電子・陽電子観測の最新成果

早稲田大学理工学術院総合研究所
赤池陽水

Galactic cosmic rays

銀河宇宙線の標準加速モデル

- 超新星残骸による衝撃波加速
- 銀河系内を拡散的に伝播

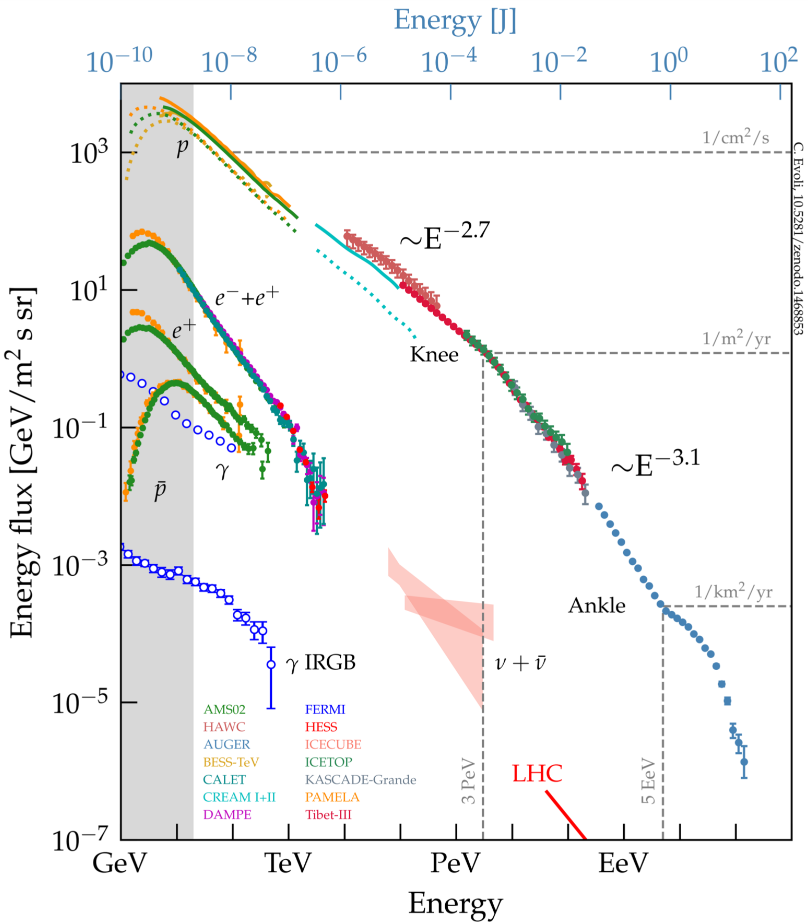
➡ 単一の冪型のエネルギースペクトル(dN/dE∝ $E^{-\gamma-\delta}$)
電荷に比例した加速限界(Ec ~ 100 Z TeV) など

標準モデルを超える観測事実

- 陽電子過剰
- スペクトル硬化 など

電子観測の重要性

- 地球近傍の加速源探索
- 宇宙暗黒物質の間接探索



C. Evoli

空気シャ

Features of cosmic-ray electrons

- 電子は銀河内伝播中に急激にエネルギーを失うため、遠方の源から地球に届かない
- 地球に届くTeV以上の電子は、近傍の加速源（R<1kpc, t<10万年）に限られる

● 輸送方程式

$$\frac{\partial}{\partial t} f\left(t,\varepsilon_e,\vec{x}\right) = D(\varepsilon_e)\nabla^2 f + \frac{\partial}{\partial \varepsilon_e}\left[b\varepsilon_e^2 f\right] + q\left(t,\varepsilon_e,\vec{x}\right)$$

拡散項

エネルギー損失
- シンクロトロン放射
- 逆コンプトン散乱

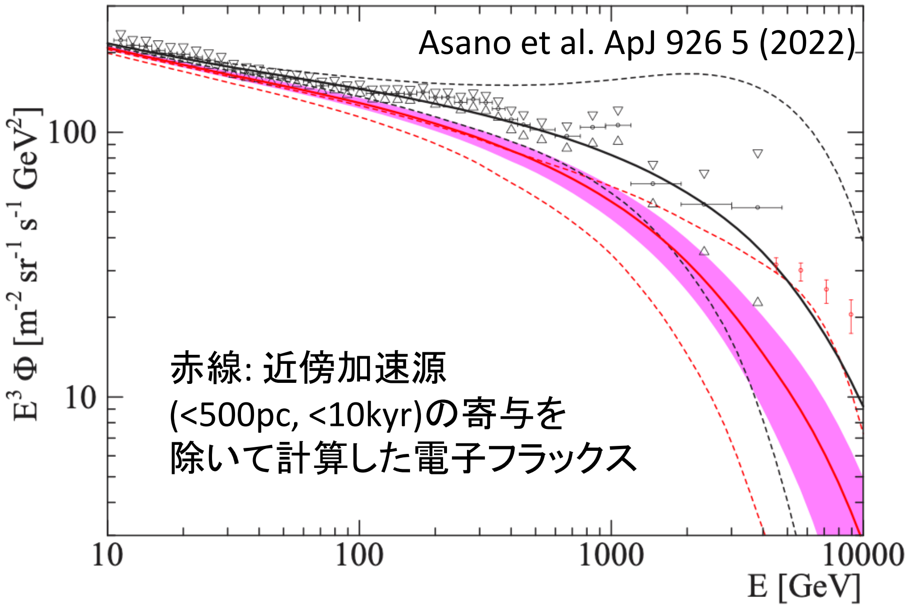
ソース項

● エネルギー損失

$$-\frac{dE}{dt} = bE^2, \qquad b = \frac{4\sigma c}{3{m_e}^2 c^4}\left(\frac{B^2}{8\pi} + w_{\mathrm{ph}}\right)$$

➡ $\frac{1}{E(t)} = bt + \frac{1}{E_0}$ (E_0: 電子の初期のエネルギー)

➡ $t \sim 1/bE_{cut}$, $R=(2Dt)^{1/2}$



Features of cosmic-ray electrons

- 電子は銀河内伝播中に急激にエネルギーを失うため、遠方の源から地球に届かない
- 地球に届くTeV以上の電子は、近傍の加速源（R<1kpc, t<10万年）に限られる

● 輸送方程式

$$\frac{\partial}{\partial t} f\left(t,\varepsilon_e,\vec{x}\right) = D(\varepsilon_e)\nabla^2 f + \frac{\partial}{\partial \varepsilon_e}\left[b\varepsilon_e^2 f\right] + q\left(t,\varepsilon_e,\vec{x}\right)$$

拡散項

エネルギー損失
- シンクロトロン放射
- 逆コンプトン散乱

ソース項

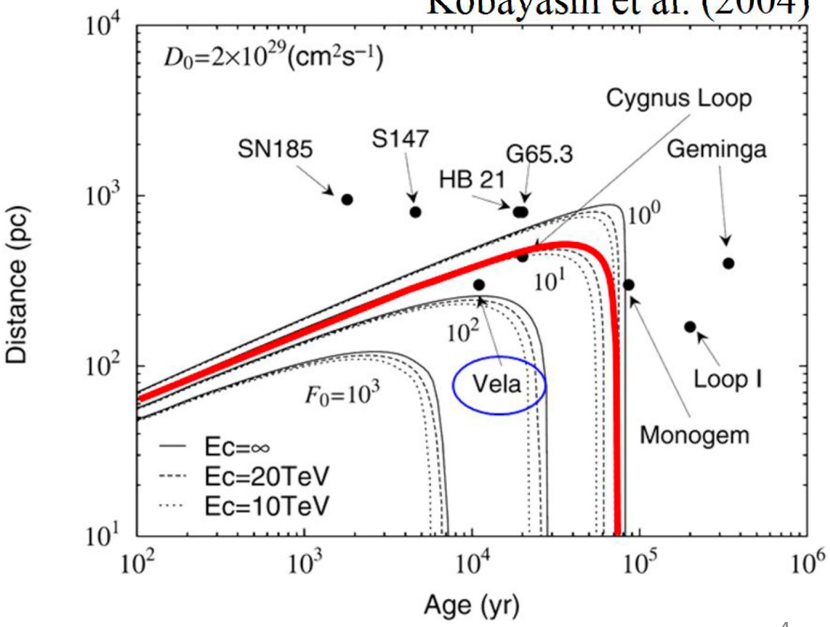
● エネルギー損失

$$-\frac{dE}{dt} = bE^2, \qquad b = \frac{4\sigma c}{3{m_e}^2c^4}\left(\frac{B^2}{8\pi} + w_{\mathrm{ph}}\right)$$

➡ $\frac{1}{E(t)} = bt + \frac{1}{E_0}$ (E_0: 電子の初期のエネルギー)

