宇宙線反重陽子の探索

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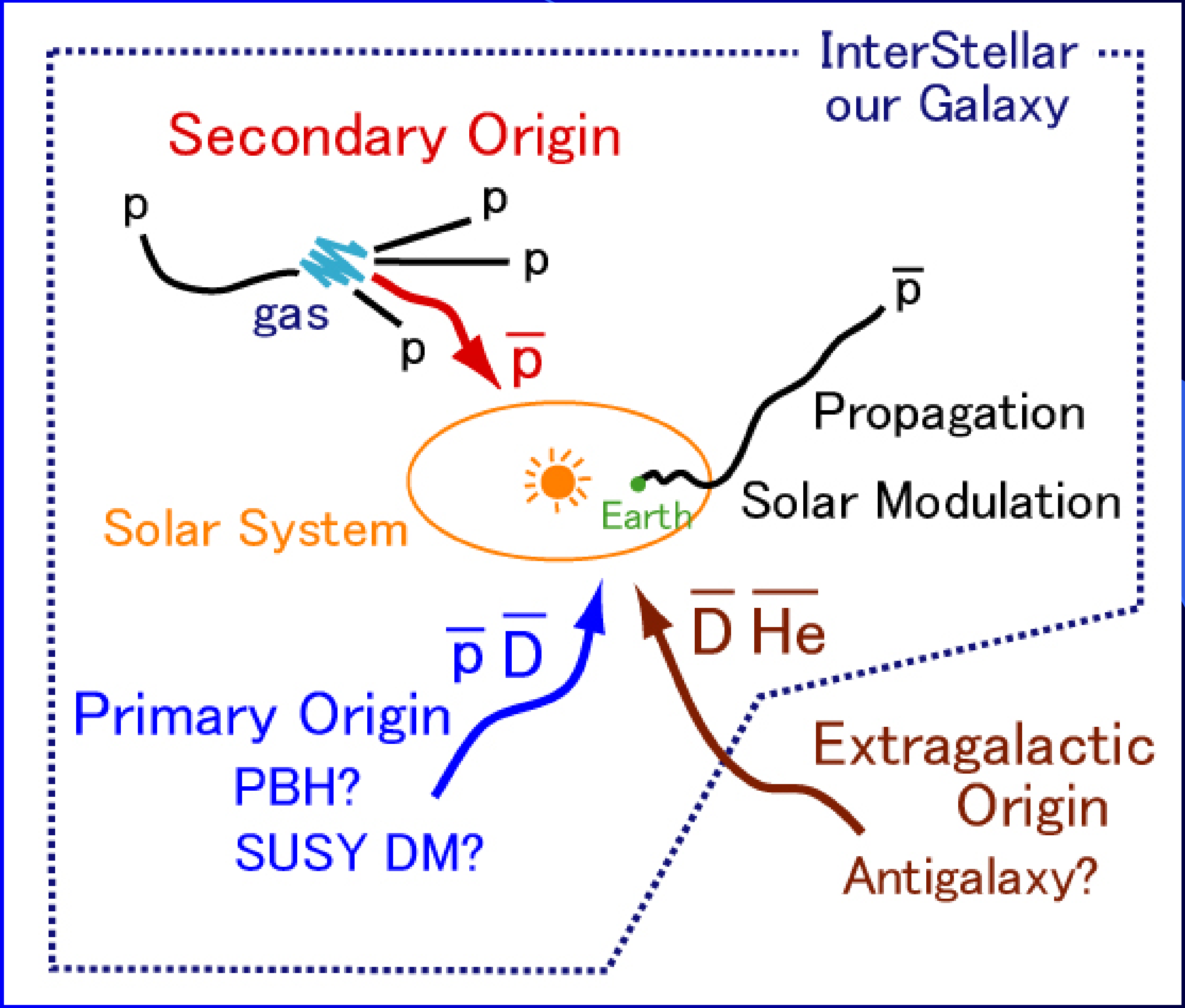
I. イントロ
II. 反重陽子探索（結果）
  a. BESS測定器、気球実験
  b. 解析
  c. 結果
  d. ディスカッション
III. 将来計画 ー BESS-Polar実験 ー
IV. まとめ

Introduction

$\bar{D}$ の起源は？



InterStellar
our Galaxy
Secondary Origin
p
p
p
gas
p
$\bar{p}$
$\bar{p}$
Propagation
Solar System
Earth
Solar Modulation
$\bar{p}$ $\bar{D}$
$\bar{D}$ $\overline{He}$
Primary Origin
PBH?
SUSY DM?
Extragalactic
Origin
Antigalaxy?

宇宙線 $\bar{p}$

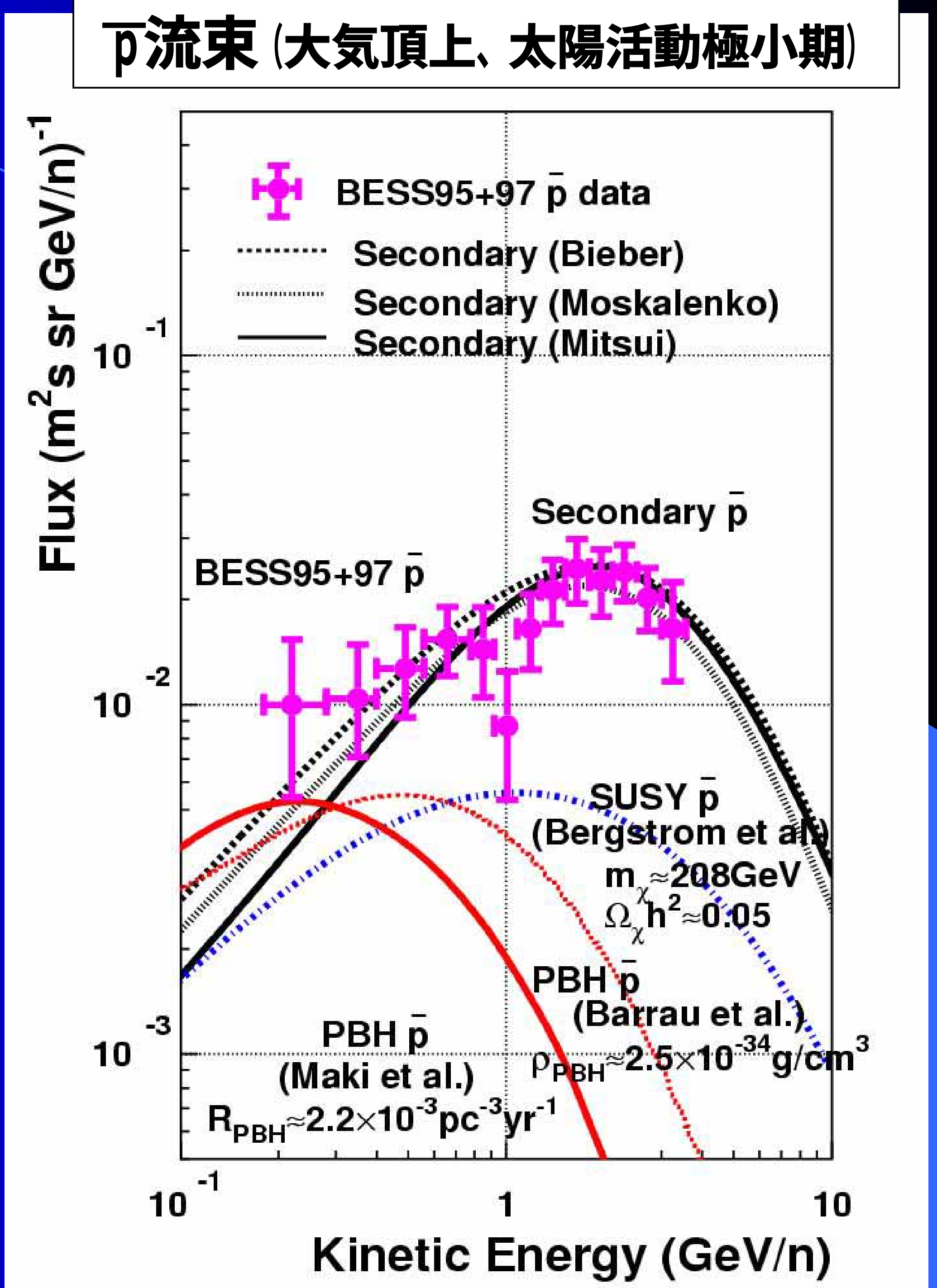
- ✓ ～2GeVにピーク
  → 大半が二次起源
- ✓ 低エネルギー(<1GeV)
  → ややフラット

