

BESS実験と宇宙線反粒子

吉村浩司 岡山大学

@物理学会秋季大会 2013.9.21

内容

- ✦ BESS気球実験
 - ✦ BESSからBESS-Polarへ
- ✦ 反陽子
- ✦ 反ヘリウム
- ✦ 現在解析中の物理
- ✦ BESS測定器の現状と今後の展望

BESS気球実験

BESSからBESS-Polarへ

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

BESS Collaboration



Institute of Space and
Astronautical Science/JAXA



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Space Administration
Goddard Space Flight Center



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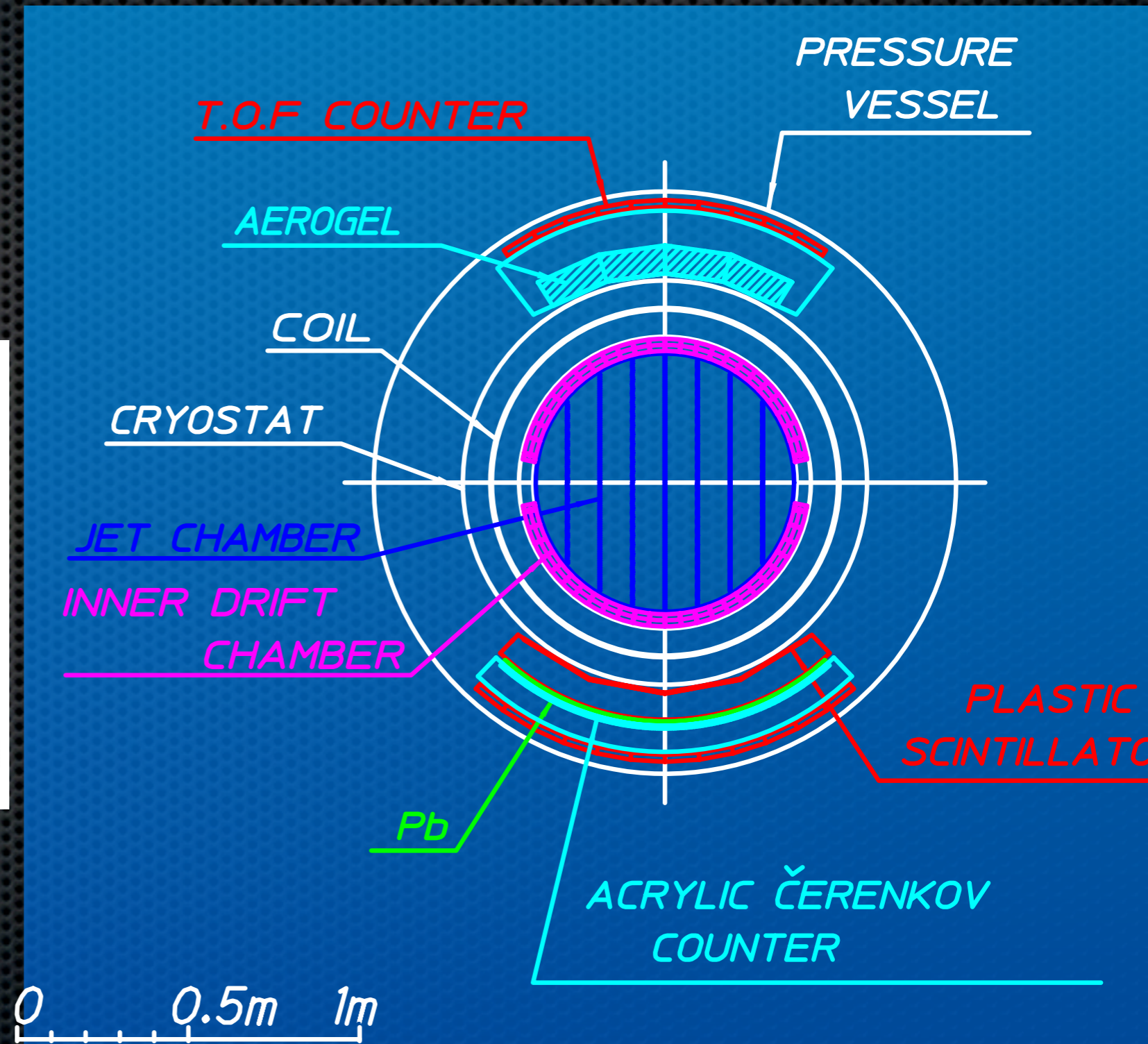
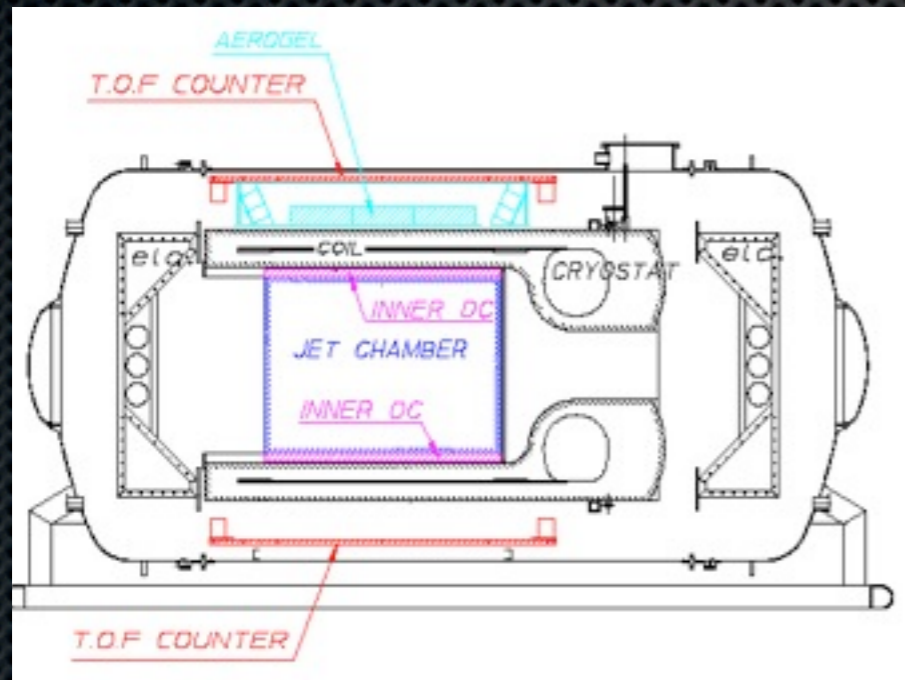


Institute of Space and
Astronautical Science/JAXA



BESS Experiment

Balloon-borne Experiment with a Superconducting Spectrometer

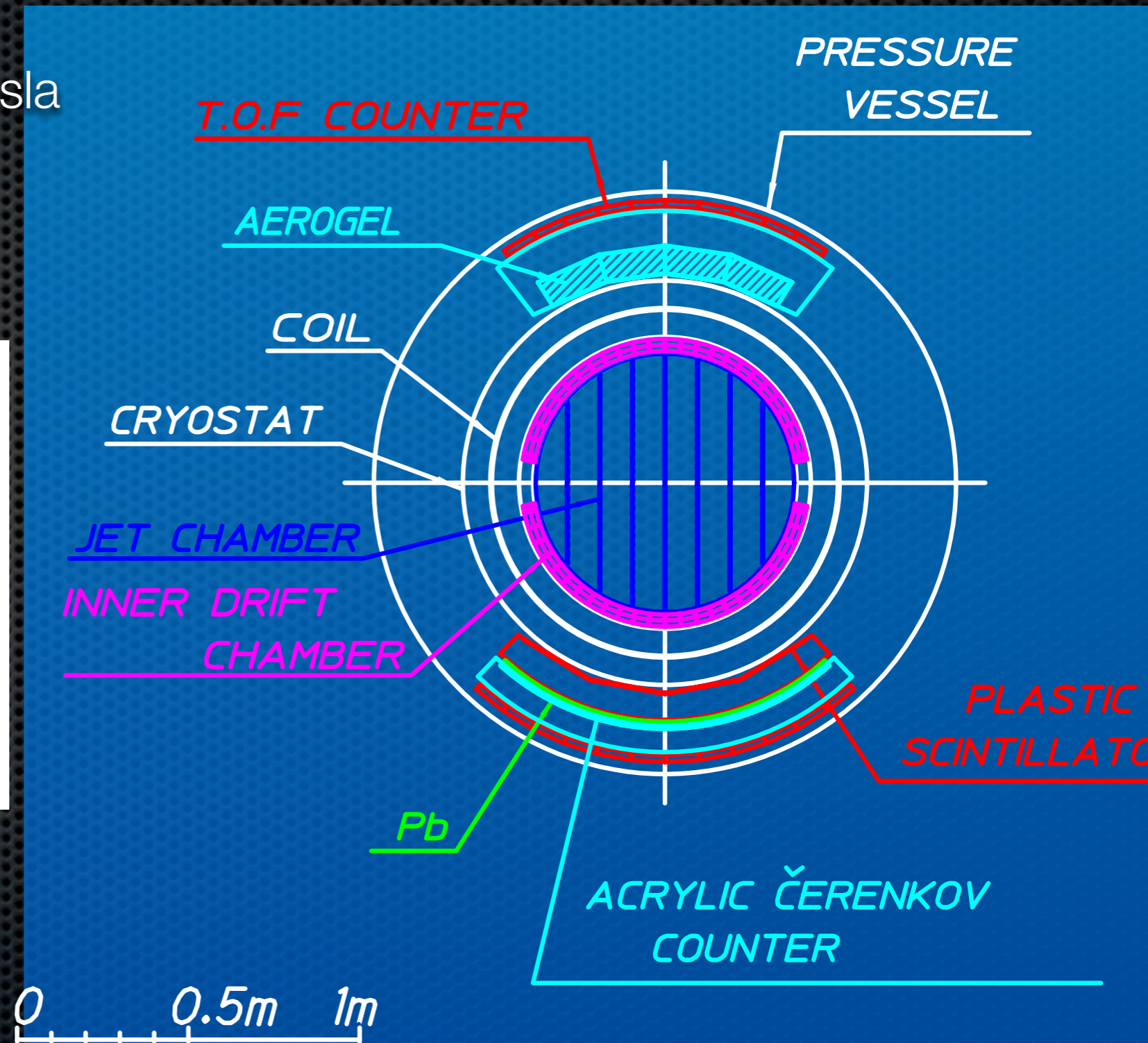
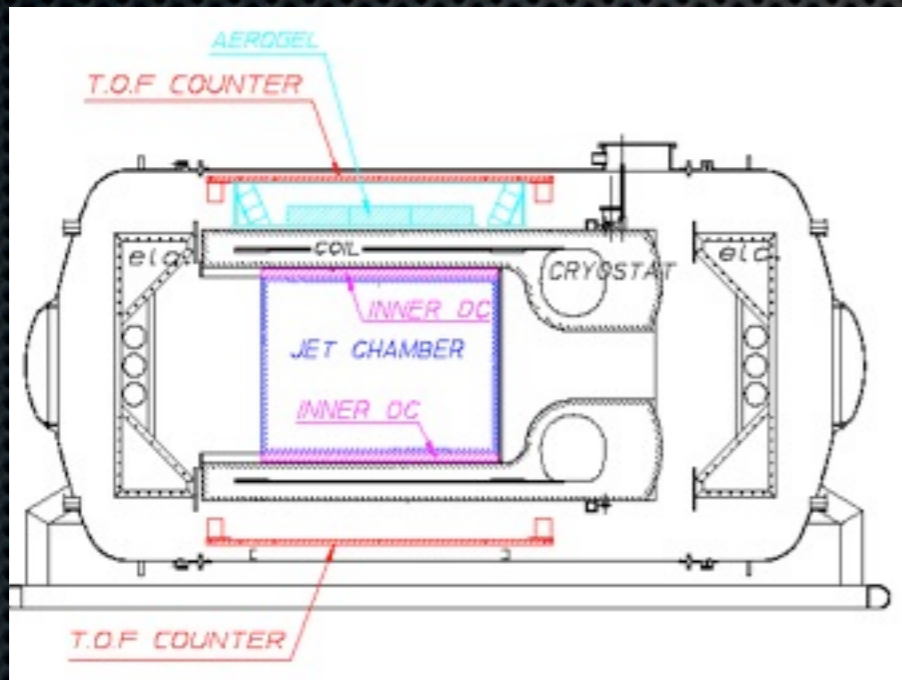


BESS Experiment

Balloon-borne Experiment with a Superconducting Spectrometer

大面積立体角

- 一様ソレノイド磁場 ~ 1 Tesla
- 同軸状配置
- $0.3 \text{ m}^2\text{sr}$ ~ 従来の100倍



BESS Experiment

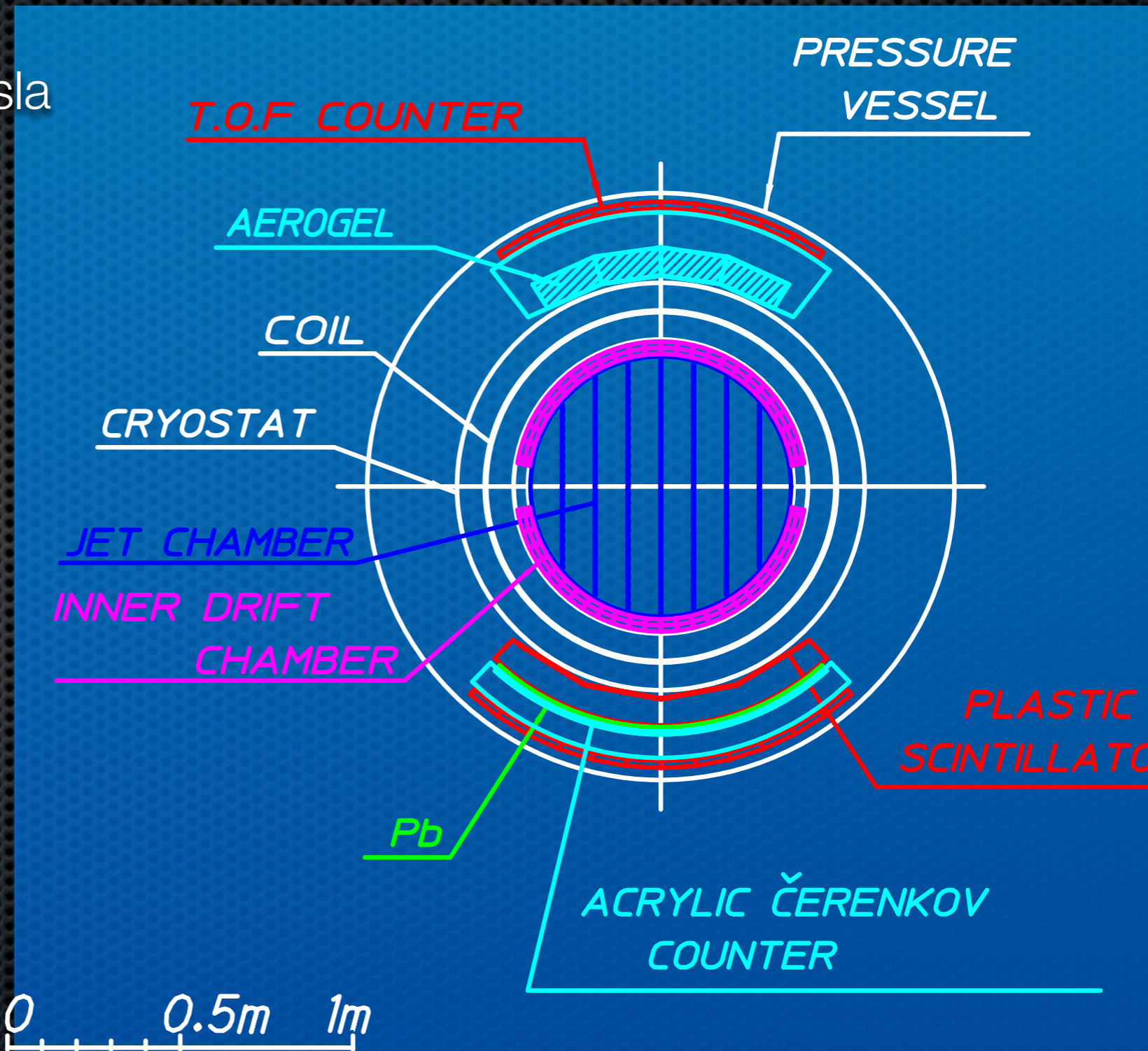
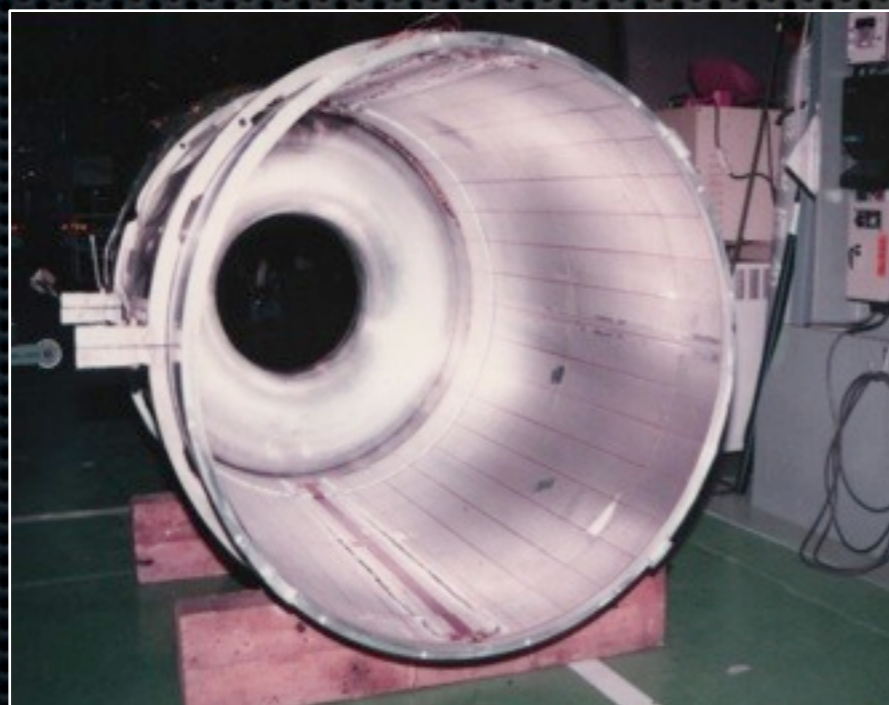
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優れた粒子透過性

