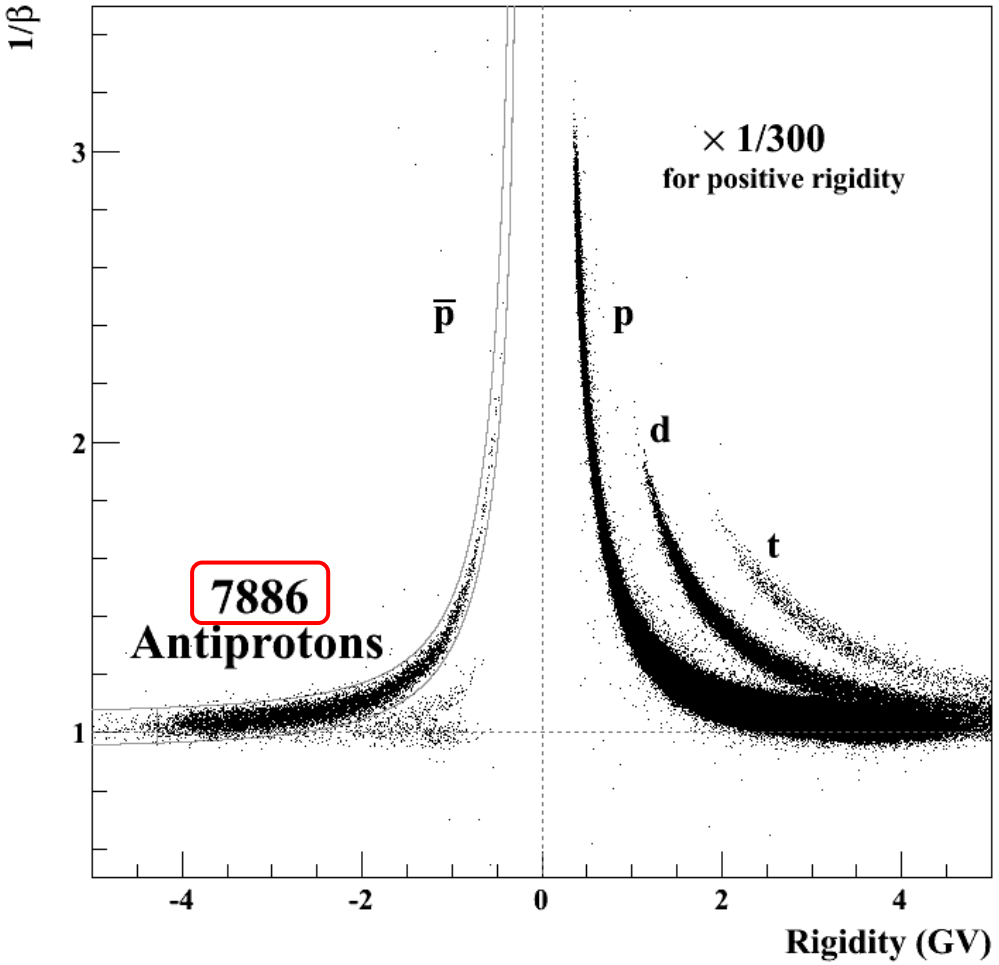


Particle Identification
in BESS-Polar II

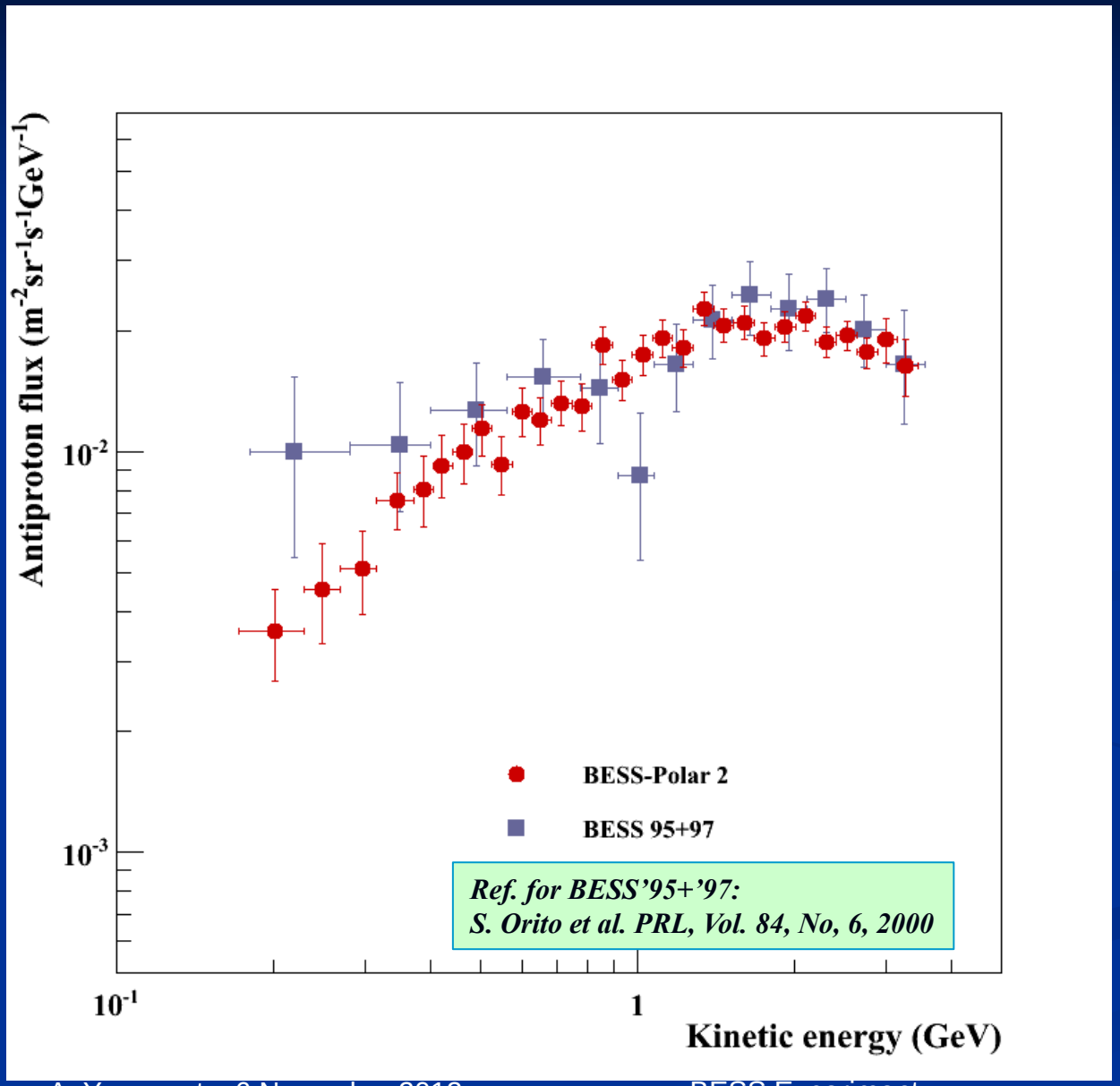
Year	Energy range range (GeV)	Events observed
BESS-93	0.18 - 0.5	6
BESS-94	0.18 - 0.5	2
BESS-95*	0.18 - 1.5	43
BESS-97*	0.18 - 3.6	415
BESS-98	0.18 - 4.2	384
BESS-99	0.18 - 4.2	668
BESS-00	0.18 - 4.2	558
BESS-02 (TeV)	0.18 - 4.2	166
BESS-04 (Polar-I)	0.10 - 4.2	1,520
BESS-07*(Polar-II)	0.17 - 3.5	7,886