⇩

- ✓ 一次起源の
  存在を示唆 ？

⇕

- ✓ 理論的不定性
  統計精度

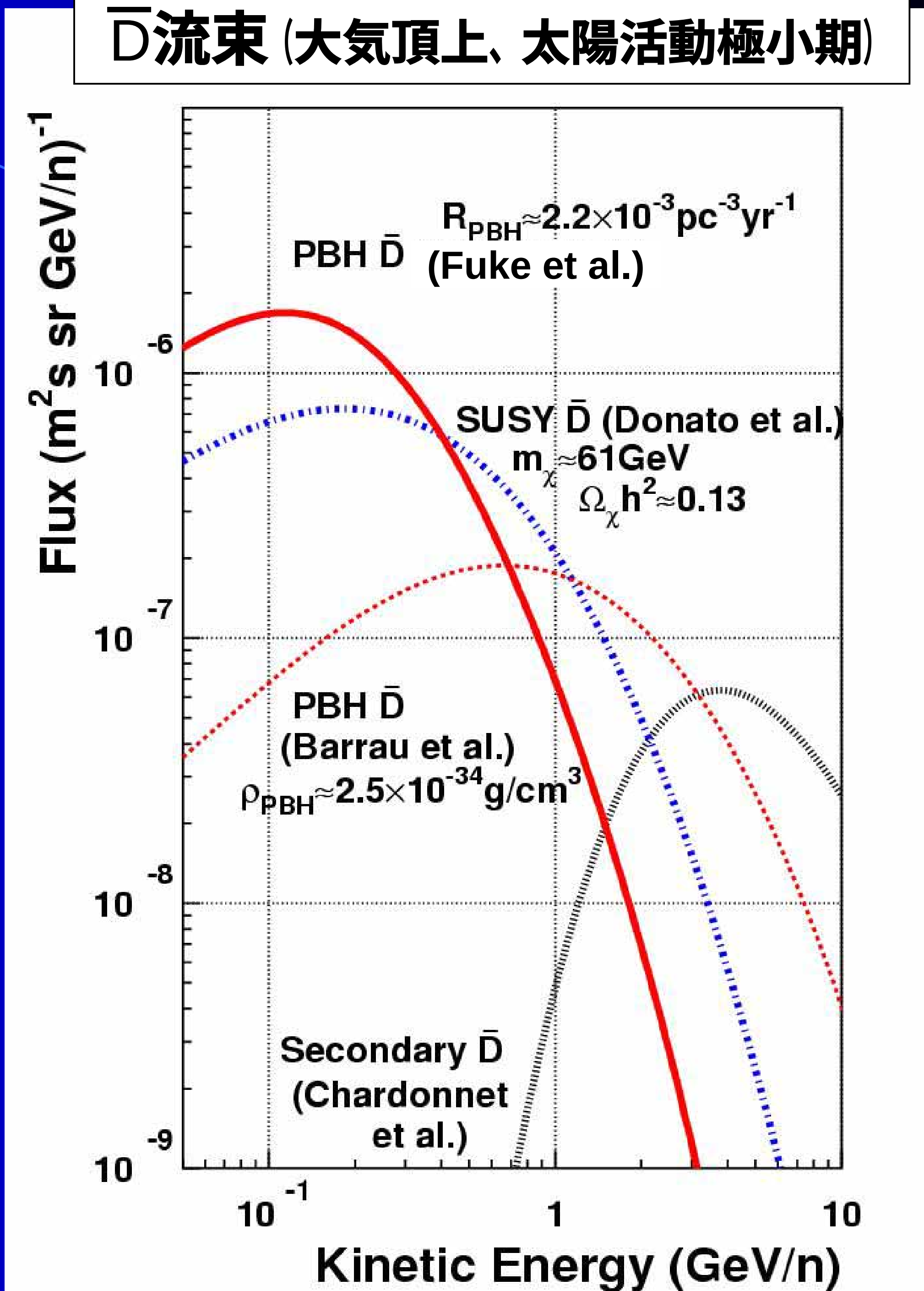


低エネルギー $\bar{D}$ は B.G. free

- ✓ 二次起源$\bar{D}$スペクトラム：高エネルギー側にシフト
- ✓ 一次起源$\bar{D}$スペクトラム：ソフトと期待

⇩

- ✓ 低エネルギー$\bar{D}$ (<1GeV/n) が観測されれば → 一次起源の存在を強く示唆
- ✓ $\bar{p}$と相補的なプローブ

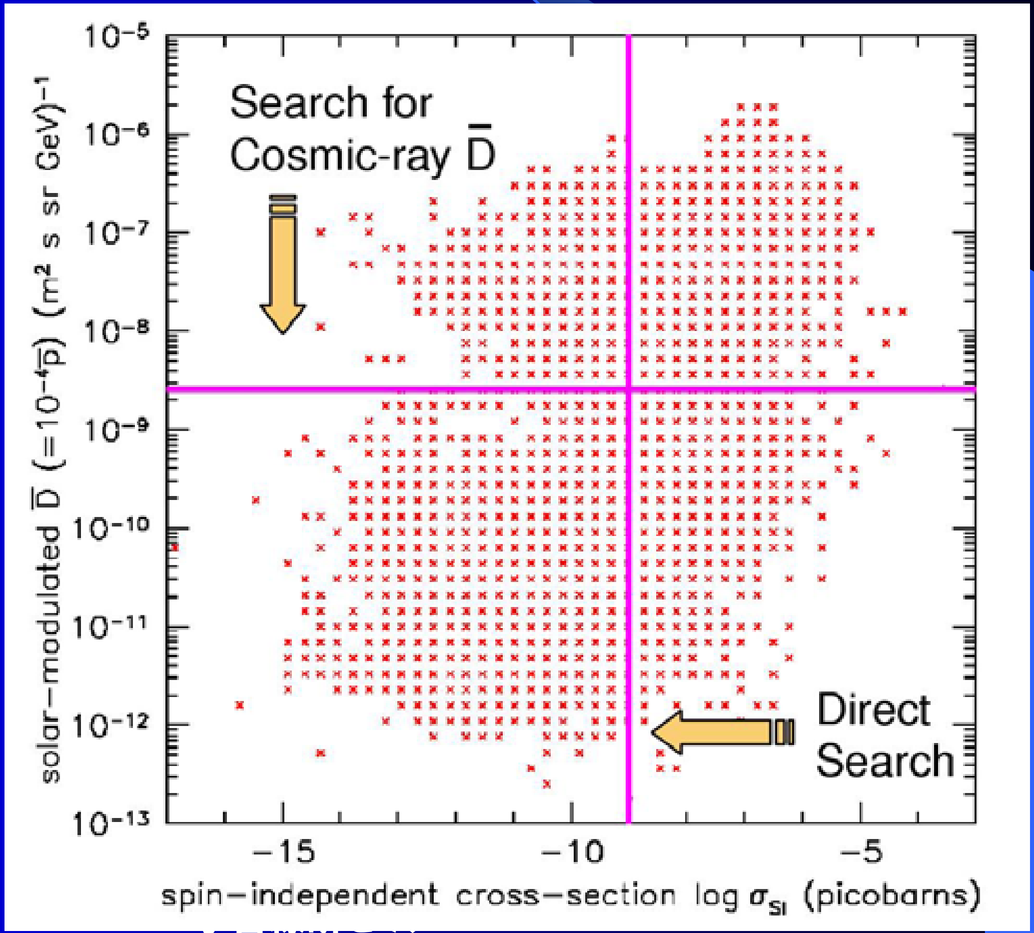


ニュートラリーノ·ダークマターの対消滅

LSP → WIMP Dark Matter？

→ χ の対消滅→ jet fragmentation → $\bar{D}$ 生成？

直接探索と相補的



K.Mori et al, APJ 566 (2002) 604

原始ブラックホール (PBH) の蒸発

- ✓ 宇宙初期に生成？
  ←密度揺らぎ、真空の相転移、etc
- ✓ ホーキング輻射による粒子放出
- ✓ 質量～10^{15}gのPBHが現在蒸発？

jet fragmentation により $\overline{\mathrm{D}}$ 生成？

- ✓ とりわけ Local PBH に対して sensitive

目的

- ✓ 低エネルギー宇宙線 $\overline{\mathrm{D}}$ の探索

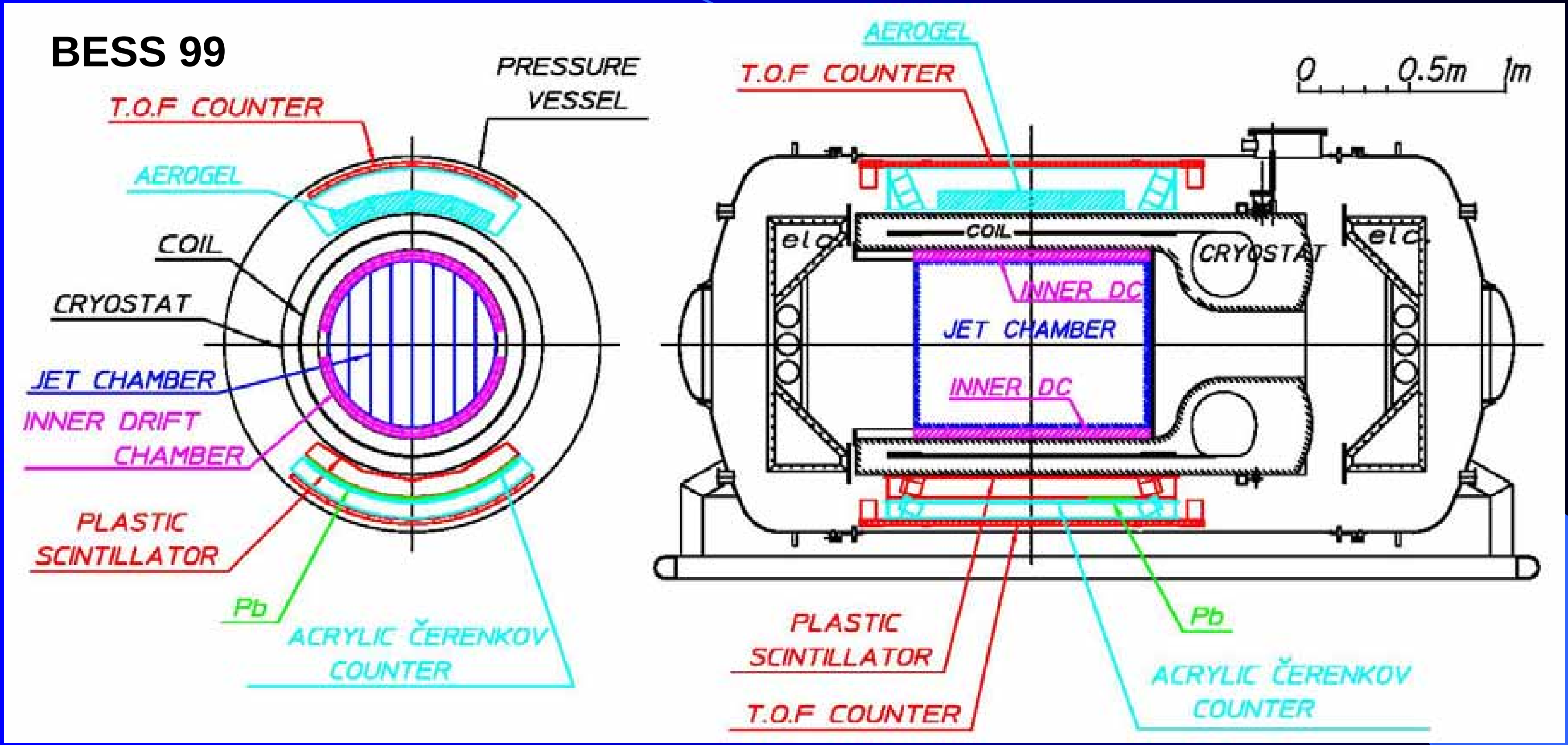
- ✓ BESS フライトデータ

  1997 - 2000 : σ_t 向上＆ エアロジェル $\breve{\mathrm{C}}$

  磁気カットオフ低い場所で

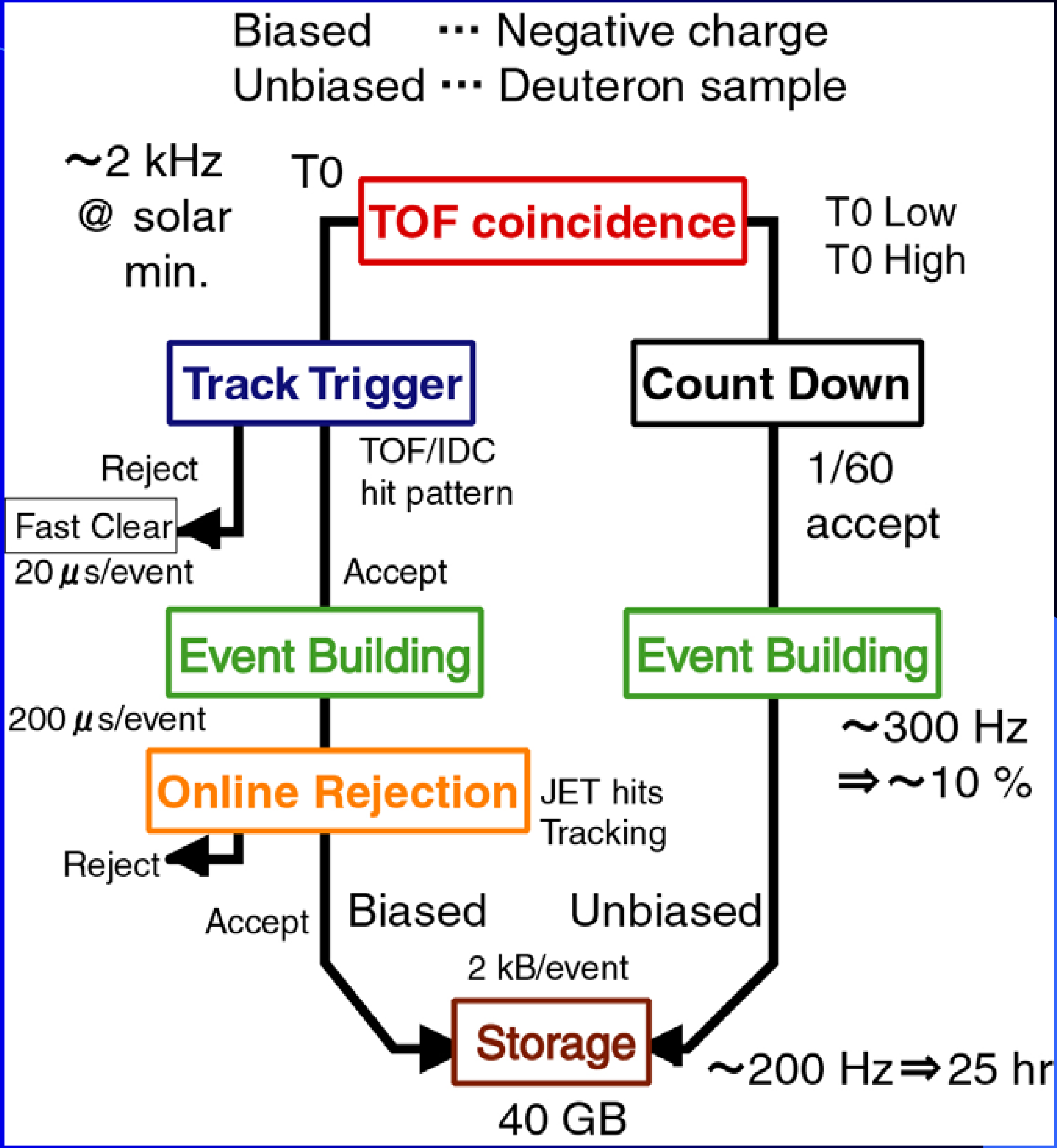
BESS Detector

BESS Spectrometer



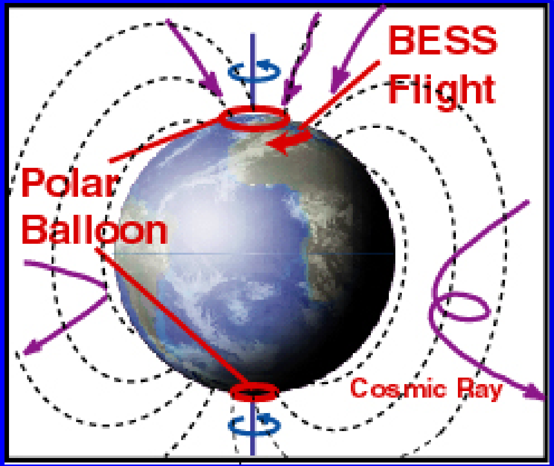
- 薄肉超伝導ソレノイド、均一磁場 1T
- 大面積立体角 ~ 0.3m^{2}sr, ~8-10 g/cm^2/ wall
- Rigidity (=Pc/Ze), β (σ_t ~70ps) , dE/dx

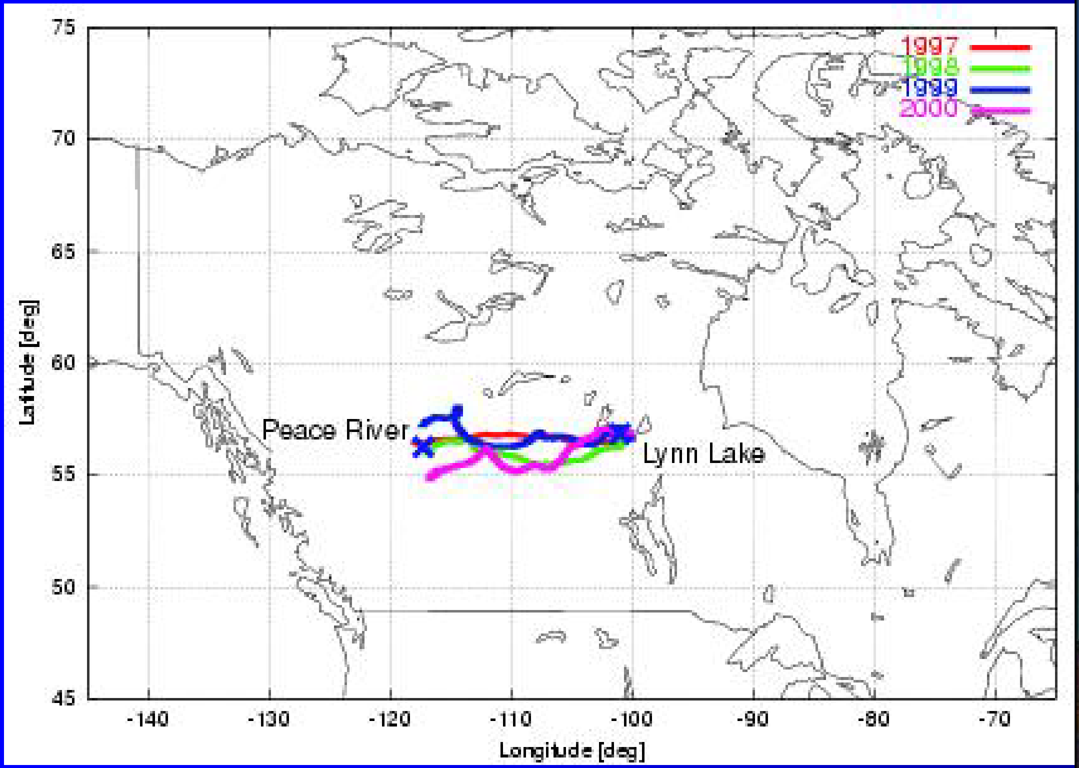
Trigger

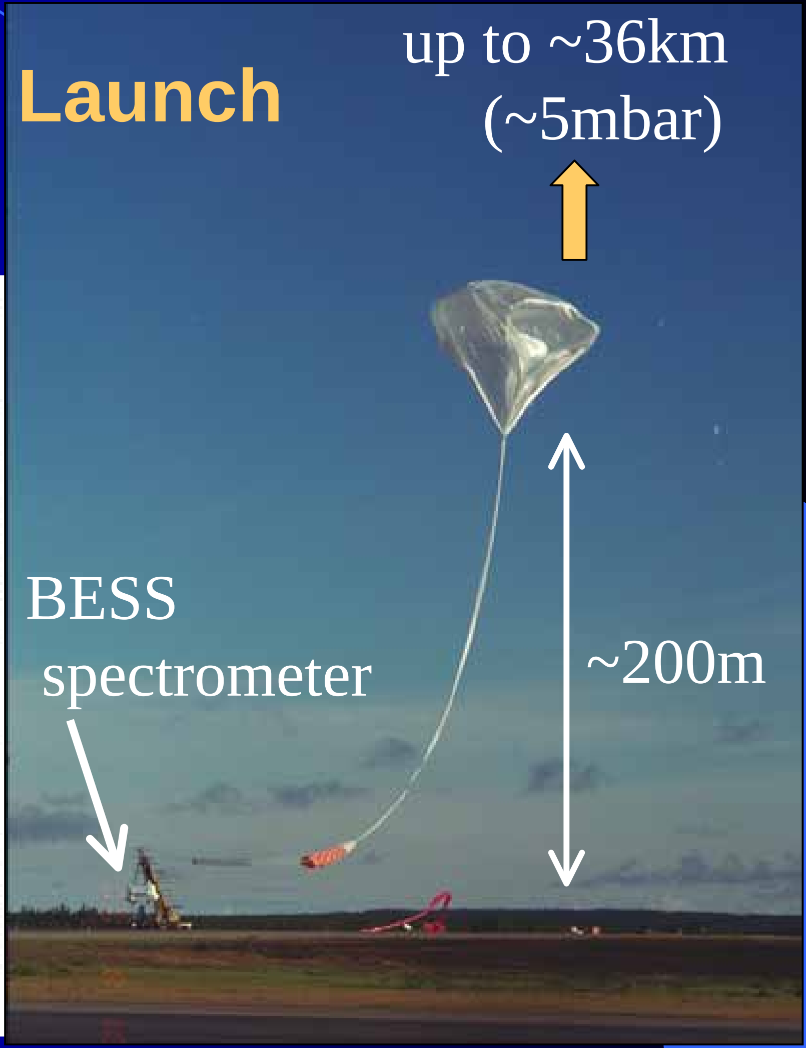

Biased ··· Negative charge
Unbiased ··· Deuteron sample
~2 kHz
@ solar
min.
T0
TOF coincidence
T0 Low
T0 High
Track Trigger
Count Down
Reject
TOF/IDC
hit pattern
1/60
accept
Fast Clear
20 μs/event
Accept
Event Building
Event Building
200 μs/event
~300 Hz
⇒~10 %
Online Rejection
JET hits
Tracking
Reject
Accept
Biased
Unbiased
2 kB/event
Storage
~200 Hz⇒25 hr
40 GB

Balloon Flights

BESS Balloon Flight

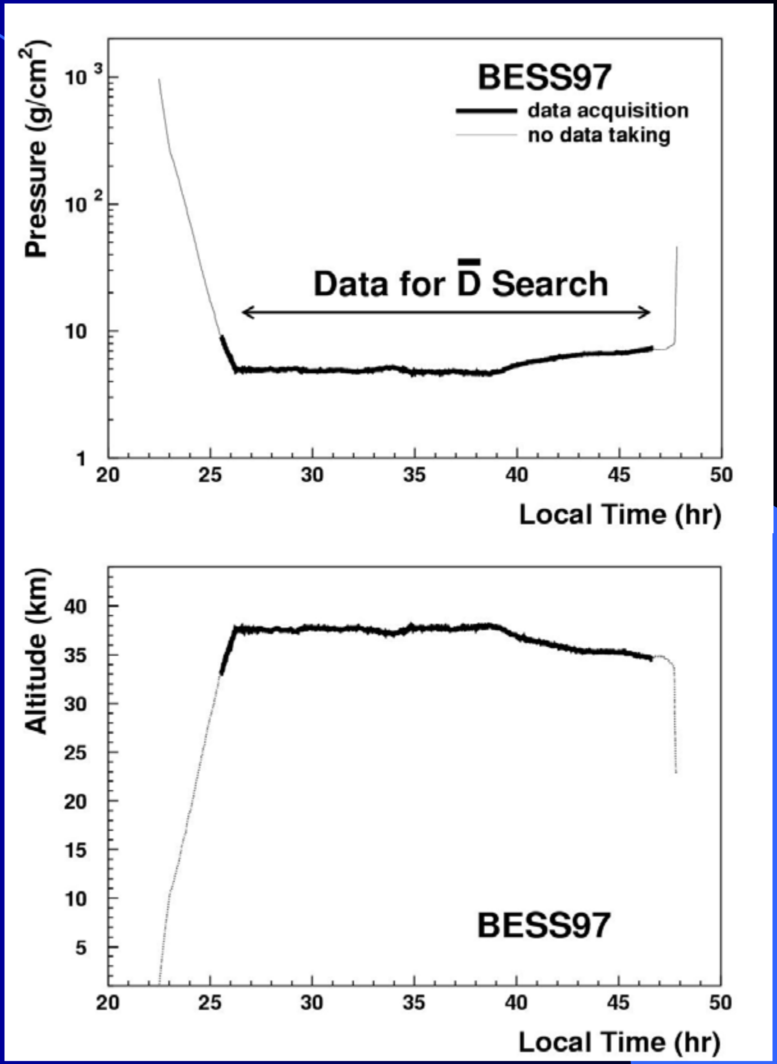






Data Taking

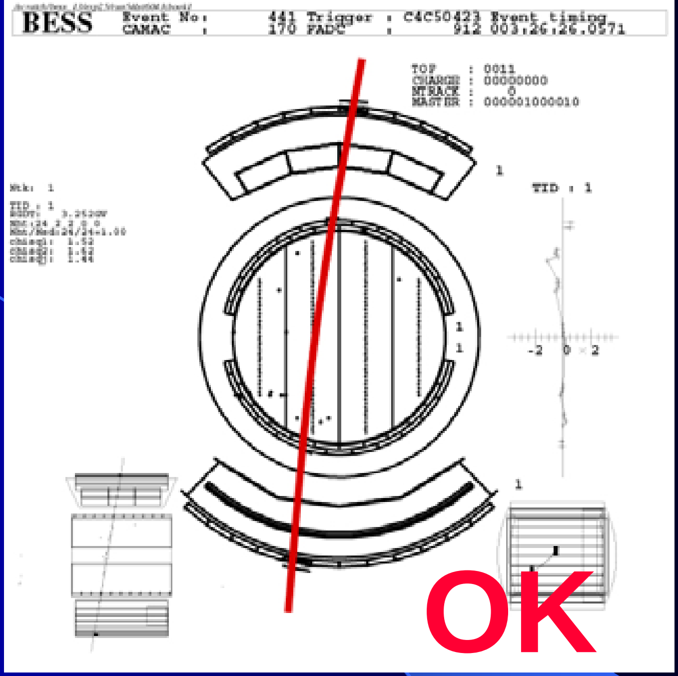
	1997	1998	1999	2000
Live Time (hr)	15.8	16.8	27.4	28.7
Mean Air Depth (g/cm^2)	5.4	5.2	3.9	5.9