➡ $t \sim 1/bE_{cut}$, $R=(2Dt)^{1/2}$

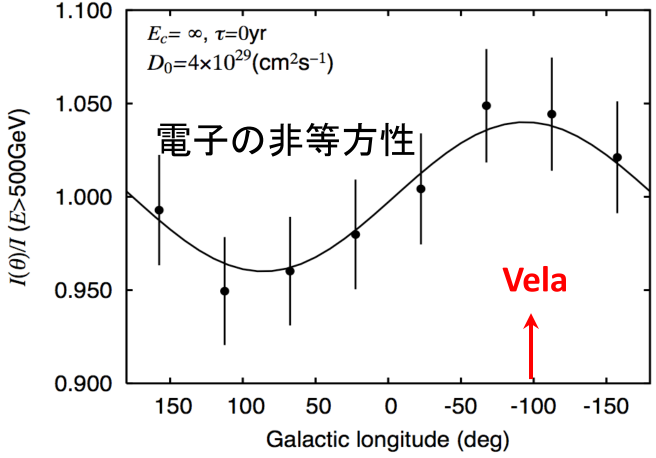
地球における電子3TeVの予想強度

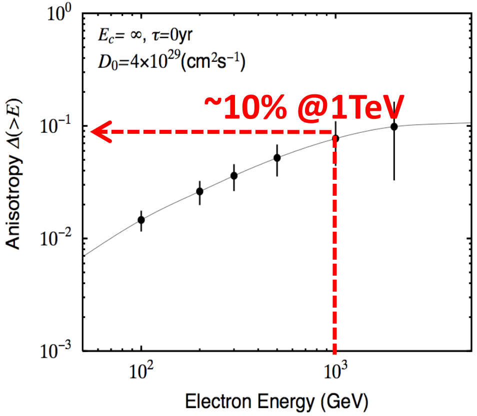


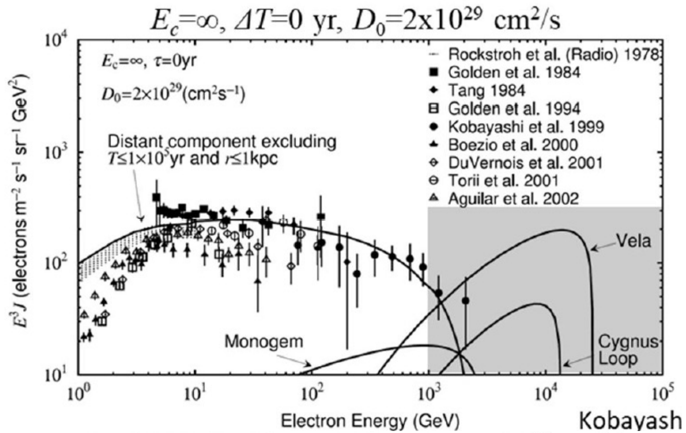
Contributions from nearby sources

- TeV領域に近傍加速源(Vela)の直接的な影響が現れる
- Velaの寄与が大きければ、非等方性が現れる

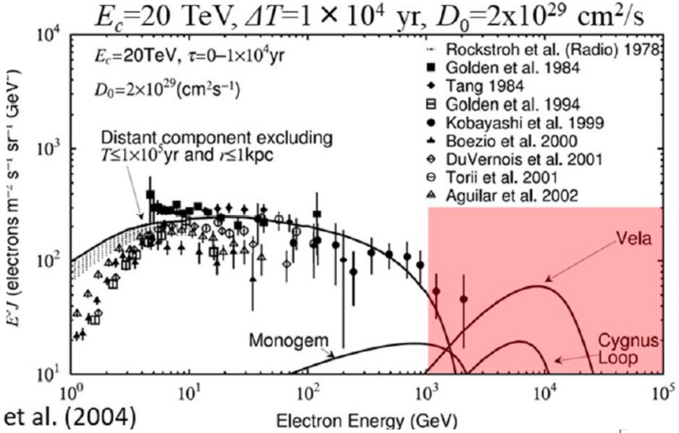
TeV領域の電子観測
➡ 荷電粒子として初めて宇宙線加速源を同定







Kobayash

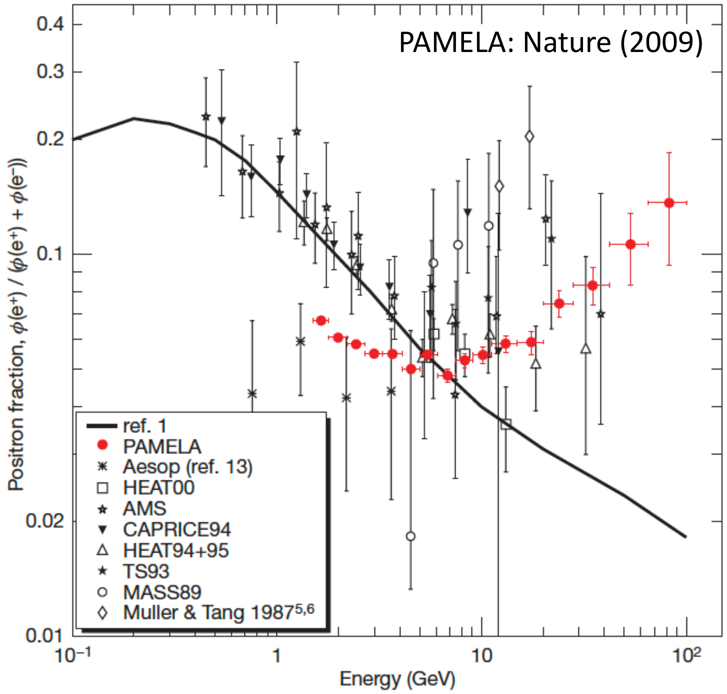


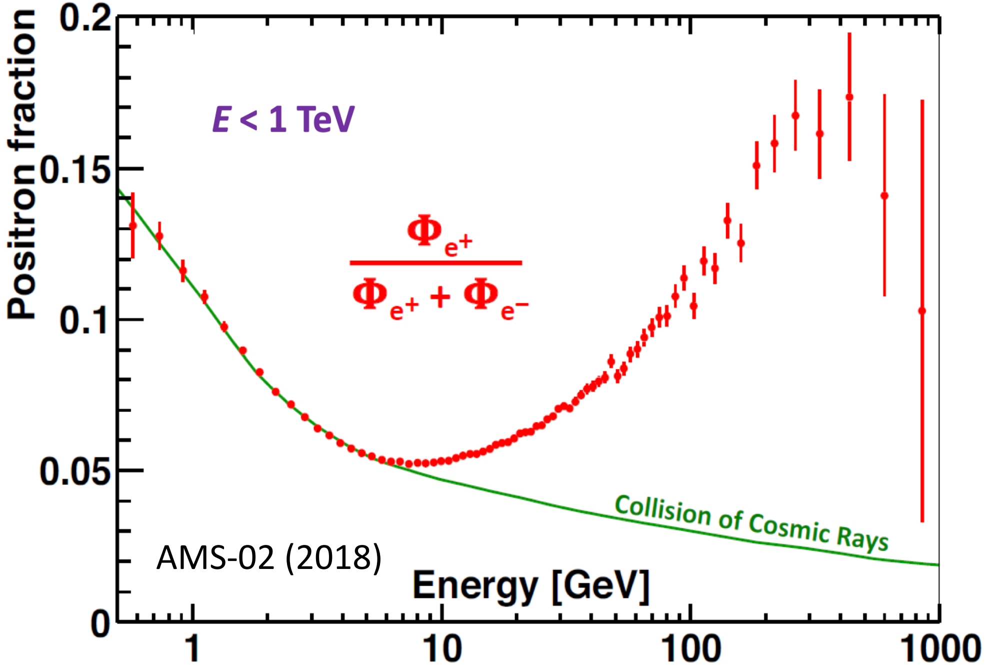
et al. (2004)

Kobayashi et al. (2004)

Positron fraction

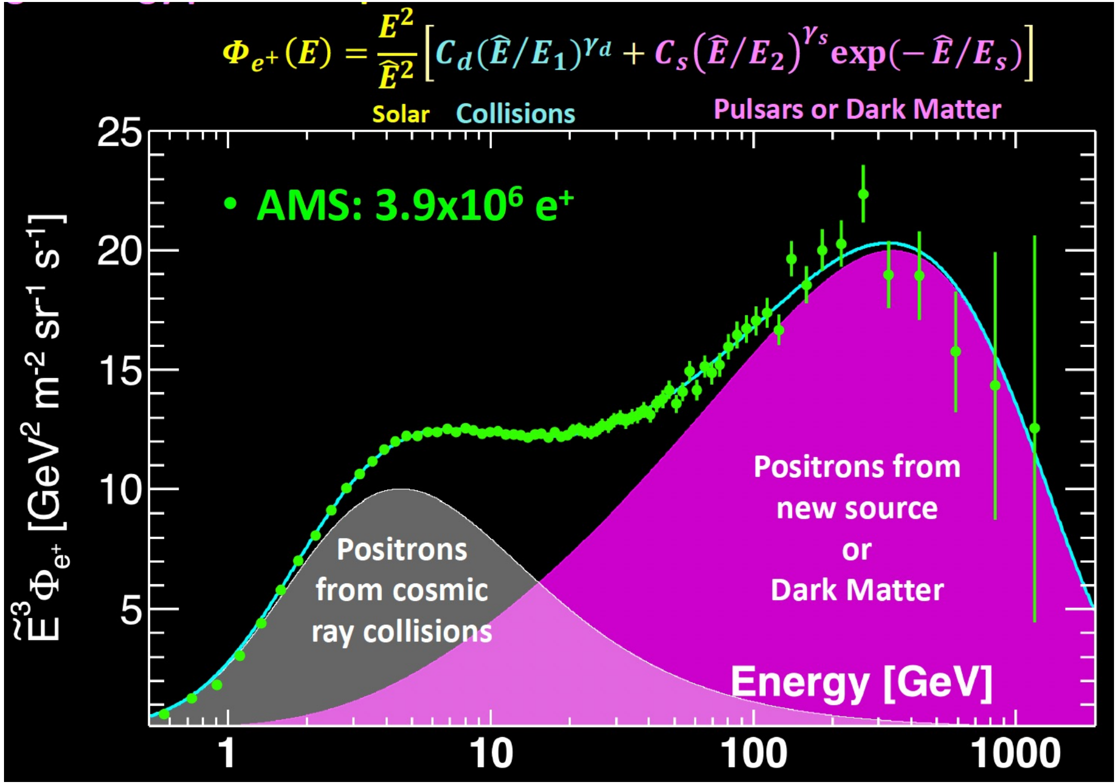
標準モデルによると、陽電子は陽子等が星間物質との相互作用でできる二次的生成物。エネルギーとともに減少
PAMELAが陽電子の増加を発見。AMS-02が1TeVまで伸ばし、250GeVをピークに減少傾向

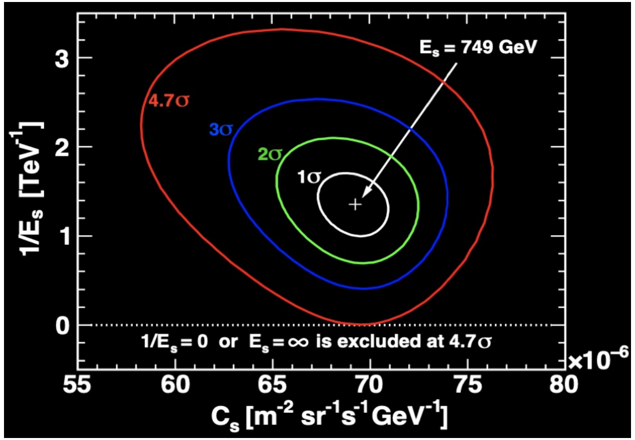




Positron excess

AMS-02: PoS(ICRC2023) 065





Possible explanations:

e$^+$ - e$^-$ pairs are produced

- Astrophysical sources

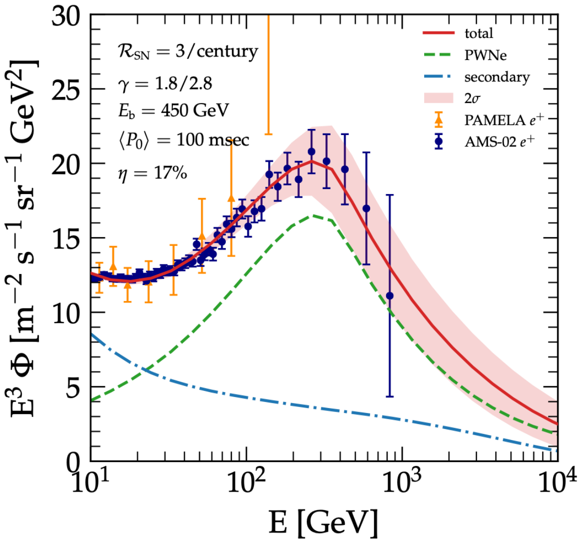
  Pulsar, PWN, old SNRs, …

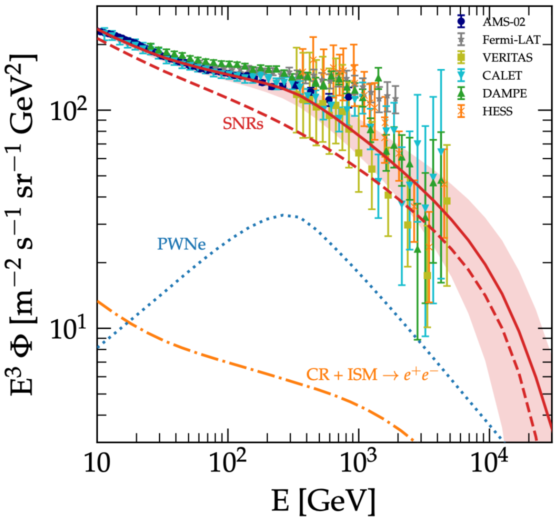
- Decay/Annihilation of dark matter

Interpretations of positron excess

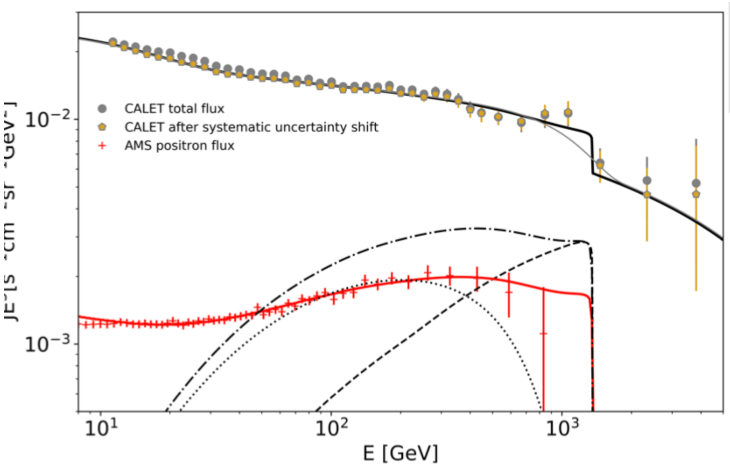
陽電子(+電子)対の一次成分;
- 天体起源(パルサー、PWN, SNRなど)
- 暗黒物質
- 伝播モデル　　PAMELAの論文は1700のcitations

Astrophysical sources; PRD 103, 083010 (2021)