* Observation at solar minimum period.





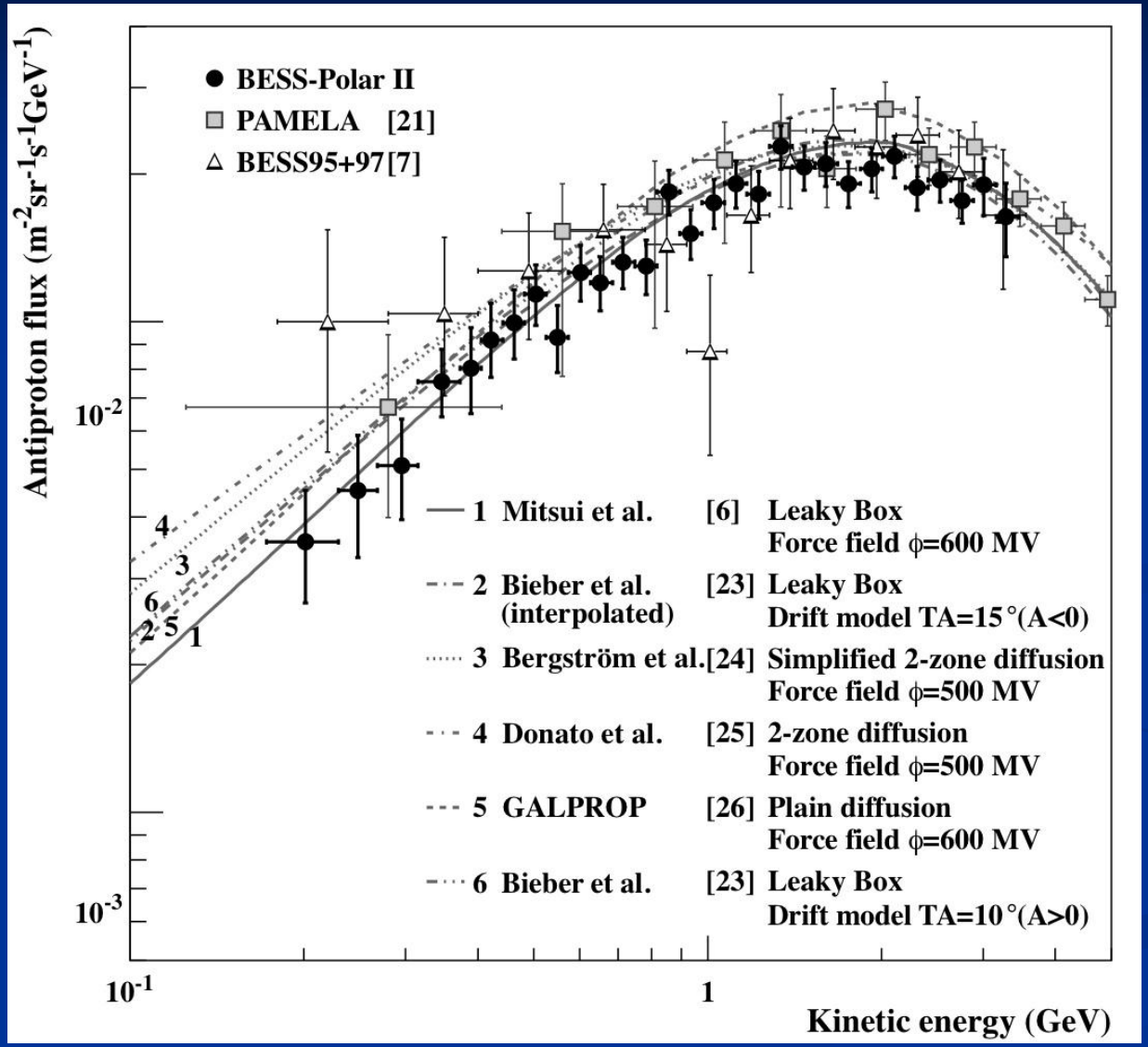
BESS-Polar II Antiproton Spectrum



Compared with BESS'95+'97:

- **x 14 statistics** at < 1 GeV
- Flux peak consistent at 2 GeV,
- Spectral shape different at low energies.
- Result published:

Comparison with secondary models



BESS-Polar II results

- generally **consistent** with secondary p-bar calculations under solar minimum conditions.

Secondary p-bar flux calculated using:

Propagation model
× Solar modulation

Phys. Rev. Lett., 108, 051102 (2012)