- 薄肉ソレノイド $0.2 X_0/\text{wall}$



BESS Experiment

Balloon-borne Experiment with a Superconducting Spectrometer

大面積立体角

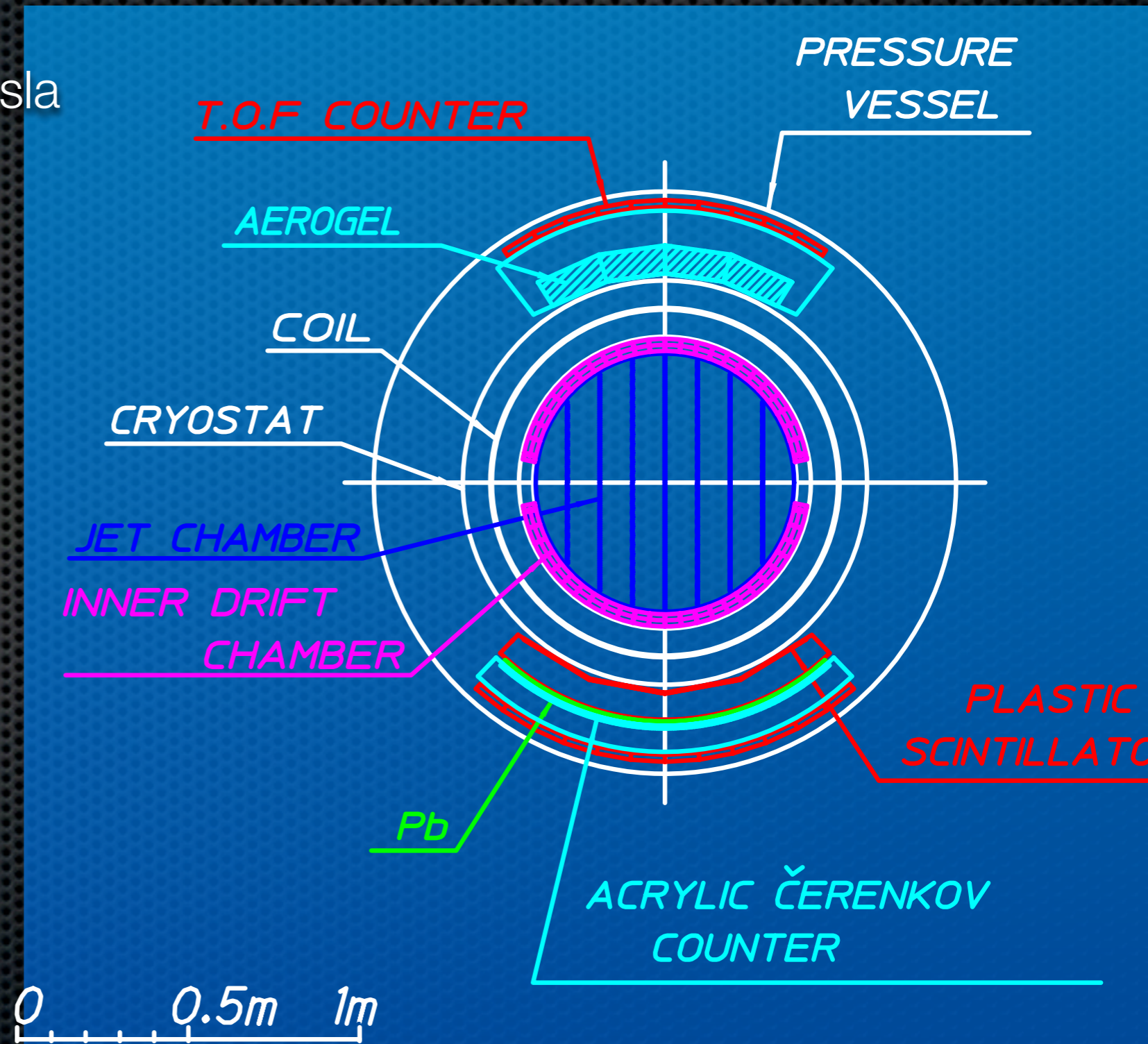
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高精度運動量測定

- 中央飛跡検出器 $\sigma=200\mu\text{m}$
- $\sim 200 \text{ GV}$



BESS Experiment

Balloon-borne Experiment with a Superconducting Spectrometer

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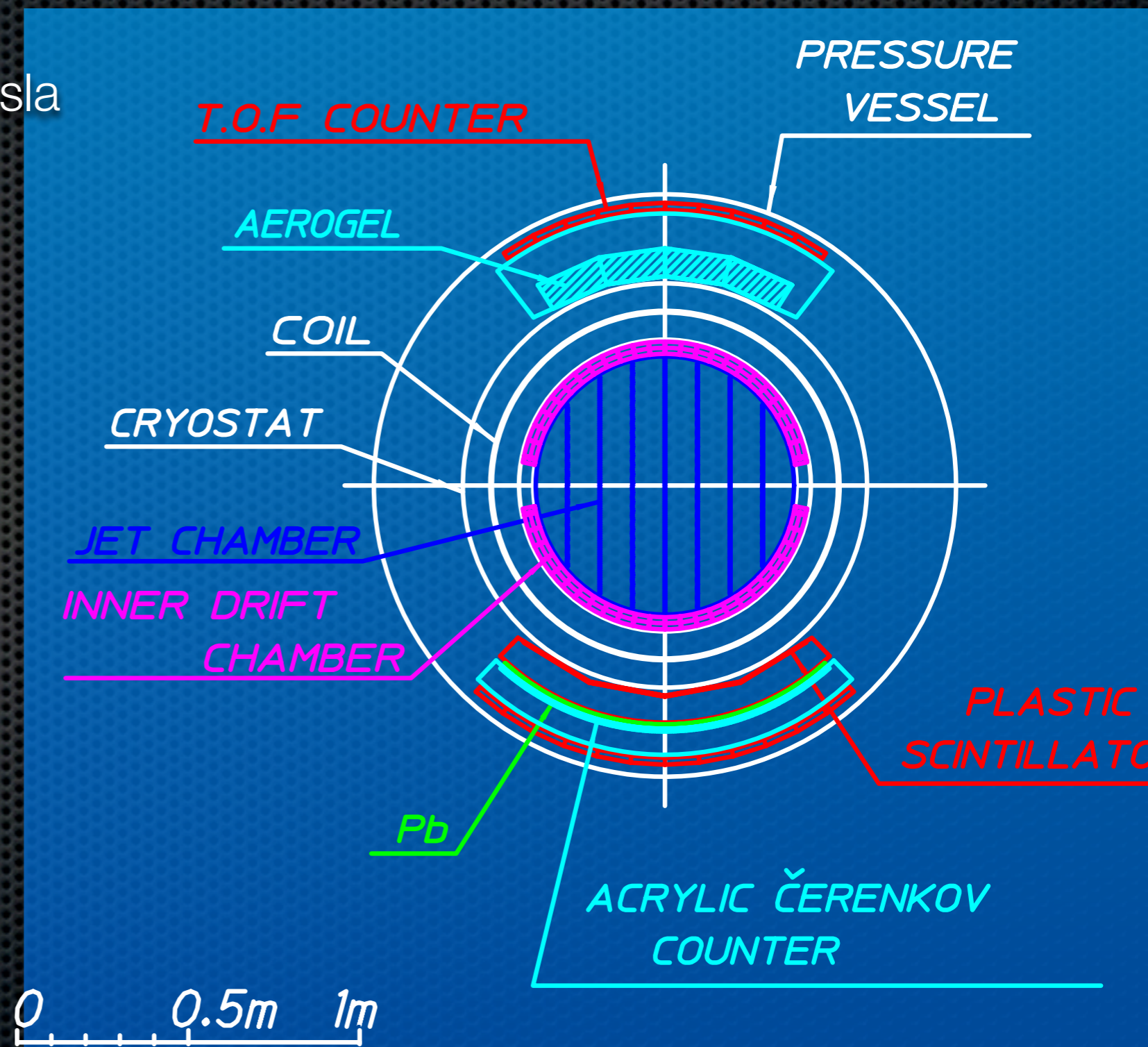
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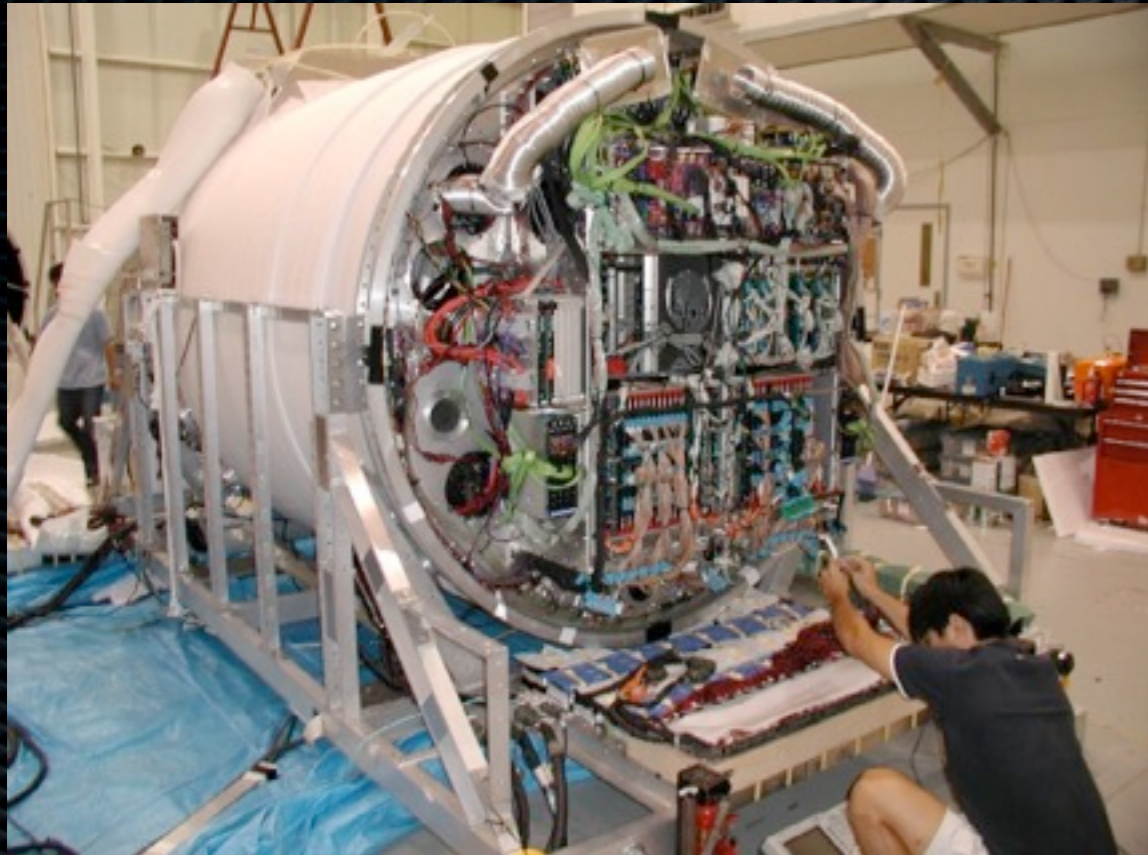
多様な粒子識別装置

- TOF ~ 50 ps
- ACC, dE/dX



BESS Experiment

Balloon-borne Experiment with a Superconducting Spectrometer



気球観測

気球高度 (37km, 1/200気圧)