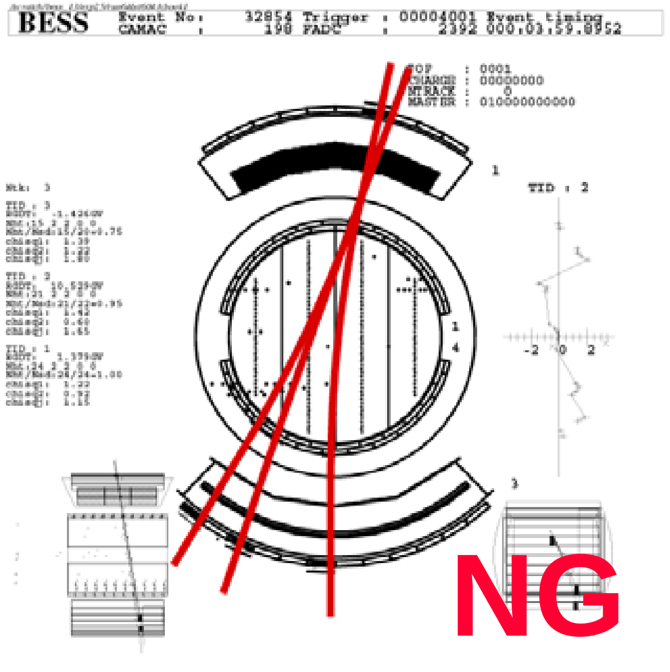


Analysis

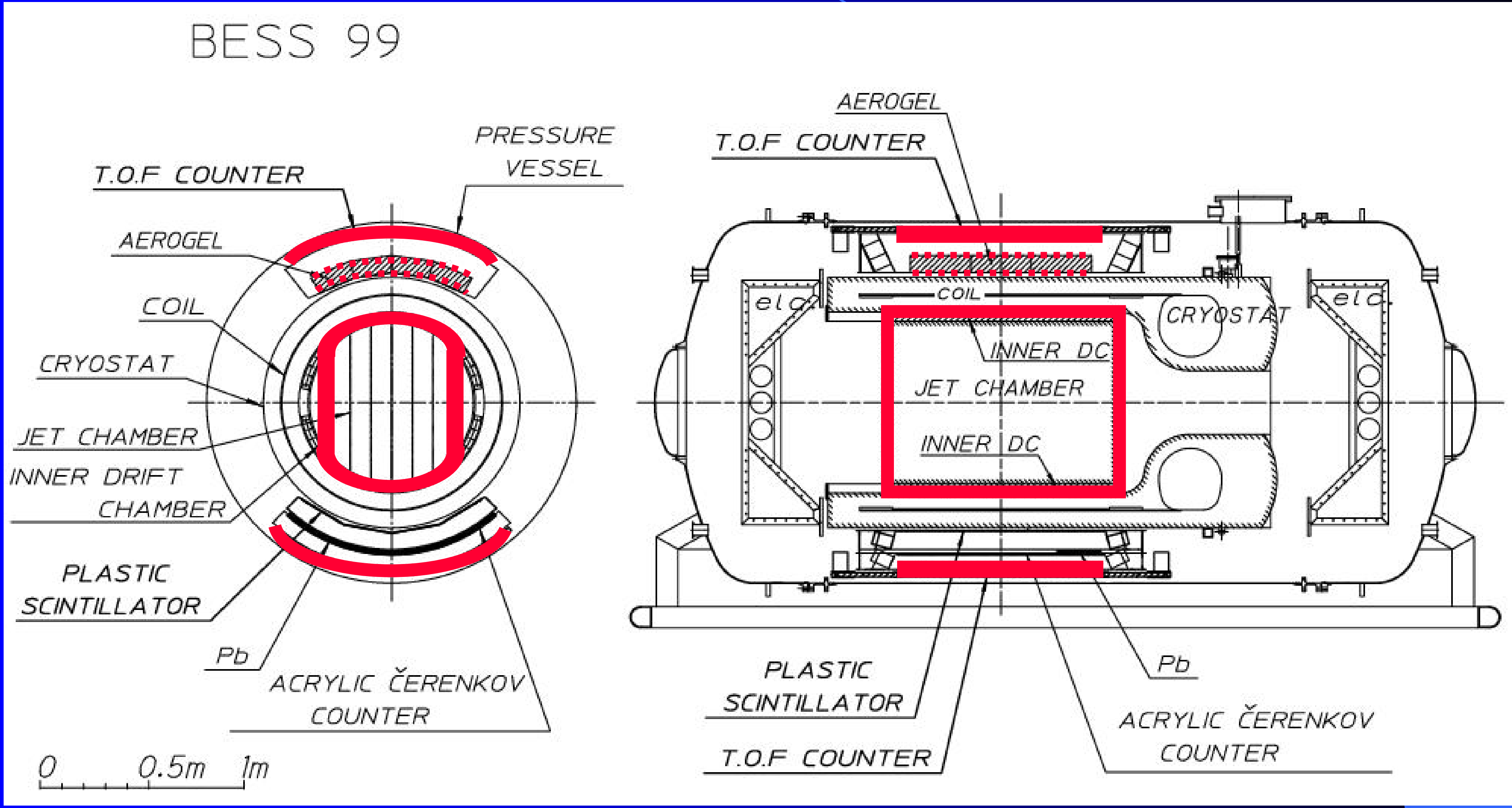
Event Selection

- ➢ Pre-Selection
  - ✓ single track
  - ✓ downward going
  - ✓ fully contained
  - ✓ N_{TOF}= 1 or 2
  - ✓ Upper TOF dE/dx
- ➢ Quality Cut
  - ✓ trajectory fitting
- ➢ Paticle Identification
  - ✓ dE/dx vs Rigidity
  - ✓ 1/β vs Rigidity
  - ✓ Aerogel Chrenkov





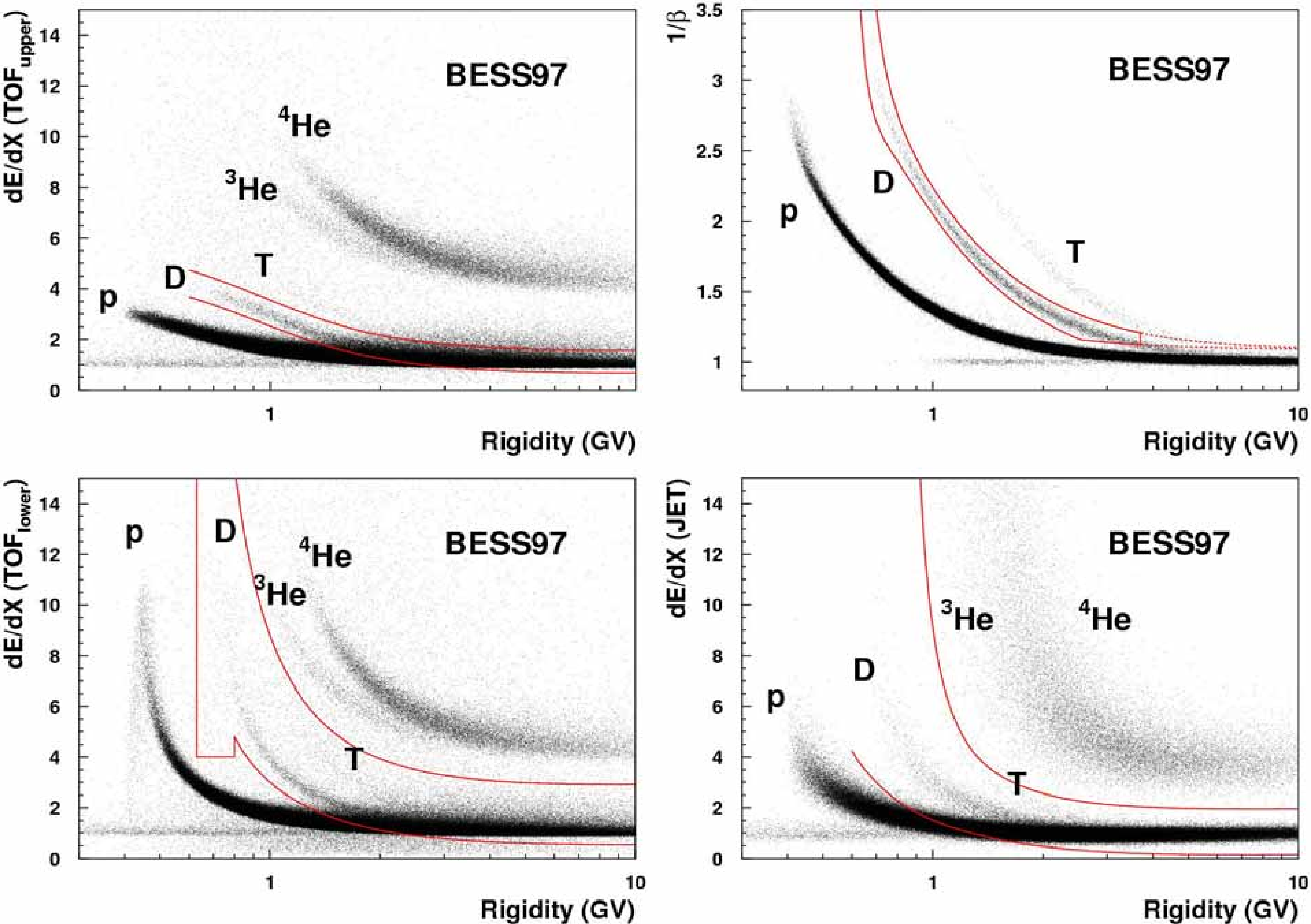
Fiducial Volume



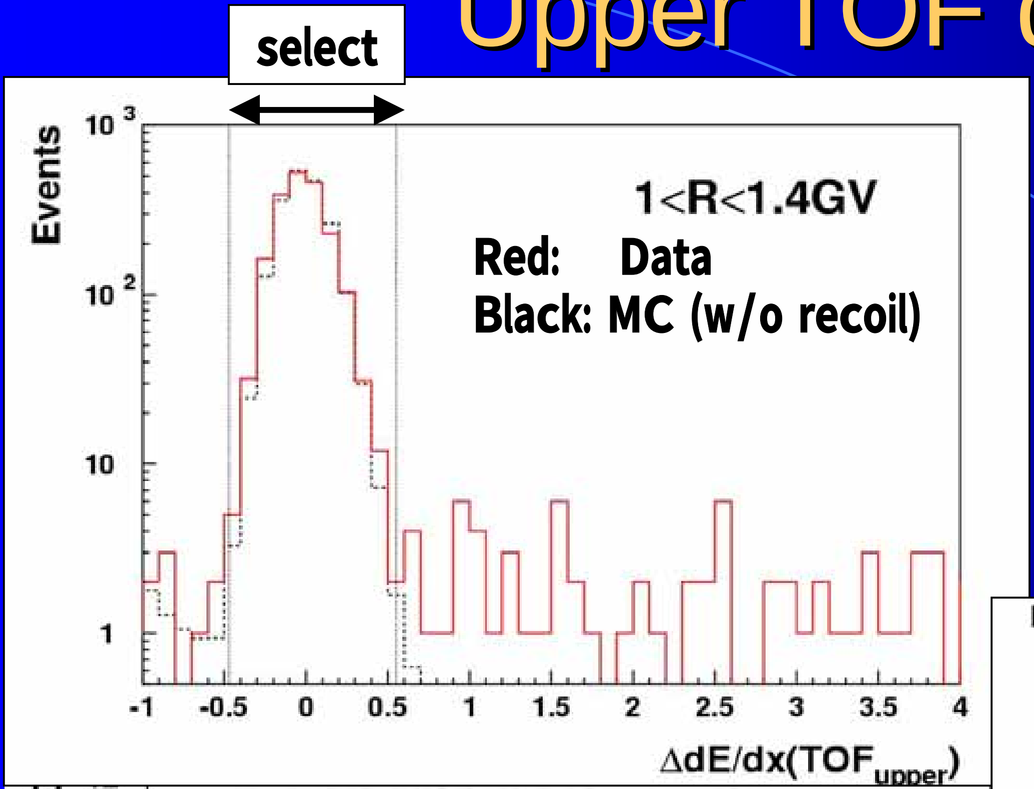
Quality Cuts

- ✓ Hits used in trajectory fitting
- ✓ χ^2 of trajectory fitting
- ✓ Dropped hits
- ✓ Trajectory agreement with IDC hits (r-ϕ, z)
- ✓ Trajectory agreement with TOF hits (r-ϕ, z)
  (TOF, dE/dx)

Particle ID


BESS97
dE/dX (TOF$_{upper}$)
^{4}He
^{3}He
T
D
p
Rigidity (GV)
BESS97
1/β
D
p
T
Rigidity (GV)
BESS97
dE/dX (TOF$_{lower}$)
p
D
^{4}He
^{3}He
T
Rigidity (GV)
BESS97
dE/dX (JET)
^{3}He
^{4}He
D
p
T
Rigidity (GV)