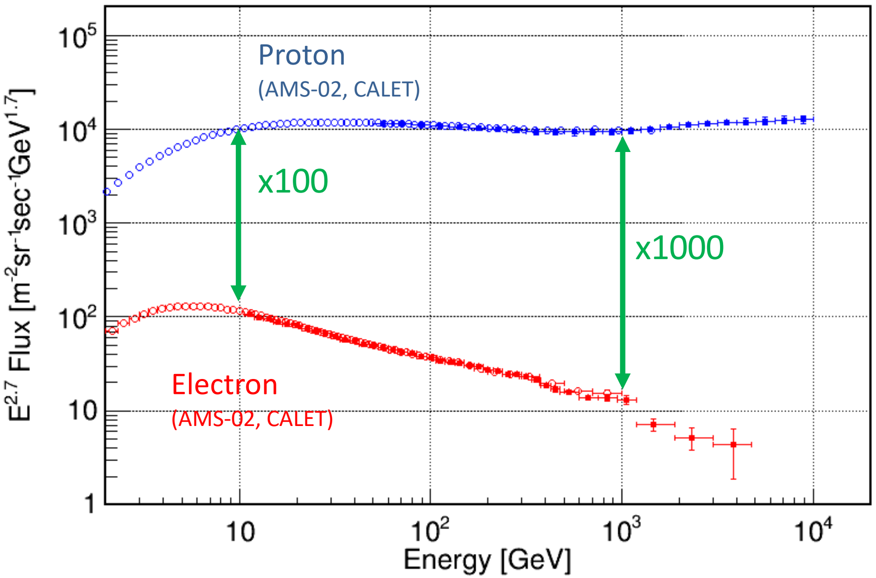
Dark matter; PRD 102, 083019 (2020)



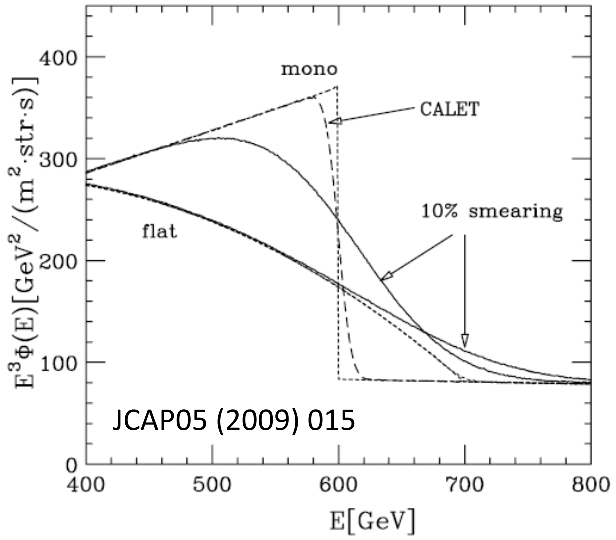
Requirements for electron measurements

Requirements for the electron measurements:

1. Electron flux is rare (2-5 events / $m^{-2}sr^{-1}$day for E>1TeV)
2. Large proton background
3. Excellent energy resolution is required

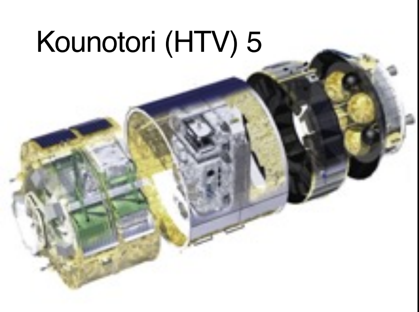


Energy spectra for monochromatic and float spectra before and after taking account of the energy resolution



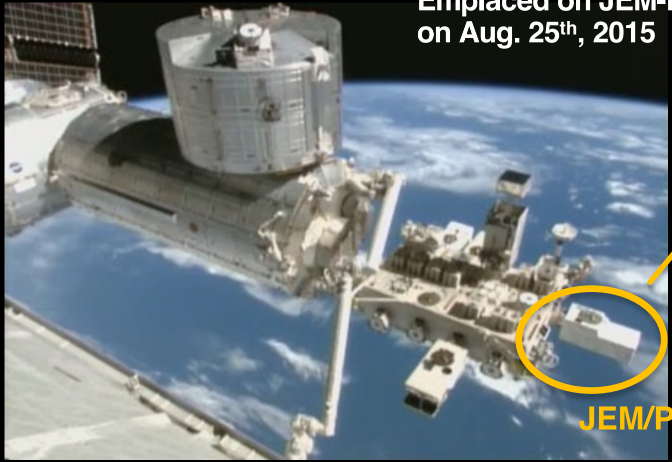
JCAP05 (2009) 015

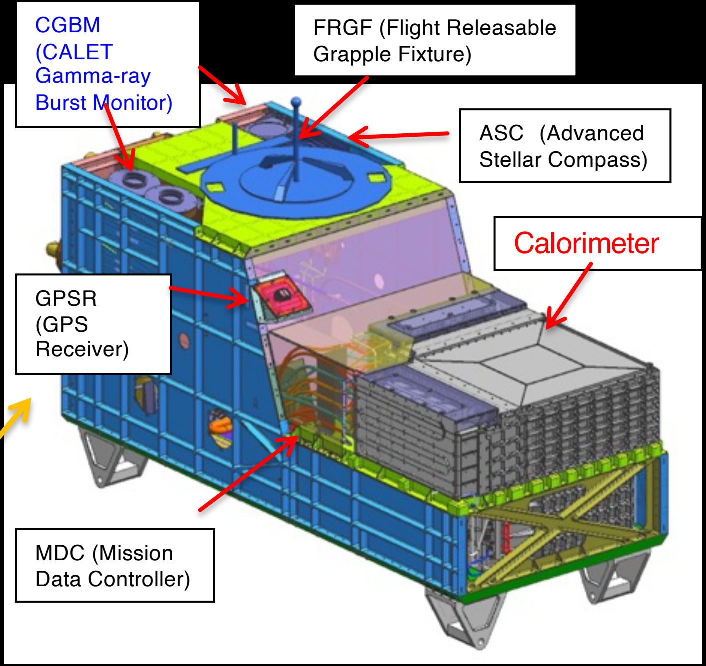
CALET Payload



Launched on Aug. 19th, 2015 by the Japanese H2-B rocket

Emplaced on JEM-EF port #9 on Aug. 25th, 2015





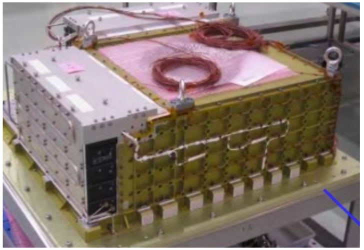
- **Mass: 612.8 kg**
- **JEM Standard Payload Size:**
  1850mm(L) × 800mm(W) × 1000mm(H)
- **Power Consumption: 507 W (max)**
- **Telemetry:**
  Medium 600 kbps (6.5GB/day) / Low 50 kbps

Yosui Akaike

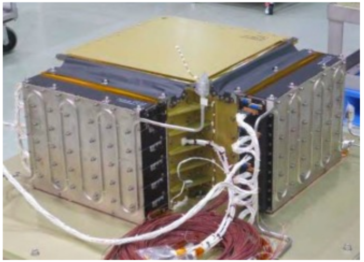
Overview of the CALET Detector

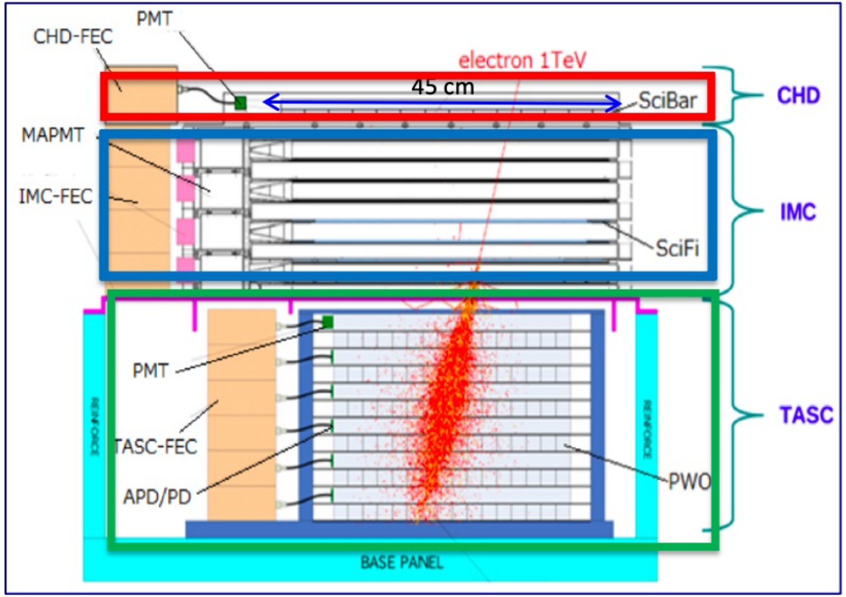
A 30-radiation length deep calorimeter designed to detect electrons and gamma-rays to 20 TeV and cosmic rays up to 1 PeV

CHD/IMC



TASC





CHD – Charge Detector

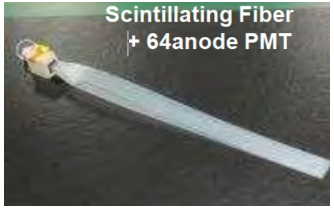
- 2 layers x 14 plastic scintillating paddles
- **single element charge ID** from p to Fe and above (Z = 40)
- charge resolution ~0.1-0.3 e

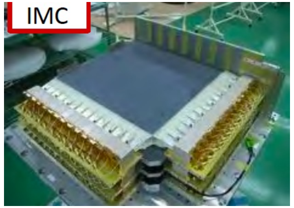
IMC – Imaging Calorimeter

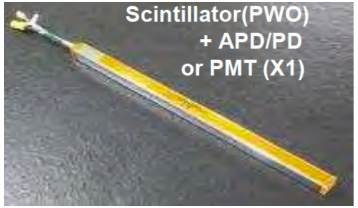
- Scifi. + tungsten absorbers: **3 X_0**
- 8 x 2 x 448 plastic scintillating fibers (1mm) **readout individually**
- **tracking** (~0.1° angular resolution) + **Shower imaging**
- **angular resolution:** 0.2° for gamma-rays > ~50 GeV

TASC – Total Absorption Calorimeter

- 6 x 2 x 16 lead tungstate ($PbWO_4$) logs: **27 X_0, 1.2 λ_I**
- **energy resolution:** ~2 % (>10GeV) for e , γ
  ~30-35% for p, nuclei
- **e/p separation:** ~10^{-5}