直径150mの大気球

高地磁気緯度

カナダ北部で観測

低地磁気カットオフ

各種宇宙線の高精度な観測

反陽子

反ヘリウム

一次宇宙線

大気宇宙線

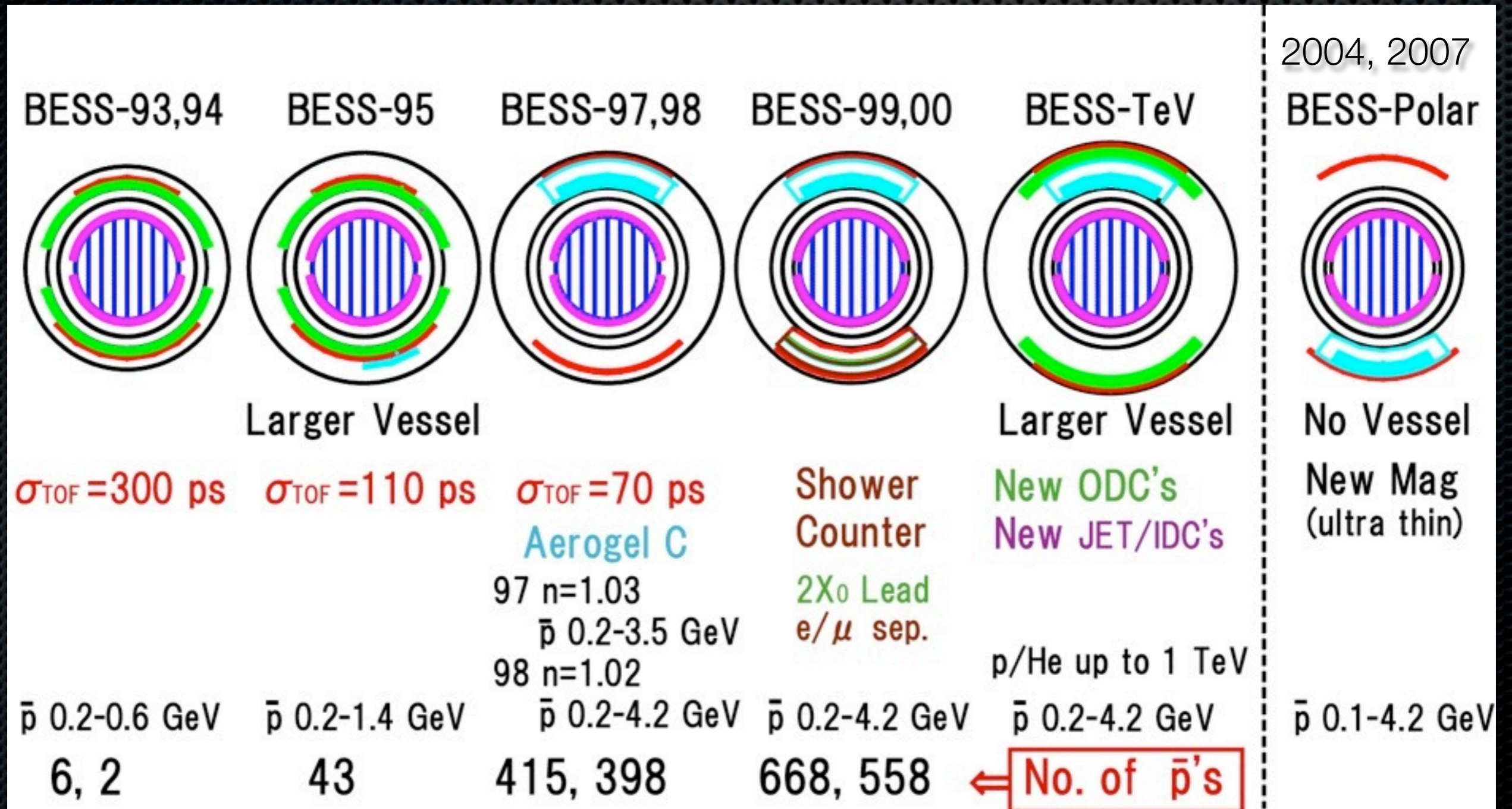
Evolution of the BESS Instrument

11 BESS Flights during 1993 ~ 2008 with improved detectors

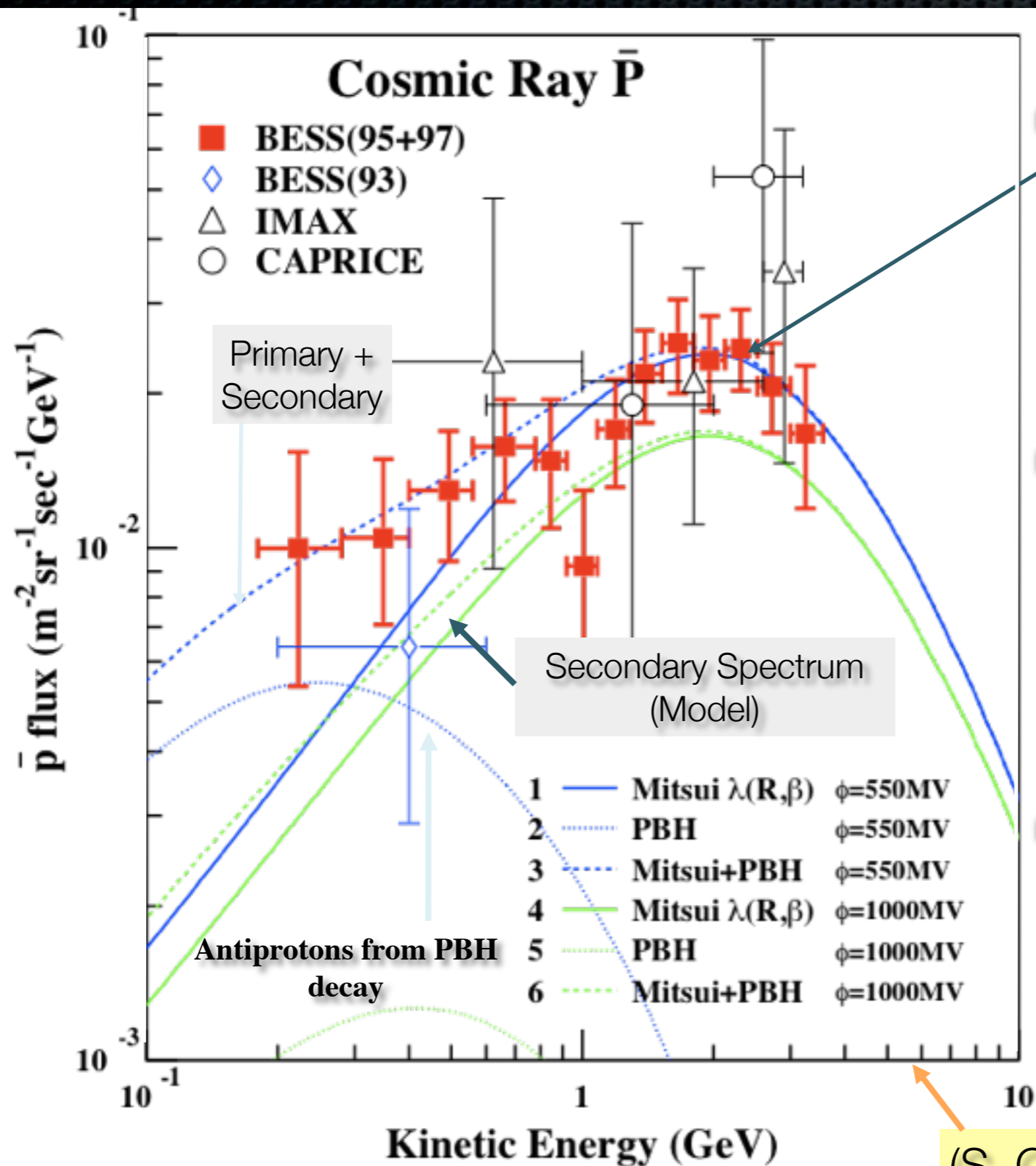
Same systematics => Directly compare

Various cosmic-ray species, Different solar modulation

2004, 2007



前々回の太陽活動極小期95+97



- 2GeV付近に特徴的なピーク
 $p + p, N \rightarrow \bar{p} + X$
 - 衝突起源の反陽子の計算値と10~15%で一致
- 低エネルギーで過剰???
 - エキゾチックなソース?
 - 一次起源?
- 長時間観測が必要
 - BESS-Polar ^ !

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

BESS-Polar 実験

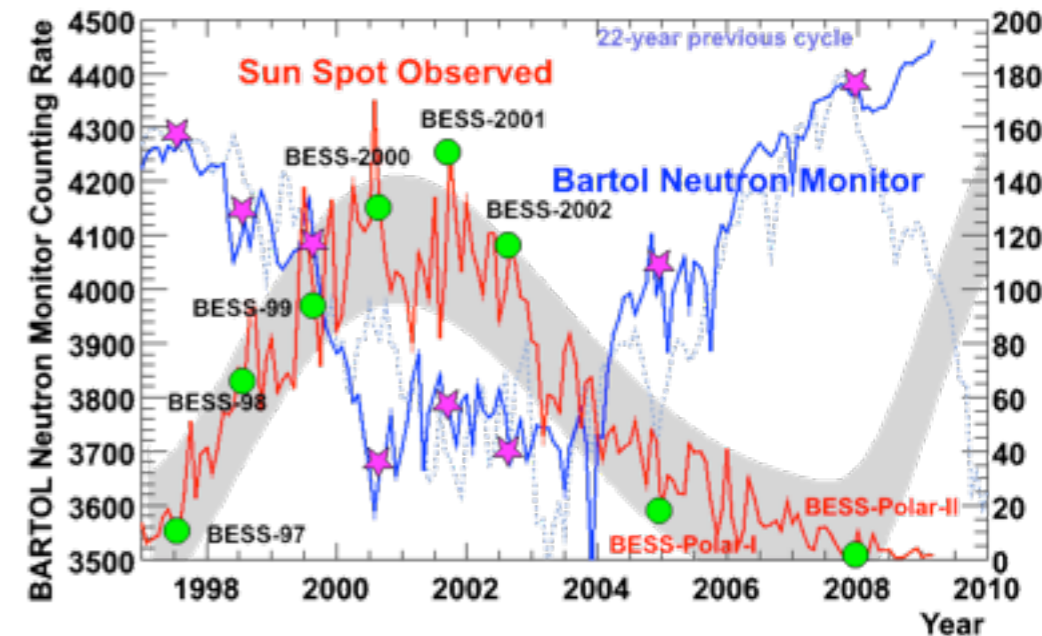
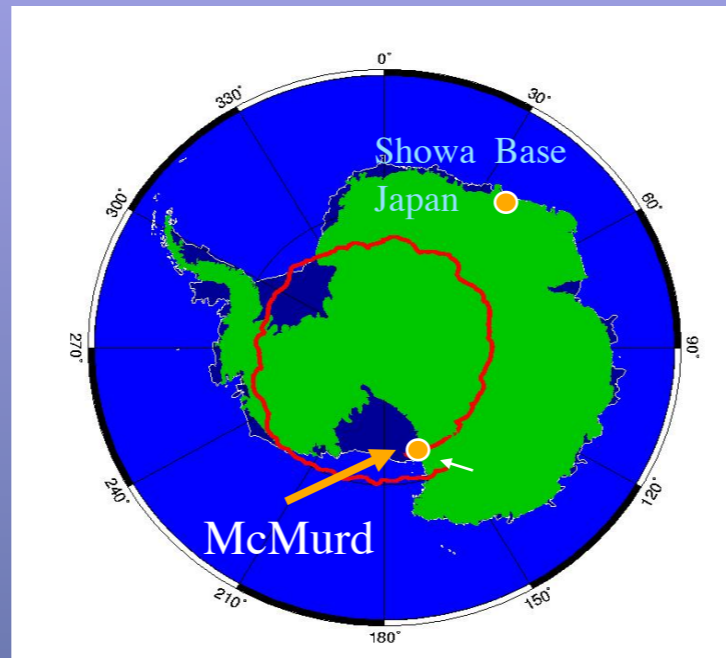
低エネルギー反陽子の超精密測定

南極周回飛行による

長時間観測

高緯度

太陽活動極小期

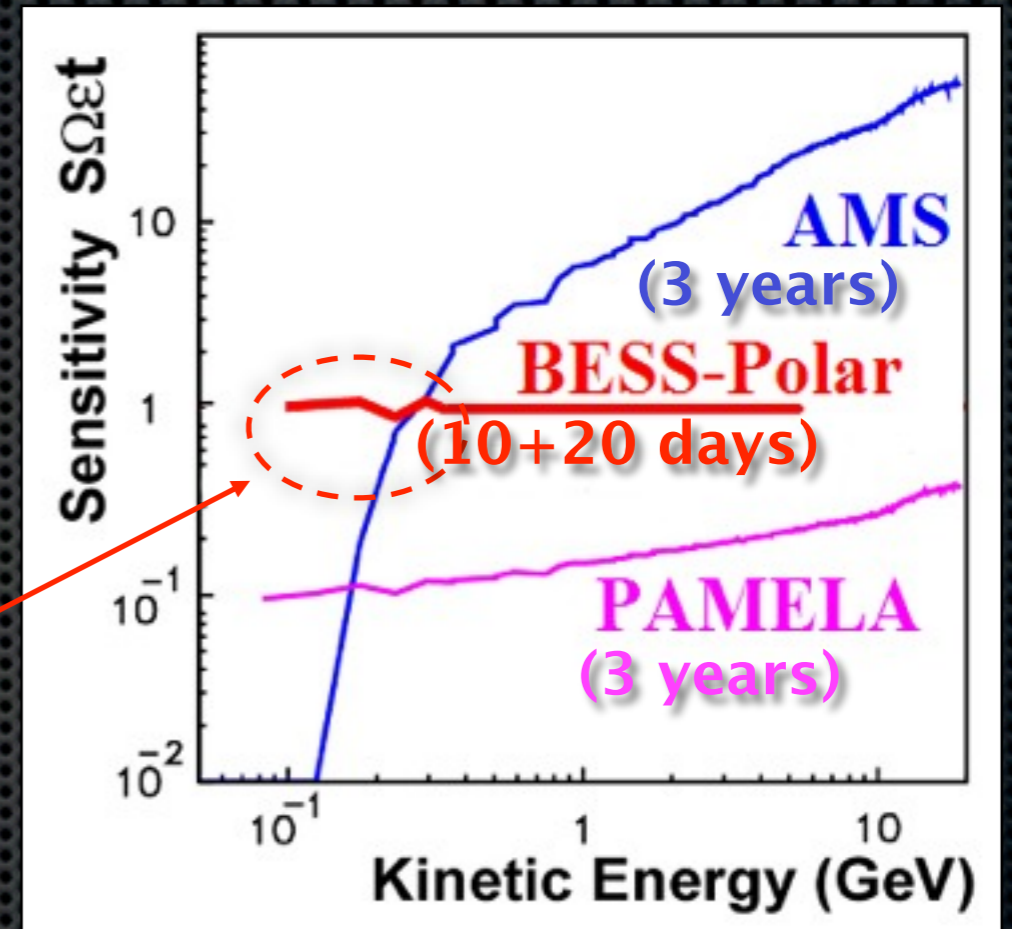
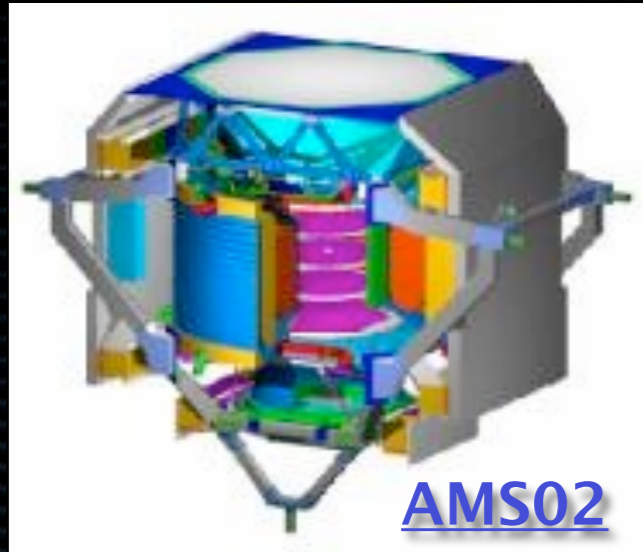


新しい測定器の開発

超薄型マグネット、太陽電池



宇宙実験との比較



BESS-Polar realize the best sensitivity in lowest energy

	Acceptance (m ² sr)	Flight Time	Latitude	Altitude (km)	Launch
AMS	0.5	3 years	< 51.7	280~500	2008
PAMELA	0.0021	3 years	<70.4	350-600	2006
BESS-Polar2	0.3	30 days	> 75	36	2007

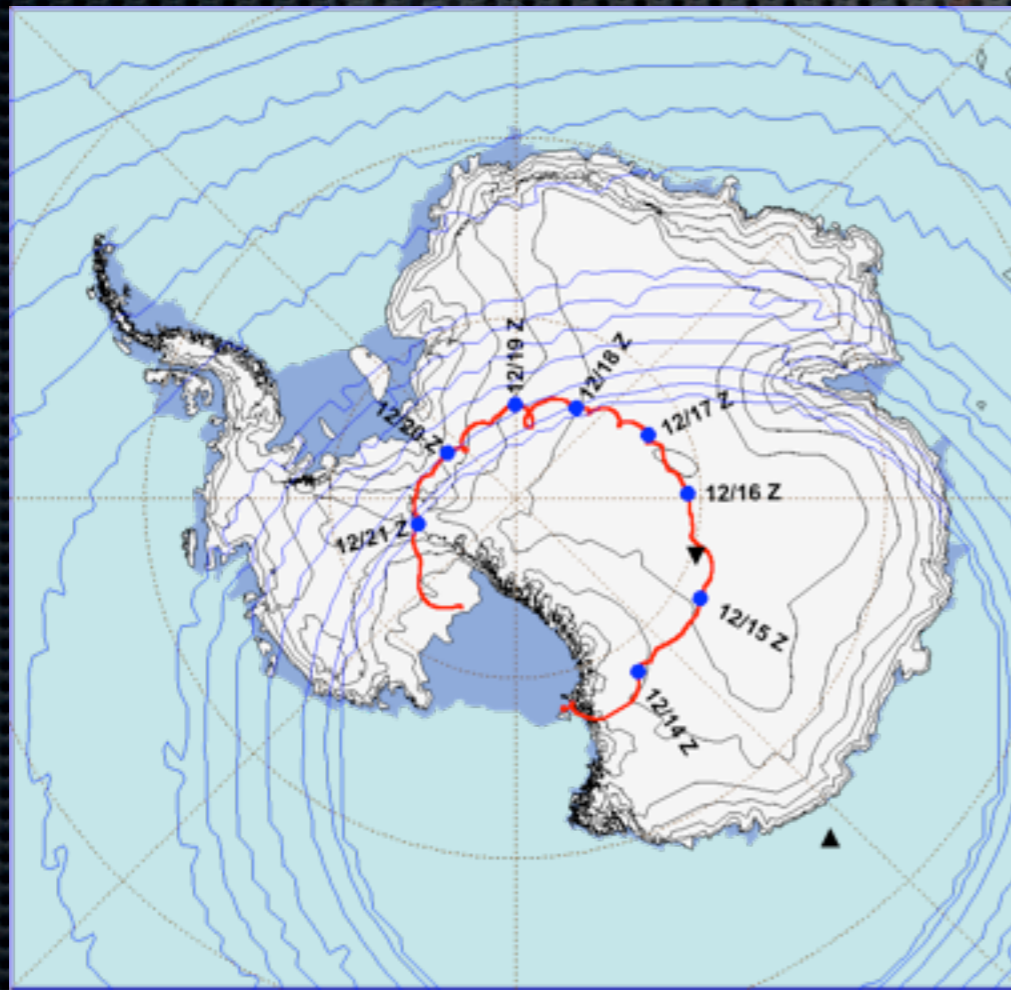
BESS-Polar



Long duration balloon flights

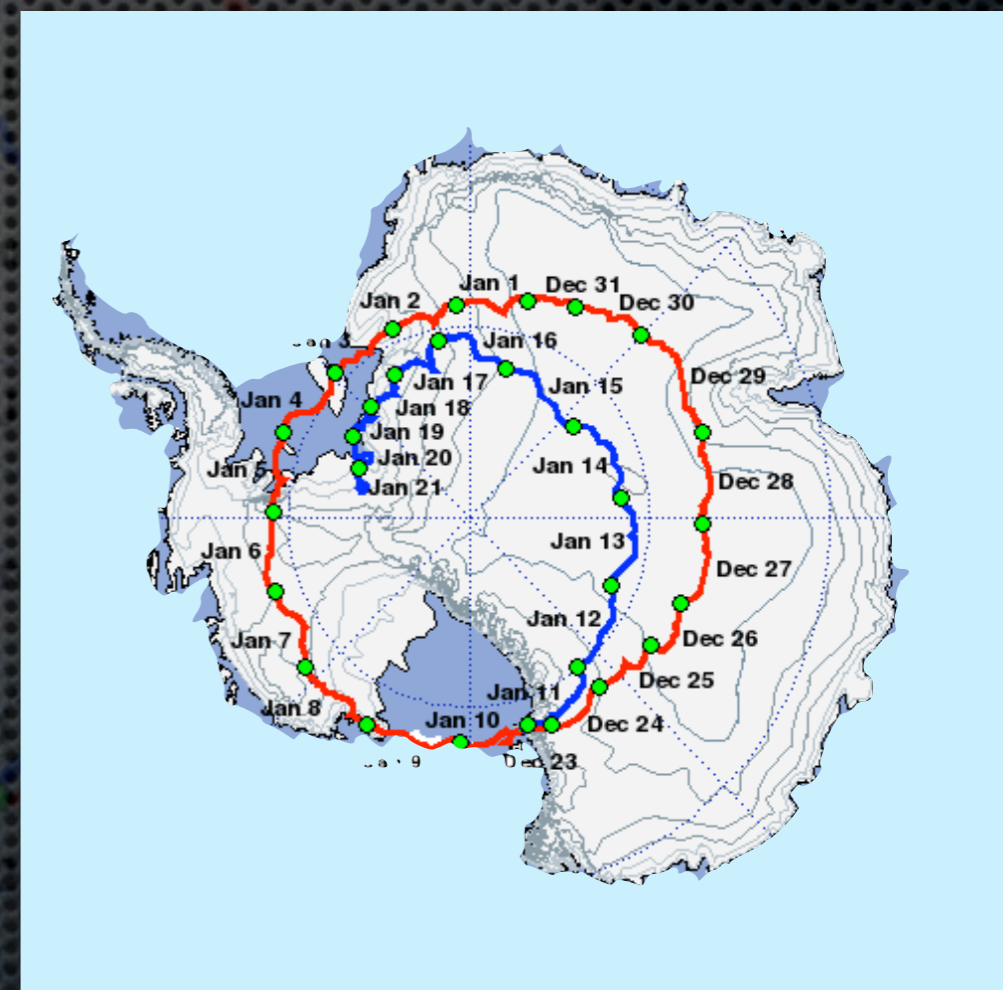
2 weeks ~ Month

New Spectrometer with a ultra thin solenoid
Solar Power system



First Flight 2004.12.13-22

8.5 days



Second Flight 2007.12.23-1.21

24.5 days

反陽子流束の測定

Based on Kenichi Sakai's Analysis
Published in PRL 108, 051102 (2012)