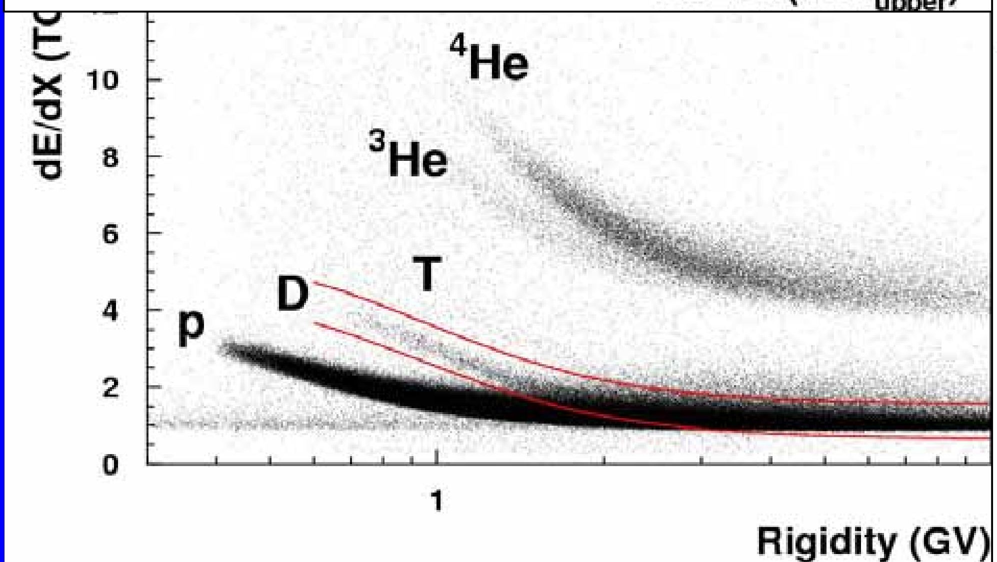
Upper TOF dE/dx cut

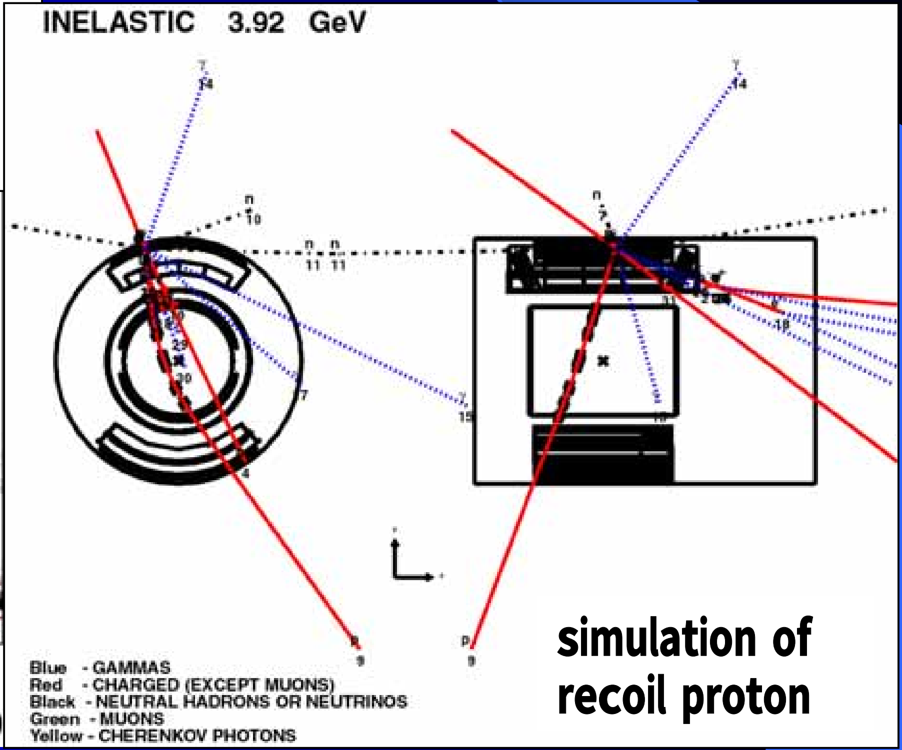


Eliminate “recoil” deuterons
(“fake” events)
← broad tail in upper dE/dx

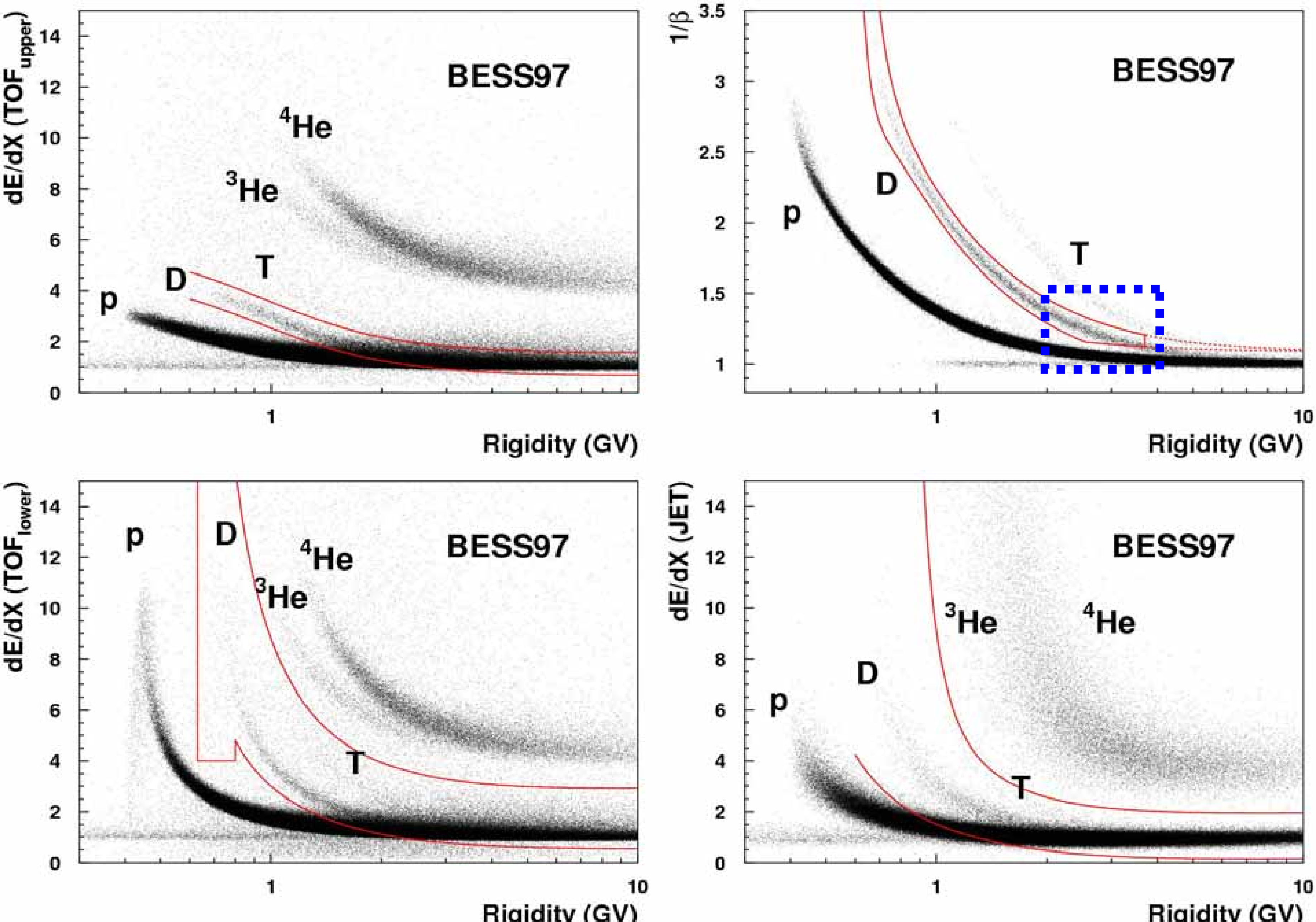
↓

Tighter than lower / JET dE/dx





Particle ID



BESS97
dE/dX (TOF$_{upper}$)
^{4}He
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D
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Rigidity (GV)
BESS97
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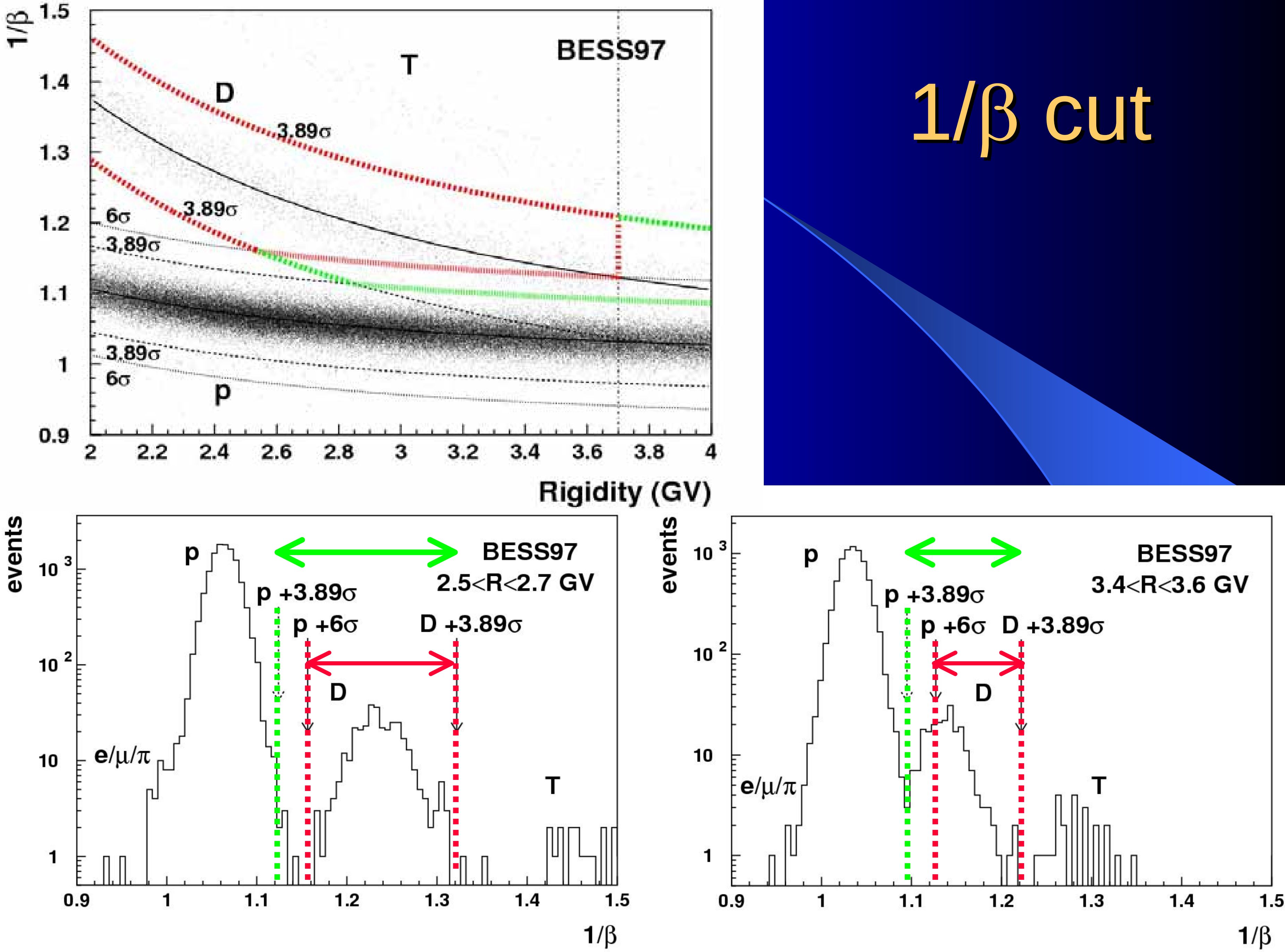
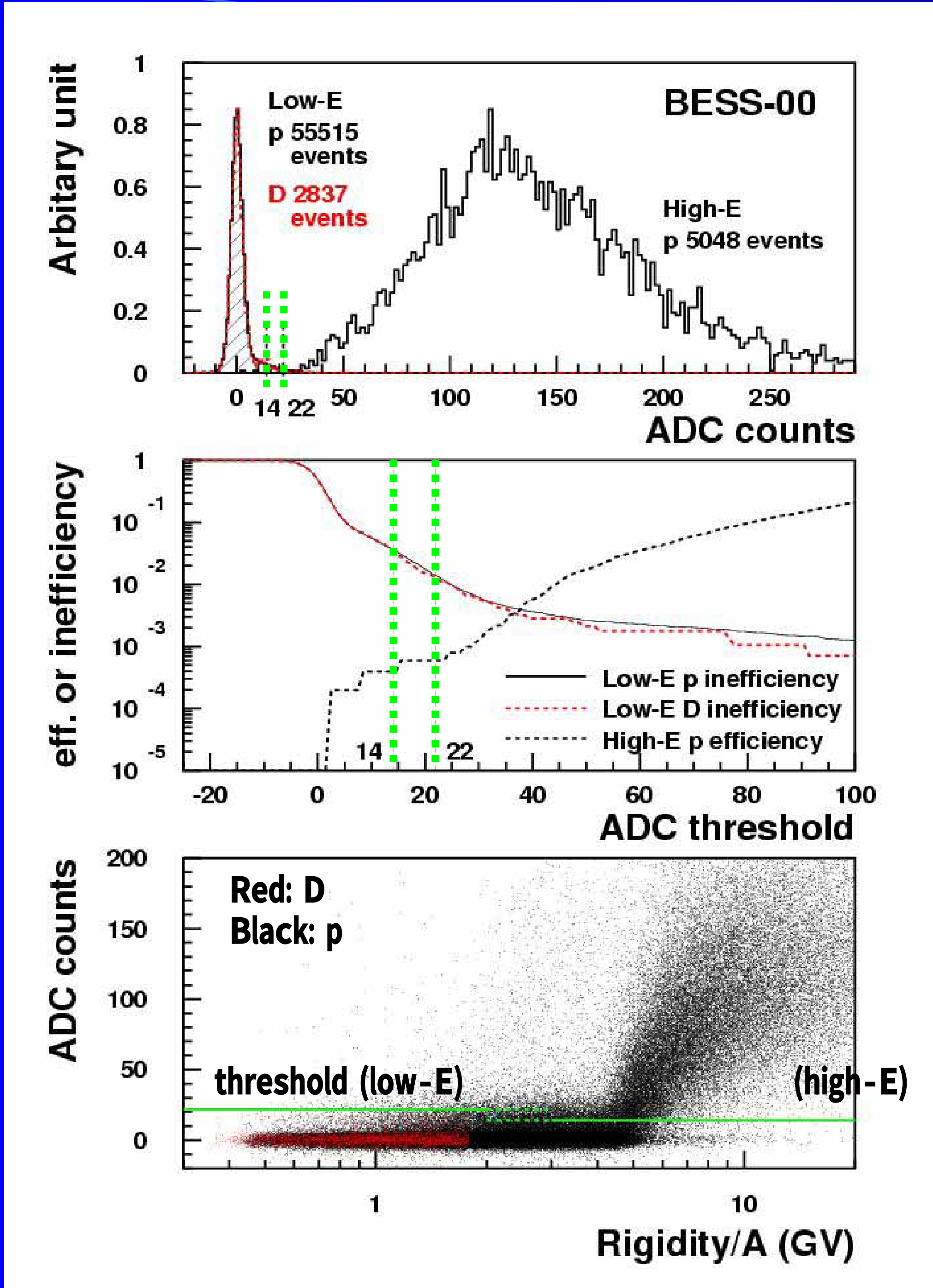
D
p
T
Rigidity (GV)
BESS97
dE/dX (TOF$_{lower}$)
p
D
^{4}He
^{3}He
T
Rigidity (GV)
BESS97
dE/dX (JET)
^{3}He
^{4}He
D
p
T
Rigidity (GV)

1/β cut



BESS97
1/β
Rigidity (GV)
D
T
p
3.89σ
6σ
events
e/μ/π
p +3.89σ
p +6σ
D +3.89σ
2.5<R<2.7 GV
3.4<R<3.6 GV

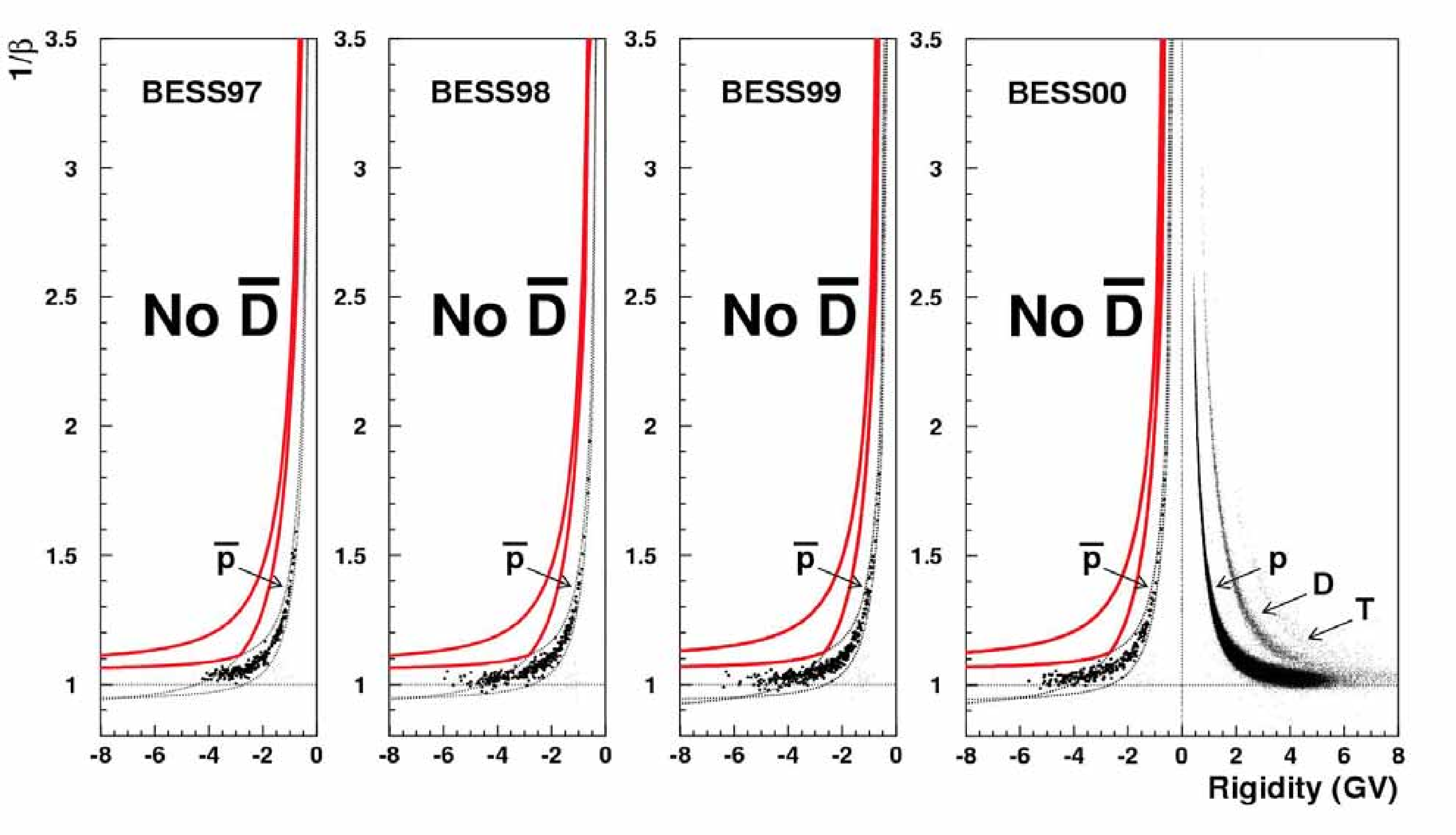


Silica aerogel veto cut

eliminate e^-/μ^- backgrounds
especially in
high β region ($1/\beta < 1.1$)