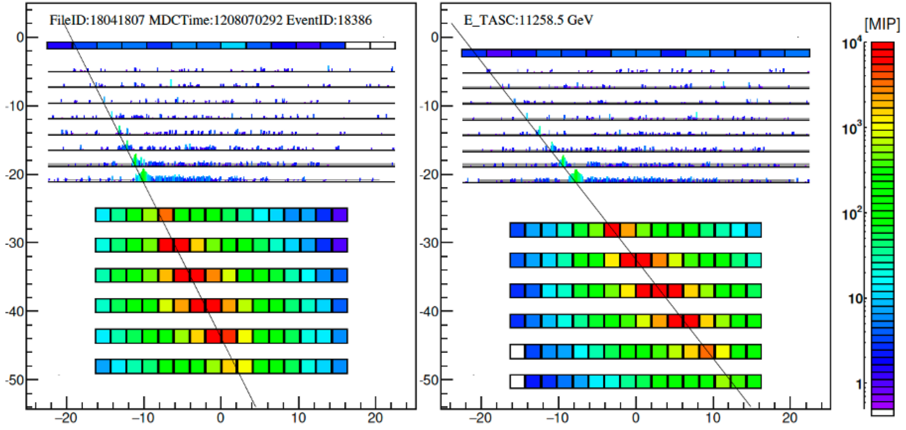


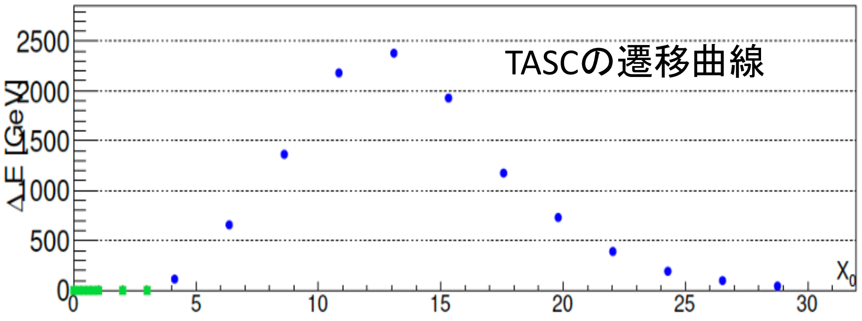




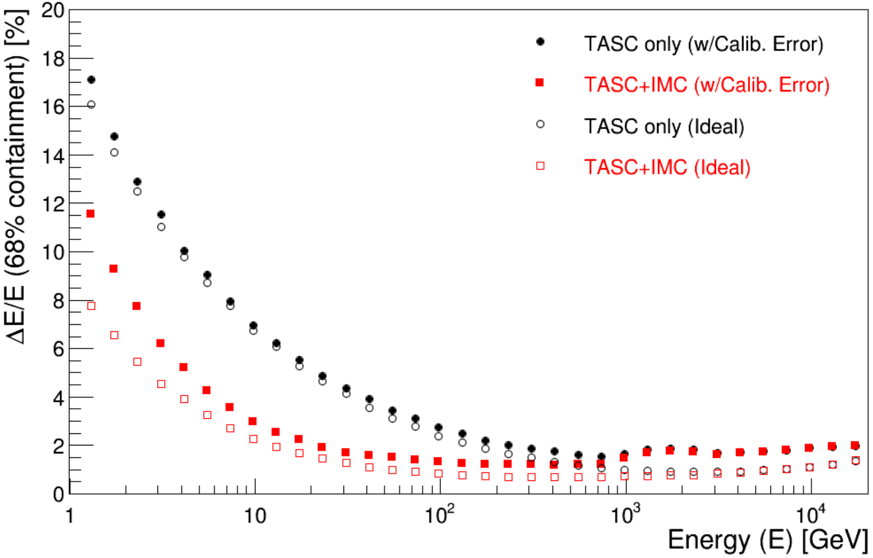
Energy resolution with CALET

12TeVの電子検出例





Energy resolution



Electron identification with CALET

Simple Two Parameter Cut

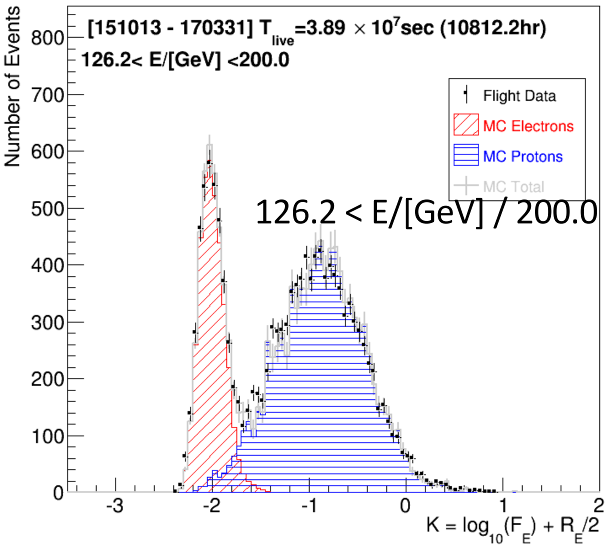
E<476GeV

F_E: Energy fraction of the bottom layer sum to the whole energy deposit sum in TASC

R_E: Lateral spread of energy deposit in TASC-X1

Cut Parameter K is defined as follows:

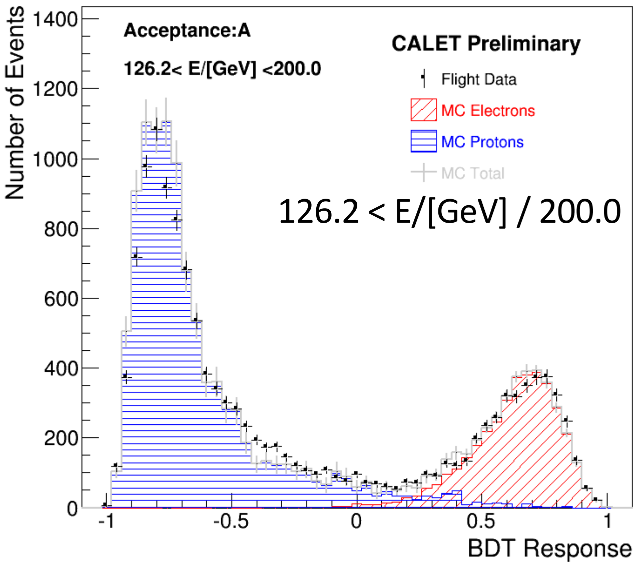
$$K = \log_{10}(F_E) + 0.5\, R_E \ (\text{/cm})$$



Boosted Decision Trees (BDT)

E>476GeV

In addition to the two parameters in the left, TASC and IMC shower profile fits are used as discriminating variables with 9 parameters



Electron identification with CALET

The discriminate variables for BDT are optimized;

1. Lateral spread : R_E
2. Shower development : F_E
3. *Shower concentration ratio on IMC Y8 : C_E

- The fitting of TASC transition curve
  4. ***α/b***
  5. ***b***
  6. χ^2/NDF
  7. $T_{5\%}$

$$\frac{dE}{dt} = E_0 \frac{b^{\alpha+1}}{\Gamma(\alpha+1)} t^{\alpha} e^{-bt}$$

($T_{5\%}$: Development the ratio of energy deposit is 5%)

- Exponential fitting of IMC transition curve
  8. ***p0***
  9. ***p1***
  10. χ^2/NDF

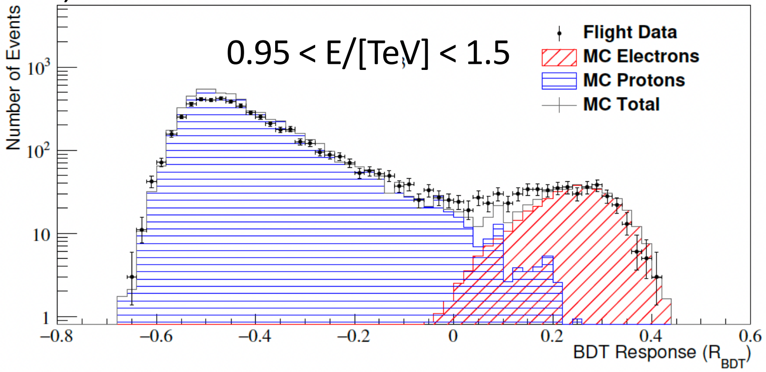
$$\frac{dE}{dt} = e^{(p_1 t + p_0)}$$

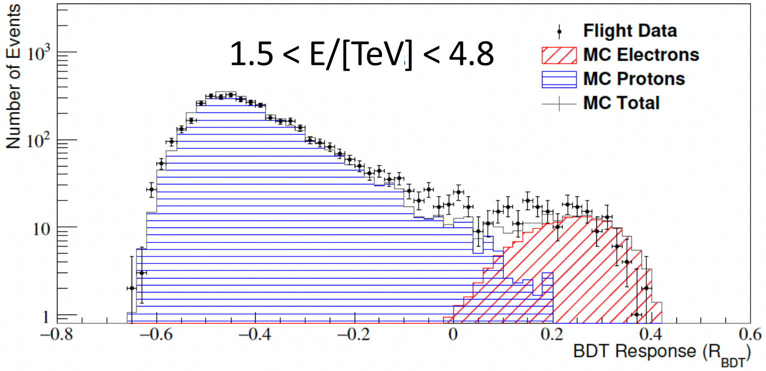
11. *The sum of CHD energy deposit : S_{CHD}

- Energy ratio between adjacent IMC layers
  12. * R_{max}
  13. * R_{67}

* New parameters

➡ The total BG protons are less than 10% up to 7.5 TeV with 70% electron efficiencies





Detectors for cosmic-ray electrons

- 直接観測
  - Magnetic spectrometer
    電子・陽電子を識別可能
    - PAMELA (MDR = ~1.2 TV, SΩ=~0.002m^2sr)
    - AMS-02 (MDR = ~2 TV, SΩ=~0.05 m^2sr)

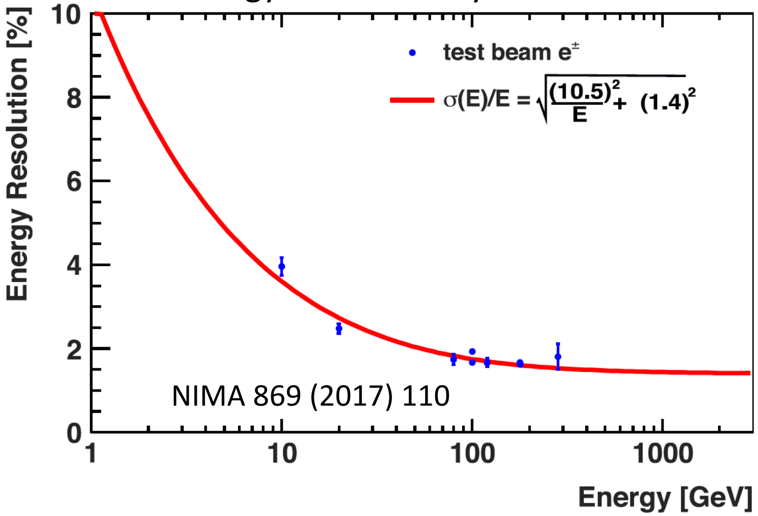
  - Calorimeter
    TeV以上の領域まで測定可能
    - Fermi-LAT (8.6(12)X_0, SΩ=1~2.5 m^2sr)
    - CALET (30X_0, SΩ=~0.1 m^2sr)
    - DAMPE (32X_0, SΩ=~0.3 m^2sr)

- 地上観測
  - Imaging Atmospheric Cherenkov Telescope
    膨大な観測量
    - HESS, MAGIC, VERITAS

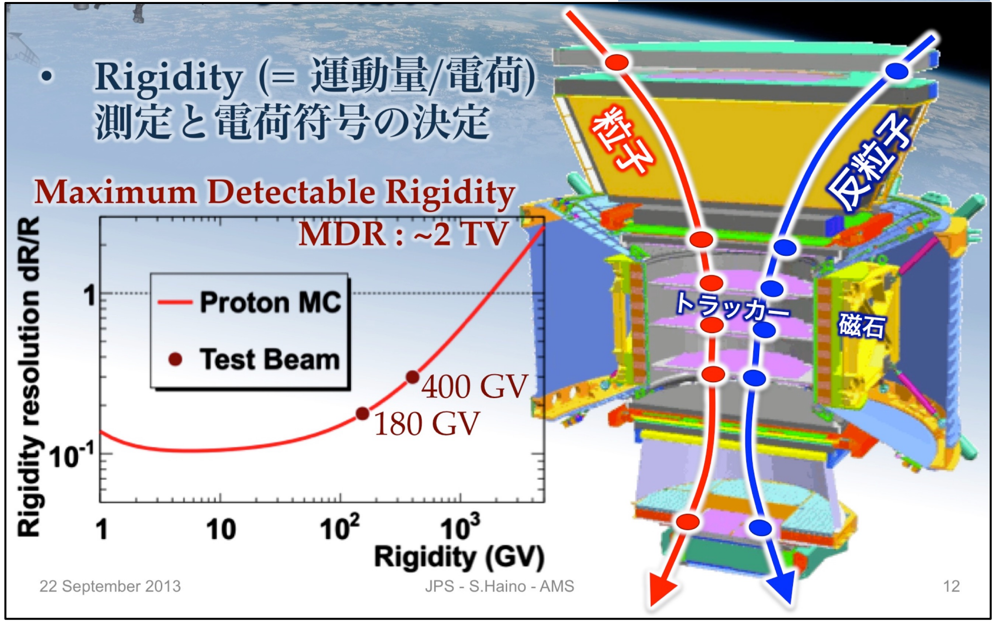
Magnet spectrometer (AMS-02): rigidity and energy resolution

- 直接観測
  - Magnetic spectrometer
    電子・陽電子を識別可能
    - PAMELA (MDR = ~1.2 TV, SΩ=~0.002m^{2}sr)
    - AMS-02 (MDR = ~2 TV, SΩ=~0.05 m^{2}sr)

Energy resolution by ECAL of AMS-02



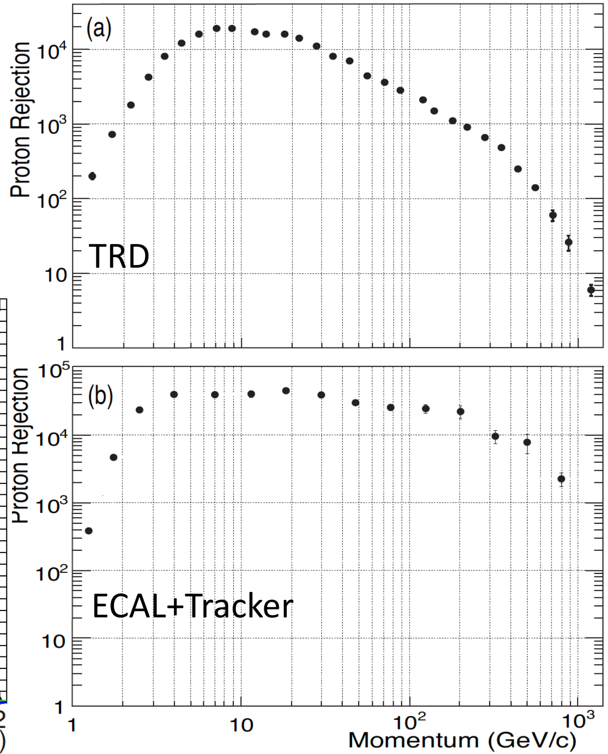
$$\Delta(1/R) = \frac{\Delta R}{R^2} \approx \frac{8\Delta s}{0.3BL^2}$$