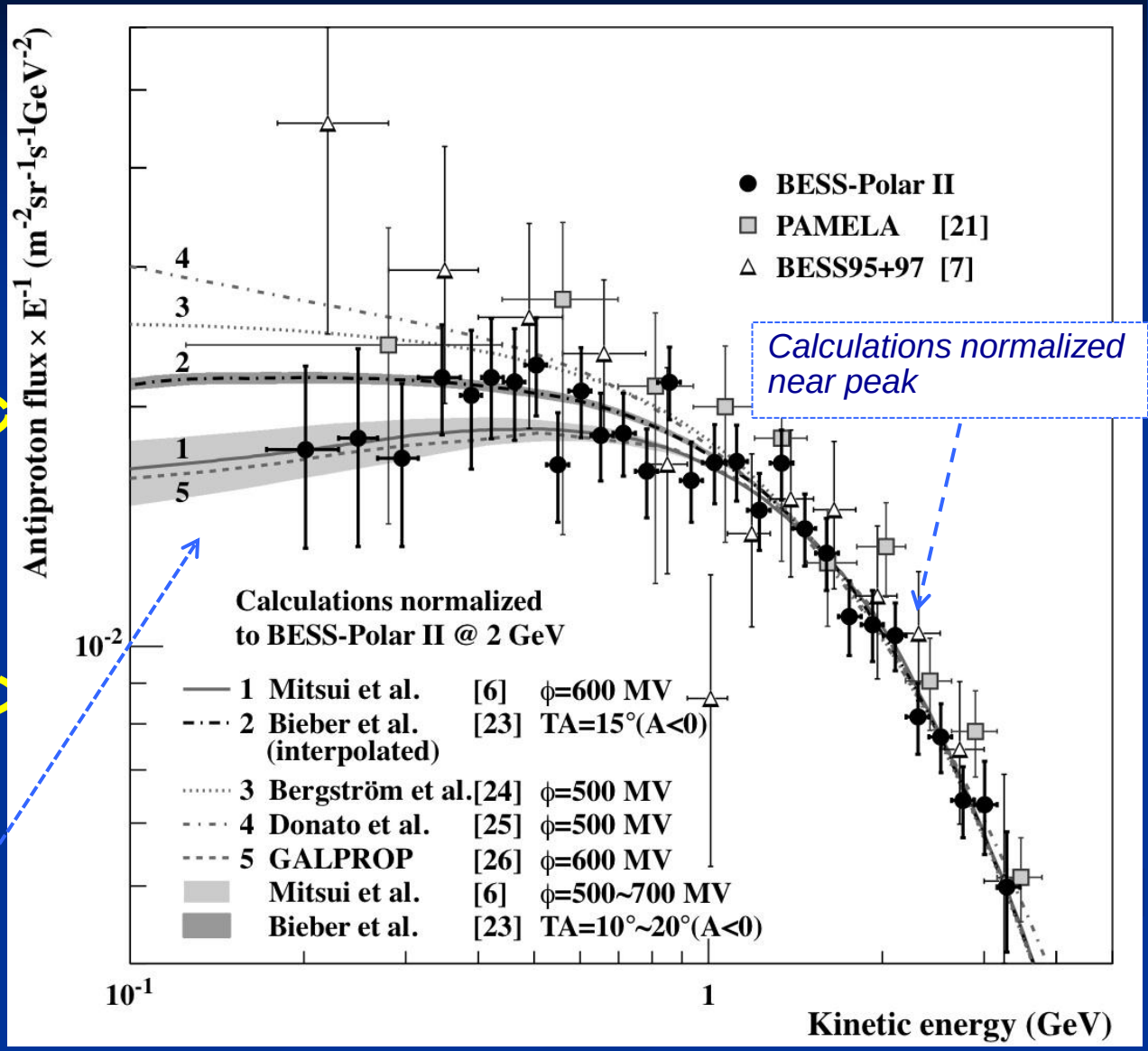
Comparison of Spectral Shapes

Favored Models

- no low energy enhancement

ID	Model	C^2 (<1.0GeV)
1	Mitsui(600MV)	0.57
2	Bieber	0.56
3	Bergstrom	1.24
4	Donato	1.59
5	Galprop(PD)	0.63

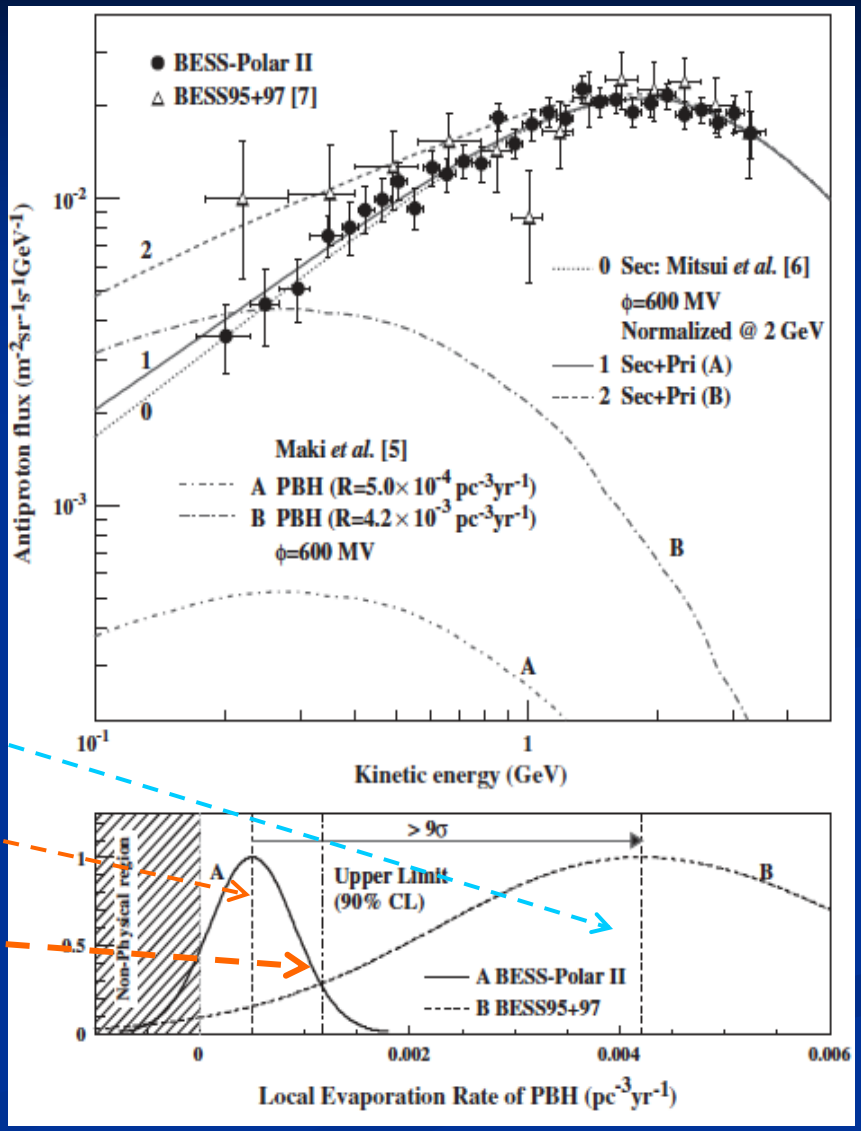
The shaded band indicates the small variation that results from uncertainty in the modulation parameter.