’97 … n=1.03
’98~’00 … n=1.02

Survived Events －No $\bar{D}$ candidate－



Deuteron Samples

	Number of D samples	Rigidity (GV)
1997	7545	< 3.70
1998	7183	< 3.65
1999	8050	< 3.58
2000	5204	< 3.59

⇒ Efficiencyの算出 や カットの決定に利用

Possible Contamination

- $\bar{\mathbf{D}}$ (in |R|>2.3 GV where $\bar{p}$ 1/β band overlaps $\bar{D}$ band)
  - $\bar{p}$ … ~ 1 event / 4 flights (+3.89σ)
    (c.f. ~ 0.1 event / 4 flights (+6σ))
  - e^-/μ^- … ~ 0.1 times $\bar{p}$ contamination
- **D**
  - p … < 0.5 %
  - T … < 1 %
  - e^+/μ^+, He … << 0.1 %

Results
－ $\bar{D}$ 流束上限値の算出－

Outline

最も conservative な $\overline{\mathrm{D}}$ 流束上限値を求める
(スペクトラムの形とは independent)

$$\Phi_{\overline{D}} \equiv \frac{N_{\text{obs}}}{\left|S\Omega\cdot\varepsilon_{\text{total}}\right|_{\min} T_{\text{live}}(E_2 - E_1)(1 - sys.err)}$$

$$\varepsilon_{\text{total}} = \varepsilon_{\text{trig}}\,\varepsilon_{\text{rec}}\,\varepsilon_{\text{pre}}\,\varepsilon_{\text{qual}}\,\varepsilon_{\mathrm{d}E/\mathrm{d}x}\,\varepsilon_{1/\beta}\,\varepsilon_{\text{agl}}\,\varepsilon_{\text{acctrk}}\,\varepsilon_{\text{acchit}}\,\varepsilon_{\text{air}}$$

Normalization , Correction

3.09 for 95% C.L. upper limit (with null b.g.)

$$\Phi_{\overline{D}} \equiv \frac{N_{\mathrm{obs}}}{\left. S\Omega \cdot \varepsilon_{\mathrm{total}} \right|_{\min} T_{\mathrm{live}} (E_2 - E_1)(1 - sys.err)}$$

Monte Carlo simulation (GEANT)

Measured by 1 MHz-clock

Normalization，Correction

$$\varepsilon_{\mathrm{total}} = \varepsilon_{\mathrm{trig}}\,\varepsilon_{\mathrm{rec}}\,\varepsilon_{\mathrm{pre}}\,\varepsilon_{\mathrm{qual}}\,\varepsilon_{\mathrm{d}E/\mathrm{d}x}\,\varepsilon_{1/\beta}\,\varepsilon_{\mathrm{agl}}\,\varepsilon_{\mathrm{acctrk}}\,\varepsilon_{\mathrm{acchit}}\,\varepsilon_{\mathrm{air}}$$

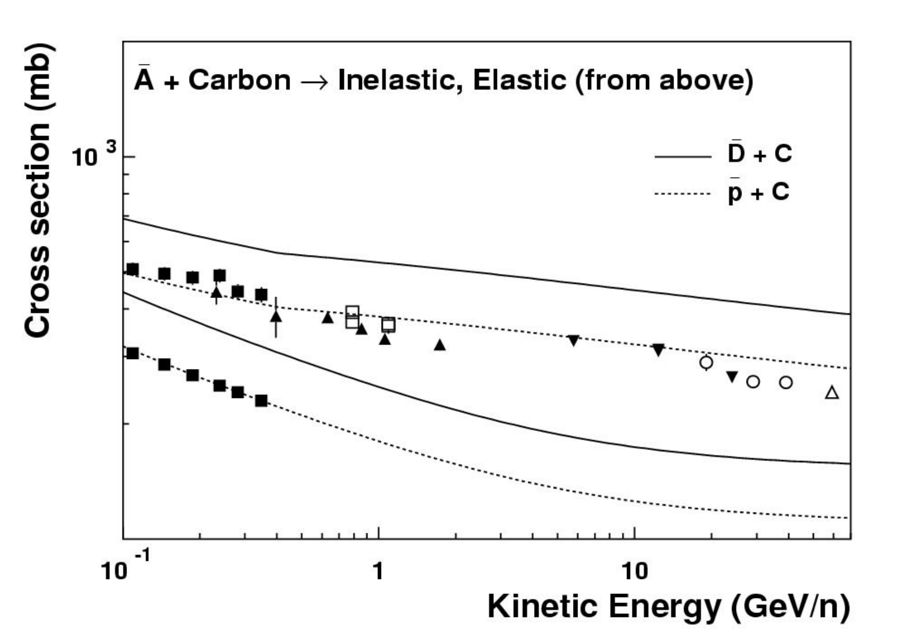
	$\varepsilon_{\mathrm{trig}}$	$\varepsilon_{\mathrm{rec}}$	$\varepsilon_{\mathrm{pre}}$	$\varepsilon_{\mathrm{qual}}$	$\varepsilon_{\mathrm{d}E/\mathrm{d}x}$	$\varepsilon_{1/\beta}$	$\varepsilon_{\mathrm{agl}}$	$\varepsilon_{\mathrm{acctrk}}$	$\varepsilon_{\mathrm{acchit}}$	$\varepsilon_{\mathrm{air}}$
D sample		○		○	○	○	○			
p sample		○		○			○			
random								○	○	
p beam	○									
M.C.			○	○						○

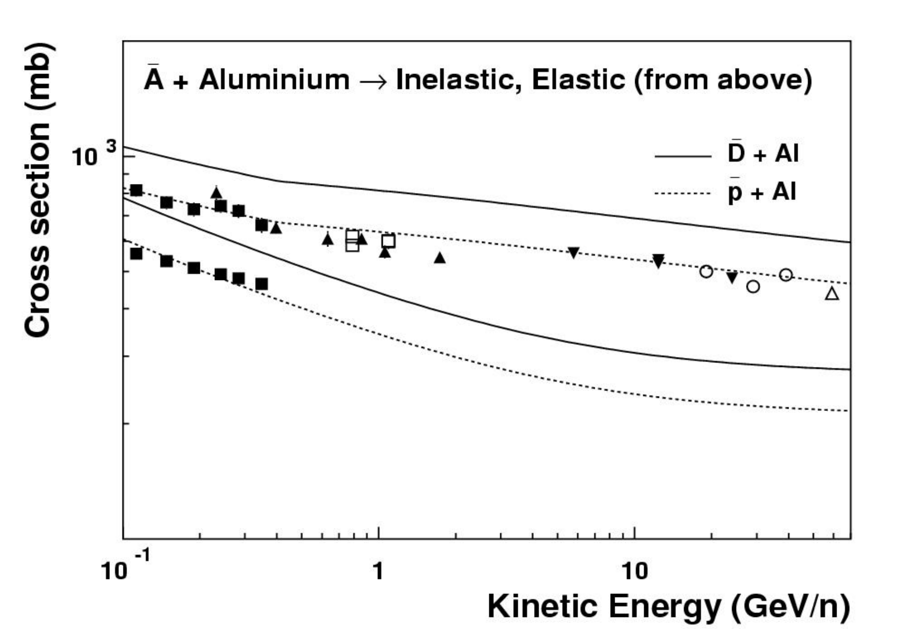
Cross section

- ✓ Elastic/inelastic cross sections of $\bar{D}$
  ← scale those of $\bar{p}$ by hard sphere model

$$\sigma(A_i, A_t) \propto \left[A_i^{1/3} + A_t^{1/3} - 0.71(A_i^{-1/3} + A_t^{-1/3}) \right]^2$$

- ✓ Inelastic interaction
  → $\bar{D}$ is fragmented or annihilated



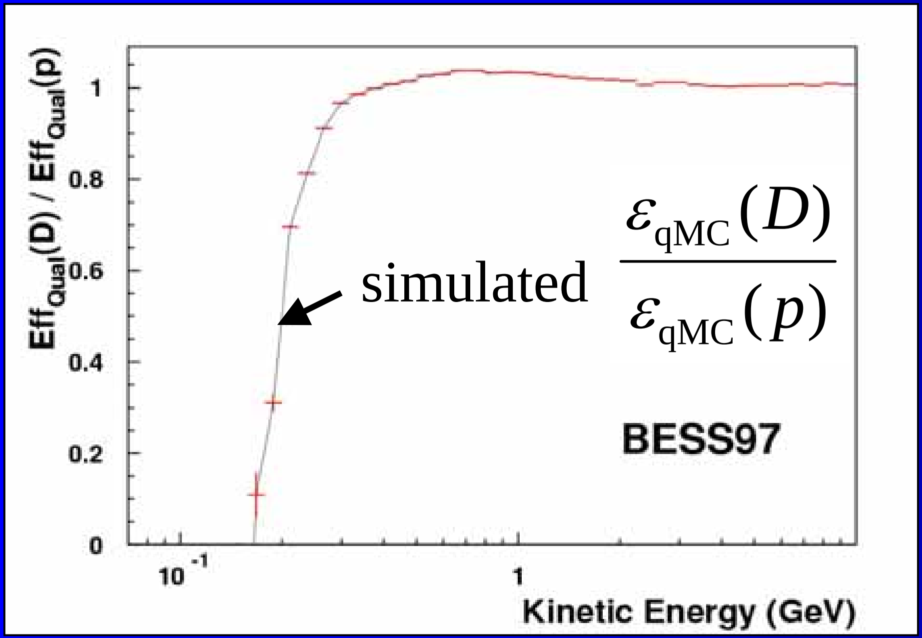


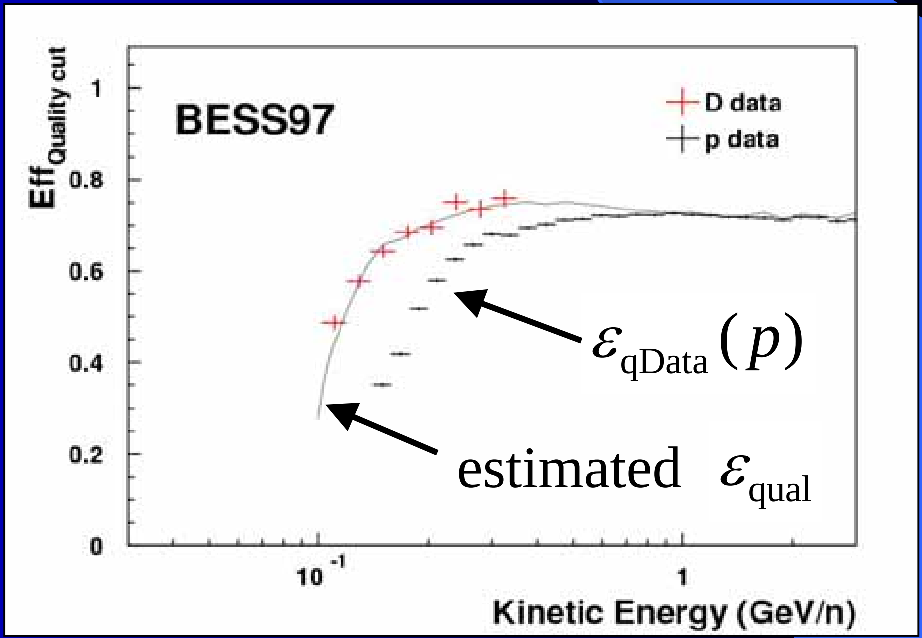
Efficiency of Quality Cut

- ✓ Quality cut efficiency ← basically from Deuteron data.
- ✓ In high-E region, quality cut is essential for p/D separation.

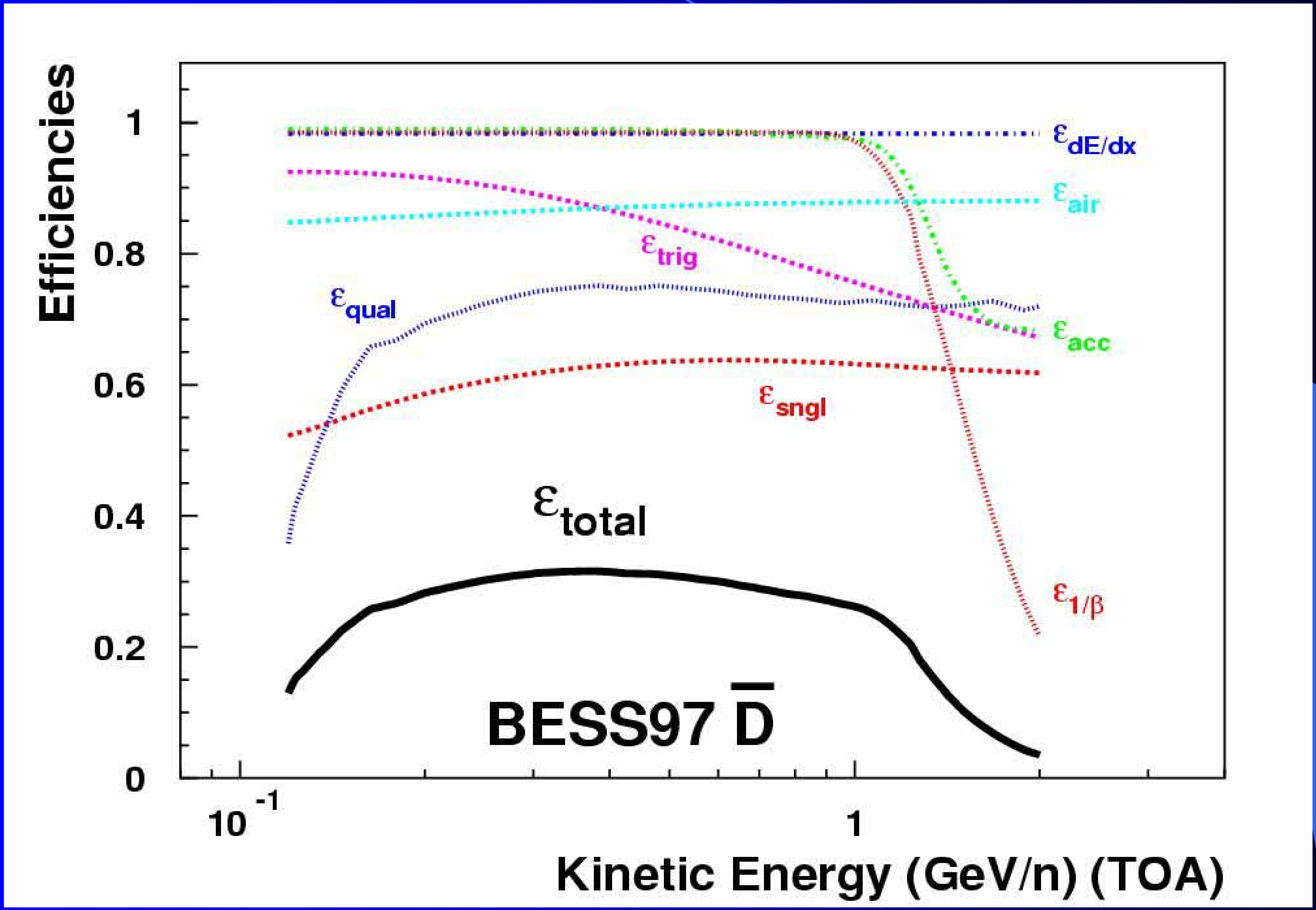
⇒ Estimated by using both of data and MC.

$$\varepsilon_{\text{qual}} = \varepsilon_{\text{qData}}(p) \cdot \frac{\varepsilon_{\text{qMC}}(D)}{\varepsilon_{\text{qMC}}(p)}$$