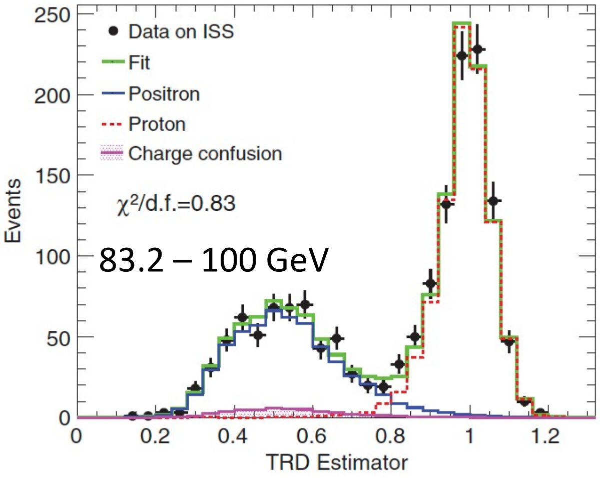
Magnet spectrometer (AMS-02): electron identification

- 直接観測
  - Magnetic spectrometer
    電子・陽電子を識別可能
    - PAMELA (MDR = ~1.2 TV, SΩ=~0.002m^{2}sr)
    - AMS-02 (MDR = ~2 TV, SΩ=~0.05 m^{2}sr)

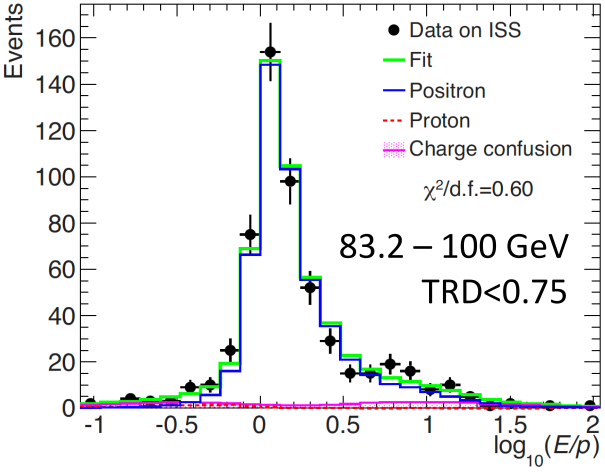
AMS-02: Proton rejection for e$^{\pm}$
with 90% efficiency for each



AMS-02: TRD estimator



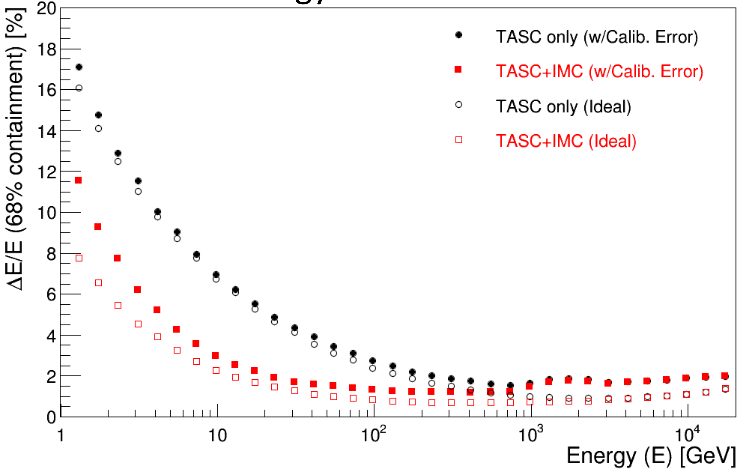
AMS-02: E/p ratio



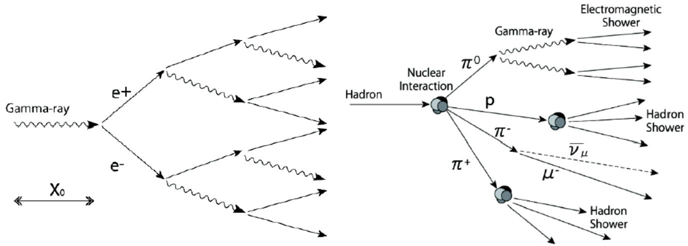
Calorimeter

- 直接観測
  - Calorimeter
    TeV以上の領域まで測定可能
    - Fermi-LAT (8.6(12)X_0, SΩ=1~2.5 m^2sr)
    - CALET (30X_0, SΩ=~0.1 m^2sr)
    - DAMPE (32X_0, SΩ=~0.3 m^2sr)

CALET: energy resolution

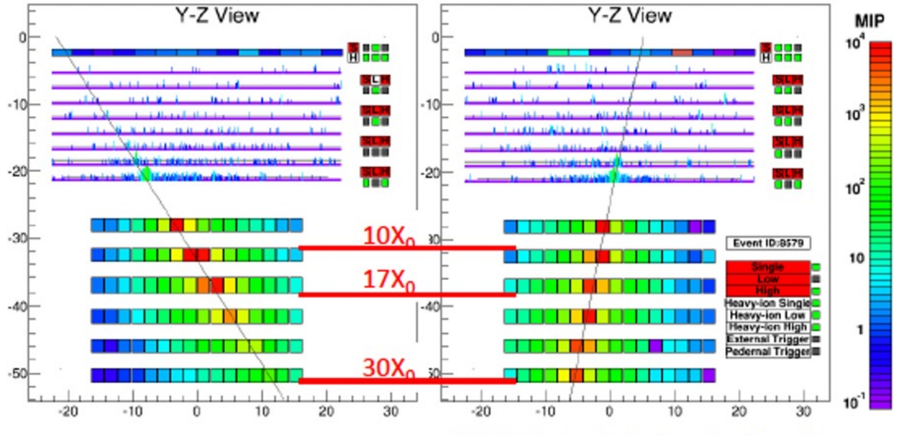


電磁シャワー vs ハドロンシャワー



3TeV Electron Candidate

Corresponding Proton Background

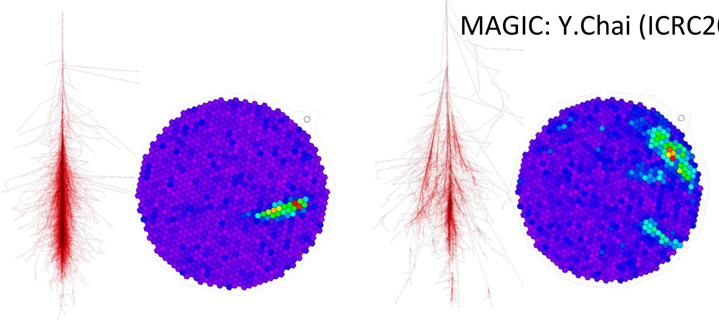


(Flight data; detector size in cm)

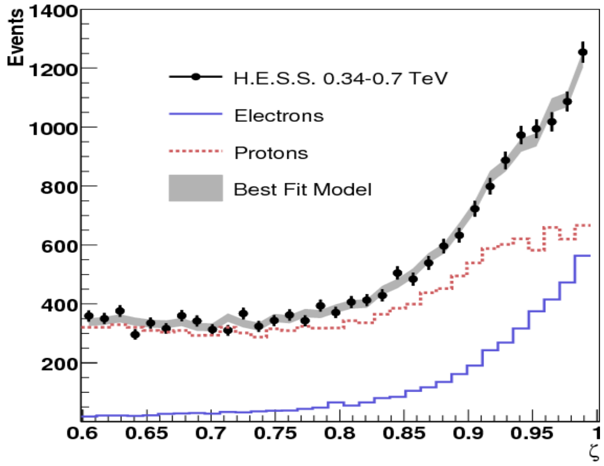
IACT: Energy resolution and electron identification

- 地上観測
  - Imaging Atmospheric Cherenkov Telescope
    膨大な観測量
    - HESS, MAGIC, VERITAS
    - ✓ SΩT=~980 m^2sr day (HESS: PRL 101, 261104 (2009))
    - ✓ ΔE/E = 15-20% (VERITAS: PRD 98, 062004 (2018)

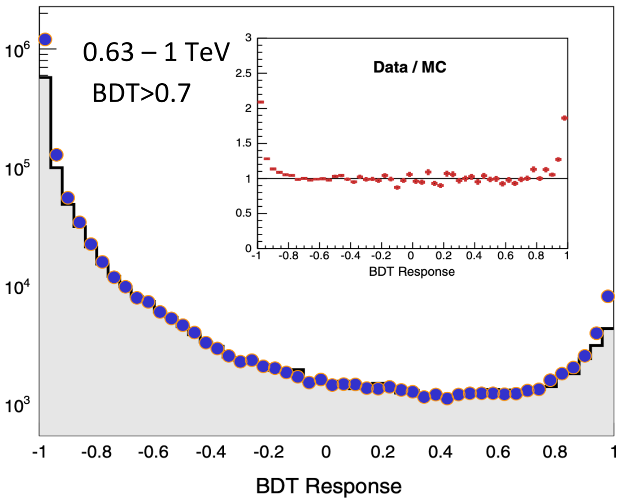
MAGIC: Y.Chai (ICRC2023)



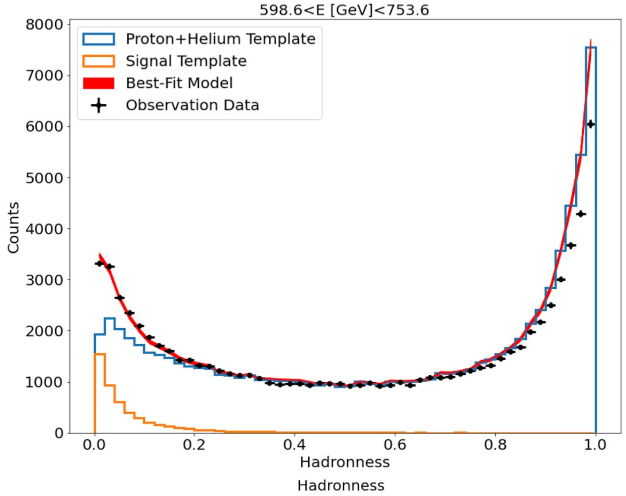
HESS: A&A 508, 561 (2009)



VERITAS: PRD 98, 062004 (2018)