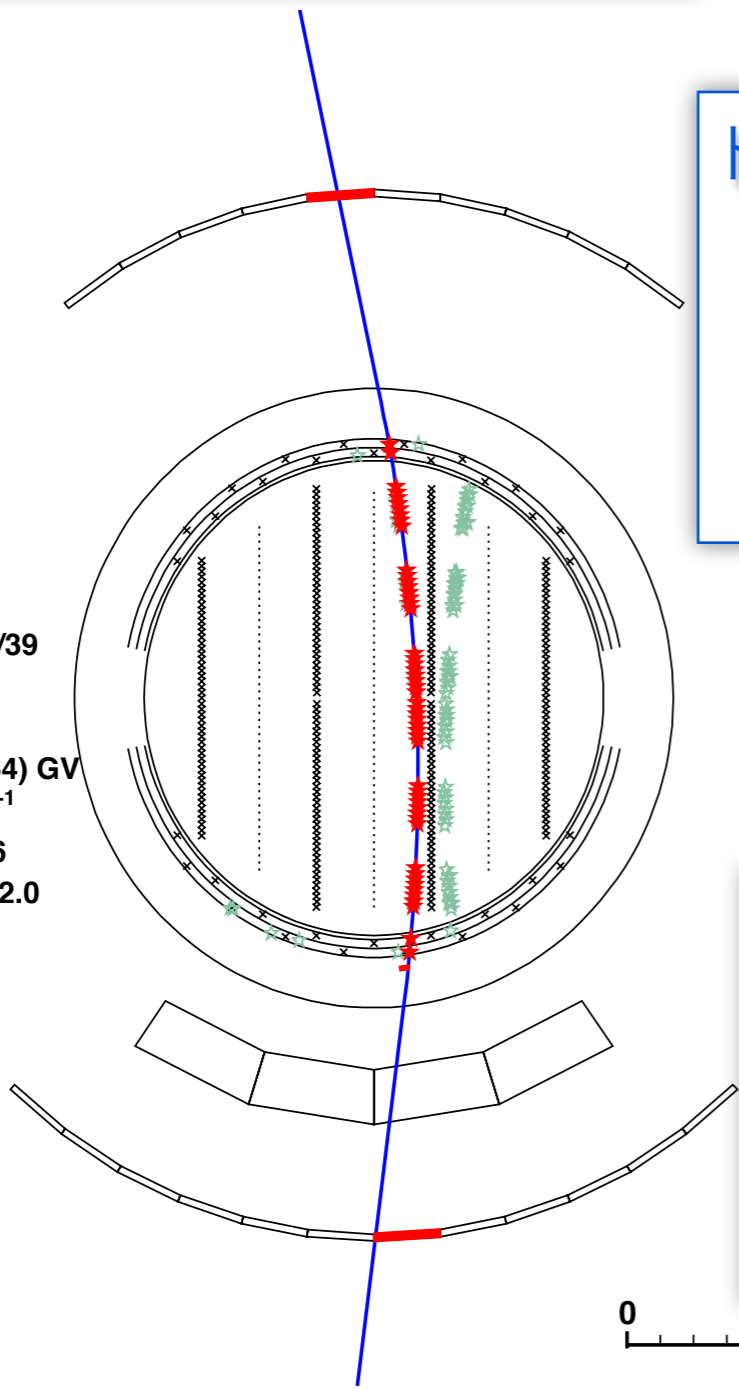
反陽子事象の選別



シングルトラック事象

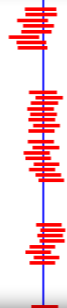
../bessp_ext.root
 e: 20.16.03.648
 2282 FEND: 904
 : 1 LTOF: 1

../bessp_ext.root
 Event Time: 20.16.03.648
 Run: 1112 Event: 2759685 (61) Size: 3235 FADC: 2282 FEND: 904
 Trigger: 001001011 JET: 66 IDC: 5 UTOF: 1 MTOF: 1 LTOF: 1

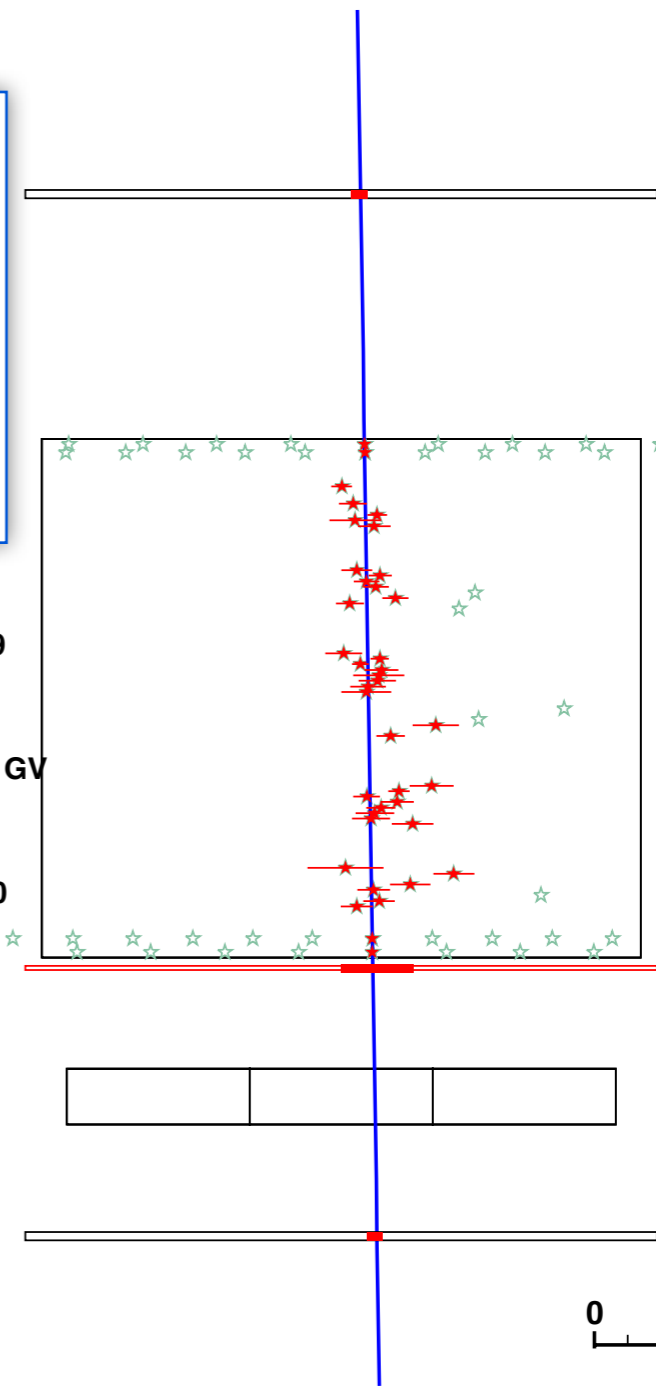


Nhit: 48(48)/4(4)/39
 Nshd: 48
 χ^2 : 0.26/2.09
 RGT: -0.64 (-0.64) GV
 $\sigma_{1/R}$: 0.0051 GV⁻¹
 1/ β : 1.781/1.736
 dE: 2.5/2.5/2.5/2.0
 Agel: 116.1

トラックオリティ
 Max52点のヒット
 Nhit, χ^2 ,
 TOFとのマッチング



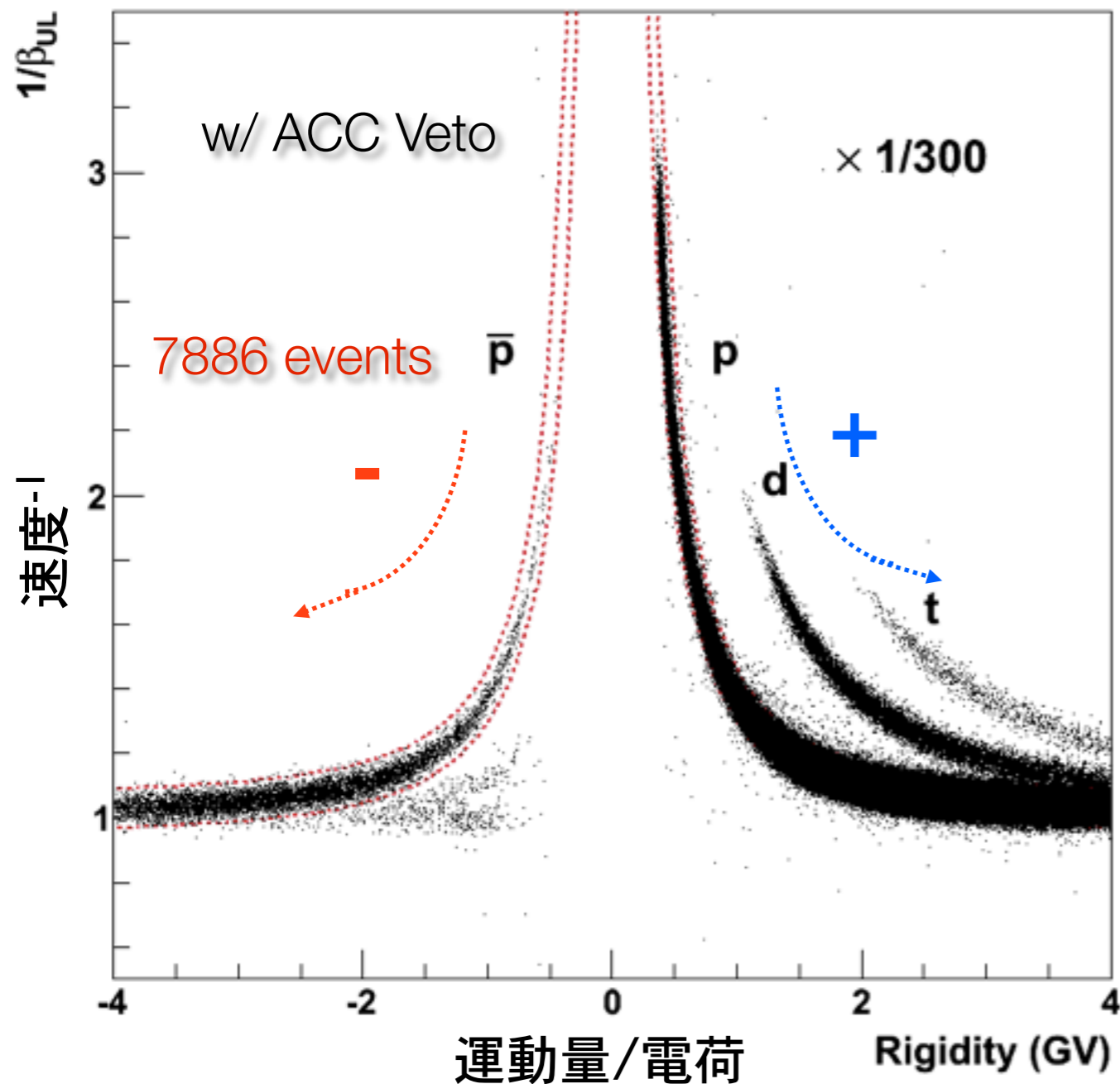
粒子識別
 TOF
 dE/dX
 ACC Veto



Nhit: 48(48)/4(4)/39
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 5/2.5/2.5/2.0
 6.1



粒子識別



$$m^2 = R^2 e^2 Z^2 (\beta^{-2} - 1)$$

質量同定という
確実な方法により
7886例の反陽子観測

反陽子流束

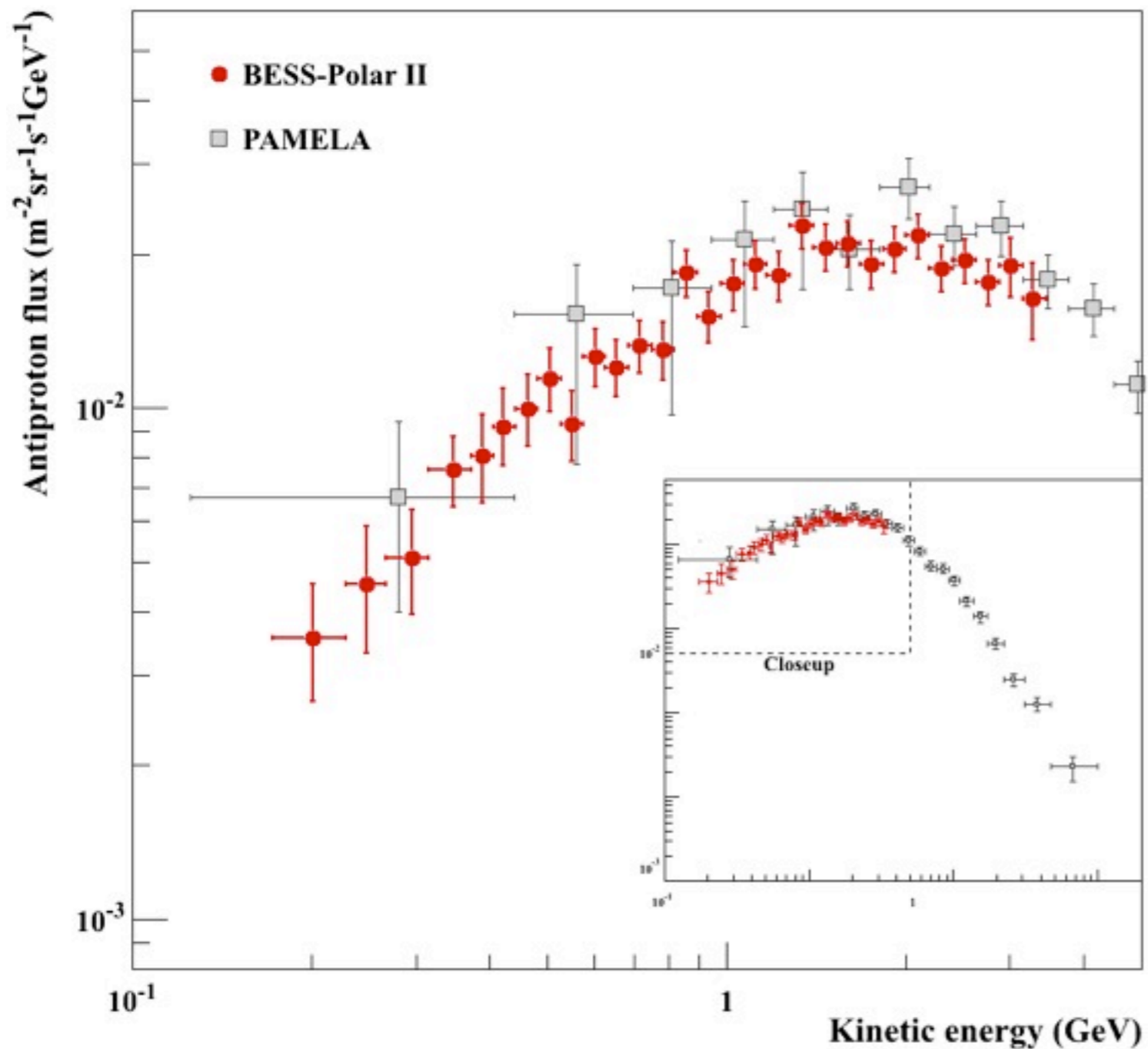


PAMELA実験との比較

低エネルギー領域では
10%~20%の統計誤差で一致

28倍の統計量

PAMELA (2006.6~2008.12)



理論計算との比較



様々な宇宙線伝播モデルとの比較

モデルによる違い

宇宙線伝播 (SLB, Diffusion)

