

宇宙線直接観測と 暗黒物質の間接探索

2019年7月6日 @ダークマターの懇談会2019
早稲田大学理工学術院・総合研究所 浅岡陽一



Room for “unknown” unknowns

- There are **known knowns**; there are things we know we know.
- We also know there are **known unknowns**; that is to say we know there are some things we do not know.
- But there are also **unknown unknowns**—the ones we don't know we don't know.

quote from Rumsfeld in 2002, but the original idea was created by Joseph Luft (1916–2014) and Harrington Ingham (1916–1995)

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unknown knowns = Dark Matter

WIMPパラダイム

WIMP: Weakly Interacting
Massive Particle (wimp = 弱虫)

宇宙論・宇宙物理学

- 多数の観測・高精度化
⇒ 統一的描像
- 通常物質に暗黒物質
の候補存在せず

弱い相互作用
をする**未知の
重い素粒子**
“WIMP”

素粒子物理学

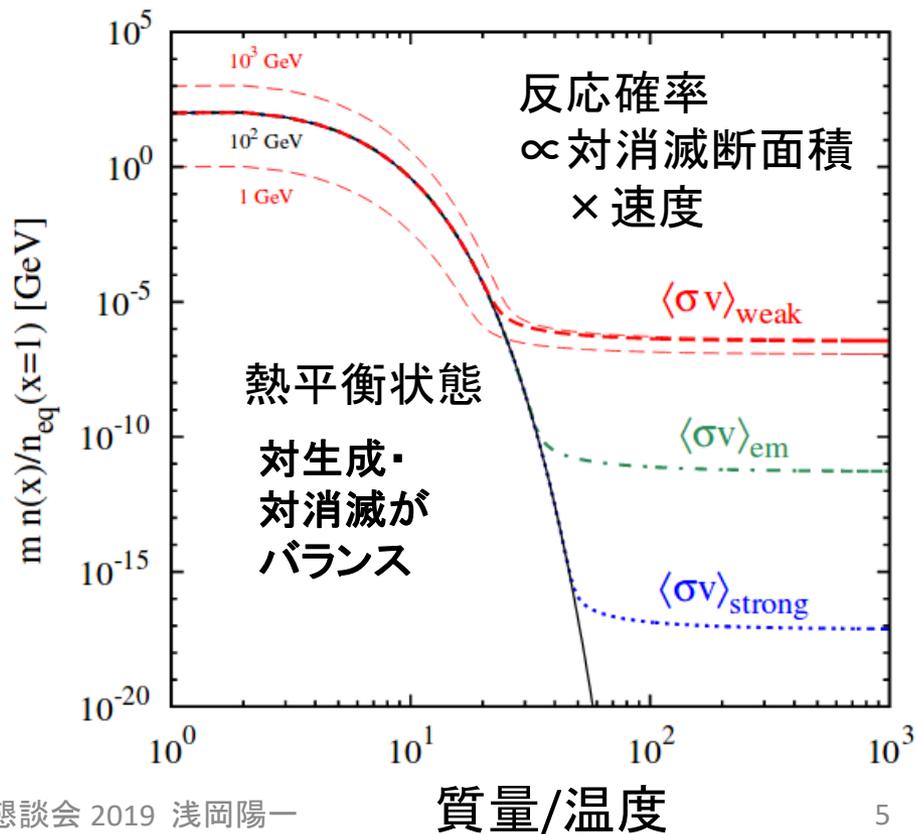
- 標準模型を超える
新物理への要請
 - 超対称性
 - 余剰次元
- 数々の新粒子 ⇒ 安定な粒子

熱平衡状態からの分離・凍結
⇒ 初期宇宙からの残存
“粒子”暗黒物質

- 熱平衡状態からの分離は初期宇宙
の基本的プロセス (ニュートリノ・光)
- 「弱い相互作用」の絶妙な強さ
⇒ 現在の暗黒物質残存量とぴったり
- 全てをこれ以上なくシンプルに説明
(オッカムの剃刀)

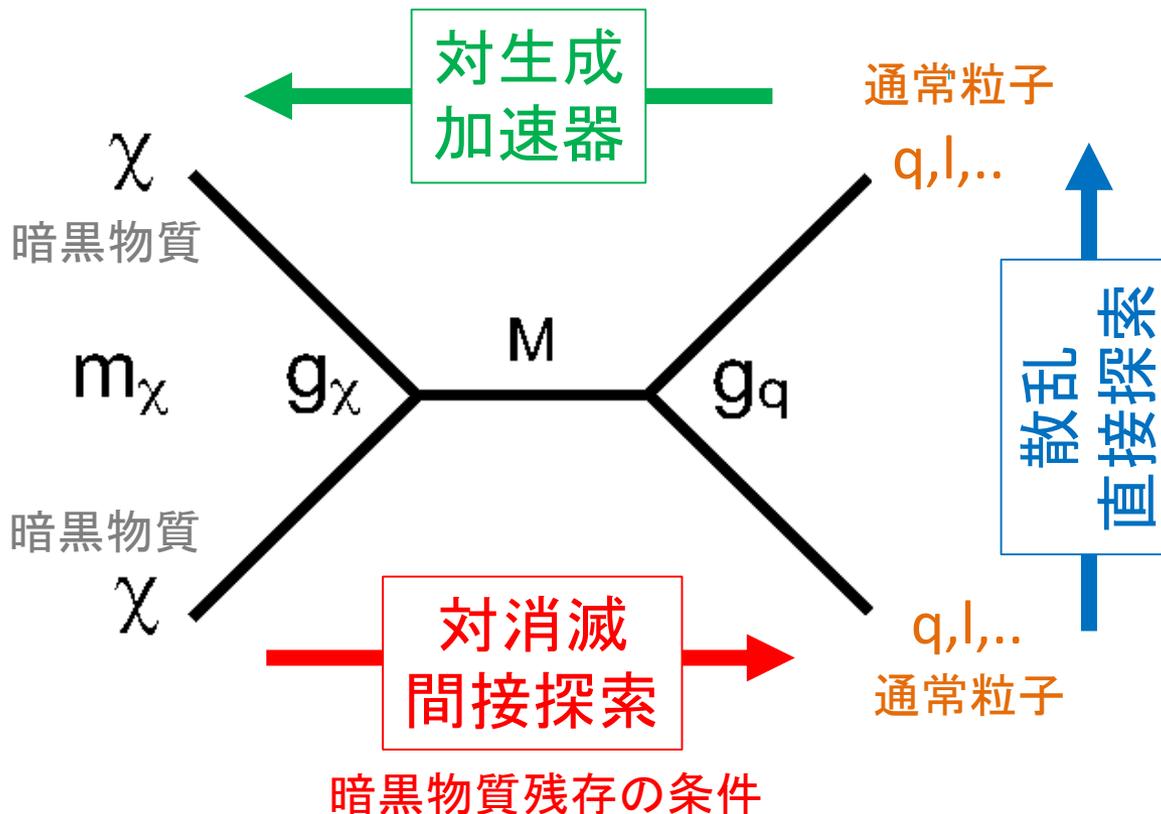
“WIMP Miracle”

奇跡に見えるのは物理(必然)だからでしょう



“粒子”暗黒物質の探索

WIMP発見 = (1) 暗黒物質の正体究明
 (2) 宇宙創成直後($10^{-10} \sim 14$ 秒)の観測、
 (3) 素粒子標準モデルを超える新物理の発見！



- 3つの手法がありそれぞれが相補的
- 世紀の大発見を目指し熾烈な競争
 - 多種の直接探索実験
- 加速器では消えた質量による検出が必要となり困難
 - モデル依存大
- 間接探索は暗黒物質残存の条件を“直に”プローブ可能

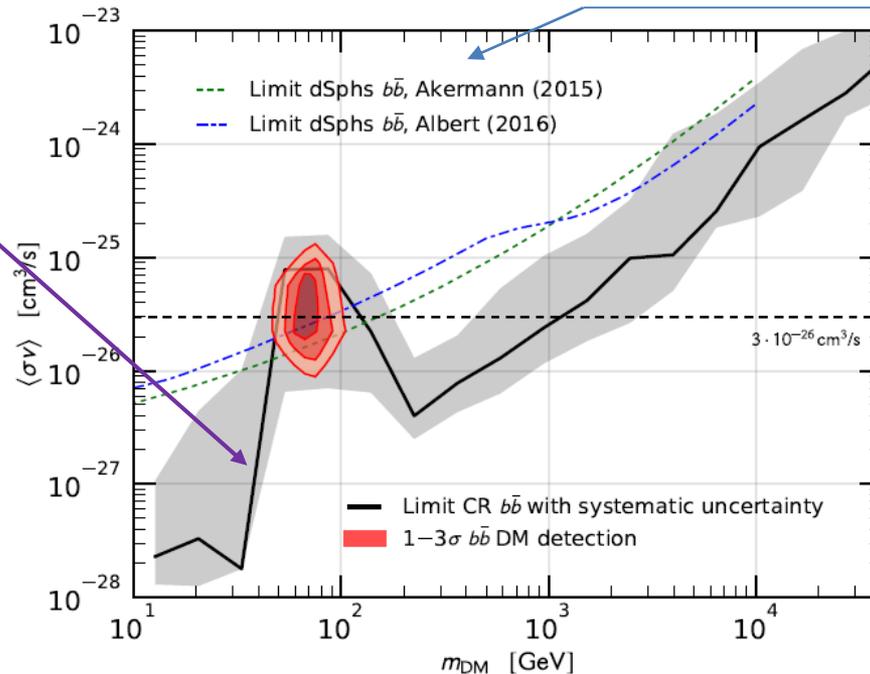
間接探索：ガンマ線＋荷電粒子（反粒子）

- 特徴：初期宇宙における熱的残存条件を直接探査
 - 暗黒物質密度と合致する対消滅頻度 $\Rightarrow \langle\sigma v\rangle \sim 3 \times 10^{-26} \text{ cm}^3/\text{s}$
 - 2系統の生成物：ハドロンチャンネル・レプトンチャンネル
- 困難：銀河宇宙線(+二次生成物) がバックグラウンド、不定性大
- 例：ガンマ線、陽電子、反陽子、他の宇宙線
 - ガンマ線：大きな質量を探索（銀河中心、矮小楕円体銀河の重合）
 - 反粒子：低バックグラウンド

AMS-02 反陽子測定
からの制限

暗黒物質がクォーク対
に対消滅し、そのハド
ロン化によって生成さ
れる反陽子流束の期
待値を用いて制限

Cuoco, Kramer, Korsmeier
PRL 118(2017)191102



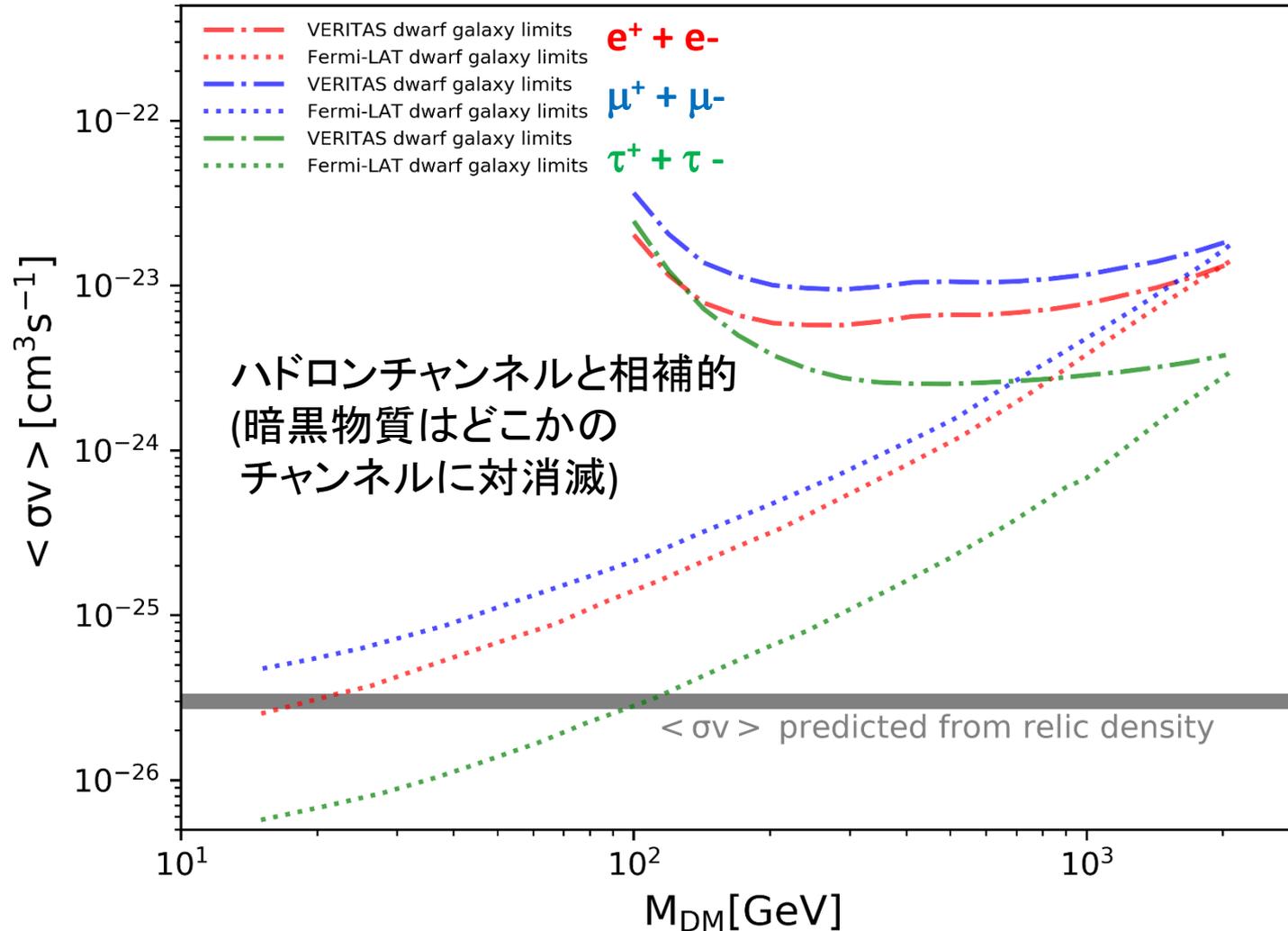
Fermi-LATの制限

ハドロン化の過程で
生成されるガンマ線
の連続成分を用い
て制限。質量が大き
く静かなドwarf銀
河からのガンマ線を
スタックして解析。
注：J-Factorの見積
りに不定性

(本結果はNFW使用)

暗黒物質制限:レプトンチャンネル

レプトン対への崩壊 \Rightarrow 陽電子の測定、ガンマ線の測定による制限



ガンマ線観測
ドwarf銀河の観測

VERITAS
チェレンコフ望遠鏡
(地上)

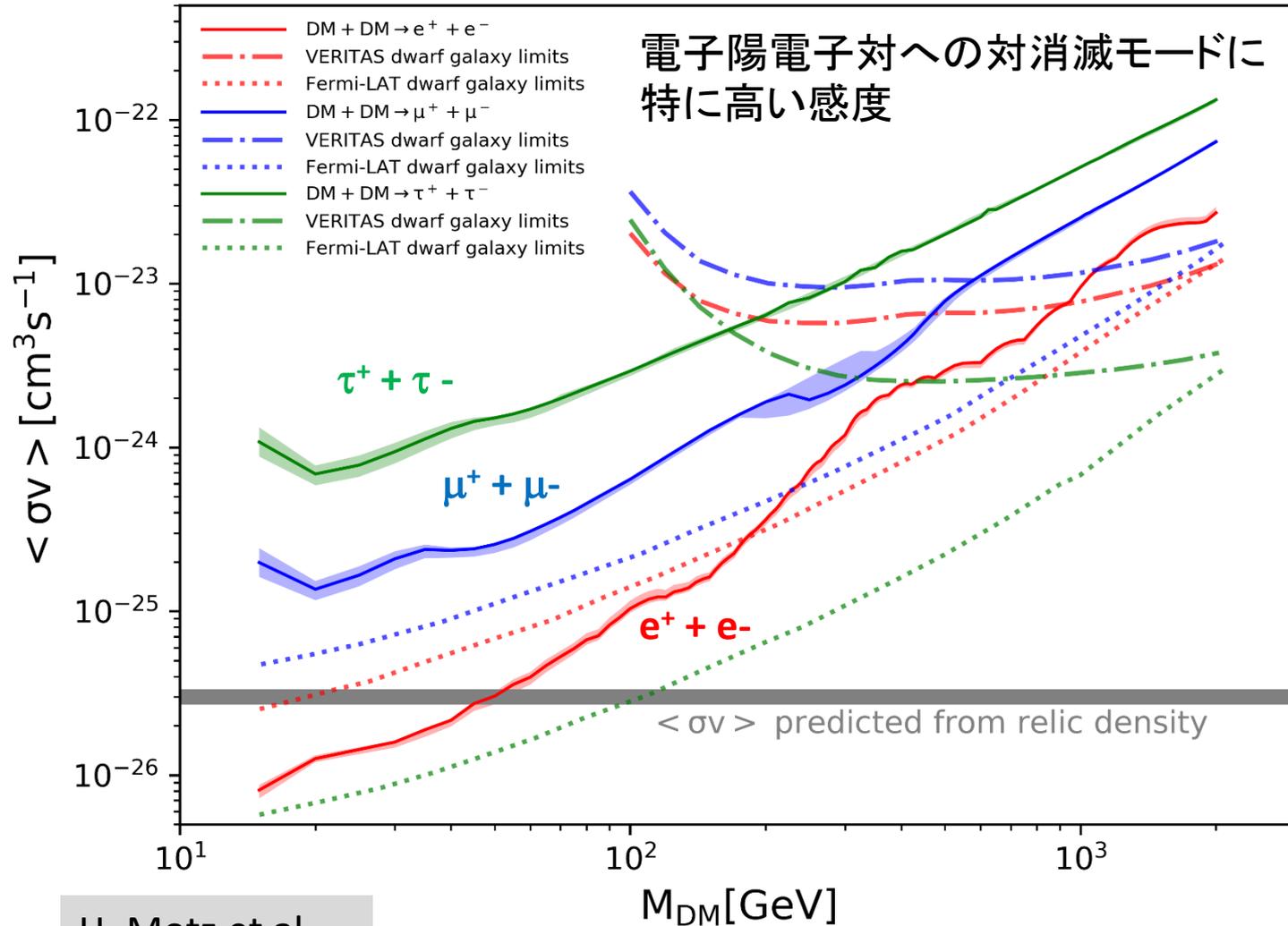
Fermi-LAT
電子対生成望遠鏡
(衛星)

VERITAS limits from
Physical Review D 95,
082001 (2017)

Fermi-LAT limits from
Phys. Rev. Lett. 115,
231301 (2015) (SM)

CALETによる暗黒物質制限

AMS-02 陽電子流束 (2014) + CALET全電子流束 (2018)



Shaded regions show variation from:

- solar modulation potential between 0.3, 0.4, 0.5, 0.6, 0.7 GV

- E_{cut} between 2 TeV, 4 TeV, 10 TeV

- low energy break smoothness s between 0.03, 0.05, 0.1

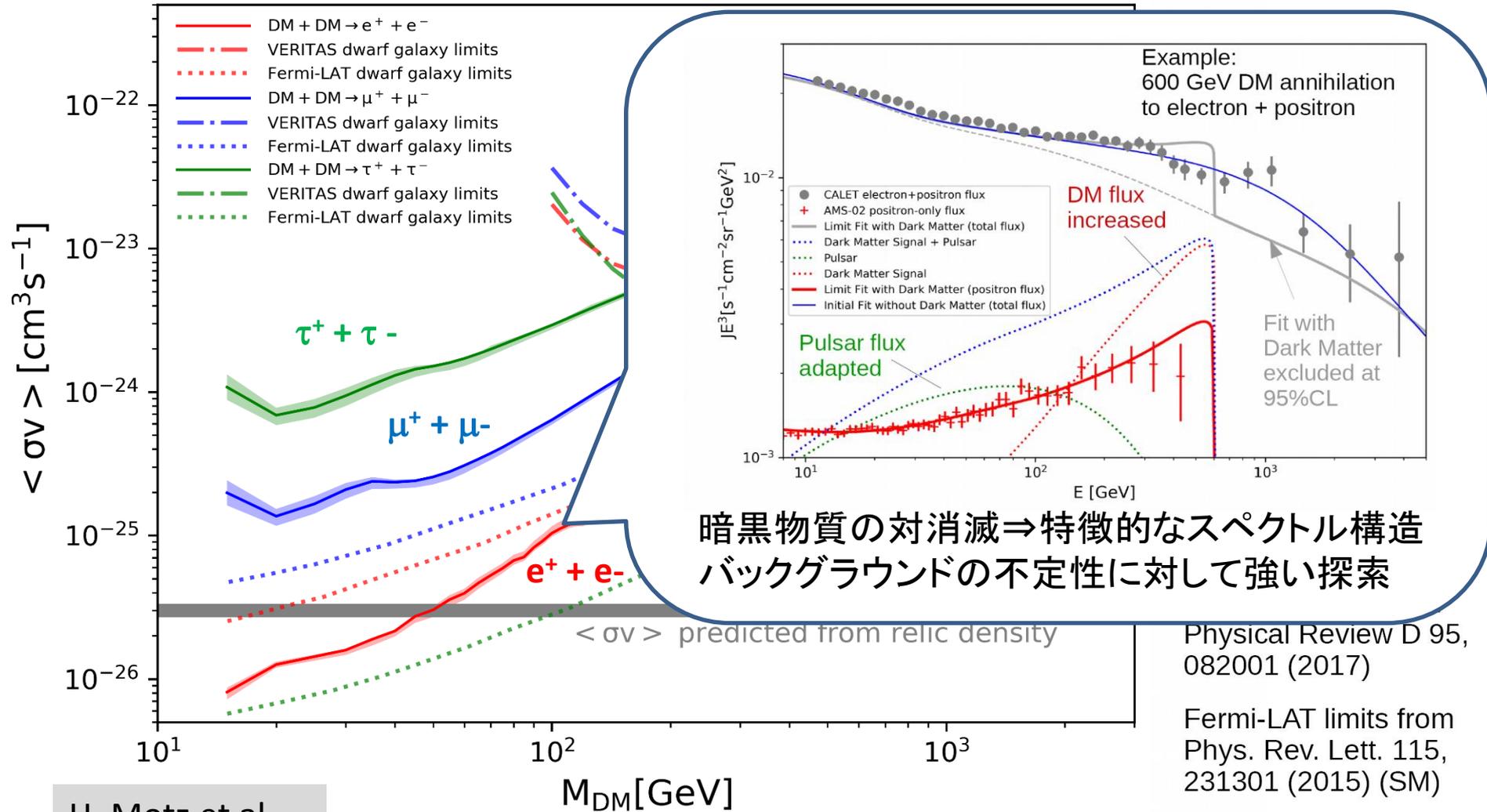
VERITAS limits from Physical Review D 95, 082001 (2017)

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H. Motz et al.,
JPS, Sept. 2018.