MAGIC: PoS(ICRC2023) 323



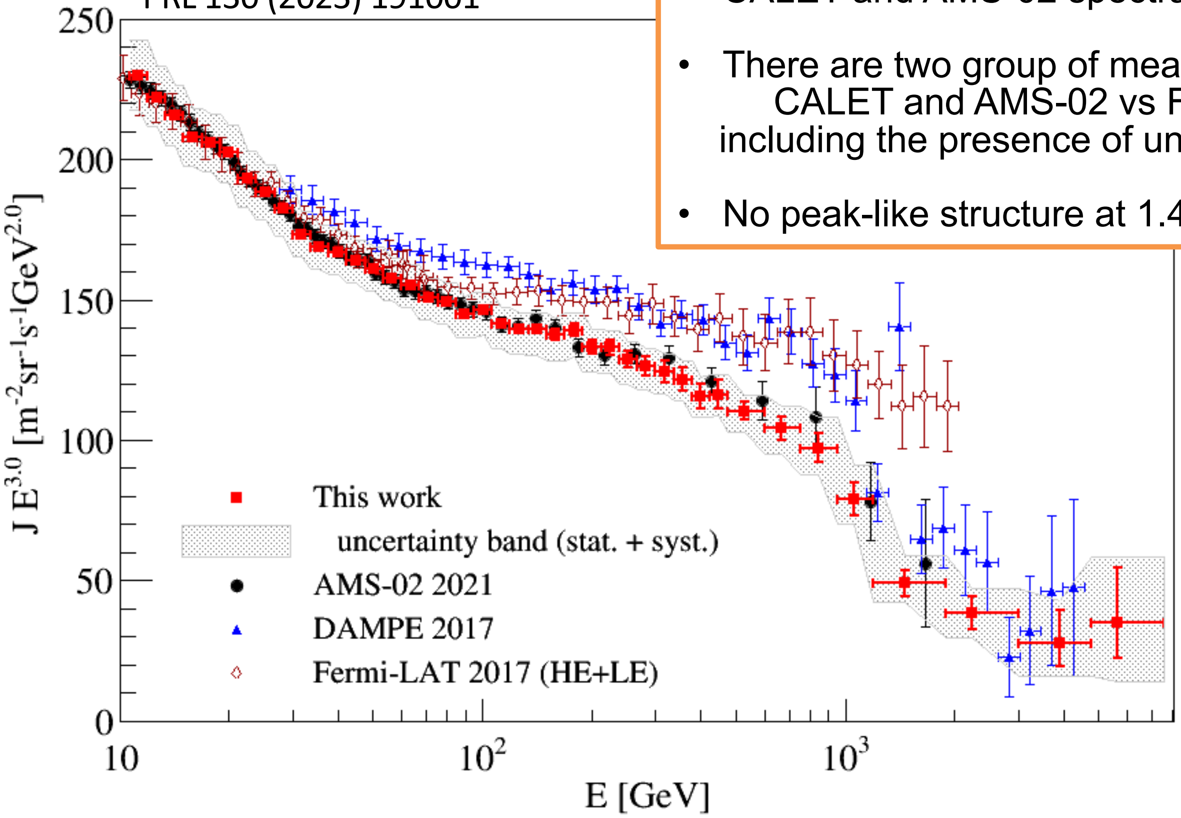
Detectors for cosmic-ray electrons

- 直接観測
  - Magnetic spectrometer
    電子・陽電子を識別可能
    - PAMELA (MDR = ~1.2 TV, SΩ=~0.002m^2sr)
    - AMS-02 (MDR = ~2 TV, SΩ=~0.05 m^2sr)
  - Calorimeter
    TeV以上の領域まで測定可能
    - Fermi-LAT (8.6(12)X_0, SΩ=1~2.5 m^2sr)
    - CALET (30X_0, SΩ=~0.1 m^2sr)
    - DAMPE (32X_0, SΩ=~0.3 m^2sr)
- 地上観測
  - Imaging Atmospheric Cherenkov Telescope
    膨大な観測量
    - HESS, MAGIC, VERITAS

	エネルギー領域 [GeV]	エネルギー分解能	e/p 識別性能
PAMELA	1 – 700	5% (@200GeV)	10^5
AMS-02	1 – 2,000	10%(@100GeV)	10^4 - 10^5
Fermi-LAT	10 – 1,000	5-20% (20-1000GeV)	10^3 - 10^4
CALET	1 – 20,000	2% (>20GeV)	10^5
DAMPE	1 – 20,000	2% (>20GeV)	10^5
IACT	100 – 20,000	15-20%	10^3 - 10^4

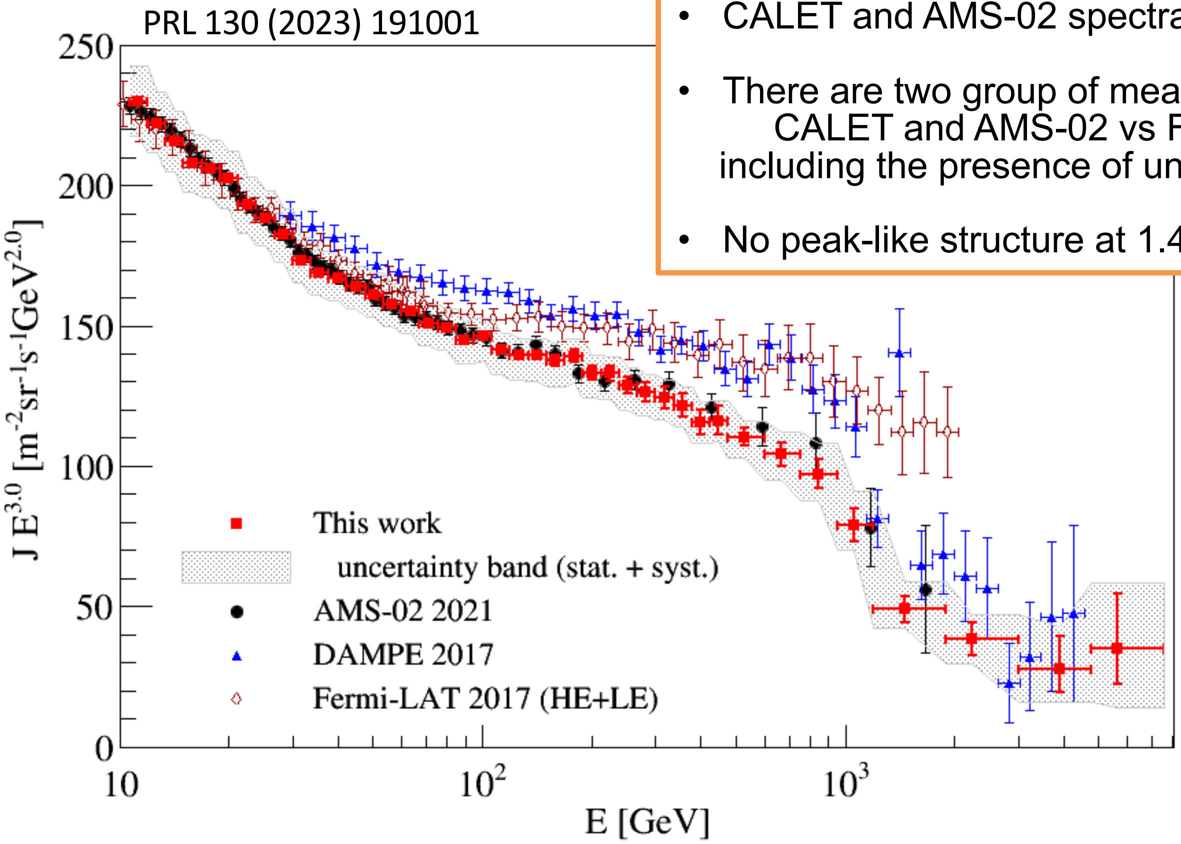
Electron spectrum

PRL 130 (2023) 191001



- CALET and AMS-02 spectra are in good agreement up to 2 TeV.
- There are two group of measurements:
  CALET and AMS-02 vs Fermi-LAT and DAMPE
  including the presence of unknown systematic errors
- No peak-like structure at 1.4 TeV in CALET data

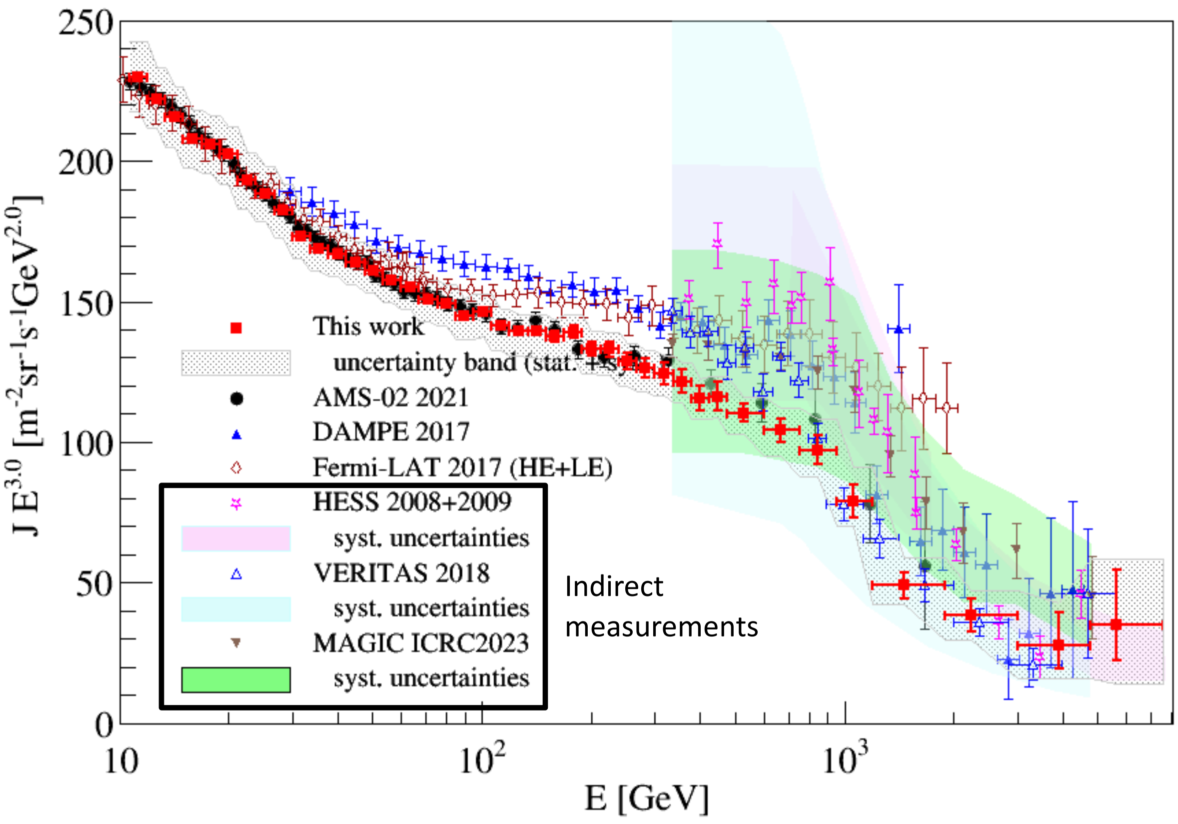
Electron spectrum



- CALET and AMS-02 spectra are in good agreement up to 2 TeV.
- There are two group of measurements:
  CALET and AMS-02 vs Fermi-LAT and DAMPE
  including the presence of unknown systematic errors
- No peak-like structure at 1.4 TeV in CALET data

- CALET observes a flux suppression above 1 TeV with a significance > 6.5σ, which is consistent with DAMPE within errors

Electron spectrum: space and ground observations



- CALET observes a flux suppression above 1 TeV with a significance > 6.5σ, which is consistent with DAMPE within errors
- Indirect measurements indicates spectral break around 1 TeV, although their systematic uncertainties are very large.

Fitting to all-electron spectrum

□ Fits of the CALET all-electron spectrum in 30 GeV – 4.8 TeV

- Broken power law

  $$J(E) = C(E/100\ GeV)^{\gamma}(1+(E/E_b)^{\Delta\gamma/s})^{-s}$$

  γ = - 3.15 ± 0.01, $\Delta\gamma$ = -0.77 ± 0.22
  Eb = 761 ± 115 GeV (χ^2 /NDF=3.6/27)

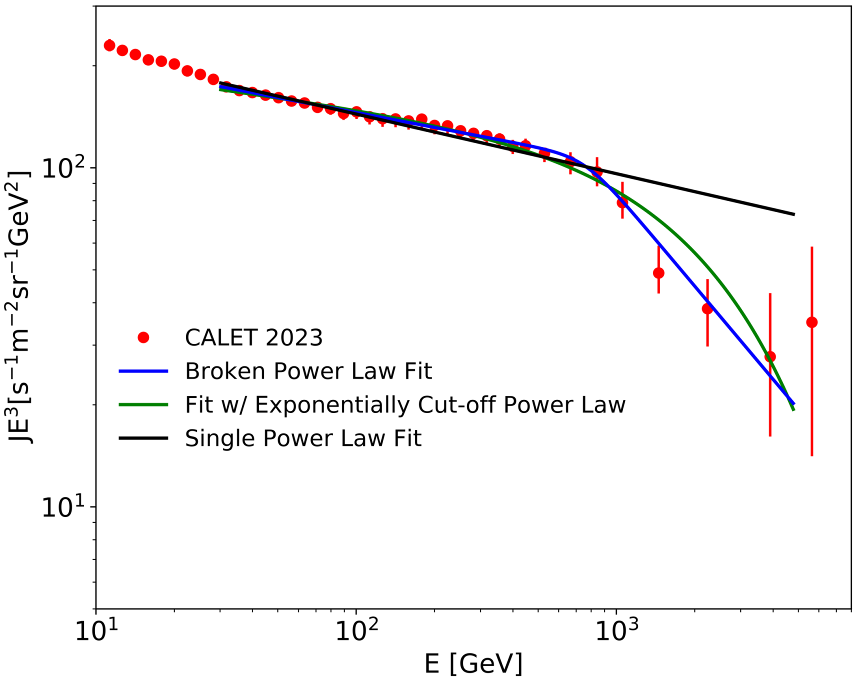
- Exponential cut-off power law [PRL, 2018]

  γ = - 3.10 ± 0.01
  Ec = 2.854 ± 0.305 TeV
  (χ^2 /NDF=12/28)

- Single power law

  γ = -3.18 ± 0.01 (χ^2 /NDF=56/29)

The significance of both fits of softening spectrum is more than 6 σ, which is considerably improved comparing to ~4 σ obtained in PRL2018.