Phys. Rev. Lett., 108, 051102 (2012)

Evaluation of PBH Antiproton

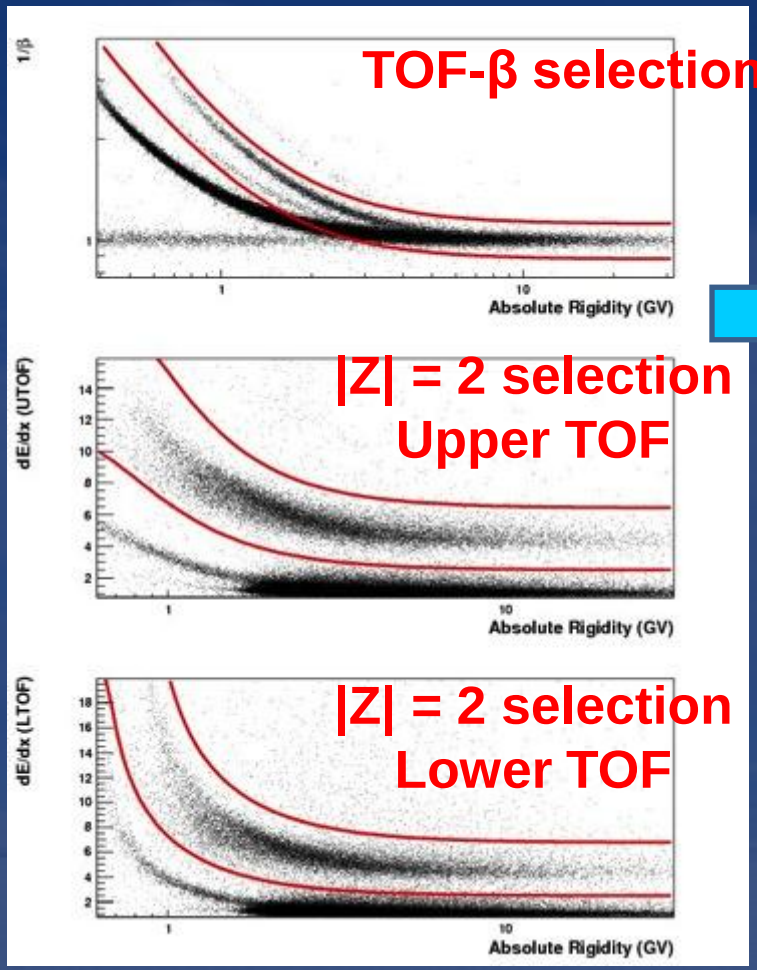
- **PBH antiproton evaluated by:**
  - {p-bar flux observed}
    - {Secondary flux*}
    - **calculated by using Mitsui: SLB+Fisk model,*
- **PBH evaporation rate, R :**
  - BESS'95+'97:
    $4.2 \times 10^{-3}/pc^3/yr$
  - BESS-Polar II:
    $5.2 \times 10^{-4}/pc^3/yr$
  - **Upper limit (90% C.L.):**
    $1.2 \times 10^{-3}/pc^3/yr$
- **No evidence of primary $\bar{p}$ from PBH evaporation**



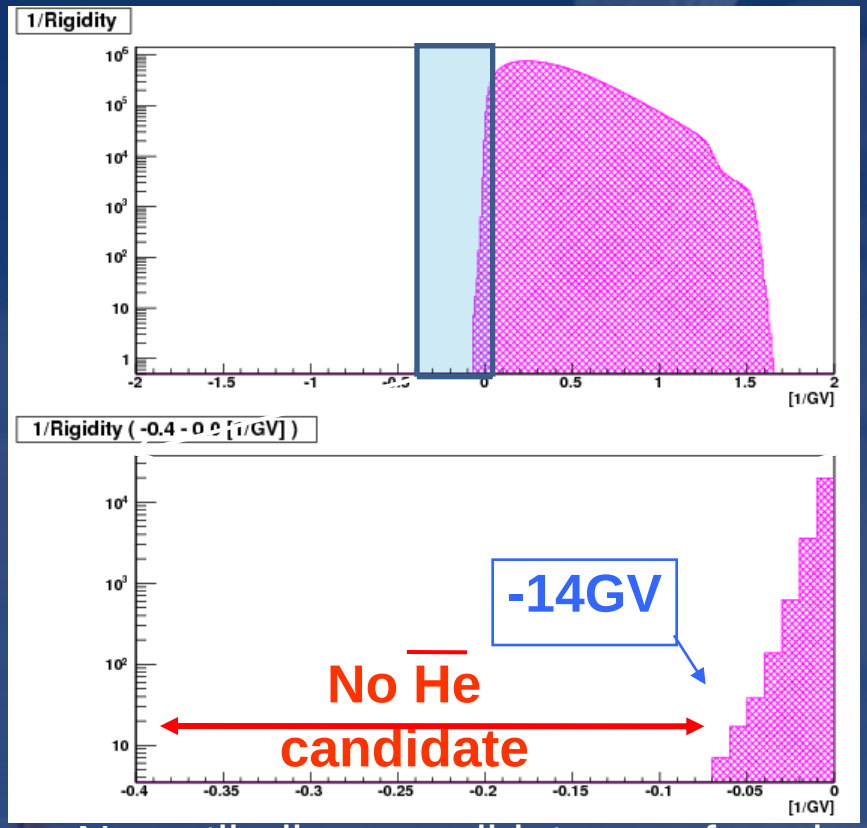
Phys. Rev. Lett., 108, 051102 (2012).