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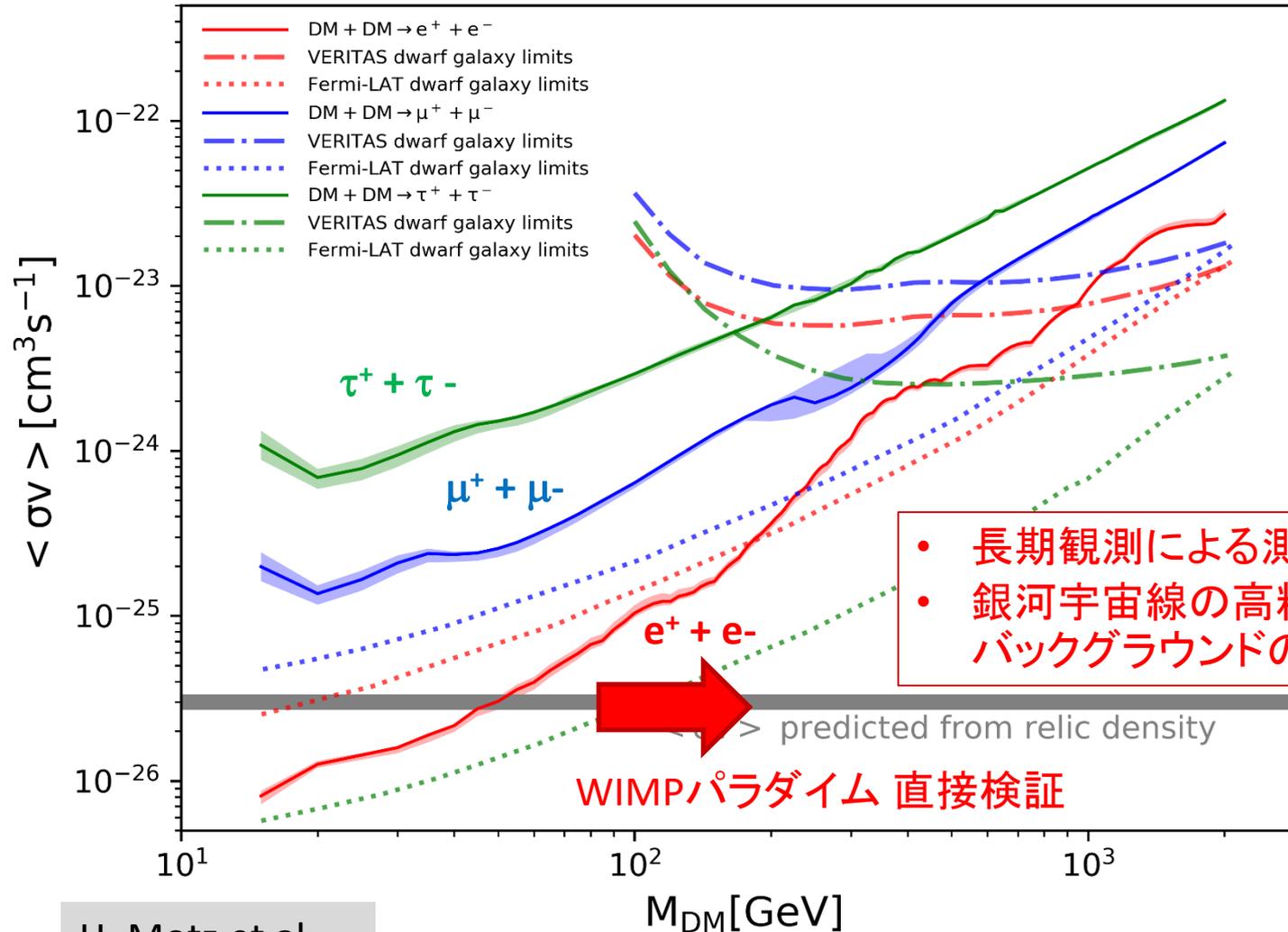
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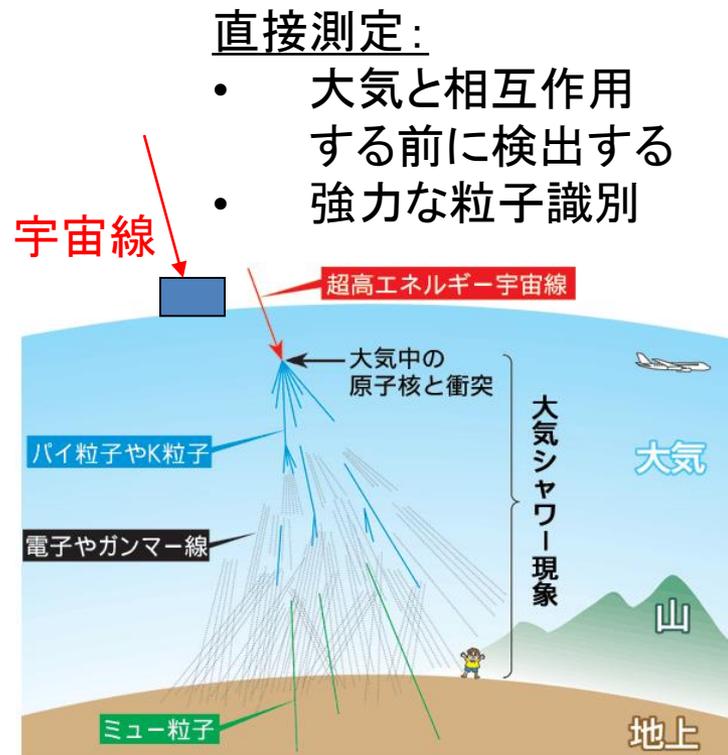
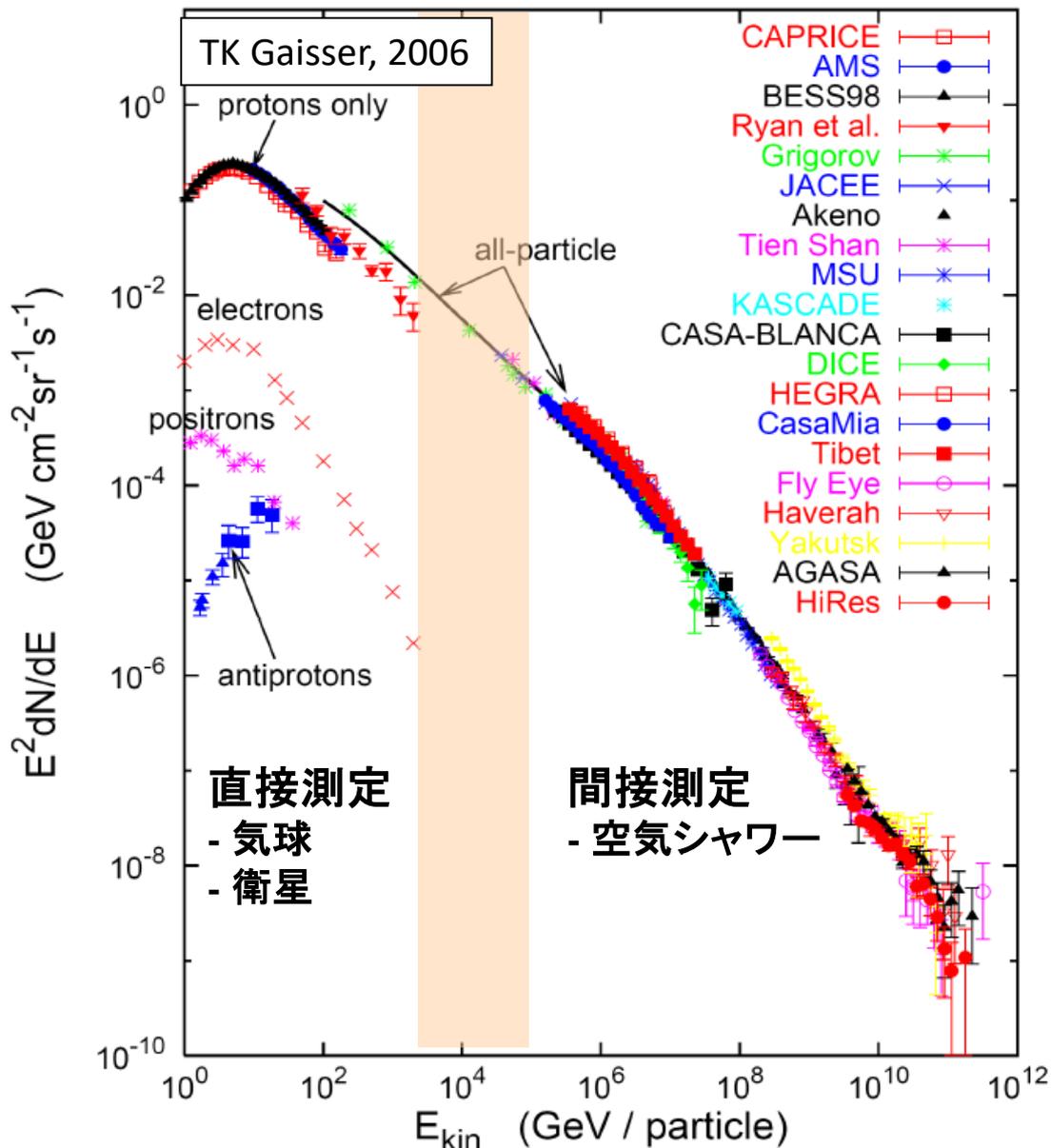
- 長期観測による測定精度向上
- 銀河宇宙線の高精度理解によるバックグラウンドの予測精度向上

VERITAS limits from Physical Review D 95, 082001 (2017)

Fermi-LAT limits from Phys. Rev. Lett. 115, 231301 (2015) (SM)

H. Motz et al., JPS, Sept. 2018.

宇宙線の測定方法



(Ref: KEK webページより)

空気シャワーによる間接測定:

- 大面積化可能
- 高エネルギーでないと観測できない

ISS as a "Direct-Detection" Cosmic-Ray Observatory



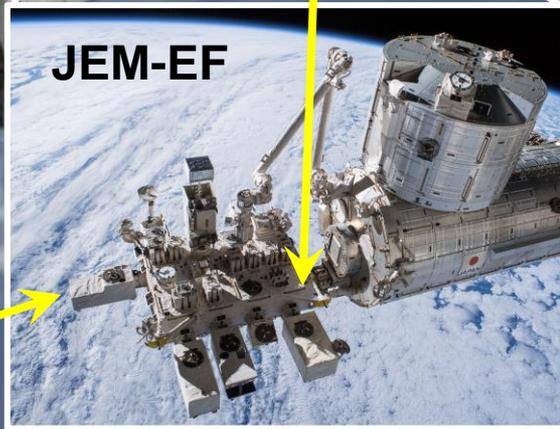
AMS Launch
May 16, 2011



ISS-CREAM Launch
August 14, 2017



CALET Launch
August 19, 2015



JEM-EF

ISS as a "Direct-Detection" Cosmic-Ray Observatory



AMS Launch
May 16, 2011

- Magnet Spectrometer
- Various PID
 - Anti-particles
 - $E \leq \text{TeV}$

- Calorimeter
- Carbon target
 - Hadrons
 - Including TeV region

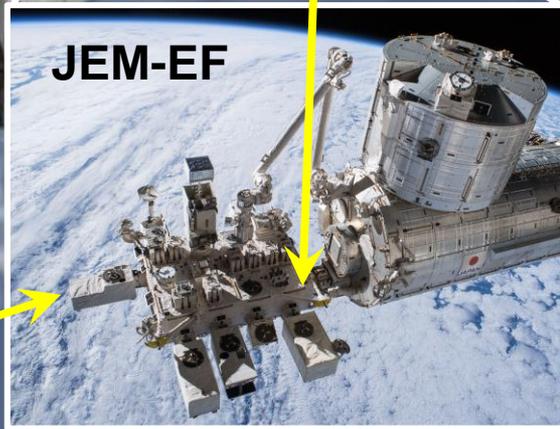


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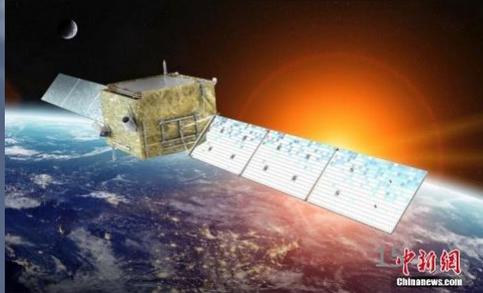


CALET Launch
August 19, 2015

Fermi-LAT Launch June 11, 2008



DAMPE Launch
December 17, 2017



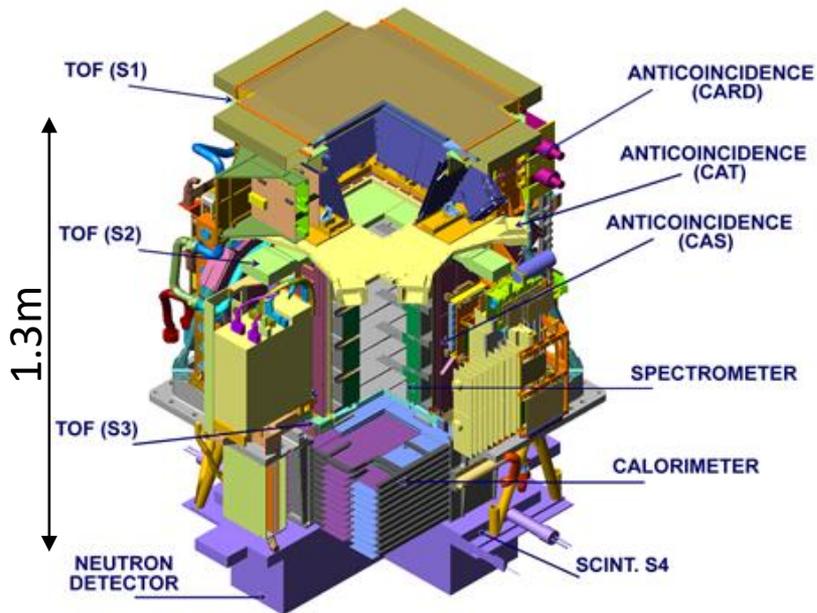
Direct measurements of cosmic rays : less room for “unknown” unknowns

1. Acceptance
2. Energy determination
 - Magnet spectrometer
 - Calorimeter
3. Particle identification
 - Rejection of background cosmic rays
4. Detection efficiency
 - Losses in the detector

宇宙線観測@宇宙空間

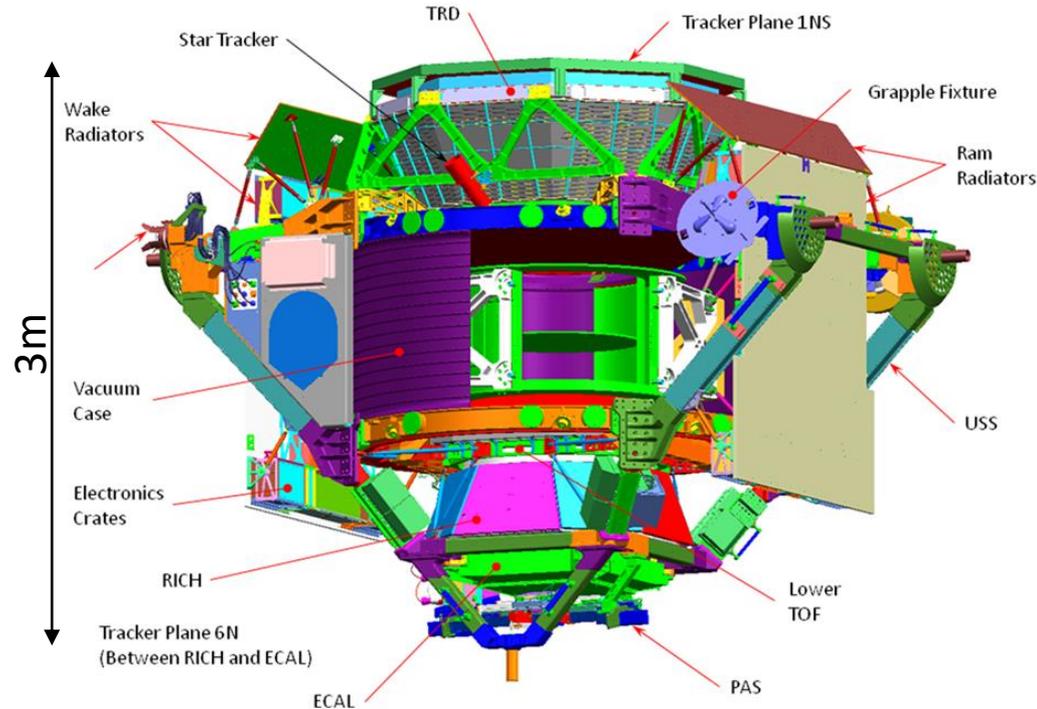
PAMELA (2006-2016)

衛星



- マグネットスペクトロメータ
- 有効面積は小さいが長期観測可能
- 2つの重要な発見
 1. 陽電子過剰
 2. 陽子ヘリウムスペクトル硬化

AMS-02 (2011-) ISS

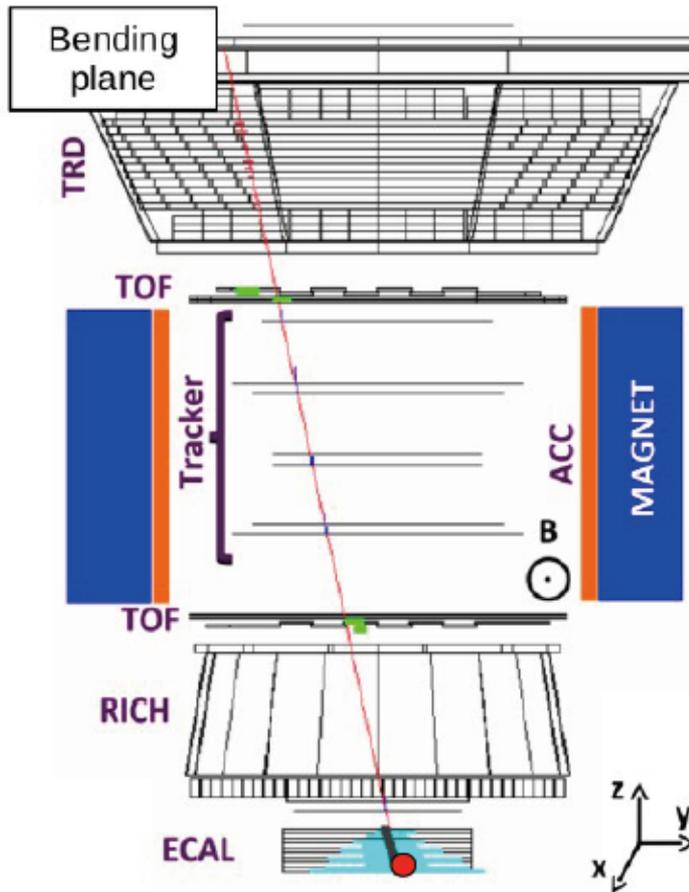


- マグネットスペクトロメータ
- 反粒子スペクトルの測定に最適化
- 多目的粒子検出器 w/強力な粒子識別装置
⇒ ~TeVの様々な粒子のスペクトルを測定
- PAMELAの発見を高精度で確認

AMS-02 Detector

贅沢な粒子識別装置

“redundant” な測定 \leftrightarrow 物質質量多



	e^-	p	He	
TRD 20 layers				e/p separation charge ($ Z $)
TOF 4 layers				trigger velocity (β) charge ($ Z $)
TRK 9 layers				momentum (p) sign ($\pm Q$) charge ($ Z $)
RICH				velocity (β) charge ($ Z $)
ECAL 20 layers				e^\pm energy e/h separation y trigger

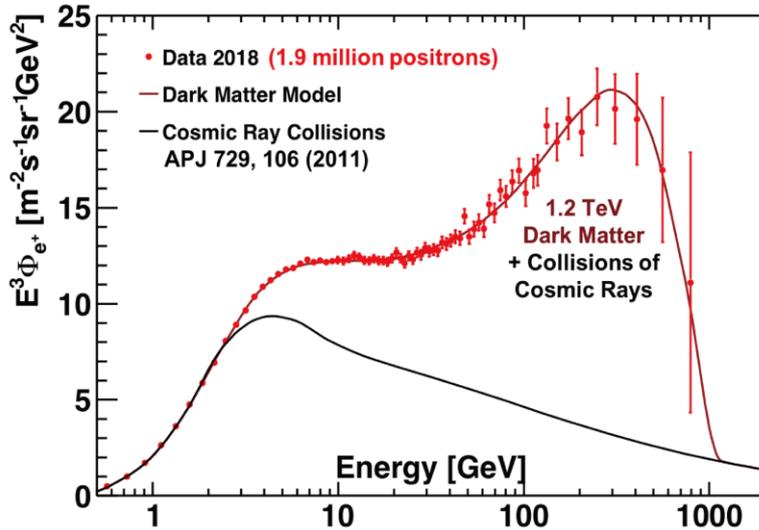
Ref.: Duranti et al.