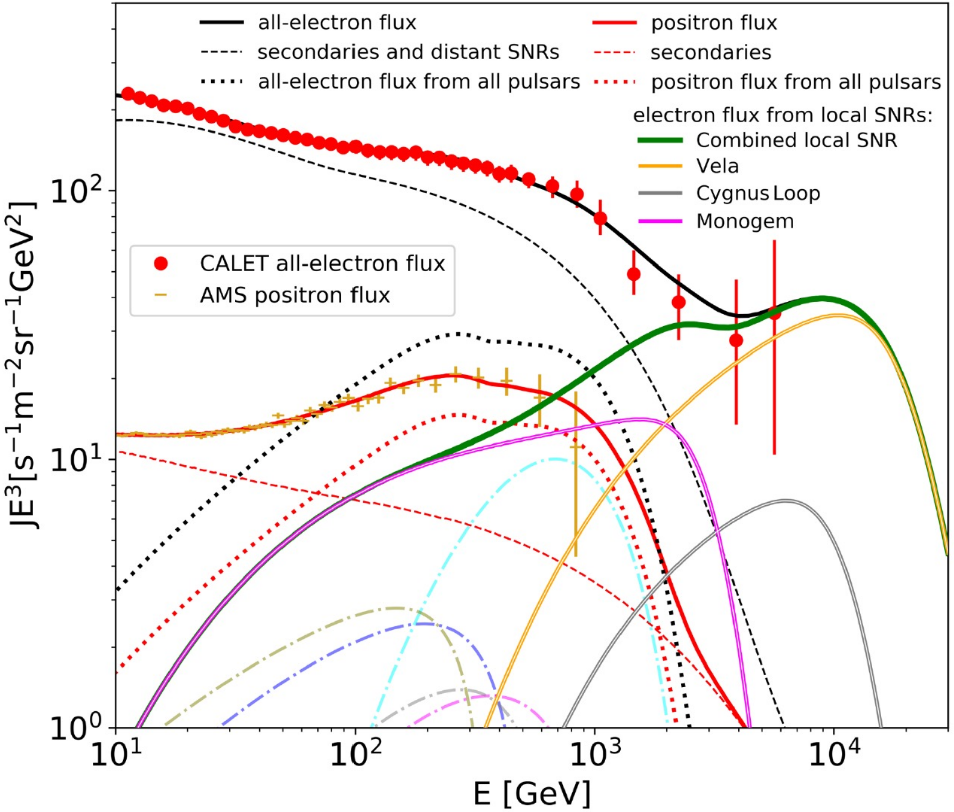


Towards an interpretation of all-electron spectrum

PRL 130 (2023) 191001

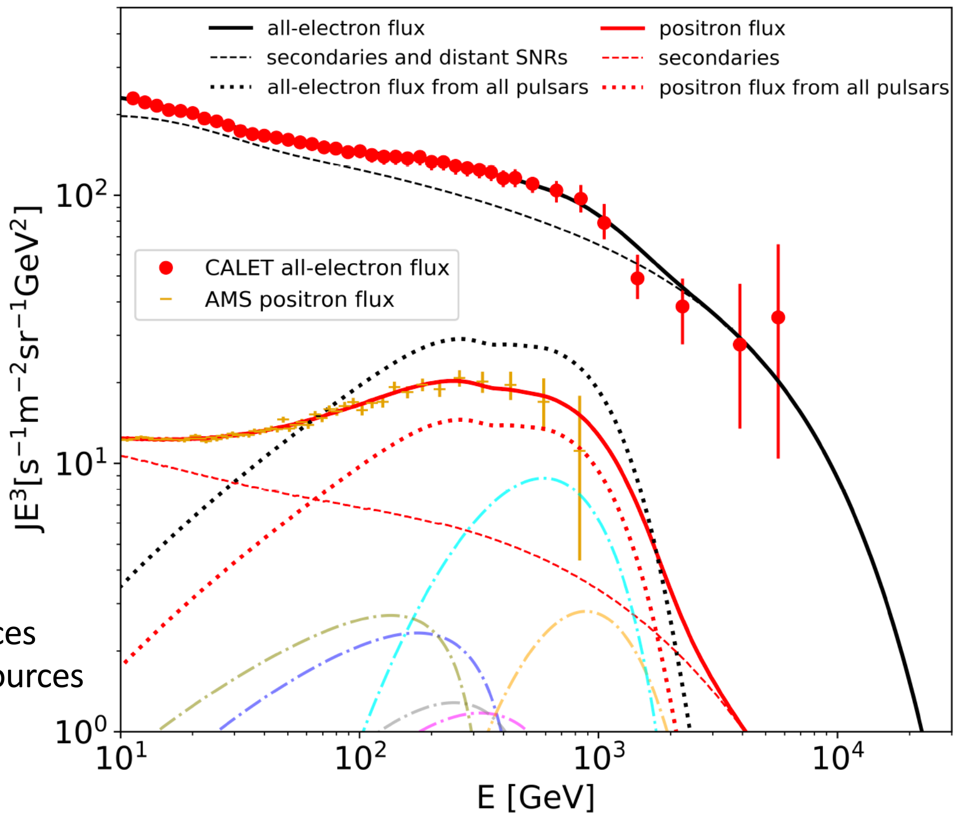
□ Possible spectral fit in whole energy region

- AMS-02 positron flux is fitted with secondaries + pulsars
- CALET electron + positron flux is fitted with secondaries + pulsars + SNRs
- The best fit: 0.8 x 10^{48} erg in E>1GeV for nearby SNR.
- $\chi^2/NDF = 34/80$ with nearby SNRs



Towards an interpretation of all-electron spectrum

PRL 130 (2023) 191001



☐ Possible spectral fit in whole energy region

- AMS-02 positron flux is fitted with secondaries + pulsars
- CALET electron + positron flux is fitted with secondaries + pulsars + SNRs
- The best fit: 0.8 x 10^{48} erg in E>1GeV for nearby SNR.
- $\chi^2/NDF = 34/80$ with nearby SNRs
- $\chi^2/NDF = 32/80$ without nearby SNRs

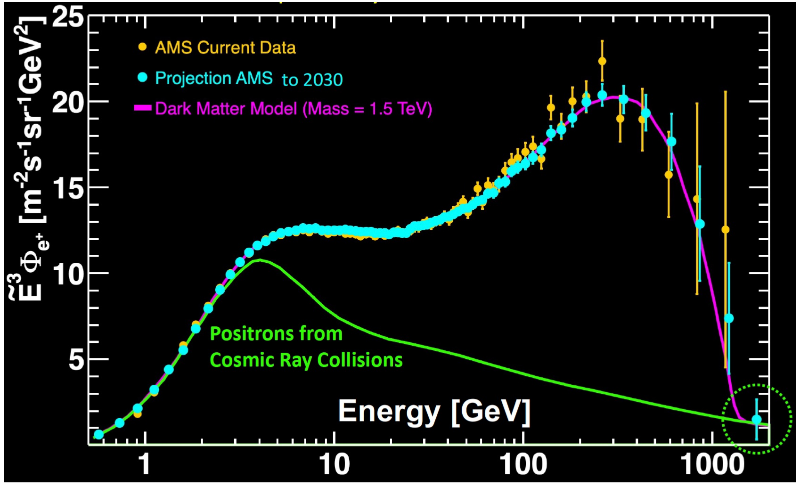
The model fitting result predicts;

- 11.0 (4.2) evts above 4.8 (7.5) TeV with nearby sources
- 4.6 (1.0) evts above 4.8 (7.5) TeV without nearby sources

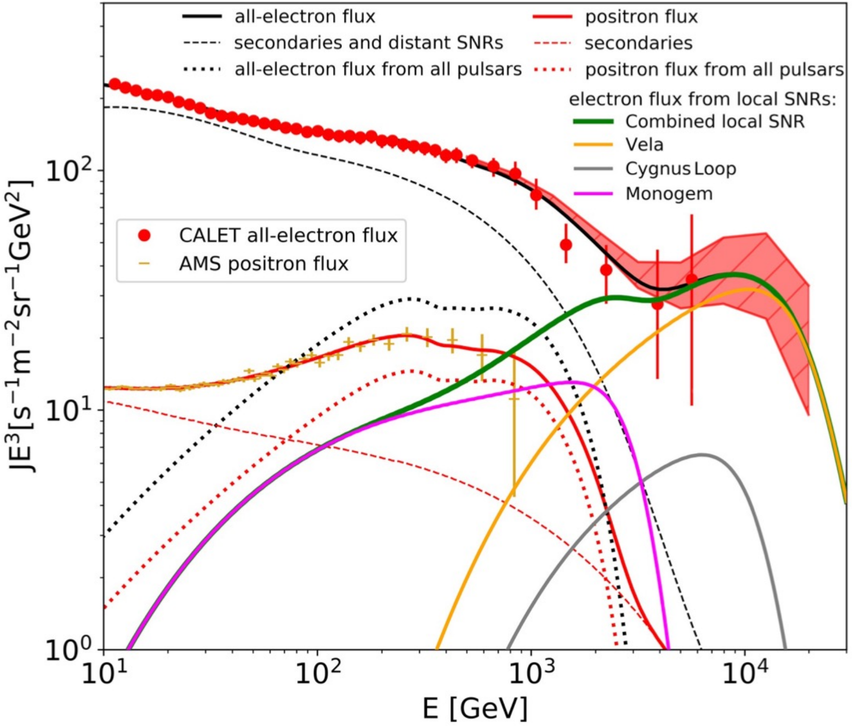
An excess 9 (4) events above 4.8 (7.5) TeV observed by the event-by event analysis

Future prospects

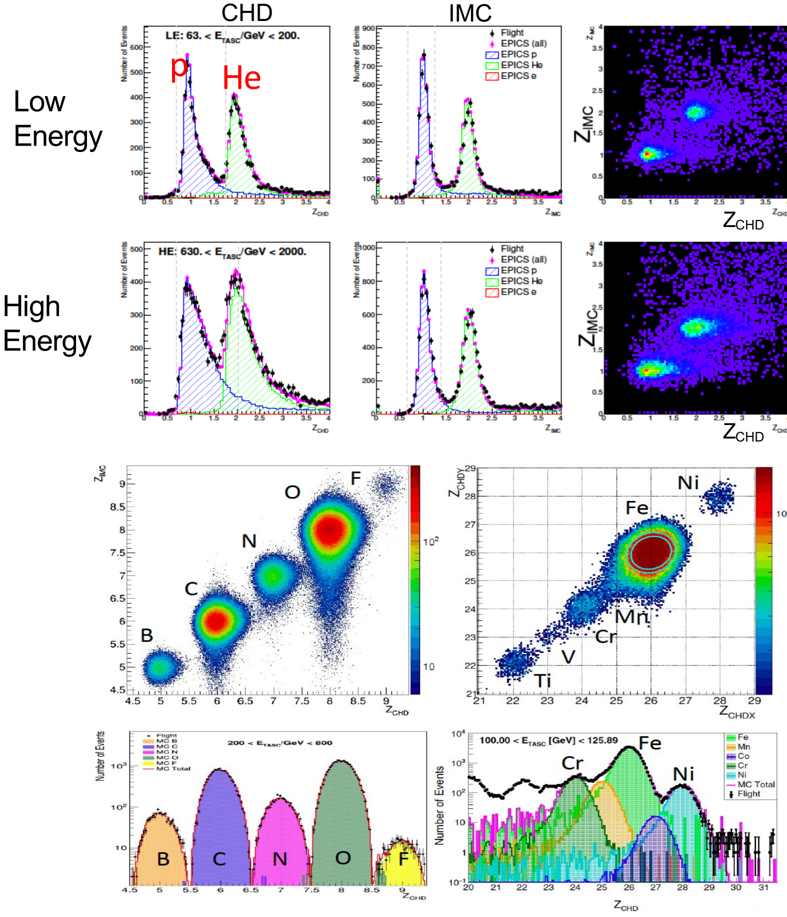
AMS-02: 2030 (ICRC2023)