Efficiencies



Systematic errors

$$\left|\frac{\Delta\left(S\Omega\cdot T_{\text{live}}\cdot\varepsilon_{\text{total}}\right)}{S\Omega\cdot T_{\text{live}}\cdot\varepsilon_{\text{total}}}\right|^2=\left|\frac{\Delta\left(S\Omega\right)}{S\Omega}\right|^2+\left|\frac{\Delta T_{\text{live}}}{T_{\text{live}}}\right|^2+\left|\frac{\Delta\varepsilon_{\text{trig}}}{\varepsilon_{\text{trig}}}\right|^2+\left|\frac{\Delta\varepsilon_{\text{rec}}}{\varepsilon_{\text{rec}}}\right|^2+\left|\frac{\Delta\varepsilon_{\text{pre}}}{\varepsilon_{\text{pre}}}\right|^2$$

$$+\left|\frac{\Delta\varepsilon_{\text{qual}}}{\varepsilon_{\text{qual}}}\right|^2+\left|\frac{\Delta\varepsilon_{\text{dE/dx}}}{\varepsilon_{\text{dE/dx}}}\right|^2+\left|\frac{\Delta\varepsilon_{1/\beta}}{\varepsilon_{1/\beta}}\right|^2+\left|\frac{\Delta\varepsilon_{\text{agl}}}{\varepsilon_{\text{agl}}}\right|^2+\left|\frac{\Delta\varepsilon_{\text{acctrk}}}{\varepsilon_{\text{acctrk}}}\right|^2+\left|\frac{\Delta\varepsilon_{\text{acchit}}}{\varepsilon_{\text{acchit}}}\right|^2+\left|\frac{\Delta\varepsilon_{\text{air}}}{\varepsilon_{\text{air}}}\right|^2$$

dominant ~ 9 %

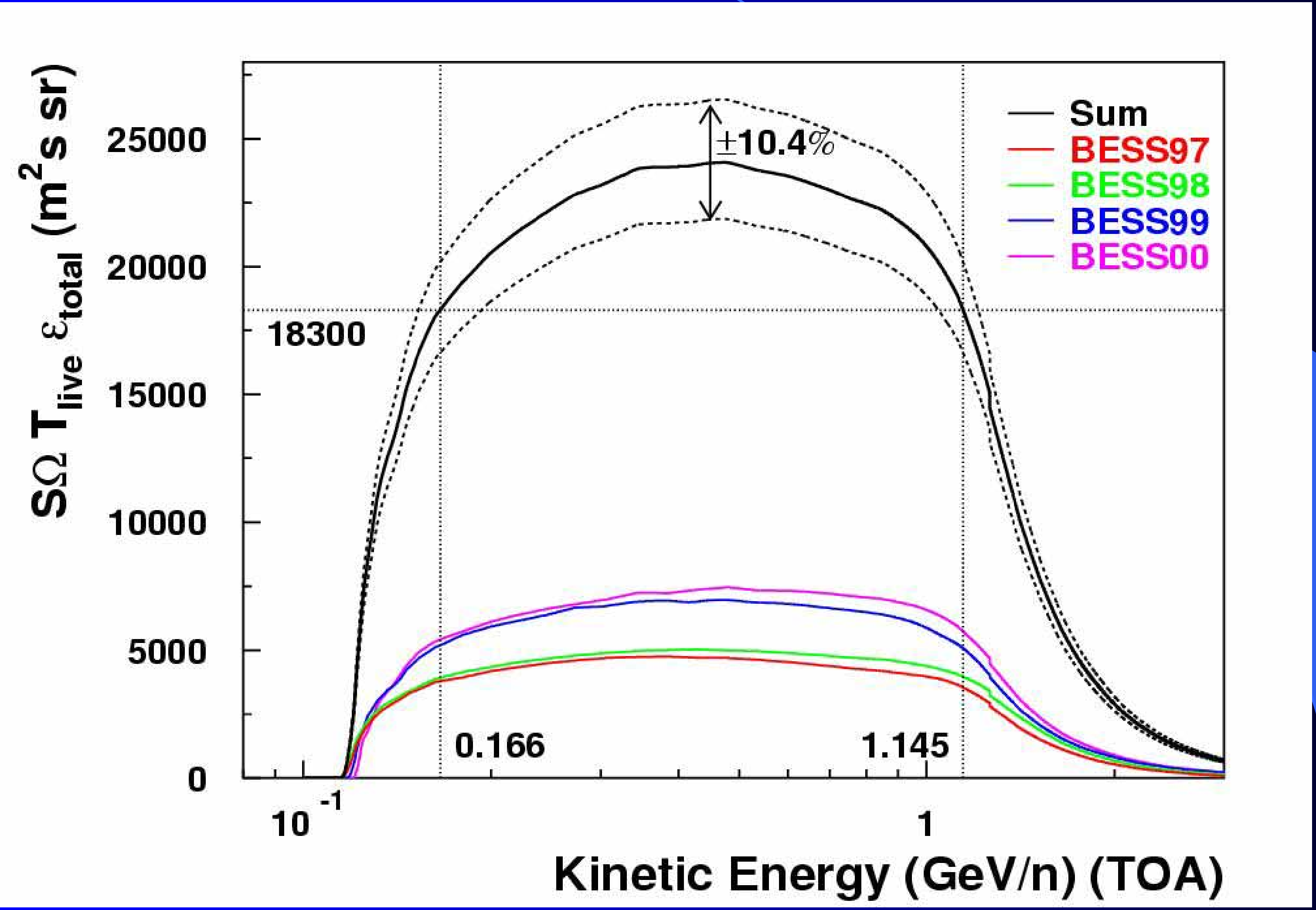
2nd largest ~ 6 %

3rd largest ~ 3 %

⇒ **Total ~ 10.4 %**

- ✓ The above three efficiencies ← from MC.
- ✓ Uncertainty in cross sections is not considered
  (∵ fixed by the assumption)

Effective exposure factor

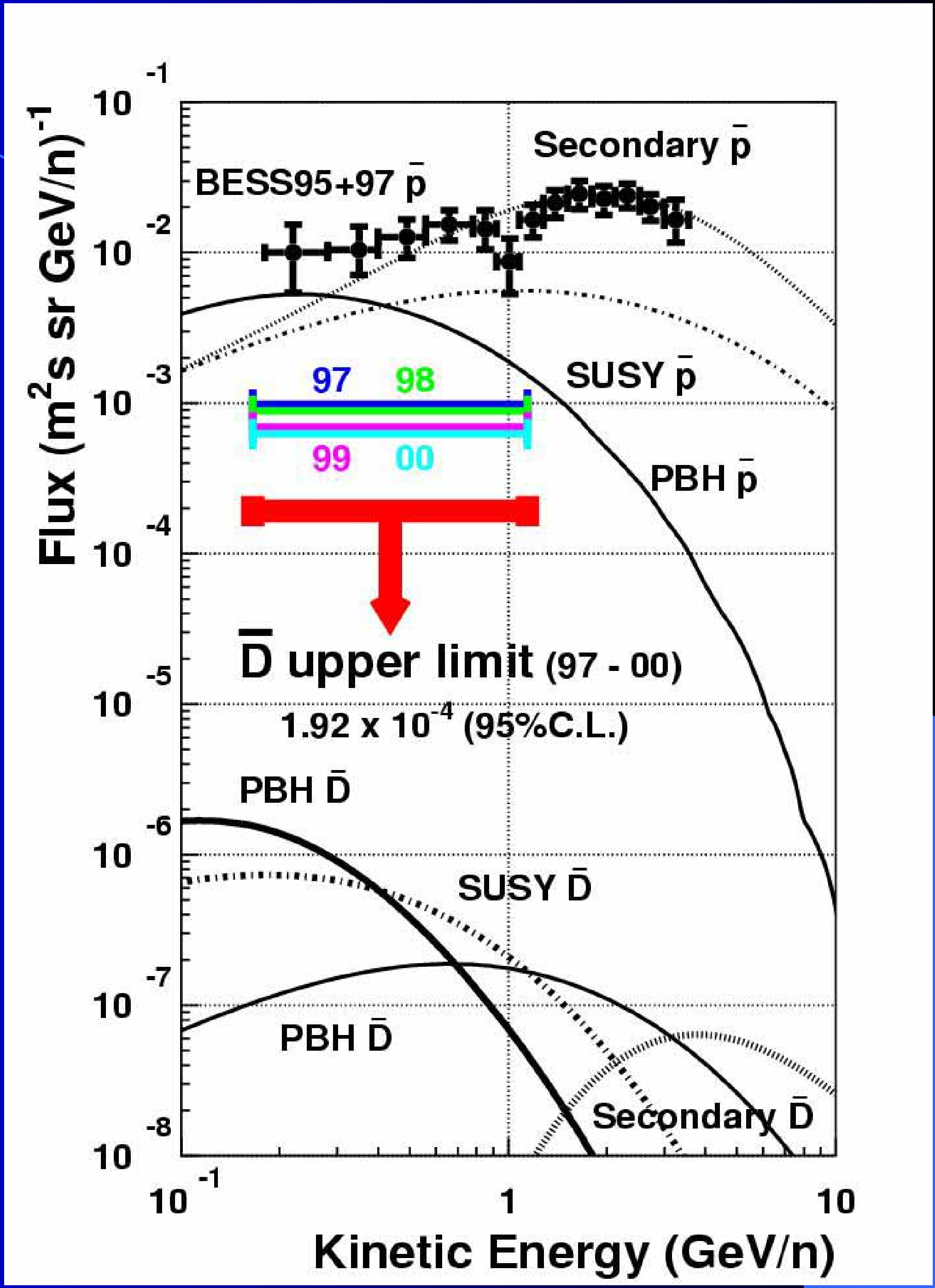


$\bar{D}$ 流束上限値

'97-'00 (sum)	1.92×10^{-4} $(m^2 s\ sr\ GeV/n)^{-1}$

1997	9.82×10^{-4}
1998	8.87×10^{-4}
1999	6.91×10^{-4}
2000	6.24×10^{-4}

0.17 - 1.15 GeV/n



Discussions

Prediction of $\bar{D}$'s from PBHs

Calculation steps

① Particle emission

② Coalescence model

③ Source spectrum

④ Interstellar spectrum

⑤ Solar modulation

① Particle Emission

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \frac{\Gamma_s \mathrm{d}Q}{2\pi\hbar[\exp(Q/kT) - (-1)^{2s}]}$$ …… emission spectrum

$$\frac{\mathrm{d}^2 N_{\bar{N}}}{\mathrm{d}E\mathrm{d}t} = -\sum_j \int_{Q=E}^{\infty} \alpha_j \frac{\Gamma_{s_j}}{2\pi\hbar[\exp(Q/kT) - (-1)^{2s_j}]} \frac{\mathrm{d}g_{j\bar{N}}(Q,E)}{\mathrm{d}E} \mathrm{d}Q$$

…… antinucleon emission rate

$$T \equiv \frac{\hbar c^3}{8\pi GMk} \approx \frac{10^{13}\,\mathrm{g}}{M}\,\mathrm{GeV}$$ …… T vs. M relation

$$M_* \approx 5.0\times10^{14}\left(\frac{t_u}{13.7\mathrm{Gyr}}\right)^{1/3}\mathrm{g}$$ …… initial mass of expring PBHs

② Coalescence model

$$\gamma\frac{d^3 n_{\bar{D}}}{dp^3} = \frac{4}{3}\pi p_0^3 \left(\gamma\frac{d^3 n_{\bar{p}}}{dp^3}\right)\left(\gamma\frac{d^3 n_{\bar{n}}}{dp^3}\right) \approx \frac{4}{3}\pi p_0^3 \left(\gamma\frac{d^3 n_{\bar{p}}}{dp^3}\right)^2$$

Coalescence momentum $p_0 = 130\mathrm{MeV}/c$

PYTHIA/JETSET

c.f.

Other predictions of $\bar{\mathrm{D}}$ spectra

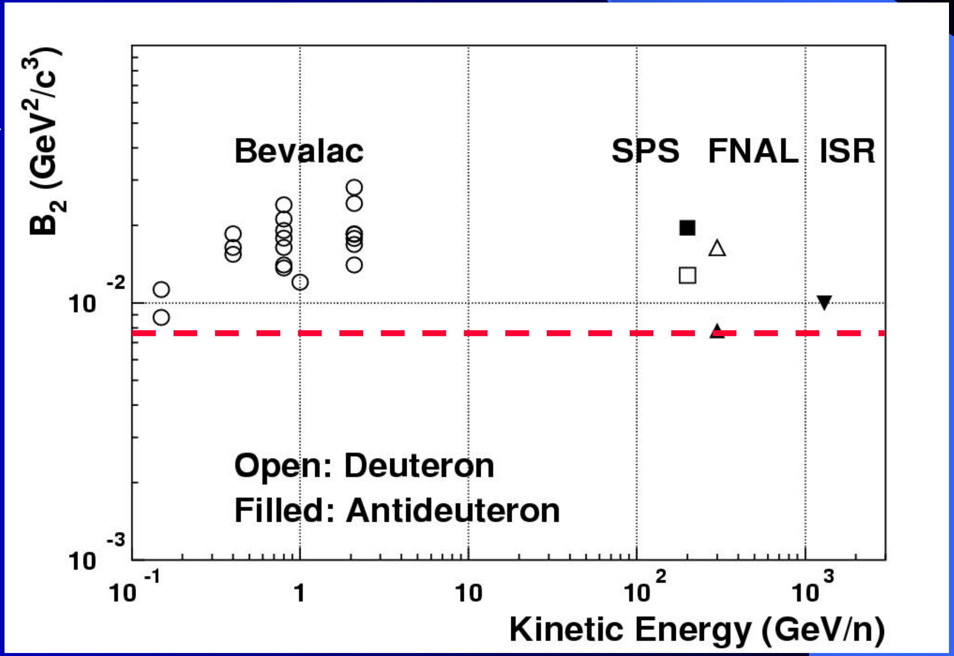
→ p_0 ~110~160MeV/c

"A+A" accelerator (Low E)