EPJ Web of Conf. 209(2019)01014

AMS-02 Highlight (anti-particle)

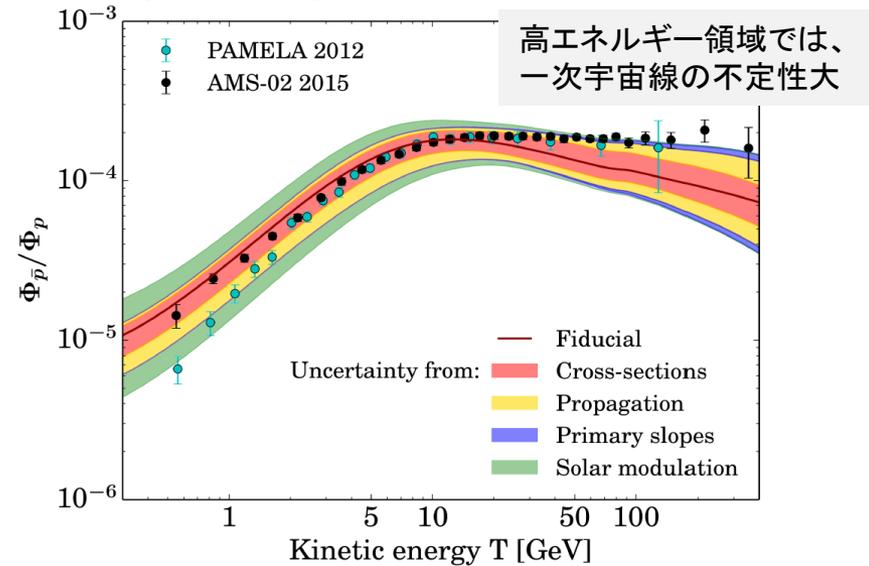
Refs: Kounine@NextGAPES, Choutko@ISCRA, Moloro@CPAN DAYS, Ting@AMS-days La Palma

Positron Spectrum PRL 122(2019)041102



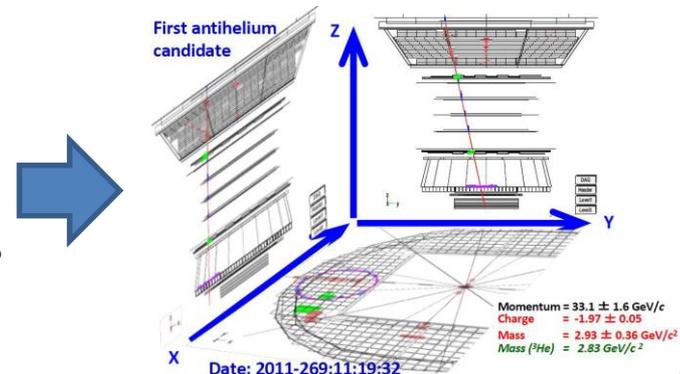
Dark Matter Model based on J. Kopp, Phys. Rev. D 88, 076013 (2013)

Antiproton Spectrum PRL 117(2015)091103



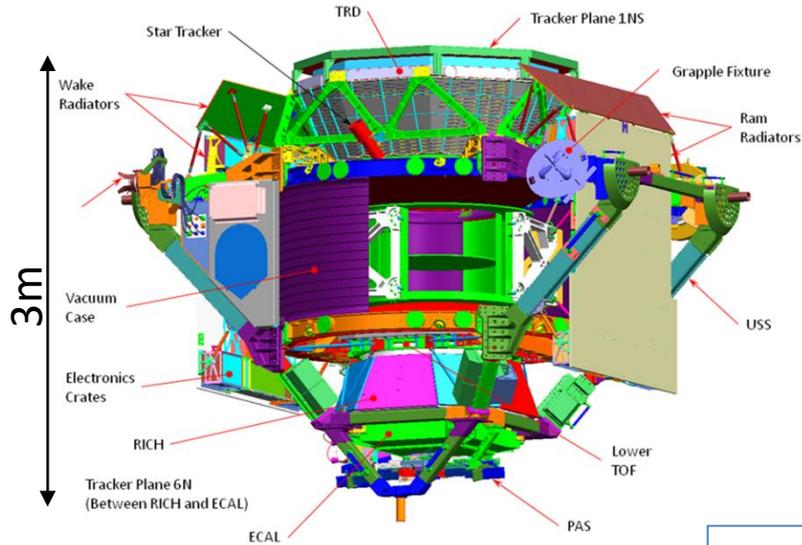
G. Giesen et al, JCAP 2015(09)023

- 反ヘリウム候補がヘリウムに対して約 10^{-8} の割合で見ついているが、それらの候補の真偽を決めるには詳細な検出器の理解が必須。
- 反重陽子の候補??? **GAPS**



全電子スペクトル測定：検出器

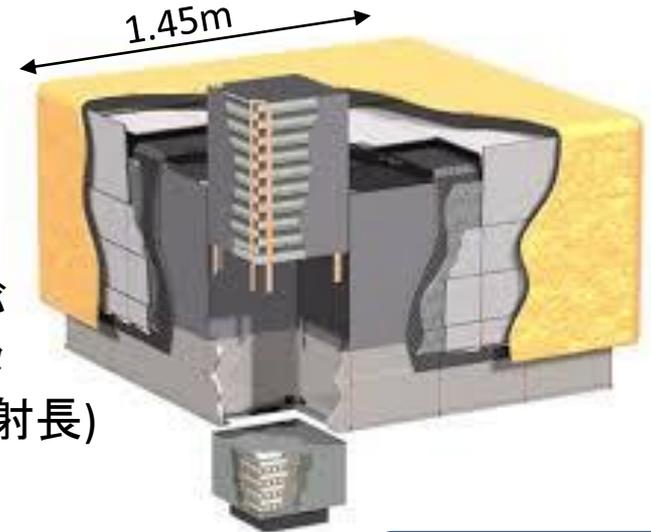
AMS-02 (2011-)



1TeVでの幾何因子は
CALETの1/3程度
カロリメータも搭載
(17放射長)

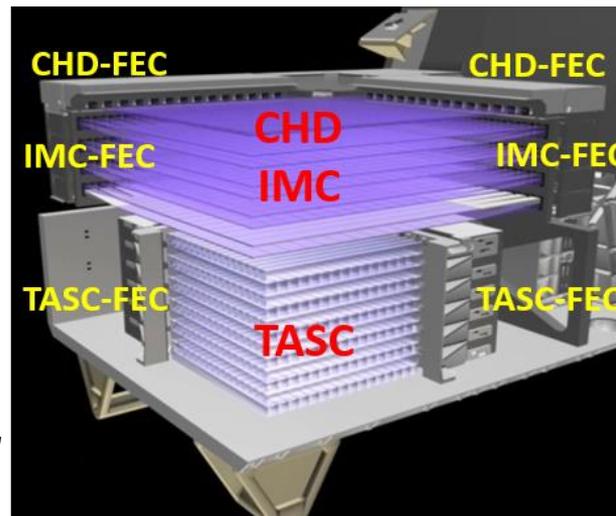
カロリメータに特化
(30放射長)

Fermi-LAT (2008-)



ガンマ線用
大面積だが
カロリメータ
薄い (10放射長)

CALET (2015-)



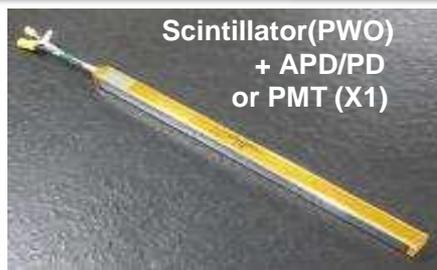
CALETの回答

チャレンジ:

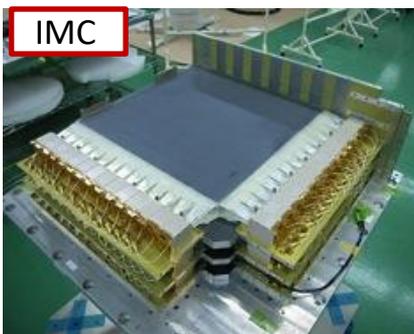
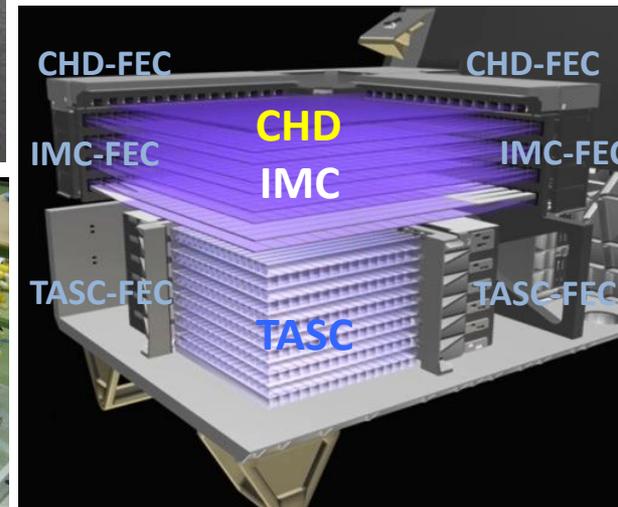
1. イベント数 (感度)
大立体角 & 長期観測
2. エネルギー測定
全吸収カロリメータ
3. 粒子識別
シャワー像イメージング



CALET Instrument



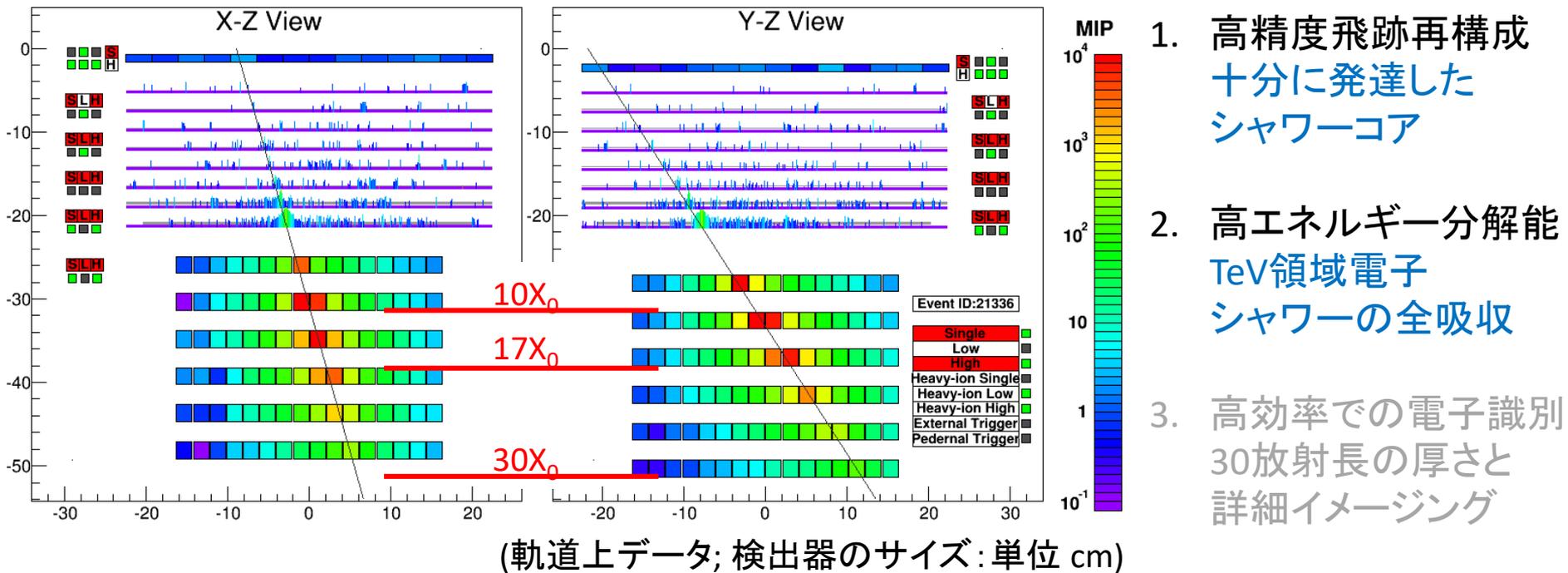
CALORIMETER



	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Measure	Charge (Z=1-40)	Tracking , Particle ID	Energy, e/p Separation
Geometry (Material)	Plastic Scintillator 14 paddles x 2 layers (X,Y): 28 paddles Paddle Size: 32 x 10 x 450 mm ³	448 Scifi x 16 layers (X,Y) : 7168 Scifi 7 W layers (3X ₀): 0.2X ₀ x 5 + 1X ₀ x 2 Scifi size : 1 x 1 x 448 mm ³	16 PWO logs x 12 layers (x,y): 192 logs log size: 19 x 20 x 326 mm ³ Total Thickness : 27 X ₀ , ~1.2 λ _i
Readout	PMT+CSA	64-anode PMT+ ASIC	APD/PD+CSA PMT+CSA (for Trigger)@top layer

CALET検出器と3TeV宇宙線シャワー

3TeV 電子候補



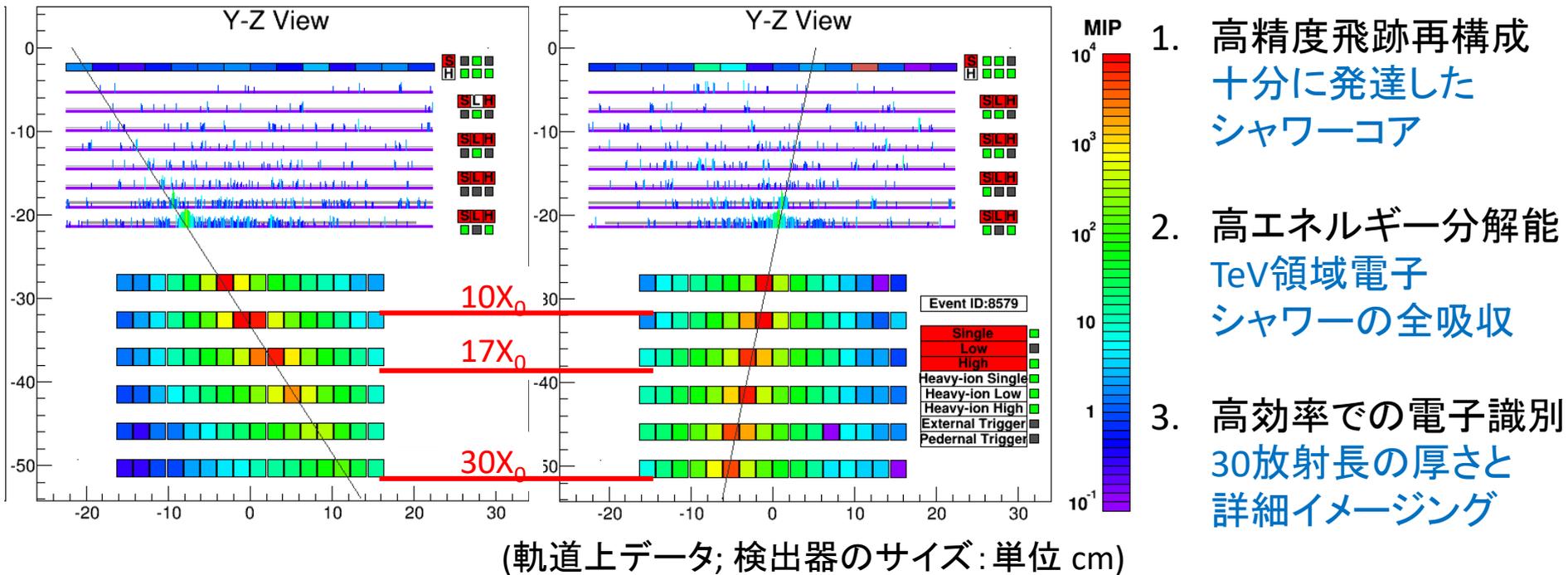
1. 高精度飛跡再構成
十分に発達した
シャワーコア
2. 高エネルギー分解能
TeV領域電子
シャワーの全吸収
3. 高効率での電子識別
30放射長の厚さと
詳細イメージング

CALETは全電子の観測に最適化された検出器
⇒ TeV領域を含む全電子スペクトルの微細構造観測

CALET検出器と3TeV宇宙線シャワー

3TeV 電子候補

対応する陽子
バックグラウンド

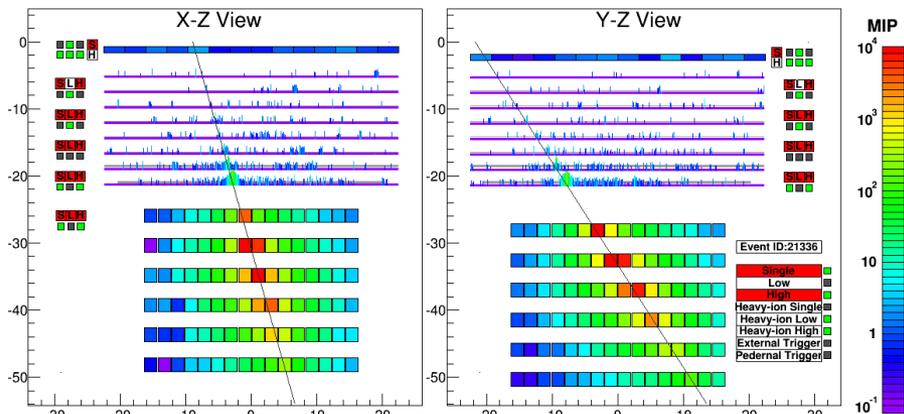


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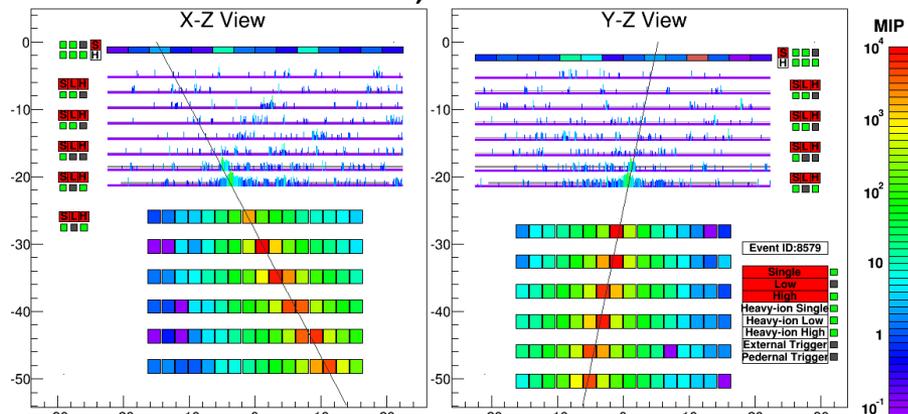
Event Examples of High-Energy Showers

Electron, $E=3.05$ TeV



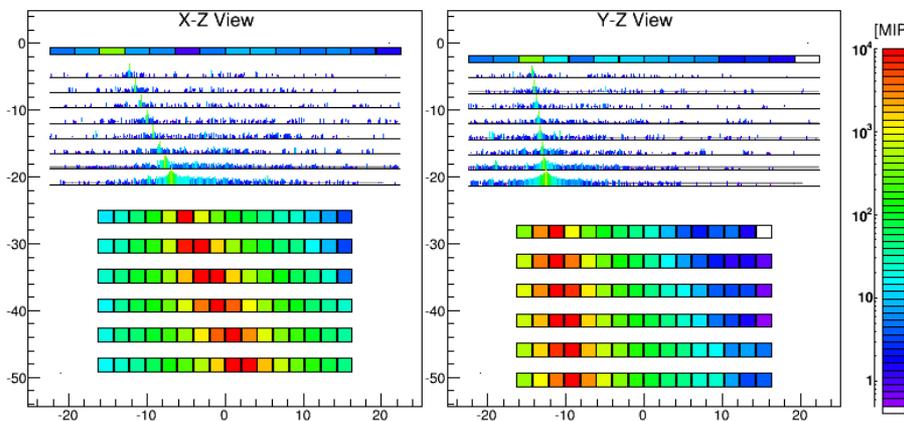
fully contained even at 3TeV

Proton, $\Delta E=2.89$ TeV



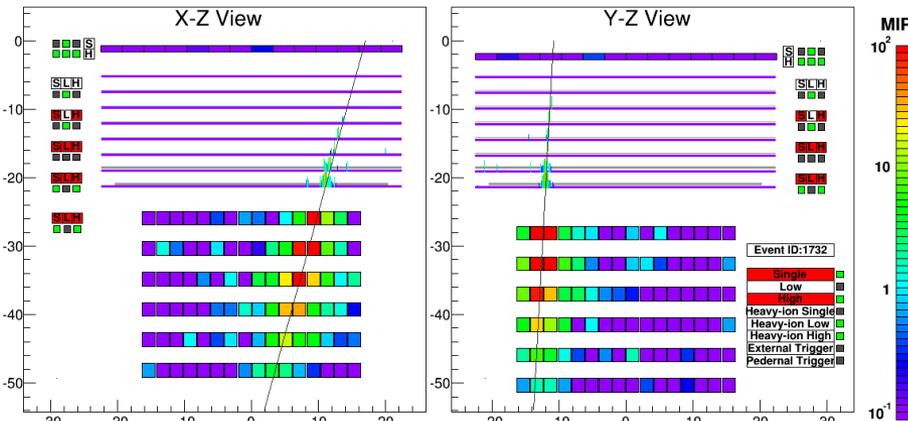
clear difference from electron shower

Fe($Z=26$), $\Delta E=9.3$ TeV



energy deposit in CHD consistent with Fe

Gamma-ray, $E=44.3$ GeV

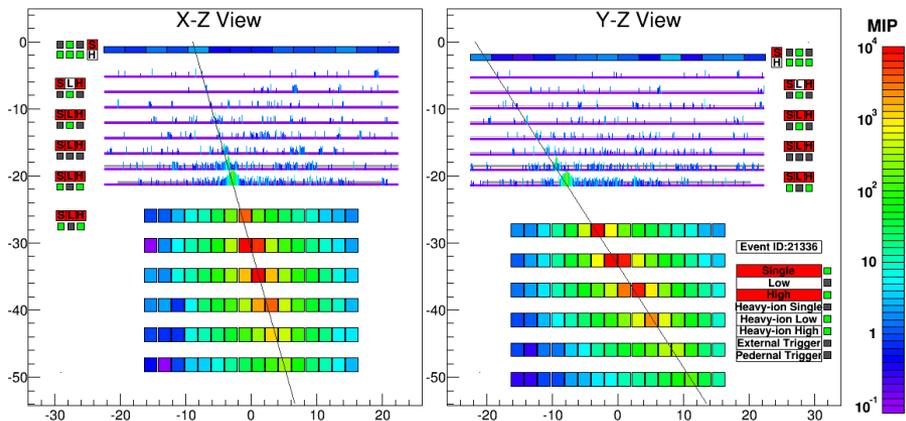


no energy deposit before pair production



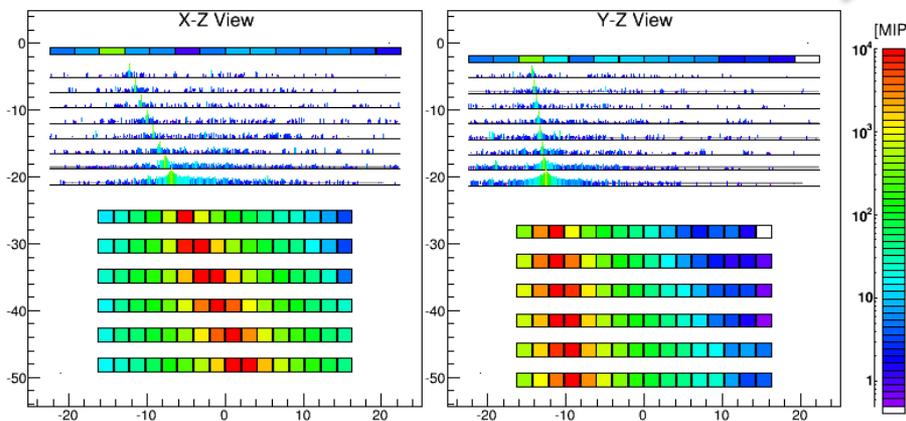
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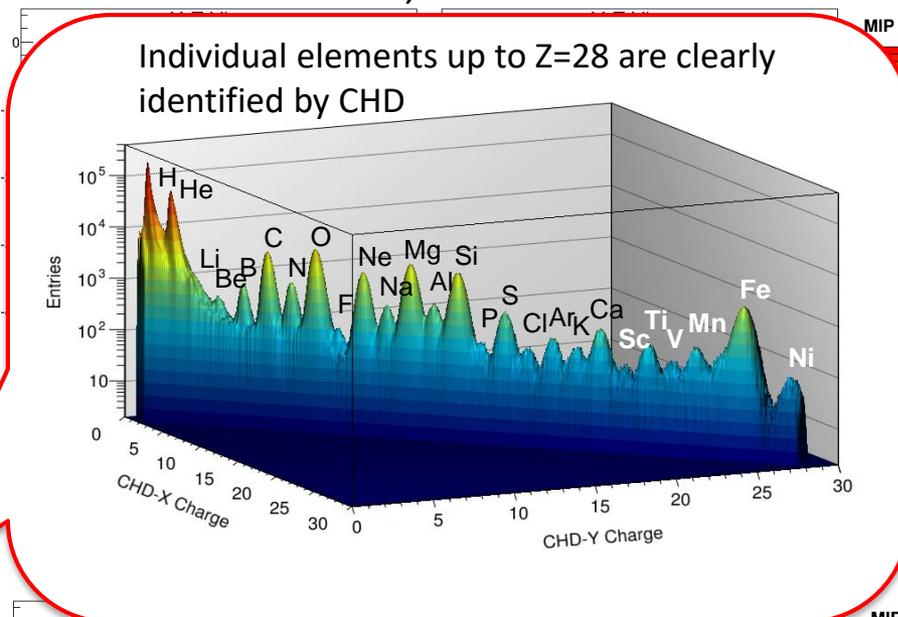
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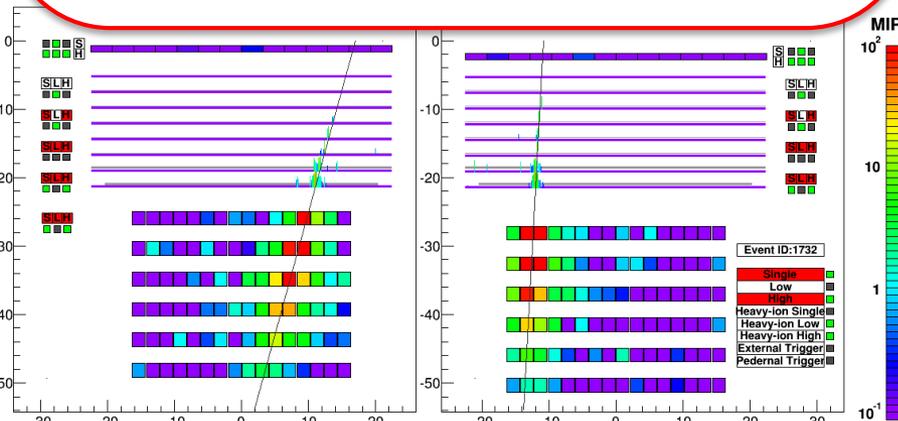