Anti-He Search

Particle Identification using the TOF information



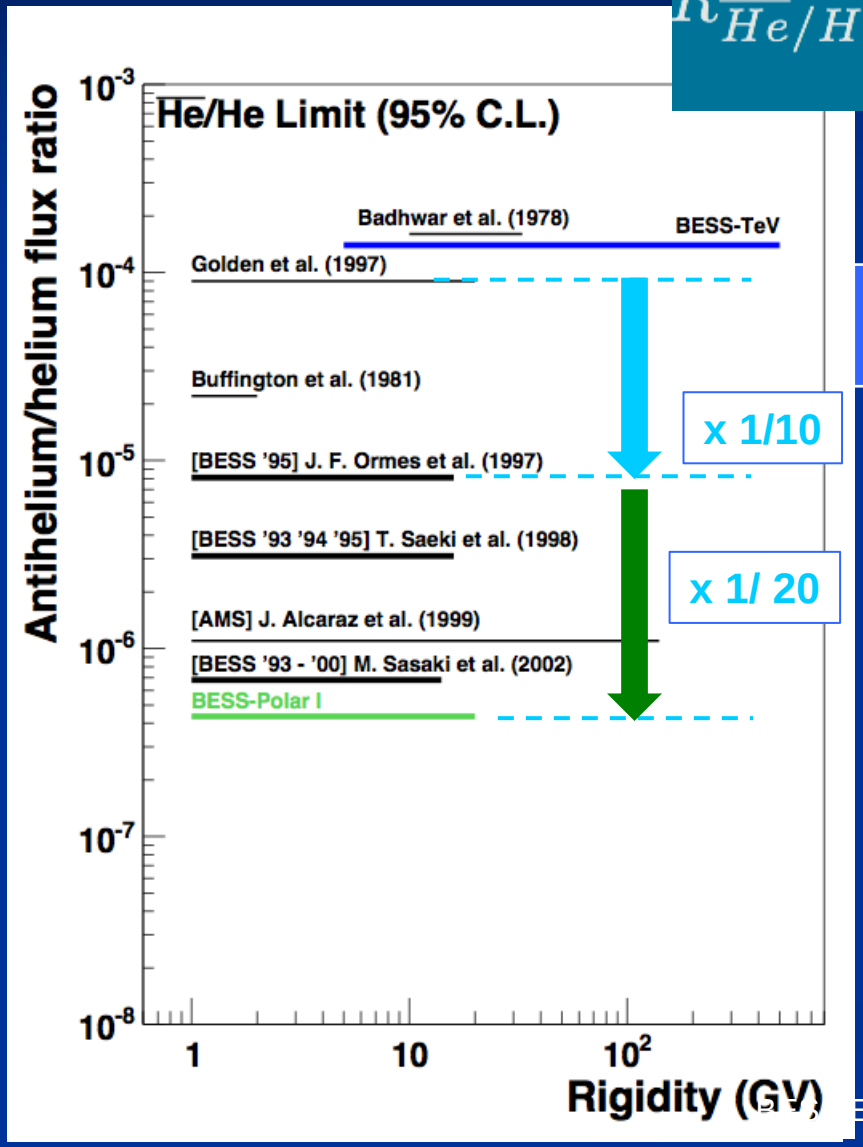
The figure below shows remaining events after all selections applied.



No antihelium candidate was found between -14 and -1 GV after all selection among 4×10^7 Helium events.

Search for Antihelium: in Previous Flights

$$R_{\overline{He}/He} = \frac{3.1}{\int N_{obs} \cdot \frac{\bar{\eta}}{\eta} \cdot \frac{\bar{\varepsilon}_{single}}{\varepsilon_{single}} \cdot \frac{\bar{\varepsilon}_{Q-ID}}{\varepsilon_{Q-ID}} dE}$$



Survival probability in the residual air for He ($\overline{He}$)

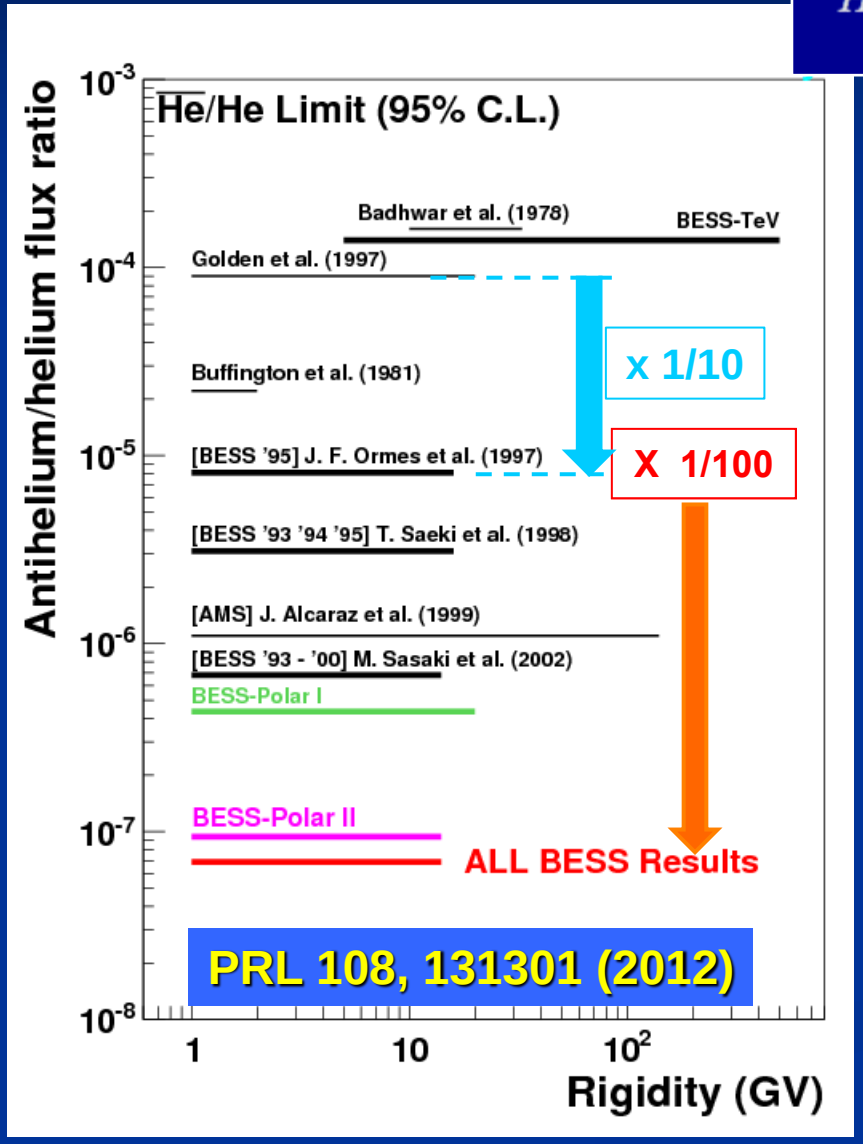
Single track efficiency for He ($\overline{He}$)

Selection efficiency for He ($\overline{He}$)

- **BESS-Polar I results:**
  He-bar/He Upper limit:
  4.4×10^{-7}

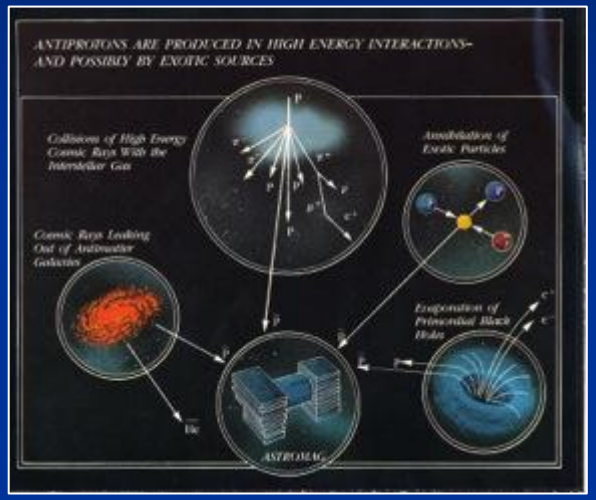
Search for Anti-He: BESS & BESS-Polar

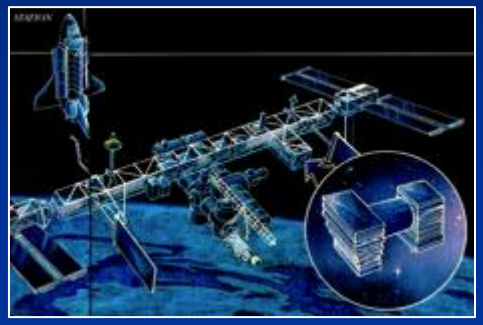
$$R_{\overline{He}/He} = \frac{3.1}{\int N_{obs} \cdot \frac{\bar{\eta}}{\eta} \cdot \frac{\bar{\varepsilon}_{single}}{\varepsilon_{single}} \cdot \frac{\bar{\varepsilon}_{Q-ID}}{\varepsilon_{Q-ID}} dE}$$