CALET: 2030

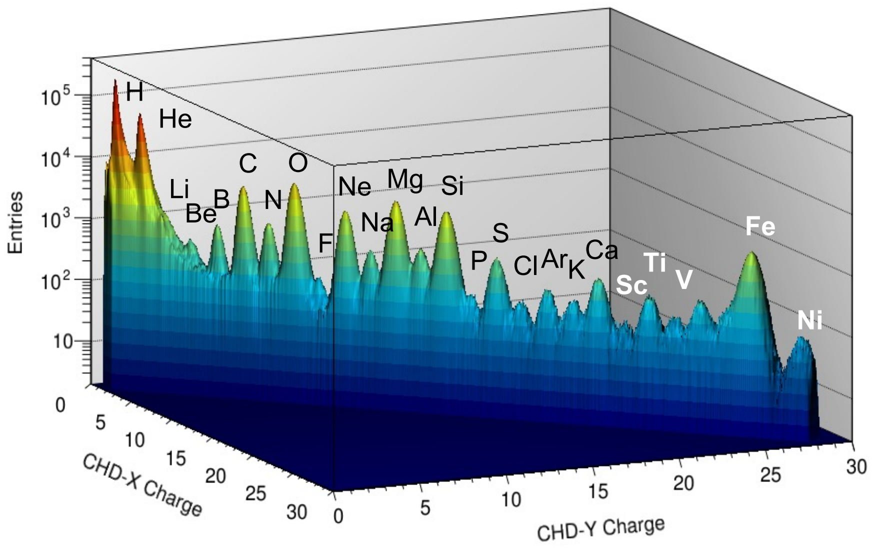


Charge identification with CALET



With excellent charge-ID of individual elements CALET is exploring the Table of Elements in the multi-TeV domain

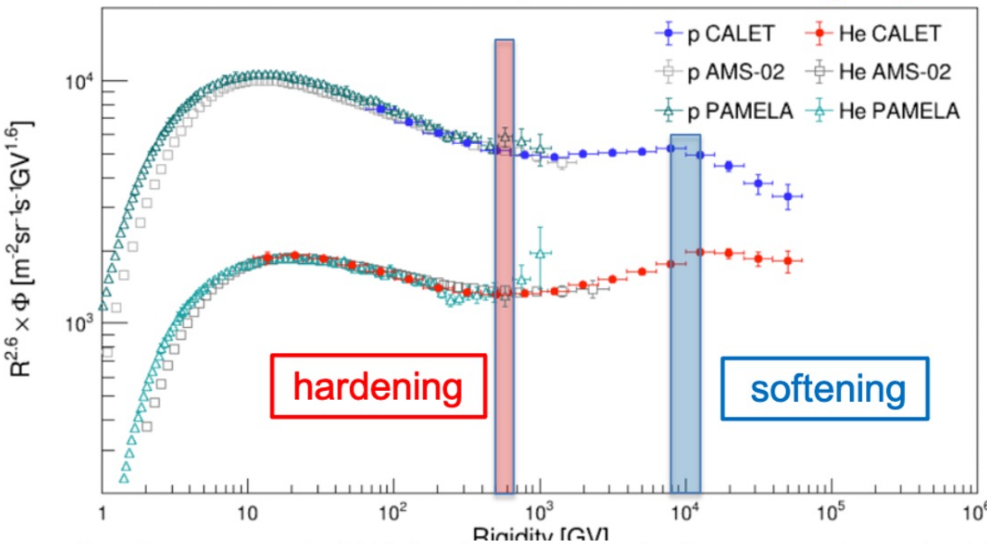
Charge distribution from Proton to Nickel
(periodic table of elements by CALET)



Observations of the spectral structures for P, He, B, C, O spectra

- 陽子・ヘリウム・ホウ素・炭素・酸素について**これまでの最高エネルギー領域での直接観測を達成**
- 従来の宇宙線の概念を変える**エネルギースペクトルの構造（硬化、軟化）の高精度観測に成功**

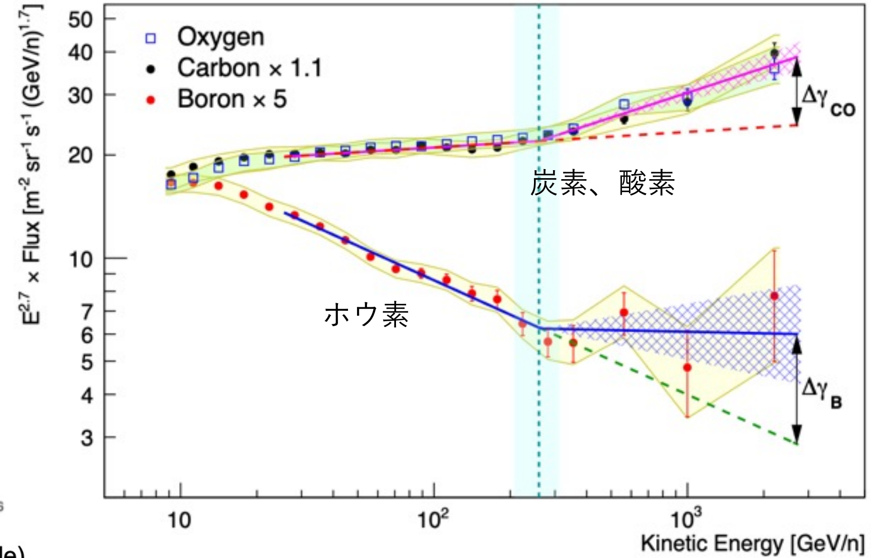
陽子･ヘリウムのエネルギースペクトル



Best fit parameters with DBPL function for proton and helium spectrum (energy/particle)

	γ	E_0 (GeV)	$\Delta\gamma$	S	E_1 (TeV)	$\Delta\gamma_1$	S_1
Proton	-2.843 ±0.005	553^{+44}_{-38}	0.29 ±0.01	2.1 ± 0.4	$9.8^{+3.2}_{-2.1}$	$-0.39^{+0.15}_{-0.18}$	~ 90
Helium	$-2.703^{+0.005}_{-0.006}$	1319^{+113}_{-93}	$0.25^{+0.02}_{-0.01}$	$2.7^{+0.6}_{-0.5}$	$33.2^{+9.8}_{-6.2}$	$-0.22^{+0.07}_{-0.10}$	30

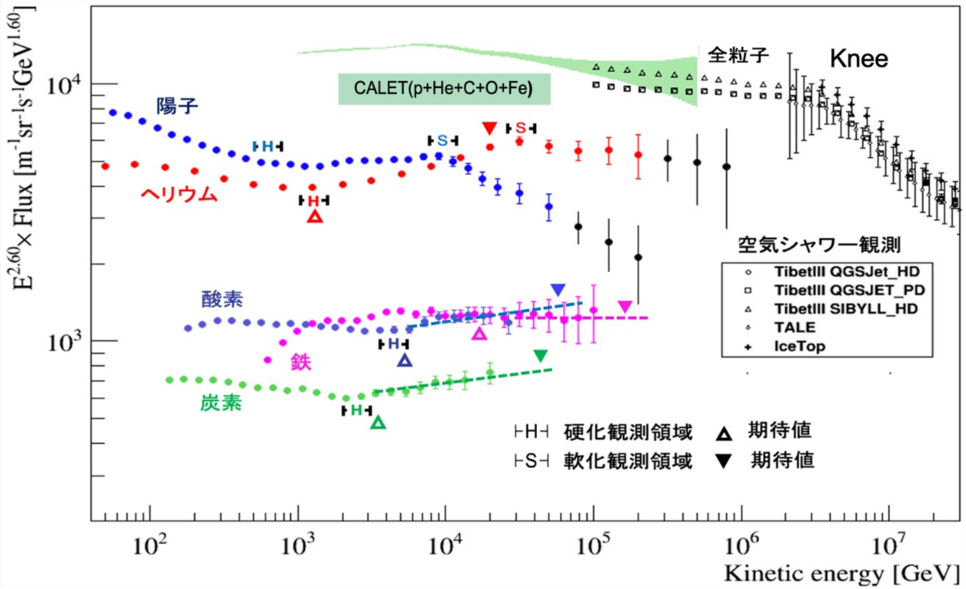
B, C, O のエネルギースペクトル

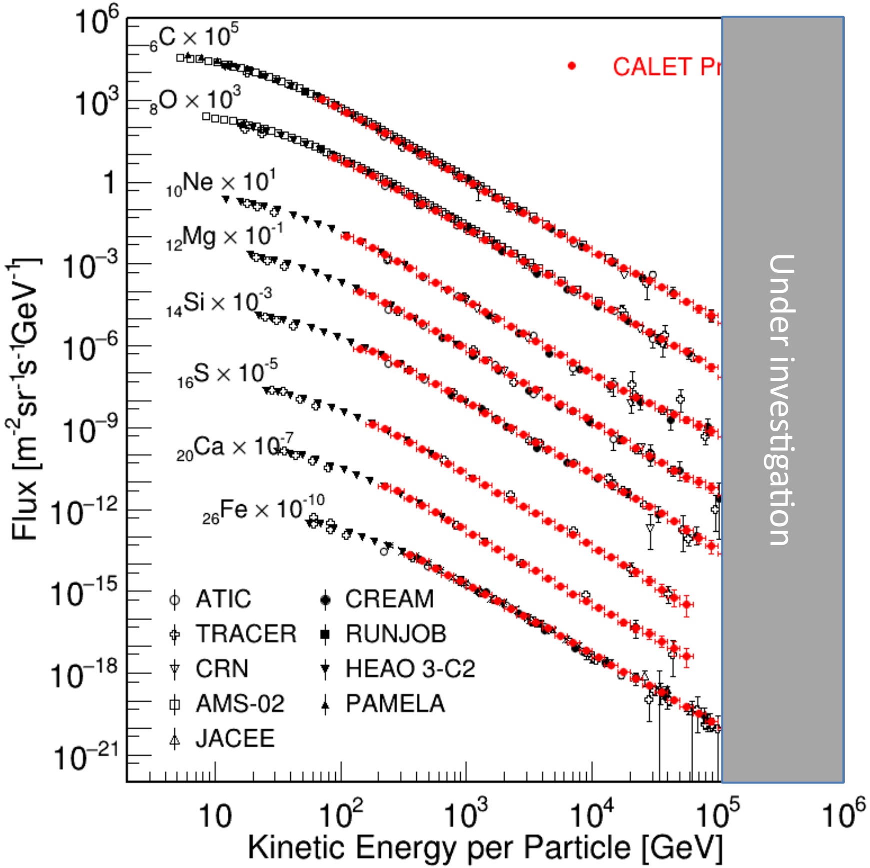


γ_{CO} = -2.66 ±0.02
$\Delta\gamma_{CO}$ = 0.19 ± 0.04
E_0 = (260 ± 50) GeV/

γ_B = -3.03 ±0.03
$\Delta\gamma_B$ = 0.32 ± 0.14
E_0 fixed from C-O

Measurements of nuclei spectra with CALET





H ：陽子・ヘリウム、炭素、酸素、鉄の観測結果と硬化領域
S ：同、軟化領域
△：陽子観測から期待される各原子核の硬化エネルギー（電荷あたり）
▼：同、軟化エネルギー（電荷あたり）
●：陽子・ヘリウムの今後の観測による期待値
緑領域：1 TeV−500 TeVでのこれらの総和のスペクトル
（Knee領域の全粒子スペクトルとの比較のため）

Summary

- 近年、電子観測が様々な測定器で行われ、観測領域は10 TeVに到達しつつある
  - AMS-02, CALET: 2030年まで観測予定
- TeV領域の電子観測は、荷電粒子として初めて近傍加速源を直接同定できる可能性がある
  - CALETの7.5TeVまでのスペクトルは、近傍加速源の存在を示唆
  - CALETとDAMPEの今後の観測に期待
- 陽電子過剰の議論のようなスペクトル構造の仔細な検証のため高いエネルギー分解能が必須
  - AMS-02, CALET, DAMPE: ~2%, Fermi-LAT, 地上観測: ~15%
  - AMS-02とCALETの測定結果の合致は陽電子、全電子の定量的な検証に重要
- 原子核の直接観測は100TeV以上の領域へ観測進展
  - スペクトルの硬化、軟化のエネルギーは鉄までの全ての原子核で観測されるか
  - スペクトルの硬化、軟化はrigidityに依存するのか核子数に依存するのか
  - 二次核/一次核の測定はモデル制限に重要