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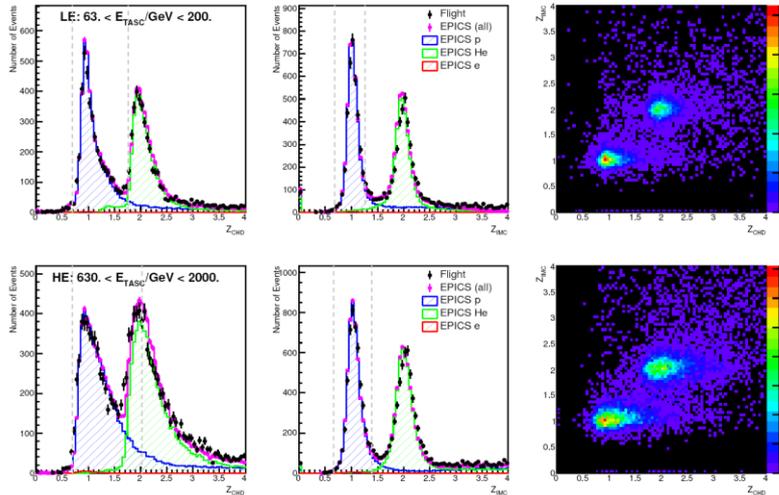


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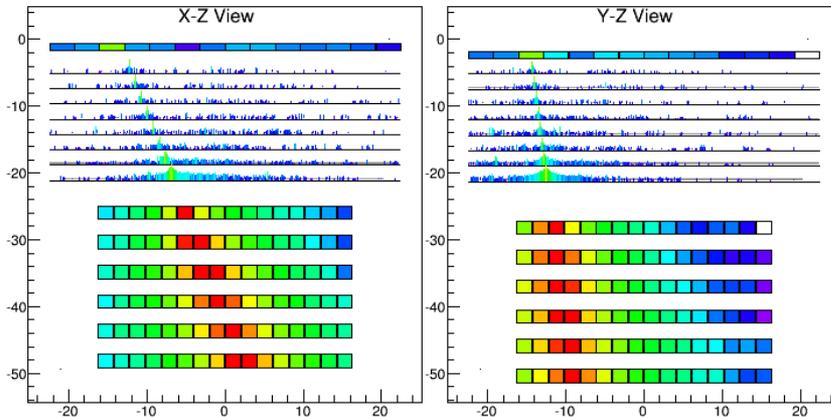


Event Examples of High-Energy Showers



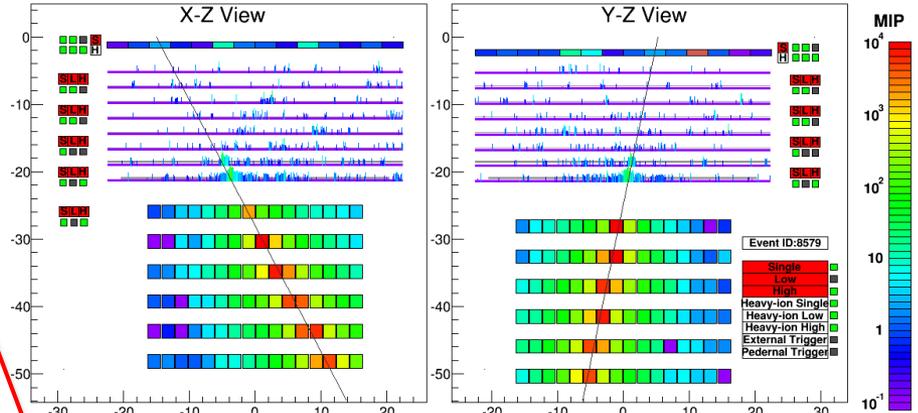
Proton/helium separation using CHD/IMC charge

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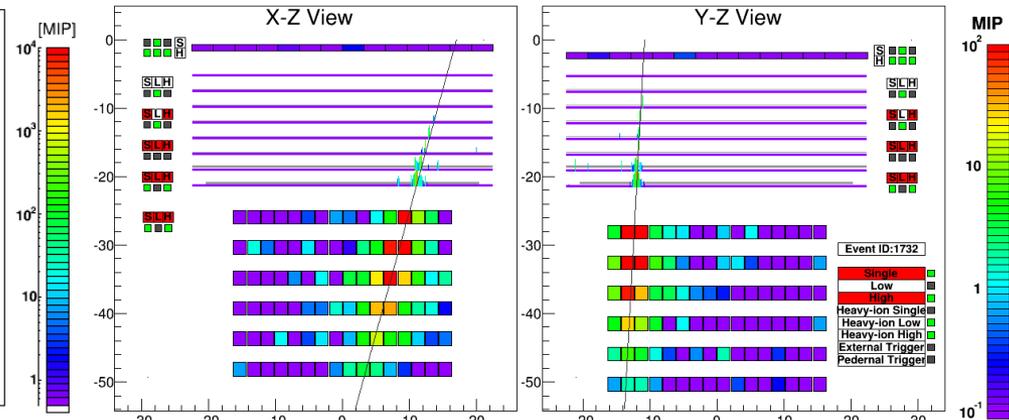
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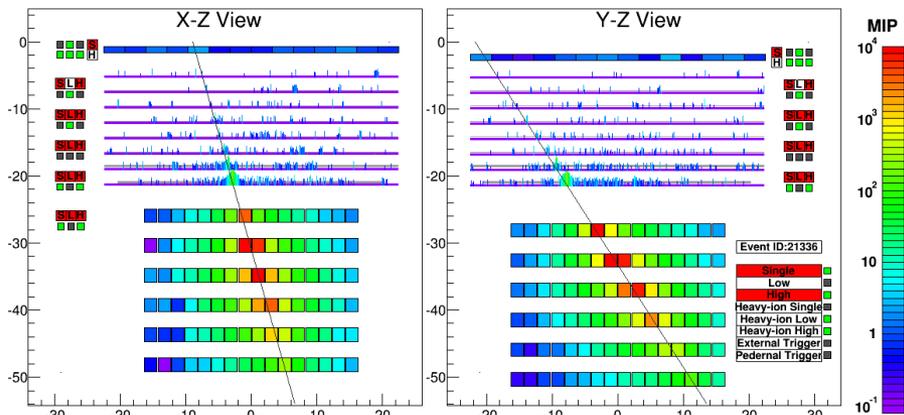


no energy deposit before pair production



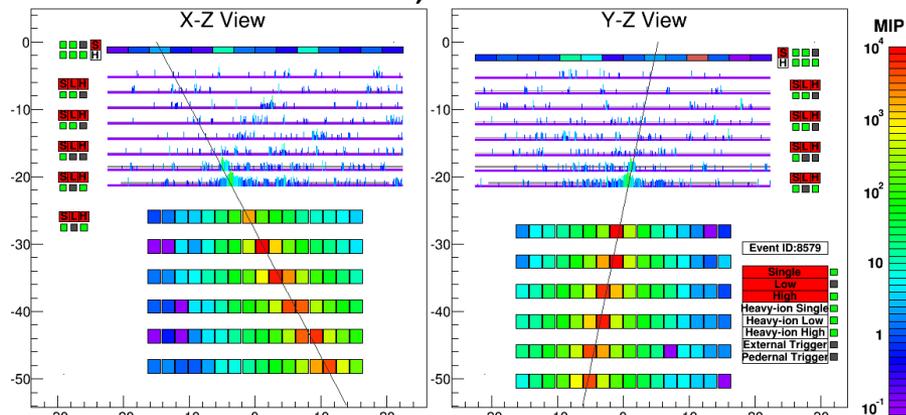
Event Examples of High-Energy Showers

Electron, $E=3.05$ TeV



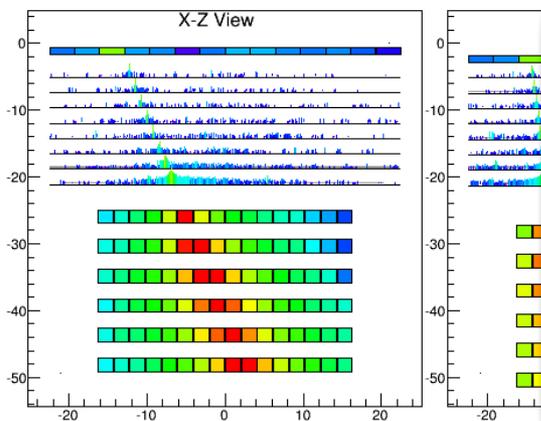
fully contained even at 3TeV

Proton, $\Delta E=2.89$ TeV



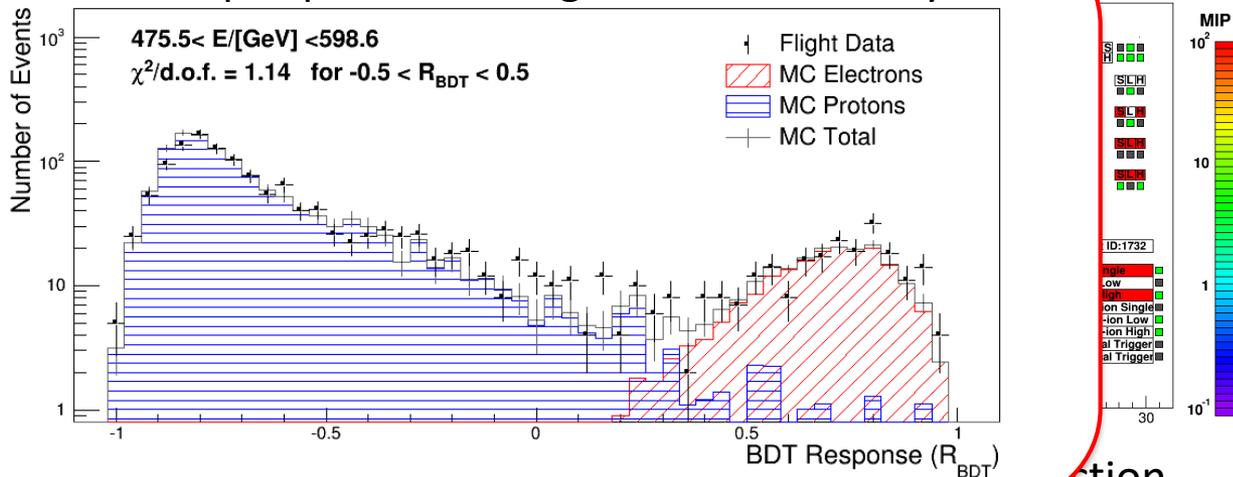
clear difference from electron shower

Fe($Z=26$), $\Delta E=9.2$ TeV



energy deposit in CHD cons.

Clear e/p separation using multivariate analysis

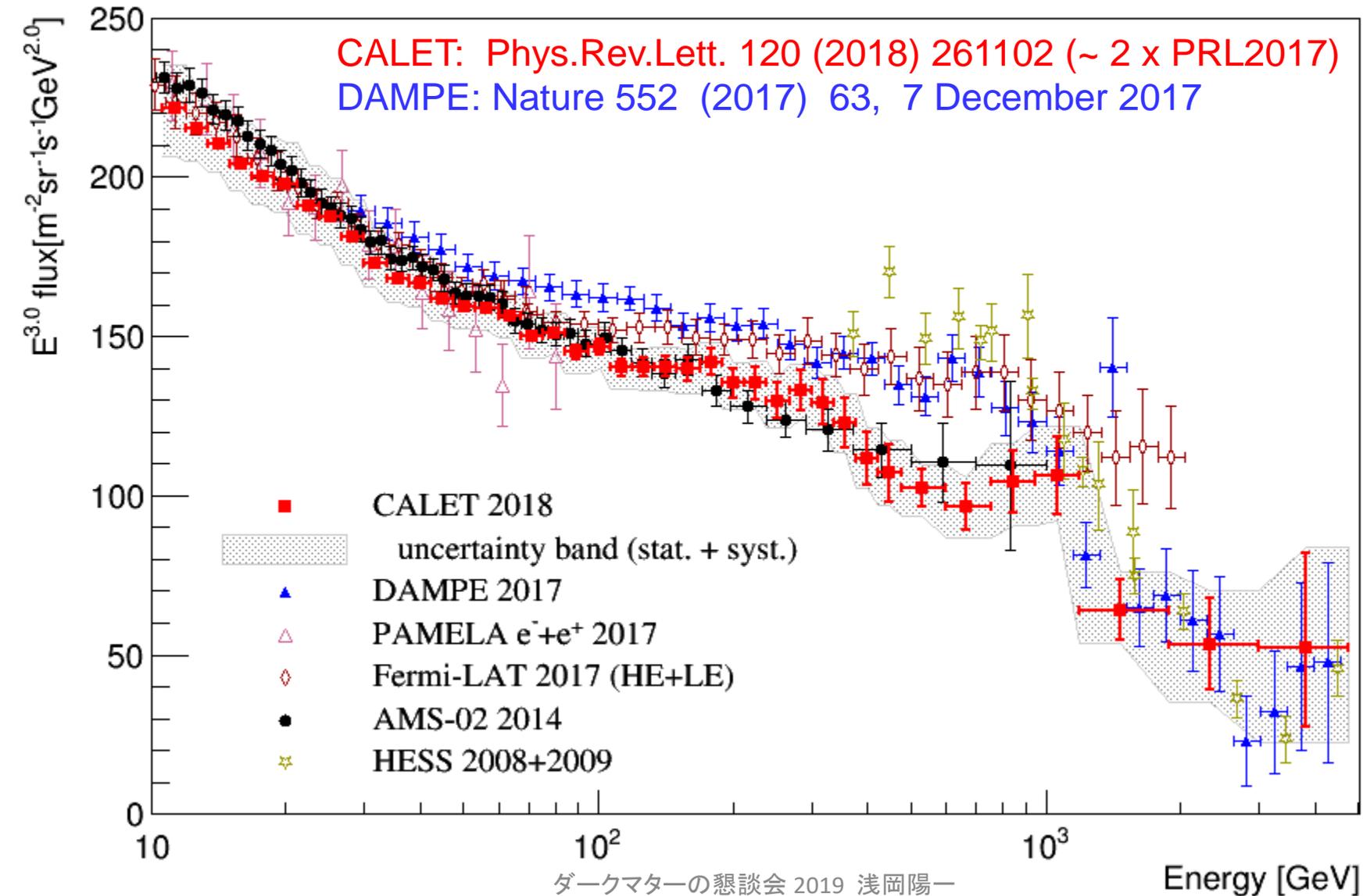


action



All Electron Spectrum: Extended Measurement by CALET

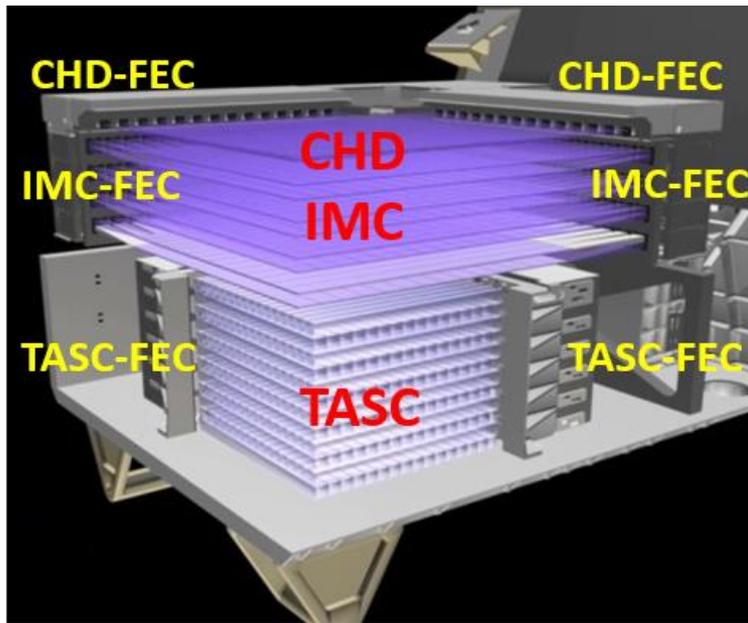
Approximately doubled statistics above 500GeV by using full acceptance of CALET



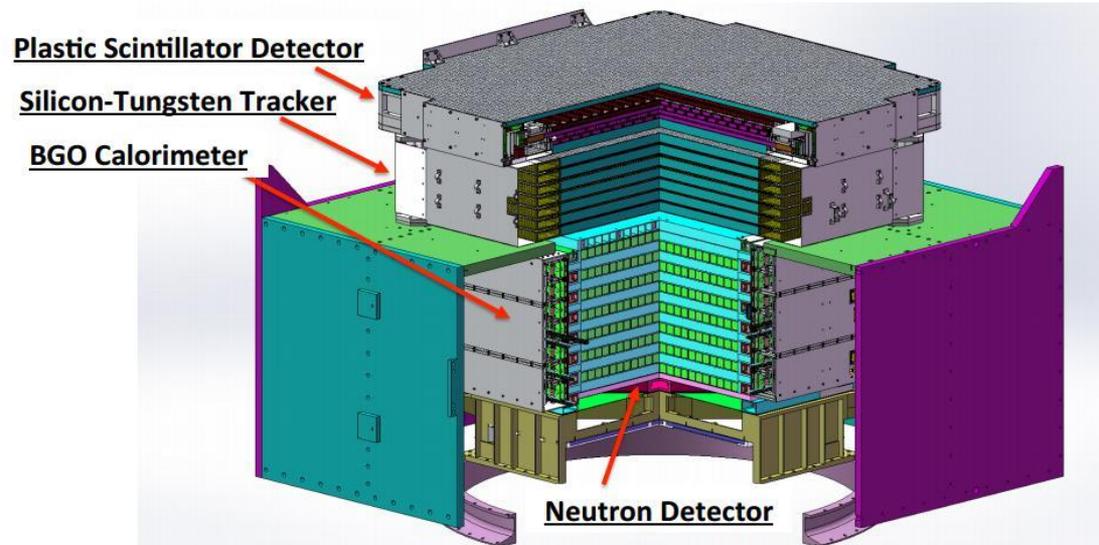
CALET vs DAMPE

両者とも、カロリメータに特化した検出器

CALET



DAMPE

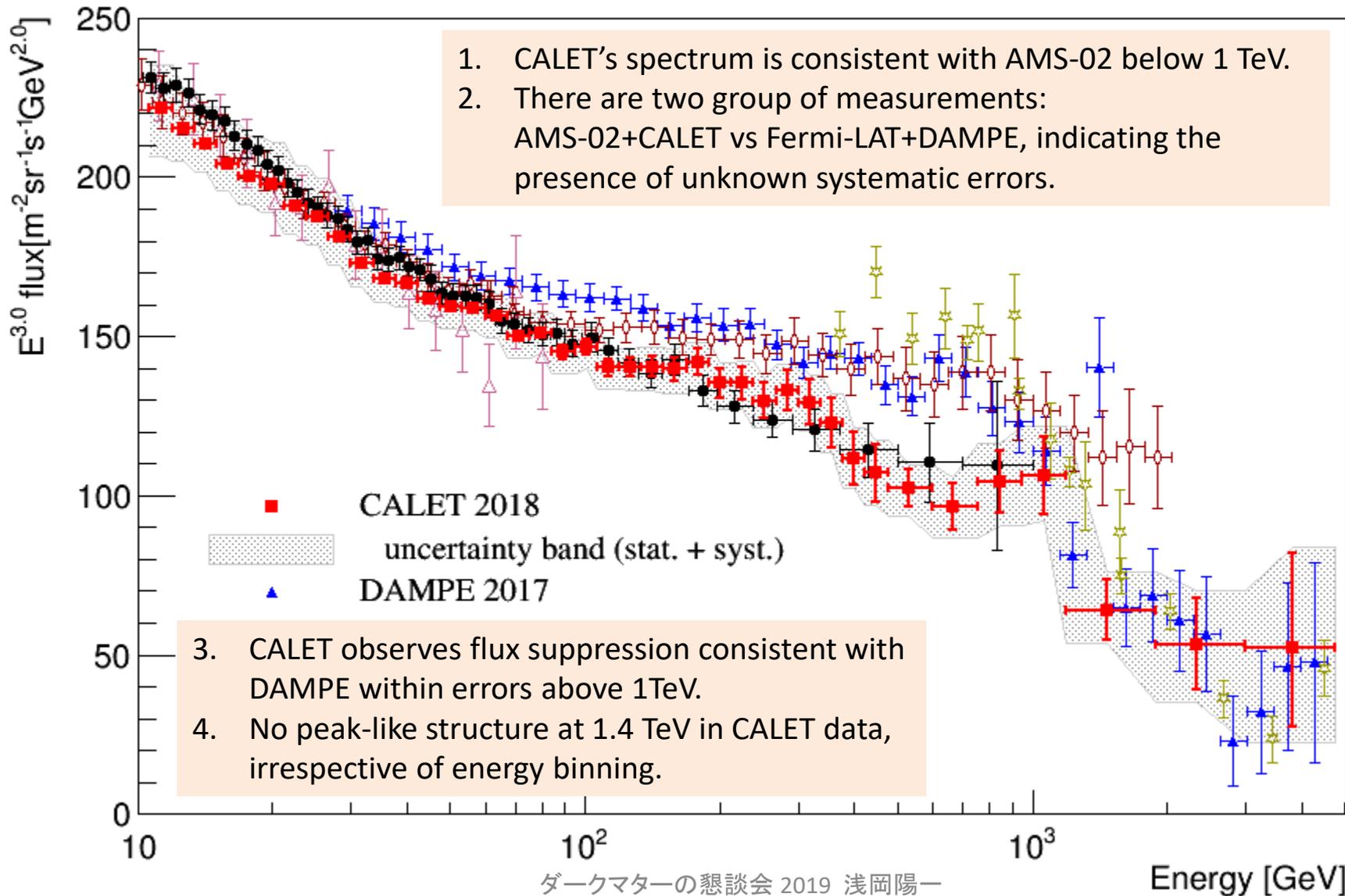


- サイズはDAMPEのほうが大きい (~3倍)
- CALETの方が全吸収カロリメータの隙間が小さい (約半分)
- CALETは地上にて全吸収カロリメータ読み出しの全ダイナミックレンジの較正を行っており、線形性が保証されている