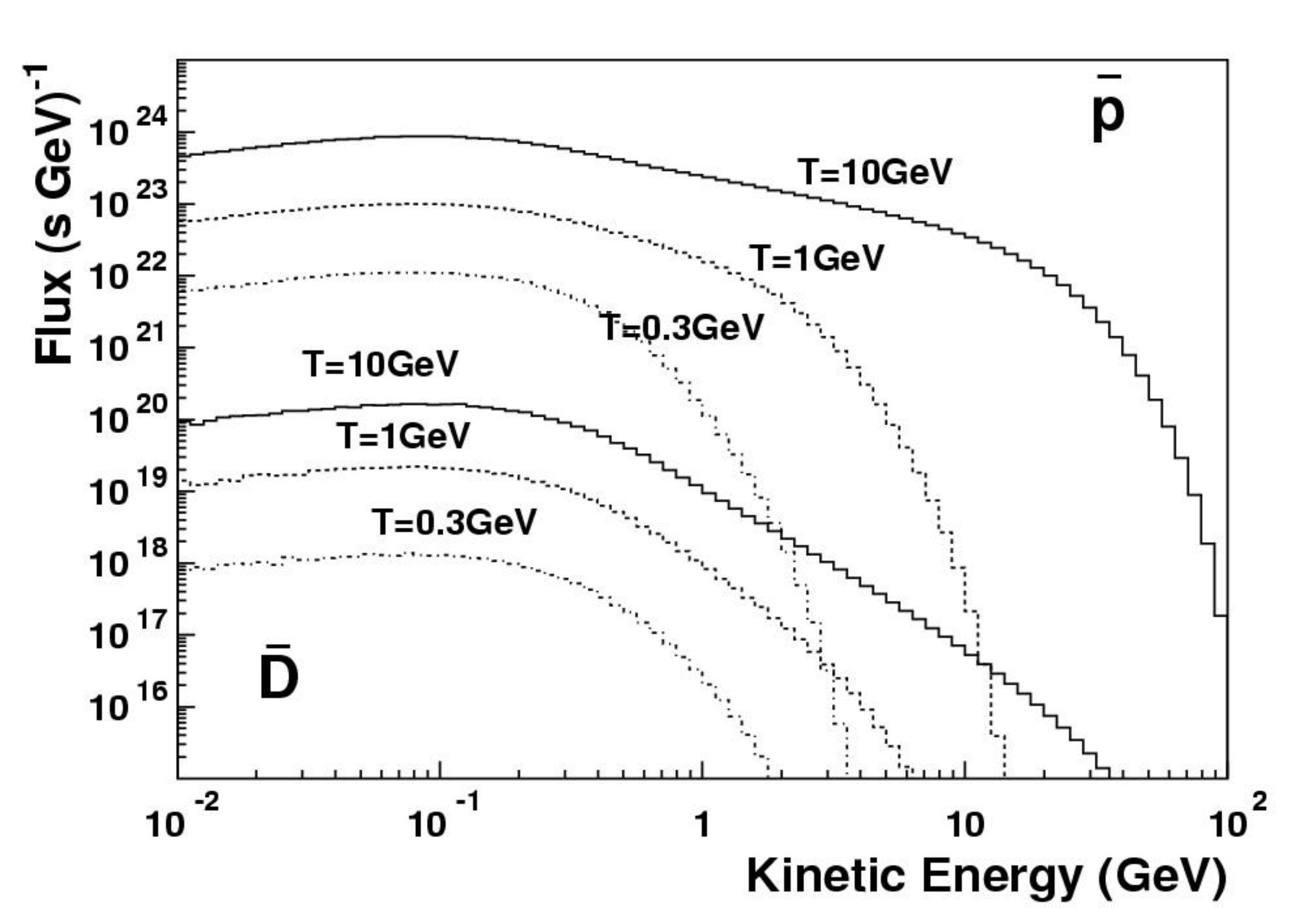
→ p_0 ~140~210MeV/c

Theoretically

→ p_0 ~100~400MeV/c



② Coalescence model

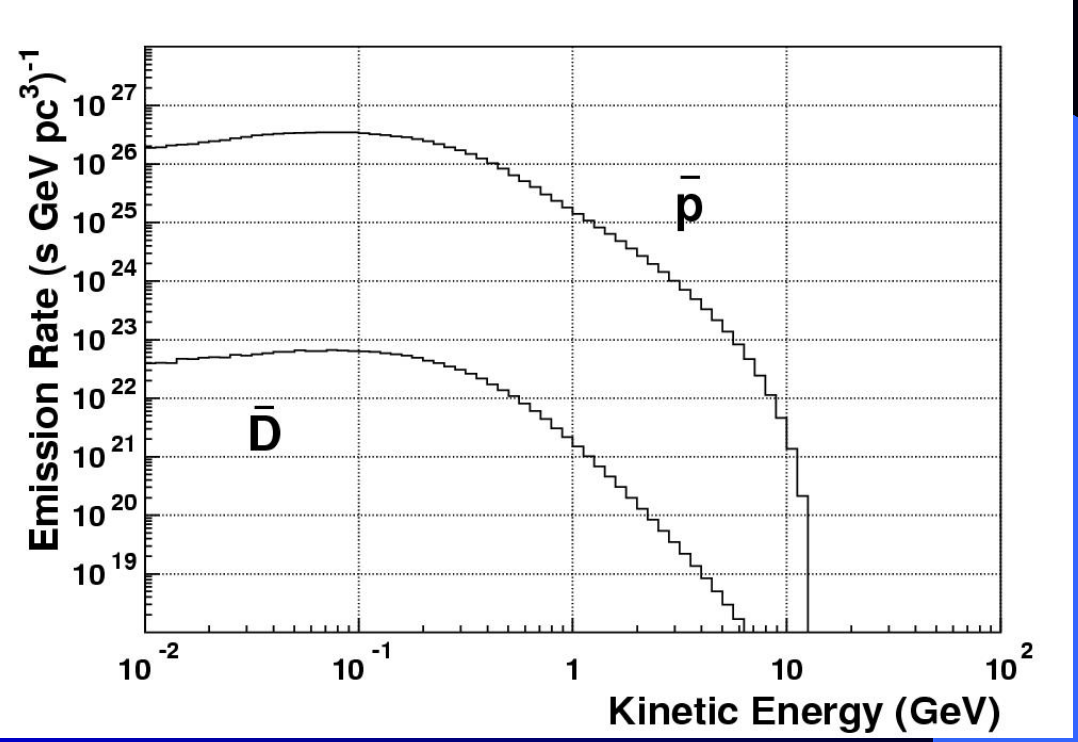


③ Source Spectrum

$$\frac{dn}{dT} \approx 5.2 \times 10^2 \left(\frac{T}{1\mathrm{GeV}}\right)^{-4.2} \left(\frac{\varepsilon_*}{10^{-8}}\right) \left(\frac{\rho_{h\odot}}{0.3\mathrm{GeV/cm}^3}\right) \left(\frac{M_*}{5.0 \times 10^{14}\,\mathrm{g}}\right)^{-2} \mathrm{GeV}^{-1}\mathrm{pc}^{-3}$$

$\rho_{h\odot}$ ……local density of halo dark matter

ε_* ……ratio of the density of PBHs with $M_i = M_*$ to $\rho_{h\odot}$



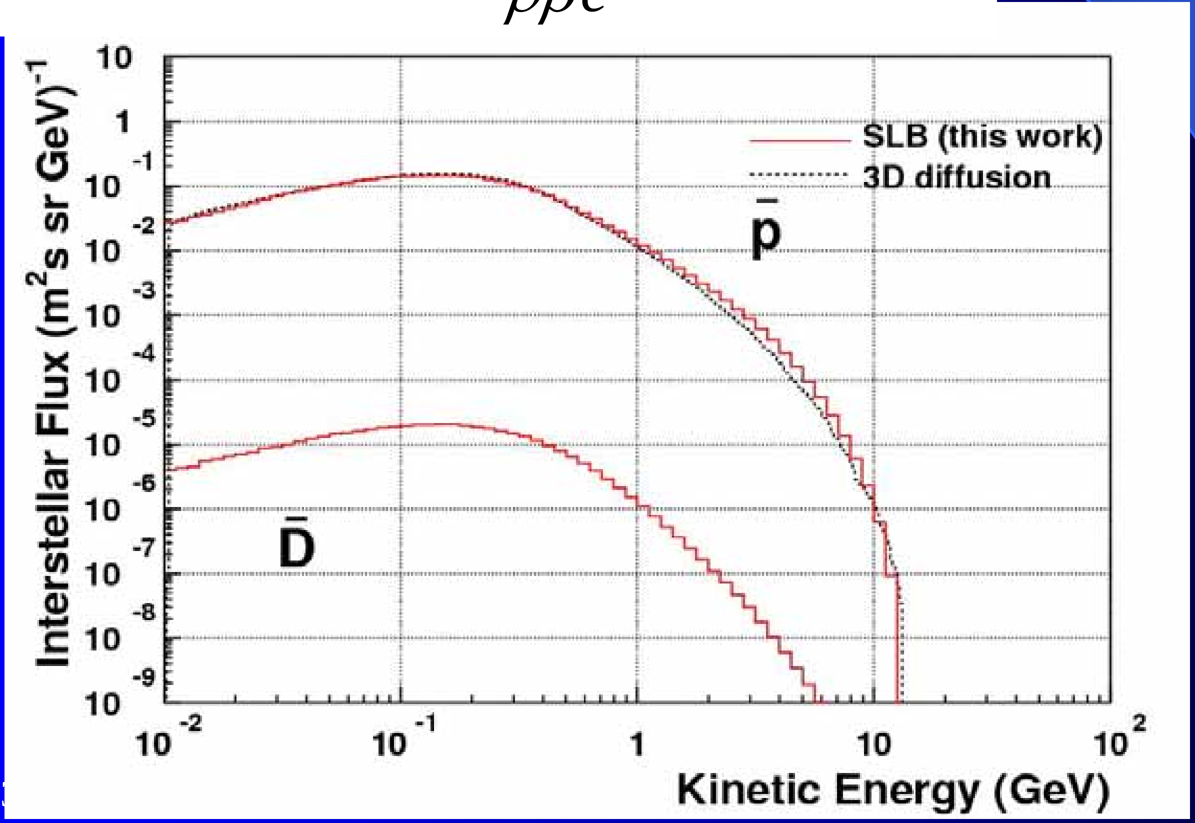
④ Interstellar Spectrum

Propagation by the Standard Leaky Box

$$\frac{1}{\lambda_{\rm esc}} I_{\bar{D}} = \frac{Q_{\bar{D}}}{4\pi\rho_{\rm m}} \quad , \qquad \lambda_{\rm esc} = \lambda_{\rm esc}(R,\beta) \approx 17 \,{\rm g/cm^2}$$

← B/C ratio, C/O ratio …

$$c.f. \quad \tau_{\rm esc} = \frac{\lambda_{\rm esc}}{\rho\beta c} \approx 3\times10^7\,{\rm yr}$$



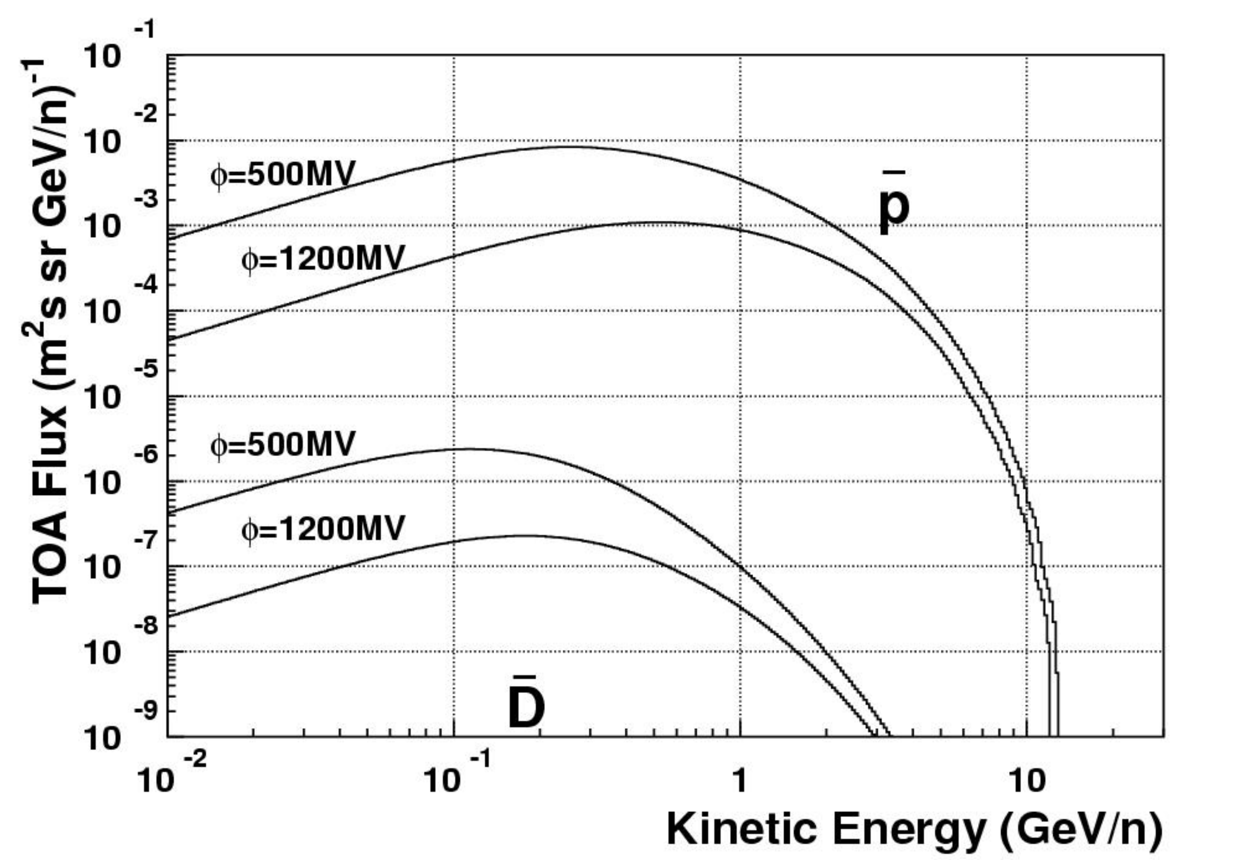
⑤ Solar Modulation

Numerical calculation of the spherically symmetric model by Fisk.

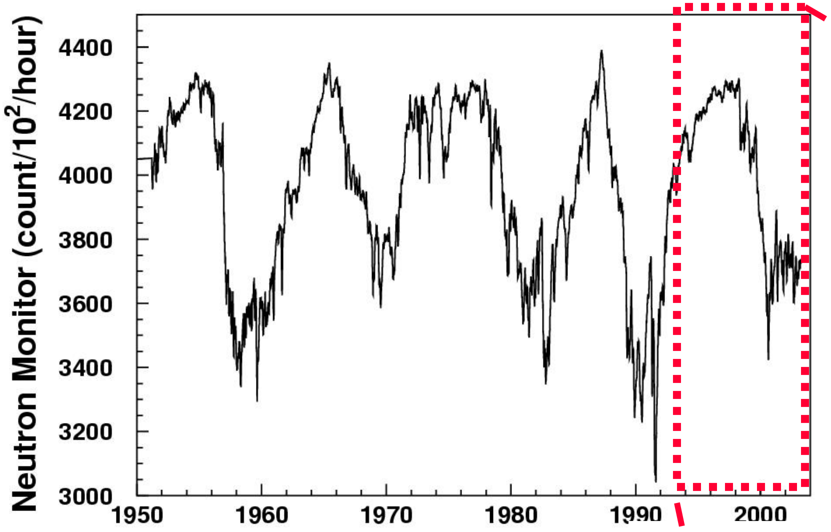
$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 S\right) = -\frac{V}{3}\frac{\partial^2}{\partial r \partial E}\left(\alpha E U\right)$$

Modulation parameter from proton spectrum

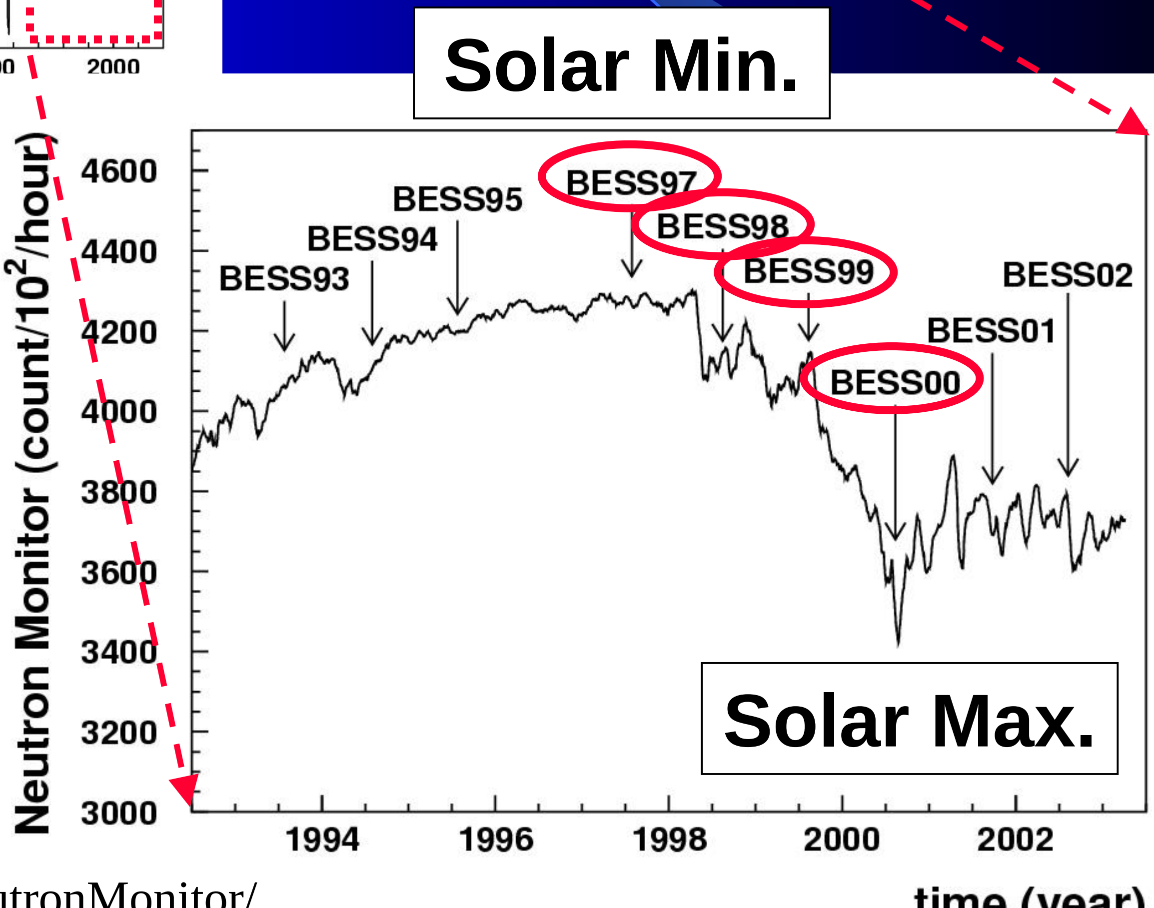
1997: $\phi =$ 500MV
1998: $\phi =$ 610MV
1999: $\phi =$ 648MV
2000: $\phi =$ 1344MV