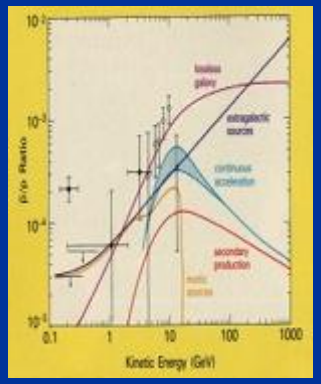


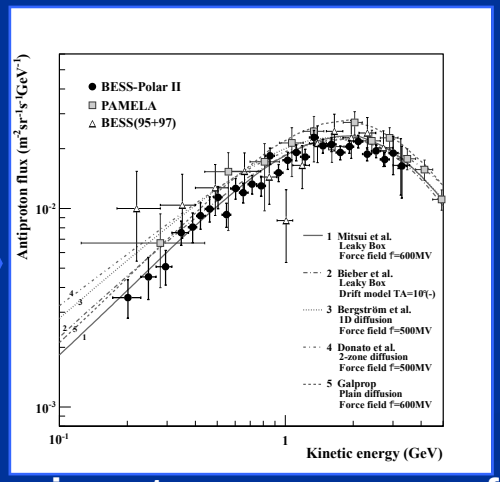
- BESS-Polar I:
  Upper limit: 4.4×10^{-7}.
- BESS-Polar II
  Upper limit: 9.4×10^{-8}
- All-BESS results combined:
  Upper limit: 6.9×10^{-8}
  (1×10^{-7} w/o spectrum assumption)
- This limit is improved by *three orders of magnitude* over first reported limits

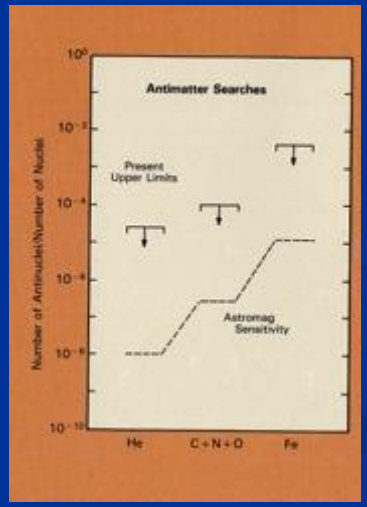
BESS has accomplished many of the Scientific Objectives expected from ASTROMAG in 1980s

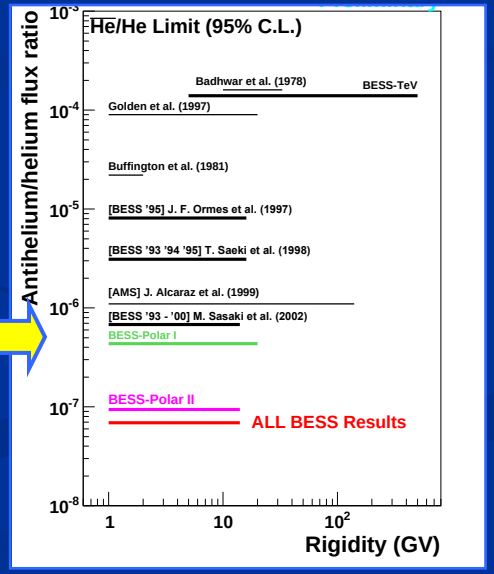






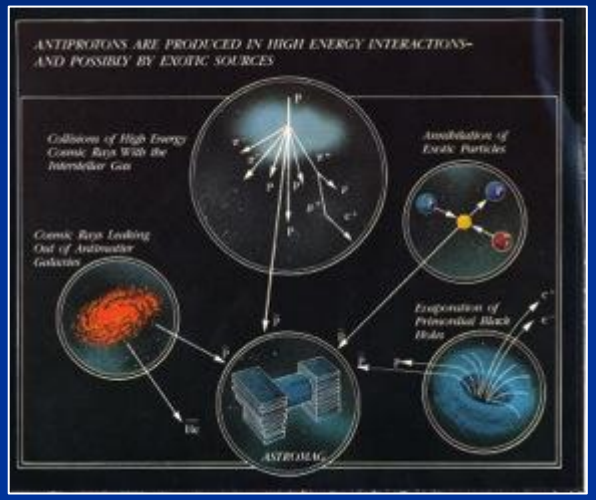


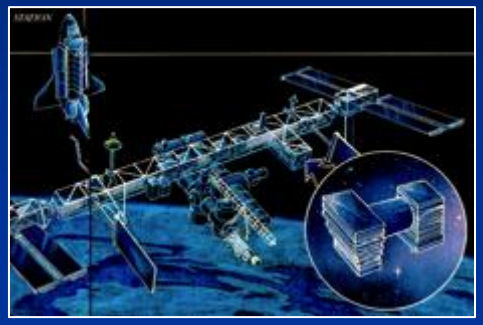


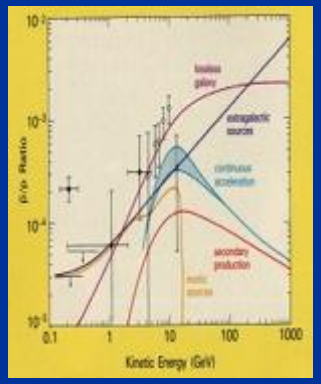


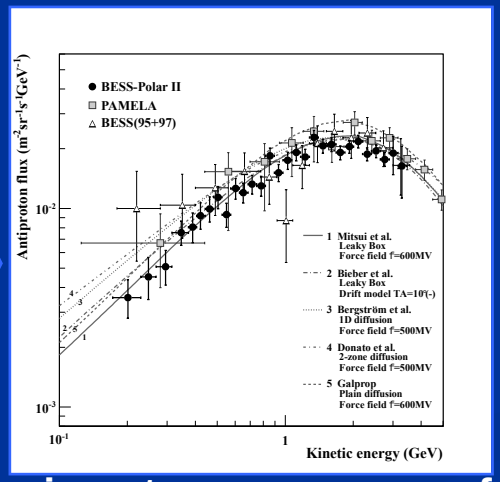
Balloon Experiments are a very useful approach for Astroparticle physics