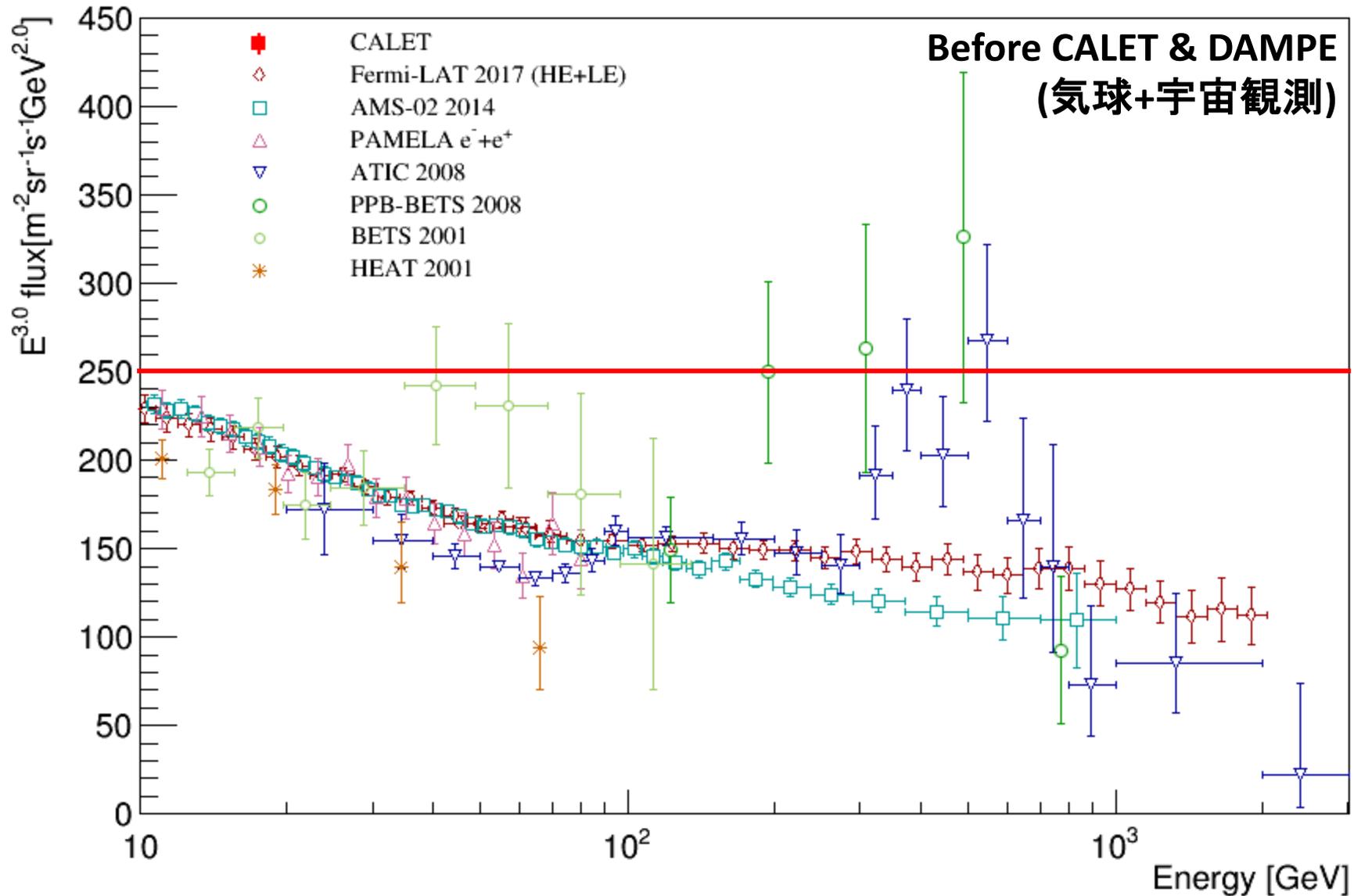


All Electron Spectrum: Extended Measurement by CALET

Approximately doubled statistics above 500GeV by using full acceptance of CALET



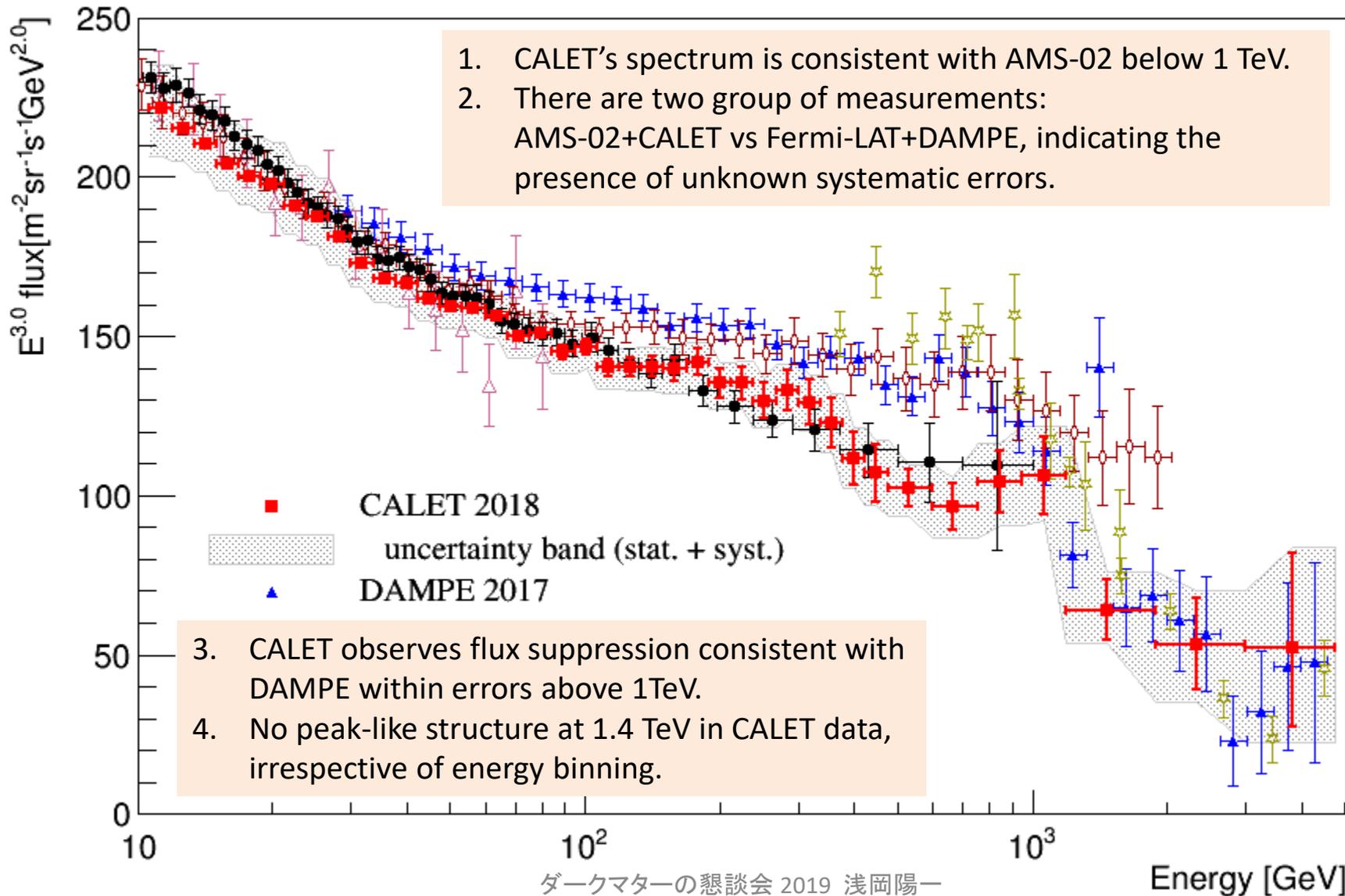
Discrepancy still exists, but improved



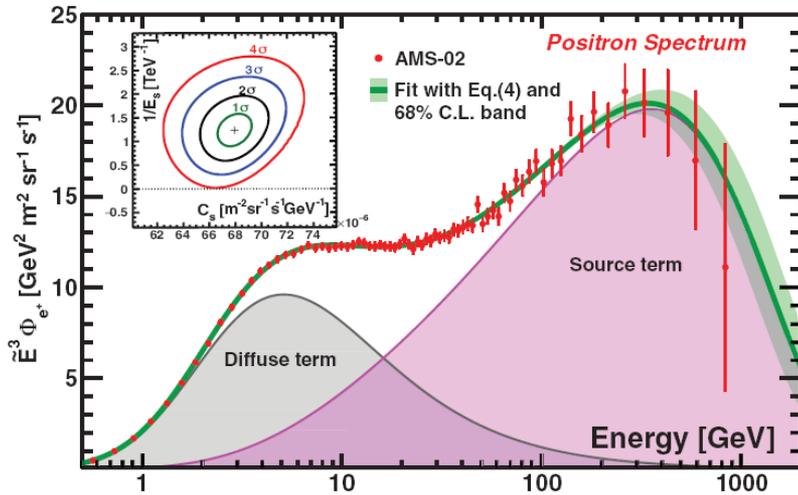


All Electron Spectrum: Extended Measurement by CALET

Approximately doubled statistics above 500GeV by using full acceptance of CALET

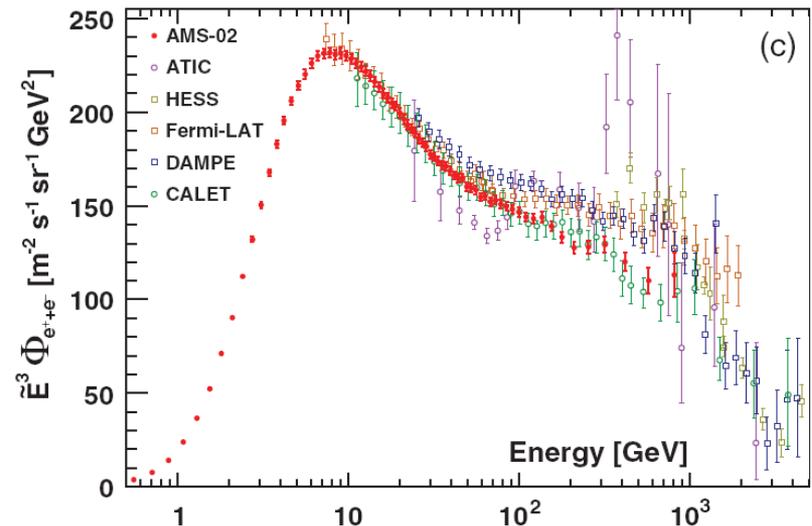
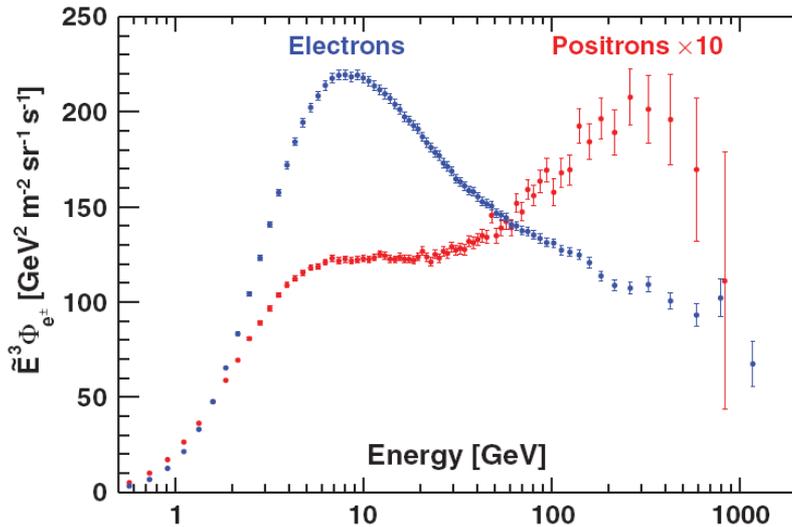


AMS-02 Updates (e^+ and e^-)

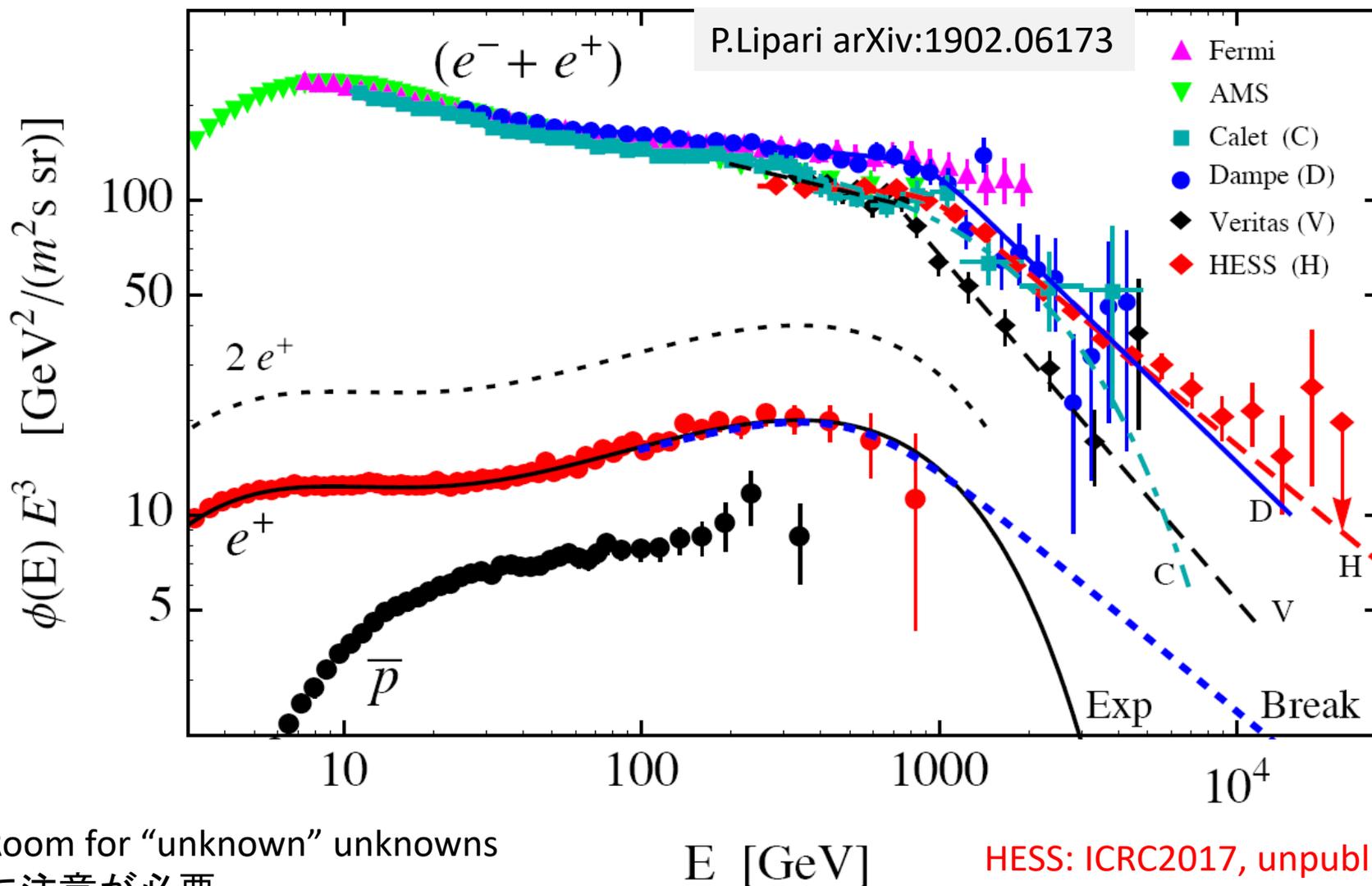


Positron: PRL 122(2019)041102
 Electron: PRL 122(2019)101101

- 電子+陽電子のスペクトルは AMS-02 の統計が上がることでより CALET に合致
 - 低エネルギー \Rightarrow 太陽変調
 - 300GeV, 1TeV付近の構造



間接測定の結果との比較



Room for “unknown” unknowns
に注意が必要

HESS: ICRC2017, unpublished

2年間のデータ蓄積により観測領域を拡張、 4.8テラ電子ボルトまでの高精度電子識別に成功

$E^{3.0}$ flux [$m^{-2}sr^{-1}s^{-1}GeV^{2.0}$]

CALET vs DAMPE (Point 4)

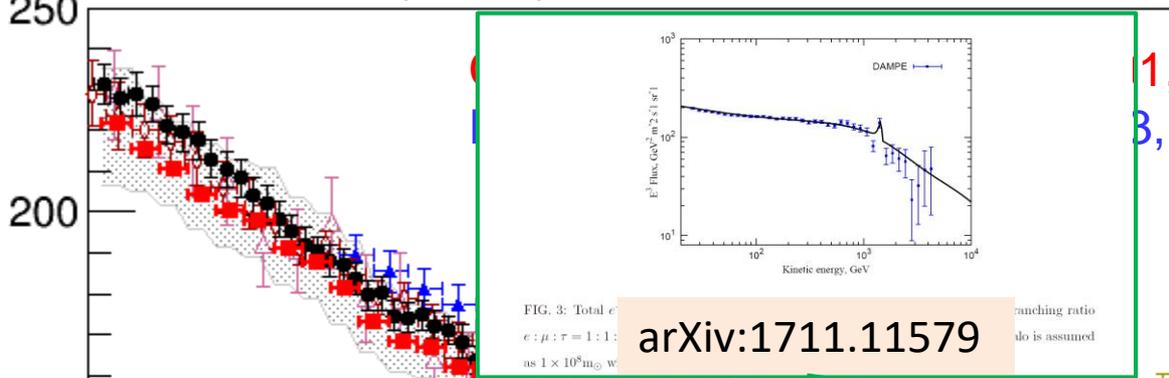
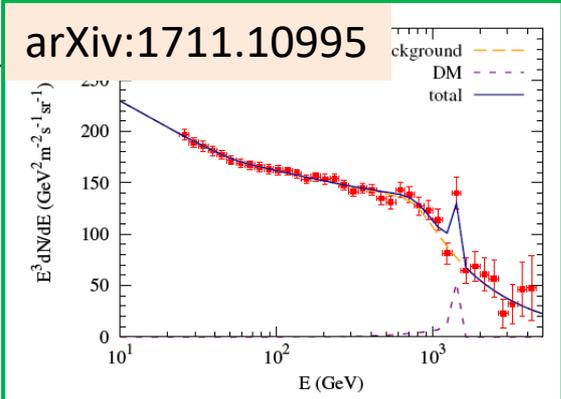


FIG. 3: Total e^+ flux... branching ratio... $e^+ : \mu^+ : \tau^+ = 1 : 1 : 1$... as $1 \times 10^8 m_\odot$ W...
arXiv:1711.11579



arXiv:1711.10995

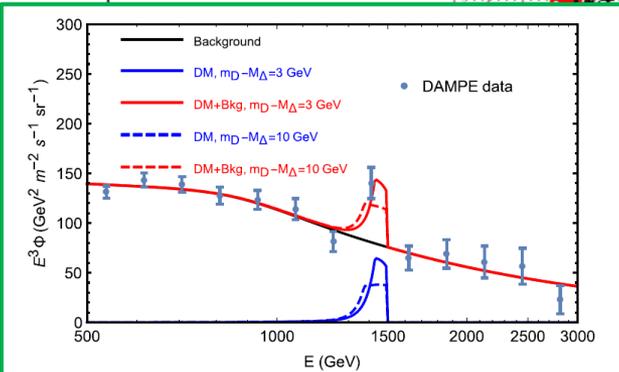
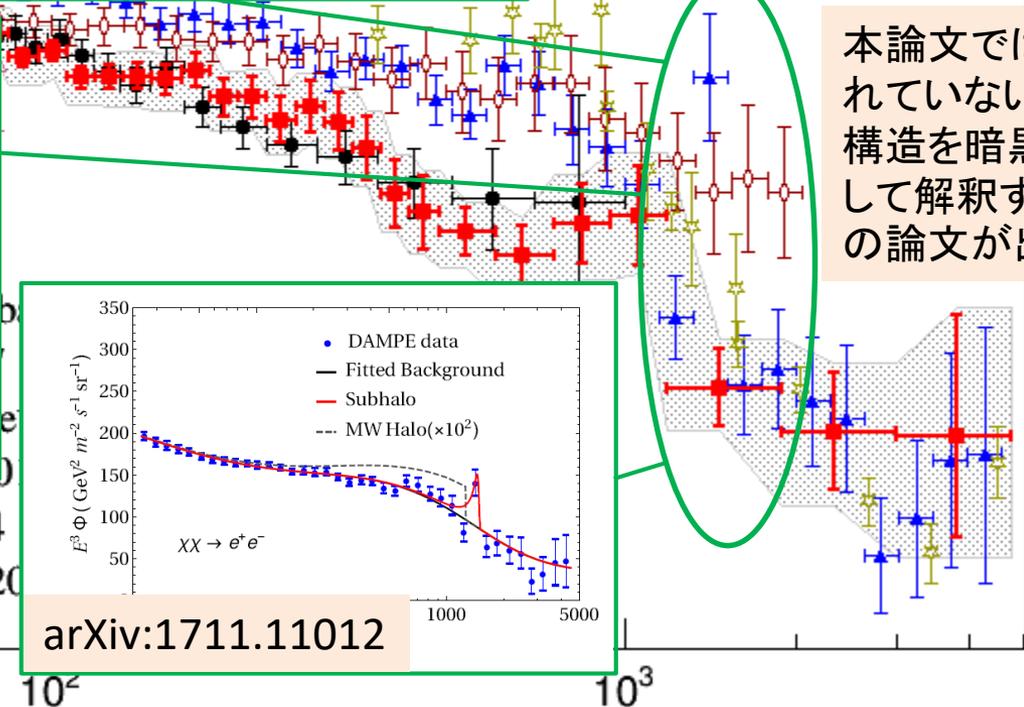