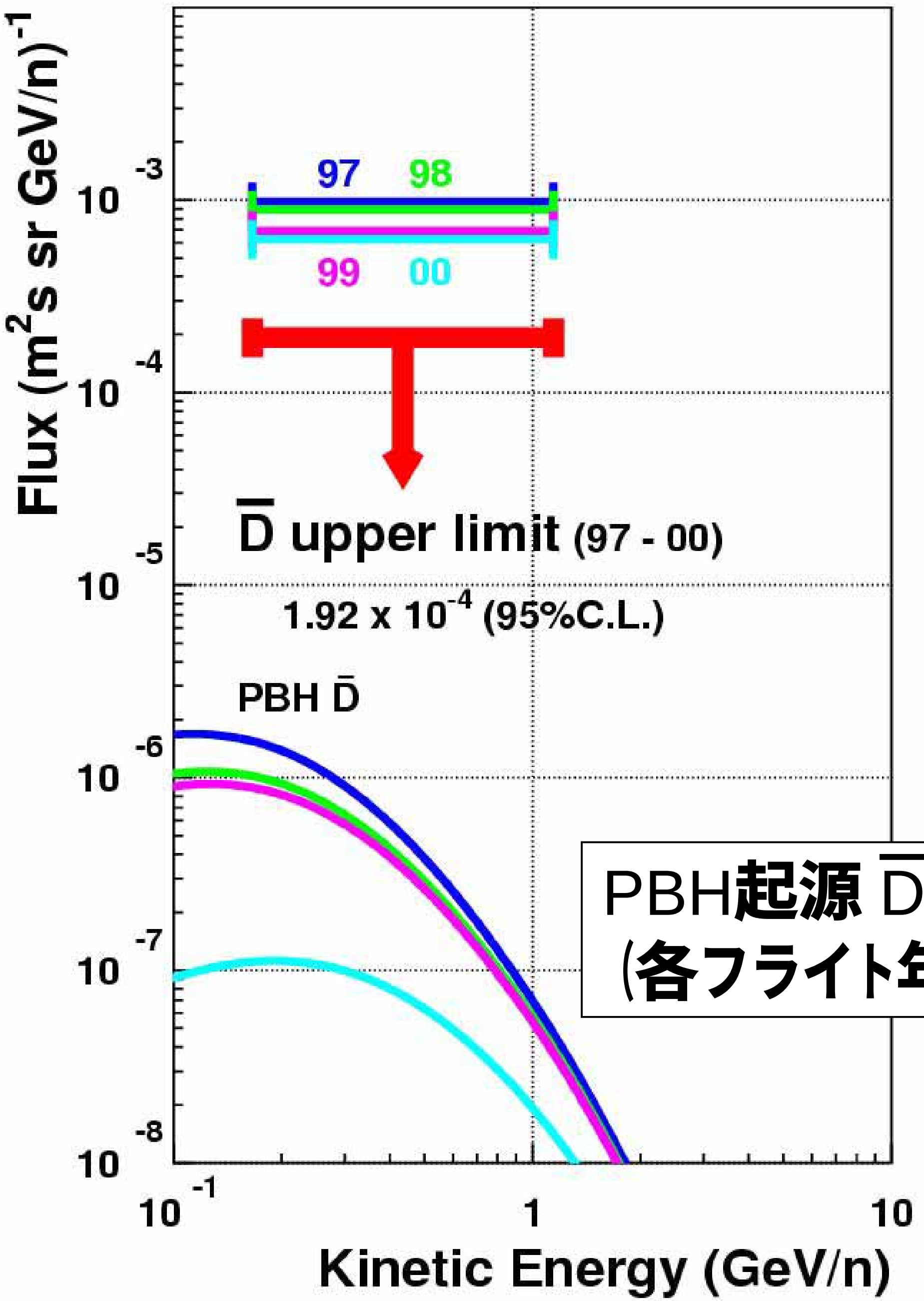
Solar Activity



Climax Neutron Monitor



http://odysseus.uchicago.edu/NeutronMonitor/



PBH**起源** $\bar{D}$ **スペクトラム**
(各フライト年に対応)

Local PBH の蒸発頻度に対する上限値

$$R_{\mathrm{PBH}} \equiv \int_{T_1}^{\infty} \frac{\mathrm{d}n}{\mathrm{d}T}\,\mathrm{d}T$$

$$\approx 3.1\times10^{-3}\left(\frac{\varepsilon_*}{10^{-8}}\right)\left(\frac{\rho_{h\odot}}{0.3\mathrm{GeV/cm^3}}\right)\left(\frac{M_*}{5.0\times10^{14}\,\mathrm{g}}\right)^{-2}\mathrm{pc^{-3}yr^{-1}}$$

95% C.L. ($\mathrm{pc^{-3}yr^{-1}}$)

'97-'00 sum	1.8×10^{0}

結果

1997	5.2×10^{0}
1998	6.9×10^{0}
1999	5.7×10^{0}
2000	2.6×10^{1}

c.f. Upper limits on R_{PBH}

$\bar{p}$ … ~10^{-2}

TeV-GRB … ~$10^{5\text{-}6}$

Diffuse γ-ray … ~10^{-1}

PBH の密度パラメータに対する上限値

$$\frac{d\varepsilon}{dM} = \frac{\varepsilon_*}{M_*}\left(\frac{M_i}{M_*}\right)^{1-\alpha} \quad , \quad \alpha = \frac{5}{2}$$

$$\Omega_{\mathrm{PBH}} \equiv \Omega_h \int_{M_*}^{\infty} \frac{\mathrm{d}\varepsilon}{\mathrm{d}M_i}\mathrm{d}M_i = 2.0\times10^{-9}\left(\frac{\varepsilon_*}{10^{-8}}\right)\left(\frac{\Omega_h}{0.1}\right)$$

95% C.L.

$\boxed{\text{'97-'00 (sum)} \quad 1.2\times10^{-6}}$ ← result

c.f. Upper limits on Ω_{PBH}

$\bar{p}$ … $\sim 10^{-8 \sim -9}$

e^+/e^- … $\sim 10^{-9}$

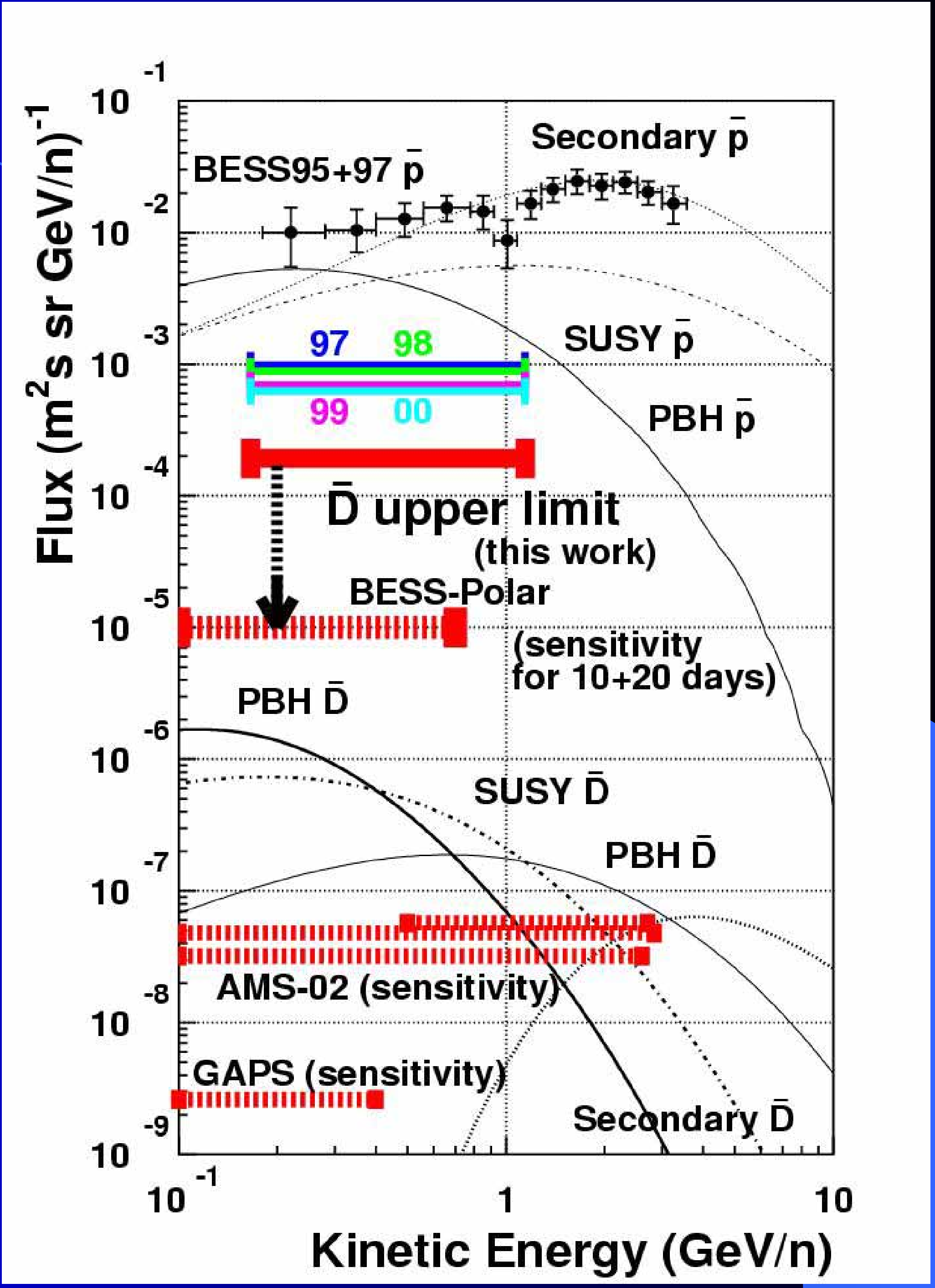
Diffuse γ-ray … $\sim 10^{-8}$

Future Prospects
ー 次期計画 BESS-Polar ー

Tiger Antarctica Flight, 2001/2002

Future Prospects

- ✓ BESS-Polar
- ✓ AMS
- ✓ PAMELA
- ✓ GAPS



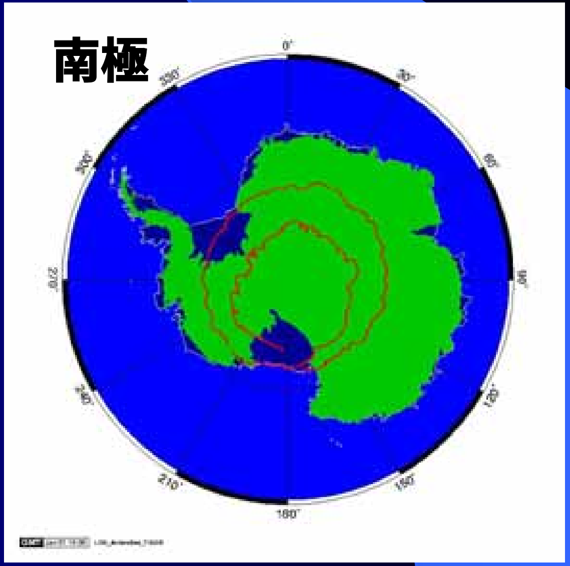
次期計画：BESS-Polar

- ✓ 極地周回気球による長時間観測
  → これまでの10倍のフライト時間
- ✓ 測定器の更なる薄肉化
  → 低エネルギー領域に特化

⇩

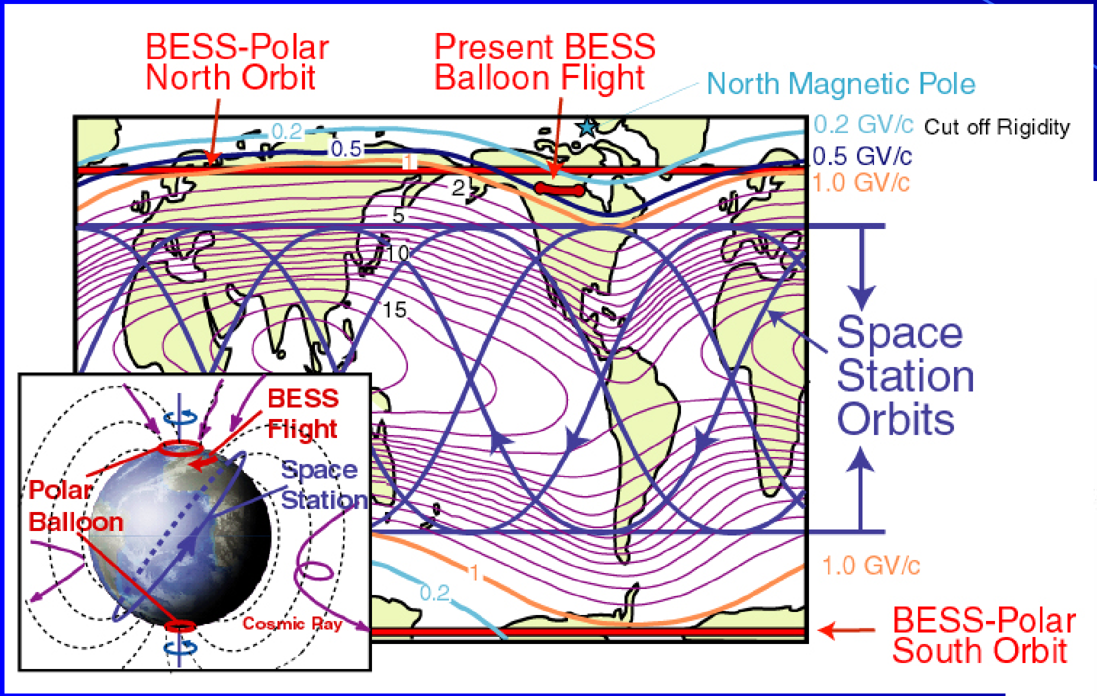
$\overline{D}$ の更なる探索

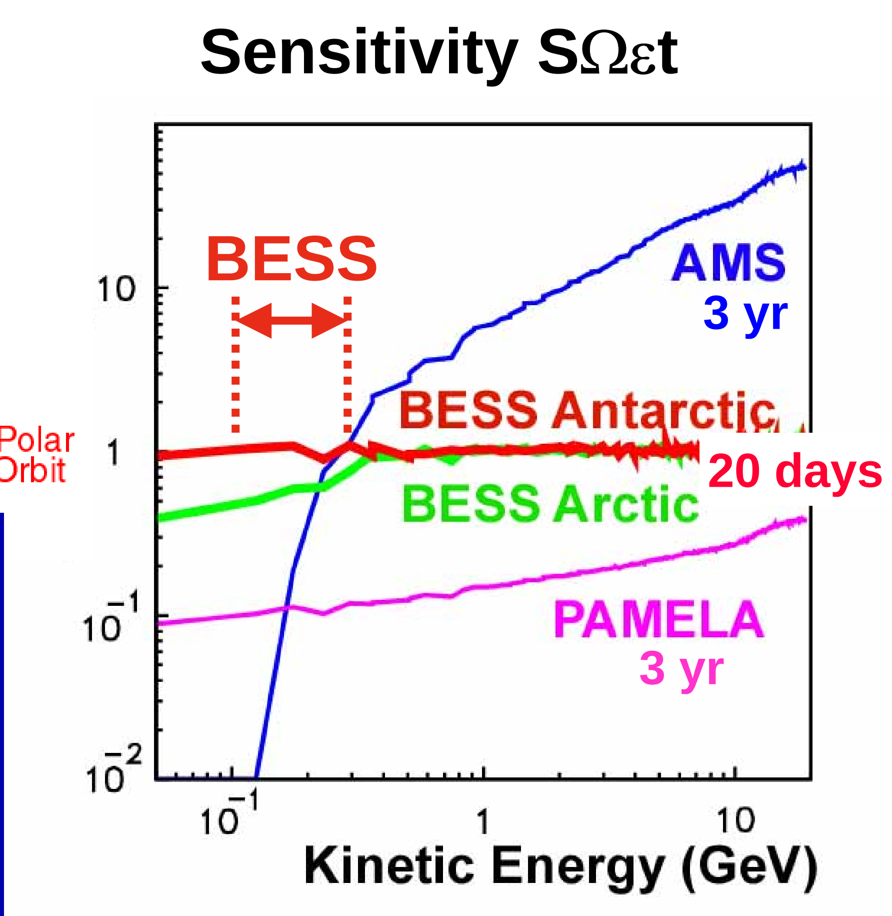
- ✓ 1st flight：2004年12月 南極周回
- ✓ 2nd flight：2006年12月 南極周回
  （太陽活動極小期）



TIGER 31日間フライト
飛翔経路（2001）

BESS-Polar / PAMELA / AMS





低エネルギーは BESS-Polar !!

3実験が相補的に


BESS-Polar テクニカルフライト
ー 長時間飛翔への試金石 ー
BESS-Polar マグネット (実機)
南極フライトに準じた通信系
太陽電池パネル (実機サイズ)
測定器は載せず


テクニカルフライト 打ち上げ
10月1日 @ Ft. Sumner

BESS-TeV
去年

BESS-Polar
今回

テクニカルフライト 軌跡


スペクトロメータを無事に回収
太陽電池パネルは設計通りに“ぺしゃんこ”

BESS-Polar スケジュール

- 2002/ 5月　テストフライト@三陸 (太陽電池システム)
- 2003/ 7月　ビームテスト@KEK (TOF/MTOF/AGL)
- 2003/ 9-10月　テクニカルフライト@Ft.Sumner

↓

- 2003/10月～　最終調整 @NASA/GSFC
- 2004/12月　第一回 BESS–Polar フライト

↓

- 2006/12月　第二回 BESS–Polar フライト (太陽活動極小期)

まとめ

- ✓ **宇宙線 $\bar{D}$ の流束上限値を初めて得た：**
  $1.9 \times 10^{-4} (m^2 s\ sr^2 GeV/n)^{-1}$　in 0.17-1.15 GeV/n
- ✓ **低エネルギー宇宙線$\bar{D}$は未知の一次起源に対するユニークなプローブ。**
- ✓ BESS '97-'00 **データを用いて$\bar{D}$を探索。候補事例なし。**
- ✓ **$\bar{D}$をプローブとする各種上限値を算出。**
  - ➢ Local PBH**蒸発頻度**、PBH**密度パラメータ。**
- ✓ **本結果により、更なる高感度探索や関連物理の発展が動機付けられる。**
  - ➢ BESS-Polar **テクニカルフライト成功。**