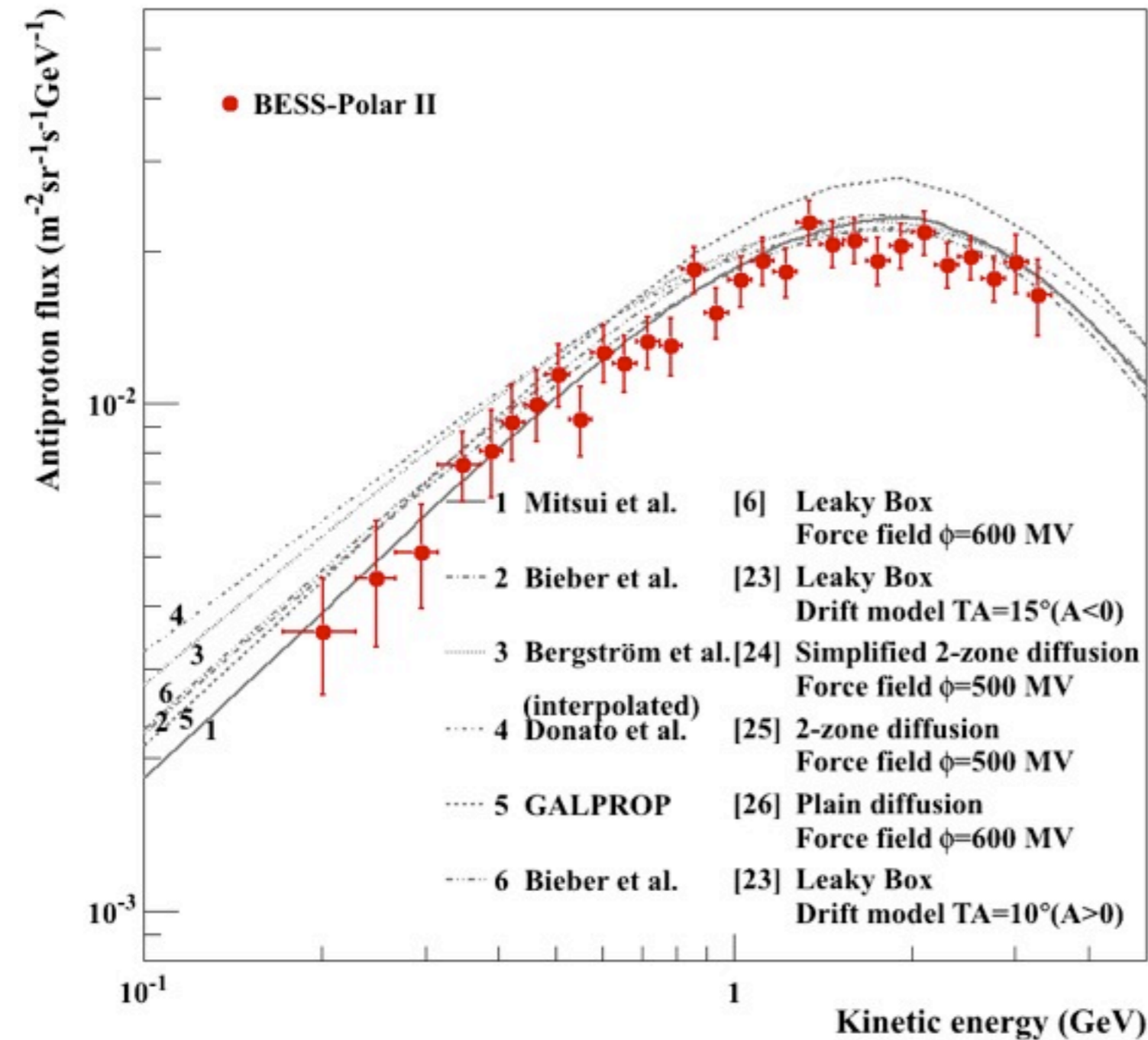
太陽変調 (FF, Drift model)

Interaction (Tertiary)

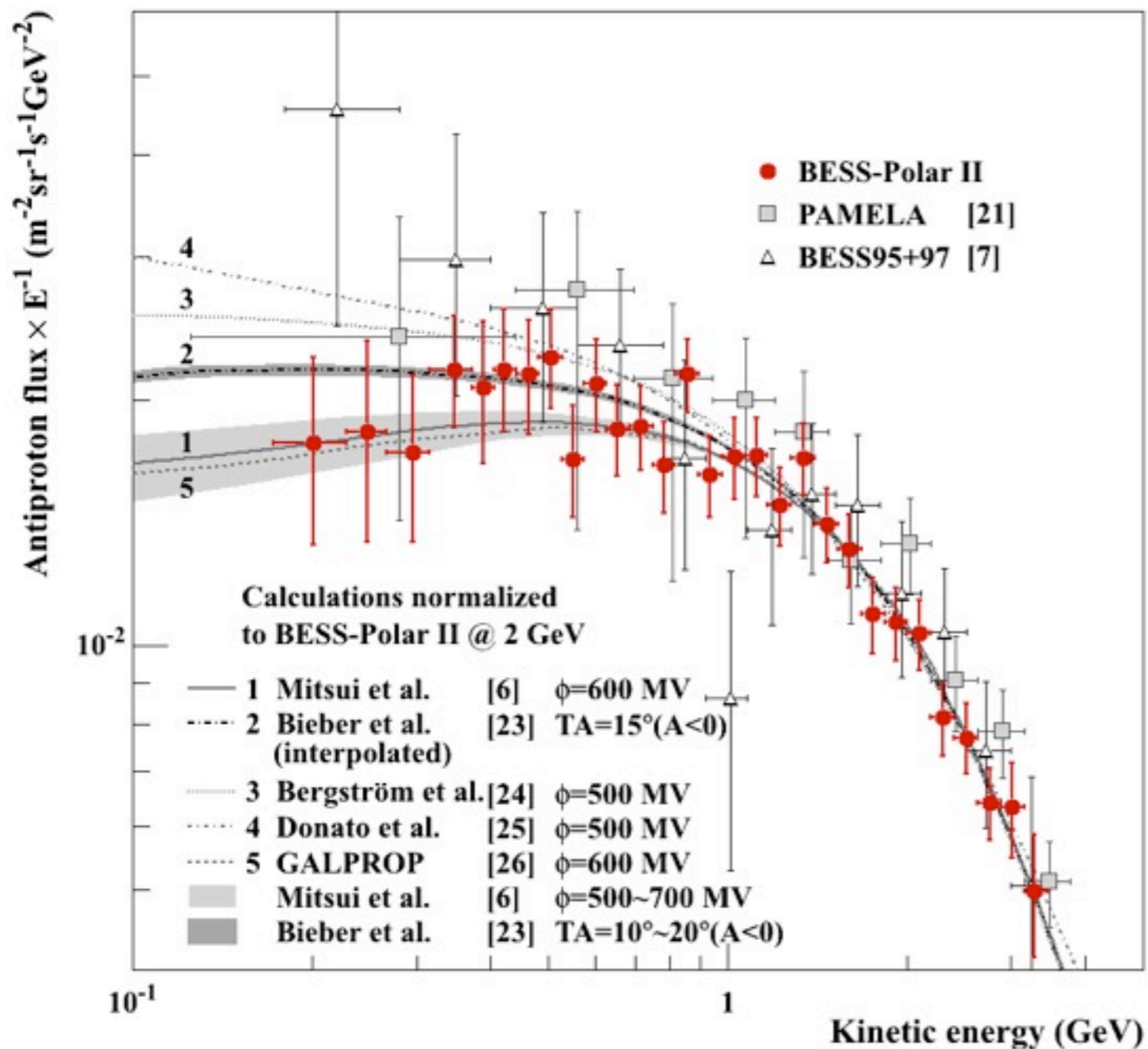
Good consistency

within 20%

非常に良くデータと一致
(~20%)



スペクトル形状

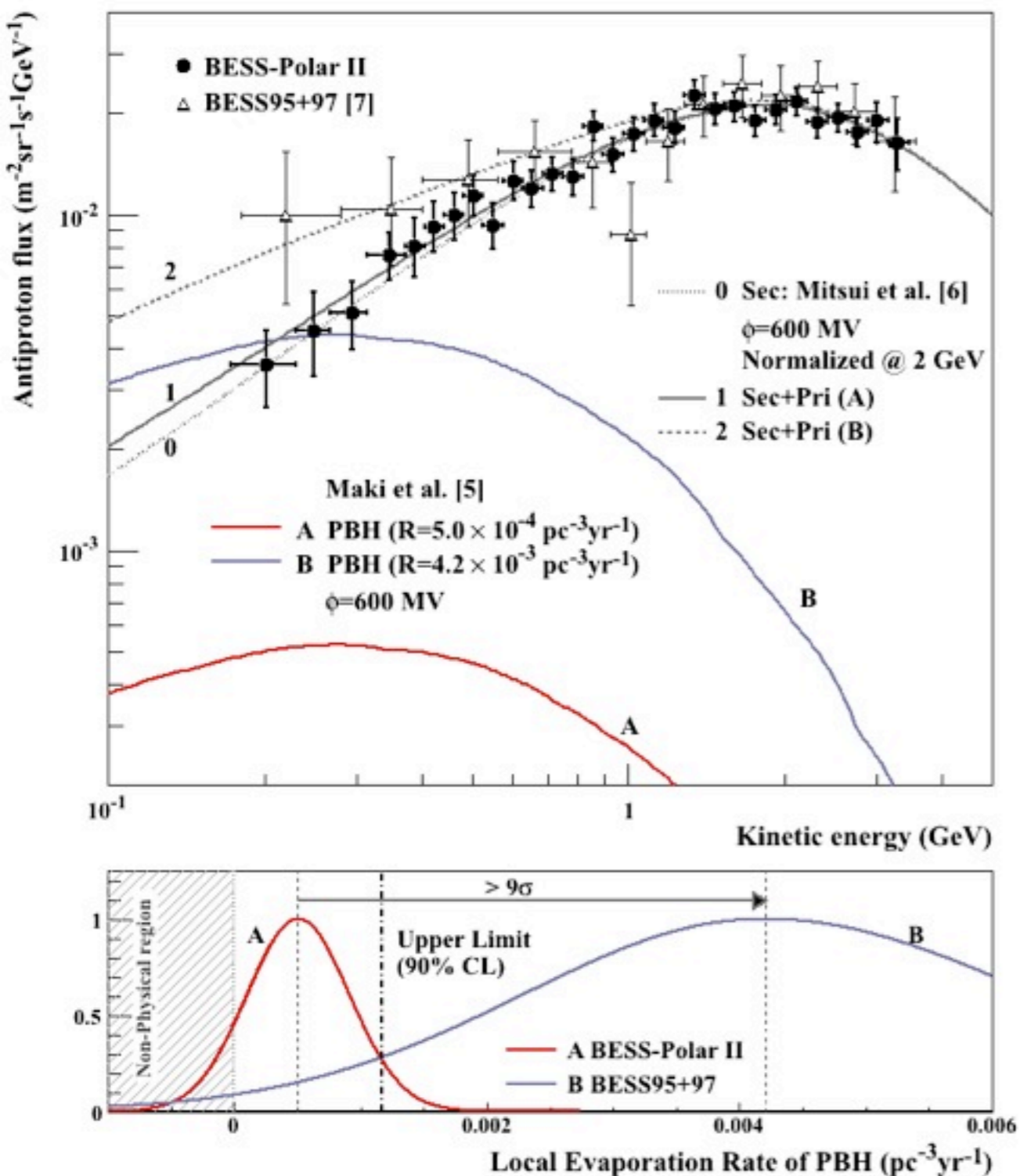


To see the relative spectral variations, calculated energy spectra are normalized at the peak.

ID	Model	χ^2
1	Mitsui	0.57
2	Bieber	0.56
3	Bergstrom	1.24
4	Donato	1.59
5	Galprop(PD)	0.63

Model w/o low energy enhancement (1,2,5) were favored.

一次起源反陽子 (原始BH)



Evaluation for evaporation rate of PBH (R).

Observation (Polar II or BESS95+97) subtracted by Secondary (Mitsui)

Evaporation rate which could explain antiproton flux in BESS'95+'97 was not observed.

Excluded by $> 9\sigma$

Upper limit

$1.2 \times 10^{-3}/pc^3/yr$ (90% C.L.)

反へリウム探索

Based on Makoto Sasaki's Analysis
Published in PRL 108, 131301 (2012)

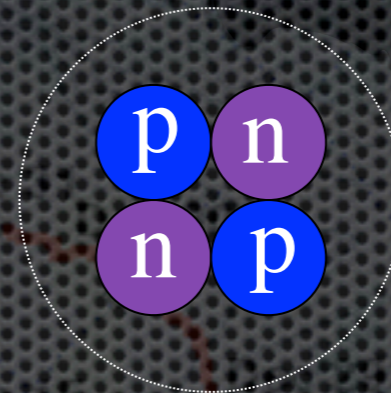
反ヘリウム



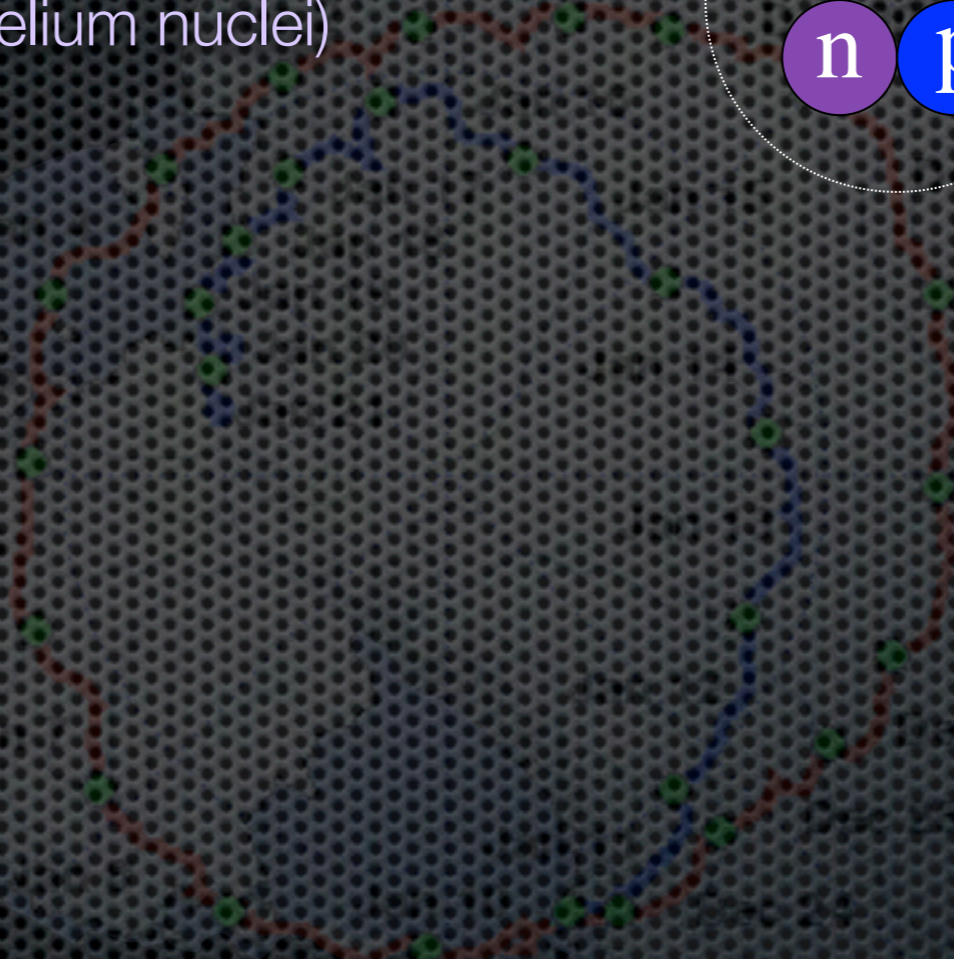
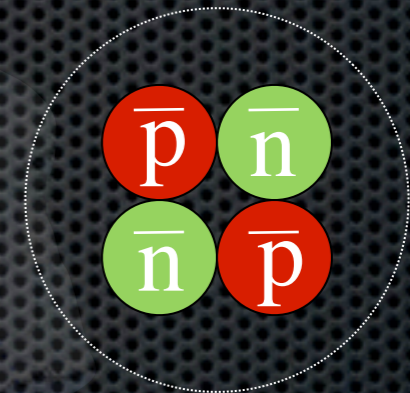
物質/反物質対称性の破れ?

Signal of antihelium is quite distinctive
(i.e. negatively charged Helium nuclei)

He



$\overline{\text{He}}$



反ヘリウム



物質/反物質対称性の破れ?