Fig. 2. The DA... $e^+e^+e^-e^-$ with... The fitted backg...
arXiv:1712.00869

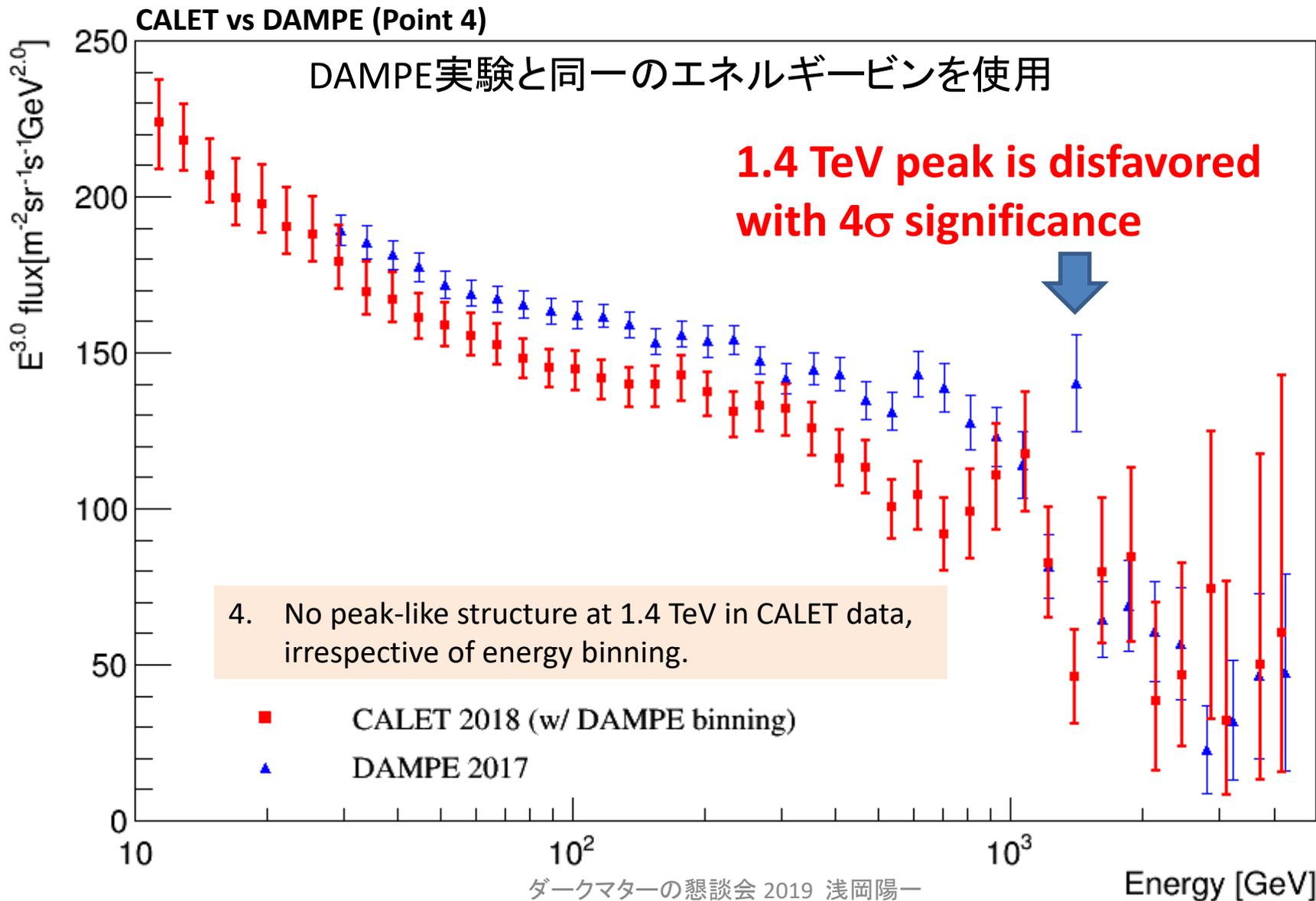


arXiv:1711.11012

本論文では議論されていないピーク構造を暗黒物質として解釈する多数の論文が出現

AMS-02 2014
HESS 2008+20

2年間のデータ蓄積により観測領域を拡張、 4.8テラ電子ボルトまでの高精度電子識別に成功

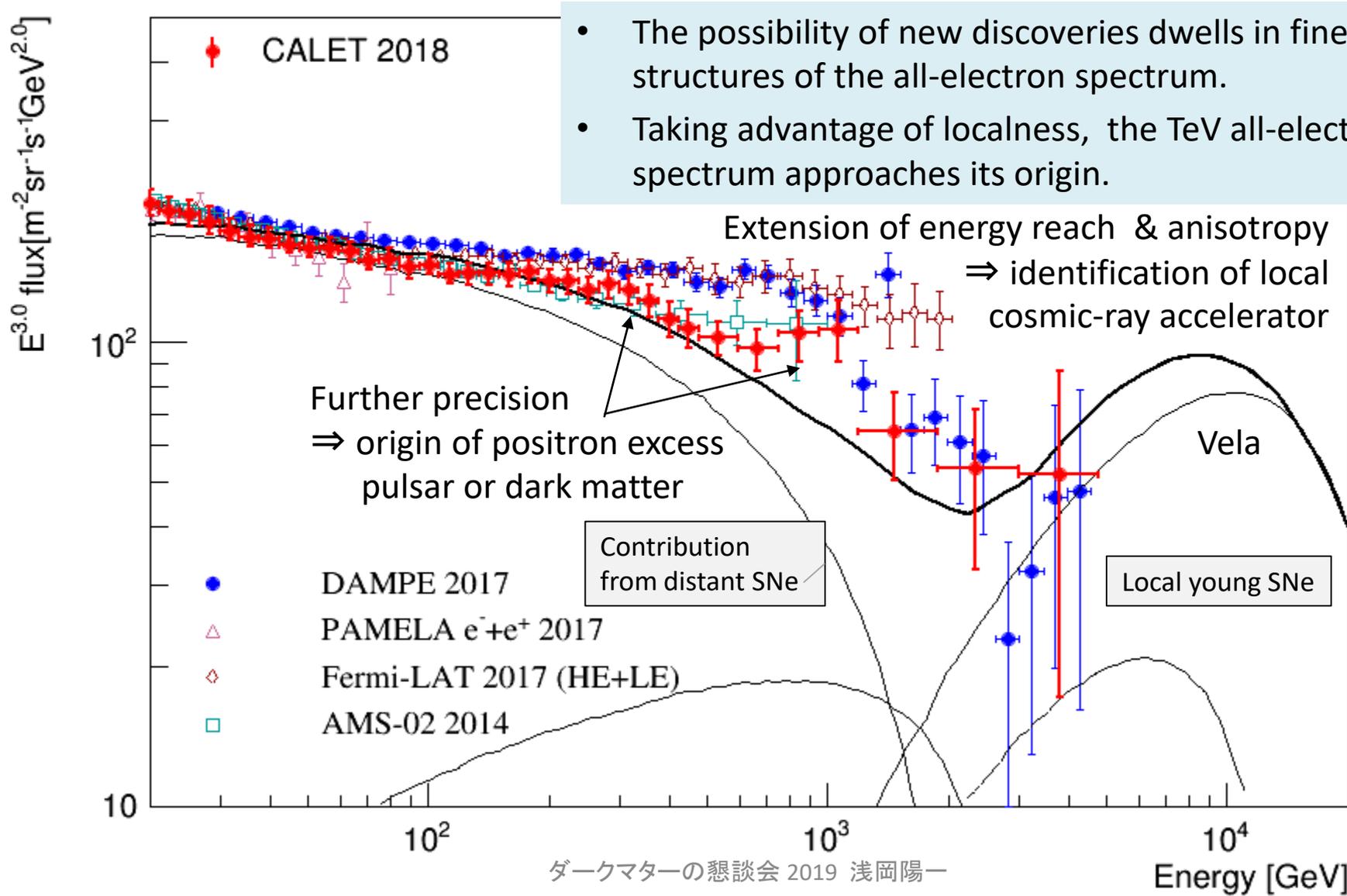




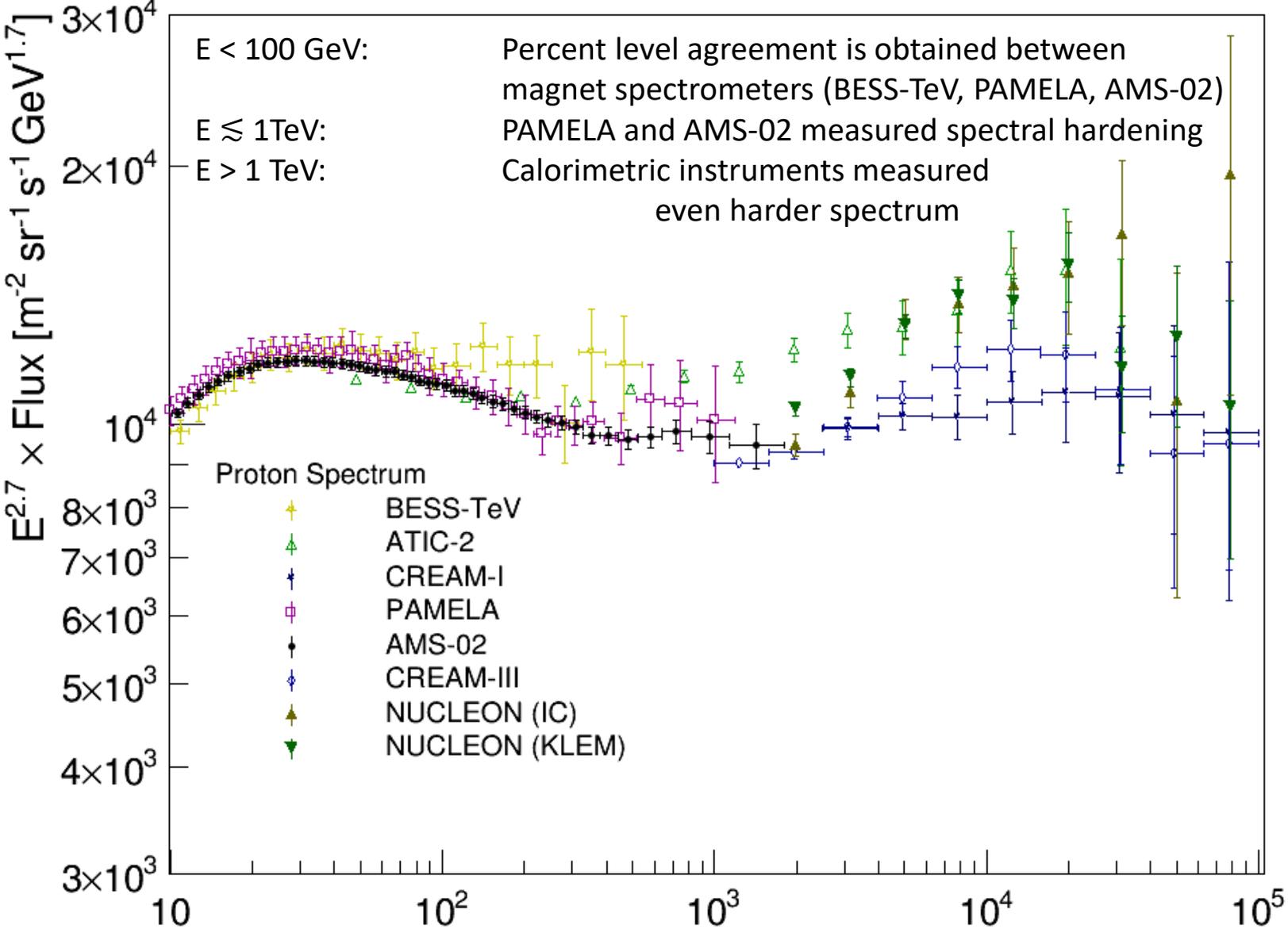
Prospects for CALET All-Electron Spectrum

Five years or more observations \Rightarrow 3 times more statistics, reduction of systematic errors

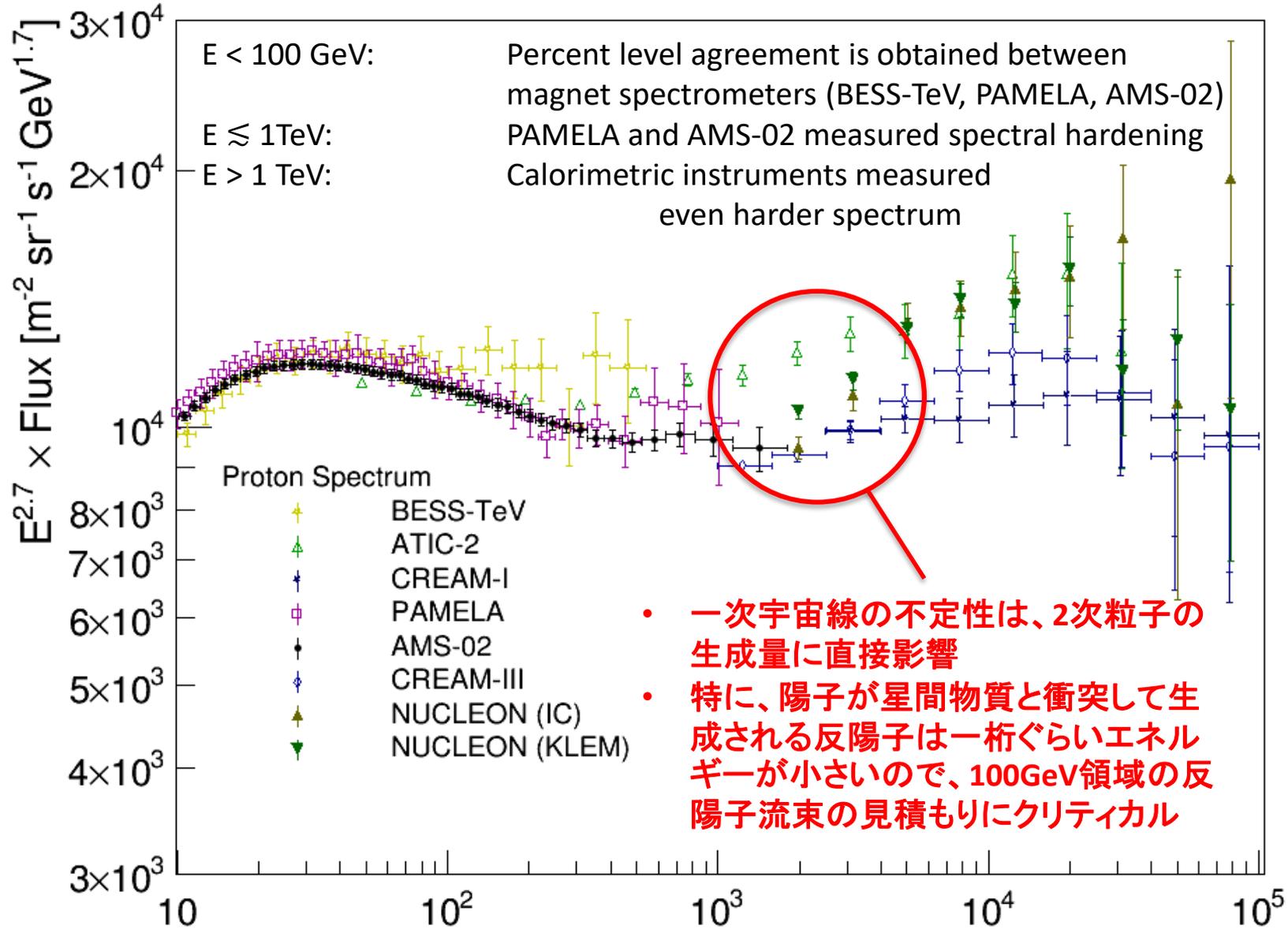
- The possibility of new discoveries dwells in fine structures of the all-electron spectrum.
- Taking advantage of localness, the TeV all-electron spectrum approaches its origin.



Status of Cosmic-Ray Proton Spectrum Measurements

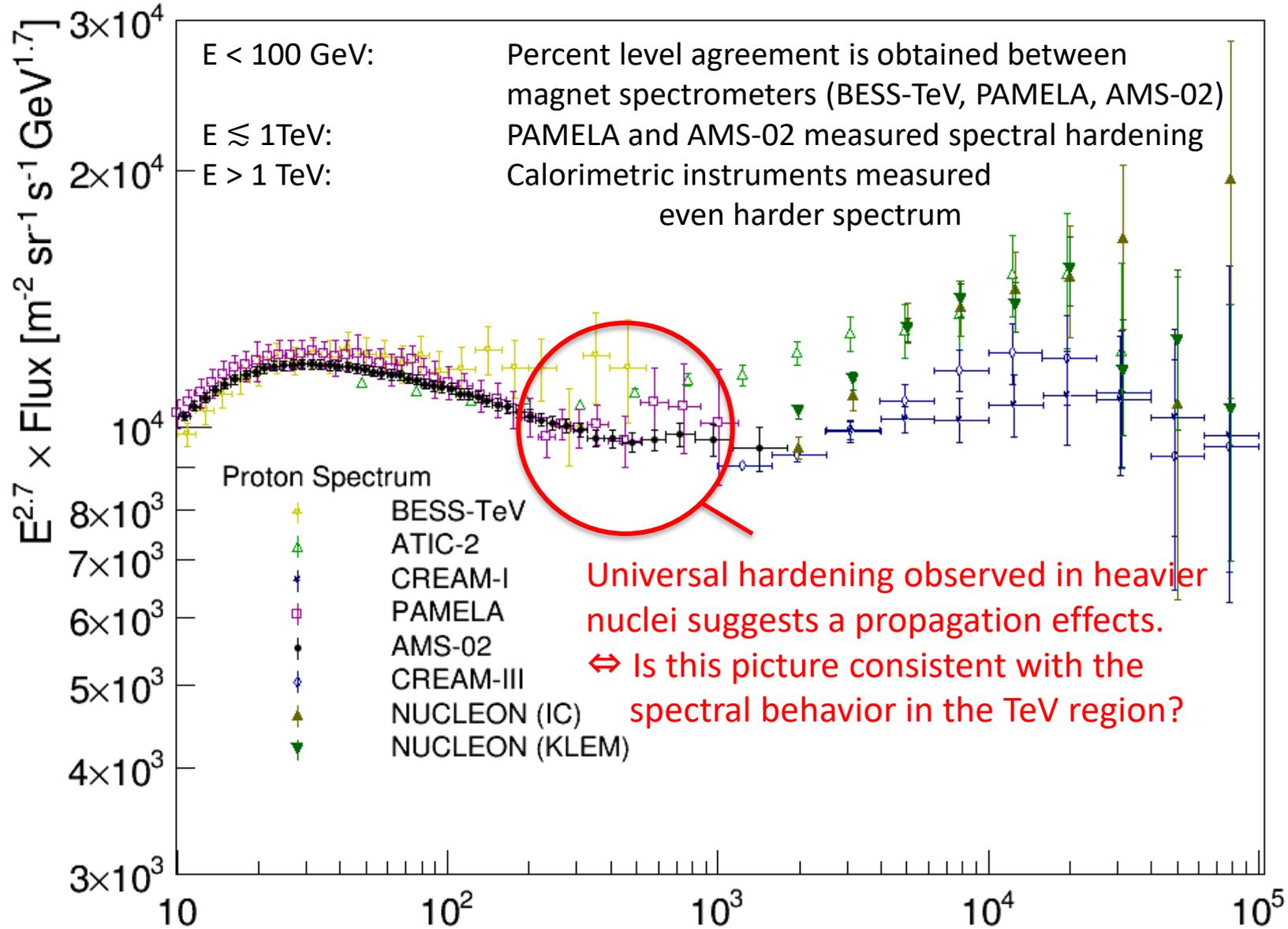


Status of Cosmic-Ray Proton Spectrum Measurements



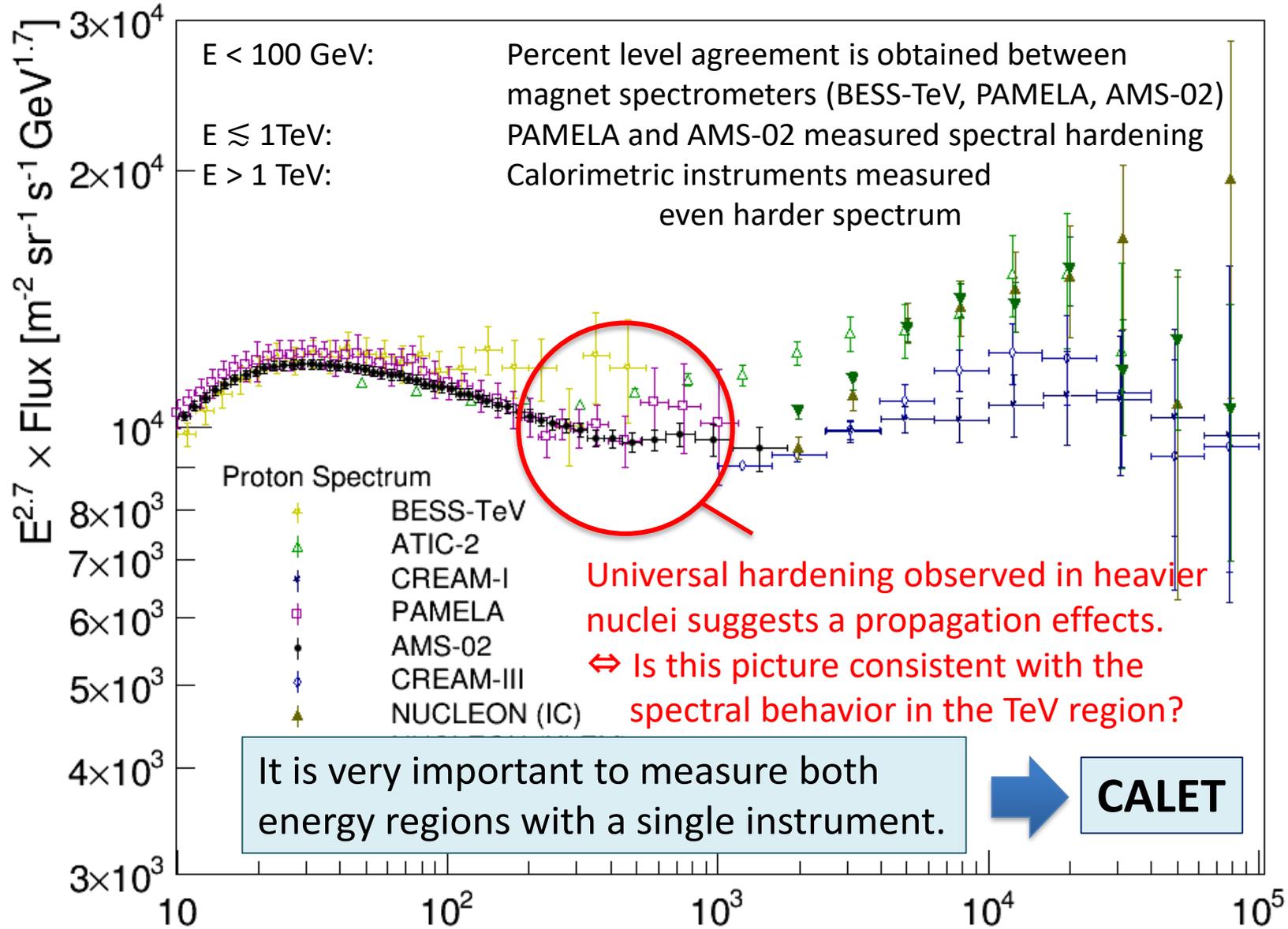
- 一次宇宙線の不定性は、2次粒子の生成量に直接影響
- 特に、陽子が星間物質と衝突して生成される反陽子は一桁ぐらいエネルギーが小さいので、100GeV領域の反陽子流束の見積もりにクリティカル