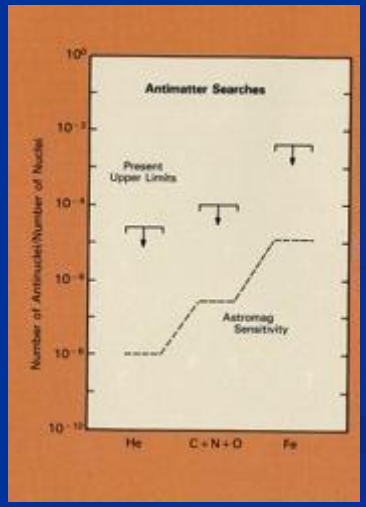
BESS has accomplished many of the Scientific Objectives expected from ASTROMAG in 1980s and they are extended to AMS

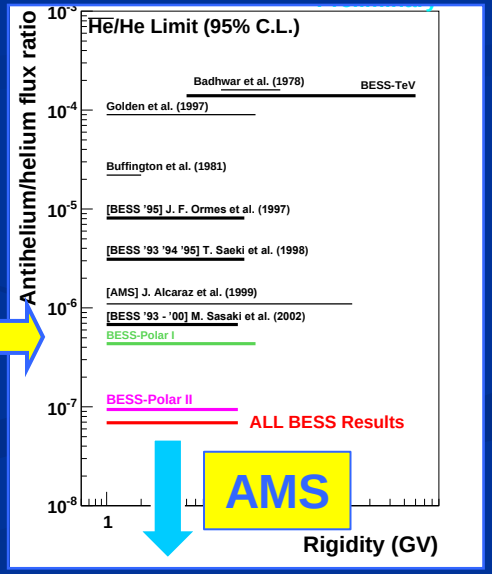






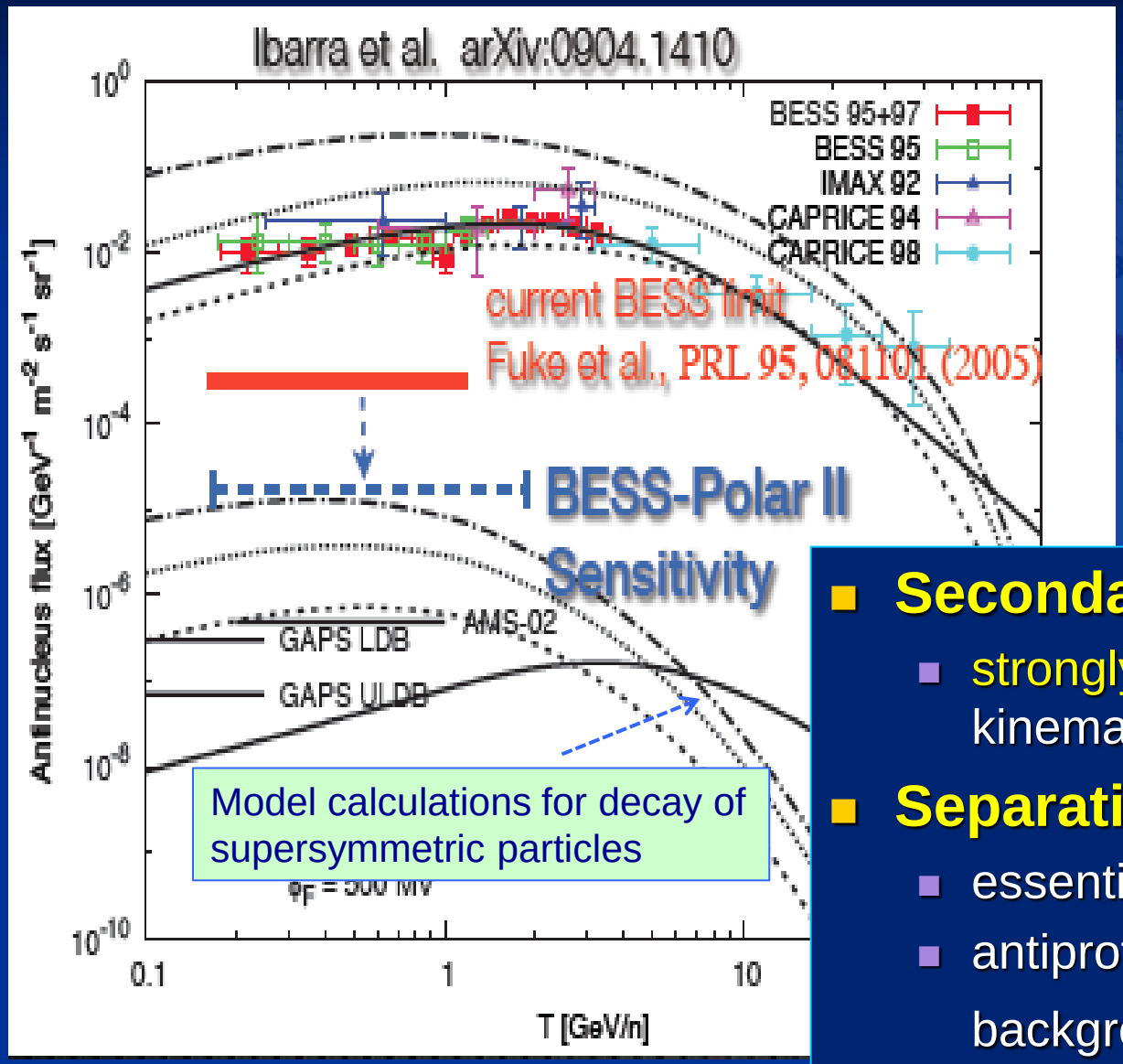






Balloon Experiments are a very useful approach for Astro-particle physics

Search for Antideuteron



Large Exposure and Superior PID Essential:

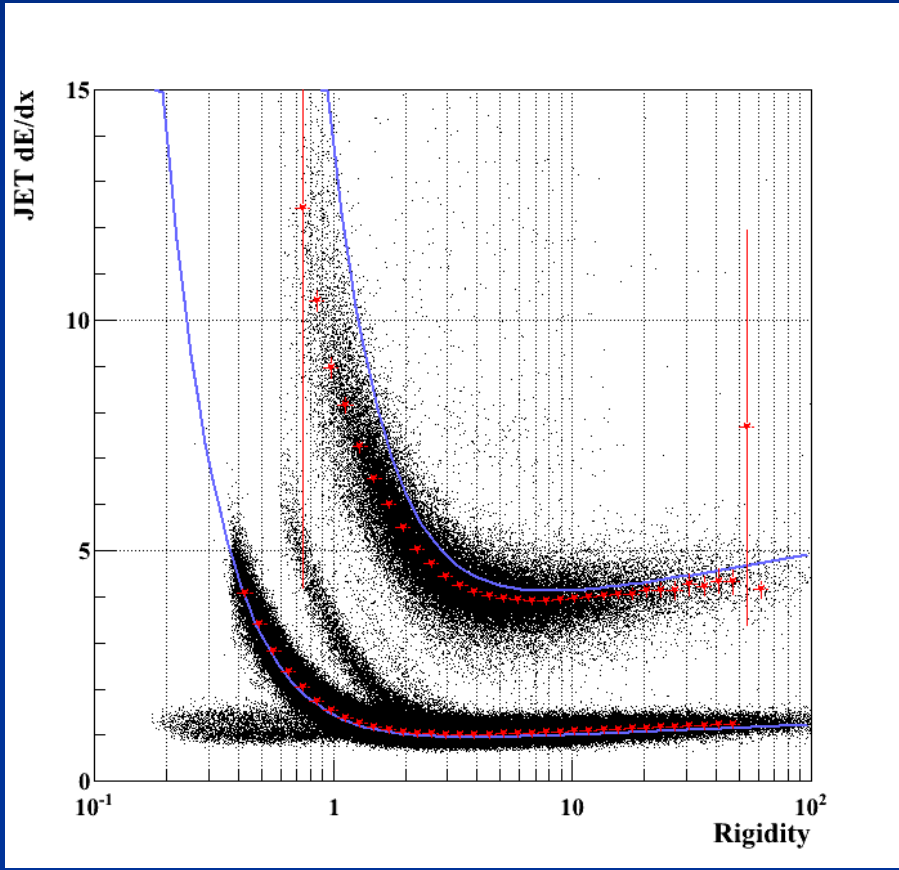
Capable detectors:
- **BESS-Polar**
- **GAPS**
- **AMS**

- **Secondary antideuteron:**
  - strongly suppressed due to strict kinematical constraint.
- **Separation from antiproton:**
  - essentially important, and
  - antiprotons would be a background.

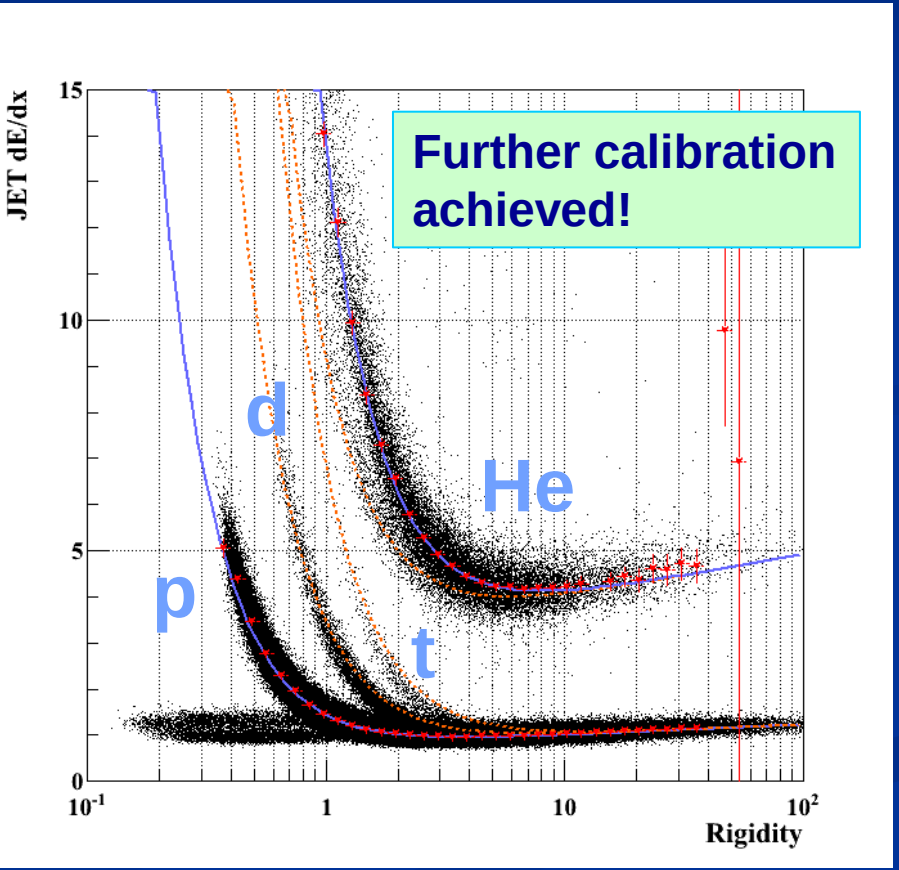
Further Data Analysis in progress

Improvement of JET (Central Tracker) dE/dx

BESS-Polar I



BESS-Polar II



BESS-Polar II p, p-bar / p ratio, and d-bar analysis, in progress

Summary

- **BESS-Polar II at Solar Minimum:**
  - Gathered cosmic-ray data with >10 times statistics to the previous solar minimum (’95 + ’97).
  - Antiproton spectrum observed is consistent with secondary antiproton calculations.
  - Result shows no evidence of primary antiprotons,
    - An evaporation rate, upper limit set: **$1.2 \times 10^{-3}/pc^3/yr$** (90% C.L.).
- **All BESS (1993 ~ 2007/8):**
  - Indicates no antihelium candidate, and
  - Sets He-bar/He upper limit **6.9×10^{-8},** and

    1×10^{-7} (with no spectrum assumption).
- **BESS Polar I and II (in analysis):**
  - Proton flux and the annual/daily time-variation.
  - Anti-deuteron search and Light-isotopes.

Acknowledgements

Our sincere thanks to:

- ***NASA-Headquarters,***
- ***NASA-Balloon Project Office and Columbia Scientific Balloon Facility,***
- ***National Science Foundation and Raytheon Polar Services Company,***
- ***NASA-GSFC, ISAS-JAXA, KEK, U-TOKYO/RESCEU,***

- ***All BESS collaborators***
  - *Special thanks to all PhD students* ***(24 PhDs since 1993)*** *for their hardest effort to bring BESS to science frontier.*