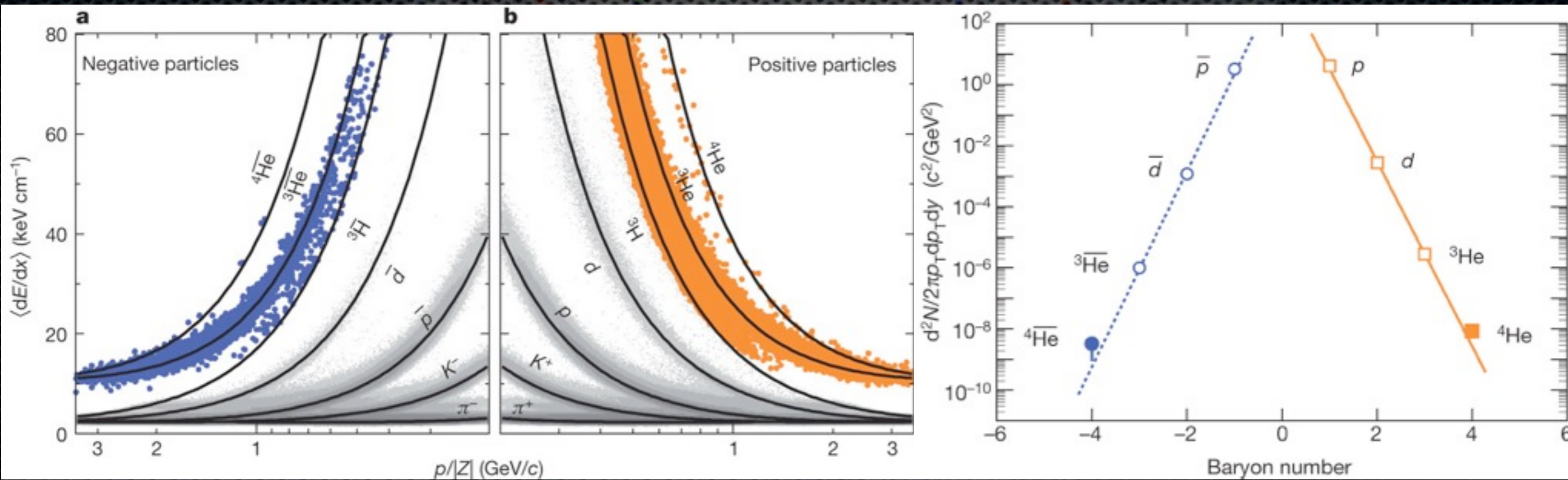
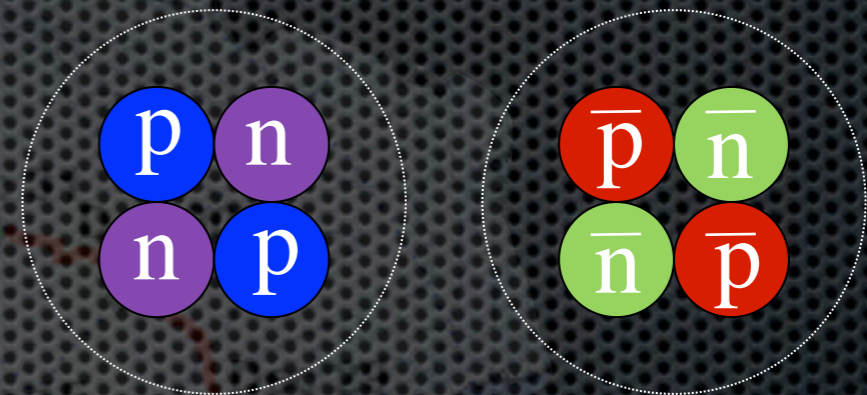
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Production in the collision is extremely small.

Antihelium4 were found in RHIC very recently !

He

$\bar{\text{He}}$



Star collaboration, Nature 10079, 2011

反ヘリウム



物質/反物質対称性の破れ?

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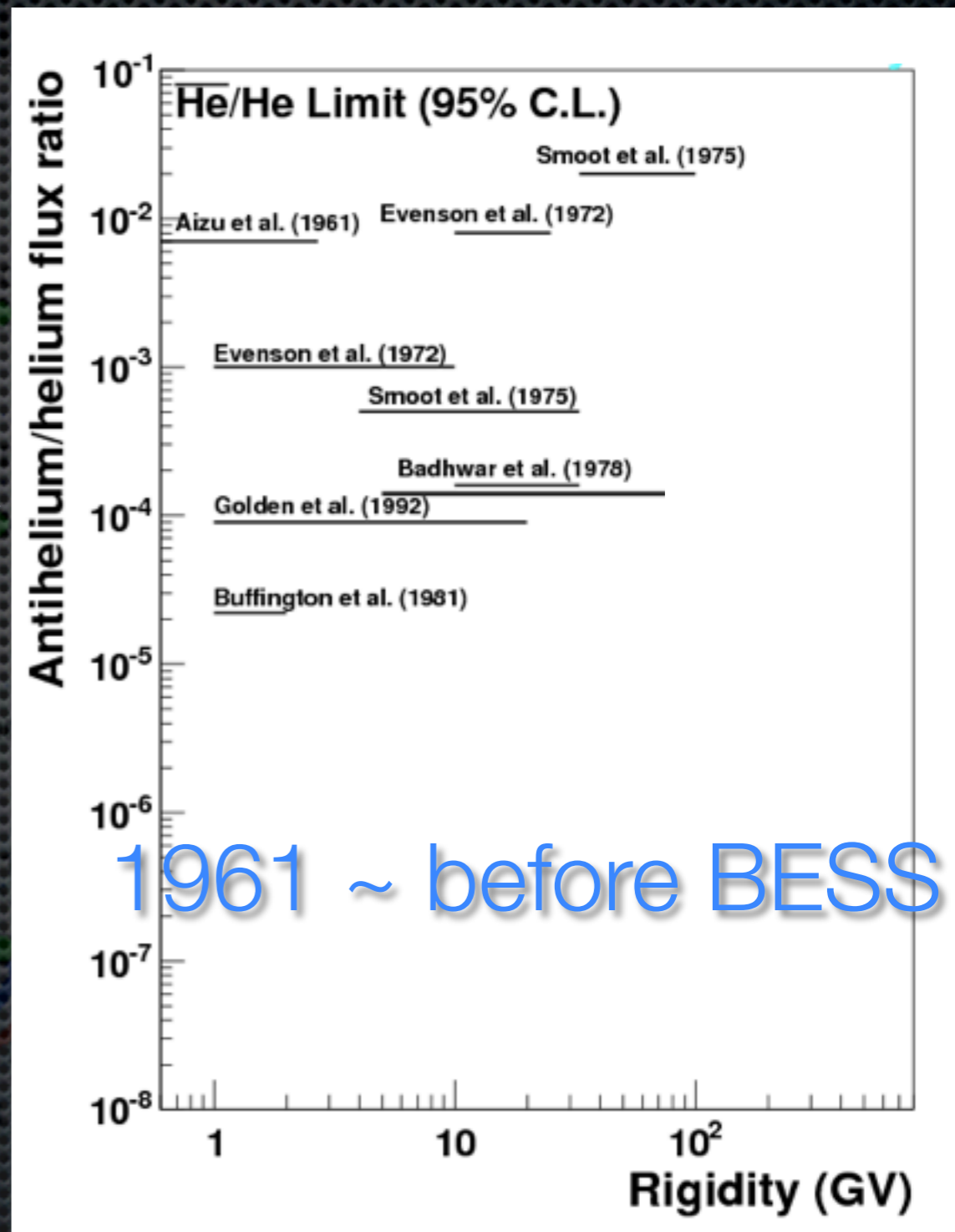
(i.e. negatively charged Helium nuclei)

Production in the collision is extremely small.

Antihelium4 were found in RHIC very recently

No antihelium was observed in cosmic ray

Single event could be a direct evidence of existence of antimatter domain.



同定 (反)へリウム



Clear event signature

$|Z| = 2$ (Charge)

dE/dX by Upper and Lower TOF

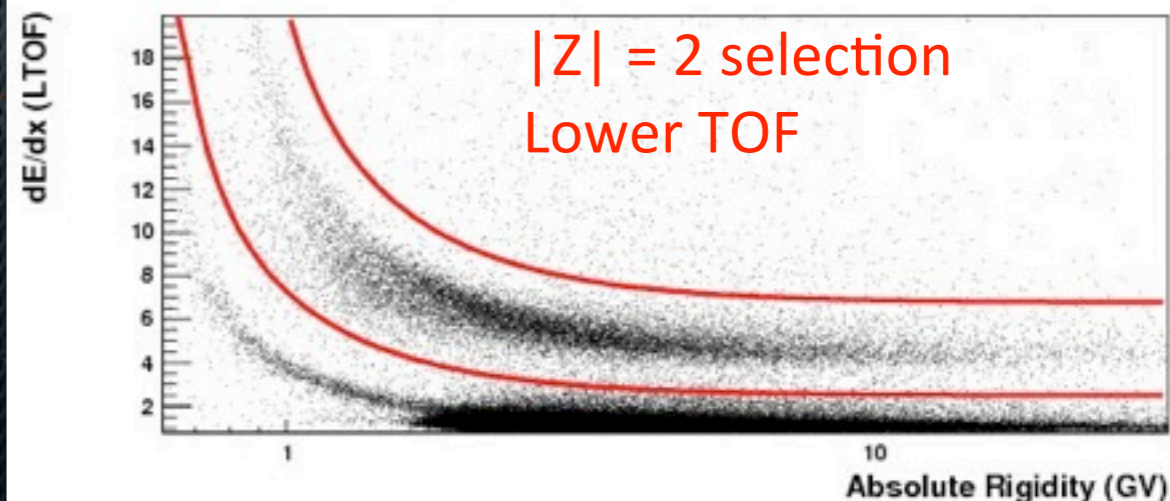
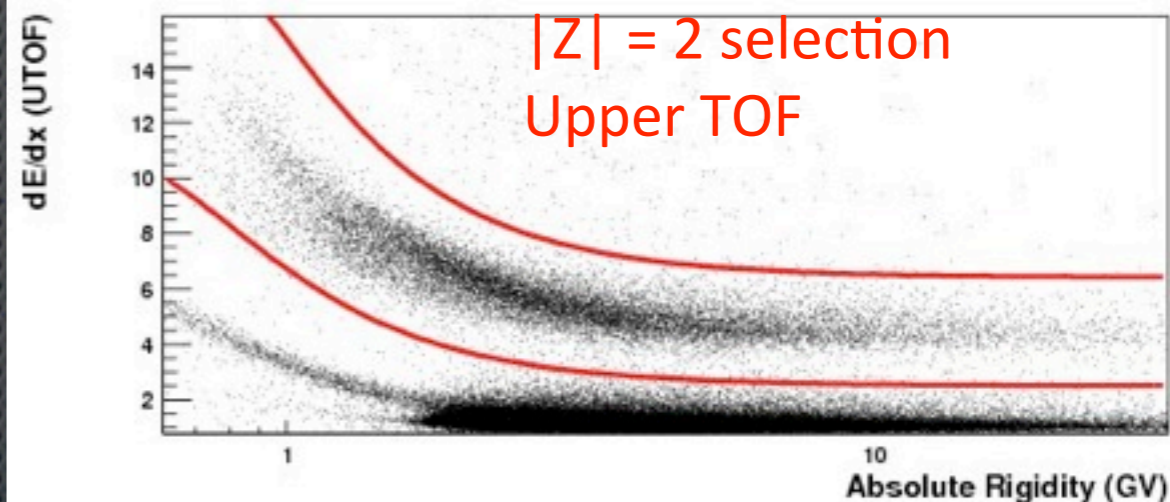
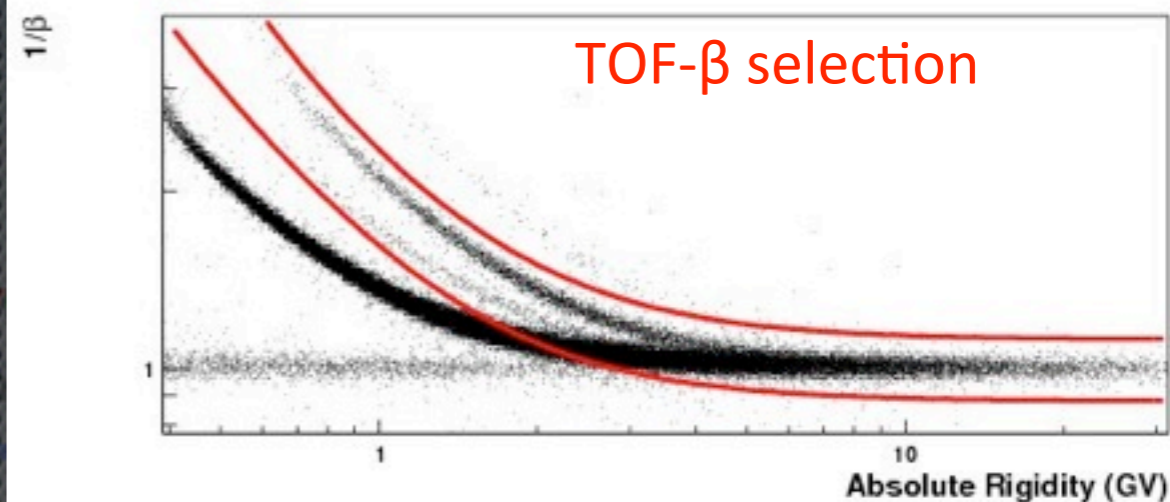
PID with $1/\beta$

Separation positive/negative

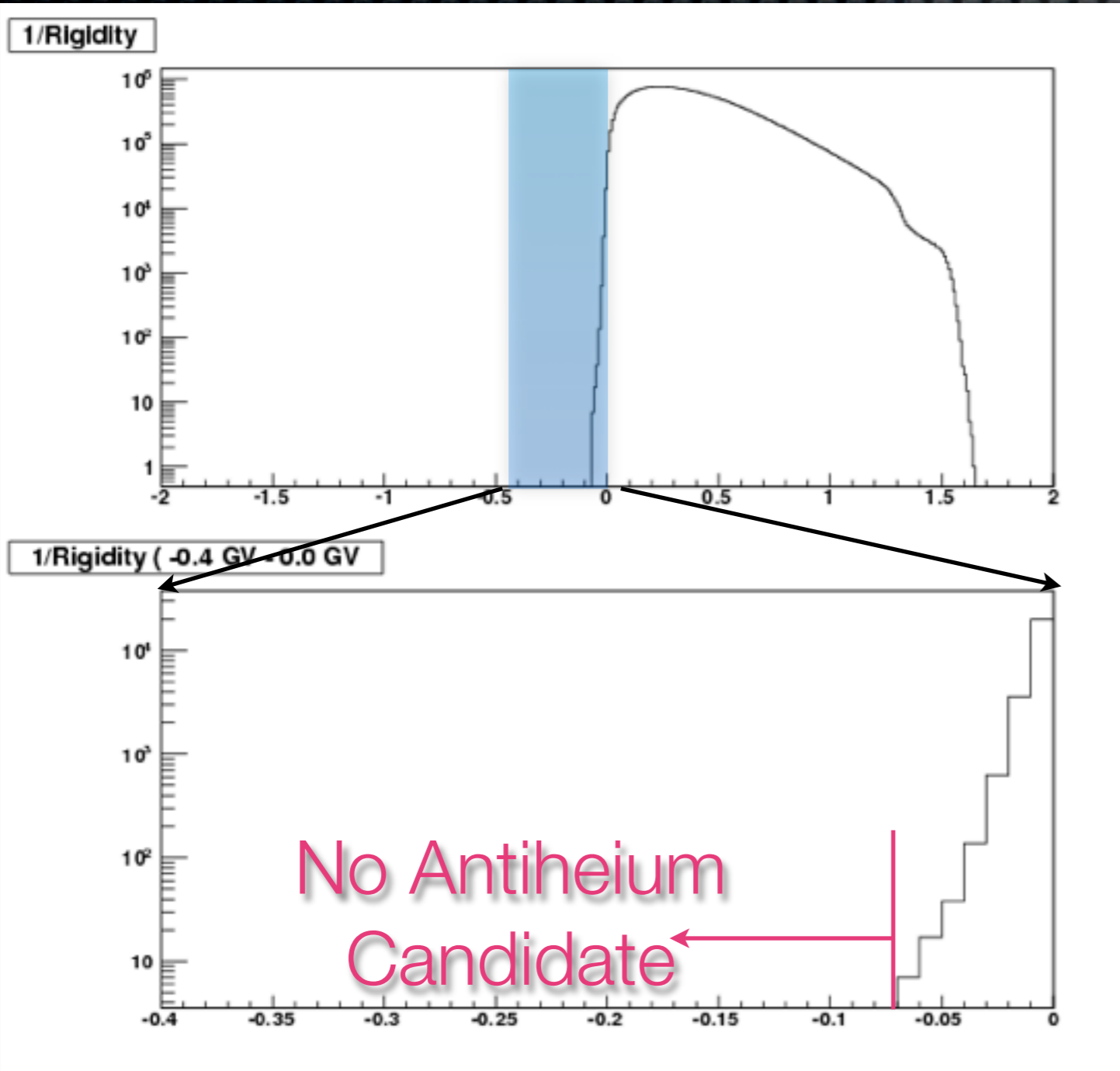
Curvature (Rigidity) measured by Tracker

Spillover from positive into negative R is unavoidable due to finite resolution of Tracking system.

Careful calibration is essential.