Status of Cosmic-Ray Proton Spectrum Measurements



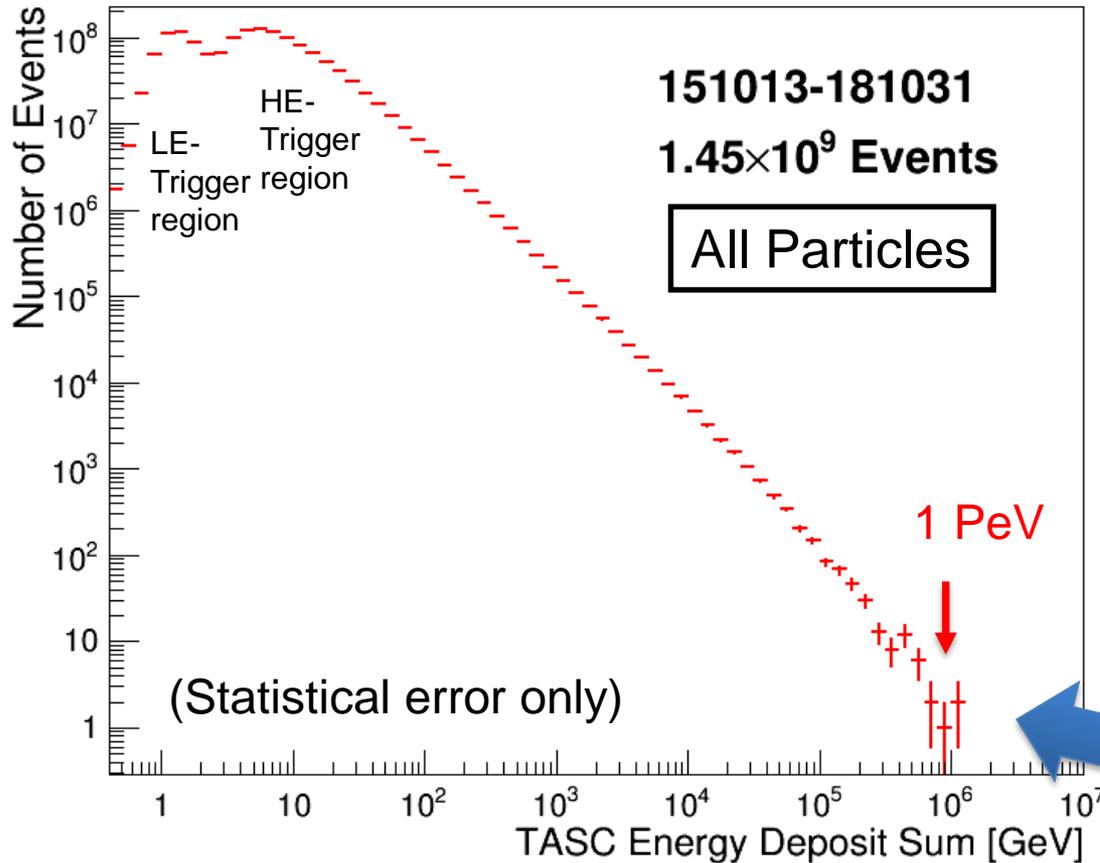
Universal hardening observed in heavier nuclei suggests a propagation effects.
 ⇔ Is this picture consistent with the spectral behavior in the TeV region?

Status of Cosmic-Ray Proton Spectrum Measurements

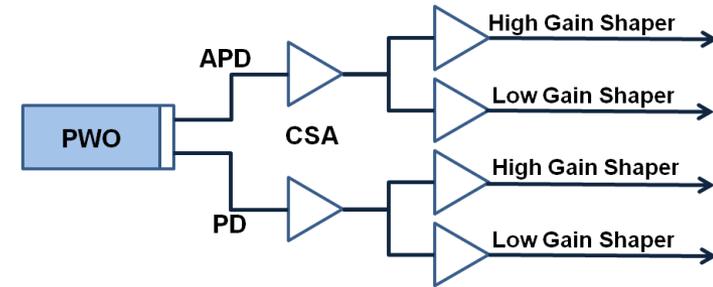
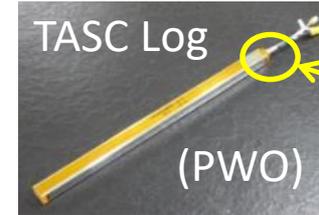


Wide Dynamic Range Energy Measurement

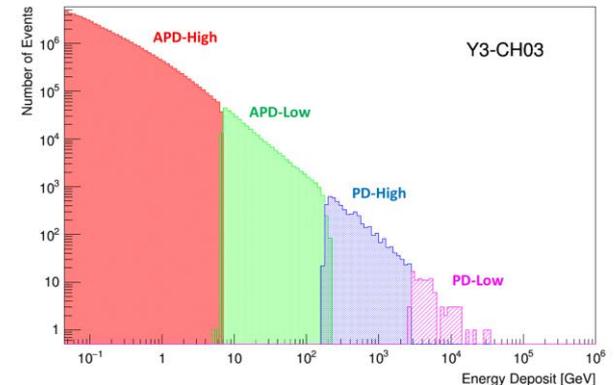
Distribution of TASC energy deposit sum



Y.Asaoka, Y.Akaike, Y.Komiya, R.Miyata, S.Torii et al. (CALET Collaboration), *Astropart. Phys.* 91 (2017) 1.

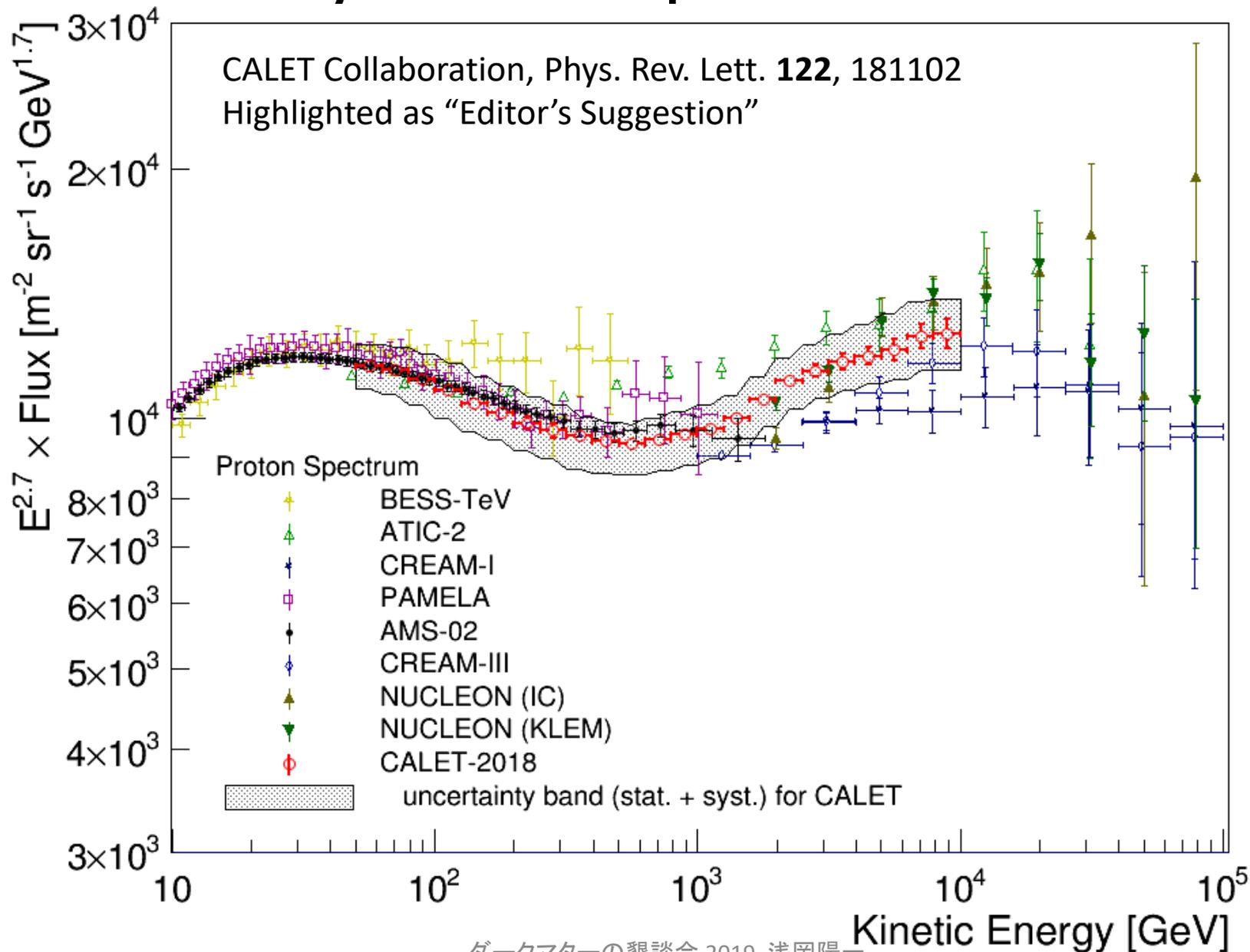


An example of gain connection in one PWO log:

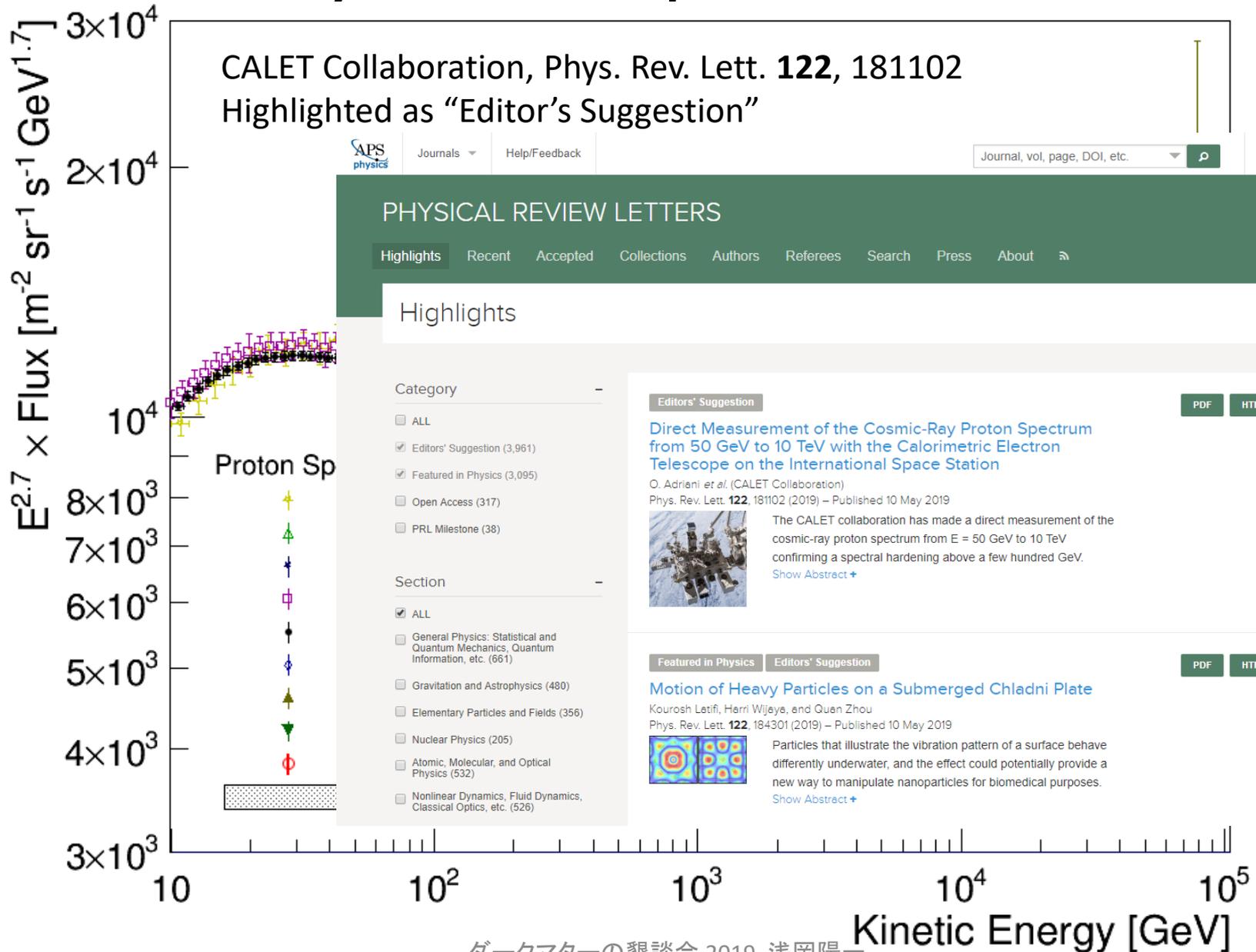


The smooth distribution clearly reflects the power-law nature of cosmic-rays, demonstrating the reliability of the energy measurement over a wide energy range.