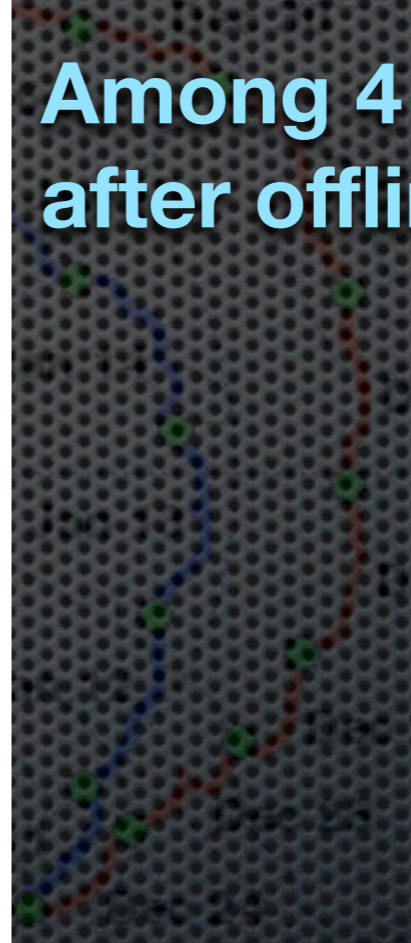


1/Rigidity for Helium ($z=2$)



No antihelium candidate was observed ($1 < R < 14$ GV)

Among 4×10^7 Helium events after offline selection.



$\bar{\text{He}}/\text{He}$ Limit



Selection efficiency for $\bar{\text{He}}$ ($\bar{\text{He}}$)

$$R_{\bar{\text{He}}/\text{He}} = \frac{3.1}{\int N_{obs} \cdot \frac{\bar{\eta}}{\eta} \cdot \frac{\bar{\epsilon}_{single}}{\epsilon_{single}} \cdot \frac{\bar{\epsilon}_{Q-ID}}{\epsilon_{Q-ID}} dE}$$

survival probability in the residual air for $\bar{\text{He}}$ ($\bar{\text{He}}$)

Single track efficiency for $\bar{\text{He}}$ ($\bar{\text{He}}$)

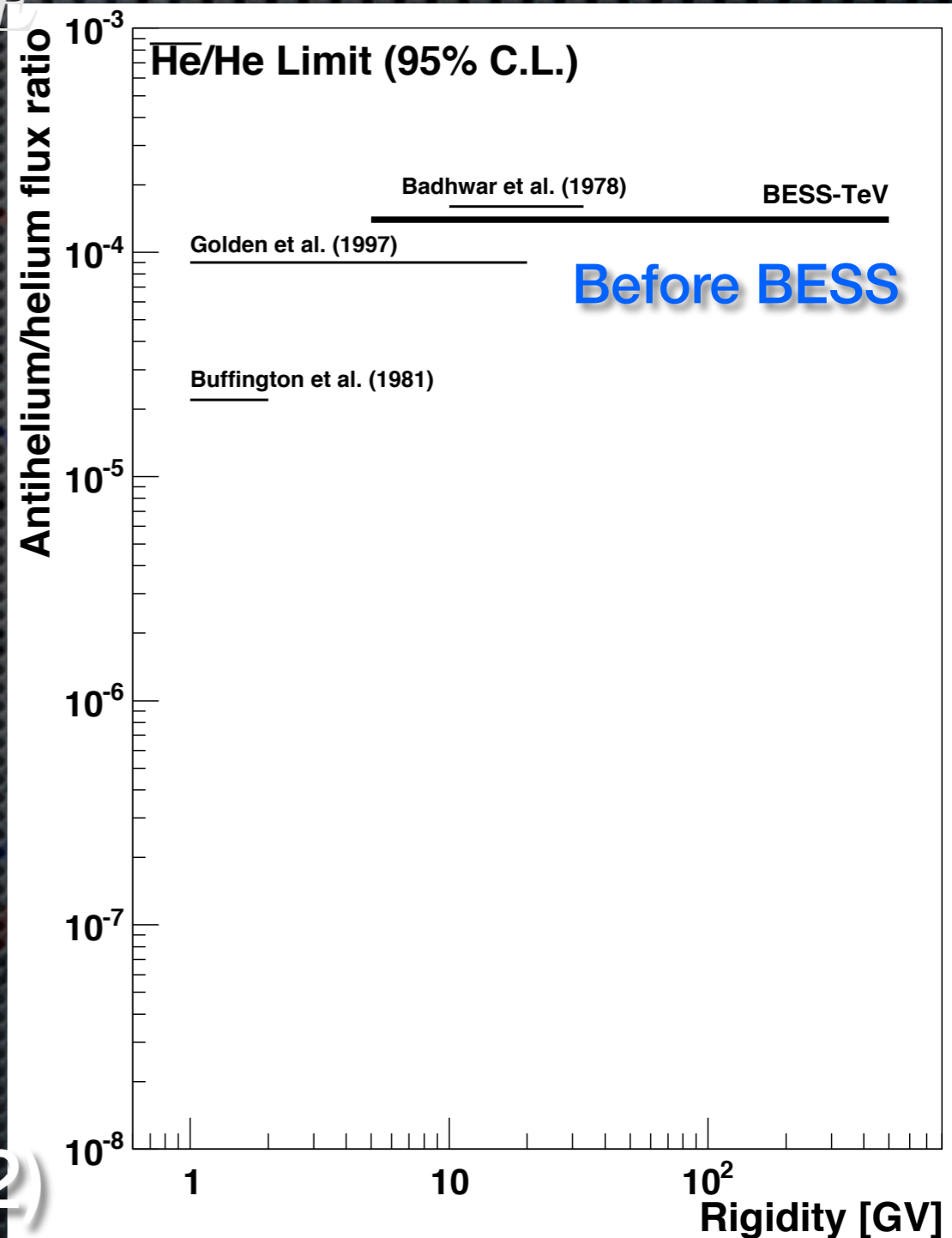
New limit on $\bar{\text{He}}/\text{He}$ ratio (95% C.L., $1 < R < 14$)

BESS-Polar II only

$$\bar{\text{He}}/\text{He} < 9.4 \times 10^{-8}$$

All BESS data

$$\bar{\text{He}}/\text{He} < 6.9 \times 10^{-8}$$



Published in PRL 108, 131301 (2012)

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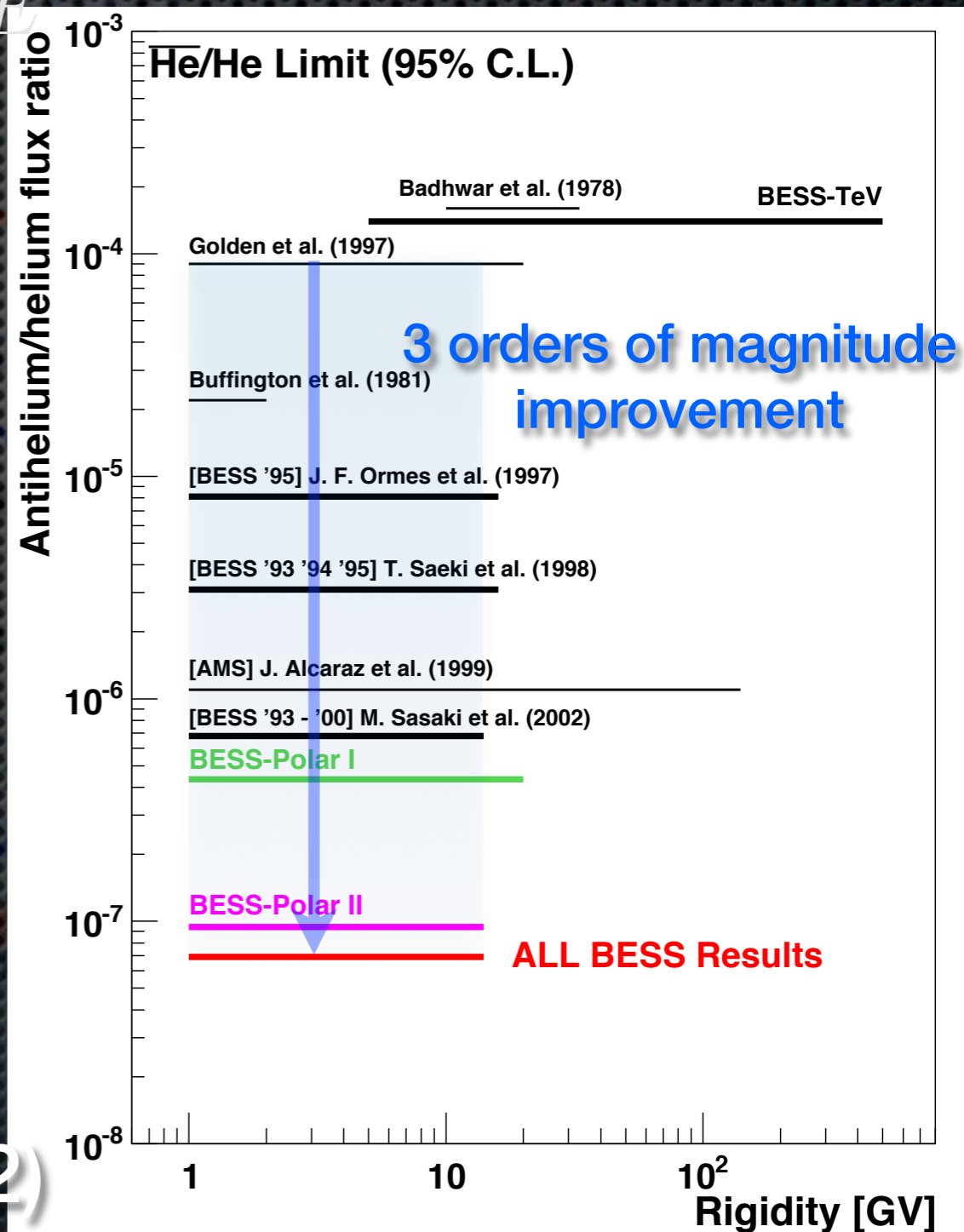
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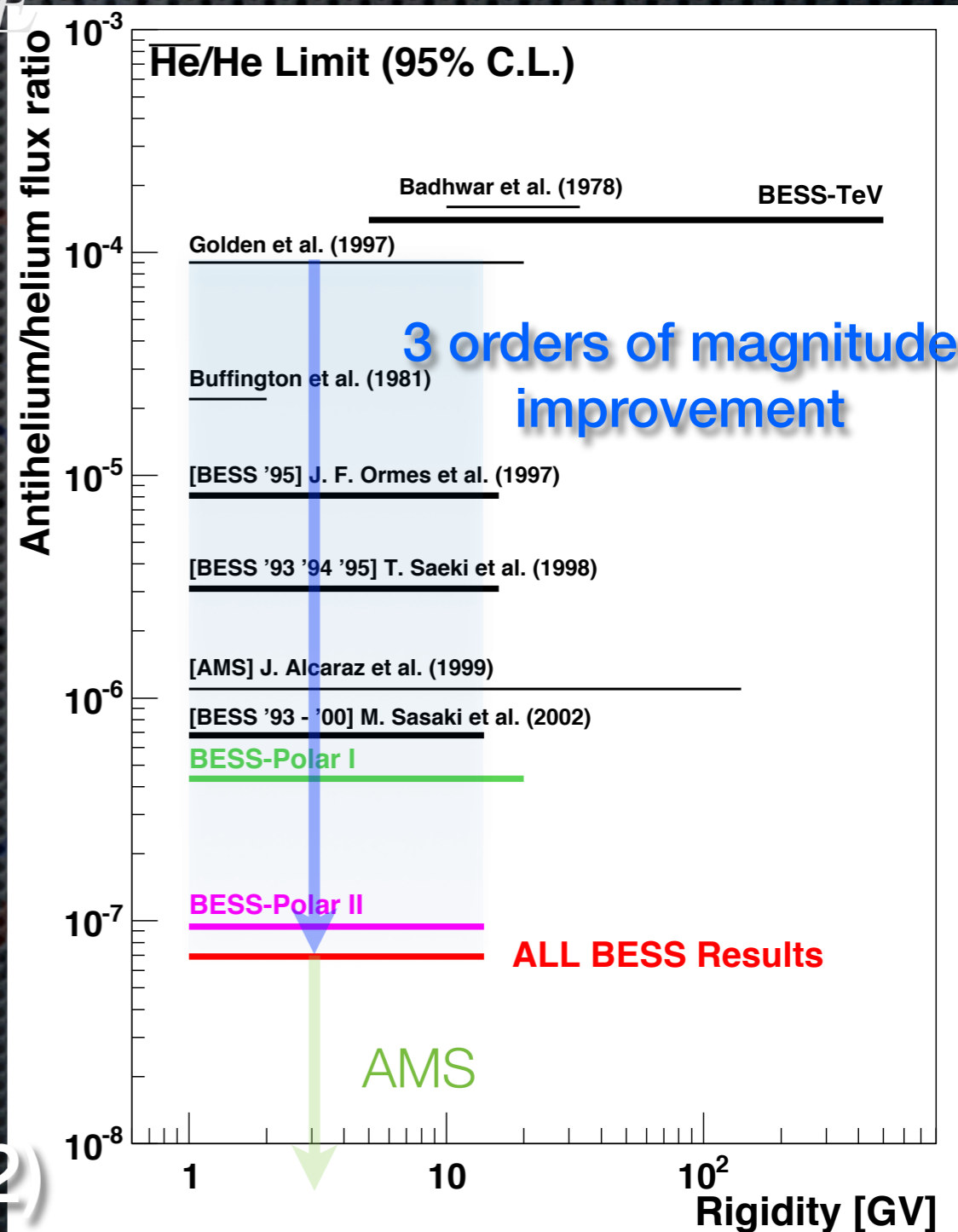
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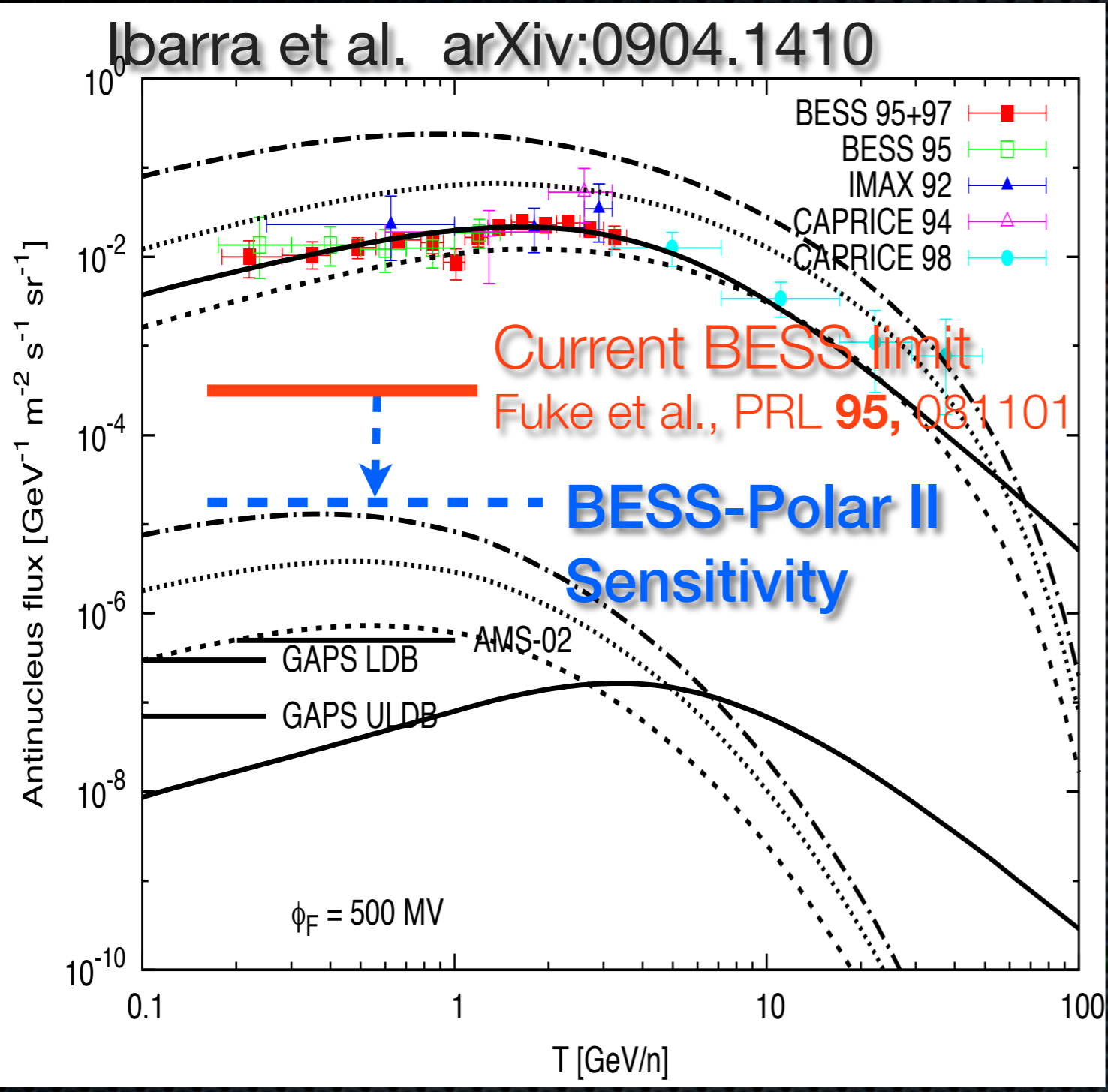
$$\bar{\text{He}}/\text{He} < 6.9 \times 10^{-8}$$



Published in PRL 108, 131301 (2012)

現在解析中の物理

宇宙線反重陽子



流束は極めて微少

大面積立体角

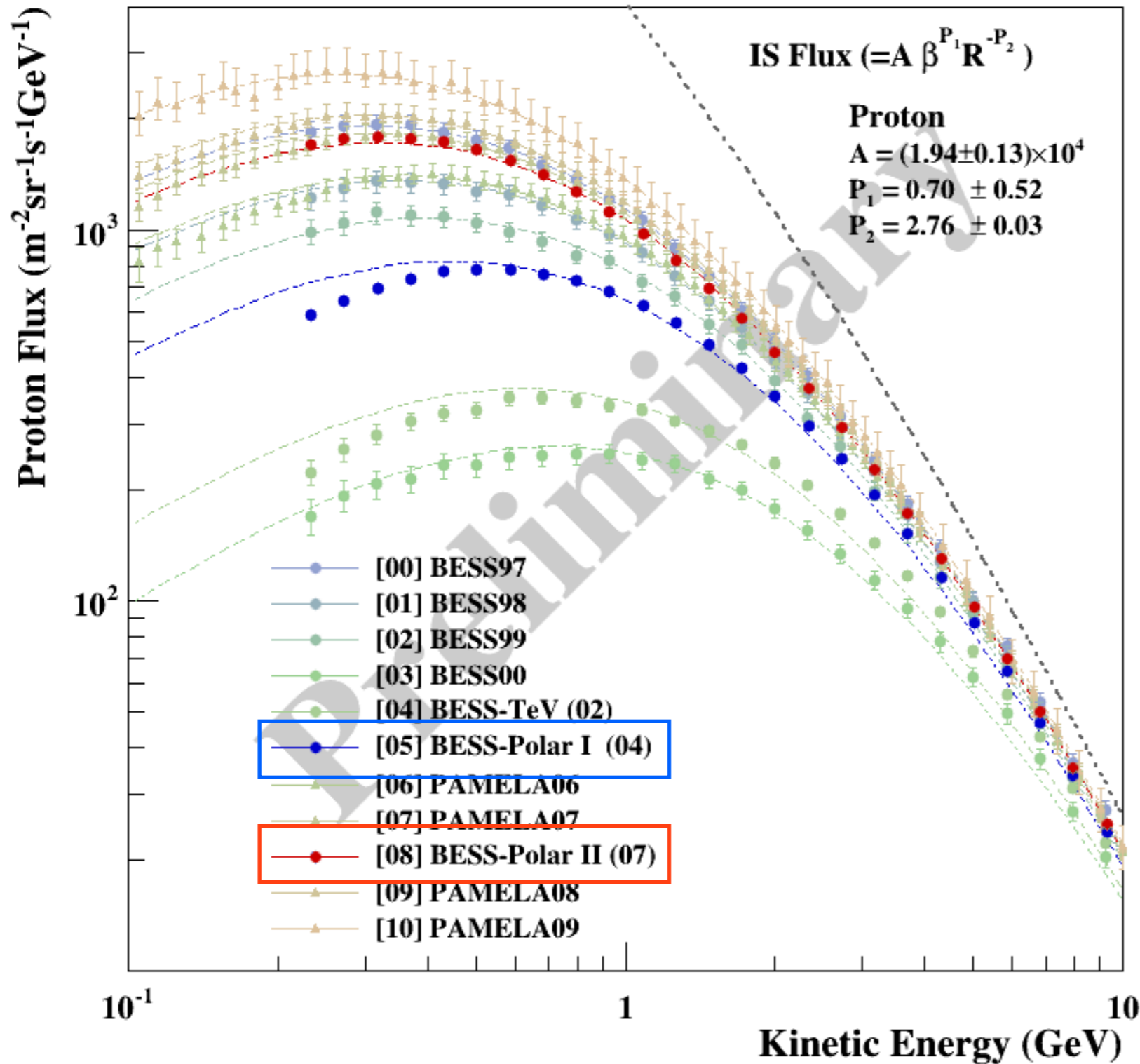
反陽子がバックグラウンド

粒子識別性能

GAPS, AMS-02,
BESS-Polar

**1事象でも見つければ、
一次起源の強い証拠！**

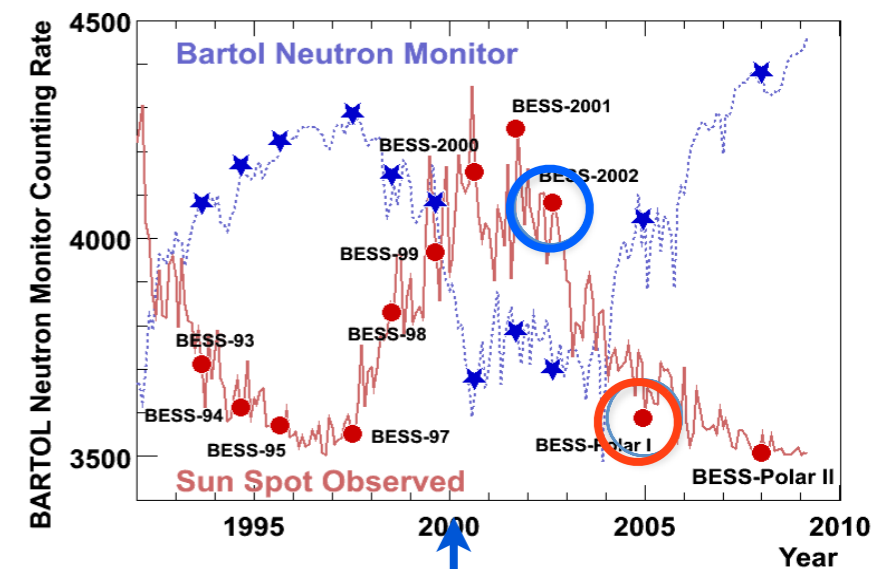
一次宇宙線 (陽子、ヘリウム)



太陽活動による変調

太陽活動の様々な段階 (磁極の反転の前後) での測定
 高精度な反陽子流束

太陽変調の荷電依存性の理解



太陽磁極の反転

宇宙線の短期変動



短期的な変動が測定可能に

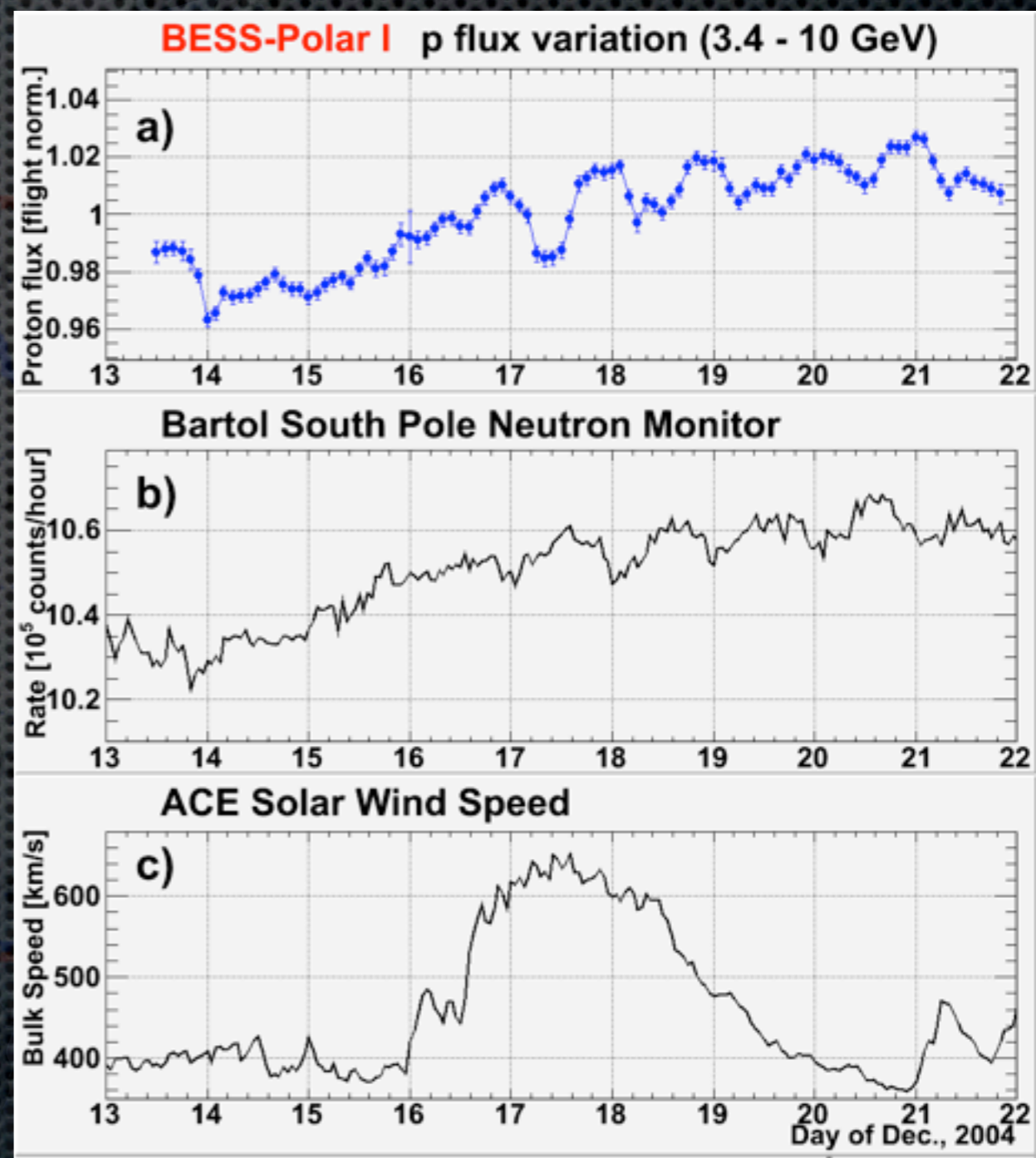
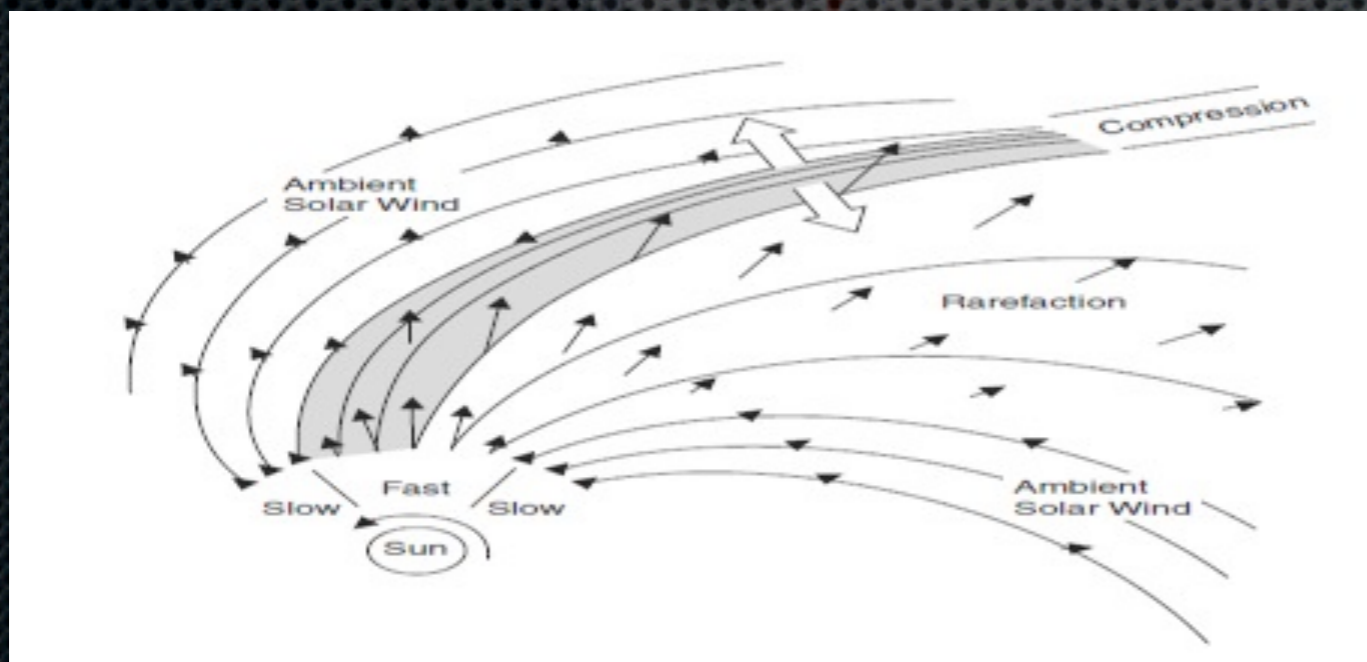
数時間～数十日

ex.: フォルビッシュ現象, 日々変化等

太陽圏内の現象の理解

惑星間磁場の影響

CME and Solar Flare, CIR (Corrotating Interaction Region) 等の擾乱



BESS-Polar I flux variation

BESS-Polar測定器の現状と 今後の展望

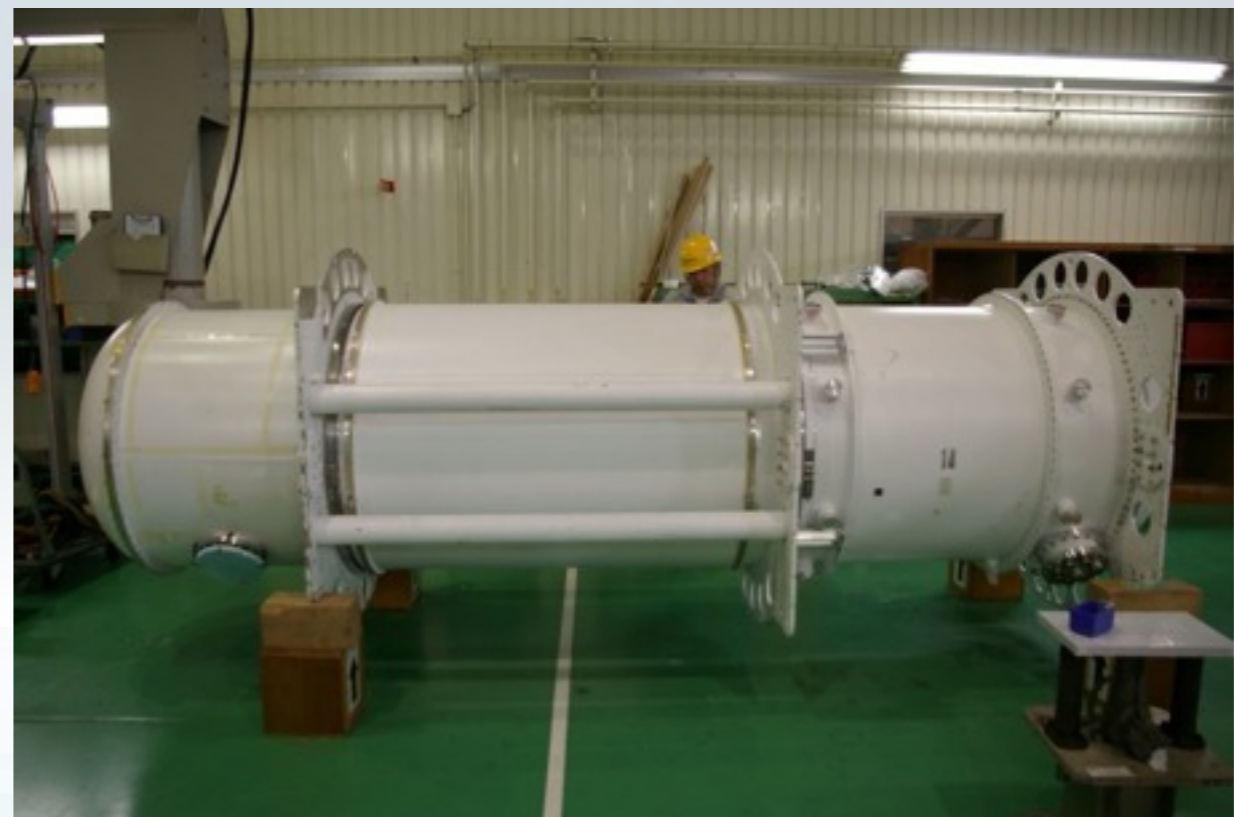
BESS-PolarII測定器の回収

2009.12 ~ 2010.1 約2ヶ月かけて雪上に2年間放置された測定器を回収に成功



測定器の現状および今後

マグネットと中央飛跡検出器は再組み立てに成功
励磁試験を行った後、NASA/GSFCで休眠中



新たな物理課題（&お金&人）があれば、いつでも出動可能

Ex. 軽元素（特に ^{10}Be ）

低エネルギー-Exotic粒子

まとめ

- BESS-Polar II の反陽子観測結果、これまでにない精度で低エネルギー反陽子流束が測定され、衝突起源モデルと高い整合性を持つことが確認された。
- BESS'95+'97の低エネルギー反陽子の過剰を説明できるようなレベルのPBHの蒸発からの反陽子は確認できなかった。
- 反ヘリウムはこれまでの最高感度での探索を行った結果、その存在は確認できず、最も厳しい上限値を得た。
- PAMELA, AMS IIの高エネルギー、BESS-Polar IIの低エネルギーデータにより、精度のよい反陽子スペクトルが確定する。
- BESS-PolarII 測定器は整備を終え、次期計画に向けて待機状態にある。