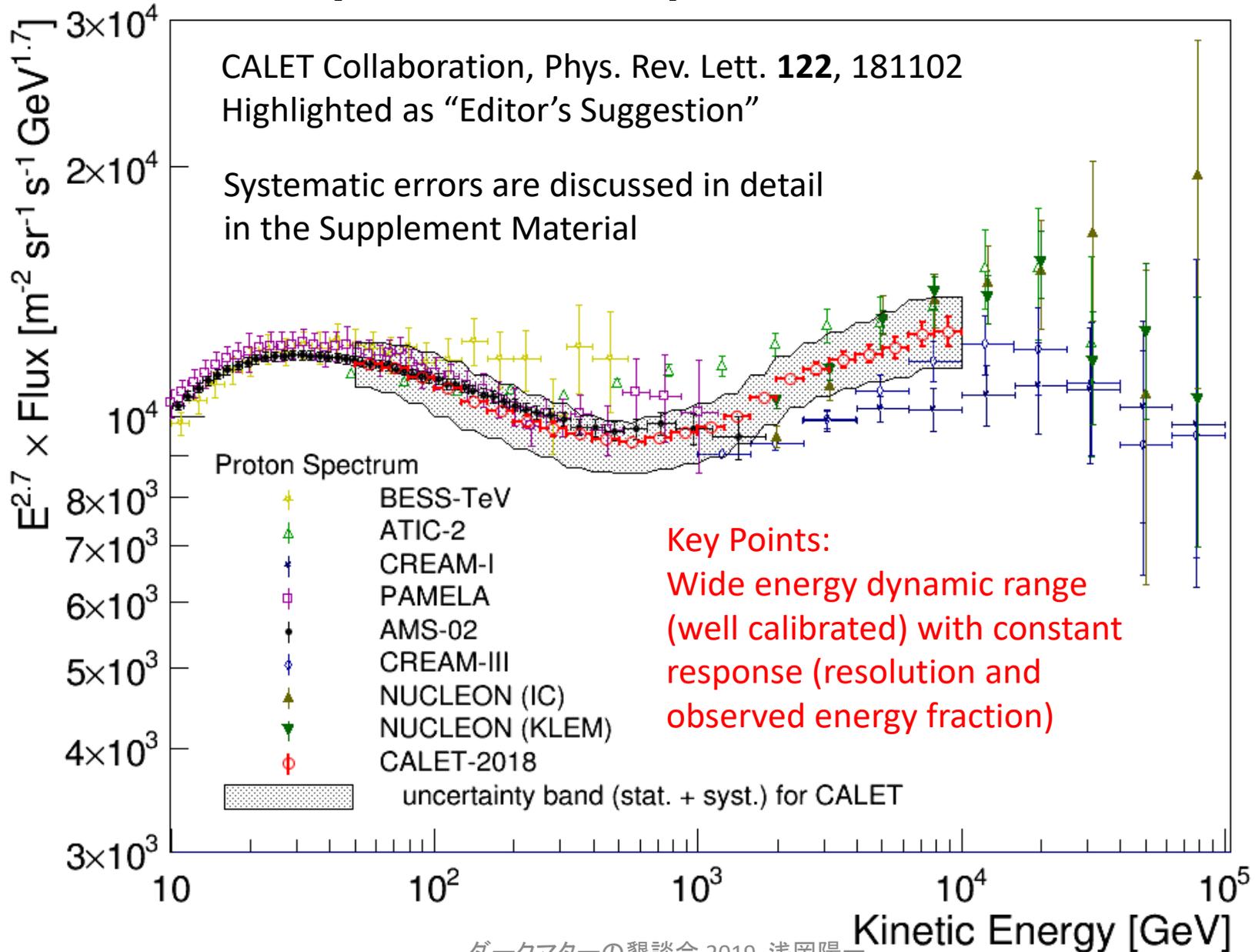
Cosmic-Ray Proton Spectrum from CALET



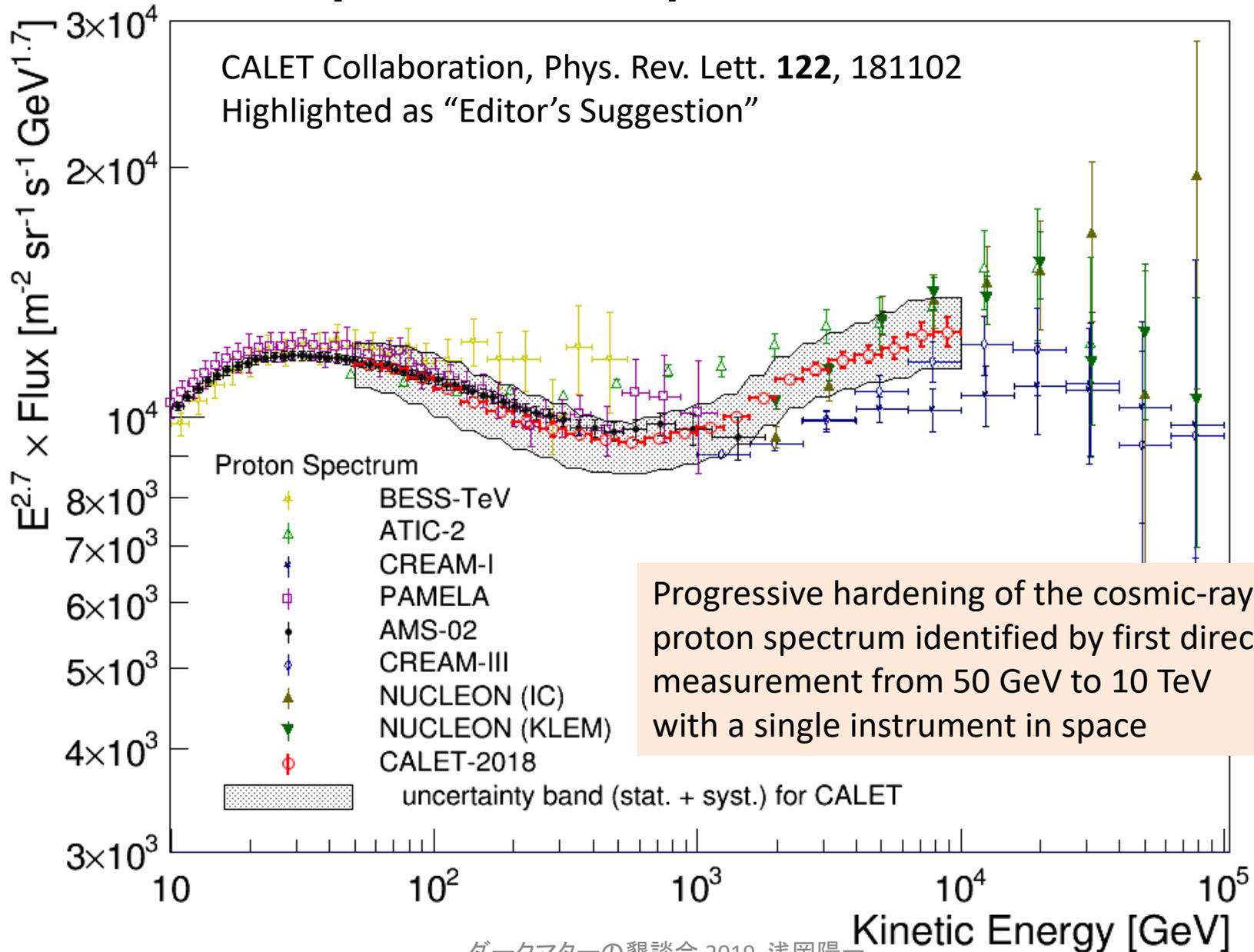
Cosmic-Ray Proton Spectrum from CALET



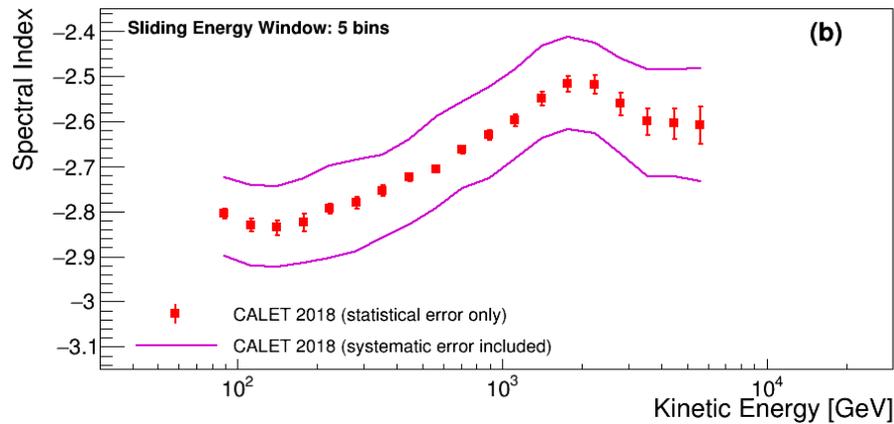
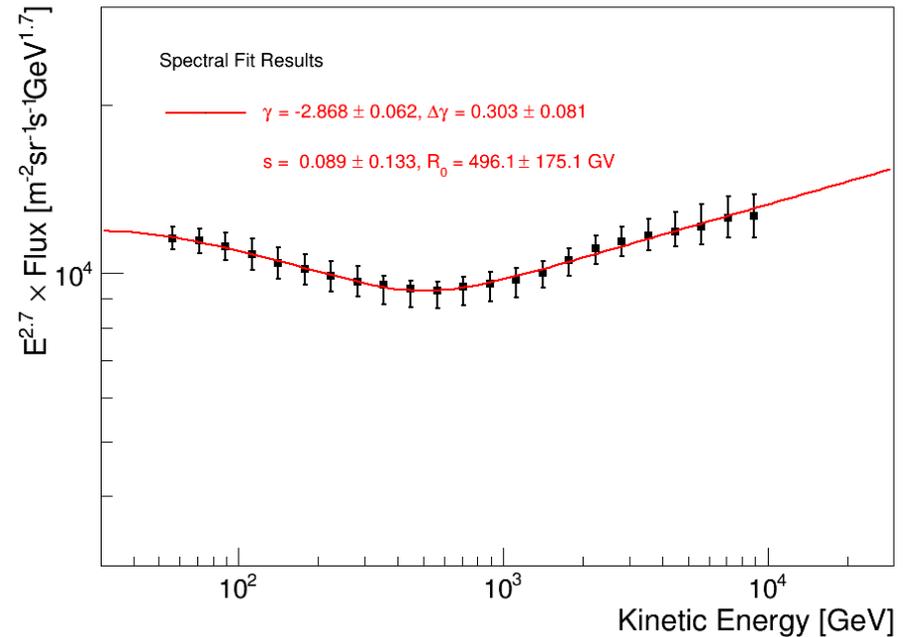
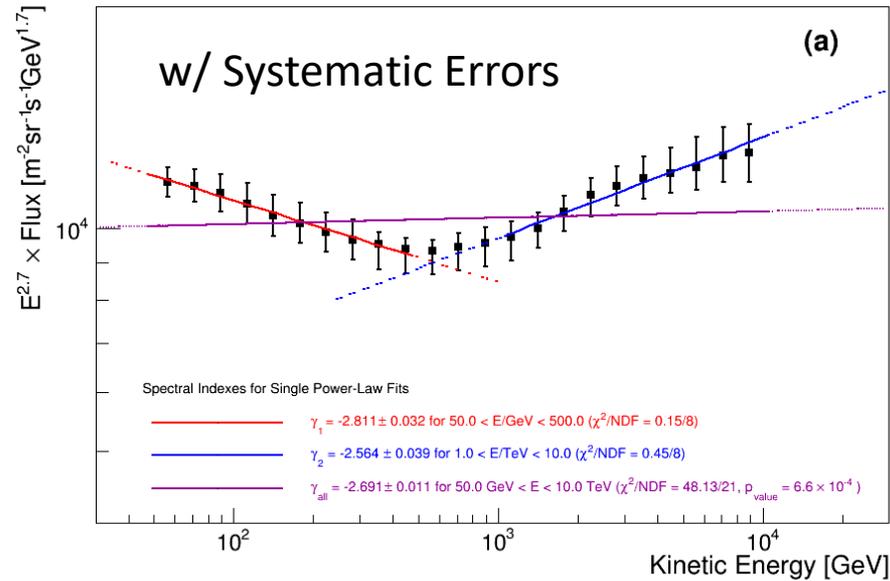
Cosmic-Ray Proton Spectrum from CALET



Cosmic-Ray Proton Spectrum from CALET



Spectral Behavior of Proton Flux



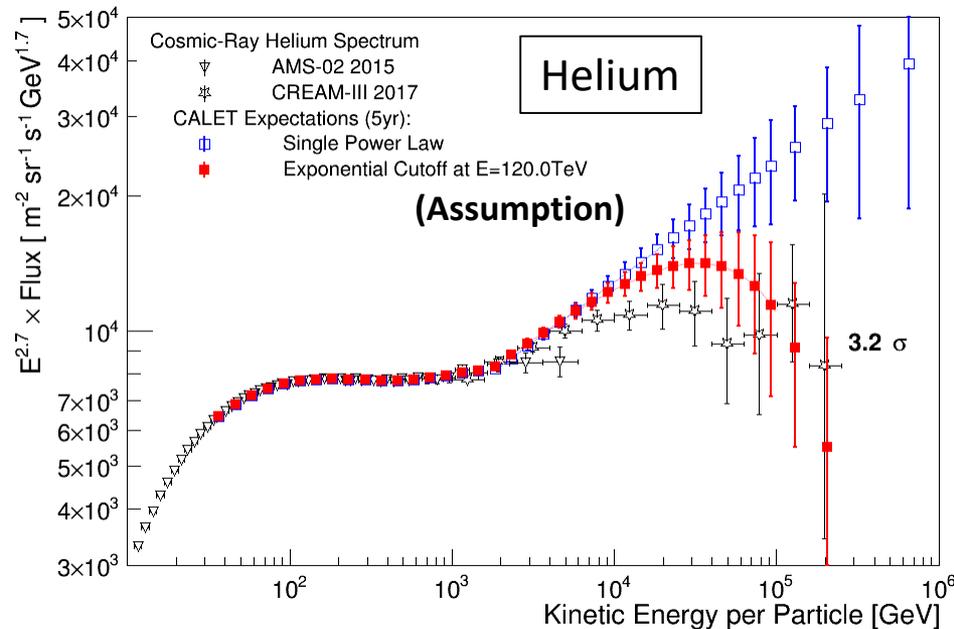
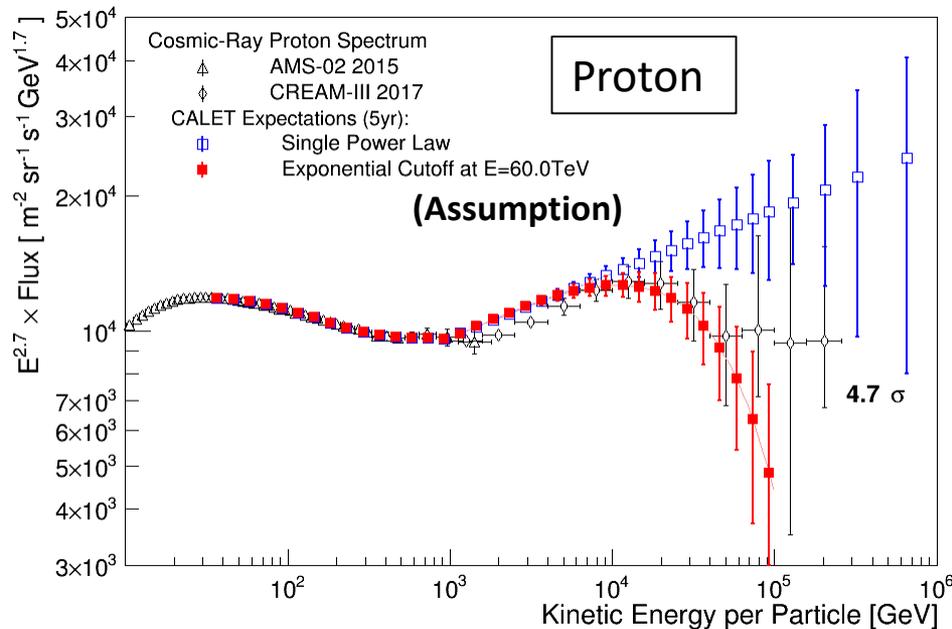
1. Subranges of 50—500GeV, 1-10TeV can be fitted with single power law function, but not the whole range (significance $> 3\sigma$).
2. Progressive hardening up to the TeV region was observed.
3. “smoothly broken power-law fit” gives power law index consistent with AMS-02 in the low energy region, but shows larger index change and higher break energy than AMS-02.

Prospects for CALET p/He spectrum measurement

- CALET's proton spectrum covers for the first time in space the whole energy interval previously investigated in separate sub-ranges by magnet spectrometers and calorimeters, making it possible to discuss the spectral behavior in detail.
 - Includes the assessment of systematic uncertainties.
 - Measured smoothness and extent of the spectral index change should have a strong impact on the interpretation of the spectral hardening.
- The future main target is to verify the charge-dependent acceleration limit of supernovae by precisely measuring the spectra of protons and helium up to the 100 TeV region.

$$E_{\max} = 6 \times 10^{13} \text{ eV } Z \left(\frac{B}{10^{-6} \text{ G}} \right) \left(\frac{u_1}{10^4 \text{ km/s}} \right)^2 \left(\frac{t_{\text{free}}}{200 \text{ year}} \right)$$

Phys. Soc. Japan vol67.12 p834
(Ohira, Yamazaki, Terasawa) in Japanese



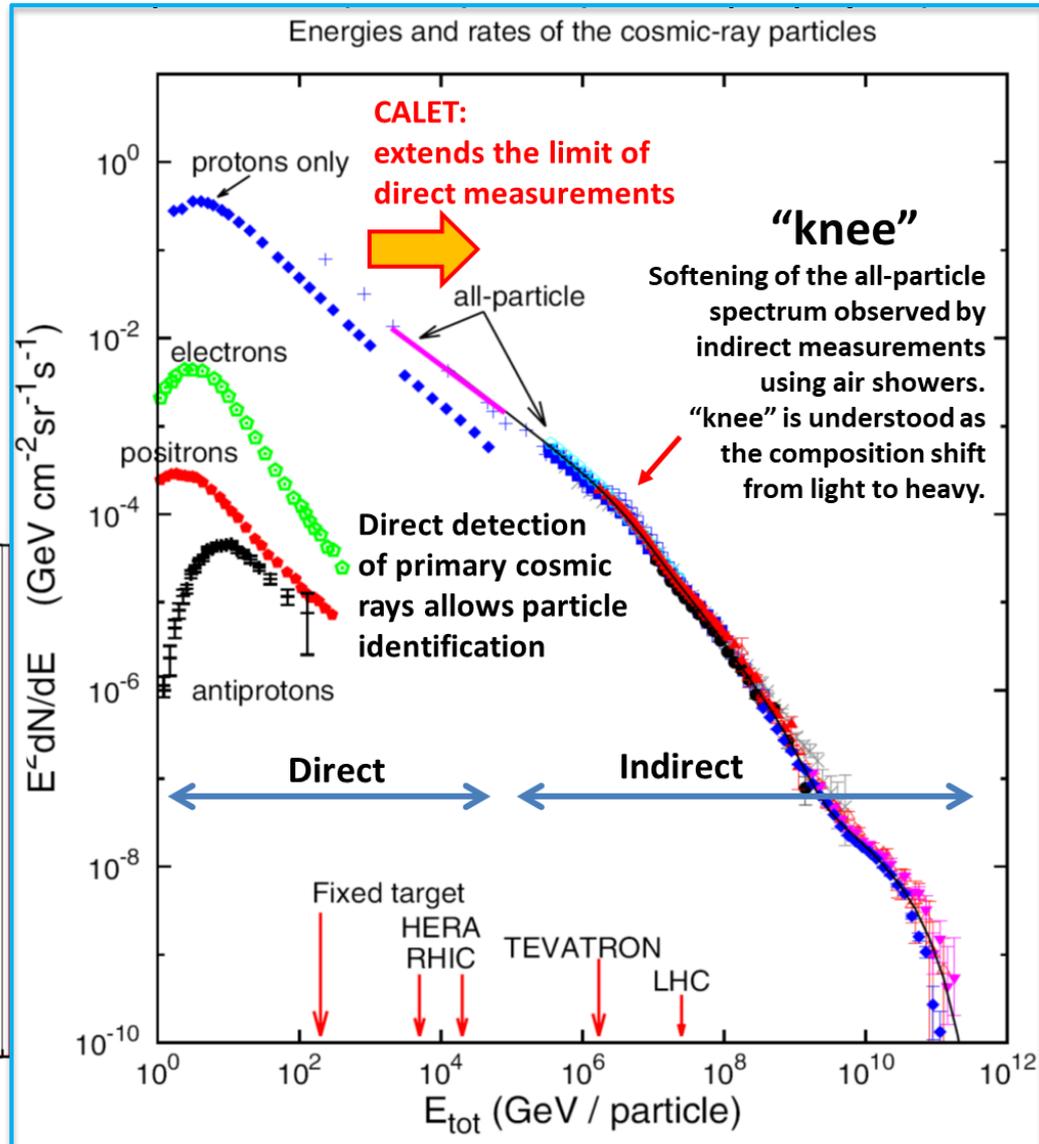
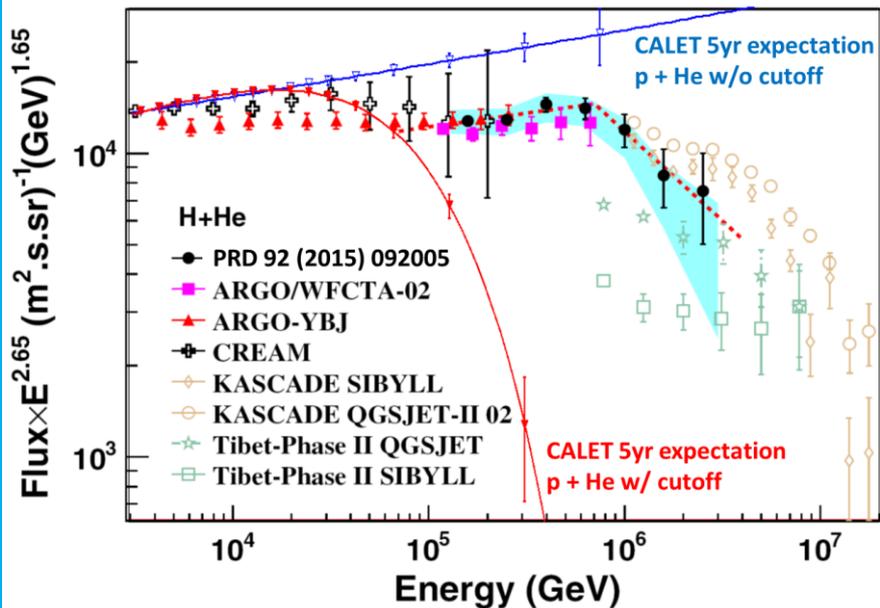
Prospects for CALET p/He spectrum measurement

- CALET's proton spectrum covers for the first time in space the whole energy interval previously investigated in separate sub-

The maximum energy extracted from typical supernova parameters are much smaller than the "knee" energy (3 PeV)

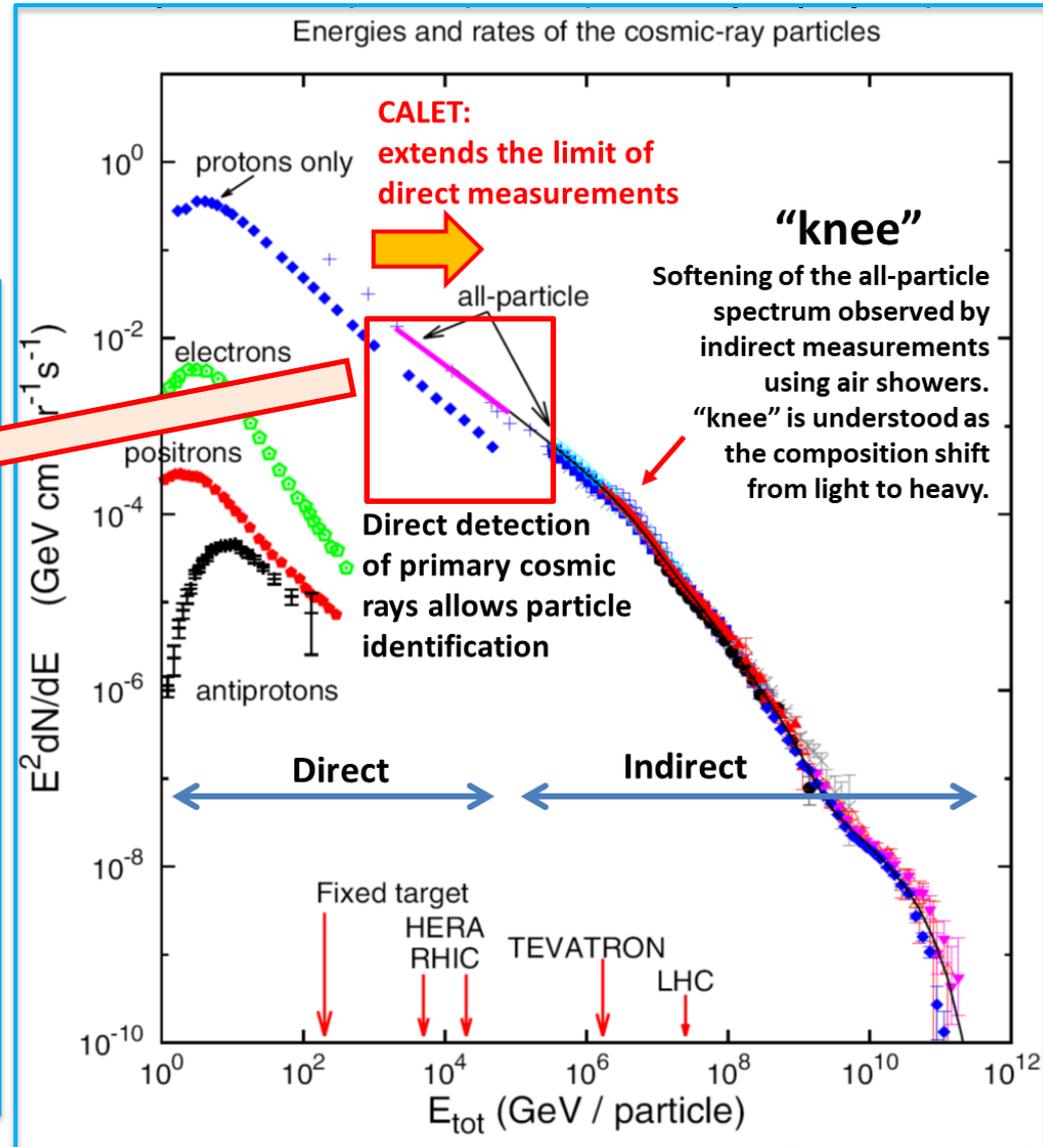
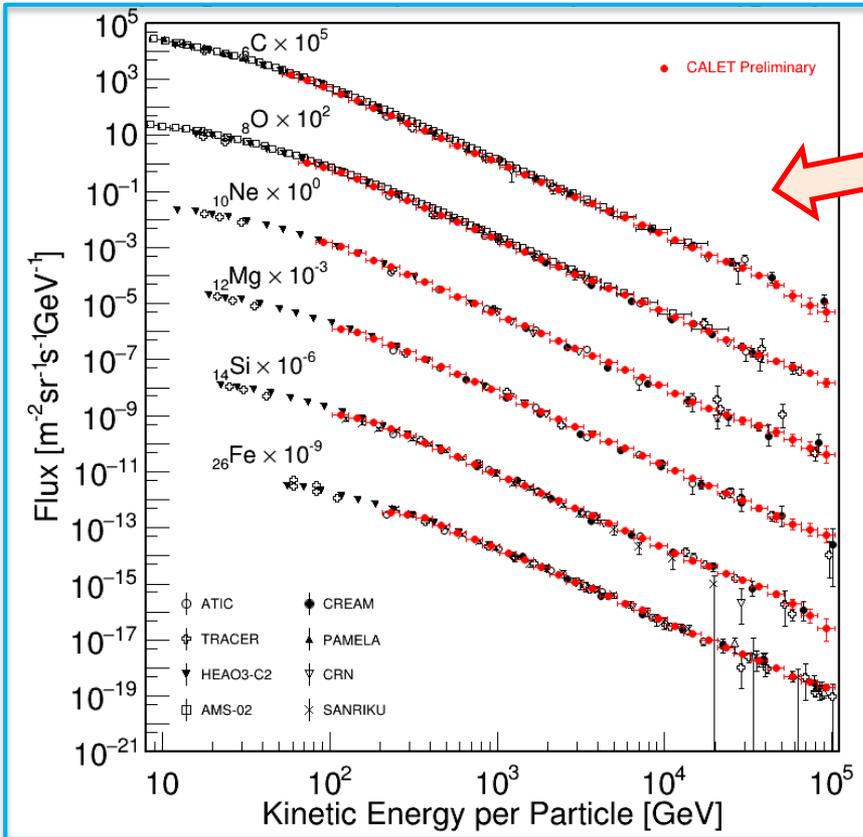
- The future target is to verify the by precisely measuring the spectra of

$$E_{\max} = 6 \times 10^{13} \text{ eV } Z \left(\frac{B}{10^{-6} \text{ G}} \right) \left(\frac{10^4}{\dots} \right)$$



Prospects for CALET nuclei spectrum measurement

- CALET's proton spectrum covers for the first time in space the whole energy interval previously investigated in separate sub making it possible to discuss the spect
 - Includes the assessment of systematic unce
 - Measured smoothness and extent of the sp interpretation of the spectral hardening.



まとめ

- 暗黒物質間接観測の意義
 - 暗黒物質の熱的残存条件を“直に”プローブ可能
 - バックグラウンドの不定性をどう抑えるかが重要
- 宇宙線直接観測の状況
 - 長年の夢だった宇宙空間における宇宙線直接観測が実現
 - PAMELA, AMS-02, CALET, DAMPE (+Fermi-LAT)
 - “unknown” unknowns の余地に注意
(宇宙線間接観測の場合は特に注意必要)
- 今後の展望
 - CALET, DAMPE が順調に観測を継続しており、
今後注目
 - AMS-02 からは、反物質(反重陽子, 反ヘリウム)の
結果がでてくるか